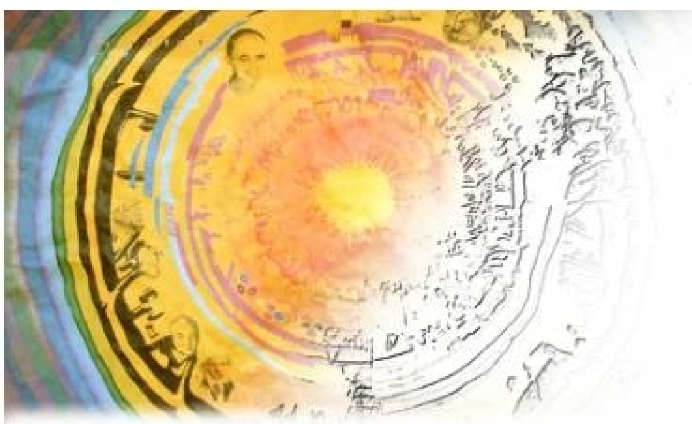
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Oxford Physics

Recent Results from the MINOS Experiment



Alfons Weber

(Oxford/RAL)

IoP Meeting on Neutrinos, QMUL
18-Apr-2011

Overview

- The NuMI Project: MINOS
  - Beam & Detectors
  - Muon Neutrino Disappearance
  - Neutral Current Events
  - Electron Neutrino Appearance
- Outlook

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!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

weak "flavour eigenstates"

Mass eigenstates m_1, m_2, m_3

Unitary mixing matrix: 3 mixing angles & complex phases

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

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

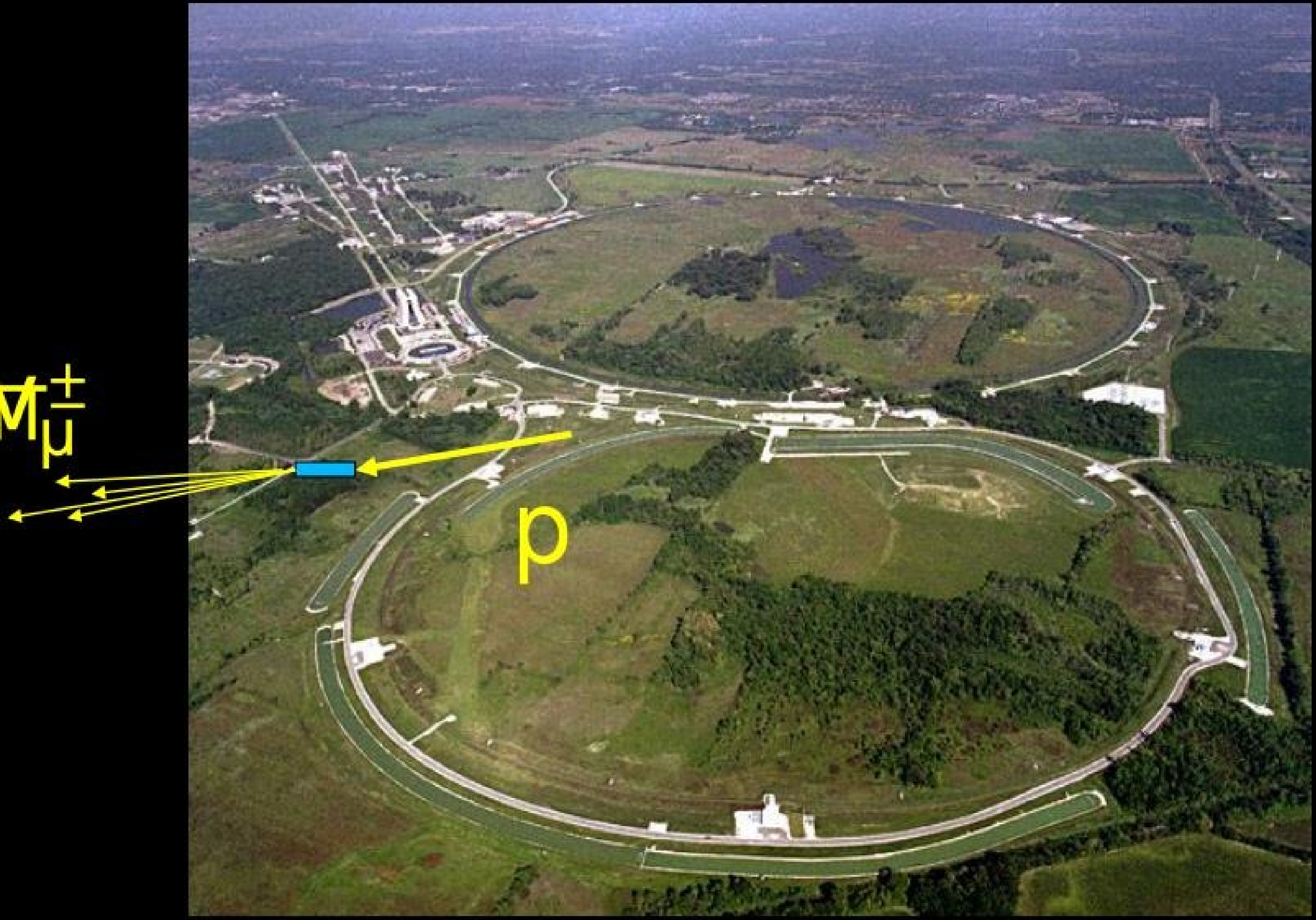
The MINOS Collaboration

**Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas
Fermilab • Harvard • IIT • Indiana • Minnesota-Duluth • Minnesota-Twin Cities
Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford
Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary**

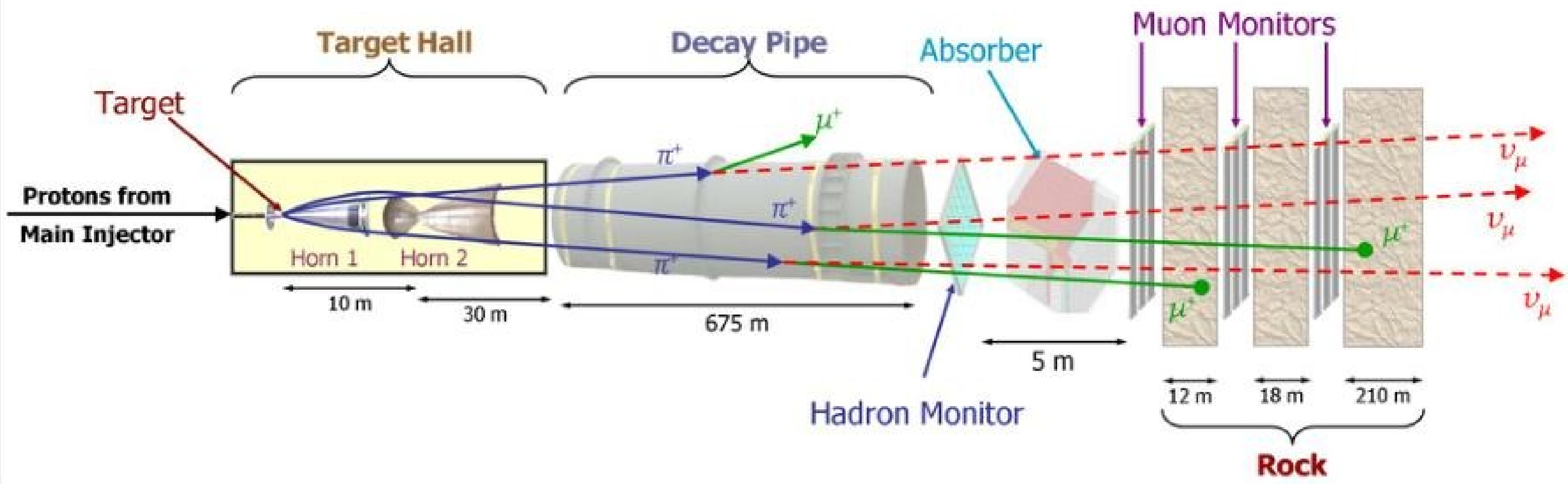
Experimental Setup

- **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

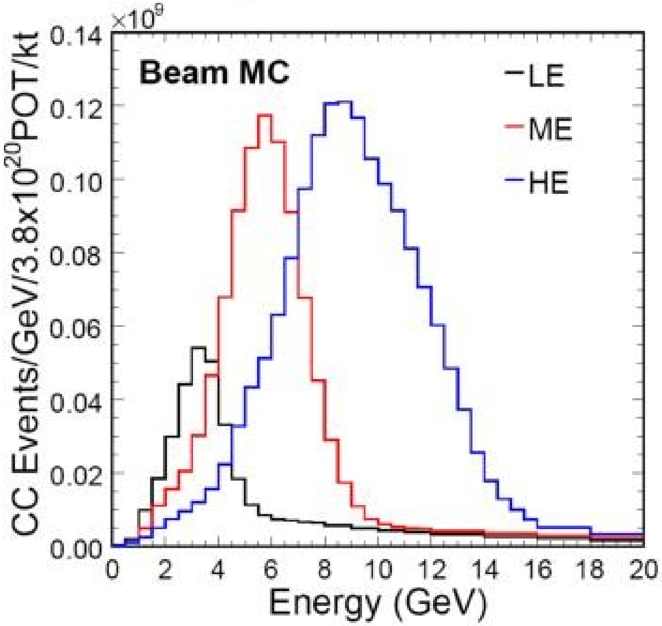
Making Neutrinos



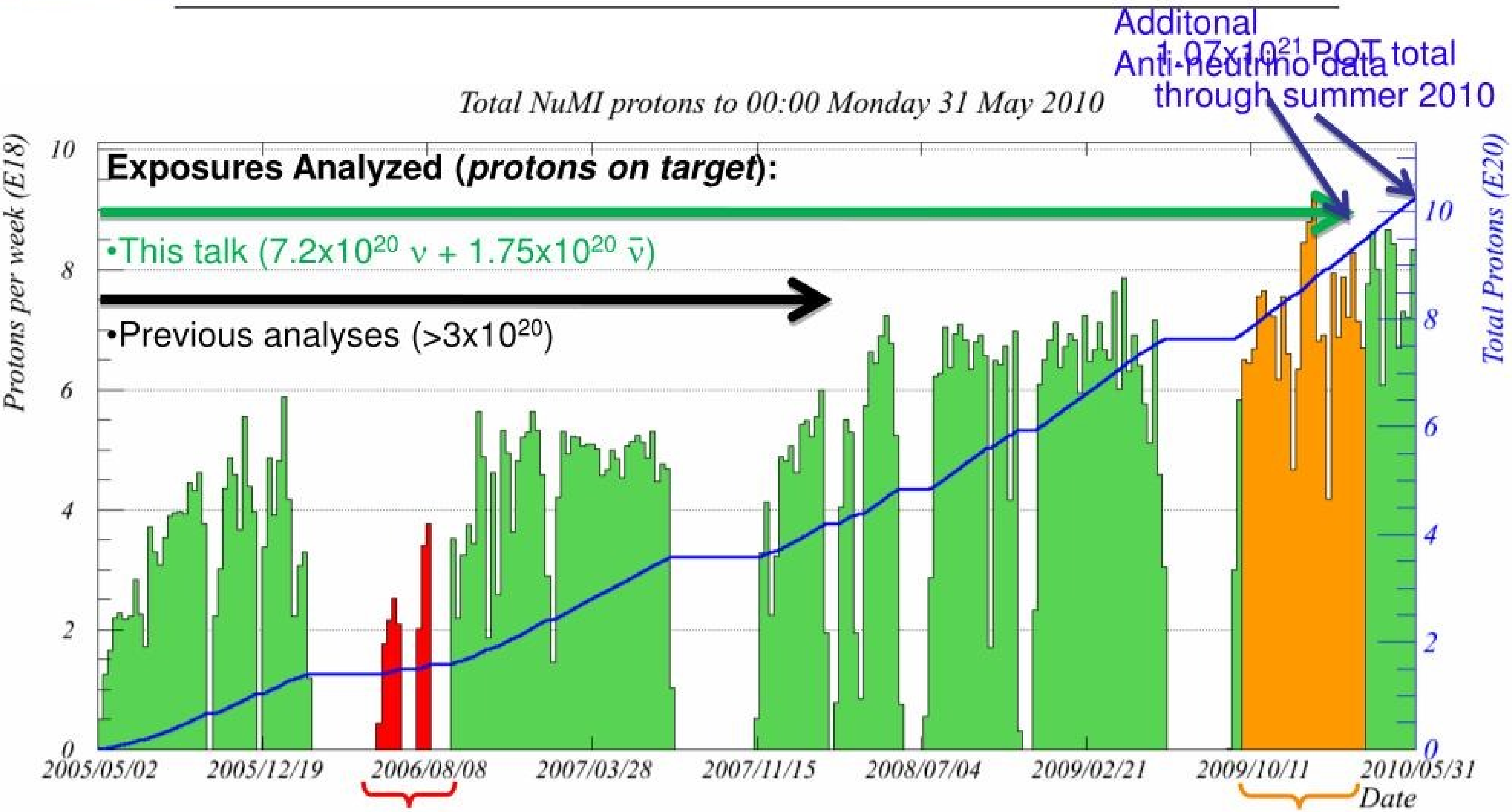
Making Neutrinos (II)



- 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



Beam Data Analyzed



HE beam:
0.15×10^{20} POT

Anti-nu beam:
1.75×10^{20} POT

Far Det
>98% live!

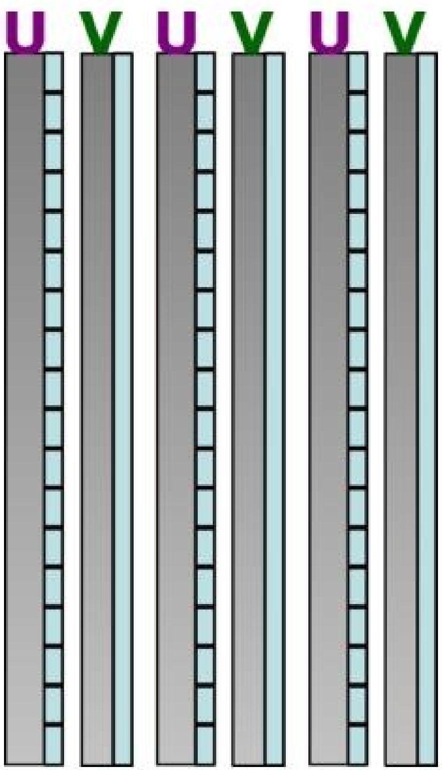
Soudan Underground Lab

- former iron mine, now a state park, home of
  - Soudan-1 & 2 , CDMS-II , and MINOS experiments

MINOS Construction Challenge

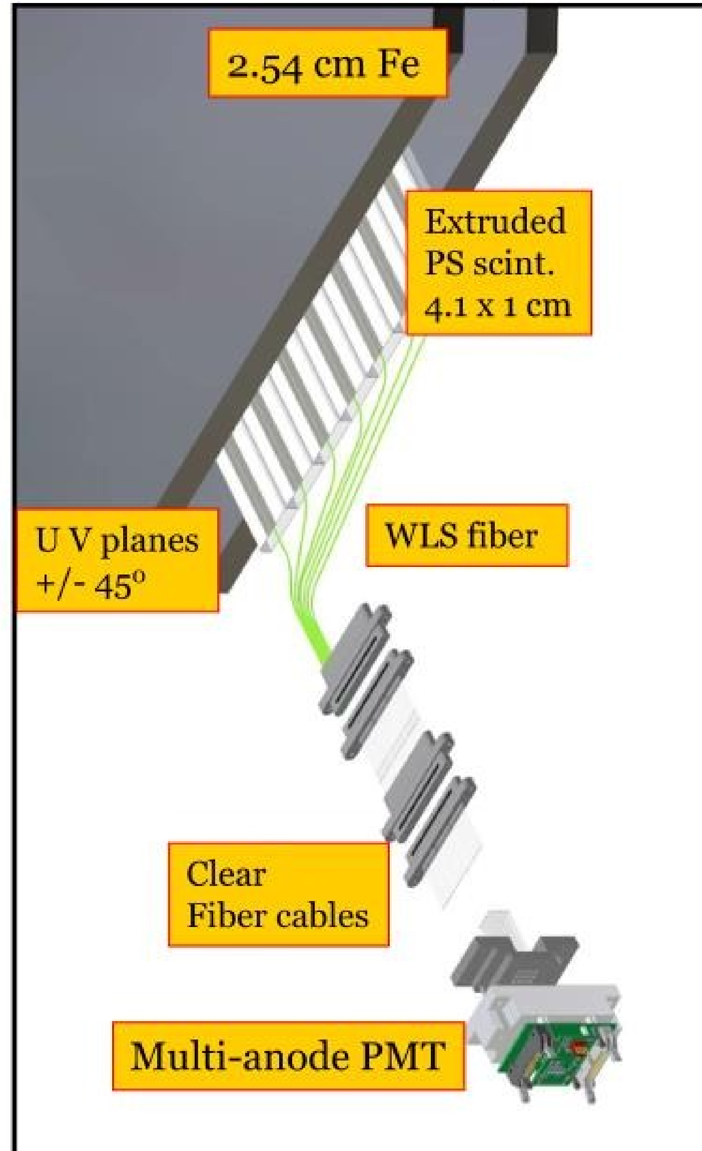
Detector Construction (I)

