Antineutrino Oscillations in the Atmospheric Sector



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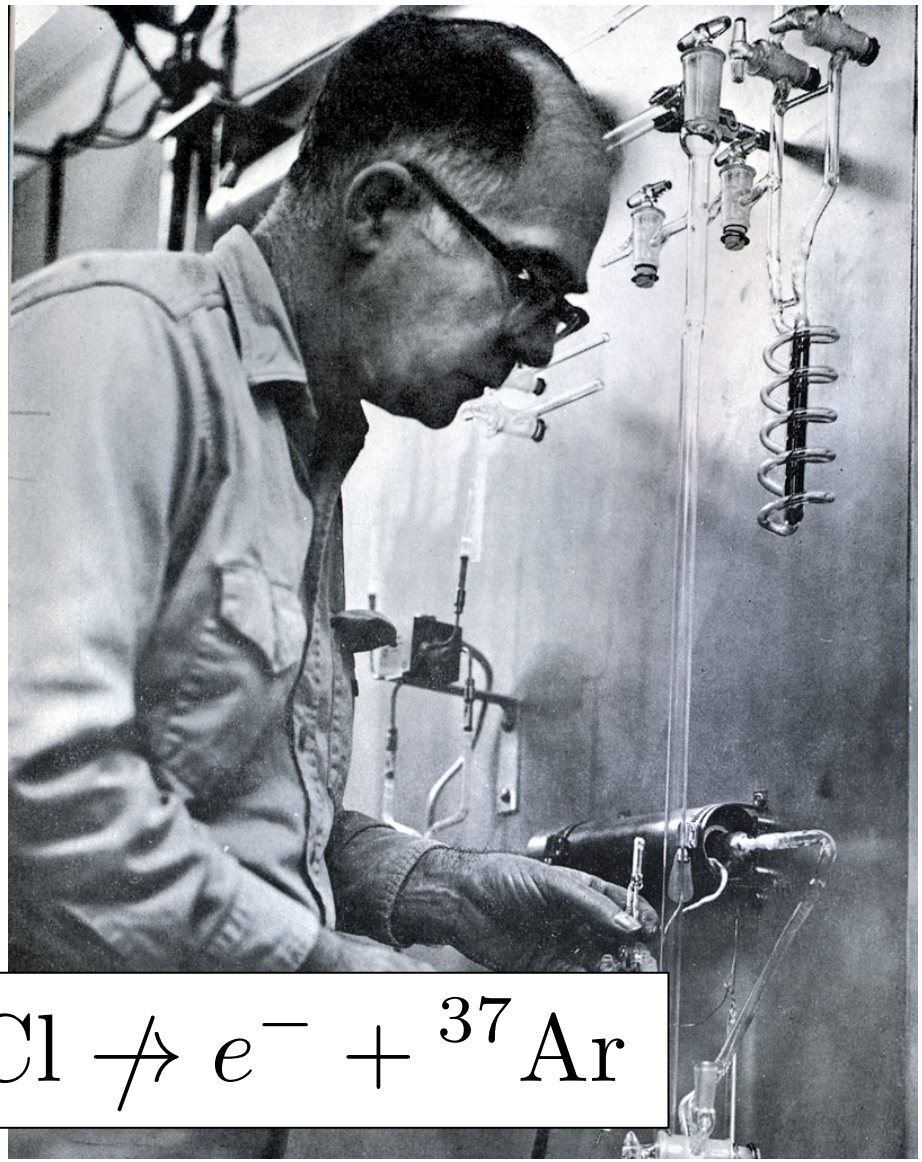
Introduction

- Why study neutrinos and antineutrinos?
- Antineutrinos in the NuMI neutrino beam (3x10^{20} POT)
  - Selection
  - Extrapolation
  - Fitting
  - Results
- Antineutrinos in the NuMI antineutrino beam (1.7x10^{20} POT)
  - Selection
  - Results

