



Long-Baseline Neutrino Experiments: Present and Future

Colloquium at

Alexandre Sousa
Harvard University



Desembre 15, 2011

València, Espanya

Outline

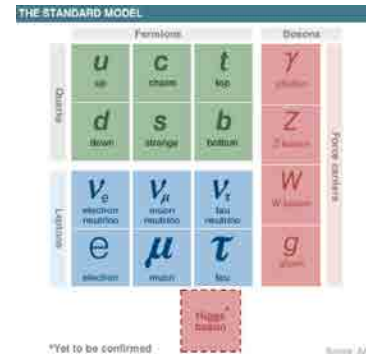
- Introduction
 - Neutrino Physics
 - Measuring Neutrinos with Long-Baseline Experiments
- Neutrino Disappearance Measurements
- Neutrino Appearance Measurements
- Neutrino Time-of-Flight Prospects
- Next Generation Experiments
- Outlook

The Standard Model Building Blocks

Three Generations of Matter (Fermions)				
	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name→	u up	c charm	t top	γ photon
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d down	s strange	b bottom	g gluon
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	W[±] weak force

- First generation of Matter accounts for most visible matter. Particles from II and III are increasingly massive (and unstable) replicas of generation I
- **Neutrinos are neutral elementary particles**
 - Only couple to the weak force (and gravity)
 - Considered massless in the Standard Model
 - Known to undergo flavor change
 - Evidence for neutrino mass was the first clue of physics beyond the Standard Model

Why Are Neutrinos Interesting?



Fundamental Particles and Interactions

- Masses are anomalously low. From CMB data $m_\nu < 0.2 \text{ eV}/c^2 = 0.0000004 m_e$
- Only fundamental fermion that can be its own antiparticle (Majorana particle)
- May open window on the GUT Scale ($\Lambda_{\text{GUT}} \sim 10^{16} \text{ GeV}$) via seesaw mechanism
- Could explain the matter/antimatter asymmetry of the universe (leptogenesis)

Seesaw Mechanism

- Attempt to provide framework to explain lightness of the neutrino
- Since right-handed neutrinos have no weak interactions, they are not confined to the weak mass scale
 - Add a **GUT-scale right-handed Majorana neutrino** N_R to the SM lagrangian, including both Majorana and Dirac mass terms

$$\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M N_R^2 + \lambda(\nu_L, l_L) \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} N_R + \text{h.c.}$$

- The resulting mass matrix is

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \quad m \approx \langle \phi \rangle \sim \mathcal{O}(100 \text{ GeV})$$

- The physical masses are obtained from the matrix eigenvalues

$$m_N \approx M \quad m_\nu = \frac{m^2}{M}$$

- For $M \sim 10^{15} \text{ GeV}/c^2$, the light neutrino mass is $m_\nu \sim 0.05 \text{ eV}/c^2$



Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;
Minkowski

Baryon Asymmetry

- Matter/Antimatter asymmetry is one of the great mysteries of modern physics

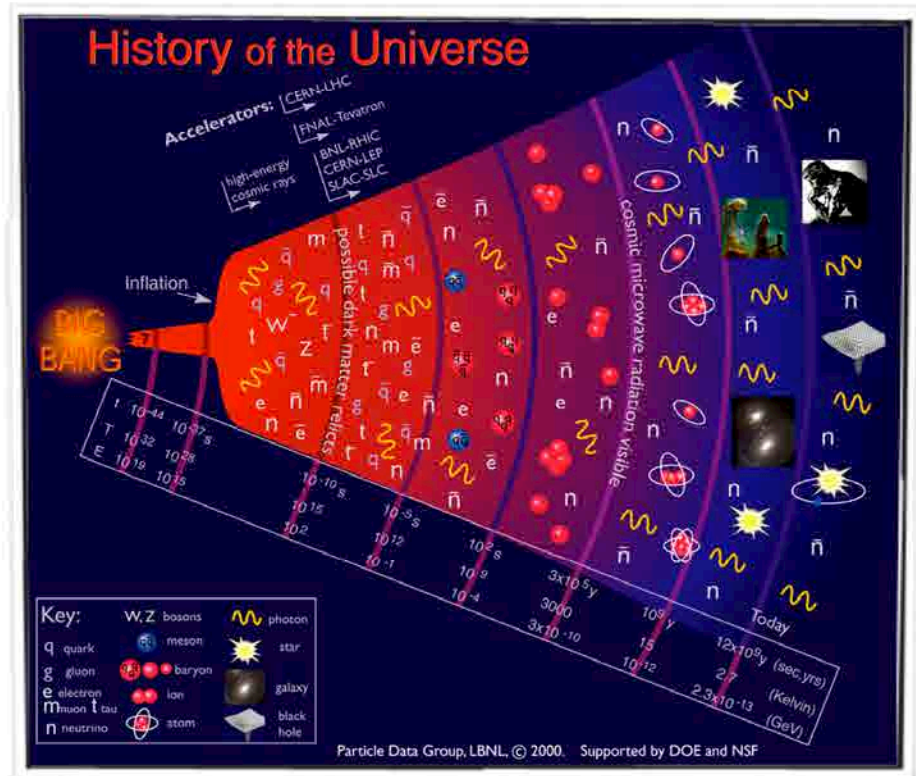
- $\frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$ (Big Bang Nucleosynthesis, consistent with WMAP results)

- Sakharov (1967):

$$B \equiv n_B - n_{\bar{B}} = 0 \Rightarrow B \neq 0$$

requires violation of CP symmetry

- CP violation in quark sector of standard model is not large enough to explain matter/antimatter asymmetry

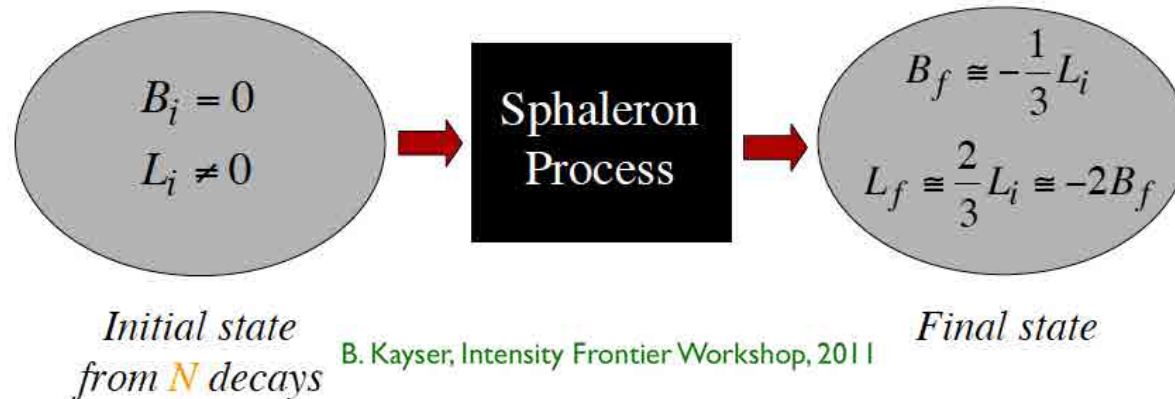


Leptogenesis

- If the seesaw heavy neutrino exists, **Leptogenesis** may explain the observed baryon asymmetry through CP-violating heavy neutrino decays (Fukugita, Yanagida)

$$\Gamma(N_R \rightarrow \nu + H^0) \neq \Gamma(N_R \rightarrow \bar{\nu} + \overline{H^0})$$

- GUT-level (B - L)-conserving interactions convert the lepton-number asymmetry to a baryon asymmetry



- CP-violation in heavy neutrino decays is very likely to be manifest in light neutrinos
- **Look for CP violation in light neutrino sector!**

Neutrino Oscillations

- Neutrino oscillations occur because the flavor (weak) eigenstates do not coincide with the mass eigenstates

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle \quad (\alpha = e, \mu, \tau) \quad U_{PMNS} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}$$

- The neutrinos interact as a flavor state, but propagate as a superposition of the three mass states. Over a distance L , changes in the relative phases of the mass states may induce neutrino flavor change
- Assume two neutrino flavors for simplicity:

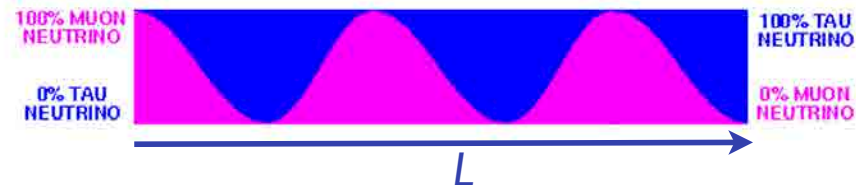
$$\begin{bmatrix} \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \nu_2 \\ \nu_3 \end{bmatrix} \quad |\nu_\mu(t)\rangle = \cos \theta e^{-iE_2 t} |\nu_2\rangle + \sin \theta e^{-iE_3 t} |\nu_3\rangle$$

$$E_i = \sqrt{p^2 + m_i^2}$$

- Probability that a ν_μ remains ν_μ after some time t :

$$P(\nu_\mu \rightarrow \nu_\mu) = |\langle \nu_\mu | \nu_\mu(t) \rangle|^2 \simeq 1 - \sin^2(2\theta) \sin^2 \left(1.27 \Delta m_{32}^2 \frac{L[\text{km}]}{E[\text{GeV}]} \right)$$

- Neutrino oscillations depend on L , the neutrino energy E , and the mixing parameters



Neutrino Oscillation Discovery

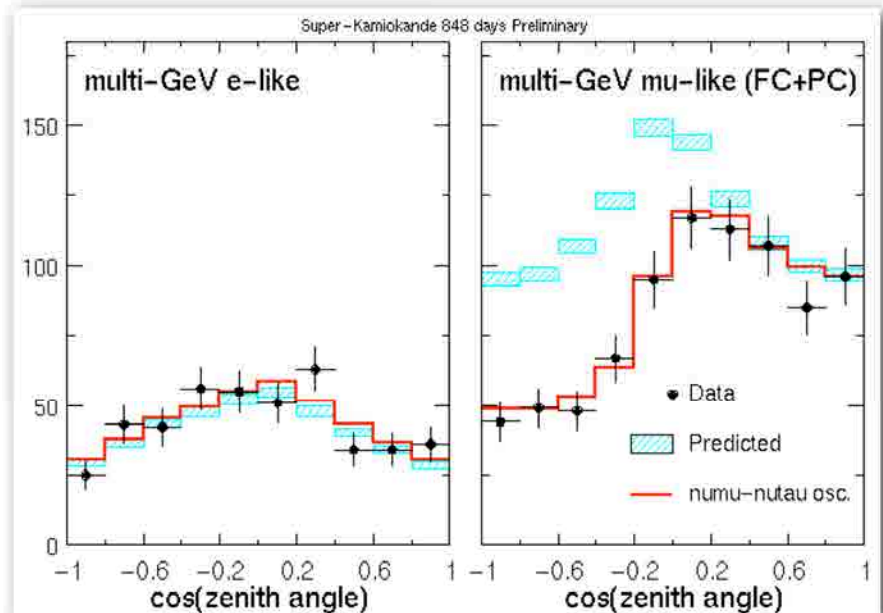
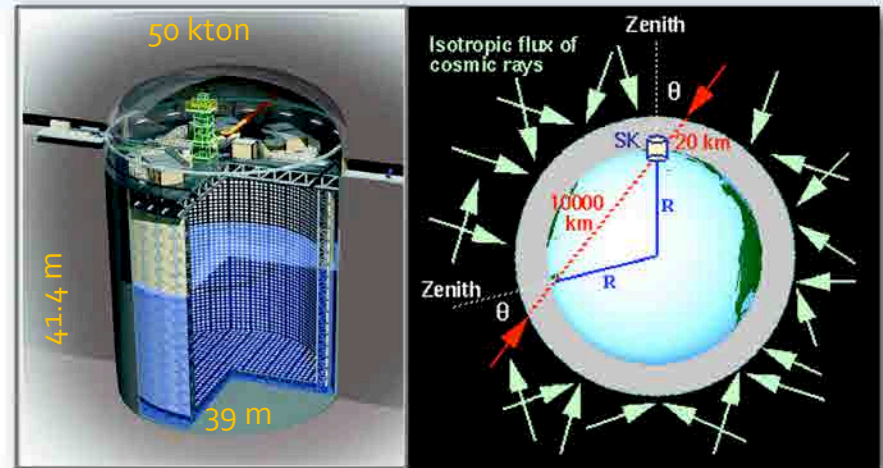
- The SuperKamiokande experiment in Japan measures atmospheric neutrinos with a 50 kton Čerenkov water tank
- SuperK compared the angular distribution of downward-going neutrinos with upward-going neutrinos
- In 1998, SuperK announced the observed deficit in upward-going neutrinos is best explained by $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations

- 2011 results:

$$|\Delta m_{32}^2| = 2.2_{-0.15}^{+0.15} \times 10^{-3} \text{eV}^2$$

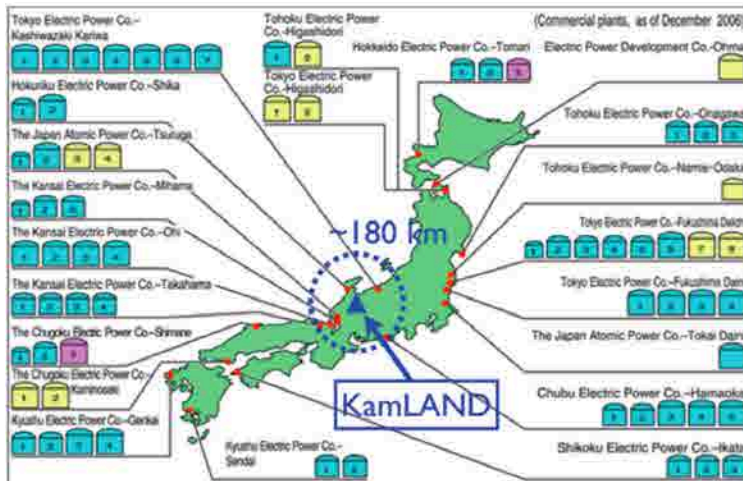
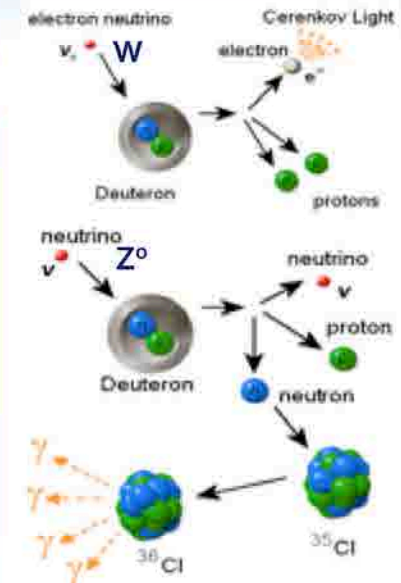
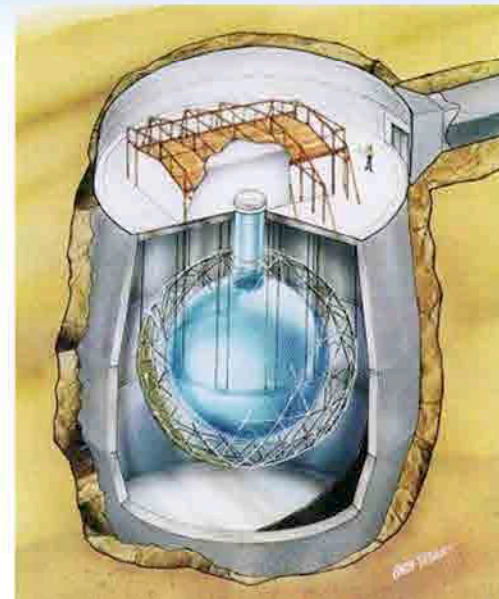
$$\sin^2(2\theta_{23}) > 0.96 \text{ (90\% C.L.)}$$

R. Wendell, DPF 2011



Solar Neutrino Oscillations

- Sudbury Neutrino Observatory (SNO) in Canada used a heavy water (D₂O) target to detect solar neutrinos
- SNO was sensitive to ν_e via charged-currents and to all three neutrino flavors via neutral currents
- Confirmed ν_e deficit and solar model in 2001

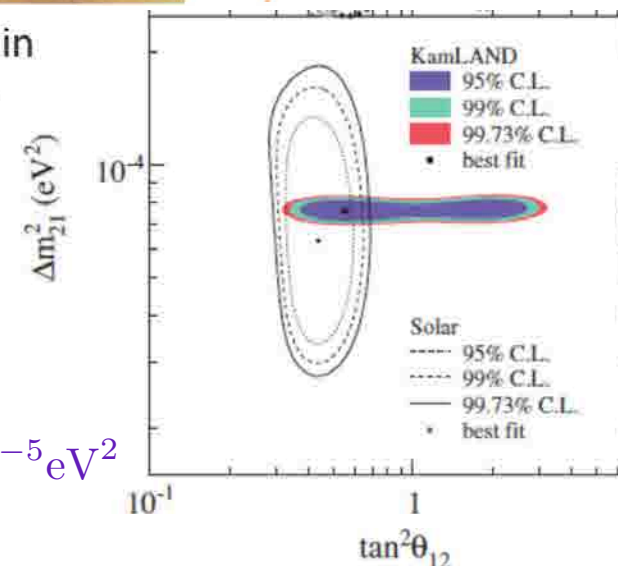


- KamLAND experiment in Japan measured reactor antineutrinos over long baselines (~180 km)

- Both experiments consistent with $\nu_e \rightarrow \nu_\mu, \nu_\tau$ mixing:

$$|\Delta m_{21}^2| = 7.59_{-0.21}^{+0.20} \times 10^{-5} \text{eV}^2$$

$$\theta_{21} = 34.06_{-0.84}^{+1.16} \text{deg}$$



Current Three ν Oscillation Picture

Atmos. + Accelerator Reactor+Accelerator Solar+Reactor

$$U_{\text{PMNS}} = \begin{bmatrix} 1 & & & \\ & c_{23} & -s_{23} & \\ & s_{23} & c_{23} & \\ & & & 1 \end{bmatrix} \begin{bmatrix} c_{13} & & -s_{13} e^{-i\delta_{CP}} & \\ & 1 & & \\ s_{13} e^{-i\delta_{CP}} & & c_{13} & \\ & & & 1 \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & & \\ -s_{12} & c_{12} & & \\ & & & 1 \end{bmatrix}$$

$$c_{lk} = \cos\theta_{lk}$$

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

• Two mass splittings

• **Atmos.:** $\Delta m^2_{\text{atm}} \approx \Delta m^2_{32} \sim 10^{-3} \text{ eV}^2$

• **Solar:** $\Delta m^2_{\text{sol}} \approx \Delta m^2_{21} \sim 10^{-4} \text{ eV}^2$

• Large atmospheric mixing

• $\theta_{23} \sim 45^\circ$

• Non-maximal solar mixing

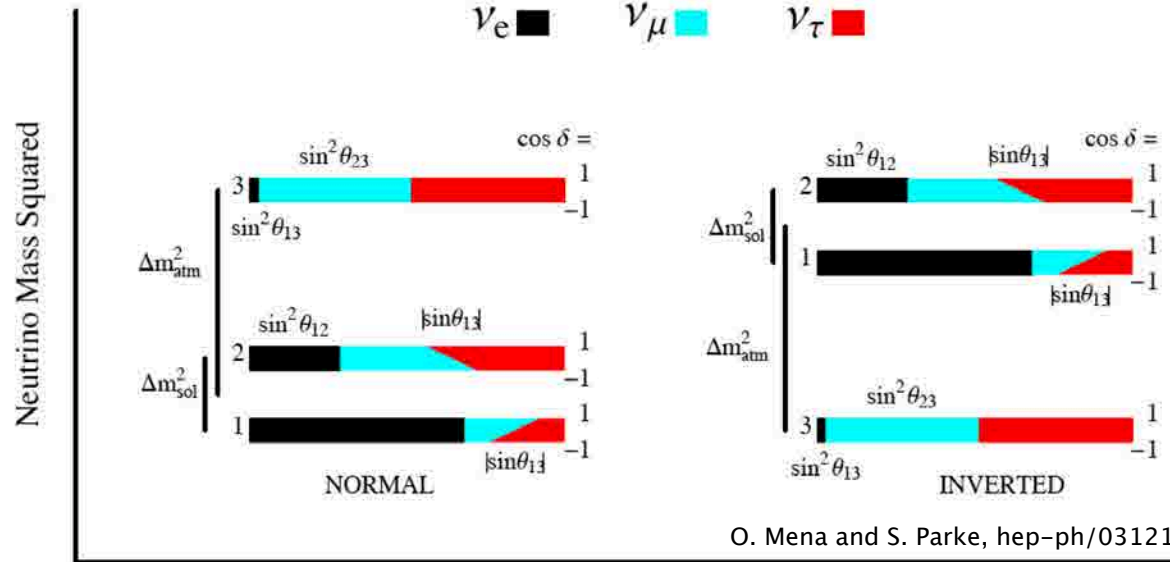
• $\theta_{12} \sim 34^\circ$

• Mixed sector unknown (is it?)

• θ_{13} known to be small

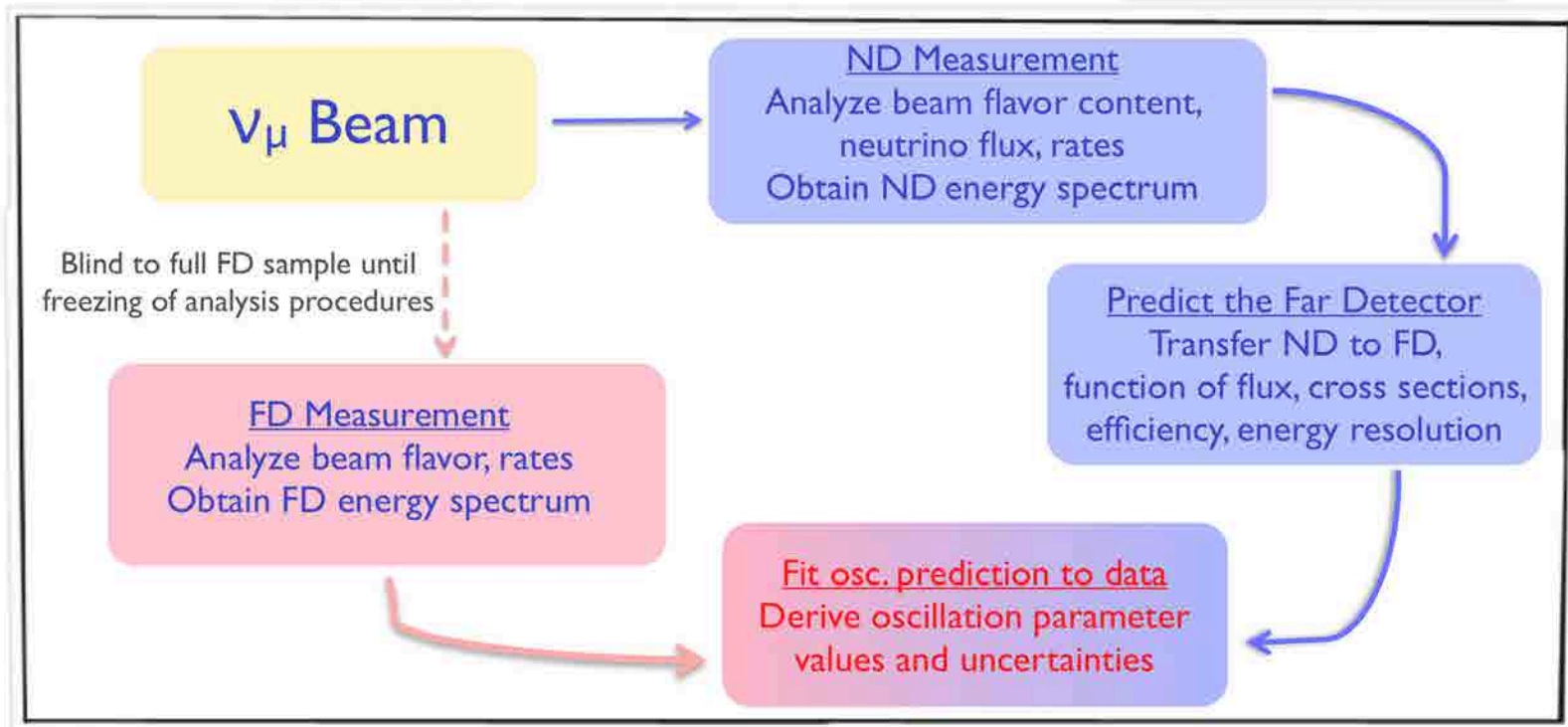
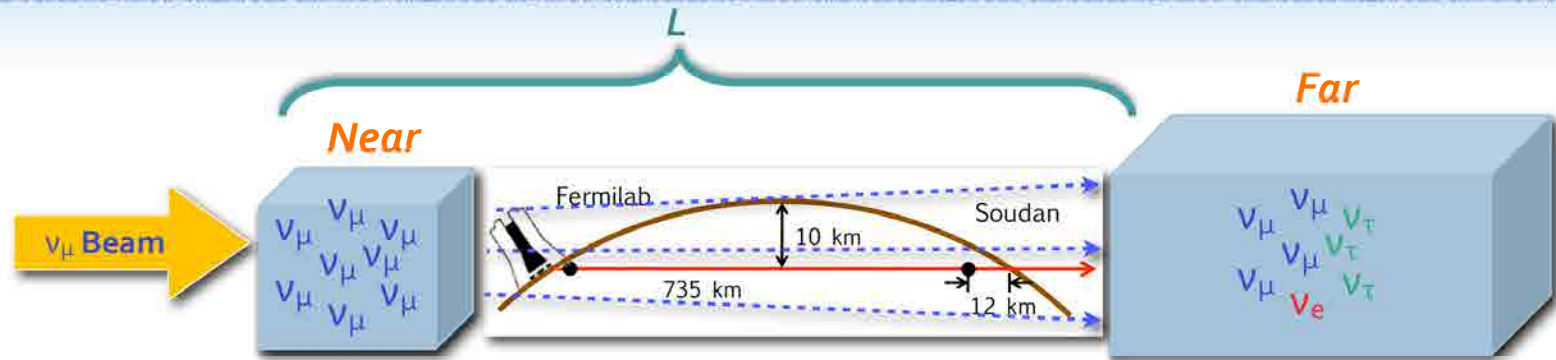
• $\delta_{CP} \neq 0? \Rightarrow P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq P(\nu_\mu \rightarrow \nu_e)$

• **Neutrino Mass hierarchy unknown**



Fractional Flavor Content varying $\cos \delta$

A Long-Baseline Neutrino Experiment



- Aim to make precision measurements of osc, parameters, search for θ_{13} and CP violation

Where can we find them?



