GLoBES Tutorial: Advanced Usage of AEDL

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This tutorial will adress basic and advanced features of the **A**bstract **E**xperiment **D**efinition **L**anguage AEDL. The syntax of AEDL is comprehensive and thus allows to define all different kinds of neutrino oscillation experiments with different neutrino sources and different detector technologies. Within this tutorial we will define a toy experiment by using the most important features of AEDL and get familiar with the AEDL syntax. Then we will modifiy the experiment description going from basic usage of AEDL to more advanced features. After that we will explore some of the pre-defined AEDL files that come with GLoBES 3.0 and analyze advanced features in their AEDL description.

The toy experiment for this tutorial is absolutely fictious, although the attributes of the detector roughly follow the response of a huge Water Cerenkov detector. However, all efficiencies and migration matrices are coming from a fake Monte Carlo simulation and do **not** exactly correspond to the true attributes of a Water Cerenkov detector. So, all files prepared for this tutorial do **not** correspond to a real detector response and are just to be used for this tutorial.

Part 1: AEDL implementation of a toy experiment

Suppose you work for a collaboration that plans to build a long baseline neutrino oscillation experiment with a flavor-pure neutrino beam, that consists either of ν_e or $\bar{\nu}_e$. It is planned to build a huge *modified* Water Cerenkov detector. Now, you want to analyze the future potential of the experiment and maybe try to optimize some of the attributes. Your decision is to do the analysis with GLoBES. So, first you have to build the experiment description in AEDL, *i.e.* write the corresponding `glb`-file. One of your colleagues sends the results from a Monte Carlo analysis (see Fig. 1). It is also important to implement the background from single pion production in neutral current events. Therefore, the colleague sends the Monte Carlo sample of NC events (see Fig. 2). Additionally you receive the energy dependent signal efficiencies of the charged current $\nu_\mu/\bar{\nu}_\mu$ events from the Monte Carlo simulations. These include the Cerenkov threshold for muons and are given for 18 bins of $\Delta\mathrm{E} = 0.1\,\mathrm{GeV}$ between 0.2 GeV and 2.0 GeV (the list of these energy dependent efficiecies is given in the files `NUMUeff.dat` and `NUMUBAReff.dat`). Furthermore, he tells you that the rejection factor for the NC events should be 10^{-3}. This is all the information needed to reconstruct smearing matrices out of the data that can be used to describe the experiment in an AEDL file.

<u>Problem 1:</u> Warm-Up

The smearing matrices are provided in the files `CCmigration.dat`, `CCBARmigration.dat`, and `NCmigration.dat`. They are already given in the right syntax, so that they can be implemented into an AEDL file. However, try to qualitatively understand, how these matrices can be reconstructed from the data given above. If you are not familiar with the usage of manually defined smearing matrices, please consult the GLoBES manual on pages 101-102.

