Liquid Argon TPCs for T2K experiment and future long baseline neutrino experiments

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Neutrino oscillation physics

Neutrino oscillations (1)

- Neutrino 3-flavour oscillation is well established both at the solar and atmospheric scale.
- This means that mass eigenstates and flavour eigenstates are different.
- Neutrinos are produced in weak interactions i.e. as flavour eigenstates and propagate as mass eigenstates (Hamiltonian eigenstates).
- The relationship between the two eigenstate bases can be expressed with a matrix equation:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}_{e1} & \mathrm{U}_{e2} & \mathrm{U}_{e3} \\ \mathrm{U}_{\mu 1} & \mathrm{U}_{\mu 2} & \mathrm{U}_{\mu 3} \\ \mathrm{U}_{\tau 1} & \mathrm{U}_{\tau 2} & \mathrm{U}_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \longrightarrow |\nu_\alpha(t)\rangle = \sum_{i=1}^{n} U^*_{\alpha i} |\nu_i(t)\rangle$$

- The matrix can be written in terms of 3 mixing angles (θ_{ij}) and 1 complex (δ) phase as:

$$\mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric scale — Interference — Solar scale

$s_{ij} = sin(\theta_{ij})$
$c_{ij} = cos(\theta_{ij})$

Neutrino oscillations (2)

- Using the standard plane wave approximation we can write the neutrino propagation as:

$$|\nu_i(t)\rangle = e^{-iE_i t}|\nu_i(0)\rangle$$

- Knowing that neutrinos are relativistic we can use the approximation:

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p + \frac{m_i^2}{2E}$$

- It results that the oscillation probability $P_{\alpha\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2$ has terms proportional to:

$$\sin^2(\Delta m_{ij}^2 L/4E)$$

where

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

L = baseline (normally distance between ν source and detector)

E = ν energy

- The probability of oscillation from a flavour to a different one can be expressed as a function of the **3 mixing angles (θ_{12}, θ_{13}, θ_{23})**, **the complex phase (δ)** and **2 neutrino mass differences (Δm^2_{21}, Δm^2_{31})**.

NOTE: neutrino oscillations are **NOT** sensitive to absolute masses but only to mass differences.

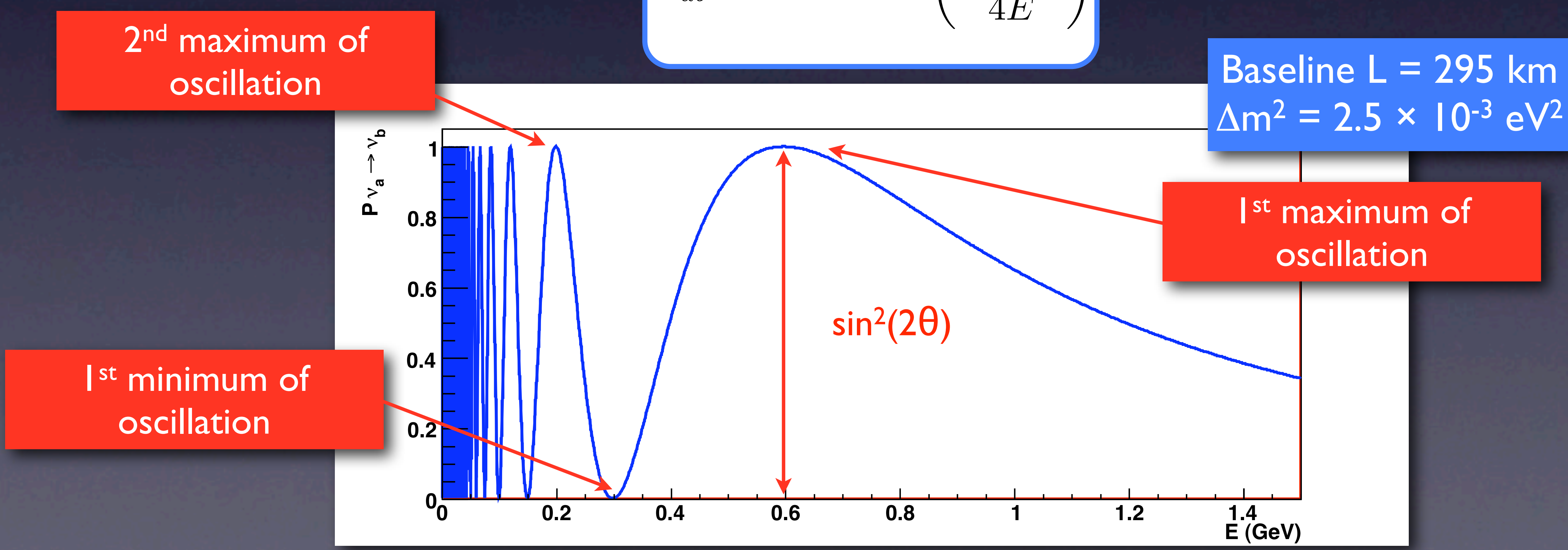
Neutrino oscillations (3)

- As an example we take the 2-flavour case. The mixing matrix can be written as:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- The probability of oscillation from neutrino "a" to neutrino "b" is:

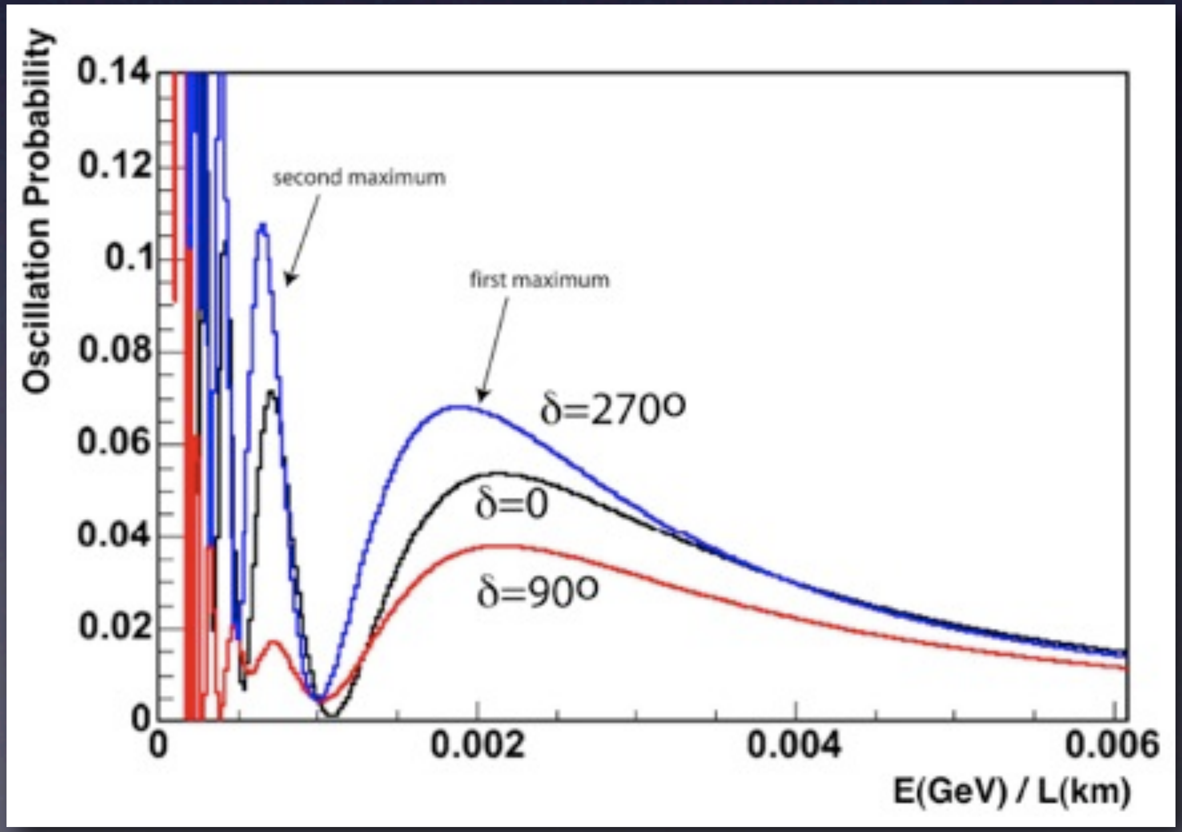
$$P_{ab} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Neutrino oscillations (4)

- The presence of matter affects neutrino oscillations since the mass eigenstates (i.e. the ones relevant for the propagation) are different, due to a new potential term present in the system Hamiltonian.
- The probability of oscillation of neutrinos and antineutrinos is affected in a different way: this **"fakes" a CP violation effect**.
- In order to measure intrinsic CP violation due to δ_{CP} phase we need to disentangle the two phenomena and this can be done in 2 ways:

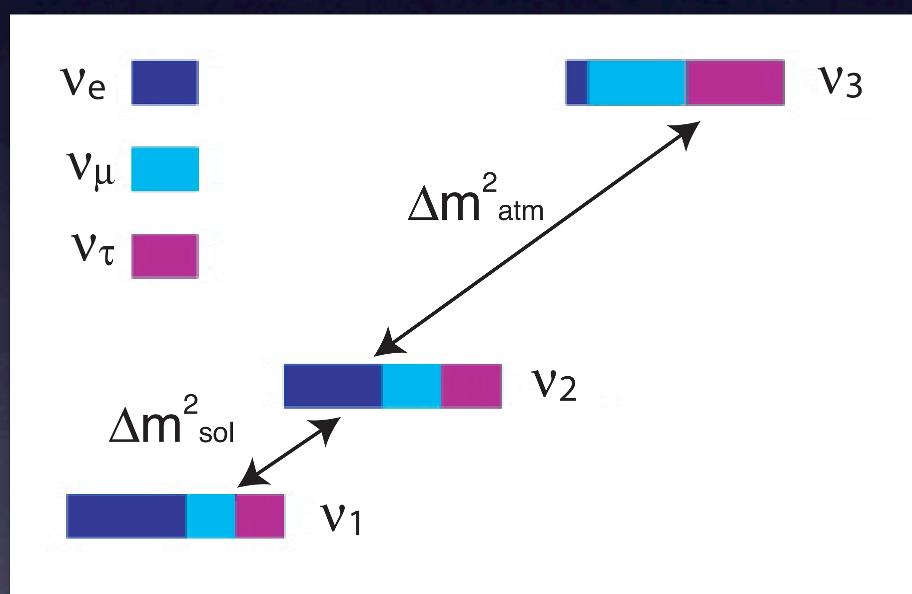
1. Measuring the same maximum of oscillation at different baselines.
2. Measuring two maxima of oscillation at the same baseline.



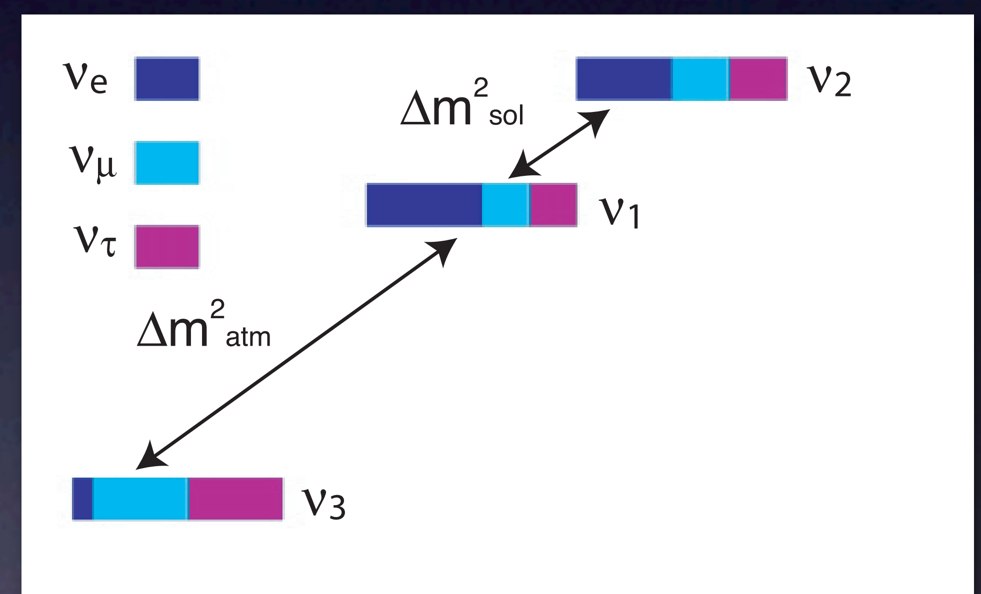
Neutrino oscillations (5)

- The fact that mass hierarchy (i.e. Sign (Δm^2_{31})) is unknown makes things harder since changing hierarchy the effects of matter on neutrino and antineutrino are swapped.

Normal hierarchy



Inverted hierarchy



- To measure the hierarchy the best option would be to have a very long baseline (a few thousands km) so that matter effect is strong and it is easy to measure if neutrino oscillations are enhanced or reduced.

Present knowledge

Parameter	Present knowledge (90% C.L.)	Channel	Experiments	Future
θ_{23}	$\sin^2(2\theta_{23}) \geq 0.92$	$P(\nu_\mu \rightarrow \nu_\mu)$	SK, (K2K, MINOS)	T2K
θ_{12}	$0.82 \leq \sin^2(2\theta_{12}) \leq 0.89$	Solar ν + $P(\text{anti } \nu_e \rightarrow \text{anti } \nu_e)$	SK, SNO, KamLAND	
θ_{13}	$\sin^2(2\theta_{13}) \leq 0.19$	$P(\text{anti } \nu_e \rightarrow \text{anti } \nu_e)$ $P(\nu_\mu \rightarrow \nu_e)$	CHOOZ	T2K, Double CHOOZ Future LBL
Δm^2_{21}	$7.7 \leq \Delta m^2_{21}$ / 10^{-5} eV$^2 \leq 8.3$	Solar ν + $P(\text{anti } \nu_e \rightarrow \text{anti } \nu_e)$	SK, SNO, KamLAND	
$\lvert\Delta m^2_{31}\rvert$	$1.9 \leq \lvert\Delta m^2_{31}\rvert$ / 10^{-3} eV$^2 \leq 3.0$	$P(\nu_\mu \rightarrow \nu_\mu)$	SK, MINOS	MINOS, T2K
Sign (Δm^2_{31})	Unknown	$P(\nu_\mu \rightarrow \nu_e)$ Vs $P(\text{anti } \nu_\mu \rightarrow \text{anti } \nu_e)$		Future LBL
δ_{CP}	Unknown	$P(\nu_\mu \rightarrow \nu_e)$ Vs $P(\text{anti } \nu_\mu \rightarrow \text{anti } \nu_e)$		T2K+Reactor Future LBL

Goals

- The goal of **long baseline** neutrino oscillation experiments is to precisely measure the relevant parameters and answer to important questions such as:

  ✓ Is θ_{23} mixing maximal?

  ✓ Is θ_{13} different from zero?

  ✓ Is there CP violation in the leptonic sector? (i.e. is $\delta \neq 0$?)

  ✓ Is there normal or inverted hierarchy? (i.e. which is the sign of Δm^2_{31}?)

Strategy (1)

- The goal of **long baseline** neutrino oscillation experiments is to precisely measure the relevant parameters and answer to important questions such as:

✓ Is θ_{23} mixing maximal? → ν_μ disappearance: $P(\nu_\mu \rightarrow \nu_x) \sim \cos^4\theta_{13} \sin^2(2\theta_{23}) \sin^2(\Delta m^2_{32} L/(4E_\nu))$

✓ Is θ_{13} different from zero?

✓ Is there CP violation in the leptonic sector? (i.e. is $\delta \neq 0$?)

✓ Is there normal or inverted hierarchy? (i.e. which is the sign of Δm^2_{31}?)