NOvA (in construction)
14 kt Liquid Scint
Tracking Calorimeter
810km, $E \gg 2\text{GeV}$
Off-axis beam

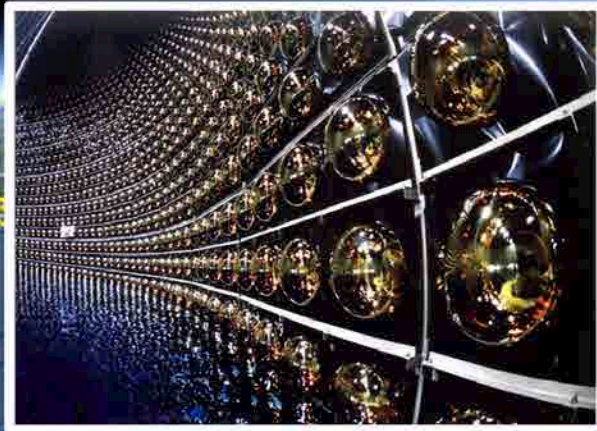


MINOS
5.4kt Fe/Scint
Magnetized
Tracking Calorimeter
735km, $E \gg 3.5\text{ GeV}$

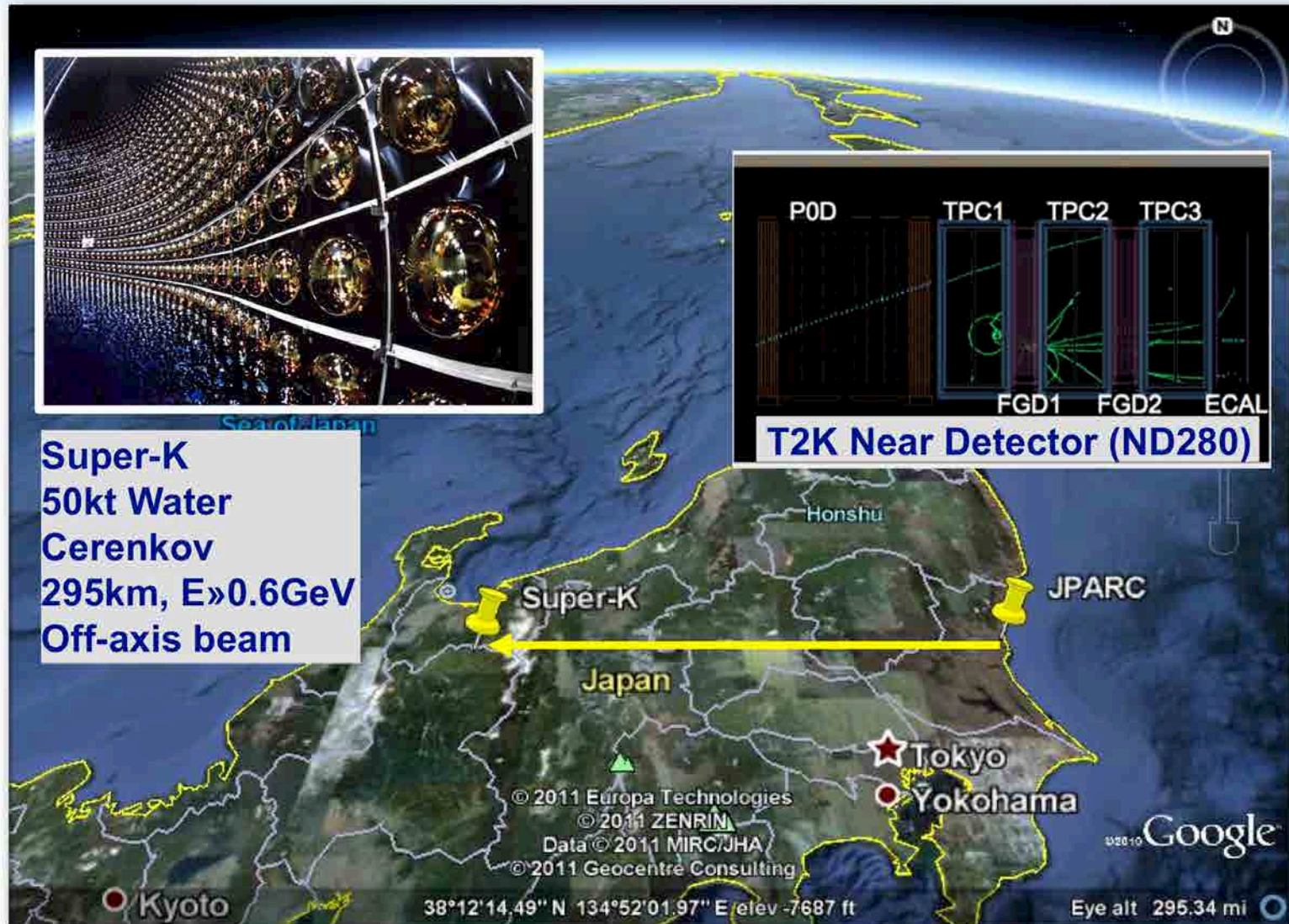
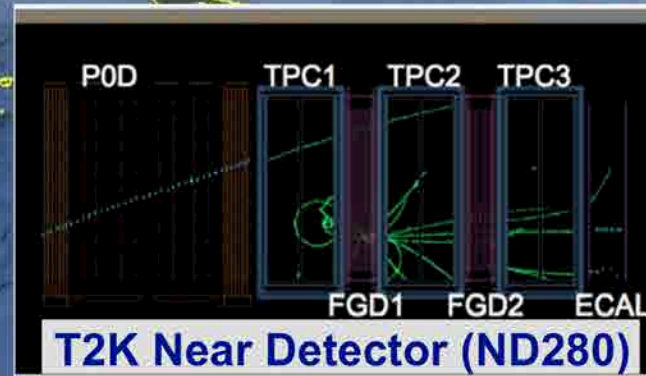
**Weak Interaction
= Big Detectors!**



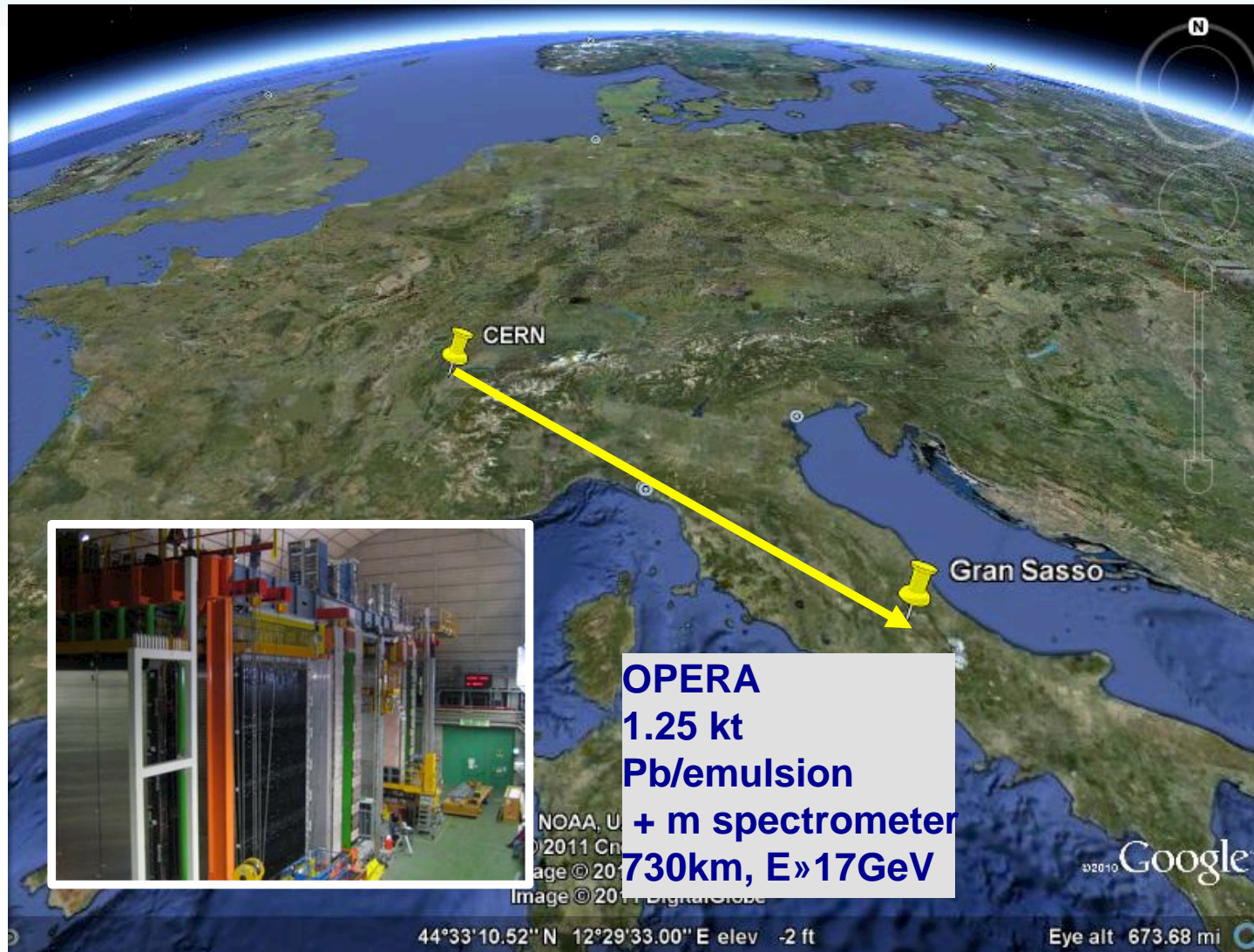
Where can we find them?



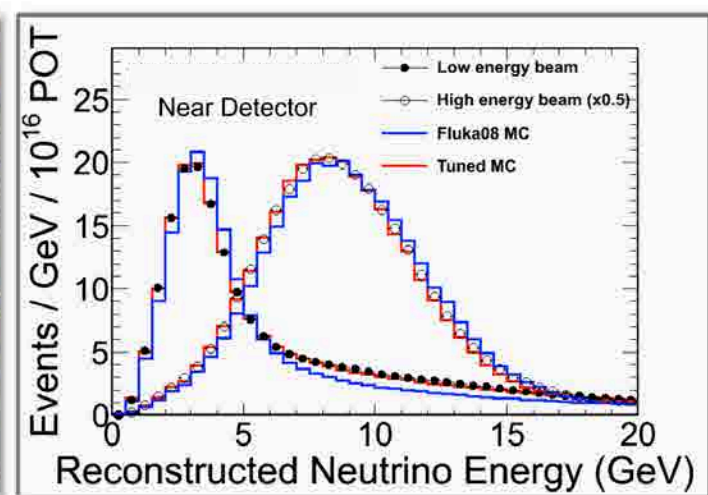
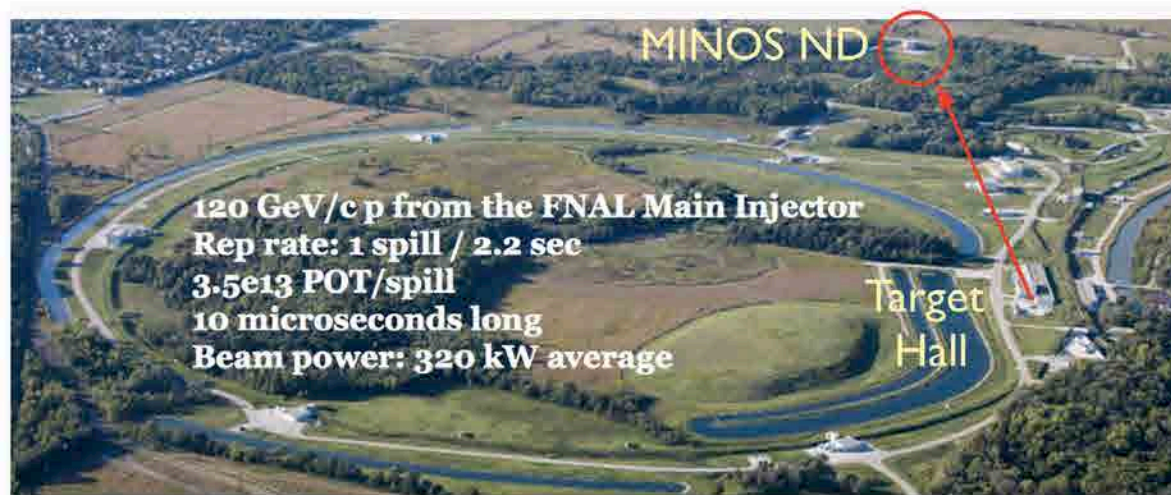
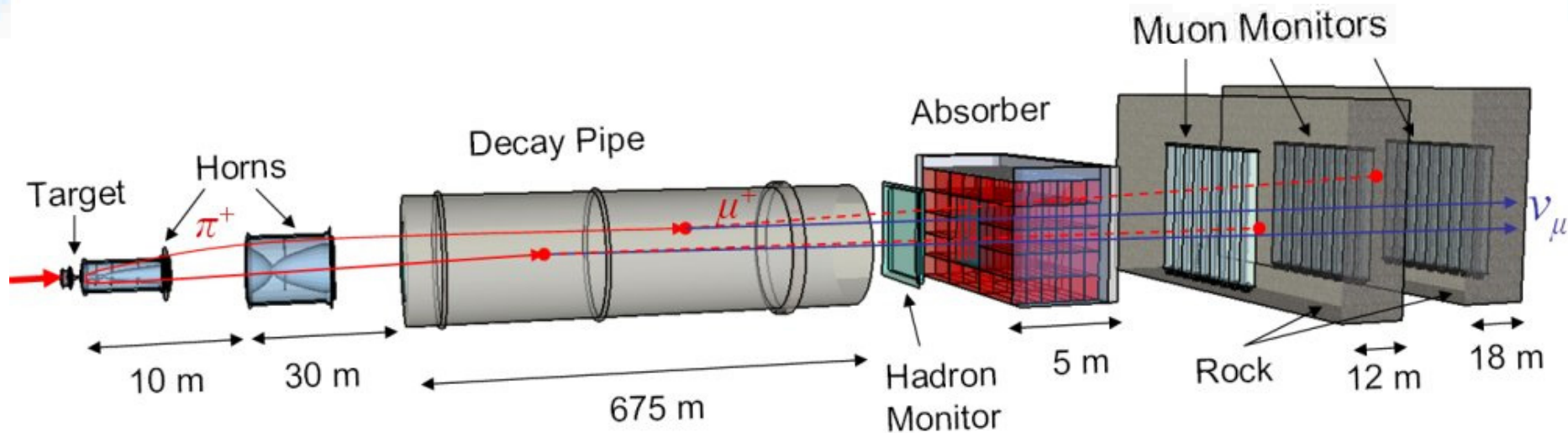
Super-K
50kt Water
Cerenkov
295km, $E \gg 0.6\text{GeV}$
Off-axis beam



Where can we find them?



Creating a Muon Neutrino Beam

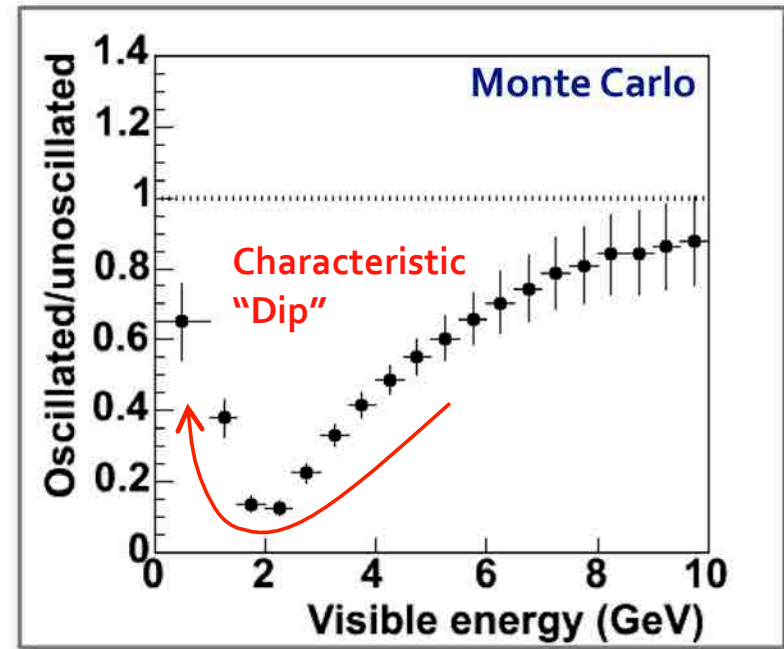
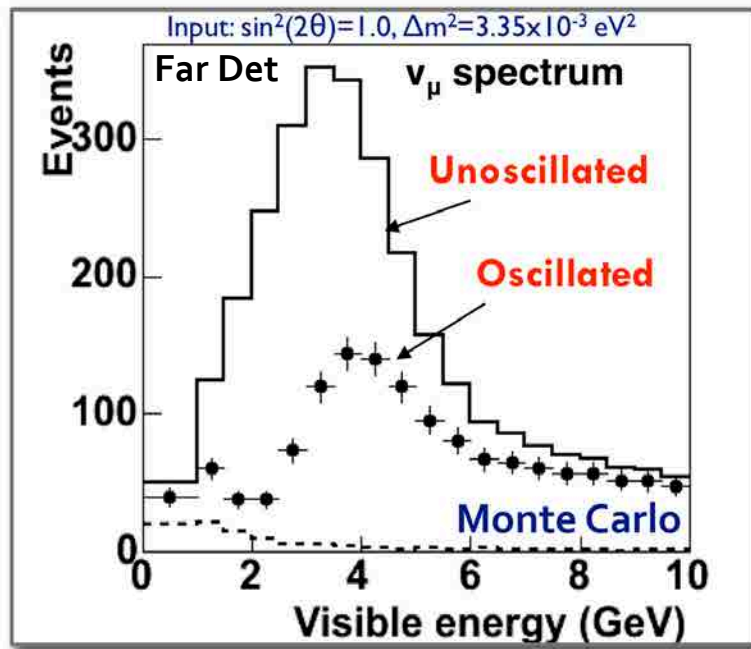


Neutrino Disappearance Measurements

Oscillation Parameter Measurement

- Compare unoscillated Far Detector prediction from Near Detector with Far Detector measurement
 - Neutrino oscillations deplete rate and distort the energy spectrum

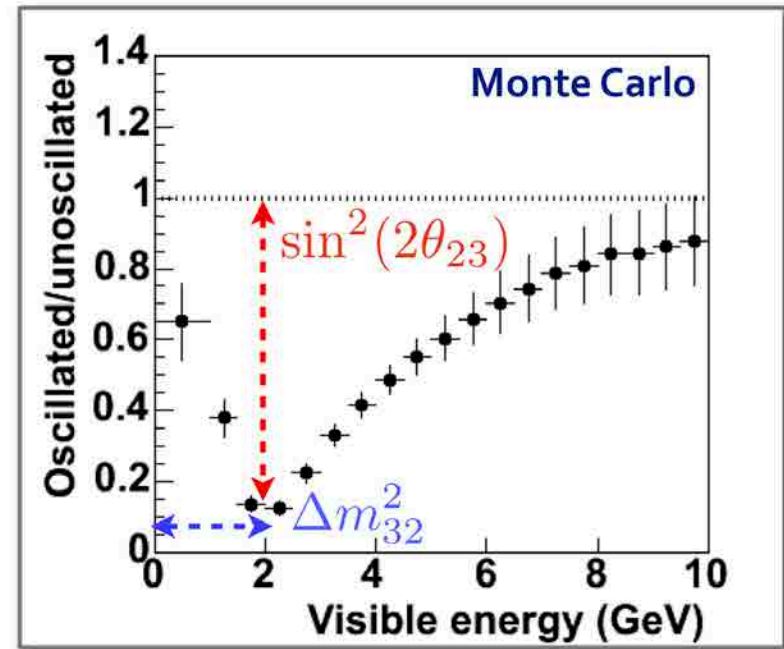
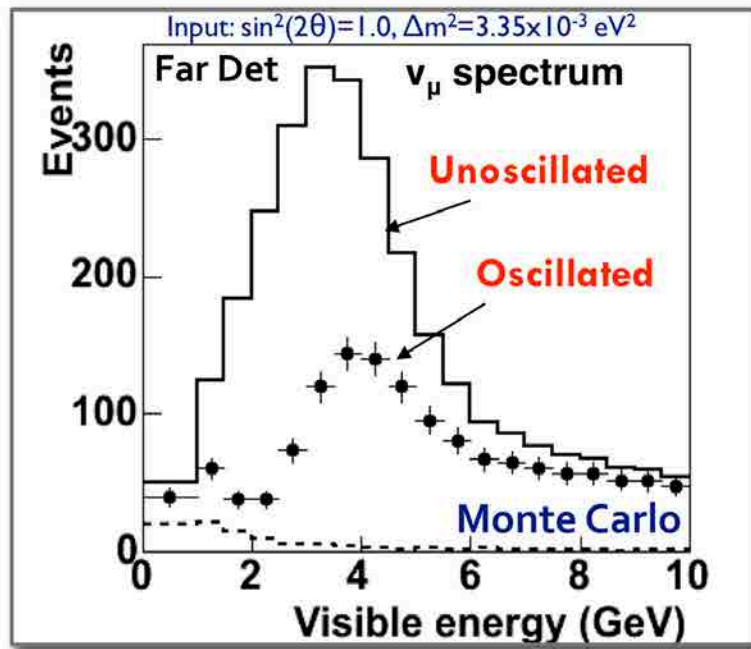
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267 \Delta m_{32}^2 \frac{L}{E}\right)$$



Oscillation Parameter Measurement

- Compare unoscillated Far Detector prediction from Near Detector with Far Detector measurement
 - Neutrino oscillations deplete rate and distort the energy spectrum

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267 \Delta m_{32}^2 \frac{L}{E}\right)$$



The MINOS Experiment



Main Injector Neutrino Oscillation Search



- 735 km baseline from Fermilab to Soudan Mine
- Using NuMI ν_μ beam
 - 2.5×10^{13} protons/pulse
 - 320 kW beam power
 - 3.3 GeV average E_ν

- Detectors are planar steel/scintillator calorimeters
 - Functionally identical
 - Magnetized with $\langle B \rangle \sim 1.3T$
 - Cancellation of ν flux and cross-section uncertainties



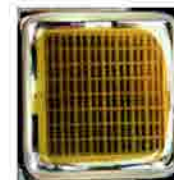
Detector Technology



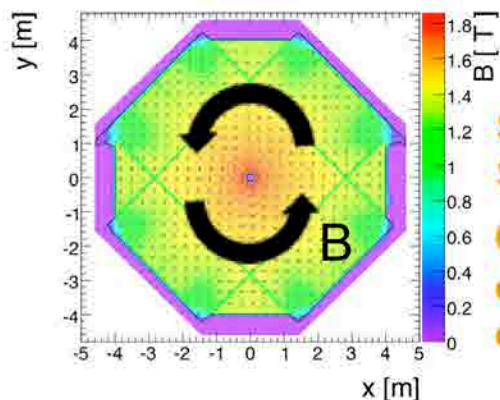
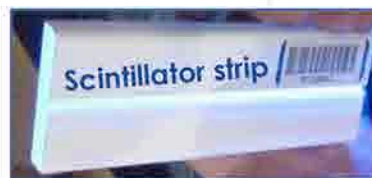
- Steel/Scintillator Tracking Calorimeters
 - 2.54 cm-thick steel plates (5.96 cm between plates)
 - 1 cm-thick, 4.1 cm-wide extruded polystyrene scintillator strips
- Both magnetized with $\langle B \text{ field} \rangle \sim 1.3\text{T}$
 - Can measure muon energy from range in detector or from curvature in B field
 - Able to distinguish μ^+ from μ^-



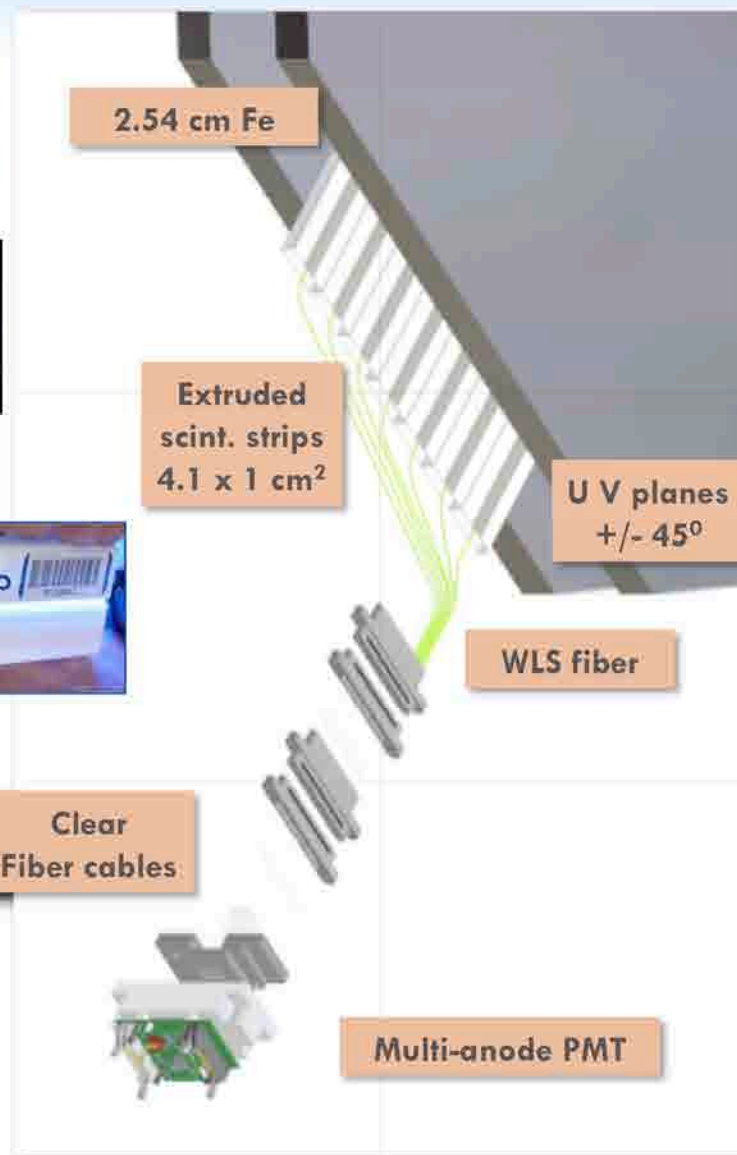
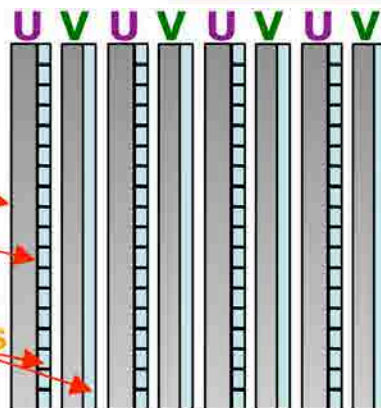
M16



M64



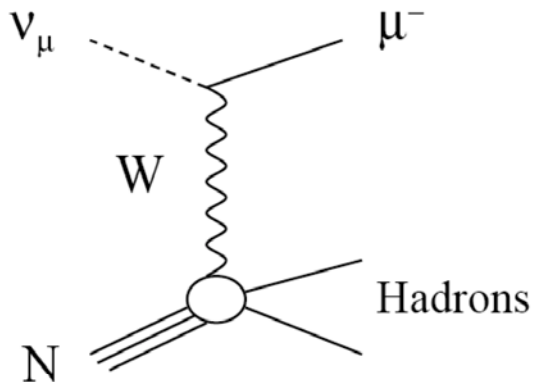
Steel
Scintillator
Orthogonal
orientations
of strips



