Latest developments in Neutrino Physics

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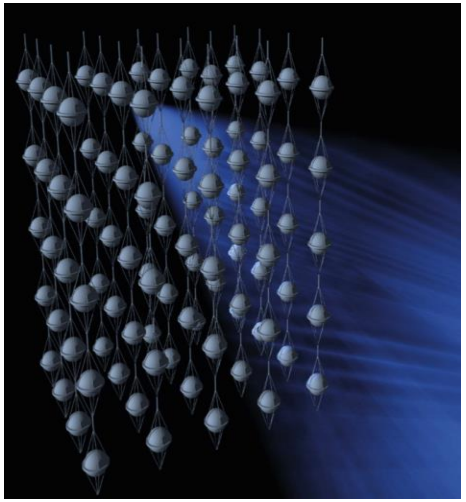
Outline

- Introduction to neutrino physics
- Short historical excursus
- Results from Moriond, the “spring showcase” for HEP

Why neutrinos are so interesting?

Neutrinos play a key role in several physics sectors:

- **Particle physics**: neutrino oscillations are the only (up to now) experimental hint pointing towards physics beyond the Standard Model (SM)
  First steps beyond EW scale, new particles? …
- **Cosmology**: important role during the Big Bang, could they explain the matter/antimatter asymmetry?
  Leptogenesis, Large Scale Structure…
- **Astrophysics**: they are the most abundant particles in the Universe, and they rule the life and death of the stars. They can be carriers of information from very far away!
  Neutrino astronomy, direct test of stellar evolution…



Unexpected particle still surprising us
A bottom-up story! From phenomenology to theory
Starting from the neutrino particle itself…

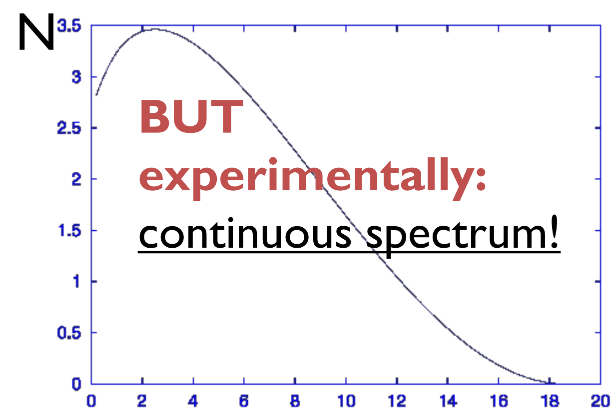
The “desperate remedy”

The neutrino was postulated by Wolfgang Pauli in 1930 as a “desperate remedy” to explain the continuous β-ray spectrum via a 3-body decay, rather than the expected 2-body decay

Visible decay products:

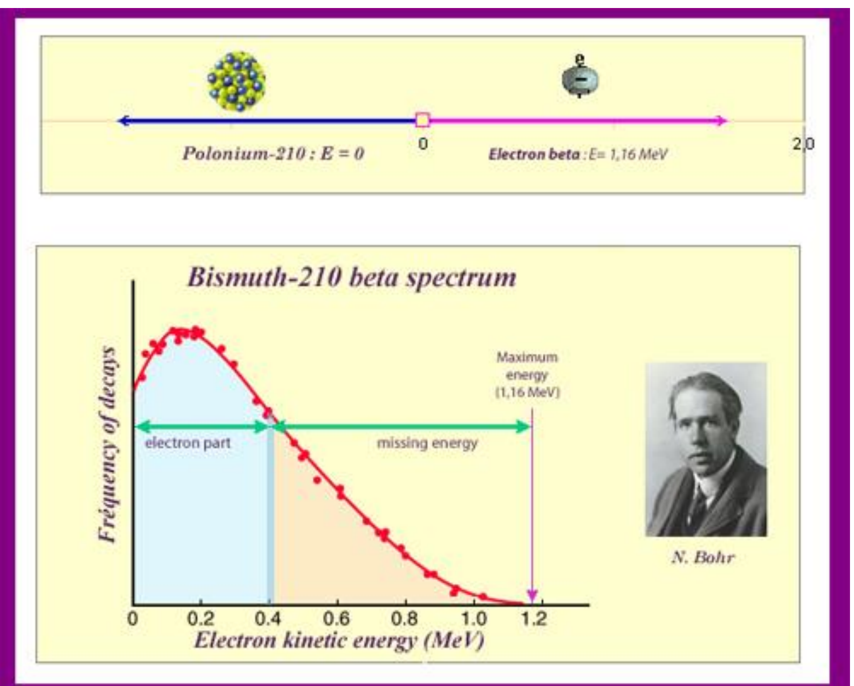
n → p + e-

2-body decay
→ monochromatic electrons!



BUT experimentally:
<u>continuous spectrum!</u>

Beta-particle energy



Violation of energy conservation (Bohr!) ?!?
NO!
Pauli postulates the right reaction:

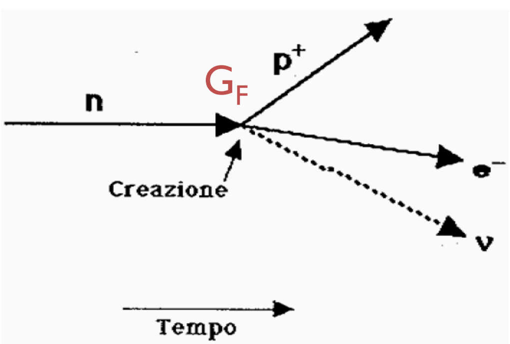
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Neutrino properties

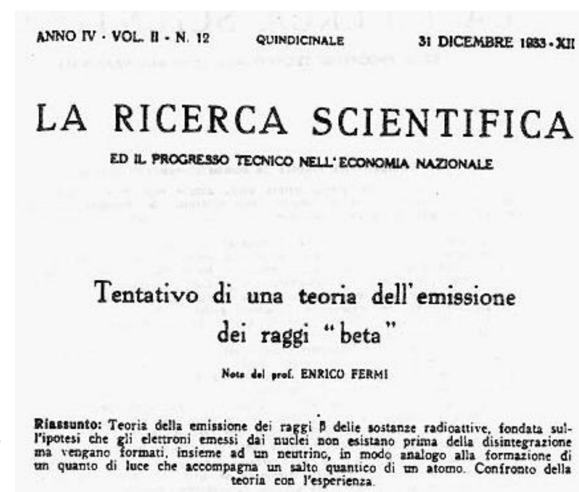
The neutrino from the β-decay:

- must be very light, possibly massless:
  (sometimes, the electron takes all the energy in the decay)
- must be electrically neutral:
  (charge conservation in beta decay)
- is produced along with an electron:
  (they can't be made on their own...)
- must interact very rarely:
  (it always escapes the detector without being seen)

Properties still valid!



1933 Fermi: theory of weak interactions (point-like)
→ neutrino created together with the charged lepton


ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

Fermi's theory still stands! (Parity violation added in the 50's)

Neutrino history

"I have done a terrible thing today by proposing a particle that cannot be detected; it is something that no theorist should ever do." (Pauli)

After the calculation of ν interaction length ~ some light years of lead!
"[…] one obviously would never be able to see a neutrino" (Bethe & Peierls, 1934)

- Luckily they were wrong… we can observe neutrinos e.g. via the inverse β-decay (Fermi theory): same reaction as the production one, but "reversed" (Pontecorvo, 1955)

$$\bar{\nu}_e + p \rightarrow n + e^+$$

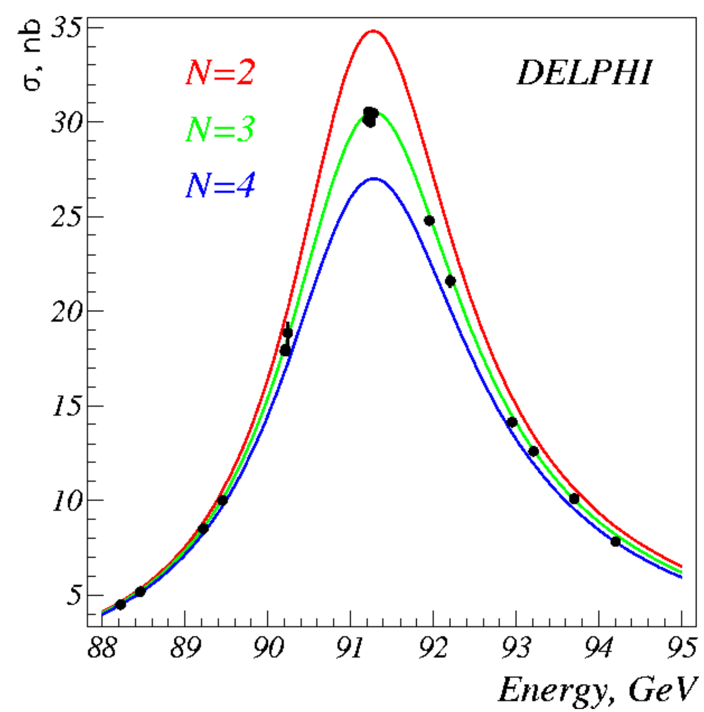
- Cowan & Reines (1956): (anti) neutrino observation!

Neutrinos in the Standard Model

- Only weak interactions: that's why they are so "elusive"
  → to detect them we need a very large and massive detector
  and a powerful source of neutrinos!
- Neutrinos are produced in weak interactions together with their charged lepton:

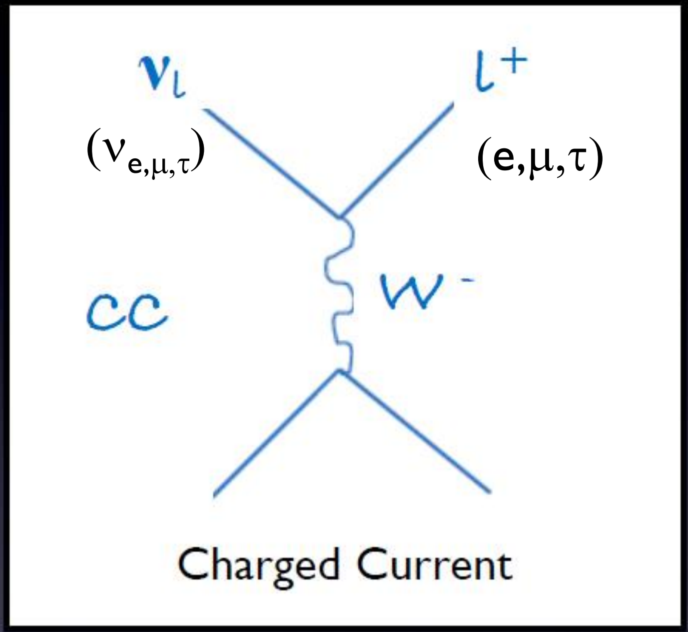
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{matrix} \leftarrow & q = 0 \\ \leftarrow & q = -1 \end{matrix}$$

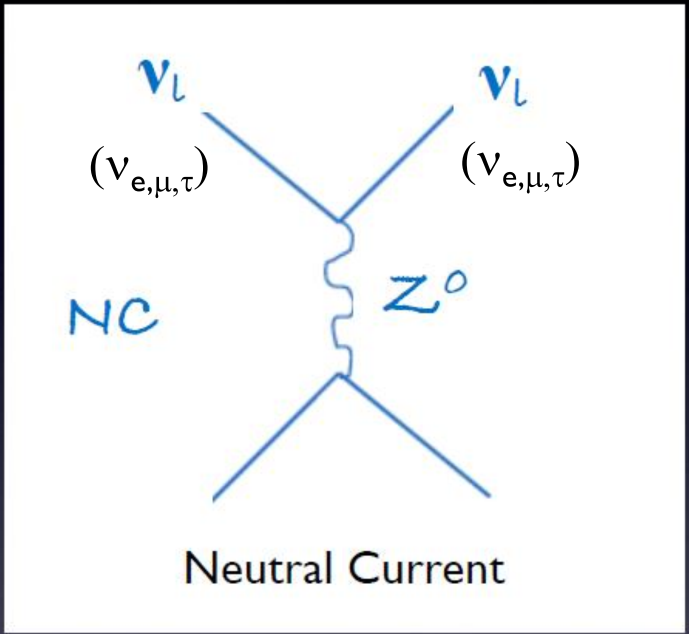
From LEP: **N_ν = 2.984 ± 0.008**
only 3 "light" neutrinos ($m_\nu < M_Z/2$)
couple with the Z
→ 3 ν flavors, i.e. 3 lepton families



Before direct detection of ν_τ! (DONUT, 2000)

Two Basic Interactions





Most interactions are limited to two basic type of interactions:

A charge $W^{\pm}$ is exchanged: Charged Current Exchange

A neutral Z^0 is exchanged: Neutral Current Exchange

All neutrino reactions involve some version of these two exchanges.

Neutrinos in the SM

Experimentally: weak interactions are not mirror-symmetric (P maximally violated) (Wu, 1957):

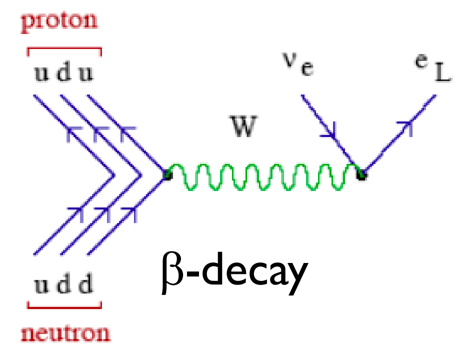
- In the SM, neutrinos are created in chiral interactions (maximal parity violating in V-A chiral structure)
- The weak gauge bosons $W^{\pm}$ act on left-handed doublets (CC interactions)

  ν is left-handed (LH) (1957-58, Helicity of neutrinos = -1)

  anti-ν is right-handed (RH)

In the SM, only LH fields couple with W and Z bosons

$SU(2)_L \times U(1)$ theory



β-decay

RH fields are idle

→ RH neutrinos cannot be created in weak interactions (as LH anti-neutrinos)

→ So ν do not participate in the Higgs mechanism:

in the SM neutrinos are massless!

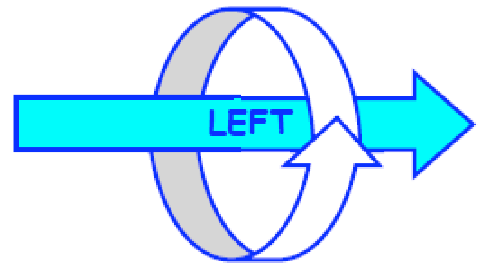
The two component explanation (Lee &Yang, '50s) was so convincing that created a prejudice…

Drell: "[…] The success of the Standard Model was too dear to give up."

Such interactions are chiral (= not mirror-symmetric):

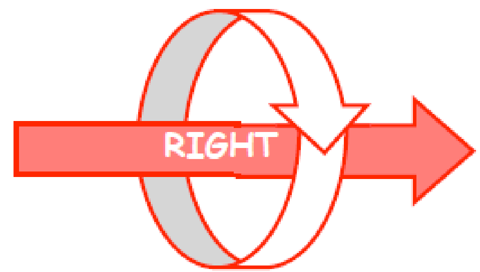
Neutrinos are created in
a left-handed (LH) state

ν



Anti-nus are created in
a right-handed (RH) state

$\bar{\nu}$

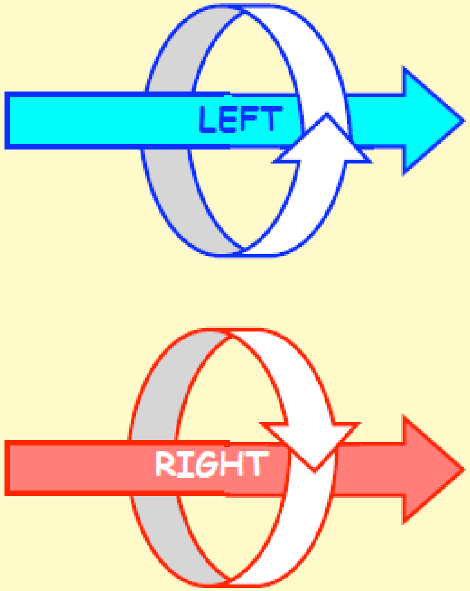


Neutrinos couldn't see themselves in a mirror... like vampires!

For massless neutrinos: handedness is a constant of motion

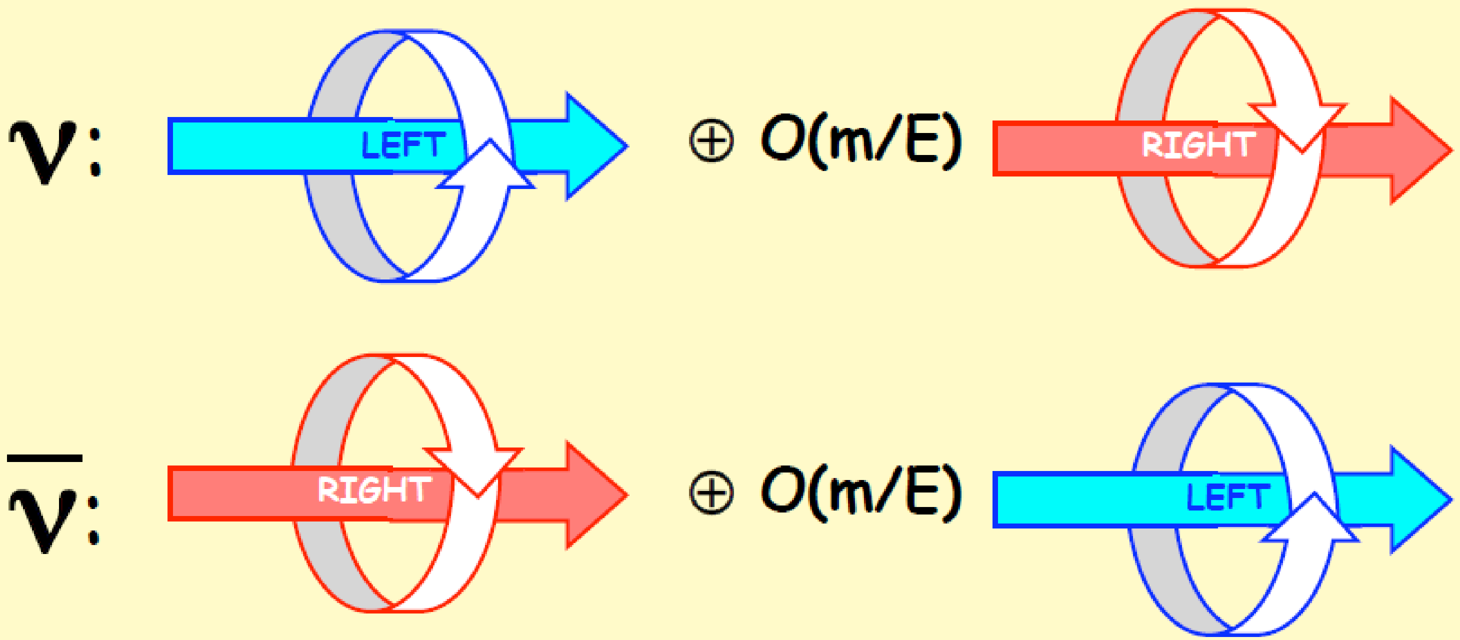
ν:

$\bar{\nu}$:



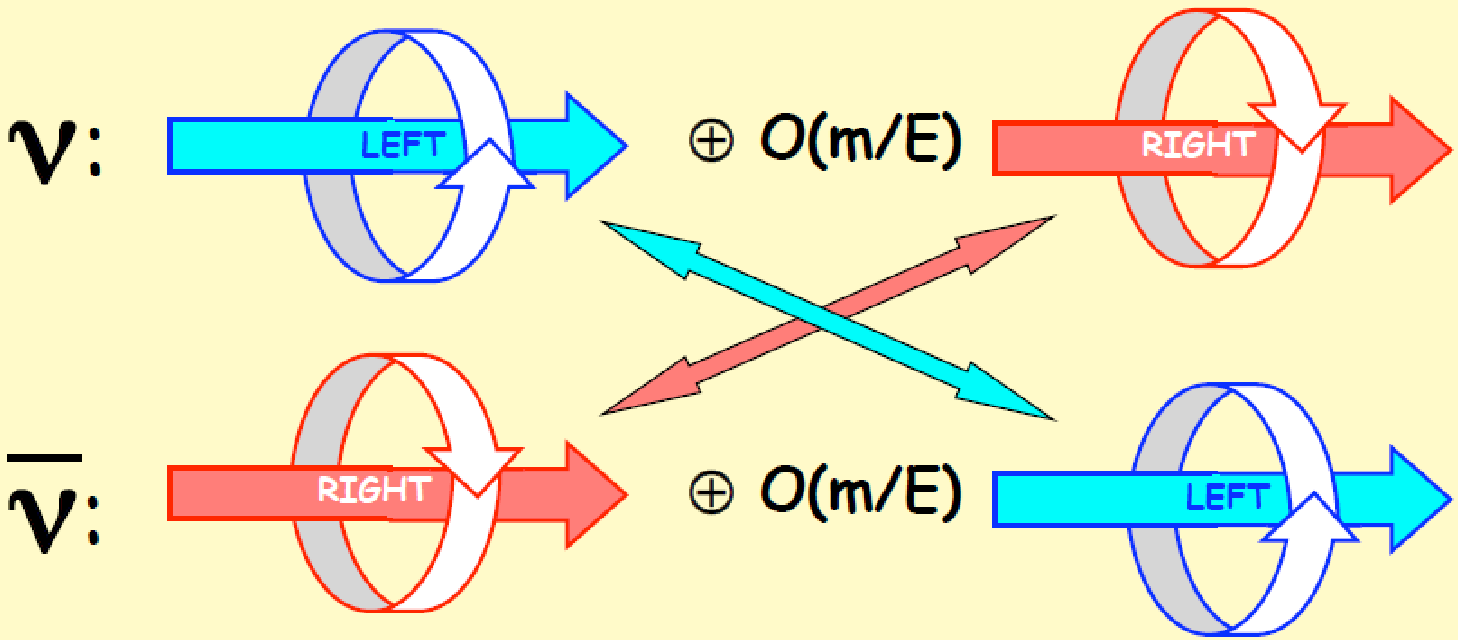
2 independent d.o.f.: massless ("Weyl") 2-spinor

But: massive ν can develop the "wrong" handedness at O(m/E)
(the Dirac equation mixes RH and LH states for $m_\nu \neq 0$):



If these 4 d.o.f. are independent: massive ("Dirac") 4-spinor
[→ Distinction between neutrinos and antineutrinos, as for electrically charged fermions. Can define a "lepton number"]

But, for neutral fermions, 2 components might be identical !



Massive (“Majorana”) 4-spinor with 2 independent d.o.f.
[No distinction between neutrinos and antineutrinos, up to a phase:
A *very* neutral particle: no electric charge, no leptonic number…]

Exercise 1. Define the electron neutrino as the neutral particle emitted in β+ decay, and the electron antineutrino as the neutral particle emitted in β- decay. Reactions which have been observed:

$$\nu_e + n \rightarrow p + e^- \qquad \overline{\nu}_e + p \rightarrow n + e^+$$

while the following reactions have not been observed:

$$\overline{\nu}_e + n \rightarrow p + e^- \qquad \nu_e + p \rightarrow n + e^+$$

If neutrinos and antineutrinos are different (Dirac case), that's easy to understand. Try to understand the same (non)observations in the case of Majorana neutrinos.

Summary of options for neutrino spinor field:

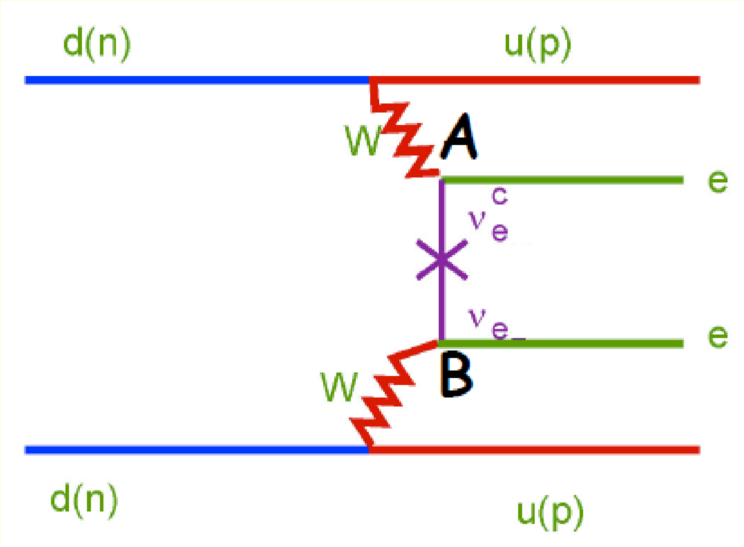
m=0, Weyl:	$\psi = \psi_R$ or $\psi = \psi_L$	massless field with 2 d.o.f.
m≠0, Majorana:	$\psi = \psi_R + \psi_R^c = \psi^c$ or $\psi = \psi_L + \psi_L^c = \psi^c$	massive field with 2 d.o.f.
m≠0, Dirac:	$\psi = \psi_R + \psi_L \neq \psi_c$	massive field with 4 d.o.f.

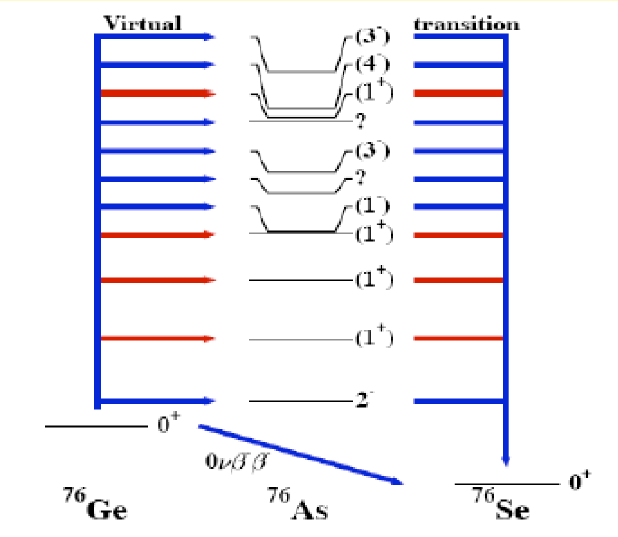
Conjugation operator: $\psi^c = \mathcal{C}(\psi) = i\gamma^2\psi^*$, $\psi_{\text{antiparticle}} = \mathcal{C}(\psi_{\text{particle}})$

Appendix: Majorana masses and "see-saw" mechanism to explain their smallness

Experiments: A unique experimental handle →

Neutrinoless double beta decay: (A,Z) → (A,Z+2)+2e





Can occur only for Majorana neutrinos. Intuitive picture:

1) A RH antineutrino is emitted at point "**A**" together with an electron
2) If it is massive, at O(m/E) it develops a LH component (not possible if Weyl)
3) If neutrino=antineutrino, this component is a LH neutrino (not possible if Dirac)
4) The LH (Majorana) neutrino is absorbed at "**B**" where a 2nd electron is emitted

[EW part is "simple". Nuclear physics part is rather complicated and uncertain.]

The "neutrino puzzle": beginning

… but some experimental facts came unexpected:

the "**solar neutrino problem**"

Studying the "solar neutrinos" produced in the nuclear fusion in the Sun, predicted by the Standard Solar Model (SSM, Bahcall):

The Homestake Chlorine experiment

(Ray Davis, 600 ton chlorine tank)

$$^{37}Cl + \nu_e \rightarrow ^{37}Ar + e$$

(1968, Davis and Bahcall experiment)

Measured flux was only one third the predicted value !

R = Data/SSM **= 0.33 ± 0.01**

Neutrino deficit!

The "neutrino puzzle"

Deficit confirmed by other experiments, with different techniques:

Radiochemical experiments: Gallex/GNO and SAGE

$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

R = Data/SSM = **0.56** ± 0.05

Water Cherenkov: Kamiokande

R = Data/SSM **= 0.46** ± 0.13

"**solar neutrino problem**": three possible explanations:

✓ Solar neutrino flux is wrong? NO! *Helioseismology independently confirmed the SSM*

✓ Experimental errors? NO! *All the following experiments confirmed the deficit*

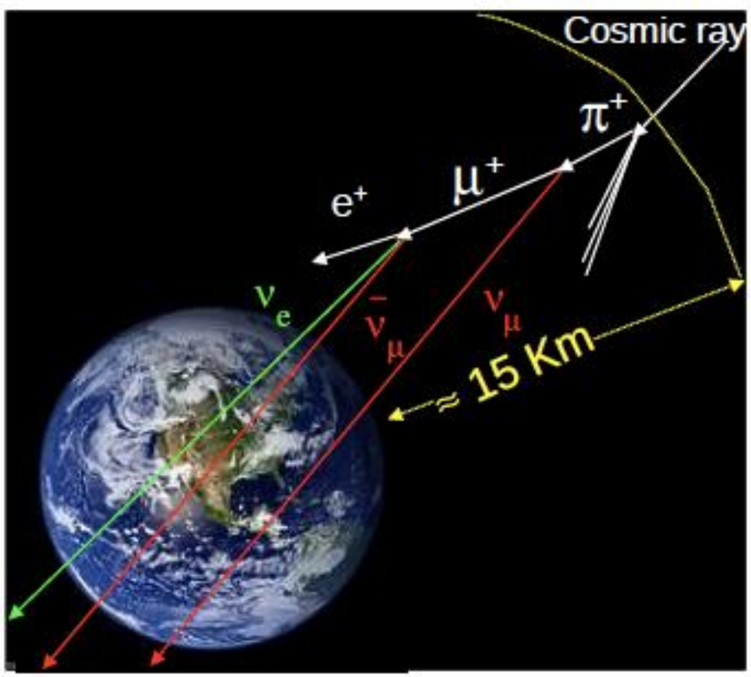
✓ Something happens to neutrinos along their travel… YES!

Already in 1969: neutrino flavor oscillation proposed by Pontecorvo & Gribov!
But very few physicists took the idea seriously at that time…

Neutrino anomaly complicate the "neutrino puzzle"

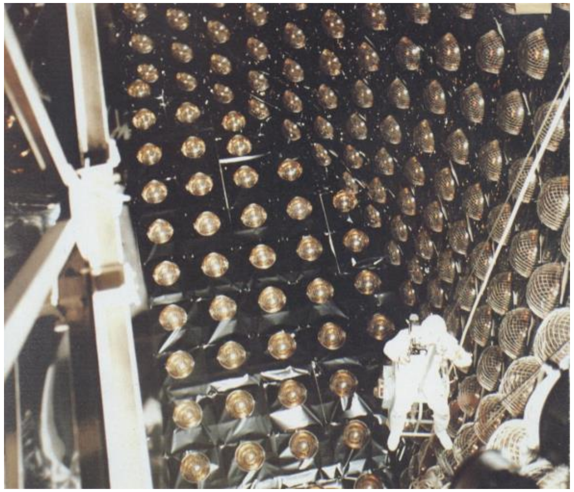
- In the '70s, GUT theories predicted the proton decay with measurable livetime
  ➔ $\tau_p = 10^{30 \pm 2}$ years
- Proton could decay in (for instance) $p \rightarrow e^+ \pi^0 \nu_e$
- Underground Detectors: 10^3 m^3, and mass 1kt (=10^{31} p)
- Main background : Atmospheric neutrinos interacting inside the experiment

- Water Cherenkov Experiments (IMB, Kamiokande)
- Tracking calorimeters (NUSEX, Fréjus, KGF)
- Result: **NO p decay ! But some anomalies on the neutrino measurement!**



IMB
(USA)
3300ton

Kamiokande
(Japan)
1000ton



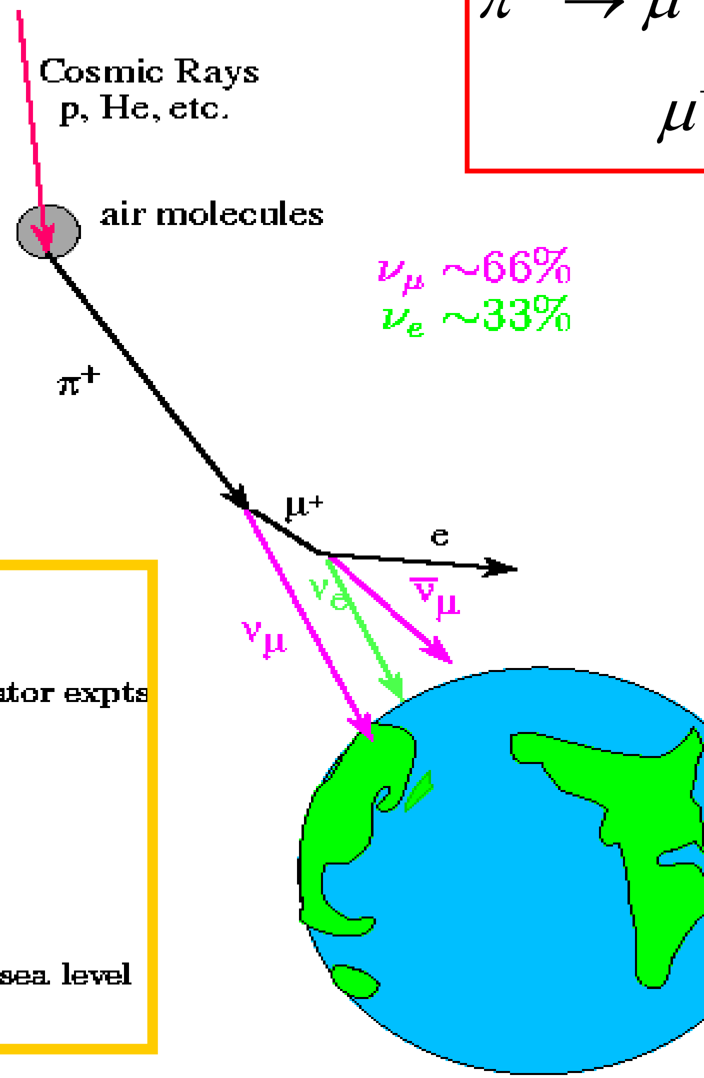
The recipes for the evaluation of the atmospheric neutrino flux

The Atmospheric Neutrino flux

We cannot measure the flux of incoming neutrinos.
We have to rely on Monte Carlo...

The flux Monte Carlos:

- Flux of primary cosmics from atmospheric expts
- Secondary production from accelerator expts
- Geomagnetic effects are included
- "1-dimensional" model
- Nuclear effects are not included
- Detector position is assumed to be sea level



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Experiments identify the ν flavor through the lepton produced in ν–CC interaction

"Atmospheric" neutrinos

Main sources of atmospheric neutrinos:

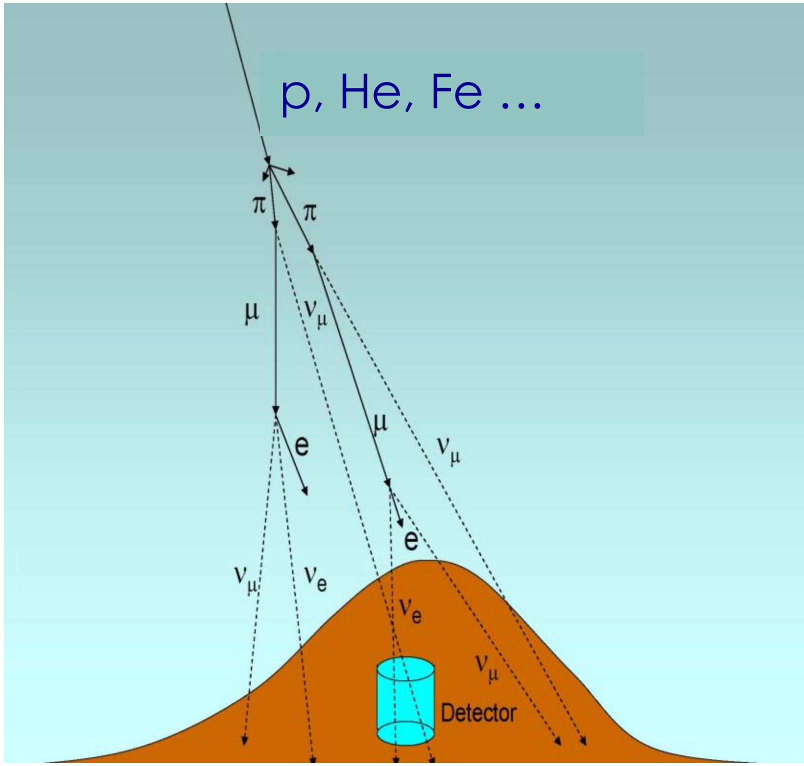
$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu)$$
$$\rightarrow e^{\pm} + \nu_e(\overline{\nu}_e) + \nu_\mu(\overline{\nu}_\mu)$$

For energies $E < 2$ GeV most pions and muons decay before reaching the Earth:

$$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \approx 2$$

At higher energies most muons reach the Earth before decaying:

$$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} > 2$$ (increasing with E)



Experiment examine the ratio-of ratios (the production systematics cancels)

$$R = \frac{(\nu_\mu/\nu_e)_{DATA}}{(\nu_\mu/\nu_e)_{MC\ (no\ osc.)}} \stackrel{?}{=} 1$$

Actually they measure

$$R' = \frac{\left(\frac{\mu\text{-like}}{e\text{-like}}\right)_{\text{Single-ring evts}}}{\left(\frac{\mu\text{-like}}{e\text{-like}}\right)_{MC}}$$

Water Cherenkov

$$\frac{\left(\frac{\text{tracks}}{\text{showers}}\right)_{\text{Single-prong evts}}}{\left(\frac{\text{tracks}}{\text{showers}}\right)_{MC}}$$

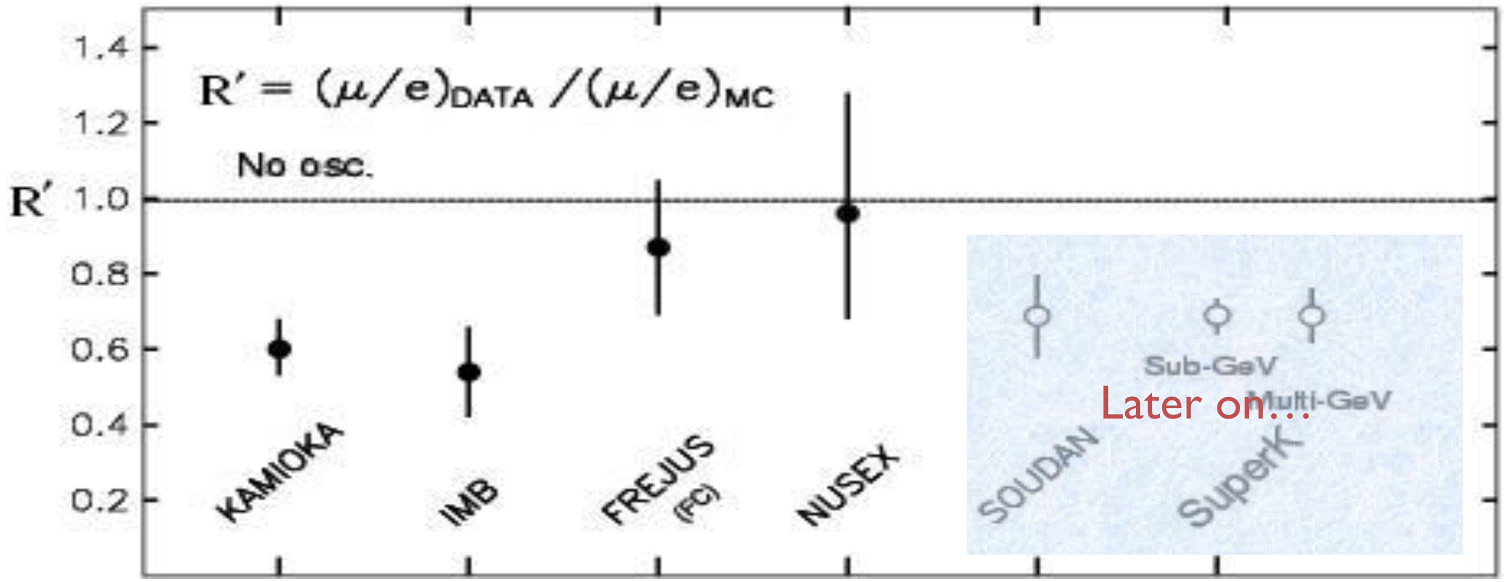
Tracking Detectors

Atmospheric neutrino anomaly

Summary of results since the mid 1980's:

$$R' = \frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$$

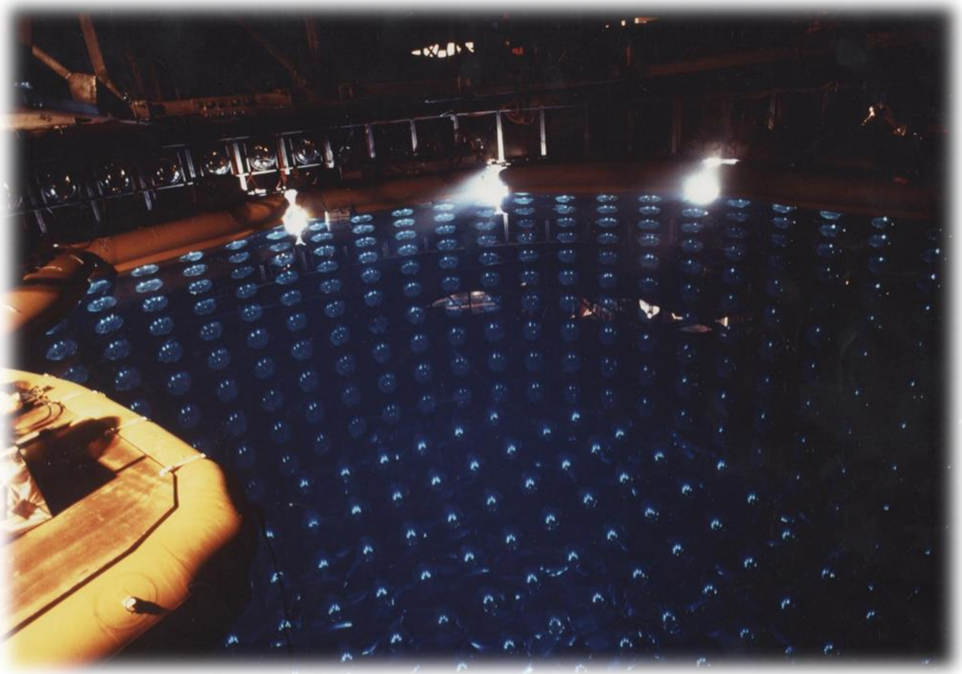
Double ratio between the number of detected and expected ν_μ and ν_e



Water Cherenkov

Calorimeters

First result on the μ/e ratio (1988)



Kamiokande

(3000ton Water Ch. ～1000ton fid. Vol.)

2.87 kton・year

	Data	MC prediction
e-like ($\sim$CC ν_e)	93	88.5
μ-like ($\sim$CC ν_μ)	85	144.0

"We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data."

Phys.Lett.B 205 (1988) 416.

Neutrino deficit in solar and atmospheric sectors: where are the missing neutrinos?