→ ν_e appearance: $\nu_\mu \rightarrow \nu_e$ oscillation

Strategy (2)

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

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

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

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

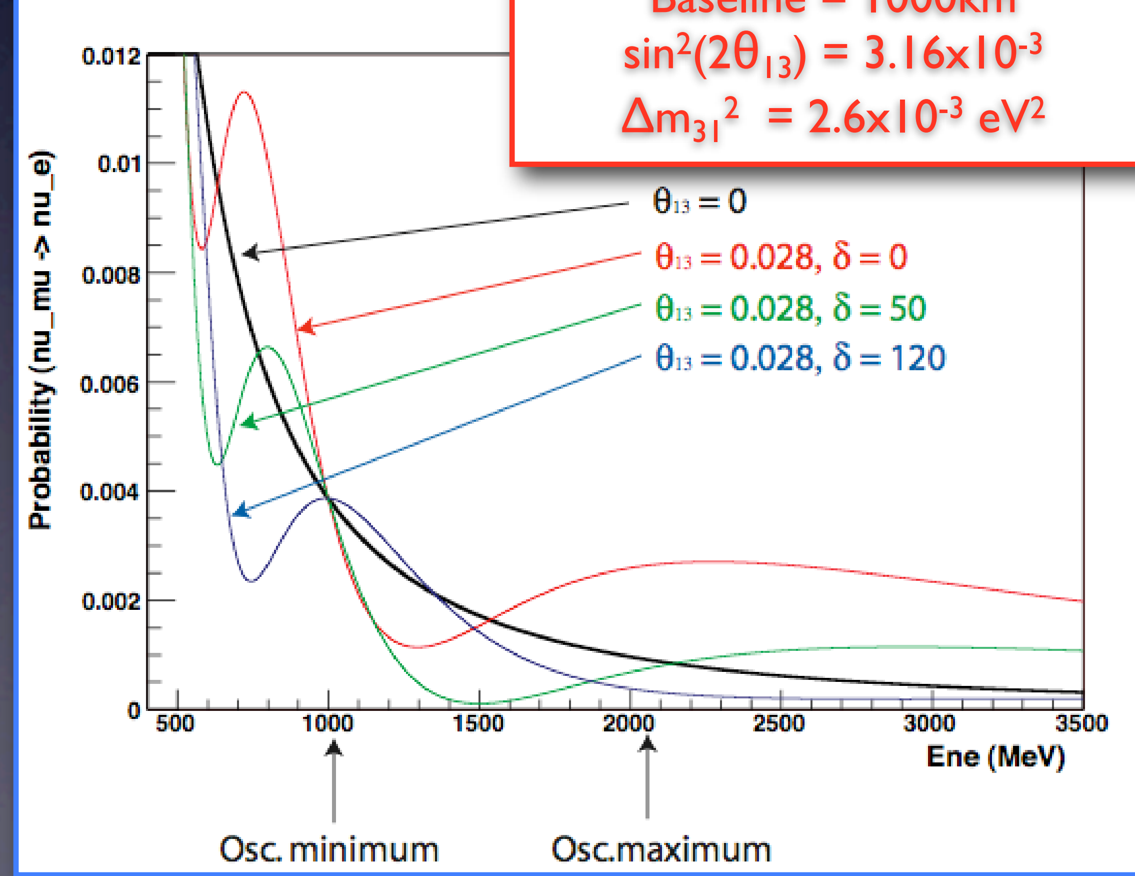
$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

← Interference terms (P_3, P_4)

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

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

Baseline = 1000km
$\sin^2(2\theta_{13}) = 3.16\times10^{-3}$
$\Delta m_{31}^2 = 2.6\times10^{-3}$ eV^2



T2K experiment

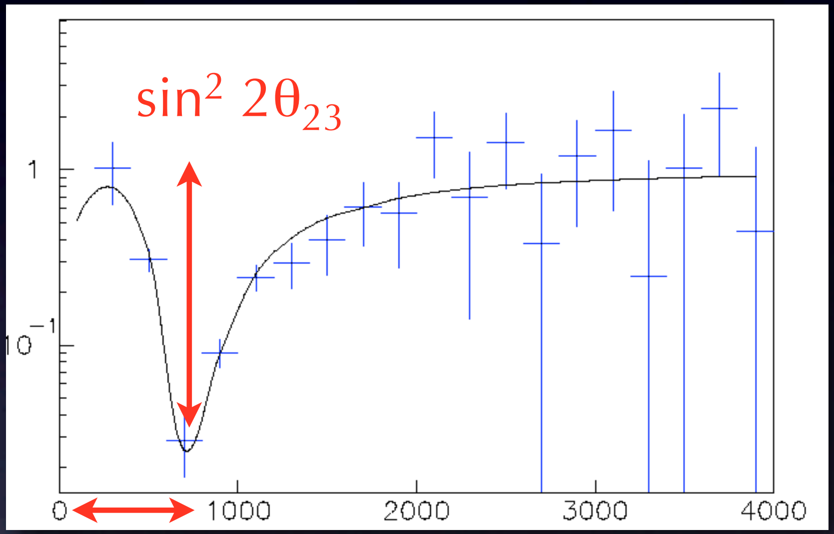
T2K goals

Using a conventional neutrino beam (mainly ν_μ with a contamination of 0.4% ν_e at peak) the goals are:

- **ν_μ disappearance:**

$$P(\nu_\mu \rightarrow \nu_x) \sim \cos^4\theta_{13} \sin^2(2\theta_{23}) \sin^2(\Delta m^2_{32} L/(4E_\nu))$$

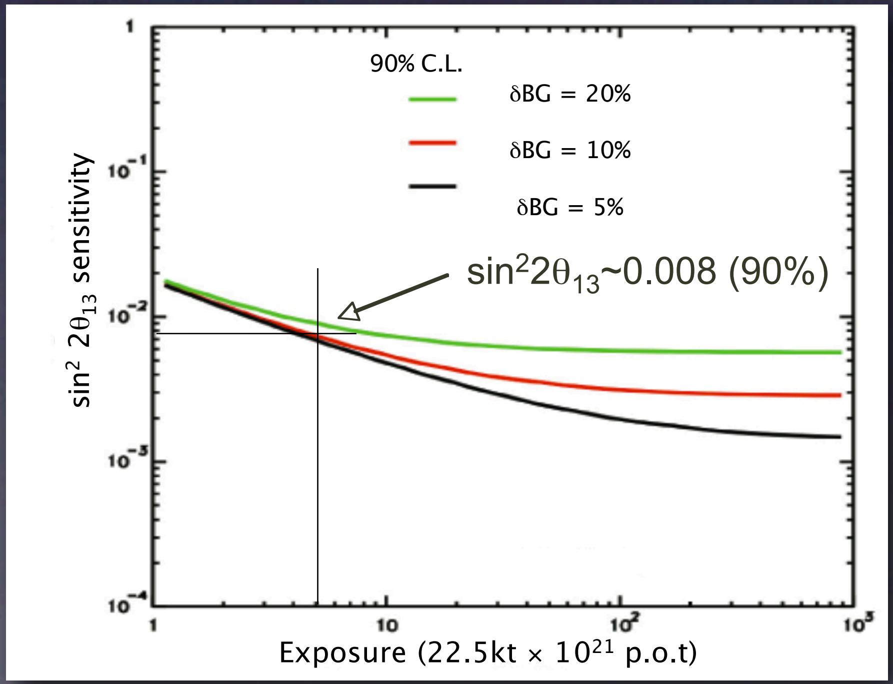
Sensitivity: $\delta(\sin^2(2\theta_{23})) \sim 0.01$ (≈1%)
$\delta(\Delta m^2_{32}) \leq 3 \times 10^{-5}$ eV^2 (≈1%)



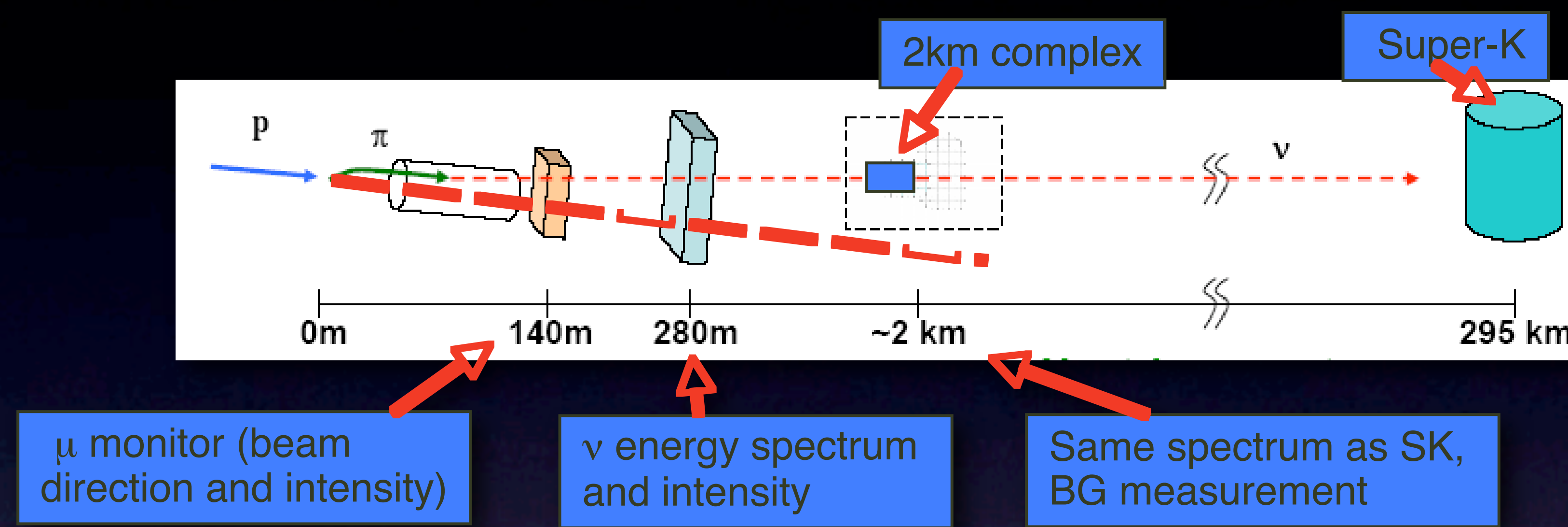
- **ν_e appearance:**

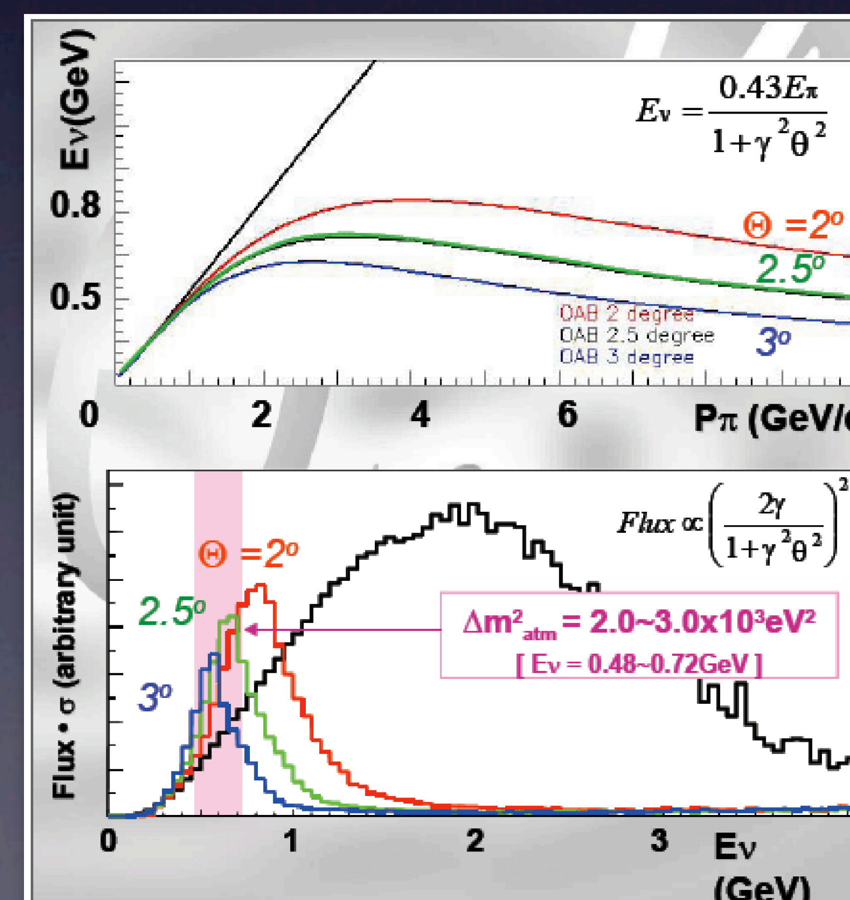
This measurement will allow to discover a non-zero value or set a smaller limit on the θ_{13} mixing angle.

Sensitivity: $\sin^2(2\theta_{13}) \leq 8 \times 10^{-3}$ (90% C.L.)



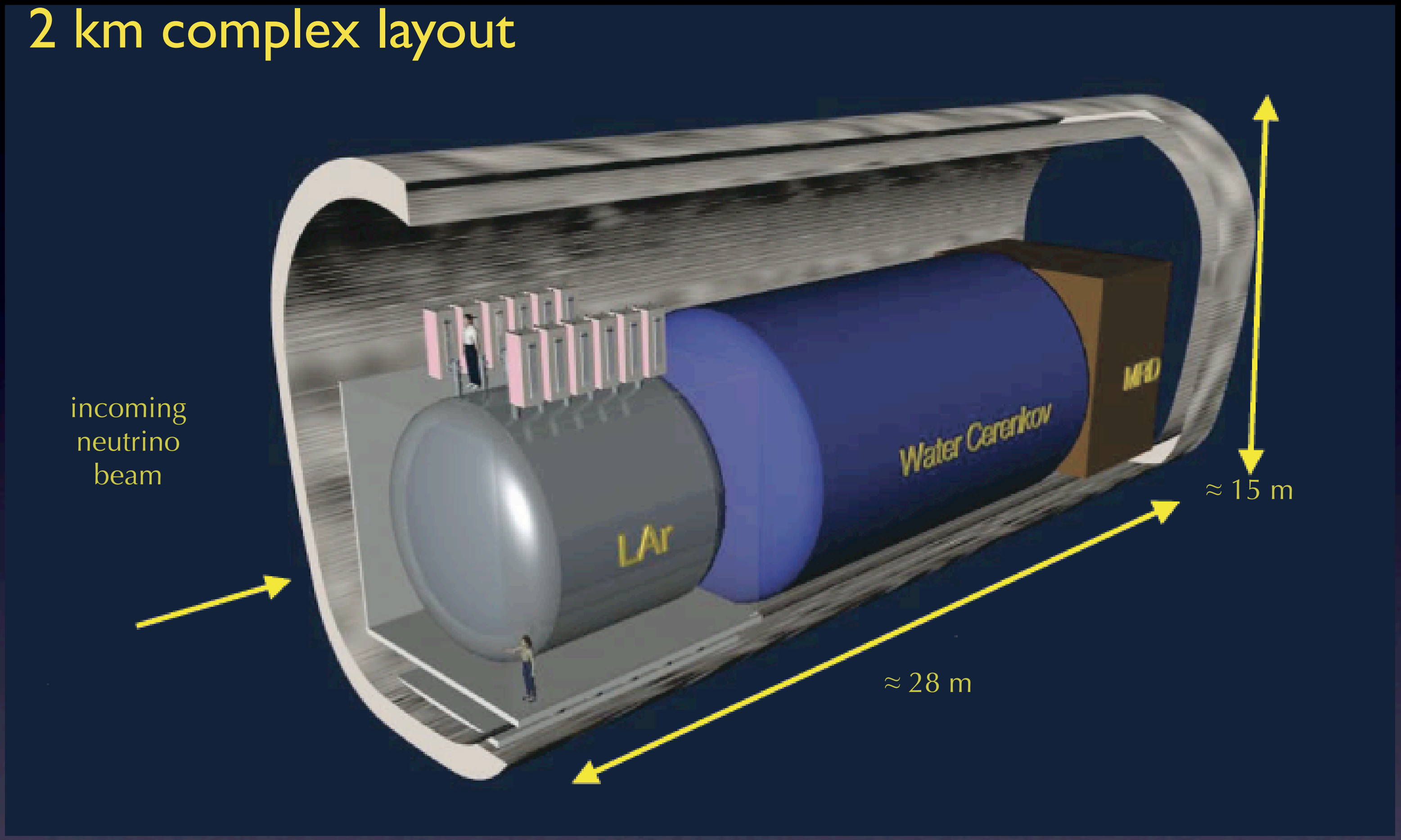
T2K experiment





- Long baseline (295 km) neutrino oscillation experiment.
- Low E (less than 1 GeV) Super Beam: ~ 10^{21} p.o.t./year.
- Off axis by 2.5 degrees.
- Start in 2009 aiming to reach a power of 0.75 MW from a 30 GeV proton synchrotron (upgrades to 1.6 MW and 4 MW under study).

T2K experiment: 2 km complex



- The 2 km complex has been proposed but not approved yet, it is not foreseen before ~ 2012.
- This detector complex would be located off axis at 2km from the target.
- It is made up of a 100 ton LAr TPC (fine grained detector), a 1 kton Water Cerenkov detector and a muon range detector.

Far/Near ratio

F/N ratio

- Both appearance and disappearance analyses rely on the neutrino spectra measured at SK (far detector) and the spectra extrapolated at SK from the near detector measurement (ND280):

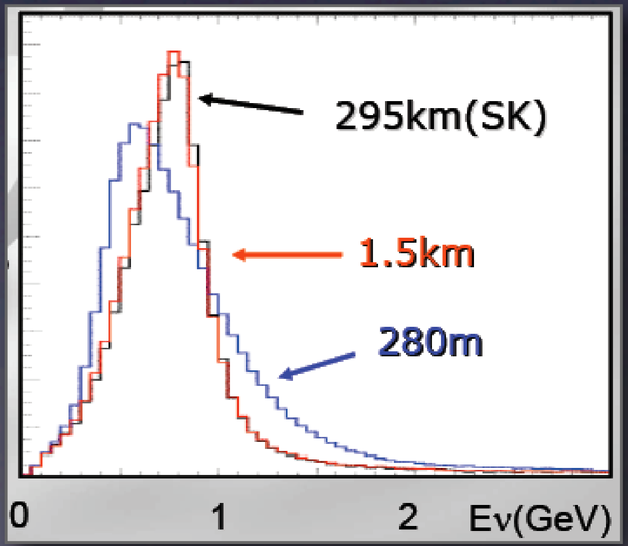
$$\Phi^{SK}_{\mu,e}(E_\nu) = R_{\mu,e}(E_\nu) \times \Phi^{ND}_{\mu,e}(E_\nu)$$

extrapolated at far detector — Far to Near (F/N) ratio — measured at the near detector

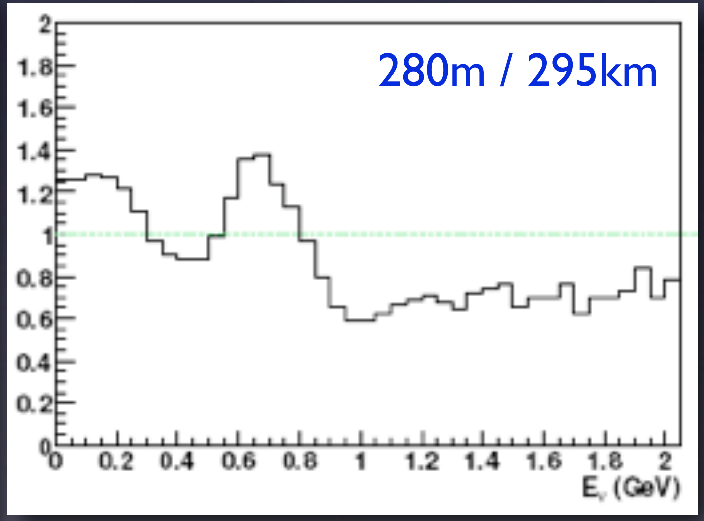
- In case of a point-like and isotropic neutrino source, the ratio is given by the solid angle (i.e. it scales as L^{-2} where L is the baseline).

