Recent results from MINOS

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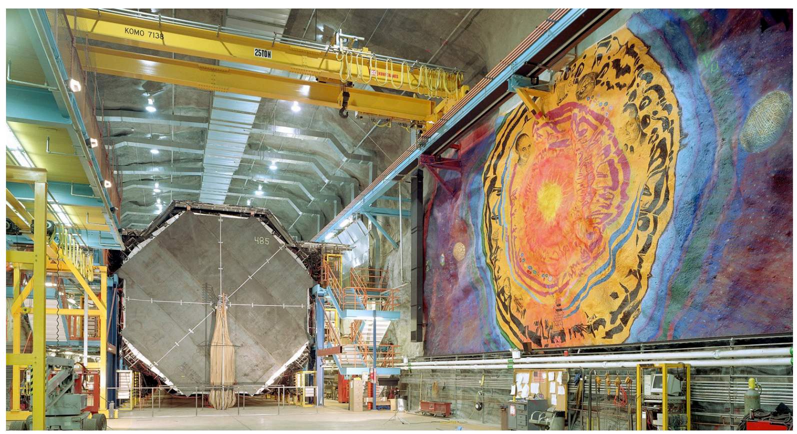
University of Texas at Austin

On behalf of the MINOS Collaboration

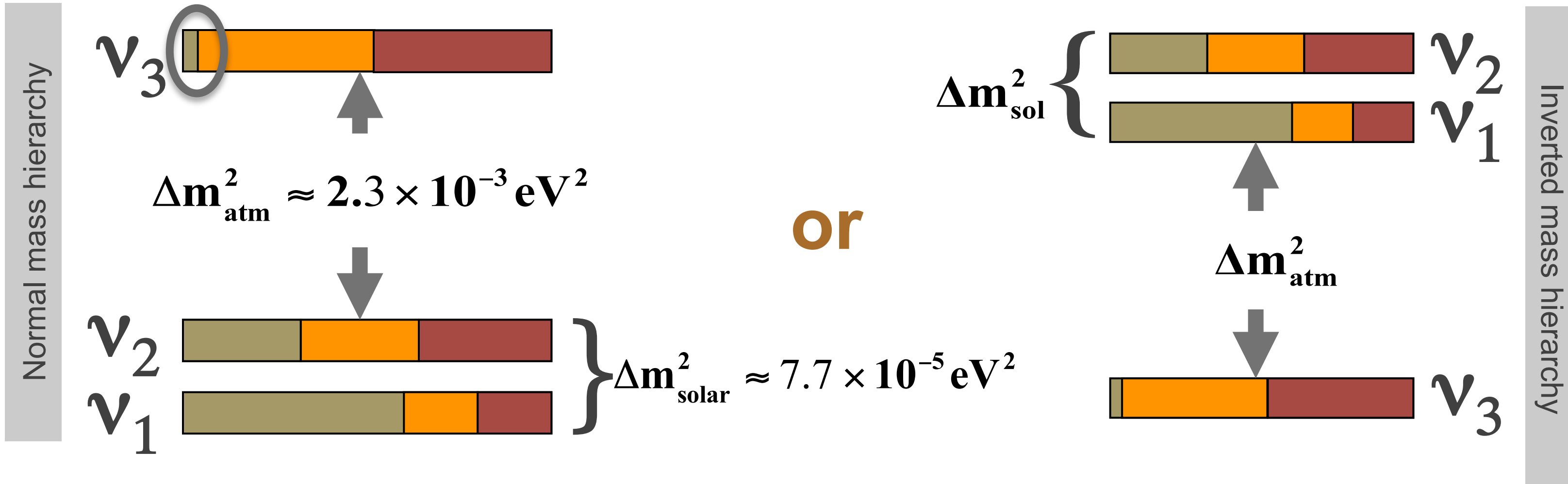


"Towards CP Violation in Neutrino Physics"
Prague 7 Oct 2011

OUTLINE

- MINOS and ν beam
- Recent results
  - ✓Charged Current Disappearance
    - neutrinos
    - anti-neutrinos
  - ✓ θ_{13}
- Outlook & summary

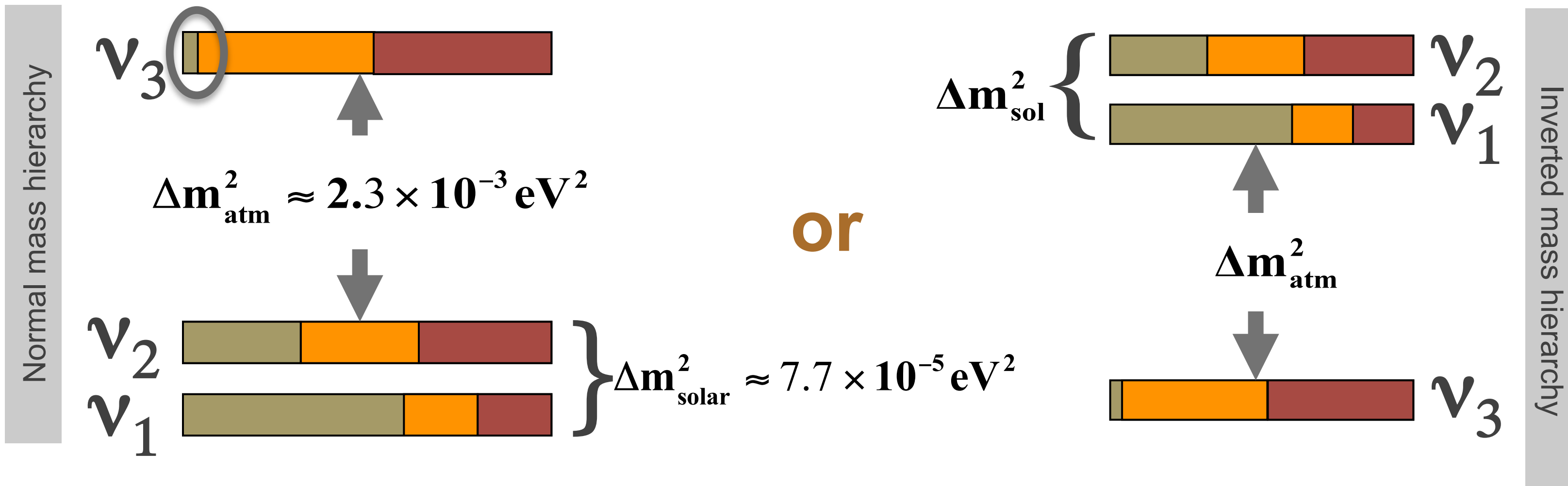
MINOS program: Δm^2_{atm}, θ_{13}, sterile ν's, CP, CPT, …



Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

MINOS program: Δm^2_{atm}, θ_{13}, sterile ν's, CP, CPT, …



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MINOS

For neutrinos and anti-neutrinos

$$U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}\cdot e^{i\delta} \\ & 1 & \\ -s_{13}\cdot e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

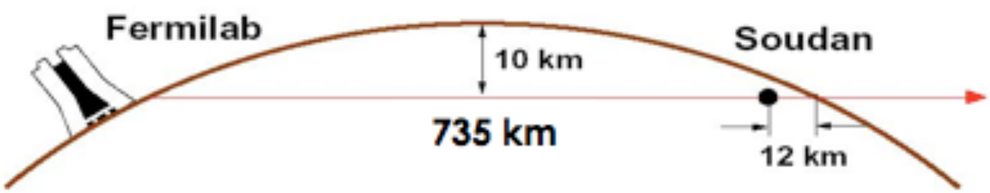
Solar | **Atmospheric Reactor** $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$ | **Atmospheric** $\nu_\mu \leftrightarrow \nu_\tau$ | **Majorana Phases** $0\nu\beta\beta$

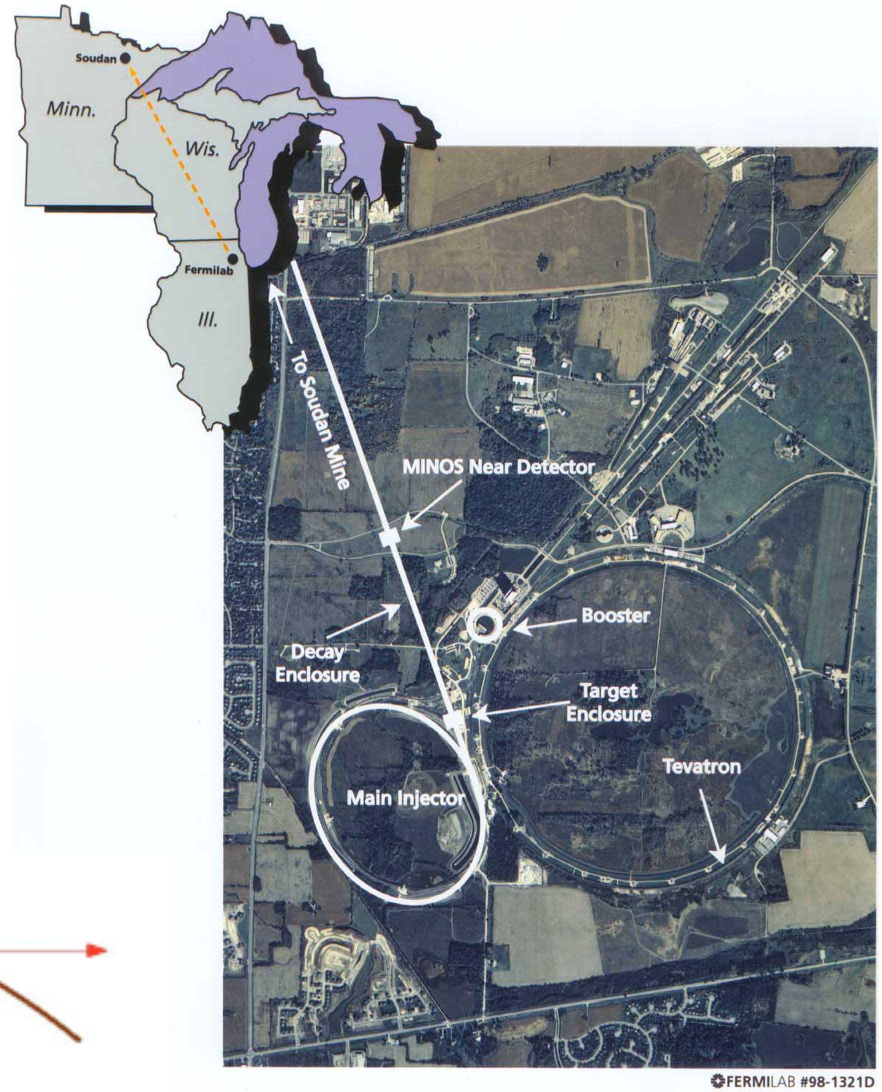
MINOS

Main Injector Neutrino Oscillation Search

Strategy:

- Two functionally similar magnetized detectors
  - ⇨ separated by a long baseline (734km)
  - ⇨ underground (CR shielding + physics)
- High intensity beam from 120 GeV Main Injector
  - ⇨ 3.5×10^{13} protons/pulse (0.32 MW beam)
  - ⇨ single turn extraction (~10 μs)
- Flexible & well-controlled beam
  - ⇨ two magnetic horns
  - ⇨ movable target (→ adjustable energy spectrum)





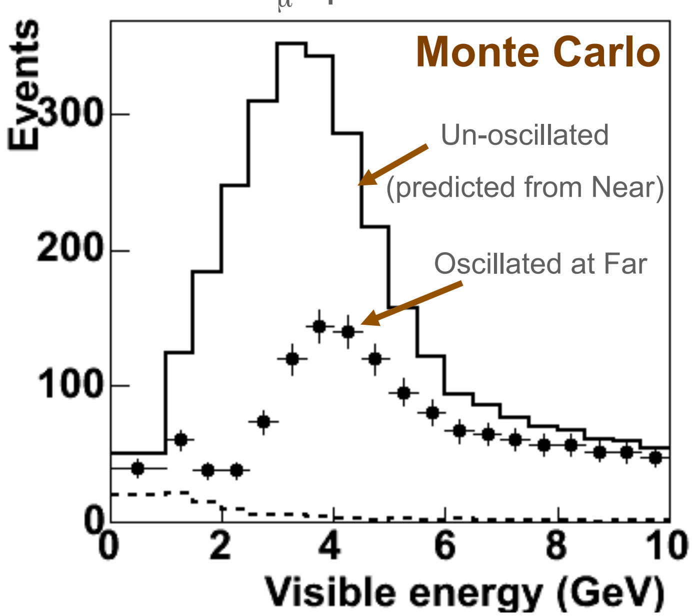
The paradigm

✓ Use Near Detector for high statistics measurements
✓ Project these measurements and compare at the Far Detector

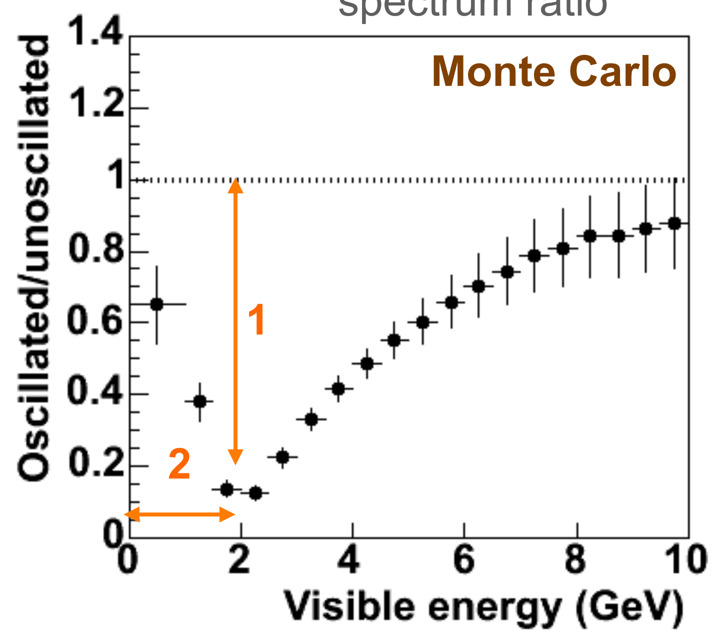
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \bullet \sin^2(1.267\Delta m^2 L/E)$$

1 2

ν_μ spectrum

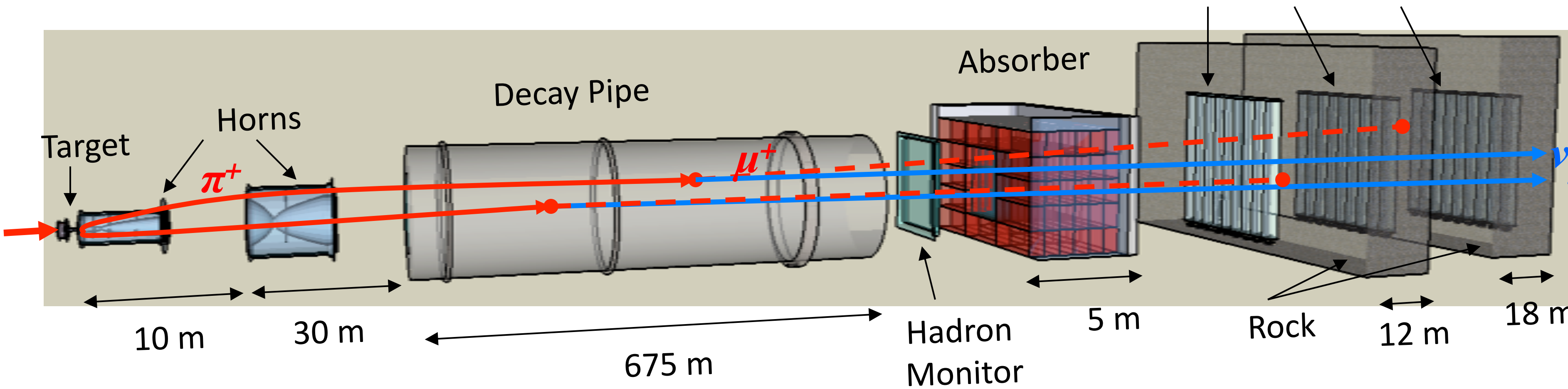


spectrum ratio

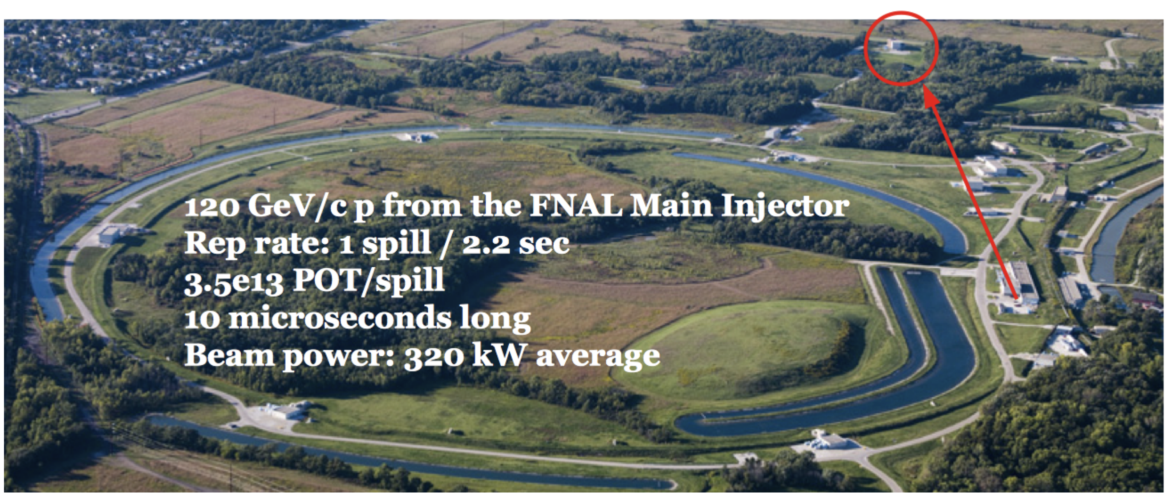


MC for $\Delta m^2 = 0.003\ eV^2$ and 7.4×10^{20} pot

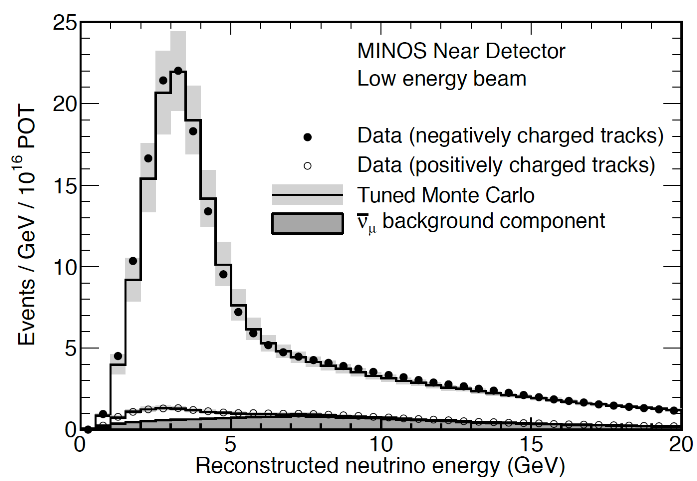
NuMI beam



Target
Horns
Decay Pipe
Absorber
π^+
μ^+
ν_μ
10 m
30 m
675 m
Hadron Monitor
5 m
Rock
12 m
18 m

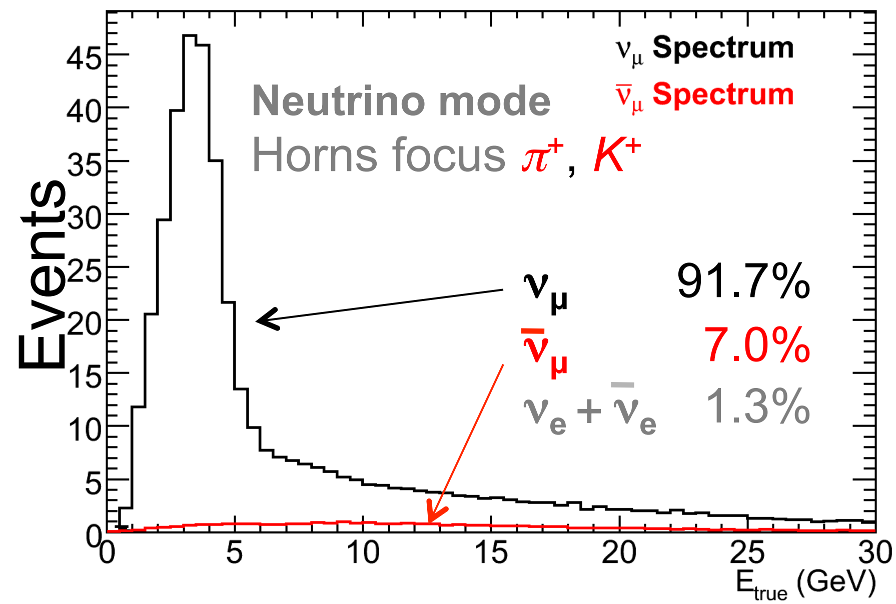


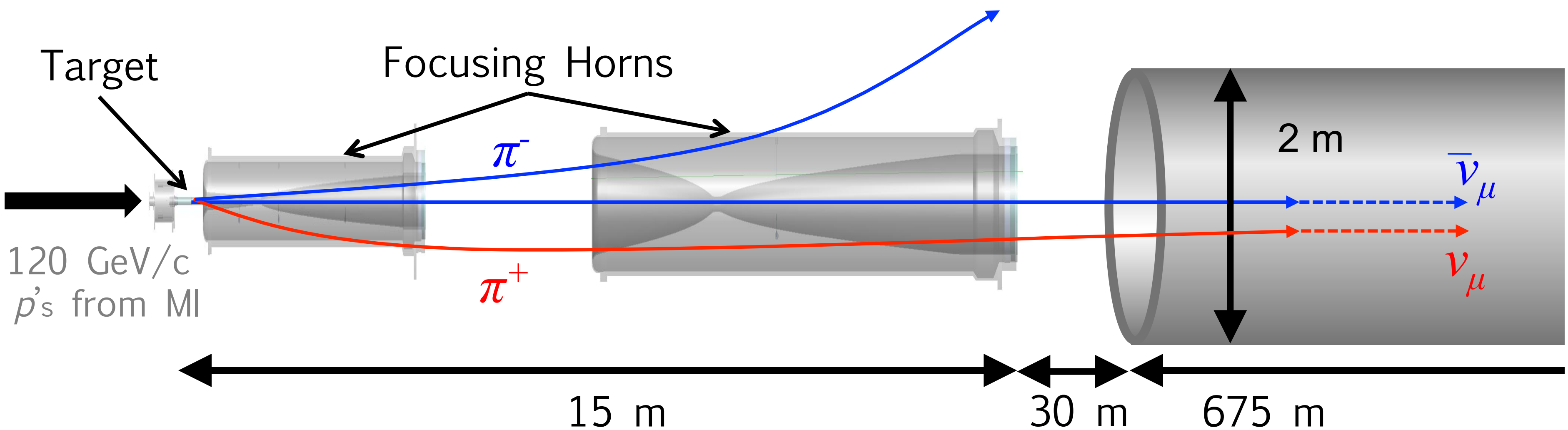
120 GeV/c p from the FNAL Main Injector
Rep rate: 1 spill / 2.2 sec
3.5e13 POT/spill
10 microseconds long
Beam power: 320 kW average



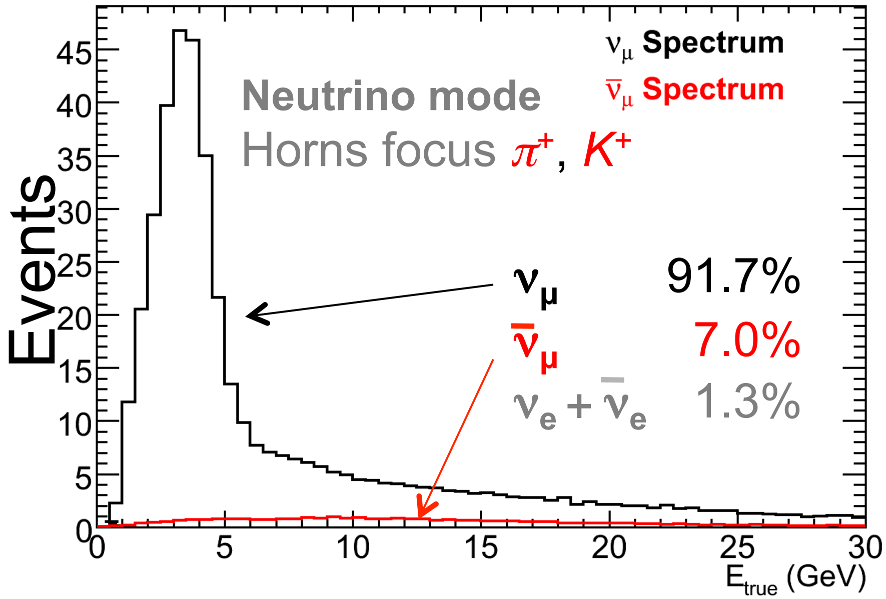
MINOS Near Detector
Low energy beam
Data (negatively charged tracks)
Data (positively charged tracks)
Tuned Monte Carlo
$\bar{\nu}_\mu$ background component
Events / GeV / 10^{16} POT
Reconstructed neutrino energy (GeV)

