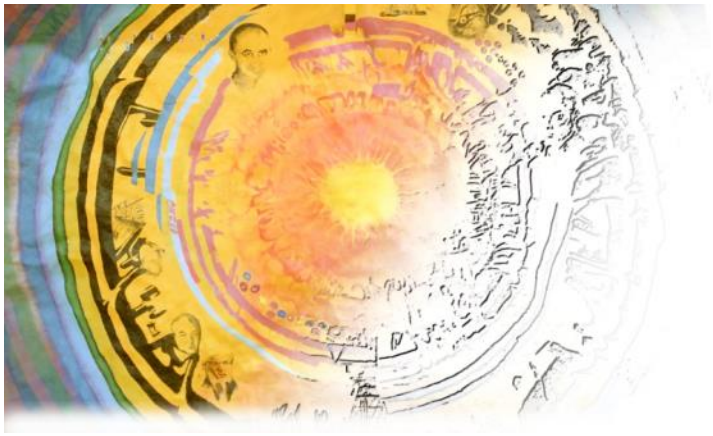
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Oxford Physics

Results from LBL ν-Oscillation Experiments at Accelerators



Alfons Weber
University of Oxford
STFC/RAL

Solvay-Francqui Workshop on Neutrinos
from reactors to the cosmos
Brussels, 27-29 May 2015

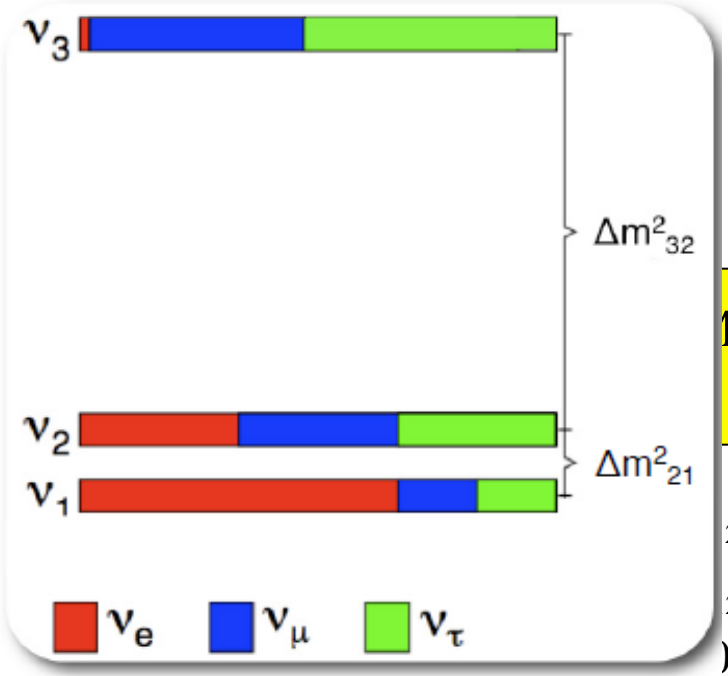
Overview

- Introduction
  - Measurement Principle
- LBL Accelerator Experiments
  - MINOS
  - T2K
  - OPERA
  - NOvA
- Summary & Outlook

Neutrino Mixing
The PMNS Matrix

Pontecorvo-Maki-Nakagawa-Sakata

- Assume that neutrinos do have mass:
  - mass eigenstates ≠ weak interaction eigenstates
  - Analogue [illegible] sector!



weak
"flavour eigenstates"

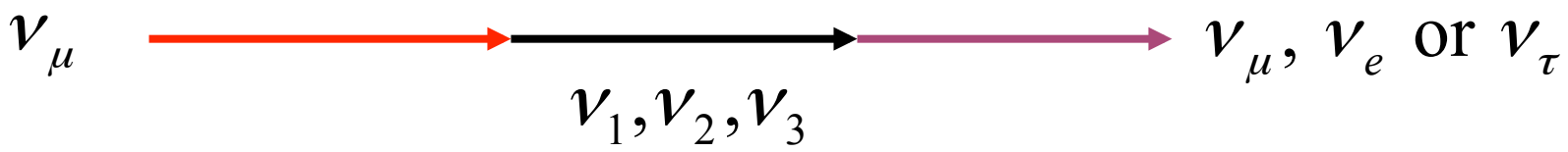
Mass eigenstates
m_1, m_2, m_3

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & & \\ 0 & c & \\ 0 & - & \end{pmatrix} \begin{pmatrix} & & 0 \\ & & 0 \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij}), s_{ij} = \sin(\theta_{ij}), \theta_{ij} =$ mixing angle and $\Delta m^2_{ij} =$ mass^2 difference

Neutrino Oscillations

- If mass and weak eigenstates are different:
  - Neutrino is produced in weak eigenstate
  - It travels a distance L as a mass eigenstate
  - It will be detected in a (possibly) different weak eigenstate



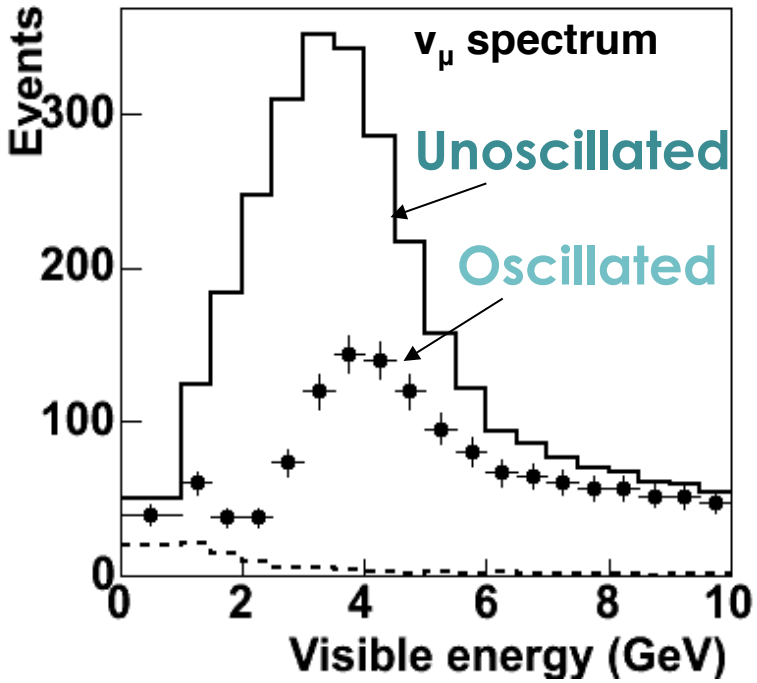
$$\begin{pmatrix} \nu_\mu \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

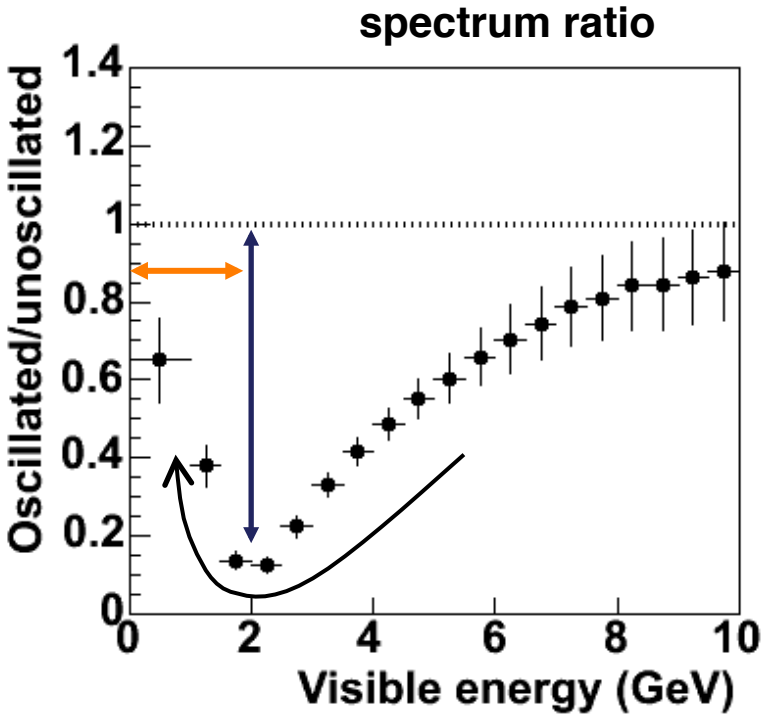
Muon Neutrino Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

Monte Carlo

(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2, 735 km)





Who is Who

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

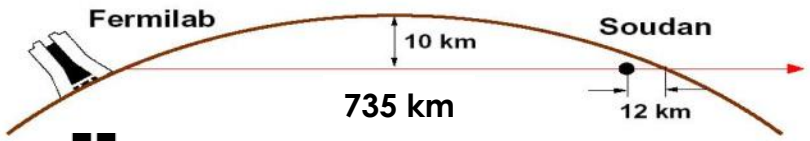
ν_μ disappearance

ν_e disappearance in ν_μ beam

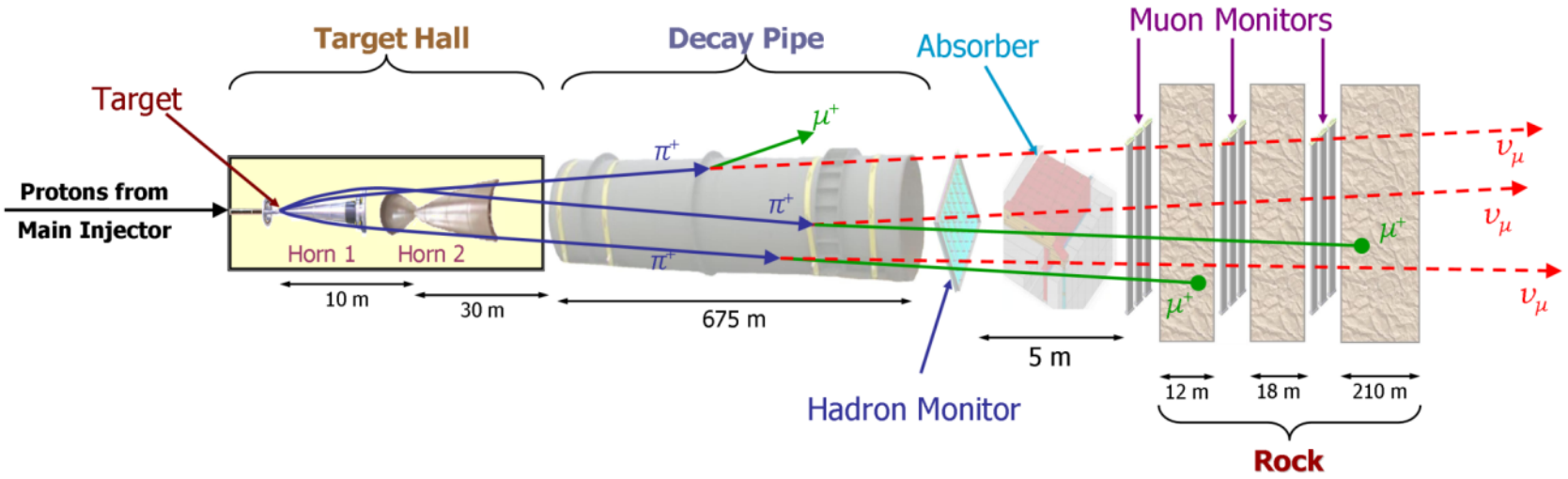
MINOS Experiment

MINOS:
Main Injector Neutrino Oscillation Search

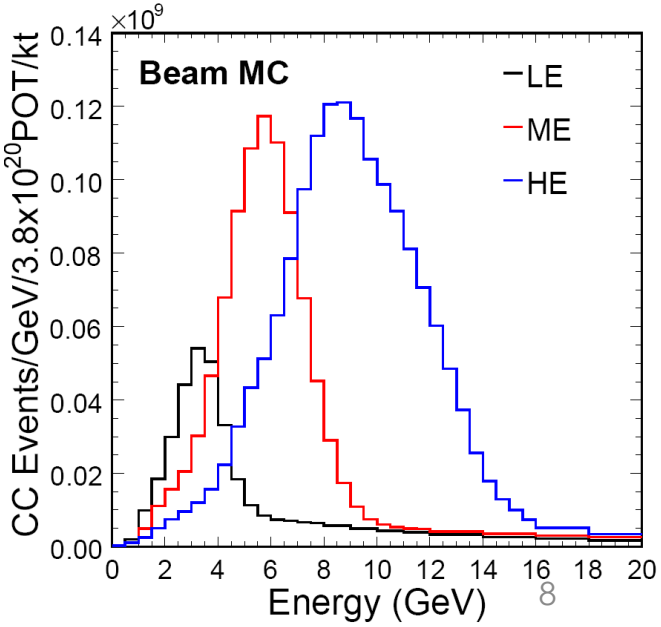
- A long-baseline neutrino oscillation experiment
- Near Detector at Fermilab to measure the beam composition
- Far Detector deep underground in the Soudan Underground Lab, Minnesota, to search for evidence of oscillations



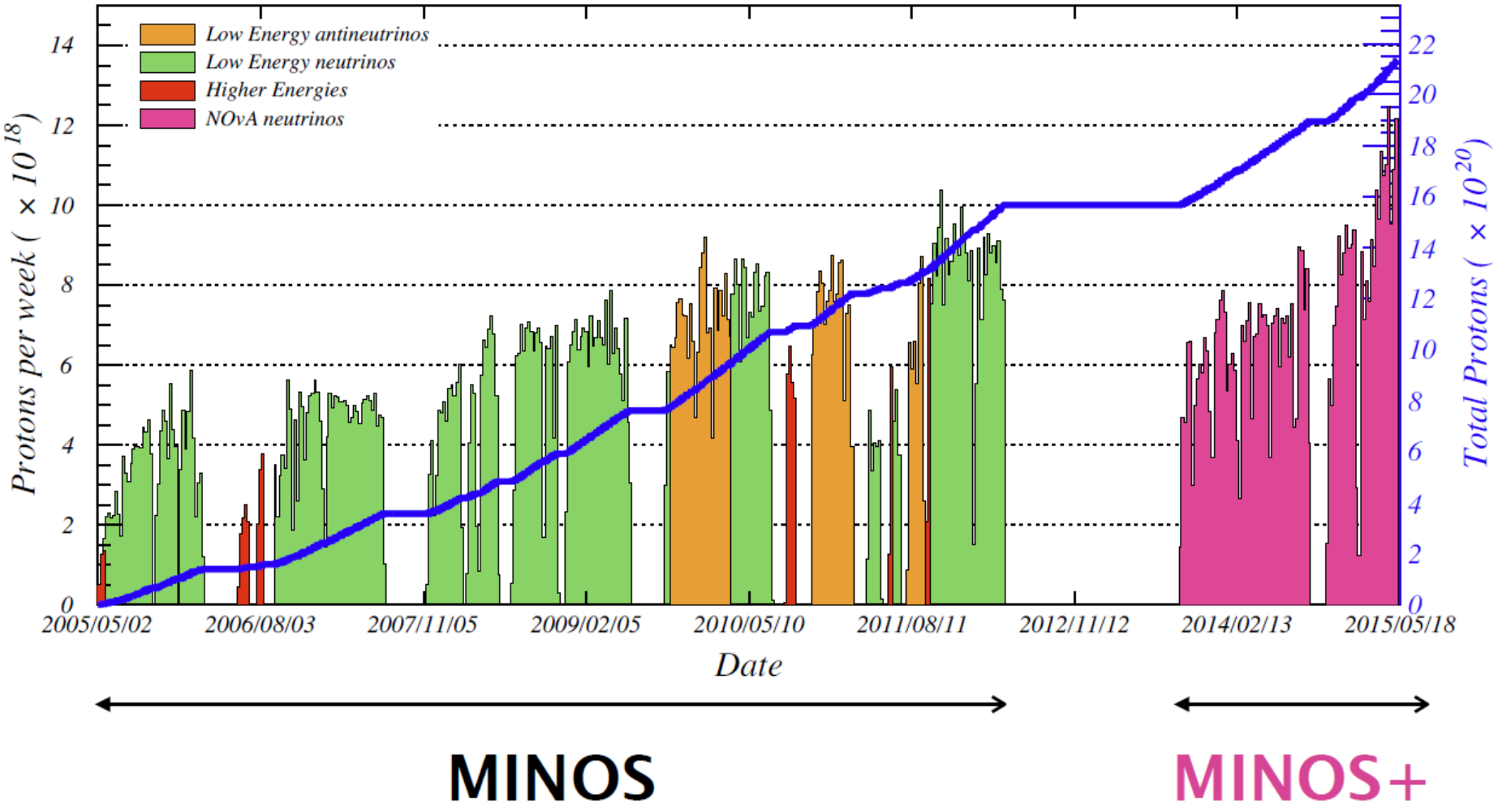
Making Neutrinos



- Neutrinos from the Main Injector (NuMI)
- 10 μs spill of 120 GeV protons every 2.2 s
- 300 kW typical beam power
- 3×10^{13} protons per pulse
- Neutrino spectrum changes with target position

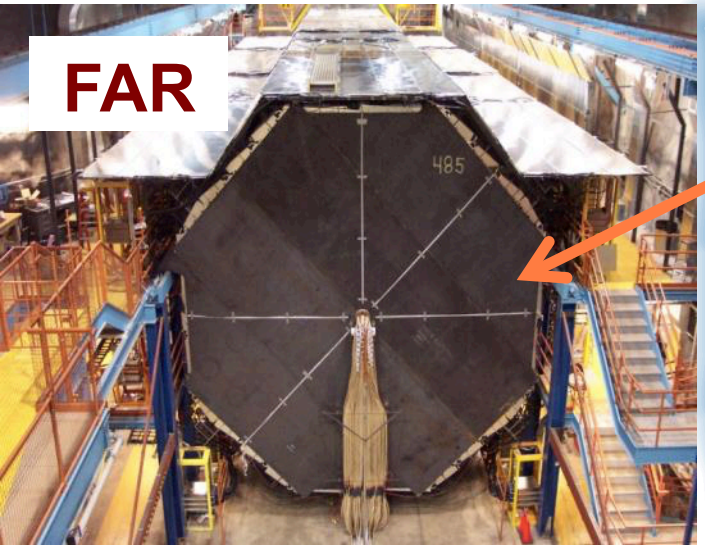


Protons on Target



MINOS Detectors

alternating layers of steel plates and scintillator strips in a ~1.3 T toroidal magnetic field



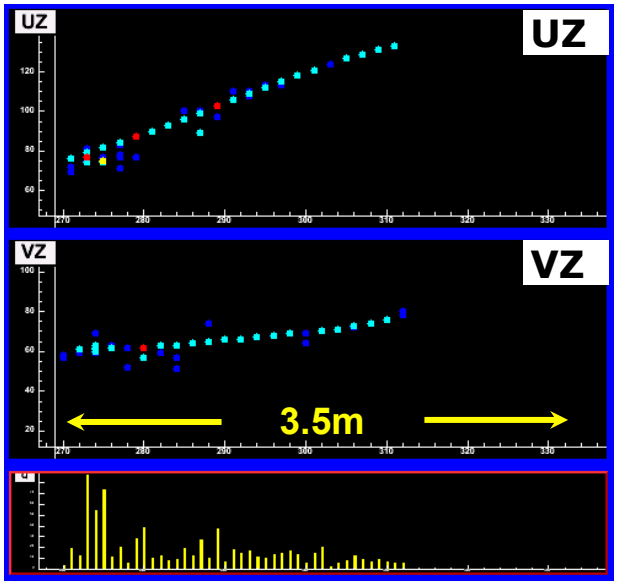
735 km from the target
5.4 kilotons
8 m tall planes
486 planes (30 m)
700 m underground
Few neutrino interactions/day

1 km from the target
1 kiloton
~4 m tall planes
282 planes (15 m)
100 m underground
Few neutrino interactions/spill

Event Topologies

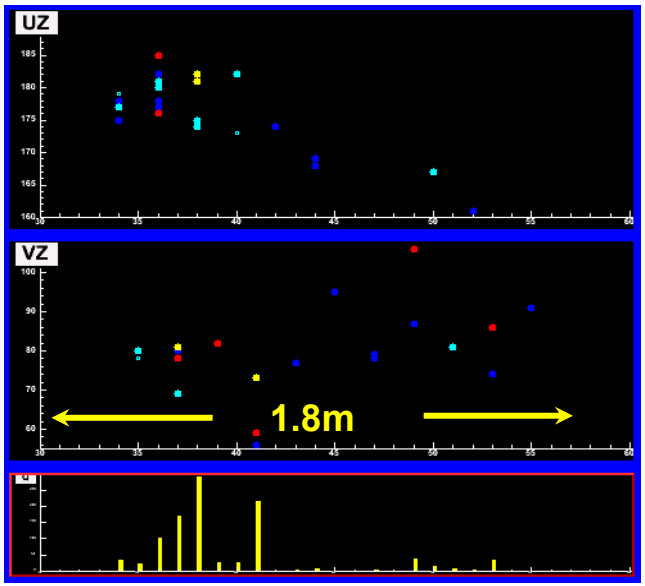
Monte Carlo

ν_μ CC Event



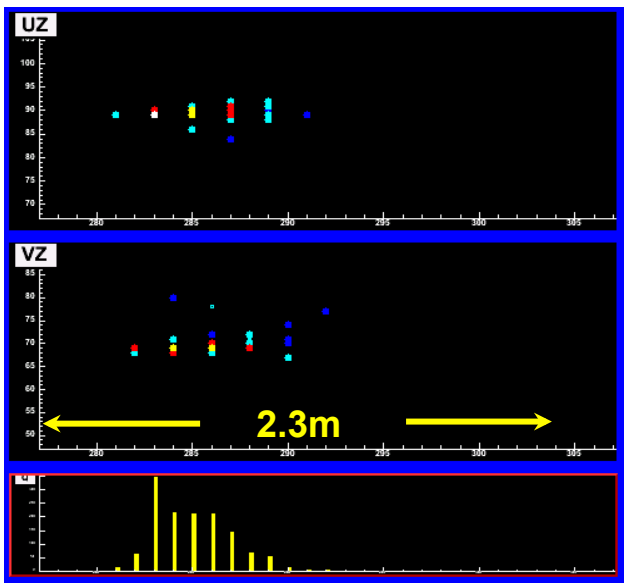
long μ track & hadronic activity at vertex