Detector Technology



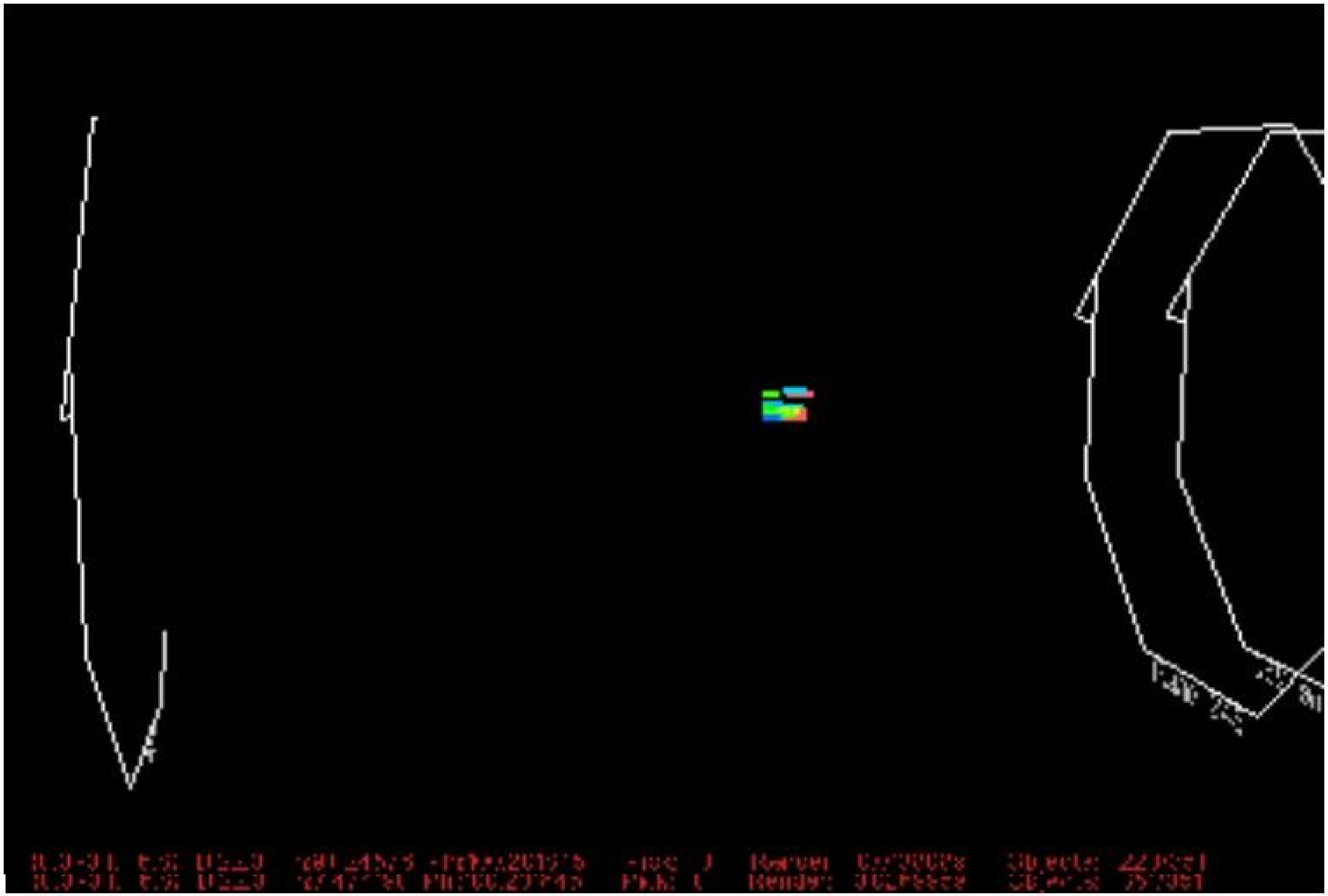
Near and Far Detectors are functionally identical:

- 2.54cm thick magnetised steel plates
- co-extruded scintillator strips
- orthogonal orientation on alternate planes – U,V
- optical fibre readout to multi-anode PMTs



The MINOS Cavern

MINOS Far Detector

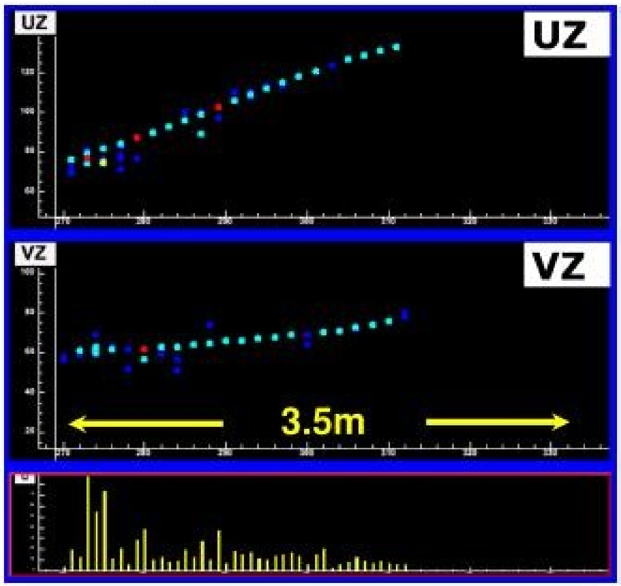


What it sees **What we reconstruct**

Event Topologies

Monte Carlo

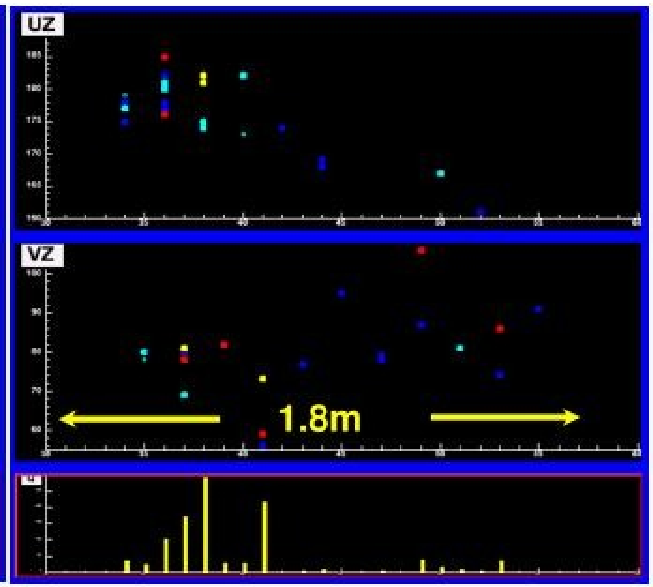
ν_μ CC Event



long μ track & hadronic activity at vertex

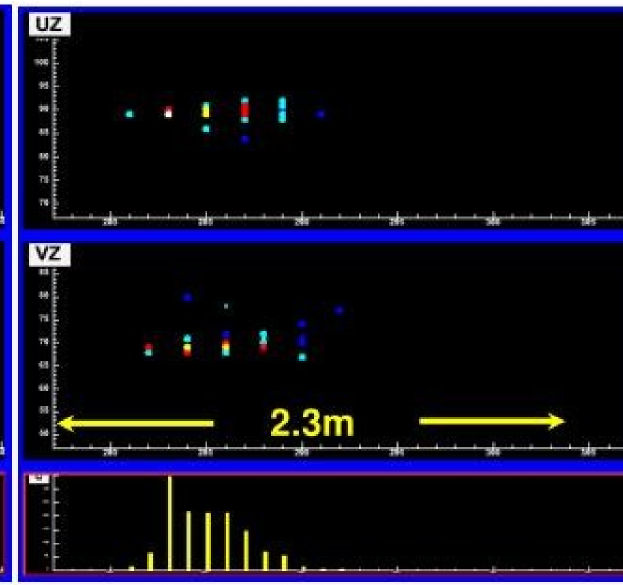
$$E_\nu = E_{shower} + p_\mu$$

NC Event



short event, often diffuse

ν_e CC Event

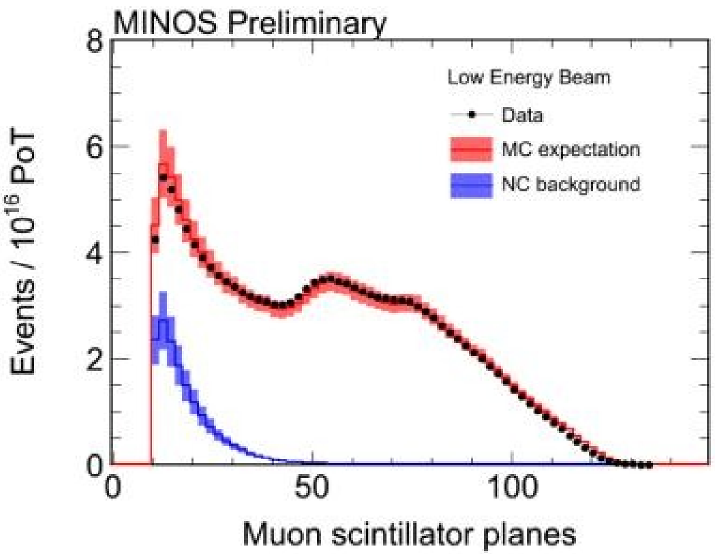


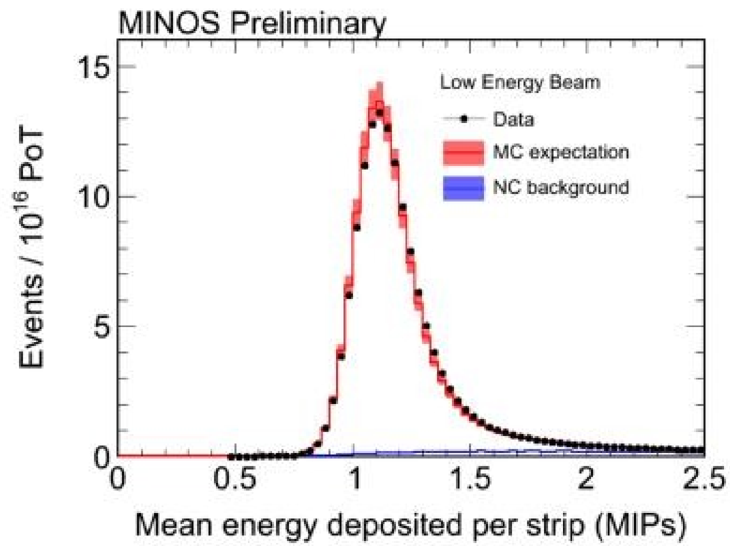
short, with typical EM shower profile

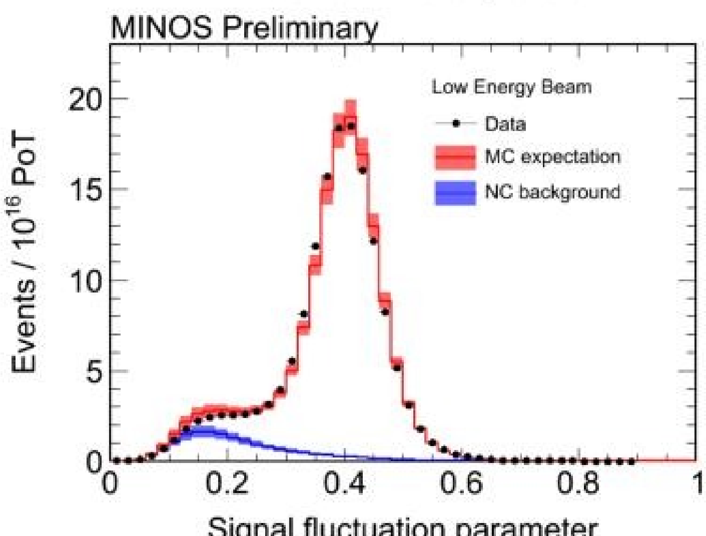
Energy resolution

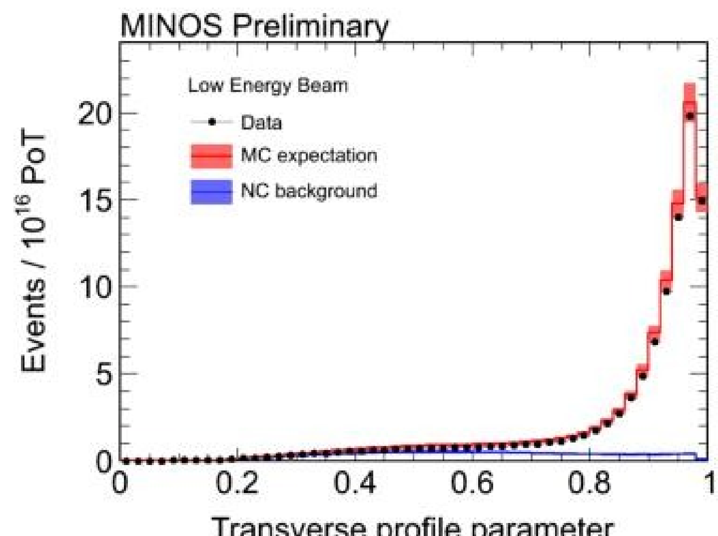
- $\pi^\pm$: 55%/$\sqrt{E(GeV)}$
- $\mu^\pm$: 6% range, 10% curvature

Identifying CC Events



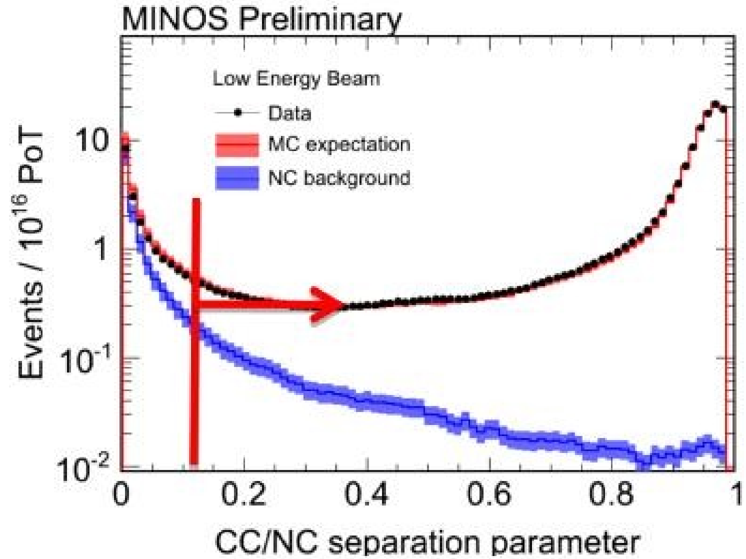




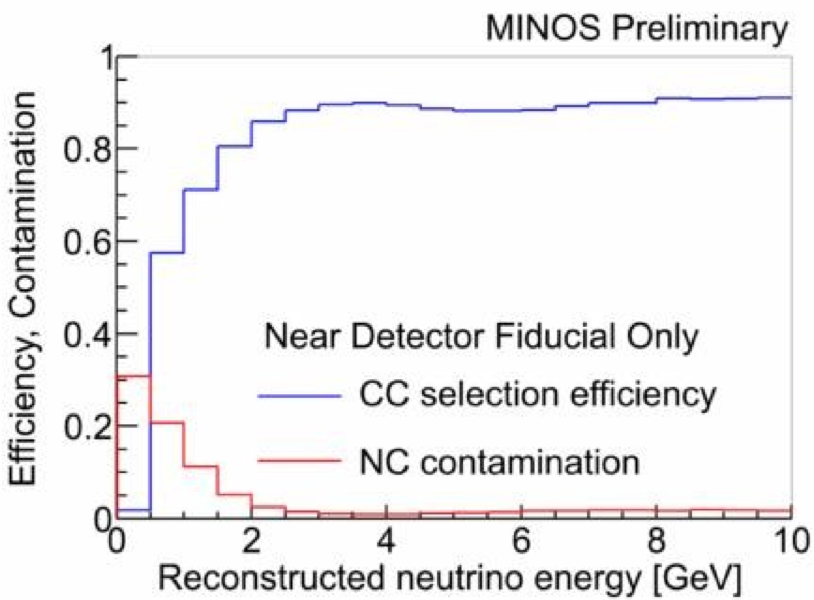


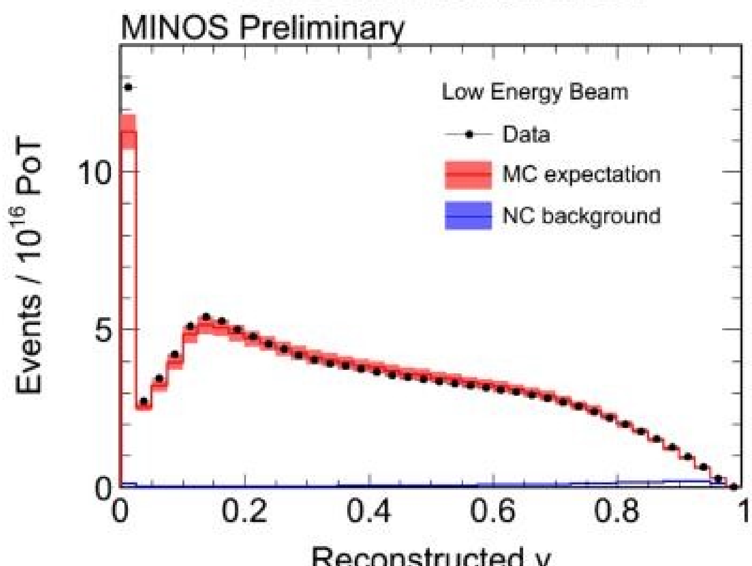
Particle ID

- Quantify "blobby-ness"
  - k-nearest neighbor (kNN) PID
  - Matches real events with similar-looking MC data