- In practice, due to the finite size of the source, the F/N ratio depends on the neutrino energy.

ν_μ Flux (normalised to SK)



F/N ratio (ν_μ)



Requirements on F/N ratio

- The background in **ν_e appearance** is mainly due to ν_μ NC π^0 interactions and intrinsic beam ν_e:

$$
\begin{aligned}
N_{BG} &= N_{BG}^{\pi^0} + N_{BG}^{e} \\
&= \Phi_\mu^{SK} \cdot \sigma_{NC\pi^0} \cdot \varepsilon_{SK}^{\pi^0} + \Phi_e^{SK} \cdot \sigma_e \cdot \varepsilon_{SK}^{e} \\
&= R_\mu \Phi_\mu^{ND} \cdot \sigma_{NC\pi^0} \cdot \varepsilon_{SK}^{\pi^0} + R_e \Phi_e^{ND} \cdot \sigma_e \cdot \varepsilon_{SK}^{e}
\end{aligned}
$$

- To achieve the goals of the experiment the systematics should be no more than 10%, therefore **$\delta(N_{BG}) \leq 10\%$**.

- The **ν_μ disappearance** oscillation is measured as:

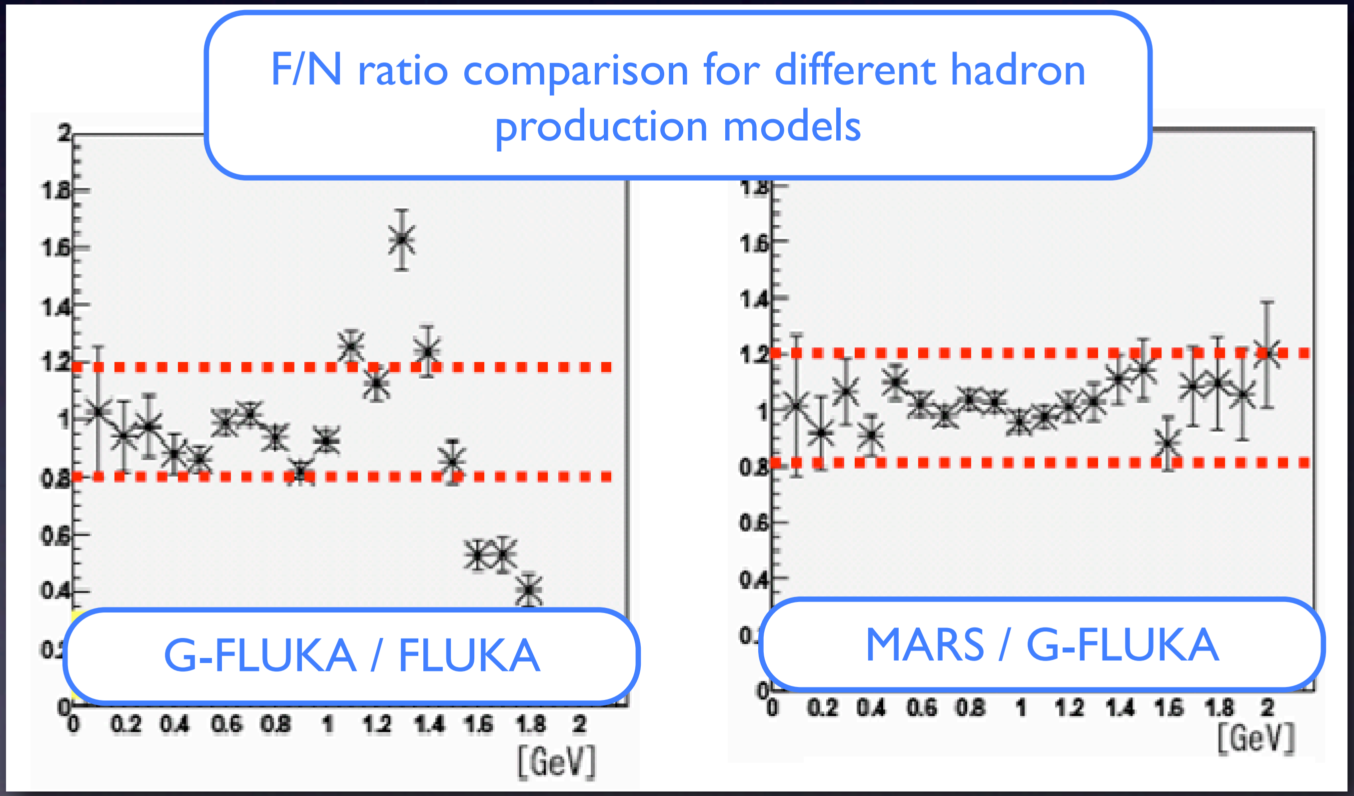
$$
\begin{aligned}
N_{sig}(E_\nu) &= P_{osc} \cdot \Phi_\mu^{SK}(E_\nu) \cdot \sigma_{\nu\mu CC}(E_\nu) \cdot \varepsilon_{SK}^{\nu\mu CC}(E_\nu) \\
&= P_{osc} \cdot R_\mu \Phi_\mu^{ND}(E_\nu) \cdot \sigma_{\nu\mu CC}(E_\nu) \cdot \varepsilon_{SK}^{\nu\mu CC}(E_\nu)
\end{aligned}
$$

- MC studies on how systematics on F/N ratio affects the precision of T2K measurements showed that if **$\delta(R_{\mu,e}) \approx 2$ - 3%** the contribution to the systematics is negligible compared to other contributions (due to ND280 spectrum measurements, cross sections, efficiencies, etc.) and it results into:

$\delta(N_{BG}) \approx 2\%$ | **$\delta(\Delta m^2_{32}) \approx \pm 1.5 \times 10^{-5}$ eV^2** | **$\delta(\sin^2 2\theta_{23}) \approx \pm 0.005$**

F/N ratio measurement

- No data for p+C interaction at 30 GeV exist, therefore the only way to evaluate F/N ratio is to rely on MC simulation.
- No model has been validated in this range, therefore we can assume as systematic error on F/N ratio the difference between MARS and G-FLUKA models i.e.:



- This corresponds to the following error on the N/F ratio:

$$\delta(R_\mu) \approx 20\%$$

F/N ratio measurement (2)

- The error on F/N ratio of ≈ 20% corresponds to:

$\delta(\sin^2 2\theta_{23}) \approx \pm 0.015 - 0.030$

$\delta(\Delta m^2_{32}) \approx \pm(5 - 10) \times 10^{-5}\ eV^2$

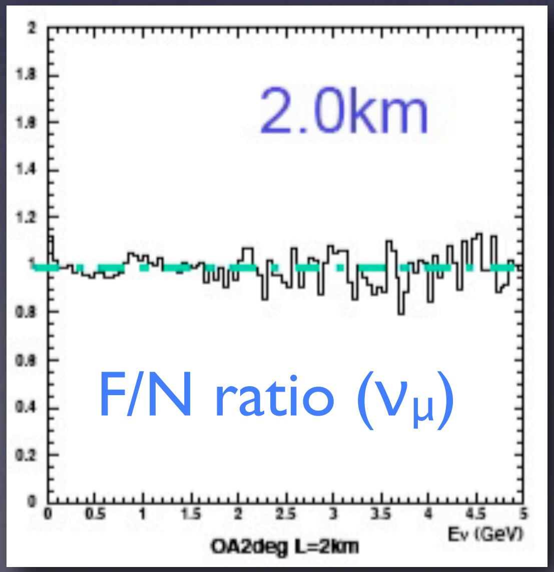
→ Larger than T2K goal:
$\delta(\sin^2(2\theta_{23})) \sim 0.01$
$\delta(\Delta m^2_{32}) \leq 3 \times 10^{-5}\ eV^2$

$\delta(N_{BG}) \approx 15\%$

→ Larger than the required error on background:
$\delta(N_{BG}) \leq 10\%$.

- A measurement of the hadron (pions and kaons) production off the T2K target is therefore mandatory to reach the desired sensitivity → **NA61/SHINE experiment**.

- Another option would be the measurement of the neutrino flux at the **2km detector complex** since at this distance the approximation of a point-like source is quite good and a flat F/N ratio within a 5% error can be achieved simply scaling for the distance.

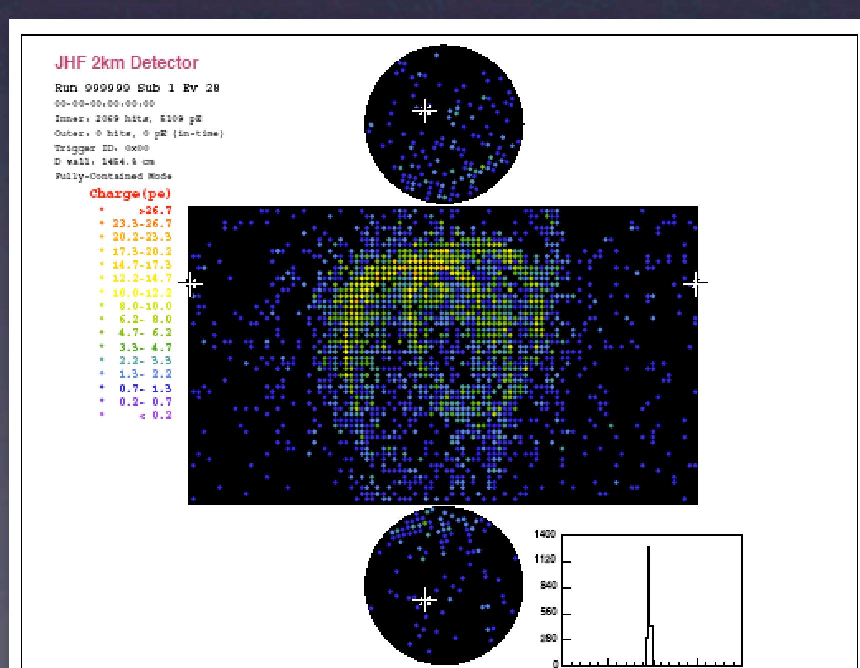


2 km complex

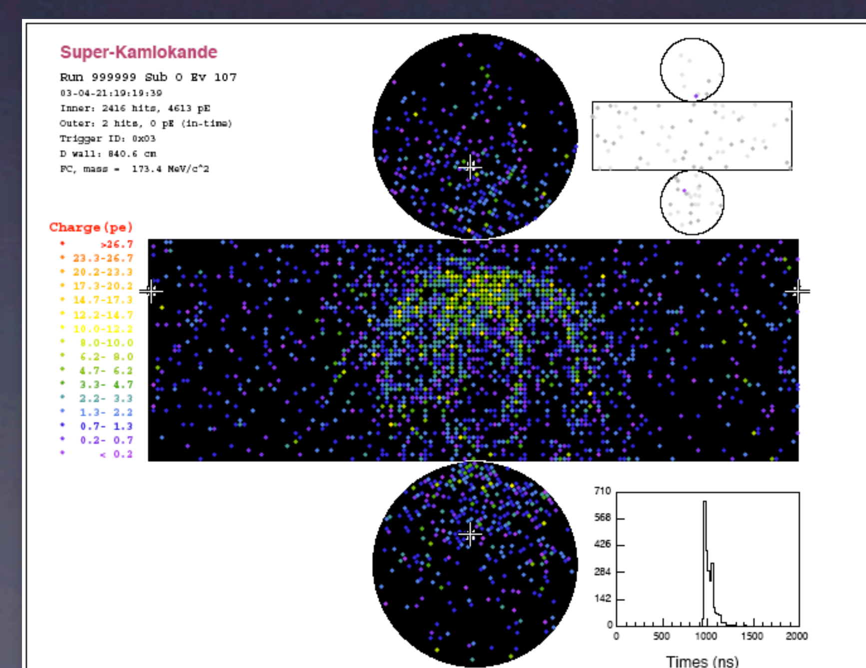
Further motivations for a 2km complex

- As stated before the flux measured at 2 km will allow to reduce one of the the main sources of systematics: the F/N flux ratio.
- In addition, the 2 km complex would profit from a Water Cerenkov detector crucial to minimise the systematics in prediction at SK, since it has the same target but most important the same events reconstruction procedure.
- A fine grained detector (e.g. LAr TPC) is needed in order to reconstruct recoiling protons, low momentum hadrons, asymmetric decays of π^0, etc., in an unbiased way.

π^0 - MC 2 km



π^0 - Real event SK



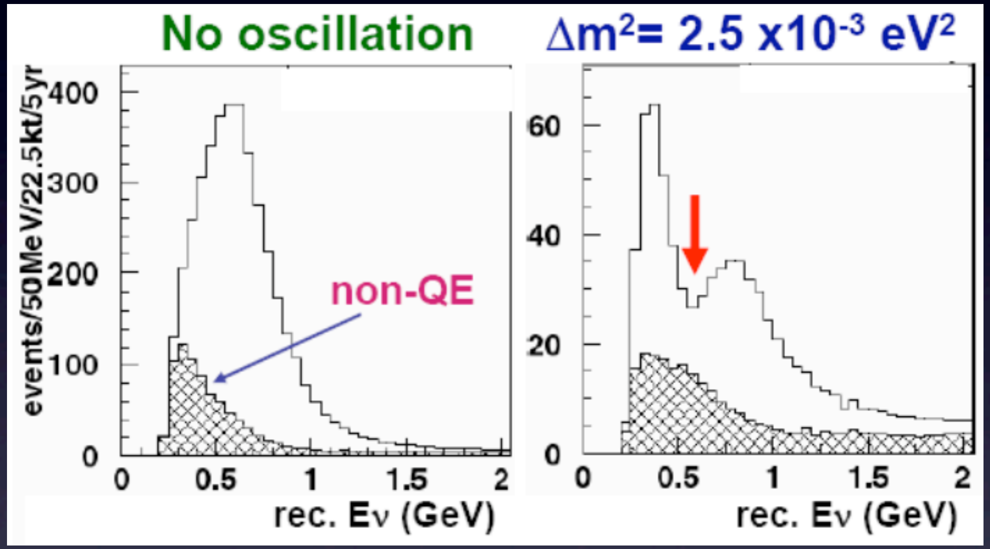
LAr TPC physics contribution

- According to the different goals and physics scenarios, the LAr TPC will play several important roles for the final T2K measurements.

ν_μ disappearance

↓

Measurement of QE/nQE ratio.

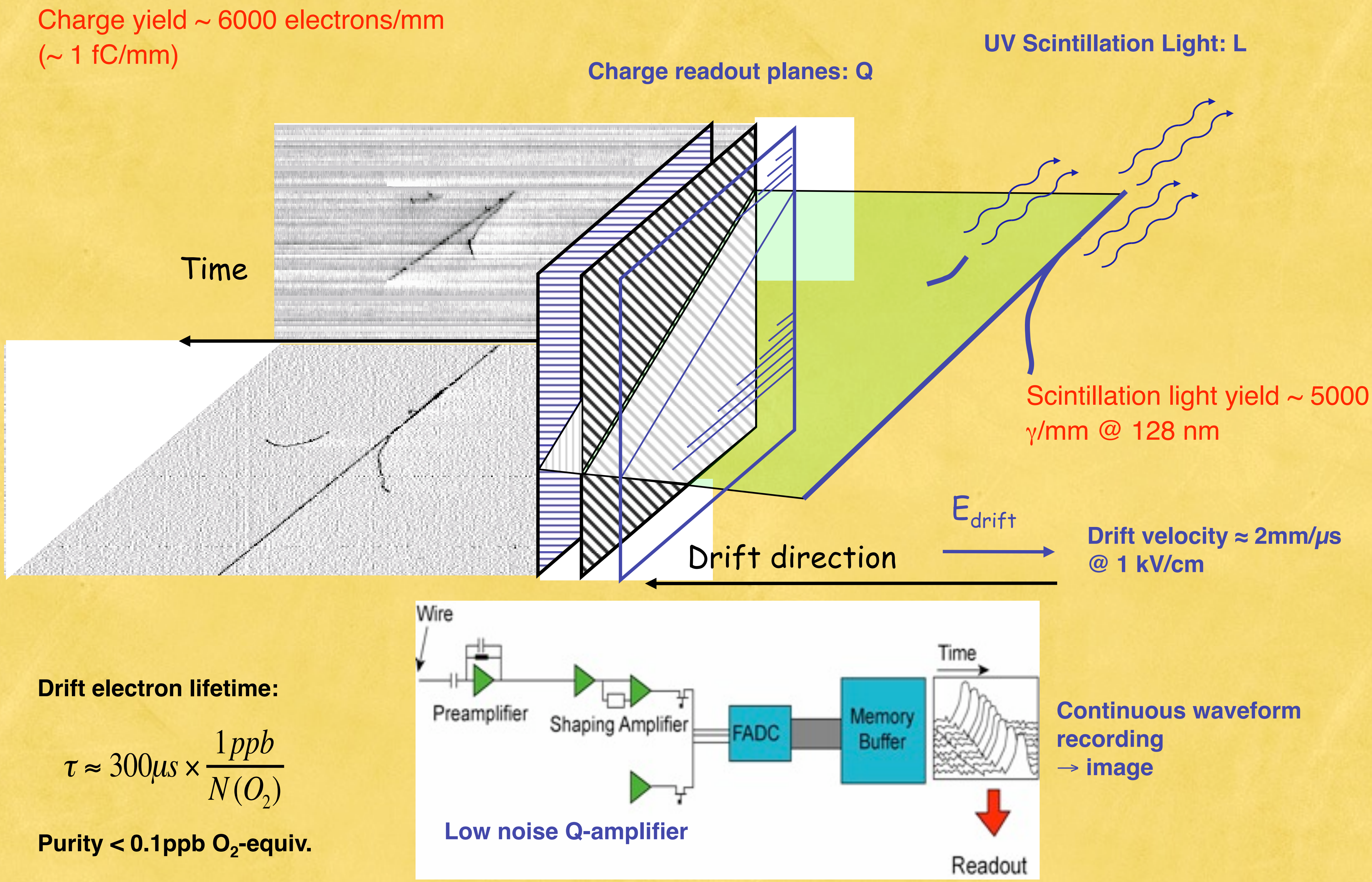


ν_e appearance

↓

Reduction of the systematics on the different components of the background.

