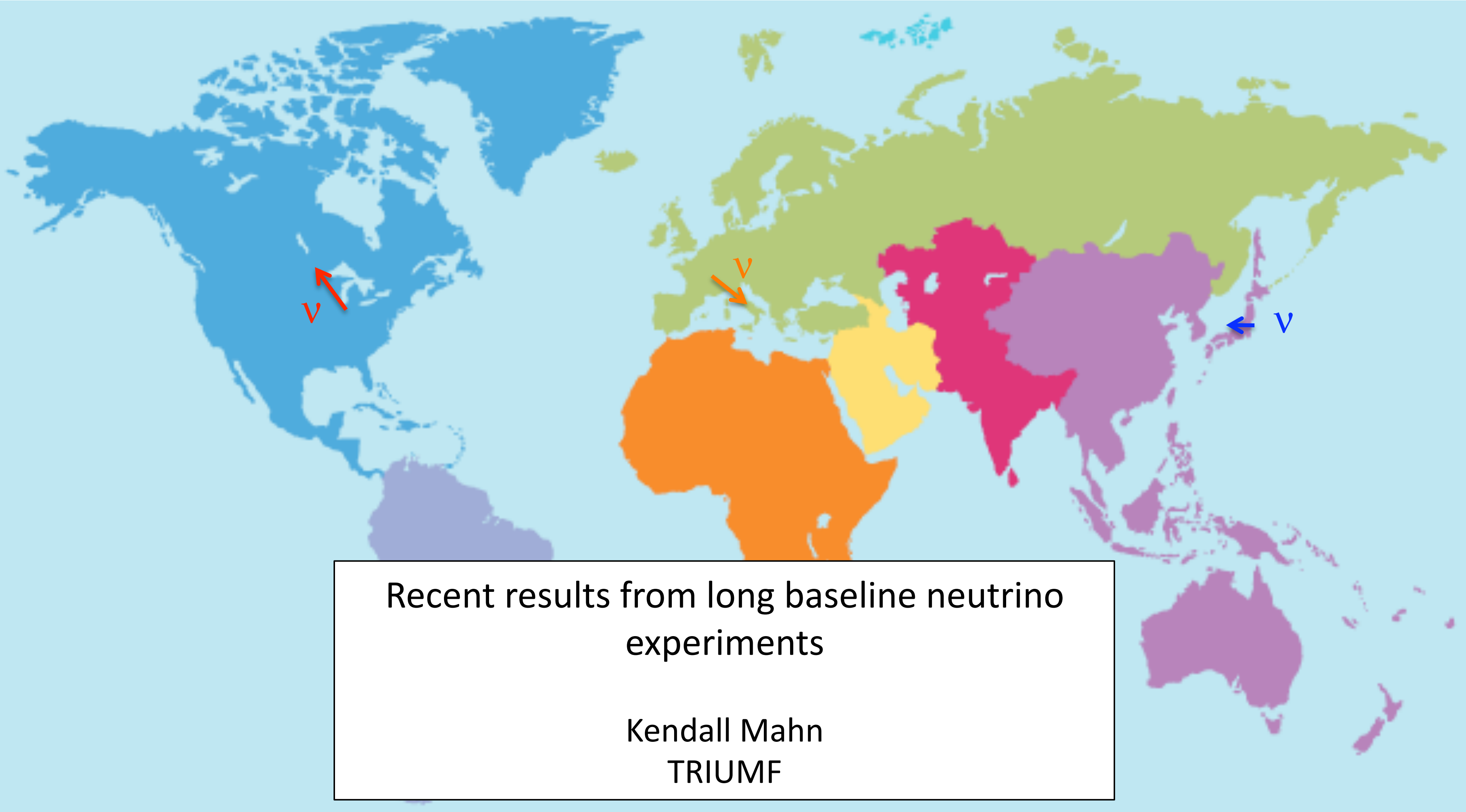


Recent results from long baseline neutrino experiments

Kendall Mahn
TRIUMF

What physics is beyond the Standard Model?

Massive neutrinos

as determined from neutrino oscillation experiments

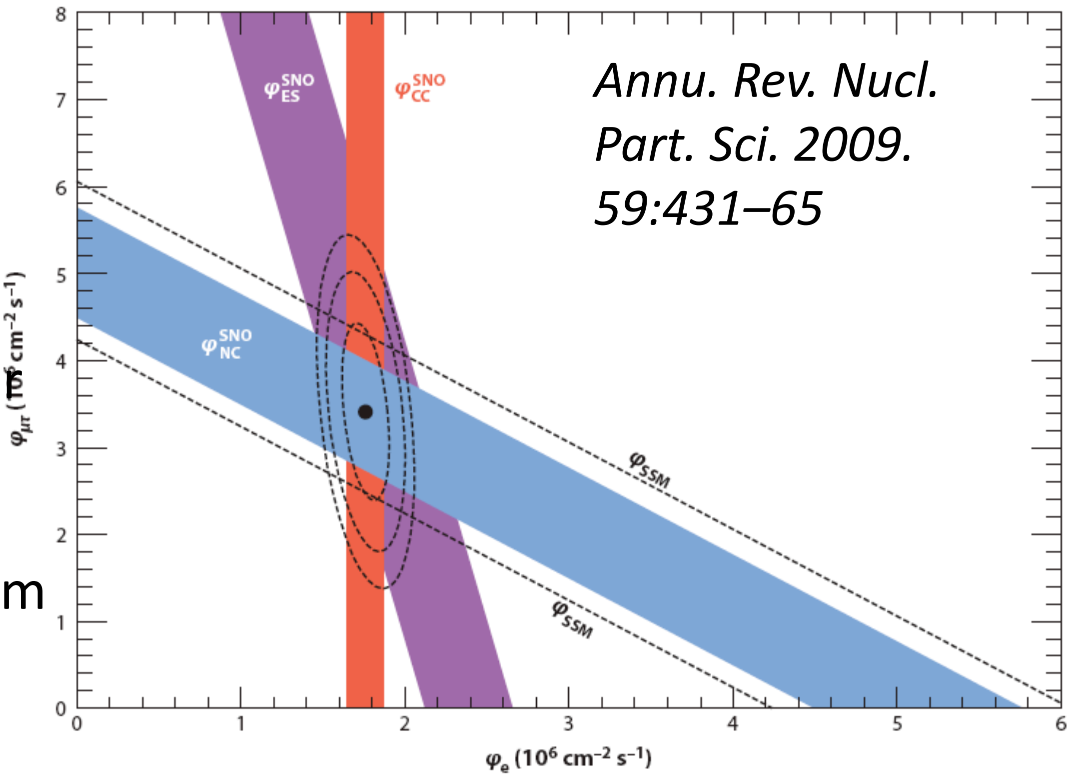
What is neutrino oscillation?

Neutrino oscillation, the mixing between flavor and mass states, has been observed through deficits relative to expectation of different neutrino flavors. Evidence from:

- Electron neutrinos (ν_e) from the Sun
- Electron antineutrinos (anti-ν_e) from reactors
- Muon (ν_μ) neutrinos from the atmosphere

Sudbury Neutrino Observatory (SNO) experiment measured the flux of ν_e from the Sun

- ν_e flux determined through charged current interactions (CC) where flavor of the neutrino corresponds to the final state lepton
- Total flux of ν_e, ν_μ, ν_τ determined from neutral current interactions (NC)



Annu. Rev. Nucl. Part. Sci. 2009. 59:431–65

Clear deficit of ν_e flux "ν_e disappearance"
Clear increase of ν_μ, ν_τ flux "appearance"

What is neutrino oscillation?

Neutrino oscillation, the mixing between flavor and mass states, has been observed through deficits relative to expectation of different neutrino flavors. Evidence from:

- Electron neutrinos (ν_e) from the Sun
- Electron antineutrinos (anti ν_e) from reactors
- Muon (

Evidence* consistent with three active flavors of neutrinos

Do we directly observe neutrino oscillation through CC flavor tagging (ν_μ to ν_e, ν_τ “appearance”)

Do we observe the same transitions for neutrinos as for antineutrinos? Is there CP violation in neutrino oscillations?

**Excluding outstanding questions about sterile neutrinos*

Sudbury N
experimen
from the S

- ν_e flux c
  current
  of the n
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- Total flu
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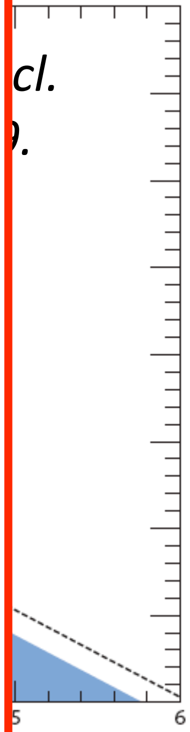


Clear deficit of ν_e flux “ν_e disappearance”
Clear increase of ν_μ, ν_τ flux “appearance”

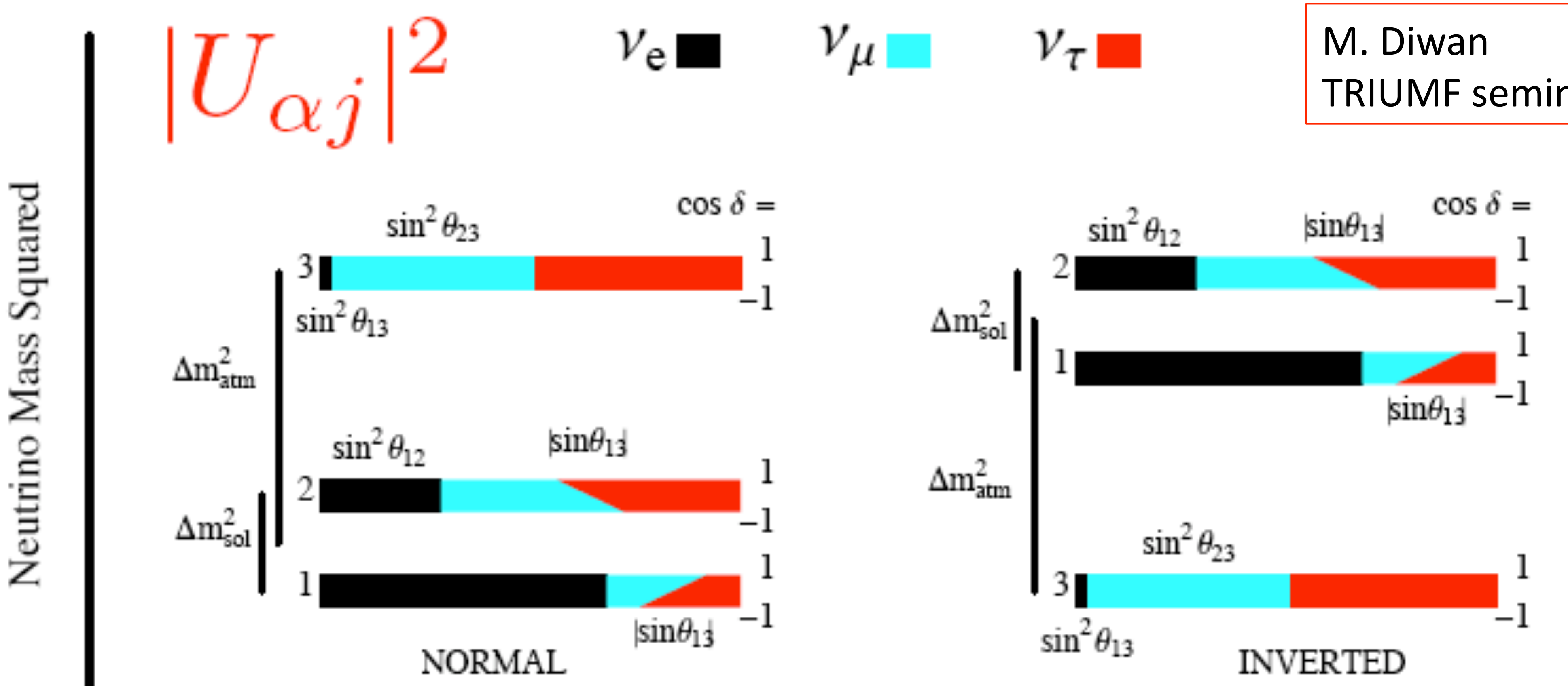
Framework of neutrino oscillation

Neutrino oscillation between three active flavors is described by the PMNS mixing matrix, U, which is unitary and contains three mixing angles: θ_{12}, θ_{23}, θ_{13}, and two mass splittings:

- Δm^2(atmospheric) = $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2
- Δm^2(solar) = $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2

The matrix also contains an unknown CP violating phase δ_{CP}. The ordering of the mass eigenstates (mass hierarchy) is also unknown: $\Delta m^2_{32} > 0$ or $\Delta m^2_{32} < 0$?