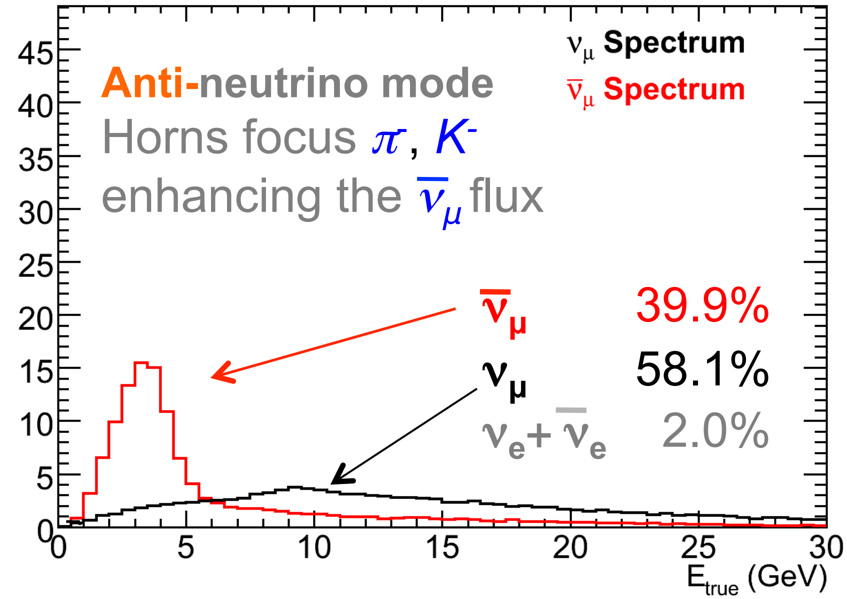
Making a neutrino beam

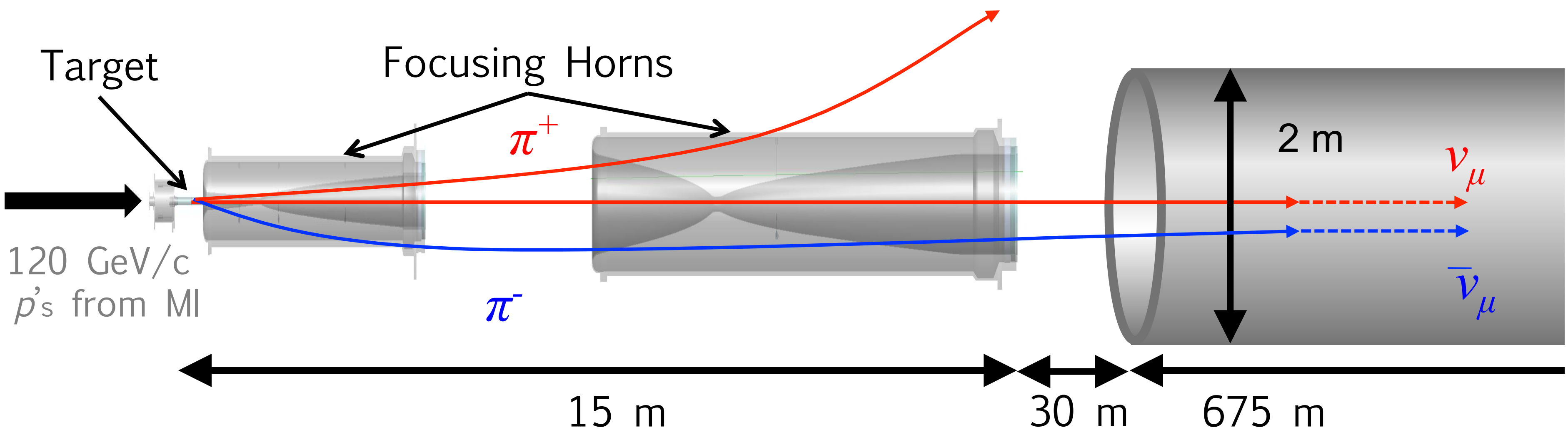




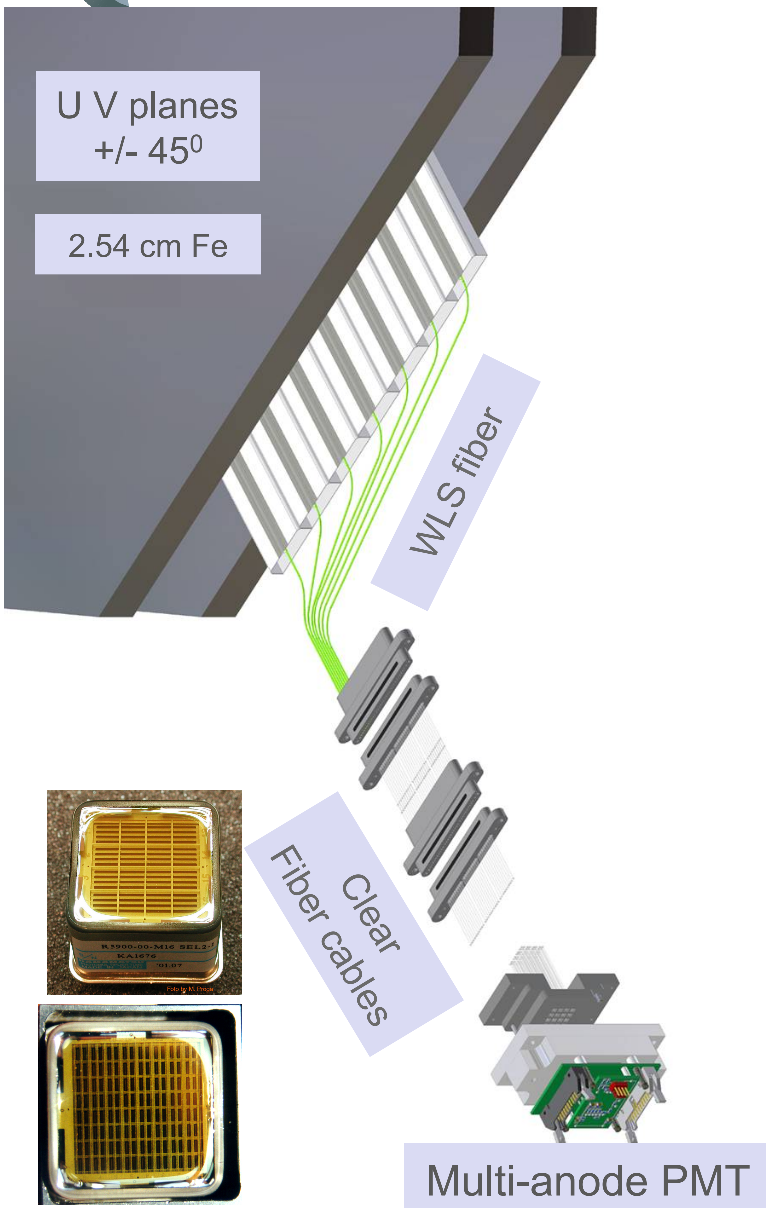
Making an anti-neutrino beam

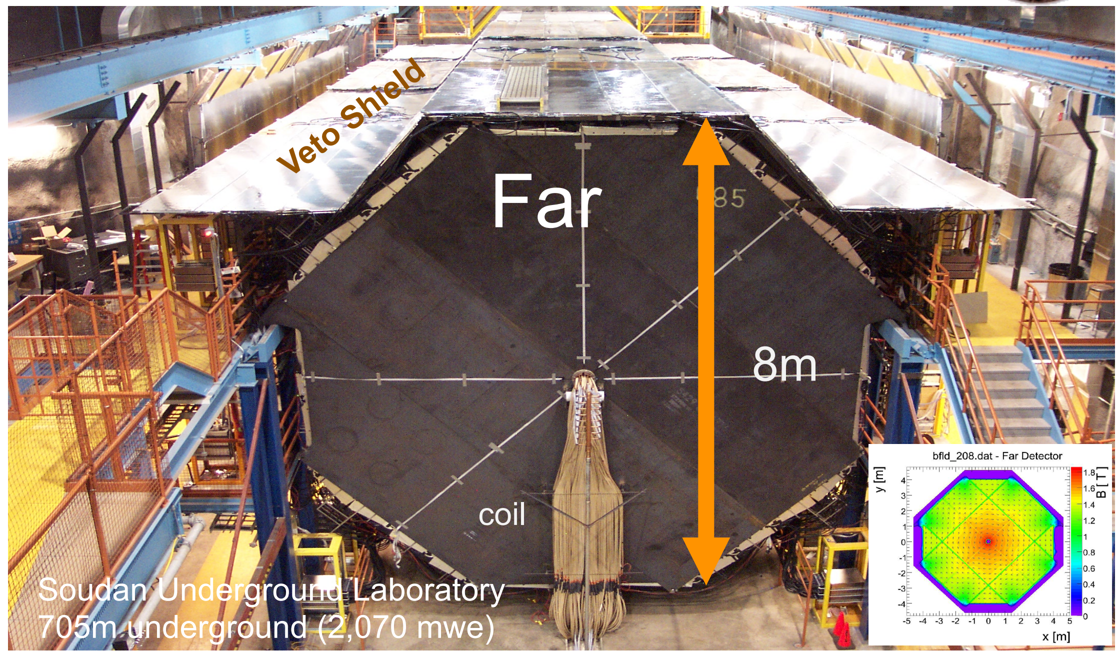


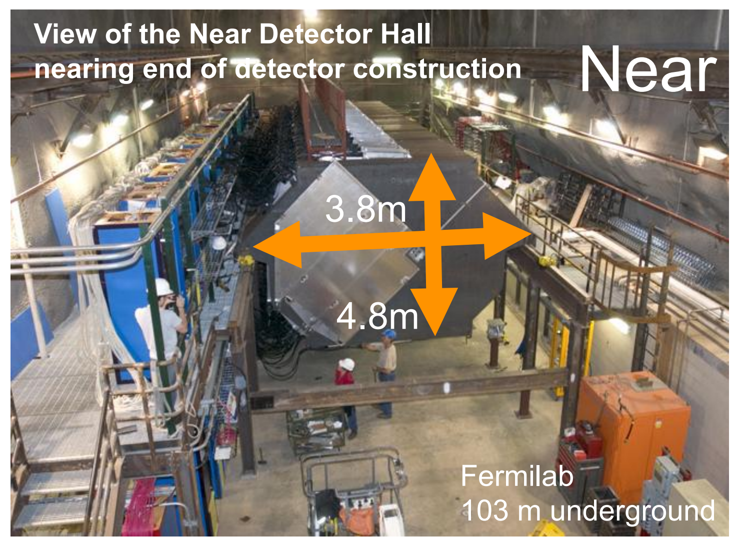




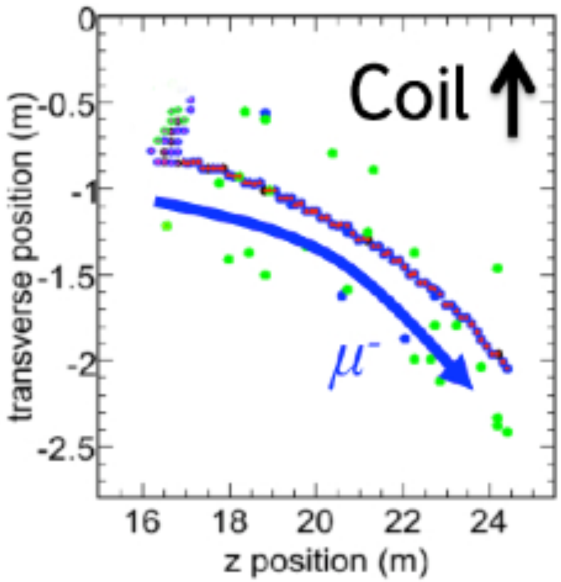
Near and Far Detectors



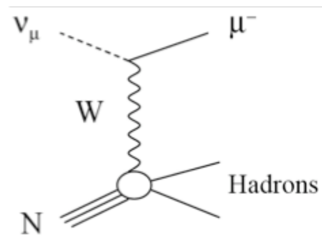


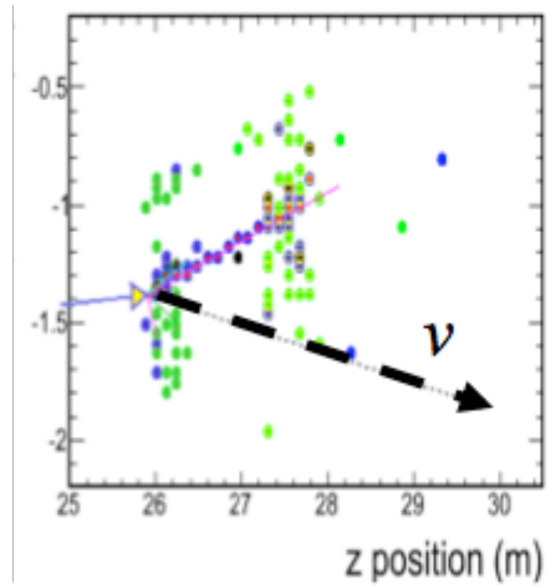


MINOS event topologies

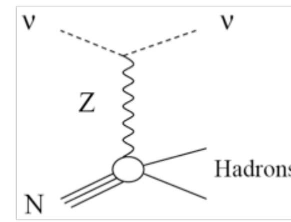


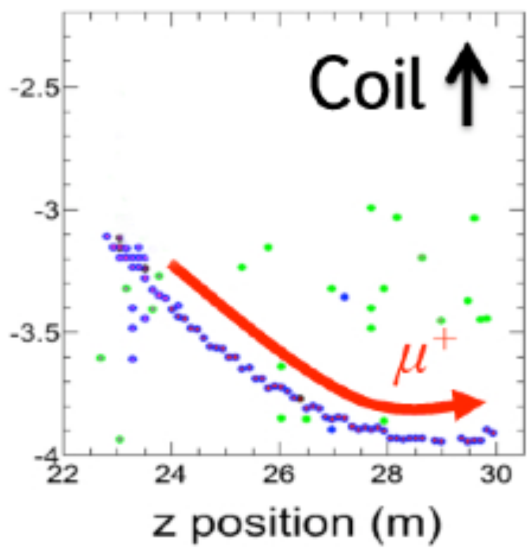
Charged Current neutrino event



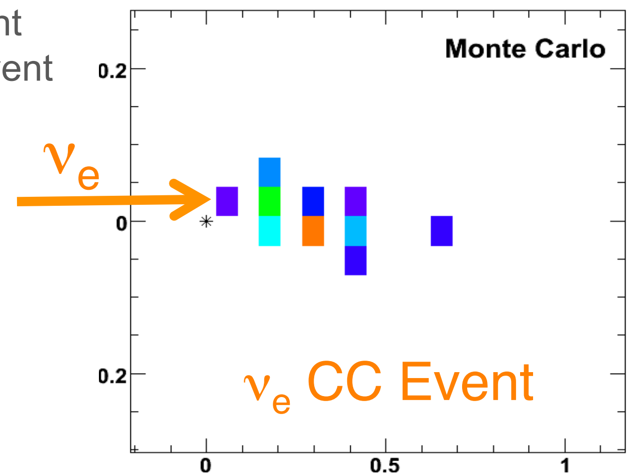


Neutral Current neutrino event





Charged Current anti-neutrino event

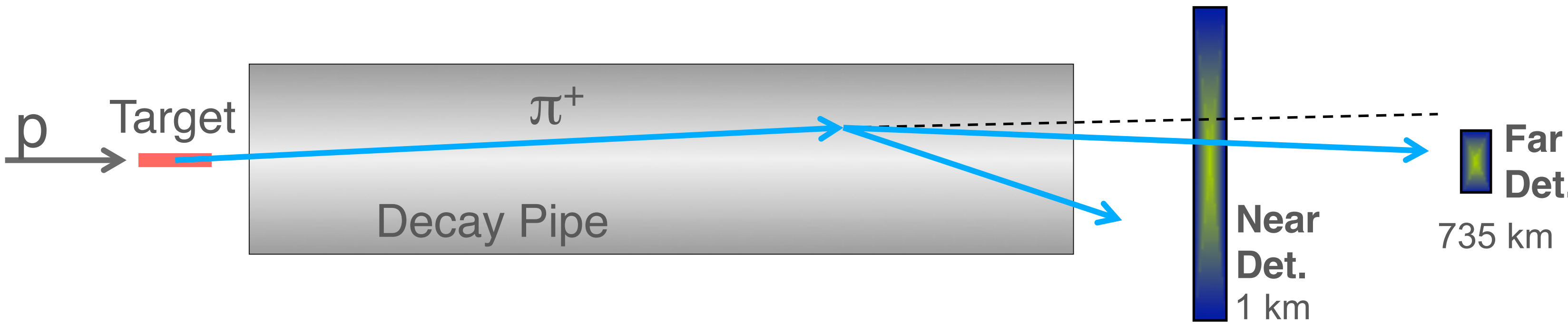


Charged Current electron-neutrino event

Near → Far

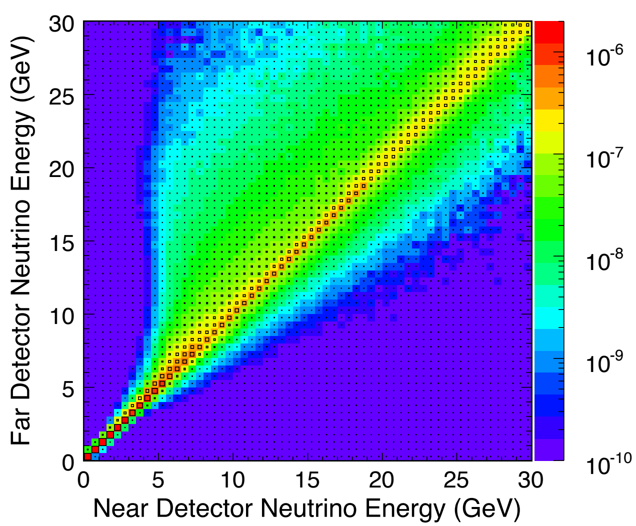
- ✓ Higher energy pions decay further along decay pipe
- ✓ Angular distributions different between Near and Far

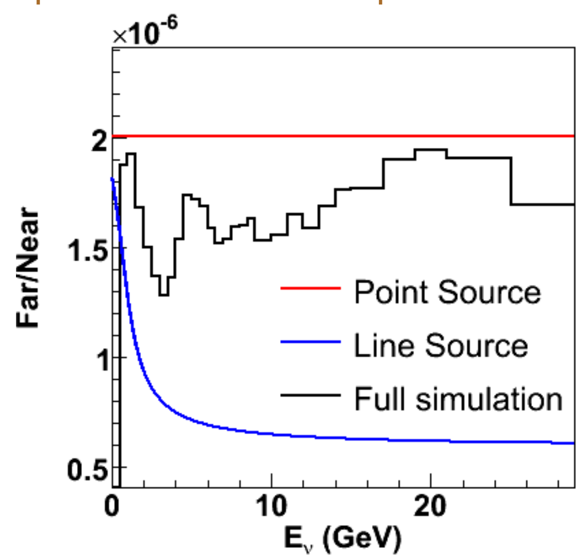
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$



- ✓ Muon-neutrino and anti-neutrino analyses: beam matrix for FD prediction of track events
- ✓ NC and electron-neutrino analyses: Far over Near spectrum ratio for FD prediction of shower events

"Matrix"

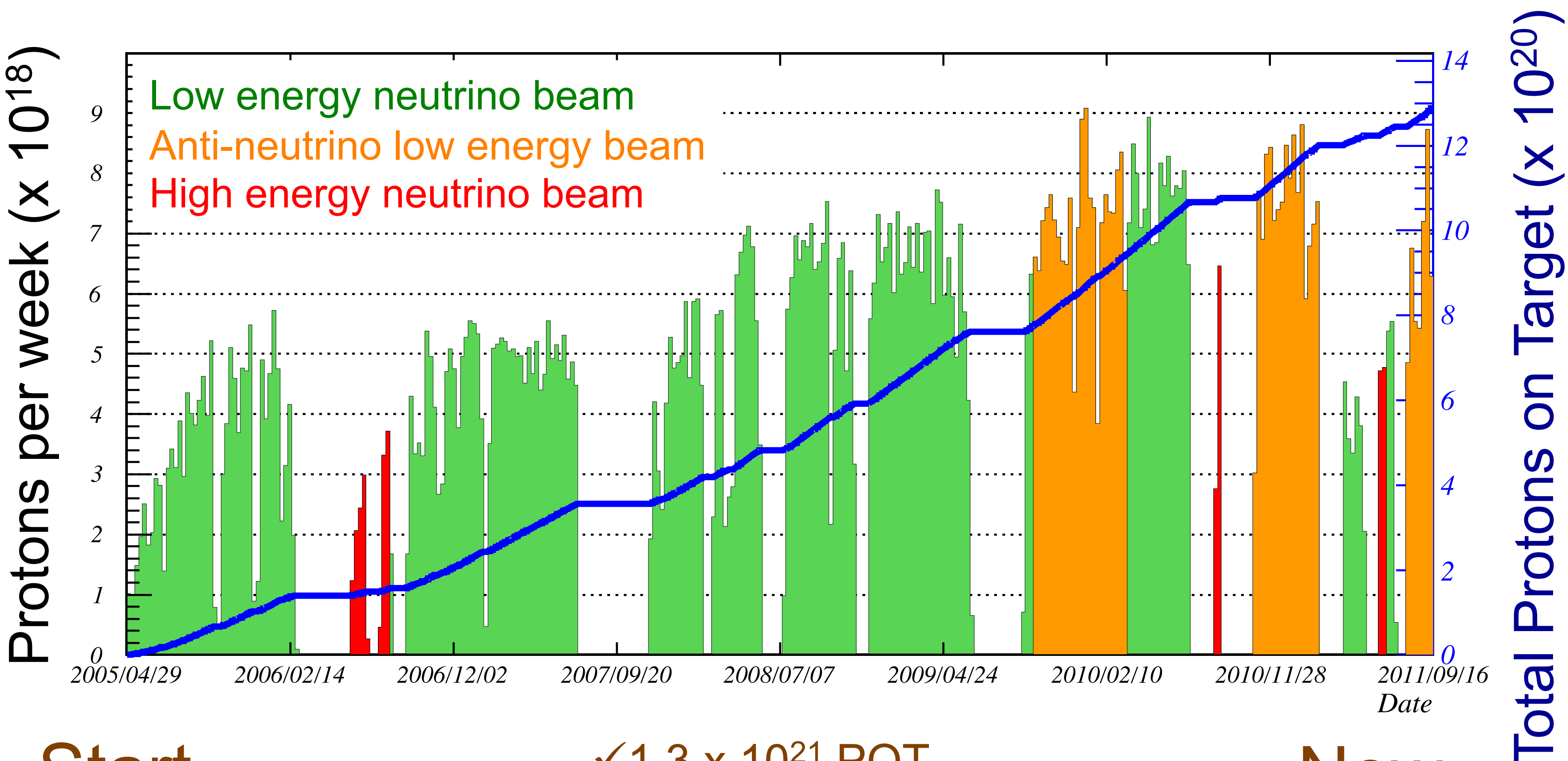




"Far over Near"

History of MINOS POT

(Protons on Target)



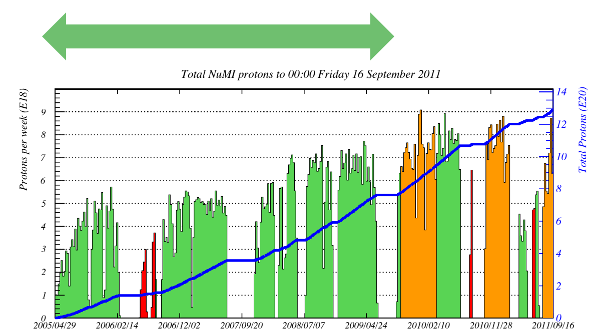
Start 2005

✓1.3 x 10^{21} POT
✓7 beam configurations
✓Mostly low energy
✓6 targets
✓4 horns

Now 2011

NEUTRINO CHARGED CURRENT DISAPPEARANCE

These data
7.25×10^{20} POT
(low + some high energy beam setting)

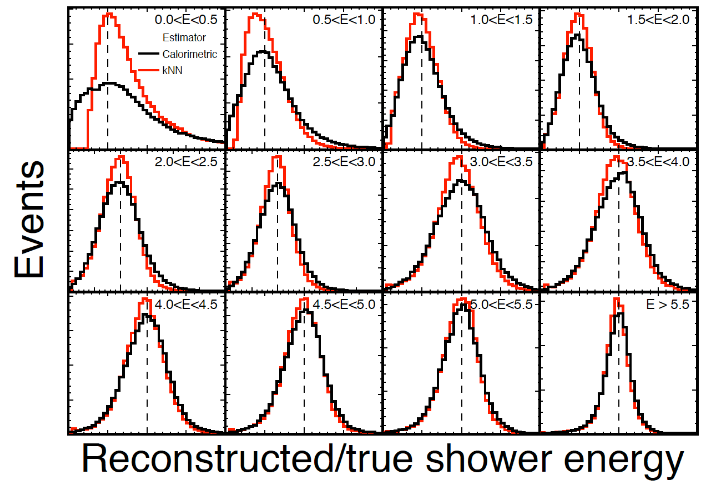


Start
2005

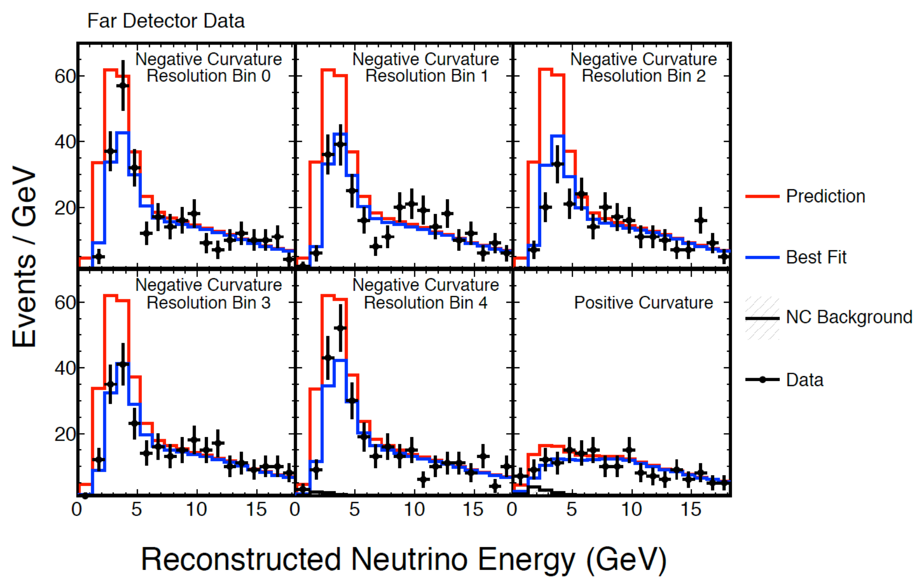
Now
2011

Main recent CC analysis improvements

- k-Nearest-Neighbor (kNN) shower energy estimator



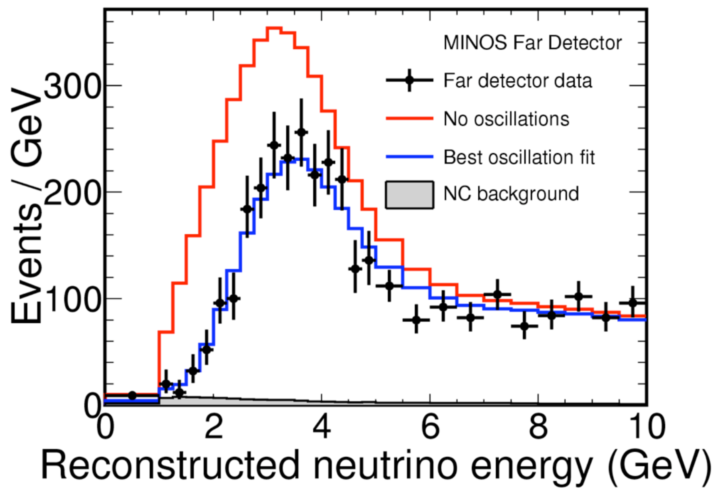
- Fitting in bins of energy resolution

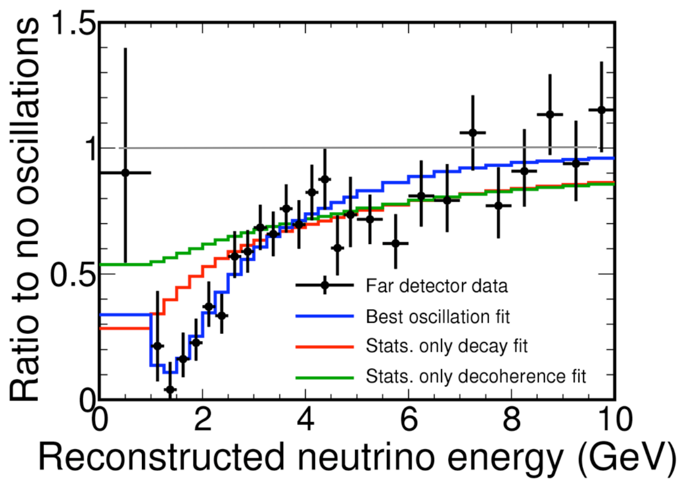


- Include partially reconstructed events (high statistics but poor E_{reco} → limited impact)

Neutrino Charged Current disappearance

Using 7.25 x 10^{20} POT

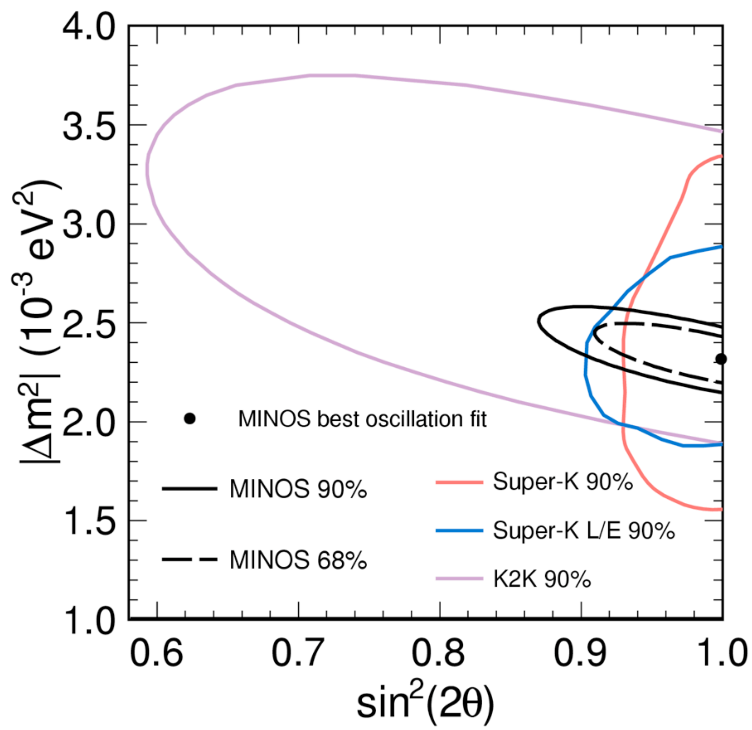




Phys. Rev. Lett. 106, 181801 (2011)

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

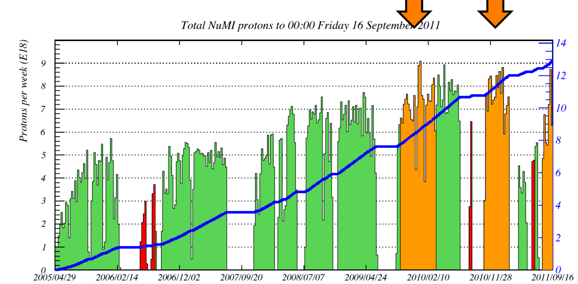
$$\sin^2(2\theta_{23}) > 0.90 \ (90\%\ \mathrm{C.L.})$$



✓Pure neutrino decay excluded at 7 σ
✓Pure neutrino decoherence excluded at 9 σ

ANTI-NEUTRINO CHARGED CURRENT DISAPPEARANCE

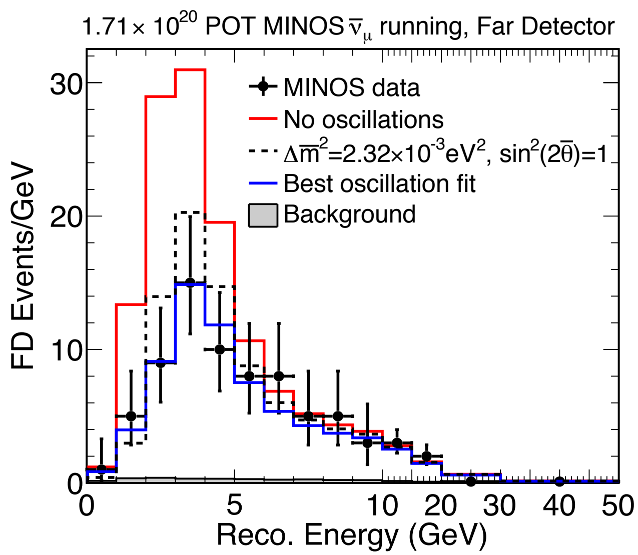
These data
2.95×10^{20} POT

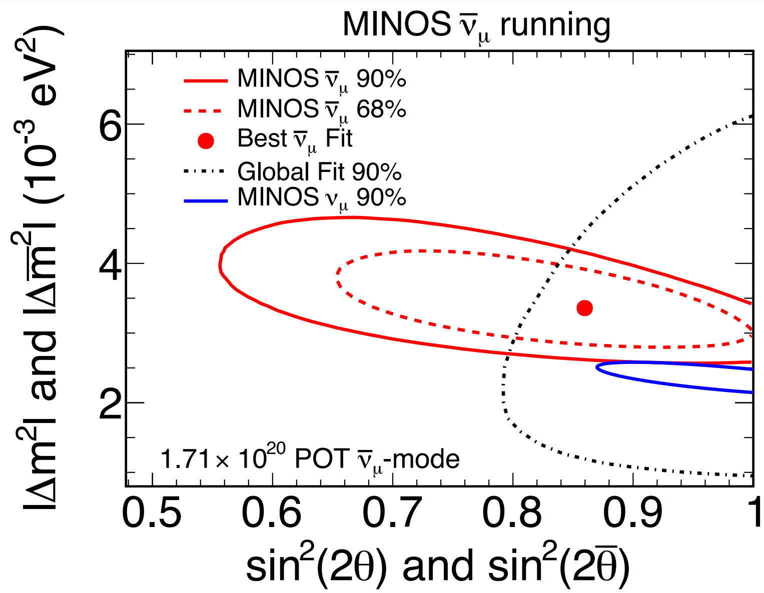


Start 2005

Now 2011

Anti-neutrinos in the anti-neutrino beam
Results from 2010





→**156** expected without oscillations

→ **97** observed

→ No-oscillations hypothesis excluded at **6.3σ**

anti-neutrinos (results from 2010)

$$\left|\Delta\bar{m}^2_{atm}\right| = 3.36^{+0.46}_{-0.40}(\text{stat}) \pm 0.06(\text{syst}) \times 10^{-3}\ \text{eV}^2$$

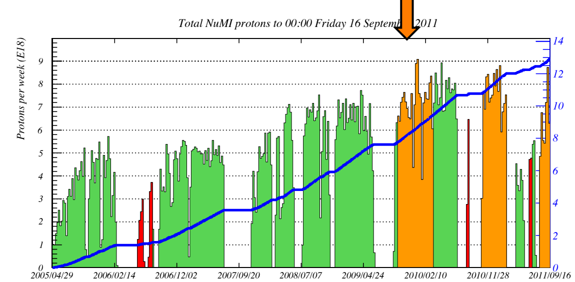
$$\sin^2\left(2\bar{\theta}_{23}\right) = 0.86^{+0.11}_{-0.12}(\text{stat}) \pm 0.01(\text{syst})$$

neutrinos

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

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

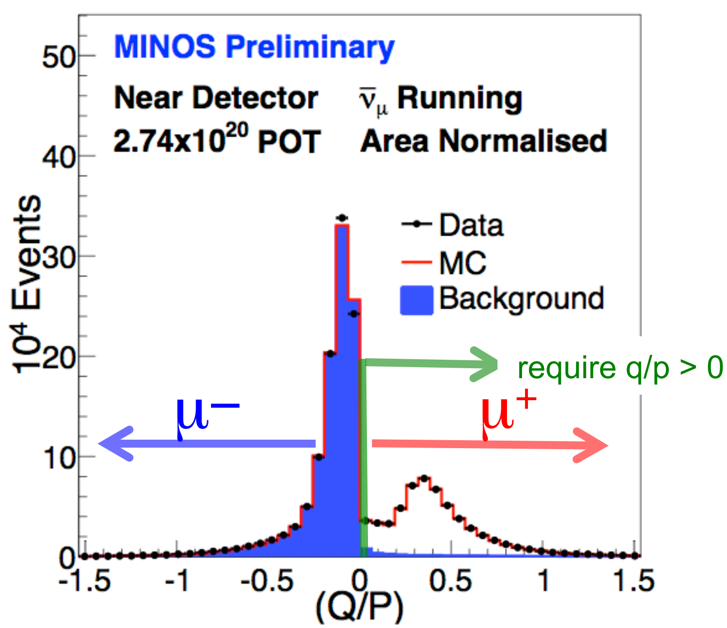
These data 1.71 x 10^{20} POT

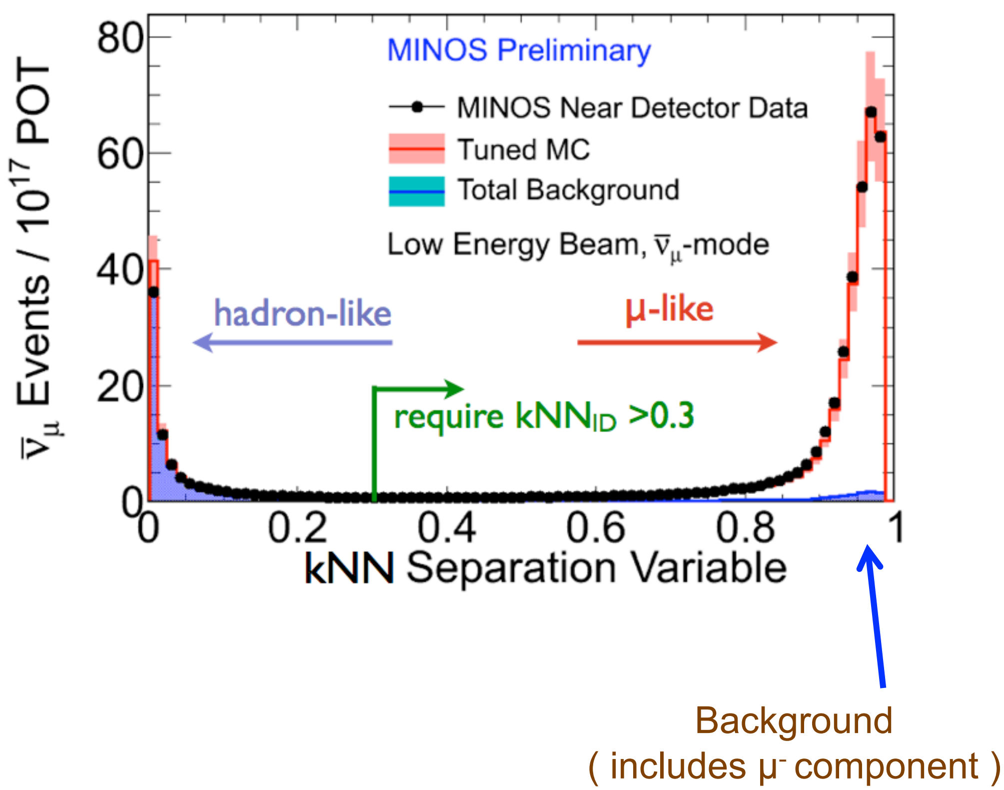


2011 Analysis

CC-NC separation and μ^+ charge identification

- Use kNN discriminant for the CC-NC separation
- Use kNN for the shower energy estimation
- Use magnetic field bending and track fitting for charge identification

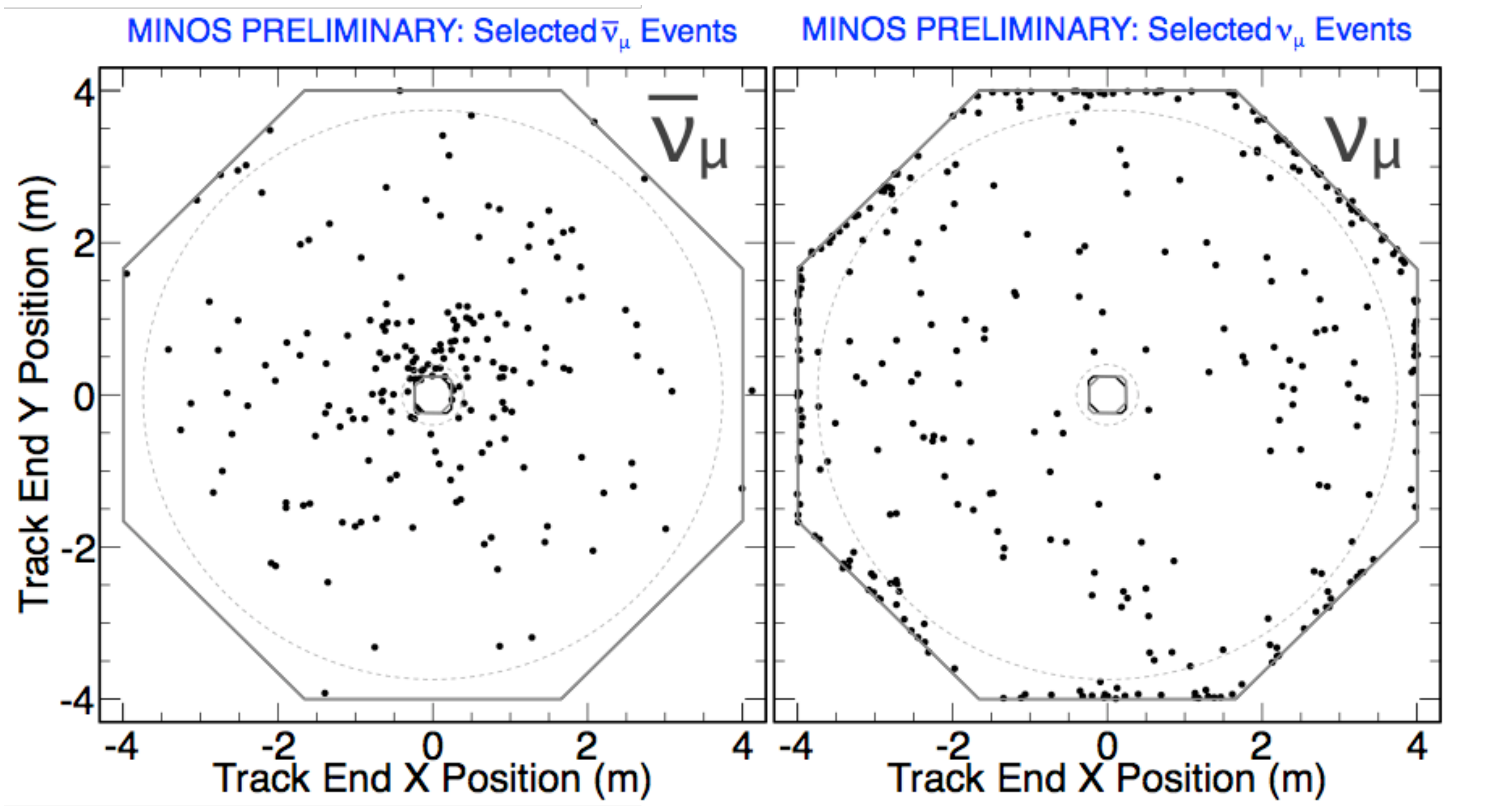




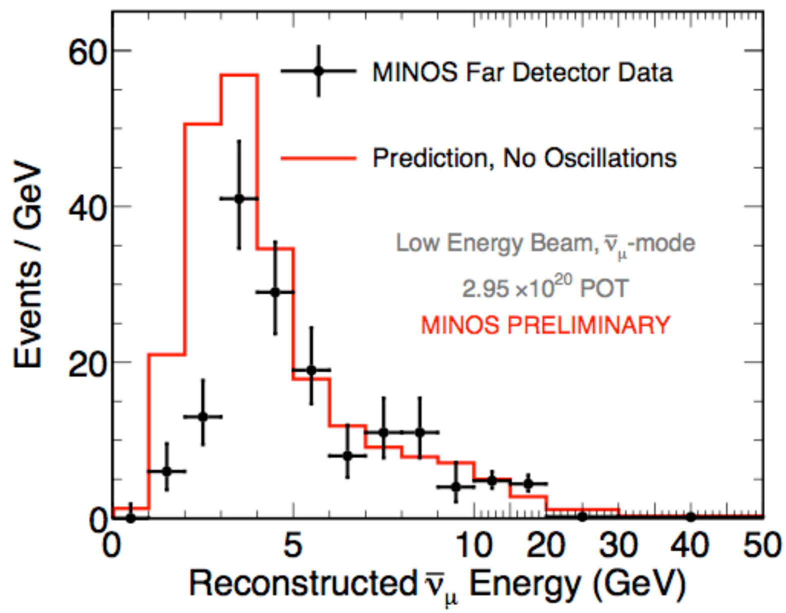
μ+ vs μ-

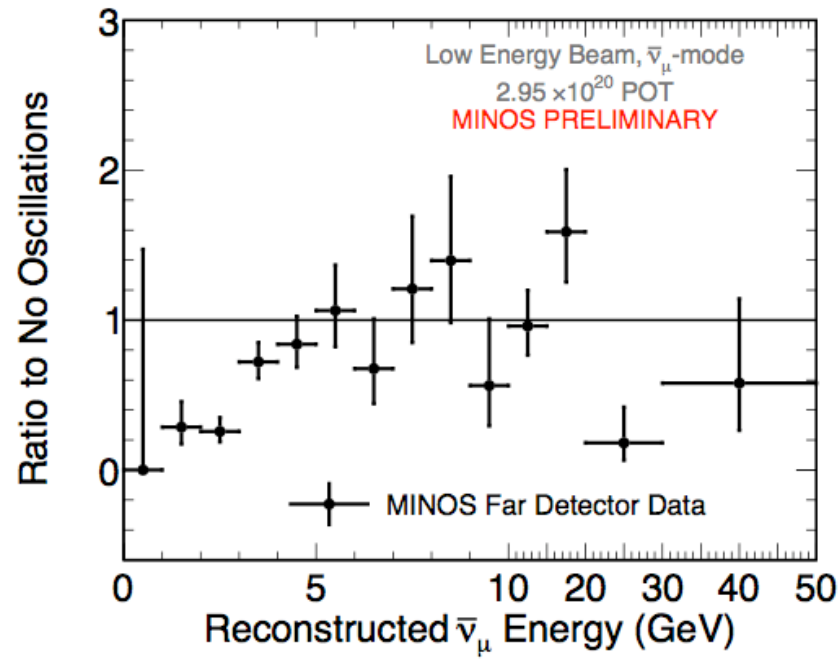
Track-end positions in Far Detector

- ✓ Anti-neutrinos are focused towards the magnetic coil,
- ✓ Neutrinos are defocused outwards



