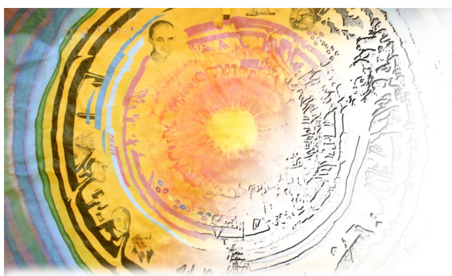
New Results from Long Baseline Neutrino Oscillation Experiments



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Overview

- Introduction
- The Experiments
  - MINOS
  - T2K
- Measurements
  - Disappearing muon neutrinos
  - Appearing electron neutrinos
- Global Analysis
- Summary

Neutrino Mixing
The PMNS Matrix

Pontecorvo-Maki-Nakagawa-Sakata

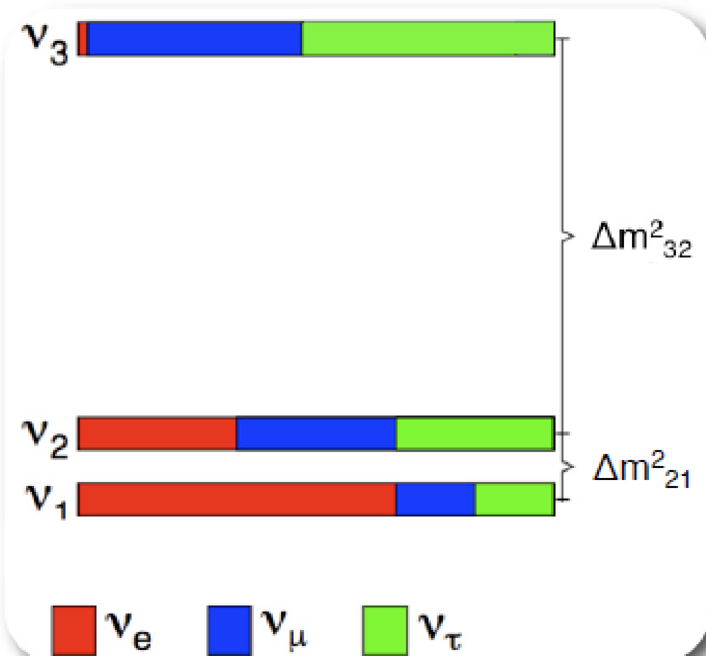
- Assume that neutrinos do have mass:
  - mass eigenstates ≠ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

weak
“flavour eigenstate

Mass eigenstates
m_1, m_2, m_3

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \left(\cdots \quad \begin{matrix} s_{12} & 0 \\ c_{12} & 0 \\ 0 & 1 \end{matrix} \right) \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, s … $m_{ij}^2 = \text{mass}^2$ difference



Neutrino Oscillations

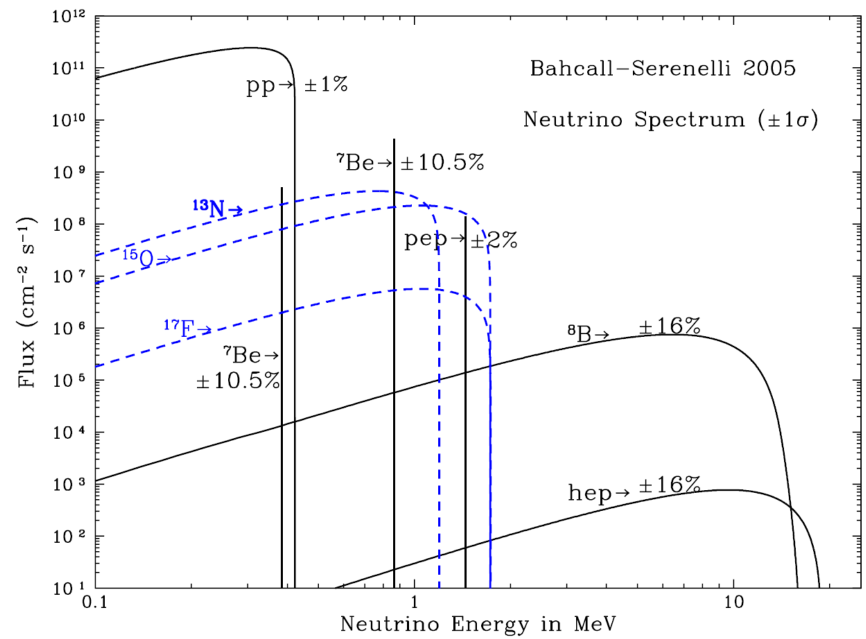
- If mass and weak eigenstates are different:
  - Neutrino is produced in weak eigenstate
  - It travels a distance L as a mass eigenstate
  - It will be detected in a (possibly) different weak eigenstate

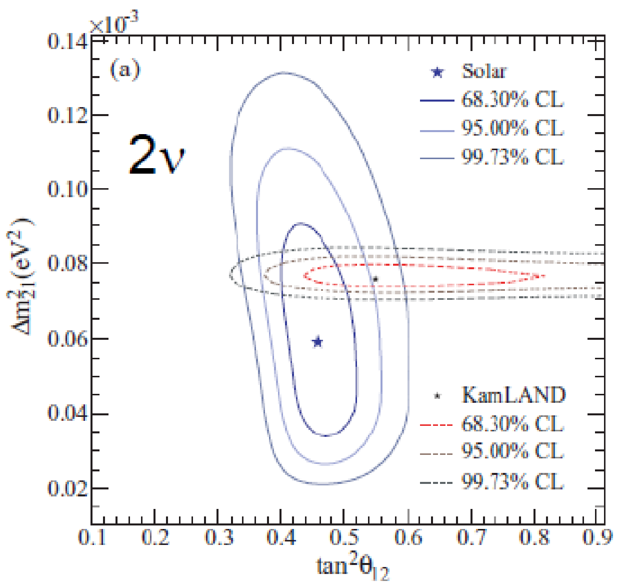
$$\nu_\mu \longrightarrow \underset{\nu_1,\nu_2,\nu_3}{\longrightarrow} \longrightarrow \nu_\mu,\ \nu_e \text{ or } \nu_\tau$$

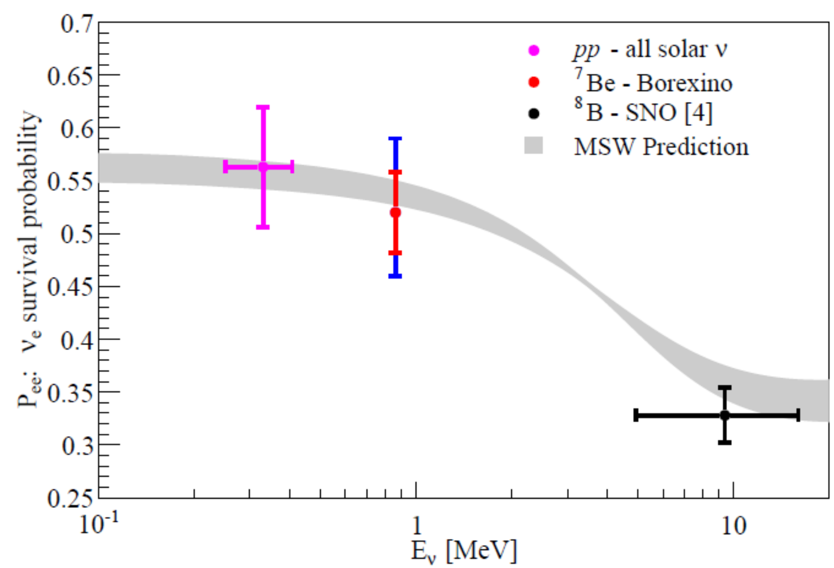
$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_e \to \nu_x) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Measuring "Solar" Neutrinos

- Neutrinos are produce in the sun via nuclear fusion
- Only a small fraction of the expected neutrinos flux is detected on earth
- Electron neutrinos disappear
  - Solar matter effects are important
- Same disappearance observed in electron anti-neutrinos from reactors





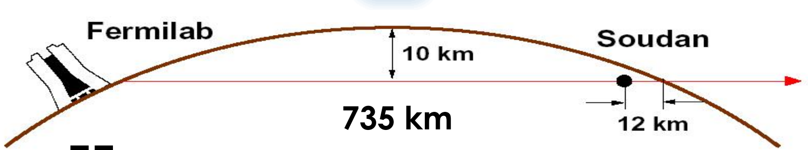


Two Main Experiments

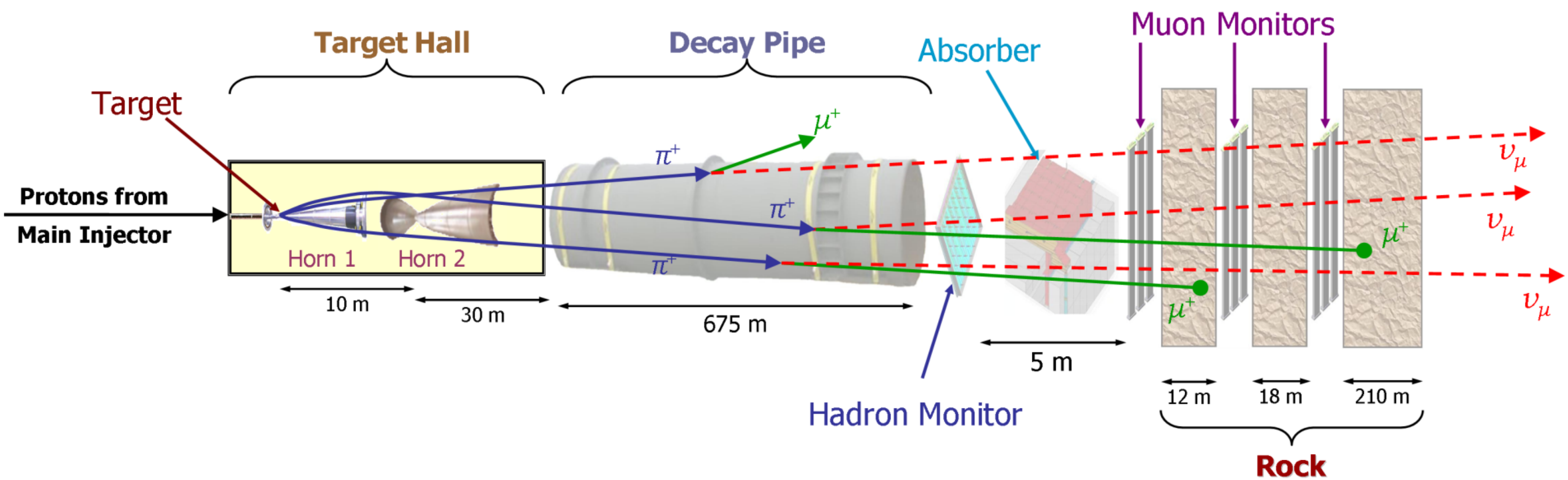
- MINOS
  - Mature experiment taking data since 2005
  - Beam generated by Main Injector at Fermilab
  - Far Detector close to Canadian border in Soudan Underground mine
- T2K
  - Started taking data in 2010
  - Beam generated at J-PARC
    - New accelerator centre on Japanese east coast
  - Far detector is SuperKamiokande
    - on the Japanese west coast
    - Mature detector taking data since many years

Experimental Setup

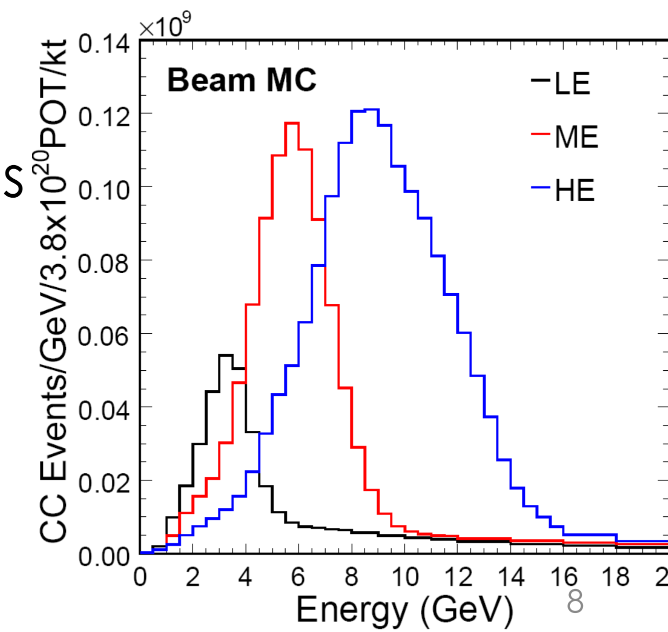
- **MINOS (Main Injector Neutrino Oscillation Search)**
  - A long-baseline neutrino oscillation experiment
  - Near Detector at Fermilab to measure the beam composition
  - Far Detector deep underground in the Soudan Underground Lab, Minnesota, to search for evidence of oscillations



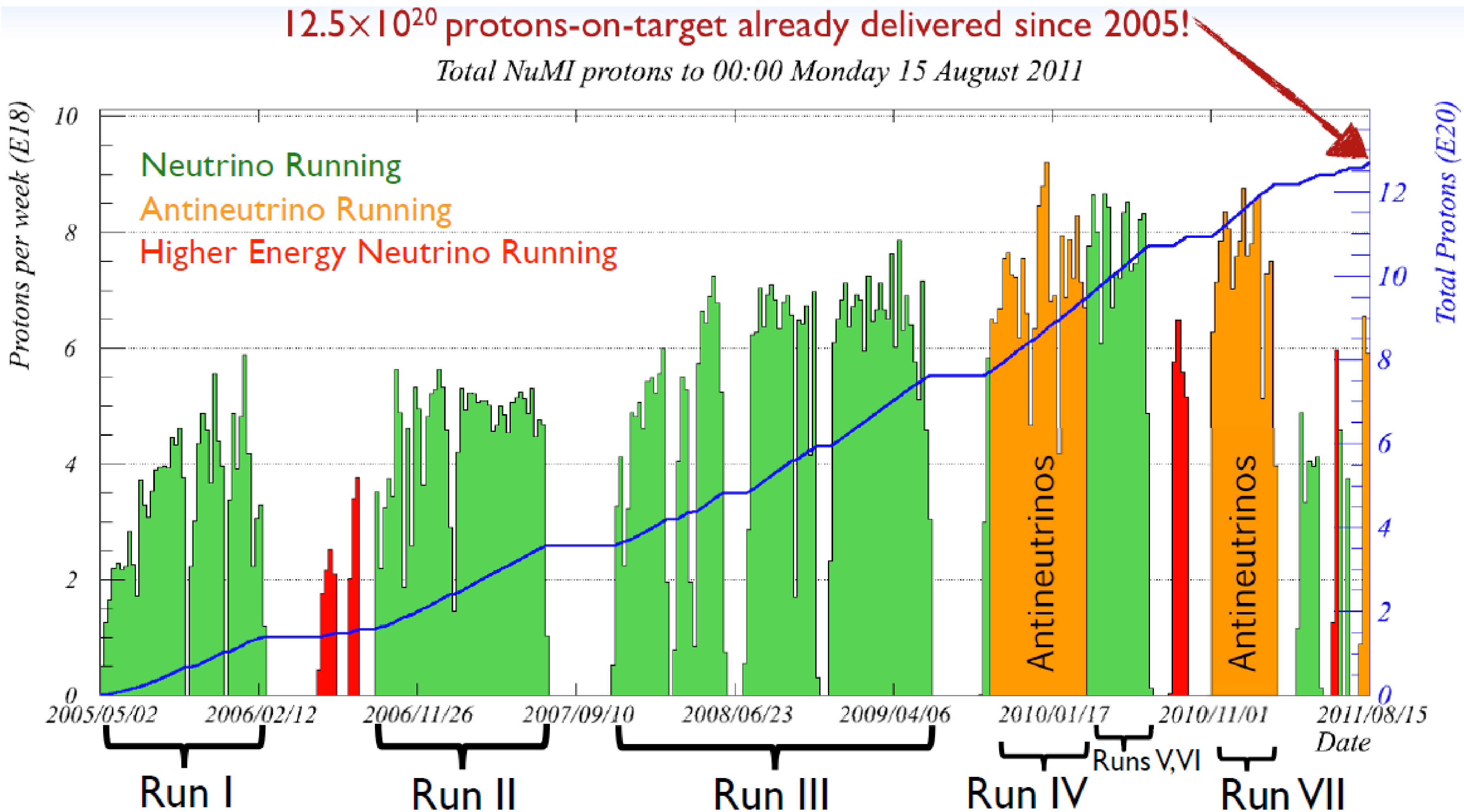
Making Neutrinos



- 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

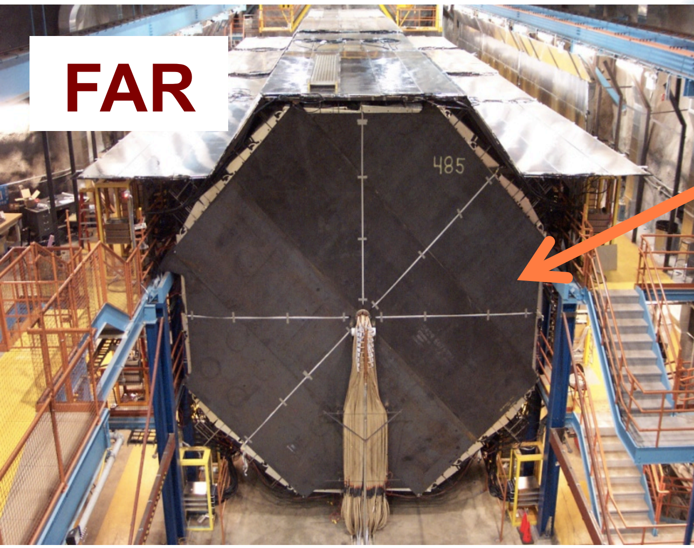


Protons on Target



MINOS Detectors

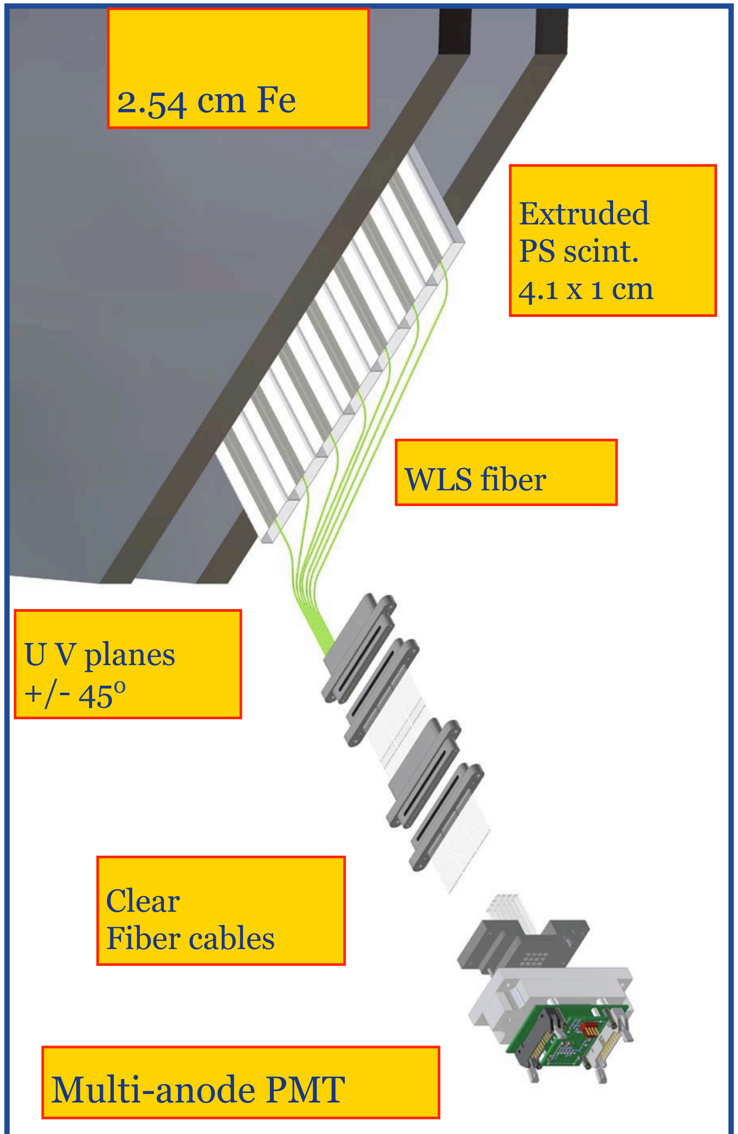
alternating layers of steel plates and scintillator strips in a ~1.3 T toroidal magnetic field



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

MINOS Technology



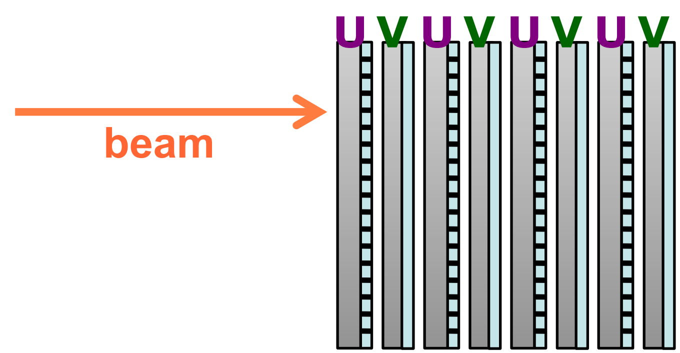
Steel thickness: 2.54 cm (~1.4 rad. lengths)

