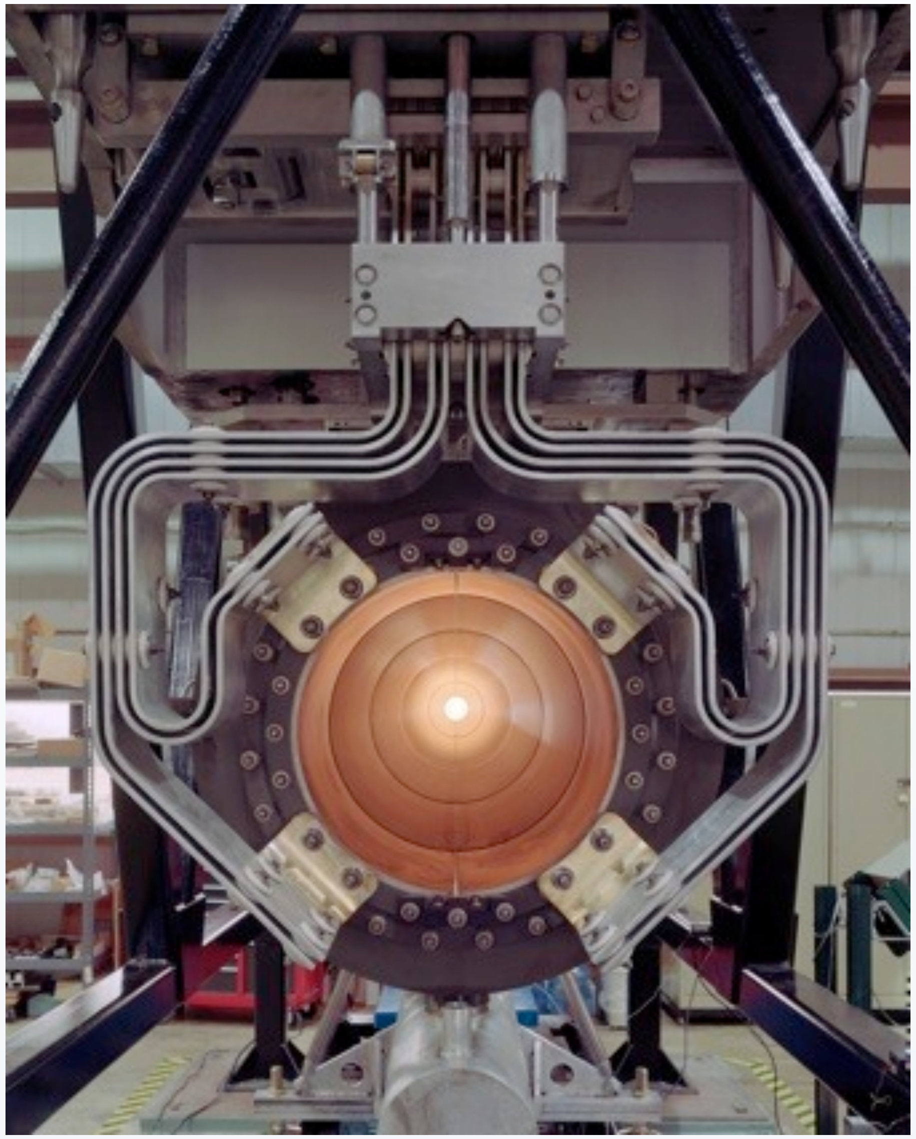
MINOS Results and Future Prospects



Ryan Nichol

Beyond 3 Neutrinos, LNGS 2011

Outline

- Overview of the MINOS Experiment
  - MINOS Physics Goals
  - NuMI Beam
  - MINOS Detectors
- Recent Results
  - Muon-Neutrino Disappearance *Updated*
  - Muon-Antineutrino Disappearance *Updated*
  - Electron-Neutrino Appearance (won’t cover in this talk)
  - Sterile Neutrino Search
- Future Prospects
  - MINOS+

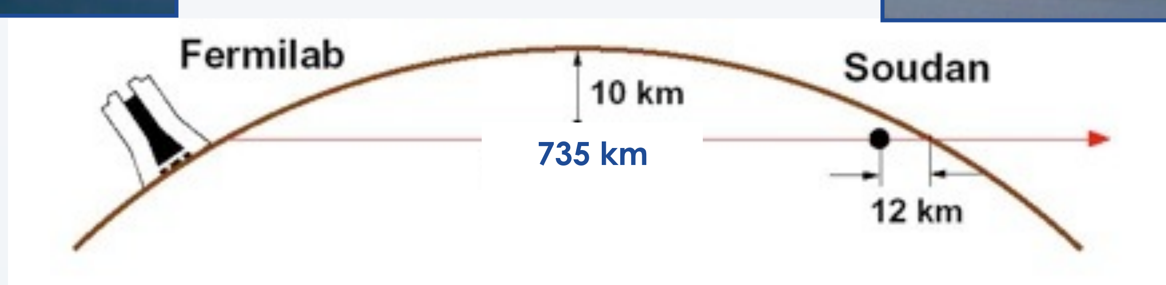
MINOS Physics Goals

- Precision measurements of oscillation parameters
  - Confirm oscillation hypothesis vs decay, ...
- Use magnetised detector for precision antineutrino tests
- Search for subdominant oscillations to ν_e
- Search for evidence of sterile neutrinos
- Atmospheric neutrino & cosmic ray studies
- Cross-sections, ...

MINOS Collaboration

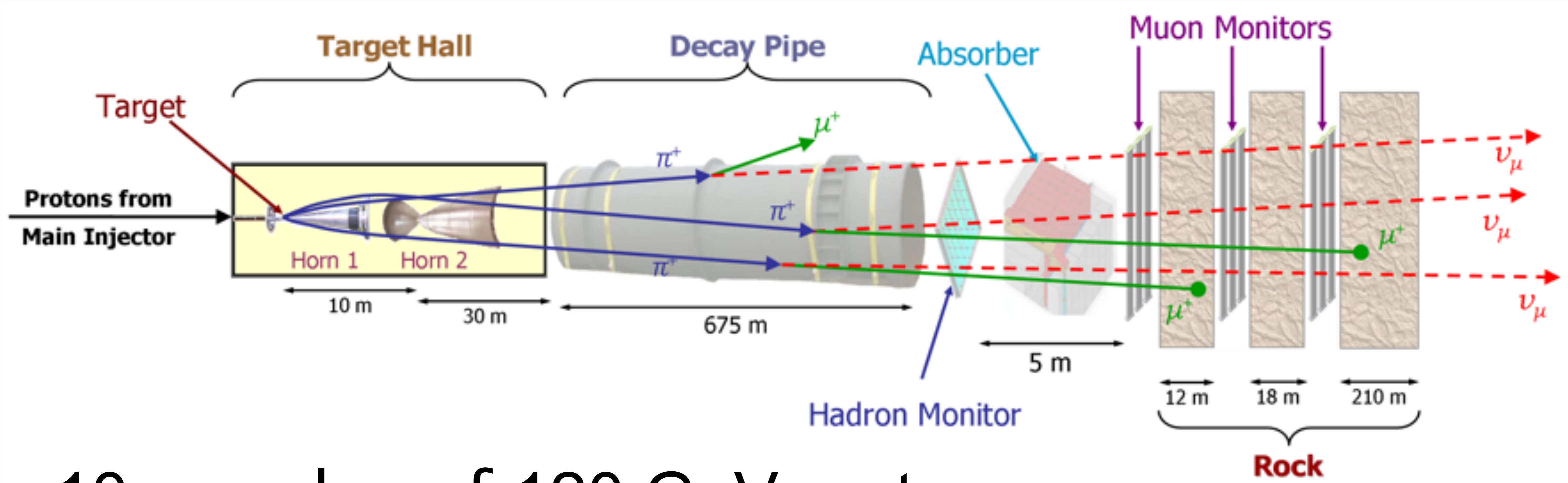
Argonne • Arkansas Tech • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab • Harvard • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw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

MINOS Concept

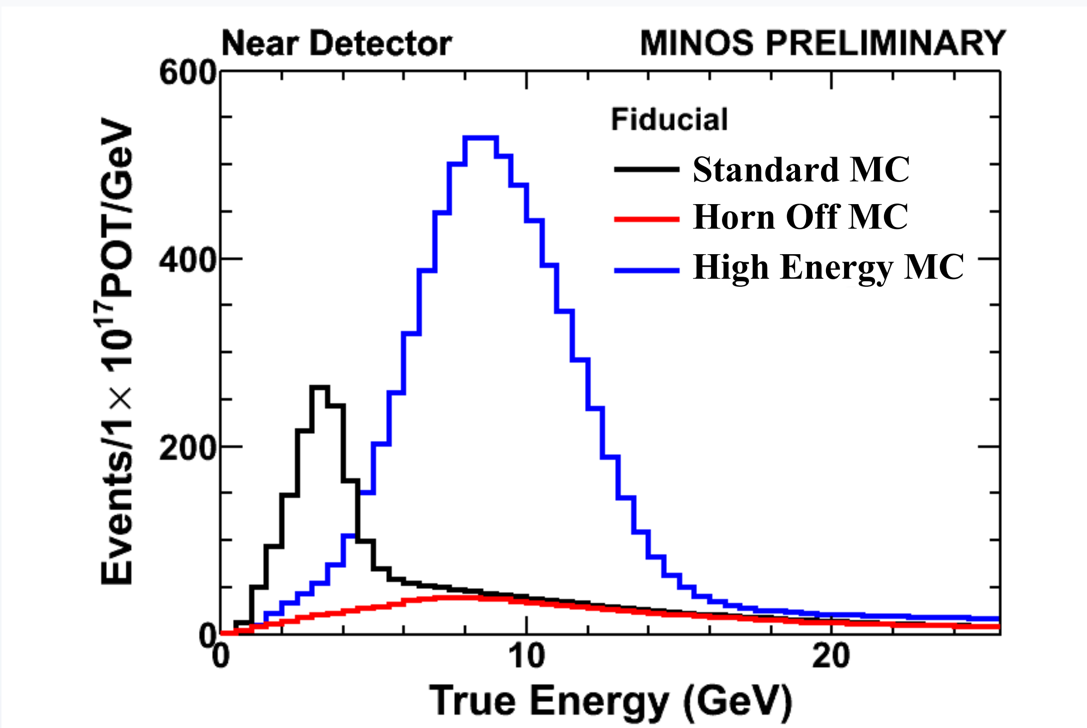


- MINOS (Main Injector Neutrino Oscillation Search)
  - Long-baseline neutrino oscillation experiment
- Basic Concept
  - Measure energy spectrum at Near Detector
  - Measure energy spectrum at Far Detector
  - Compare measurements to study oscillations

Neutrinos at the Main Injector (NuMI)

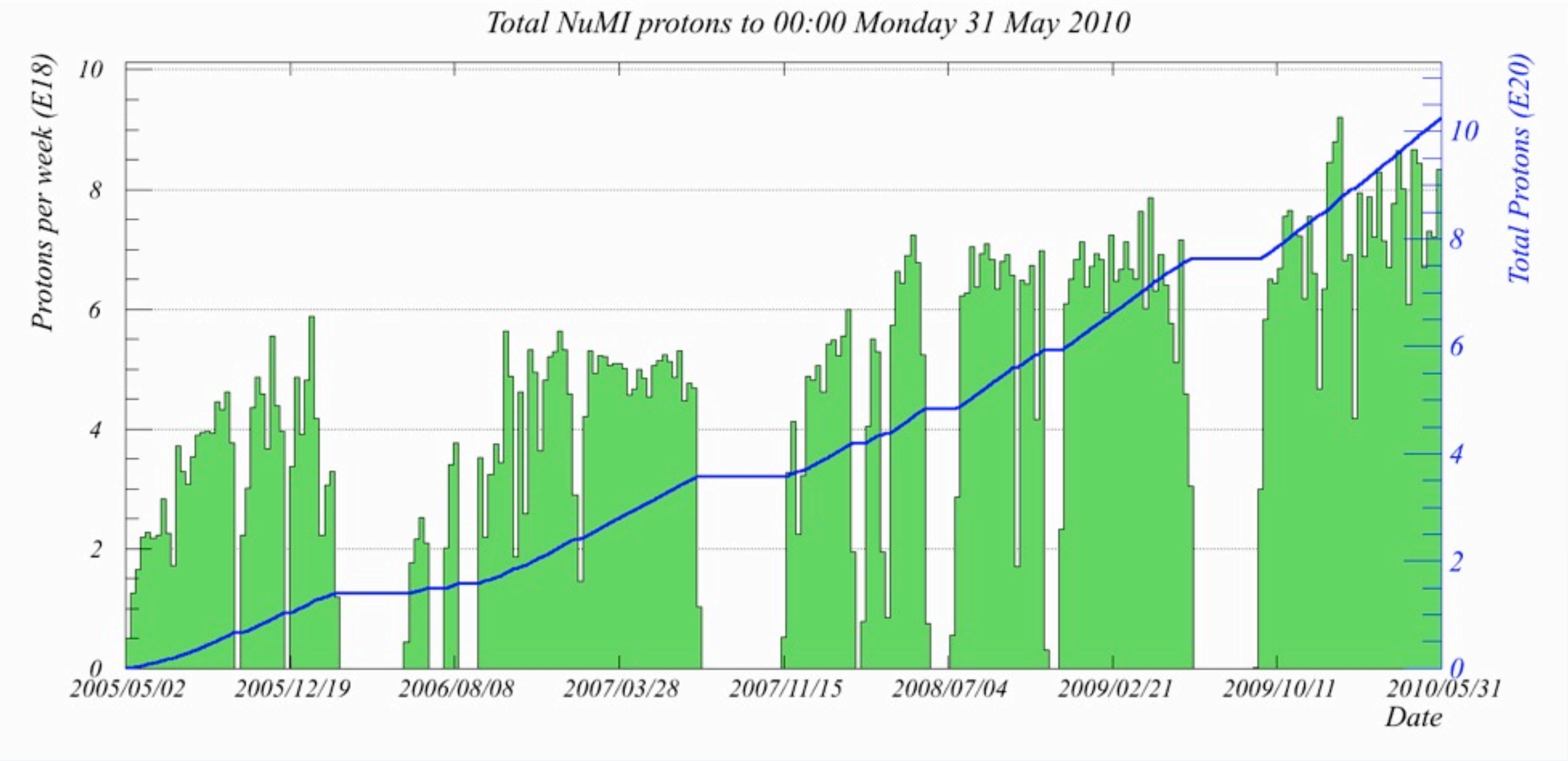


- 10μs pulse of 120 GeV protons every 2.2s
- 3.0 x 10^{13} protons per pulse
- 275kW typical beam power
- Can tune energy spectrum by varying relative positions of target and horns, in low energy:

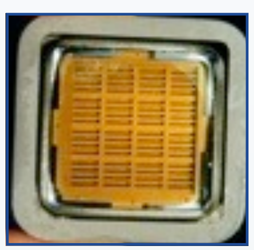


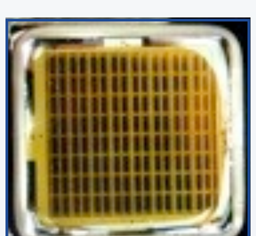
$$92.9\%\ \nu_\mu,\ 5.8\%\ \bar{\nu}_\mu,\ 1.3\%\ \nu_e + \bar{\nu}_e$$

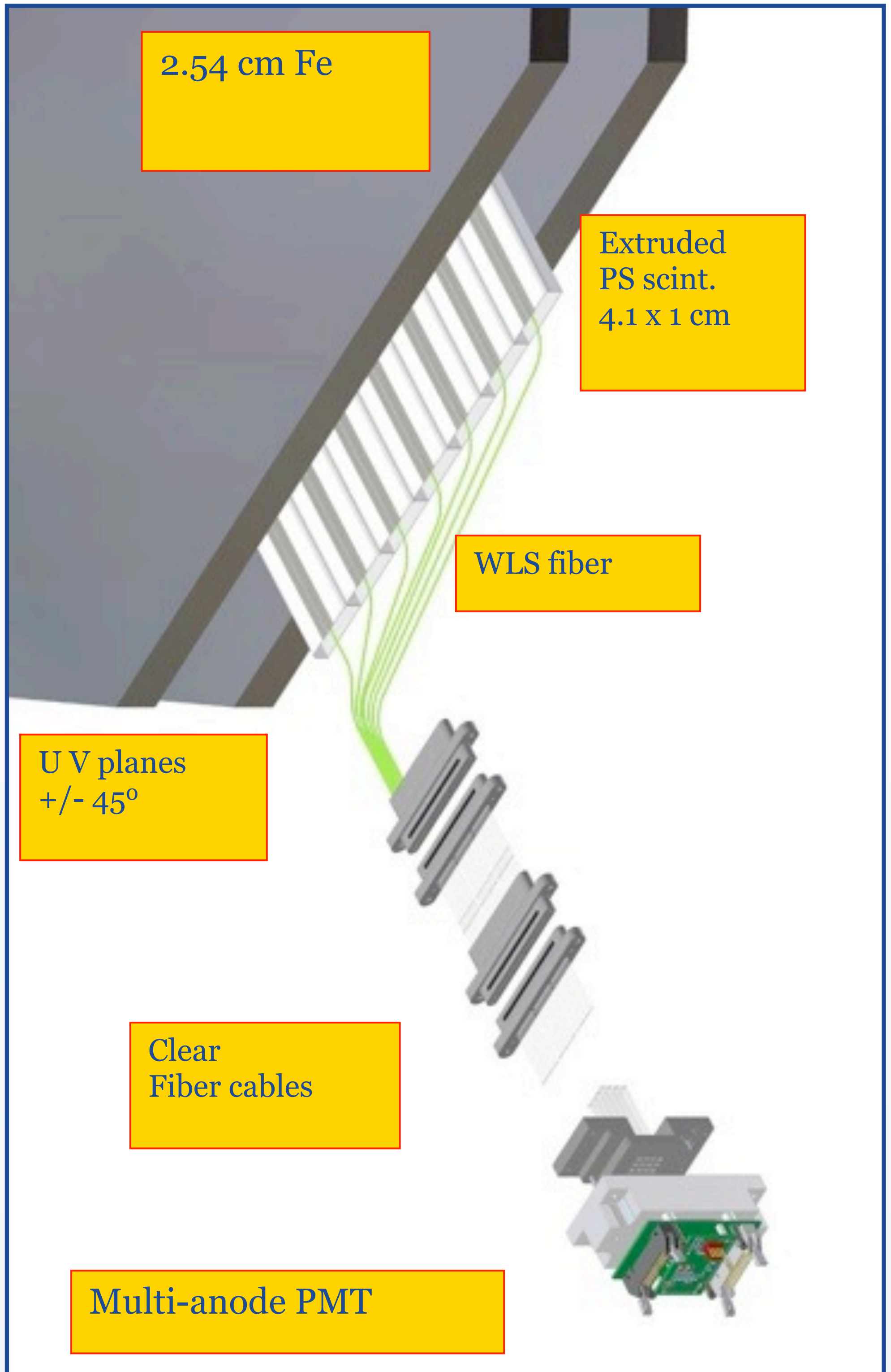
NuMI Beam Performance



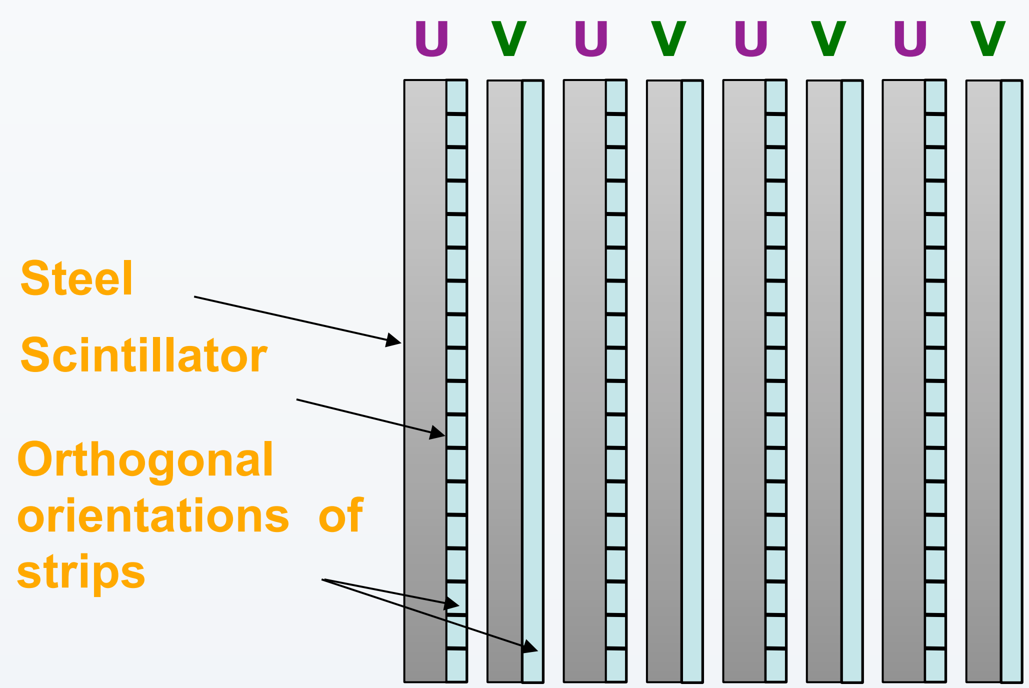
MINOS Detector Technology


M16


M64

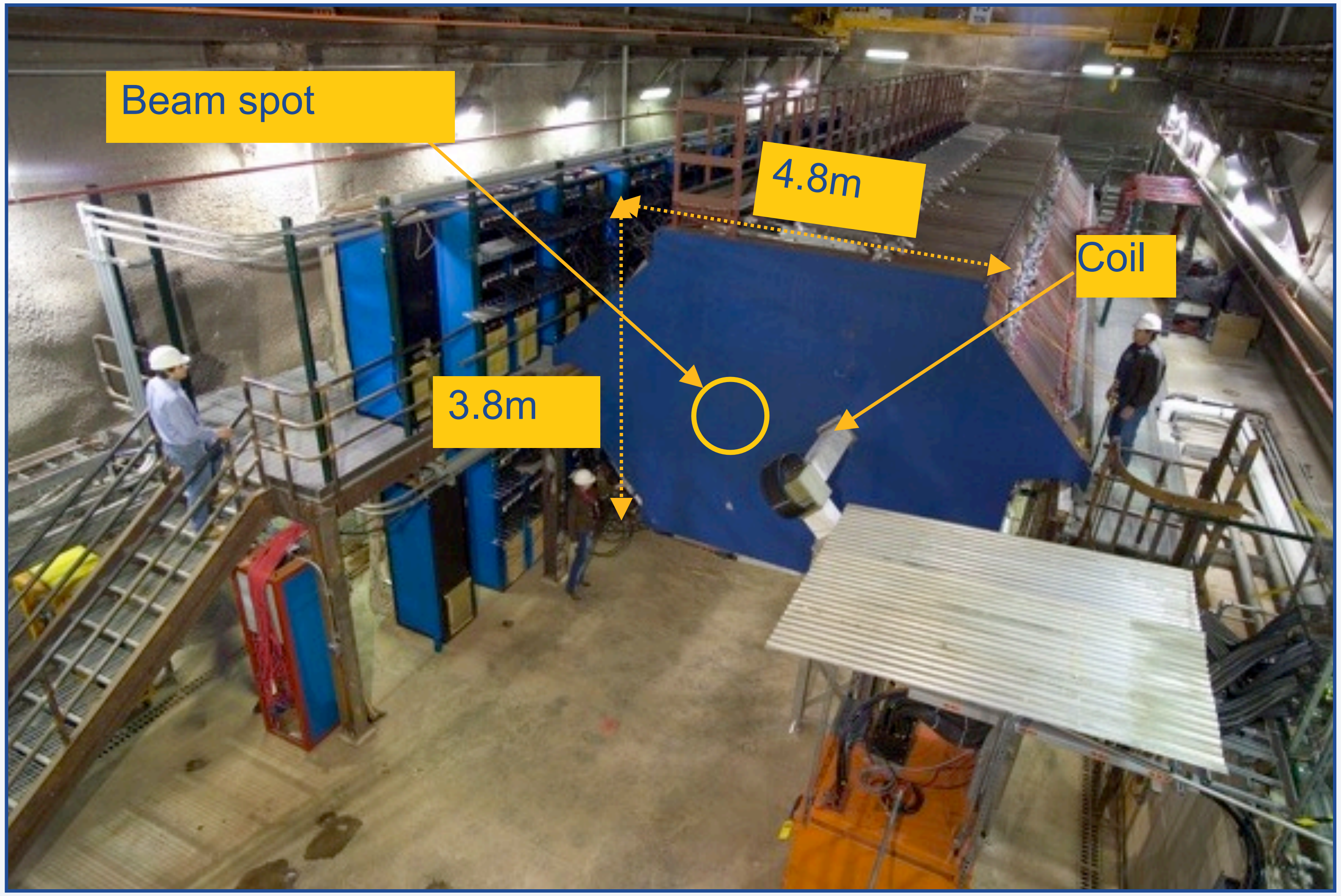


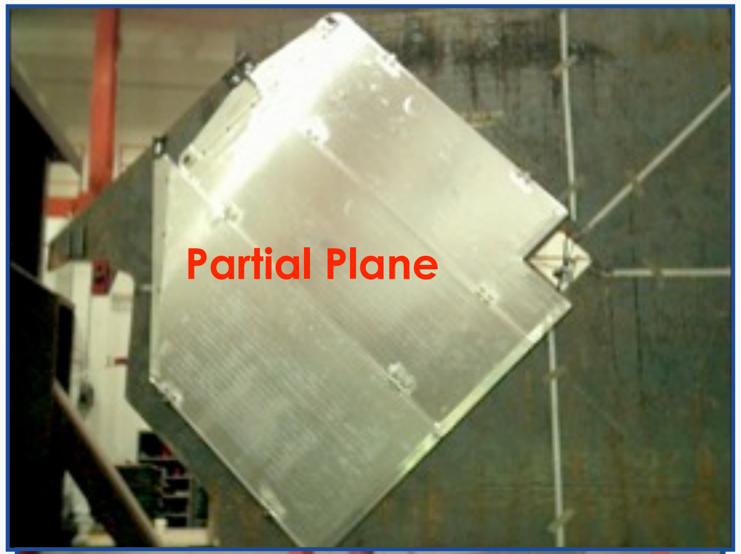
- Magnetised steel-scintillator calorimeters
  - 2.54cm Steel
  - ~1.3T B field
  - orthogonal strips of co-extruded polystyrene

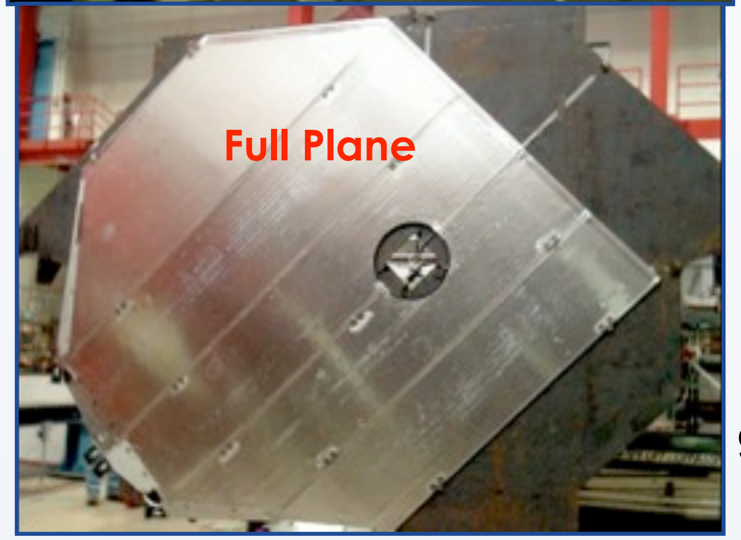


Near Detector

- ~1kT Detector located 1km downstream of the target
- Consisting of 282 steel, 153 scintillator planes
- Fast QIE electronics for continuous sampling of beam spill.



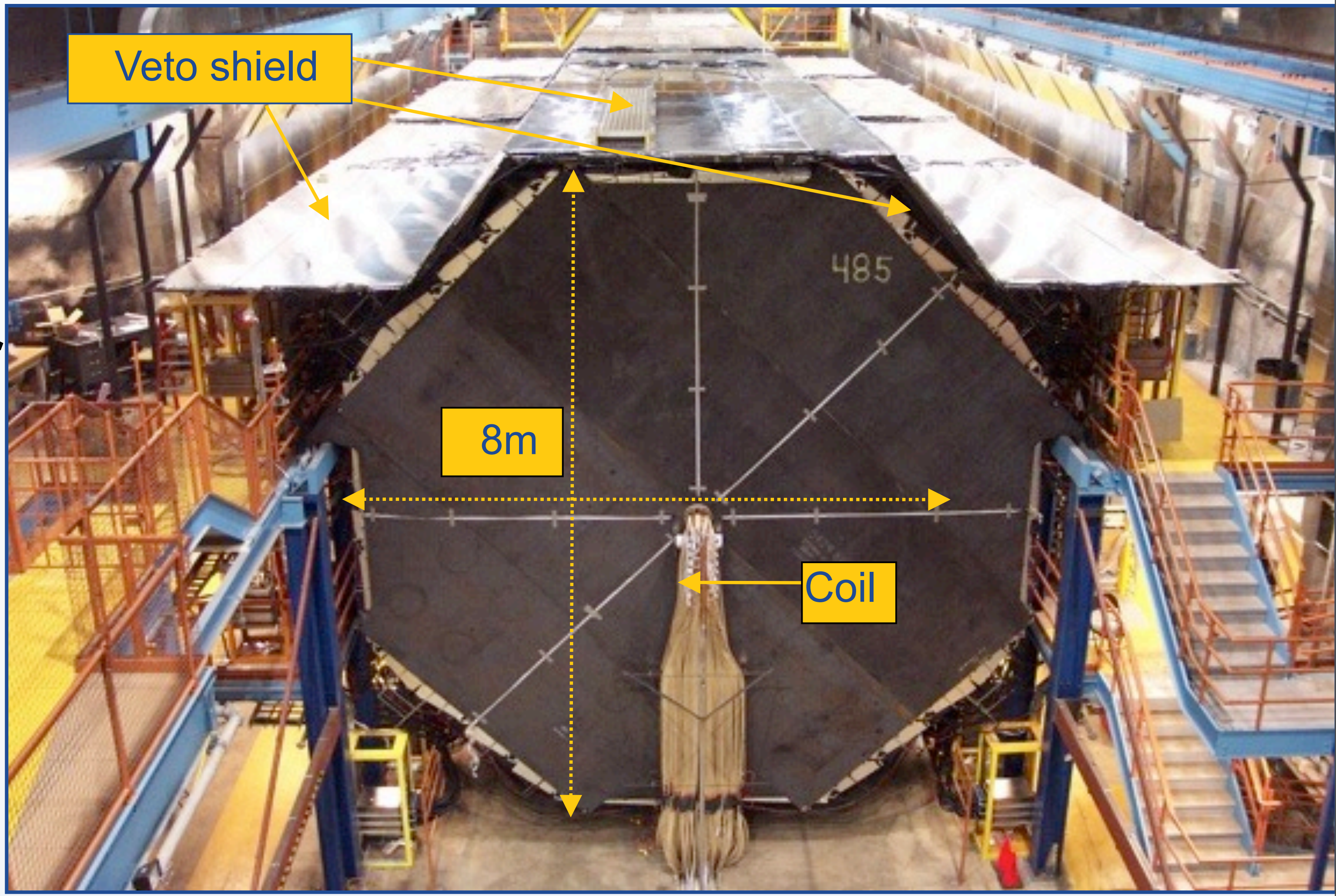




Far Detector

- 735km away at the Soudan mine, MN
- 5.4kT, 8m octagonal planes
- 486 steel planes
- 484 scintillator planes
- Veto shield (scintillator modules)
- Spill trigger from Fermilab for beam trigger

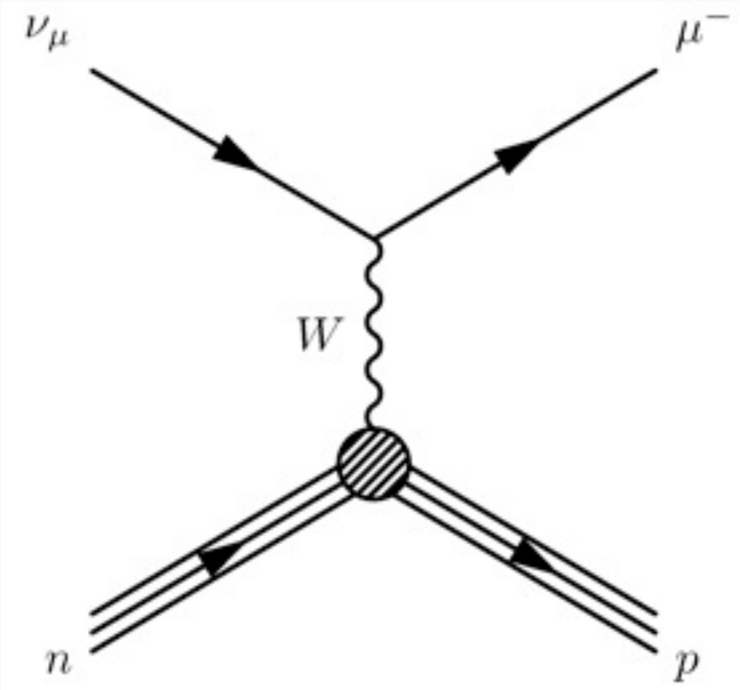
Located in the place of coldest recorded temperature in mainland US (-67 F)



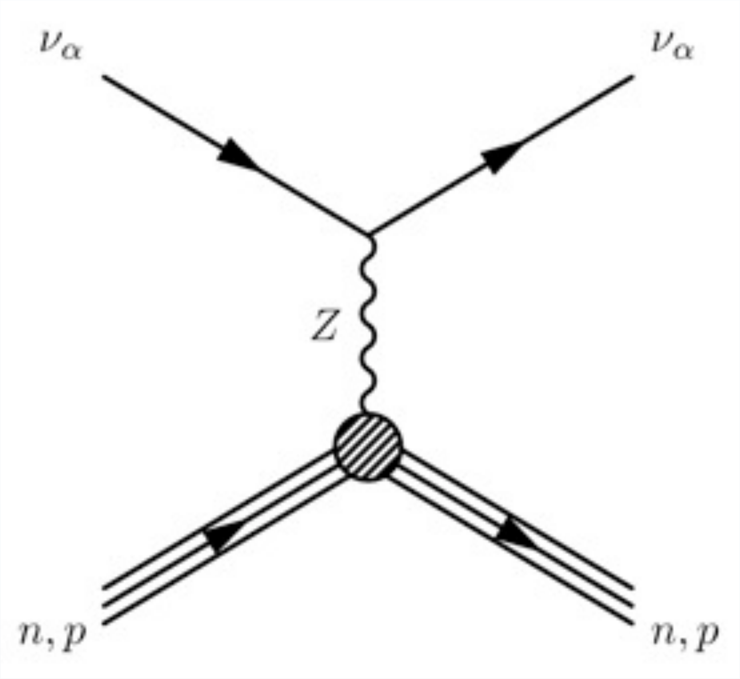
Event Topologies

- Three classifications of events

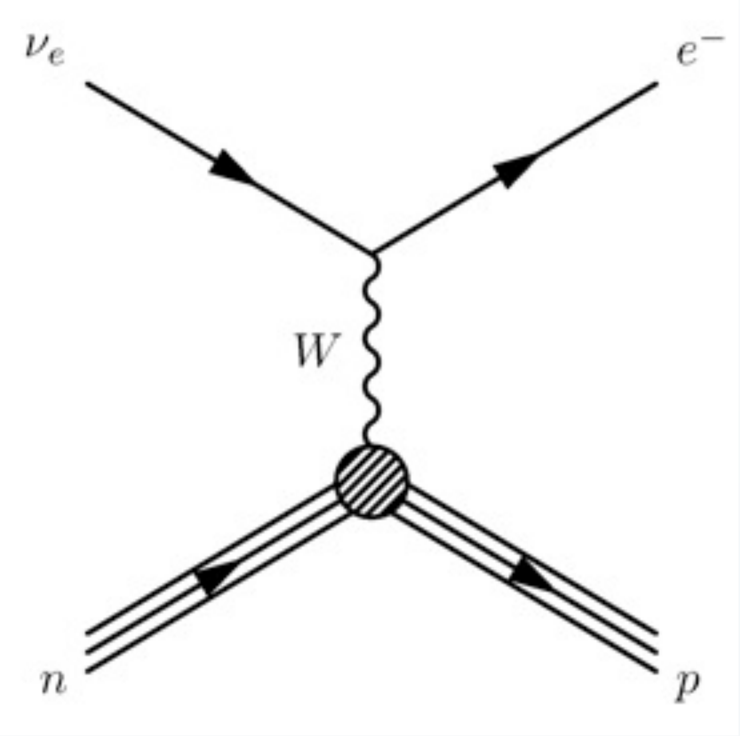
ν_μ CC Event



NC Event

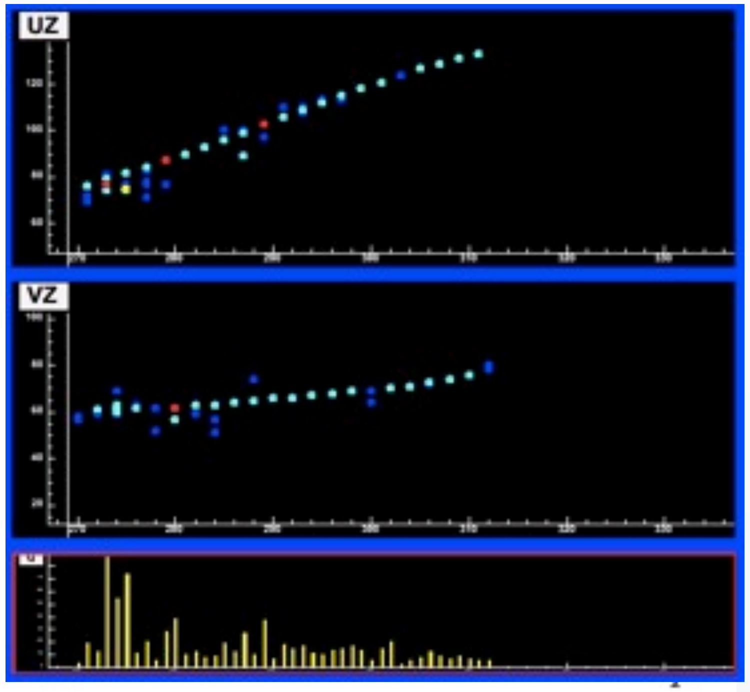
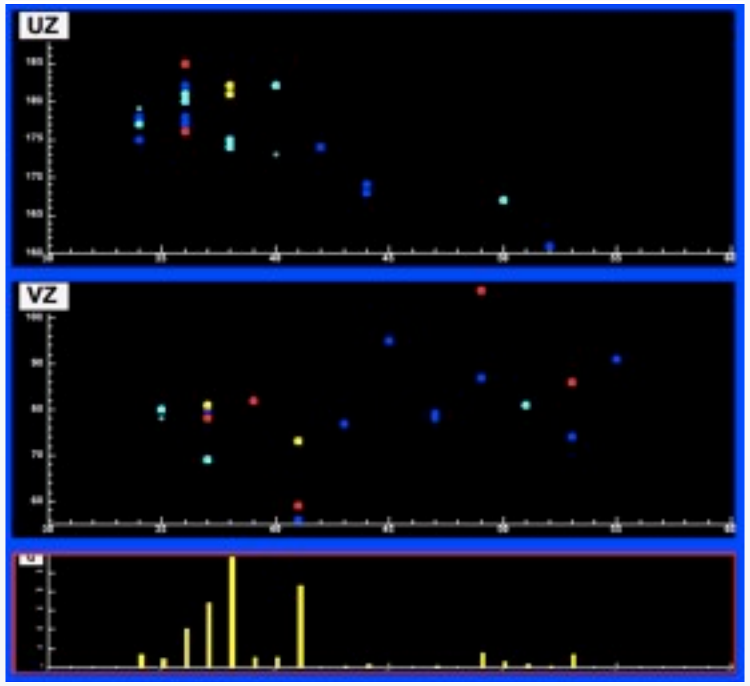
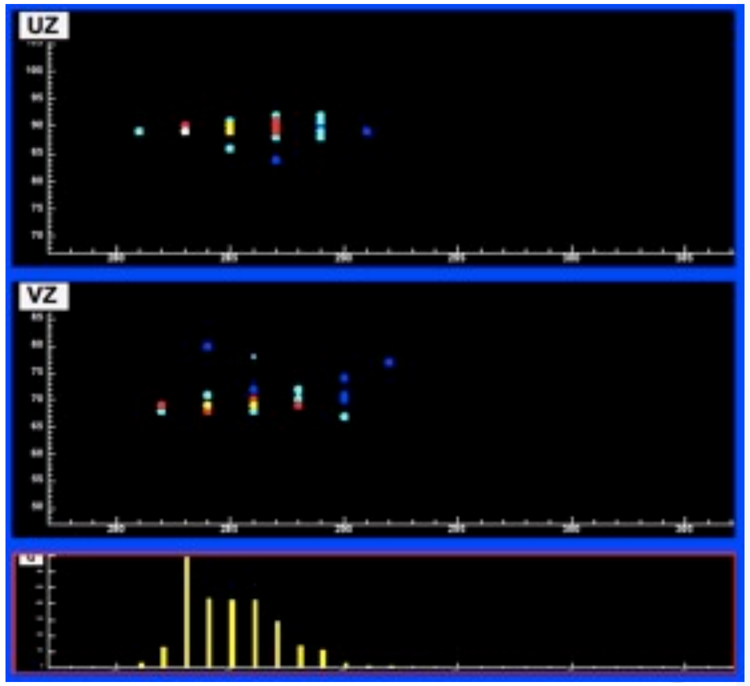


