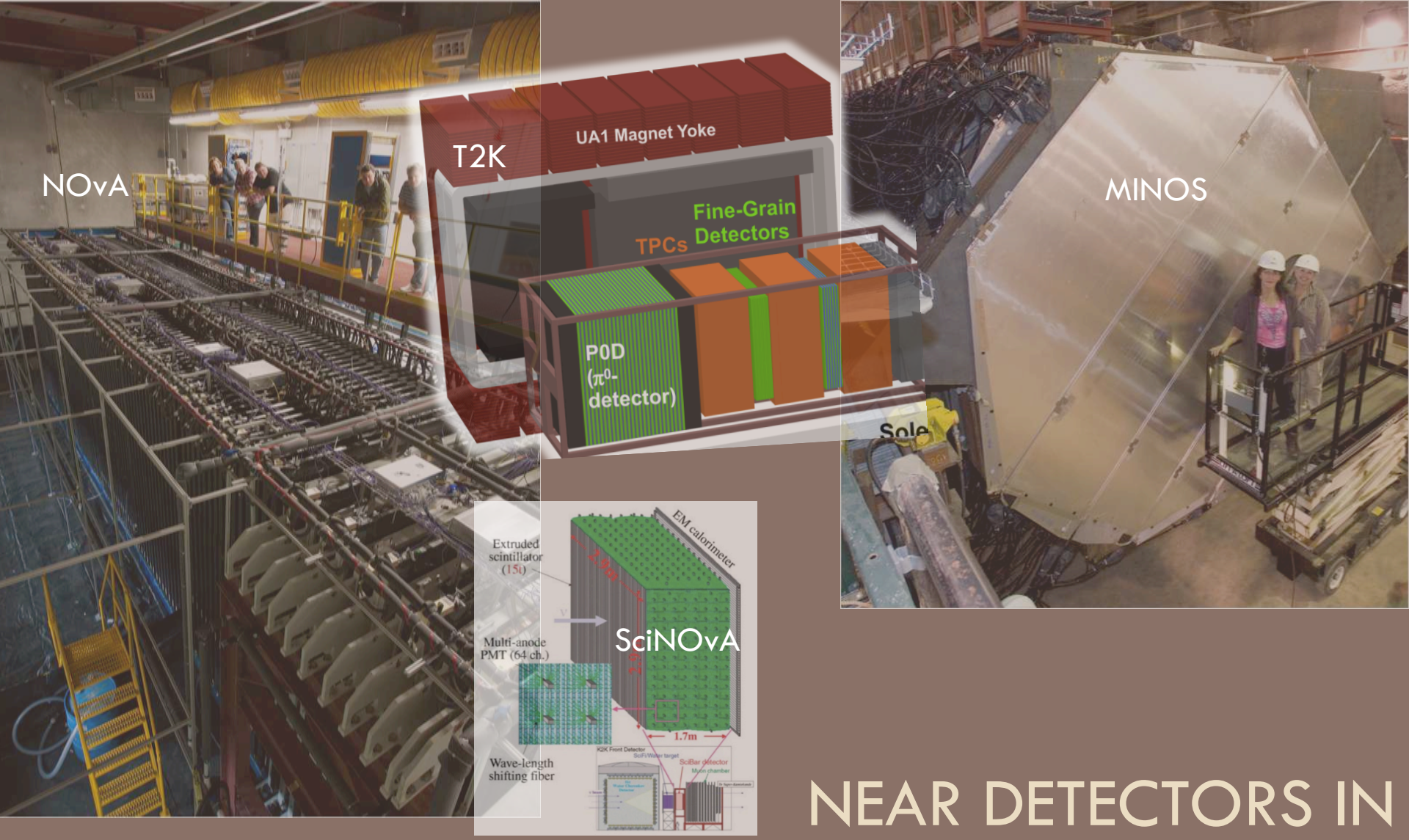
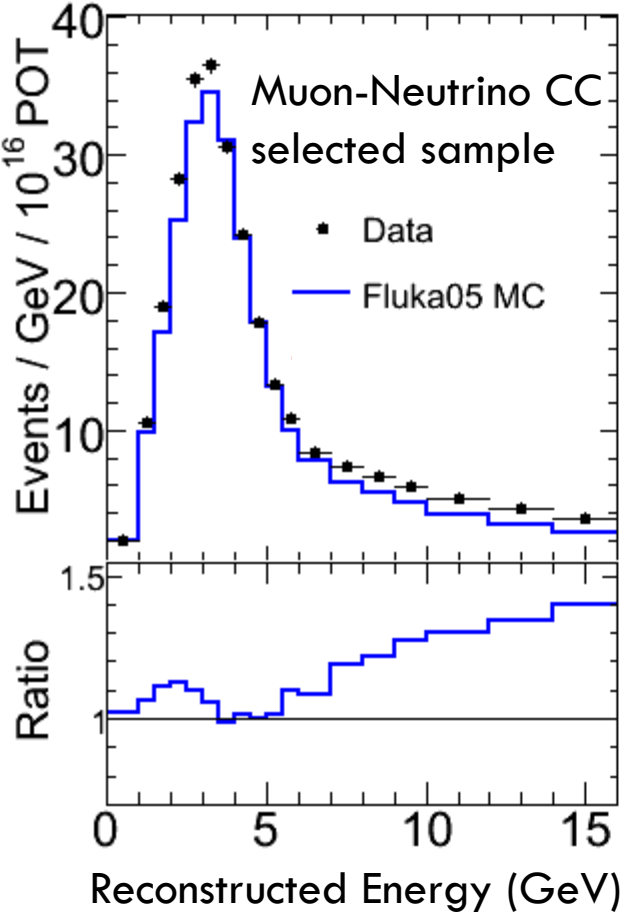


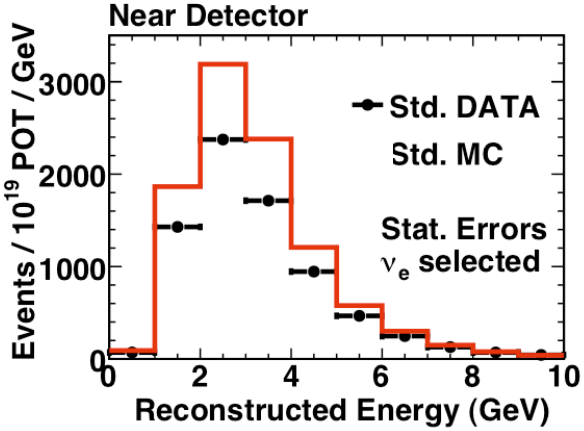
NEAR DETECTORS IN OSCILLATION EXPERIMENTS

Patricia Vahle,
College of William and Mary

Outline

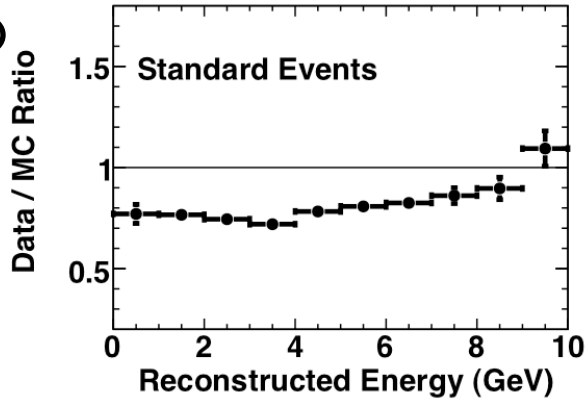
- Near Detectors are crucial in the control of many large systematic uncertainties facing oscillation experiments
  - Flux mis-modeling
  - interaction uncertainties
  - hadronization and final state interaction uncertainties





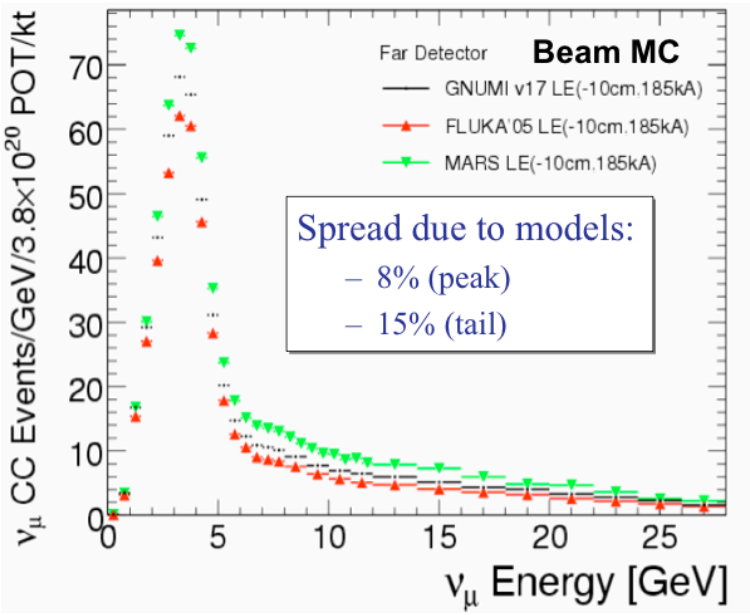
In this talk:

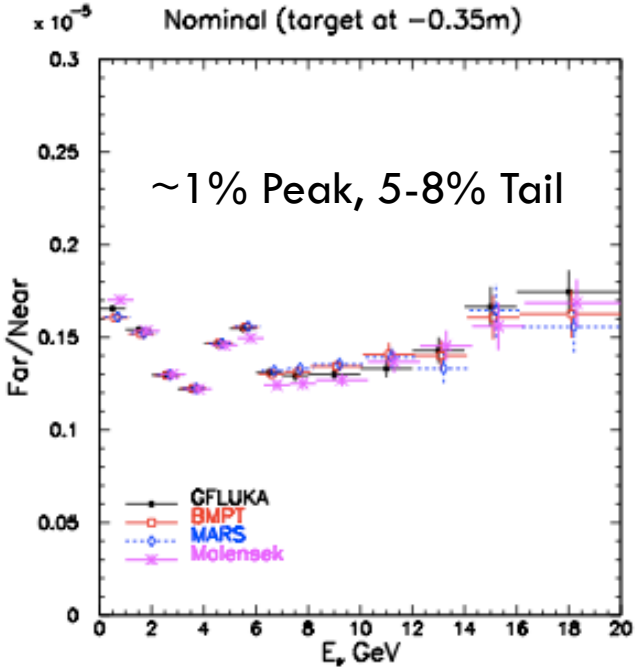
- How MINOS used its ND
- How T2K uses ND280
- How NOvA plans to use its ND and how SciNOvA can enhance it



Predicting the Flux

Hadron Production Uncertainty



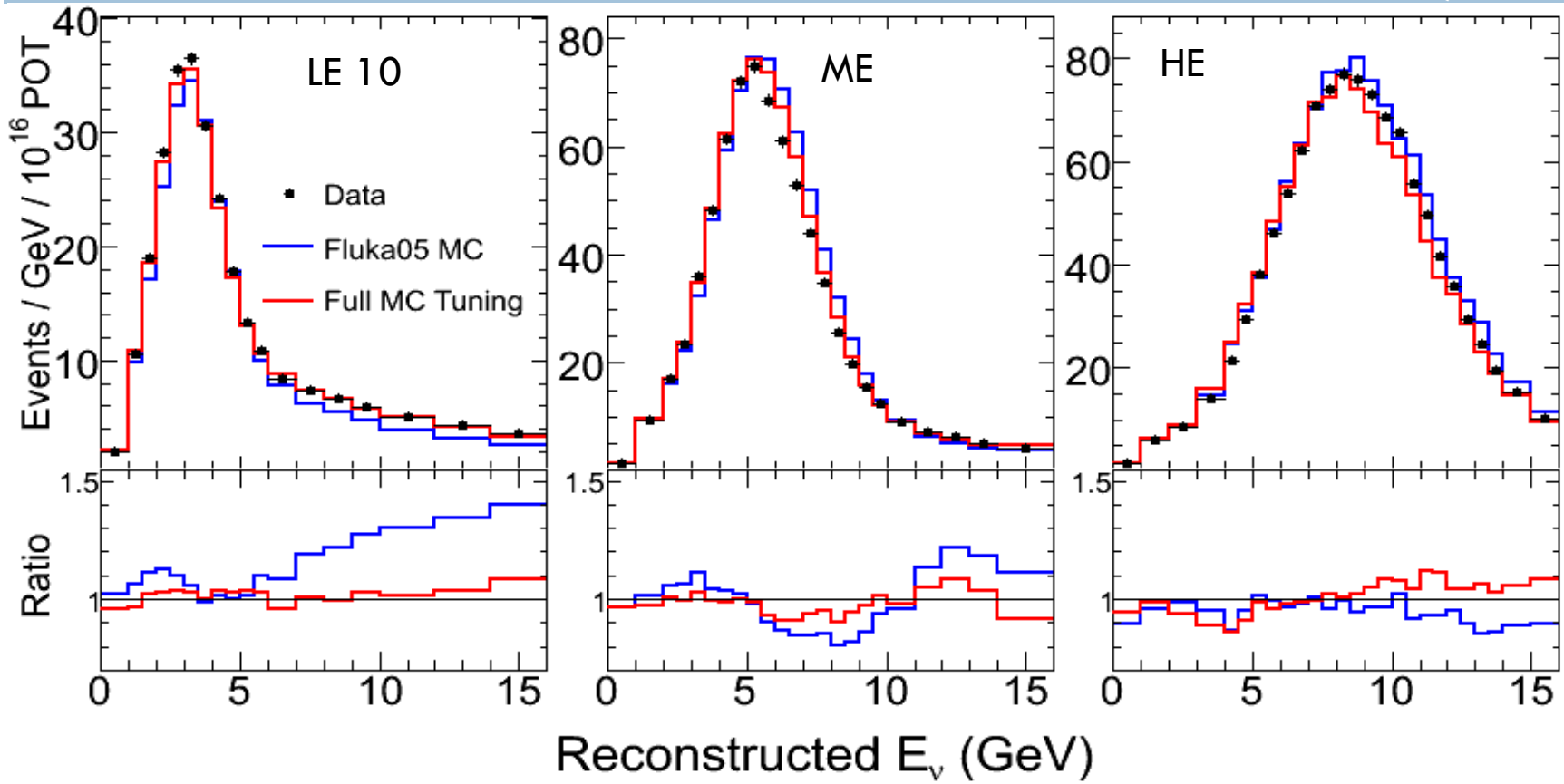


- Flux an extrapolation of (sparse) external data to MINOS beam energy, target thickness, target material
- Systematics originally evaluated using model spread, with additional systematics from focusing system alignment, horn current calibration, skin depth, etc

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

Initial ND Data

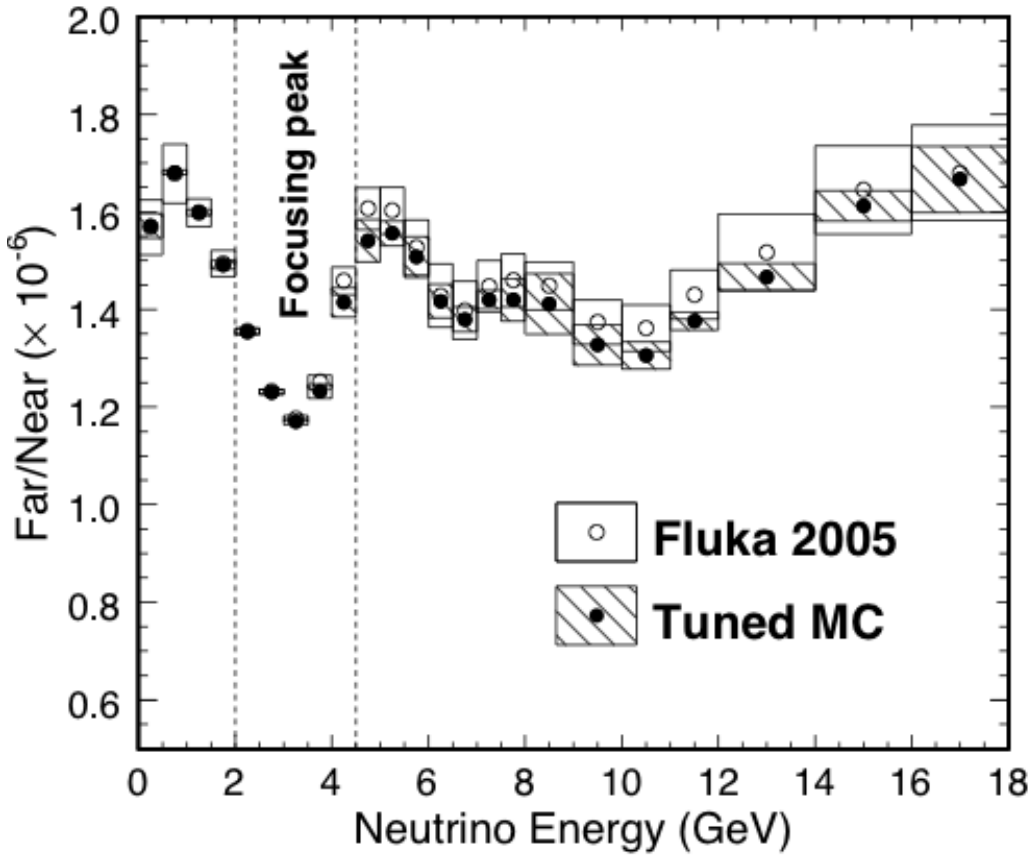
(Refs: Z. Pavlovich, UT Austin, 2008, Phys. Rev. D77 (2008) 072002)



- Discrepancy between Data/MC changes energy with different beam tunes, suggests production of Hadrons off the target is to blame.
- After adjusting hadron production, data/MC discrepancies ~5-10% level
- Fit errors a better estimate of systematic error than (correlated) model spread

Resulting Beam Systematics

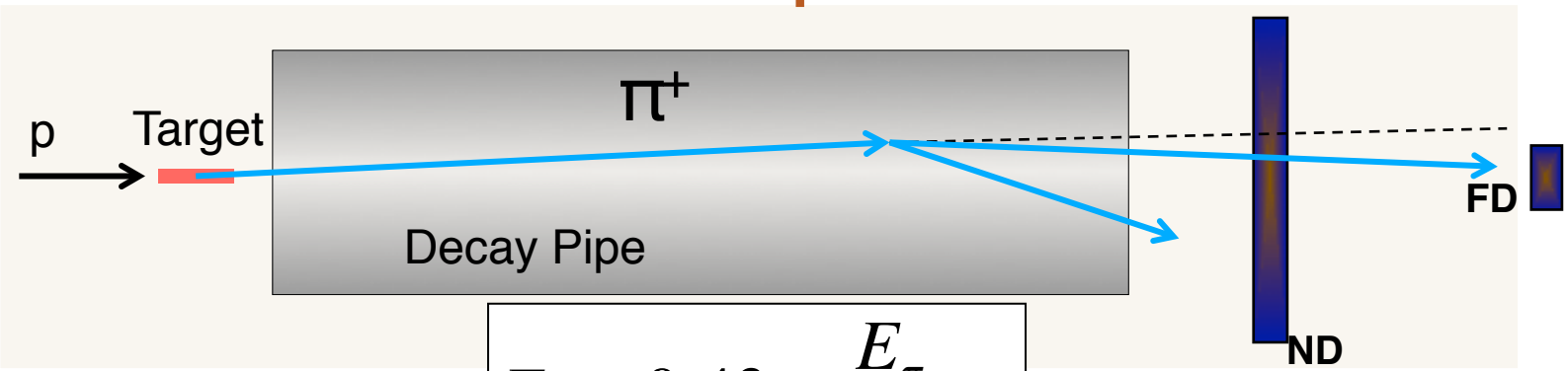
- F/N from simulation constrained by the beam fit
- Ratio changes very little in focusing peak
  - errors at sub percent level
- Ratio pulled few % lower in tail
  - still consistent within errors
  - errors further reduced



Phys. Rev. D77 (2008) 072002

Near to Far

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

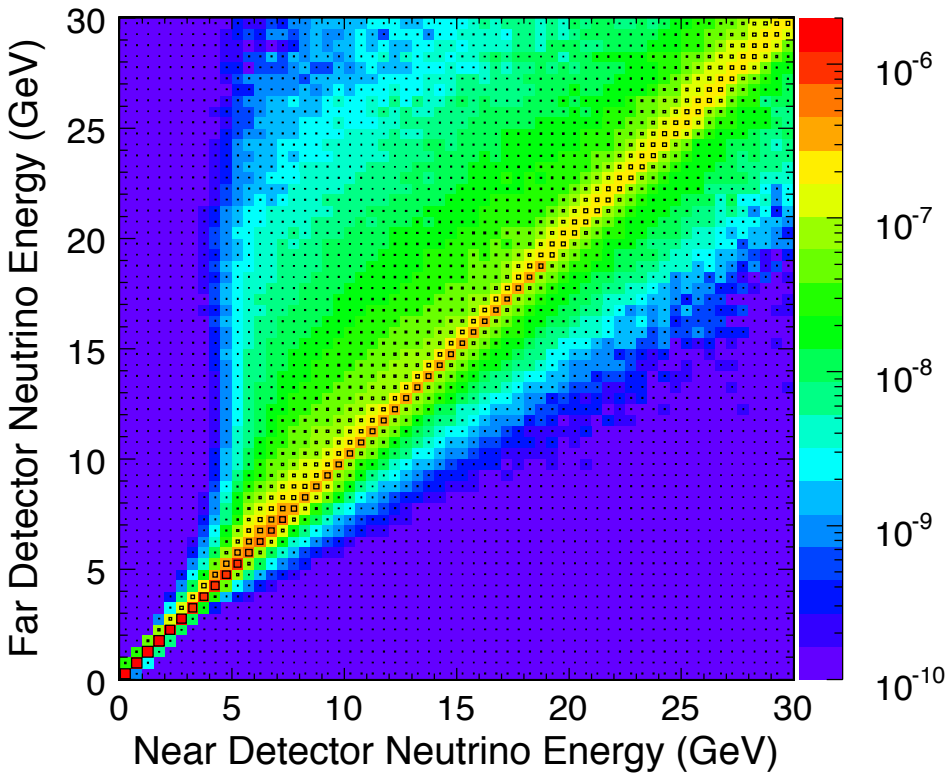


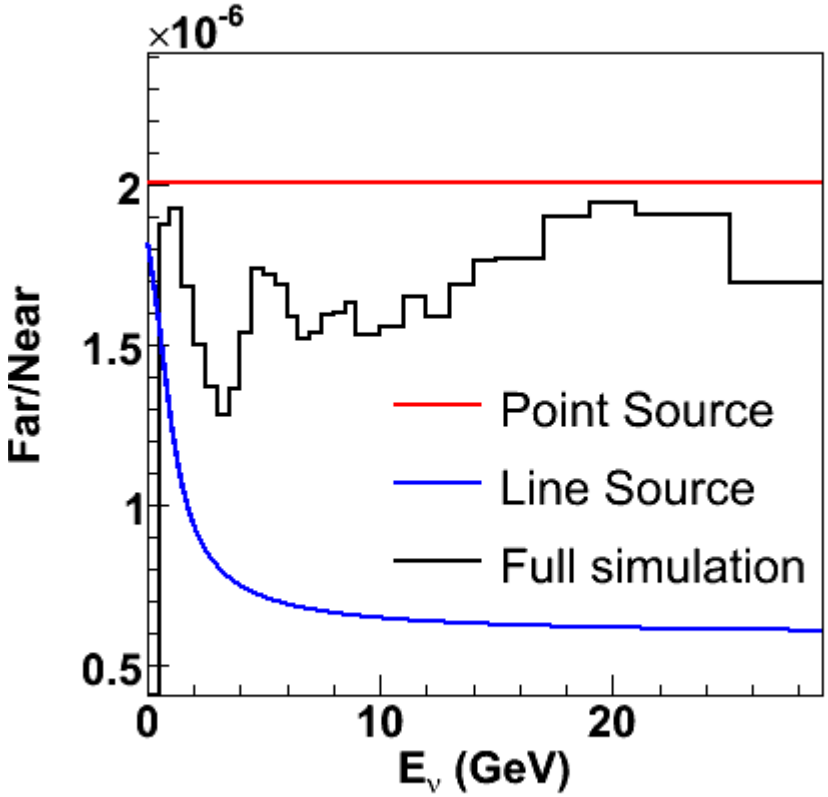
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- 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

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



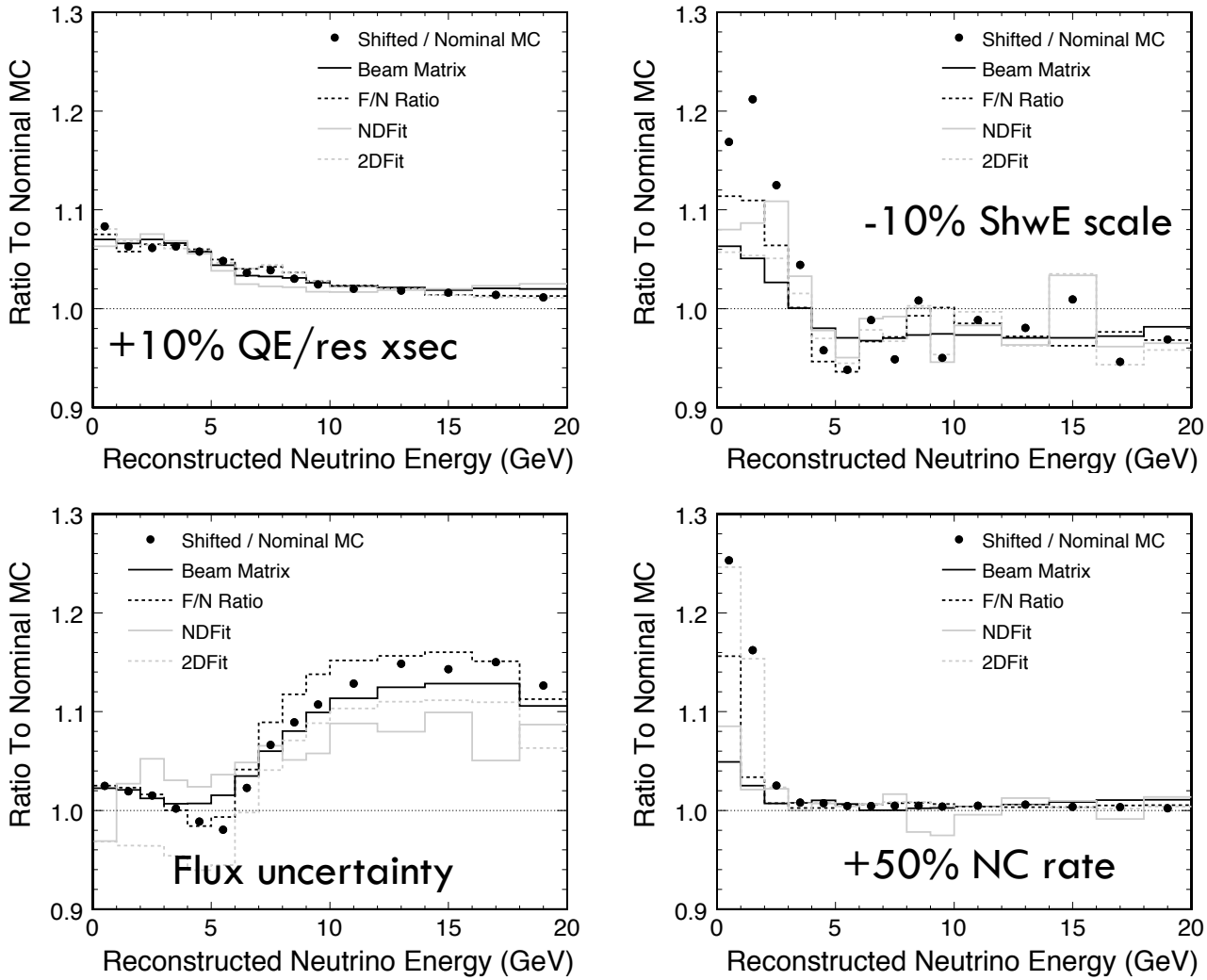


Phys. Rev. D77 (2008) 072002

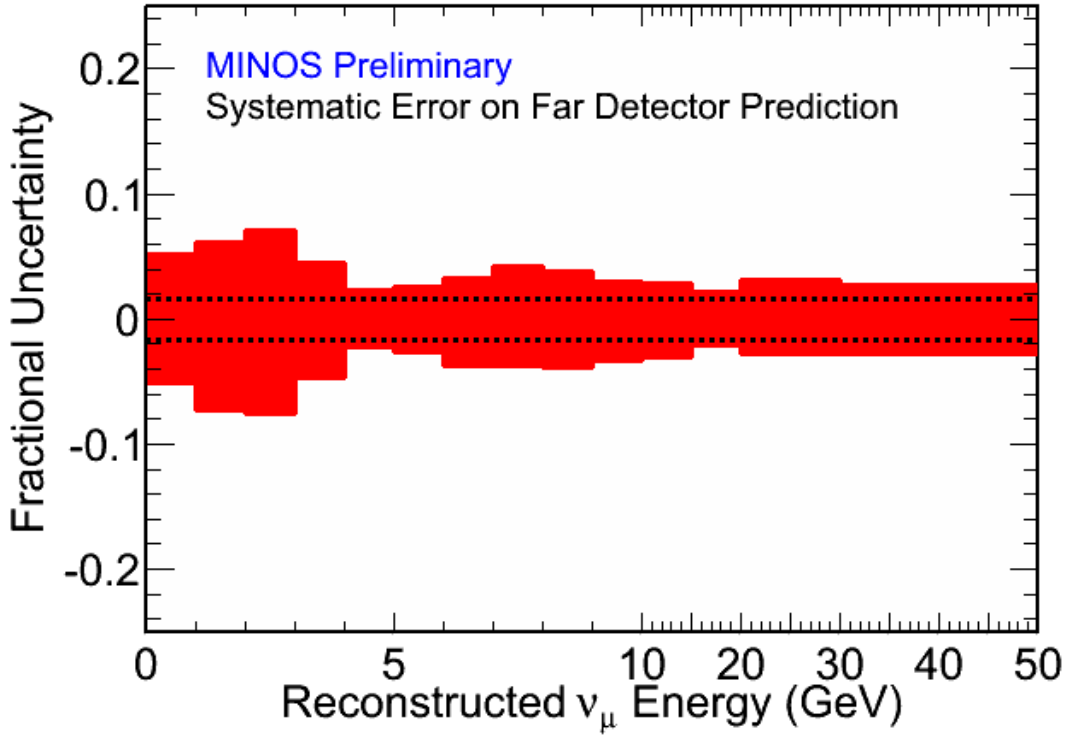
Systematic Uncertainties

P. Vahle, SLAC 2013

Extrapolation mitigates most systematic uncertainties



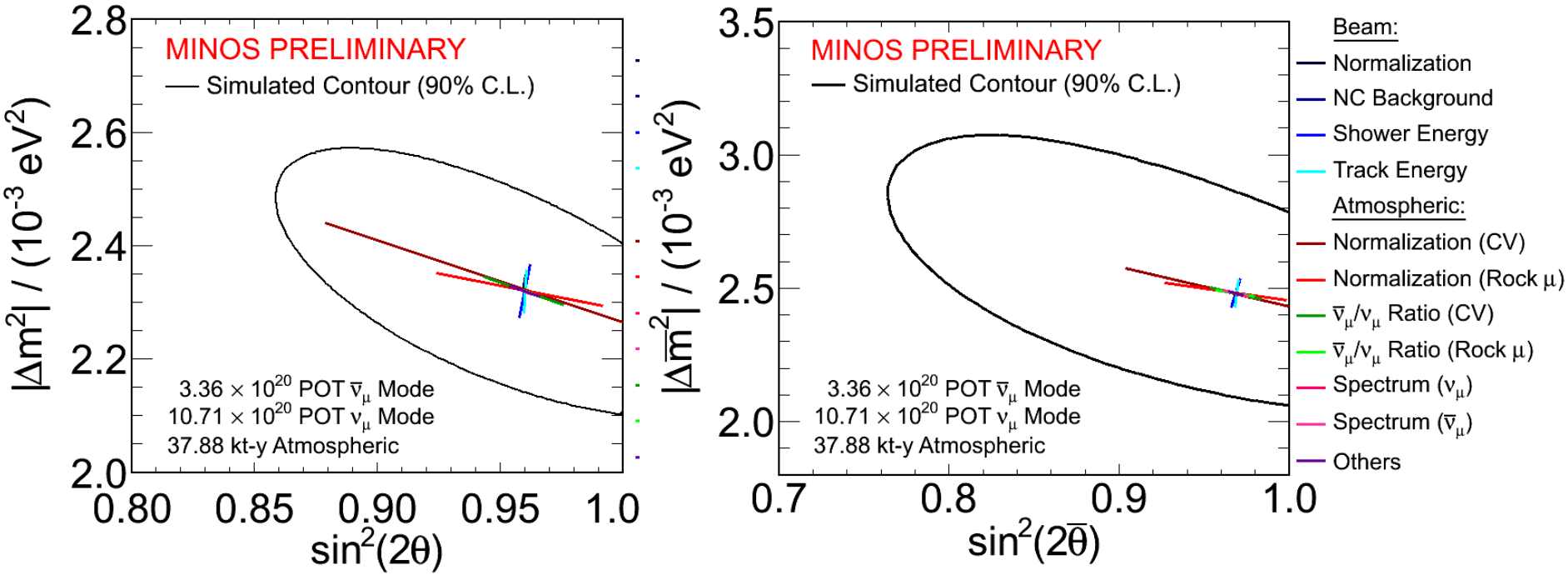
Systematic Error



- Dominant systematics:
  - hadronic energy calibration: energy dependent, ~7% below 3GeV
  - track energy calibration: 2% if by range, 3% if by curvature
  - NC background: 20% normalization
  - relative Near to Far normalization (uptime, Fid. Mass): 1.6%