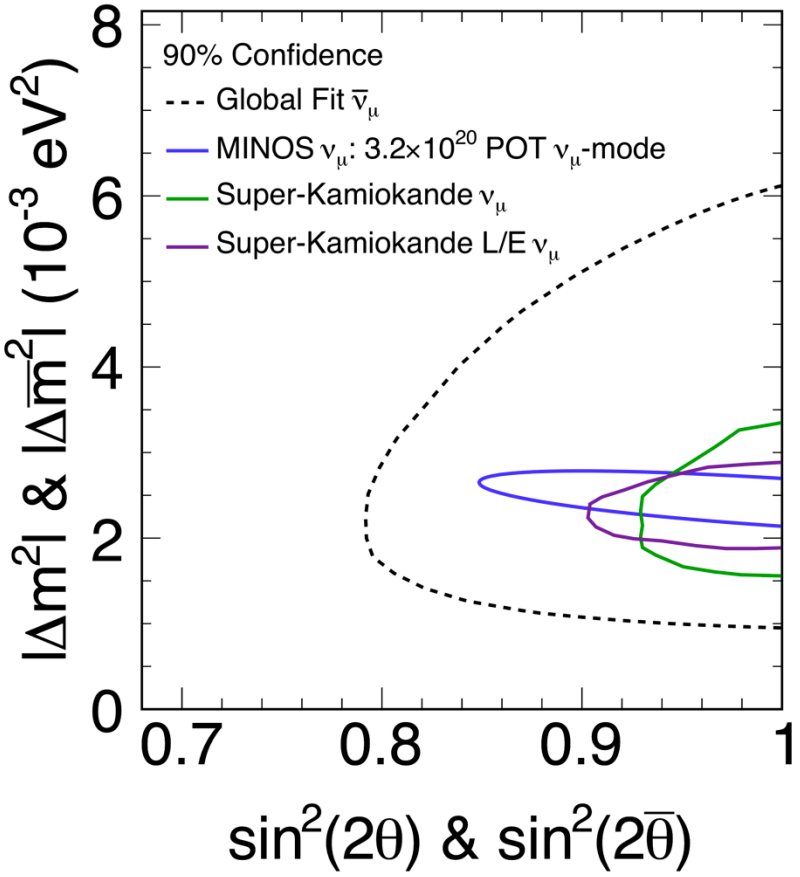


$$\bar{\nu} + {}^{37}\mathrm{Cl} \not\rightarrow e^{-} + {}^{37}\mathrm{Ar}$$

Why study ν_μ and $\bar{\nu}_\mu$?

$$P\left(\nu_\mu \rightarrow \nu_\mu\right) \stackrel{?}{=} P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu\right)$$

- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation



- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.

P. Adamson, et. al, Phys. Rev. Lett. 101:131802 (2008)
Y. Ashie, et. al., Phys. Rev. D 71:112005 (2005)
Y. Ashie, et. al., Phys. Rev. D 71:112005 (2005)
M.C. Gonzalez-Garcia & M. Maltoni, Phys. Rept. 460:1-129 (2008)

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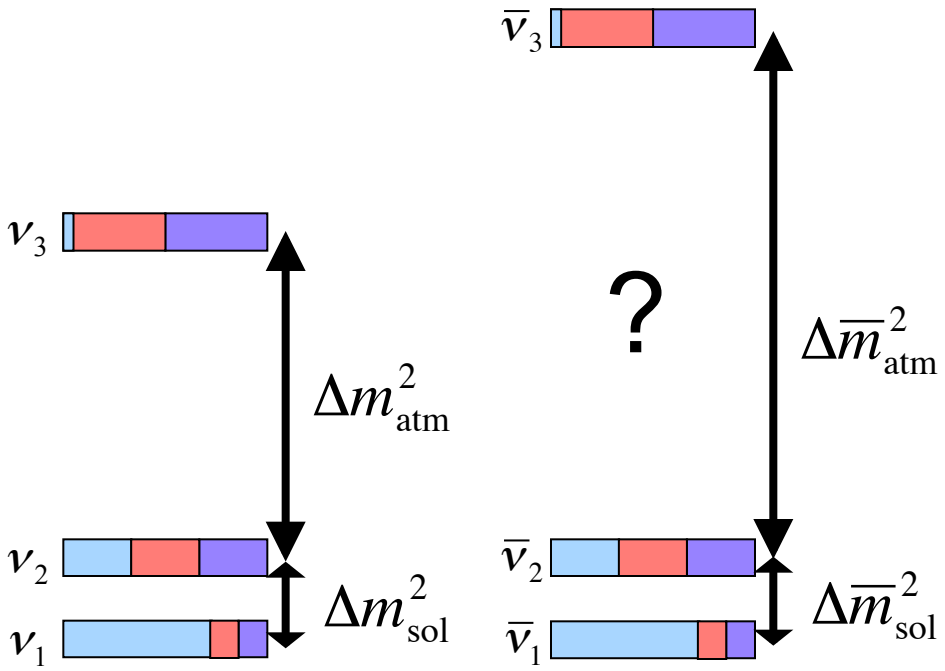

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Why study ν_μ and $\bar{\nu}_\mu$?