ν_e CC Event



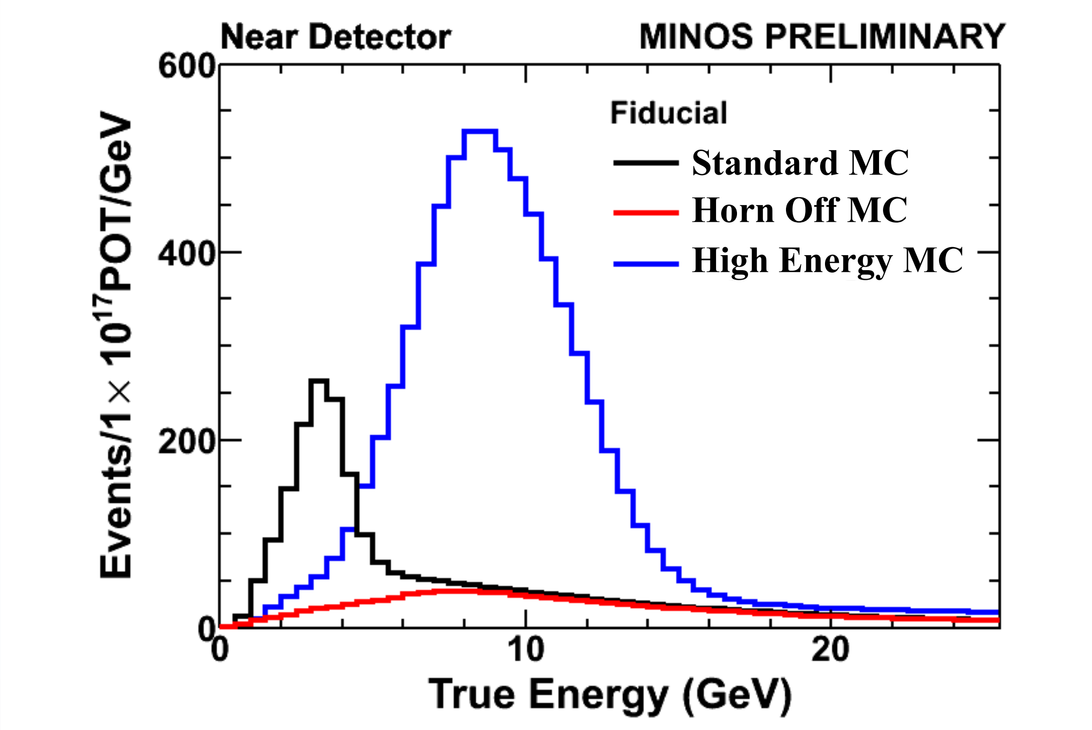
Event Topologies

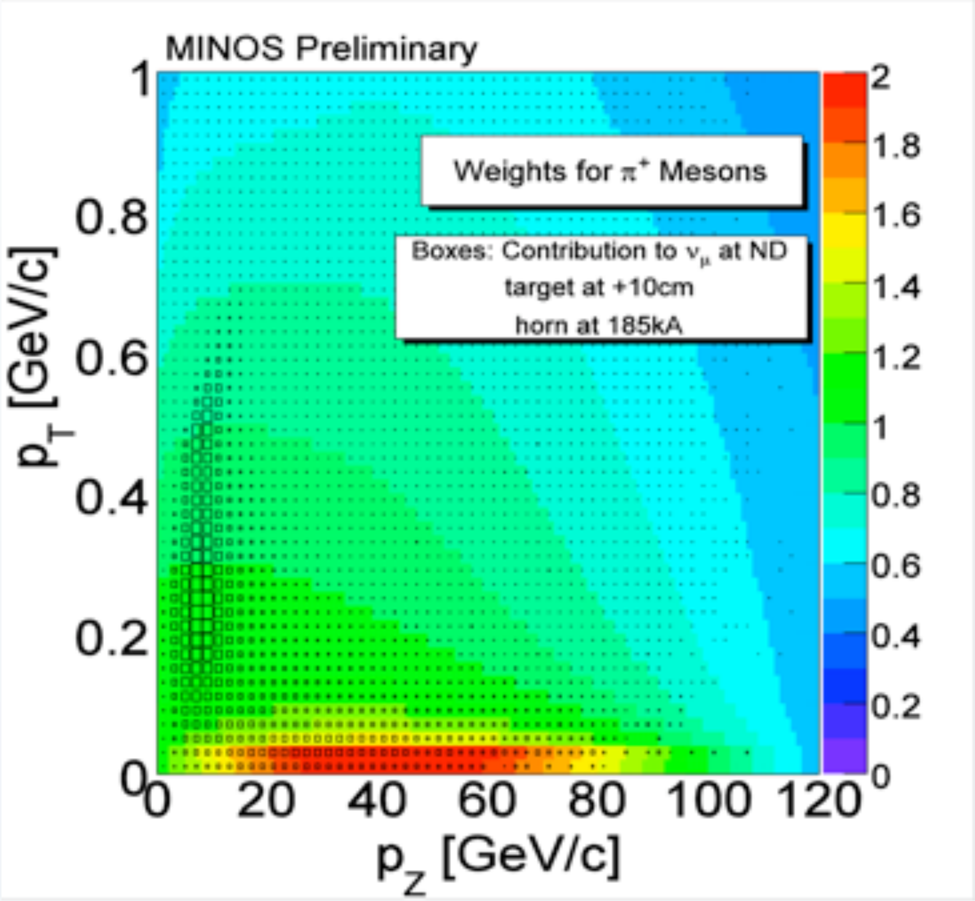
Monte Carlo

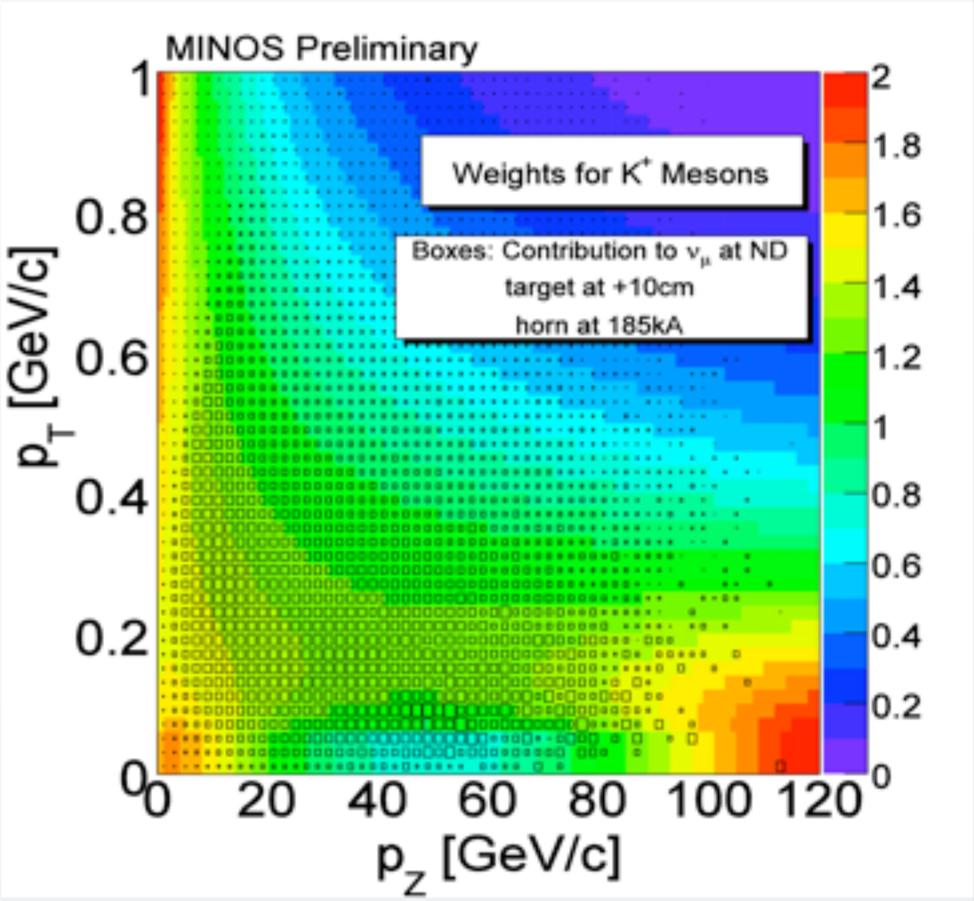
ν_μ CC Event	NC Event	ν_e CC Event
		
long μ track & hadronic activity at vertex	short event, often diffuse	short, with typical EM shower profile

Hadron Production Tuning

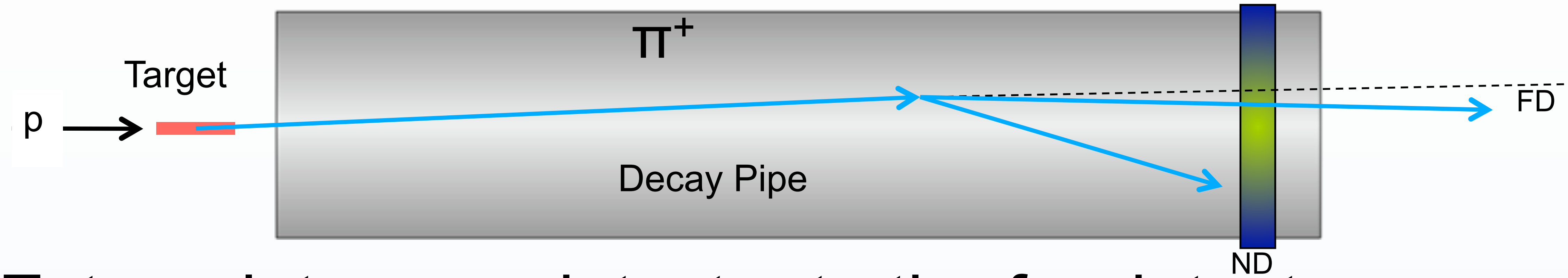
- Hadron production from the NuMI target has substantial uncertainties
  - Fit CC data taken in nine beam configurations to configurations to improve the hadron production model



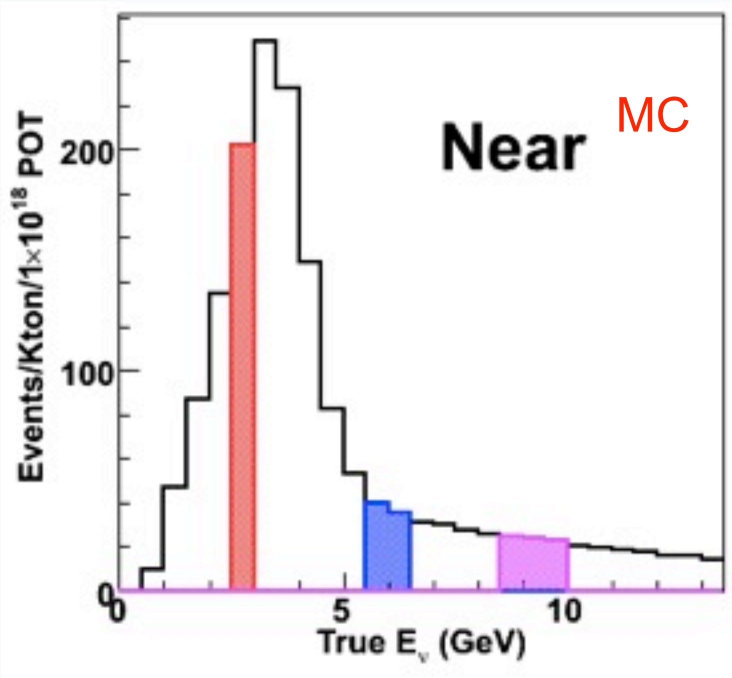


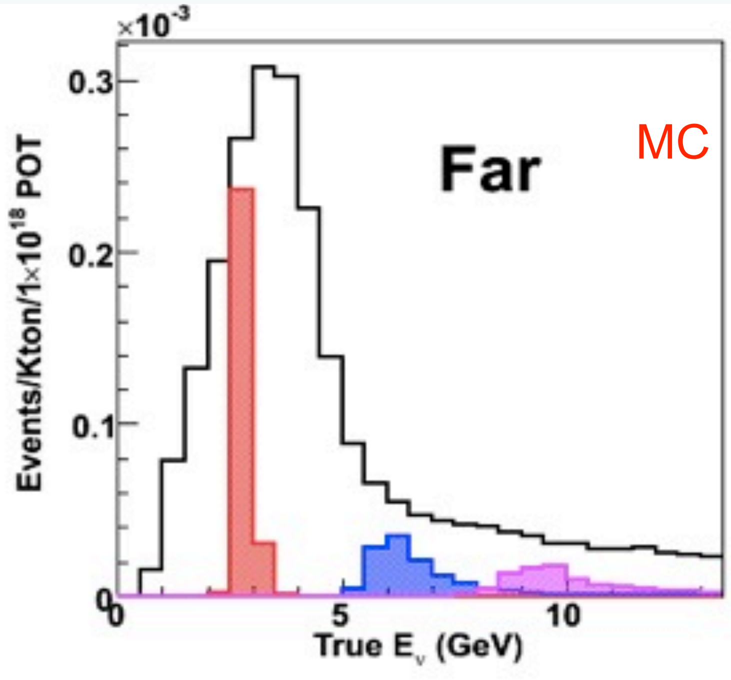


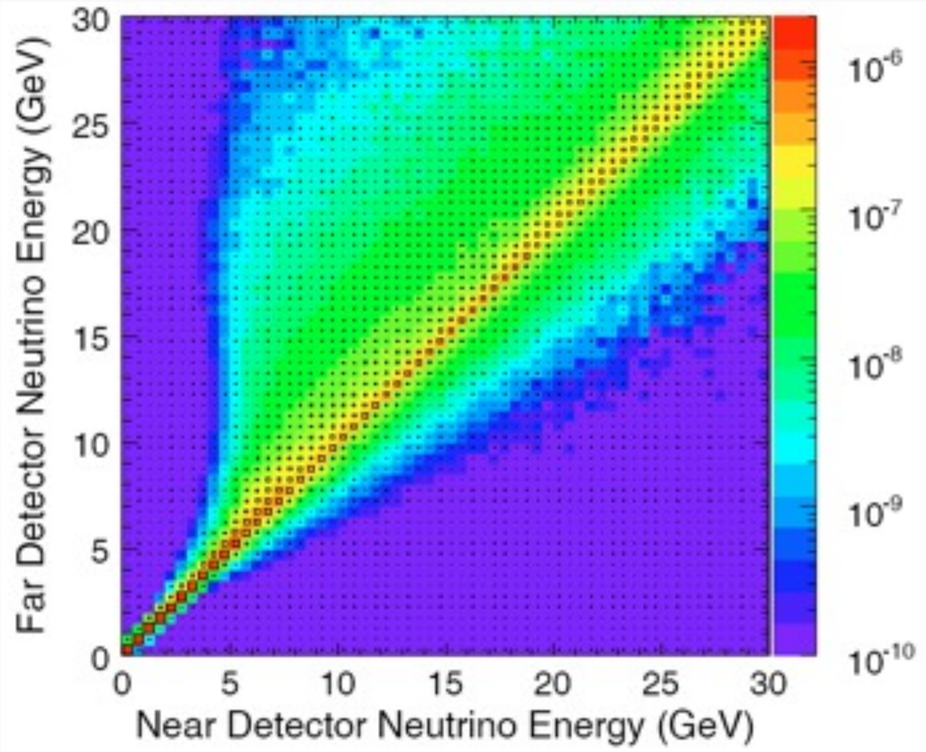
Near to Far Extrapolation



- Extrapolate near detector to the far detector
  - Use Monte Carlo to provide corrections for energy smearing and acceptance
  - Encode pion decay kinematics & the geometry of the beamline into a matrix

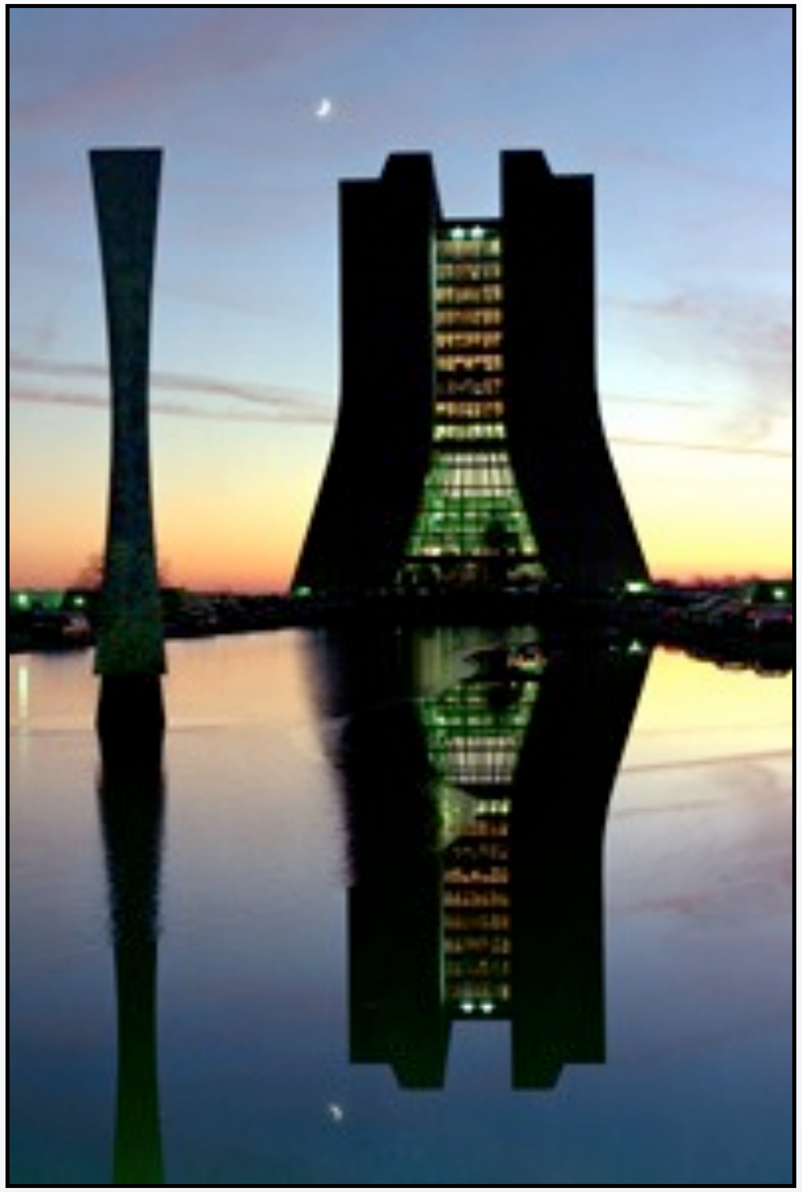






Muon Neutrino Disappearance

Precision measurement of neutrino mixing in the atmospheric sector

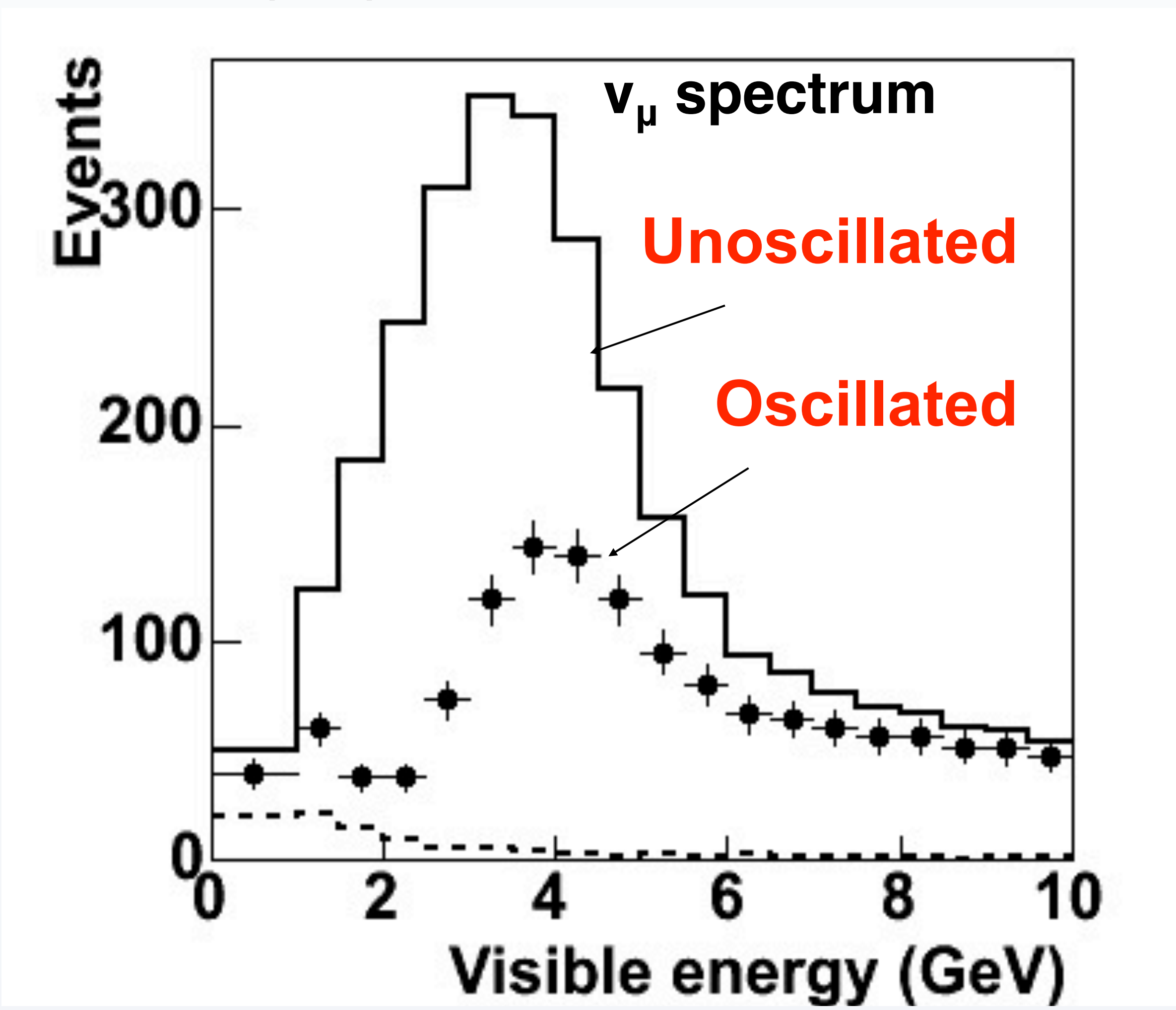


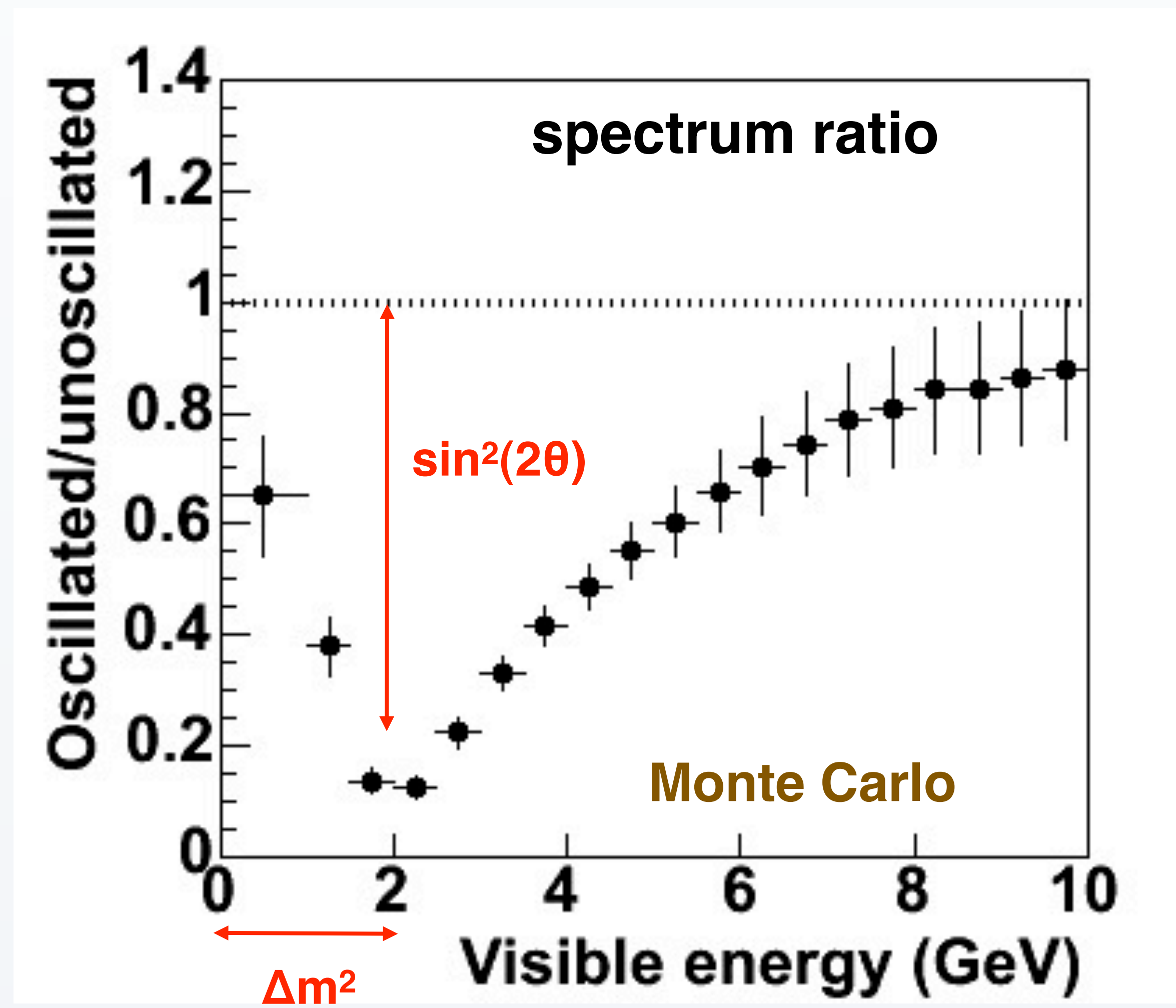
ν_μ Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$

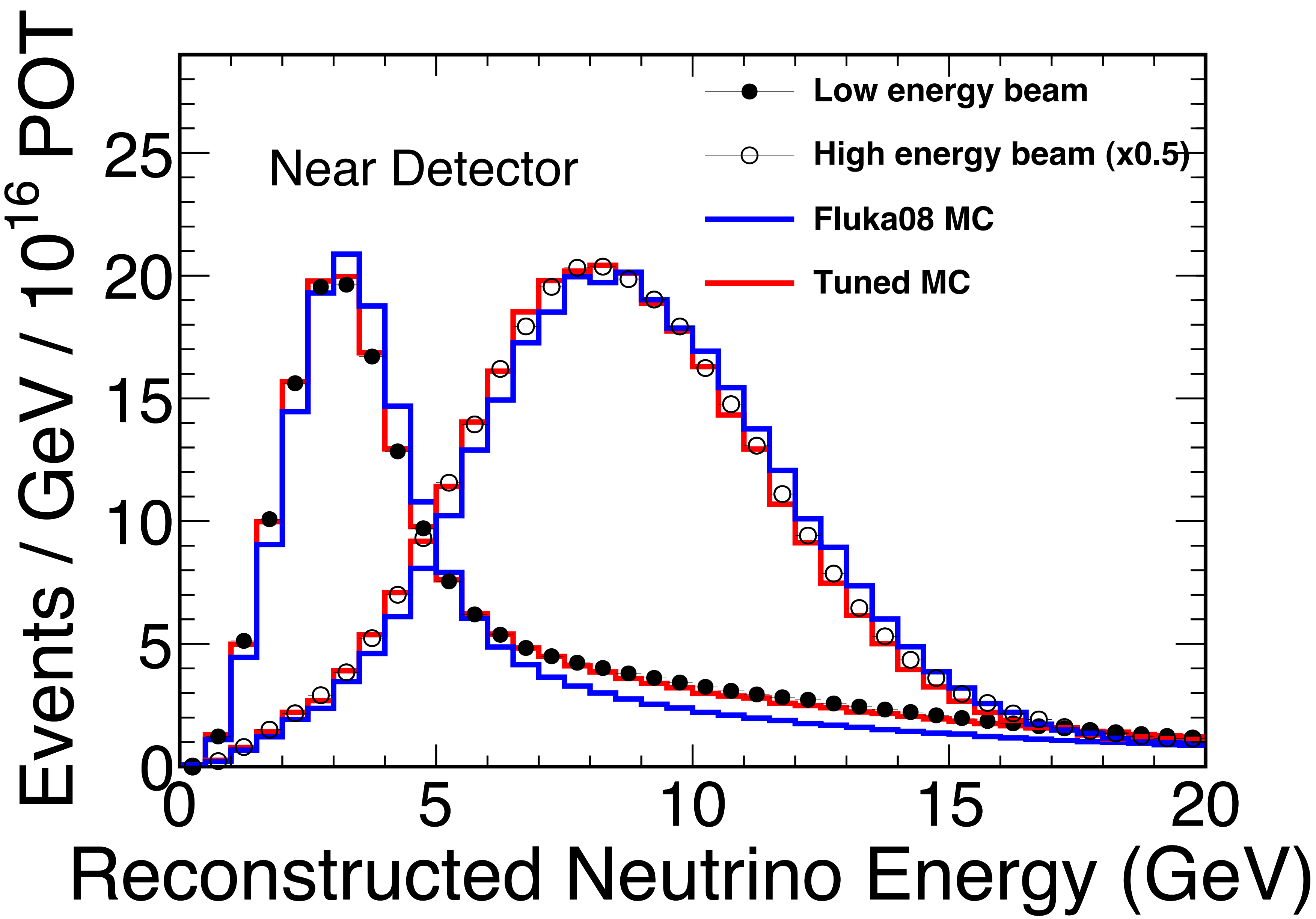
'Toy' Monte Carlo

(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}$ eV^2)





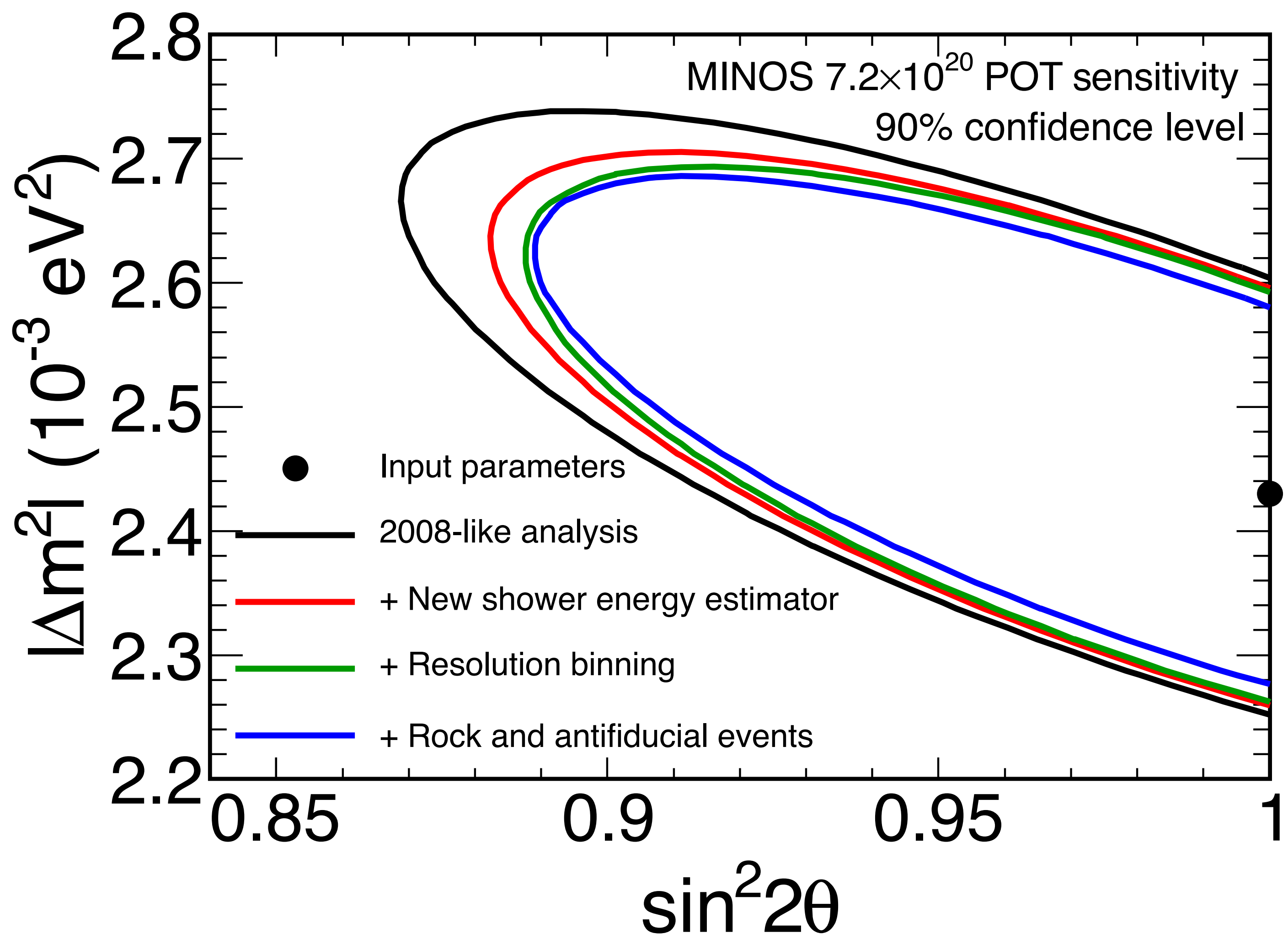
CC events in the Near Detector



- Majority of data from low energy beam
- High energy beam improves statistics in energy range above oscillation dip
- Additional exposure in other configurations for commissioning and systematics studies

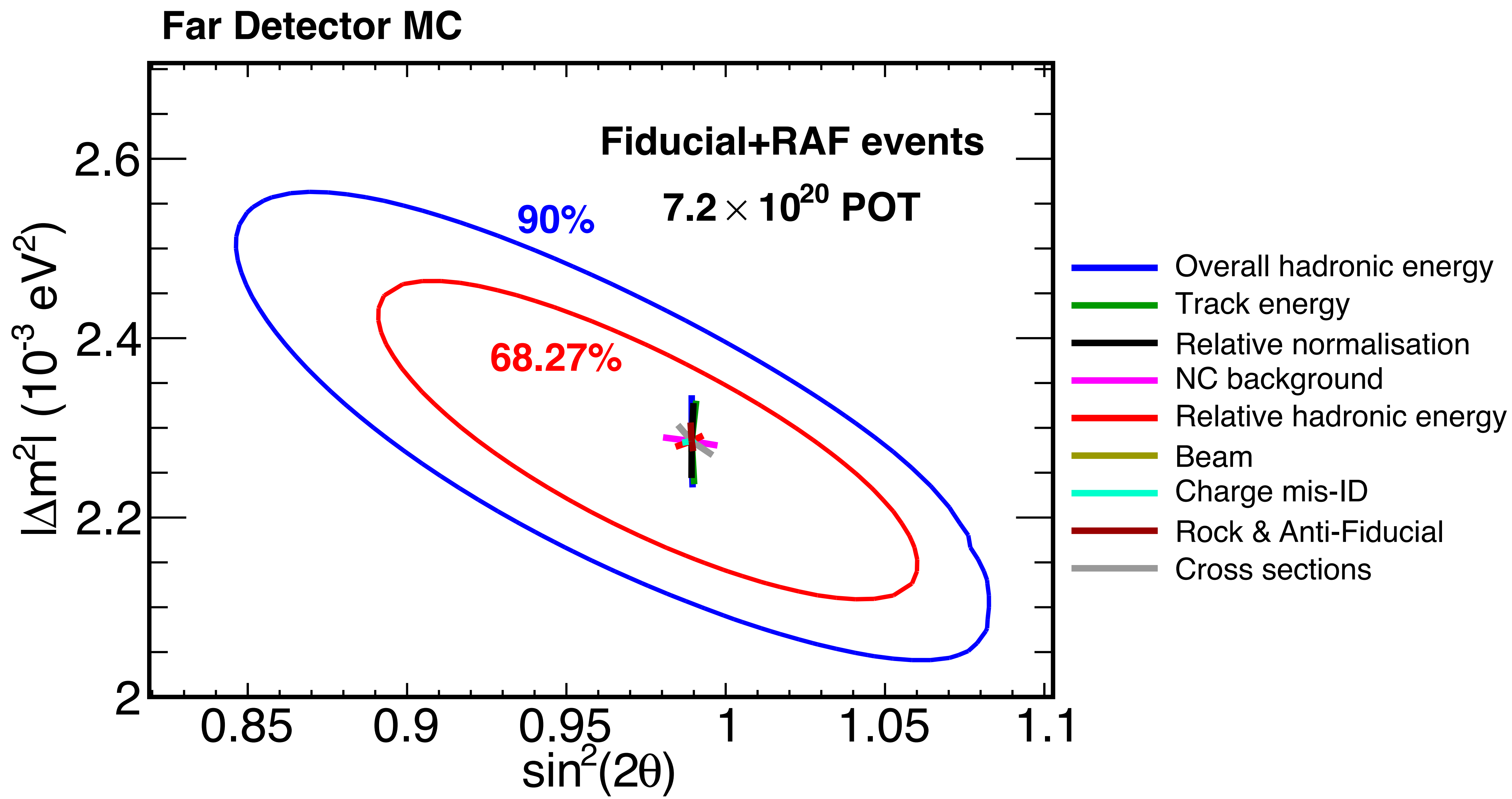
Analysis Improvements

- Since 2008
- Additional data
  - $3.4 \times 10^{20} \rightarrow 7.2 \times 10^{20}$ POT
- Main Analysis improvements
  - improved shower energy resolution
  - separate fits in bins of energy resolution
  - inclusion of events originating outside of the Far Detector's fiducial volume
    - These are the Rock and Anti-Fiducial (RAF) Events

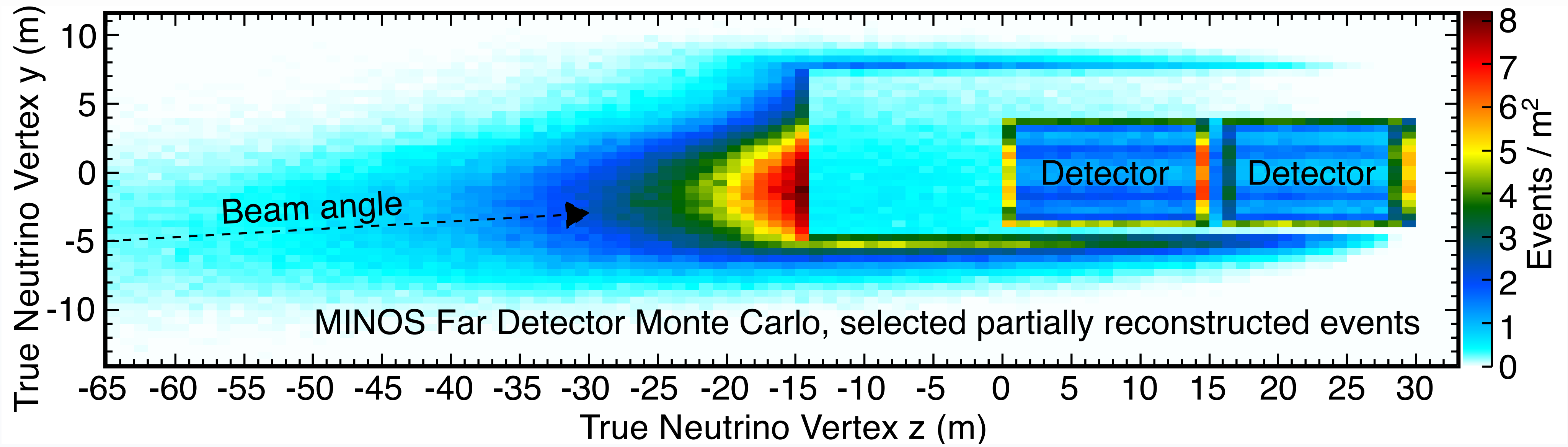


Systematic Uncertainties

- Evaluated effect of systematic uncertainties by fitting modified MC in place of the data

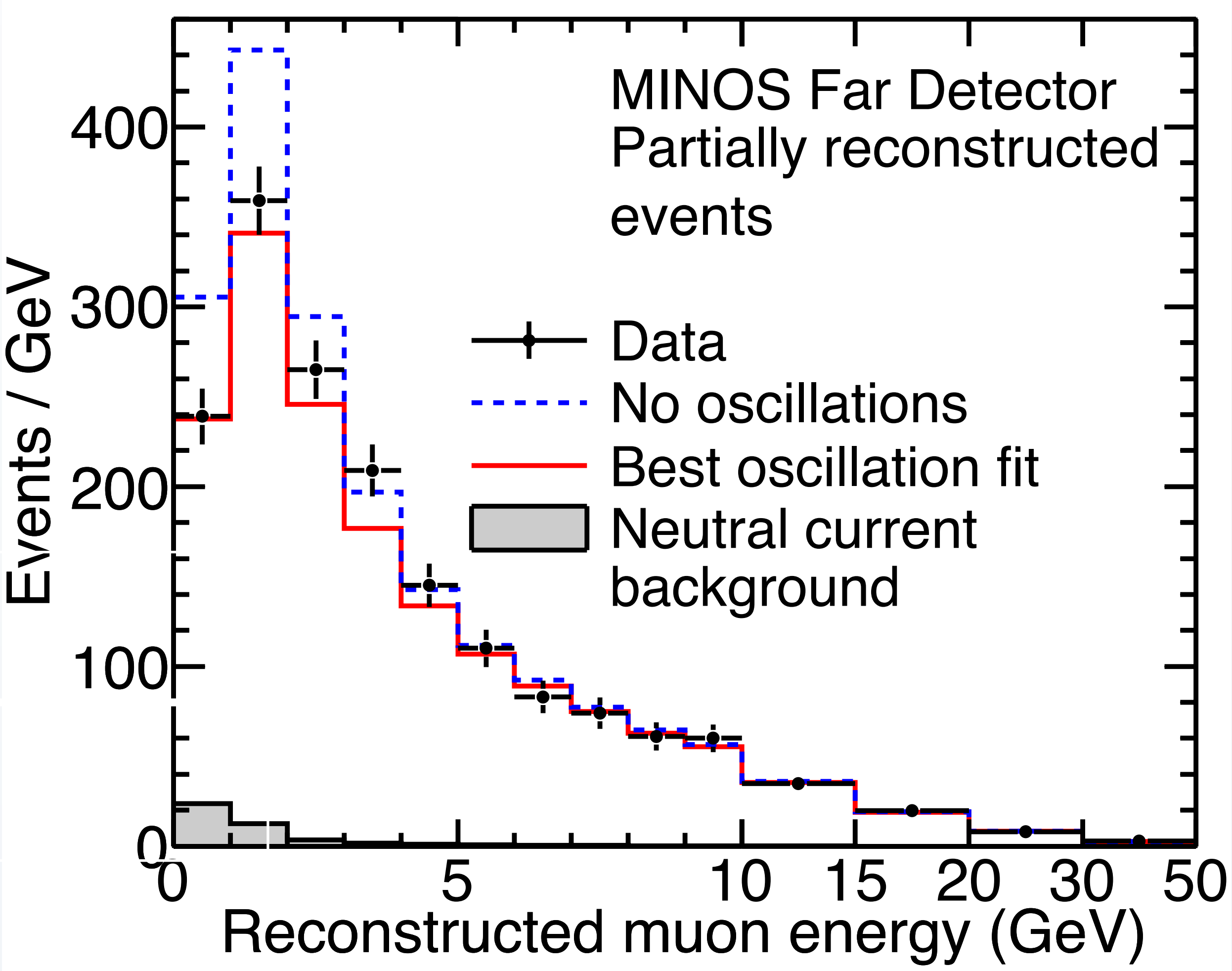


Rock and Anti-Fiducial Events

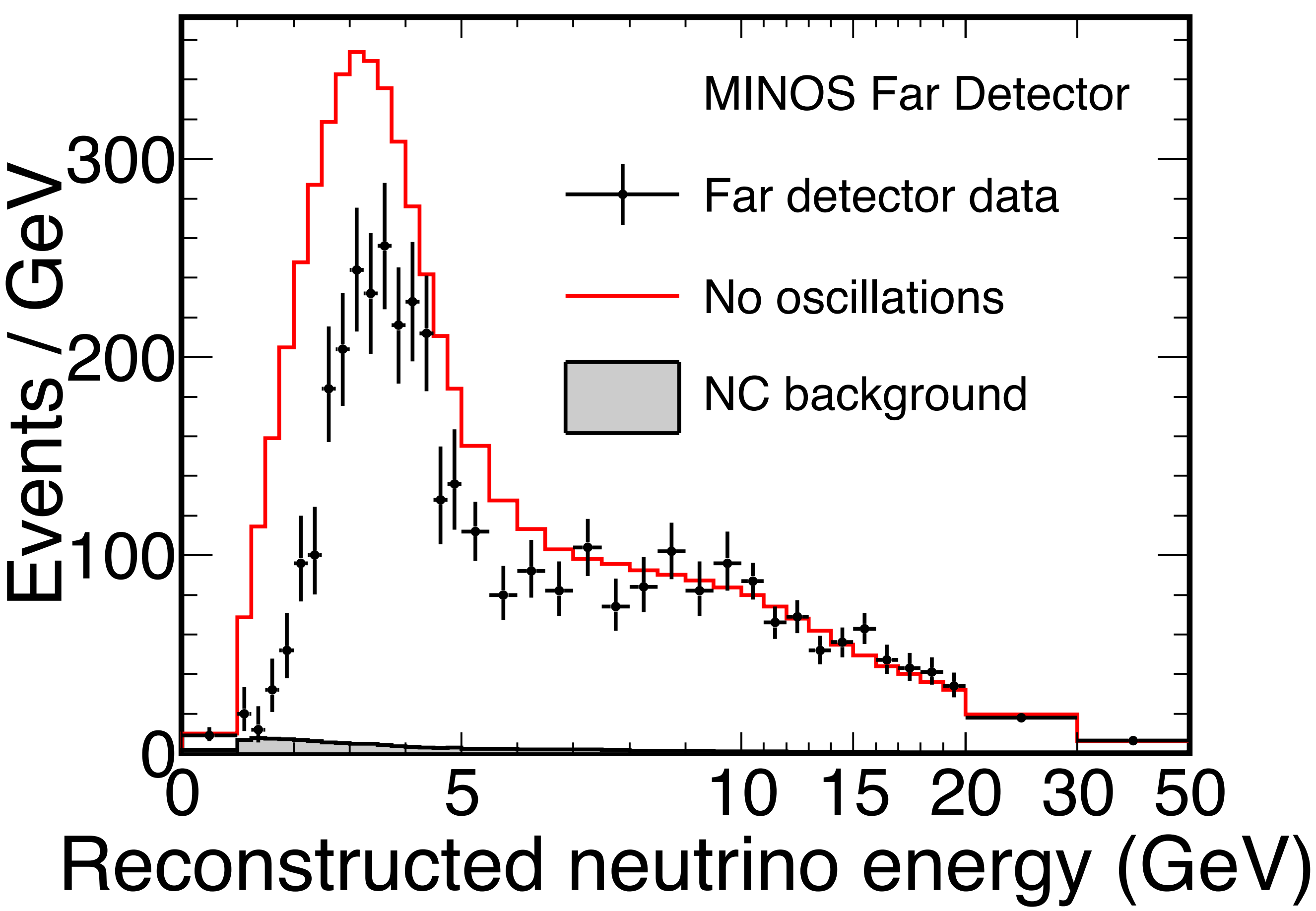


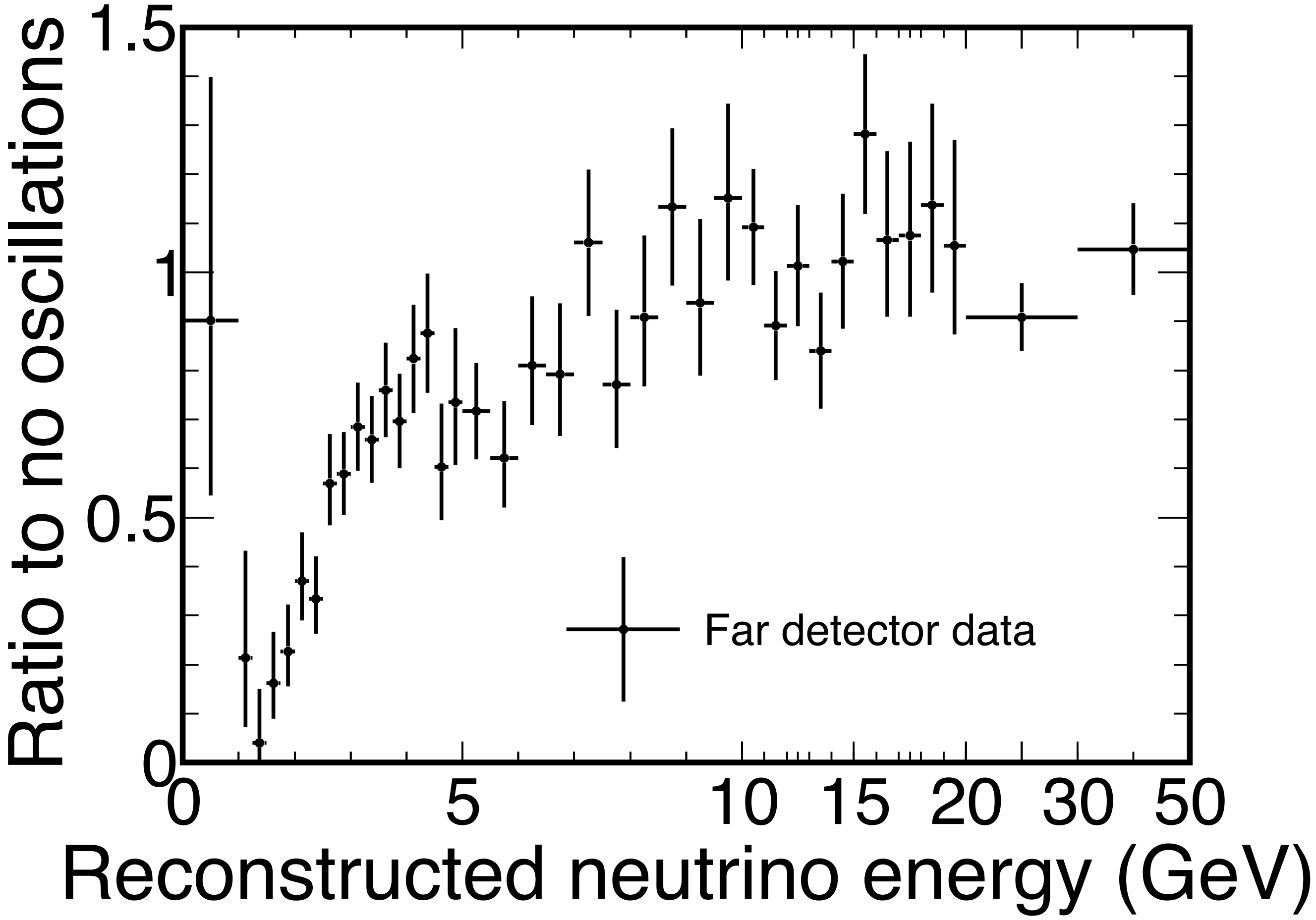
- High statistics low energy resolution sample of events

