Application of GLoBES: GLACIER on conventional neutrino beams

A.Meregaglia, A.Rubbia (ETH Zürich)

Workshop on Physics and Applicationsof the GLoBES software - Heidelberg 26-01-07

Introduction

- GLoBES was used in the framework of a long-baseline neutrino experiment considering different beams and using GLACIER (The Giant Liquid Argon Charge Imaging ExpeRiment) as detector.

- In particular we studied the performance of the detector when operated on two different neutrino beams: an upgraded CNGS beam (see **JHEP 0611:032,2006**), and an upgraded (4MW) T2K beam (see A.Rubbia's invited Talk at 2nd International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam).

- Despite the effortless and straight forward use of the software, the "`@norm`" parameter was quite tricky to set and it was tuned "by hand" so that the event rate corresponded the expected one.

- We introduced some minor modifications to the `glb_minimize.c` code in order to force the following conditions when performing fit:

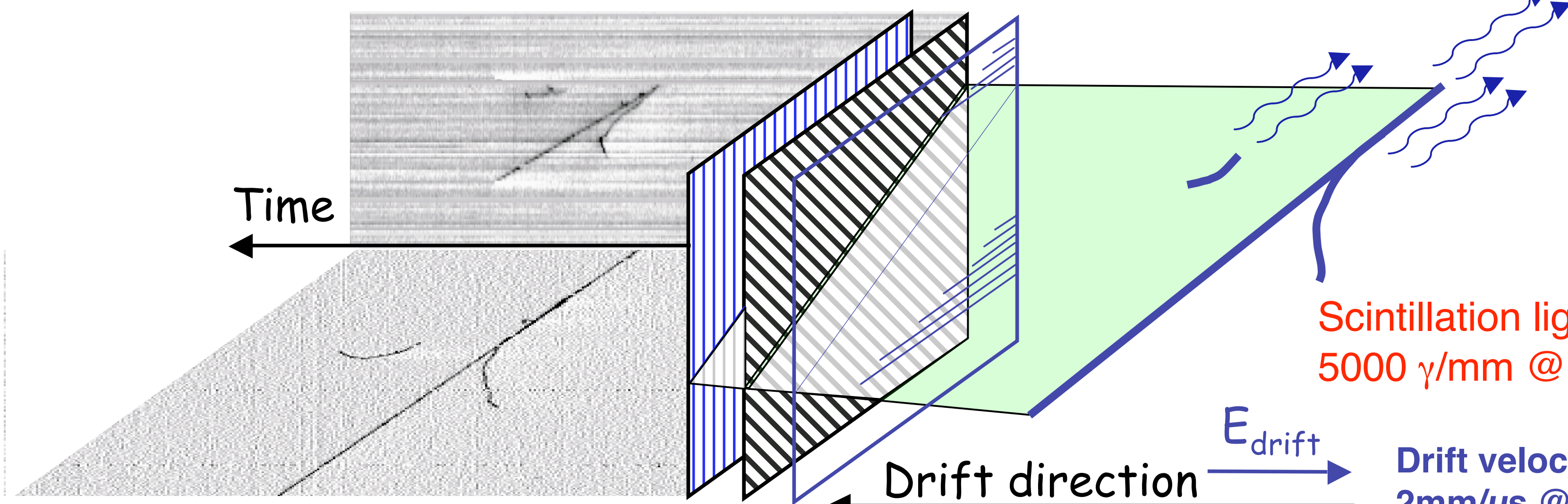
  1. $\theta_{13} > 0$
  2. $0 < \delta_{cp} < 2\pi$

The LAr TPC principle

Charge yield ~ 6000 electrons/mm (~ 1 fC/mm)

Charge readout planes: Q

UV Scintillation Light: L



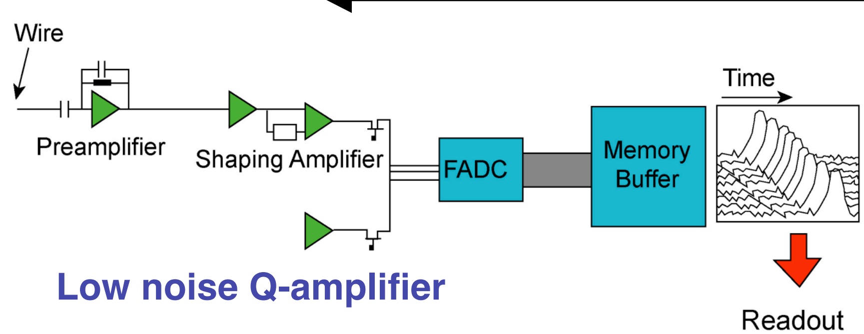
Scintillation light yield ~ 5000 γ/mm @ 128 nm

Drift velocity ≈ 2mm/μs @ 1 kV/cm

Drift electron lifetime:

$$\tau \approx 300\mu s \times \frac{1\,ppb}{N(O_2)}$$

Purity < 0.1ppb O_2-equiv.



Low noise Q-amplifier

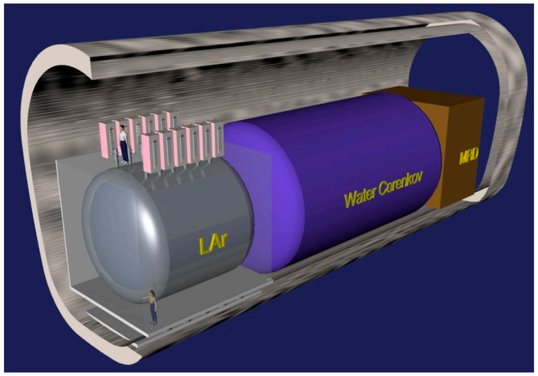
Continuous waveform recording → image

History

- Within the ICARUS program, our group has been working for many years on the development of large cryogenic detectors based on noble liquid gases like Argon. A series of several modules of different sizes have been operated, to study all the basic features of such a detector.

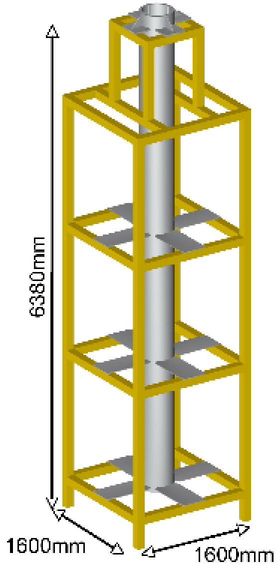
- The largest detector ever built has a mass of 600 tons to be used in the ICARUS experiment at Gran Sasso.

- A 100 ton LAr TPC has been proposed as fine grained detector for the 2km site of the T2K experiment.