Strip width: 4.1cm
Moliere radius ~3.7cm

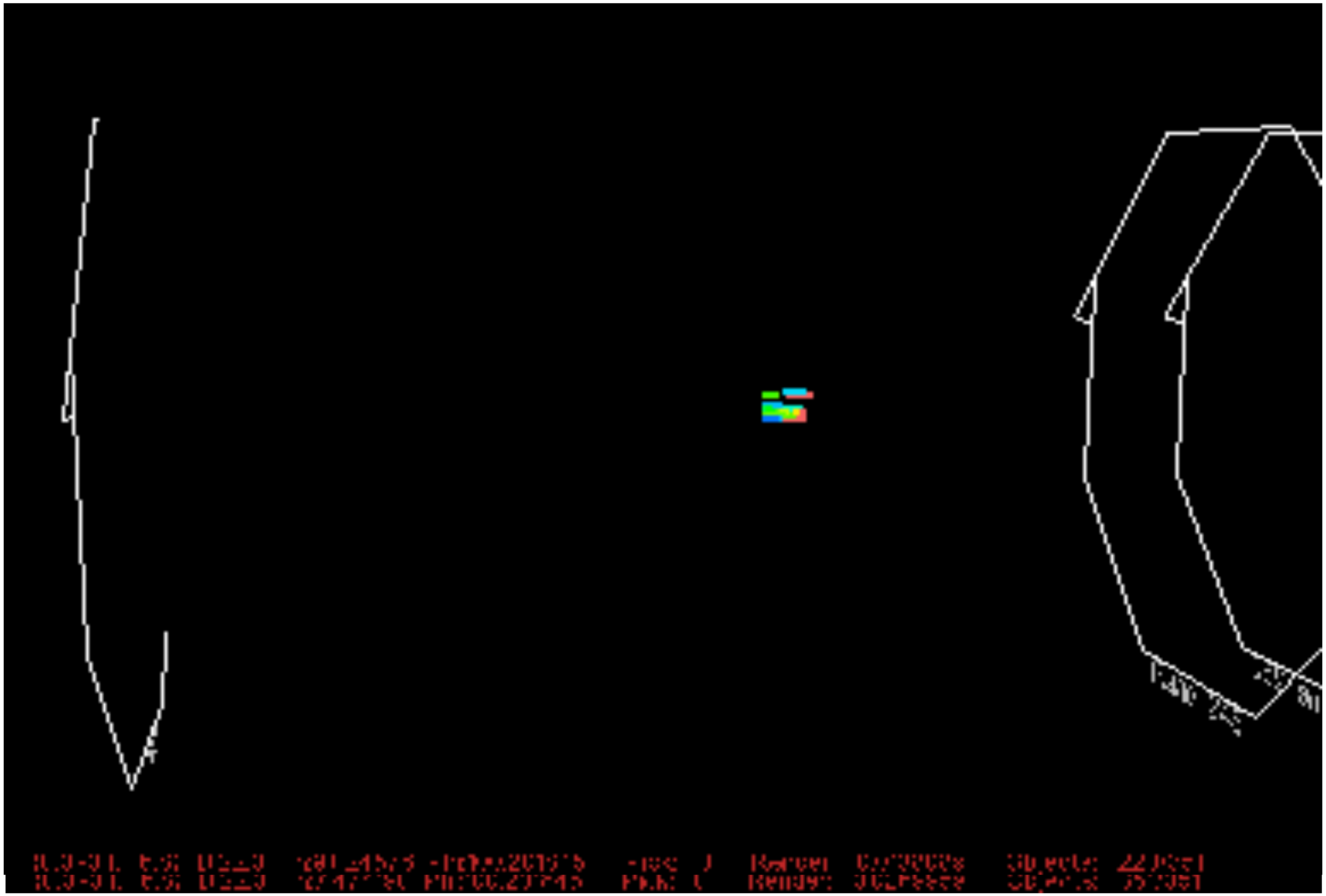
Strips in adjacent planes are oriented orthogonally enabling 3D reconstruction

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



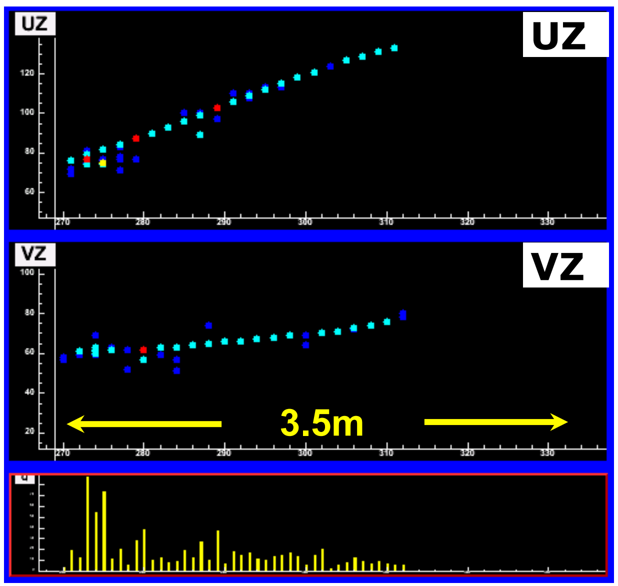
What it sees

What we reconstruct

Event Topologies

Monte Carlo

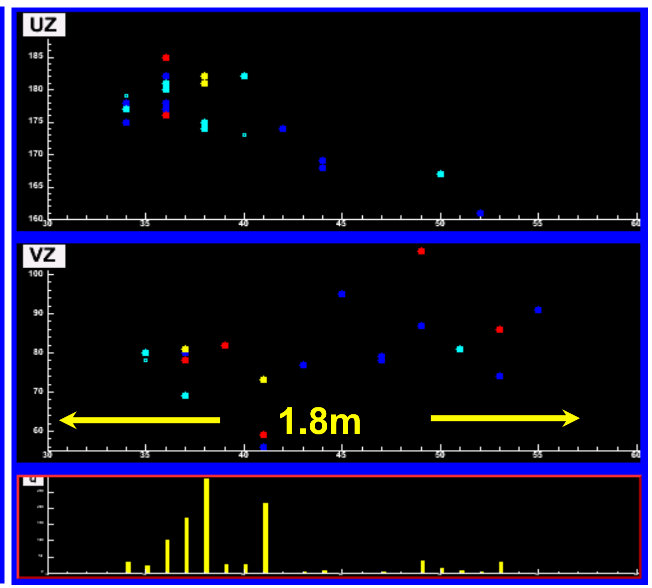
ν_μ CC Event



long μ track & hadronic activity at vertex

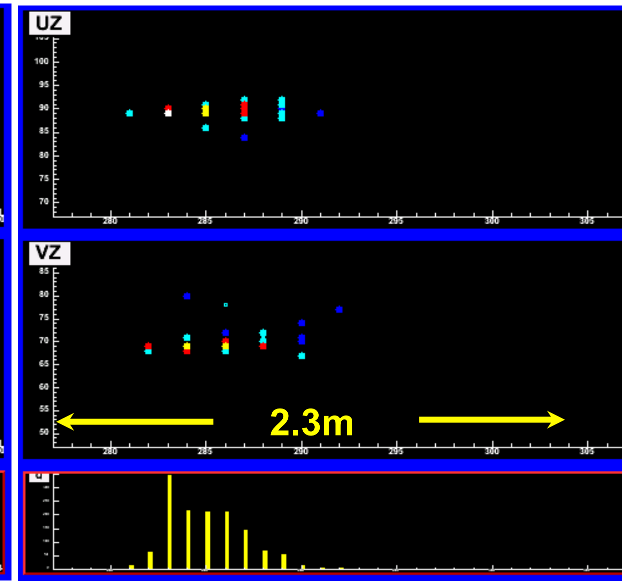
$$E_\nu = E_{shower} + p_\mu$$

NC Event



short event, often diffuse

ν_e CC Event



short, with typical EM shower profile

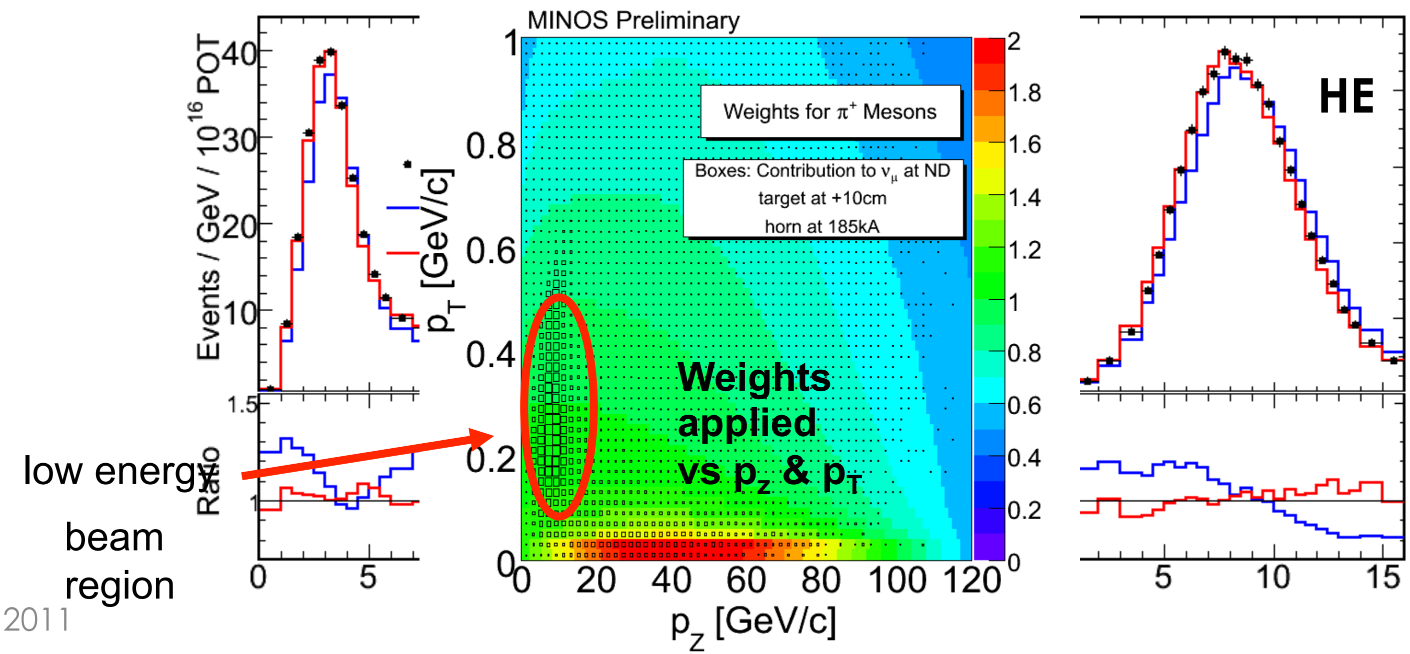
Energy resolution

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

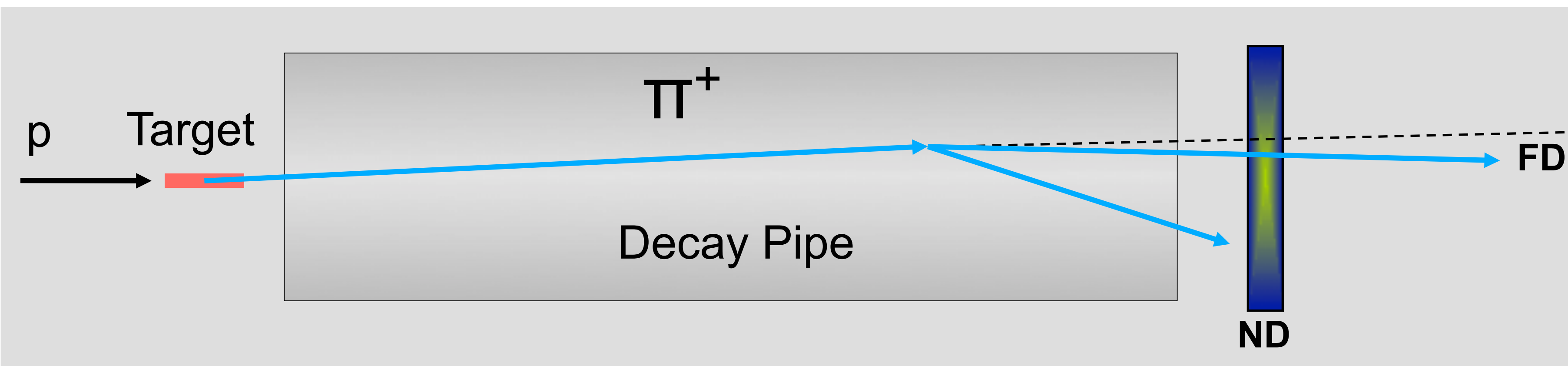
MINOS SEARCH FOR MUON NEUTRINOS

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

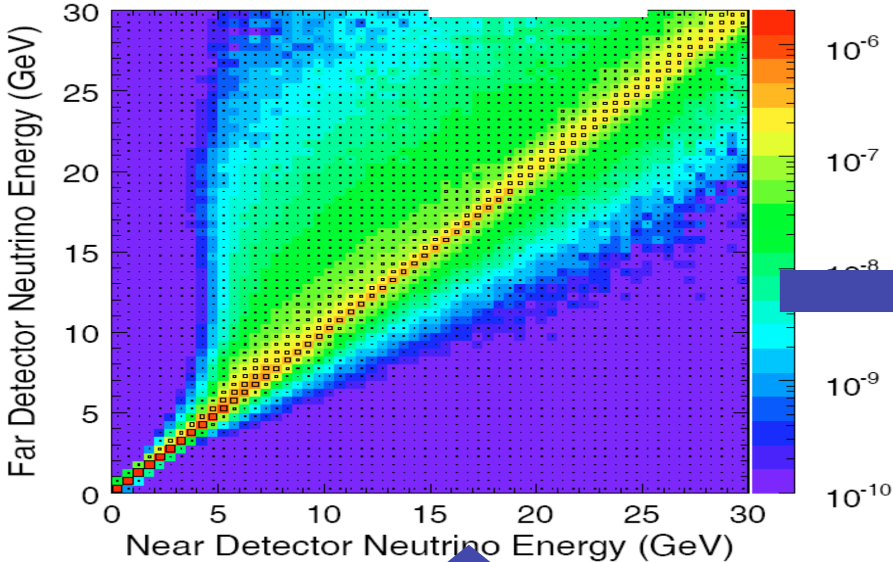


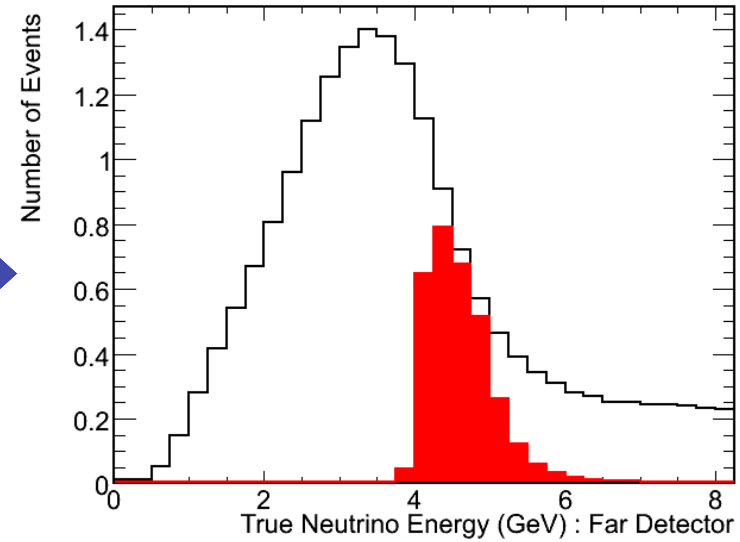
Predicting the FD Spectrum

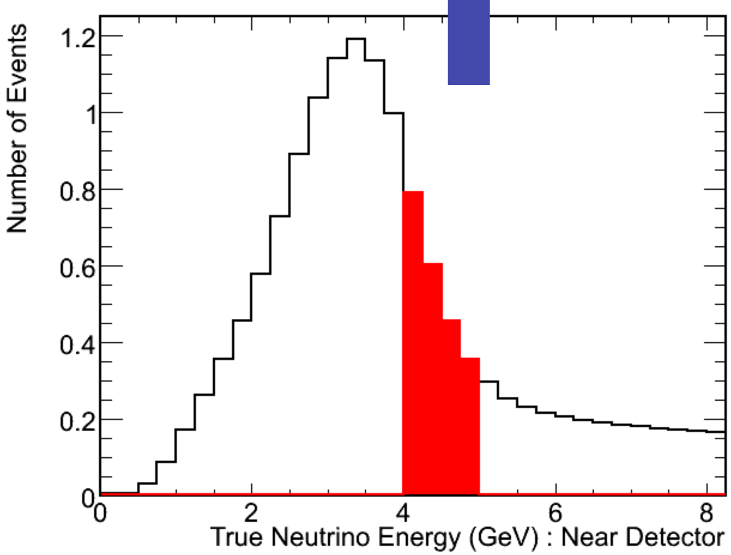


$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 \qquad E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

Near to Far Extrapolation

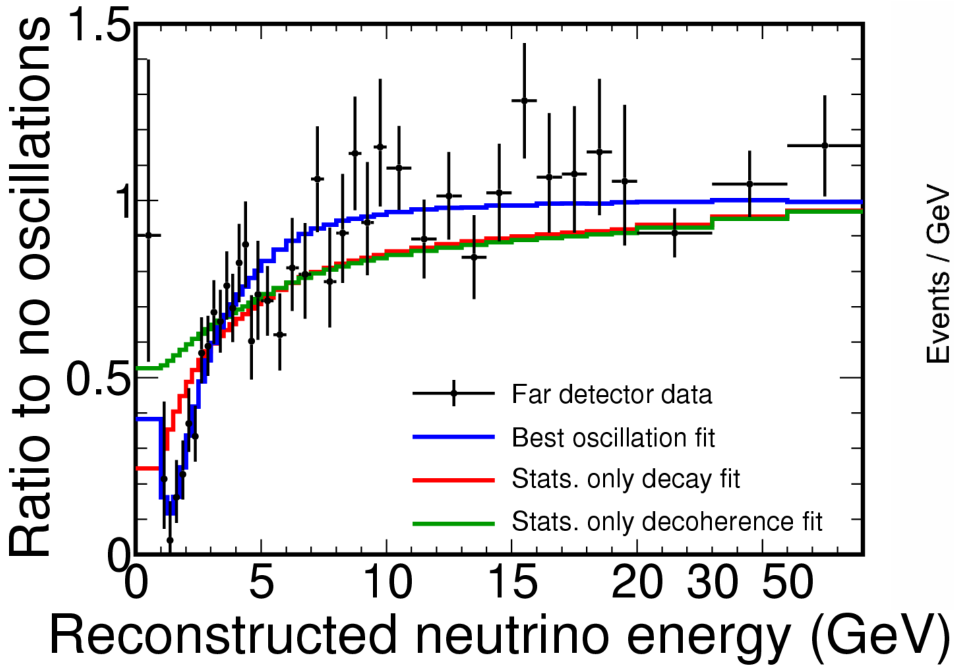


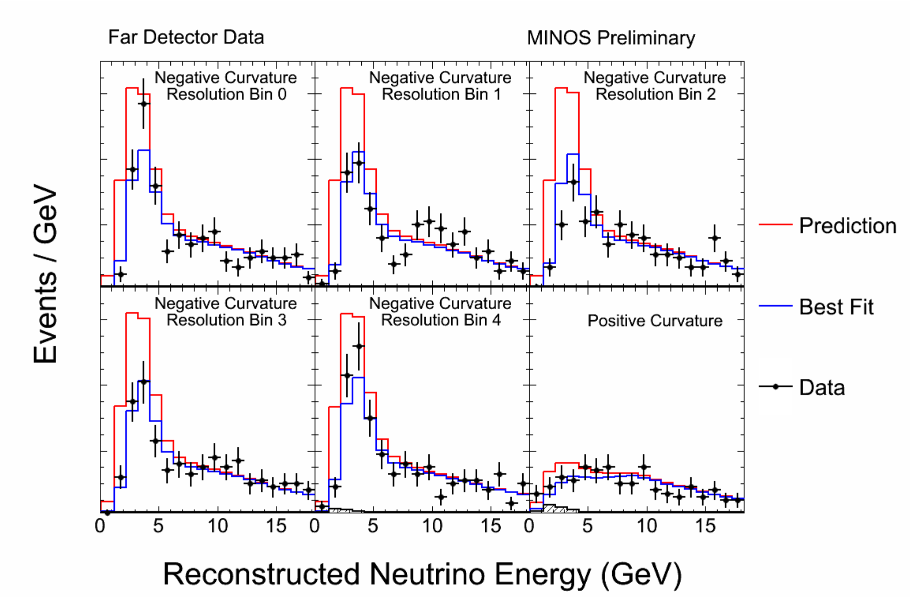




- Pion/Kaon decay kinematics are encapsulated in matrix
- Measured ND spectrum is transported to FD
- Largely reduce systematics
  - hadron production
  - cross section

