Accelerator Neutrino Experiments (LBL)

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HQL2014 Aug 26

Outline

- MINOS and MINOS+ **(NuMI)**
- T2K **(J-PARC)**
- ICARUS and OPERA **(CNGS)**
- Summary

Rob Plunkett's presence was required for DOE-CD4 review of NOvA.
I will be summarizing Neutrino 2014 LBL Osc results.

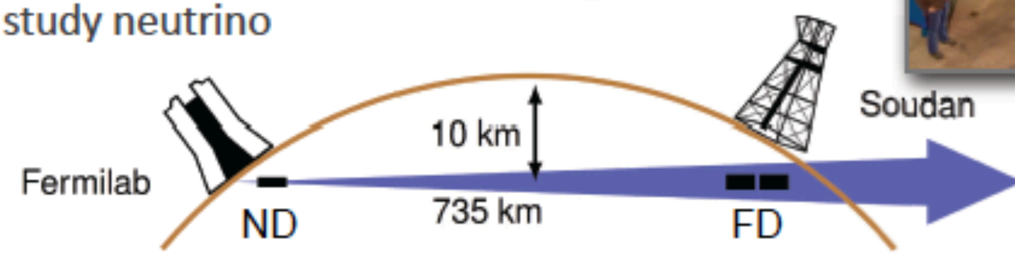
First MINOS+ Data and New Results from MINOS

Alex Sousa – U. Cincinnati

The MINOS+ Concept

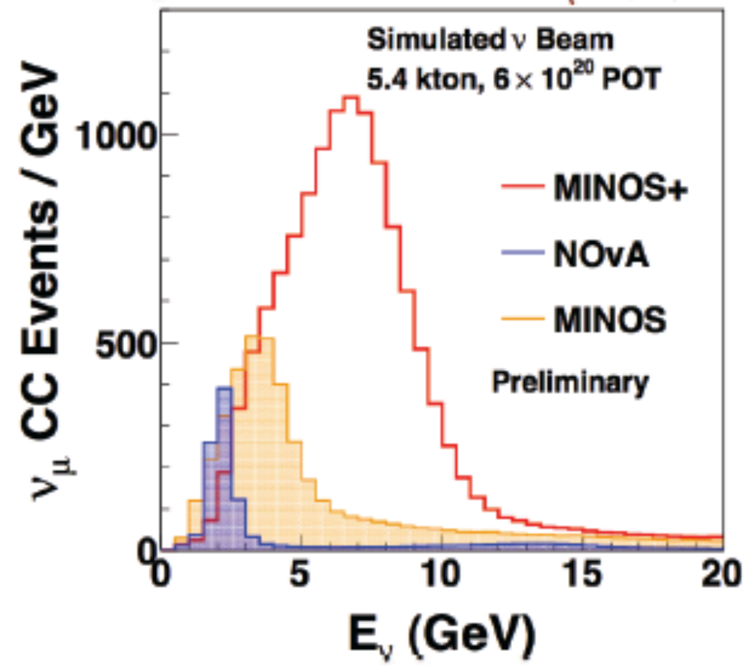
- Long-baseline neutrino oscillation experiment
- Measure NuMI Neutrino beam energy and flavor composition with two detectors over 735 km
  - L/E ~ 500 km/GeV

- Near Detector at Fermilab
- Far Detector at Soudan Underground Lab, MN
- Compare Near and Far measurements to study neutrino mixing



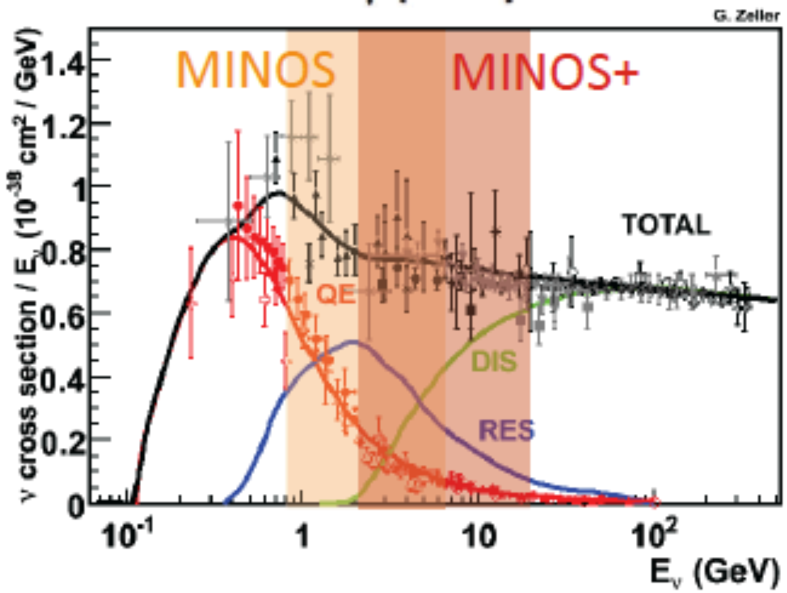
The MINOS+ Concept

- **+ $\Longrightarrow$ New Neutrino Beam**
  - Run the MINOS detectors concurrently with NOvA operations with updated NuMI beam



- **+ $\Longrightarrow$ More Statistics**
  - Expect ~4000 ν_μ CC events/year at the FD

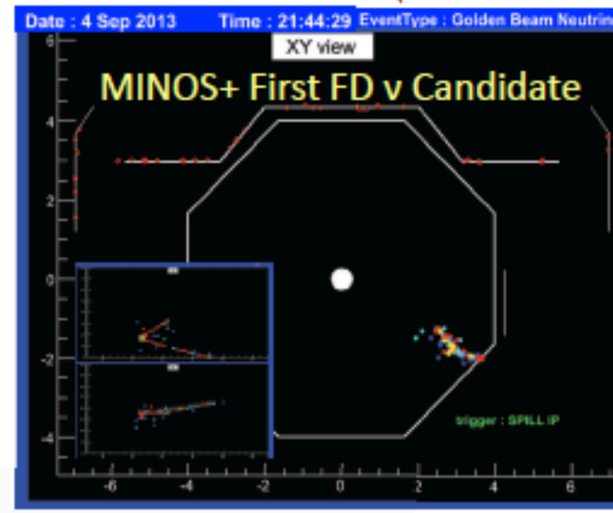
- **+ $\Longrightarrow$ Higher Energy**
  - Cross-check MINOS in different energy region
  - With different beam and cross section systematics

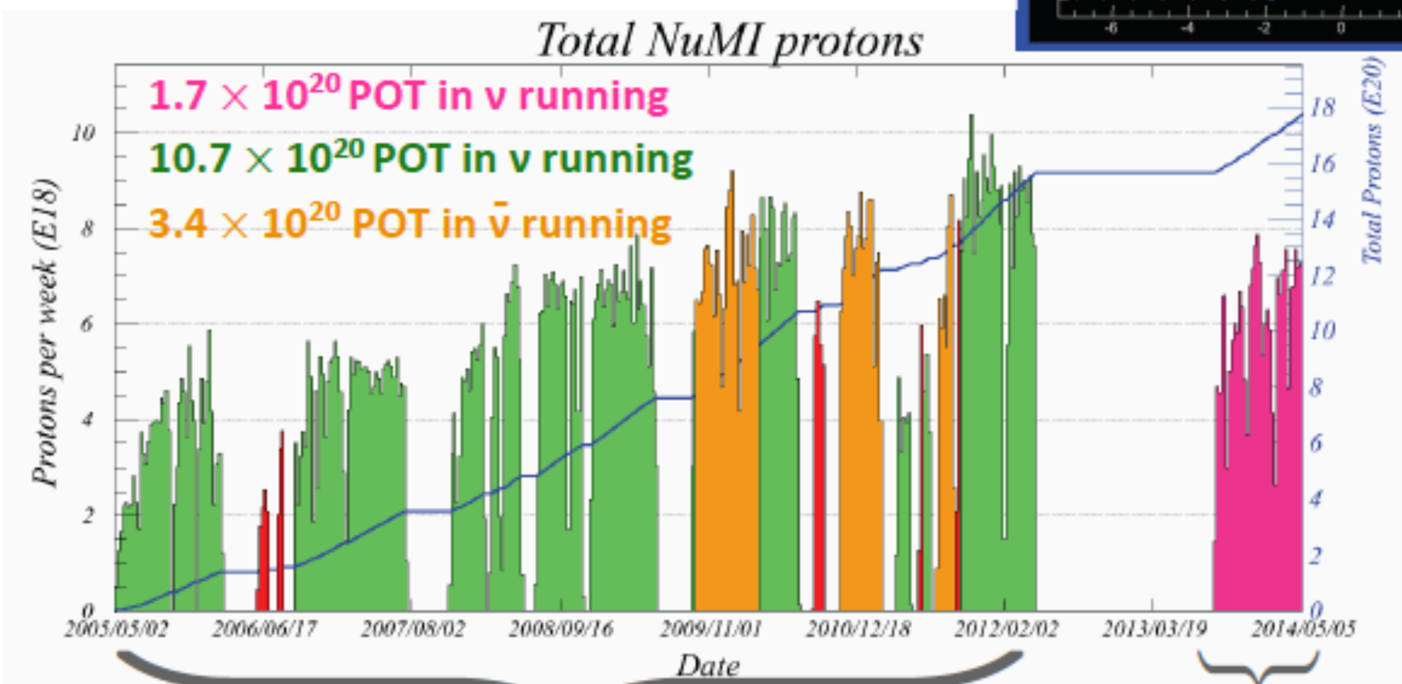


- **+ $\Longrightarrow$ More Physics**
  - Only wide-band beam long-baseline experiment in operation during this decade
  - **Look for new physics!**

First MINOS+ Beam Data

- Upgraded NuMI beam returned in Sept. 4, 2013
  - Current (**Design**) beam running
  - 2.4×10^{13} (**5×10^{13}**) protons/pulse
  - 280 kW (**700 kW**) beam power
  - Beam spill every 1.7 s (**1.33 s**)