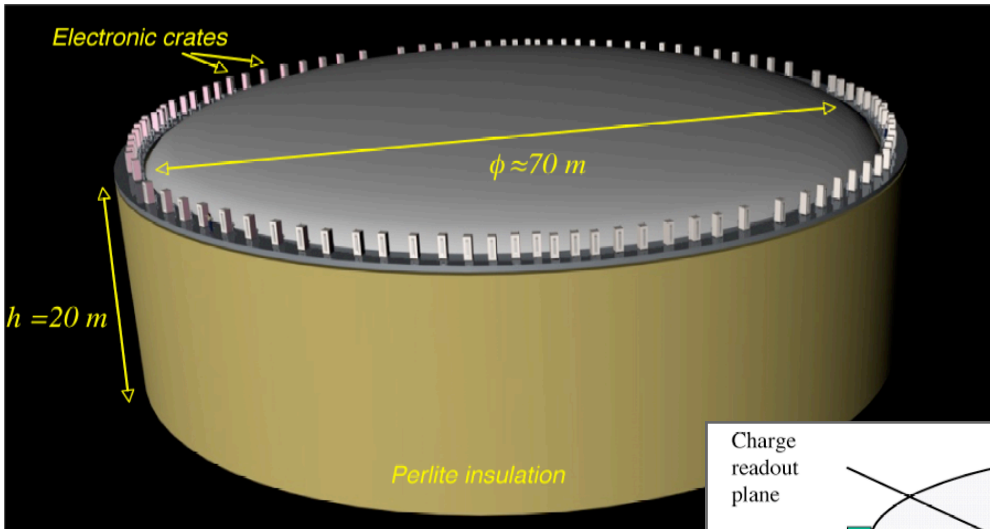
- Intensive R&D on long-drift, new methods of read-out and high voltage will be carried out in the ARGONTUBE project.

- Large LAr detectors (~ 100 kton) have been considered for future neutrino physics, related in particular to super beams and neutrino factories.



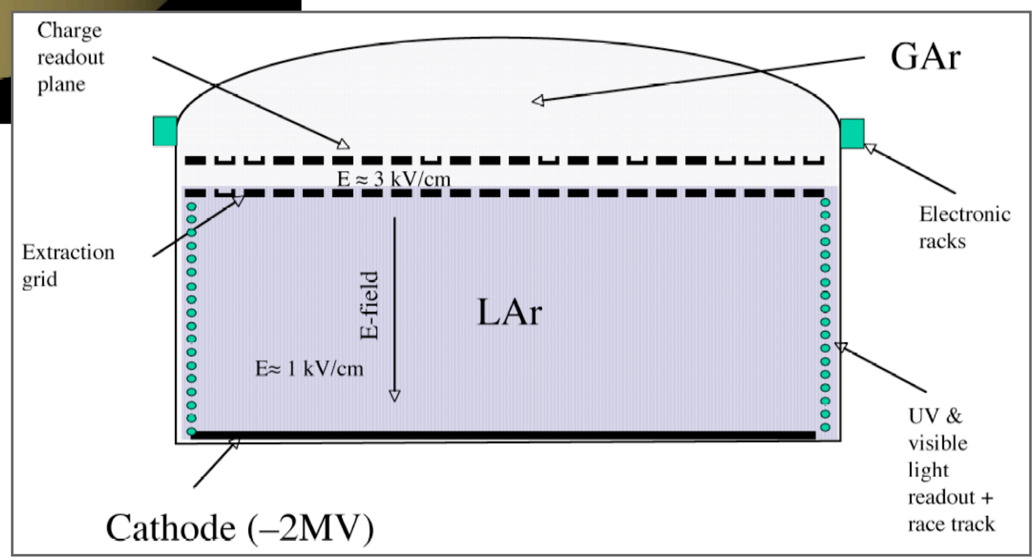
GLACIER

The Giant Liquid Argon Charge Imaging ExpeRiment



- Long drift of about 20 m.
- New method readout: wires not suitable for such dimensions.

- Double phase detector: electron drift in liquid, multiplication in gas.
- New high voltage supply: difficult to bring in 2 MV with standard feed-through method.



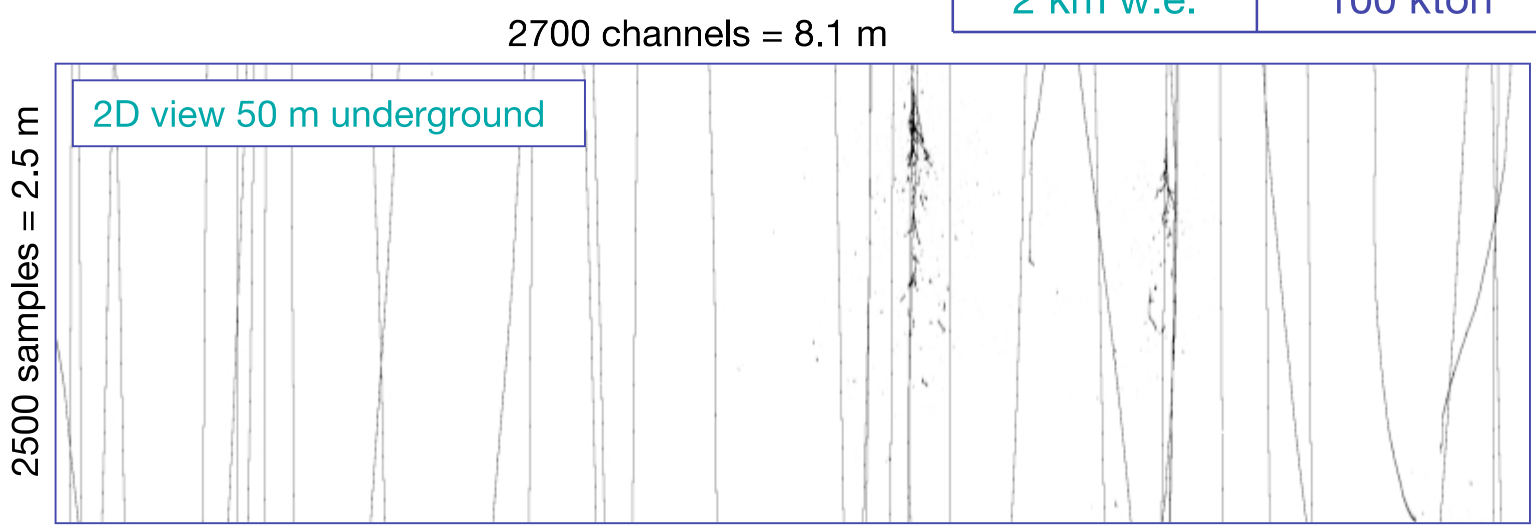
GLACIER (2)

- Single module tanker based on industrial LNG technology.
- Scalable design.
- Possibility to magnetize the LAr volume.
- Feasibility study carried out by Thecnodyne. Possibility to build such a detector underground with some extra costs.

Surface or underground?

- Muon flux on surface = 70 m^{-2} s^{-1} sr^{-1} with E_{μ} > 1GeV.
- Surface location are not suitable but there is no need of deep underground sites.
- Shallow depth (~ 200 m) in a green field would do.
- A shallow depth location is suitable also for astroparticle physics searches such as nucleon decay (**hep-ph/0701101**).