No Oscillations:	2206
Observation:	**2017**



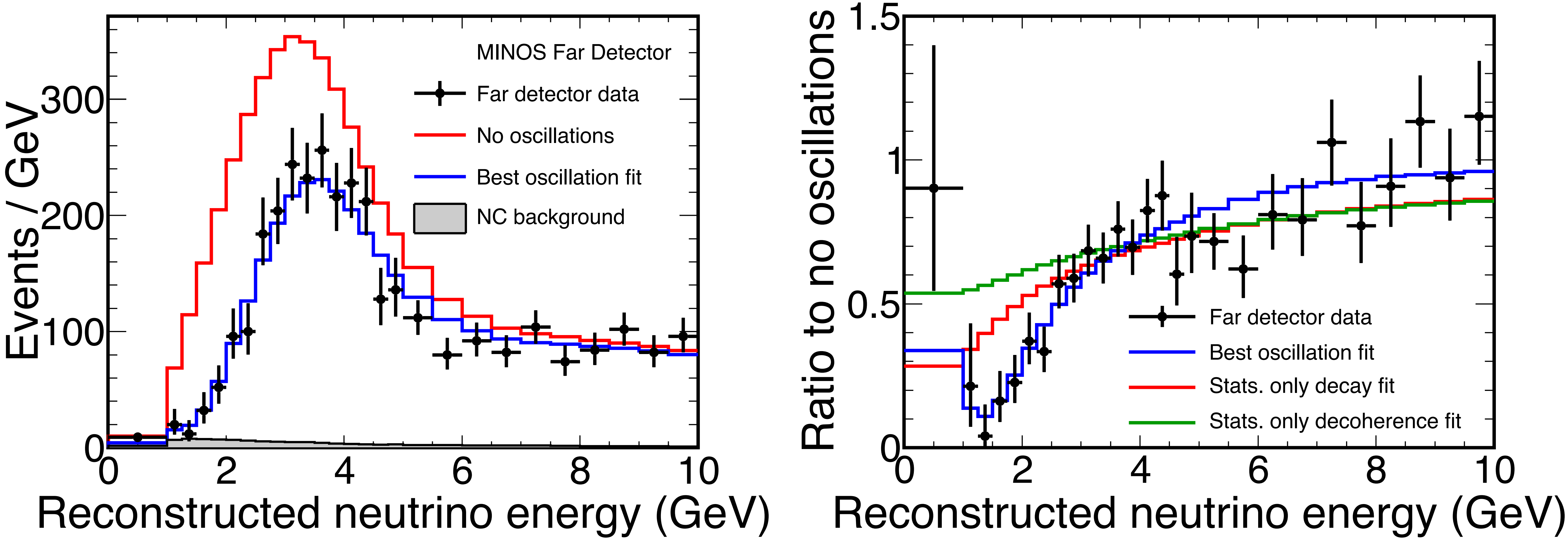
Fully Reconstructed Event Energy Spectrum





No Oscillations:	2451
Observation:	**1986**

Far Detector Energy Spectrum



- Combined fit to contained and rock/anti-fiducial events
  - Over 58% of mock experiments have larger log-likelihood
- Pure decoherence† disfavoured at **9σ**
- Pure decay‡ disfavoured at **7σ**

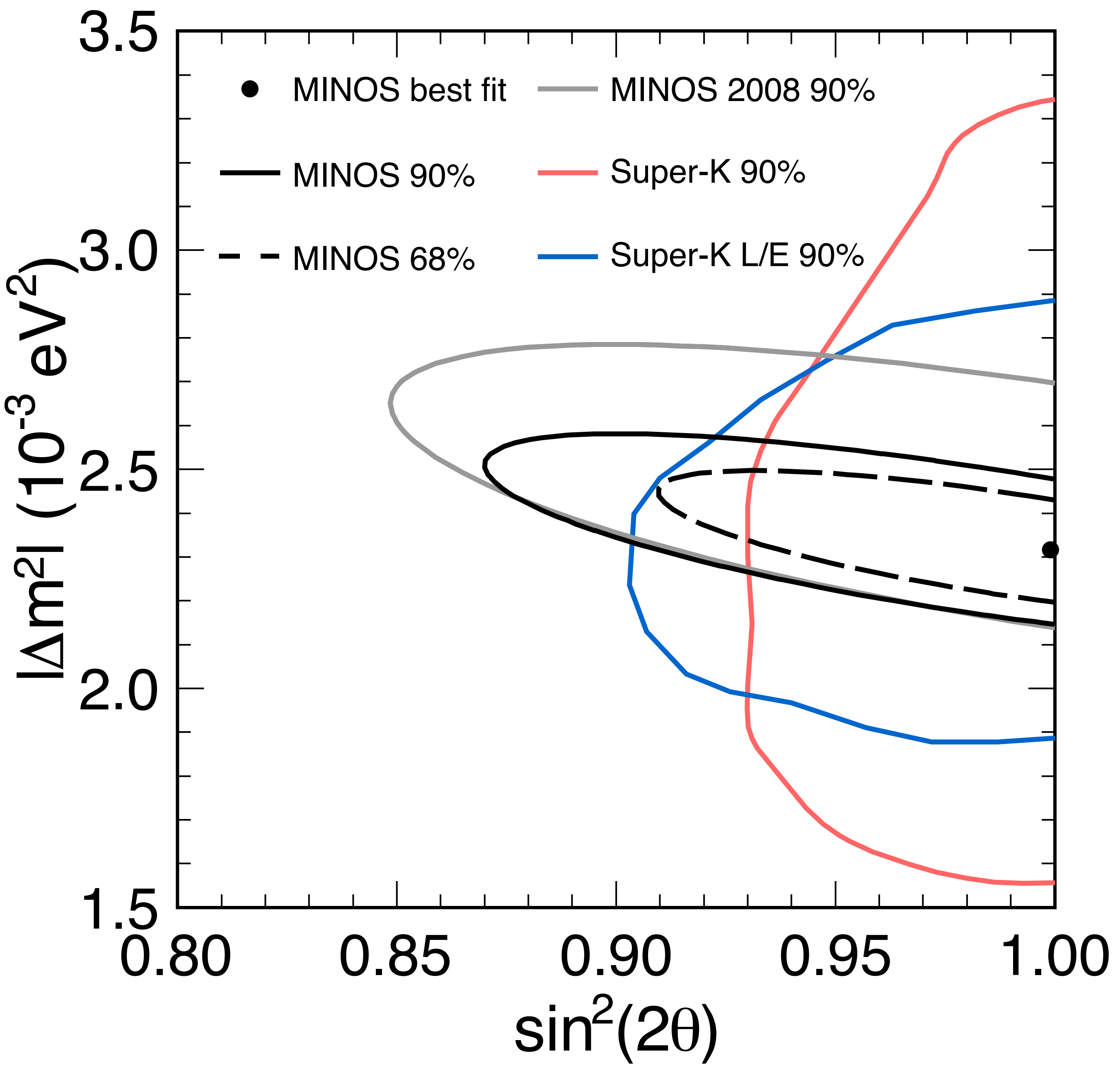
†G.L. Fogli *et al.*, PRD 67:093006 (2003) ‡V. Barger *et al.*,PRL 82:2640 (1999)

Contours

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

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

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

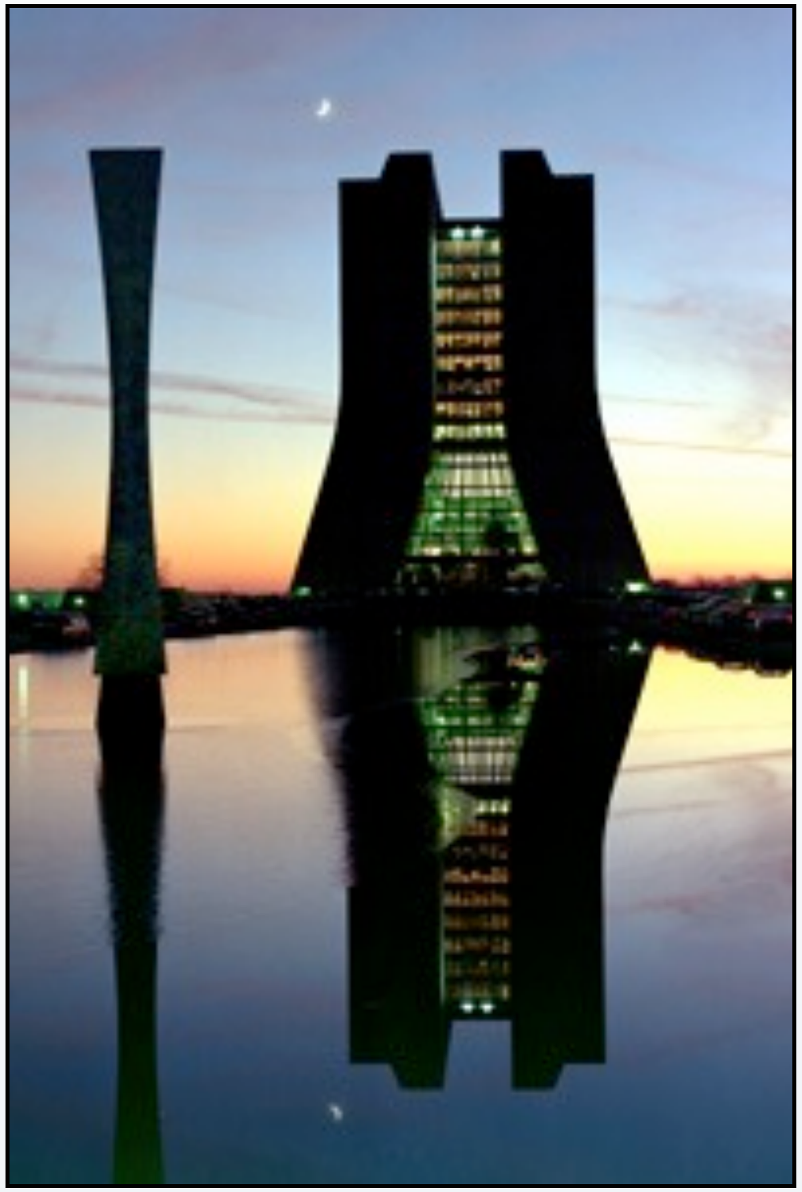


Published yesterday.
Phys. Rev. Lett. 106, 181801 (2011)

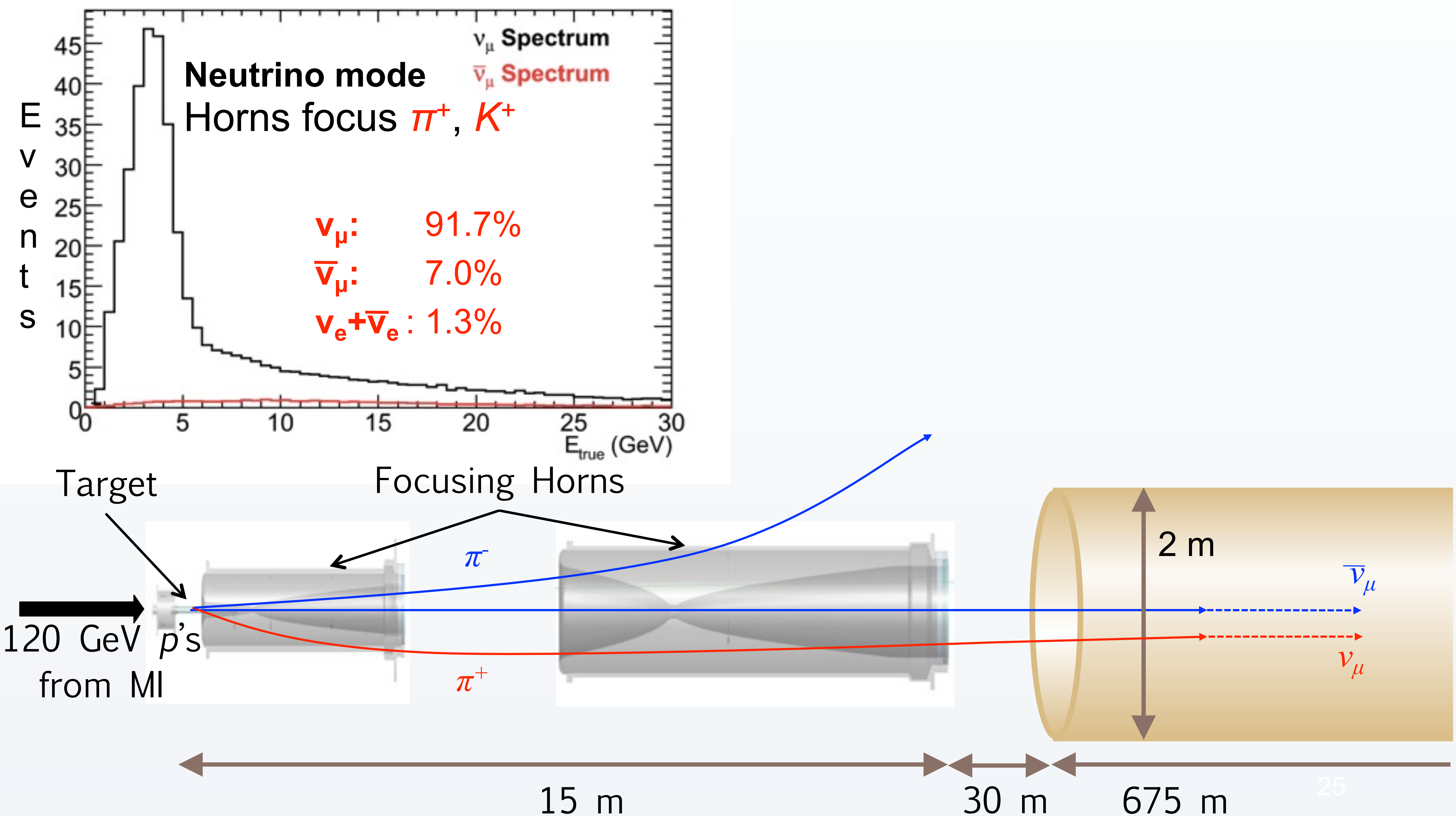
Note: These are the last published Super-K contours, not the improved ones shown at Neutrino2010

Muon-Antineutrino Disappearance Analysis

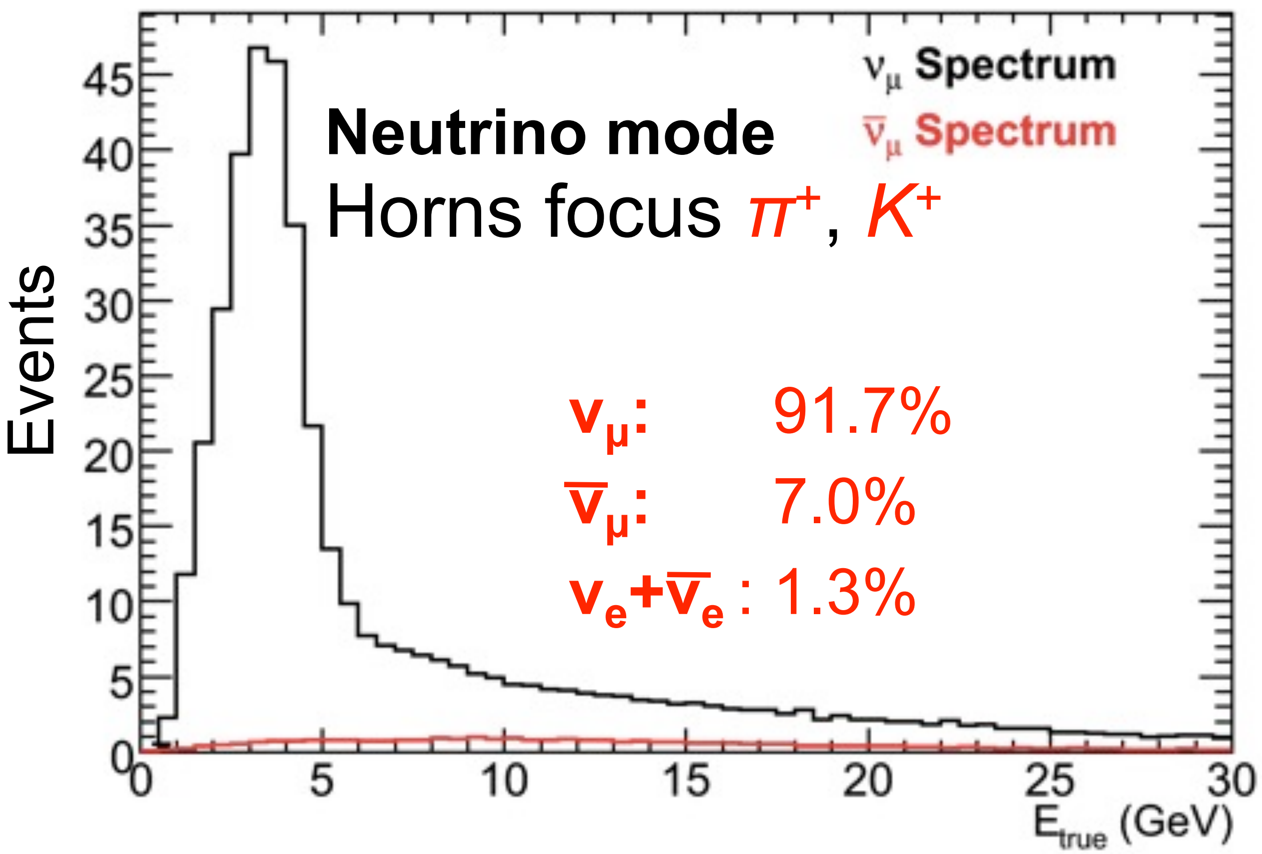
Do antineutrinos do it the same?

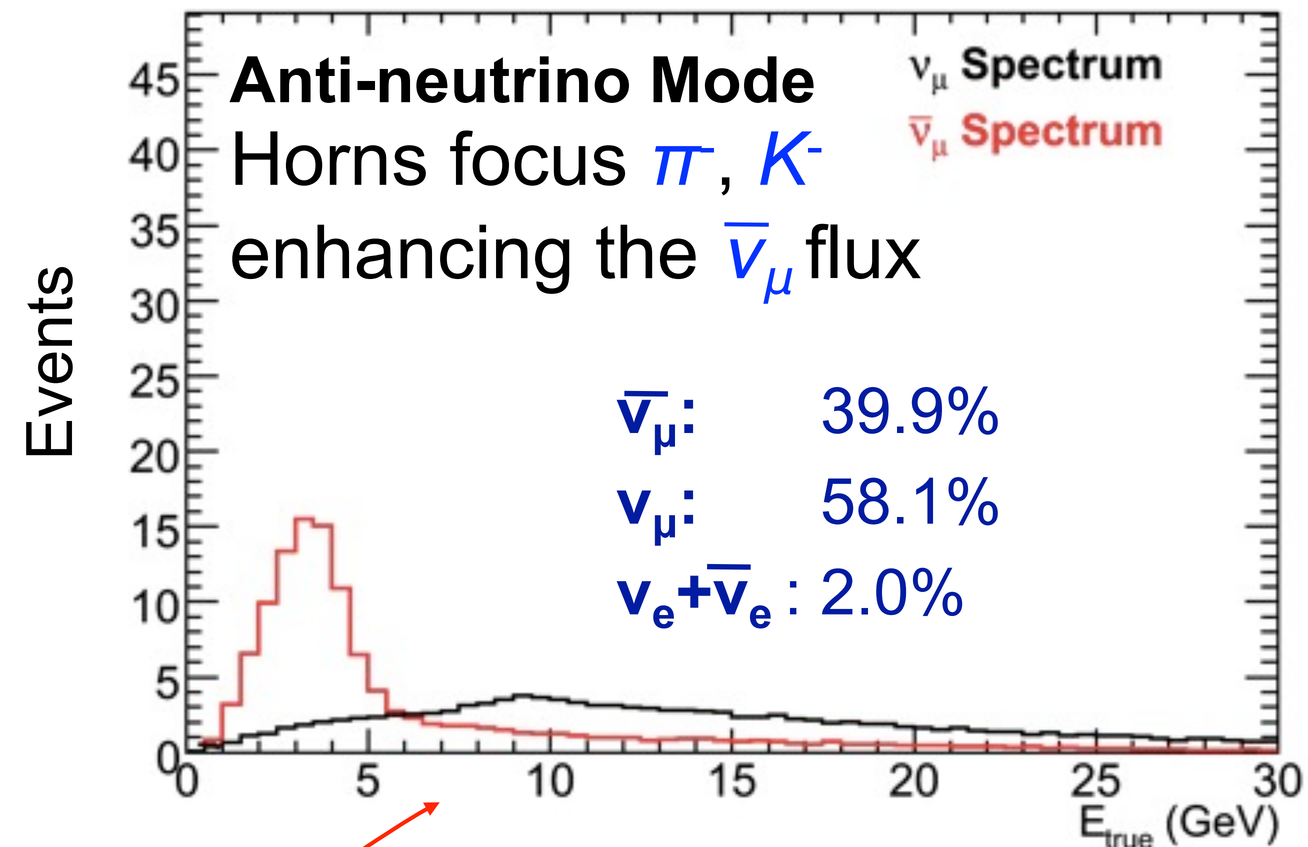


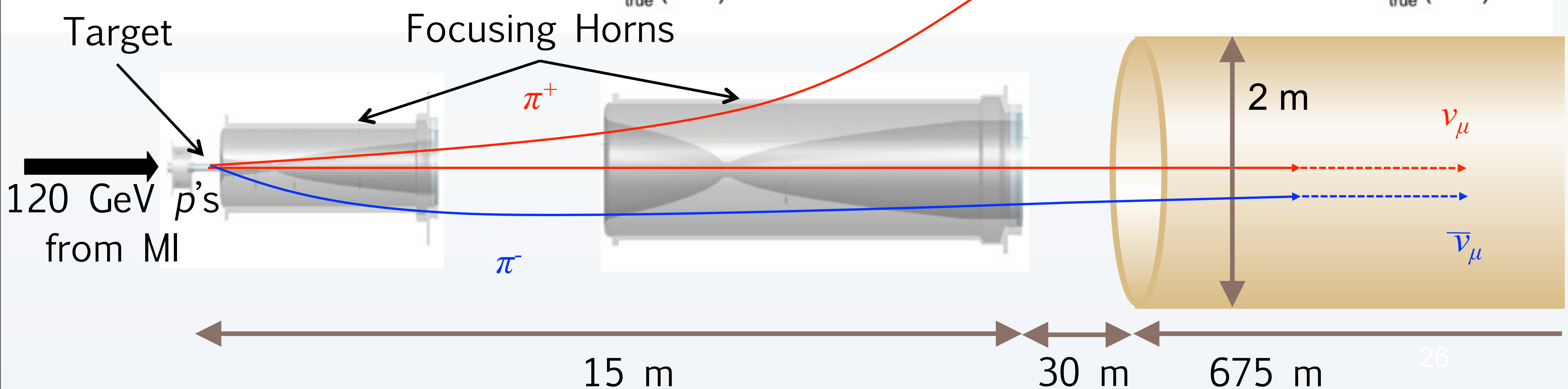
Making a neutrino beam



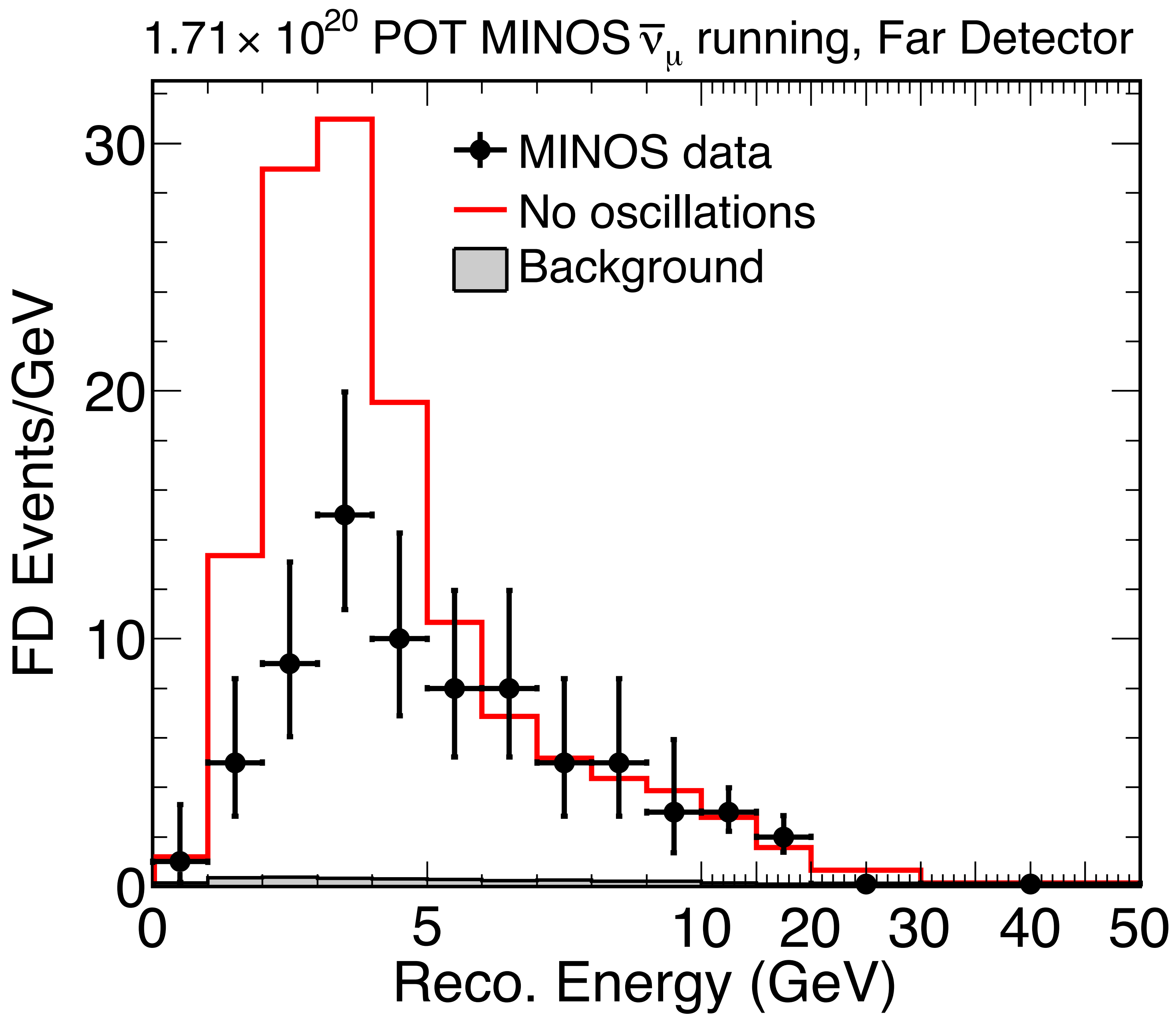
Making an anti-neutrino beam





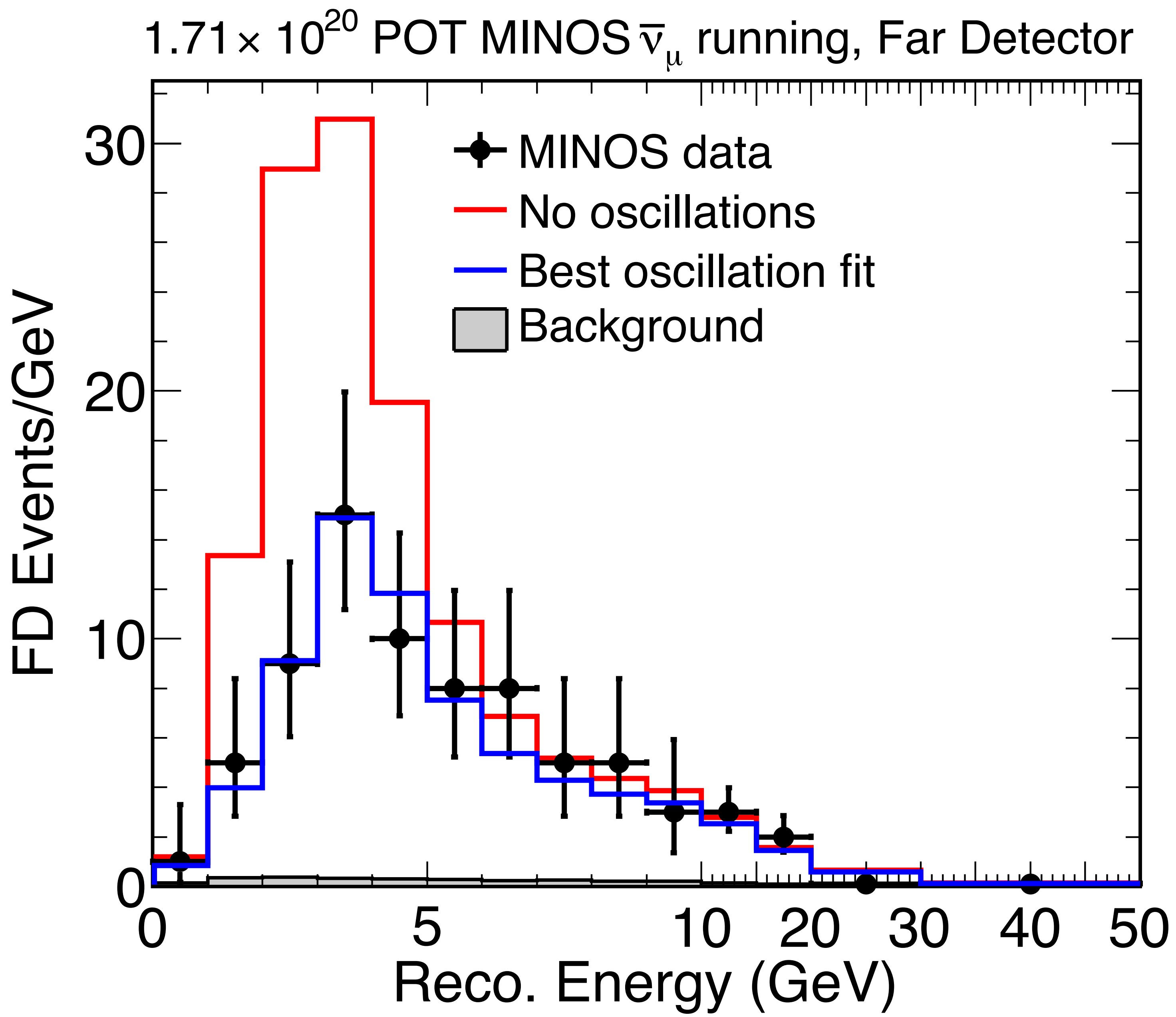


FD Data



- No oscillation Prediction: **155**
- Observe: **97**
- No oscillations disfavoured at 6.3σ

FD Data

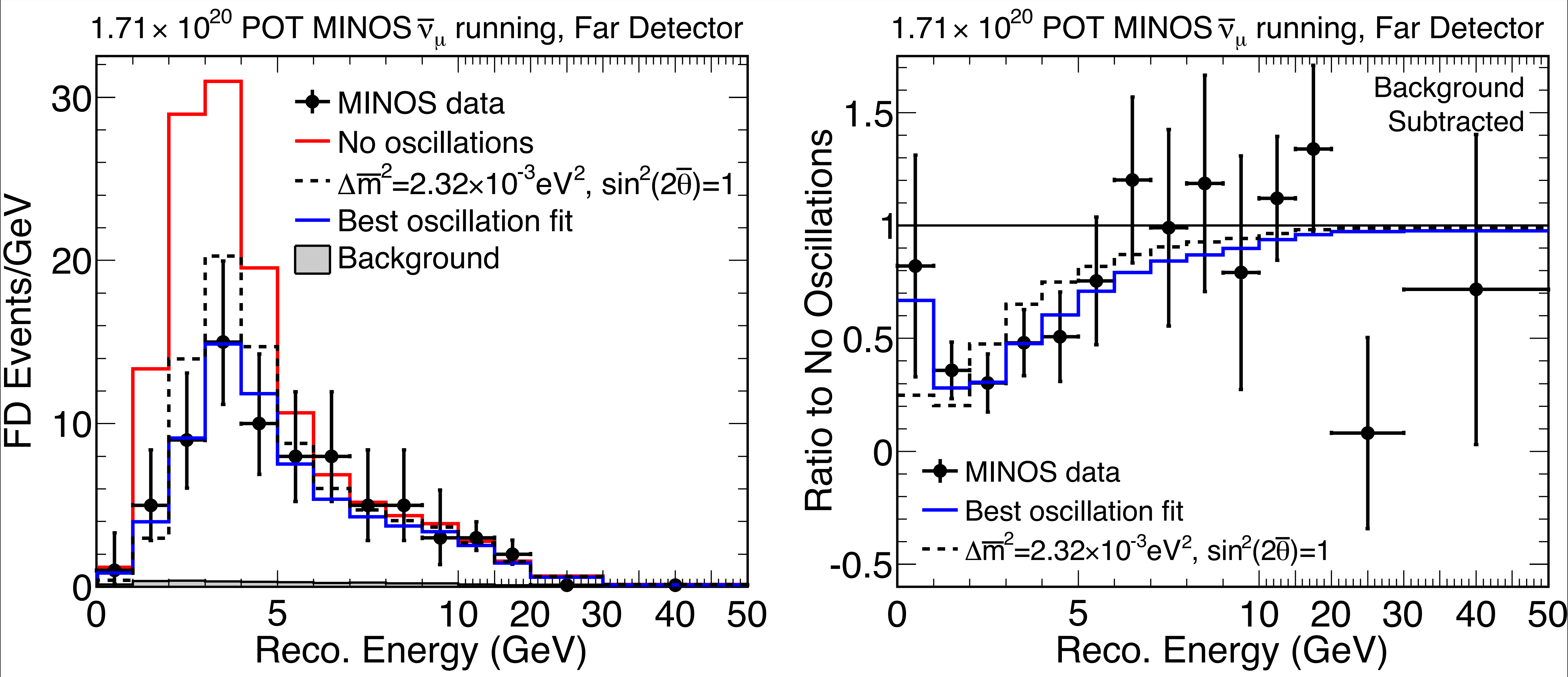


- No oscillation Prediction: **155**
- Observe: **97**
- No oscillations disfavoured at 6.3σ

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\text{eV}^2$$

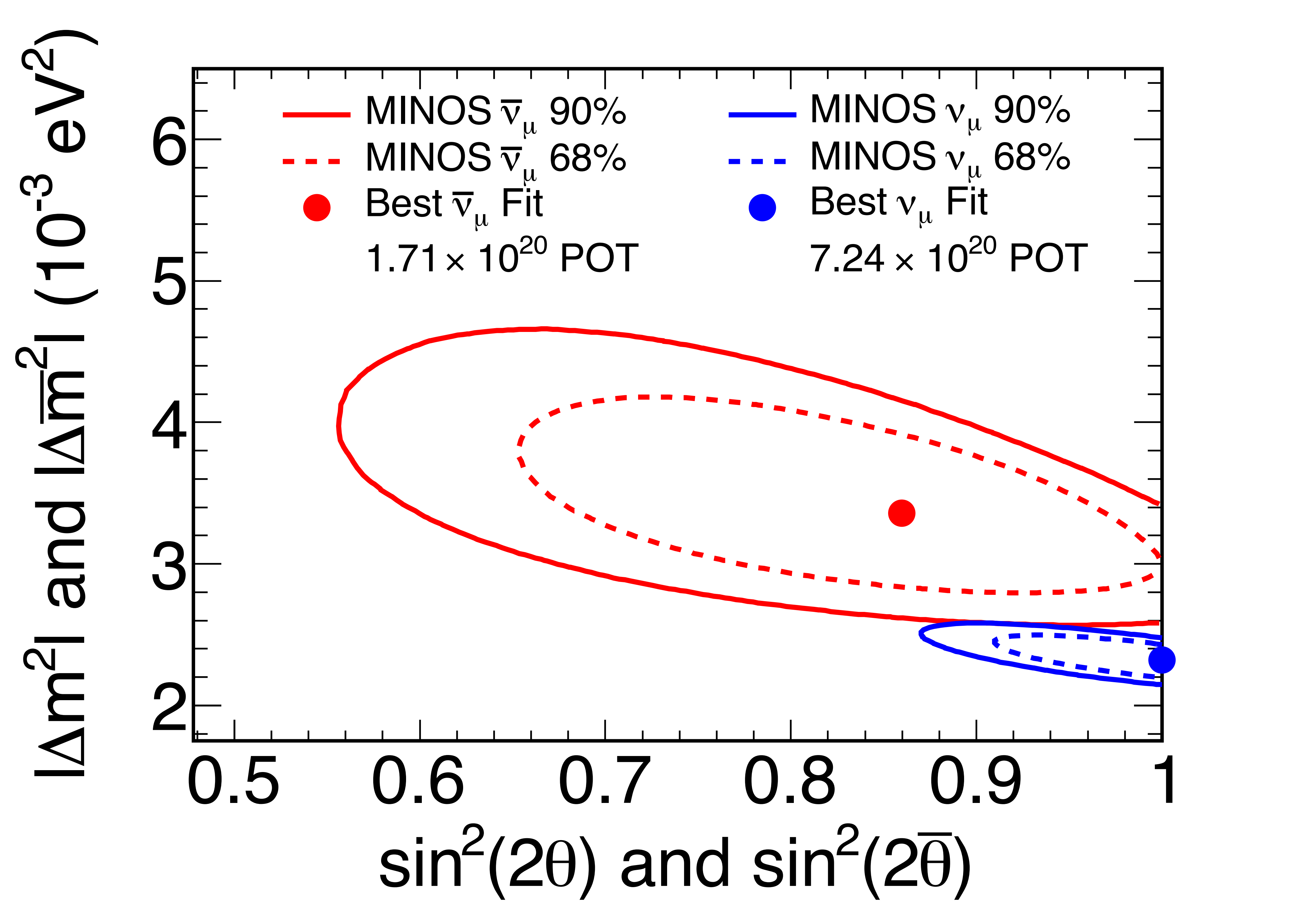
$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