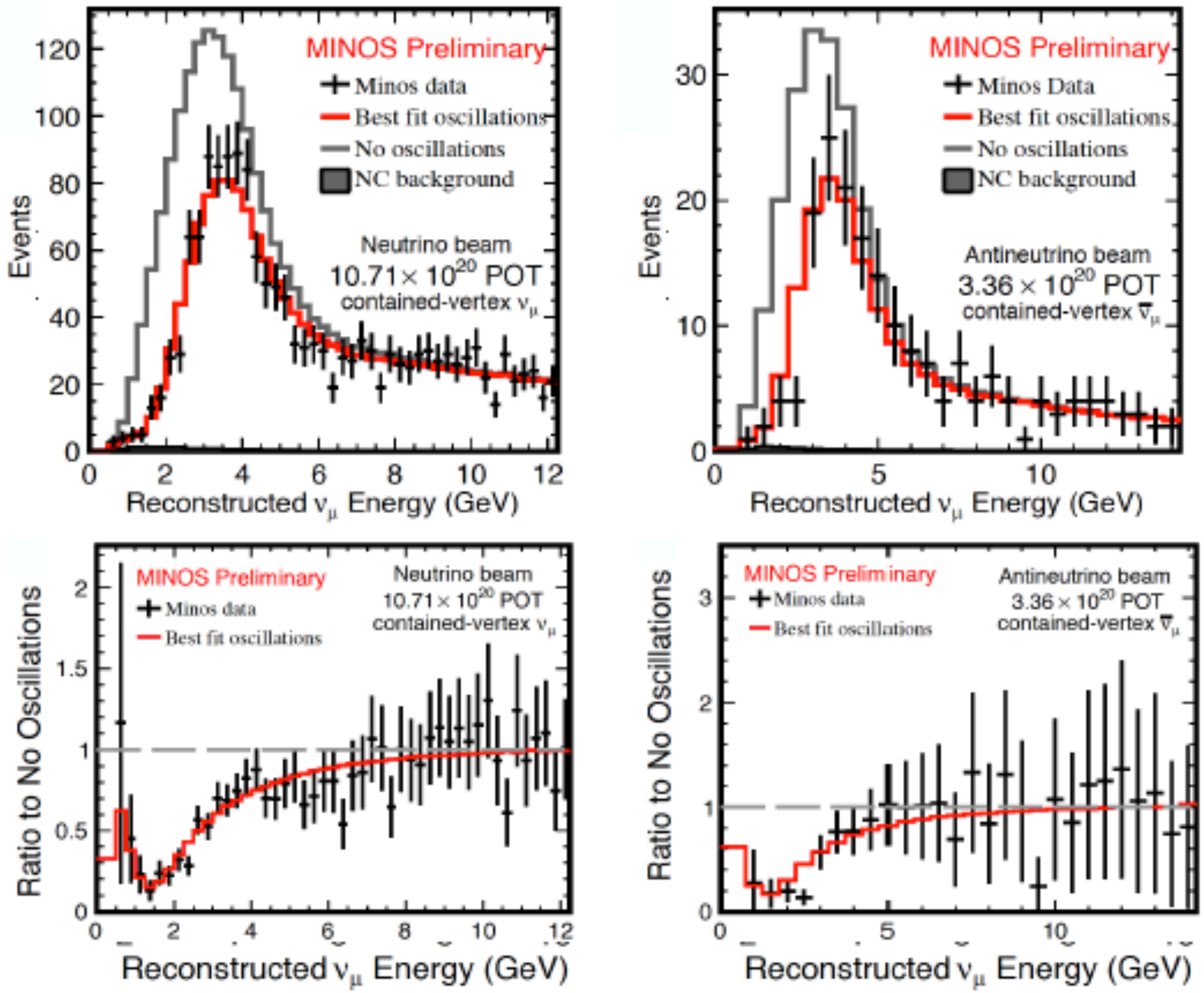
MINOS (2005-2012)

MINOS+

MINOS FD Beam Data

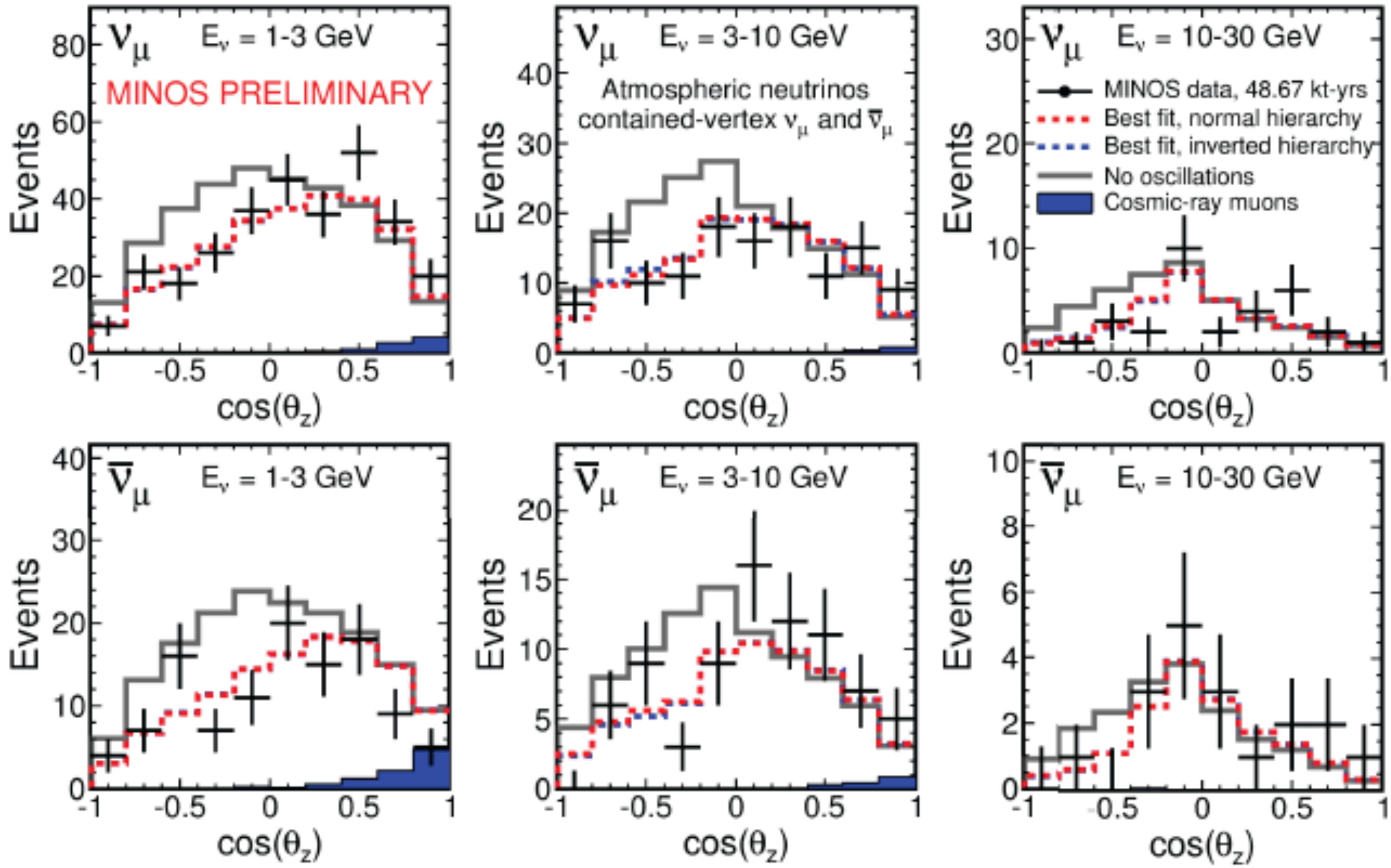
- Showing three-flavor oscillations fit to FD disappearance beam data

Neutrinos | Antineutrinos



FD Atmospherics Data

- Showing three-flavor oscillations fit to FD atmospherics data

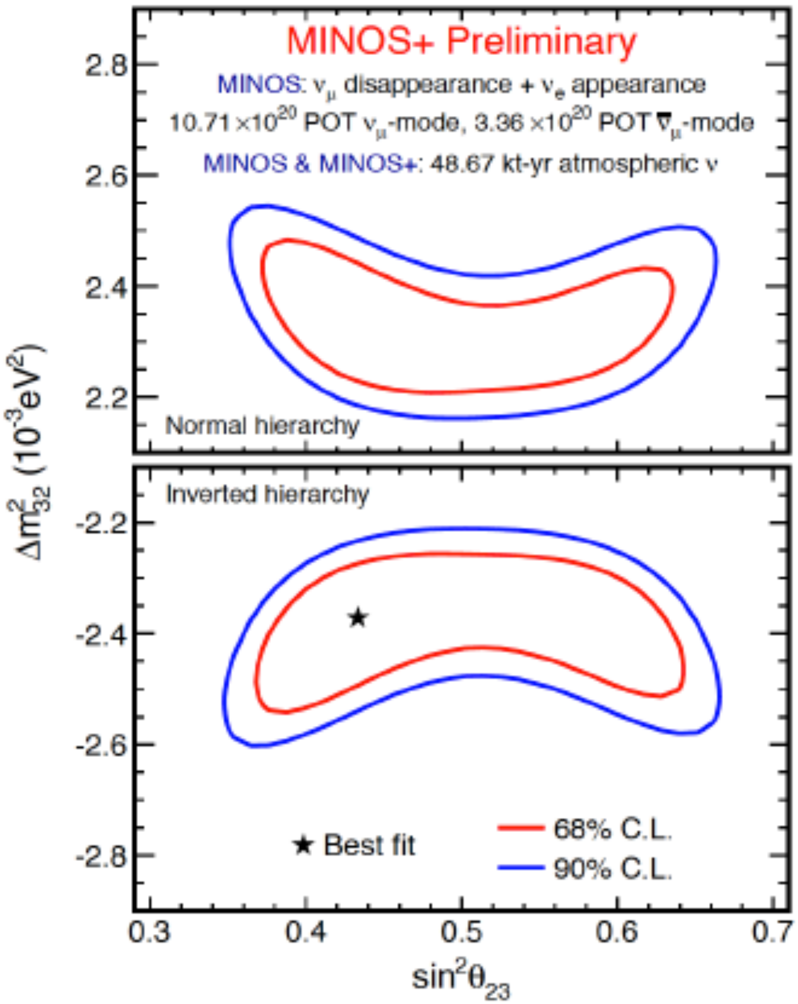


Neutrinos

Antineutrinos

- Plots show several ranges of E_ν for contained-vertex ν_μ events
- Non-fiducial events also included in the fit

Combined Fit Allowed Regions



Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

Normal Hierarchy

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

- **Most precise measurement of $|\Delta m^2_{32}|$**
- Consistent with maximal mixing

- Solar mixing parameters fixed to $\Delta m^2_{21} = 7.54\times10^{-5}$ eV^2 and $\sin^2\theta_{12} = 0.307$ *Fogli et al., PRD **86**, 013012 (2012)*
- θ_{13} fit as nuisance parameter, constrained by reactor results: $\sin^2\theta_{13} = 0.0242 \pm 0.0025$ (θ_{13}=8.95°)
- δ_{CP}, θ_{23}, Δm^2_{32} unconstrained
- 19 systematic uncertainties (4 for beam+15 for atmospherics) included as nuisance parameters