Depth Rock	Fiducial mass after slice of 10 cm around each muon is vetoed	Total crossing muons (E>1GeV) in 10ms
Surface	...	13000
50 m	50 kton	100
188 m	98 kton	3.2
1km w.e.	100 kton	0.65
2 km w.e.	100 kton	0.062



Neutrino oscillations

- The full 3-flavour neutrino oscillation probability for $\nu_\mu \rightarrow \nu_e$ is given by:

$$P(\nu_\mu \rightarrow \nu_e) = \Sigma_{i=1,4} P_i$$

$$P_1 = \sin^2\theta_{23}\sin^2(2\theta_{13})\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

Atmospheric term

$$P_2 = \cos^2\theta_{23}\sin^2(2\theta_{12})\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

Solar term

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

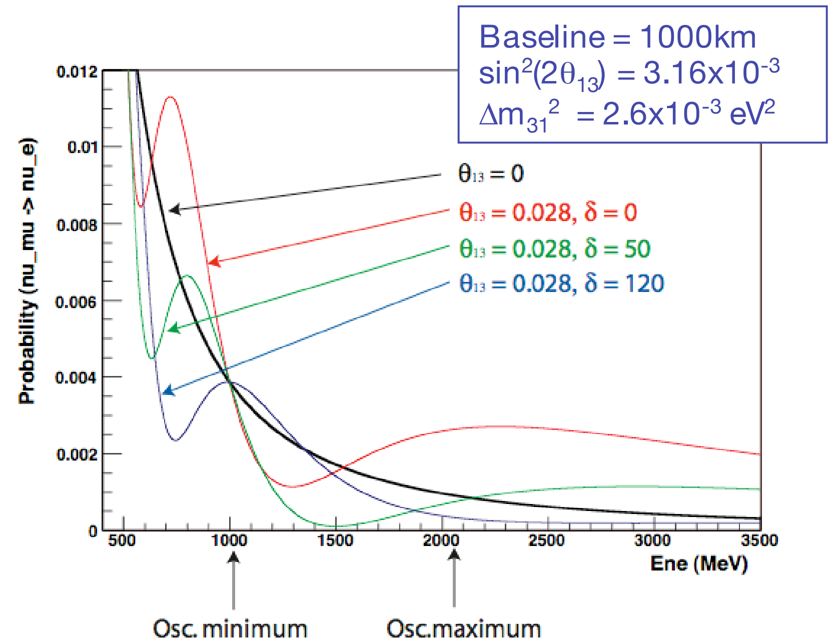
Interference terms

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$
$$A = \sqrt{2}G_F n_e$$
$$B_\pm = |A \pm \Delta_{13}|$$
$$J = \cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})$$

- θ_{13} is crucial for the atmospheric part of the oscillation, and it must be proved to be non-zero.

- In case of a value of θ_{13} different from zero, the oscillation probability depends strongly on the value of δ_{CP}.

- The so far unknown **sign of Δm_{31}^2** also affects the oscillation probability and mass hierarchy must be determined.

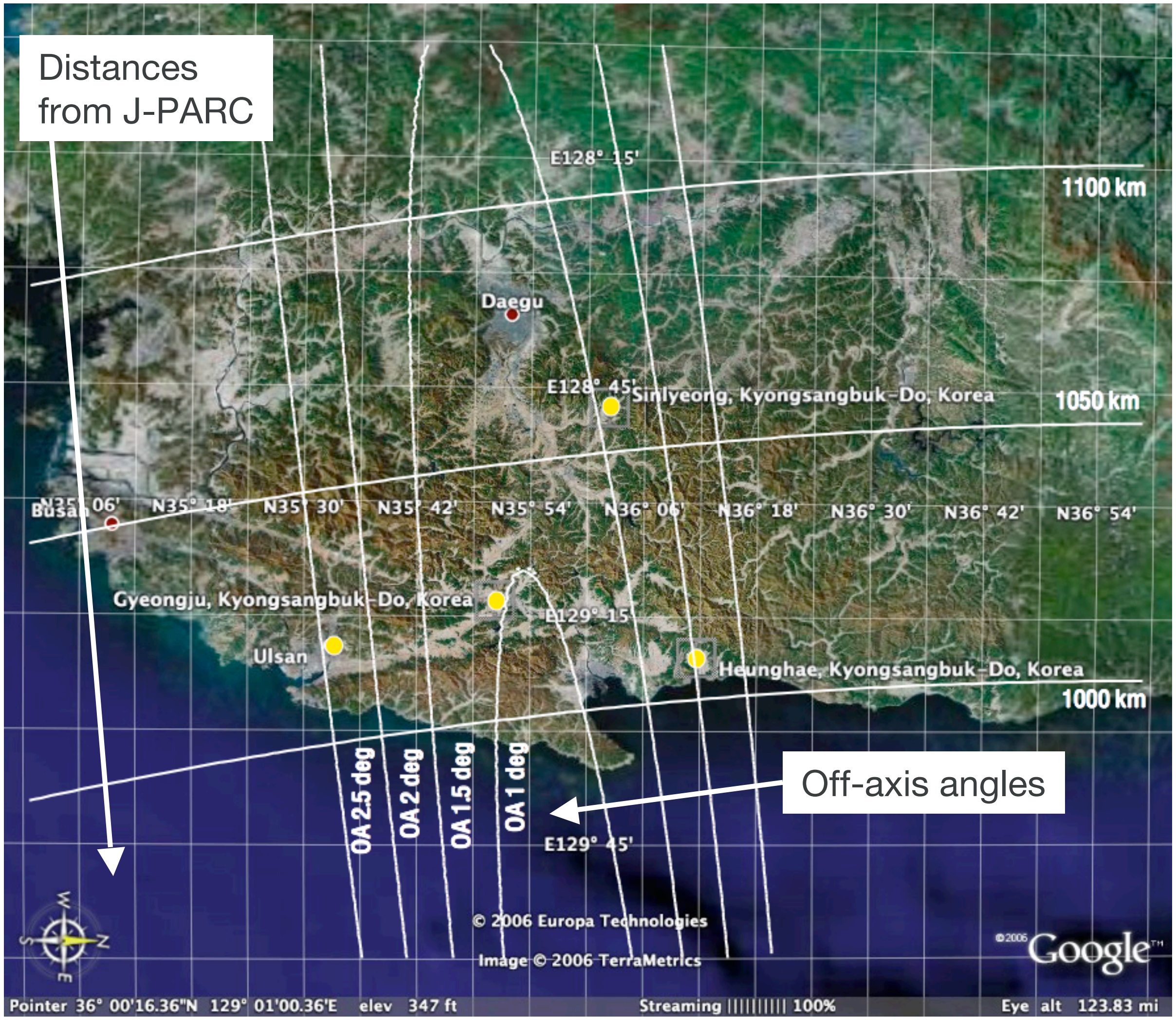


Neutrino beams

- We considered conventional neutrino beams only.
- We studied the performance of GLACIER in terms of θ_{13}, CP-Violation and mass hierarchy sensitivity.
- Two beams in particular have been investigated: the T2K one and a optimized version of the CNGS one.
- For the T2K one we considered the upgraded 4 MW setup whereas for the CNGS one we considered an upgraded version with a new PS to increase the number of protons per pulse and the efficiency. The optics has also been re-designed for the CNGS beam.