Neutrino oscillations

"Neutrinos have a multiple personality disorder" (Bahcall)

- The origin of the personality disorder is a quantum mechanical process called **neutrino oscillations**
- The weak interaction state is a coherent superposition of three mass eigenstates
  → constructive interference between wave packets
- Typical quantum mechanical phenomenon: deal with a probability

Neutrinos are created or annihilated as **W.I.** eigenstates

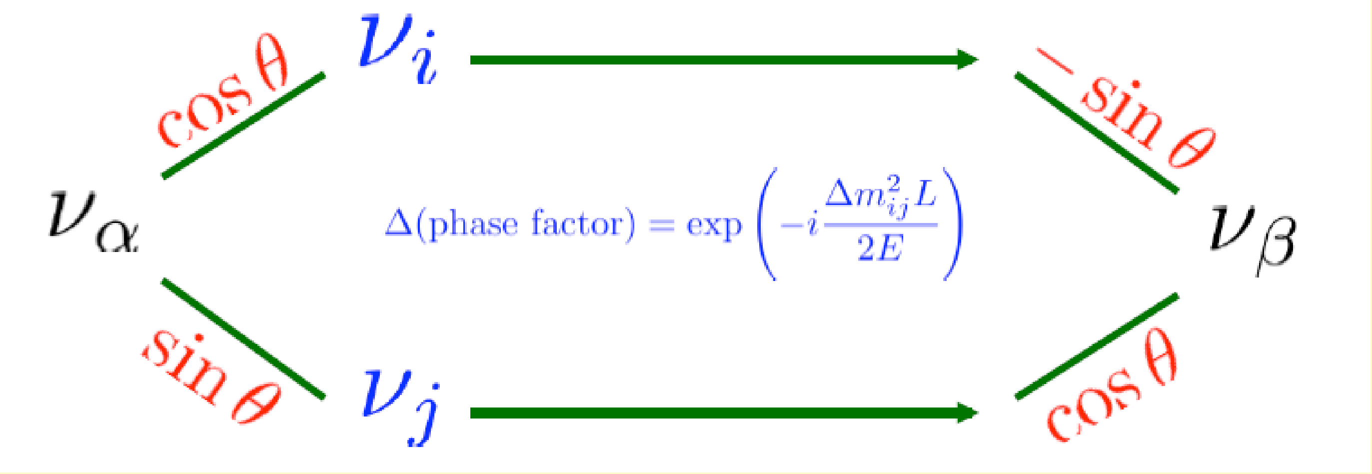
$|\nu_e\rangle$, $|\nu_\mu\rangle$, $|\nu_\tau\rangle$ =Weak Interactions (WI) eigenstates

$|\nu_1\rangle$, $|\nu_2\rangle$, $|\nu_3\rangle$ =Mass (Hamiltonian) eigenstates

Neutrinos propagate as a superposition of **mass** eigenstates

ν mass ≠ ν weak

Analogy with a two-slit interference experiment in vacuum:



This is the simplest case (only 2 neutrinos involved, no interactions with matter). It shows that, if neutrinos are massive and mixed (like quarks), then flavor is not a good quantum number during propagation. Indeed, it changes ("oscillates") significantly over a distance L (≈Δt) dictated by the uncertainty relation:

$$1 \sim \Delta E \Delta t \simeq \frac{m_i^2 - m_j^2}{2E}\, L$$

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)}
\end{aligned}
$$

where

$$
M^e = \mathbf{U}_L^{e\dagger}\begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}\mathbf{U}_R^e, \quad M^\nu = \mathbf{U}_L^{\nu\dagger}\begin{pmatrix} m_{\nu_e} & 0 & 0 \\ 0 & m_{\nu_\mu} & 0 \\ 0 & 0 & m_{\nu_\tau} \end{pmatrix}\mathbf{U}_R^\nu, \quad M^u = \mathbf{U}_L^{u\dagger}\begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}\mathbf{U}_R^u, \quad M^d = \mathbf{U}_L^{d\dagger}\begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}\mathbf{U}_R^d
$$

$$
e'_L = \mathbf{U}_L^e e_L, \quad e'_R = \mathbf{U}_R^e e_R, \quad \nu'_L = \mathbf{U}_L^\nu \nu_L, \quad \nu'_R = \mathbf{U}_R^\nu \nu_R, \quad u'_L = \mathbf{U}_L^u u_L, \quad u'_R = \mathbf{U}_R^u u_R, \quad d'_L = \mathbf{U}_L^d d_L, \quad d'_R = \mathbf{U}_R^d d_R,
$$

$$
e_L = \mathbf{U}_L^{e\dagger} e'_L, \quad e_R = \mathbf{U}_R^{e\dagger} e'_R, \quad \nu_L = \mathbf{U}_L^{\nu\dagger} \nu'_L, \quad \nu_R = \mathbf{U}_R^{\nu\dagger} \nu'_R, \quad u_L = \mathbf{U}_L^{u\dagger} u'_L, \quad u_R = \mathbf{U}_R^{u\dagger} u'_R, \quad d_L = \mathbf{U}_L^{d\dagger} d'_L, \quad d_R = \mathbf{U}_R^{d\dagger} d'_R
$$

A question for you

Why, if neutrinos and quarks are so similar, we do not study "quark oscillations"?

Exercise 2. Prove that a neutrino created with flavor α can develop a different flavor β with a periodical oscillation probability in **L/E**:

$$P(\nu_\alpha \to \nu_\beta) = 4\sin^2\theta\cos^2\theta\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

(B. Pontecorvo)

Amplitude (vanishes for θ=0 or π/2)

Phase difference (vanishes for degenerate masses)

Note : This is the flavor "appearance" probability.
The flavor "disappearance" probability is the complement to 1.

Exercise 3. The oscillation effect depends on the **difference** of (squared) masses, not on the **absolute masses**. Why?

Exercise 4 . Show that:

$$\frac{\Delta m^2 L}{4E} = 1.267\left(\frac{\Delta m^2}{\mathrm{eV}^2}\right)\left(\frac{L}{\mathrm{km}}\right)\left(\frac{\mathrm{GeV}}{E}\right)$$

Neutrino mixing

Weak eigenstates ν_e, ν_μ, ν_τ are not **mass eigenstates**
→ The weak state does not have a definite mass, otherwise there would be no oscillation
They are linear superpositions of mass eigenstates ν_1, ν_2, ν_3 with masses m_1, m_2, m_3

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

$\alpha = e, \mu, \tau$ (flavour index)
$i = 1, 2, 3$ (mass index)

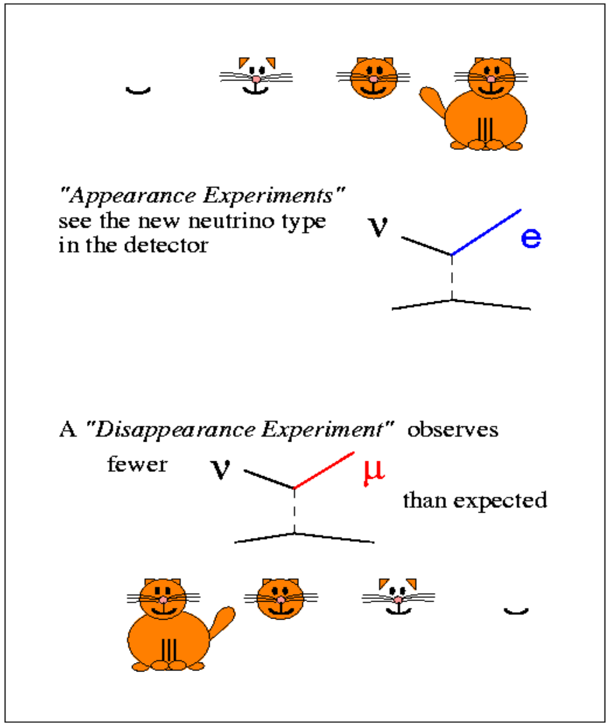
***$U_{\alpha i}$* : unitary mixing matrix** (CKM-like)

$$|\nu_i\rangle = \sum_\alpha V_{i\alpha}|\nu_\alpha\rangle$$

$$V_{i\alpha} = (U_{\alpha i})^*$$

Even if the idea was old (Pontecorvo, 1957; Maki, Nakagawa, Sakata, 1962), the prediction came from proposal of neutrino oscillation to explain the experimental deficits

Neutrino oscillations: observation modes



Appearance Mode

Neutrino source: ν_α

Detect ν_β $(\beta \neq \alpha)$ at distance *L* from source

Appearance probability $P_{\alpha\beta}$

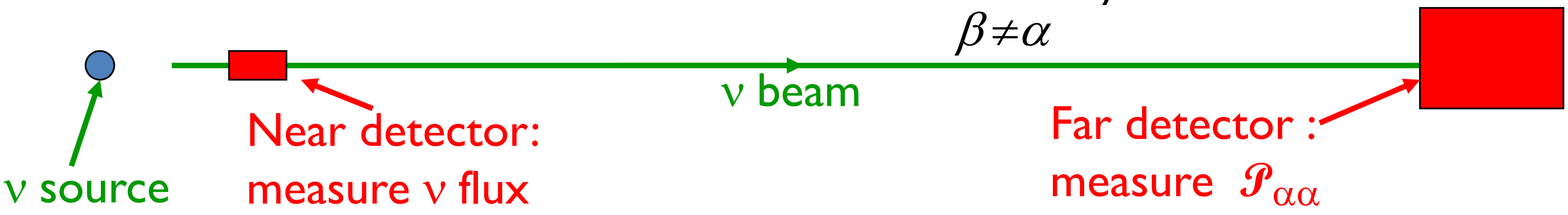
Disappearance Mode

Neutrino source: ν_α

Measure ν_α flux at distance *L* from source

Disappearance probability

$$\mathcal{P}_{\alpha\alpha} = 1 - \sum_{\beta \neq \alpha} \mathcal{P}_{\alpha\beta}$$



Three neutrino mixing

The problem of "missing neutrinos" can be resolved if neutrinos have mass:
→ The interference pattern varies along the travelling path with different ratio of the flavors at any particular point.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \times diag(e^{i\alpha 1/2}, e^{i\alpha 2/2}, 1)$$

Atmospheric Reactor Solar (Majorana phase)

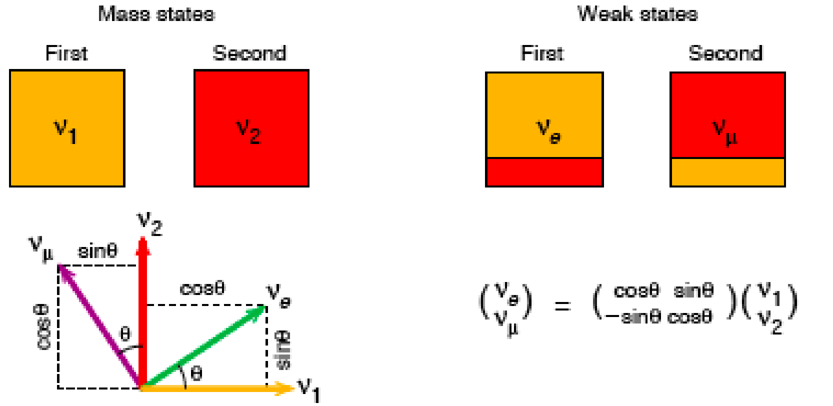
The complex three neutrino mixture can be resolved in two sectors:
atmospheric and solar neutrino oscillations are nearly decoupled
(θ_{13} is small and two of the mass states are very close compared to the third

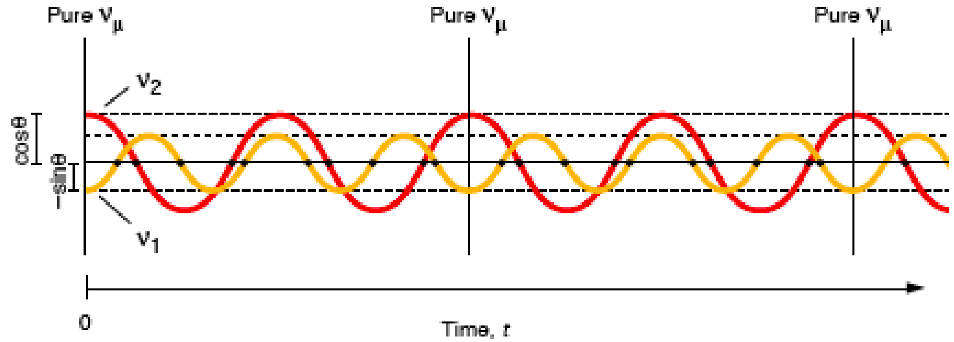
Phenomenon described by:

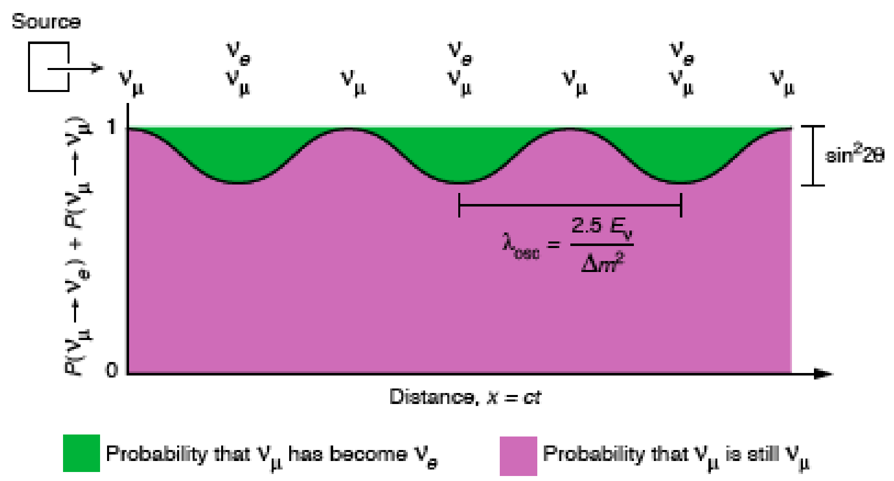
3 angles + 1 CP phase + 2 (signed) Δm^2 (+ 2 Majorana phases)

Two flavor approximation:

$P(\nu_l \rightarrow \nu_{l'}) = f(\theta, \Delta m^2, L/E_\nu)$







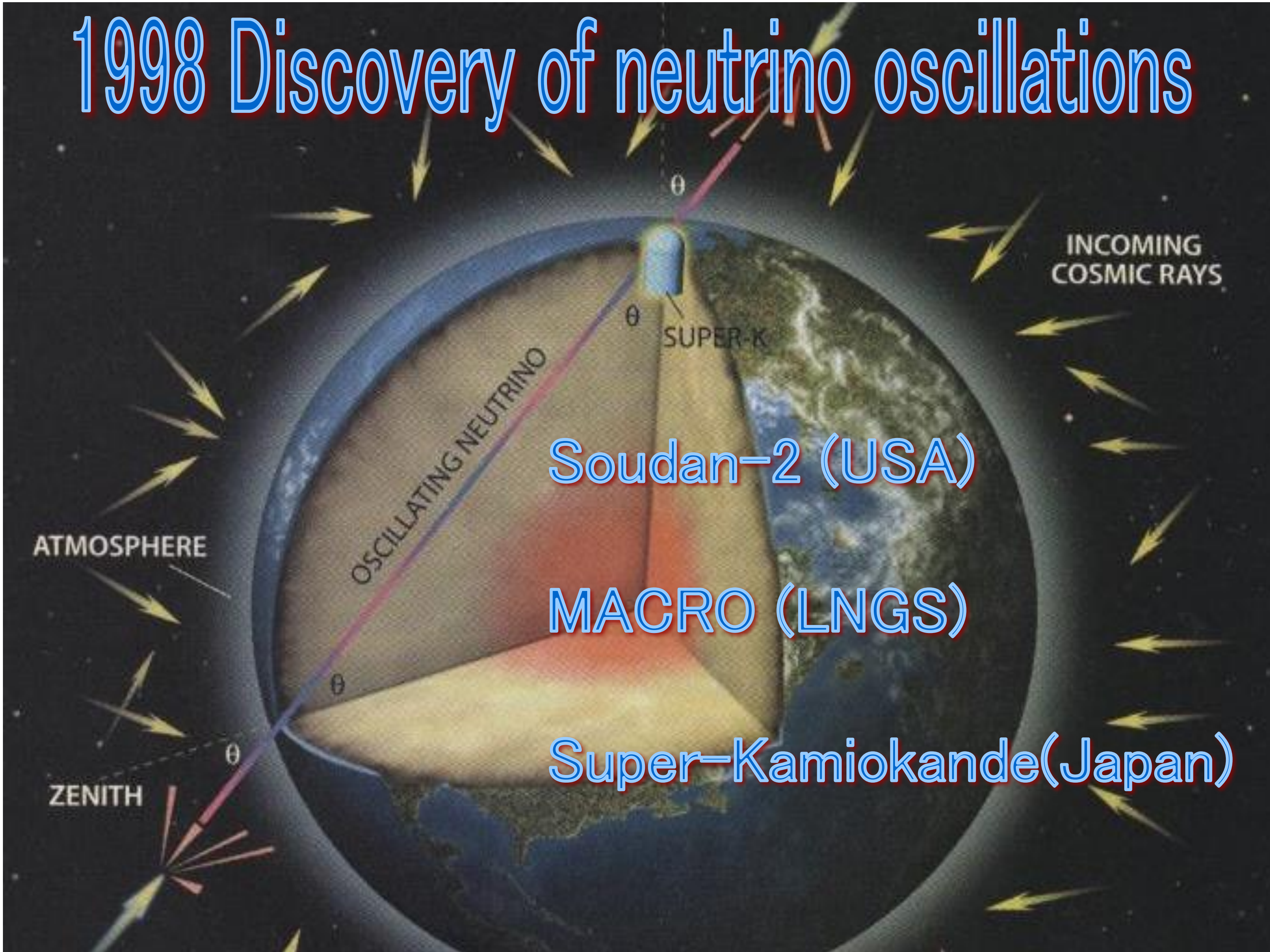
Historical note:

Once the prejudice on massless neutrinos was undermined, another theoretical prejudice (due to analogy with quark mixing):

→small mixing angles!

(Experiments looking to large Δm^2-small θ, instead of small δm^2-large θ)

1998 Discovery of neutrino oscillations



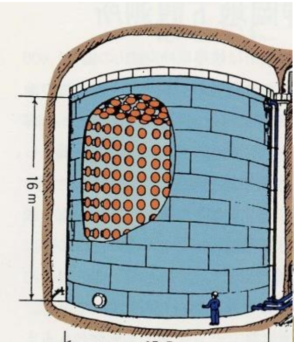
Soudan-2 (USA)

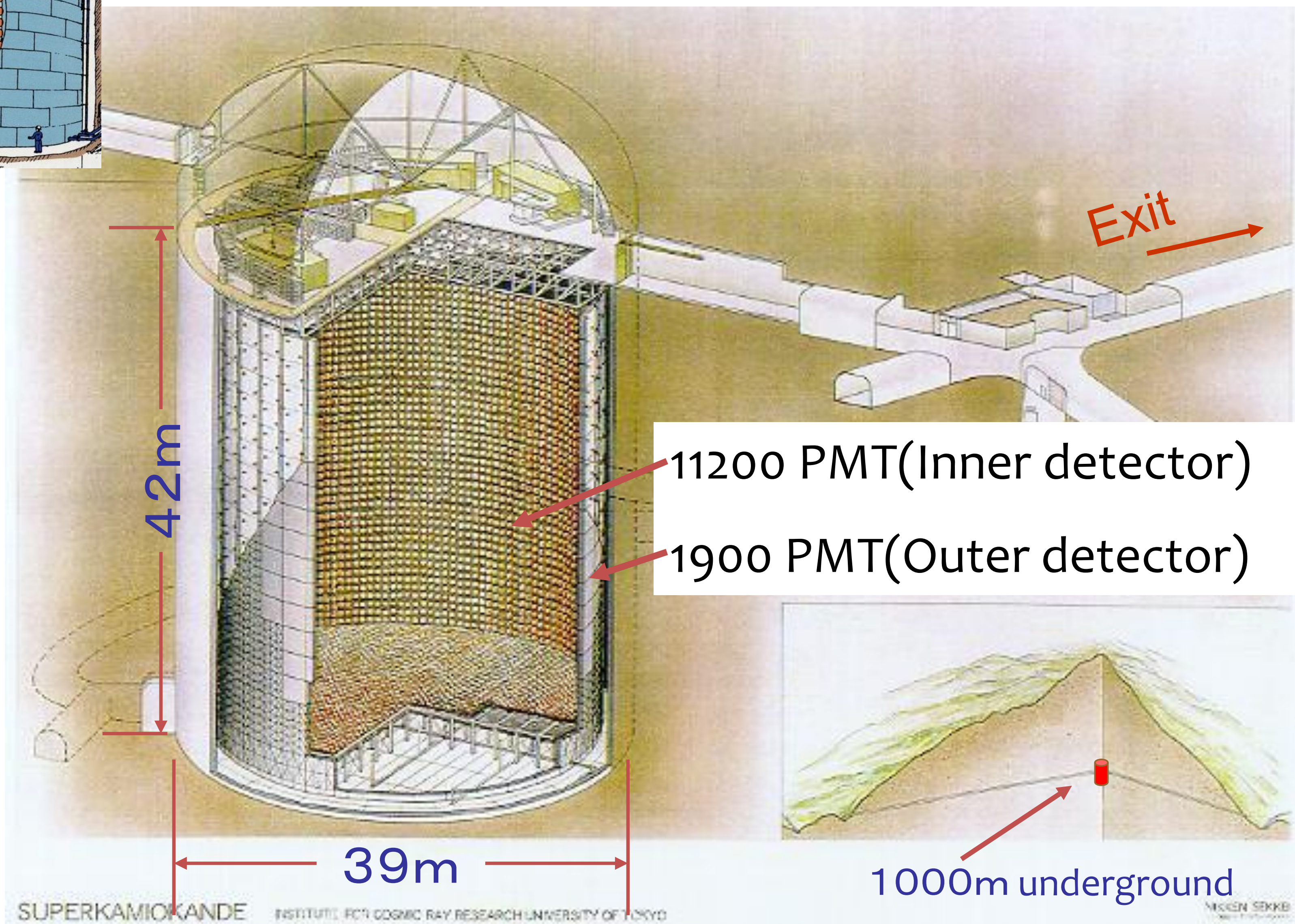
MACRO (LNGS)

Super-Kamiokande(Japan)

Super-Kamiokade detector

50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)

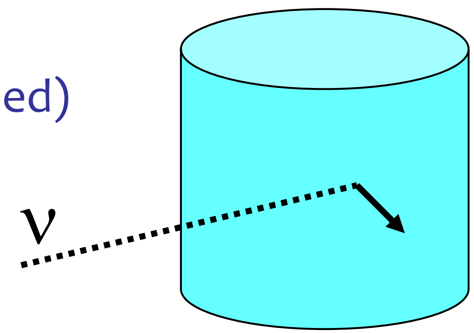


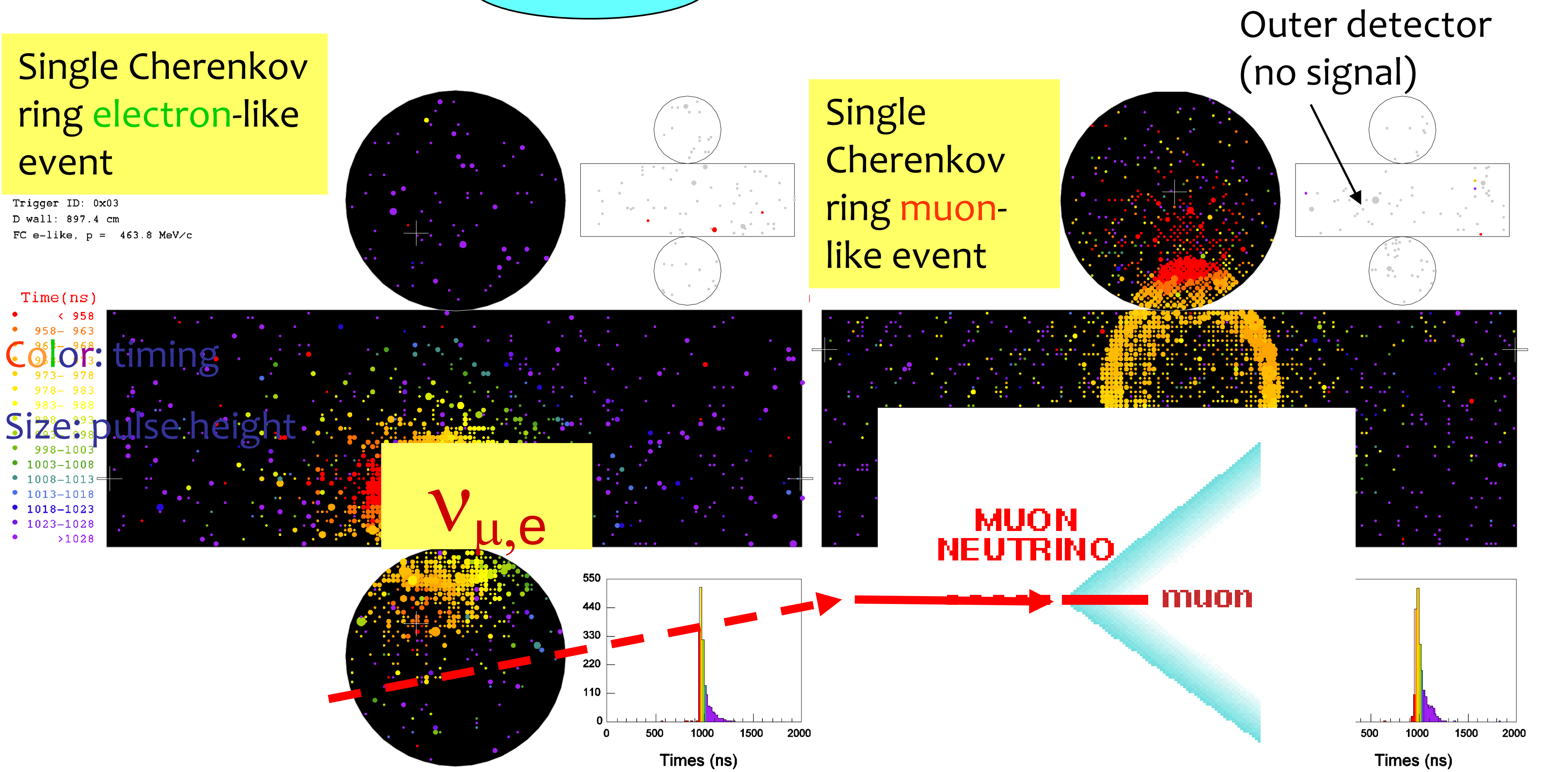


Atmospheric neutrino events in SK

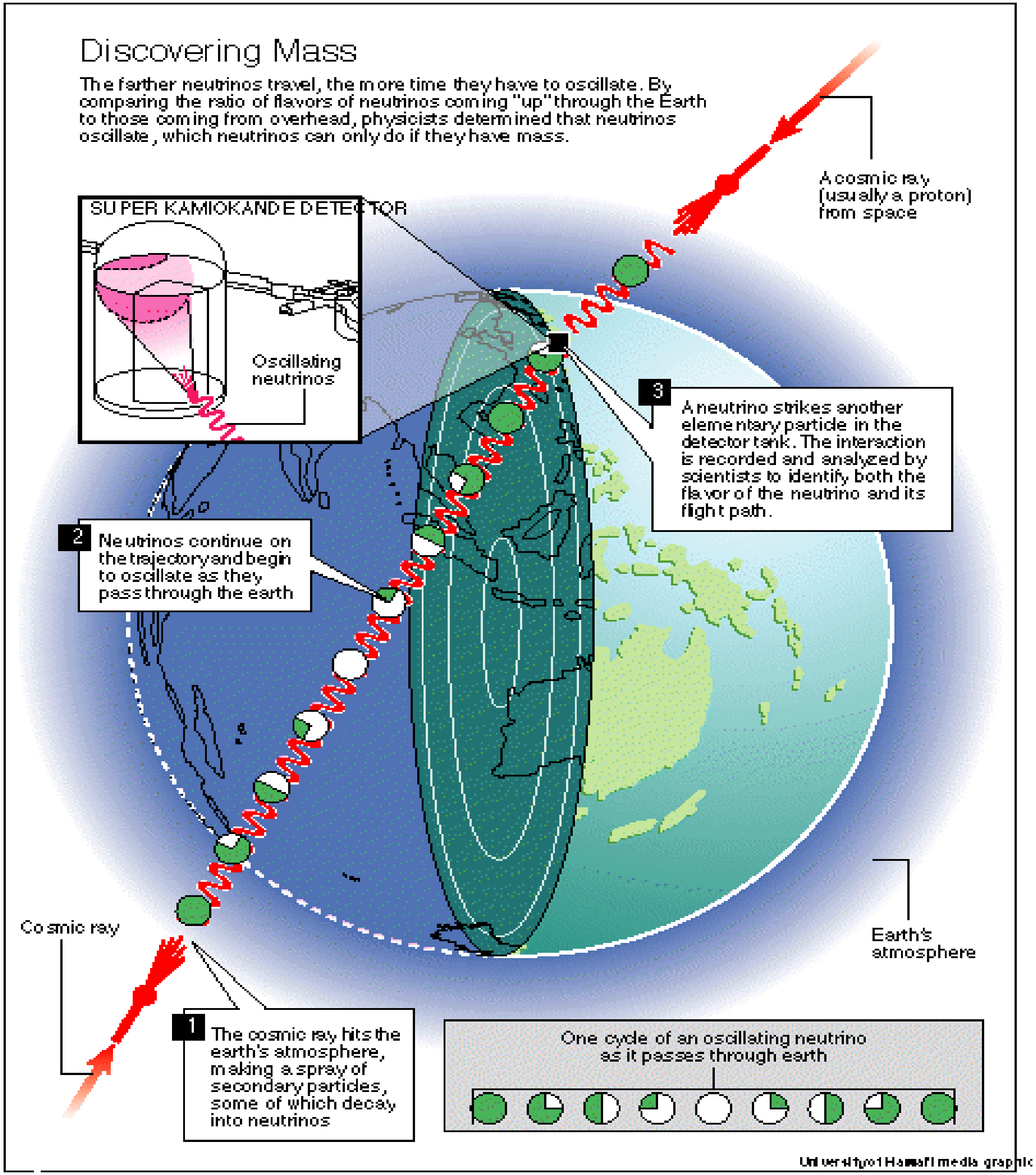
- Both CC ν_e and ν_μ (+NC)
- Need particle identification to separate ν_e and ν_μ

FC (fully contained)





Zenith angle dependence is the smoking gun: different path L → different oscillation phase



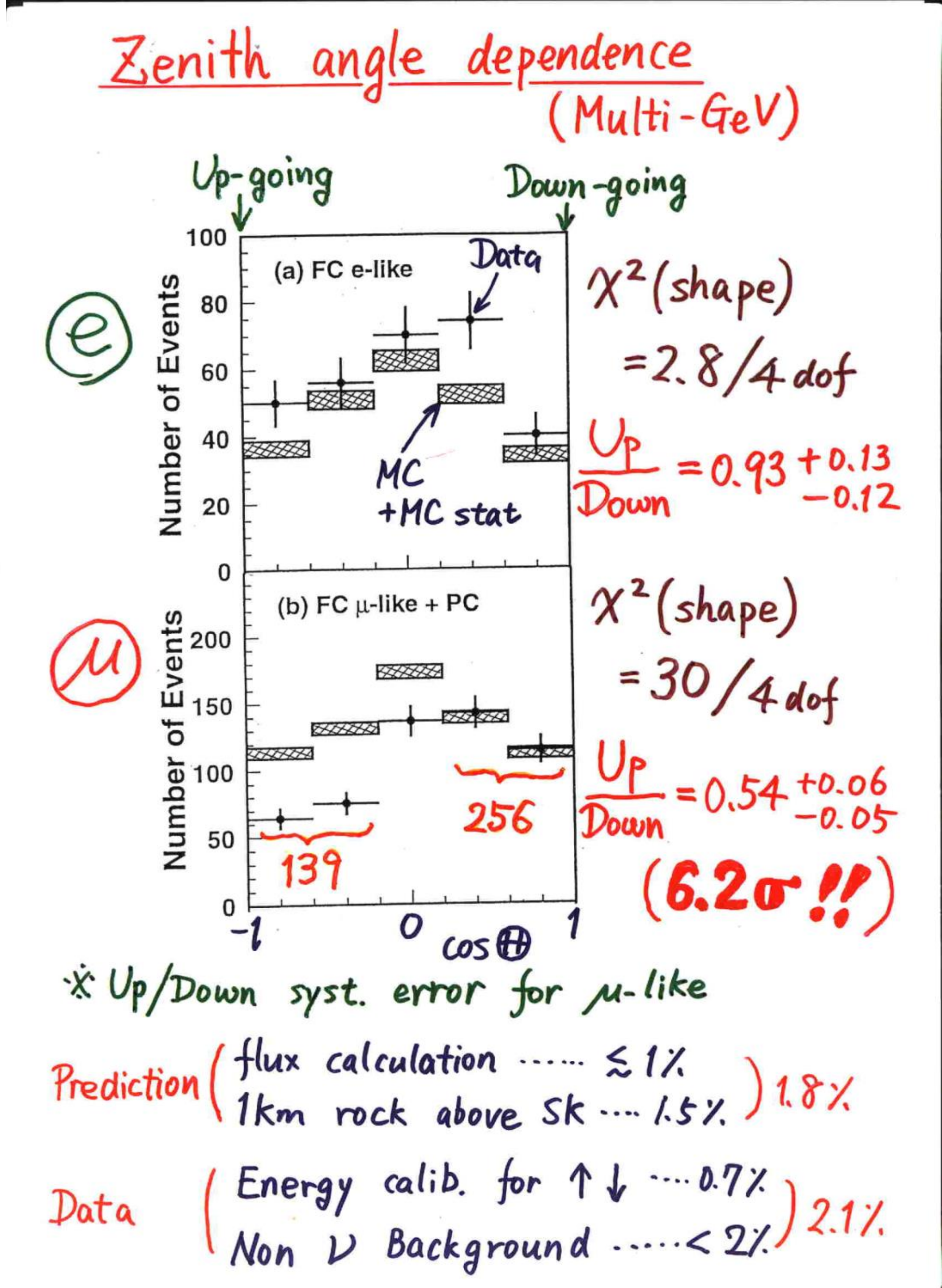
Super-K @Neutrino98

Fully-Contained, 1-ring events

with $E_{visible}$ > 1.33GeV

+ Partially-Contained events

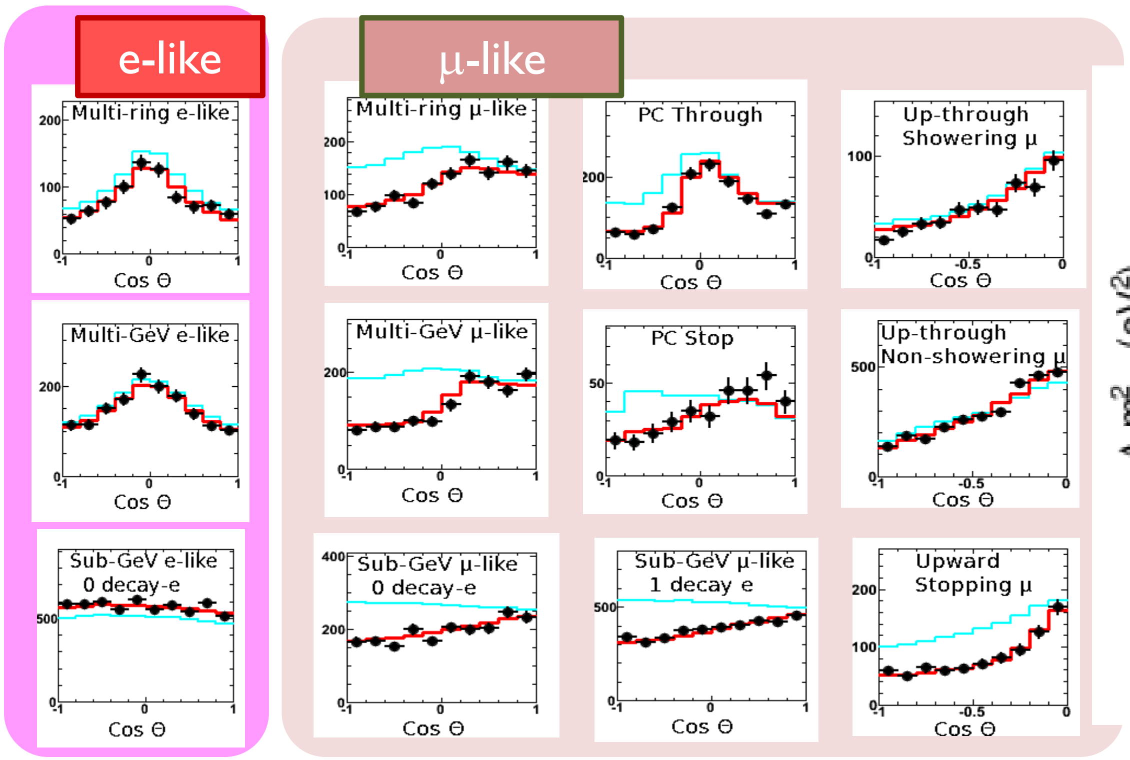
SK concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.



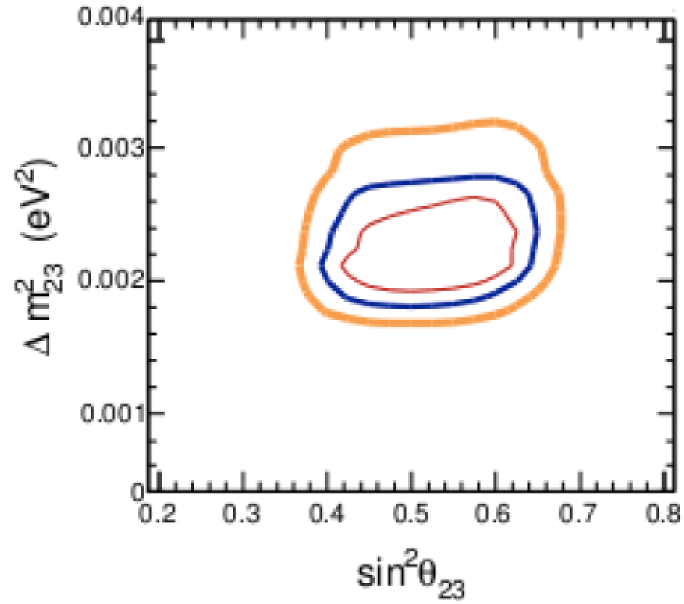
Super-K atmospheric neutrino data now

Super-K-I+II+III (2806 days (173kton・yr) for FC+PC, 3109 days for up-μ)

energy



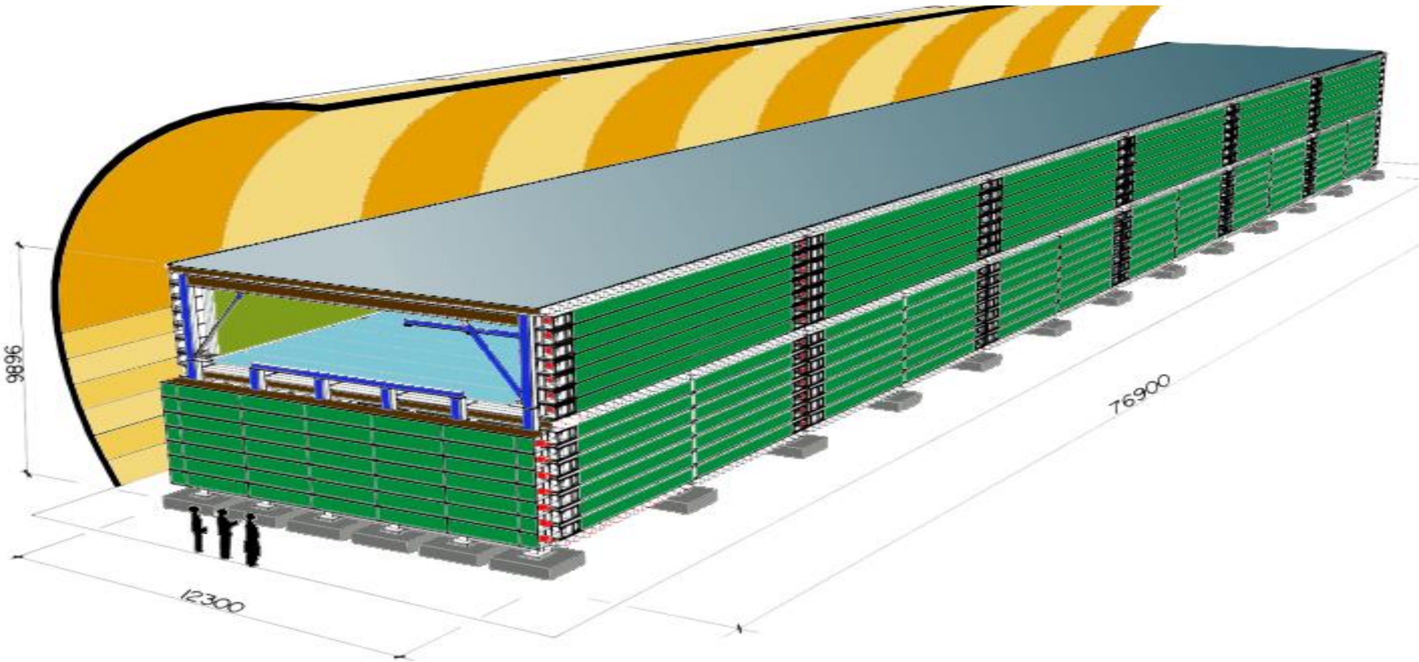
+ DATA
— MC (no osc.)
— MC (best-fit)



Best Fit:
$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$
$\sin^2 2\theta = 1.00$

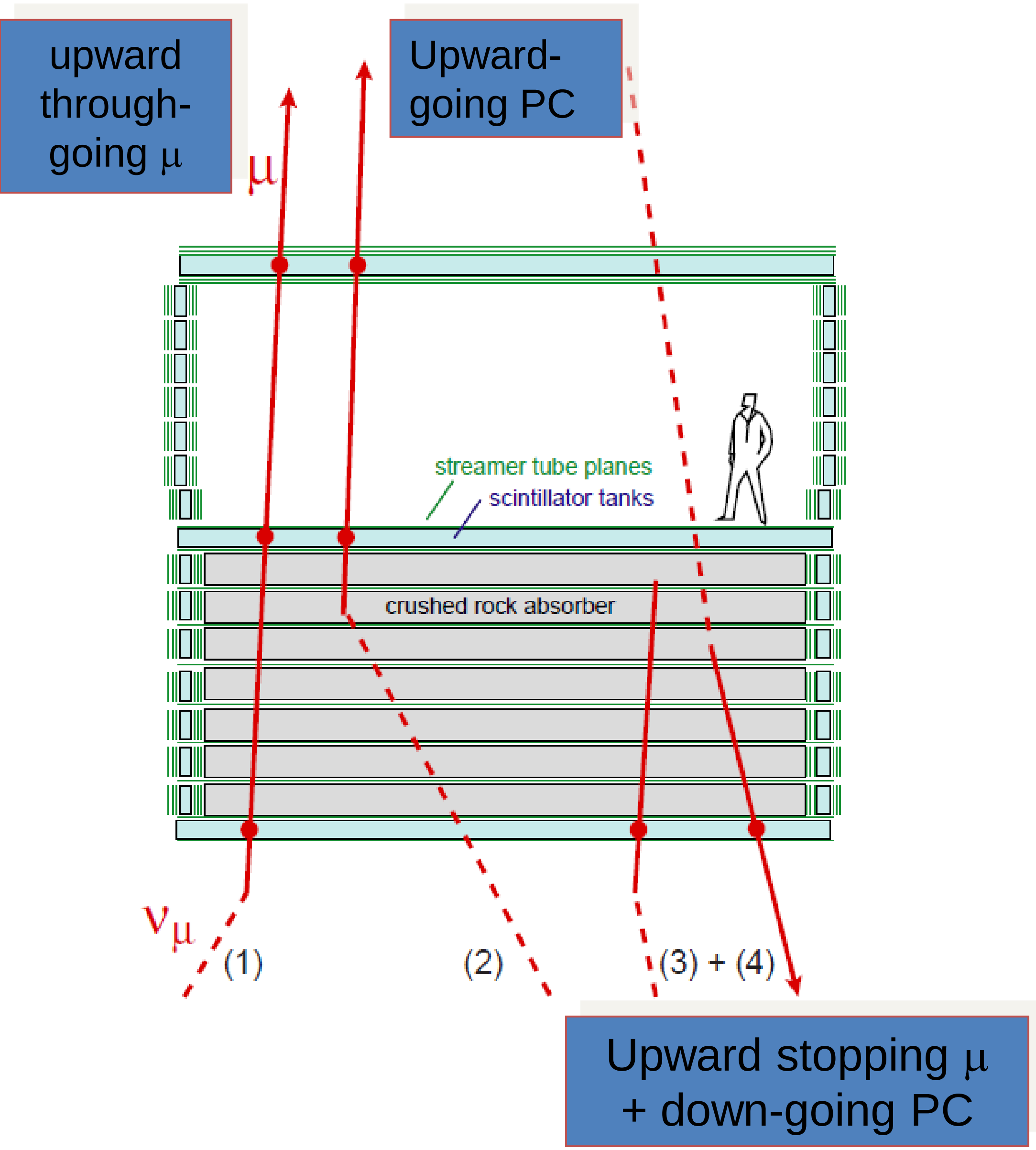
MACRO

At the Gran Sasso underground Lab, under 3600 m.w.e.

