Physique des neutrinos avec les expériences à longue ligne de base

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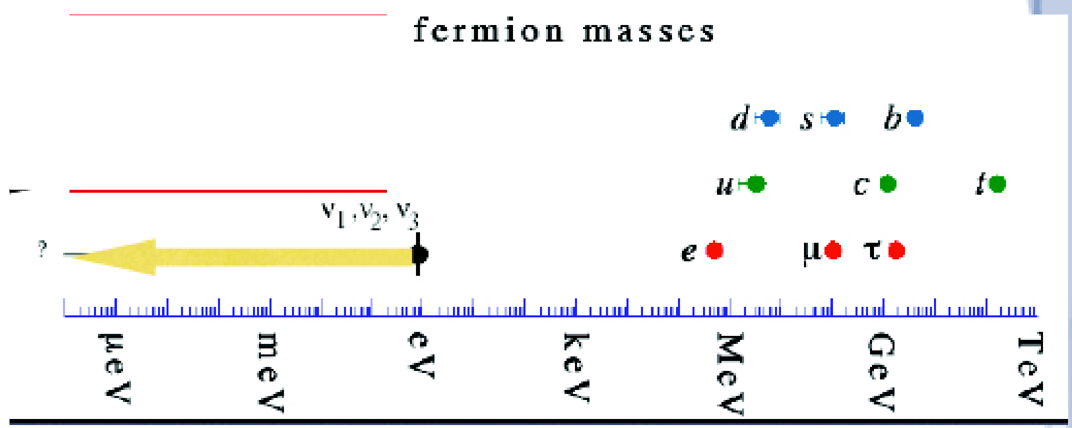
Outline

- Introduction and motivations
- Physics with a long baseline experiment
- Long Baseline (LB) experiment: beam, near detector, far detector
-
- Results of LB:
  - Nu tau Appearance experiments: OPERA
  - Precision numu disappearance experiments
  - Nue Appearance experiments: T2K, NovA
  - The next generation: HyperKamiokande (HK) and DUNE
- Other interesting physics with a large underground detector (SK, HK, DUNE)

Neutrino physics: surprising results

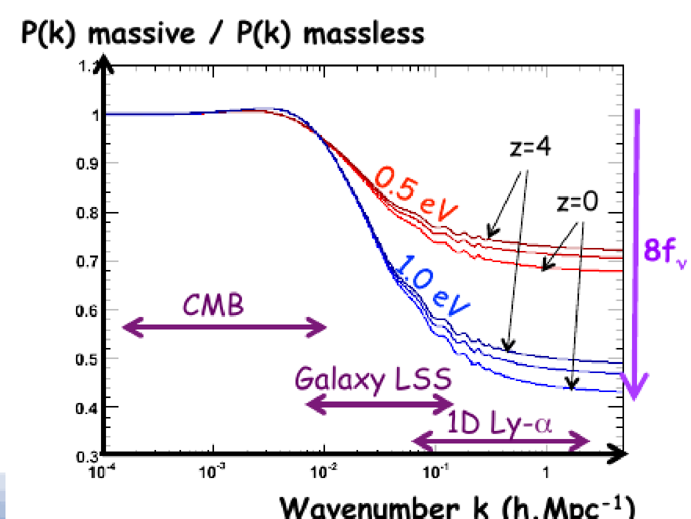
- The extreme lightness of neutrino masses begs a compelling explanation



- The neutrino mixing angles are large, at variance with the quark mixing angles: large CP violation effects are allowed

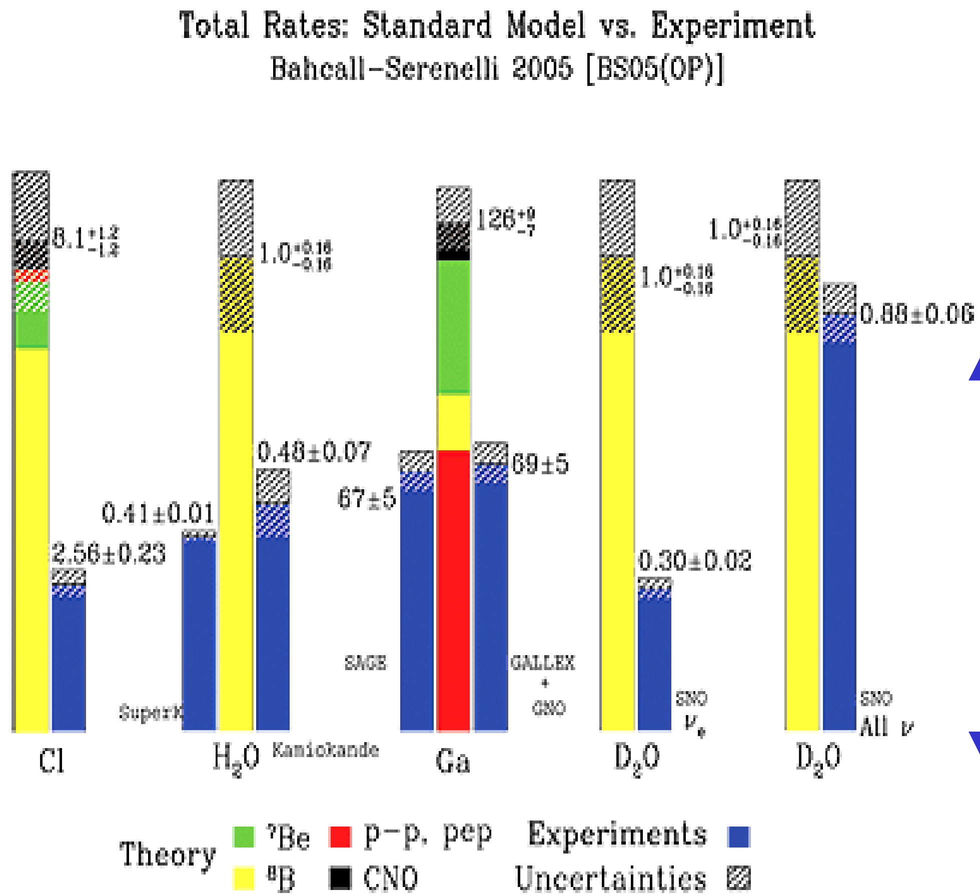
$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Neutrinos play an important role in the evolution of the Universe. Can they explain matter-antimatter asymmetry ?



Why were long baseline neutrino experiments planned and built around the year 2000 ?

Fact 1 : the solar neutrino defic



Predicted

Measured

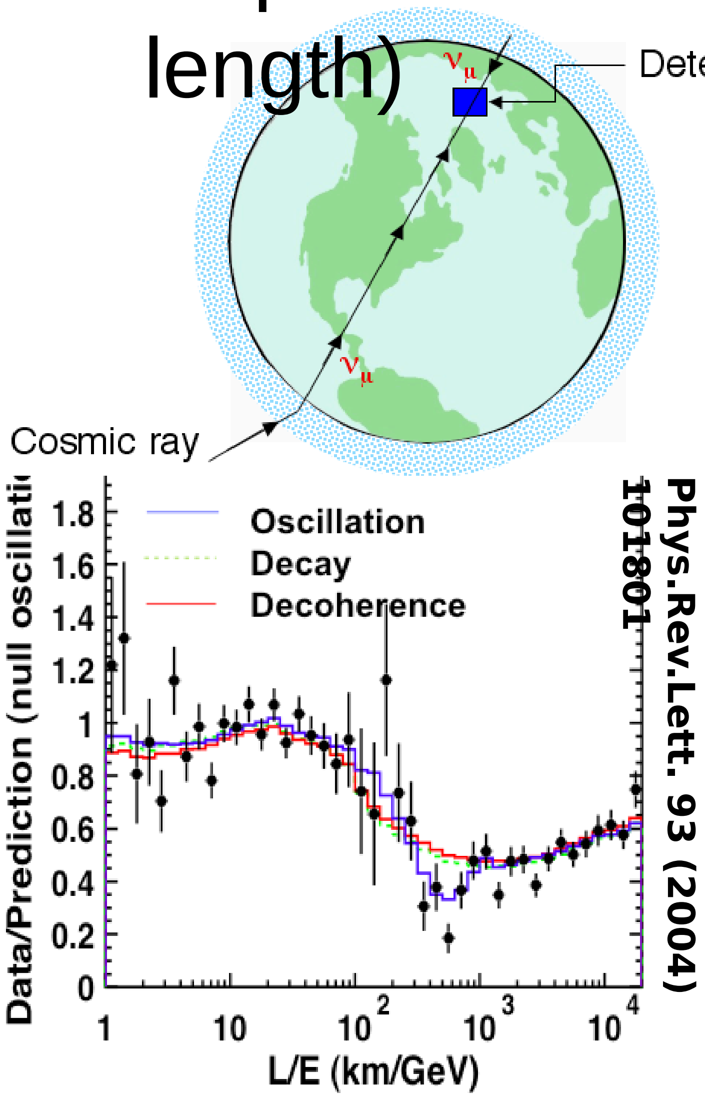
Homestake (Cl)
SAGE (Ga)
Gallex (Ga)
Kamiokande (H_2O)

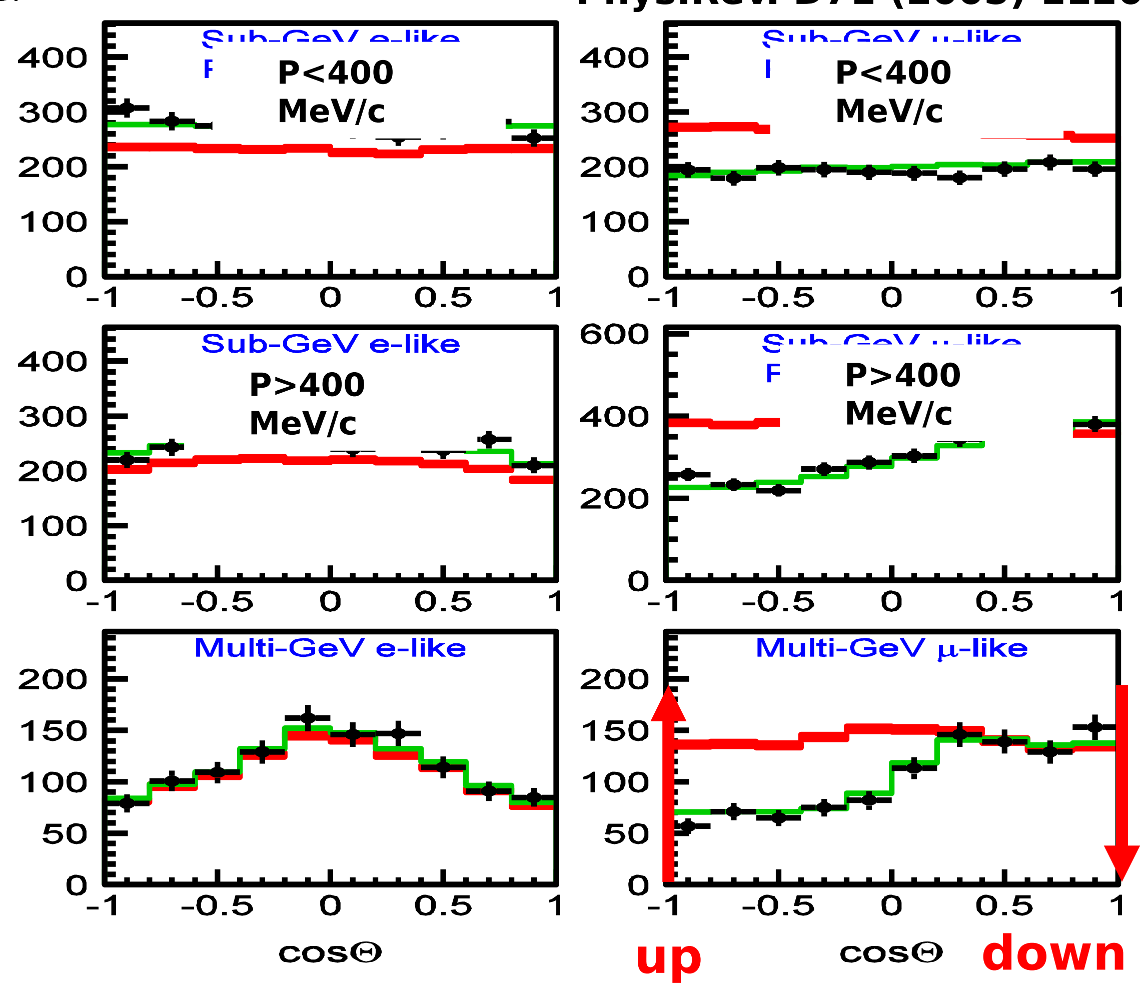
- Sun is the a very bright source of neutrinos
- Normalize the flux by the measured solar power (solar constant)
- Long and difficult experiments
- Is it neutrino physics or solar model ?

Evidence for atmospheric oscillation : SK

1-1/2sin²2θ

- Dependence on zenith angle (oscillation length)





Neutrino physics circa 2001

- The neutrino oscillations scenario was reasonably established (however explanations like decoherence or decays were still allowed)
- But a clear oscillatory pattern in experimental data was missing
- Other unknowns:
  - numu → nutau or numu-> sterile ?
  - Precise measurement of Delta Δm^2_{atm}
  - Only upper limits on the third mixing angle theta13
- This motivated a new program to study neutrino oscillation with beam and large underground experiments

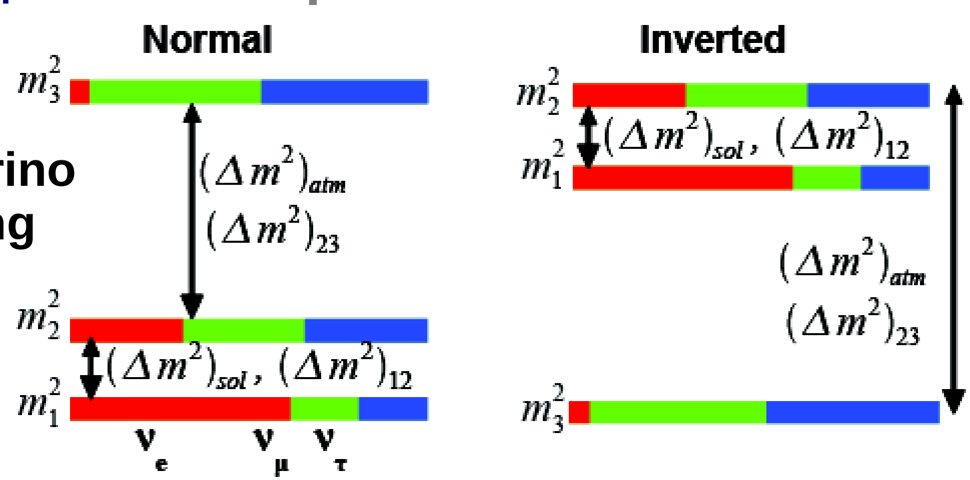
Today: next steps in neutrino physics

1) Is θ_{23} =45°? which octant ?
2) Determine the mass ordering
3) Measure the CP violation parameter δ
4) Precision tests of the PMNS paradigm (ideally at the % level, as for the CKM matrix)
5) Are there any new neutrino states ?
6) Dirac or Majorana ?