Far Detector spectrum and Far/Near

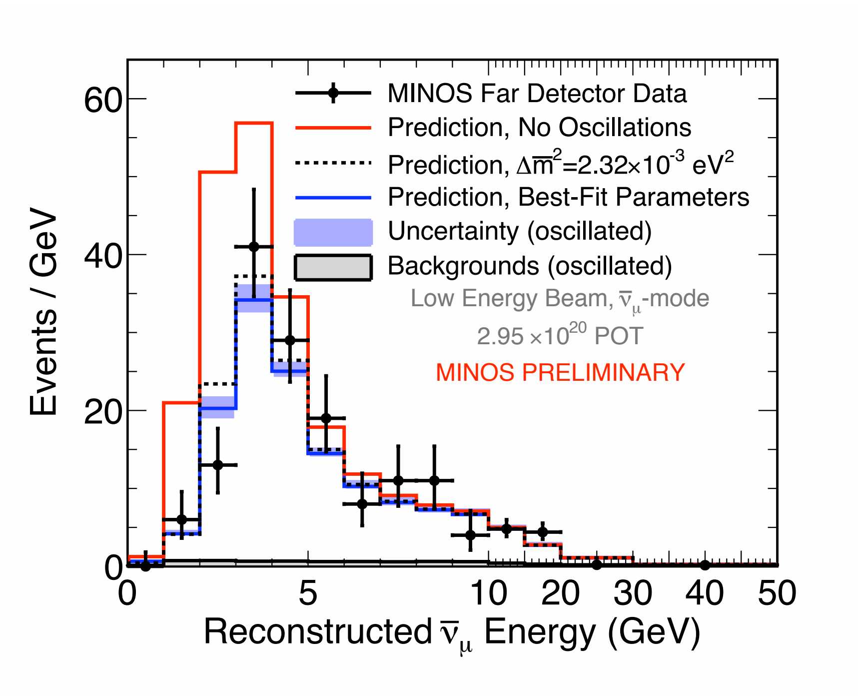


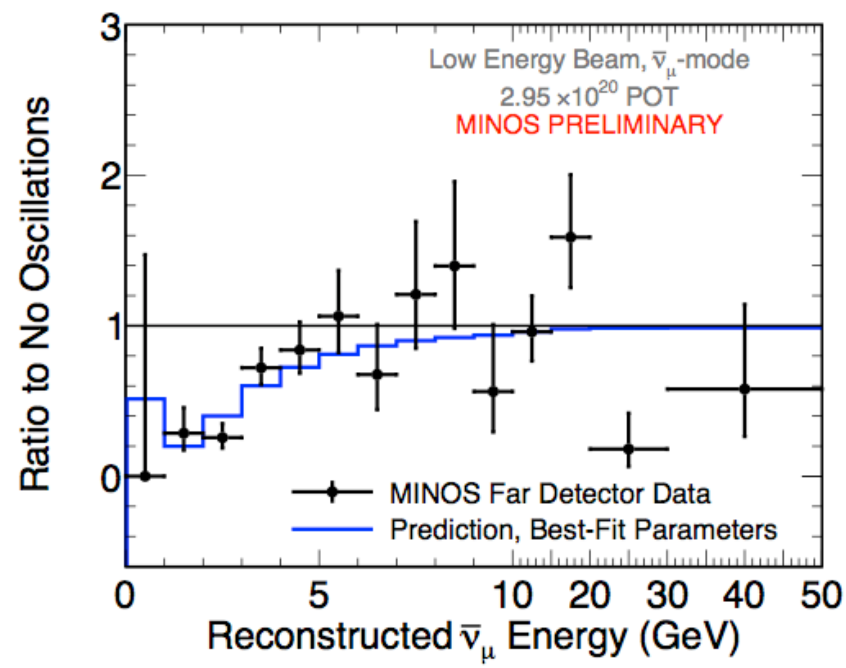


Predicted w/ no oscillations 273
Selected 193

Exclude no oscillations at 7.3σ

FD energy spectra and FD/ND





Predicted w/ no oscillations	273
Selected	193
Exclude no oscillations at	7.3σ

Anti-neutrino oscillations Best Fit parameters

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

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

Anti-neutrino vs. neutrino

Neutrinos

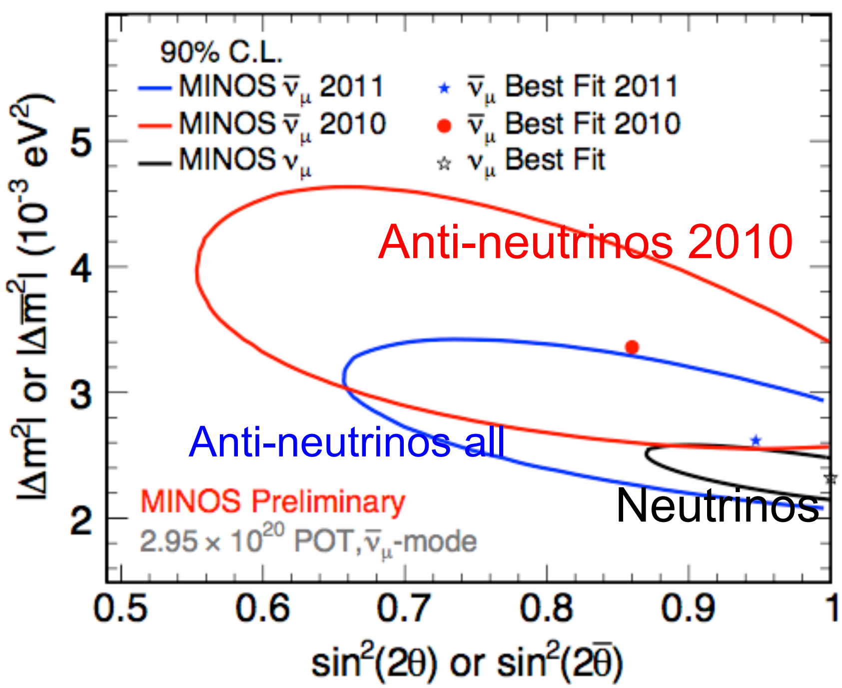
$$\left|\Delta m^2_{atm}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

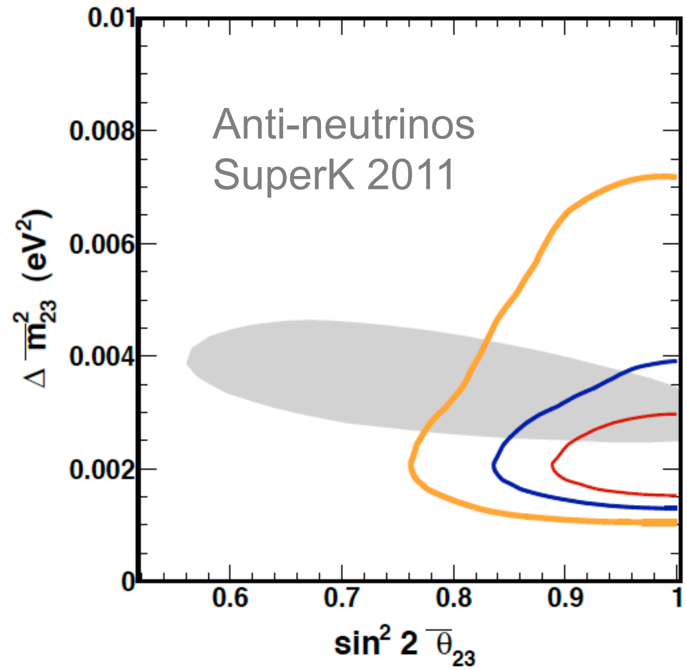
$$\sin^2(2\theta_{23}) > 0.90\ (90\%\ \mathrm{C.L.})$$

Anti-neutrinos

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

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

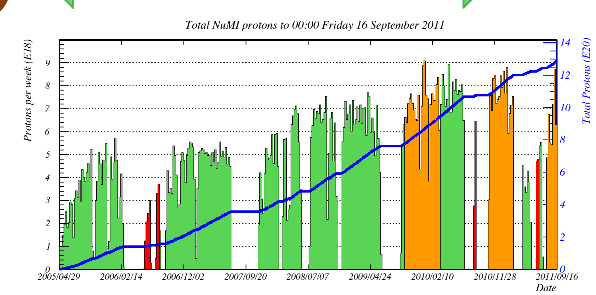




arXiv:1109.1621v1 [hep-ex] 8 Sep 2011

ELECTRON-NEUTRINO CHARGED CURRENT APPEARANCE

These data
8.2×10^{20} POT



2005

2011

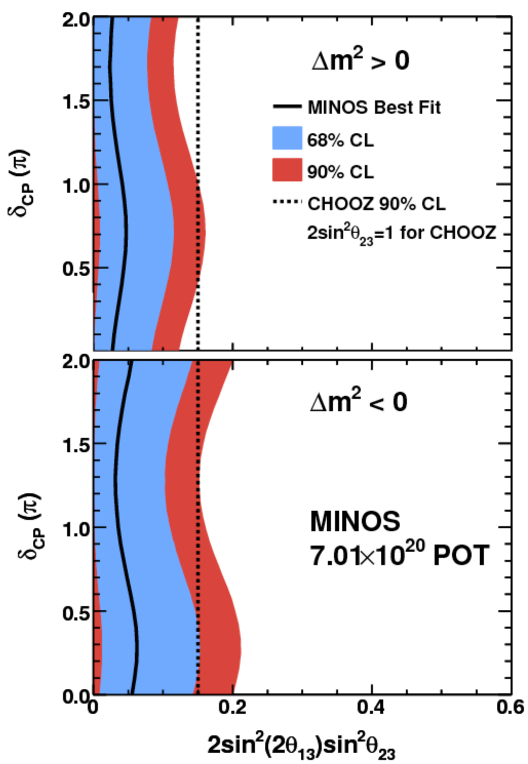
θ_{13} : electron-neutrino appearance

- The appearance probability $P(\nu_\mu \rightarrow \nu_e)$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2(\frac{\Delta m^2_{atm} L}{4E})$$

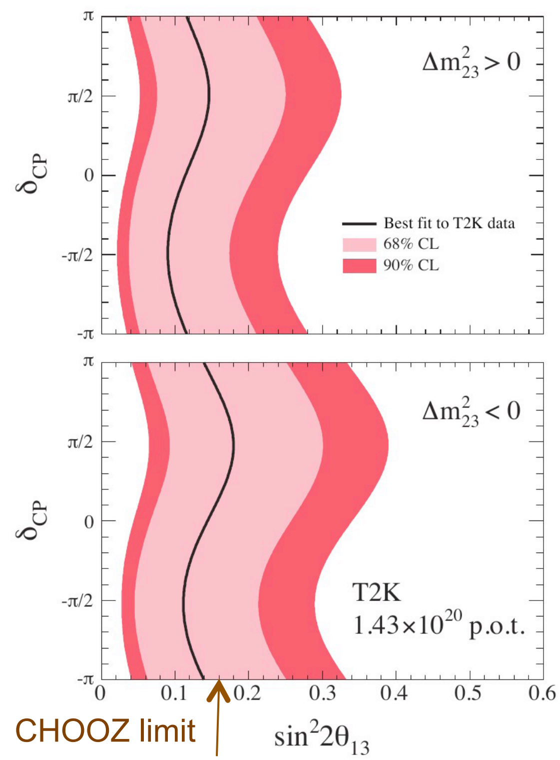
dominant term

- Also depends on δ and mass hierarchy
- MINOS 2010 and T2K 2011



MINOS 2010 observed 54 events with 49 expected bkg events

PhysRevD.82.051102

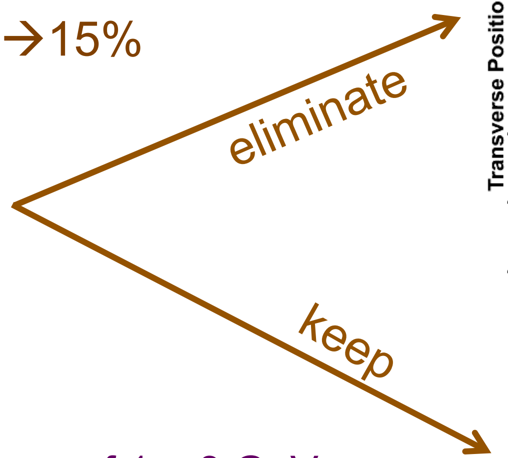


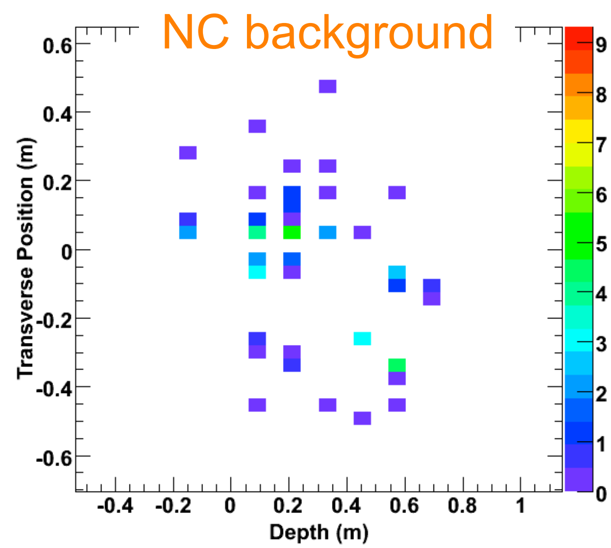
T2K 2011 observed 6 events with 1.5 expected bkg events

Phys. Rev Lett. 107 (2011) 041801

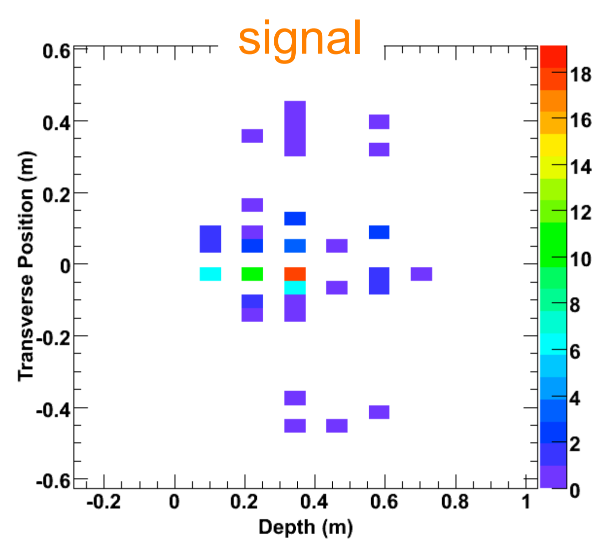
2011electron-neutrino appearance analysis

- Main sensitivity gains
  - ⇨ 17% more data (by 1.2×10^{20} POT)
  - ⇨ Improved event selection → 15%
  - ⇨ Shape fit → 12%



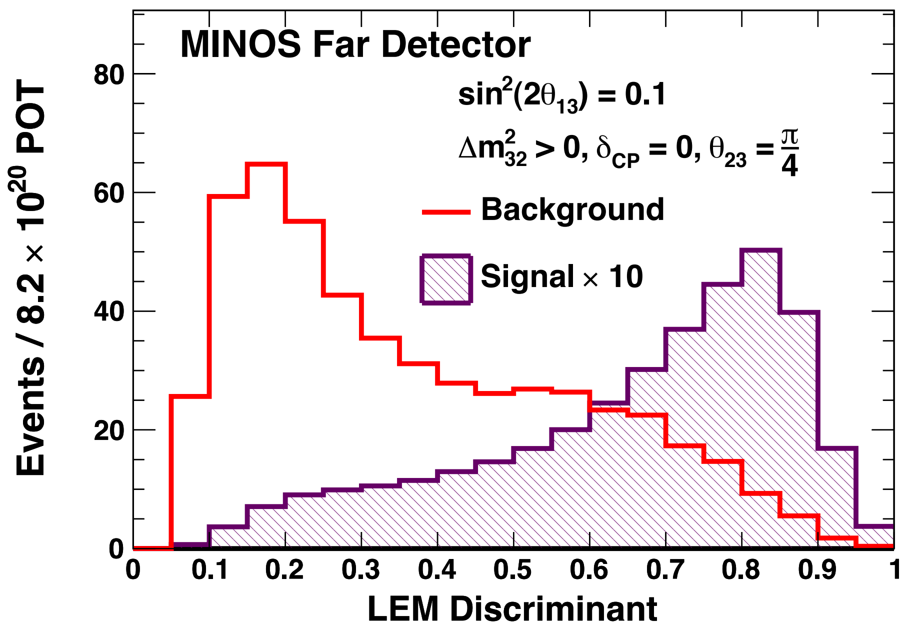


- Analysis flow:
  - ⇨ Filter (preselect) events
    - ✓ No long tracks, good shower of 1 – 8 GeV
  - ⇨ Select candidate events
  - ⇨ Use ND to predict background at FD
  - ⇨ Compare predicted to measured spectra

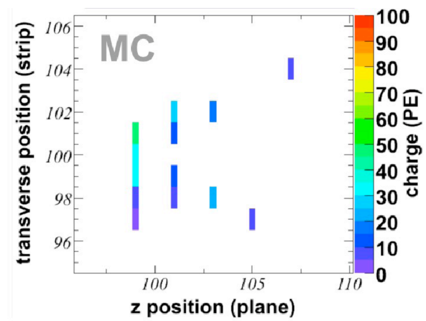


Event selection: Library Event Matching (LEM)

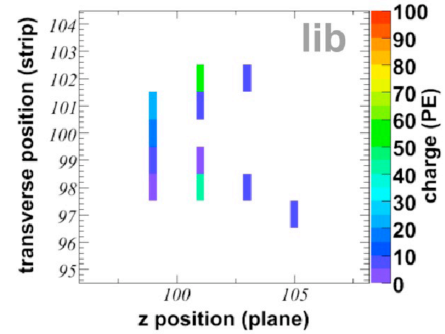
- LEM technique: compare candidate events to library (20M signal and 30M bkg events).
  - ⇨ Form discriminant using information from 50 best matches.
  - ⇨ Based on strip-level information (pattern and pulse-height).
  - ⇨ 15% improvement in sensitivity over previous technique. (ANN technique used high-level reconstructed quantities (Phys. Rev. D 82, 051102 (2010)).



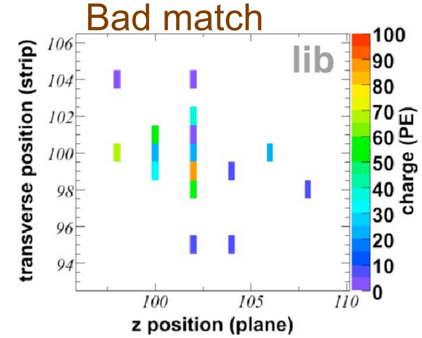
Querried event



Good match



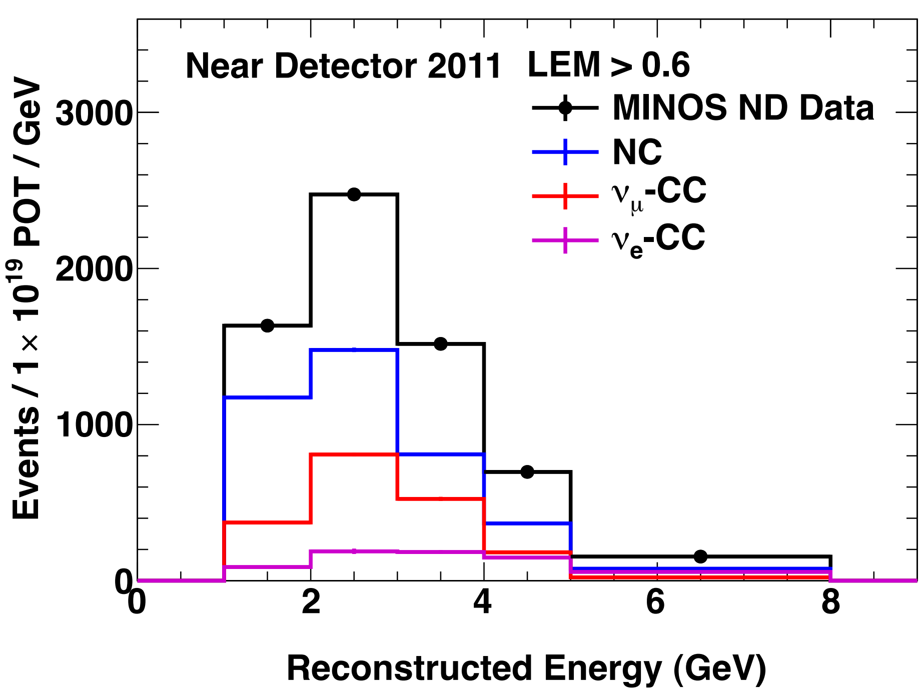
Bad match



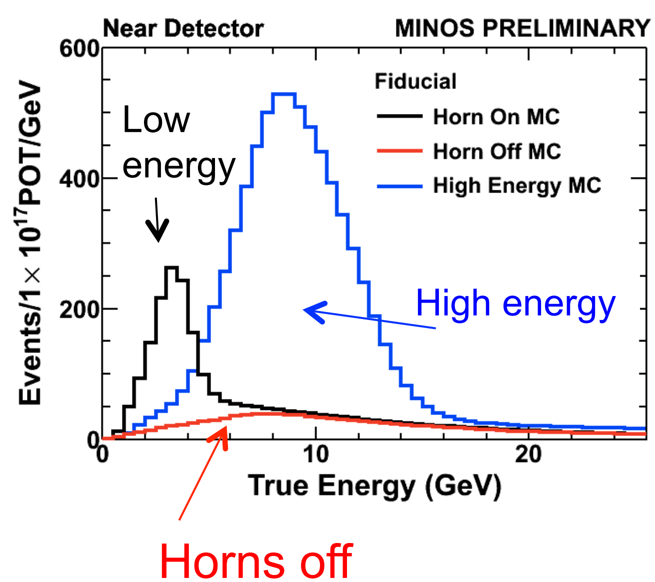
Backgrounds (Near Detector)

Main sources of background:

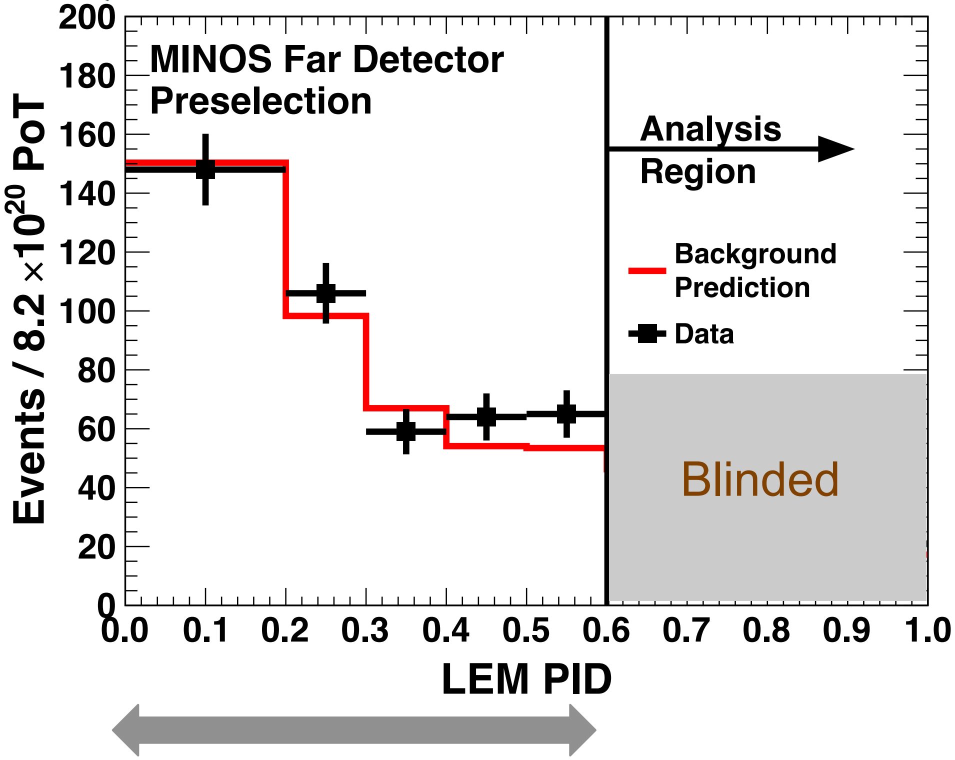
- neutral current (NC)
- charged current ν_μ (CC)
- beam contamination ν_e charged current (ν_e-CC)



Use data to extract bkg
Normalize to ND



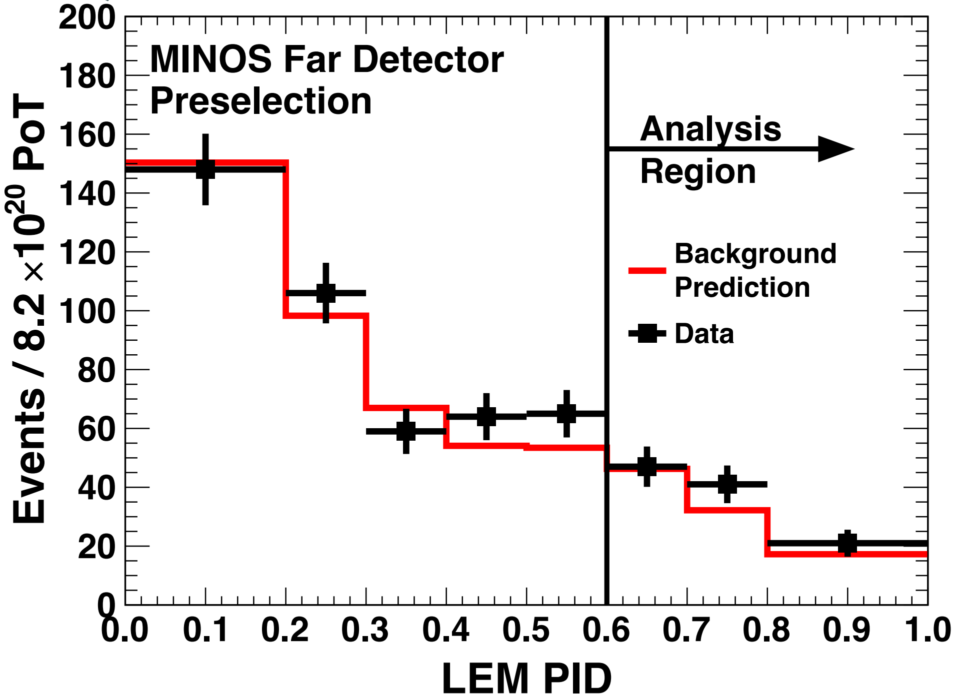
MINOS: “sideband”



LEM < 0.5
observe 377 events
expect 370 +- 19(stat) (@ θ_{13} = 0)

Test of entire analysis chain - bkg calculation
and extrapolation to far detector

MINOS ν_e signal region

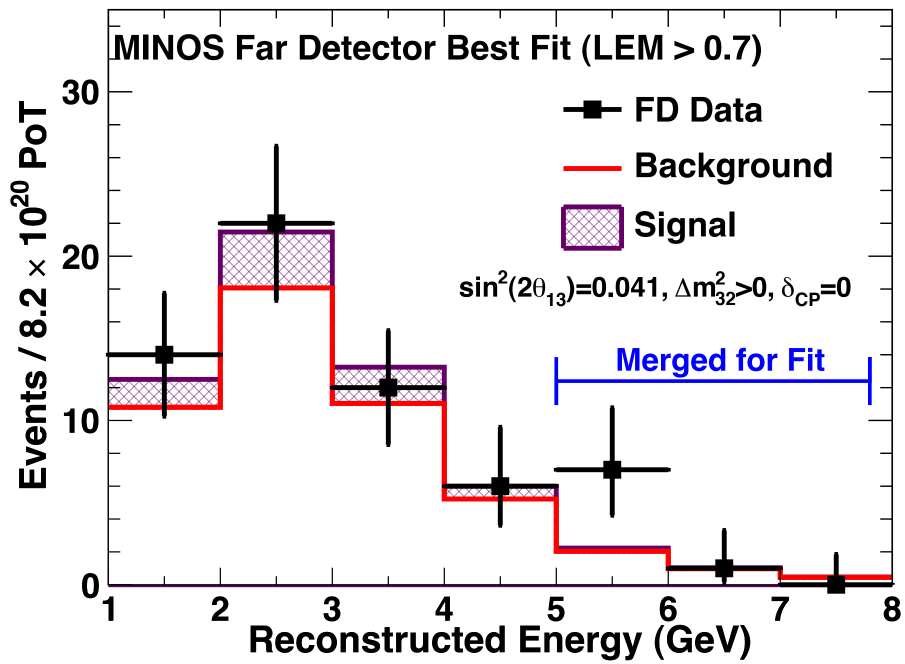


In signal-enhanced region (LEM>0.7):

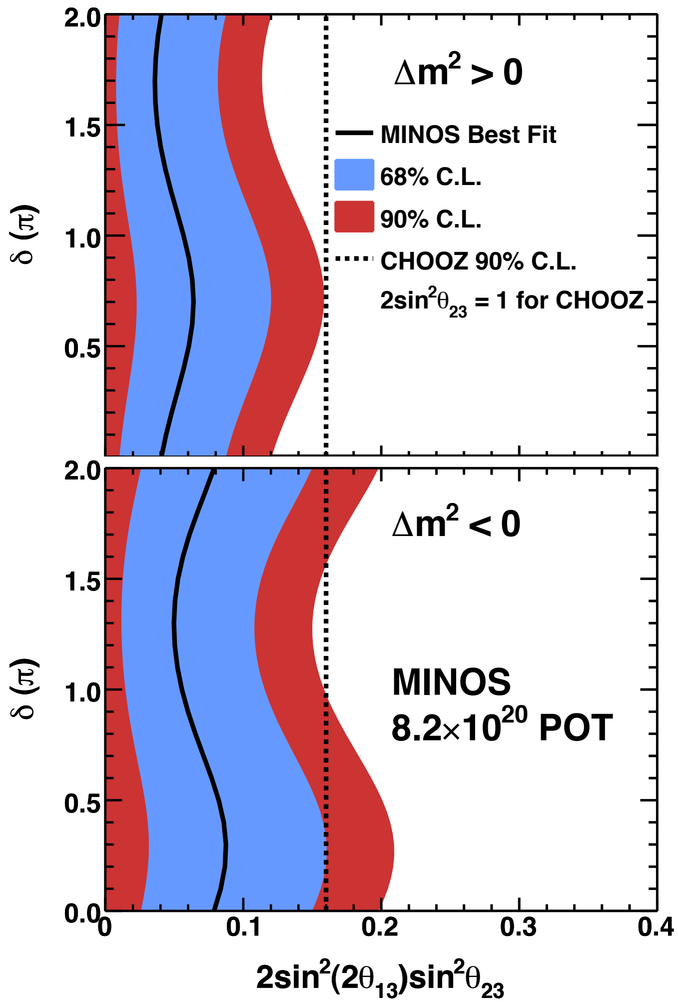
- Expected bkg (θ_{13}=0):
  - ⇨ **49.6 +- 2.7 (syst) +- 7.0 (stat)**
- Observed data: **62**

LEM < 0.5
observe 377 events
expect 370 +- 19(stat) (@ θ_{13} = 0)

Test of entire analysis chain - bkg calculation and extrapolation to far detector