NC Event



short event, often diffuse

ν_e CC Event



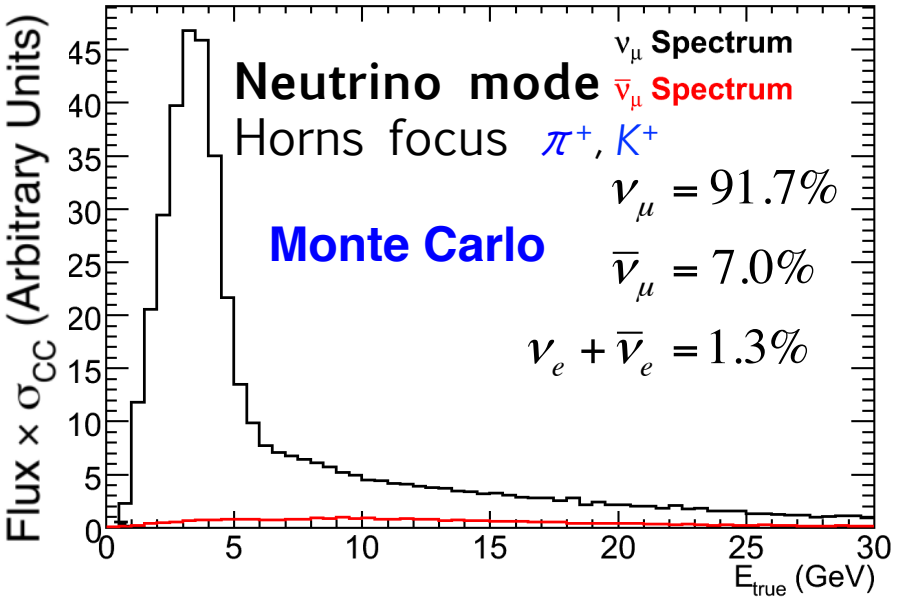
short, with typical EM shower profile

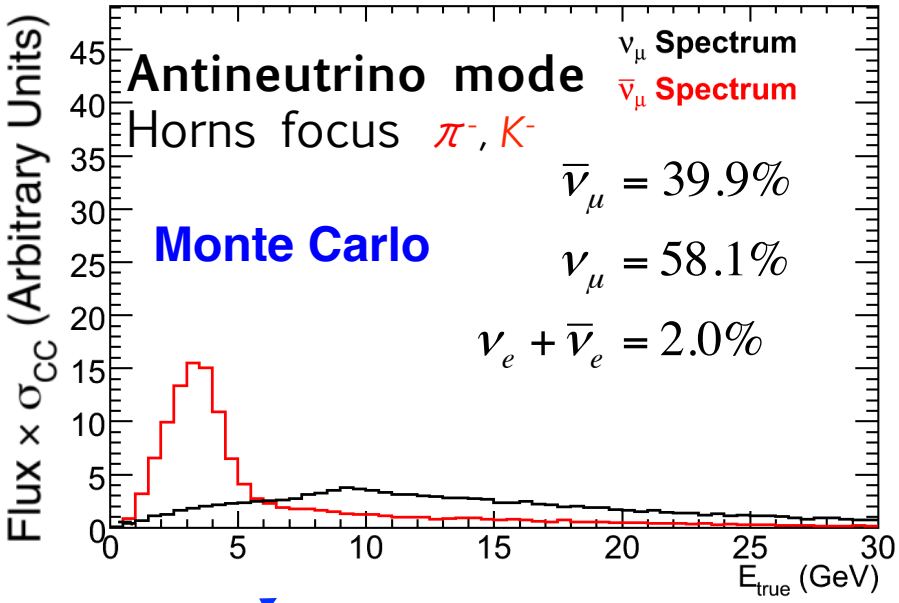
$E_\nu = E_{shower} + p_\mu$

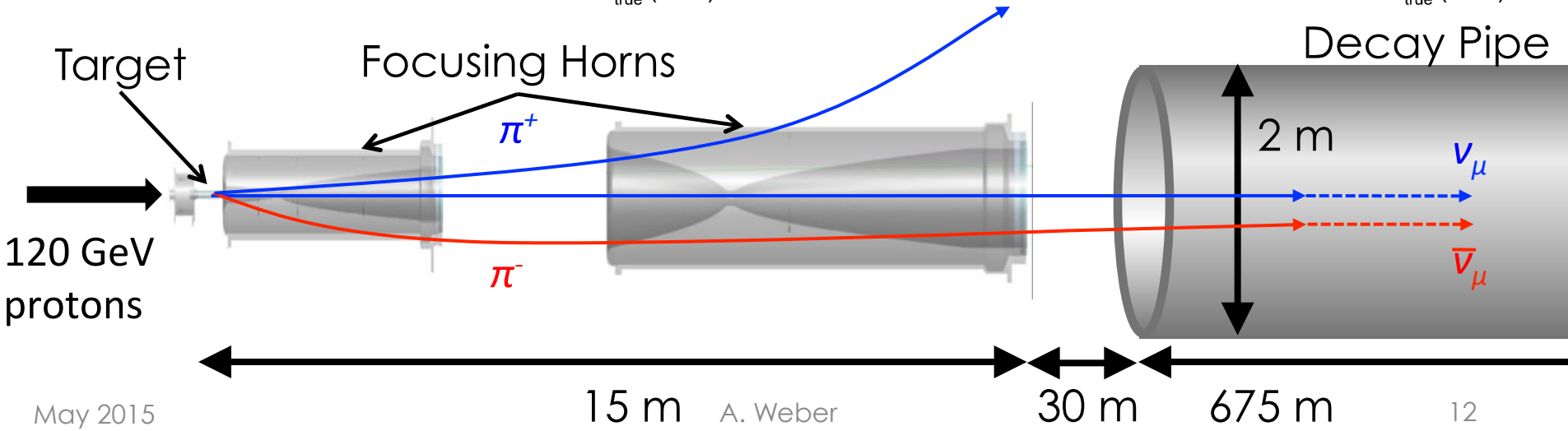
Energy resolution

- $\pi^\pm$: 55%/√E(GeV)
- $\mu^\pm$: 6% range, 10% curvature

(Anti)-Neutrino Mode

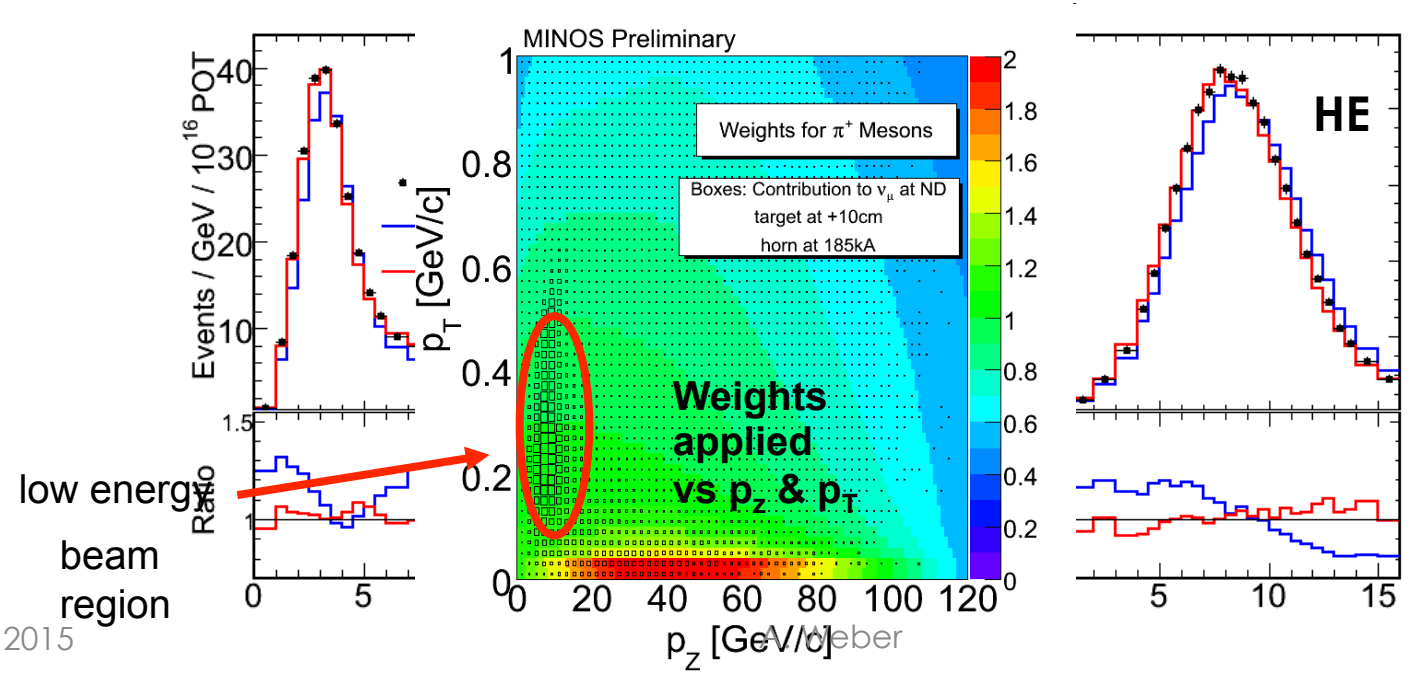




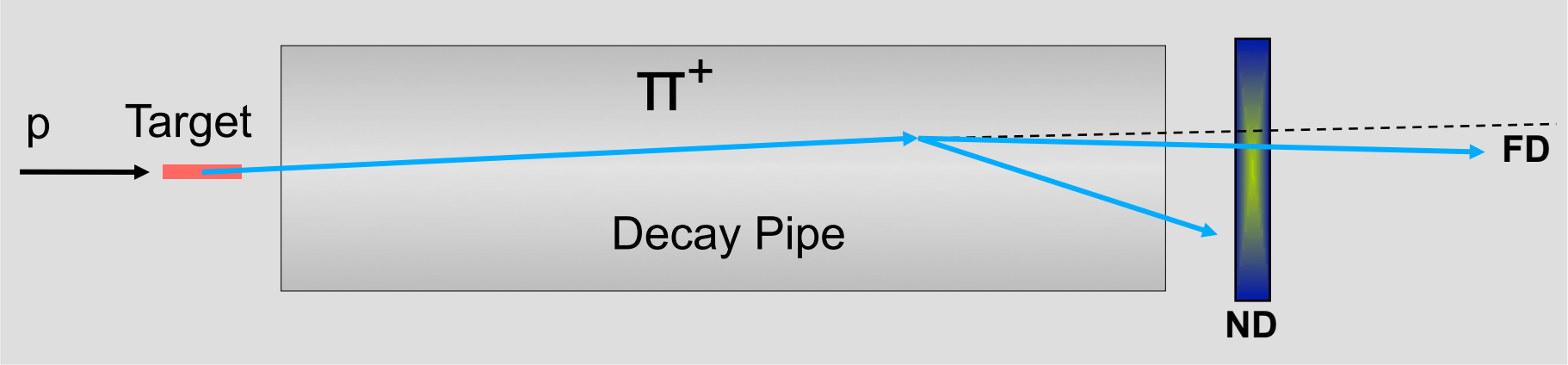


Hadron Production Tuning

- Select events with muon and hadronic shower
  - Use different beam configurations
- Hadron production of proton target has big uncertainties
  - neutrino flux unknown
- Use Fluka2005 hadron production
  - modify: re-weight as $f(x_F, p_T)$
- include in fit
  - Horn focusing, beam misalignments, neutrino energy scale, cross section, NC background

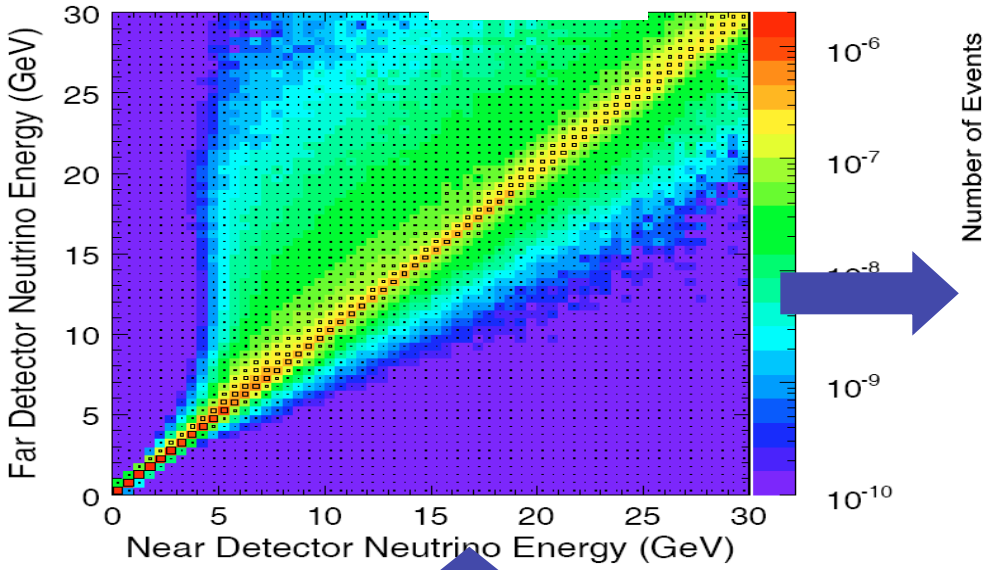


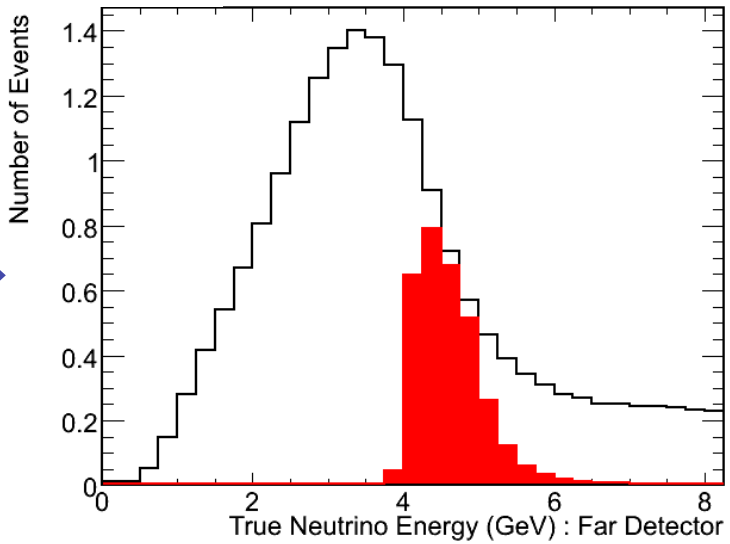
Predicting the FD Spectrum

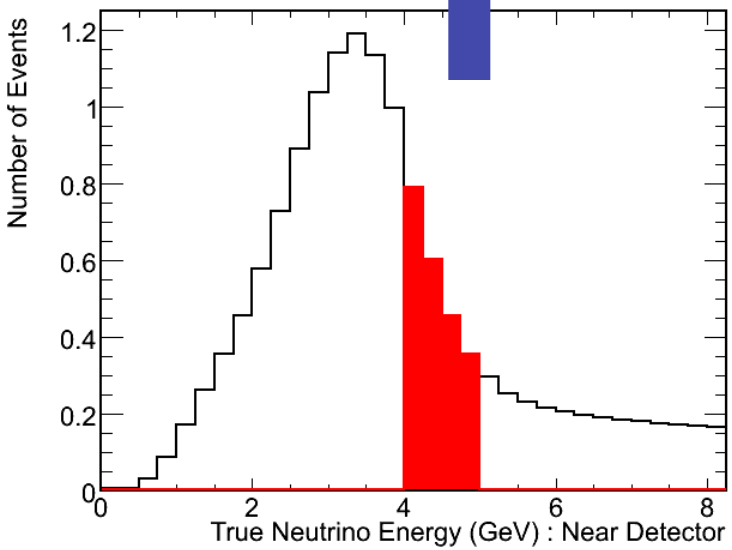


$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 \qquad E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

Near to Far Extrapolation

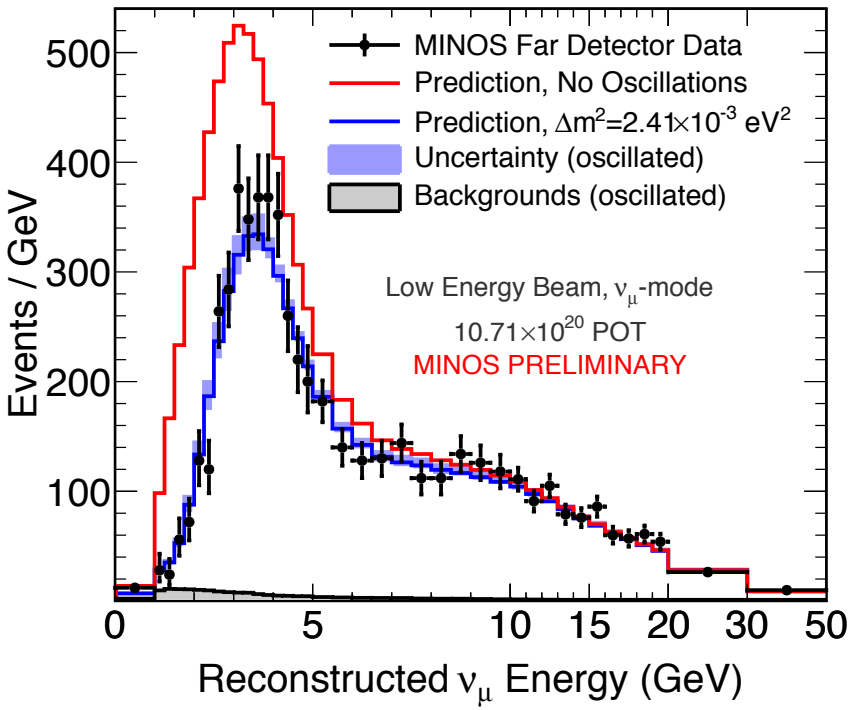


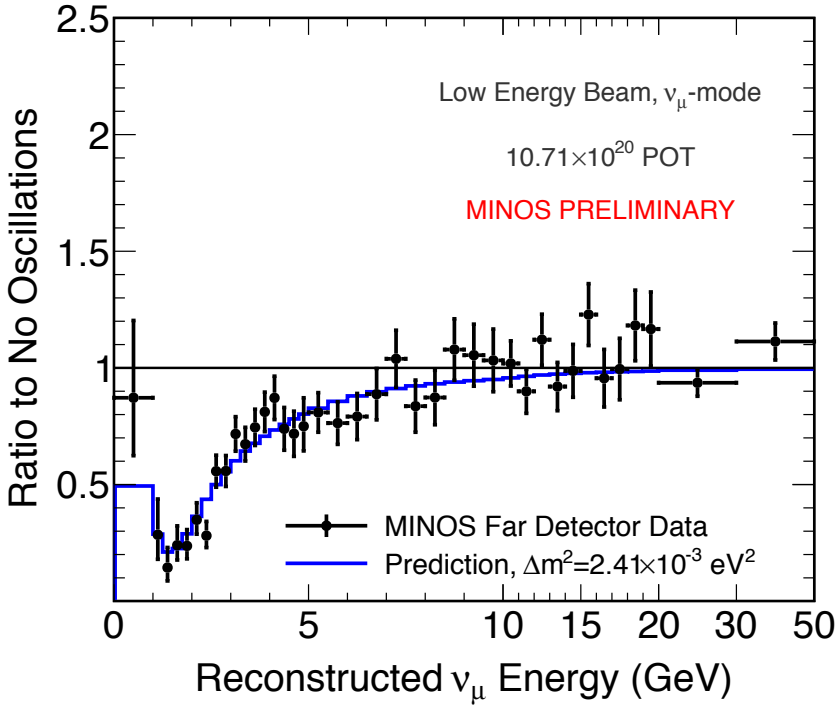




- Pion/Kaon decay kinematics are encapsulated in matrix
- Measured ND spectrum is transported to FD
- Largely reduce systematics
  - hadron production
  - cross section

Muon Neutrino Oscillation



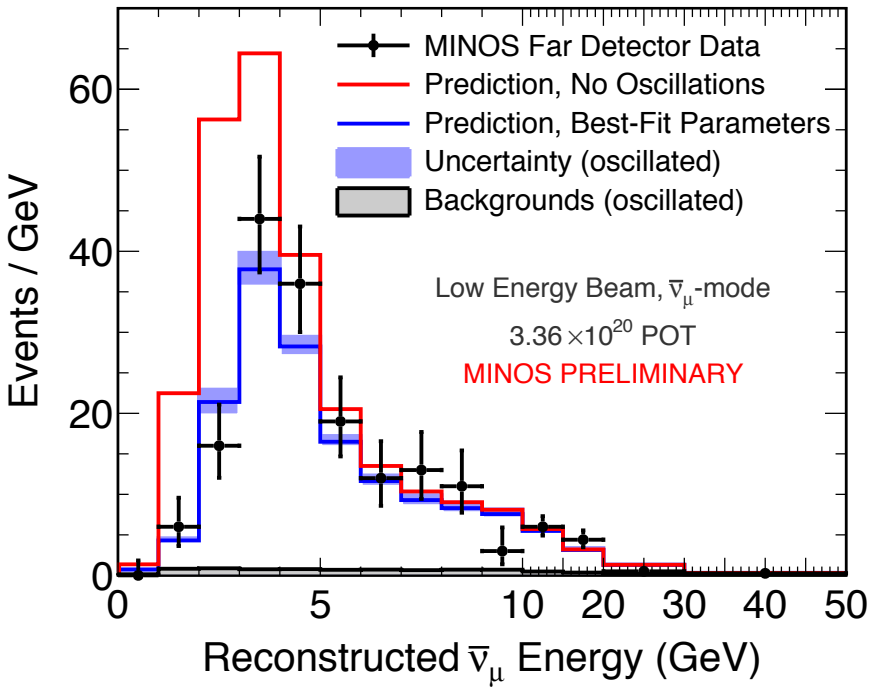


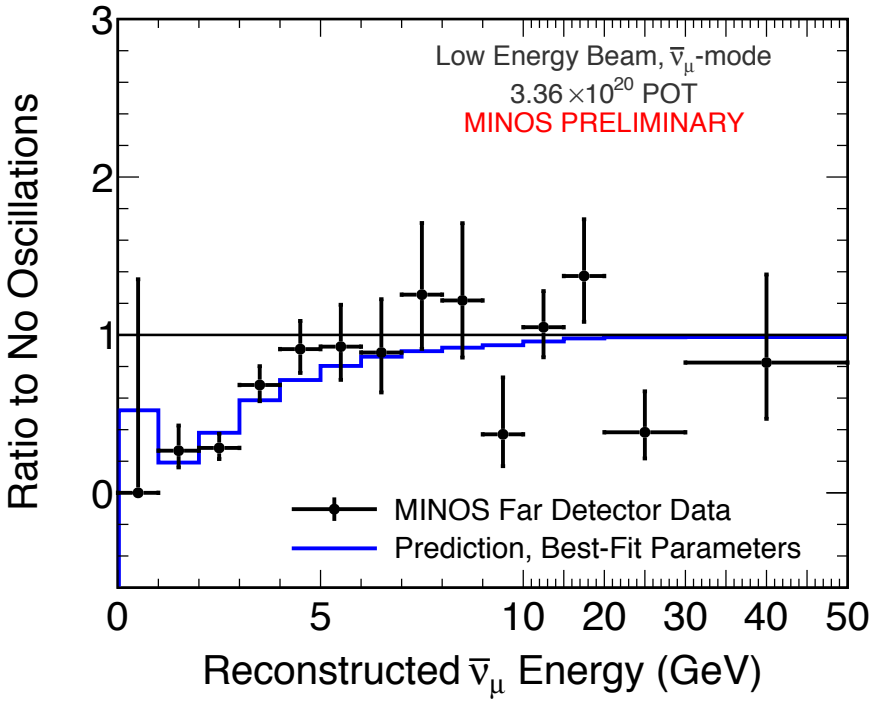
- No Oscillations: 3564
- Observed: 2894

$$\left|\Delta m^2\right| = 2.41^{+0.11}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$$