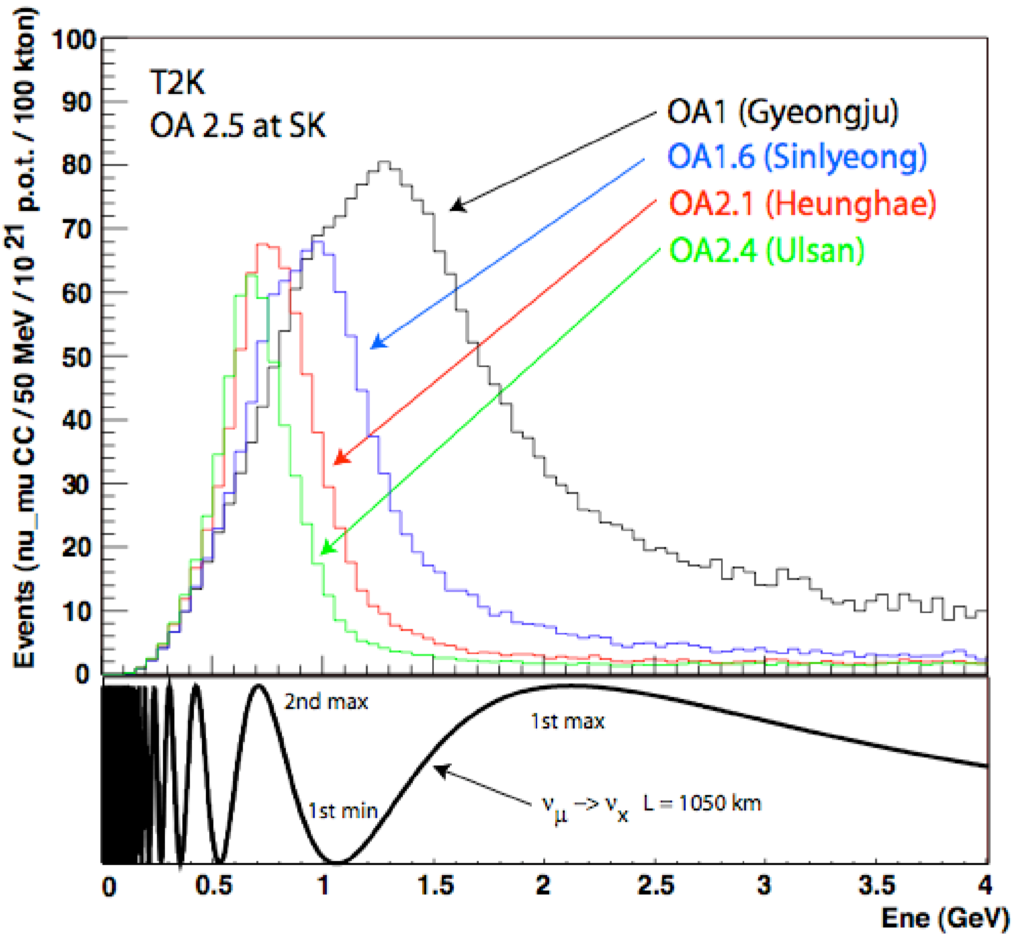
	T2K		CNGS	
	Upgraded	Baseline	Upgraded	Baseline
Proton energy	40 GeV/c		400 GeV/c	
Protons per pulse (x 10^{13})	>33	33	14	4.8
p.o.t. per year (x 10^{19})	700	100	33	7.6
Running (days/year)	130		200	
Efficiency	1		0.83	0.55
Beam power (MW)	4	0.6	1.2	0.3
Energy x p.o.t. (x 10^{22} GeV x p.o.t/year)	28	4	13.2	3

T2K beam



- The beam is tuned in order to have an off-axis angle of 2.5 degrees at SK.
- With the chosen angle, the energy is peaked at about 0.6 GeV at SK (baseline = 295 km): this corresponds to the first maximum of oscillation for $\Delta m^2 = 2.6\times10^{-3}$ eV^2.
- The location of GLACIER would be in Korea, at a baseline between 1000 km and 1100 km and a minimum off-axis angle of about 1 degree.

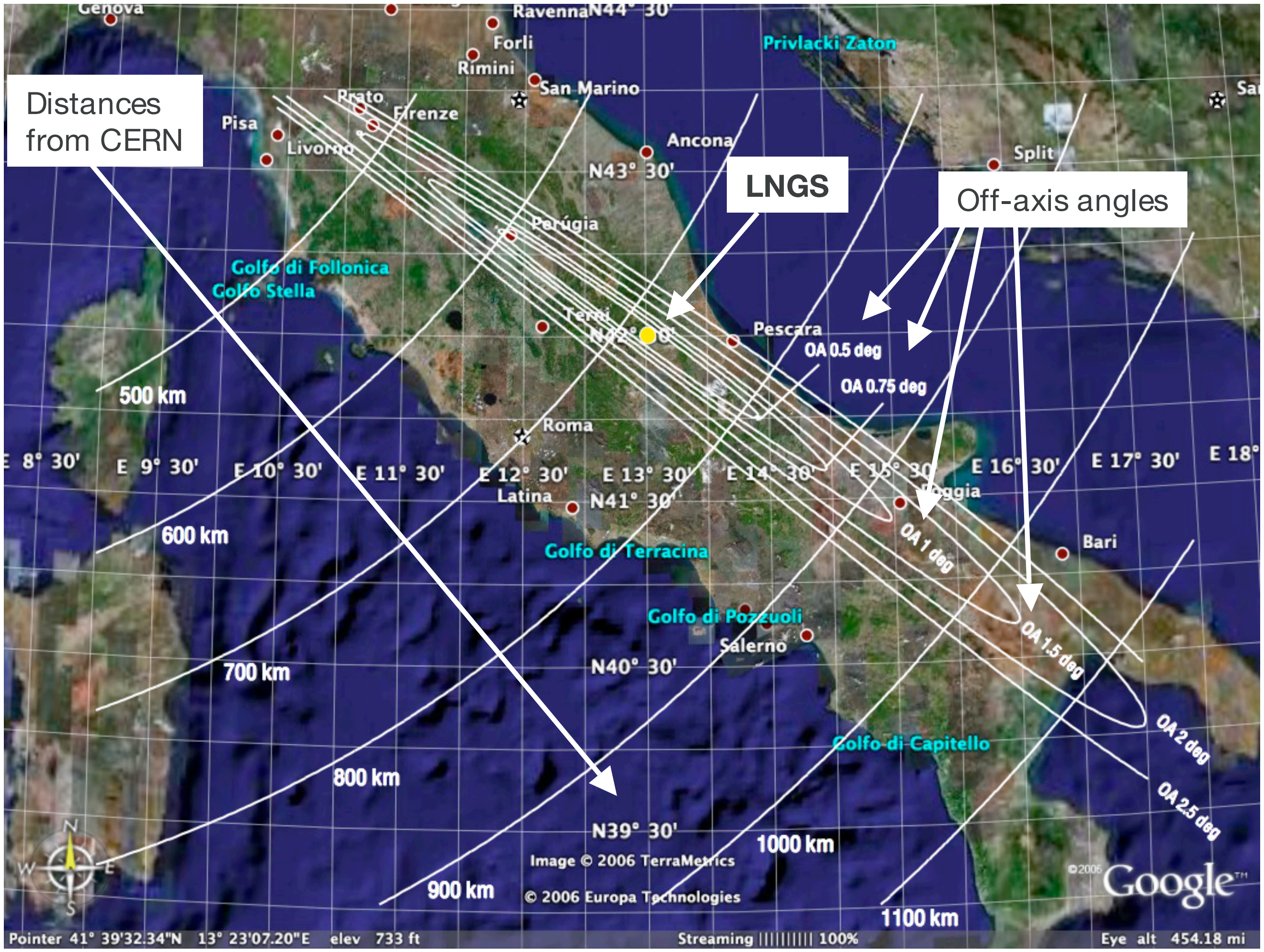
T2K beam: location selection



- The smallest off-axis angles gives a beam that best covers the first maximum, first minimum and second maximum of oscillation.
- That location (Gyeongju) is also favored since the ratio $\nu_e CC/\nu_\mu CC$ (i.e. background over signal) is smallest.
- The running time considered in the analysis is 4+4 (neutrino and antineutrino polarities) years.