Current Day Systematic Uncertainties

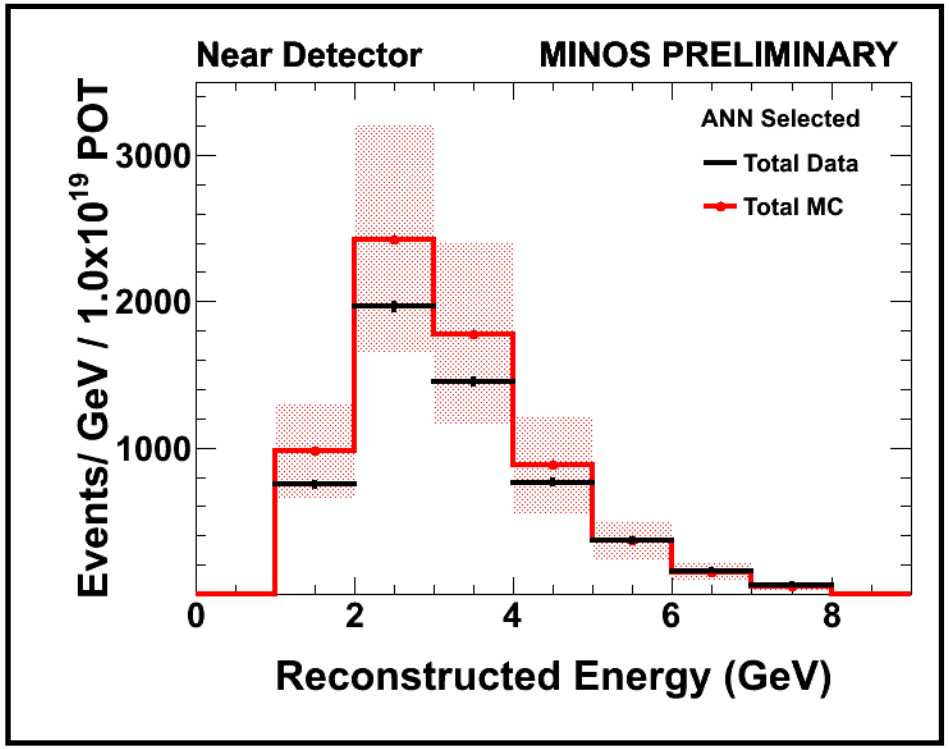
P. Vahle, SLAC 2013



- MINOS now combines beam and atmospheric data
- Dominant systematic uncertainties included in fit as nuisance parameters
- Effects even smaller in final quoted parameter errors

Initial Nue ND Data

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

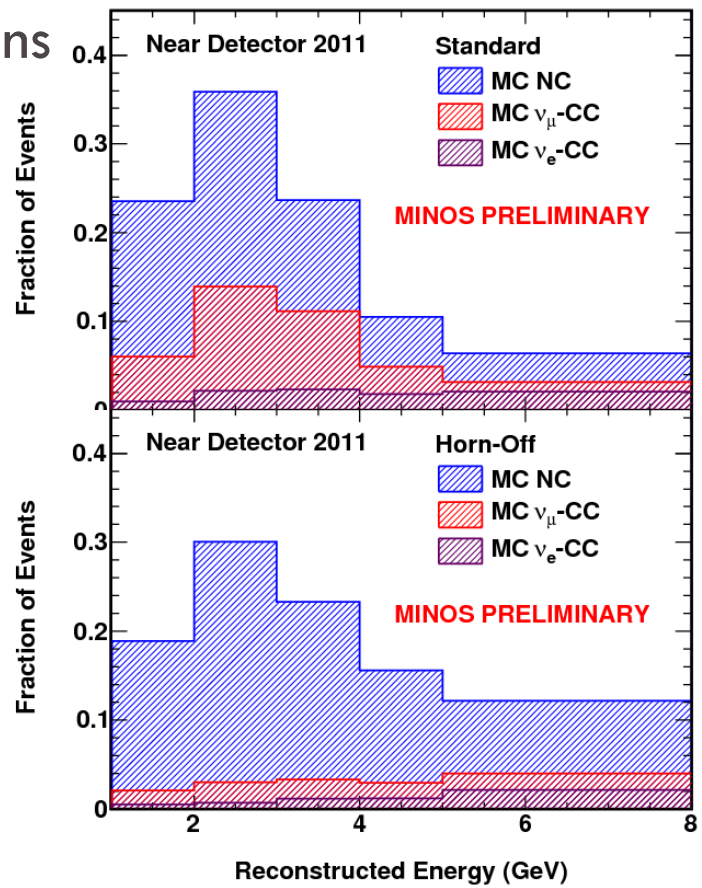


Phys. Rev. Lett. 103 (2009) 261802

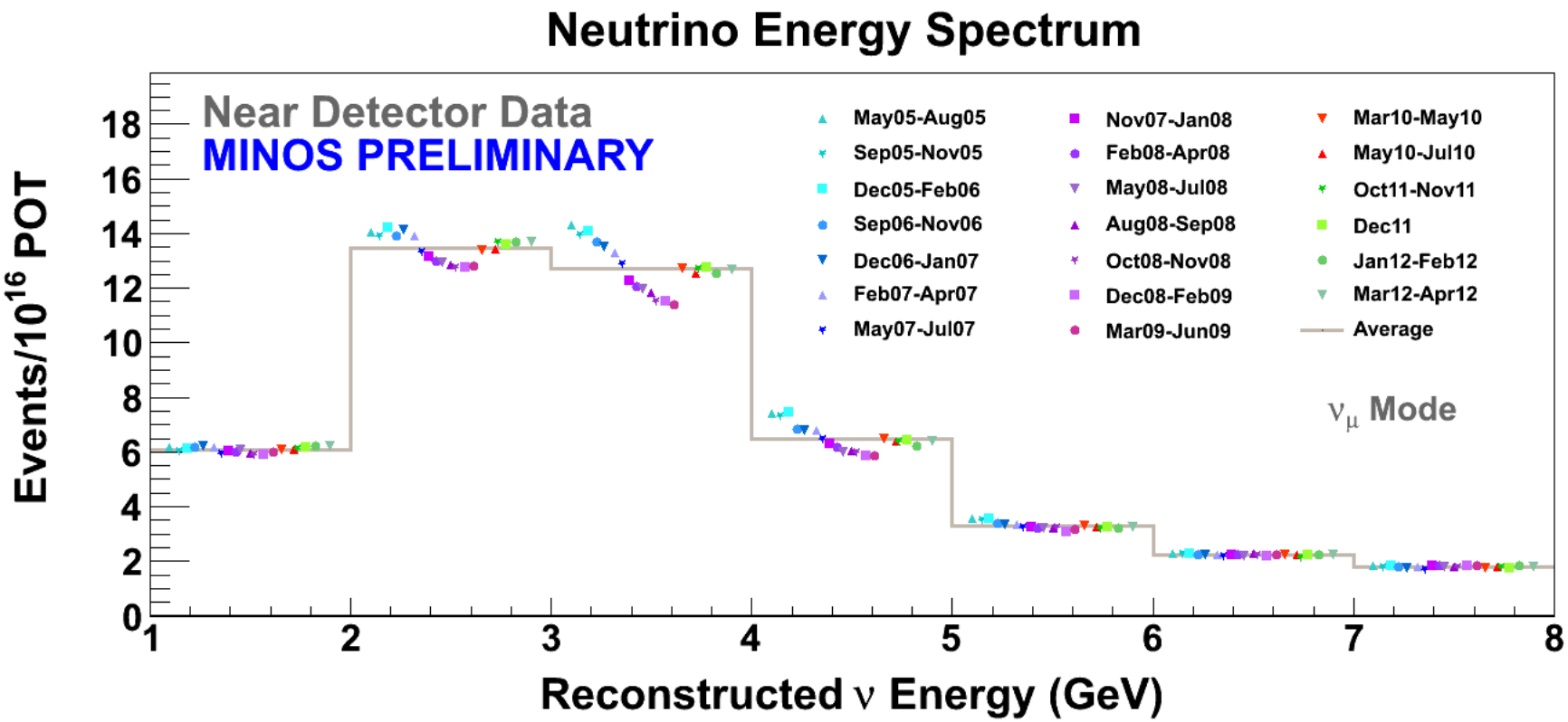
Measuring the Background

- 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

	Nu Mode	Anti-nu mode
BG Systematic	3.8%	4.8%
Signal Systematic	5.5%	5.5%
Statistical	8.8%	23.9%



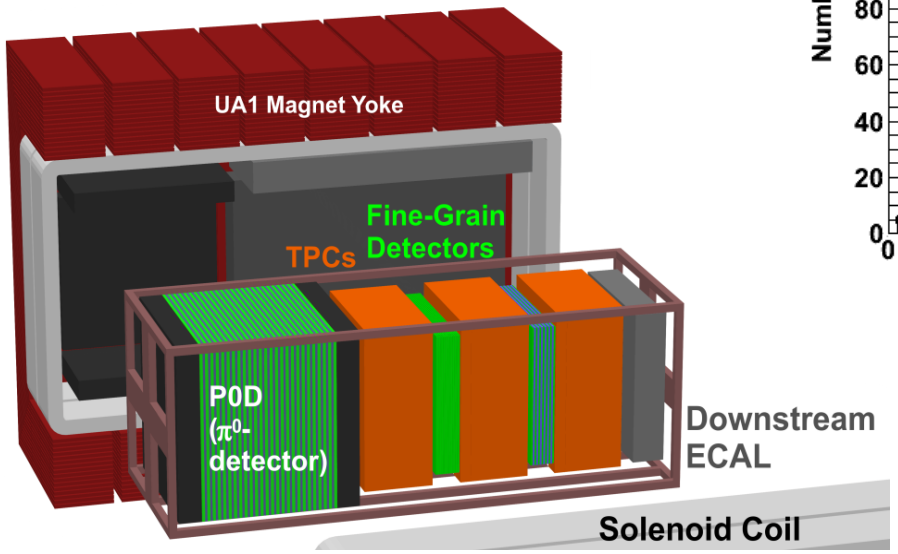
Beam Monitoring

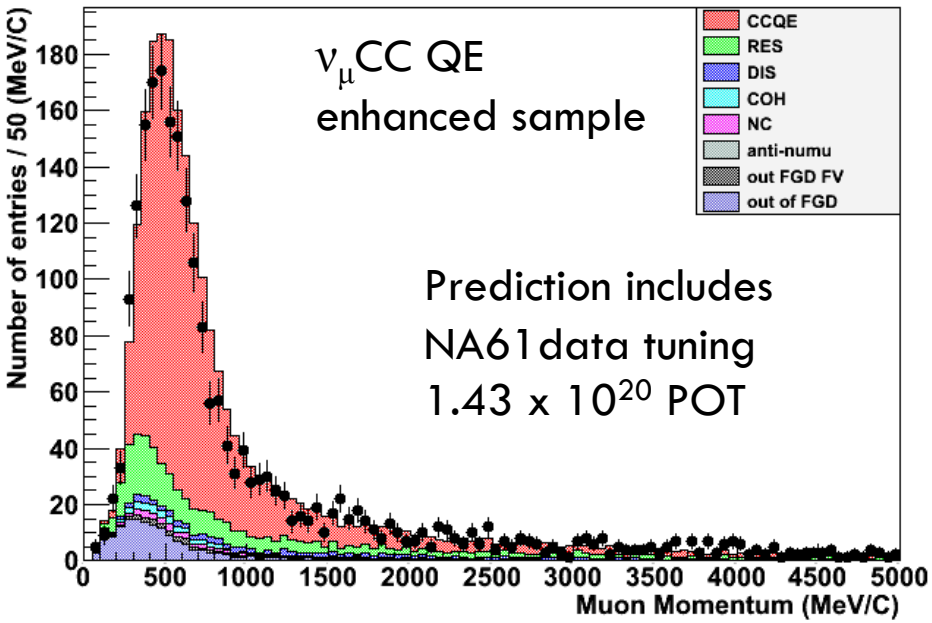


- ND data naturally accounts for time variation of beam conditions and beam line hardware
  - Different targets, helium in decay pipe, target degradation

T2K

- T2K Data agrees with MC out of the box
  - benefits from NA61 hadron production and MiniBooNE xsec measurement+uncertainties
  - off axis experiment
  - cross checked against SciBooNE and K2K



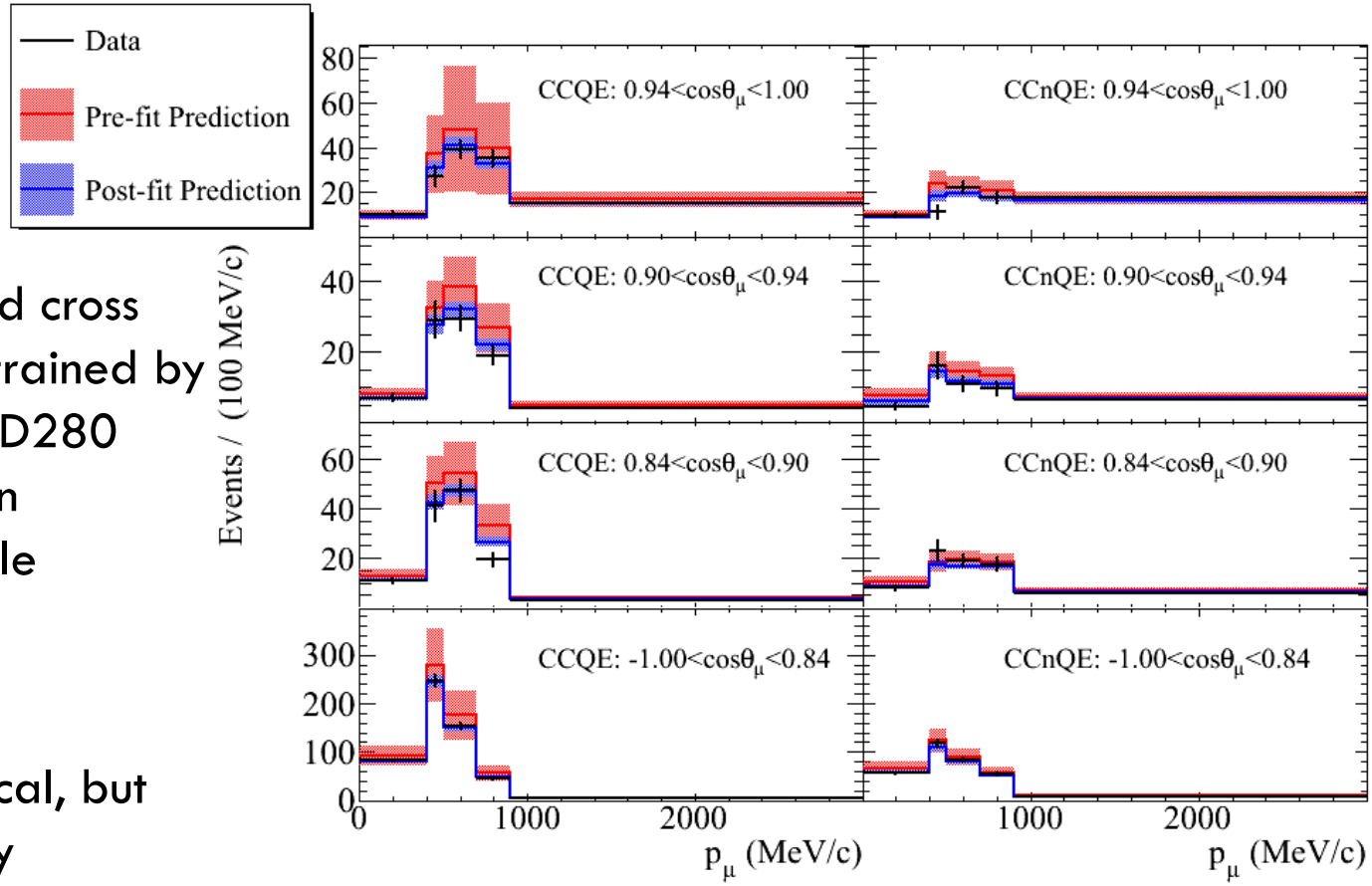


Ref: K. Mahn, NuFACT2012
Phys.Rev.C 84, 034604 (2011)
Phys.Rev.C 85, 035210 (2012)

Ref: K. Mahn, NuFACT2012

T2K Fits

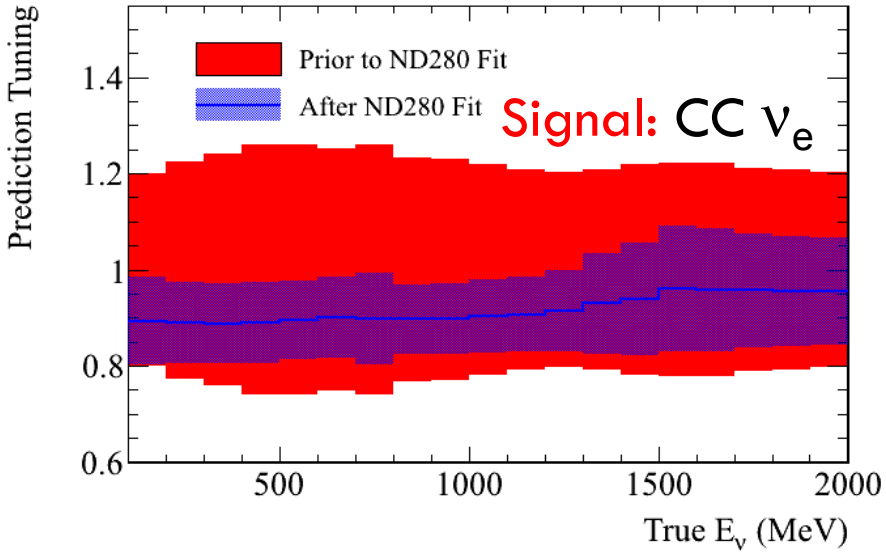
- Further tune flux and cross section model (constrained by external data) to ND280 data in bins of muon momentum and angle
- Apply results to SK prediction
- Detectors not identical, but ND280 substantially constrains the overall rate and kinematics of CC interactions

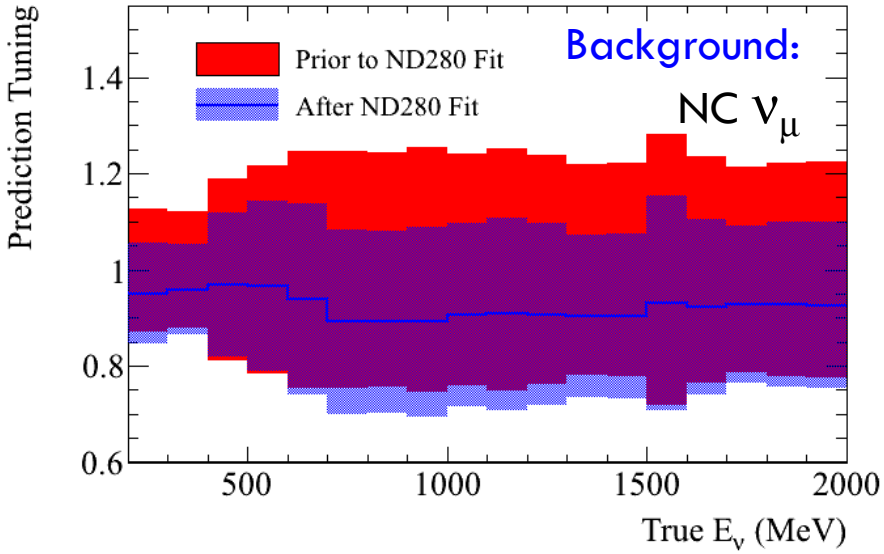


$\Delta\chi^2 = 29.1$ (p-value 0.925 from pseudo-experiments)

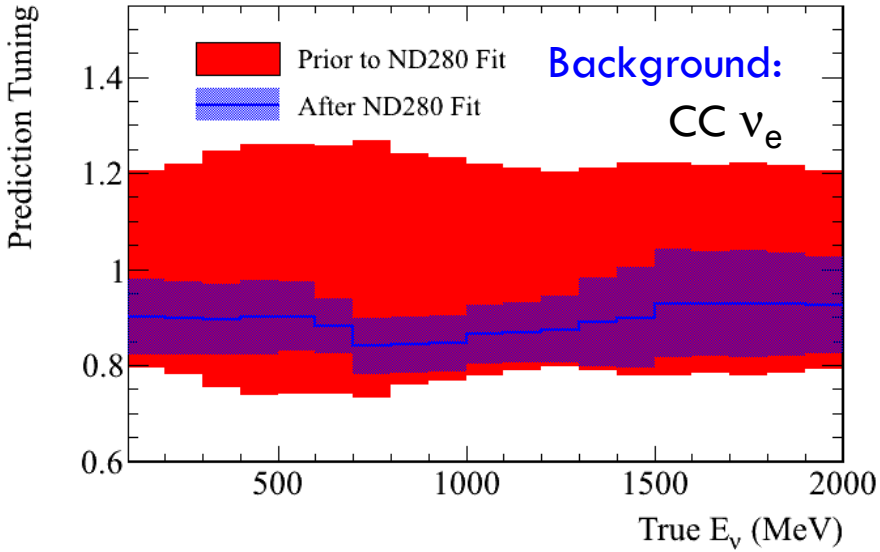
Ref: K. Mahn, NuFACT2012

T2K Systematics



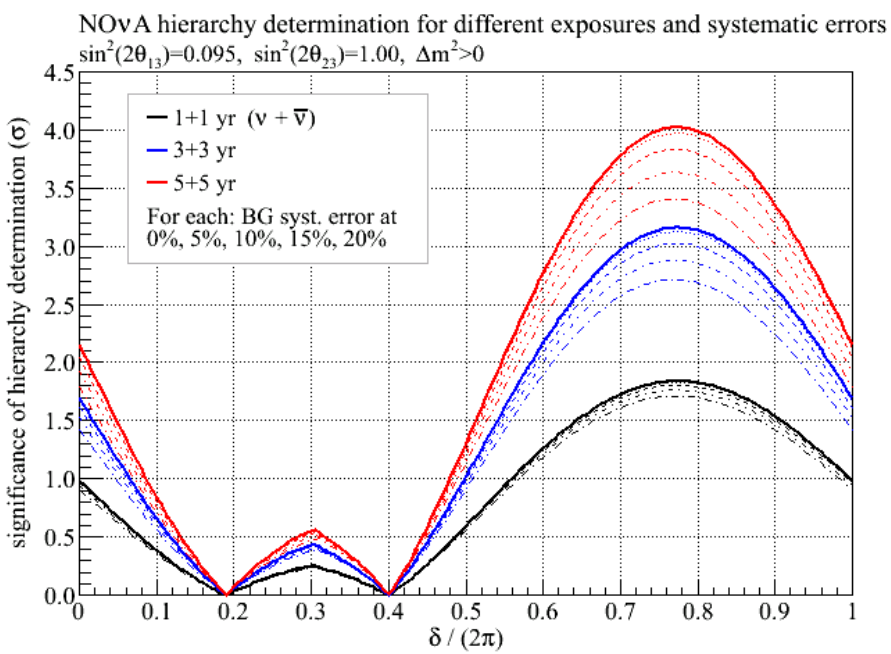


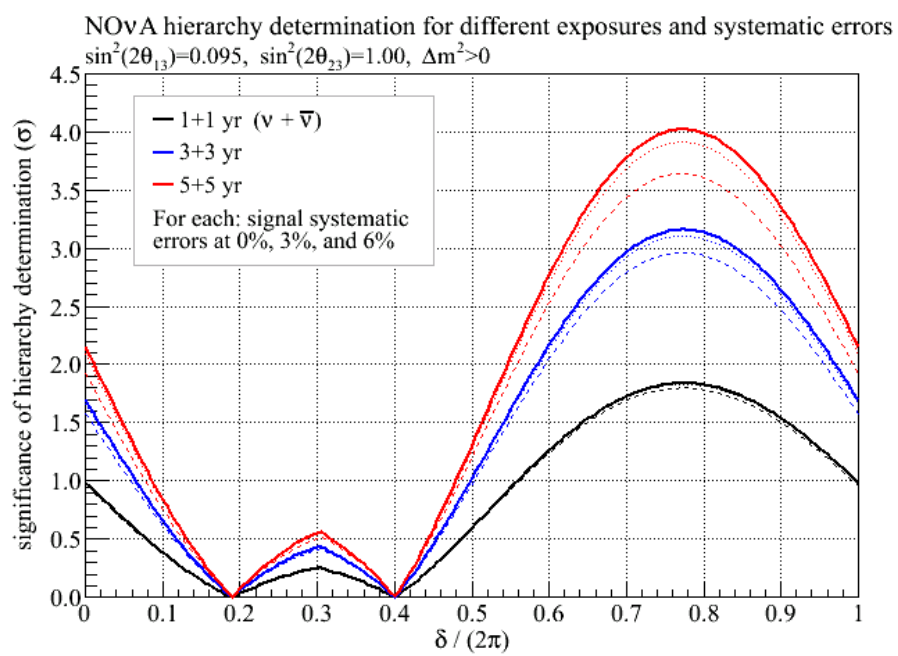
- ND280 constraint reduces a 22% systematic error on signal+BG rate in FD to 10%