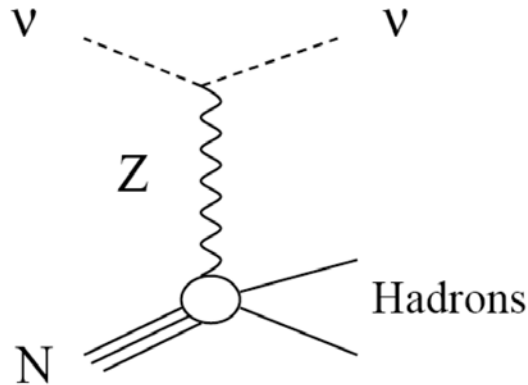
Event Topologies



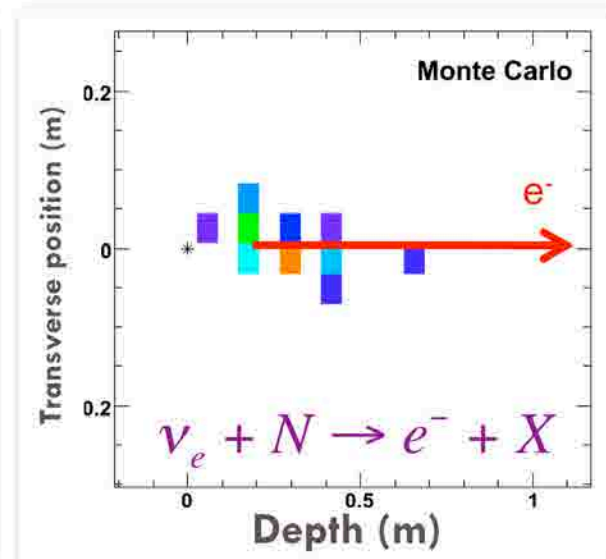
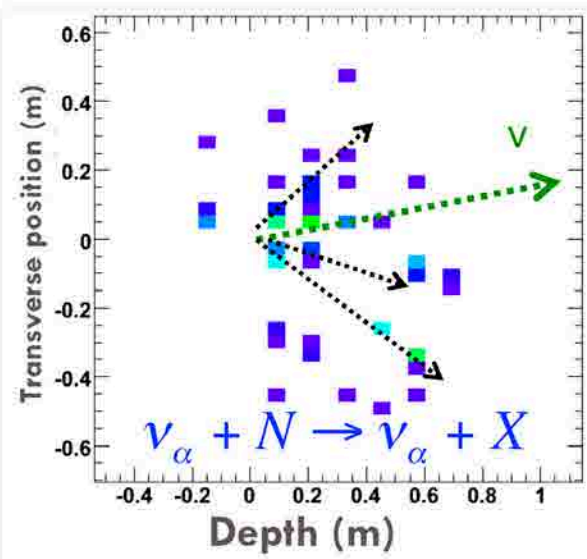
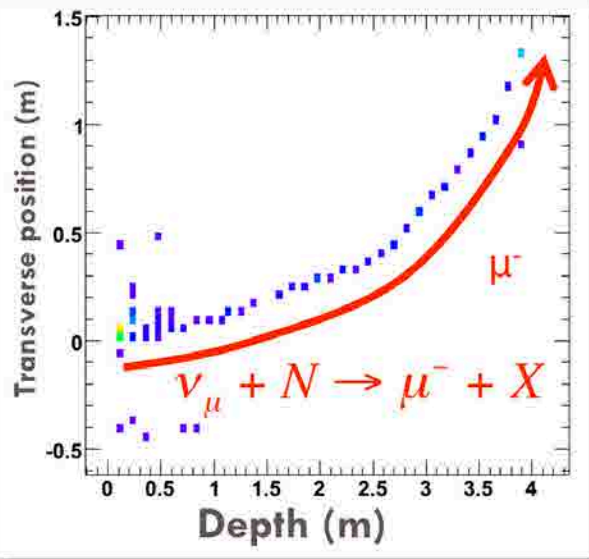
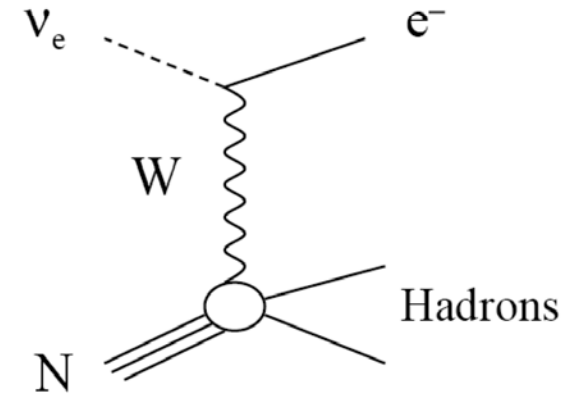
ν_μ CC Event



NC Event



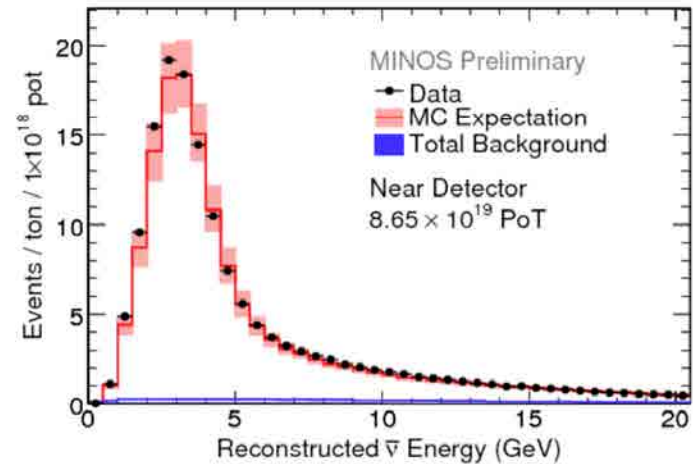
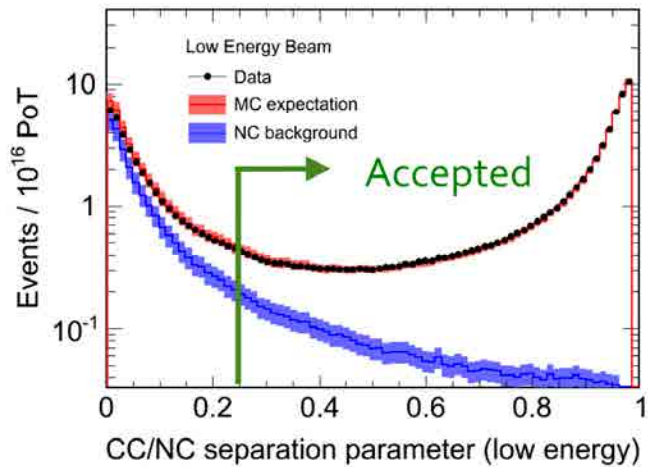
ν_e CC Event



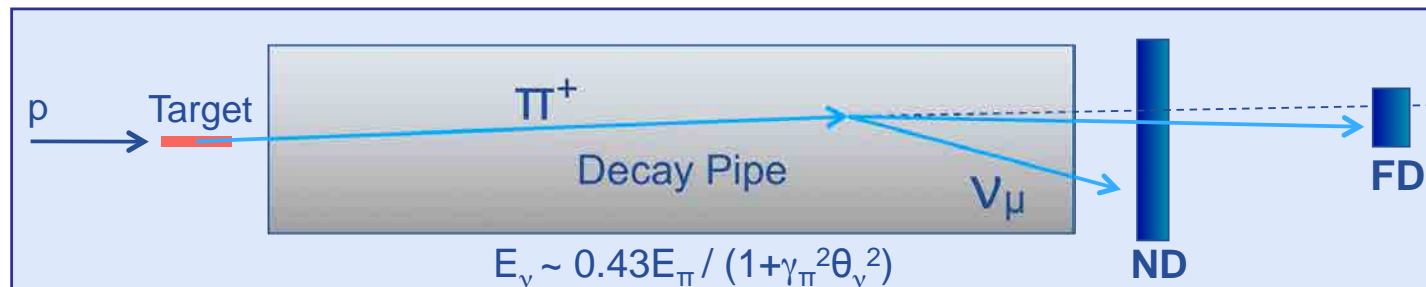
Predicting the FD Spectrum



- Separate CC from NC interactions in the ND using a k-Nearest Neighbors algorithm



- FD energy spectrum without oscillations is similar to $1/R^2$ -scaled ND but not the same

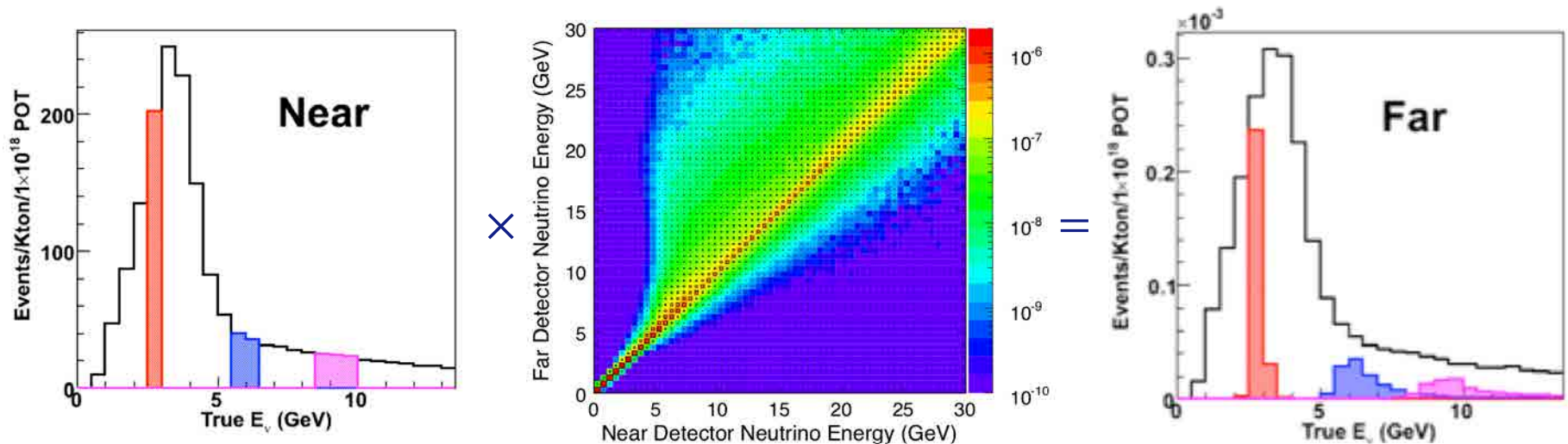


- Neutrino energy depends on angle with original pion direction pion energy
- Near Detector covers a wider solid angle
- Higher energy π travel further downstream the decay pipe and decay closer to the ND

Beam Matrix Extrapolation



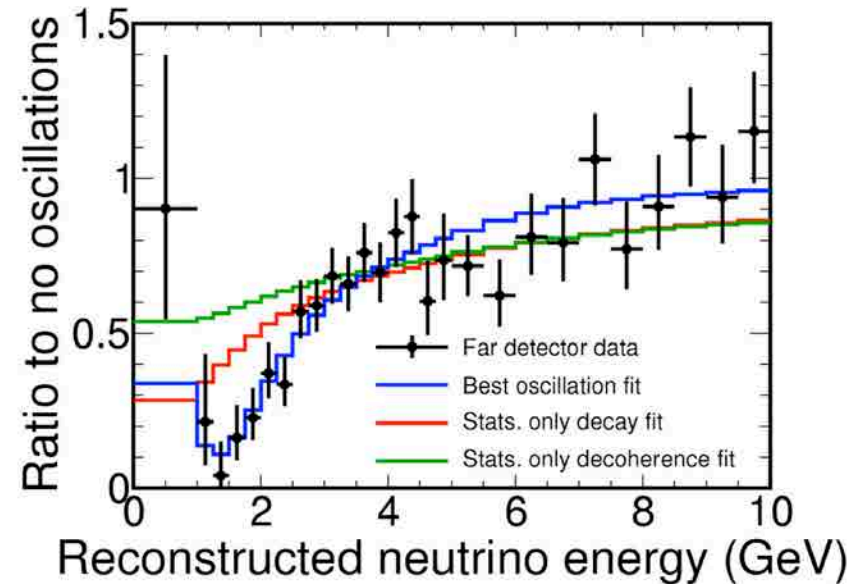
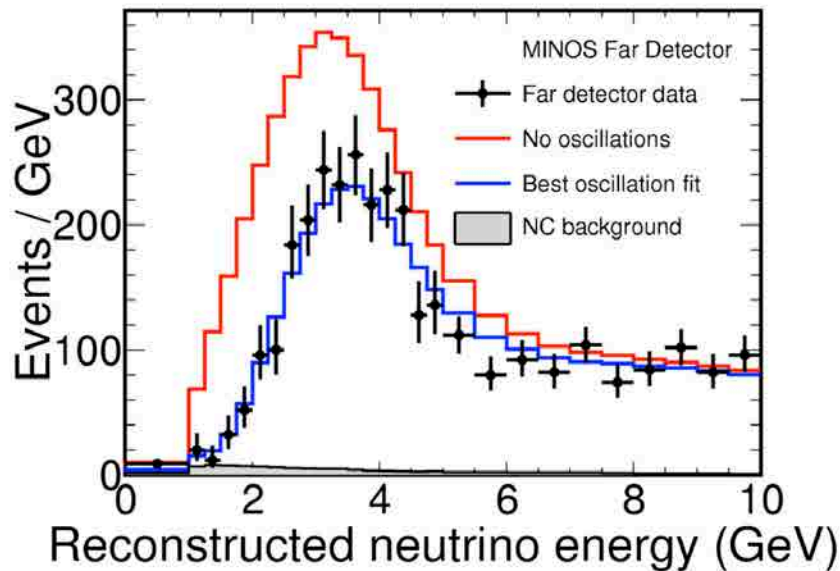
- Start with measured Near Detector neutrino energy spectrum
- Use Monte Carlo to provide corrections due to energy smearing and acceptance
- Obtain Far Detector spectrum from Near Detector using a **beam transfer matrix**
 - Matrix encodes knowledge of meson decay kinematics and beamline geometry



Neutrino Disappearance



- Charged-current events selected in the Far Detector



[Phys. Rev. Lett. 106, 181801 \(2011\)](#)

2467 events predicted w/o oscillations, **1986 events** observed

- **Best fit to data from neutrino oscillations**

- Pure decoherence disfavored $> 8\sigma$
- Pure decay disfavored $> 6\sigma$

Neutrino Disappearance



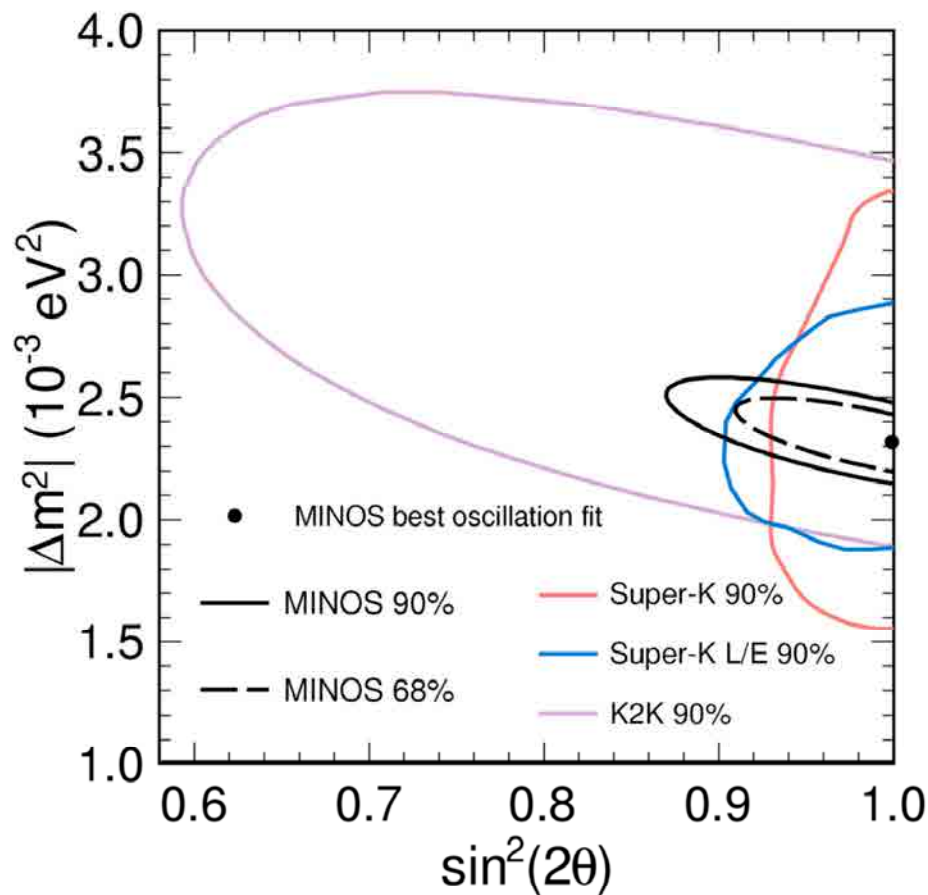
- Best fit values for oscillation parameters

$$|\Delta m_{\text{atm}}^2| = 2.32_{-0.08}^{+0.12} \times 10^{-3} \text{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.90 \text{ (90\% C.L.)}$$

World's most precise $|\Delta m_{\text{atm}}^2|$ measurement!

- Best measurement of θ_{23} from SuperK:

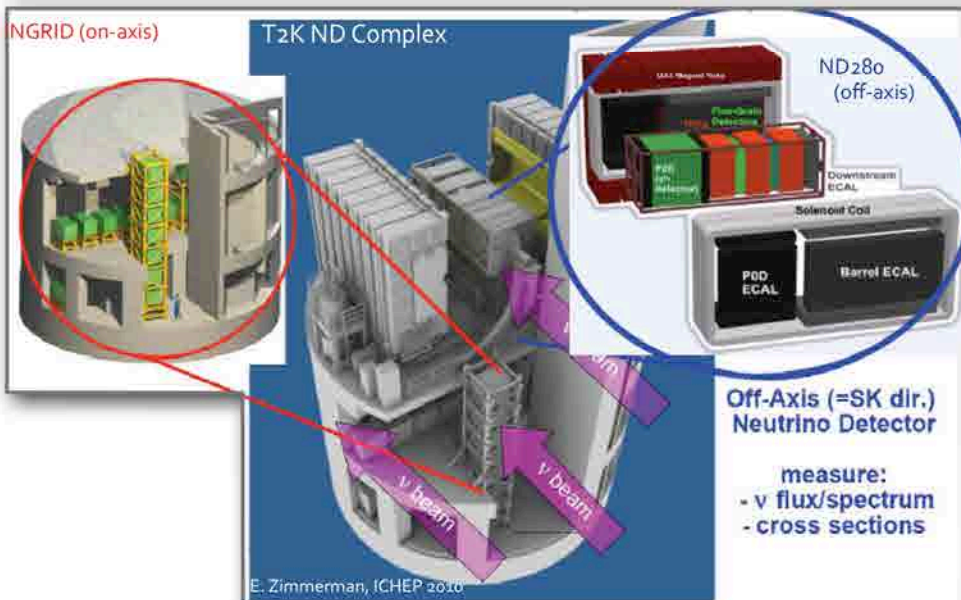
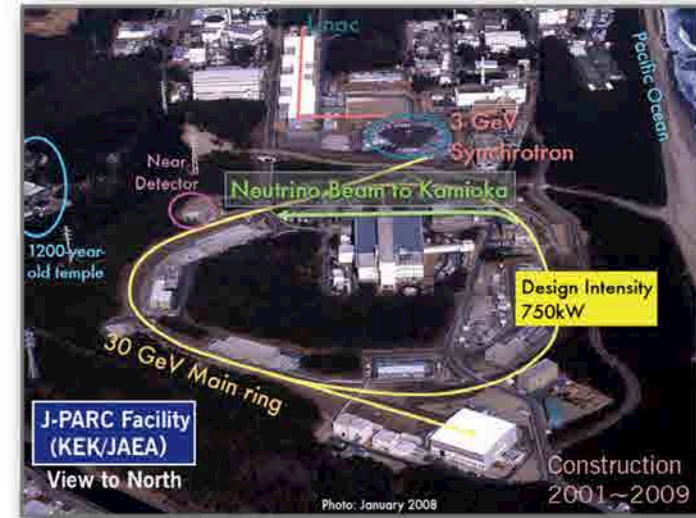
$$\sin^2(2\theta_{23}) > 0.96 \text{ (90\% C.L.)}$$



The T2K Experiment

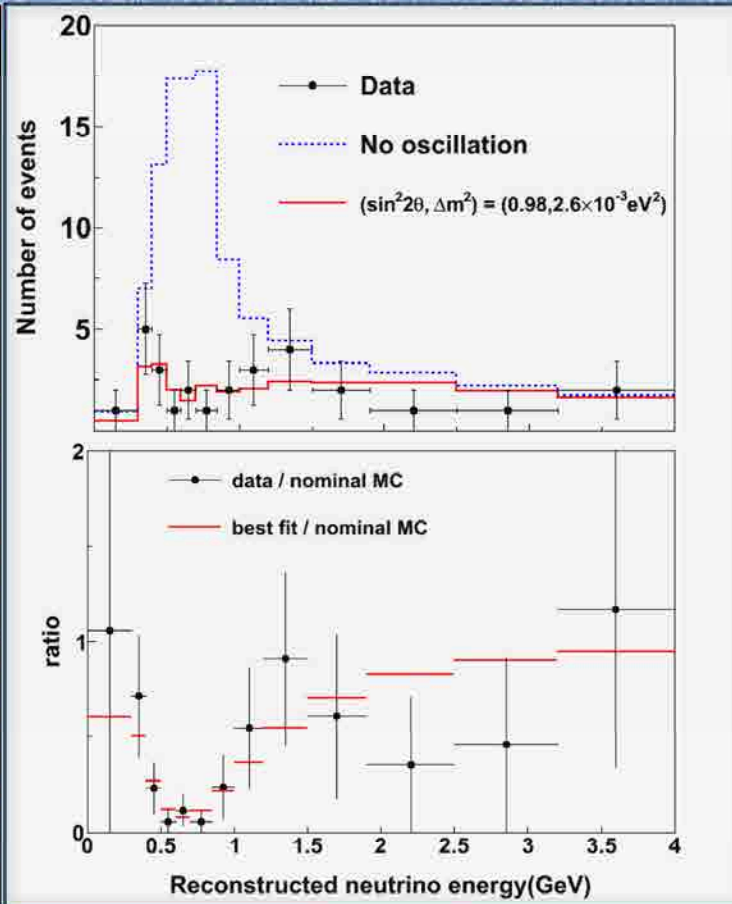
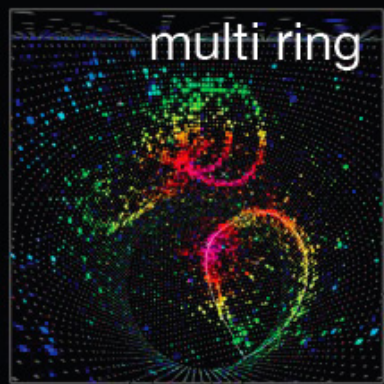
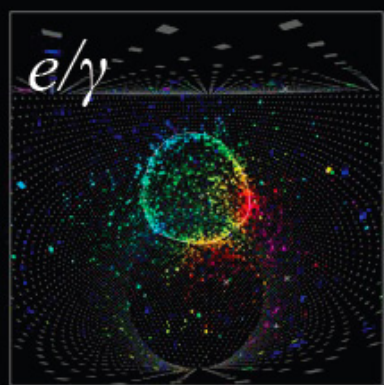


- 295 km baseline from **T**okai **2** **K**amioka using JPARC beam



- Next Generation long-baseline experiment
 - Far Detector (SuperK-IV) placed 2.5° off-axis
 - Two near detectors
 - On-axis INGRID detector to measure beam profile and direction
 - Off-axis ND280 detector to measure flux, cross-sections and flavor composition

T2K ν_μ Disappearance



- Selection for muon neutrinos:
- fiducial (88 events).
- single mu-like ring (33)
- Muon momentum larger than 200 MeV/c (33)
- 0 or 1 decay electrons (**31**)
- **104 events** predicted without oscillations

H. Tanaka, Lepton-Photon 2011

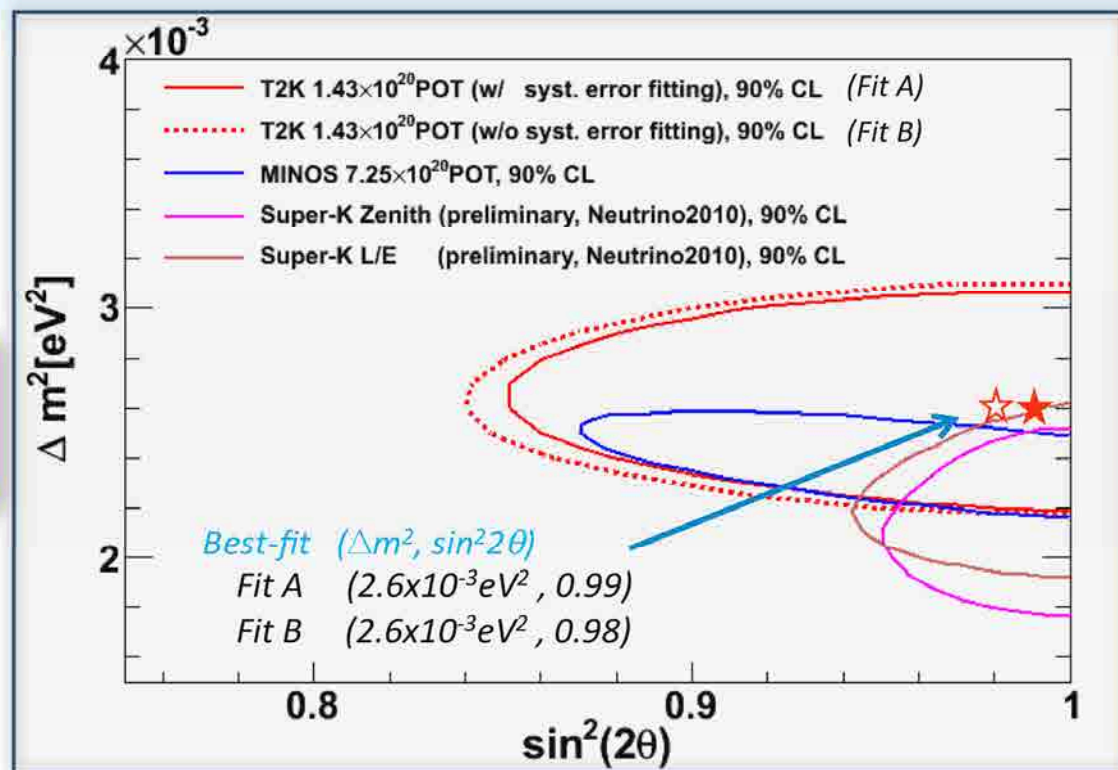
	Data	MC w/ 2-flavor oscillation					MC w/o osc.
		Total	ν_μ CCQE	ν_μ nCCQE	ν_e CC	NC	
Selected Events	31	28.4	17.3	9.2	<0.1	1.8	104
Efficiency	-	20%	72%	21%	0.4%	3%	43%

Allowed Regions



- 90% C.L., Method A(B:)

$$2.1 \times 10^{-3} < |\Delta m^2| < 3.1 \times 10^{-3} \text{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.85 \text{ (0.84)}$$

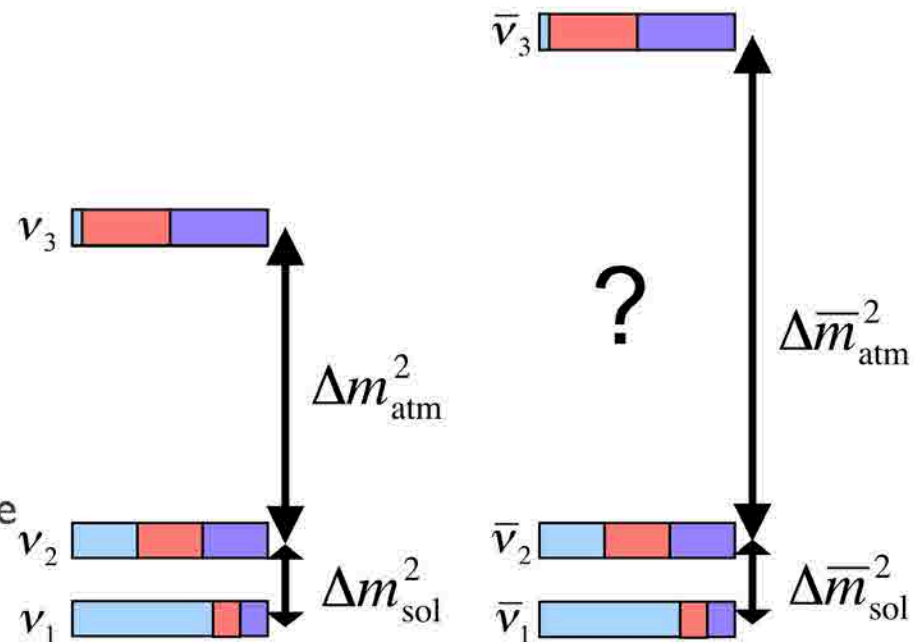


- No oscillation hypothesis excluded at 4.5σ
- Systematics coming from Far and Near detectors efficiencies, cross sections and beam flux simulations are $\sim 15\%$
- Analyses with and without fitting for systematics give consistent answers

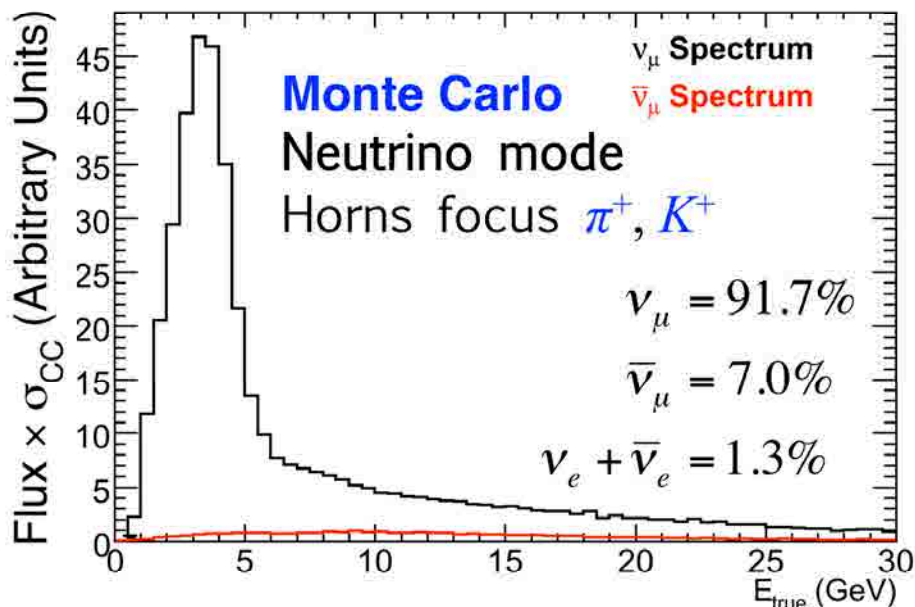
What About $\bar{\nu}_\mu$?