→

1) Is there a symmetry between ν_μ and ν_τ ?
2) Help model builders. Impact on cosmology.
3) Link with leptogenesis. Are we born out of (heavy) neutrinos ?
4) How different are neutrinos ?
5) New states are expected btw 1eV and 10**16 GeV
6) Majorana mass term: major discovery

Normal neutrino mass ordering



Inverted neutrino mass ordering

Next steps in neutrino physics

Important input from LB experiments

1) Is θ_{23} =45°? which octant ?
2) Determine the mass ordering
3) Measure the CP violation parameter δ
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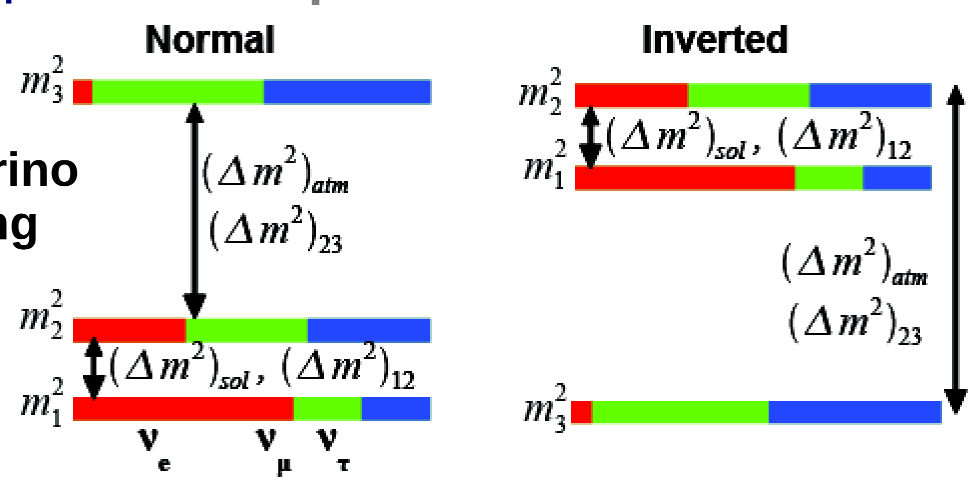
Normal neutrino mass ordering



Inverted neutrino mass ordering

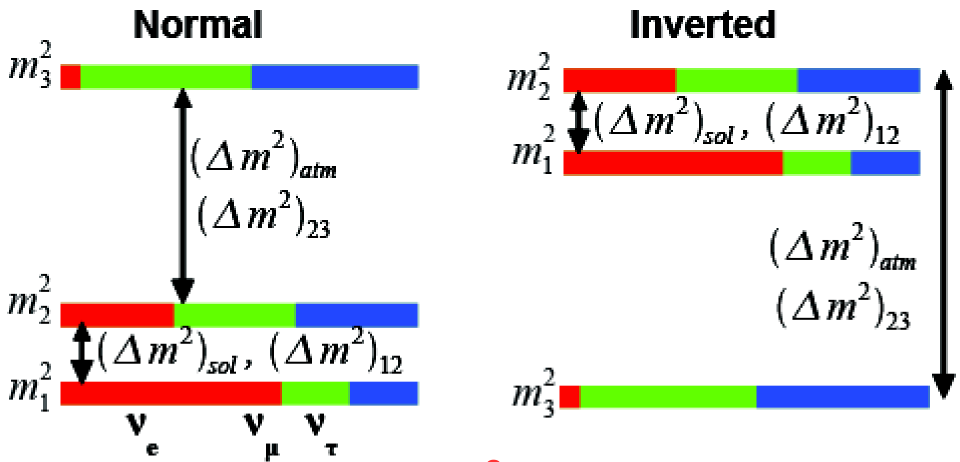
Baryon asymmetry in the Universe and leptonic CP violation

- To explain the Baryon Asymmetry in the Universe (BAU) (i) C and CP violation, (ii) B violation and (iii) processes out of thermal equilibrium are needed (Sakharov 1967)
- The observed CP violation in the quark sector is many order of magnitudes below what is needed to explain BAU
- The decay of heavy neutral leptons with CP violation may produce a lepton asymmetry first, later converted into a baryon asymmetry: leptogenesis model (Fukugita Yanagida 1986)
- Observing CP violation in the neutrino sector would be a supporting piece of evidence for leptogenesis (NB not a proof!)

Neutrino masses and ordering

- Neutrinos have a tiny mass : m < 2 eV from measurement of the beta spectrum (Katrin will push this limit to 0.2 eV)
- Since they oscillate, neutrino have masses (NB clear sign of phenomena BSM)
- Oscillations have measured two mass splitting: $|\Delta m^2_{atm}| = 2.4\ 10^{-3}\ eV^2$ and $\Delta m^2_{sol} = 7.5\ 10^{-5}\ eV^2$ and vacuum leading order measurements are not sensitive to the absolute mass scale

The lightest solution is: m1~0, m2~7 meV and m3~50 meV



The lightest solution is: m3~0, m1~m2~50 meV

- The measurement of the sign of Δm^2_{atm} has implications for the theoretical understanding of the nu mass mechanism, long baseline CP violation measurements, 0-nu double beta decay, and cosmology

Fogli et al 1205.5254

Impact of neutrino mass ordering

- Mass ordering has an impact on neutrinoless double beta decay and cosmology
- It has no impact on the design of future long baseline experiments

β decay, sensitive to the "effective electron neutrino mass":

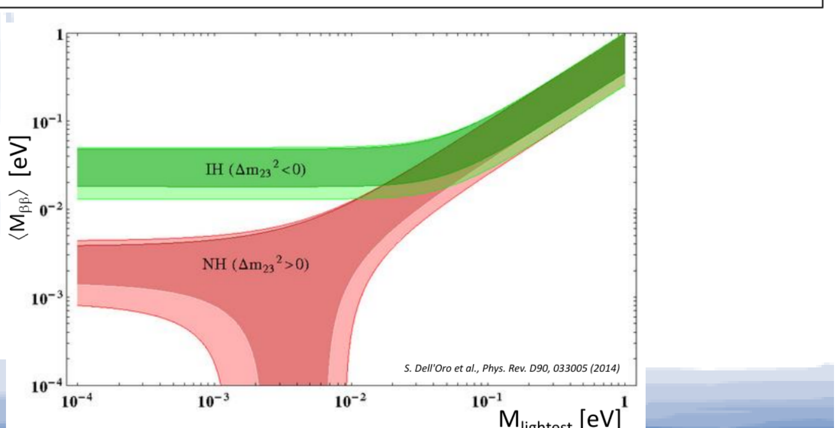
$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

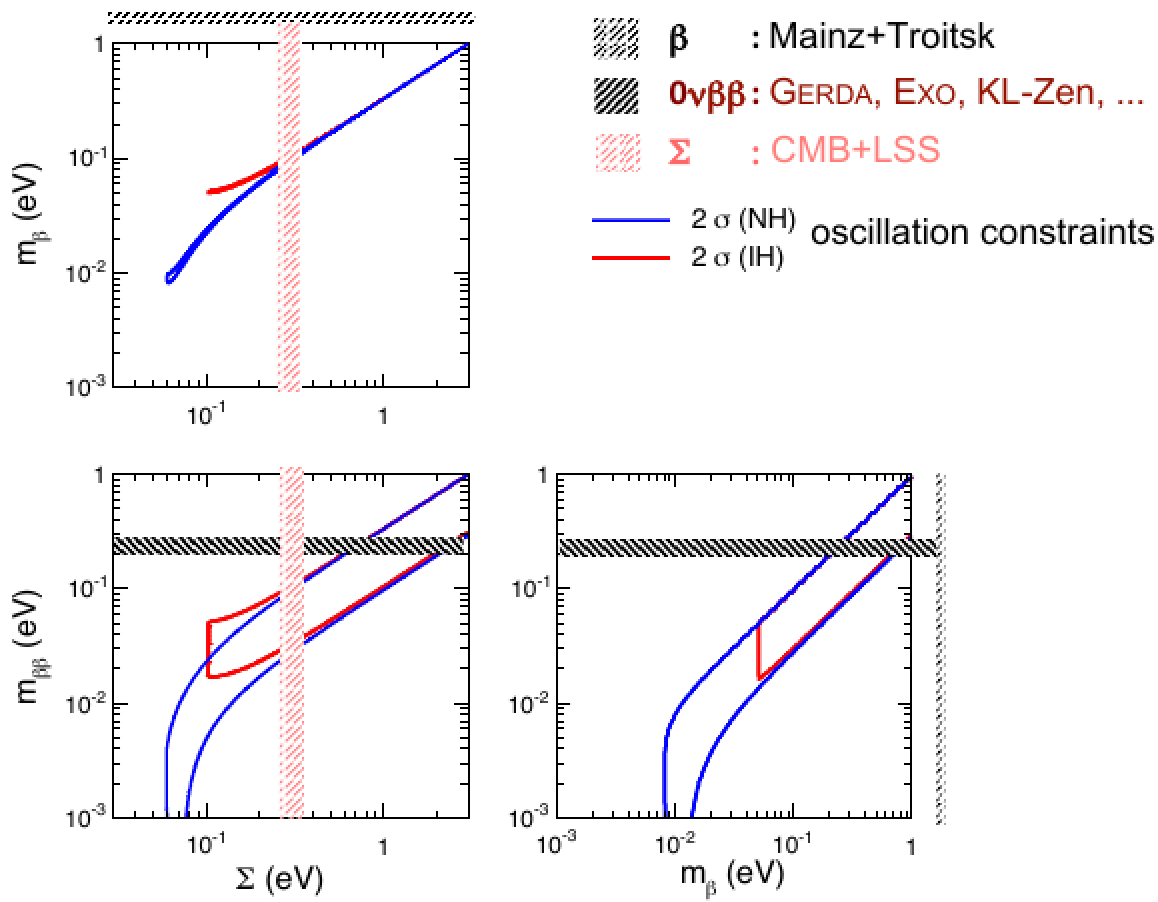
0νββ decay: only if Majorana. "Effective Majorana mass":

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Cosmology: Dominantly sensitive to sum of neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$





- To summarize: LB experiments were planned to demonstrate the oscillation mechanisms and make more precise measurements of several oscillation parameters
- Today, further fundamental questions like CP and mass ordering are in front of us and new facilities are taking data (T2K, NovA) or are planned (HyperKamiokande, DUNE)

Neutrino oscillations

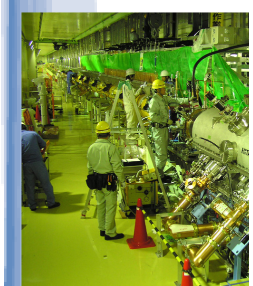
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

If neutrino flavor eigenstates are different from mass eigenstates, propagation induces a phase shift with the appearance of a new flavor

$\nu_\mu = -\sin\theta\, \nu_1 + \cos\theta\, \nu_2$

Propagation

Source



W ν_μ μ

$\nu_1 \rightarrow \exp(-ip_1 x)\, \nu_1$

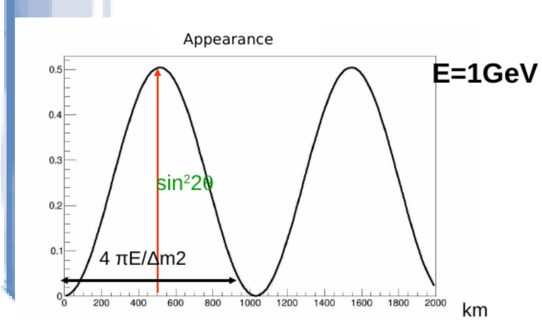
$\nu_2 \rightarrow \exp(-ip_2 x)\, \nu_2$

$\Delta\varphi = \Delta m^2 L/(4E)$

ν_e e

Detector

L



$\mathrm{Prob}(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\, \sin^2(\Delta m^2 L/4E)$

This is a simplified two neutrino scenario

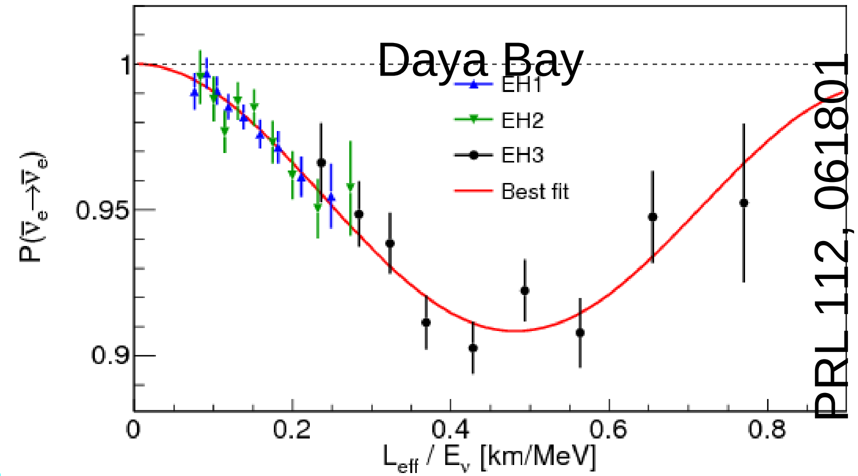
Notice that the expression is invariant replacing Deltam**2 → -Deltam**2

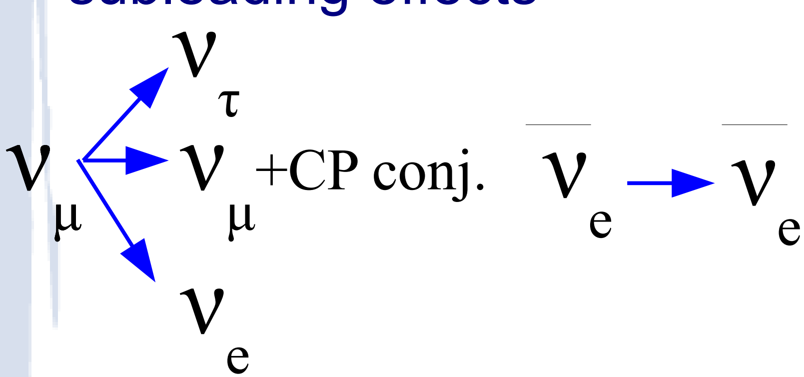
The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

$s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix} = \begin{pmatrix} 1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The oscillation phenomena have been convincingly observed using solar, atmospheric (Nobel prize 2015), reactor and accelerator neutrinos, establishing the three neutrino SM paradigm
- Currently unveiling three-neutrino subleading effects





Parameter	Value	Precision (%)
Δm^2_{21}	$7.5\ 10^{-5}$ eV^2	2.6
θ_{12}	34°	5.4
Δm^2_{32}	$2.4\ 10^{-3}$ eV^2	2.6
θ_{23}	42°	~10
θ_{13}	8.4°	4 (Daya Bay 2016)