NOvA

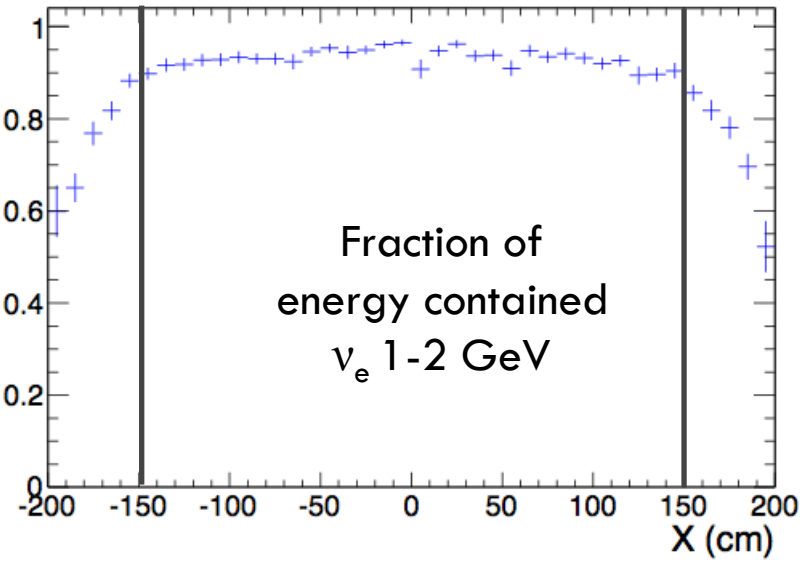
- NOvA will use ND in similar ways as MINOS
  - ND must set overall normalization (signal and BG)
  - Must get decomposition of BG from ND data
- Off-axis technique makes flux shape robust to systematics
- Better signal to noise, but need even stronger BG rejection

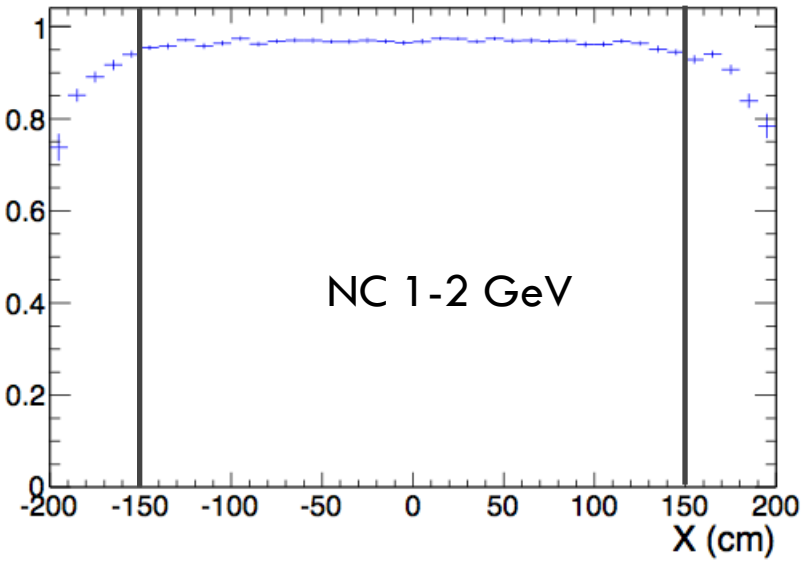




NOvA F/N Differences

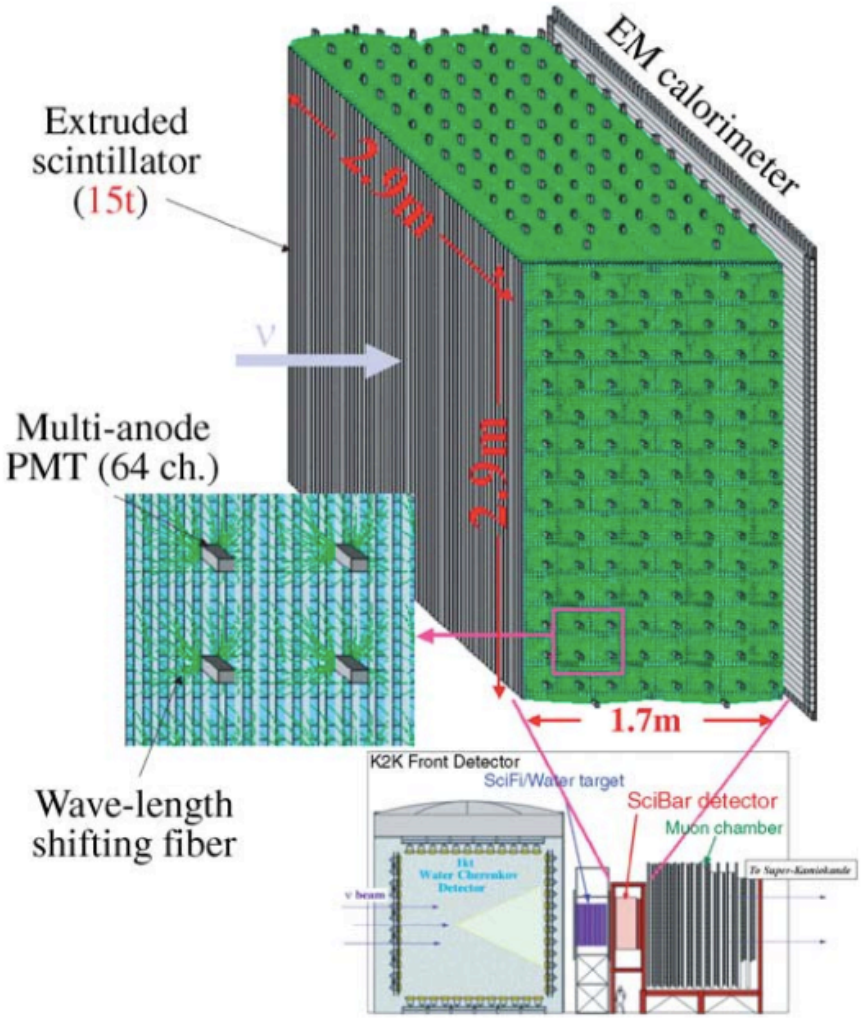
- Event containment different between NOvA ND/FD
  - 82-87% of events contained in ND
  - Up to 10% of NC lose a pi0
- Light levels different between the detectors





Energy	ν_e CC	ν_μ CC	NC	NC w/lost π^0
1-2 GeV	85 ± 1%	59 ± 1%	87 ± 2%	10 ± 2%
2-3 GeV	85 ± 1%	48 ± 1%	82 ± 3%	8 ± 2%

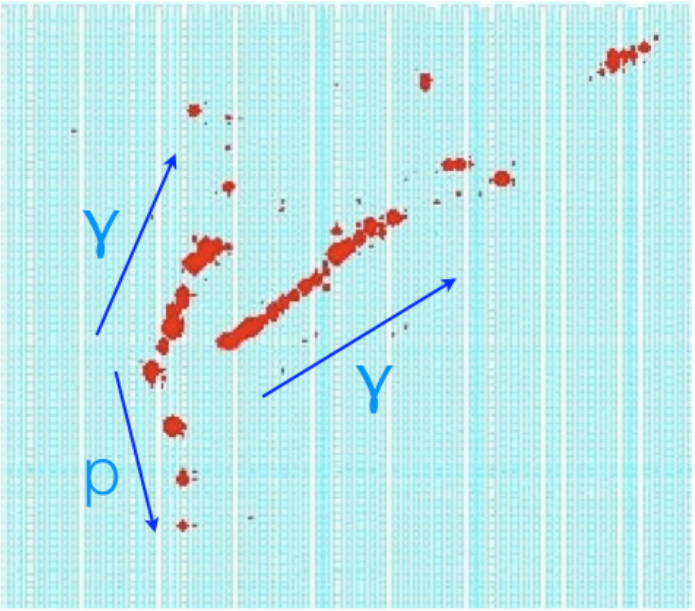
SciNoVA



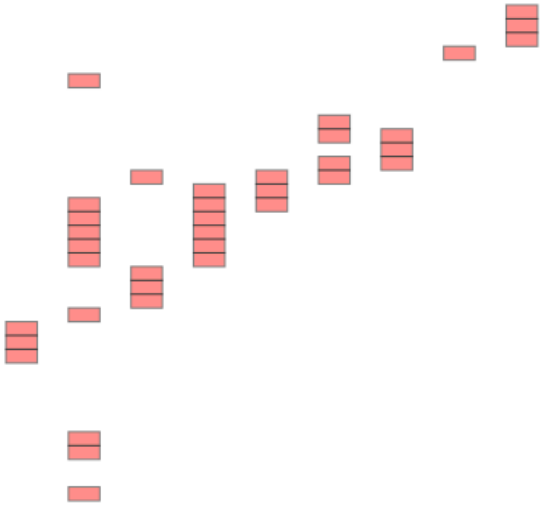
- Copy of the SciBar detector (of K2K and SciBooNE fame)
- installed upstream of NOvA ND
- Cross section measurements in a narrow band 2 GeV beam
  - Fine grained—smoking gun evidence of di-nuceon states in QE scattering?
  - rate and spectrum of pi0 production in NC events
- $2.4M for scintillator production, PMTs, readout and installation

http://www.fnal.gov/directorate/program_planning/Nov2010PACPublic/1003_SciNOvA_Proposal_2010_15_10.pdf

Using SciNOvA



p + π^0 in SciBar



Same event resampled in NOvA

- Double scan with event resampling provides a powerful cross check of NOvA selection efficiency and BG rejection power
  - Sum SciBar hits to degrade resolution to NOvA cell size
  - Perform NOvA reco and selection to new event, compare to selection of original event

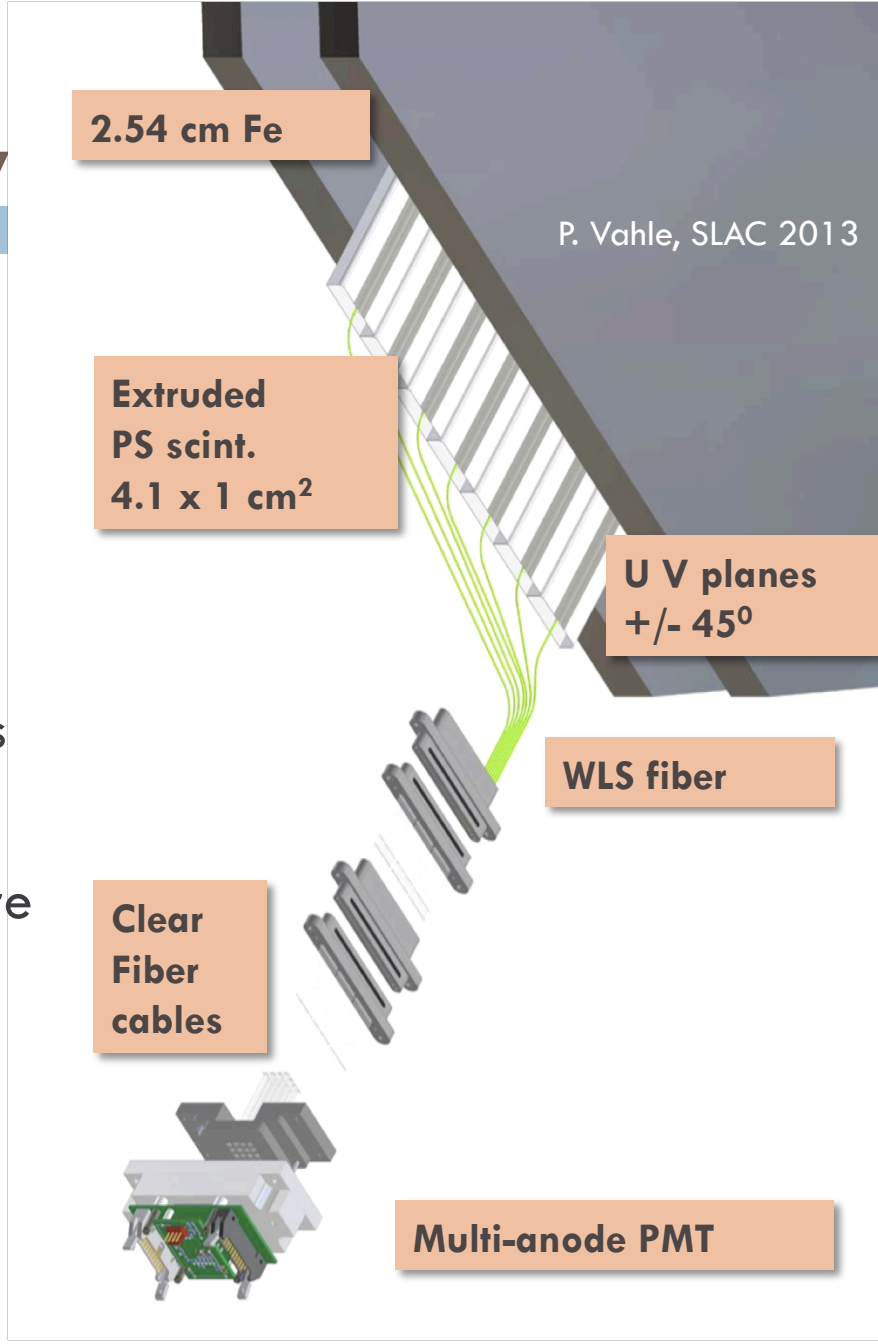
http://www.fnal.gov/directorate/program_planning/Nov2010PACPublic/1003_SciNOvA_Proposal_2010_15_10.pdf

Summary

- NDs provide the means for precision oscillation measurements
  - control systematic uncertainties in cross sections and flux
- With NDs, Robust FD predictions are obtained
  - ~5% bin-to-bin for muon neutrino CC rate
  - better than 5% error on BG to electron neutrino appearance search
- NDs directly account for time dependent variations in beam conditions/beam line hardware
- Modest investment in ND complex provide valuable cross checks
  - better physics
  - less technical risk

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 $\mu+$ from $\mu-$
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)

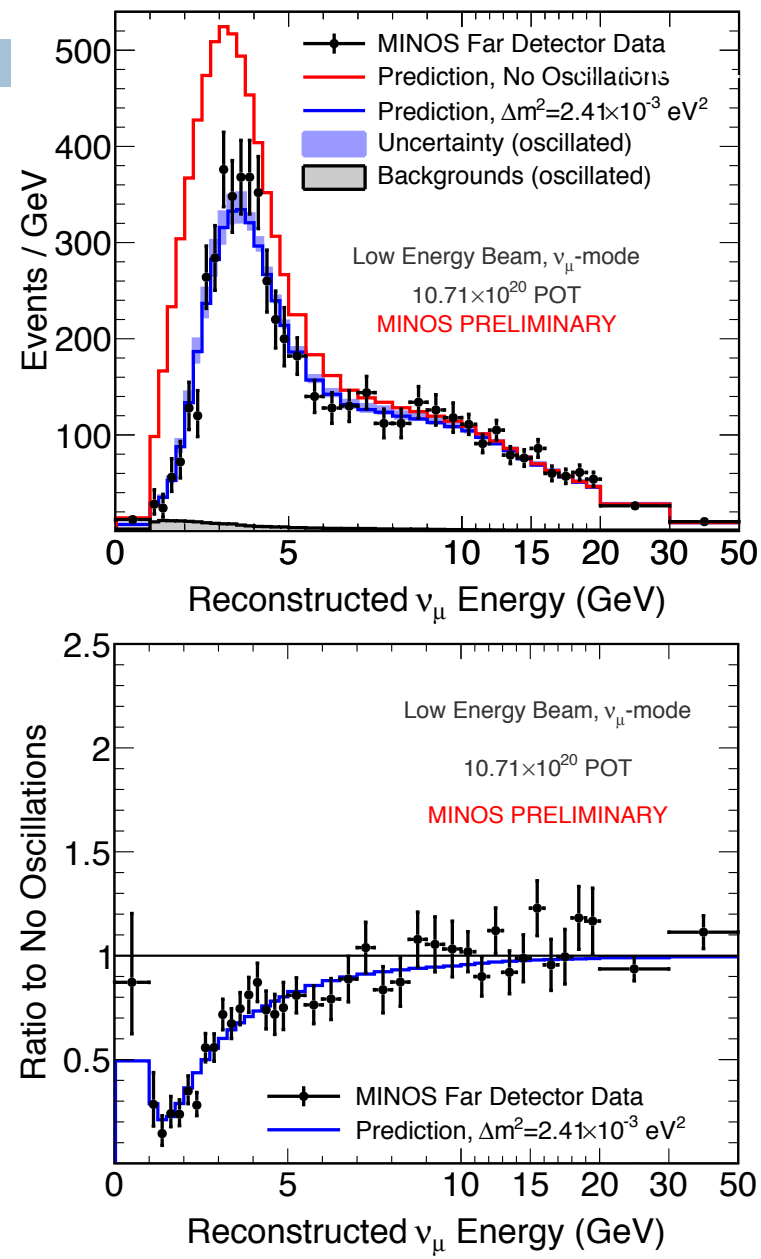


Muon Neutrino Oscillation Results

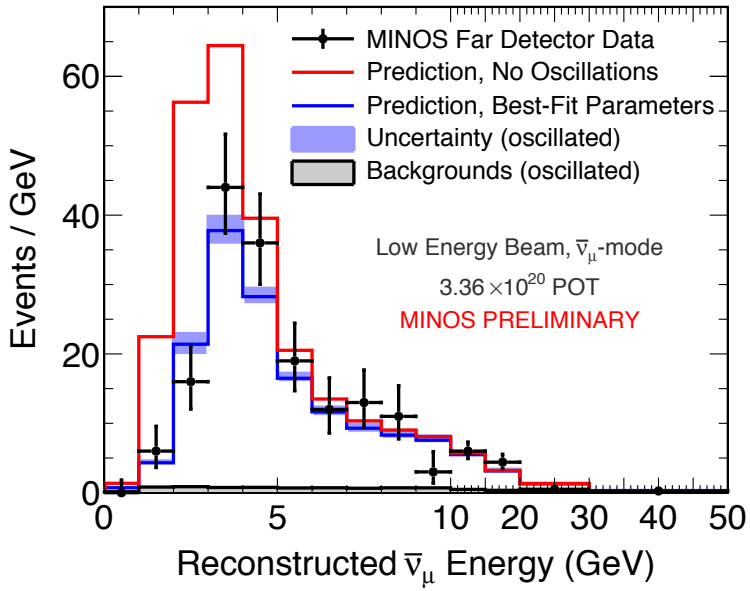
- No Oscillations: 3564
- Observed: 2894
- Best Fit:

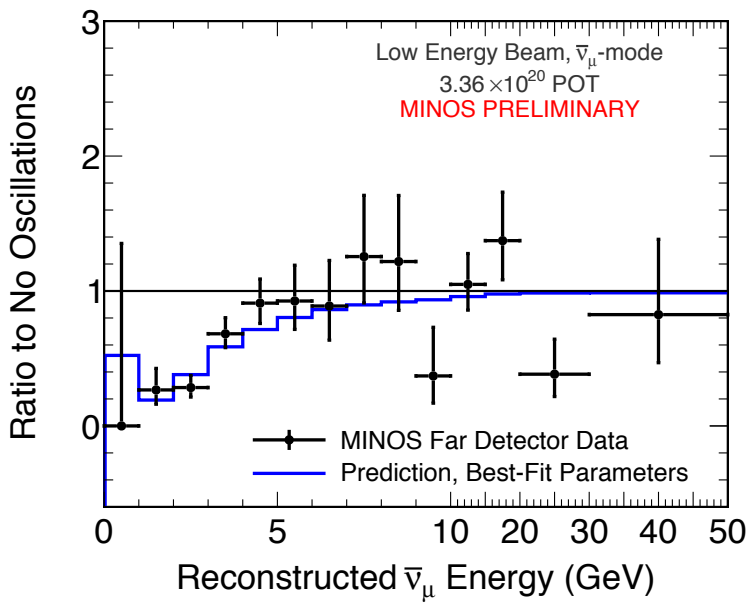
$$\left|\Delta m^2\right| = 2.41^{+0.11}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

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



Muon Antineutrino Oscillation Results





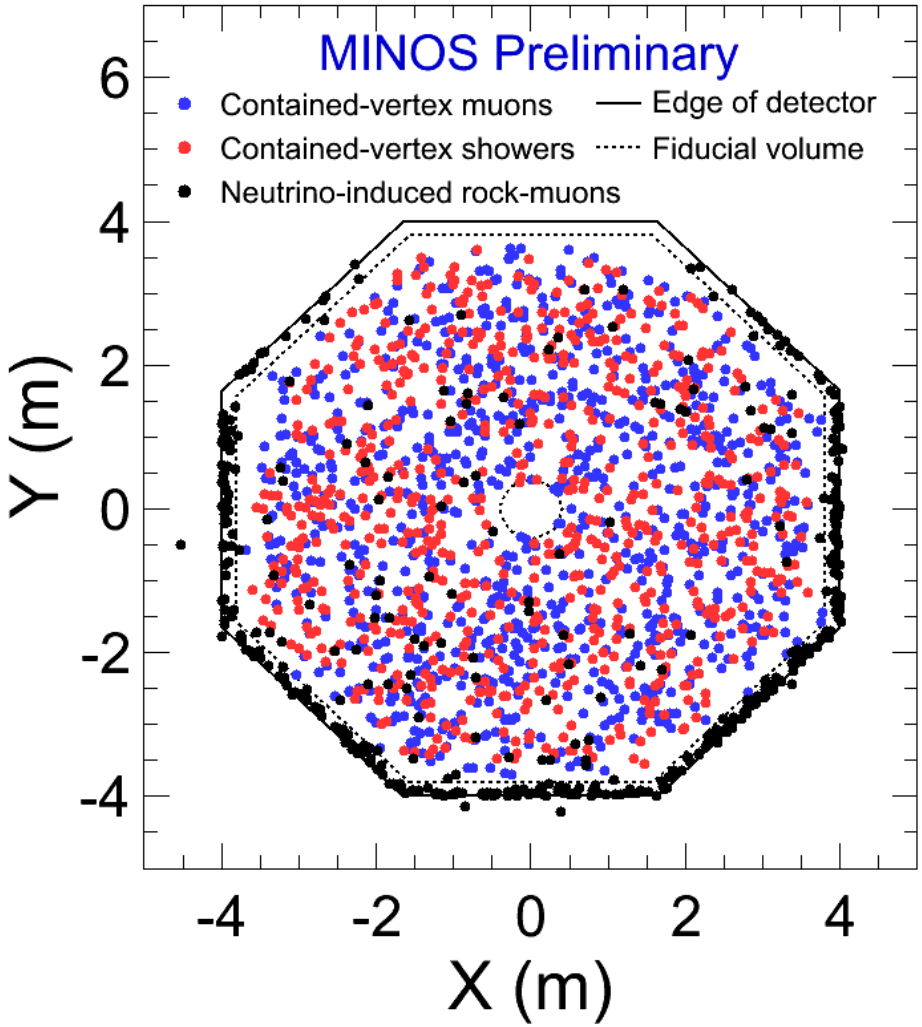
- No Oscillations: 312
- Observed: 226
- Best Fit:

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

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

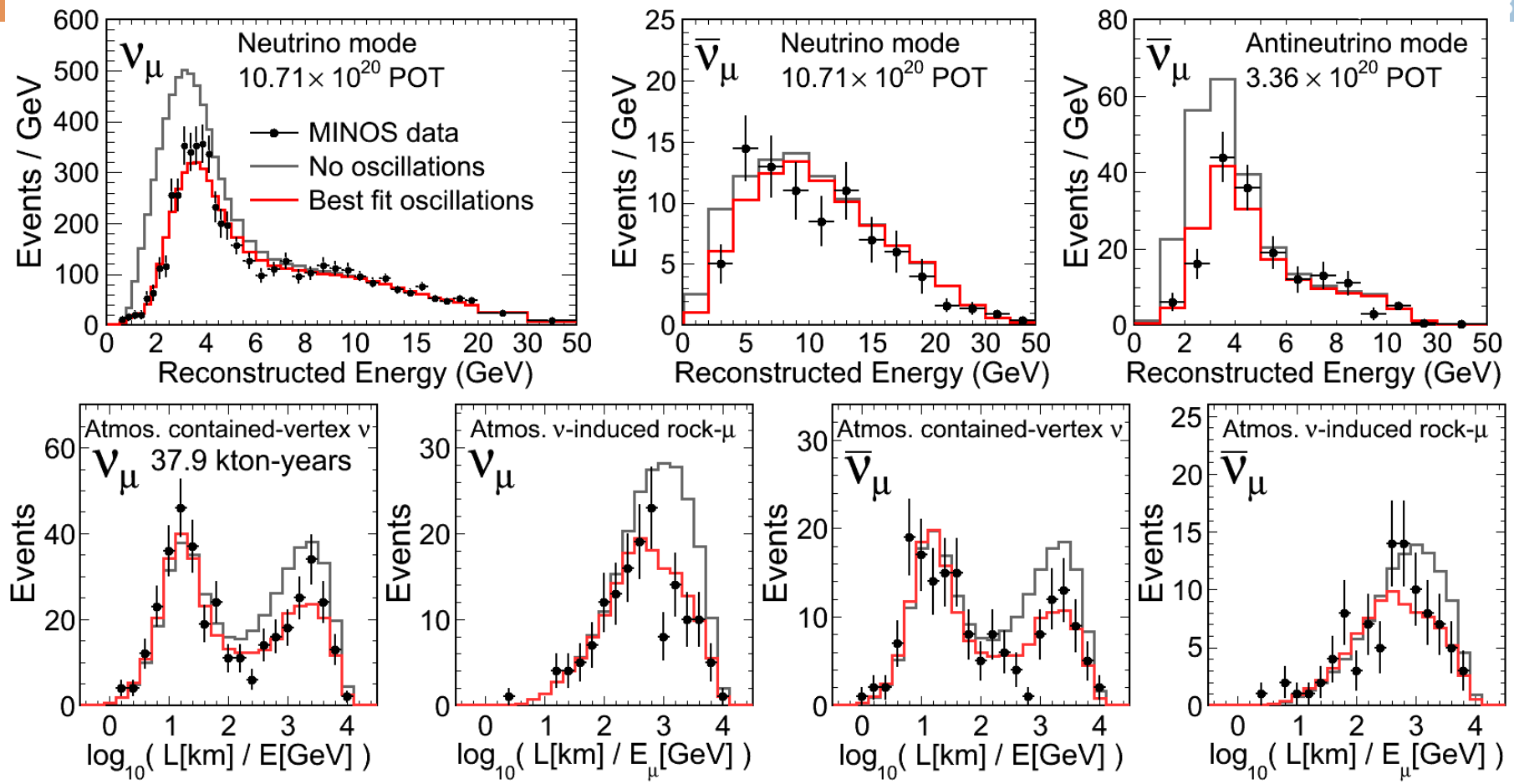
Atmospheric Neutrinos

- 39.7 kton years of atmospheric neutrino data collected since 2003
- 2072 additional neutrino events
  - 905 contained vertex muon events
  - 466 neutrino induced rock muon events
  - 701 contained vertex showers



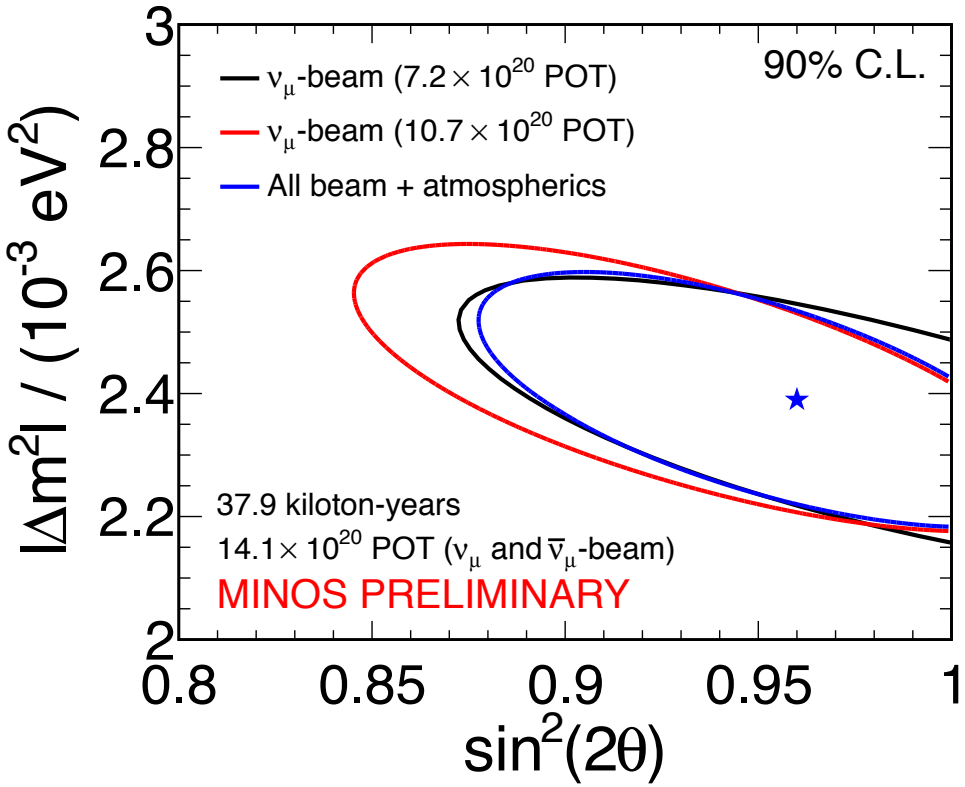
Atmospheric Neutrinos

MINOS PRELIMINARY



- 15 sources of systematic uncertainty included as nuisance parameters
- Oscillations fit the data well: 64% of pseudo experiments have worse χ^2

Combined Neutrino Contours



- Combined MINOS neutrino oscillation parameters:

$$\left|\Delta m^2\right| = 2.39^{+0.09}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$