The LAr TPC principle



Drift electron lifetime:

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

Purity < 0.1ppb O_2-equiv.

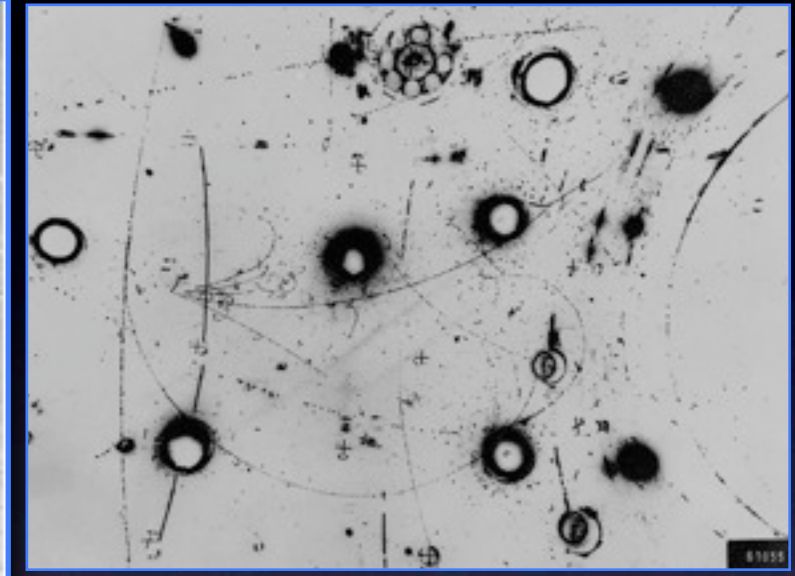
LAr TPC features (1)

- Fully active, homogeneous, high-resolution device: **high statistics neutrino interaction studies with bubble chamber accuracy**.
- Reconstruction of low momentum hadrons (below Cerenkov threshold), especially recoiling protons.

Real event in ICARUS

High granularity: Sampling = 0.02 X_0
"bubble" size $\approx 3\times3\times0.4$ mm^3

Gargamelle bubble chamber

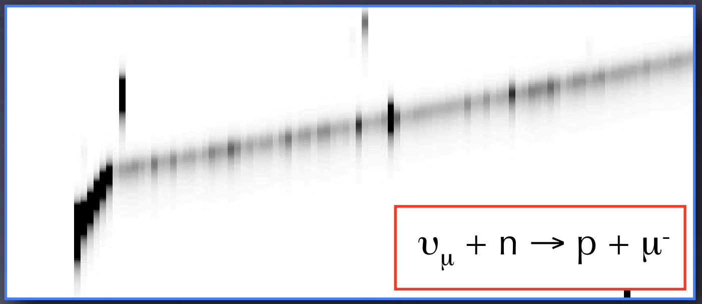


bubble diameter $\approx$3mm

Protons

Kinetic energy T (MeV)	Momentum p (MeV/c)	Range in LAr (cm)
10	43	0.14
40	280	0.93
70	370	4.19
100	446	7.87
300	813	51.9
500	1094	116

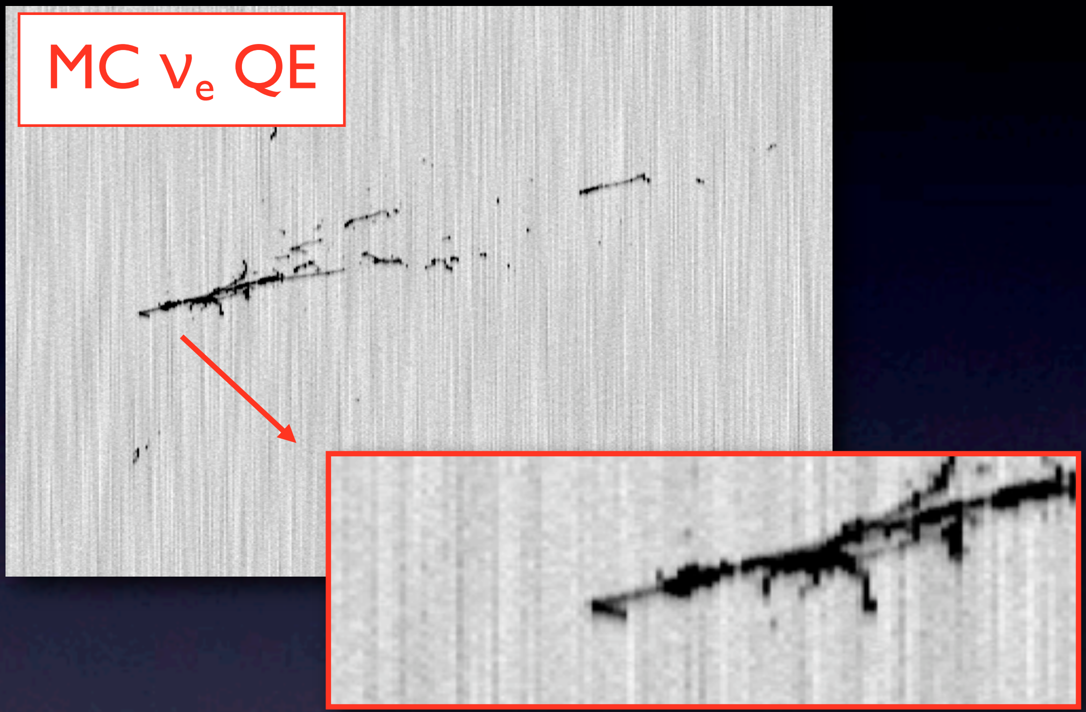
Cherenkov threshold in Water:
p = 1070 MeV/c

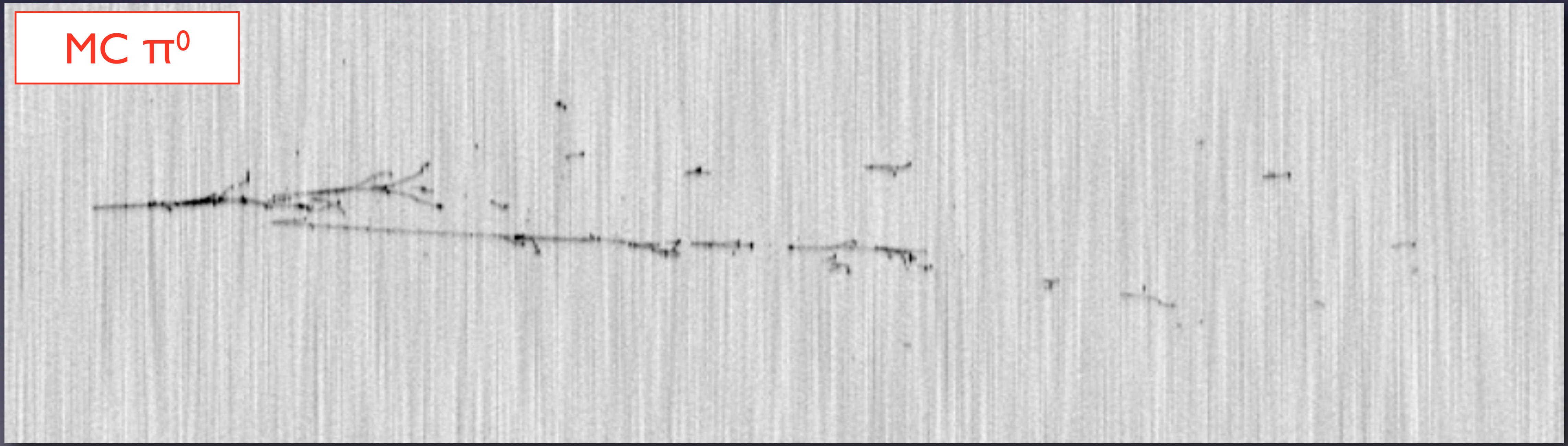


MC QE event.
Proton momentum = 490 MeV/c

LAr TPC features (2)

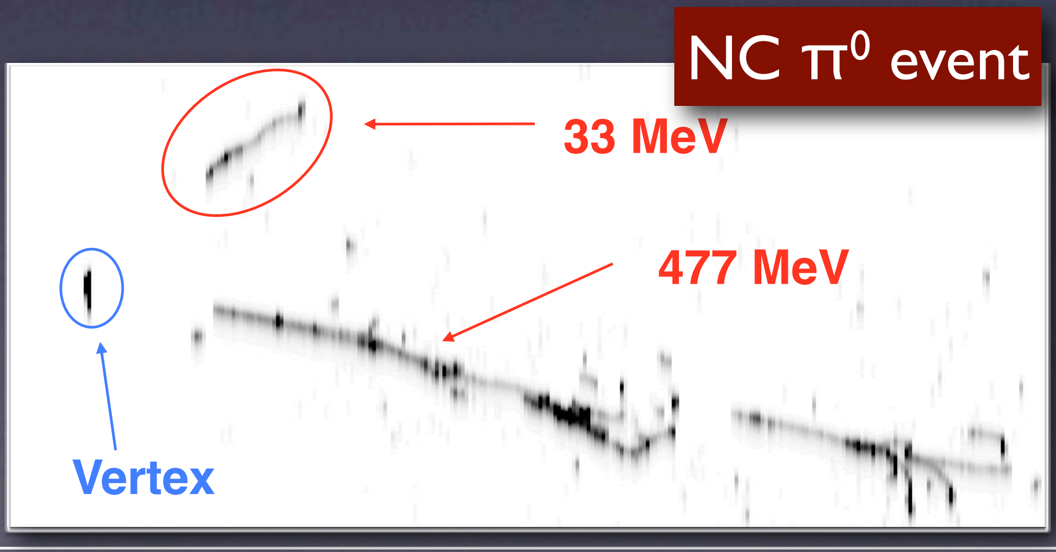
- Exclusive measurement of νNC events with clean π^0 identification for an independent determination of systematic errors on the NC/CC ratio.
- Precise measurement of ν_eCC events.

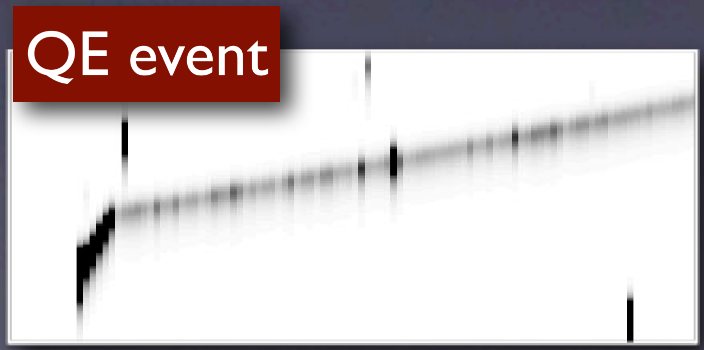




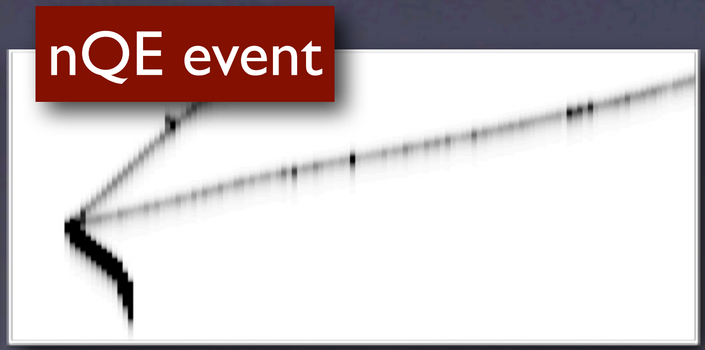
LAr TPC performance

- Several studies have been carried out to assess the detector performance:
  - ✓ **Energy reconstruction** finding an overall r.m.s. of 20%.
  - ✓ Use of **inner target** finding that an extrapolation from Argon to Water is possible with an error of the order of 3%.
  - ✓ **QE/nQE event separation** crucial for the ν_μ disappearance measurement, finding a conservative error of 18%, that can be strongly reduced taking into account correctly nuclear reinteractions.
  - ✓ **NC π^0 event selection** which is one of the relevant background for appearance measurement: 84% of the events that are misidentified in Water Cerenkov detector are correctly reconstructed.





Proton momentum = 490 MeV/c



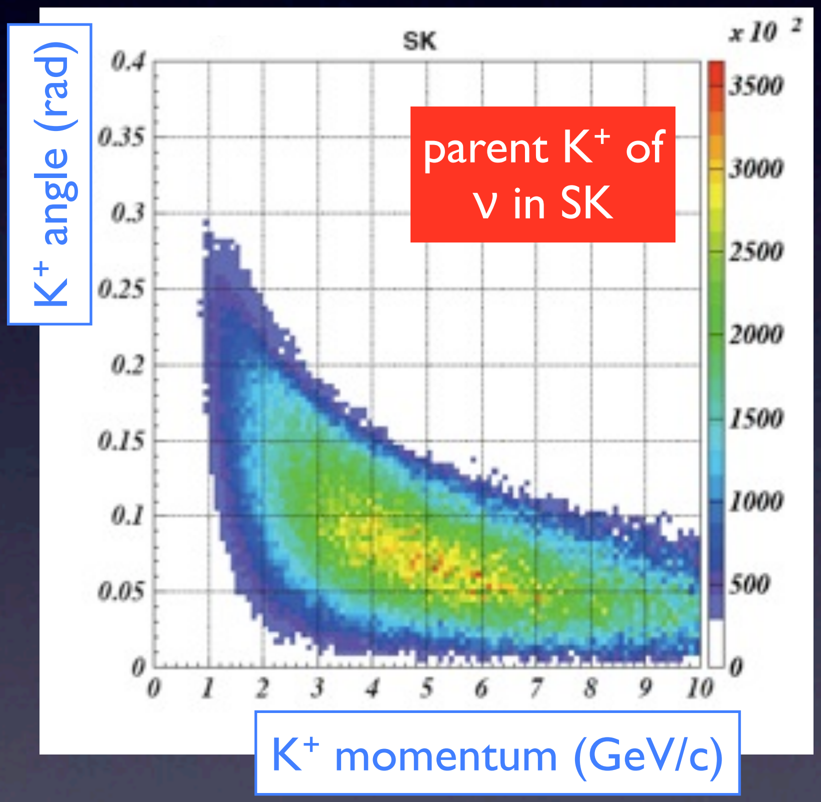
Proton momentum = 480 MeV/c, π^+ momentum = 377 MeV/c

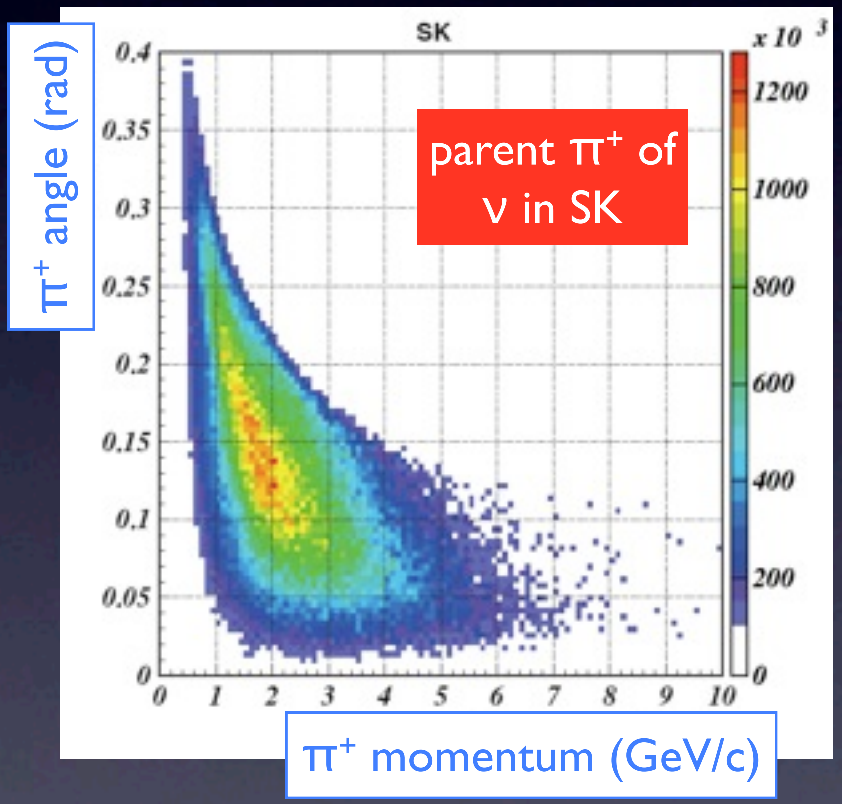
NA61/SHINE

NA61: goal and requirements

- The goal of NA61 experiment related to T2K is the **measurement of hadron production** form 30 GeV proton colliding on a replica of the T2K target, in order to correctly extrapolate the neutrino flux at SK from the measurement at the near detector.

