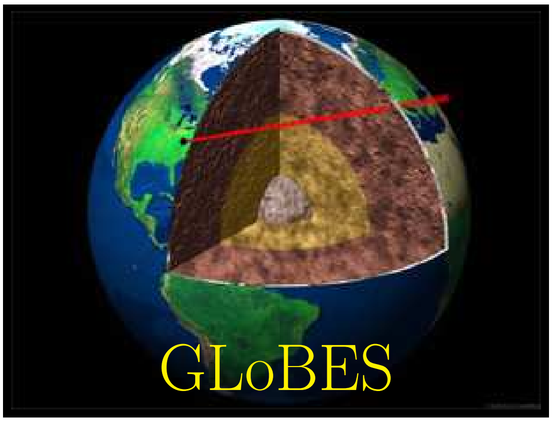
GLoBES

General Long Baseline Experiment Simulator

User's and experiment definition manual

Patrick Huber[a], Manfred Lindner[b], Walter Winter[c]



Version from March 15, 2005 for GLoBES 2.0.11

[a] *Physics Department, University of Wisconsin, 1150 University Av., Madison, WI 53706, USA*
[b] *Institut für Theoretische Physik, Physik–Department, Technische Universität München, James–Franck–Strasse, D–85748 Garching, Germany*
[c] *Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*

What is GLoBES?

GLoBES ("General Long Baseline Experiment Simulator") is a flexible software package to simulate neutrino oscillation long baseline and reactor experiments. On the one hand, it contains a comprehensive abstract experiment definition language (AEDL), which allows to describe most classes of long baseline experiments at an abstract level. On the other hand, it provides a C-library to process the experiment information in order to obtain oscillation probabilities, rate vectors, and $\Delta\chi^2$-values. Currently, GLoBES is available for GNU/Linux. Since the source code is included, the port to other operating systems is in principle possible. The software as well as up-to-date versions of this manual can be found at this URL: `http://www.ph.tum.de/~globes`

GLoBES allows to simulate experiments with stationary neutrino point sources, where each experiment is assumed to have only one neutrino source. Such experiments are neutrino beam experiments and reactor experiments. Geometrical effects of a source distribution, such as in the sun or the atmosphere, can not be described. In addition, sources with a physically significant time dependencies can not be studied, such as supernovæ. It is, however, possible to simulate beams with bunch structure, since the time dependence of the neutrino source is physically only important to suppress backgrounds.

On the experiment definition side, either built-in neutrino fluxes (*e.g.*, neutrino factory) or arbitrary fluxes can be used. Similarly, arbitrary cross sections, energy dependent efficiencies, the energy resolution function, the considered oscillation channels, backgrounds, and many other features can be specified. For the systematics, energy normalization and calibration errors can be simulated. Note that the energy ranges and windows, as well as the bin widths can be (almost) arbitrarily chosen, which means that variable bin widths are allowed. Together with GLoBES comes a number of pre-defined experiments in order to demonstrate the capabilities of GLoBES and to provide prototypes for new experiments.

With the C-library, one can extract the $\Delta\chi^2$ for all defined oscillation channels for an experiment or any combination of experiments. Of course, also low-level information, such as oscillation probabilities or event rates, can be obtained. GLoBES includes the simulation of neutrino oscillations in matter with arbitrary matter density profiles, as well as it allows to simulate the matter density uncertainty. As one of the most advanced features of GLoBES, it provides the technology to project the $\Delta\chi^2$, which is a function of all oscillation parameters, onto any subspace of parameters by local minimization. This approach allows the inclusion of multi-parameter-correlations, where external input (*e.g.*, from solar parameters) can be imposed, too. Applications of the projection mechanism include the projections onto the $\sin^2 2\theta_{13}$-axis and the $\sin^2 2\theta_{13}$-δ_{CP}-plane. In addition, all oscillation parameters can be kept free to precisely localize degenerate solutions.

Terms of usage of GLoBES

Referencing the GLoBES software

GLoBES is developed for academic use. Thus, the GLoBES Team would appreciate being given academic credit for it. Whenever you use GLoBES to produce a publication or a talk indicate that you have used GLoBES and please cite the reference [1]

> P. Huber, M. Lindner and W. Winter
> Simulation of long baseline neutrino oscillation experiments with GLoBES
> arXiv:hep-ph/0407333.

but *not* this manual. This manual itself is not a scientific publication and will not be submitted to a scientific journal. It will evolve during time since it is intended for regular revision. Besides that, many of the data which are used by GLoBES and distributed together with it should be properly referenced. For details see below.

Apart from that, GLoBES is free software and open source, *i.e.*, it is licensed under the GNU Public License.

Referencing the data in GLoBES

GLoBES wouldn't be useful without having high quality input data. Much of these input data have been published elsewhere and the authors of those publications would appreciate to be cited whenever their work is used. It is solely the user's responsibility to make sure that he understands where the input material for GLoBES comes from and if additional work has to be cited in addition to the GLoBES paper [1]. To assist with this task, we provide the necessary information for the data coming along together with GLoBES.

When using the built-in Earth matter density profile, the original source is Ref. [2].

All files ending with `.dat` or `.glb` in the `data` subdirectory of the GLoBES tar-ball have on top a comment field which clearly indicates which works should be cited when using a certain file. Make sure that dependencies are correctly tracked, *i.e.*, in some cases files included by other files need to be checked, too (for example, cross section or flux files). One can use the `-v3` option to `globes` to see which files are included.

It is recommended that you use the same style for your own input files, since, in case they are distributed, everybody will know how to correctly reference your work.

Contents

How to use this manual

As it is illustrated in Fig. 1, GLoBES consists of several modules. AEDL("Abstract Exper-

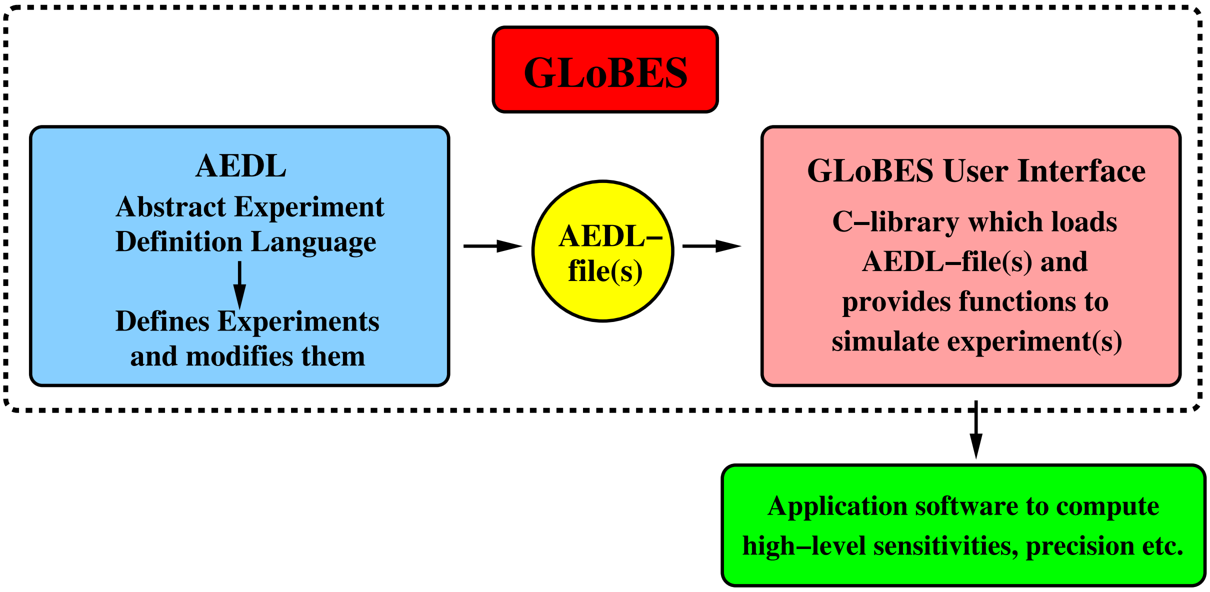


Figure 1: Different modules in GLoBES.

iment Definition Language") is a language to define experiments in form of ordinary text files. One or more of the resulting AEDL files can then be processed together with supporting flux or cross section files by the user interface. The user interface is a C-library, which loads one or more AEDL file(s) containing the experiment definition(s). The user interface is linked against the application software, and provides the user interface functions for the intended experiment simulation.

The application software is, except from some example files, not part of GLoBES, since the evaluation of the experiment performance is often a matter of taste and definition. In addition, the algorithms depend, especially for high-precision instruments, very much on the oscillation parameters. In general, it is quite simple to simulate superbeams and reactor experiments. However, because of the more complicated topology, the simulation of neutrino factories is much more difficult. In order to demonstrate some of these difficulties, we present in this manual only examples with neutrino factories. These examples can be found in Part I within the boxed pages. As complete files, they are also available in the GLoBES software package.

The GLoBES software may have two target groups: Physicists, who are mainly interested in optimizing the potential of specific experimental setups, and others, who are mainly interested in the physics potential of different experiment types from a theoretical point of view. For the first group, AEDL could be the most interesting aspect of GLoBES, where the user interface is only a tool to obtain specific parameter sensitivities. In this case, GLoBES could, serve as a unified tool for the comparison and optimization of different experiment setups on equal footing, where it is the primary objective to simulate the experiments as accurate as possible. In addition, changes in experimental parameters, such as efficiencies or the energy resolutions, can quickly be tested. For the second user group, the pre-defined experiment definition files might already be sufficient to test new conceptual approaches, and the user interface is the most interesting aspect for sophisticated applications including correlations, degeneracies, and multi-experiment setups. In either case, the GLoBES software could serve as a platform for the exchange of experiment definitions, and for an efficient splitting of work between experimentalists and theorists.

The user interface functions are described in Part I of this manual, which is the "user's manual". In there, first of all a short GLoBES tour is given in Chapter 1 in order to have an overview over GLoBES. After that, the user interface is successively introduced from very basic to more sophisticated functions. Eventually, it is demonstrated how one can change many experiment parameters at running time (such as baseline or target mass), and how one can obtain low-level information. We recommend that everybody interested in GLoBES should become familiar at least with the concepts in Chapter 1 and some of the examples on the boxed pages. The examples can be directly compiled from the respective directory in the GLoBES software package.

In Part II of the manual, AEDL is described. After an introductory chapter, all functions are defined in greater detail. This part might be more interesting for the experimental users who want to modify or create AEDL files. A useful tool in this context is the software program `globes`, which returns event rates and other information for individual AEDL files without further programming. For example, flux normalizations can with this tool be easily adjusted to reproduce the event rates of a specific experiment. It is described in the last chapter of Part II.

Note: All examples for application software in C do require a C++ compiler to be properly compiled. For pedagogical reasons, variable declarations are done at that place where the variable is needed for the first time, which is at variance with C syntax but not with C++ syntax. That is the only way in which the examples deviate form ISO C. Moreover the actual numerical values of the results of the examples may be different from the ones in this manual.

Part I

User's manual

Chapter 1

A GLoBES tour

In this first chapter, we show a GLoBES tour illustrating the main features of GLoBES. The complete example can be found as `example-tour.c` in the `example` subdirectory of your GLoBES distribution. The output is written to `stream`, which can be either `stdout`, or a file. Details about how to use GLoBES with C can found in Chapter 2 and the following chapters. You can also find a summary of the most important GLoBES χ^2-functions in Table 1.1. Note that this chapter can be skipped without loss of relevant information.

Initialize the GLoBES library:

```
glbInit(argv[0]);
```

Define my standard oscillation parameters:

```
double theta12 = asin(sqrt(0.8))/2;
double theta13 = asin(sqrt(0.001))/2;
double theta23 = M_PI/4;
double deltacp = M_PI/2;
double sdm = 7e-5;
double ldm = 2e-3;
```

Load one neutrino factory experiment:

```
glbInitExperiment("NuFact.glb",&glb_experiment_list[0],
                   &glb_num_of_exps);
```

Initialize a number of parameter vectors we are going to use later:

```
glb_params true_values = glbAllocParams();
glb_params fit_values = glbAllocParams();
glb_params starting_values = glbAllocParams();
glb_params input_errors = glbAllocParams();
glb_params minimum = glbAllocParams();
```

Function	Purpose	Parameters → Result
Systematics only:		
`glbChiSys`	χ^2 with systematics only	(`glb_params in, int exp, int rule`) → `double` χ^2
Projections onto axes:		
`glbChiTheta`	Projection onto θ_{13}-axis	(`glb_params in, glb_params out, int exp`) → `double` χ^2
`glbChiDelta`	Projection onto δ_{CP}-axis	(`glb_params in, glb_params out, int exp`) → `double` χ^2
`glbChiTheta23`	Projection onto θ_{23}-axis	(`glb_params in, glb_params out, int exp`) → `double` χ^2
`glbChiDm`	Projection onto Δm^2_{31}-axis	(`glb_params in, glb_params out, int exp`) → `double` χ^2
`glbChiDms`	Projection onto Δm^2_{21}-axis	(`glb_params in, glb_params out, int exp`) → `double` χ^2
Projection onto plane:		
`glbChiThetaDelta`	Projection onto θ_{13}-δ_{CP}-plane	(`glb_params in, glb_params out, int exp`) → `double` χ^2
Projection onto any hyper-plane:		
`glbChiNP`	Projection onto any n-dimensional hyper-plane	(`glb_params in, glb_params out, int exp`) → `double` χ^2 Needs `glbSetProjection` before!
Localization of degeneracies:		
`glbChiAll`	(Local) Minimization over all parameters	(`glb_params in, glb_params out, int exp`) → `double` χ^2

Table 1.1: The GLoBES standard function to obtain a χ^2-value with systematics only or systematics and correlations. The parameters `rule` and `exp` can either be `GLB_ALL` for all initialized experiment or the experiment number (0 to `glb_num_of_exps`-1) for a specific experiment. The format of `glb_params` is discussed in detail in Chapter 2. Note that all functions but `glbChiSys` are using minimizers which have to be initialized with `glbSetInputErrors` and `glbSetStartingValues` first.

Assign values to our standard oscillation parameters:

```
glbDefineParams(true_values,theta12,theta13,theta23,deltacp,sdm,ldm);
```

Compute the simulated data with our standard parameters:

```
glbSetOscillationParameters(true_values);
glbSetRates();
```

Return the oscillation probabilities in vacuum and matter for the electron neutrino as initial flavor:

```
int i;
fprintf(stream,"\nOscillation probabilities in vacuum:  ");
for(i=1;i<4;i++) fprintf(stream,"1->%i:  %g",i,
                      glbVacuumProbability(1,i,+1,50,3000));
fprintf(stream,"\nOscillation probabilities in matter:  ");
for(i=1;i<4;i++) fprintf(stream,"1->%i:  %g ",i,
                      glbProfileProbability(0,1,i,+1,50));
```

→ Output:

Oscillation probabilities in vacuum: 1->1: 0.999953 1->2: 2.69441e-05 1->3: 1.98019e-05
Oscillation probabilities in matter: 1->1: 0.999965 1->2: 2.02573e-05 1->3: 1.49021e-05

Now assign fit values, where we will test the fit value $\sin^2 2\theta_{13} = 0.0015$:

```
glbCopyParams(true_values,fit_values);
glbSetOscParams(fit_values,asin(sqrt(0.0015))/2,GLB_THETA_13);
```

Compute χ^2 with systematics only for all experiments and rules:

```
chi2 = glbChiSys(fit_values,GLB_ALL,GLB_ALL);
fprintf(stream,"chi2 with systematics only:  %g\n\n",chi2);
```

→ Output:

chi2 with systematics only: 22.3984

This we would obtain from the first appearance channel only:

```
chi2 = glbChiSys(fit_values,0,0);
fprintf(stream,"This we would have from the CP-even appearance
channel only:  %g\n\n",chi2);
```

→ Output:

This we would have from the CP-even appearance channel only: 21.6223

The sum over all rules again gives:

```
chi2 = glbChiSys(fit_values,GLB_ALL,0)+ glbChiSys(fit_values,GLB_ALL,1)+
       glbChiSys(fit_values,GLB_ALL,2)+ glbChiSys(fit_values,GLB_ALL,3);
fprintf(stream,"The sum over all rules gives again: %g\n\n",chi2);
```

→ Output:

The sum over all rules gives again: 22.3984

Let's prepare the minimizers for taking into account correlations. Set errors for external parameters, too: 10% for each of the solar parameters, and 5% for the matter density.

```
glbDefineParams(input_errors,theta12*0.1,0,0,0,sdm*0.1,0);
glbSetDensityParams(input_errors,0.05,GLB_ALL);
glbSetStartingValues(true_values);
glbSetInputErrors(input_errors);
```

Then we can calculate χ^2 including the full multi-parameter correlation, and show where GLoBES actually found the minimum (note that this takes somewhat longer than systematics only). This corresponds to a projection onto the $\sin^2 2\theta_{13}$-axis:

```
chi2 = glbChiTheta(fit_values,minimum,GLB_ALL);
fprintf(stream,"chi2 with correlations: %g \n",chi2);
fprintf(stream,"Position of minimum: theta12, theta13, theta23,
   delta, sdm, ldm, rho\n");
glbPrintParams(stream,minimum);
fprintf(stream,"Note that s22theta13 is unchanged/kept fixed:
   %g! \n\n", pow(sin(2*glbGetOscParams(minimum,GLB_THETA_13)),2));
```

→ Output:

chi2 with correlations: 2.1038
Position of minimum: theta12,theta13,theta23,delta,sdm,ldm,rho
0.542002 0.0193698 0.747915 1.77688 6.66156e-05 0.00200817
1.00434
Iterations: 1693
Note that s22theta13 is unchanged/kept fixed: 0.0015!

Instead of including the full correlation, we can take the correlation with every parameter except from δ_{CP}, *i.e.*, we keep (in addition to θ_{13}) δ_{CP} fixed. This corresponds to projection onto the $\sin^2 2\theta_{13}$-δ_{CP}-plane:

```
chi2 = glbChiThetaDelta(fit_values,minimum,GLB_ALL);
fprintf(stream,"chi2 with correlations other than with deltacp:
%g \n\n",chi2);
```

→ Output:

chi2 with correlations other than with deltacp: 4.32831

Similarly, we can only take into account the correlation with δ_{CP}. For this, we need to define our own (user-defined) projection, where only δ_{CP} is a free parameter:

```
glb_projection myprojection = glbAllocProjection();
glbDefineProjection(myprojection,GLB_FIXED, GLB_FIXED, GLB_FIXED,
   GLB_FREE, GLB_FIXED, GLB_FIXED);
glbSetProjection(myprojection);
chi2 = glbChiNP(fit_values,minimum,GLB_ALL);
fprintf(stream,"chi2 with correlation only with deltacp:
   %g \n\n",chi2);
glbFreeProjection(myprojection);
```

→ Output:

chi2 with correlation only with deltacp: 2.80651

We can also switch of the systematics and compute the statistics χ^2 only:

```
glbSwitchSystematics(GLB_ALL,GLB_ALL,GLB_OFF);
chi2 = glbChiSys(fit_values,GLB_ALL,GLB_ALL);
glbSwitchSystematics(GLB_ALL,GLB_ALL,GLB_ON);
fprintf(stream,"chi2 with statistics only:
   %g\n\n",chi2);
```

→ Output:

chi2 with statistics only: 39.143

Let us now locate the exact position[1] of the sgn-degeneracy:

```
glbDefineParams(input_errors,theta12*0.1,0,0,0,sdm*0.1,ldm/3);
glbDefineParams(starting_values,theta12,theta13,theta23,
   deltacp,sdm,-ldm);
glbSetDensityParams(input_errors,0.05,GLB_ALL);
glbSetStartingValues(starting_values);
glbSetInputErrors(input_errors);
chi2=glbChiAll(starting_values,minimum,GLB_ALL);
fprintf(stream,"chi2 at minimum:  %g \n",chi2);
fprintf(stream,"Position of minimum:
   theta12,theta13,theta23,delta,sdm,ldm,rho\n");
glbPrintParams(stream,minimum);
```

[1]For a exact definition of inverted hierarchy, see page 19.

→ Output:

```
chi2 at minimum: 6.20025
Position of minimum: theta12,theta13,theta23,delta,sdm,ldm,rho
0.591812 0.0264717 0.72763 1.08709 8.0004e-05 -0.00206094
0.970685
Iterations: 1946
```

After testing these functions with only one experiment, let us now go to a two-experiment setup with two different neutrino factory baselines. Since the GLoBES parameter vectors depend on the number of experiments, we have to free them first:

```
glbFreeParams(true_values);
glbFreeParams(fit_values);
glbFreeParams(starting_values);
glbFreeParams(input_errors);
glbFreeParams(minimum);
```

Then we clear the experiment list and load the new experiments:

```
fprintf(stream,"\nNOW: TWO-EXPERIMENT SETUP
   NuFact at 3000km+NuFact at 7500km\n\n");

glbClearExperimentList();

glbInitExperiment("NuFact.glb",&glb_experiment_list[0],
   &glb_num_of_exps);
glbInitExperiment("NuFact.glb",&glb_experiment_list[0],
   &glb_num_of_exps);
```

→ Output:

```
NOW: TWO-EXPERIMENT SETUP NuFact at 3000km+NuFact at 7500km
```

Then we need to change the baseline of the second experiment, where we set the density to the average density of this baseline:

```
double* lengths;
double* densities;
glbAverageDensityProfile(7500,&lengths,&densities);
fprintf(stream,"Magic baseline length:  %g,
   Density:  %g\n\n",lengths[0],densities[0]);
glbSetProfileDataInExperiment(1,1,lengths,densities);
free(lengths);
free(densities);
```

→ Output:

```
Magic baseline length: 7500, Density: 4.25286
```

Now we can re-initialize our parameter vectors again:

```
true_values = glbAllocParams();
fit_values = glbAllocParams();
starting_values = glbAllocParams();
input_errors = glbAllocParams();
minimum = glbAllocParams();
glb_params minimum2 = glbAllocParams();
```

In addition, we repeat the procedure for the simulated rates and the fit parameter vector:

```
glbDefineParams(true_values,theta12,theta13,theta23,deltacp,sdm,ldm);
glbSetOscillationParameters(true_values);
glbSetRates();

glbCopyParams(true_values,fit_values);
glbSetOscParams(fit_values,asin(sqrt(0.0015))/2,GLB_THETA_13);
```

Here comes the χ^2 with systematics only for all experiments and rules:

```
chi2 = glbChiSys(fit_values,GLB_ALL,GLB_ALL);
fprintf(stream,"chi2 with systematics for all exps:
   %g\n",chi2);
```

→ Output:

```
chi2 with systematics for all exps: 31.0797
```

Compute χ^2 for each experiment and compute the sum:

```
chi2 = glbChiSys(fit_values,0,GLB_ALL);
fprintf(stream,"chi2 with systematics for 3000km:  %g\n",chi2);
chi2b = glbChiSys(fit_values,1,GLB_ALL);
fprintf(stream,"chi2 with systematics for 7500km:  %g\n",chi2b);
fprintf(stream,"The two add again to:
   %g\n\n",chi2+chi2b);
```

→ Output:

```
chi2 with systematics for 3000km: 22.3984
chi2 with systematics for 7500km: 8.68131
The two add again to: 31.0797
```

Similarly, compute the χ^2 with correlations for each experiment and their combination. Compare it to the χ^2 for all experiments: the sum of the individual results is not equal to the χ^2 of the combination anymore. Note that there are now two densities in the output vectors.

```
glbDefineParams(input_errors,theta12*0.1,0,0,0,sdm*0.1,0);
glbSetDensityParams(input_errors,0.05,GLB_ALL);
glbSetStartingValues(true_values);
glbSetInputErrors(input_errors);
chi2 = glbChiTheta(fit_values,minimum,0);
fprintf(stream,"chi2 with correlations for 3000km:  %g \n",chi2);
glbPrintParams(stream,minimum);
chi2b = glbChiTheta(fit_values,minimum,1);
fprintf(stream,"\nchi2 with correlations for 7500km:
   %g \n",chi2b);
glbPrintParams(stream,minimum);
chi2sum = glbChiTheta(fit_values,minimum,GLB_ALL);
fprintf(stream,"\nchi2 with correlations for combination:
   %g \n",chi2sum);
glbPrintParams(stream,minimum);
fprintf(stream,"\nThe sum of the two chi2s is %g,
   whereas the total chi2 is %g !\n\n",chi2+chi2b,chi2sum);
```

→ Output:

```
chi2 with correlations for 3000km: 2.1038
0.542002 0.0193698 0.747915 1.77688 6.66156e-05 0.00200817
1.00434 1
Iterations: 1693

chi2 with correlations for 7500km: 1.08421
0.557356 0.0193698 0.771359 4.77751 7.00762e-05 0.00200105
1 1.01517
Iterations: 661

chi2 with correlations for combination: 3.90835
0.544432 0.0193698 0.770175 1.78502 6.61621e-05 0.00200303
1.00431 1.03679
Iterations: 1636

The sum of the two chi2s is 3.18801, whereas the total chi2 is 3.90835!
```

Now find the $\mathrm{sgn}(\Delta m^2_{31})$-degeneracies for both individual experiments and test if they are still there in the combination of the experiments.

```
glbDefineParams(input_errors,theta12*0.1,theta13,theta23,
   deltacp,sdm*0.1,ldm/3);
glbDefineParams(starting_values,theta12,theta13,theta23,
   deltacp,sdm,-ldm);
glbSetDensityParams(input_errors,0.05,GLB_ALL);
glbSetStartingValues(starting_values);
glbSetInputErrors(input_errors);

chi2=glbChiAll(starting_values,minimum,0);
fprintf(stream,"chi2 at minimum, L=3000km:  %g \n",chi2);
glbPrintParams(stream,minimum);

chi2b=glbChiAll(starting_values,minimum2,1);
fprintf(stream,"\nchi2 at minimum, L=7500km:  %g\n",chi2b);
glbPrintParams(stream,minimum2);

chi2=glbChiAll(minimum,minimum,GLB_ALL);
fprintf(stream,"\nchi2 for combination at minimum of Exp.  1:
   %g \n",chi2);
glbPrintParams(stream,minimum);

chi2b=glbChiAll(minimum2,minimum2,GLB_ALL);
fprintf(stream,"\nchi2 for combination at minimum of Exp.  2:
   %g \n",chi2b);
glbPrintParams(stream,minimum2);
```

→ Output:

chi2 at minimum, L=3000km: 6.71794
0.591497 0.0257396 0.729058 1.11537 7.98867e-05 -0.00206005
0.970499 1
Iterations: 2104

chi2 at minimum, L=7500km: 47.1013
0.590347 0.0018489 0.768372 0.984827 8.23415e-05 -0.00204588
1 0.780995
Iterations: 1270

chi2 for combination at minimum of Exp. 1: 70.6353
0.607988 0.0165985 0.767682 1.41422 8.44573e-05 -0.00204853
0.96147 1.1831
Iterations: 1549

chi2 for combination at minimum of Exp. 2: 70.6357

```
0.608454 0.0165823 0.767757 1.41481 8.43864e-05 -0.00204853
0.961129 1.18304
Iterations: 1447
```

Finally, we have to free the parameter vectors again:

```
glbFreeParams(true_values);
glbFreeParams(fit_values);
glbFreeParams(starting_values);
glbFreeParams(input_errors);
glbFreeParams(minimum);
glbFreeParams(minimum2);
```

Chapter 2

GLoBES basics

In this first chapter of the user's manual, we assume that the GLoBES software is readily installed on your computer system. For the installation, see Appendix 10.2 and the `INSTALL` file in the software package. We demonstrate how to load pre-defined experiments and introduce the basic concepts of GLoBES. We do not go into details of the programming language, which means that standard parts of the program code common to all of the examples in the following chapters are, in general, omitted. An example of a minimal GLoBES program in C can be found on page 14. Furthermore, the files of the examples in this part can be found in the `example` subdirectory of your GLoBES distribution. After the installation of GLoBES, they can be compiled using the `Makefile` in the `examples` directory. The `Makefile` has been correctly setup by the `configure` script to take into account details of the installation on your system. Thus you've just to type `make` and you're done. [1] This `Makefile` very well serves as a template for your own applications.