Capozzi et al.
ArXiv:1312.2878

- What can we study with a neutrino beam ?
- To understand this we will consider the propagation of muon neutrino beam (for reasons to be explained later) of E~GeV in matter for L~100-1000 km

The 3 neutrino oscillation formula in vacuum

$$Prob(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j=1}^{3} \mathrm{Re}\, J_{\alpha\beta i j} \sin^2 \Phi_{ij} + 4 \sum_{i>j=1}^{3} \mathrm{Im}\, J_{\alpha\beta i j} \sin\Phi_{ij} \cos\Phi_{ij}$$

Change sign for antineutrinos

$$J_{\alpha\beta i j} = U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \qquad \Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

$$Prob(\nu_\alpha \to \nu_\beta) = 4 |U_{\alpha 3}|^2 |U_{\beta 3}|^2 \sin^2 \frac{\Delta m^2_{31} L}{4E} \quad if \ \frac{\Delta m^2_{21} L}{4E} \ll 1$$

Atmospheric driven oscillations

$$Prob(\nu_\alpha \rightarrow \nu_\beta) \simeq 4|U_{\alpha 3}|^2 |U_{\beta 3}|^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \quad if\ \frac{\Delta m_{21}^2 L}{4E} \ll 1$$

$$Prob(\nu_\mu \rightarrow \nu_\tau) \simeq 4|U_{\mu 3}|^2 |U_{\tau 3}|^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

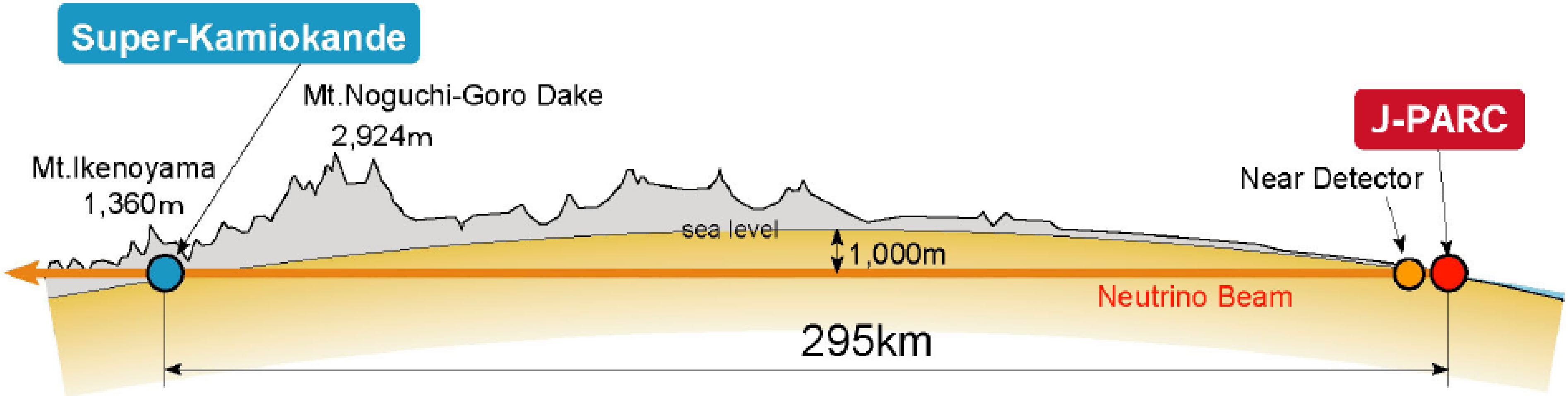
$$Prob(\nu_\mu \rightarrow \nu_e) = 4|U_{\mu 3}|^2 |U_{e 3}|^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

$$Prob(\nu_\mu \rightarrow \nu_\mu) = 1 - (\sin^2 \theta_{23} \sin^2 2\theta_{13} + \cos^4 \theta_{13} \sin^2 2\theta_{23}) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

These formulae are very similar to two neutrino oscillation formulae. Notice however the sensitivity to both θ_{23} (included the octant) and θ_{13}

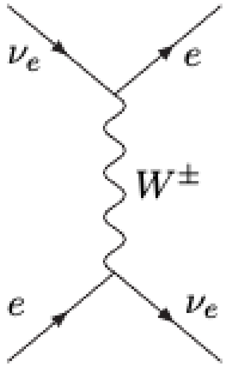
We will now introduce two additional effects:

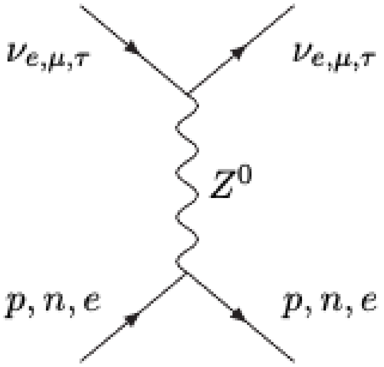
- Neutrino propagation takes place in the earth crust, so matter effects are present
- The PMNS matrix might be complex (Dirac phase), so additional terms beyond the leading order could be present
- Long baseline experiments are especially sensitive to these terms because thev can



Neutrino oscillation in matter

- Neutrino forward scattering on electrons, equivalent to light refraction index, leads to an additional phase for electron neutrinos proportional to $G_F\ N_e$
- The sign of the phase depends on neutrino vs antineutrino and normal/inverted ordering
- NC diagrams do not contribute to the phase shift (same for ν_e, ν_μ and ν_τ)





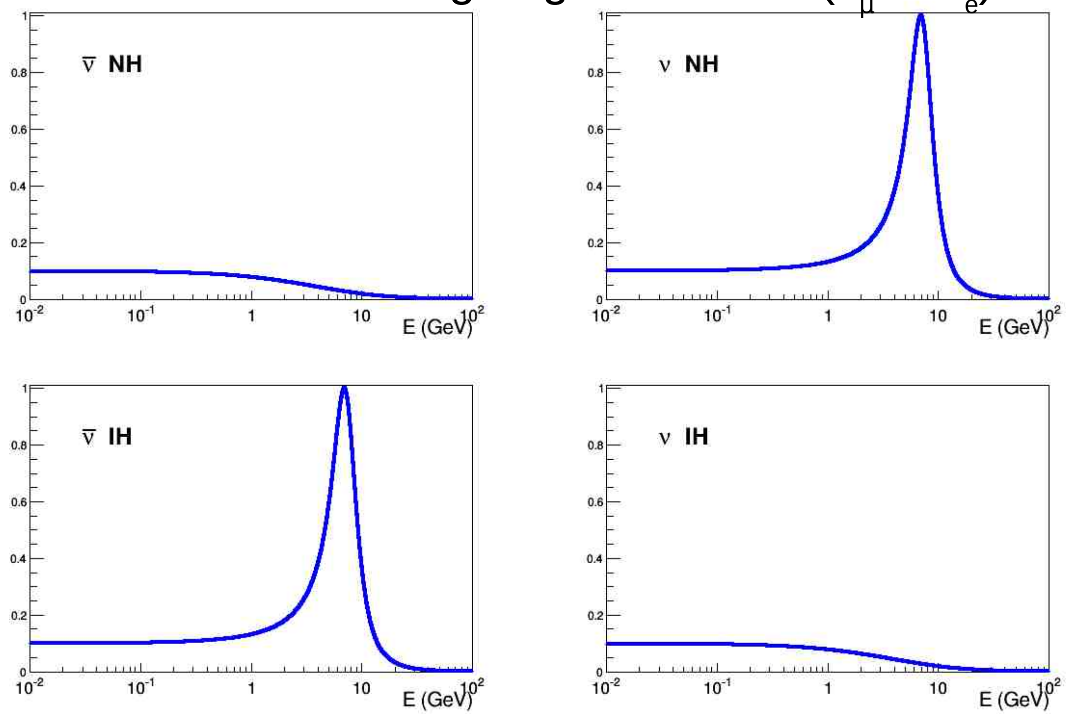
Neutrino oscillation in matter

In the constant density case, the effective mixing angle reads

$$\sin^2(2\theta_m)=\frac{(\Delta m^2/2E)^2\sin^2(2\theta_0)}{((\Delta m^2/2E)\cos(2\theta_0)-2\sqrt{2}G_F N_e)^2+(\Delta m^2/2E)^2\sin^2(2\theta_0)}$$

This expression has a resonant behavior, the effective mixing angle can be maximal even if the vacuum mixing is tiny (MSW effect)

Effective mixing angle in matter ($\nu_\mu \to \nu_e$)



Eres = 7 GeV for atm mass splitting and 4.5 g/cm**3 density

For the three neutrino case, for Normal Ordering matter effect enhance Prob ($\nu_\mu \to \nu_e$) and suppress it for antineutrinos. Viceversa for Inverted Ordering.

CP violation effects
$\nu_\mu \to \nu_e$: beyond the leading term in vacuum

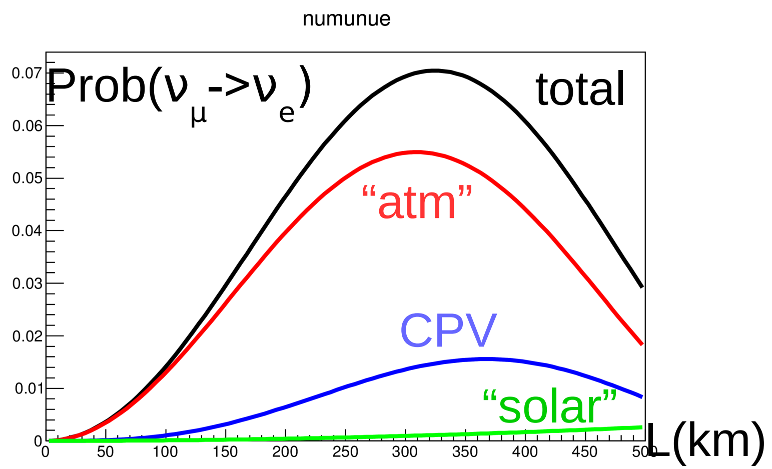
$$P(\nu_\mu \to \nu_e) \approx 4 C^2_{13} S^2_{13} S^2_{23} \sin^2 \Phi_{31}$$ "Atmospheric" term

$$\mp 8 C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CP violating term

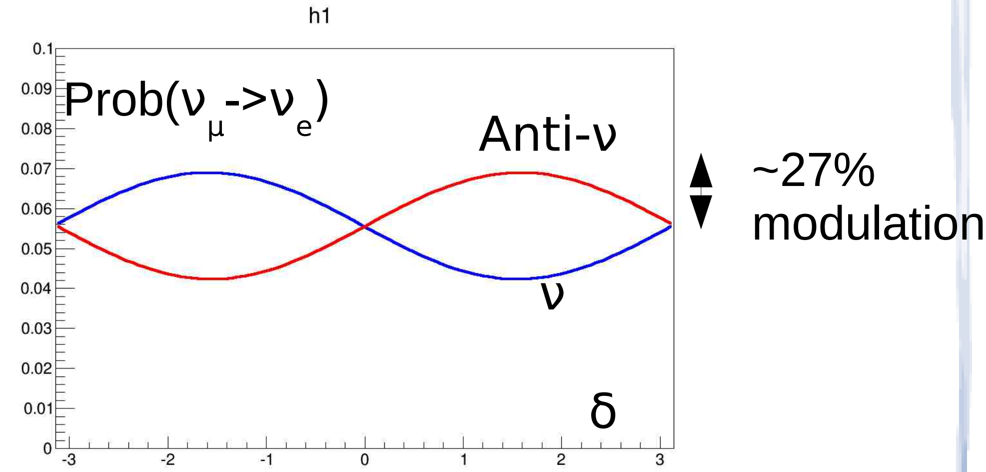
$$+4 S^2_{12} C^2_{13} (C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$ "Solar" term

$$C_{ij} = \cos(\theta_{ij})$$
$$\Phi_{ij} = \Delta m^2_{ij} L / 4E$$

Change sign from nu to anti-nu! An accelerator based neutrino beam is ideal to study this, as either neutrinos or antineutrinos can be produced

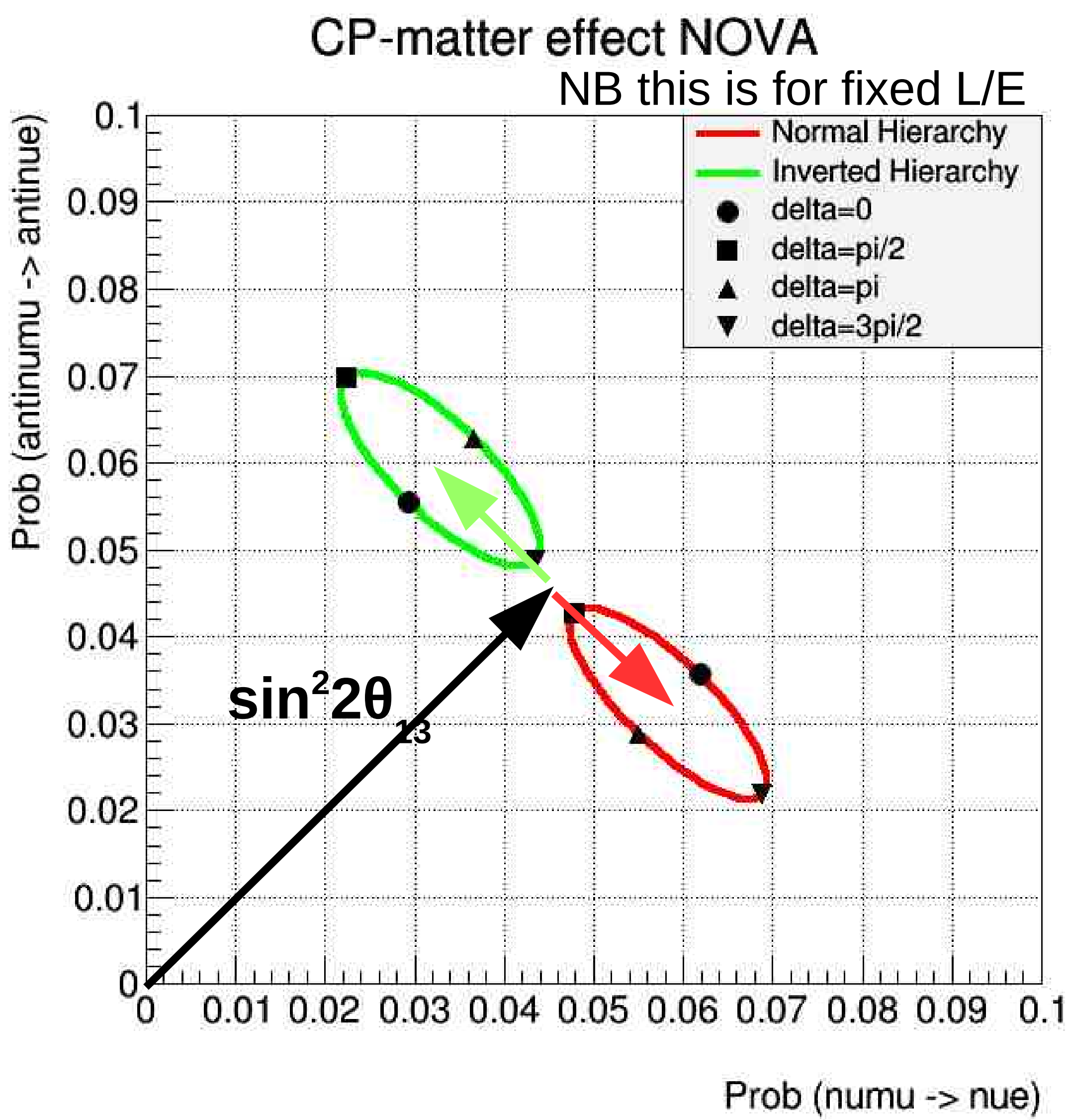


E=0.6 GeV

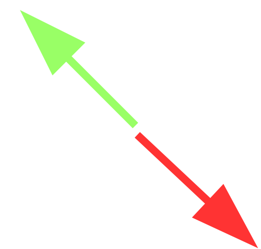


Caution: indicative plots !!