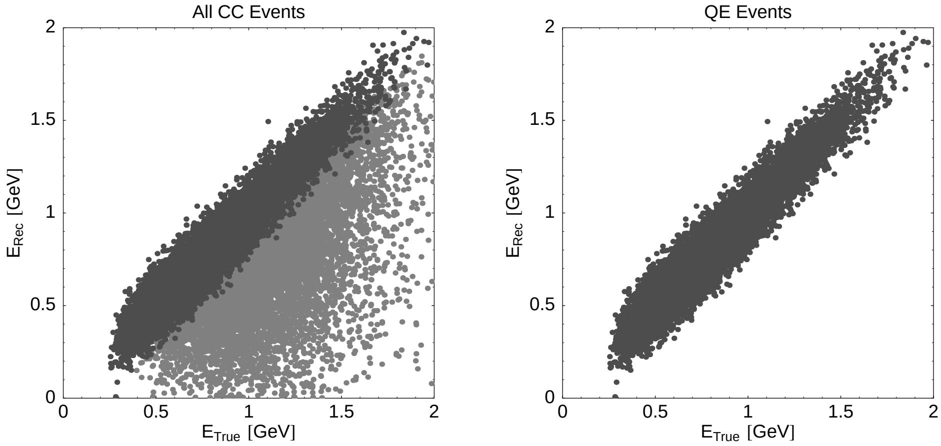

Figure 1: The sample of 20000 charged current ν_μ events on the left-hand side. The quasi-elastic sample is shown in dark grey while the inelastic part of the sample is shown in bright grey. The quasi-elastic part of the sample alone is plotted at the right-hand side. It can be seen that this sample allows to recontruct the true neutrino energy at a certain level, while this is not possible for the inelastic part of the sample.

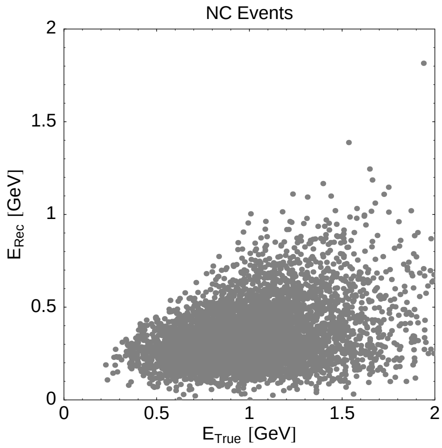

Figure 2: The sample of 5000 neutral current events. It can be seen that the reconstructed energy is systematically smaller than the true neutrino energy since there is missing energy due to the undetected neutrino in the NC event.

<u>Problem 2:</u> Finding the Normalization

Another colleague of yours provides you with the data of the neutrino beam flux. It is given in the files `TOYplus.dat` (ν_e) and `TOYminus.dat` ($\bar{\nu}_e$), already provided in the right syntax for GLoBES. The implementation of neutrino fluxes from a data file is described in the GLoBES manual on pages 89-90. Unfortunately, your colleague does not know the units of the flux data anymore, but he tells you that his Monte Carlo simulation showed that in case of no oscillations he would get at total number of 13503.5 ν_e charged current events and 4612.18 $\bar{\nu}_e$ charged current events per kt and year at the planned baseline of L = 350 km. He tells you that they estimated a new average matter density along the

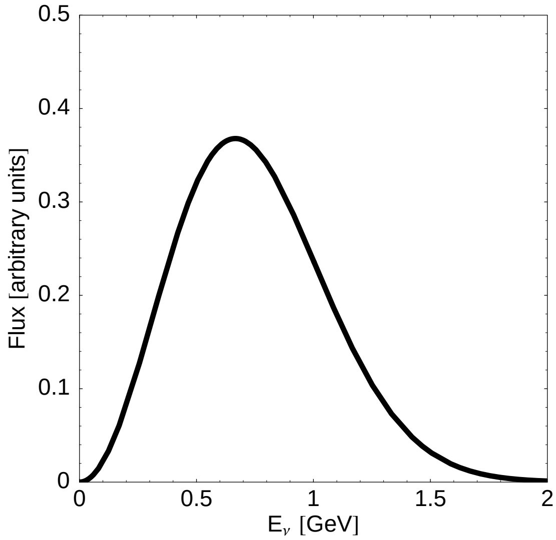

Figure 3: The neutrino flux of the toy experiment as a function of the neutrino energy. The flux is given in arbitrary units so the right normalization has to be found.

baseline of $\rho = 2.95\, g/cm^3$.

Start from the draft file `TOYdraft.glb` and build an AEDL file that uses the flux files and allows to calculate the unoscillated $\nu_e/\bar{\nu}_e$ CC events per kt and year. Use 18 bins from 0.2 GeV to 2 GeV (necessary, since the migration matrices are given for this binning). Calculate the event rates with the command `globes` from the `/source` directory of GLoBES. Within `TOYdraft.glb` you can find some hints where the corresponding AEDL features are documented in the GLoBES manual.