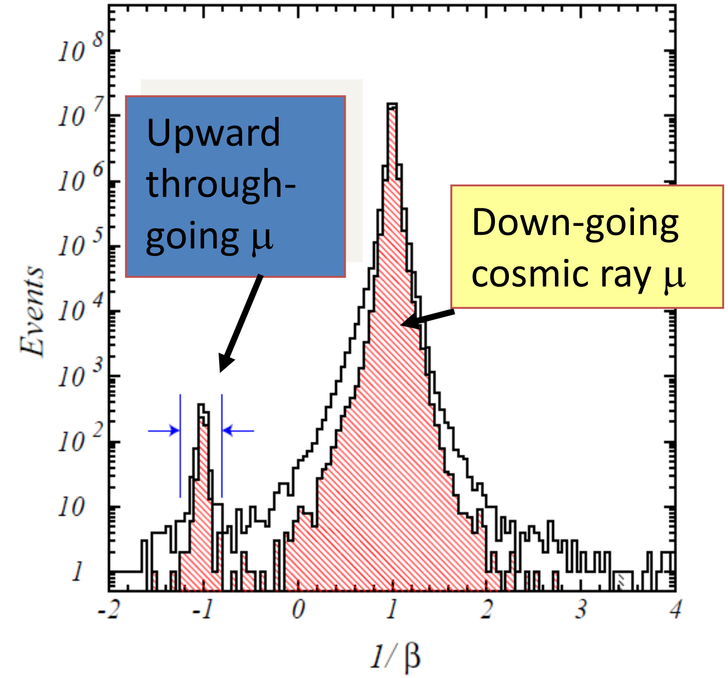


- Large acceptance (~10000 m^2sr for an isotropic flux)
- Low downgoing μ rate (~10^{-6} of the surface rate)
- ~600 tons of liquid scintillator to measure T.O.F. (time resolution ~500psec)
- ~20000 m^2 of streamer tubes (3cm cells) for tracking (angular resolution < 1°)

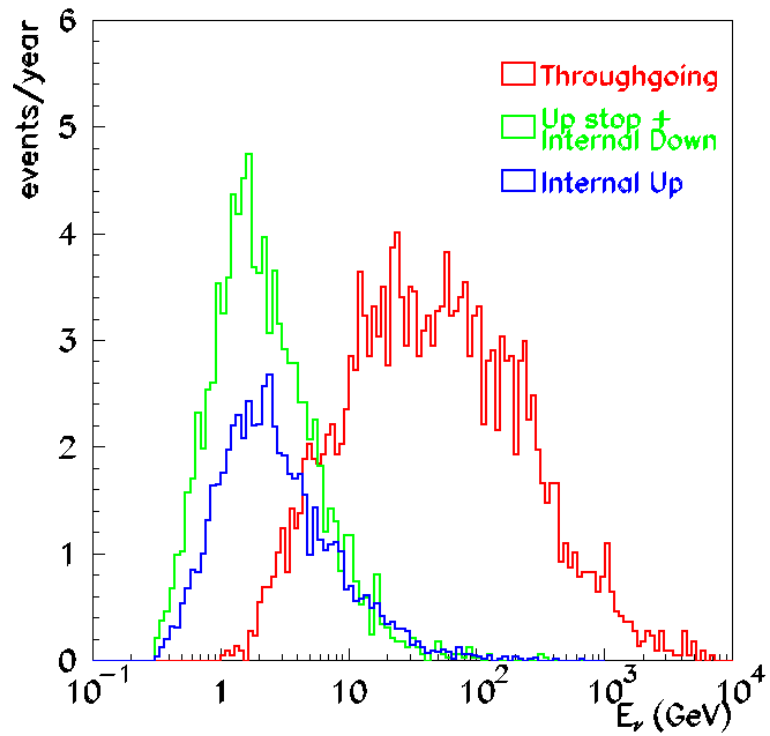
MACRO



upward through-going μ
Upward-going PC
μ
streamer tube planes
scintillator tanks
crushed rock absorber
ν_μ
(1)
(2)
(3) + (4)
Upward stopping μ + down-going PC

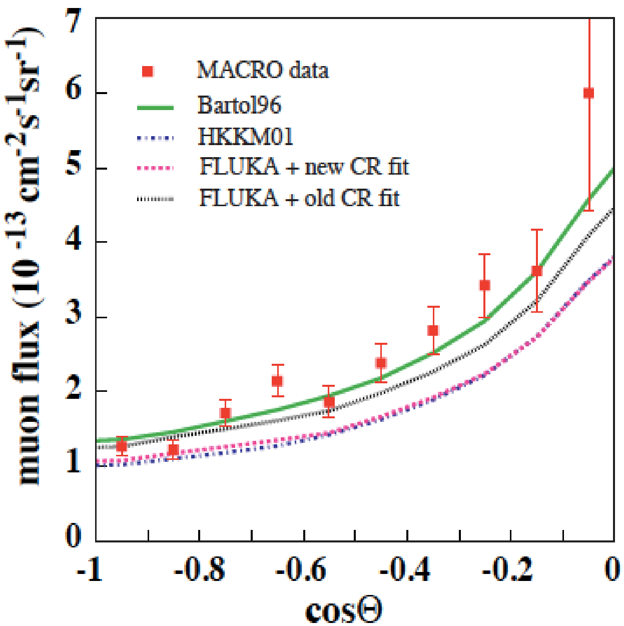


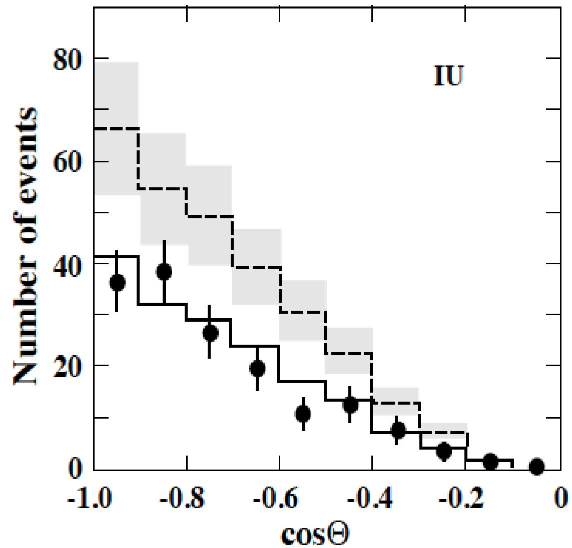
Events
1/β
Upward through-going μ
Down-going cosmic ray μ

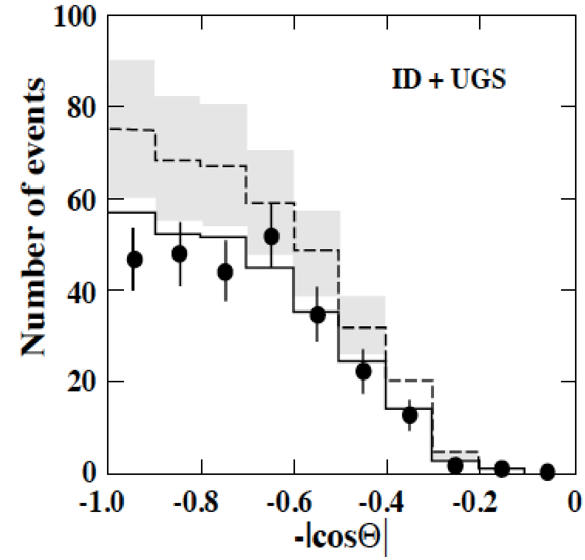


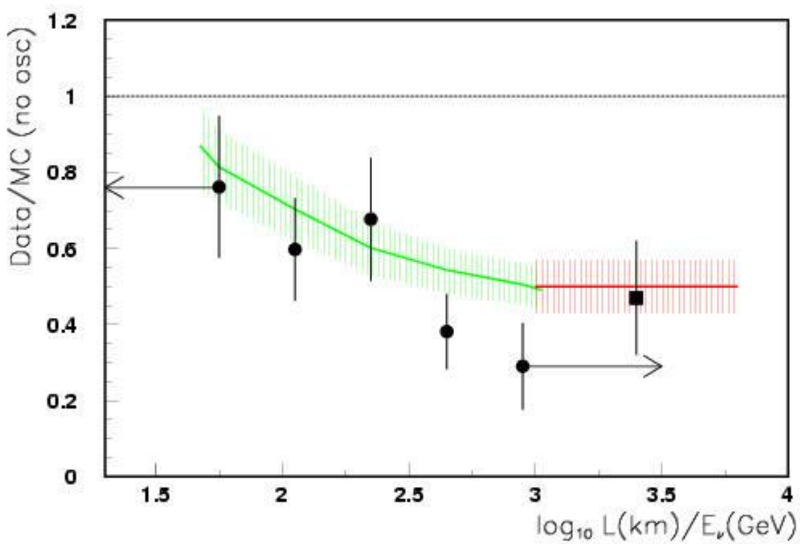
events/year
Throughgoing
Up stop + Internal Down
Internal Up
E_ν (GeV)

MACRO: Zenith Angle Distributions









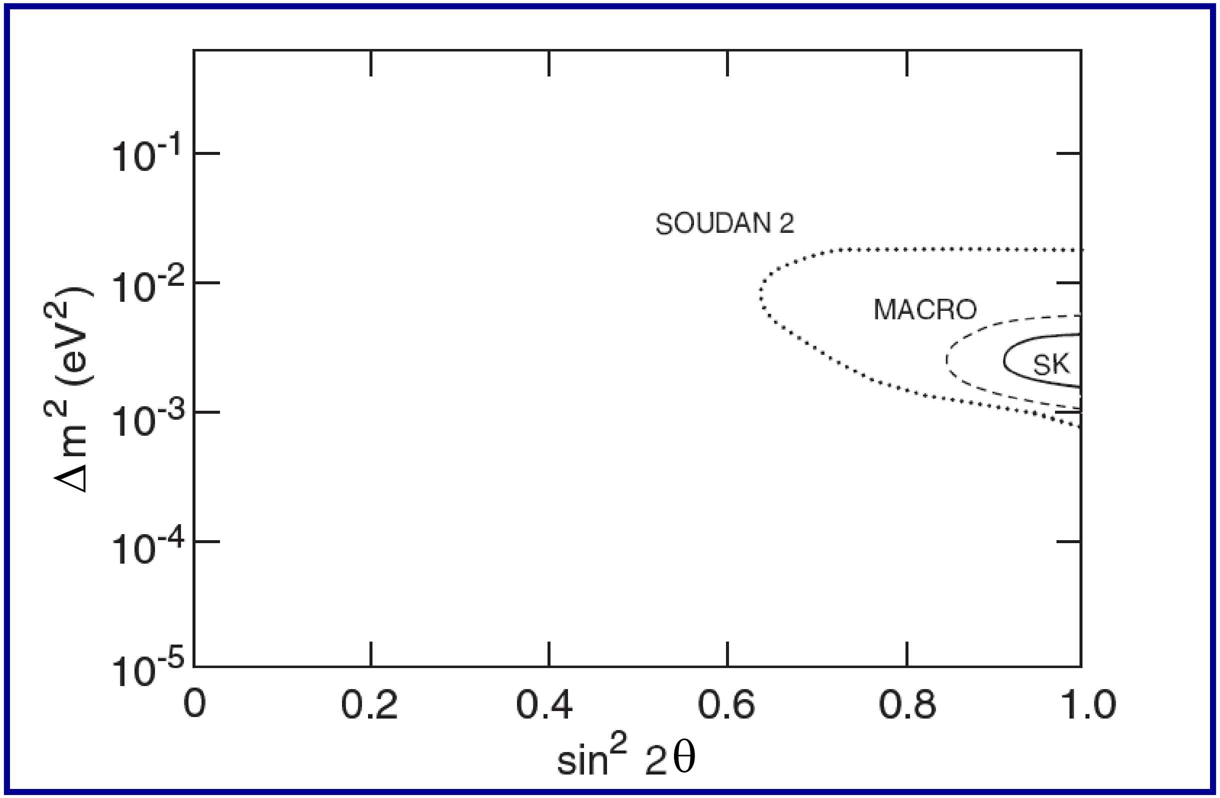
MACRO : L/E$_\nu$ distribution

$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu}\right]$$

1.9 x 10^{-3} eV^2 < Δm^2 < 3.1 x 10^{-3} eV^2

sin^2 2θ > 0.93 (90% CL)

The 1998 revolution



$\nu_\mu \to \nu_\tau$ best fit parameters

SOUDAN2 $\Delta m^2 = 5.2\ 10^{-3}\ eV^2$; $\sin^2 2\theta = 1$

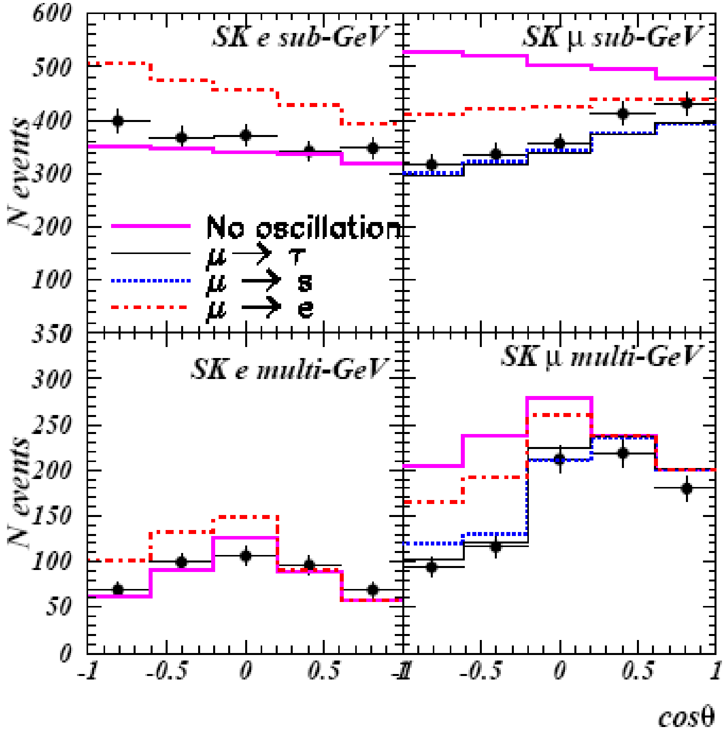
MACRO $\Delta m^2 = 2.3\ 10^{-3}\ eV^2$; $\sin^2 2\theta = 1$

SuperK $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$; $\sin^2 2\theta = 1$

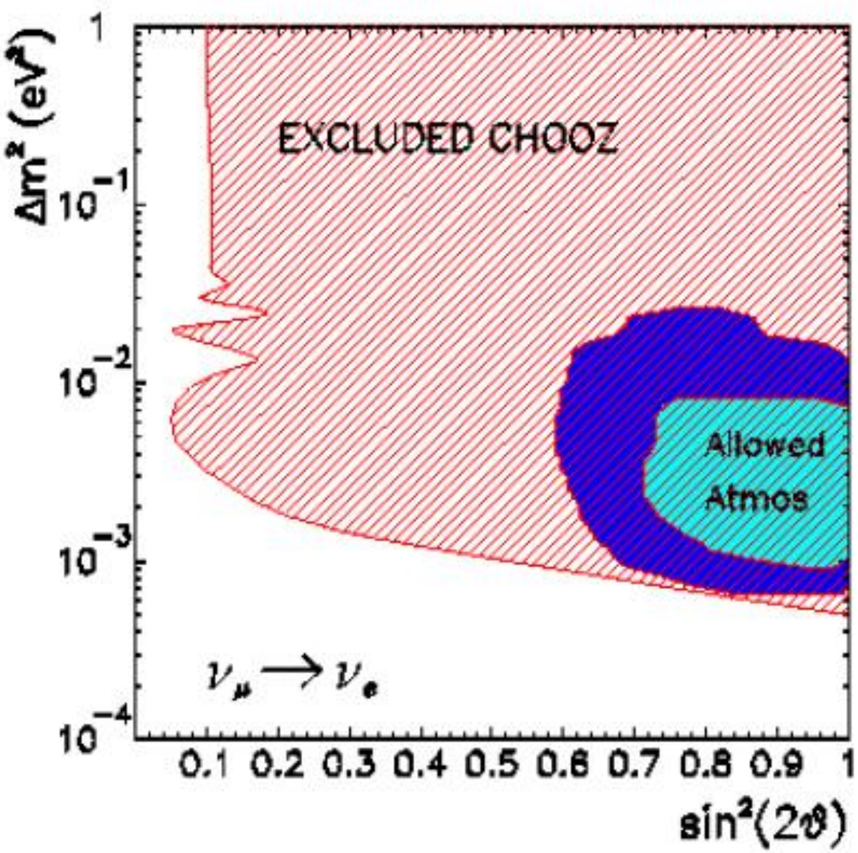
NO OSCILLATION HYPOTHESIS RULED OUT BY ~ 5 σ

Why not $\nu_\mu \rightarrow \nu_e$?

SK



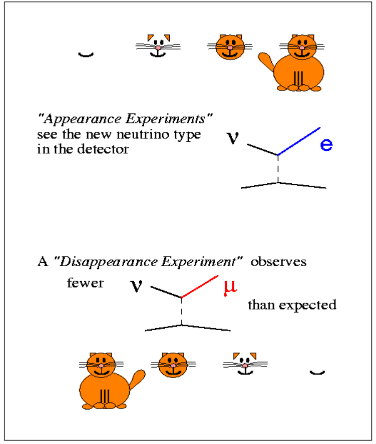
Apollonio et al., CHOOZ Coll., Phys.Lett.B466,415



The CHOOZ experiment excluded this area in the parameter plot

→ $\nu_\mu \rightarrow \nu_e$ oscillations are not responsible of the atmospheric neutrino deficit

Long Baseline Accelerator Experiments



i) confirm atmospheric neutrino oscillation
ii) precision measurements of oscillation parameters

Disappearance experiments

K2K (KEK to Kamioka beam)
Near Detector and Far Detector (SuperK)
Ratio=measured/expected <1 →

Baseline 250 km
$<E_\nu> \sim 1$ GeV
$\Delta m_{23}^2=2.8\ 10^{-3}\ eV^2$

MINOS on NuMI beam from Fnal to Soudan
Near Detector (1kt) , Far Detector (5.5kt)
Ratio=measured/expected < 1 →

Baseline 735 km
$<E_\nu> \sim 3$ GeV (L.E)
$\Delta m_{23}^2=2.41\ 10^{-3}\ eV^2$
ν_μ disappearance → $\theta_{23,}\ \Delta m_{23}^2$

Appearance experiments

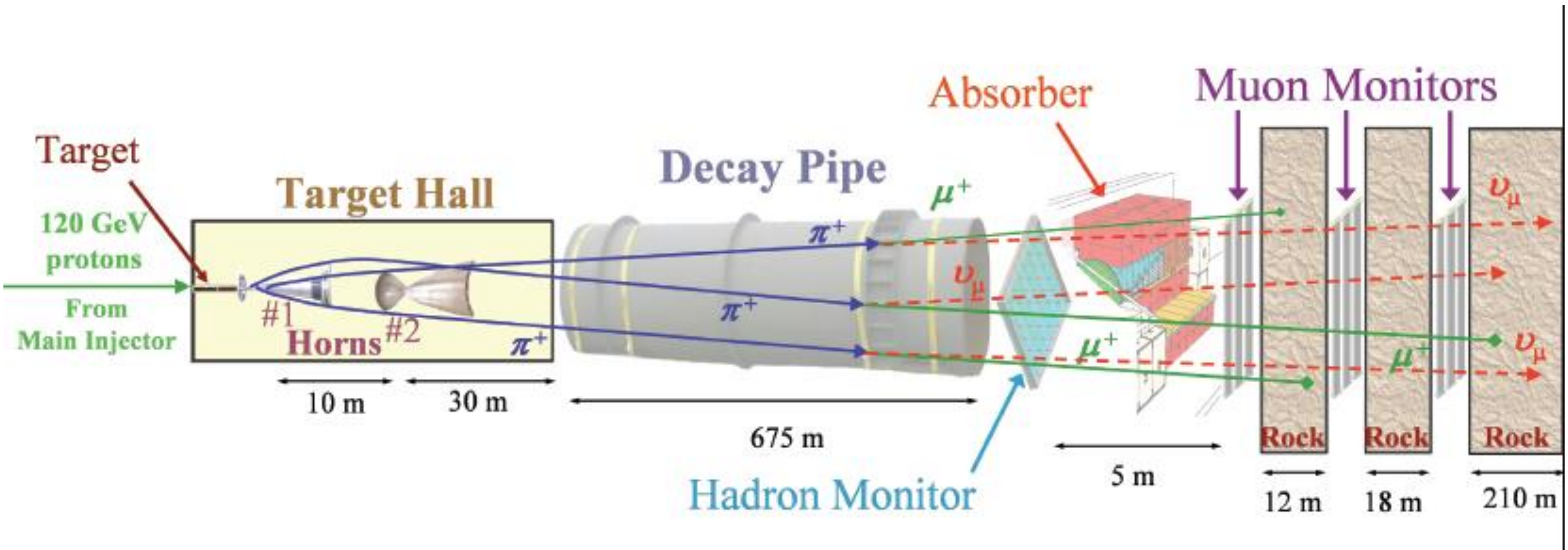
CNGS beam from CERN to Gran Sasso
Opera, Icarus-T600 at LNGS

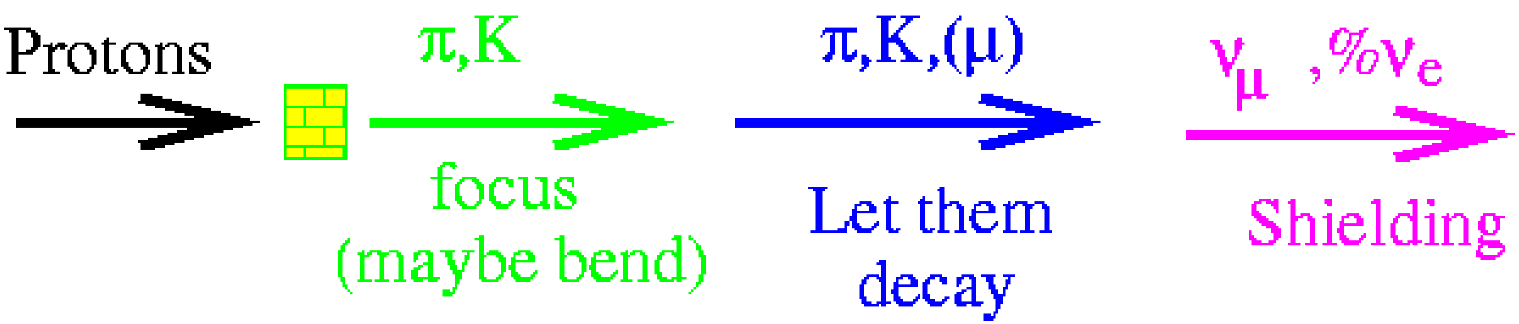
Baseline 732 km
$<E_\nu> \sim 17$ GeV
Appearance of ν_τ in ν_μ beam

T2K (Tokai To Kamioka)

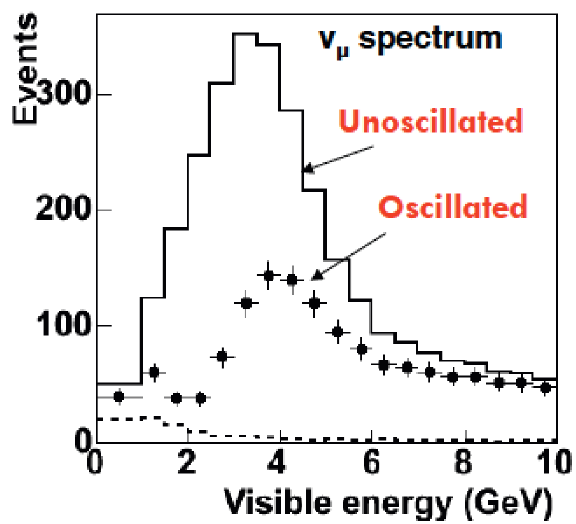
Baseline 295 km
$<E_\nu> \sim 0.6$ GeV
"Off axis" Super-beam , O(MW)
ν_e appearance → Determine θ13

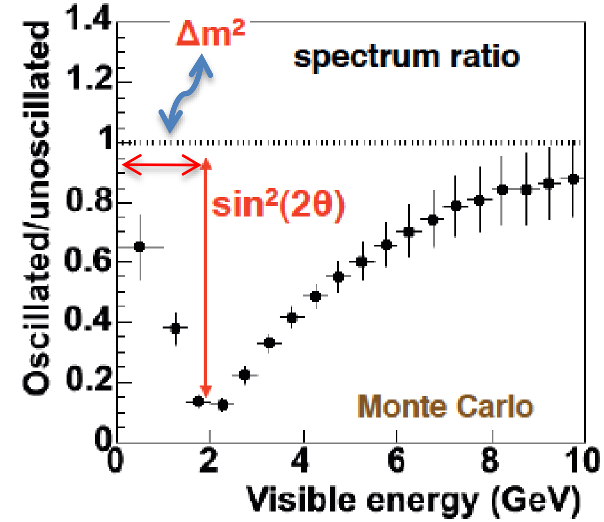
How to make a conventional neutrino beam





K2K/Minos: confirm atmospheric oscillations with a ν_μ beam

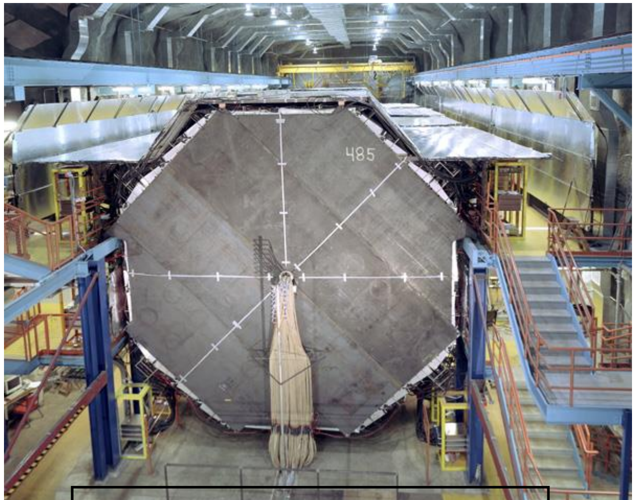




E_{K2K} ~1GeV=> L~250 km

E_{Numi} ~3GeV => L~750 km

Near → Far detector concept



Far detector 5400 t

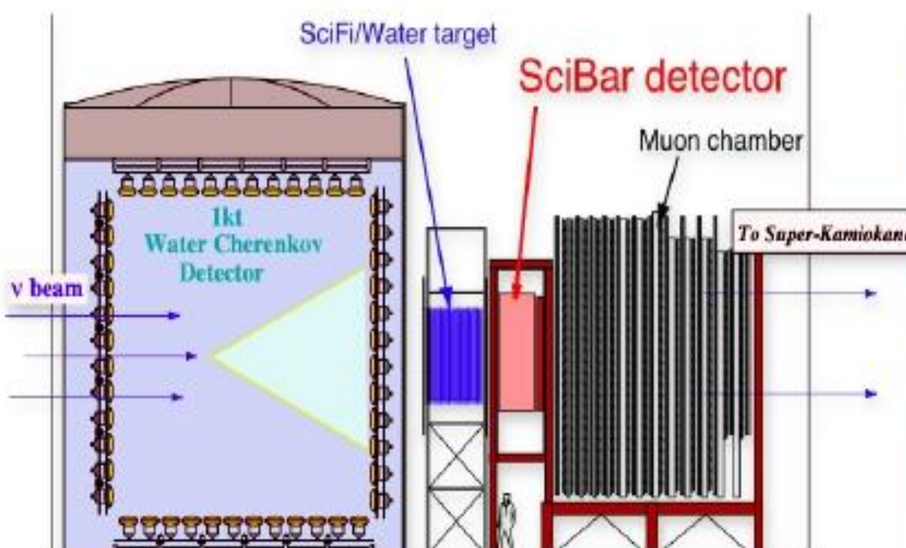
Near detector 920t

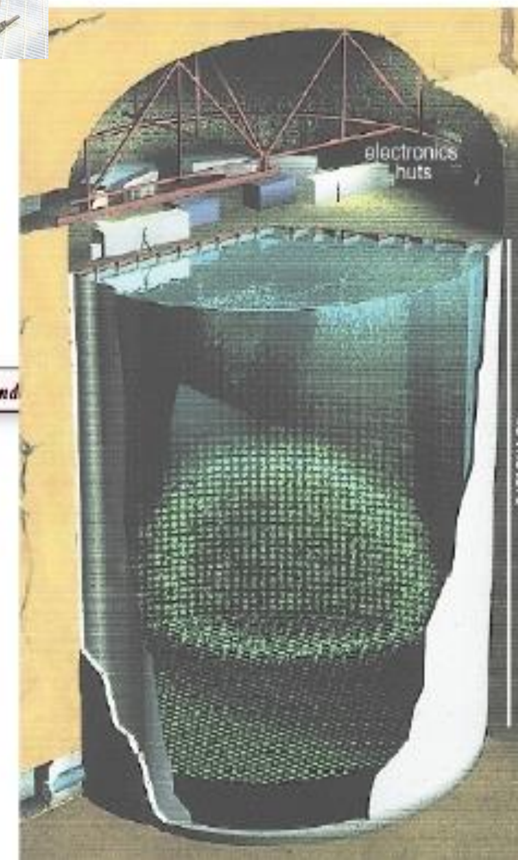
MINOS

Identical magnetized-iron - scintillator calorimeters

K2K

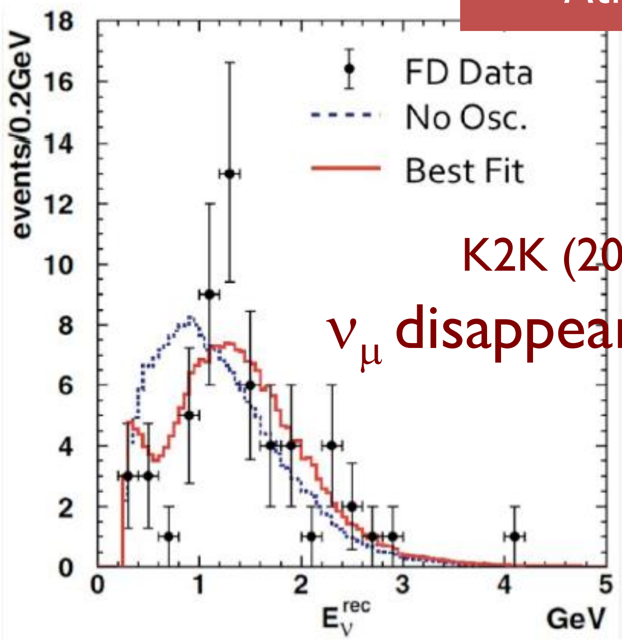
Two different technologies: Water & Iron





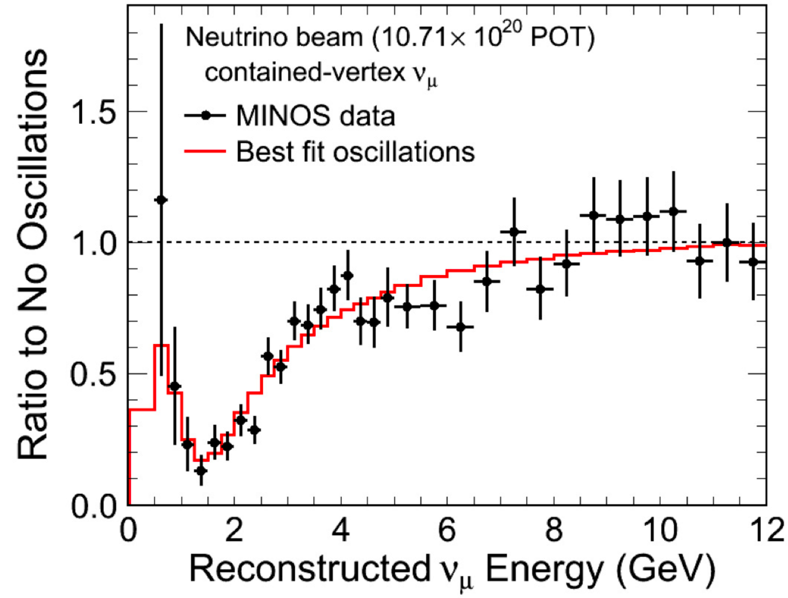
Atmospheric Oscillations confirmed

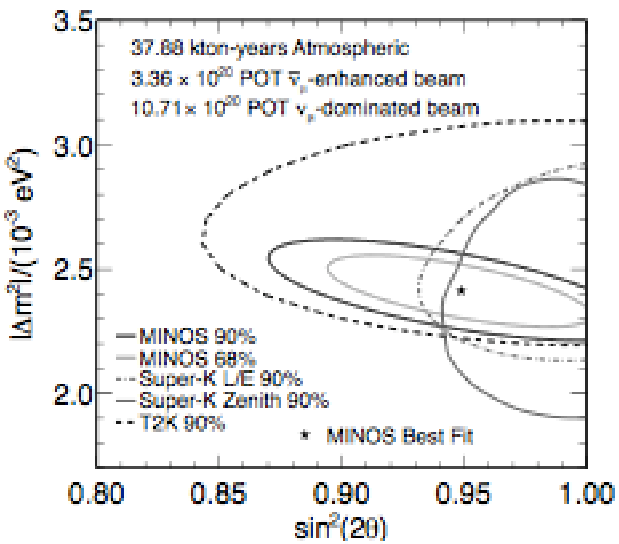
MINOS (2013)



K2K (2006)

ν_μ disappearance





MINOS final result (2013, arXiv:hep-ex/1304.6335)

ν_μ disappearance

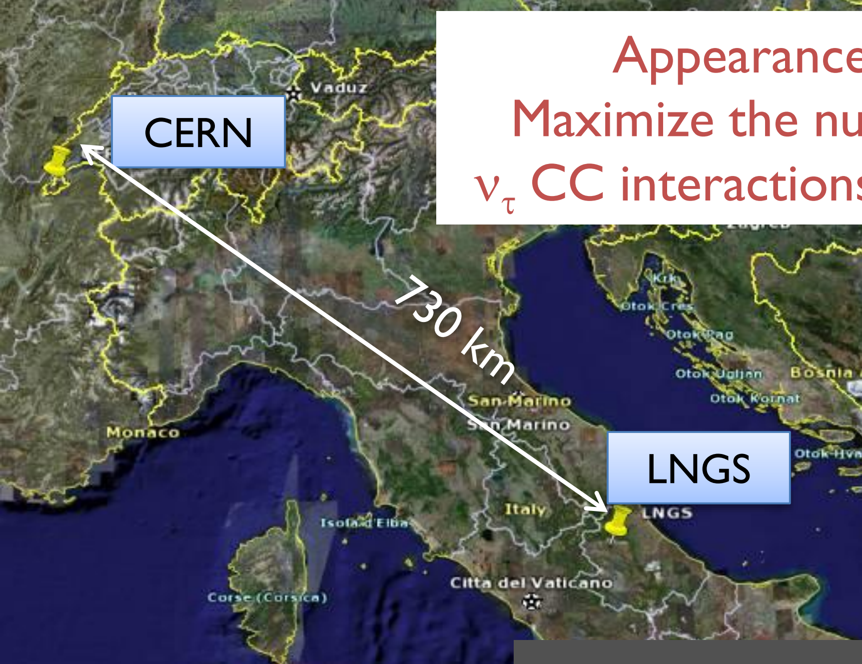
$|\Delta m^2| = 2.41^{+0.009}_{-0.10} \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\theta) = 0.950^{+0.035}_{-0.036}$

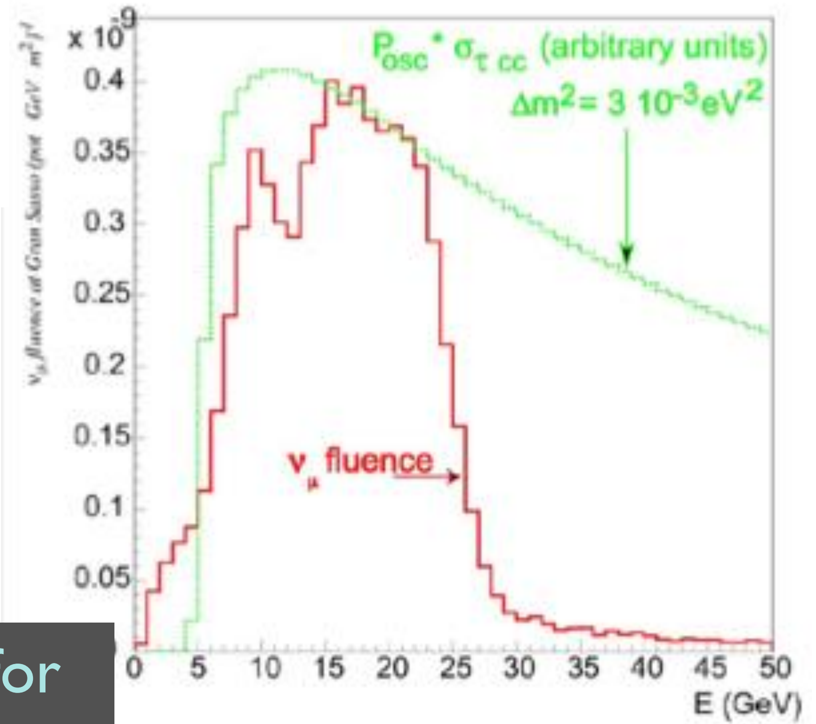
$\sin^2(2\theta) > 0.890$ (90% C.L.)

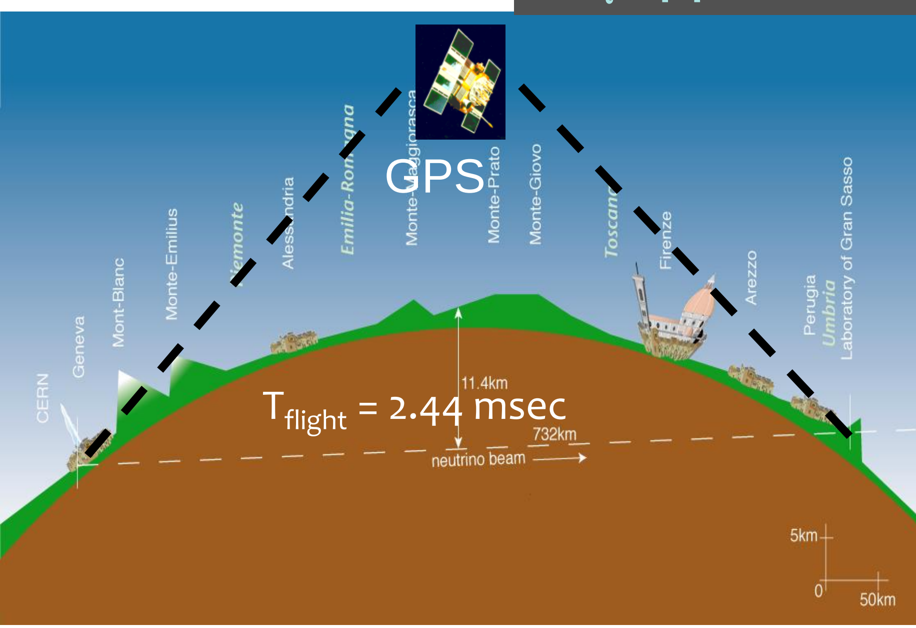
Precise atmospheric oscillation parameter determination!

Appearance →
Maximize the number of
ν_τ CC interactions at LNGS



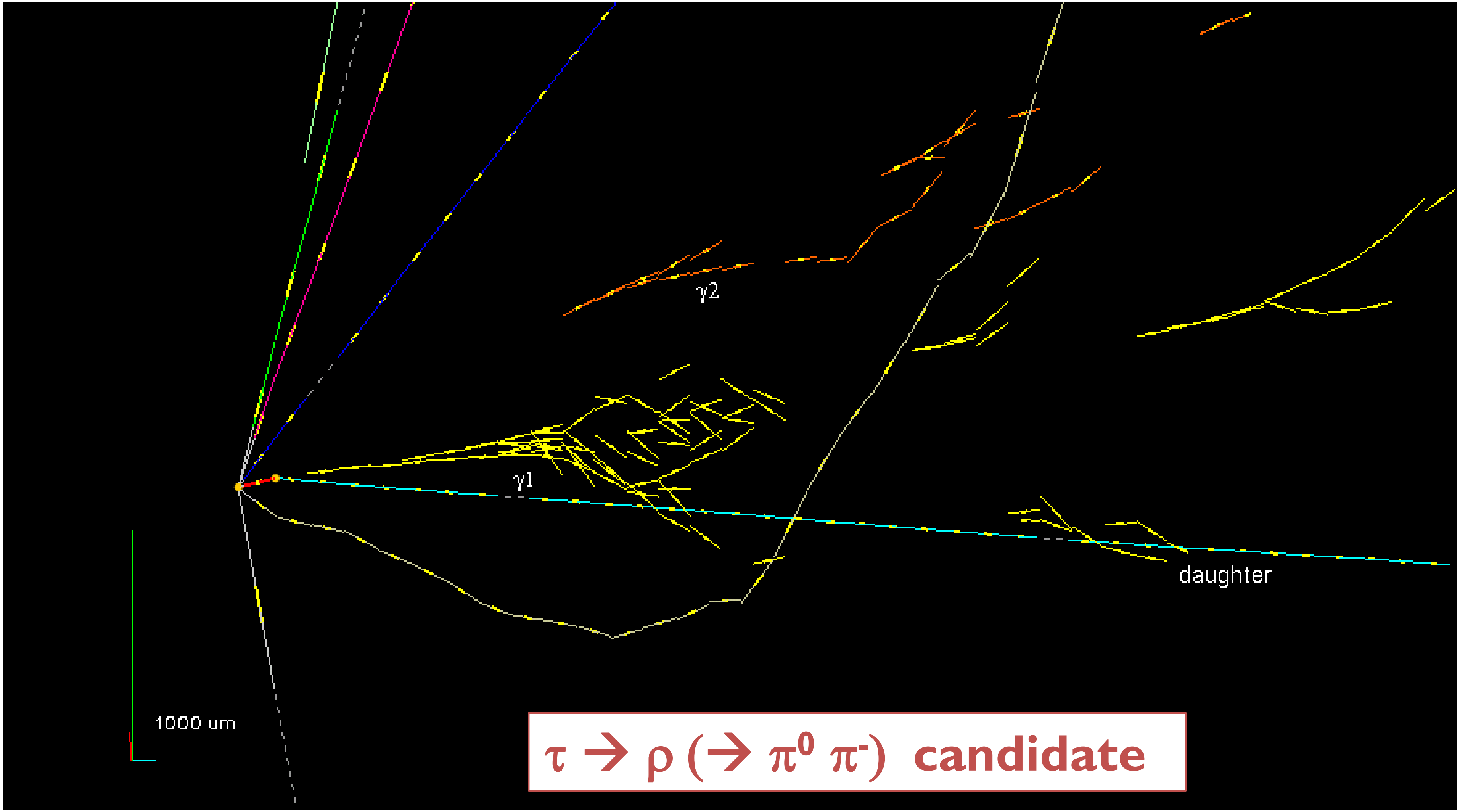
CNGS beam: tuned for ν_τ-appearance at LNGS





$< E_{\nu_\mu} >$	17.7 GeV
L	730 km
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %
$\bar{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	Negligible

First ν_τ candidate



THE KNOWNS AND THE UNKNOWNS

from NuFit 2016

Solar parameters

$$\theta_{12} = 33.6 \pm 0.8^{o}$$

$$\Delta m^2_{21} = +(7.5 \pm 0.2) \times 10^{-5} \mathrm{eV}^2$$

$P(\nu_e \to \nu_{\mu,\tau})$ SNO , SK, BOREXINO, GALLEX, SAGE..

$P(\bar{\nu}_e \to \bar{\nu}_e)$ KamLAND

Atmospheric parameters

$$\theta_{23} = (38 - 50)^{o} (3\sigma)$$ *Octant*

$$|\Delta m^2_{32}| \approx (2.5 \pm 0.4) \times 10^{-3} \mathrm{eV}^2$$

Mass Hierarchy

$P(\nu_\mu \to \nu_\mu)$ Kamiokande, SK, IMB, K2K, MINOS, T2K, NOvA

$P(\nu_\mu \to \nu_\tau)$ (Opera)

$$\theta_{13} = 8.4 \pm 0.2^{o}$$

$P(\bar{\nu}_e \to \bar{\nu}_e)$ Daya-Bay, RENO, Double Chooz

$P(\nu_\mu \to \nu_e)$ T2K, NOvA

$$\delta_{CP} = [0, 2\pi]$$

T2K, NOvA

CP violation

THE KNOWNS AND THE UNKNOWNS

Accelerator- based experiments

- $P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\Delta m^2_{31}\frac{L}{4E}$

- $$\begin{aligned} P(\nu_\mu \to \nu_e) \sim\ & \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & -\alpha\sin\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\alpha\cos\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\mathcal{O}(\alpha^2) \end{aligned}$$

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31}L}{4E} \qquad x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

matter effects

M. Freund, Phys.Rev. D64 (2001) 053003

Reactor- based experiments

- $$\begin{aligned} P(\bar\nu_e \to \bar\nu_e) = 1 & - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ & - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \end{aligned}$$

HOW DO WE MEASURE δ_{CP}?