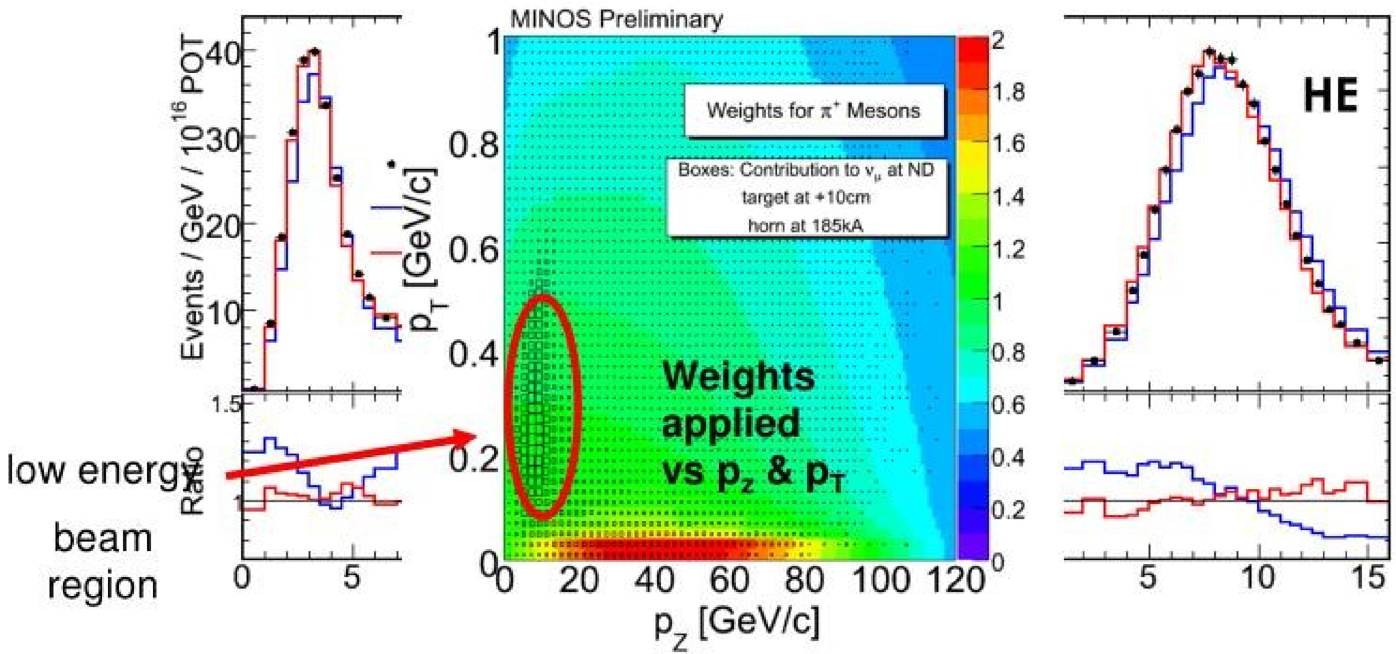
Eff: 88.7%
Pur: 98.3%



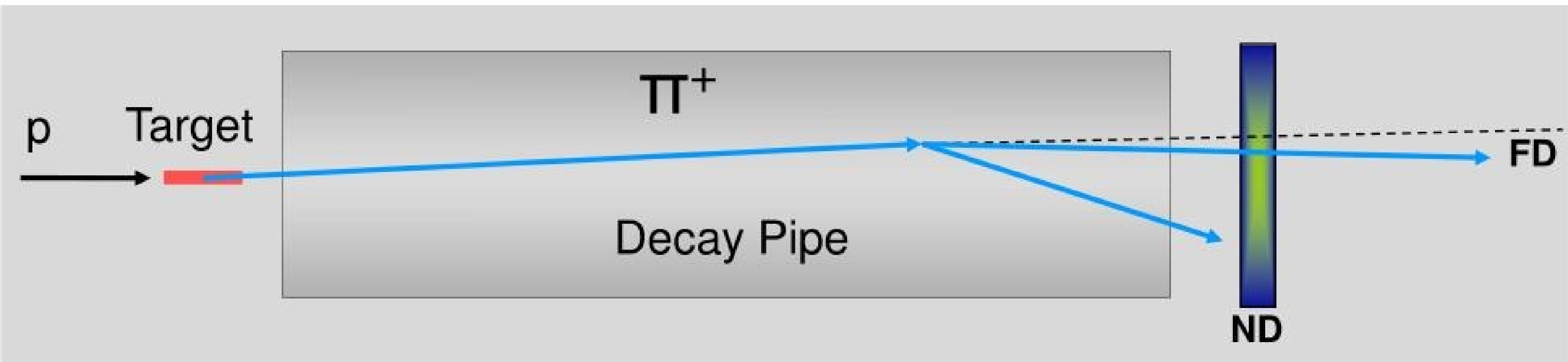


Hadron Production Tuning

- 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

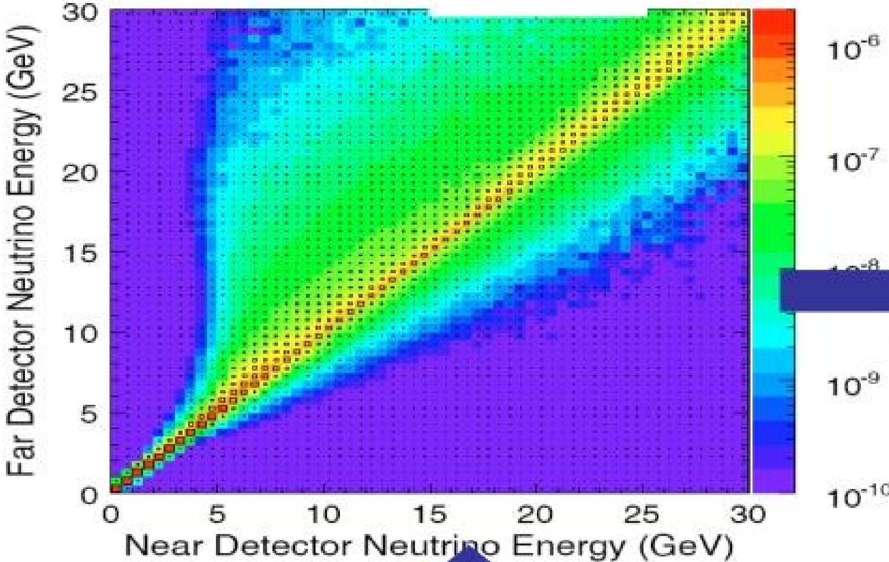


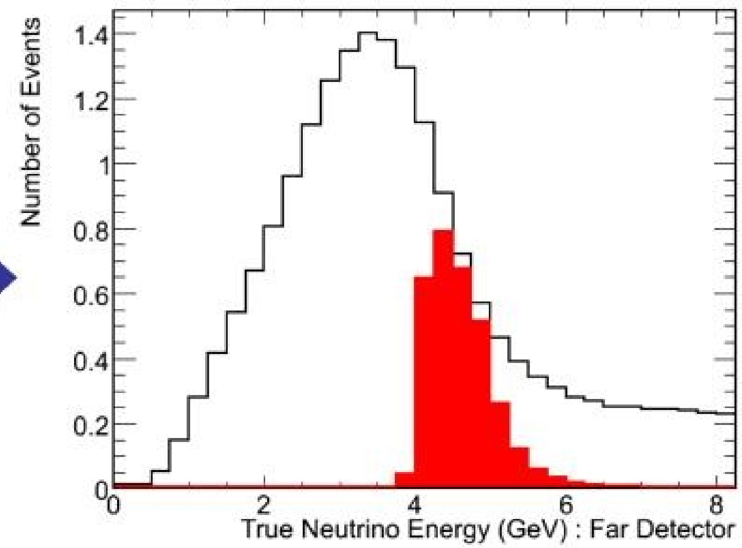
Predicting the FD Spectrum

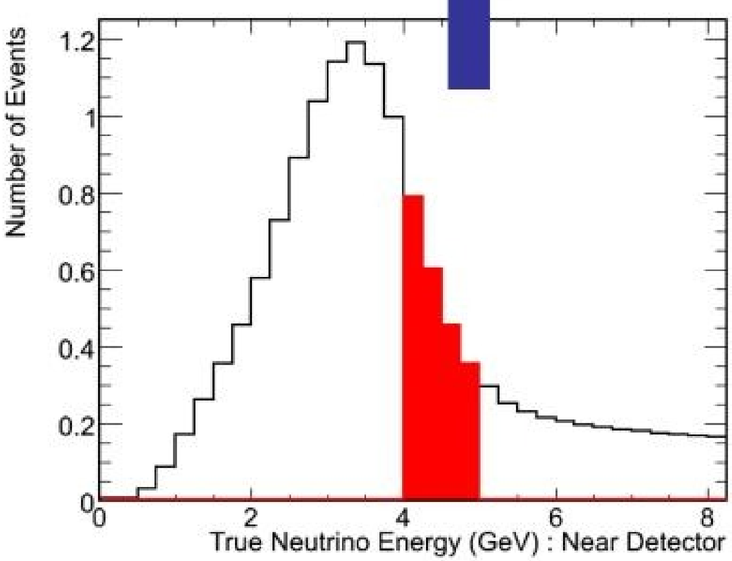


$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 \qquad E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

Near to Far Extrapolation

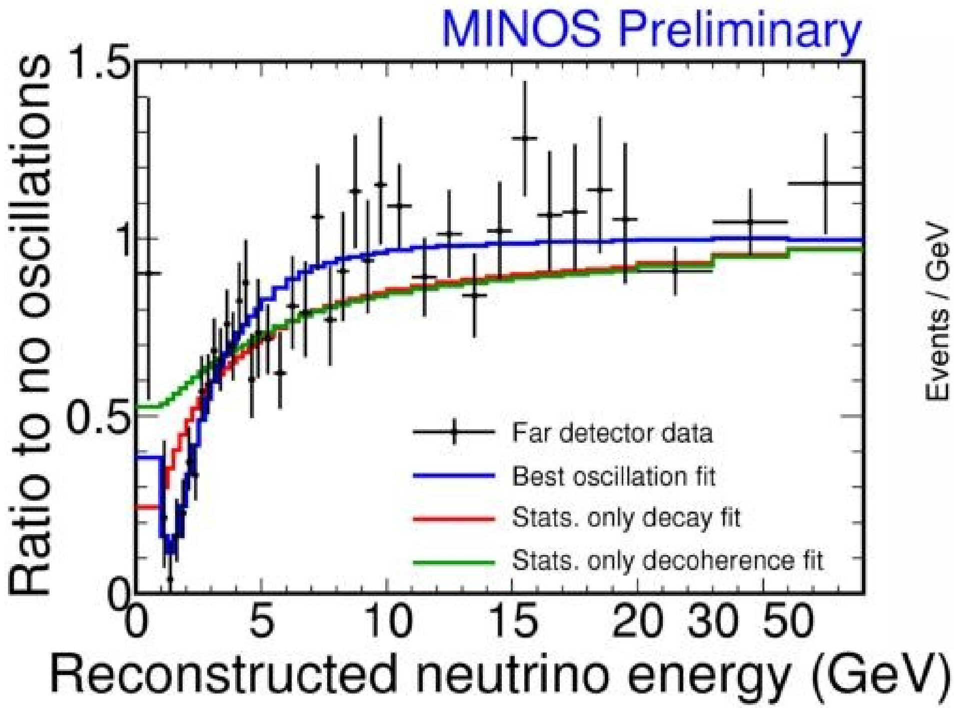


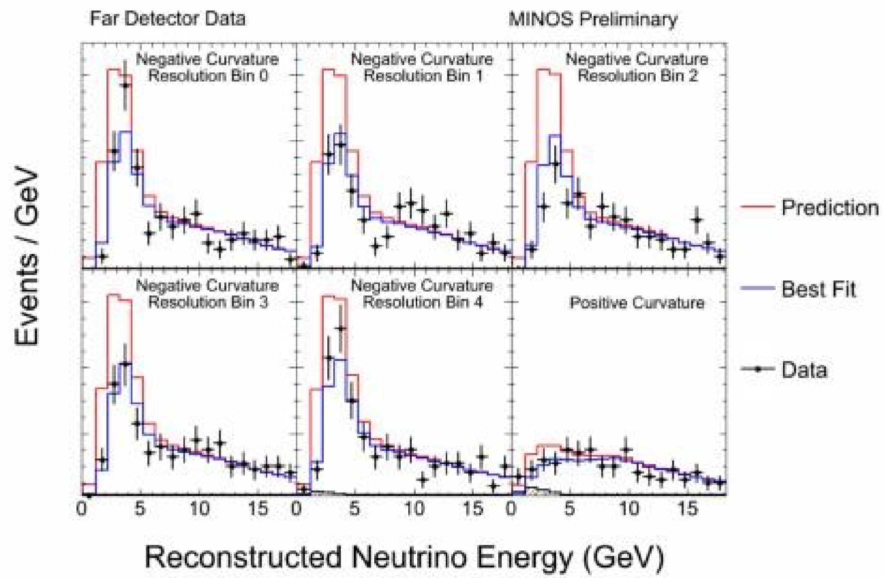




- Pion/Kaon decay kinematics are encapsulated in matrix
- Measured ND spectrum is transported to FD
- Largely reduce systematics
  - hadron production
  - cross section

Spectrum





Expect 2451 without oscillations

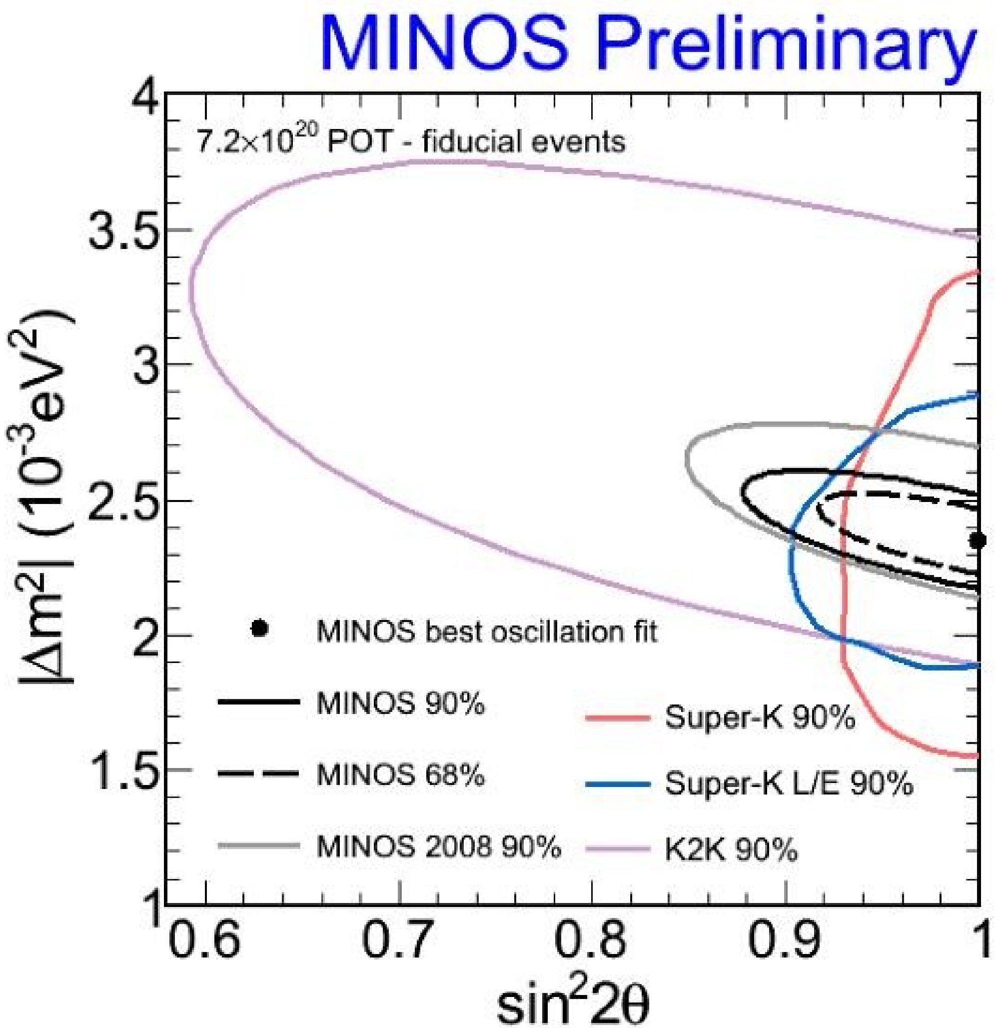
includes ~1 CR μ, 8.1 rock μ, 41 NC, ~3 ν_τ BG