- Antineutrino oscillation parameters known with much less precision
 - MINOS currently the only experiment that can perform event-by-event $\bar{\nu}_\mu$ identification
 - Allows for **direct precision measurements of antineutrino oscillations**
- Differences in neutrino and antineutrino oscillations could be manifest in the respective mass-squared splittings
 - **would be indication of new physics in the neutrino sector!**

$$P(\nu_\mu \rightarrow \nu_\mu) \stackrel{?}{=} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$



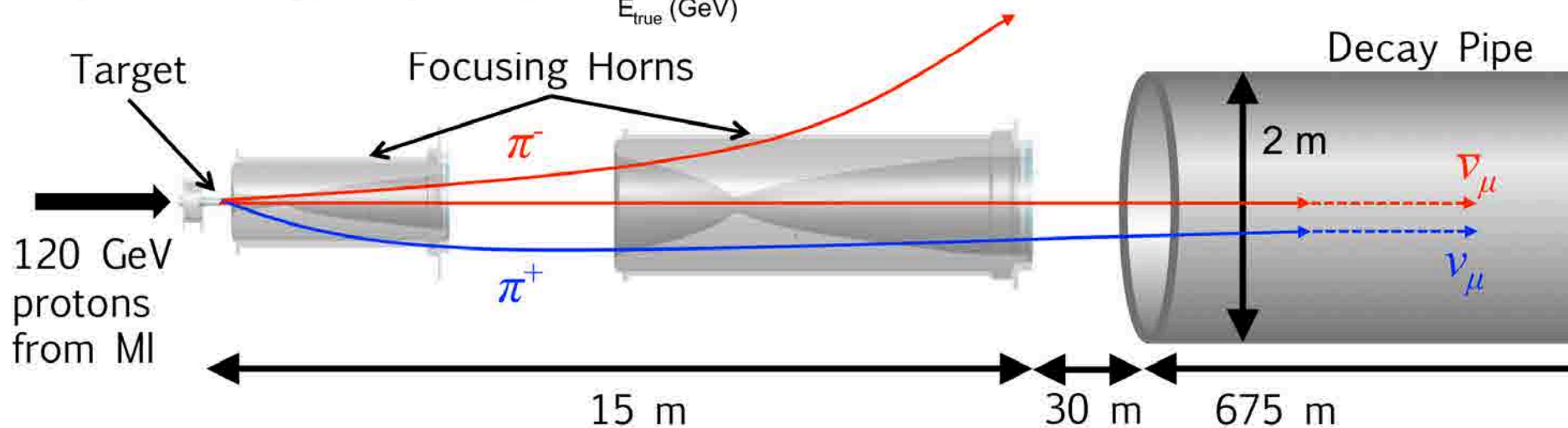
Neutrino Running - Reminder



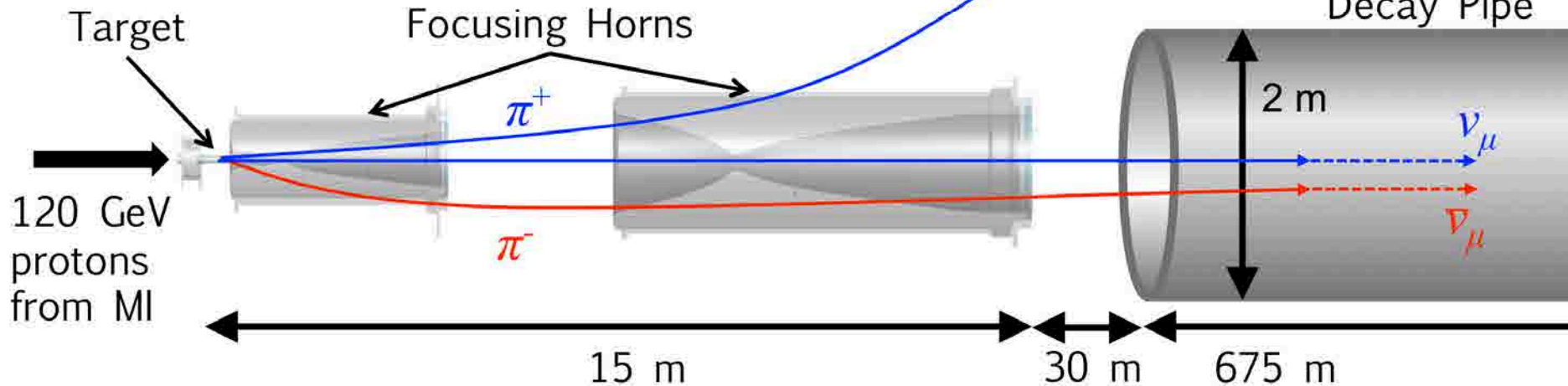
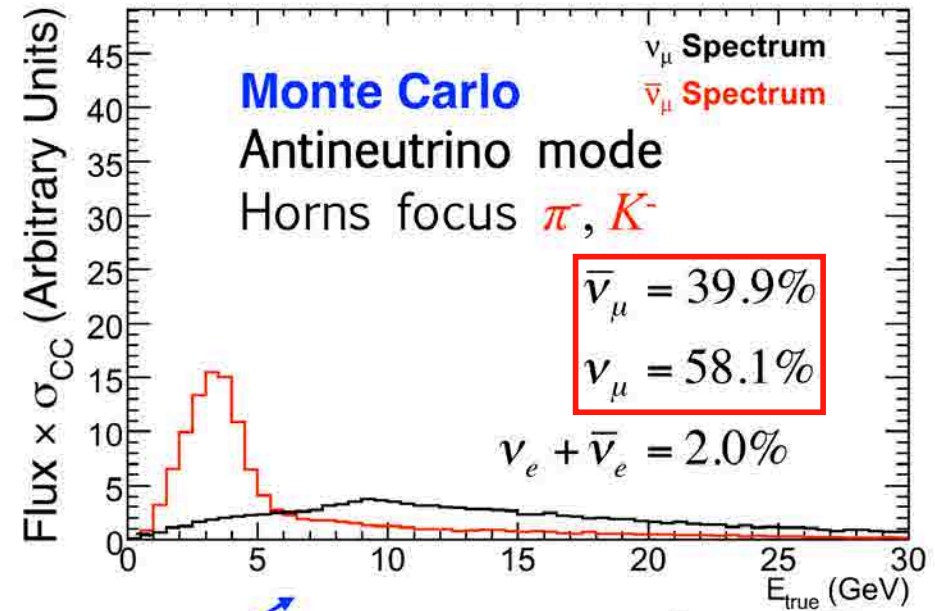
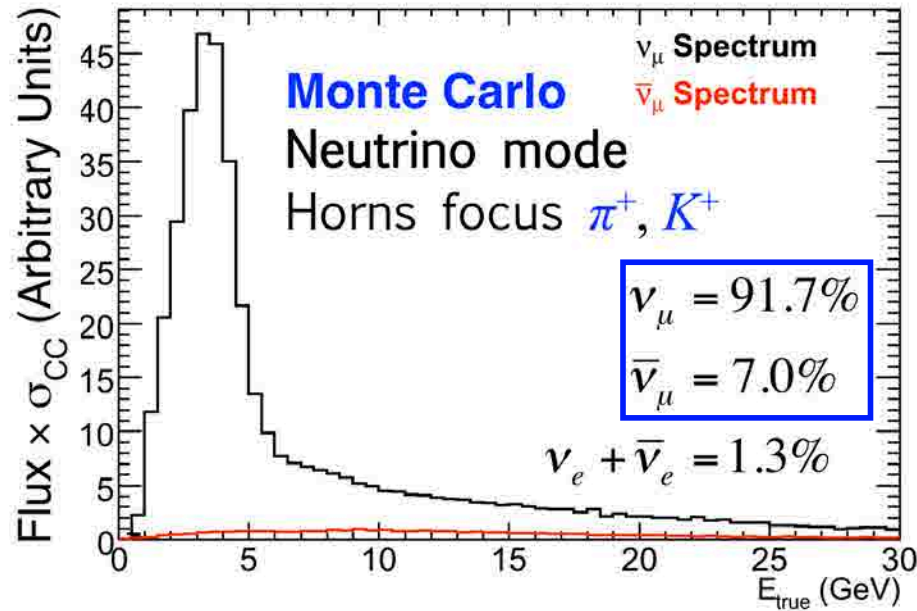
Horns focus π^+ , K^+ , which decay into ν_μ

Higher energy $\bar{\nu}_\mu$ from very forward π^-

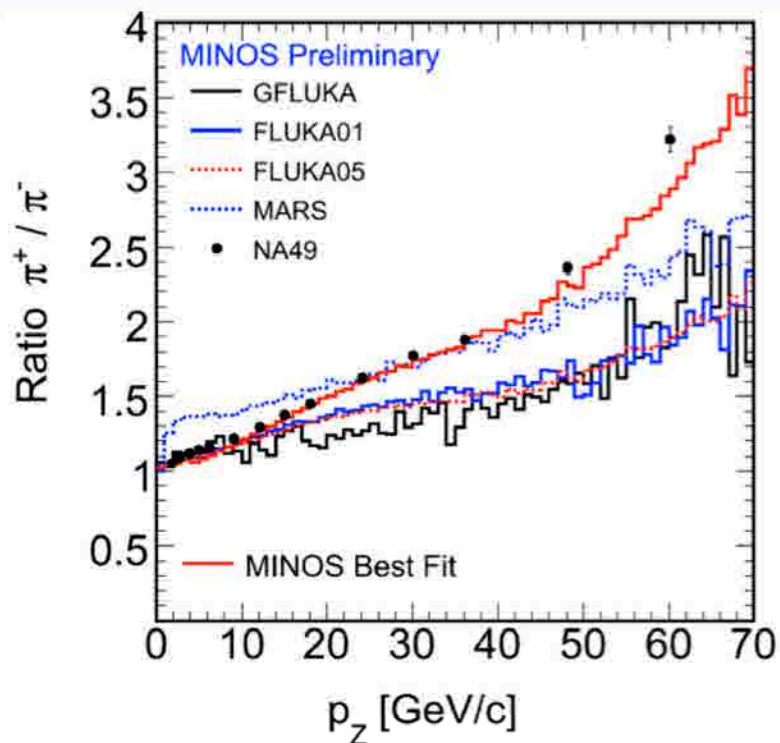
Most of MINOS beam data taken in this configuration



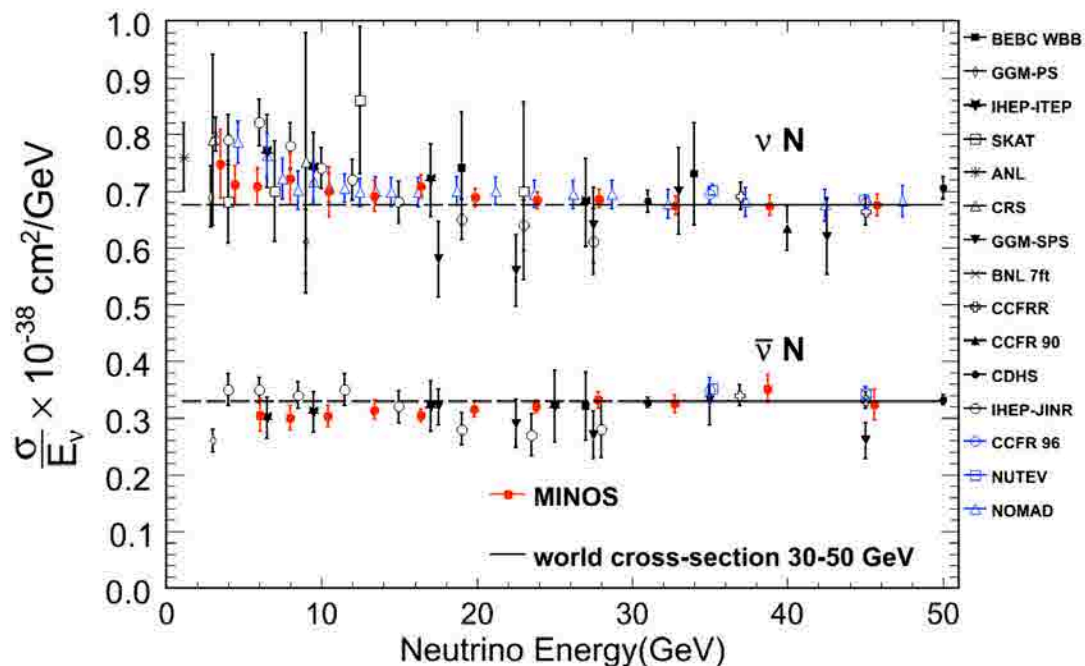
Creating a $\bar{\nu}_\mu$ Beam



Antineutrino Cross Sections



Eur. Phys. J. C 49 897 (2007)



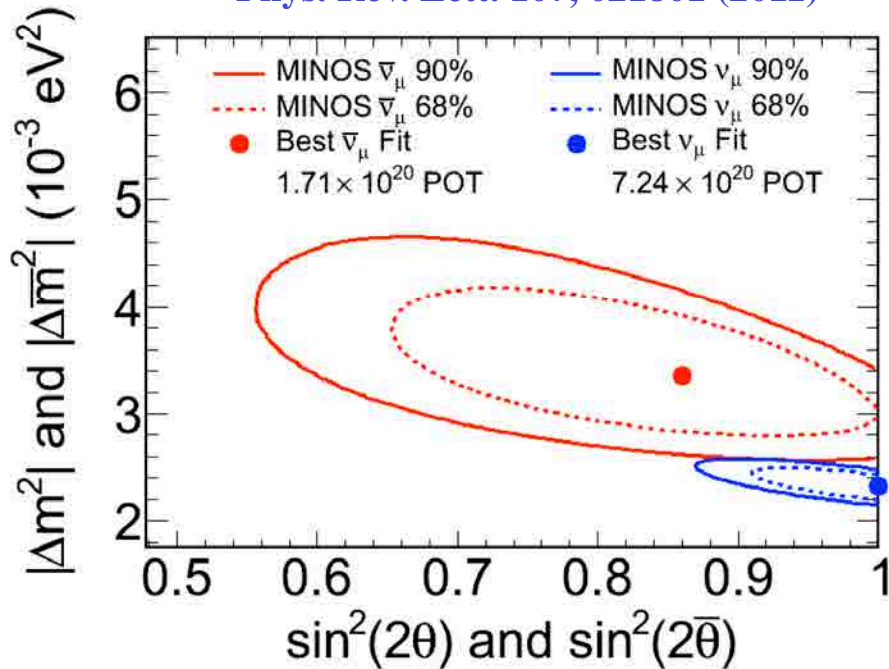
Phys. Rev. D 81 072002 (2010)

- Why is the $\bar{\nu}_\mu$ peak lower by a factor of 3?
 - × 1.3 from lower π^- production
 - × 2.3 from lower $\bar{\nu}_\mu$ cross section

MINOS 2010 $\bar{\nu}_\mu$ Measurement



Phys. Rev. Lett. 107, 021801 (2011)



- Possible explanations in literature:

- CPT and Lorentz Violation

L. Liu, J. Tian and Z. Zhao, *Phys.Lett. B702 154 (2011)*

J.S. Diaz and V.A. Kostelecký, *arXiv:hep-ph/1108.1799*

- Non-Standard Interactions

J. Kopp, P.A.N. Machado and S.J. Parke,

Phys.Rev. D82 113002 (2010)

W.A. Mann, D. Cherdack, W. Musial and T. Kafka,

Phys.Rev. D82 113010 (2010)

physicsworld.com

Neutrino surprise emerges from MINOS

Jun 18, 2010 15 comments

The MINOS experiment was set up to study neutrino oscillation by making the first high precision measurements of a controlled beam of neutrinos produced within a particle accelerator environment. Each experimental run begins at Fermilab near Chicago where a target is bombarded with energetic protons to produce a beam of neutrinos, called the NuMI beam. This is fired through the Earth towards the Soudan mine in

It would not just demolish any particular model, it would require revision of the whole way we do particle physics.

David Wark, Imperial College

Took 70% more $\bar{\nu}_\mu$ data for 2010/2011

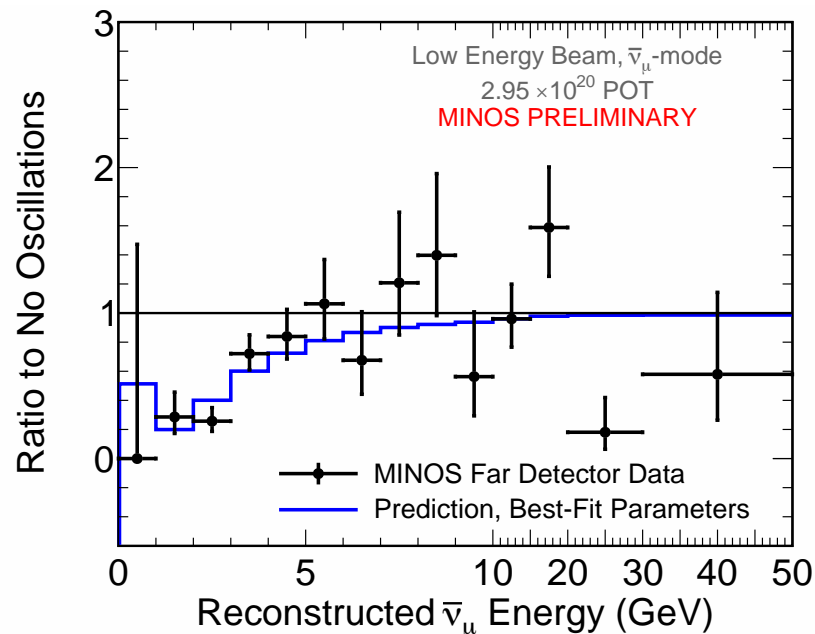
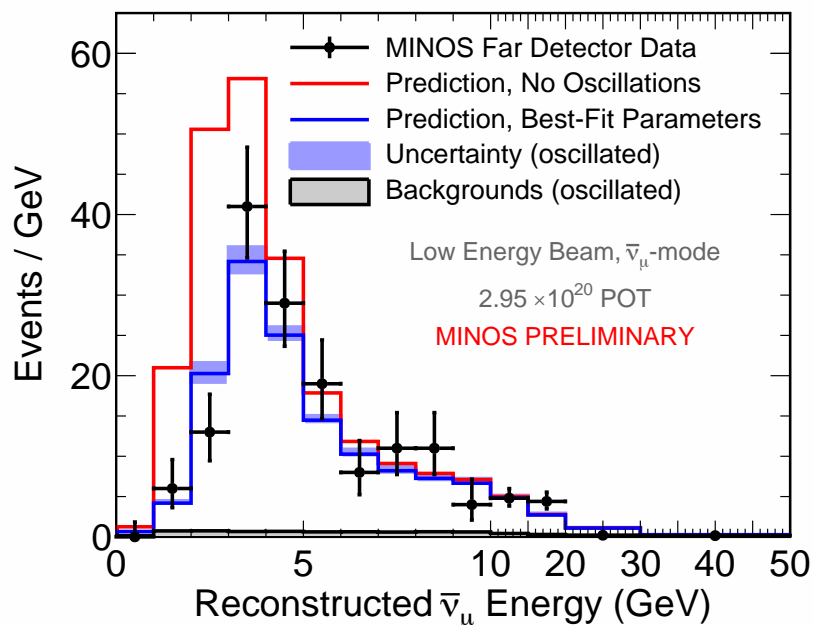
$$|\Delta\bar{m}_{\text{atm}}^2| = 3.36_{-0.40}^{+0.46} \times 10^{-3} \text{eV}^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.86_{-0.12}^{+0.11}$$

$$|\Delta m_{\text{atm}}^2| = 2.32_{-0.08}^{+0.12} \times 10^{-3} \text{eV}^2$$

$$\sin^2(2\theta_{23}) > 0.90 \text{ (90\% C.L.)}$$

Far Detector Energy Spectrum



Prediction, No Oscillations: **273 events**

Observed: **193 events**

Null-oscillations excluded at **7.3σ**

$\bar{\nu}_\mu$ Oscillations Best Fit Parameters

$$|\Delta\bar{m}_{\text{atm}}^2| = [2.62_{-0.28}^{+0.31}(\text{stat}) \pm 0.09(\text{syst})] \times 10^{-3} \text{eV}^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.95_{-0.11}^{+0.10}(\text{stat}) \pm 0.01(\text{syst})$$

Contour Comparisons



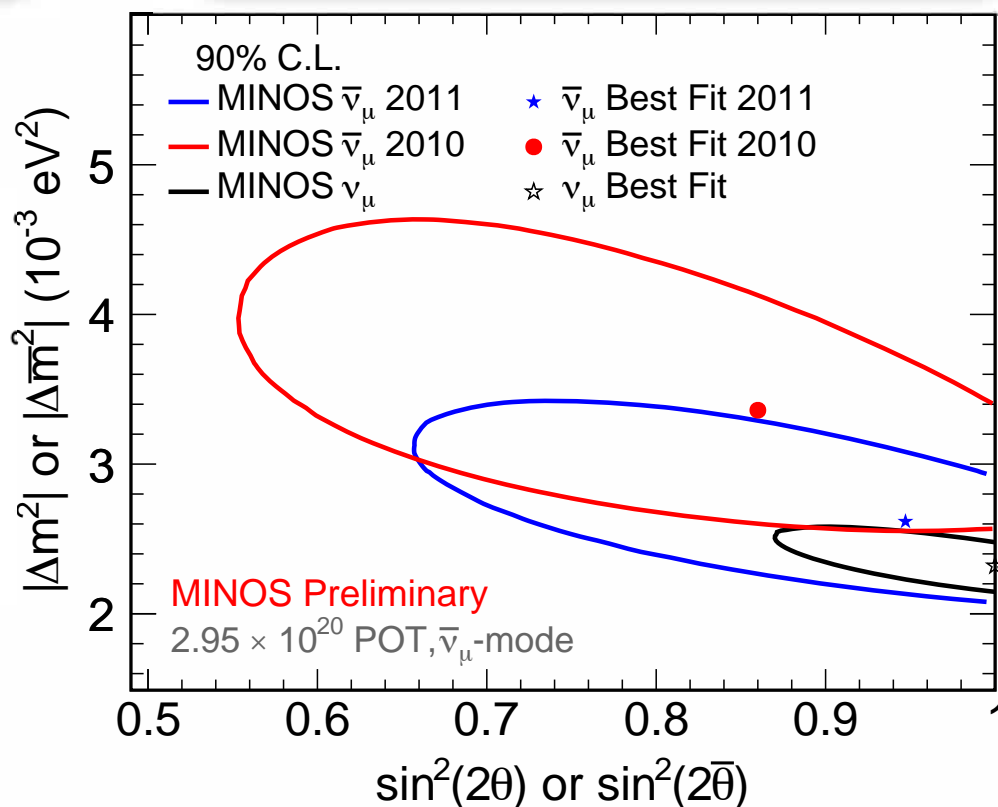
Antineutrinos

$$|\Delta\bar{m}_{\text{atm}}^2| = 2.62_{-0.28}^{+0.31} \times 10^{-3} \text{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) > 0.75 \text{ (90\% C.L.)}$$