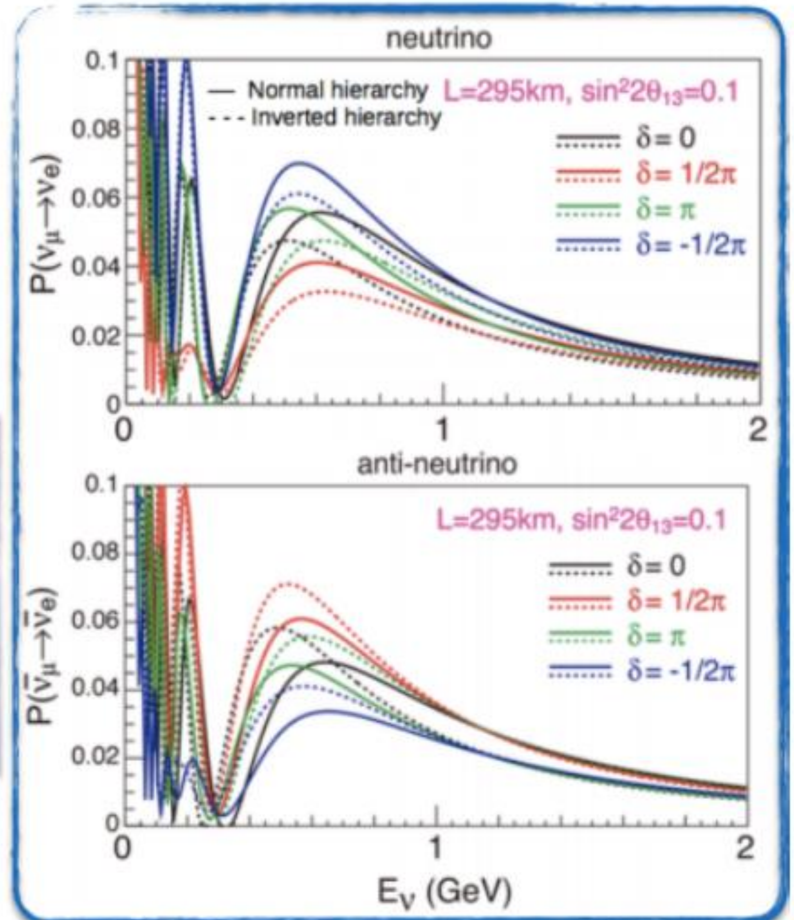
- δ_{CP} **can be measured only by accelerator-based LBL experiment.** Reactor experiments do NOT have access to this parameter

- The measurement is (in principle) simple: looking for a **different behaviour (shape and normalisation) between neutrino and anti-neutrino oscillations**

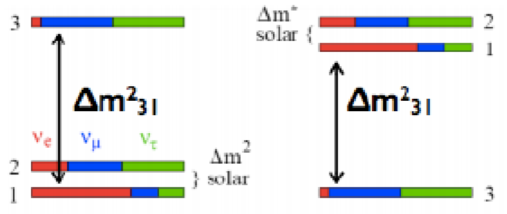
  e.g. if δ_{CP} = :
  - $0, \pi$: no CP violation $P(\nu_\mu \to \nu_e) = P(\overline{\nu_\mu} \to \overline{\nu_e})$
  - $-\pi/2$: enhance $P(\nu_\mu \to \nu_e)$ suppress $P(\overline{\nu_\mu} \to \overline{\nu_e})$
  - $+\pi/2$: suppress $P(\nu_\mu \to \nu_e)$ enhance $P(\overline{\nu_\mu} \to \overline{\nu_e})$

  - **Matter effects,** if significative, **make the measurement more complicate**

- δ_{CP} strongly correlated with θ_{13}. δ_{CP} **can be extracted using reactor constraints**



HOW DO WE MEASURE THE MASS HIERARCHY?



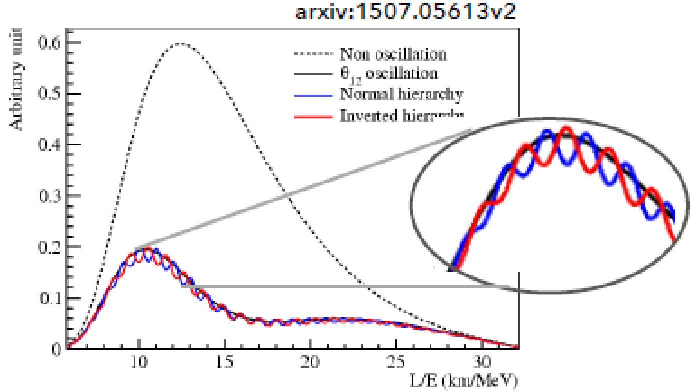
Two approaches :

Oscillation interference:

Spectral distortion on medium baseline reactor experiment (3% effect)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

arxiv:1507.05613v2



JUNO

Matter effect:

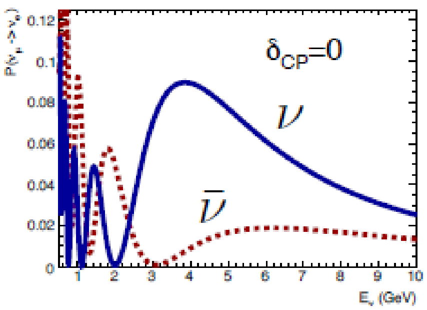
ν/anti-ν oscillations enhanced depending from the MH (need LBL)

$$A = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

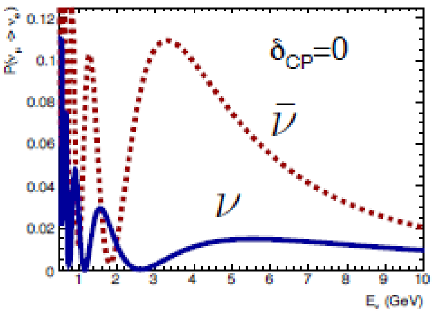
+ for ν

- for anti-ν

Normal Hierarchy



Inverted Hierarchy



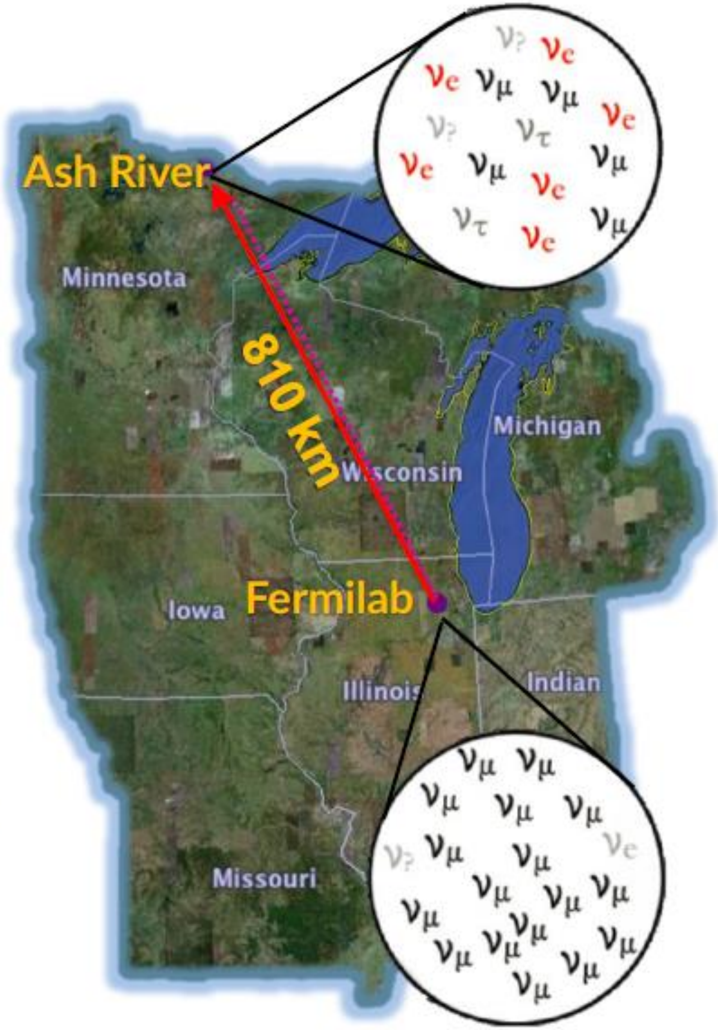
NOvA, DUNE, HK ..

Fresh results from Moriond 2017

NOvA on θ_{23}

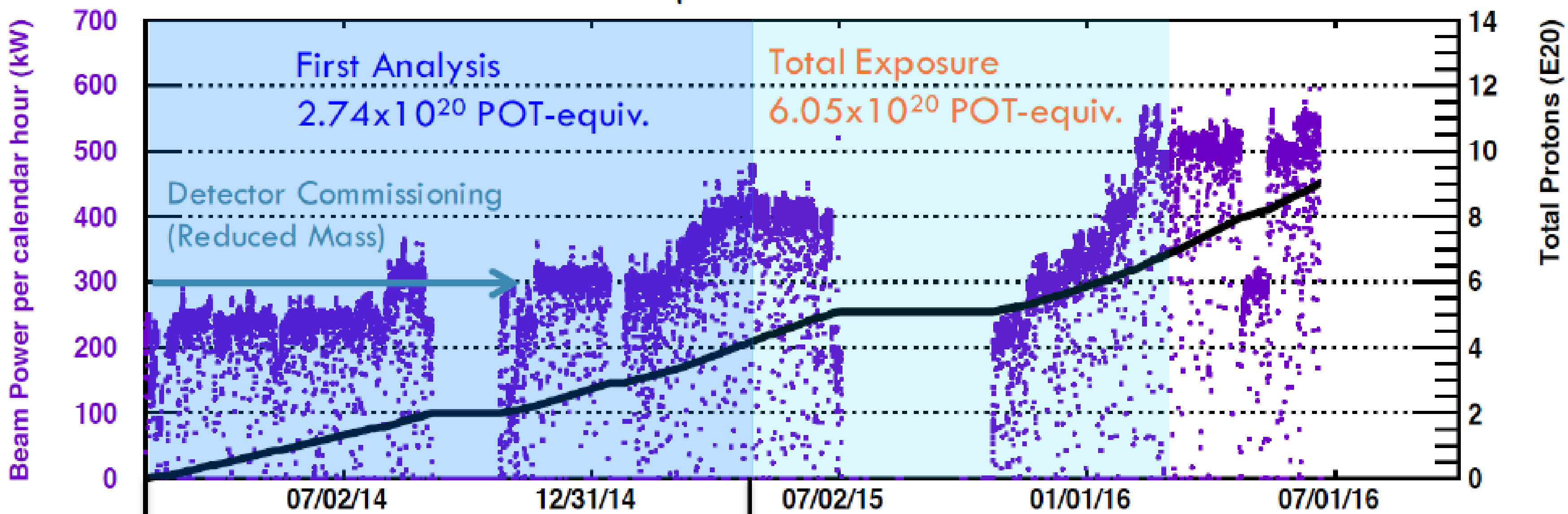
NuMI Off-axis ν_e Appearance Experiment

- Long-baseline, two-detector ν oscillation experiment
- Looks for ν_e in ν_μ NuMI beam
- 14 mrad off-axis
- 2 liquid scintillator detectors
- FD (14 kton), ND (0.3 kton)
- Cooled APD readout (live)
- Appearance & disappearance
- Exotics, non-beam…



Beam status

- Data from Feb 6, 2014 – May 2, 2016
- Achieved the 700kW design goal (750 kW)
- Switched to RHC ($\bar{\nu}_\mu$) Feb 20th, 2017



$\nu_\mu \rightarrow \nu_\mu$: Phys.Rev.D93.051104

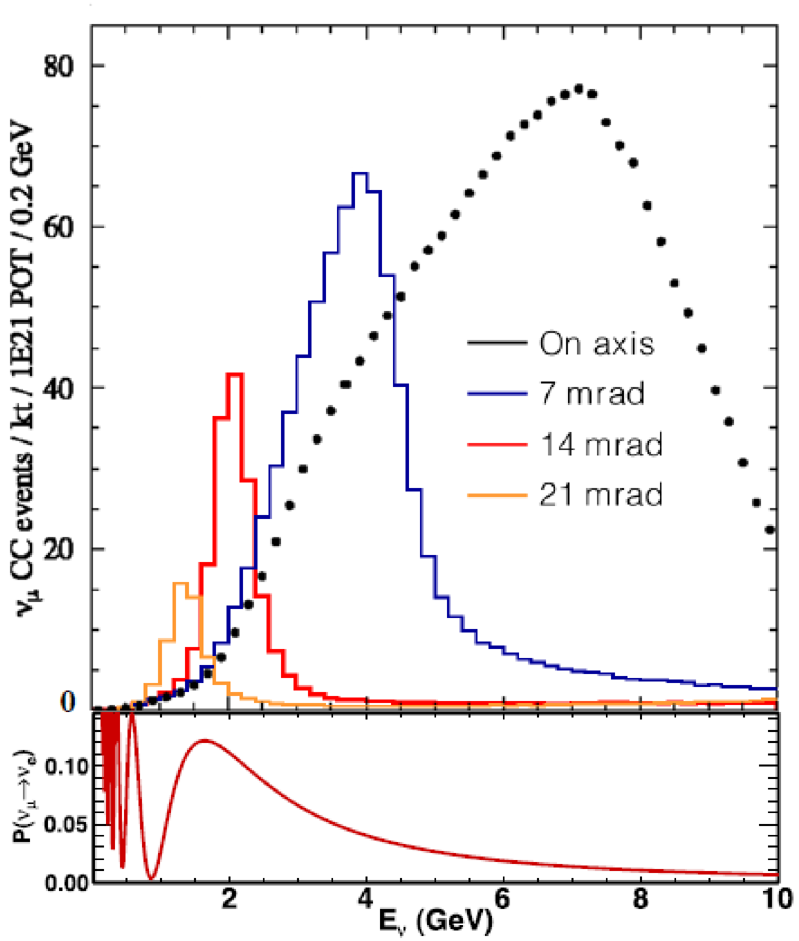
$\nu_\mu \rightarrow \nu_e$: PRL.116.151806

Why off-axis?

NuMI Off-axis ν_e Appearance

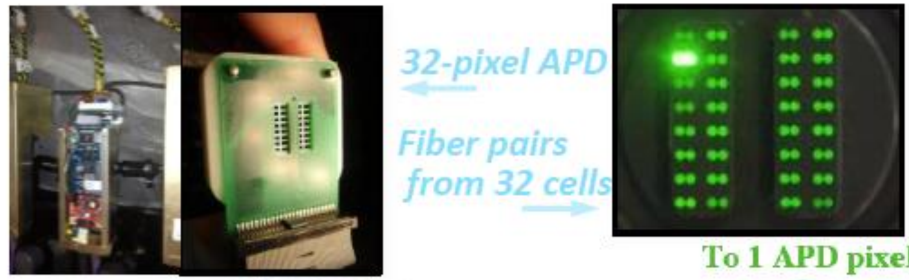
The choice of a 14 mrad off-axis position from the NuMI beam for the NOvA detector, allows for a narrow band beam which in conjunction with topology of final state particles, allows one to more easily reject potential backgrounds

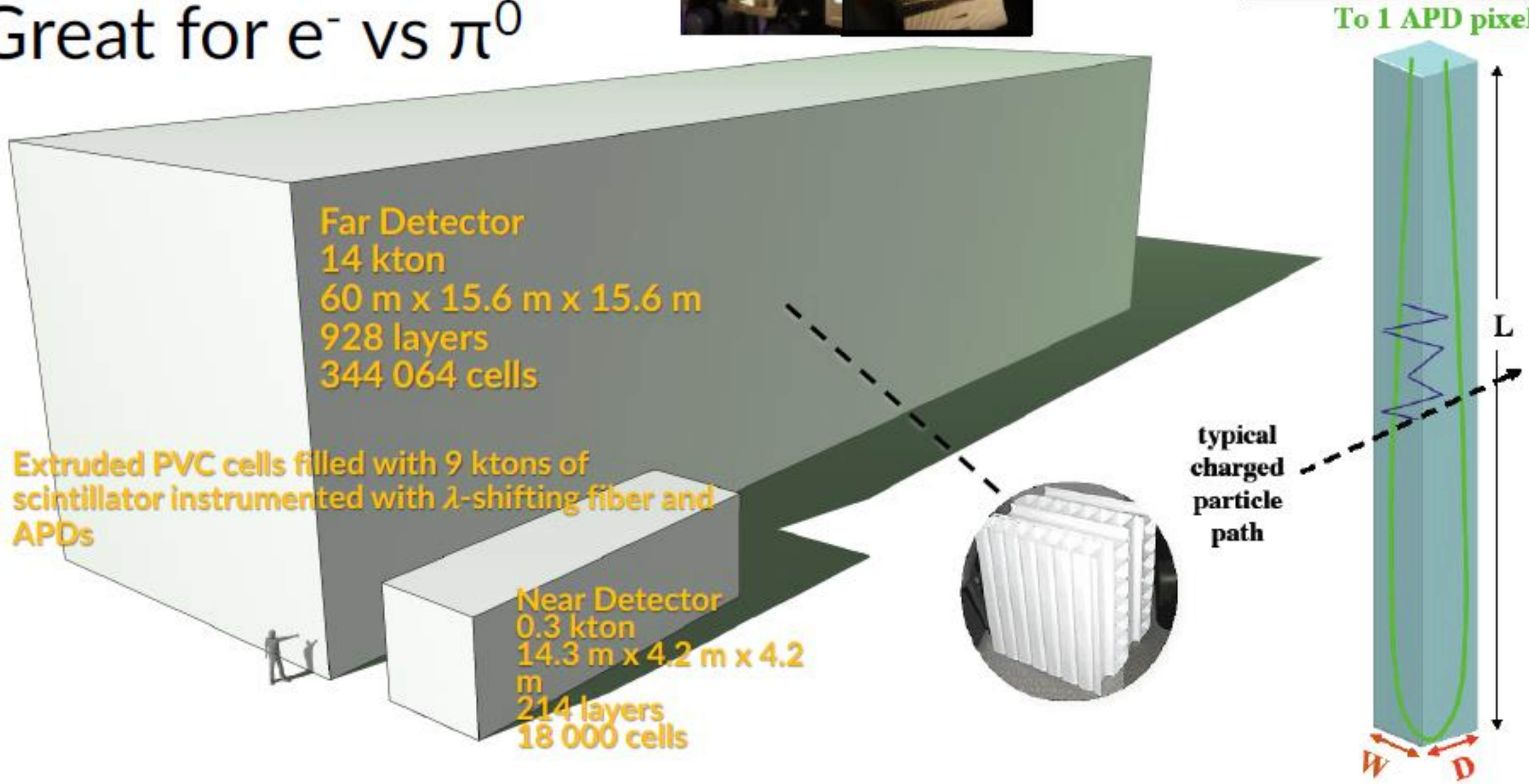
The peak of the beam coincides with the oscillation maximum for ν_e appearance at 810km distance



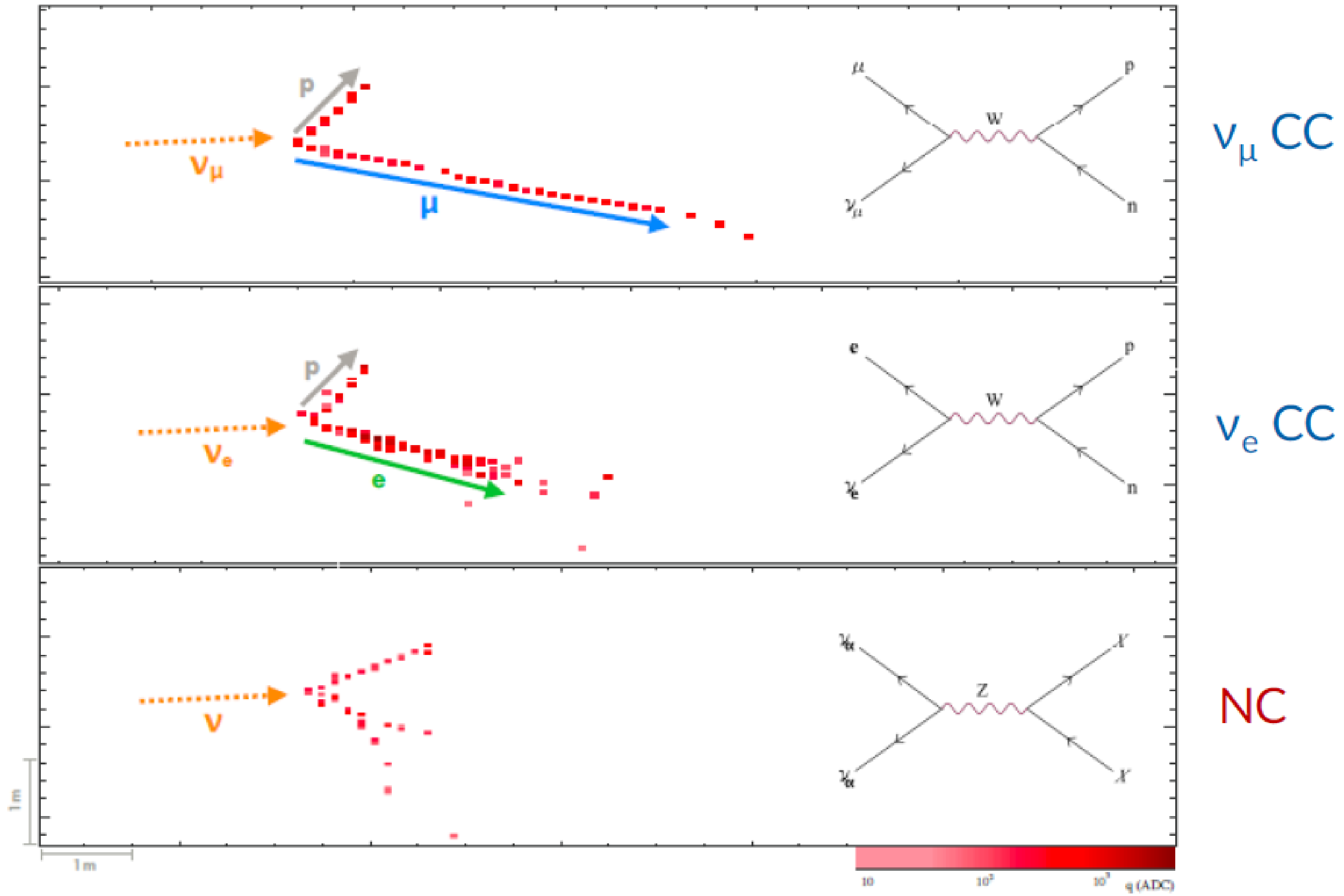
The NOvA detectors

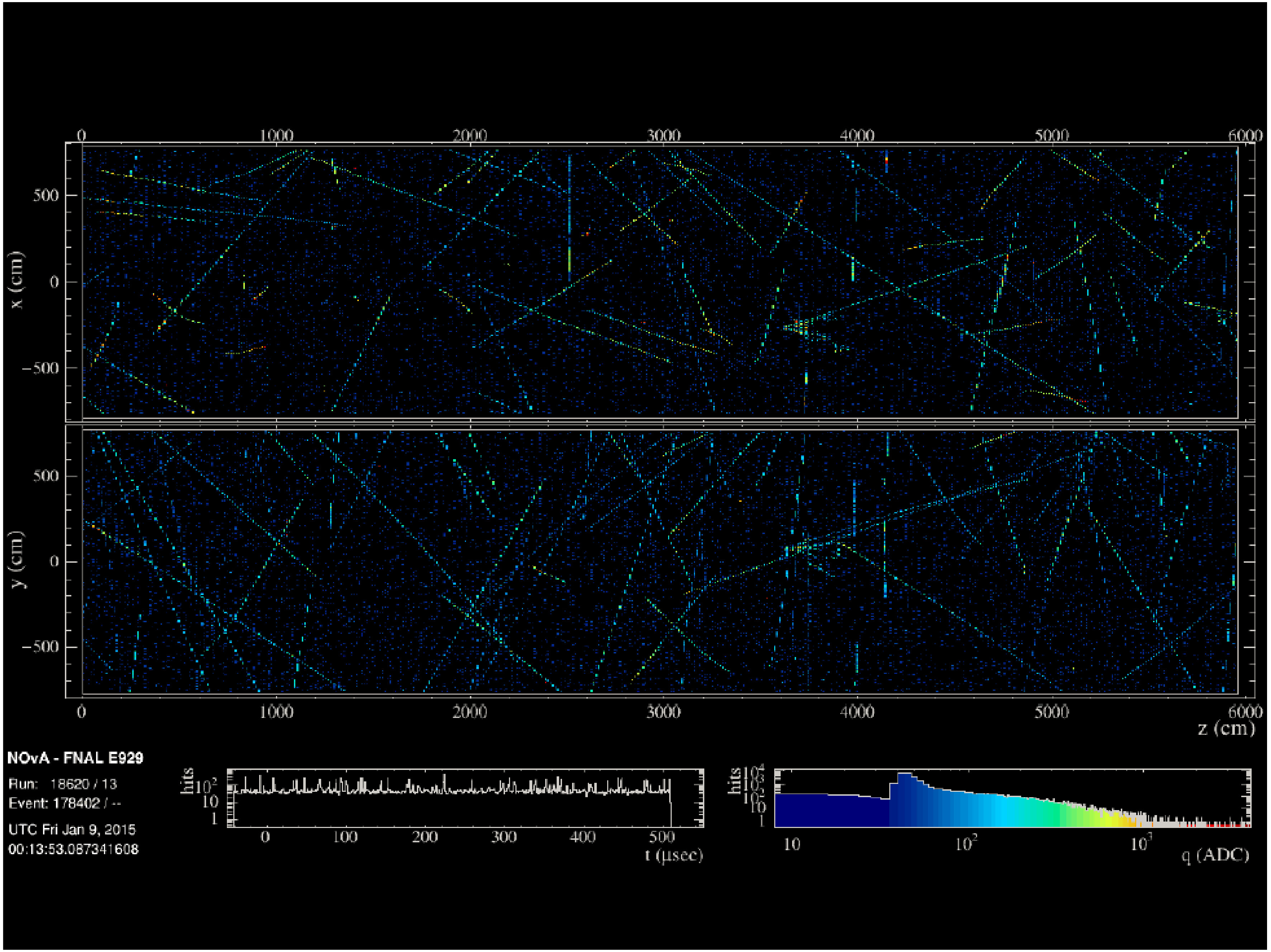
- 65% active detectors
- Each plane 0.17 X_0
  Great for e^- vs π^0



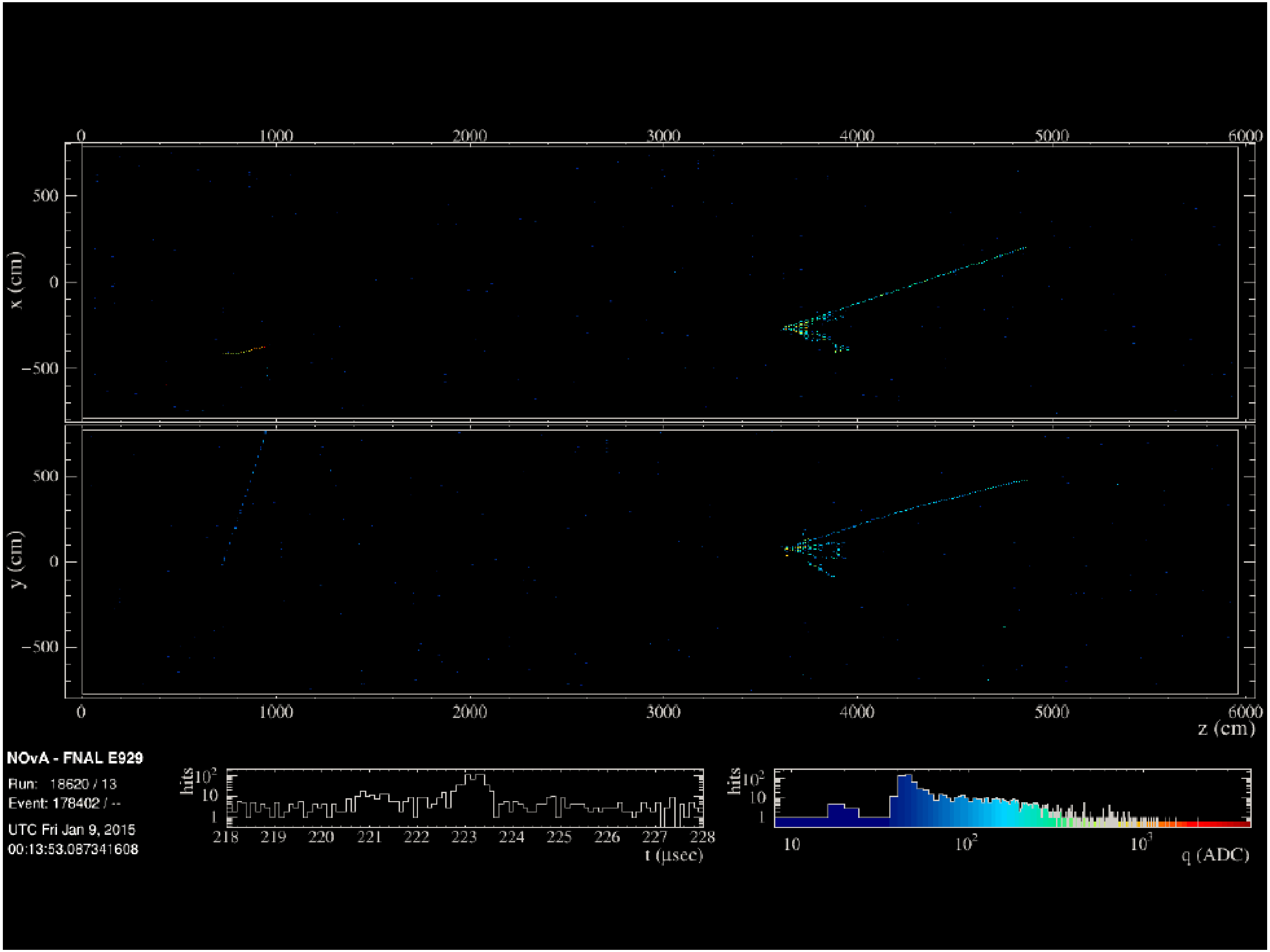


NOvA Neutrino Event Topologies





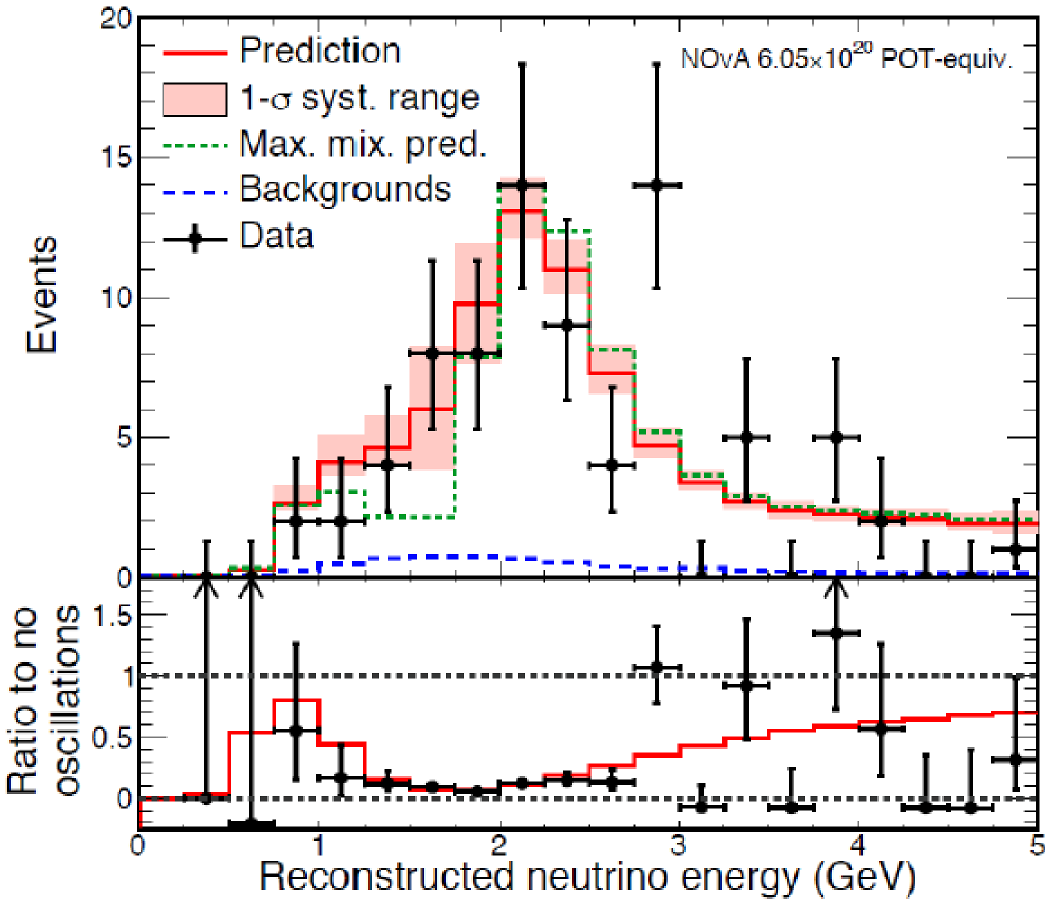
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)



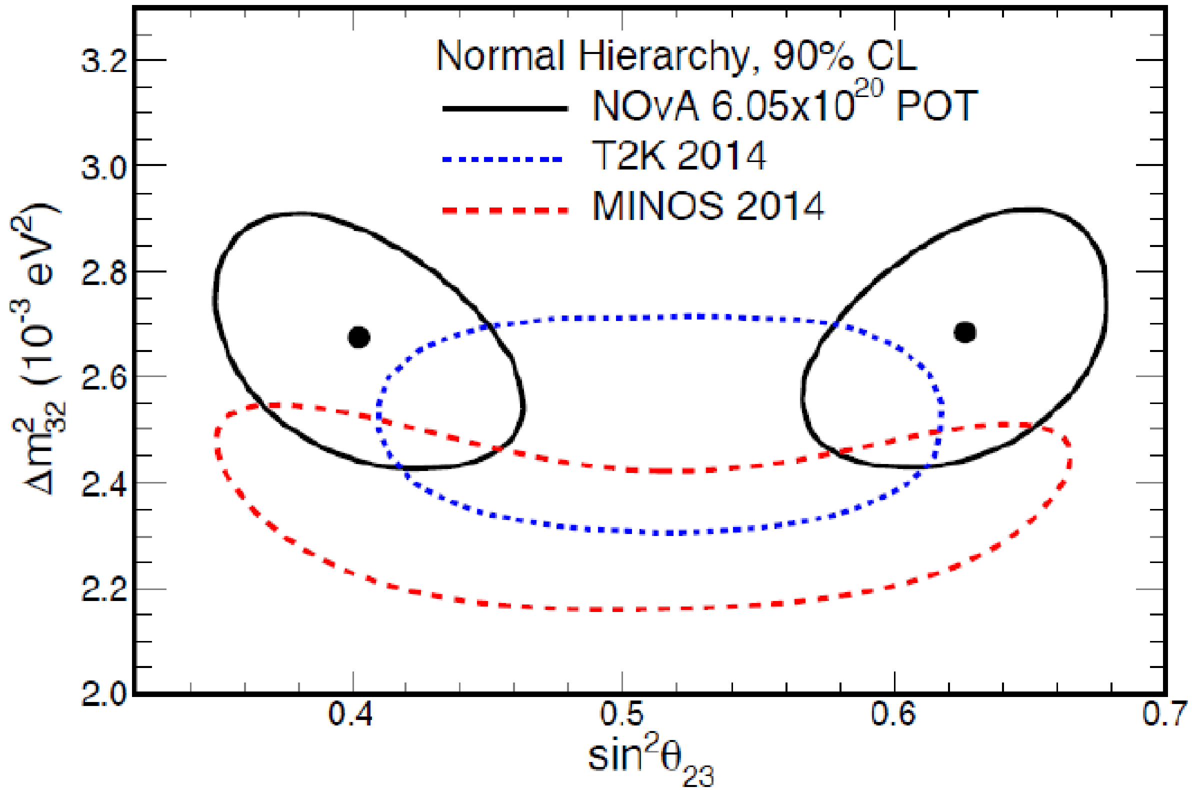
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)

ν_μ disappearance results

- 473 ± 30 events predicted in the absence of oscillations
- 78 events observed
- 82 events predicted at the best fit point
  - including 3.7 beam bkg
  - 2.9 cosmic induced



ν_μ disappearance results



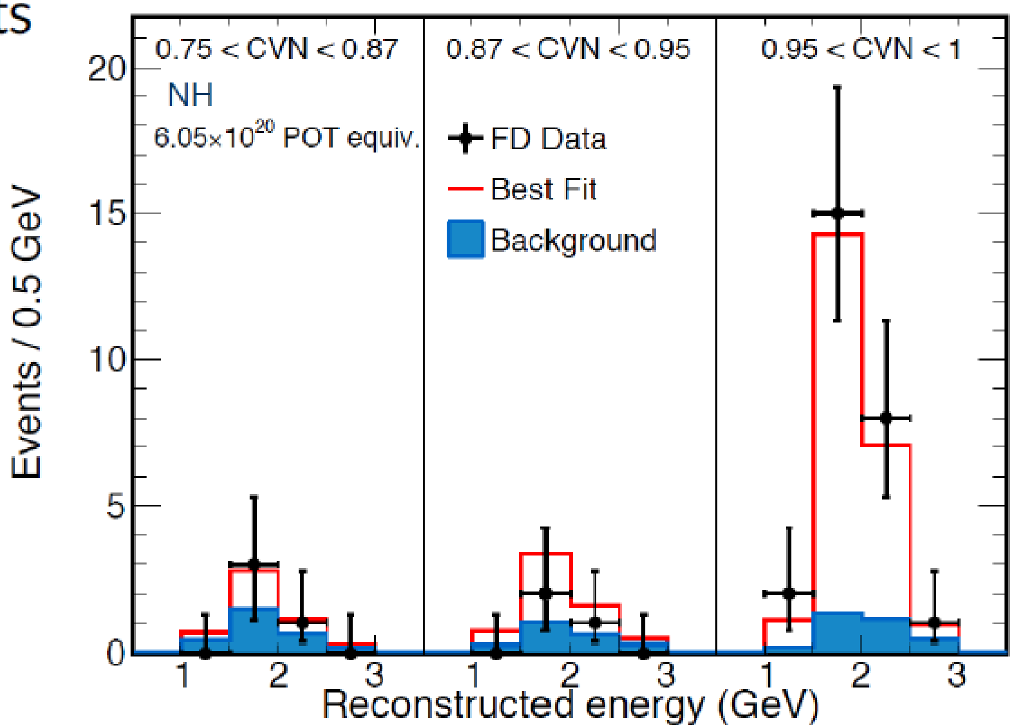
$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022} (0.624^{+0.022}_{-0.030})$$

Maximal mixing disfavored at 2.6 σ

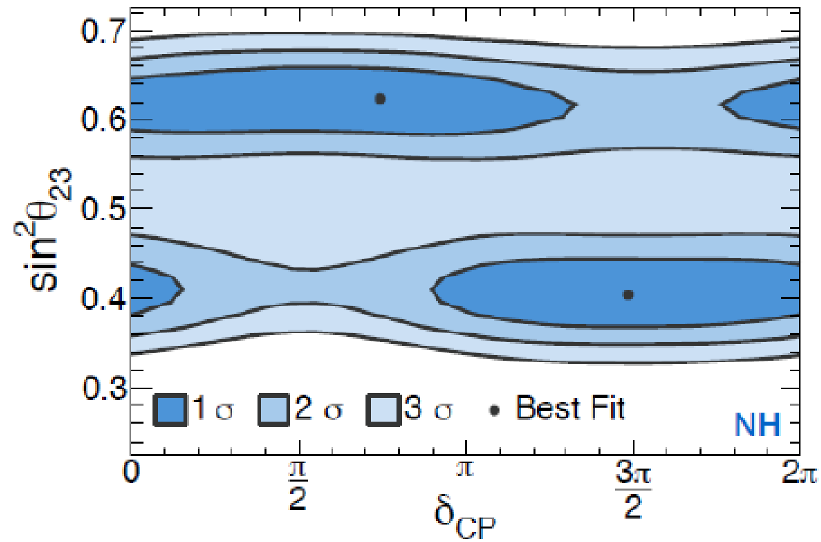
ν_e appearance analysis

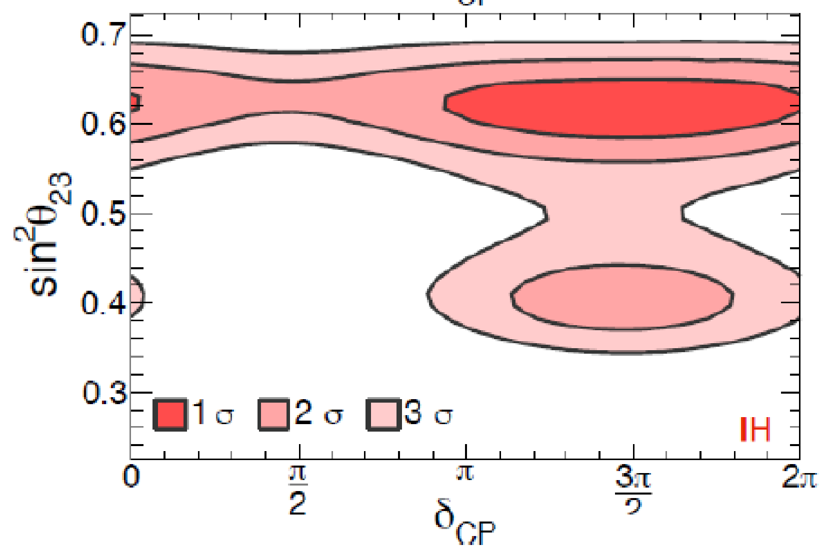
- ~30% more efficient than previous PID
- 4 energy bins, 3 PID bins
- Observe 33 events on a background of 8.2 ± 0.8
- θ_{13} to reactor experiments
- Joint fit with ν_μ spectrum



ν_e appearance results

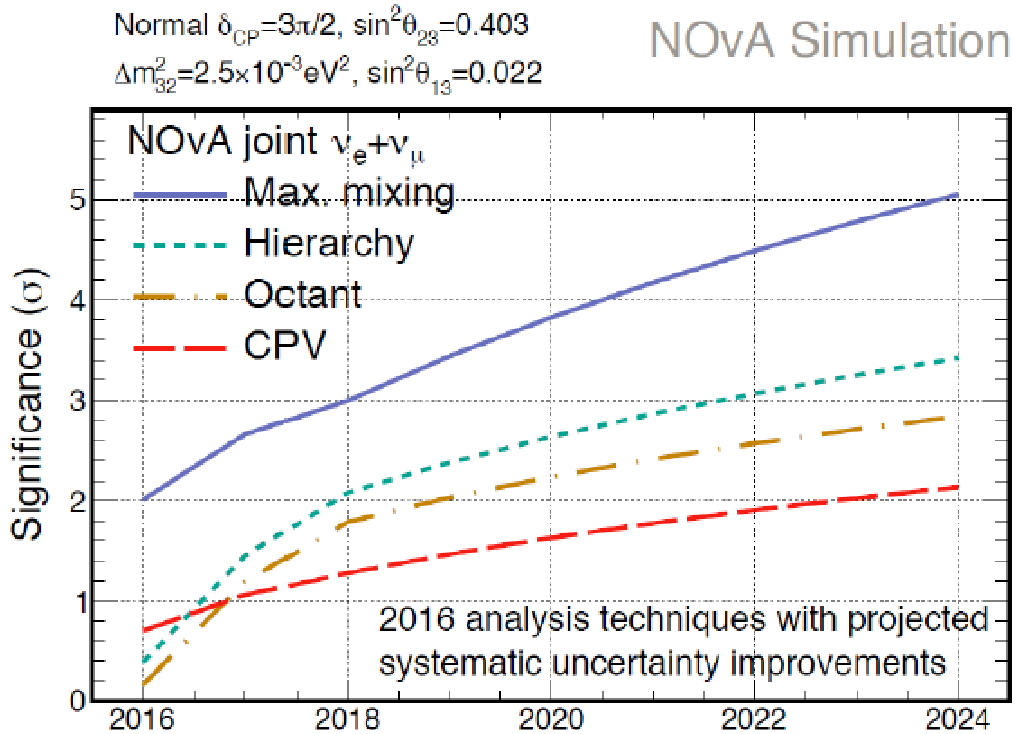
- 2 degenerate best fit points:
  - NH, $\delta_{CP} = 1.48\pi$
    $\sin^2\theta_{23} = 0.404$
  - NH, $\delta_{CP} = 0.74\pi$
    $\sin^2\theta_{23} = 0.623$
- Inverted hierarchy slightly disfavored - $\Delta\chi^2 = 0.47$
- Lower octant in the IH is disfavored at 93% CL
- arXiv:1703.03328





Outlook

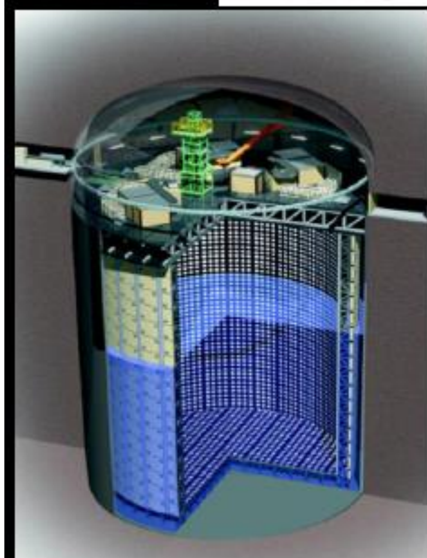
- RHC anti-neutrino running from February 2017
- Run 50% neutrino, 50% anti-neutrino past 2018
  - 3σ sensitivity to maximal mixing of θ_{23} in 2018
  - 2σ sensitivity to mass hierarchy and θ_{23} octant in 2018-19

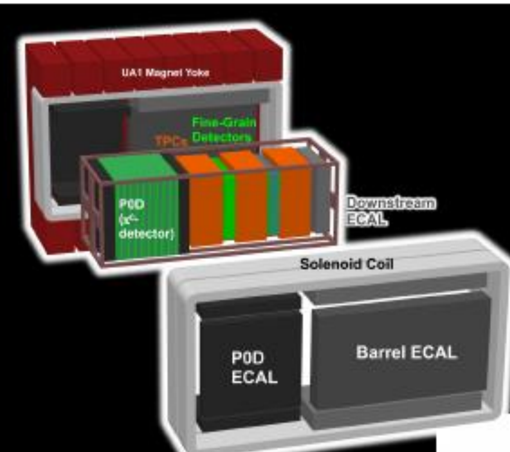


Fresh results from Moriond 2017

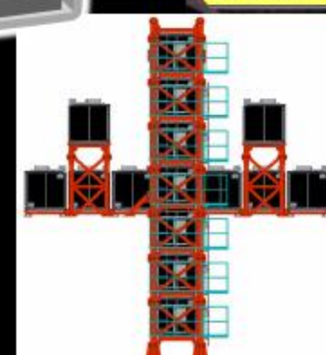
T2K on δ_{CP}

T2K experiment





- Off-axis detector : ND280

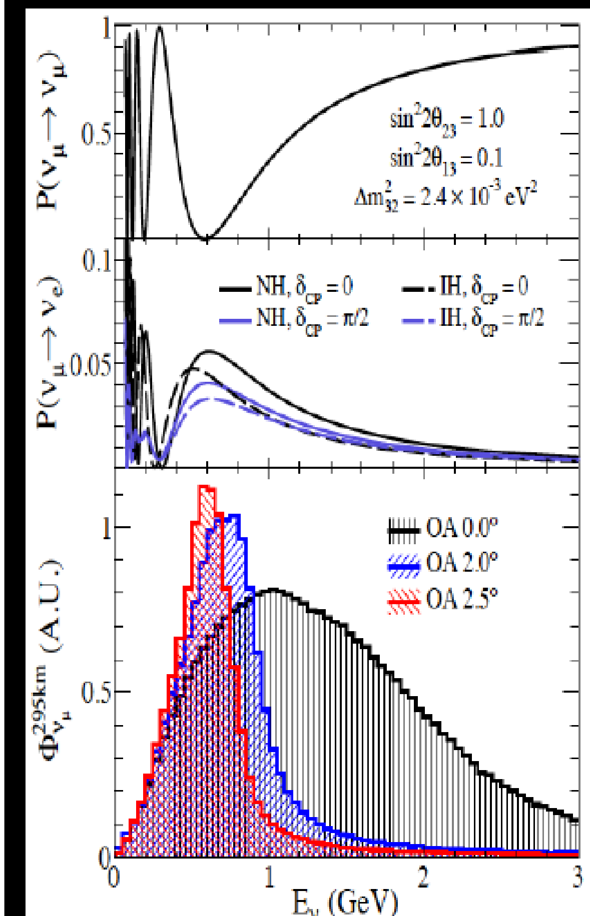


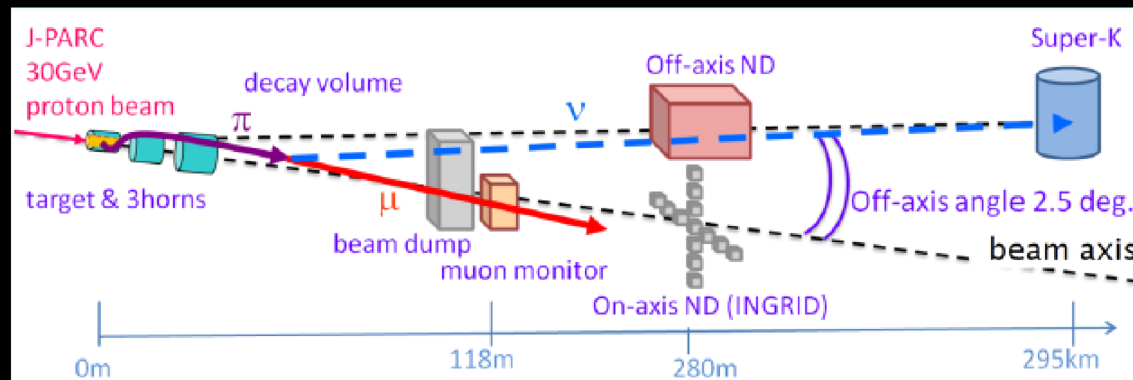
- 50 kt Water Cherenkov detector (Fiducial 22.5 kt) @ underground (2700 m water equivalent)
- Events on the beam timing are selected using GPS.