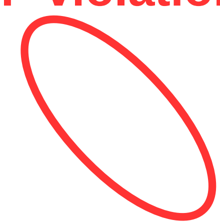
Combined effect of CP and matter



Effect of **inverse** or **direct** mass ordering

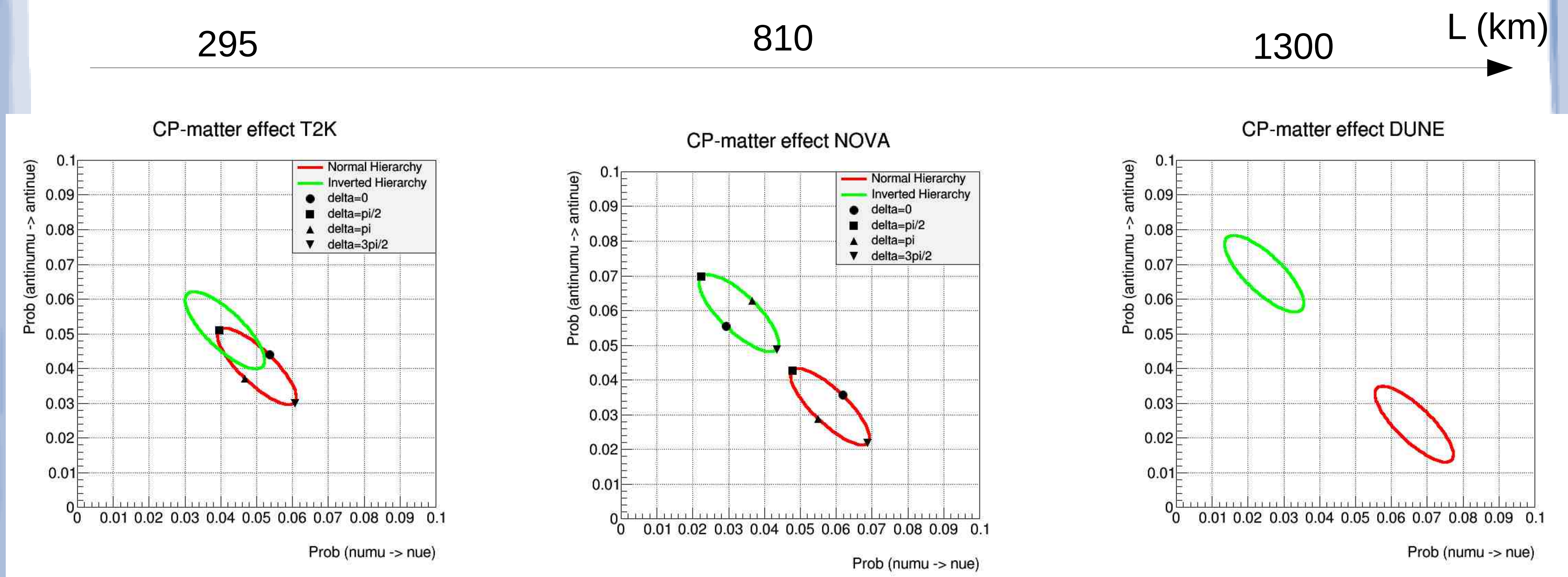


CP violation



NB A precise measurement in this plane can determine theta13, MH, delta, octant

Combined effect of CP and matter



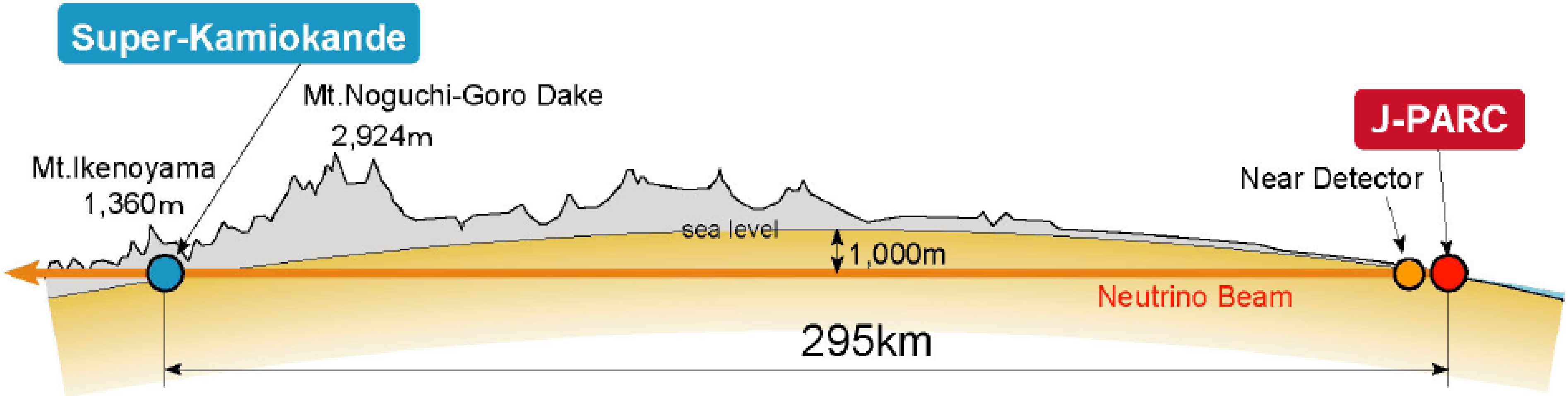
The relative increase of matter effect versus CP effect is due to the fact that these experiments are tuned to the L/E of the first oscillation maximum. The increasing L and E are such that Prob (numu->nue) climbs the slope of the MSW resonance.

For T2K, CP modulation +-27%, Matter effect ~10%

Long baseline schematic

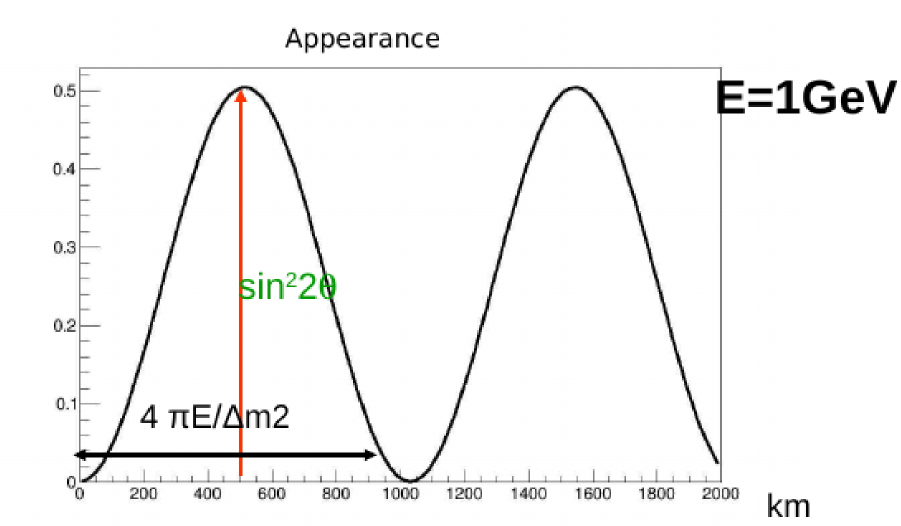
A long baseline neutrino experiments requires

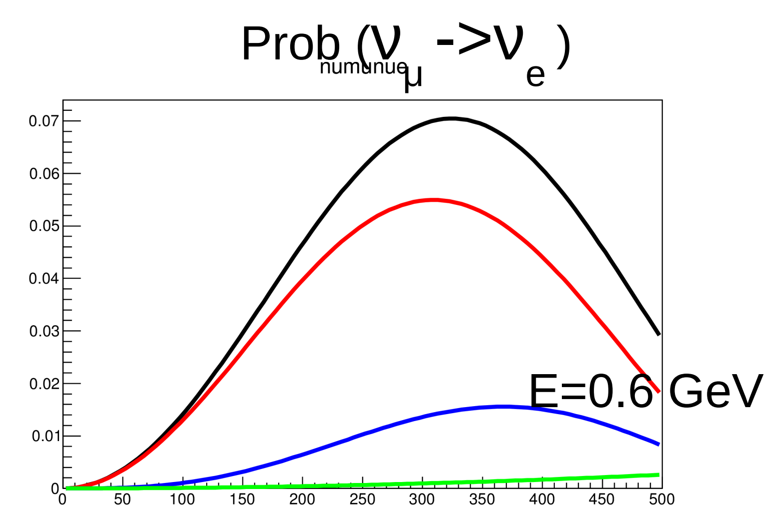
1) A powerful neutrino beam
2) A near detector complex
3) A very massive far detector, best if underground



Design of a long baseline exp.

- Define L and E such that Δm^2_{32} L/4E = π/2 (eg 480 km for 1 GeV)
- Then maximum of ν_μ disappearance and ν_e appearance probability
- Choice of L depends on external constraint (including the possibility to build or use an underground laboratory in a particular location
- Choice of E depends (weakly) on the proton beam energy and strongly on the detection technique



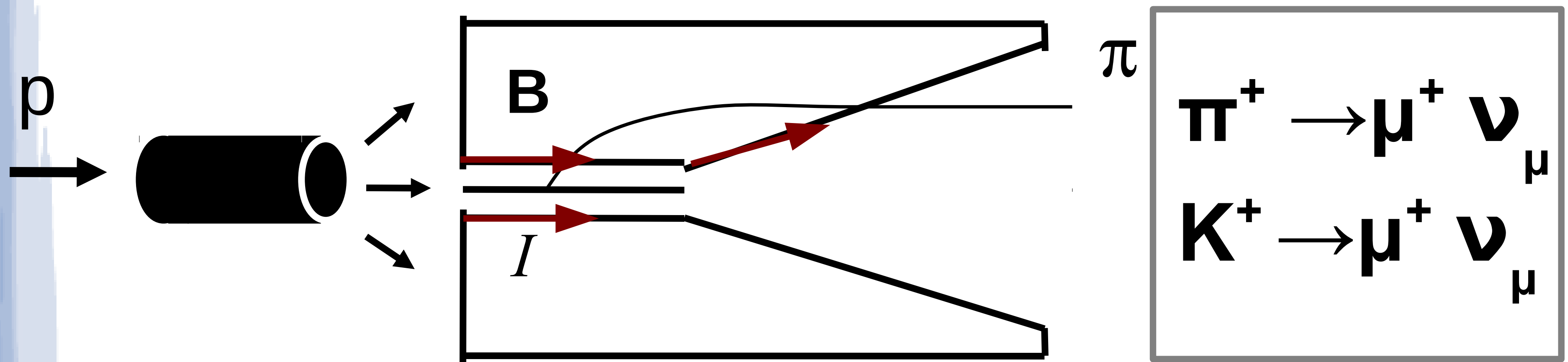


Paramètres des LB

Exp.	Energie (GeV)	Puissance (kW)	L (km)	FD mass (kt)
K2K	30	15	250	22.5
MINOS	120	700	790	5.4
OPERA	450	500	732	1.8
T2K	30	750	295	22.5
NOvA	120	700	810	14
HK	30	1300	295	380
DUNE	120	1200	1300	40

TABLE 1 – Paramètres des expériences long baseline. FD est la masse fiducielle du détecteur lointain. L'énergie est celle du faisceau de protons, la puissance est celle nominale.

Producing a neutrino beam



Primary proton beam on target

p C → π + X

Focusing the pions with a magnetic device (horn). The current allows to focus either **π+** (numu) or **π**-(numubar)

Decay volume. Need to stop the mu before they decay. Otherwise nue are produced by

$$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$$

$$K^+ \rightarrow \pi^0 e^+ \nu_e$$

The first discovery with a neutrino beam

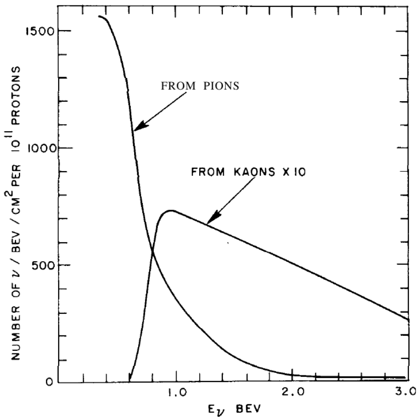
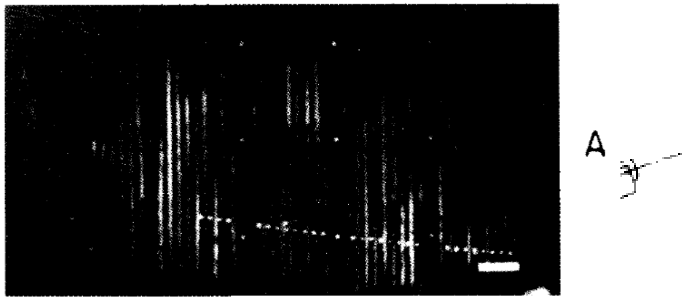


Figure 2. Energy spectrum of neutrinos as expected for A.G.S. running at 15 GeV.

$\pi \to \mu\ \bar{\nu}$

But is $\nu=\nu_e$ or $\nu=\nu_\mu$?