MINOS allowed space



Feldman-Cousins contours

Assuming: $\delta = 0 \quad \theta_{23} = \pi/4$

$\Delta m^2 > 0 \quad (\Delta m^2 < 0)$

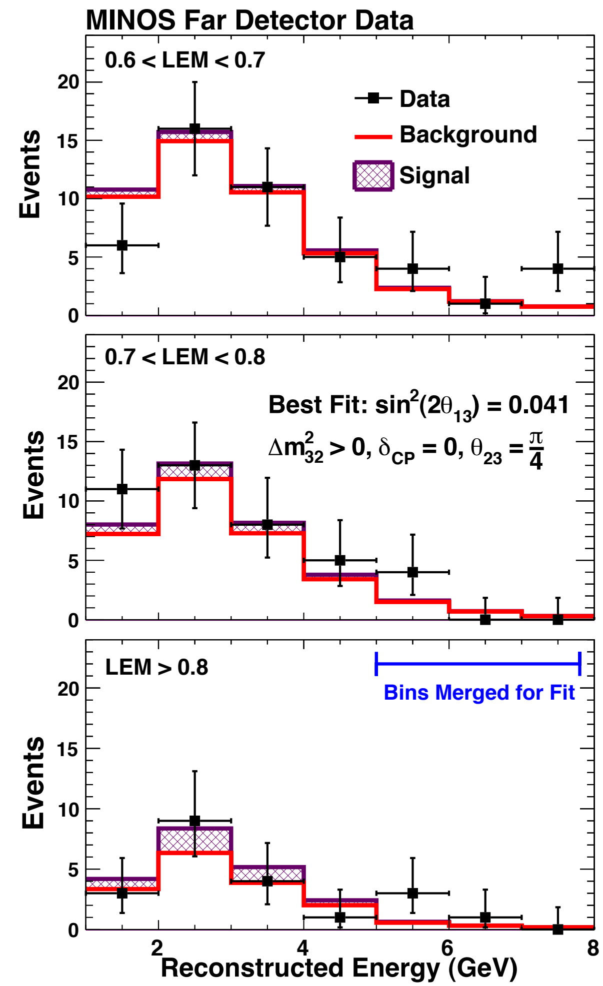
$\sin^2(2\theta_{13}) < 0.12\ (0.20)$

90% CL

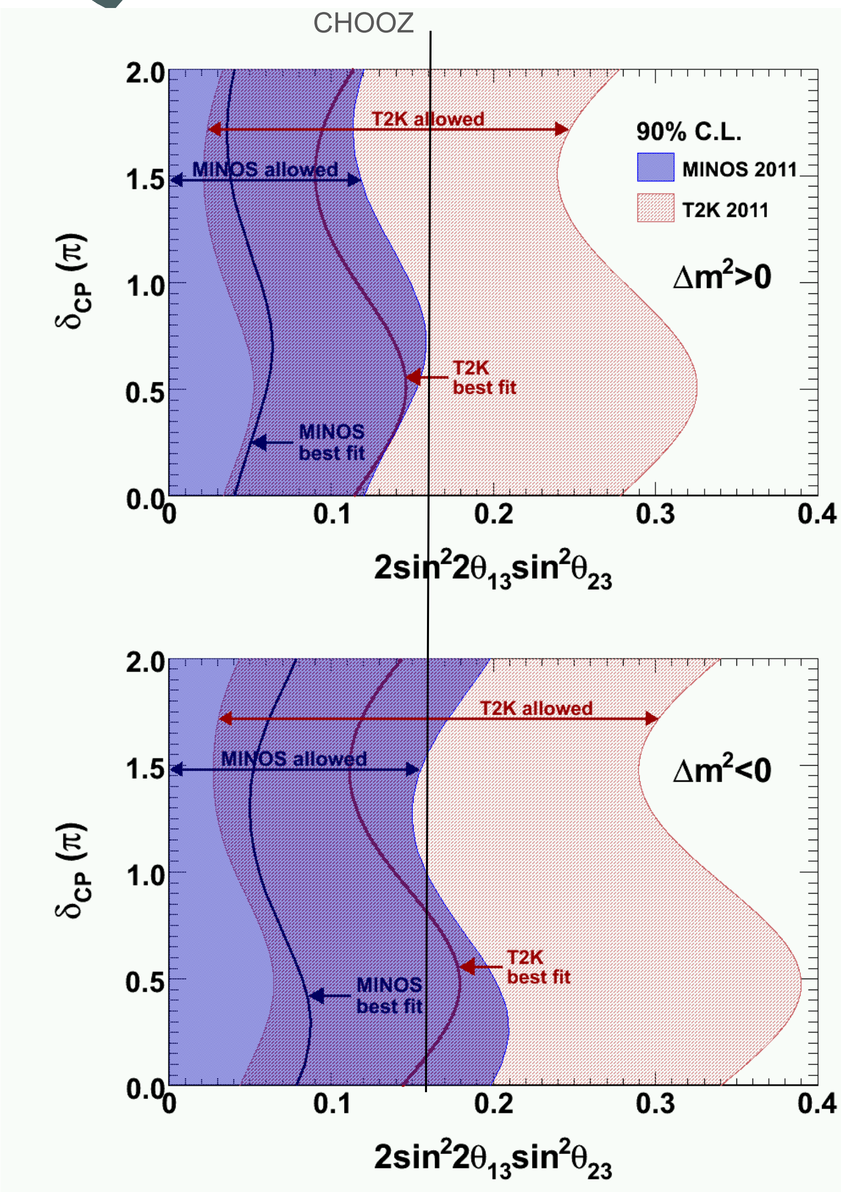
$\sin^2(2\theta_{13}) = 0.04\ (0.08)$

Best fit

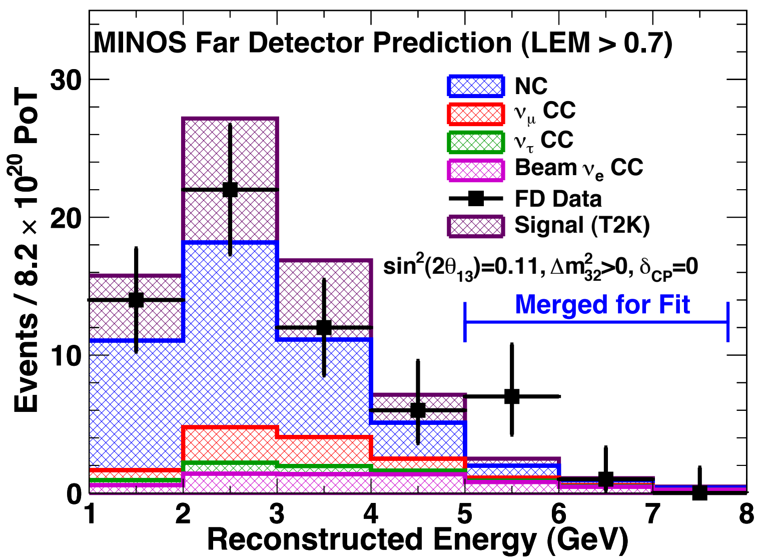
Uncertainties in the other oscillation parameters are included



MINOS vs T2K

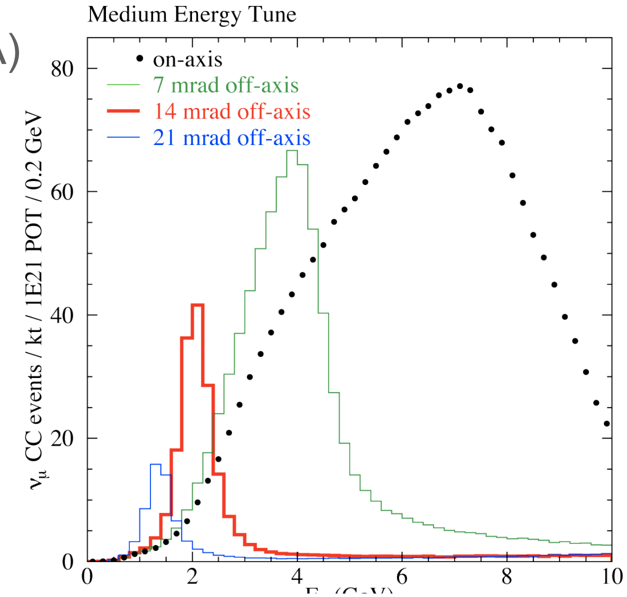


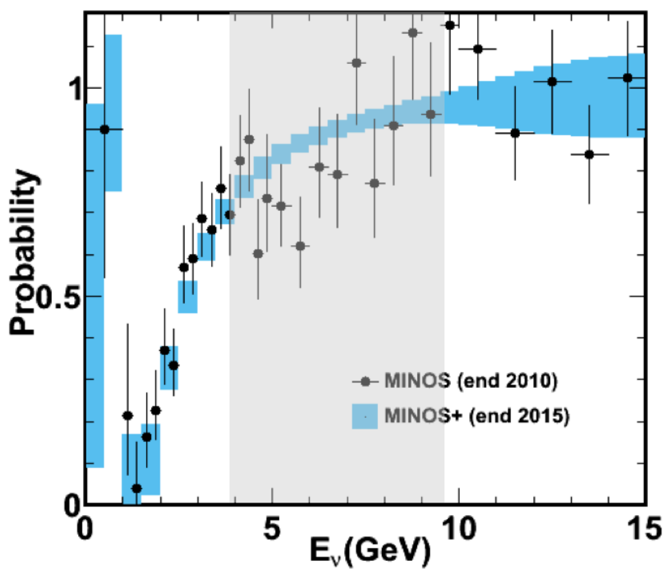
MINOS signal prediction
at T2K's best fit $\sin^2(2\theta_{13})=0.11$

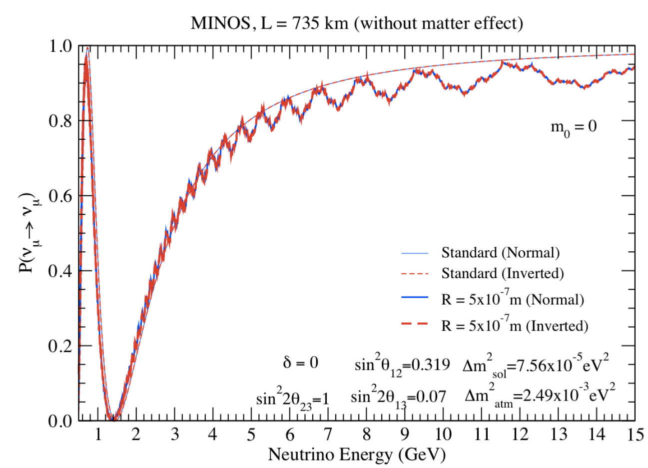


Outlook: MINOS+

- Run with medium energy beam (required by NOvA)
- High-statistics in 4-10 GeV range
- Program:
  - ⇨ Improve disappearance measurements
    - ✓ Neutrinos and anti-neutrinos
  - ⇨ Search for sterile neutrinos
  - ⇨ Test exotic hypotheses (e.g., extra dimensions)
  - ⇨ Constrain non-standard interactions
  - ⇨ Neutrino TOF
  - ⇨ Continue MINOS observatory measurements



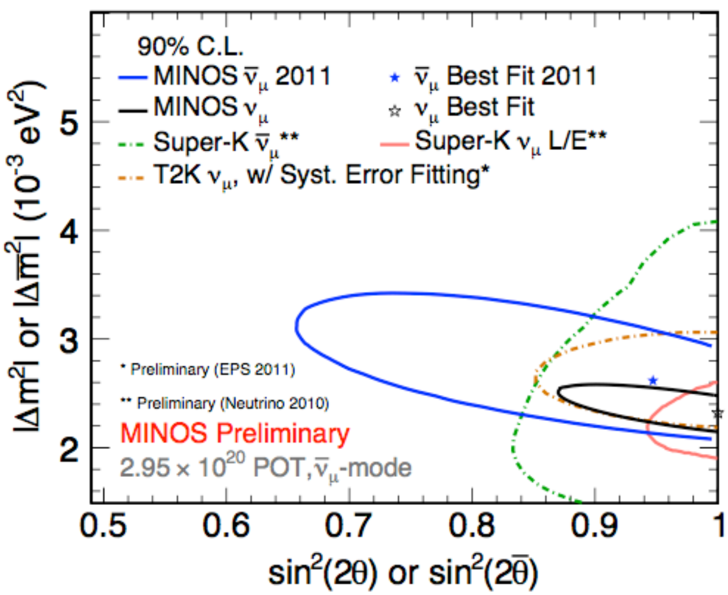


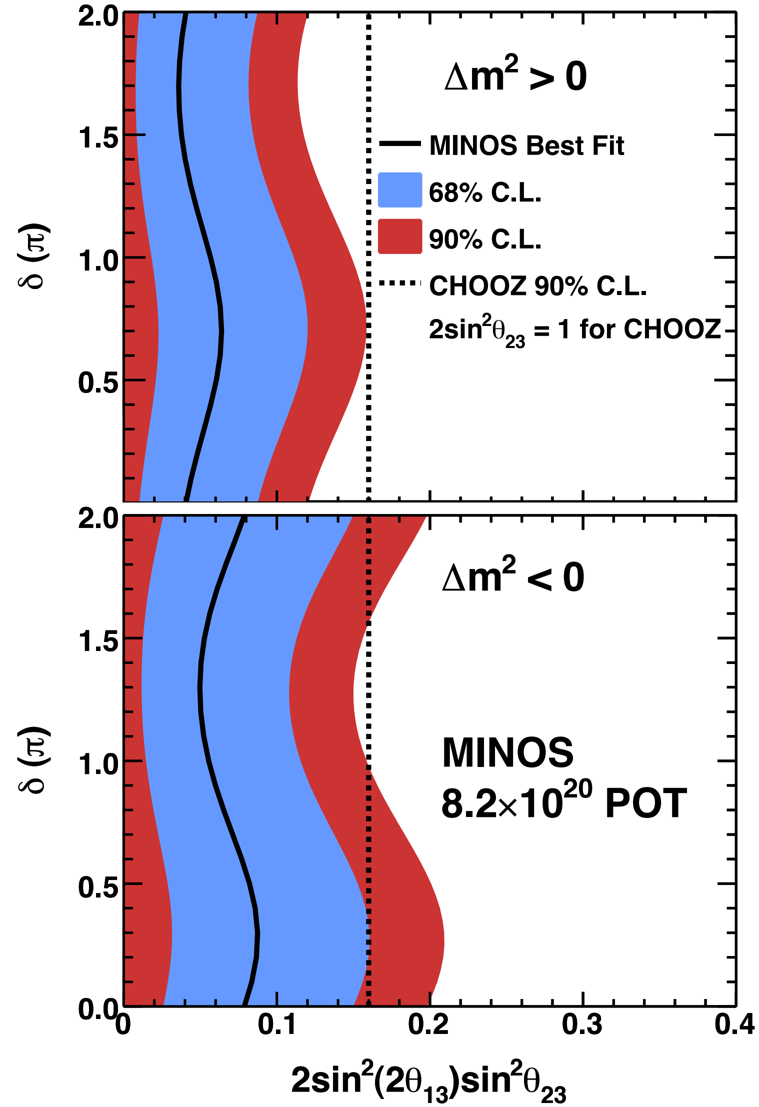


P.A.N. Machado, H. Nunokawa,R. Zukanovich-Funchal, hep-ph/1101.003v1.

Summary

- Anti-neutrinos = neutrinos
- Strong constraints on θ_{13}
- *Many other results not discussed here*
- More results to come
  - ⇨ Include more data
  - ⇨ Include electron anti-neutrinos
  - ⇨ Further analysis improvements





BACKUP SLIDES

Neutrino Time-of-Flight

- OPERA in 2011: arXiv:1109.4897 →
  - ⇨ *"Measurement of the neutrino velocity with the OPERA detector in the CNGS beam"*
  - ⇨ [60.7 ± 6.9 (stat) ± 7.4 (syst)] ns
  - ⇨ (v-c)/c = [2.48 ± 0.28 (stat.) ± 0.30 (sys.)] x 10^{-5} (claim: 6 sigma)

- MINOS published in 2007
  - ⇨ *"Measurement of neutrino velocity with MINOS detectors and NuMI neutrino beam"*, Phys. Rev. D 76, 072005 (2007)
  - ⇨ [126 ± 32(stat) ± 64(syst)] ns 68%C.L.
  - ⇨ (v-c)/c = [5.1 ± 2.9 (stat + sys)] x 10^{-5}

$$m_\nu < 50\, MeV/c^2 \quad (stat + syst) \quad 99\% C.L.$$

TABLE II. Sources of uncertainty in ν relative time measurement.

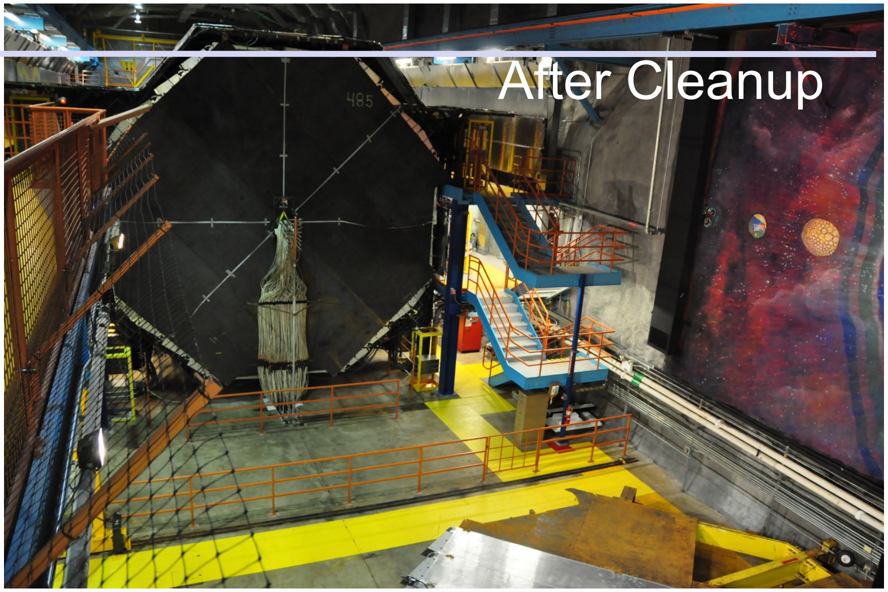
	Description	Uncertainty (68% C.L.)
A	Distance between detectors	2 ns
B	ND antenna fiber length	27 ns
C	ND electronics latencies	32 ns
D	FD antenna fiber length	46 ns
E	FD electronics latencies	3 ns
F	GPS and transceivers	12 ns
G	Detector readout differences	9 ns
Total (sum in quadrature)		64 ns

MINOS+ plan

- MINOS+ proposal to run in medium energy beam was approved
- The proposal called for a significantly improved ν-TOF measurement
- Proposed improvements
  - GPS receivers/modems: common view, TWSTFT (two-way transfer)
  - New precision clocks (Cs)
  - New auxiliary detectors at FD and ND
  - Involve NIST, Accelerator Division, others ? (e.g., Minerva, …)
  - Redundancy
- Working on it (faster than originally intended) …
  - Will re-measure existing system soon
  - ...

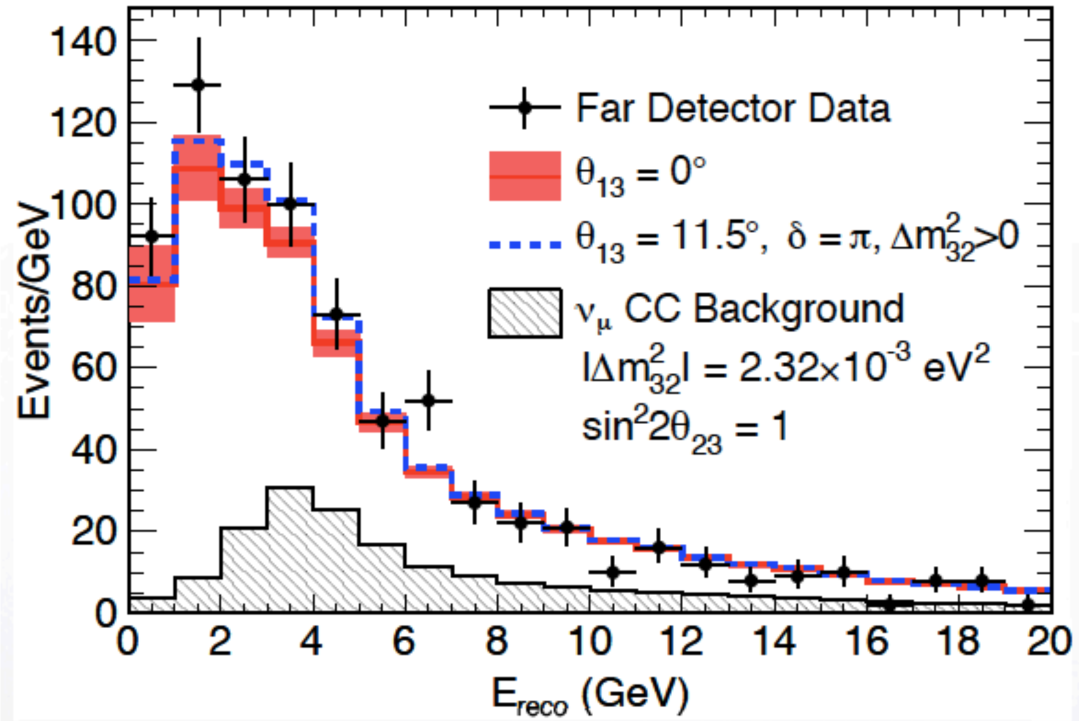
Argonne · Athens · Benedictine · Brookhaven · Caltech · Cambridge · Campinas ·
Fermilab · Harvard · Holy Cross · IIT
Indiana · Iowa State · Lebedev · Livermore
Minnesota-Twin Cities · Minnesota-Duluth· Otterbein · Oxford Pittsburgh · Rutherford ·
Sao Paulo · South Carolina
Stanford · Sussex · Texas A&M · Texas-Austin · Tufts · UCL
Warsaw · William & Mary

Soudan Fire in 2011



- March 17, smoke detected in FD hall due to a fire in the shaft
- Power to the lab shut off automatically
- Foam pumped in to extinguish the fire
- No damage to the MINOS detector
- Detector returned to full operations May 19

Neutral Currents in the Far Detector



- ✓ Expect: 754 events $\pm 28_{(stat)} \pm 37_{(syst)}$
- ✓ Observe: 802 events
- ✓ No deficit of NC events

$$R = \frac{N_{data} - BG}{S_{NC}}$$

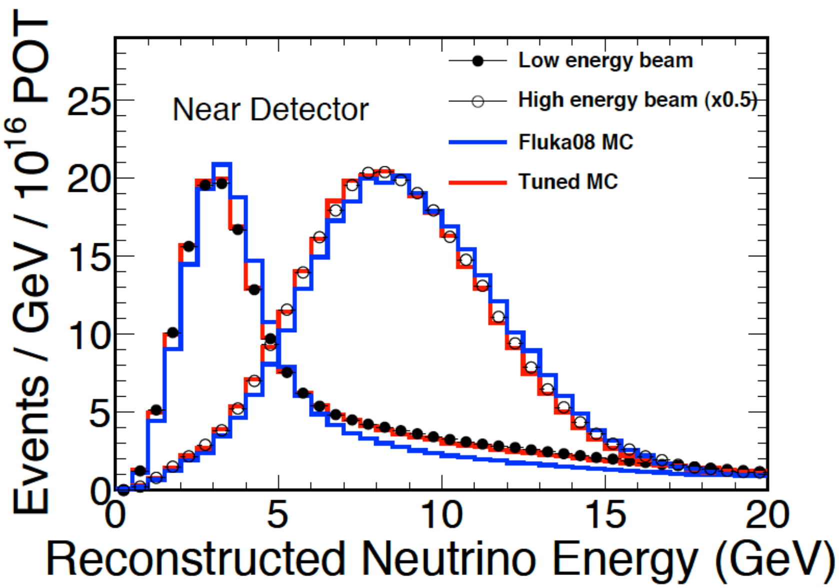
$$R = 1.09 \pm 0.06\,(\text{stat.}) \pm 0.05\,(\text{syst.})$$
(no ν_e appearance)

$$R = 1.01 \pm 0.06\,(\text{stat.}) \pm 0.05\,(\text{syst.})$$
(with ν_e appearance)

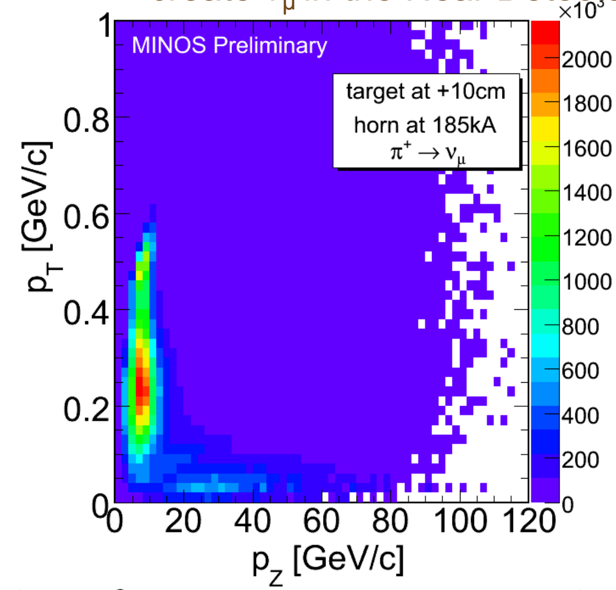
$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ (0.40)\quad (90\%\ \text{C.L.})$$

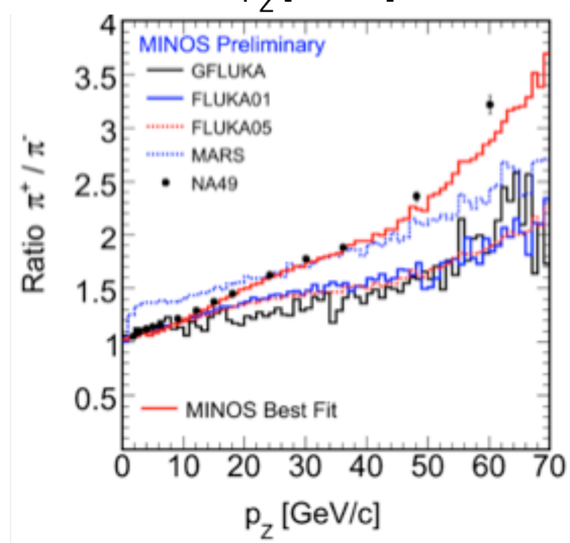
no (with) ν_e appearance

Near Detector CC events



p_T and p_z of π which create ν_μ in the Near Detector



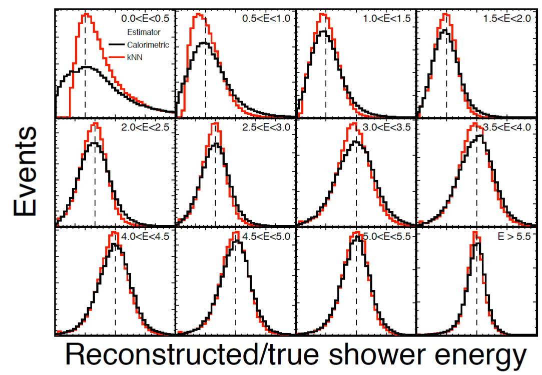


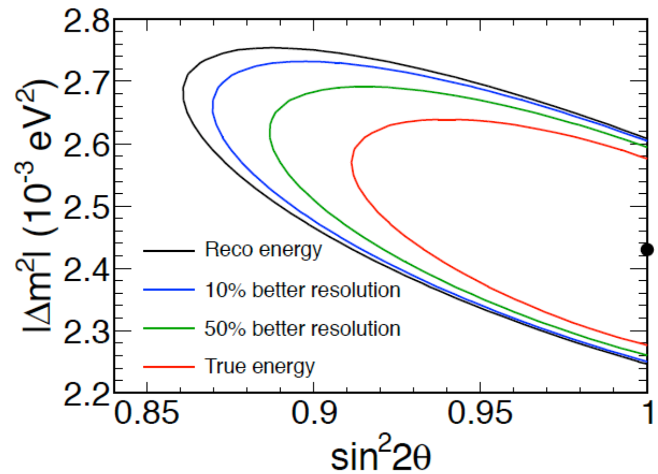
The beam spectrum modeling tuned

- Hadron production reweighted using 7 beam configurations
- NA49 data used to constrain $\pi+/\pi-$ and π/K ratios in fits

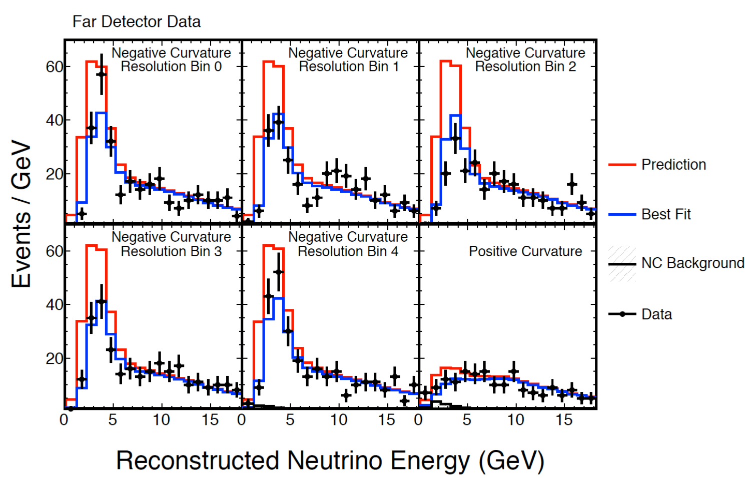
Main recent (2010-2011) CC analysis improvements

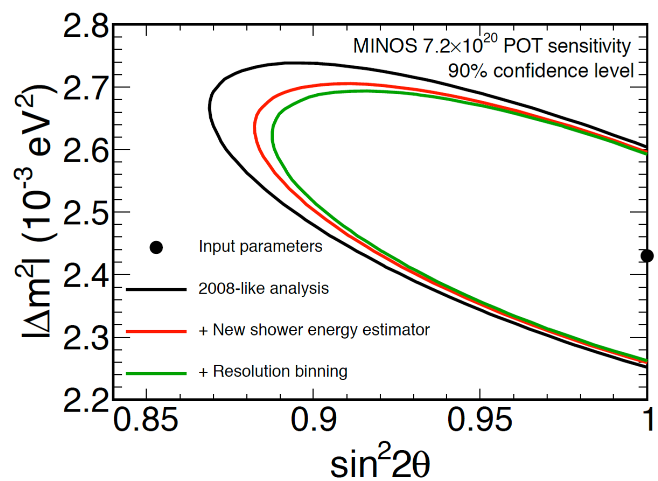
- k-Nearest-Neighbor (kNN) energy estimator





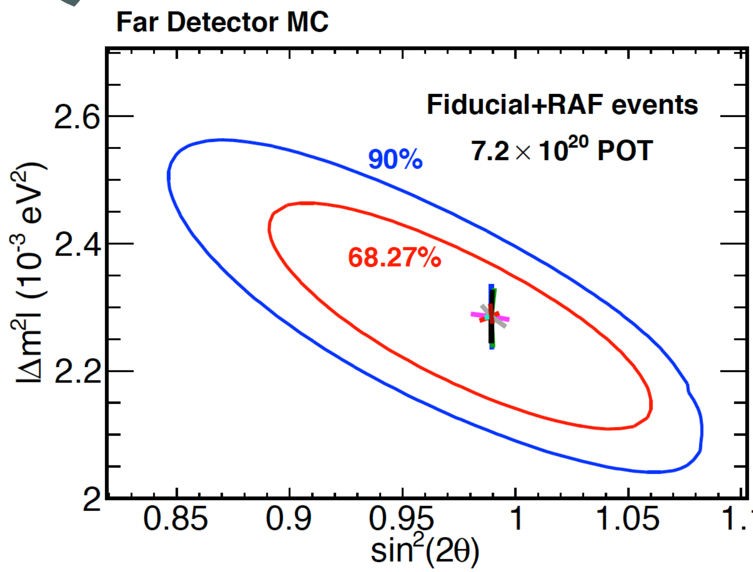
- Fitting in bins of energy resolution





- Include partially reconstructed events (high statistics but poor E_{reco} → limited impact)

Systematic uncertainties of neutrino disappearance



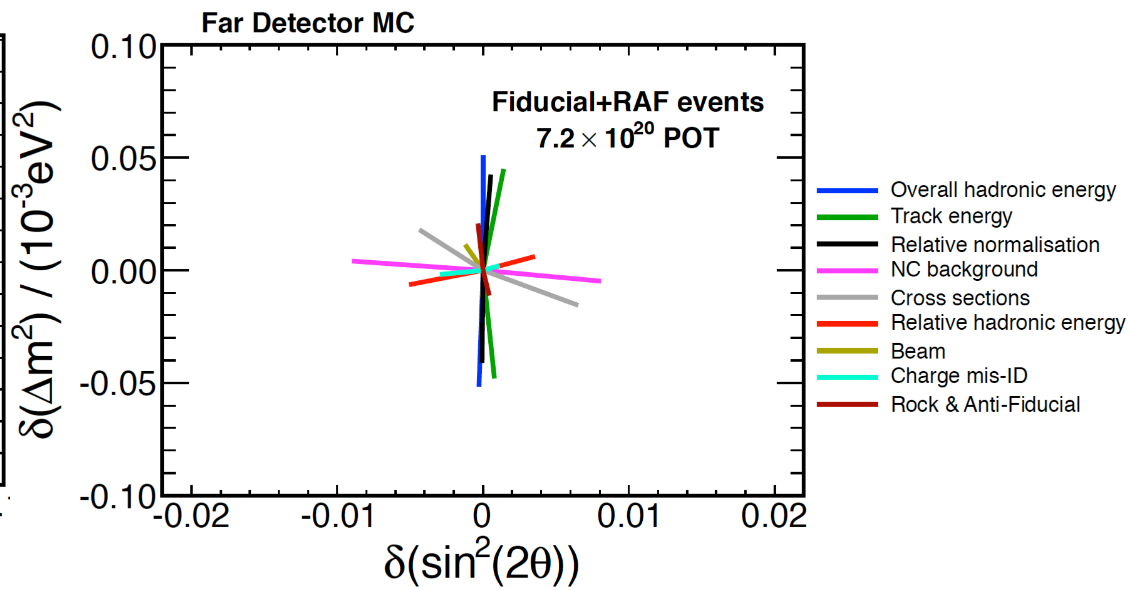
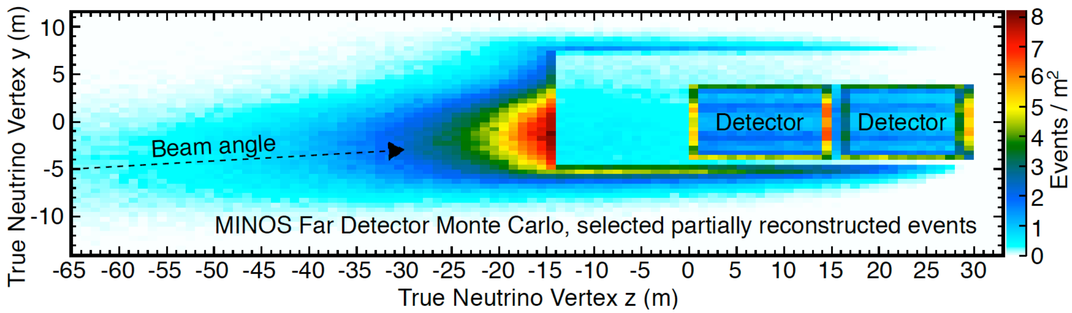


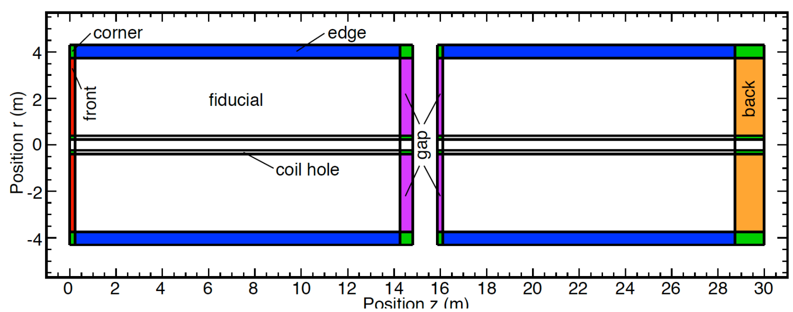
TABLE I. Sources of systematic uncertainties and their impact on fitting oscillation parameters.