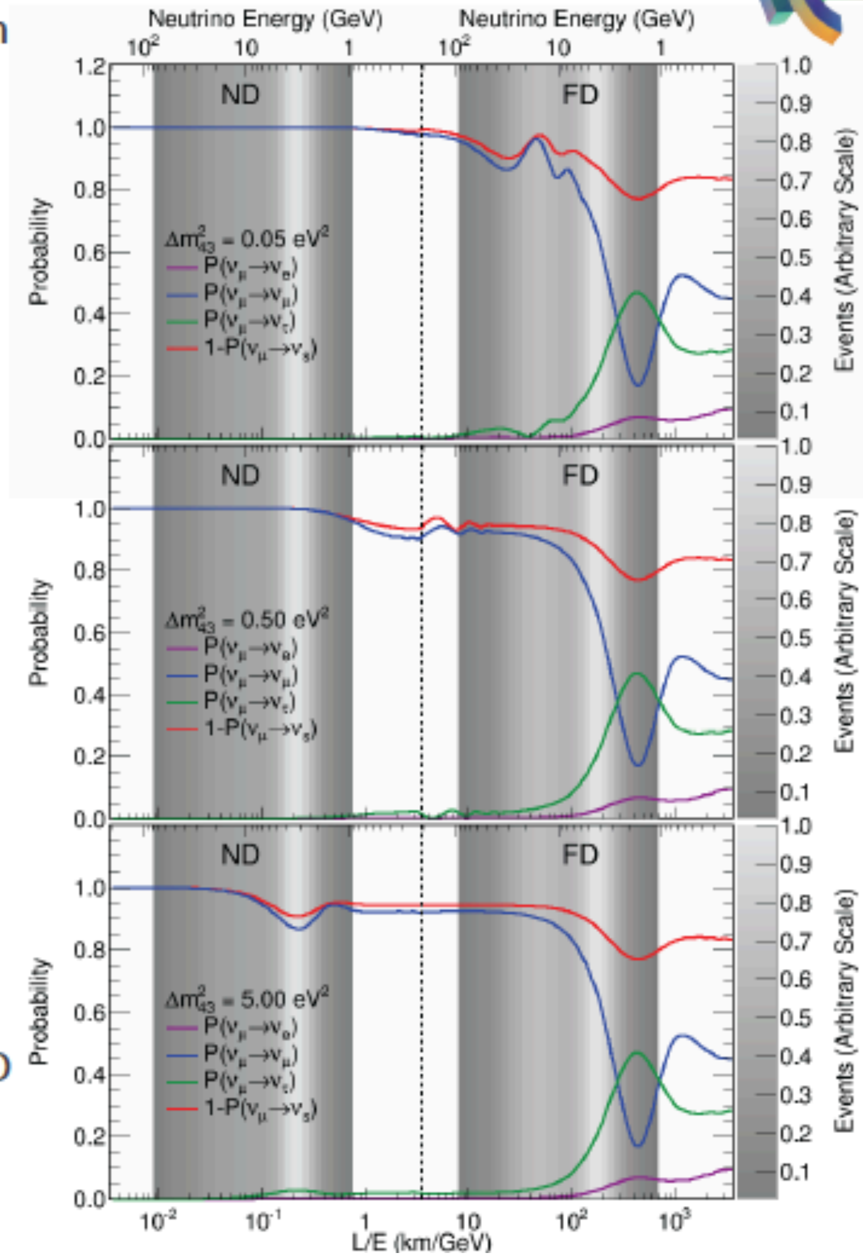
4-Flavor Oscillations

- $\nu_\mu \rightarrow \nu_s$ mixing causes energy-dependent depletion of NC and ν_μ-CC energy spectra w.r.t 3-flavor mixing

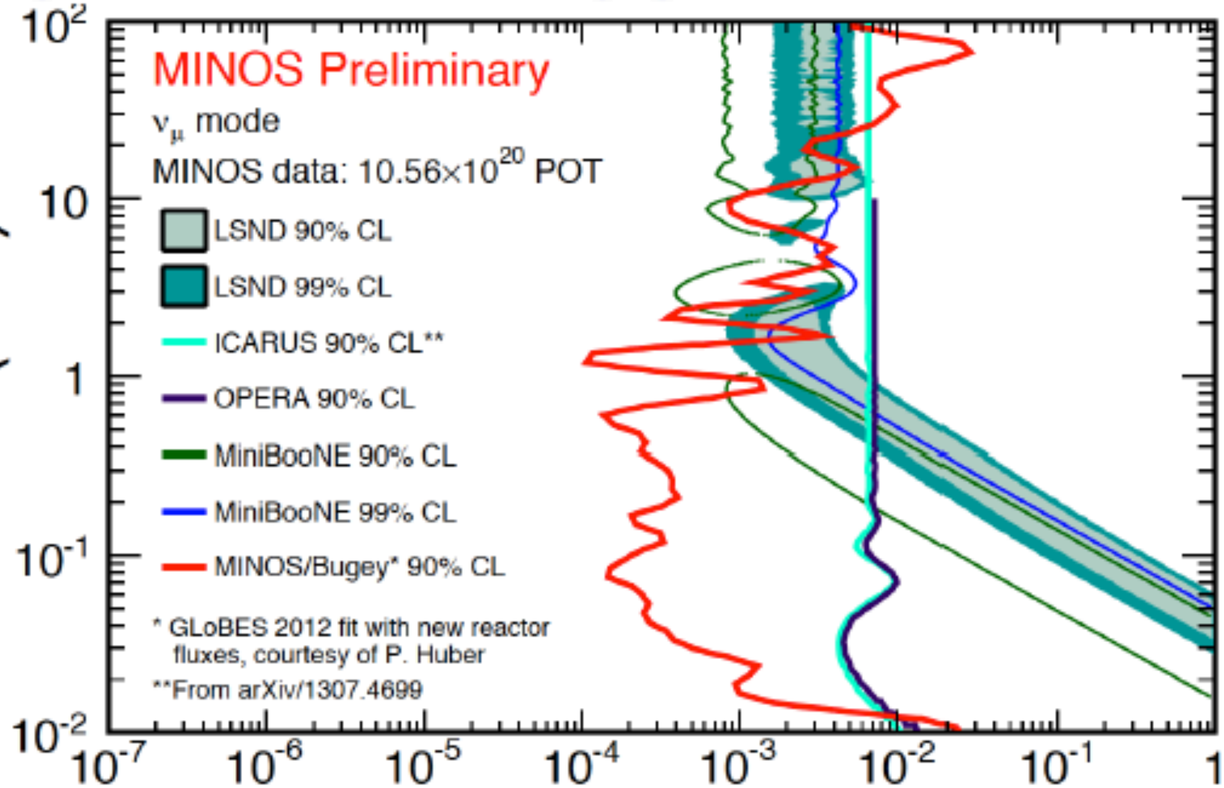
- Small Δm^2_{43} (> Δm^2_{32}):
  - FD spectral distortions at energies above 3-flavor oscillation maximum
  - No ND effects

- Medium Δm^2_{43}:
  - Rapid oscillations at FD average out
  - No ND effects
  - Counting experiment

- Large Δm^2_{43}:
  - Rapid oscillations at FD average out
  - ND spectral distortions affect extrapolation to FD



Comparison to Appearance Results



Similar results for anti-neutrinos

- **With MiniBooNE Neutrino Mode**
- Assuming 3+1 model, combine MINOS disappearance 90% C.L. limit in θ_{24} to Bugey reactor experiment 90% C.L. disappearance limit in θ_{14}
- Bugey limit computed from GLoBES 2012 fit using new reactor fluxes, provided by Patrick Huber

MINOS data increases tension between null and signal results for $\Delta m^2_{43} < 1$ eV^2

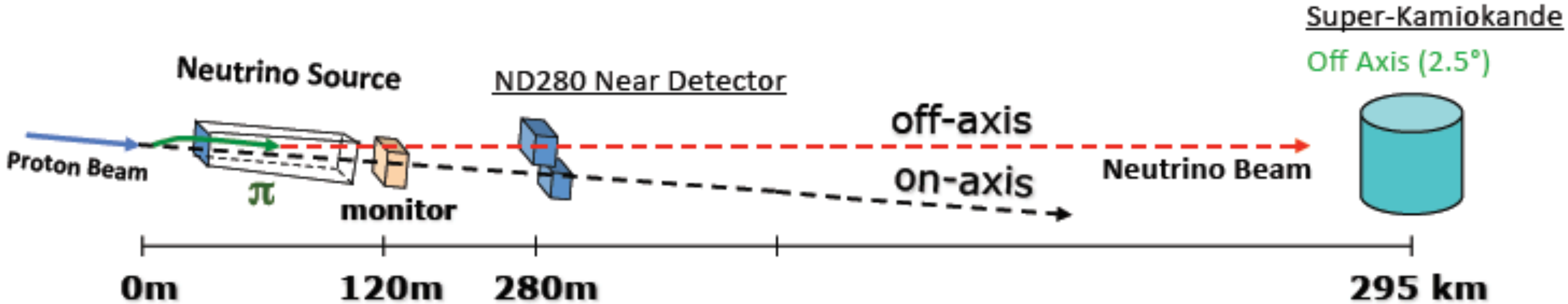
The T2K Experiment

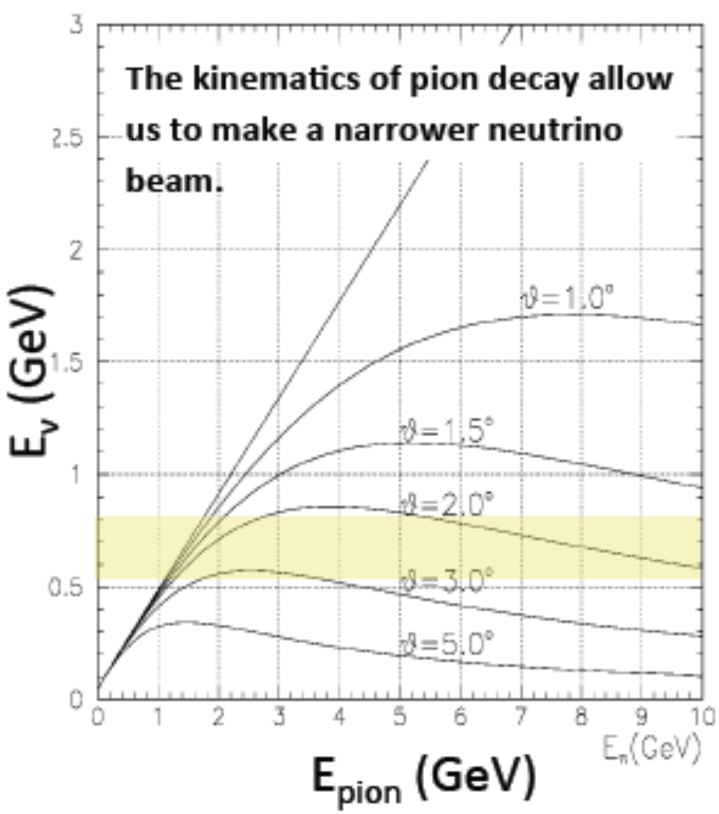
~500 Collaborators / 340 Authors / 59 Institutions / 11 Countries