Muon Antineutrino



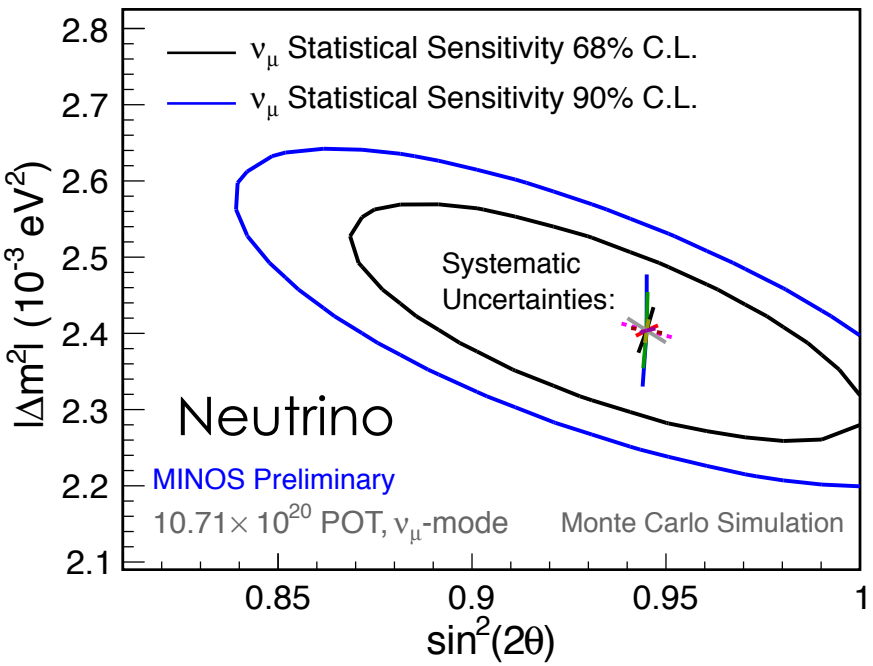


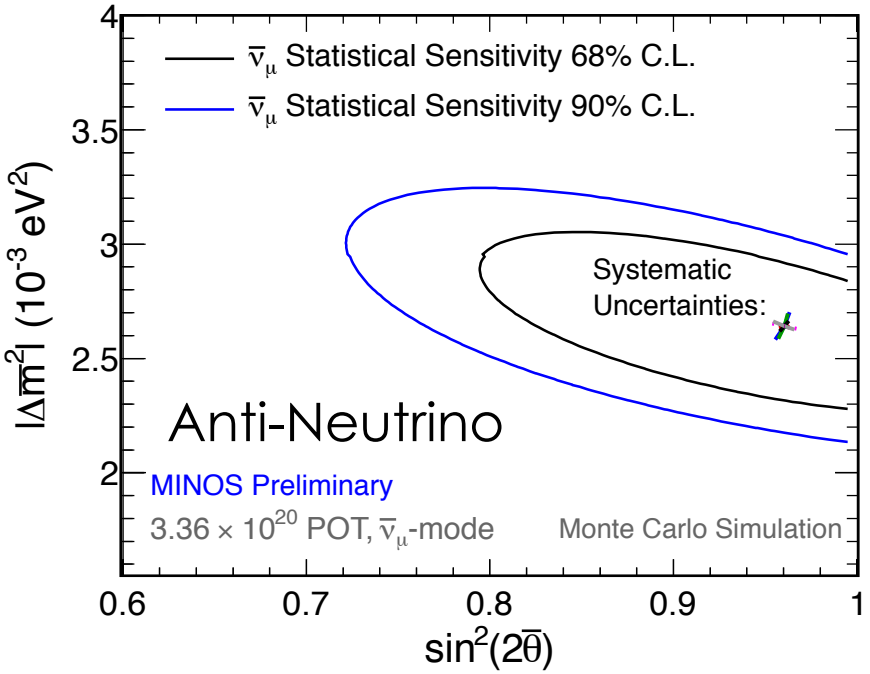
- No Oscillations: 313
- Observed: 226

$$\left|\Delta\bar{m}^2\right| = 2.64^{+0.28}_{-0.27}\times10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.78\ (90\%\ \mathrm{C.L.})$$

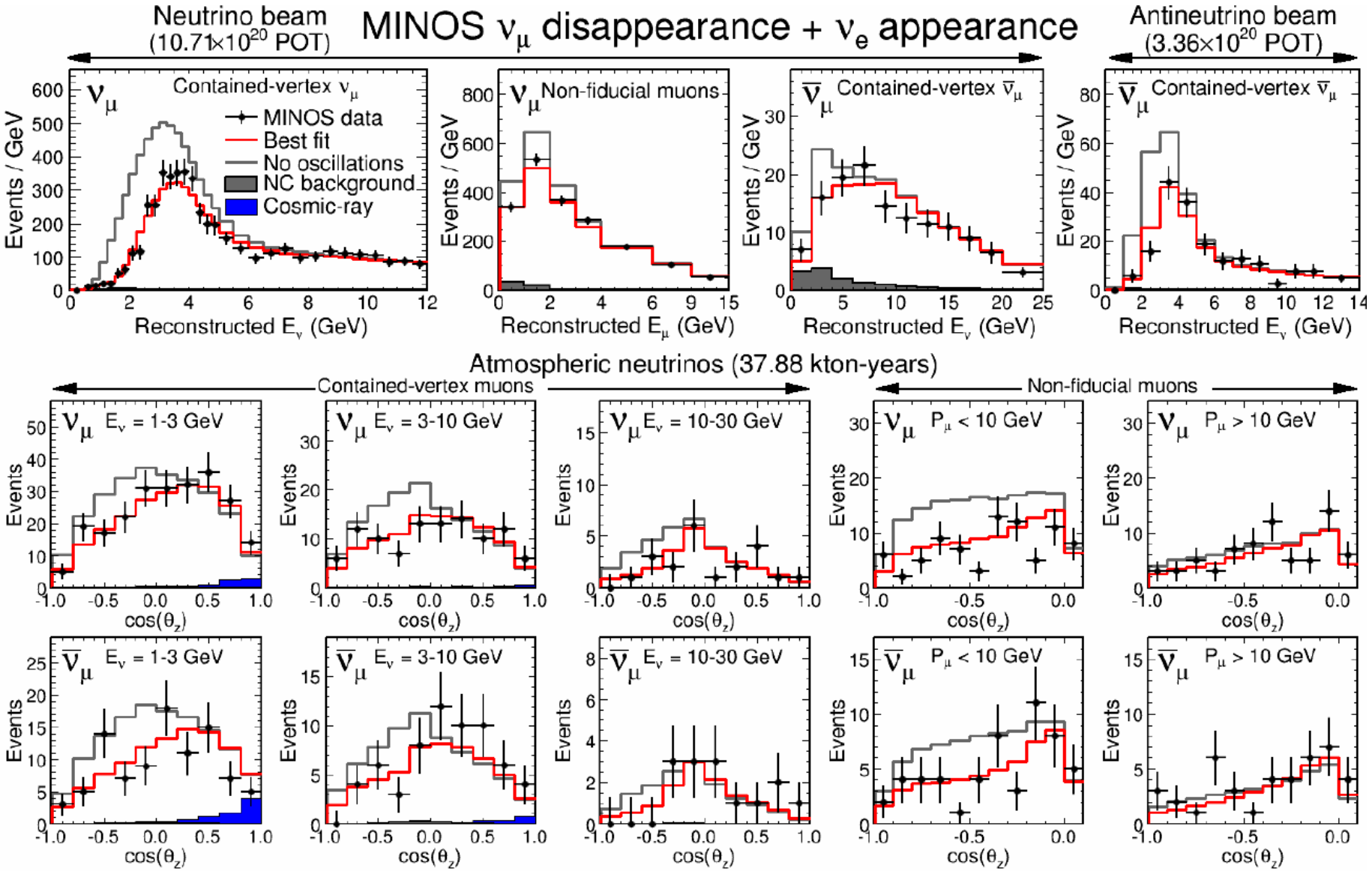
Systematics





- Largest sources of systematic uncertainty:
  - Hadronic Energy Scale
  - Track Energy Scale
  - Neutral Current background
- Still statistics dominated in both modes

Acc & Atmospheric ν



A Little Bit of Math

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm^2_{ij} = mass^2 difference

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m^2_{31} L}{4E} \times \left(1 + \frac{2a}{\Delta m^2_{31}} \left(1 - 2S_{13}^2\right)\right)$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E}$$

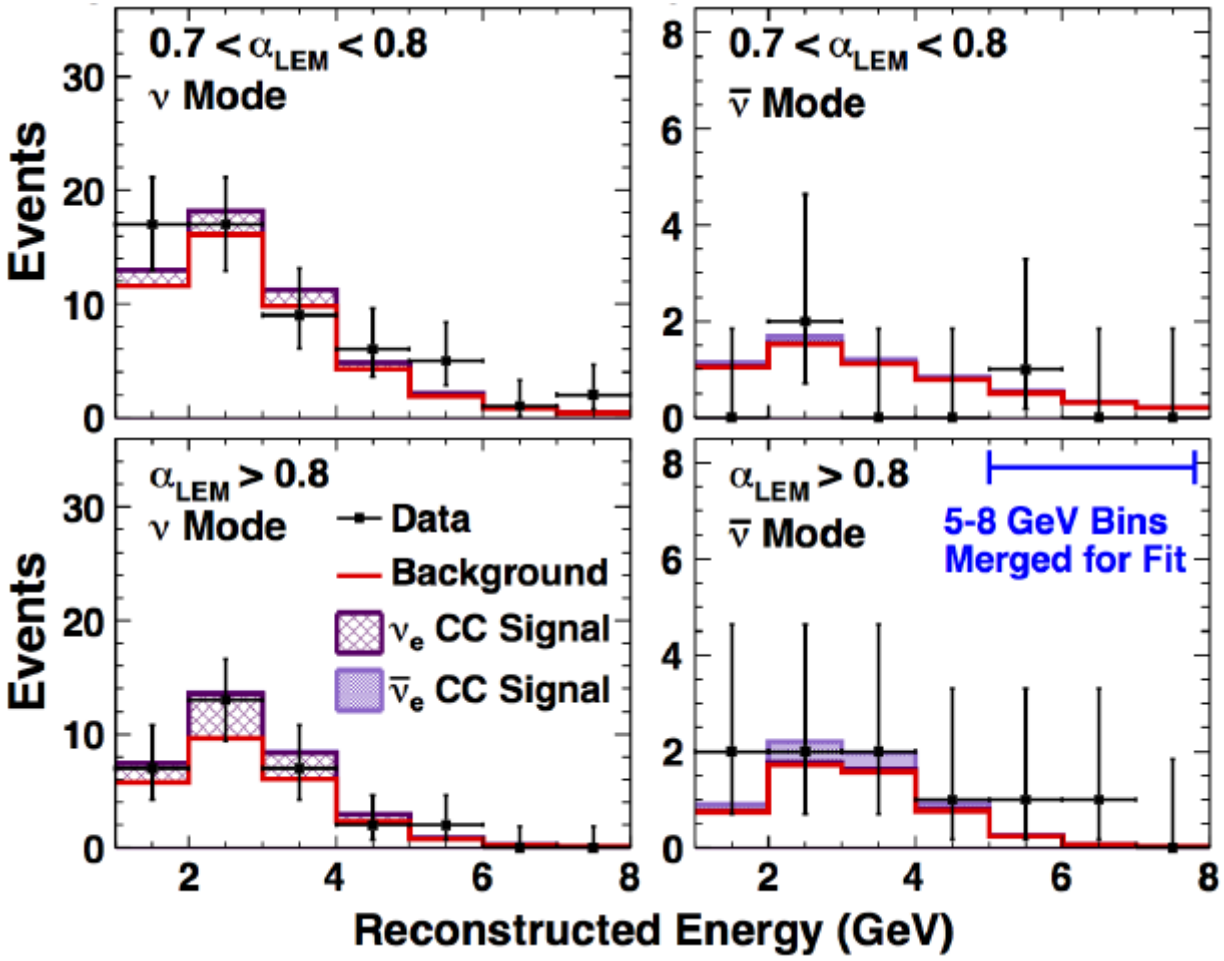
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E}$$

$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)$$

Electron Neutrino Appearance

- If θ_{13}=0: 69.1 BG Events
- If $\sin^2(2\theta_{13})$=0.1: +26.0 Events
- Observe: 88 Events



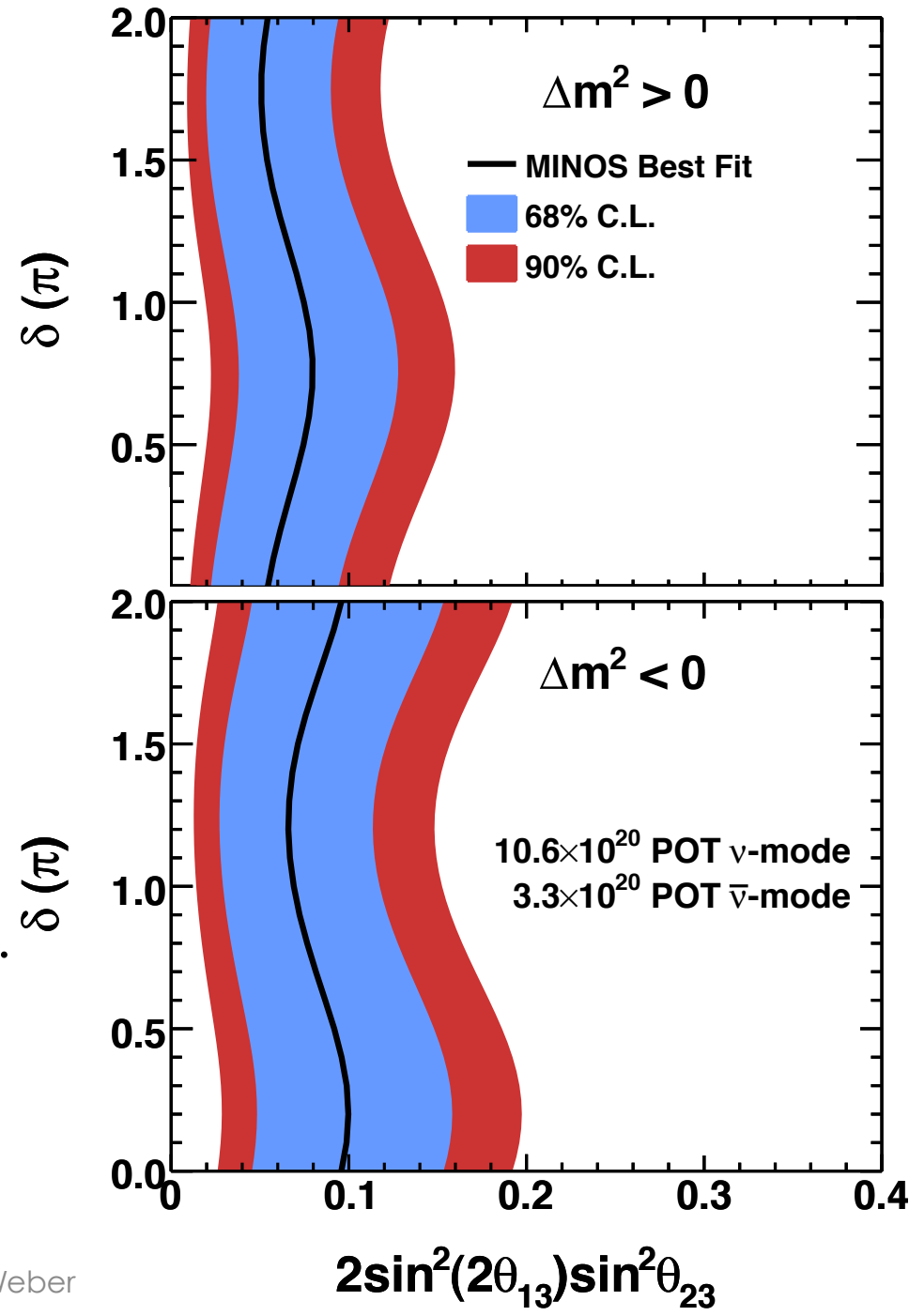
Appearance Contour

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

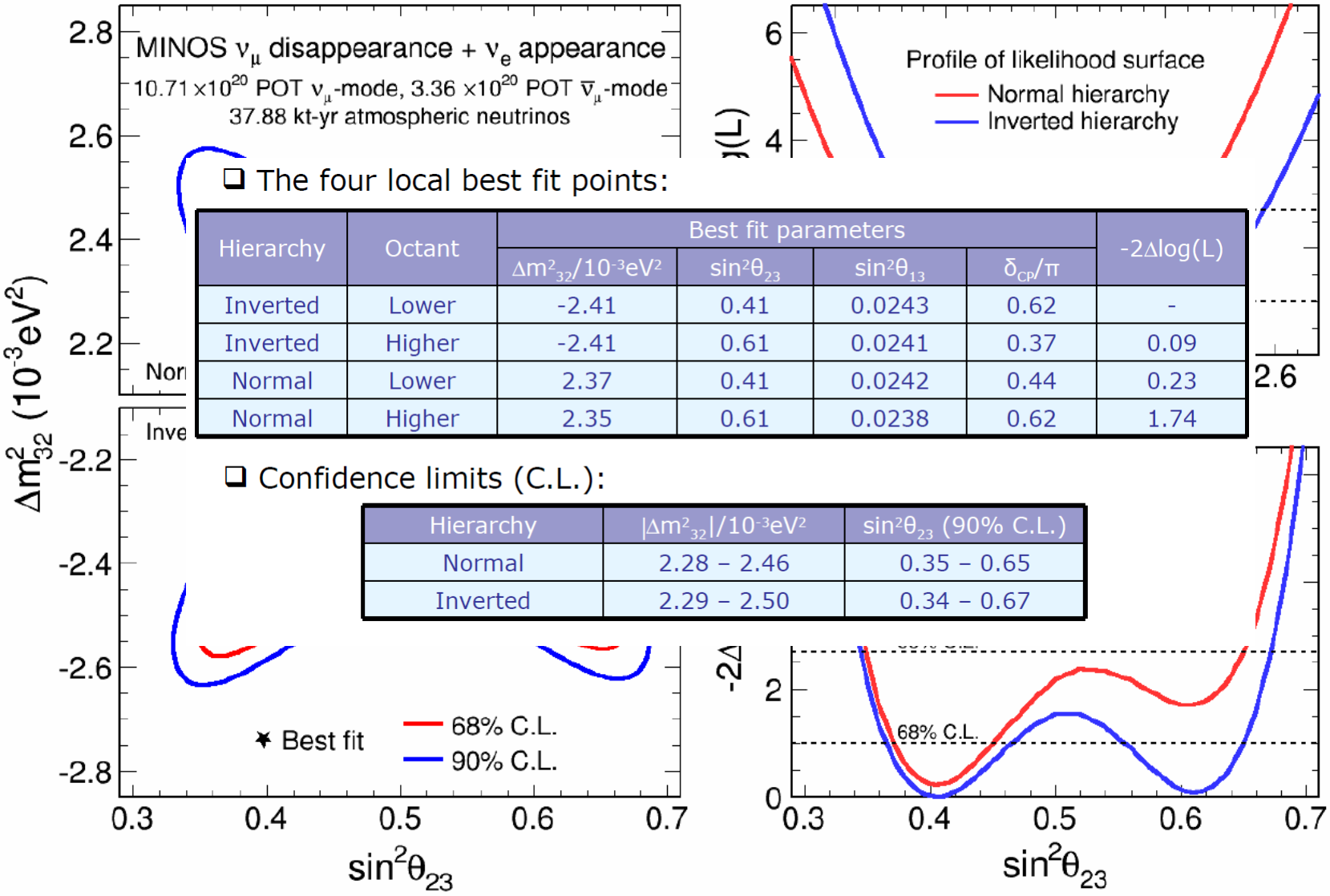
$\sin^2(2\theta_{13}) = 0.053$ (0.094) at best fit

$0.01 < \sin^2(2\theta_{13}) < 0.12$ at 90% C.L.
(0.03) (0.19)

$\sin^2(2\theta_{13}) = 0$ excluded at 96%



Combined Oscillation Fit



- The four local best fit points:

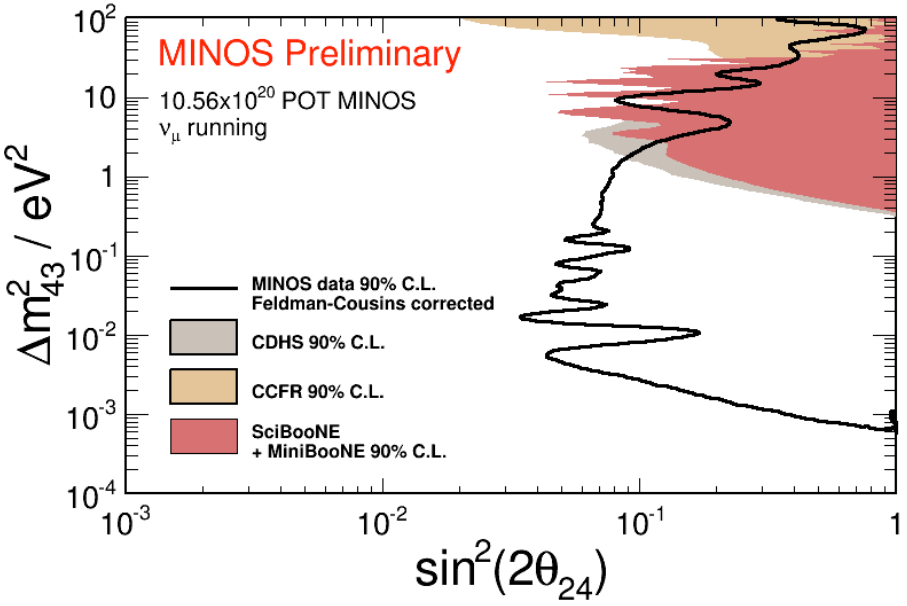
Hierarchy	Octant	Best fit parameters				-2Δlog(L)
		$\Delta m^2_{32}/10^{-3}$eV^2	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}/π	
Inverted	Lower	-2.41	0.41	0.0243	0.62	-
Inverted	Higher	-2.41	0.61	0.0241	0.37	0.09
Normal	Lower	2.37	0.41	0.0242	0.44	0.23
Normal	Higher	2.35	0.61	0.0238	0.62	1.74