Problem 3: Describing the Experiment

Now, that we have found the right normalization, we can describe the toy experiment. The detector will be located at the baseline of L = 350 km and have a fiducial mass of 500 kt. The experiment will measure ν_μ-appearance and $\bar{\nu}_\mu$-appearance. For collecting comparable amount of data in both channels, it is planned to have split mode of operation, *i.e.* 2 years in ν_e mode and 6 years in $\bar{\nu}_e$ mode. It is assumed that the overall normalization uncertainty of the signal events will be 2.5% and 20% on the background events.

Build up an AEDL file that decribes the experiment and makes use of the migration matrices. Note, that the migration matrices are for CC and NC events.

Check your AEDL file with the `globes` command for the following oscillation parameters:

$$\begin{aligned}\sin^2\theta_{12} &= 0.3\\ \sin^2 2\theta_{13} &= 0.1\\ \sin^2 2\theta_{23} &= 1\\ \delta_{CP} &= \pi/2\\ \Delta^2_{21} &= 7.9\cdot 10^{-5}\, eV^2\\ \Delta^2_{31} &= 2.6\cdot 10^{-3}\, eV^2 \end{aligned} \tag{1}$$

This can either be done with the command

```
./globes -p'0.5796,0.1609,0.7854,1.5708,7.9e-5,2.6e-3' NAME.glb
```

or just with `./globes NAME.glb` within a shell session if the values are defined as the default parameters:

```
export GLB_CENTRAL_VALUES='0.5796,0.1609,0.7854,1.5708,7.9e-5,2.6e-3'
```

This is what approximately should be obtained (signal and background event numbers):

```
------ #NU_MU_Appearance ------
233787 || 233787
4640.85 || 4640.85


------ #NU_MU_BAR_Appearance ------
173047 || 173047
4911.57 || 4911.57
```

The binned event rates can be calculated with the command `./globes -s NAME.glb`. The screen output that should be derived is given in the appendix.

Furthermore, the program `th13delta.c` and the script `th13delta.gnuplot` can be used to produce a contour plot of the best fit solution in the $\sin^2 2\theta_{13}$-δ_{CP}-plane (there are still degenerate solutions left in different locations of the parameter space, *i.e.* the intrinsic and the sign-degeneracy). Do not forget to enter the Name of your AEDL file into `th13delta.c`. Note, that another AEDL file is loaded within `th13delta.c`, `T2K_disappearance_only.glb`. This is due to the fact, that the leading atmospheric parameters cannot be measured at the toy experiment. This can spoil the results through parameter correlations. Thus, the simulated disappearance data from T2K is included. The T2K appearance data is missing, so that information on $\sin^2 2\theta_{13}$ and δ_{CP} can only be derived from the toy experiment data. The effect can be seen in Fig. 7 in the appendix.

Problem 4: Experiment Description without Smearing Matrices

One of your colleagues tells you, that the energy reconstruction of the quasi-elastic events follows a gaussian energy resolution function with a width of $\sigma = 0.085\, GeV$. The smearing is due to Fermi Motion and so in his analysis he found that this width is independent of the neutrino energy over the whole energy window up to 2 GeV.

Modify the AEDL file in such a way that no migration matrices are used anymore. You will need the efficiency and background rejection data from the files `NUMUeff.dat`, `NUMUBAR-eff.dat`, `NC_bckg_rej.dat`, and `NCBAR_bckg_rej.dat`. Make use of the GLoBES built-in energy resolution function. Then, compare the event rates and the best-fit solution you get from this file with the file from the former problem. You should approximately end up with this output:

```
------ #NU_MU_Appearance ------
222833 || 222833
4640.5 || 4640.5


------ #NU_MU_BAR_Appearance ------
171644 || 171644
4911.57 || 4911.57
```

The binned event rates again can be derived with the command `./globes -s NAME.glb`. The screen output that should be obtained is given in the appendix.
Now we can compare the best-fit solution from the file with migration matrices and the file without migration matrices:

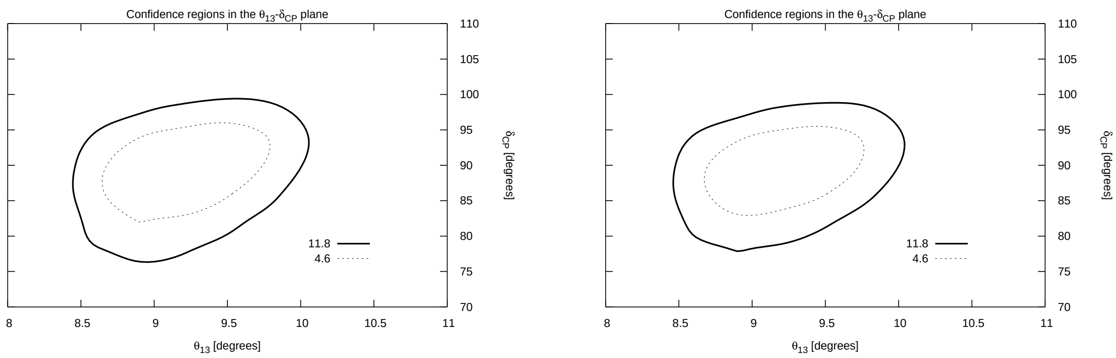

Figure 4: Left-Hand Side: The allowed best-fit solution obtained with `th13delta.c` and the toy experiment description using manually defined migration matrices. Right-Hand Side: The allowed best-fit solution obtained with `th13delta.c` and the toy experiment description using the GLoBES internal energy resolution function.

<u>Problem 5:</u> List Interpolation in AEDL

The description of the experiment without migration matrices has one big advantage in comparison to the description with migration matrices. Suppose, one of your colleagues wants to compare your analyisis with your analysis. Unfortunately, he uses 16 bins instead of 18 and asks you to do the same. One could either do the same procedure again and prepare completely new migration matrices, this time 16×16. But, this would of course be very time consuming. Or one can use the former description and introduce the efficiencies by applying the AEDL feature of list interpolation as described in the GLoBES manual on pages 84-85. The result should of course look extremely similar.

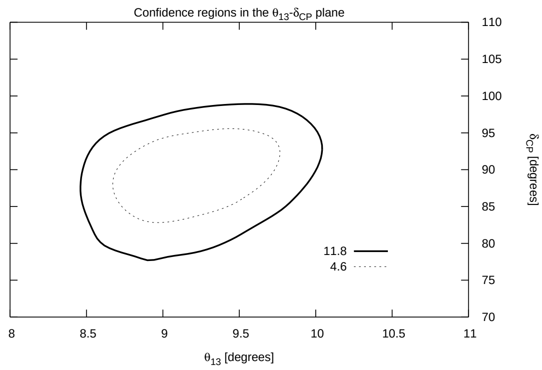

Figure 5: The allowed best-fit solution obtained with `th13delta.c` and the toy experiment description using the GLoBES internal energy resolution function. and 16 bins with efficiencies obtained with the AEDL list interpolation feature.

<u>Problem 6:</u> Usage of Total Rates

The former files only make use of the quasi-elastic event sample, there energy reconstruction is possible to a certain level. However, this reduces the statistics of the experiment, because all inelastic events are omitted.

The CC events can be included to the file and the systematics function `chiTotalRatesTilt` within the corresponding rule can be used to only account for total rates. The spectral information still comes from the QE events. However, now double counting of events has to be avoided. Therefore the QE events have to be taken into account with a free normalization. The explanations about the necessary systematics functions can be found in the GLoBES manual on pages 105-106. You can also explore the `T2K.glb` file. There, this technique is already implemented. Please discuss the systematics function, that has to be used for the QE events in case of no treatment of systematics.

