FLUX AND CROSS SECTION UNCERTAINTIES IN MINOS

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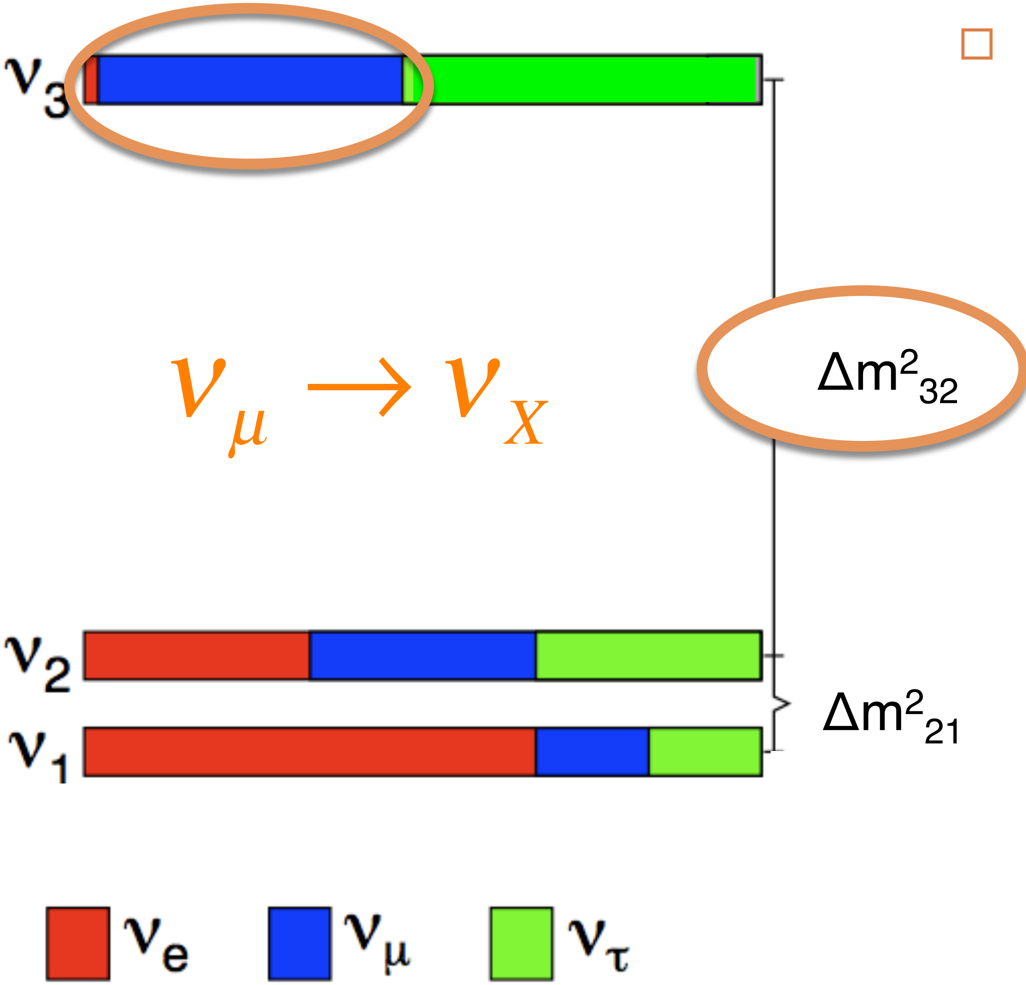
The MINOS Experiment

P. Vahle, INFO 2011

- Long-baseline neutrino oscillation experiment
  - Neutrinos from NuMI beam line
  - L/E ~ 500 km/GeV
    - atmospheric Δm^2

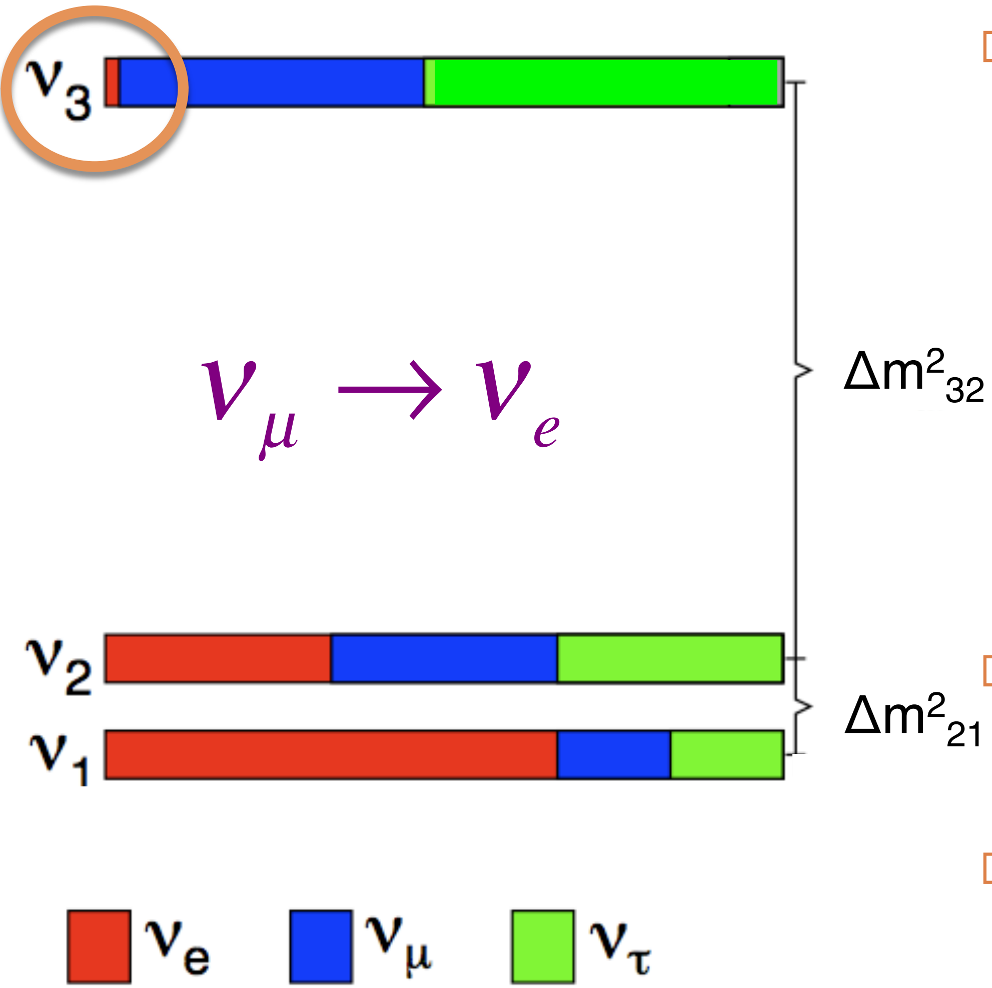
- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties

MINOS Physics Goals



- **Measure ν_μ disappearance as a function of energy**
  - Δm^2_{32} and $\sin^2(2\theta_{23})$
  - test oscillations vs. decay/ decoherence
  - look for differences between neutrino and anti-neutrinos

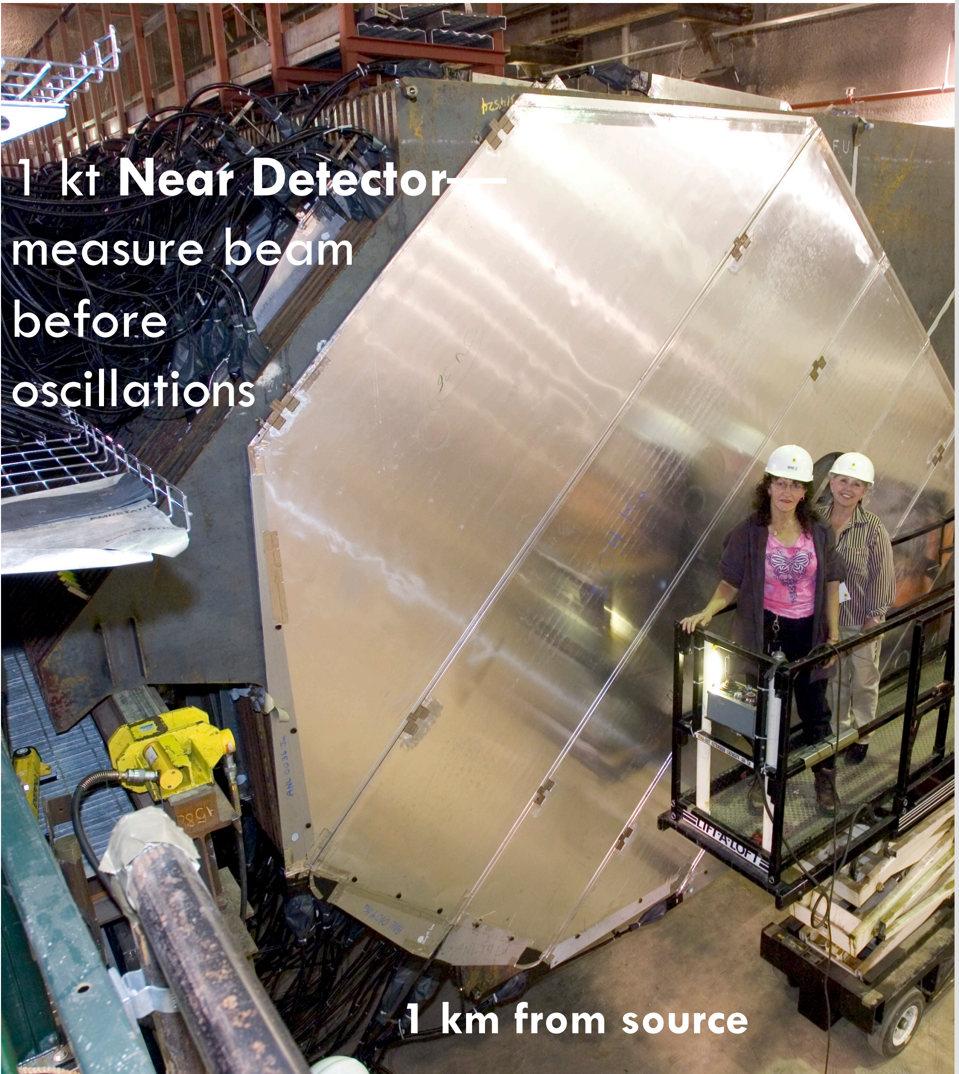
MINOS Physics Goals

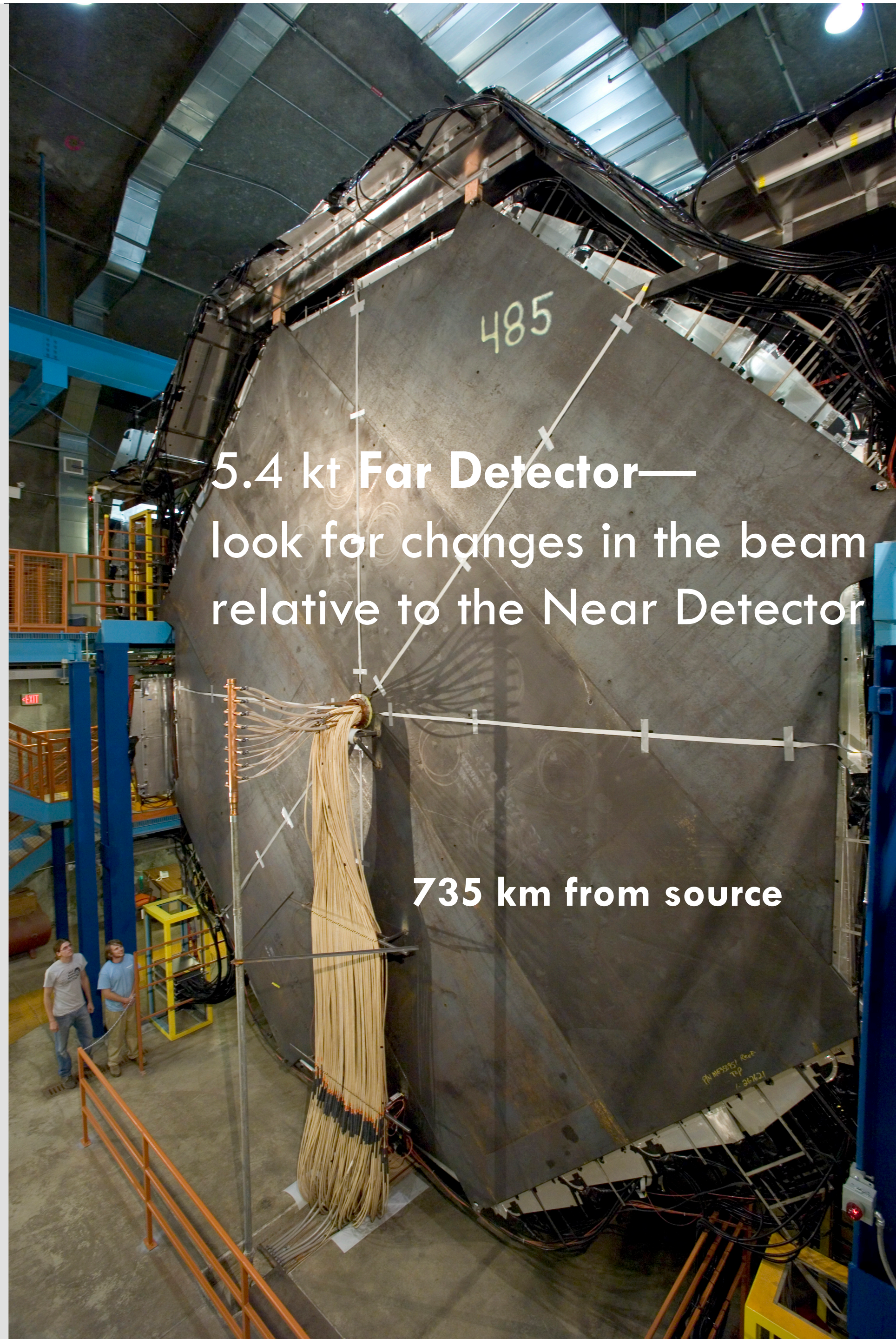


- Measure ν_μ disappearance as a function of energy
  - Δm^2_{32} and $\sin^2(2\theta_{23})$
  - test oscillations vs. decay/ decoherence
  - look for differences between neutrino and anti-neutrinos
- **Study $\nu_\mu \to \nu_e$ mixing**
  - measure θ_{13}
- Mixing to sterile neutrinos? (not covered today)

The Detectors

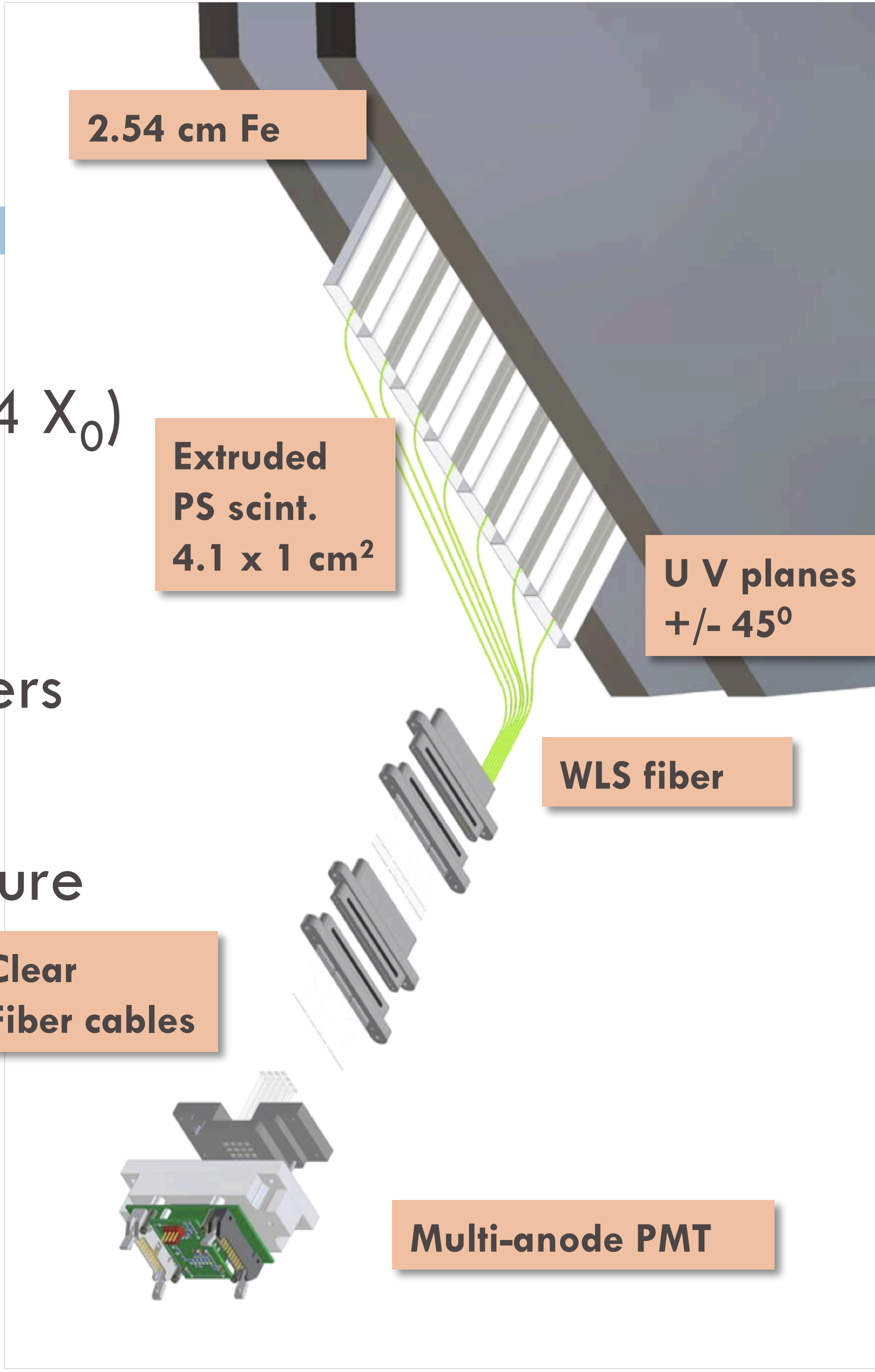
Magnetized, tracking calorimeters





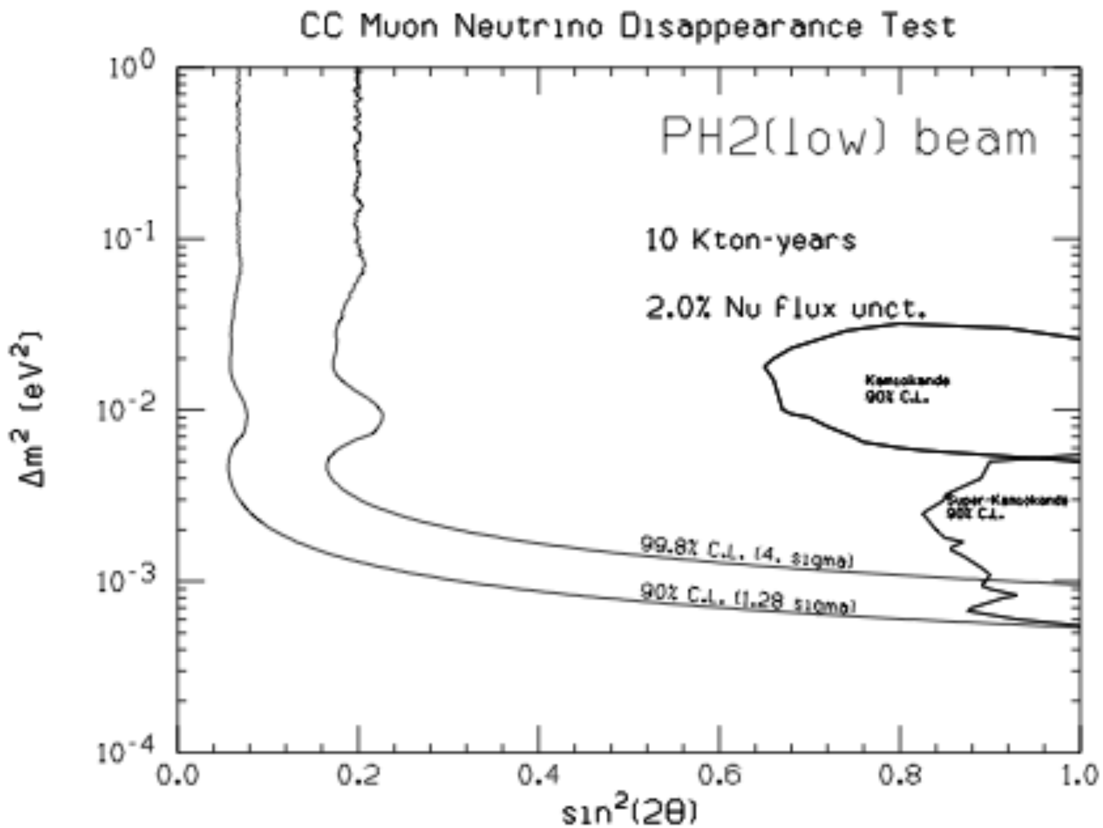
Detector Technology

- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



TDR Era Uncertainties

- TDR (1998) refers to "hints" of neutrino oscillations
  - Kamiokande favored big $\Delta m^2 \sim 10^{-2}$ eV^2
  - SuperK favored smaller $\Delta m^2 \sim$ few x 10^{-3} eV^2
  - MINOS planned to run in the High Energy configuration
  - Optimistic that we could see taus
  - most appropriate for the larger mass splitting, but we had a backup plan for small mass splitting



TDR Era Uncertainties

- First MINOS thesis (D. Petyt, Oxford 1998)
  - Mostly dealt w/HE beam
  - 1 chapter on LE scenario
  - Major systematics:
    - Relative/Absolute energy calibration—needed to be better than 2%/4%
    - Neutrino flux systematics—relative normalization expected to be 2-4% less than 10 GeV, less than 8% ~25 GeV

Calibration detector would address energy scale, but beam systematics continued to be a concern

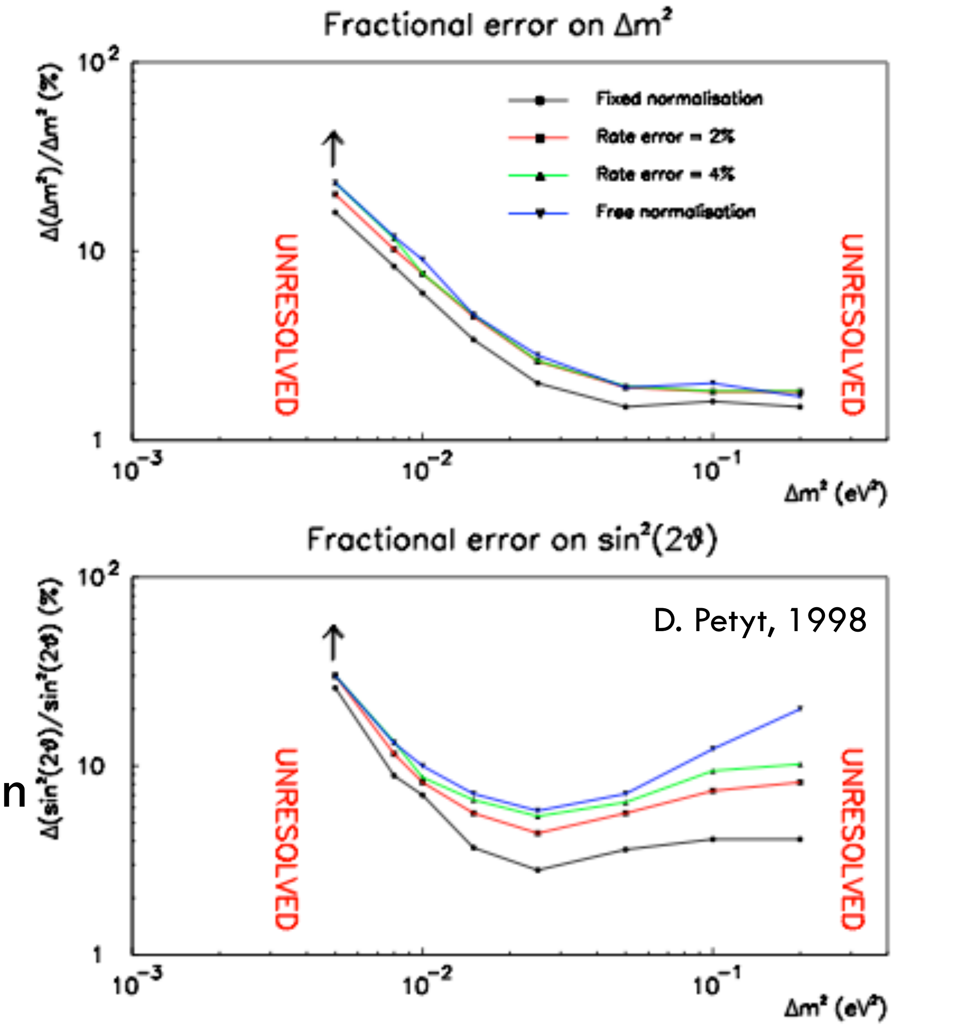
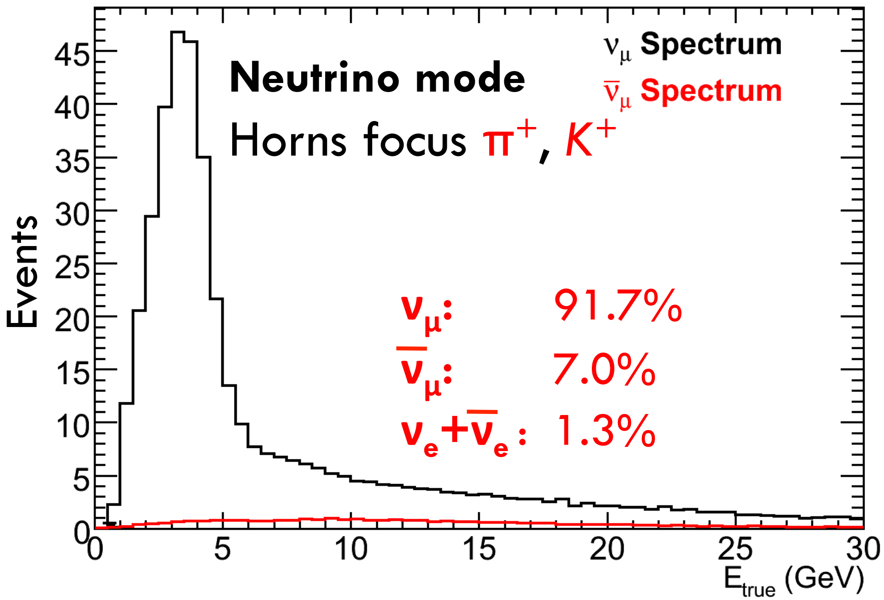
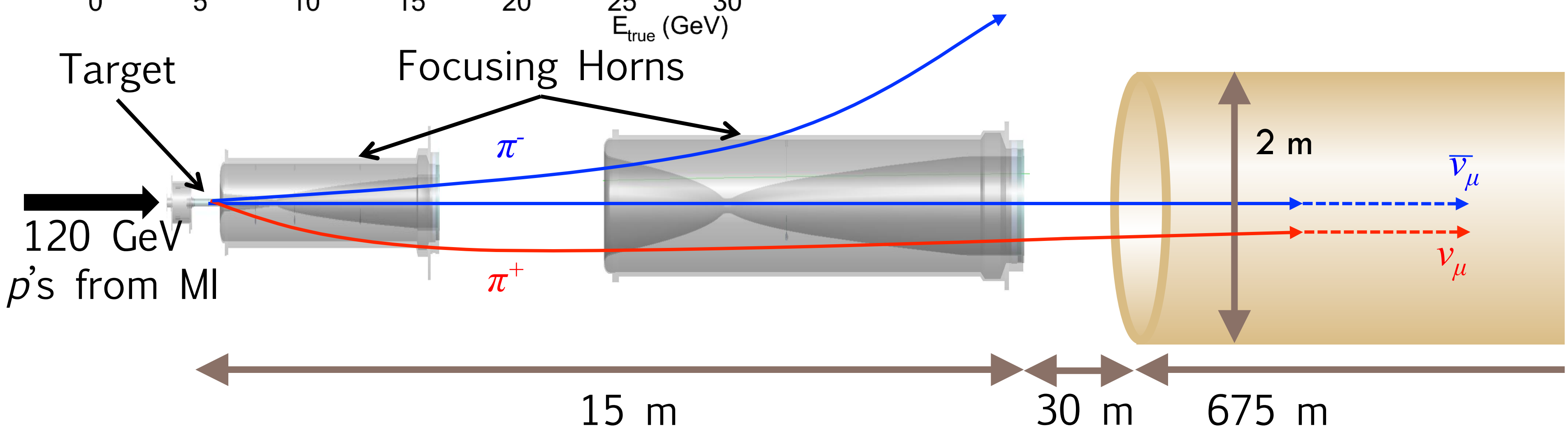


Figure 4.14 – Summary of parameter measurement errors for fits to neutrino oscillations with various values of Δm^2 and $\sin^2 2\theta = 0.7$. The lines correspond to different assumptions about the relative near/far rate normalisation.