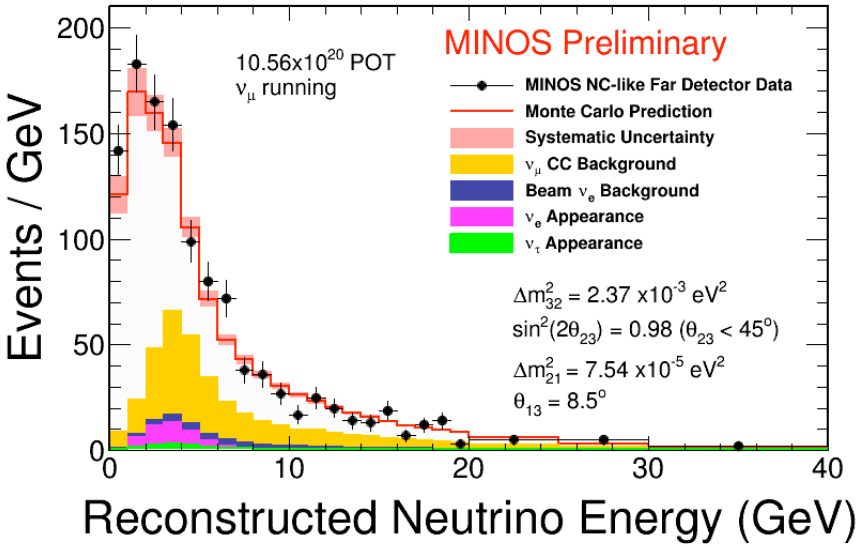
- Confidence limits (C.L.):

Hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}$eV^2	$\sin^2\theta_{23}$ (90% C.L.)
Normal	2.28 – 2.46	0.35 – 0.65
Inverted	2.29 – 2.50	0.34 – 0.67

Sterile Neutrinos

- NC events would disappear, if muon neutrinos oscillation into sterile neutrinos

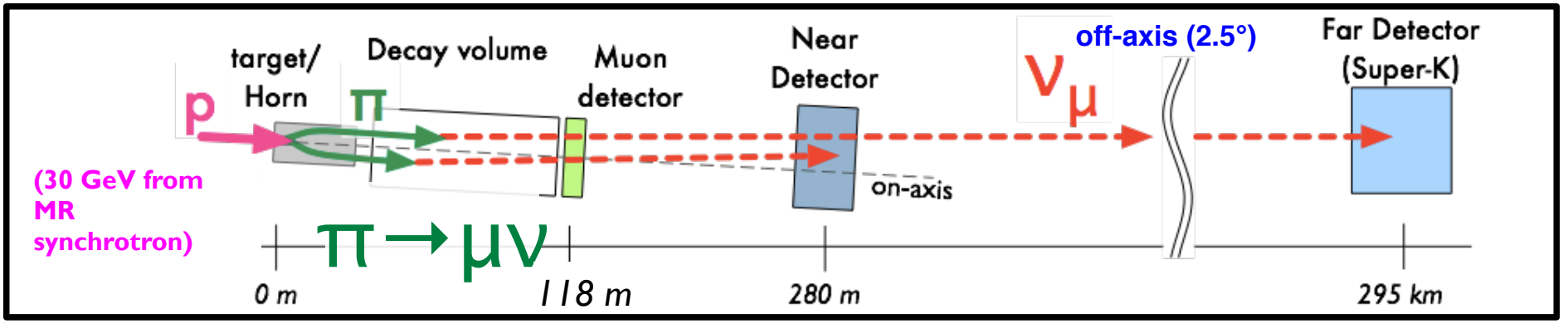


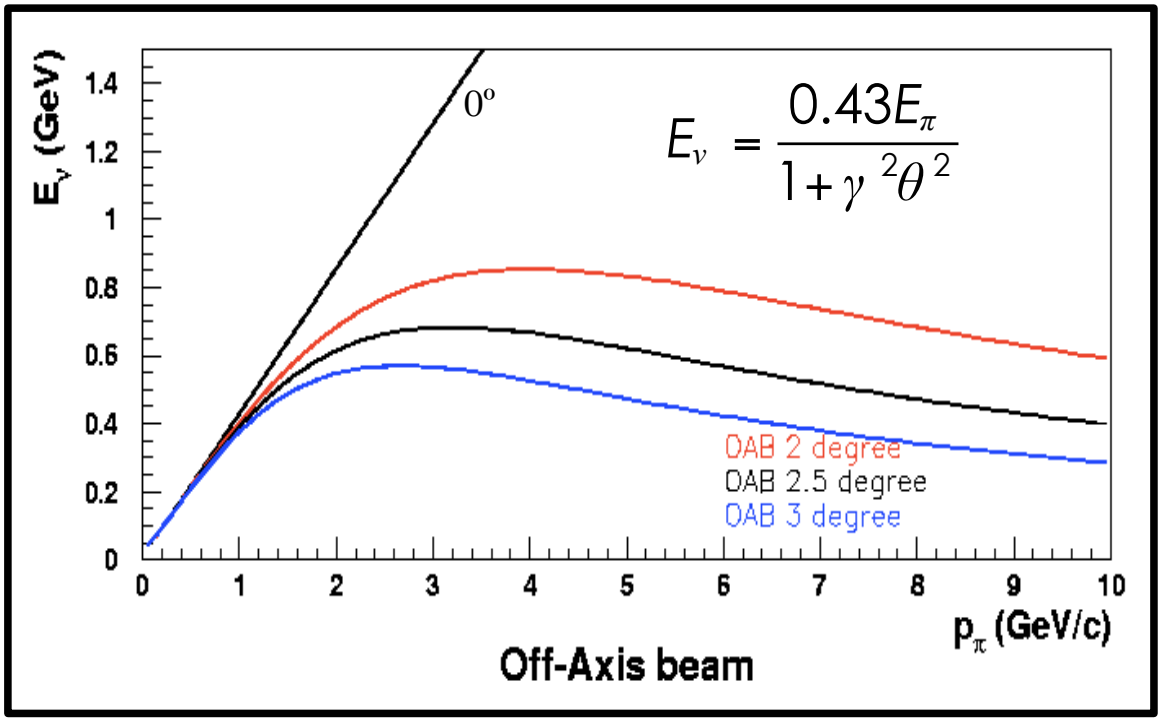


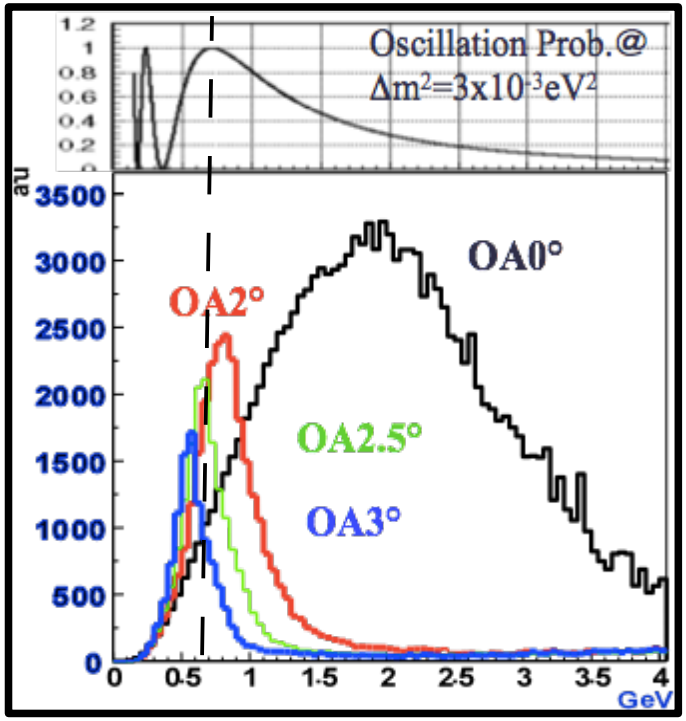
E_{reco} (GeV)	N_{Data}	S_{NC}	$B_{CC}^{\nu_\mu}$	$B_{CC}^{\nu_\tau}$	$B_{CC}^{\nu_e}$
0 – 3	327	245.6	32.5	3.2	2.7 (12.4)
3 – 200	476	267.8	157.4	9.3	30.6 (44.7)
0 – 200	803	513.4	190.0	12.5	33.2 (57.0)
0 – 3	$R = 1.14 \pm 0.07 \pm 0.08$				
3 – 200	$R = 0.99 \pm 0.08 \pm 0.06$				
0 – 200	$R = 1.06 \pm 0.06 \pm 0.06$				

T2K Experiment

Design Principle

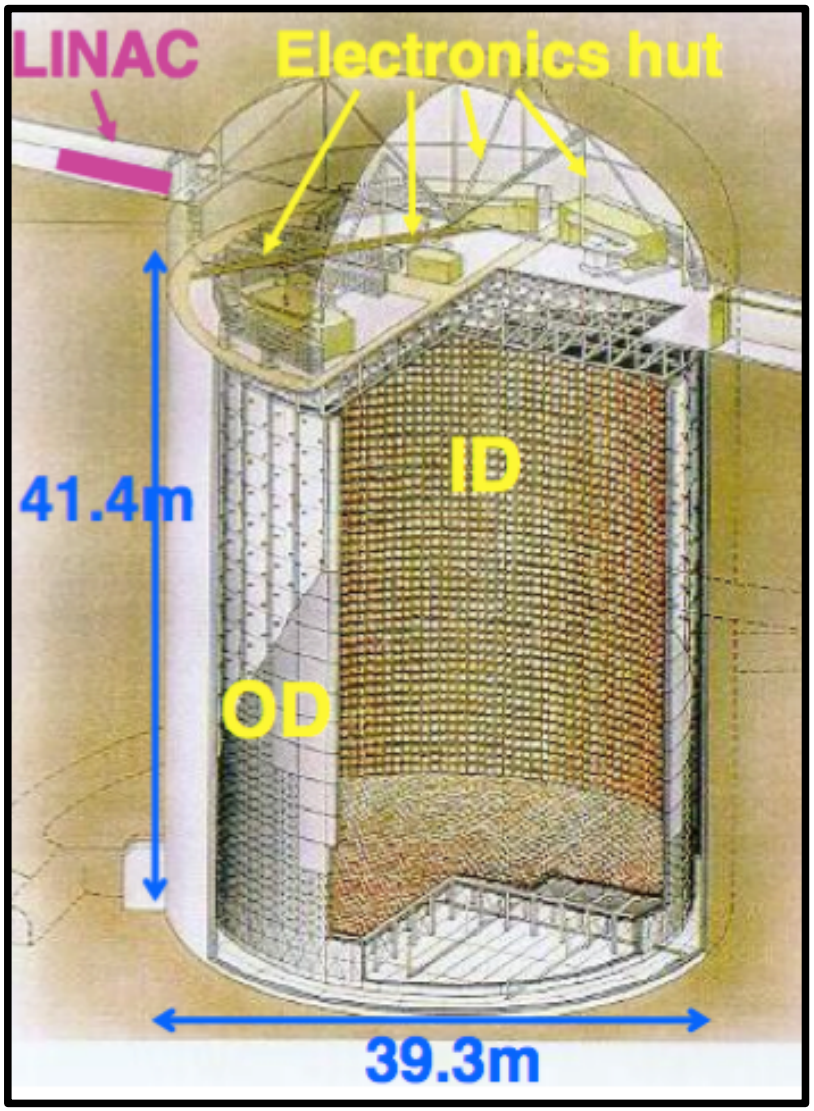




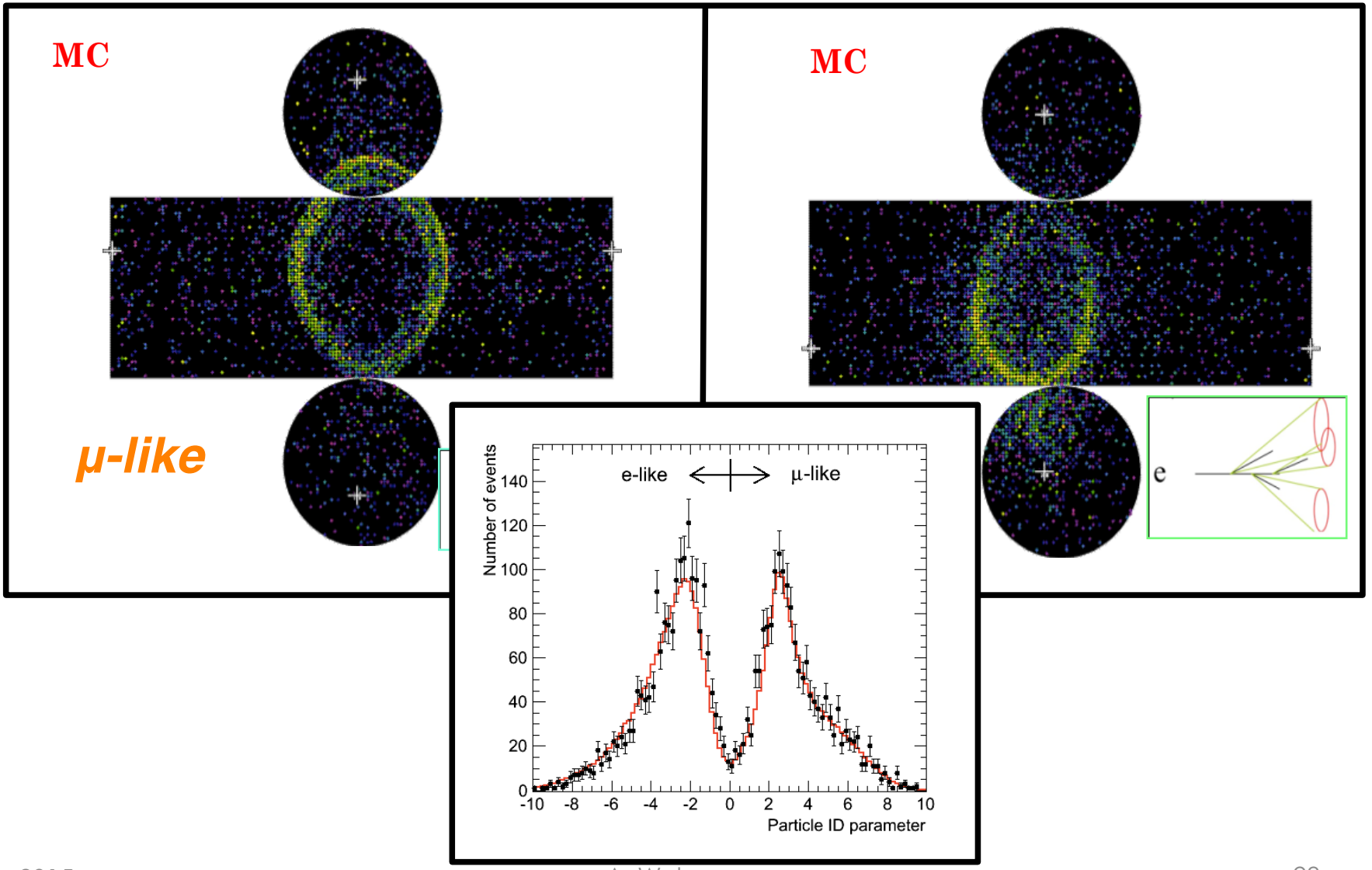


Super-K detector

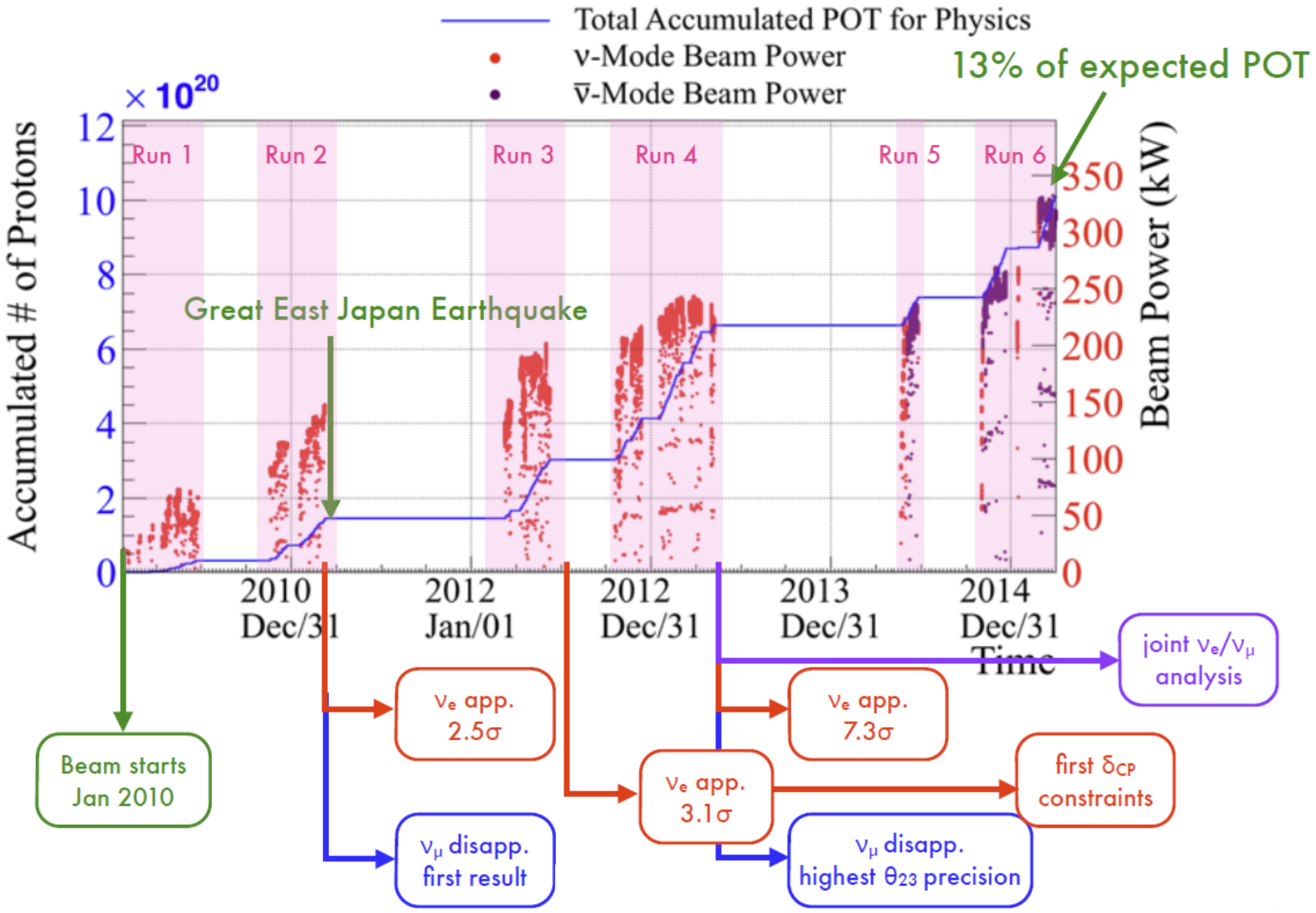
- Located in Mozumi mine
  - **2700 m.w.e.** overburden
- water Cherenkov detector
  - **22.5 kt** fiducial mass
- Inner detector
  - 11000 20-inch PMTs
- Outer veto
  - 1900 8-inch PMTs
- New DAQ system
  - 100% livetime
- **Excellent μ /e separation**
  - Probability to reconstruct μ as e ~ 1%



Particle Identification

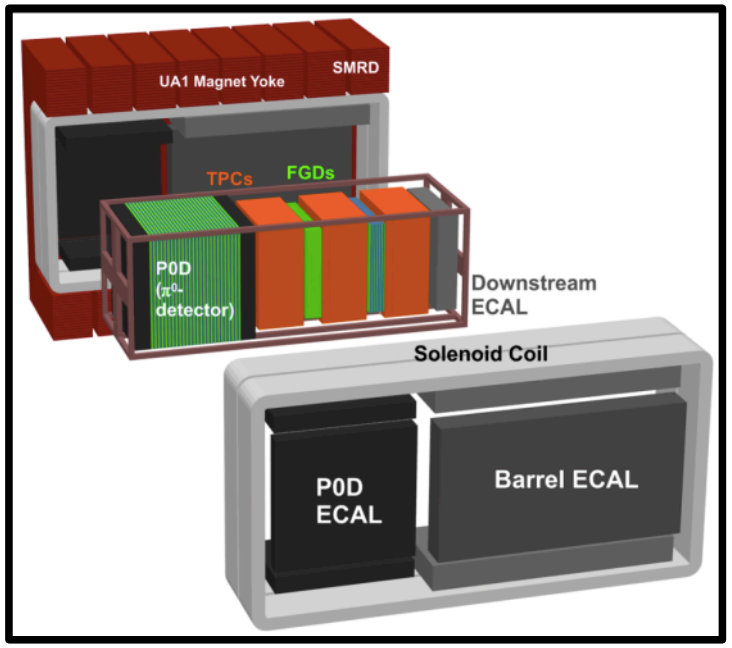


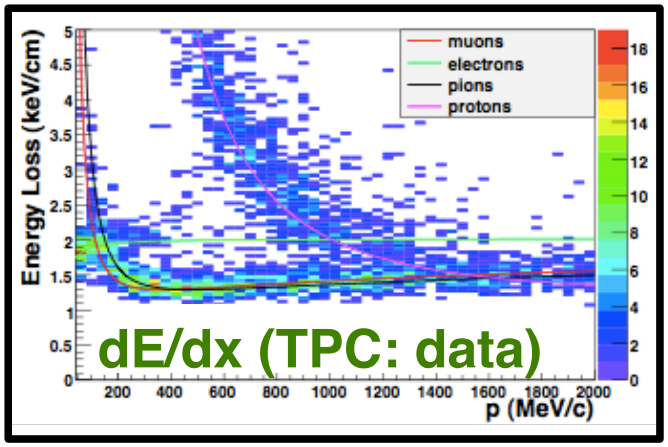
Data Sample

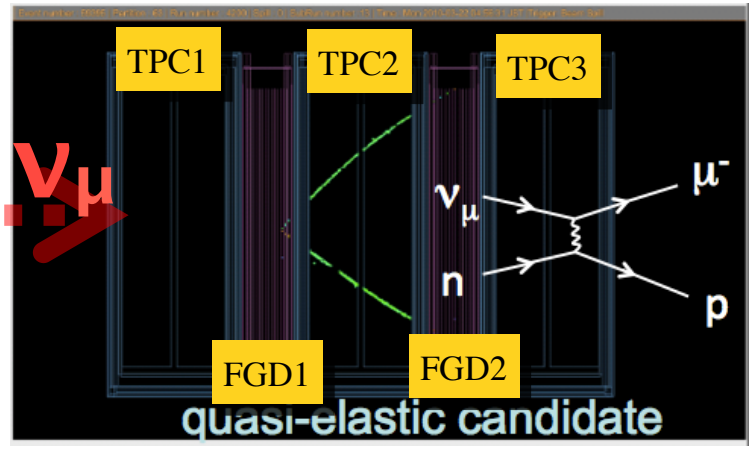

Total Accumulated POT for Physics
ν-Mode Beam Power
ν̄-Mode Beam Power
13% of expected POT
× 10^20
Accumulated # of Protons
Beam Power (kW)
Run 1
Run 2
Run 3
Run 4
Run 5
Run 6
Great East Japan Earthquake
2010 Dec/31
2012 Jan/01
2012 Dec/31
2013 Dec/31
2014 Dec/31
Time
Beam starts Jan 2010
νe app. 2.5σ
νμ disapp. first result
νe app. 3.1σ
νe app. 7.3σ
νμ disapp. highest θ23 precision
first δCP constraints
joint νe/νμ analysis