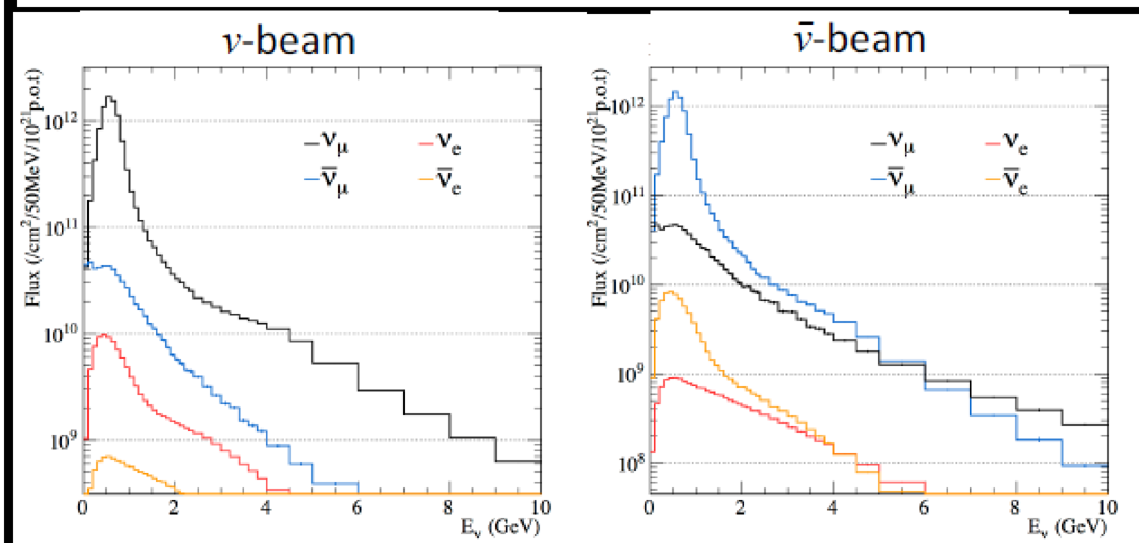
- On-axis detector : INGRID

J-PARC neutrino beam

- Narrow band beam by off-axis method.
- ν-beam and $\bar{\nu}$-beam can be switched by changing the field polarity of horns.
- Neutrino flux is estimated from beam MC using the hadron production of 30 GeV p-C measured by CERN NA61/SHINE experiment, etc.

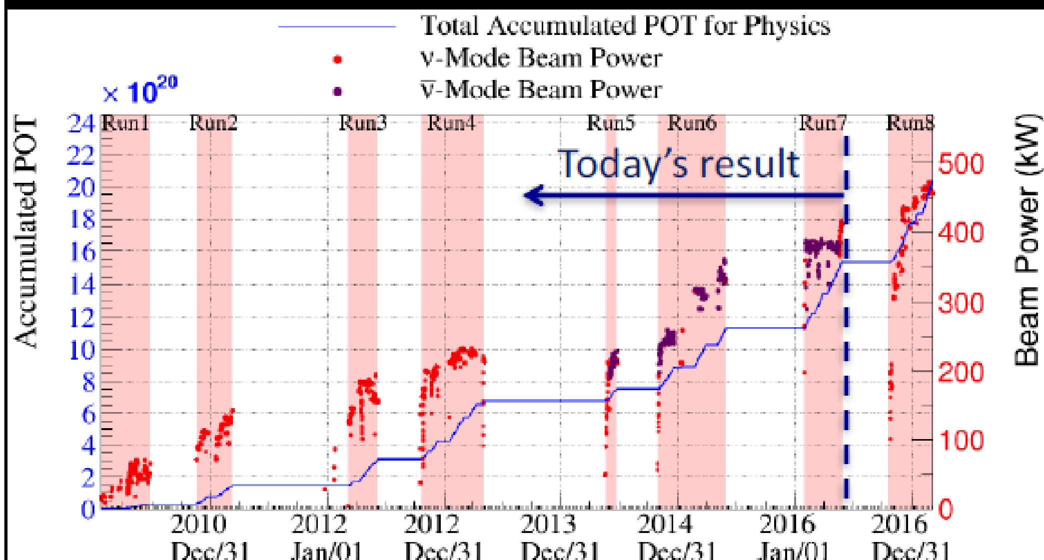


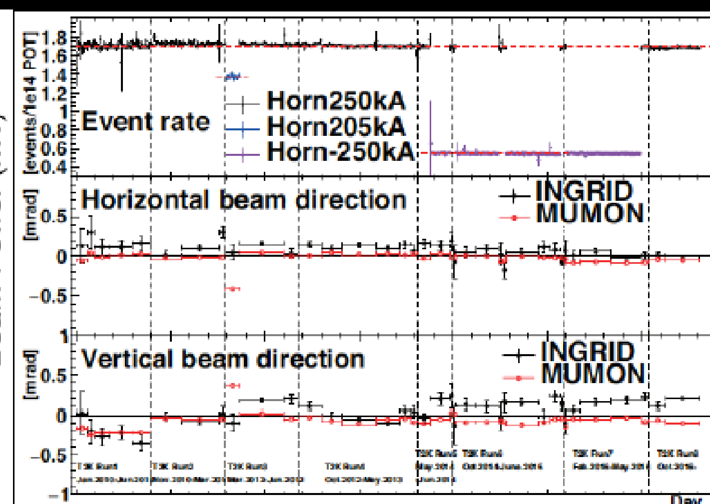




T2K data-taking status

- T2K has been taking physics data from Jan. 2010.
- From 2014, $\bar{\nu}$-beam data are also produced.
- Beam quality is stable for entire run period.
- Today's result is based on data up to May, 2016.
  - ν-beam data: 7.482×10^{20} POT (Protons-On-Target)
    $\bar{\nu}$-beam data: 7.471×10^{20} POT
- As of Mar 8th, beam power for physics run is ~470kW. Accumulated POT for T2K exceeds 2×10^{21} POT.



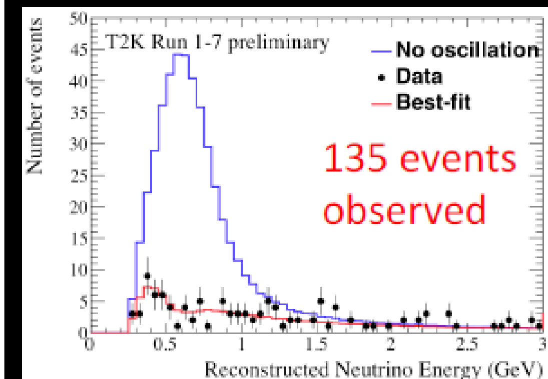


Observed SK neutrino event candidates

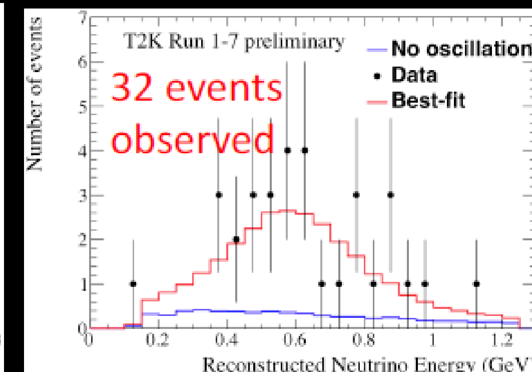
- Oscillation parameter is determined by fitting 5 event categories simultaneously.

New event sample

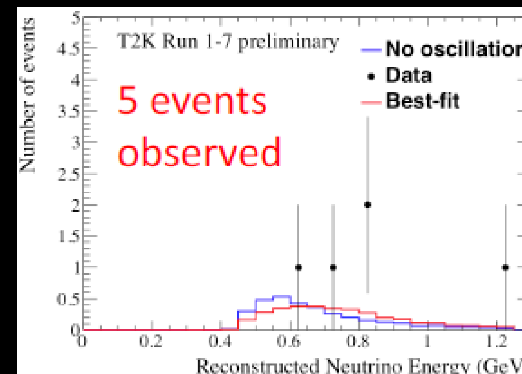
$\nu_\mu/\bar{\nu}_\mu$ CC-QE in ν-beam



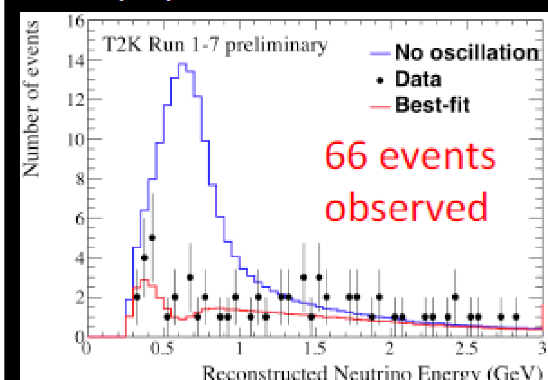
$\nu_e/\bar{\nu}_e$ CC-QE in ν-beam



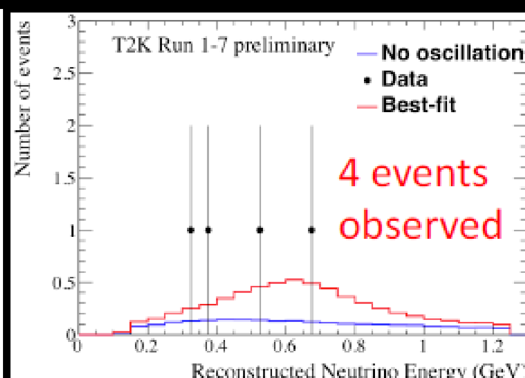
$\nu_e/\bar{\nu}_e$ CC-1π in ν-beam



$\nu_\mu/\bar{\nu}_\mu$ CC-QE in $\bar{\nu}$-beam



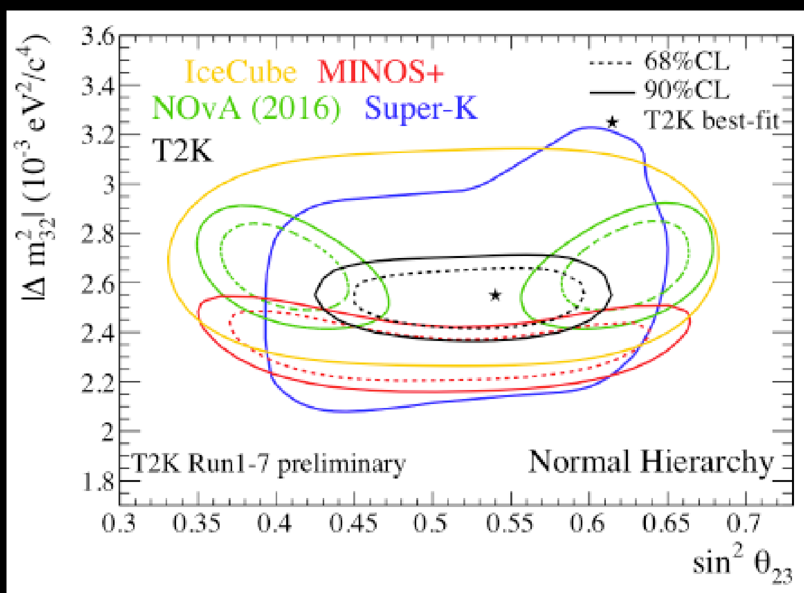
$\nu_e/\bar{\nu}_e$ CC-QE in $\bar{\nu}$-beam

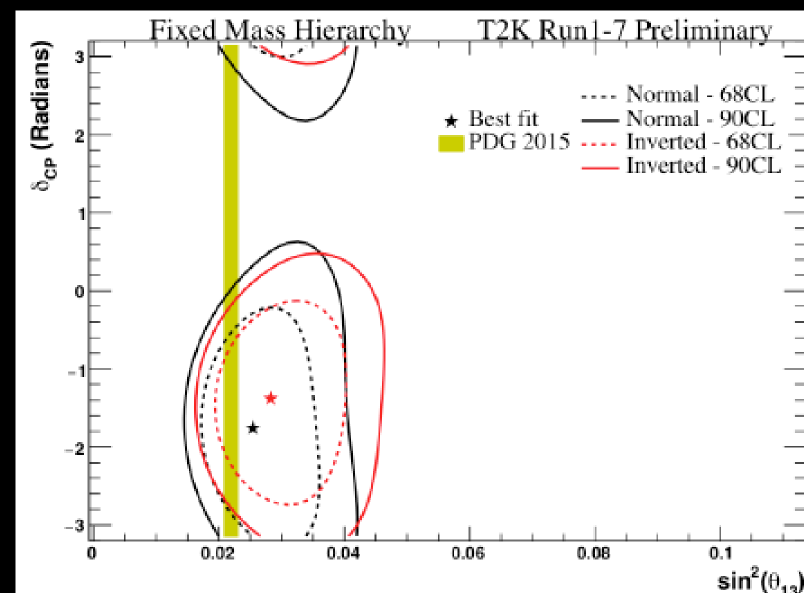


Expected # of events		δ_{CP} -1.6	δ_{CP} 0
ν-beam	$\nu_\mu/\bar{\nu}_\mu$ CC-QE	135.8	135.5
	$\nu_e/\bar{\nu}_e$ CC-QE	28.7	24.2
	$\nu_e/\bar{\nu}_e$ CC-1π	3.1	2.7
$\bar{\nu}$-beam	$\nu_\mu/\bar{\nu}_\mu$ CC-QE	64.2	64.1
	$\nu_e/\bar{\nu}_e$ CC-QE	6.0	6.9

Results on oscillation parameters

- T2K results consistent with the max. oscillation ($\sin^2\theta_{23}$=0.5).

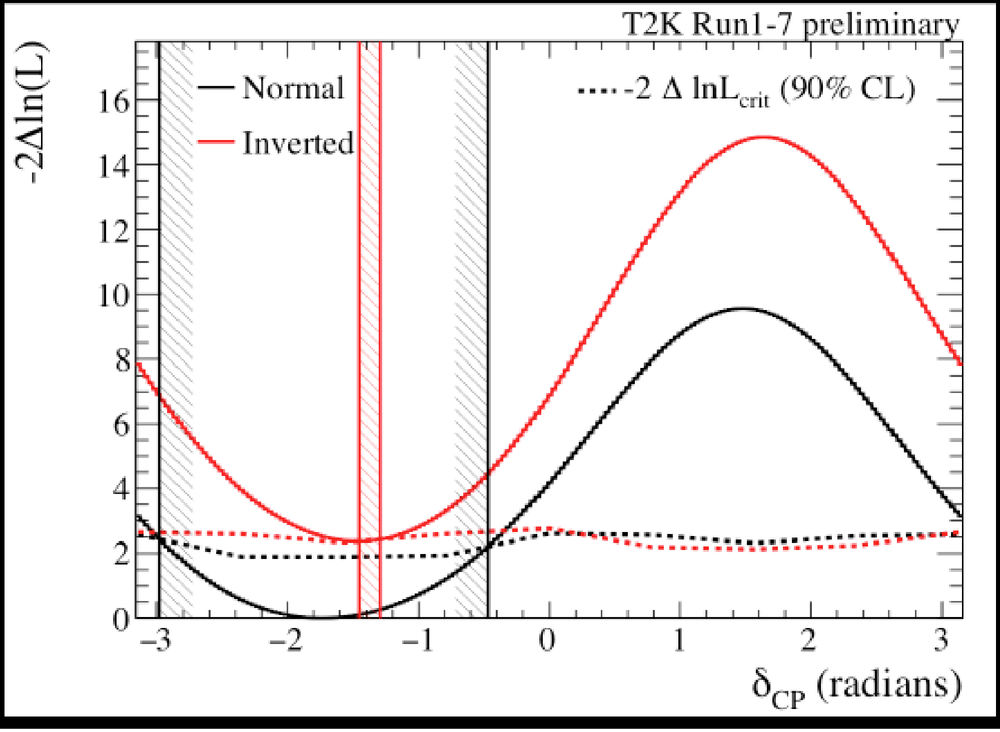




Super-K: PoS ICRC2015 (2015) 1062
Minos+: Neutrino 2014
NOvA : ICHEP2016
IceCube DeepCore: Phys.Rev. D91 (2015) 072004

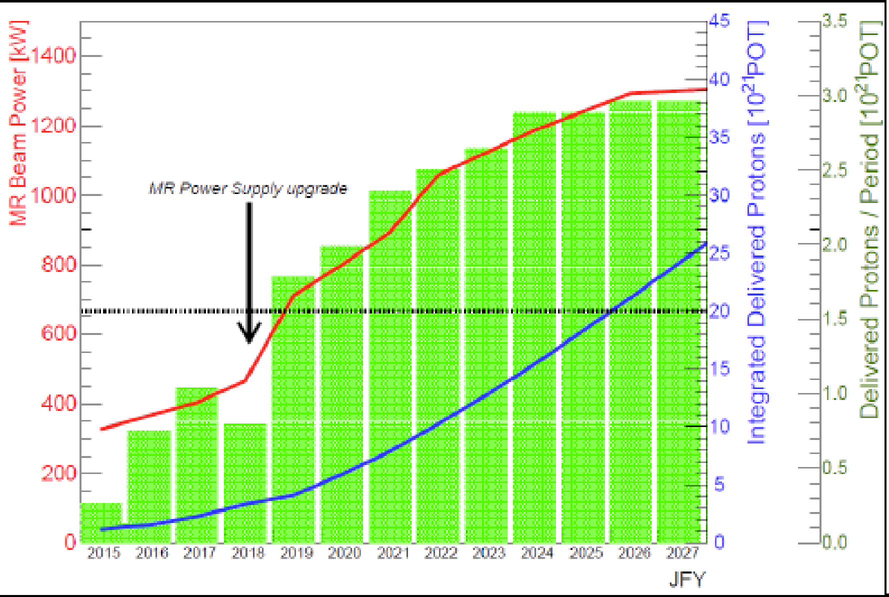
Obtained results on CP

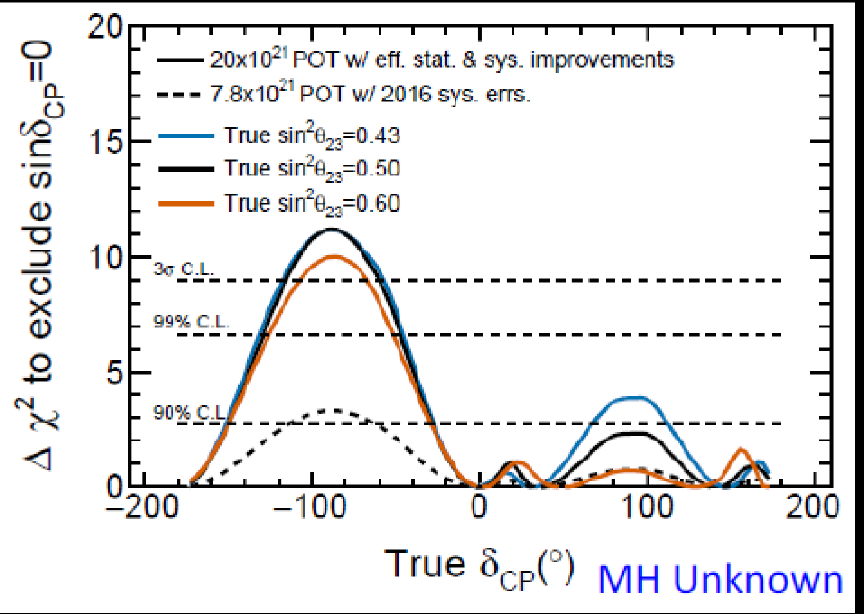
- Constrain θ_{13} with the results by reactor exp.
- CP-conservation hypothesis ($\sin\delta_{CP}=0$) is excluded with 90% CL.
- Confidence interval (90 %CL): NH -2.978 ~ -0.467 [rad]
  IH -1.466 ~ -1.272 [rad]



T2K-II (Running time extension)

- T2K proposes to collect 20×10^{21} POT data to search for evidence of CP violation in the lepton sector with 3σ sensitivity. (arXiv:1609.04111 [hep-ex])
  - J-PARC PAC recognizes the scientific merit and gave stage-1 status in 2016.





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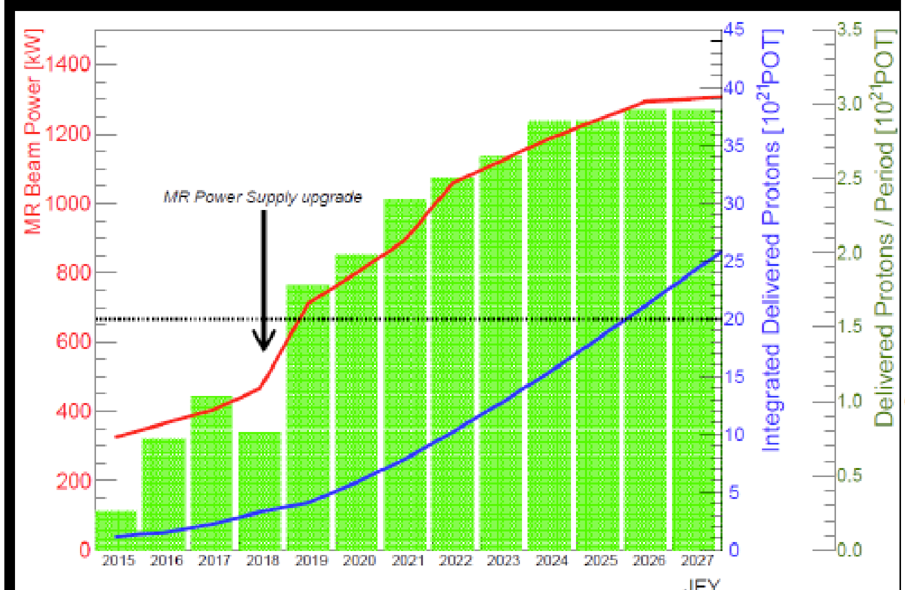
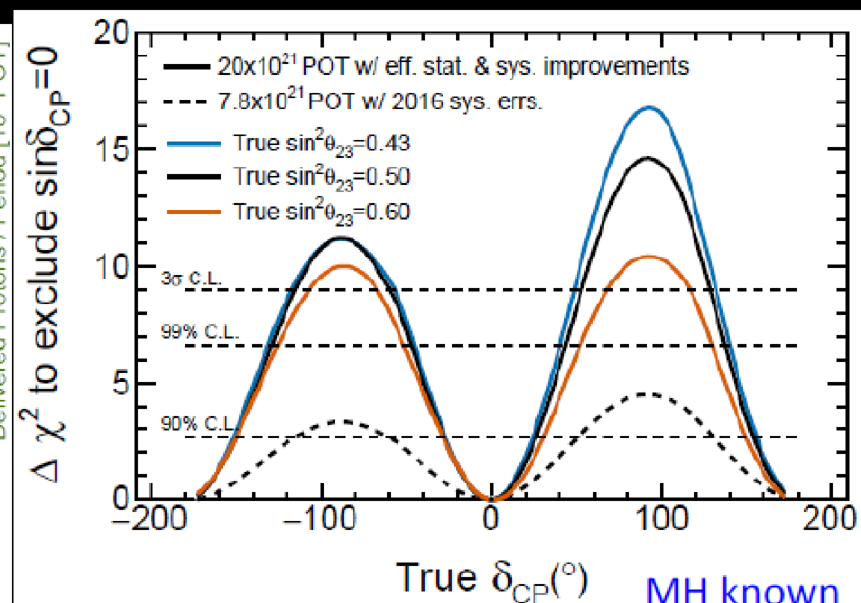




Fresh results from Moriond 2017

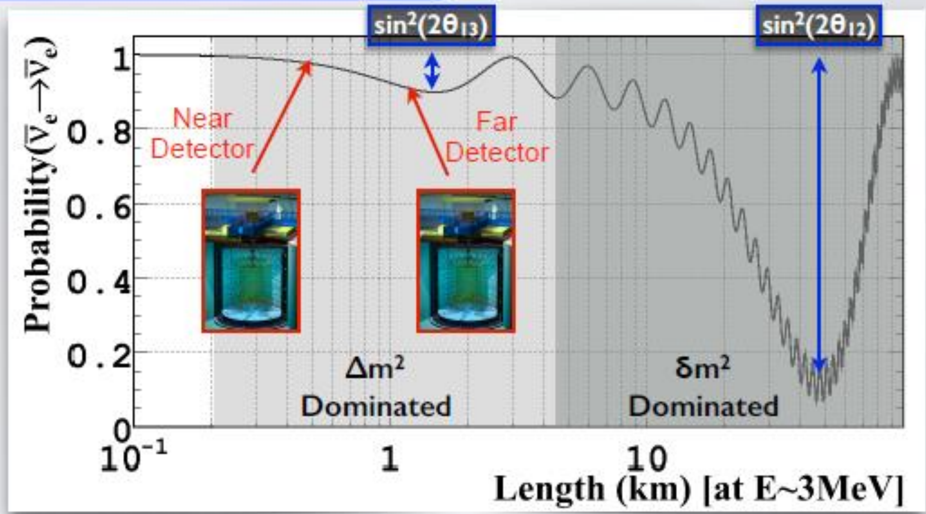
Double Chooz on θ_{13}

INTRODUCTION (1)

- Reactor oscillation experiments aim at the measurement of θ_{13} through the observation of $\overline{\nu}_e \rightarrow \overline{\nu}_e$ transition according to the oscillation probability:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

- The use of two detectors allows to measure the flux before and after the oscillation to cancel out the associated systematics.



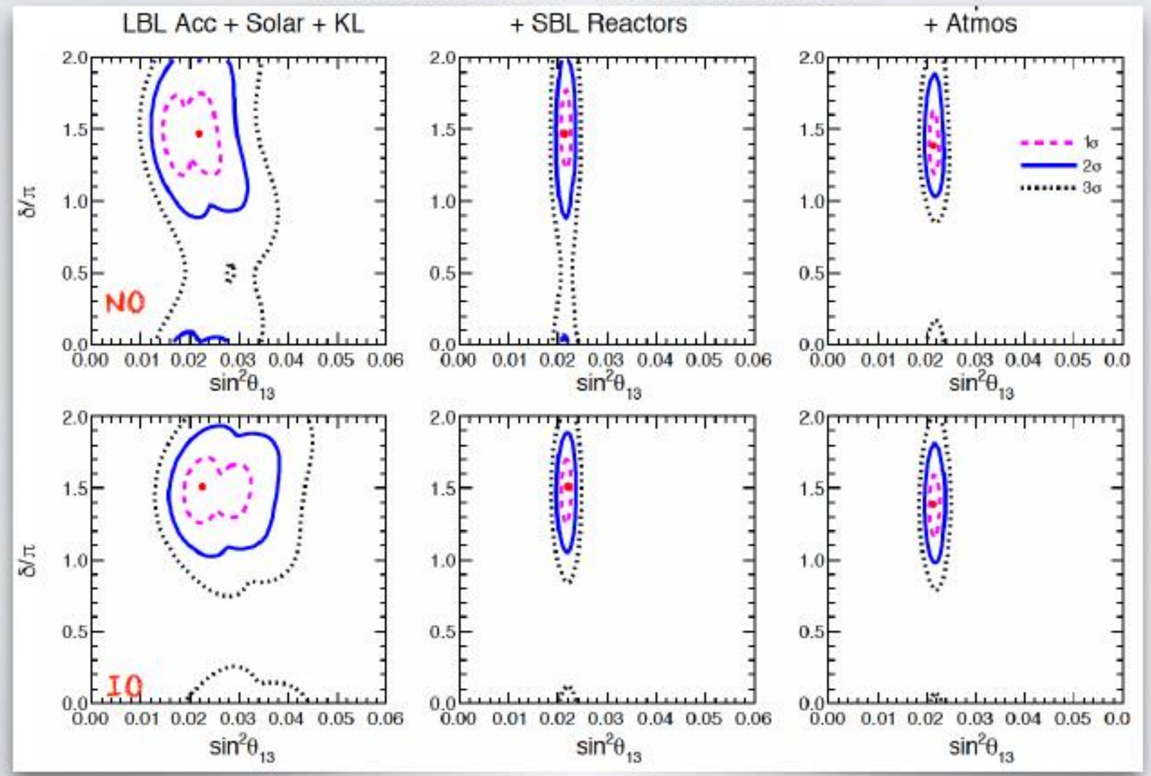
- The advantages of this measurement with respect to long baseline oscillation experiments is a ***clean measurement*** of θ_{13} since:

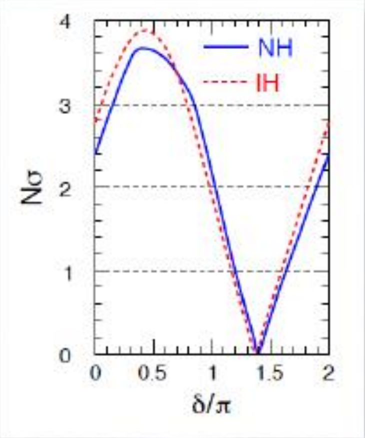
1. It is a disappearance experiment, therefore insensitive to the value of the δ-CP phase.
2. It has a short baseline (order of 1 km) and it is therefore insensitive to matter effects.
3. The dependence on Δm^2_{21} is very weak : O ($\Delta m^2_{21}/\Delta m^2_{31}$).

INTRODUCTION (2)

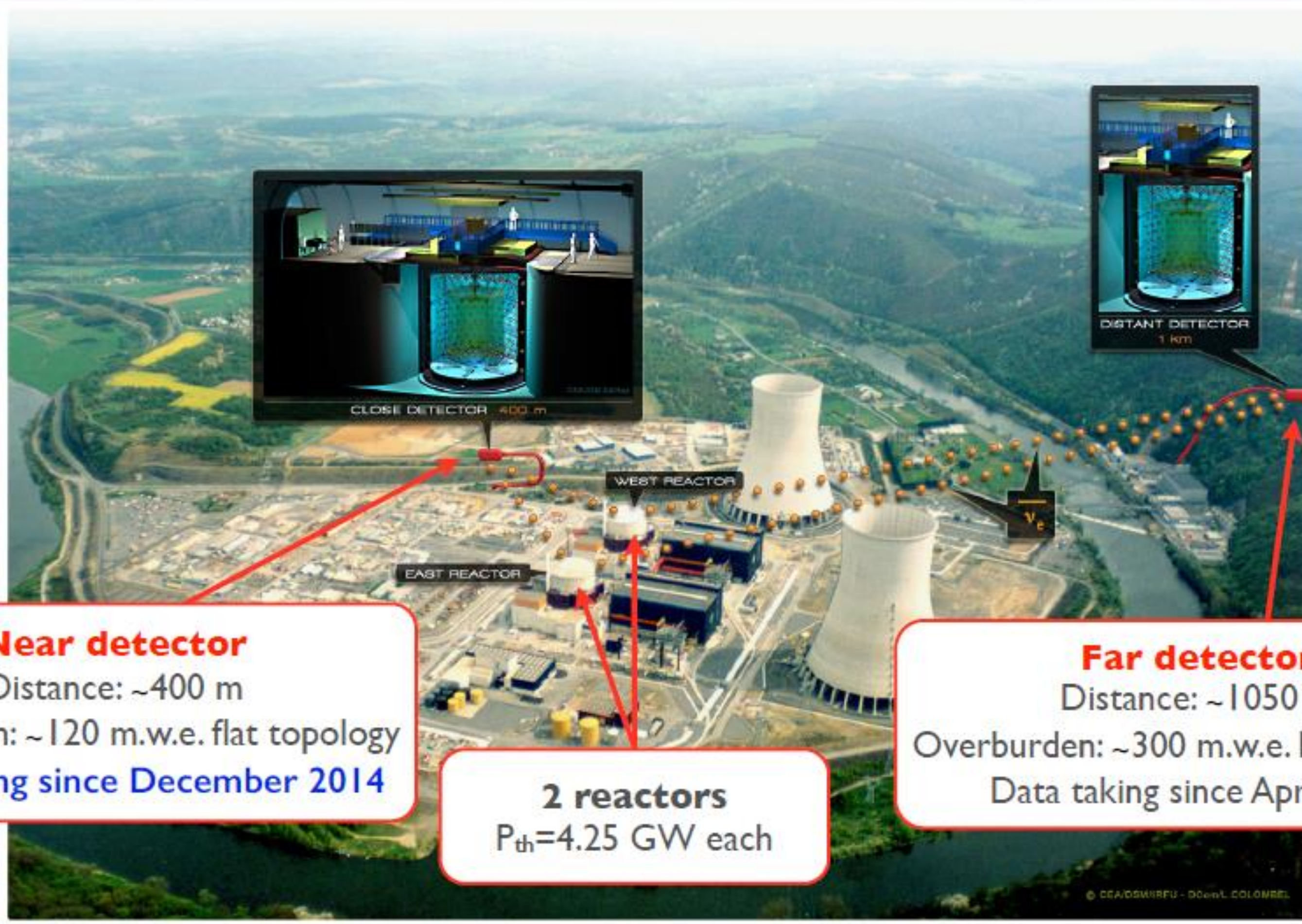
- The reactor measurement is ***complementary*** with respect to the long baseline oscillation experiments.
- The combination of the two results in hints of maximal CP violation.

Marrone et al. - Neutrino2016





Double Chooz OVERVIEW

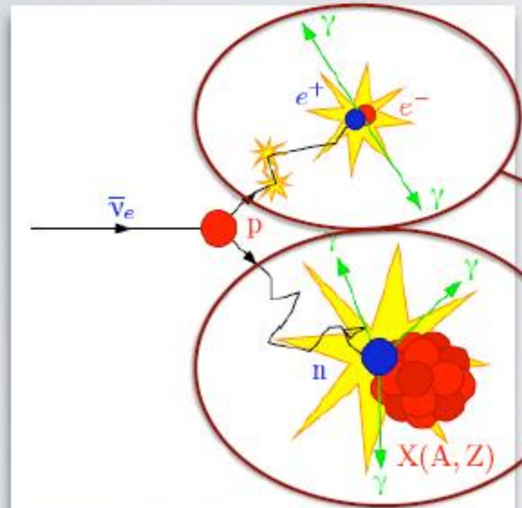


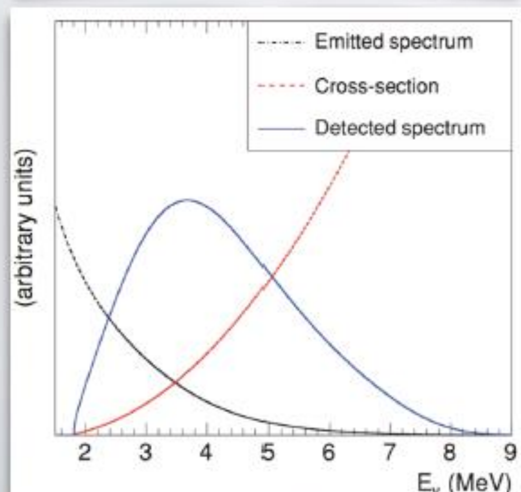
Near detector
Distance: ~400 m
Overburden: ~120 m.w.e. flat topology
Data taking since December 2014

2 reactors
P_{th}=4.25 GW each

Far detector
Distance: ~1050 m
Overburden: ~300 m.w.e. hill topology
Data taking since April 2011

NEUTRINO DETECTION





- Neutrinos are observed via Inverse Beta Decay (IBD):

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- The signal signature is given by a **twofold coincidence**:

1. Prompt photons from e^+ ionisation and annihilation (1-8 MeV).
2. Delayed photons from **n** capture on Gadolinium (~8 MeV) or H (2.2 MeV).
3. Time correlation: Δt ~30 μs for Gd and Δt ~200 μs for H.
4. Space correlation (< 1m).

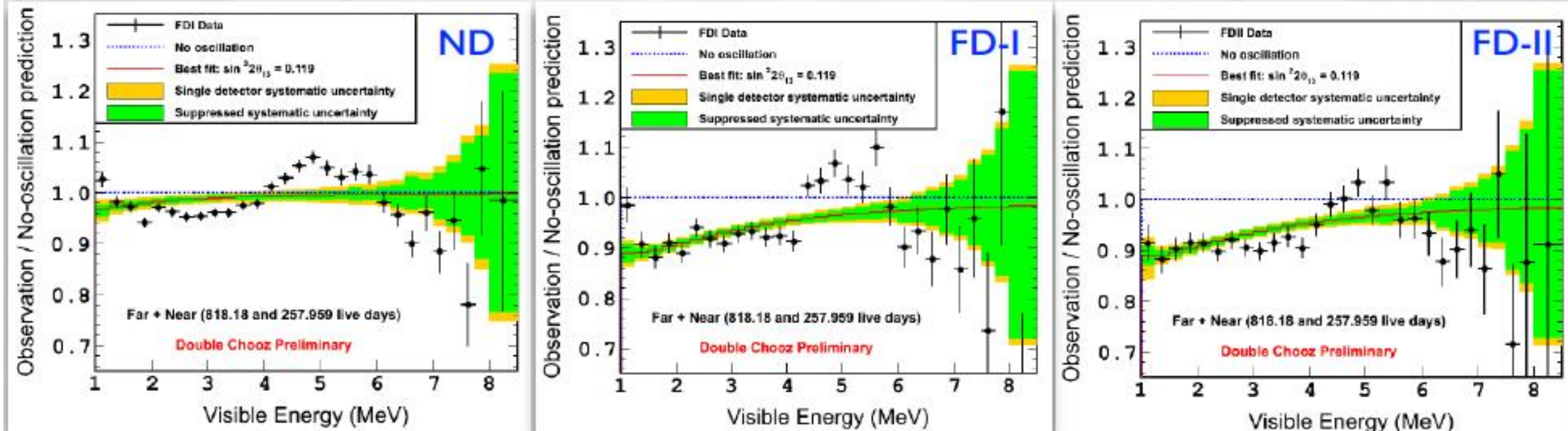
- The energy spectrum is a convolution of flux and cross section (threshold at 1.8 MeV).
- The prompt energy is related to $\overline{\nu}_e$ energy:

$$E_{prompt}=E_\nu-T_n-0.8 \text{ MeV}$$

- The survival probability depends on E_ν therefore we have a measurement of θ_{13} using rate and spectral deformation.