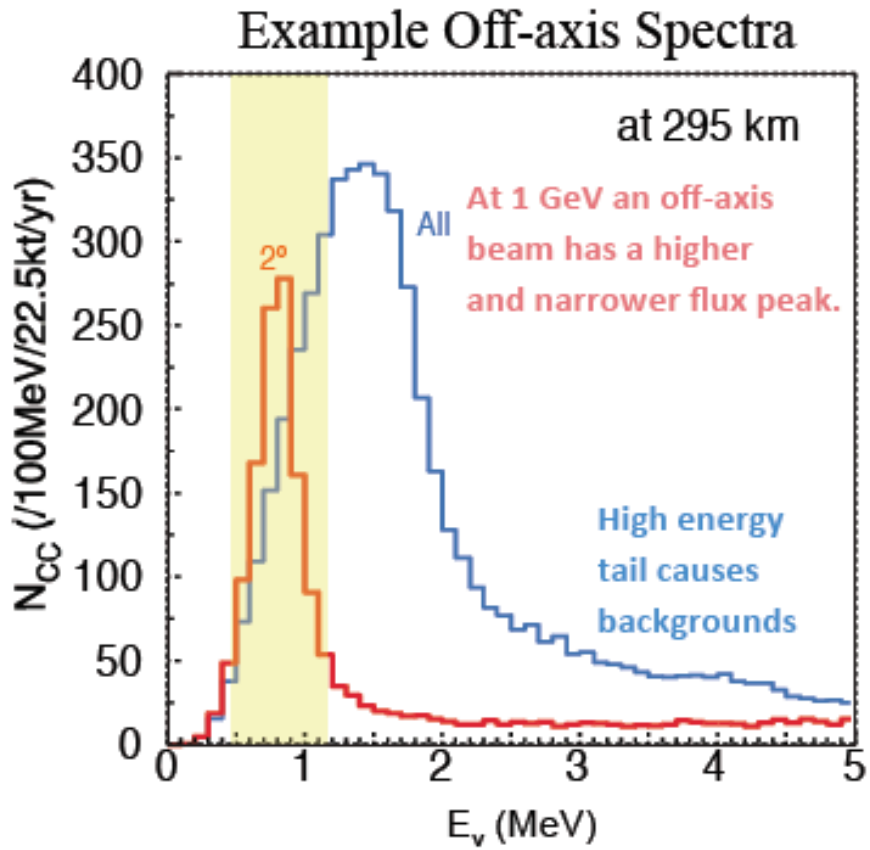
(Canada / France / Germany / Italy / Japan / Poland / Russia / Spain / Switzerland / UK / USA)

Chris Walter - Duke

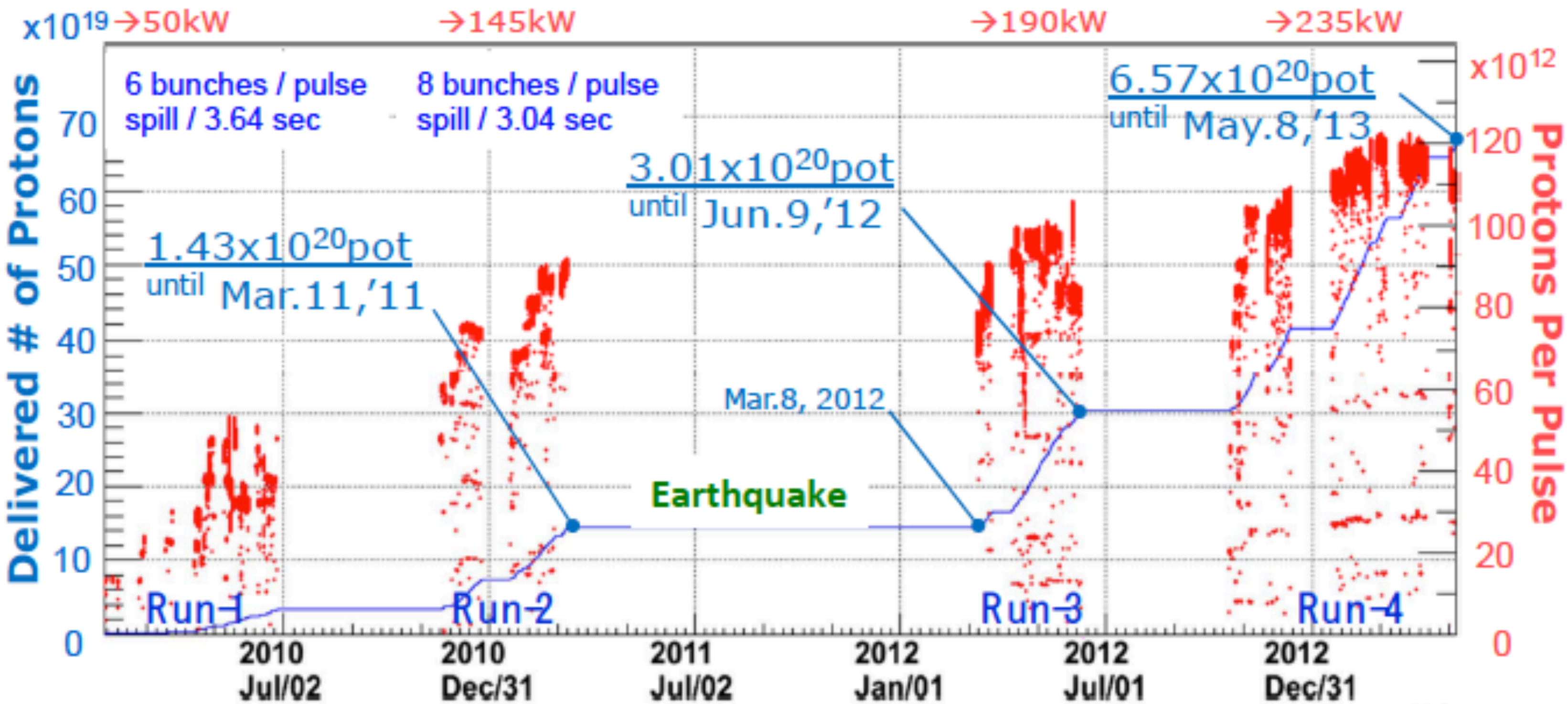
The T2K Off-Axis Beam







Analysis Data Set



- Data sets contain 6.57×10^{20} POT
- Run 1 instantaneous power reached 50 kW
- ➔ Increased # bunches/pulse, protons/bunch, repetition rate
- Run 4 stable power reached **235 kW**

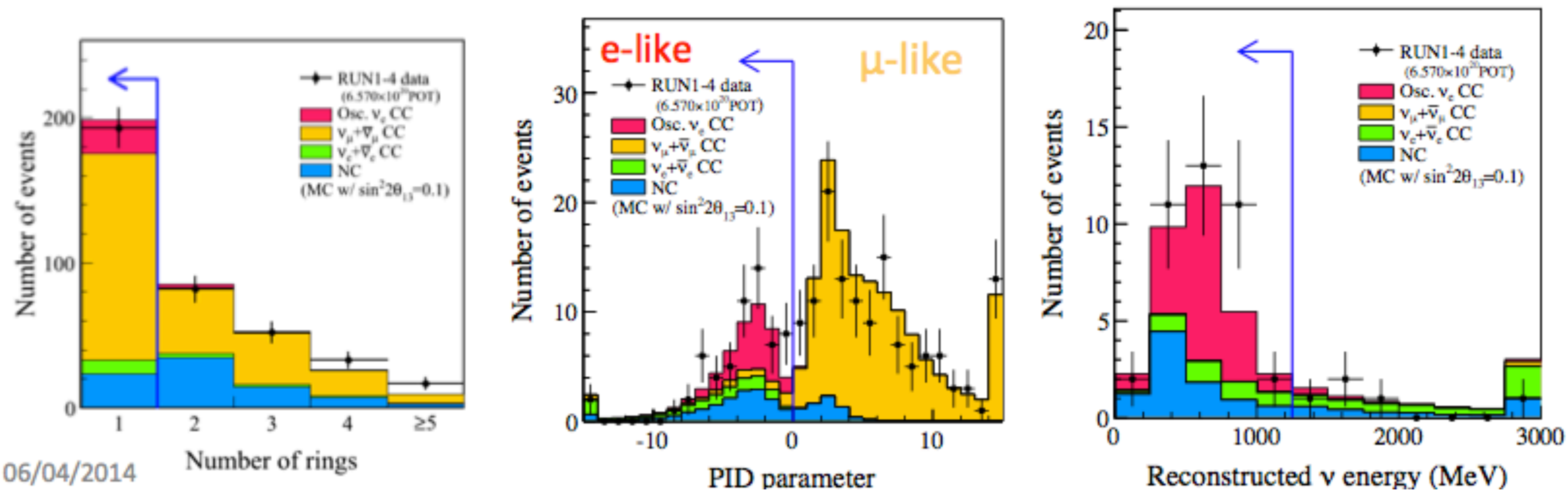
POT ~8% of final design goal

ν_e event selection

T2K has made improvements in background and error reduction.

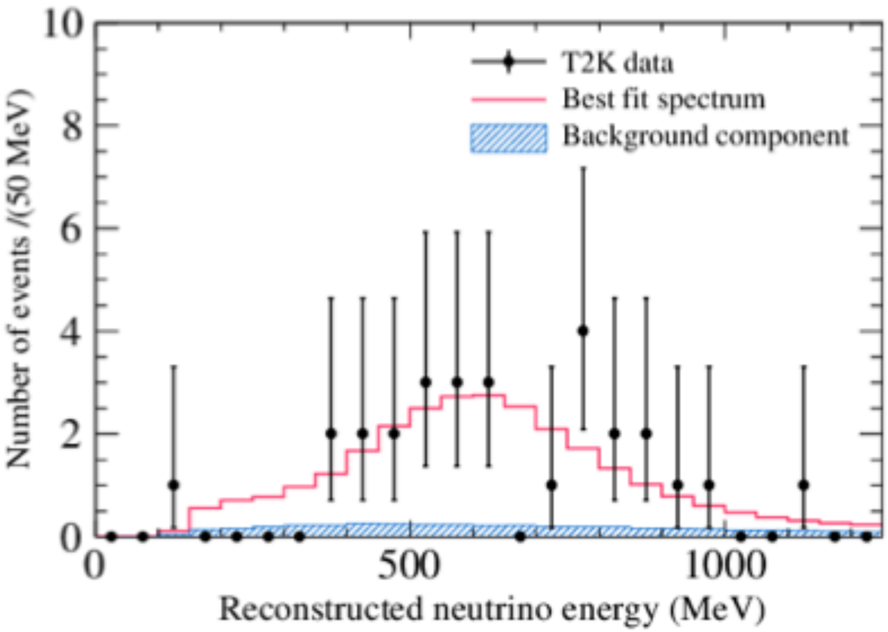
- Fully-contained fiducial volume (FCFV) event
- Single-ring e-like event
- $E_{visible} > 100$ MeV
- # of decay electron = 0
- $0 < E_{\nu}^{rec} < 1250$ MeV
- π^0 cut