ND280 detector

- 0.2 T magnet (recycled from UA1)
- Plastic scintillator detectors:
  - Fine Grained Detector (FGD)
    - 1.6 ton fiducial mass for analysis
  - π^0 detector (P0D)
  - ECals and SMRD
- Time projection chambers (TPC)
  - better than 10% dE/dx resolution
  - 10% momentum resolution at 1GeV/c

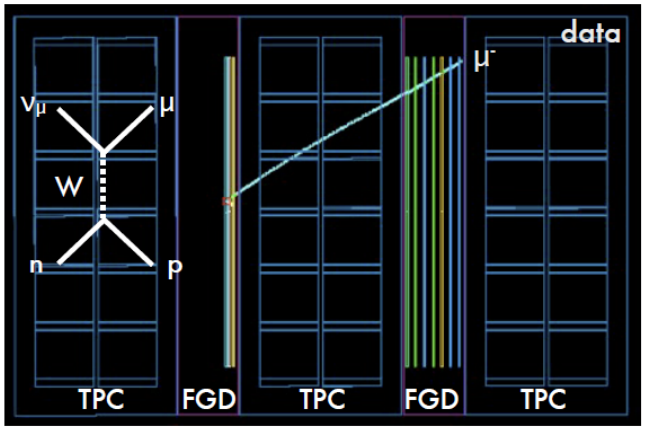




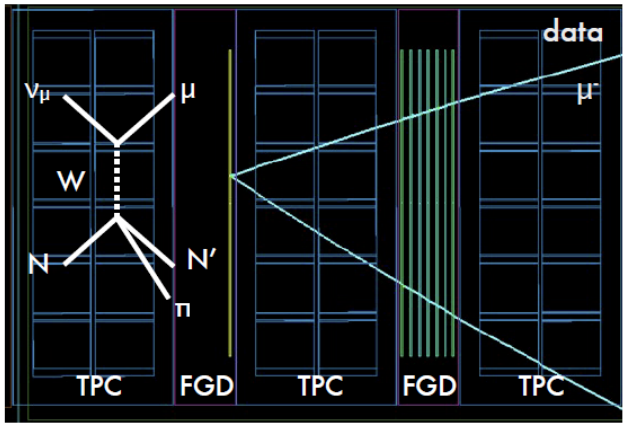


ND280

CC0π

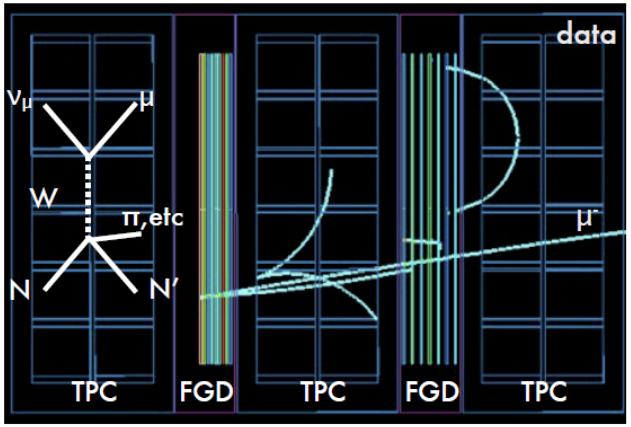


CC1π+

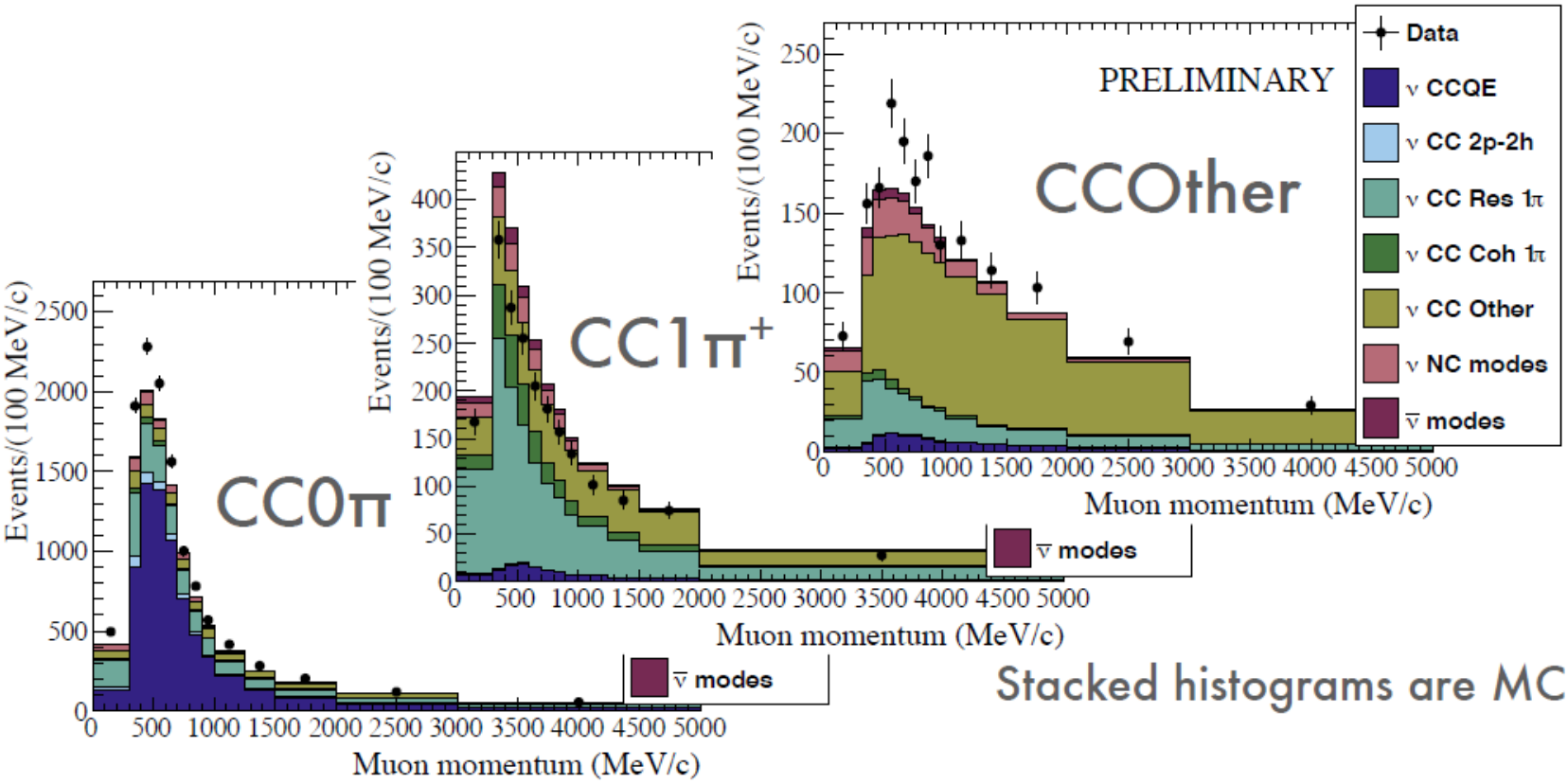


CC other

Beam



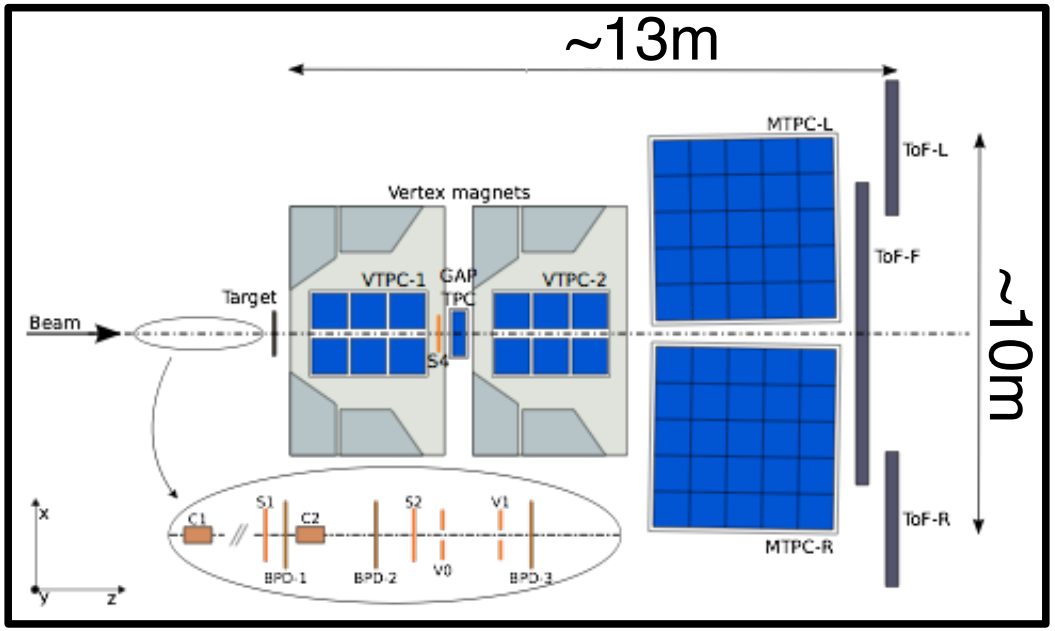
ND280 Data Constrains



Stacked histograms are MC prefit

NA61/SHINE

- Goal: measure hadron(π , K) yield distribution in **30 GeV p + C** inelastic interaction
- High-acceptance ToFs and spectrometers
- **2cm** thin target - 4% λ_I
- π^+ analysis:
  - **dE/dx only** analysis for low momenta
  - **dE/dx+ToF** selection for high momenta

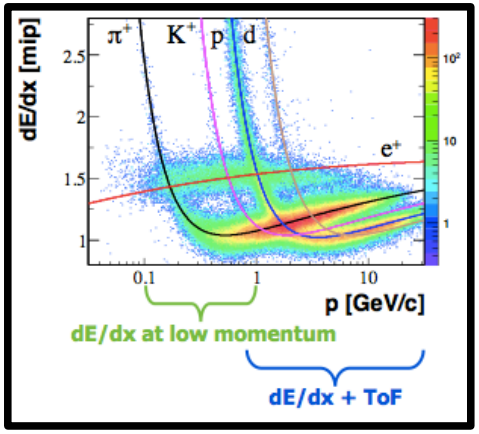


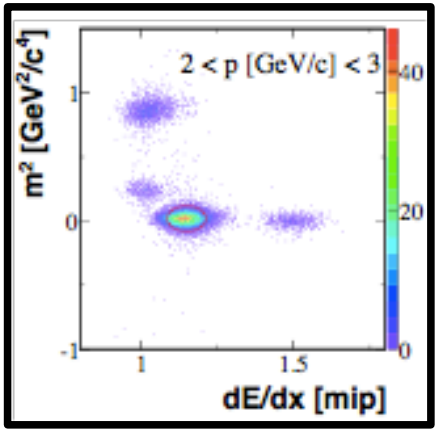
$$\sigma(p)/p^2 \approx 2\times10^{-3},\ 7\times10^{-3},\ 3\times10^{-2}(\mathrm{GeV/c})^{-1}$$

$$\text{for } p > 5,\ p = 2,\ p = 1 \text{ GeV/c}$$

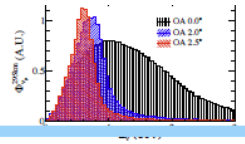
$$\sigma(\mathrm{dE/dx})/\langle \mathrm{dE/dx}\rangle \approx 0.04$$

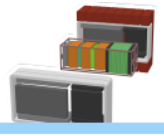
$$\sigma(\text{TOF-F}) \approx 115 \text{ ps}$$





Analysis Strategy





NA61/SHINE Data

INGRID/Beam Monitor Data

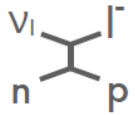
External Cross Section Data

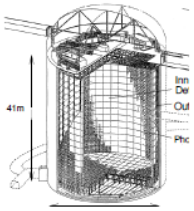
Flux Model

ND280 Detector Model

ND280 Data

Cross Section Model





SK Data

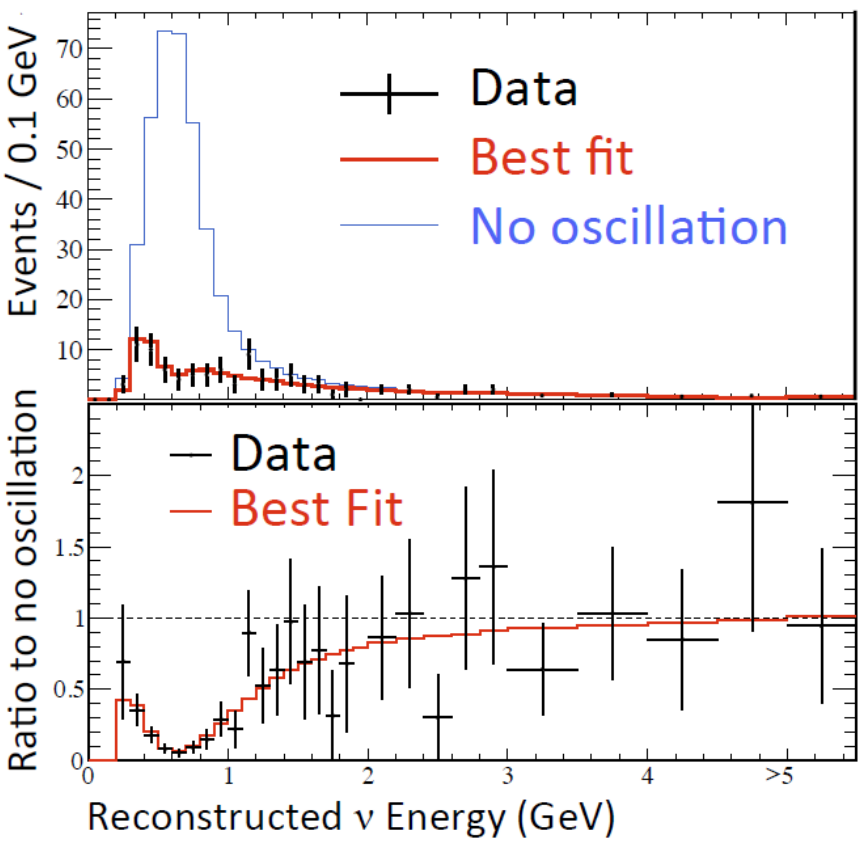
Oscillation Fit

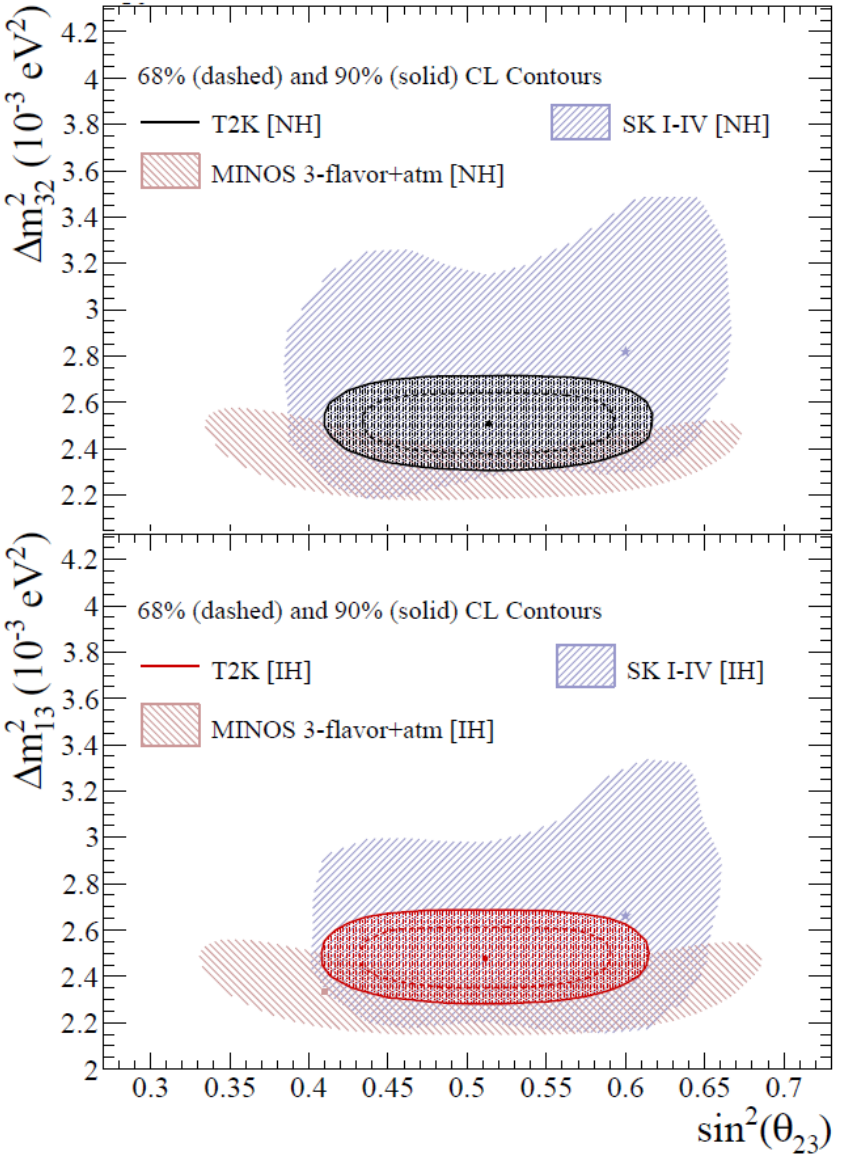
SK Detector Model

Oscillation Parameters

ND data primarily constrains flux and cross section uncertainties

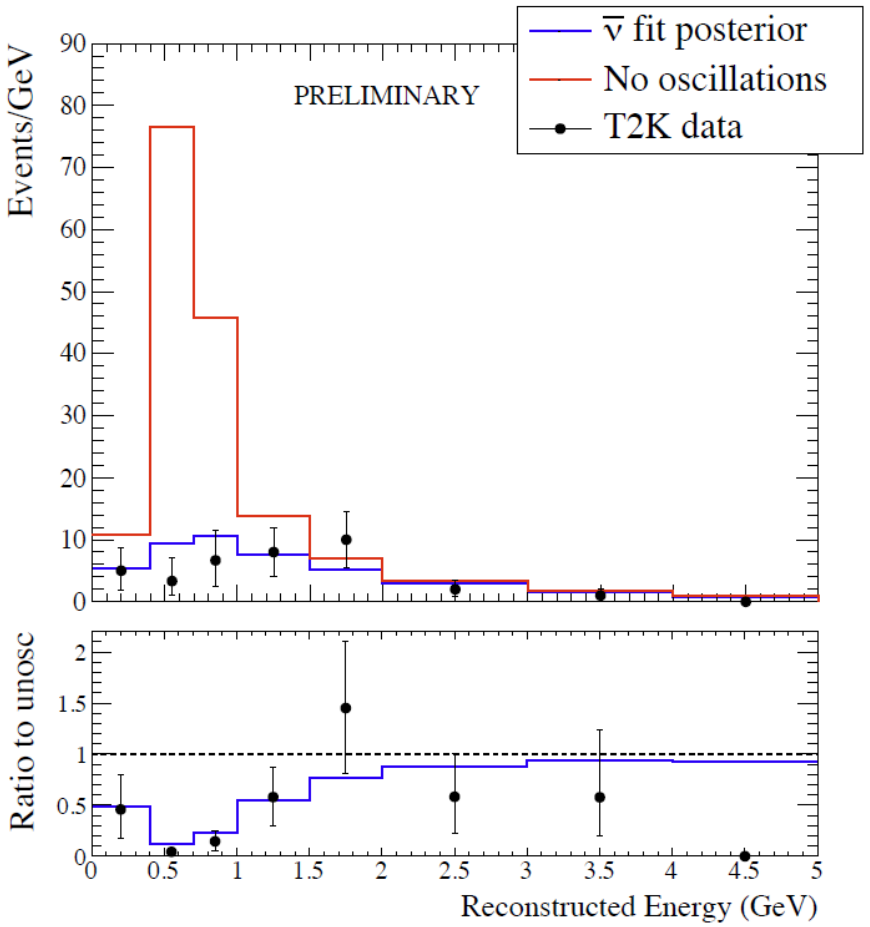
Muon Neutrino Energy Spectrum

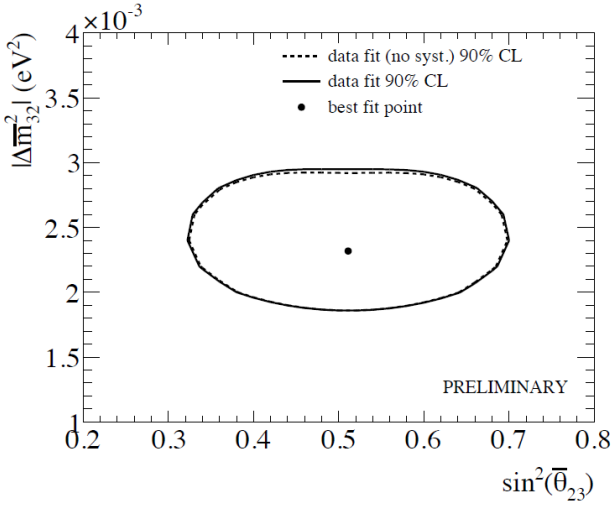


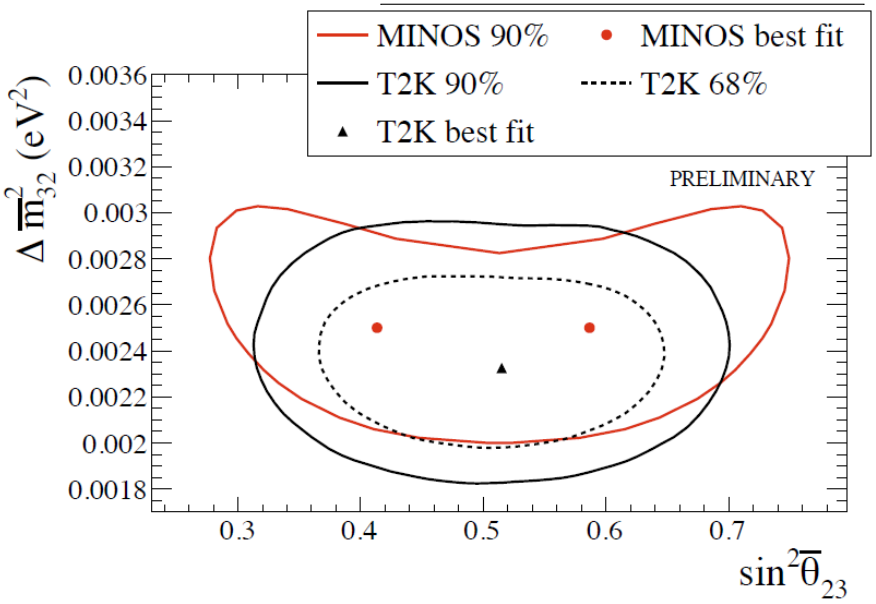


- World leading measurement of θ_{23}!
- Phys. Rev. Lett. **112**, 181801, May 2014