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

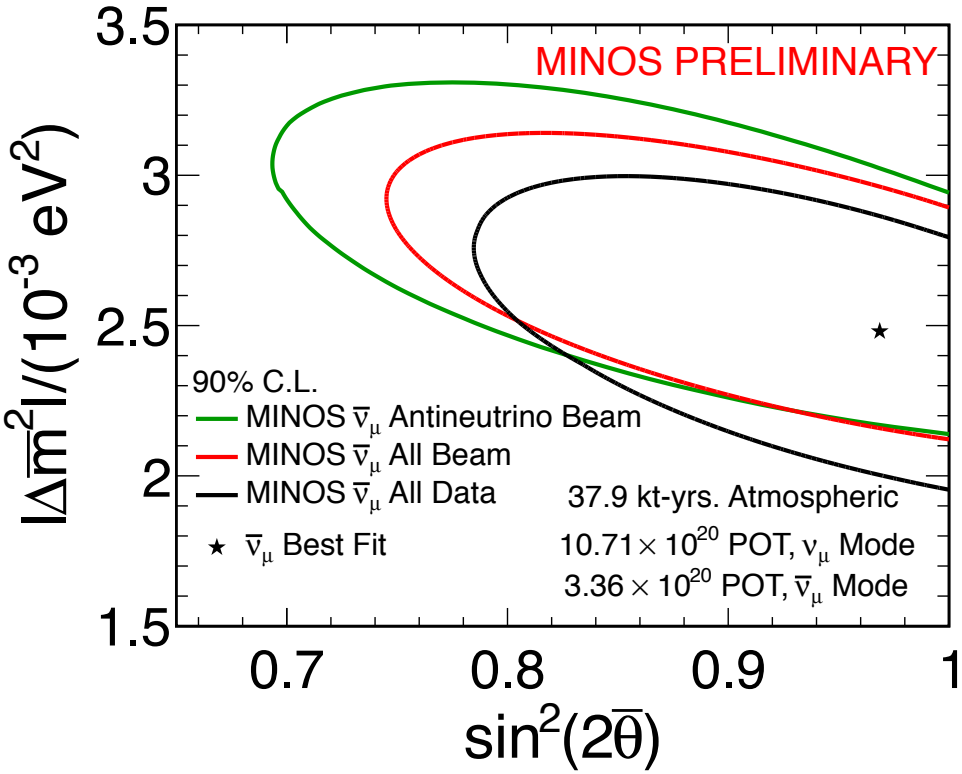
All beam and atmospheric samples in a two parameter fit (assumes neutrinos and antineutrinos oscillate the same)

Combined Antineutrino Contours

- Combined MINOS antineutrino oscillation parameters:

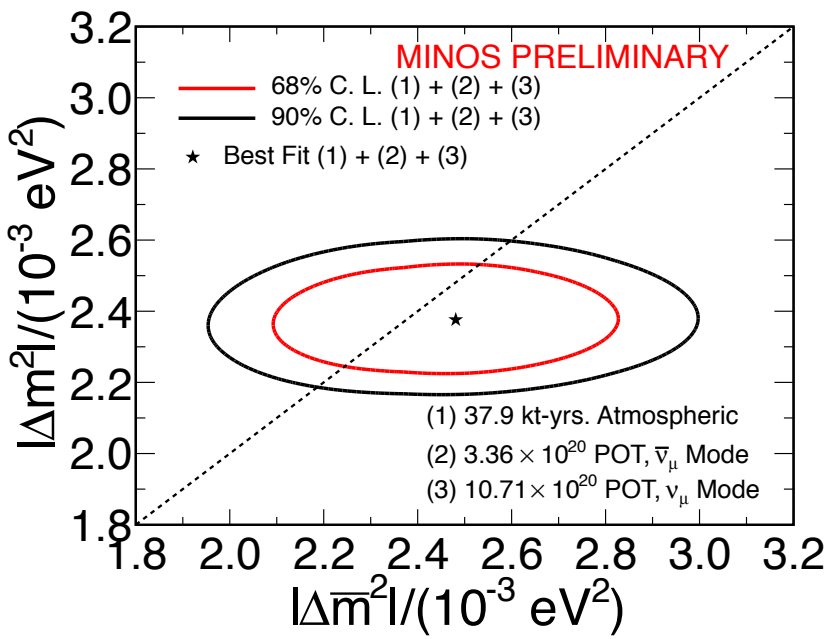
$$\left|\Delta\bar{m}^2\right| = 2.48^{+0.22}_{-0.27} \times 10^{-3}\,\mathrm{eV}^2$$

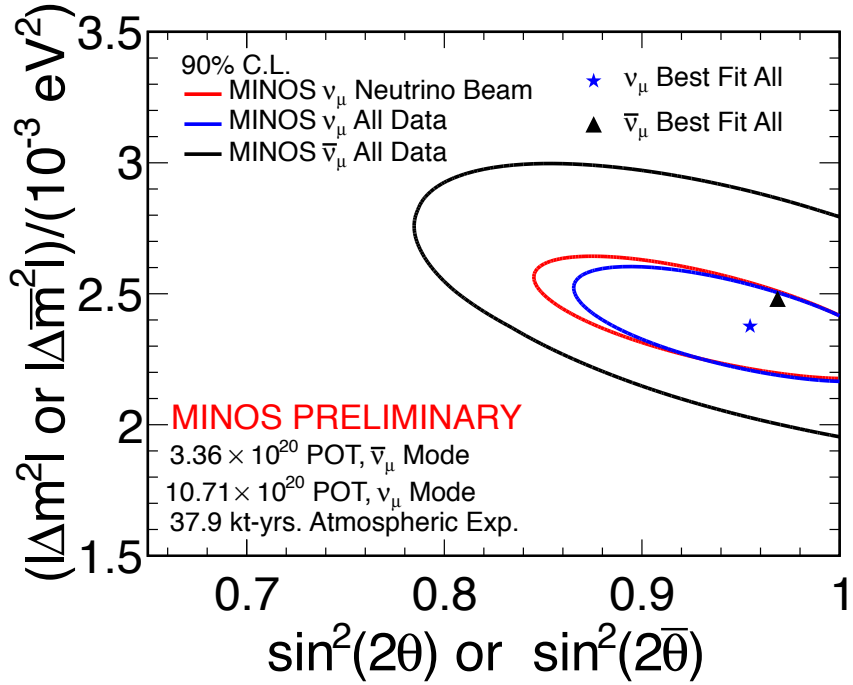
$$\sin^2(2\bar{\theta}) > 0.83\ (90\%\ \mathrm{C.L.})$$



All beam and atmospheric samples in a four parameter fit (neutrinos and antineutrino are allowed to oscillate differently)

Comparing Neutrinos and Antineutrinos

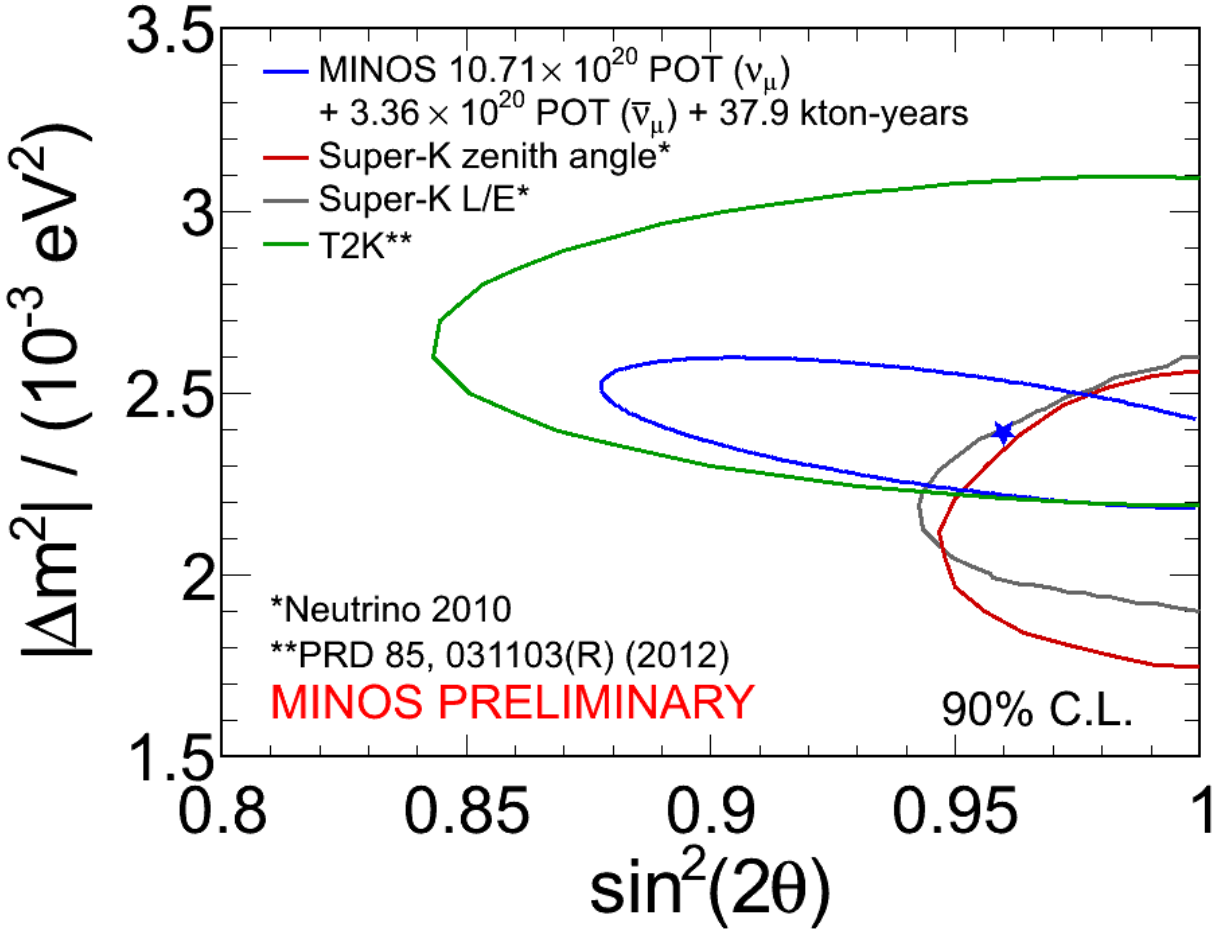




$$\left|\Delta\bar{m}^2\right| - \left|\Delta m^2\right| = 1.0^{+2.4}_{-2.8} \times 10^{-4}\,\mathrm{eV}^2$$

New data has resolved tension between neutrino and antineutrino results

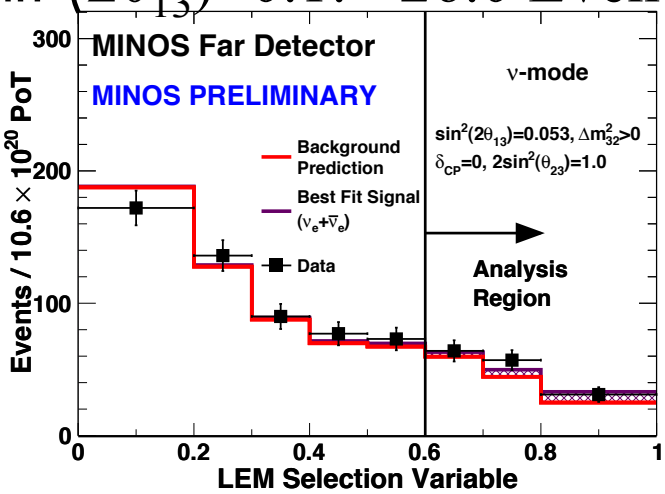
MINOS v. The World

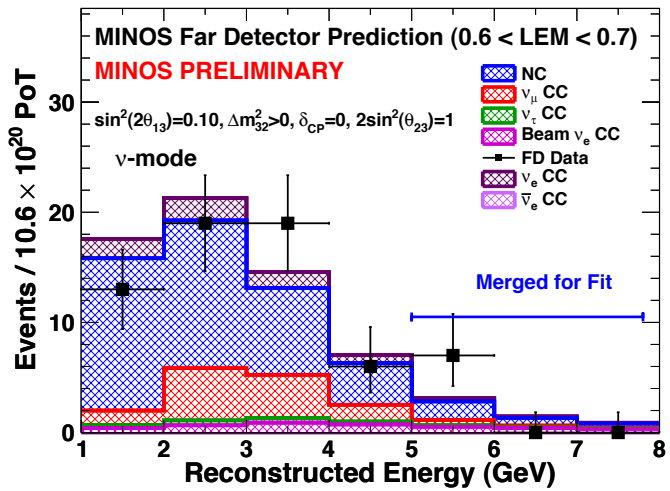


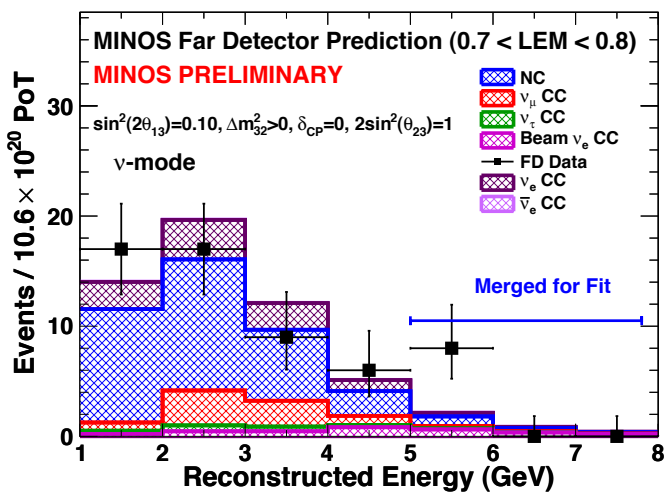
Electron Neutrino Appearance: FHC Beam

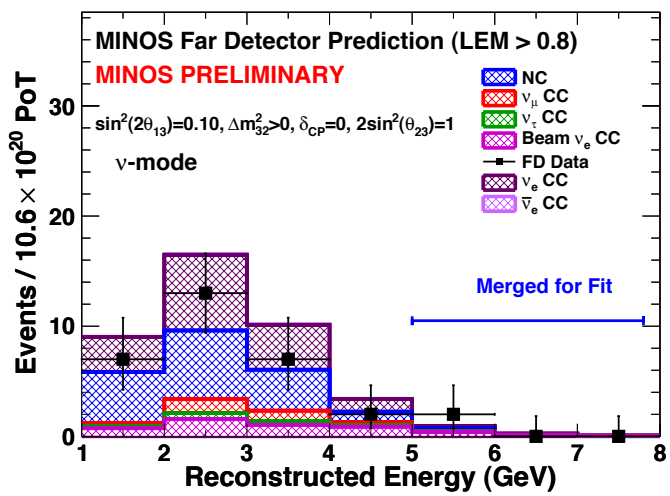
In Signal Enhanced Region:

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







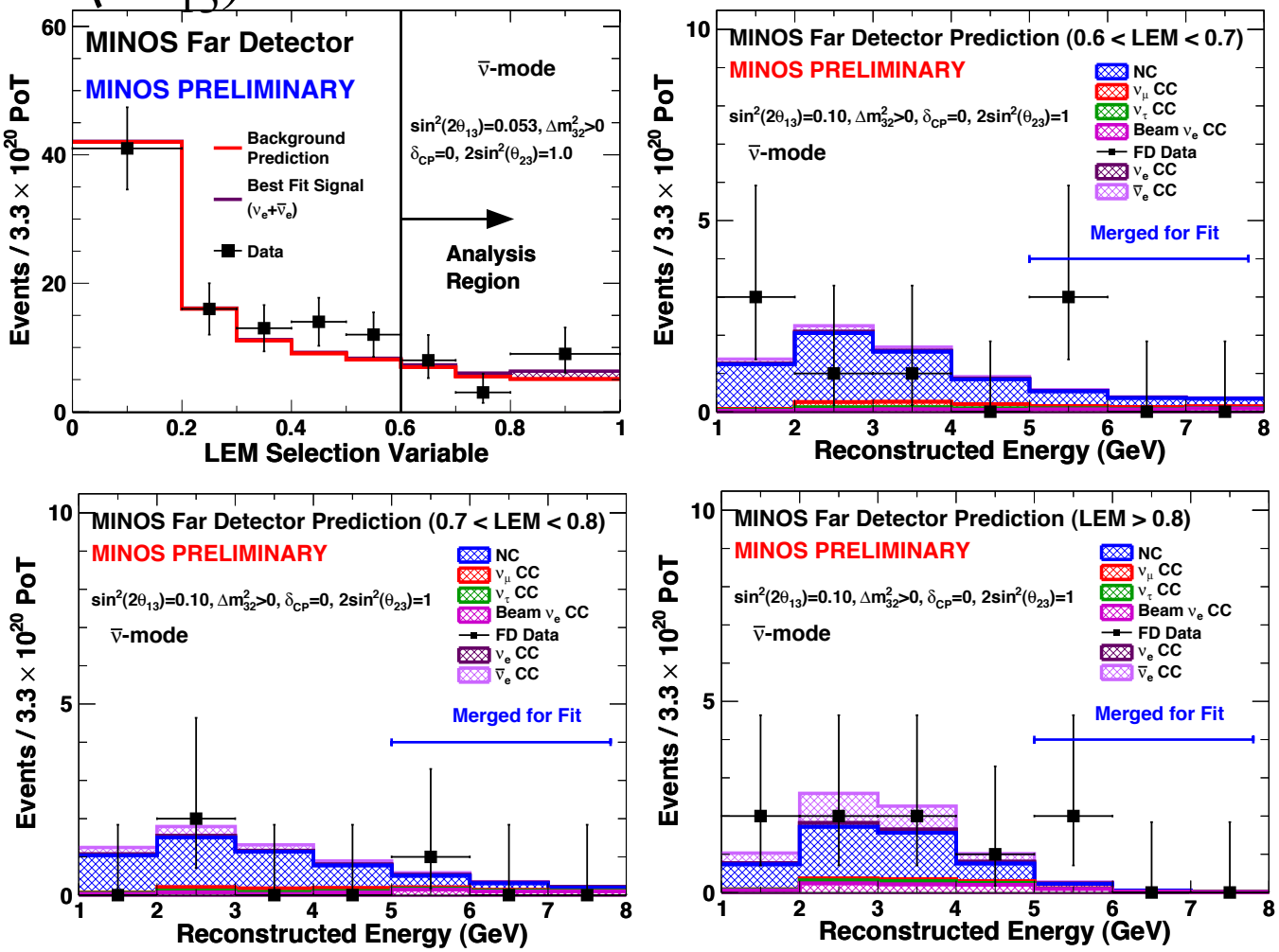


Electron Neutrino Appearance: RHC Beam

In Signal Enhanced Region:

P. Vahle, SLAC 2013

- If θ_{13}=0: 10.5 BG Events
- If $\sin^2(2\theta_{13})$=0.1: +3.1 Events
  - Observe: 12 Events



Combined Electron Neutrino Appearance Contour

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

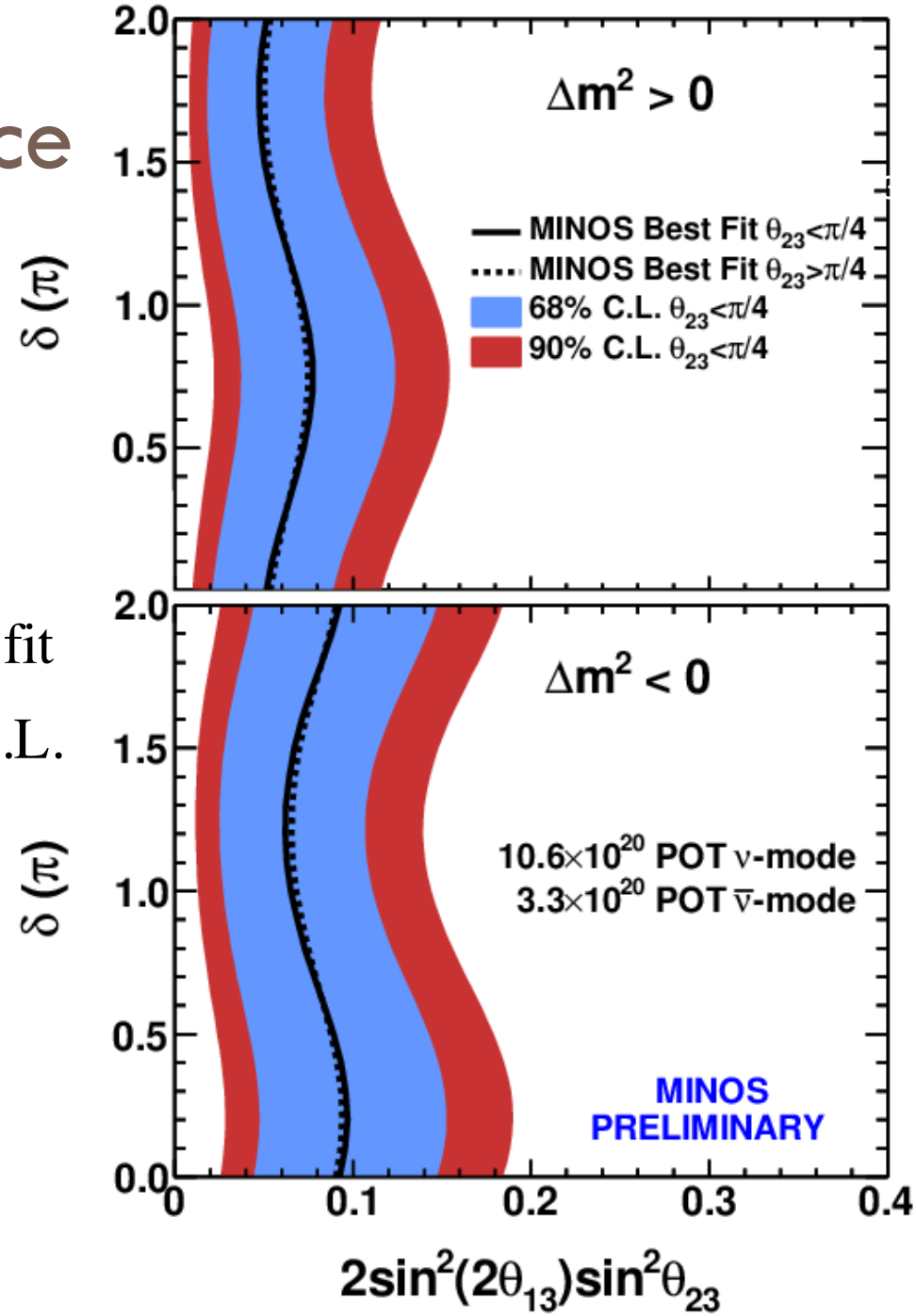
normal (inverted) hierarchy

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

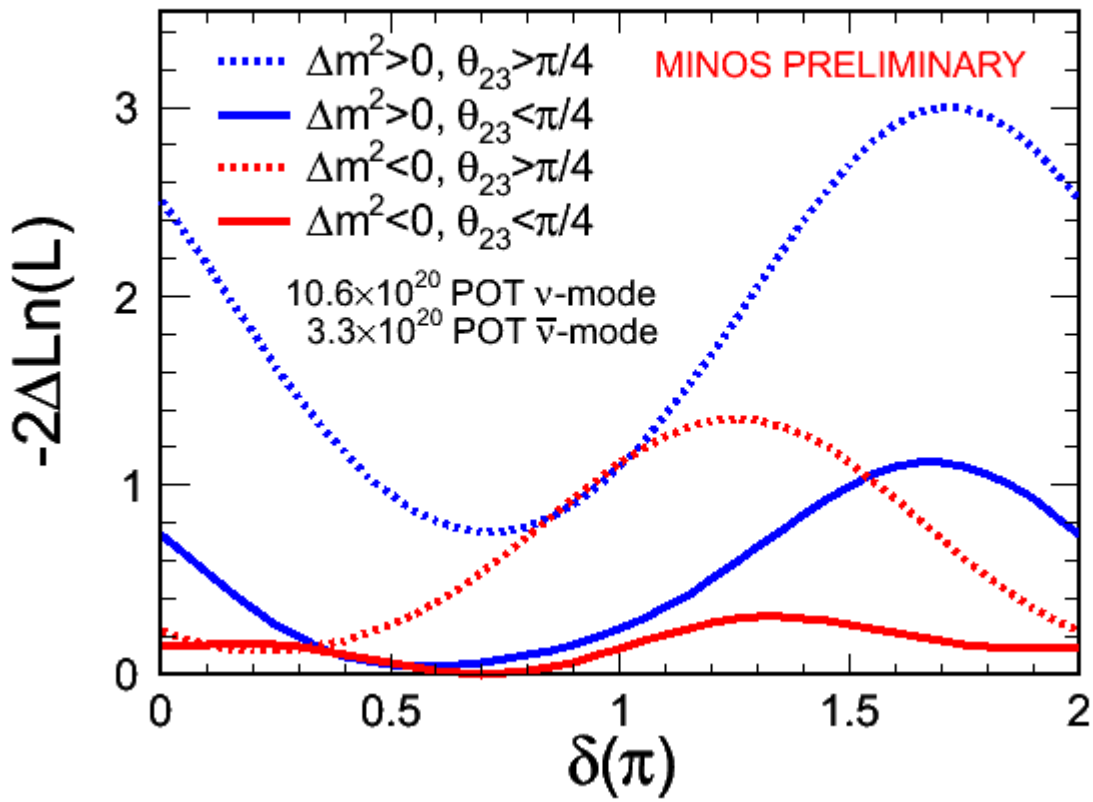
$0.01 < \sin^2(2\theta_{13}) < 0.12$ at 90% C.L.

(0.03) (0.19)

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

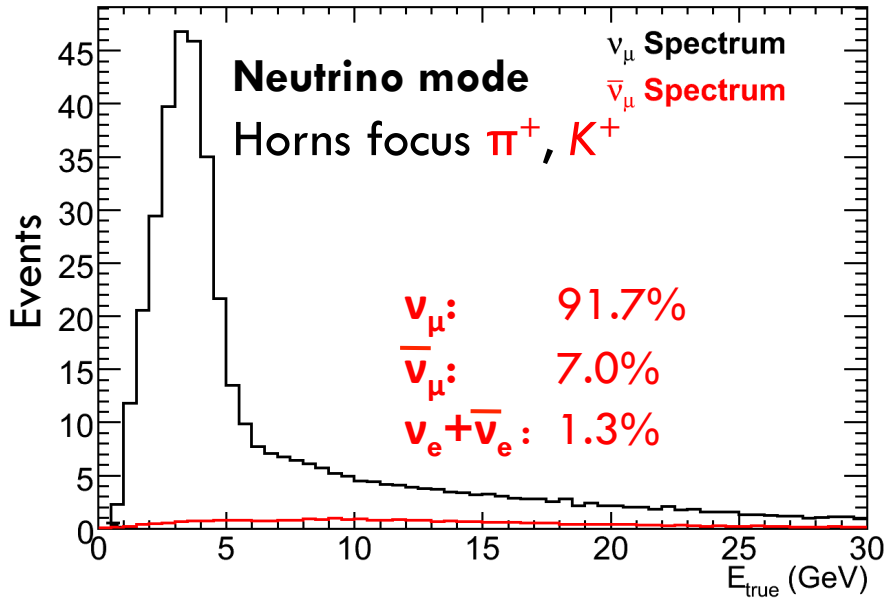


Delta and the Hierarchy

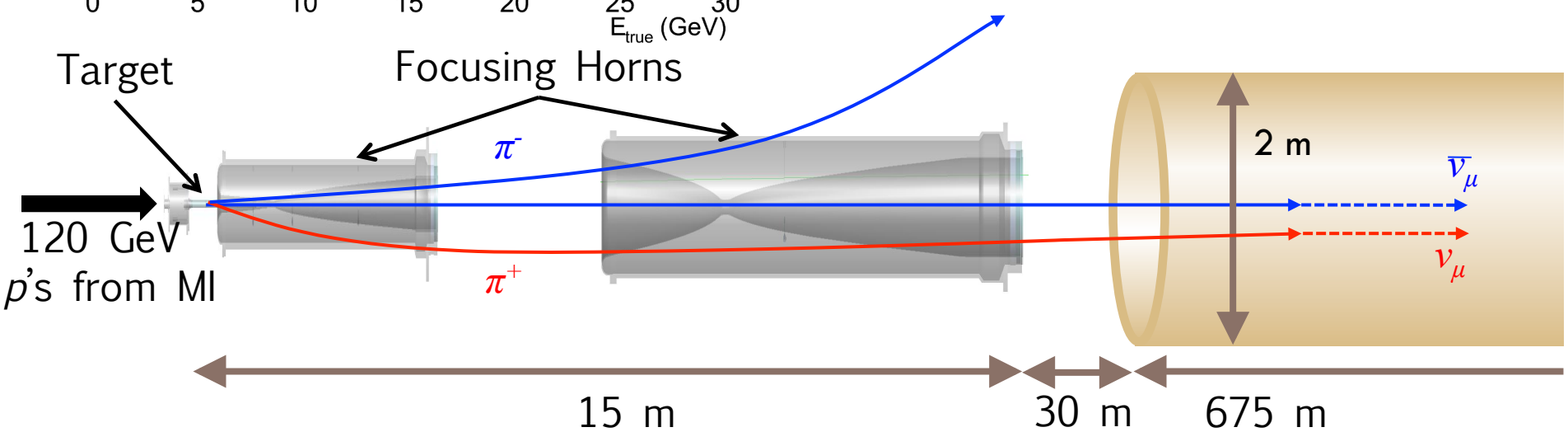


- With $\theta_{13}=0.0982\pm0.0131$ (from D.B., Reno, D.C.), inverted hierarchy preferred at 0.631 units of $-2\Delta \ln L$ for upper octant (0.041 for lower octant)