Spectrum





Expect 2451 without oscillations

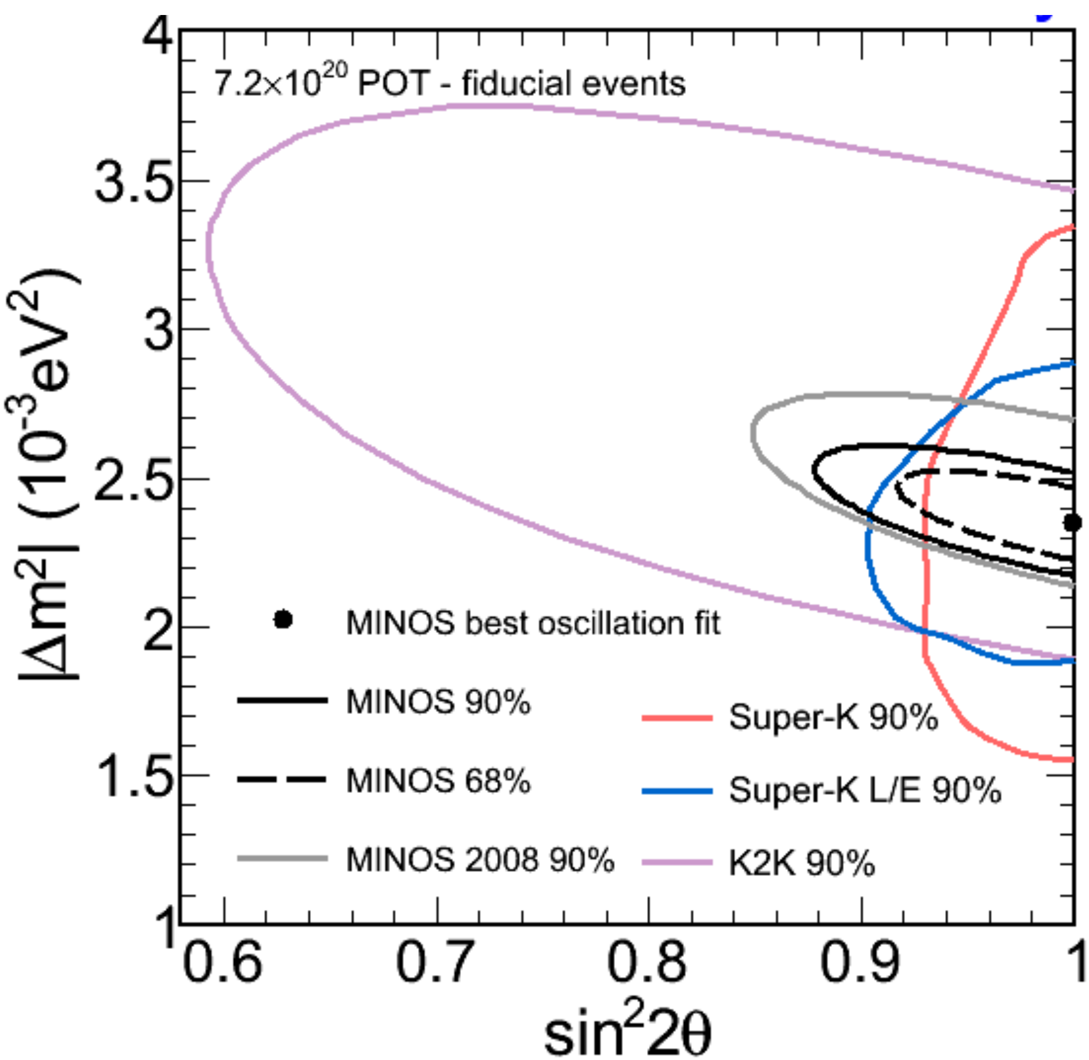
includes ~1 CR μ, 8.1 rock μ, 41 NC, ~3 ν_τ BG

See only 1986 in the FD.

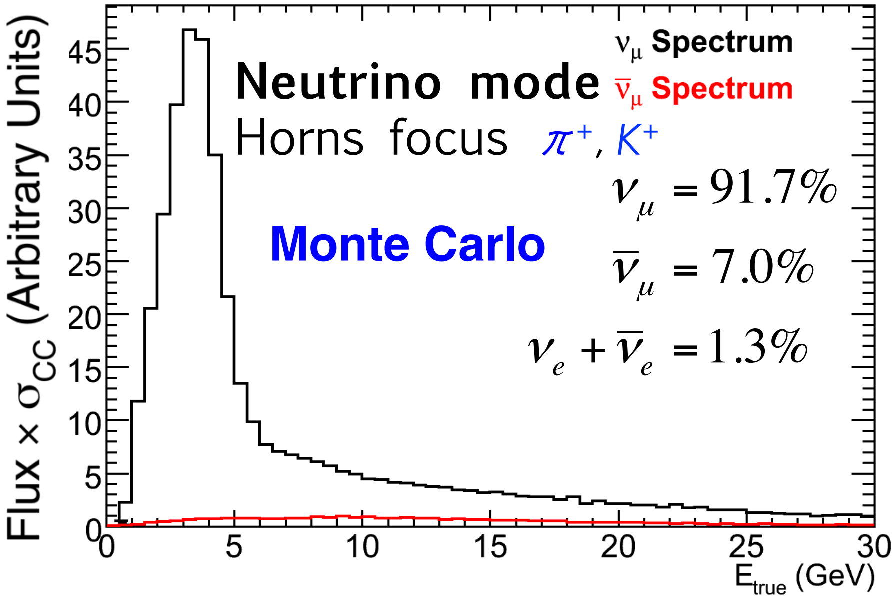
Split up sample into five bins by energy resolution, to let the best resolved events carry more weight (plus a sixth bin of wrong-sign events)

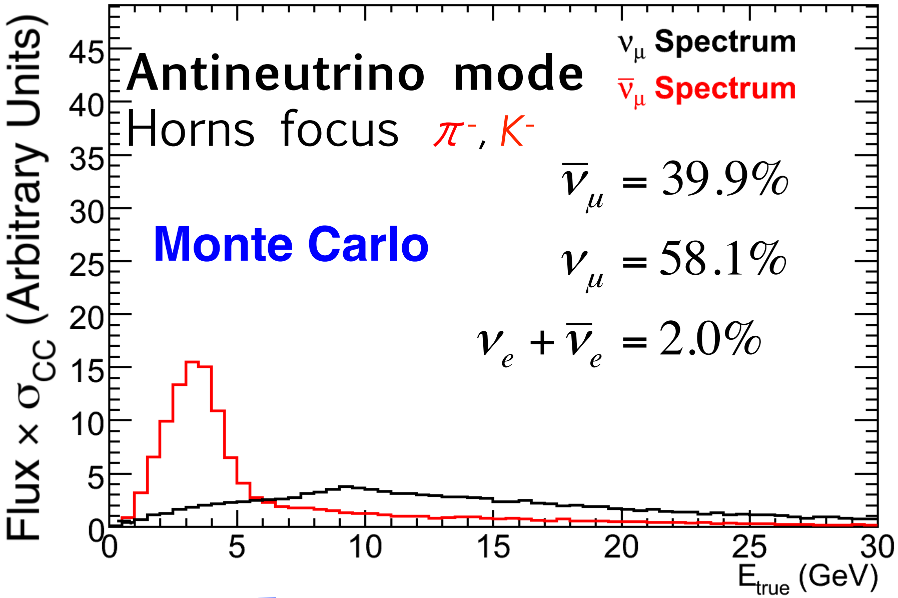
Fit everything simultaneously…

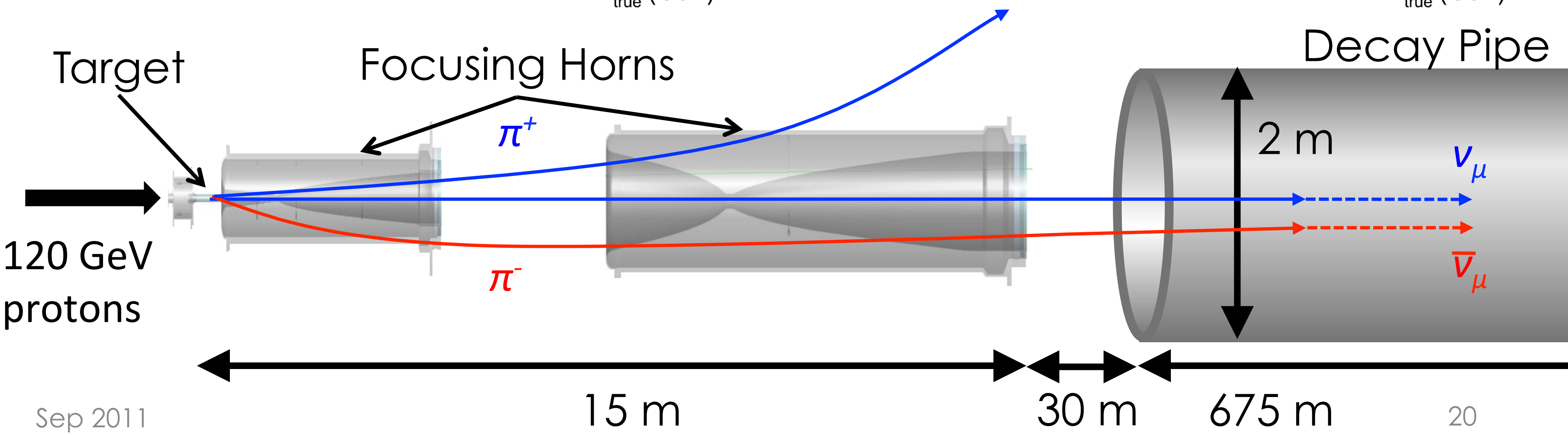
Allowed Region



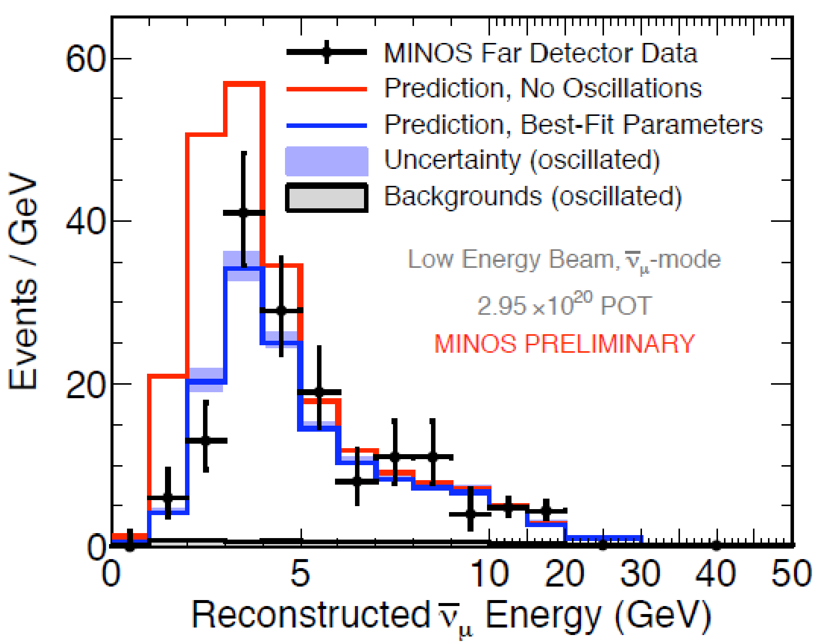
Anti-neutrino Mode

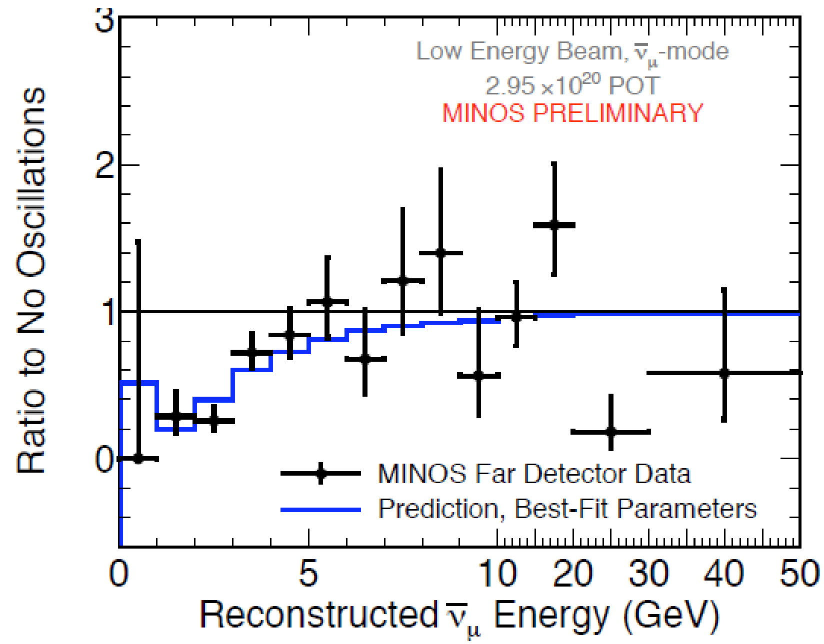






Anti-Neutrino Results





- Prediction for no oscillations
  - 273 events
- Observed
  - 193
- 7.3 σ deficit

Parameter Space

Antineutrinos

$$\left|\Delta\bar{m}^2_{atm}\right| = 2.62^{+0.31}_{-0.28} \times 10^{-3}\text{eV}^2$$

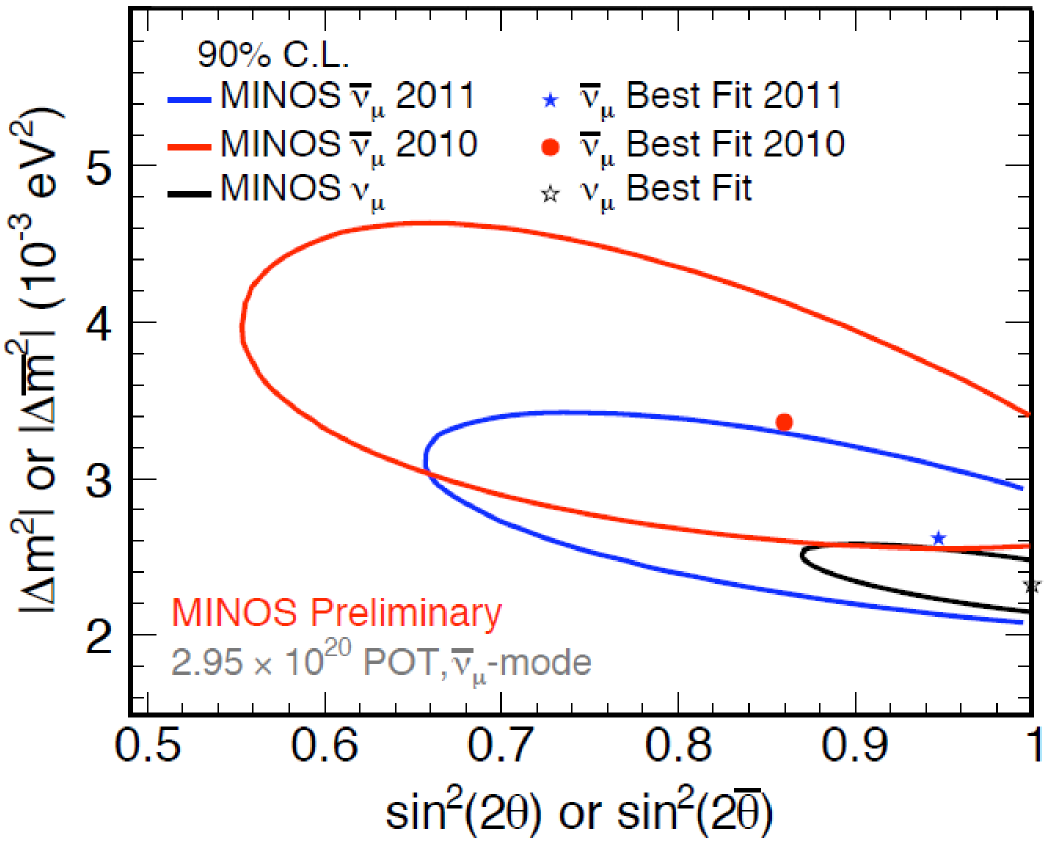
$$\sin^2(2\bar{\theta}_{23}) > 0.75 \ (90\%\ \text{C.L.})$$

Neutrinos

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

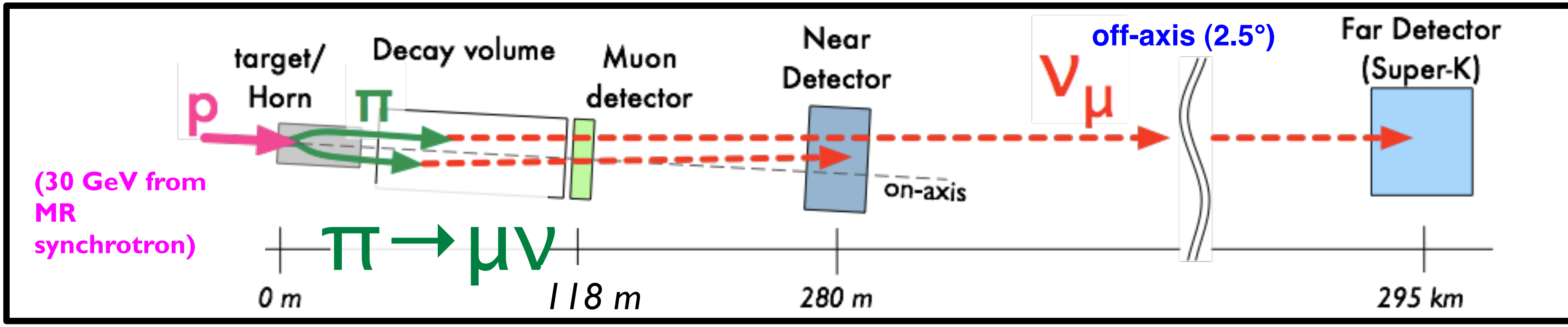
$$\sin^2(2\theta_{23}) > 0.90 \ (90\%\ \text{C.L.})$$

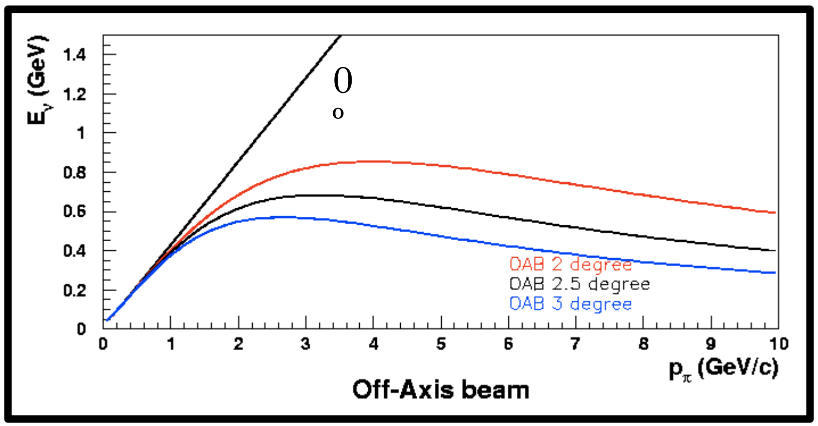
- Comparison with MINOS 90% C.L. contour for Run IV antineutrino data
- Comparison with MINOS 90% C.L. contour for neutrino mode

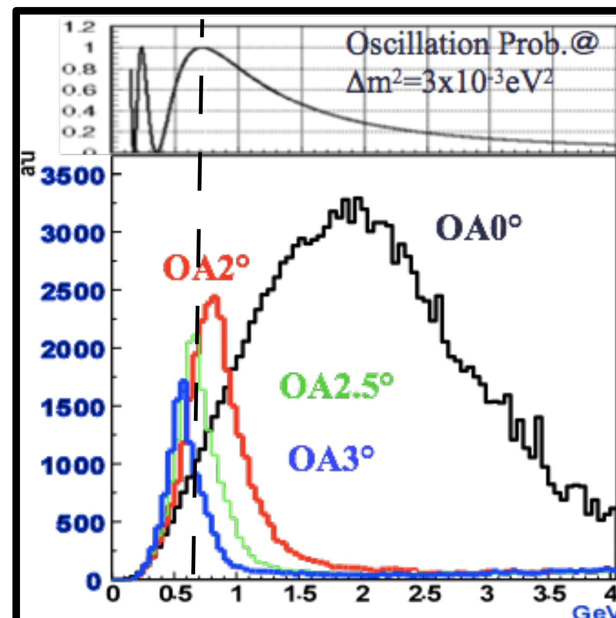


T2K Experiment

Design Principle



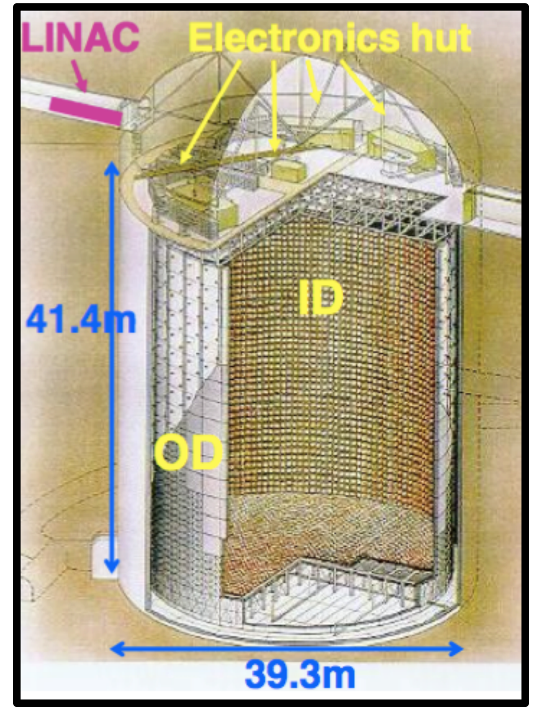


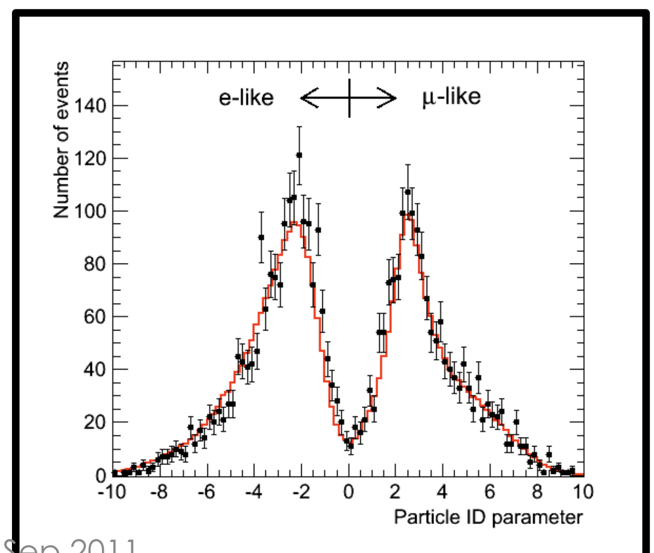


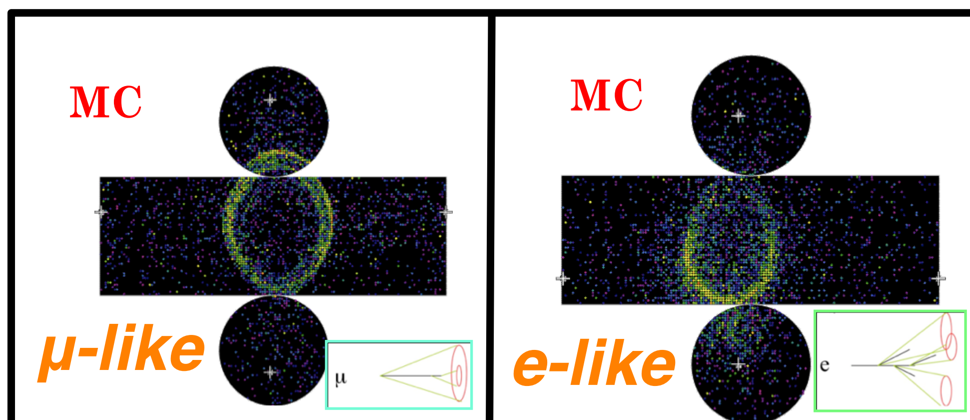
- Main feature :
  off-axis beam to reduce high-energy tail
  - Narrow-band beam around oscillation maximum
  - Feed-down from miss-reconstructed DIS/ resonance events at SK into analysis region reduced.