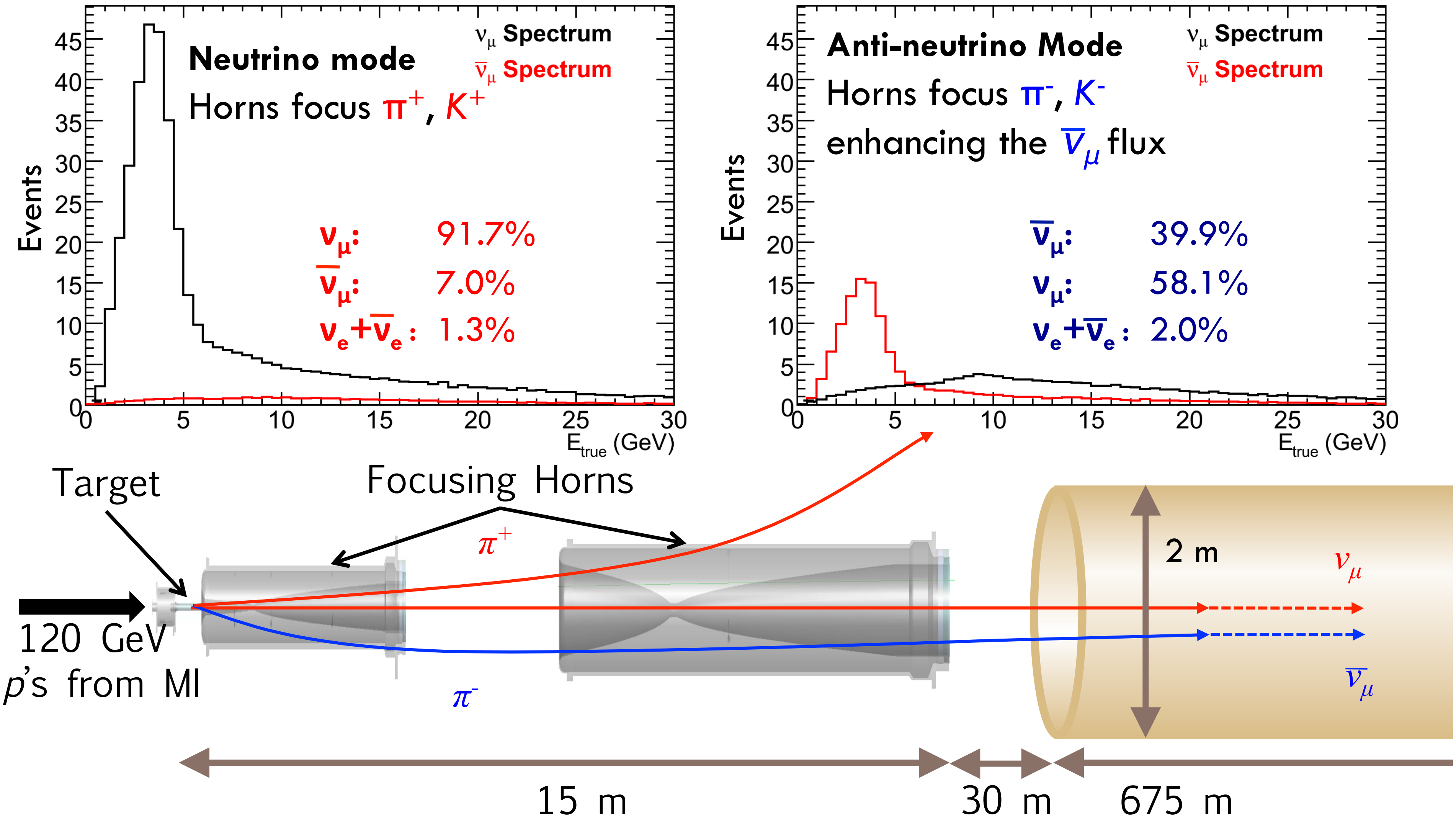
Making a Neutrino Beam



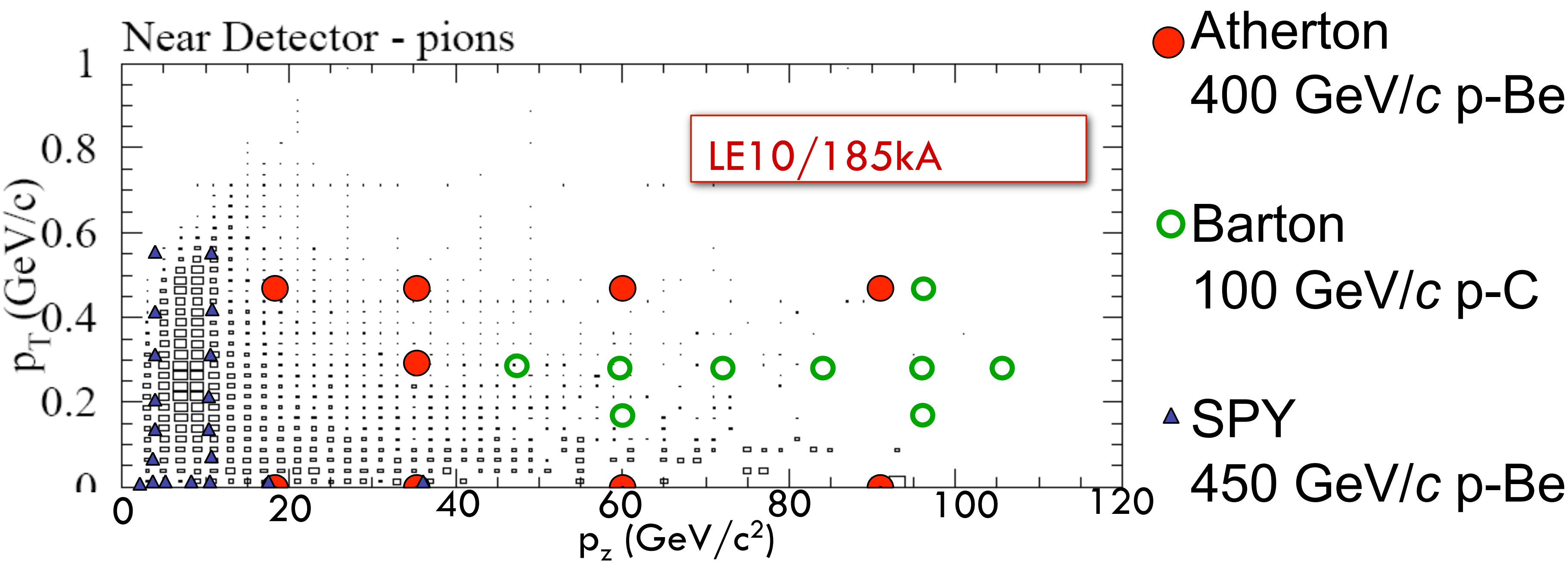
- Production: 120 GeV p^+ on 2 interaction length C target
- Focusing: π/K focused/sign selected by two horns
- Decay: π/K decay in 2m diameter decay pipe to ν_μ with wide range of energies



Making an Anti-neutrino Beam



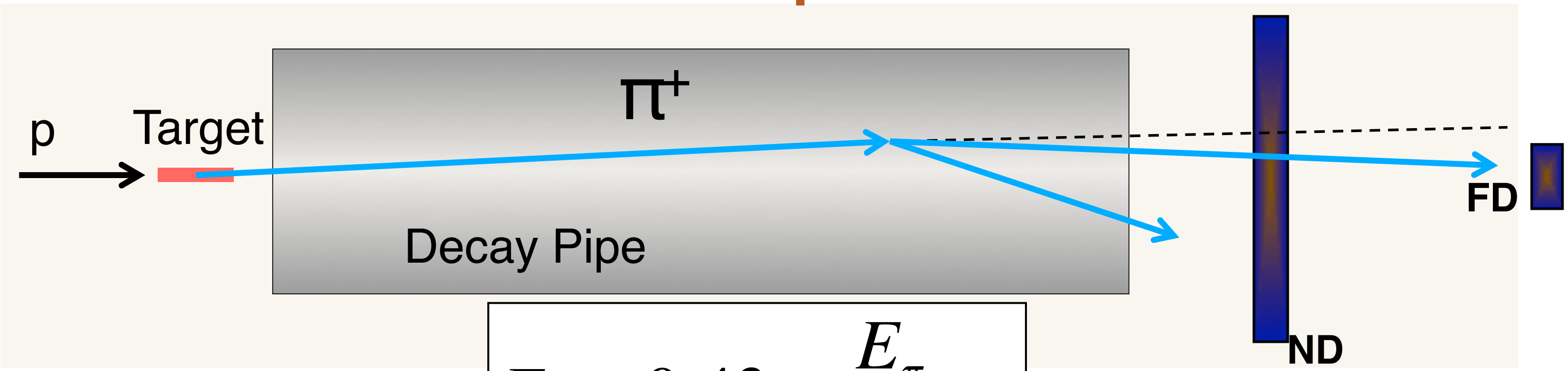
Predicting the Flux



- Paucity of data in region of interesting phase space
- Extrapolation of existing data to MINOS beam energy, target thickness, target material
- Systematics originally evaluated using model spread
- Additional systematics from focusing system alignment, horn current calibration, skin depth, etc

Near to Far

Far spectrum without oscillations is similar, but not identical to the Near spectrum!



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

- Neutrino energy depends on angle wrt original pion direction and parent energy
  - higher energy pions decay further along decay pipe
  - angular distributions different between Near and Far

Near to Far

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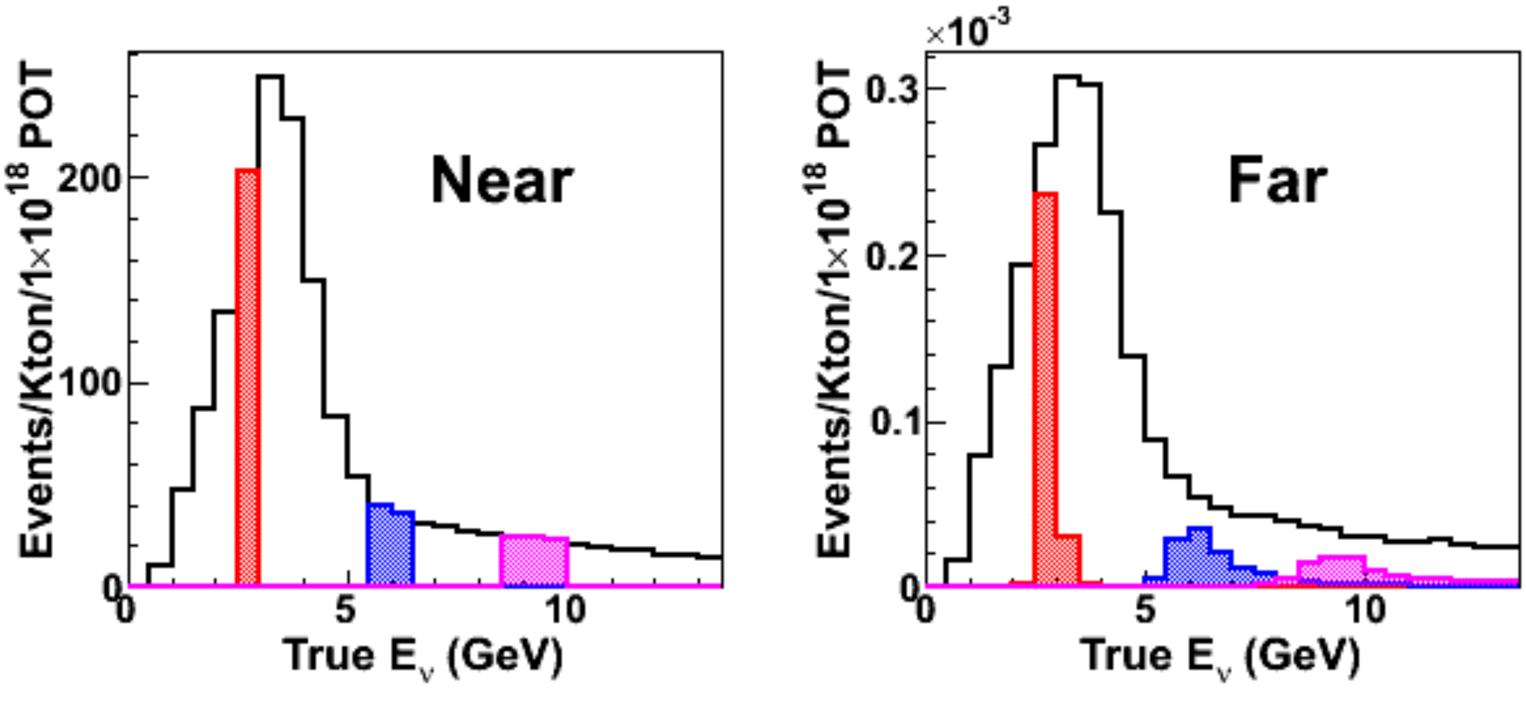
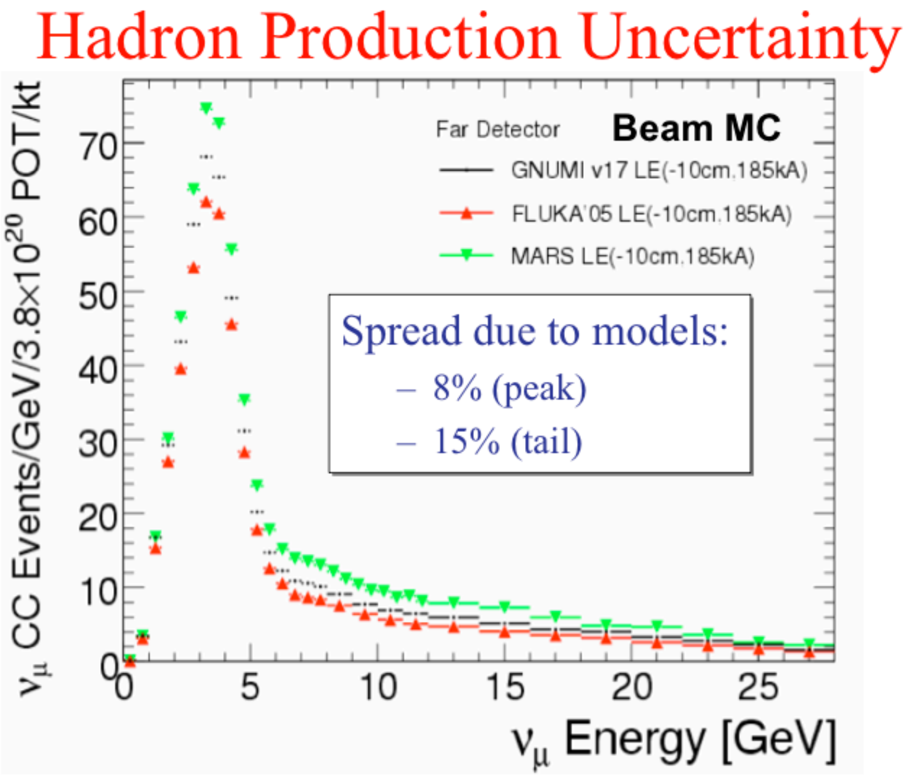
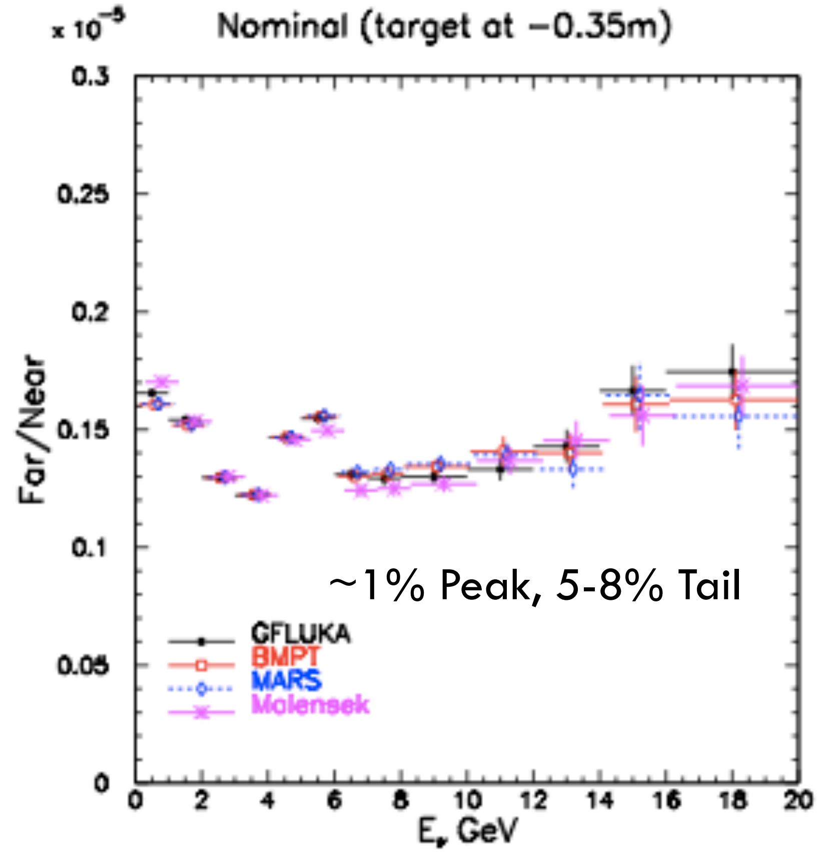


Hadron Production Uncertainties



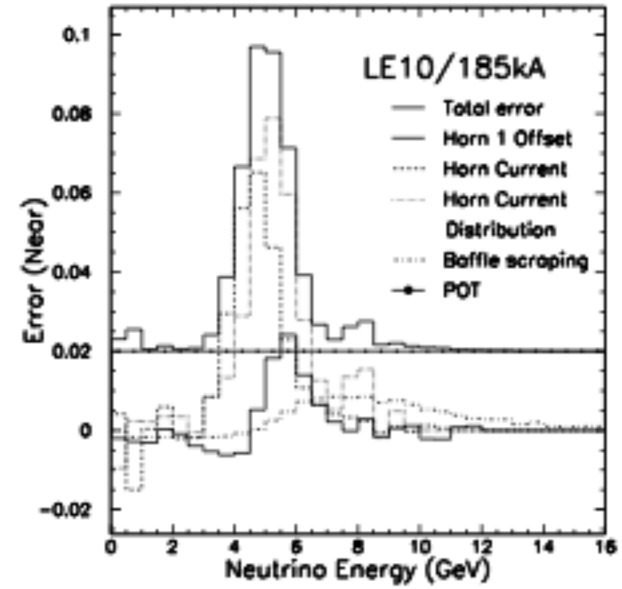


Uncertainties in the neutrino flux cause large uncertainties in the ND simulated spectrum, but the errors largely cancel in the Far to Near Comparison

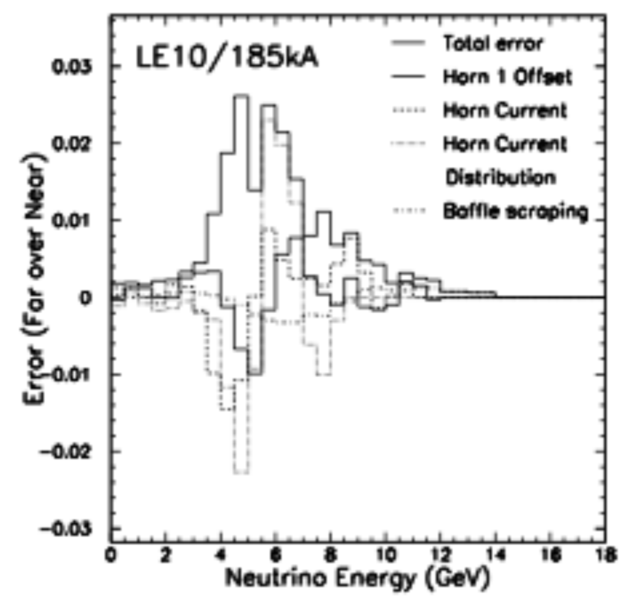
This is what we understood about the flux right before our 1st analysis in 2006

Beam Systematics

- Additional flux uncertainties arise from focusing and alignment uncertainties
- Errors in flux estimated using comparisons between nominal (pbeam) simulation and systematically offset simulation sets
- Offsets determined from beam survey measurements, target scans, hadron/muon monitoring, etc. (Documented in R. Zwaska thesis, UT Austin, 2005)



(a)

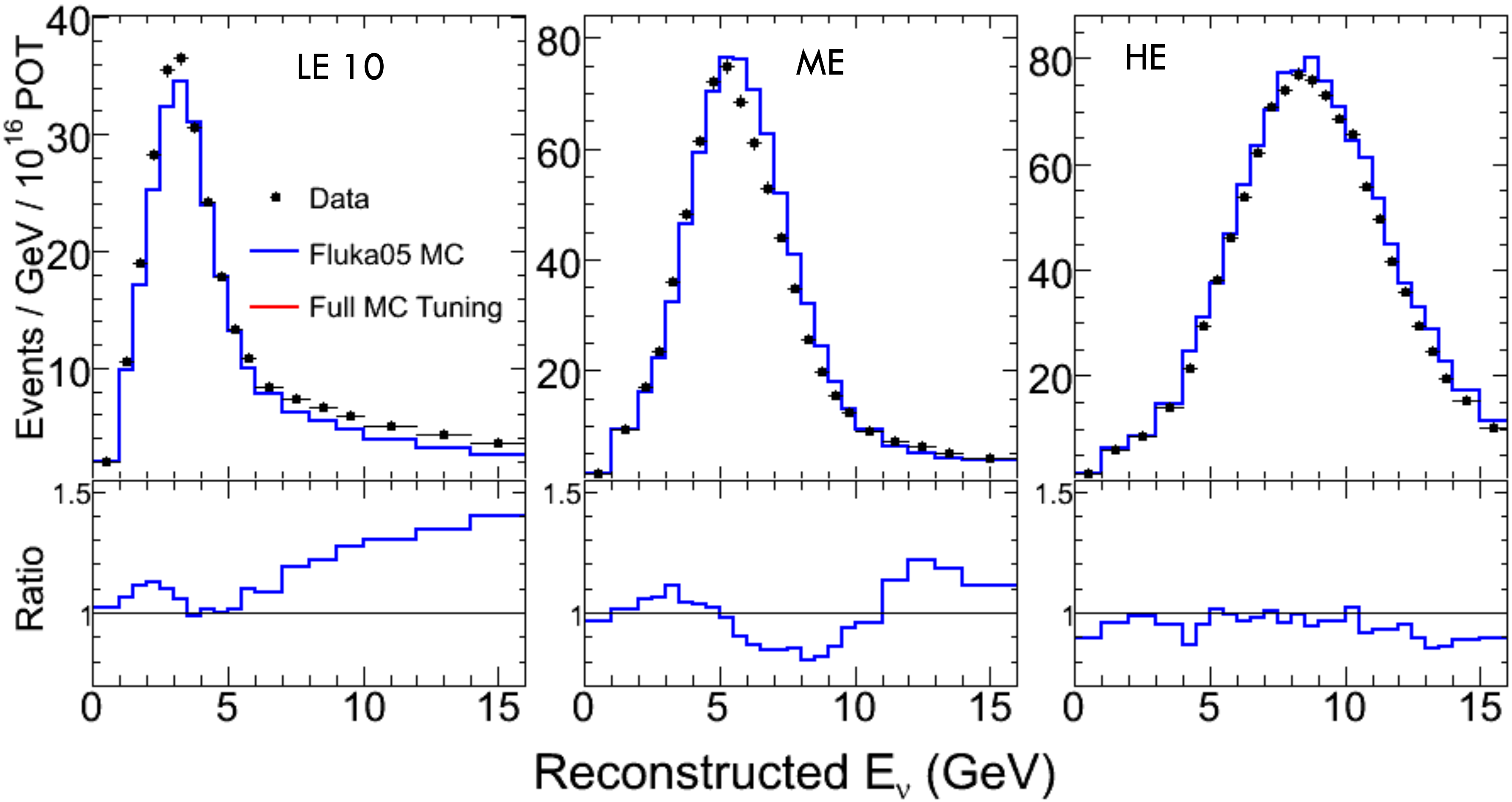


(b)

(Horn angles, horn 2 offset errors also evaluated, small, not shown on plots)

Initial ND Data

(Refs: Z. Pavlovich, UT Austin, 2008, Phys. Rev. D76 (2007) 072005)