Source of systematic uncertainty	$\delta(\Delta m^2)$ (10^{-3} eV^2)	$\delta[\sin^2(2\theta)]$
(a) Hadronic energy	0.051	<0.001
(b) μ energy (range 2%, curv. 3%)	0.047	0.001
(c) Relative normalization (1.6%)	0.042	<0.001
(d) NC contamination (20%)	0.005	0.009
(e) Relative hadronic energy (2.2%)	0.006	0.004
(f) $\sigma_\nu(E_\nu < 10$ GeV)	0.020	0.007
(g) Beam flux	0.011	0.001
(h) Neutrino-antineutrino separation	0.002	0.002
(i) Partially reconstructed events	0.004	0.003
Total systematic uncertainty	0.085	0.013
Expected statistical uncertainty	0.124	0.060

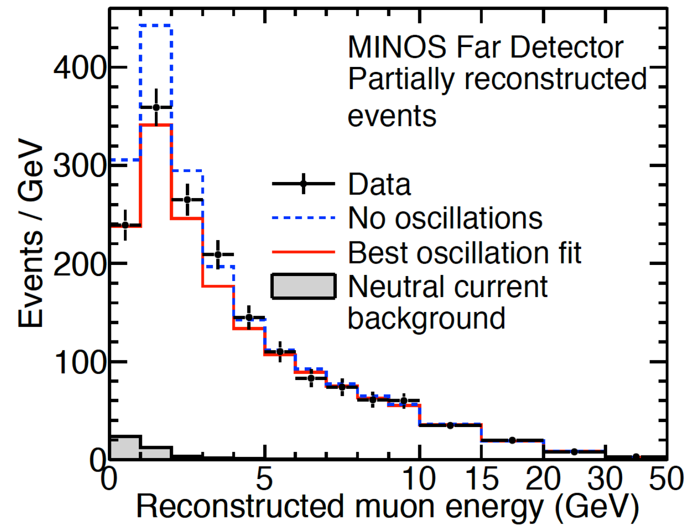
Partially reconstructed events originating in rock and outer detector parts

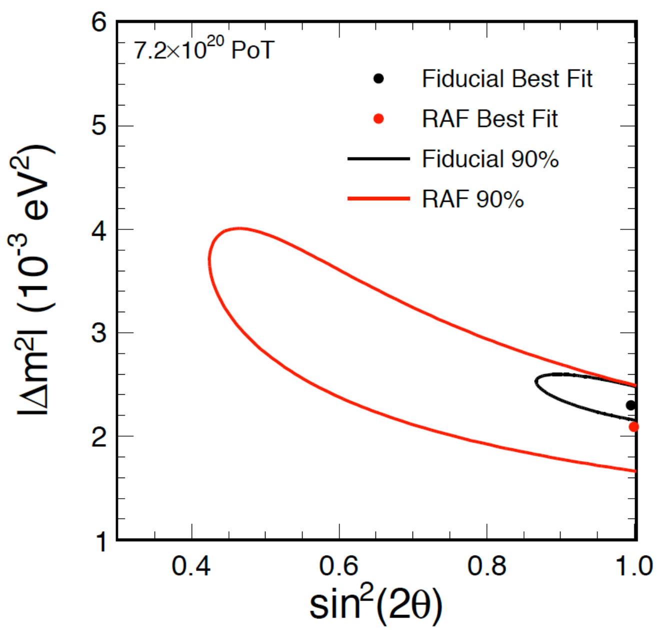
- aka Rock and Ant-Fiducial (RAF) events
- Included in analysis
- High statistics but limited impact





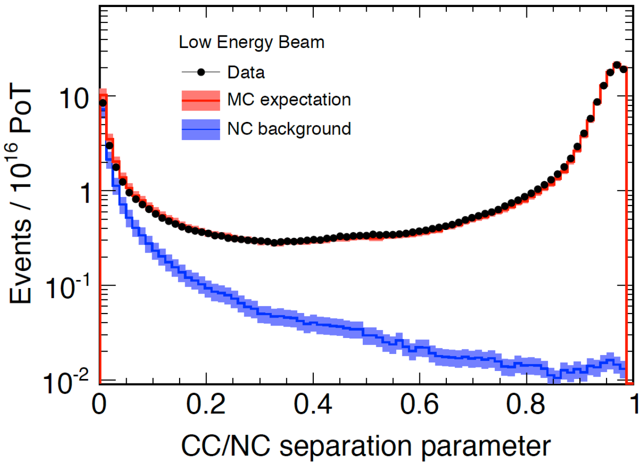
Far Detector

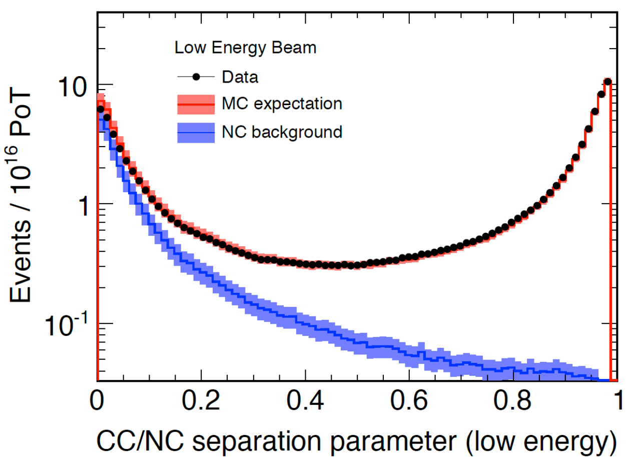


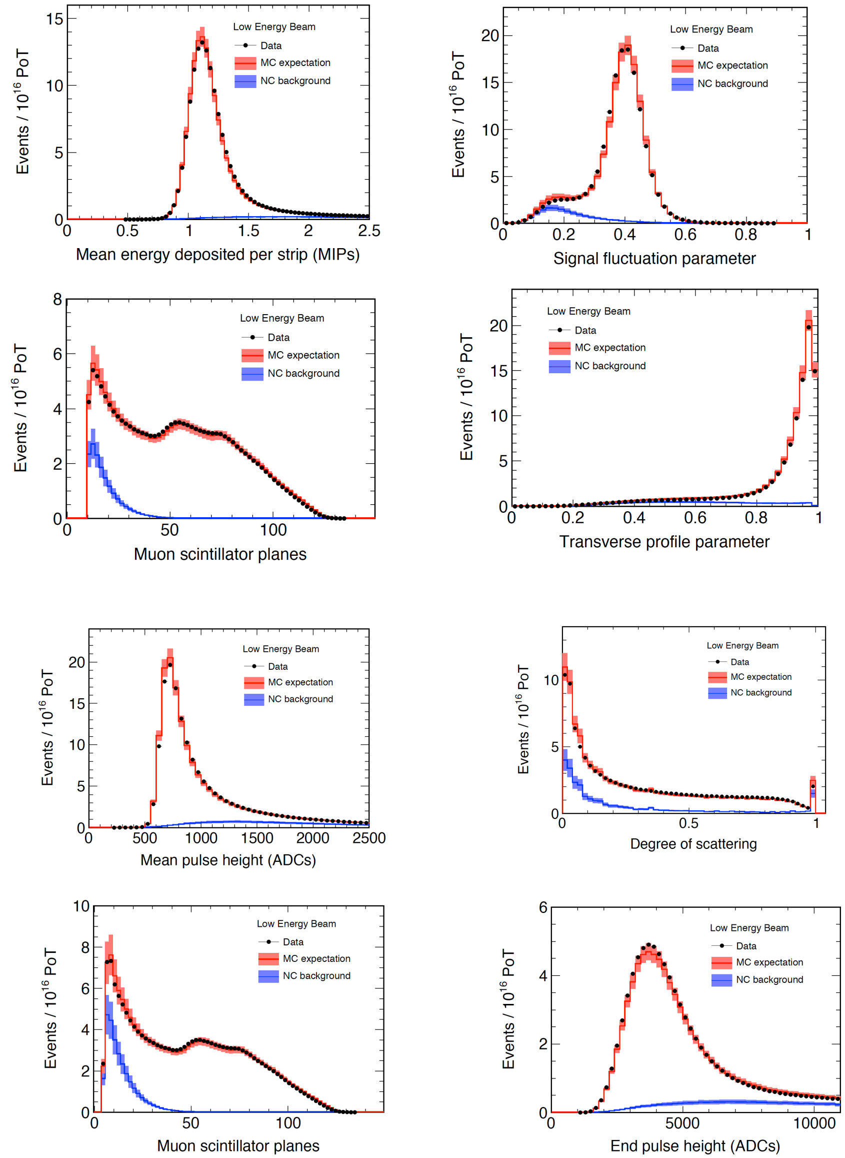


Run period	POT (10^{20})	Predicted (no oscillations)		Observed (FD)	
		Fully	Partially	Fully	Partially
I	1.269	426	375	318	357
II	1.943	639	565	511	555
III	3.881	1252	1130	1037	977
High energy	0.153	134	136	120	128
Total	7.246	2451	2206	1986	2017

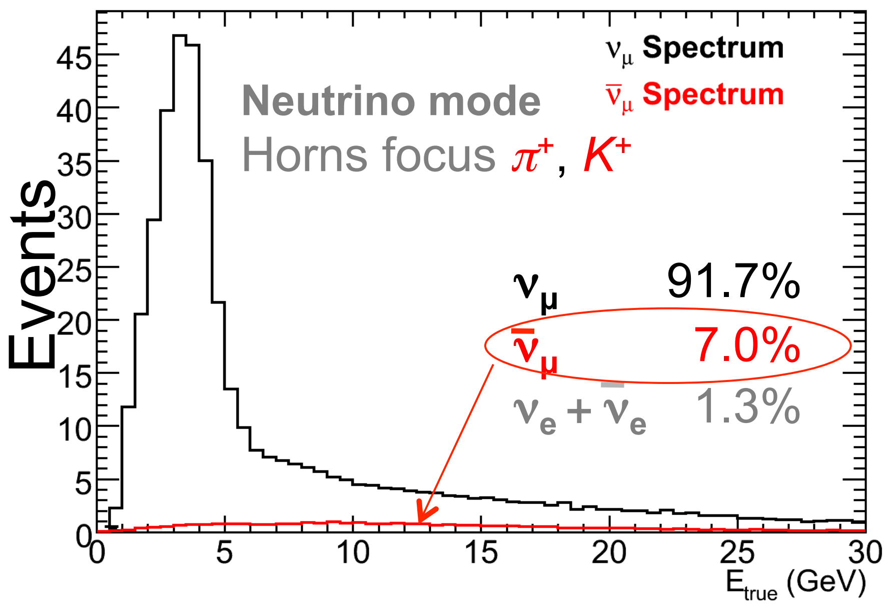
CC-NC separation (PID)





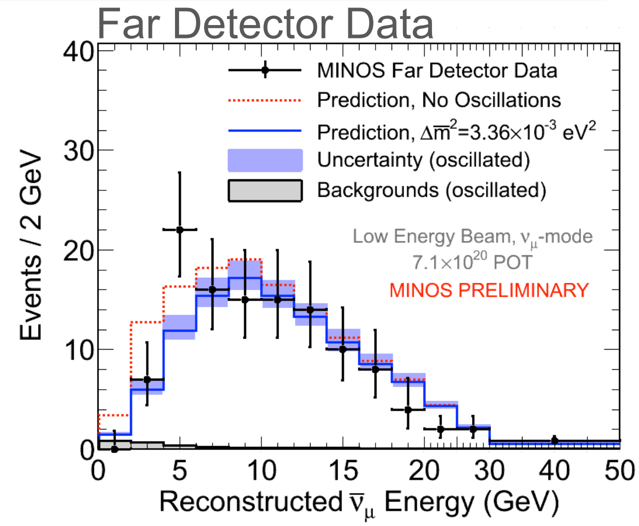


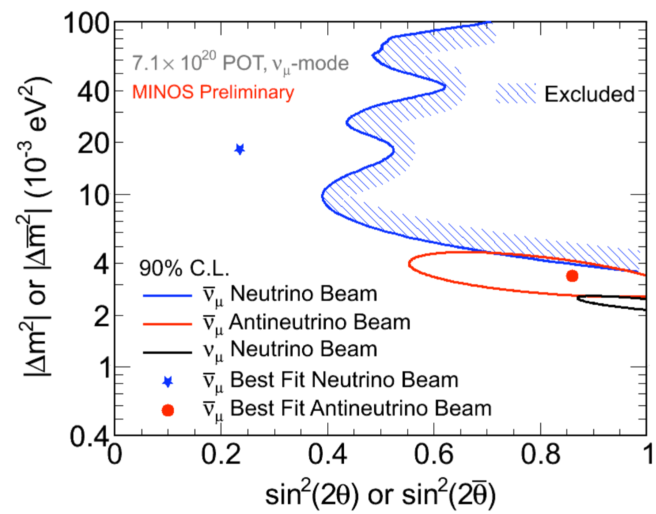
Anti-neutrinos in neutrino beam



- Analyze 7% antineutrino component of neutrino beam
- Complementary information from higher energy events
- Results consistent with the other MINOS disappearance analysis

arXiv:hep-ex/1108.1509, submitted to Phys. Rev. D (RC)



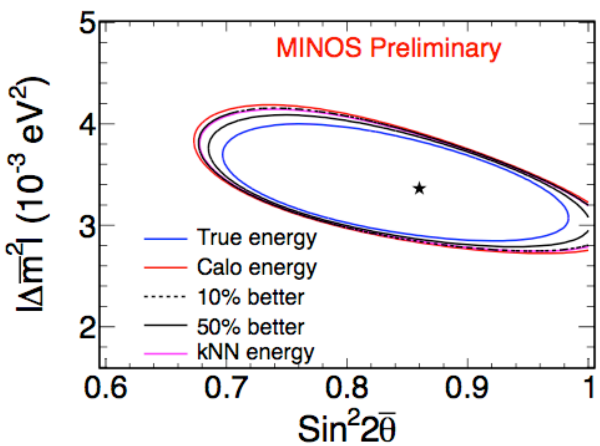


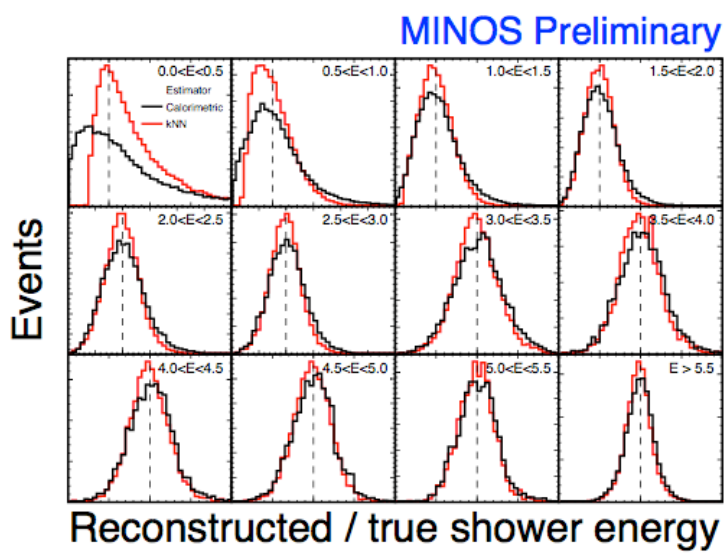
$$\left|\Delta\bar{m}^2_{atm}\right| < 3.37\times10^{-3}\,\mathrm{eV}^2$$

$$\textit{if}\quad \sin^2(2\bar{\theta}_{23}) = 1.0$$

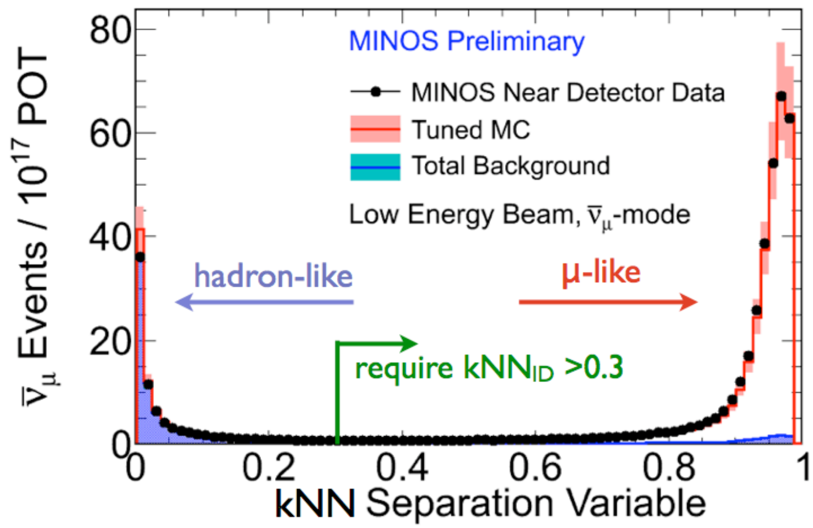
Anti-neutrinos in the anti-neutrino beam
Latest results (2011)

Anti-neutrino kNN shower estimate

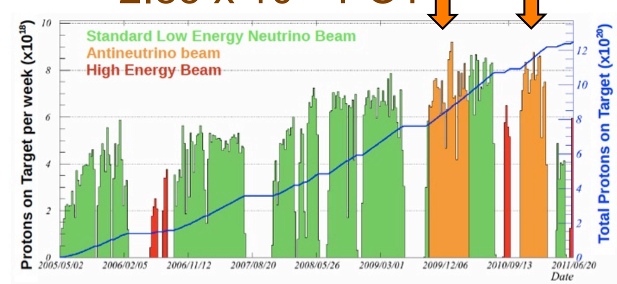




CC/NC separation



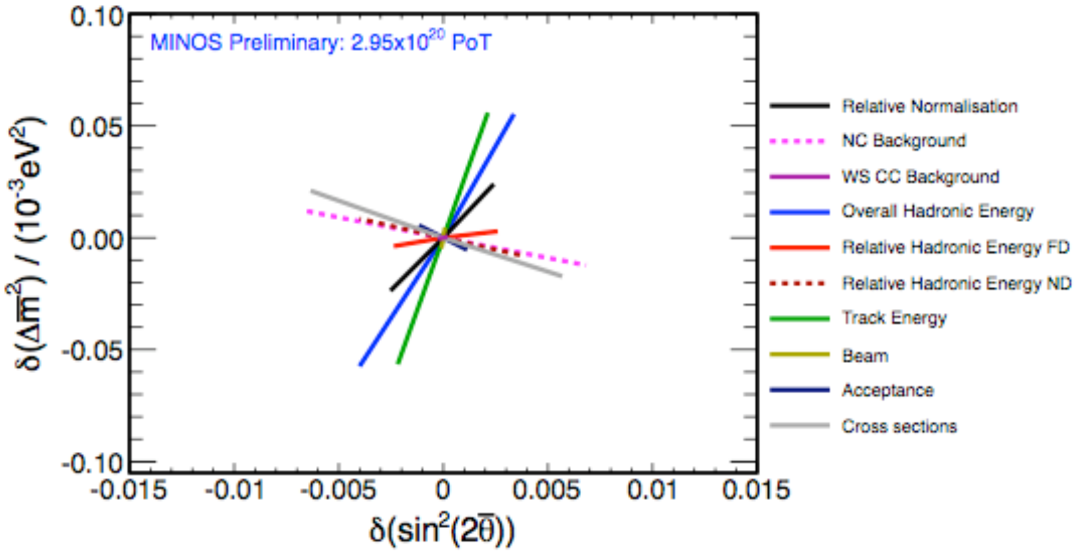
These data
2.85×10^{20} POT



Start 2005

Now 2011

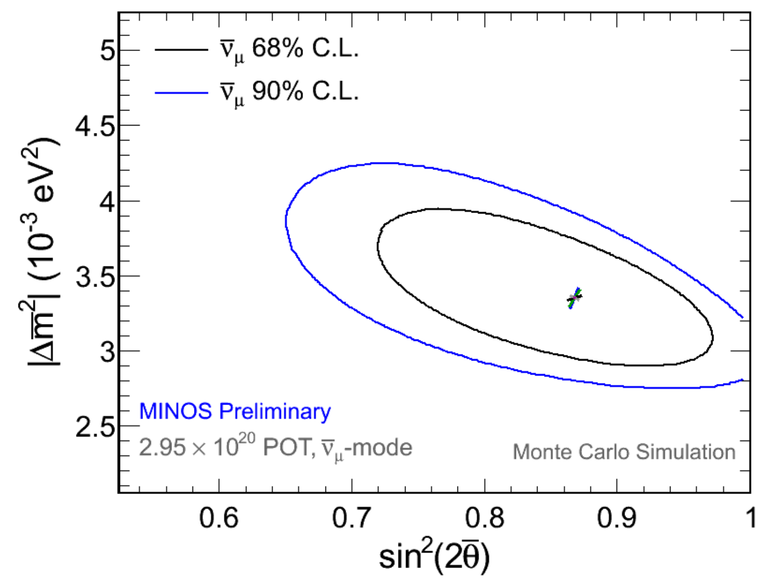
Systematic uncertainties for anti-neutrinos



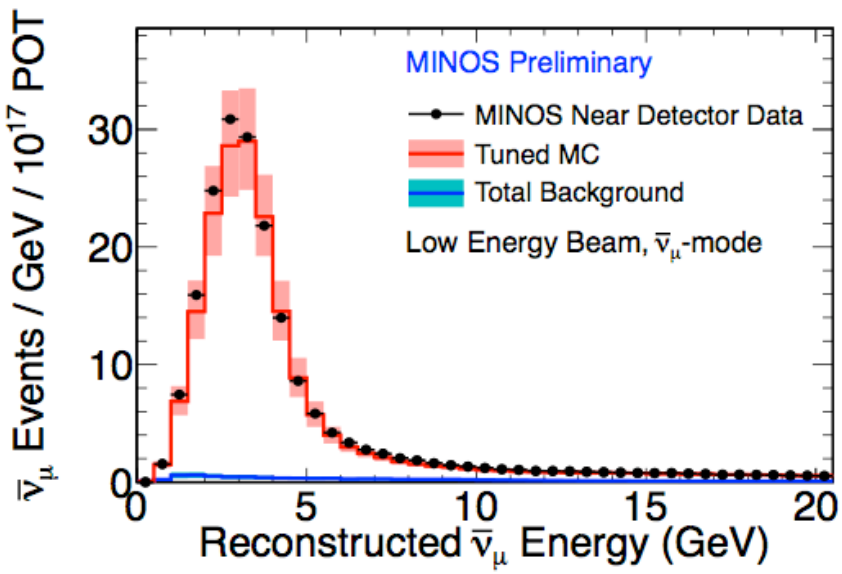
Effect of uncertainties estimated by fitting systematically shifted MC samples

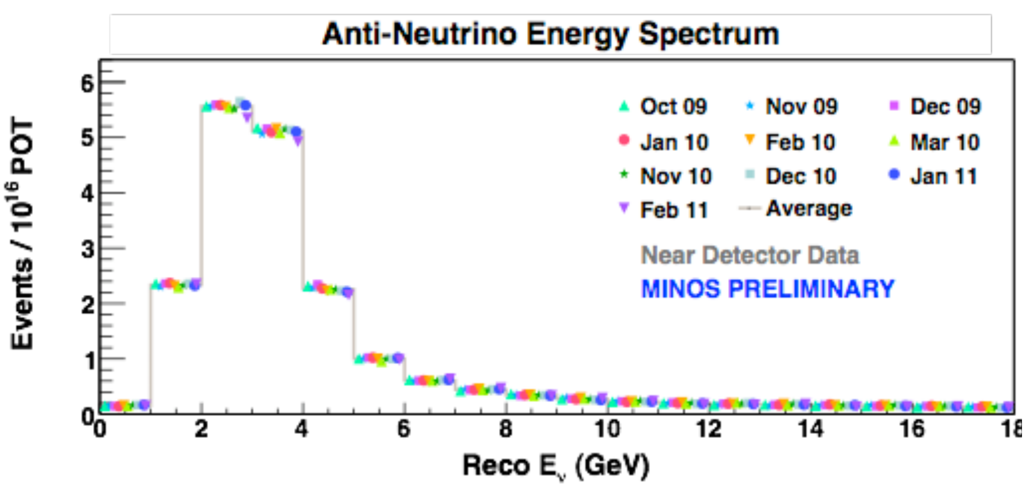
Plot on the right shows a comparison of statistical sensitivity contours for current antineutrino exposure with size of systematic uncertainties

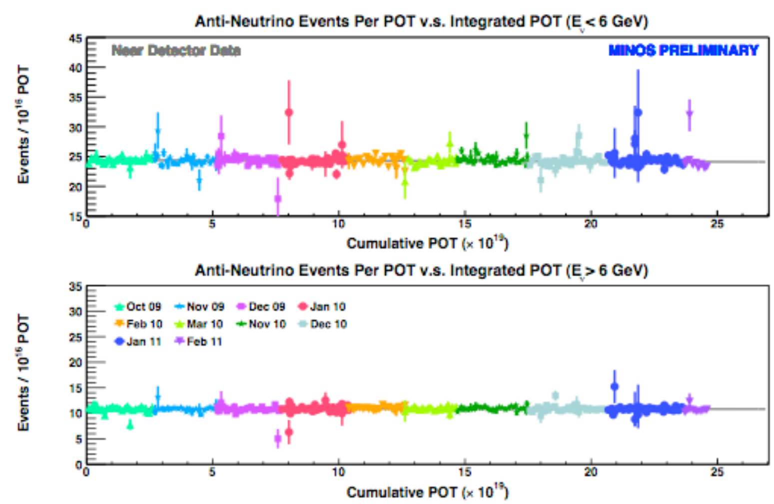
Still statistically-limited



Near Detector and data stability

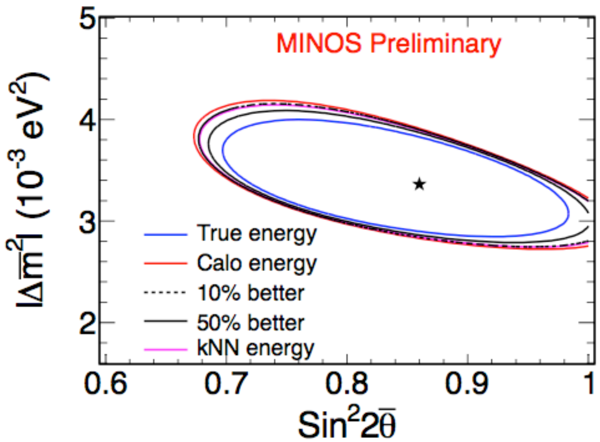


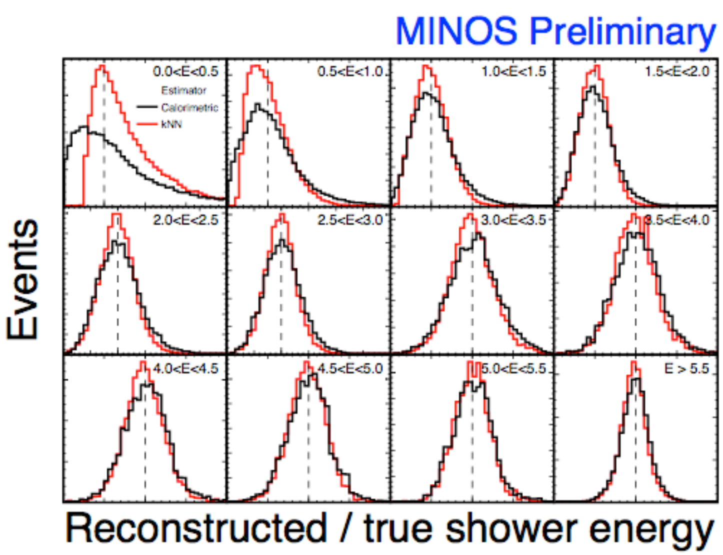




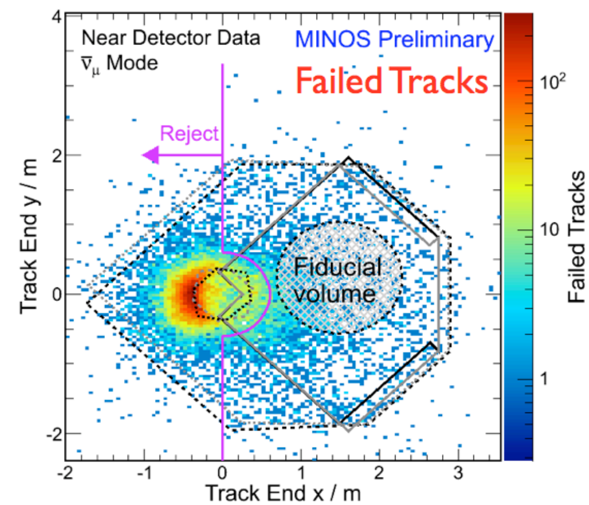
Anti-neutrinos in the anti-neutrino beam
Latest results (2011)

Anti-neutrino kNN shower estimate

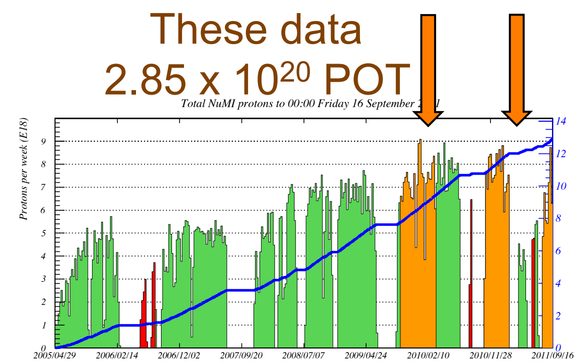




Remove all tracks ending near the coil
To improve MC and Data agreement



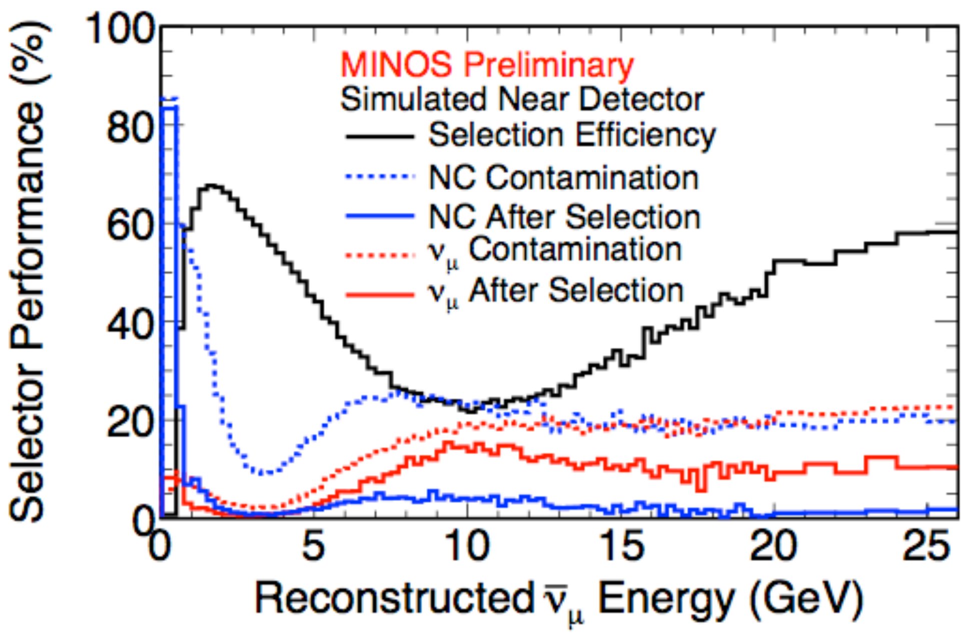
End positions of tracks failed by track fitter

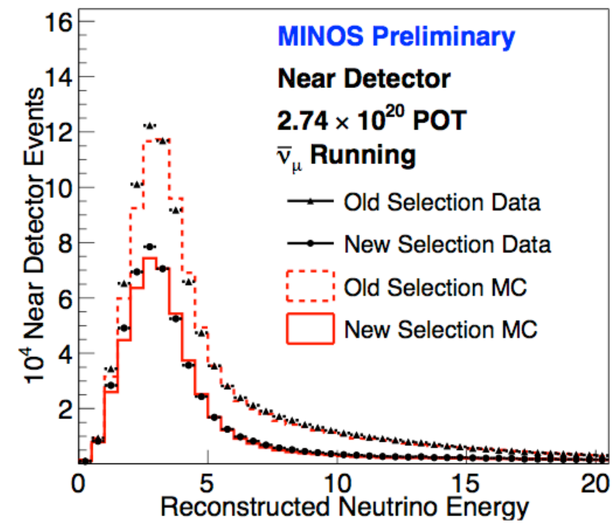


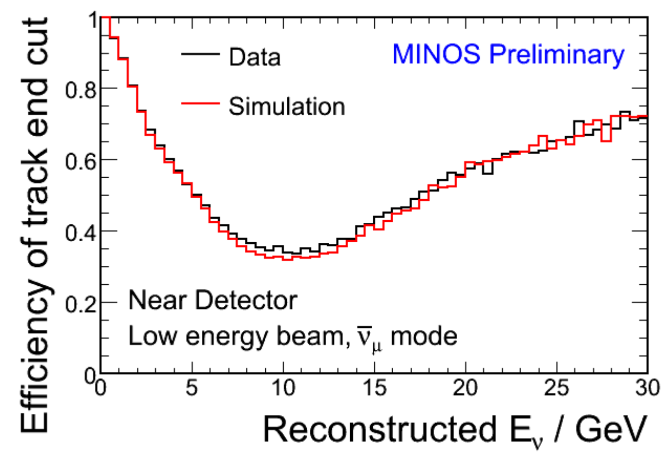
Start
2005

Now
2011

Efficiency and Purity of anti-neutrinos







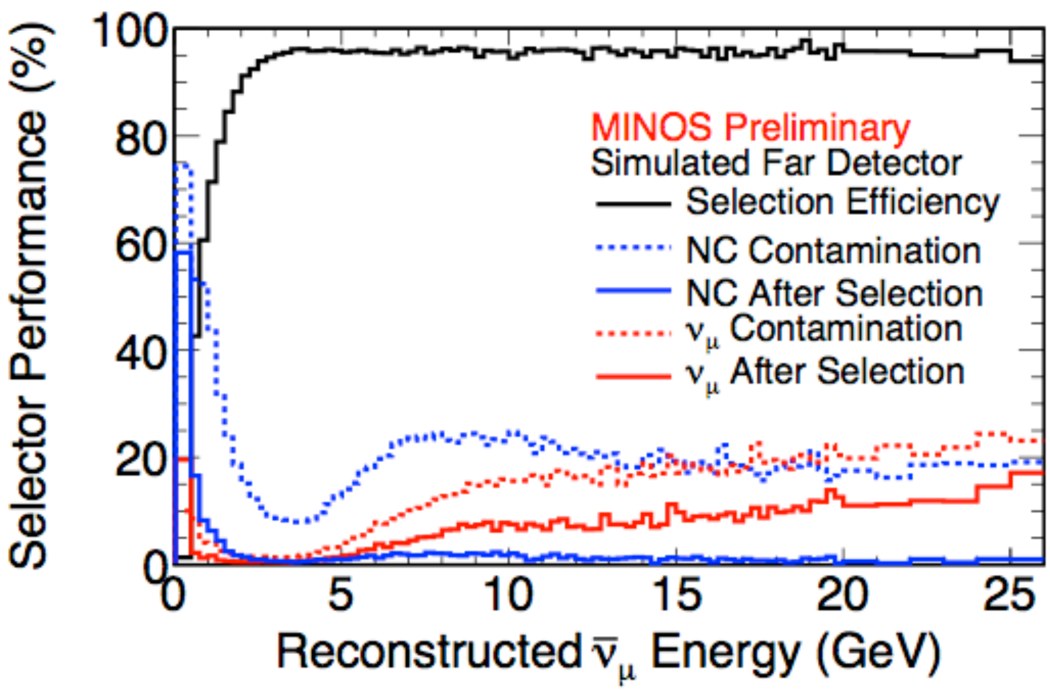
✓Broad dip in efficiency due to coil hole selection