M. Diwan
TRIUMF seminar



Framework of neutrino oscillation

ν_μ to ν_e appearance probability:

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} << 1$$

$$\Delta = \frac{\Delta m^2_{32} L}{4E_\nu}$$

$$A = 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$$

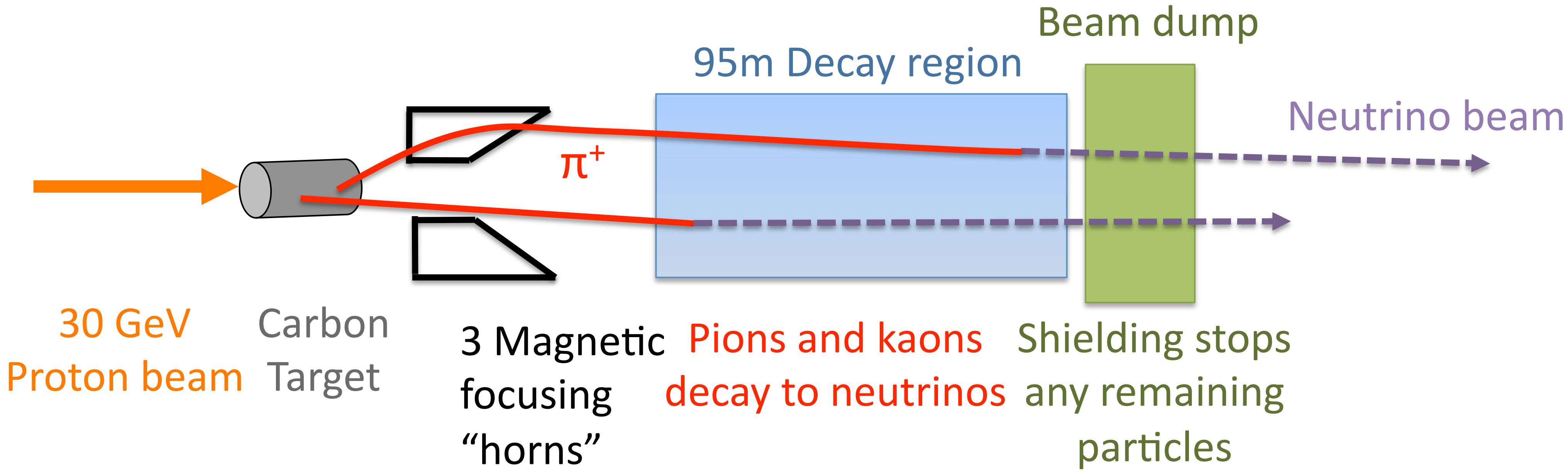
$$\begin{aligned} P_{\nu_\mu \rightarrow \nu_e} = & \frac{1}{(A-1)^2} \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2[(A-1)\Delta] \\ & -(+)\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{12} \times \\ & \sin\delta_{CP} \sin\Delta \sin A\Delta \sin[(1-A)\Delta] \\ & + \frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{12} \times \\ & \cos\delta_{CP} \cos\Delta \sin A\Delta \sin[(1-A)\Delta] \\ & + \frac{\alpha^2}{A^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 A\Delta \end{aligned}$$

Depends on δ_{CP}, mass hierarchy through matter effects (A)

Measurements of ν_μ *to* ν_e *appearance are sensitive to new or exotic physics provided information on* Δm^2_{32}, θ_{23}, Δm^2_{21}, θ_{12} *and* θ_{13}

Measurements of ν_μ *disappearance determine* Δm^2_{32} *and* θ_{23}

Accelerator-driven neutrino sources



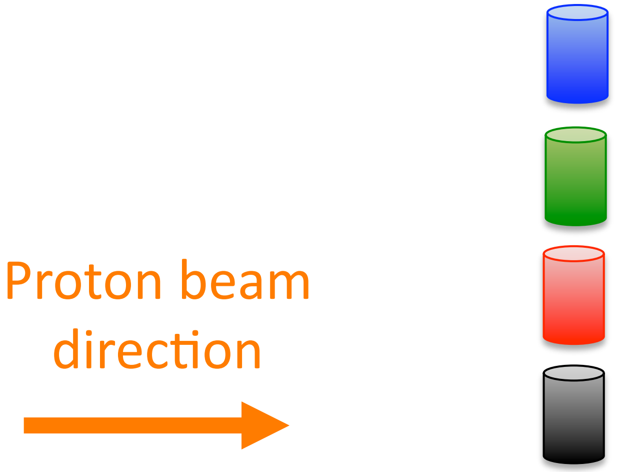
Neutrinos are produced as a tertiary beam:

1. Protons hit a target, producing pions and kaons which decay to neutrinos

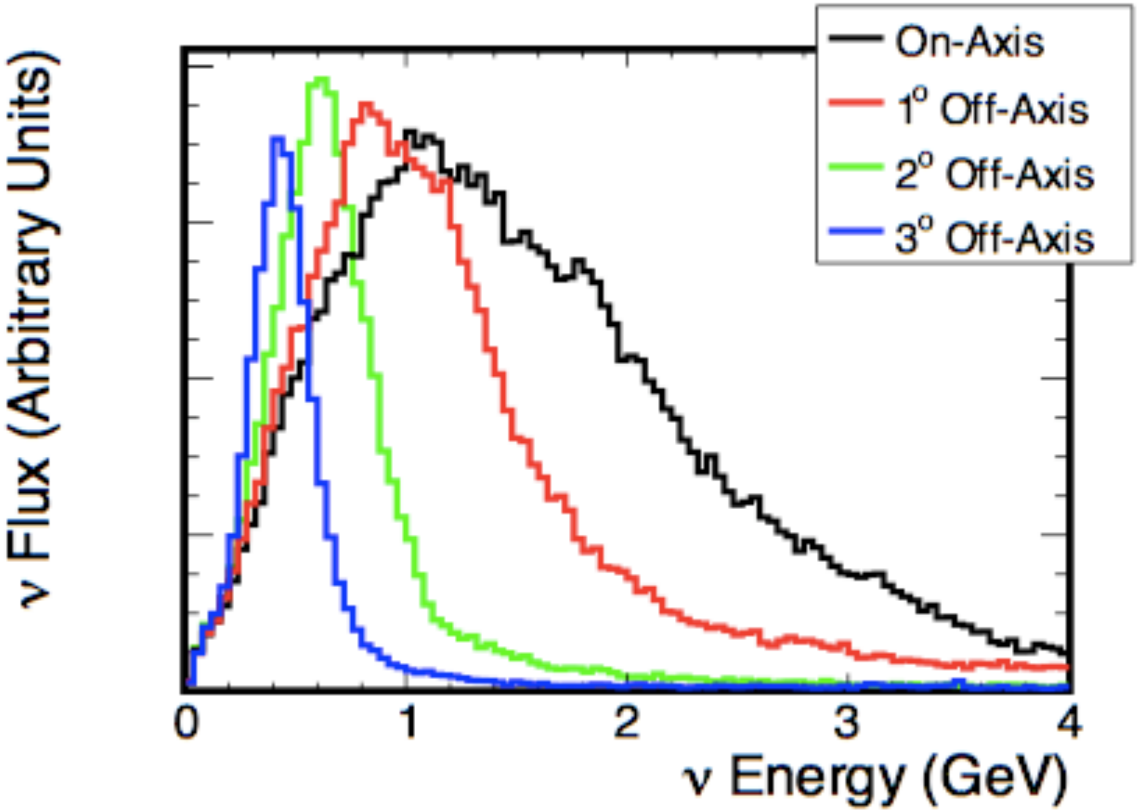
Advantages of an accelerator-driven neutrino source for precision studies of neutrinos and antineutrinos:

1. >99% muon neutrino flavor, small ν_e component from muon, kaon decay
2. "Known", scalable source (intensity of proton beam increases neutrino rate)
3. Switch magnetic horn polarization to focus π^- and produce an predominantly antineutrino beam (with a ~30% neutrino component)

Accelerator-driven neutrino sources



Proton beam direction



Accelerator based sources also are tunable as the neutrino energy spectrum depends on:

- Proton beam energy
- Position of the detector relative to the proton beam direction

"On axis" or "Wide band beam" is along proton beam direction

"Off axis" or "Narrow band beam" is at an angle to the proton beam

- *Concept developed at TRIUMF*

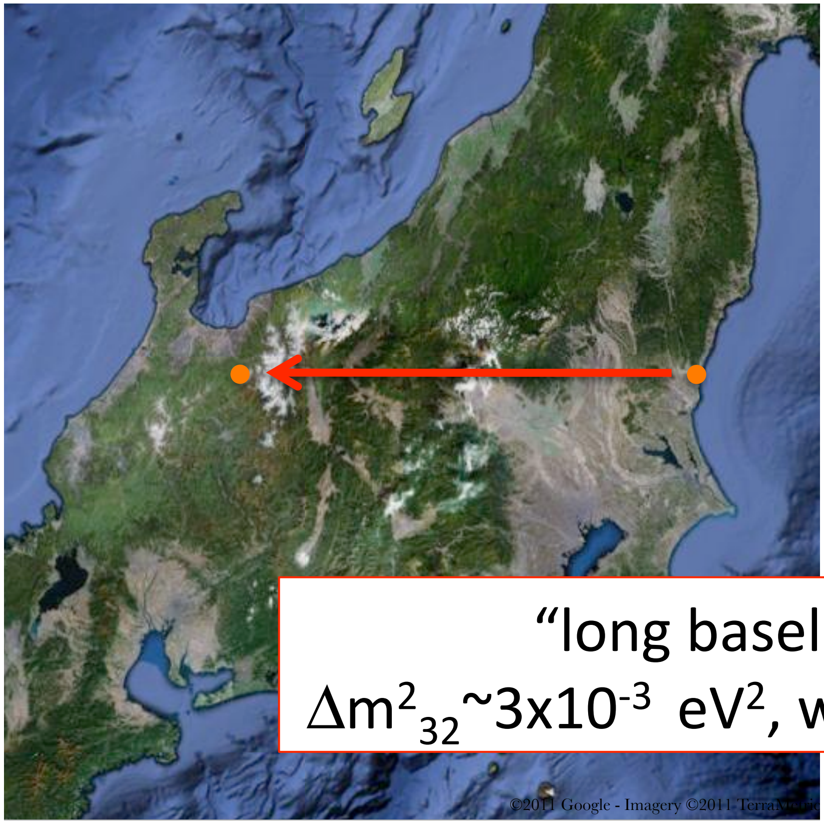
Oscillation experiments

The oscillation probability, P, for ν_μ to oscillate is sinusoidal and depends on the distance L (km) the neutrinos travel and their energy E (GeV):

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)\left[\sin^2 2\theta_{23}\cos^4\theta_{13} + \sin^2\theta_{23}\sin^2 2\theta_{13}\right]$$

Tokai To Kamioka (T2K) experiment:

Eν(peak) ~0.6GeV, L=295km



MINOS experiment:

Eν(peak) ~3 GeV, L=735km

"long baseline experiments" require

Δm^2_{32}~3×10^{-3} eV^2, want $\sin^2(\Delta m^2 L/E)$ to be of order 1

Oscillation experiments

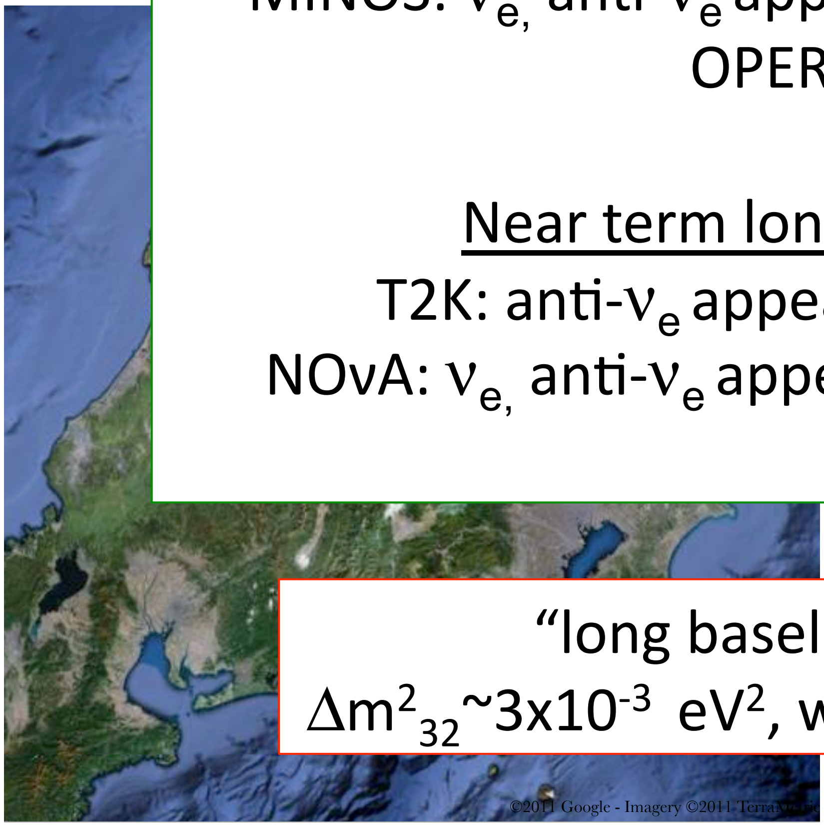
The oscillation probability, P, for ν_μ to oscillate is sinusoidal and depends on the distance L (km) the neutrinos travel and their energy E (GeV):

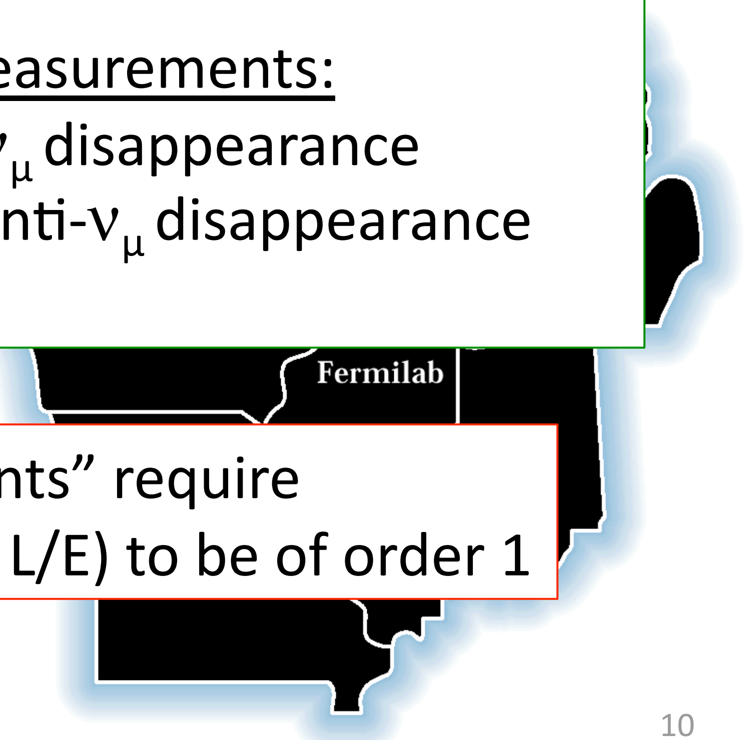
$P(\nu$ $1.27\Delta m^2\ L$

Tokai To

Ev(peak)

n





Recent long baseline measurements:

T2K: ν_e appearance, ν_μ disappearance

MINOS: ν_e, anti-ν_e appearance, ν_μ, anti-ν_μ disappearance

OPERA: ν_τ appearance

Near term long baseline measurements:

T2K: anti-ν_e appearance, anti-ν_μ disappearance

NOvA: ν_e, anti-ν_e appearance, ν_μ, anti-ν_μ disappearance

"long baseline experiments" require

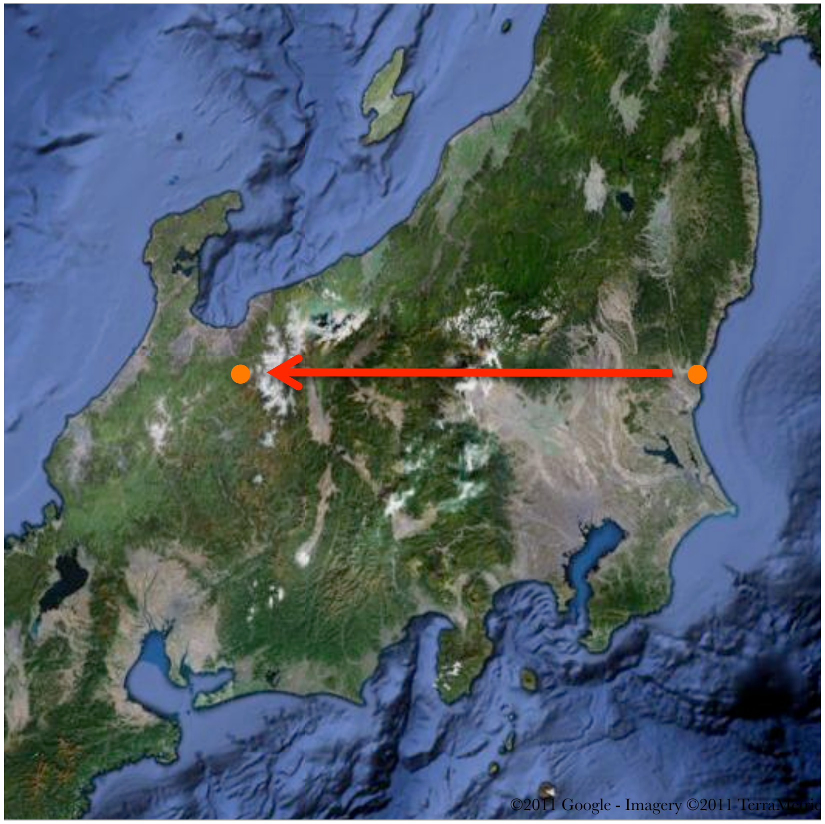
Δm^2_{32}~3×10^{-3} eV^2, want $\sin^2(\Delta m^2\ L/E)$ to be of order 1