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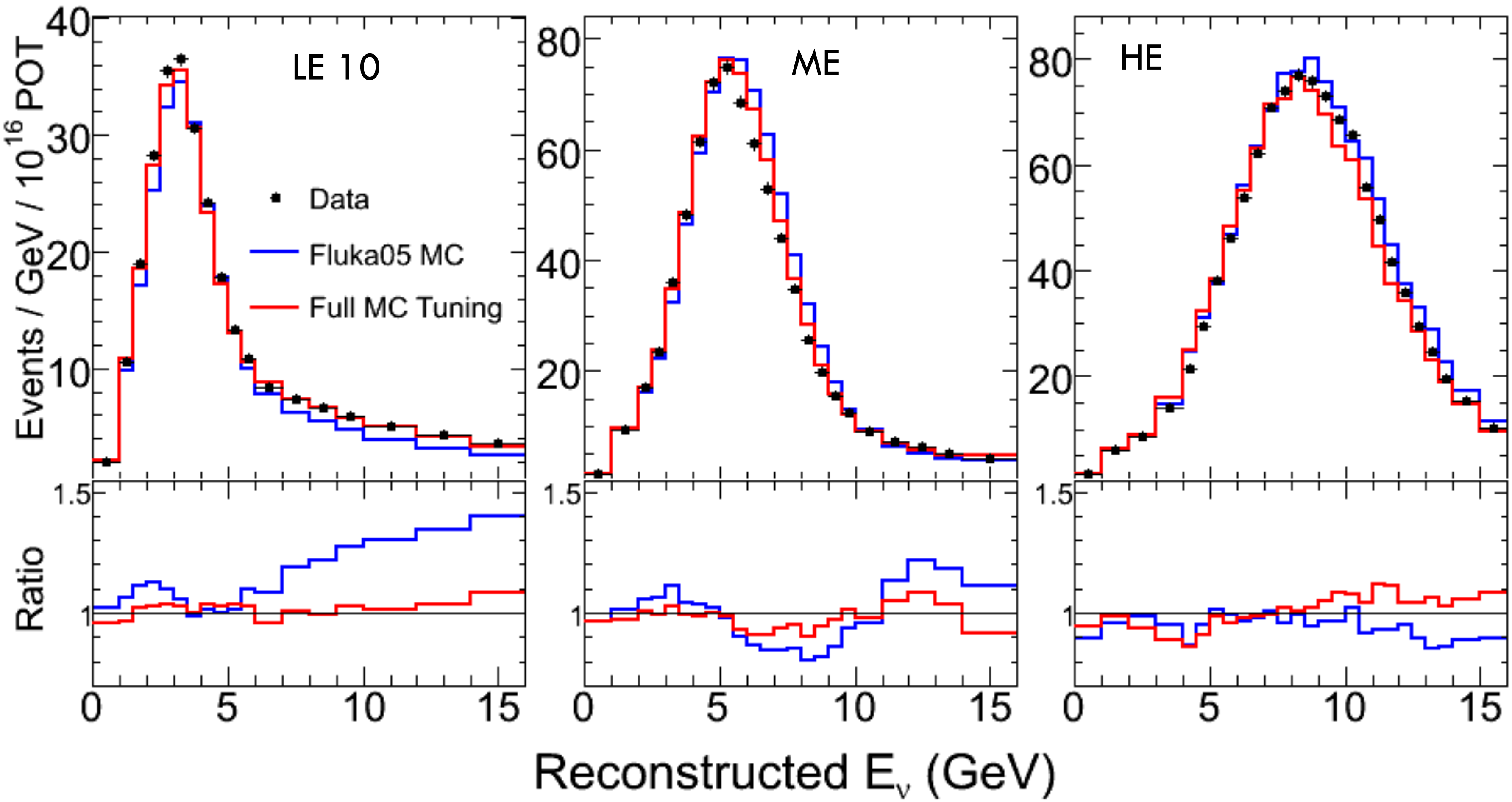
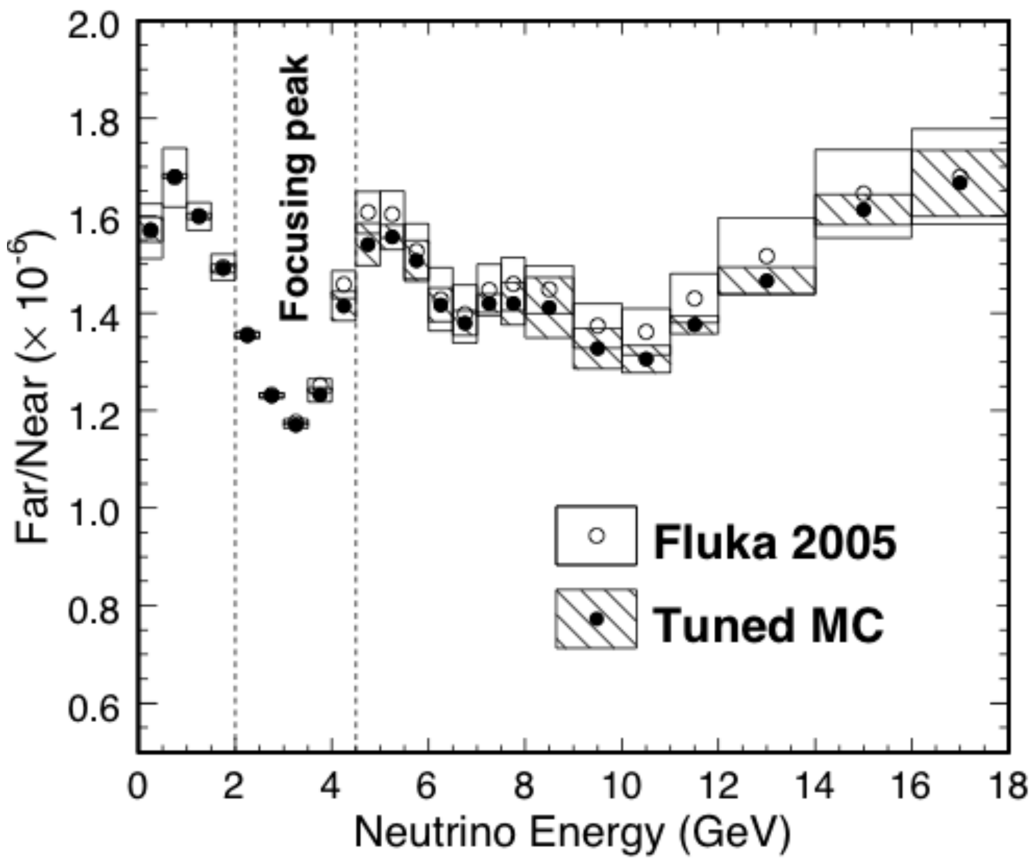


- Remaining data/MC discrepancies ~5-10% level
- Fit errors provide a better estimate of systematic error than (correlated) model spread

Resulting Beam Systematics

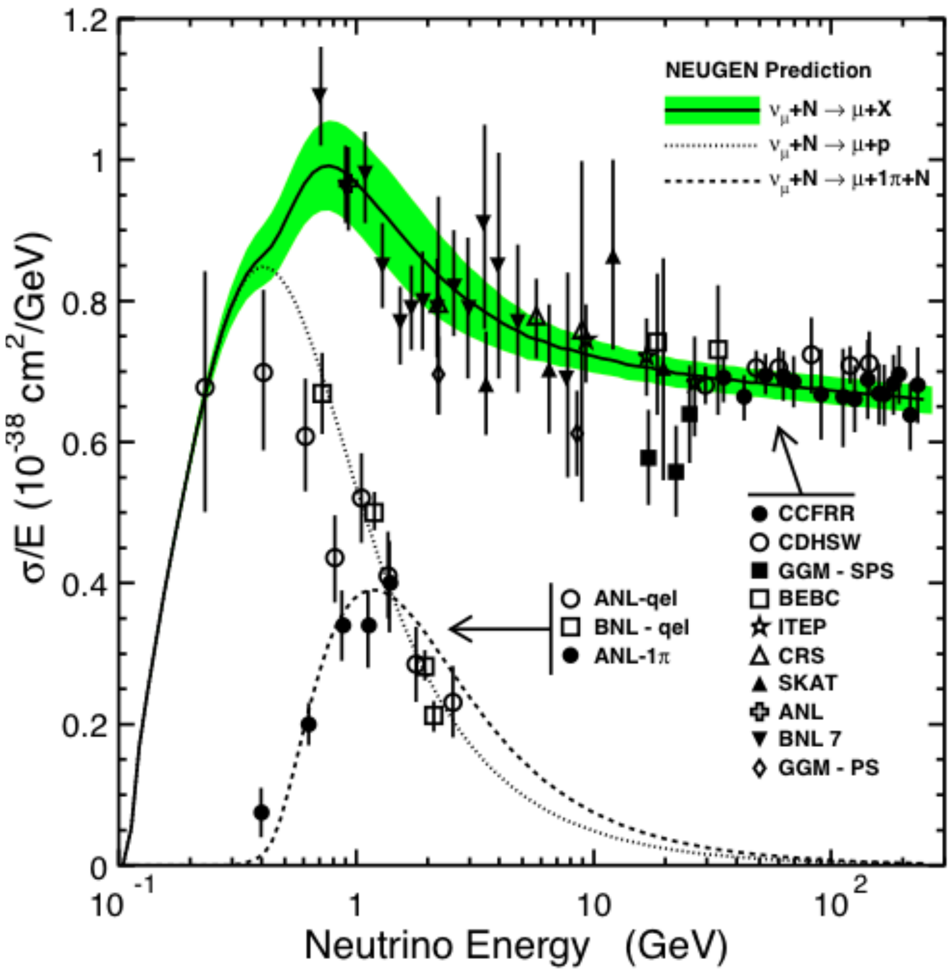
- F/N from simulation constrained by the beam fit
- Ratio changes very little in focusing peak
  - errors at sub percent level
- Ratio pulled few % lower in tail
  - still consistent within errors
  - errors further reduced



Phys. Rev. D76 (2007) 072005

Cross Section Uncertainties

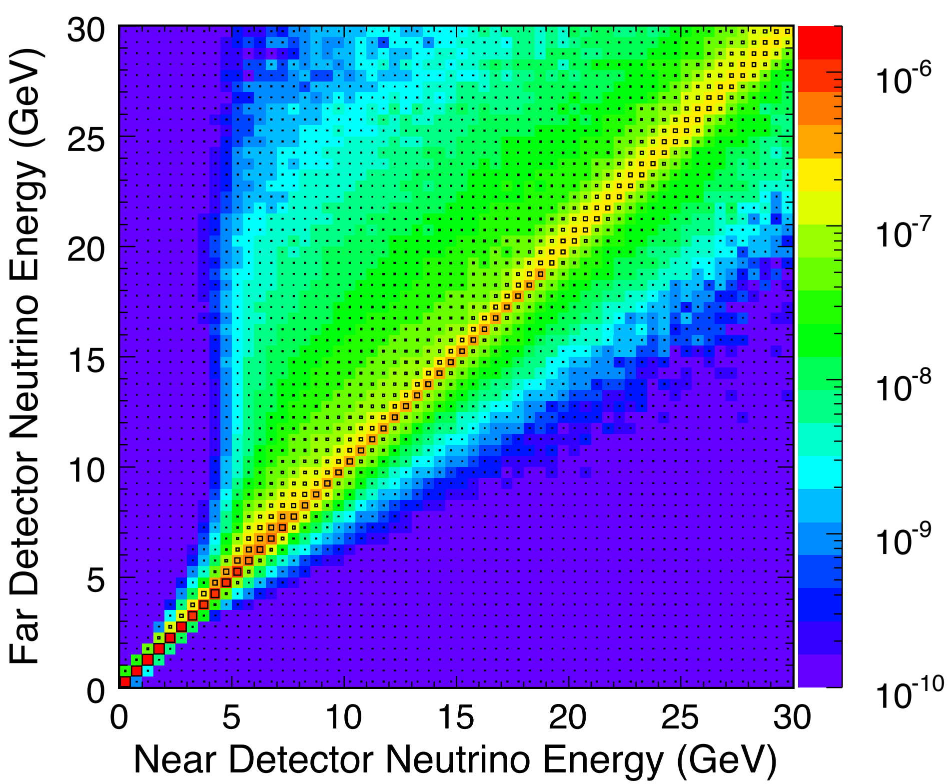
- Uncertainties determined from comparison of MC to independent data
- fits to both inclusive and exclusive channel data, in different invariant mass regions
  - 3% on the normalization of the DIS (W > 1.7GeV/c2) cross-section
  - 10% uncertainty in the normalization of the single-pion and quasi-elastic cross-sections.
  - 20% uncertainty in the relative contribution of non-resonant states to the 1π and 2π production cross-sections for W < 1.7 GeV/c2.

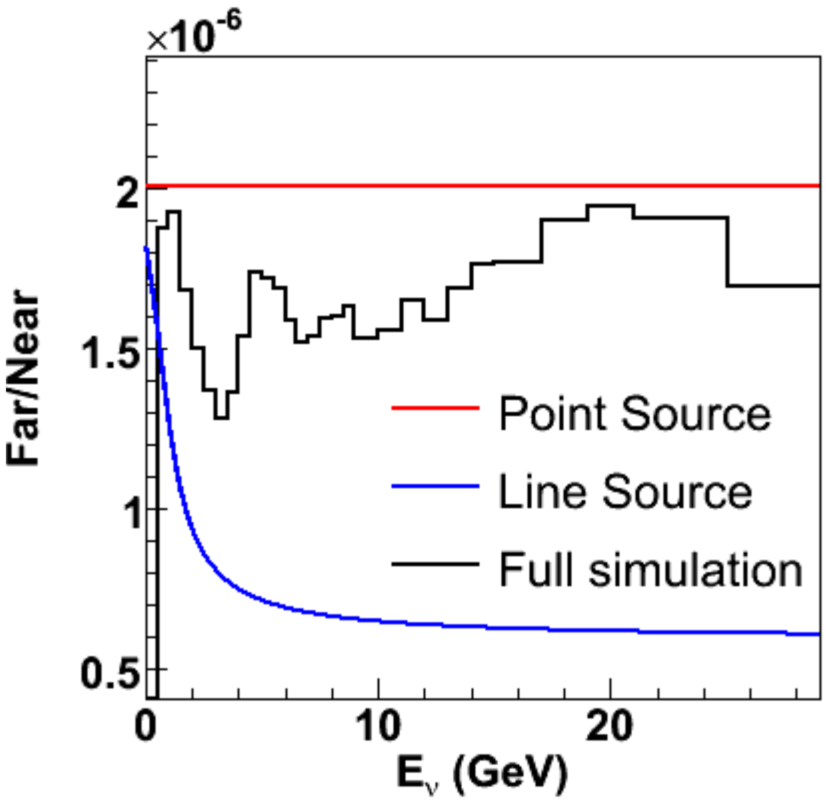


Phys. Rev. D76 (2007) 072005

Direct Extrapolation

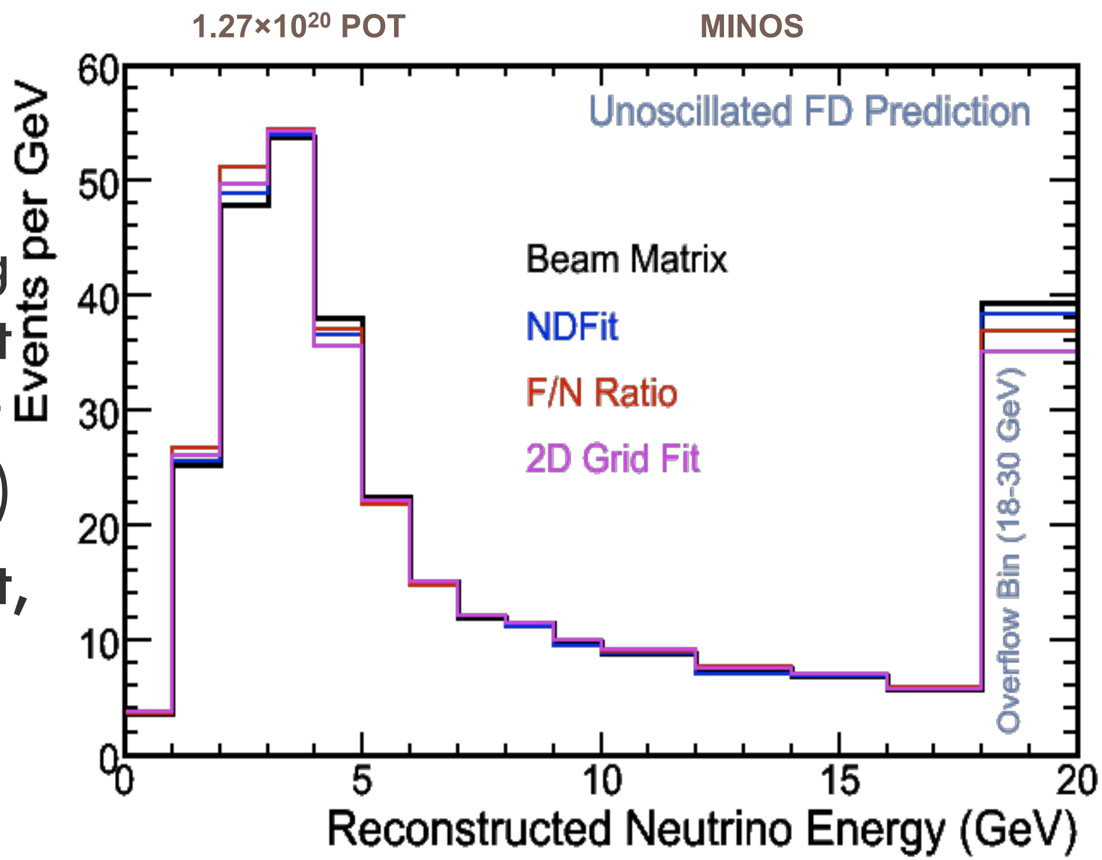
- Muon-neutrino and anti-neutrino analyses: beam matrix for FD prediction of track events
- NC and electron-neutrino analyses: Far to Near spectrum ratio for FD prediction of shower events





Indirect Extrapolation

- In first analysis, also had two extrapolation methods that described ND distributions by fitting physics quantities, predict FD spectrum from best fit (e.g., by reweighting MC)
- These methods less robust, as they had difficulty fitting all the features of the data distribution

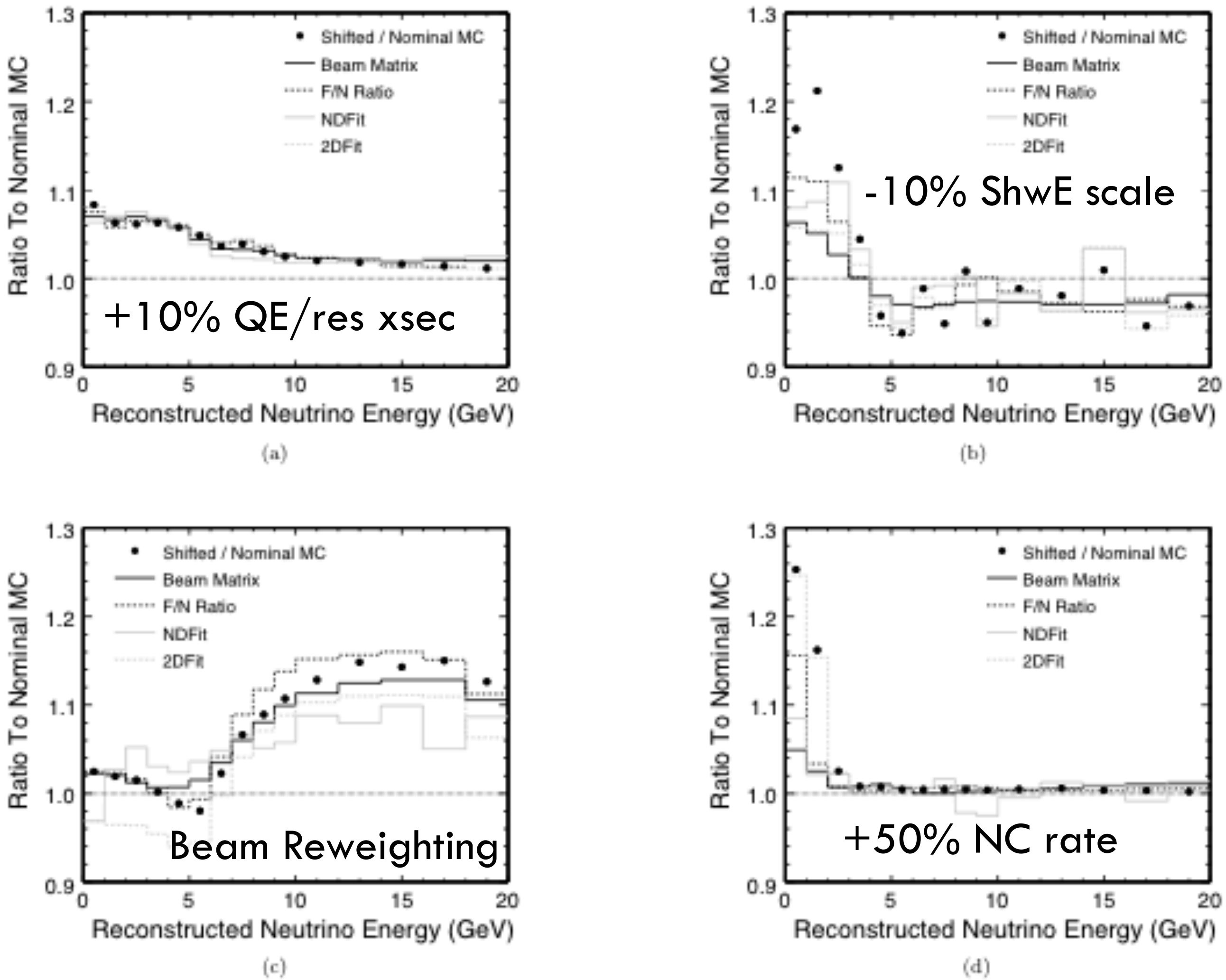


Prediction from all methods agreed to within ~ 5% bin-by-bin

Phys. Rev. D76 (2007) 072005

Systematic Uncertainties

Systematic uncertainties are different for each extrapolation method



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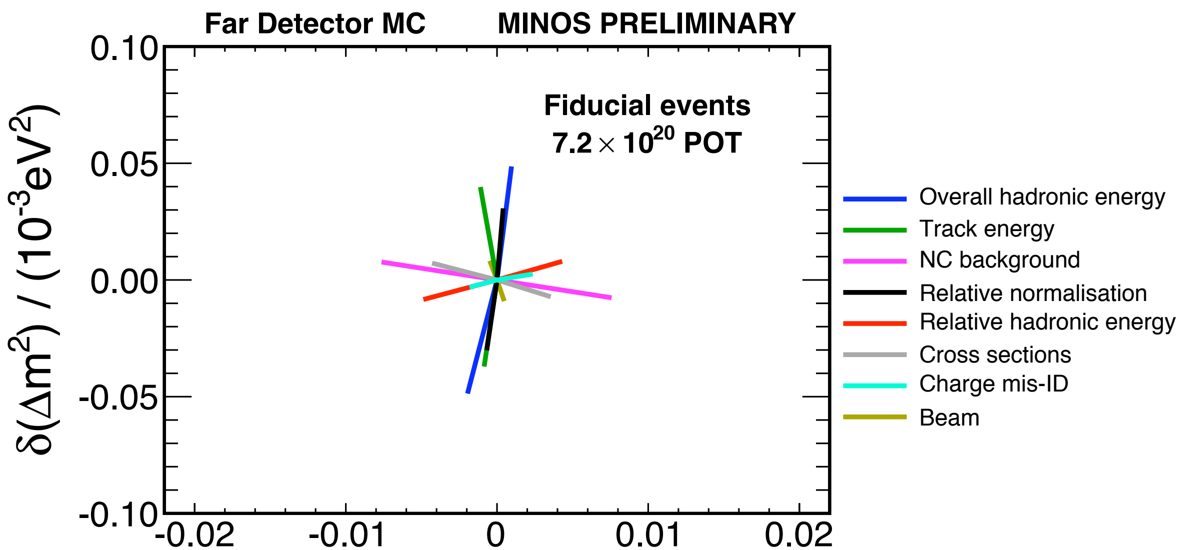
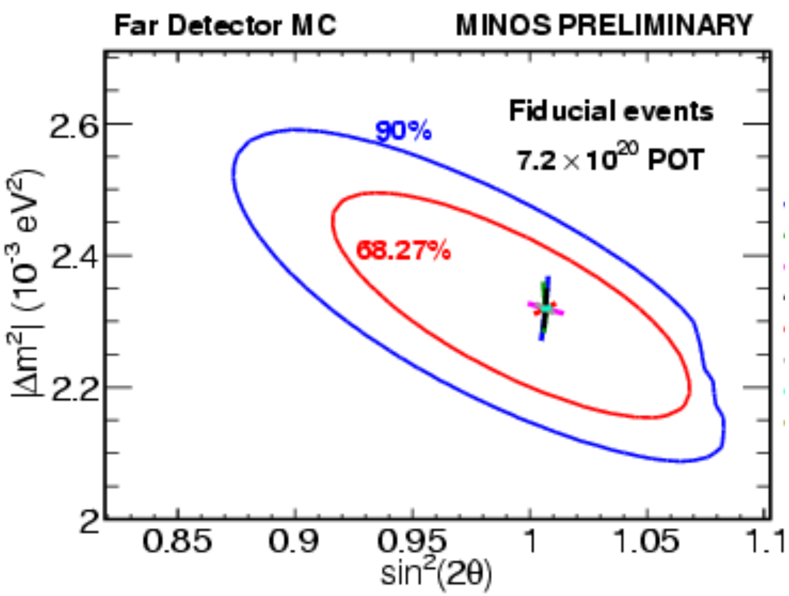
Current Day Systematic Uncertainties