We will in this part not go into details of the experiment definition. The pre-defined experiment prototypes in the `data` subdirectory are summarized in Table 2.1. They correspond (except from minor modifications) to the experiments in the respective references in the table. These files are installed to the directory `${prefix}/share/globes` which usually defaults to `/usr/local/share/globes`. It is useful to add this path to the value of `GLB_PATH`.

2.1 Initialization of GLoBES

Before one can use GLoBES, one has to initialize the GLoBES library :

Function 2.1 `void glbInit(char *name)` *initializes the library* `libglobes` *and has to be called in the beginning of each* GLoBES *program. It takes the name* `name` *of the program as a string to initialize the error handling functions. In many cases, it is sufficient to use the first argument from the command line as the program name (such as in example on page 14).*

[1] The data files (AEDL and supporting files) needed by the examples are already in place.

Example: Using GLoBES *with C*

Here comes the C-code skeleton, which is (more or less) common to all of our GLoBES examples:

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>

#include <globes/globes.h>    /* Include GLoBES library */

#include "myio.h"    /* Include "housemade" I/O-routines */

/* If filename given, write to file; if empty, to screen:  */
char MYFILE[]="testX.dat";

int main(int argc, char *argv[])
{

   glbInit(argv[0]);    /* Initialize GLoBES library */

   glbInitExperiment("NuFact.glb",&glb_experiment_list[0],
      &glb_num_of_exps);    /* Initialize experiment NuFact.glb */

   /* Initialize housemade output function */
   InitOutput(MYFILE,"Format:  ...  ...  ...  \n");

   /* Initialize parameter vector(s) */
   glb_params true_values = glbAllocParams();
   /* ...  */

   /* Assign:  theta12,theta13,theta23,deltacp,dm2solar,dm2atm */
   glbDefineParams(true_values,
        asin(sqrt(0.8))/2,asin(sqrt(0.001))/2,M_PI/4,M_PI/2,7e-5,2e-3);

   /* The simulated data are computed */
   glbSetOscillationParameters(true_values);
   glbSetRates();

   /* ...  CODE ...  */

   /* Free parameter vector(s) */
   glbFreeParams(true_values);
   /* ...  */

   exit(0);
}
```

Experiment	Filename	Short description	Ref.
Conventional beams:			
MINOS	`MINOS.glb`	MINOS exp., 5 yr running time	[3]
OPERA	`OPERA.glb`	OPERA exp., 5 yr running time	[3]
ICARUS	`ICARUS.glb`	ICARUS exp., 5 yr running time	[3]
First-generation superbeams:			
T2K	`JHFSKnew.glb`	J-PARC to Super-K, 5 yr ν-running	[4]
	`JHFSKantinew.glb`	J-PARC to Super-K, 5 yr $\bar{\nu}$-running	[4]
	`JHFSKcomb.glb`	Same, but 1.25 yr ν- and 3.75 yr $\bar{\nu}$-running	[4]
NOνA	`NUMI9.glb`	NuMI OA 9 km/712 km, 5 yr ν-running	[4]
	`NUMI9anti.glb`	NuMI OA 9 km/712 km, 5 yr $\bar{\nu}$-running	[4]
	`NUMI9comb.glb`	NuMI OA 9 km/712 km, 1.43 yr ν- and 3.57 yr $\bar{\nu}$-running	[4]
	`NUMI12.glb`	NuMI OA 12 km/712 km, 5 yr ν-running	[4]
	`NUMI12anti.glb`	NuMI OA 12 km/712 km, 5 yr $\bar{\nu}$-running	[4]
	`NUMI12comb.glb`	NuMI OA 12 km/712 km, 1.43 yr ν- and 3.57 yr $\bar{\nu}$-running	[4]
Superbeam upgrade:			
J-PARC-HK	`JHFHKAll.glb`	J-PARC to Hyper-K, 2 yr ν- and 6 yr $\bar{\nu}$-running	[5]
Neutrino factories:			
NuFact-I	`NuFact1.glb`	Initial stage NF, 2×2.5 yr running time (each pol.), $m_{\mathrm{Det}} = 10\,\mathrm{kt}$, $P_{\mathrm{Tg}} \simeq 0.75\,\mathrm{MW}$	[5]
NuFact-II	`NuFact2.glb`	Advanced stage NF, 2×4 yr running time (each pol.), $m_{\mathrm{Det}} = 50\,\mathrm{kt}$, $P_{\mathrm{Tg}} \simeq 4\,\mathrm{MW}$	[5]
Reactor experiments:			
Reactor-I	`Reactor1.glb`	Small reactor exp., $\mathcal{L} = 400\,\mathrm{t\,GW\,yr}$	[6]
Reactor-II	`Reactor2.glb`	Large reactor exp., $\mathcal{L} = 8\,000\,\mathrm{t\,GW\,yr}$	[6]
β-Beams:	In preparation		

Table 2.1: Pre-defined experiment prototypes, their filenames (to be used in `glbInitExperiment`), their short descriptions, and the references in which they are originally used and discussed (except from minor modifications, such as a different implementation of the energy threshold function). Note that some of these experiments are outdated in terms of integrated luminosities, baseline, fluxes, efficiencies, or other factors. In any case these file are installed along with GLoBES.

In principle, the GLoBES user interface can currently handle up to 32 of different long-baseline experiments simultaneously, where the number of existing experiment definition files can, of course, be unlimited. This means that their $\Delta\chi^2$-values are added *after* the minimization over the systematics parameters, and *before* any minimization over the oscillation parameters. Note that each experiment assumes a specific matter density profile, which means that it makes sense to simulate different operation modes within one experiment definition, and physically different baselines in different definitions. For details of the rate computation and simulation techniques, we refer at this place to Part II. Though the simplest case of simulating one experiment may be most often used, using more than one experiments are useful in many cases. For example, combinations of experiments can be tested for complementarity and competitiveness by equal means within one program. In general, many GLoBES functions take the experiment number as a parameter, which runs from 0 to `glb_num_of_exps`-1 in the order of their initialization in the program.[2] In addition, using the parameter value `GLB_ALL` as experiment number initiates a combined analysis of all loaded experiments.

In general `GLB_ALL` can be used in many cases where there is an argument selecting 'i out of N', *e.g.* the 1st experiment out of 5, or the 5th rule of 20. In those cases using `GLB_ALL` is equivalent to calling the corresponding function for *all* i in N and 'add' the effect of each invocation, like in

```
for (i=0;i<N;i++) result += some_function(i);
```
is the same as
```
result = some_function(GLB_ALL);
```

Here the meaning of 'add' is, that whatever the desired result of calling `some_function` is, this result is obtained for each i in N, *e.g.* setting the baseline in all experiments to a certain value or or compute the χ^2 for each experiment and return the total result. There are however some functions where the action performed or the result is so complex that is not possible or sensible to perform this for all i in N. Calling these functions with `GLB_ALL` as argument will in any case result in an exit status indicating failure and the function will produce an error message[3].

For storing the experiments, GLoBES uses the initially empty list of experiments `glb_experiment_list`. To add a pre-defined experiment to this list, one can use the function `glbInitExperiment`:

Function 2.2 `int glbInitExperiment(char *inf, glb_exp *in, int *counter)` *adds a single experiment with the filename* `inf` *to the list of currently loaded experiments. The* `counter` *is a pointer to the variable containing the number of experiments, and the experiment* `in` *points to the beginning of the experiment list. The function returns zero if it was successful.*

Normally, a typical call of `glbInitExperiment` is

[2]Note that the global variable `glb_num_of_exps` must not be modified by the user.

[3]if the verbosity level is set accordingly

Quantities	Examples	Units
Angles	θ_{13}, θ_{12}, θ_{23}, δ_{CP}	Radians
Mass squared differences	Δm_{21}^2, Δm_{31}^2	eV^2
Matter densities	ρ_i	$\mathrm{g/cm}^3$
Baseline lengths	L_i	km
Energies	E_ν	GeV
Fiducial masses	m_{Det}	t (reactor exp.) or kt (accelerator exp.), depends on experiment definition
Time intervals	t_{run}	yr
Source powers	P_{Source}	Useful parent particle decays/yr (Neutrino factory, β-Beam), GW thermal power (reactor exps.), or MW target power (superbeams); depends on flux definition
Cross sections/E	σ_{CC}/E	$10^{-38}\,\mathrm{cm}^2/\mathrm{GeV}^2$

Table 2.2: Quantities used in GLoBES, examples of these quantities, and their standard units in the application software.

```
glbInitExperiment("NuFact.glb",&glb_experiment_list[0],
                                         &glb_num_of_exps);
```

In this case, the experiment in the file `NuFact.glb` is added to the internal global list of experiments, and the experiment counter is increased. The experiment then has the number `glb_num_of_exps`-1. The elements of the experiment list have the type `glb_exp`, which the user will not need to access directly in most cases. The experiment definition files, which usually end with `.glb`, and any supporting files, are first of all searched in the current directory, and then in the path given in the environment variable `GLB_PATH`.

A list of pre-defined experiment prototypes, their filenames, their short descriptions, and the references of their definitions can be found in Table 2.1. If the program cannot find these files, or some of them are syntactically not correct, it will break at this place.

One can also remove all experiments from the evaluation list at running time:

Function 2.3 `void glbClearExperimentList()` *removes all experiments from the internal list and resets all counters.*

Note that changing the number of experiments requires a new initialization of all parameters of the types `glb_params` and `glb_projection` if the number of experiments changes, since these parameter structures internally carry lists for the matter densities of all experiments. Similarly, once should never call `glbAlloc...` before the experiment initialization.

2.2 Units in GLoBES and the integrated luminosity

While interacting with the user interface of GLoBES, parameters are transferred to and from the GLoBES library. In GLoBES, one set of units for each type of quantity is used in order to avoid confusion about the definition of individual parameters. Table 2.2 summarizes the units of the most important quantities. In principle, the event rates are proportional to the product of source power $\times$ target mass $\times$ running time, which we call "integrated luminosity". Since especially the definition of the source power depends on the experiment type, the quantities of the three luminosity components are not unique and depend on the experiment definition. Usually, one uses detector masses in kilotons for beam experiments, and detector masses in tons for reactor experiments. Running times are normally given in years, where it is often assumed that the experiment runs 100% of the year. Thus, for shorter running periods, the running times need to be renormalized. Source powers are usually useful parent particle decays per year (neutrino factories, β-beams), target power in mega watts (superbeams), or thermal reactor power in giga watts (reactor experiments). Since the pre-defined experiments in Table 2.1 are given for specific luminosities, it is useful to read out and change these parameters of the individual experiments:

Function 2.4 `void glbSetSourcePower(int exp, int fluxno, double power)` *sets the source power of experiment number* `exp` *and flux number* `fluxno` *to* `power`*. The definition of the source power depends on the experiment type as described above.*

Function 2.5 `double glbGetSourcePower(int exp, int fluxno)` *returns the source power of experiment number* `exp` *and flux number* `fluxno`*.*

Function 2.6 `void glbSetRunningTime(int exp, int fluxno, double time)` *sets the running time of experiment number* `exp` *and flux number* `fluxno` *to* `time` *years.*

Function 2.7 `double glbGetRunningTime(int exp, int fluxno)` *returns the running time of experiment number* `exp` *and flux number* `fluxno`*.*

Function 2.8 `void glbSetTargetMass(int exp, double mass)` *sets the fiducial detector mass of experiment number* `exp` *to* `mass` *tons or kilotons (depending on the experiment definition).*

Function 2.9 `double glbGetTargetMass(int exp)` *returns the fiducial detector mass of experiment number* `exp`*.*

Thus, these functions also demonstrate how to use the assigned experiment number and others. These numbers run from 0 to the number of experiments-1, fluxes-1, *etc.*, where the individual elements are numbered in the order of their appearance. Note that the source power and running time are quantities defined together with the neutrino flux, whereas the target mass scales the whole experiment. Thus, if one has, for instance, a neutrino and an antineutrino running mode, one can scale them independently.

2.3 Handling oscillation parameter vectors

Before we can set the simulated event rates or access any oscillation parameters, we need to become familiar with the concept GLoBES uses for oscillation parameters. In order to transfer sets of oscillation parameter vectors $(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}, \Delta m_{21}^2, \Delta m_{31}^2)$, the parameter type `glb_params` is used. In general, this type is often transferred to and from GLoBES functions. Therefore, the memory for these vectors has to be reserved (allocated) before they can be used, and it has to be returned (freed) afterwards. GLoBES functions usually use the pointers of the type `glb_params` for the input or output to the functions. As an input parameter, the pointer has to be created and point towards a valid parameter structure, where the oscillation parameters are read from. As an output parameter, the pointer has to be created, too, and point towards a structure which will contain the return values will be written to. This parameter transfer concept seems to be very sophisticated, but, as we will see in the next chapters, it hides a lot of complicated parameter mappings which otherwise need to be done by the user. For example, not only the oscillation parameters are stored in the pointer structure, but also information on the matter densities of all of the initialized experiments. Since GLoBES treats the matter density as a free parameter known with some external precision to include matter density uncertainties, the minimizers also use fit values and external errors for the matter densities of all loaded experiments. More precisely, the matter density profile of each experiment i is multiplied by a scaling factor $\hat{\rho}_i$, which is stored in the density information of `glb_params`. Each of these scaling factors has 1.0 as pre-defined value. Since it is in most cases not necessary to change this value, the user does not need to take care of it. For a constant matter density, it is simply the ratio of the matter density and the average matter density specified in the experiment definition, *i.e.*, $\hat{\rho}_i \equiv \rho_i / \bar{\rho}_i$. For a matter density profile, it acts as an overall normalization factor: The matter density in each layer is multiplied by this factor. In most cases one wants to take a scaling factor of 1.0 here, which simply means taking the matter density profile as it is given in the experiment definition. For the treatment of correlations, however, an external precision of the scaling factor might be used to include the correlations with the matter density uncertainty. Note that the `glb_params` structures must not be initialized before all experiments are loaded, since the number of matter densities can only be determined after the experiments are initialized. Similarly, any change in the number of experiments requires that the parameter structures be re-initialized, *i.e.*, freed and allocated again.

Note: Inverting the mass hierarchy is not precisely the same than to change from $\Delta m_{31}^2 \to -\Delta m_{31}^2$. In this case the absolute value of Δm_{32}^2 changes also, which introduces a new frequency to the problem. Therefore, if we assume normal hierarchy whenever $\Delta m_{31}^2 > 0$, the corresponding point in parameters space for inverted hierarchy is given by $\Delta m_{31}^2 \to -\Delta m_{31}^2 + \Delta m_{21}^2$, because with this defintion the absolute value of Δm_{32}^2 is unchanged and no new frequency is introduced.

Another piece of information will be returned from the minimizers (*cf.*, Chapter 4) and transferred into the `glb_params` structure is the number of iterations used for the minimization, which is proportional to the running time of the minimizer. In general, the user does not need to access the elements in `glb_params` directly. A number of functions is provided to handle these parameter structures:

Function 2.10 `glb_params glbAllocParams()` *allocates the memory space needed for a parameter vector and returns a pointer to it.*

Function 2.11 `void glbFreeParams(glb_params stale)` *frees the memory needed for a parameter vector* `stale` *and sets the pointer to* `NULL`*.*

Function 2.12 `glb_params glbDefineParams(glb_params in, double theta12, double theta13,double theta23, double delta, double dms, double dma)` *assigns the complete set of oscillation parameters to the vector* `in`*, which has to be allocated before. The return value is the pointer to* `in` *if the assignment was successful, and* `NULL` *otherwise.*

Function 2.13 `glb_params glbCopyParams(const glb_params source, glb_params dest)` *copies the vector* `source` *to the vector* `destination`*. The return value is* `NULL` *if the assignment was not successful.*

Function 2.14 `void glbPrintParams(FILE *stream, const glb_params in)` *prints the parameters in* `in` *to the file* `stream`*. The oscillation parameters, all density values, and the number of iterations are printed as pretty output. Use* `stdout` *for* `stream` *if you want to print to the screen.*

In addition to these basic functions, there are functions to access the individual parameters within the parameter vectors:

Function 2.15 `glb_params glbSetOscParams(glb_params in, double osc, int which)` *sets the oscillation parameter* `which` *in the structure* `in` *to the value* `osc`*. If the assignment was unsuccessful, the function returns* `NULL`*.*

Function 2.16 `double glbGetOscParams(glb_params in, int which)` *returns the value of the oscillation parameter* `which` *in the structure* `in`*.*

In both of these functions, the parameter `which` runs from 0 to 5, where the parameters in GLoBES always have the order θ_{12}, θ_{13}, θ_{23}, δ_{CP}, Δm^2_{21}, Δm^2_{31}. Alternatively to the number, the constants `GLB_THETA_12`, `GLB_THETA_13`, `GLB_THETA_23`, `GLB_DELTA_CP`, `GLB_DM_SOL`, or `GLB_DM_ATM` can be used.

Similarly, the density parameters or number of iterations (returned by the minimizers) can be accessed:

Function 2.17 `glb_params glbSetDensityParams(glb_params in, double dens, int which)` *sets the density parameter* `which` *in the structure* `in` *to the value* `dens`*. If the assignment was unsuccessful, the function returns* `NULL`*. If* `GLB_ALL` *is used for* `which`*, the density parameters of all experiments will be set accordingly.*

Function 2.18 `double glbGetDensityParams(glb_params in, int which)` *returns the value of the density parameter* `which` *in the structure* `in`*.*

Function 2.19 `glb_params glbSetIteration(glb_params in, int iter)` *sets the number of iterations in the structure* `in` *to the value* `iter`*. If the assignment was unsuccessful, the function returns* `NULL`*.*

Function 2.20 `int glbGetIteration(glb_params in)` *returns the value of the number of iterations in the structure* `in`*.*

In total, the parameter vector handling in a program normally has the following order:

```
glbInitExperiment(...);
/* ... more initializations ... */

glb_params vector1 = glbAllocParams();
/* ... more vectors allocated ... */

/* Program code: assign and use vectors */

glbFreeParams(vector1);
/* ... more vectors freed ... */

/* ... end of program or glbClearExperimentList ... */
```

2.4 Computing the simulated data

Compared to existing experiments, which use real data, future experiments use simulated data. Thus, the *true parameter values* and their results in form of the reference event rate vectors are simulated. After setting the true parameter values, the *fit parameter values* can be varied in order to obtain information on the measurement performance for the given set of true parameter values. Therefore, it is often useful to show the results of a future measurement as function of the true parameter values for which the reference rate vectors are computed – at least within the currently allowed ranges. The true parameter values for the vacuum neutrino oscillation parameters have to be set by the function `glbSetOscillationParameters` and the reference rate vector, *i.e.* the data, has to be computed by a call to `glbSetRates`. This has to be done *before* any evaluation function is used and *after* the experiments have been initialized and also the experiment parameters have been adjusted which could change the rates (such as baseline or target mass). This means that after any change of an experiment parameter, `glbSetRates` has to be called. Matter effects are automatically included as specified in the experiment definition. We have the following functions to assign and read out the vacuum oscillation parameters:

Function 2.21 `int glbSetOscillationParameters(const glb_params in)` *sets the vacuum oscillation parameters to the ones in the vector* `in`*.*

Function 2.22 `int glbGetOscillationParameters(glb_params out)` *returns the vacuum oscillation parameters in the vector* `out`*. The result of the function is* 0 *if the call was successful.*

The reference rate vector is then computed with:

Function 2.23 `void glbSetRates()` *computes the reference rate vector for the neutrino oscillation parameters set by* `glbSetOscillationParameters`*.*

A complete example for a minimal GLoBES program can be found on Page 14.

2.5 Version control

In order to keep track of the used version of GLoBES, the software provides a number of functions to check the GLoBES and experiment versions. It is up to the user to implement mechanisms into the program and AEDL files to check whether

- The program should only run with this specific version of GLoBES
- The program can only run with a minimum version of GLoBES
- The program can only run up to a certain GLoBES version.

The same holds for AEDL files: For example, some features may not be supported by earlier versions of GLoBES anymore. The program can then check the version of the AEDL file and break if it is too old.

The functions in GLoBES for version control are:

Function 2.24 `int glbTestReleaseVersion(const char *version)` *returns* 0 *if the* `version` *string of the format "X.Y.Z" is exactly the used* GLoBES *version,* 1 *if it is older, and* -1 *if it is newer.*

Function 2.25 `int glbTestLibraryVersion(const char *version)` *returns* 0 *if the* `version` *string of the format "X.Y.Z" is exactly the used* GLoBES *version,* 1 *if it is older, and* -1 *if it is newer. Note that the library and* GLoBES *versions are not the same.*

Function 2.26 `const char* glbVersionOfExperiment(int experiment)` *returns the version string of the experiment number* `experiment`*. The version string is allocated within the experiment structure, which means that it cannot be altered and must not be freed by the user.*

Chapter 3

Calculating χ^2 with systematics only

Calculating a χ^2-value with or without systematics, but no correlations and degeneracies, is the simplest and fastest possibility to obtain high-level information on an experiment. In general, GLoBES uses the six independent oscillation parameters θ_{12}, θ_{13}, θ_{23}, δ_{CP}, Δm_{21}^2, Δm_{31}^2, as well as the matter density scaling factor $\hat{\rho}$ of each experiment. Thus, there are six plus the number of experiments parameters determining the rate vectors. Using the matter density scaling factors in addition to the oscillation parameters will allow the simulation of the correlations with matter density uncertainties: In this approach, the matter density profile normalization $\hat{\rho}$ can be treated as parameter to be measured by the experiment, where an external precision given by observations is imposed (typically up to 5%). For this section, it is important to keep in mind that there are more parameters than just the oscillation parameters determining the simple χ^2. However, as we have described in the last section, the mechanism for the matter density scaling factors is hidden in the definition of `glb_params`: Each of the scaling factors is initially set to 1.0. Therefore, for the calculation of χ^2 with systematics only, we do not have to care about the matter density scaling factors.

Keeping all oscillation parameters and matter density scaling factors fixed, one can use the following functions to obtain the total χ^2 of all specified oscillation channels including systematics:

Function 3.1 `double glbChiSys(const glb_params in,int exp, int rule)` *returns the* χ^2 *for the (fixed) oscillation parameters* `in`*, the experiment number* `exp`*, and the rule number* `rule`*. For all experiments or rules, use* `GLB_ALL` *as parameter value.*

Note that the result of `glbChiSys` for all experiments or rules corresponds to the sum of all of the individual `glbChiSys` calls. This equality will not hold for the minimizers in the next sections anymore. An example how to use `glbChiSys` can be found on page 24.

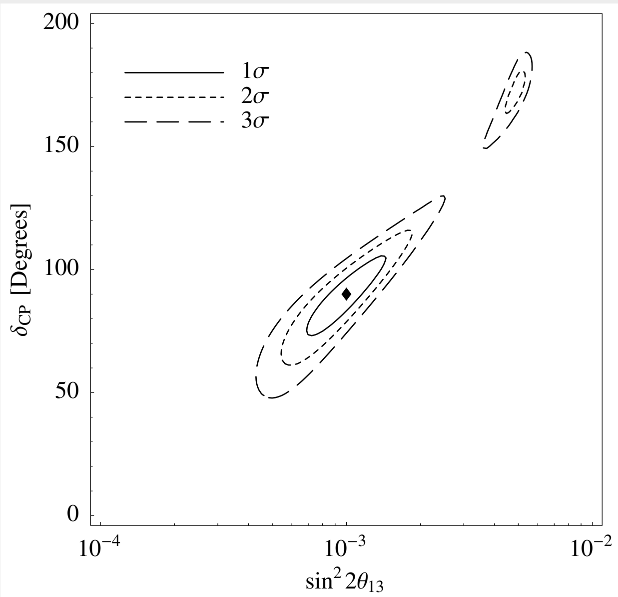
The treatment of systematics in GLoBES is performed by the so-call *pull method* with the help of auxiliary systematics parameters. They are taken completely uncorrelated among different rules, and treated with simple Gaußian statistics. In general, a rule is a set of signal and background event rates coming from different oscillation channels, where the event rates of all rule contributions are added. For more details of the rule concept, see Part II of this manual, and for the treatment of systematics, see Sec. 9.6.

Example: Correlation between $\sin^2 2\theta_{13}$ *and* δ_{CP}

A typical and fast application for **glbChiSys** is the visualization of two-parameter correlations using systematics only. For example, to calculate the two-parameter correlation between $\sin^2 2\theta_{13}$ and δ_{CP} at a neutrino factory, one can use the following code excerpt from `example1.c`:

```
/* Initialize parameter vector(s) and compute simulated data */
glbDefineParams(true_values,theta12,theta13,theta23,deltacp,sdm,ldm);
glbDefineParams(test_values,theta12,theta13,theta23,deltacp,sdm,ldm);
glbSetOscillationParameters(true_values); glbSetRates();

/* Iteration over all values to be computed */
double x,y,res;
for(x=-4.0;x<-2.0+0.01;x=x+2.0/50)
for(y=0.0;y<200.0+0.01;y=y+200.0/50)
{
    /* Set parameters in vector of test values */
    glbSetOscParams(test_values,asin(sqrt(pow(10,x)))/2,GLB_THETA_13);
    glbSetOscParams(test_values,y*M_PI/180.0,GLB_DELTA_CP);

    /* Compute Chi2 for all loaded experiments and all rules */
    res=glbChiSys(test_values,GLB_ALL,GLB_ALL);
    AddToOutput(x,y,res);
}
```

The resulting data can then be plotted as a contour plot (2 d.o.f.):



One example for a systematics parameter the signal normalization error, *i.e.*, an error to the overall normalization of the signal. For illustration, we assume that the signal event rate in the ith bin s_i^0 of one oscillation channel is altered by the overall normalization auxiliary parameter of this channel, *i.e.*,

$$s_i = s_i(n_s) = s_i^0 \cdot (1 + n_s), \tag{3.1}$$

where n_s is the signal normalization parameter. The total number of events in the ith bin x_i also includes the background event rates b_i, *i.e.*, $x_i = s_i + b_i$, which may have their own systematics parameters. In order to implement an overall signal normalization error σ_{n_s}, the χ^2, which includes all event rates x_i of all bins, is minimized over the auxiliary parameter n_s:

$$\hat{\chi}^2 = \min_{n_s} \left(\chi^2(n_s, \ldots) + \frac{(n_s)^2}{\sigma_{n_s}^2} \right). \tag{3.2}$$

This minimization is done independently for all auxiliary parameters of the rule. The total χ^2 for the considered experiment is finally obtained by repeating this procedure for all rules and adding their χ^2-values. In general, the situation is more complicated because of the usage of many systematical errors. More details about systematics parameters and the definition of signal, background, and oscillation channels can be found in Sec. 9.6, too.

The systematics minimization of an experiment can be easily switched on and off with `glbSwitchSystematics`, *i.e.*, one can also compute the χ^2 with statistics only. In addition, several options for systematics are available, such as only using total event rates without spectral information. For details, we refer to Chapter 7.

Chapter 4

Calculating χ^2-projections: how one can include correlations

This chapter deals with the rather complicated issue of n-parameter correlations. It is one of the greatest strengths of this software to include the full n-parameter correlation in the high-dimensional parameter space with reasonable effort. Of course, calculating χ^2-projections is somewhat more complicated than using systematics only. Therefore, we use a simple step by step introduction to the problem.

4.1 Introduction

In principle, the precision of an individual parameter measurement including correlations in the χ^2-approach can be obtained as the projection of the n-dimensional fit manifold onto the respective axis. Similarly, one can project the fit manifold onto a plane, such as the $\sin^2 2\theta_{13}$-δ_{CP}-plane, if one wants to show the allowed region in this plane with all the other parameter correlations included. In practice, this projection is very difficult: a grid-based method would need $(N_{\mathrm{grid}})^n$ function calls of `glbChiSys` to calculate the projection onto one dimension including the full n-parameter correlation, where N_{grid} is the number of points in each direction of the lattice. For example, taking only $N_{\mathrm{grid}} = 20$ and $n = 7$ (six oscillation parameters and matter density) would mean more than one billion function calls of `glbChiSys`. One can easily imagine that these would be too many for any reasonable application.

The solution to this problem is using a n-dimensional, local minimizer for the projection instead of a grid-based method, where we will illustrate this minimization process later. It turns out that such a minimizer can include a full 6-parameter correlation with of the order of 1 000 function calls of `glbChiSys`. For the minimization we use a derivative free method due to Powell in a modified [7] version[1].

[1] Not needing derivatives is highly desired since the event rate depends in a non-linear way on the oscillation parameters, thus there is no easy analytical way to obtain derivatives of the χ^2 function.

Thus, for each point on the projection axis/plane, one can obtain a result within about 10 to 30 seconds on a modern computer, which means that the complete measurement precision for one fixed true parameter set can be obtained in as much as 10 to 15 minutes. One can easily imagine that such a minimizer makes more sophisticated applications possible with the help of overnight calculations, such as showing the dependencies on the true parameter values.

This approach also has one major disadvantage: There is *no* such thing as a global minimization algorithm or even an algorithm which guarantees to find *all* local minima of a function. In practice this means using a local minimizer, one may end up in an unwanted local minimum and not in the investigated (possibly global) one or one may miss a local minimum which affects the results[2]. The only way out of this dilemma is to use some heuristic approach, *i.e.* although one can not guarantee anything one can use schemes which work in most cases and announce their failure loudly. In order to use such a heuristic some (analytical or numerical) knowledge on the topology of the fit manifold is necessary. With this knowledge it is possible to obtain an approximate position for each local minimum and thus to start the local minimizer close enough to the investigated minimum. Fortunately, this can be done quite straightforward in most cases, since the structure of the neutrino oscillation formulas does not cause very complicated topologies of the fit manifolds. Especially the simulation of reactor experiments and conventional beams or superbeams is rather simple with purely numerical approaches. Neutrino factories have, especially for small values of θ_{13}, a much more complicated topology. In this case, results of the many analytical discussions of this issue can be used. This means that one can implicitly use the analytical knowledge to obtain better predictions for the location of a minimum. One can easily imagine that the used methods then also depend on the region of the parameter space. In this manual, we only use examples with a neutrino factory, since some of these complications can be illustrated there. Albeit the methods described here are neither complete nor will they work everywhere in the parameter space. It is in any case up to the user to make sure that the results are what he/she thinks.

Some more words of warning with respect to results obtained by projecting the χ^2: The results obtained this way are always only a *upper* bound on the value of the projected χ^2 function, *i.e.* an undiscovered minimum decreases the value of the the projected χ^2 function. If the value of the χ^2 function in the missed minimum is larger than the previously found ones it will not influence the value of the projected value. Thus, one can only run the danger to obtain a too optimistic solution if one does not find the other local minima appearing below the chosen confidence level. Thus, with this approach and proper usage, it should not possible to produce a too pessimistic solution. However, if one is not careful enough to locate all local minima, one can easily produce too optimistic solutions. This danger can be summarized as follows:

$$\text{Too pessimistic result} < \underbrace{\text{Real result}}_{\text{Located by careful usage}} \leq \text{GLoBES result} < \text{Too optimisitic result}$$

[2]NB – Implementing a grid-based method which guarantee to find all local minima is not straightforward either, to say the least.

In many cases, the fit manifold is restricted by the knowledge from earlier experiments. For example, the knowledge on the solar parameters will in most cases be supplied by the solar neutrino experiments. If the external precision of a parameter is at the time of the measurement better than the one of the experiment itself, one usually will use this external, better knowledge and impose a corresponding constraint on this parameter. This external knowledge may reduce the extension of the n-dimensional fit manifold in the respective direction. In the most extreme case, keeping all parameters but the measured one fixed in the analysis is equivalent to the assumption that all parameters are determined externally with infinitively high precisions. As this is a quite strong assumption, one should *always* check the consequences of relaxing it and using realistic errors. Only if such a test has demonstrated that the impact of the uncertainty on a given fit parameter is negligible it can be assumed as fixed safely. The inclusion of external input in GLoBES is done by the use of Gaußian *priors*: We assume that an external measurement has determined the measured parameter to be at the central value (which we call *starting value*) with a 1σ Gaußian error (which we call *input error*). The explicit definition of these priors will be shown in the next section.

4.2 The treatment of external input

It is one of the strengths of the GLoBES software to use external input in order to reduce the extension of the fit manifold with the knowledge from external (earlier) measurements. The treatment of external input is done by the addition of Gaußian so-called *priors* to the systematics-minimized χ^2-function. For example, for the matter density, one obtains as the final projected χ^2_F after minimization over the matter density scaling factor $\hat{\rho}$

$$\chi^2_F = \min_{\rho} \left(\chi^2(\hat{\rho}) + \frac{(\hat{\rho} - \hat{\rho}^0)^2}{\sigma^2_{\hat{\rho}}} \right). \tag{4.1}$$

This example is a very simple one, since in fact the minimization is simultaneously performed over all priors and free oscillation parameters. In Eq. (4.1), $\hat{\rho}^0$ is the *starting value* of the prior, and $\sigma_{\hat{\rho}}$ the 1σ absolute (half width) *input error*. Thus, it is assumed that an external measurement has determined the matter density with a precision (input error) $\sigma_{\hat{\rho}}$ at the central value $\hat{\rho}^0$. Usually, the starting value is fixed at the best-fit value, and the input error to the 1σ half width of the external measurement. For the matter density, $\hat{\rho}^0$ is usually set to 1.0 corresponding to the actual matter density profile such as given by the experiment definition file, and $\sigma_{\hat{\rho}}$ to the relative matter density uncertainty (*e.g.*, 0.05 for 5% uncertainty).

In principle, one can set the priors for the matter density and all oscillation parameters. For example, if the disappearance channels of the experiment determine the leading oscillation parameters with unprecedented precisions, one can omit the respective input errors. In GLoBES, a value of 0 corresponds[3] to neglecting the prior. If, however, earlier external

[3]to be precise, a value for the error in between -10^{-12} and $+10^{-12}$

measurements provide better information, one can set their absolute precisions with the input errors. The starting values are usually chosen to be the best-fit values of this external experiments, such as for the input from solar experiments. In some cases, it may be necessary to adjust them, such as for artificial constraints to the oscillation parameters. In other cases, minor modifications of the starting values can cause a faster convergence of the algorithm. For example, for the investigation of the opposite-sign solution, one can use the prior to constrain Δm^2_{31} in order to force the minimizer not to fall into the (unwanted) true-sign solution. In this case, the starting value of Δm^2_{31} would be set to $\rho^0_{\Delta m^2_{31}} = -\Delta m^2_{31}$, and a $\sigma_{\Delta m^2_{31}}$ of the order of Δm^2_{31} would be imposed. For the algorithm, it would then be rather difficult to converge into the unwanted true-sign solution. However, note that one should in this case check that the actually determined value for Δm^2_{31} after minimization is close enough to the guessed value $-\Delta m^2_{31}$ in order to avoid significant artifical contributions of the priors to the final χ^2. Alternatively one could re-run the minimizer with the position of the previously found minimum as starting position but now with switching off the constraint on Δm^2_{31}.

In order to set the starting values and input errors, two function have to be called *before the usage of any minimizer*:

Function 4.1 `int glbSetStartingValues(const glb_params in)` *sets the starting values for all of the following minimizer calls to* `in`.

Function 4.2 `int glbSetInputErrors(const glb_params in)` *sets the input errors for all of the following minimizer calls to* `in`. *An input error of* 0 *corresponds to not taking into account the respective prior.*

Accordingly, there are functions to return the actually set starting values and input errors:

Function 4.3 `int glbGetStartingValues(glb_params out)` *writes the currently set starting values to* `out`.

Function 4.4 `int glbGetInputErrors(glb_params out)` *writes the currently set input errors to* `out`.

All functions take or return as many matter density parameters as there are initialized experiments. In addition, they return -1 if the operation was not successful.

Eventually, a typical initialization of the external input with 10% external precisions for the solar parameters[4], and 5% matter density uncertainties for all experiments looks like this:

```
glbDefineParams(input_errors,theta12*0.1,0,0,0,sdm*0.1,0);
glbSetDensityParams(input_errors,0.05,GLB_ALL);
glbSetStartingValues(true_values);
glbSetInputErrors(input_errors);
```

[4]In fact, accelerator-based long-baseline experiments are primarily sensitive to the product $\sin 2\theta_{12} \cdot \Delta m^2_{21}$, which means that these errors effectively add up to an error of this product of about 15%.

In this example, the starting values are set to the true (simulated) values. Remember that initially the matter density scaling factors are all 1.0, which means that they do not need to be adjusted for the starting values.

Though the priors are an elegant way to treat external input, there are also some complications with priors. The following hints are for the more advanced GLoBES user:

1. The priors are only added once to the final χ^2, no matter how many experiments there are simulated. This is already one reason (besides the minimization) why the sum of all projected χ^2's of the individual experiments cannot correspond to the χ^2 of the combination of all experiments.

2. Priors are not used for parameters which are not minimized over, *i.e.*, kept fixed. This will be important together with arbitrary projections using `glbChiNP`. A more subtile consequence is the comparison of fit manifold sections and projections for the solutions where the absolute minimum χ^2 is larger than zero, *i.e.*, degeneracies other than the true solution. In this case, the sections and projections are not comparable if not corrected by the prior contributions, where the correction can be obtained as the χ^2-difference at the minimum. For example, projecting the $\mathrm{sgn}(\Delta m^2_{31})$-degeneracy onto the θ_{13}-δ_{CP}-plane and comparing it with the section (all other parameters fixed), the section region would in many cases be larger than the projection region if the priors are not added to the section. At the true solution, this problem usually does not occur because the prior contributions are close to zero.

3. Currently, GLoBES only supports Gaußian priors for the individual oscillation parameters. Especially for the solar parameters, this is only an approximation, since they are imposed on θ_{12} and not on $\sin 2\theta_{12}$, $\sin 2\theta_{12} \cdot \Delta m^2_{21}$, or $\sin\theta_{12}$. Later versions of GLoBES may include more alternatives.

4.3 Projection onto the $\sin^2 2\theta_{13}$- or δ_{CP}-axis

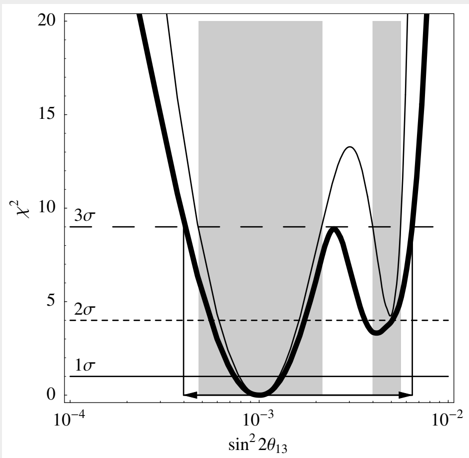
The projection onto the $\sin^2 2\theta_{13}$- (or δ_{CP}-) axis is performed by fixing $\sin^2 2\theta_{13}$ (or δ_{CP}) and minimizing the χ^2-function over all free fit parameters and the matter densities. We illustrate this method at the example of the projection of the two-dimensional manifold in the $\sin^2 2\theta_{13}$-δ_{CP}-plane onto the $\sin^2 2\theta_{13}$-axis in Fig. 4.1. In this figure, the left-hand plot shows the correlation in the $\sin^2 2\theta_{13}$-δ_{CP}-plane computed with `glbChiSys`. The right-hand plot illustrates the projection of this two-dimensional manifold onto the $\sin^2 2\theta_{13}$ axis by minimizing χ^2 over δ_{CP}. In this simple example, the minimization is done along the vertical gray lines in the left hand plot. The obtained minima are located on the thick gray curve, which means the the right-hand plot represents the χ^2-value along this curve. In fact, one can easily see that one obtains the correct projected 3σ errors in this example (*cf.*, arrows). This figure illustrates the projection of a two-parameter correlation. In general, the full n-parameter correlation is treated similarly by the simultaneous (local) minimization over all free fit parameters.

Example: Projection of two- and n-dimensional manifold onto $\sin^2 2\theta_{13}$*-axis*

This example demonstrates how to project the fit manifold onto the $\sin^2 2\theta_{13}$-axis, *i.e.*, how one can include correlations. We compute two sets of data: one for keeping all parameters but δ_{CP} fixed (two-parameter correlation), and one for keeping all parameters free (multi-parameter correlation). However, we impose external precisions for the solar parameters and the matter density. The following code excerpt is from `example2.c`:

```
/* Set starting values and input errors for all projections */
glbDefineParams(input_errors,theta12*0.1,0,0,0,sdm*0.1,0);
glbSetDensityParams(input_errors,0.05,GLB_ALL);
glbSetStartingValues(true_values);
glbSetInputErrors(input_errors);

/* Define my own two-parameter projection for glbChiNP: Only deltacp is free!  */
glbDefineProjection(th13_projection,GLB_FIXED,GLB_FIXED,GLB_FIXED,GLB_FREE,GLB_FIXED,GLB_FIXED);
glbSetProjection(th13_projection);

/* Iteration over all values to be computed */
double x,res1,res2;
for(x=-4;x<-2.0+0.001;x=x+2.0/50)
{
    /* Set fit value of stheta */
    glbSetOscParams(test_values,asin(sqrt(pow(10,x)))/2,1);

    /* Guess fit value for deltacp in order to safely find minimum */
    glbSetOscParams(test_values,200.0/2*(x+4)*M_PI/180,3);

    /* Compute Chi2 for user-defined two-parameter correlation */
    res1=glbChiNP(test_values,NULL,GLB_ALL);

    /* Compute Chi2 for full correlation:  minimize over all but theta13 */
    res2=glbChiTheta(test_values,NULL,GLB_ALL);