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…

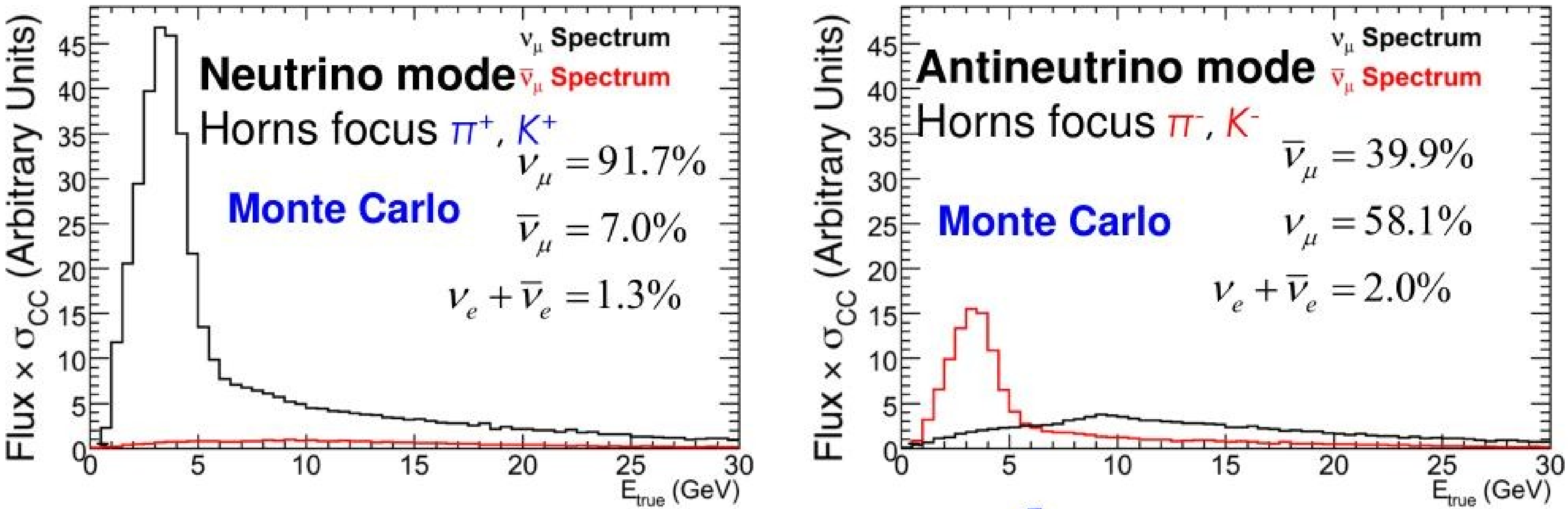
Allowed Region

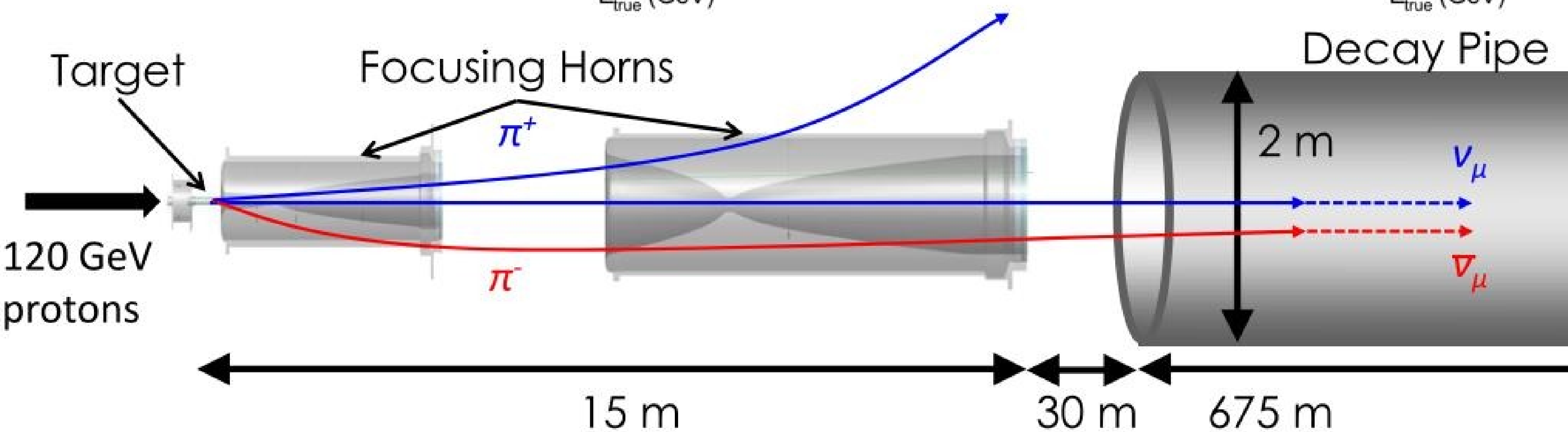


- Fit includes systematic penalty terms
- Best physical fit:
  $|\Delta m|^2 = 2.35 \times 10^{-3}\ eV^2$
  $\sin^2(2\theta)=1.00$
- Unconstrained:
  $|\Delta m|^2 = 2.34 \times 10^{-3}\ eV^2$
  $\sin^2(2\theta)=1.007$

Earlier results are in:
Phys.Rev. Lett. 101:131802, 2010

Anti-neutrino Mode



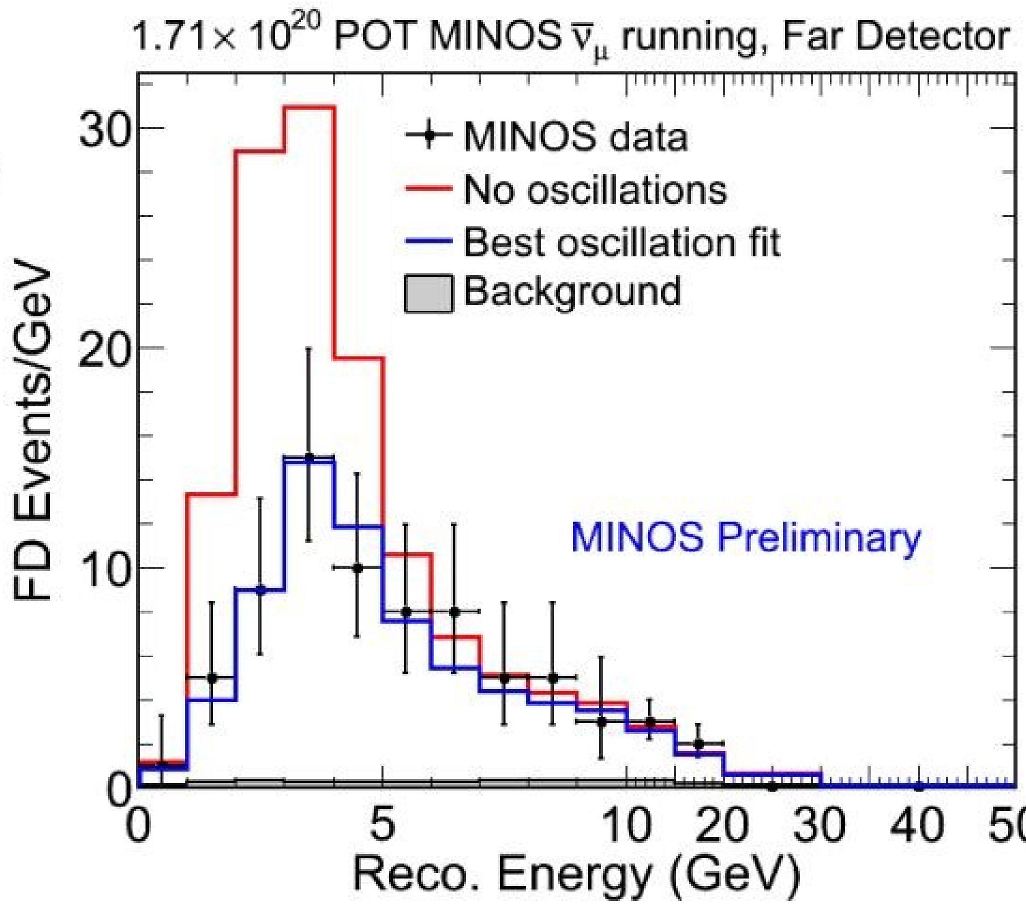


$\bar{\nu}_\mu$ Results

- 97 events seen, 155 expected (no osc)
- No- oscillations scenario disfavored at 6.3σ
- Same sort of oscillation fit yields:
- dominated by statistics
  - Includes additional 30% uncertainty on the ν_μ background

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40}(stat) \pm 0.06(syst) \times 10^{-3}\,\mathrm{eV}^2$$

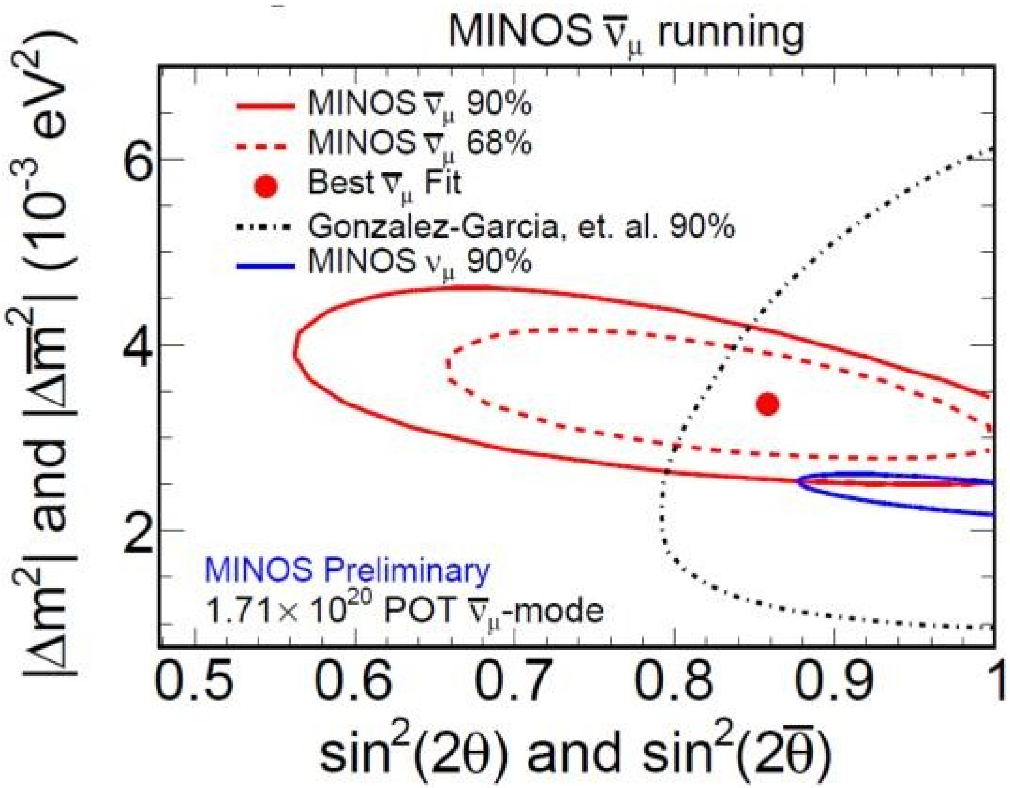
$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11(stat) \pm 0.01(syst)$$



- Plan to double anti-nu statistics after initial Minerva run

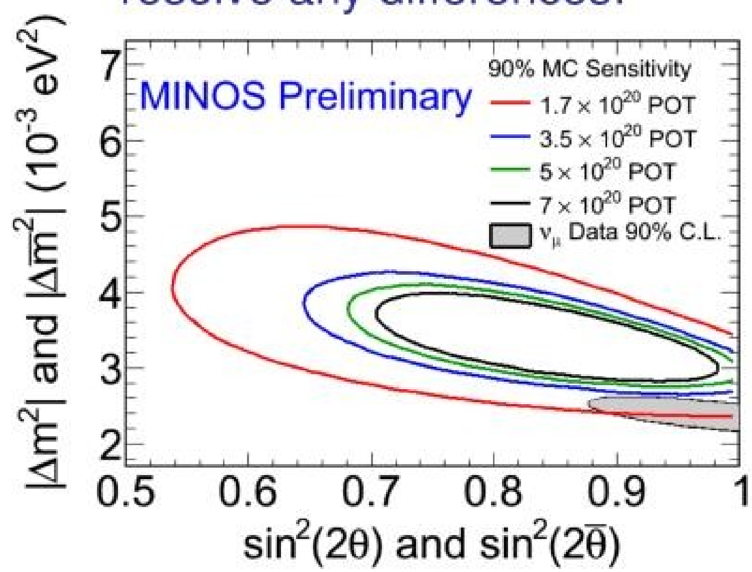
$\bar{\nu}_\mu$ Results

- Interestingly, oscillation parameters differ from the ν_μ results at a not terribly significant level, ~2σ



Global fit from Gonzalez-Garcia & Maltoni, *Phys. Rept.* 460 (2008), SK data dominates

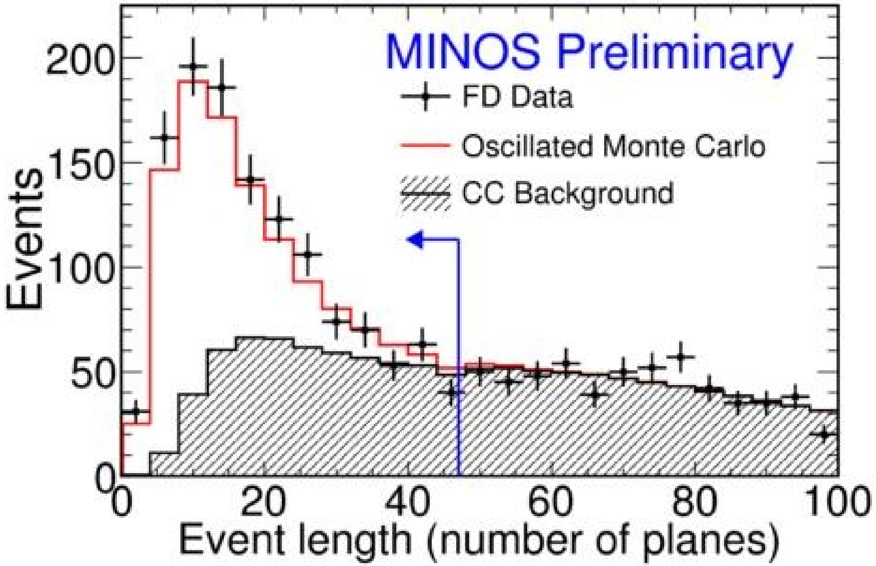
MC Sensitivity studies show doubling the data should better resolve any differences:

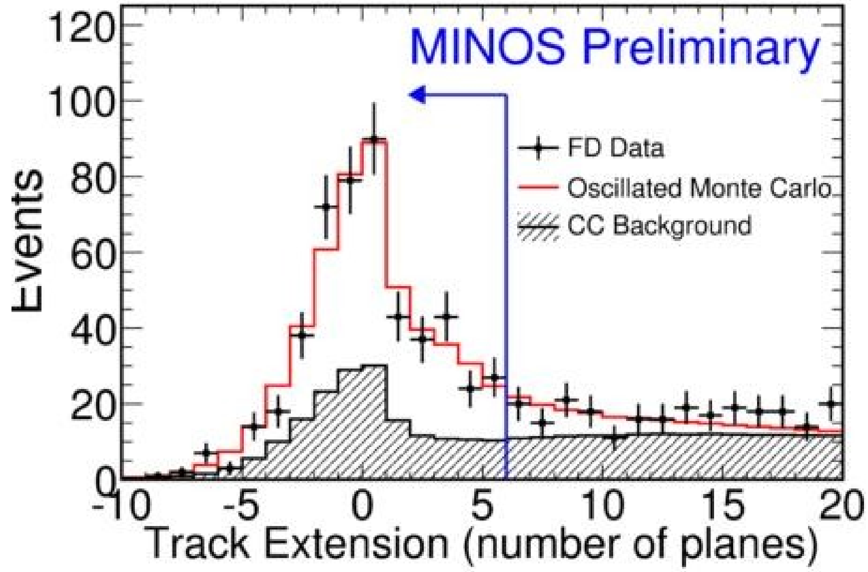


So what are the ν_μ disappearing to?