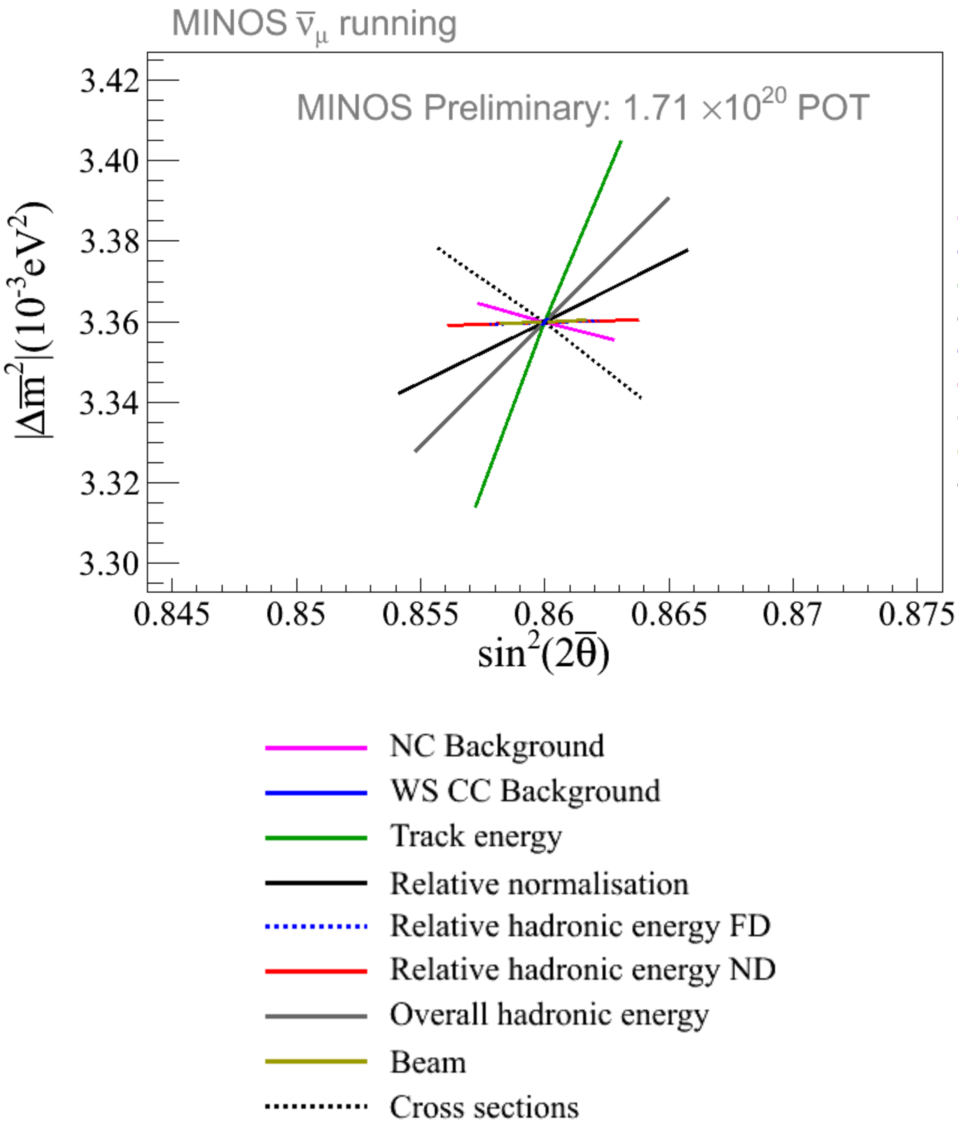


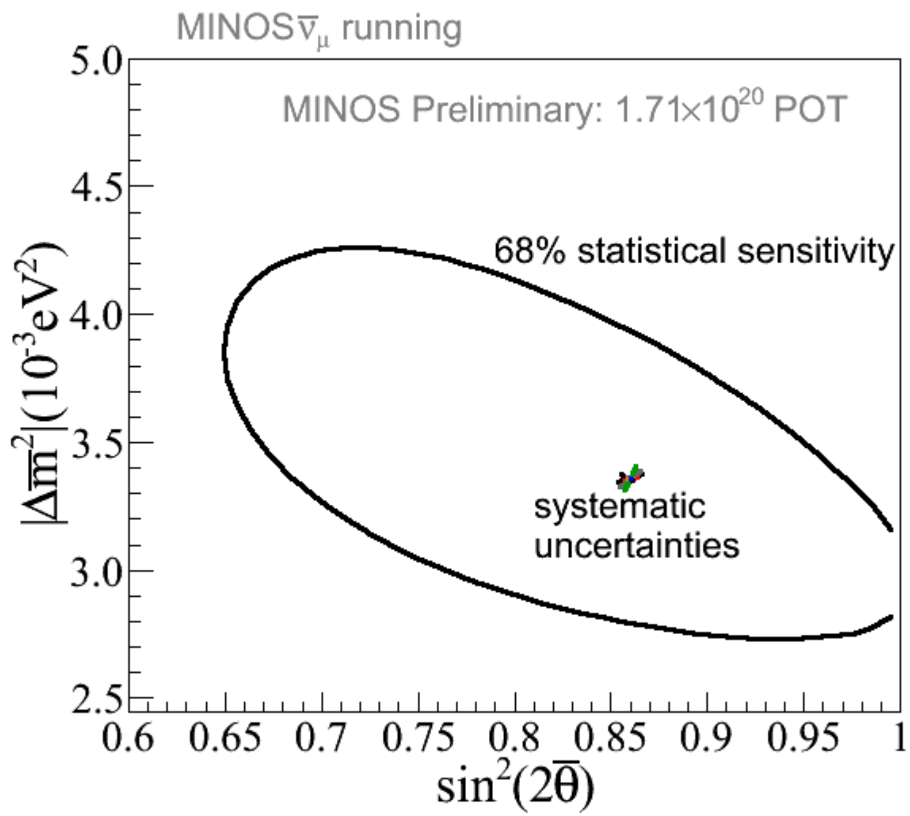
	error on Δm^2	error on $\sin^2(2\theta)$
Expected Statistical	0.124	0.060
Total Systematic	0.085	0.013



- Dominant systematic uncertainties included in fit as nuisance parameters
  - hadronic energy calibration
  - track energy calibration
  - NC background
  - relative Near to Far normalization (uptime, Fid. Mass)

Anti-neutrino Systematics



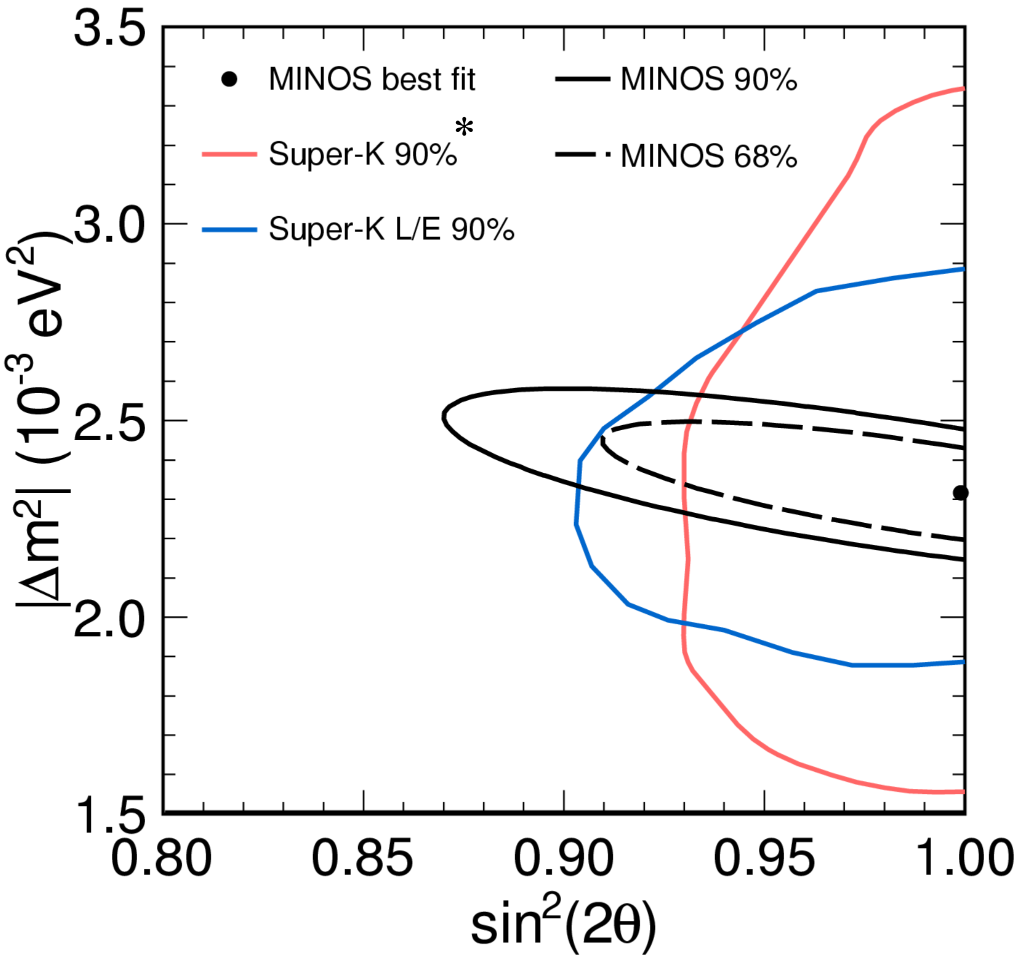


Current Neutrino Results

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

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

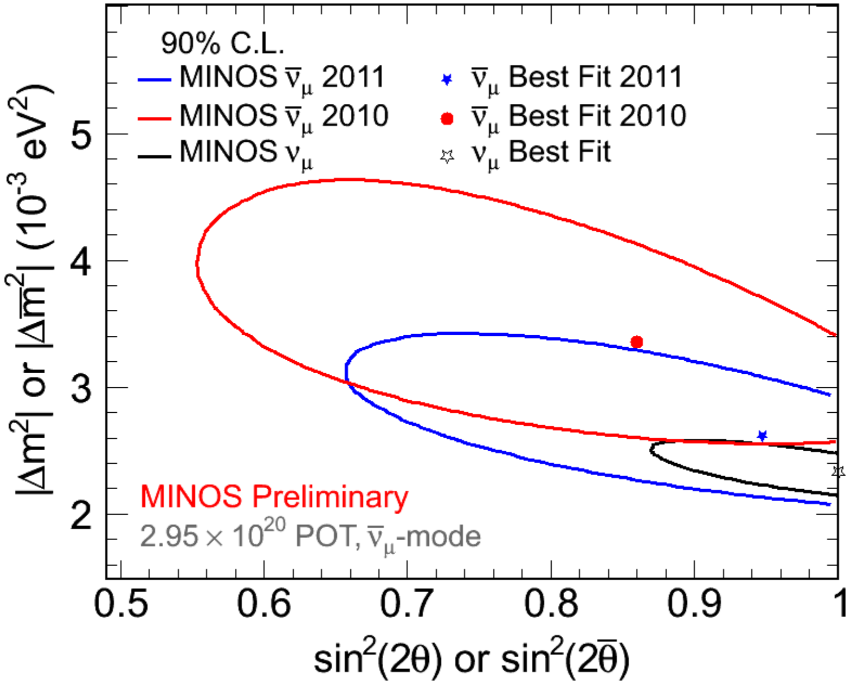
- Pure decoherence† disfavored at **9σ**
- Pure decay‡ disfavored at **7σ**



Phys. Rev. Lett. 106 181801 (2011)

†G.L. Fogli *et al.*, PRD 67:093006 (2003)
‡V. Barger *et al.*, PRL 82:2640 (1999)
*J. Hosaka et al., Phys. Rev. D 74, 032002 (2006)

Current Antineutrino Results



- No oscillations: 276
- Oscillated Prediction: 196
- Observe: 197
- No oscillations disfavored at 7.3σ

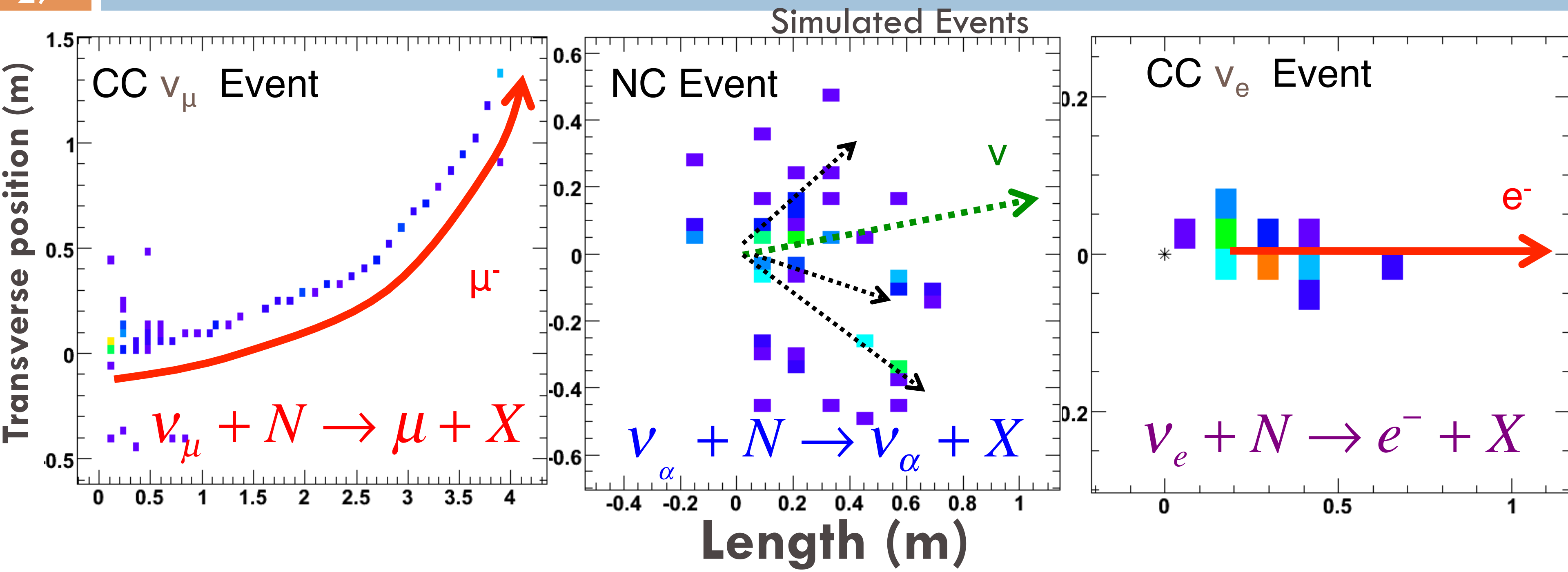
$$\left|\overline{\Delta m^2}\right| = (2.62^{+0.31}_{-0.28}\ (\text{stat.}) \pm 0.09\ (\text{syst.})) \times 10^{-3}\,\text{eV}^2$$

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

- Assuming identical underlying oscillation parameters, the neutrino and antineutrino measurements are consistent at the 42% C.L. (compared to 2% in 2010)

arXiv:1202.2772 [hep-ex]

Nue Appearance in MINOS



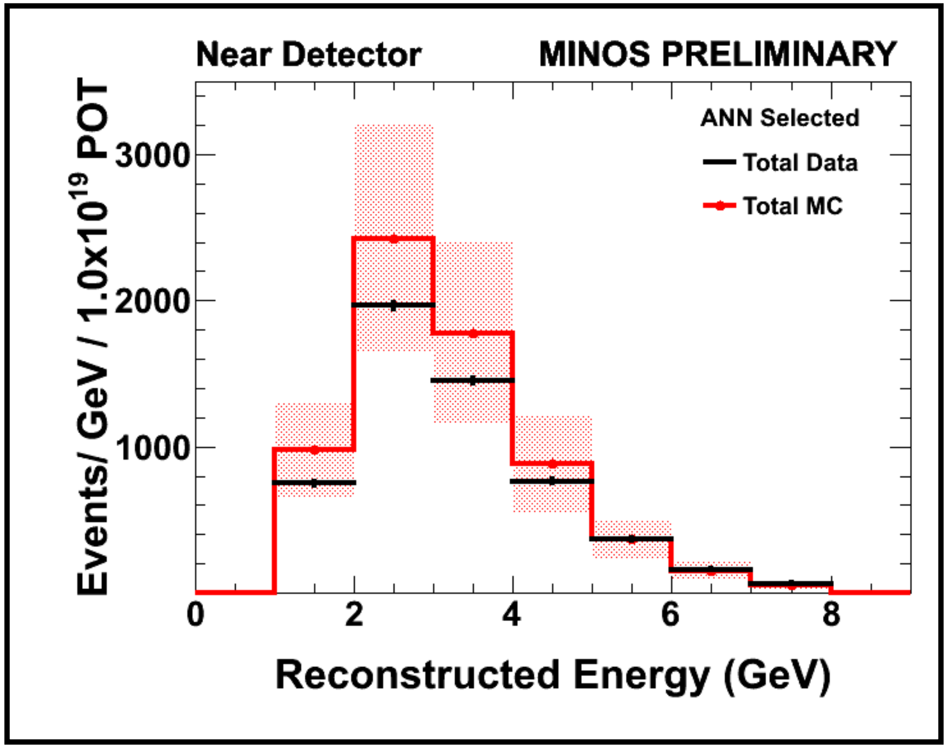
- long μ track, hadronic activity at vertex
- energy sum of muon energy (range or curvature) and shower energy

- short, diffuse shower
- energy from calorimetric response

- compact shower with EM core
- energy from calorimetric response

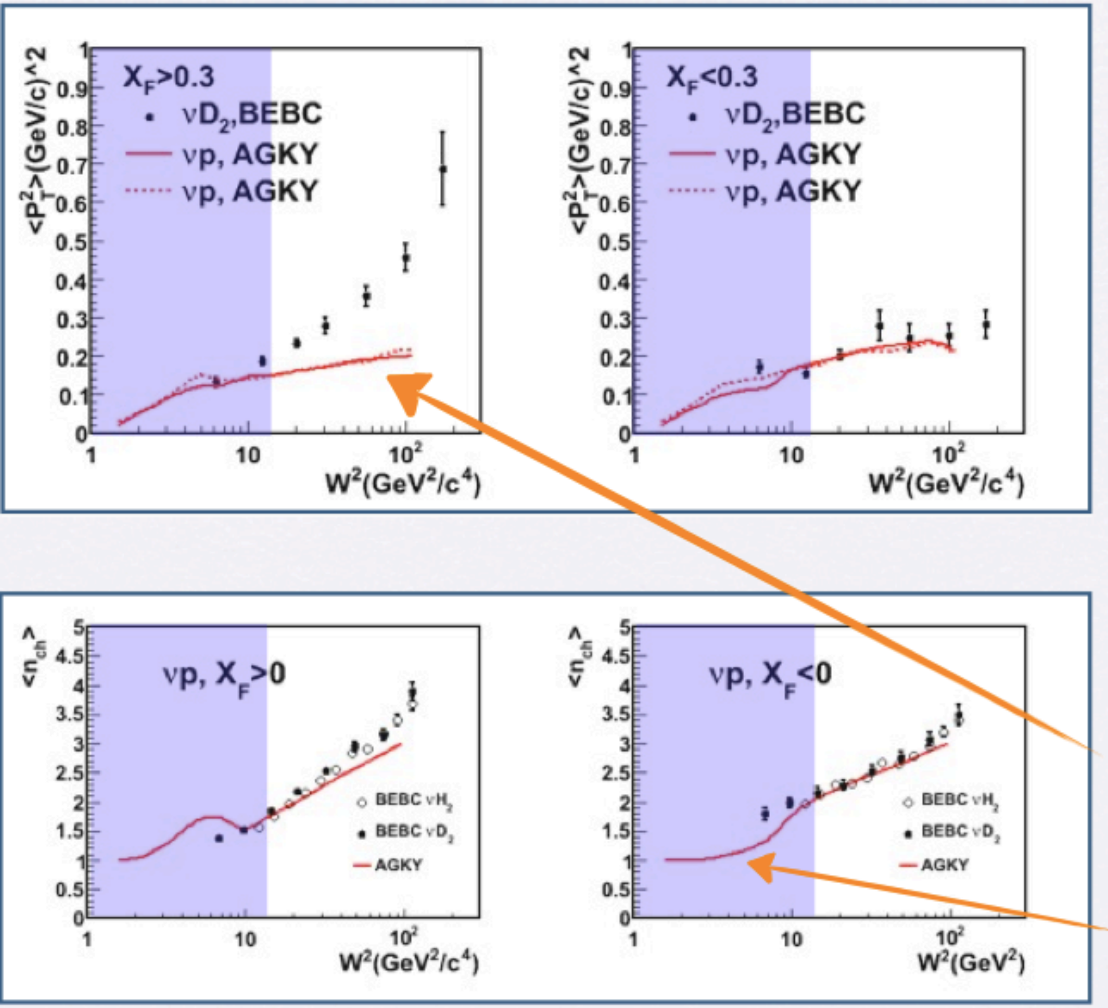
Initial Nue ND Data

- ND predicts backgrounds ~20% higher than observed
  - Hadronization and final state interactions uncertainties give rise to large uncertainties in ND prediction
  - External data sparse in our region of interest
  - Strong background suppression—select tails of BG distributions



Phys. Rev. Lett. 103 (2009) 261802

Hadronization Model Tuning



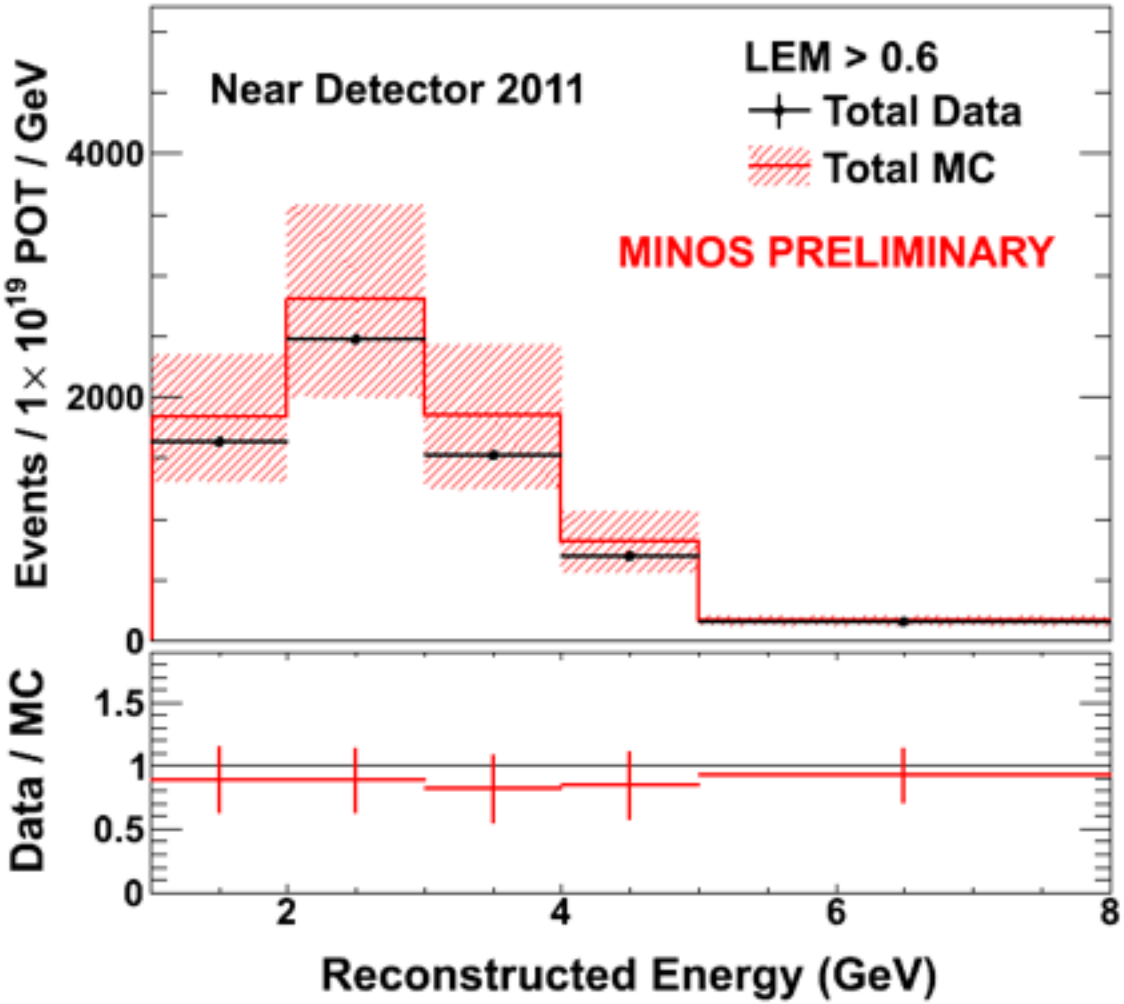
Region of interest: 1 - 15 GeV^2 in W^2

- MC tuned to external bubble chamber data for hadronization models.
- Tuning focused in the following quantities:
  - Charged/neutral pion multiplicity and dispersion.
  - Forward/backward fragments.
  - Fragmentation functions.
  - Transverse momentum.
- Transverse momentum still too low in forward hemisphere.
- Model at lower W^2 is an extrapolation.

Ref: T. Yang Thesis, Stanford 2009

(Slide from M. Sanchez, W&C April 2009)

Current Near Detector Data

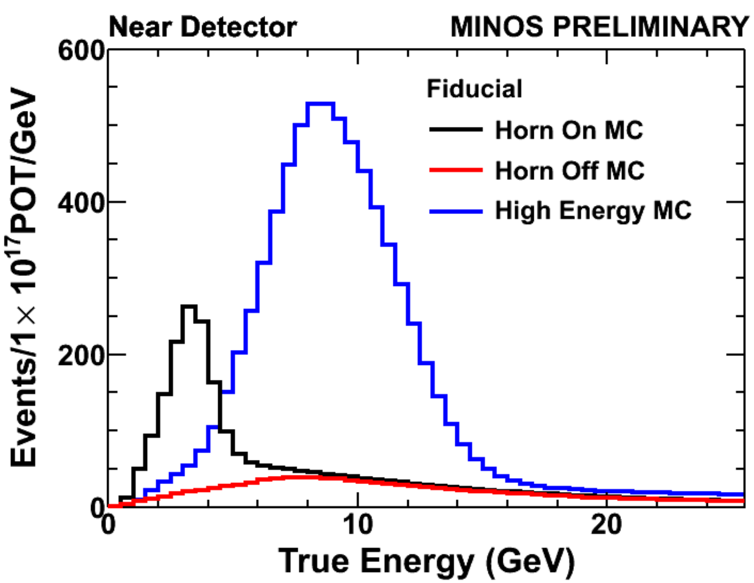


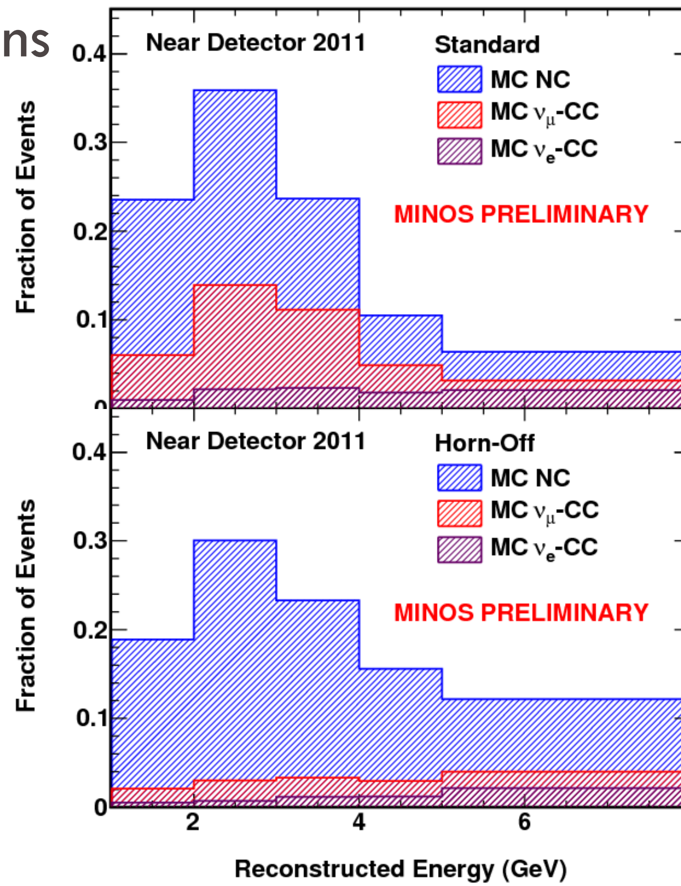
Improvements to nuclear rescattering model in MC has reduced data/MC discrepancies in current analyses