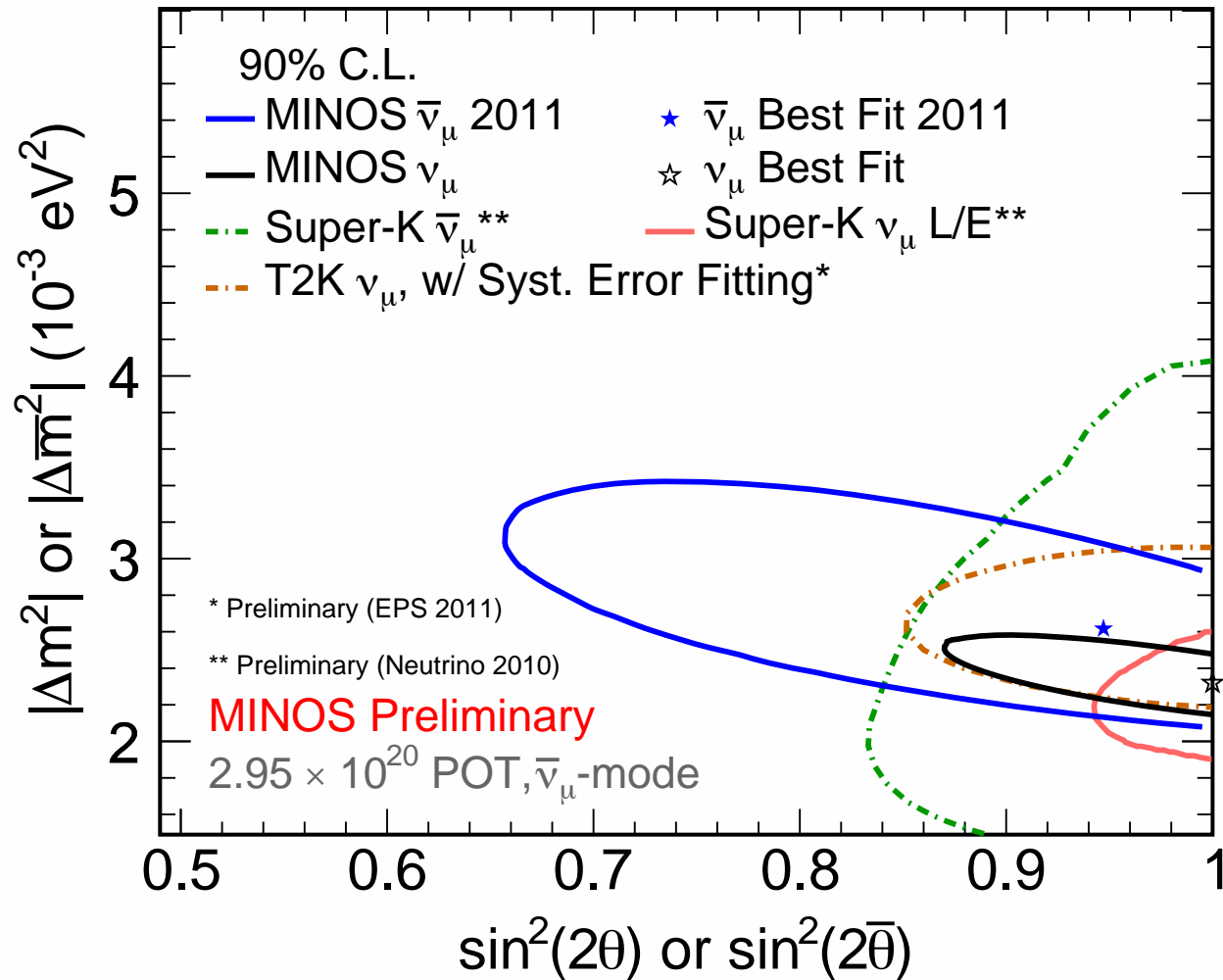
- Assuming identical underlying oscillation parameters, the $\bar{\nu}_\mu$ and ν_μ oscillation measurements are consistent at the 42% C.L. (was 2% in 2010 analysis)

Neutrinos

$$|\Delta m_{\text{atm}}^2| = 2.32_{-0.08}^{+0.12} \times 10^{-3} \text{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.90 \text{ (90\% C.L.)}$$



World Picture (MINOS, SuperK, T2K)



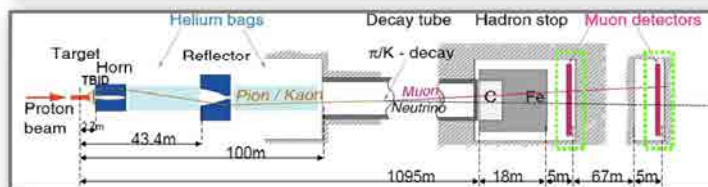
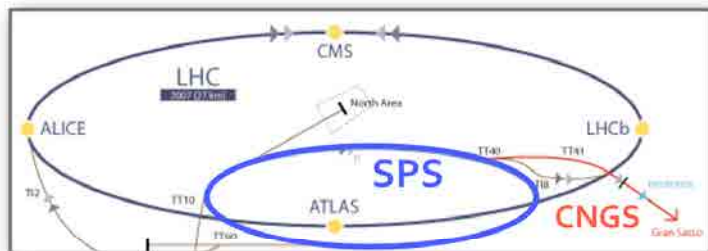
Neutrino Appearance Measurements

The OPERA Experiment

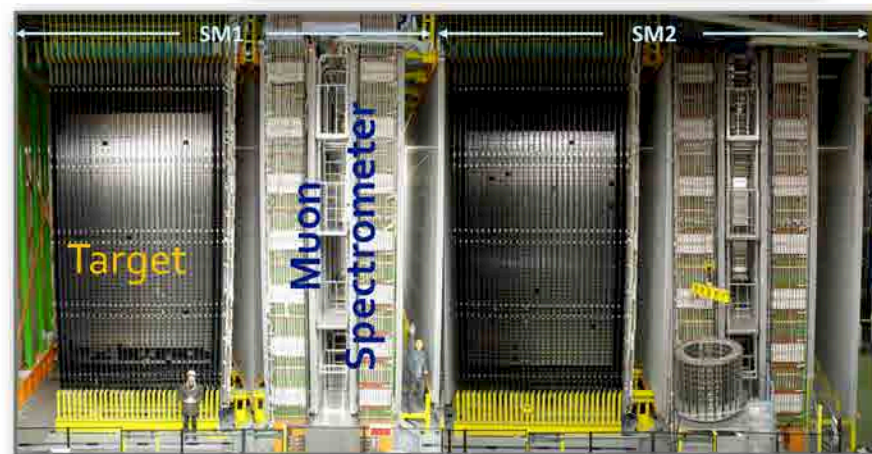


Oscillation Project with Emulsion tRacking Apparatus

- Look for ν_{τ} appearance to directly confirm $\nu_{\mu} \rightarrow \nu_{\tau}$ dominant oscillation mode



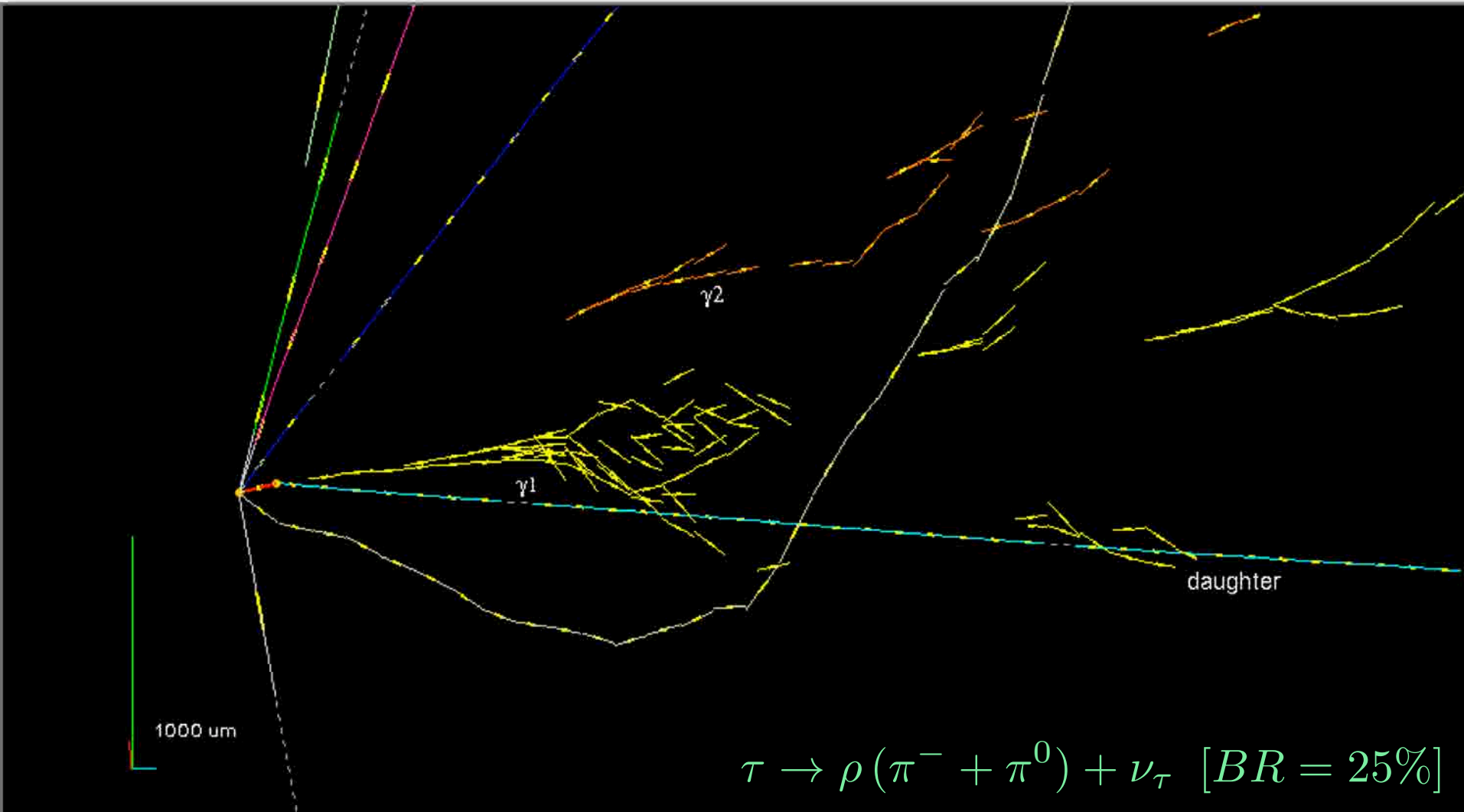
- 730 km baseline from CERN to Gran Sasso
- CNGS ν_{μ} beam from SPS's 400 GeV protons
- Far detector divided into two Super-Modules
 - Target composed of lead/emulsion bricks
 - Muon spectrometers magnetized with 1.5T



OPERA ν_τ Appearance



- OPERA's first (and so far only) ν_τ appearance candidate, from Spring 2010



OPERA ν_τ Appearance



- Analyzed 92% of the '08-'09 data
 - 4.8×10^{19} POT
 - 2.6 times more data than previous analysis

- Significant improvements in the analysis and simulation chain.
- Including better charm cross sections and reduction of charm background.

- **No new tau neutrinos found**

[arxiv:hep-ex/1107.2594](https://arxiv.org/abs/hep-ex/1107.2594)

Decay channel	Number of signal events expected for $Dm^2 = 2.5 \times 10^{-3} \text{ eV}^2$	
	22.5×10^{19} p.o.t.	Analysed sample
$\tau \rightarrow \mu$	1.79	0.39
$\tau \rightarrow e$	2.89	0.63
$\tau \rightarrow h$	2.25	0.49
$\tau \rightarrow 3h$	0.71	0.15
Total	7.63	1.65

- One tau neutrino observed in the $\tau \rightarrow h$ channel.
- Observation compatible with expectation of 1.65 signal events and a background of 0.05 ± 0.01 .
- Significance of observation is 95% (was 98.2% in previous analysis).

ν_e Appearance - Search for θ_{13}

Probability for ν_e appearance in a ν_μ beam is given by:

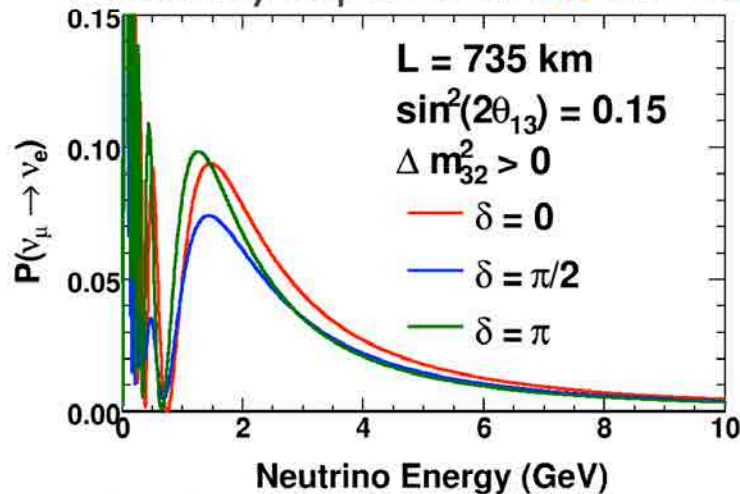
$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11 \text{ GeV}} \quad \Delta \equiv \frac{\Delta m_{31}^2 L}{4E} \quad \alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sim \frac{1}{30}$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2 A\Delta}{A^2}$$

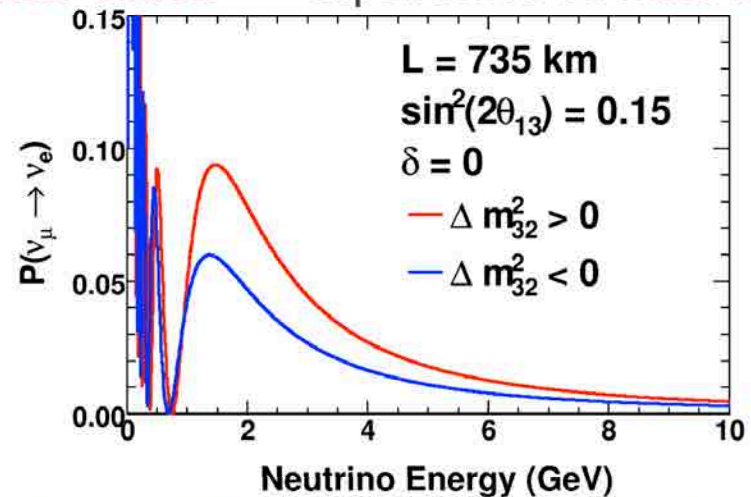
$$+ 2\alpha \sin \theta_{13} \cos \delta_{\text{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos \Delta$$

$$- 2\alpha \sin \theta_{13} \sin \delta_{\text{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin \Delta$$

Probability depends on θ_{13} and δ_{CP}



Matter effects => dependence on mass hierarchy

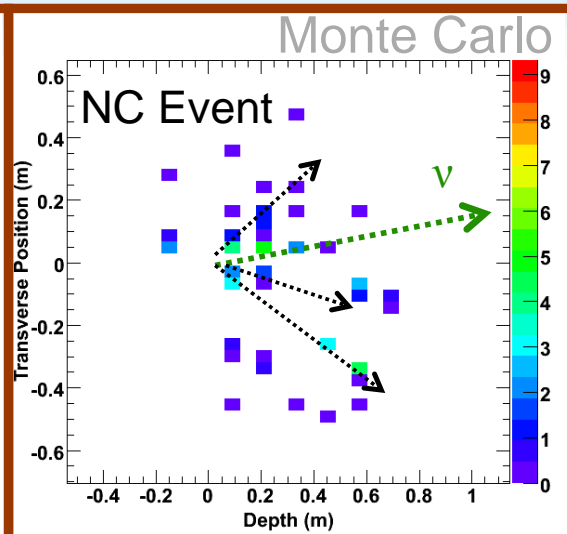
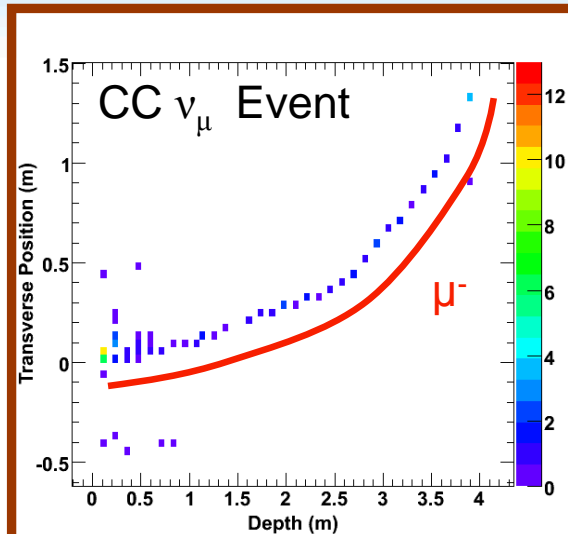


Long-Baseline experiments can measure $\sin^2 2\theta_{13}$ by searching for ν_e events in Far Detector

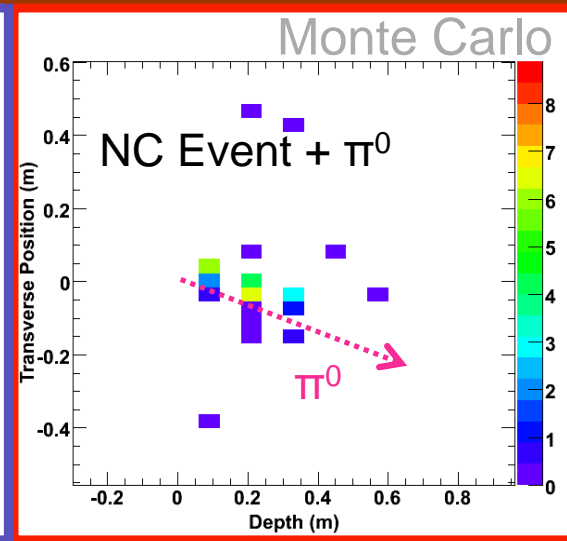
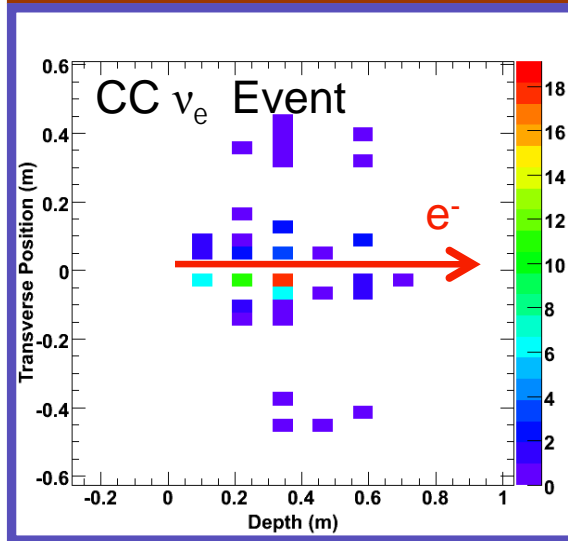
MINOS Signal and Backgrounds



Reducible
Background



Signal



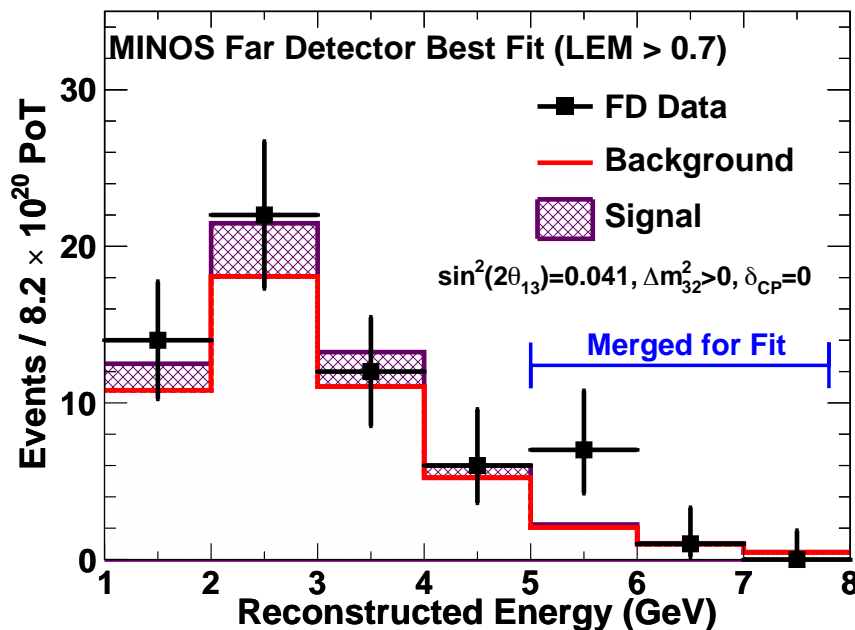
Irreducible
Background

- Steel thickness ~ 1.4 radiation lengths, strip width $>$ Molière radius

MINOS ν_e Appearance Results



- Background/signal prediction and systematic errors finalized before looking at data in Far Detector signal region

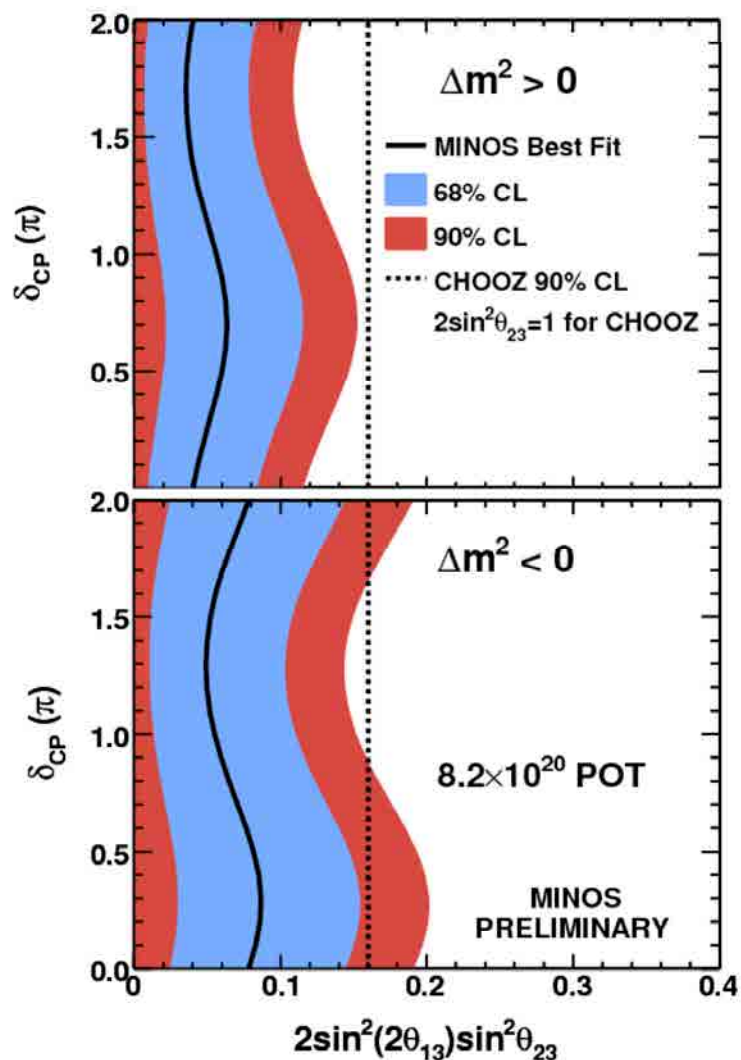


Observed: 62 events

Prediction: $49.5 \pm 7.0(\text{stat}) \pm 2.8(\text{syst})$ events

- Measurement still very statistically-limited

ν_e Appearance Contours



Phys. Rev. Lett. 107, 181802 (2011)

- Assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$
- Best fit for normal (inverted) hierarchy:

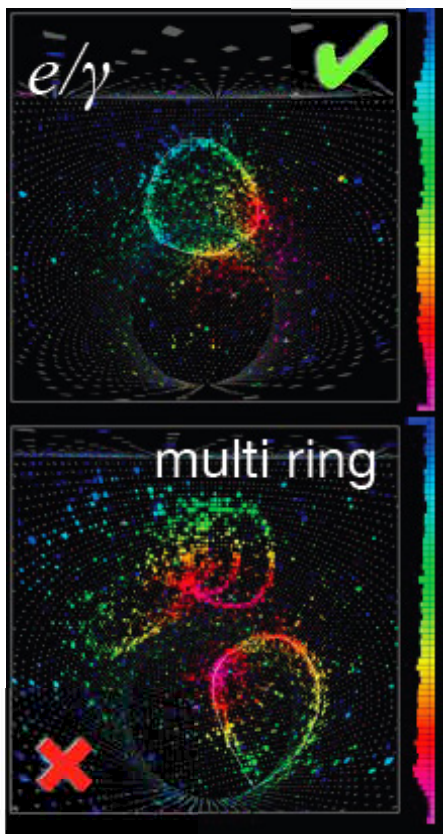
$$\sin^2 2\theta_{13} = 0.04 \text{ (0.08)}$$

- Exclusion limits

$$\sin^2 2\theta_{13} < 0.12 \text{ (0.20) at 90\% C.L.}$$

- $\sin^2 2\theta_{13}=0$ excluded at 89% CL
- Uncertainties in the other oscillation parameters are included in the contours

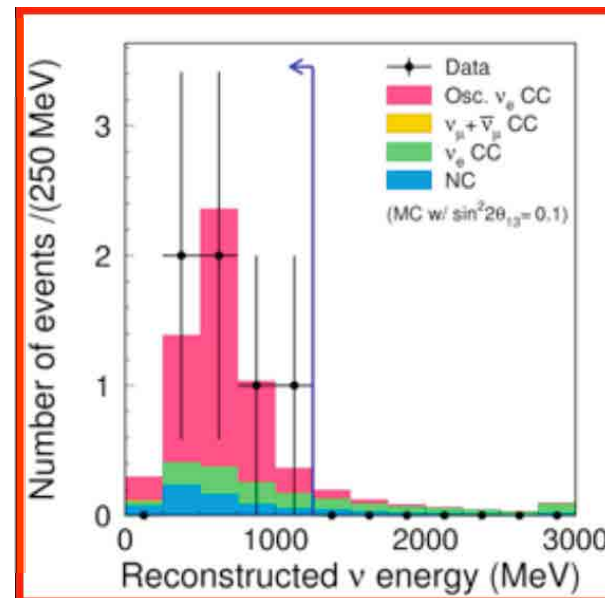
T2K ν_e Appearance



- Selection for muon neutrinos:
- Single e-like ring (8 events)
- Visible energy larger than 100 MeV (7)
- No decay electrons (6)
- Small invariant mass (6)
- E_ν in oscillation region **(6)**