The T2K experiment

Tokai-mura to Kamioka (295km)

Off-axis beam (2.5°) produced at JPARC

E_ν(peak) ≈0.6 GeV


©2011 Google - Imagery ©2011 TerraMetrics

T2K physics run:

Operating from 2010 onward

Neutrinos: 6.57×10^{20} POT

Antineutrinos: test run ongoing

Measurements of:

ν_μ disappearance

ν_e appearance

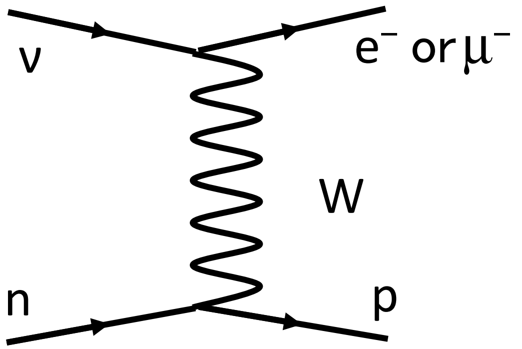
Oscillation analyses on T2K

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)\left[\sin^2 2\theta_{23}\cos^4\theta_{13} + \sin^2\theta_{23}\sin^2 2\theta_{13}\right]$$

Oscillation probability depends on neutrino energy

For T2K’s neutrino spectrum, dominant process is Charged Current Quasi-Elastic:

CCQE

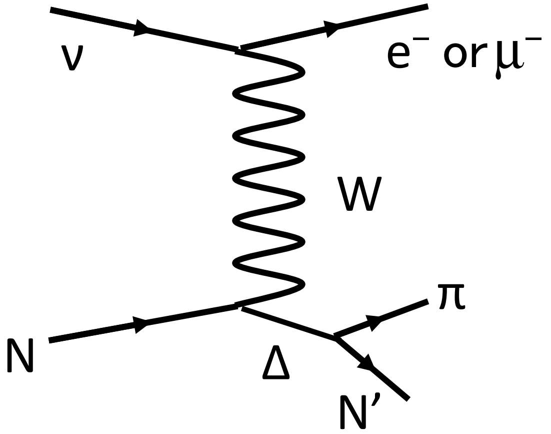


Infer neutrino properties from the lepton momentum and angle:

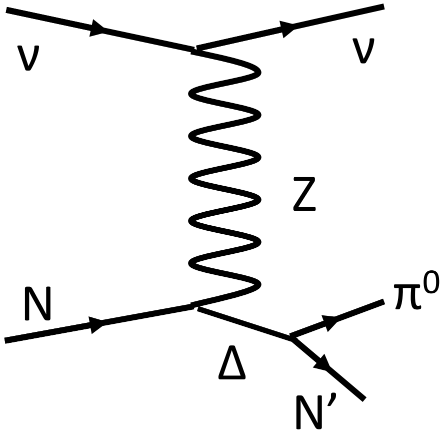
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

CCπ



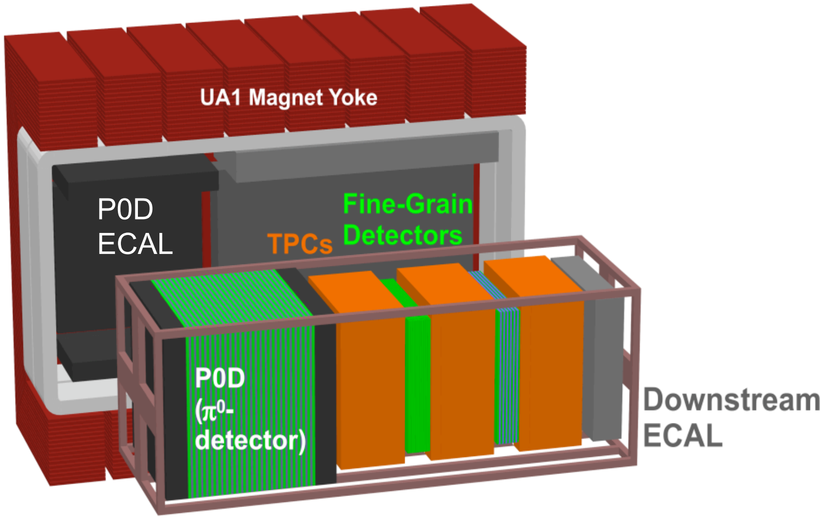
NCπ⁰



Background processes are:

- Charged current single pion production (CCπ)
- Neutral current single pion production (NCπ⁰)

Event selection on the T2K experiment

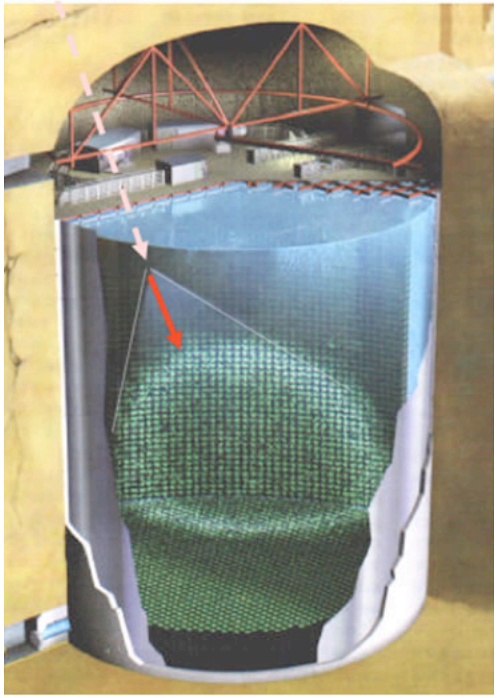


Select CC ν_μ candidates prior to oscillations in an off axis tracking detector (ND280)

- Neutrino interacts on scintillator tracking detector
- Muon momentum determined from curvature in magnetic field (with TPCs)
- Events separated based on presence of charged pion in final state (CC0π, CC1π, CC other)

Select CC ν_e and ν_μ candidates after oscillations, in a 50kton water Cherenkov detector (Super-Kamiokande)

- Select single ring events, determine lepton flavor from ring shape and topology
- Reject CC nonQE interactions using ring multiplicity and decay electron tagging
- NC events with π^0 removed based on invariant mass



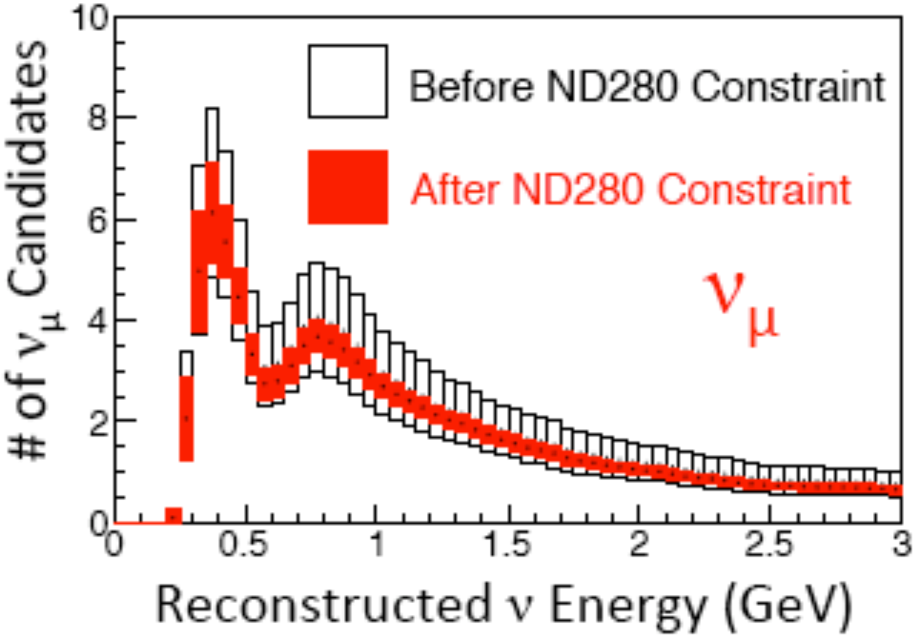
Use of near detectors on T2K

Expected number of events at the far detector is modified based on near detector information; provides a substantial constraint on the uncertainties of ν_e and ν_μ events:

$$FD(\nu_e) = \boxed{\Phi \times \sigma} \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$
$$ND(\nu_\mu) = \boxed{\Phi \times \sigma} \times \epsilon_{ND}$$

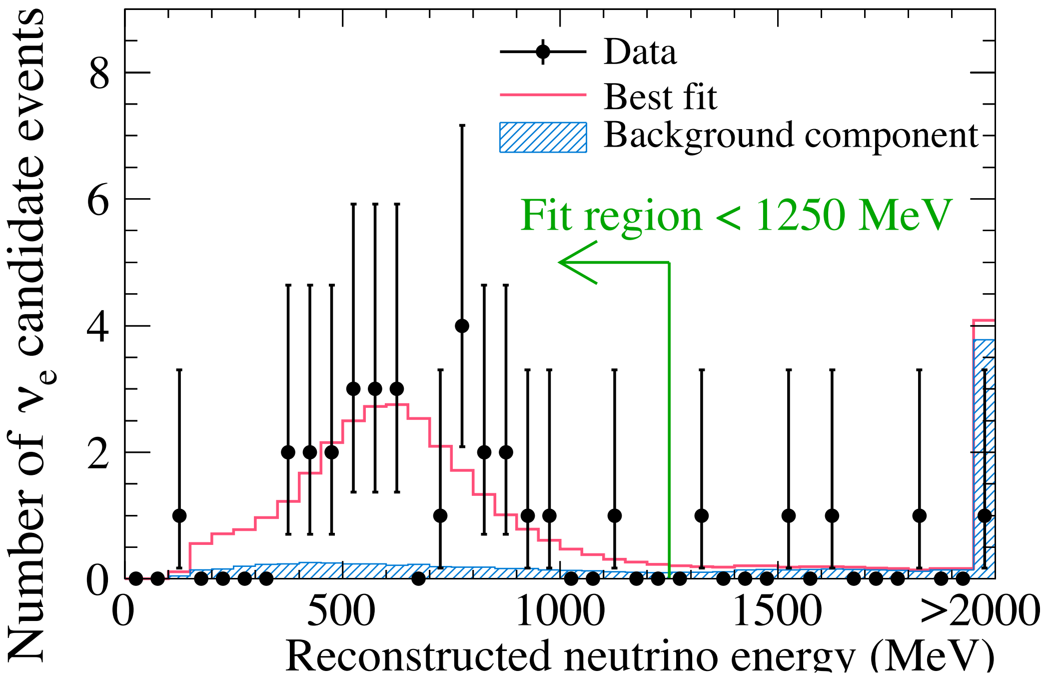
uncertainties for nue appearance	**ν_e sig+bkrd**	**ν_e bkrd**
ν flux+xsec (before) after ND constraint	(25.9%) ±2.9%	(21.7%) ±4.8%
ν unconstrained xsec	±7.5%	±6.8%
Far detector	±3.5%	±7.3%
Total	(27.2%) ±8.8%	±11.1%

After ND: expect 21.6 ν_e candidates (background only: 4.92)



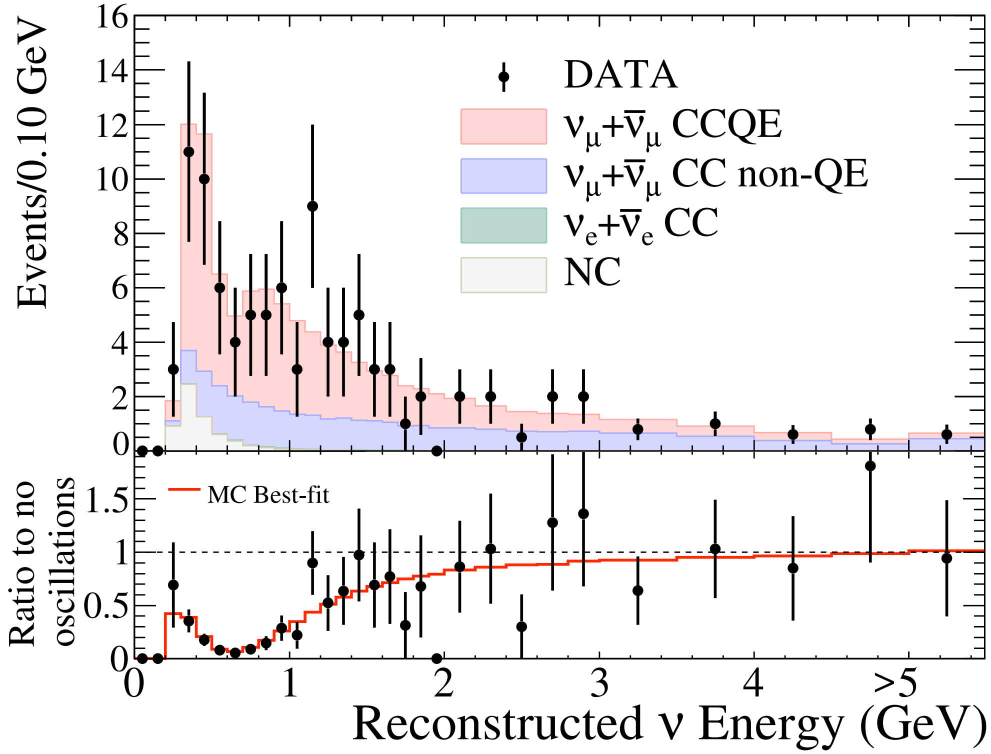
After ND: expect 124.8 ν_μ events (background only: 49.2)