Phys. Rev. Lett. 107 (2011) 181802

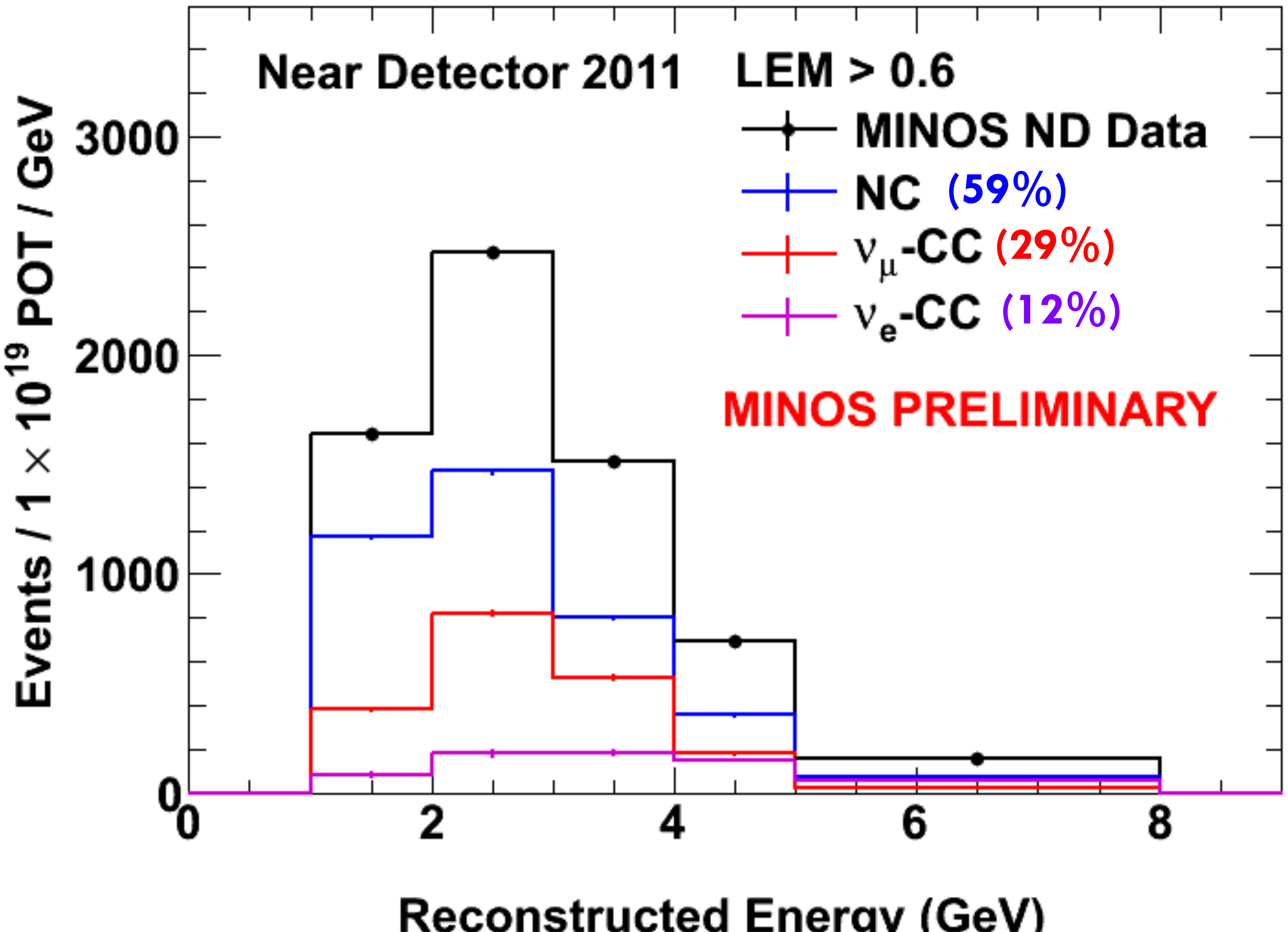
Measuring the Background

- Large uncertainties from hadronization will cancel in extrapolation to FD
- But ND data comprised of 3 parts, each extrapolates differently
- Use ND data in different configurations to extract relative components

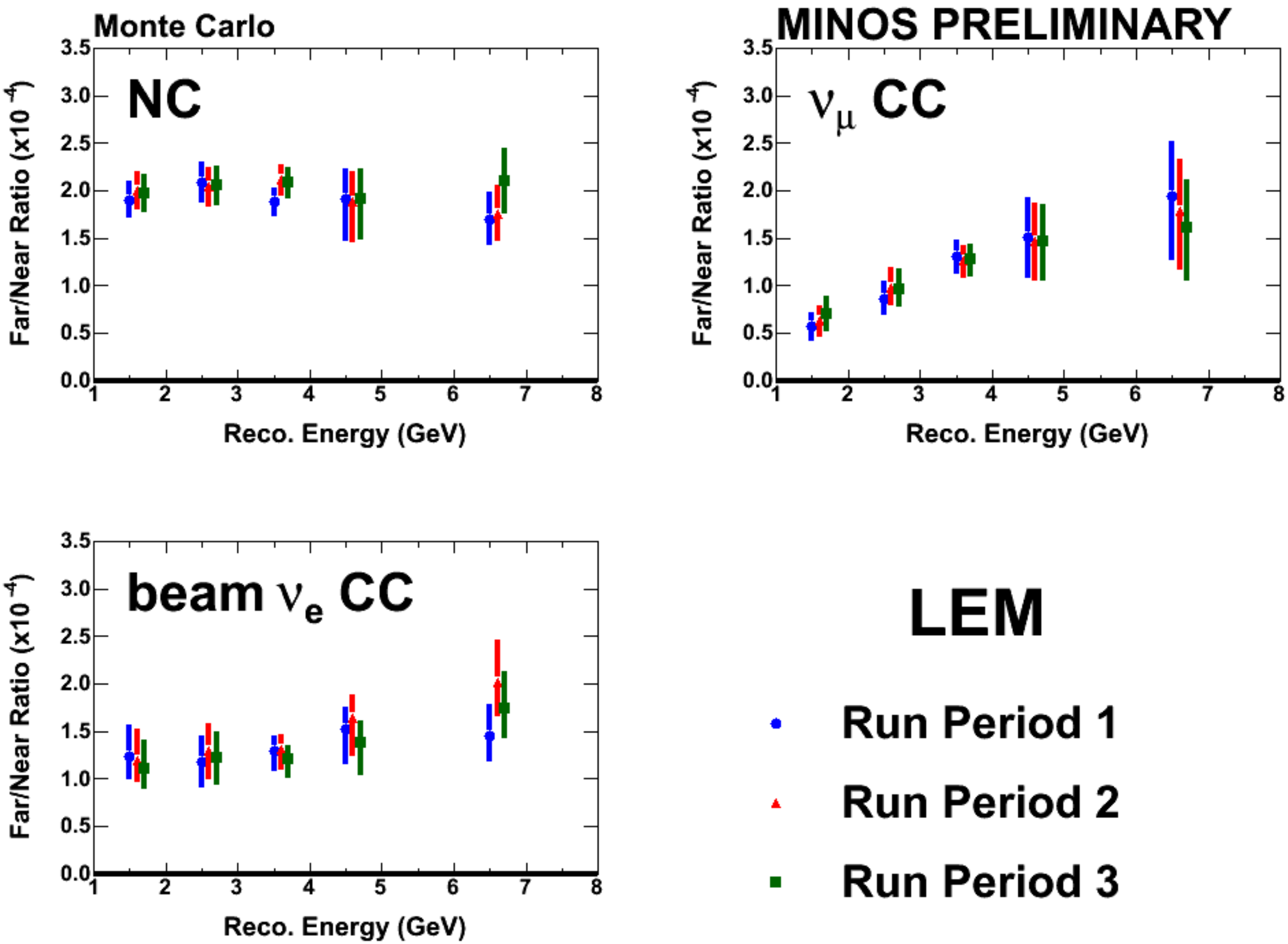




Decomposition



Electron-neutrino F/N ratios



Current Electron-neutrino Systematics

- Systematics evaluated using modified MC
- Systematics in each bin included in fit as nuisance parameters

Systematic	
Calibration	$\pm 4.2\%$
Hadronic Errors	$\pm 0.8\%$
Cross Section and Intranuclear Model	$\pm 0.7\%$
Normalization	$\pm 1.9\%$
Beam Model	$\pm 0.7\%$
Crosstalk	$\pm 2.0\%$
Total Far/Near Ratio	$\pm 5.3\%$
ν_τ CC Component Uncertainties	$\pm 2.1\%$
ND Decomposition Error	$\pm 0.3\%$
Total Systematic Uncertainty	$\pm 5.7\%$
Preliminary	

Early estimates predicted a 10% systematic error on the BG prediction

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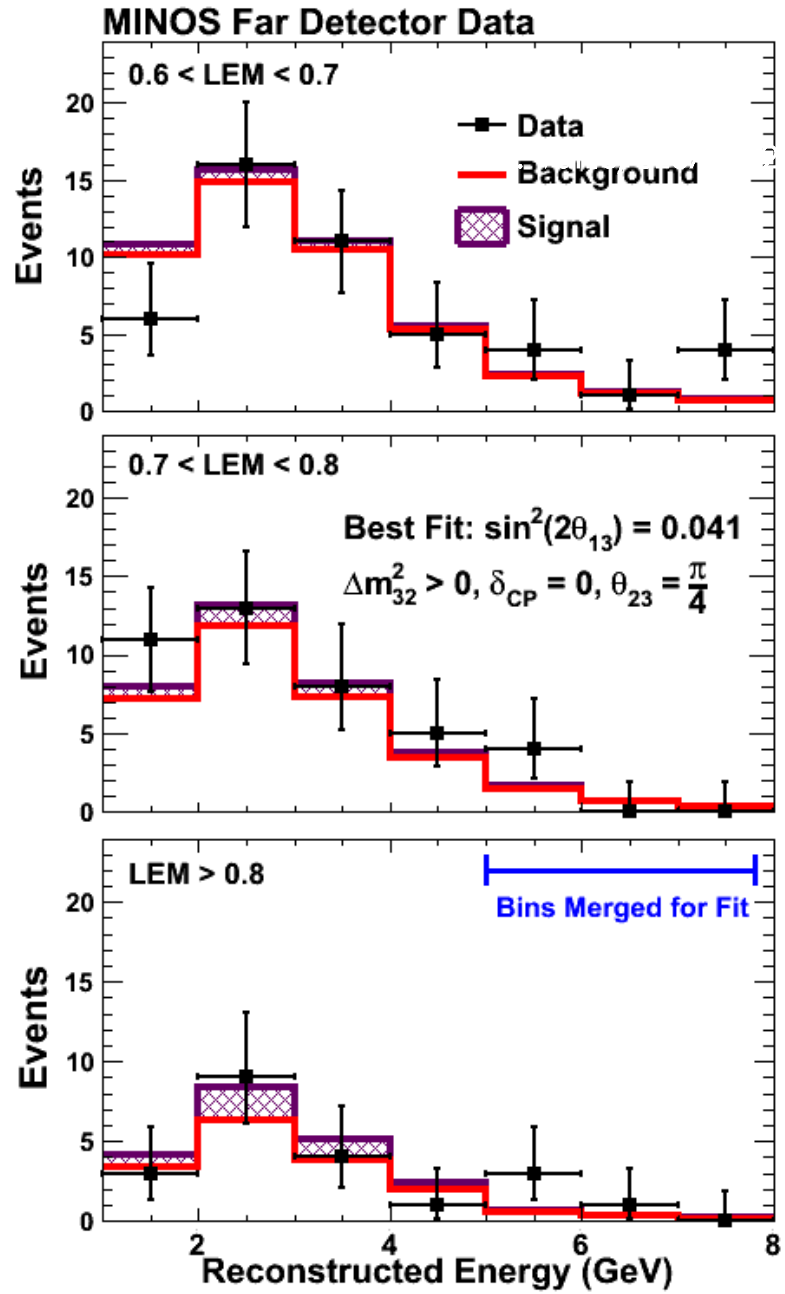
Fitting to Oscillations

- Expect: **49.6±7.0(stat.)±2.7(syst.)**

  (in signal enhanced region)
- Observe: **62** events in the FD
- Best fit: $\sin^2(2\theta_{13})=0.041$

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



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ν_e Appearance Results

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

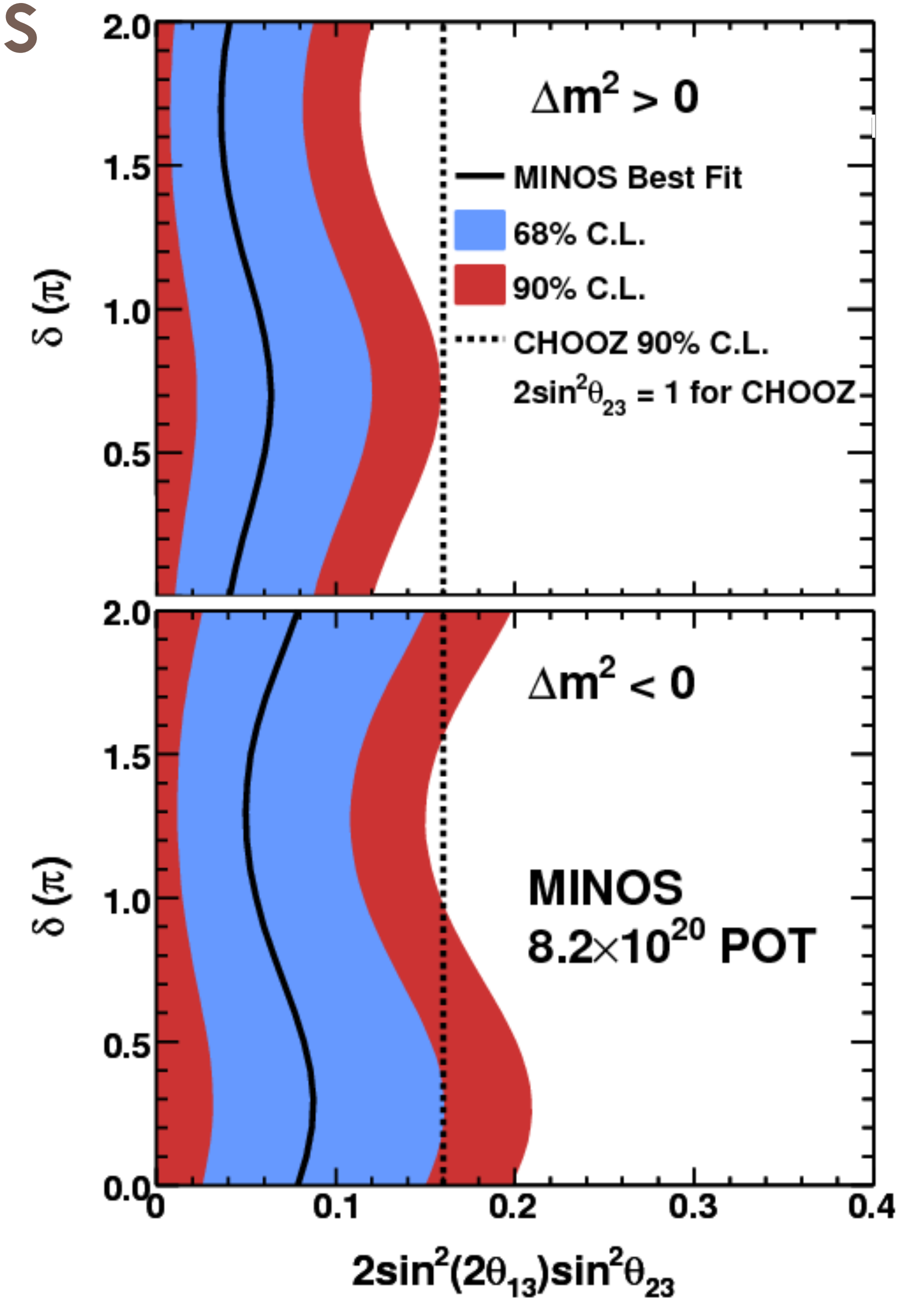
$|\Delta m^2_{32}| = 2.32 \times 10^{-3}\ \text{eV}^2$

$\sin^2(2\theta_{13}) = 0.041\ \ (0.079)$ at best fit

$\sin^2(2\theta_{13}) < 0.12\ \ (0.20)$ at 90% C.L.

$\sin^2(2\theta_{13}) = 0$ excluded at 89%

hep-ex:1108.0015



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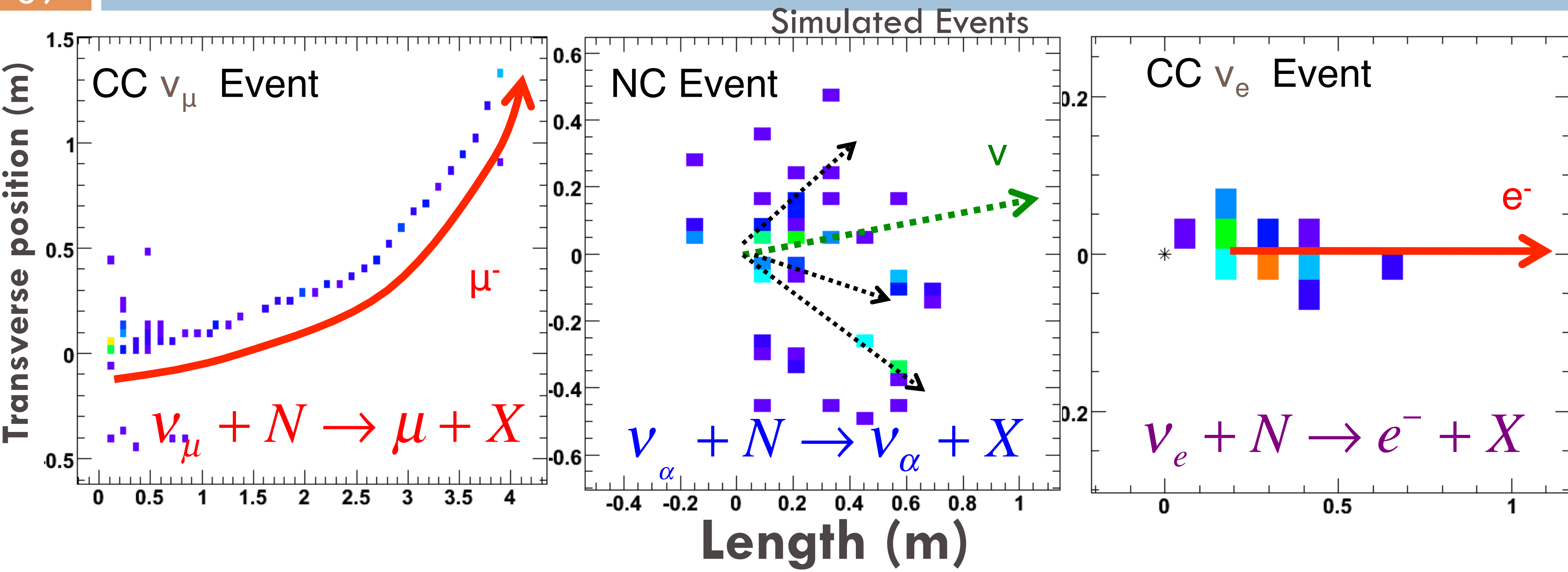
Summary

- Two detector design mitigates major uncertainties
  - Cross section uncertainties
  - Neutrino flux and beam systematic uncertainties
- Different extrapolation techniques provide same prediction at 5% level
  - some techniques control systematics better than others, but all do fine with xsec and beam uncertainties
- Analyses are still statistics limited
  - Measure neutrino mass splitting to 5%
  - Measure antineutrino mass splitting to 12%
  - Systematic error on BG to nue appearance search <6%

Events in MINOS



- long μ track, hadronic activity at vertex
- energy sum of muon energy (range or curvature) and shower energy

- short, diffuse shower
- energy from calorimetric response

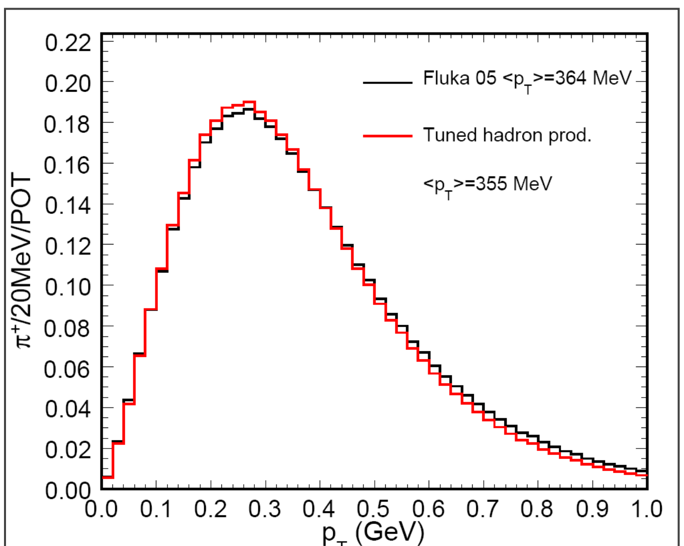
- compact shower with EM core
- energy from calorimetric response

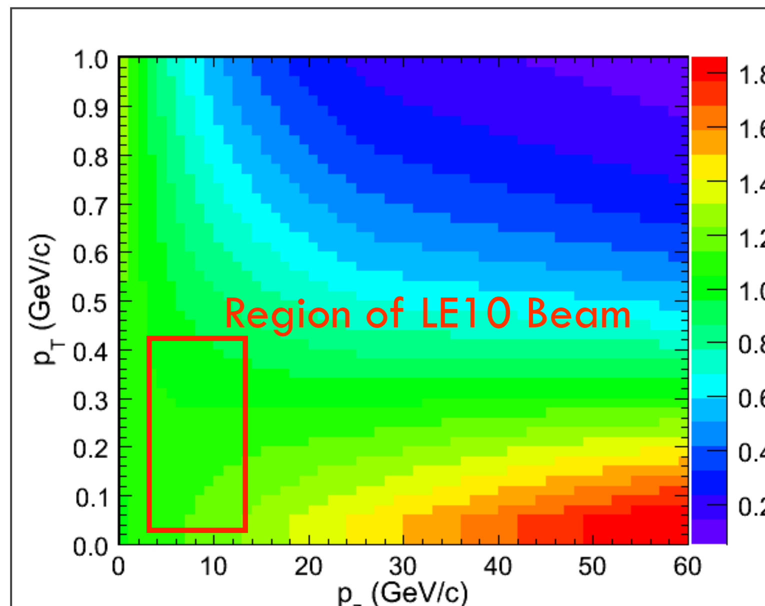
Hadron Production Tuning

Model	$\langle p_T \rangle$ (GeV/c)
GFLUKA	0.37
Sanf.-Wang	0.42
CKP	0.44
Malensek	0.50
MARS – v.14	0.38
MARS – v.15	0.39
Fluka 2001	0.43
Fluka 2005	0.364
Fluka2005 Tuned	0.355

Weights ~20% in region of p_T vs p_z that produces MINOS neutrinos

Hadron production tuning changes mean p_T less than model spread





SKZP

Fit Fluka p_T distributions for different p_z to:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}p_z \mathrm{d}p_T} = \left[A(p_z) + B(p_z) p_T \right] e^{(-C(p_z) p_z^{3/2})}$$

Parameterize A, B, C as functions of p_z

$$A(p_z) = 0.186\left(1 - p_z\right)^{3.63} \left(1 + 1501.3 p_z\right) p_z^{-2.89}$$

$$B(p_z) = 0.57\left(1 - p_z\right)^{2.94} \left(1 + 9716.8 p_z\right) p_z^{-3.03}$$

$$C(p_z) = \frac{26.8}{p_z^{0.0326}} - 24.7$$

Warp A, B, C, weight MC to fit data:

$$A' = par[0] A(p_z)$$

$$B' = (1 + par[1](0.1 - p_z) B(p_z)$$

$$C' = par[2] C(p_z)$$

$$w = \frac{A' + B p_T}{A + B p_T} e^{(-(C' - C) p_T^{3/2})}$$

Initial CC Systematics

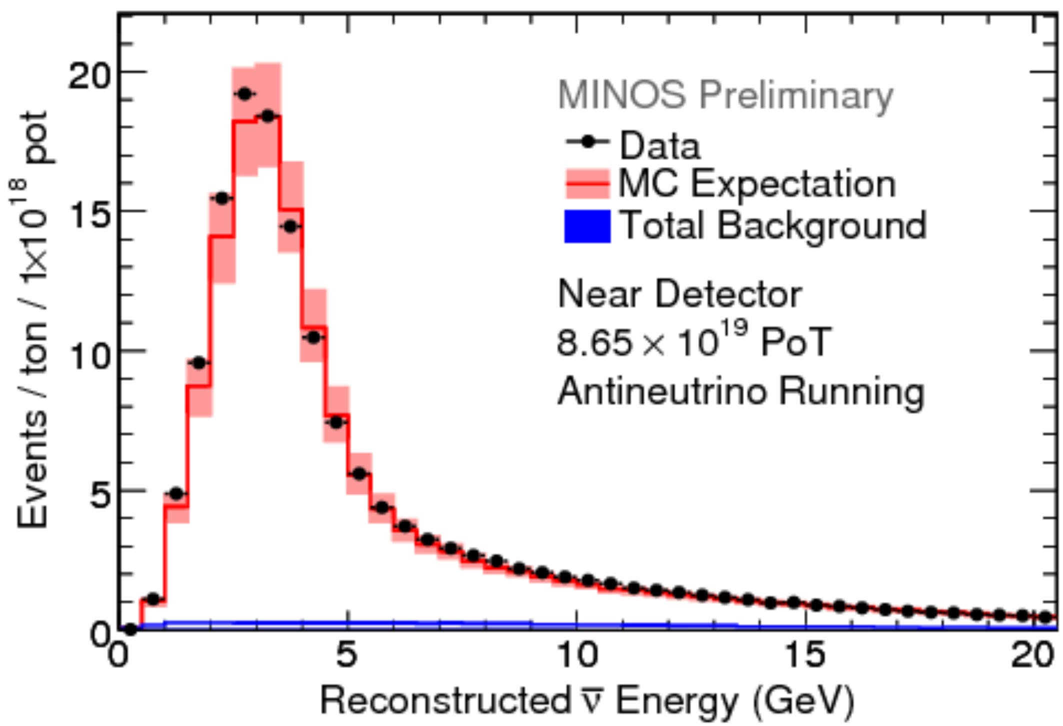
Uncertainty		$\lvert\Delta m^2\rvert$ $(10^{-3}\,\mathrm{eV}^2/c^4)$	$\sin^2 2\theta$
(a) Normalization	(±4%)	0.050	0.005
(b) Abs. hadronic E scale	(±11%)	0.057	0.048
(c) NC contamination	(±50%)	0.090	0.050
(d) Beam uncertainties		0.015	<0.005
(e) Cross sections		0.011	0.005
All other systematics		0.041	0.013
Statistical Error		0.35	0.13

Shower Energy systematic

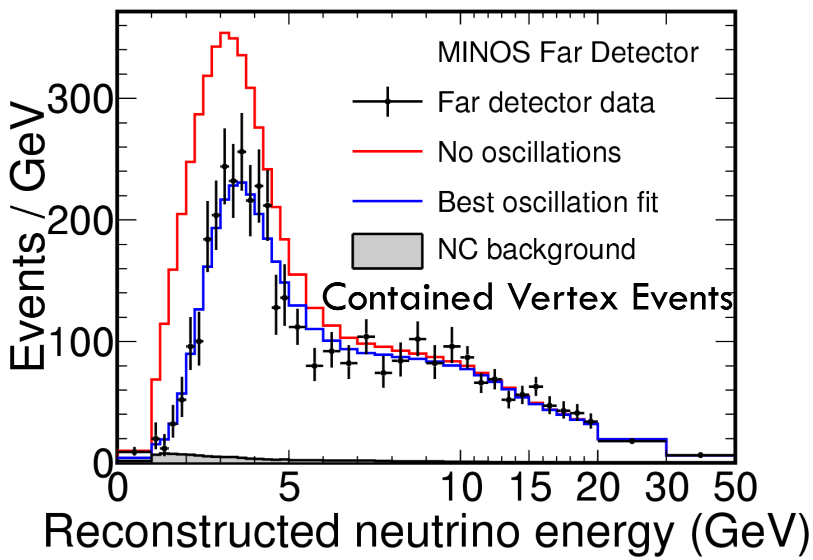
- Final state interactions are expected to have a significant effect on the visible energy of the hadronic final state [41]. In particular there are significant uncertainties in the rate of pion absorption, the mechanism for transferring the pion's energy to a nucleon cluster, and the amount of energy eventually visible to the detector. We account for these uncertainties by studying the shift in the reconstructed shower energy when we turn the simulation of final-state interactions off, and when we modify the simulation so that all of an absorbed pion's energy is lost. We find that the predicted response to hadronic showers changes by approximately 10% [41] in these two extreme cases and use this as a conservative estimate of the uncertainty on the absolute hadronic energy scale.