Total	ν_μ CC	ν_e CC	NC	solar $\nu_\mu \rightarrow \nu_e$
1.5	0.03	0.8	0.6	0.09

Expected Background 1.5 ± 0.3

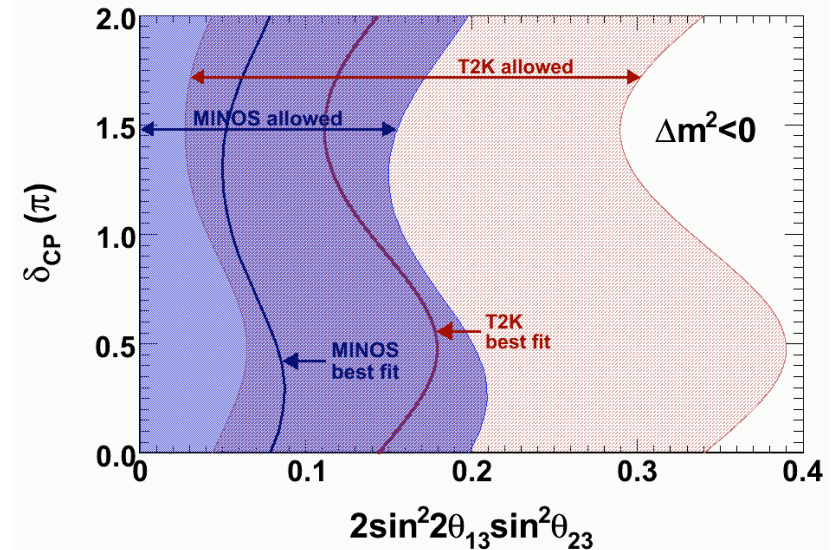
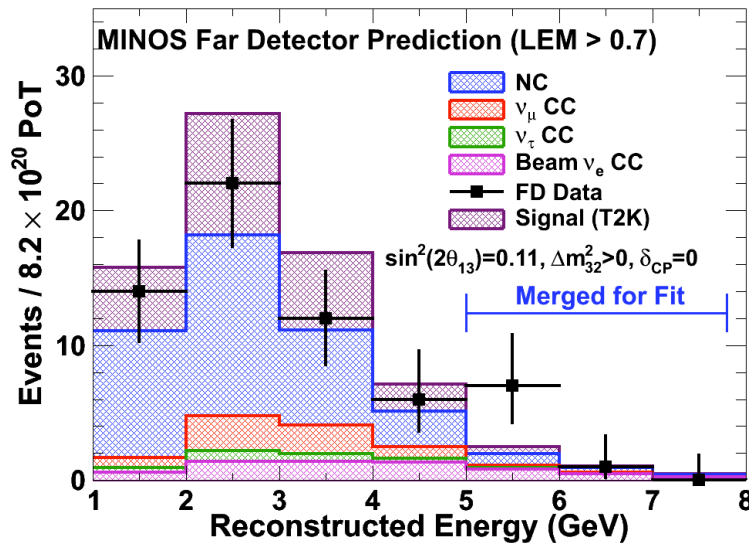
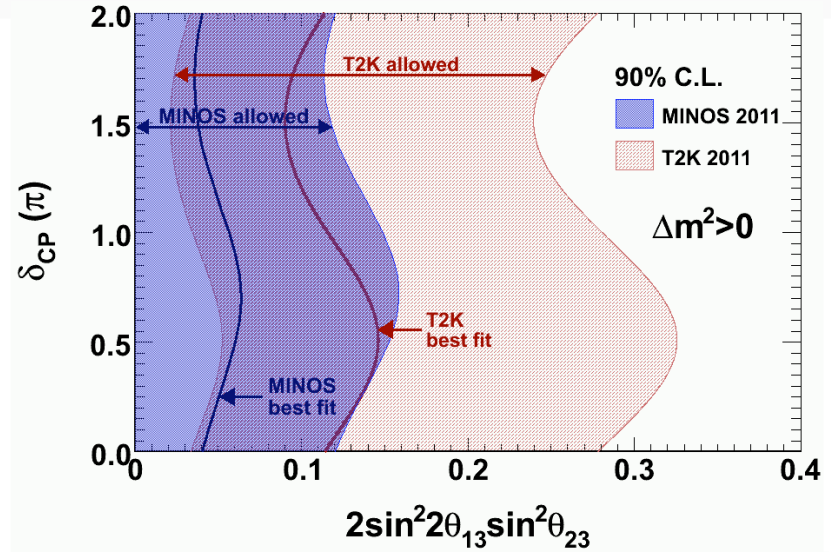
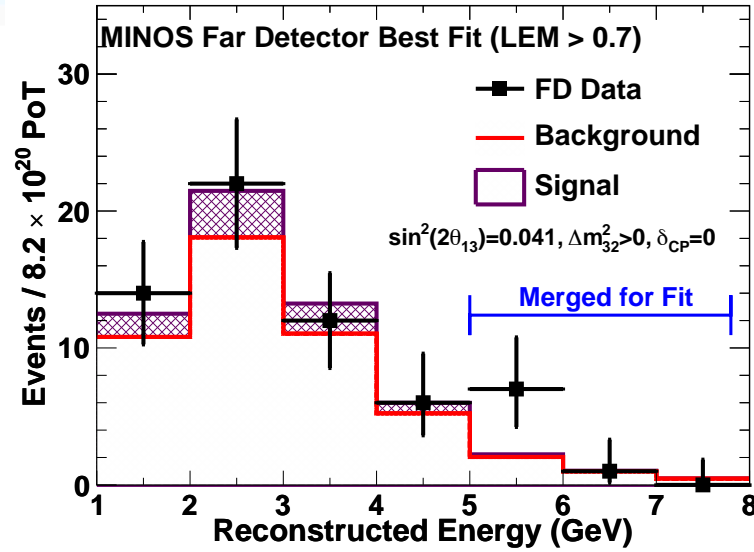


- Null oscillations excluded at **99.3% C.L.**

Phys. Rev. Lett. 107, 041801 (2011)



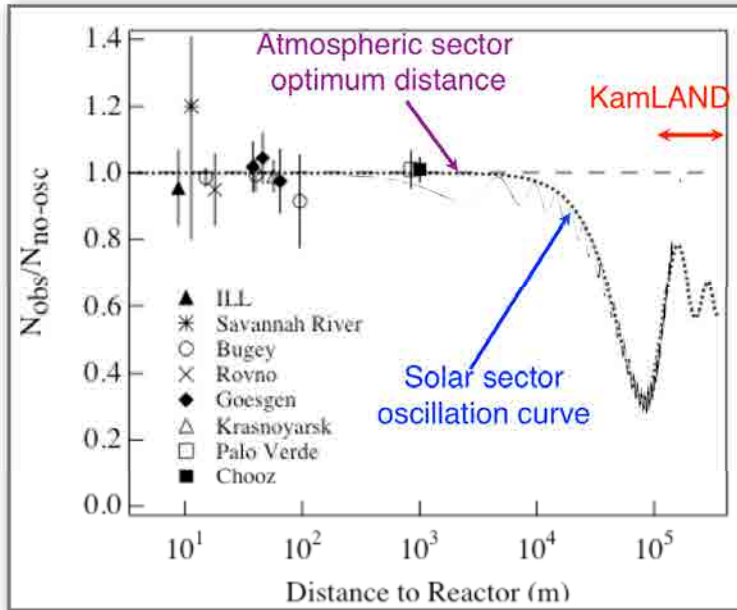
MINOS and T2K



Double Chooz Reactor Expt.

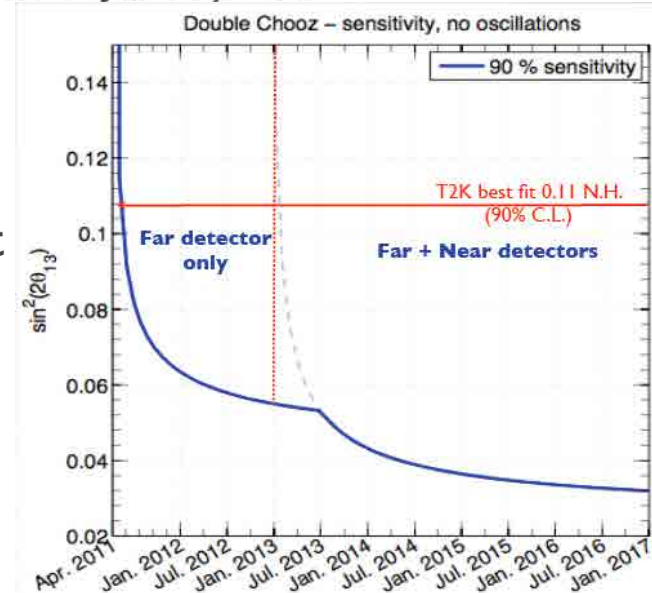


- Reactor experiments look for disappearance of the reactor $\bar{\nu}_e$ flux, thus are insensitive to CP violation and make an unambiguous measurement of $\sin^2 2\theta_{13}$:

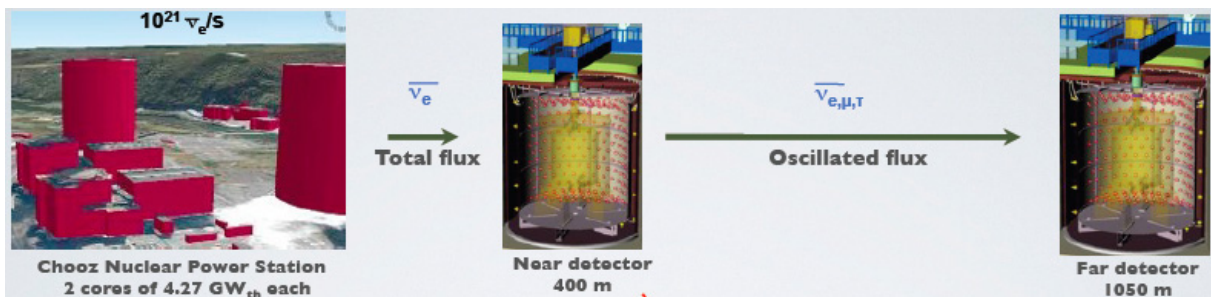


$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right)$$

- Double Chooz taking data with Far detector since April 2011
- Near detector turn on in January 2013



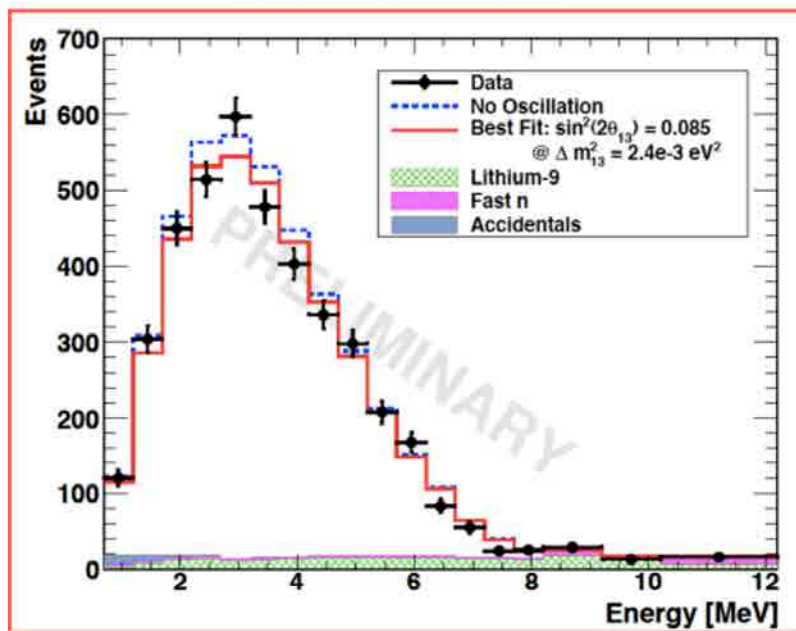
Double Chooz is a second generation reactor experiment



MINOS, T2K and Double Chooz

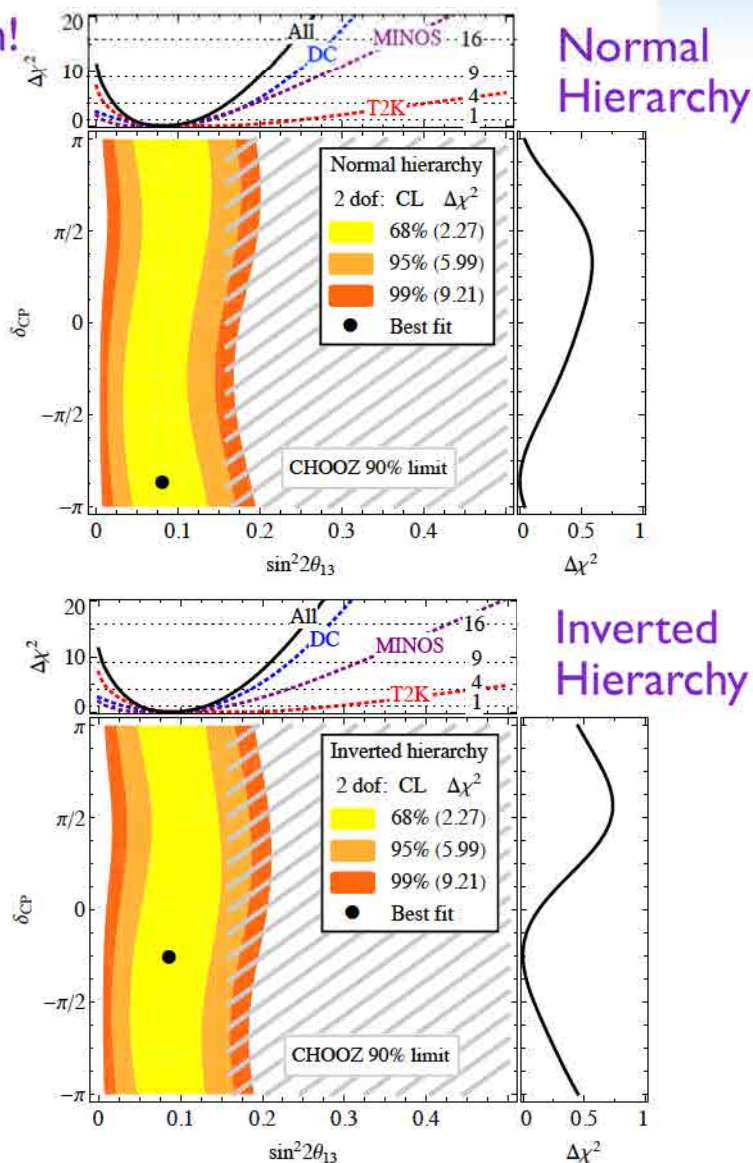
First Double Chooz results announced last month!

H. de Kerret, LowNu 2011



Rate + Shape Analysis:
 $\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$

Combined results disfavor $\theta_{13}=0$
 at more than 3σ !
 $\sin^2 2\theta_{13} = 0.081 (0.087)$

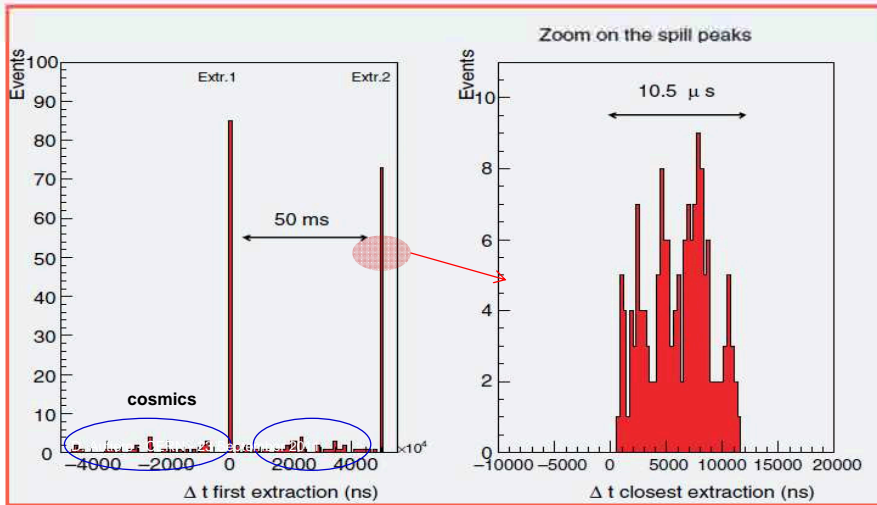


P. A. N. Machado, H. Minakata, H. Nunokawa,
 and R. Zukanovich Funchal, arXiv:1111.3330

One more thing...

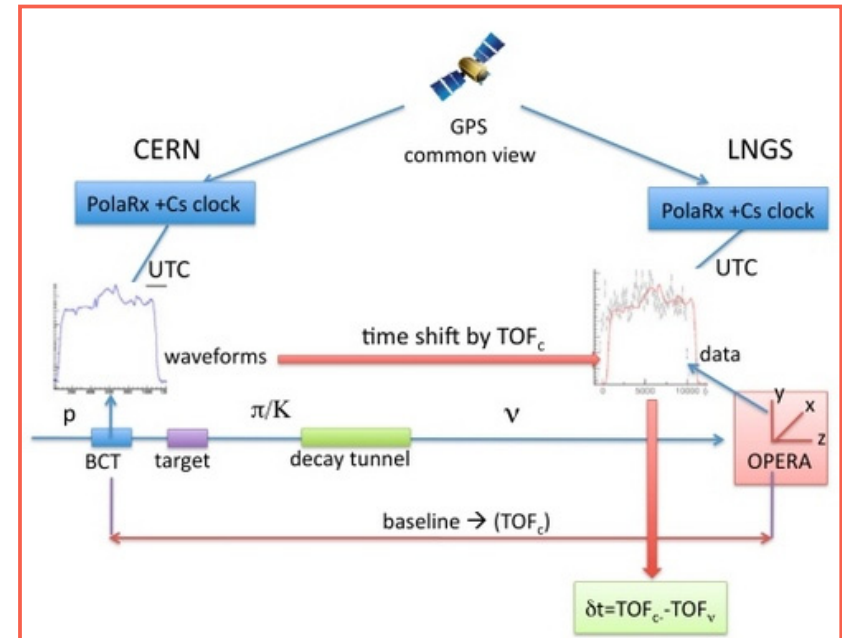


OPERA Measurement

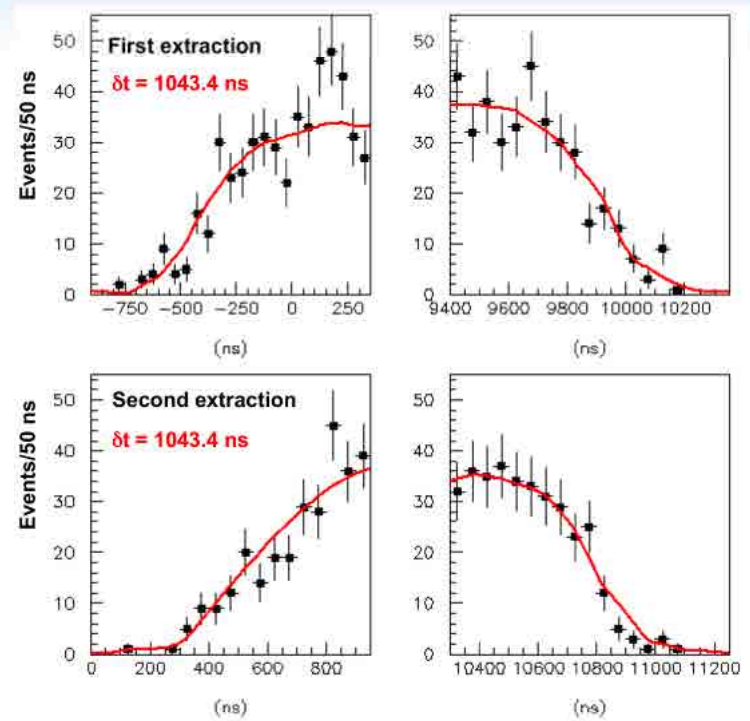
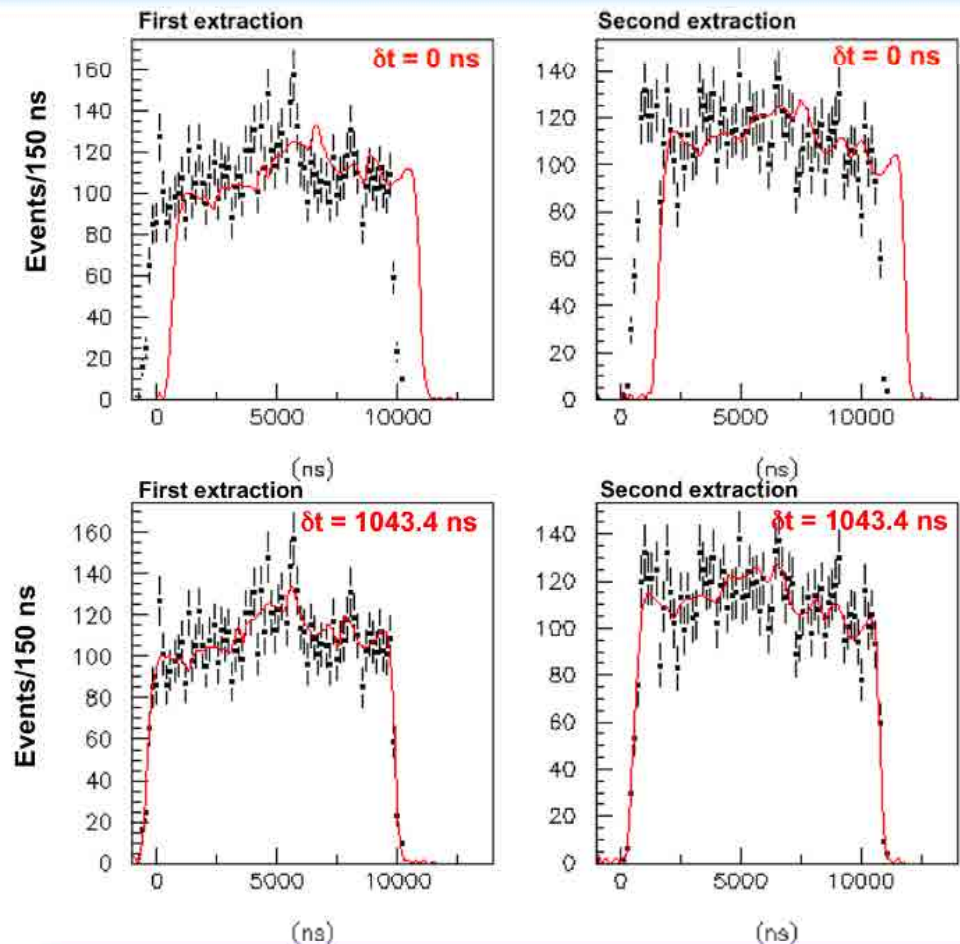


- CNGS Beam:
- SPS protons at 400 GeV/c
- Cycle length 6 s
- Two extractions of 10.5 μsec, separated by 50 ms.
- Pure muon neutrino beam with peak at 17 GeV.

- Tag neutrino production time using proton timing measured by Beam Current Transformer (BCT) device
- Tag neutrino interaction time at LNGS
- Measure baseline precisely (20 cm over 730 km)
- Synchronize beam and detector timing using GPS common view (1 ns error)
- Use 15k events (overall precision ~10 ns)
- Measure $\delta t = \text{TOF}_c - \text{TOF}_\nu$



OPERA TOF Results



- Blind data correction: $\delta t = -985.6$ ns
- After fit $\chi^2 / \text{ndof} \sim 1$: $\delta t = 1043.4$ ns
- Neutrinos arrive 58 ns earlier!

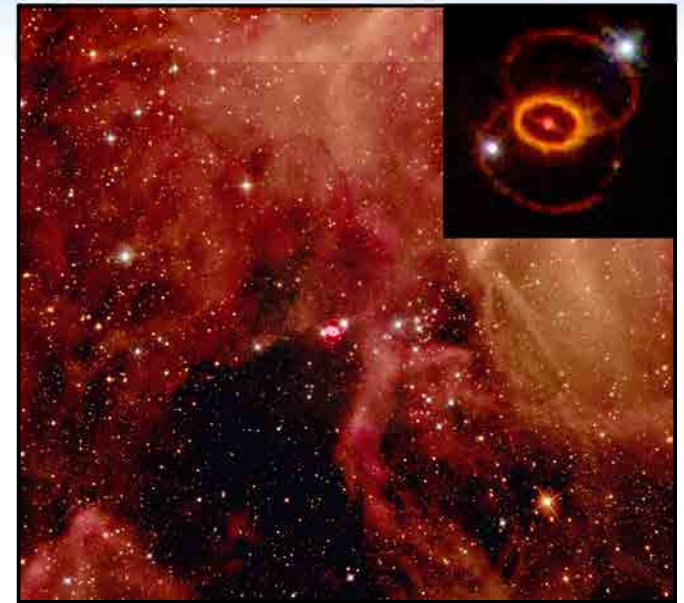
$$\delta t = \text{TOF}_c - \text{TOF}_\nu = (57.8 \pm 7.8 \text{ (stat.) } {}^{+8.3}_{-5.9} \text{ (sys.)}) \text{ ns}$$

$$(v-c)/c = \delta t / (\text{TOF}'_c - \delta t) = (2.37 \pm 0.32 \text{ (stat.) } {}^{+0.34}_{-0.24} \text{ (sys.)}) \times 10^{-5}$$

<http://arxiv.org/abs/1109.4897>

Caveat - Supernova 1987a

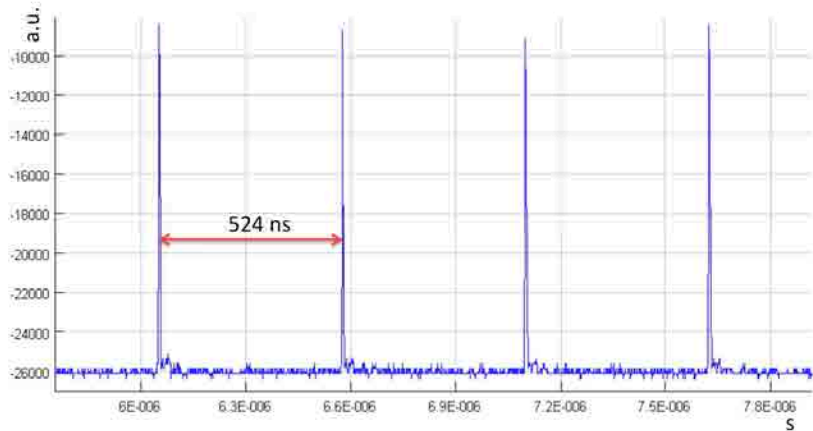
- II neutrinos from supernova 1987a (51 kparsec away) were observed at Kamiokande-II in time with photons - PRL 58 1490 (1987).
- IMB [PRL 58 1494 (1987)] and Baksan [JETP Lett. 45 589 (1987)] also observed in time neutrinos.
 - Total of 24 neutrinos observed
 - These are electron anti-neutrinos with energies $\sim 10\text{-}40$ MeV.
- If OPERA result applies to all neutrinos, they should have arrived 3.9 years earlier than the light from the Supernova



IMB			Kamiokande II		
t (s)	E (MeV)	σ_E (MeV)	t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	38	7	$t \equiv 0.0$	20.0	2.9
0.412	37	7	0.107	13.5	3.2
0.650	28	6	0.303	7.5	2.0
1.141	39	7	0.324	9.2	2.7
1.562	36	9	0.507	12.8	2.9
2.684	36	6	1.541	35.4	8.0
5.010	19	5	1.728	21.0	4.2
5.582	22	5	1.915	19.8	3.2
Baksan			9.219	8.6	2.7
t (s)	E (MeV)	σ_E (MeV)	10.433	13.0	2.6
$t \equiv 0.0$	12.0	2.4	12.439	8.9	1.9
0.435	17.9	3.6			
1.710	23.5	4.7			
7.687	17.6	3.5			
9.099	10.3	4.1			

Table from
J. Ellis *et al.* (2008)

What Happens Next?



- OPERA took data with a single extraction of 3 ns bunches separated by 524 ns
- Eliminate systematics due to proton time structure
- Results consistent with main analysis:

$$\delta t = (62.1 \pm 3.7) \text{ ns}$$

also JPARC!