T2K observed event distributions



28 candidate ν_e events observed

- First observation of CC ν_e appearance!
    - Phys. Rev. Lett. 112, 061802 (2014)
- Transition depends on all mixing parameters (Δm^2_{32}, θ_{23} θ_{13} and δ_{CP}, mass hierarchy and Δm^2_{21}, θ_{12})



120 candidate ν_μ events observed

- Determine Δm^2_{32}, $\sin^2\theta_{23}$ from distortion to neutrino energy spectrum
    - Phys. Rev. Lett. 112, 181801 (2014)

Fit both ν_e and ν_μ samples simultaneously
Include solar, reactor determinations of Δm^2_{21}, θ_{12}, θ_{13}

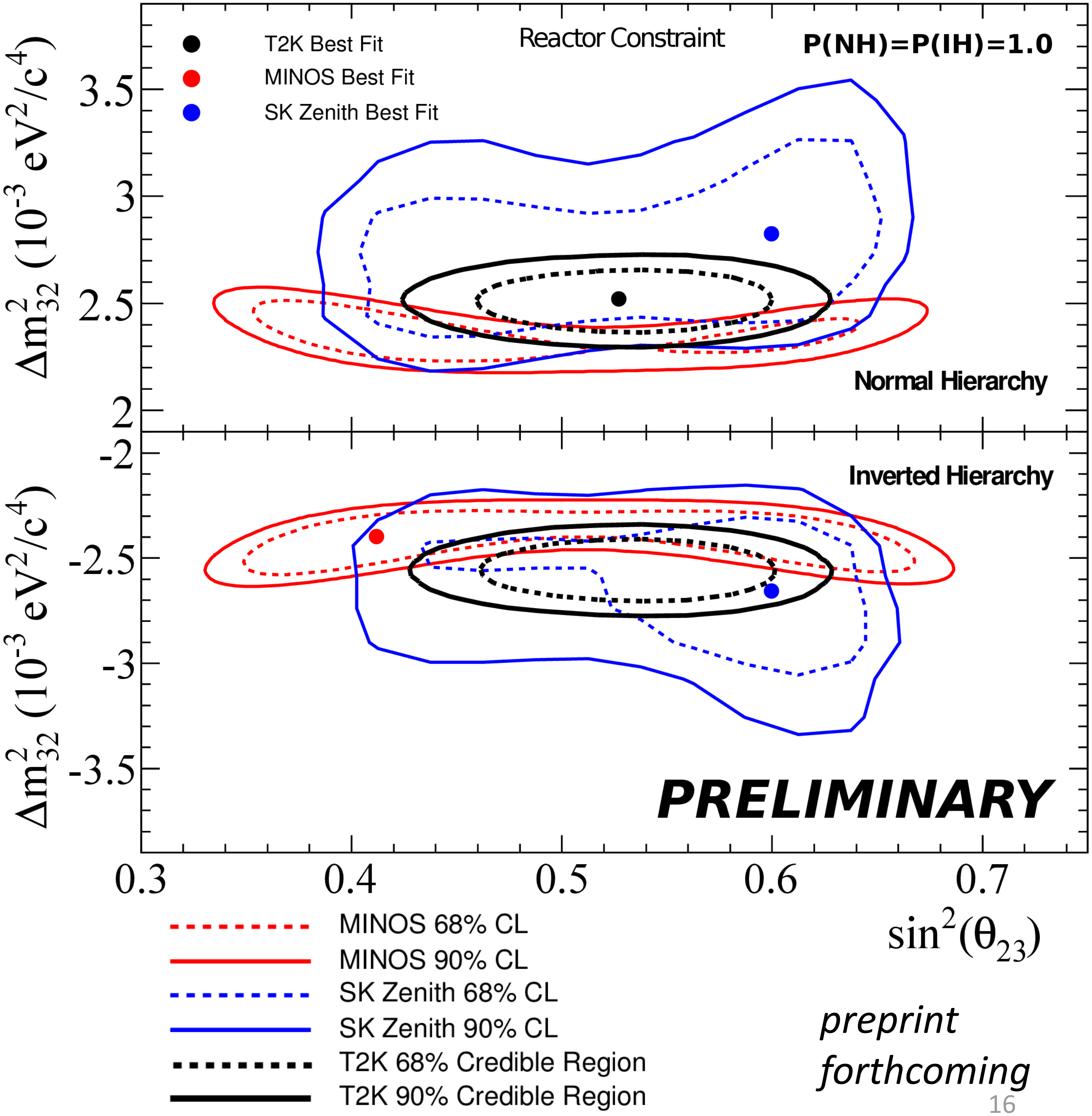
T2K joint ν_μ-ν_e fit results: Δm^2_{32}, $\sin^2\theta_{23}$

Markov Chain Monte Carlo-based analysis

- Simultaneous fit to near detector ν_μ, far detector ν_μ, ν_e samples
- Includes correlations between ν_μ, ν_e samples

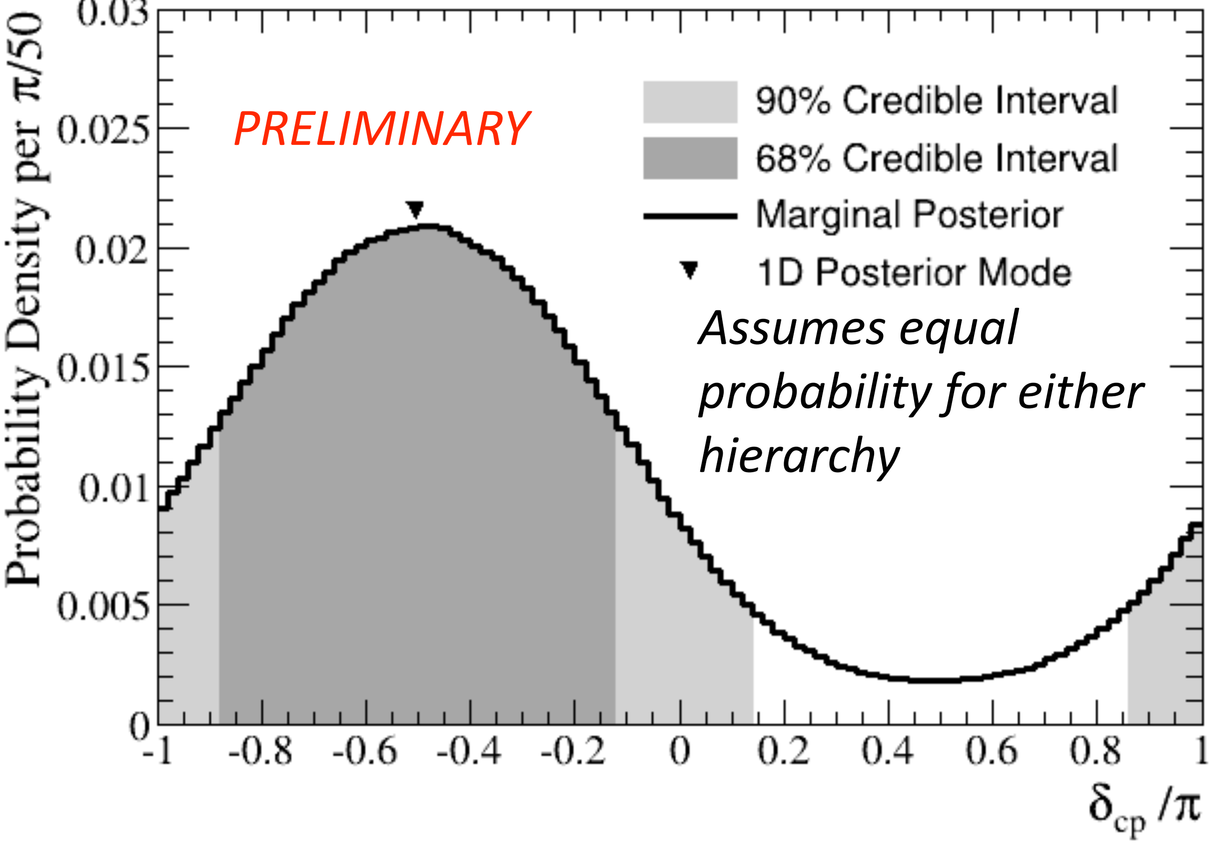
T2K data favors maximal disappearance

- Provides best constraint on θ_{23} to date
- Consistent with maximal (45°) mixing
- Caveat: Baysian analysis, credible regions are shown with confidence intervals from other experiments
- T2K CL are similar to CI regions



preprint forthcoming

T2K joint ν_μ-ν_e fit results: δ_{CP}, mass hierarchy



Assumes equal probability for either hierarchy

90% credible interval, removes dependence of all other oscillation parameters

- Excludes δ_{CP} values (~π/2)

Comparison of probabilities for each combination of θ_{23} octant, mass hierarchy:

Probability	$\Delta m^2_{32}>0$	$\Delta m^2_{32}<0$	Sum
$\sin^2\theta_{23} \leq 0.5$	18%	8%	26%
$\sin^2\theta_{23} > 0.5$	50%	24%	74%
Sum	68%	32%	

The MINOS (and MINOS+) experiments

FNAL to Soudan, MN (735km)

On-axis beam, two main configurations:

E_ν(peak) ≈3 GeV

Also can detect atmospheric neutrinos

MINOS physics run:

Operated from: 2003-2011

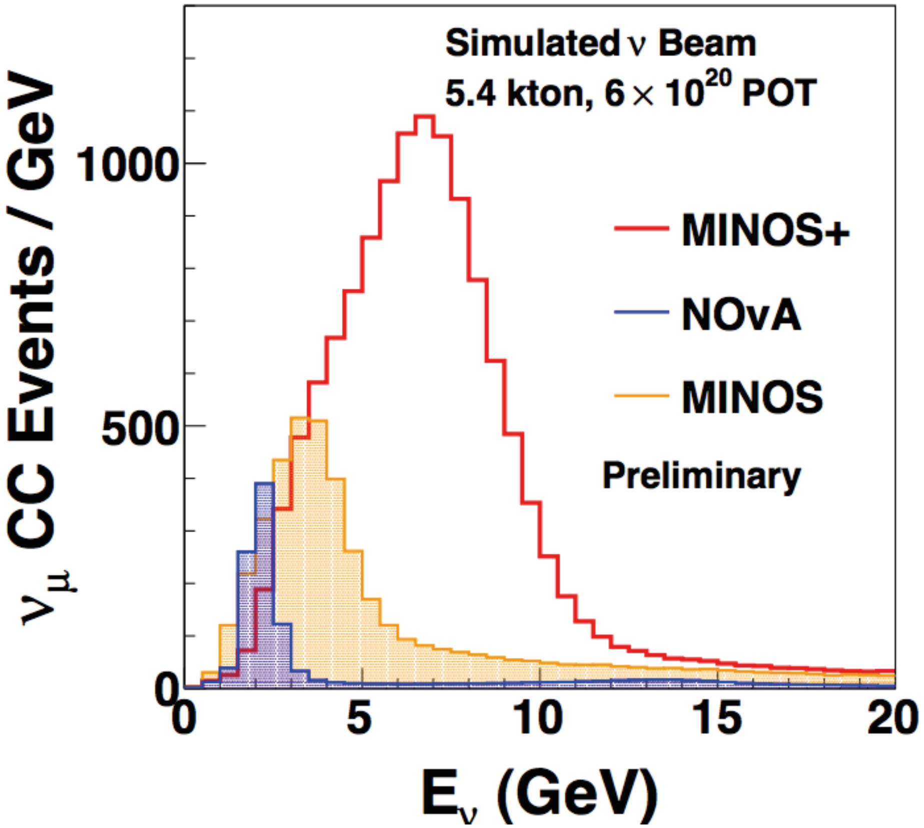
Neutrinos: 10.71×10^{20} POT

Antineutrinos: 3.36×10^{20} PO

Measurements of:

ν_μ, anti-ν_μ disappearance

ν_e, anti-ν_e appearance

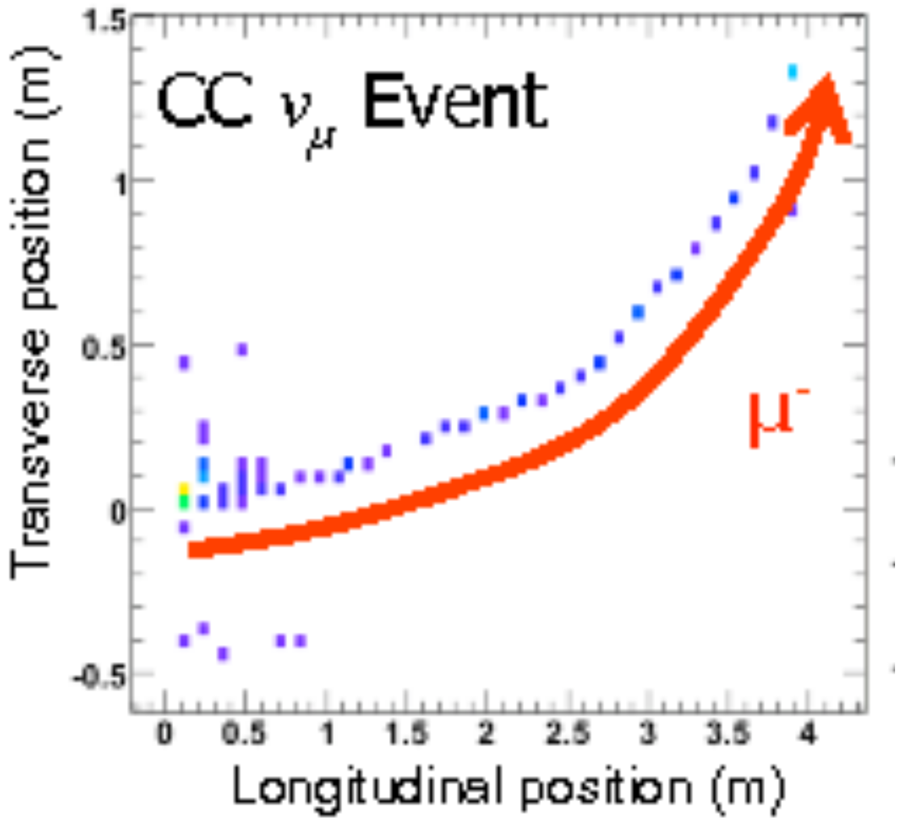


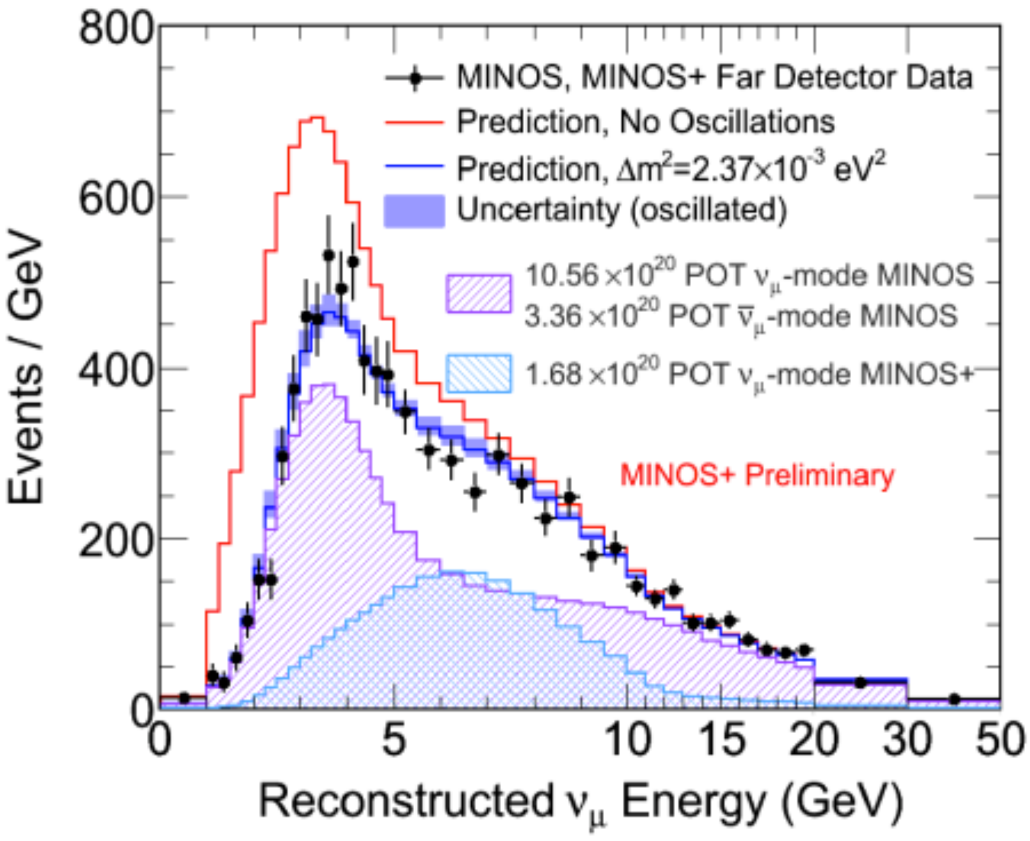
MINOS plots from A. Sousa, Neutrino2014

Event selection at MINOS

Near and far detectors are magnetized steel-scintillator tracking detectors

- Momentum of the muon is determined by curvature, sign indicates ν or anti-ν
- Multivariate analysis techniques used to select CC ν_μ, CC ν_e candidates





- Reconstructed neutrino energy is determined from muon and/or hadronic shower information
- CC ν_e selection has substantial backgrounds due to NC interactions

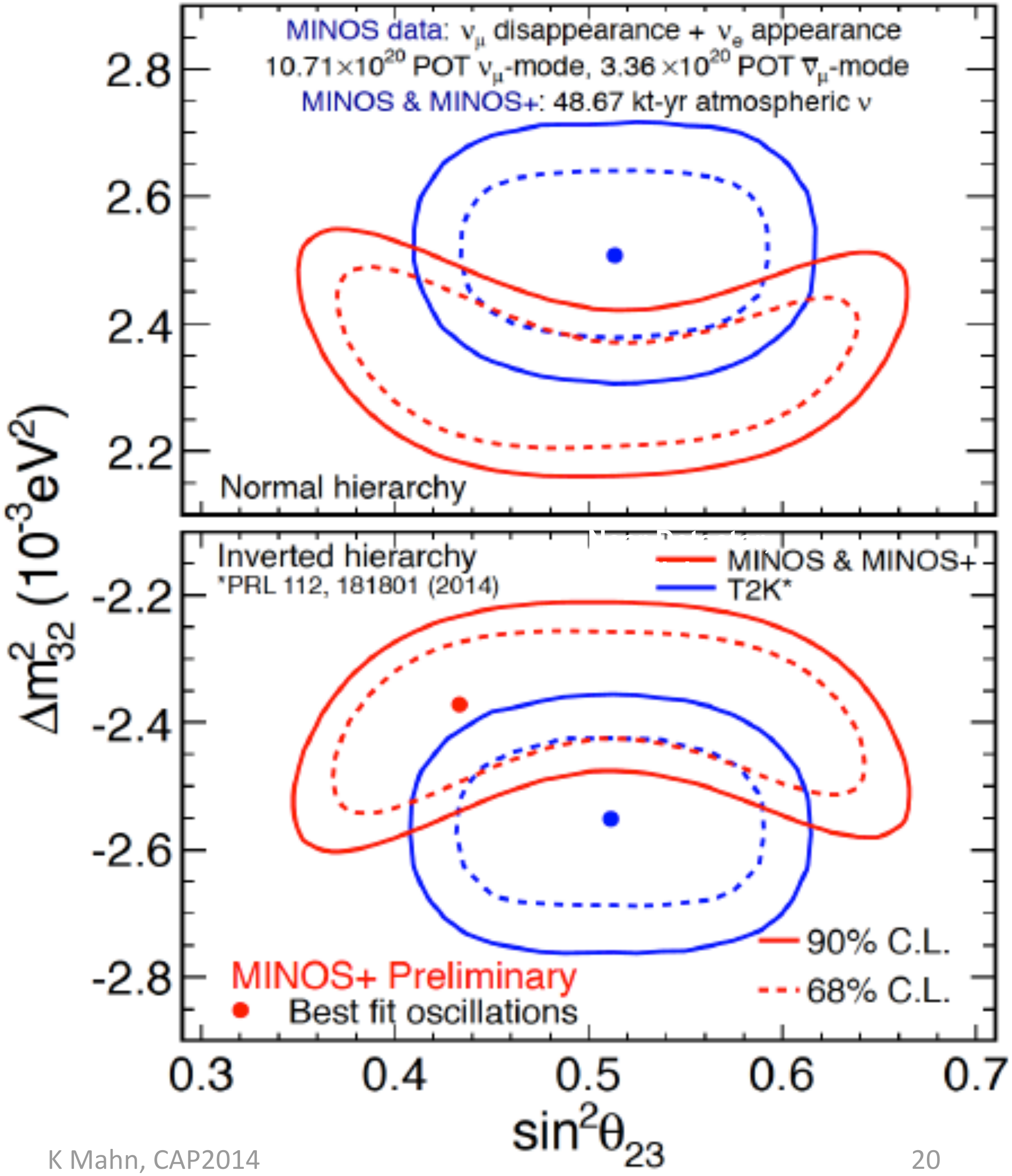
MINOS results: Δm^2_{32}, $\sin^2\theta_{23}$

Fit includes:

- MINOS neutrino, antineutrino beam data sets
- Also includes atmospheric neutrino data set

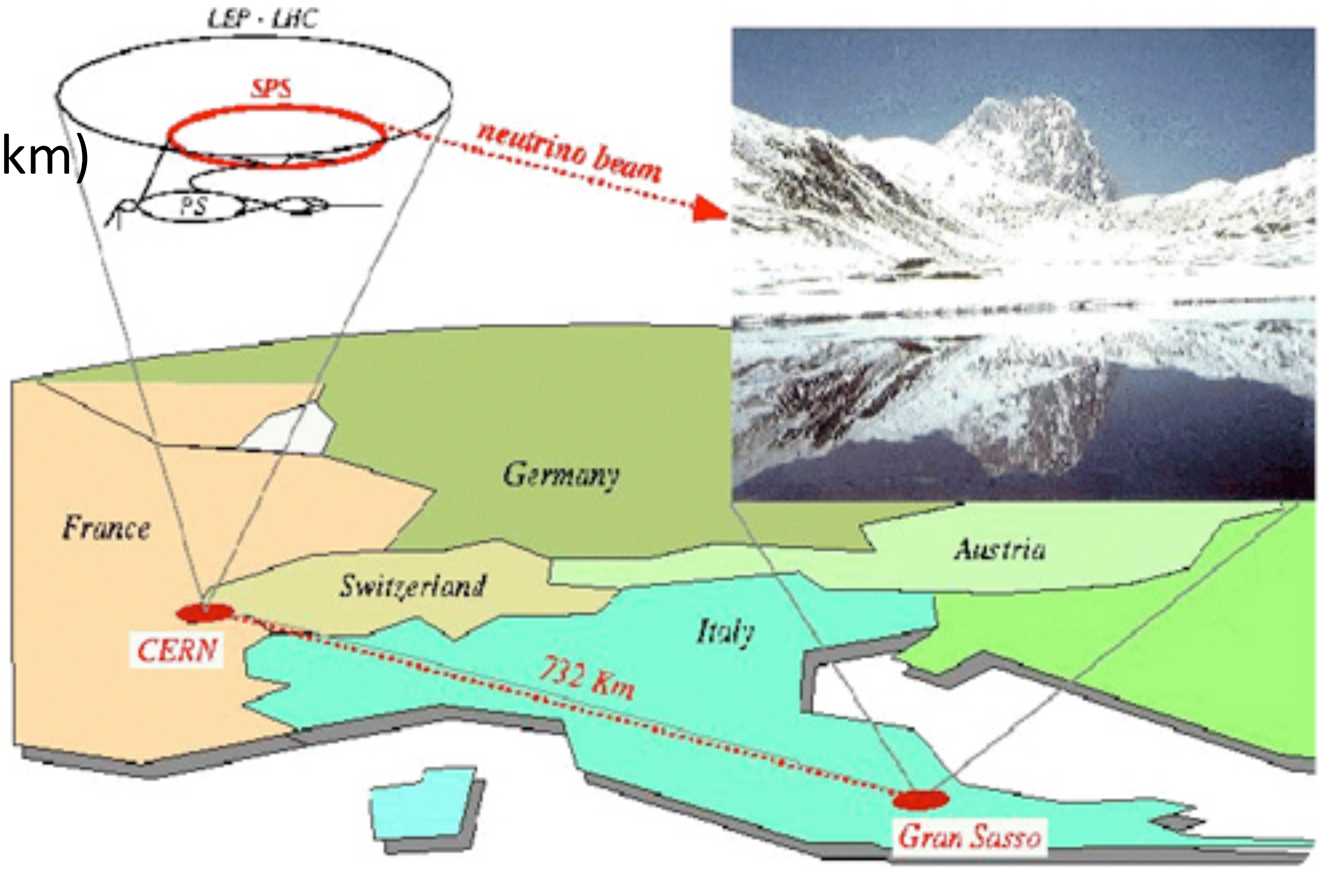
MINOS provides the best constraint on $|\Delta m^2_{32}|$

- Consistent with T2K



The OPERA experiment

On-axis beam (E$_{\nu}$≈17 GeV)
CERN to Gran Sasso, Italy (730km)

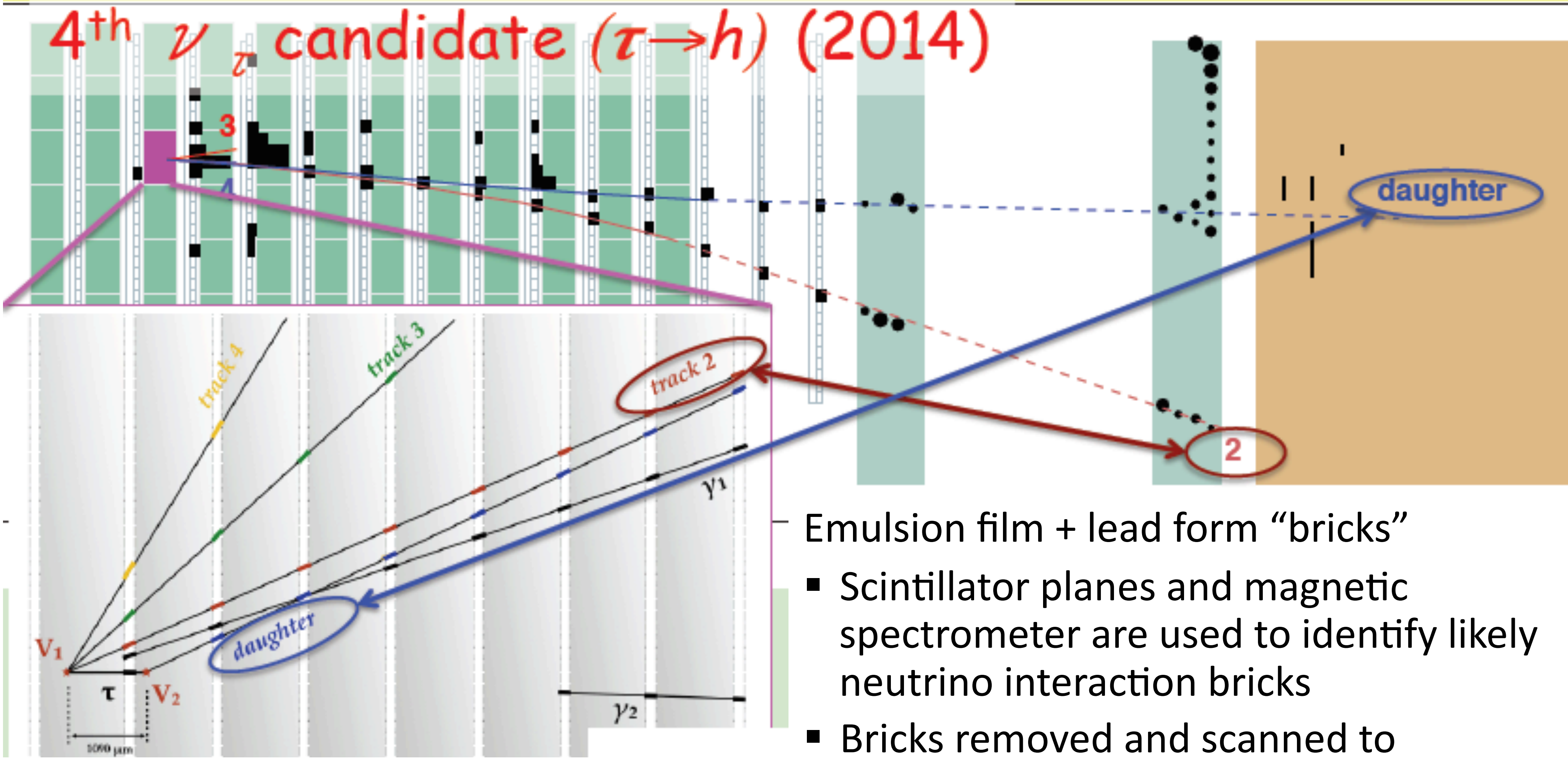


<u>OPERA physics run:</u>
Operated from 2008-2012
Neutrinos: 1.8x10^{20} POT

<u>Measurements of</u>:
ν_τ appearance

OPERA plots from
S. Dusini, Neutrino2014

OPERA ν_τ appearance results



Emulsion film + lead form “bricks”