- In particular we need to measure pions and kaons whose daughter neutrinos goes through SK.





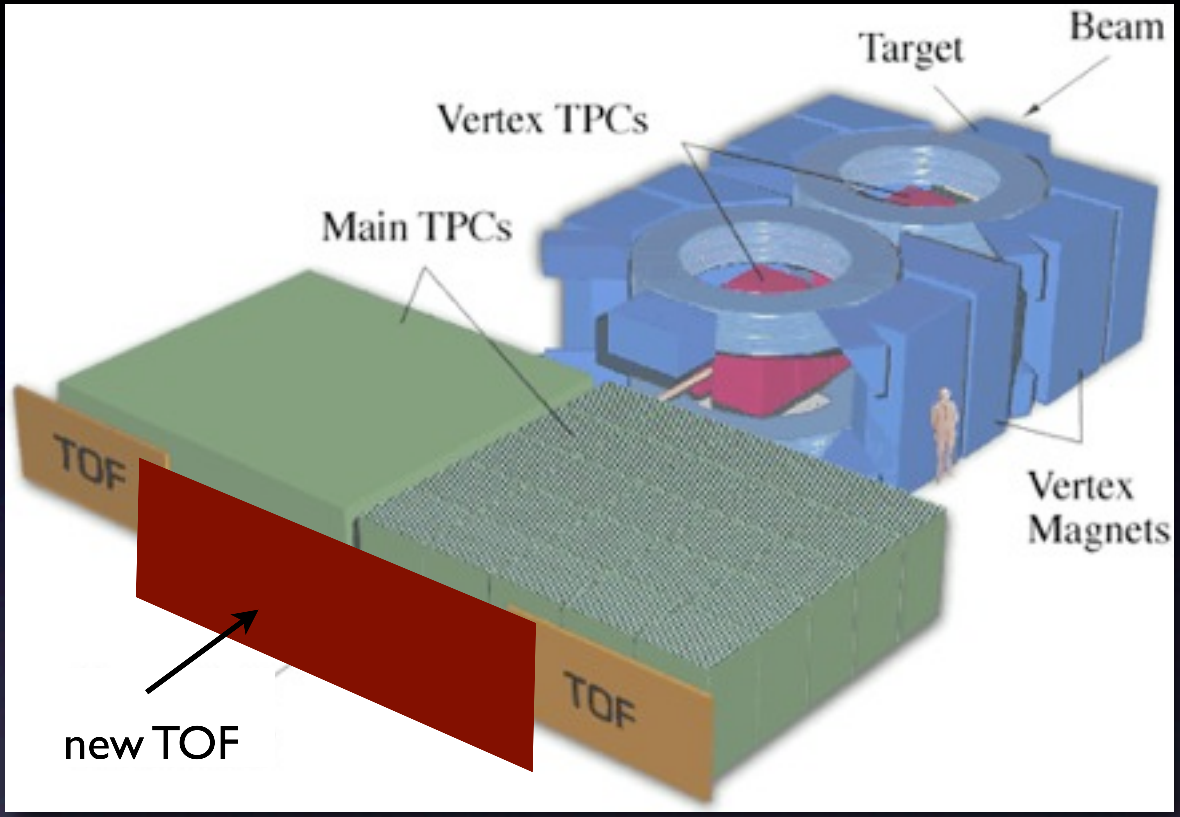
- To reach the desired precision on the Far/Near ratio of less than 3% we need to measure **~200k π^+ reconstructed tracks**.

- We also need to measure the K/π ratio with an uncertainty **δ(K/π)<10%**.

NA61 experiment

- The NA61 experiment is a fixed target experiment located on the H2 line of SPS at CERN.

- It uses the same detector setup of the NA49 experiment (heavy ions physics) with some modifications to optimise the performance for the T2K measurements.

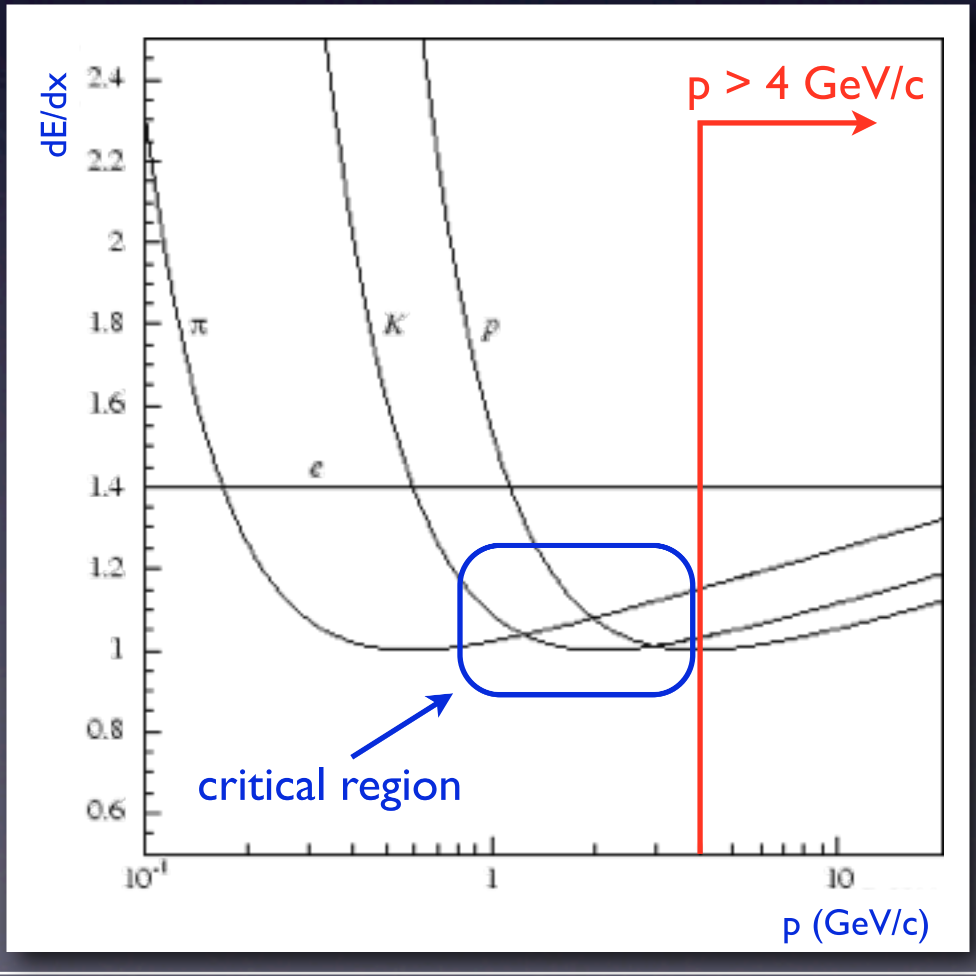


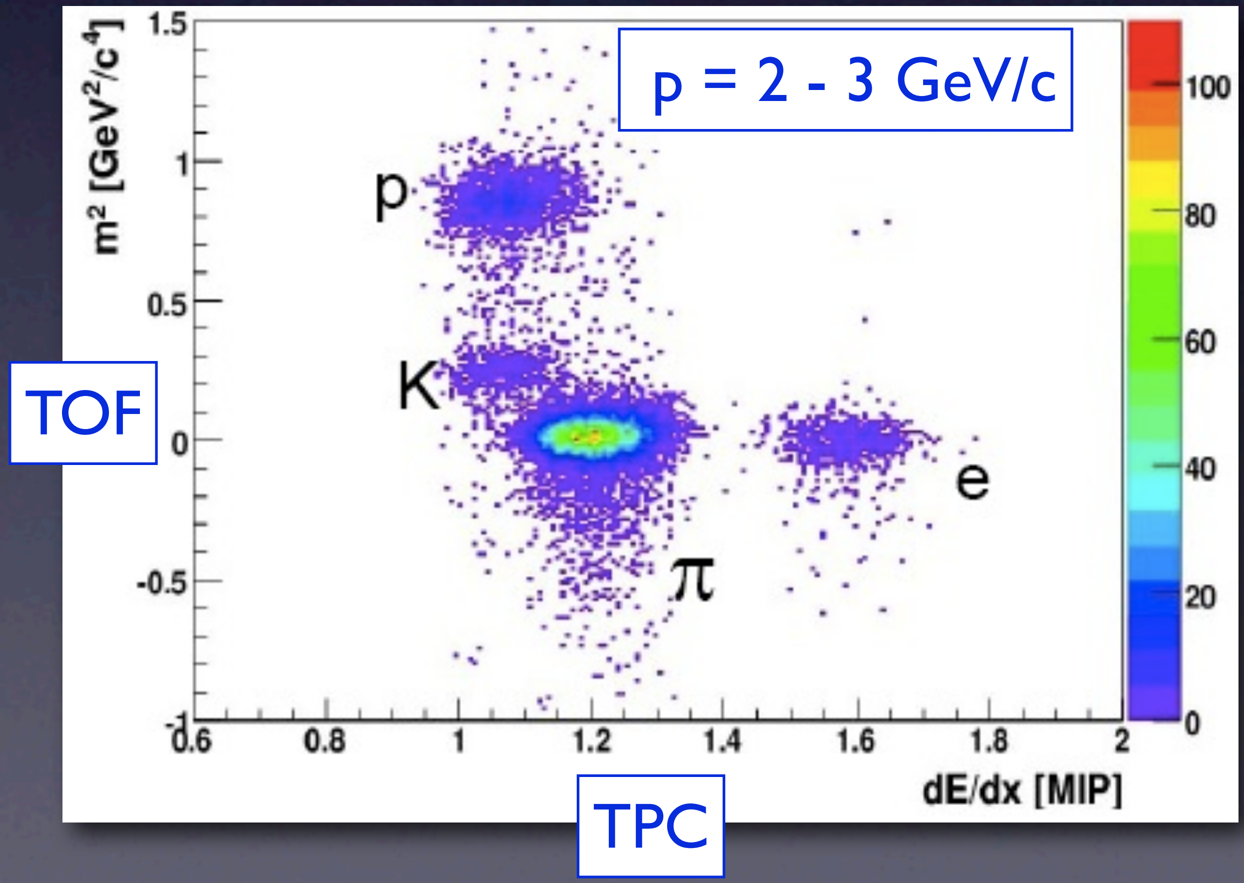
- The main components are:

1. 2 dipole magnets with a bending power of about 1.2 Tm over 7 m length.
2. 2 "vertex" TPC located inside the magnet (measurement of tracks momentum).
3. 2 "main" TPC (measurement of dE/dx)
4. 3 TOF , one especially built for the T2K purpose (measurement of the particle mass to be combined to dE/dx for particle ID).

Detector sensitivity

- The momentum resolution is $dp/p^2 \sim 10^{-4}$ $(GeV/c)^{-1}$.
- For tracks with momentum larger than about 4 GeV/c the particle ID is performed essentially by dE/dx.
- In the critical region of 1 - 4 GeV/c momentum the information from the TOF is crucial for a correct particle ID.





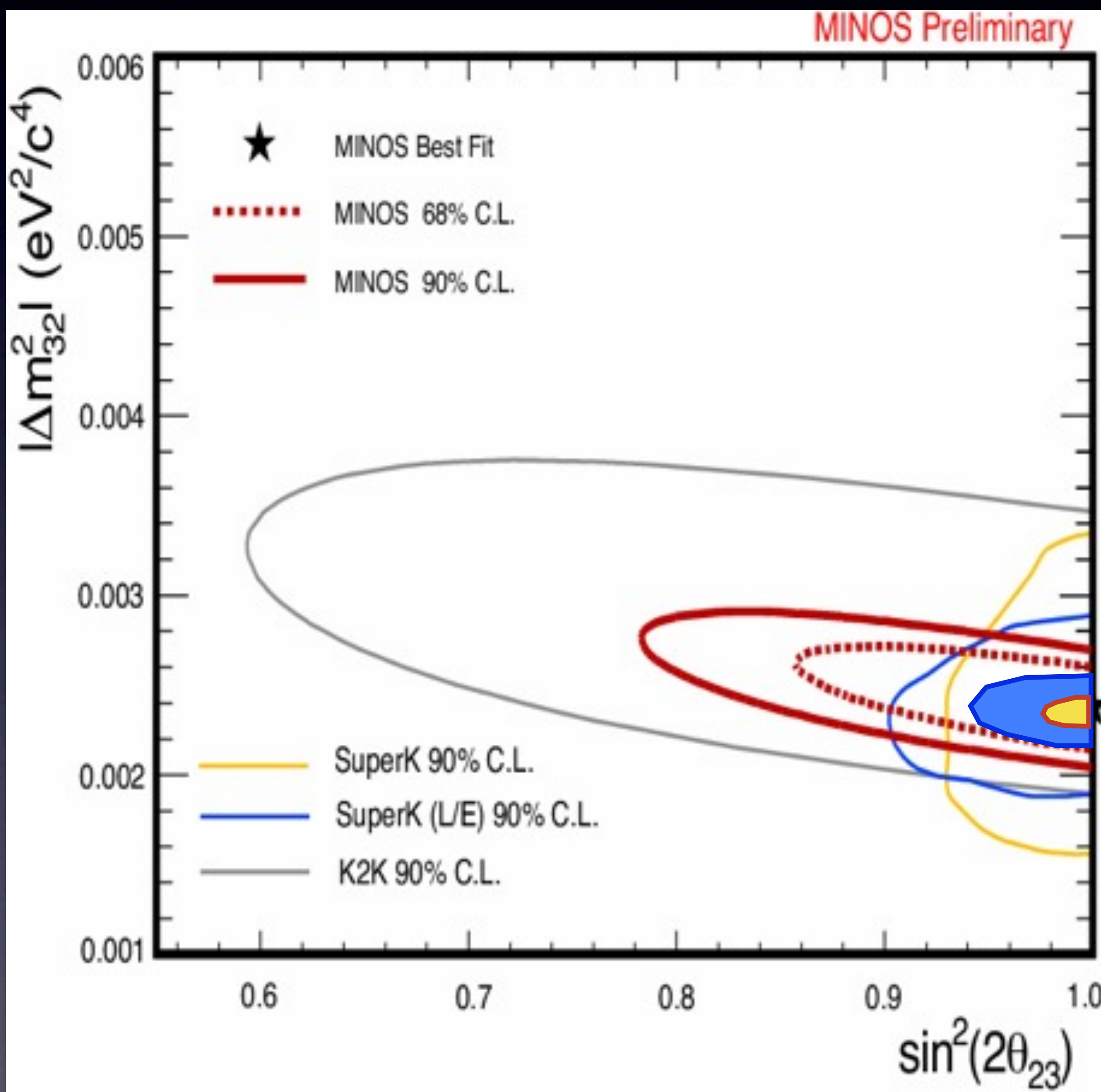
NA61 strategy and results

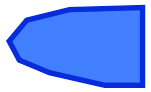
- The hadron production should be measured for **protons at 30, 40 and 50 GeV/c** momentum (as request by present and future plans of the T2K experiment) on 2 **graphite targets**:

1. 2 cm thick graphite target (~ 4% λ_{int}) to measure in detail the cross section for $p+C \rightarrow \pi^{+}+X$ and $p+C \rightarrow K^{+}+X$.
2. 90 cm long T2K replica target (~ 180% λ_{int}) to study in detail the secondary interactions, quite critical as the beam energy increases.

- In 2007 a pilot run was taken and in 2008 full statistics was expected. However, due to the LHC accident, the goal was not achieved and postponed to 2009.
- In 2008 run we registered enough trigger of protons and pions at 30 GeV and 75 GeV to confirm the preliminary results from 2007 run and complete the proton-carbon cross section measurement.
- Analysis is almost finished, results expected to be made public by summer 2009.

Visual impact of NA61





T2K without NA61

T2K with NA61

Future long baseline neutrino experiments

Perspectives

- Thanks to NA61 experiment and potentially with the 2 km detector complex, the T2K experiment will reach a limit on **$\sin^2(2\theta_{13}) \leq 8 \times 10^{-3}$**.
- T2K results will be crucial to determine the future of neutrino physics: in case a signal is measured, it would open the search for **CP violation** in the leptonic sector.
- What will the future be?