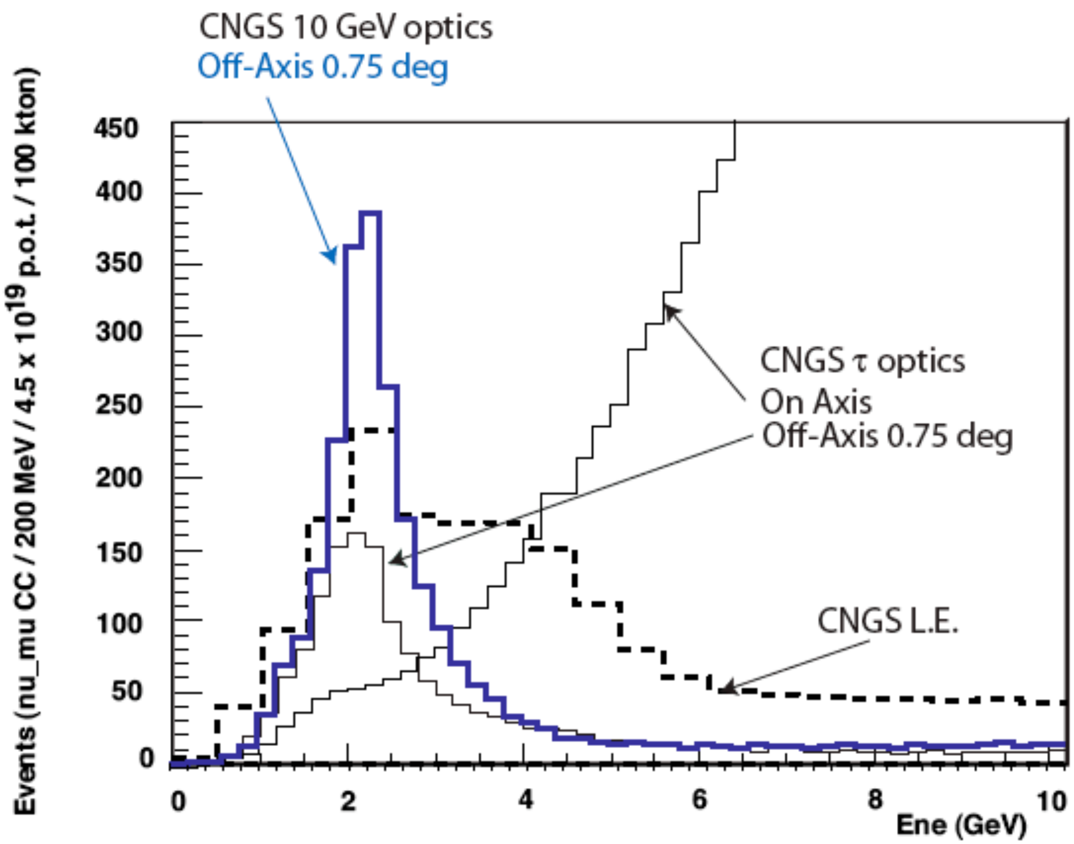
Location	$\nu_e CC/\nu_\mu CC$
Gyeongju	8.3×10^{-3}
Sinlyeong	1.2×10^{-2}
Heunghae	1.7×10^{-2}
Ulsan	1.9×10^{-2}

CNGS beam



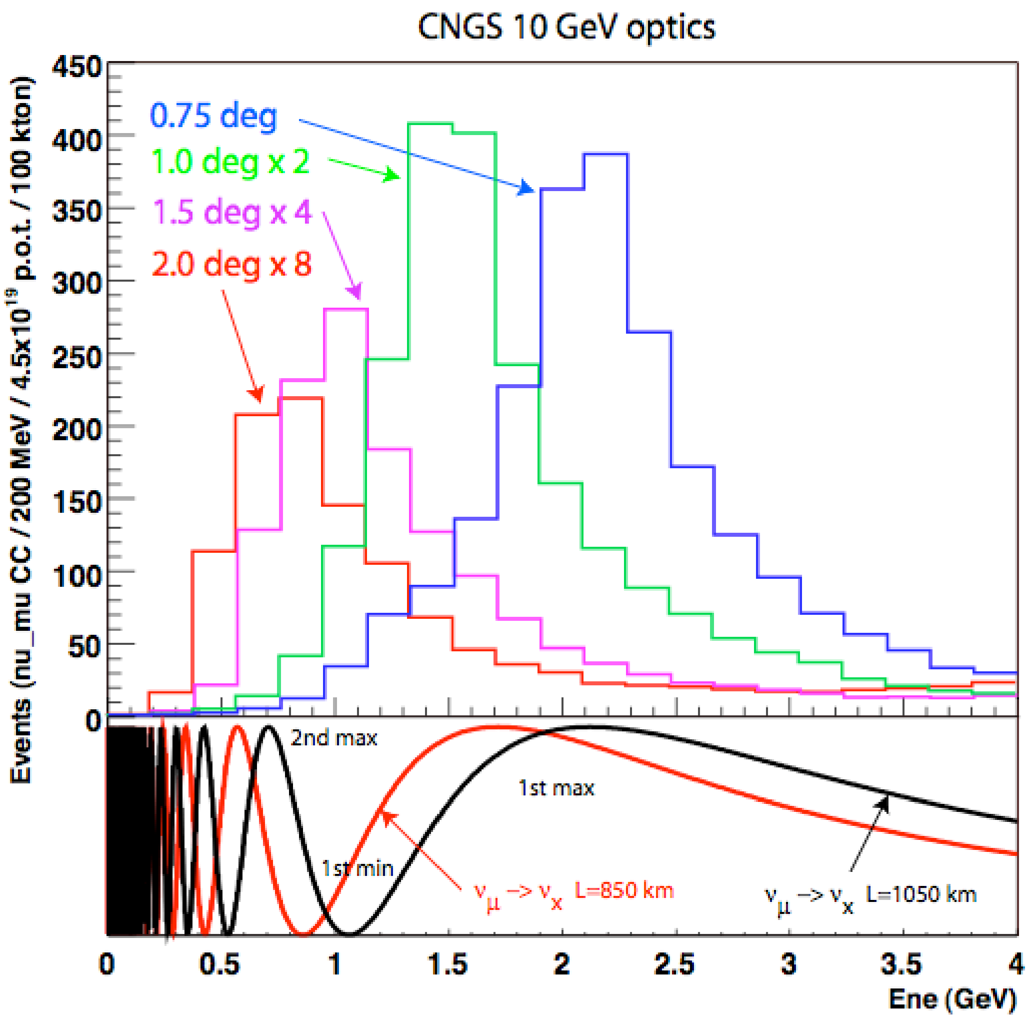
- The beam is tuned to point towards Gran Sasso Laboratory.
- The energy is tuned in order to observe τ-neutrino appearance (about 20 GeV neutrinos).
- The location of GLACIER would be in Italy with a baseline between 500 km and 1050 km. The limits on the maximal off-axis angle are related to the baseline considered.

CNGS beam: beam optimisation



- In order to use the CNGS beam to perform ν_e appearance measurements, we need to increase the spectrum at low energy.
- Optics was re-designed to have on-axis low energy neutrino beam (CNGS L.E.).
- With the original (τ) optics and using the off-axis technique similar results are achieved (30% less below 2 GeV compared to CNGS L.E. but less high energy tail).
- A factor of 2 can be gained with a new optics to focus pions of 10 GeV.