Super-K detector

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

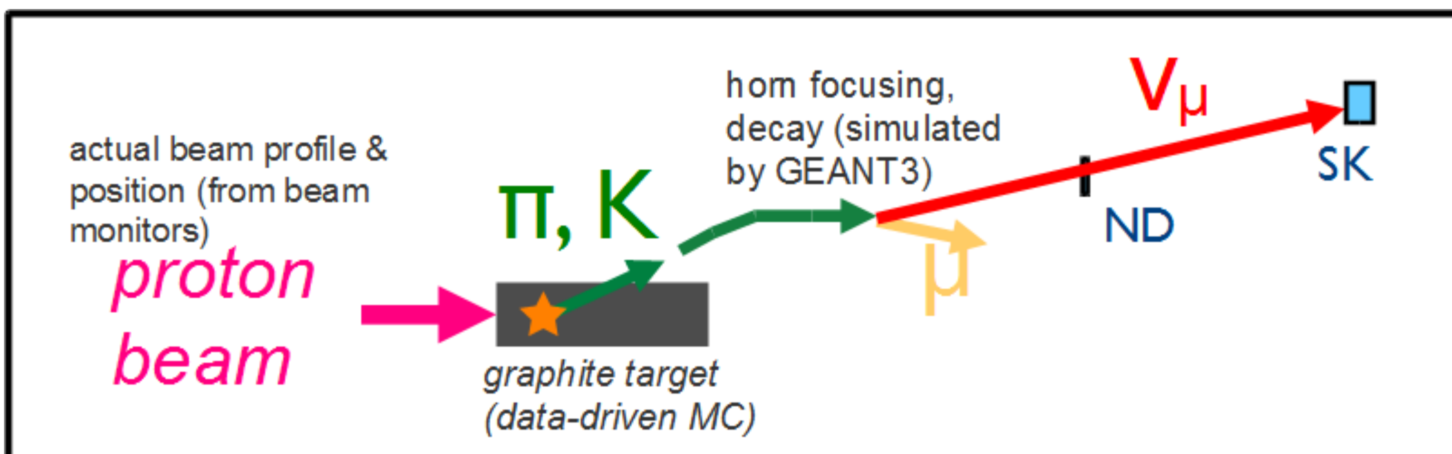






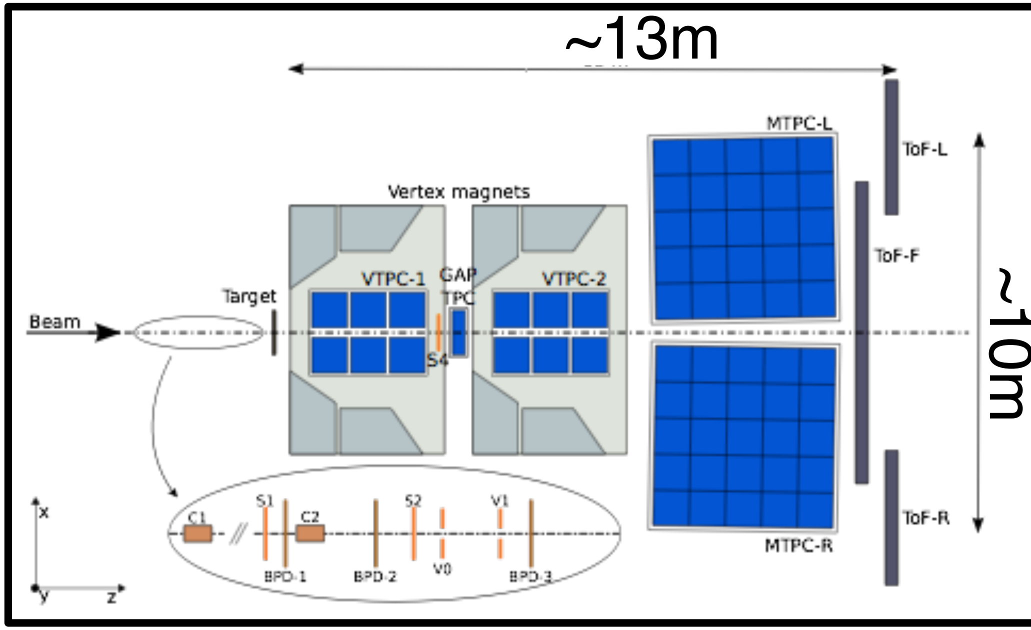
Beamline MC

- Flux estimated from beamline MC with inputs from data
- Primary beam data from **beamline monitors**
- Hadronic interactions
  - Pions - use **CERN NA61/SHINE pion measurement (large acceptance: >95% coverage of ν parent pions)**
  - Pions outside NA61 acceptance, other interaction (inc. kaons) based on **FLUKA simulation**
  - Secondary interactions outside the target based on experimentally measured cross-sections
- **GEANT3 transport simulation used downstream of target**



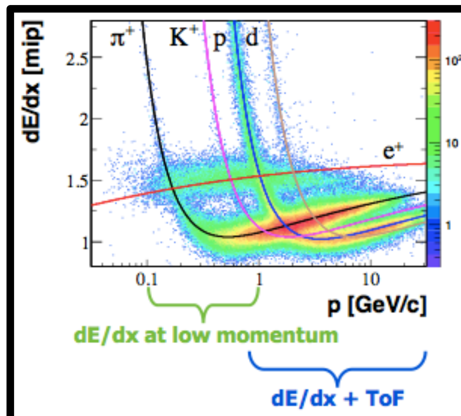
NA61/SHINE

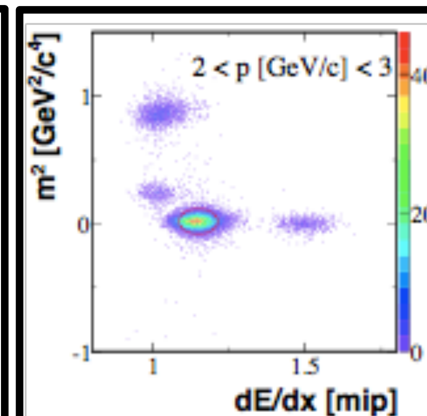
- Goal: measure hadron(π, K) yield distribution in **30 GeV p + C** inelastic interaction
- High-acceptance ToFs and spectrometers
- **2cm** thin target - 4% λ_I
- π^+ analysis:
  - **dE/dx only** analysis for low momenta
  - **dE/dx+ToF** selection for high momenta



$$\sigma(p)/p^2 \approx 2\times10^{-3},\ 7\times10^{-3},\ 3\times10^{-2}(\mathrm{GeV/c})^{-1}$$
$$\text{for } p>5,\ p=2,\ p=1\ \mathrm{GeV/c}$$

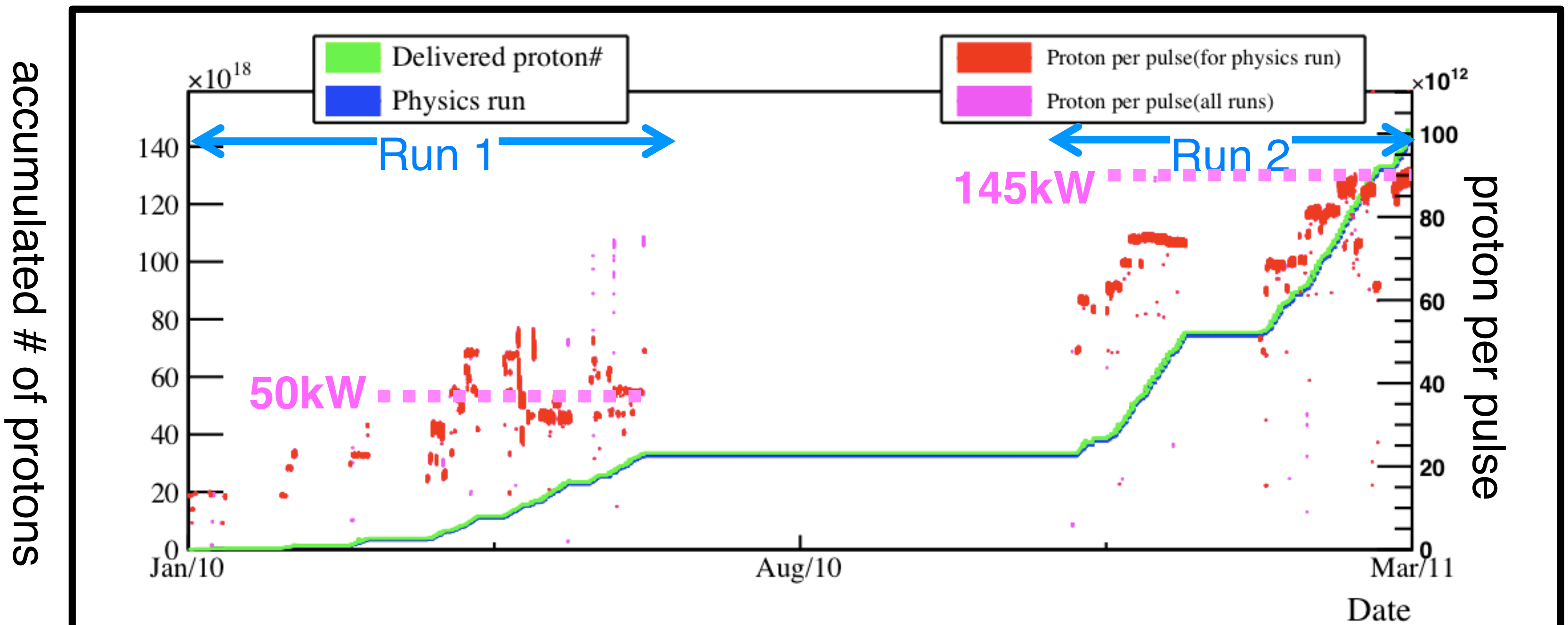
$$\sigma(\mathrm{dE/dx})/\langle\mathrm{dE/dx}\rangle \approx 0.04$$
$$\sigma(\mathrm{TOF\text{-}F}) \approx 115\ \mathrm{ps}$$



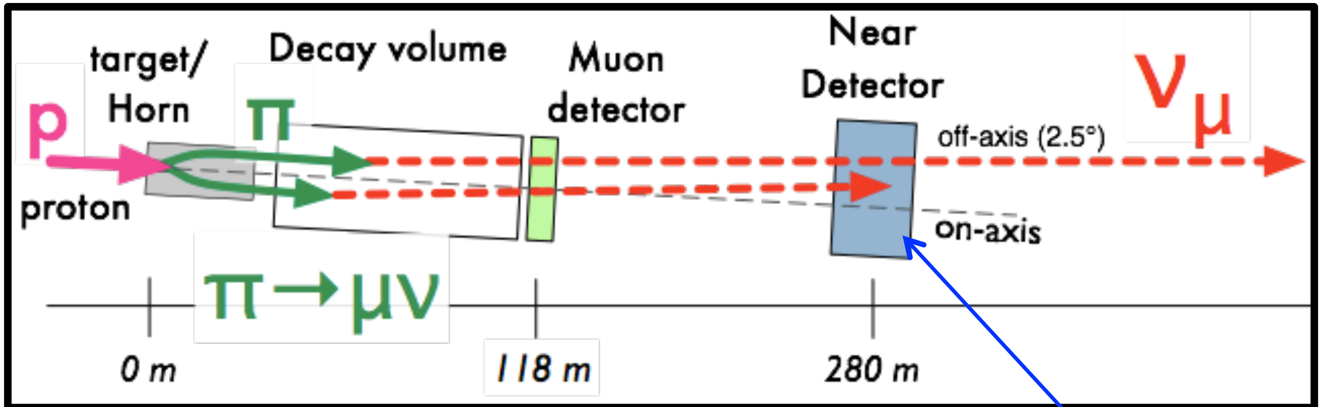


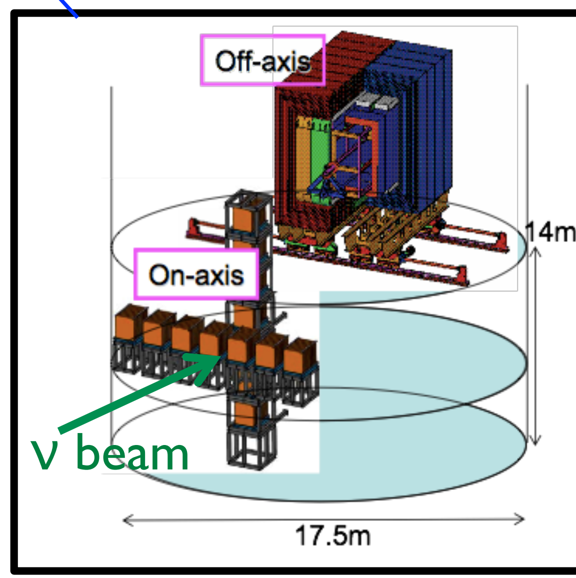
Data Sample

- All good physics data taken to date was used for this analysis:
  - Run 1 – **3.23×10^{19} p.o.t** with **50kW** beam, Jan '10 – Jun '10
  - Run 2 – **11.08x10^19 p.o.t.** with **145kW** beam, Nov '10 – Mar '11
- Total **1.43×10^{20} p.o.t.** – **2%** of T2K final goal



Near detectors

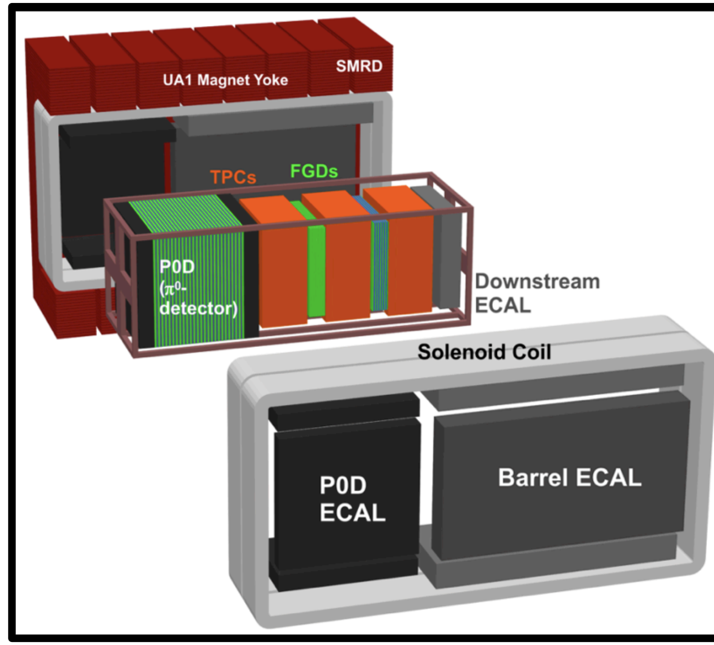


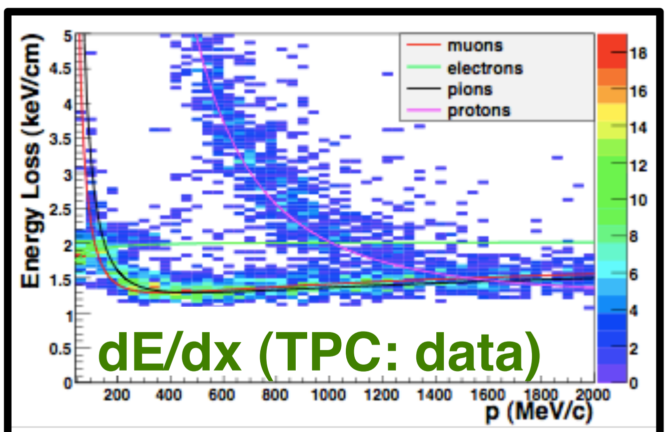


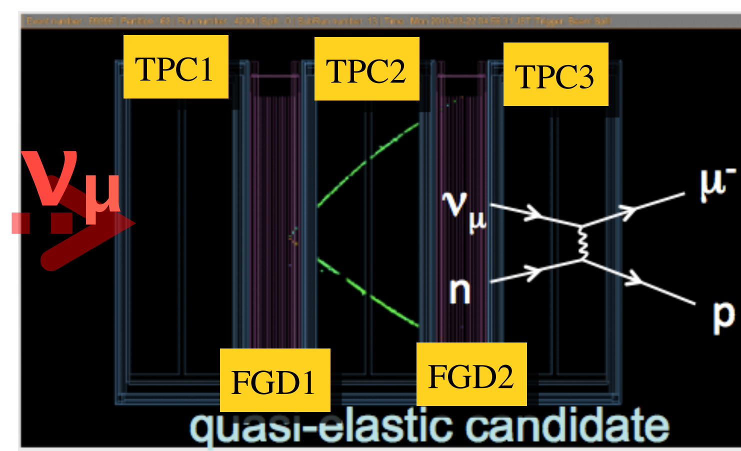
- **Muon monitor** for spill-spill monitoring
- On-axis detector (**INGRID**) measures beam intensity/direction
  - ~**1 mrad** precision in 1 day
- **ND280** detector at same off-axis angle as SK
  - Detailed flux measurement
  - Exclusive cross-section measurements

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
- For 1st analysis use total ν_μ-CC event rate in FGDs only

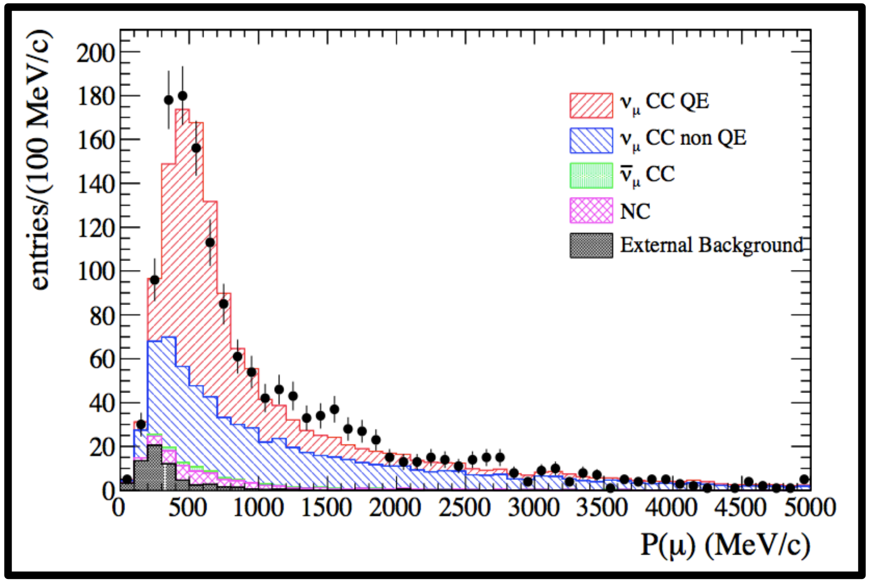






ND280 Input

- Measure **inclusive ν_μ-CC event rate** in near detector
  - Total event rate, no shape measurement for this analysis
  - Events with vertex in FGD and muon-like track in TPC selected
  - Achieve purity of **90% ν_μ-CC**