    AddToOutput(x,res1,res2);
}
```

The two lists of data then represent the $\sin^2 2\theta_{13}$ precisions with two-parameter correlations (gray-shaded) and multi-parameter correlations (arrows):



(Same parameters as on page 24 and in Fig. 4.1, but 1 d.o.f.)

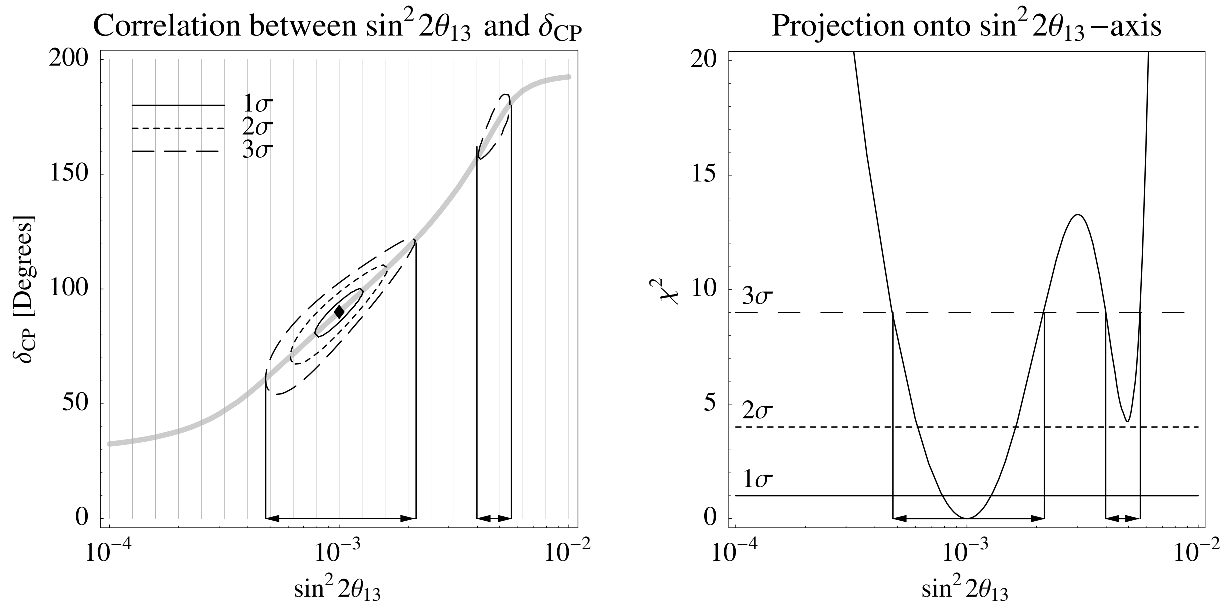


Figure 4.1: Left plot: The correlation between $\sin^2 2\theta_{13}$ and δ_{CP} as calculated in the example on page 24, but for 1 d.o.f. only. Right plot: The χ^2-value of the projection onto the $\sin^2 2\theta_{13}$-axis as function of $\sin^2 2\theta_{13}$. The projection onto the $\sin^2 2\theta_{13}$-axis is obtained by finding the minimum χ^2-value for each fixed value of $\sin^2 2\theta_{13}$ in the left-hand plot, *i.e.*, along the gray vertical lines. The thick gray curve marks the position of these minima in the left-hand plot. The arrows mark the obtained fit ranges for $\sin^2 2\theta_{13}$ at the 3σ confidence level (1 d.o.f.), *i.e.*, the precision of $\sin^2 2\theta_{13}$.

The following functions are some of the simplest minimizers provided by GLoBES:

Function 4.5 `double glbChiTheta(const glb_params in, glb_params out, int exp)` *returns the projected χ^2 onto the θ_{13}-axis for the experiment* `exp`*. For the simulation of all initialized experiments, use* `GLB_ALL` *for* `exp`*. The values in* `in` *are the guessed fit values for the minimizer (all parameters other than θ_{13}) and the fixed fit value of θ_{13}. The actually determined parameters at the minimum are returned in* `out`*, where θ_{13} is still at its fixed value. If* `out` *is set to* `NULL`*, this information will not be returned.*

Function 4.6 `double glbChiDelta(const glb_params in, glb_params out, int exp)` *returns the projected χ^2 onto the δ_{CP}-axis for the experiment* `exp`*. For the simulation of all initialized experiments, use* `GLB_ALL` *for* `exp`*. The values in* `in` *are the guessed fit values for the minimizer (all parameters other than δ_{CP}) and the fixed fit value of δ_{CP}. The actually determined parameters at the minimum are returned in* `out`*, where δ_{CP} is still at its fixed value. If* `out` *is set to* `NULL`*, this information will not be returned.*

All of the minimization functions have a similar parameter structure: The fixed fit parameter value and the guessed starting point of the minimizer, *i.e.*, the guessed position of the minimum, are transferred in the list `in`. Part of this list are the matter density scaling factors of all experiments, which are also minimized over. The minimizer is then started at the guessed point and runs into the local minimum, where the fit parameter of the projection axis is fixed. For the true solution, it is usually sufficient to start the minimizer at the true parameter values. However, the convergence speed might be better by starting it slightly off this point. In addition, there are problems in many cases with more complicated topologies, which means that better guesses for the position of the minimum are needed. The position of the minimum is then returned in `out` together with the number of iterations used for the minimization. It is very often useful to print the output of the minimization with `glbPrintParams` in order to check that the minimum is the appropriate one. For example, if the minimizer ends up in the wrong-sign solution in Δm^2_{31}, priors can be used to force it into the tested minimum. In addition, the number of iterations used allows an optimization of the convergence speed. Note that before any minimization, `glbSetStartingValues` and `glbSetInputErrors` have to be used at least once. In addition, note that the resulting χ^2 of `glbChiTheta` (or `glbChiDelta`) for the combination of more than one experiment is not equal to the sum of the individual χ^2-values anymore. This has two reasons: First, the topology of the fit manifold is altered by the addition of χ^2-values of different experiments. Thus, after the minimization, the position of the minimum can be different to the ones of the individual experiments. Second, the priors for the external knowledge on the parameters are only added once – independent of the number of experiments.

The output of the minimizer in `out` carries as many matter density scaling factors as there are experiments. Either one (for the simulation of one experiment) or all (for the simulation of all experiments) are different from 1.0 if matter density uncertainties are present, since each experiment may face other matter density conditions. The minimizers of individual experiments "know" which experiment they are currently treating, which means that they only returned the matter density scaling factor of the appropriate experiment. For example, calculating `glbChiTheta` for the last experiment number, the last density value will be returned. This approach turns out to be extremely useful together with the simulation of more than one experiment. One can, for instance, locate the degeneracies of all individual experiments. In order to test if these degeneracies are still present in the combination of all experiments (which has a very different topology), one can test the combination of experiments with the output `out` from the individual experiments. In this case, even the correct matter density scaling factor output is used.

The example on page 32 demonstrates how one can obtain Fig. 4.1 (right) with keeping all parameters but δ_{CP} fixed, as well as how one can include the full n-parameter correlation with external input. It also demonstrates how these two compare to each other. One can easily read off this example that there is a substantial impact of the correlation with oscillation parameters other than δ_{CP}. Note that it uses the function `glbChiNP` for arbitrary projections from the next section for the minimization over δ_{CP}. In addition, there is one interesting feature in guessing the oscillation parameters in this example: In order to avoid falling into the wrong minimum, the fit value of δ_{CP} is guessed from Fig. 4.1 (left). This quite sophisticated "guessing" is typical for neutrino factories because of the $(\delta_{\mathrm{CP}}, \theta_{13})$-degeneracy, whereas it is for superbeams often sufficient to use the true values. A strong indication for a wrong guessing are discontinuous jumps in the projected χ^2-function, where the minimizer jumps from one minimum to another. In such cases, the starting point of the minimizer has to be adjusted to help it find the true minimum.

Other examples for projections onto a parameter axis while keeping exactly one parameter fixed are `glbChiTheta23`, `glbChiDm`, and `glbChiDms`, which can be found in Table 1.1 on page 4.

4.4 Projection onto any hyperplane

In general, one can show the measurement result in any k-dimensional hyperplane, where k is smaller than the dimension of the parameter space n, and thus the dimension of the fit manifold. In this case, k parameters are fixed and $n-k$ parameters are minimized over. One such example is the projection of the fit manifold onto the $\sin^2 2\theta_{13}$-δ_{CP}-plane, *i.e.*, $k=2$ here. In this case, the two parameters $\sin^2 2\theta_{13}$ and δ_{CP} are kept fixed, and the others are minimized over. The corresponding function is

Function 4.7 `double glbChiThetaDelta(const glb_params in, glb_params out, int exp)` *returns the projected* χ^2 *onto the* θ_{13}-δ_{CP}*-plane for the experiment* `exp`. *For the simulation of all initialized experiments, use* `GLB_ALL` *for* `exp`. *The values in* `in` *are the guessed fit values for the minimizer (all parameters other than* θ_{13} *and* δ_{CP}*) and the fixed fit values of* θ_{13} *and* δ_{CP}. *The actually determined parameters at the minimum are returned in* `out`, *where* θ_{13} *and* δ_{CP} *are still at their fixed values. If* `out` *is set to* `NULL`, *this information will not be returned.*

This function works analogously to the ones in the last section. They can, for example, be used to obtain a figure similar to Fig. 4.1, left. The example on page 32 illustrates then the difference between the projections of the "eggs" within the $\sin^2 2\theta_{13}$-δ_{CP}-plane onto the θ_{13}-axis. Though the running time for one call of these functions is somewhat shorter than the one for the $\sin^2 2\theta_{13}$- or δ_{CP}-projections, one has to compute a two-dimensional array for such a figure (instead of a one-dimensional list). Therefore, the overall computational effort is much higher, *i.e.*, in the order of hours. In many cases, it is therefore convenient to run `glbChiSys` first to obtain a picture of the manifold and to adjust the parameter ranges. Then, one can run `glbChiThetaDelta` for a complete evaluation of the problem including correlations.

In principle, one can also use three- or more-dimensional projections. In addition, one may want to use a different set of parameters for single- or two-parameter projections. The very flexible function `glbChiNP` is designed for this purpose. However, because of its flexibility, it involves more sophistication.

In order to define arbitrary projections, we introduce the vector `glb_projection`, which is very similar to the oscillation parameter vector `glb_params`. Normally, the user does not need to access this type directly: A set of function similar to the ones for `glb_params` is provided. The purpose of `glb_projection` is to tell GLoBES what parameters are fixed, and what are minimized over. Thus, in comparison to `glb_params`, it does not take values for the parameters, but flags `GLB_FIXED` or `GLB_FREE`. For example, the projection onto

Function	Purpose	Parameters → Result
`glbAllocProjection`	Allocate projection vector	`()`
`glbFreeProjection`	Free projection vector `stale`	`(glb_projection stale)`
`glbDefineProjection`	Assign projection vector `in`	`(glb_projection in, int theta12, int theta13, int theta23, int delta, int dms, int dma)`
`glbCopyProjection`	Copy vector `source` to `dest`	`(const glb_projection source, glb_projection dest)`
`glbPrintProjection`	Print vector `in` to file `stream`	`(FILE* stream, const glb_projection in)`
`glbSetProjectionFlag`	Set flag for oscillation parameter `which` in vector `in` to value `flag`.	`(glb_projection in, int flag, int which)`
`glbGetProjectionFlag`	Return flag for oscillation parameter `which` in vector `in`.	`(const glb_projection in, int which)` → `int` flag
`glbSetDensity-ProjectionFlag`	Set flag for density parameter `which` in vector `in` to value `flag`.	`(glb_projection in, int flag, int which)`
`glbGetDensity-ProjectionFlag`	Return flag for density parameter `which` in vector `in`.	`(const glb_projection in, int which)` → `int` flag

Table 4.1: Different functions handling the `glb_projection` type. Flags are either `GLB_FIXED` or `GLB_FREE`. The (un-shown) return values of the `Set-` and `Define-` functions point either to the assigned vector if successful, or they are `NULL` if unsuccessful.

the θ_{13}-axis `glbChiTheta` is nothing else than a special case of `glbChiNP` with θ_{13} fixed and all the other parameters free. Similar to `glb_params`, the type `glb_projection` has to be allocated first, and freed later. The access functions for `glb_projection` are summarized in Table 4.1. Since the complete set is very similar to the one for `glb_params`, we do not go into greater details here.

As soon as we have defined a projection, we can assign it:

Function 4.8 `int glbSetProjection(const glb_projection in)` *sets the projection to* `in`*. The return value is* 0 *if successful, and* -1 *if unsuccessful.*

Similarly, the currently assigned projection can be returned with:

Function 4.9 `int glbGetProjection(glb_projection out)` *writes the currently set projection to* `out`*. The return value is* 0 *if successful, and* -1 *if unsuccessful.*

After setting the starting values, input errors, and the projection, we can run the minimizer:

Function 4.10 `double glbChiNP(const glb_params in, glb_params out, int exp)` *returns the projected* χ^2 *onto the hyperplane specified by* `glbSetProjection` *for the* *experiment* `exp`. *For the simulation of all initialized experiments, use* `GLB_ALL` *for* `exp`. *The values in* `in` *are the guessed fit values for the minimizer (all free parameters) and the fit values on the hyperplane (all fixed parameters). The actually determined parameters at the minimum are returned in* `out`, *where the fixed parameters are still at their input values. If* `out` *is set to* `NULL`, *this information will not be returned.*

As an example, the projection sequence for a minimization over δ_{CP} only looks like this:

```
glb_projection th13_projection = glbAllocProjection();
glbDefineProjection(th13_projection,GLB_FIXED,GLB_FIXED,GLB_FIXED,
          GLB_FREE,GLB_FIXED,GLB_FIXED);
glbSetProjection(th13_projection);
res1=glbChiNP(test_values,NULL,GLB_ALL);
glbFreeProjection(th13_projection);
```

In this case, only the correlation with δ_{CP} is taken into account. Note that in the example on page 32 this projection is compared with the result including the full multi-parameter correlation.

Chapter 5

Locating degenerate solutions

In the last chapter, we introduced the projection of any set of k parameters onto any $n-k$ dimensional hyperplane, which was performed by the minimization over the k free fit parameters. Similarly, one can minimize over *all* n parameters to find the local minimum close to any starting point. This approach is very useful for the exact numerical location of a degeneracy if its approximate position is known. For the determination of the approximate position, one can use analytical approaches or an educated guess. Though the usage of the all-parameter minimizers is quite simple, one should keep in mind that they are local minimizers. Therefore, one may need a very sophisticated application software to find all degenerate solutions.

The function to perform the all-parameter minimization is `glbChiAll`:

Function 5.1 `double glbChiAll(const glb_params in, glb_params out, int exp)` *returns the minimized* χ^2 *over all parameters for the experiment* `exp`*. For the simulation of all initialized experiments, use* `GLB_ALL` *for* `exp`*. The values in* `in` *are the guessed fit values for the minimizer. The actually determined parameters at the minimum are returned in* `out`*. If* `out` *is set to* `NULL`*, this information will not be returned.*

This function takes the suspected position of the local minimum and returns its actual position in `out`, as well as the χ^2-value at the minimum as return value. Thus, the return value can be immediately used to judge whether the located degeneracy appears at the chosen confidence level.

The example on page 40 illustrates how to locate the $\mathrm{sgn}(\Delta m_{31}^2)$-degeneracy and show the corresponding degenerate solution in the $\sin^2 2\theta_{13}$-δ_{CP}-plane together with the original solution. In this case, the position of the degeneracy can be easily guessed to be at the true parameter values but with inverted[1] Δm_{31}^2. The minimizer then runs off the plane of these parameters into the local minimum. It is very important to take into account the position of the degeneracy off this plane, since the actual χ^2 in the minimum is probably lower than in the plane. Thus, the degeneracy may not even appear at the chosen confidence level in the plane, but it does appear at the real minimum. The two sections through the fit

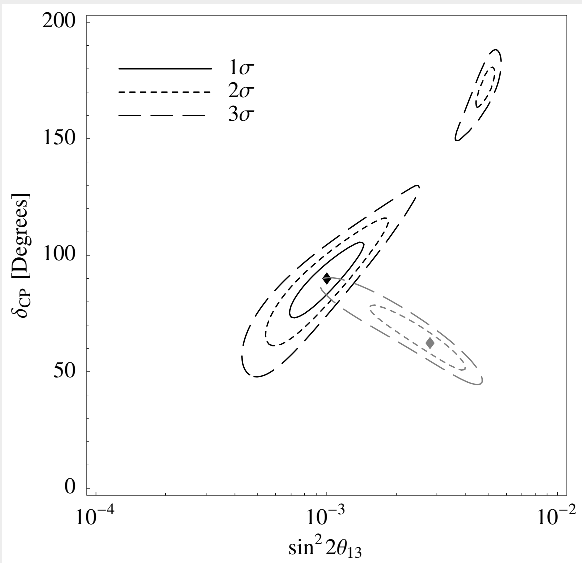
[1] For a exact definition of inverted hierarchy, see page 19.

Example: Finding the $\mathrm{sgn}(\Delta m^2_{31})$*-degeneracy*

In many cases, one can find the exact position of the $\mathrm{sgn}(\Delta m^2_{31})$-degeneracy with `glbChiAll`, where one starts the local minimizer at the suspected position and let it run into the minimum. The following code excerpt corresponds to finding the degenerate solution for the example on page 24, and it is from `example3.c`:

```
/* Set starting vales to suspected position at opposite sign of ldm */
glbDefineParams(starting_values,theta12,theta13,theta23,deltacp,sdm,-ldm);

/* Set input errors for external input, where some information on ldm
   is imposed in order to avoid falling into the right-sign solution */
glbDefineParams(input_errors,theta12*0.1,0,0,0,sdm*0.1,ldm/3);
glbSetDensityParams(input_errors,0.05,GLB_ALL);

glbSetStartingValues(starting_values);
glbSetInputErrors(input_errors);

/* Localize degenerate solution by minimization over all parameters
*/
double CL=glbChiAll(starting_values,deg_pos,GLB_ALL);

/* Now:  CL is the chi2 of the deg. solution and deg_pos the position */
```

Using `ent_pos` to obtain a section of the degeneracy in the $\sin^2 2\theta_{13}$-δ_{CP}-plane (*cf.*, `example3.c`), one can plot it as a contour plot in addition to the original solution (2 d.o.f., gray curves):



manifold shown in the figure on page 40 therefore do not appear at the same oscillation parameter values (except from the ones shown in the figure).[2]

For the more advanced reader, a number of tricks can be useful for the numerical localization of degenerate solutions:

Minimum χ^2 larger than threshold. If a located degeneracy has a minimum χ^2 larger than the corresponding confidence level threshold for the discussed quantity of interest, the degeneracy can be immediately ignored. This saves a lot of computation time.

Locating degeneracies in more complicated topologies. For more complicated topologies, such as for neutrino factories, it is often useful to use multi-step location procedures or analytical knowledge. For example, for a numerical procedure, one may first of all switch off the systematics and keep $\sin^2 2\theta_{13}$ or δ_{CP} fixed, *i.e.*, use `glbChiTheta`, where $\sin^2 2\theta_{13}$ or δ_{CP} is fixed at the best-fit value. The result can then be used as a starting point for `glbChiAll` for the individual experiments with the systematics switched on again.

Forcing the minimizer into the targeted solution. In addition to switching off the systematics, it can be useful to reduce the input errors during some steps of the localization process in order to make the minimizer not to run away too much from the targeted solution. The example on page 40 illustrates this with the input error for Δm_{31}^2: Since the guessed starting point might be quite far away from the real degeneracy, the algorithm may in some cases find the original solution instead of the degeneracy (which can be immediately seen from the output vector). The input error for Δm_{31}^2 gives the algorithm a "bias" against the original solution. However, note that the input error must not be too small in order to avoid a significant contribution of the prior to the final χ^2. Alternatively, one could once again run `glbChiAll` with the located minimum as `in` vector, and Δm_{31}^2 kept free.

Finding degeneracies with multiple experiments. For multiple experiments, it turns out to be useful to locate the degeneracies for individual experiments first. Then, all of the found degeneracies below the threshold can be tested for the combination of all experiments.

Finally, note that any degenerate solution below the confidence level threshold which can not be located makes the result appear better than it actually is. Thus, one should be careful with the determination of the degenerate solutions in order to find all of them.

[2]The discussed figure on page 40 is produced by `glbChiSys` and thus only represents a section through the fit manifold. For the projection including correlations, one may rather want to use `glbChiThetaDelta`.

Chapter 6

Obtaining low-level information

In this chapter, we discuss possibilities to obtain low-level information in GLoBES, *i.e.*, about oscillation probabilities, rates, and other information lower than on the χ^2-level.

6.1 Oscillation probabilities

GLoBES can compute the probabilities in vacuum with the following function:

Function 6.1 `double glbVacuumProbability(int l, int m, int panti,double E, double L)` *returns the neutrino oscillation probability* $\nu_l \to \nu_m$ *for the energy* `E` *and the baseline* `L` *in vacuum. The parameter* `panti` *is* $+1$ *for neutrinos and* -1 *for antineutrinos.*

In addition, the oscillation probabilities in matter can be obtained with:

Function 6.2 `double glbProfileProbability(int exp, int l, int m, int panti,double E)` *returns the neutrino oscillation probability* $\nu_l \to \nu_m$ *for the energy* `E` *in matter, where the matter density profile is the one of experiment* `exp`*. The parameter* `panti` *is* $+1$ *for neutrinos and* -1 *for antineutrinos. The matter density profile including baseline is the one from the last evaluated experiment.*

6.2 AEDL names

Since in AEDL rules, cross section, fluxes etc. carry a 'name' by which they can be refered to and in C they cary only an integer as index it is sometimes difficult to figure out the correct correspondence. Therefore the information about this correspondence obtained during parsing is stored and can be accessed within C by these two functions.

Function 6.3 `int glbNameToValue(int exp, const char* context, const char *name)` *Converts an* AEDL *name given as argument* `name` *into the corresponding C index. The variable* `context` *describes wether this name belongs to a rule, channel, flux, energy or cross type environment.* `exp` *is the number of the experiment and can not be* `GLB_ALL`*. It returns either the index in case of success or* `-1` *in case the name was not found.*

Function 6.4 `const char *glbValueToName(int exp,const char* context, int value)` *Converts a C index given as argument* `value` *into the corresponding* AEDL *name. The variable* `context` *describes wether the index belongs to a rule, channel, flux, energy or cross type environment.* `exp` *is the number of the experiment and can not be* `GLB_ALL`*. It returns either the name in case of success or* `NULL` *in case the name was not found. The returned string must not be modified.*

6.3 Event rates

One can also return event rates in GLoBES, but this feature requires some knowledge about the experiment definition. In fact, many of these functions are very advanced, which means that the reader who wants to use them should be familiar with Secs. 9.4 and Sec. 9.6 of the AEDL manual.

GLoBES currently supports rule-based and channel-based event rate functions, where the information is in written into a file or returned in a list. The rule-based functions are:

Function 6.5 `int glbShowRuleRates(FILE* stream, int exp, int rule, int pos, int effi, int bgi, int coeffi, int signal)` *prints the binned rule rates as list with energy and event rate to the file* `stream` *(either an open file, or* `stdout`*). A specific experiment* `exp` *and a specific rule* `rule` *have to be chosen, as well as the signal or background rate* `signal` *(either* `GLB_SIG` *or* `GLB_BG`*). The position* `pos` *refers to the component within the signal or background, and can also be* `GLB_ALL`*. The function may return the rates with (*`GLB_W_COEFF`*) or without (*`GLB_WO_COEFF`*) overall efficiency coefficient, as it is specified by* `coeffi`*. In addition, it may contain the post-smearing efficiencies (set* `effi` *to* `GLB_W_EFF` *or* `GLB_WO_EFF`*), and the post-smearing backgrounds (set* `bgi` *to* `GLB_W_BG` *or* `GLB_WO_BG`*). The pre-smearing efficiencies and backgrounds cannot be accessed at the rule level. The return value is* 0 *if successful, and* -1 *if unsuccessful.*

Function 6.6 `double glbTotalRuleRate(int exp, int rule, int pos, int effi, int bgi, int coeffi, int signal)` *returns the total rates with the same parameters as* `glbShowRuleRates`*.*

The function `glbTotalRuleRate` is especially useful if one wants to draw bi-rate graphs with total event rates, or look for the $(\delta_{\mathrm{CP}}, \theta_{13})$-degeneracy by the intersection of neutrino and antineutrino constant event rate curves. In order to obtain information on the structure of the rules, a number of additional functions are provided:

Function 6.7 `int glbGetNumberOfRules(int exp)` *returns the number of rules in experiment* `exp`*.*

Function 6.8 `int glbGetLengthOfRule(int exp, int rule, int signal)` *returns the length of rule* `rule` *in experiment* `exp`*. The parameter* `signal` *can be either* `GLB_SIG` *for the number of signal components or* `GLB_BG` *for the number of background components.*

Function 6.9 `double glbGetNormalizationInRule(int exp, int rule, int signal)` *returns the normalization (normalization or background center) in rule* `rule` *of the experiment* `exp`*. The parameter* `signal` *refers to signal (*`GLB_SIG`*) or background (*`GLB_BG`*).*

Function 6.10 `int glbGetChannelInRule(int exp, int rule, int pos, int signal)` *returns the channel number in rule* `rule` *at the position* `pos` *of the experiment* `exp`*. The parameter* `signal` *refers to signal (*`GLB_SIG`*) or background (*`GLB_BG`*).*

Function 6.11 `double glbGetCoefficientInRule(int exp, int rule, int pos, int signal)` *returns the coefficient of the component* `pos` *in rule* `rule` *of the experiment* `exp`*. The parameter* `signal` *refers to signal (*`GLB_SIG`*) or background (*`GLB_BG`*).*

In addition, GLoBES has channel-based rate functions:

Function 6.12 `int glbShowChannelRates(FILE *stream, int exp, int channel, int smearing, int effi, int bgi)` *prints the binned channel rates as list with energy and event rate to the file* `stream` *(either an open file, or* `stdout`*). A specific experiment* `exp` *and a specific channel* `channel` *have to be chosen. The function may return the rates before (*`GLB_PRE`*) or after (*`GLB_POST`*) the energy smearing, as it is specified by* `smearing`*. In addition, it may contain the pre- and post-smearing efficiencies (set* `effi` *to* `GLB_W_EFF` *or* `GLB_WO_EFF`*), and the pre- and post-smearing backgrounds (set* `bgi` *to* `GLB_W_BG` *or* `GLB_WO_BG`*). Note that the post-smearing efficiencies and backgrounds cannot be taken into account if the rates are returned before the energy smearing. The return value is* 0 *if successful, and* -1 *if unsuccessful.*

Function 6.13 `int glbGetChannelRates(double** data, size_t* length, int exp, int channel, int smearing)` *writes the binned raw channel rates to the list* `data` *and the length of this list to* `length`*. A specific experiment* `exp` *and a specific channel* `channel` *have to be chosen. The function may return the rates before (*`smearing` *is* `GLB_PRE`*) or after (*`smearing` *is* `GLB_POST`*) the energy smearing, where no user-defined data (pre-/post-smearing efficiencies or backgrounds) are taken into account. The return value is* -1 *if unsuccessful.*

Function 6.14 `int glbGetUserData(double** data, size_t* length, int exp, int channel, int smearing, int bgeff)` *writes the binned user-defined backgrounds or efficiencies to the list* `data` *and the length of this list to* `length`*. A specific experiment* `exp` *and a specific channel* `channel` *have to be chosen. The function may return the pre- (*`smearing` *is* `GLB_PRE`*) or post- (*`smearing` *is* `GLB_POST`*) smearing backgrounds (*`bgeff` *is* `GLB_BG`*) or efficiencies (*`bgeff` *is* `GLB_EFF`*). The return value is* -1 *if unsuccessful.*

Since GLoBES reserves the memory for the lists returned in these functions, which it allocates on an internal stack, one has to reset the stack at the end of the rates access with

Function 6.15 `void glbResetRateStack()` *resets the rate stack used for the lists returned from* `glbGetChannelRates` *or* `glbGetUserData`*.*

A code excerpt to show the channel rates may look like this:

```
double* rates;
size_t length;
glbGetChannelRates(&rates,&length,0,0,GLB_PRE);
int i;
for(i=0;i<length;i++) printf("%g \n",rates[i]);
glbResetRateStack();
```

Finally, one can find the number of channels of an experiment:

Function 6.16 `int glbGetNumberOfChannels(int exp)` *returns the number of channels of experiment* `exp`*.*

6.4 Fluxes and cross sections

Another piece of low-level information, which can be returned by GLoBES, are the numbers from the loaded fluxes and cross sections. The following functions interpolate on the loaded fluxes and cross sections, *i.e.*, any value in the allowed energy range can be given as input:

Function 6.17 `double glbFlux(int exp, int ident, double E, double distance, int l, int anti)` *returns the flux of flux number* `ident` *of the experiment* `exp` *for the flavor* ν_l *and polarity* `anti` *(*$+1$*: neutrinos,* -1*: antineutrinos) at the energy* `E` *and distance* `distance`*.*

Function 6.18 `double glbXSection(int exp, int ident, double E, int l, int anti)` *returns the cross section of experiment* `exp`*, cross section number* `ident` *for the flavor* ν_l *and polarity* `anti` *(*$+1$*: neutrinos,* -1*: antineutinos) at the energy* `E`*.*

Chapter 7

Changing experiment parameters at running time

Many of the parameters in experiment definitions can be changed at running time. For example, we have introduced in Sec. 2.2 possibilities to change the integrated luminosity, which consists of source power, running time, and target mass. In this chapter, we discuss more sophisticated experiment changes. However, since GLoBES computes a lot of information only once when an experiment is loaded, many parameters can not be changed at running time. For example, the energy resolution function or the number of bins are used to compute the smearing matrix already at the initialization of the experiment, which saves a lot of computation time for most applications. In Sec. 7.3, we introduce a mechanism how one can even change these AEDL parameters during running time.

7.1 Baseline and matter density profile

In order to change the baseline of an experiment, it is important to keep in mind that each experiment has a profile type defined in the AEDL file (average density, PREM profile with a given number of steps, or arbitrary profile). One can check the currently used profile type with

Function 7.1 `int glbGetProfileType(int exp)` *returns the matter density profile type of experiment* `exp`*.*

For each profile type, one can easily change the baseline with `glbSetBaselineInExperiment`, where the average density or the PREM profile are re-computed, or the steps in the arbitrary profile are re-scaled. If this behaviour is not the desired one, one has to use `glbSetProfilDataInExperiment` as explained below.

Function 7.2 `int glbSetBaselineInExperiment(int exp, double baseline)` *sets the baseline length in experiment* `exp` *to* `baseline`*. The function returns* -1 *if it was not successful.*

Note that `glbSetBaselineInExperiment` does not change the profile type in the experiment. The counterpart of this function is:

Function 7.3 `double glbGetBaselineInExperiment(int exp)` *returns the baseline length currently used for experiment* `exp`*.*

One can not change the profile type of an experiment manually during running time. However, one can change the matter density profile, where the profile type is automatically changed to 3, *i.e.* arbitrary matter density profile. In addition, a number of functions are provided to compute possible matter density profiles (average density, PREM profile). In general, a matter density profile in GLoBES with N layers is represented by a list of lengths

$$\text{Lengths} = (x_1, x_2, \ldots, x_N) \tag{7.1}$$

and a list of densities

$$\text{Densities} = (\rho_1, \rho_2, \ldots, \rho_N), \tag{7.2}$$

where the baseline is given by

$$L = \sum_{i=1}^{N} x_i. \tag{7.3}$$

In C, lists are represented as pointers to the first element:

```
double* lengths;
double* densities;
```

Many of the GLoBES baseline functions take and return such lists as parameters, and are therefore more sophisticated to handle. In general, any function *returning* lists allocates the memory for them. It is then up to the user to free this memory! In addition, they normally provide the length of the lists N by means of an additinal argument which is a pointer to `size_t`. Normally, it is enough to declare a variable of the type `size_t` and to give its address to the function. The following functions return matter density profiles:

Function 7.4 `int glbLoadProfileData(const char* filename, size_t *layers, double **lengths, double **densities)` *loads a density file from the file* `filename`*. It returns the number of layers* `layers`*, the list of lengths* `lengths`*, and the list of densities* `densities`*.*

The file should contain in each line a length and density for one layer, which are separated by an empty space.

Function 7.5 `int glbStaceyProfile(double baseline, size_t layers, double **lengths, double **densities)` *creates a PREM/Stacey matter density profile with a number of* `layers` *steps for the baseline* `baseline`*. The list of lengths* `lengths` *and the list of densities* `densities` *are returned.*

Function 7.6 `glbAverageDensityProfile(double baseline, double **lengths, double **densities)` *creates a average matter density profile from the PREM/Stacey profile with one step for the baseline* `baseline`*. The list of lengths* `lengths` *and the list of densities* `densities` *are returned.*

The average matter density $\bar{\rho}(L)$ for a matter density profile $\rho(x)$ along the baseline L baseline is defined as

$$\bar{\rho}(L) = \frac{1}{L} \int\limits_0^L \rho(x) dx = \frac{1}{L} \int\limits_0^L \tilde{\rho}\left(d(x)\right) dx \,, \tag{7.4}$$

where $\tilde{\rho}(d)$ is the PREM matter density as function of the distance d to the Earth's core, and $d(x) = \sqrt{x^2 + R^2 - 2xR\cos\theta}$ is the purely geometrical relationship between d and x with the Earth radius R and the nadir angle $\cos\theta = L/(2R)$.

Function 7.7 `int glbGetProfileDataInExperiment(int exp,size_t *layers, double** lengths, double** densities)` *returns the matter density profile currently used for experiment* `exp`*. The number of layers* `layers`*, the list of lengths* `lengths`*, and the list of densities* `densities` *are returned.*

All these functions return -1 if they were not successful.

The counterpart of these functions to assign a specific matter density profile to an experiment is

Function 7.8 `int glbSetProfileDataInExperiment(int exp, size_t layers,const double* lengths, const double* densities)` *sets the matter density of experiment* `exp` *to an arbitrary profile with* `layers` *steps. The density layers are specified by the lists* `lengths` *and* `densities`*. The function returns -1 if it was not successful.*

Note that this function requires that the memory space for the lists be reserved already.

Finally, let us take a look at two examples. This example changes the baseline length to 7 500 km, where the average matter density is manually computed:

```
double* lengths;
double* densities;
glbAverageDensityProfile(7500,&lengths,&densities);
glbSetProfileDataInExperiment(0,1,lengths,densities);
free(lengths);
free(densities);
```

In the second example, we change the baseline to a PREM profile with 100 matter density steps and print them:

```
double* lengths;
double* densities;
glbStaceyProfile(7500,100,&lengths,&densities);
int i;
for(i=0;i<100;i++) printf("%g %g \n",lengths[i],densities[i]);
glbSetProfileDataInExperiment(0,100,lengths,densities);
free(lengths);
free(densities);
```

7.2 Systematics

Changing the systematics at running time can be useful to investigate the impact factors affecting the measurement. In GLoBES, the systematics is defined rule-based, *i.e.*, each rule has its own systematics. In addition, AEDL requires that it has to be defined in each rule what "Systematics on" and "Systematics off" means. Therefore, it is usually very simple to switch the systematics on and off:

Function 7.9 `int glbSwitchSystematics(int exp, int rule, int on_off)` *switches the systematics in experiment* `exp` *and rule* `rule` *on (*`on_off` *is* `GLB_ON`*) or off (*`on_off` *is* `GLB_OFF`*). For the experiment or rule index, one can also use* `GLB_ALL`*.*

In the example on page 51, the application of `glbSwitchSystematics` is demonstrated to show the impact of systematics, correlations, and degeneracies.

The error dimension (for the definition, see Sec. 9.6) can also be accessed directly with

Function 7.10 `int glbSetErrorDim(int exp, int rule, int on_off, int value)` *sets the error dimension for systematics on (*`on_off` *is* `GLB_ON`*) or off (*`on_off` *is* `GLB_OFF`*) of experiment* `exp` *and rule* `rule` *to the value* `value`*. The function returns* -1 *if not successful.*

Function 7.11 `int glbGetErrorDim(int exp, int rule, int on_off)` *returns the error dimension for systematics on (*`on_off` *is* `GLB_ON`*) or off (*`on_off` *is* `GLB_OFF`*) of experiment* `exp` *and rule* `rule`*.*

Except from the general treatment of systematics, one can read out and write the signal and background errors, as well as the background centers. For the definitions of these quantities, see Sec. 9.6.

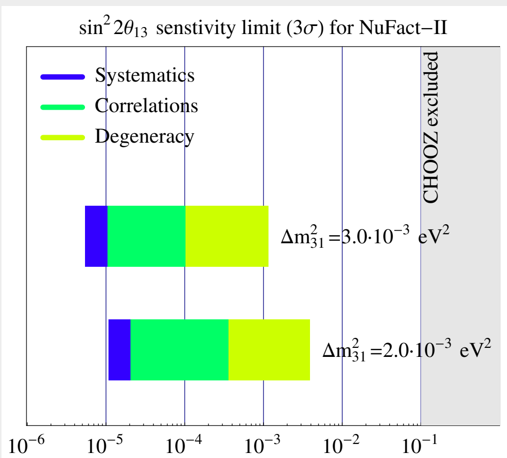
Function 7.12 `int glbSetSignalErrors(int exp, int rule, double norm, double tilt)` *sets the signal errors of experiment* `exp` *and rule* `rule` *to* `norm` *(normalization error) and* `tilt` *(tilt/calibration error).*

Example: The impact of systematics, correlations, and degeneracies

Here it is demonstrated how one can successively include systematics, correlations, and degeneracies at the example of the $\sin^2 2\theta_{13}$-sensitivity limit. An important part of this example is how two switch the systematics off, *i.e.*, how to obtain the sensitivity limit from statistics only. Since this example is very advanced, we only show the respective function of the code:

```
/* Calculate chi2 with statistics only */
double CalcNoSystematics(double theldm,double thex)
{
   /* Switch systematics off for all exps and all rules */
   glbSwitchSystematics(GLB_ALL,GLB_ALL,GLB_OFF);

   /* Calculate Chi2-list as if systematics were on */
   double res=CalcSystematics(theldm,thex);

   /* Switch systematics on for all exps and all rules */
   glbSwitchSystematics(GLB_ALL,GLB_ALL,GLB_ON);

   return res;
}
```

The complete code can be found as `example4.c` with the software, which consists of many of the applications from the earlier examples. In addition, it uses a little trick: It avoids falling into the wrong solution with `glbChiTheta` by using the fit value of δ_{CP} from the step before as prediction of the position of the current calculation.
The returned lists of data from the example represent χ^2 as function of the fit value of $\sin^2 2\theta_{13}$. The intersections of these curves with the line $\chi^2 = 9$ give the $\sin^2 2\theta_{13}$ sensitivity limits at the 3σ confidence level, where we do not include the $\mathrm{sgn}(\Delta m^2_{31})$- and $(\delta_{\mathrm{CP}}, \theta_{13})$-degeneracies in the sensitivity limit with correlations only (green bar):



Function 7.13 `int glbGetSignalErrors(int exp, int rule, double* norm, double* tilt)` *writes the signal errors of experiment* `exp` *and rule* `rule` *to* `norm` *(normalization error) and* `tilt` *(tilt/calibration error).*

Function 7.14 `int glbSetBGErrors(int exp, int rule, double norm, double tilt)` *sets the background errors of experiment* `exp` *and rule* `rule` *to* `norm` *(normalization error) and* `tilt` *(tilt/calibration error).*

Function 7.15 `int glbGetBGErrors(int exp, int rule, double* norm, double* tilt)` *writes the background errors of experiment* `exp` *and rule* `rule` *to* `norm` *(normalization error) and* `tilt` *(tilt/calibration error).*

Function 7.16 `int glbSetBGCenters(int exp, int rule, double norm, double tilt)` *sets the background centers of experiment* `exp` *and rule* `rule` *to* `norm` *(normalization center) and* `tilt` *(tilt/calibration center).*

Function 7.17 `int glbGetBGCenters(int exp, int rule, double* norm, double* tilt)` *writes the background centers of experiment* `exp` *and rule* `rule` *to* `norm` *(normalization center) and* `tilt` *(tilt/calibration center).*

As usual, all these functions return -1 if they were not successful.

7.3 External parameters in AEDL files

Using external parameters in AEDL files is a very powerful feature to change experiment parameters at running time which require that the experiment be re-initialized. For example, one can change the energy resolution function or the number of energy bins. However, in some cases there might be complications, such that the number of pre- or post-smearing efficiencies does not correspond to the number of energy bins anymore. Therefore, this feature needs to be used with care.

In order to use external parameters in AEDL files, one simply introduces them. For example, an energy resolution function

```
energy(#EnergyResolution1)<
      type = 1
      @sigma_e = { myres ,0,0 }
>
```

might be defined in AEDL, where the energy resolution is proportional to `myres` $\times$ energy.

In order to use the user-defined variable, one has to assign it with `glbDefineAEDLVariable` *before* the experiment is initialized with `glbInitExperiment`:

Function 7.18 `void glbDefineAEDLVariable(const char* name, double value)` *assigns the value* `value` *to the* AEDL *variable* `name`.

In our energy resolution example, one could now loop over the energy resolution such as with

```
int i;
for(i=5;i<20;i++)
{
      glbClearExperimentList();
      glbDefineAEDLVariable("myres",0.01*i);
      glbInitExperiment(...);

      /* do something */
}
```

Note that one does not have do re-initialize the oscillation parameter vectors every time within the loop as long as the number of experiments does not change.

In order to clear the external variable stack if one is excessively using it, one can use

Function 7.19 `void glbClearAEDLVariables()` *clears the* AEDL *variable list.*

This function is called automatically upon exit of the program.

7.4 Algorithm parameters: Filter functions

The oscillation frequency filters to filter fast oscillations can also be accessed by the user interface. For details of the filter functions, we refer to Sec. 9.5 of the AEDL manual.

In particular, there are a number of functions:

Function 7.20 `int glbSetFilterState(int on_off)` *sets the currently used filter state to on (*`GLB_ON`*) or off (*`GLB_OFF`*).*

Function 7.21 `int glbGetFilterState()` *returns the currently used filter state.*

Function 7.22 `int glbSetFilterStateInExperiment(int exp, int on_off)` *sets the filter state in experiment* `exp` *to on (*`GLB_ON`*) or off (*`GLB_OFF`*).*

Function 7.23 `int glbGetFilterStateInExperiment(int exp)` *returns the filter state of experiment* `exp`*.*

Analogously, the filter value can be accessed:

Function 7.24 `int glbSetFilter(double filter)` *sets the currently used filter to the value* `filter`*.*

Function 7.25 `double glbGetFilter()` *returns the currently used filter value.*

Function 7.26 `int glbSetFilterInExperiment(int exp, double filter)` *sets the filter in experiment* `exp` *to the value* `value`.

Function 7.27 `double glbGetFilterInExperiment(int exp)` *returns the filter value of experiment* `exp`.

The return value of all `Set-` functions is -1 if they were not successful.

Part II

The Abstract Experiment Definition Language – AEDL

Chapter 8

Getting started

Here the general concept of the AEDL is described and illustrated by an example. In addition, a short introduction to the syntax of the AEDL is given.

8.1 General concept of the experiment simulation

The goal of AEDL is to describe a large number of complex and very different experiments by a limited number of parameters. It allows a representation of very different setups within one data structure, and thus implements universal rate and χ^2 computation methods. For experiment simulations, usually a new piece of code is written and compiled for each different experiment. In many cases, even parameter changes, such as the number of bins, require the recompilation of the source code. However, such a technique soon reaches its limits when the simulated experiments are rather complex, or more than one type of experiment is studied simultaneously. Furthermore, it is very difficult to verify the correctness of the obtained results, since every time a new piece of code is added to deal with a new experiment type, new errors will be introduced.

Thus, a general and flexible experiment description language is needed. The description of a neutrino experiment can be split into three parts: Source, oscillation, and detection. The neutrino sources within GLoBES are assumed to be stationary point sources, where each experiment has only one source. This restricts the classes of neutrino sources which can be studied with GLoBES:

- Experiments using many point-like sources can only be approximated. One example are reactor experiments using many distant reactor blocks.
- Geometrical effects of a source distribution, such as in the sun or the atmosphere, can not be described.
- Sources with a physically significant time dependency can not be studied, such as supernovæ. It is, however, possible to study beams with bunch structure, since the time dependence of the neutrino source is physically only important to suppress backgrounds.

The description of the neutrino oscillation physics is, at least numerically, relatively simple. We use the *evolution operator method* [8] to compute the neutrino oscillation probabilities and divide the matter density profile into layers of constant matter density. For each of these layers, the Hamiltonian in matter is diagonalized in order to propagate the neutrino transition amplitudes. Finally, the transition probability is obtained by the absolute square of the total neutrino transition amplitudes. Depending on the precision of the studied experiment, this approach turns out to be precise enough in Earth matter even if only a small number matter density steps is used. Since we allow an uncertainty of the matter density profile, it is, in fact, in most cases sufficient to consider only one density step with the average matter density together with a matter density uncertainty [9]. Note that this approach may not be applicable to quickly varying extraterrestrial matter density profiles.

While it is comparatively simple to define a general neutrino source and to compute the oscillation physics, the general properties of a detector simulation are much more complicated. The basic assumption in building an abstract detector description is *linearity*, *i.e.*, that two neutrino events do not interfere with each other. Furthermore it is assumed that all information on the oscillation physics is given by the *reconstructed* flavor and energy of a neutrino event. The term "reconstructed" implies that the well-defined energy of the incident neutrino, which can not be directly observed, translates via secondary particles and the detection properties into a distribution of possible energy values. This process is illustrated in Fig. 8.1 for the energy variable. The same, in principle, applies to the nature

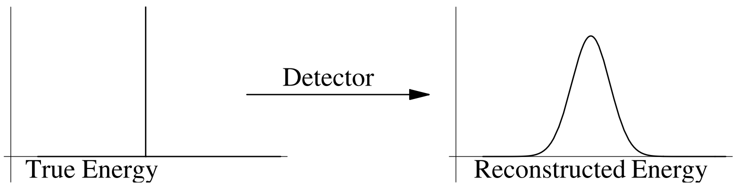


Figure 8.1: A detector maps a true parameter value onto a distribution of reconstructed parameter values. This is illustrated here for there energy.

of the neutrino flavor. However, in this case only discrete values are applicable. Note that the reconstructed neutrino energy and the neutrino flavor are the only observables in GLoBES.

This picture can also be formulated in a more mathematical way. Let us define x as the true parameter value and x' as the reconstructed parameter value. Similarly, $f(x)$ is the distribution of true parameters values and $p(x')$ is the distribution of reconstructed parameter values. Then the detector function $D(x, x')$, which describes the mapping performed by the detector, is given by

$$p(x') \quad = \quad \int dx\, f(x) \cdot D(x, x') \,. \tag{8.1}$$

Obviously Eq. (8.1) only describes the detector properly if the linearity condition is fulfilled. Within this model, a detector is completely specified by a set of $D(E, E')$ for the

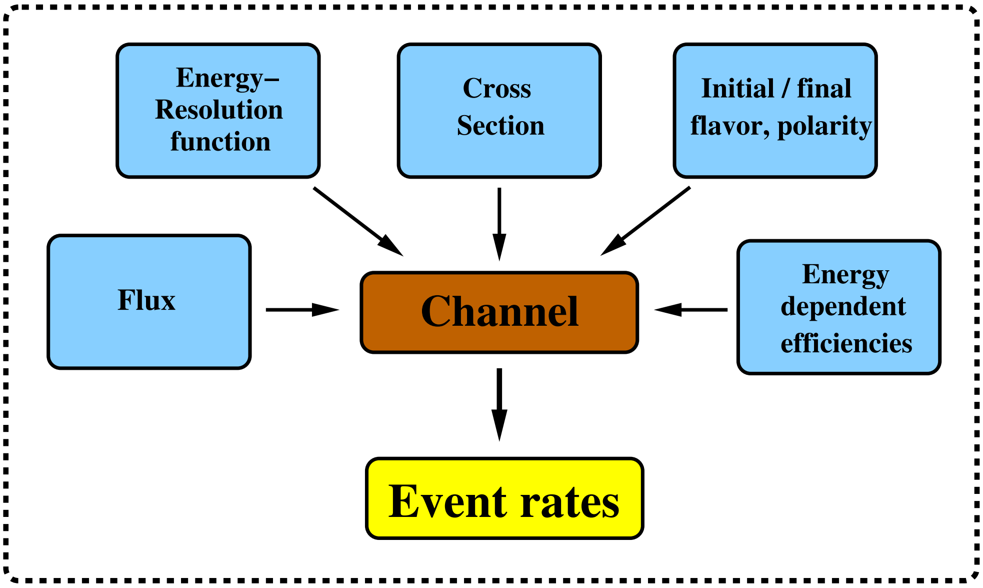


Figure 8.2: General concept of a "channel".

energy variable E, and a set $D(F, F')$ for the flavor variable F. In general, $D(E, E', F)$ also depends on the incident neutrino flavor F, as well as $D(F, F', E)$ depends on the incident neutrino energy E. These sets of mapping functions usually are obtained from a full detector simulation and can be obtained by using as input distribution $f(x)$ a delta distribution $\delta(x - x_0)$.

In order to implement a experiment definition including various sources of systematical errors, we use several abstraction levels. The first level is the so-called "channel", which is the link between the oscillation physics and the detection properties for a specific oscillation pattern (*cf.*, Fig. 8.2). A channel specifies the mapping of a specific neutrino flavor produced by the source onto a reconstructed neutrino flavor. For example, a muon neutrino oscillates into an electron neutrino and subsequently interacts via quasi-elastic charged current scattering. The measured energy and direction of the secondary electron in the detector then allows to reconstruct the neutrino energy. The connection from the source flux of the muon neutrino, via the probability to appear as a electron neutrino, to its detection properties (such as cross sections and energy smearing) is encapsulated into the channel.

The channels are the building blocks for the so-called "rules". In general, a rule consists of one or more "signal" and "background" oscillation channels, which are normalized with efficiencies (*cf.*, Fig. 8.3). The event numbers from these channels are added *before* the $\Delta\chi^2$-value is calculated.[1] In addition, each rule implements an *independent* systematics, such as signal and background normalization errors. Eventually, each rule gives a $\Delta\chi^2$-

[1]Note that in this manual, the χ^2 and $\Delta\chi^2$ are equal, since for simulated data $\Delta\chi^2 = 0$ at the best-fit point. Thus, we are using χ^2 and $\Delta\chi^2$ as equal quantities.

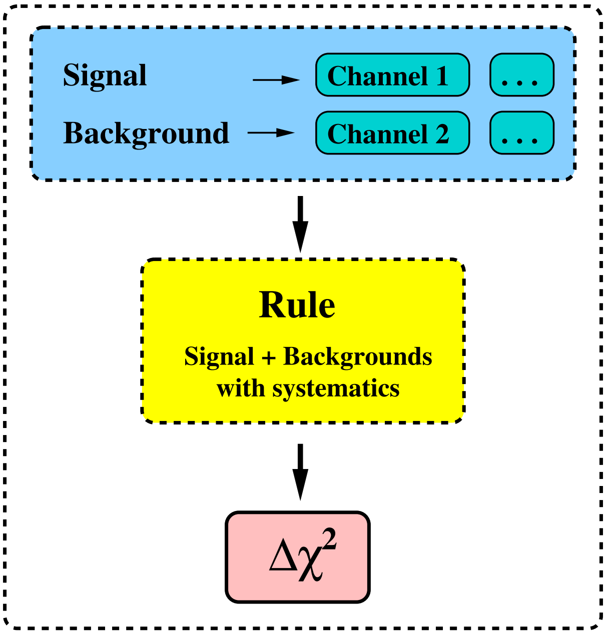


Figure 8.3: General concept of a "rule".

value, and the total $\Delta\chi^2$ of one experiment is obtained by adding the $\Delta\chi^2$'s of all rules (*cf.*, Fig. 8.4). An example for a rule could look like this: We want to detect electron neutrino appearance ("signal"), where the overall efficiency for quasi-elastics electron neutrino events is 0.4. There is a fraction of 0.01 of all neutral current events which are mis-identified as quasi-elastic electron neutrino events ("background"). The neutral current fraction is only known within 10% ("background uncertainty") and there is an energy scale uncertainty of 100 MeV ("energy calibration error"). All this systematics is independent of the other rules. Thus, a rule connects the event rates to the calculation of a $\Delta\chi^2$ which properly includes systematical errors. The resulting $\Delta\chi^2$ is then the starting point for the oscillation physics analysis. Note again that

- Within each rule the event numbers are added.
- Within each rule the systematics is treated independently from the other rules.
- For each rule the $\Delta\chi^2$ is computed; the $\Delta\chi^2$'s from all rules are added.

Of course, an abstract experiment definition language can not simulate all possible types of experiments. As we have seen, there are several assumptions for source and detector. However, it turns out that GLoBES can be applied to a large number of experiment types, such as conventional beams, superbeams, neutrino factories, β-Beams, and reactor experiments.

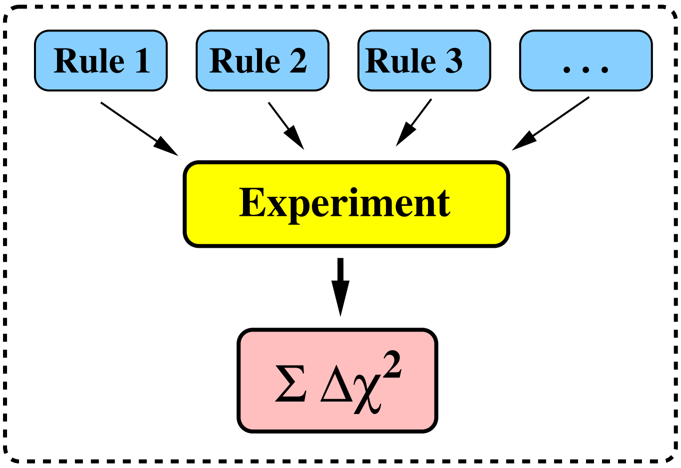


Figure 8.4: General concept of an "experiment".

8.2 A simple example for AEDL

Experiments are in GLoBES defined by the Abstract Experiment Definition Language (AEDL). The experiment definition is written into a text file using the AEDL syntax. Currently, a number of pre-defined experiment definition files are provided with GLoBES, which have to be modified manually in order to define new experiments. The application software then uses this text file to initialize the experiment, where other secondary files might read for source fluxes, cross sections *etc.*. In this section, we show the definition of a very simple neutrino factory in AEDL, where we do not go into details. In the next chapter, we will discuss each of the individual steps in detail.

The first line of every experiment definition file has to be

```
!%GLoBES
```

in order not to confuse it with some other file format. First, we instruct GLoBES to use the built-in source flux for a neutrino factory originating from stored μ^+'s. This achieved by setting the `@builtin` variable to 1. Next, we specify the muon energy to be 50 GeV by the `@parent_energy` variable. We assume that there will be $5.33 \cdot 10^{20}$ useful muon decays per year and that this luminosity is available for 8 years, *i.e.*, a total number of $4.264 \cdot 10^{21}$ muons is stored:

```
/* beam */
flux(#mu_plus)<
   @builtin = 1
   @parent_energy = 50.0
   @stored_muons = 5.33e+20
   @time = 8.0
>
```

Note that we tell GLoBES that we want to refer to this neutrino source later as as `#mu_plus`. Let us now define a very simple detector with a target mass of 50 kt and 20 energy bins between 4 GeV and 50 GeV:

```
$target_mass = 50
$bins = 20
$emin = 4.0
$emax = 50.0
```

Then we specify the file which contains the cross sections we want to use:

```
/* cross section */
cross(#CC)<
  @cross_file = "XCC.dat"
>
```

The command `cross` tells the parser that a cross section environment begins. It has the name `#CC`, which can later be used to refer to this specific environment, and thus to the file `XCC.dat`. Note that each name begins with a leading `#`. Of course, the baseline and matter profile have to be specified, too, where we use an arbitrary matter density profile here:

```
/* baseline */
$profiletype = 3
$densitytab = {3.5}
$lengthtab = {3000.0}
```

The curly brackets used for the definition of `$densitytab` and `$lengthtab` refer to a list of numbers. Here, the lists contain only one element, because we only use one density layer: We initialize a baseline length of 3000 km with a constant matter density of $3.5\,\mathrm{g/cm^3}$. As another ingredient, we have to define the energy resolution function:

```
/* energy resolution */
energy(#MINOS)<
  @type = 1
  @sigma_e = {0.15,0.0,0.0}
>
```

The `energy` command starts the energy environment, which has the name `#MINOS` here. Out of several possibilities, it uses algorithm one, the simplest and fastest one. The actual energy resolution is specified by the energy resolution variable, which is a list of three elements. Each element is one parameter of the general resolution function as defined in Eq. 9.12. Now we have all pieces to be able to define the appearance and the corresponding disappearance channel of a neutrino factory: $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ (μ^+ stored).