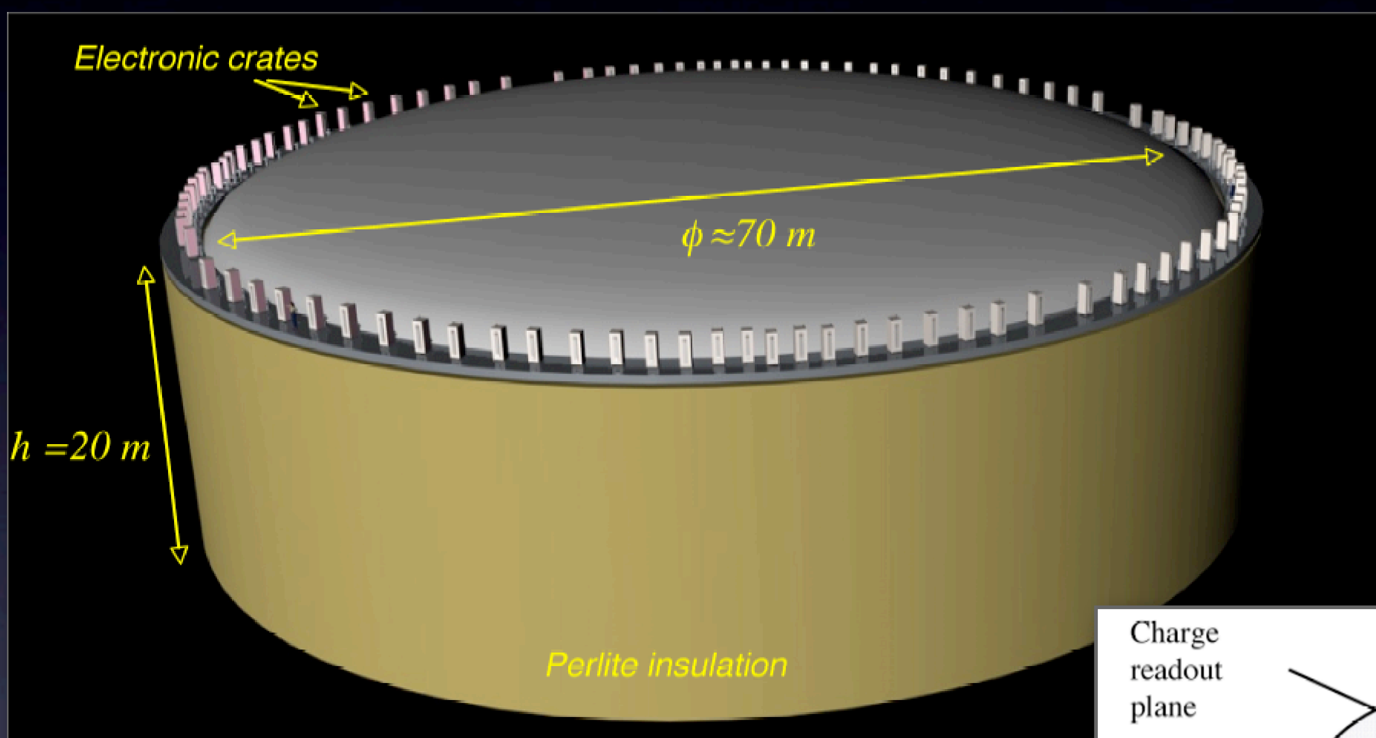
Detectors	→	Larger O(100)	GLACIER MEMPHIS LENA
Beams	→	More powerful O(10)	J-PARC upgrade FNAL upgrade CNGS upgrade
		New technology: Beta Beams Neutrino Factories	

Perspectives (2)

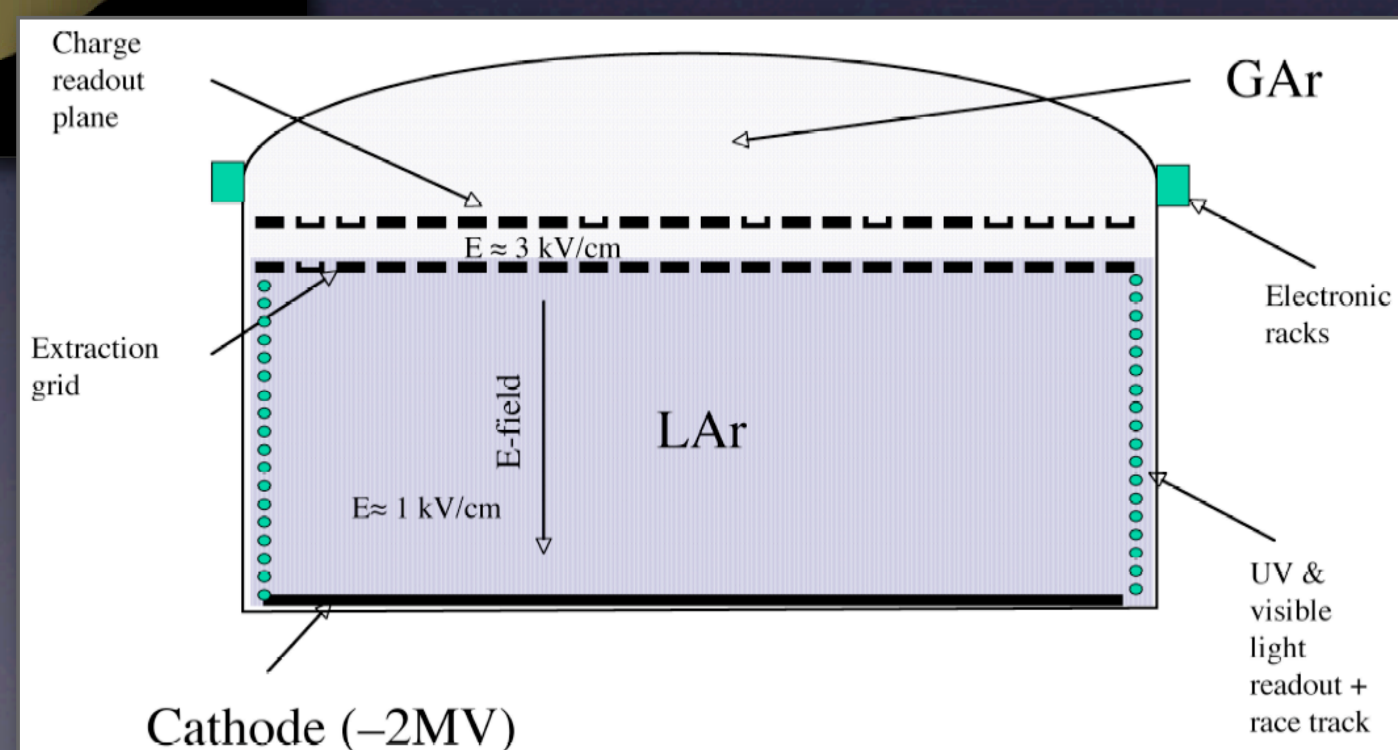
- Given the amount of money required for the next generation neutrino long baseline oscillation experiments, people try to find a "common solution" (ISS, LAGUNA, BENE, EUROν).
- Do we really need expensive new beam technologies? The answer lies in the true value of θ_{13}.
- In any case a large detector will profit from data taking on a Super Beam while deciding if new technologies are really worth it.
- Several studies have been carried out on the performance of a large (100 kton) LAr TPC on possible upgrades of J-PARC and CNGS neutrino beams.
- I will shortly discuss the general feature of the result found on the J-PARC beam only (arXiv:0801.4035), since the conclusion for the CNGS beam (JHEP 0611:032,2006) are quite similar.

GLACIER detector

- GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment) is a 100 kton LAr TPC.



- The drift is 20 m long and a new readout other than wires is needed.
- It will be a double phase detector: electrons are drifted in liquid and multiplied in gas.



- New HV supply needed since it is not possible to bring in 2MV with standard feed-through method.
- R&D already ongoing with ArDM, ARGONTUBE, T2K.

J-PARC neutrino beam

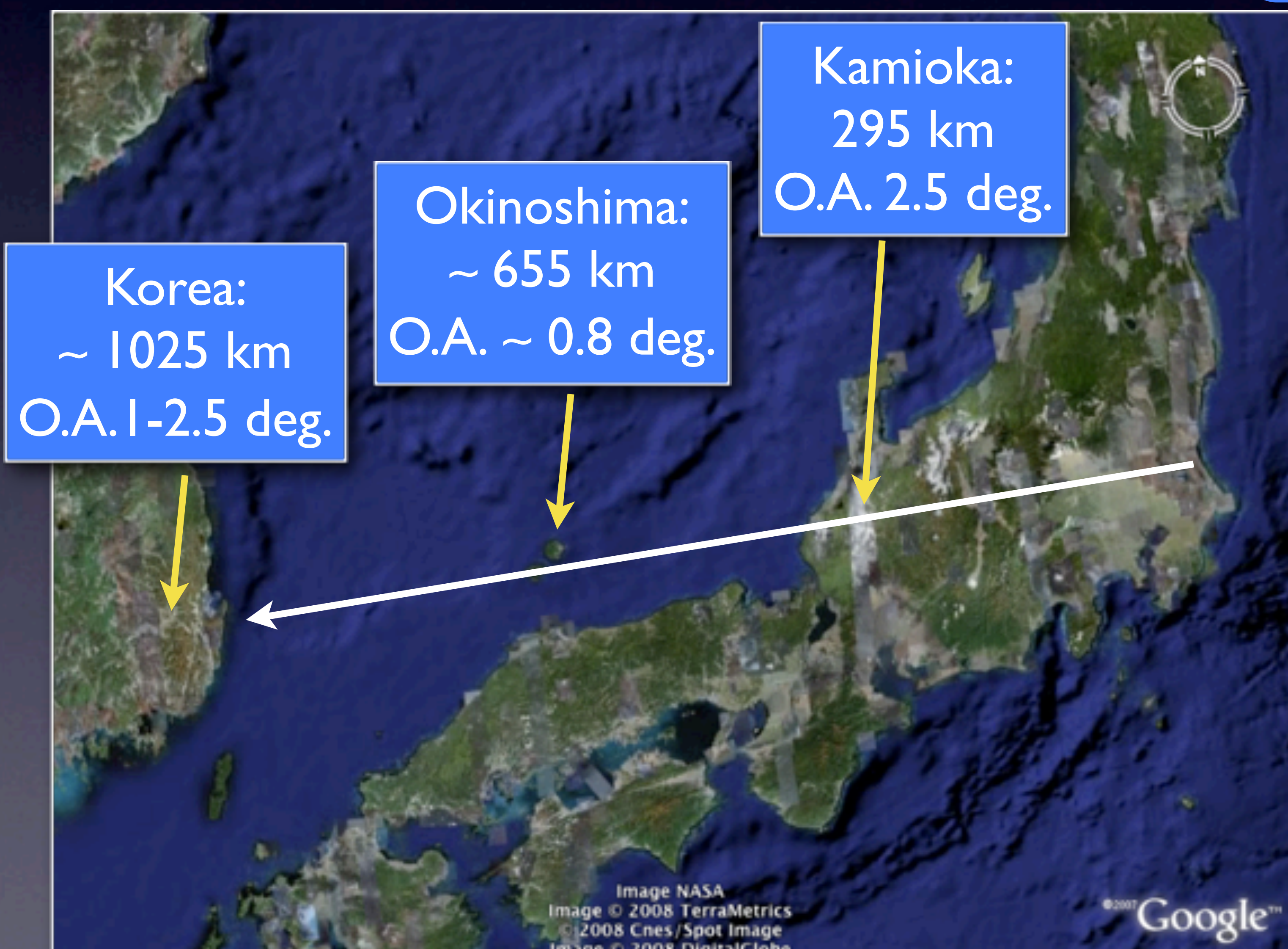
- The same neutrino beam used for the T2K experiment can be measured at different locations:

different off axis angles (different energy spectra) → higher maxima of oscillation

different baselines → different contribution from matter effects

↓

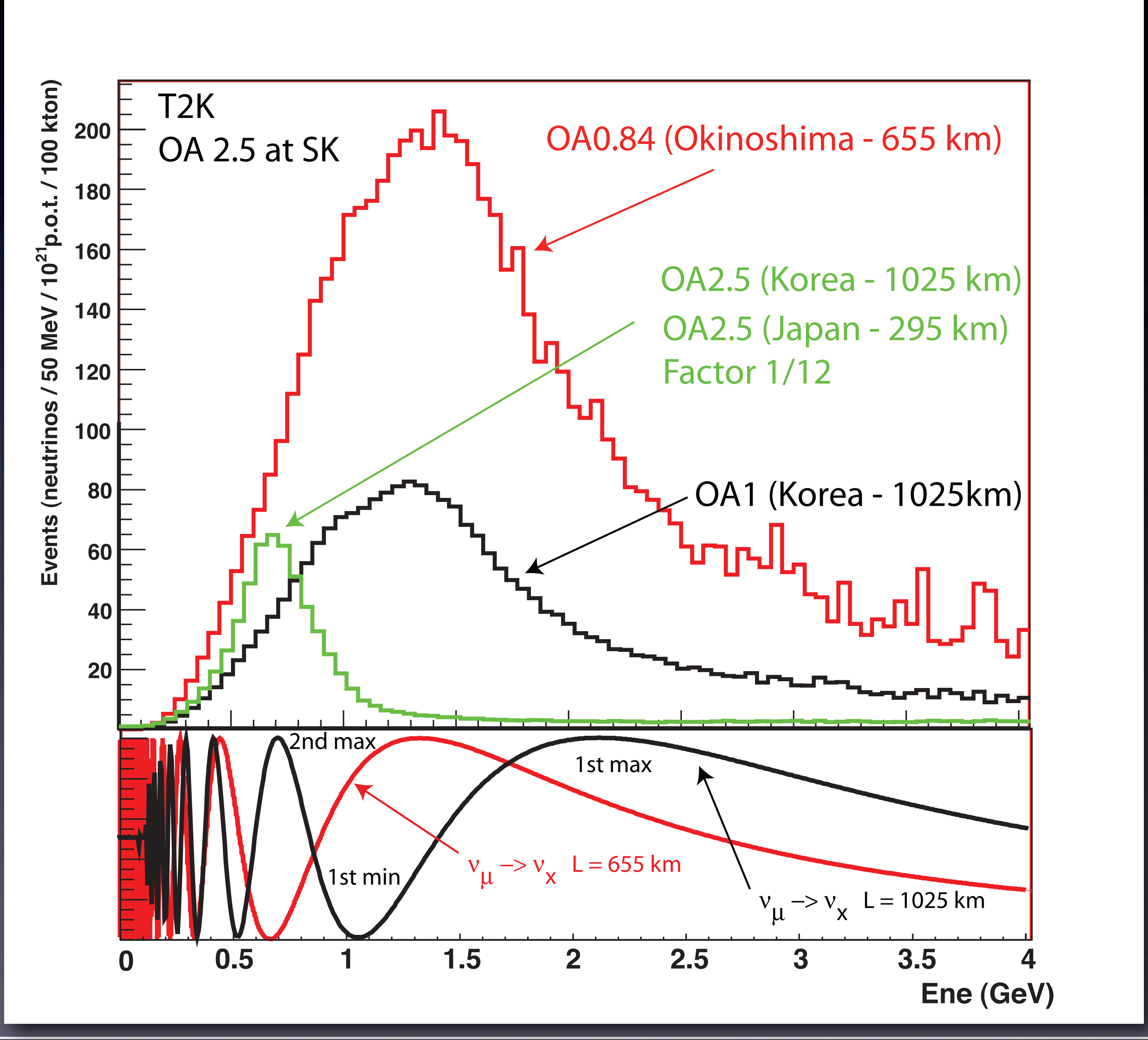
Measurement of **CP violation** and **mass hierarchy**



- We located GLACIER in 4 different positions (3 baselines).
- We assumed a beam power upgrade of 4 MW.
- 5 years of neutrino beam and 5 years of antineutrino beam have been assumed in the analysis.

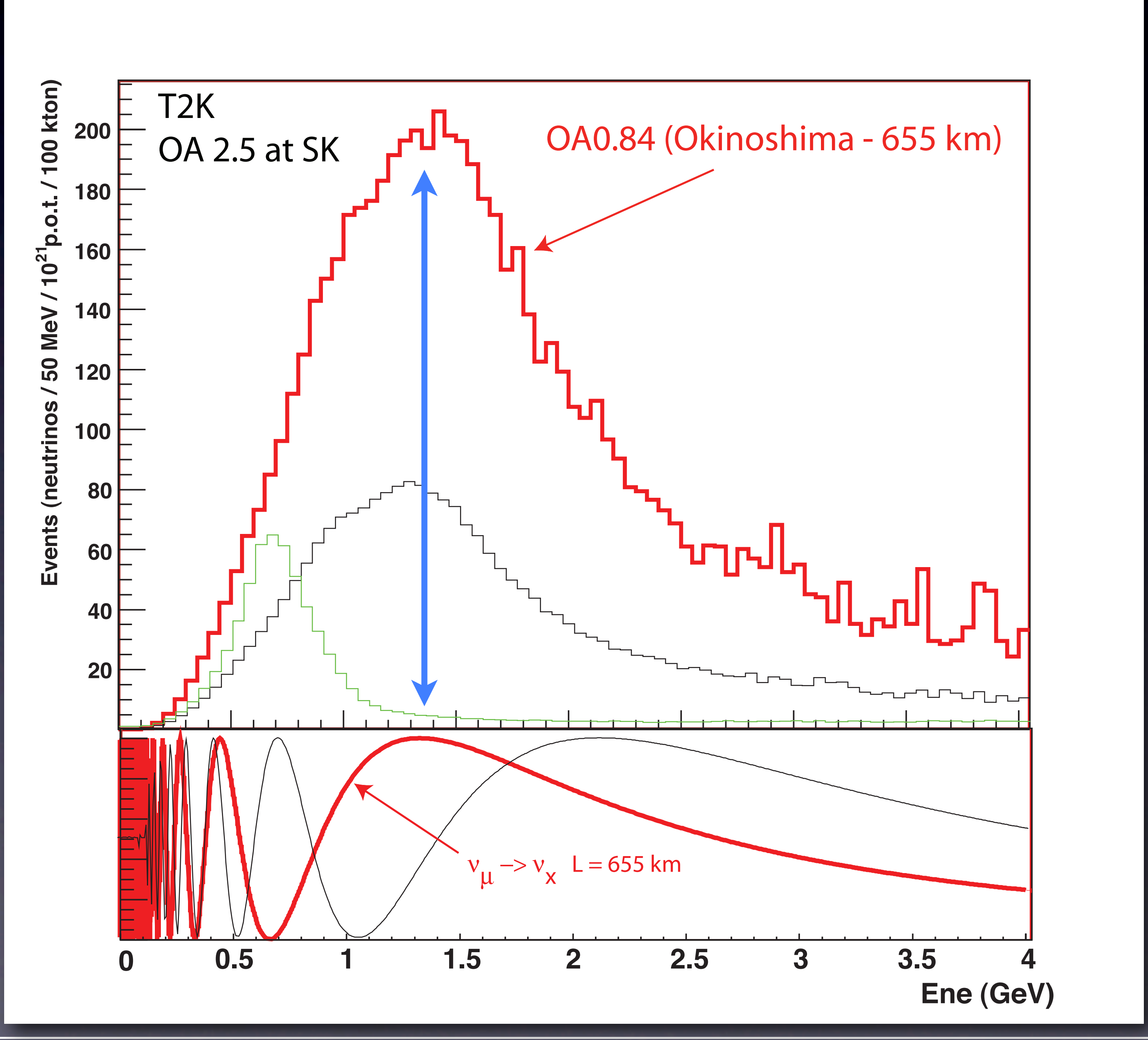
Spectra

- We calculated the spectra of ν_μ CC at the various locations.