- Good agreement of data with beam MC+neutrino interaction generator, without any tuning to ND data.

$$R_{ND}^{\mu,\,Data} = 1529 \ \text{events} \ / \ 2.9 \times 10^{19} \ \text{p.o.t.}$$

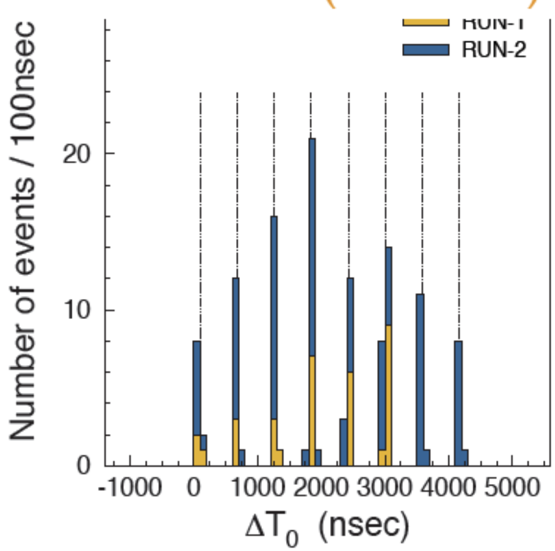
$$\frac{R_{ND}^{\mu,\,Data}}{R_{ND}^{\mu,\,MC}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

T2K SEARCH FOR MUON NEUTRINOS

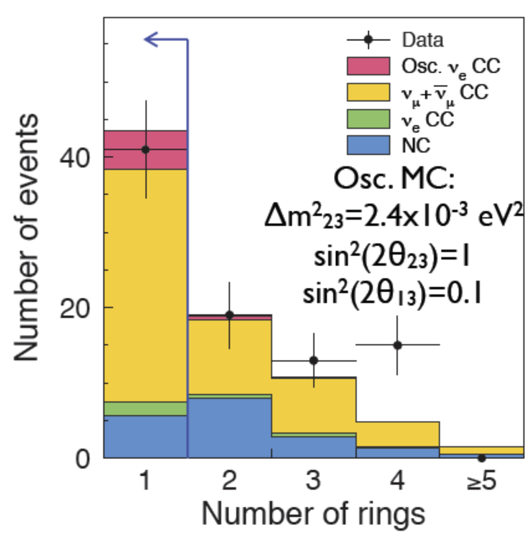
Selecting Events in SK

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

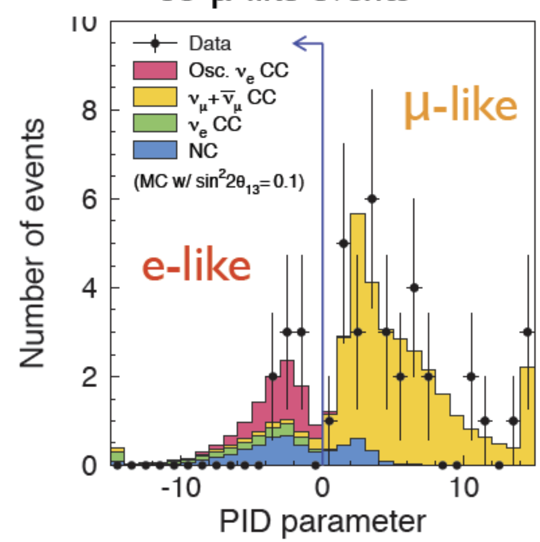
121 FC events (8 bunches)



41 single ring

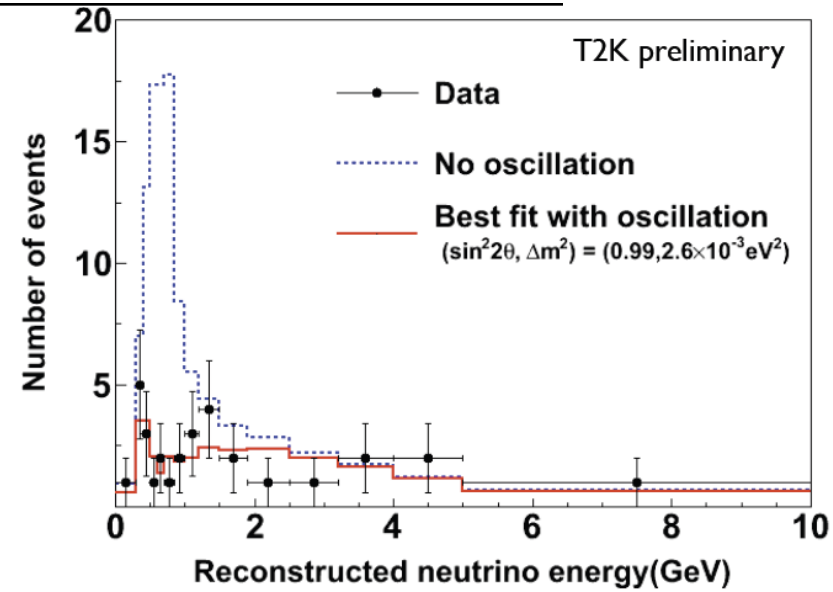


8 e-like events
33 μ-like events



Energy Spectrum

- Fit to muon neutrino energy spectrum
  - With & without fitting systematic parameters



Method A

Best fit:

$\sin^2(2\theta_{23}) = 0.99$, $|\Delta m^2_{23}| = 2.6\text{x}10^{-3}\ \text{eV}^2$

90% C.L:

$\sin^2(2\theta_{23}) > 0.85$

$2.1\text{x}10^{-3} < \Delta m^2_{23}(\text{eV}^2) < 3.1\text{x}10^{-3}$

Method B

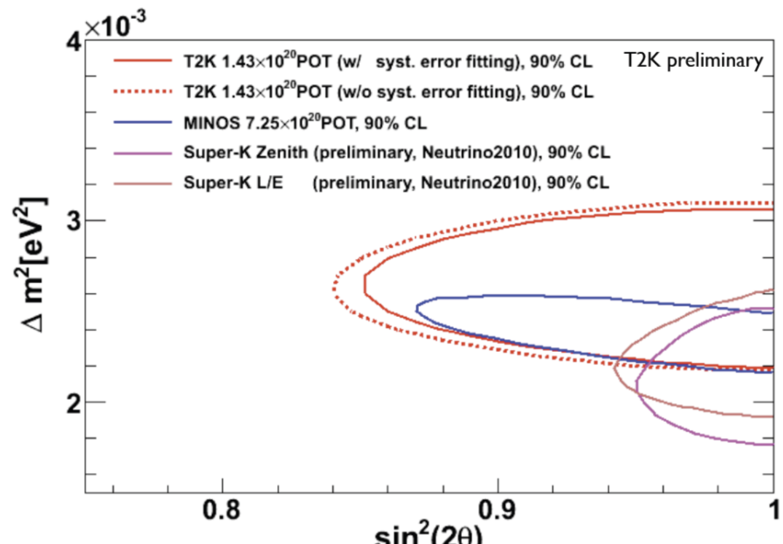
Best fit:

$\sin^2(2\theta_{23}) = 0.98$, $|\Delta m^2_{23}| = 2.6\text{x}10^{-3}\ \text{eV}^2$

90% C.L.:

$\sin^2(2\theta_{23}) > 0.84$

$2.1\text{x}10^{-3} < \Delta m^2_{23}(\text{eV}^2) < 3.1\text{x}10^{-3}$



World Knowledge

from solar/reactor ν
(Kamland, SNO)

$$\Delta m^2_{21} = 8 * 10^{-5}\,\mathrm{eV}^2$$

$$\theta_{12} \approx 34^\circ$$

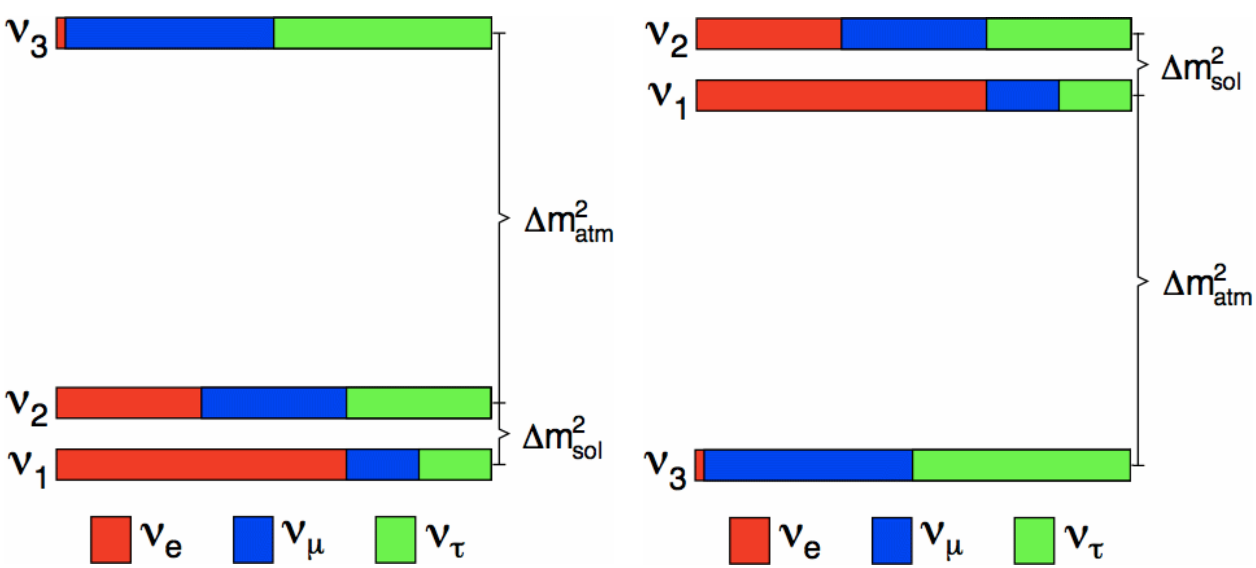
from atmospheric/ accelerator ν
(Super-Kamiokande, MINOS, T2K)

$$\left|\Delta m^2_{32}\right| = 2.3 * 10^{-3}\,\mathrm{eV}^2$$

$$\theta_{23} \approx 45^\circ$$

Open questions:

Normal Hierarchy or Inverted Hierarchy?



$$\theta_{13} = ?$$

$$\delta = ?$$

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_{ij}^2 = mass^2 difference

$$P_{e\mu} \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta$$

$$\mp \alpha \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta$$

$$- \alpha \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin 2\Delta$$

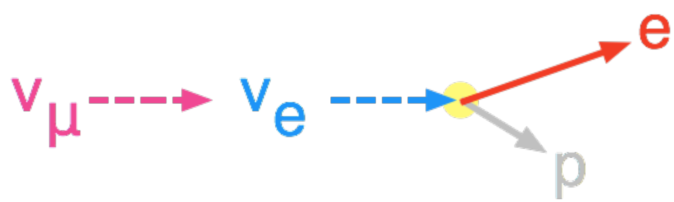
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta$$

where $\alpha = \Delta m_{21}{}^2 / \Delta m_{31}{}^2$ and $\Delta = \Delta m_{31}{}^2 L / 4E$

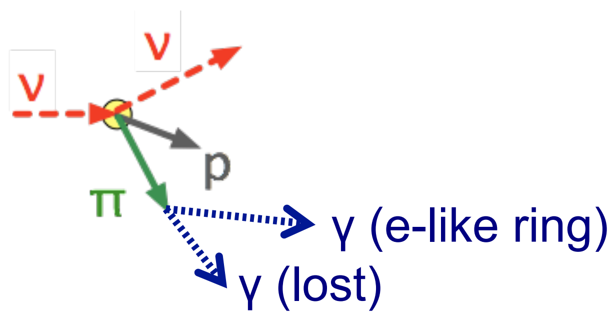
T2K SEARCH FOR ELECTRON NEUTRINOS

Appearance analysis

- Basic idea
  - Apply selection criteria to Super-K data to isolate **ν_e-CCQE** events



  - Compare with expected number of background events → measure appearance probability
- Backgrounds
  - **Intrinsic ν_e contamination** from μ, K decays in decay pipe
  - **NC-π^0** interactions of ν_μ (missed or merged gamma-rays → single e-like ring detected)



Estimate SuperK Event Rate

- Events at SK:
  - **Signal events**, depending on ν_μ flux and oscillation parameters
  - ν_e **background**, depending on intrinsic beam ν_e flux
  - ν_μ **background**, depending on ν_μ flux
- Inputs to event number estimation
  - **ND280** ν_μ-CC event rate
  - **Beam MC** predictions for near and far detector rates,

F/N ratio from MC

$$\boxed{N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}}$$

Measured ND280 event rate

Total BG Estimate

- Final estimates:
  multiply MC predictions by data/MC ratio of event rate in ND:

$$N^{exp}_{SK\ beam\ \nu_e\ bkg.} = R^{\mu,\ Data}_{ND} \times \frac{N^{MC}_{SK\ beam\ \nu_e\ bkg.}}{R^{\mu,\ MC}_{ND}}$$

$$N^{exp}_{SK\ NC\ bkg.} = R^{\mu,\ Data}_{ND} \times \frac{N^{MC}_{SK\ NC\ bkg.}}{R^{\mu,\ MC}_{ND}}$$

- Calculate total for **1.43 x 10^{20} p.o.t., θ_{13}=0:**

	Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
N^{exp}_{SK}	**0.8**	**0.6**	**0.1**	**1.5**

- ν_μCC BG is insignificant

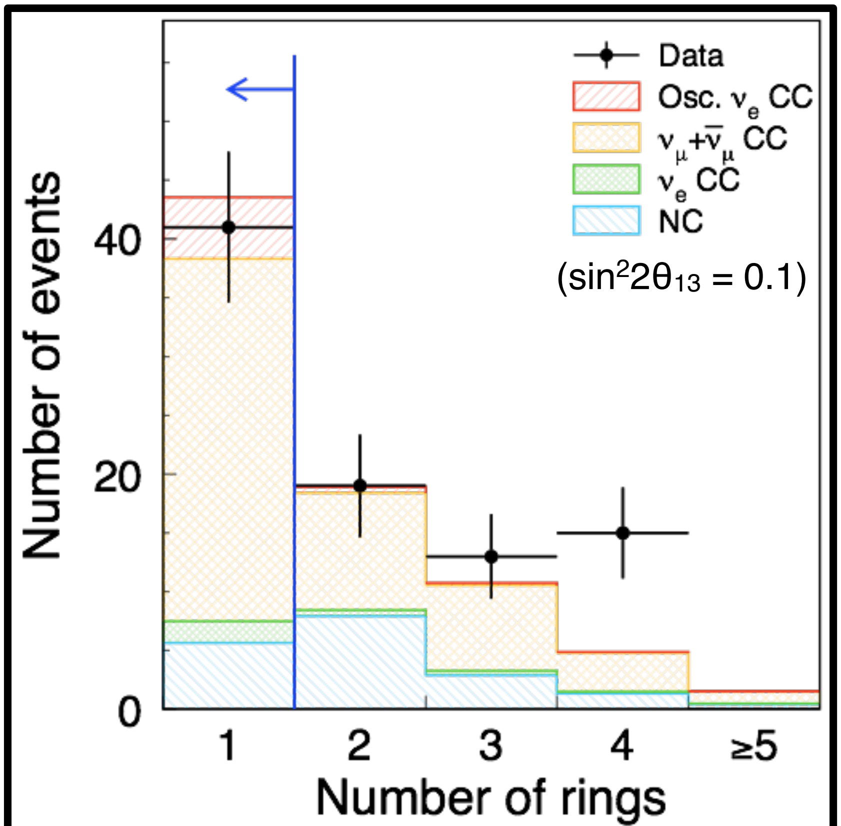
Systematic Errors

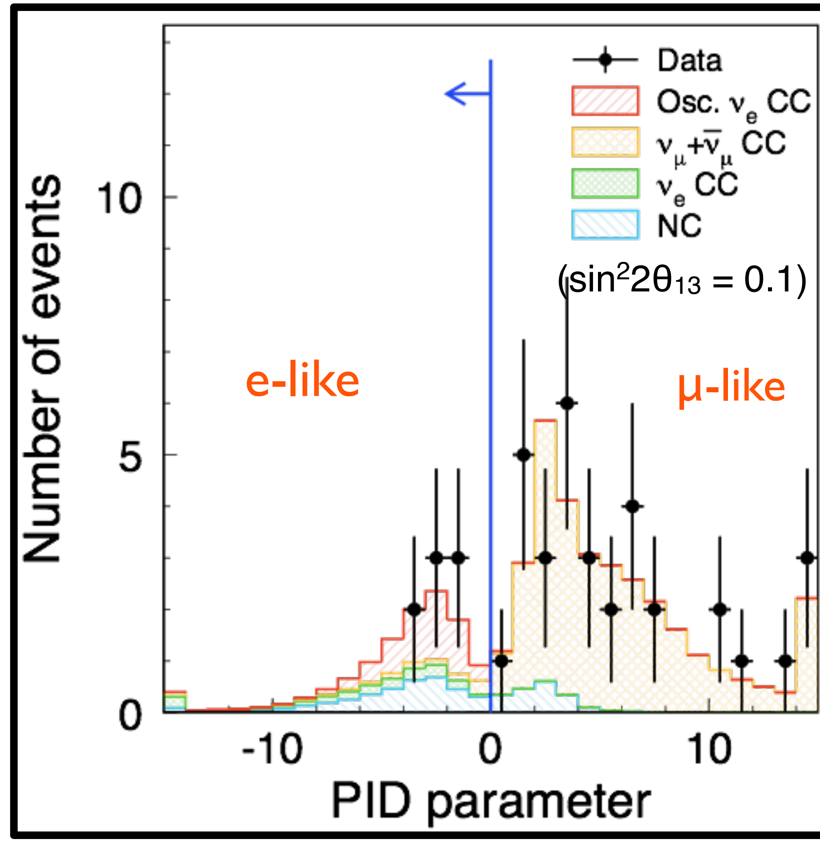
Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

Smaller for $\theta_{13} \neq 0$
due to small uncertainties on signal

Selection (1)

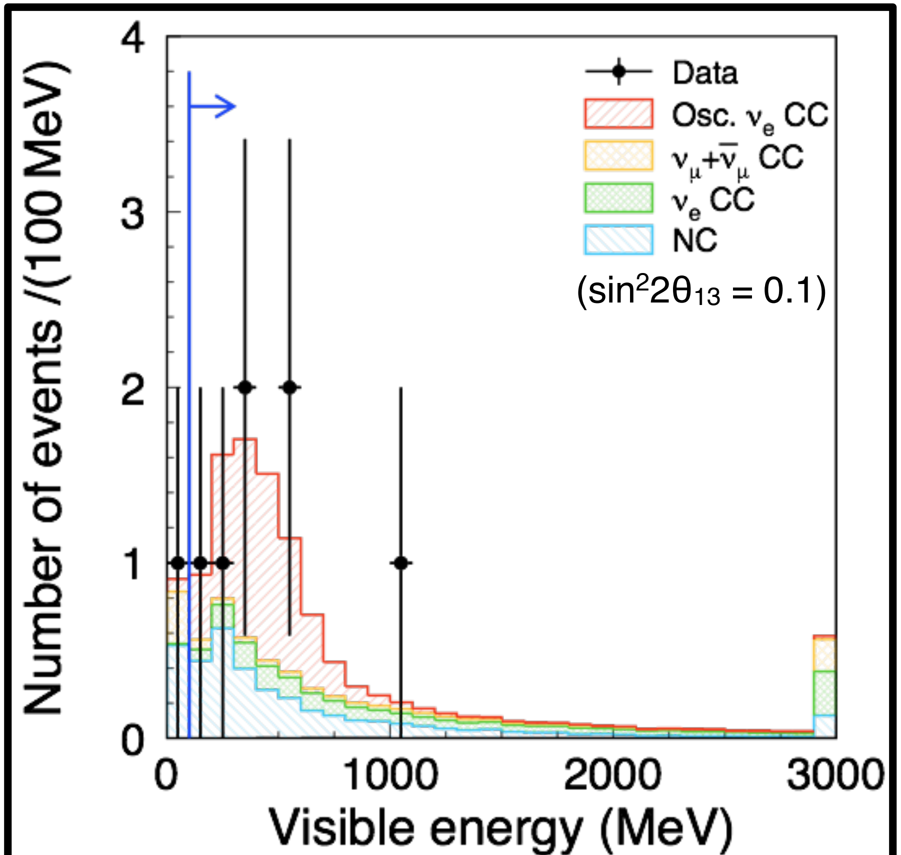
Single e-like ring



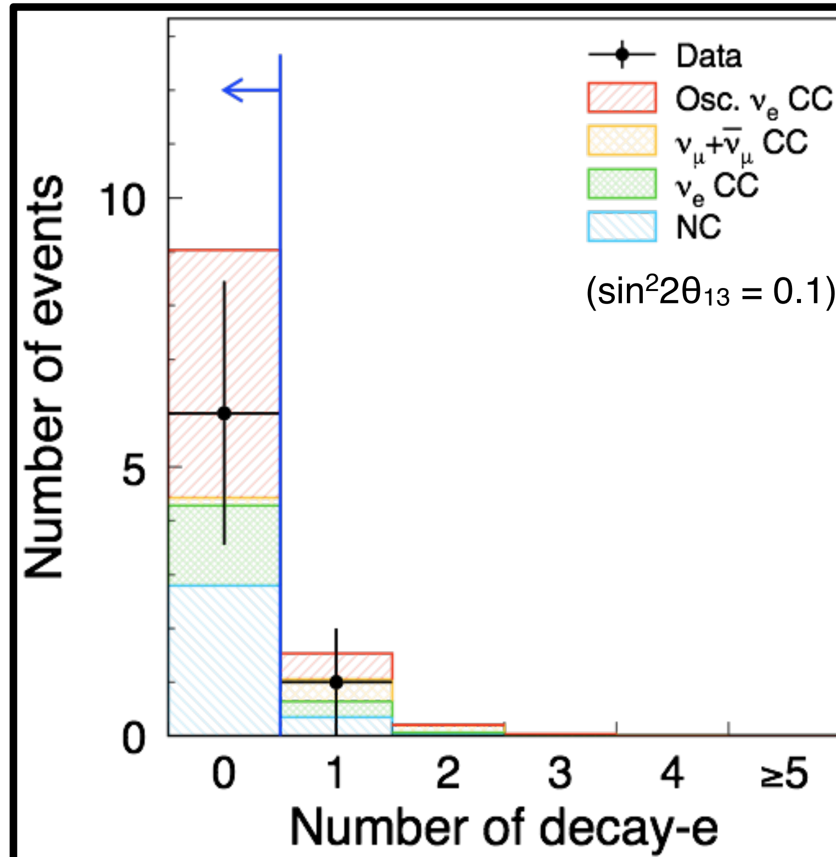


Selection(2)