28 events
in 6.57×10^{20} POT



Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of ν_e Appearance

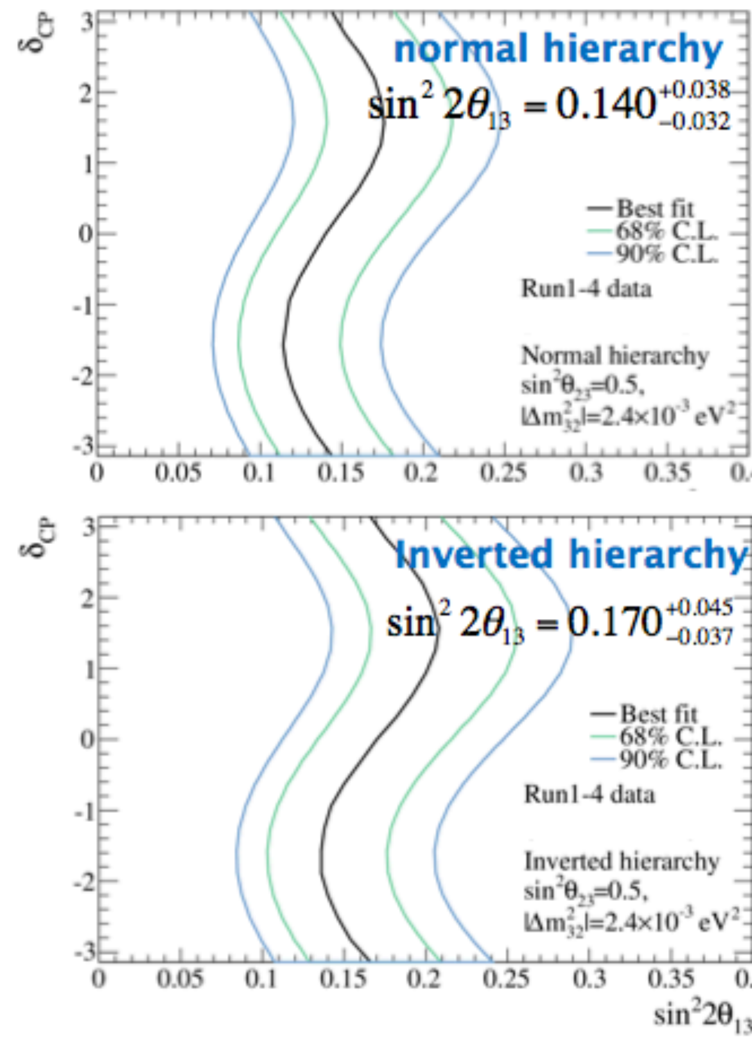


4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13} = 0.1$

$\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

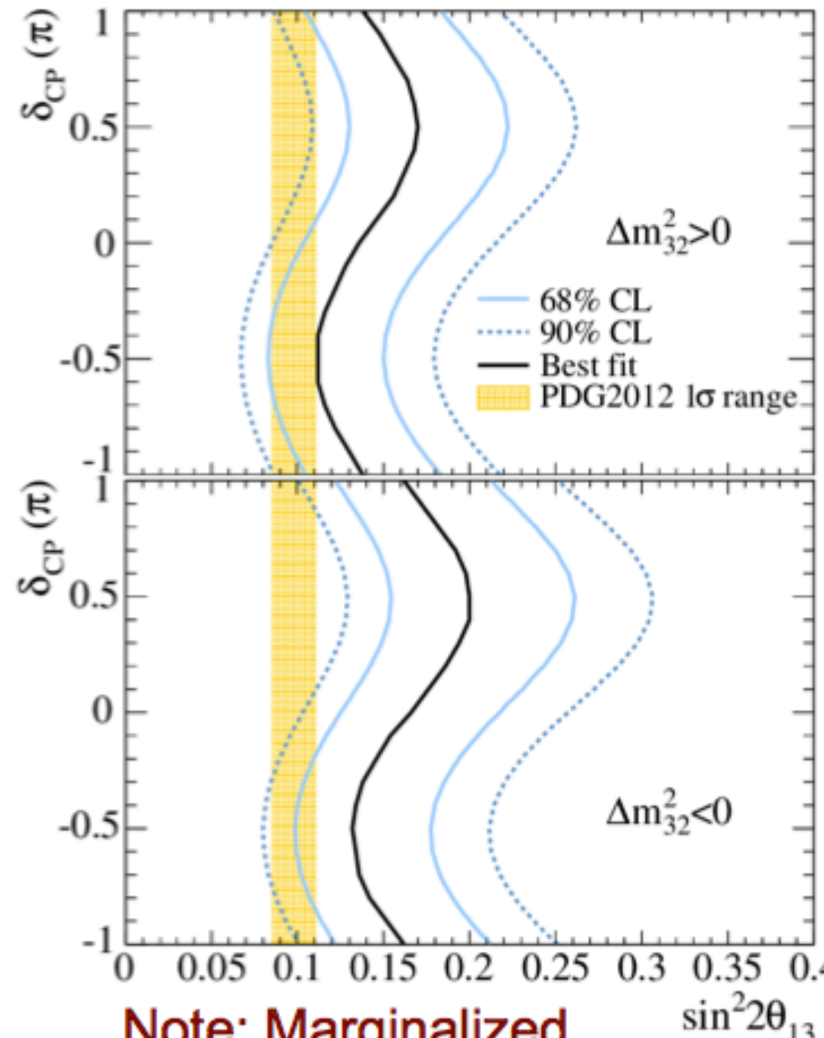


7.3 σ significance for non-zero θ_{13}

<u>First ever observation (>5σ) of an explicit ν appearance channel</u>

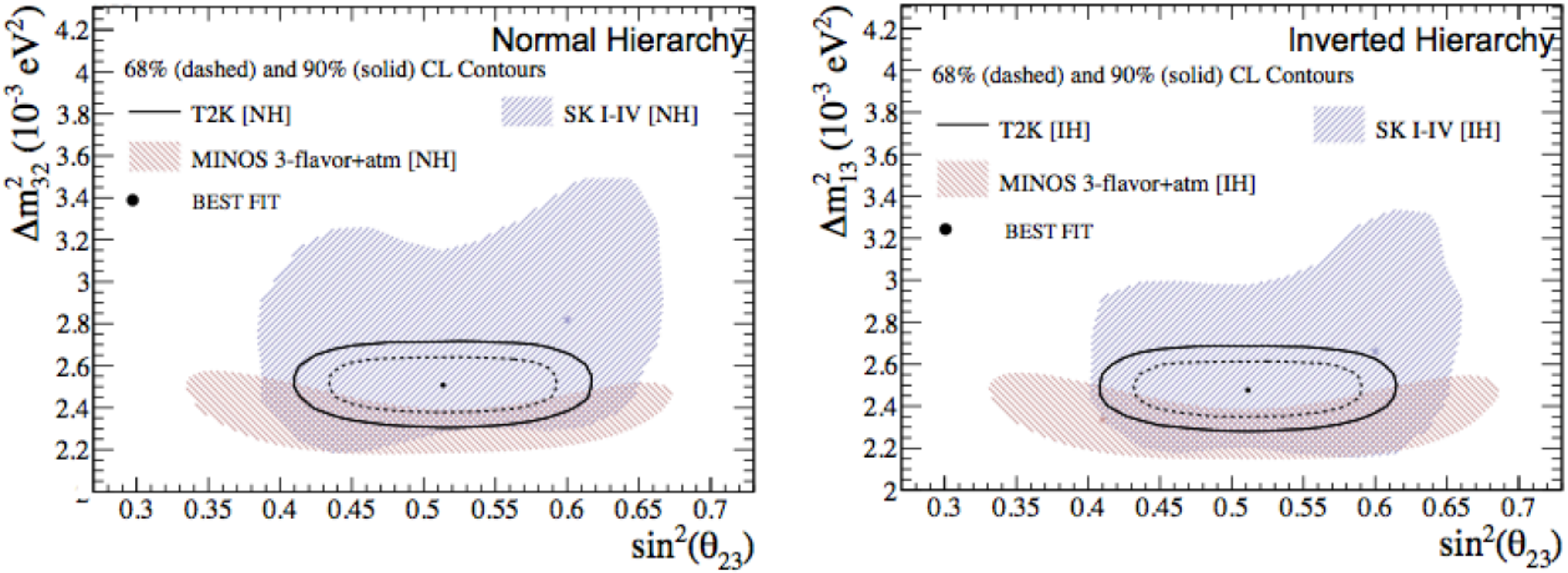
Let's think about these regions!

- Comparing with the external reactor constraint the best overlap is for the normal hierarchy with $\delta_{cp}=-\pi/2$.
- This is a **lucky point**!
- You also need to increase the θ_{23} mixing angle to account for the number of observed events.



Note: Marginalized over θ_{23} and Δm^2_{32}

Compare with other experiments



For the first time, the mixing angle is better constrained by an accelerator experiment than by atmospheric neutrinos!

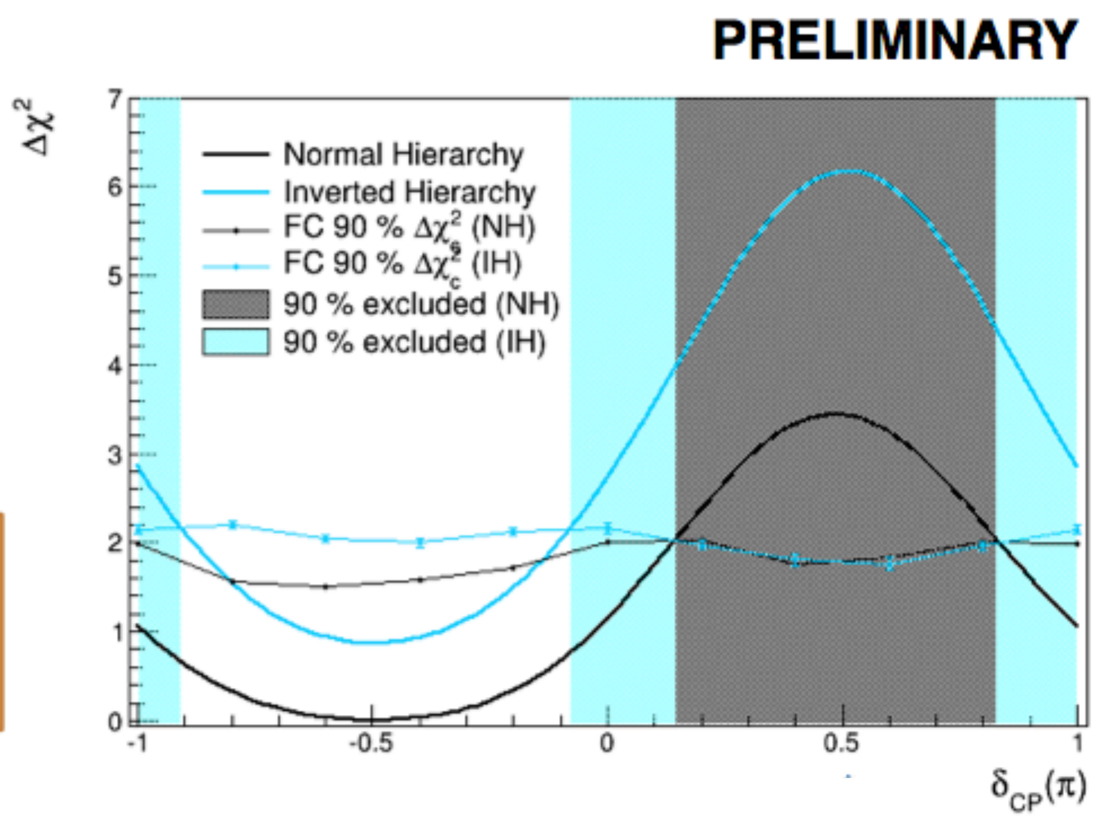
		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

T2K Joint $\nu_\mu + \nu_e$ Analysis: Constraints on δ_{CP}

Likelihood ratio fit to both $\nu_\mu + \nu_e$ event samples

Plot includes constraint from reactor experiments as given by PDG 2013.