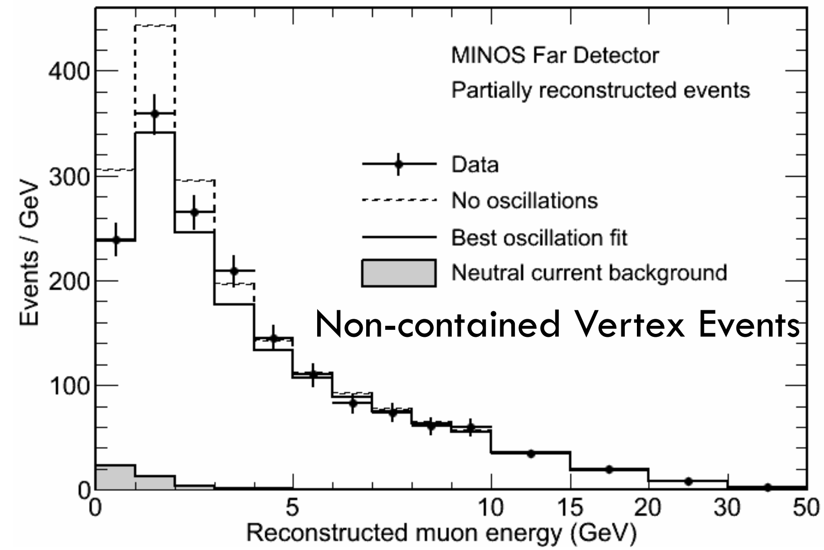
ND Anti-neutrino Data

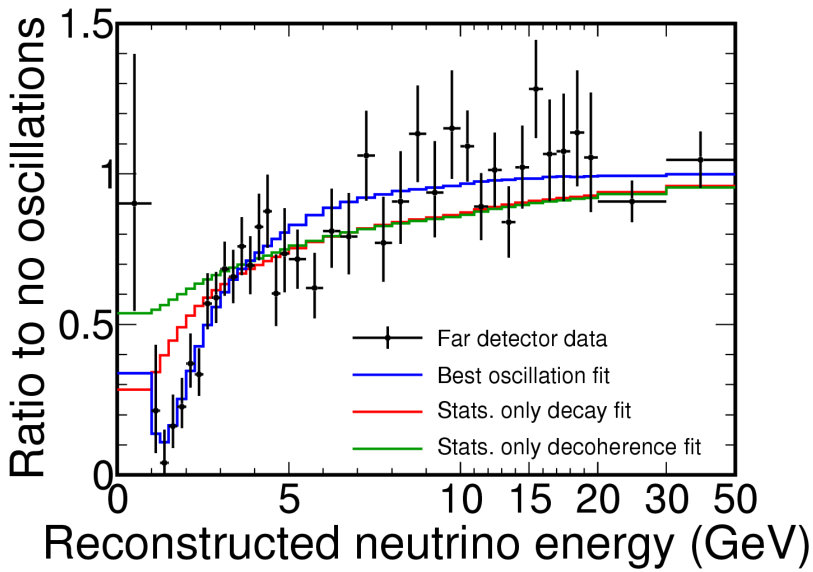
- Focus and select positive muons
  - purity 94.3% after charge sign cut
  - purity 98% < 6GeV
- Analysis proceeds as (2008) neutrino analysis
- Data/MC agreement comparable to neutrino running
  - different average kinematic distributions
  - more forward muons



Far Detector CC Events





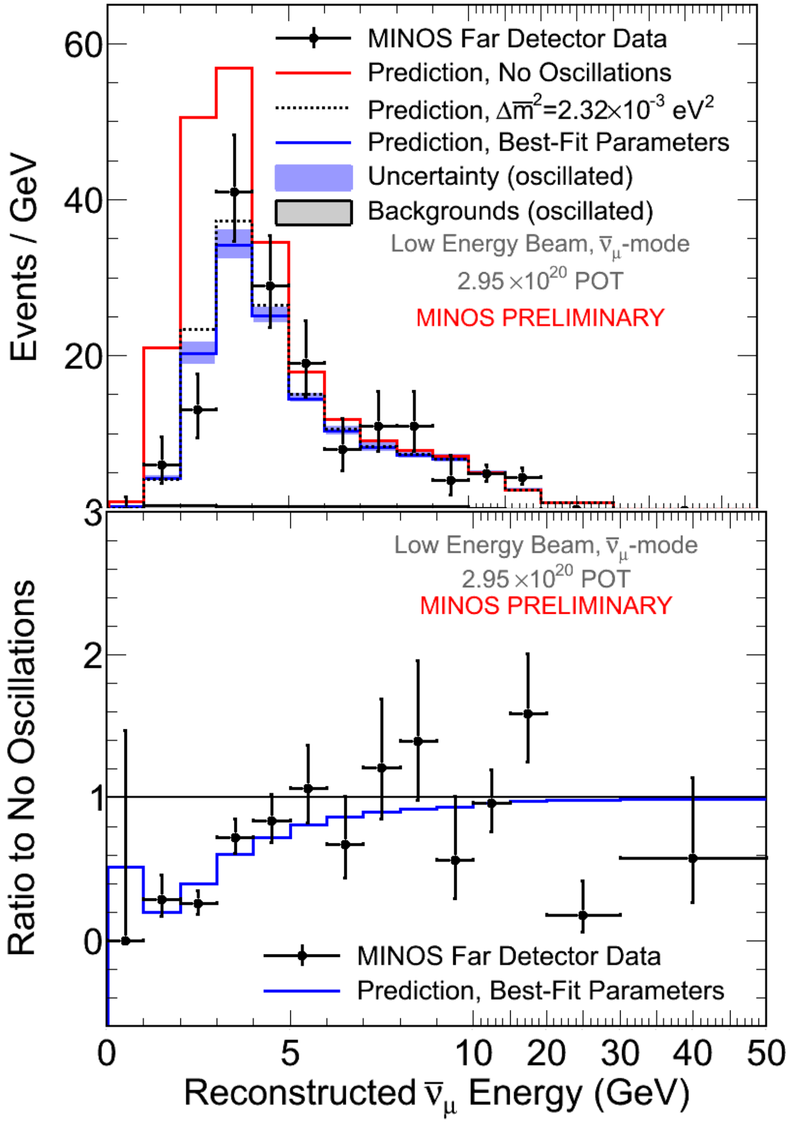


	Predicted (no osc.)	Observed
Contained	2451	1986
Non-contained	2206	2017

- Oscillations fit the data well, 66% of experiments have worse χ^2

P. Adamson *et al.*, Phys.Rev.Lett. 106 181801 (2011)

Anti-ν_μ Disappearance

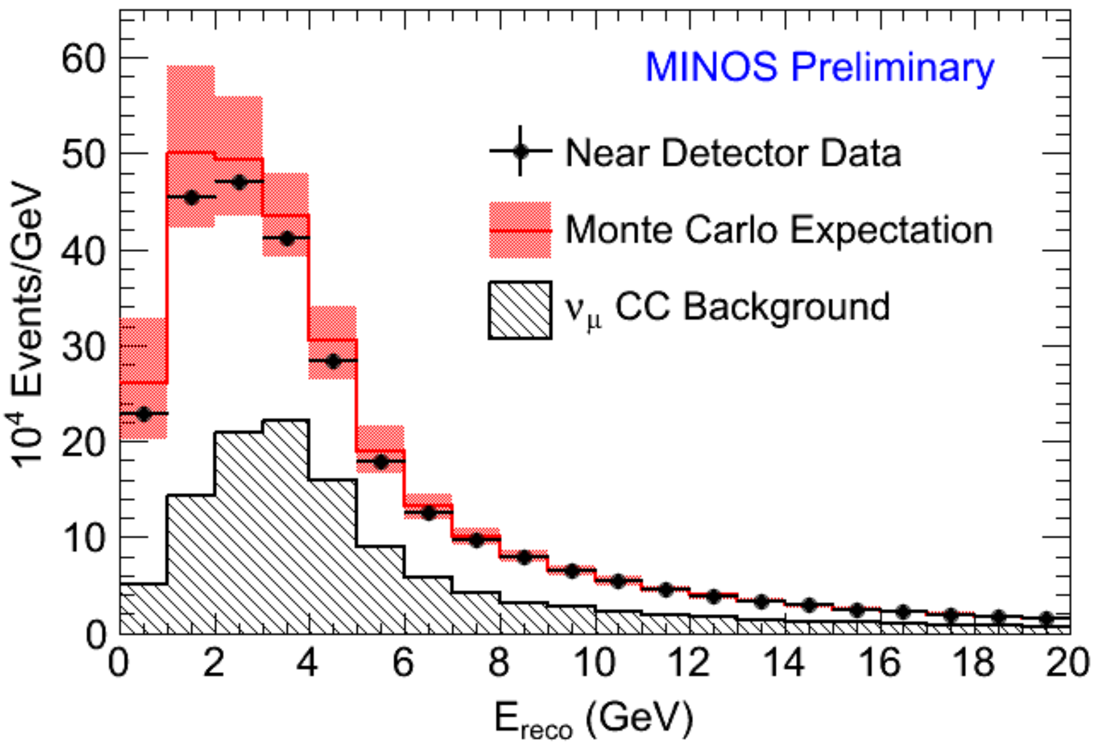


- No oscillations: 276
- Oscillated Prediction: 196
- Observe: 197
- No oscillations disfavored at 7.3σ

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

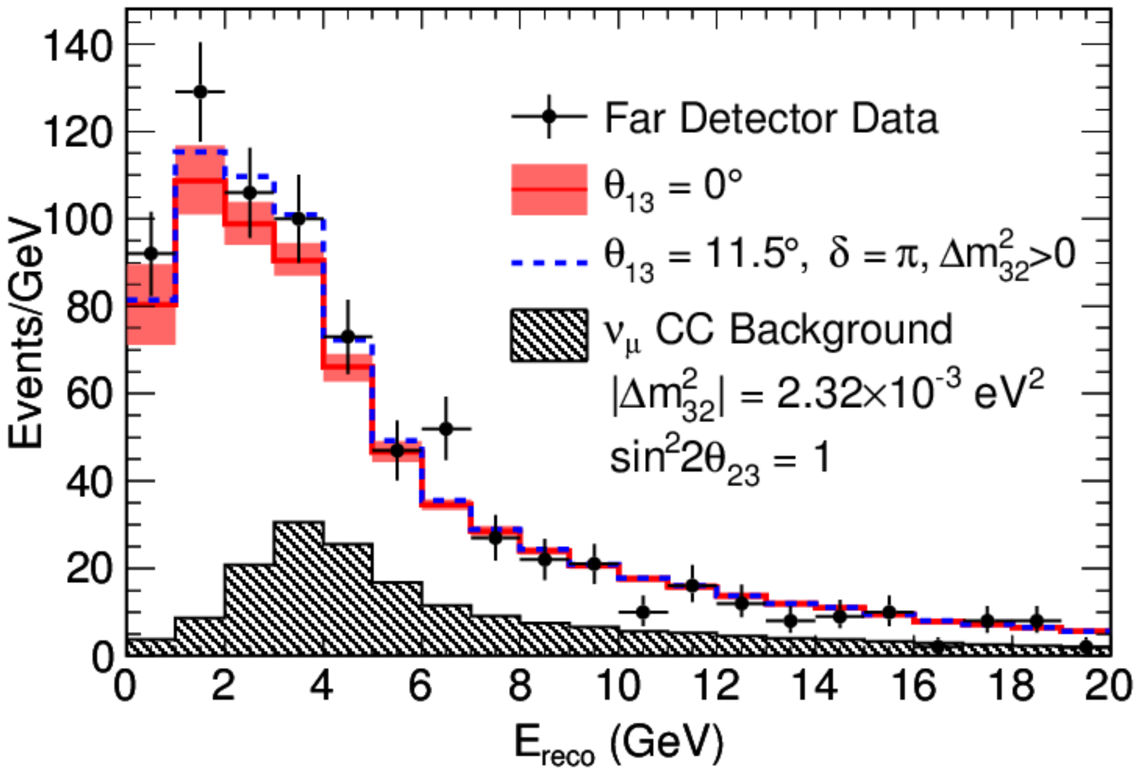
$$\sin^2(2\overline{\theta}) > 0.75\ (90\%\ \text{C.L.})$$

Neutral Current Near Event Rates



- Neutral Current event rate should not change in standard 3 flavor oscillations
- A deficit in the Far event rate could indicate mixing to sterile neutrinos
- ν_e CC events would be included in NC sample, results depend on the possibility of ν_e appearance

Neutral Currents in the Far Detector



- Expect: **757** events
- Observe: **802** events
- No deficit of NC events

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

$1.09 \pm 0.06\,(\text{stat.}) \pm 0.05\,(\text{syst.})$

(no ν_e appearance)

$1.01 \pm 0.06\,(\text{stat.}) \pm 0.05\,(\text{syst.})$

(with ν_e appearance)

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

no (with) ν_e appearance

ν_e Appearance

- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m_{32}^2 L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \quad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

"Atmospheric" Term
Depends on Δm^2
and unknown θ_{13}

"Solar" Term
<1% for current
accelerator experiments

ν_e Appearance

- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}} e^{-i(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp})} + \sqrt{P_{sol}} \right|^2$$

$$2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos\left(\frac{\Delta m^2_{32} L}{4E}\right) \cos\delta_{CP} \mp 2\sqrt{P_{atm}}\sqrt{P_{sol}} \sin\left(\frac{\Delta m^2_{21} L}{4E}\right) \sin\delta_{CP}$$

Interference Term

- for neutrinos

+ for antineutrinos

if $\delta_{CP} \neq 0$,

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

ν_e Appearance

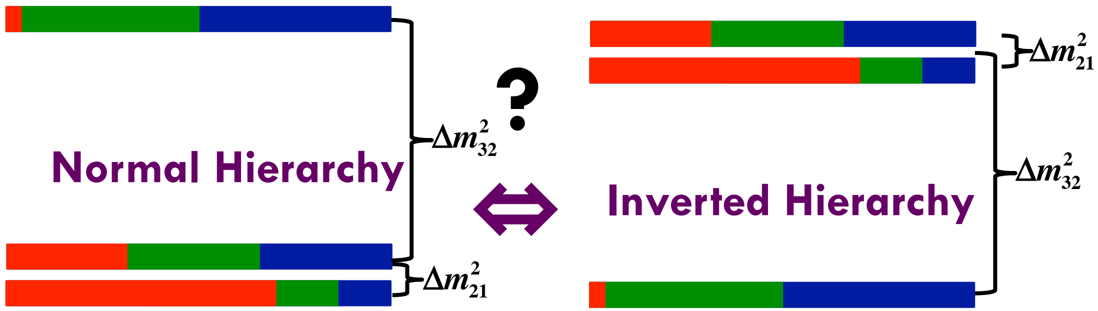
- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E} - aL\right)\left(\frac{\frac{\Delta m^2_{31}L}{4E}}{\left(\frac{\Delta m^2_{31}L}{4E} - aL\right)}\right)^2$$

$$P_{sol} \approx \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(aL)\left(\frac{\frac{\Delta m^2_{21}L}{4E}}{aL}\right)^2$$

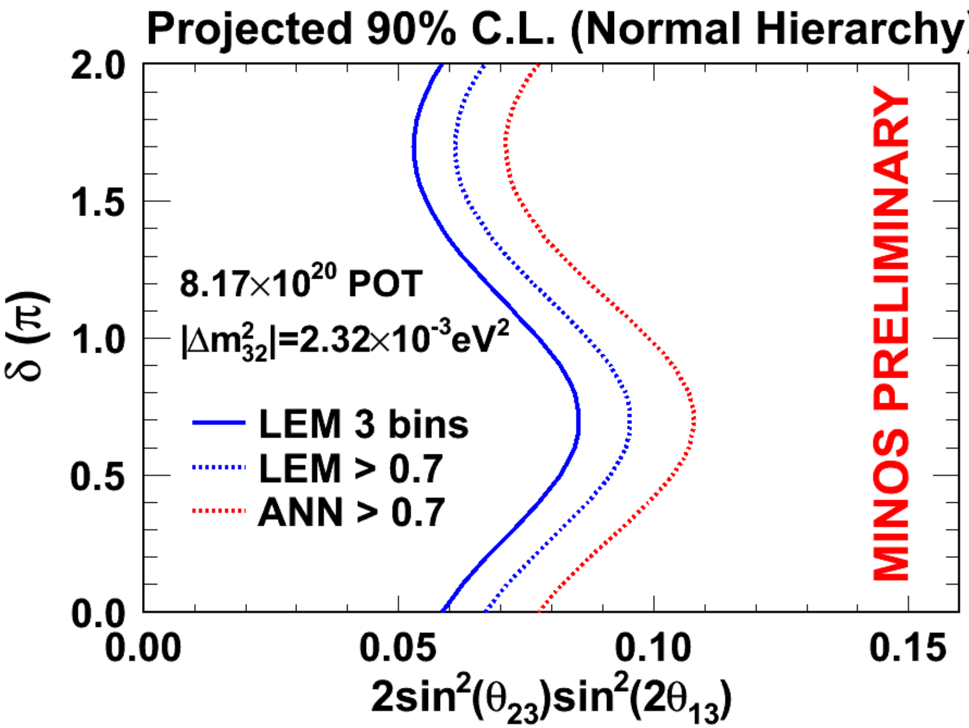
$$a = \pm\frac{G_F N_e}{\sqrt{2}} \approx (4000\ \text{km})^{-1}$$



In matter, additional term in Hamiltonian from ν_e + e CC scattering modifies oscillation probability, ~30% effect in MINOS

The Updated Analysis

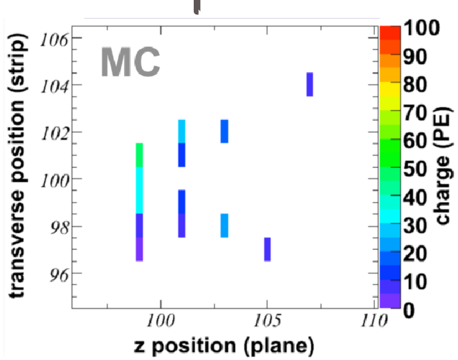
- Look for an excess of ν_e in the FD compared to prediction from ND measurement
  - select events with a ν_e topology
  - apply selection to ND, determine fraction of each background type
  - extrapolate each background type separately
  - fit FD data to extract oscillation parameters
- Updated analysis:
  - new event selection
  - new fitting technique in the FD
  - more data



Looking for Electron-neutrinos

- New electron neutrino selection technique
- Compare candidate events to a library of simulated signal and background events
- Comparison made on a strip by strip basis
- Discriminating variables formed using information from 50 best matches

Input (data or MC)

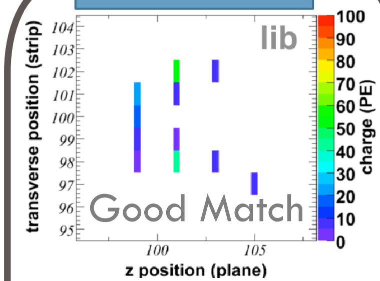


Compare to MC Library

$$L = \sum_{i=1}^{N_{strips}} \ln\left(\int_0^{\infty} P(n_A^i;\lambda)P(n_B^i;\lambda)\,d\lambda \right)$$

$$\Delta L = -(L_{lib} - L_{self})$$

Library Event #1

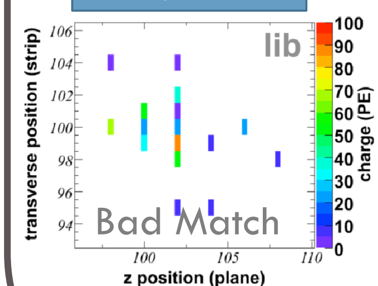


Library Event #2

Library Event #3

. . .

Library Event #k



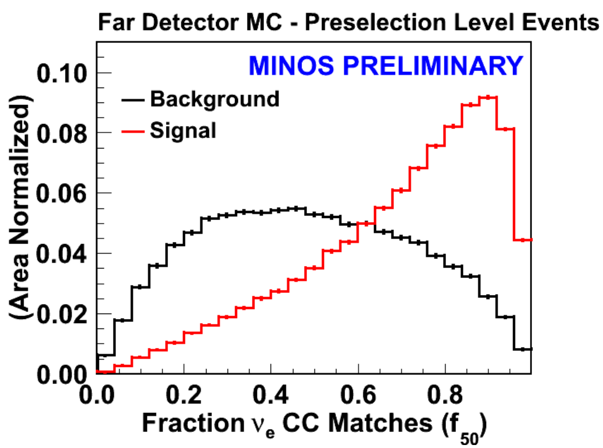
. . .

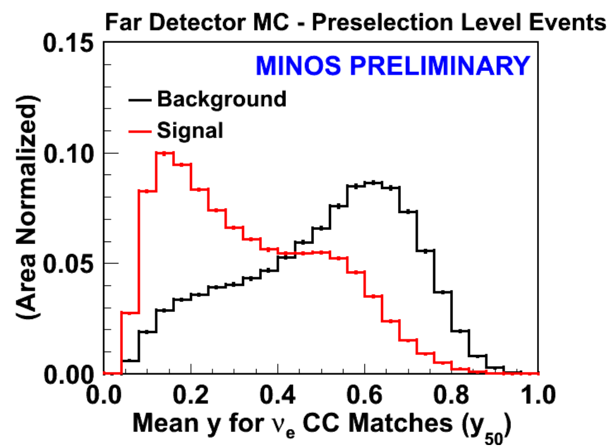
Library Event #30M

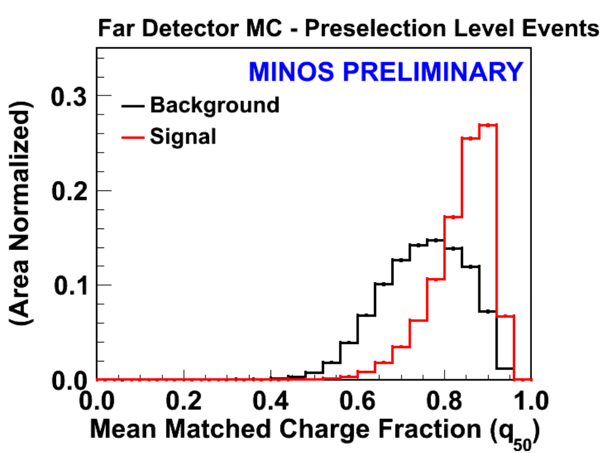
Compute variables using information from best N matches

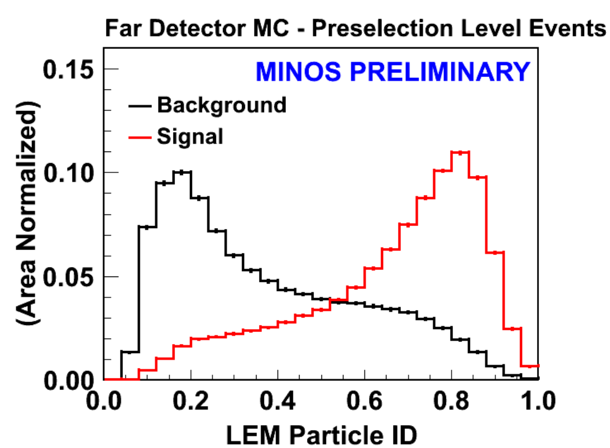
Discriminating Variables

- Three discriminating variables combined in neural net
- Achieve ~40% signal efficiency, ~98% BG rejection