Visible energy >100MeV



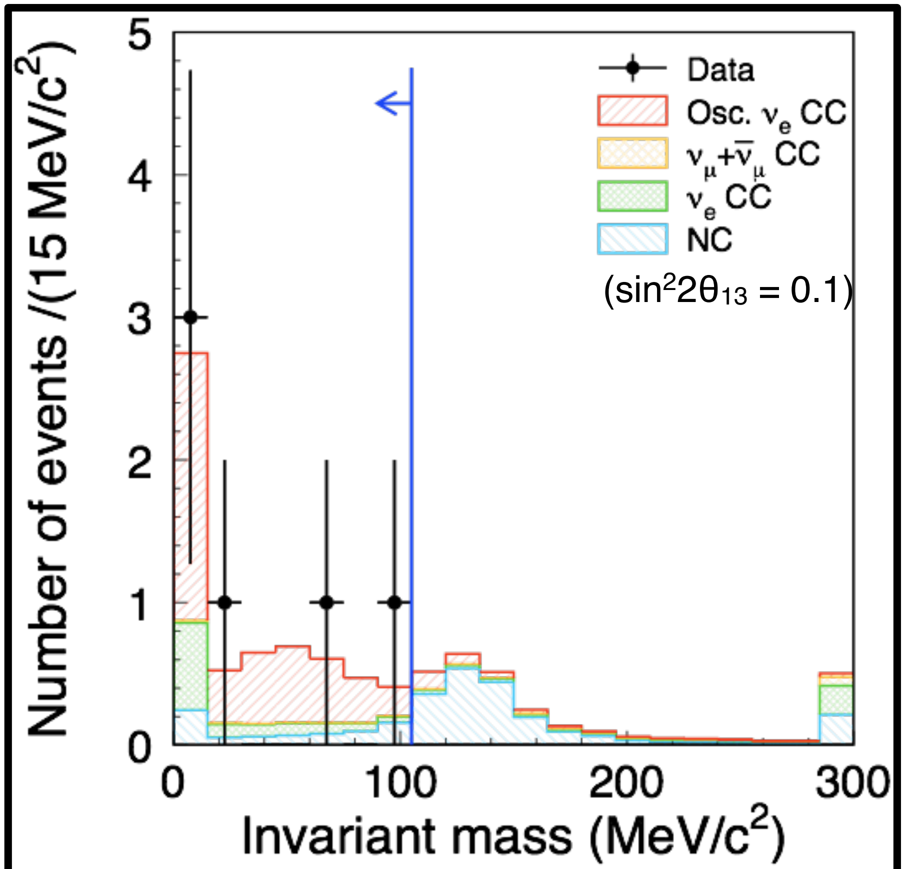
No decay electron

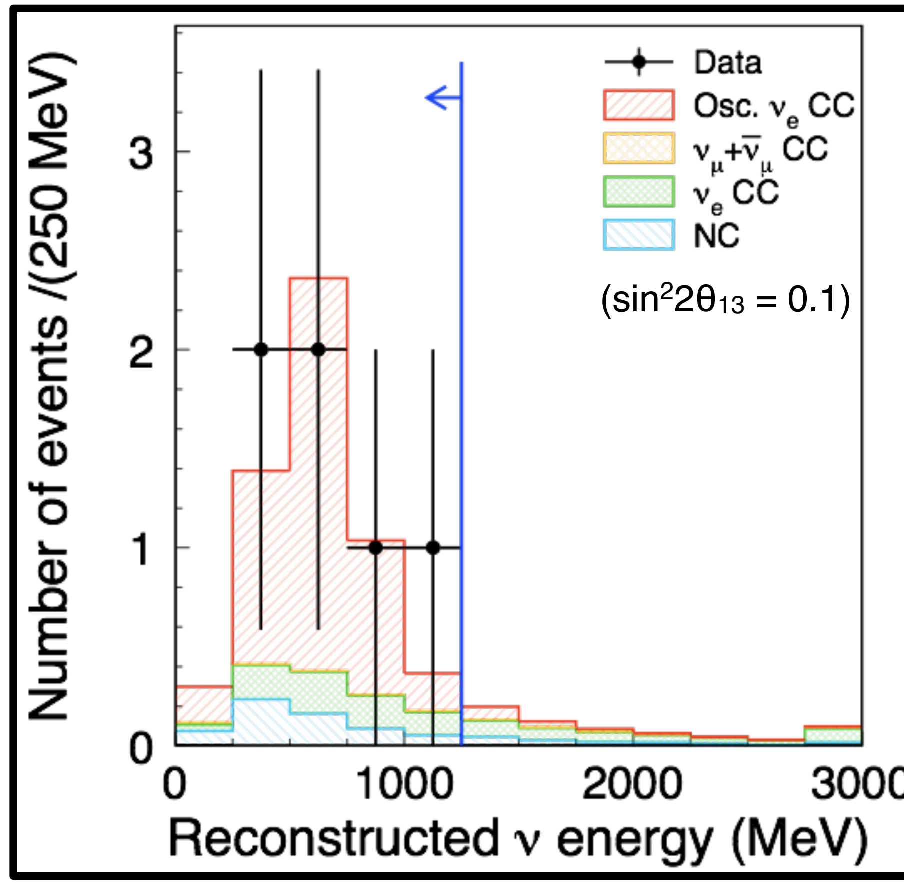


Selection (3)

"P0LFit" invariant mass cut

Reconstructed nu energy <1250MeV





Final Result

6 candidate ν_e events after all cuts

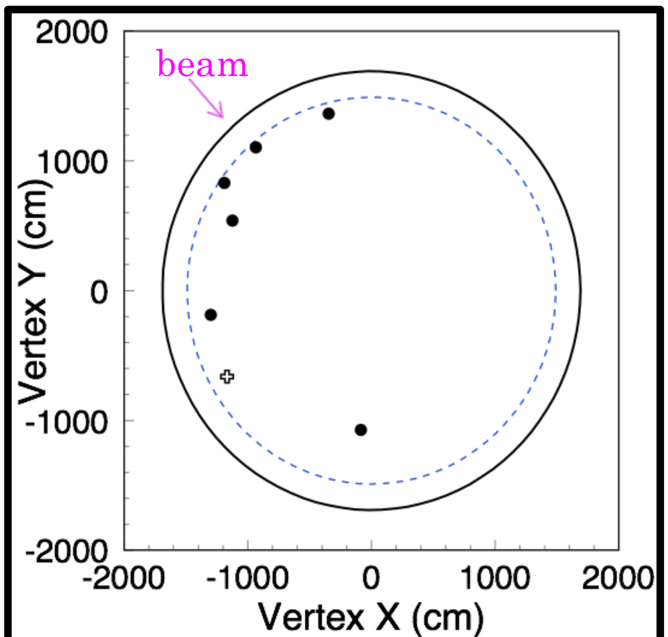
Expected BG of 1.5+/-0.3 events for $\sin^2 2\theta_{13}=0$

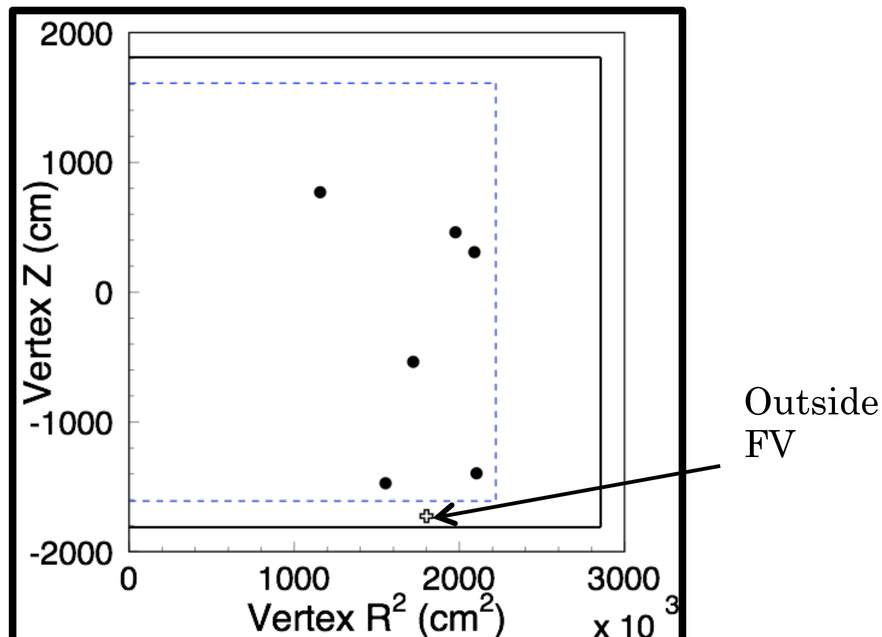
p-value of 0.7% for null hypothesis

Equivalent to 2.5σ

Vertex distribution

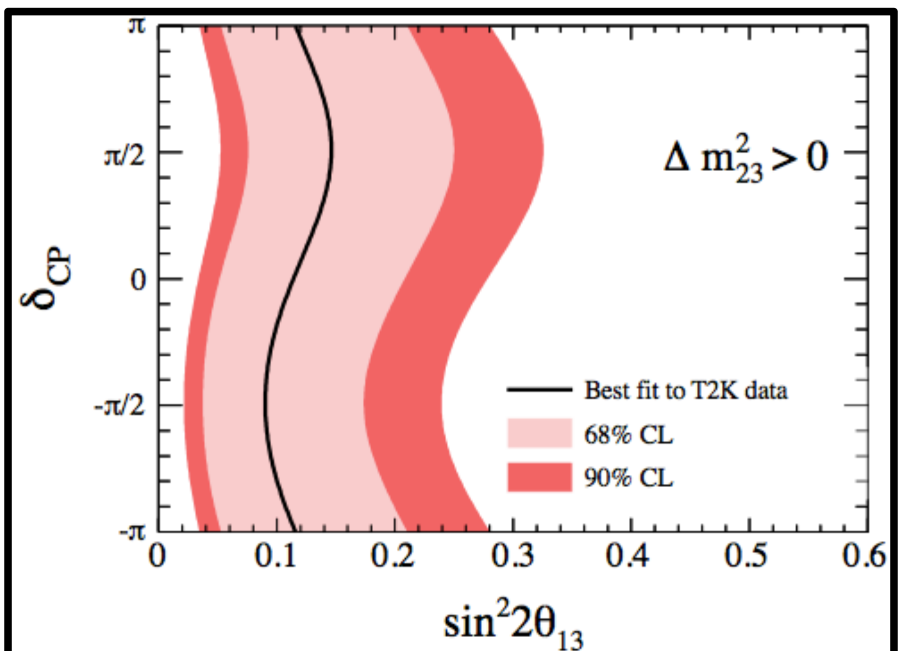
- Most events clustered at high *R* in upstream part of FV
  - No corresponding excess in OD or outside FV - no evidence of any plausible background contamination
- Difficult to meaningfully calculate probability of this distribution after the fact
  - K.S. test on the R^2 distribution yields a p-value of 3%
  - Next analysis will define procedure to check this distribution before looking at the data

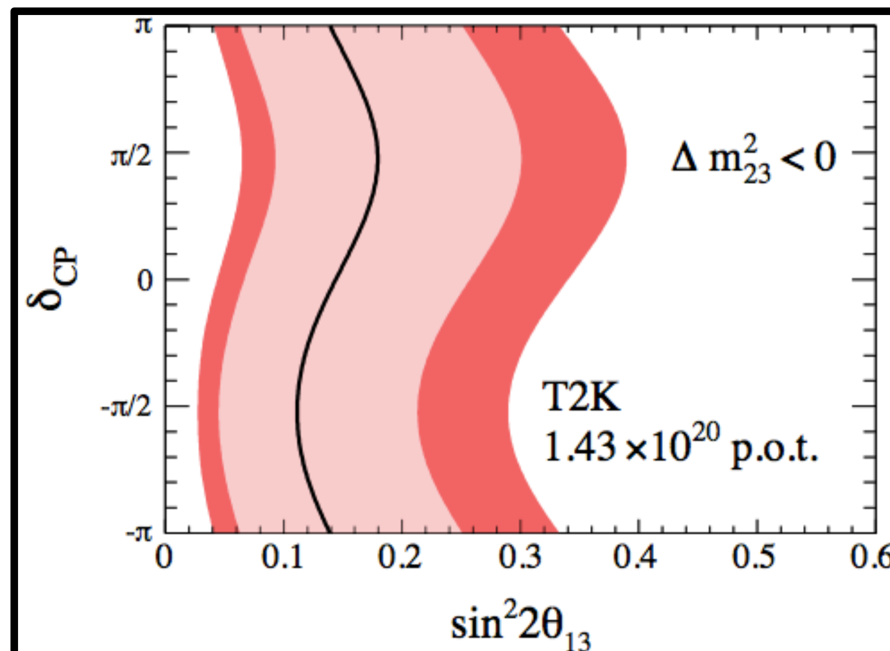




Oscillation fit

- Contour calculated using Feldman-Cousins method:
  - Ensure **correct coverage** by performing many **toy experiments** at each point in $(\theta_{13}, \delta_{CP})$ space and finding $\delta\chi^2_{crit}(\theta_{13}, \delta_{CP})$ s.t. (68%, 90%) of toy experiments have $\delta\chi^2 < \delta\chi^2_{crit}$ at true $(\theta_{13}, \delta_{CP})$
  - Exclude points in $(\theta_{13}, \delta_{CP})$ space where $\delta\chi^2(\theta_{13}, \delta_{CP}; \text{data}) > \delta\chi^2_{crit}(\theta_{13}, \delta_{CP})$
  - **Systematics** included in **toy experiment generation**





MINOS SEARCH FOR ELECTRON NEUTRINOS

Library Event Matching (LEM)

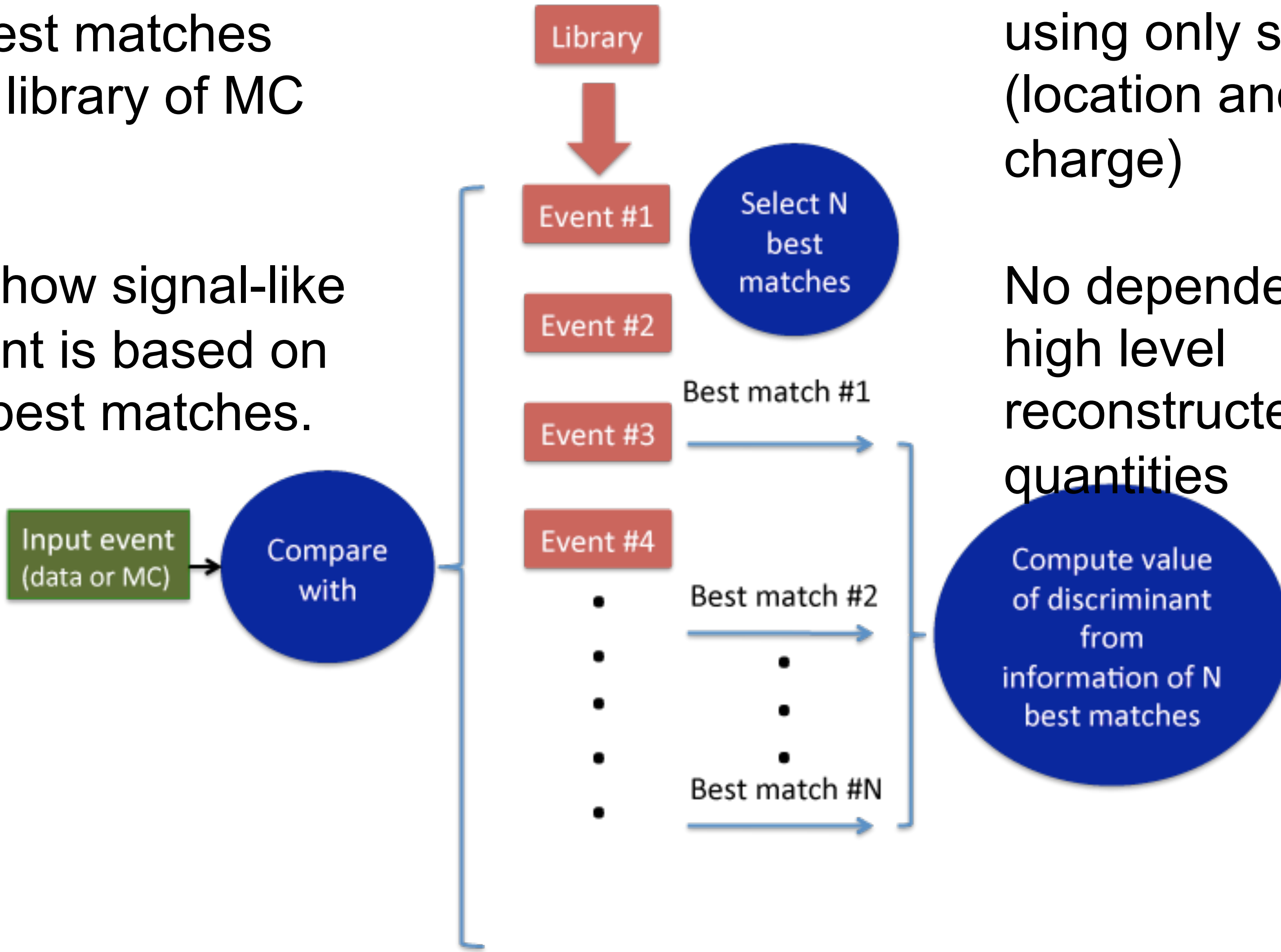
New selection variable!

Find best matches from a library of MC events

Judge how signal-like an event is based on those best matches.

Matching is done using only strip info (location and charge)

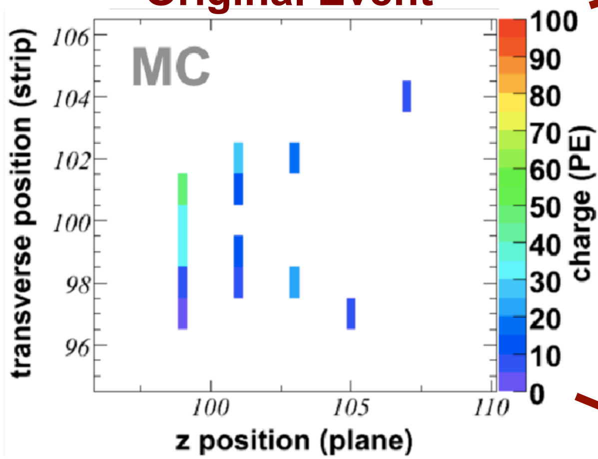
No dependence on high level reconstructed quantities



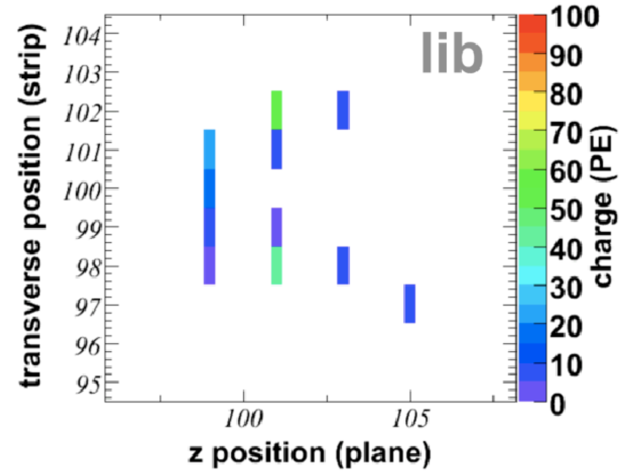
Matching

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.