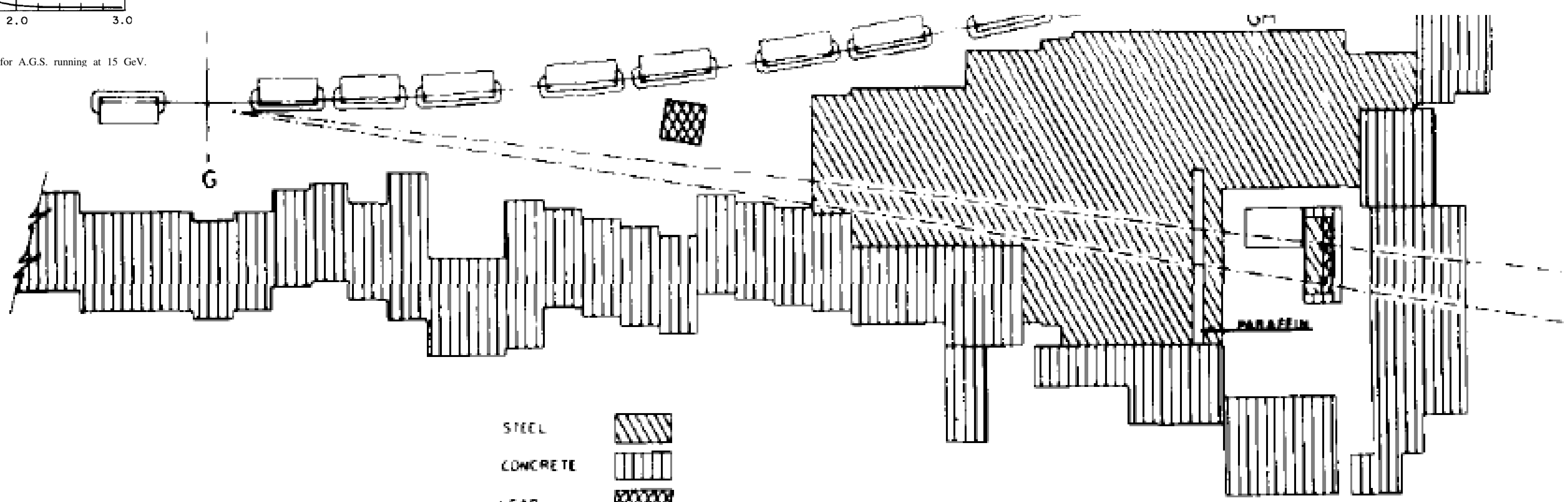


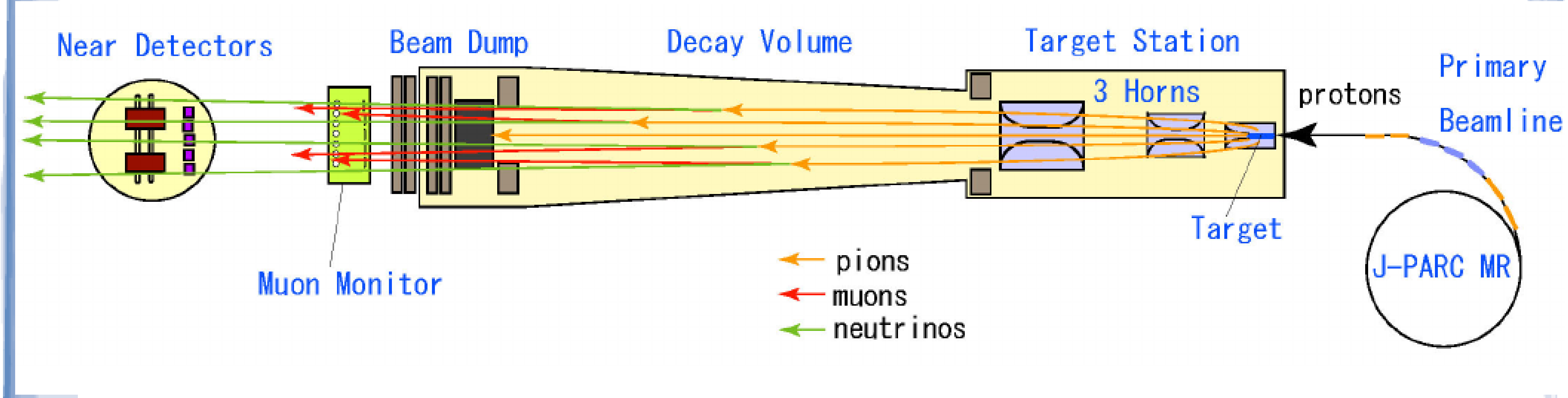
Figure 1. Plan view of the A.G.S. neutrino experiment.

In 1962 L. Lederman, Steinberger and M. Schwartz (Nobel 1988) produced a neutrino beam from pion and kaon decays.
This tested and demonstrated the „two neutrino hypothesis“ (neutrino in pion decays are muon neutrinos). No shower was observed.

Magnetic horn: a long history in particle physics

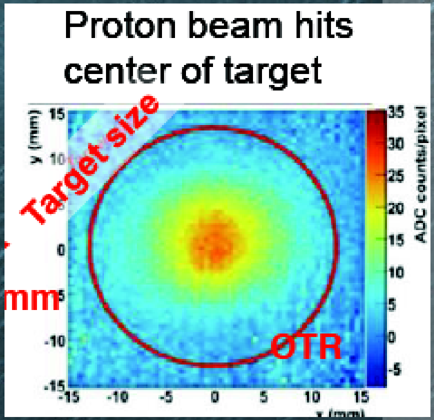
Simon van der Meer, CERN-61-07 1961

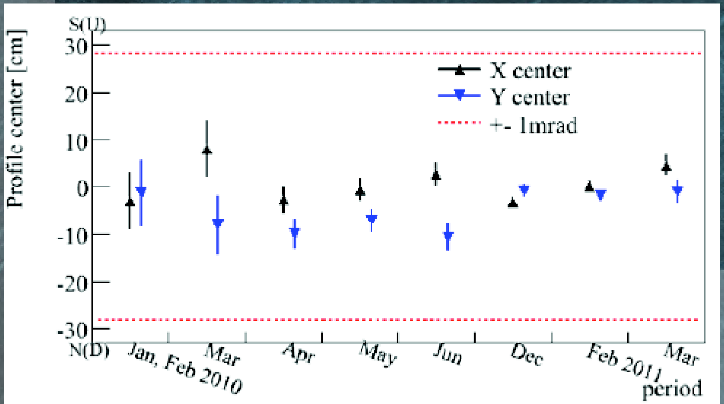
The T2K neutrino beam

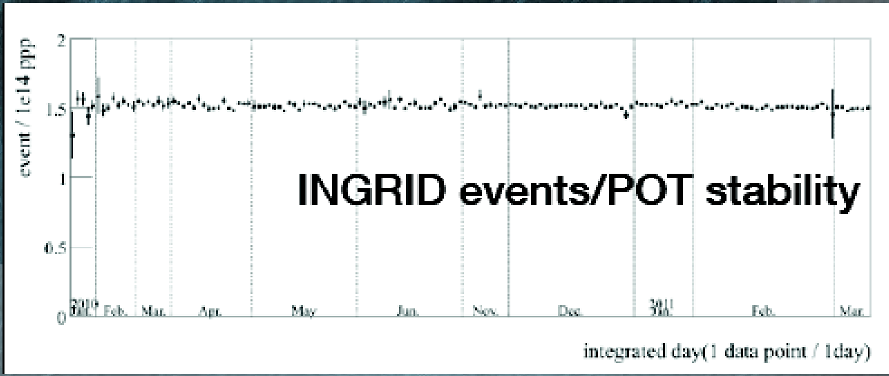


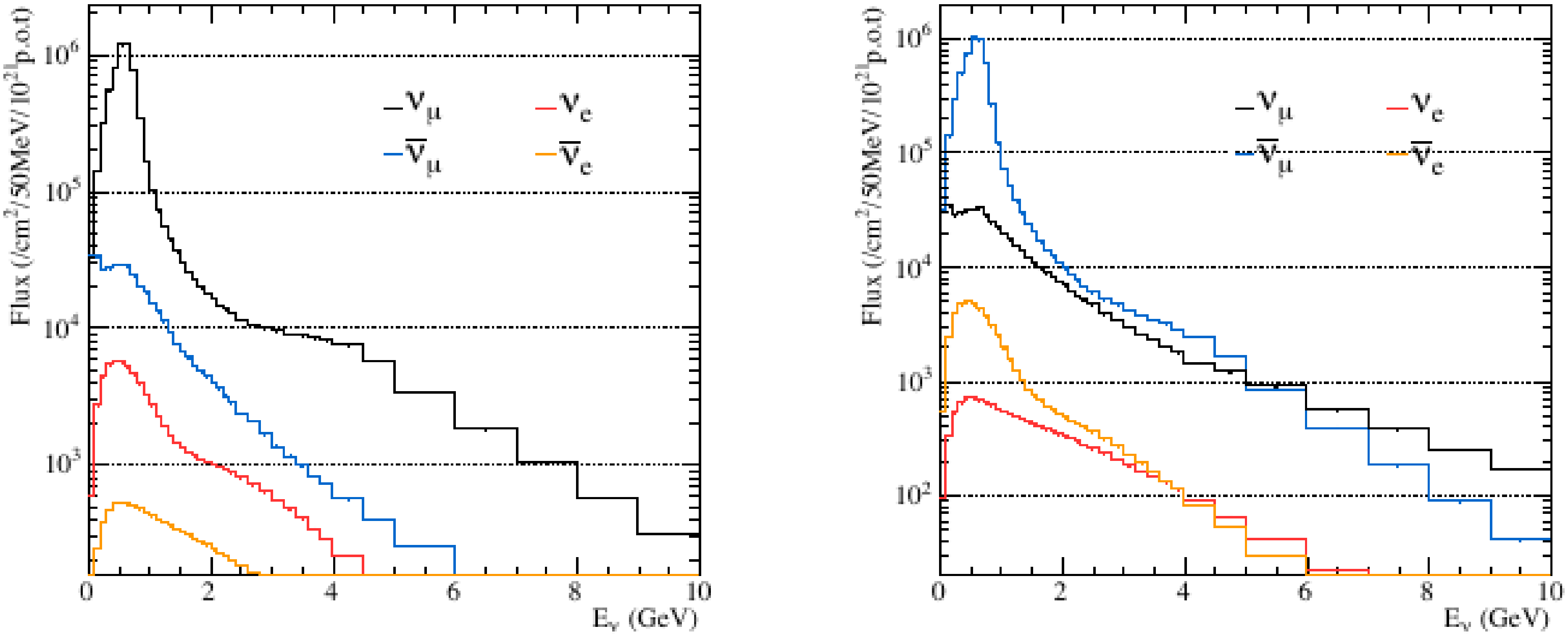
T2K Beam monitoring

- Beam position on target within 1 mm
- Muon monitor : beam direction within 1 mrad, intensity stable (<1%)
- Neutrino beam monitoring on axis







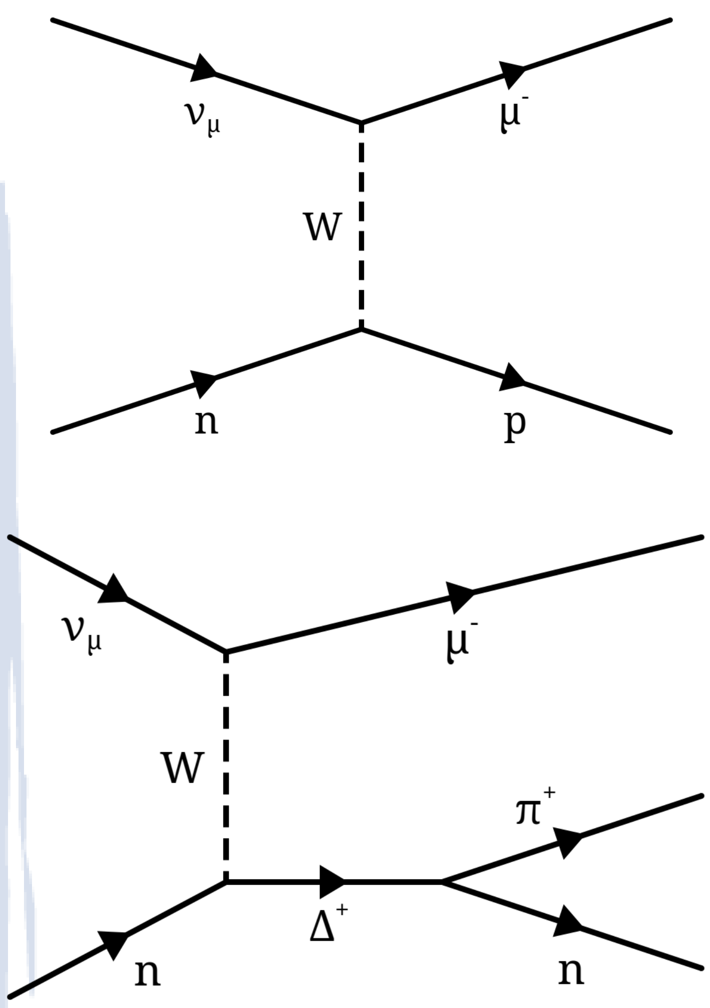


T2K beam flux for neutrino mode (left) and antineutrino mode (right)

Controlling the neutrino flux and cross-sections with near detectors

- Two strategies:
- 1) use a near detector (almost) identical to far detectors (eg reactor experiments)
- 2) use the most sophisticated near detector possible (T2K)

Neutrino nucleus interactions-1



Charged current quasi-elastic (CCQE) interaction.

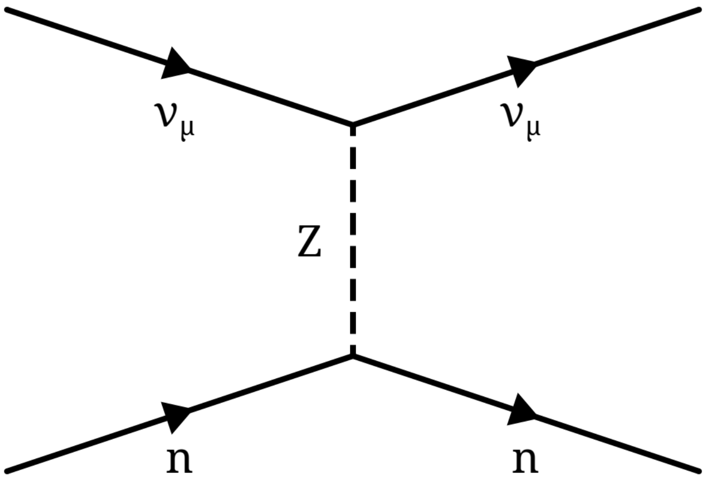
The neutrino energy can be reconstructed from the measurement of the lepton

$$E_\nu \simeq \frac{m^2_p - m^2_n - m^2_\mu + 2 m_n E_\mu}{m_n - E_\mu + p_\mu \cos\theta}$$

Charged current resonant production. Production of an excited nucleon states like Delta, then decaying with pion production. Might look like CCQE if the pion is not detected !