T2K has a slight hint for the normal hierarchy with a value of δ_{CP} of $-\pi/2$

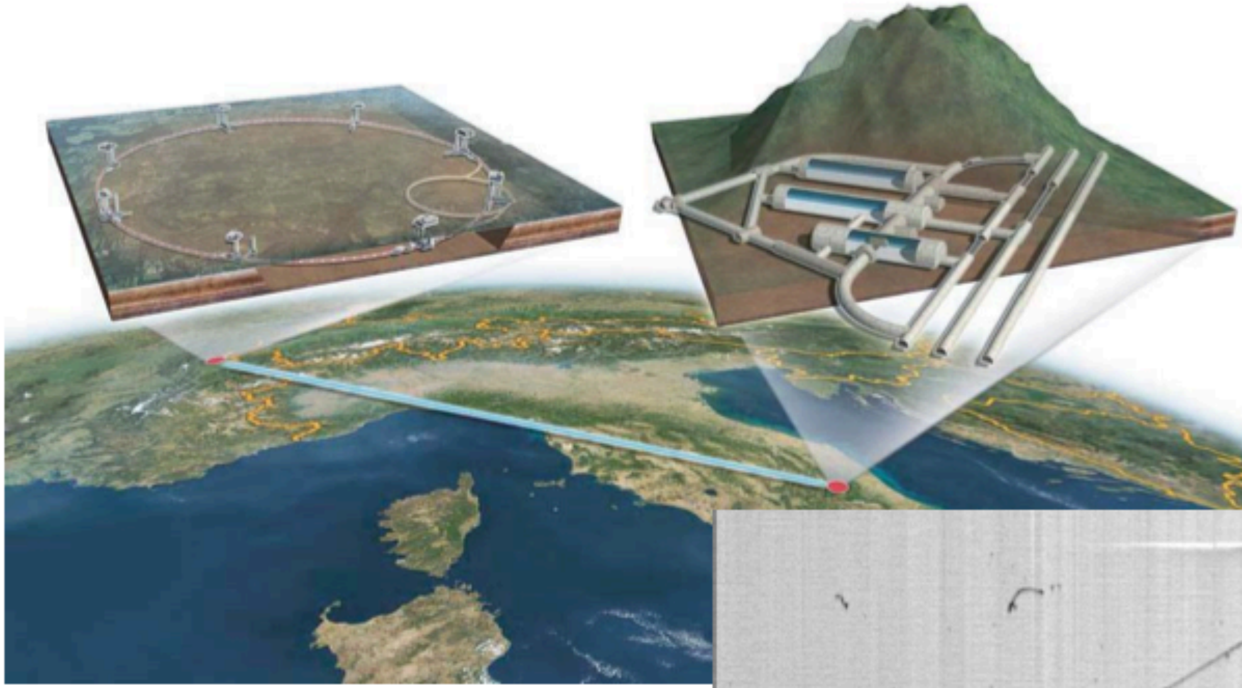


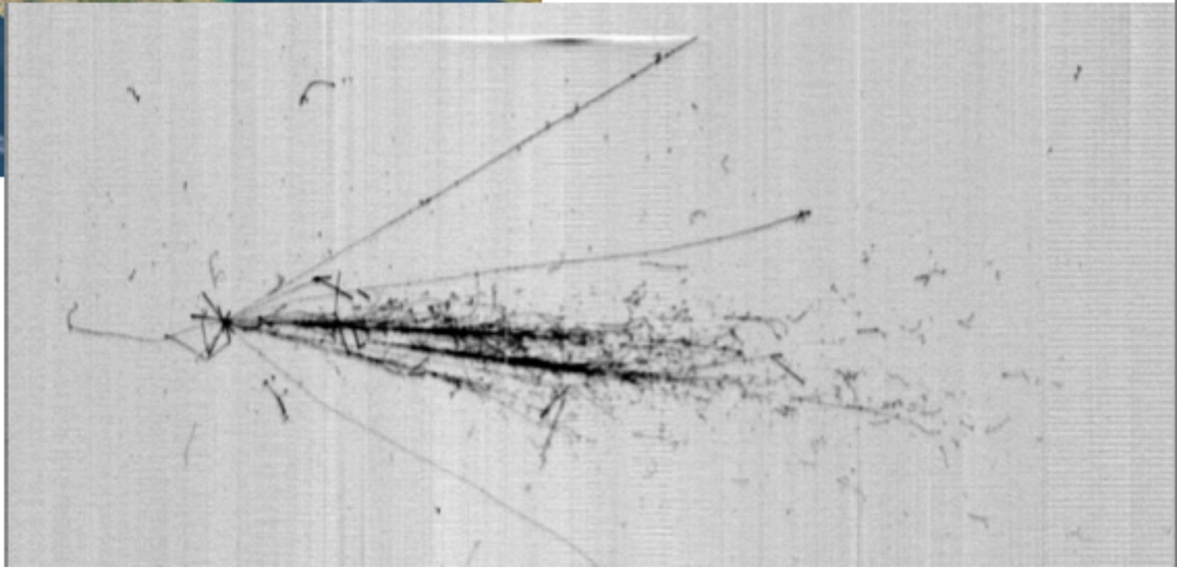
FUTURE -> Neutrino + Antineutrino running!

Some recent results from ICARUS

C. FARNESE
INFN Padova

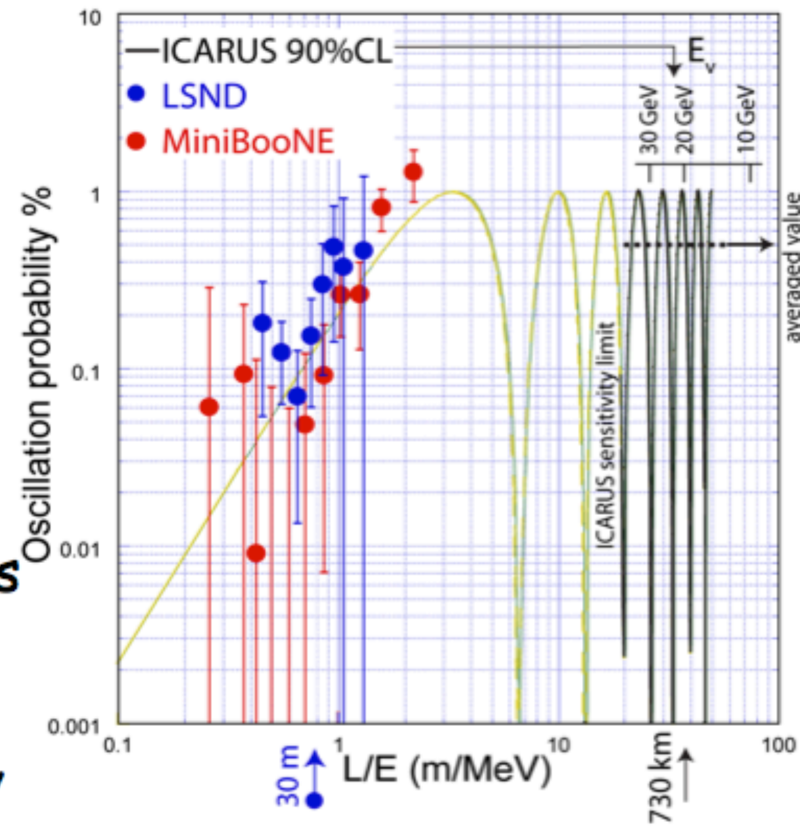
On behalf of the ICARUS Collaboration





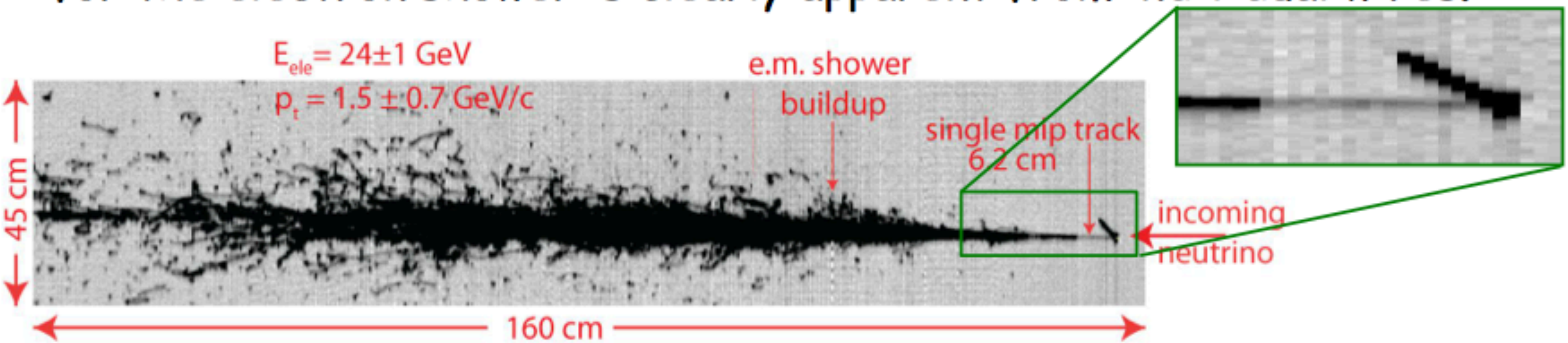
NEUTRINO 2014
Boston 2-7 June 2014

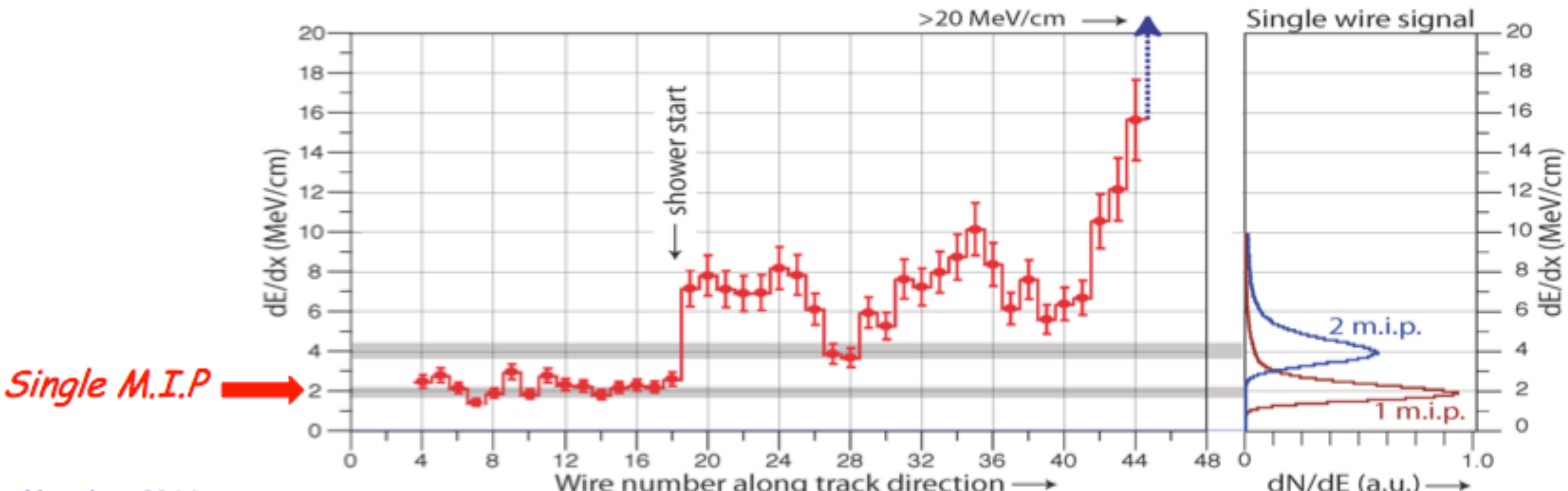
- *The CNGS facility delivered an almost pure ν_μ beam in 10-30 GeV E_ν range (beam associated ν_e ~1%) at a distance L=732 km from target.*
- There are differences w.r.t. LSND exp.
  - L/E_ν ~1 m/MeV at LSND, but $L/E_\nu \approx 36.5$ m/MeV at CNGS
  - LSND-like short distance oscill. signal averages to $\sin^2(1.27\Delta m^2_{new} L/E) \sim 1/2$ and $\langle P \rangle_{\nu\mu\to\nu e} \sim 1/2 \sin^2(2\theta_{new})$
- When compared to other long baseline results (MINOS and T2K) ICARUS operates in a L/E_ν region in which contributions from standard ν oscillations [mostly $\sin(\theta_{13})$] are not yet too relevant.
- Unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.