✓53% integrated efficiency, 94% purity

✓Shape and magnitude of dip are well modeled by Monte Carlo

Far Detector anti-neutrinos

Antineutrinos in the Far Detector are selected in the same way as in the Near Detector, but no coil cut is applied

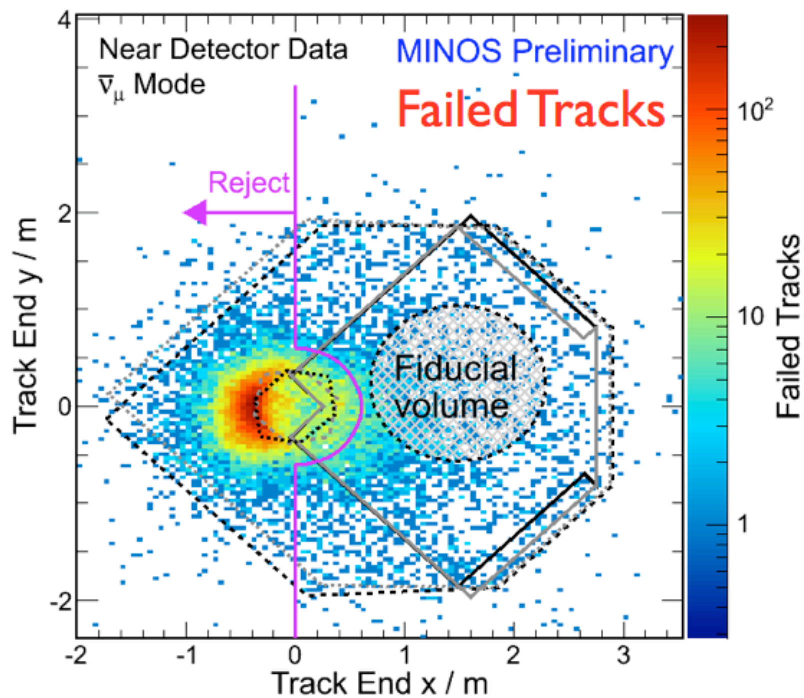


	Efficiency	Purity
0 - 6 GeV	96%	98%
6 -20 GeV	98%	91%
20-50 GeV	98%	78%
0-50 GeV	97%	95%

✓Overall efficiency in Far Detector is 97%, with 94% sample purity

✓Contamination at higher antineutrino energies does not affect oscillation measurement

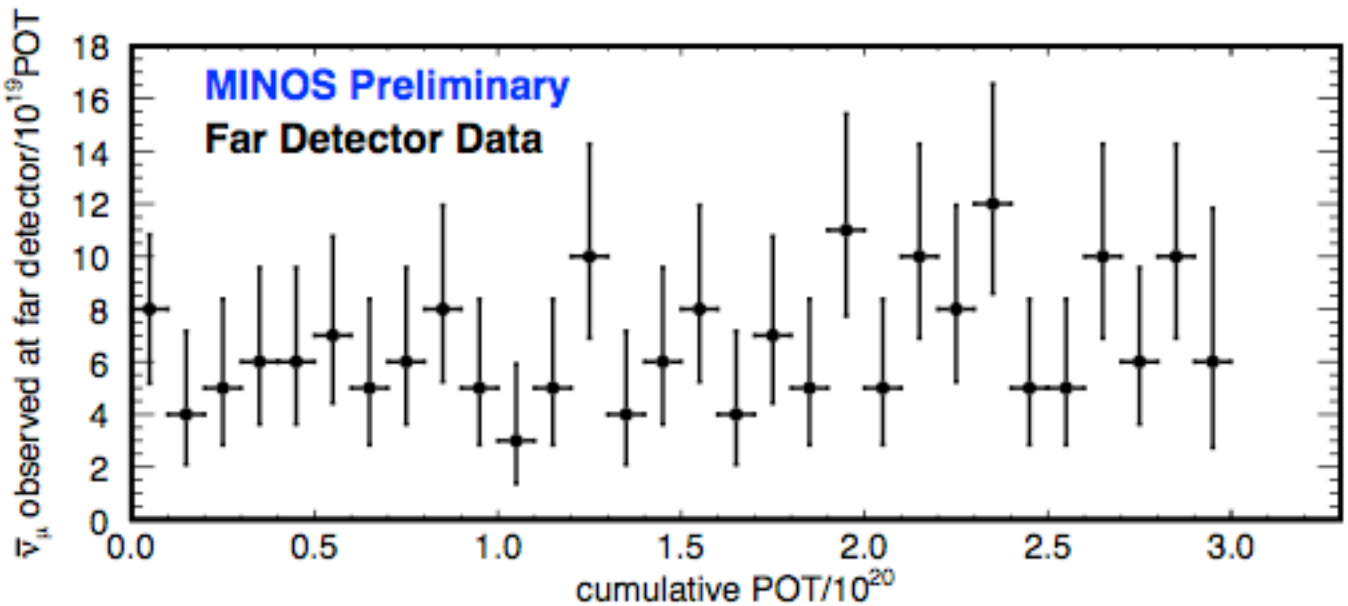
Coil hole selection



End positions of tracks failed by track fitter

- Track fitter occasionally fails
  - ⇨ Most failed tracks end near the coil
  - ⇨ ND coil difficult to model in MC
  - ⇨ 4.2% failures in MC, 6.1% in data
- Coil Hole Selection
  - ⇨ Remove all tracks ending near the coil
  - ⇨ Selection well modeled in MC
  - ⇨ After selection, failed tracks ~1% in both MC and Data
  - ⇨ Can safely remove fitter failures

Far Detector anti-neutrino rate vs exposure/POT

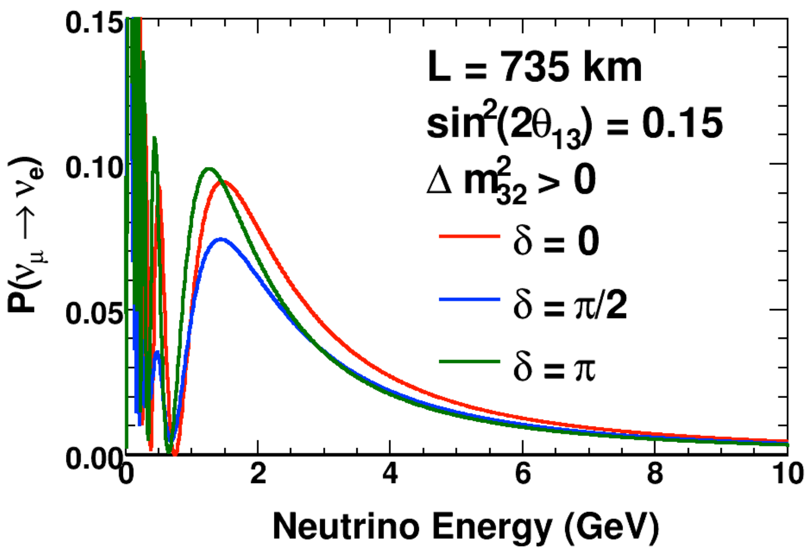


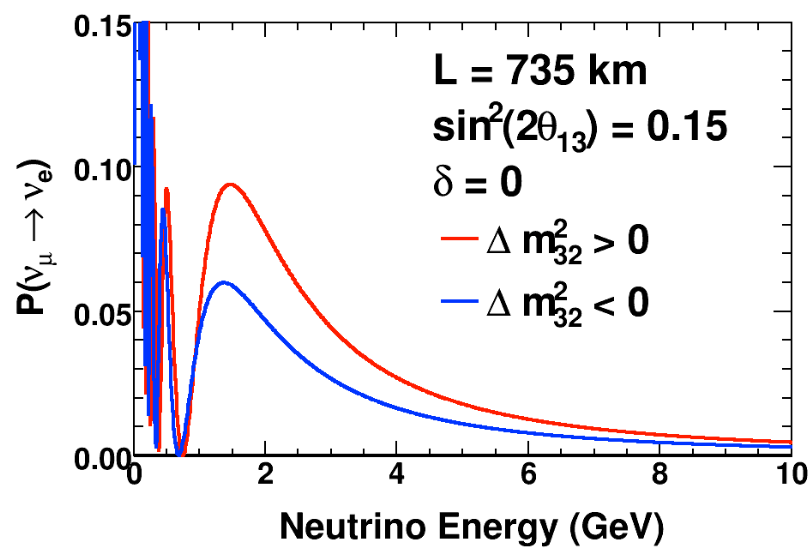
θ_{13} : electron-neutrino appearance probability

- The appearance probability $P(\nu_\mu \rightarrow \nu_e)$ dominant term

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

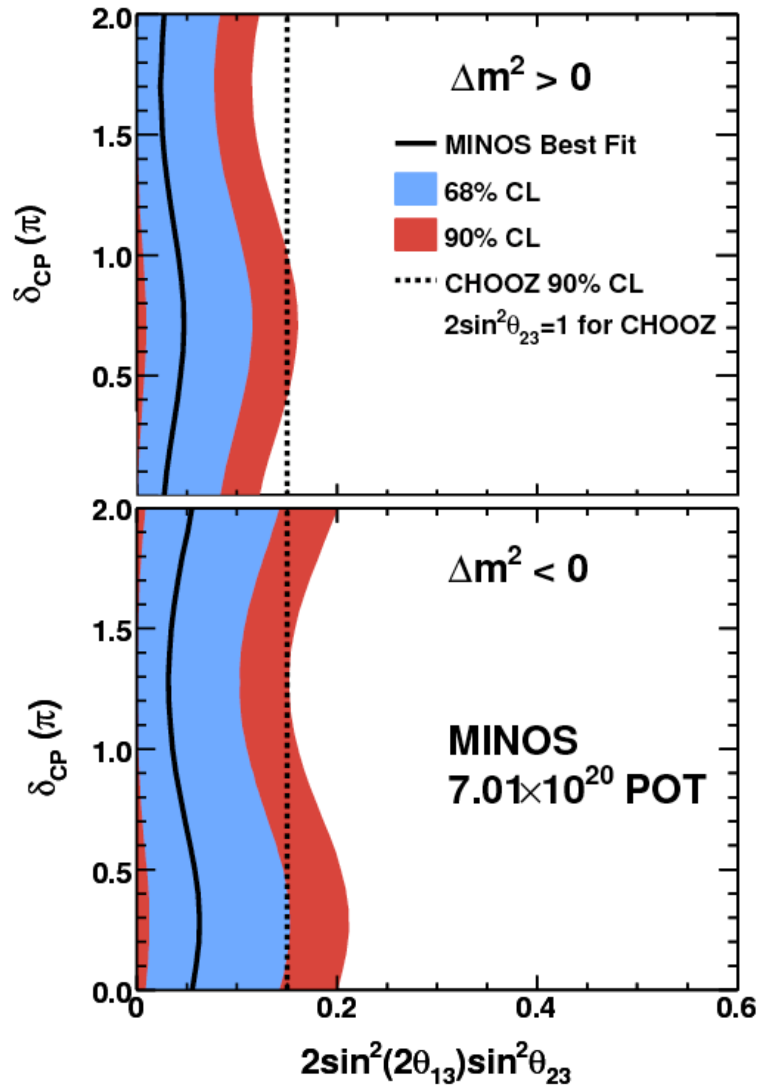
- … but it also depends on δ and mass hierarchy





Recent θ_{13} measurements

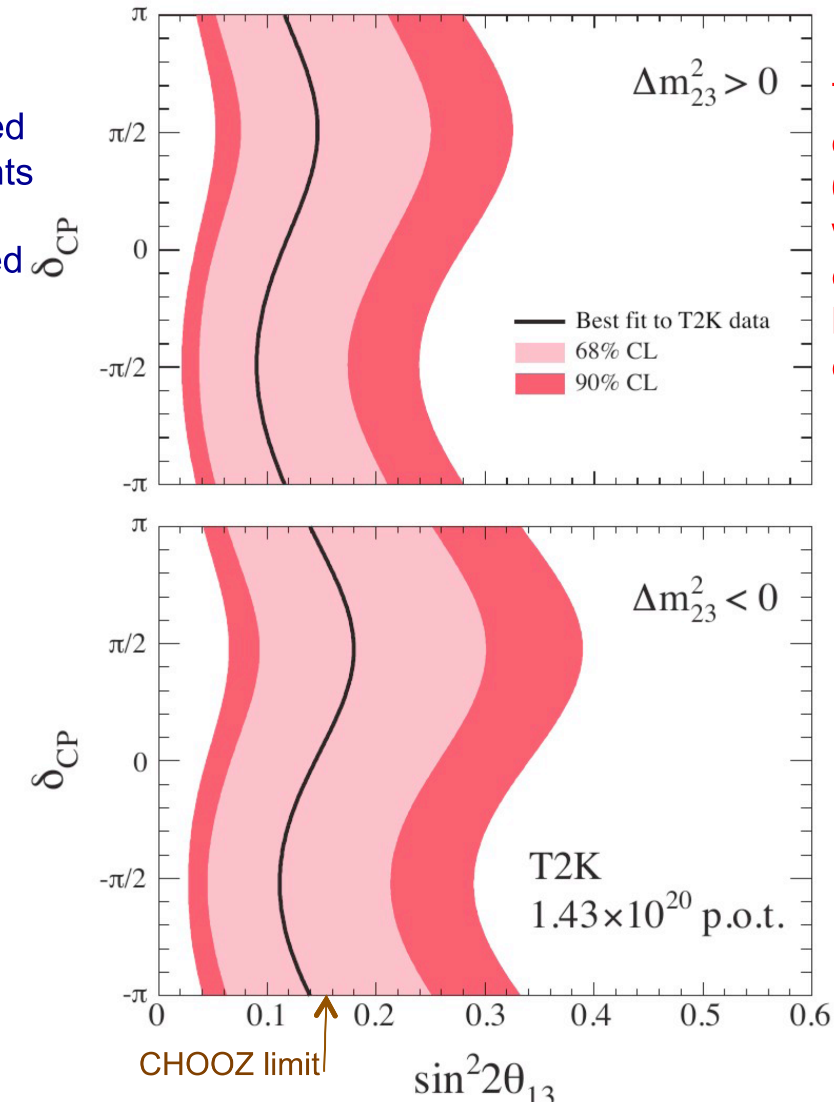
MINOS 2010



MINOS observed 54 events with 49 expected bkg events

PhysRevD.82.051102

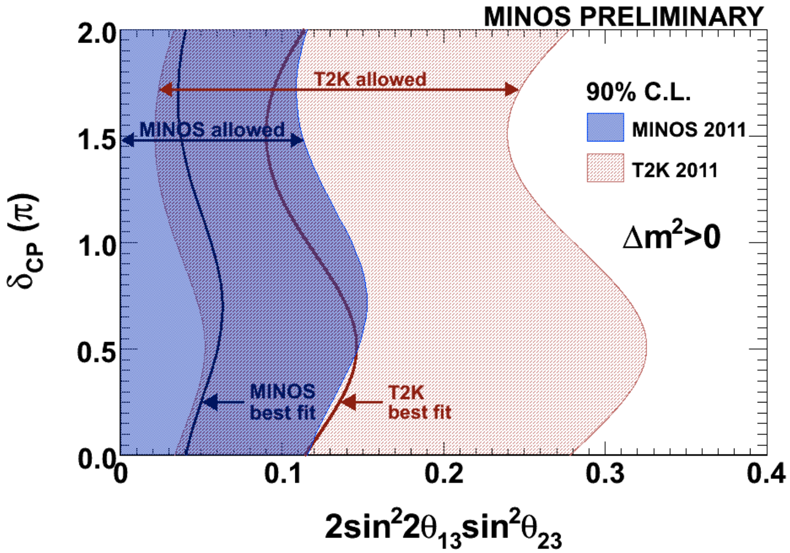
T2K 2011

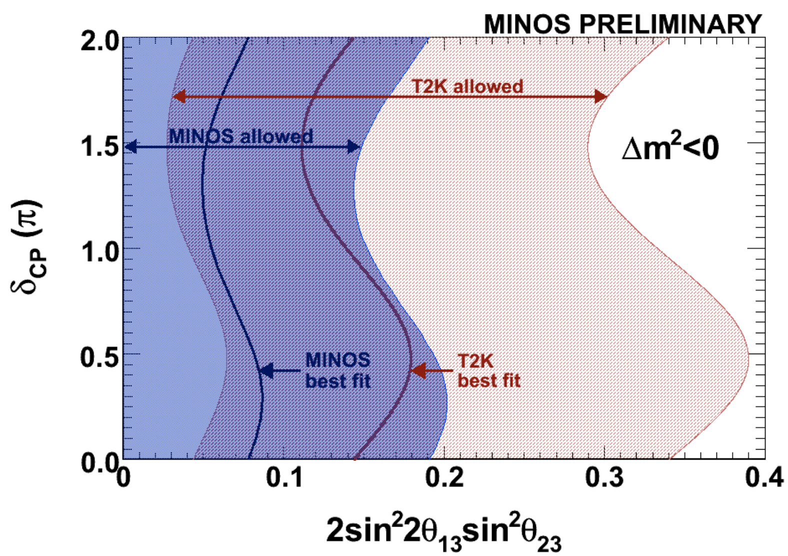


T2K observed 6 events with 1.5 expected bkg events

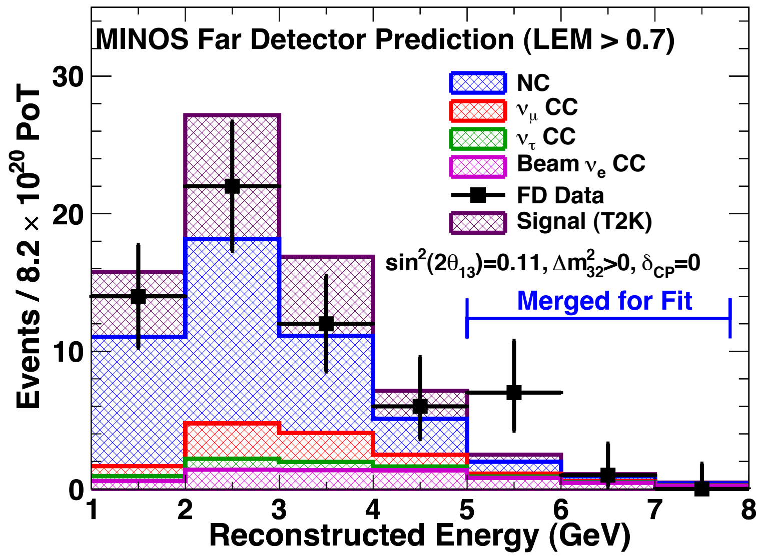
Phys. Rev Lett. 107 (2011) 041801 arXiv:1106.2822

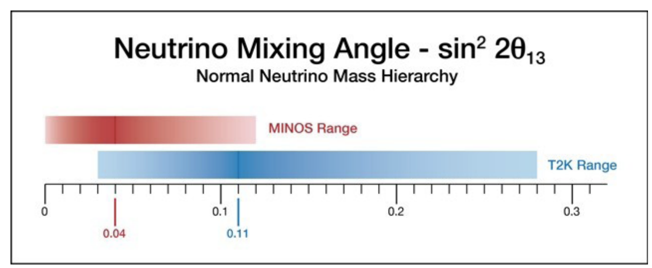
MINOS vs T2K

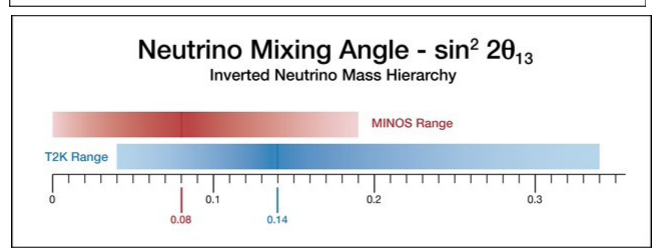




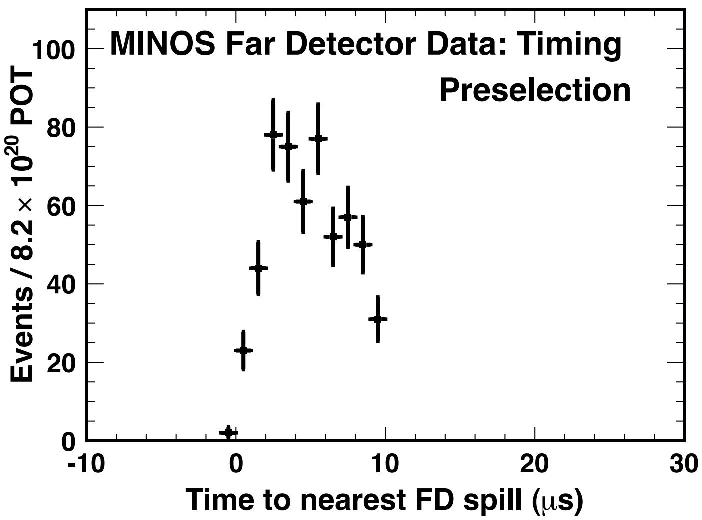
MINOS signal prediction at T2K's best fit ($\sin^2(2\theta_{13})=0.11$)

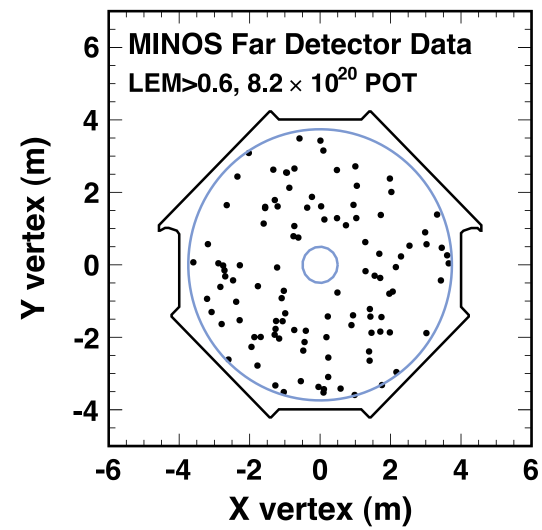


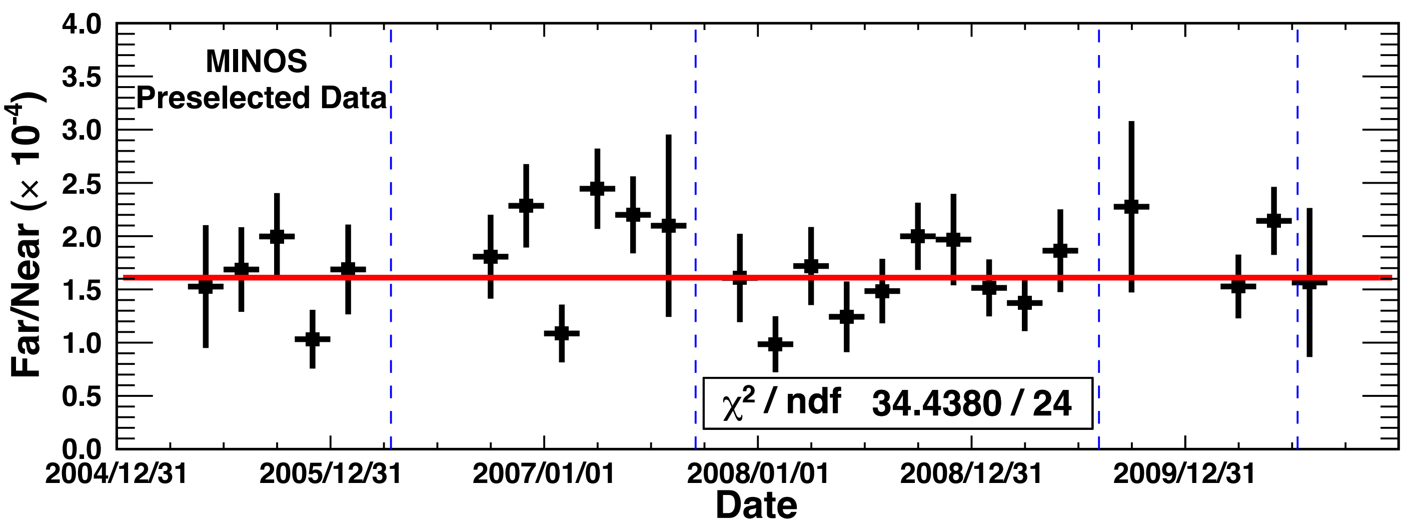




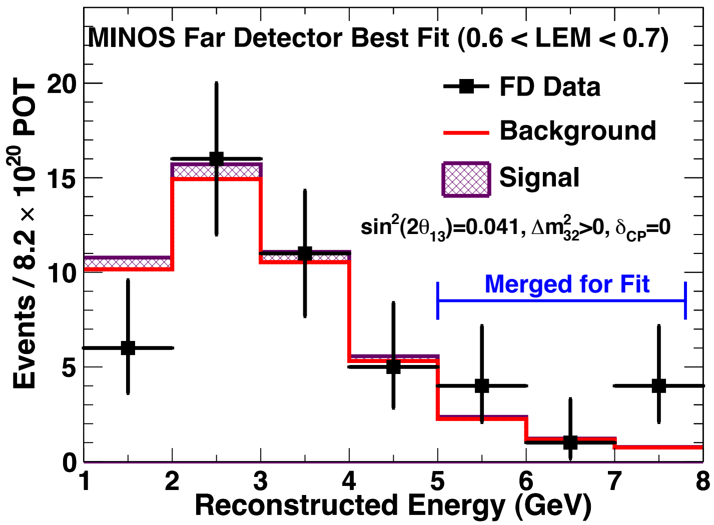
Far Detector preselected electron-neutrino candidate events

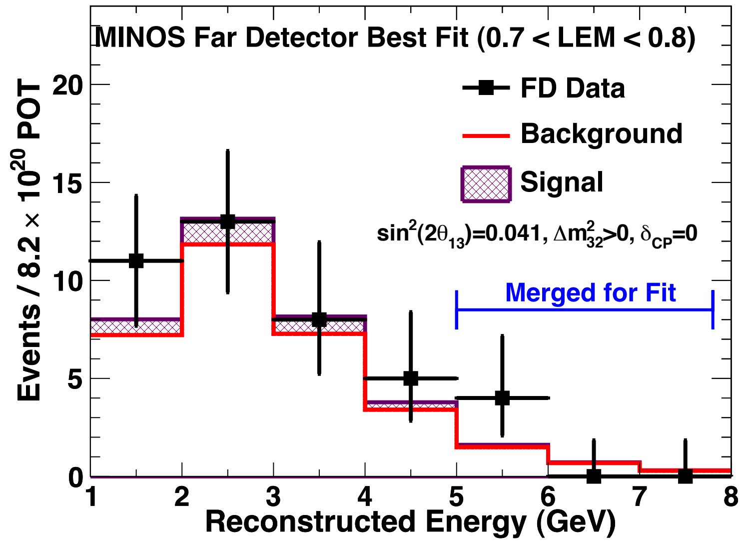


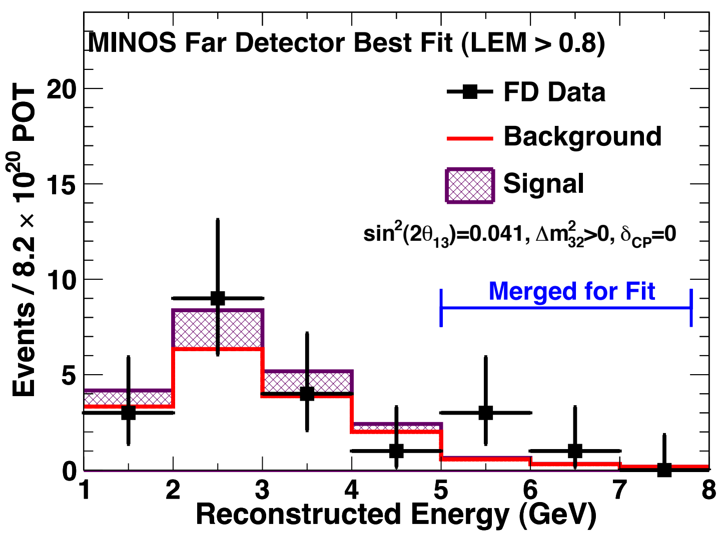




Best fit for ν_e appearance



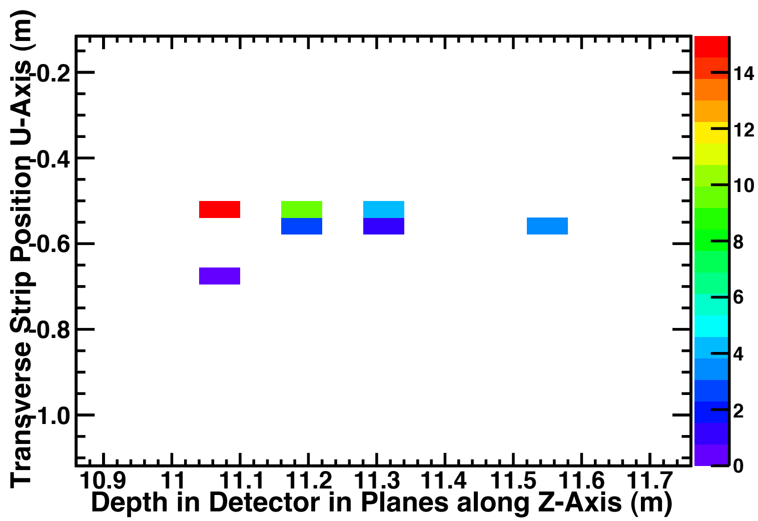


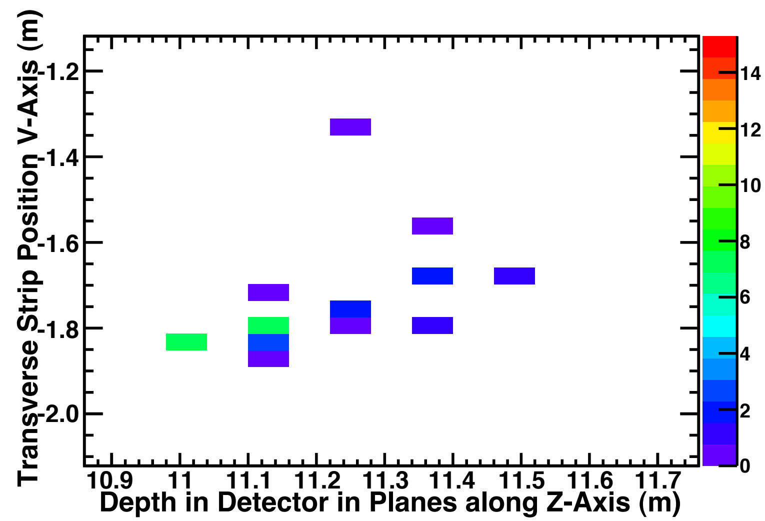


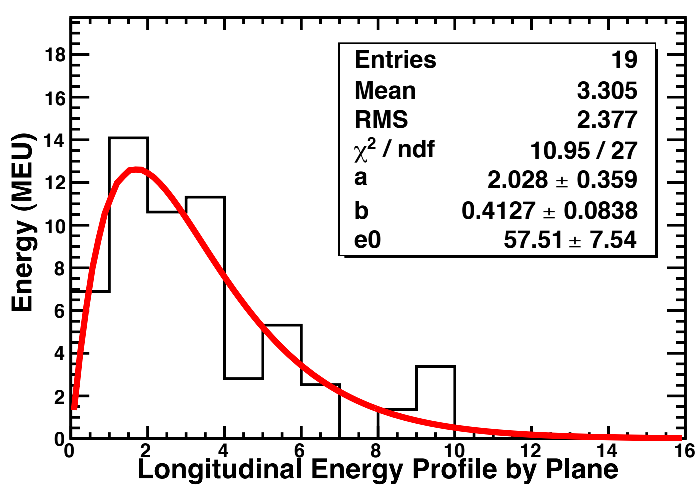
Best fit $\sin^2(2\theta_{13}) = 0.040$

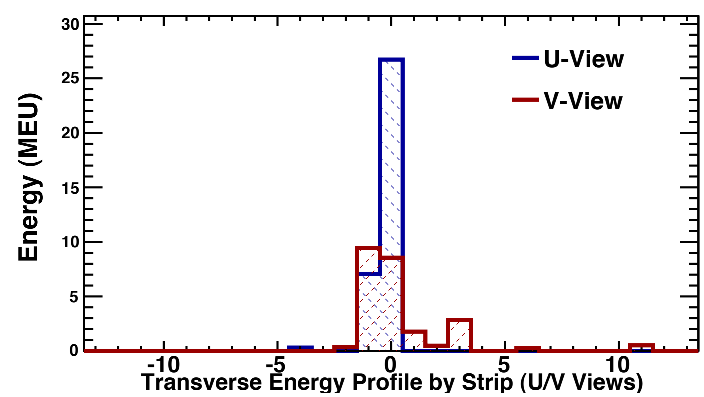
⇨ (Assuming $\delta=0$, $\theta_{23}=\pi/4$, normal hierarchy)