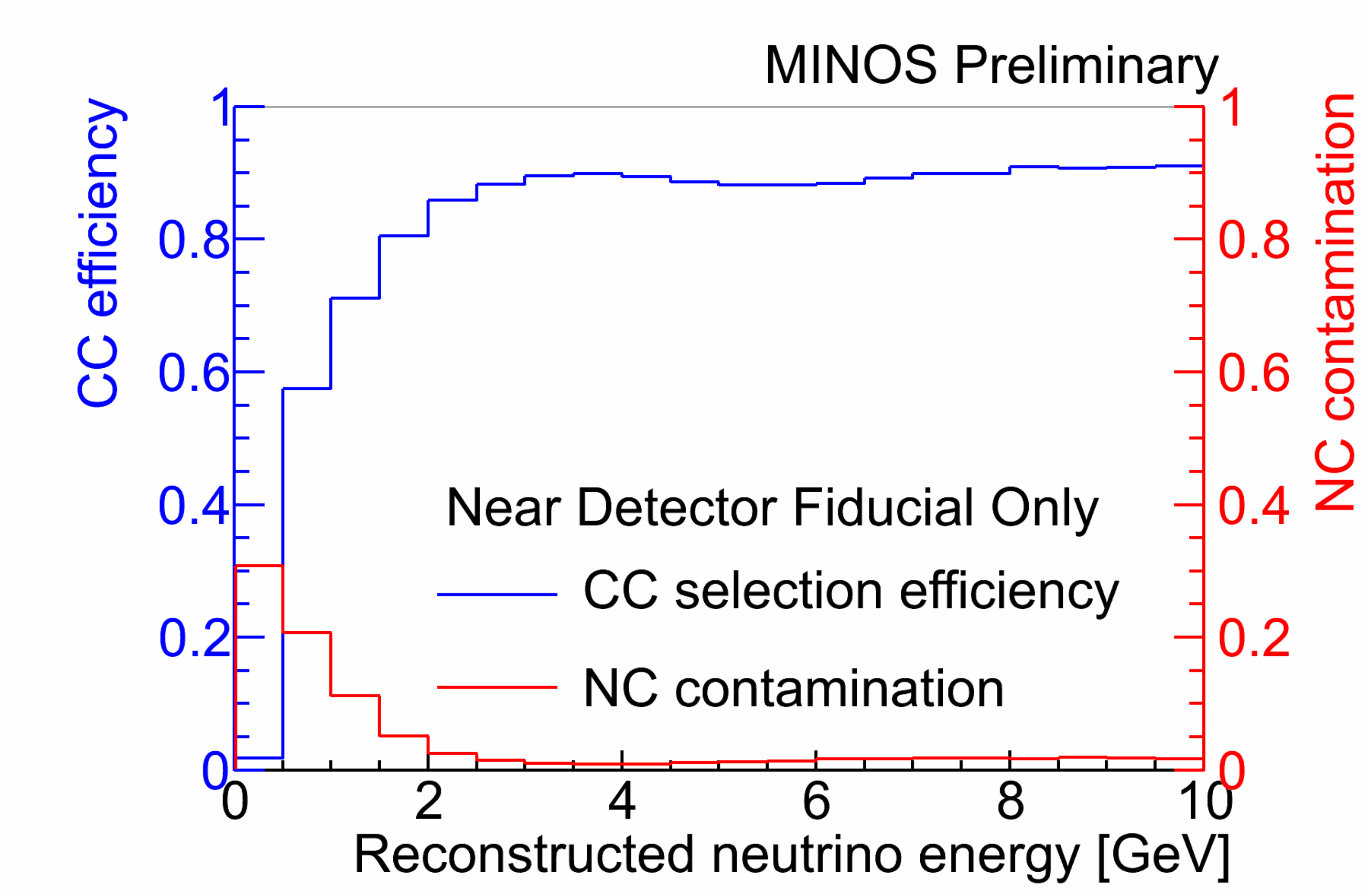


Far/Near differences

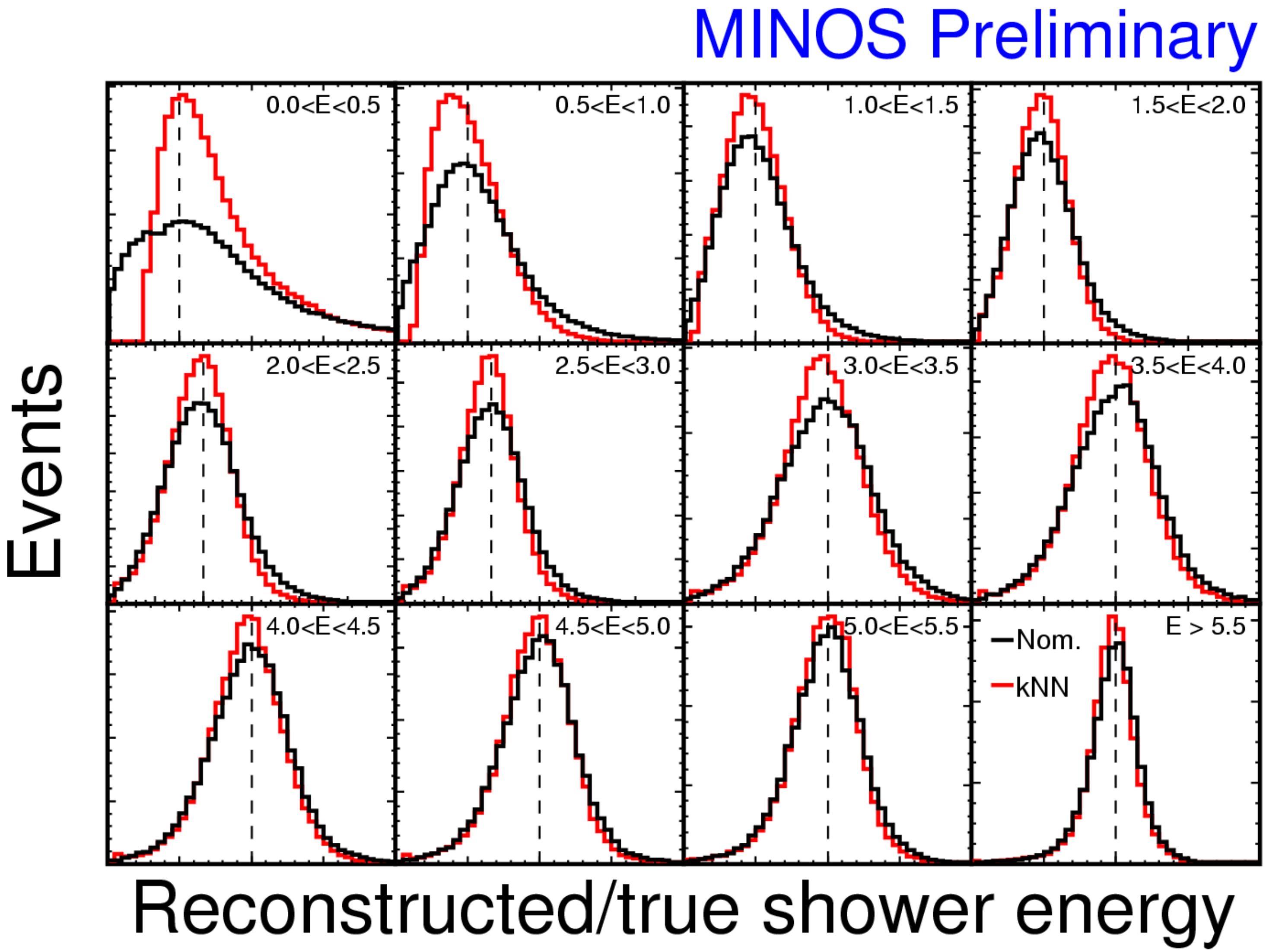
- ν_μ CC events oscillate away
- Event topology
  - Light level differences (differences in fiber lengths)
  - Multiplexing in Far (8 fibers per PMT pixel)
  - Single ended readout in Near
- PMTs (M64 in Near Detector, M16 in Far):
  - Different gains/front end electronics
  - Different crosstalk patterns
- Neutrino intensity
- Relative energy calibration/energy resolution

Account for these lower order effects using detailed detector simulation

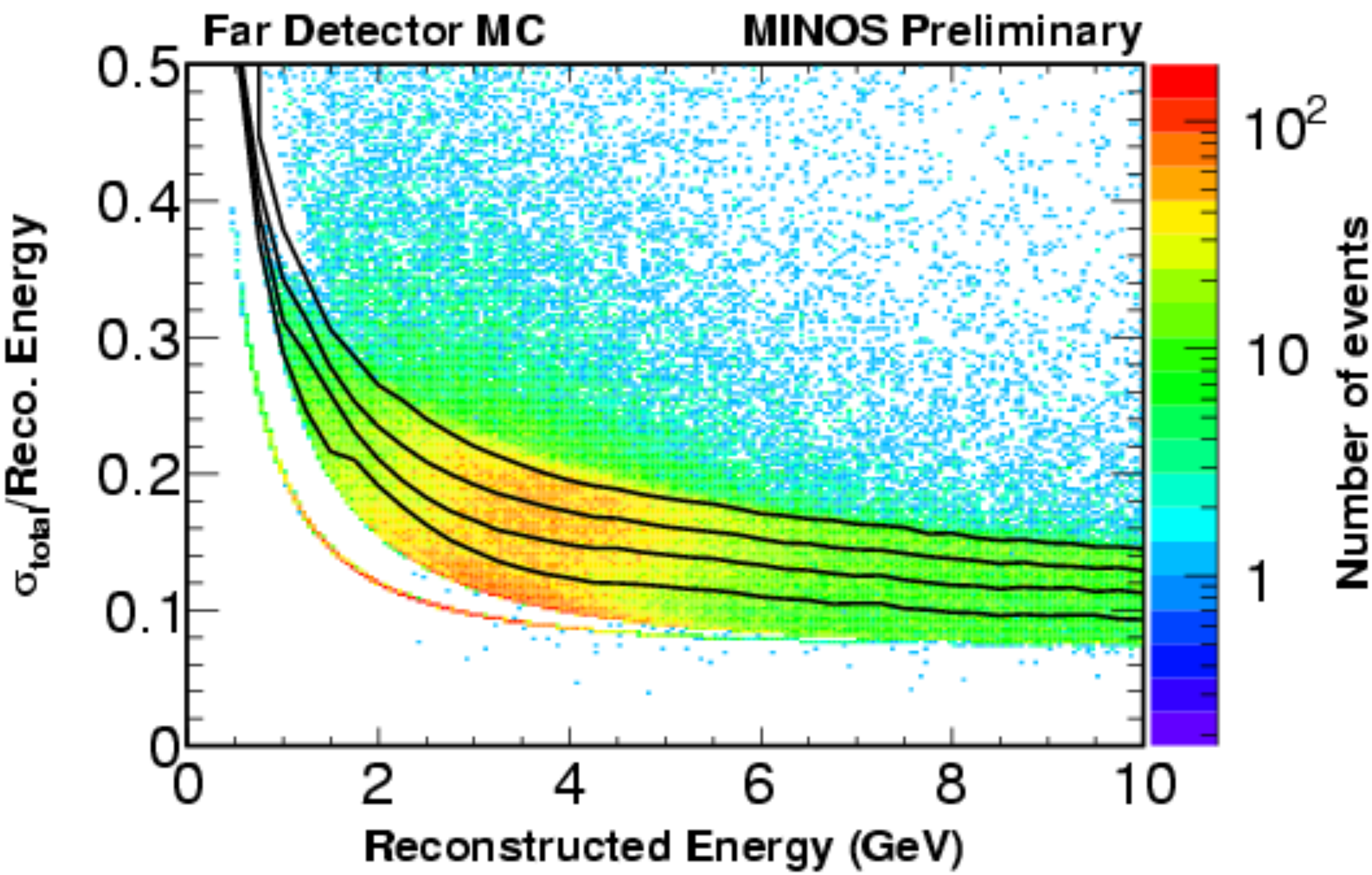
New Muon-neutrino CC Selection



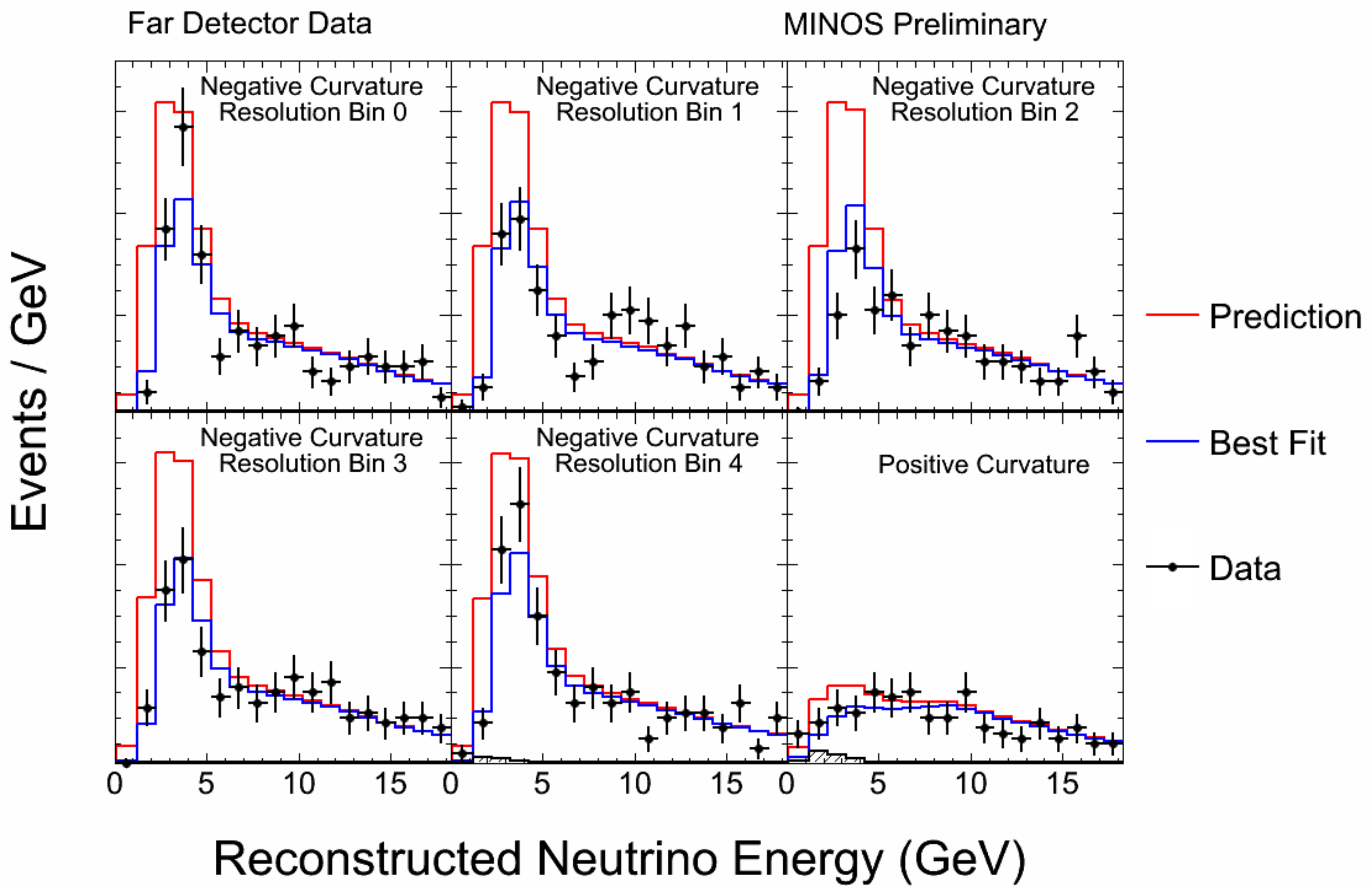
Shower Energy Resolution



Energy Resolution Binning

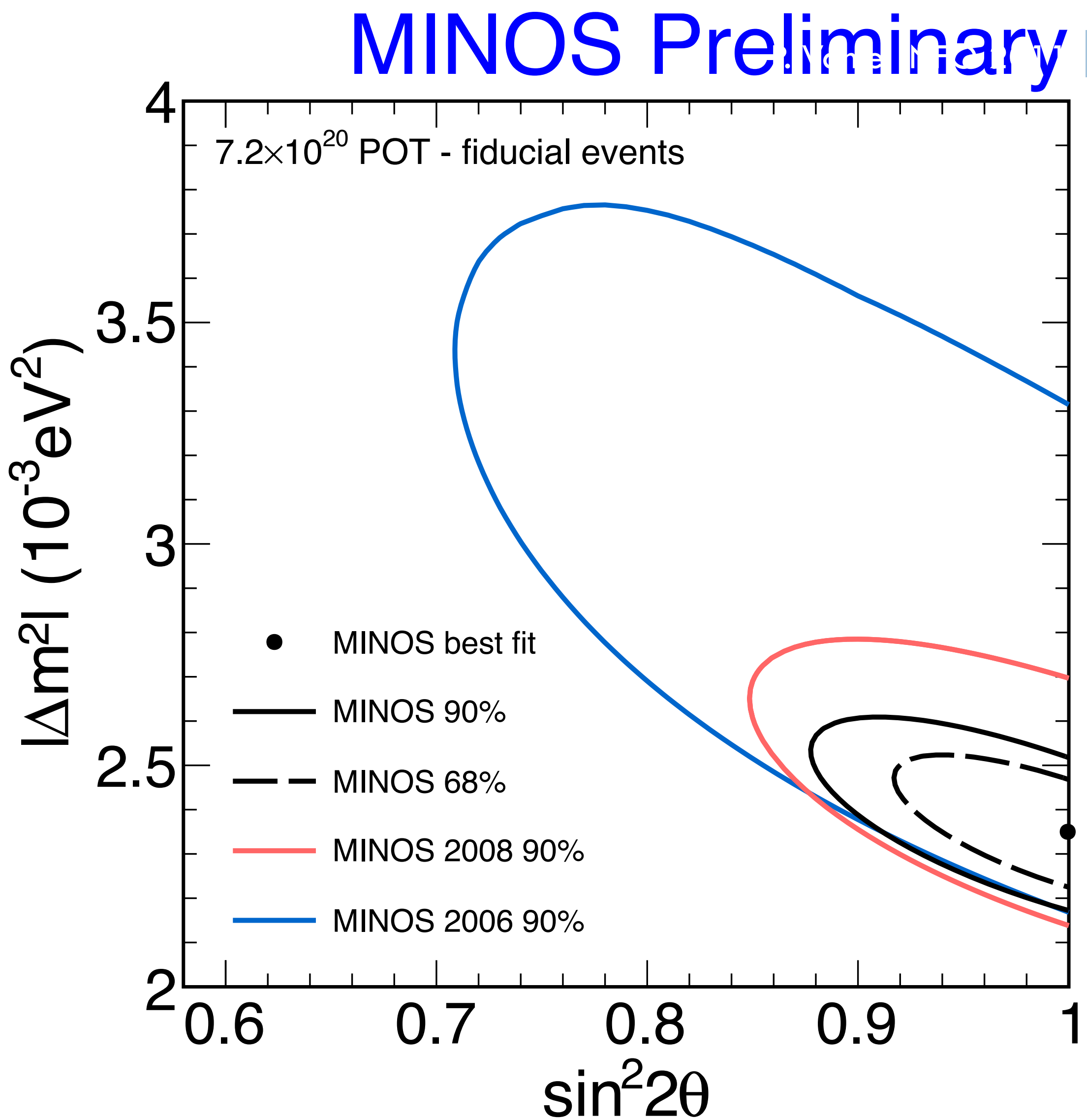


Resolution Binning

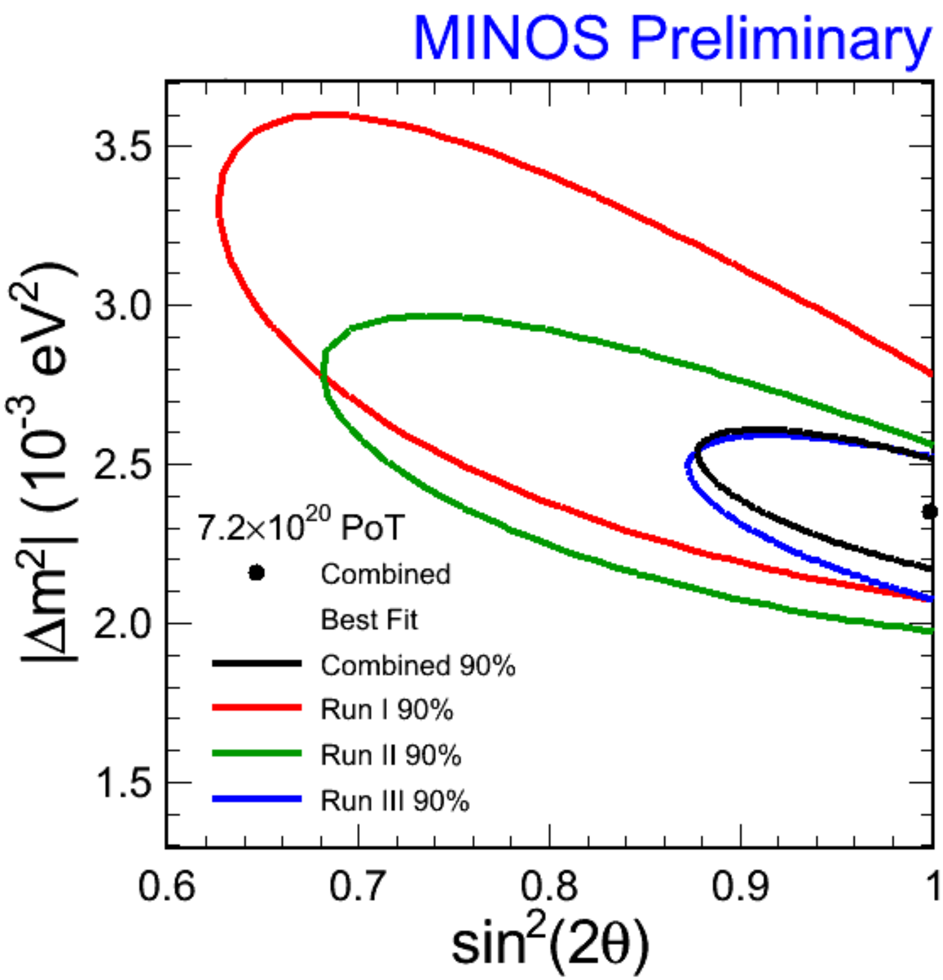


Contours

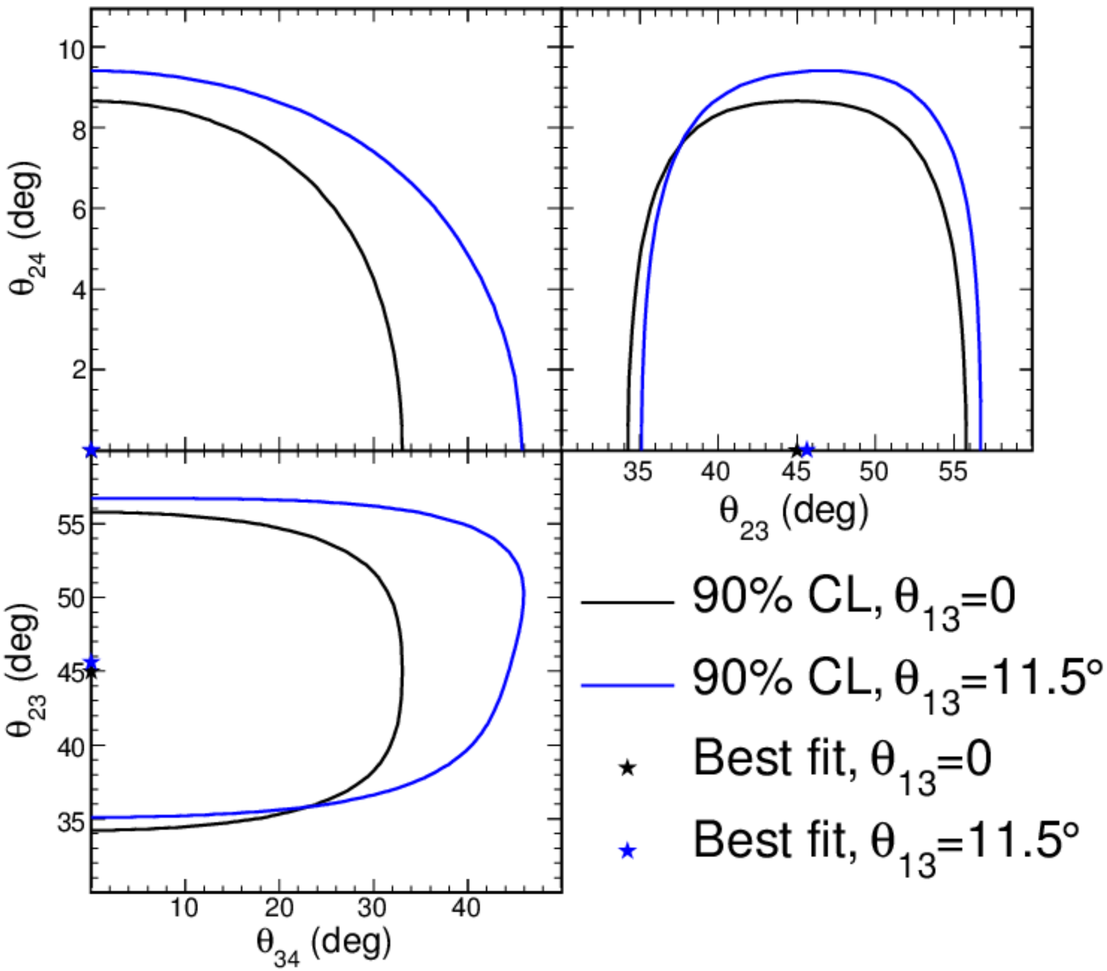
- Contour includes effects of dominant systematic uncertainties
  - normalization
  - NC background
  - shower energy
  - track energy



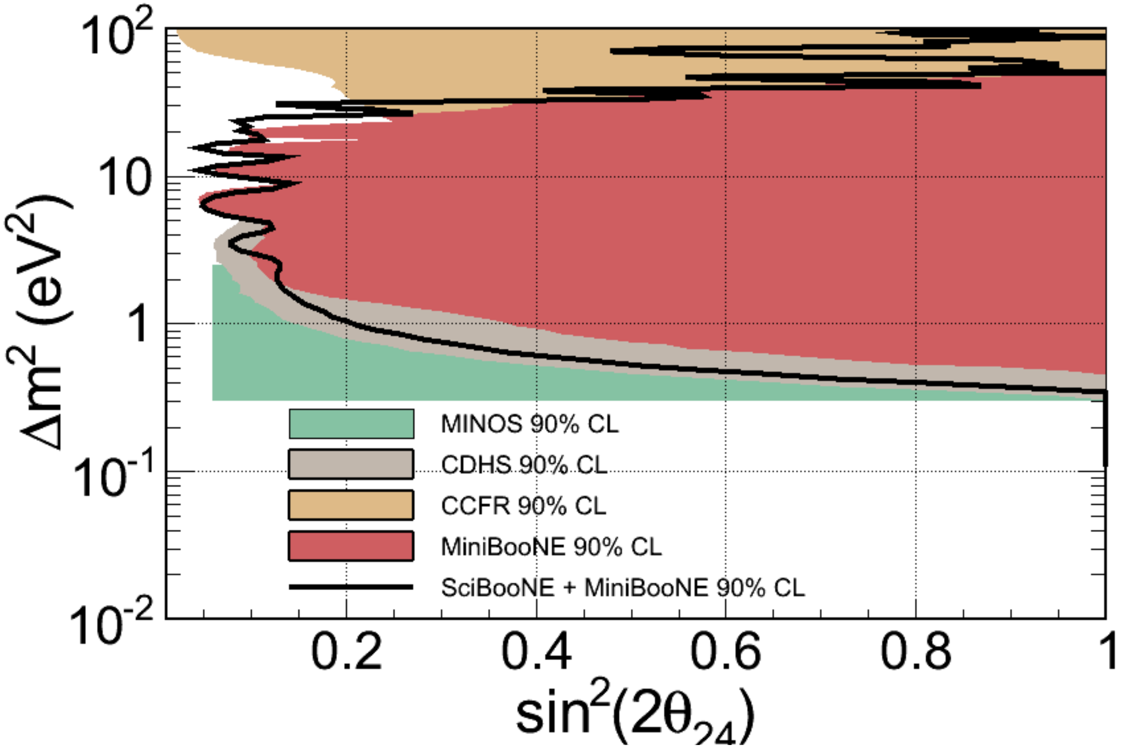
Contours by Run Period



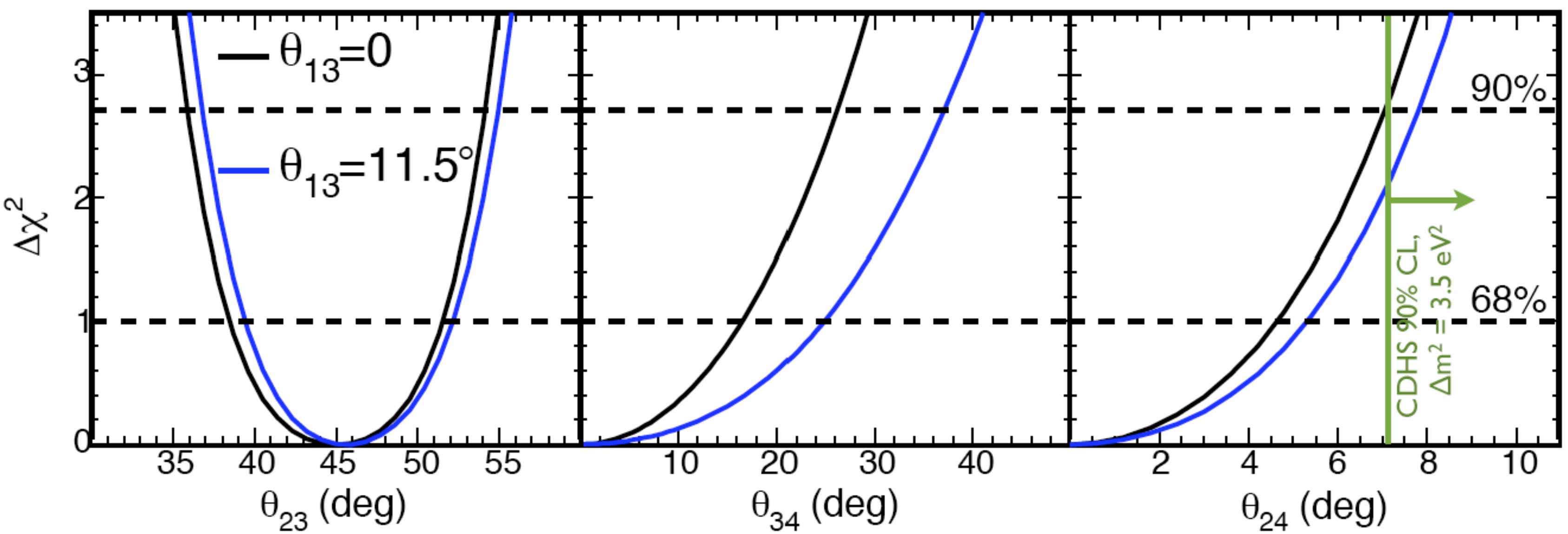
Fits to NC



- Fit CC/NC spectra simultaneously with a 4th (sterile) neutrino
- 2 choices for 4th mass eigenvalue
  - $m_4 >> m_3$
  - $m_4 = m_1$