Comparisons to Neutrinos



Submitted to PRL, arXiv:1104.0344

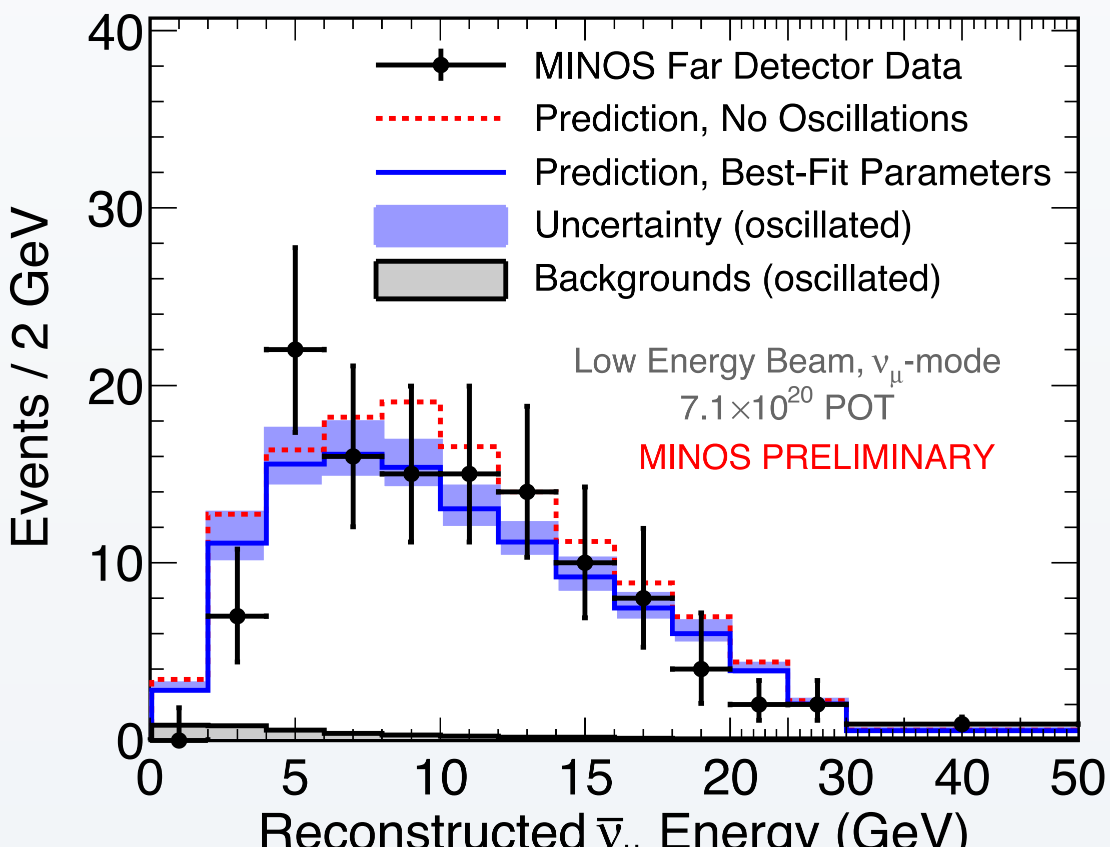
Comparisons to Neutrinos

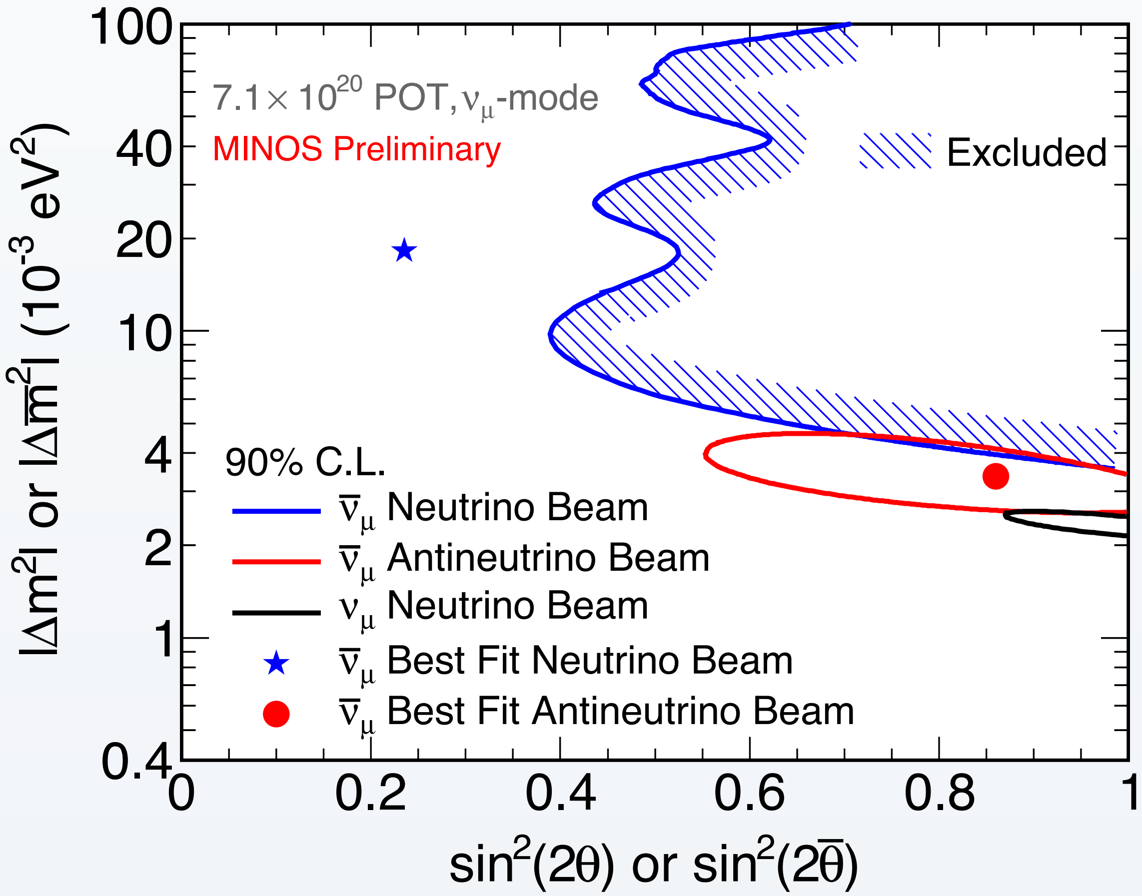


A 2% chance of seeing such a discrepancy if the underlying parameters are the same

Antineutrinos in the neutrino beam

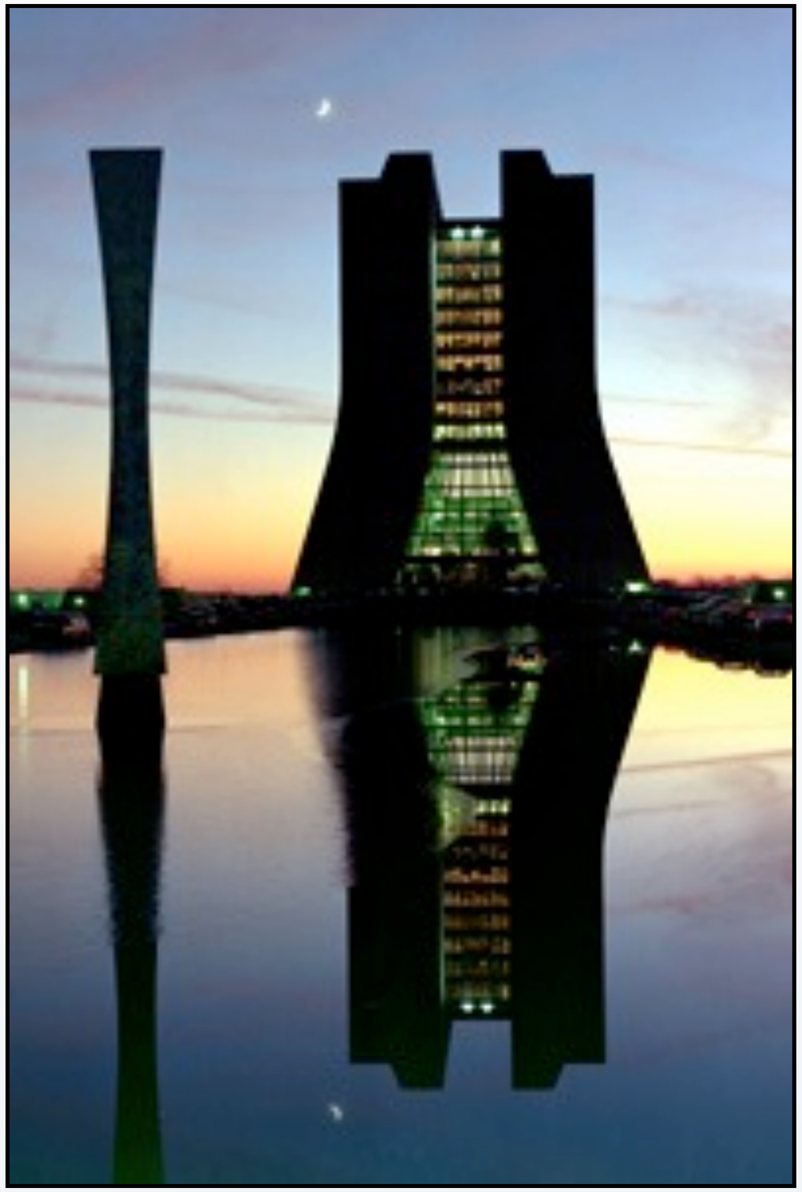
- We have analysed the sample of antineutrinos in the neutrino beam
  - Low statistics, higher energy sample
- Consistent with both the neutrino and antineutrino results





Neutral Current Analysis

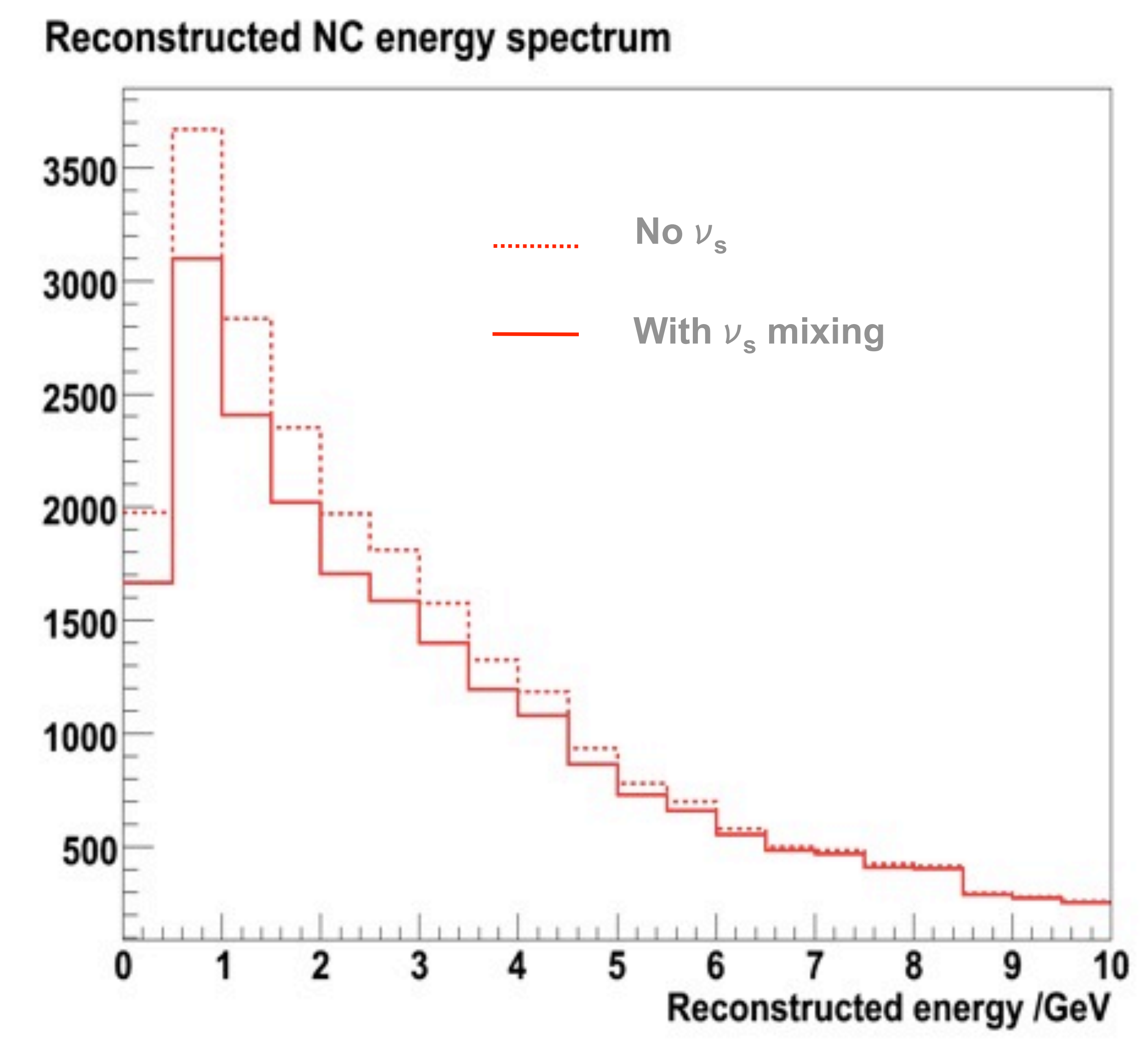
Searching for evidence of oscillations to sterile neutrinos



Motivation: Neutral Current

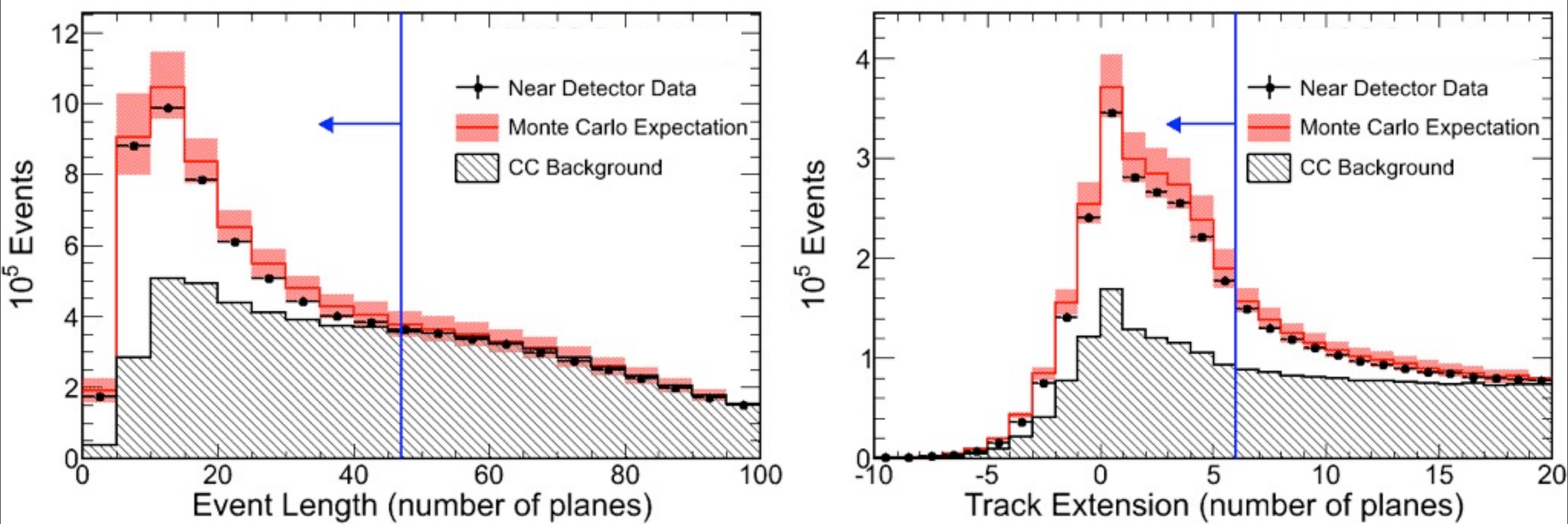
- In the standard 3-flavor picture neutrinos are oscillating between ν_e, ν_μ, ν_τ.
- Oscillations into ν_s affect number of observed NC interactions as ν_s do not interact in the detector.
- Look for NC disappearance at the Far Detector

- Sterile neutrino mixing would deplete NC energy spectrum

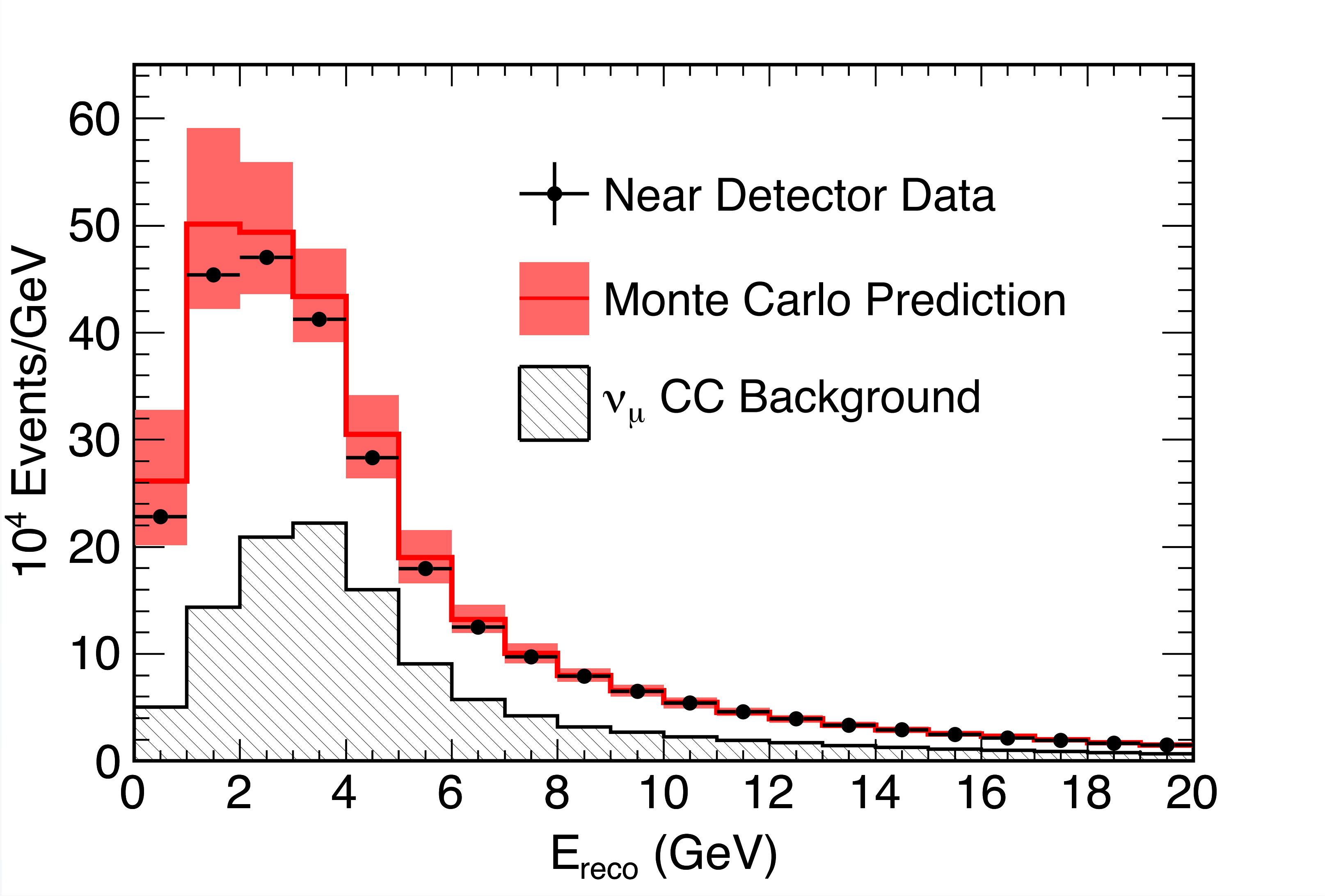


Near Detector NC Event Selection

- Neutral current selects events with one or zero reconstructed tracks
- Two selection variables

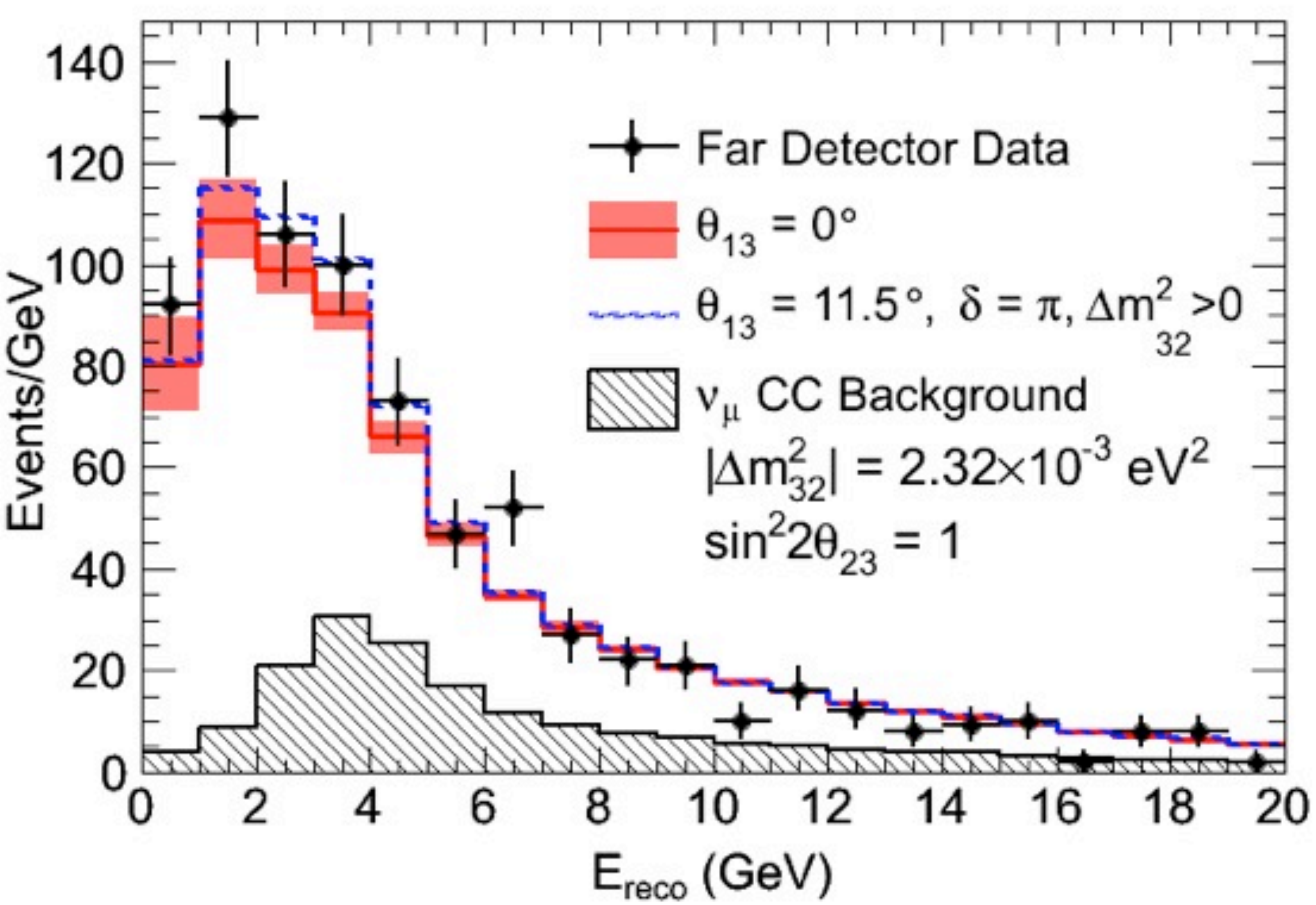


Neutral Current Near Event Rates



- 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: **754** 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)

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

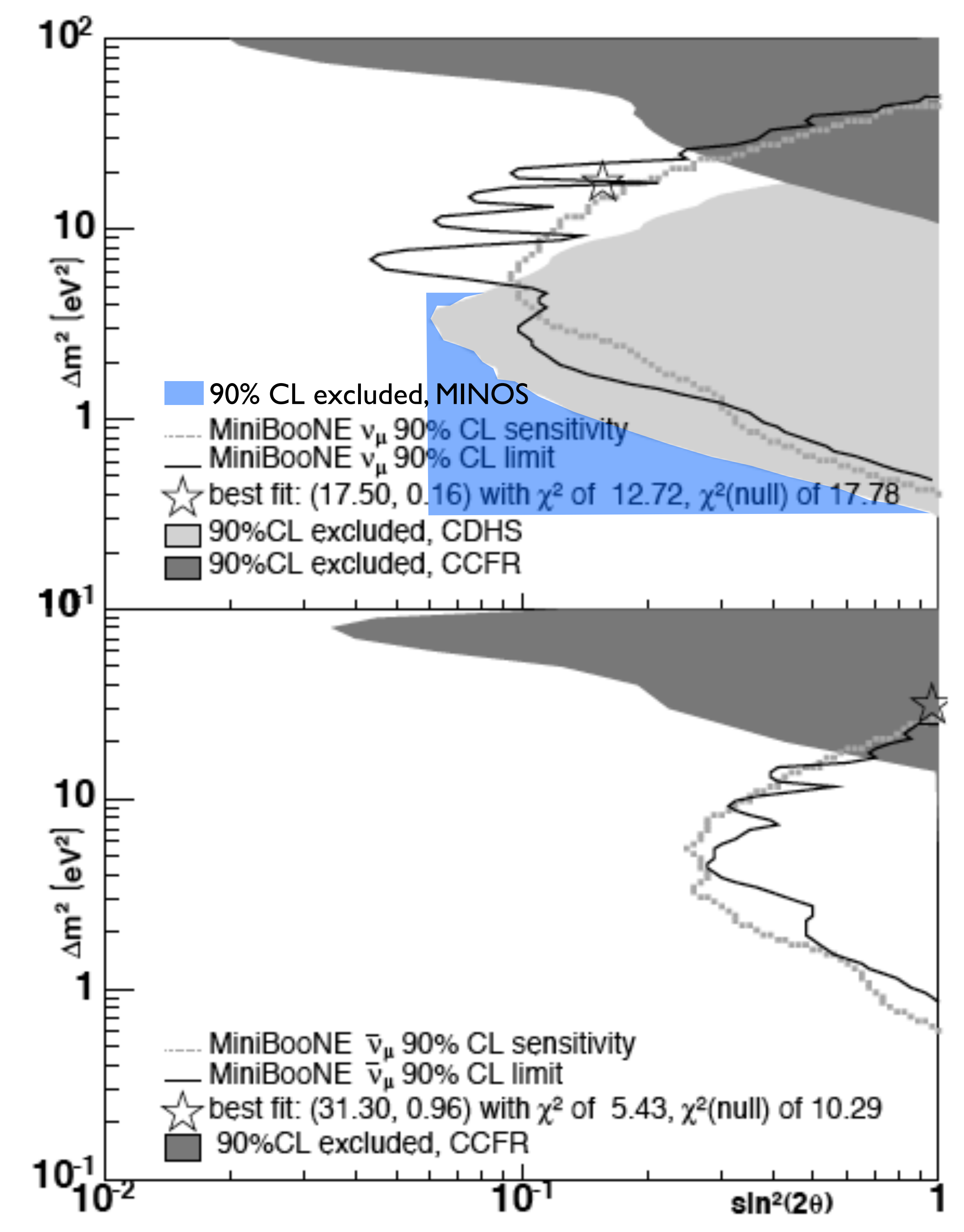
(with ν_e appearance)

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

no (with) ν_e appearance

Submitted to PRL, arXiv:1104.3922

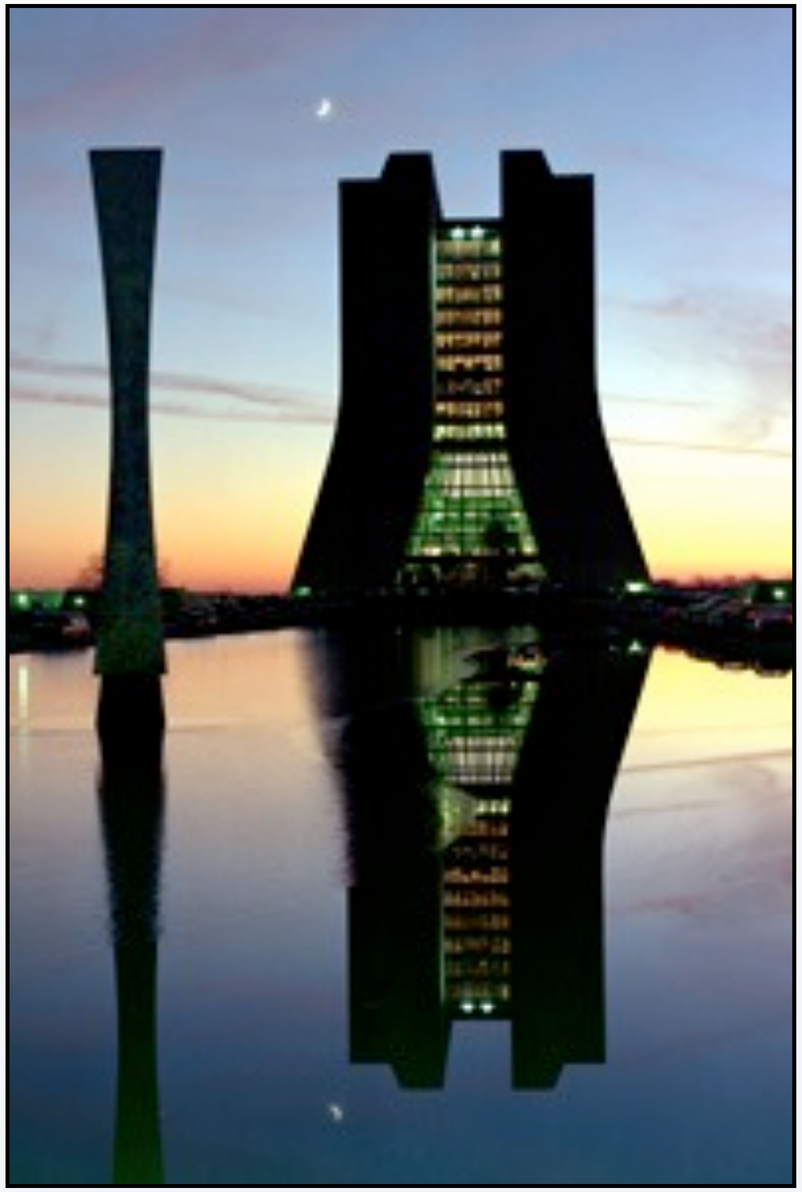
Neutral Current Limits



- At the 90% C.L the MINOS neutral current result excludes sterile mixing for a range of parameters
  - Including the region suggested by the reactor antineutrino anomaly
    - arXiv:1101.2755
  - But not for antineutrino mixing...

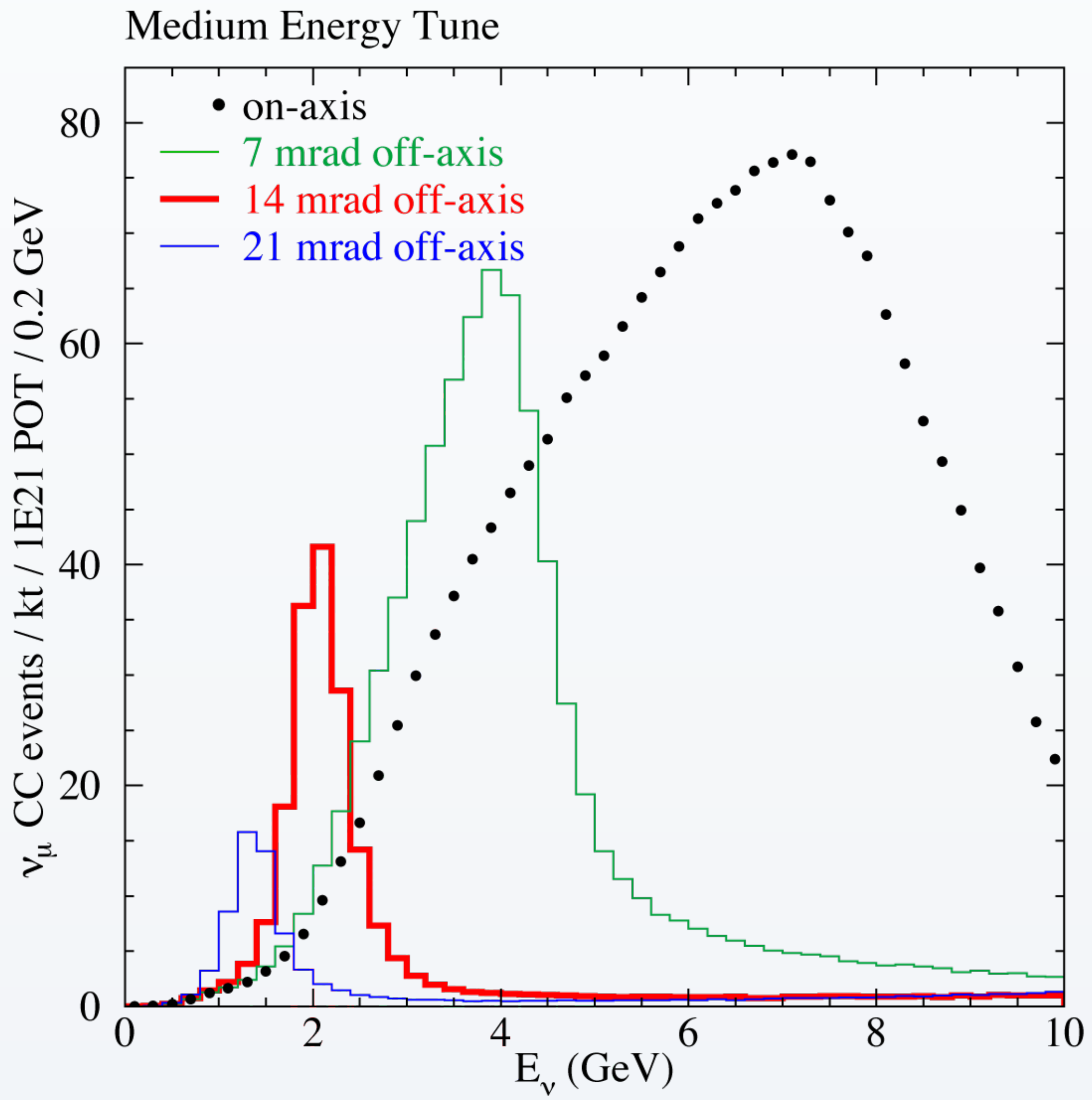
MINOS+

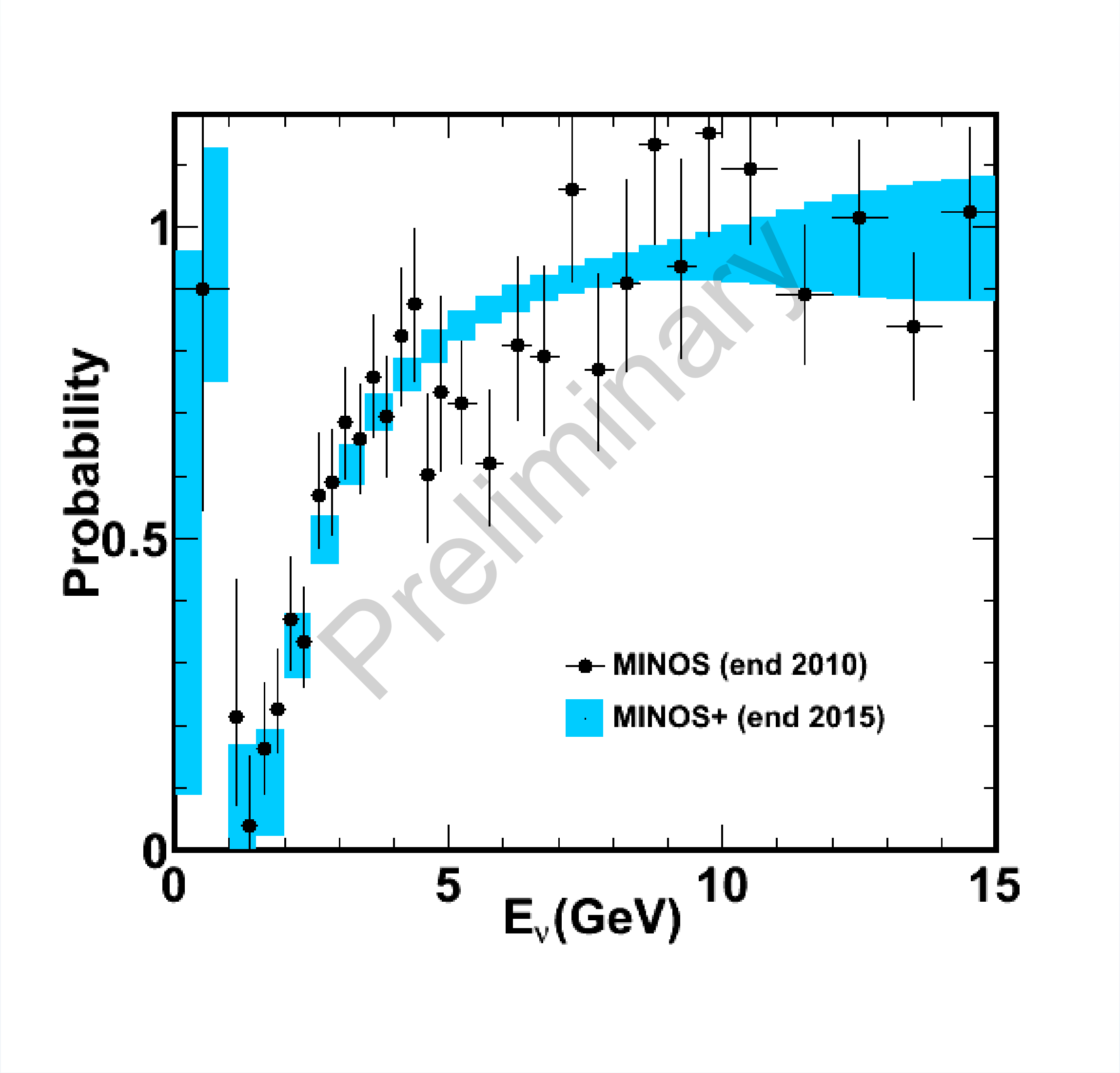
Future prospects for the MINOS experiment in the NoVA era



MINOS+

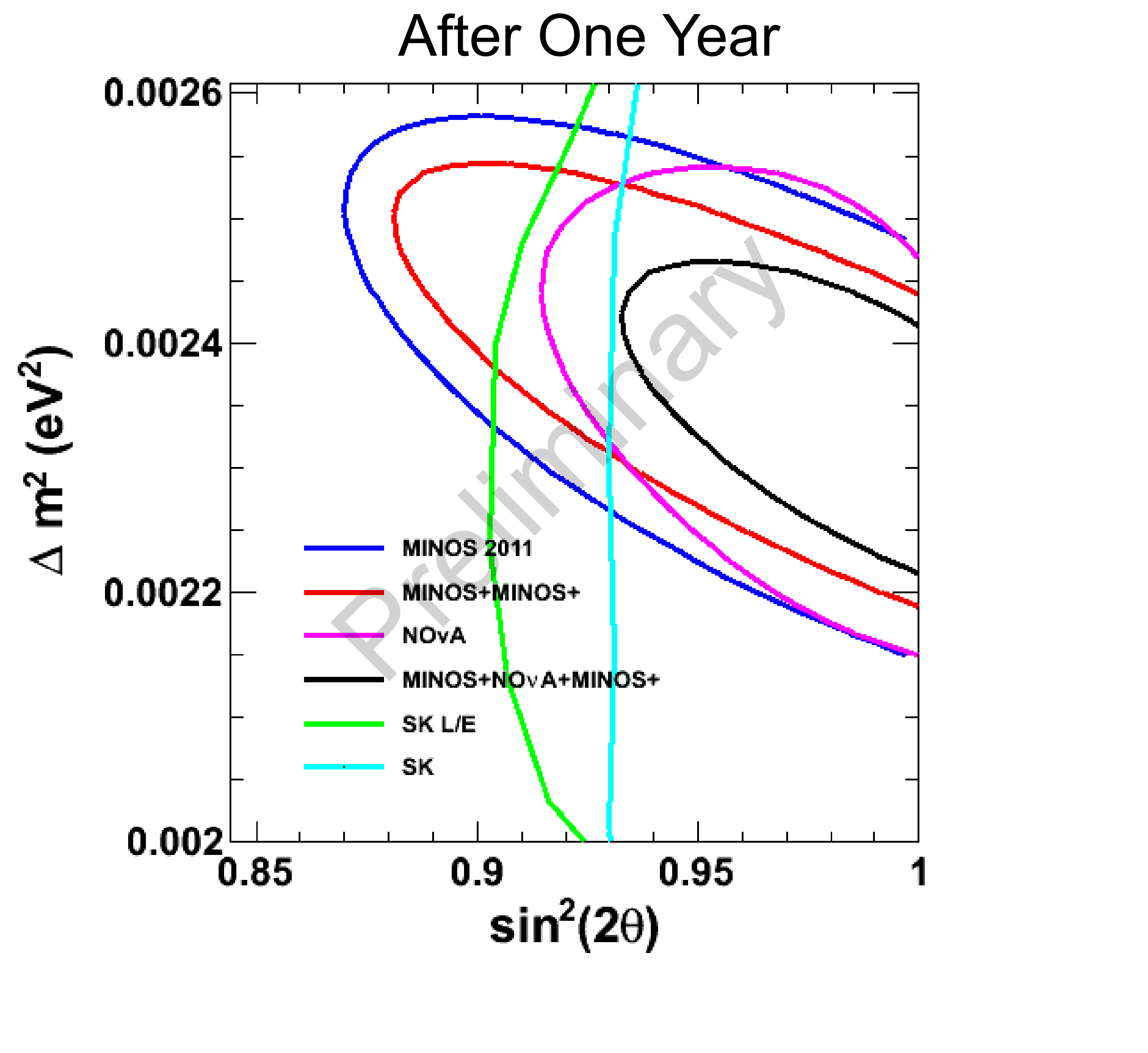
- In January 2013 the NuMI beam is scheduled to switch to medium energy configuration for the NoVA experiment