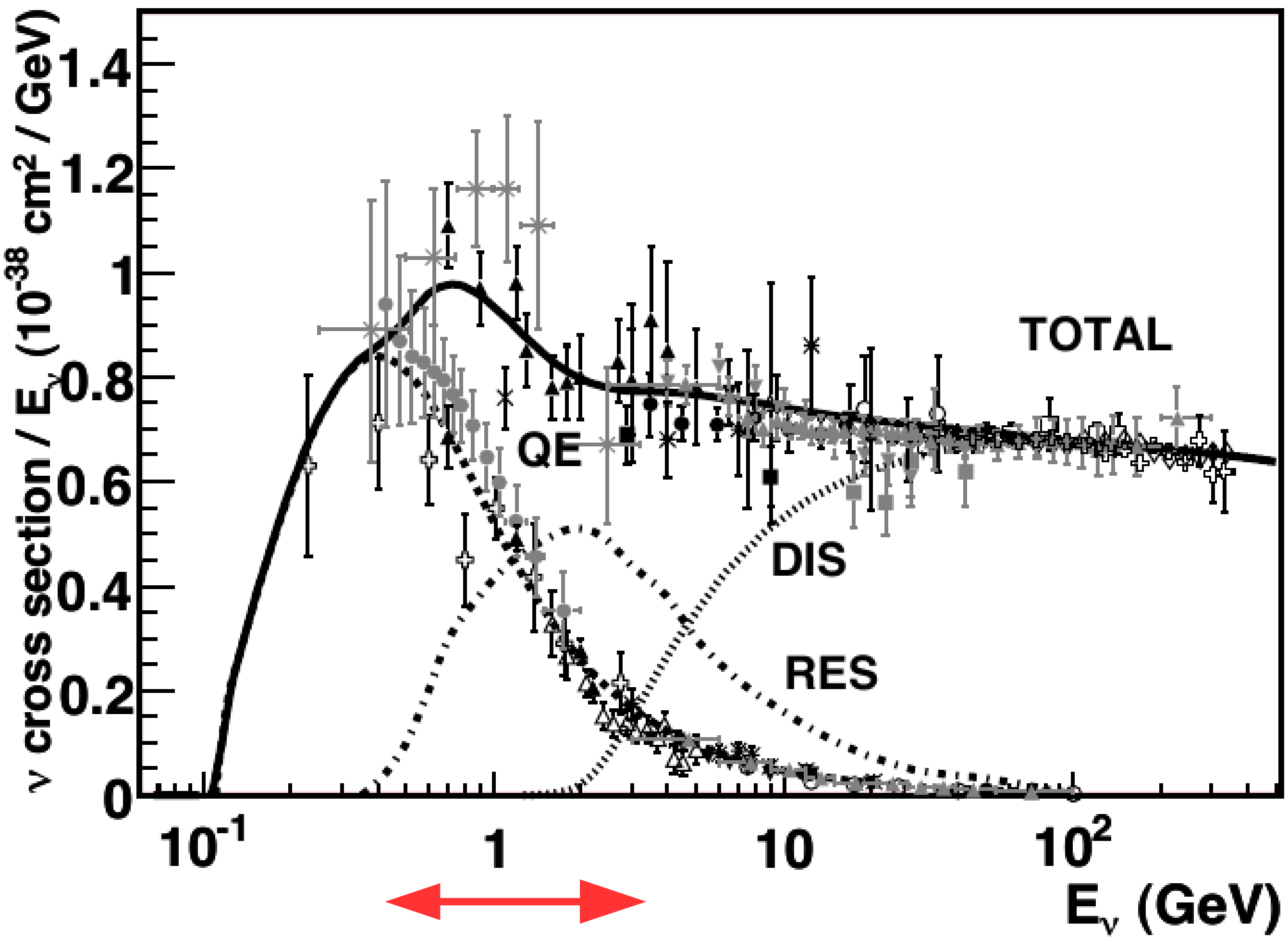
Another charge current process is the deep inelastic scattering (DIS) at higher energies. The neutrino breaks the nuclon and initiate a quark „jet".

Neutrino nucleus interactions-2



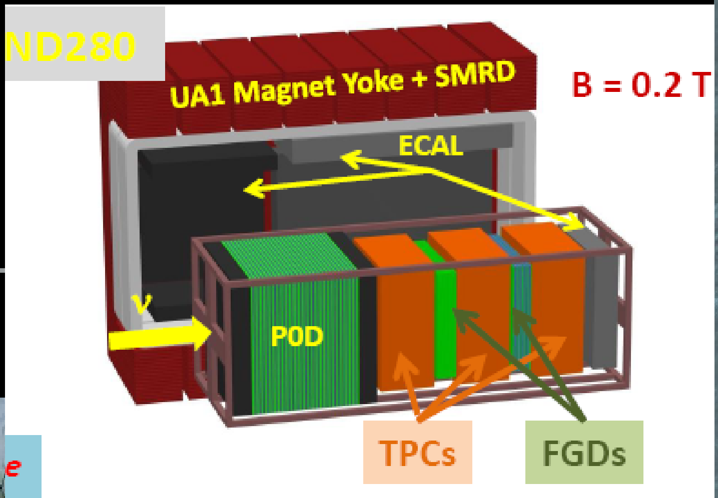
Neutral current interaction. Can also produce resonant states and pi0 in the final state.
Often difficult to distinguish a pi0->gamma gamma from one electron in the final state