- For ν oscillations in this "atmospheric" sector, we like to blame ν_μ oscillating to ν_τ,
  - Most ν below τ production threshold
  - Few τ that aren't produce very messy decays which get rejected by our analysis
- Some very well might be going to ν_e as well, depending on the currently unknown θ_{13} (known to be less than 0.21 from Chooz)
- A fourth, sterile neutrino could also be the culprit
  - By definition, ν_s interact with nothing save gravity

Selecting Neutral Current Events

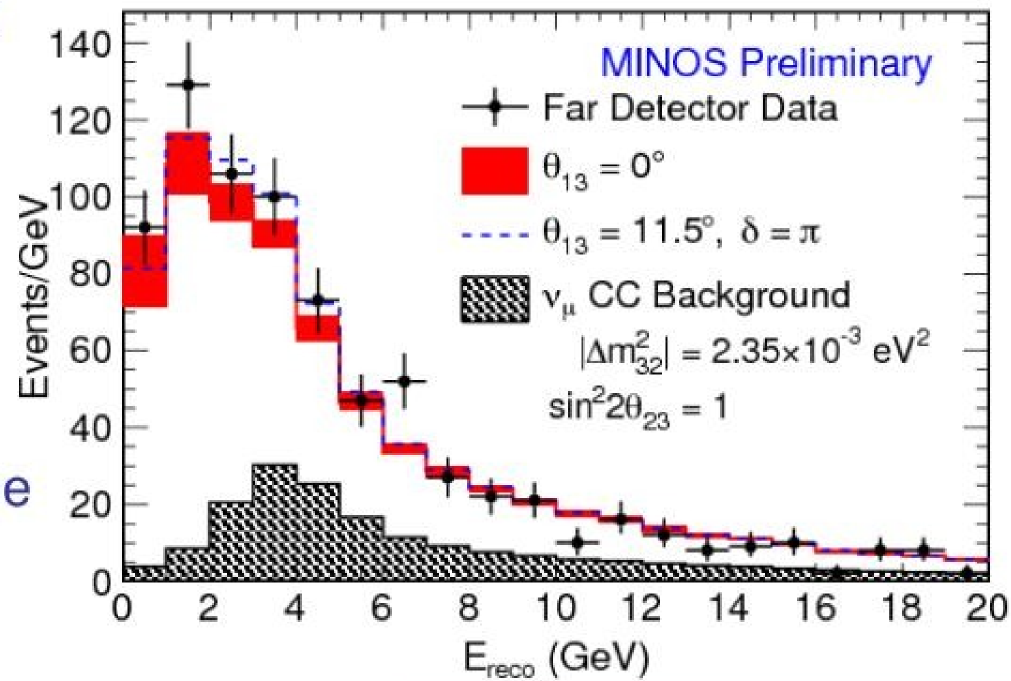




- ND data quality cuts exclude poorly reconstructed events due to high ν interaction rate
- Cuts applied to both ND & FD: (*distributions similar, lower stats @FD*)
  - < 47 planes;
  - no track extends beyond 6 planes from the shower
- MC oscillated using MINOS best ν_μ fit

NC Analysis Results

- FD NC energy spectrum for Data and oscillated MC predictions
  - Form ratio R, data are consistent with no ν_μ disappearing to νs
- Simultaneous fit to CC and NC energy spectra yields the fraction of ν_μ that could be oscillating to ν_s:



$$R \equiv \frac{N_{Data} - B_{CC}}{S_{NC}}$$

	$R \pm$ stat $\pm$ syst
$\theta_{13}=0$	1.09 ± 0.055 ± 0.053
$\theta_{13}=11.5°$	1.01 ± 0.055 ± 0.058

$$f_s = \frac{P(\nu_\mu \rightarrow \nu_s)}{1 - P(\nu_\mu \rightarrow \nu_\mu)}$$

$$f_s < 0.22 \quad (0.40\nu_e)@(90\%\,\text{C.L.})$$

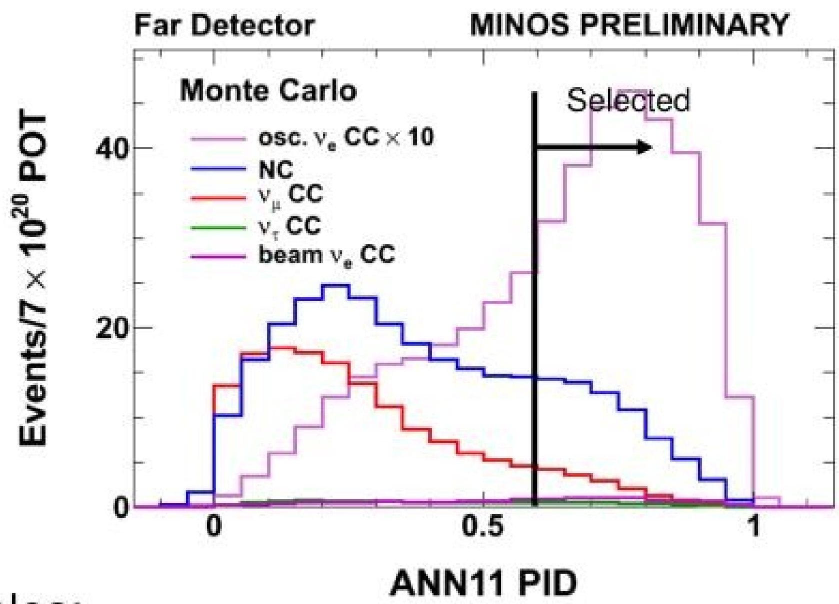
Earlier results are in:
Phys.Rev.D81:052004, 2010

ν_e Appearance

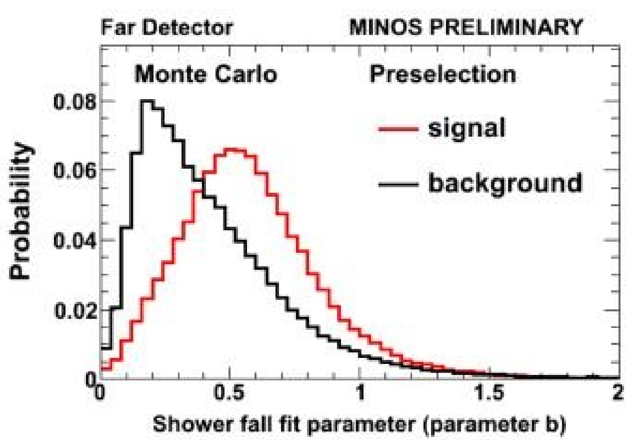
- Are some of the disappearing ν_μ re-appearing as ν_e?
  - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$
    - Plus CP-violating δ and matter effects, included in fits
- Need to select events with compact shower
  - MINOS optimized for muon tracking, limited EM shower resolution
    - Steel thickness 2.5 cm = 1.4 X_0
    - Strip width 4.1cm ~ Molière radius (3.7cm)
  - At CHOOZ limit, expect a ~2% effect
    - Do blind analysis – establish all cuts, backgrounds, errors first
    - Crosscheck in three sidebands
    - Only then look at the data to see what pops out

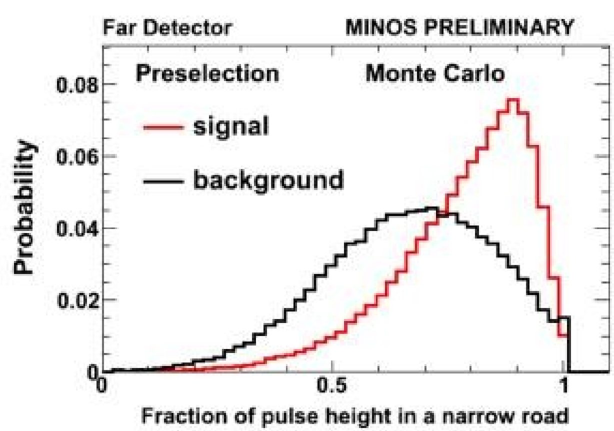
ν_e Selection

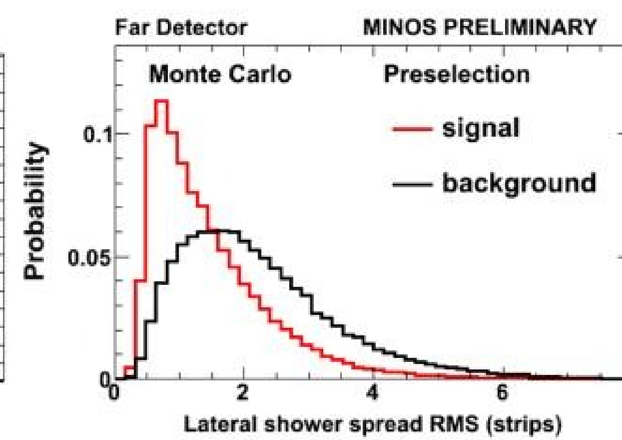
- 11 variables chosen describing length, width and shower shape
- A Neural Net ("ANN") algorithm achieves:
  - S/N 1:2, signal efficiency 42%
  - NC rejection 94.6%
  - ν_μCC rejection 99.6%
- Crosschecks using a second "Library Event Method" agree



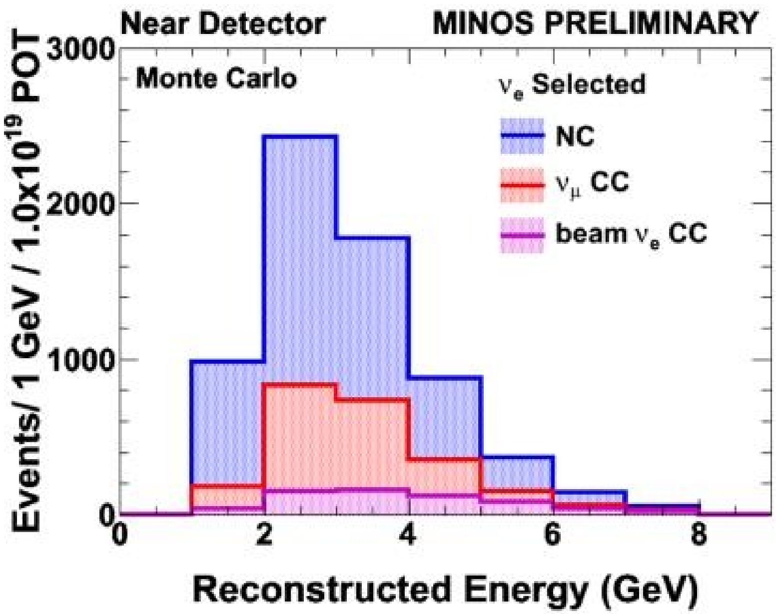
Some variables:

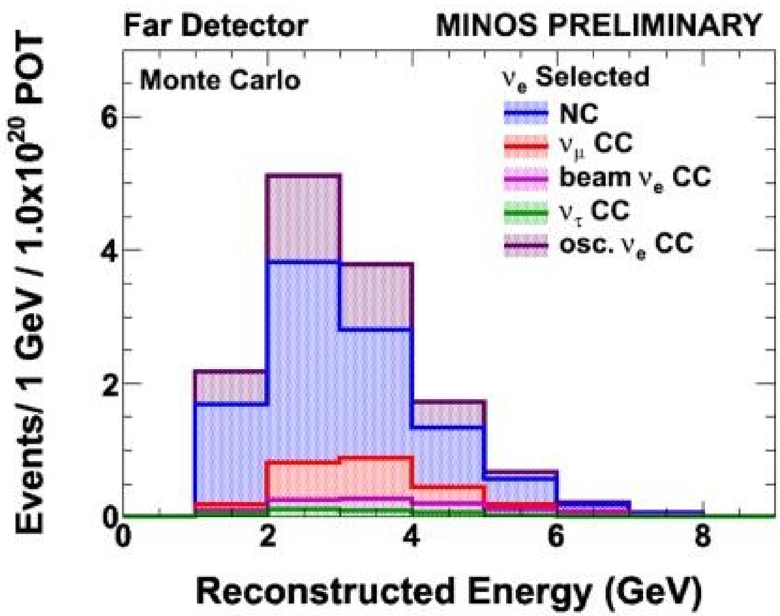






MC Expectations

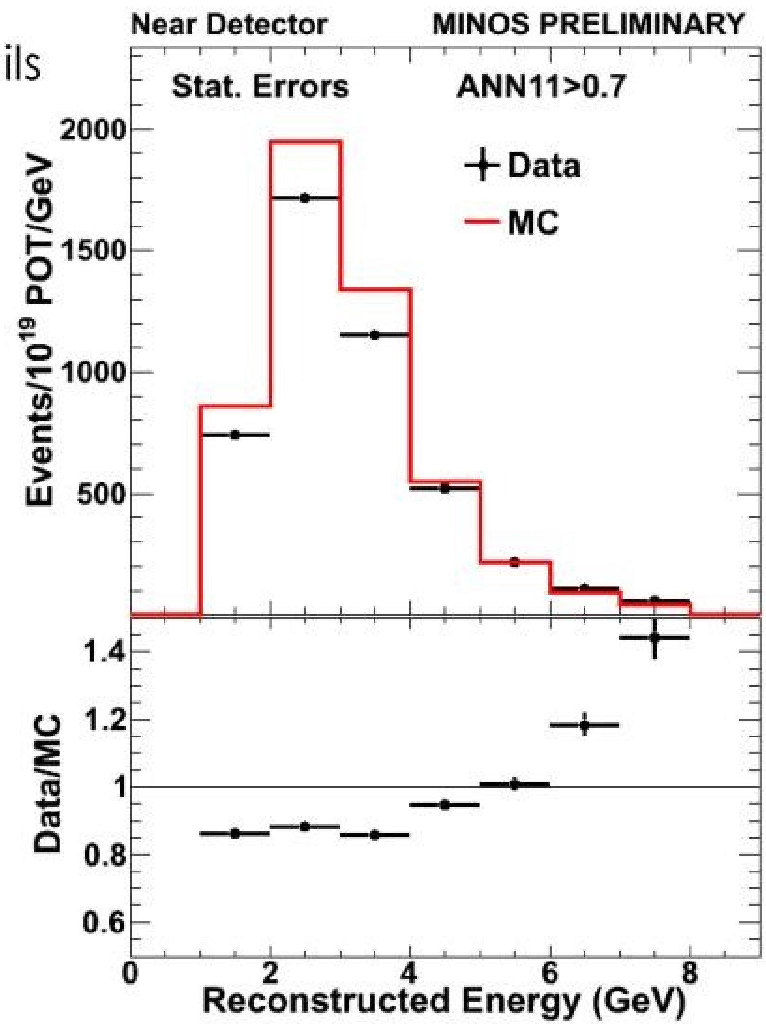




- Background is mostly NC interactions
  - Usually with a π^0
  - Also high-y CC (π again), beam ν_e, oscillated ν_τ showers
- Purple (*on right*) shows ν_e appearance signal at the Chooz limit ($\sin^2 2\theta_{13}=0.15$)

MC meets RL

- Turns out that the MC is off by ~15% (for E<6 GeV) when compared to the Real Life ND data
  - Harsh cuts leave only the ill-modeled tails
  - Within systematic errors for things such as hadronic shower modeling
- Need to correct using ND data-driven approaches
  - All ν_e-like events at ND are background, so use this pure "noise" dataset to predict FD background
  - Compare horn on vs. horn off spectra
  - Also look at "muon removed" CC events
- Use background measured in ND to characterize FD backgrounds

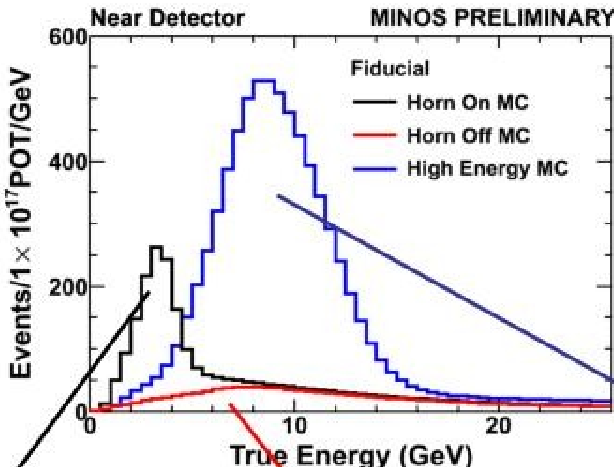


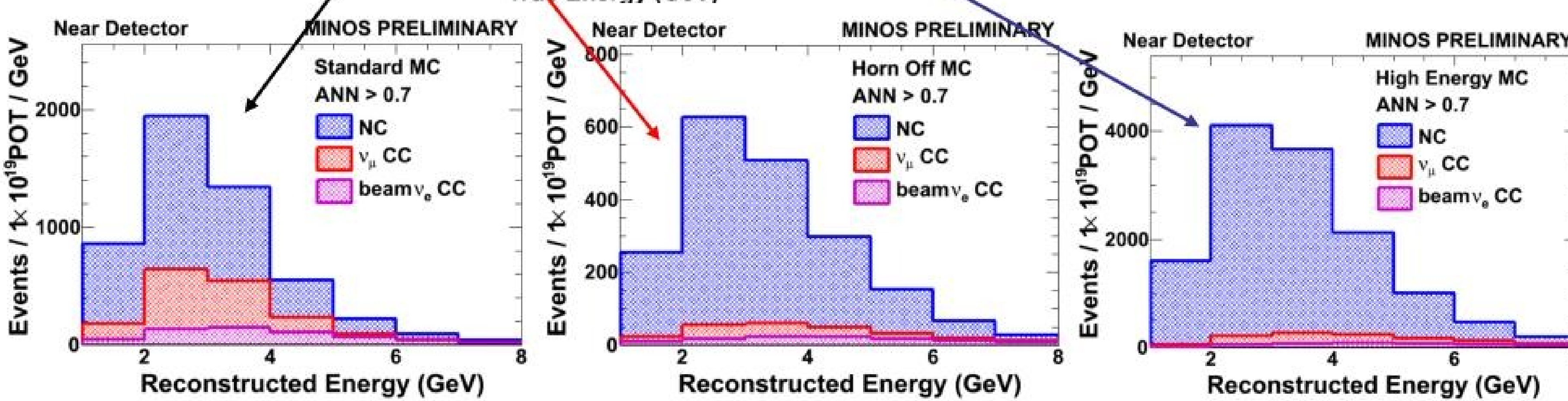
Extrapolation and Errors

FD background prediction:

49.1 ± 7(stat) ± 2.7(sys)

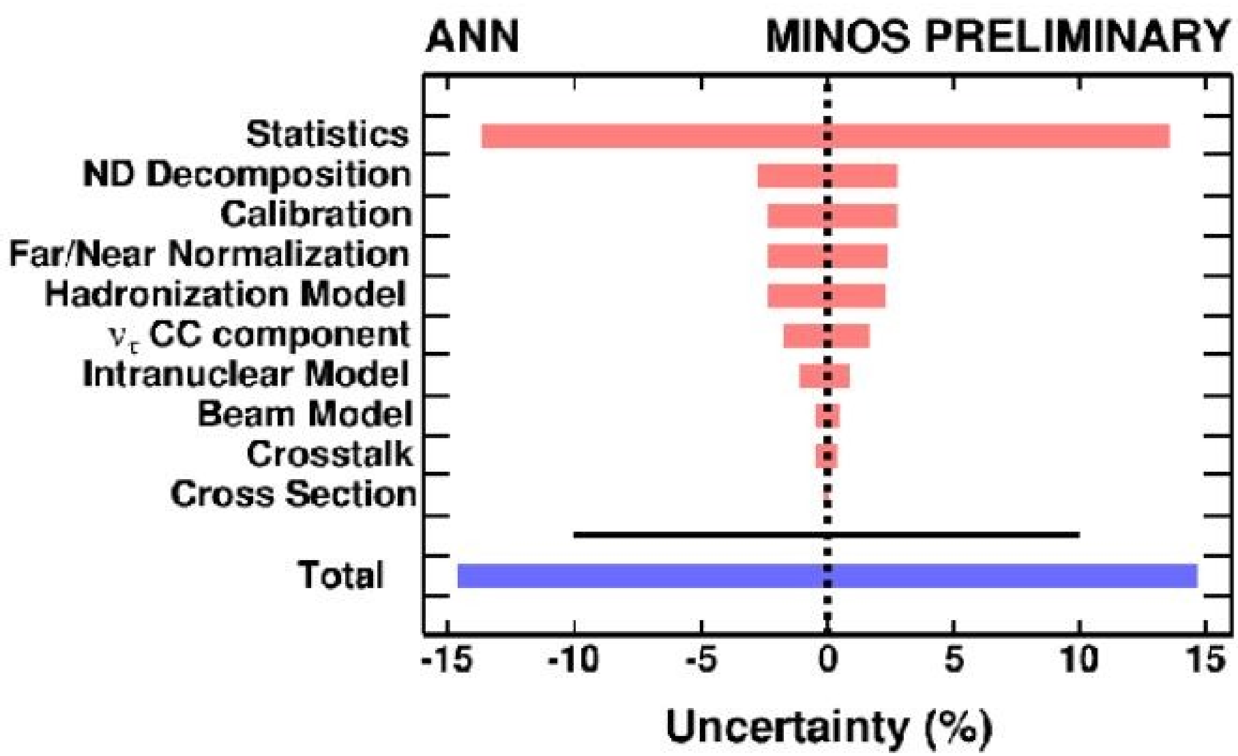
- Very different spectra allow de-convolution of ND BG
  - 2^{nd} method using μ-removed CC events agrees
- Different BG components extrapolate differently to FD
  - Understanding BG composition important
  - 73% NC, 13% CC, 10% beam ν_e, 4% ν_τ
  - Signal/Noise 1:2 @ CHOOZ limit (24 ν_e)





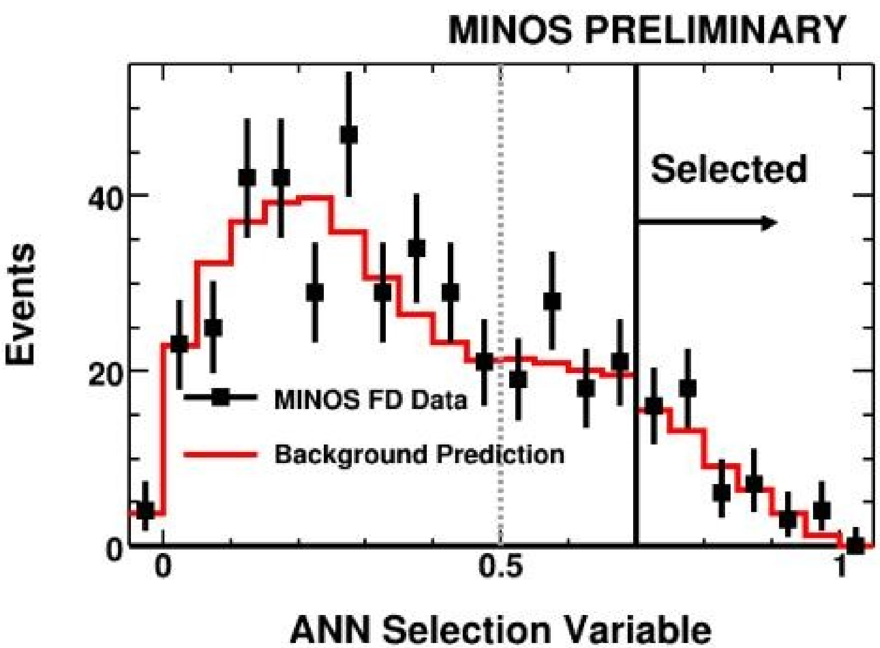
Systematic Errors

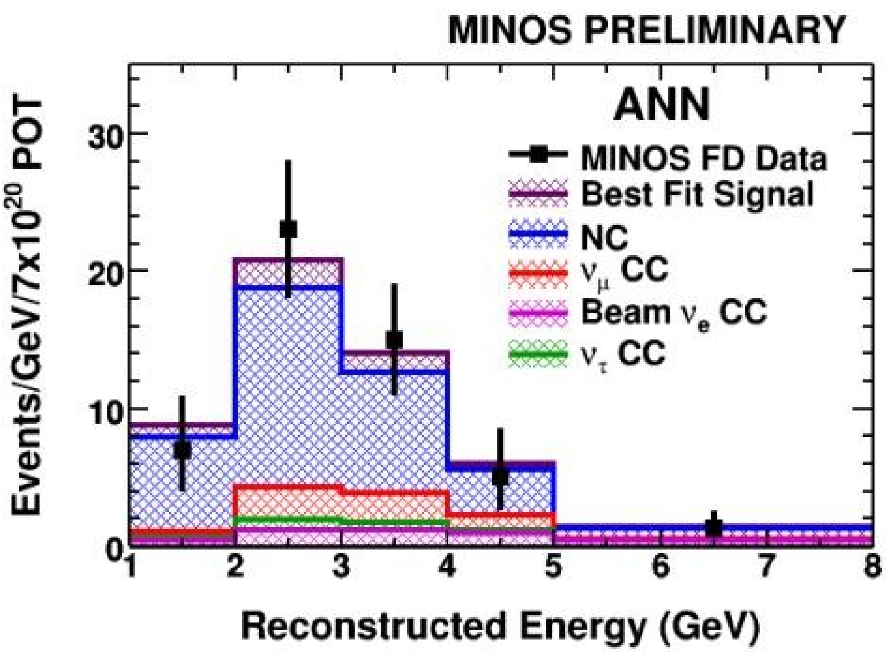
- Evaluate systematic uncertainties in the Far Detector predictions
  - Still dominated by statistics



ν_e Appearance Results

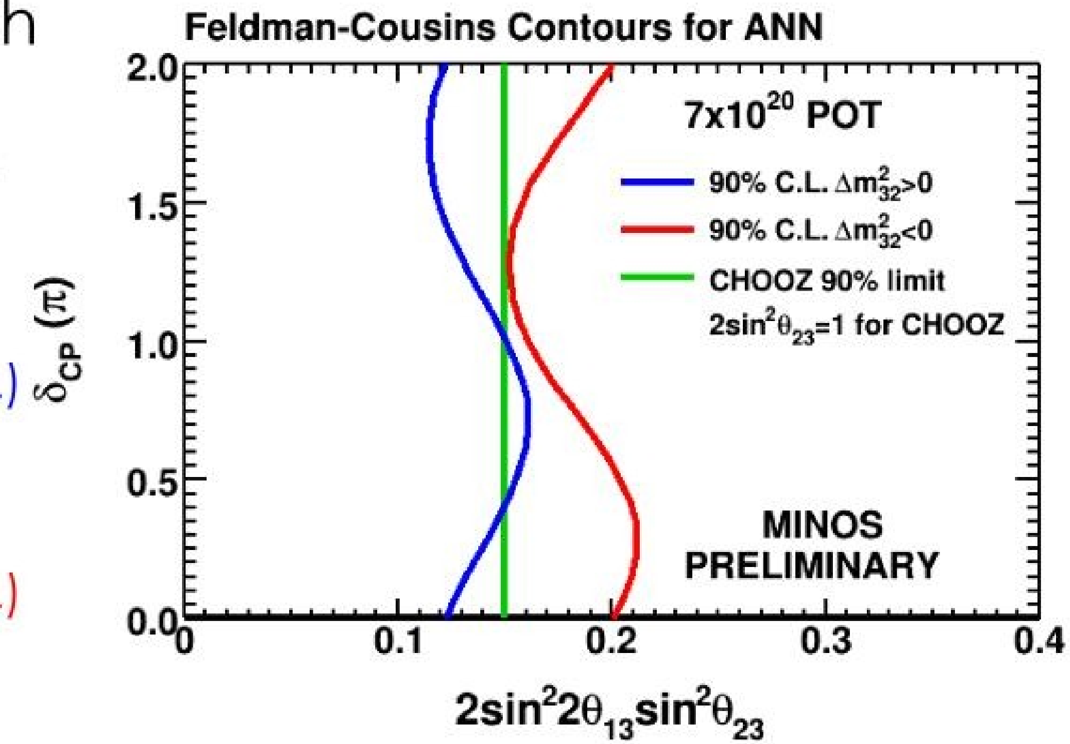
- FD background prediction:
  - **49.1±7(stat)±2.7(sys)**
- Observed:
  - **54** (0.7σ excess)





ν_e Appearance Results

- No significant excess seen, find allowed upper limits using F-C approach
  - For both Normal and Inverted mass hierarchies
  - Normal hierarchy ($\delta CP=0$):
    - $\sin^2(2\theta_{13}) < 0.12$ (90% C.L.)
  - Inverted hierarchy ($\delta CP=0$):
    - $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)

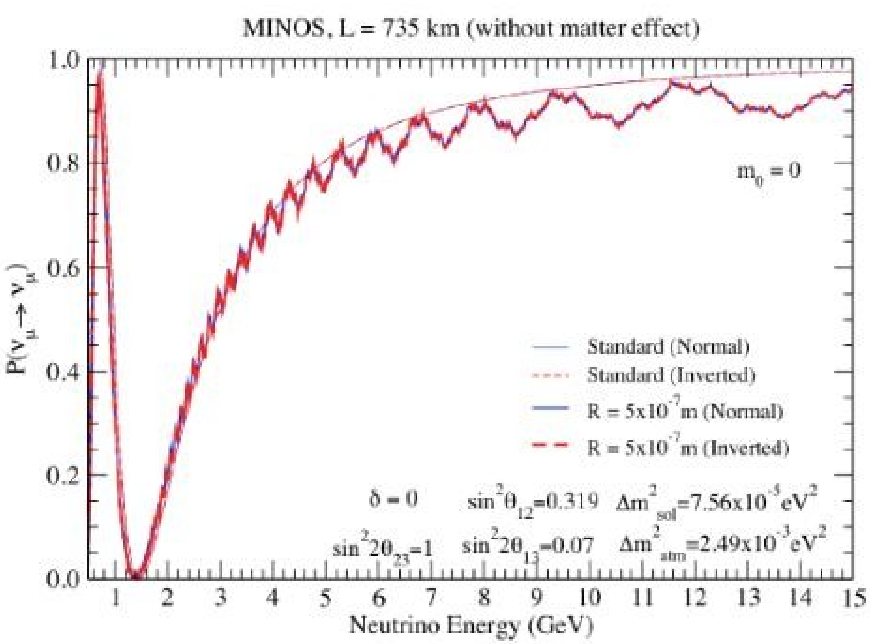


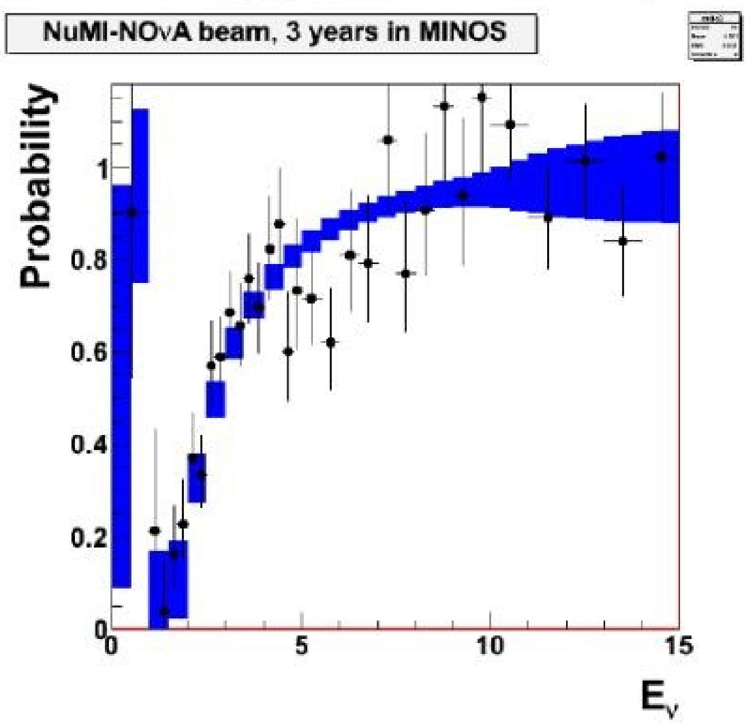
- **More sensitive analysis ready for summer**

A paper about this:
arXiv:1006.0996 [hep-ex]

MINOS+

- Precision Neutrino Physics???
  - Not yet.
  - Compare Z-lineshape to oscillation spectrum

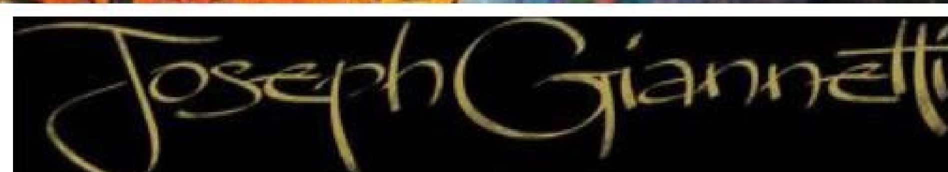




Summary

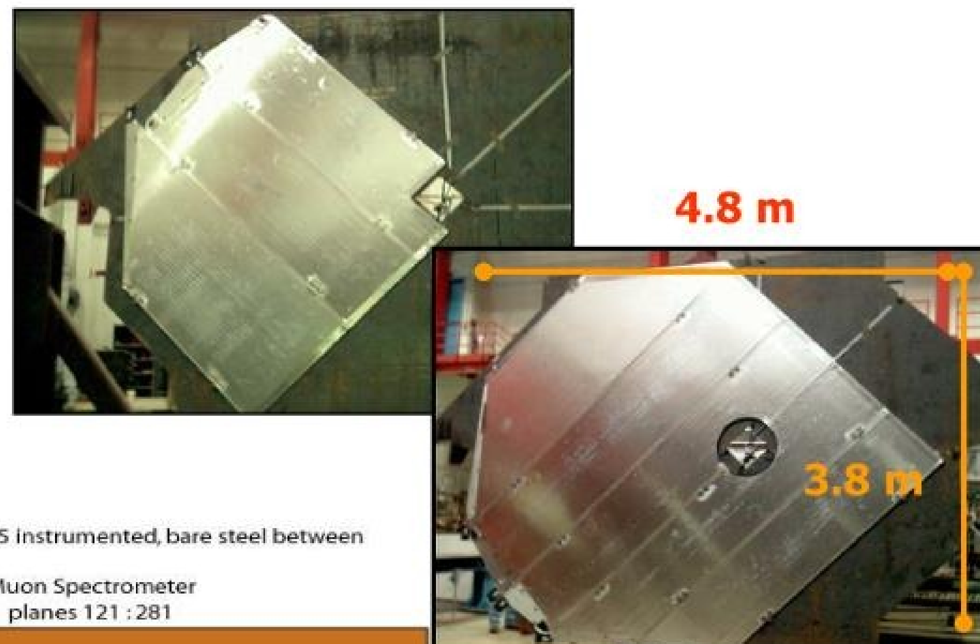
- MINOS had a very successful running over the past years
- Precision measurement of neutrino-oscillation parameters
  - Neutrinos
  - Anti-neutrinos
- Limits on oscillation into
  - Electron neutrinos
  - Sterile neutrinos
- Further anti-neutrino running
  - Almost doubled statistics
  - Hope for more before summer
- And …