FIT AND RESULT

- The fit is done comparing FD-I, FD-II and ND data to the Monte Carlo (prediction + BG).
- Correlation of systematics errors are included in the fit as well as energy non linearities.
- BG rate and shapes are estimated by data (Li BG rate is not constrained in the fit and only shape information is used)

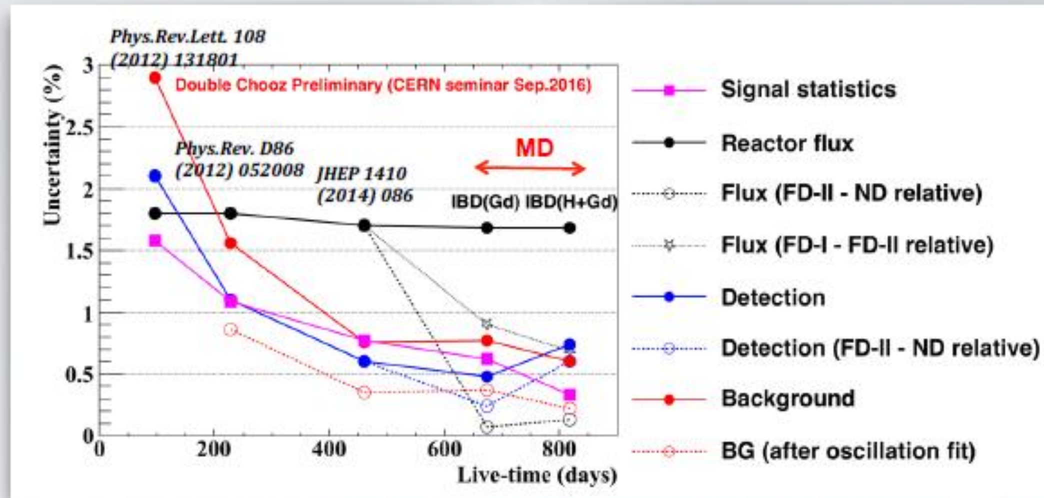


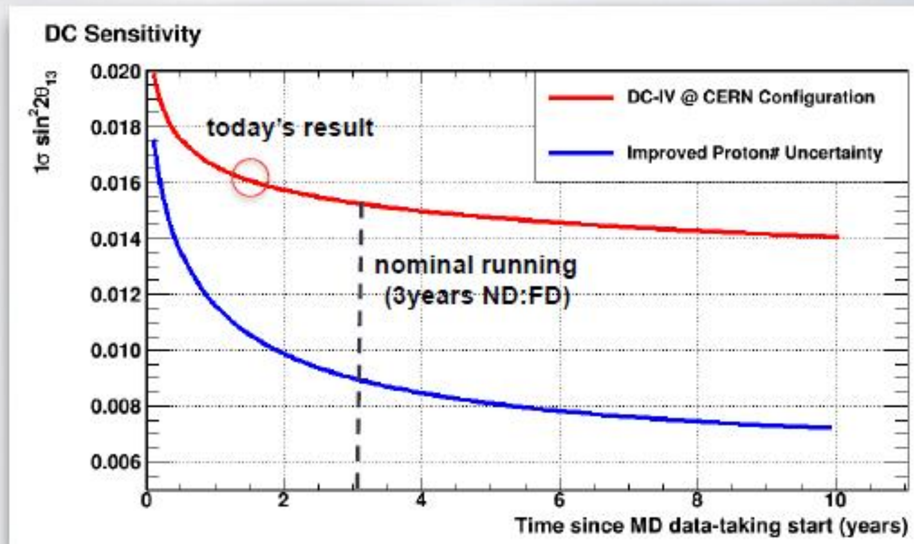
$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$ (stat.+syst.) (χ^2/dof = 236.2/114)

Background	Estimation FD	Fit output FD	Estimation ND	Fit output ND
^{9}Li (β-n)	2.59 ± 0.61	2.55 ± 0.23	11.11 ± 2.96	14.4 ± 1.2
Correlated	2.54 ± 0.10	2.51 ± 0.05	20.77 ± 0.43	20.85 ± 0.31

EXTRAPOLATION

- With the multi detector analysis (Gd+H) the statistics is no more a limiting factor.
- The largest systematics comes from detection systematics: the uncertainty on the proton number in the GC limits the sensitivity to 0.76% whereas if we consider only the neutrino target the detection systematics is 0.3%.
- With a reduction on the proton number uncertainty **we could reach a sensitivity ≤ 0.01** (work in progress).



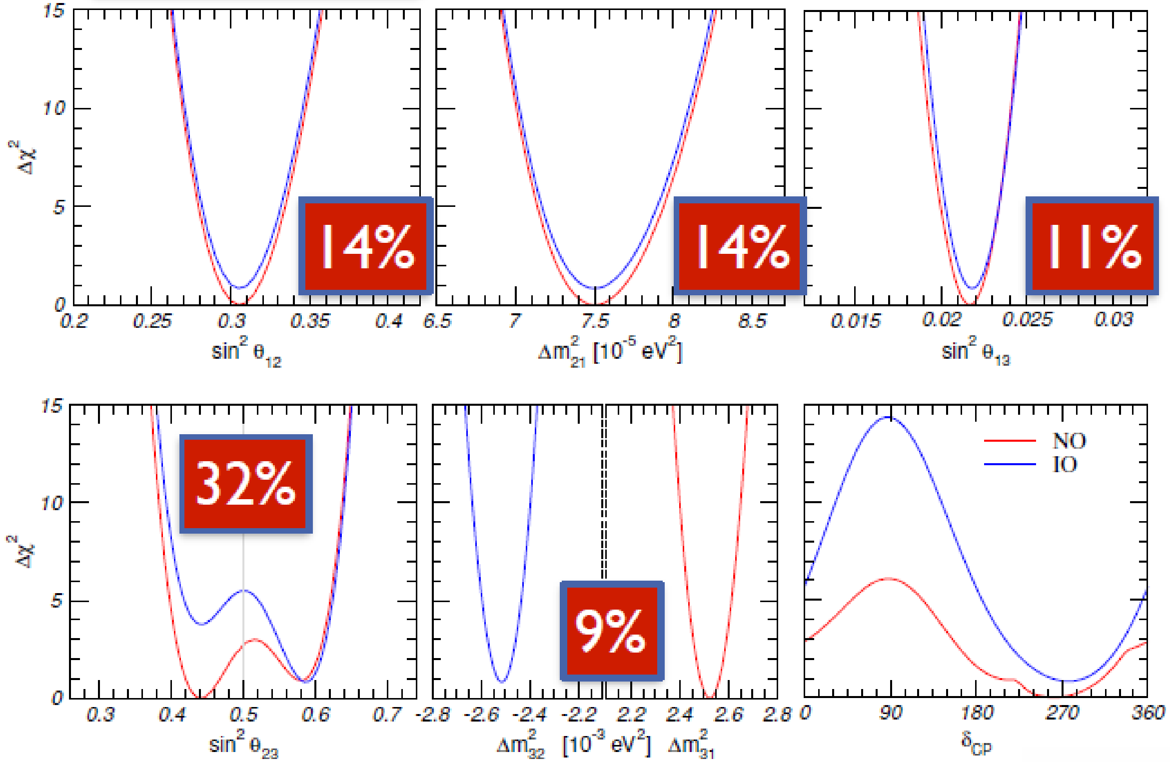


Fresh results from Moriond 2017

Global fits

3-flavour mixing - global fit as of fall 2016

precision at 3σ:



- well determined parameters

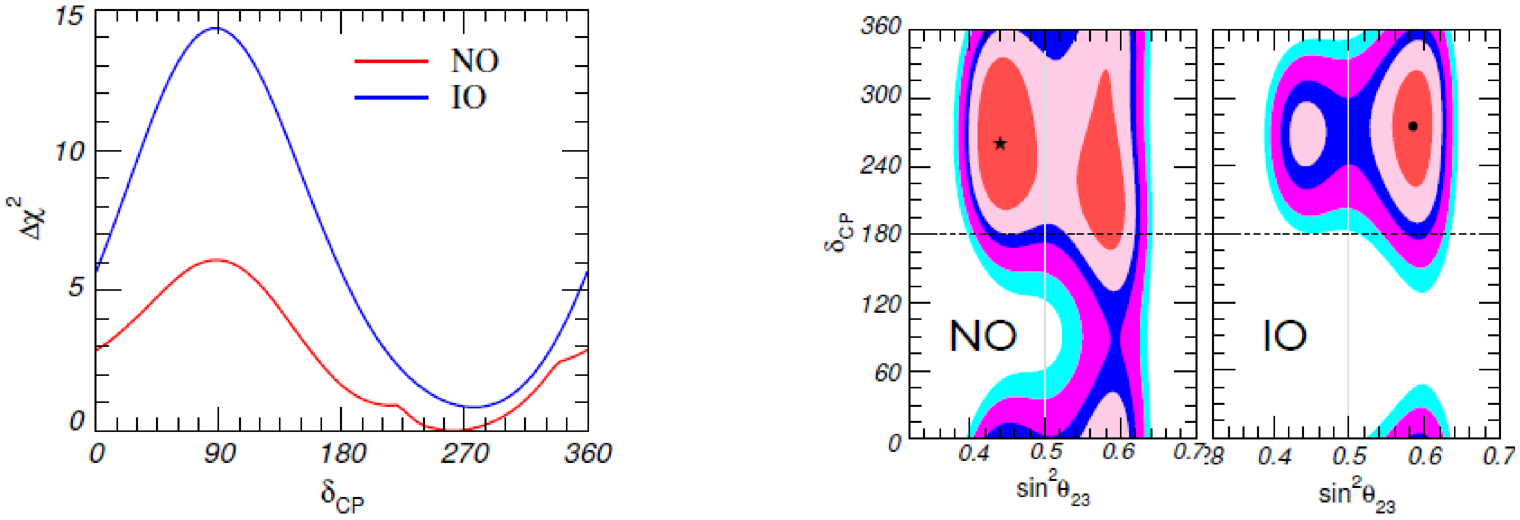
  $\theta_{12}\ \theta_{13}\ \Delta m^2_{21}\ |\Delta m^2_{31}|$

open issues:

- θ_{23}: octant/maximality
- mass ordering
- δ_{CP} : preference for $180° < \delta_{CP} < 360°$

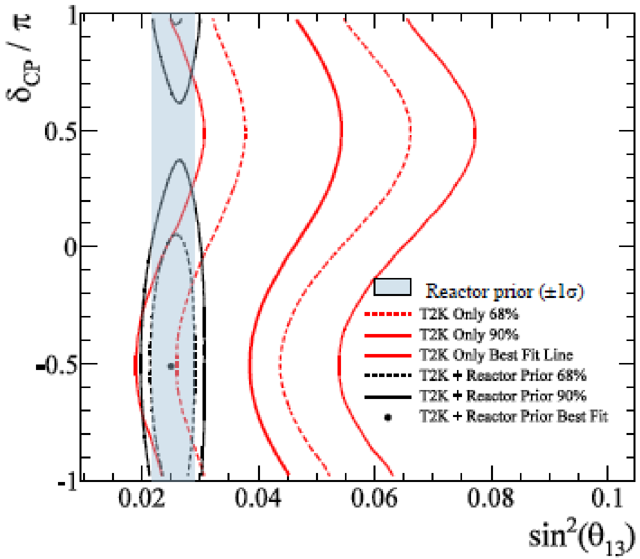
NuFIT 3.0, Esteban et al., 1611.01514 www.nu-fit.org

CP phase from present data



- best fit at $\delta_{CP} \approx 270°$
- correlations with θ_{23}
- CP conservation allowed at 70% CL (NO), 97% CL (IO)
- $\delta_{CP} \approx 90°$ disfavoured with $\Delta\chi^2 \approx 6$ (14) for NO (IO)

Sensitivity from reactor - accelerator complementarity



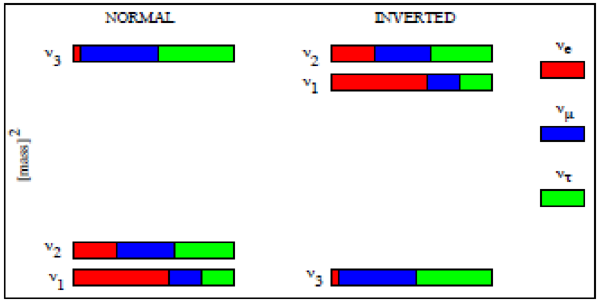
	ν_e		$\bar{\nu}_e$	
Mass hierarchy	Normal	Inverted	Normal	Inverted
$\delta_{CP} = -\pi/2$	28.8	25.5	6.0	6.5
$\delta_{CP} = 0$	24.2	21.2	6.9	7.4
$\delta_{CP} = \pi/2$	19.7	17.2	7.7	8.4
$\delta_{CP} = \pm\pi$	24.2	21.6	6.8	7.4
Data	32		4	

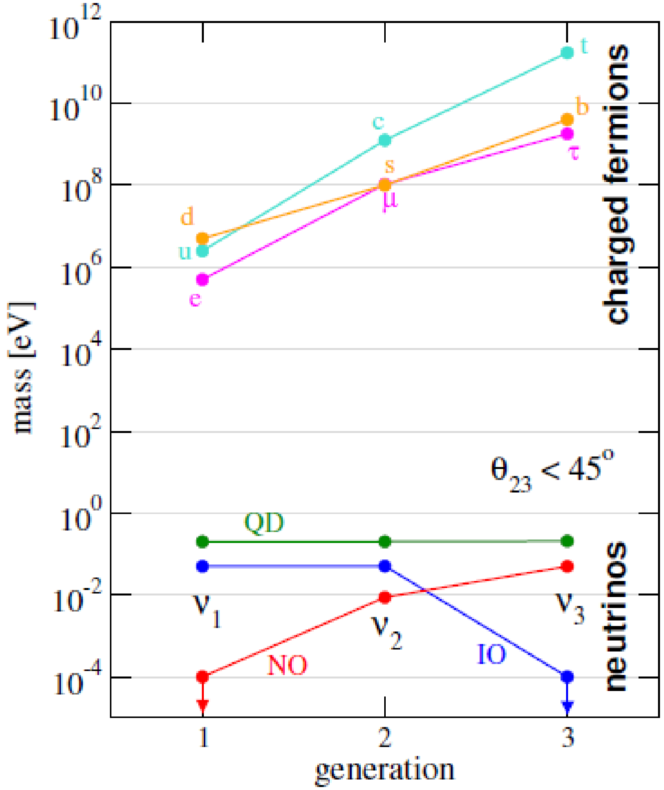
T2K coll., K. Duffy, NuPhys2016, London

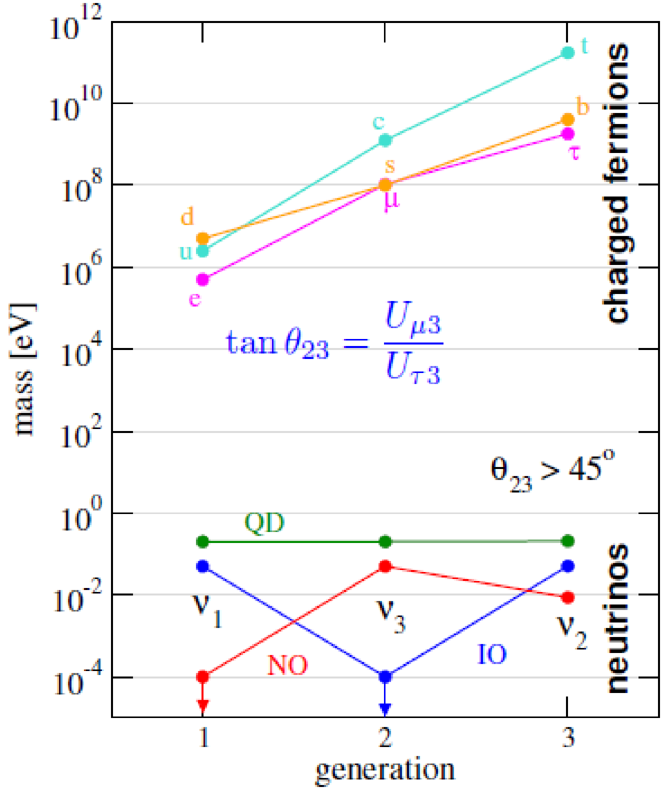
- „lucky“ fluctuation in T2K?
- significance may grow slower than sqrt-N
- significant progress on CP expected in the long term (DUNE, T2HK)

Neutrino mass spectrum

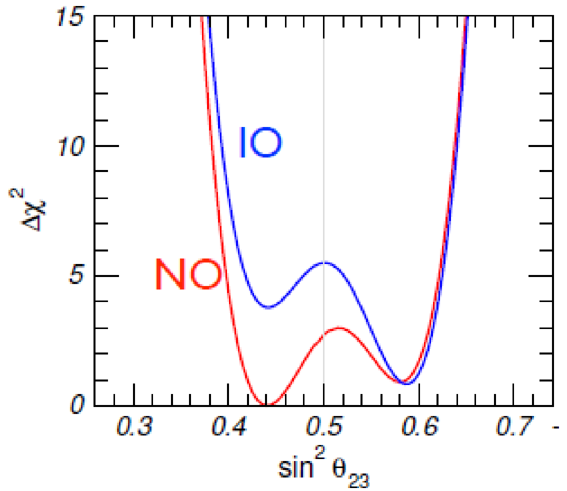
for inverted ordering and/or $\theta_{23} > 45°$
lepton mixing is very different from quarks







Mass ordering and θ_{23}



CL from MC study of LBL and reactor data:

$\delta_{\mathrm{CP,true}}$	NO/2nd Oct.	IO/1st Oct.	IO/2nd Oct.
0°	62%	91%	28%
180°	56%	89%	32%
270°	70%	83%	27%
Gaussian	72%	94%	46%

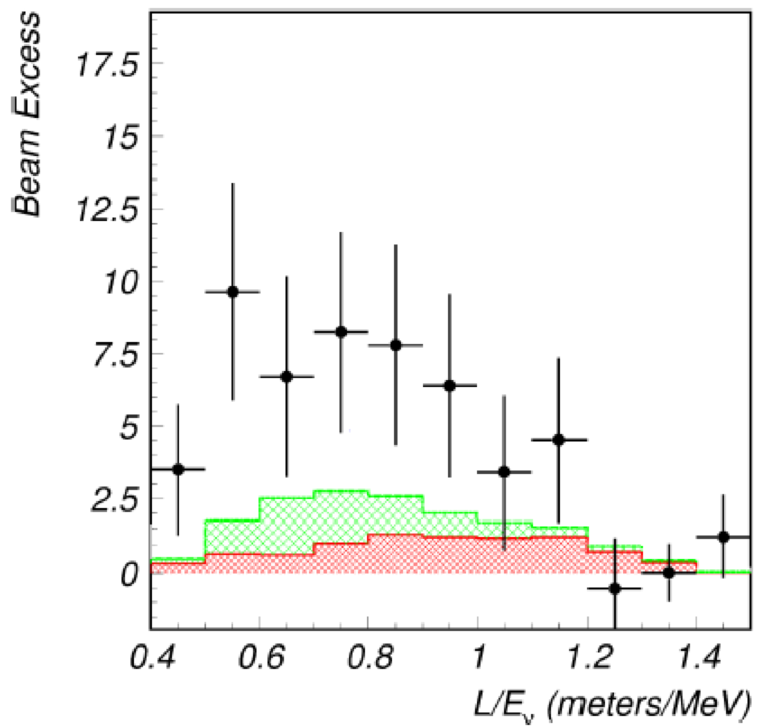
- preferred octant depends on MO, poor sensitivity to octant
- results from global fit for normal vs inverted: $\Delta\chi^2 \approx 1$

Sterile neutrinos

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e \qquad 20\,\text{MeV} \leq E \leq 52.8\,\text{MeV}$



- Well-known and pure source of $\bar{\nu}_\mu$

$$p + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow[\text{at rest}]{} e^+ + \nu_e + \bar{\nu}_\mu$$

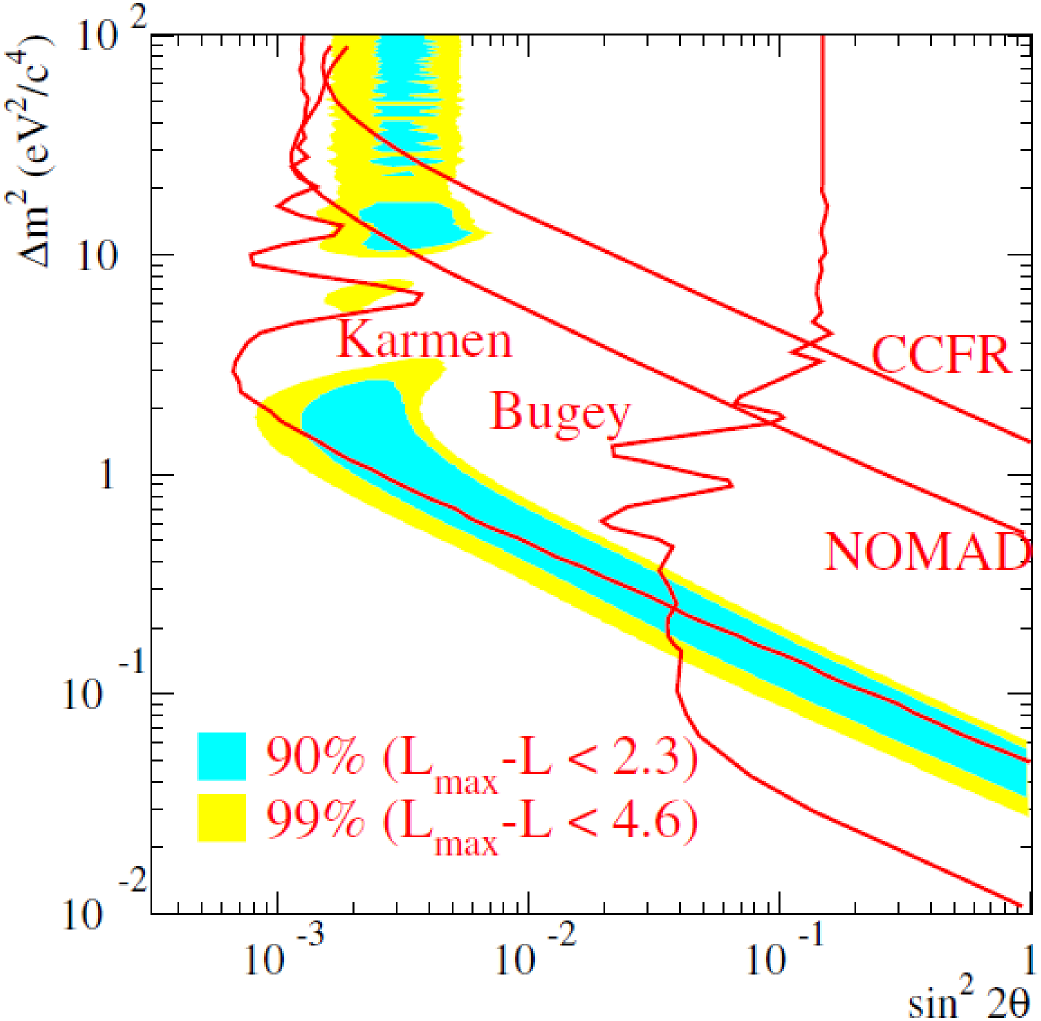
$L \simeq 30\,\text{m}$

$$\bar{\nu}_e + p \to n + e^+$$

Well-known detection process of $\bar{\nu}_e$

- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

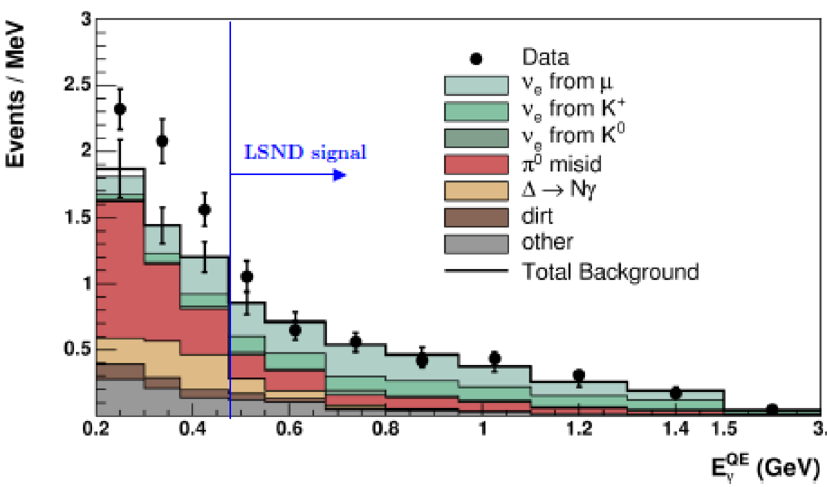


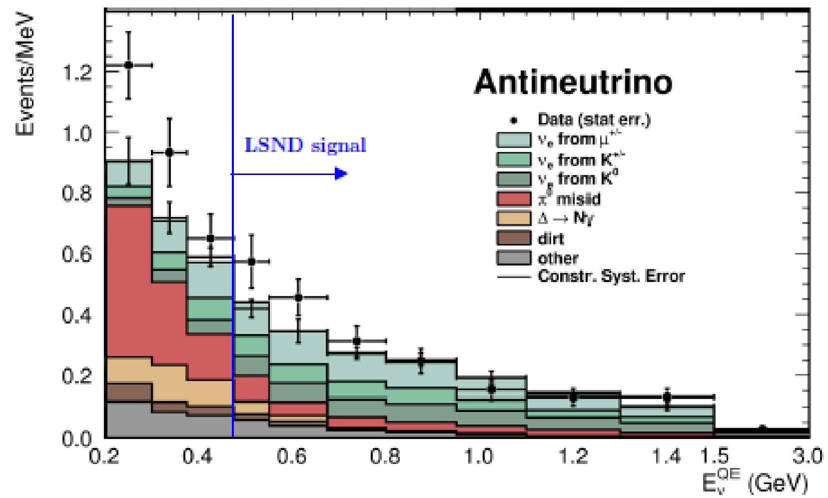
$$\Delta m^2_{\rm SBL} \gtrsim 3 \times 10^{-2}\,{\rm eV}^2 \gg \Delta m^2_{\rm ATM} \simeq 2.5 \times 10^{-3}\,{\rm eV}^2 \gg \Delta m^2_{\rm SOL}$$

MiniBooNE

$L \simeq 541\,\mathrm{m}$ $\quad$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802] $\quad$ $\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]





- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\mathrm{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

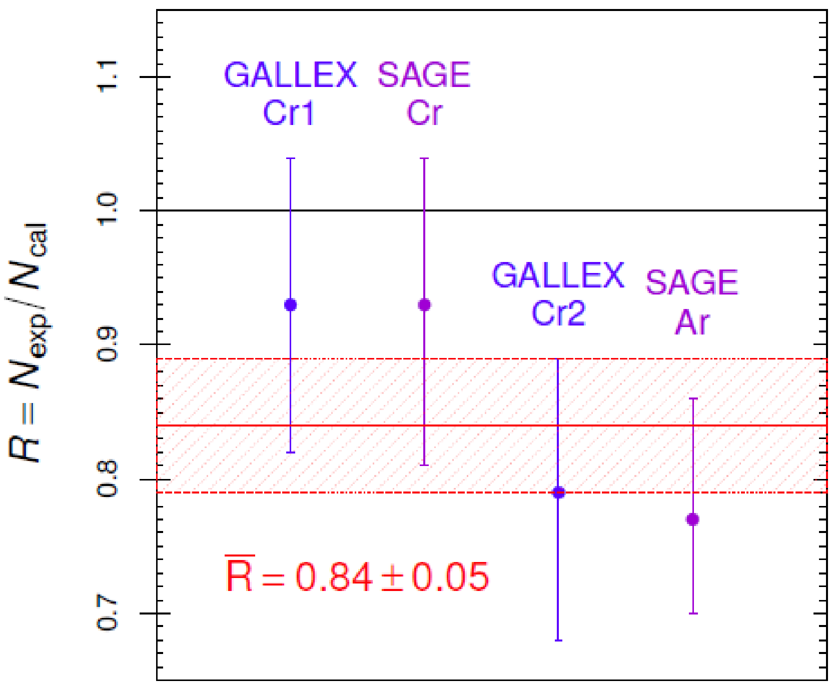
Gallium Anomaly

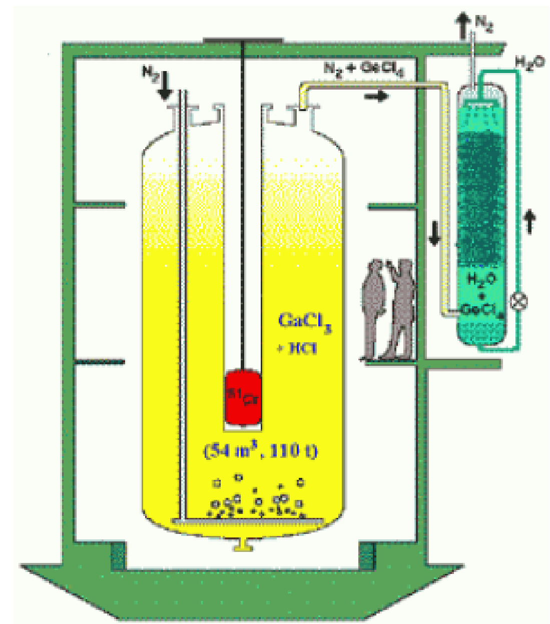
Gallium Radioactive Source Experiments: GALLEX and SAGE

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad$ $e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

$E \simeq 0.75\,\text{MeV}$ $\quad$ $E \simeq 0.81\,\text{MeV}$

Test of Solar ν_e Detection: $\quad$ $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$



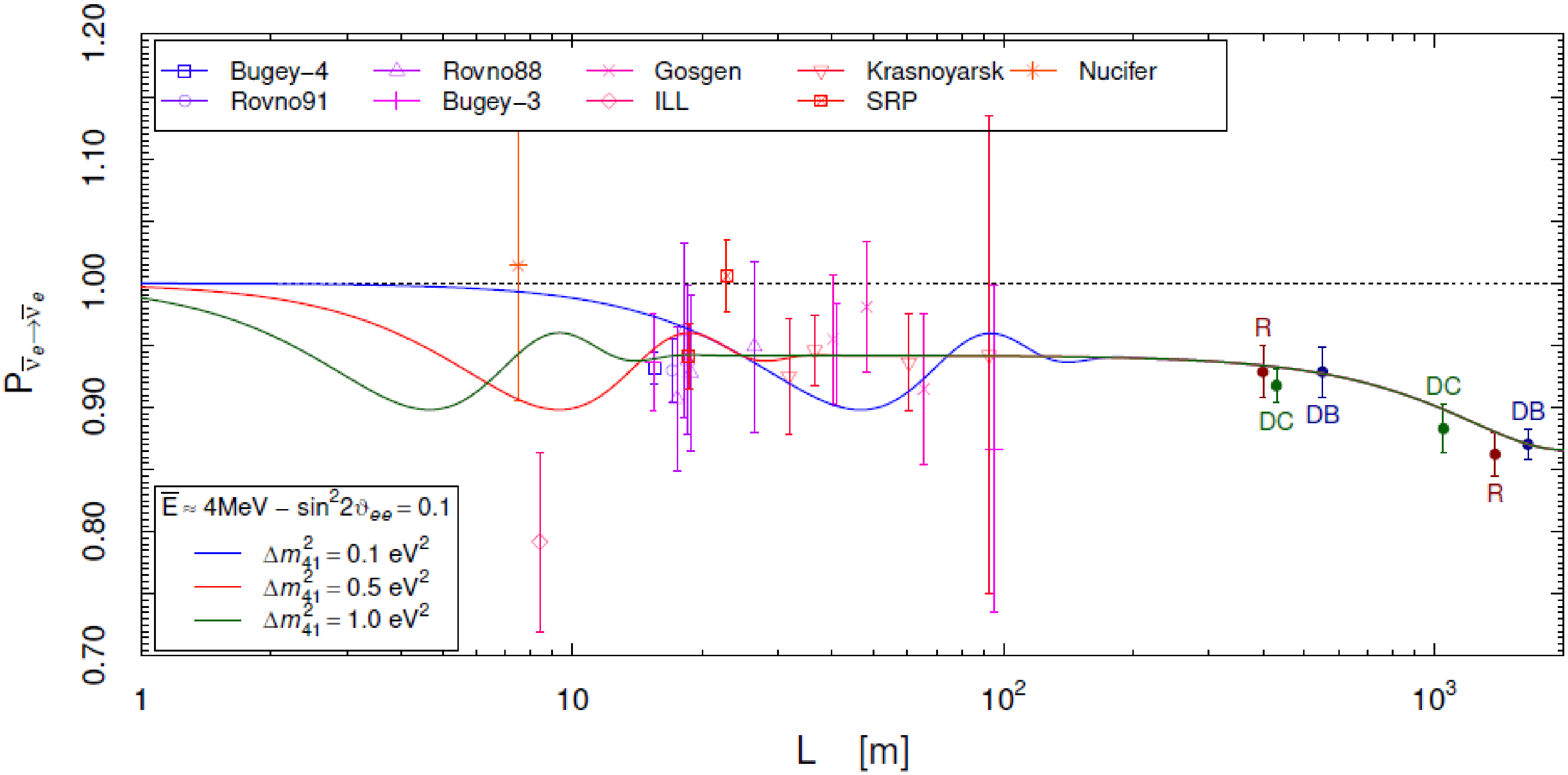


$\approx 2.9\sigma$ deficit

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$ $\quad$ $\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

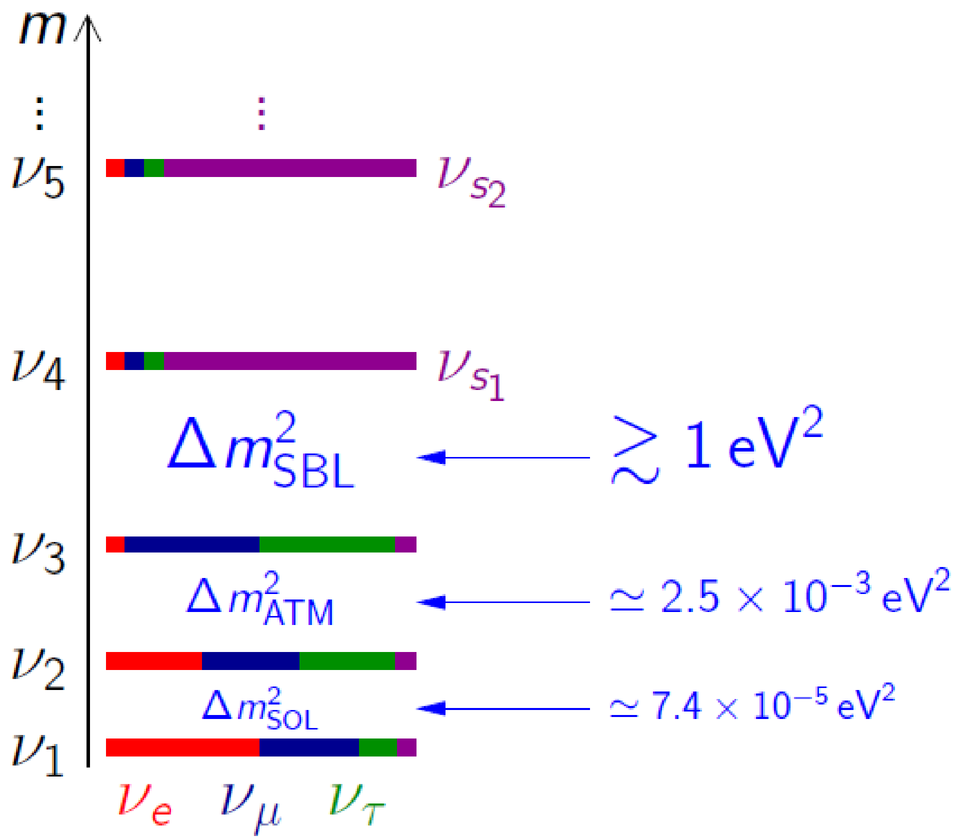
$$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$$

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]



$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$$

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino
means: a eV-scale massive neutrino which is mainly sterile

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

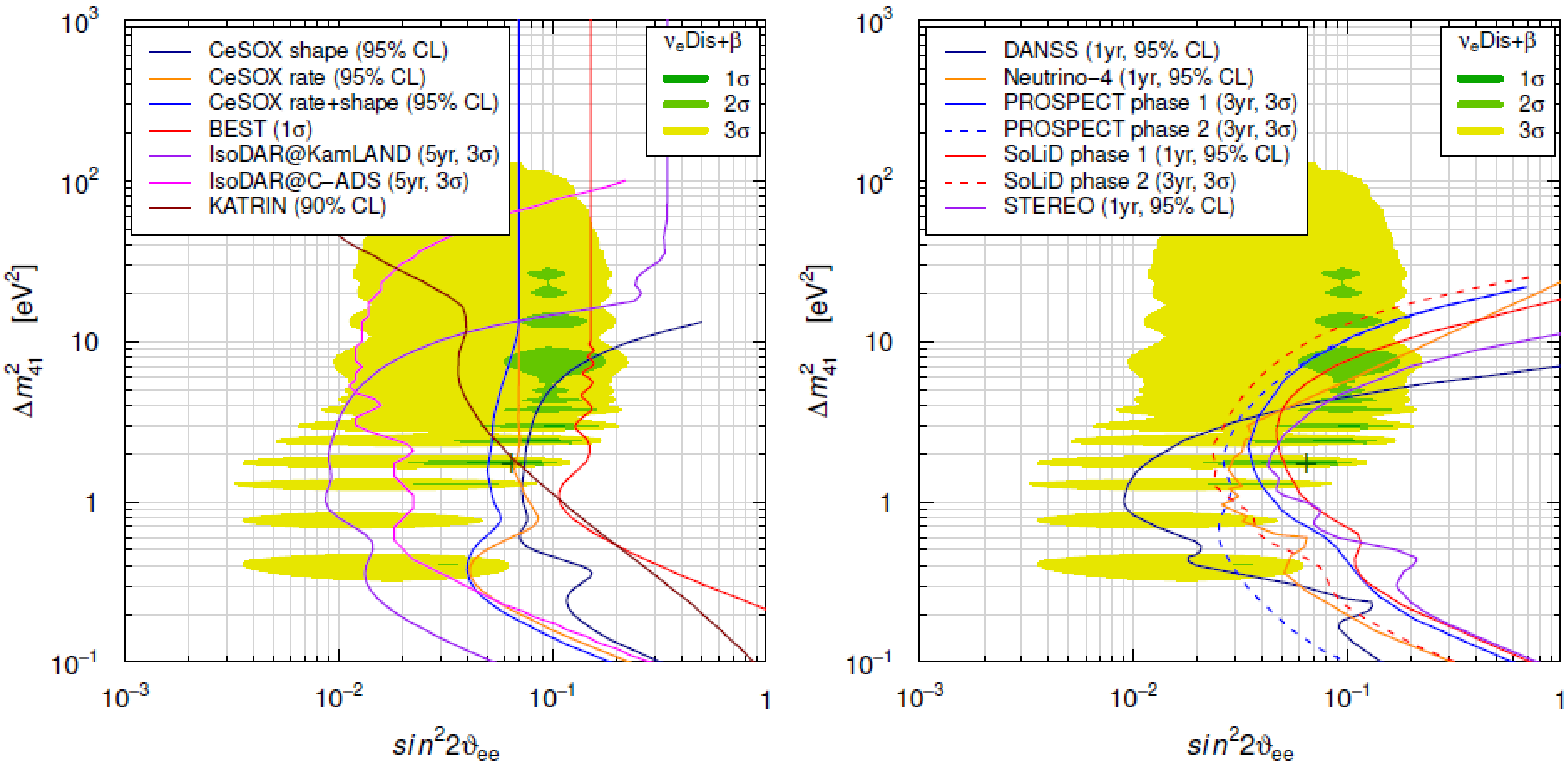
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL (4th column)

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Gandhi et al, JHEP 1511 (2015) 039] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

The Race for ν_e and $\bar{\nu}_e$ Disappearance



CeSOX (Gran Sasso, Italy) $^{144}\text{Ce} \to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

BEST (Baksan, Russia) $^{51}\text{Cr} \to \nu_e$
$L \simeq$ 5-12m [PRD 93 (2016) 073002]

IsoDAR@KamLAND (Kamioka, Japan)
$^{8}\text{Li} \to \bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

IsoDAR@C-ADS (Guangdong, China)
$^{8}\text{Li} \to \bar{\nu}_e$ $L \simeq$ 15m [JHEP 1601 (2016) 004]

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]

Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]

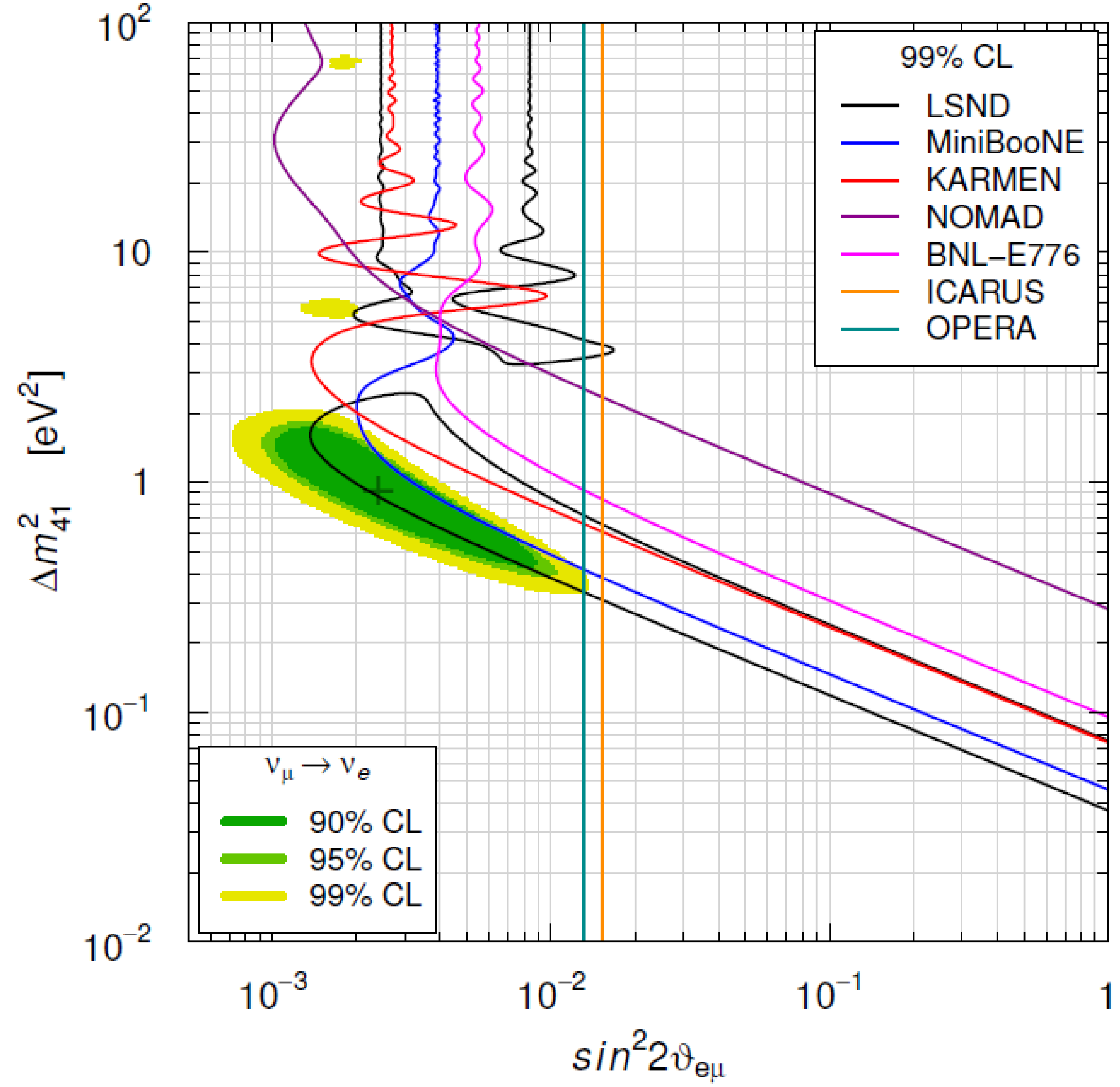
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]

SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]