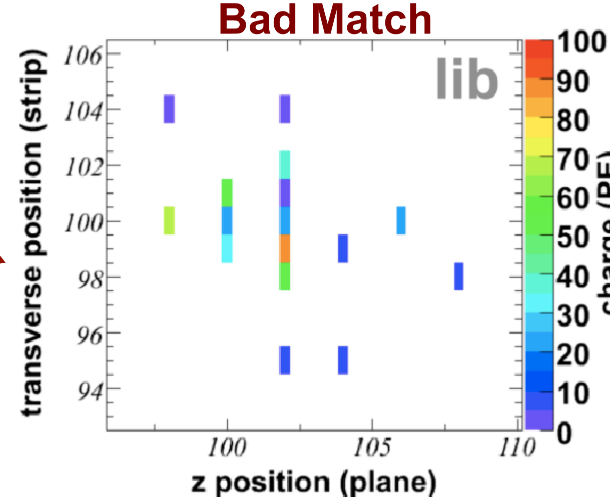
Original Event



Good Match



Bad Match



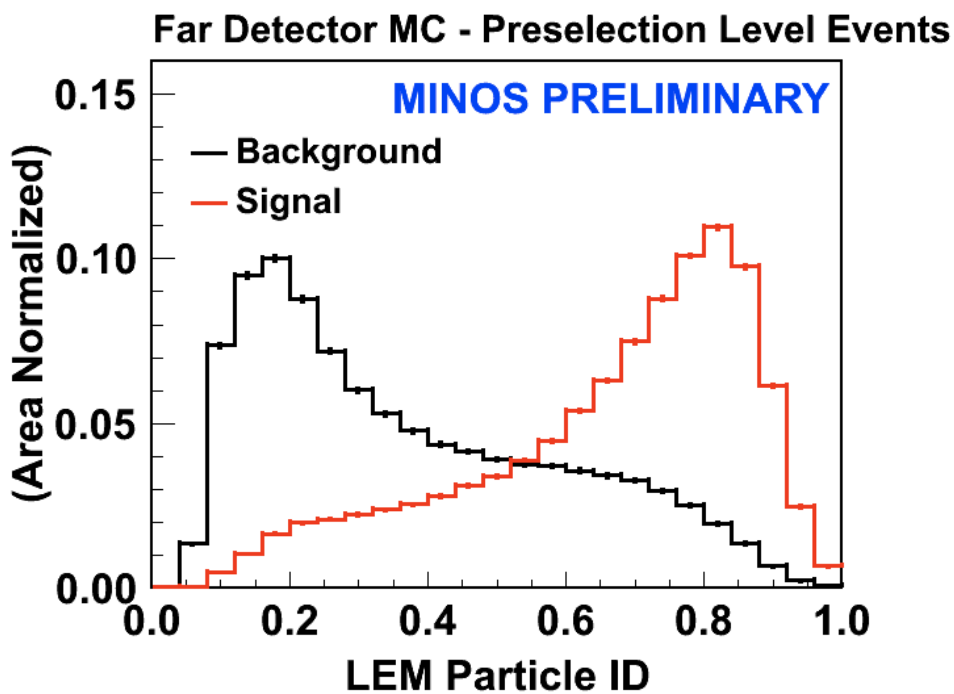
The library consists of:

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

LEM Particle ID

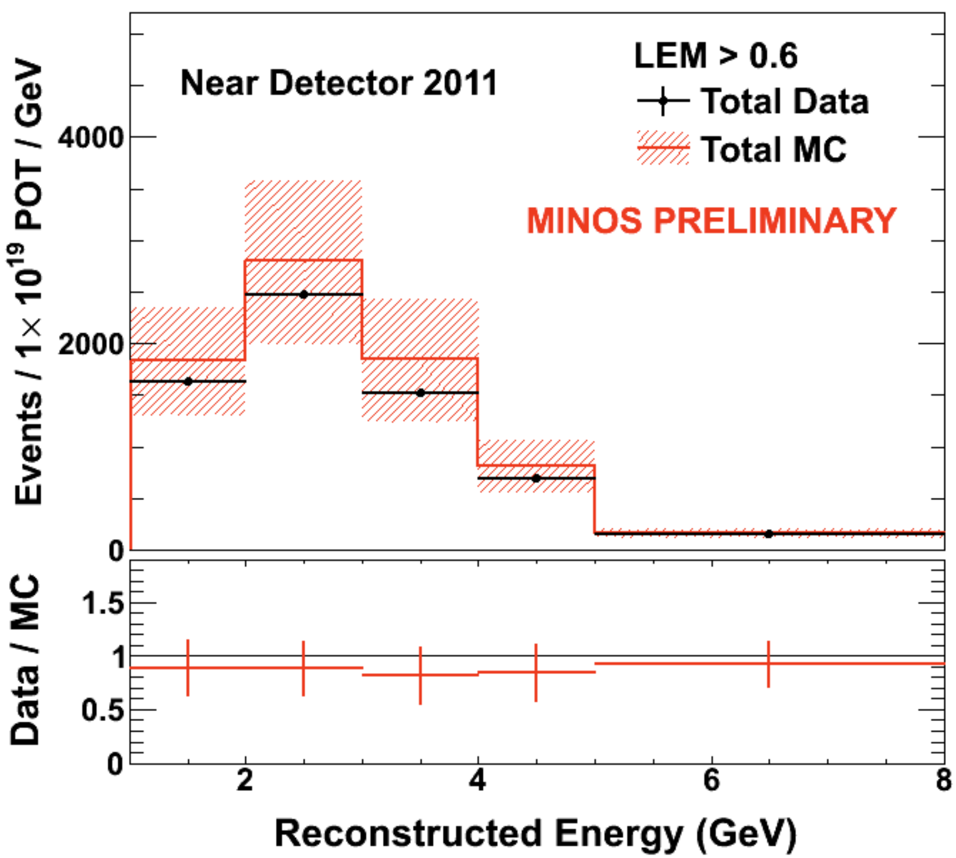
3 variables + reconstructed energy used as inputs to a neural net

Output of neural net is the LEM selection variable



Near Detector Data

Apply the n_e selection criteria to the ND data:



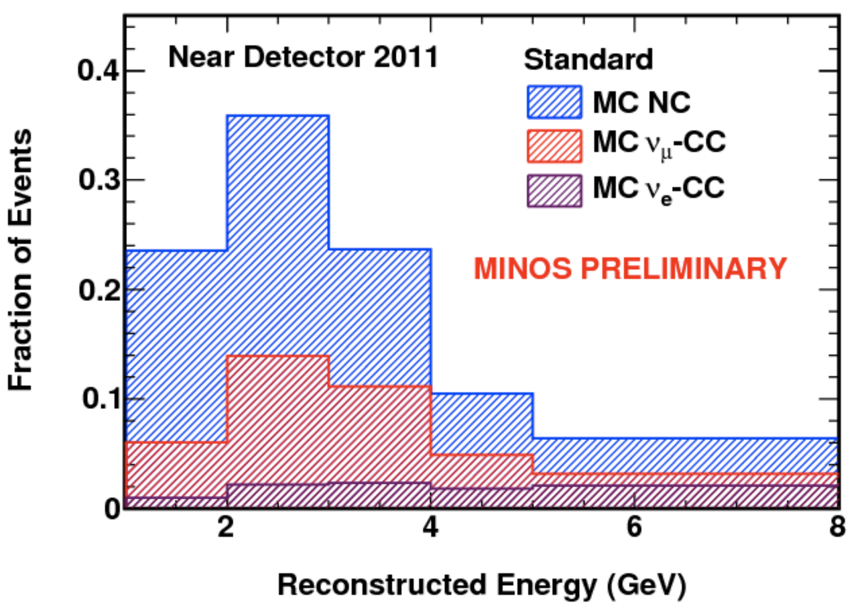
- Red shaded area is the systematic uncertainty on the MC simulation – dominated by uncertainties in modeling hadron production in n interactions
- Having a near detector is essential – no need to rely solely on MC to predict the background in the far detector!

Near Detector Background

Oscillations affect each background component differently!

Need to know how much of each component in the ND data:

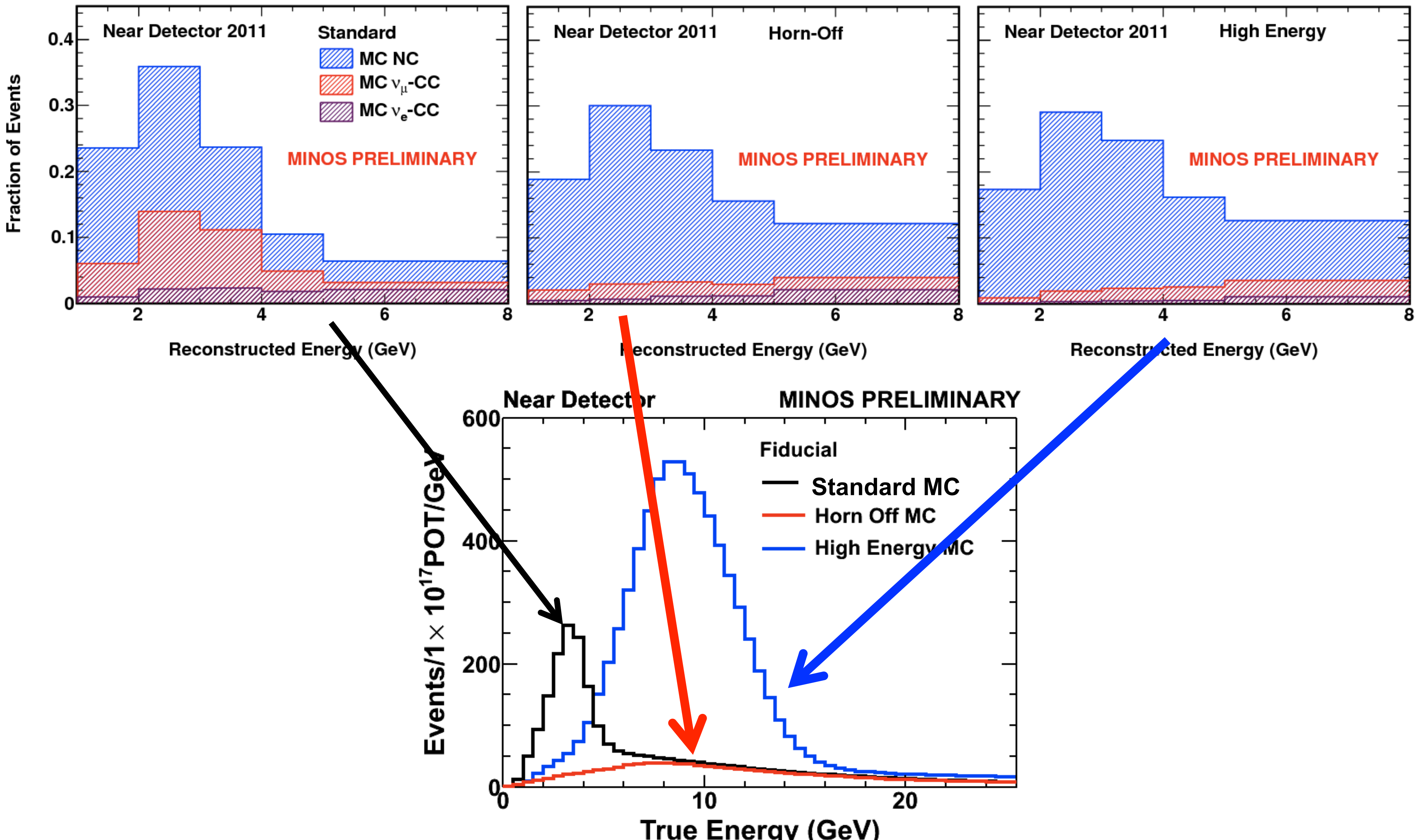
- neutral current
- charged current ν_μ,
- charged current ν_e (from beam contamination)



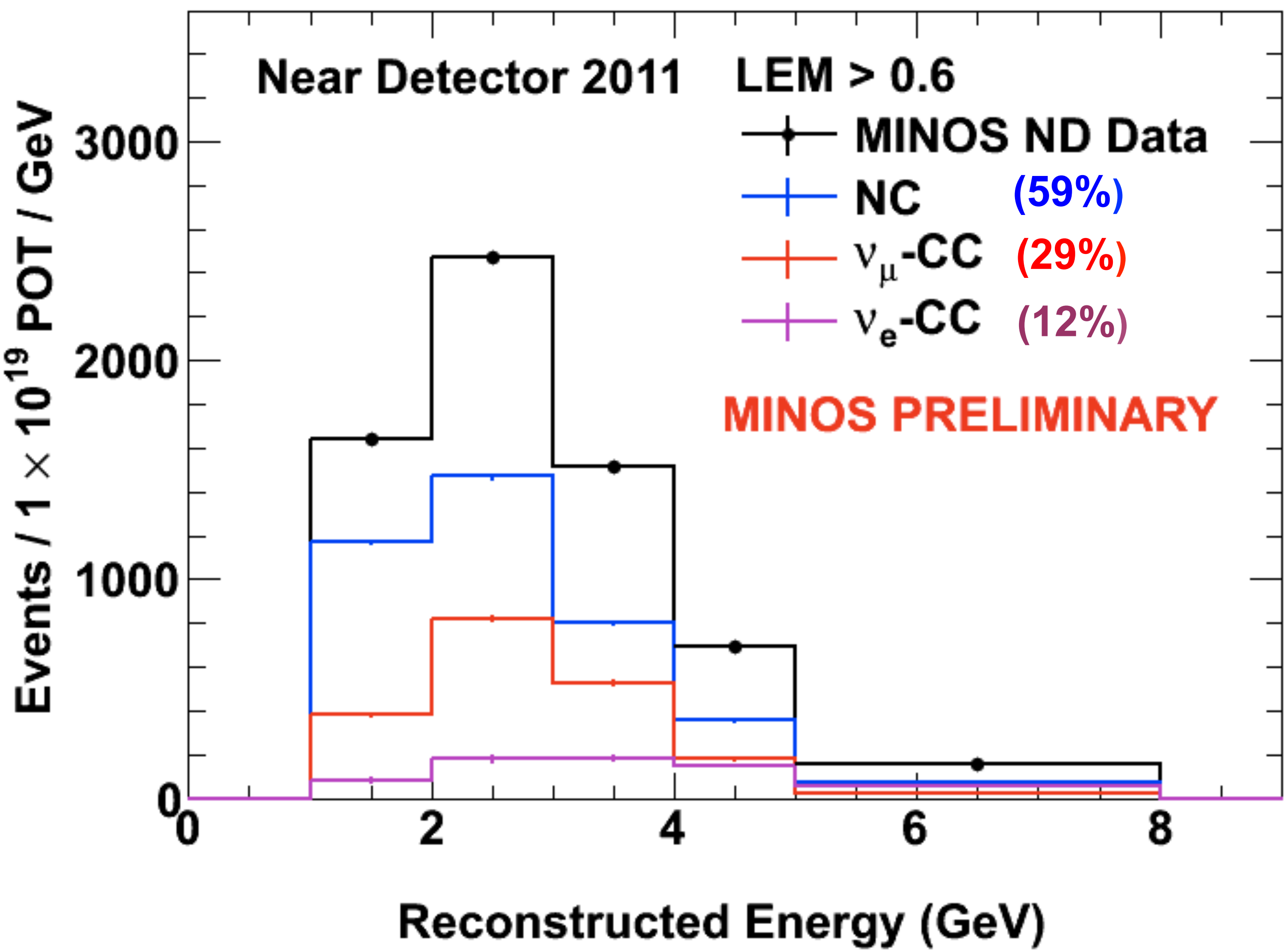
Extract it from the data – don't rely on the simulation

Due to the flexibility of our beam, we can use near detector data taken with different beam configurations to do this...

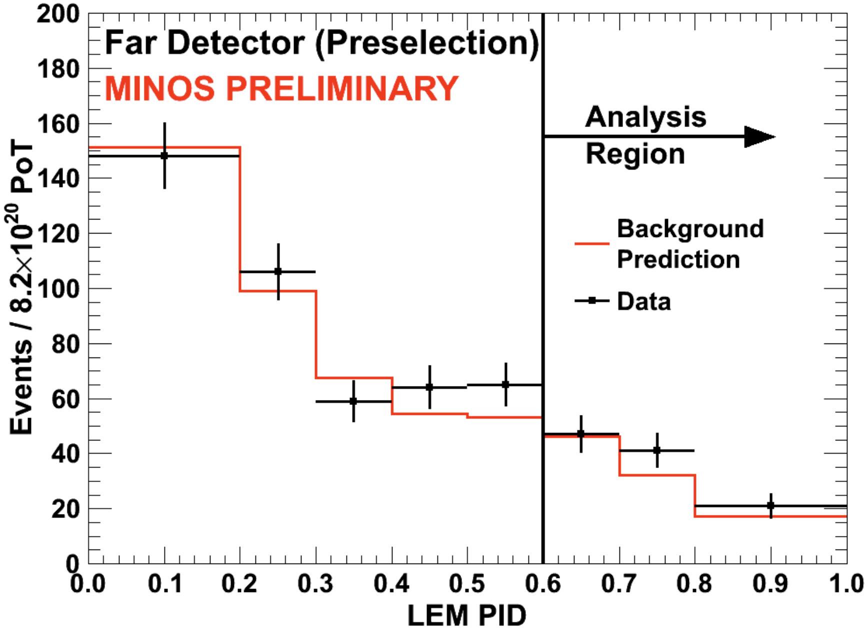
Diff. Beam Configurations



Data-Driven BG



Event Count

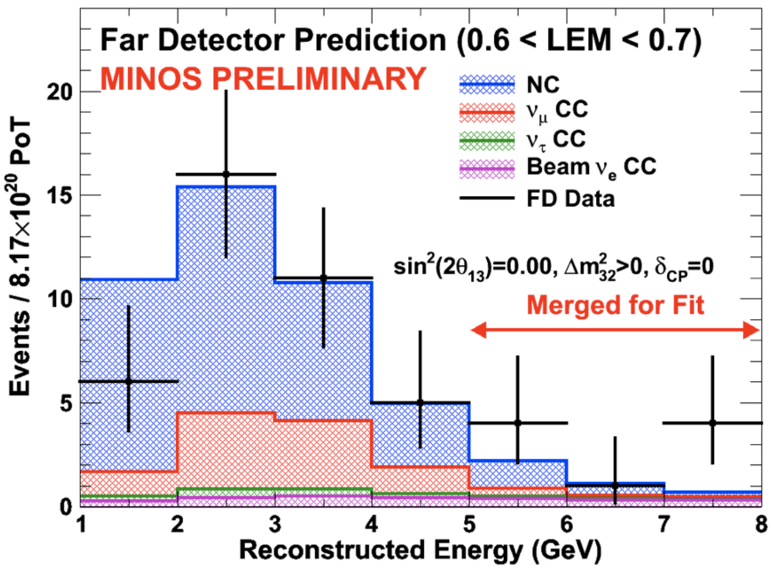


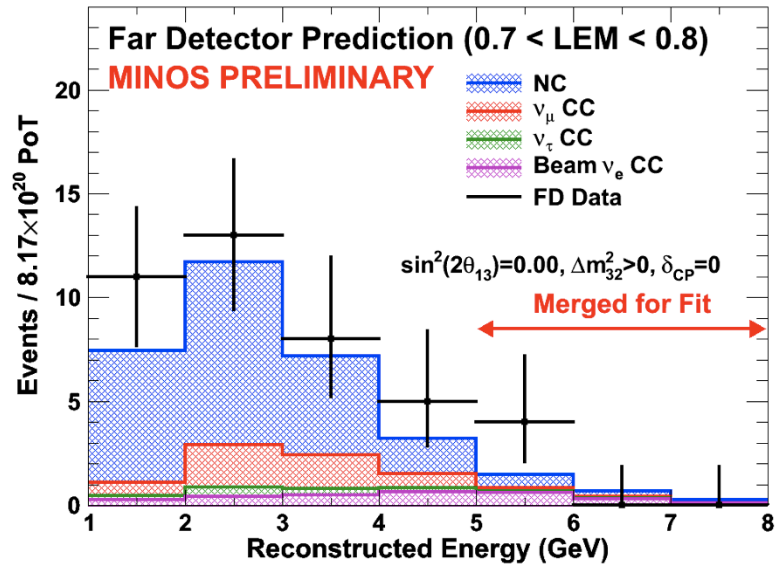
In signal-enhanced region (LEM>0.7):

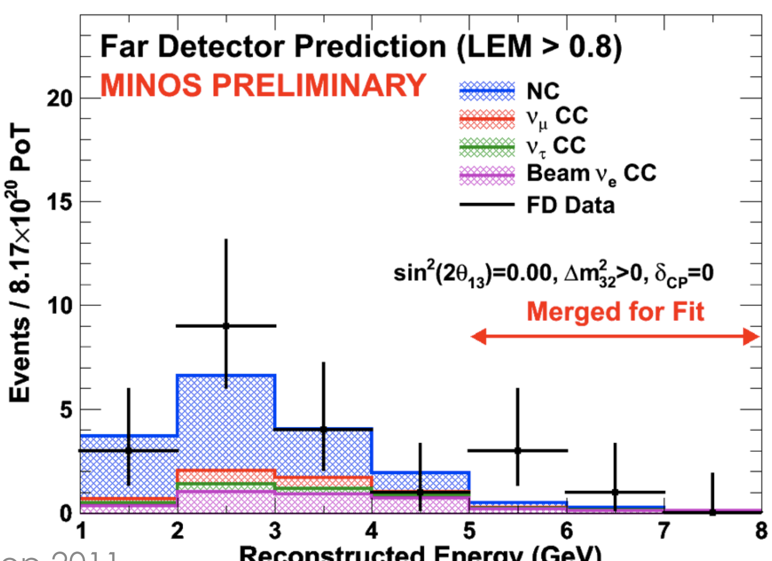
Expected background (θ_{13}=0):
49.5 ± 2.8 (syst) ± 7.0 (stat)