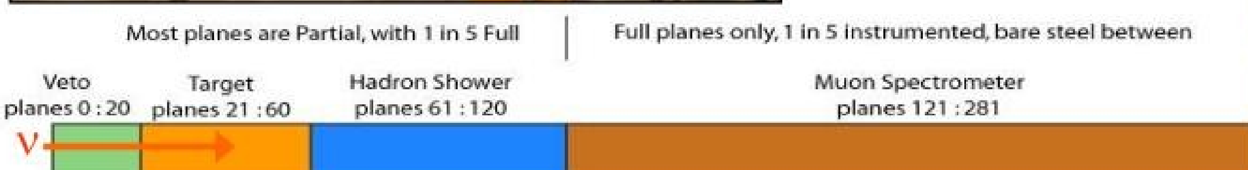
The MINOS Mural



Near Detector

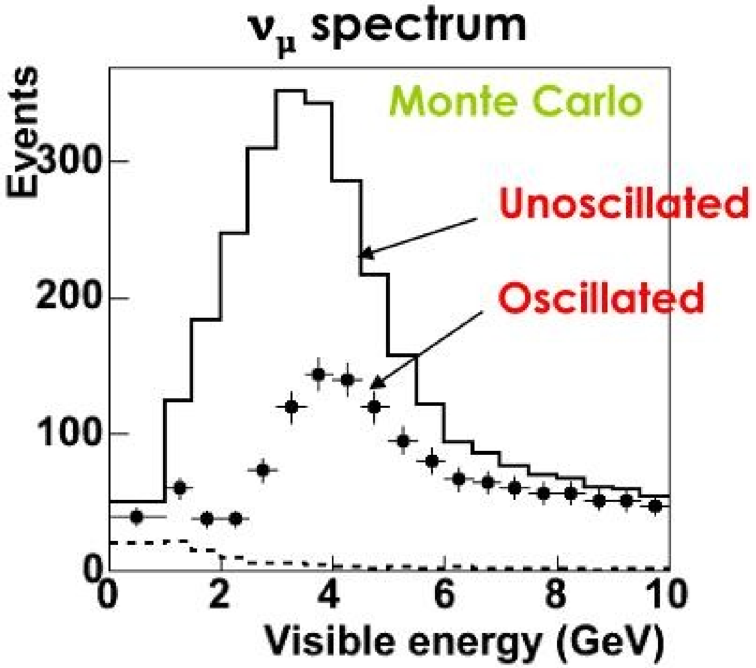
- 282 planes, 980 tons total
  - Same 1" steel,1 cm plastic scintillator planar construction, B-field
  - 3.8x4.5 m, some planes partially instrumented, some fully, some steel only
  - 16.6 m long total
- Light extracted from scint. strips by wavelength shifting optical fiber
  - One strip ended read out with Hamamatsu M64 PMTs, fast QIE electronics
  - No multiplexing upstream, 4x multiplexed in spectrometer region

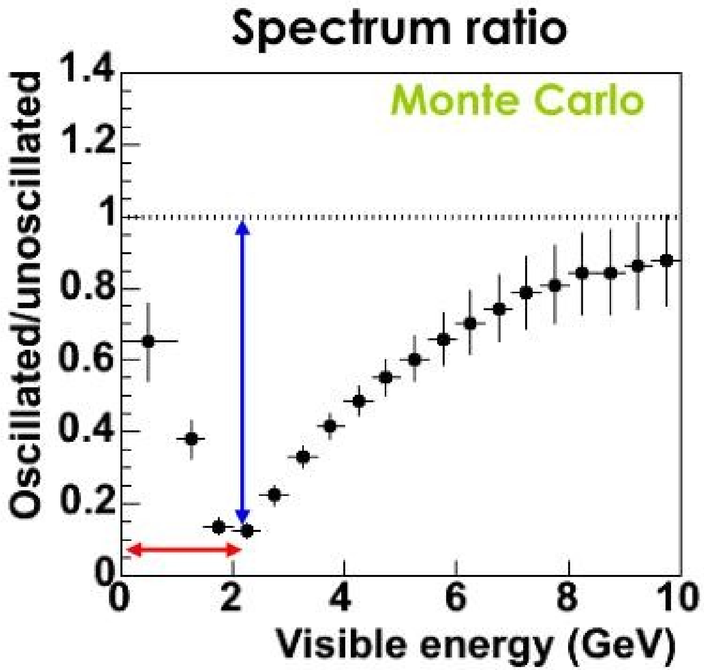




MINOS Oscillation Measurement

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E}\right)$$





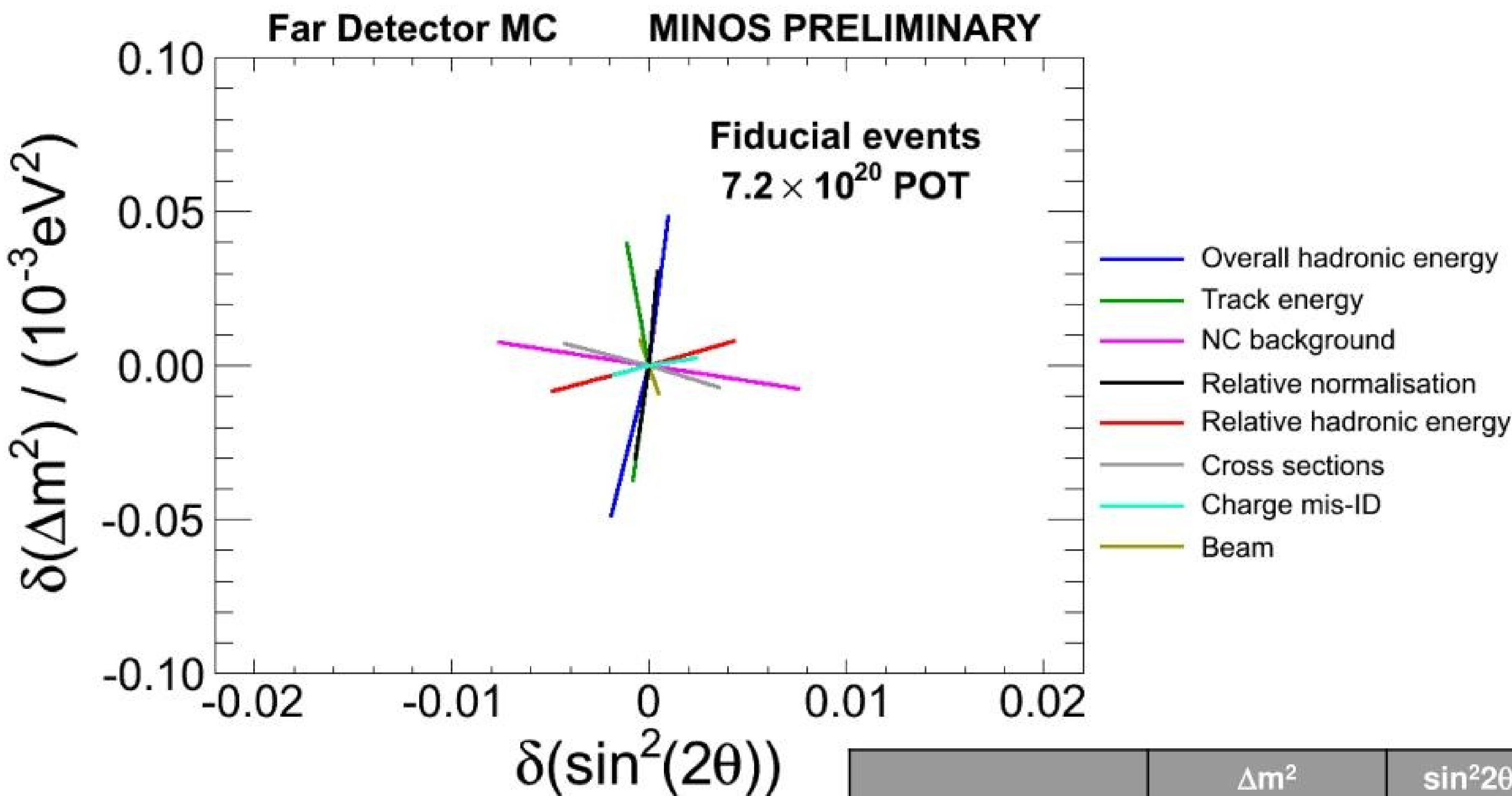
Use charge current events to measure neutrino energy spectrum

Systematic Errors

Systematic shifts in the fitted parameters are computed using MC "fake data" samples

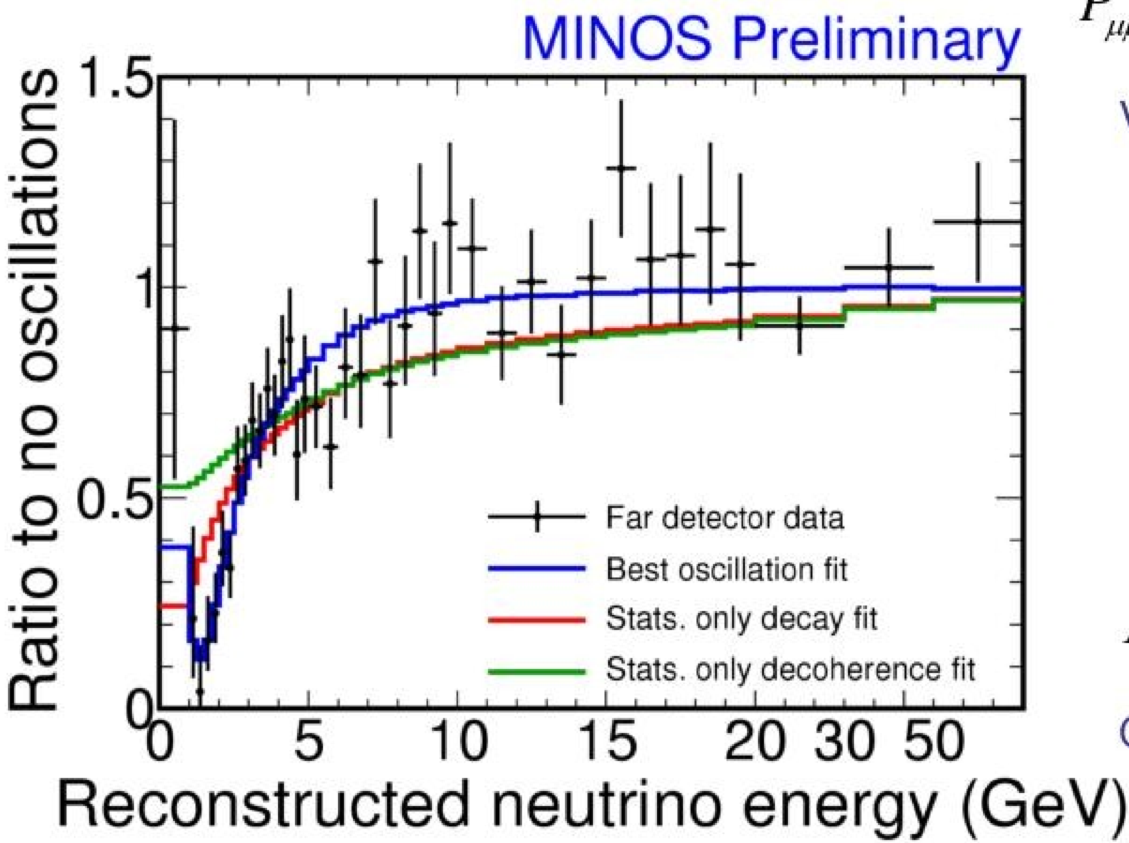
Preliminary Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2 2\theta$
Absolute shower energy scale ±10%	0.049	0.001
Relative shower energy scale ±1.9%(ND) 1.1%(FD)	0.008	0.004
Near/Far normalization ±1.6%	0.030	0.001
NC contamination ±20%	0.008	0.008
μ momentum (range 2% curvature 3%)	0.038	0.001
σ_ν (E_ν < 10 GeV) ±12%	0.007	0.004
Beam flux	0.009	0.000
Anti-nu wrong sign ±30%	0.003	0.002
Total systematic (summed in quadrature)	0.071	0.010
Statistical spread (data)	+0.13 -0.12	0.06

Systematic Errors



	Δm^2	$\sin^2 2\theta$
Total systematic	±0.071	± 0.010
Statistical (data)	+0.13/-0.12	± 0.06

Alternative ν_μ Disappearance Models



Decay:

$$P_{\mu\mu} = \left(\sin^2\theta + \cos^2\theta \exp(-\alpha L/E)\right)^2$$

V. Barger *et al.*, PRL82:2640(1999)

χ^2/ndof = 2165.81/2298

$\Delta\chi^2 = 46.3$

disfavored at 6.8σ

Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006 (2003)