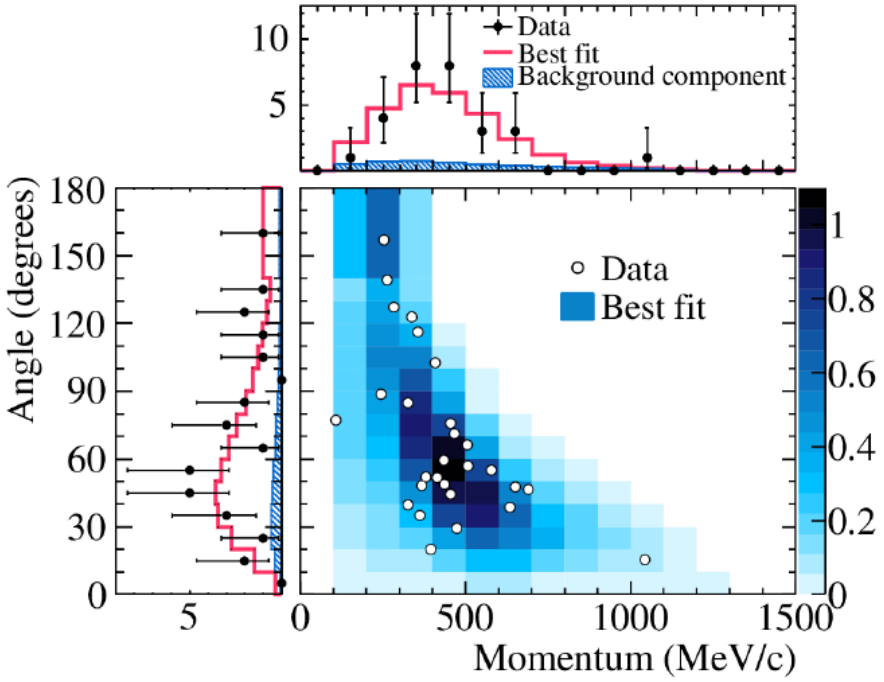
Anti-Neutrinos

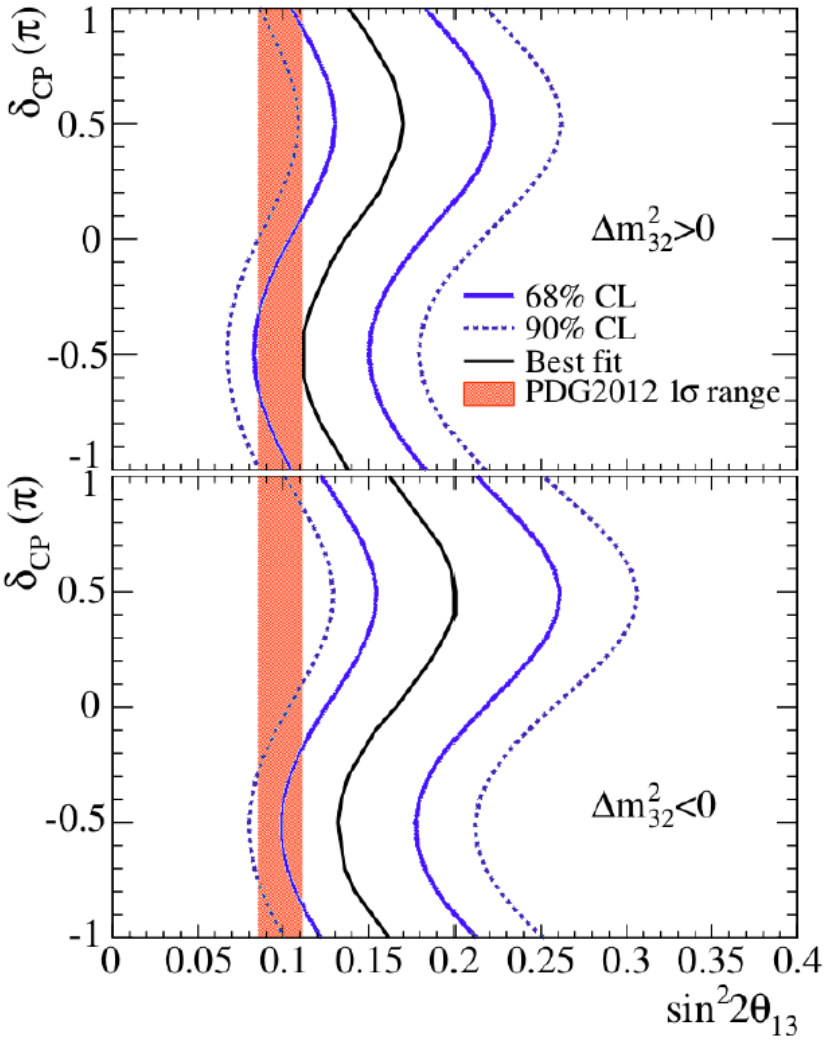






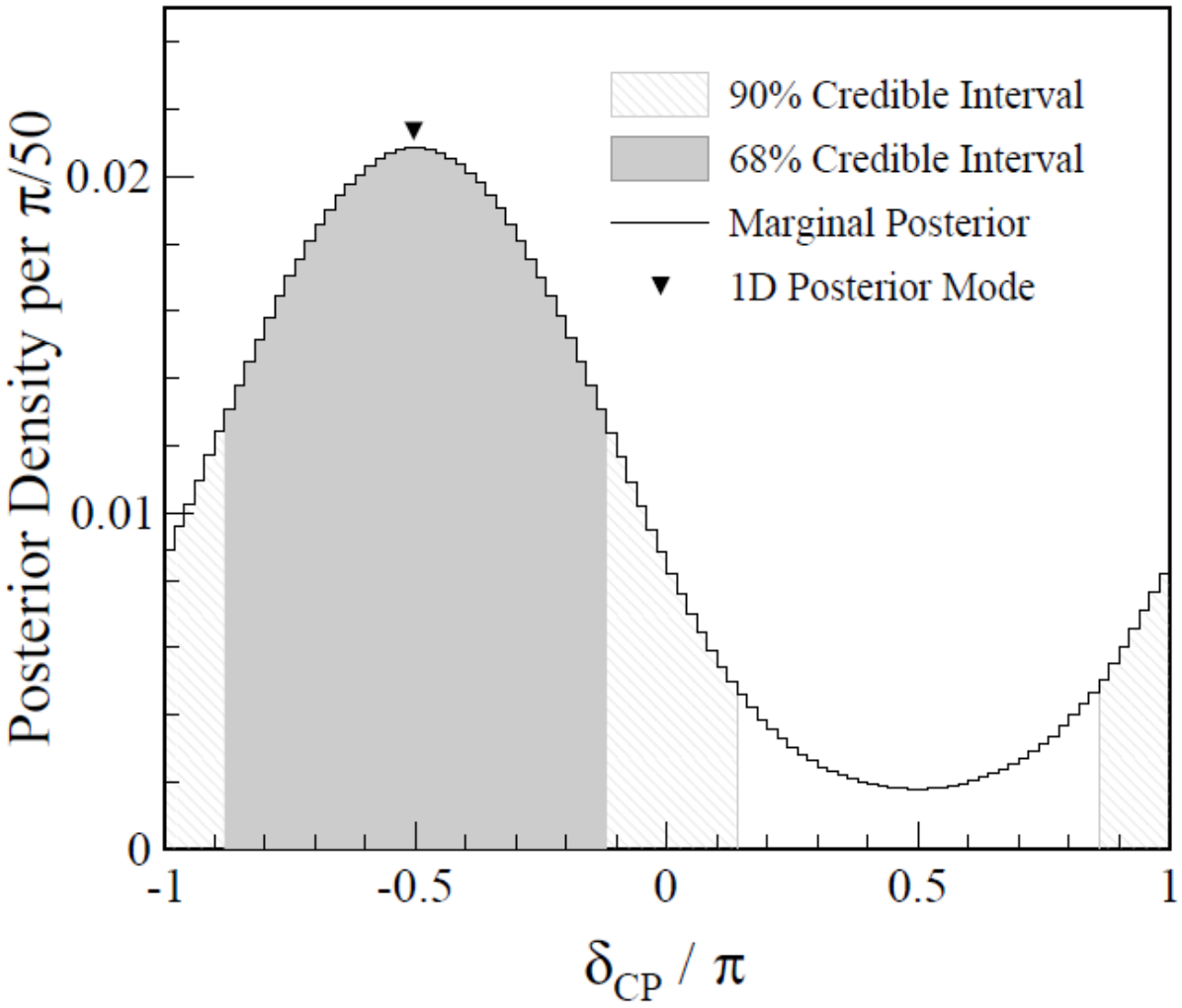
Results



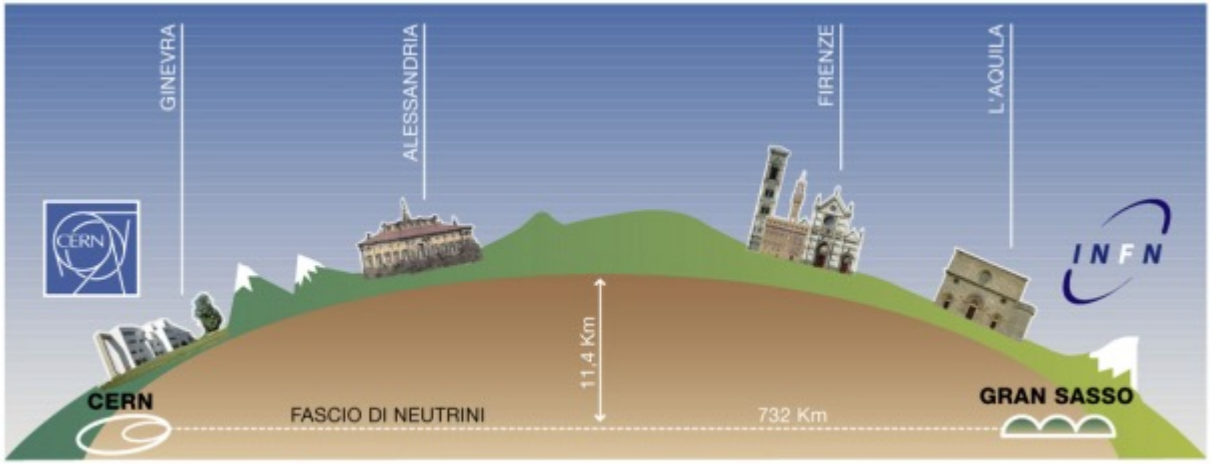


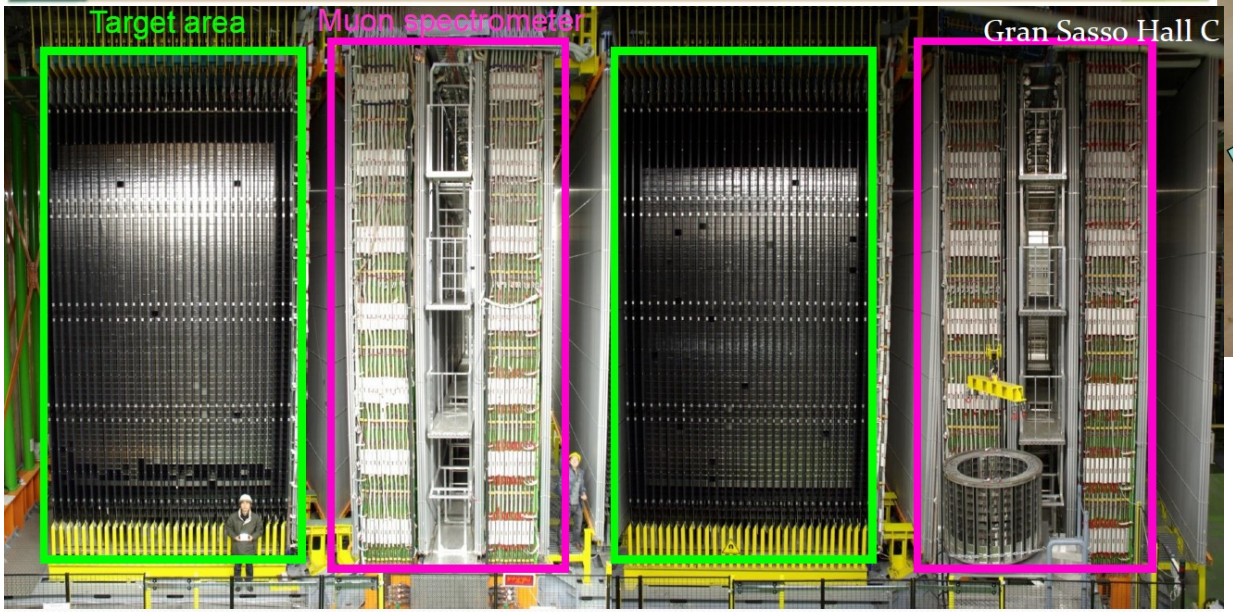
- Discovery of $\nu_\mu \rightarrow \nu_e$ at 7.3σ!
- Phys. Rev. Lett. **112**, 061802, February 2014

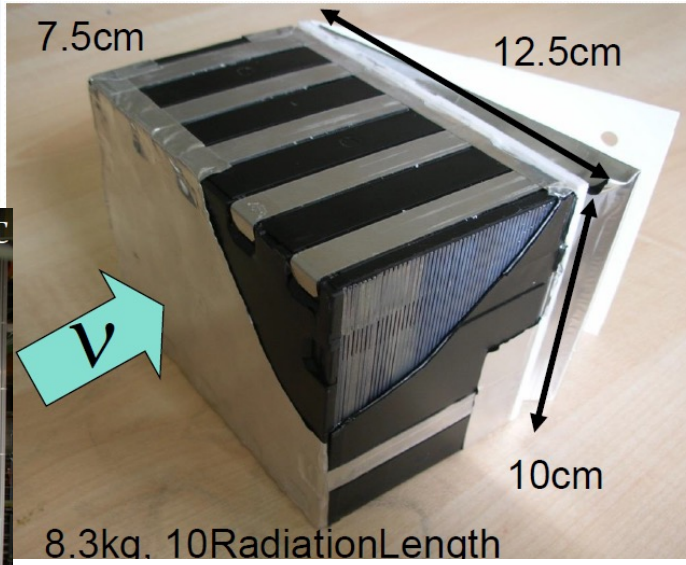
Results II


90% Credible Interval
68% Credible Interval
Marginal Posterior
1D Posterior Mode
Posterior Density per π/50
0.02
0.01
0
-1
-0.5
0
0.5
1
δCP / π

OPERA Experiment

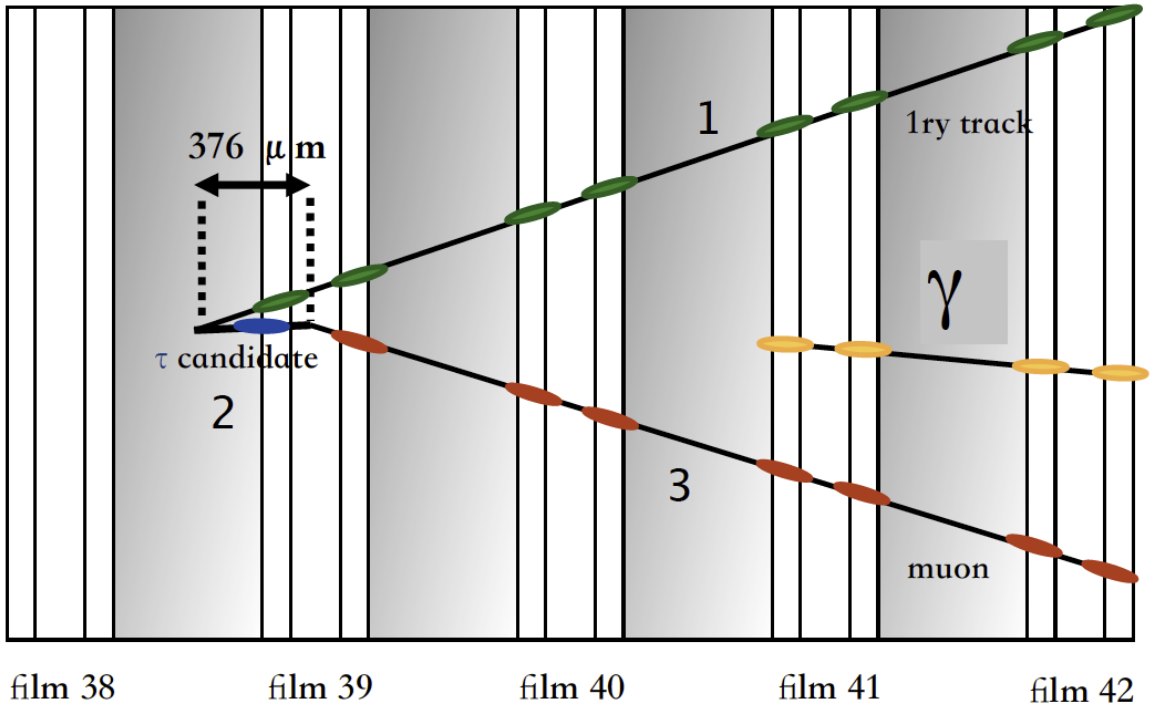




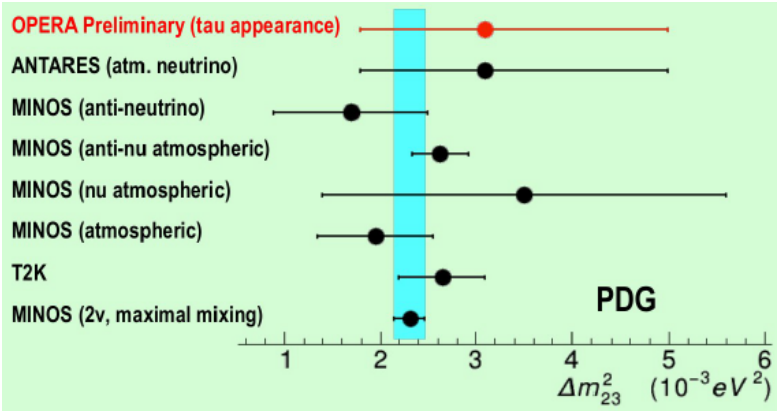


- 150,000 ECC bricks = 1.25 ktons of active target

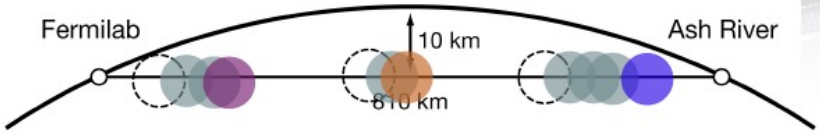
OPERA



Decay channel	Expected signal $\Delta m_{23}^2 = 2.32$ meV^2	Total background	Observed
τ→h	0.41 ± 0.08	0.033 ± 0.006	2
τ→3h	0.57 ± 0.11	0.155 ± 0.030	1
τ→μ	0.52 ± 0.10	0.018 ± 0.007	1
τ→e	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4



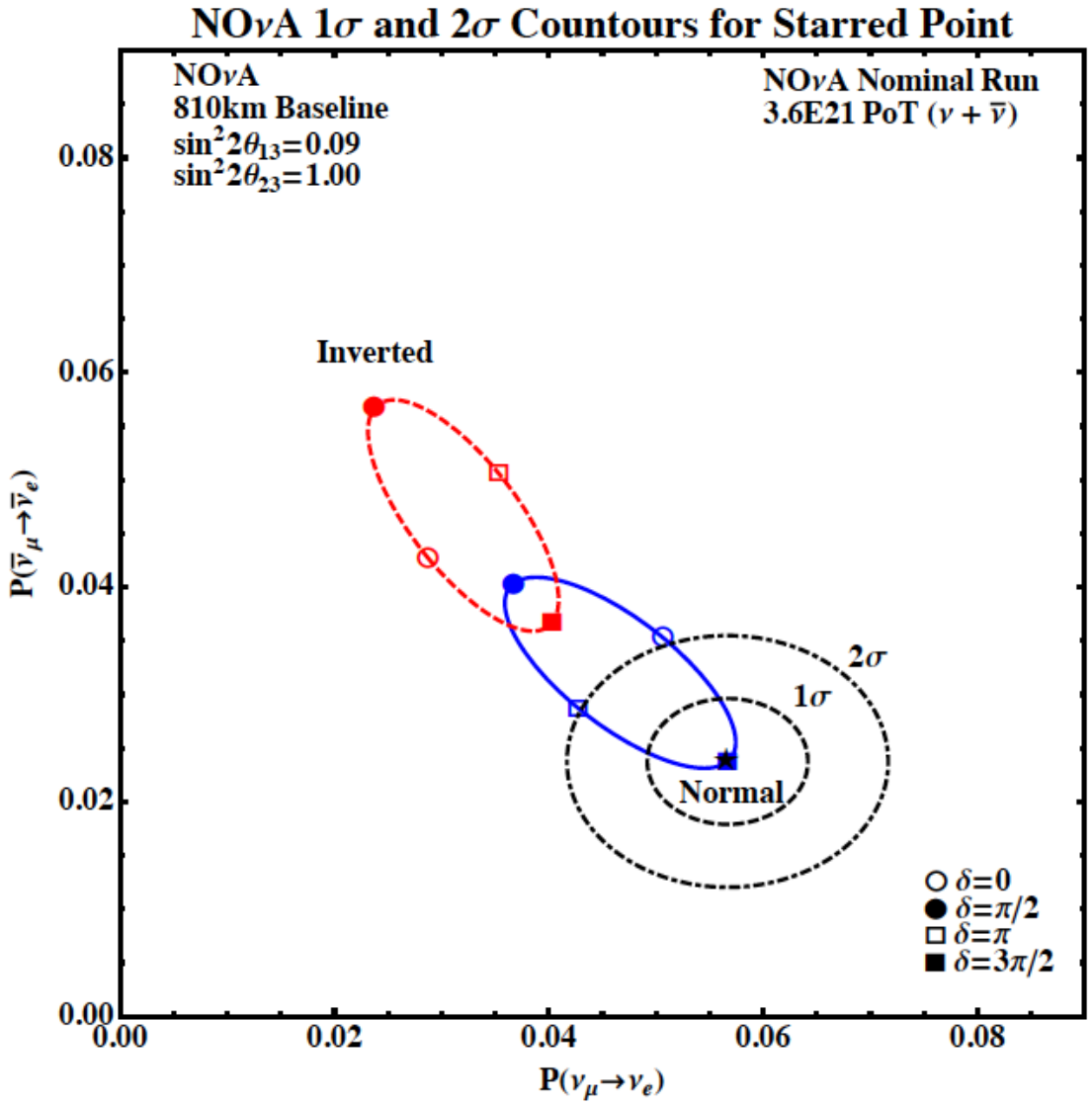
NOvA Experiment



14,000-ton *surface* far detector sited at first oscillation maximum.