- Scintillator planes and magnetic spectrometer are used to identify likely neutrino interaction bricks
- Bricks removed and scanned to determine τ decay candidate interactions

ν_τ appearance expected signal 2.10±0.4, background 0.23±0.04

Observed 4 candidate events (no oscillation excluded at 4.2σ)

Near term experiments: NOvA

FNAL to Ash River, MN (810km)

Off-axis (0.8°deg) beam (E$_\nu \approx$2 GeV)

<u>NOvA physics run:</u>

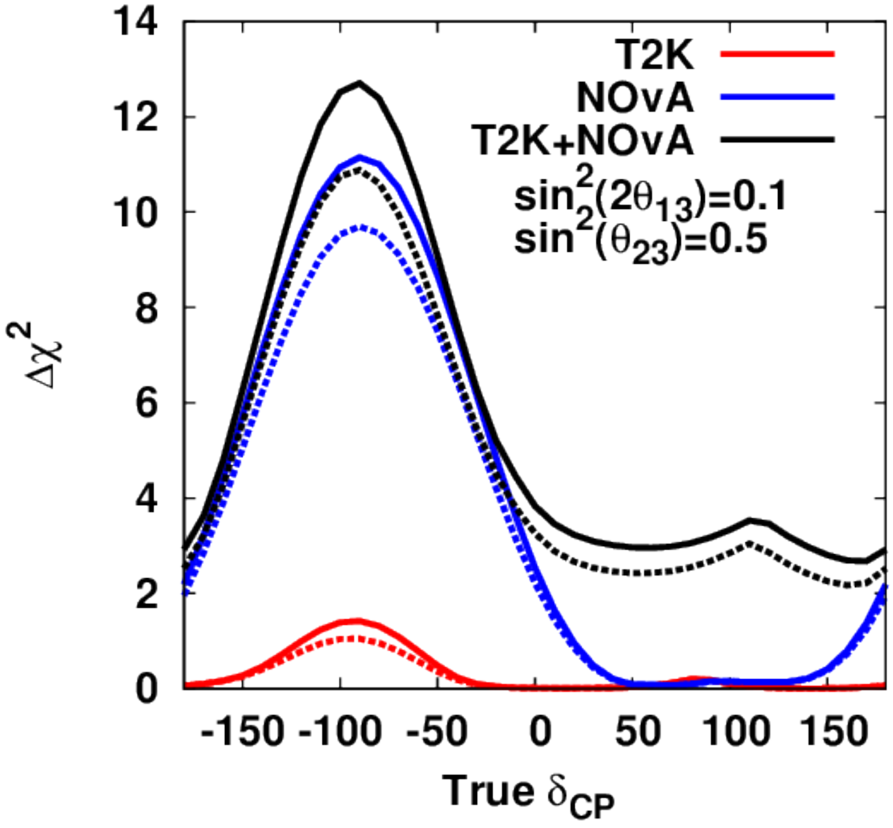
Neutrinos since Feb 2014

<u>Planned measurements of:</u>

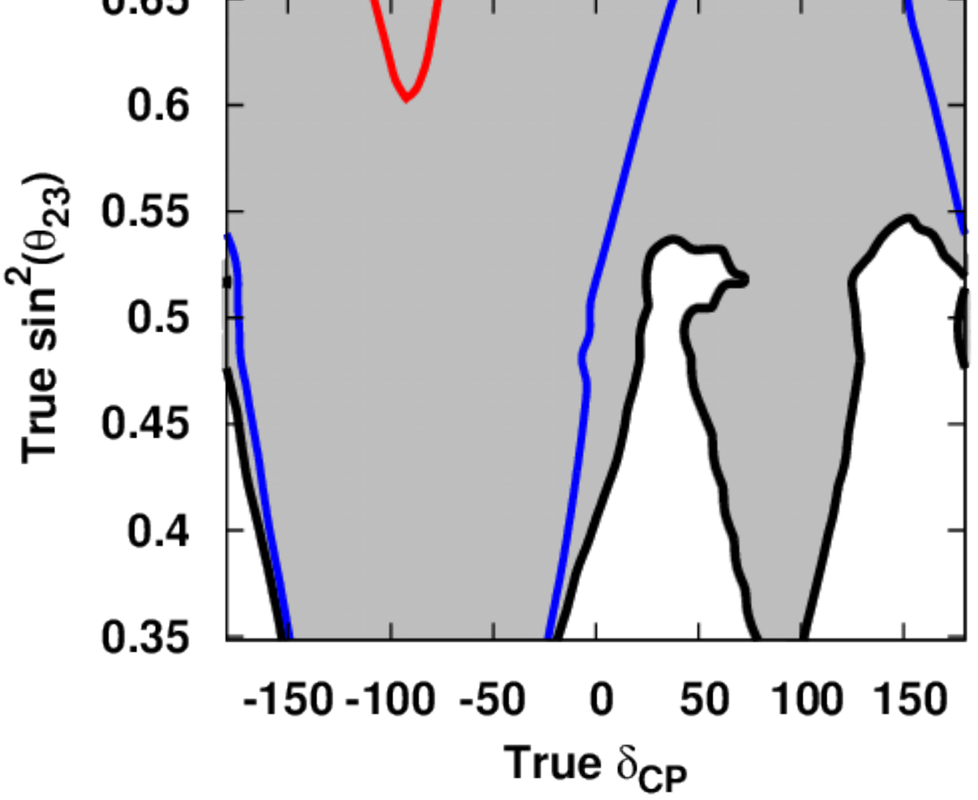
ν_μ, anti-ν_μ disappearance

$\nu_{e,}$ anti-ν_e appearance

Complementarity of T2K, NoVA



Gray regions are where the mass hierarchy can be determined to 90% CL



Matter effects alter the appearance oscillation probability, depending on the sign of Δm^2_{32}, the mass hierarchy

- NOvA's higher energy and longer baseline relative to T2K give NOvA more sensitivity to the mass hierarchy through matter effects
- Combinations of the two measurements exploit the different dependency of δ_{CP} and the mass hierarchy in the oscillation probability

Future long baseline experiments

To measure CP violation, future experiments propose to compare ν_e appearance to anti-ν_e appearance to determine an asymmetry:

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

With θ_{13} “large”, then A_{CP} is small (~20-30%), so a measurement of δ_{CP} will need systematic uncertainties of <5% or better

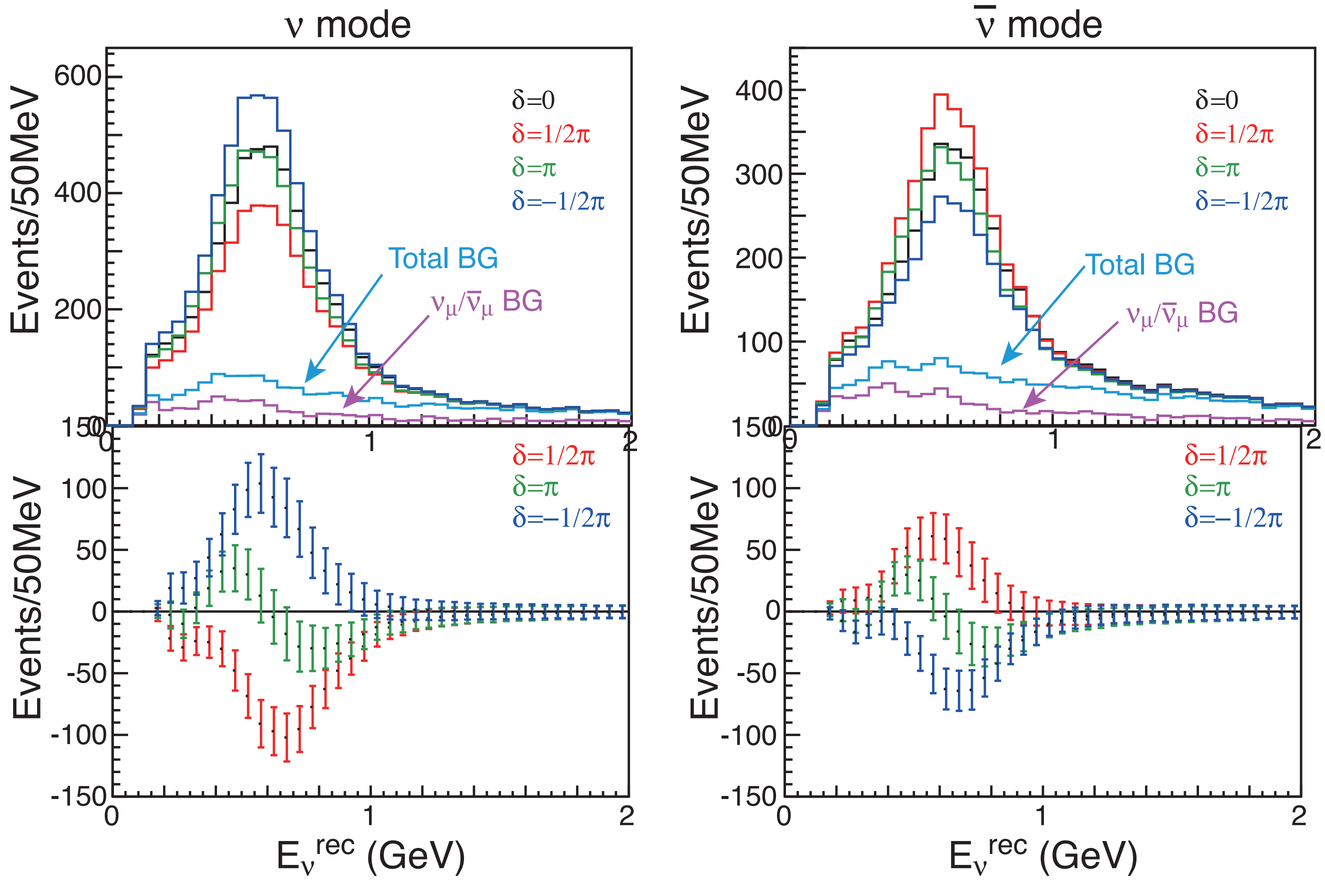
- T2K’s current statistics: 28 events (ν_e appearance probability)
- Need more raw event rate, with a larger detector and/or intense beam

Future narrow band beam experiments

T2HK: same neutrino beamline and off-axis angle as T2K

Would use a new detector (Hyper-Kamiokande) in a different cavern

- Event rate enhanced over T2K’s with a much larger ~1Mton far detector (approximately 25x T2K’s current far detector)
- Technique requires mass hierarchy is known, assuming determined from cosmology, $0\nu\beta\beta$, atmospheric neutrinos, or T2K-NOvA combination

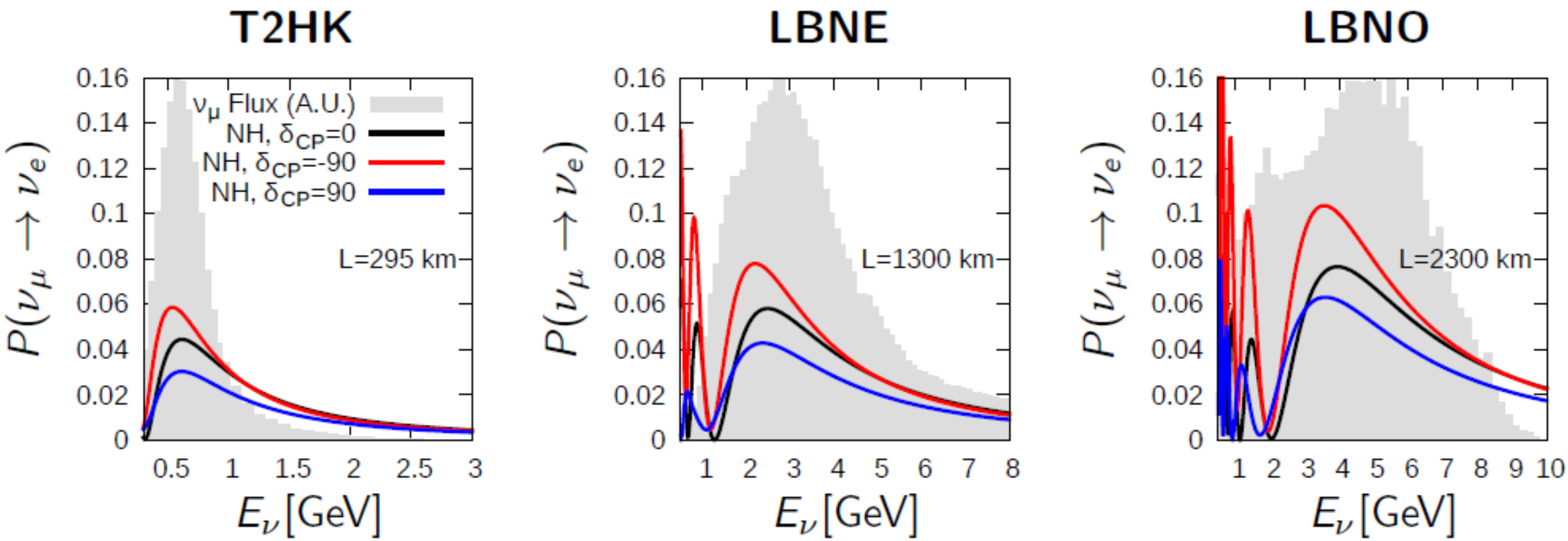


Hyper-Kamiokande LOI: arXiv:1109.3262

Future wide band beam experiments

Wide band (on-axis) beams can be used to directly test energy dependence of oscillation and determine the mass hierarchy and δ_{CP} simultaneously

- LBNE: 1300km distance (FNAL to South Dakota),
- LBNO/LAGUNA: 2300km distance (CERN to Finland)
- Both are considering LAr-based far detector technology of ~20-50kton size



M. Bass, NuInt2014

Conclusion

Neutrino oscillation physics is entering the precision era with accelerator driven long-baseline neutrino experiments:

From T2K:

- Discovery of CC ν_e appearance
- World's best measurement of θ_{23}

From MINOS:

- World's best measurement of Δm^2_{32}

From OPERA

- Discovery of CC ν_τ appearance

The next few years test our assumptions about three-flavor oscillation with:

- Improved measurements of ν_μ and anti-ν_μ mixing (T2K, NOνA)
- Searches for CC anti-ν_e appearance (T2K, NOνA)
- Combinations of different long baseline experiments, and atmospheric neutrino measurements may provide hints of the mass hierarchy

Future long baseline experiments (T2HK, LBNE, LBNO) propose to search for CP violation with enormous detectors and powerful beams

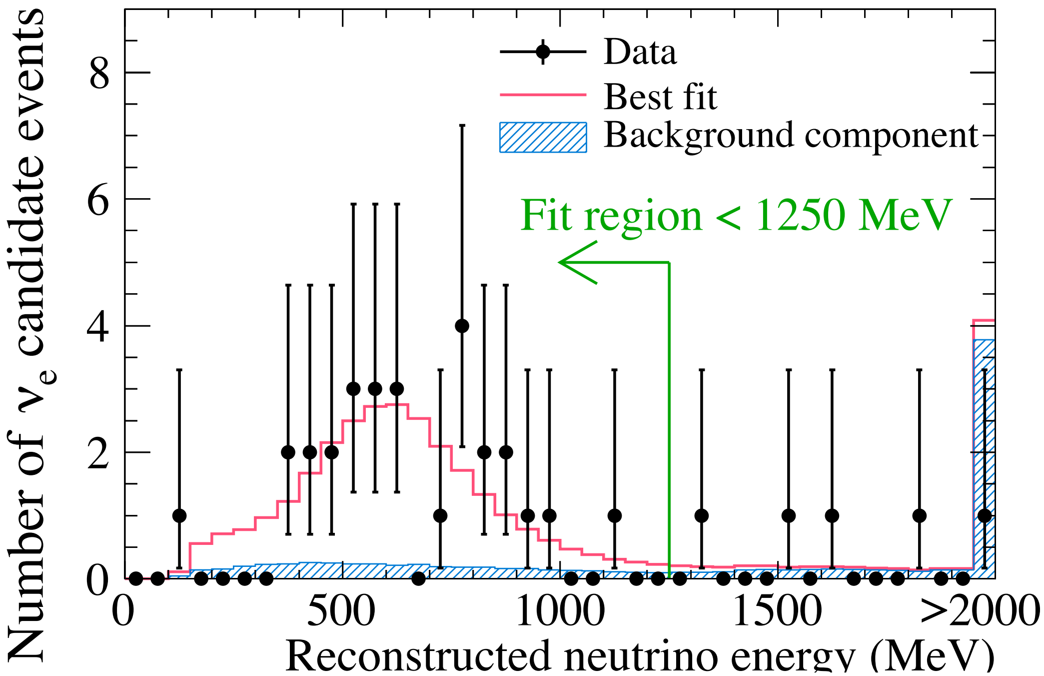
Backup slides

Possible slides

Backup: flux errors and how they affect the spectrum

Complementary results of MINOS+?