Electron-neutrino candidate



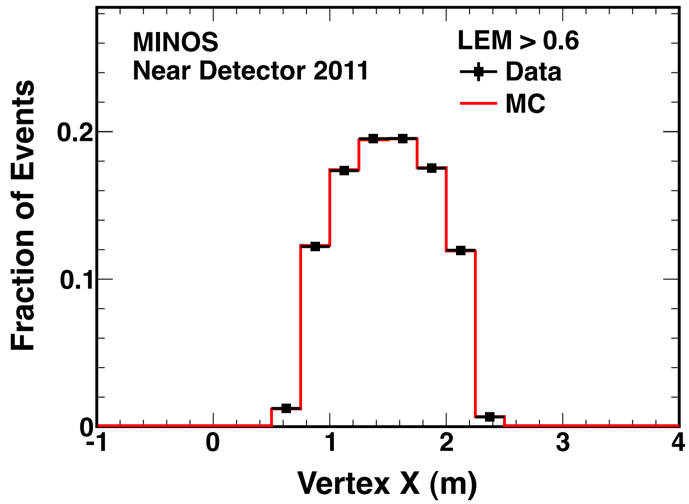


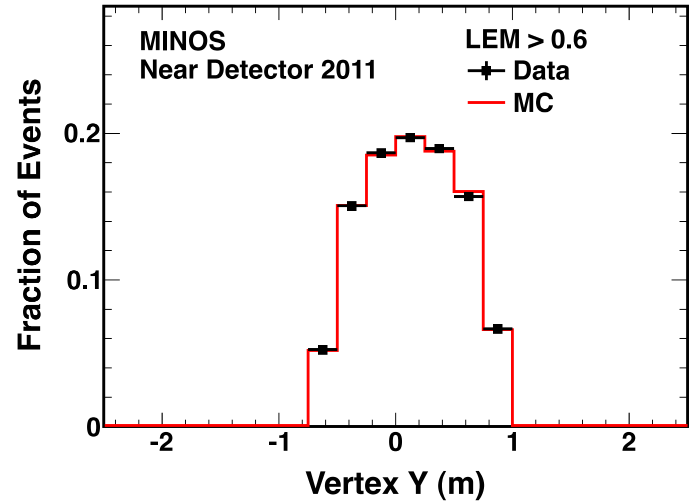


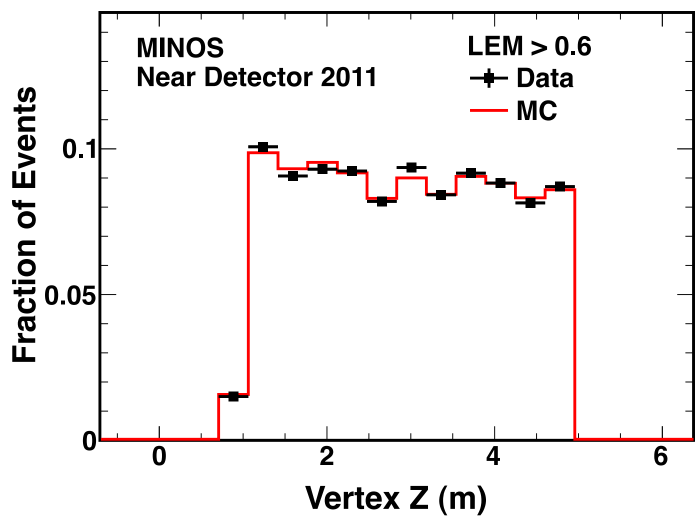


FD RUN = 37761	LEM PID = 0.91 *
EVENT ID = 13602	ANN PID = 0.98 *
Reco. Energy = 2.58 GeV	

Electron neutrino appearance

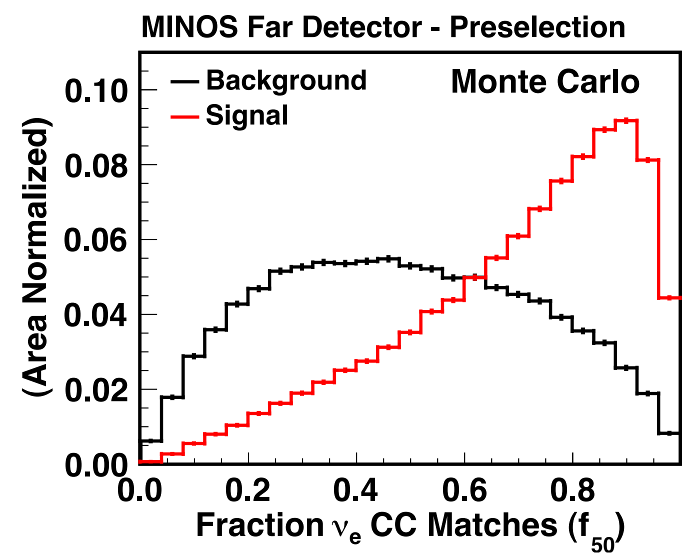


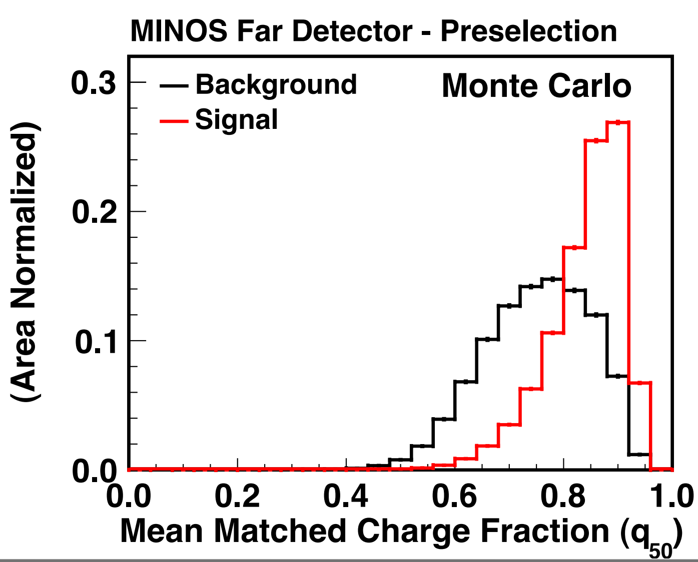


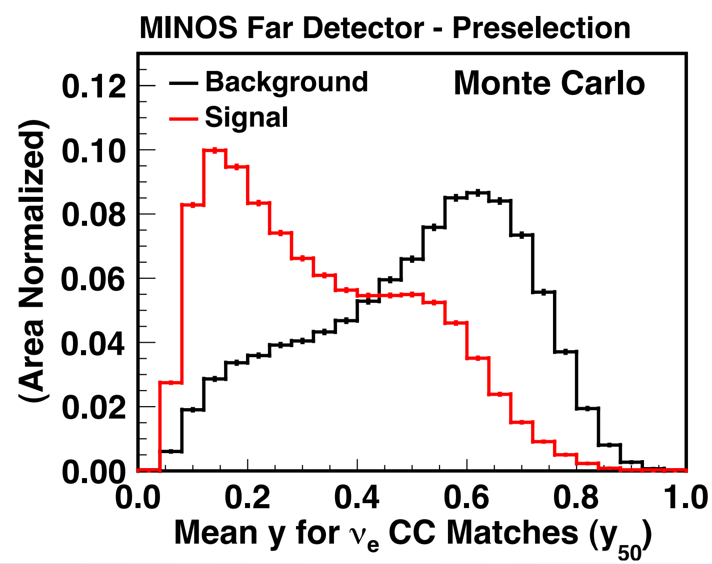


Use resulting 3 quantities to form an ANN

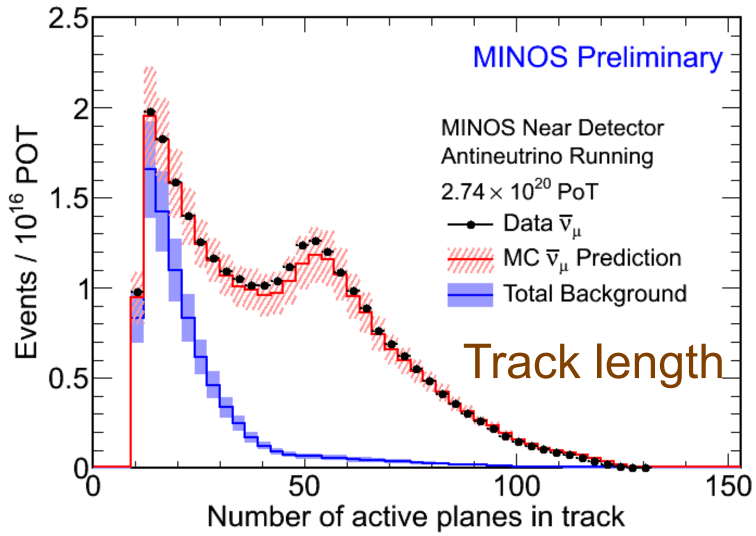
- Each input event is compared to the library events by calculating the likelihood that the photoelectrons in each event came from the same energy deposition.
  - ⇨ How many of the best matches are signal?
  - ⇨ How well do the charges overlap between the input event and the best matches?
  - ⇨ How EM-like is the shower in the best matches? *y = fraction of ν energy in the hadronic shower)*

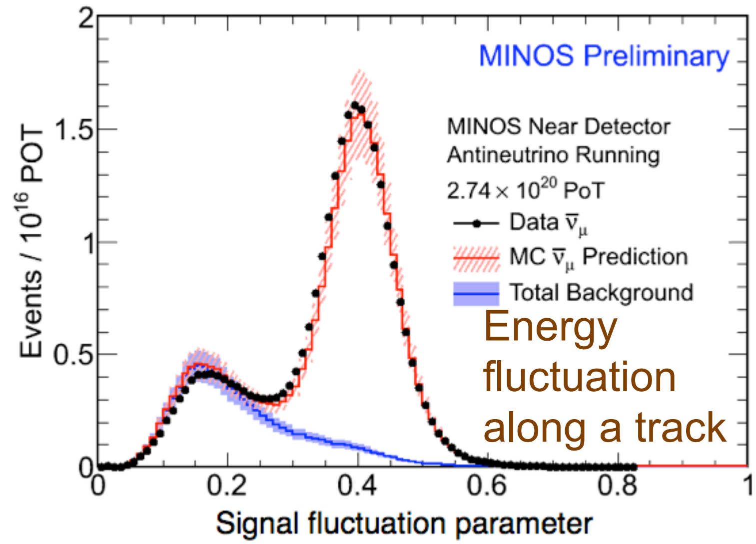


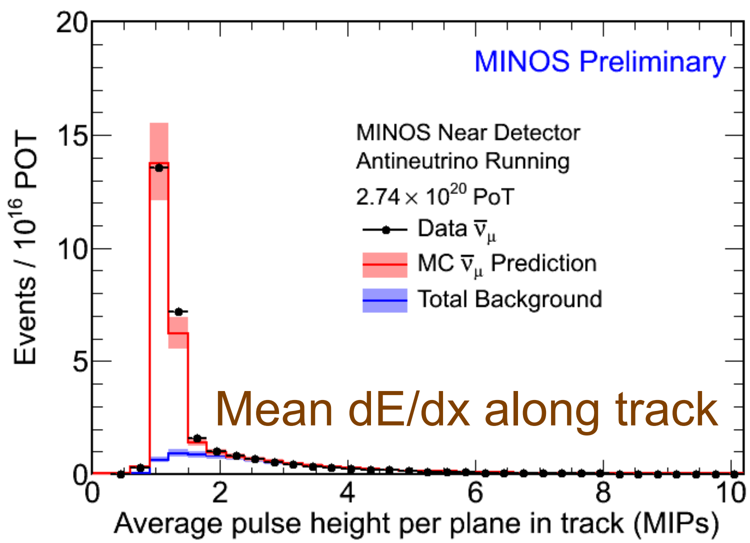


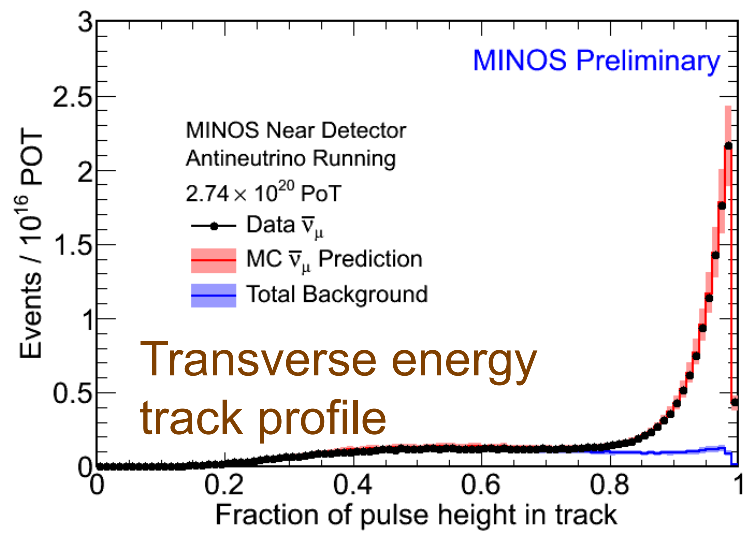


CC – NC separation (anti-neutrinos)









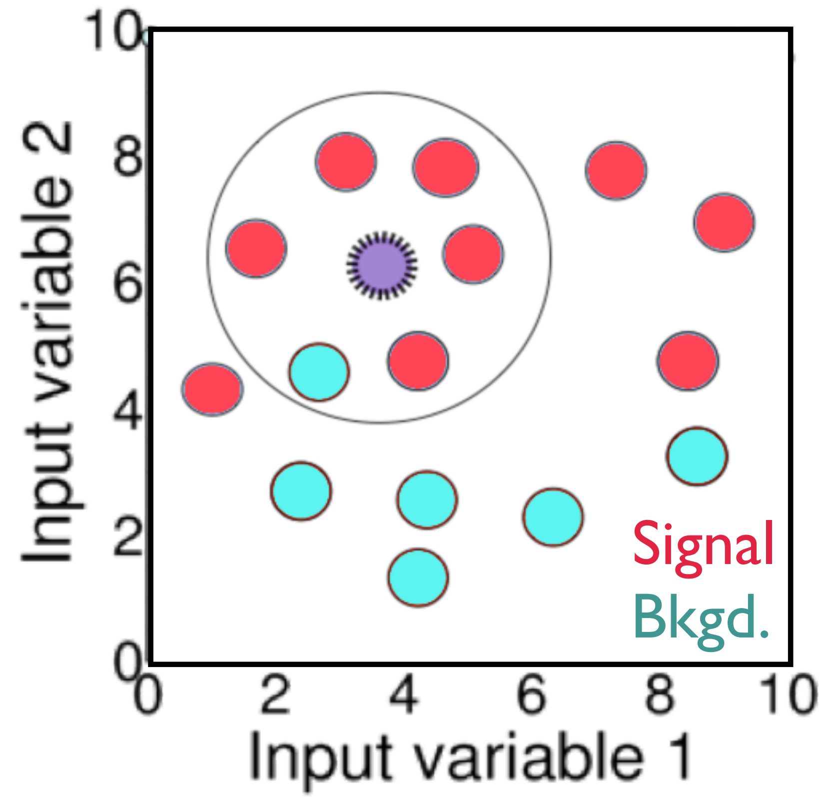
K Nearest Neighbor discriminant

- Store MC events of two types (NC & CC) with their N distinguishable features in a static library of N-dim space. (left example w/ N=2)

$$D_{Q\to MC} = \sum_{i=1}^{N} \sqrt{(x_Q^i - x_{MC}^i)^2}$$

- Count number of CC event out of those k nearest, i.e and the PID track for that query event is

kNN example with 2 variables



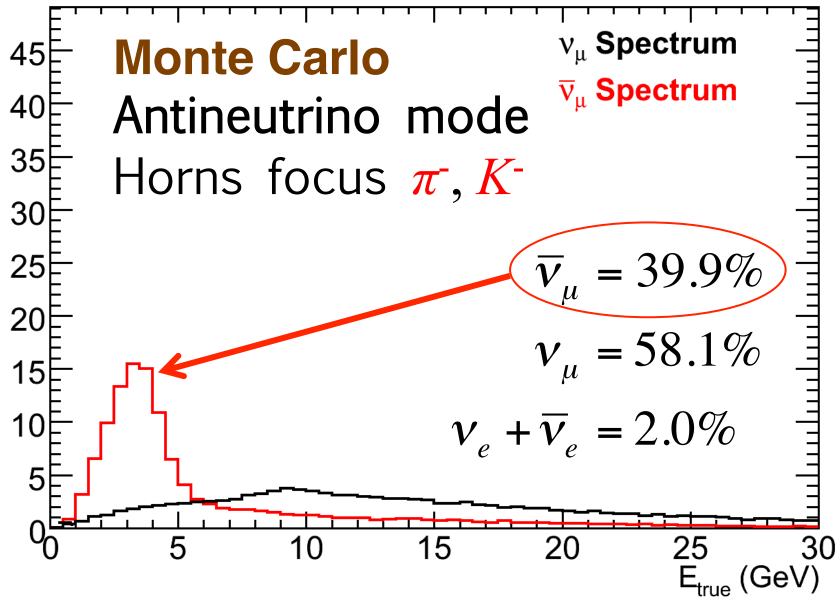
$$\text{kNN separation variable} = kNN_{ID} = \frac{k_S}{k_S + k_B} = \frac{k_S}{k}$$

- In MINOS:
  - ⇨ N = 4
  - ⇨ k = 80

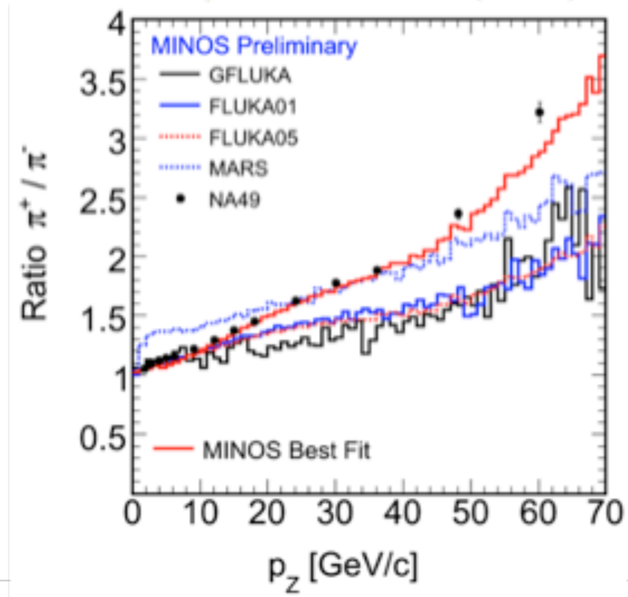
Here: $k=6$, $k_S=5$, $k_B=1$ ⇒ $kNN_{ID}=5/6$

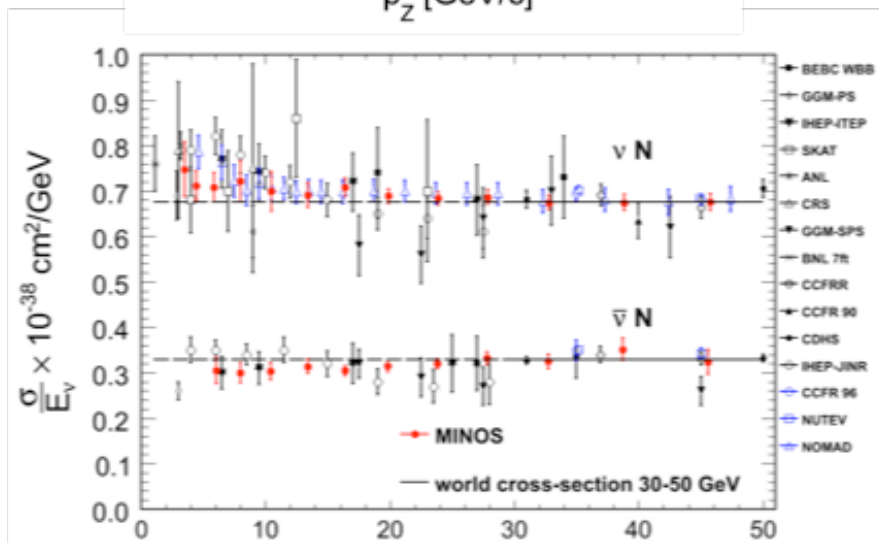
Anti-neutrinos in the anti-neutrino beam

Near Detector MC



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





Phys. Rev. D 81 072002 (2010)

Anti-neutrino statistics poorer :

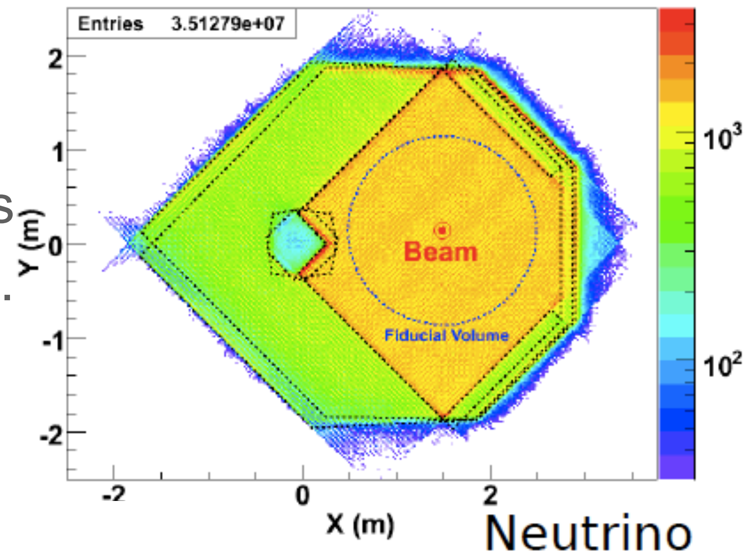
- x 1.3 from lower π^- yield
- x 2.3 from lower anti-neutrino cross-section

Neutrino and anti-neutrino cross-section (PRD in the works)

- Based on 2.45×10^{20} POT (LE beam) [June 2005 – April 2007]
- Based on 1.94×10^{6} (3-50 GeV) neutrinos and 1.59×10^{5} (5-50 GeV) anti-neu.
- use

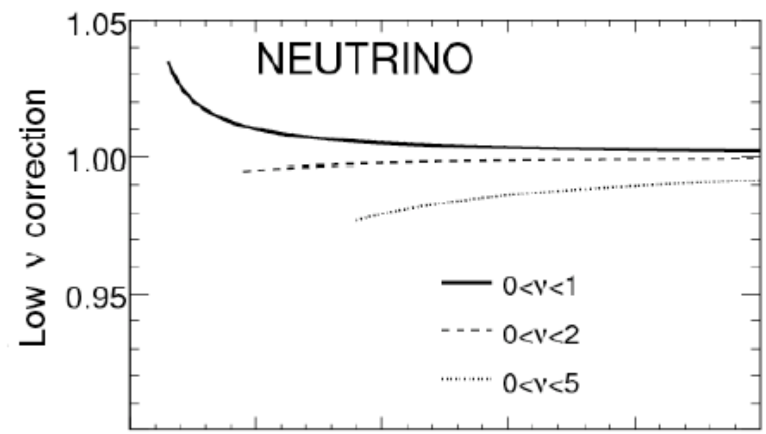
$$\frac{d\sigma}{d\nu} = A\left[1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{2A}\frac{\nu^2}{E^2}\right]$$

$d\sigma/d\nu \rightarrow$ constant as $\nu/E \rightarrow 0$

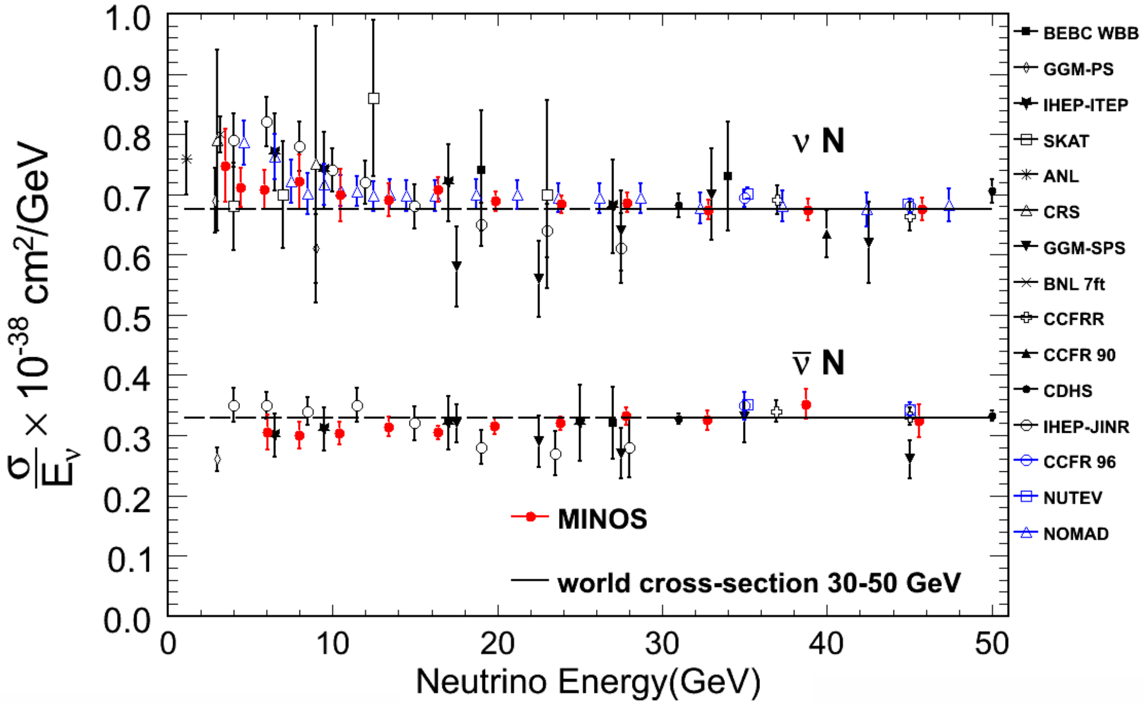


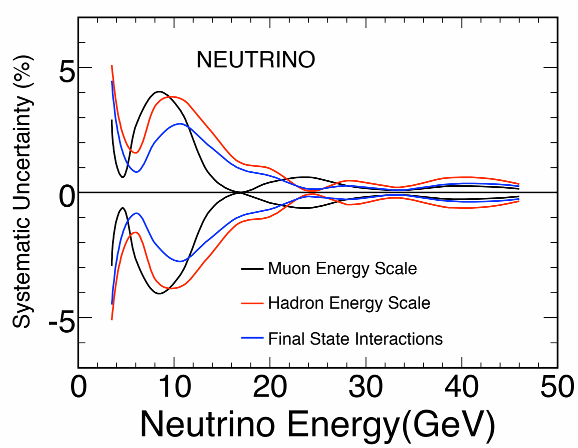
Neutrino Tomography!

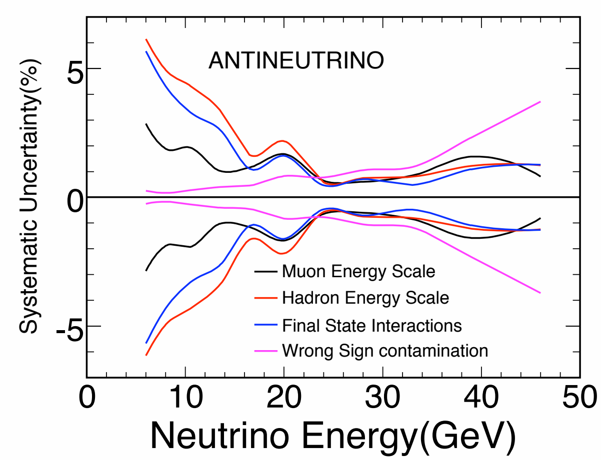
- Constrain data 30-50 GeV to the world average
- Use NEUGEN Monte Carlo for
  - ⇨ acceptance
  - ⇨ finite ν/E, QEL, RES part



Final results





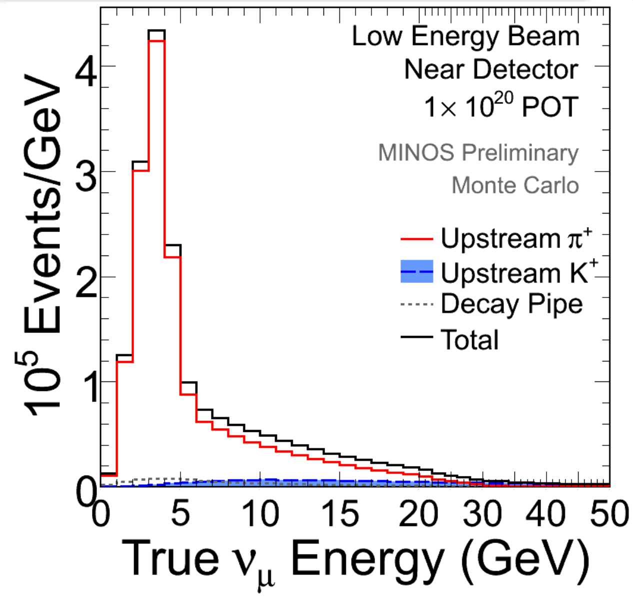


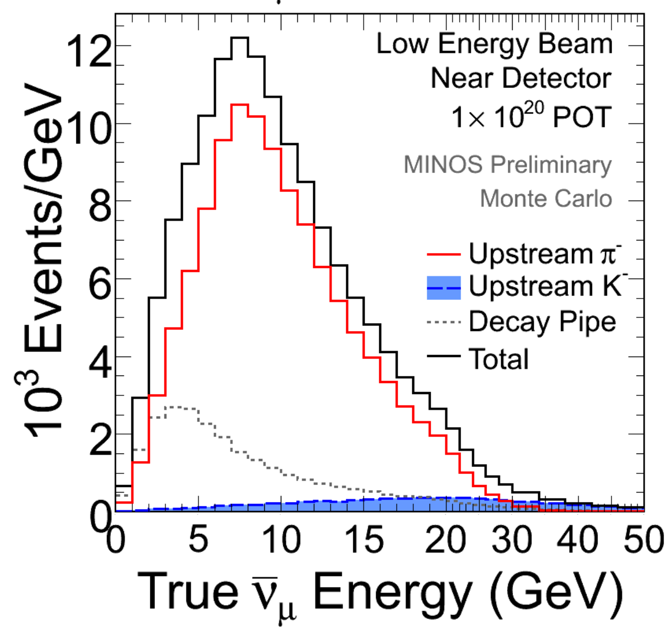
Where do the ν_μ and $\bar{\nu}_\mu$ originate?

- ν_μ originate almost entirely from π^+ produced upstream of decay pipe

- $\bar{\nu}_\mu$ spectrum has significant components that originate from:
  - ⇨ Upstream produced K^-
    - constrained by external hadron production data
    - K^0 < 1% of total
  - ⇨ μ^+ from π^+ (small and well constrained)
  - ⇨ Interaction of primary protons and secondary hadrons downstream
    - Decay pipe production in walls

- Due to different solid angle acceptances for the two detectors, the upstream and downstream fractions are different at the two locations

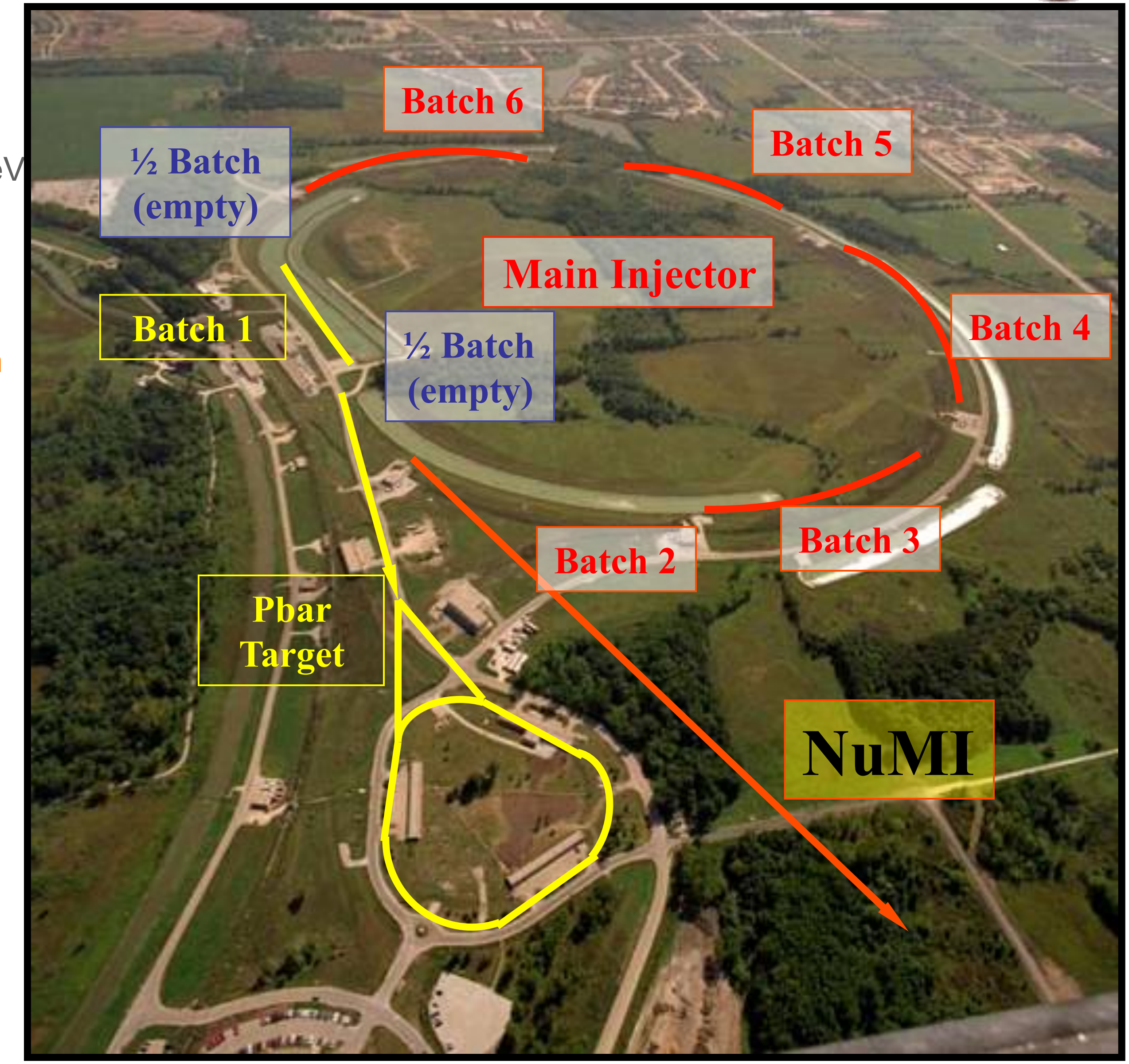




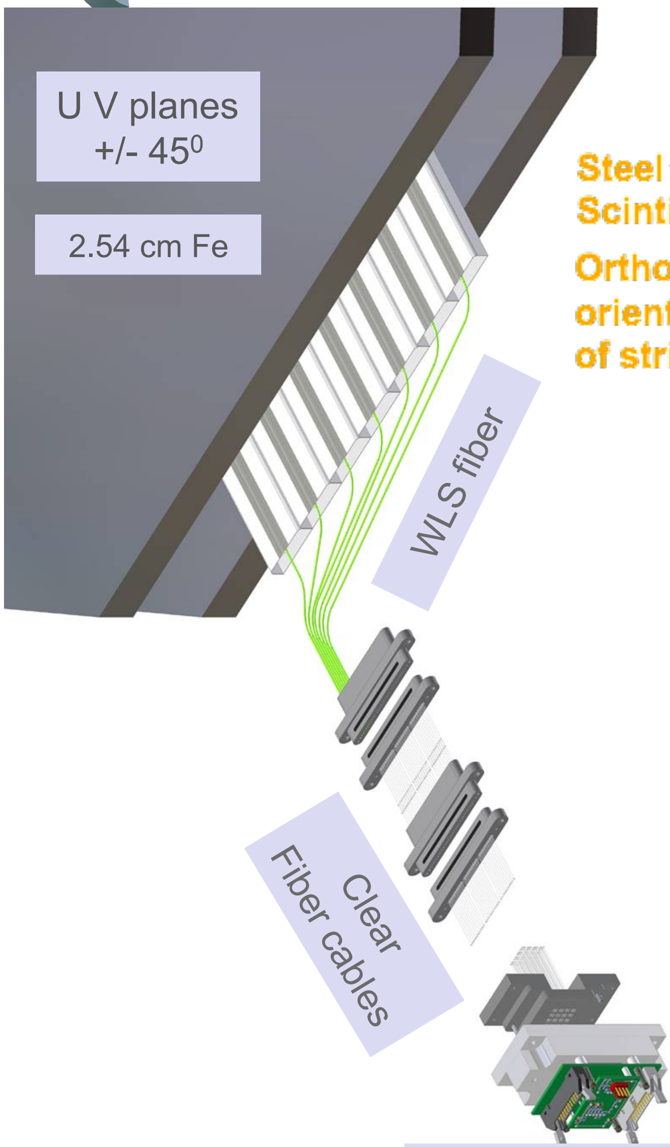
Beam: a how to

(Main Injector = MI)