In the end you should end up at:

```
------ #NU_MU_Appearance_QE ------
222706 || 222706
4840.44 || 4840.44


------ #NU_MU_BAR_Appearance_QE ------
171630 || 171630
5169.42 || 5169.42


------ #NU_MU_Appearance_CC ------
379842 || 379842
4840.44 || 4840.44


------ #NU_MU_BAR_Appearance_CC ------
265792 || 265792
5169.42 || 5169.42
```

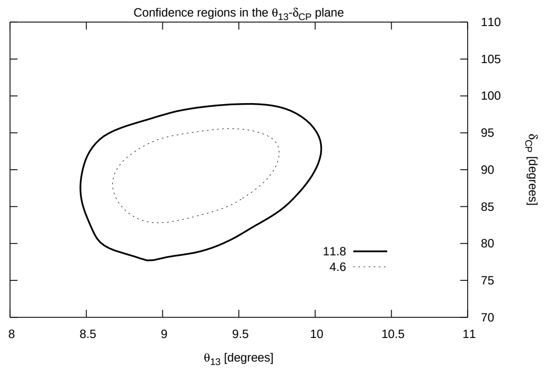

Figure 6: The allowed best-fit solution obtained with `th13delta.c` and the toy experiment description using the GLoBES internal energy resolution function. Here, the total rates data from all CC events and the spectral data from the QE sample with a free normalization is used within the analysis.

The difference to the former simulations is not very large. This is due to the fact that the true value of $\sin^2 2\theta_{13}$ is chosen quite large. For smaller $\sin^2 2\theta_{13}$ the effect becomes more important, since overall statistics decrease and the additional statistics improves the results in a more dramatic way.

Part 2: Features of the Pre-Defined AEDL Experiments

Now, we can have a look at the pre-defined AEDL experiments. The problems of Part 1 have made us familiar with the syntax of AEDL. One of the most important AEDL features used in the variable AEDL files is the usage of AEDL variables. For instance the file `data/NuFact/Variable/NFvar.glb` is defined with free variables. First, we can have a look at the implementation of the neutrino factory flux. In contary to the toy experiment, the fluxes are not loaded from a data file, but derived from the built-in flux feature of GLoBES. The parent energy and the baseline of the experiment are kept free and can be specified by the usage of the AEDL variables `emax` and `BASELINE`.

Copy the file `source/globes` to the directory with the `NFvar.glb` file and try the command:

```
./globes -DBASELINE=3000 -Demax=50 NFvar.glb
```

Furthermore, the file `NFvar.glb` makes use of the AEDL feature to allow variable bin-widths. The binwiths are chosen such that the bins at smaller energies are more narrow than for larger energies. This is done, because the energy resolution is proportional to the neutrino energy and a better resolution is obtained at smaller energies, which requires smaller binning. However, the absolute position of the bins depends on `emax` so that it is not possible to give fixed efficiency lists. Here, the new interpolation feature of GLoBES is necessary.

The implementation of a built-in beta beam flux can be explored in the variable beta beam file `data/BetaBeam/BB_WC/BBvar_WC.glb`. Here, also AEDL variables have been introduced to allow an analysis of beta beams by modifying the γ factor and the baseline. Since for this experiment migration matrices cannot be used to maintain the variability, the same technique as in Problem 6 is used.

A Effect of T2K Disappearance Data

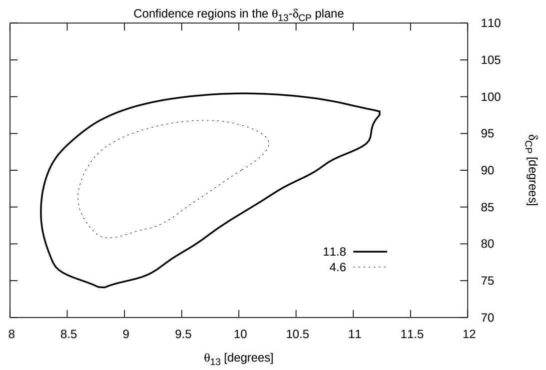

Figure 7: The allowed best-fit solution obtained with `th13delta.c` and the toy experiment description using migration matrices. The disappearance data from T2K is **not** used here.