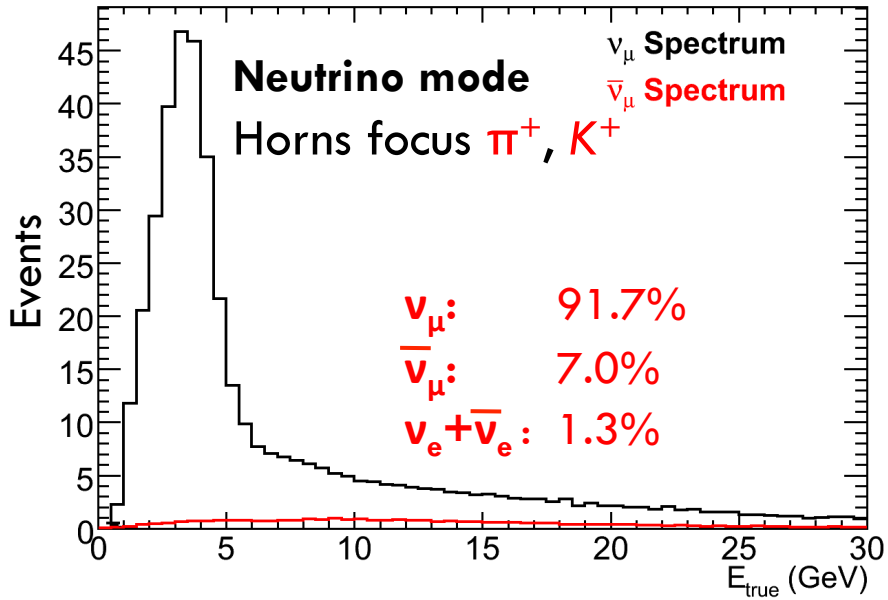
Making a Neutrino Beam

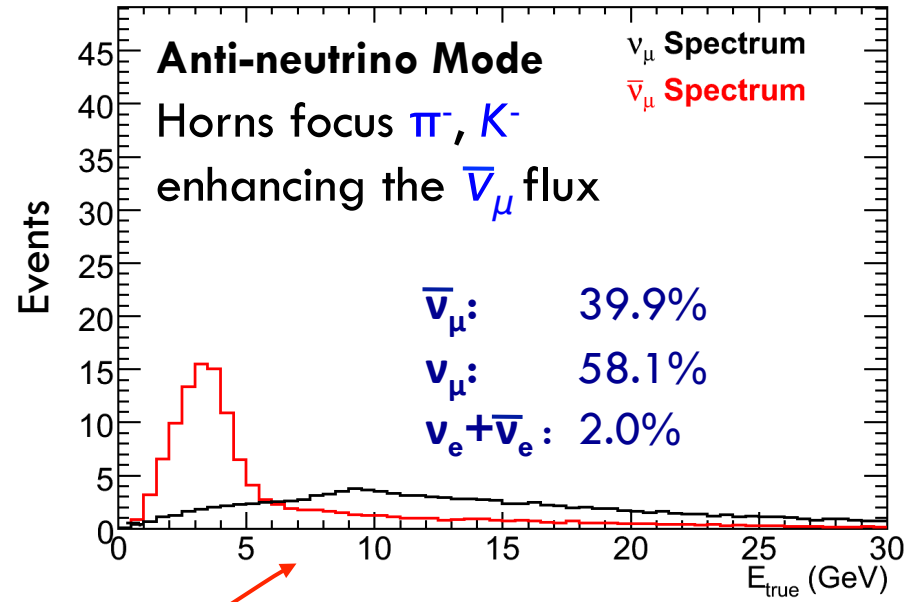


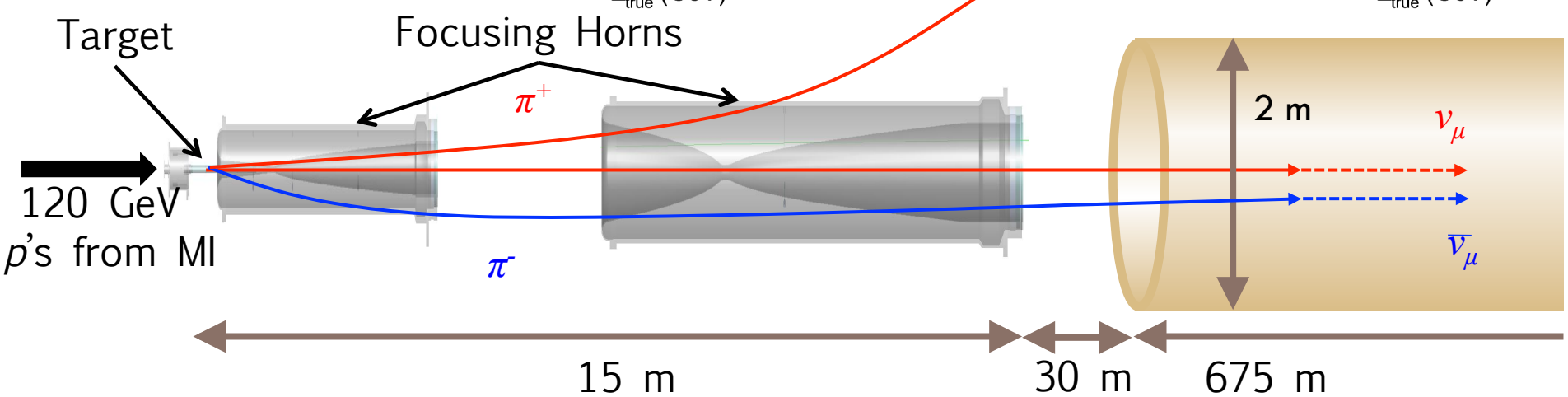
- Production: 120 GeV p^+ on 2 interaction length C target
- Focusing: π/K focused/sign selected by two horns
- Decay: π/K decay in 2m diameter decay pipe to ν_μ with wide range of energies



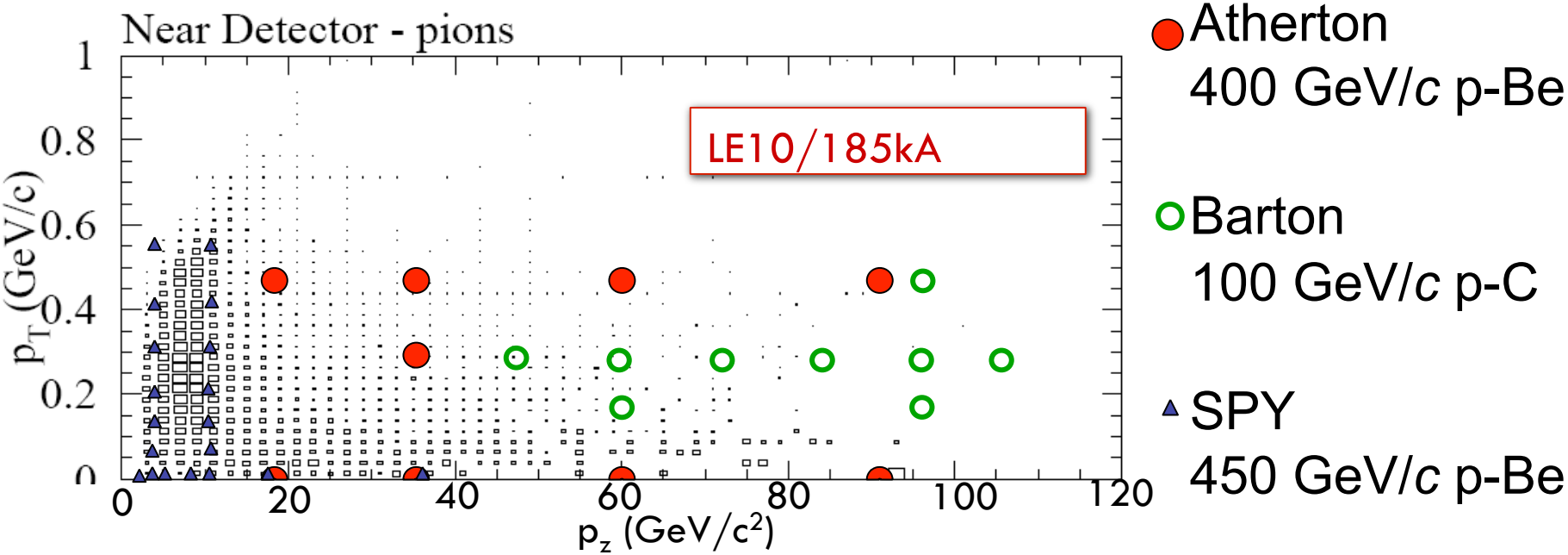
Making an Anti-neutrino Beam







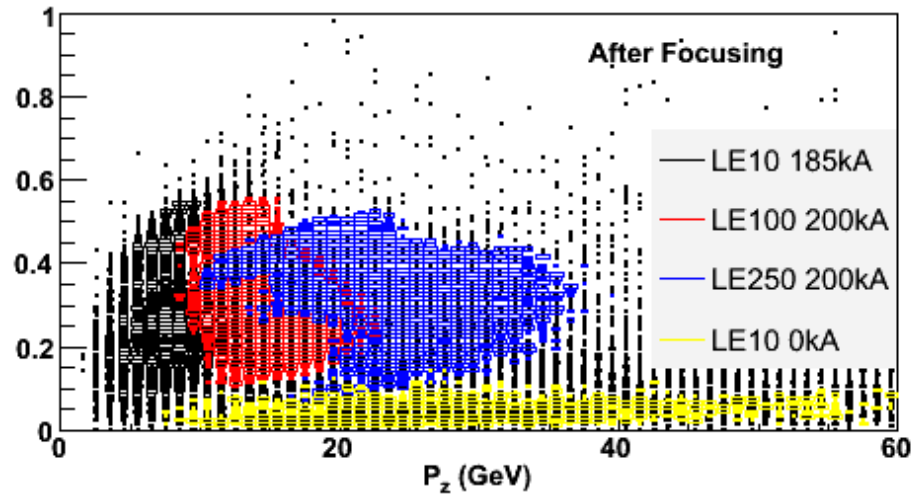
Predicting the Flux

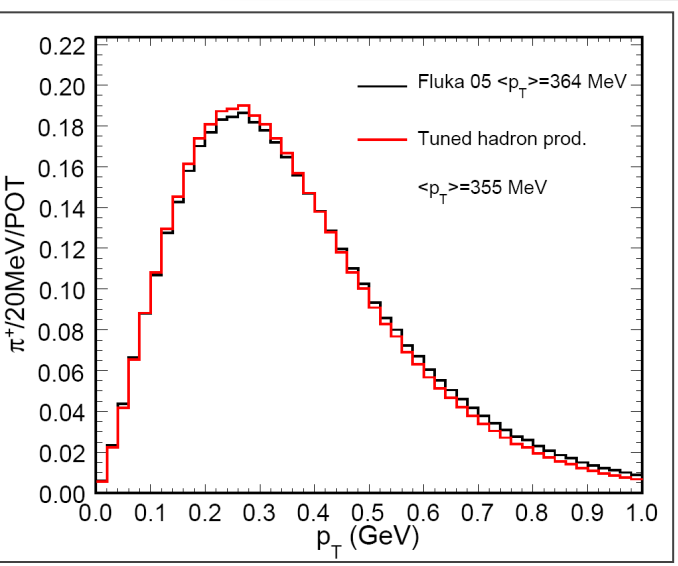


- Paucity of data in region of interesting phase space
- Extrapolation of existing data to MINOS beam energy, target thickness, target material
- Systematics originally evaluated using model spread
- Additional systematics from focusing system alignment, horn current calibration, skin depth, etc

Hadron Production Tuning

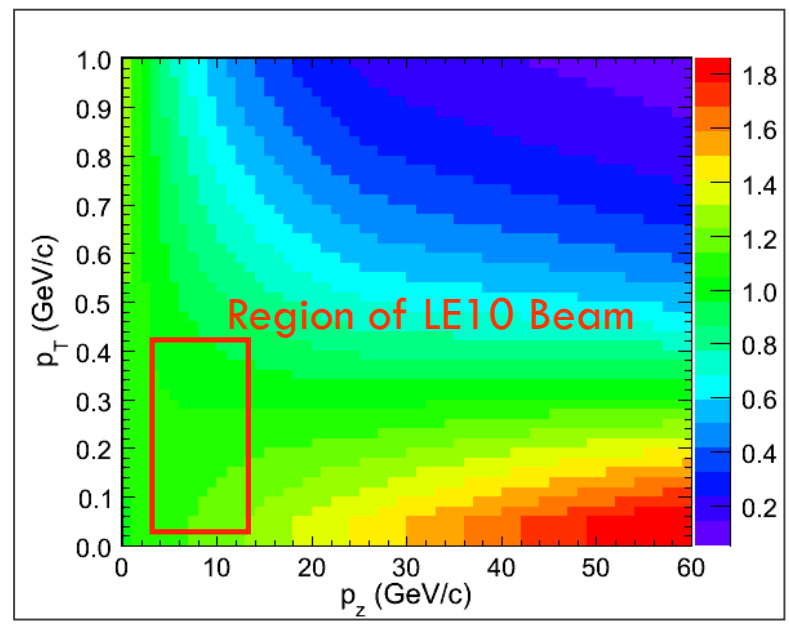
Model	mean pt (GeV/c)
GFLUKA	0.37
Sanf.-Wang	0.42
CKP	0.44
Malensek	0.50
MARS – v.14	0.38
MARS – v.15	0.39
Fluka 2001	0.43
Fluka 2005	0.364
Fluka2005 Tuned	0.355





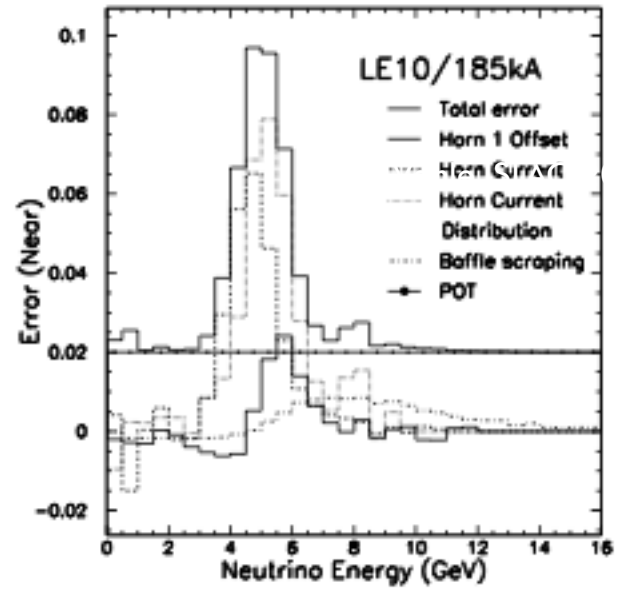
Weights ~20% in region of p_T vs p_z that produces MINOS neutrinos

Hadron production tuning changes mean p_T less than model spread

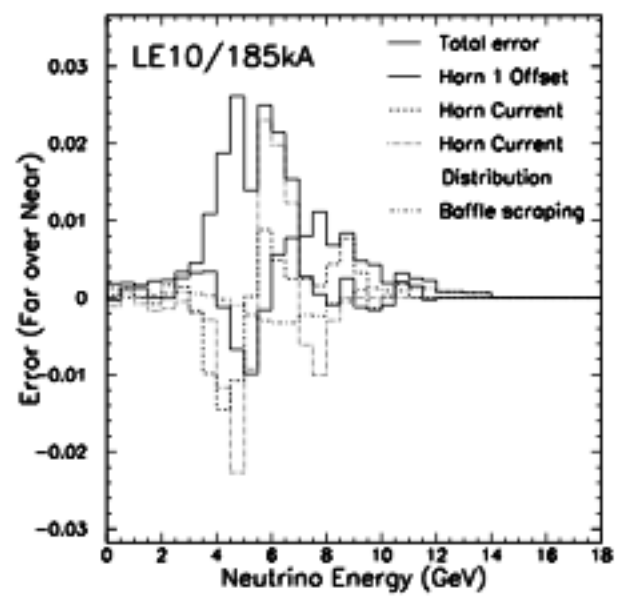


Beam Systematics

- 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)



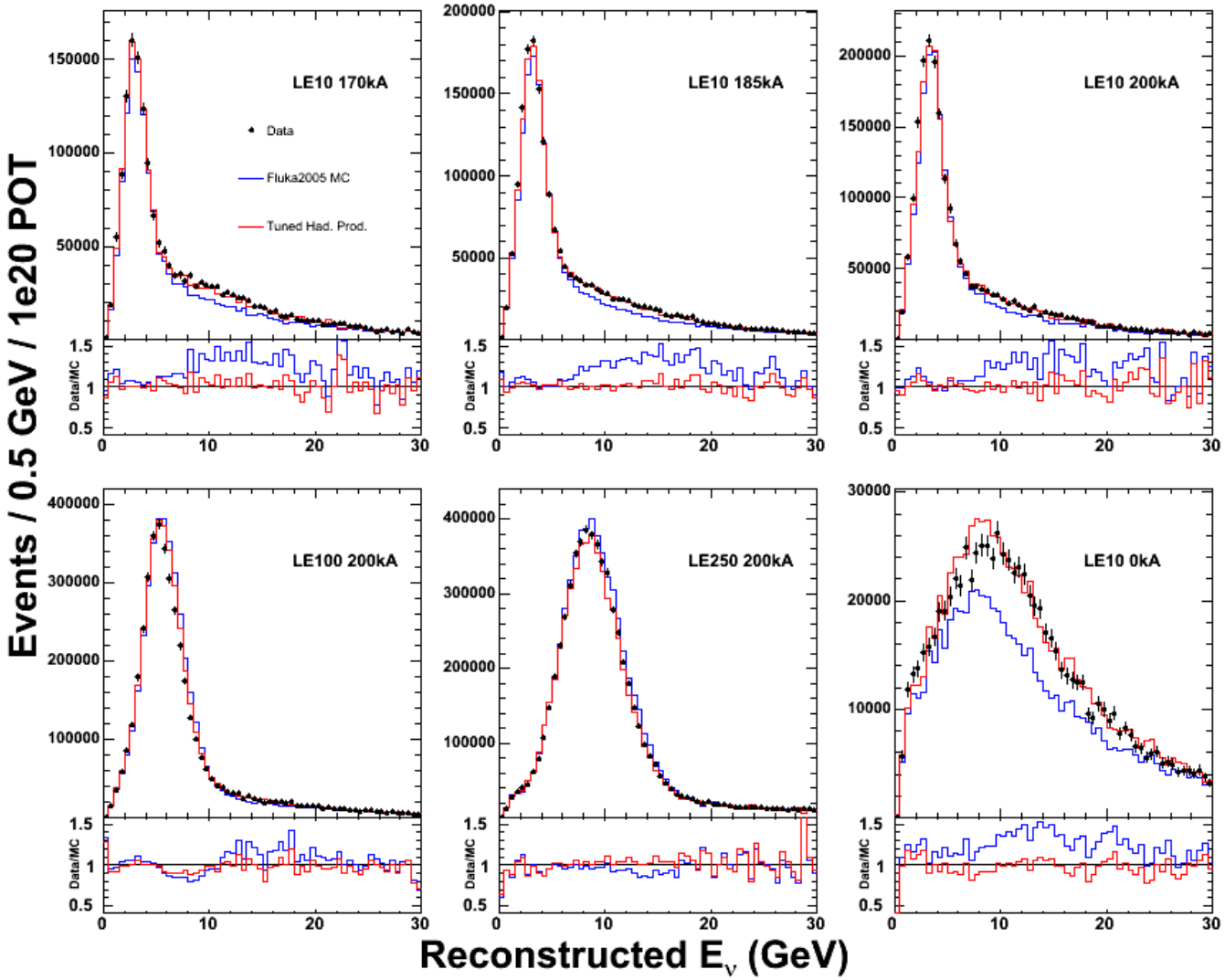
(a)



(b)

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

Beam Tuning


LE10 170kA
Data
Fluka2005 MC
Tuned Had. Prod.
LE10 185kA
LE10 200kA
LE100 200kA
LE250 200kA
LE10 0kA
Events / 0.5 GeV / 1e20 POT
Data/MC
Reconstructed E_ν (GeV)

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:

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

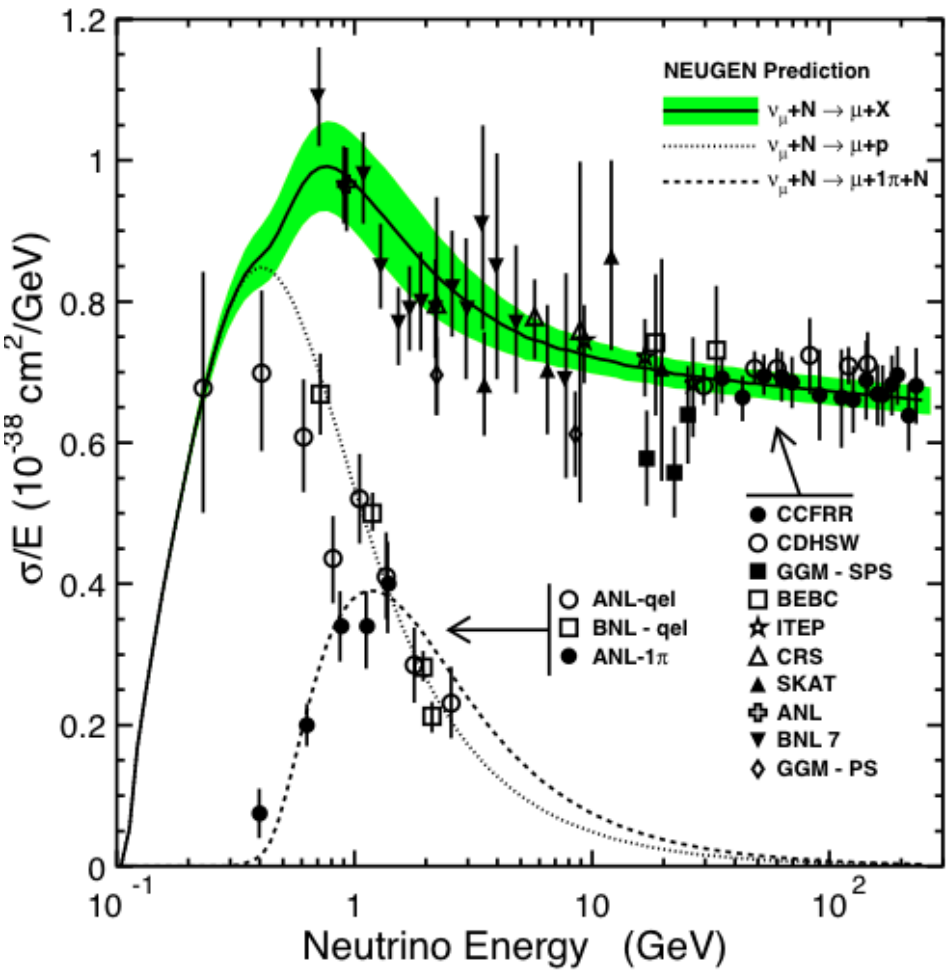
$$B' = (1 + par[1](0.1 - p_z) B(p_z)$$

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

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

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.



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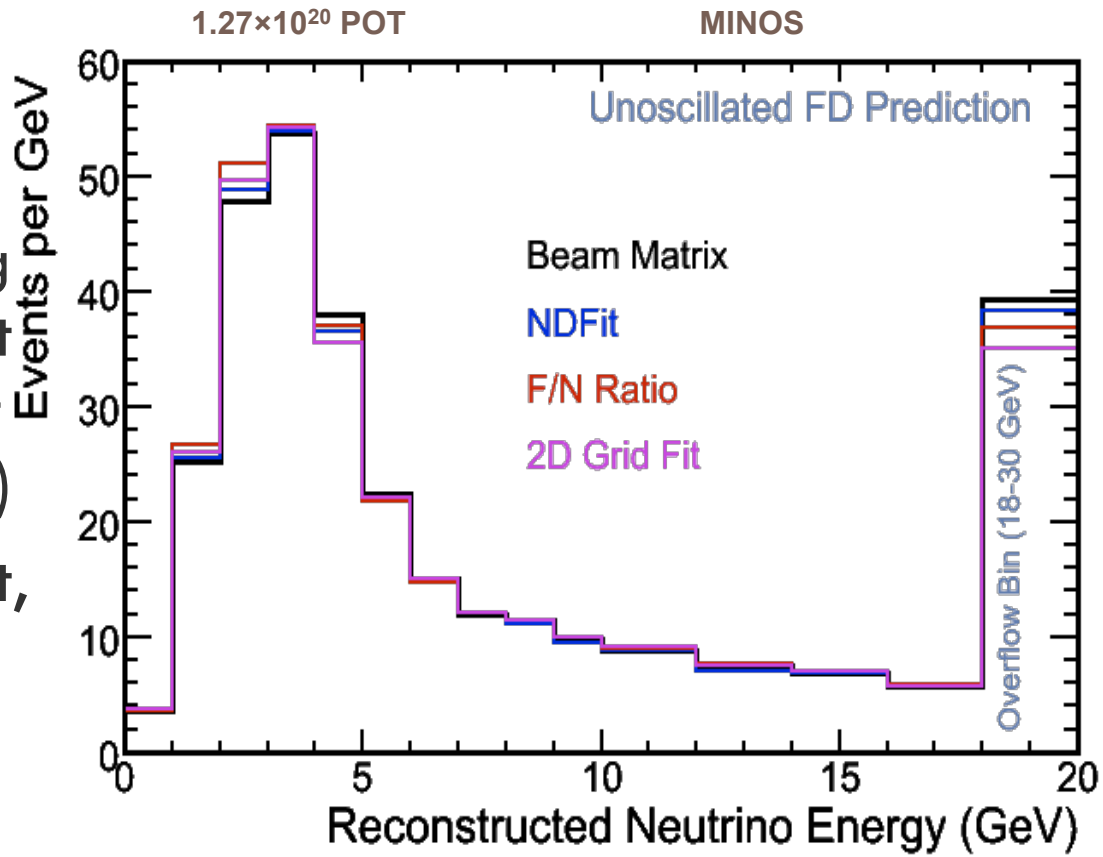
Indirect Extrapolation

- 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

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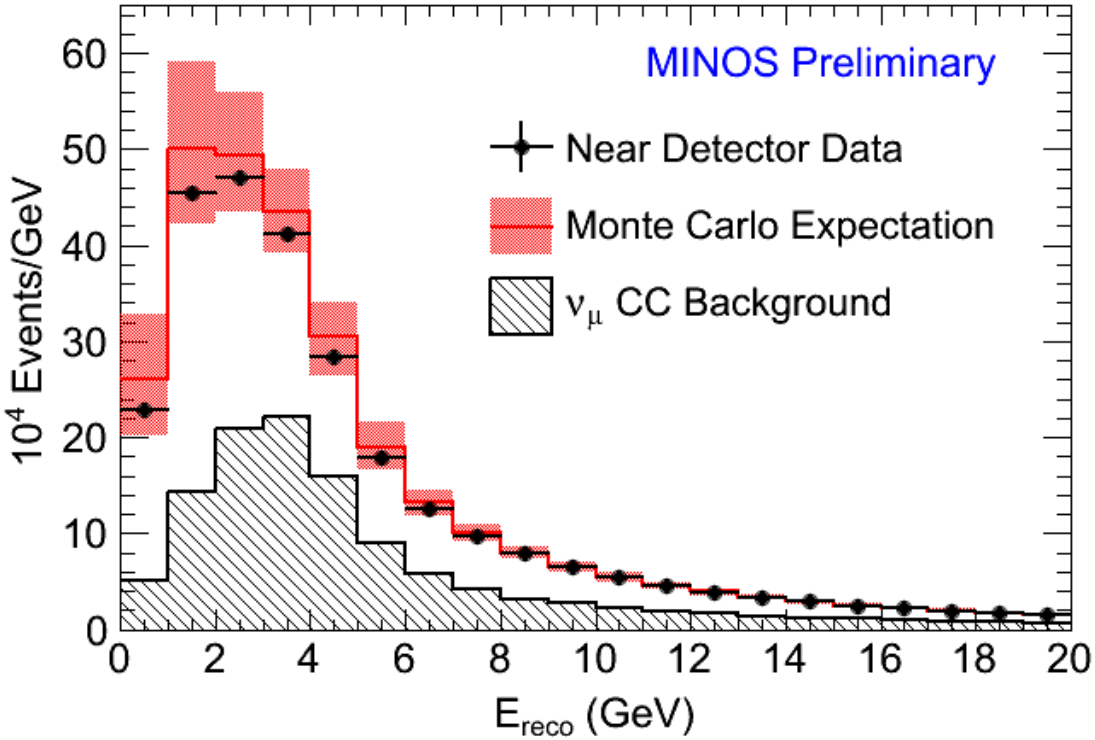
Initial CC Systematics