CNGS beam: location selection



- We selected two locations for GLACIER on the CNGS beam.
- The first option is 0.75 degrees off-axis at 850 km, to optimize the rate at the first maximum of oscillation (good for θ_{13} sensitivity).
- The second option is 1.5 degrees off-axis at 1050 km, to optimize the rate at the first minimum and second maximum of oscillation (good for CP-Violation and mass hierarchy sensitivity).
- A combination of the 2 was also considered where the total 100 kton mass was split into 30 kton at 850 km and 70 kton at 1050 km.
- The running time considered in the analysis is 5+5 (neutrino and antineutrino polarities) years.

θ_{13} sensitivity

- To discover a non-zero value of the parameter θ_{13}, the hypothesis of $\sin^2(2\theta_{13})=0$ must be ruled out at a certain C.L.

- As input, a true non-vanishing value of $\sin^2(2\theta_{13})$ is chosen in the simulation and a fit with $\sin^2(2\theta_{13}) = 0$ is performed, yielding the “discovery” potential.

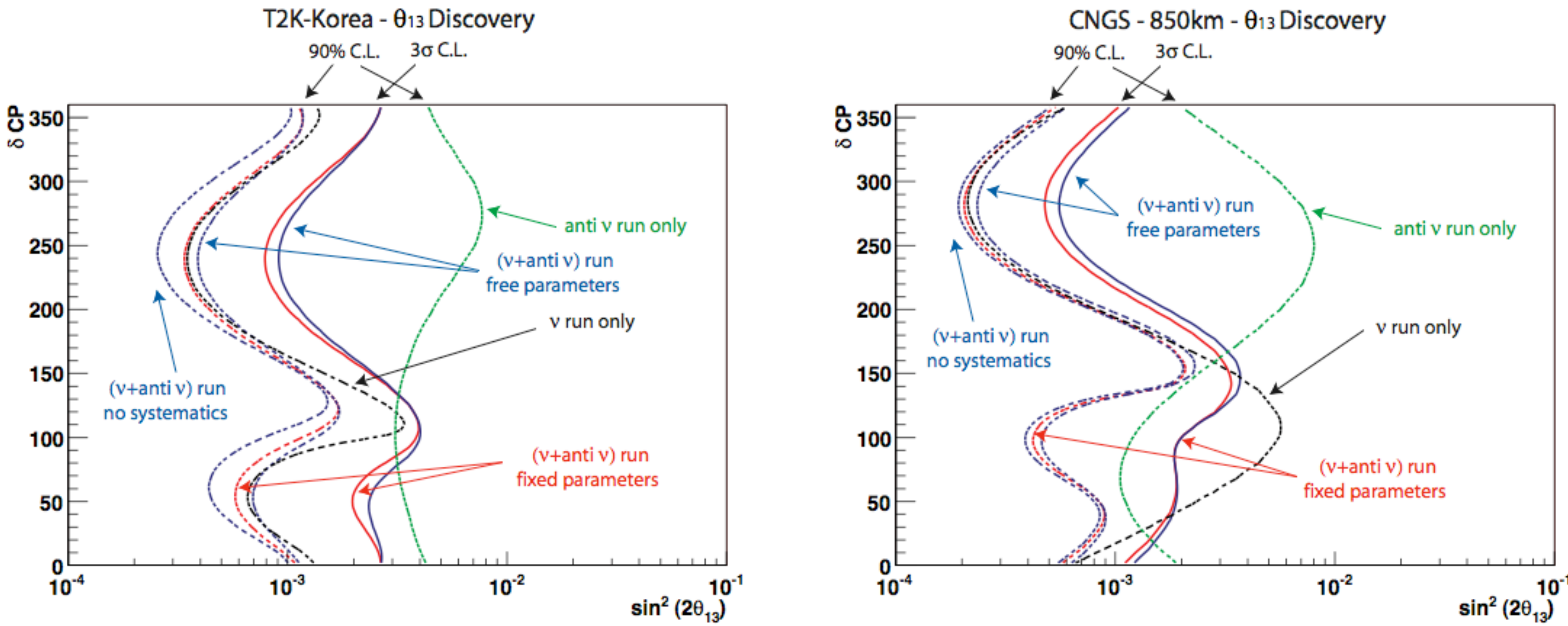
- The fit is performed using the GLoBES software, leaving oscillation parameters free within their priors, and taking into account degeneracies and parameters correlations.

- This procedure is repeated for every point in the ($\sin^2(2\theta_{13})$, δ_{CP}) plane.

Oscillation parameters used →

$$\Delta m^2_{31} = 2.5^{+0.025}_{-0.025} \cdot 10^{-3}\,\mathrm{eV}^2 \quad \sin^2\theta_{23} = 0.5^{+0.008}_{-0.008}\,,$$
$$\Delta m^2_{21} = 7.0^{+0.7}_{-0.7} \cdot 10^{-5}\,\mathrm{eV}^2 \quad \sin^2\theta_{12} = 0.31^{+0.06}_{-0.05}\,,$$
$$\sin^2\theta_{13} = 0 \quad \delta_{cp} = 0$$