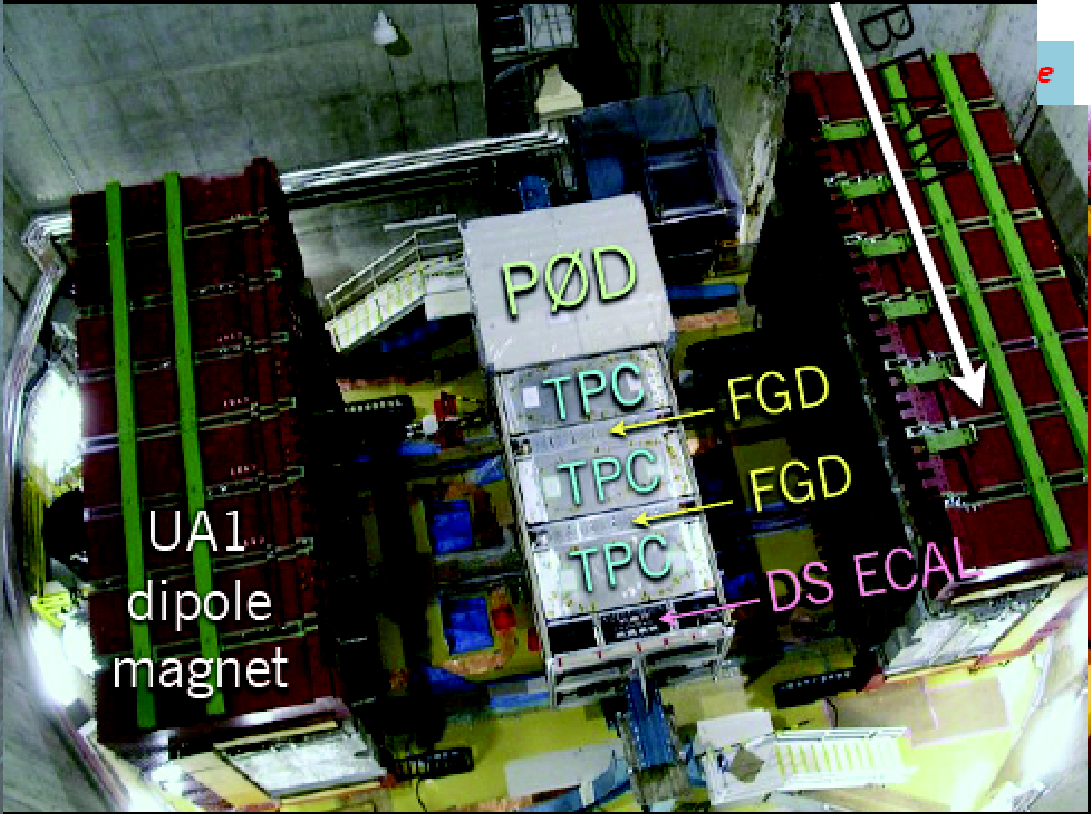
The neutrino nucleus cross section

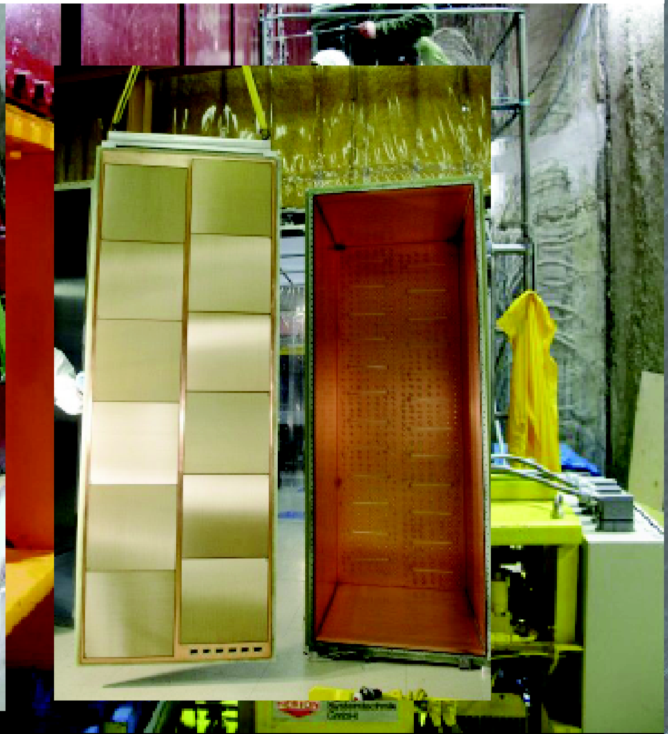


Typical range used for LB experiments

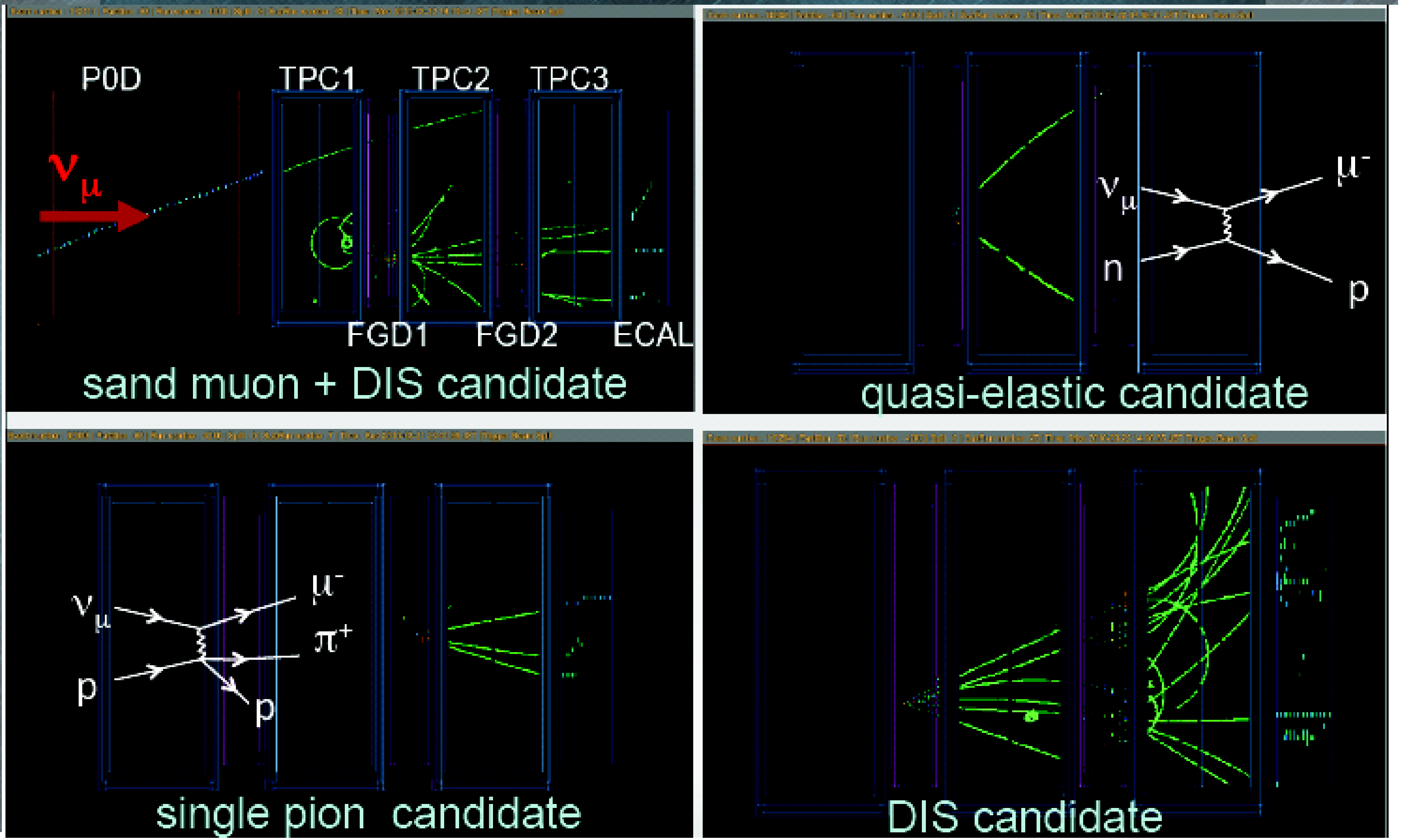
Off-axis Near Detector



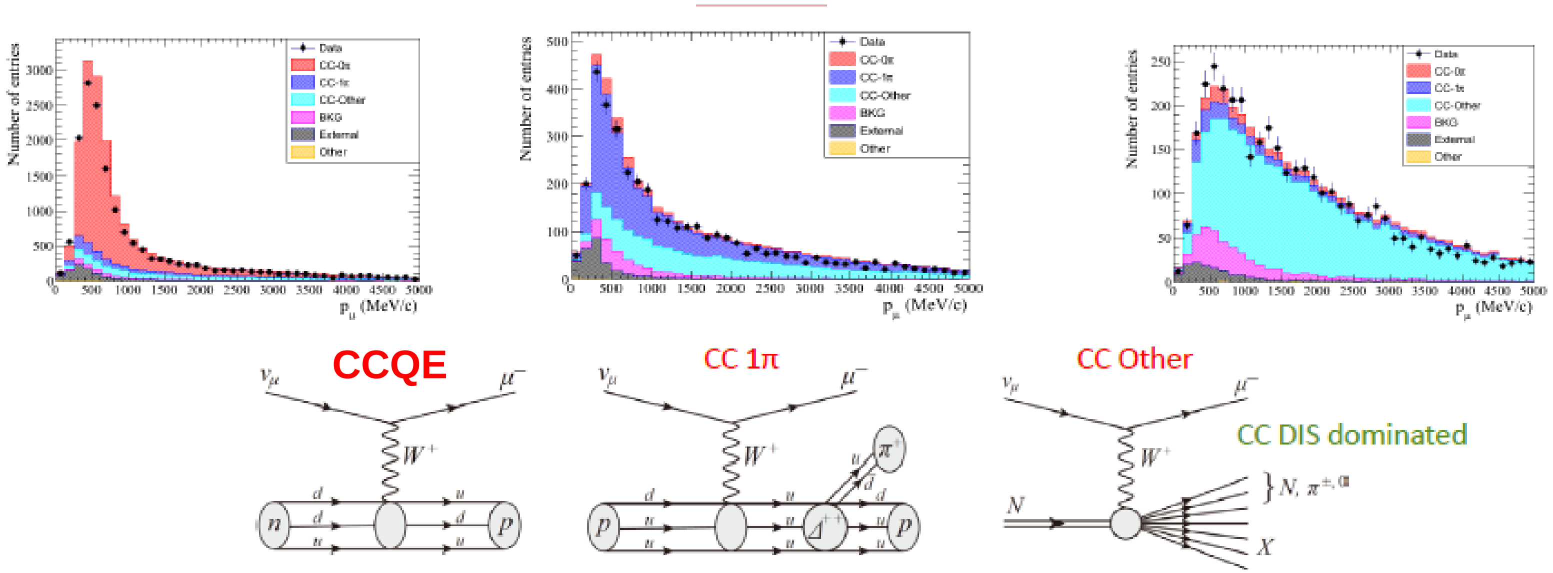




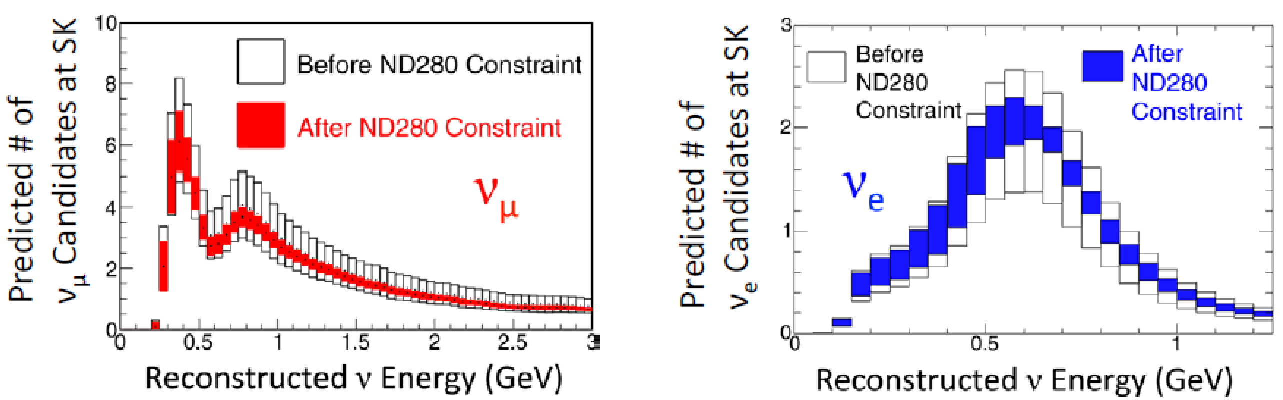
Neutrino interactions in ND280



T2K Near detector constraint



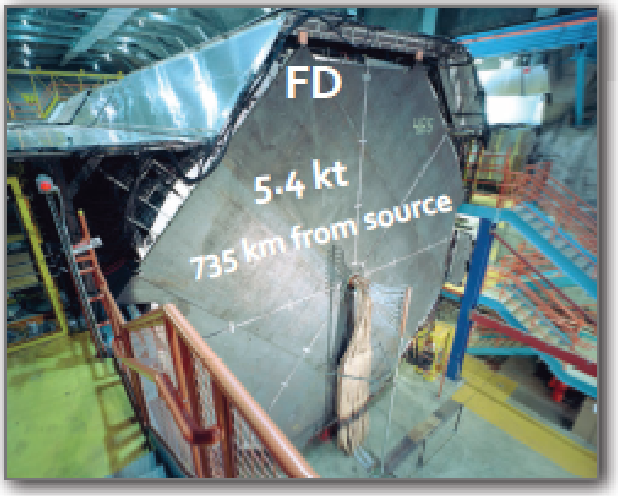
Flux and cross-section systematic uncertainty on N_{SK} significantly reduced to ~7%



Neutrino detectors

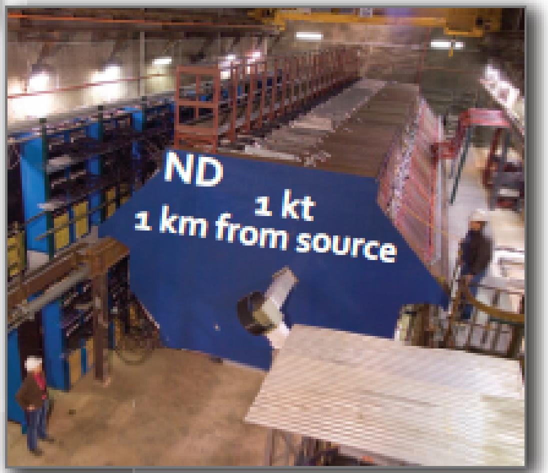
- Need a large instrumented mass to overcome the small cross-section
- A calorimeter fulfills the requirements, especially if it is totally active
- Main options
  - Magnetised iron, scintillator (MINOS) ~kt
  - Water Cherenkov (SuperKamiokande 50kt, Antares, IceCube....) (1 Mt)
  - Liquid Scintillator (Kamland, JUNO)
  - Liquid Argon TPC (Icarus, DUNE) ~10kt

The MINOS+ Concept

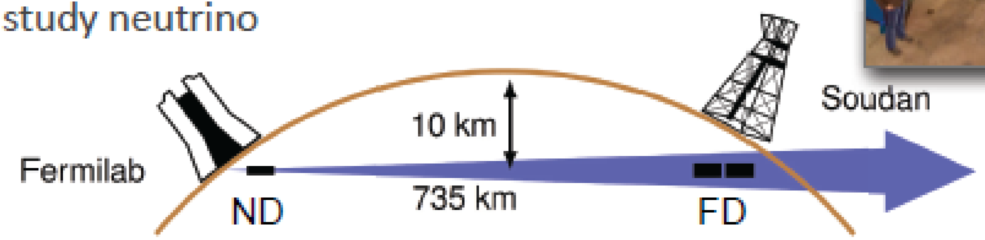


- Long-baseline neutrino oscillation experiment
  - Measure NuMI Neutrino beam energy and flavor composition with two detectors over 735 km
    - L/E ~ 500 km/GeV

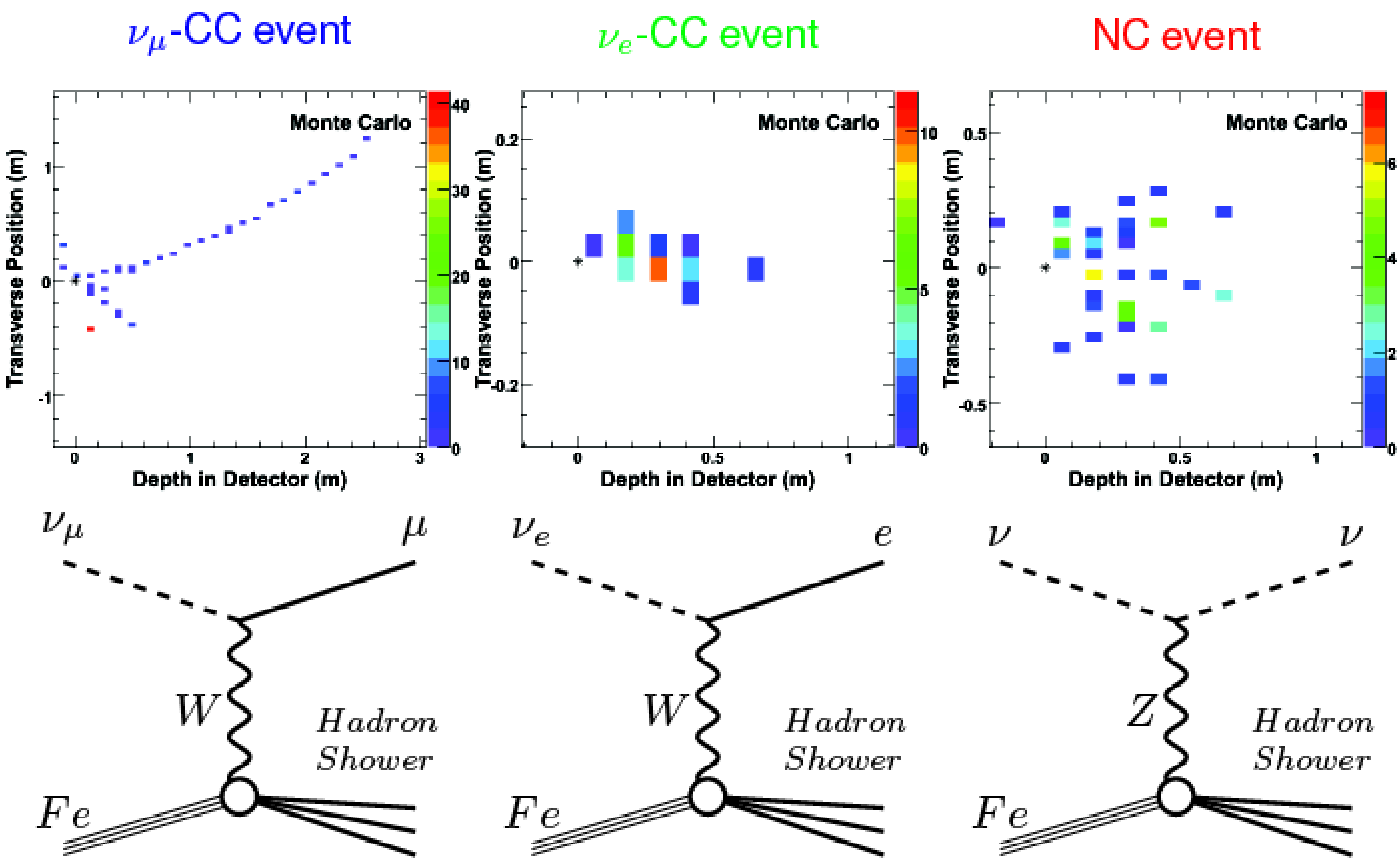
- Near Detector at Fermilab
- Far Detector at Soudan Underground Lab, MN



- Compare Near and Far measurements to study neutrino mixing



MINOS event topology



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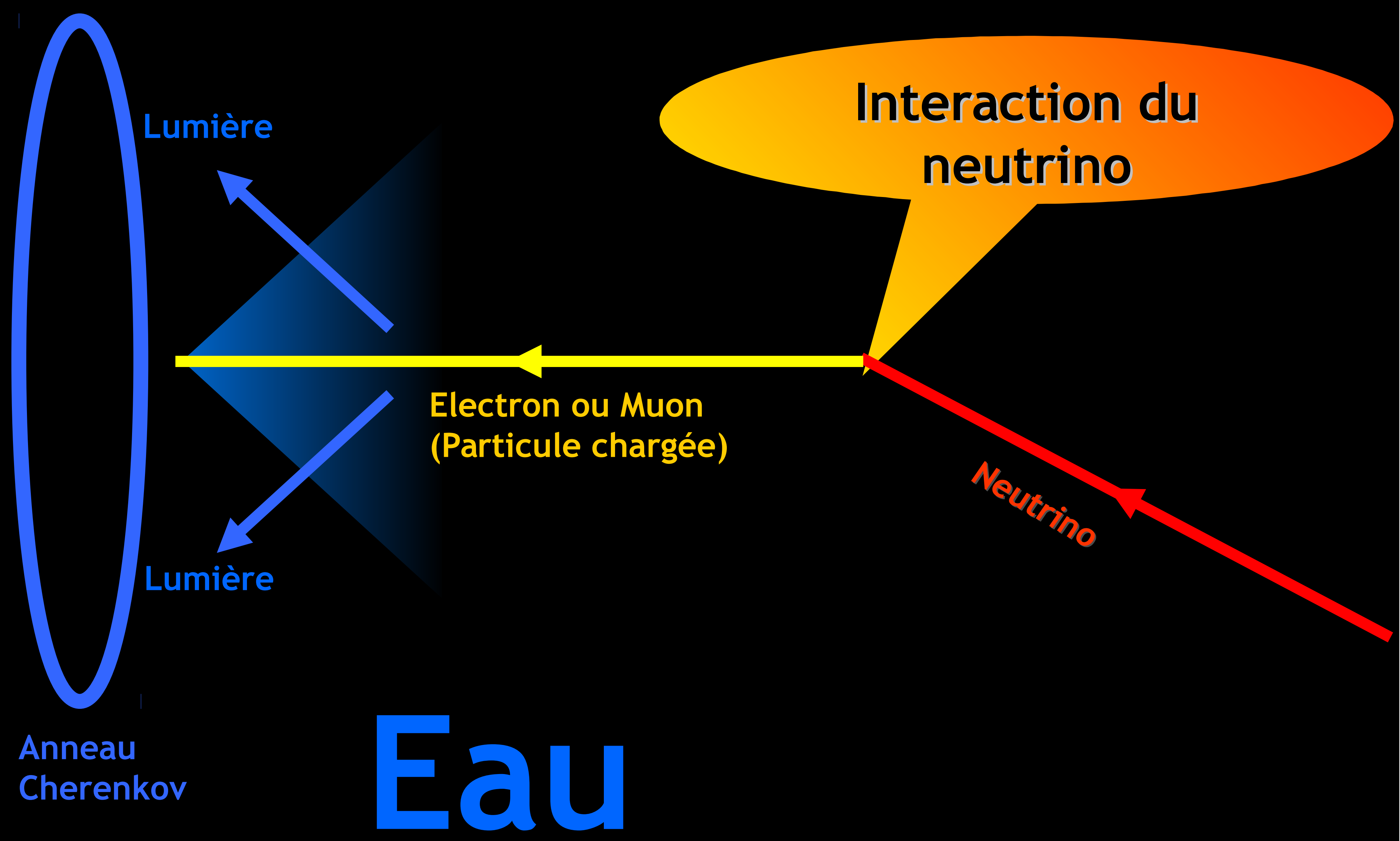
Large Water Cherenkov detectors

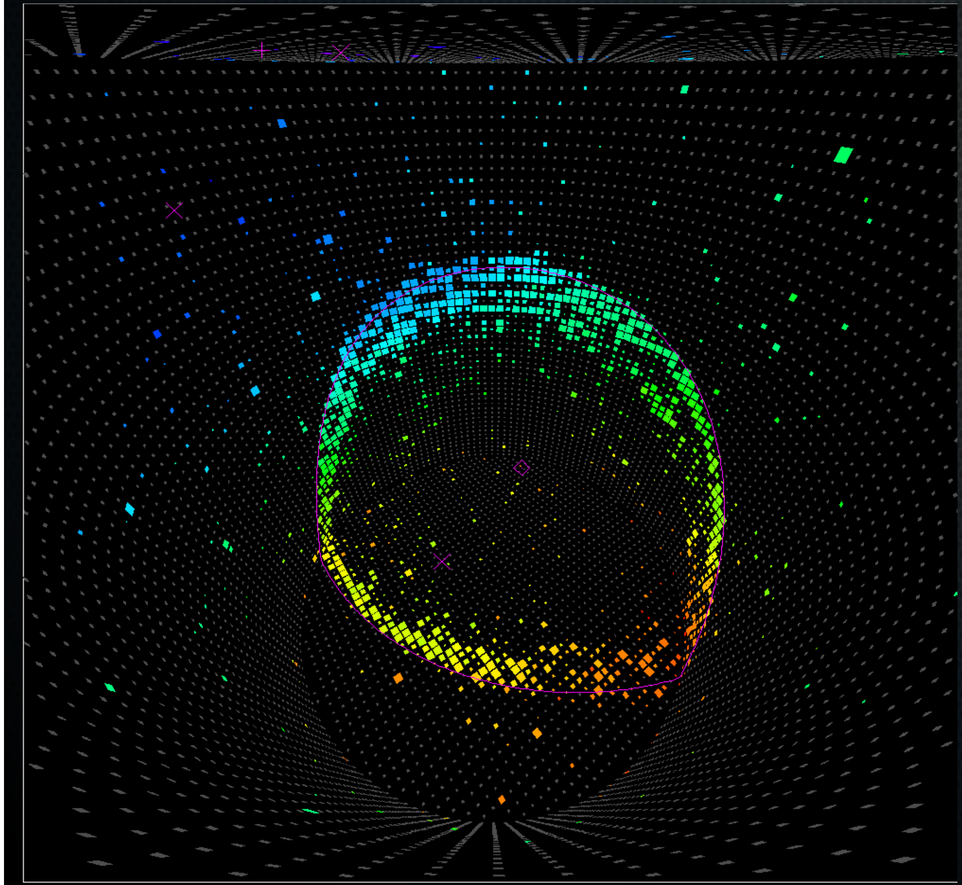
- These detectors are in operation since the 1980 (IMB, Kamiokande) and were actually built originally to study the proton lifetime
- The light signal is due to Cherenkov light: only from charged particle above the Cherenkov threshld in water (n=1.33) (eg only protons above p~1.07 GeV/c)
- PID: possibility to distinguish a nue from numu
- For LB physics it works best below GeV: CCQE nu interaction. The neutrino energy can be reconstructed from the lepton momentum and angle
- Amazing variety of physics: from solar neutrinos (threshold 3.5 MeV) to SN neutrinos all the way up to multi-GeV atmospheric neutrinos !