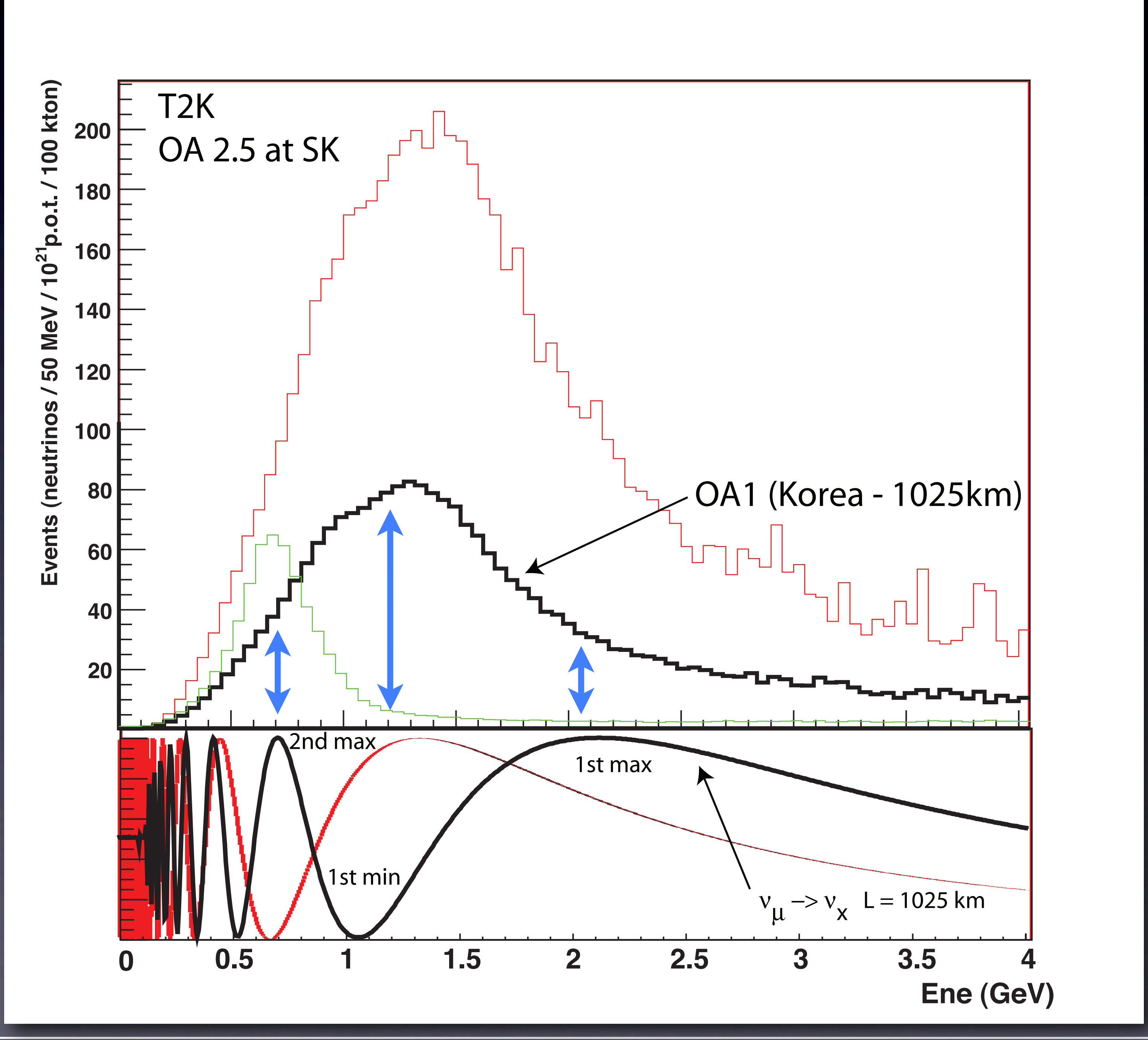
Spectra

- At Okinoshima, as well as at Kamioka (as we saw for T2K experiment), the peak corresponds to the first maximum of oscillation.



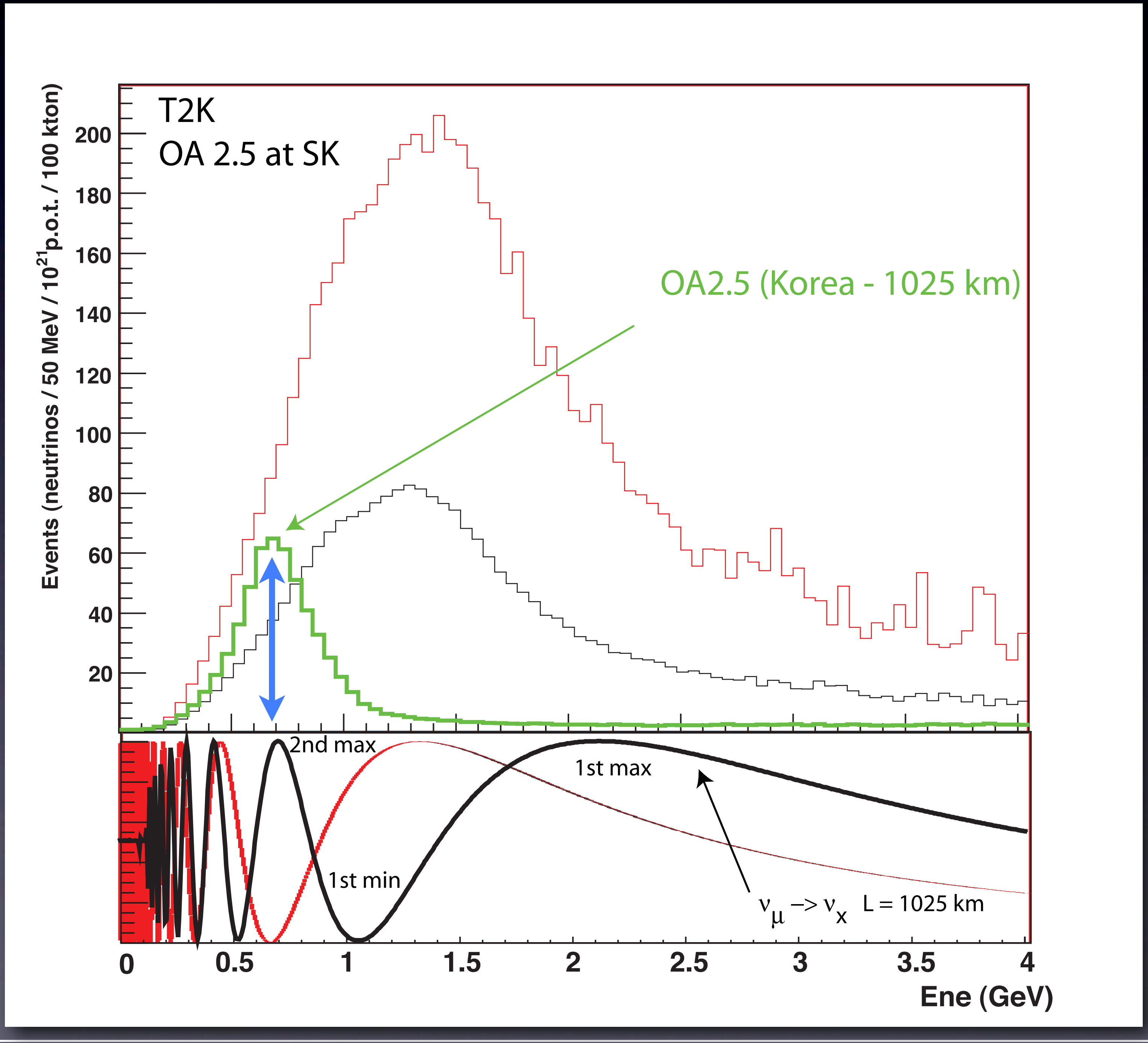
Spectra

- For the long baseline of 1025 km in Korea at OA 1 deg. the spectra is almost peaked at the first minimum and covers both the first and second maxima of oscillations.



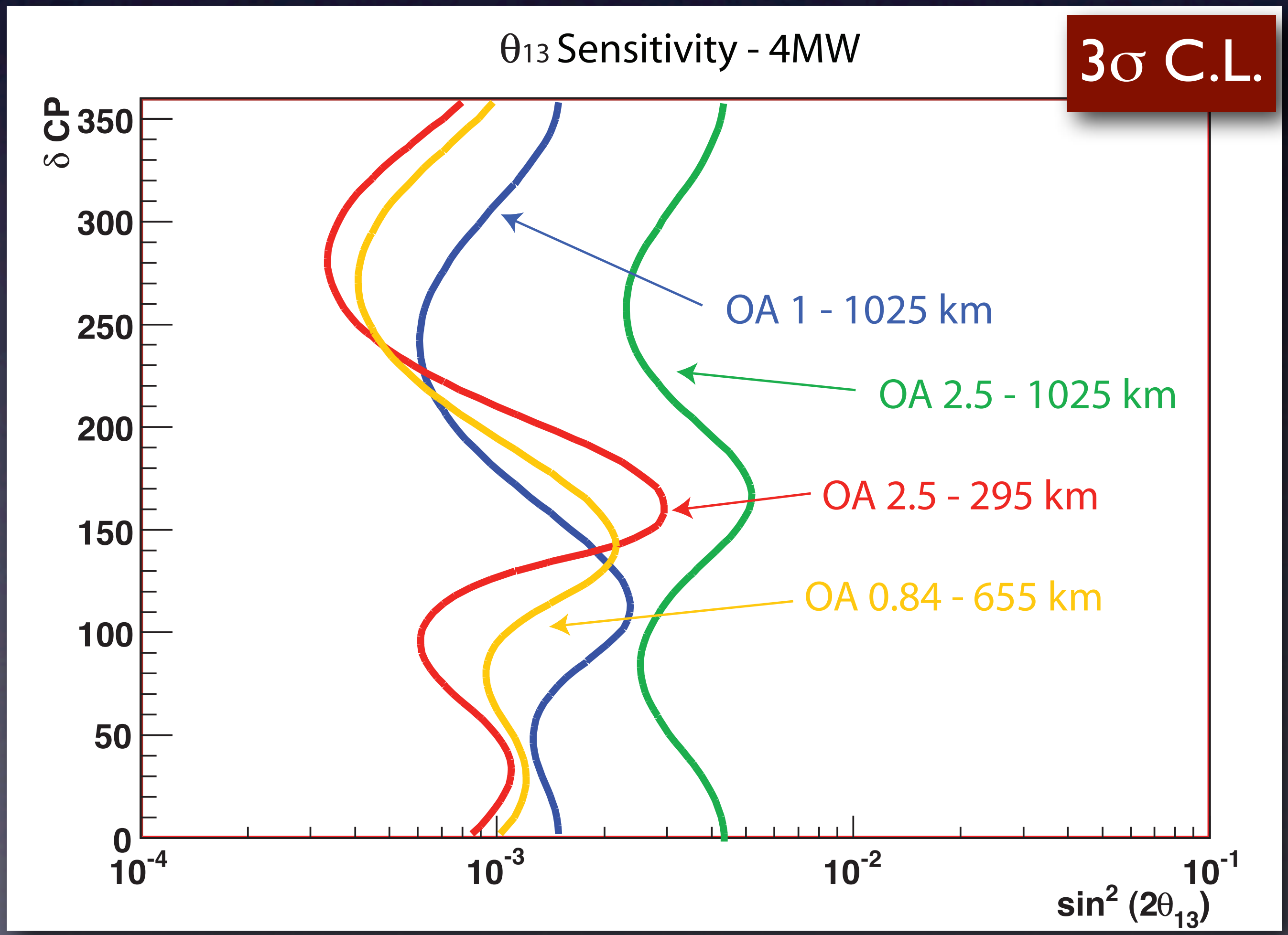
Spectra

- For the long baseline of 1025 km in Korea at OA 2.5 deg. the spectra is peaked at the second maximum of oscillations.



θ_{13} sensitivity

- The sensitivity on θ_{13} depends simply on the number of oscillated events over the background.
- Therefore, the best option is to peak the spectrum on the first maximum of oscillation and have the largest flux as possible.
- As expected, the best configuration for the discovery of a non-zero θ_{13}, is the short baseline of 295 km at 2.5 deg. OA.