Results: θ_{13} sensitivity

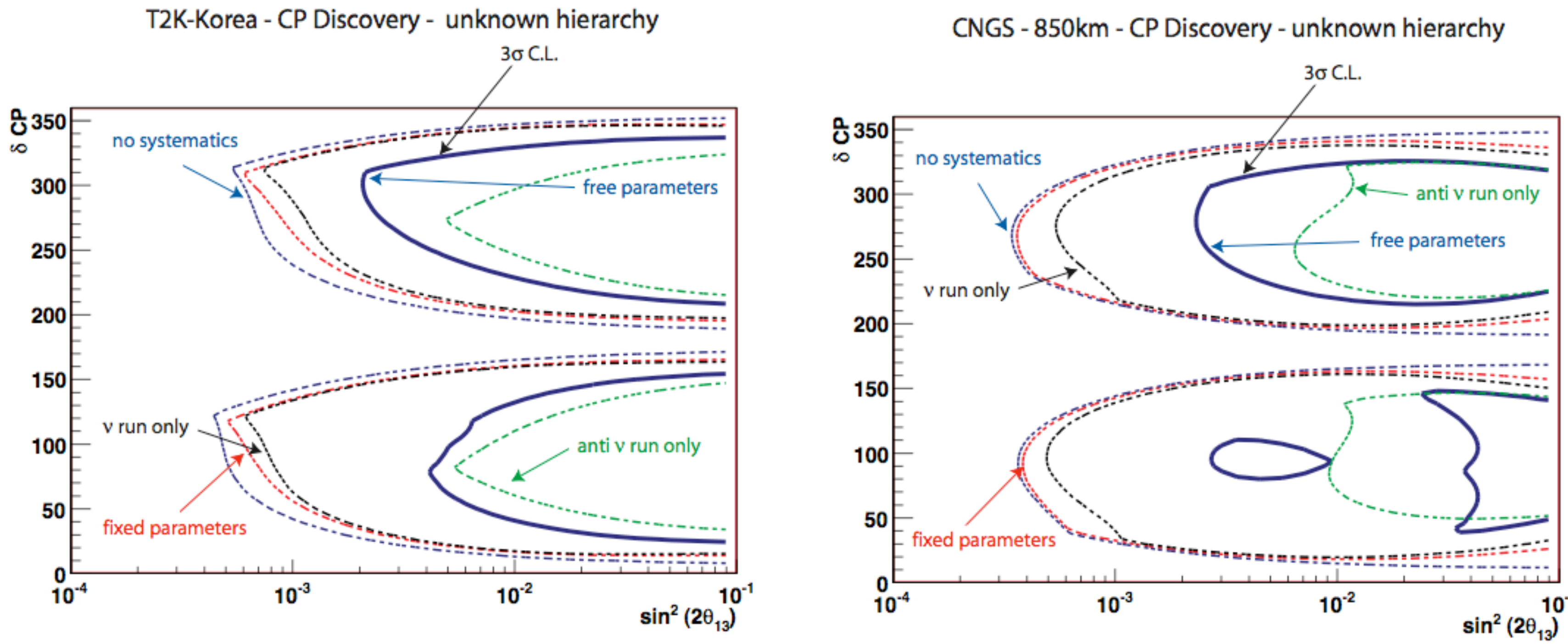


- The sensitivity obtained with T2K and CNGS beam (850 km configuration) are similar.
- The antineutrino run is more important for CNGS than it is for the T2K beam.
- The CNGS 1050 km configuration (not shown here) is about a factor 10 worse due to the smaller statistics (both because of the increased baseline and increased off-axis angle).

δ_{CP} Violation

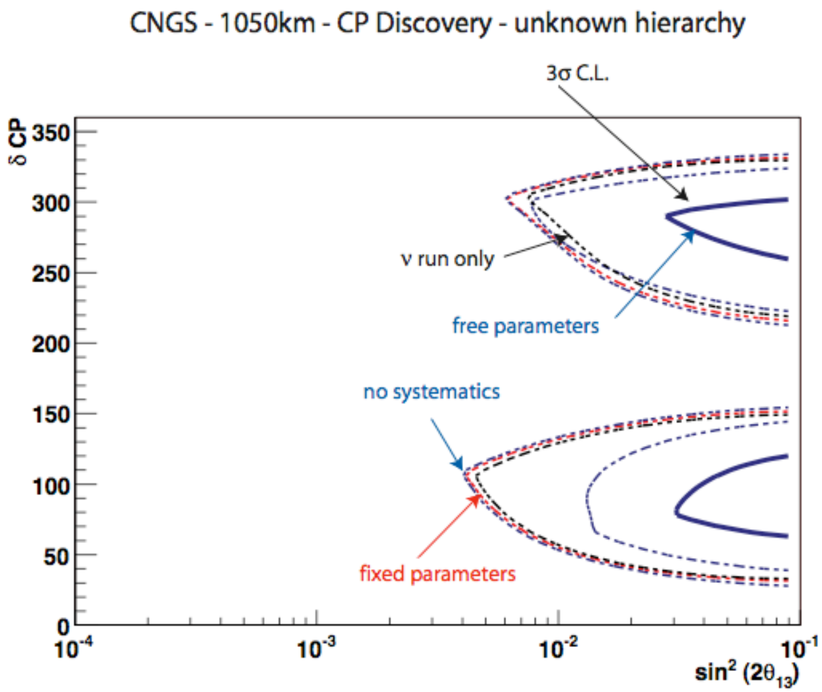
- If θ_{13} is proved to be non-zero, search for CP-Violation can be performed.
- To observe CP-Violation, the CP conserving values (δ_{CP} =0, δ_{CP} =π) must be excluded at a certain C.L.
- Data (neutrino event rates) are computed in the ($\sin^2(2\theta_{13})$, δ_{CP}) plane using the point coordinates as "true" input values, and are fitted with the two CP conserving values of δ_{CP} leaving all other parameters free (including $\sin^2(2\theta_{13})$).
- The opposite mass hierarchy is also fitted and the minimum of all cases is taken as final χ^2.
- GLoBES software has been used and the parameter were set as in the study of θ_{13} sensitivity.

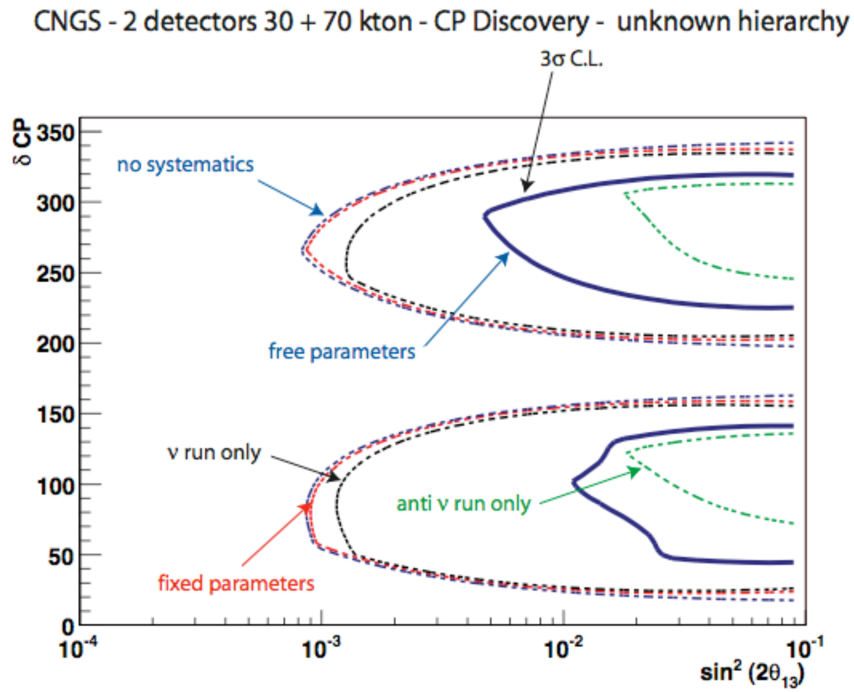
Results: δ_{CP} sensitivity



- The T2K beam gives the best performance.
- The “island” obtained using the CNGS 850 km is due to the fact that the mass hierarchy is unknown (see next) ⇒ introduction of a clone solution.

Results: δ_{CP} sensitivity (2)

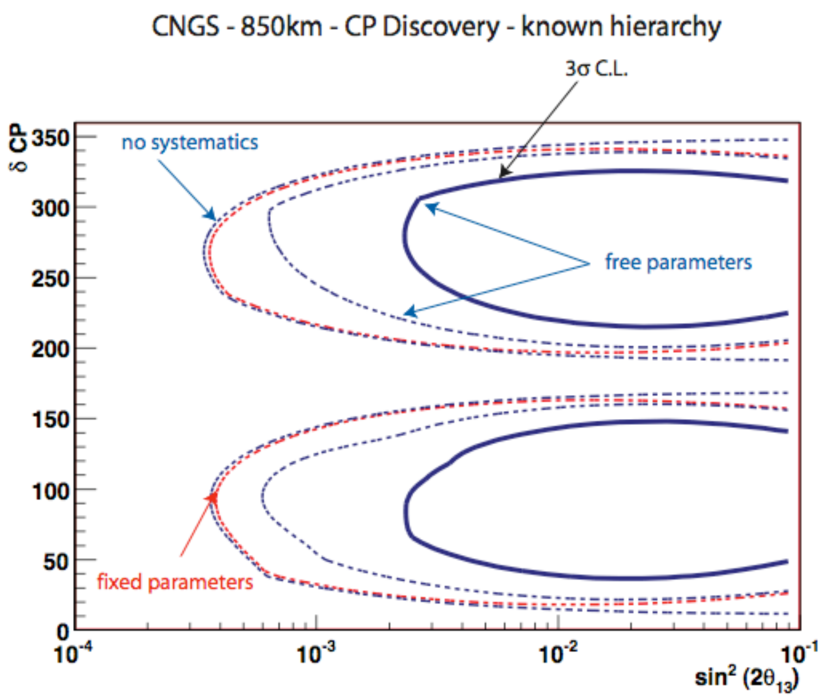




- The CNGS 1050 km configuration suffers from low statistics but not from the mass hierarchy degeneracy.