The new ICARUS result with 2450 ν interactions

- Event with a clear electron signature found in the sample of 2450 ν interactions (7.23 10^{19} pot).
- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.

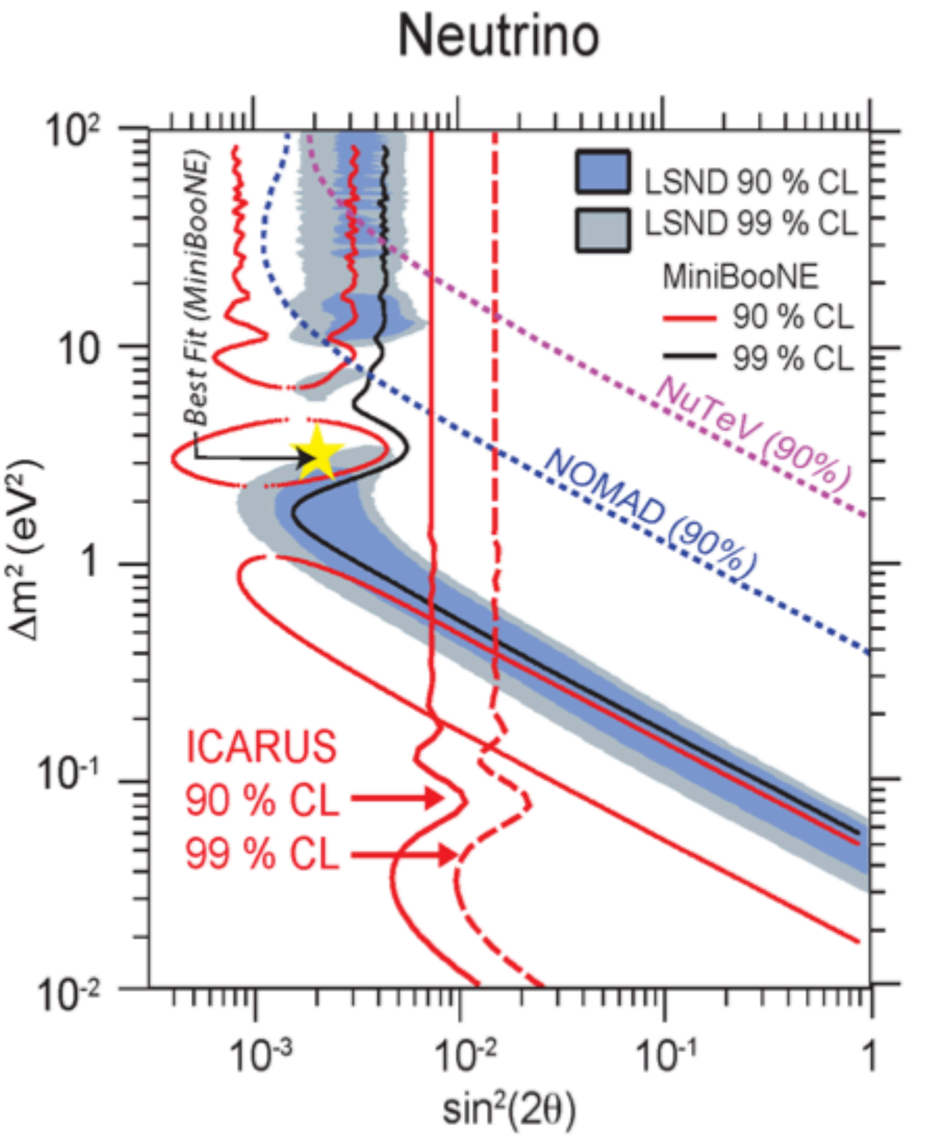




Neutrino_2014

ICARUS result on the search of the LSND-anomaly

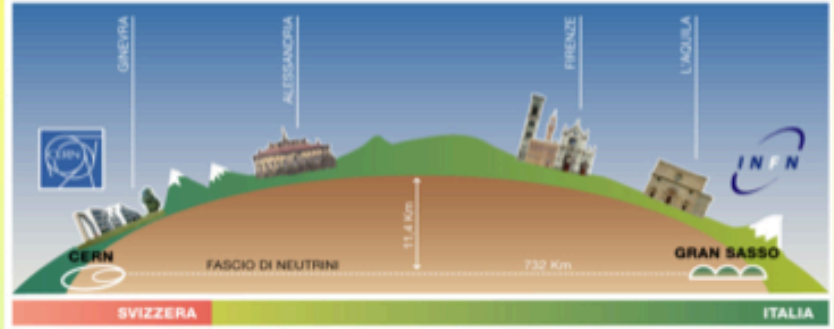
- 6 ν_e events have been observed in agreement with the expectations 7.9 ± 1.0 due to the conventional sources (the probability to observe ≤6 ν_e events is ~33%).
- Weighting for the efficiency, ICARUS limits on the number of events due to LSND anomaly are: 5.2 (90 % C.L.) and 10.3 (99 % C.L.).
- These provide the limits on the oscillation probability:
  - $P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}$ (90 % C.L.)
  - $P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \times 10^{-3}$ (99 % C.L.)



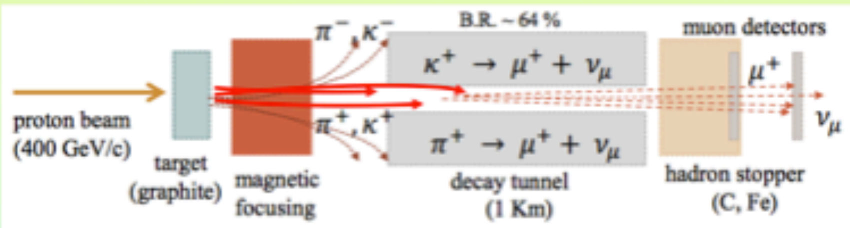
Neutrino_2014

CNGS beam

Opera
S. Dusini
INFN Padova



Beam requirements
1) high neutrino energy,
2) long baseline,
3) high beam intensity,



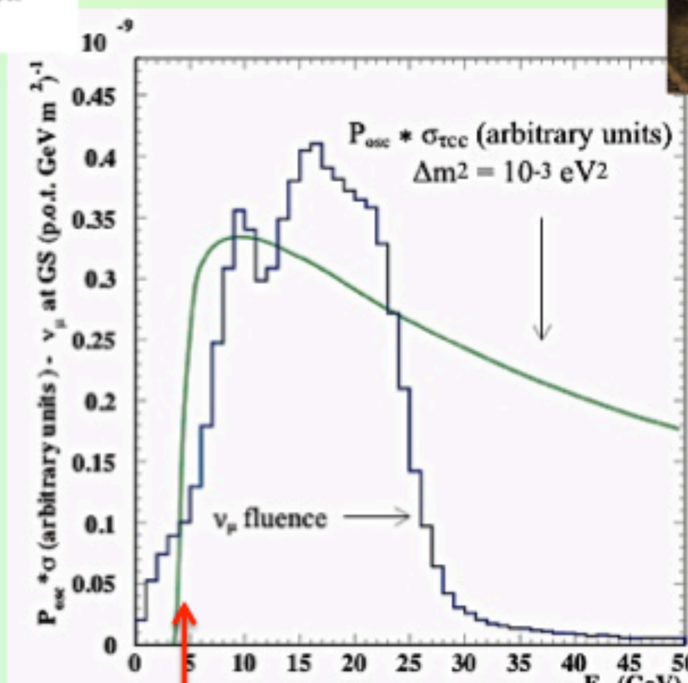
732 km

$$< E_{\nu_\tau} > \sim 17 \text{ GeV}$$

$$\frac{L}{< E_{\nu_\tau} >} \sim 43 \text{ Km/GeV}$$

High energy beam optimized to maximize tau production

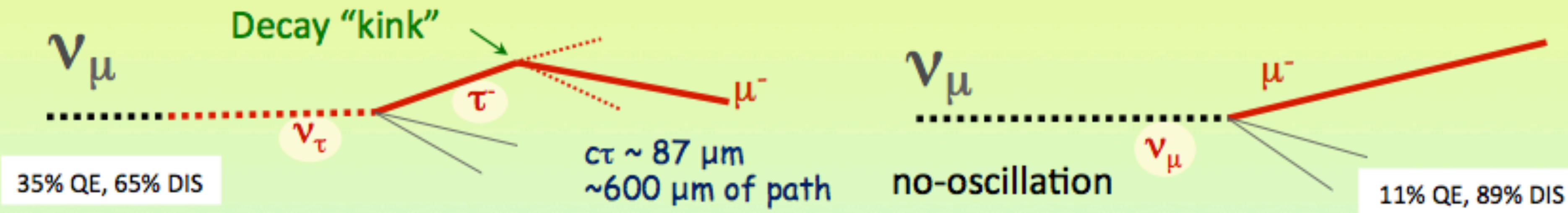
$P(\nu_\mu \rightarrow \nu_\tau) \sim O(1)\%$



tau production threshold $E_\nu \sim 3.5$ GeV

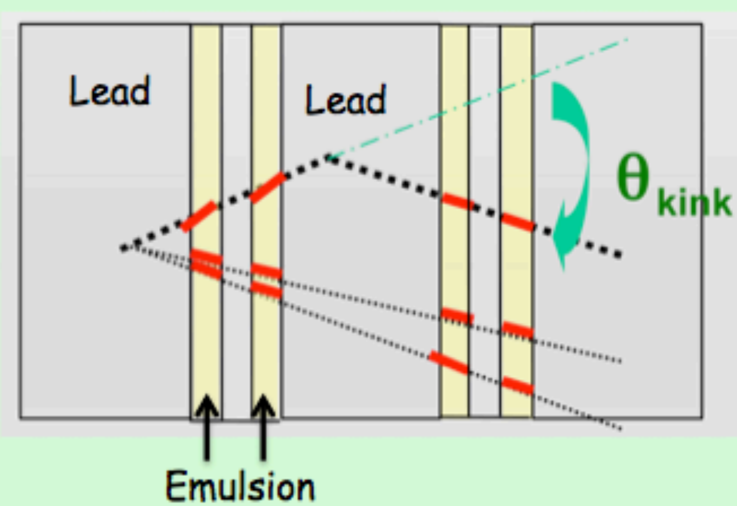
τ detection $\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau + N \to \tau^- + X$

The separation of the $\nu_\tau CC$ from the dominant ν_μ interactions
event-by-event, of the peculiar decay topology of the τ.