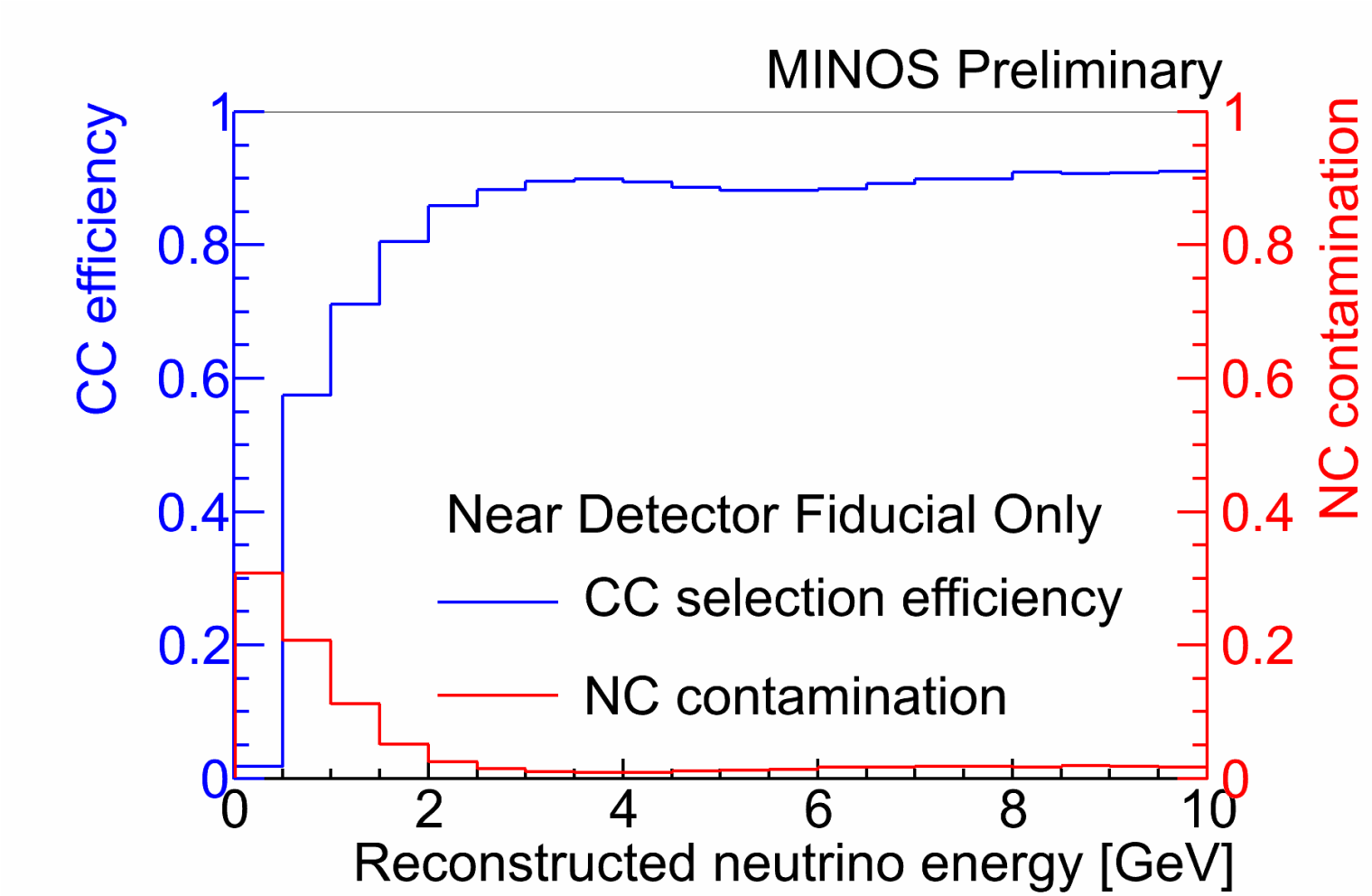
Uncertainty		$\lvert\Delta m^2\rvert$ ($10^{-3}\,\mathrm{eV}^2/c^4$)	$\sin^2 2\theta$
(a) Normalization	($\pm 4\%$)	0.050	0.005
(b) Abs. hadronic E scale	($\pm 11\%$)	0.057	0.048
(c) NC contamination	($\pm 50\%$)	0.090	0.050
(d) Beam uncertainties		0.015	<0.005
(e) Cross sections		0.011	0.005
All other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

Neutral Current Near Event Rates

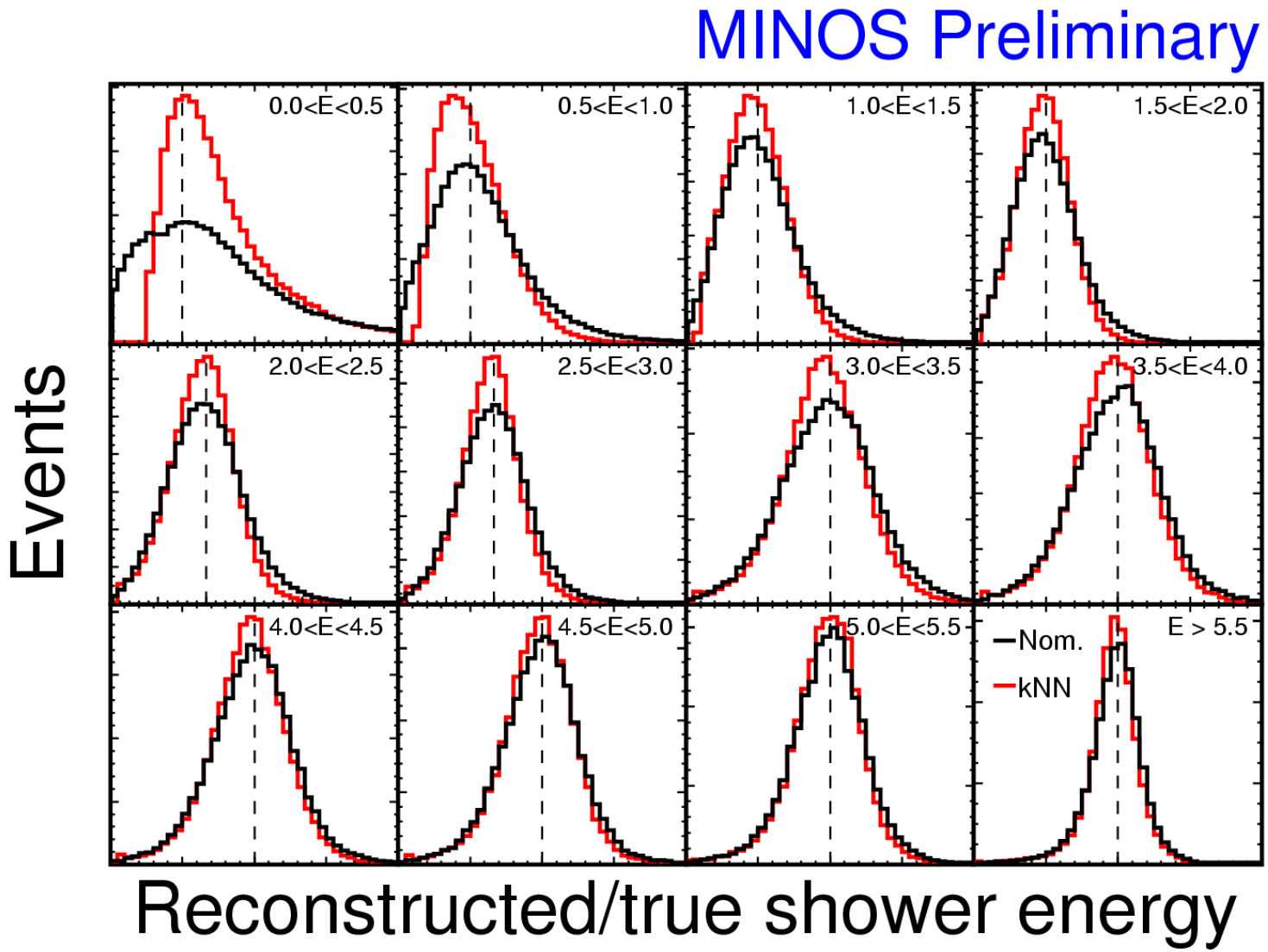


- Neutral Current event rate should not change in standard 3 flavor oscillations
- A deficit in the Far event rate could indicate mixing to sterile neutrinos
- ν_e CC events would be included in NC sample, results depend on the possibility of ν_e appearance

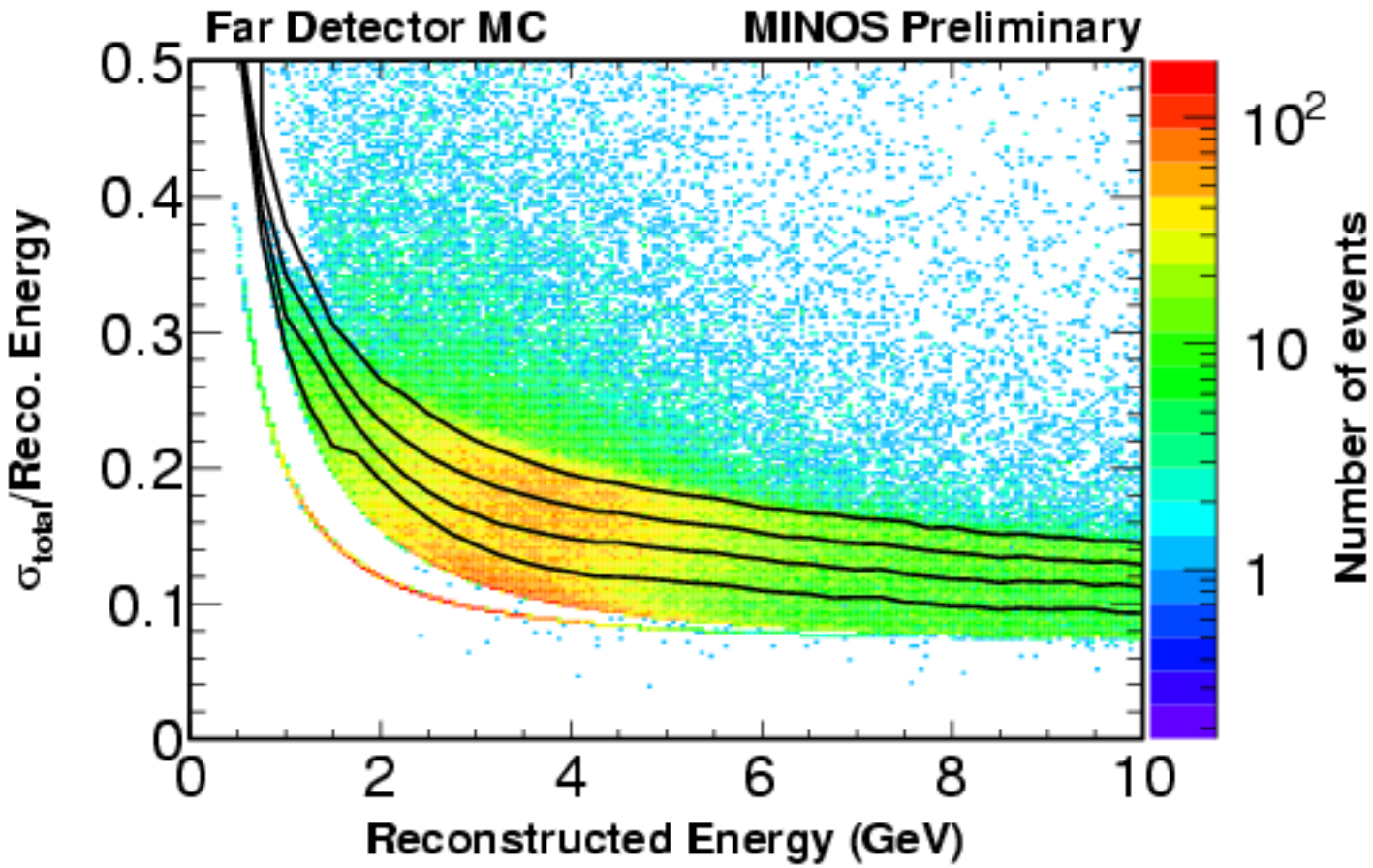
New Muon-neutrino CC Selection



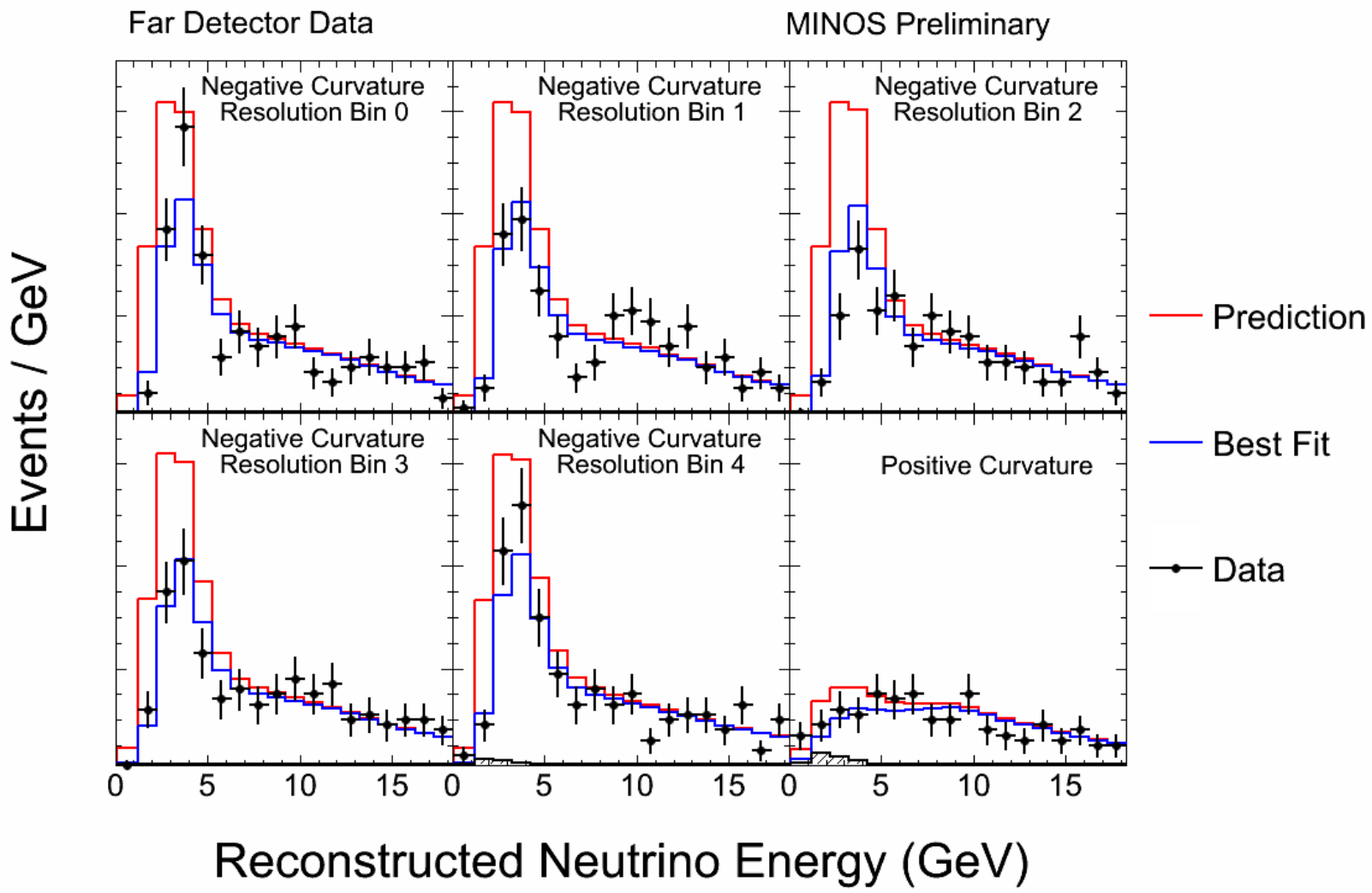
Shower Energy Resolution



Energy Resolution Binning

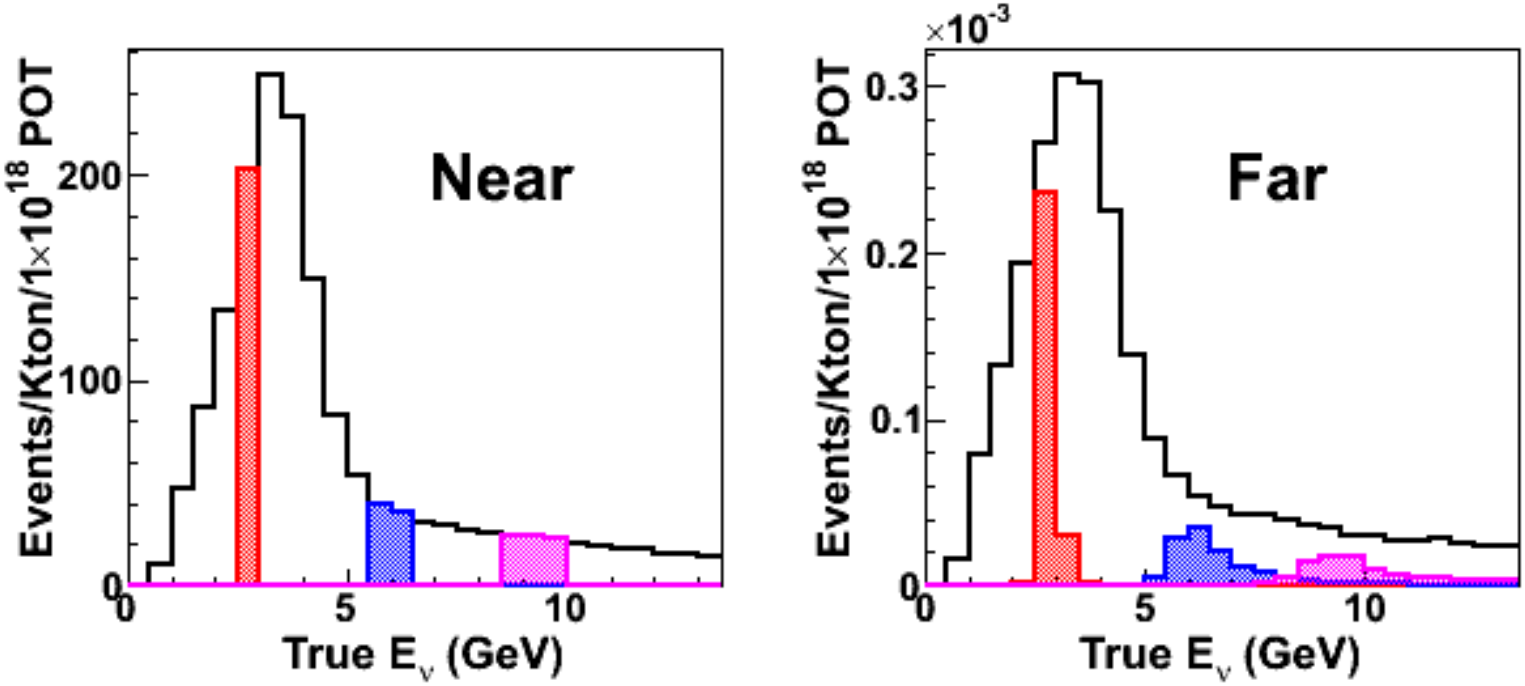


Resolution Binning

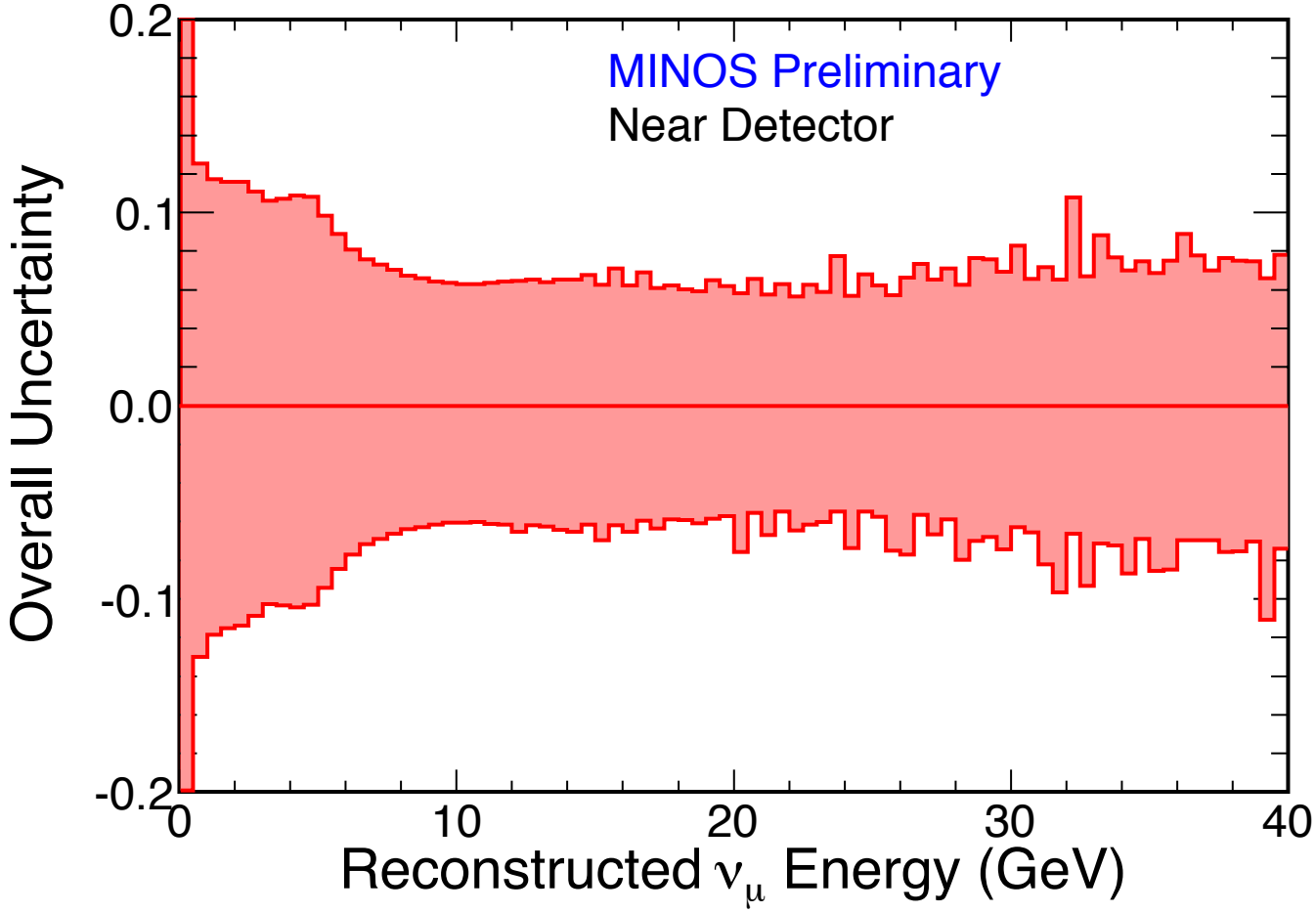


Near to Far

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



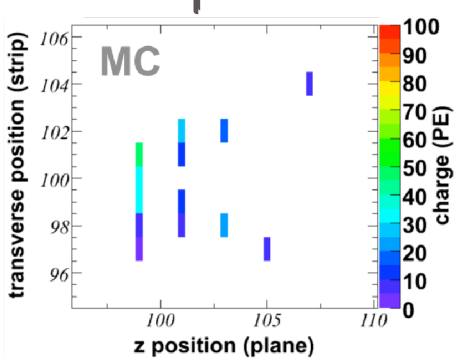
ND Systematics



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)

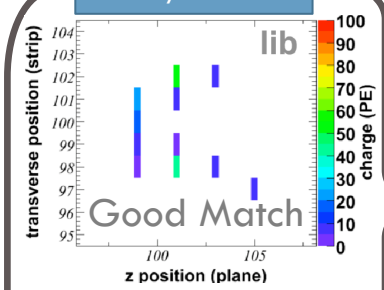


Compare to MC Library

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

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

Library Event #1

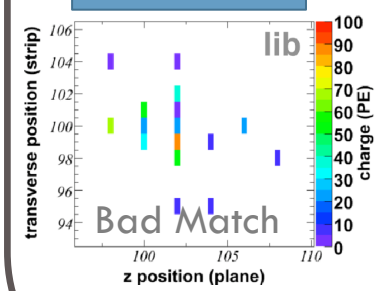


Library Event #2

Library Event #3

• • •

Library Event #k



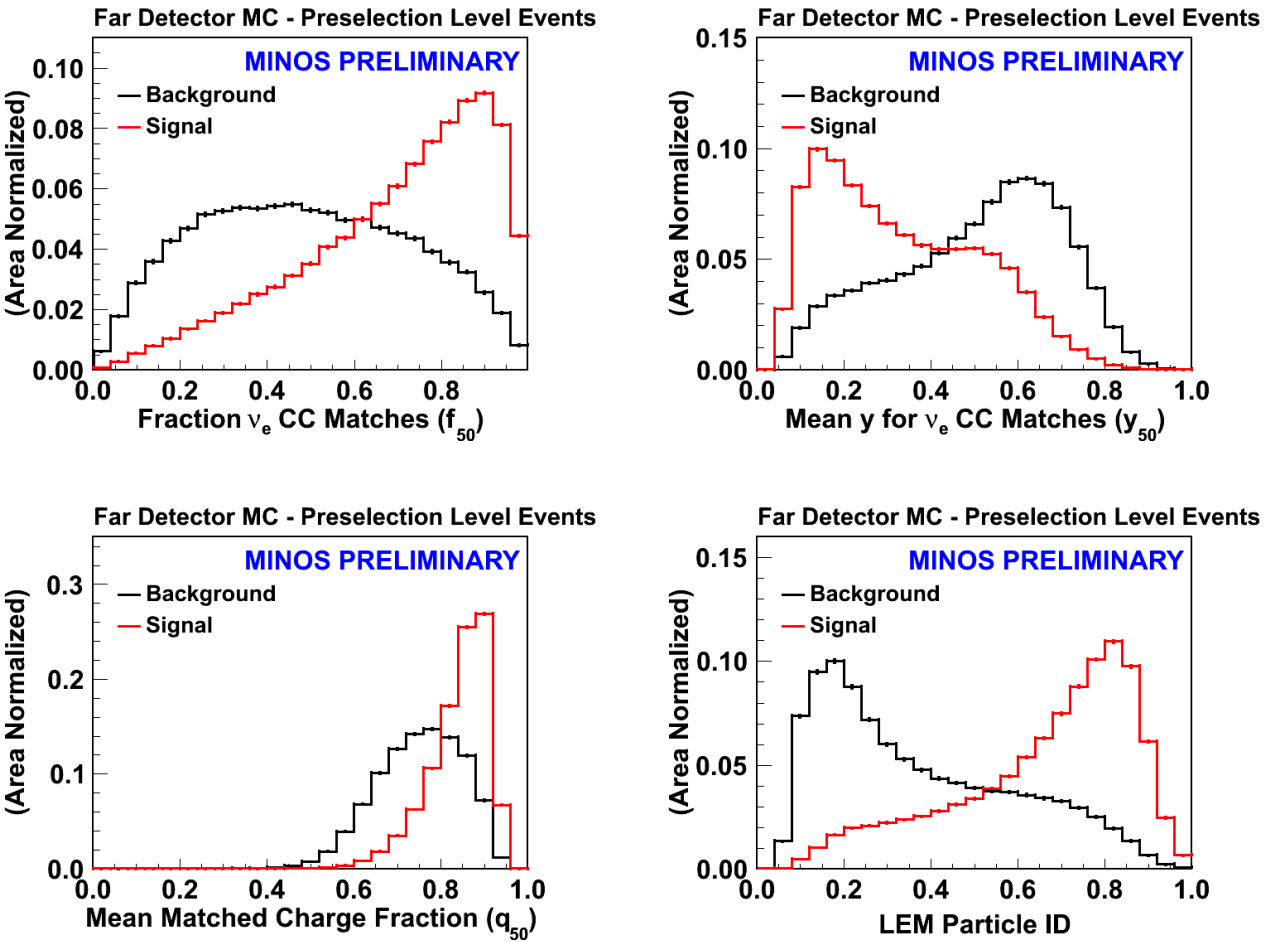
• • •

Library Event #30M

Compute variables using information from best N matches

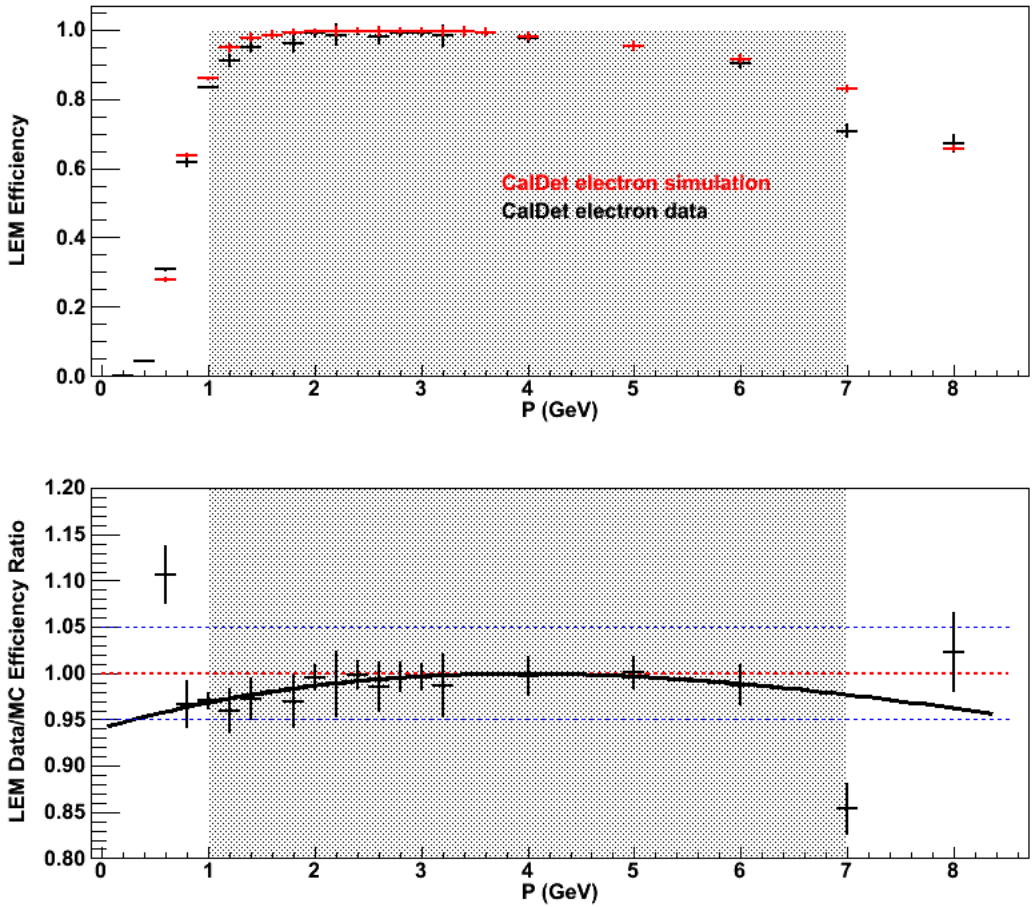
Discriminating Variables

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



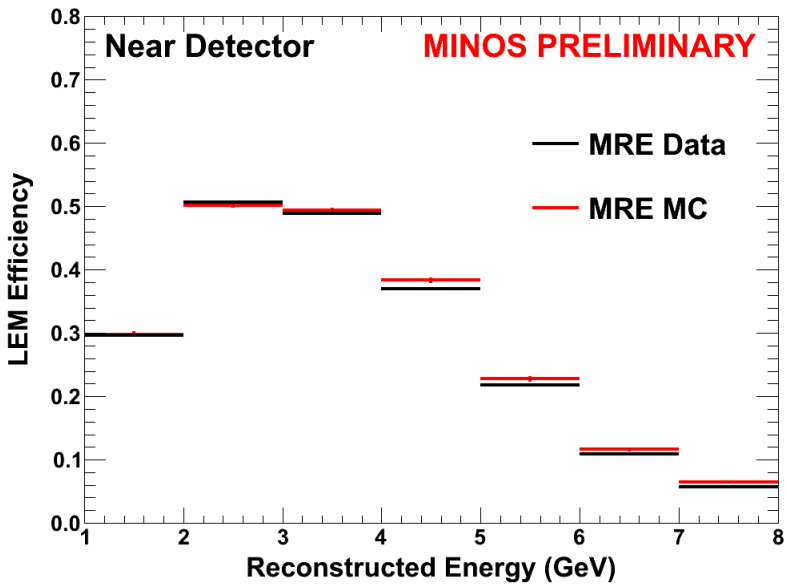
Checking Signal Efficiency

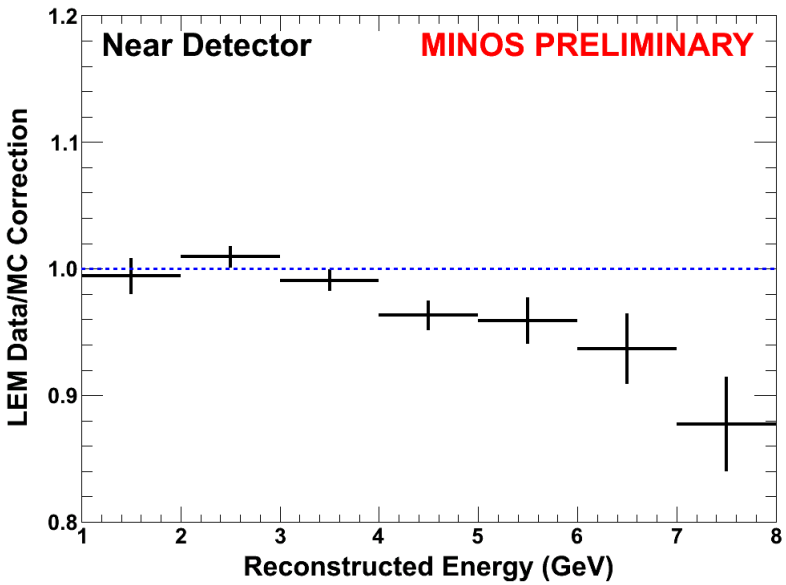
- Test beam measurements demonstrate electrons are well simulated