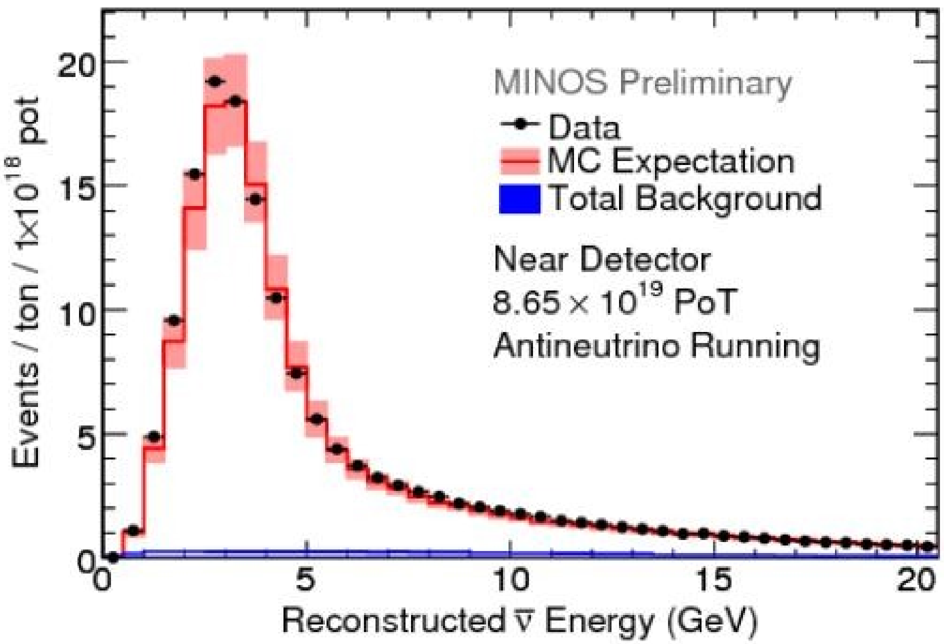
χ^2/ndof = 2197.59/2298

$\Delta\chi^2 = 78.1$

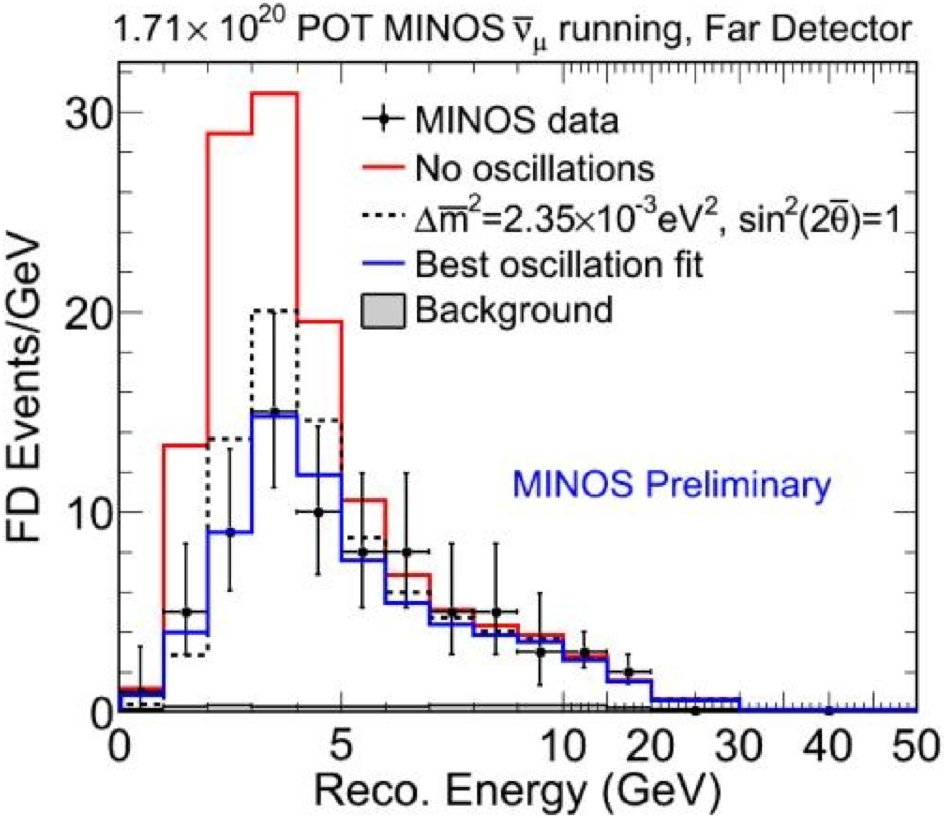
disfavored at 8.8σ

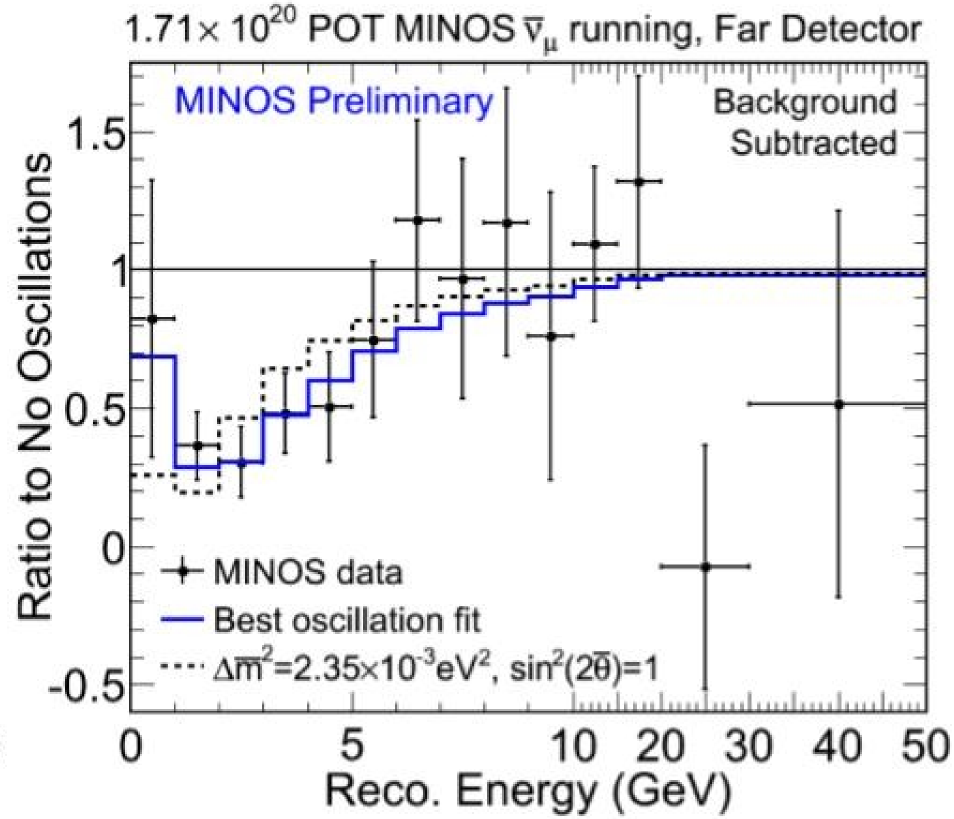
$\bar{\nu}_\mu$ Analysis

- Same analysis done as ν_μ disappearance
  - At low energies where oscillations occur (<6 GeV), curvature is obvious: antinu sample is 93.5% efficient and 98% pure (BG is 51% NC, 49% ν_μ)
  - Lower anti-hadron production and anti-nu interaction cross sections make for much lower statistics, about 2.5x less events per-pot
- Same great MC, data agreement (albeit with lower statistics)

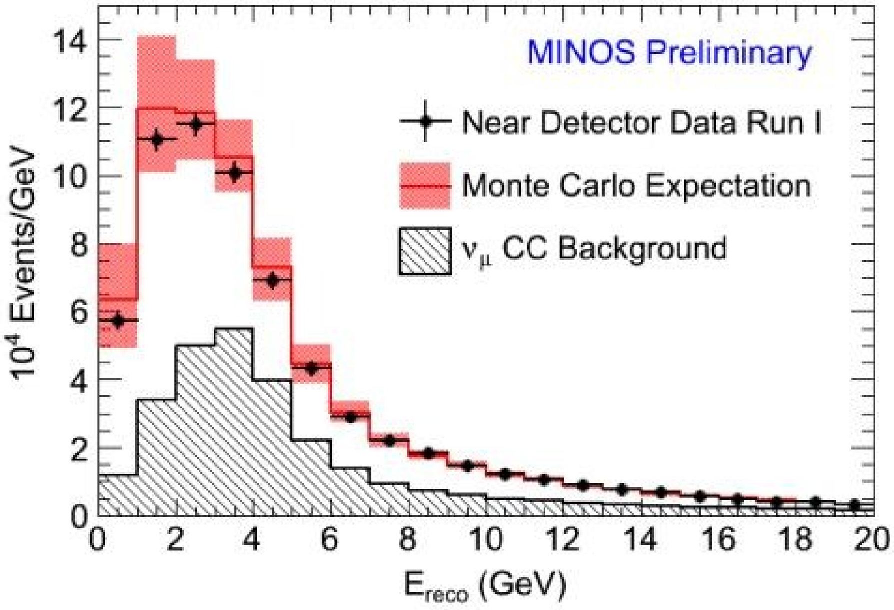


Compared to ν_μ

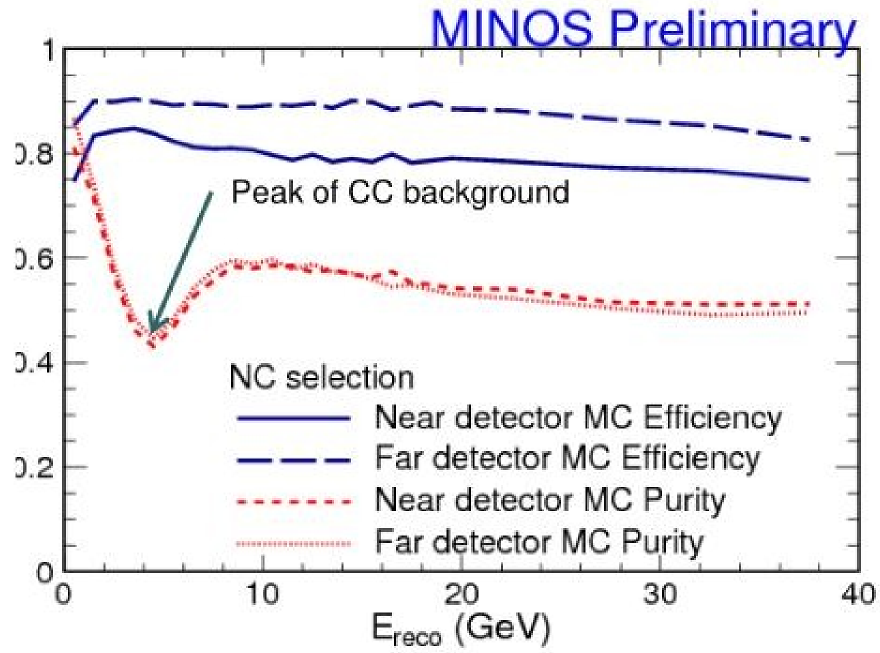




NC Spectrum



ND NC Data

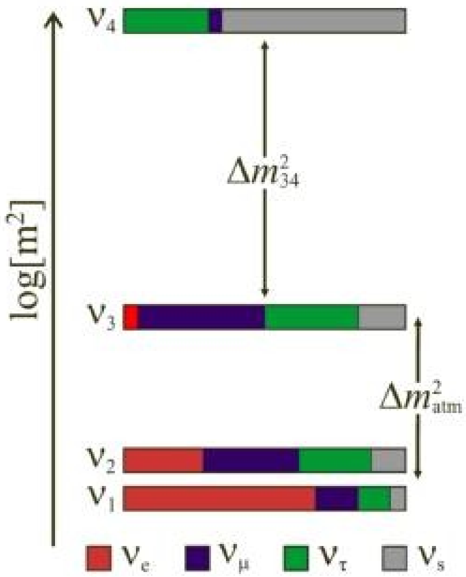


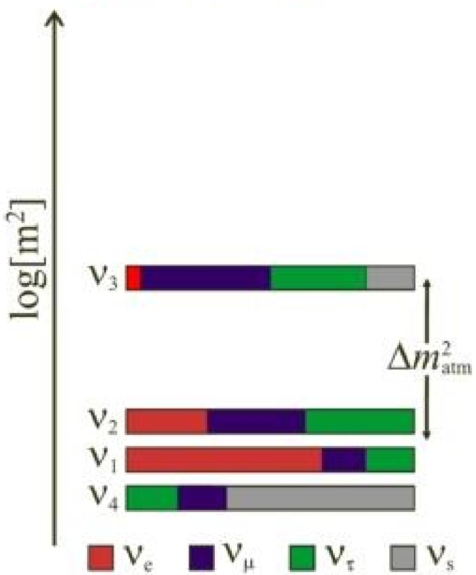
89% Efficient, 61% Pure

- NC events can be used to search for sterile neutrino component in FD
  - via disappearance of NC events at FD
  - If oscillation is confined to active neutrinos instead, NC spectrum will be unchanged

NC Analysis Results 4-flavor fit

- Assume one sterile neutrino and additional Δm^2. Consider two mass scales:
  - $m_4 >> m_3$ and $m_4 = m_1$
- Active ↔ sterile mixing determined by θ_{34} and θ_{24} (*if $m_4>>m_3$*)
- Simultaneous fit to CC and NC energy spectra:
  - Best fit value of 0° found for both θ_{34} and θ_{24}





Did any NC go missing?

- Compare the NC energy spectrum with the expectation of standard 3-flavor oscillation physics
- Pick the oscillation parameter values
  - $\sin^2 2\Theta_{23} = 1$, $\Delta m^2_{32} = 2.35\times10^{-3}$ eV^2
  - Δm^2_{21} = 7.59×10^{-5} eV^2, $\Theta_{12} = 0.61$ from KamLAND+SNO
  - Θ_{13} = 0 or 0.21 (normal MH, $\delta=3\pi/2$) from Chooz Limit
    - (*n.b.* - CC ν_e are classified as NC by this analysis, so more Θ_{13} causes more background)
- Make comparisons in terms of the ***R*** statistic:
  - $R\rightarrow1$ if no ν_s
- For different energy ranges
  - 0-3 GeV
  - 3-120 GeV
  - All events (0-120 GeV)

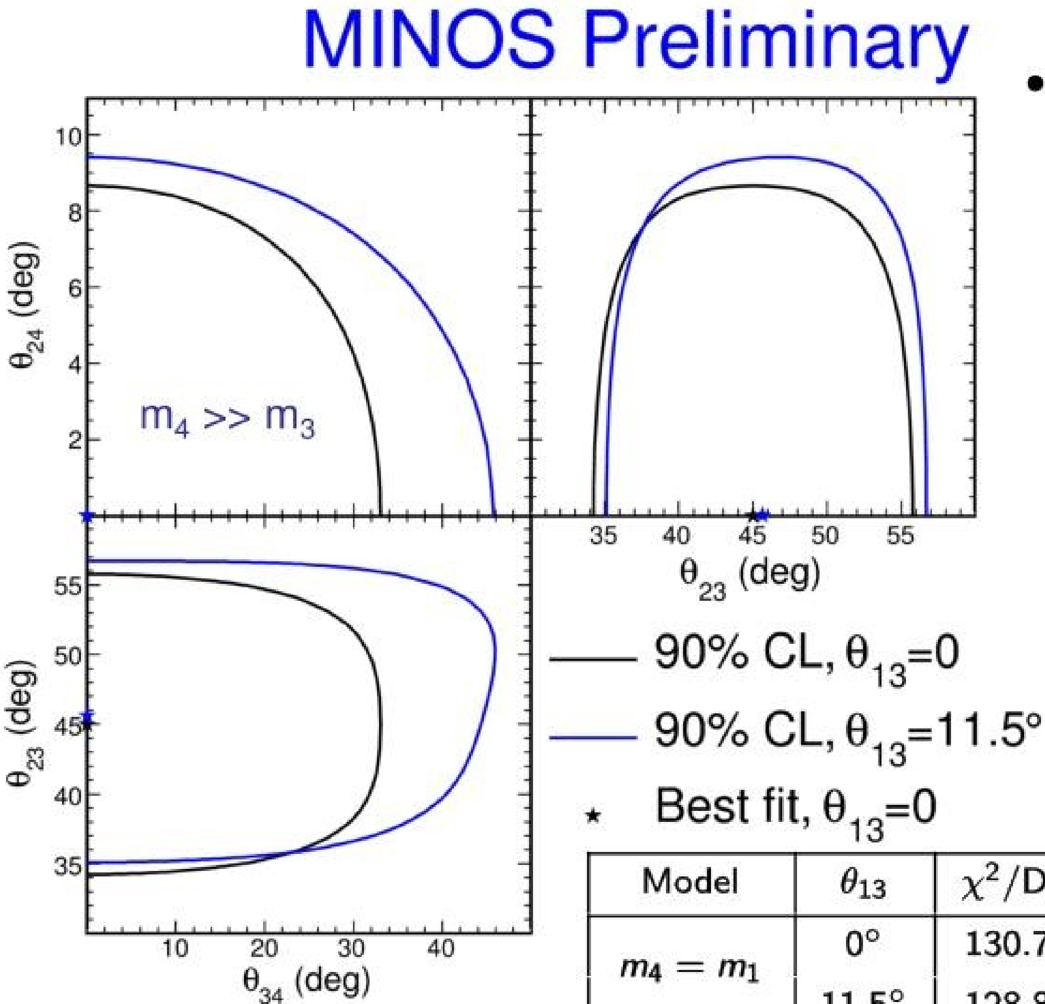
$$R \equiv \frac{N_{Data} - B_{CC}}{S_{NC}}$$

Predicted CC background from all flavors

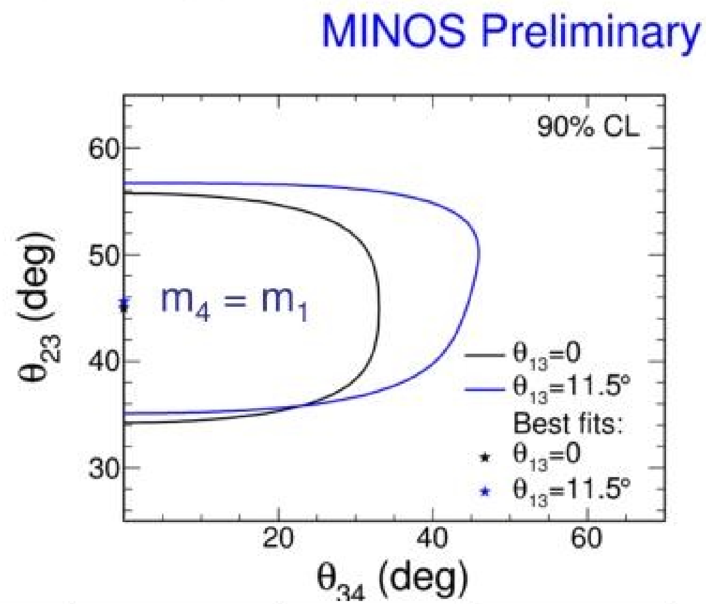
Predicted NC interaction signal

R is fraction of all NC events which go missing

NC Analysis Results
4-flavor fit



- Limits placed on oscillation parameters for these models:



Model	θ_{13}	χ^2/D.O.F.	θ_{23}	θ_{24}	θ_{34}
$m_4 = m_1$	0°	130.7/123	$45.0^{\circ}{}^{+7.2}_{-7.2}$	–	$0.0^{\circ}{}^{+16.8}$
	11.5°	128.8/123	$45.6^{\circ}{}^{+6.6}_{-6.9}$	–	$0.0^{\circ}{}^{+25.2}$
$m_4 \gg m_3$	0°	130.7/122	$45.0^{\circ}{}^{+7.2}_{-7.2}$	$0.0^{\circ}{}^{+4.8}$	$0.0^{\circ}{}^{+16.8}$
	11.5°	128.8/122	$45.6^{\circ}{}^{+6.6}_{-6.9}$	$0.0^{\circ}{}^{+5.4}$	$0.0^{\circ}{}^{+25.2}$

ν_e Appearance Backgrounds

- Use Near Detector data-driven methods to estimate ν_e appearance backgrounds
  - At Near Detector, all ν_e events are background not ν_e appearance
  - Apply NN-based ν_e selection to the ND data, get an all-background sample
  - Find what fraction of those background events are NC showers, mis-ID'd CC events, or real ν_e from the beam
- Use these background estimates to correct Far Detector MC backgrounds for unknowns in hadronic shower modeling etc.
- Two independent methods agree