Observed data:
62

Fitting to Oscillations



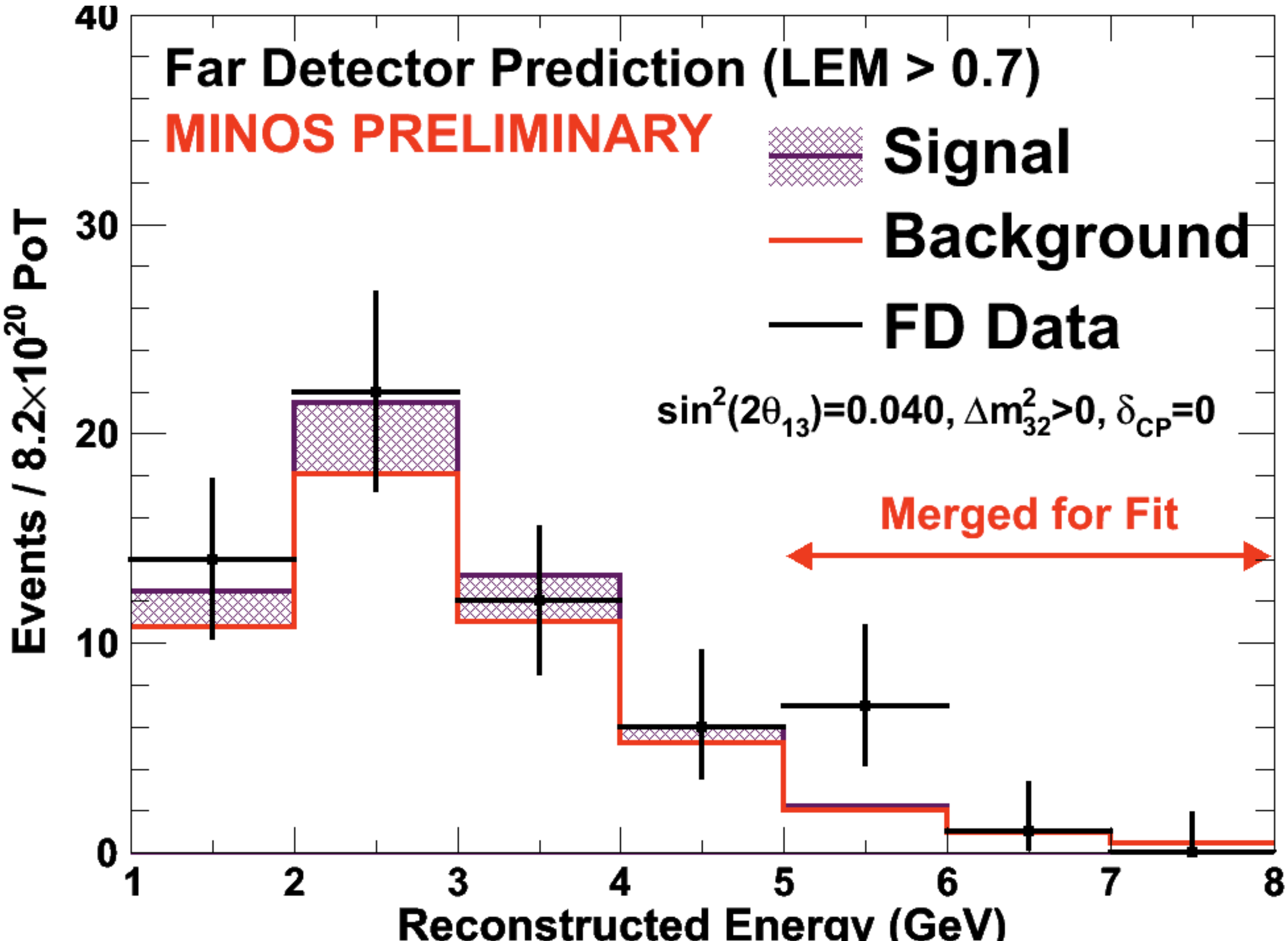




15 bin fit

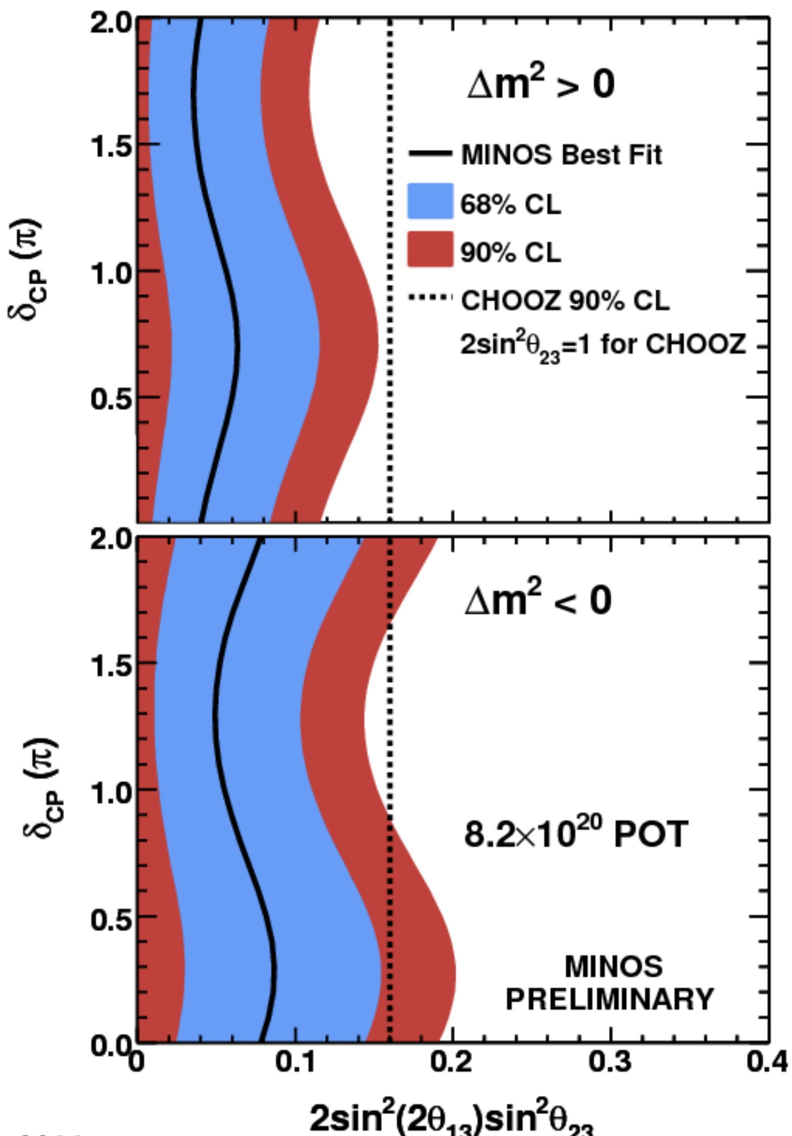
3 LEM bins x 5 energy bins

Best Fit



Far Detector Prediction (LEM > 0.7)
MINOS PRELIMINARY
Signal
Background
FD Data
$\sin^2(2\theta_{13})=0.040, \Delta m^2_{32}>0, \delta_{CP}=0$
Merged for Fit
Events / 8.2×10^20 PoT
Reconstructed Energy (GeV)
0
10
20
30
40
1
2
3
4
5
6
7
8

Allowed Regions



Assuming:
$\delta=0$, $\theta_{23} = \pi/4$
normal (inverted) hierarchy

$$\sin^2(2\theta_{13}) < 0.12(0.19) \quad 90\% \text{ CL}$$

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

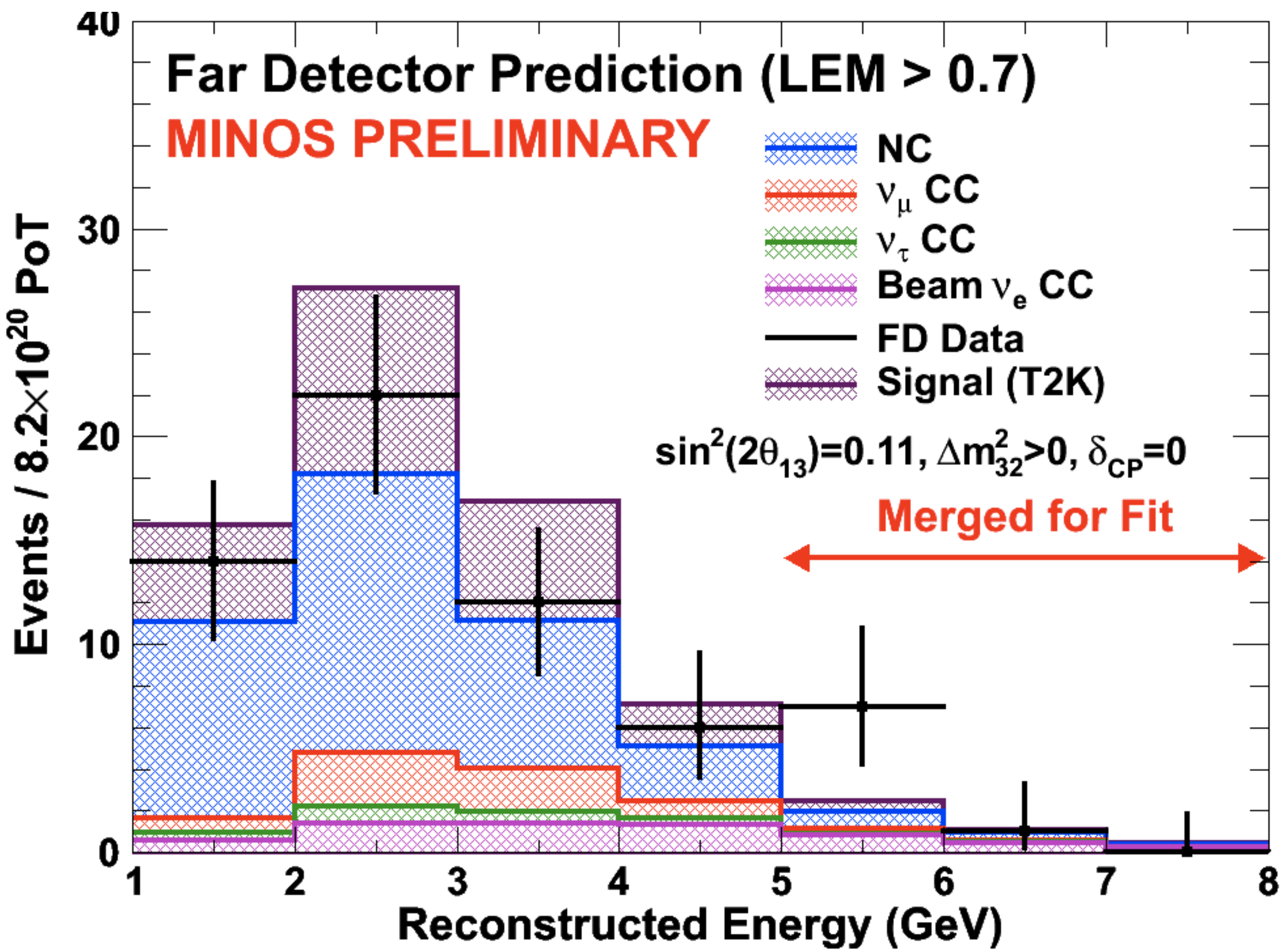
We exclude $\sin^2 2\theta_{13}=0$ at 89% CL

Feldman-Cousins contours

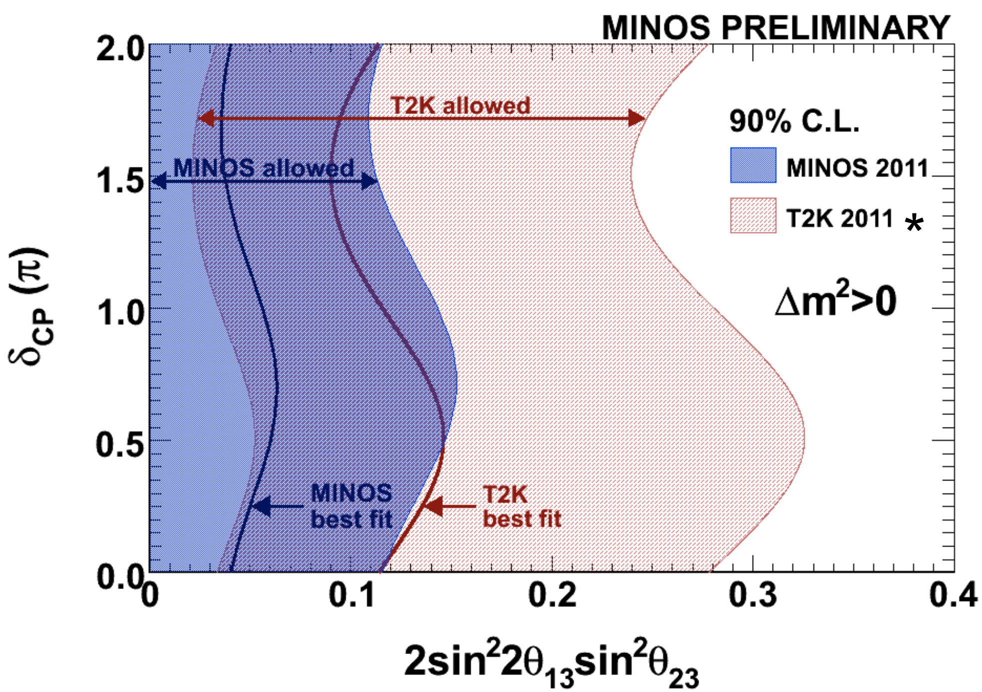
Uncertainties in the other oscillation parameters are included

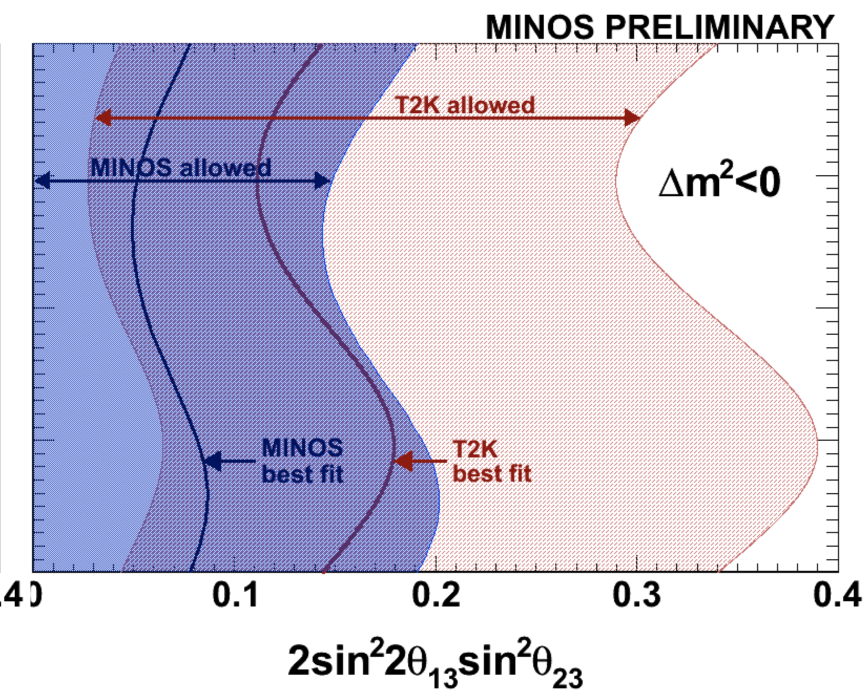
Comparison to T2K

How does MINOS signal prediction compare with T2K's best fit?
($\sin^2 2\theta_{13}=0.11$)



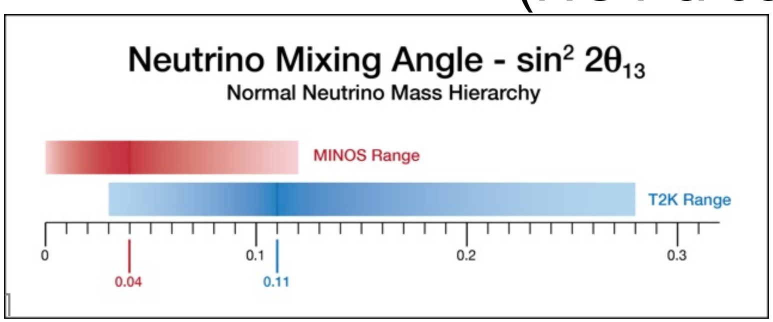
Comparison

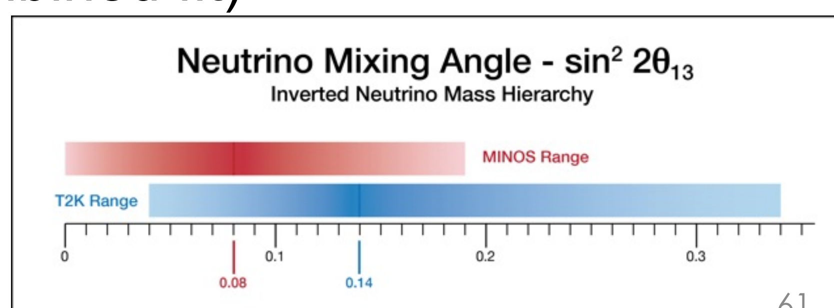




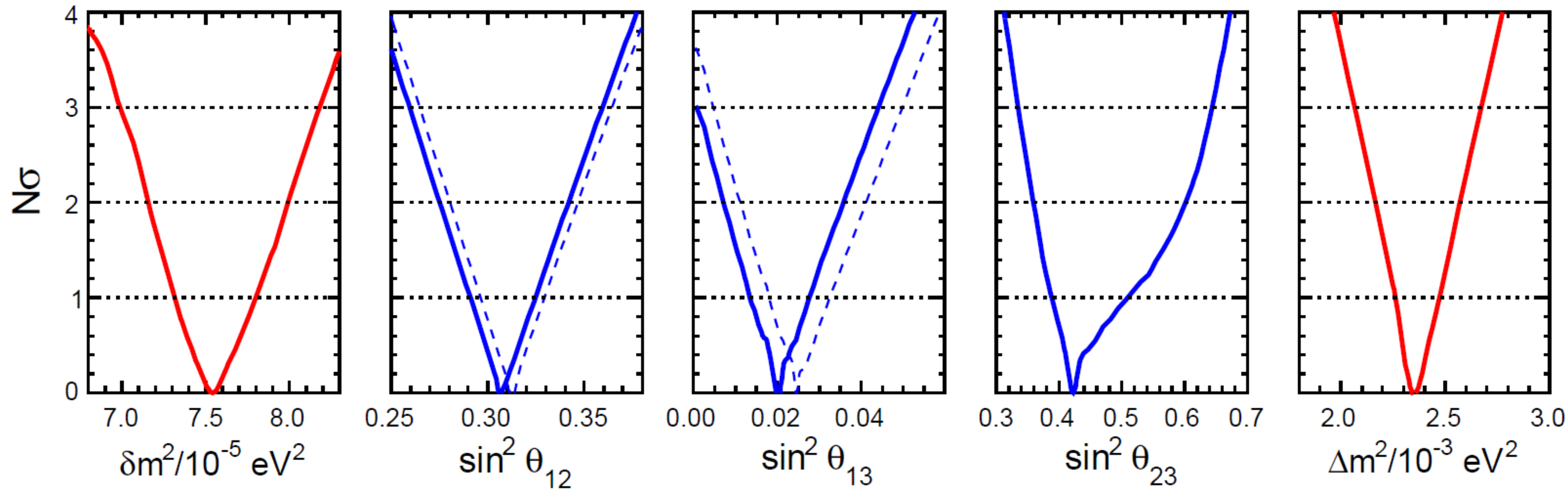
* arXiv:1106.2822

Overlay of MINOS and T2K allowed region
(NOT a combined fit)

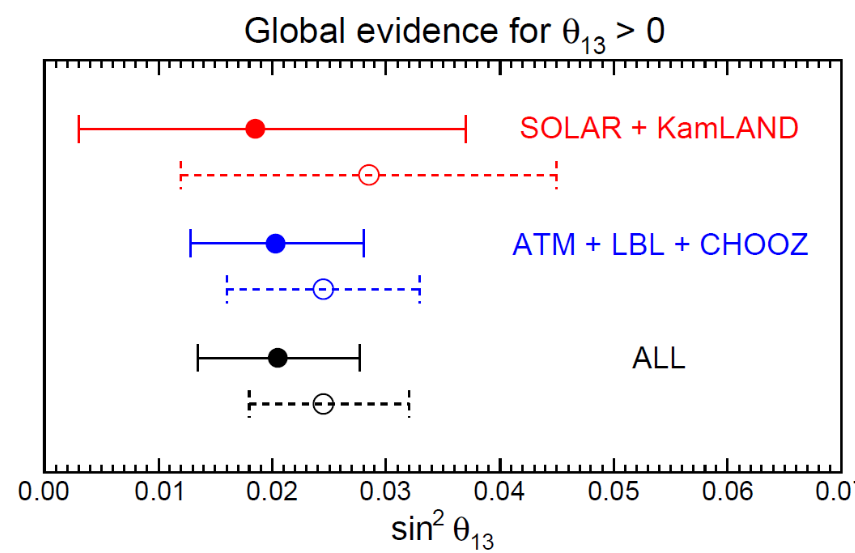




Global Fit (Fogli et al.)



- Combine World neutrino oscillation data
  - Solar experiments
  - Reactors (short & long BL)
  - LBL
  - Atmospheric neutrinos



Summary

- Exciting time for Neutrino physicists
- Precision measurements from
  - Solar neutrino experiments
  - Atmospheric neutrinos
  - Accelerator based long baseline experiments
- Results from LBL experiments
  - Neutrinos and Anti-neutrinos oscillate the same
  - Indications that $\theta_{13}>0$ from MINOS and T2K
  - Improved by global fit
- Future
  - Much more data from T2K
  - Reactor experiments
  - Start planning for CP violation in neutrino section