Neutrino-to-antineutrino Transitions

- MINOS is sensitive to helicity-flipping transitions

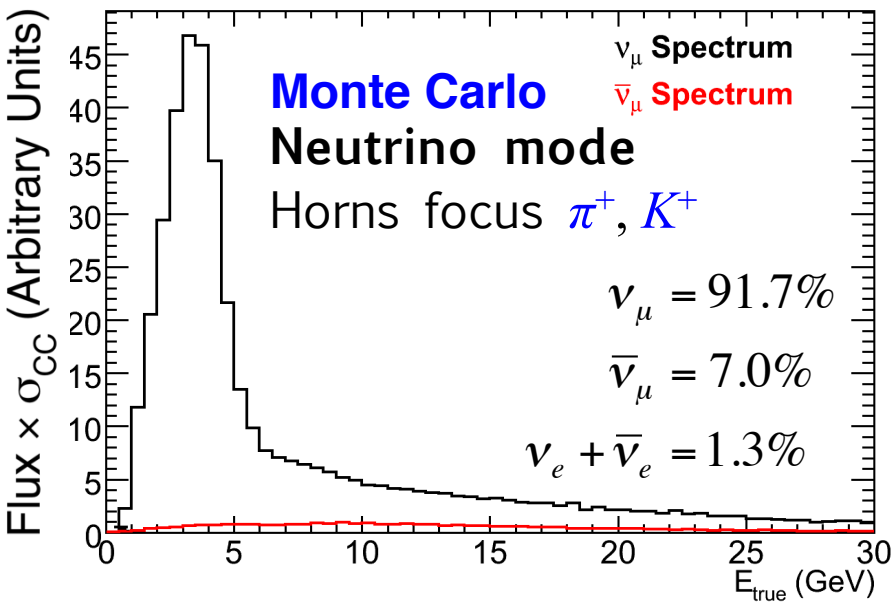
$$\nu_L \rightarrow (\nu_L)^c = \nu_R$$

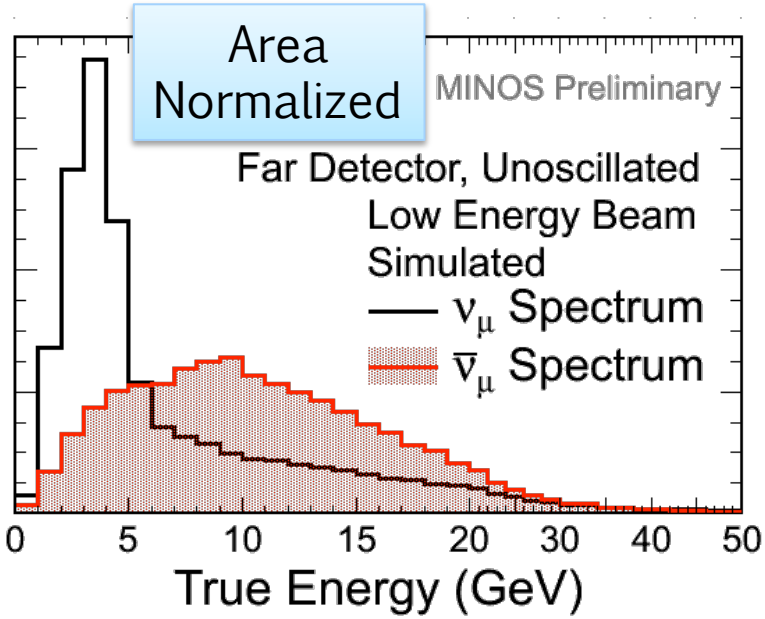
- due to Majoranna mass terms

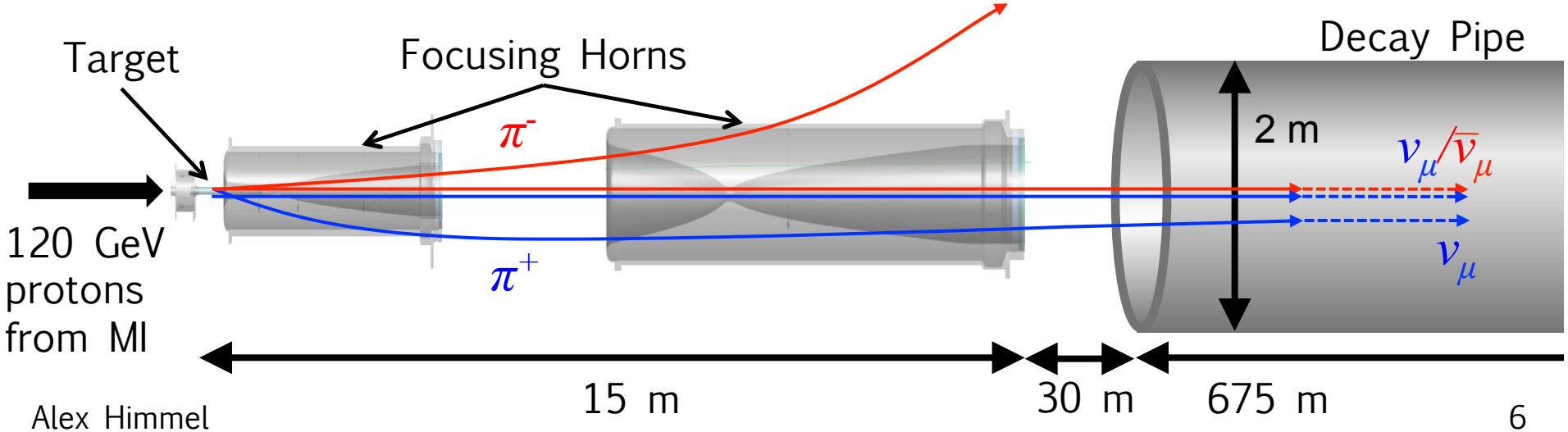