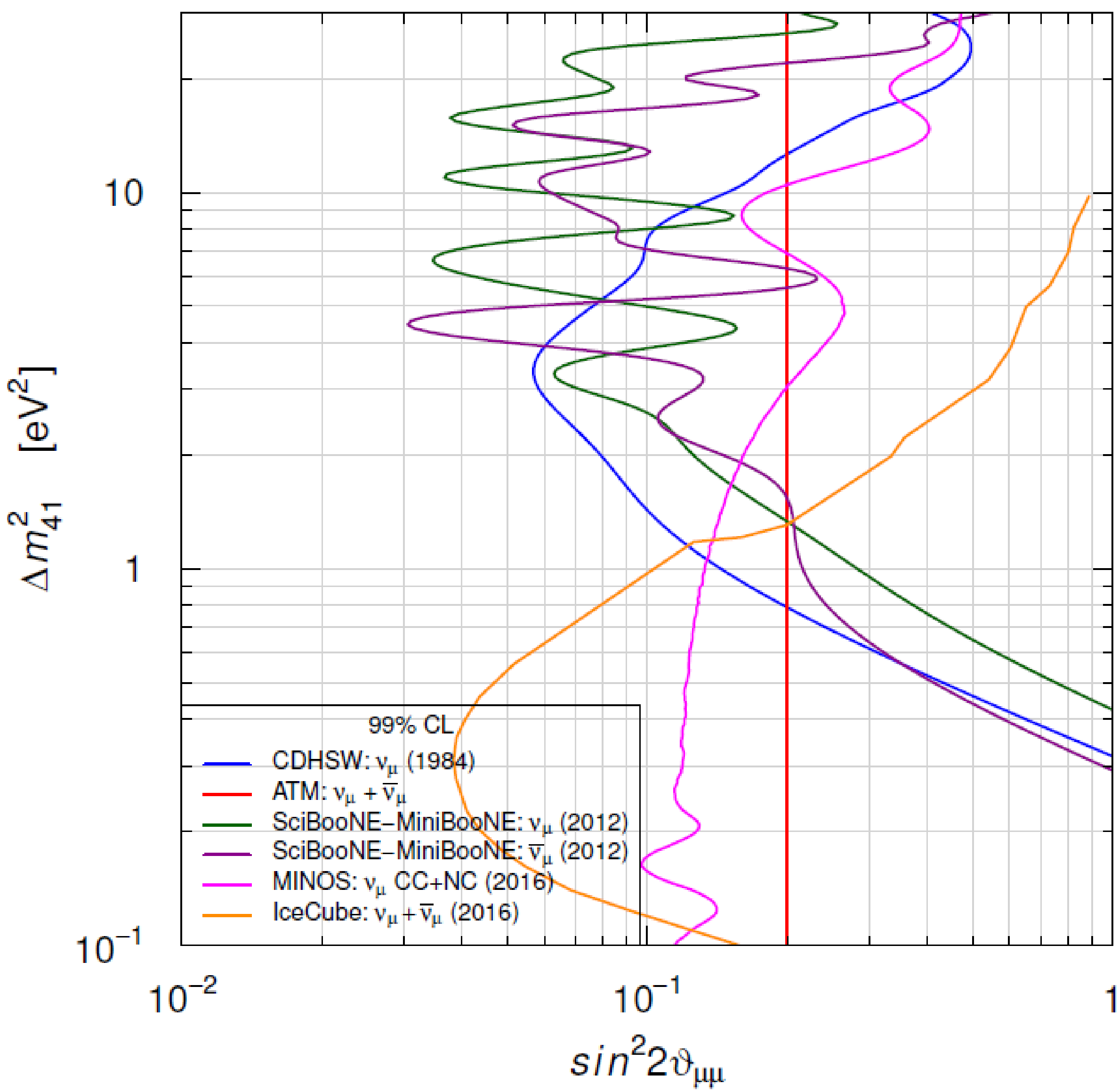
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

KATRIN (Karlsruhe, Germany) $^{3}\text{H} \to \bar{\nu}_e$ [Drexlin@NOW2016]

$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

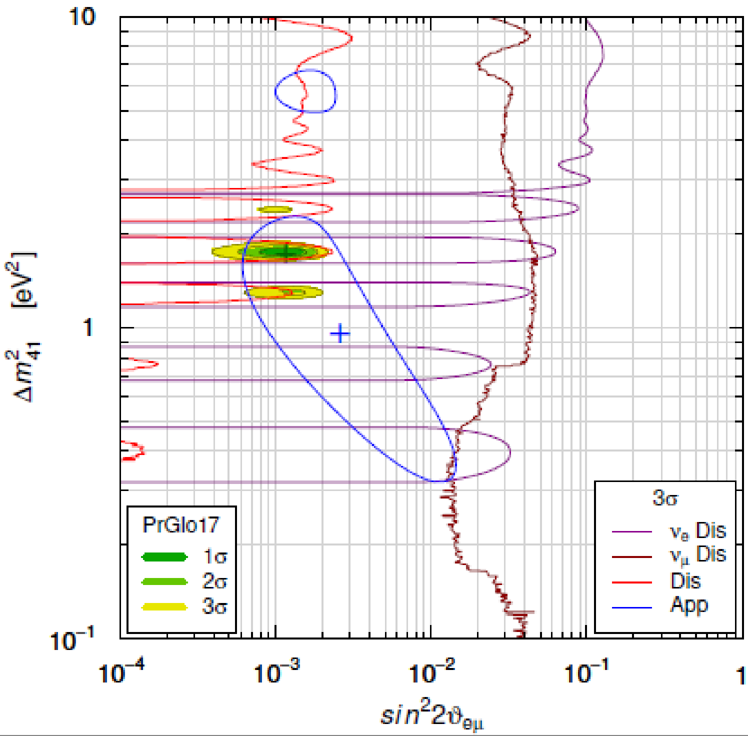
ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- PrGlo17 = Pragmatic Global Fit 2017
  [Gariazzo, CG, Laveder, Li, arXiv:1703.00860]
- $\Delta\chi^2_{\text{NO}} = 46.5 \Rightarrow \approx 6.0\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $|U_{e4}|^2 = 0.019 \quad |U_{\mu4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 594.8/579 \Rightarrow \text{GoF} = 32\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 3\%$
- Similar tension in 3+2, 3+3, ..., 3+N_s
  [CG, Zavanin, MPLA 31 (2015) 1650003]

Conclusions

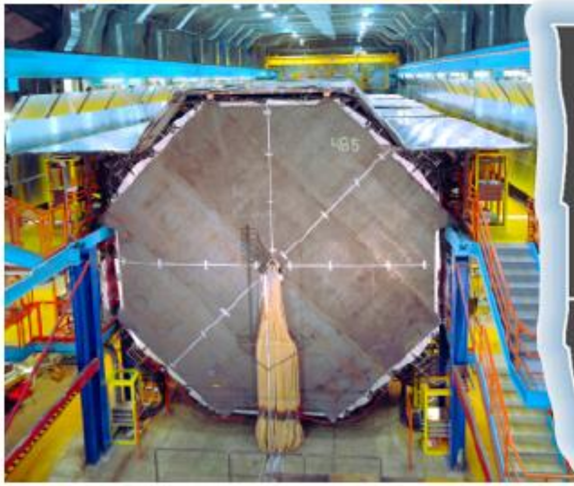
- Exciting indications of light sterile neutrinos at the eV scale:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.
  - Gallium ν_e disappearance.
  - Reactor $\bar{\nu}_e$ disappearance.
- Vigorous experimental program to check conclusively in a few years:
  - ν_e and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.
  - $\nu_\mu \to \nu_e$ transitions with accelerator neutrinos.
  - ν_μ disappearance with accelerator neutrinos.
- Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.
- Cosmology: strong tension with $\Delta N_{\text{eff}} = 1$ and $m_4 \approx 1\,\text{eV}$. It may be solved by a non-standard cosmological mechanism.
- Possibilities for the next years:
  - Reactor and source experiments ν_e and $\bar{\nu}_e$ observe SBL oscillations: big excitement and explosion of the field.
  - Otherwise: still marginal interest to check the LSND appearance signal.
  - In any case the possibility of the existence of sterile neutrinos related to New Physics beyond the Standard Model will continue to be studied (e.g keV sterile neutrinos).

Fresh results from Moriond 2017

MINOS+ on sterile νs

MINOS Detectors

Far Detector



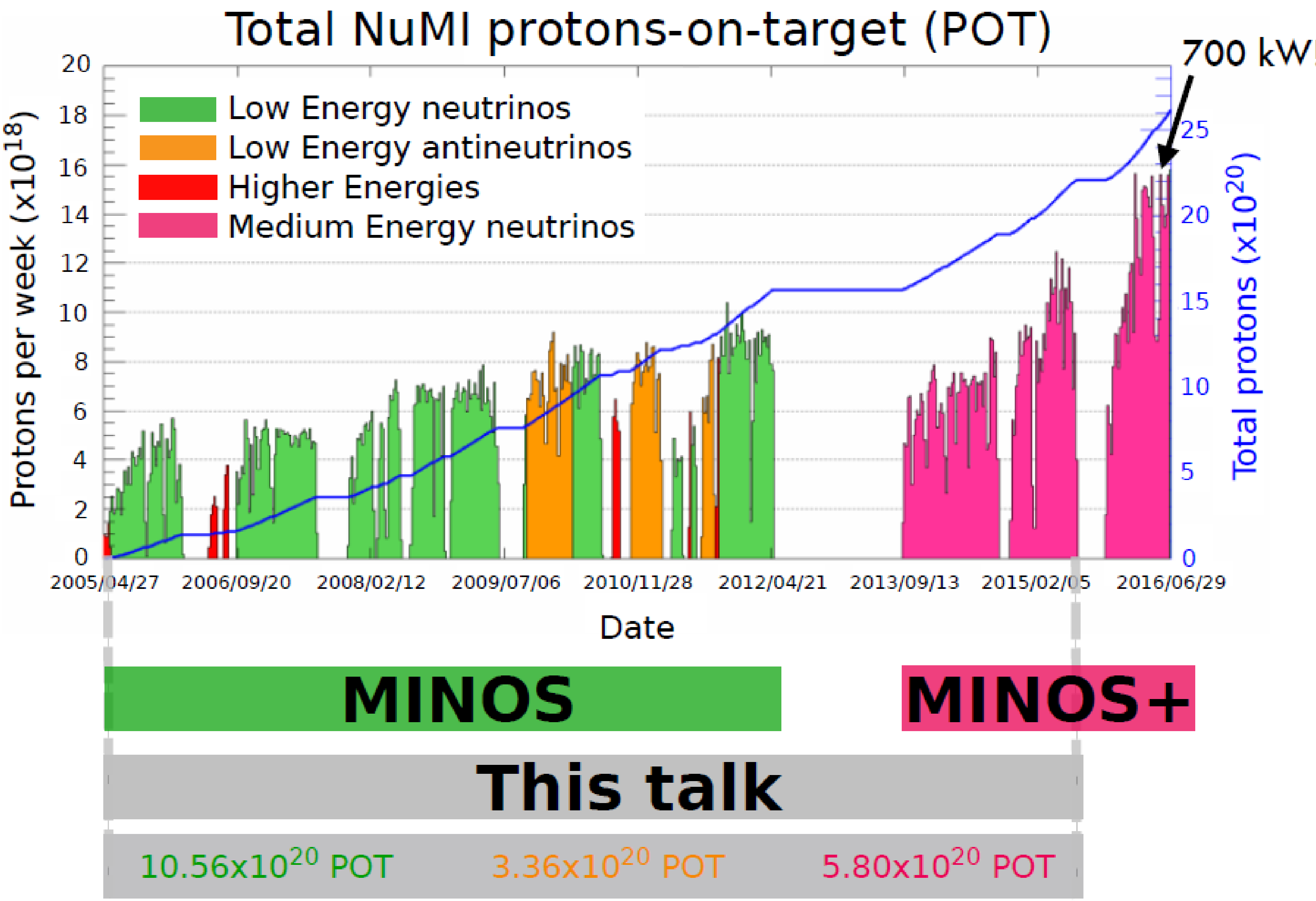
- 735 km from target
- 705 m underground
- 5.4 ktons

Near Detector

- 1 km from target
- 104 m underground
- 980 tons

- On-axis long-baseline neutrino oscillation experiment
- Functionally equivalent detectors
- Magnetized steel tracking sampling calorimeters

Data



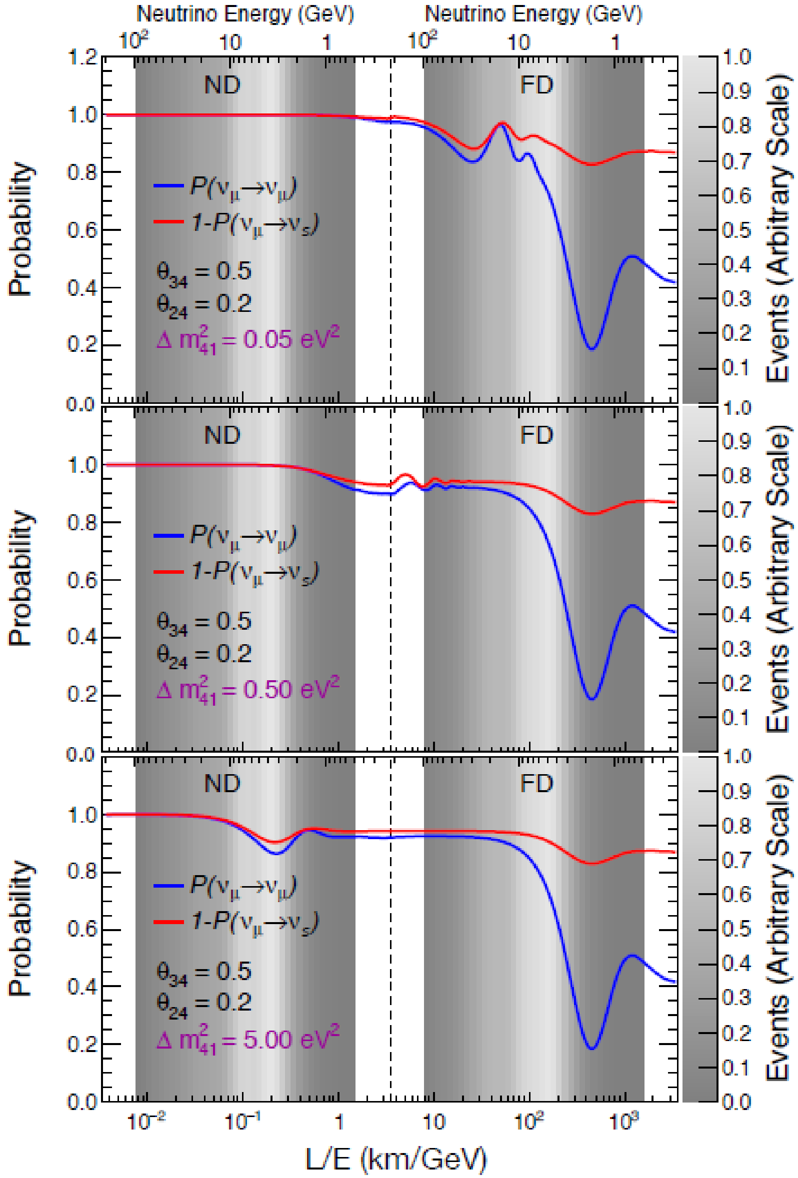
Total NuMI protons-on-target (POT)
700 kW!
Low Energy neutrinos
Low Energy antineutrinos
Higher Energies
Medium Energy neutrinos
Protons per week (x10^18)
Total protons (x10^20)
20
18
16
14
12
10
8
6
4
2
0
25
20
15
10
5
0
2005/04/27
2006/09/20
2008/02/12
2009/07/06
2010/11/28
2012/04/21
2013/09/13
2015/02/05
2016/06/29
Date
MINOS
MINOS+
This talk
10.56x10^20 POT
3.36x10^20 POT
5.80x10^20 POT

4-Flavor Oscillations at MINOS

Small

Δm^2_{41}

Large



- Small Δm^2_{41}
  - Oscillations at the FD
- Medium Δm^2_{41}
  - Rapid oscillations at the FD
- Large Δm^2_{41}
  - Large oscillations at the ND

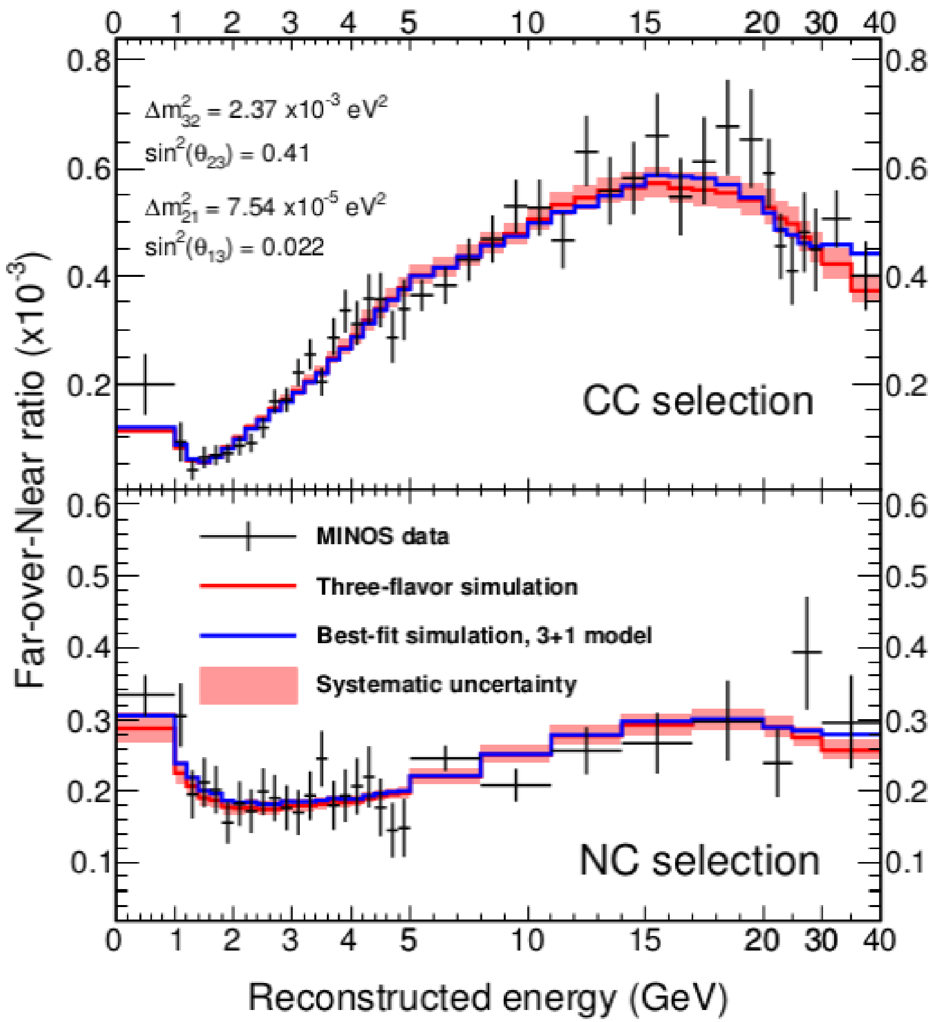
MINOS 4-Flavor Analysis

- Fit oscillated Far-over-Near MC energy spectrum ratio directly to Far-over-Near data energy spectrum ratio

- Fit the CC and NC spectra simultaneously to determine θ_{23}, θ_{24}, θ_{34}, Δm^2_{32}, and Δm^2_{41}

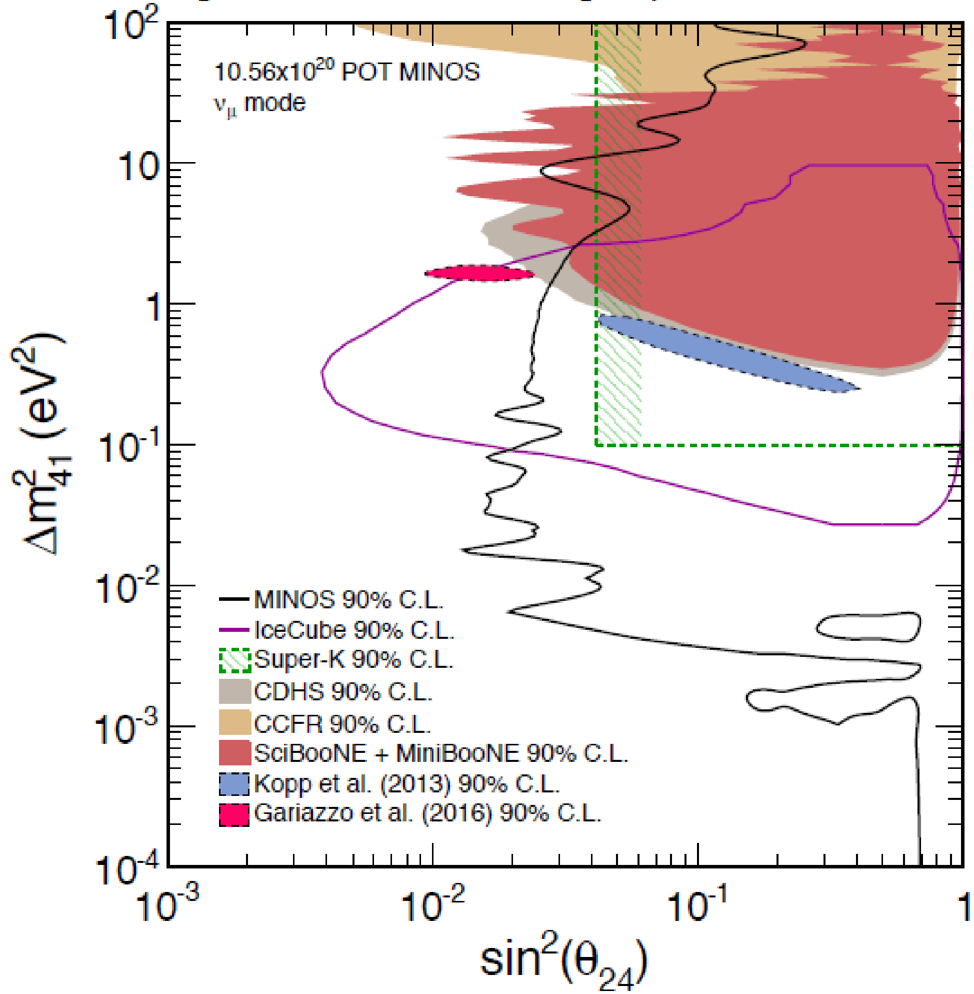
- Fix δ_{13}, δ_{14}, δ_{24}, and θ_{14} to zero (insensitive to these terms)

- The systematics are included through a covariance matrix



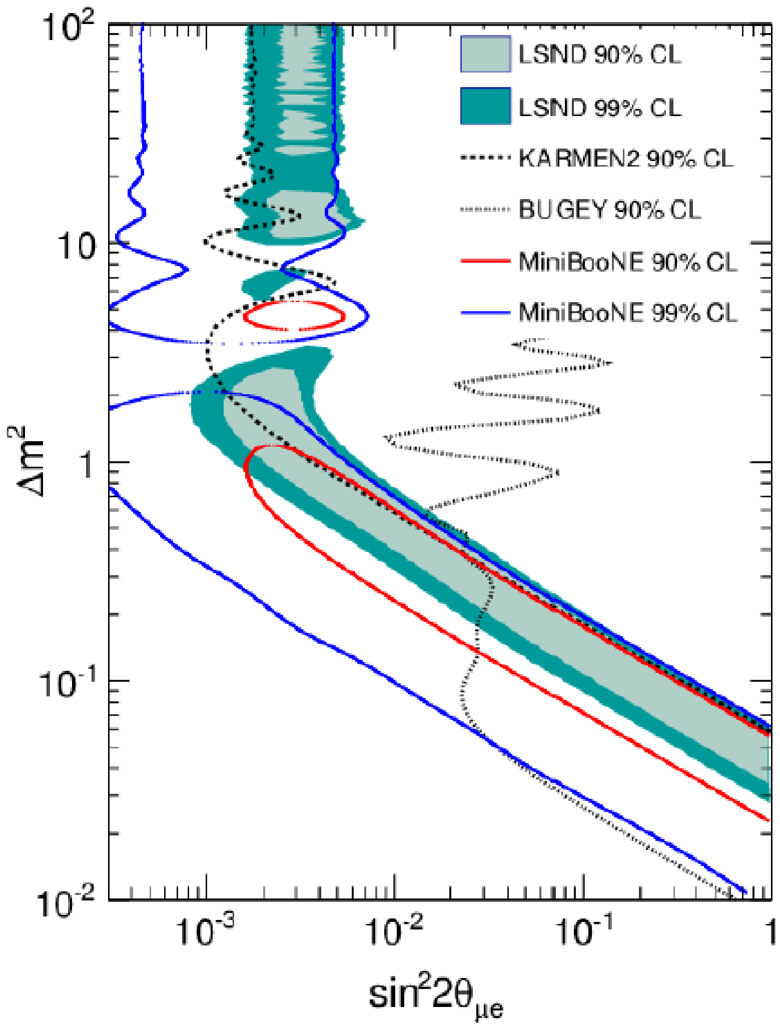
ν_μ Disappearance Limit

P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. Lett. **117**, 151803 (2016)



Global Fits:
1) J. Kopp, P. Machado, M. Maltoni, T. Schwetz, JHEP 1305:050 (2013)
2) S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J. Phys. G **43**, 033001 (2016)

Combination with ν_e Disappearance



$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

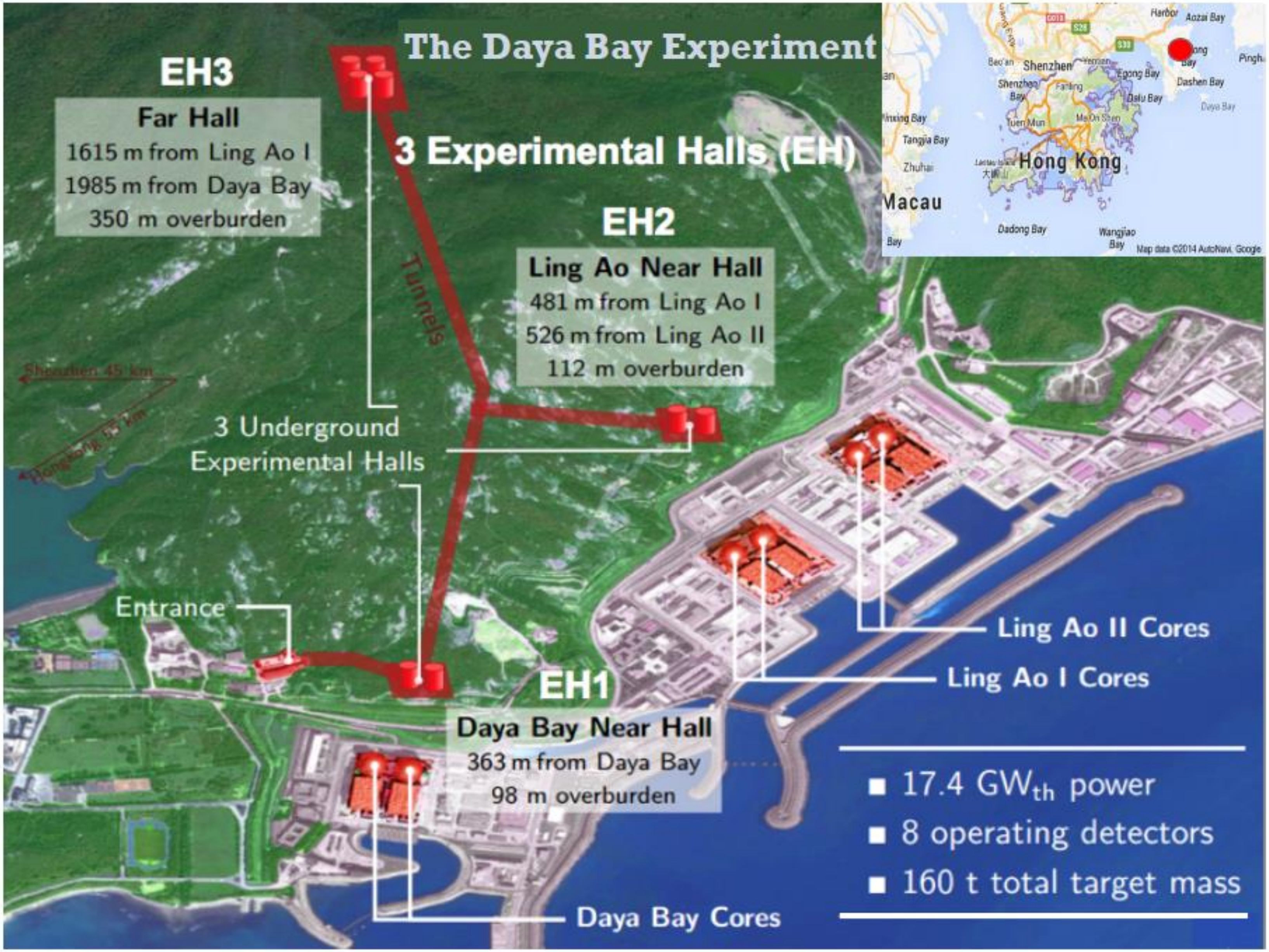
ν_μ disappearance

ν_μ to ν_e appearance

$$\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}|^2|U_{\mu 4}|^2$$

ν_e disappearance

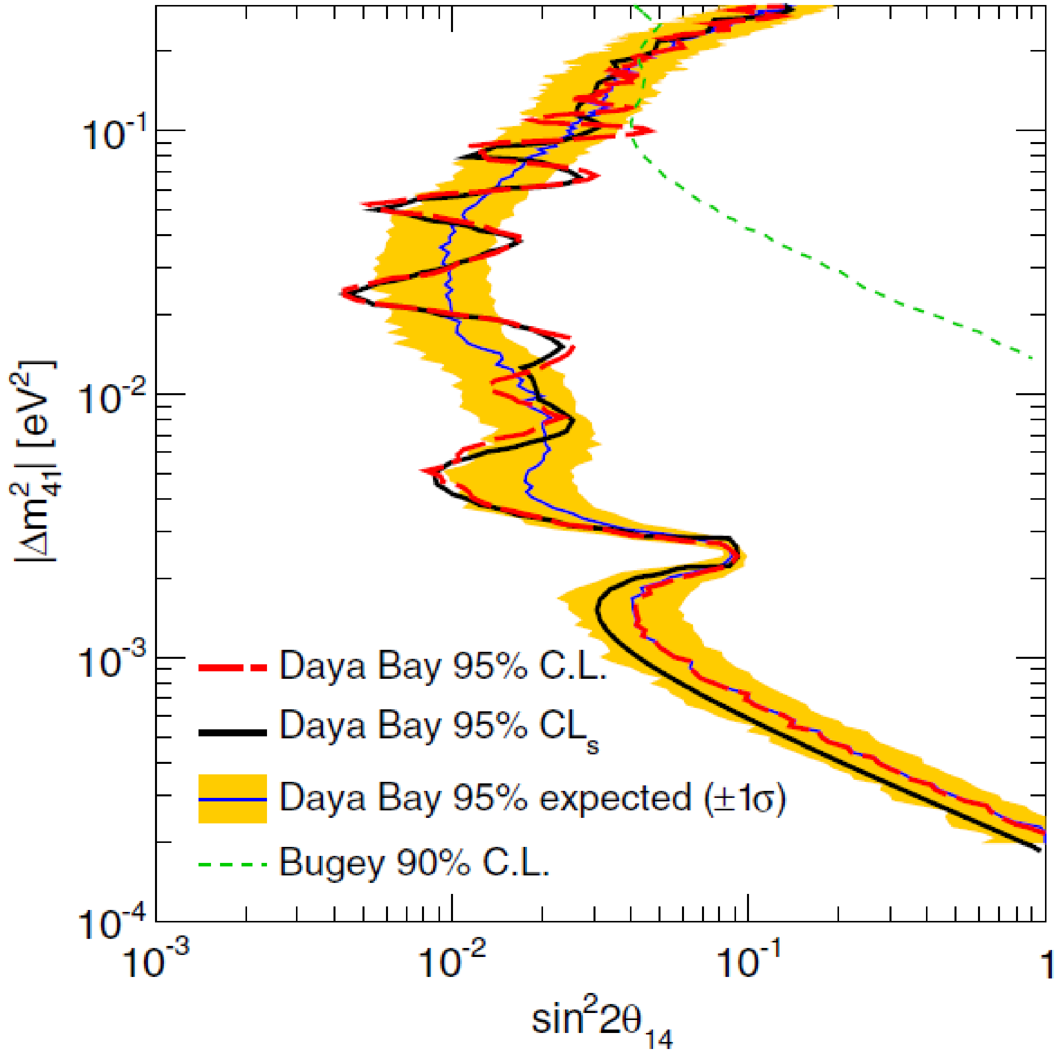
$$\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$$



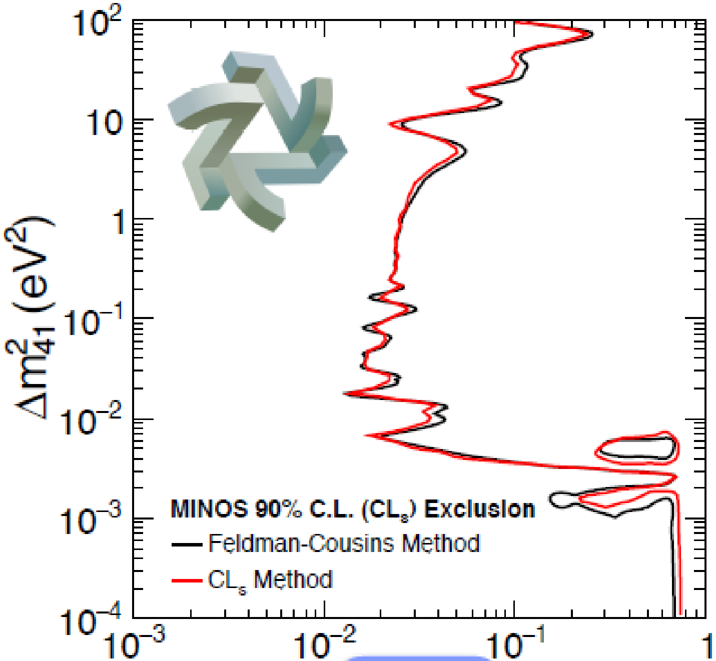
The Daya Bay Experiment
EH3
Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden
3 Experimental Halls (EH)
Tunnels
EH2
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
3 Underground
Experimental Halls
Entrance
EH1
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Cores
■ 17.4 GW_{th} power
■ 8 operating detectors
■ 160 t total target mass
Shenzhen
Hong Kong
Macau

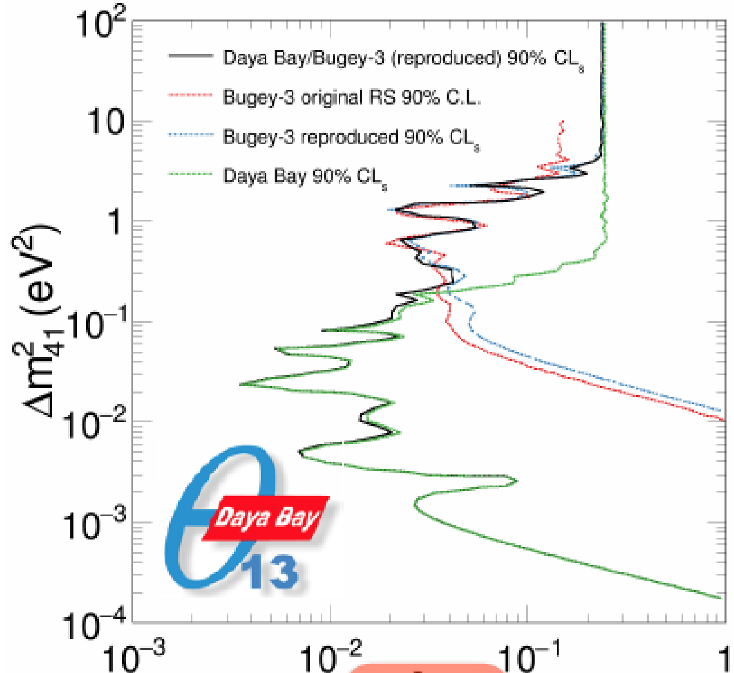
Daya Bay $\bar{\nu}_e$ Disappearance Limit

F. P. An *et al.* [Daya Bay Collaboration], Phys. Rev. Lett. **117**, 151802 (2016)



Combination Method



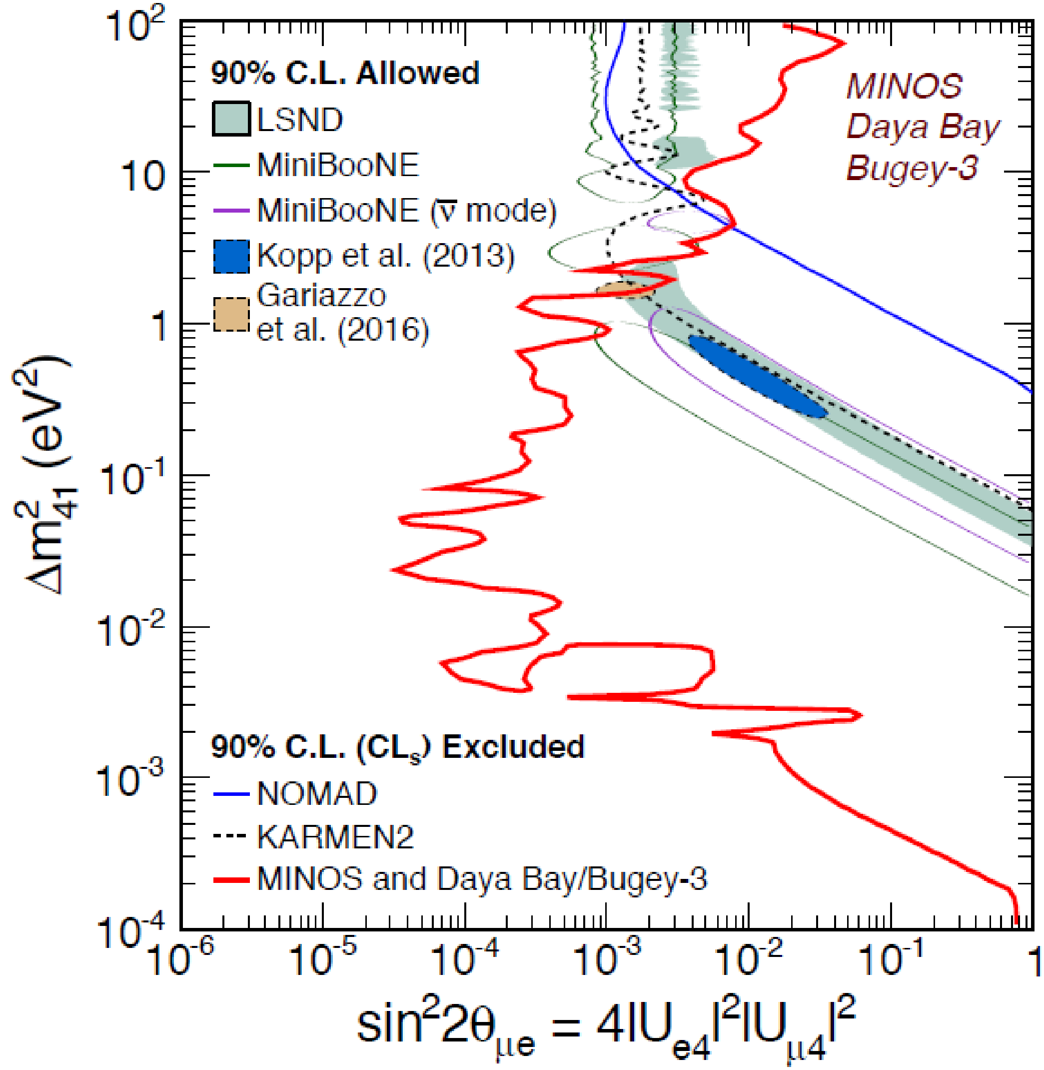


$\sin^2\theta_{24}$ $\sin^2 2\theta_{14}$

LSND & MiniBooNE $$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

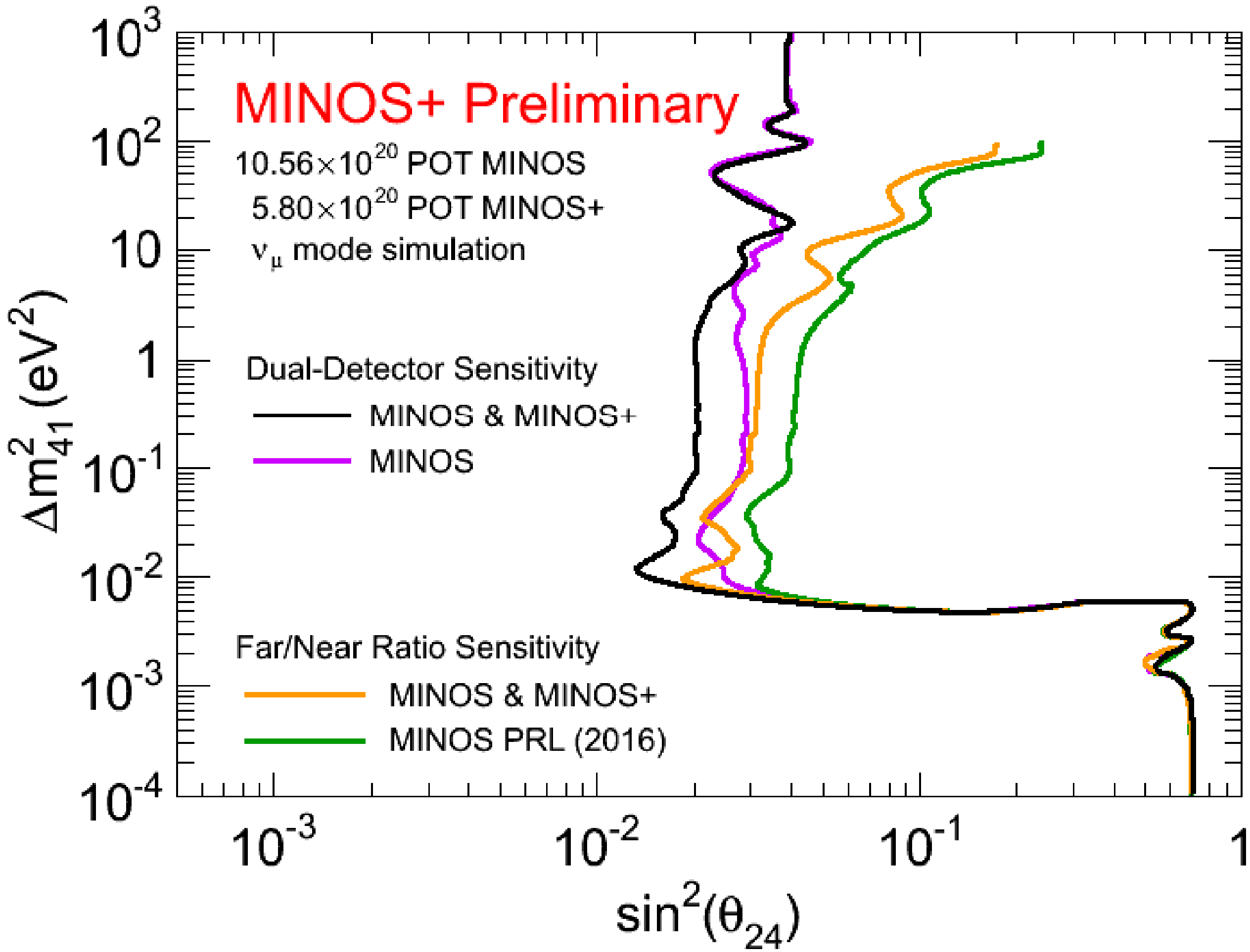
Combined - 90% C.L.