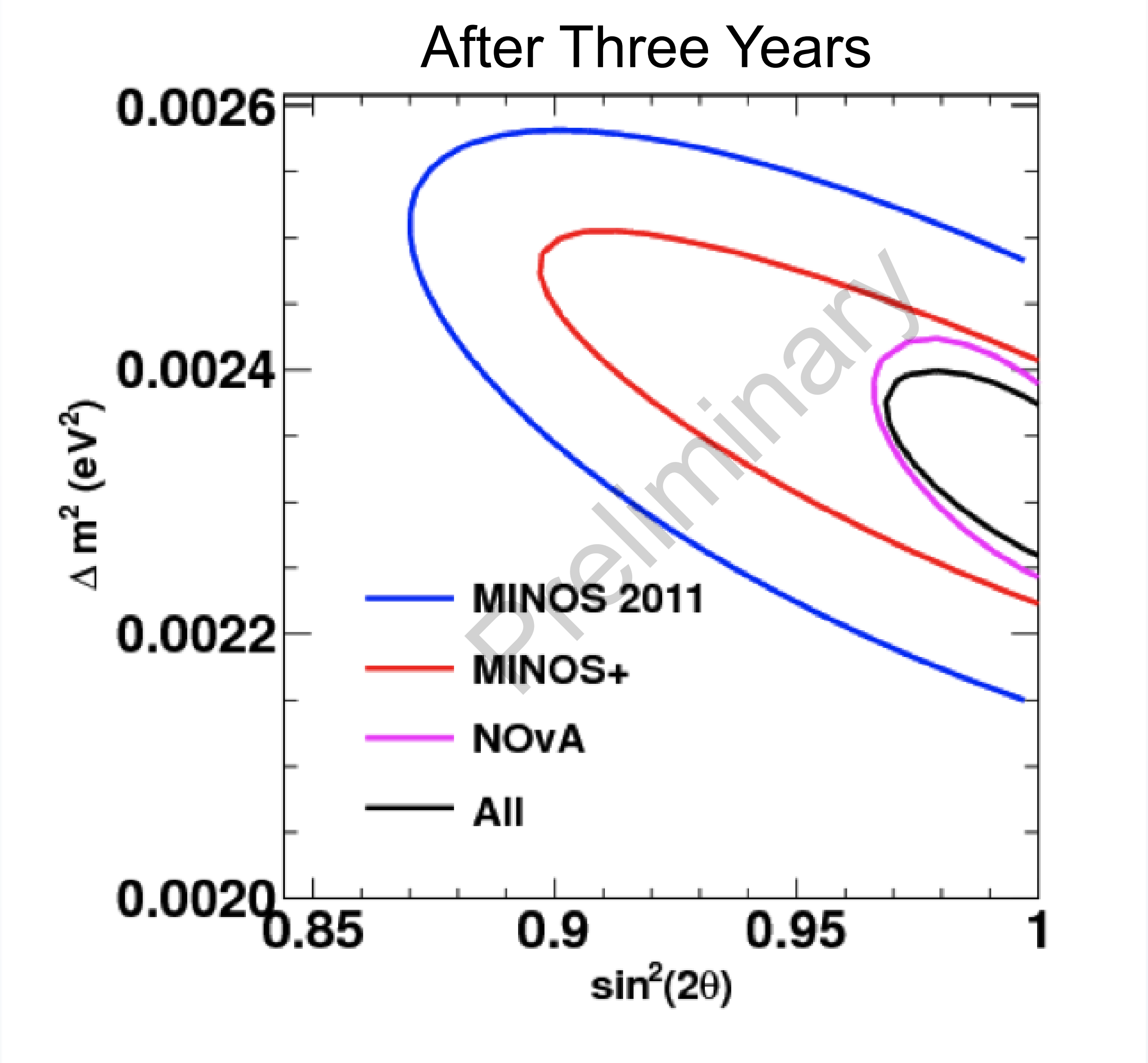




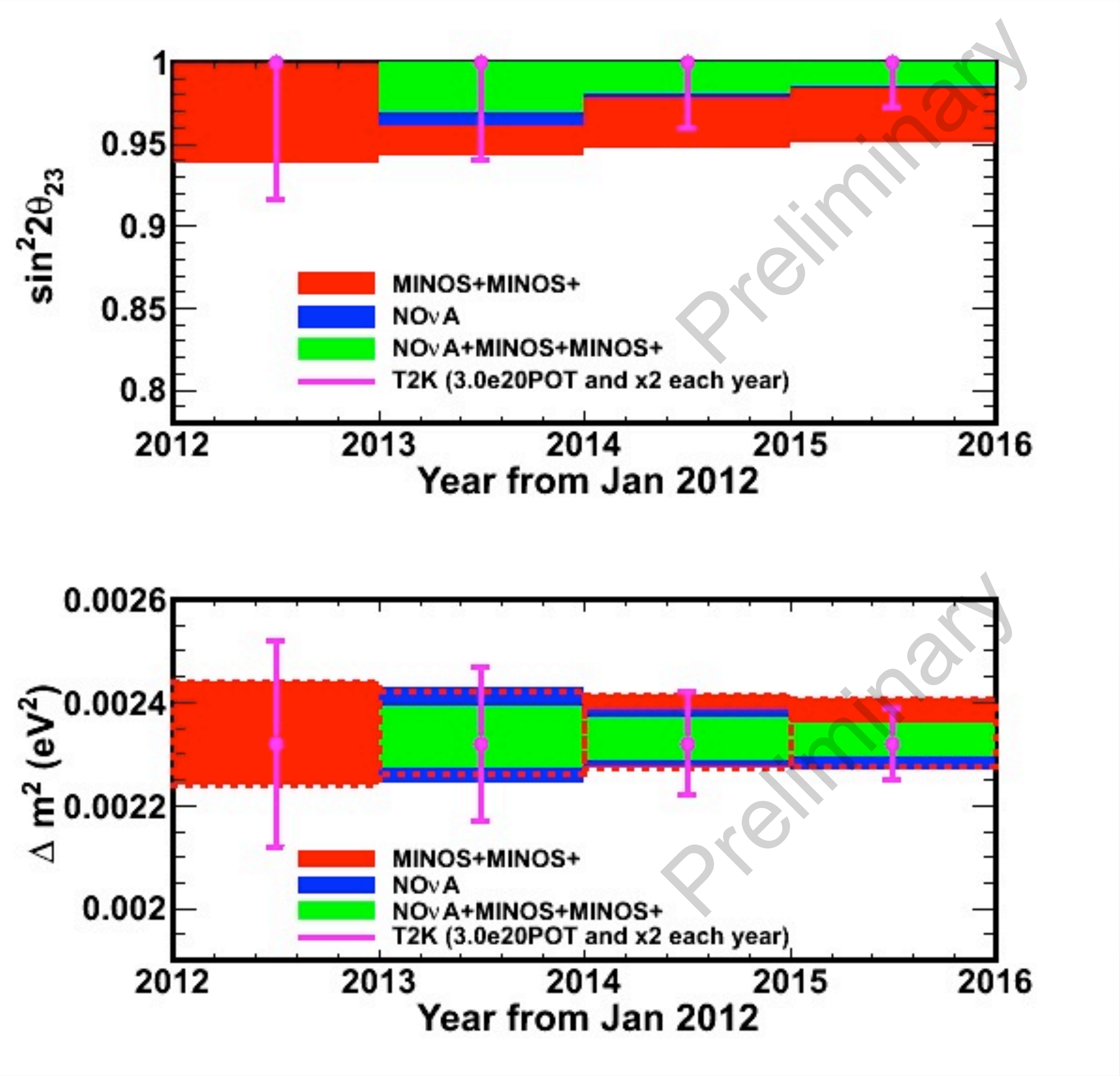
MINOS+ Muon Disappearance Analysis

- For the first two years MINOS+ would contribute to the world's most precise determination of the mass-splitting



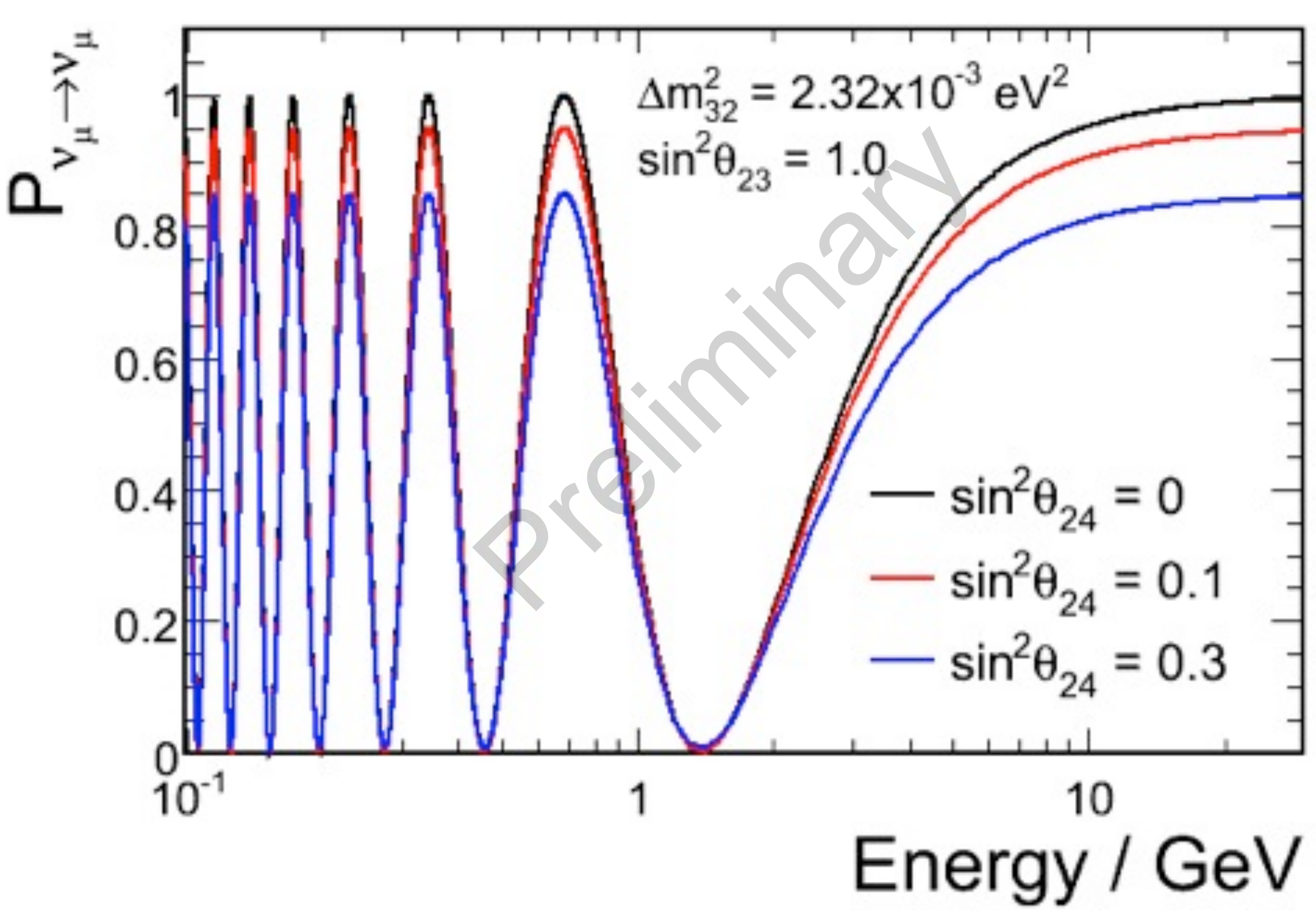


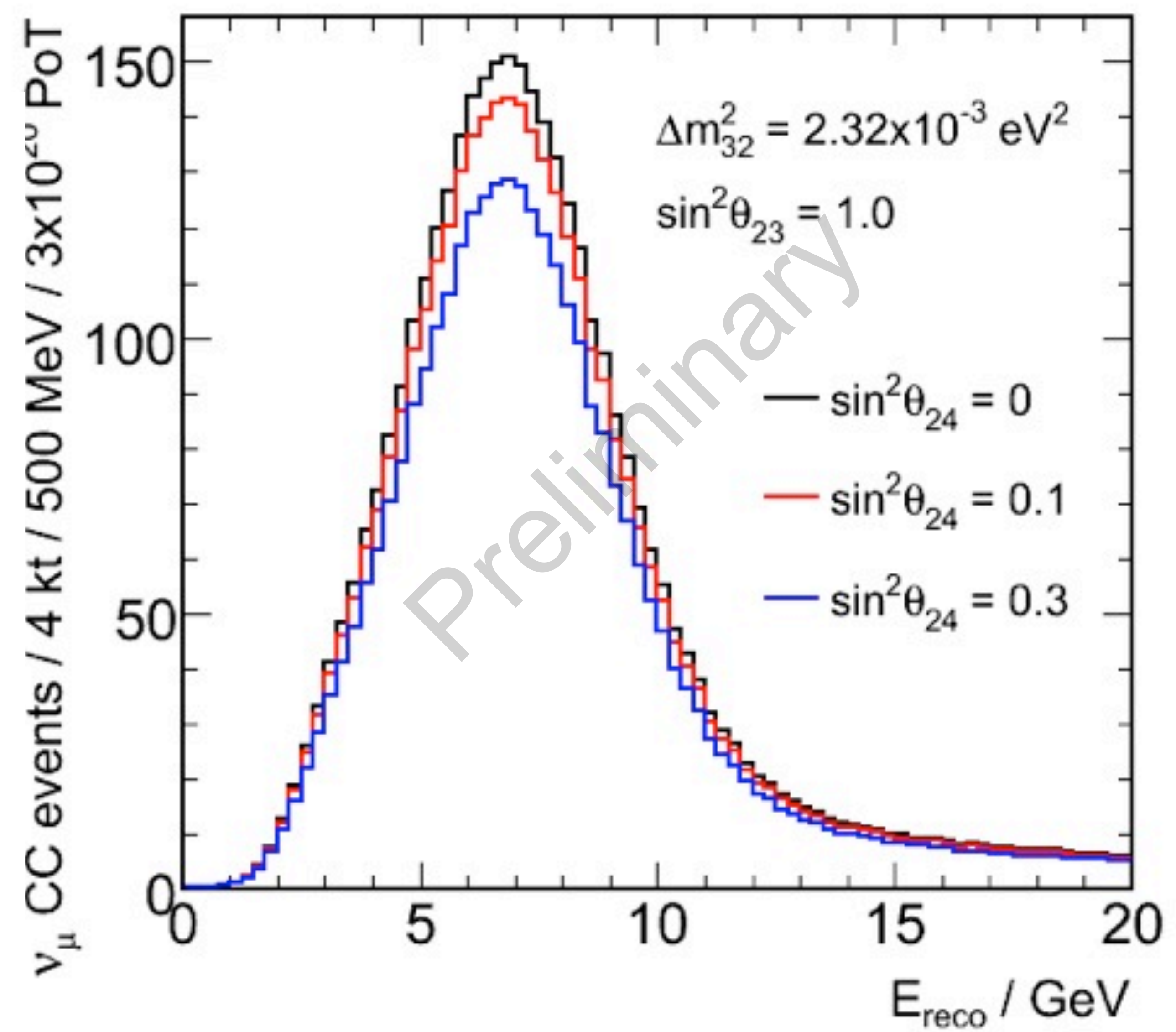
MINOS+ Comparison



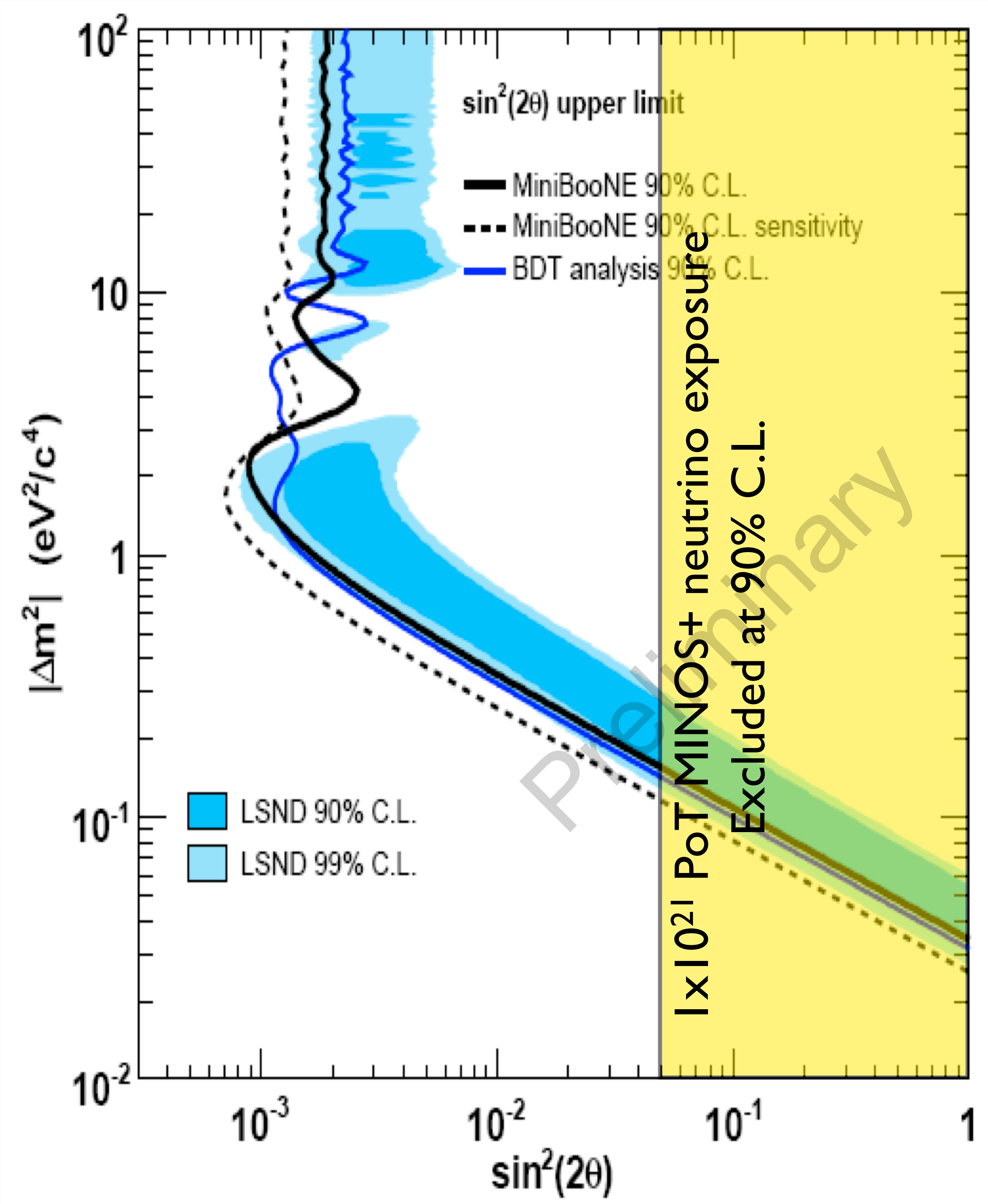
MINOS+ Sterile Neutrinos in the FD

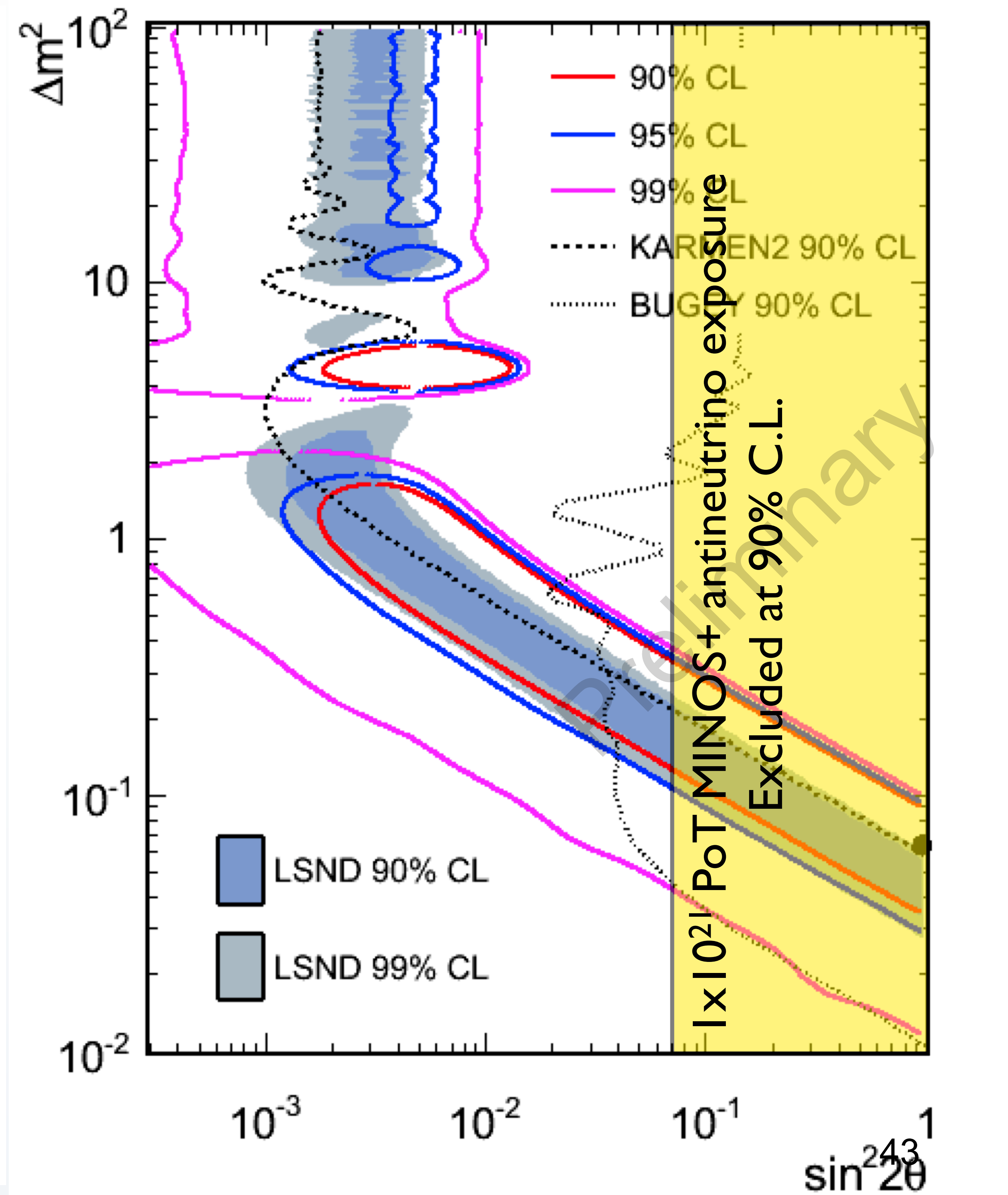
- A large mass scale sterile neutrino would cause a deficit of high energy muon neutrinos at the Far Detector





MINOS+ Sterile Neutrinos in the FD

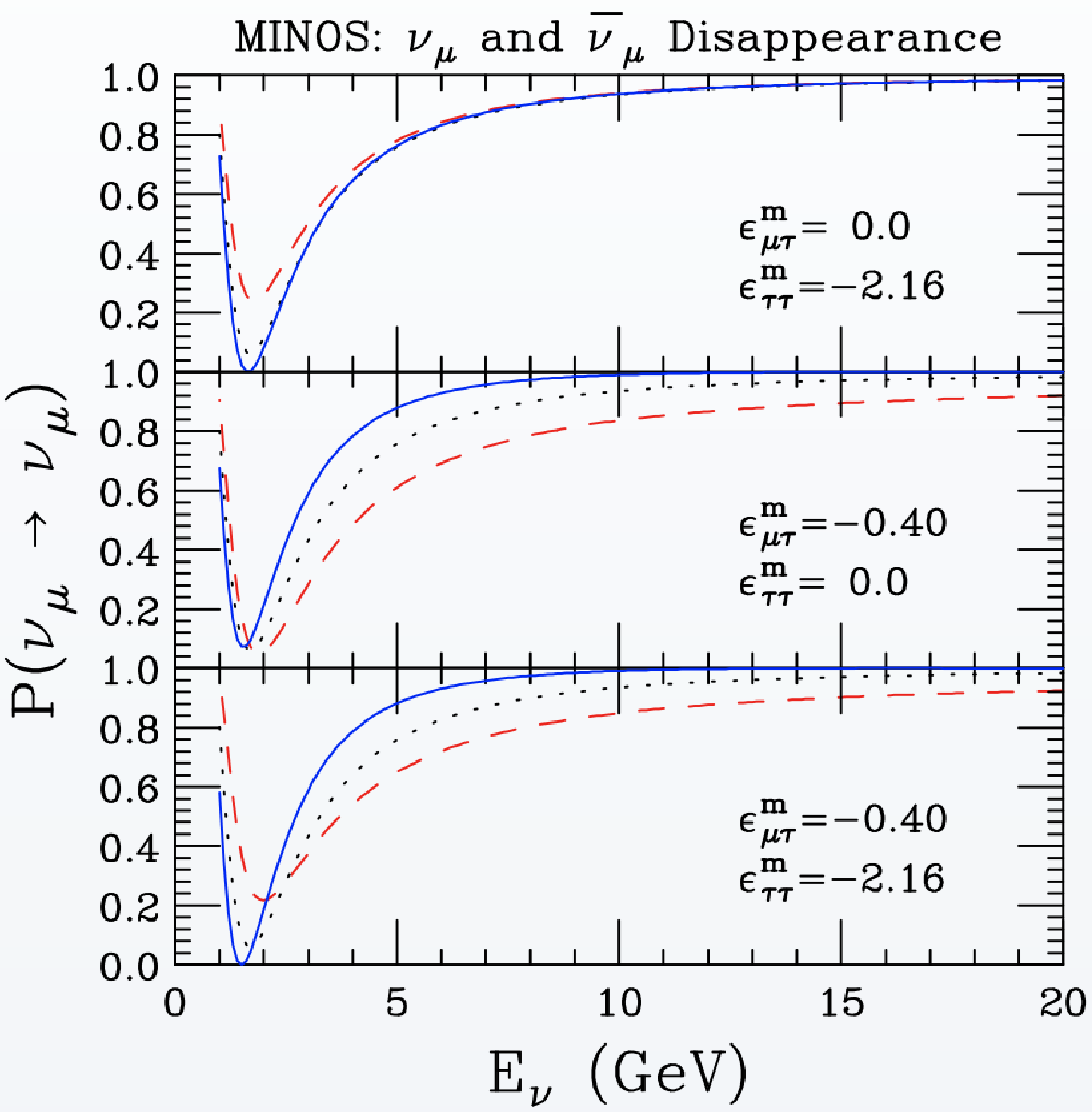




MINOS+ Sterile Neutrinos in the ND

- The MINOS Near Detector is sensitive to oscillations with large mass splitting (above 1eV^2)
  - However single detector measurements are much more difficult.
    - Such experiments have greater exposure to systematic uncertainties in beam and cross-section
  - With MINOS+ these could be partially mitigated by comparing neutrino mode to antineutrino mode beam
    - Assuming the sterile coupling is different between neutrinos and antineutrinos

MINOS+ Exotic Models

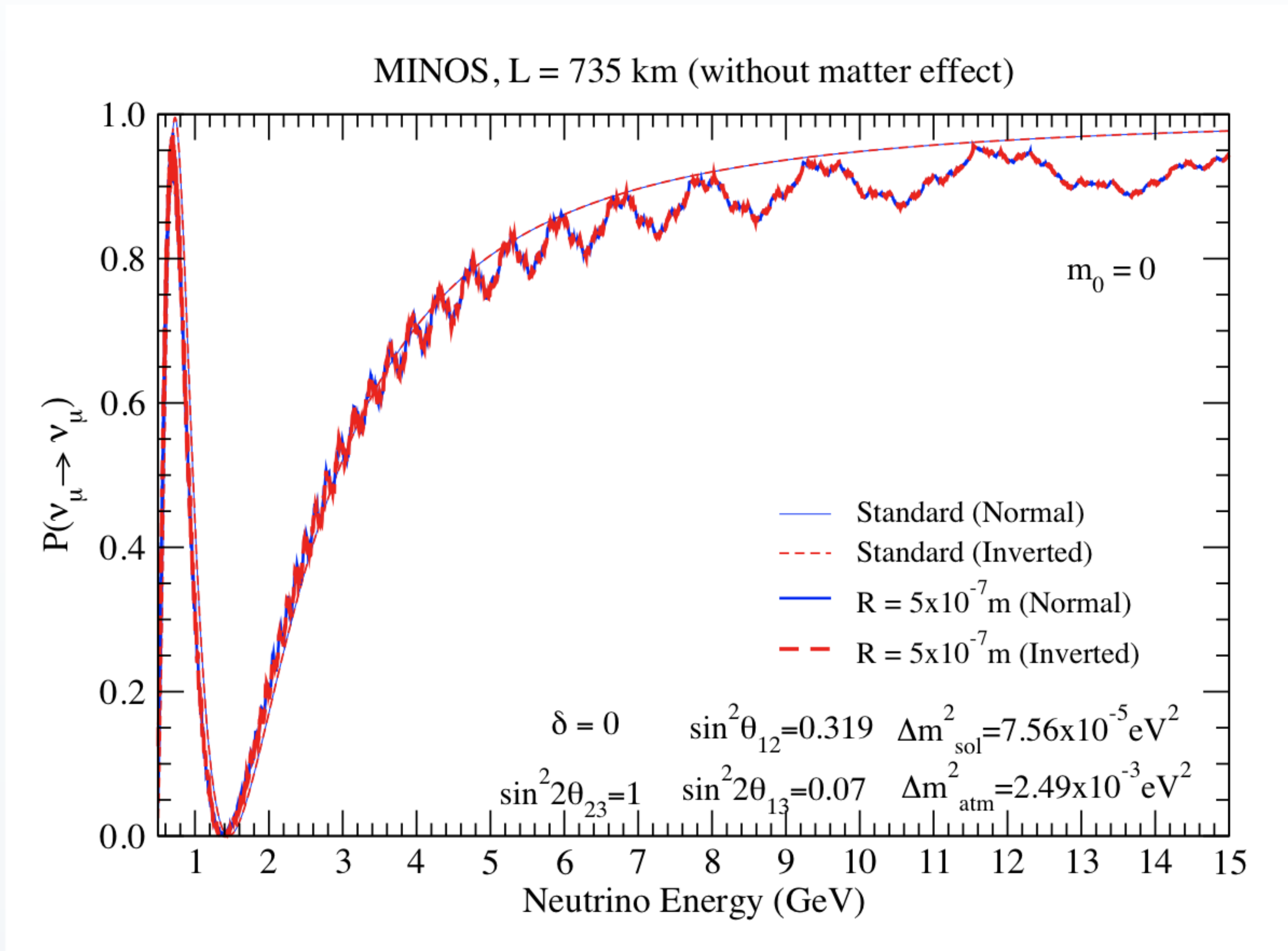


- Non-standard interactions with matter can introduce differences between the observed neutrino and antineutrino mixing
- MINOS+ can probe this with unprecedented precision at higher energies

Model from J. Kopp, P.A.N. Machado and S.Parke, Phys.Rev.D82:113002,2010

MINOS+ Exotic Models

- Some exotic models predict a modulation of the oscillation probability at the Far Detector



arXiv.org > hep-ph > arXiv:1101.1686

High Energy Physics – Phenomenology

Probing Extra Dimensions with Neutrino Oscillations

P. A. N. Machado, H. Nunokawa, R. Zukanovich Funchal

(Submitted on 9 Jan 2011)

MINOS+ Summary

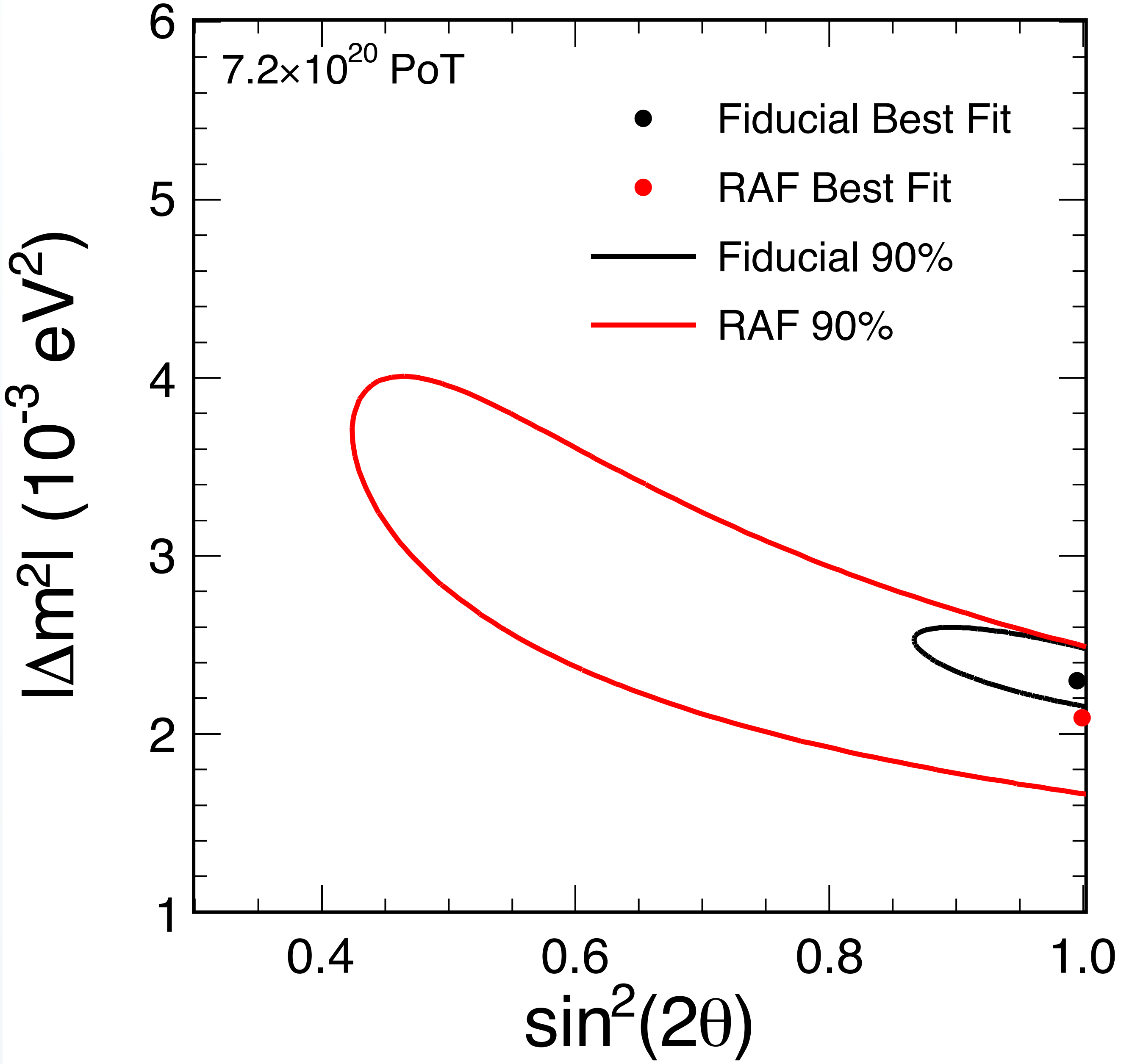
- The NuMI upgrade to a medium energy high intensity neutrino beam for NoVA that is aimed directly at the MINOS Far Detector
  - This presents MINOS with the opportunity to really make precision measurements of the Far Detector energy spectrum and survival probability
  - New physics from sterile neutrinos to non-standard interactions to large extra dimensions, predict a measurable distortion in the neutrino energy spectrum as measured at the Far Detector
  - Most of these effects would not be easily distinguishable at the narrow-band off-axis experiments (i.e. NoVA and T2K)

Conclusion

- The MINOS experiment is one of the world's leading neutrino oscillation experiment
  - We have made some of world's best measurements in the atmospheric, sterile, "unknown" and antineutrino sectorsInteresting tension between neutrino and antineutrino oscillation measurements
- New results expected this year
  - Improved electron appearance analysis
  - Muon antineutrino analysis
- MINOS+
  - There are compelling reasons to continue running the MINOS experiment in the NoVA beam

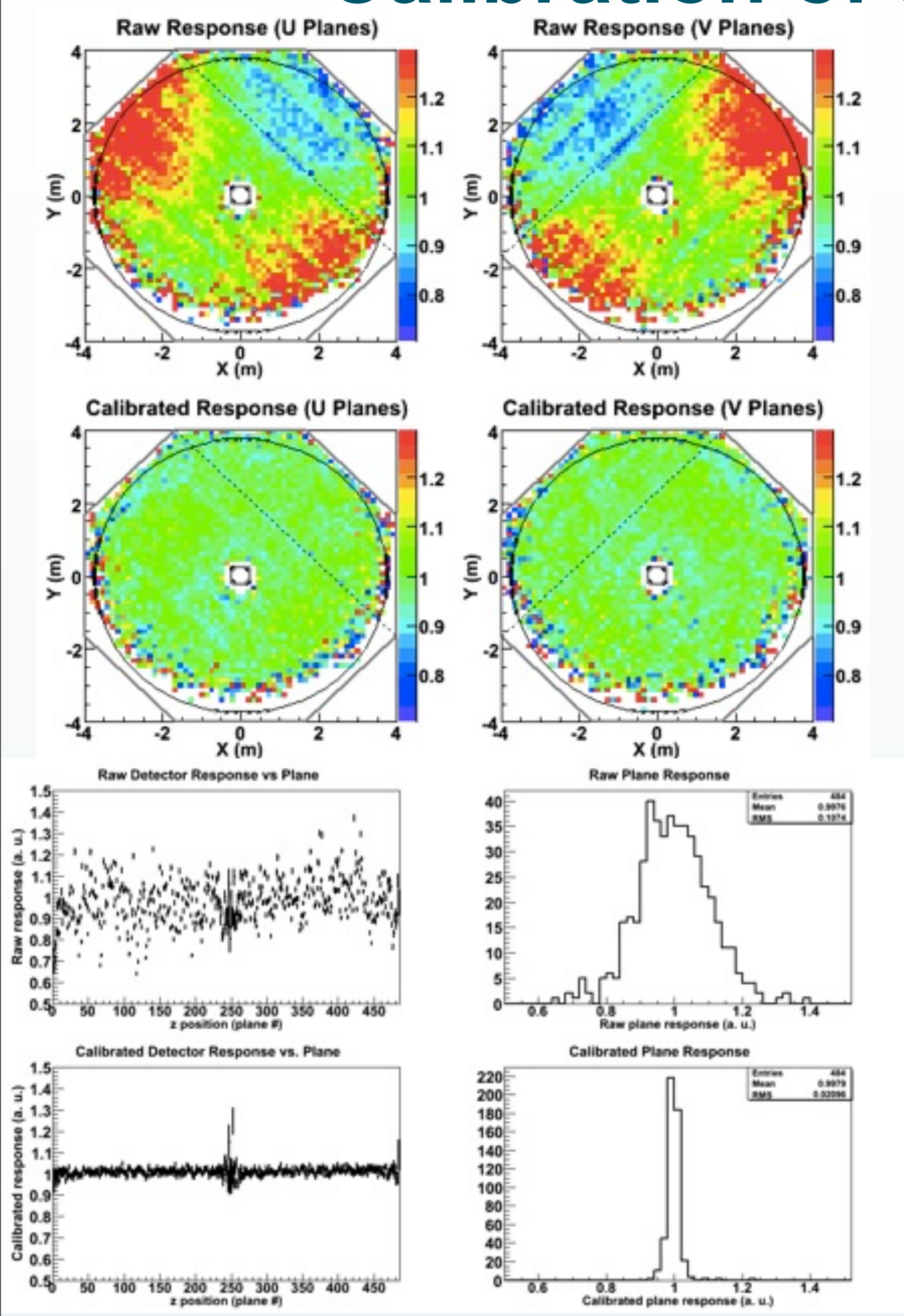
Backup Slides

Rock and Anti-Fiducial Events

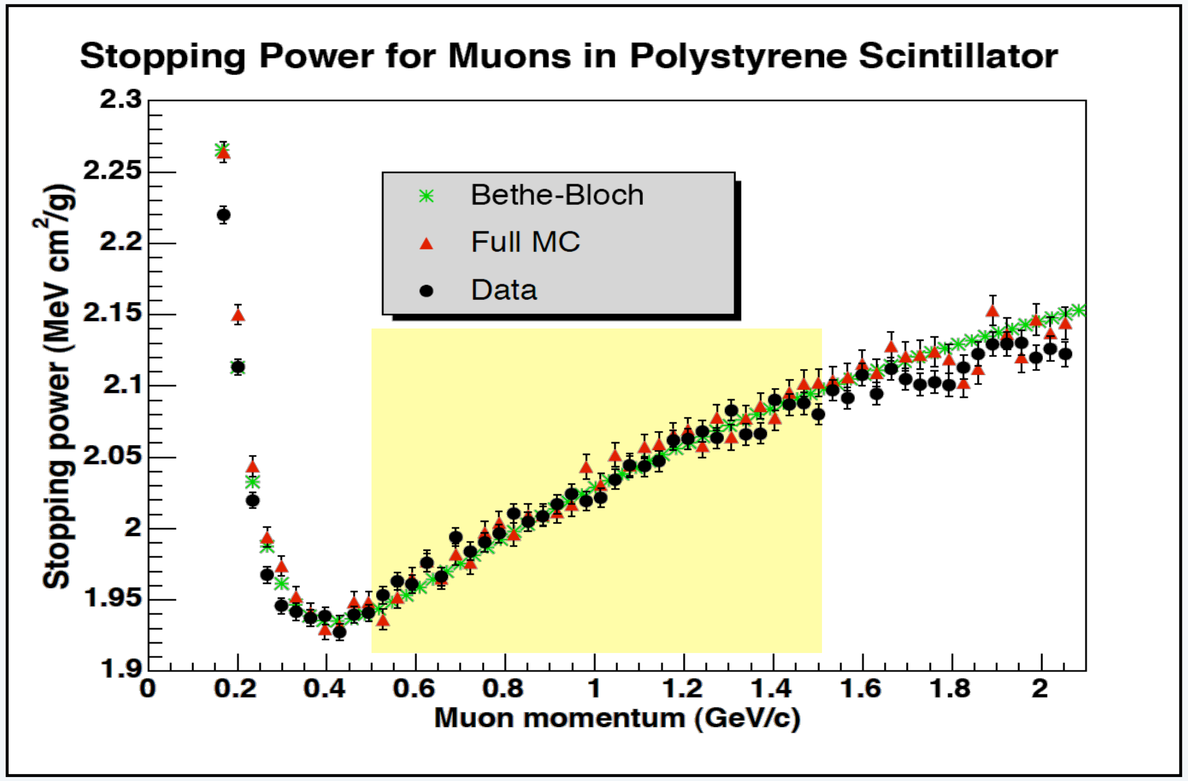


Calibration of the MINOS Detectors

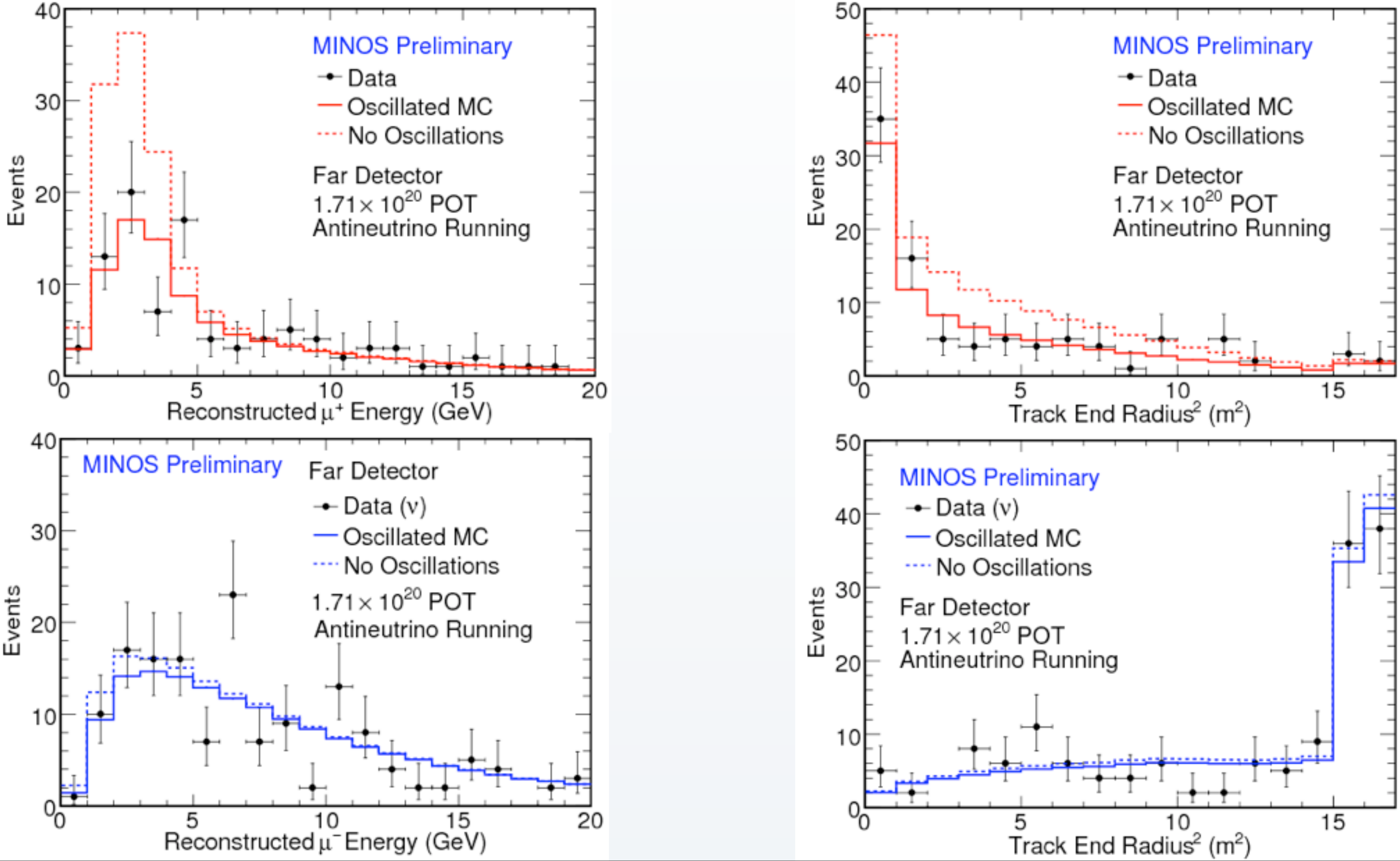
Incidentally, the title of my thesis



- Light-Injection System (PMT gain + linearity)
- Cosmic Ray Muons (spatial and temporal variations)
- Stopping Muons (detector-to-detector energy scale)
- Calibration Detector (overall energy scale)