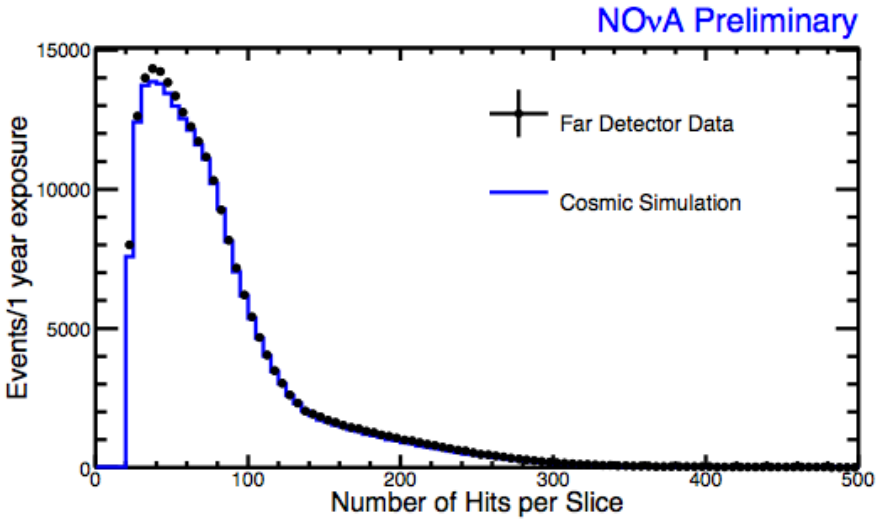
- Totally active, low Z, range stack/calorimeter.
- Liquid scintillator filled PVC.
- 896 alternative X-Y planes.
- "Largest plastic structure built by man".

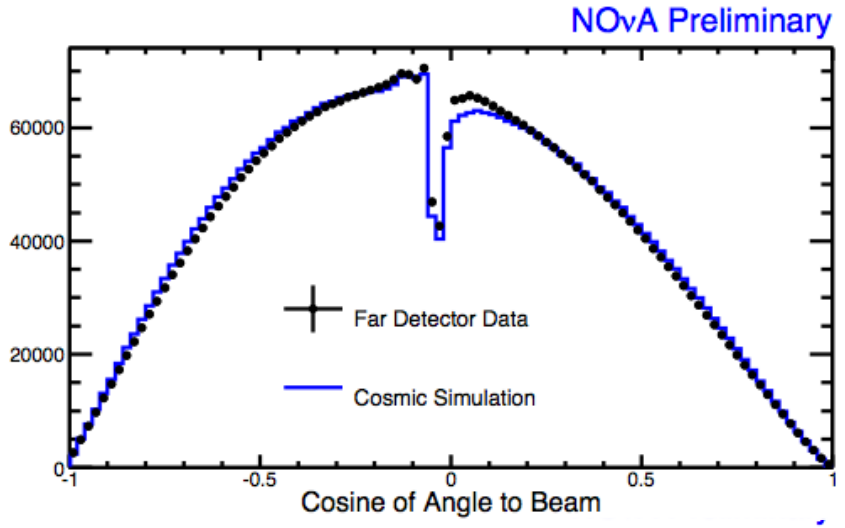
NOvA Physics



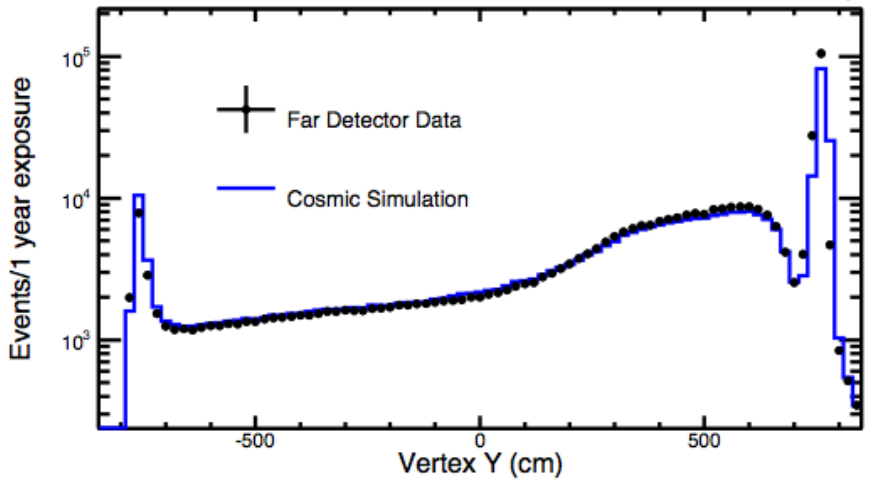
Detector

Far detector cosmic-ray data / simulation comparisons

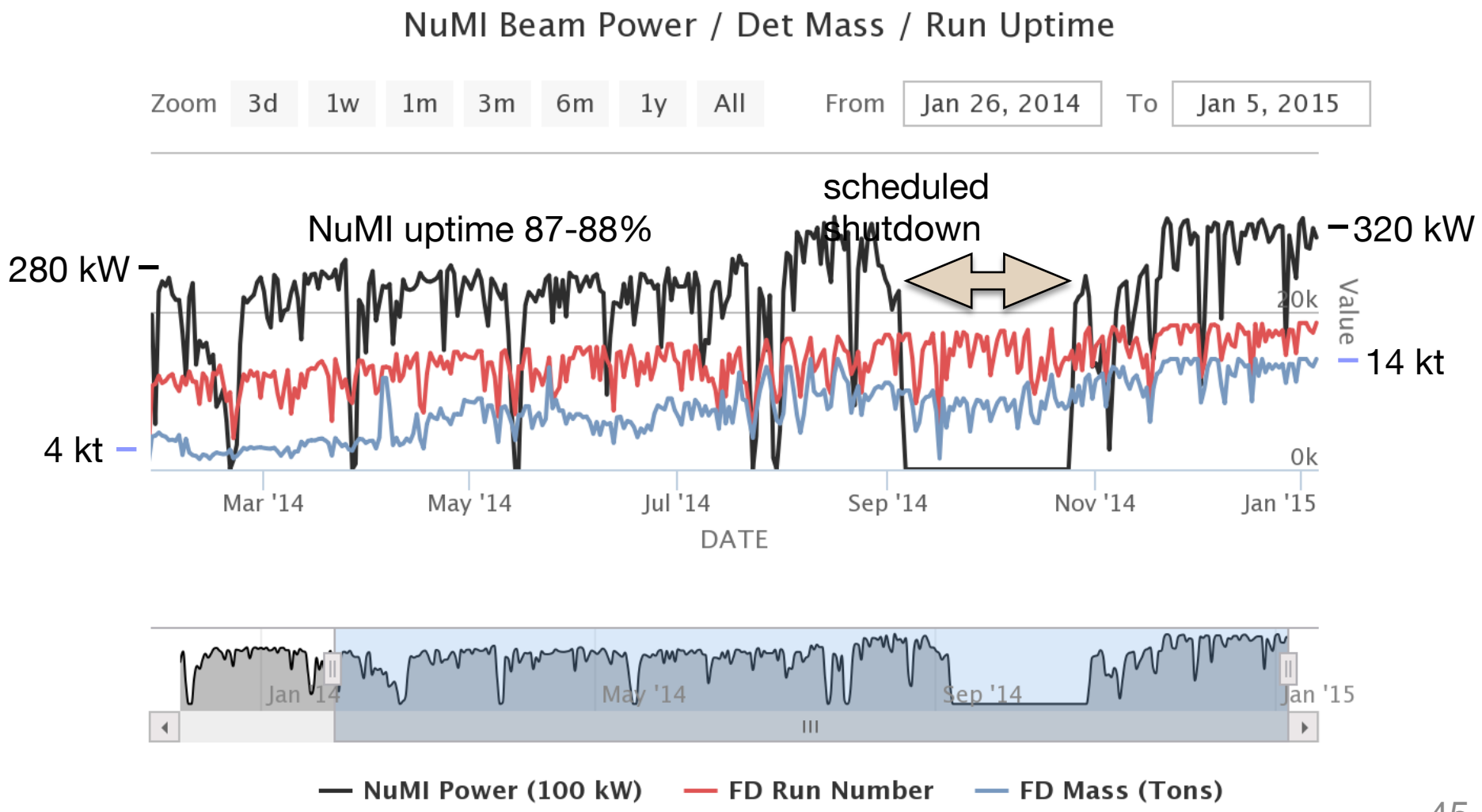




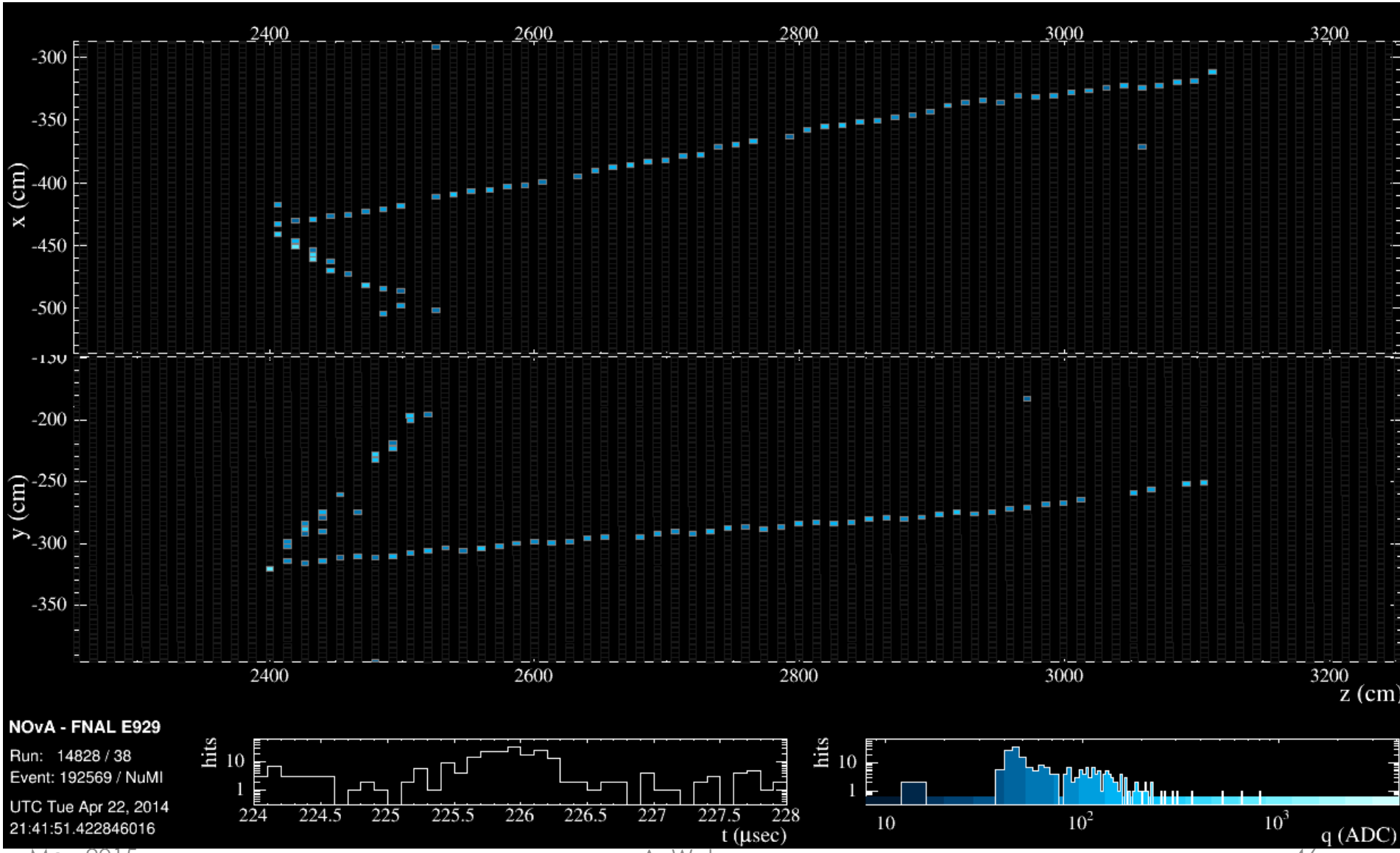
- Results from cosmic-ray fitter. Require 20 or more hits in event ("slice").
- Compare to CRY cosmic-ray simulation



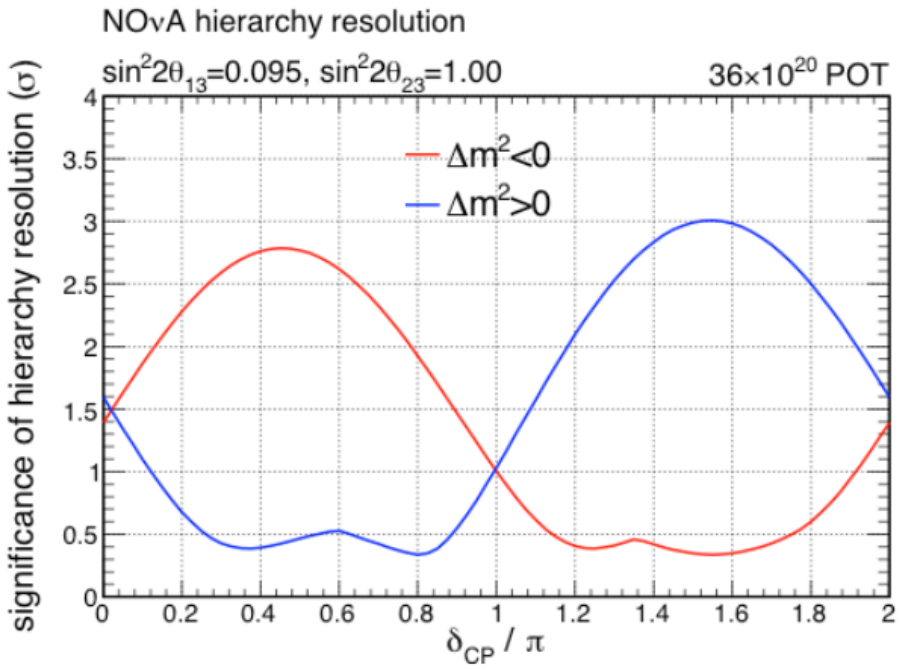
2014 - 2015 NuMI and NOvA Summary

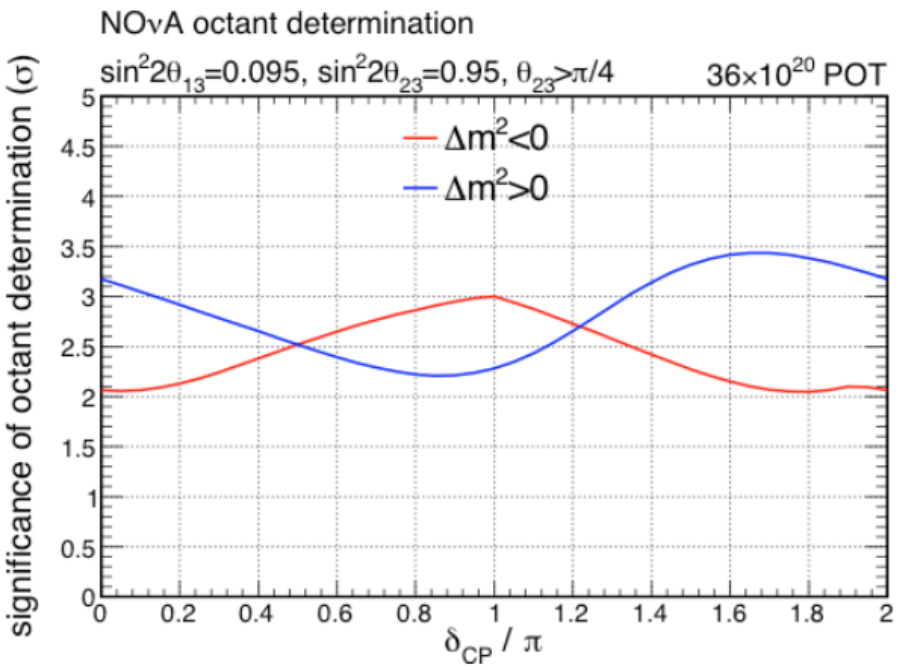


Event Display



NOvA Sensitivity





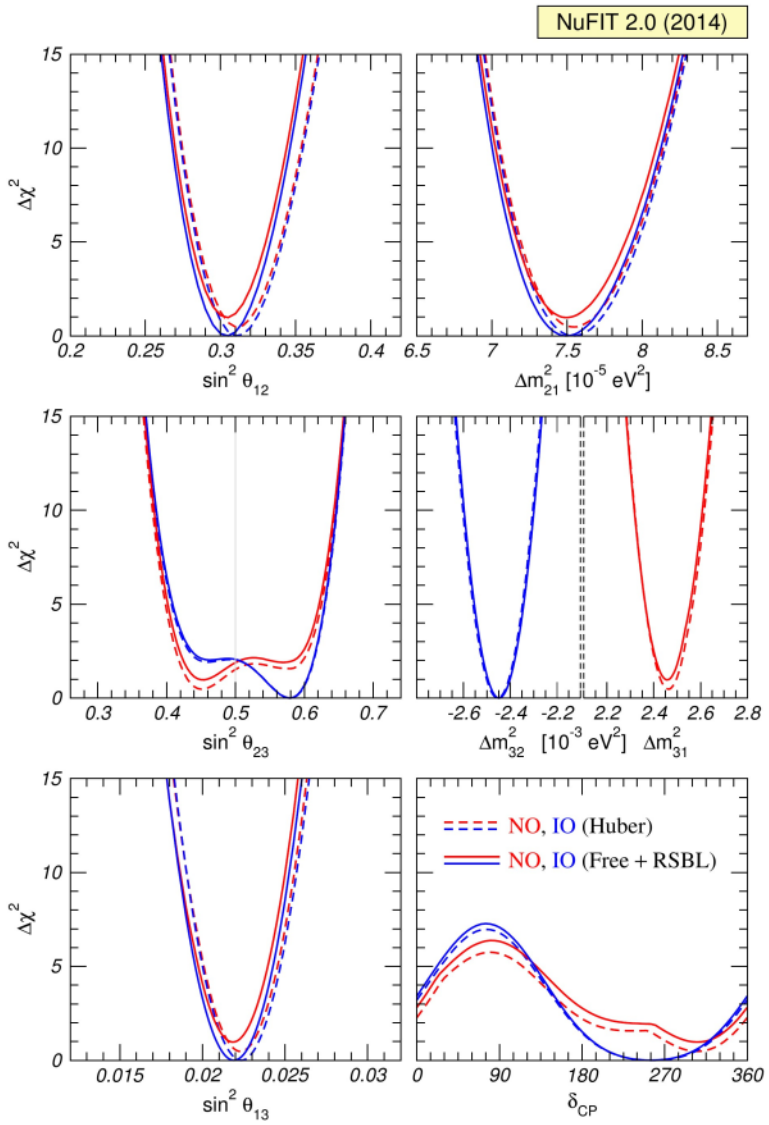
Putting it all together

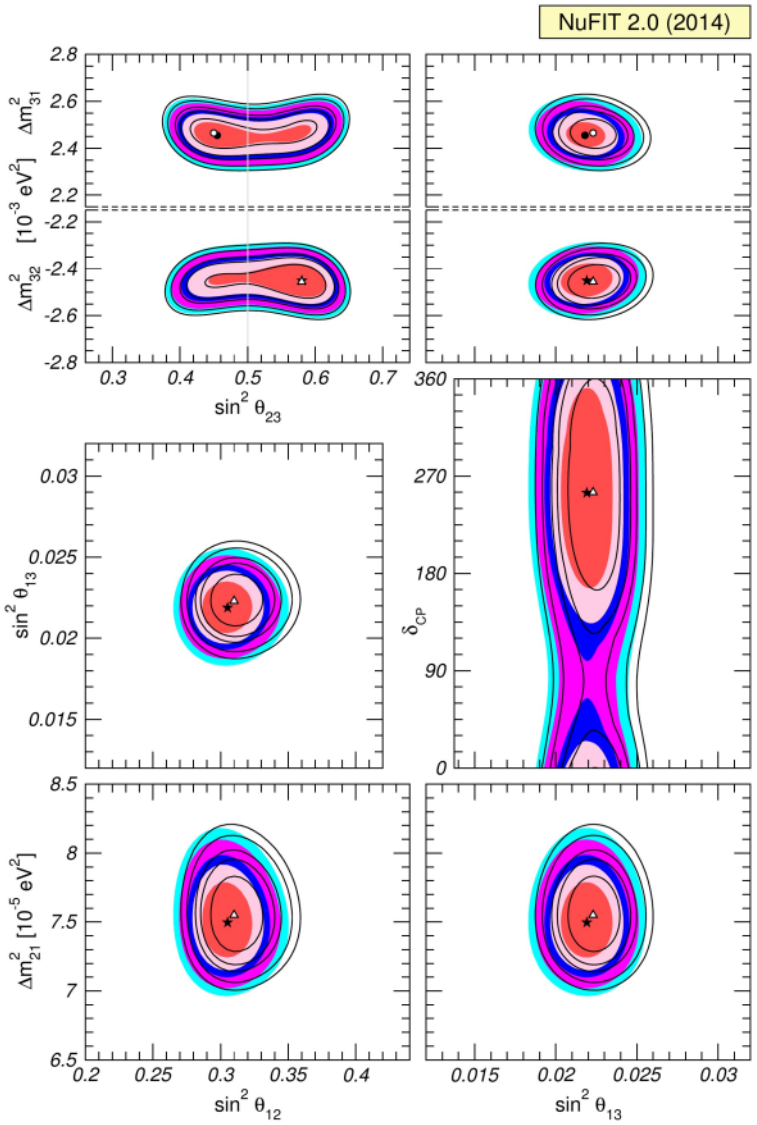
JHEP 11 (2014) 052 [arXiv:1409.5439]