Fermilab Will Double-Check CERN's Revolutionary Faster-Than-Light Claim

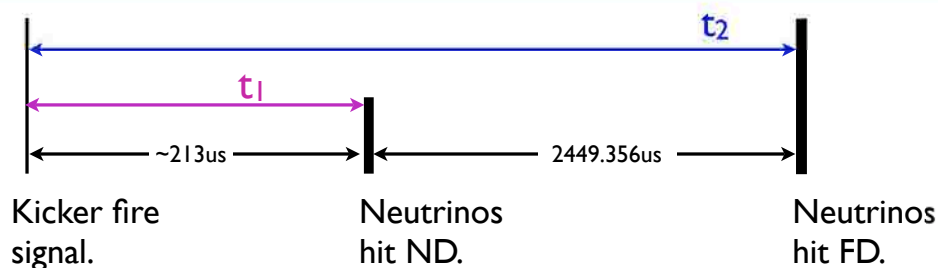
By Rebecca Boyle · Posted 09.26.2011 at 11:29 am · 12 Comments

- The profound implications of these results call for independent verification
- MINOS and T2K are in position to remeasure the neutrino velocity to try to confirm or rule out OPERA's perplexing results
- MINOS baseline very similar to OPERA's (735km)
- Neutrino energy is lower than OPERA (3.3 GeV)



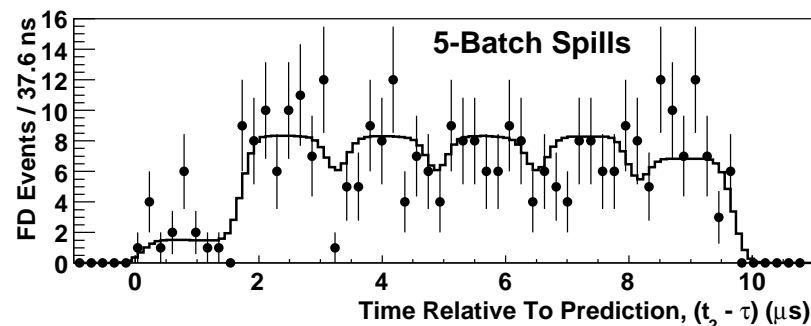
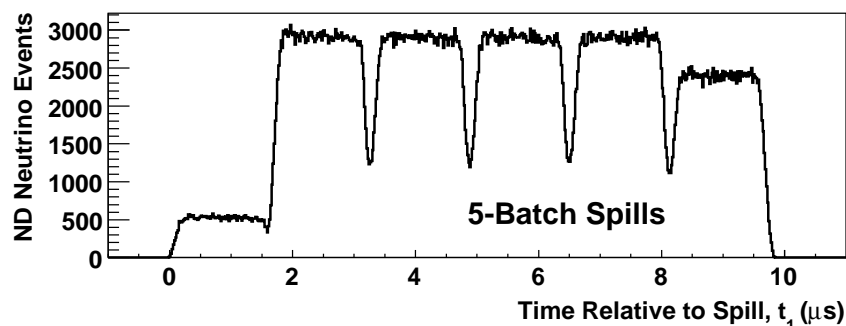
MINOS Experiment Far Detector NuMI/Fermilab

2007 MINOS Measurement



Measure time of flight as $t_2 - t_1$

- Time of flight is measured with neutrinos from ND and FD
 - Cancels out systematics relative to the proton beam time profile
 - 10 μs spill every 2.06 s
 - Five or six 1.6 μs batches with 100 ns gaps



$$\delta = -126 \pm 32 \text{ (stat.)} \pm 64 \text{ (sys.) ns} \quad 68\% \text{ C.L.}$$

$$-2.4 \times 10^{-5} < (v - c)/c < 12.6 \times 10^{-5} \quad 99\% \text{ C.L.}$$

Phys.Rev.D **76**, 072005 (2007)

- Time distributions in the Far Detector are predicted on the basis of measured neutrinos in the Near Detector
- **MINOS makes a neutrino to neutrino measurement**

MINOS TOF Plans



- **Short Term (next 6 months) - Retrospective Analysis:**
 - Analyze data sample increased by a factor of 9 with respect to 2007 result
 - Reduce major systematics - remeasure antenna cable lengths and electronics delays
- **Medium Term (~1 year):**
 - Upgrade timing system with atomic clocks to take new data from now up to 2012 shutdown with better timing
 - Crosscheck OPERA directly using proton beam timing profile by installing atomic clock at NuMI
 - Collaborating with external experts from US NIST
- **Longer Term (~2013 onwards):**
 - MINOS+: Run MINOS detectors with 700 kW NuMI beam in the NOvA era
 - Resurvey distance between detectors (error~10 cm)
 - Use auxiliary detectors to further constrain readout and electronics differences

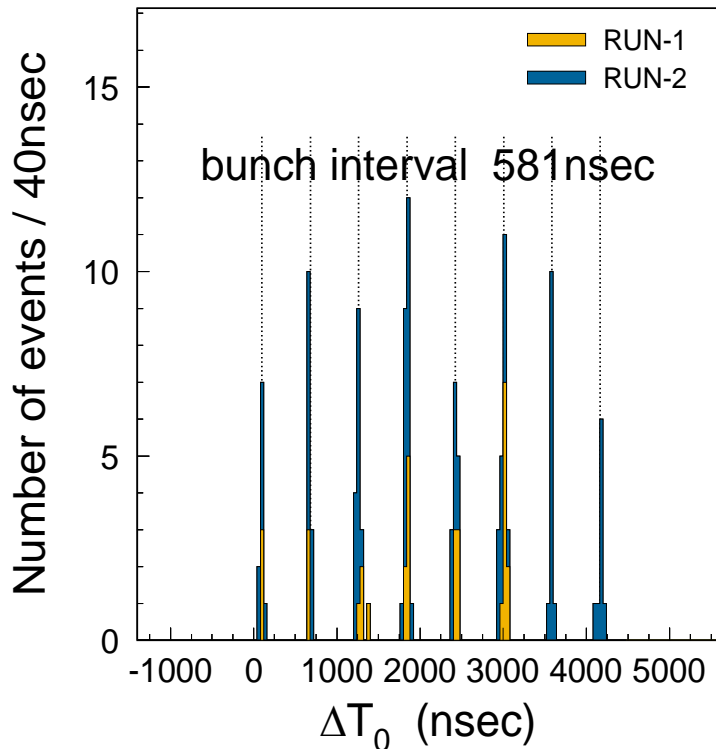
MINOS neutrino velocity schedule			
2011	2012	2013	2014 onwards
Reanalyze existing data ~18-32 ns precision			MINOS+ data-taking Precision comparable to OPERA
	Data up to spring 2012 shutdown 11-18 ns precision		

What about T2K?



- Official Statement:

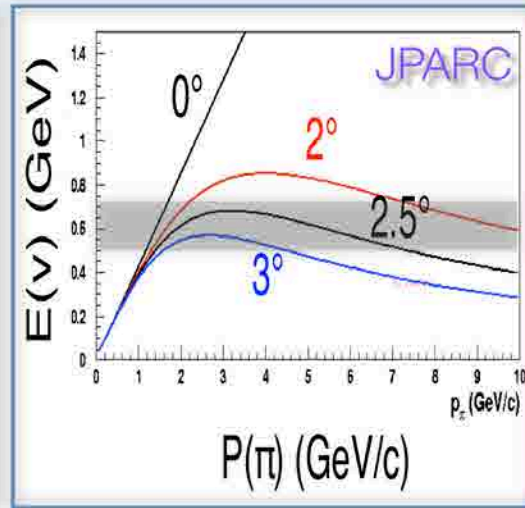
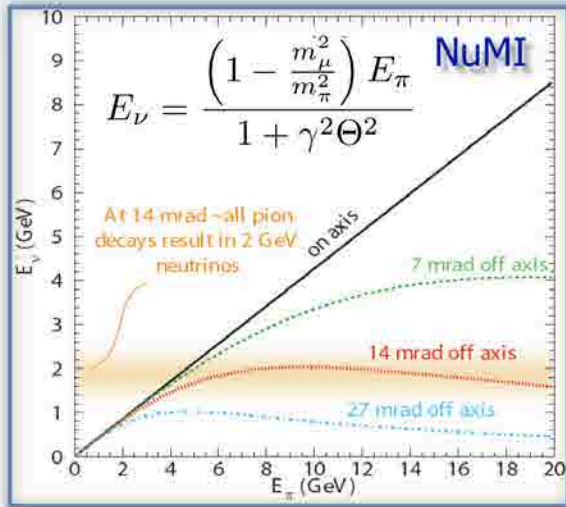
- “T2K will assess a possibility to improve our experimental sensitivity for a measurement to cross-check the OPERA anomaly in the future.”



- Distance between the target and center position at Super-Kamiokande: $295,335.2 \pm 0.7$ m
- Beam neutrino energy peaked at ~ 0.6 GeV
 - Proton beam extracted every 3 sec
 - Beam spill width $\sim 5 \mu\text{sec}$
 - 6 bunches/8 bunches before/after Summer '10
 - ~ 10 ns bunches separated by 581 ns
- Already uses Rb atomic clocks to provide time base for GPS receivers
- Shorter baseline and reconstruction resolution makes measurement more challenging

LONG-BASELINE NEUTRINO EXPERIMENTS
THE NEXT GENERATION

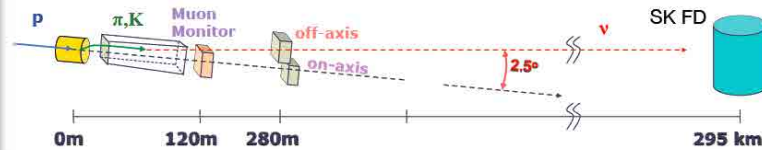
Off-Axis ν_μ Beams



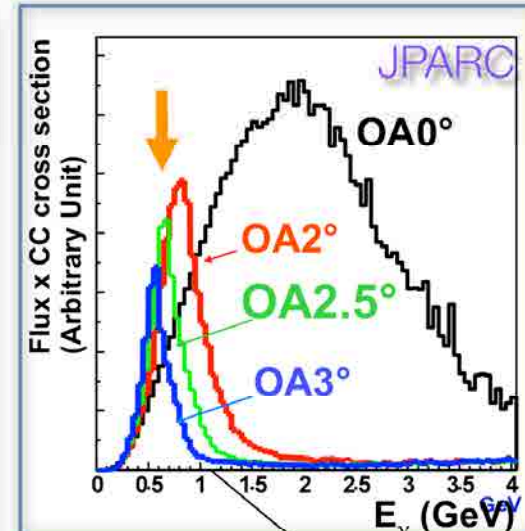
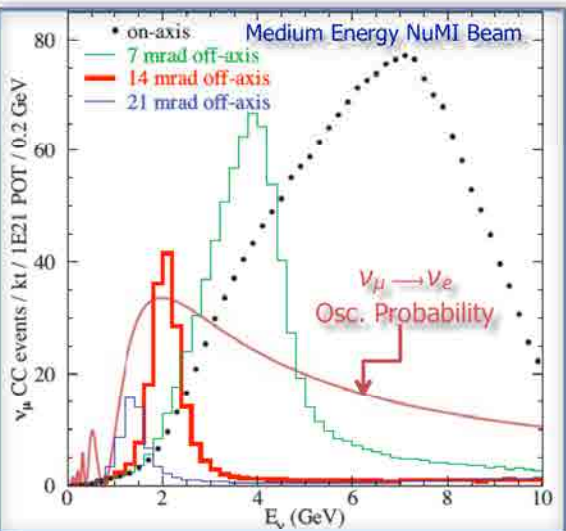
- Next generation of LBL experiments focuses on measuring $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Main challenge is rejection of neutral current background from high energy neutrino interactions

- Place detectors off beam axis
- Narrow band beam peaked near oscillation max



- Use large(r) Far detectors to increase statistics

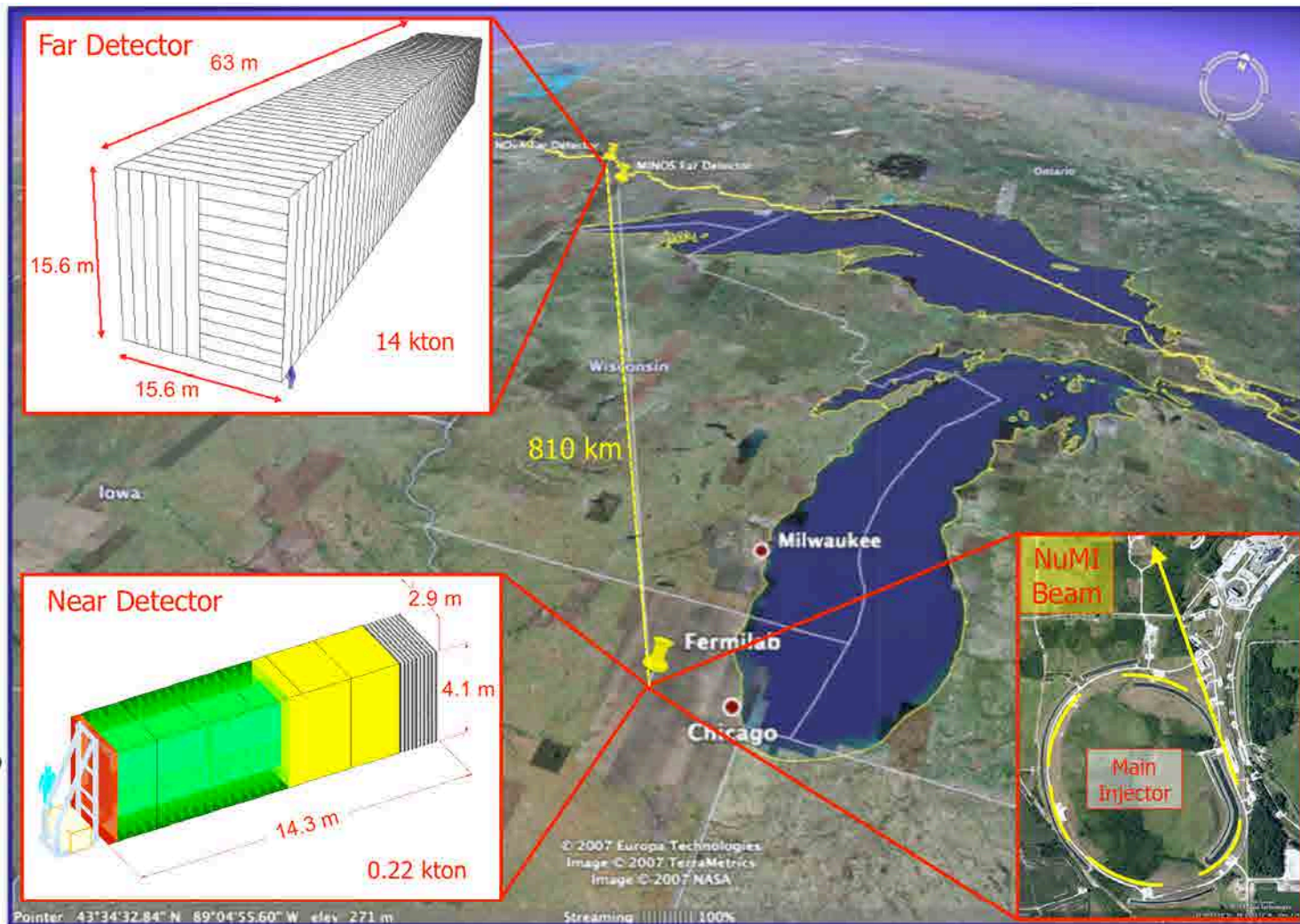


The NOvA Experiment



NuMI Off-Axis ν_e Appearance Experiment

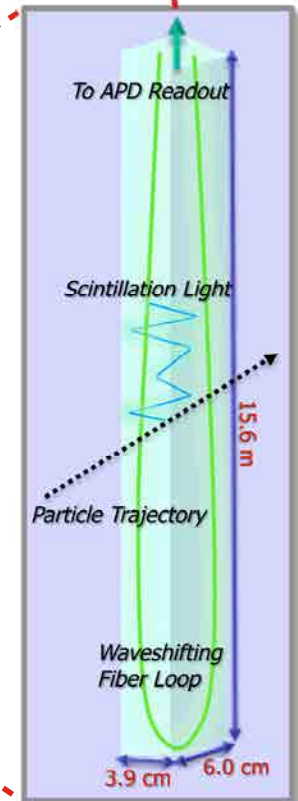
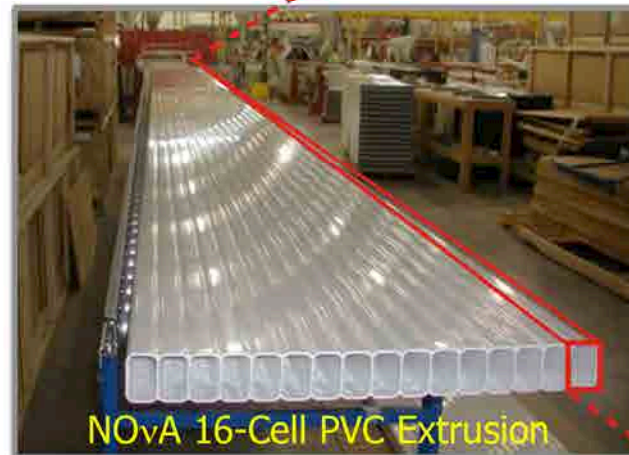
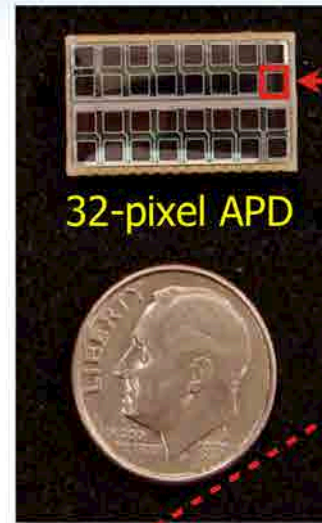
- 810 km baseline from Fermilab to Ash River, in northern MN
- 700 kW NuMI neutrino beam
- Near and Far PVC/liquid scintillator detectors placed 14 mrad off the NuMI beam axis
- Search for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations to:
 - Measure θ_{13}
 - Determine the neutrino mass hierarchy
 - Constrain δ_{CP}



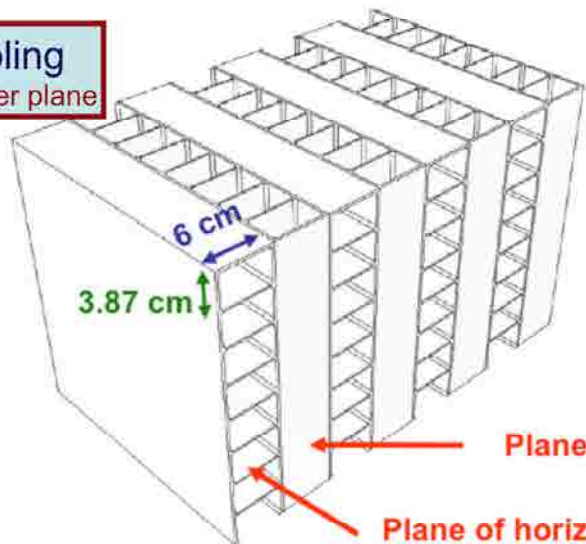
NOvA Detector Technology



- Near and Far detectors composed of highly reflective 16-cell PVC extrusions (15% TiO₂)
 - 357 120 cells in Far Detector
- Extrusions filled with liquid scintillator (mineral oil + 5% pseudocumene)
- Each cell read out by a wavelength-shifting fiber into one pixel of a 32-pixel avalanche photodiode (APD)
 - 85% quantum efficiency, cooled to -15°C



Sampling
0.15 X₀ per plane

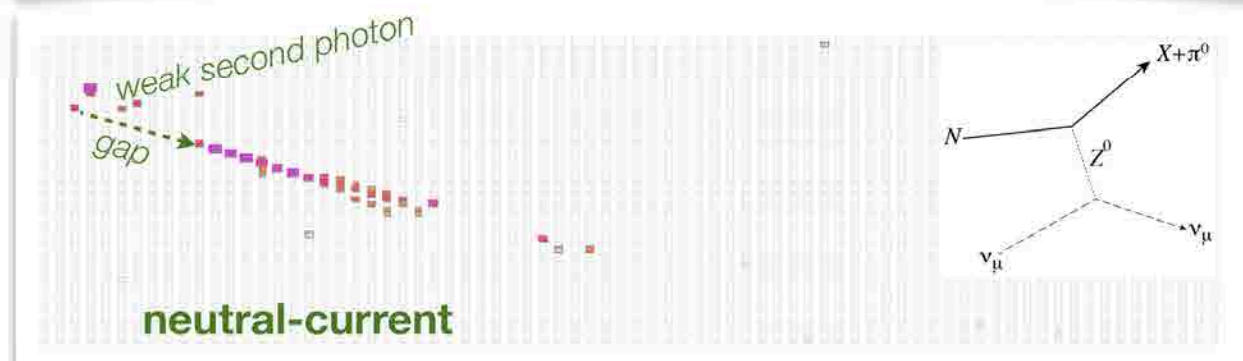
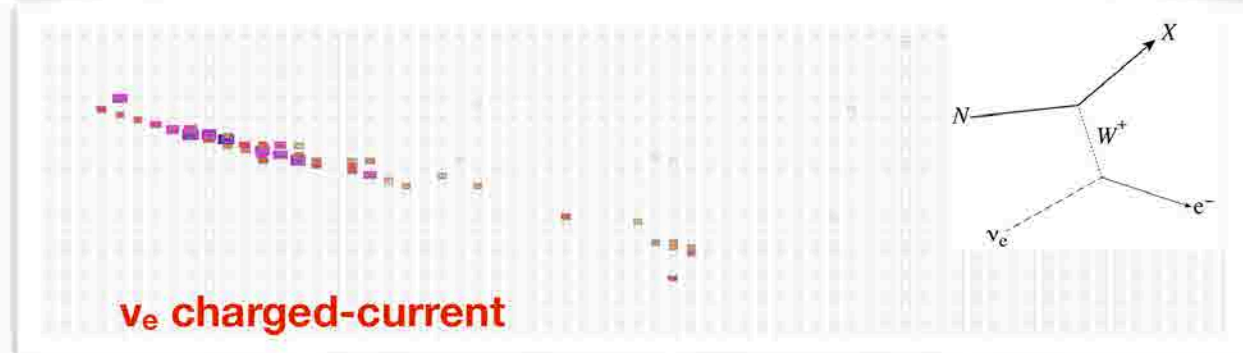
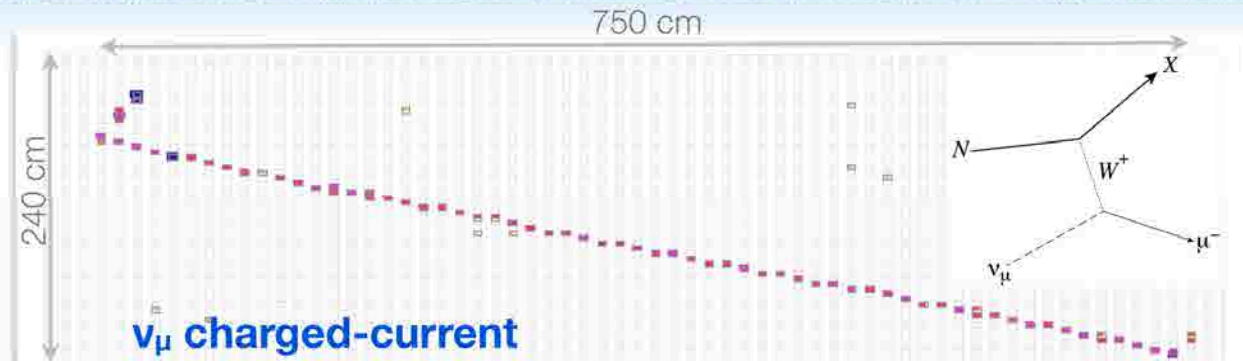


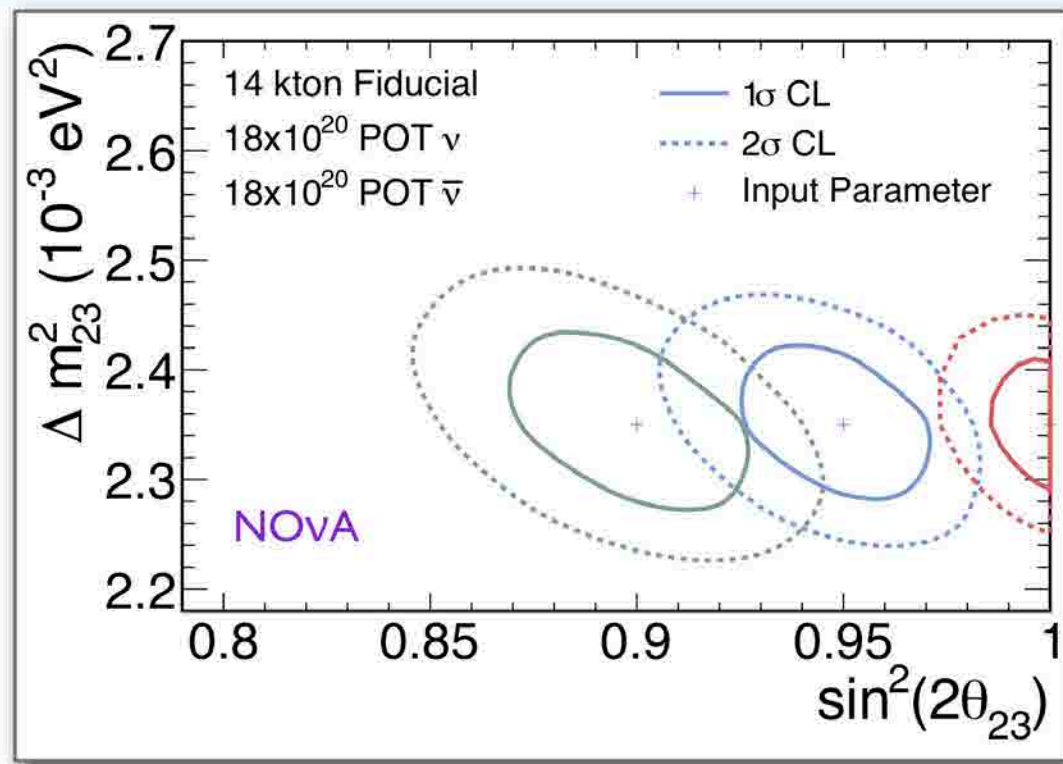
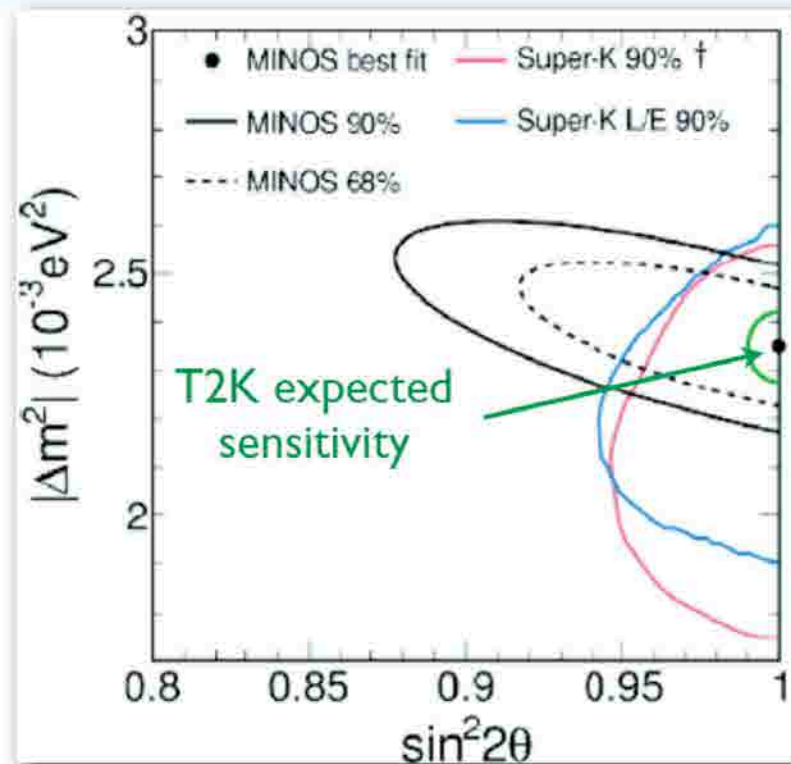
Plane of vertical cells
Plane of horizontal cells