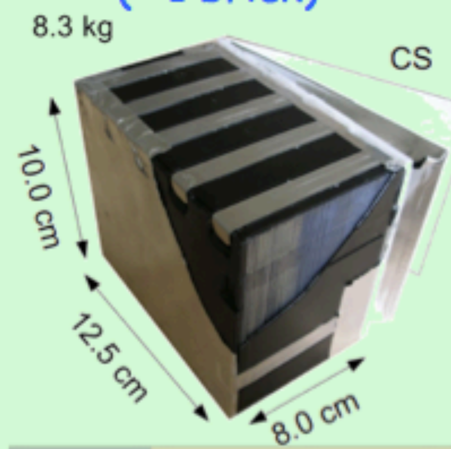


Hybrid detector

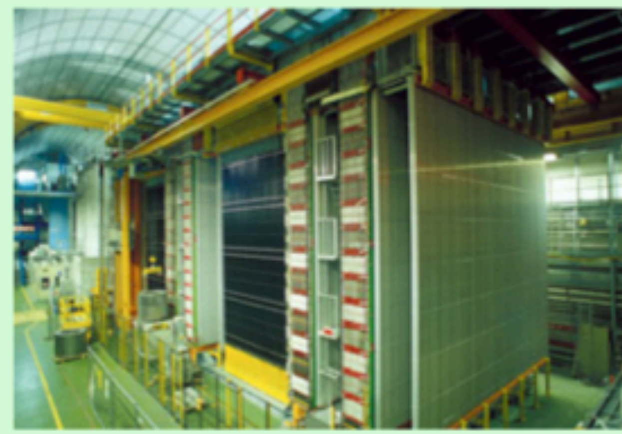
micrometric resolution



Emulsion Cloud Chamber (= 1 brick)

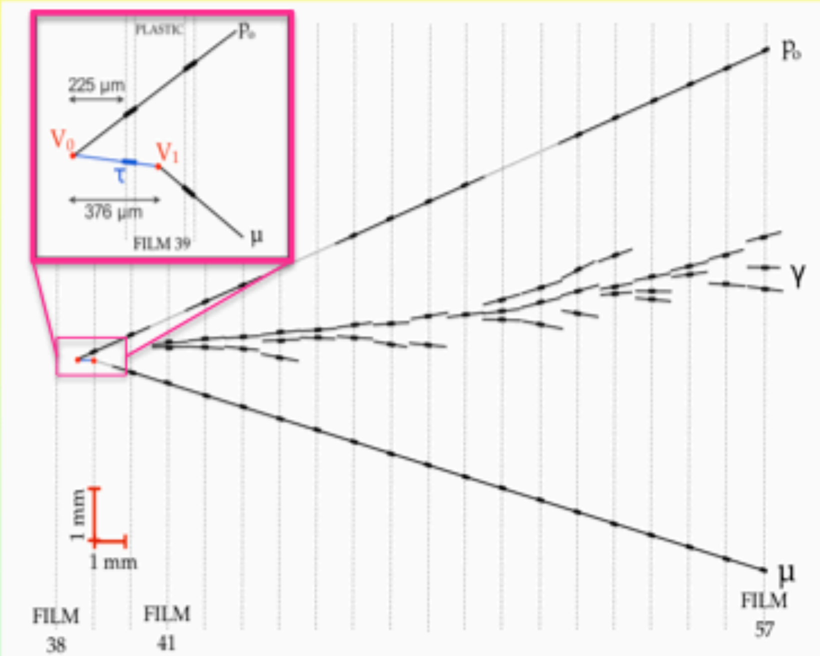


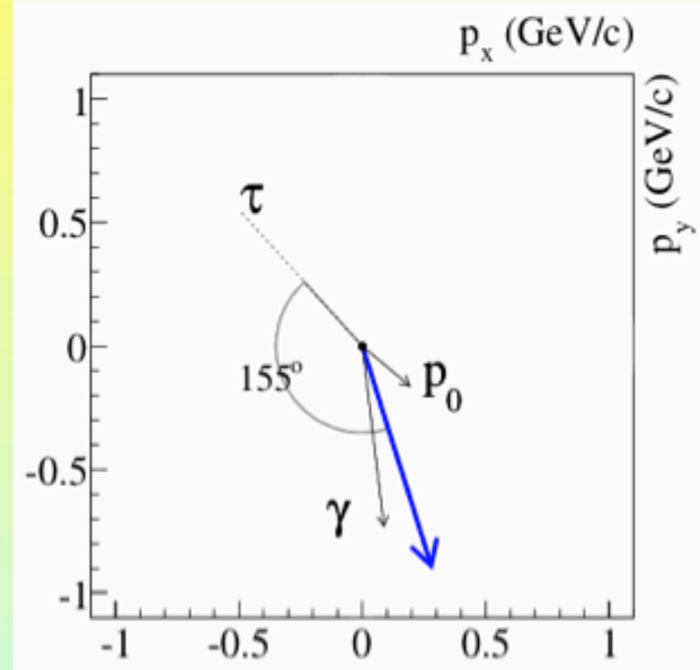
~150000 bricks (1.25 kton) + electronic detectors

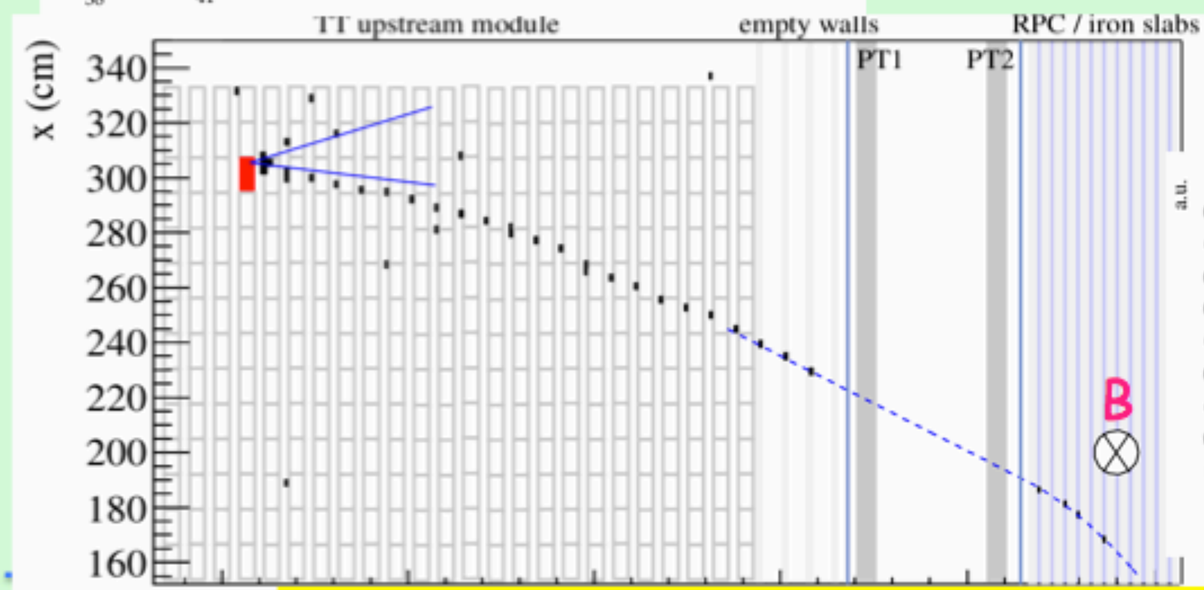


3rd ν_τ candidate $(\tau \rightarrow \mu)$ (2013)

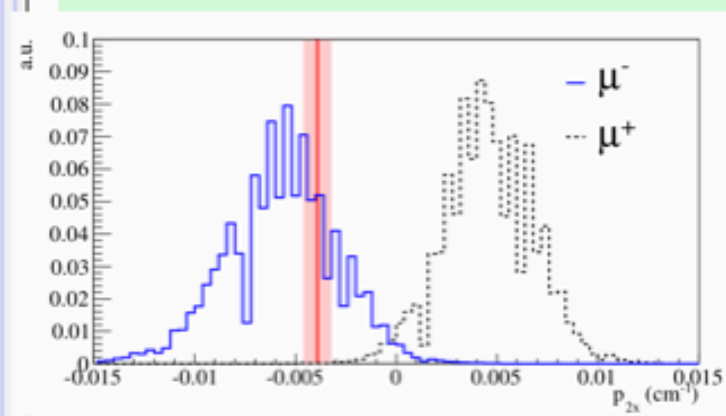
PHYSICAL REVIEW D 89 (2014) 051102(R)







Negative muon measured in the muon spectrometer



First measurement of the lepton charge in appearance mode

Data sample:

2008/09 : 398 (0μ events) + 1553 (1μ events)

2010/11/12 : 582 (0μ events) + 2153 (1μ events)

The expected signal and background is normalized to the number of located events

$$n^{0\mu}(\nu_\tau^{CC}) = \frac{\langle\sigma(\nu_\tau^{CC})\rangle}{\langle\sigma(\nu_\mu^{CC})\rangle} \frac{\langle\epsilon^{0\mu}(\nu_\tau^{CC})\rangle}{\langle\epsilon^{0\mu}(\nu_\tau^{CC})\rangle + \alpha\langle\epsilon^{0\mu}(\nu_\tau^{NC})\rangle} n^{0\mu} \qquad \alpha = \frac{NC}{CC}$$

Decay channel	Expected signal $\Delta m_{23}^2 = 2.32\ meV^2$	Total background	Observed
$\tau \to h$	0.4 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.03	1
$\tau \to \mu$	0.52 ± 0.1	0.018 ± 0.007	1
$\tau \to e$	0.61 ± 0.12	0.027 ± 0.005	0
Total	2.1 ± 0.42	0.23 ± 0.04	4

Two statistical method :

- Fisher combination of single channel p-value
- Likelihood ratio

p-value = 1.03×10^{-5} of no oscillation

no oscillation excluded at 4.2 σ CL

Summary

- The Full 3-flavor oscillation model is probed by the high precision data of MINOS(+) and T2K.
- New results from these experiments and ICARUS and OPERA severely limit a simple interpretation of the low energy anomalies from LSND and MiniBooNE.
- OPERA gains additional tau events and is consistent with the 3 flavor oscillation.
- Many analyses from these facilities could not be shown.