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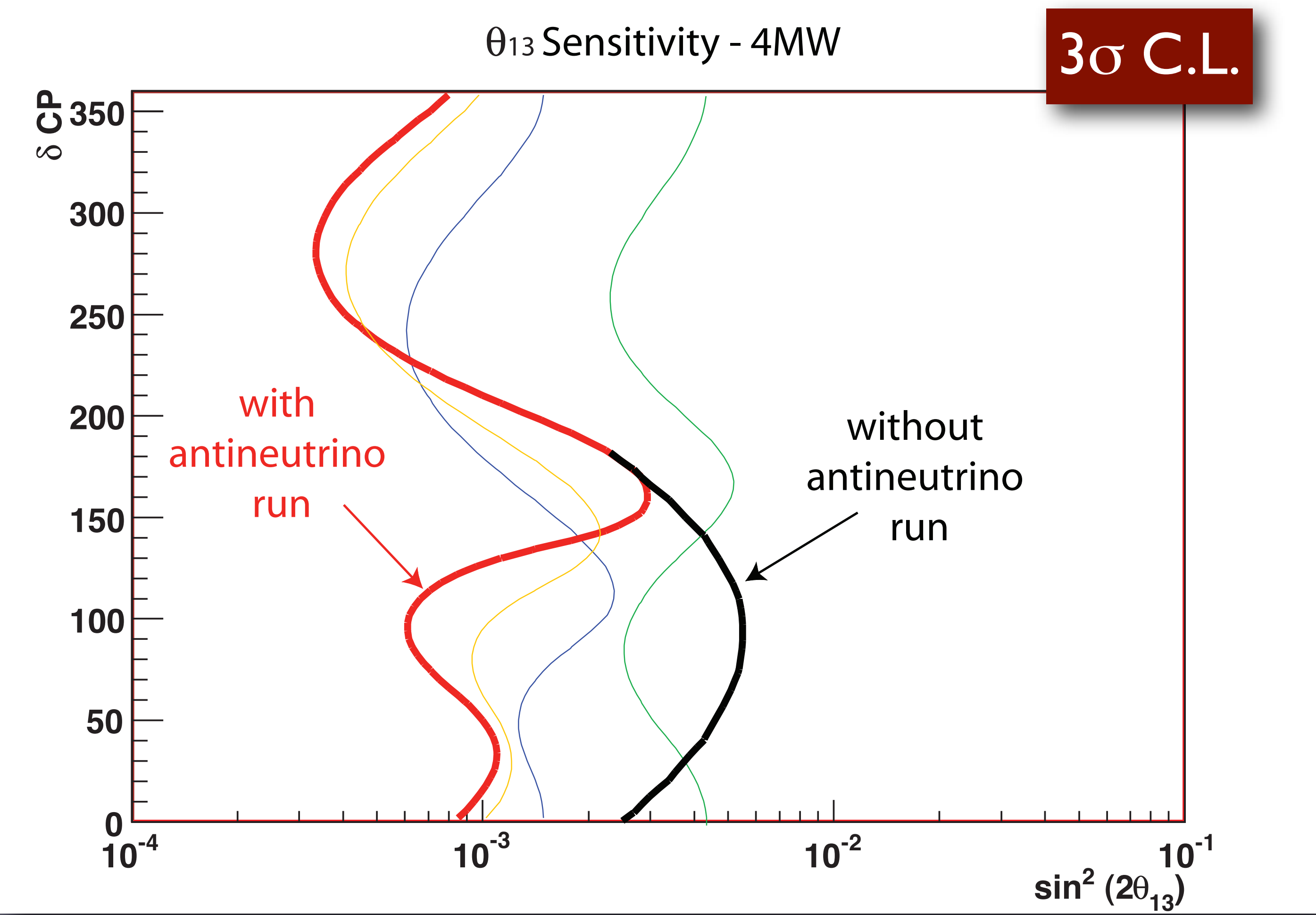
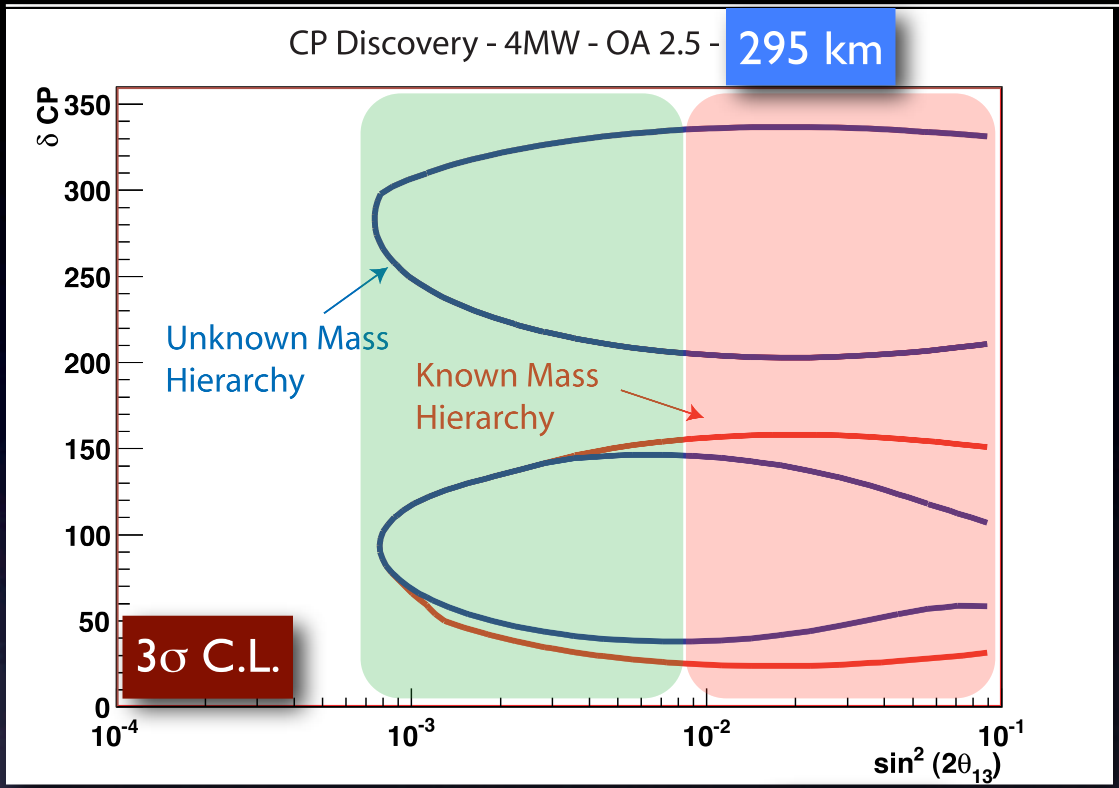
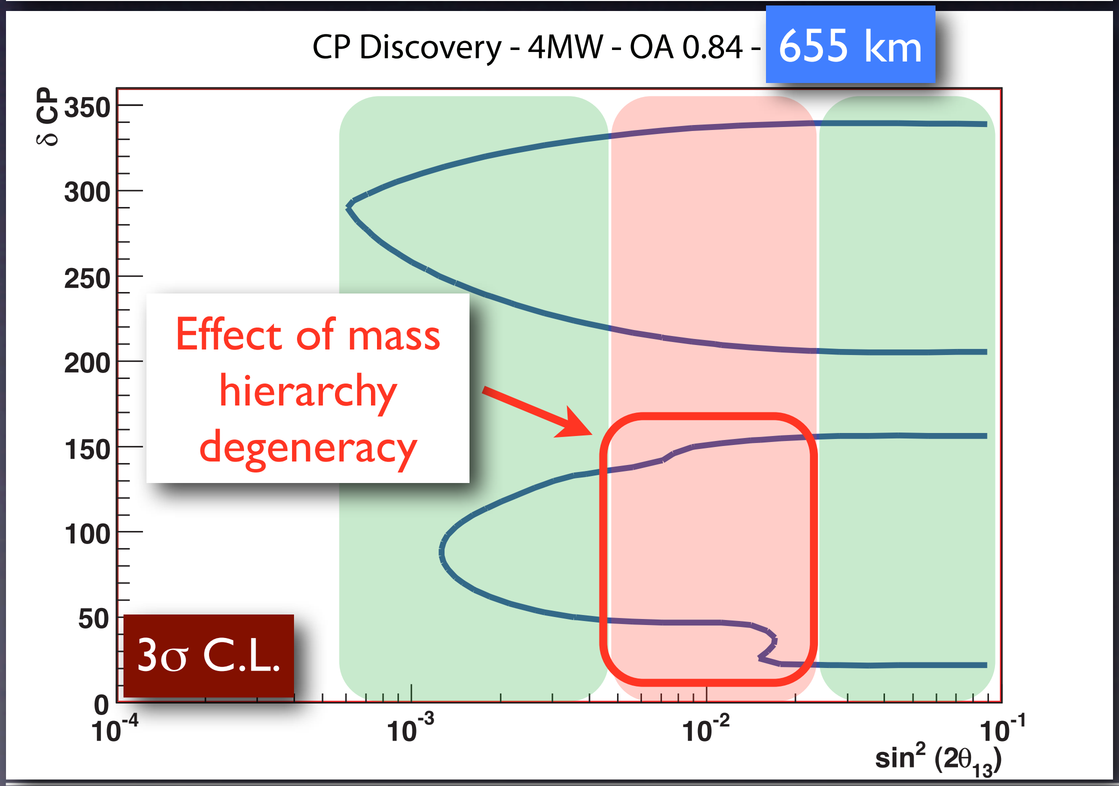


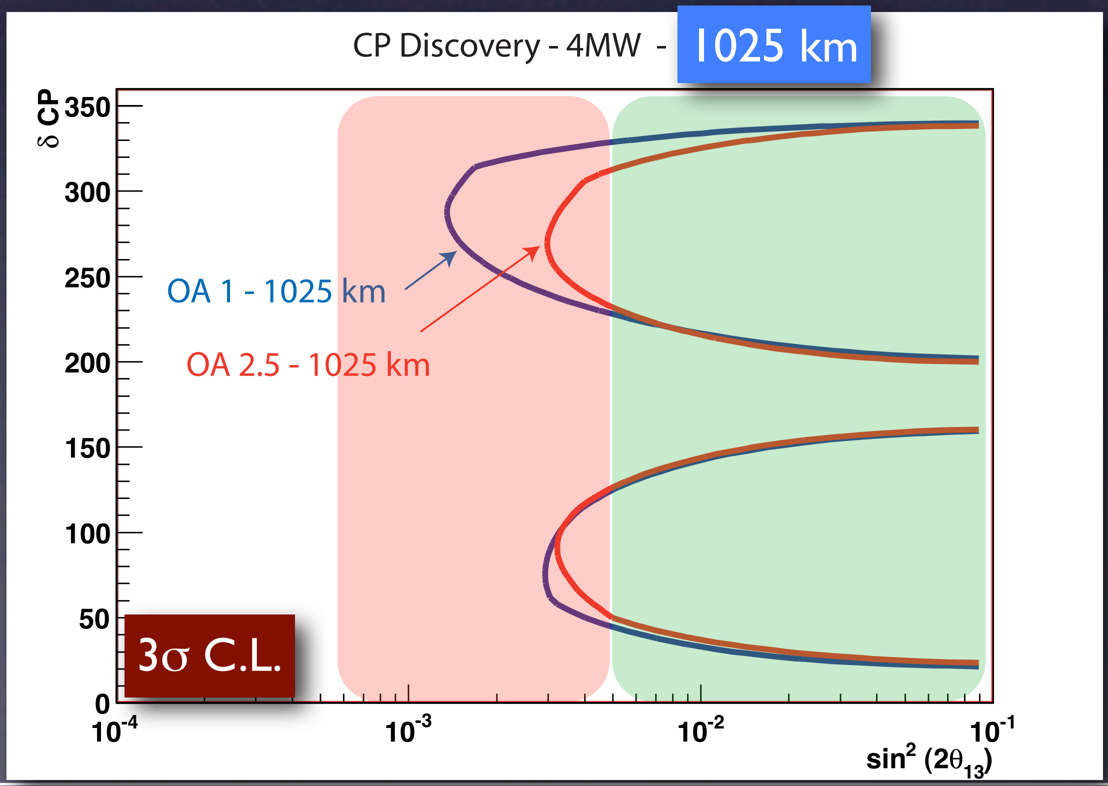
- Note that thanks to the antineutrino run, the characteristic "S" shape is not present and the sensitivity is improved in the region of δ_{CP} between 0 and 180 degrees.

CP violation



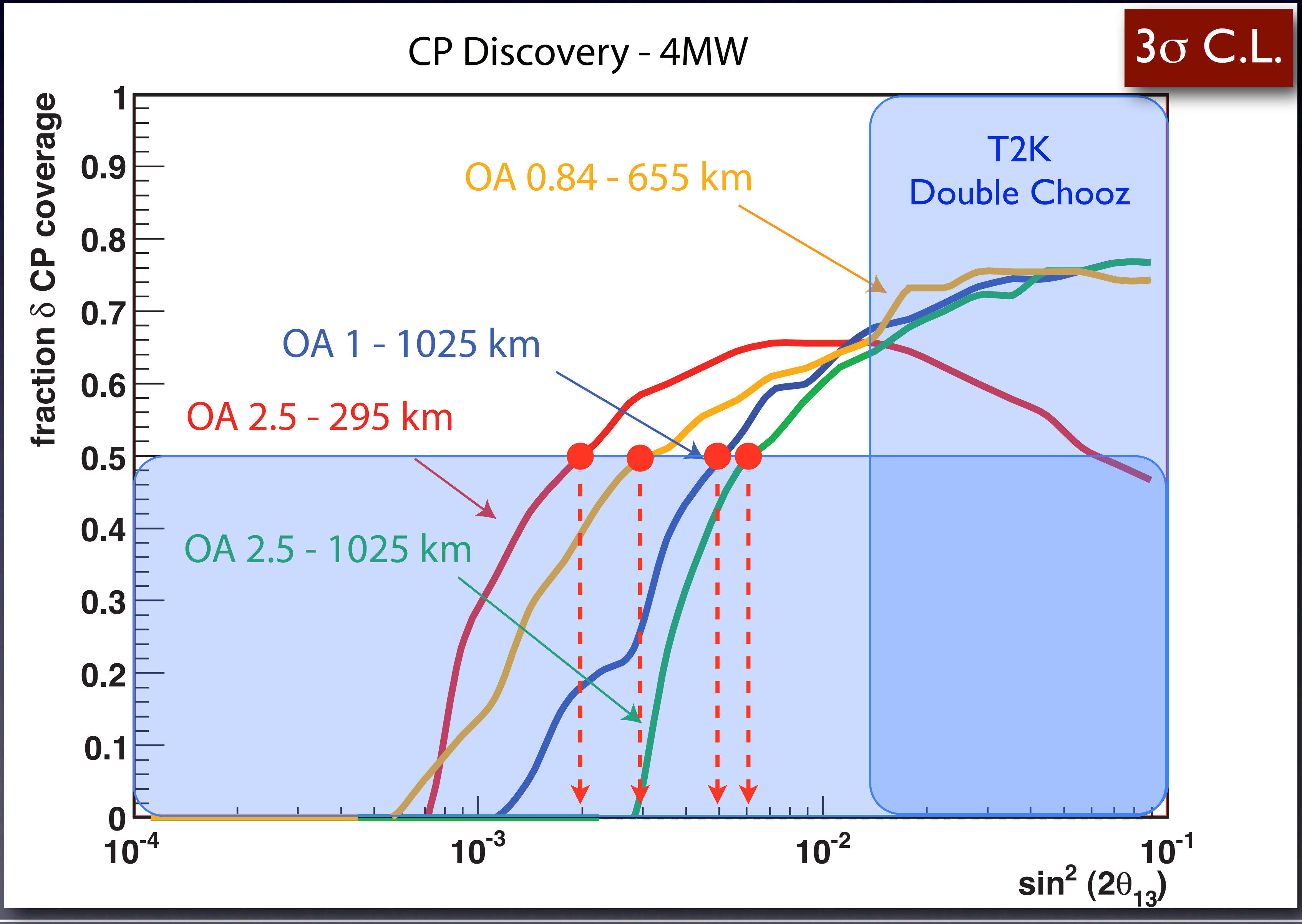


- The optimal configuration to observe CP violation (i.e. measure a value of δ_{CP} different from 0 or 180 degrees) is less evident and depends on the value of θ_{13}.
- Mass hierarchy degeneracy makes things harder: in some regions (normal hierarchy, CP violation) is equal to (inverted hierarchy, CP conservation).



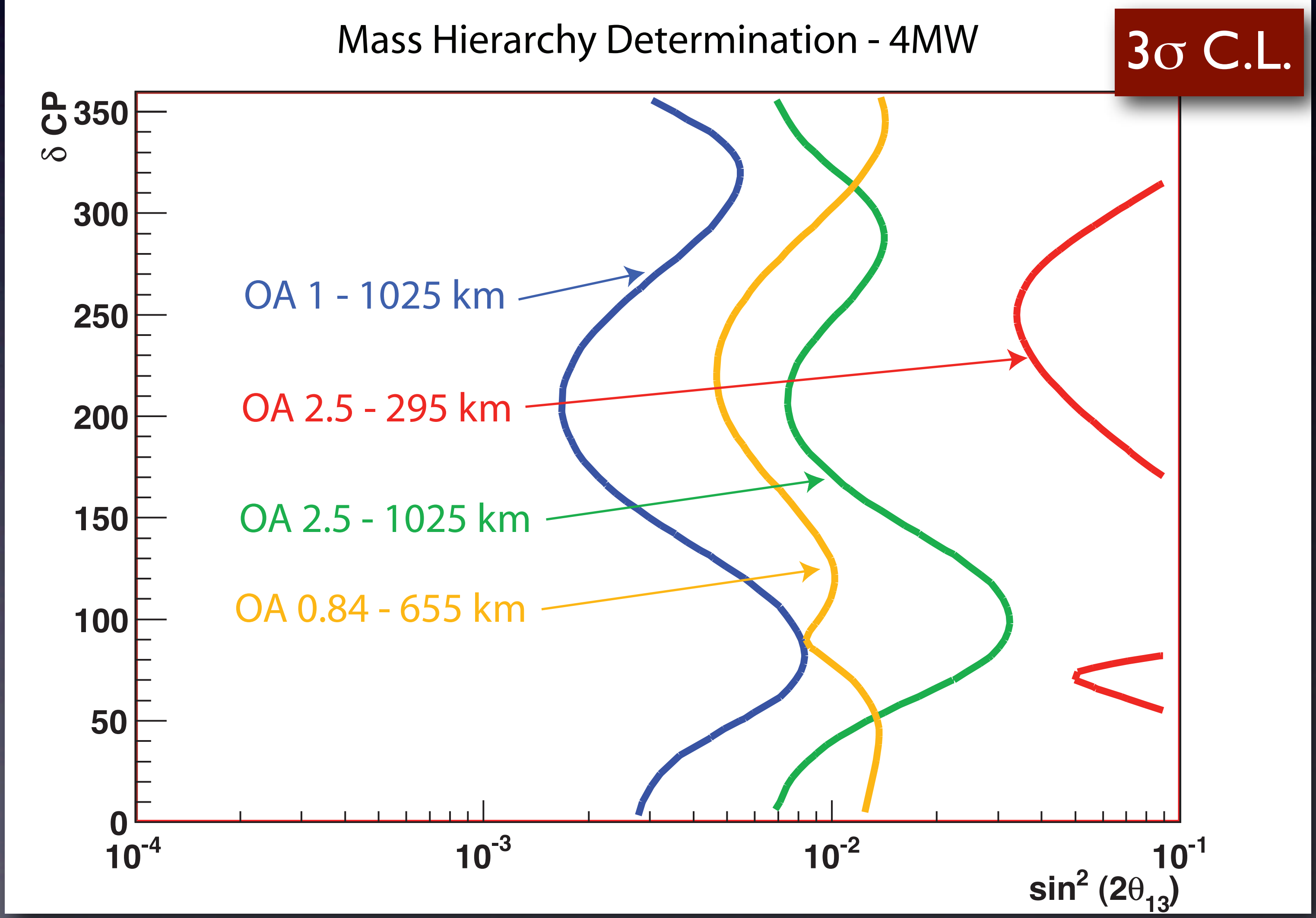
CP coverage

- According to the value of θ_{13} the choice of the "optimal" configuration for δ_{CP} discovery is different.
- Results from present experiments (T2K, Double Chooz) are crucial in order to choose which way to follow.



Mass hierarchy

- To determine the mass hierarchy the best solution is represented by the longest baseline.
- Of course the higher the flux the better it is, therefore once the baseline is set, the optimal configuration is given by the smallest off-axis angle (i.e. between the studied configuration the optimal option is 1025 km at 1 deg. OA).



Conclusions

- We studied the performance of a very large LAr TPC on future neutrino beams.
- We found that a “best” location does not exist and different locations are selected according to the measurement to be done (i.e. θ_{13}, δ_{CP} and mass hierarchy determination) and for δ_{CP} on the value of θ_{13} (namely $\sin^2(2\theta_{13}) < 10^{-2}$ or $\sin^2(2\theta_{13}) > 10^{-2}$).
- Present experiments such as **T2K and Double Chooz will represent a turning point** for choices concerning the future of long baseline neutrino oscillation experiments in particular as far as accelerator technologies are concerned.
- The results presented are independent from the detector technology: similar results have been found with large water Cerenkov detector (about a factor of 3 in mass with respect to LAr). However, the LAr technology presents some advantages in terms of resolution, background reduction and volume.

The end