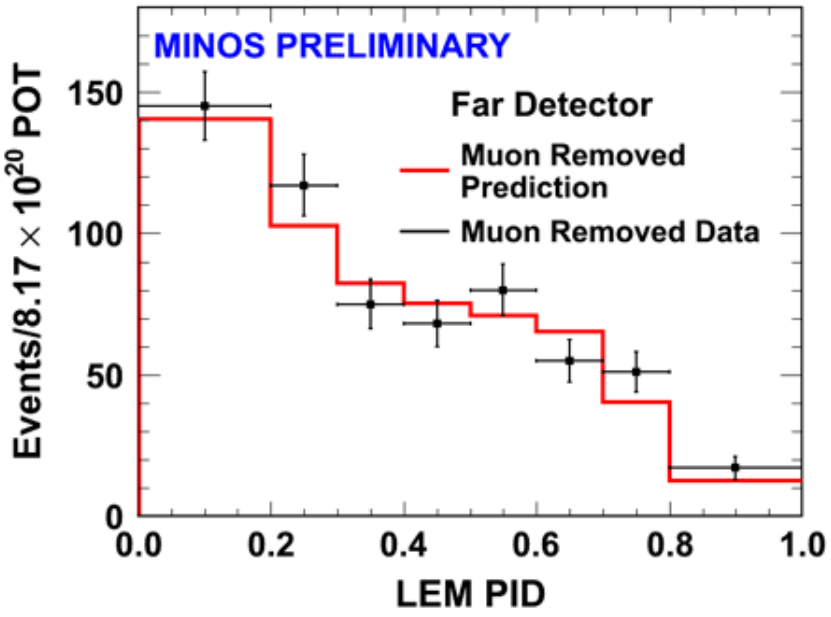
Checking Signal Efficiency

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





Muon Removed Sample

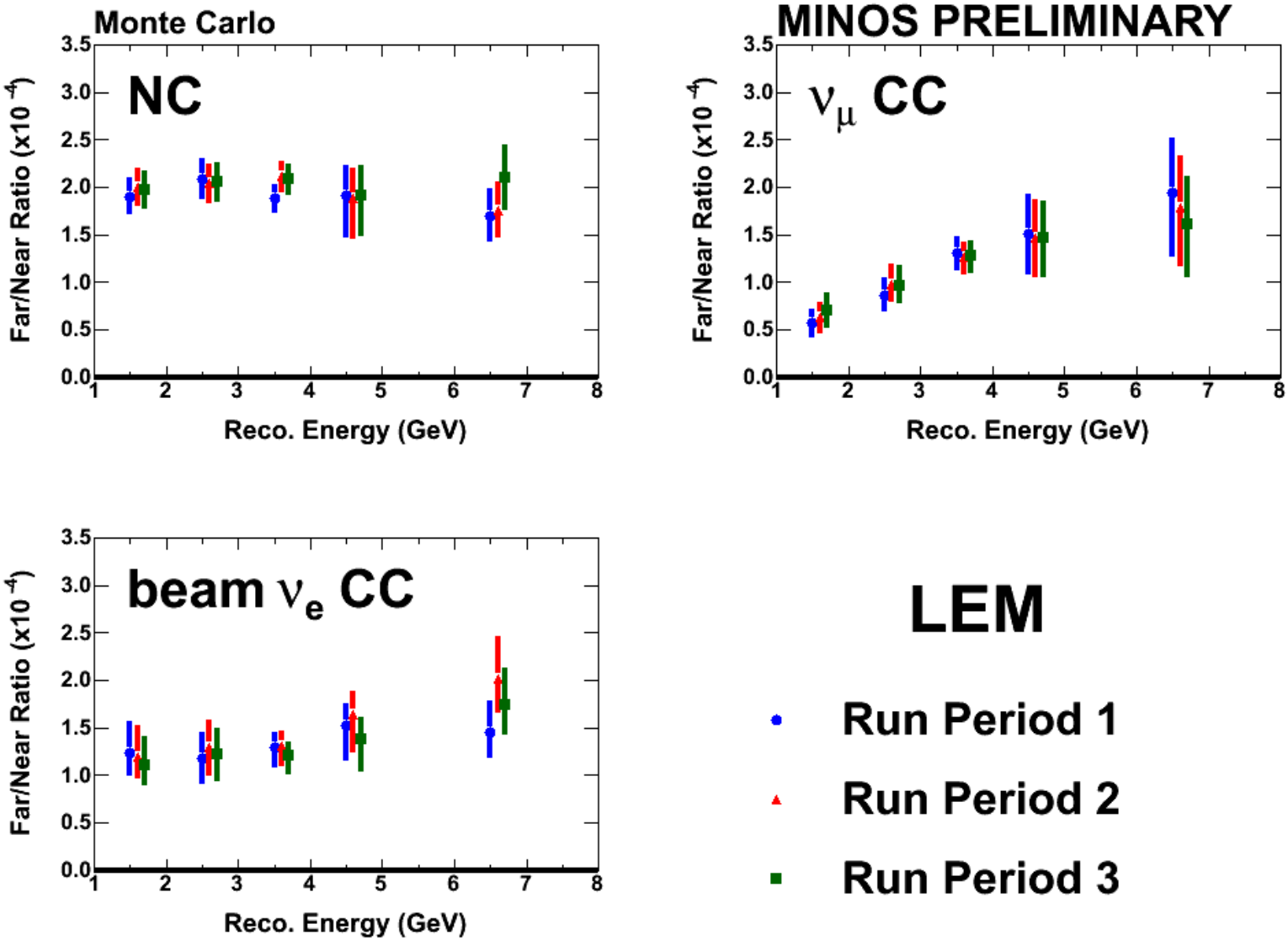


Far/Near differences

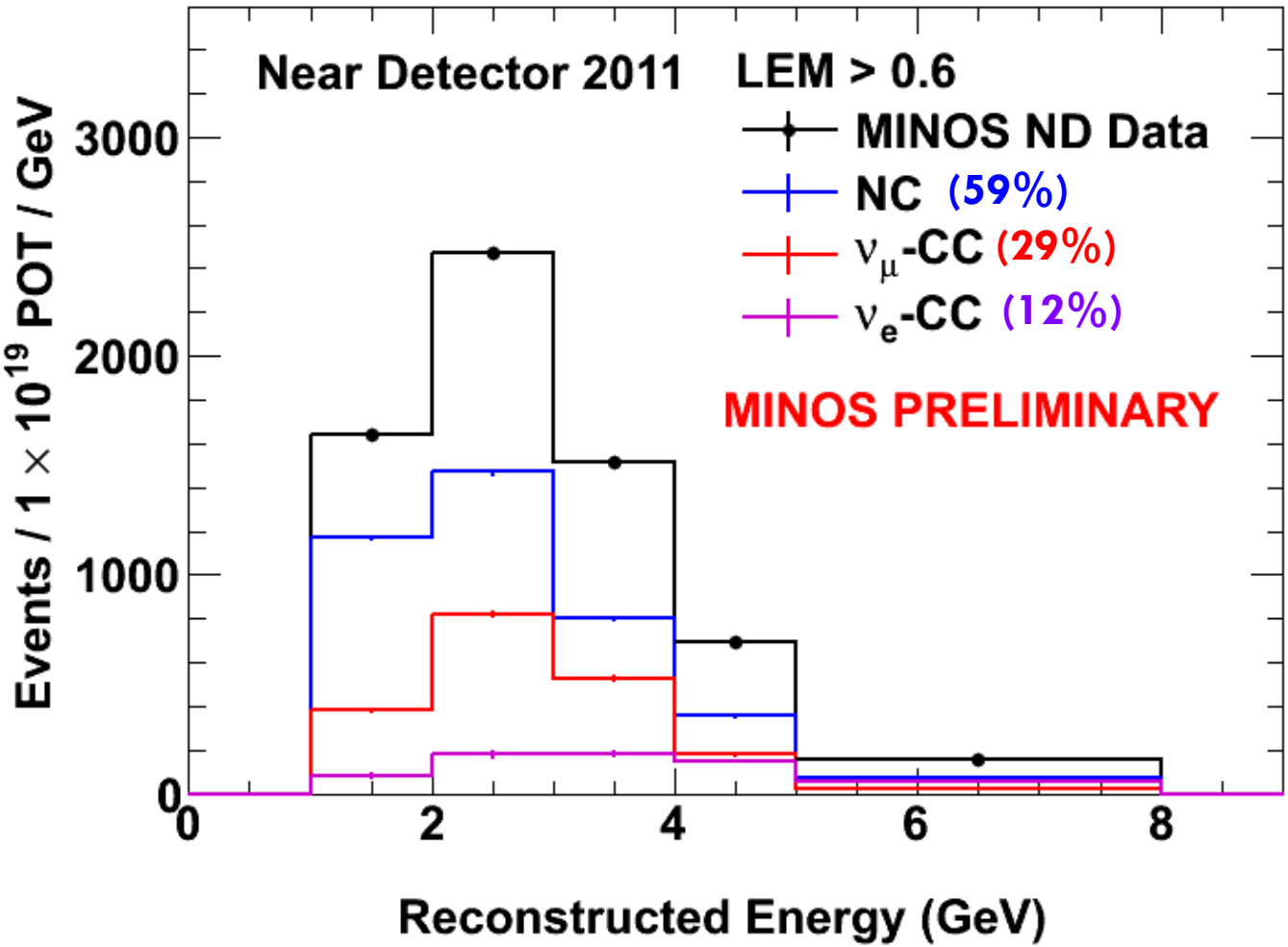
- ν_μ CC events oscillate away
- Event topology
  - Light level differences (differences in fiber lengths)
  - Multiplexing in Far (8 fibers per PMT pixel)
  - Single ended readout in Near
- PMTs (M64 in Near Detector, M16 in Far):
  - Different gains/front end electronics
  - Different crosstalk patterns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

Account for these lower order effects using detailed detector simulation

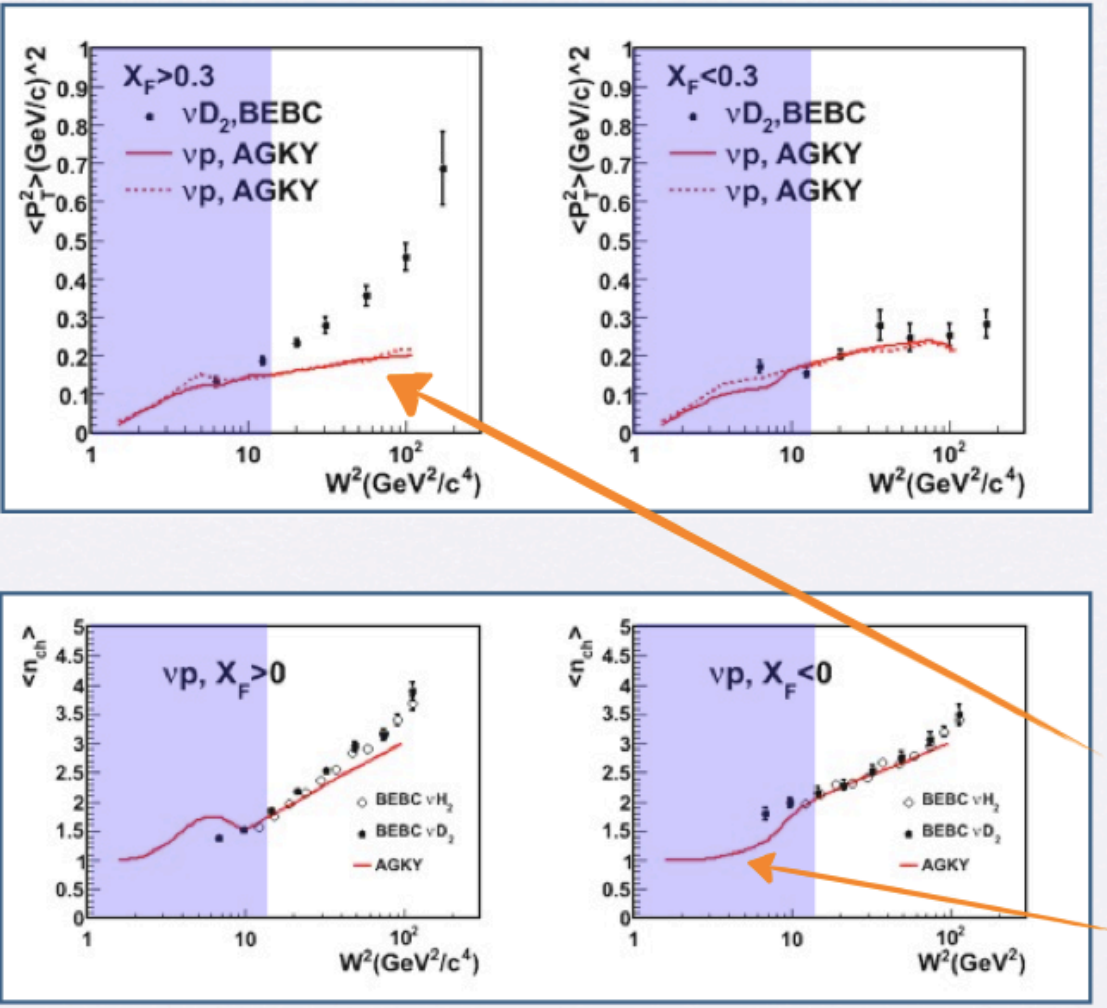
Electron-neutrino F/N ratios



Decomposition



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 Electron-neutrino Systematics

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

Event Type	ν beam mode	$\bar{\nu}$ beam mode
NC	89.4	13.9
ν_μ-CC and $\bar{\nu}_\mu$-CC	21.6	1.0
Intrinsic ν_e-CC and $\bar{\nu}_e$-CC	11.9	1.8
ν_τ-CC and $\bar{\nu}_\tau$-CC	4.8	0.8
$\nu_\mu \to \nu_e$-CC	33.0	0.7
$\bar{\nu}_\mu \to \bar{\nu}_e$-CC	0.7	3.2
Total	161.4	21.4
Data	152	20

TABLE II: Expected FD event yields for events with a value of $\alpha_{LEM} > 0.6$, assuming $\sin^2(2\theta_{13}) = 0.1$, $\delta = 0$, $\theta_{23} = \pi/4$, and a normal mass hierarchy.

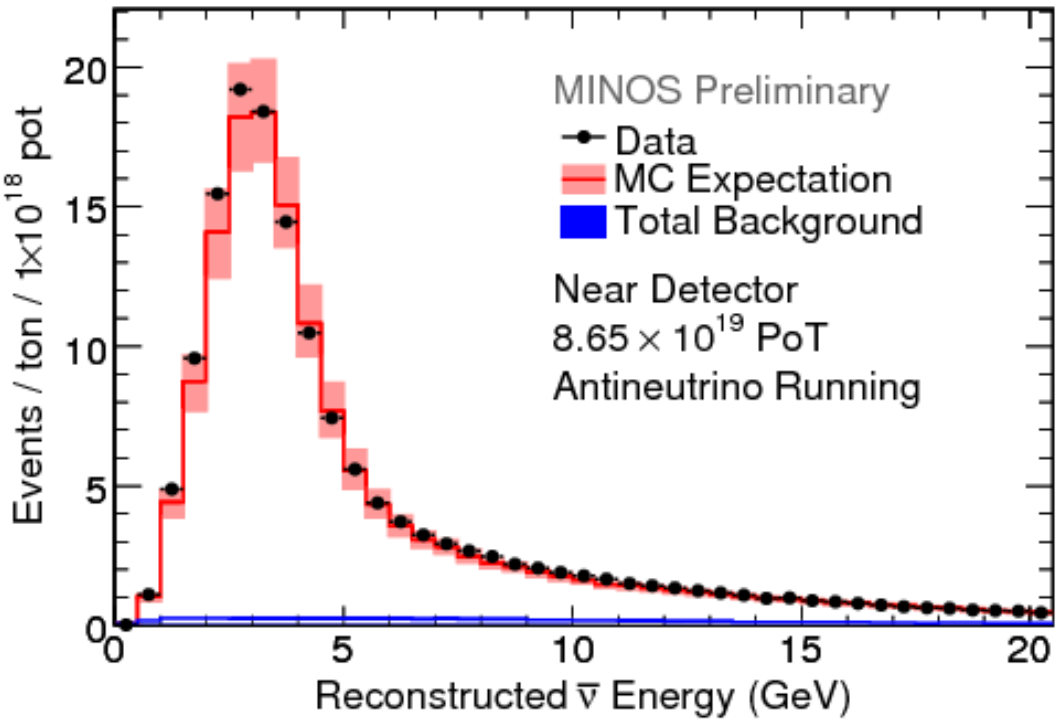
Systematic Effect	Uncertainty ν mode	Uncertainty $\bar{\nu}$ mode
Energy Scale	2.7%	3.0%
Normalization	1.9%	1.9%
ν_τ cross-section	1.7%	2.0%
All Others	0.8%	2.5%
Total Systematic	3.8%	4.8%
Total Statistical	8.8%	23.9%

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

hep-ex:1301.4581

ND Anti-neutrino Data

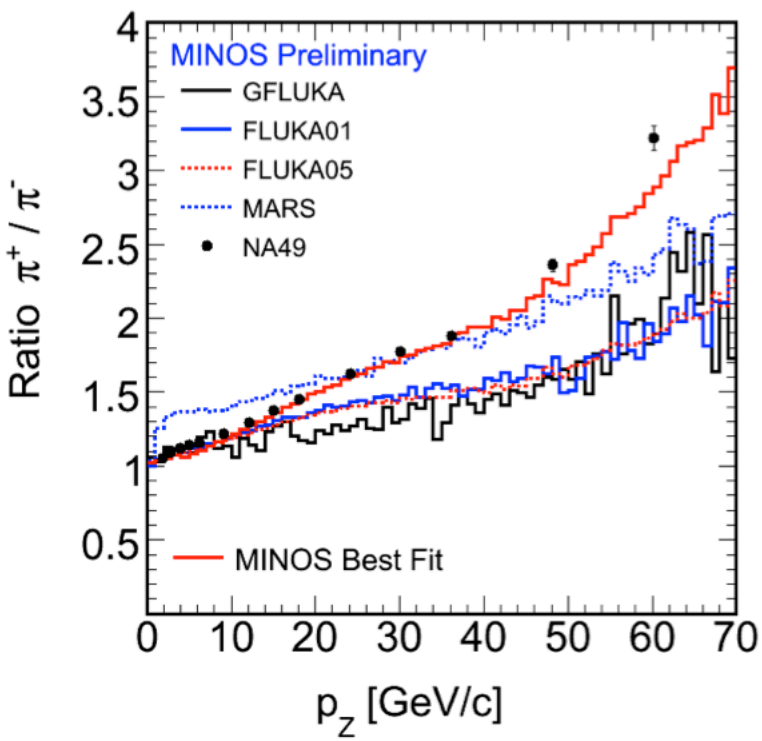
- Focus and select positive muons
  - purity 94.3% after charge sign cut
  - purity 98% < 6GeV
- Analysis proceeds as (2008) neutrino analysis
- Data/MC agreement comparable to neutrino running
  - different average kinematic distributions
  - more forward muons

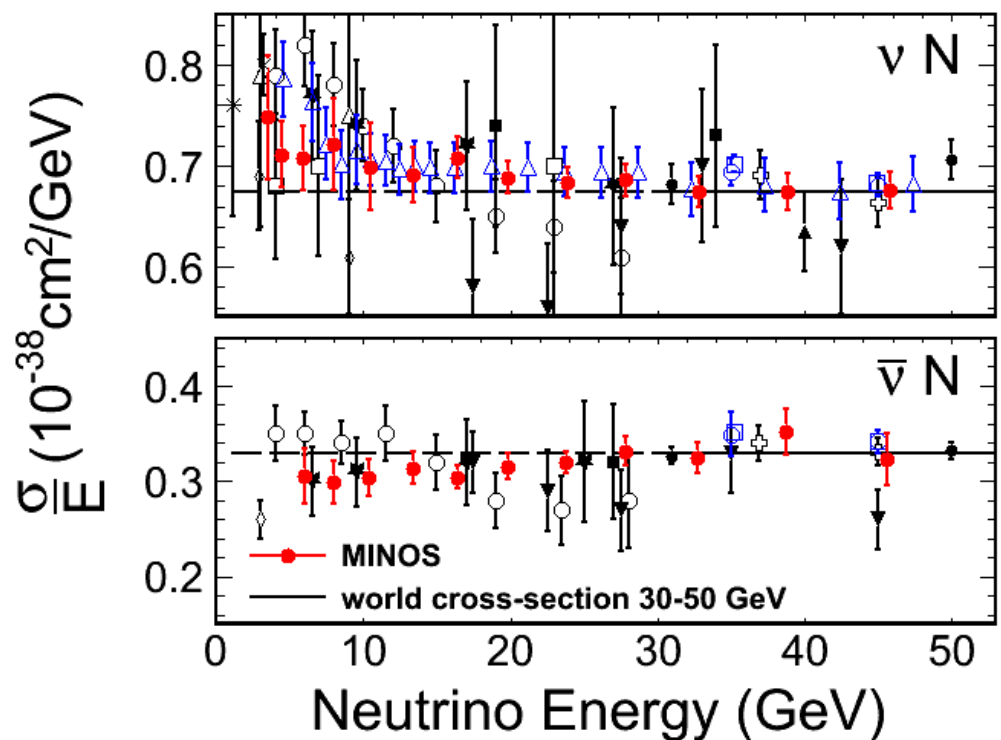


Making an antineutrino beam

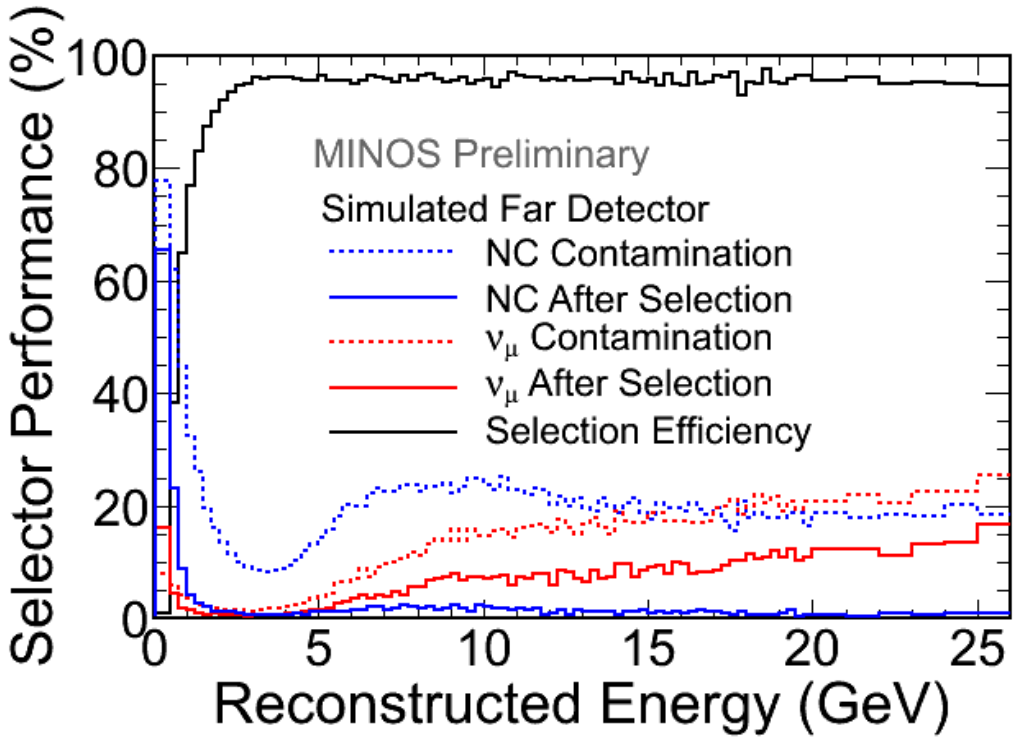
- Hadron production and cross sections conspire to change the shape and normalization of energy spectrum

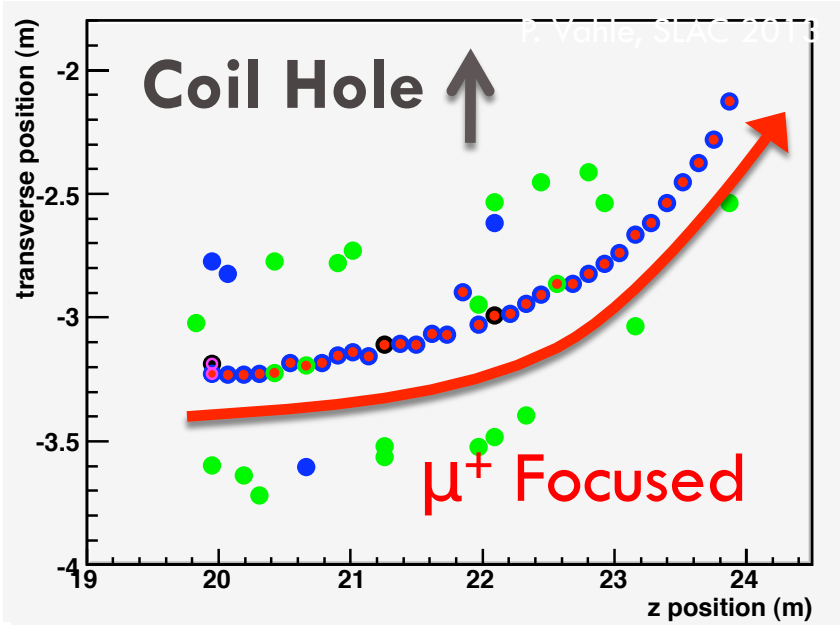
  ~3x fewer antineutrinos for the same exposure