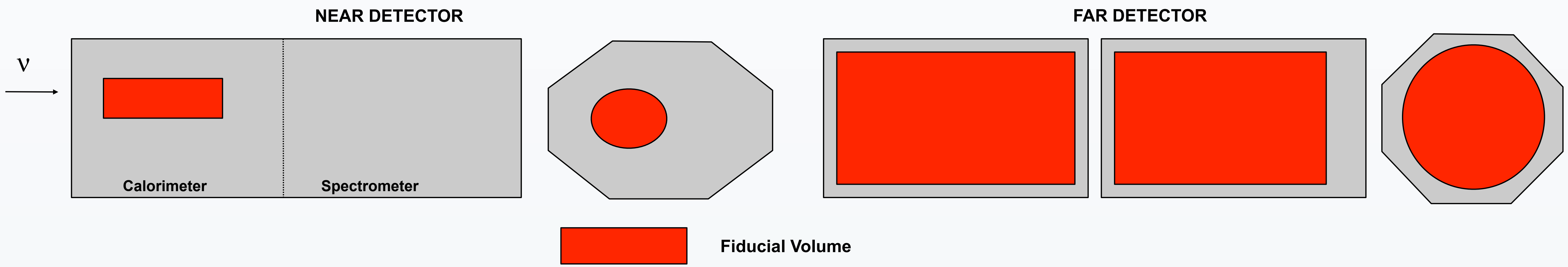


FD Data


MINOS Preliminary
Data
Oscillated MC
No Oscillations
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Reconstructed μ+ Energy (GeV)
Track End Radius² (m²)
MINOS Preliminary
Far Detector
Data (ν)
Oscillated MC
No Oscillations
1.71× 10^20 POT
Antineutrino Running
Reconstructed μ− Energy (GeV)

CC Event Pre-Selection

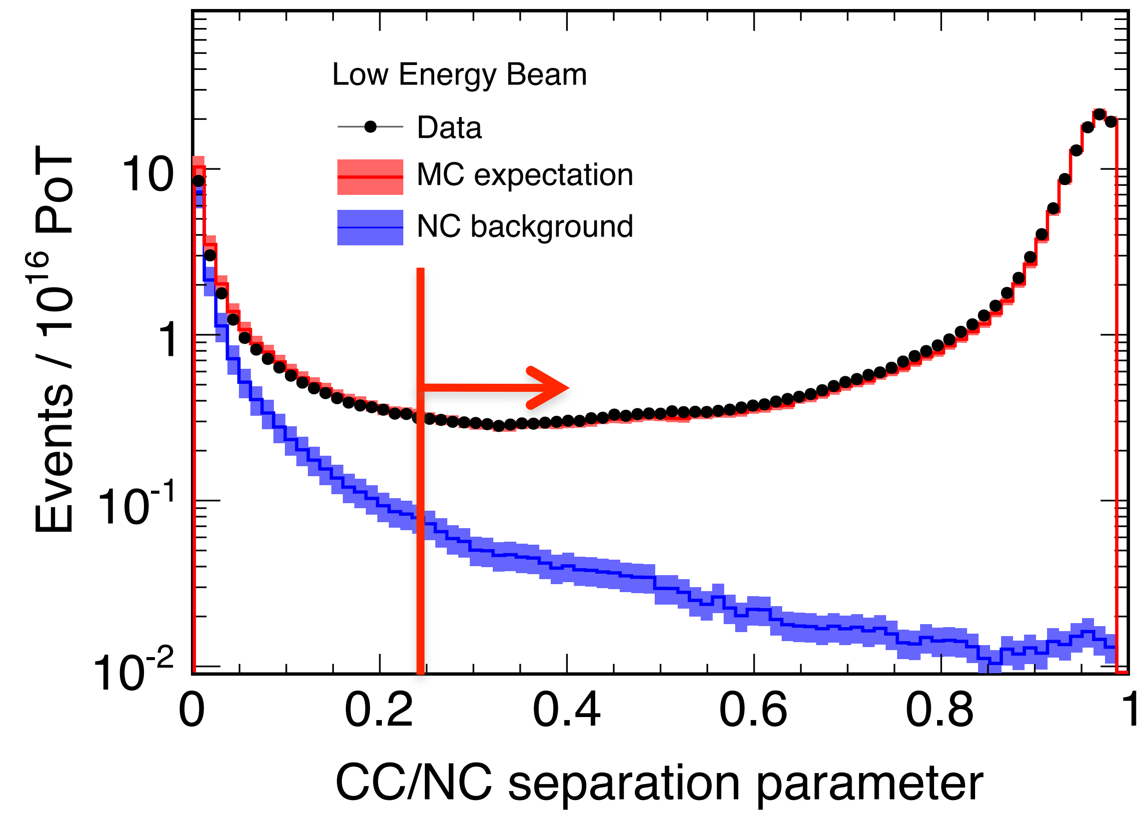
- To select ν_μ require:
  - At least one track per event
  - Reconstructed event vertex in the fiducial volume

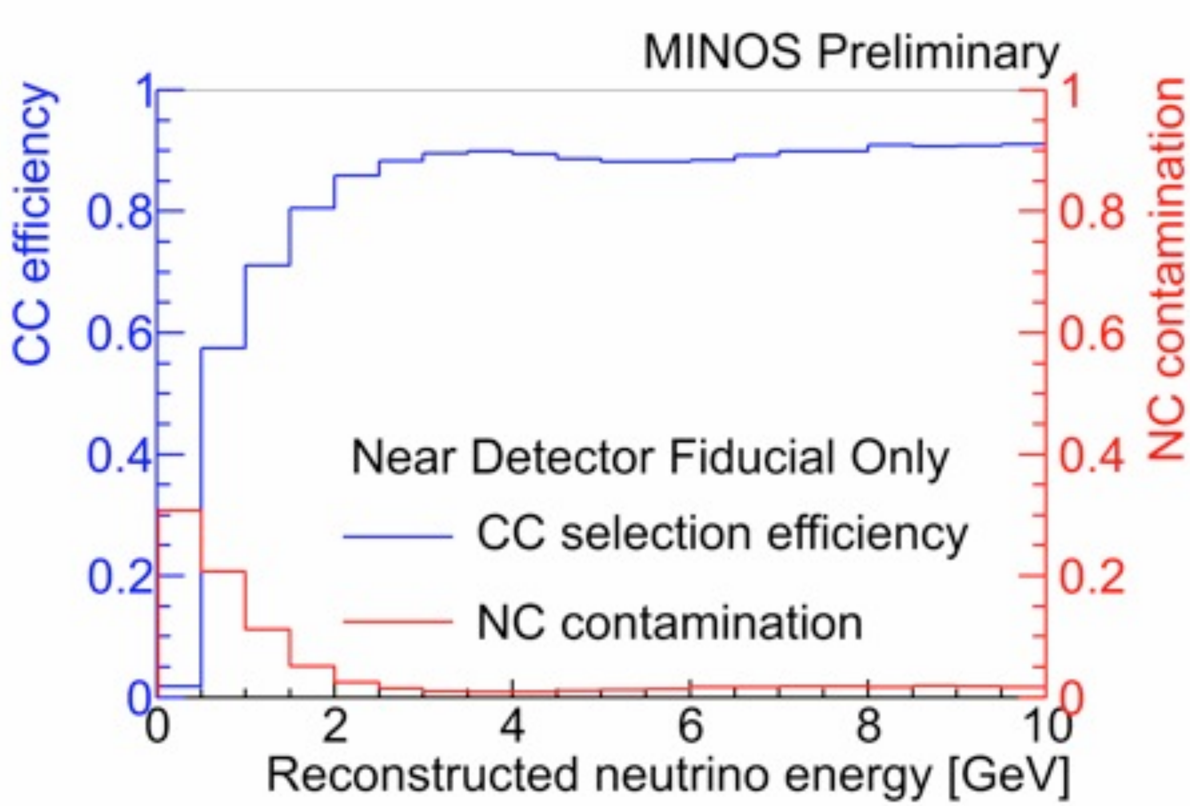


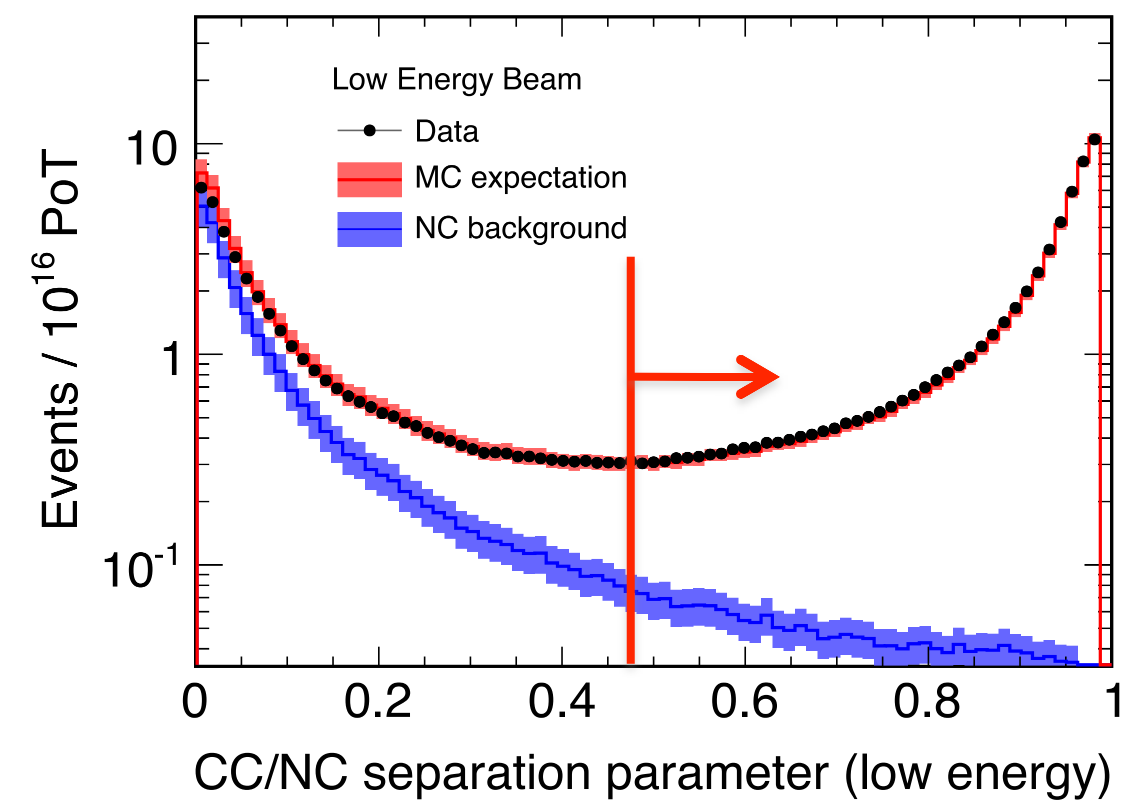
  - Coil hole cut
    - To exclude poorly reconstructed events
  - The fitted track curvature should have negative charge
    - To select only ν_μ events

CC Event Selection

- Use kNN to separate NC background
  - Improvement in efficiency over the 2008 analysis
  - Monte carlo and data in

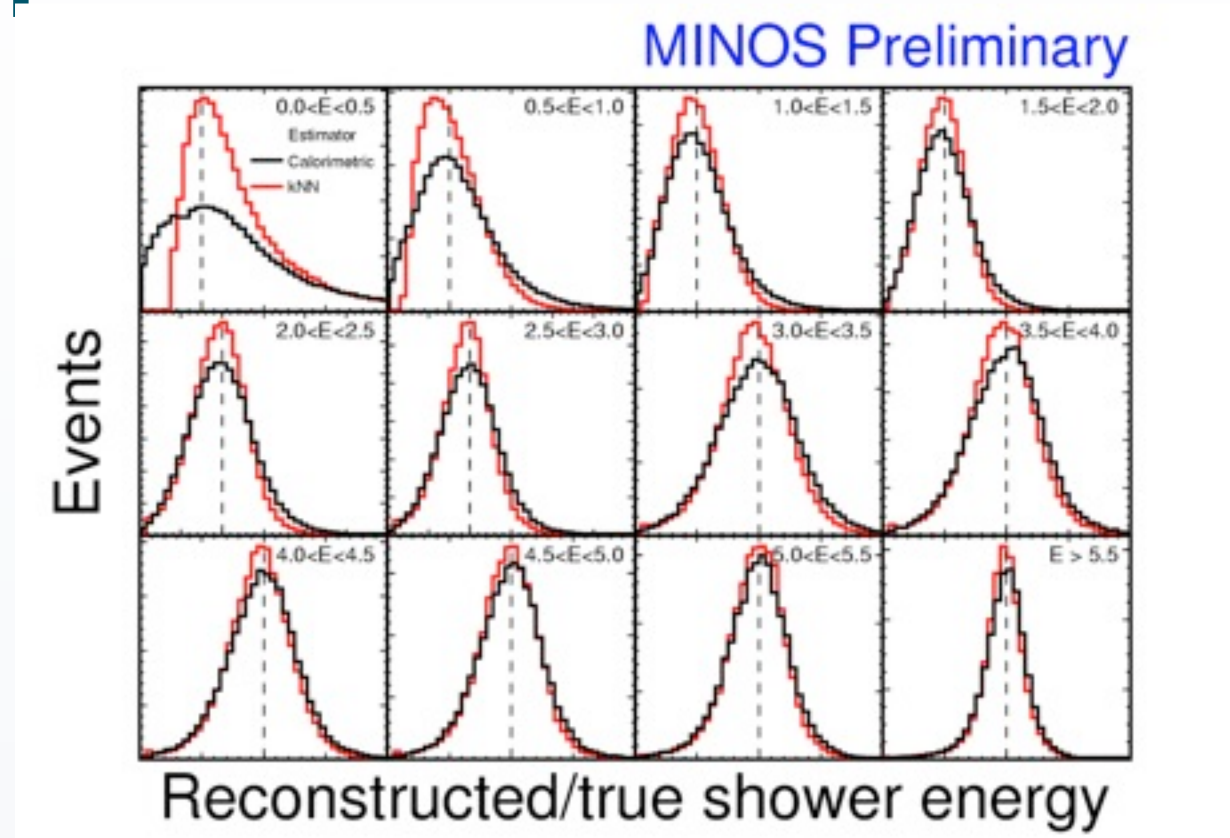


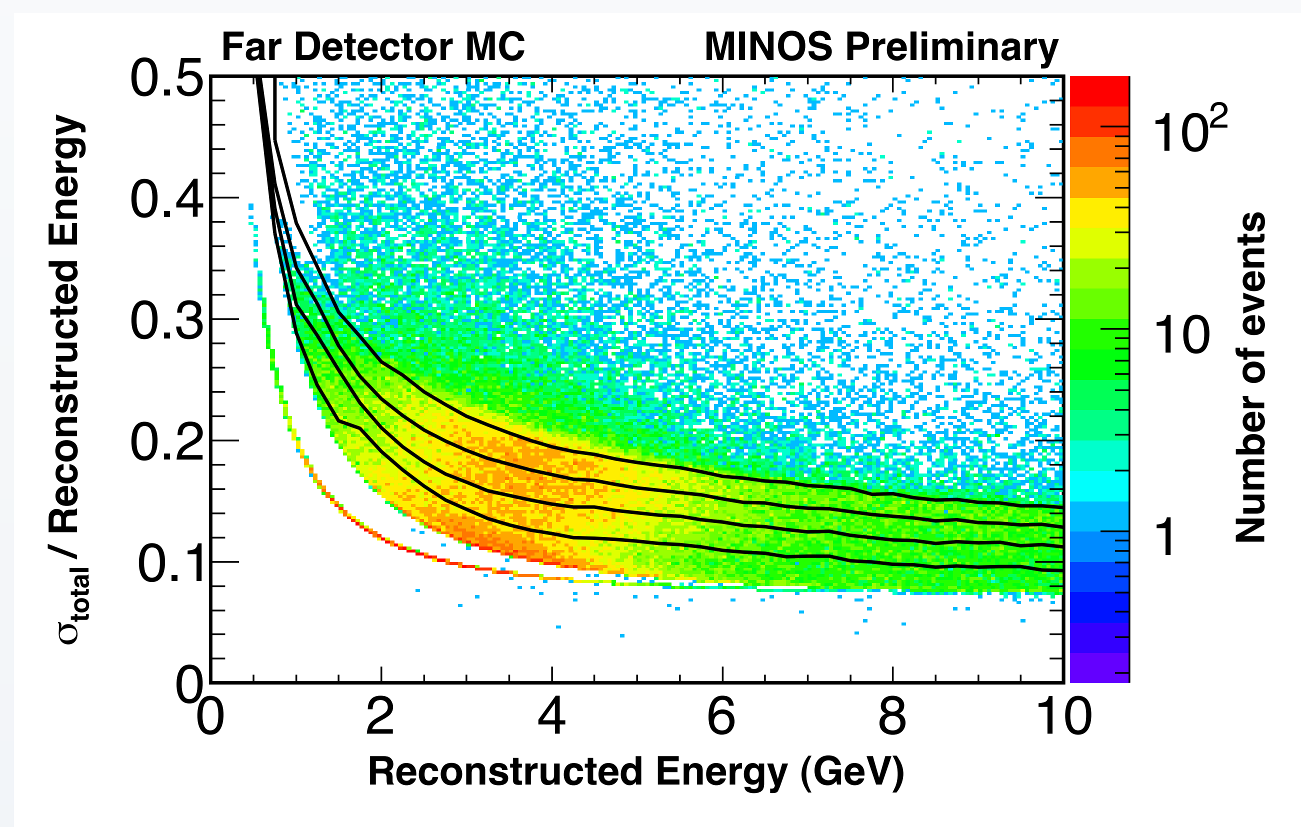




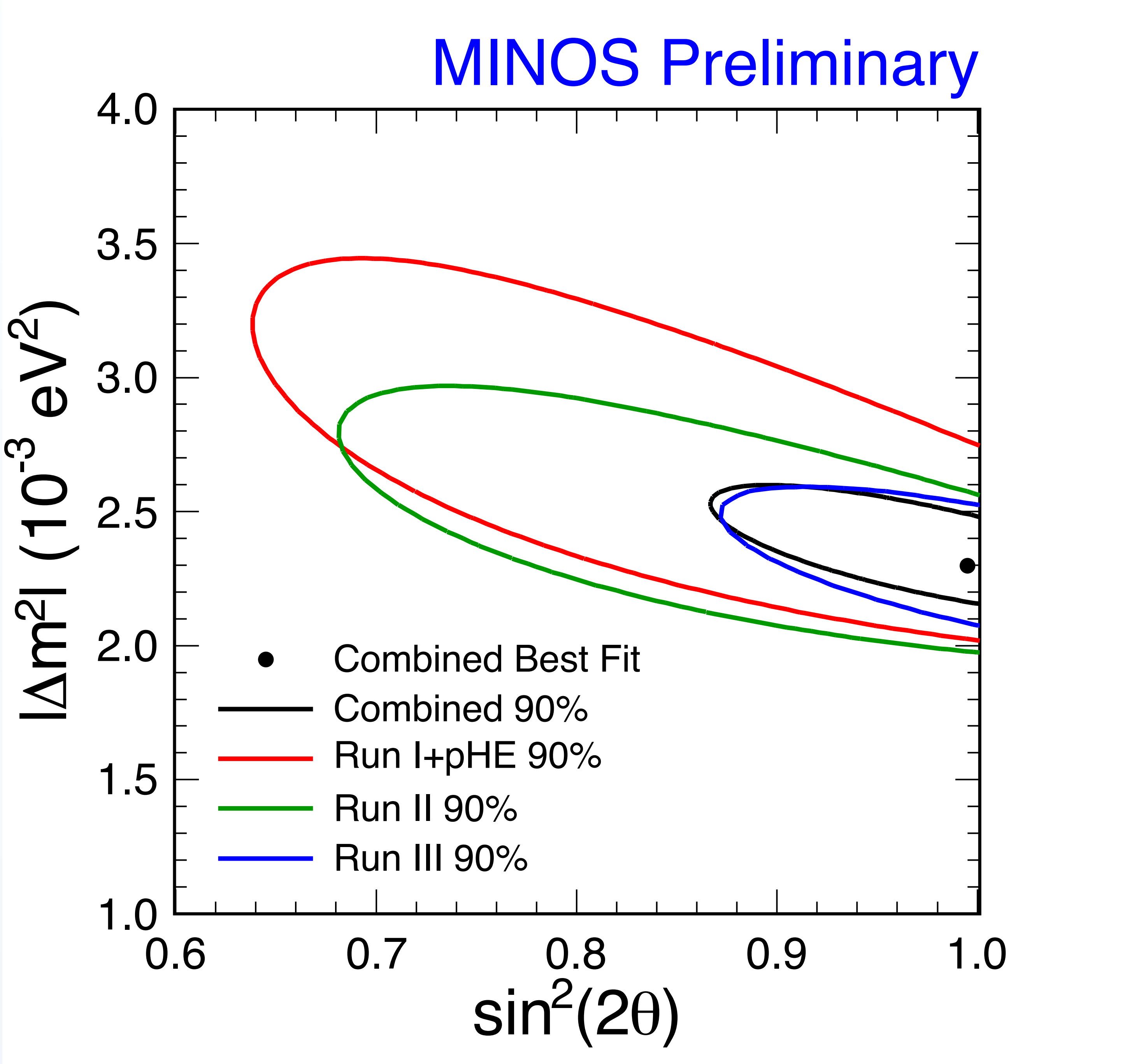
Analysis Improvements

- Since PRL 101:131802, 2008
- Additional data
  - $3.4 \times 10^{20} \rightarrow 7.2 \times 10^{20}$ POT
- Analysis improvements
  - updated reconstruction and simulation
  - new selection with increased efficiency
  - no charge sign cut
  - improved shower energy resolution
  - separate fits in bins of energy resolution
  - smaller systematic uncertainties



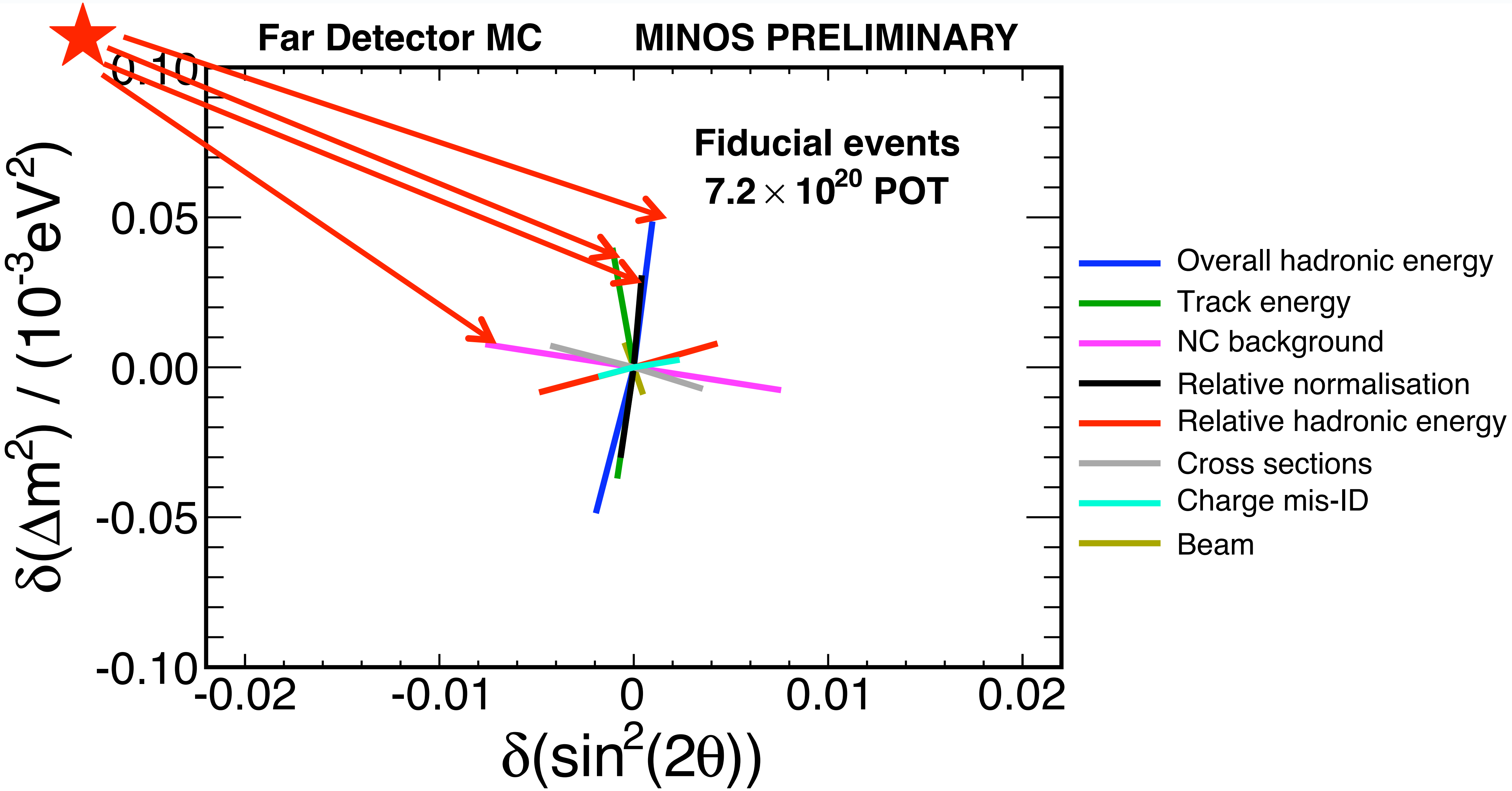


MINOS Runs Consistency Check



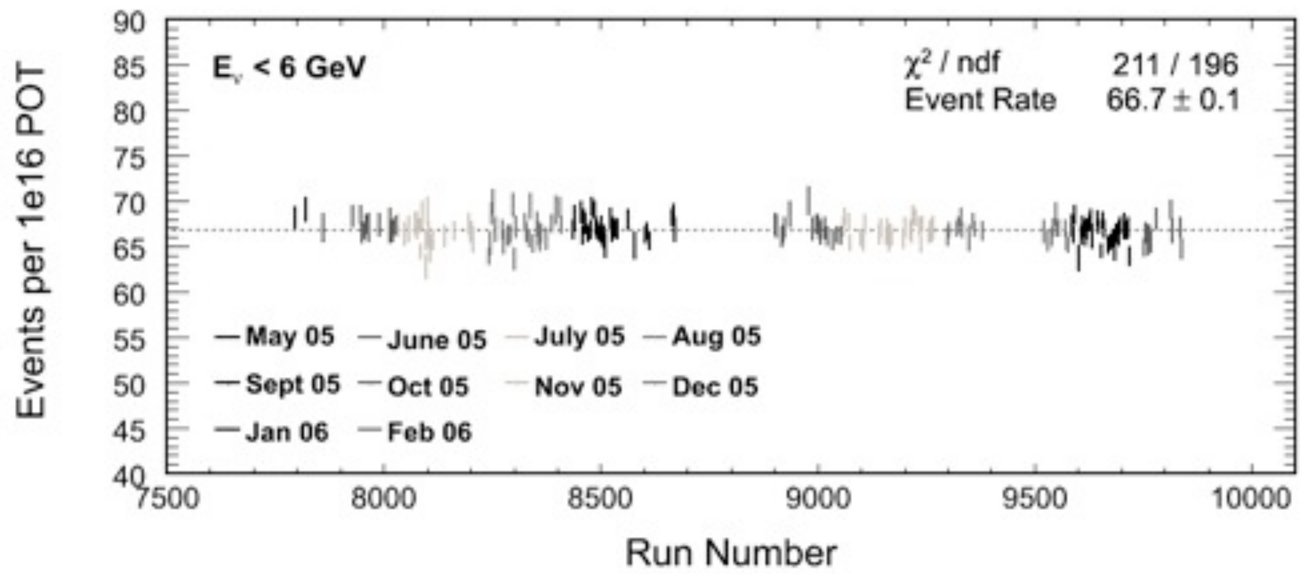
Systematic Uncertainties

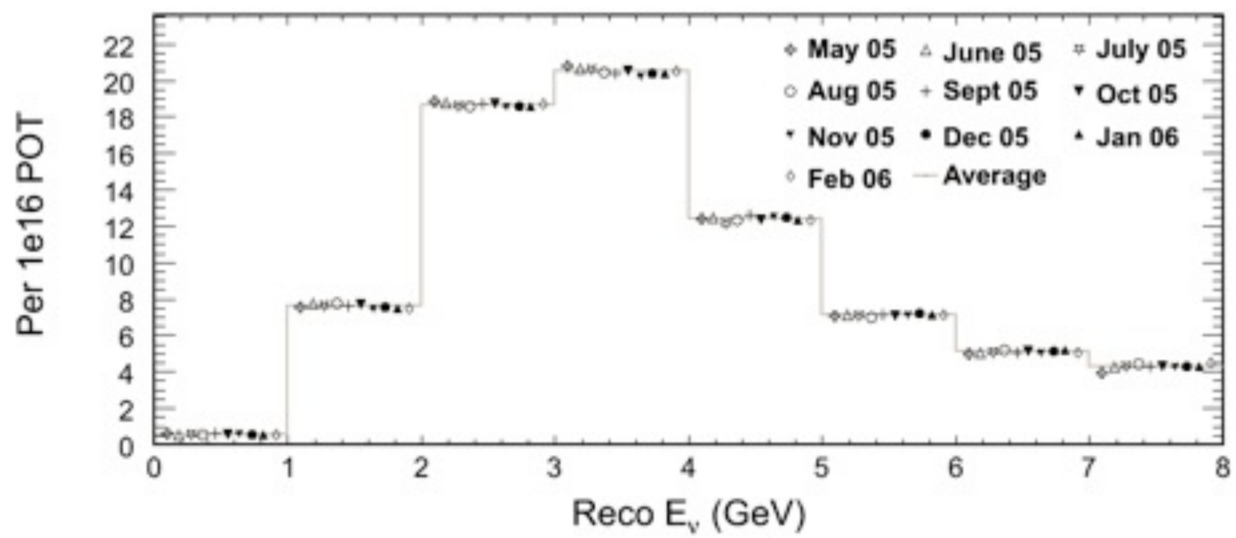
- Evaluated effect of systematic uncertainties by fitting modified MC in place of the data

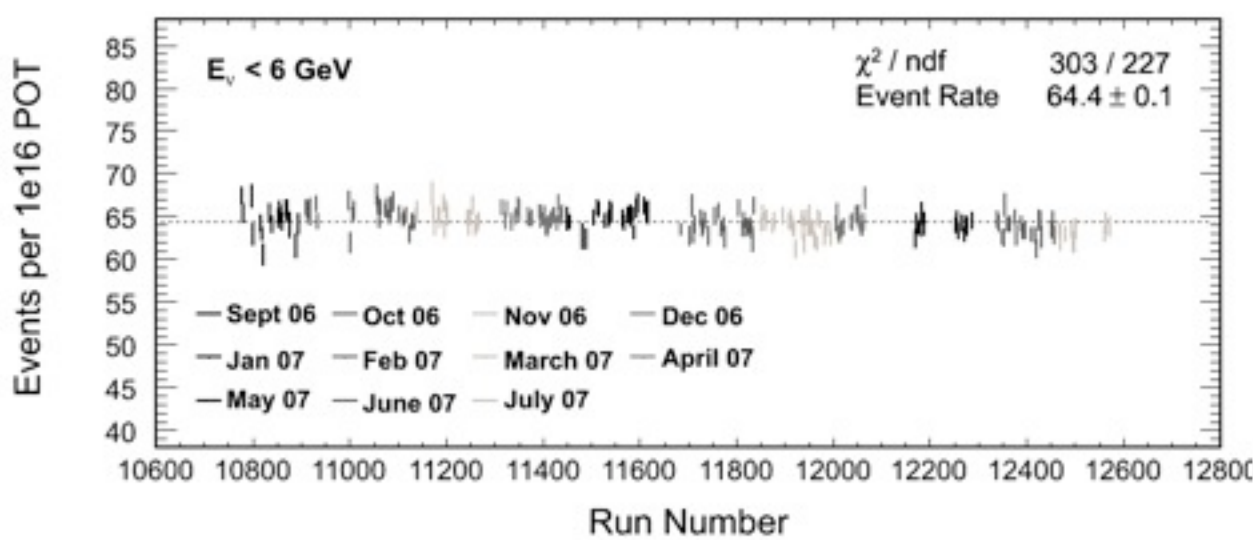


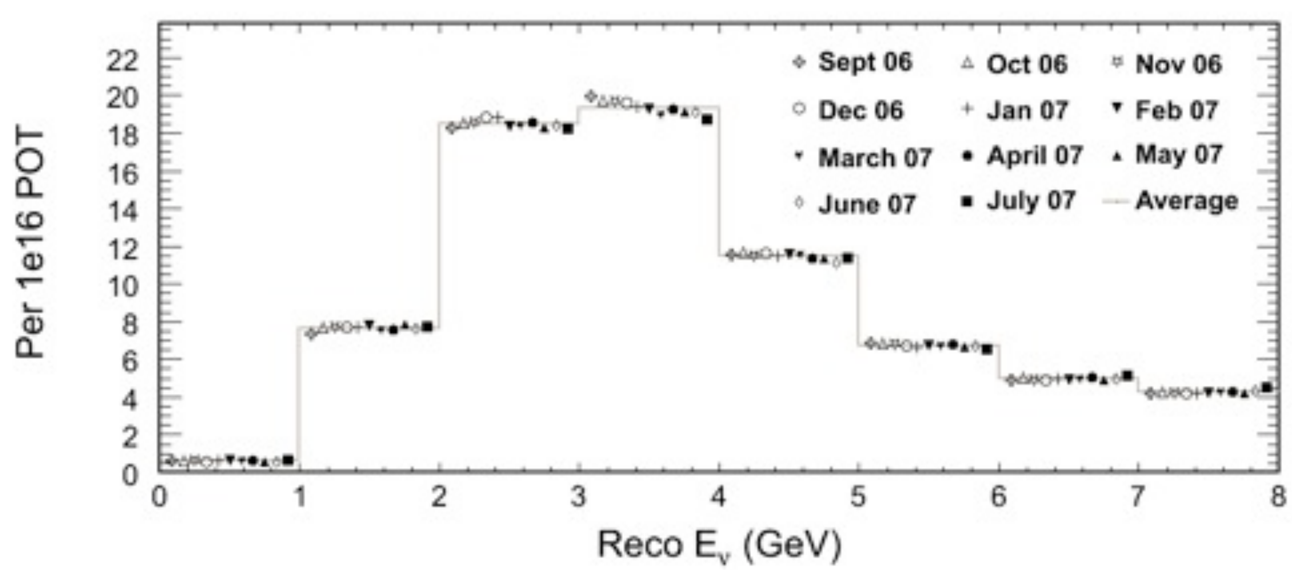
★ *The four largest will be included as nuisance parameters in the oscillation fit.*

Event Rate/Spectrum Stability



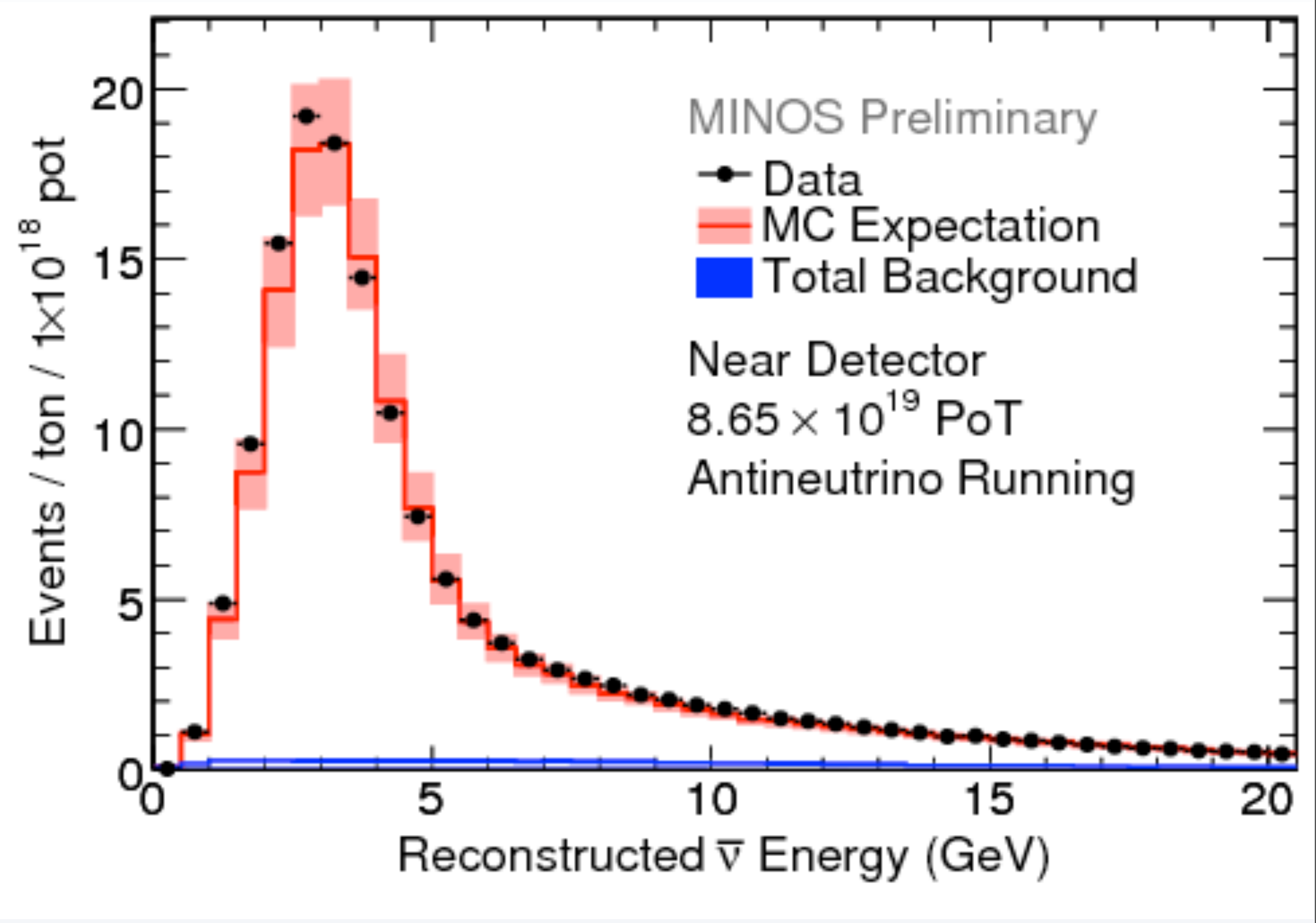




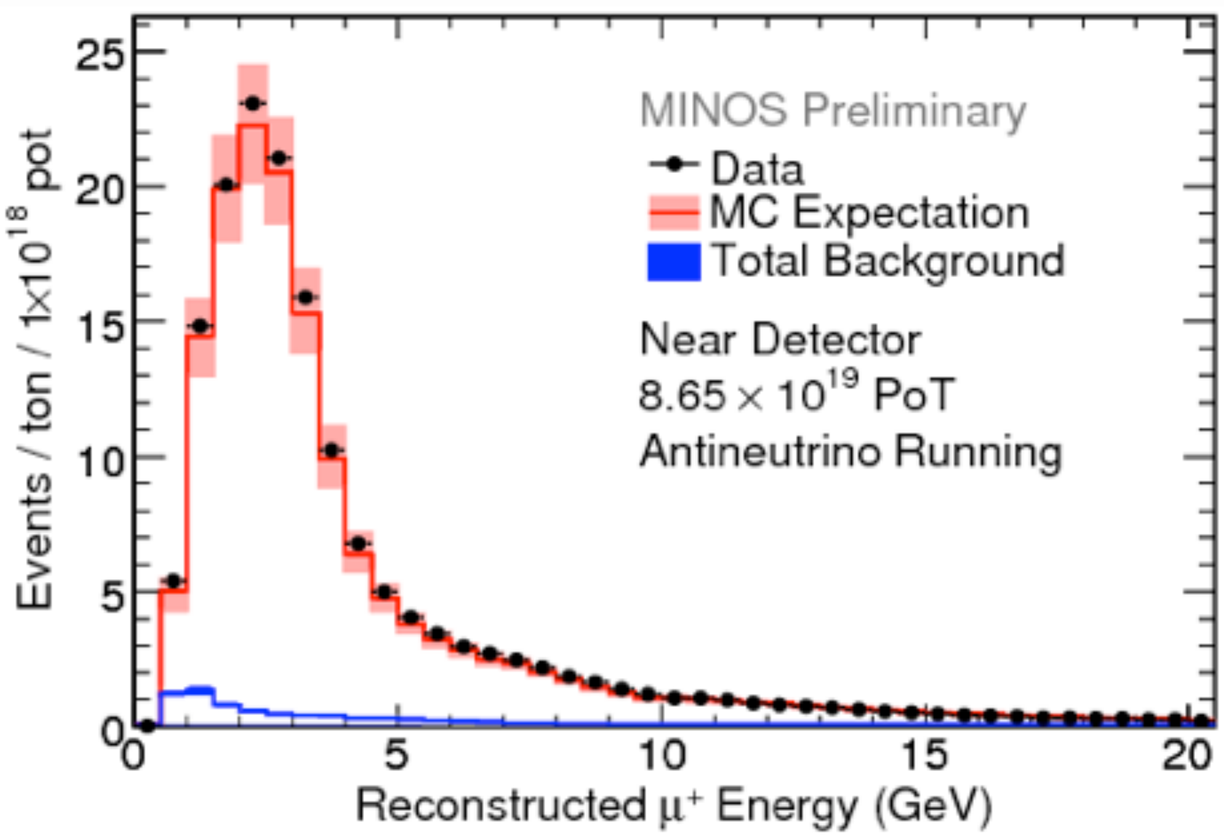


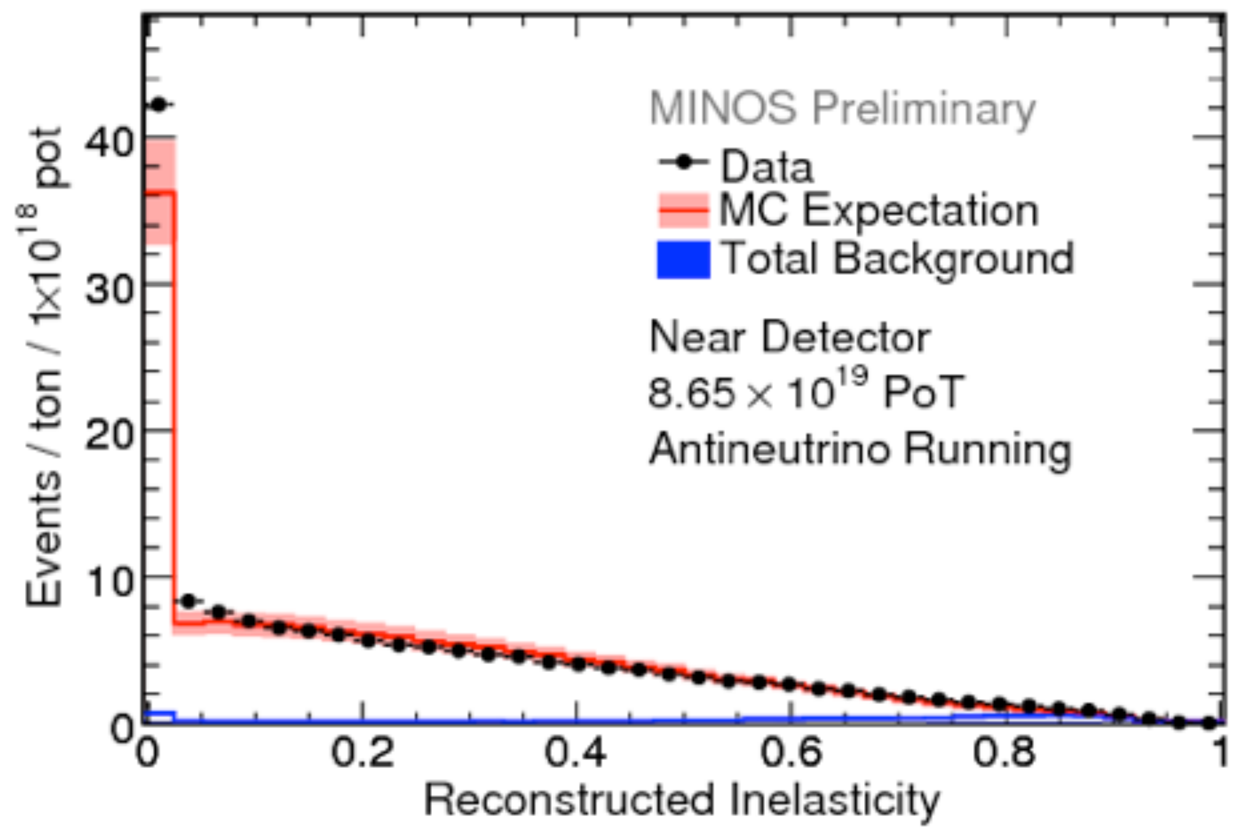
ND Anti-neutrino Data

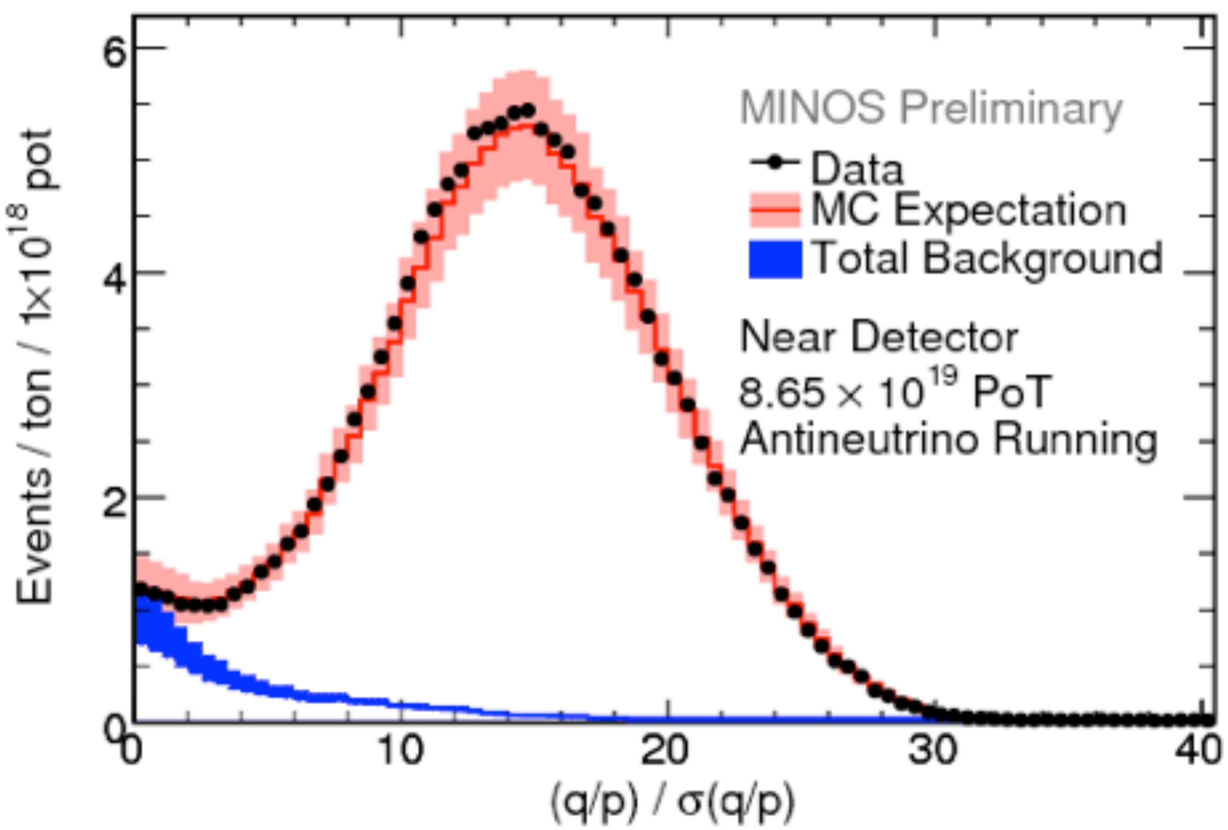
- Focus and select positive muons
  - purity 94.3% after charge sign cut
  - purity 98% < 6GeV
- Analysis proceeds as (2008) neutrino analysis
- Data/MC agreement comparable to neutrino running
  - different average kinematic distributions
  - more forward muons