MINOS 90% CL
CDHS 90% CL
CCFR 90% CL
MiniBooNE 90% CL
SciBooNE + MiniBooNE 90% CL
Δm^2 (eV^2)
$\sin^2(2\theta_{24})$



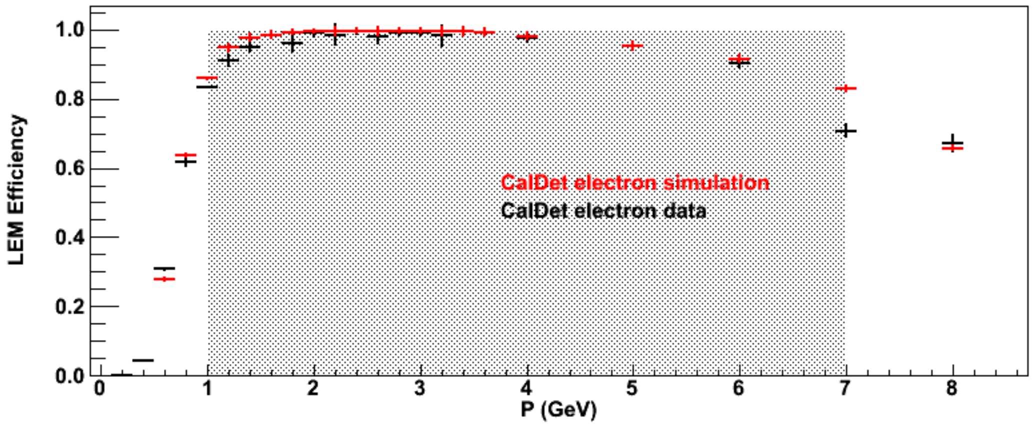
θ_{13}=0
θ_{13}=11.5°
$\Delta\chi^2$
90%
68%
CDHS 90% CL,
Δm^2 = 3.5 eV²
θ_{23} (deg)
θ_{34} (deg)
θ_{24} (deg)

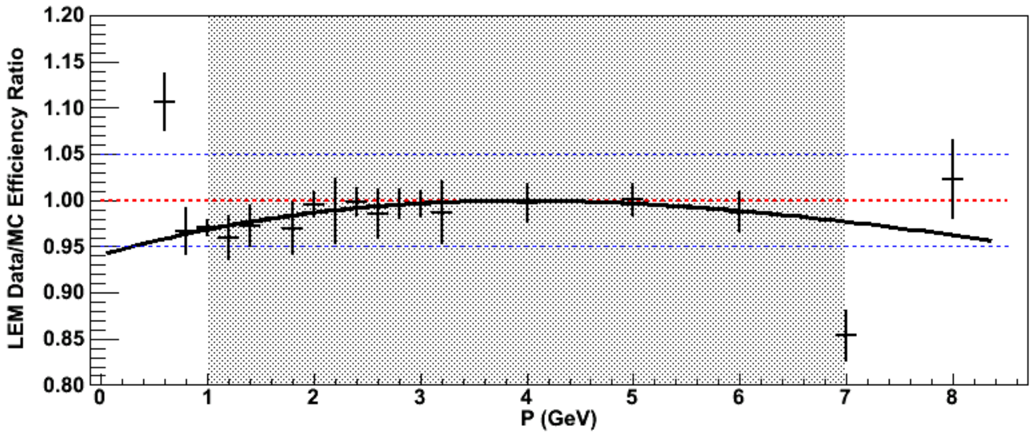
Electron-neutrino prediction in FD

- Total BG: 49
  - NC: 34
  - Muon-neutrino CC: 7
  - beam electron-neutrinos: 6
  - tau-neutrino CC: 2
- Signal at CHOOZ limit: 30

Checking Signal Efficiency

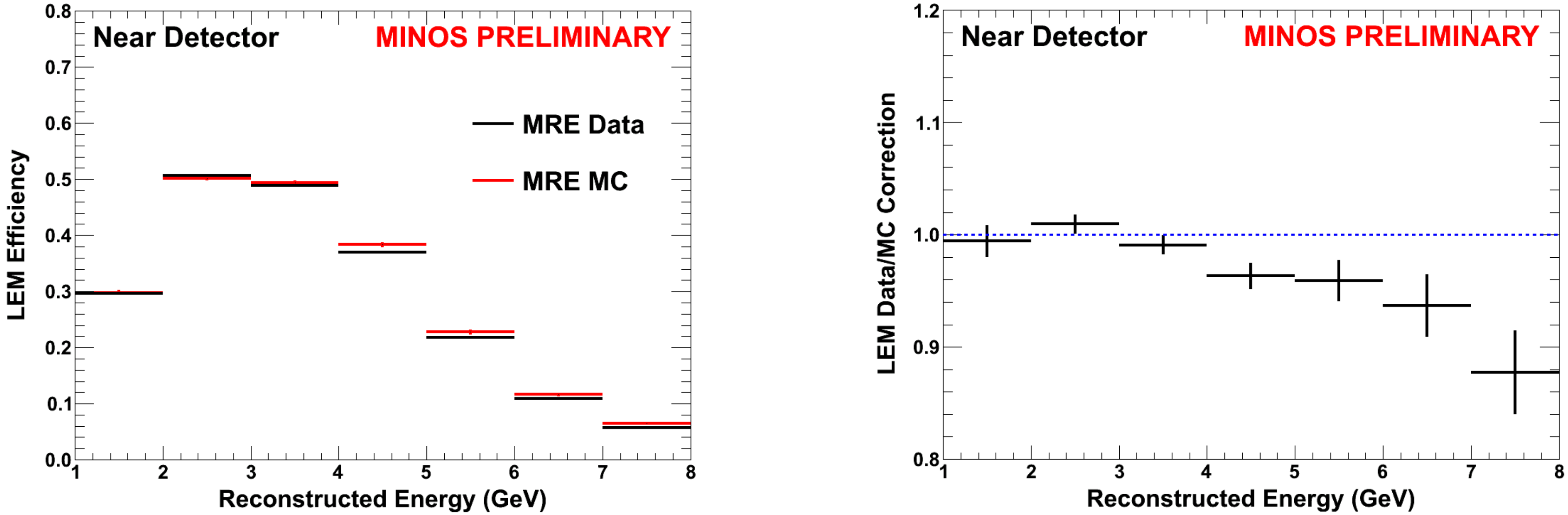
- Test beam measurements demonstrate electrons are well simulated



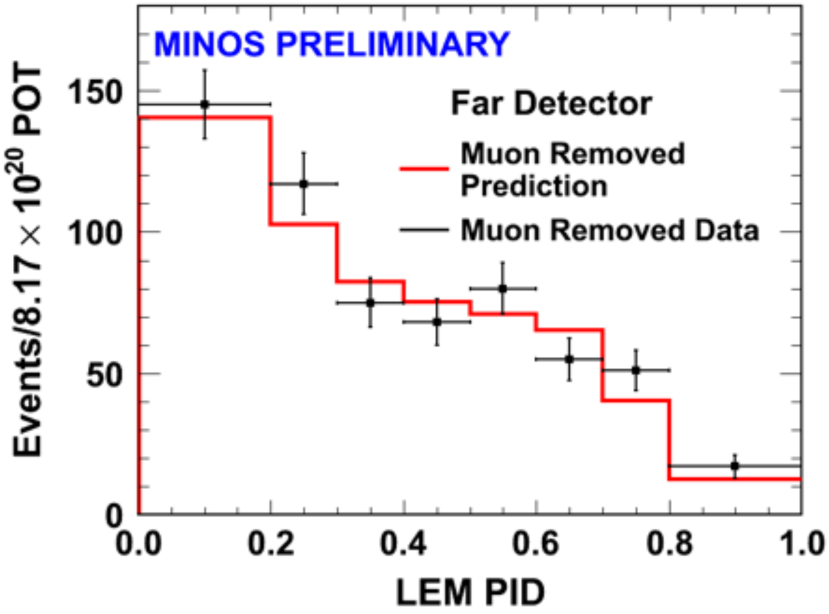


Checking Signal Efficiency

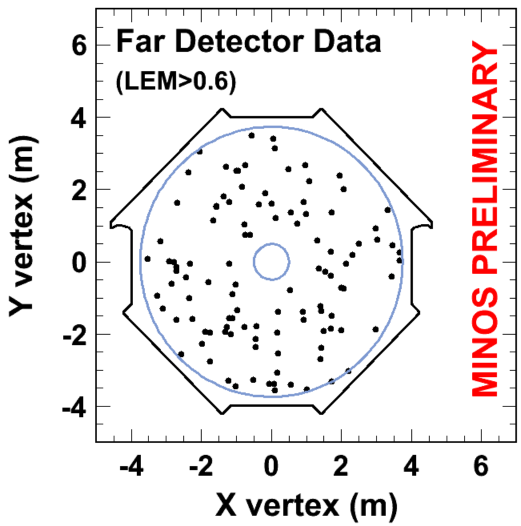
- Check electron neutrino selection efficiency by removing muons, add a simulated electron

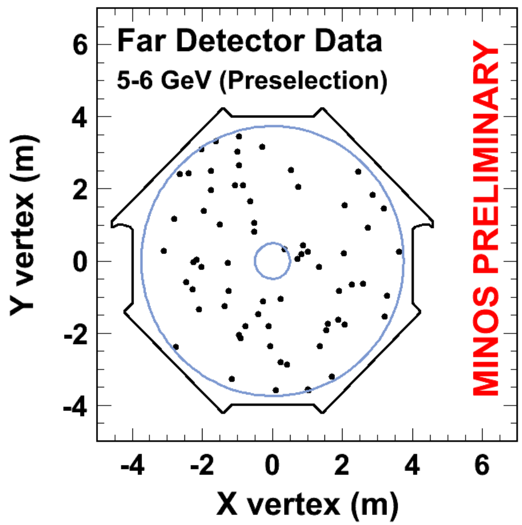


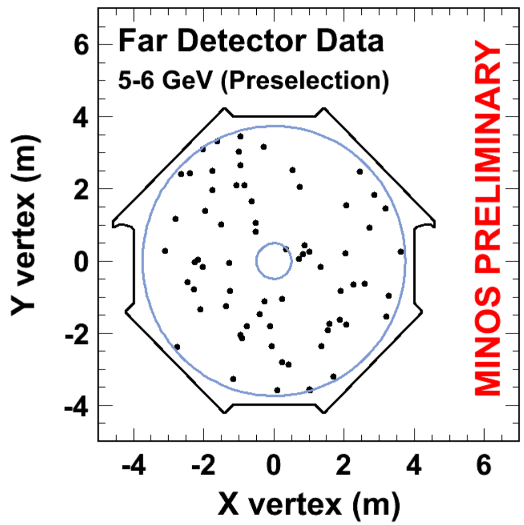
Muon Removed Sample



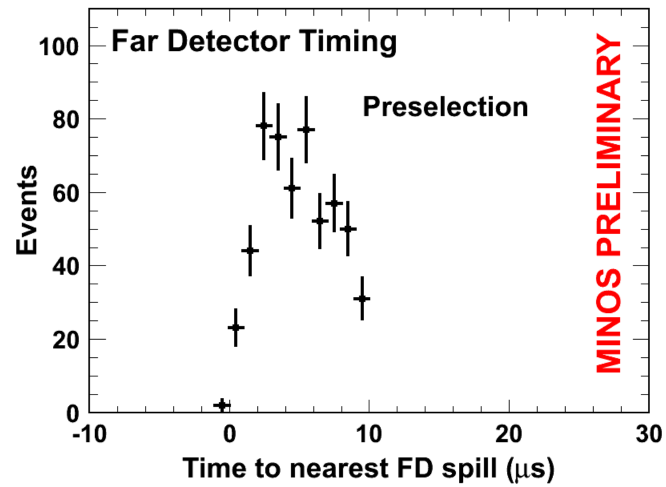
FD Electron-neutrinos Vertices

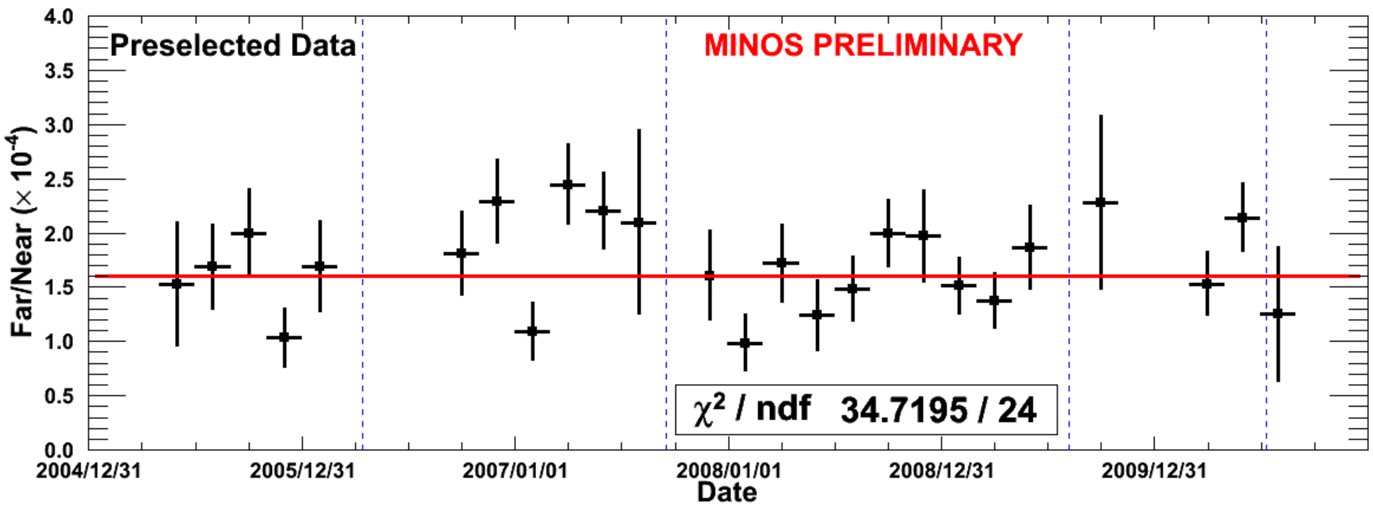




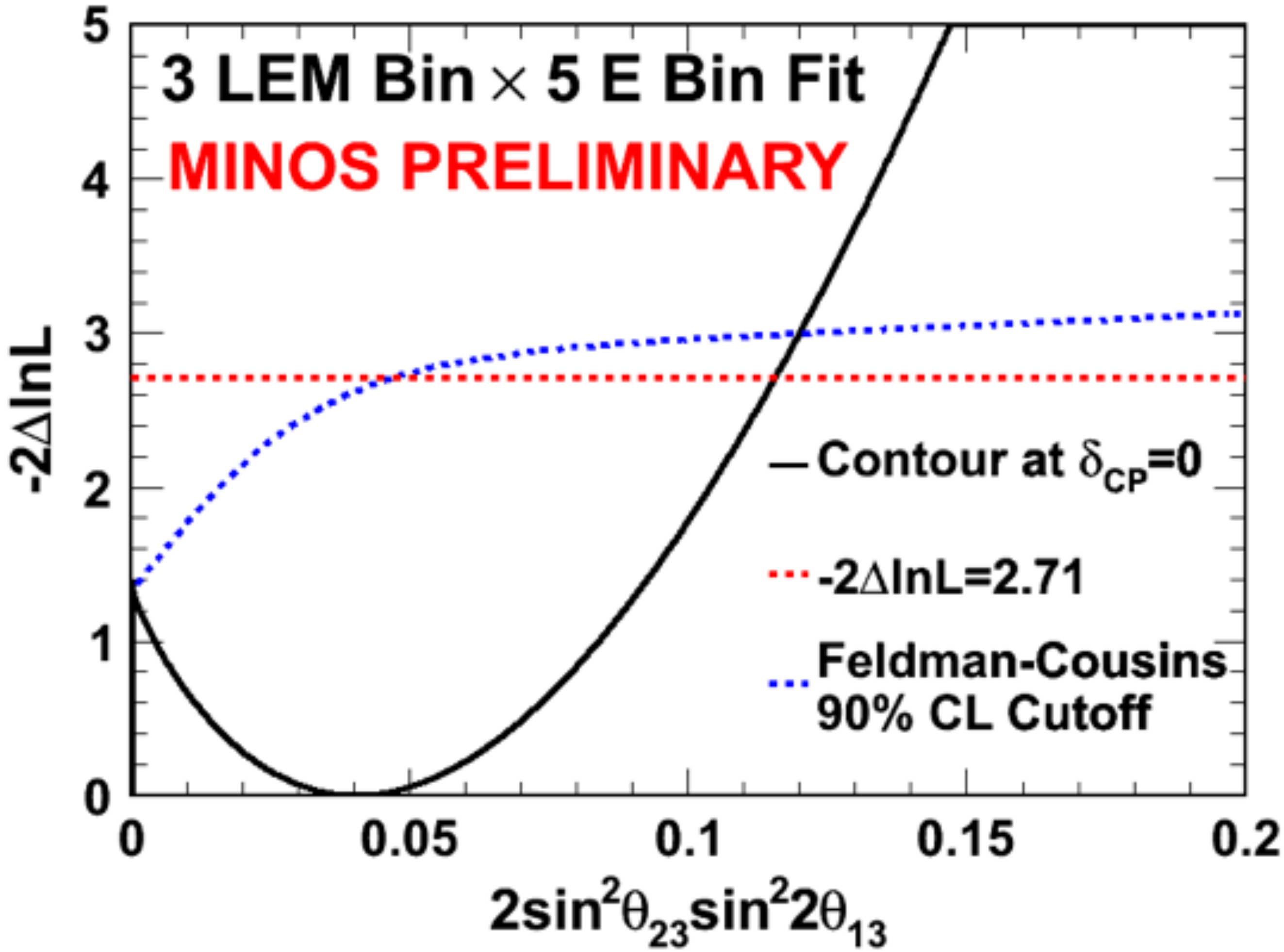


Electron-neutrino Event Rate





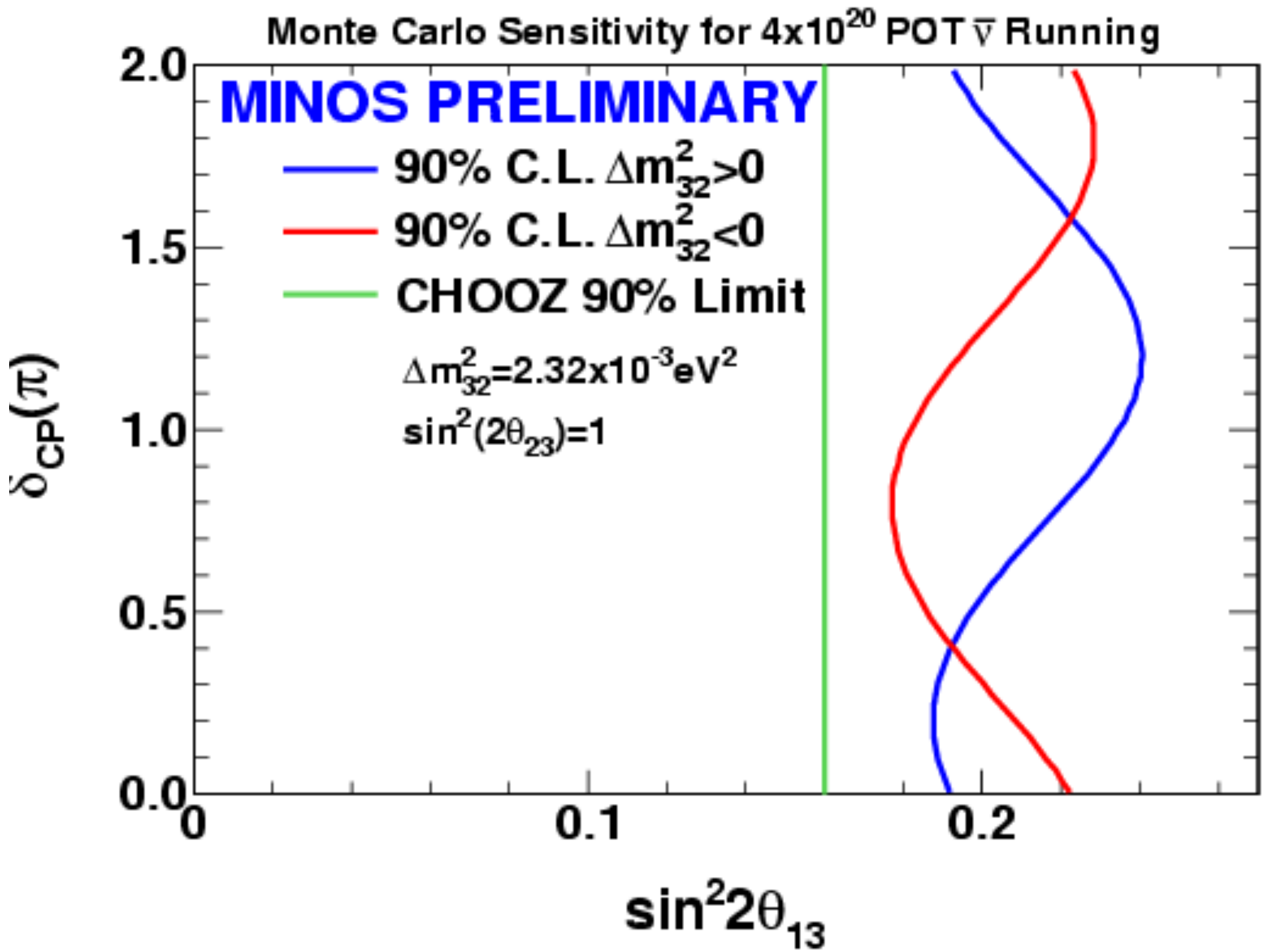
Feldman-Cousins Effect



Cross Check Fits

OFFICIAL FIT	**0.040**	**0.115**
LEM energy shape fit < 5 GeV	0.021	0.089
ANN energy shape fit	0.046	0.135
ANN energy shape fit < 5 GeV	0.045	0.136
2010-style analysis (ANN rate-only)	0.041	0.130
LEM rate-only	0.064	0.147
LEM shape fit	0.046	0.121
Official fit excluding new data	0.057	0.144

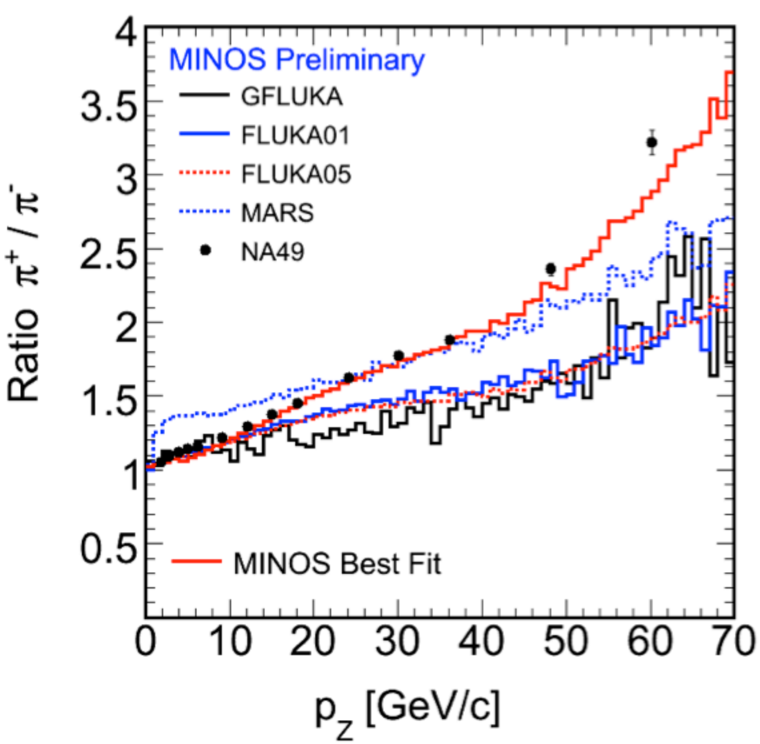
electron anti-neutrino appearance

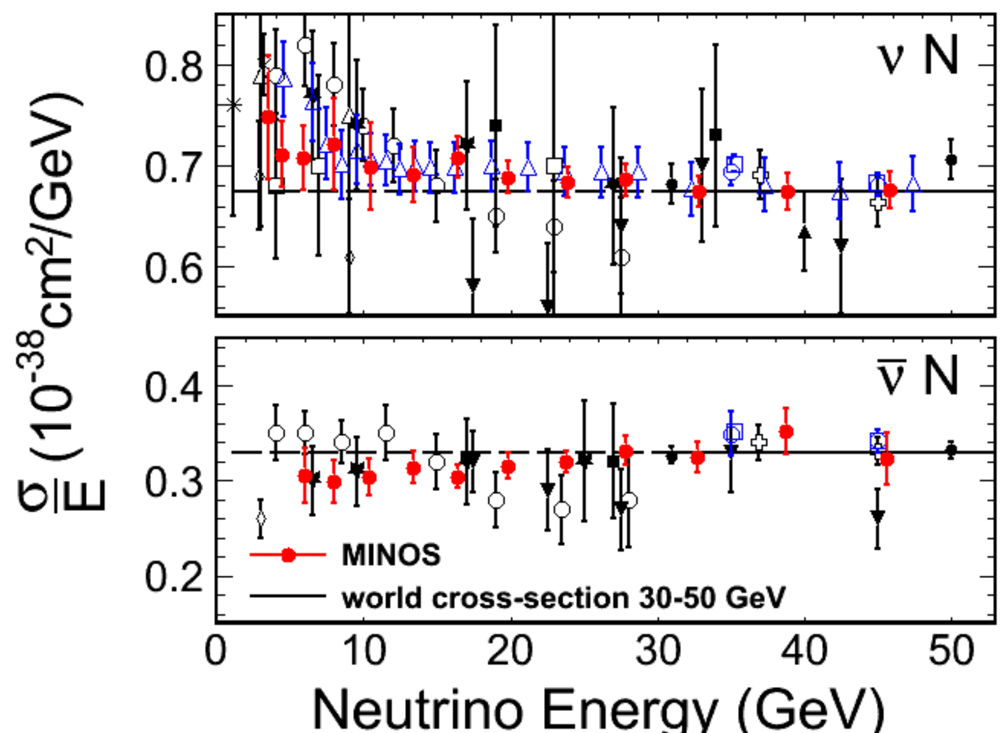


Making an antineutrino beam

- Hadron production and cross sections conspire to change the shape and normalization of energy spectrum

~3x fewer antineutrinos for the same exposure





Anti-neutrino Selection