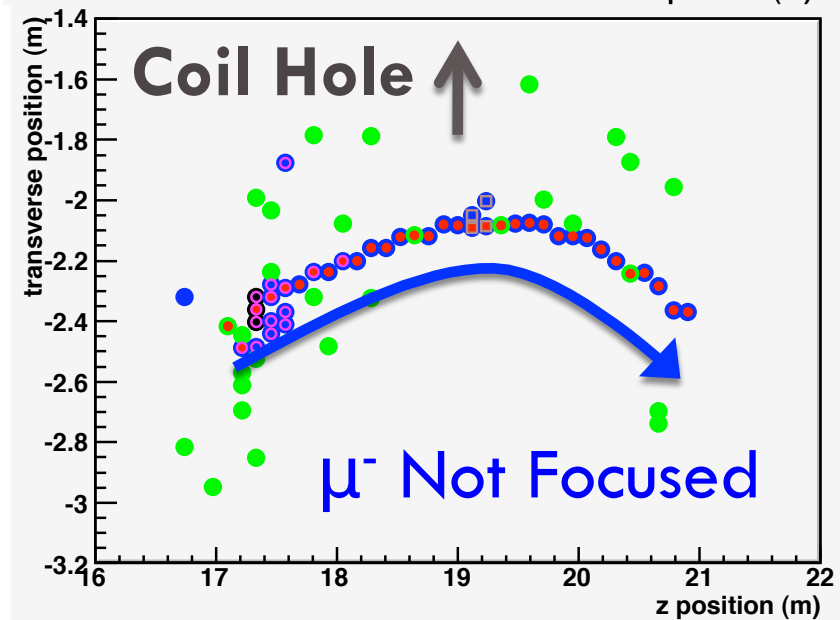




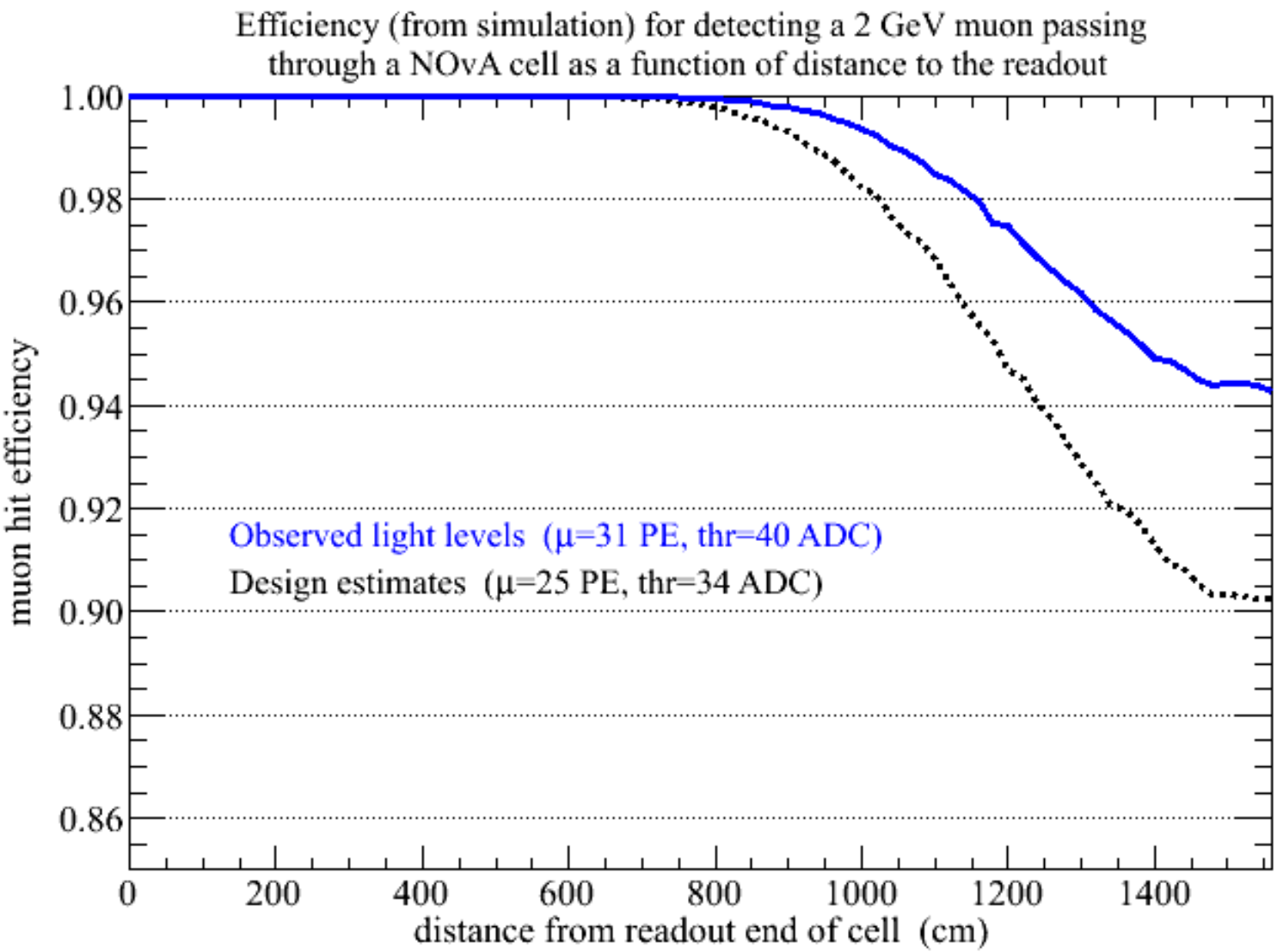
Anti-neutrino Selection



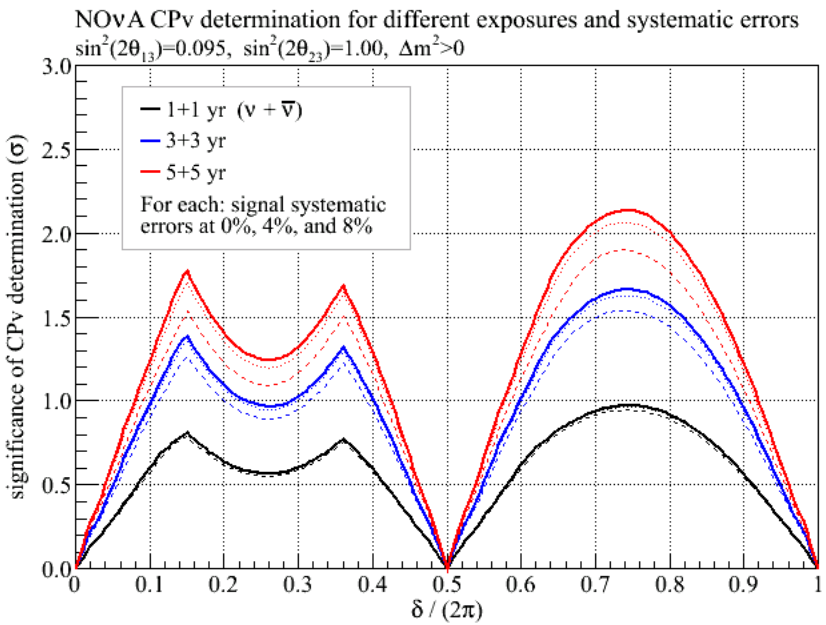


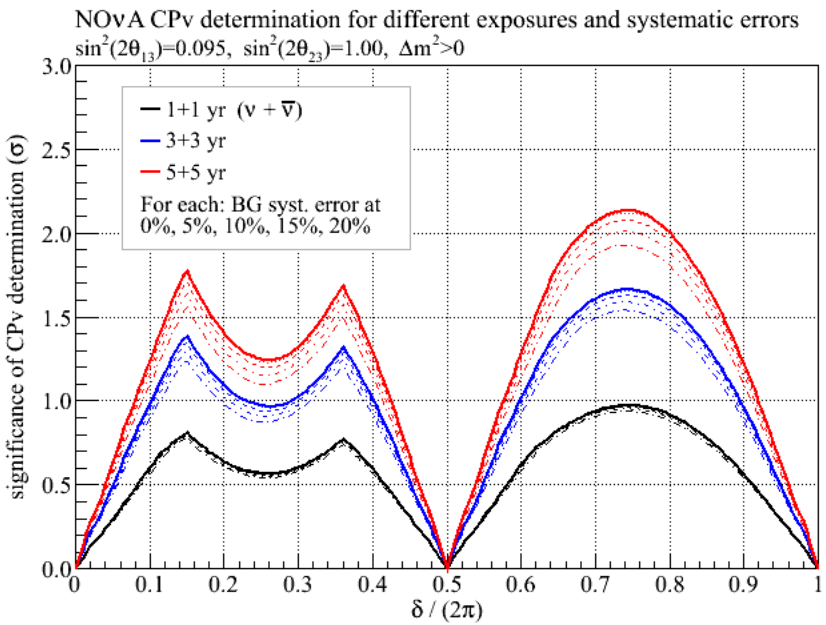


NOvA Light Level F/N Differences

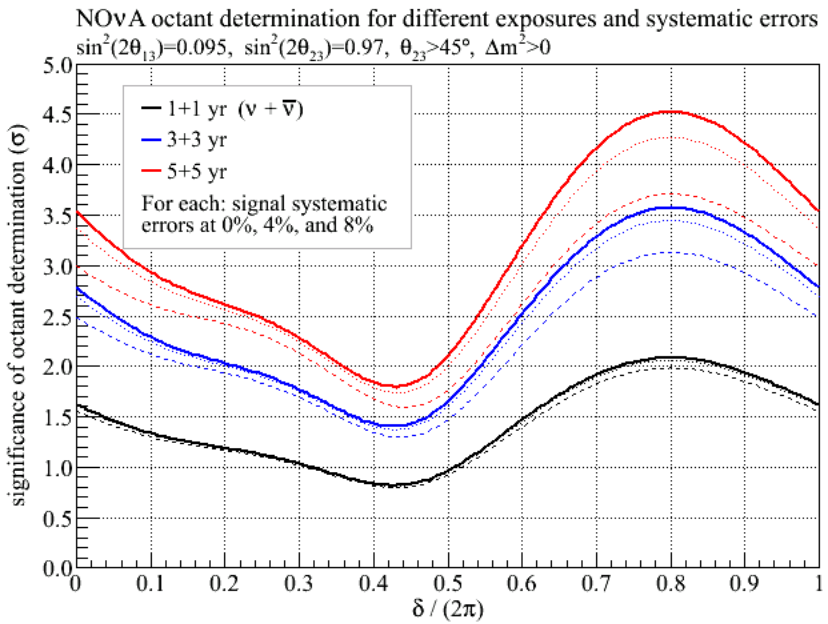


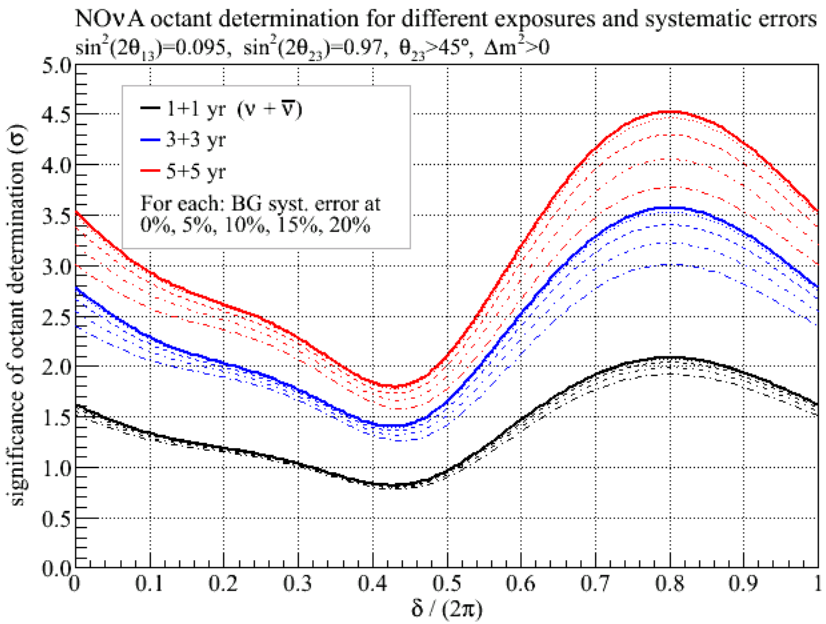
CPV Systematics



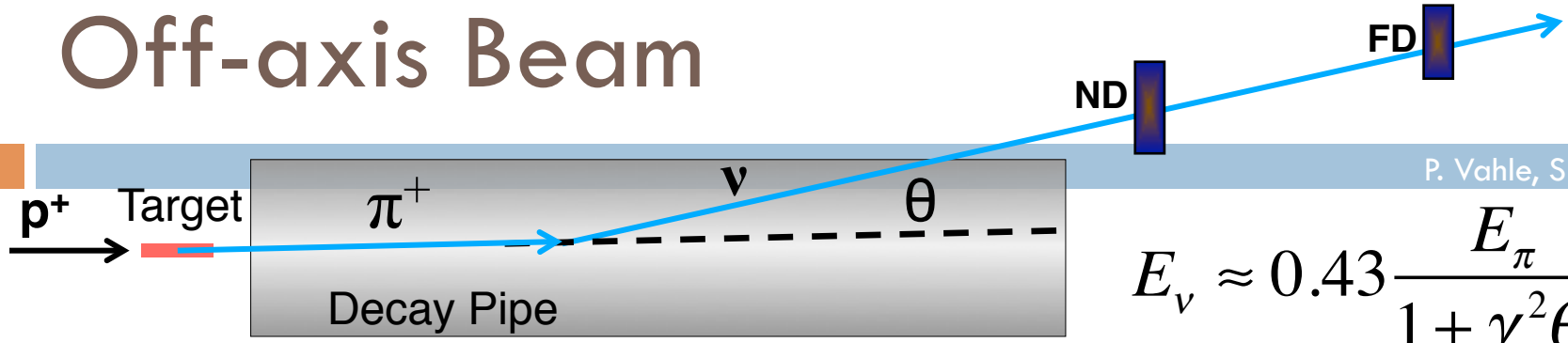


Octant


NOνA octant determination for different exposures and systematic errors
sin²(2θ13)=0.095, sin²(2θ23)=0.97, θ23>45°, Δm²>0
1+1 yr (ν + ν̄)
3+3 yr
5+5 yr
For each: signal systematic errors at 0%, 4%, and 8%
significance of octant determination (σ)
δ / (2π)

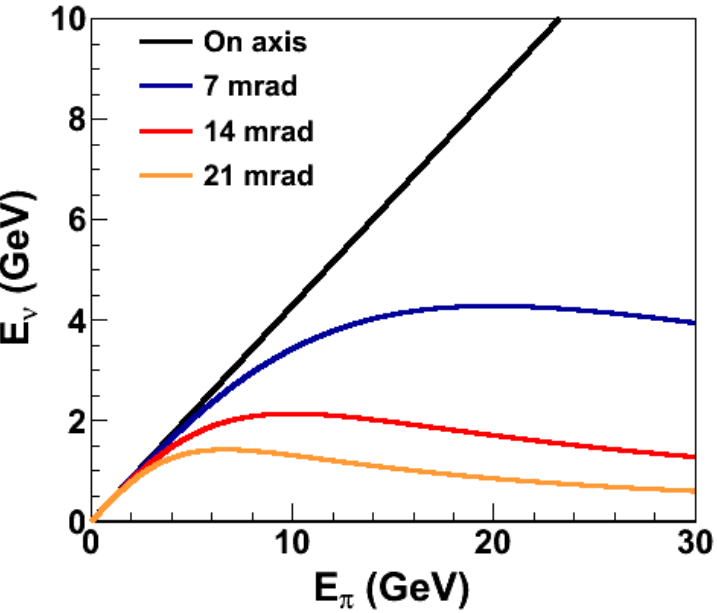

NOνA octant determination for different exposures and systematic errors
sin²(2θ13)=0.095, sin²(2θ23)=0.97, θ23>45°, Δm²>0
1+1 yr (ν + ν̄)
3+3 yr
5+5 yr
For each: BG syst. error at 0%, 5%, 10%, 15%, 20%
significance of octant determination (σ)
δ / (2π)

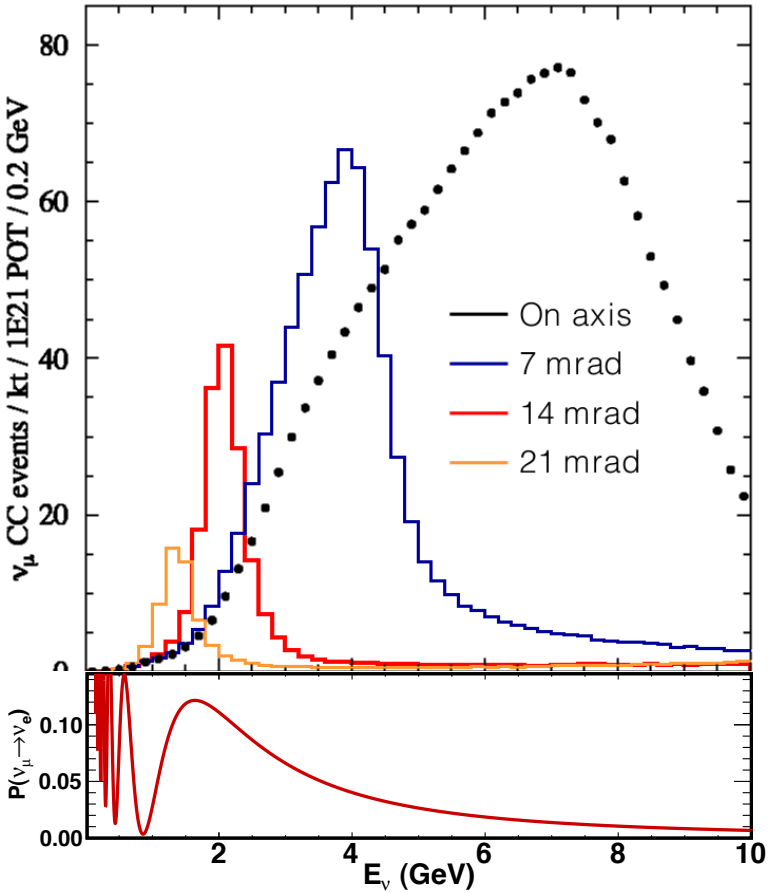
Off-axis Beam



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

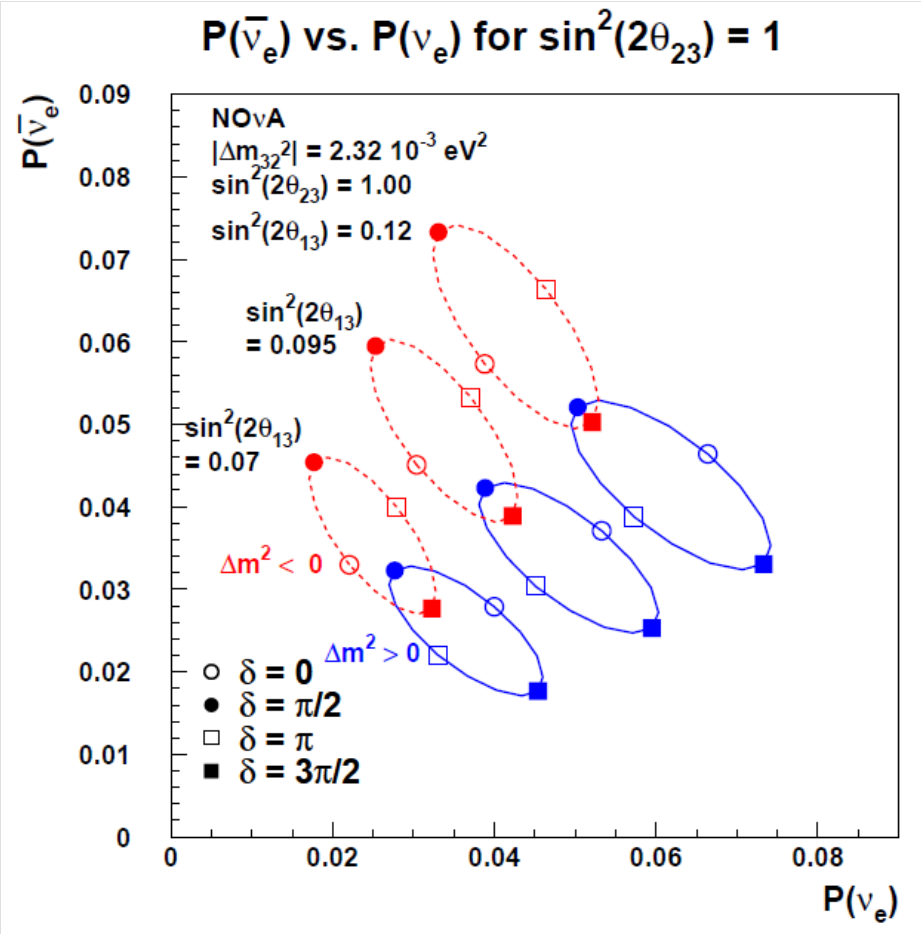
- 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events





How its done

- Compare oscillation probability measured with neutrinos and antineutrinos

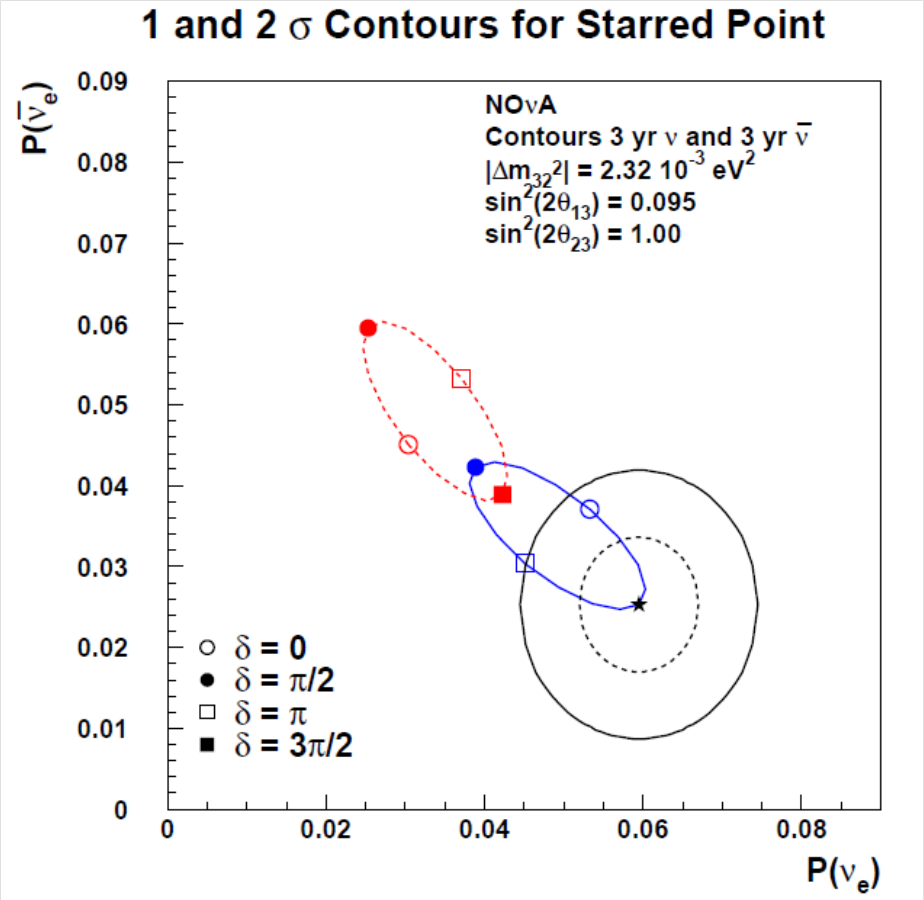
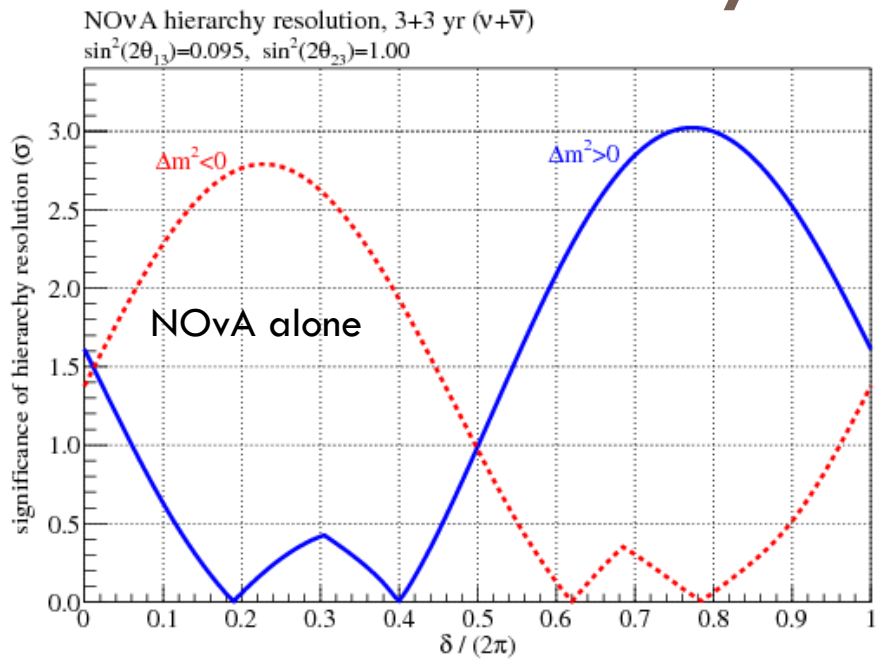
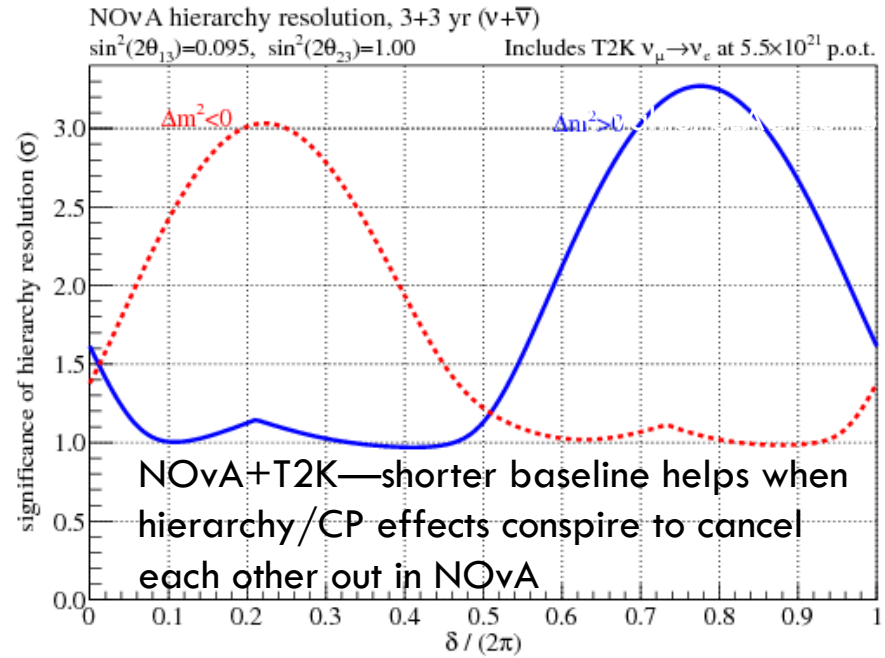
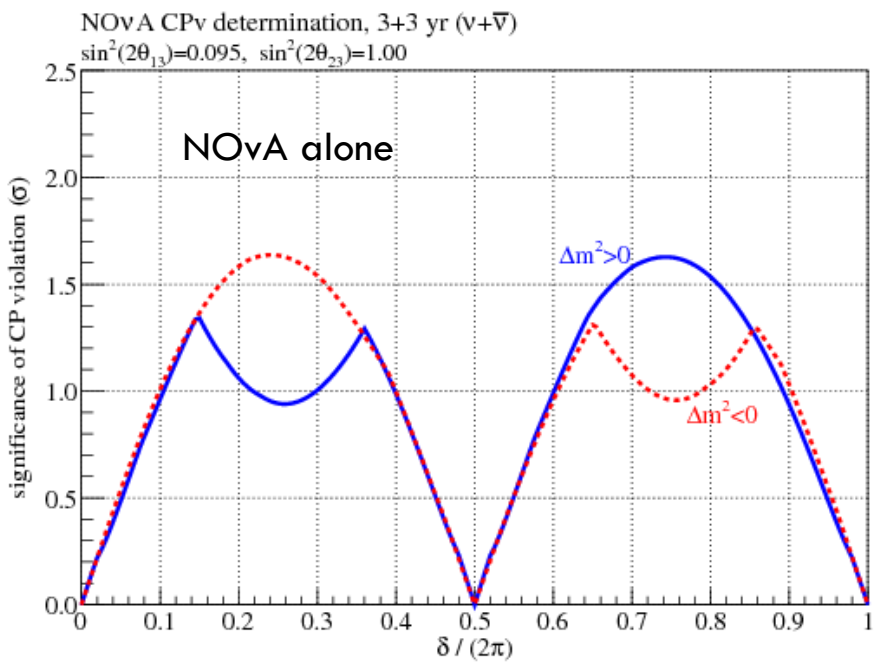
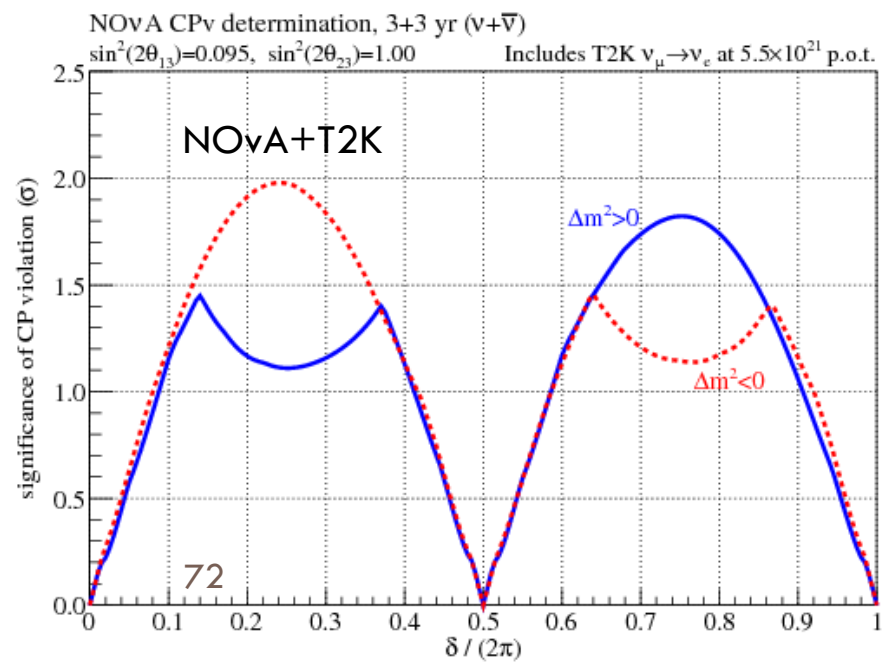


Events ($\sin^2(2\theta_{13})$=0.095)	ν	anti-ν
NC	19	10
ν_μ CC	5	<1
beam ν_e	8	5
Tot. BG	32	15
Signal	68	32

"Representative" event counts from 3 years neutrinos+3 years antineutrinos

How its done

- Compare oscillation probability measured with neutrinos and antineutrinos



Mass Hierarchy & Delta CP