NuFIT 2.0 (2014)

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{\rm CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

Global Fits


NuFIT 2.0 (2014)
$\Delta\chi^2$
$\sin^2\theta_{12}$
Δm^2_{21} [10^{-5} eV^2]
$\sin^2\theta_{23}$
Δm^2_{32} [10^{-3} eV^2] Δm^2_{31}
$\sin^2\theta_{13}$
δ_{CP}
NO, IO (Huber)
NO, IO (Free + RSBL)


NuFIT 2.0 (2014)
Δm^2_{31} [10^{-3} eV^2]
Δm^2_{32}
$\sin^2\theta_{23}$
$\sin^2\theta_{13}$
δ_{CP}
Δm^2_{21} [10^{-5} eV^2]
$\sin^2\theta_{12}$
$\sin^2\theta_{13}$

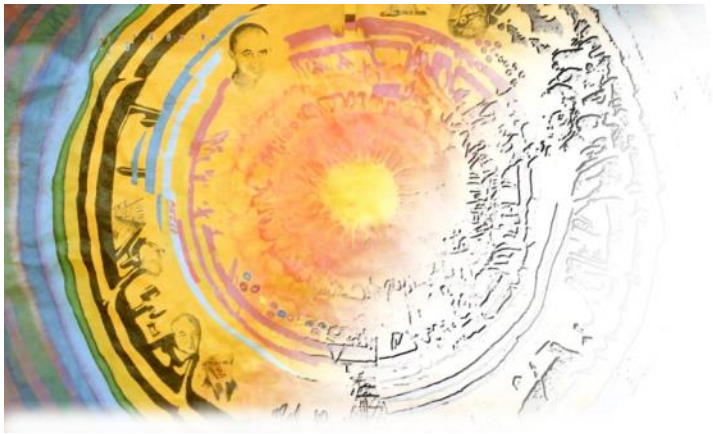
Summary

- Exciting time for Neutrino physicists
  - MINOS exploring non-standard oscillations
  - T2K looking for CPV
  - NOvA soon starting to constrain mass hierarchy
- Precision measurements from
  - Solar neutrino experiments
  - Atmospheric neutrinos
  - Reactor Experiments
  - Accelerator based long baseline experiments
- Have an almost consistent picture
  - Ignoring some SBL oddities
- Next generation of experiments (>2022)
  - Steaming ahead

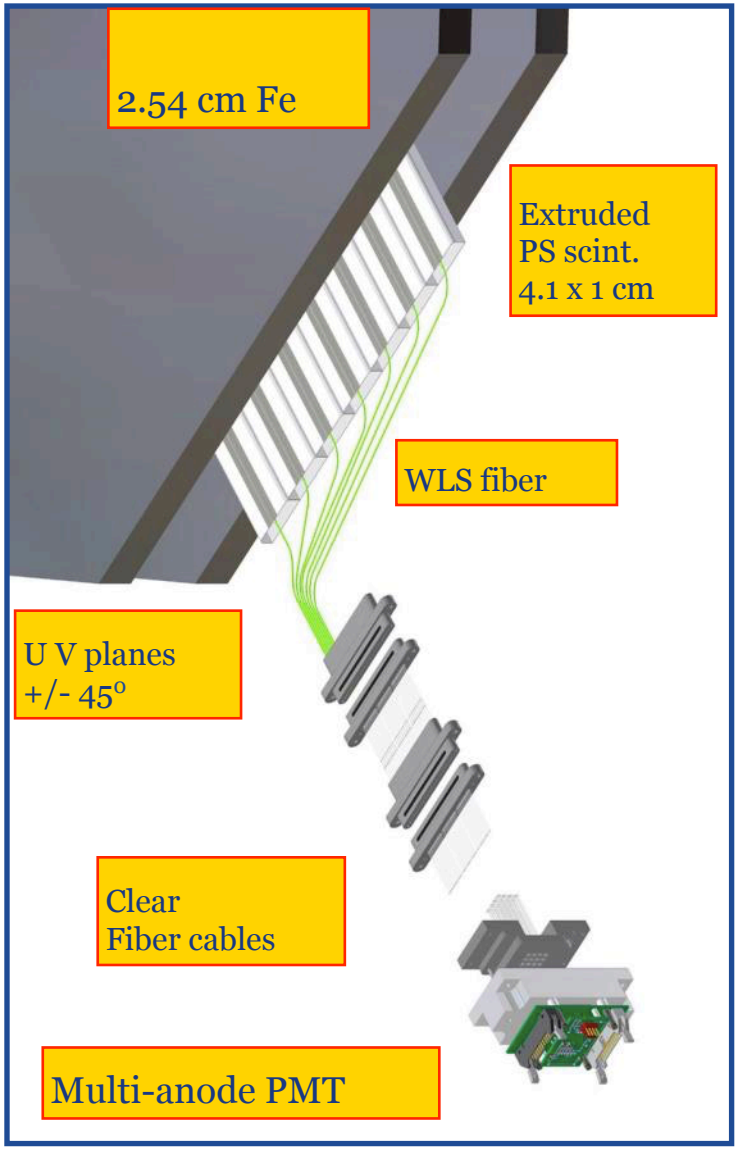
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Oxford Physics

Backup



MINOS Technology



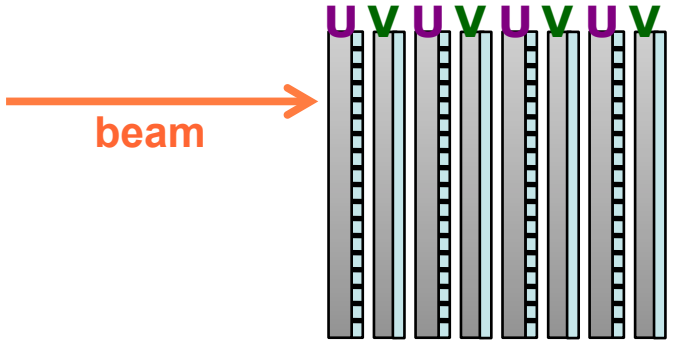
Steel thickness: 2.54 cm (~1.4 rad. lengths)

Strip width: 4.1cm
Moliere radius ~3.7cm

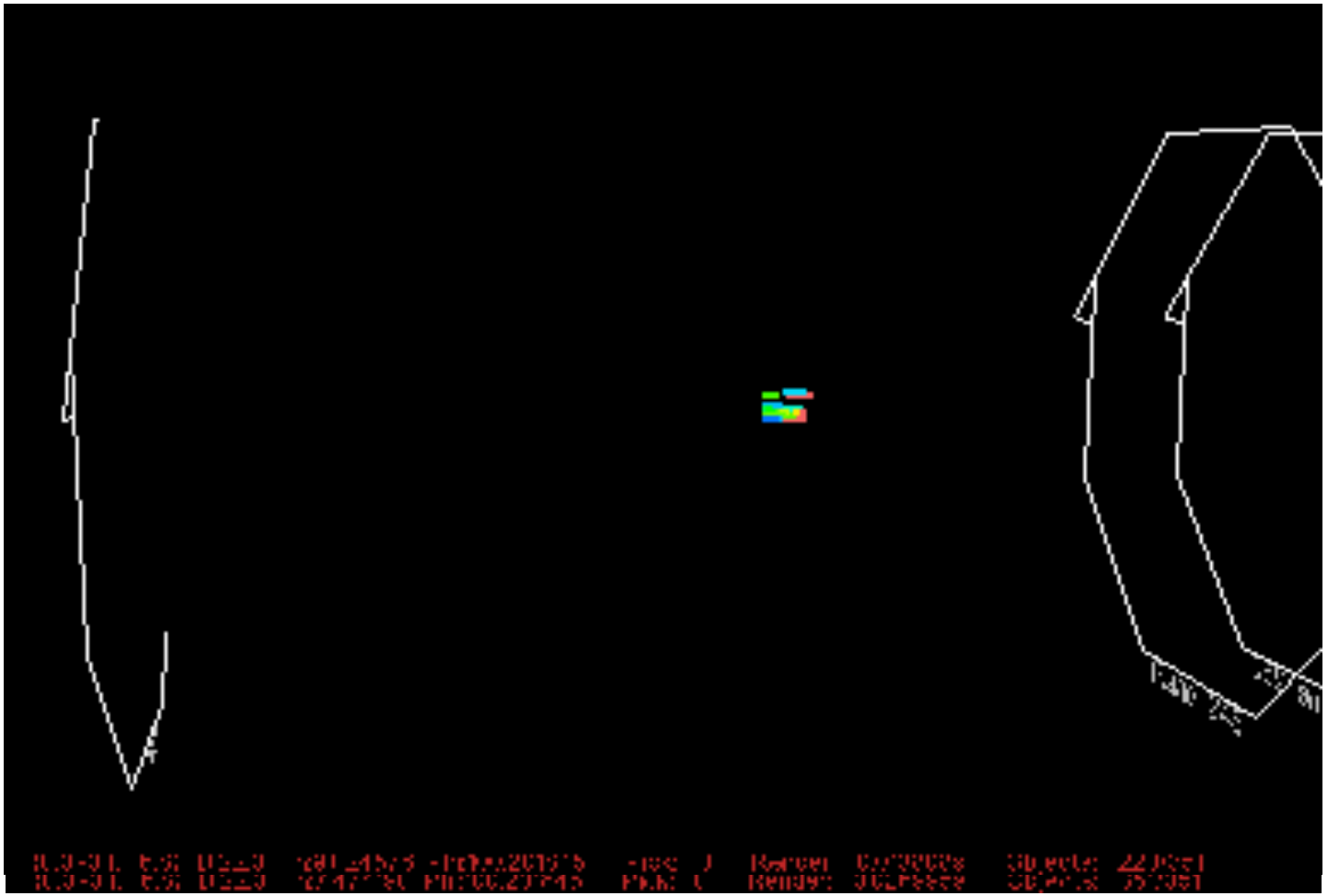
Strips in adjacent planes are oriented orthogonally enabling 3D reconstruction

Each strip is read out by a wavelength shifting fiber connected to a multi-anode photomultiplier tube

U/V strips oriented ±45° from vertical



MINOS Far Detector

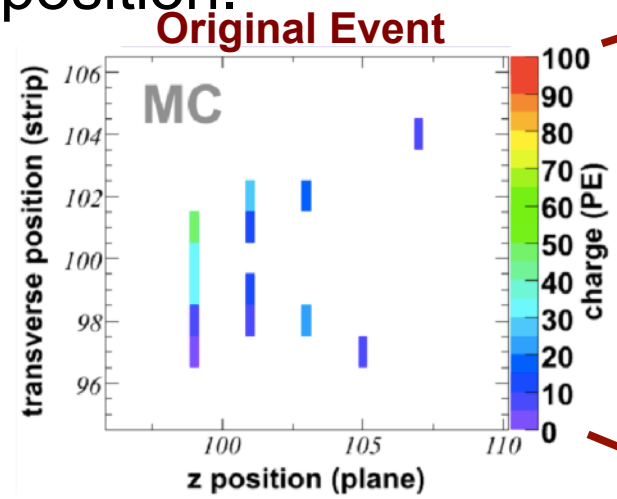


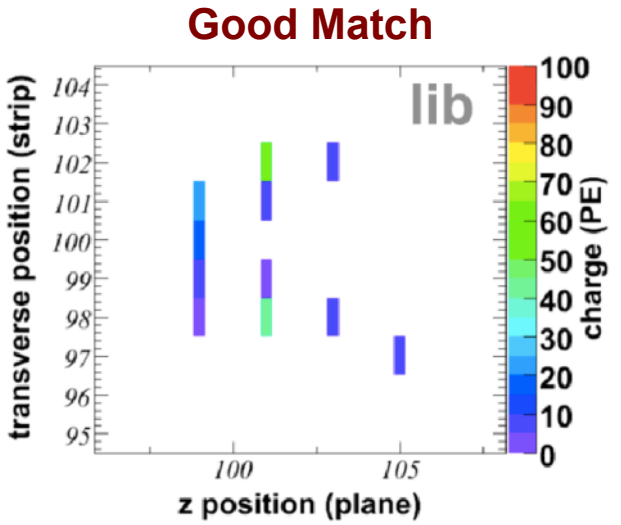
What it sees

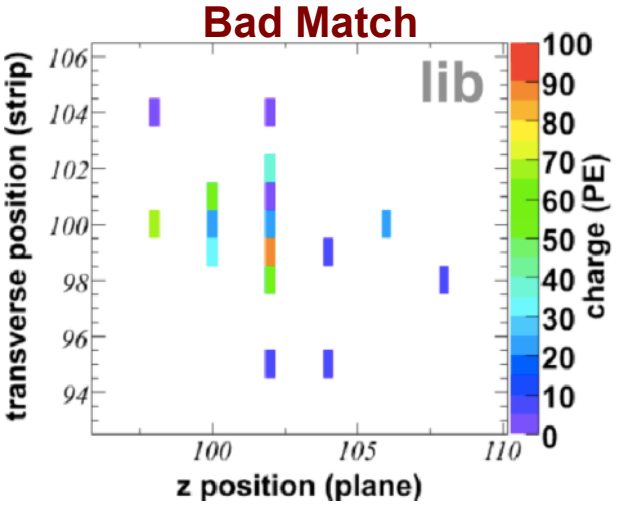
What we reconstruct

Event Matching

Each input event is compared to the library events by calculating the likelihood that the photoelectrons in each event came from the same energy deposition.





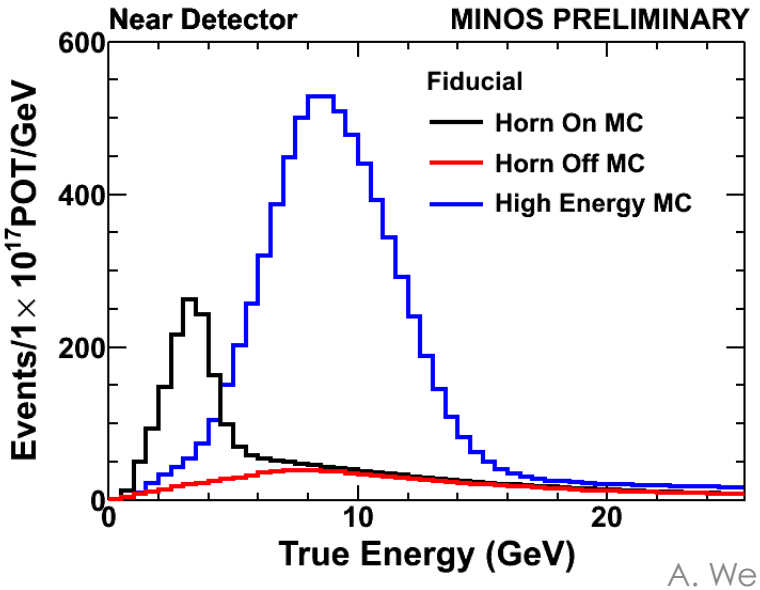


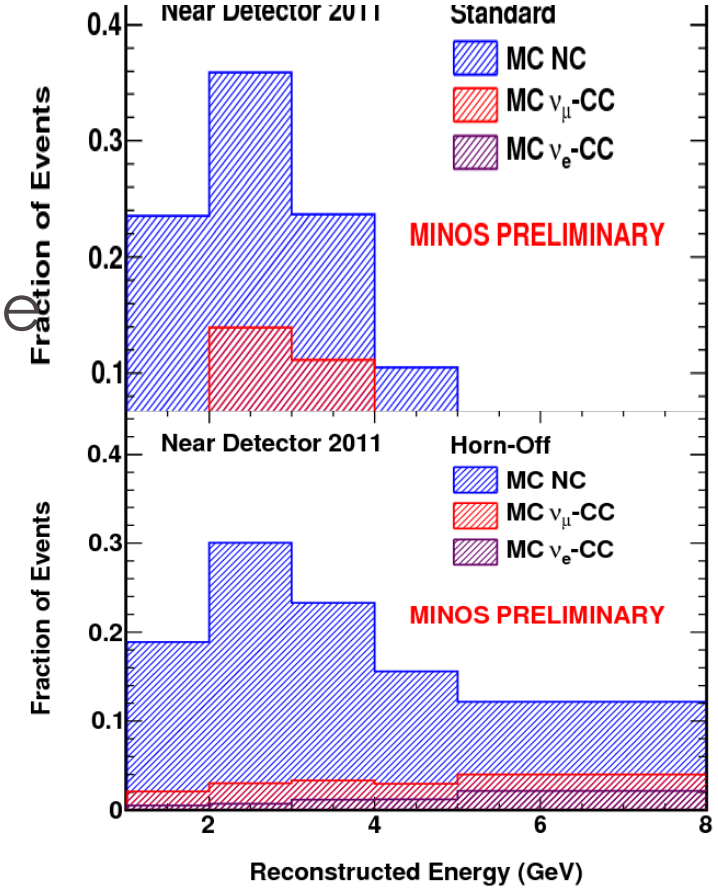
The library consists of:

- 20 million signal events
- 30 million background (NC) events

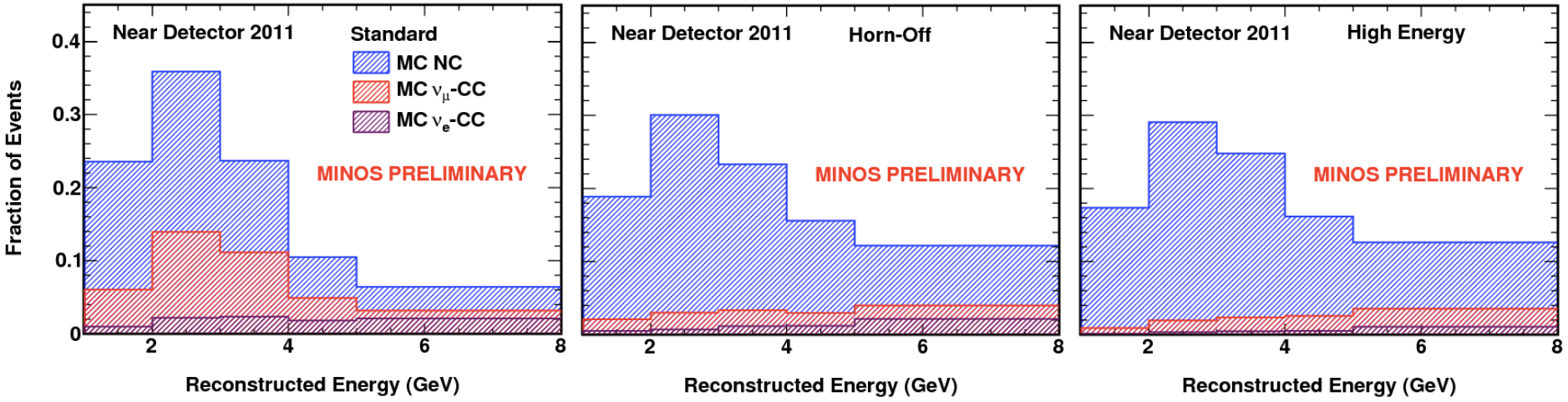
Electron Neutrino Appearance

- Selected ND data comprised of NC, ν_μ CC, and beam ν_e events
- Each extrapolates to FD differently
- Use ND data in different configurations to extract relative components of background





Data-Driven BG



Use these 3 data sets to measure the 3 background components in the standard sample...

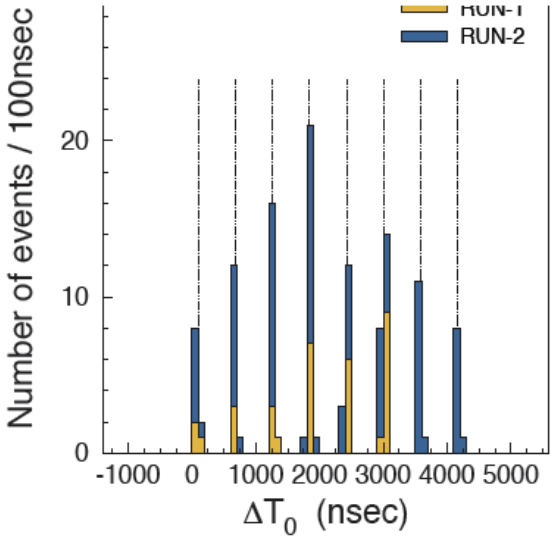
Using:

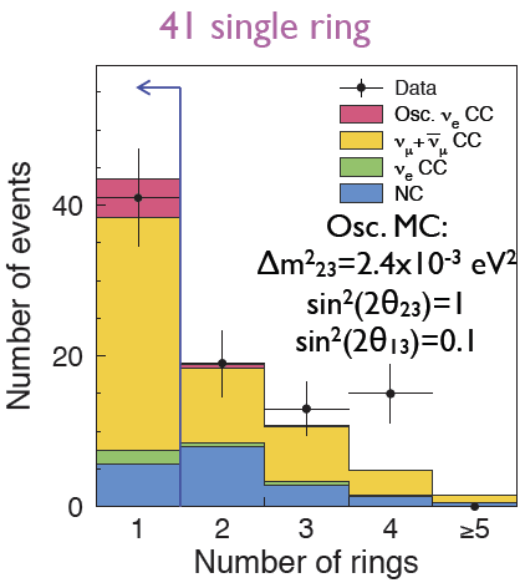
- Total measured rate in each beam configuration
- Relative interaction rates for each background component from the MC simulation

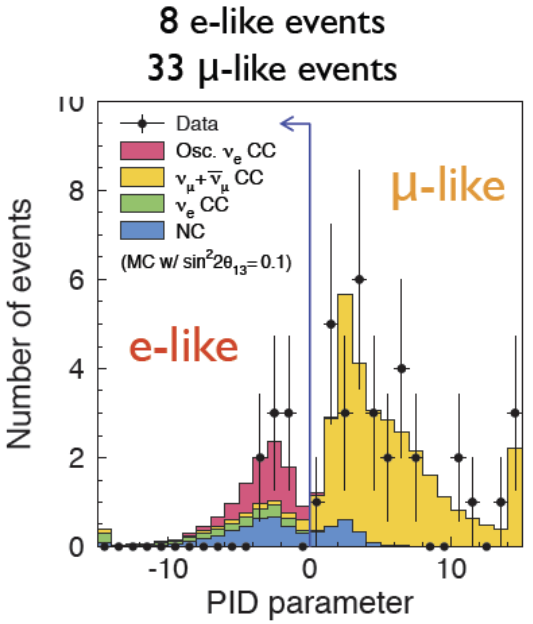
Can fit for the background components in the standard sample

Selecting Events in SK

- Select events
  - fully contained
  - Consistent with expected arrival time
  - 1ring
  - muon like
- Compare energy spectrum with expectation
  - Beam simulation
  - Near detector measurement







Electron Neutrino Selection