```
/* channels */
channel(#appearance)<
  @channel = #mu_plus:  +:  electron:  muon:  #CC: #MINOS
>
channel(#disappearance)<
  @channel = #mu_plus:  -:  muon:  muon:  #CC: #MINOS
>
```

The first element is the name of the flux, which we have defined above. The second element "$\pm$" determines whether neutrinos or anti-neutrinos are taken from the flux table (two different polarities allowed). The third position defines the initial flavor, and the forth position the final flavor, followed by the name of the cross section and energy resolution function as defined before. The last step is to encapsulate the channels into a rule:

```
/* rules */
rule(#rule1)<
  @signal = 0.45 @ #appearance
  @signalerror = 0.001 :  0.0001
  @background = 1.0e-05 @ #disappearance
  @backgroundcenter = 1 :  0.0
  @backgrounderror = 0.05 :  0.0001
  @errordim_sys_on = 0
  @errordim_sys_off = 2
  @energy_window = 4.0 :  50.0
>
```

The `@signal` refers to the "signal" in our experiment. We use the above defined channel named `#appearance` with an constant overall efficiency of 0.45. The signal error variable has two components: The first one is the normalization error of the signal, here 0.1%. The second one refers to the energy calibration error of the signal, which is defined in Sec. 9.5. The background variable specifies the composition of the beam background. In this (simplified) case, we use the fraction $1 \cdot 10^{-5}$ of the channel named `#disappearance`, *i.e.*, the muon neutrinos with a mis-identified charge. The background center variable allows to rescale the total background contribution from all background components simultaneously. It is only useful if there is more than one background component, otherwise it is usually 1. The background error variable is defined such as the signal error variable, *i.e.* we have a 5% background uncertainty and a very small energy calibration error. The "error dimension variable" `@errordim_sys_X` selects how the systematical errors are treated (*cf.*, Table 9.2).

The here defined experiment represents a first simplified version of a neutrino factory experiment. It still lacks the correct energy dependence of the efficiencies, the antineutrino disappearance channel, and the channels and rules for the symmetric operation with μ^- stored. However, it may serve as a simple, introductory example. In the next chapter, we will demonstrate that the AEDL is much more powerful than illustrated here.

8.3 Introduction to the syntax of AEDL

We now give a short introduction to the syntax of AEDL. The first eight characters have to be `%!GLoBES` in order to avoid parsing megabytes of chunk and producing thousands of error messages. Comments can be used such as in C:

```
/* This starts a comment
and here the comment ends */
```

There are pre-defined variables which all start with `$`. Their range is also checked. For example, `$bins` can be only between 0 and 500.[2] If one uses a `float` quantity where an `int` is expected, the `float` will be converted to an `int` in the same way as in C. For example, we have scalar variables

```
$bins = 10
$baseline = 1200.0
```

and simple lists

```
$densitytab={1.0,2.2343,3.3432}
```

Since there are often groups of data which we want to refer to later, environments can be used. This is illustrated with the channel definition part:

```
channel(#ch1)<
  ...
>
```

The first part is the type of environment, which is `channel` here. There are the following types of environment in AEDL:

```
flux
cross
channel
energy
rule
```

Besides the environment type, there is a user-defined name beginning with `#` in the above example: `#ch1`. It can be used later to refer to the channel defined in `<...>`. Those names are so-called "automatic variables" and have to start with `#`. Note that these names have to be unique and can only be refered to after their definition. However, similar to C, one can give a declaration without definition before:

```
channel(#ch2)<>
```

[2]The upper limit is only there for safety reasons, the memory is allocated dynamically.

Now one can refer to the name `#ch2`, while the actual channel definition comes later. The internal representation of this automatic variable is a number, which obtains its value from a counter for each type of environment. For example, for `channel` the counter is `numofchannels`. The counter keeps track of how many different names there are for one type of environment, which means that it counts the number of channels, rules, energy resolution functions *etc.*. Thus, the automatic variables are numbered in the order of their definition, and the number can later be used to refer to them in the C code (from 0 to `numof...`-1). In order to facilitate the the mapping from names in AEDL to indices in C there are two functions `glbNameToValue` and `glbValueToName` which make this transition (see Sec. 6.2, page 43).

Within each environment type, there are several variables beginning with `@`, which can only be used within the appropriate type of environment. In many cases, they have a special syntax, such as `@channel`.

If you want to have several experiments in one file, separate the different experiments by

```
#NEXT#
```

This command resets the counters for channels, rules, fluxes, cross section and energy resolution environments. All variables have their scope limited by either `%!GLoBES, #NEXT#` or `EOF`. This allows a consistent treatment of various experiments in one file.

As another feature of AEDL one can use include files with the `include` command. Includes can be nested up to `MAX_INCLUSION_DEPTH`, which is currently set to 10. Error reporting works for nested includes, too. The included file is not required to begin with `%!GLoBES` to facilitate cut and paste:

```
include "./file_1"
```

With this include mechanism, one can use constructions such as

```
include "NuFact.gls"
#NEXT#
include "JHFHK.gls"
```

in order to initialize a combined analysis of the experiments defined in the files `NuFact.gls` and `JHFHK.gls`. Note that one has to use quotation marks for filenames in AEDL. Even if one uses the automatic variable `#CC` in both experiments, but the cross section data are different (for example, because of different target nuclei), the correct cross section data will be applied to each of the experiments. Note that, alternatively, one can also load both files successively by two separate calls of `glbInitExperiment`.

Furthermore, one can define constants such as

```
Pi = 3.141
```

These constants can not only be defined within one AEDL file, but also by the calling C program, which allows to use a simple but powerful variable substitution mechanism as described in Sec. 7.3.

In addition, some simple algebraic manipulations are possible, such as

```
Pi+1
Pi^2
sin(Pi/2)
```

The following mathematical functions from `<math.h>` are available: `sin`, `cos`, `tan`, `asin`, `acos`, `atan`, `log`, `log10`, `exp`, `sqrt`.

These functions can be used everywhere, where otherwise only a scalar number would appear. However, they can not be applied to lists, such as `sin({1,2,3})` will not work.

Finally, note that a line feed character `\n` is necessary at the end of the input – alternatively you can put a comment at the end.

Chapter 9

Experiment definition with AEDL

In this chapter, we give a detailed definition of the AEDL features. We also show the underlying mathematical concepts, where applicable. We do not exactly follow the separation of source, oscillation, and detection properties, since most issues more or less involve the detection. Instead, we illustrate many of the features of the GLoBES simulation successively in the logical order of their definition, and demonstrate how they translate into AEDL .

9.1 Source properties and integrated luminosity

As we have disussed before, GLoBES can only deal with point sources. Thus, it is not possible to study effects from the finite size of the neutrino production region, such as in the sun or in reactor experiments with many neutrino sources (*e.g.*, KamLAND). Therefore, a neutrino source in GLoBES can, in general, be characterized by the flux spectrum for each neutrino flavor, the CP sign (neutrinos or antineutrinos), and the total luminosity of the source.

Before we come to the definition of the source properties, let us discuss the total integrated luminosity of the experiment. In GLoBES, the total number of events is in general proportional to the product of

$$\text{Fid. detector mass [kt/t]} \times \text{Running time [yr]} \times \left\{ \begin{array}{c} \text{Source power [MW/GW]} \\ \text{Useful muon decays [yr}^{-1}\text{]} \end{array} \right. . \tag{9.1}$$

Thus, the source power corresponds to either the amount of energy produced per time frame in the target (such as for nuclear reactors or sources based on pion decay), or the useful muon decays per time frame (neutrino factories). In addition, the definition of the source power makes only sense together with the flux normalization, the running time, and fiducial detector mass in order to define the total integrated luminosity. Therefore, one can, in principle, use arbitrary units for these components as long as their product gives the wanted neutrino flux. However, it is recommended to use normalizations such that the source power units are MW for a proton-based beam, and $\text{GW}_{\text{thermal}}$ for a reactor experiment. Correspondingly, the detector mass units should be kilotons for a proton-based beam, and tons for a reactor experiment. In any case it is a good idea to document the choices made by the user by corresponding comments in AEDL.

The quantity which can be used to scale the overall integrated luminosity of an experiment, is the fiducial detector mass. For example,

```
$target_mass = 50.0
```

defines a 50 kt detector for a neutrino factory.

There are two principal ways to initialize a neutrino flux: Either one can use a built-in source, or one can provide a file. In both cases, a flux is defined by the environment `flux`, such as

```
flux(#name)<
   ...
   @time = 8.0
>
```

with a running time of 8 years. Note that the running time is used within the `flux` environment. This feature can be used to load the neutrino and antineutrino fluxes separately, in order to combine them with different running times within one experiment. The name of the flux `#name` will later be refered to in the channel definitions.

For a built-in neutrino source, one has to specify which built-in spectrum has to be used, as well as its parameters. The software will then automatically calculate the neutrino spectrum. Note that in this case, there is no degree of freedom in the choice of the source units. Currently, two built-in fluxes are available: μ^+-decay (`@builtin = 1`) and μ^--decay (`@builtin = 2`). In these cases, the muon energy (enery of the parent particle) has to be specified together with the number of useful decays per year. Thus, an example to set up a neutrino factory flux is

```
flux(#mu_plus)<
   @builtin = 1
   @parent_energy = 50.0
   @stored_muons = 5.33e+20
   @time = 8.0
>
```

For a user-defined flux, one has to give it the file name:

```
flux(#user)<
   @flux_file = "user_file_1.dat"
   @time = 2.0
   @power = 4.0
   @norm = 1e+8
>
```

In this case, the `@norm` variable is an overall normalization which defines a conversion factor from the fluxes in the file to the units in GLoBES. In general, there are many ways to give the source power of a neutrino source, such as neutrinos per proton on target per area per time frame. Right now, each flux has its own normalization factor, which is not always straightfoward to calculate. Often, one has to take into account many things, such as the number of target particles per unit mass. In addition, the fluxes will be rescaled by $1/L^2$, which means that the normalization must contain a factor L_0^2. Here L_0 is the distance from the source for which the flux is given to the actual neutrino production region. At the end, it is left to the user to ensure that the numbers in the flux file give, after the multiplication with `@norm`, the proper numbers of produced neutrinos corresponding to the chosen target power `@power`. Usually this adjustment of `@norm` is performed by comparison with known energy spectra for a specific experiment.

The software assumes that the given flux file has seven columns and 501 lines with equidistant energies. The format is:

$$E \quad \Phi_{\nu_e} \quad \Phi_{\nu_\mu} \quad \Phi_{\nu_\tau} \quad \Phi_{\bar{\nu}_e} \quad \Phi_{\bar{\nu}_\mu} \quad \Phi_{\bar{\nu}_\tau}$$

In order to access fluxes at arbitrary energies, linear interpolation is used by the software. In general, it is advisable to provide the flux between `$sampling_min` and `$sampling_max` (*cf.*, Sec. 9.5), since these values are used by the software. However, if the energy leaves the range of values given in the file, zero is returned. The the columns for the fluxes for unused flavours have to be filled all the same,*e.g.* with zeros.

The flux files accept one-line comments, which start with `#` and end with the linefeed character '`\n`', they are not counted as a line and their content is discarded. This comments are useful to provide meta information about the fluxes like units or the origin of the information. This is also the default method to point the user to the references he/she should to cite when using a particular flux.

9.2 Baseline and matter density profile

The baseline and matter density profile determine, besides energy and involved flavors, the neutrino oscillation physics at the experiment description level. All of the neutrino oscillation parameters are defined at running time.

The baseline is given by

```
$baseline = 3000.0
```

Note that baseline lengths are always assumed to be in kilometers.

Furthermore, the matter density profile along the baseline has to be specified. The simplest matter density profile is a constant matter density profile with the average matter density from the PREM [2] onion shell model of the earth :

```
$profiletype=1
```

`$profiletype`	Additional variables	Description
1	`$baseline`	Average density (constant)
2	`$baseline`, `$densitysteps`	PREM profile with given number of equidistant steps
3	`$lengthtab`, `$densitytab`	Arbitrary profile (table of layer thicknesses, table of densities)

Table 9.1: Different matter density profiles which can be used with GLoBES.

If your using this option please cite reference [2].

For a better approximation of the realistic earth matter density profile, one can use an arbitrary number of equidistant steps of the PREM profile:

```
$profiletype=2
$densitysteps=20
```

Note that the value of `$densitysteps` is time-critical, since the computation time of oscillation probabilities is directly proportional to the number of layers. As a third possibility, one can specify the matter density profile manually with a list of thicknesses and densities of the matter density layers. This example uses two density steps with two different densities:

```
$profiletype=3
$densitytab={2.8, 3.5}
$lengthtab={1000.0, 2000.0}
```

It is important that both lists have the same length and that the thicknesses given in `$lengthtab` add up to the length of the baseline, which does not have to be explicitely specified anymore. In addition, matter densities are always given in g/cm^3. This approach can also be used for a constant matter density profile with a specific matter density:

```
$profiletype=3
$densitytab={3.5}
$lengthtab={3000.0}
```

The possible options for matter density profiles are summarized in Table 9.1.

9.3 Cross sections

Cross sections will later be used as part of the channel definition (see Sec. 9.4). Similar to the source fluxes, they are provided by the user as a data file:

```
cross(#name)<
  @cross_file ="user_file_1.dat"
>
```

This cross section can later be refered to by `#name`.

Cross sections are in GLoBES given as differential cross section per energy:

$$\hat{\sigma}(E) = \sigma(E)/E \left[10^{-38}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}^2}\right] \tag{9.2}$$

The software assumes that the cross section files are text files with seven columns and 1001 lines of the form

$$\log_{10}E \quad \hat{\sigma}_{\nu_e} \quad \hat{\sigma}_{\nu_\mu} \quad \hat{\sigma}_{\nu_\tau} \quad \hat{\sigma}_{\bar{\nu}_e} \quad \hat{\sigma}_{\bar{\nu}_\mu} \quad \hat{\sigma}_{\bar{\nu}_\tau}$$

Here the logarithms of the energy values have to be equidistant. For arbitrary energies, linear interpolation is used. If the energy leaves the range of values given in the file, 0.0 will be assumed. In general, it is advisable to provide the cross sections in the range between `$sampling_min` and `$sampling_max` (*cf.*, Sec. 9.5). Unused cross sections have to be filled with zeros, and can not be just omitted.

Like the flux files, the cross section files accept one-line comments, which start with `#` and end with the linefeed character '`\n`', they are not counted as a line and their content is discarded. This comments are useful to provide meta information about the cross sections like units or the origin of the information. This is also the default method to point the user to the references he/she should to cite when using a particular cross section.

9.4 Oscillation channels

Channels in GLoBES represent an intermediate level between the pure oscillation physics given by the oscillation probability $P_{\alpha\beta}$, and the total event rates composed of signal and background. A channel describes the path from one initial neutrino flavor in the source to the event rates in the detector for one specific interaction type (IT) and final flavor. Therefore, a channel contains the description of the initial neutrino flavor, its CP eigenvalue (neutrino or antineutrino)[1], the detected neutrino flavor, the interaction cross sections for the chosen interaction type, and the energy resolution function of the detector.

Before we come to the definition of the channel in AEDL, we introduce the general concept for the calculation of event rates. The first step is to compute the number of events for each IT in the detector for each initial and final neutrino flavor and energy bin. The second step is to include the detector effects coming from the insufficient knowledge in the event reconstruction. These two steps combined lead to the differential event rate spectrum for each initial and final flavor and IT as seen by the detector, which we call the "channel". In this section, we focus on the first step, *i.e.*, we discuss the definition of the energy resolution function in the next section, since this is a rather comprehensive issue.

[1] Currently GLoBES does not support lepton number violating transitions, *i.e.* no transitions from neutrino to antineutrino (or vice versa) are considered.

The differential event rate for each channel is given by

$$\begin{aligned}
\frac{dn_\beta^{\mathrm{IT}}}{dE'} = \quad & N \int_0^\infty \int_0^\infty dE\, d\hat{E} \quad \underbrace{\Phi_\alpha(E)}_{\text{Production}} \times \\
& \underbrace{\frac{1}{L^2} P_{(\alpha\to\beta)}(E, L, \rho; \theta_{23}, \theta_{12}, \theta_{13}, \Delta m_{31}^2, \Delta m_{21}^2, \delta_{\mathrm{CP}})}_{\text{Propagation}} \times \\
& \underbrace{\sigma_f^{\mathrm{IT}}(E) k_f^{\mathrm{IT}}(E - \hat{E})}_{\text{Interaction}} \times \\
& \underbrace{T_f(\hat{E}) V_f(\hat{E} - E')}_{\text{Detection}}, \qquad (9.3)
\end{aligned}$$

where α is the initial flavor of the neutrino, β is the final flavor, $\Phi_\alpha(E)$ is the flux of the initial flavor at the source, L is the baseline length, N is a normalization factor, and ρ is the matter density. The energies in this formula are given as follows:

- E is the incident neutrino energy, *i.e.*, the actual energy of the incoming neutrino (which is not directly accessible to the experiment)
- $\hat{E}$ is the energy of the secondary particle
- E' is the reconstructed neutrino energy, *i.e.*, the measured neutrino energy as obtained from the experiment

The interaction term is composed of two factors, which are the total cross section $\sigma_\beta^{\mathrm{IT}}(E)$ for the flavor f and the interaction type IT, and the energy distribution of the secondary particle $k_\beta^{\mathrm{IT}}(E-\hat{E})$. The detector properties are modeled by the threshold function $T_\beta(\hat{E})$, coming from the the limited resolution or the cuts in the analysis, and the energy resolution function $V_\beta(\hat{E} - E')$ of the secondary particle.

Since it is a lot of effort to solve this double integral numerically, we split up the two integrations. First, we evaluate the integral over $\hat{E}$, where the only terms containing $\hat{E}$ are $k_\beta^{\mathrm{IT}}(E - \hat{E})$, $T_\beta(\hat{E})$, and $V_\beta(\hat{E} - E')$. We define:

$$R_\beta^{\mathrm{IT}}(E, E')\, \epsilon_\beta^{\mathrm{IT}}(E') \equiv \int_0^\infty d\hat{E} \quad T_\beta(\hat{E})\, k_\beta^{\mathrm{IT}}(E - \hat{E})\, V_\beta(\hat{E} - E'). \qquad (9.4)$$

Thus, $R_\beta^{\mathrm{IT}}(E, E')$ describes the energy response of the detector, *i.e.*, a neutrino with a (true) energy E is reconstructed with an energy between E' and $E' + dE'$ with a probability $R_\beta^{\mathrm{IT}}(E, E')dE'$. The function $R(E, E')$ is also often called "energy resolution function". Actually, its internal representation in the software is a smearing matrix. The function $\epsilon_\beta^{\mathrm{IT}}(E')$ will later be refered to as "post-smearing efficiencies", since it will allow us to define cuts and threshold functions *after* the smearing is performed, *i.e.*, as function of E'.

The detailed definition and initialization of the energy resolution function is described in Sec. 9.5.

Eventually, we can write down the number of events per bin i and channel c as

$$n_i^c = \int_{E_i-\Delta E_i/2}^{E_i+\Delta E_i/2} dE' \quad \frac{dn_\beta^{\mathrm{IT}}}{dE'}(E') \tag{9.5}$$

where ΔE_i is the bin size of the ith energy bin. This means that one has to solve the integral

$$n_i^c = N/L^2 \int_{E_i-\Delta E_i/2}^{E_i+\Delta E_i/2} dE' \quad \int_0^\infty dE \; \Phi^c(E)\, P^c(E)\, \sigma^c(E)\, R^c(E,E')\, \epsilon^c(E')\,. \tag{9.6}$$

Note that the events are binned according to their *reconstructed* energy.

A simple channel definition in GLoBES consists of the flux, the CP-sign of the initial state, the initial flavor, the final flavor, the cross sections, and the energy resolution function. In order to refer to flux, cross sections, and energy resolution functions, they have to be defined before with their `#name` in the respective environments. Thus, a simple definition of a channel is

```
channel(#channel_1)<
   @channel = #flux :  +:  muon:  muon:  #cross:  #energy
>
```

It is also possible to define a channel as no-oscillation by using the prefix `NOSC_` in either the initial flavour or the final flavour, like this