P. Adamson *et al.* [Daya Bay and MINOS Collaborations], Phys. Rev. Lett. **117**, 151801 (2016)



New Fitting Technique

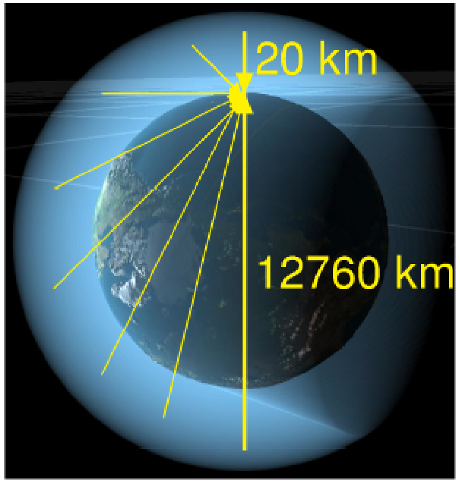
New: fit two detector energy spectra simultaneously
instead of Far-over-Near ratio



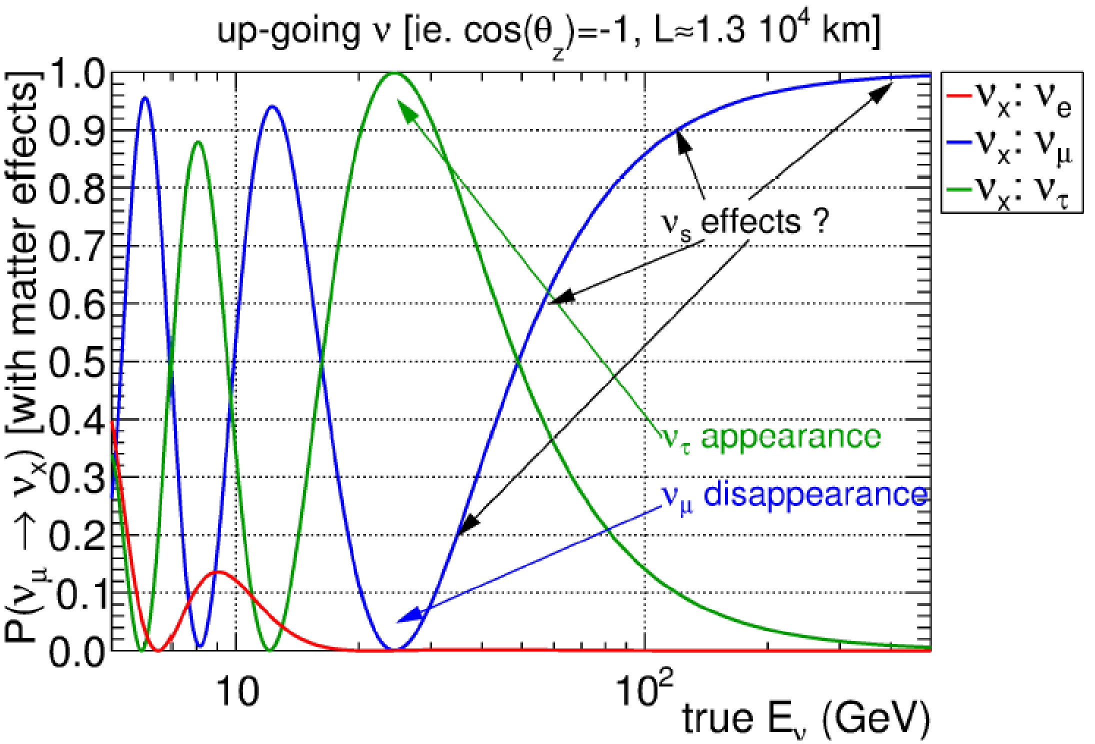
Fresh results from Moriond 2017

IceCube one sterile νs

Neutrino oscillations with atmospheric neutrinos



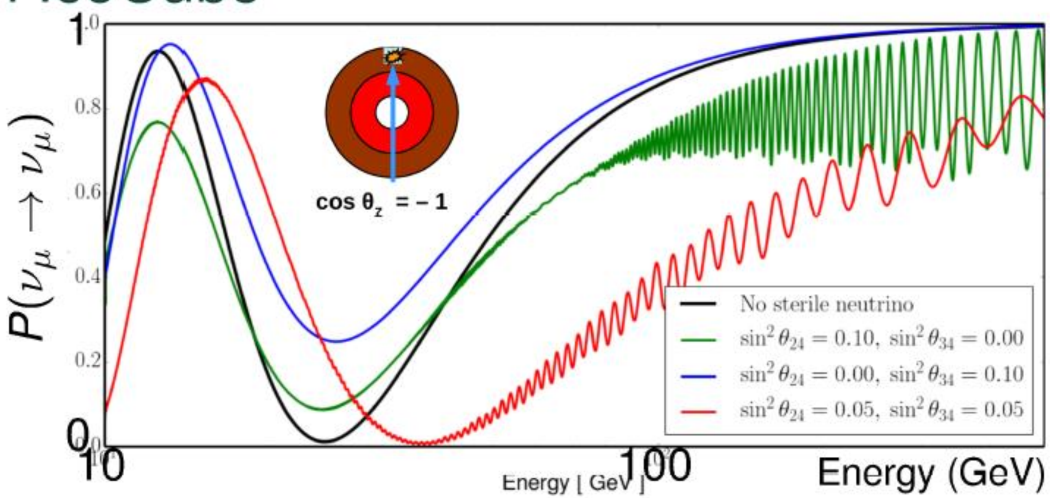
- Several baselines available
  - L/E dependency on oscillation
  - Many orders of magnitude in E
- IceCube:
  - See clear ν_μ disappearance
  - Look for distortions in regular oscillations $\Rightarrow$ sterile neutrino searches



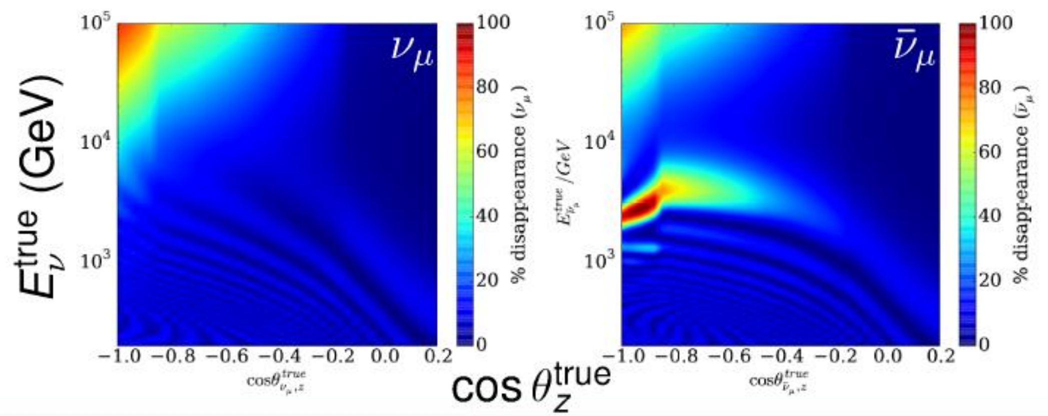
- IceCube not (very) sensitive to:
  - Neutrino mass ordering, δ_{CP}, ν_e appearance

Sterile Neutrino Signatures in IceCube

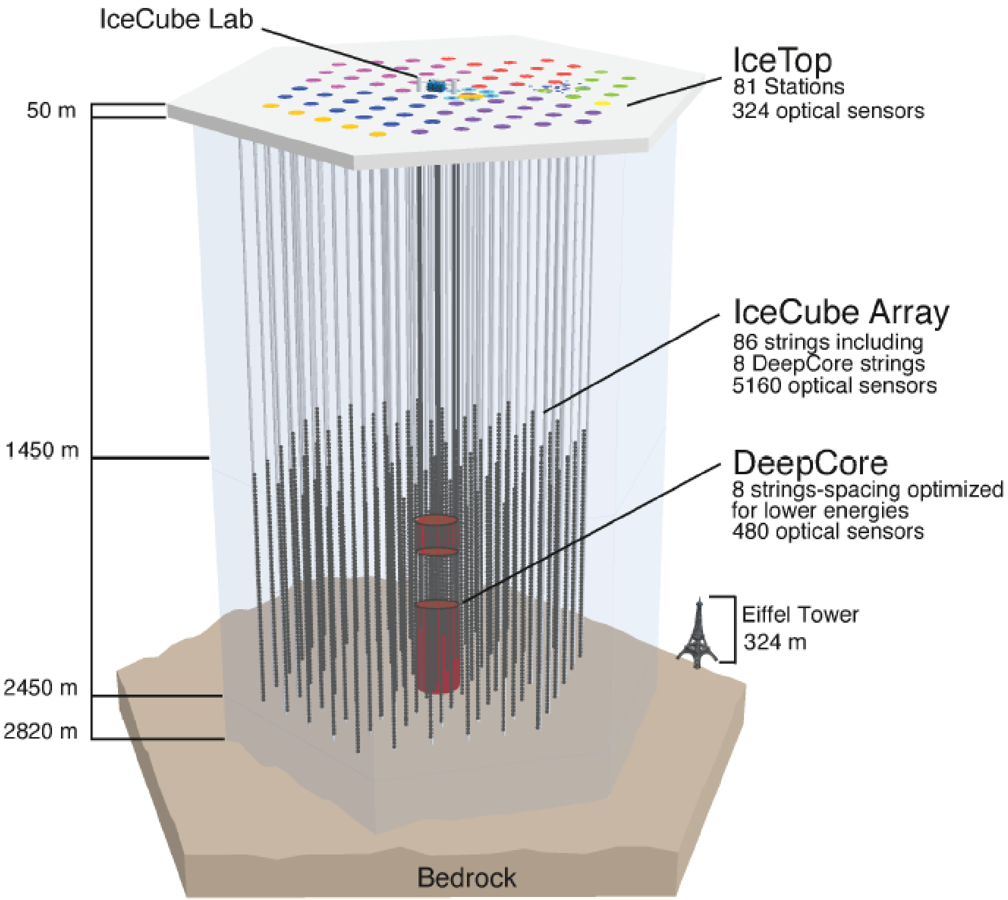
- Signature LE: distortion in ν_μ disappearance
  - At 10-100 GeV
  - Sensitive to $\nu_\mu \leftrightarrow \nu_s \leftrightarrow \nu_\tau$
  - Not sensitive to Δm^2
    - ★ "Averaged out" effect



- Signature HE: new ν_μ disappearance maxima
  - At 0.5-10 TeV
  - Sensitive to $\nu_\mu \leftrightarrow \nu_s$
  - Sensitive to Δm^2
  - Resonant enhancement from matter effects
    - ★ highly sensitive to θ



IceCube

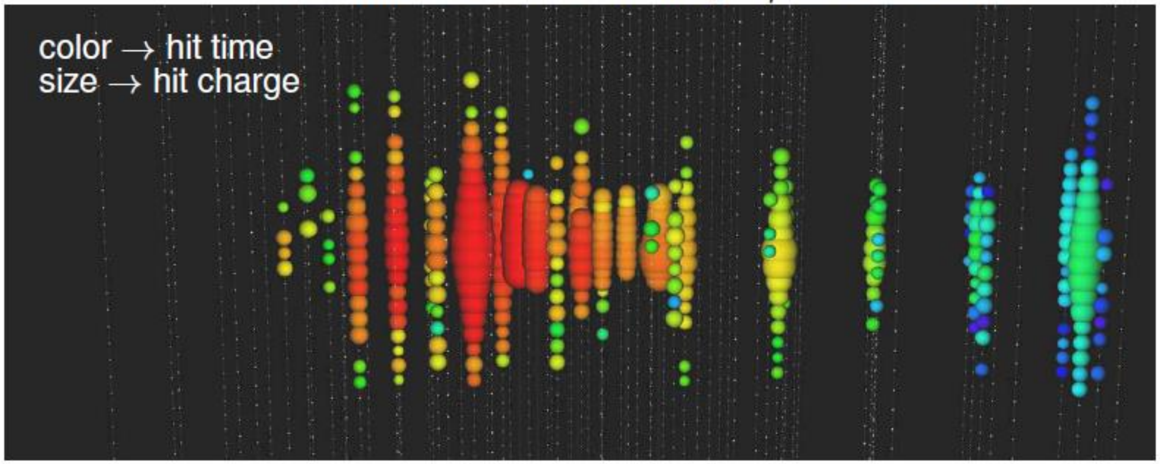


- Instrument 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical ν discovered!
  - Sensitive to the ν_s HE signature
- At it's center: DeepCore
  - $\sim$10 Mton region with denser instrumentation
  - $\Rightarrow$ lower E threshold
  - $\Rightarrow$ study neutrino oscillations
  - $\Rightarrow$ sensitive to the ν_s LE signature
  - Surrounding detector used as active veto against atmospheric μ

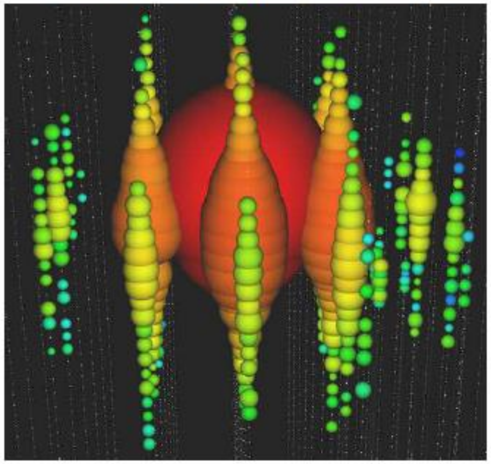
Events in IceCube

- μ produce long tracks in detector $\Rightarrow$ use that to categorize events
  - At high energy: 1° pointing accuracy for track-likes $\rightarrow$ know L well

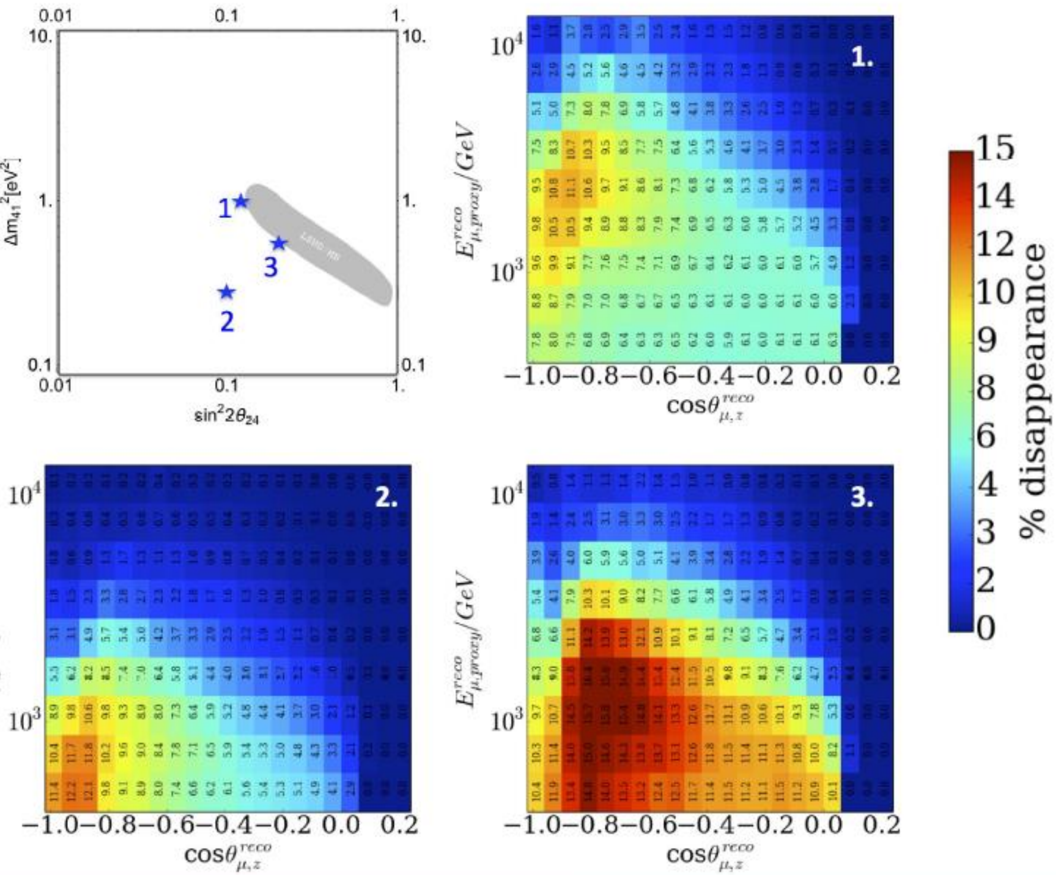
Track-like events: mainly ν_μ CC events



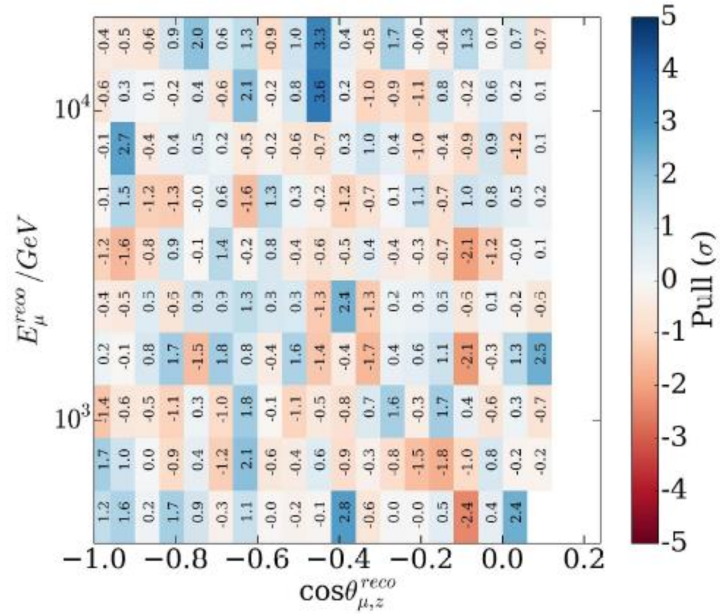
Cascade-like events



What possible signals would look like. . .



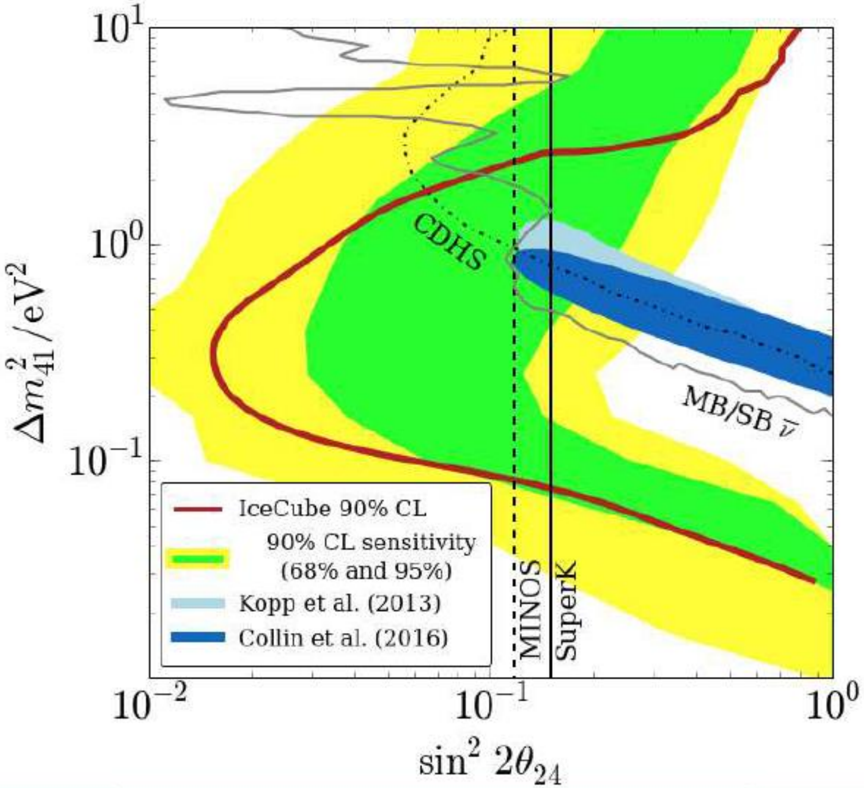
and what we measured



Statistical pulls from data at no-sterile best fit

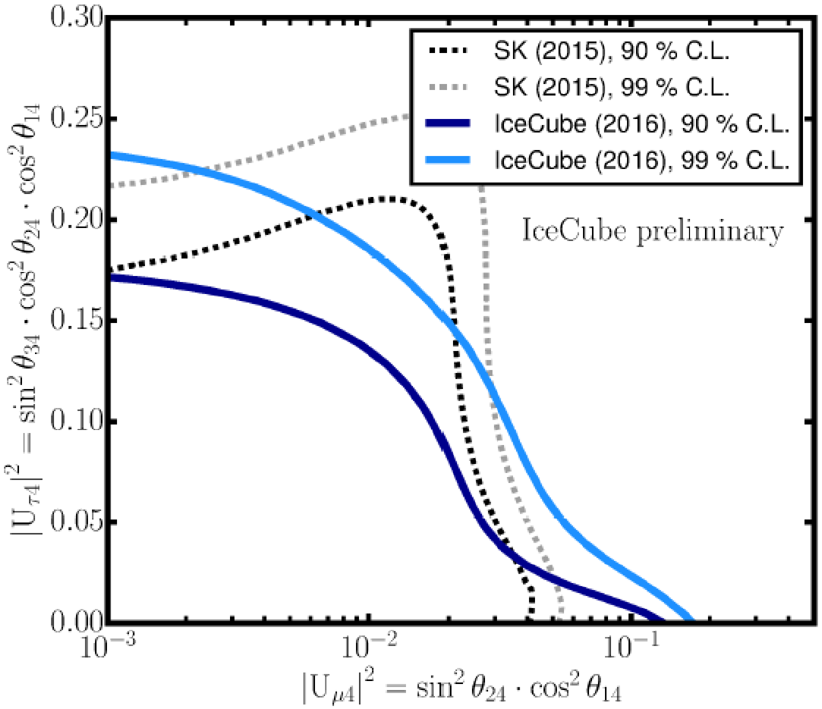
Results from HE sterile search

- Result compatible with no-sterile hypothesis ⇒ set new limit
  - Only using 1 year of data, statistics limited → more to come



IceCube-DeepCore: LE Sterile Neutrino result

- Result compatible with no-sterile hypothesis
- Limits comparable to those of SK
  - Strong limits on $|U_{\tau 4}|^2$, not accessible from HE ν_s search



Submitted to journal and to arXiv:1702.05160

Fresh results from Moriond 2017

VSB reactors on sterile vs

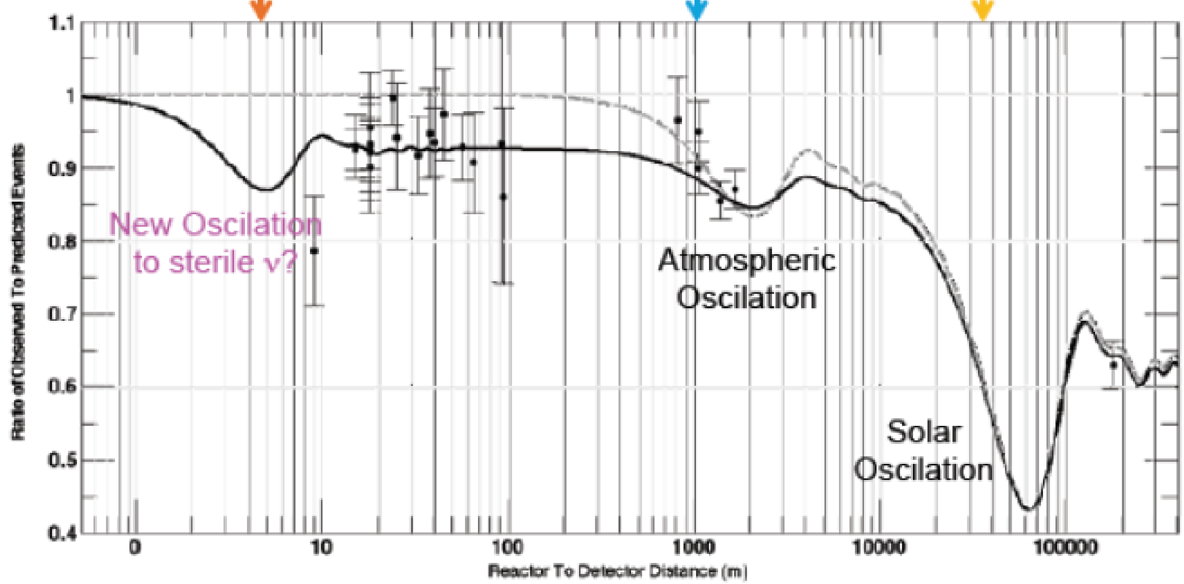
There are several ~3σ indications of 4^{th} neutrino

LSND, MiniBoone: $\bar{\nu}_e$ appearance
SAGE and GALEX ν_e deficit
Reactor $\bar{\nu}_e$ deficit

→

Indication of a sterile neutrino
$\Delta m^2 \sim 1\ eV^2$
$\sin^2 2\theta_{14} \sim 0.1$ (wait for C.Giunti talk)
=> Short range neutrino oscillations

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\Theta_{14} \sin^2(1.27\Delta m^2_{41} \frac{L}{E}) - c^4_{14} \sin^2 2\Theta_{13} \sin^2(1.27\Delta m^2_{31} \frac{L}{E}) - c^4_{14} c^4_{13} \sin^2 2\Theta_{12} \sin^2(1.27\Delta m^2_{21} \frac{L}{E})$$



G. Mention et al. Phys Rev D 83 073006 (2011)

Reactor models do not describe well neutrino spectrum

Measurements at one distance are not sufficient!

Many reactor experiments plan to search for sterile neutrino
(only 2 in this talk. Aurelie Bonhomme will present Stereo at YSF4)

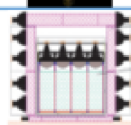
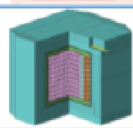
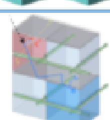
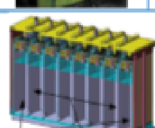
Experiment		Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)		3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)		2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)		40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)		100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)		85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)		57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Table from N.Bowden at Neutrino 2016

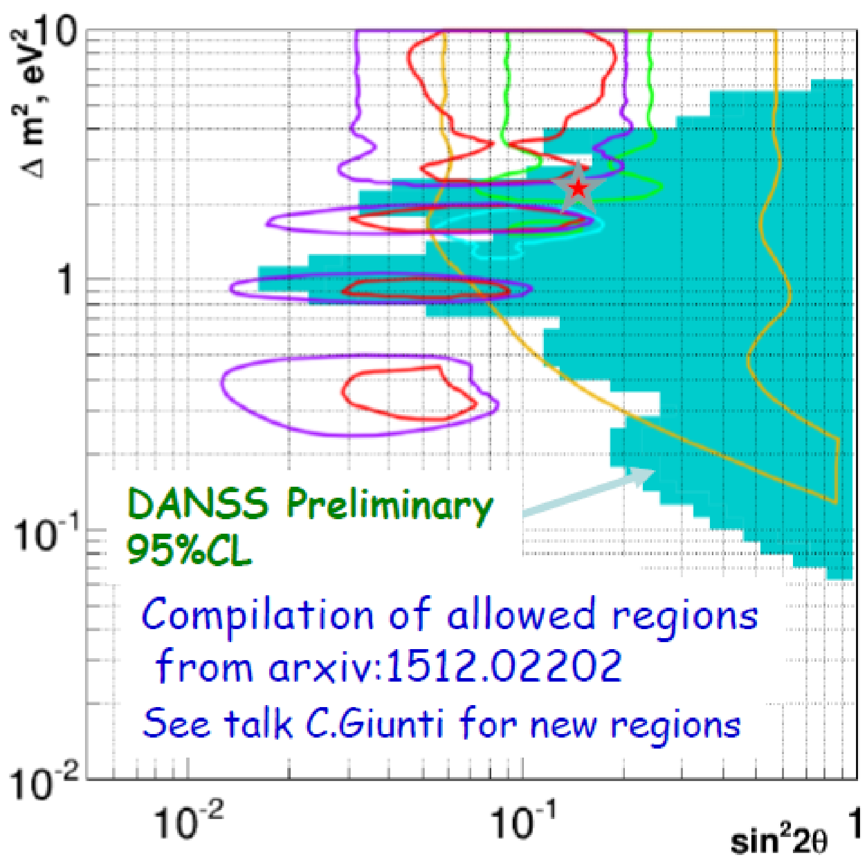
Preliminary results

Exclusion region was calculated using Gaussian $CLs = CL^{4\nu}/CL^{3\nu}$ method
$CLs < 1-\alpha$ forms a CLs region (X.Qian et al. arXiv:1407.5052/v2 [hep-ex])
CLs method is more conservative than usual Confidence Interval method

Systematics studies include variations in:
- Burning profile in reactor core
- Energy resolution
- Level of cosmics background
- Energy intervals used in fit

Systematics is small

A large fraction of allowed parameter region is excluded by preliminary DANSS results using only ratio of e+ spectrum at different L



- DANSS plans to collect 3 times more data by Summer and to include into analysis all available now data
- Detector calibration and systematics studies will be continued
- More elaborated analysis methods will be used

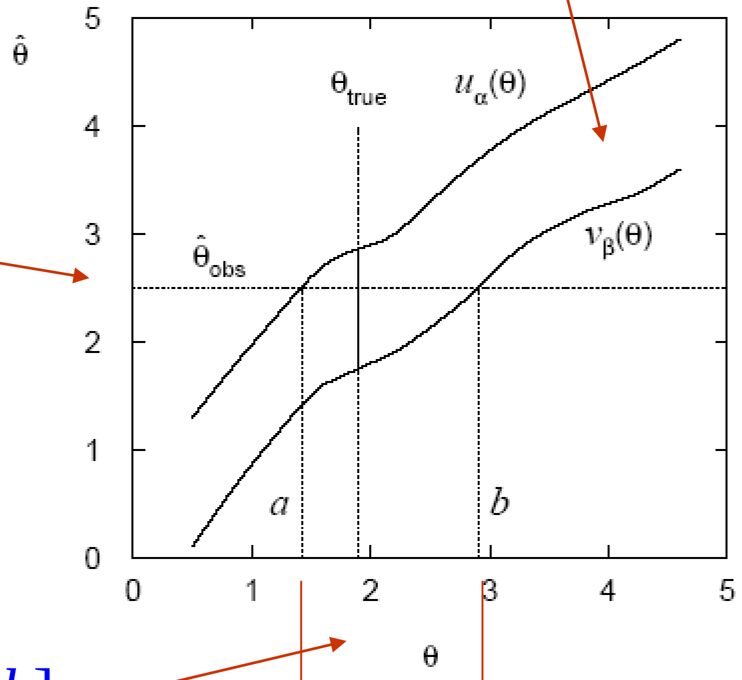
=> much better sensitivity

Note on confidence regions

Confidence interval from the confidence belt

The region between $u_\alpha(\theta)$ and $v_\beta(\theta)$ is called the confidence belt.

Find points where observed estimate intersects the confidence belt.



For every point θ, if it were true, the data would fall in its acceptance region with probability $1-\alpha$

If the data fell in that region, the point θ would be in the interval $[\theta_-, \theta_+]$

So the interval $[\theta_-, \theta_+]$ covers the true value with probability $1-\alpha$

This gives the confidence interval $[a, b]$

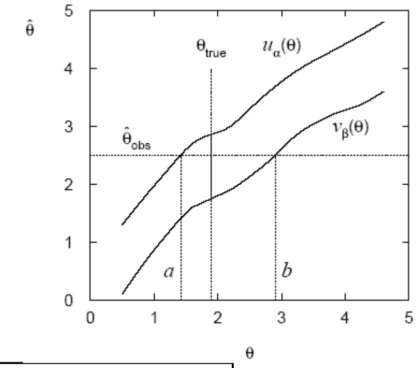
Confidence level = $1 - \alpha - \beta$ = probability for the interval to cover true value of the parameter (holds for any possible true θ).

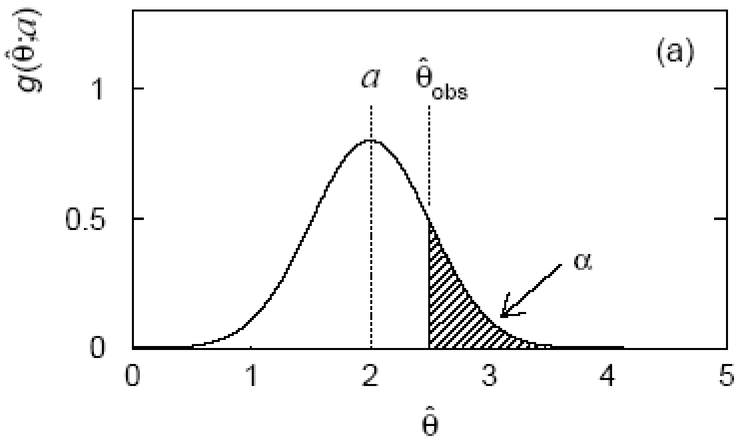
Confidence intervals in practice

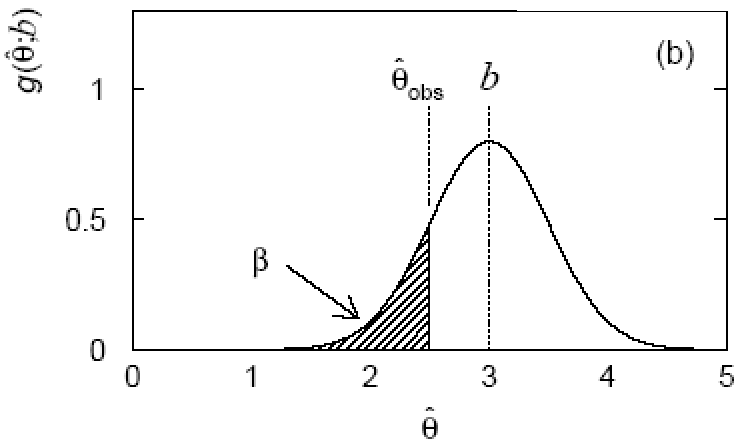
The recipe to find the interval [a, b] boils down to solving

$$\alpha = \int_{u_\alpha(\theta)}^{\infty} g(\hat{\theta};\theta)\,d\hat{\theta} = \int_{\hat{\theta}_{\rm obs}}^{\infty} g(\hat{\theta};a)\,d\hat{\theta}\,,$$

$$\beta = \int_{-\infty}^{v_\beta(\theta)} g(\hat{\theta};\theta)\,d\hat{\theta} = \int_{-\infty}^{\hat{\theta}_{\rm obs}} g(\hat{\theta};b)\,d\hat{\theta}\,.$$







→ a is hypothetical value of θ such that $P(\hat{\theta} > \hat{\theta}_{\rm obs}) = \alpha$.

→ b is hypothetical value of θ such that $P(\hat{\theta} < \hat{\theta}_{\rm obs}) = \beta$.

Confidence intervals by inverting a test

Confidence intervals for a parameter θ can be found by defining a test of the hypothesized value θ (do this for all θ):

Specify values of the data that are 'disfavoured' by θ (critical region) such that P(data in critical region) $\leq \gamma$ for a prespecified γ, e.g., 0.05 or 0.1.

If data observed in the critical region, reject the value θ.

Now invert the test to define a confidence interval as:

set of θ values that would not be rejected in a test of size γ (confidence level is $1 - \gamma$).

The interval will cover the true value of θ with probability $\geq 1 - \gamma$.

Equivalent to confidence belt construction; confidence belt is acceptance region of a test.

Approximate confidence intervals/regions from the likelihood function

Suppose we test parameter value(s) $\boldsymbol{\theta} = (\theta_1, ..., \theta_n)$ using the ratio

$$\lambda(\boldsymbol{\theta}) = \frac{L(\boldsymbol{\theta})}{L(\hat{\boldsymbol{\theta}})} \qquad\qquad 0 \leq \lambda(\boldsymbol{\theta}) \leq 1$$

Lower $\lambda(\boldsymbol{\theta})$ means worse agreement between data and hypothesized $\boldsymbol{\theta}$. Equivalently, usually define

$$t_{\boldsymbol{\theta}} = -2 \ln \lambda(\boldsymbol{\theta})$$

so higher $t_{\boldsymbol{\theta}}$ means worse agreement between $\boldsymbol{\theta}$ and the data.

p-value of $\boldsymbol{\theta}$ therefore

$$p_{\boldsymbol{\theta}} = \int_{t_{\boldsymbol{\theta},\mathrm{obs}}}^{\infty} f(t_{\boldsymbol{\theta}}|\boldsymbol{\theta})\, dt_{\boldsymbol{\theta}}$$

need pdf

Confidence region from Wilks' theorem

Wilks' theorem says (in large-sample limit and providing certain conditions hold...)

$$f(t_{\boldsymbol{\theta}}|\boldsymbol{\theta}) \sim \chi^2_n$$

chi-square dist. with # d.o.f. = # of components in $\boldsymbol{\theta} = (\theta_1, ..., \theta_n)$.

Assuming this holds, the *p*-value is

$$p_{\boldsymbol{\theta}} = 1 - F_{\chi^2_n}(t_{\boldsymbol{\theta}})$$

To find boundary of confidence region set $p_{\boldsymbol{\theta}} = \alpha$ and solve for $t_{\boldsymbol{\theta}}$:

$$t_{\boldsymbol{\theta}} = F^{-1}_{\chi^2_n}(1 - \alpha)$$

Recall also

$$t_{\boldsymbol{\theta}} = -2 \ln \frac{L(\boldsymbol{\theta})}{L(\hat{\boldsymbol{\theta}})}$$

Statistical tests for a non-established signal (i.e. a "search")

Consider a parameter μ proportional to the rate of a signal process whose existence is not yet established.

Suppose the model for the data includes both m and a set of nuisance parameters $\boldsymbol{\theta}$.

To test hypothetical values of μ, use profile likelihood ratio:

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

maximizes L for specified μ

maximize L

Neutrino Oscillations

The QM probability is:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\,\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

L **is the distance (km),** E **is the energy in GeV and** $\Delta m^2 = |m_1^2 - m_2^2|$ **is** $(\mathrm{eV/c^2})^2$**.**

The result is plotted in the Δm^2 vs. $\sin^2(2\theta)$ **plane**

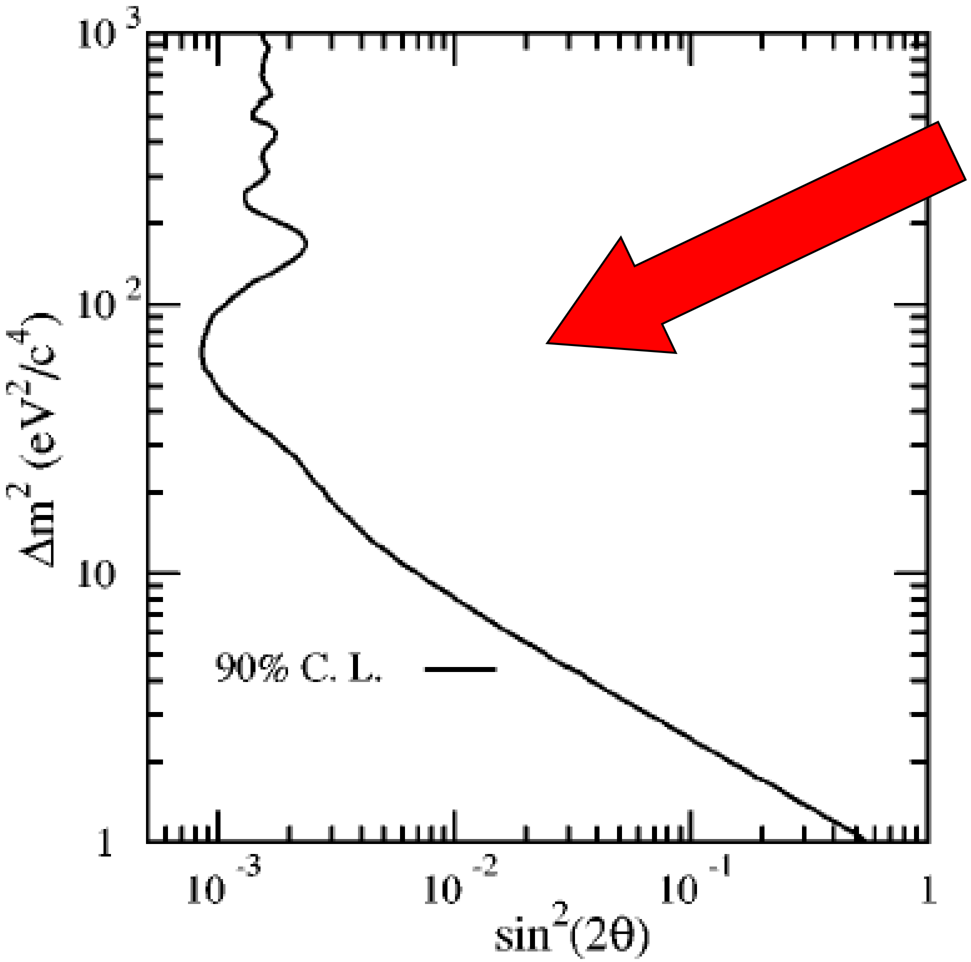
The goal is the search for an ν_e **excess (the signal) over the normal** ν_e **back-ground.**
The data are usually a bin content, the signal n_i **a and the backg.** b_i**.**
The expected number of event is:

$$\mu_{true} = \mathrm{F}\left(\propto \sin^2(2\theta)\,\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right) \right)$$

The frequentist test is

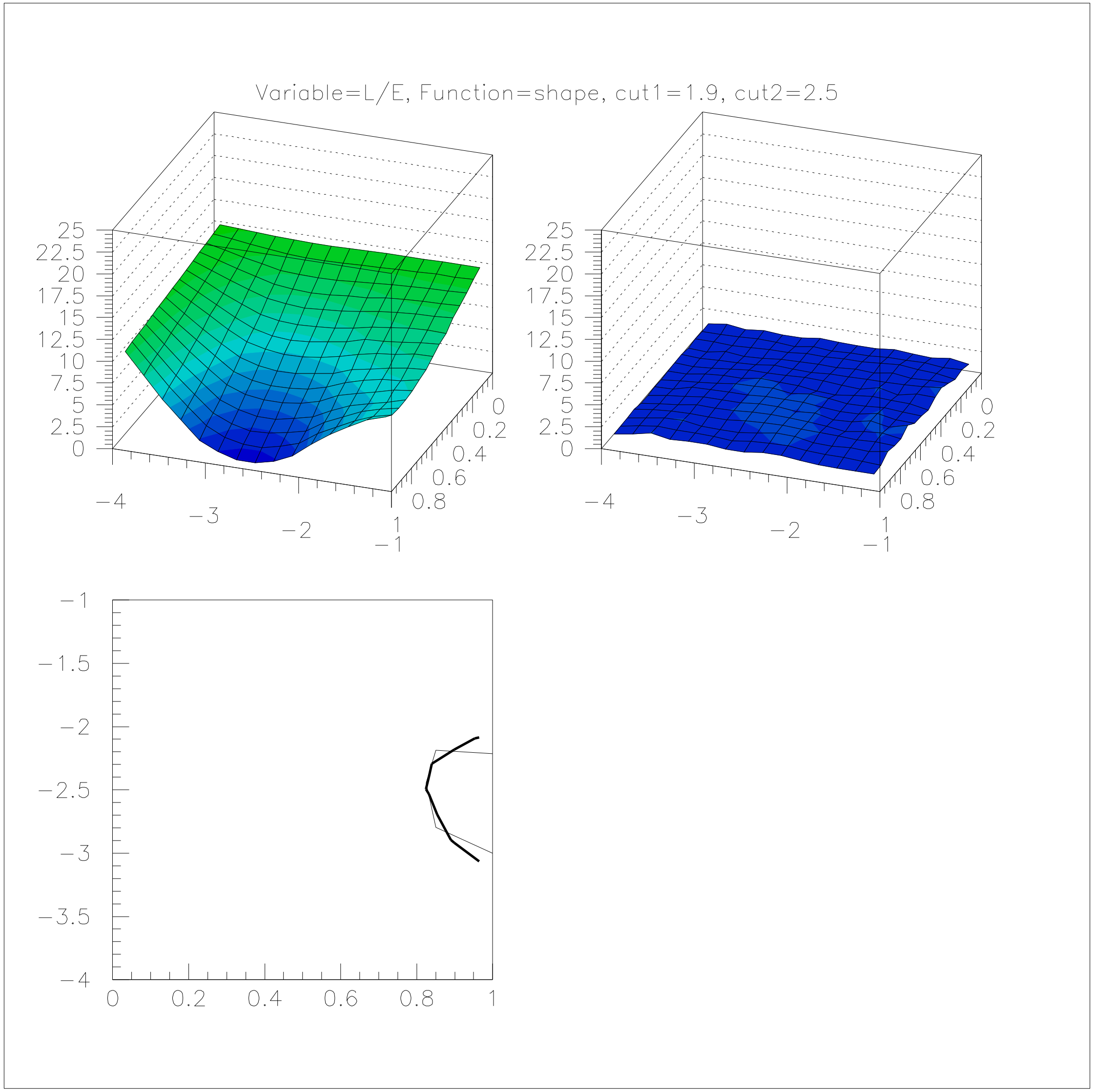
$$\chi^2 = \sum_i \frac{(n_i - b_i - \mu_i)^2}{\sigma_i^2}$$

The acceptance zone for no oscillations (Hypothesis)



if the experiment falls here, we can reject the hypothesis with 90% CL

FIG. 11. Calculation of the confidence region for an example of the toy model in which $\sin^2(2\theta)=0$. The 90% confidence region is the area to the left of the curve.



Variable=L/E, Function=shape, cut1=1.9, cut2=2.5
25
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
−4
−3
−2
−1
0
0.2
0.4
0.6
0.8
1
−1
−1.5
−2
−2.5
−3
−3.5
−4
0
0.2
0.4
0.6
0.8
1

Credits

- Most of the slides have been freely stolen from the web. Sources:
  - S. Bordoni
  - T. Carroll
  - M. Danilov
  - C. Giunti
  - F. Jediný
  - E. Lisi
  - N. Mauri
  - J. P. A. Marcondes de André
  - A. Meregaglia
  - T. Nakadaira
  - T. Schwetz-Mangold