T2K observed event distributions



28 candidate ν_e events observed

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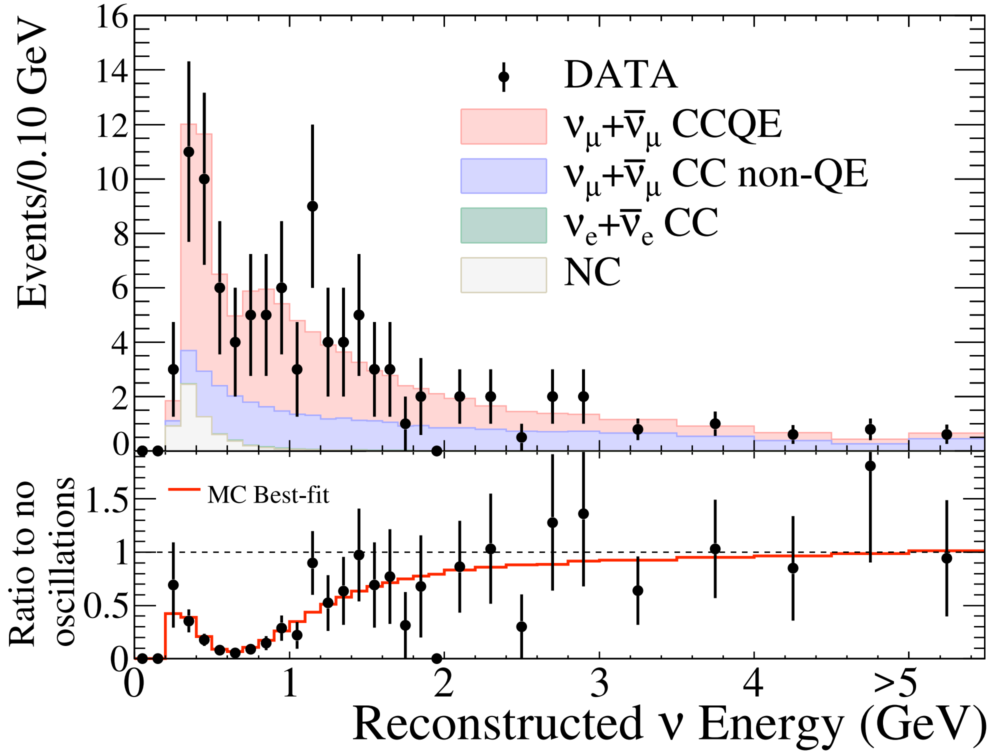
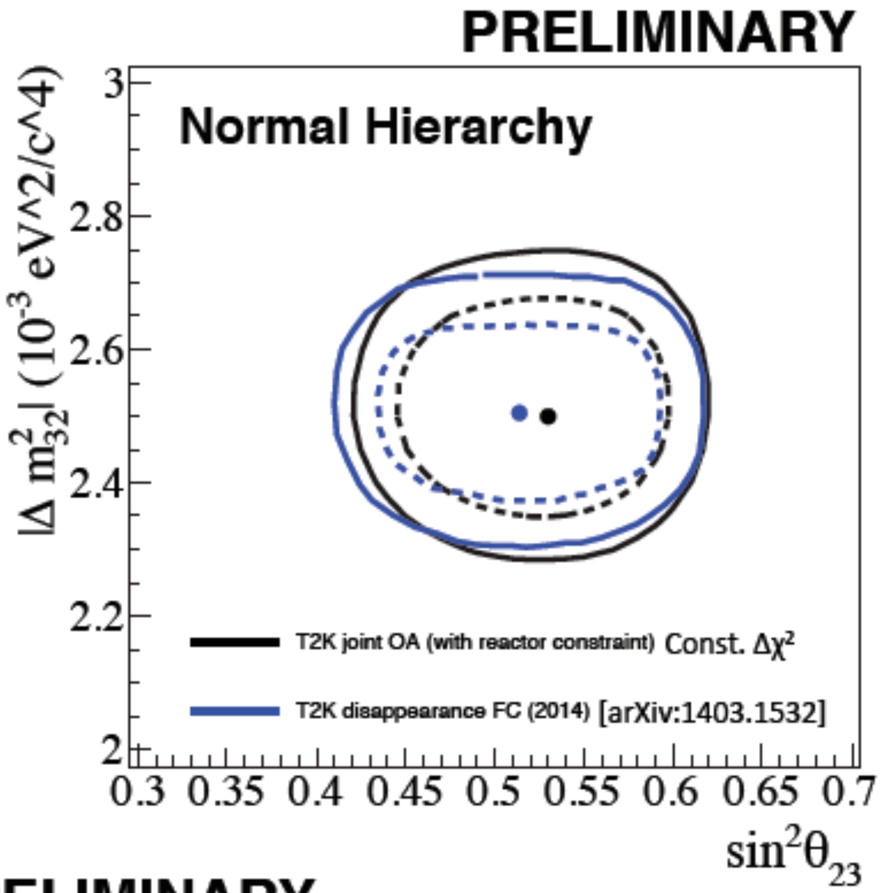
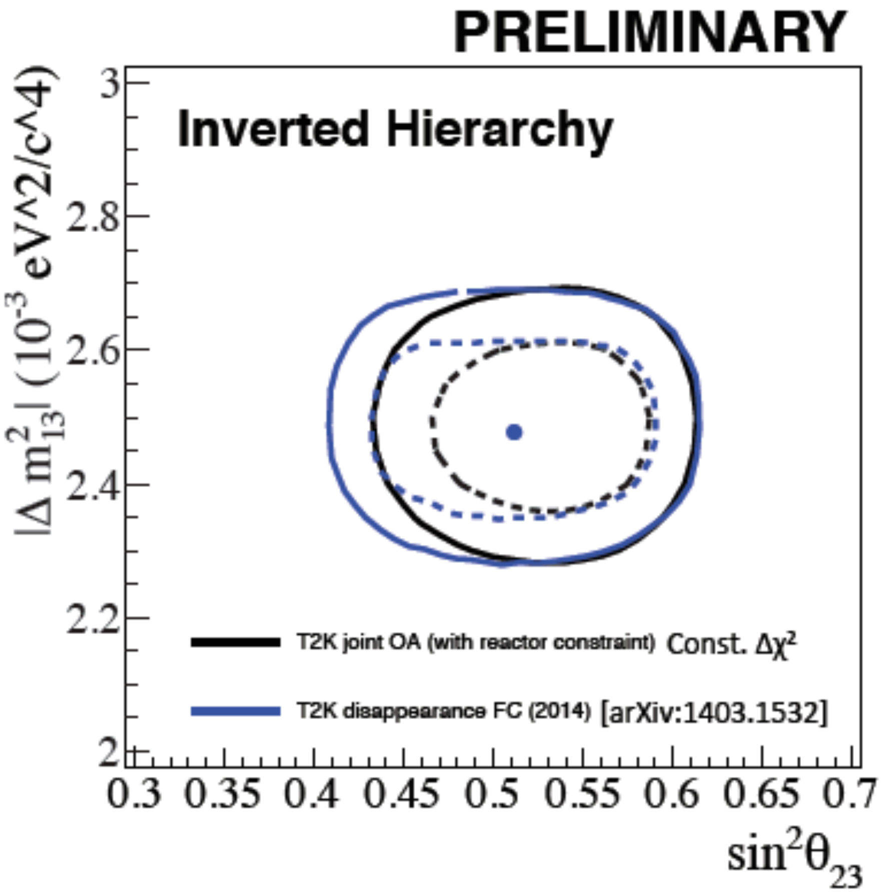


120 candidate ν_μ events observed

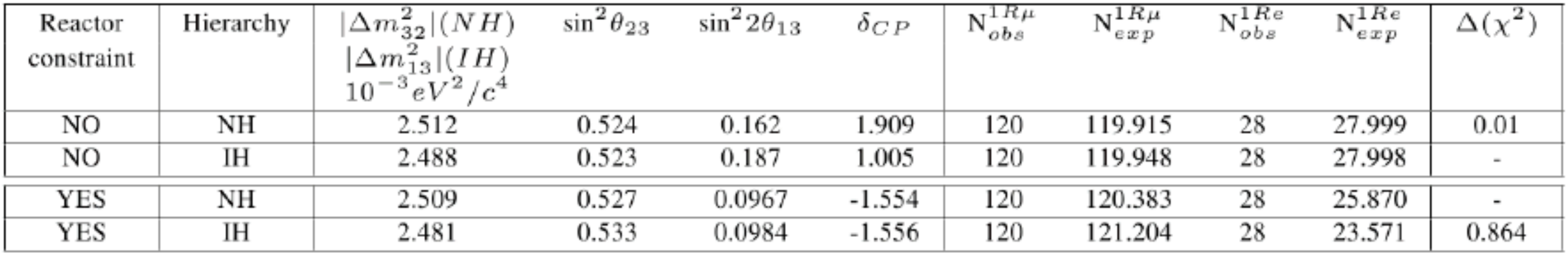
- Determine Δm^2_{32}, $\sin^2\theta_{23}$ from distortion to neutrino energy spectrum
- Phys. Rev. Lett. 112, 181801, 2014

Comparison of joint and standalone disap analyses





PRELIMINARY



Reactor constraint	Hierarchy	$\lvert\Delta m^2_{32}\rvert(NH)$ $\lvert\Delta m^2_{13}\rvert(IH)$ $10^{-3}eV^2/c^4$	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	δ_{CP}	$N^{1R\mu}_{obs}$	$N^{1R\mu}_{exp}$	N^{1Re}_{obs}	N^{1Re}_{exp}	$\Delta(\chi^2)$
NO	NH	2.512	0.524	0.162	1.909	120	119.915	28	27.999	0.01
NO	IH	2.488	0.523	0.187	1.005	120	119.948	28	27.998	-
YES	NH	2.509	0.527	0.0967	-1.554	120	120.383	28	25.870	-
YES	IH	2.481	0.533	0.0984	-1.556	120	121.204	28	23.571	0.864

MCMC joint analysis results

- Constraints on ν_μ disappearance parameters

T2K-Only Model Probabilities

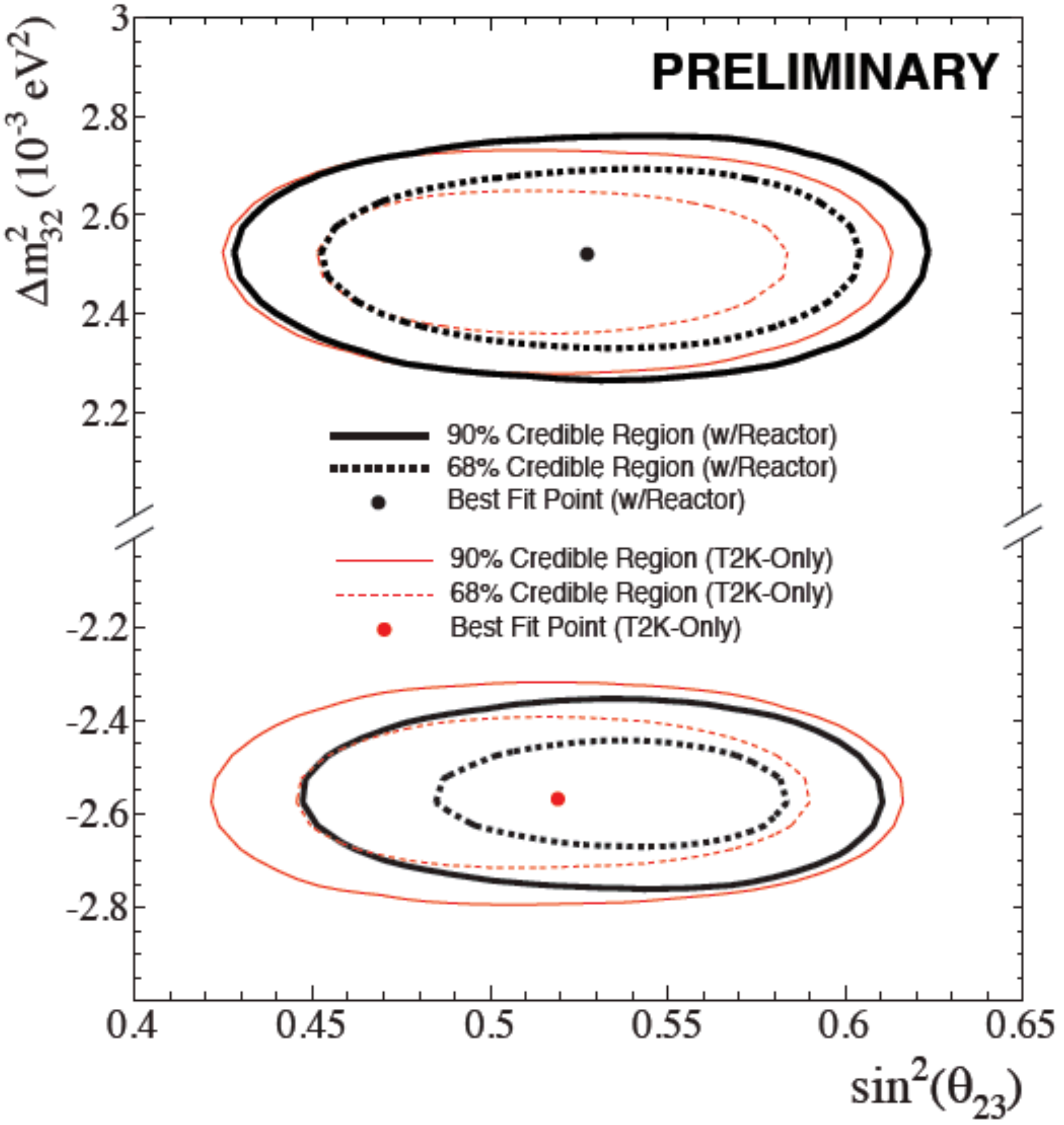
(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	16	20	36
$\sin^2\theta_{23} > 0.5$	29	35	64
Sum	45	55	