B Spectral Event Rates

Migration Matrices	Energy Resolution Function
------ #NU_MU_Appearance ------	------ #NU_MU_Appearance ------
0.25 3235.32	0.25 872.803
0.35 8516.4	0.35 4161.83
0.45 18670.5	0.45 13747.8
0.55 30845.9	0.55 27084.3
0.65 37326	0.65 35648.9
0.75 36255.2	0.75 36404.7
0.85 30234.2	0.85 32152.6
0.95 23895.9	0.95 25359.3
1.05 17472	1.05 18206.2
1.15 11164.9	1.15 12112.7
1.25 7213.56	1.25 7574.92
1.35 4387.87	1.35 4499.13
1.45 2290.2	1.45 2501.03
1.55 1175.12	1.55 1317.7
1.65 573.792	1.65 668.669
1.75 287.307	1.75 317.866
1.85 158.537	1.85 143.546
1.95 83.849	1.95 58.5287
---------------	---------------
Total: 233787	Total: 222833
0.25 1899.59	0.25 1899.63
0.35 1379.43	0.35 1379.05
0.45 707.324	0.45 707.319
0.55 347.565	0.55 347.565
0.65 161.629	0.65 161.629
0.75 75.6928	0.75 75.6928
0.85 41.3034	0.85 41.3034
0.95 17.3519	0.95 17.3519
1.05 6.3722	1.05 6.3722
1.15 3.16321	1.15 3.16321
1.25 0.53009	1.25 0.53009
1.35 0.598437	1.35 0.598437
1.45 0	1.45 0.000143515
1.55 0	1.55 8.79703e-05
1.65 0	1.65 5.08887e-05
1.75 0	1.75 2.78955e-05
1.85 0.298004	1.85 0.298002
1.95 0	1.95 7.1521e-06
---------------	---------------
Total: 4640.85	Total: 4640.5

Migration Matrices

```
------ #NU_MU_BAR_Appearance ------

0.25 1110.29
0.35 3257.3
0.45 9112.41
0.55 15748.8
0.65 19876
0.75 24939.8
0.85 24582.1
0.95 20723.2
1.05 17965.5
1.15 13890.8
1.25 8845.95
1.35 5449.44
1.45 3585.94
1.55 1870.27
1.65 1027.29
1.75 559.153
1.85 330.635
1.95 172.192
---------------
Total:  173047

0.25 1882.64
0.35 1436.5
0.45 790.672
0.55 412.492
0.65 201.96
0.75 95.6634
0.85 53.6873
0.95 22.8585
1.05 8.63062
1.15 4.40415
1.25 0.765549
1.35 0.843628
1.45 0
1.55 0
1.65 0
1.75 0
1.85 0.455293
1.95 0
---------------
Total:  4911.57
```

Energy Resolution Function

```
------ #NU_MU_BAR_Appearance ------

0.25 430.704
0.35 1595.73
0.45 5209.66
0.55 12256
0.65 20000.1
0.75 25053.5
0.85 25888
0.95 23282.3
1.05 19168.5
1.15 14457.6
1.25 10004.5
1.35 6349.17
1.45 3729.31
1.55 2099.19
1.65 1137.16
1.75 582.734
1.85 280.22
1.95 119.721
---------------
Total:  171644

0.25 1882.64
0.35 1436.51
0.45 790.666
0.55 412.492
0.65 201.96
0.75 95.6634
0.85 53.6873
0.95 22.8585
1.05 8.63062
1.15 4.40415
1.25 0.765549
1.35 0.843628
1.45 0.00019704
1.55 0.000124013
1.65 7.34927e-05
1.75 4.11518e-05
1.85 0.455293
1.95 1.0927e-05
---------------
Total:  4911.57
```