```
channel(#channel_1)<
   @channel = #flux :  +:  NOSC_muon:  muon:  #cross:  #energy
>
```

In this case all diagonal probabilities $P_{\alpha\alpha}$ are unity, and all off-diagonal probablities $P_{\alpha\beta}$ are zero. This is, for instance, useful for neutral current events, since these do not depend on any oscillation parameters[2]. The channels marked as `NOSC_` are already computed by `glbSetRates` and do not have to be recomputed in the subsequent fit (which calls the undocumented function `glbSetNewRates`). Therefore this feature can be used to speed up the rate computation considerably, especially in cases where a large set of channels exist which are only used for the computation of backgrounds. Usually it is an excellent approximation to treat backgrounds as if they were not affected by oscillations[3].

Note that the energy environment will be described in the next section. In addition, one can define pre- and post-smearing effects together with the channels, which will also be introduced together with the energy resolution function in the next section.

[2] At least in the absence of sterile neutrinos

[3] In case, the backgrounds have a sizeable dependence on the oscillation parameters they carry information on the oscillation parameters and are therefore more like a signal.

9.5 Energy resolution function

The definition and implementation of the energy resolution function is rather sophisticated in GLoBES. In particular, the choice of the proper parameters depends on the experiment and the frequencies of the involved neutrino oscillations. This choice also greatly influences the speed of the calculation.

In this section, we first discuss the principles of the energy smearing, where it is assumed that the reader is familiar with Sec. 9.4. Then we introduce an automatic energy smearing algorithm, which is fairly simple to understand and applicable to most beam-based experiments. In most cases, the reader may want to continue to the next section after reading these two subsections. In the third subsection, we describe a more elaborate (and slower) smearing algorithm, which can be used together with rather fast neutrino oscillations compared to the bin size, such as for (solar) reactor experiments to avoid aliasing effects. Eventually, we show how one can use a manual smearing matrix instead of using one of the implemented algorithms.

9.5.1 Introduction and principles

The energy resolution function $R^c(E,E')$ has been already introduced in Sec. 9.4, where a definition has been given in Eq. (9.4). Instead of using Eq. (9.4) directly, we apply a slightly different definition of the post-smearing efficiencies $\epsilon(E')$. In general, $\epsilon(E')$ has to be determined by means of a Monte Carlo simulation of the experiment. This usually involves a binning of the simulated events in the reconstructed energy E'. Therefore, one simplify Eq. (9.6) by

$$\int_{E_i-\Delta E_i/2}^{E_i+\Delta E_i/2} dE'\, R^c(E,E')\,\epsilon^c(E') \simeq \hat{\epsilon}_i^c \cdot \int_{E_i-\Delta E_i/2}^{E_i+\Delta E_i/2} dE' \quad R^c(E,E')\,. \tag{9.7}$$

Here the $\hat{\epsilon}_i^c$ are the binned "post-smearing" efficiencies, which will be set within the corresponding `channel` environment (see below). From Eq. (9.6) it is obvious that the integration with respect to the reconstructed energy E' can be performed independently of the oscillation parameters. We define the "bin kernel" K_i^c for the ith bin as

$$K_i^c(E) \equiv \int_{E_i-\Delta E_i/2}^{E_i+\Delta E_i/2} dE' \quad R^c(E,E')\,. \tag{9.8}$$

With this definition, Eq. (9.6) can be re-written as

$$n_i^c = N/L^2\,\hat{\epsilon}_i^c \int_0^\infty dE \quad \underbrace{\Phi^c(E)\,P^c(E)\,\sigma^c(E)\,K_i^c(E)}_{f(E)}\,. \tag{9.9}$$

There is no principle reason why one should not evaluate this integral directly by the usual numerical methods. However, it turns out that this is very slow in many cases.

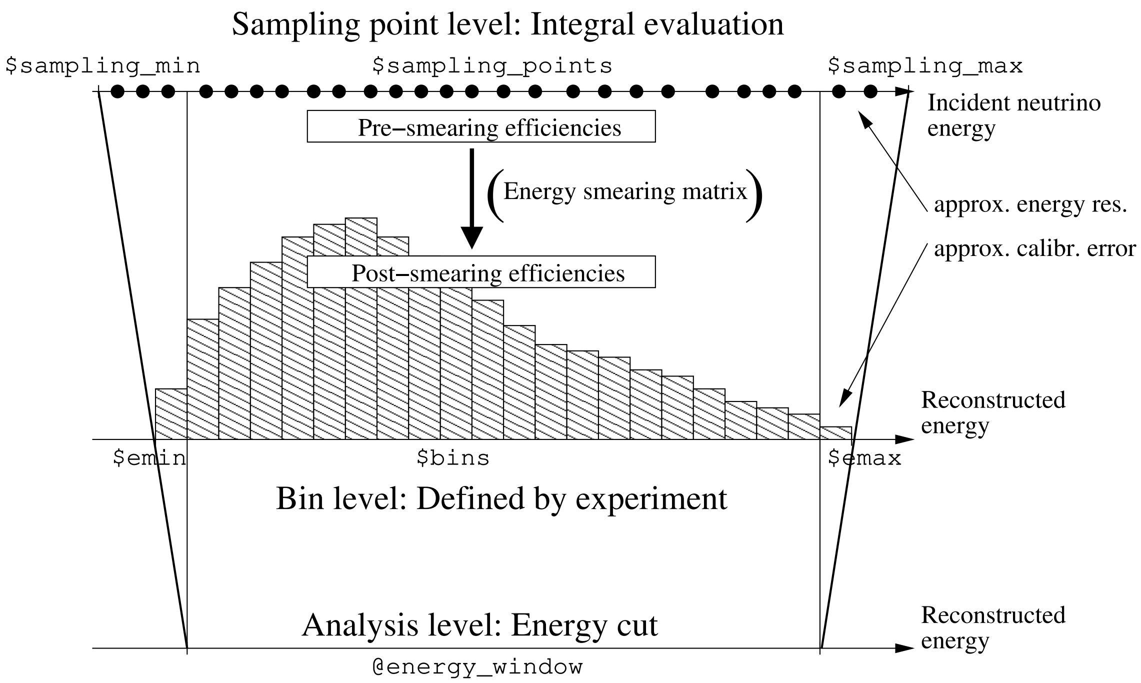


Figure 9.1: The different evaluation levels for the energy smearing in GLoBES.

Therefore, we will introduce two different approximation schemes for different applications in the next two subsections. In either case, the integrand in Eq. (9.9) has to be evaluated at fixed “sampling points”. These sampling points have to directly or indirectly be defined by the user.

Before we come to the calculation algorithms, it is useful to understand the general evaluation algorithm. As it is illustrated in Fig. 9.1, GLoBES uses several levels with respect to the energy ranges:

Sampling point level This level is used internally to evaluate the integrand in Eq. (9.9) at all sampling points. The energy scale is the actual incident neutrino energy E. For a manual definition of the sampling points, use

```
$sampling_points = 20
$sampling_min = 4.0
$sampling_max = 50.0
```

for equidistant sampling points. If no values are given for these variables they are assumed to be equal to their corresponding counter part at bin level, *i.e.* `$sampling_points = $bins`, `$sampling_min = $emin` and `$sampling_max = $emax`.

Arbitrarily spaced sampling points can be specified with `$sampling_stepsize`

```
$sampling_stepsize={1.0,2.0,3.0,4.0,5.0,...}
```

The choice of the sampling point configuration strongly depends on the experiment and required accuracy. Ideally the integrand of Eq. 9.9 is zero outside the sampling range, if this cannot be achieved it is usually sufficient that the sampling range is by about three times the energy resolution[4] larger than the bin range. The spacing of the sampling points should be somewhat smaller (a factor $\simeq 2$ usually is more than ebough) than the finest details of the integrand.

Bin level This level is determined by the experiment and its analysis. Note that energy bin sizes much smaller than the energy resolution will not improve the results. The energy bin range and the number of energy bins do always have to be specified. For the case of large values of the integrand in Eq. (9.9) at the energy range limits, it is recommended to exceed the analysis energy window by about three times the energy calibration error in order to avoid cutoff effects.

In order to define a range between E_{min} and E_{max} divided by a certain number of equidistant bins, use

```
$emin = 4.0
$emax = 50.0
$bins = 20
```

For arbitrary bins, use E_{min} and E_{max} and the size of each bin ΔE_i:

```
$emin = 4.0
$emax = 50.0
$binsize = { 15.0 , 5.0 , 20.0, 6.0 }
```

The number of bins will be automatically computed by GLoBES. Note that the bin sizes have to add up to the energy range `$emax-$emin`.

The choices at bin level are mainly determined by optimizing the performance of the experiment.

Analysis level On the analysis level, an energy window can be defined within each rule. For details, see next chapter.

In general, the energy smearing happens between the sampling point and bin levels, which means that the energy smearing matrix will have `$sampling_points` columns and `$bins` rows.

As illustrated in the figure, an interesting feature in combination with the channels are pre- and post-smearing effects. Pre-smearing effects are taken into account on the sampling point level, and post-smearing effects on the bin level. Examples for these effects are energy dependent efficiencies and (non-beam) backgrounds. Efficiencies are multiplicative factors, whereas backgrounds are added to

[4] evaluated at `$emin` and `$emax` respectively

the event rates. These components can be introduced before or after the integration in Eq. (9.9) is done. If they are introduced before, we call them `@pre_smearing_efficiencies` or `@pre_smearing_background`. If they are introduced after, we call them `@post_smearing_efficiencies` or `@post_smearing_background`. Note that pre-smearing components are always a function of the incident neutrino energy E. Thus, there have to be as many elements as there are sampling points. Examples for pre-smearing quantities are non-beam backgrounds, such as from geophysical neutrinos. The post-smearing components are always a function of the reconstructed neutrino energy E', such as the post-smearing efficiencies $\epsilon_\beta^{\mathrm{IT}}(E')$ in Eq. (9.4). Examples for post-smearing efficiencies are cuts and detection threshold functions. All post-smearing components have to have as many elements as there are energy bins. Efficiencies are multiplicative and their default value is 1, whereas backgrounds are additive and their default value is 0. Thus, a more elaborate channel can be defined as

```
channel(#channel_1)<
  @channel = #flux :  +:  muon:  muon:  #cross:  #energy
  @pre_smearing_background = {1,2,3,4,5,6,7,8,9,10}
  @post_smearing_efficiencies = {0.1,0.2,0.3,0.4,0.5}
>
```

This experiment uses 10 sampling points and 5 bins.

In the following subsections we will define the energy resolution function. All energy resolution functions are defined within an `energy` environment and can be refered to by `#name`.

```
energy(#name)<
  ...
>
```

The individual parameters of the environment will be defined below and depend on the algorithm used.

9.5.2 Bin-based automatic energy smearing

This algorithm is the simplest of the built-in algorithms for the evaluation of Eq. (9.9). It is applicable to most of the experiments which can be simulated with GLoBES.

The key idea is to use a "flat" model, *i.e.* the integrand of Eq. 9.9 is well approximated by being piecewise constant in each sampling step. This is a good approximation as long as

- No details are lost, *i.e.* the spacing of sampling points is smaller than the energy resolution.
- The edges are treated correctly.
- The neutrino oscillations are slow on a scale of the smapling point distance.

In this case, Eq. (9.9) is reduced to

$$n_i^c = N/L^2 \sum_{j=1}^{N} \Phi^c(E_j)\, P^c(E_j)\, \sigma^c(E_j)\, K_i^c(E_j)\, \Delta E_j\,. \tag{9.10}$$

The advantages of this algorithm are obvious: All factors independent of the oscillation parameters have to be only evaluated once at values of E which are known in advance, which means that they can be put into a look-up table. In addition, the probability has to be only evaluated at previously known values of the energy, which makes it possible to compute the transition amplitudes for all channels simultaneously. One assumption is that all involved factors are piece-wise constant, *i.e.*, they hardly change within each bin. This assumption seems to be very restrictive, which is however not quite correct. First of all, if one analyzes simulated data (which are simulated with the same algorithm), the errors will cancel between the simulated and fitted data. Second, and more important, this algorithm is just a very basic integration routine[5] and converges to the true result for decreasing step size. Thus if the number of sampling points is large enough this algorithm is very accurate. This algorithm is selected by

```
@type = 1
```

within the `#energy` environment. The computation of the bin kernel K_i^c is performed by GLoBES. Thus, it requires that the number of bins `$bins` and the minimum energy `$emin` and maximum energy `$emax` are given in case of equidistant bins. As far as the parameterization for the energy resolution function $R^c(E, E')$ in Eq. (9.8) is concerned, the algorithm uses a Gaußian

$$R^c(E, E') = \frac{1}{\sigma(E)\,\sqrt{2\pi}}\, e^{-\frac{(E-E')^2}{2\sigma^2(E)}}\,. \tag{9.11}$$

There are several energy resolution functions available, where by default `#standard` is used:

```
@sigma_function = #standard
```

The energy resolution function `#standard` is defined by

$$\sigma(E) = \alpha \cdot E + \beta \cdot \sqrt{E} + \gamma\,, \tag{9.12}$$

where the parameters α, β and γ are provided by the user:

```
@sigma_e = {0.15, 0.0, 0.0}
```

[5]It is planed for to have something like a Gauß-Kronrod scheme as an alternative here.

Currently, another possible choice for `@sigma_function` is `#inverse_beta`, which only uses the parameter α. It is defined by

$$\sigma(E) = \begin{cases} \alpha \cdot \sqrt{1000}^{-1} \sqrt{x - 8 \cdot 10^{-4}}\,, & \text{for } x > 1.8 \cdot 10^{-3} \\ \alpha \cdot 10^{-3}\,, & \text{for } x \leq 1.8 \cdot 10^{-3} \end{cases} \tag{9.13}$$

The somewhat complicated form is due to the fact that inverse β-decay has a neutrino threshold of 1.8 MeV and that a neutrino at threshold already produces $\simeq 1$ MeV visible energy in the detector (for more details see *e.g.* [6]).

In the actual implementation of the algorithm, the sum in Eq. (9.10) is only computed for the E_j's where $K(E_j)$ is above a certain threshold, which is by default 10^{-7}. This threshold is defined at the compiling time.

Eventually, a complete energy resolution definition of this algorithm is, for example,

```
energy(#name)<
  @type = 1
  @sigma_function = #standard
  @sigma_e = {0.15 ,0.0 ,0.0}
>
```

9.5.3 Low-pass filter

In order to ensure that fast oscillating probabilities do not lead to aliasing, it is possible to impose a low-pass filter already during the calculation of the probabilities itself. This filter is implemented has a highly experimental feature called "filter". The calculation of oscillation probabilities is, in principle, a computation of phase differences. Restricting the maximum admissible size of those phase differences effectively filters the high frequency component of the oscillation probability. This idea is implemented according to

$$P_{\alpha\beta}(E) \quad = \quad \sum_{ij} U_{\alpha j} U^*_{\beta j} U^*_{\alpha i} U_{\beta i} e^{-i\Phi_{ij}} \times e^{-\Phi^2_{ij}/\sigma_f(E)^2}\,, \tag{9.14}$$

where $\Phi_{ij} := \Delta m^2_{ij} L/2E$ is the usual phase difference and the last term is a Gaußian filter with width $\sigma_f(E)$. Choosing $\sigma_f(E) := \sigma^0_f \cdot E$ ensures that this filter behaves approximately such as an energy resolution function with constant width $\sigma_e = \sqrt{2}/\sigma^0_f$, *i.e.*

$$\int d\tilde{E} \quad P(\tilde{E}) \frac{1}{\sigma_e \sqrt{2\pi}}\, e^{-\frac{(E-\tilde{E})^2}{2\sigma_e^2}}\,. \tag{9.15}$$

The relationship between Eqs. 9.14 and 9.15 is not obvious and connected to the properties of $P_{\alpha\beta}$: see Refs. [10, 11]. This feature works *only* for vacuum and constant densities and is controlled by the filer state variable. In addition, σ_e is set by the filter value variable:

```
$filter_state = 1
$filter_value = 2.0
```

would switch the filter feature on and set the width to 2.0 GeV. The setting of `$filter_state` is ignored whenever a density profile with more than one layer is used.

With a type 1 (`@type = 1`) energy resolution function, σ_e adds on to the energy resolution function of the detector $\sigma_c(E)$ such as

$$\sigma_{\text{eff}}(E)^2 \simeq \sigma_e^2 + \sigma_c(E)^2\,. \tag{9.16}$$

Sometimes this behavior is unwanted, and therefore one can try to 'subtract' the filtering from the energy resolution function by splitting the energy resolution function $\sigma(E)_{\text{eff}}$ in two parts by

$$\sigma_{\text{eff}}(E)^2 = \underbrace{\sigma_c(E)^2 - \sigma_e^2}_{\tilde{\sigma}_c^2(E)} + \sigma_e^2\,, \tag{9.17}$$

where the truncated energy resolution function $\tilde{\sigma}_c(E)$ is used instead of $\sigma_c(E)$ in computing the smearing data. Thus one obtains as effective energy resolution

$$\sigma_{\text{eff}}(E)^2 \simeq \sigma_c(E)^2\,. \tag{9.18}$$

This scheme is used by choosing as type for the energy resolution

```
@type = 2
```

9.5.4 Manual energy smearing

In some cases, one may use the output of a detector Monte Carlo simulation directly. Then one can use "manual" energy smearing instead of the automatic energy smearing algorithms.

The energy smearing matrix K_{ij} has `$bins` rows and `$sampling_points` columns, which are numbered from 0 to `$bins`-1 or `$sampling_points`-1. It is equivalent to the bin- and sampling-point-based kernel in Eq. (9.8):

$$K_{ij} = K_i^c(E)|_{E=E_j}, \tag{9.19}$$

where E_j is the energy of the jth sampling point. In general, many of the entries in this matrix are zero, which means that it is convenient to evaluate the integrand in Eq. (9.9) only at positions where K_{ij} is non-zero. The corresponding "sampling range" range of non-zero matrix entries in K_{ij} for the ith energy bin is defined to run from column k_l^i ("lower index") to column k_u^i ("upper index"). An example for a smearing matrix is

$$K_{ij} = \underbrace{\begin{pmatrix} a_{00} & a_{01} & a_{02} & a_{03} & & & & \\ a_{10} & a_{11} & a_{12} & a_{13} & a_{14} & & & \\ & a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & & \\ & & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & \\ & & & a_{43} & a_{44} & a_{45} & a_{46} & a_{47} \\ & & & \uparrow & & \ddots & & \uparrow \\ & & & k_l^i & & & & k_u^i \end{pmatrix}}_{\texttt{\$sampling\_points}\text{ columns}} \quad \leftarrow \quad \texttt{\$bins}\text{ rows}\,, \tag{9.20}$$

where the unshown entries are zero. Thus, the values of K_{ij} have to be specified between k_l^i and k_u^i in the form $\{k_l^i, k_u^i, K_{i\,k_l^i}, K_{ik_l^i+1}, \ldots, K_{ik_u^i}\}$:

```
energy(#name)<
  @energy = {0,2, 0.8634265, 0.0682827, 4e-06}:
    {0,4, 0.1507103, 0.6965592, 0.1507103, 0.00101, 1e-07}:
    ...
    {40,42, 0.1507103, 0.6965592, 0.1507103};
>
```

The last line has to be terminated by a semicolon ';'. Note that the sum of all entries in each *column* should be equal to unity, since all of the incoming neutrinos should be assigned to energy bins. In many practical cases, however, the definition of the energy smearing can lead to sums smaller than unity, such as in the case of truncated Gaußian distributions. The sum of entries in each *row* is not defined, since the events might be unevently distributed into the energy bins according to the energy resolution function.

9.6 Rules and the treatment of systematics

The set of rules for an experiment is the final link between the event rate computation and the statistical analysis. The information in the rules specifies how the χ^2 is computed based upon the raw event rates given by the channels and possible systematical errors. Therefore a rule has two parts: The first part describes how signal and background events are composed out of the channels, and the second part specifies which systematical errors are considered, as well as their values. For a rule, the splitting in signal and background is useful for the treatment of systematics, as we will se later. Each rule will lead to a $\Delta\chi^2$-value, which means that all $\Delta\chi^2$'s of the different rules will be added for the whole experiment. Within each rule, the event rates are added, and the systematics is considered to be independent of the other rules. Thus, it is convenient to combine the above defined channels for different oscillation patterns and interaction types into one logical construction, which is the rule. For example, a superbeam usually has two rules: One for the ν_e-appearance rates, and one for the ν_μ-disappearance rates. In each case, contributions of several interaction types, as well as from the ν_e-contamination of the beam will lead to a number of contributing signal and background event channels.

For each rule, the signal event rate s_i in the ith bin can be composed out of one or more channels by

$$s_i = \alpha_{c_{s1}} \cdot n_i^{c_{s1}} + \alpha_{c_{s2}} \cdot n_i^{c_{s2}} + \ldots \tag{9.21}$$

where the α's are overall normalization factors/efficiencies determined by the properties of the detector. Note that bin-based (energy-dependent) efficiencies can be defined with the post-smearing efficiencies in the last section. In addition, note that in most cases, it makes sense to have only one signal channel and to assign all sorts of perturbations to the background. Similarly, the background event rate b_i in the ith bin can be composed out of one or more channels

$$b_i = \beta_{c_{b1}} \cdot n_i^{c_{b1}} + \beta_{c_{b2}} \cdot n_i^{c_{b2}} + \ldots , \tag{9.22}$$

where the channels can be any combination of the ones in the signal rate and additional ones. The background normalization factors very often have a specific meaning. For example, they may correspond to a fraction of mis-identified events (charge or flavor mis-identification). These basic building blocks of each rule are, within the rule environment, for example defined by

```
@signal = 0.5 @ #channel_1
@background = 0.001 @ #channel_2 :  0.005 @ #channel_3
```

For the analysis of the systematical errors, the so called "pull method" is used [12][6]. For the pull method, k systematical errors are included by introducing k additional variables ζ_k, which are the so-called "nuisance parameters". The nuisance parameters describe the dependence of the event rates on the various sources of systematical errors, such as an error on the total normalization is included by multiplying the expected number of events in each bin by a factor $(1+\zeta_1)$. The variation of ζ_1 is in the fit constrained by adding a penalty p_1 to the χ^2-function. In case of a Gaußian distributed systematical error, this penalty is given by

$$p_i = \frac{(\zeta_i - \zeta_i^0)^2}{\sigma_{\zeta_i}^2} , \tag{9.23}$$

where ζ_i^0 denotes the mean and σ_{ζ_i} the standard deviation of the corresponding nuisance parameter. We further on also refer to the mean as the "central value", and to the standard deviation as the "error". The latter corresponds to the actual systematical uncertainty. The resulting χ^2 is then minimized with respect to all nuisance parameters ζ_i, which leads to χ^2_{pull}

$$\chi^2_{\mathrm{pull}}(\boldsymbol{\lambda}) := \min_{\{\zeta_i\}} \left(\chi^2(\boldsymbol{\lambda}, \zeta_1, \ldots, \zeta_k) + \sum_{j=1}^{k} p_j(\zeta_j) \right) . \tag{9.24}$$

Here $\boldsymbol{\lambda}$ refers to the oscillation parameters including the matter density ρ. One advantage of the pull method is that whenever the number N of data points is much larger than k, it is numerically easier to compute χ^2_{pull} than to invert the $N \times N$ covariance matrix. For the experiments considered here, N is typically 20 and $k \sim 4$, which means that the pull method is numerically much faster. Moreover, it is more flexible and allows the inclusion of systematical errors also for a Poissonian χ^2-function. In Ref. [12], it has been demonstrated that the pull method and the covariance based approach are equivalent for a Gaußian and linear model. In general, there is a separate $(\chi^2_{\mathrm{pull}})^r$ for each rule r, *i.e.*, pair of signal and background spectra, with a separate set of nuisance parameters ζ_i^α. Thus, χ^2_{pull} is the sum of all individual $(\chi^2_{\mathrm{pull}})^r$'s. By the minimization, the dependence on the k nuisance parameters has been eliminated from χ^2_{pull}.

[6] In fact the pull method was employed already in Ref. [5] before Ref. [12] appeared.

Now we can introduce the different systematical errors. The two most important and most easily parameterized systematical errors are the normalization and an energy calibration errors. These errors are assumed to be independent between the signal events and the background events, which means that this systematics treatment defines the grouping into signal or background. The implementation of the normalization error is straightforward:

$$s_i(a) := a \cdot s_i \tag{9.25}$$

with an analogous definition for the background events. Here, a is the"nuisance" parameter, which will be minimized over later.

For the parameterization of an energy calibration error, two possibilities are implemented. The first one (method "T") is somewhat simpler, whereas the second one (method "C") is more accurate, but it requires a careful choice of parameters. The first option (method "T") is

$$s_i(a,b) \equiv s_i(a) + b \cdot s_i \, E'_i/(E'_{\mathrm{max}} - E'_{\mathrm{min}}), \tag{9.26}$$

where E'_{min} and E'_{max} correspond to `$emin` and `$emax`, and E'_i is the mean (reconstructed) energy of the ith bin. It is often refered to as a "tilt" of the spectrum, since it describes a linear distortion of the event rate spectrum. Note that this definition of a tilt makes only sense in combination with a large enough normalization error, since the tilt also affects the normalization. The second option (method "C") is closer to an actual energy calibration error, which means that one should test this option whenever one suspects a large impact of this systematical error. It is based upon replacing the events in the ith bin by the ones at the energy $(1+b) \cdot E'_i$. If this target energy does not exactly hit a (discrete) bin energy E_k, linear interpolation is used. We use the following approximation:

$$\begin{aligned} s_i(a,b) &= (1+b) \cdot \left[(s_{k+1}(a) - s_k(a)) \cdot (\delta - k) + s_k(a) \right] , \\ \delta &= b \cdot (i + t_0 + 1/2) + i \, , \\ k &= \mathrm{div}(\delta, 1) \, , \\ t_0 &= E'_{\mathrm{min}}/\Delta E_0 \, . \end{aligned} \tag{9.27}$$

Here ΔE_0 is the bin width (`$emax-$emin`)/`$bins` and "div" refers to the integer part of the division. Note that the factor $(1+b)$ in the first equation comes from a renormalization of the bin width, since also the bin width is altered by the replacement of the energies. Furthermore, special care has to be payed to the limits $k < 1$ or $k+1 > N_{\mathrm{bins}}$, since there s_k or s_{k+1} may not have been calculated. By default, it is assumed that s_k is zero in those cases. However, if the event rates are still large at the limits, errors will be introduced leading to a wrong estimate of the impact of the calibration error. In this case, one should truncate the analysis range by a few bins at the boundaries and therefore ensure in this way that only those s_i are used whose index k is within the range $0, \ldots, N_{\mathrm{bins}} - 1$ (*cf.*, Fig. 9.1). Thus, it is possible to constrain the analysis energy range with each rule to an energy window:

```
@energy_window = 4.0 :  50.0
```

The default energy window is given between the minimal and maximal reconstructed energy. To be on the save side, reduce analysis window compared to the bin range on each side by about three times the energy calibration error.

Eventually, the total event rate x_i in a bin i is given by

$$x_i(a,b,c,d) = s_i(a,b) + b_i(c,d)\,, \tag{9.28}$$

and is thus a function of four parameters. The four parameters a, b, c, d have been introduced in order to describe systematical uncertainties and are the nuisance parameters. Each of the four parameters has a central value and systematical error. The central values for all of the four parameters have to be always defined. They are called signal normalization (a), signal tilt/calibration (b), background normalization (c) and background tilt/calibration (d). The default values are

$$a = 1\,, \quad b = 0\,, \quad c = \texttt{not assigned}\,, \quad d = 0\,. \tag{9.29}$$

Thus, for the background normalization c, the value has to be specified in *either* case. The values for the normalization and the values of tilt/calibration are always regarded as a pairs, *i.e.*, they are given in the form `normalization : tilt`. The errors are treated in the same way. For example, we have

```
@signalerror = 0.001 :  0.01
@backgroundcenter = 0.1 :  0.0
@backgrounderror = 0.001 :  0.01
```

There is no `@signalcenter` in this definition, since by default the central value for the signal normalization is 1 and the central value for the tilt/calibration is 0.

The user has the possibility to choose the set $\{\zeta_i\}$ of nuisance parameters which are minimized over. This choice is specified with the error dimension variable, and the different possibilities are shown in Table 9.2. Since the error dimension defines the treatement of systematics it is useful to have define a matched pair of error dimensions for each rule, where on value describes how the event rate is computed for *no* systematics and the other one is with systematics (see also Sec. 7.2). The error dimensions for the case of no systematics is set for each rule by the value of `@errordim_sys_off`, whereas the error dimension for systematics on is given by `@errordim_sys_on` . Thus, for example, the complete error dimension definition could look like

```
@errordim_sys_off = 2
@errordim_sys_on = 0
```

It is foreseen to add the possiblity to extend the set of error dimensions or the set of possible systematical errors in one of the next versions of GLoBES.

Eventually, a rule looks like

Error dimension	a	b	c	d	Tilt/Calibration	Remarks
0	+	+	+	+	T	Systematics with tilt
2	-	-	-	-	-	No systematics
4	+	+	+	+	T	Total rates
7	∞	-	∞	-	-	Spectrum only
8	-	-	-	-	-	Total rates, No systematics
9	+	+	+	+	C	Systematics with calibration

Table 9.2: Possible values of the error dimensions variable in GLoBES and their meaning. If a parameter is designated with +, it will be marginalized over, and therefore the corresponding error needs to have a non-zero value. If the cases with "total rates" in the remarks, the summation over the bins is performed *before* computing the χ^2, *i.e.*, no spectral information is used. The error dimension 7 "spectrum only" leaves the normalization free ($\sigma_a = \sigma_c = \infty$), and therefore only the spectral information is used. As a consequence, the settings for the normalization error will be ignored (designated with the symbol ∞).

```
rule(#rule_1)<
  @signal = 0.5 @ #channel_1
  @background = 0.001 @ #channel_2 :  0.005 @ #channel_3
  @signalerror = 0.001 :  0.01
  @backgroundcenter = 0.1 :  0.0
  @backgrounderror = 0.001 :  0.01
  @errordim_sys_off = 2
  @errordim_sys_on = 0
  @energy_window = 4.0 :  50.0
>
```

9.7 Version control in AEDL files

In order to avoid problems which come from different versions of GLoBES and AEDL files, it is possible to use in each AEDL file a version number. For example, it may correspond to the minimum version number of the GLoBES package with which it works. Set the `$version` by

```
$version="1.8.1"
```

This information can be accessed by the versioning functions as described in Sec. 2.5.

Chapter 10

Testing & debugging of AEDL files

AEDL is a powerful language to describe a variety of different experiments. This chapter demonstrates how to test an AEDL file in order to check if it really describes a given experiment. For this application, the GLoBES package contains the program `globes`. It can either be regarded as an AEDL debugger, or as a simple command-line oriented tool to convert the rather abstract AEDL experiment description into more accessible event rates.

10.1 Basic usage of the `globes` binary

The `globes` binary is installed together with the library, but into the directory `$prefix/bin/`. In order to use the `globes` utility, this directory has to be in the path of the shell used to call the program.[1]

As an argument, `globes` takes a `.glb`-file. While parsing it, it prints any warnings and errors which have occured during reading the file. Then it uses the experiment description in the file to compute the event rates at a certain point in parameter space. Finally, it displays the result based on the options used to call `globes`. The options of `globes` follow the GNU standard. Thus, there is a `--help` option to display all other options together with short descriptions.

Calling `globes` without any options and with a `.glb`-file as argument produces an event summary at rule level. In this case, the full experiment description in the file is taken into account, *i.e.*, all efficiencies, backgrounds, and energy resolution effects. Thus, the returned event rates are the ones which will be actually used to compute the χ^2 later. By default, the oscillation parameters used to calculate the transition probability are

$$\begin{aligned} \sin^2 2\theta_{12} &= 0.8 \qquad & \Delta m^2_{21} &= 7 \cdot 10^{-5}\,\mathrm{eV}^2\,, \\ \sin^2 2\theta_{23} &= 1.0 \qquad & \Delta m^2_{31} &= 3 \cdot 10^{-3}\,\mathrm{eV}^2\,, \\ \delta &= 0 \qquad & \sin^2 2\theta_{13} &= 0.1\,. \end{aligned} \tag{10.1}$$

[1]This is automatically the case if no options are given to `configure`, and `make install` was executed with root-privilege, *i.e.*, a standard installation was done.

Of course, it is possible to change these default values either by using the option `-p` on a call by call basis, or by setting the environment variable `GLB_CENTRAL_VALUES`:

```
globes -p'0.55,0,0.785,0,0.0008,0.0025'
globes --parameters='0.55,0,0.785,0,0.0008,0.0025'
```

For example, `GLB_CENTRAL_VALUES` can be defined within the shell session or in the shell profile:

```
export GLB_CENTRAL_VALUES='0.55,0,0.785,0,0.0008,0.0025'
```

Furthermore it is possible to switch off oscillations with the `-N` option and to switch them on again with `-O` (the default). The effect of `-N` is the same as to use `NOSC_` in all oscillation channels. Thi feature is useful if one wants to normalize an expriment flux if the number of un-oscillated events is given.

The AEDL parser and interpreter have basically three levels of messages to the user: Warnings, errors and fatal errors. Fatal errors are always reported and lead to a program exit with status '1'. Usually only errors and no warnings are reported. The verbosity level can be chosen by the `-v` option, where `-v1` is default, *i.e.*, only errors and fatal errors are reported. The level -v0 corresponds to reporting fatal errors only, and `-v2` will print warnings in addition to fatal errors. It is recommended to test any new `.glb`-file with `-v2` to check the warnings at least once, and to decide whether there is a problem to be fixed. With `-v3` all files read by `globes` are displayed together with their path, and with `-v4` all files which have been attempted to be read are shown. These two setting are useful to clarify path resolution issues and shadowing of file names.

10.2 Testing AEDL files

In the process of defining a new experiment, the default output of `globes` at rule level is the final step. However, in order to arrive at this level it is often necessary to review the intermediate steps in the event rate calculation. The `globes` utility offers many possibilities to do this based on the rate access functions as described in Sec. 6.3.

By default, `globes` returns total rates corresponding to the `-t` option. This can be changed to to a full spectrum by using `-s`. The spectral rates are shown in a table where the first column always gives the central energy of the corresponding bin or the sampling point.

If there is more than one experiment in a file, *i.e.*, there is at least one `#NEXT#` command, only the event rates for one experiment will be shown. This experiment can be chosen with the `-e` option, which takes as a mandatory argument the number of the experiment (starting with zero). The default is `-e0`.

Channel level

As a first step, one may want to check if each channel produces the anticipated output. Channel rates are returned if the `-c` option is used. This option takes as an optional argument the channel number (starting at zero). If no argument is given all channels are displayed. By default, the sum of the event rates in each channel is shown. Each column has as first line the same channel name as in the file.

It is also possible to switch off one detector effect after the other. First, one can switch off the post-smearing efficiencies (`-f`) and the post-smearing backgrounds (`-g`). Next, one can switch off the energy resolution function with (`-b`) and view the rates before smearing. If the `-s` option is also used, the number of lines in the output will be given by `$sampling_points`. Another effect of the `-b` option is that the post-smearing efficiencies and backgrounds are no longer taken into account. Therefore, the `-g` and `-f` options now apply to the *pre*-smearing efficiencies and the *pre*-smearing backgrounds. Thus,

```
globes -c -b -g -f FILE
```

produces the raw event rate corresponding to the convolution of flux, probability, and cross section, which is neglecting all detector effects.

Rule level

The next logical step after checking the channel rates is to investigate the rule rates. The rule rates are returned with the option `-r`. This option takes as an optional argument the rule number (starting at zero). If no argument is given, all rules will be displayed. By default, the sum of the event rates in each rule is shown, as well as for each component within the rule. Each rule is preceeded by a line with the same rule name as in the file.

It is also possible for rules to switch off one detector effect after the other – with the limitation that rules only make sense after the energy resolution function has been applied to each channel. Therefore, it is *not* possible to use `-b` together with `-r`, or to switch off any pre-smearing efficiencies or backgrounds. One can, however, switch off the post-smearing efficiencies (`-f`) and the post-smearing backgrounds (`-g`) for each channel. Since the definition of a rule also contains so-called "coefficients", it is possible to switch them off with `-i`. This options also deactivates any setting of `@backgroundcenter`.

Output

The default output stream is `stdout`. The output can be re-directed to a file using the `-o` option, which takes as mandatory argument the file name. The default output format aims at maximal readability for a human eye. In many cases however, the output of `globes` is produced as input for other programs. There are some features to adjust the output format. Usually one would like to omit the channel and rule names by using simple printing `-S` instead of pretty printing `-P`.

There are special options for certain special formats: `-m` produces Mathematica[2] list output, which can be directly visualized by `MultipleListPlot`. The option `-u` uses the same principal formatting as `-m`, but it allows to specify the left, middle, and right delimiters in constructing the list, such as

[2] Mathematica is a trademark of Wolfram Inc.

```
left
left 1 middle 2 middle 3 right
middle
left
left 1 middle 2 middle 3 right
right
```

This is, with `left` = '{', `middle` = ',' and `right` = '}', equivalent to the list $\{\{1,2,3\},\{1,2,3\}\}$. The delimiters can be set by `-L`, `-M` and `-R` as in the following example:

```
globes -Su -R$'\n' --Middle=" " -L" " ...
```

Here `$'\n'` is the escape sequence in the shell for ANSI C-like characters, such as linefeed '`\n`'. The above example produces a a two column file such as

1.0 0.12
1.2 0.14
1.3 0.18
...

where the first column is the central energy of the bin or the sampling point, and the second column gives the event rate. Usually, the output is a concatenation of many such two columns tables, where each rule part or channel part has its own table. Thus one can, by using `-u` and user-defined delimiters, construct many different output formats.

AEDL external variable substitution

Some `.glb`-files use external AEDL variables in order to allow special purpose studies (such as the energy resolution-dependence). If the external variables are not explicitely specified, they are interpreted by the parser as zeros. Thus, it is impossible to properly parse any files with `globes` which contain such undefined variables. Hence, there is the possibility to define AEDL variables by using the define option `-D`. A call such as

```
globes -DBASELINE=3000 ...
```

would define the AEDL variable `BASELINE` to be 3000.

Acknowledgments

We would like to thank Martin Freund, who wrote the very first version of a three-flavour matter profile treatment many years ago. PH is especially thankful for the invaluable advice of Thomas Fischbacher on many design issues. In addition, we would like to thank Mark Rolinec for his help to translate the experiment descriptions into AEDL, and for creating the illustrations in this manuscript. Finally, thanks to all the people who have been pushing this project for many years, to the ones who have been continuing asking for the publication of the software, and the referees of several of our papers for suggestions which lead to improvements in the software.

This work and the development of GLoBES have been supported by:

- Physik Department der Technischen Universität München
- Max-Planck-Institut für Physik
- Sonderforschungsbereich 375 für Astro-Teilchenphysik der Deutschen Forschungsgemeinschaft
- Studienstiftung des Deutschen Volkes
- Institute for Advanced Study, Princeton
- W. M. Keck Foundation
- Physics Department of the University of Wisconsin, Madison

GLoBES installation

The installation of GLoBES is highly automated and there should not be any problems on a decently up-to-date GNU/Linux system. The installation has, however, only been tested on a limited number of platforms. The current version has been tested for SuSE, Red Hat, Fedora Core and a 64bit version of SuSE. It should also compile and work on Mac OS. We would appreciate to know your experiences with the installation on different platforms. Please send an e-mail to <`globes@ph.tum.de`>.

Prerequisites for the installation of GLoBES

Besides the usual things such as a working `libc`, you need to have

gcc The GNU compiler collection
`gcc.gnu.org`

GSL The GNU Scientific Library
`www.gnu.org/software/gsl/`

The library `libglobes` should in principle compile with any ANSI C/C++ compiler, but the `globes` binary uses the `argp` facility of `glibc` to parse its command line options. However, on platforms where `argp` is lacking GLoBES has replacement code, thus it should also work there.

All those libraries are also available as rpm's from the various distributors of GNU/Linux, see their web sites for downloads. Chances are that `gcc` and GSL are already part of your installation. For building GLoBES from source, however, not only working libaries for above packages are needed but also the headers, especially for GSL. Depending on your installation, eg. on RedHat/Fedora, of GSL this may require to additionally install a rpm-package named `gsl-devel`. If GSL has been installed from the tar-ball as provided by `gnu.org` no problems should occur. Furthmore you need a working `make` to build and install GLoBES.

Installation Instructions

GLoBES follows the standard GNU installation procedure. To compile GLoBES you will need gcc. After unpacking the distribution the Makefiles can be prepared using the configure command,

```
./configure
```

You can then build the library by typing,

```
make
```

A shared version of the library will be compiled by default.

The library can be installed using the command,

```
make install
```

The default install directory prefix is `/usr/local`. Consult the "Further Information" section below for instructions on installing the library in another location or changing other default compilation options.

The install target also will install a program with name `globes` to `$prefix/bin` and the files in the `data` directory of the tar-ball to `$prefix/share/globes`.

If you are not using `make install` you will find the static libary at `source/.lib/libglobes.a` which you can copy to any destination. However keep in mind that the linking command will be somewhat different, *i.e.* you have to specify all the dynamically linked objects besides libglobes.

The default install directory prefix is `/usr/local`. Consult the "Further Information" section below for instructions on installing the library in another location or changing other default compilation options.

Moreover a config-script called `globes-config` will be installed. This script displays all information necessary to link any program with GLoBES. For building static libaries and linking against them see the corresponding section of this file.

Basic Installation

The `configure` shell script attempts to guess correct values for various system-dependent variables used during compilation. It uses these values to create a `Makefile` in each directory of the package. Finally, it creates a shell script `config.status` that you can run in the future to recreate the current configuration, a file `config.cache` that saves the results of its tests to speed up reconfiguring, and a file `config.log` containing compiler output (useful mainly for debugging `configure`).

If you need to do unusual things to compile the package, please try to figure out how `configure` could check whether to do them, and mail diffs or instructions to `globes@ph.tum.de` so they can be considered for the next release. If at some point `config.cache` contains results you don't want to keep, you may remove or edit it.

The file `configure.in` is used to create `configure` by a program called `autoconf`. You only need `configure.in` if you want to change it or regenerate `configure` using a newer version of `autoconf`.

The simplest way to compile this package is:

1. `cd` to the directory containing the package's source code and type `./configure` to configure the package for your system. If you're using `csh` on an old version of System V, you might need to type `sh ./configure` instead to prevent `csh` from trying to execute `configure` itself.

   Running `configure` takes awhile. While running, it prints some messages telling which features it is checking for. It also prints a reminder for things to do after installation.

2. Type `make` to compile the package.

3. Type `make install` to install the programs and any data files and documentation.

4. You can remove the program binaries and object files from the source code directory by typing `make clean`. To also remove the files that `configure` created (so you can compile the package for a different kind of computer), type `make distclean`. There is also a `make maintainer-clean` target, but that is intended mainly for the package's developers. If you use it, you may have to get all sorts of other programs in order to regenerate files that came with the distribution.

5. Since you've installed a library don't forget to run `ldconfig` !

Installation without root privilege

Install GLoBES to a directory of your choice `GLB_DIR`. This is done by

```
configure --prefix=GLB_DIR
```

and then follow the usual installation guide. The only remaining problem is that you have to tell the compiler where to find the header files, and the linker where to find the library. Furthermore you have to make sure that the shared object files are found during execution. Running `configure` also produces a `Makefile` in the `examples` subdirectory which can serve as a template for the compilation and linking process, since all necessary flags are correctly filled in.

Another solution is to set the environment variable `LD_RUN_PATH` during linking to `GLB_DIR/lib` . Best thing is to add this to your shell dot-file (e.g. `.bashrc`). Then you can use: A typical compiler command like

```
gcc -c my_program.c -IGLB_DIR/include/
```

and a typical linker command like

```
g++ my_program.o -lglobes -LGLB_DIR/lib/ -o my_executable
```

More information on this issue can be obtained by having a look into the mentioned `Makefile` in `examples`.

CAVEAT It is in principle possible to have many installations on one machine. Especially the situation of having an installation by root and by a user at the same time might occur. However, it is strictly warned against this possibility, since it is *extremely* likely to create some versioning problem at some time!

LAPACK & BLAS requirements

GLoBES uses one single routine out of LAPACK (`www.netlib.org/lapack/`) named `zgeev` to diagonalize the oscillation Hamiltonian in matter. Since LAPACK is not part of the standard installation of many distributions and we need only one function, GLoBES comes with a convenience version of the required routines, which are taken from LAPACK and BLAS (`www.netlib.org/blas`) and have been translated to C with `f2c`. In case your system has a working installation of BLAS/LAPACK GLoBES will use it. However, if your system is lacking BLAS/ LAPACK the convenience version will be compiled and linked into GLoBES. If for some reason BLAS/LAPACK is installed on the system and one still wishes to use the convience version use `--enable-lapack-convenience`. Using Fortran code which has been translated to C with `f2c` requires a run-time library called `libf2c` (on some systems it is called `libg2c`). The configury of GLoBES detects the presence of either of the two and takes care of it. If none of the two is present, a convience library is used. If for some reason `libf2c` is installed on the system and one still wishes to use the convience version use `--enable-libf2c-convenience`.

GSL requirements

Sometimes the GNU scientific library is not available or is installed in a non-standard location. This situation can arise in an installation without root privileges. In this case one can specify `--with-gsl-prefix=path_to_gsl` as option to the `configure` script. If one wants to use a shared version of `libgsl` then one has to make sure that the linker finds the library at run-time. This can be achieved by setting the environment variable `LD_LIBRARY_PATH` correctly, *i.e.* (in bash)

```
export LD_LIBRARY_PATH=path_to_gsl
```

You also can use a static version of GSL by either building GLoBES with `LDFLAG=-all-static` or by configuring GSL with `--disable-shared`. In both cases no further actions like setting any environment variables is necessary.

Distributions

Fedora Core 3

FC3 is shipped with a non working version of LAPACK. Thus to make GLoBES work on FC3, configure GLoBES with `--enable-lapack-convenience`, which replaces the defunct

LAPACK with GLoBES' own version thereof. You can diagnose a non-working LAPACK by compiling one of the examples in the `examples` directory and trying to run it. It will hang forever in the function `glbSetRates()`.

RedHat – all versions

The standard rpm-based installation of GSL does not provide any header files for GSL, which are however needed to compile GLoBES. You have to install an additional rpm-package called `gsl-devel`. Altnernatively you can install GSL from a tar-ball and use the verb'–with-gsl-prefix' option to the configure script of GLoBES.

Advanced topics

Building and Using static versions of GLoBES

In certain circumstances it may be useful to use a static version of libglobes or any of the binaries, *e.g.* when running on a cluster.

The `configure` script accepts the option `--disable-shared`, in which case only static objects are built, i.e. only a static version of libglobes. In case your system does not support shared libraries the `configure` script recognizes this. If you give no options to `configure`, both shared and static versions are built and will be installed. All binaries, however, will use dynamic linking. If you want to build static binaries, use `LDFLAGS=-all-static` for building them.

Sometimes it is convenient, eg. for debugging purposes, to have a statically linked version of a program using GLoBES which is easiest achieved by just linking with `libglobes.a`. If you need a completely statically linked version, please, have a look at the Makefile in the `examples` directory.

```
make example-static
```

produces a statically linked program that should in principle run on most Linuxes. It should be straightforward to adapt this example to your needs.

All these options rely on `libtool` and a working `gcc` installation. It seems that `gcc 3.x` is broken in subtle way which makes it necessary to add a symbolic link in the `gcc` library directory. The diagnostic for this requirement is that building static programs fails with the error message `cannot find -lgcc_s`. In those cases, find `libgcc.a` and add a symbolic link in the same directory where you found it (this requires probably root privileges)

```
ln -s libgcc.a libgcc_s.a
```

If you can not write to this directory just use the following work around. Add the same link as above to the directory where you installed GLoBES into

```
cd prefix/lib ln -s path_to_libgcc.a/libgcc.a libgcc_s.a
```

and then change back into the `examples` directory and type

```
make LDFLAGS=-Lprefix/lib example-static
```

and you are done.

If you don't have libtool on your system either, then you just can use the libtool script in the GLoBES tar-ball instead. Make sure it is in a place where it is found by `make`.

Compilers and Options

Some systems require unusual options for compilation or linking that the `configure` script does not know about. You can give `configure` initial values for variables by setting them in the environment. Using a Bourne-compatible shell, you can do that on the command line like this

```
CC=c89 CFLAGS=-O2 LIBS=-lposix ./configure
```

Or on systems that have the 'env' program, you can do it like this

```
env CPPFLAGS=-I/usr/local/include LDFLAGS=-s ./configure
```

Compiling For Multiple Architectures

You can compile the package for more than one kind of computer at the same time, by placing the object files for each architecture in their own directory. To do this, you must use a version of `make` that supports the `VPATH` variable, such as GNU `make`. 'cd' to the directory where you want the object files and executables to go and run the `configure` script. `configure` automatically checks for the source code in the directory that `configure` is in and in '..'.

If you have to use a `make` that does not supports the `VPATH` variable, you have to compile the package for one architecture at a time in the source code directory. After you have installed the package for one architecture, use 'make distclean' before reconfiguring for another architecture.

Installation Names

By default, `make install` will install the package's files in `/usr/local/bin`, `/usr/local/include`, etc. You can specify an installation prefix other than `/usr/local` by giving `configure` the option `--prefix=PATH`.

Specifying the System Type

There may be some features `configure` can not figure out automatically, but needs to determine by the type of host the package will run on. Usually `configure` can figure that out, but if it prints a message saying it can not guess the host type, give it the `--host=TYPE` option. TYPE can either be a short name for the system type, such as 'sun4', or a canonical name with three fields: `CPU-COMPANY-SYSTEM`

See the file `config.sub` for the possible values of each field.

If you are building compiler tools for cross-compiling, you can also use the `--target=TYPE` option to select the type of system they will produce code for, and the `--build=TYPE` option to select the type of system on which you are compiling the package.

Sharing Defaults

If you want to set default values for `configure` scripts to share, you can create a site shell script called `config.site` that gives default values for variables like `CC`, `cache_file`, and `prefix`. `configure` looks for `PREFIX/share/config.site` if it exists, then `PREFIX/etc/config.site` if it exists. Or, you can set the `CONFIG_SITE` environment variable to the location of the site script. A warning: not all `configure` scripts look for a site script.

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