PRELIMINARY

With Reactor Constraint

(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26
$\sin^2\theta_{23} > 0.5$	50	24	74
Sum	68	32	

PRELIMINARY



Selecting CC ν_μ interactions

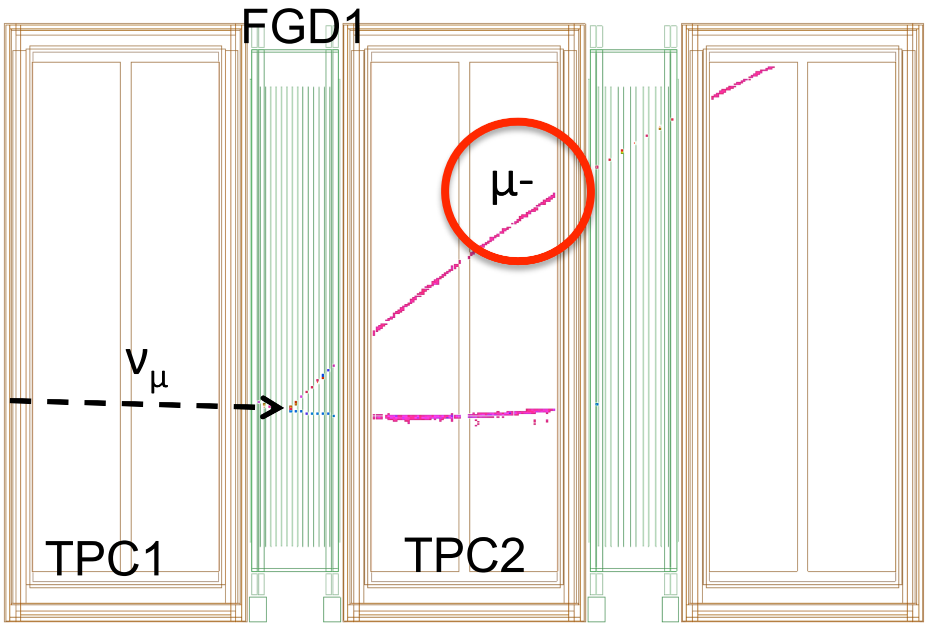
Measure unoscillated ν_μ(CC) rate

1. Neutrino interaction in FGD1

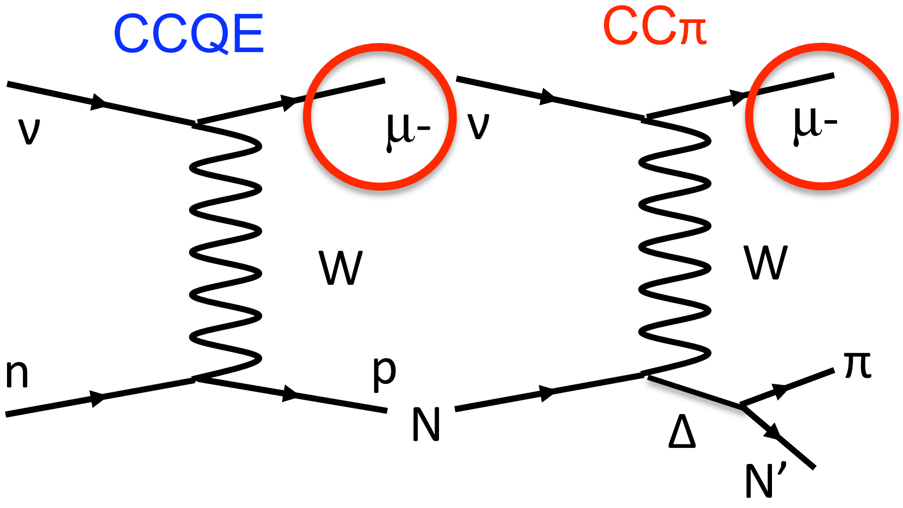
- Veto events with TPC1 tracks
- Events within FGD1 fiducial volume

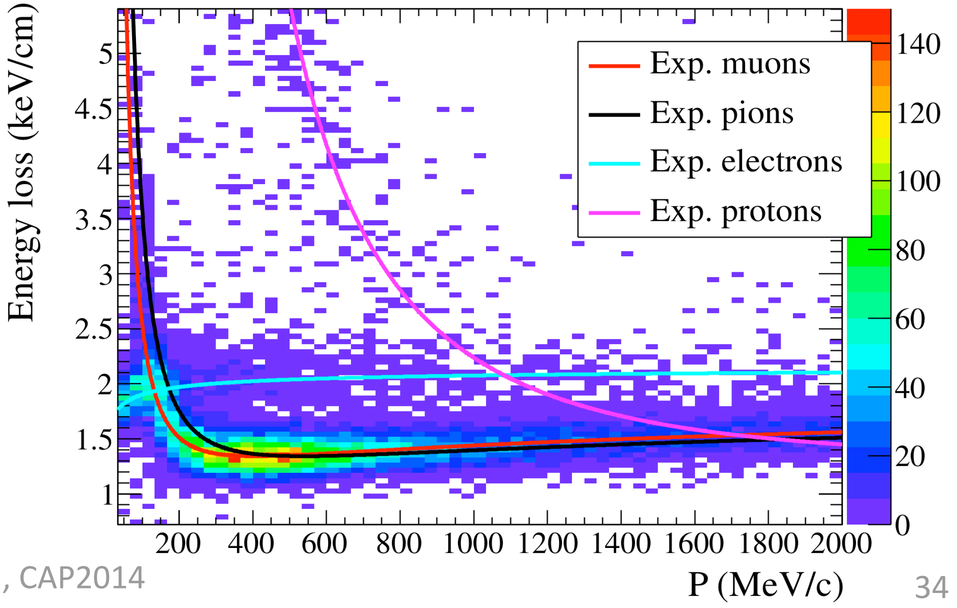
2. Select highest momentum, negative curvature track as μ^- candidate

- Energy loss of the track in TPC also consistent with muon hypothesis



MP: *TPC commissioning, data quality system and alignment*





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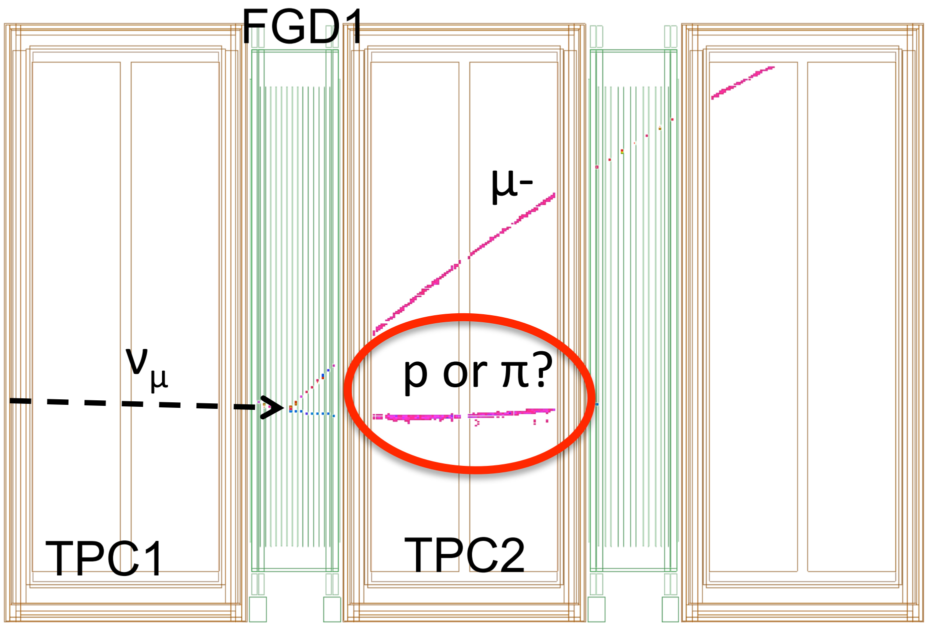
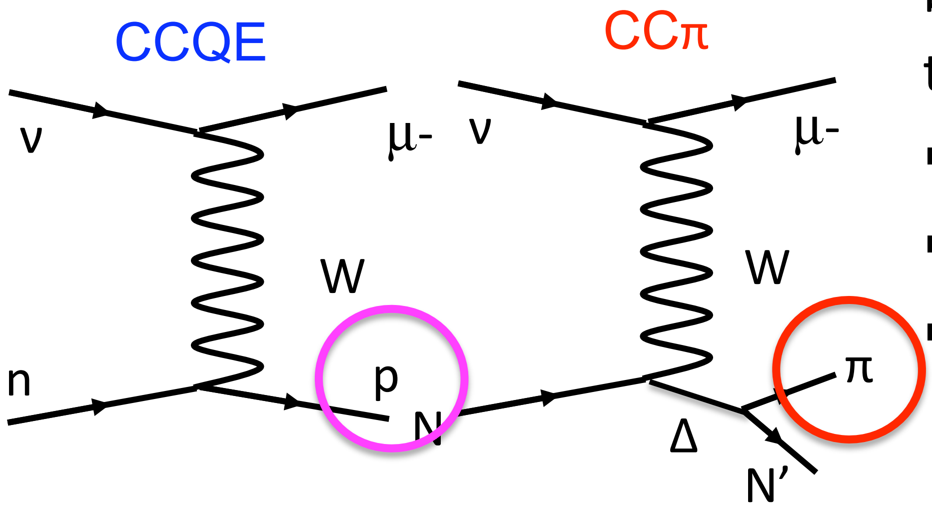


Further separate sample into three categories based on final state: CC0π / CC1π / CC other to increase sensitivity to cross section:

- FGD track: decay electron / π-p dE/dx
- TPC-FGD matched track: π-p dE/dx
- Electrons identify π^0 (often from DIS events)



Results of near detector rate fit

- Shared flux, similar CC cross section composition of near and far detector selections result in substantial reduction to CC cross sections, ν_μ flux uncertainties

Uncertainties	**ν_e sig+bkrd**	**ν_e background**
ν flux+xsec (before) after ND280 constraint	(25.9%) ±2.9%	(21.7%) ±4.8%
ν xsec (unconstrained by ND280)	±7.5%	±6.8%
Far detector	±3.5%	±7.3%
Total	±8.8%	±11.1%

$$N(\nu_e) = \boxed{\Phi(E_\nu)}\,\boxed{\sigma(E_\nu)}\;\epsilon\;P(\nu_\mu \rightarrow \nu_e)$$

$$N(\nu_\mu) = \boxed{\Phi(E_\nu)}\,\boxed{\sigma(E_\nu)}\;\epsilon$$

Expected number of ν_e candidates

After ND280 tuning, expect 21.6 events with expected ν_μ to ν_e oscillation

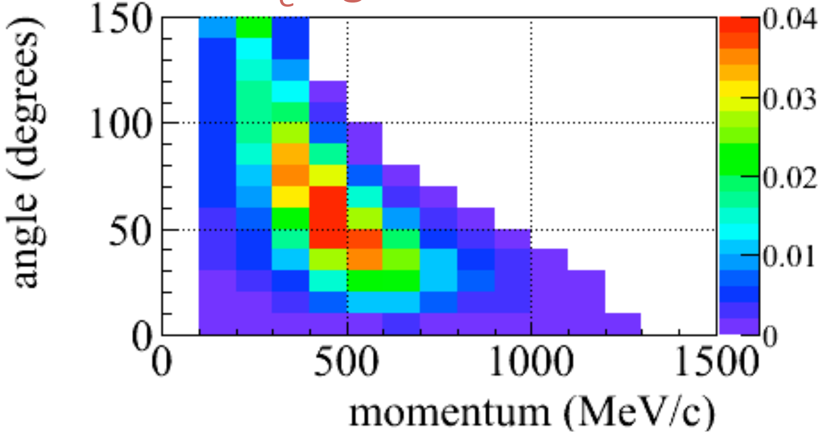
- Rate, p-θ kinematics of events distinguishes signal from background

Signal (ν_μ to ν_e osc)	**# events**
@$\sin^2 2\theta_{13}$=0.1,δcp=0	16.7

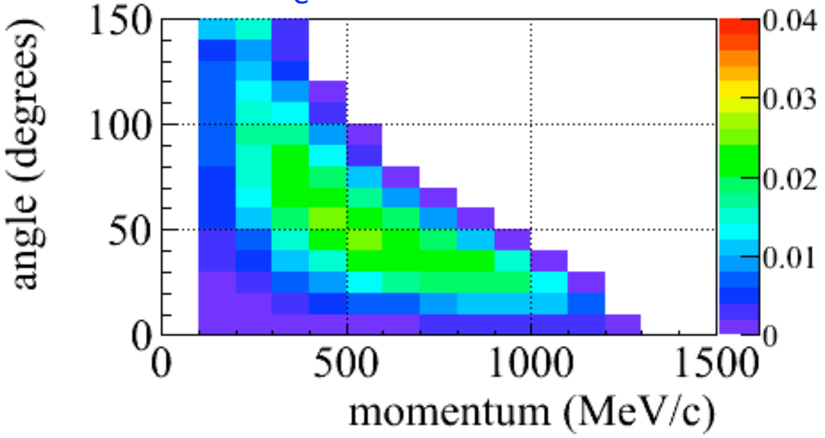
ν_e signal@Δm^2_{32} =2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1.0
Excludes θ_{12} component

Background	**# events**
beam ν_e	3.2
ν_μ (mainly NC) background	1.1
osc through θ_{12}	0.6
total assuming $\sin^2 2\theta_{13}$=0	

CC ν_e signal



CC ν_e background



Complementarity (I)

NBB (NoVA) sensitivity improves with combination of different beam energy and atmospheric neutrino statistics