Event Topologies



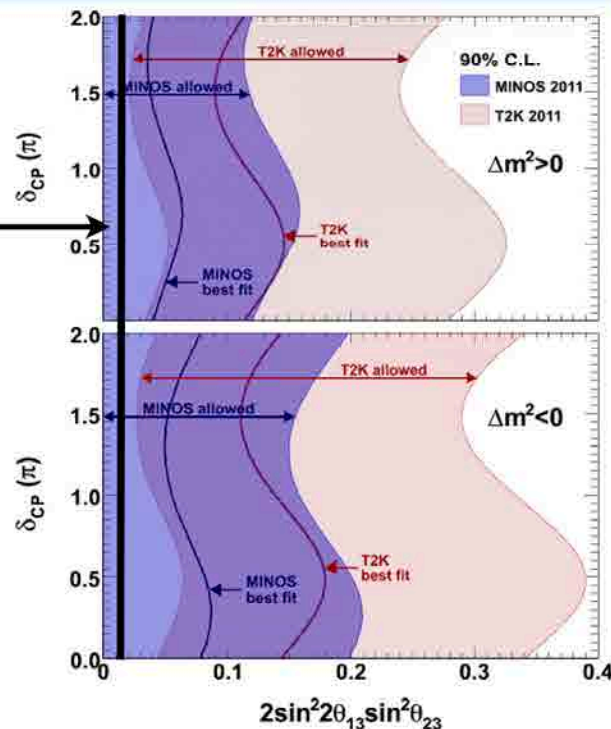
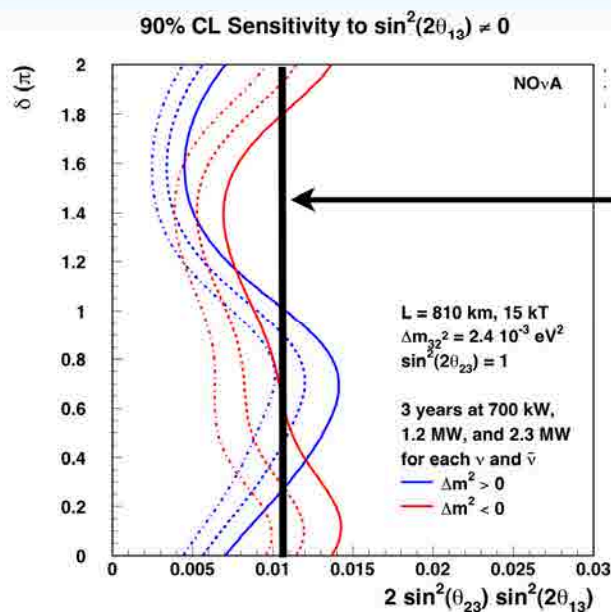
- Topologies of basic interaction channels simulated in the NOvA detectors
- Low detector density provides handles in rejection of NC π^0 background
- Expect to achieve 35% efficiency for ν_e CC while limiting NC $\rightarrow \nu_e$ CC contamination to 0.1%



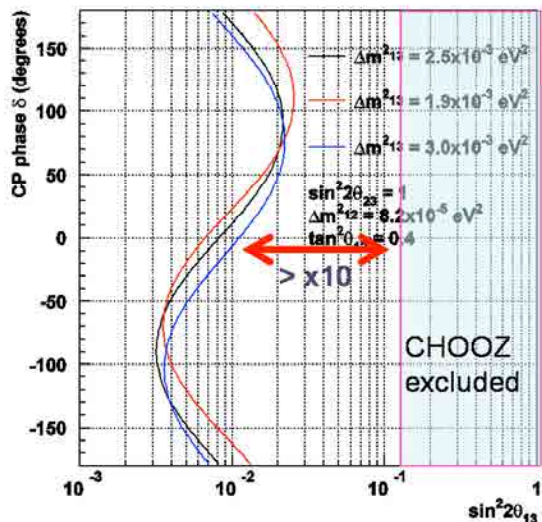


- Expect 1% measurement of atmospheric oscillation parameters
- Assess maximality of θ_{23}
- Greatly improve antineutrino disappearance measurements

NOVA

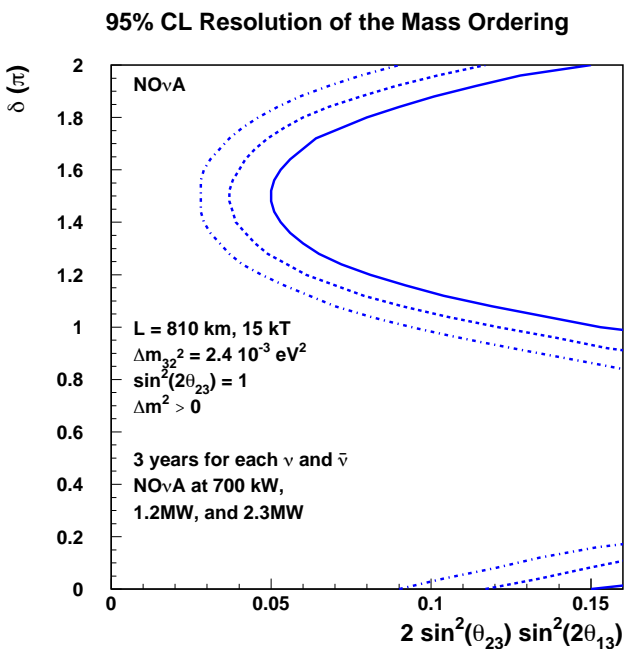


T2K

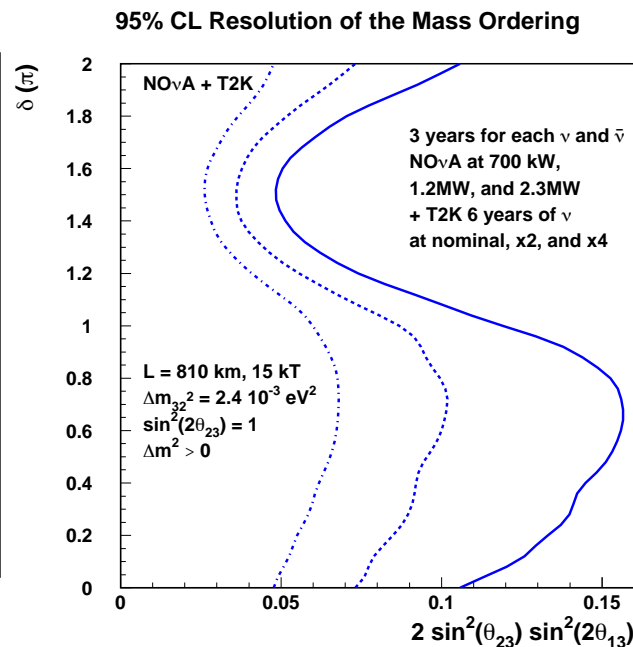


Factor of 10 improvement over previous best limit from CHOOZ

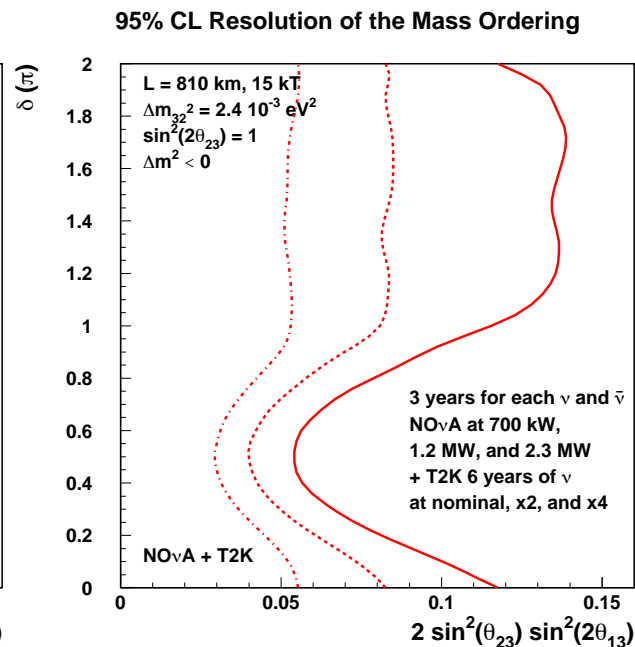
- Thanks to its 810 km baseline, NOvA may resolve ordering of neutrino mass hierarchy if $\sin^2 2\theta_{13}$ is large enough
- 95% CL resolution of mass hierarchy for values of $\sin^2 2\theta_{13}$ to the right of the curves
- Can improve sensitivity by including additional information from T2K's baseline



Normal Hierarchy
NOvA alone

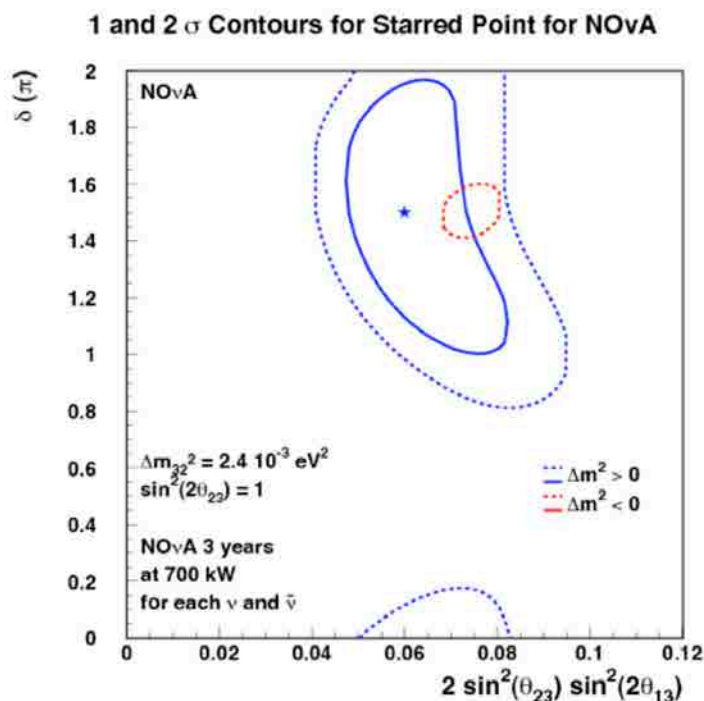


Normal Hierarchy
NOvA+T2K

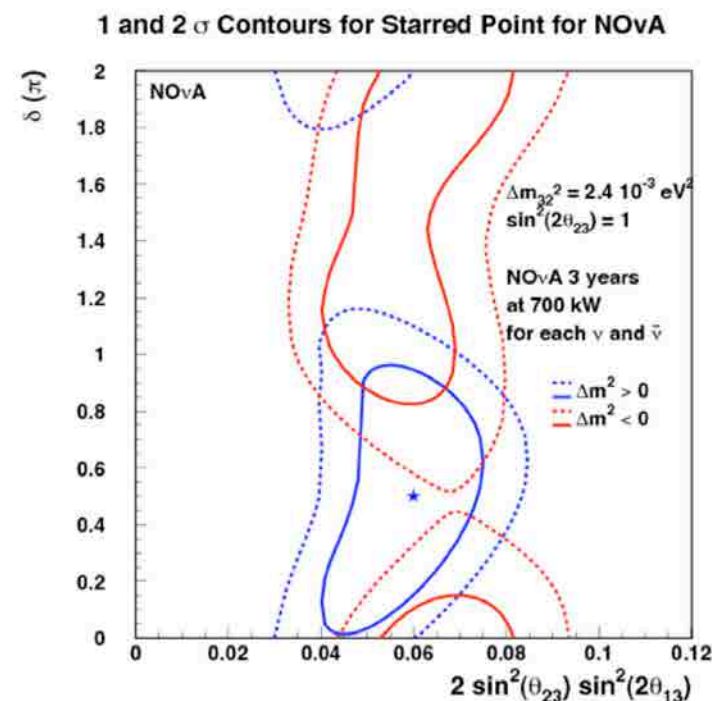


Inverted Hierarchy
NOvA+T2K

- NOvA may begin to constrain the CP violation phase space
- Depends on mass hierarchy and size of θ_{13}

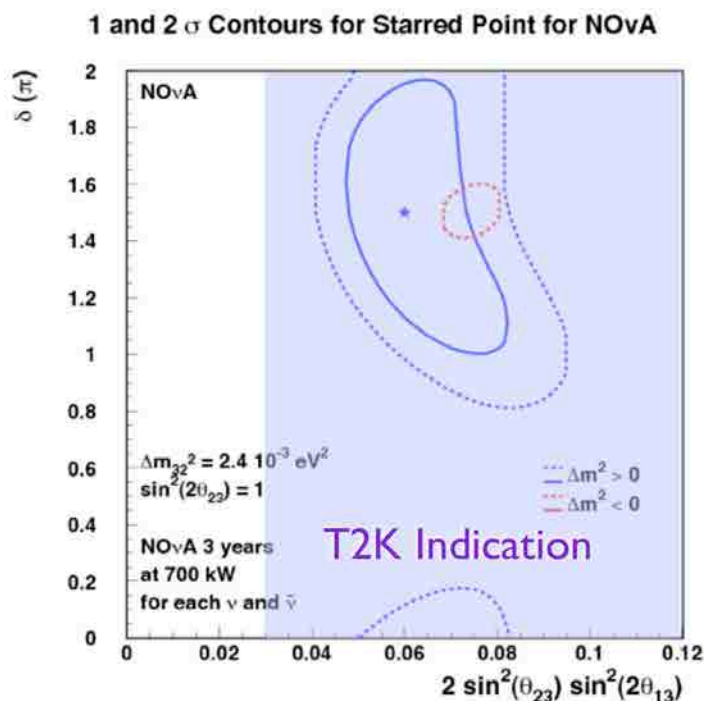


CP phase constrained to upper half plane and mass hierarchy resolved

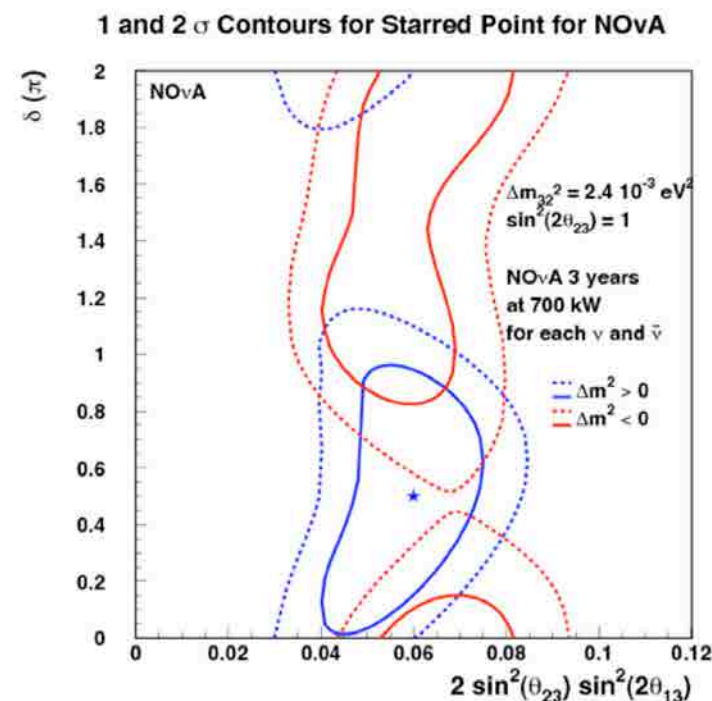


CP phase unconstrained as matter effects and CP violation effects cancel

- NOVA may begin to constrain the CP violation phase space
- Depends on mass hierarchy and size of θ_{13}

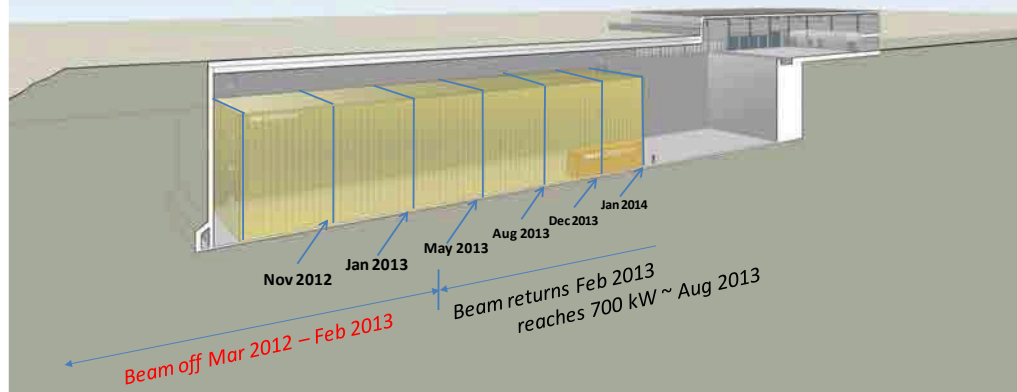
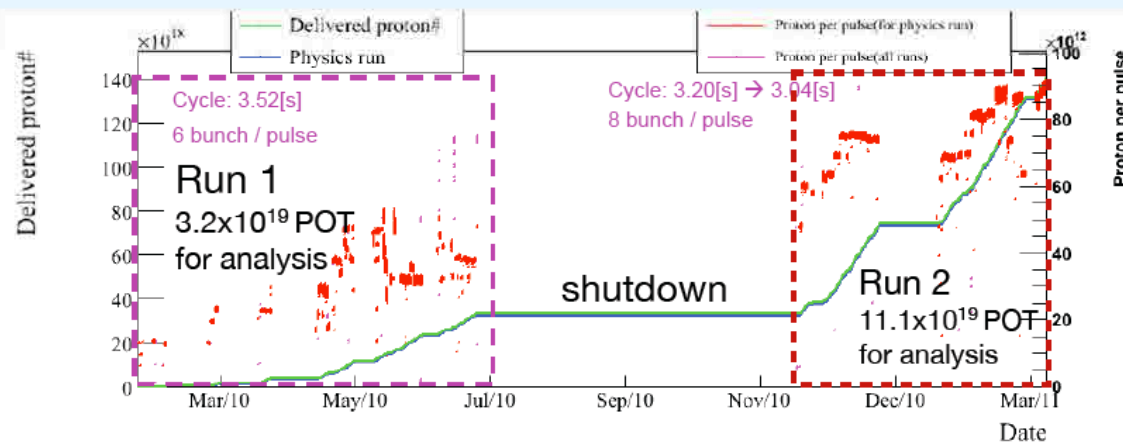


CP phase constrained to upper half plane and mass hierarchy resolved



CP phase unconstrained as matter effects and CP violation effects cancel

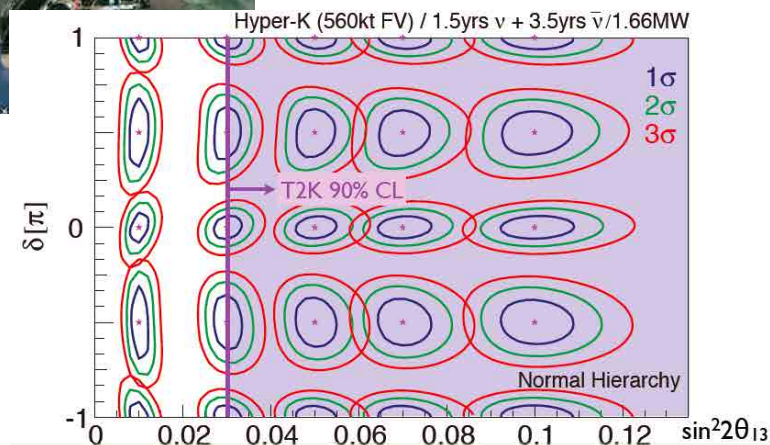
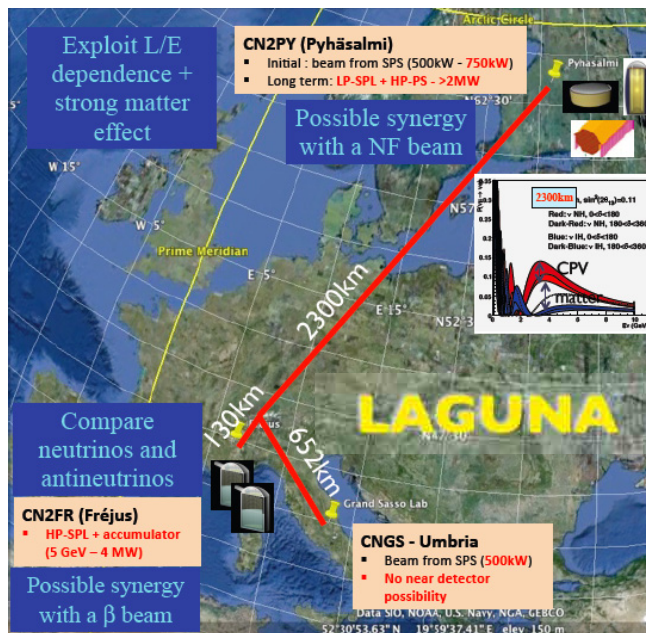
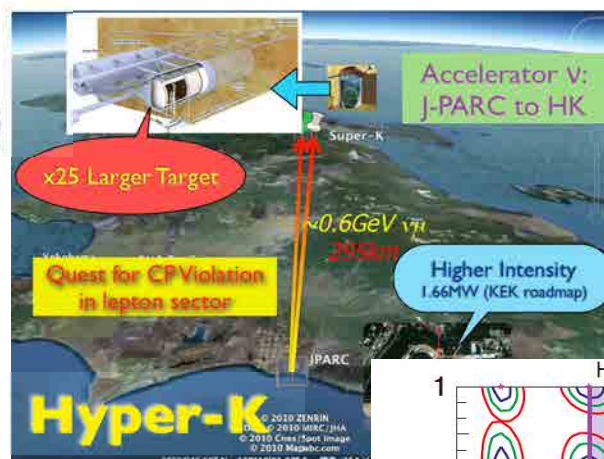
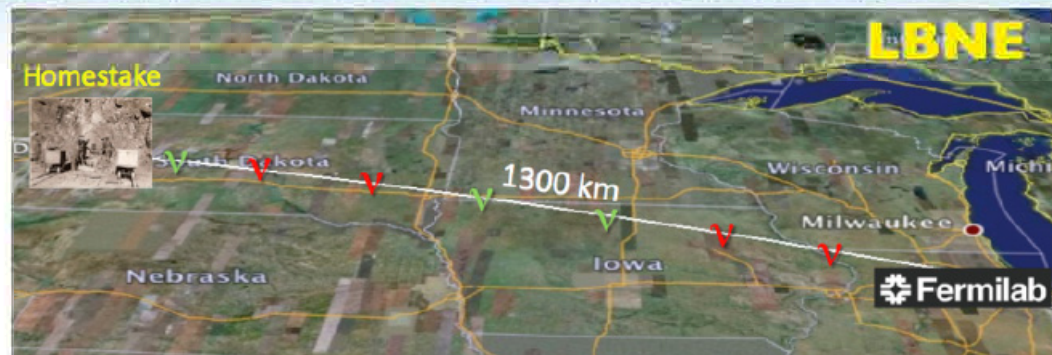
- T2K has started operations and published first results using 1.43×10^{20} POT sample
- Run stopped since the March '11 earthquake+tsunami
- Expect to resume beam data taking within next month



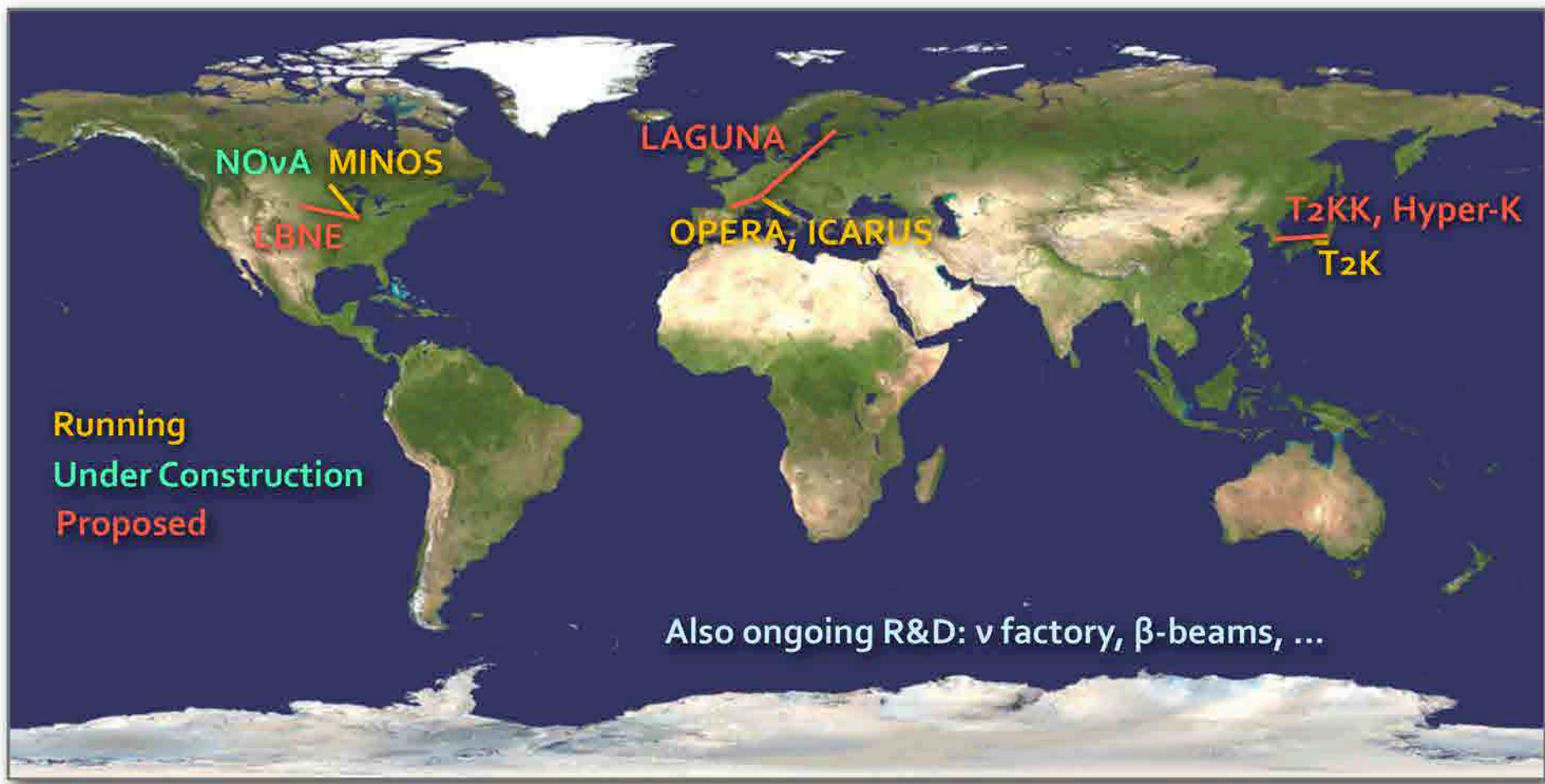
- NOVA Far Detector building ready
- Far Detector construction to start in February 2012
- NuMI beam upgrade for NOVA to start in Spring 2012
- NOVA operations with full FD begin in early 2014

Longer Term Future

- 3rd Generation LBL experiments (next decade) will focus on measuring CP violation and determining the mass hierarchy
- Different Det. technologies proposed:
 - Water Čerenkov O(100kton)
 - Liquid Argon O(50 kton)
 - Liquid Scintillator O(100 kton)



The World of LBL ν Experiments



Outlook

- Long-baseline neutrino experiments are making fundamental contributions to the measurement of neutrino masses and the understanding of the neutrino mixing matrix
- 2012/2013 should be very exciting. With new T2K data and new reactor experiments, a 5σ discovery of non-zero θ_{13} is possible!
- Determination of neutrino mass hierarchy (may happen during this decade) and measuring δ_{CP} are the major challenges that follow.
- Many ongoing R&D efforts for 3rd generation experiments. Size, scope and funding of these large projects will likely require worldwide coordination

“Unless you **expect the unexpected** you will never find [truth], for it is hard to discover and hard to attain.”

- Heraclitus (535 BC - 475 BC) -