ND Data



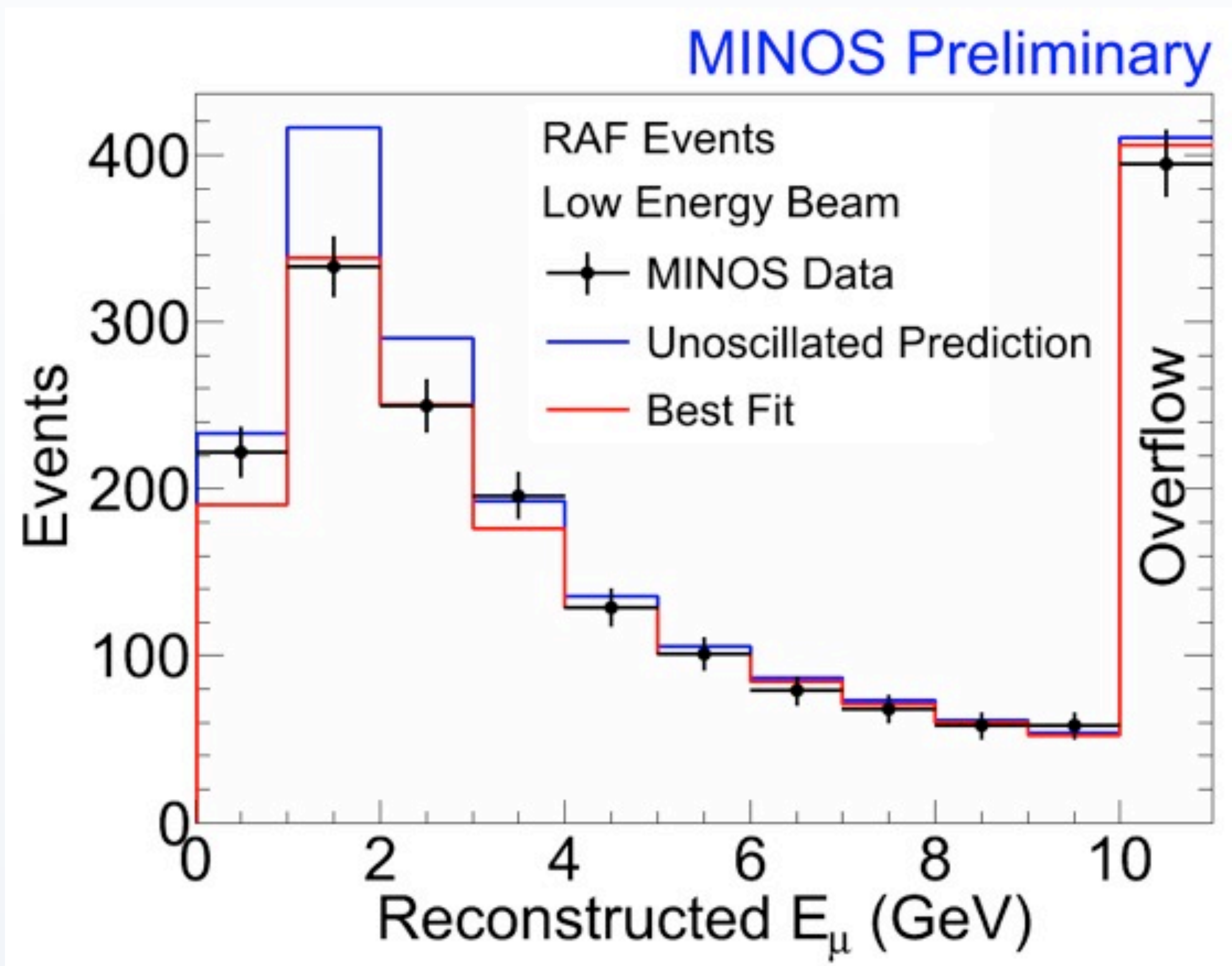




- Data/MC agreement comparable to neutrino running

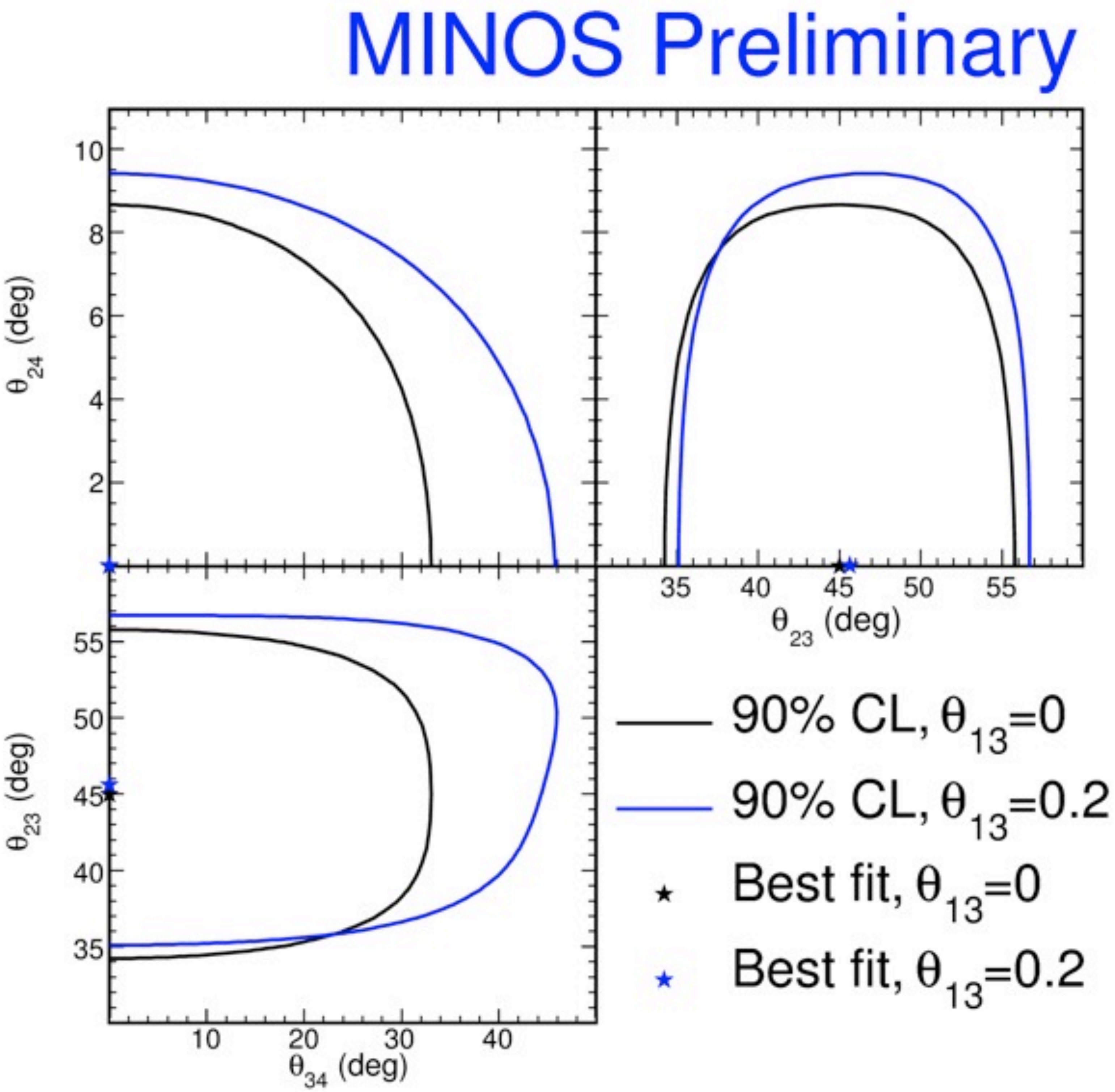
Rock and Anti-fiducial Events

- Neutrinos interact in rock around detector and outside of Fiducial Region
- These events double sample size, events have poorer energy resolution



Combined fit coming soon

Fits to NC

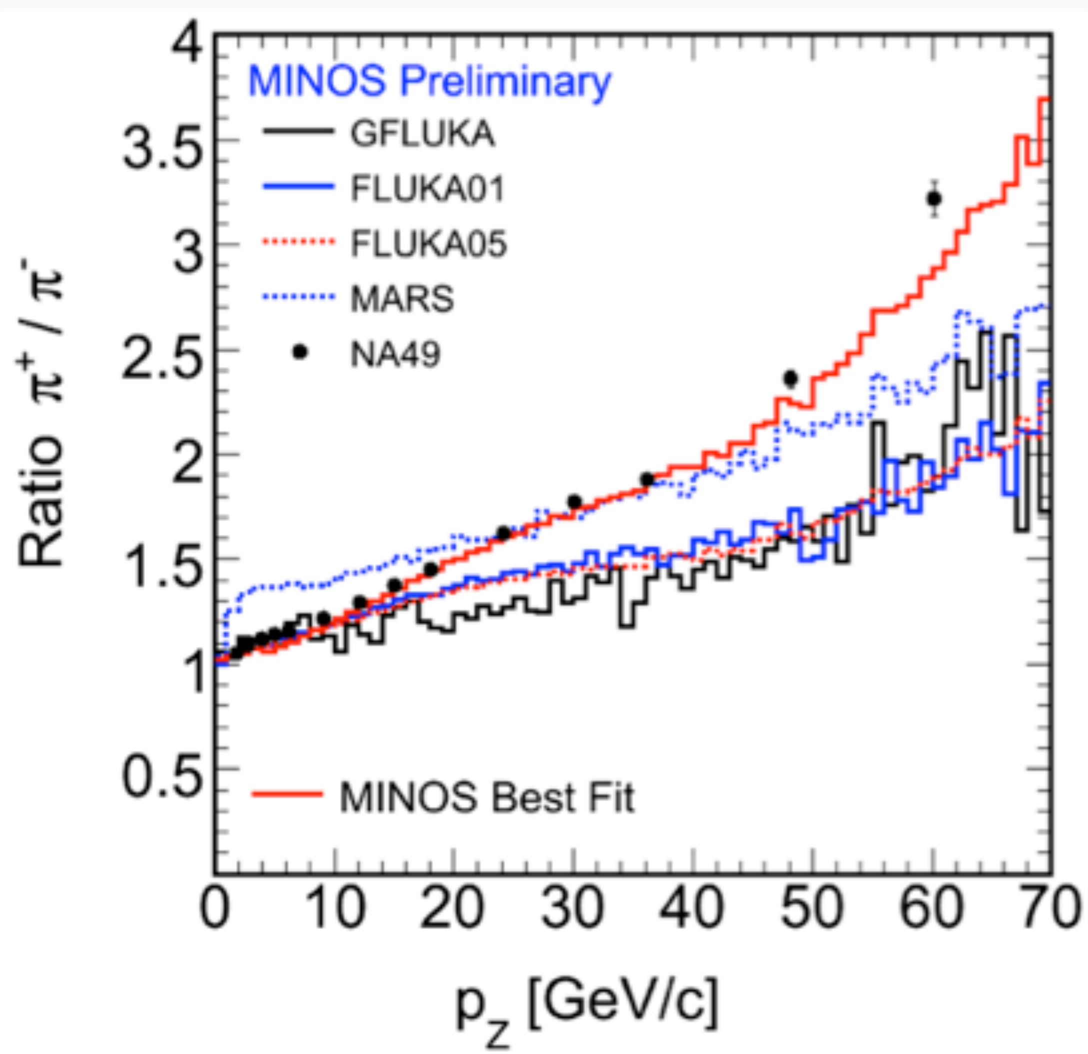


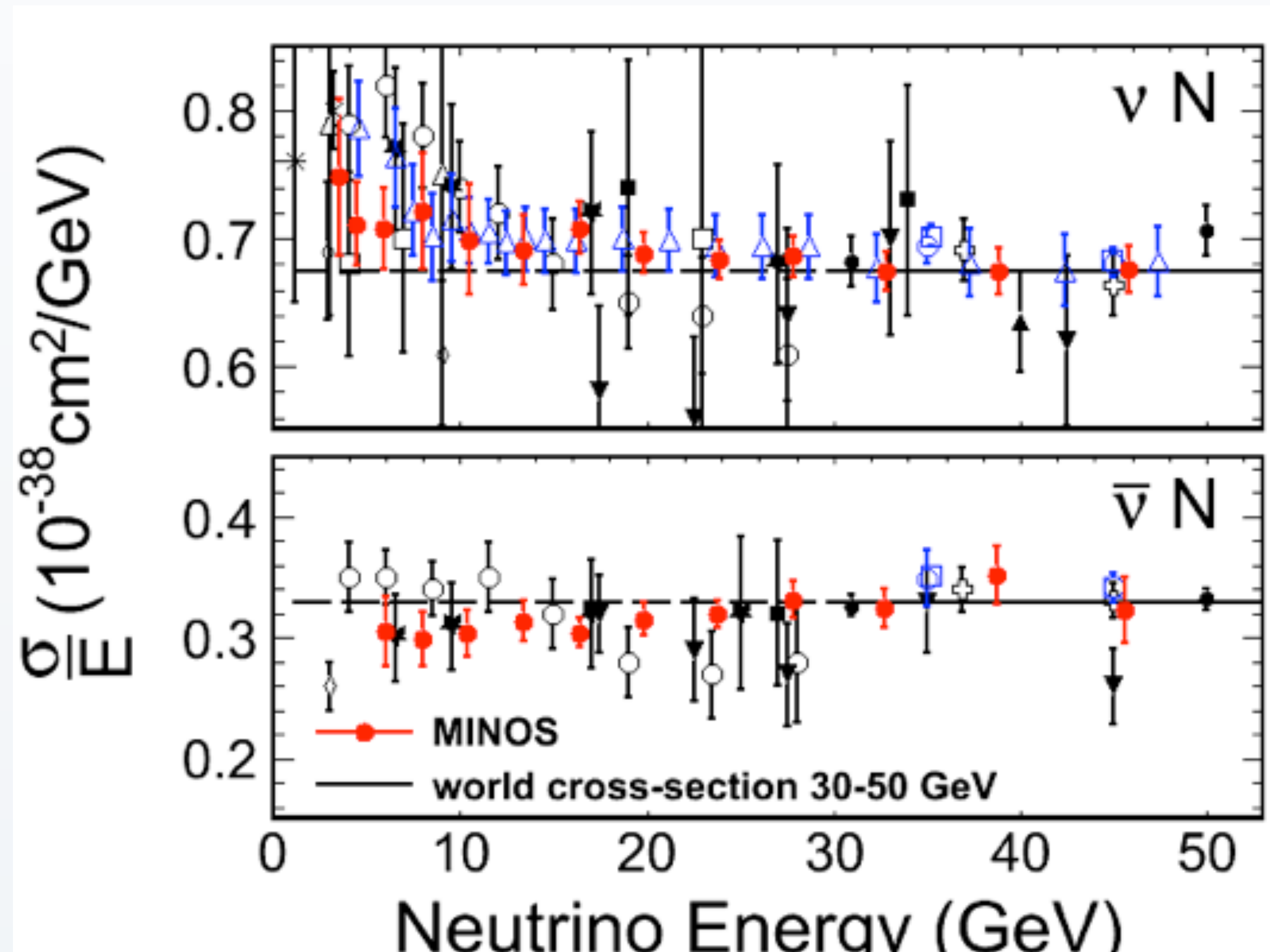
- Fit CC/NC spectra simultaneously with a 4th (sterile) neutrino
- 2 choices for 4th mass eigenvalue
  - $m_4 >> m_3$
  - $m_4 = m_1$

Making an antineutrino beam

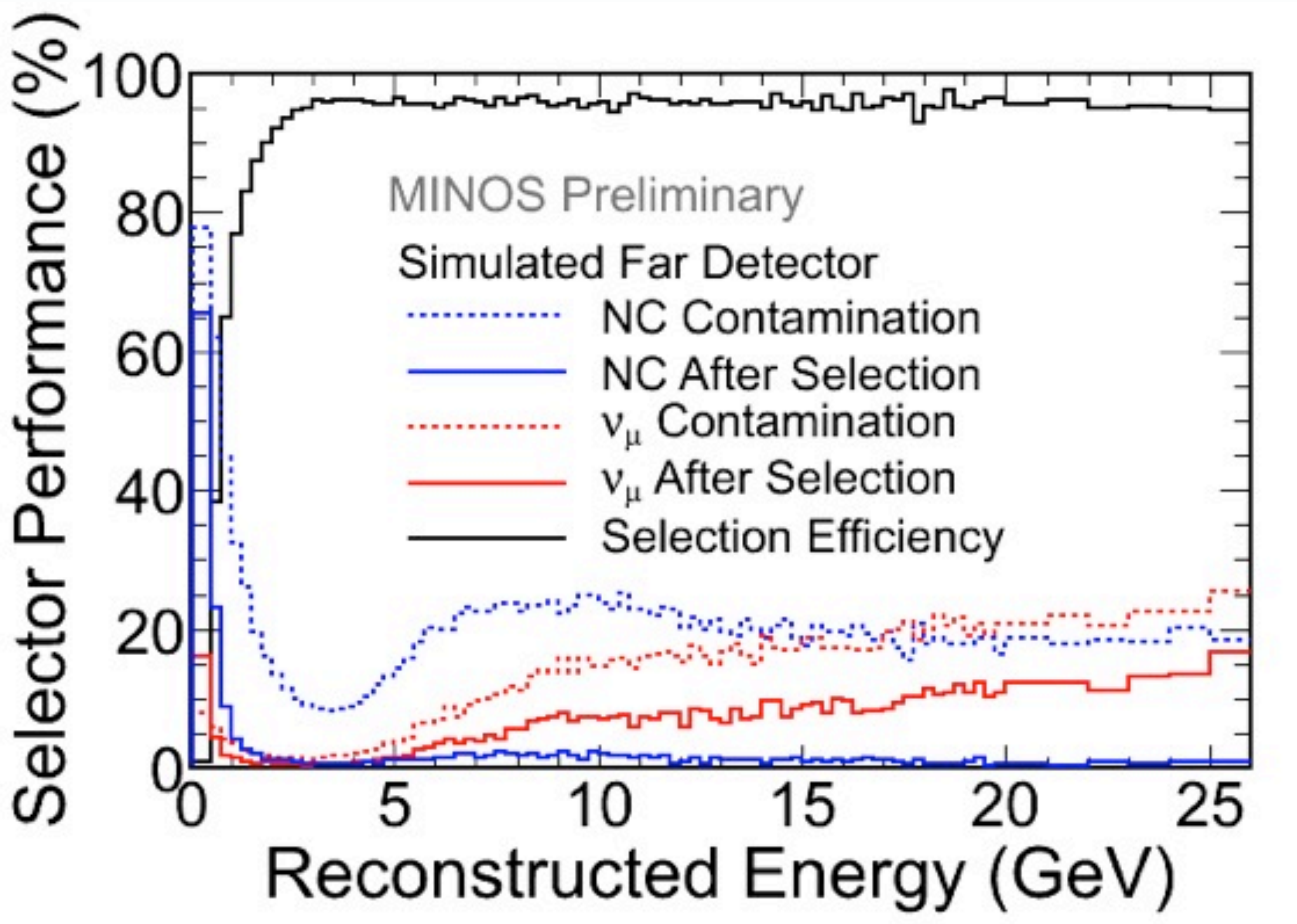
- Hadron production and cross sections conspire to change the shape and normalization of energy spectrum

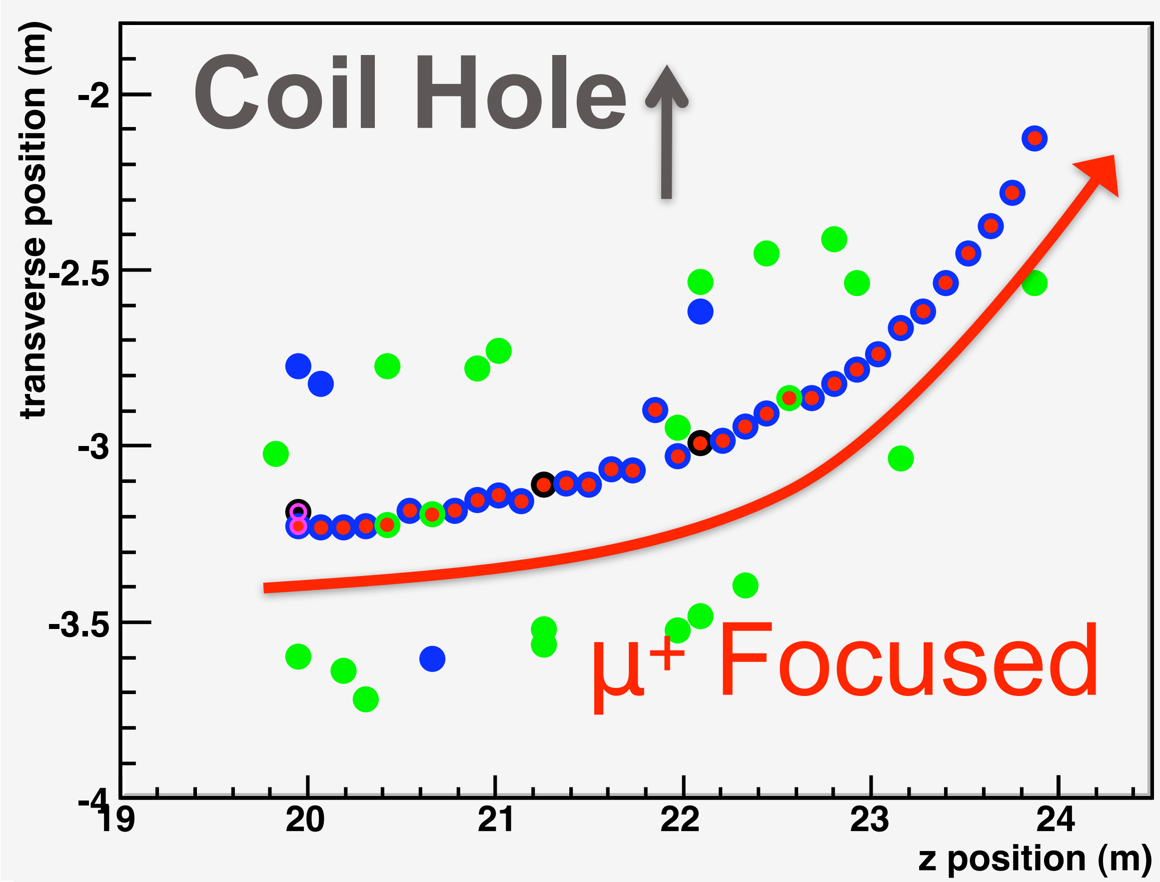
~3x fewer antineutrinos for the same exposure