L'effet Cherenkov

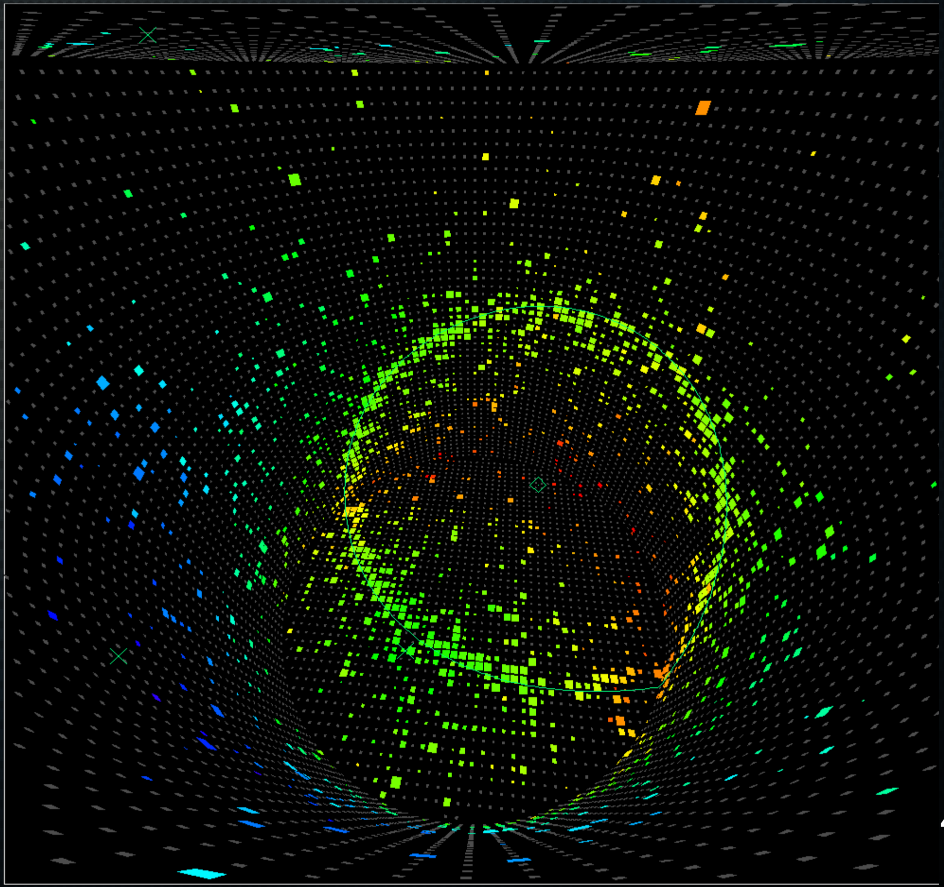


Interactions des neutrinos vues par Super-Kamiokande

- Neutrino de type muonique

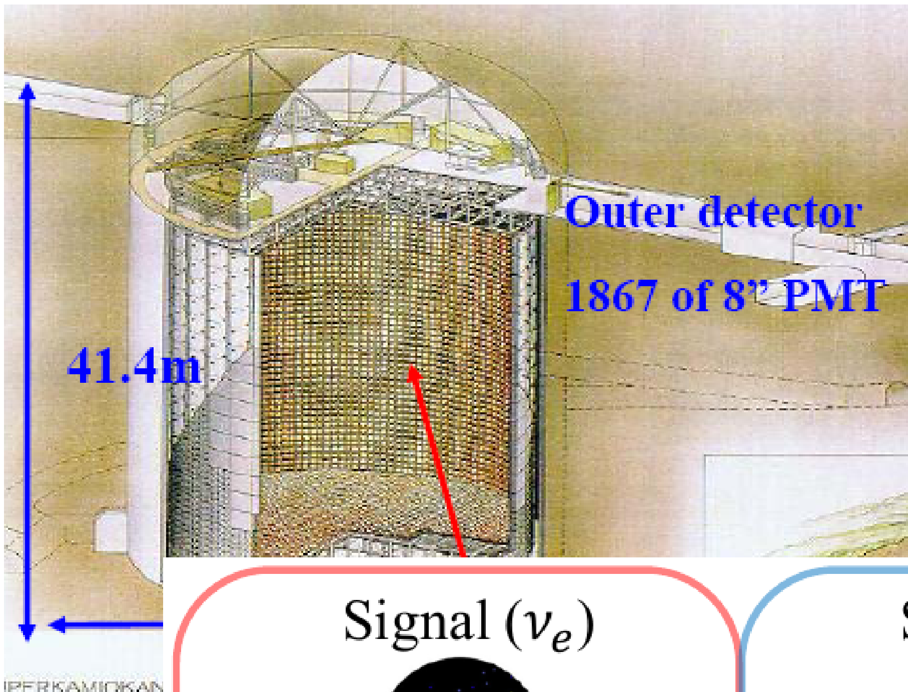


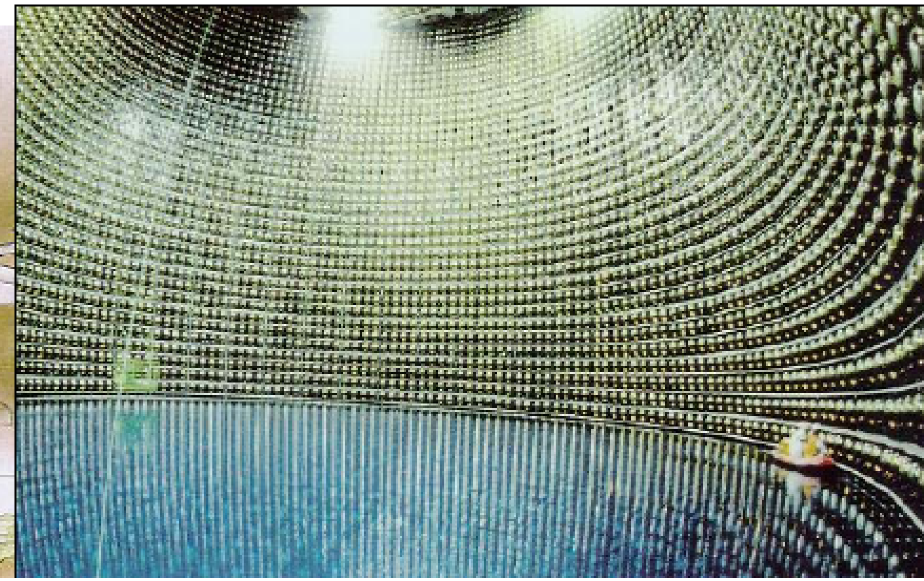
- Neutrino de type électronique

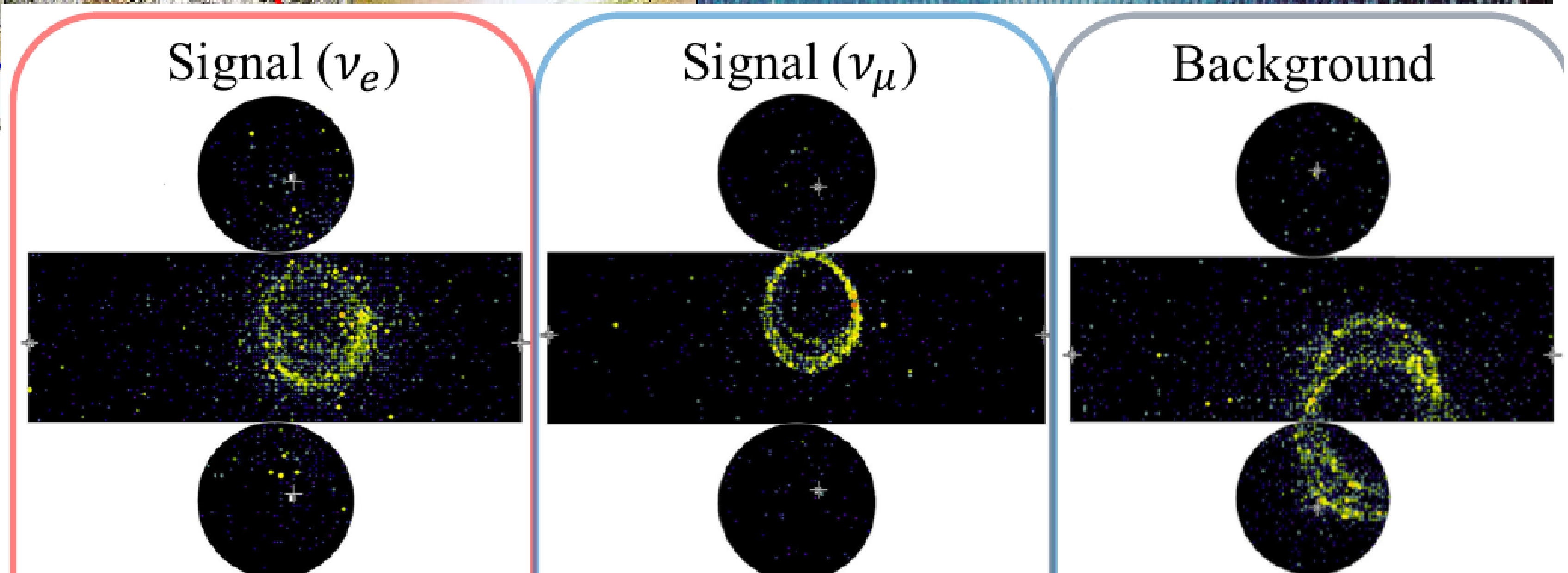


Super Kamiokande

50 kton





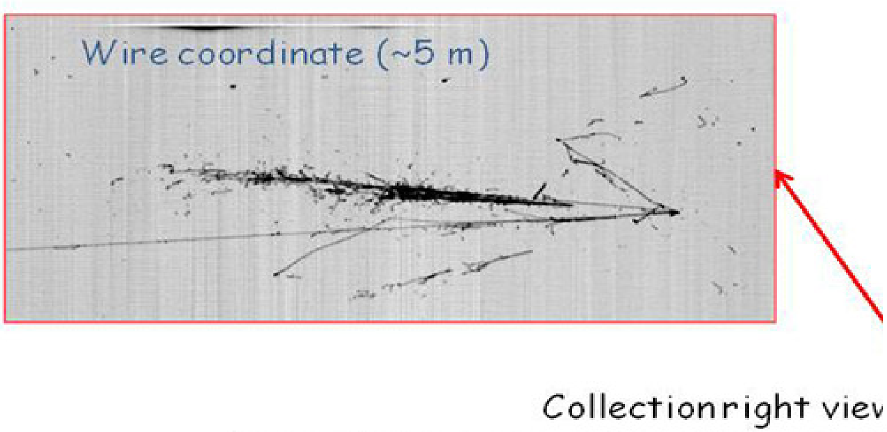


Liquid Argon TPC

- A Liquid Argon TPC is a very sensitive detector : can detect both scintillation light and the primary ionisation
- It is capable of PID by dE/dx and range
- It is an excellent calorimeter
- However it has never been tested at the multi-kt size. The largest is ICARUS 600t.
- An active R&D program to develop the new generation Liquid Argon Detector for the DUNE project

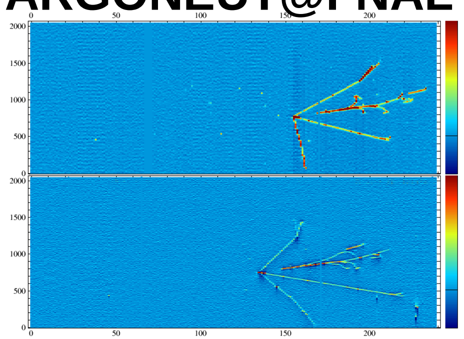
Why Liquid Argon TPC ?

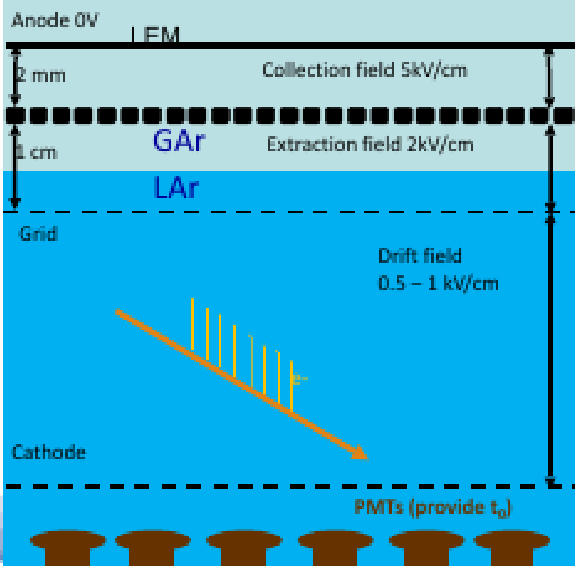
- Technology pioneered by the ICARUS collaboration
- Fully active high granularity detector (voxel ~$3x3x0.4mm^3$): a modern bubble chamber
- PID (from range and dE/dx) and high resolution calorimetry
- Sensitive to ν_μ, ν_e and ν_τ
- Currently used by the MicroBoone short baseline exp.
- A full program with several prototypes and demonstrators will lead to a large optimized underground detecto



ICARUS CNGS neutrino interaction

ARGONEUT@FNAL





Next part of the presentation: experimental results with LB