- The 2 detectors configurations is probably the most effective when the CNGS beam is considered.

CNGS: δ_{CP} sensitivity - known hierarchy

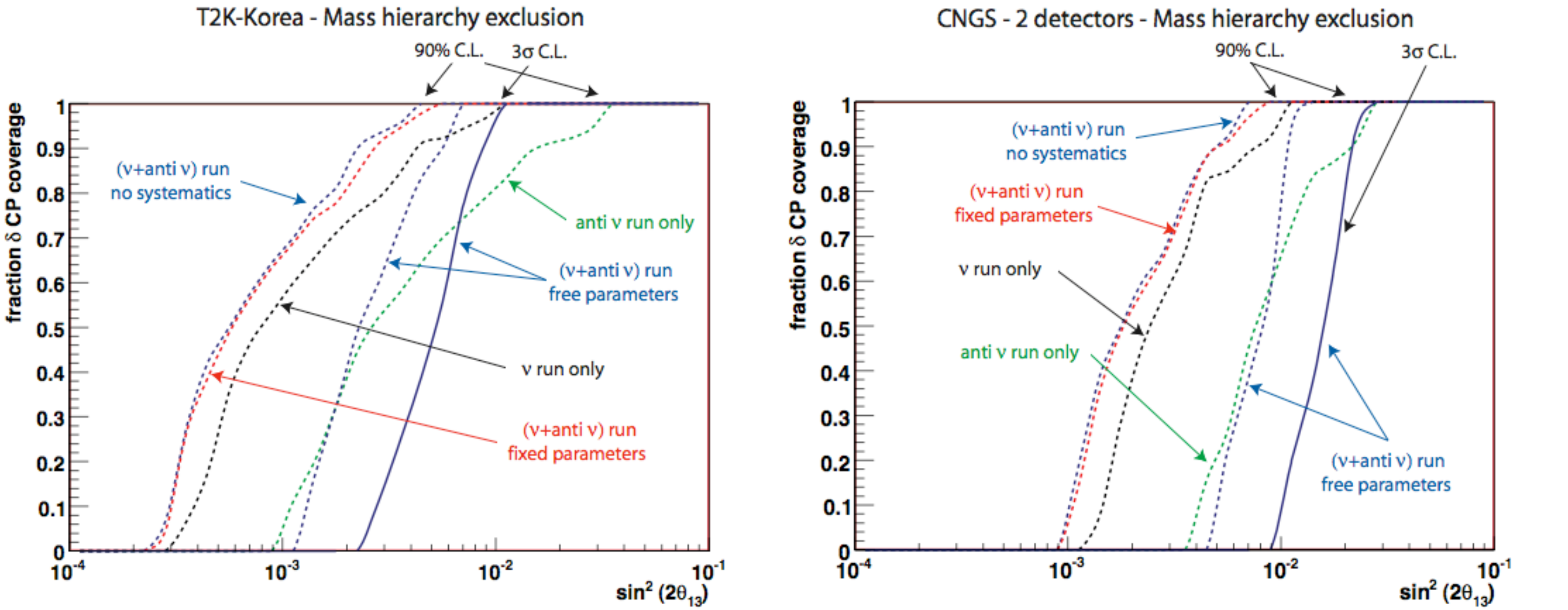


- To understand the effect of the mass hierarchy degeneracy, we repeated our calculations, for the CNGS 850 km configuration, leaving in all correlations but assuming a normal mass hierarchy (of course, knowing that the true mass hierarchy is also normal).
- The "island" we had at δ_{CP}~90 disappears.
- A symmetric situation (δ>180 deg., δ<180 deg.) is restored.
- The performance on δ_{CP} sensitivity is comparable to the one obtained using the T2K beam.

Mass hierarchy

- The presence of matter changes the neutrino oscillation probability and the effect is quite remarkable if the baseline is long enough (order of 1000 km).
- The effect is different in case of normal (sgn(Δm_{31}^2) = 1) or inverted (sgn(Δm_{31}^2) = -1) hierarchy.
- The knowledge of the mass hierarchy makes it possible to disentangle matter effects from δ_{CP} effects, hence CP violation can be measured.
- In order to determine the mass hierarchy to a given C.L., the opposite mass hierarchy must be excluded.
- A point in parameter space with normal hierarchy is chosen as true value and the solution with the smallest χ^2 value with inverted hierarchy has to be determined by global minimization of the χ^2 function leaving all oscillation parameters free within their priors.
- GLoBES software has been used and the parameter were set as in the study of θ_{13} sensitivity.

Results: mass hierarchy sensitivity



- CNGS 850 km detector configuration suffers from a short baseline and a spectrum that covers only the first maximum of oscillation.

- However, the CNGS 2 detectors configuration makes possible to measure 1st and 2nd maximum and 1st minimum of oscillation.

Comparison with FNAL-DUSEL

- Similar studies were carried out using GLoBES to estimate the performance of a 300 kton Water Cerenkov detector on a future possible FNAL neutrino beam at different baselines (**Phys.Rev.D74:073004,2006**).
- The use of the Water Cerenkov technology implies a detailed study of the π^0 background, whereas with a LAr TPC it could be reduced below the intrinsic ν_e background. Therefore, this source of background was neglected in our studies.
- The results are stated in the table below and are comparable to what we achieved in our studies.

	Best sensitivity (3σ) $\sin^2(2\theta_{13})$	Maximal coverage (3σ) $\sin^2(2\theta_{13})$
θ_{13}	$\sim 2\times10^{-3}$	100% coverage at $\sim 5\times10^{-3}$
CP-Violation	$\sim 3\times10^{-3}$	~70% coverage at 1×10^{-1}
mass hierarchy	$\sim 4\times10^{-3}$	100% coverage at $\sim 9\times10^{-3}$

Conclusions

- Physics performance of GLACIER, a liquid Argon TPC with a mass of 100 kton, on different neutrino beams has been investigated using the GLoBES software.

- We considered conventional neutrino beams with very high proton luminosity (superbeams), in particular upgraded versions of the T2K and CNGS one.

- We investigated θ_{13}, CP-Violation and mass hierarchy sensitivity obtaining the following results:

	Best sensitivity (3σ) $\sin^2(2\theta_{13})$	Maximal coverage (3σ) $\sin^2(2\theta_{13})$
θ_{13}	$\sim 5\times10^{-4}$	100% coverage at $\sim 4\times10^{-3}$
CP-Violation	$\sim 2\times10^{-3}$	~70% coverage at 1×10^{-1}
mass hierarchy	$\sim 2\times10^{-3}$	100% coverage at $\sim 1\times10^{-2}$

- The actual (CHOOZ) limit on θ_{13} is $\sin^2(2\theta_{13}) \sim 1\times10^{-1} \Rightarrow$ improvement by a factor of 200.

- The detector could be used in a second stage in conjunction with a possible beta beam or a neutrino factory.