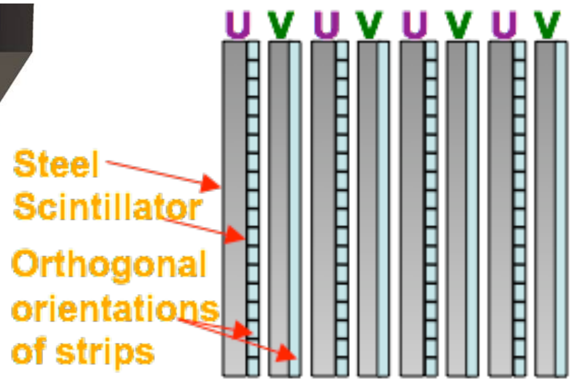
- MI is fed 1.56 μs batches from 8 GeV Booster
  (MI ramp time ~1.5sec)
- NuMI designed for
  - ➔ 8.67 μsec single turn extraction
  - ➔ 4×10^{13}ppp @ 120 GeV
  - ➔ 1.9 second cycle time
  - ➔ beam power ~400kW
- Typical performance to date:
  - ➔ 3.2×10^{13} ppp @ 120 GeV
  - ➔ 2.2 second cycle time
- Achieved records:
  - ➔ 3.7×10^{13} ppp @ 120 GeV
  - ➔ 2.0 second cycle time
  - ➔ 320 kW

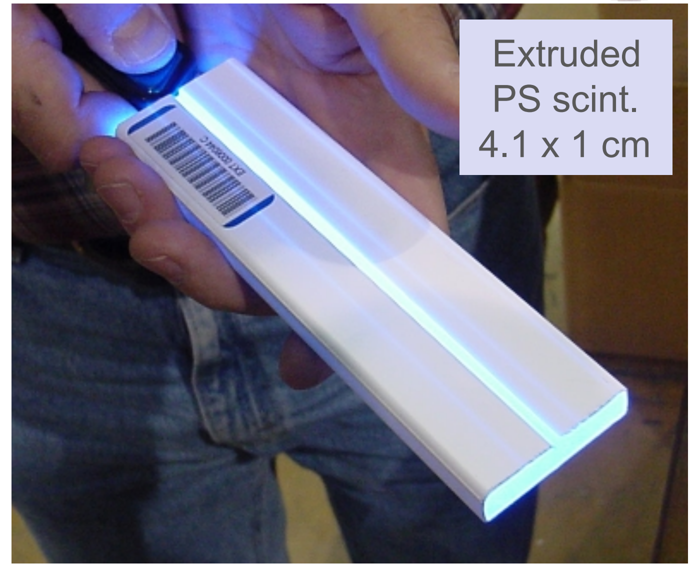


“MINOS technology”



Multi-anode PMT

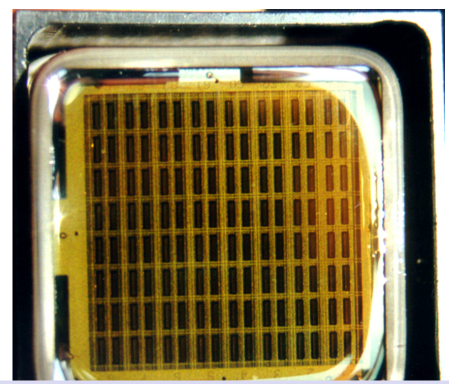




Far Det

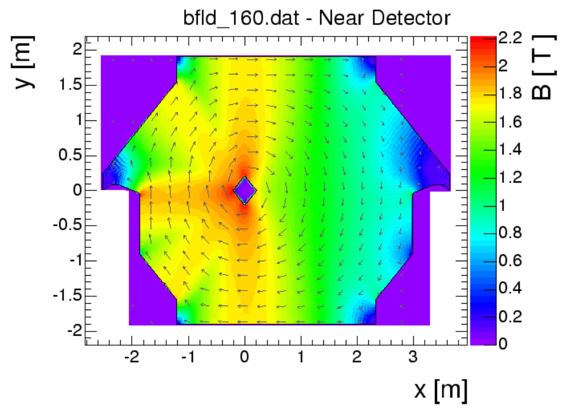
M16 8 fibers/pixel

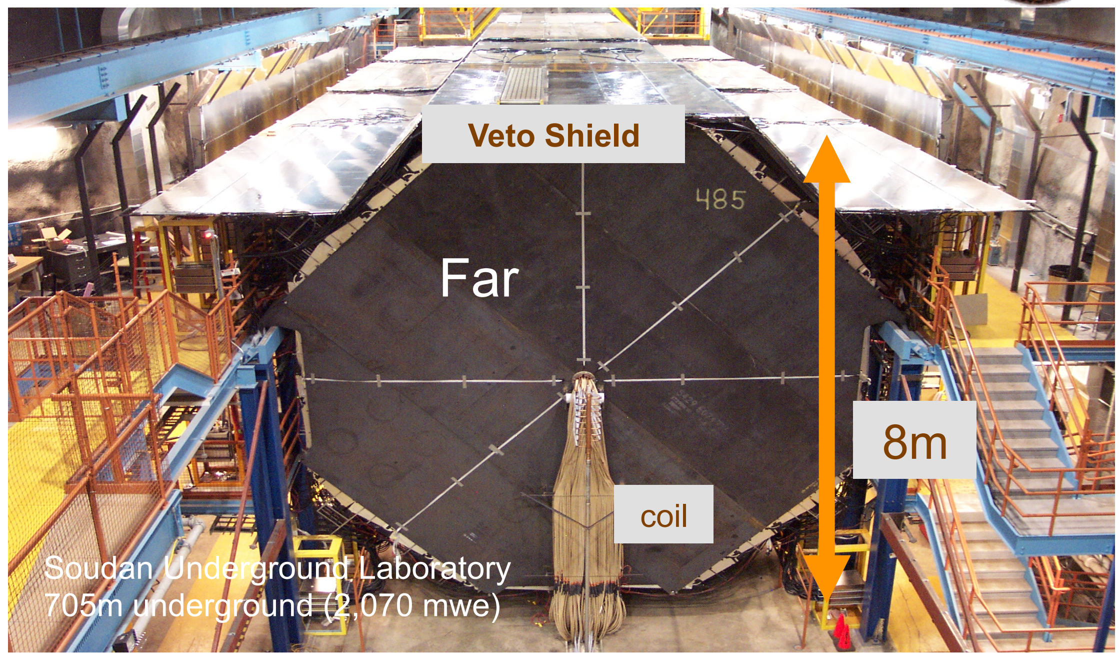
Near Det

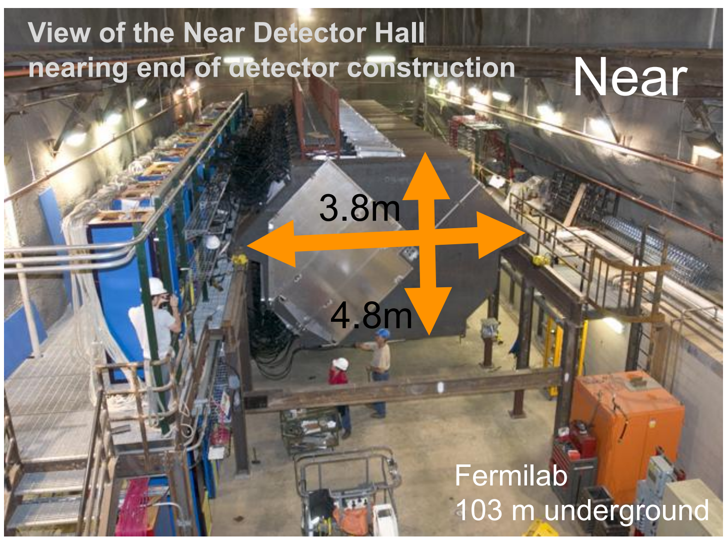


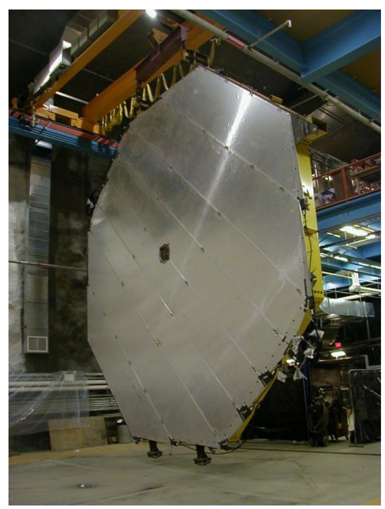
M64 1 fiber/pixel

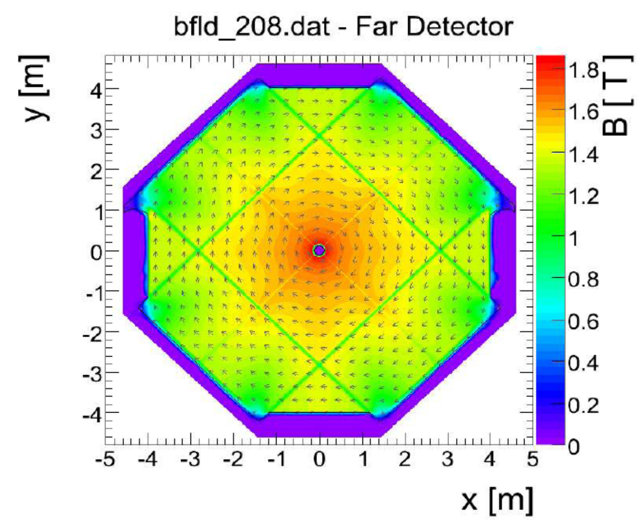
Near and Far Detectors







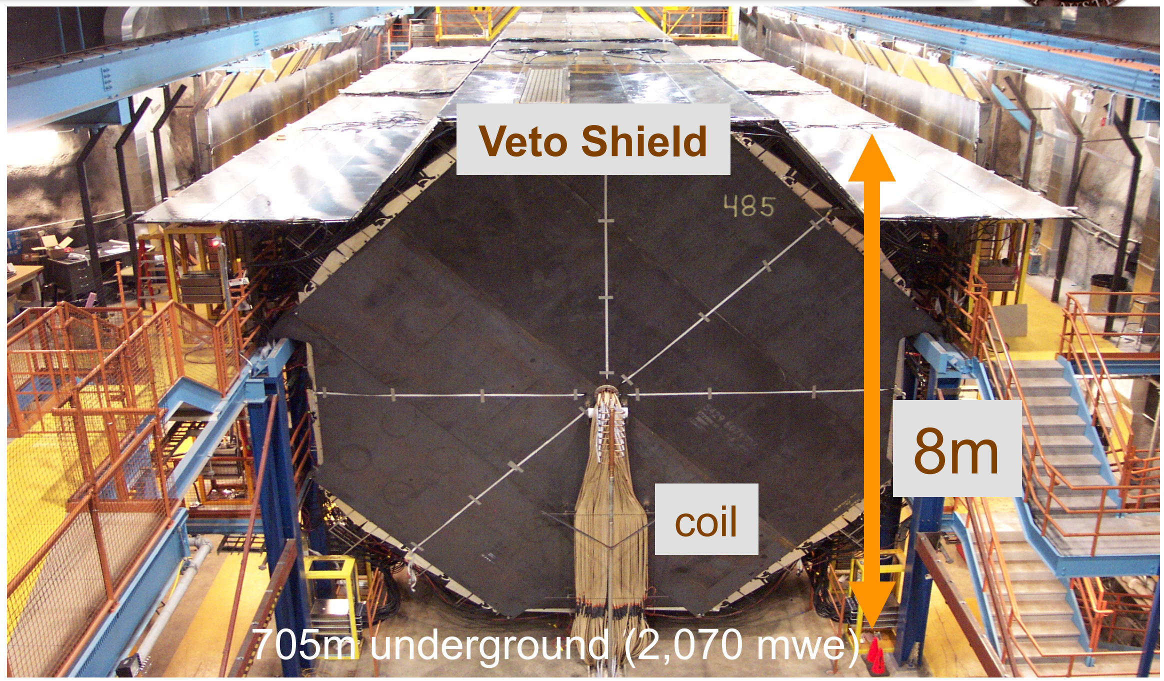


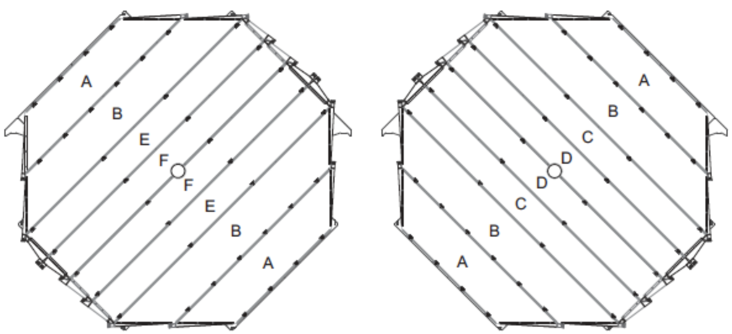


Far Detector – 735.3 km away
(Soudan Mine, Mn)

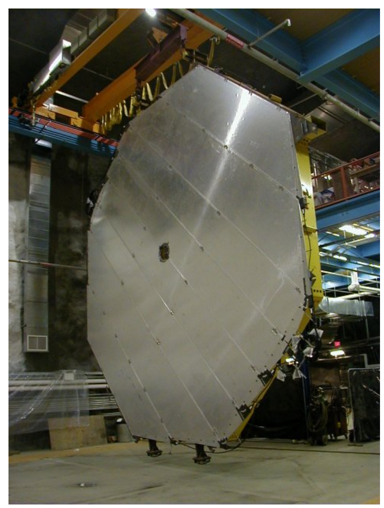
Running since July 2003

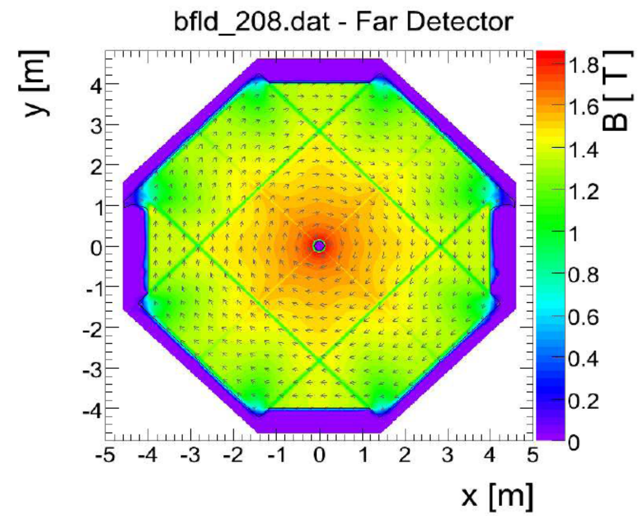
- 2 Supermodules
- 5.4 kT
- 484 scint. planes
- CR veto shield (2,070mwe)
- B ~ 1.5T (R=2m)
- 93,120 strips (4.1 x 1.0 cm)
- 8-fold MUXed 2-ended readout
- 1551 M16s
- 722 km of WLS fiber
- 794 km of clear fiber
- HAD = 56% / E $^{1/2}$
- EM = 23% / E ^{½}





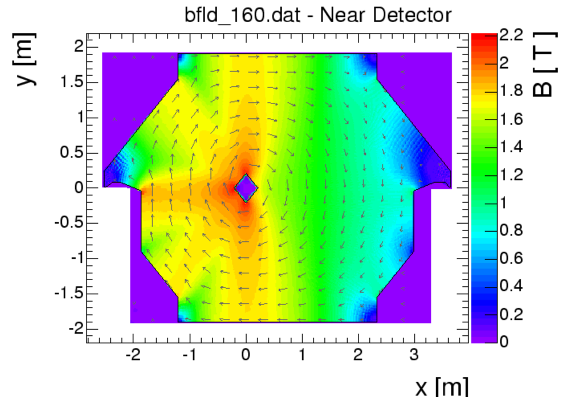
Scintillator Plane
(8 modules, 192 strips)





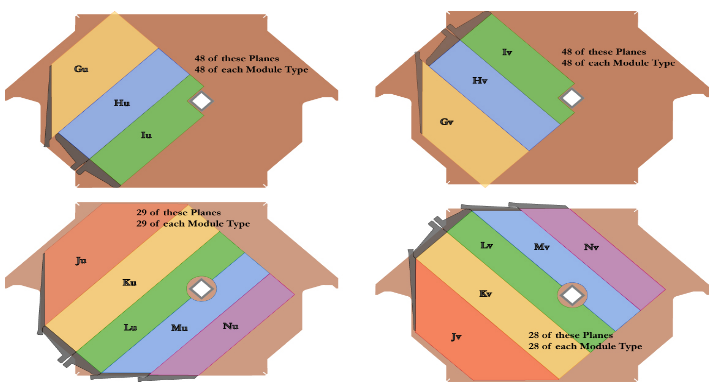
Near Detector – 1,040 m from the target at Fermilab

- veto - target - μ spectrometer
- mass = 1 kT
- 153 scintillator planes
- QIE-based front-end
- 3.8 x 4.8 “squeezed” octagon
- 12,300 scint.strips
- 1-end readout
- no-multiplexing
- 220 M64s
- 282 steel planes
- 65 km WLS fiber
- 51 km clear fiber

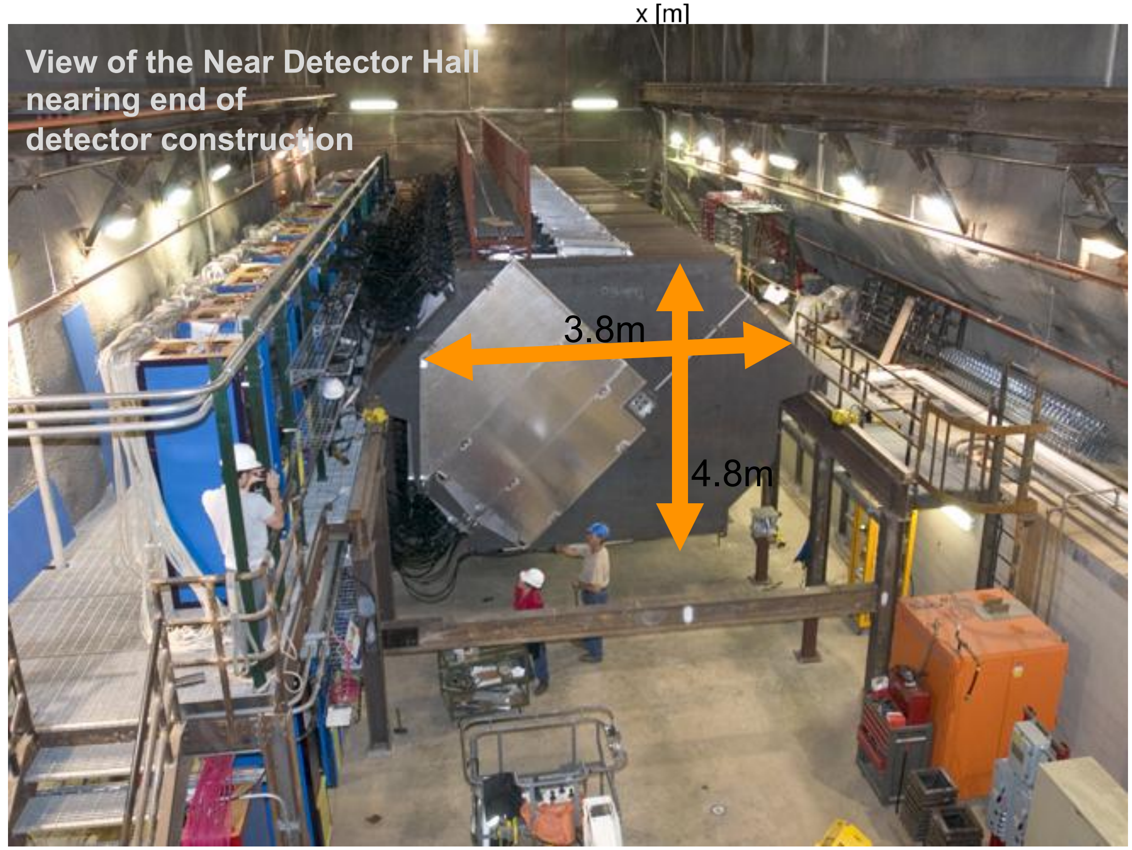


103 m underground

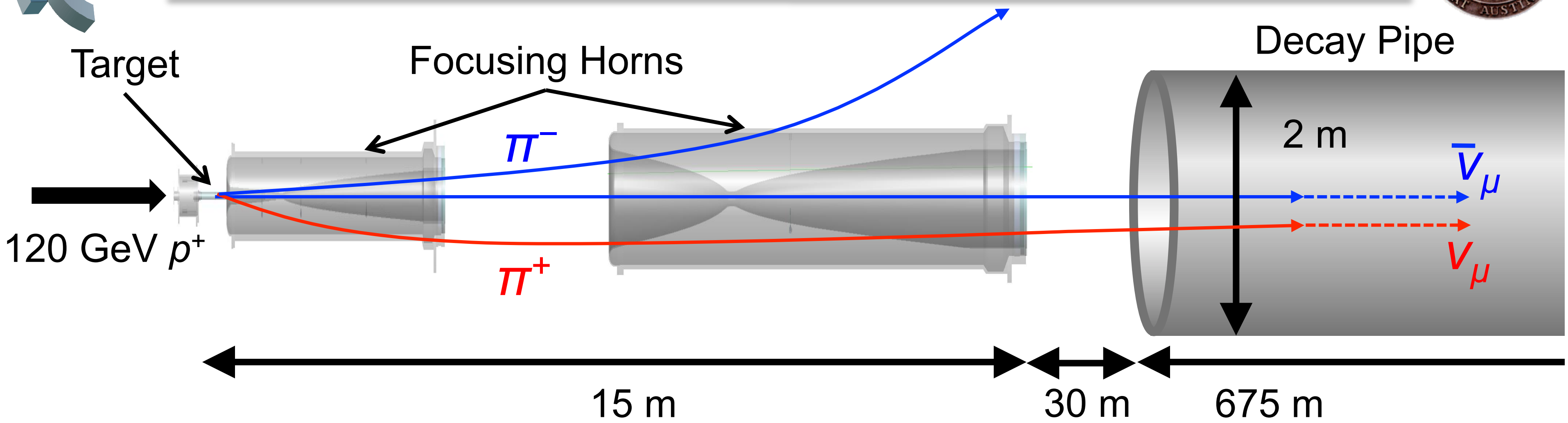
ν target region



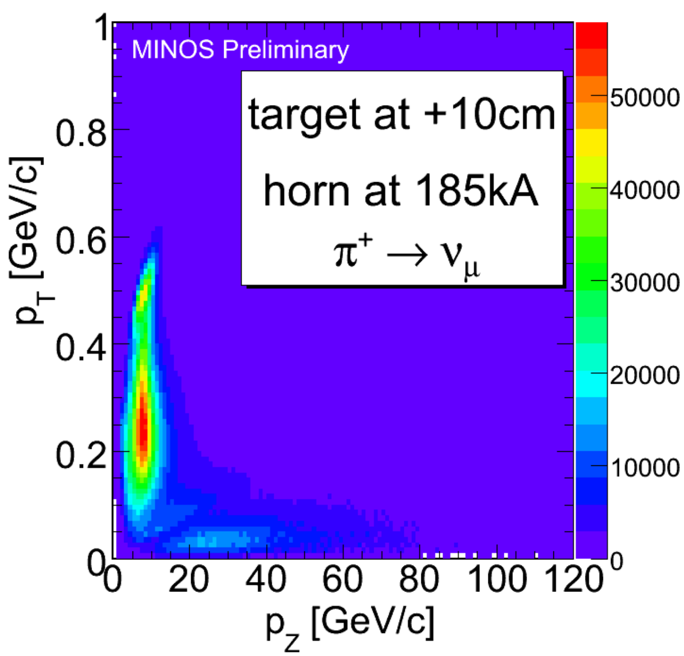
μ spectrometer region

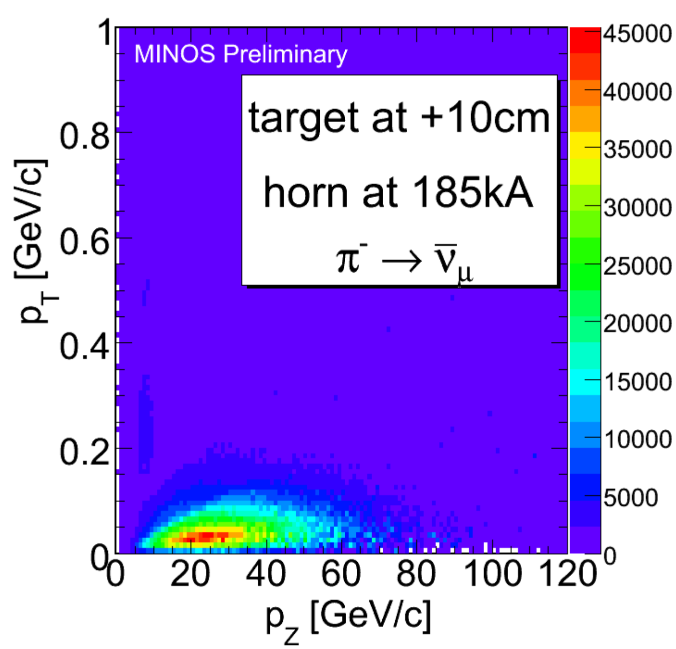


Why are the spectra so different?

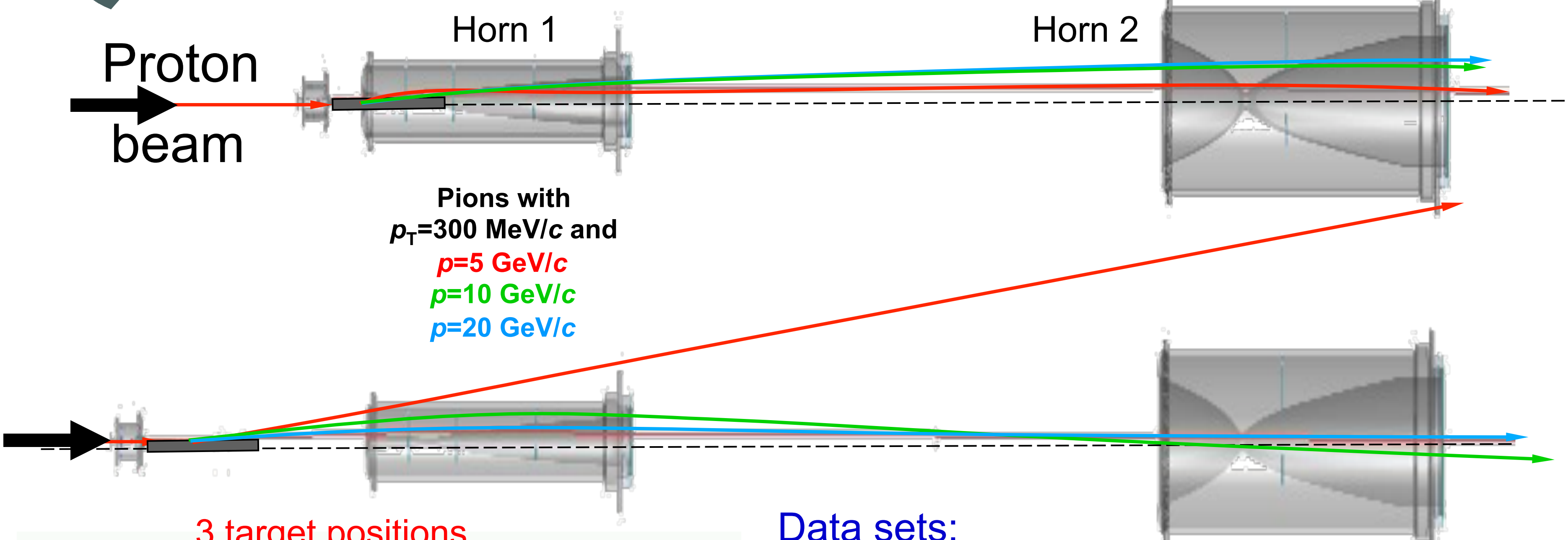


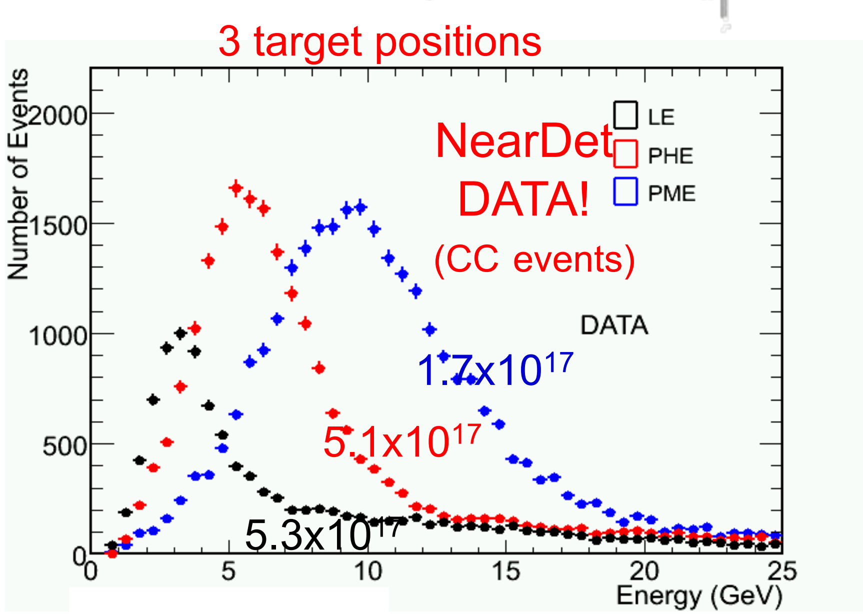
- Majority of $\bar{\nu}_\mu$ come from "neck-to-neck" low-p_T π^- that travel down the centre of the horns where there is zero magnetic field
- ν_μ spectrum dominated by focused high-p_T π^+





NuMI – multi-beam





Data sets:

Beam	Target z position (cm)	FD Events per 1×10^{20} pot	Horn Current (kA)
LE-10	-10	390	0,170, 185 ,200
pME	-100	970	200
pHE	-250	1340	200

95% data

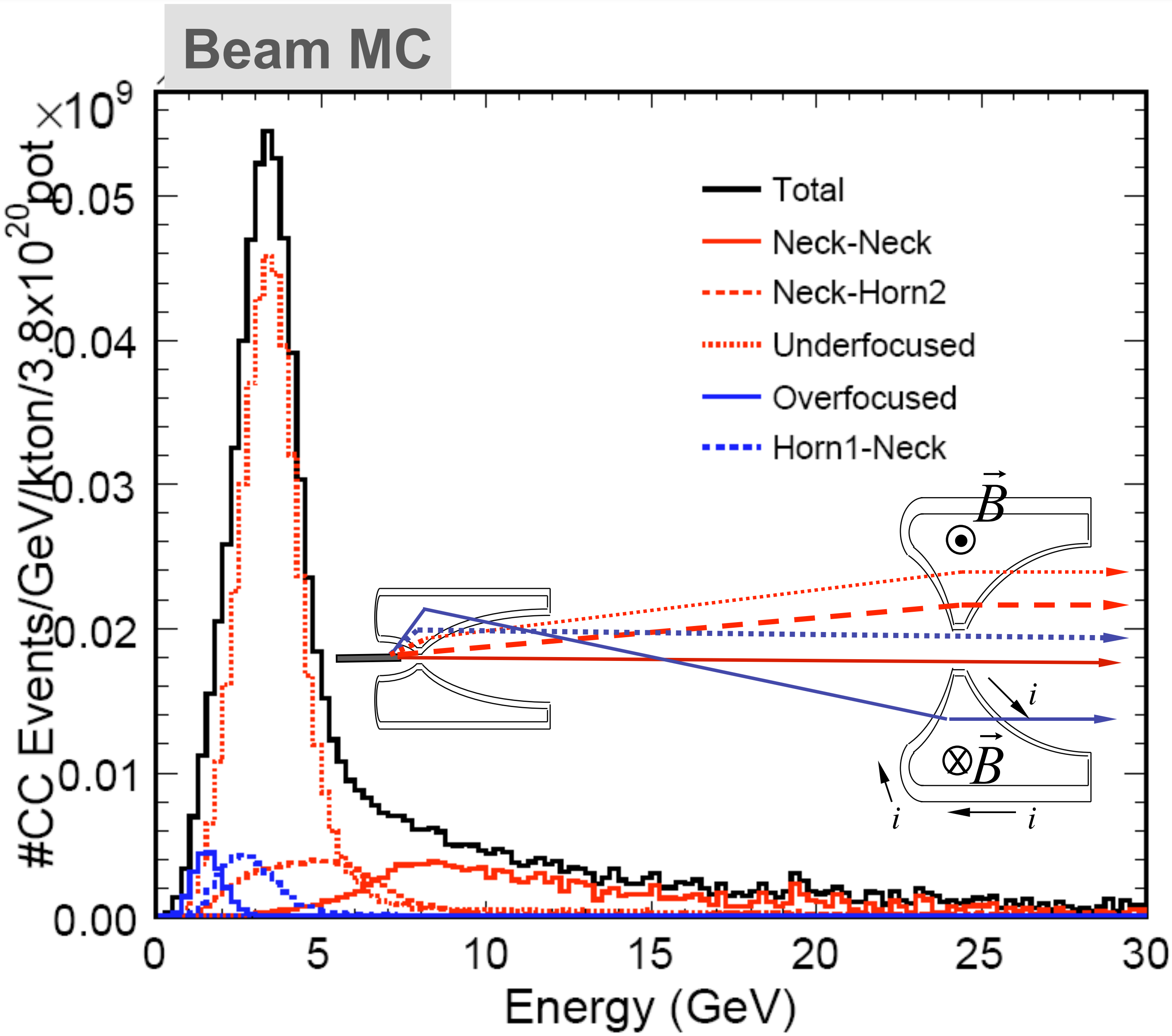
LE-10: Far Det: 1 event / ~4hrs

Flavor composition: 92.9% ν_μ

5.8% anti- ν_μ,

1.2% ν_e, 0.1%anti- ν_e

NuMI/MINOS “multi-beam”



MINOS Event Topologies