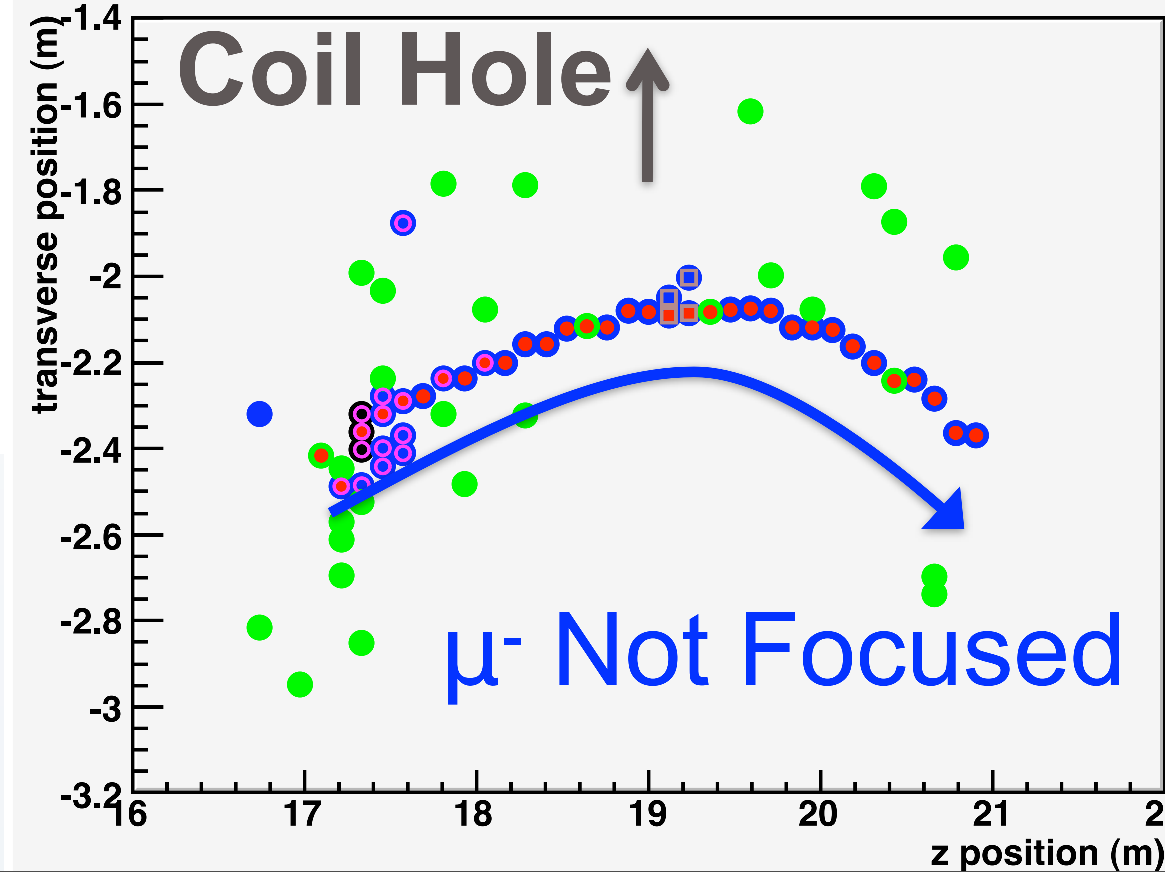




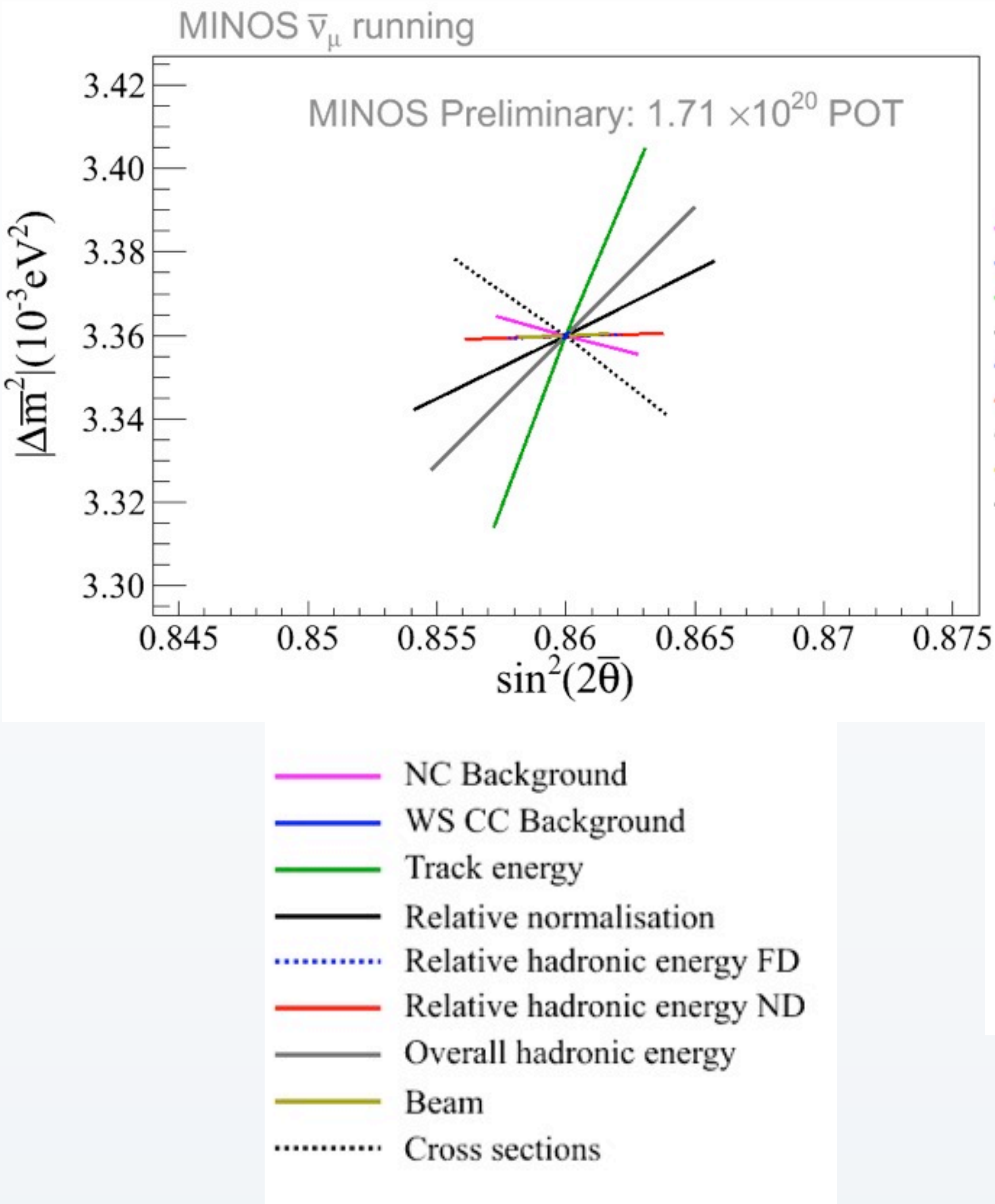
Anti-neutrino Selection

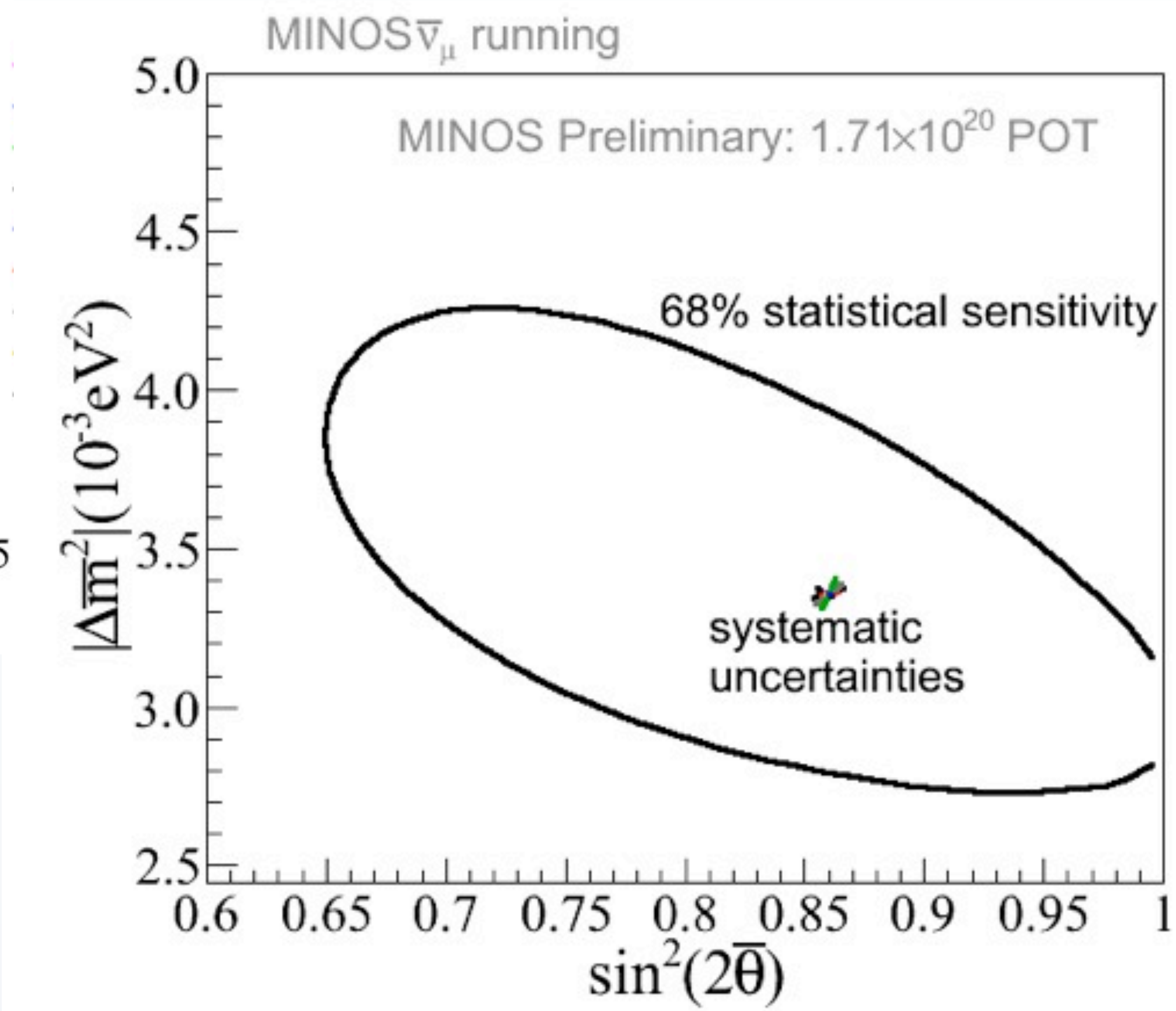




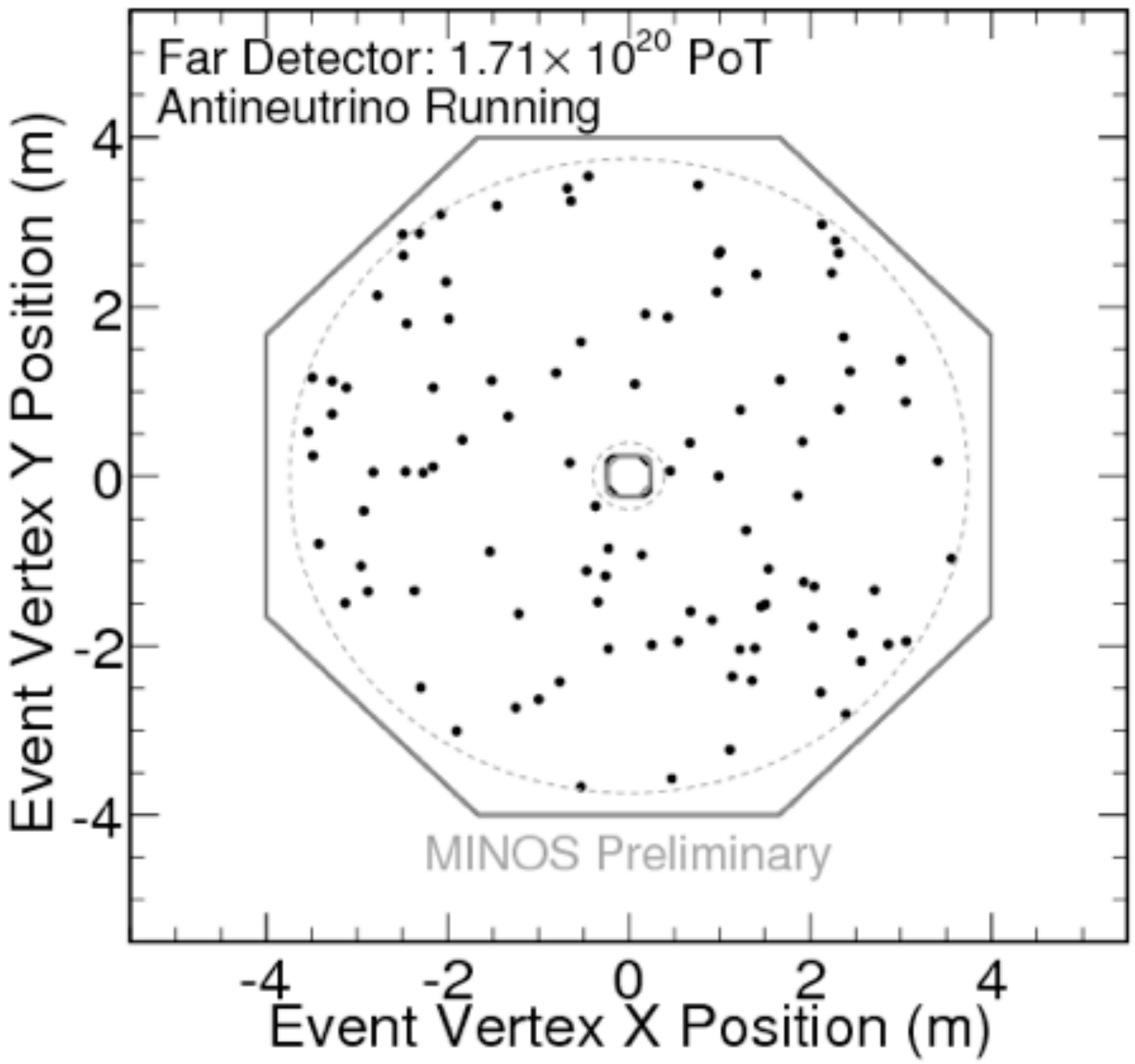


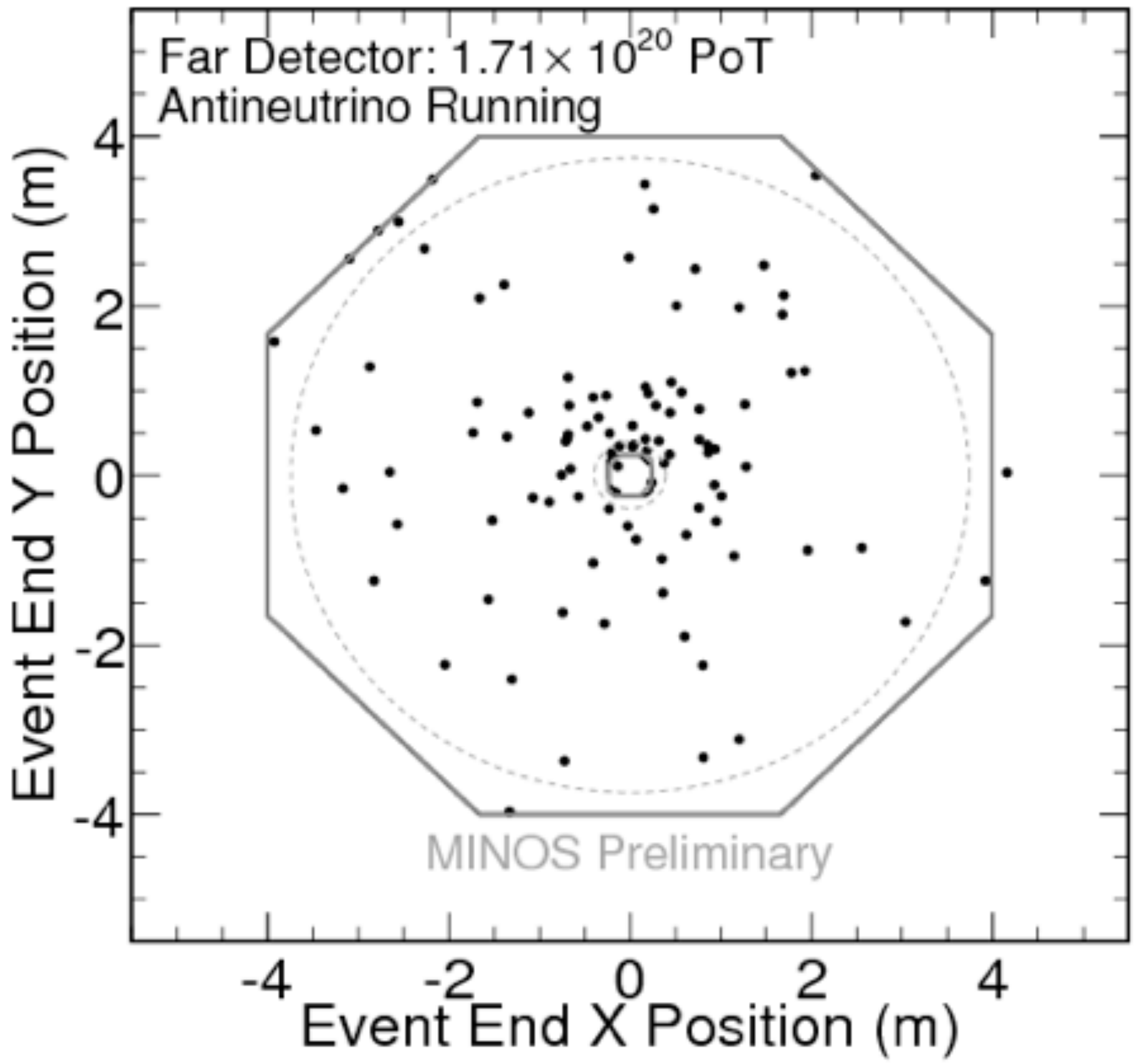
Anti-neutrino Systematics





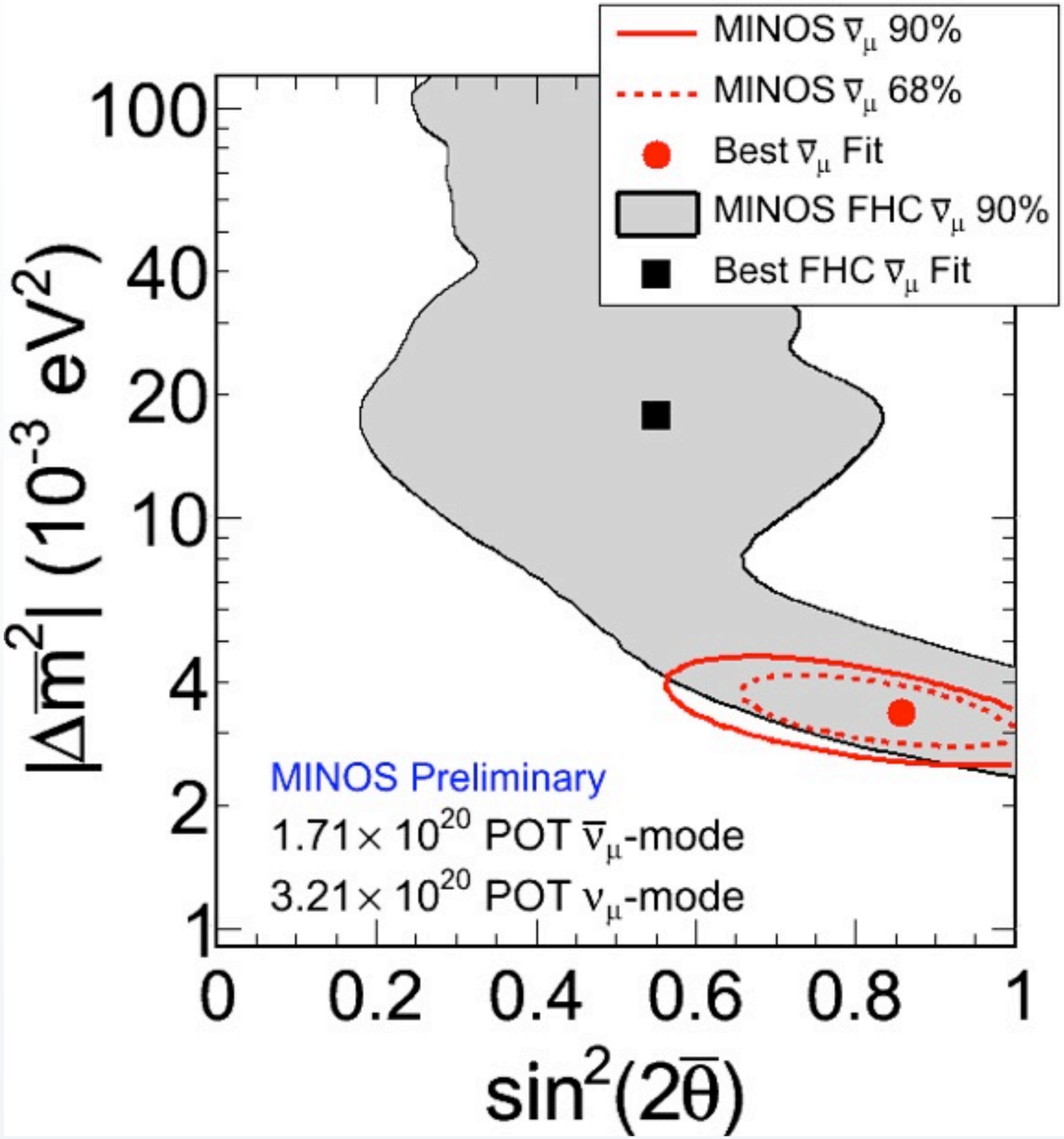
FD Anti-neutrino Data





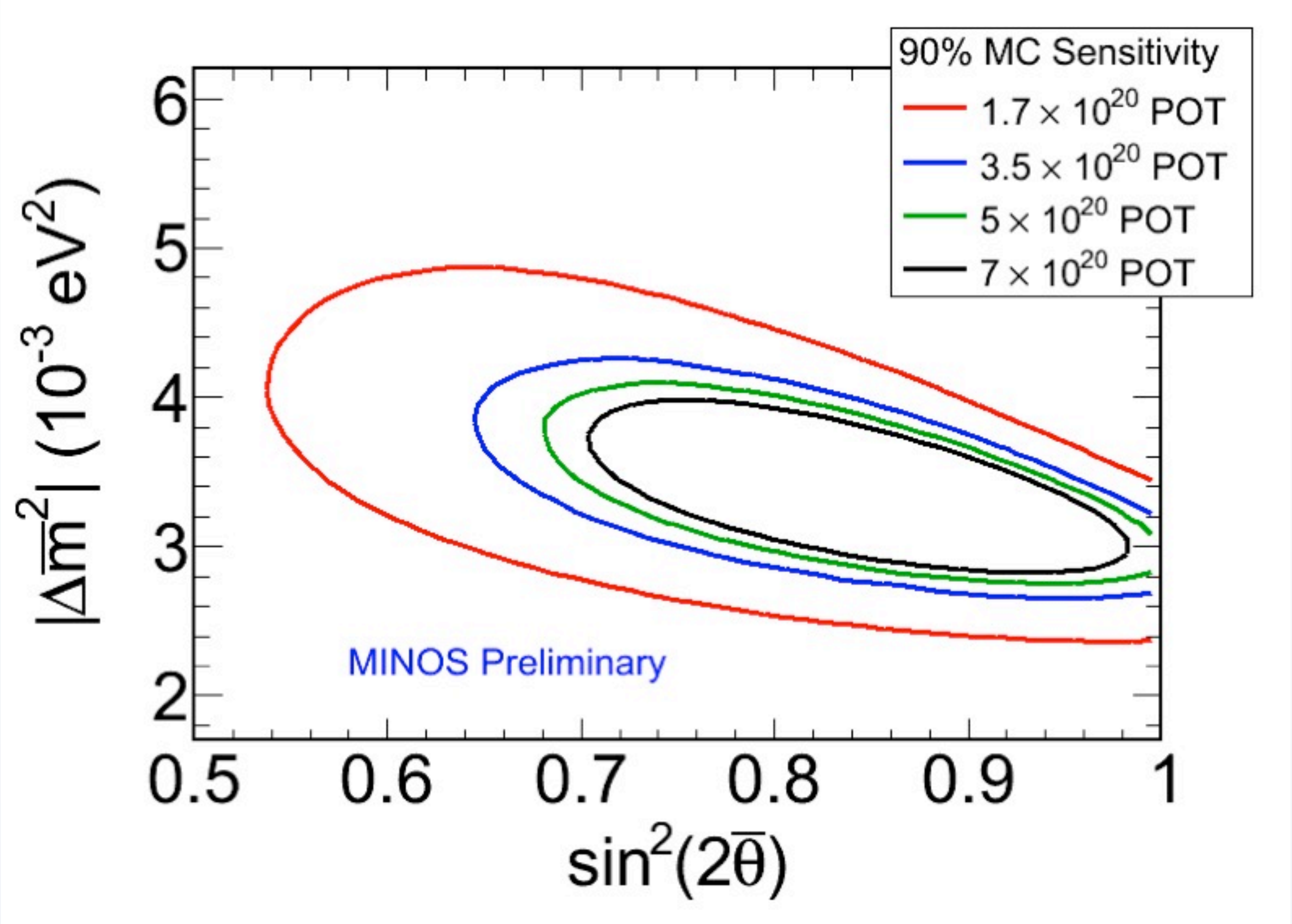
- Vertices uniformly distributed
- Track ends clustered around coil hole

Previous Anti-neutrino Results

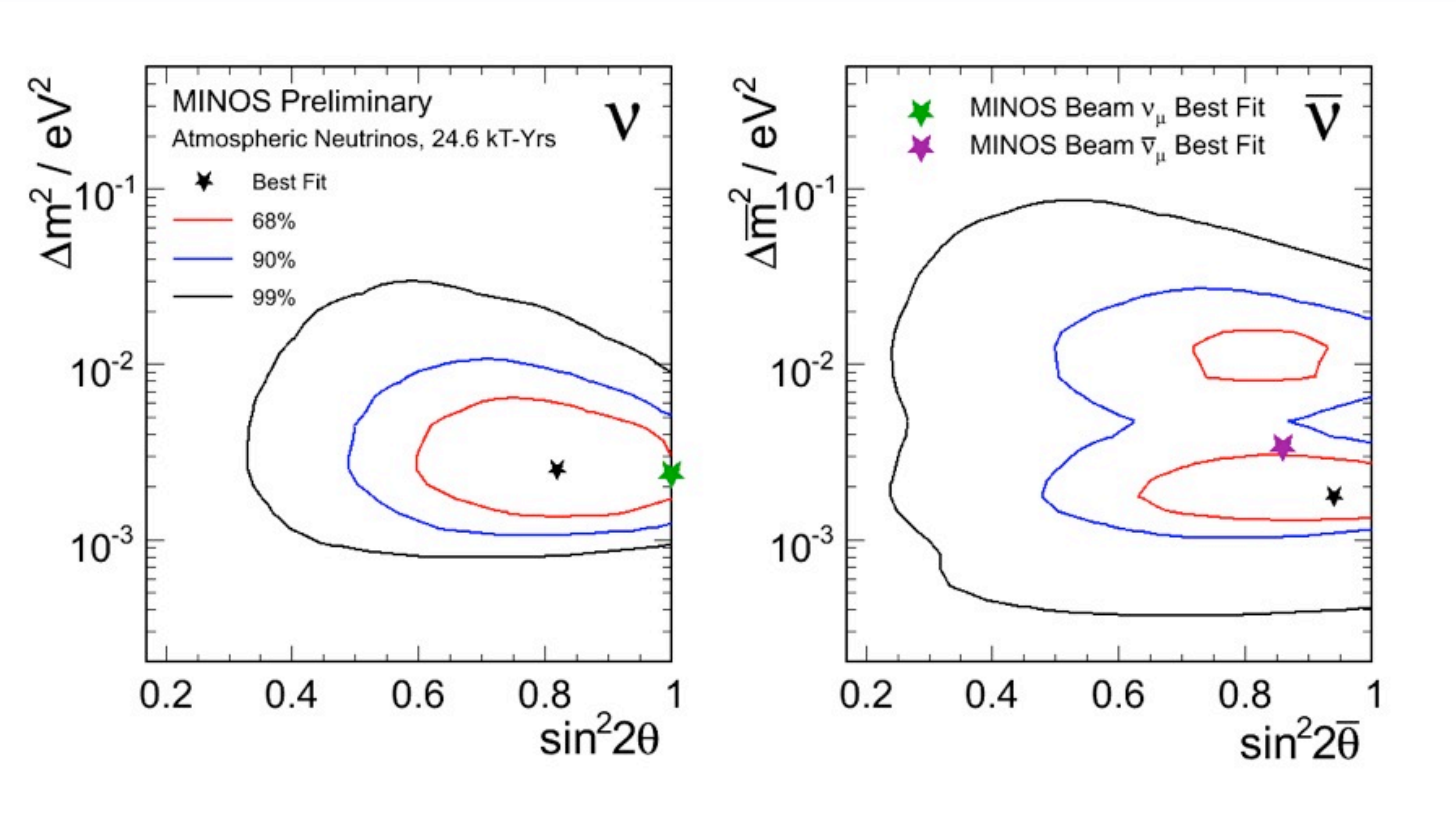


- Results consistent with (less sensitive) analysis of anti-neutrinos in the neutrino beam
  - anti-neutrinos from unfocused beam component
  - mostly high energy antineutrinos
- Analysis of larger exposure on going

Future Anti-neutrino Sensitivity



Atmospheric Neutrinos



$$R_{\bar{\nu}/\nu}^{data} \,/\, R_{\bar{\nu}/\nu}^{MC} = 1.04^{+0.11}_{-0.10} \pm 0.10$$

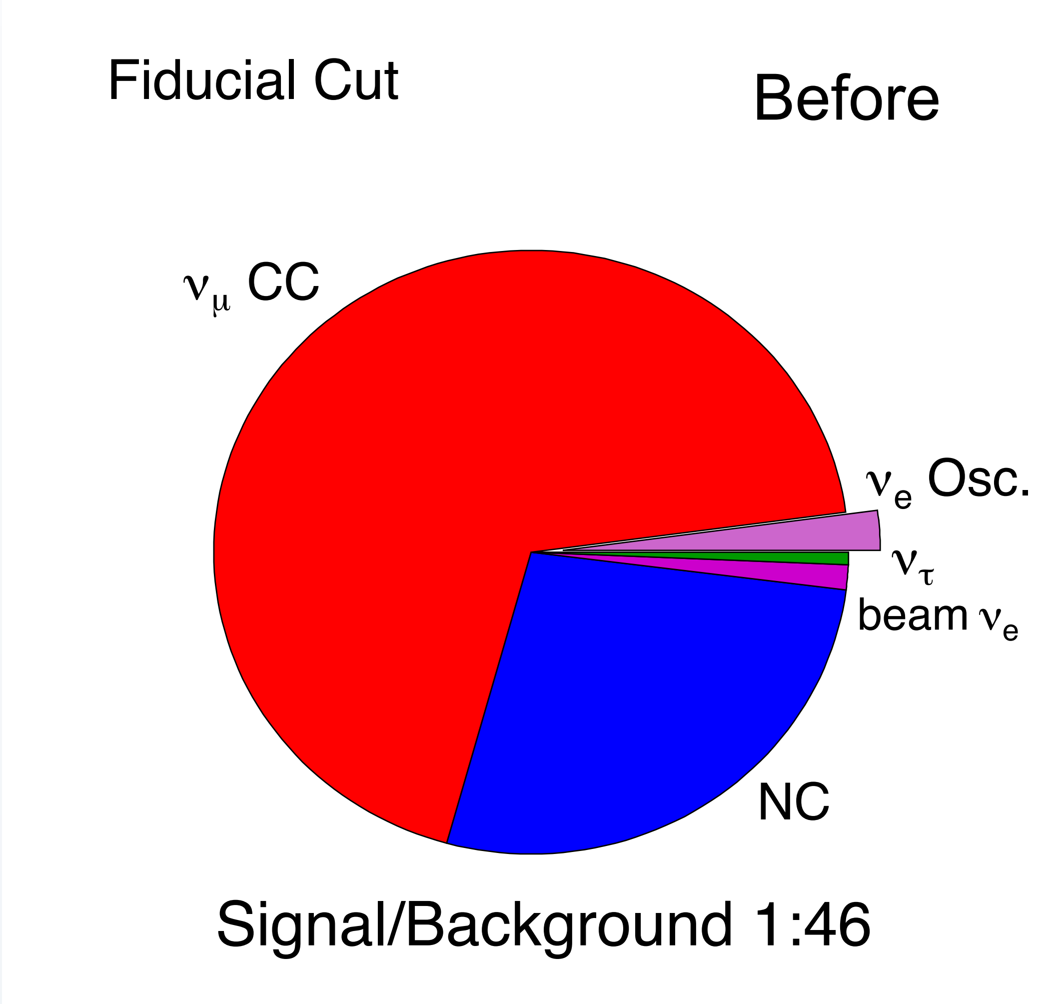
$$\left|\Delta m^2\right| - \left|\overline{\Delta m^2}\right| = 0.4^{+2.5}_{-1.2} \times 10^{-3}\,\mathrm{eV}^2$$

Electron-Neutrino Appearance

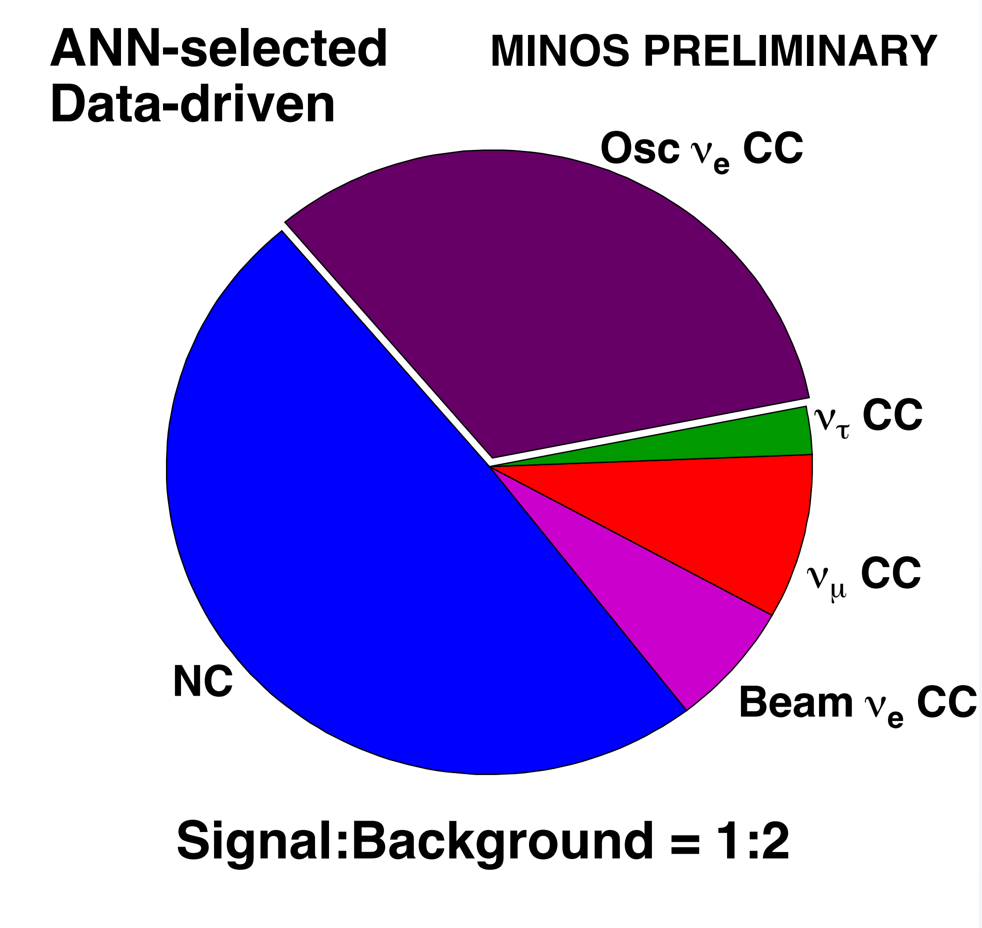
Probing beyond the Chooz limit

ν_e Appearance

- Searching for an excess of events above a large background(s)
  - Neutral current events
  - Charged current ν_μ
  - Intrinsic beam ν_e

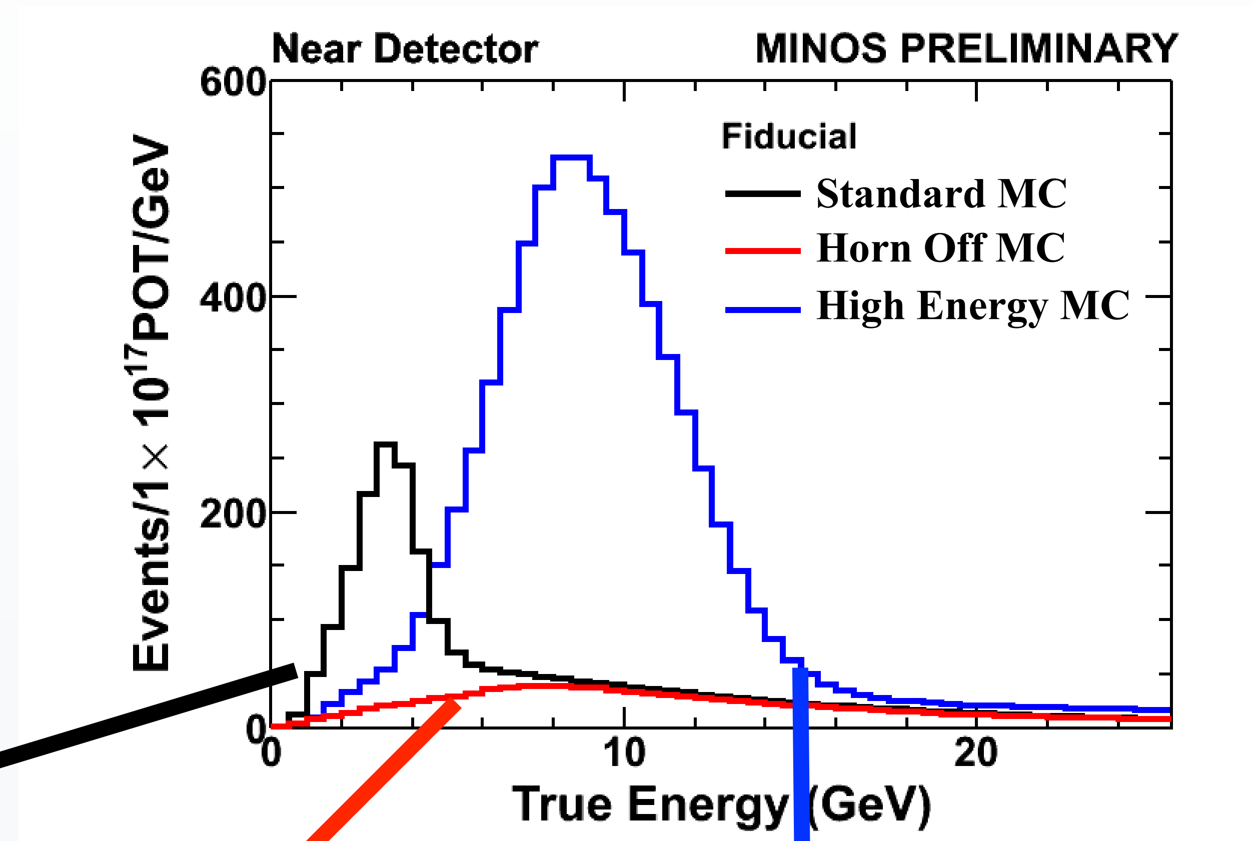


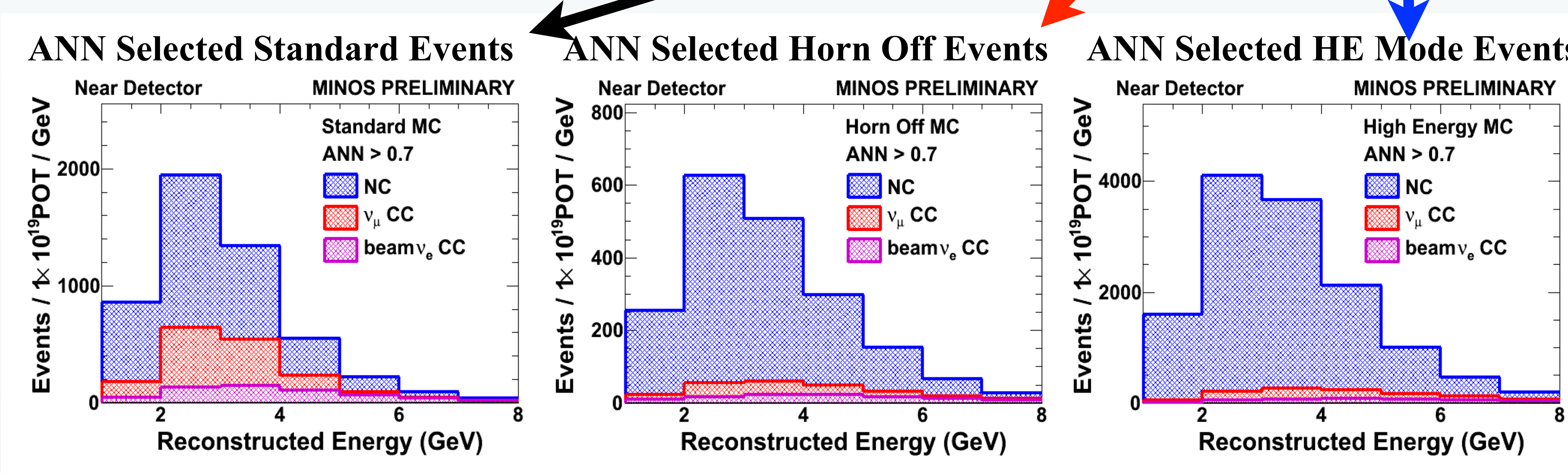
After



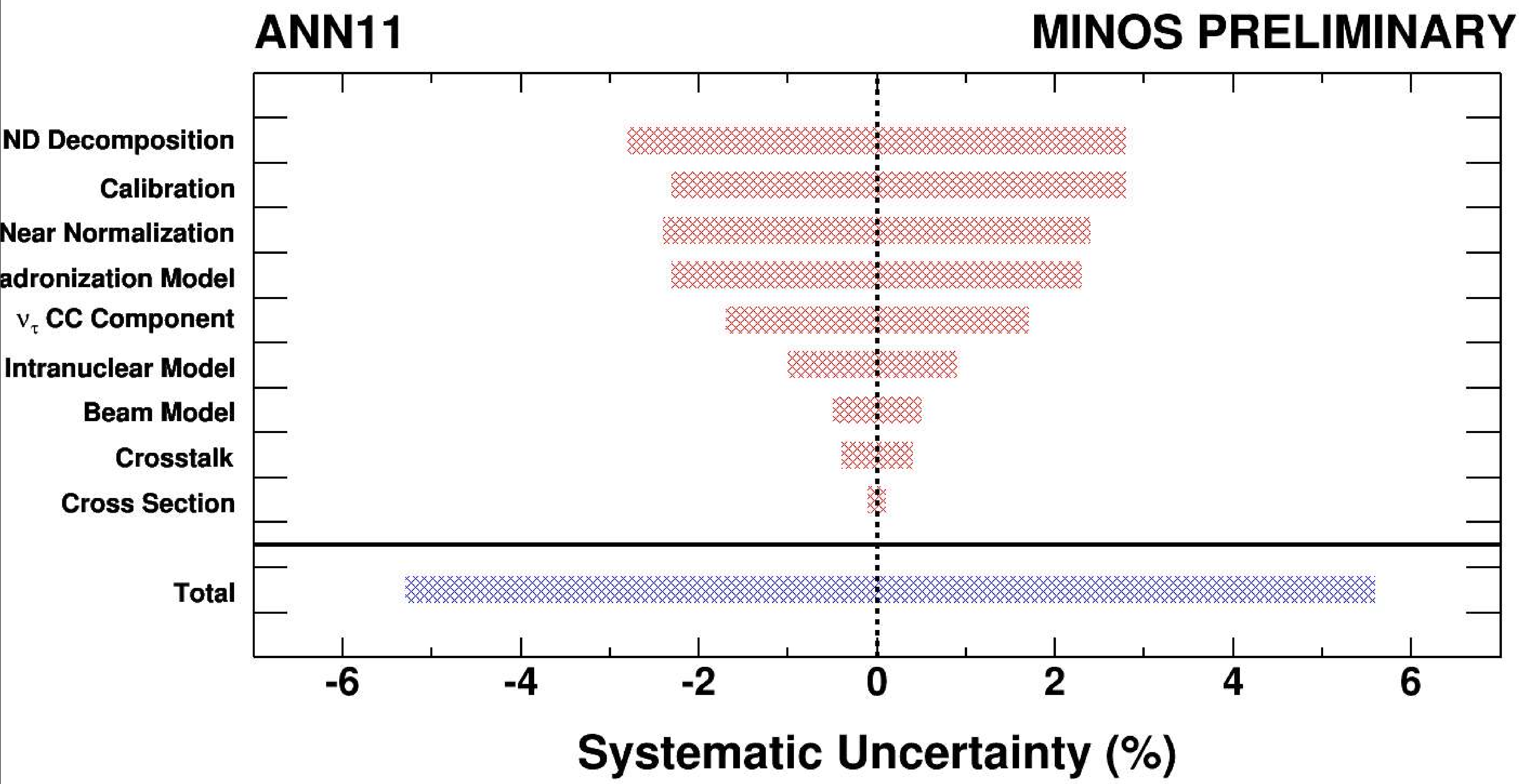
Background Decomposition

- Use multi-beam method to determine backgrounds in Near Detector
- Then extrapolate them to the Far Detector

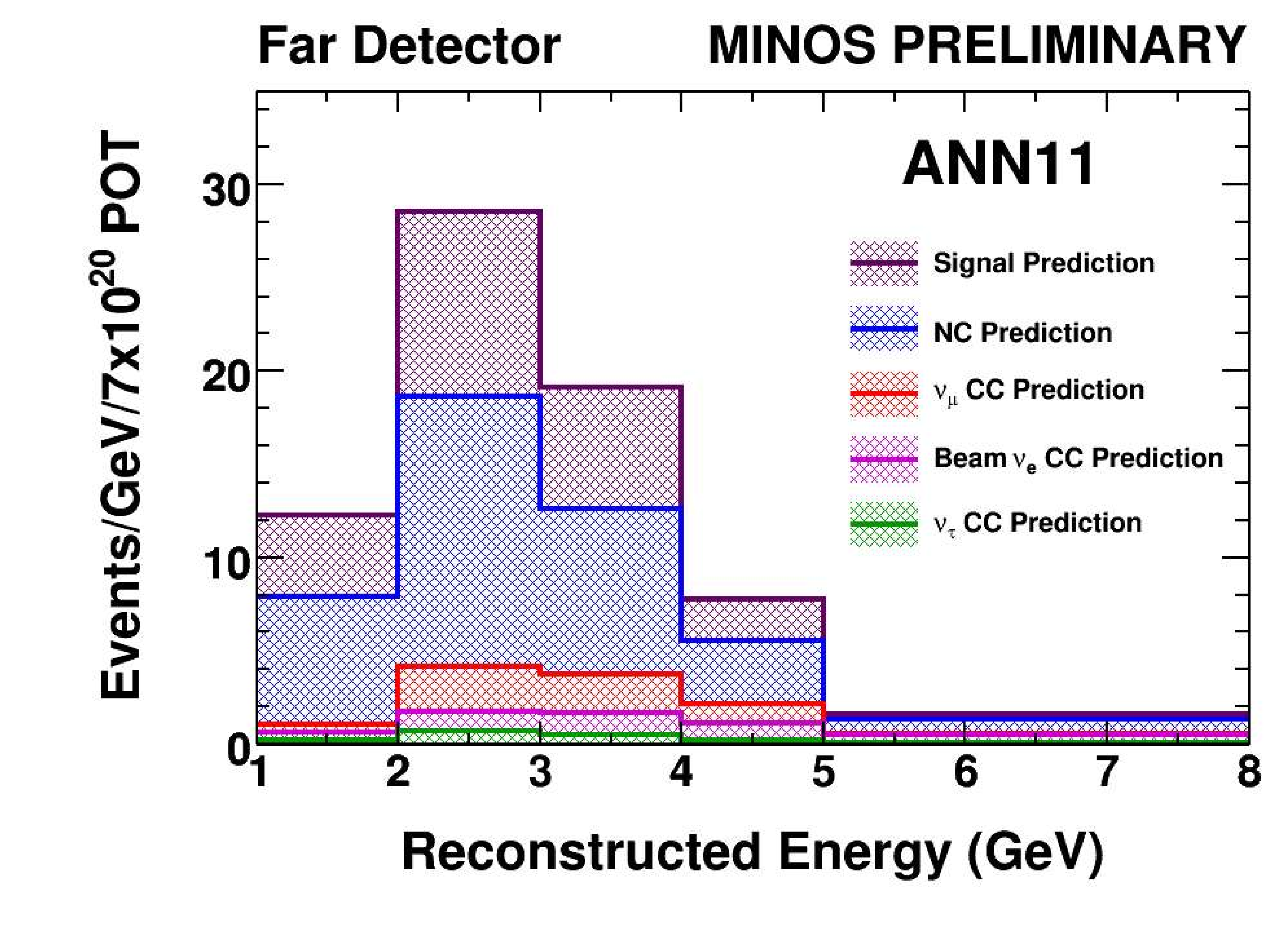




Systematic Uncertainties



Final Far Detector Prediction

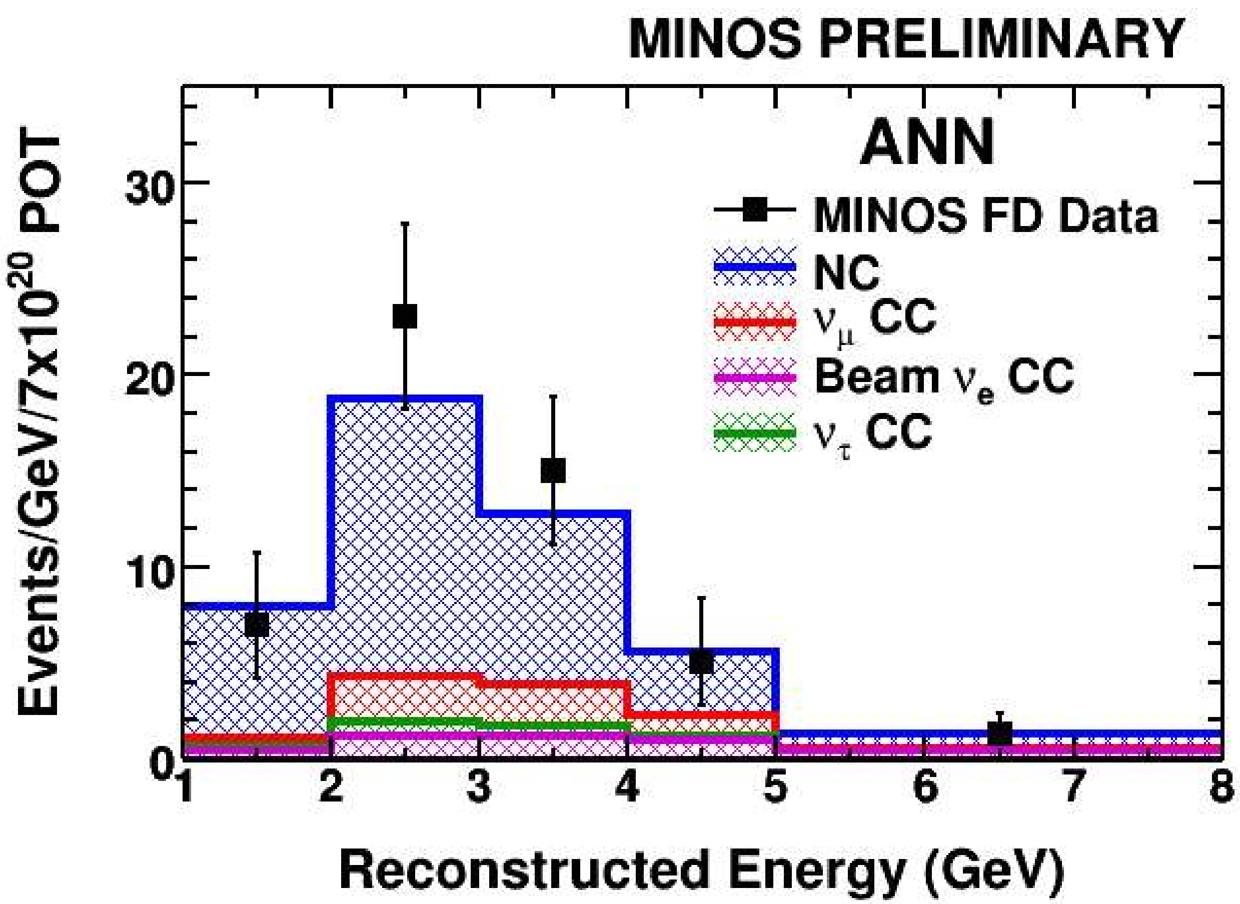


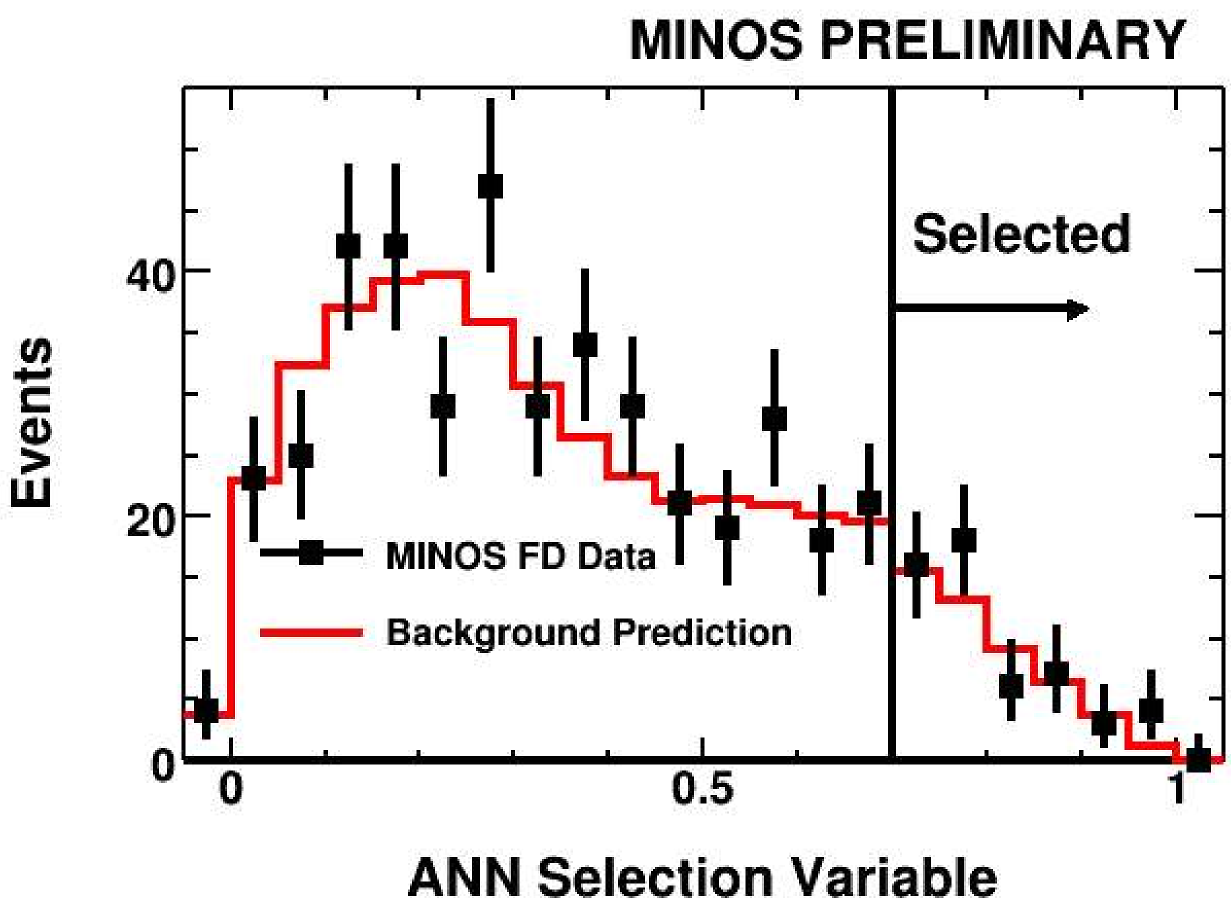
	Total	Stat. Err.	Syst. Err.	NC	CCNuMu	Beam NuE	CcNuTau
ANN11	48.6	7.0	2.7	35.8	6.3	4.7	1.8

Expected signal at Chooz limit: 23.9 events

ν_e Appearance Results

	Total	Stat. Err.	Syst. Err.	DATA	Excess	Sigma
ANN11	48.6	7	2.7	54	5.4	0.7





ν_e Appearance Results

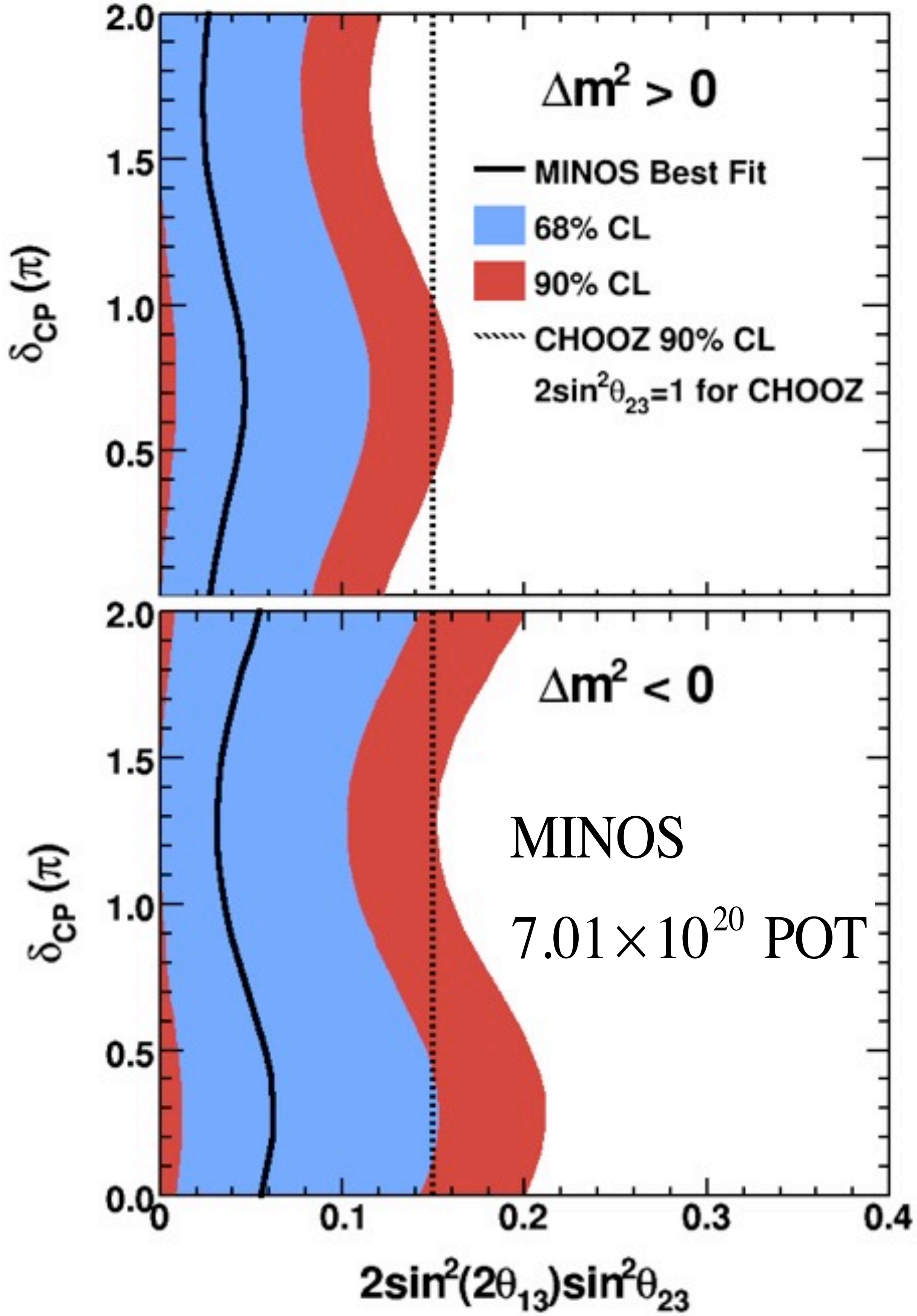
for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

$\left|\Delta m_{32}^2\right| = 2.43 \times 10^{-3}\ \text{eV}^2$

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

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

at 90% C.L.



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