$$\mathcal{L}^M_{\text{mass}} = -\frac{1}{2}\bar{\nu}_L M^M (\nu_L)^c + \text{h.c.}$$

- Predicted at the level of 10^{-7} due to (m_ν/E_ν) suppression
- Only experimentally tested with ν_e in the 1980's

Neutrino Mode

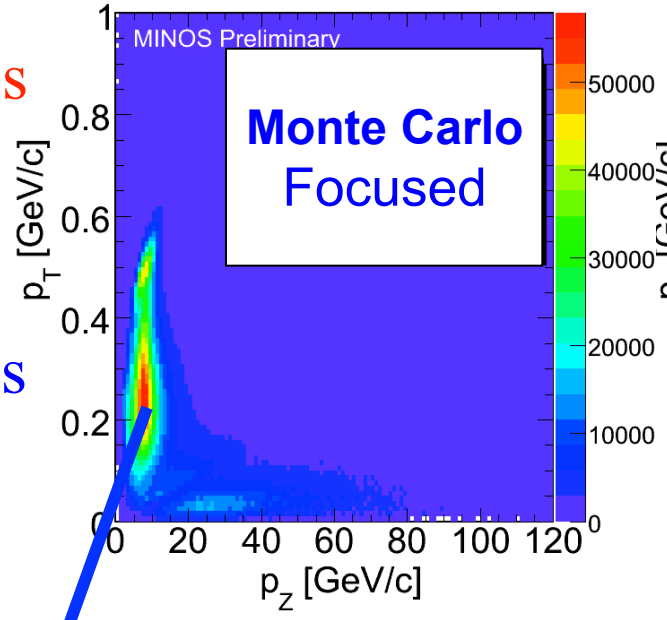


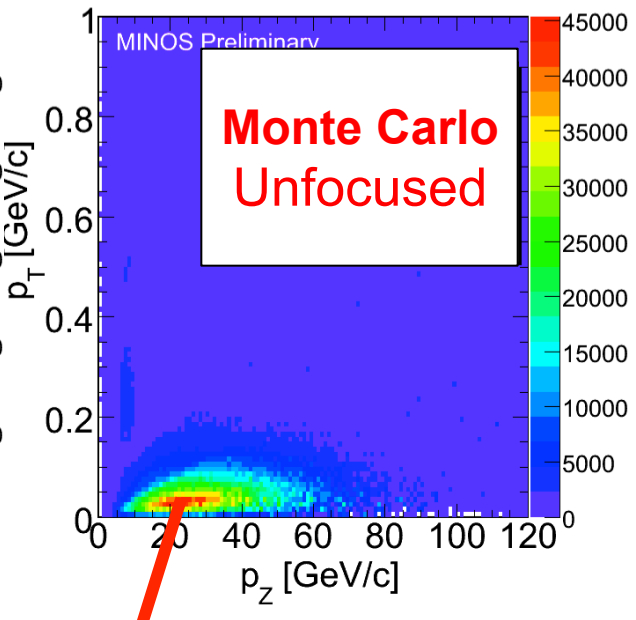


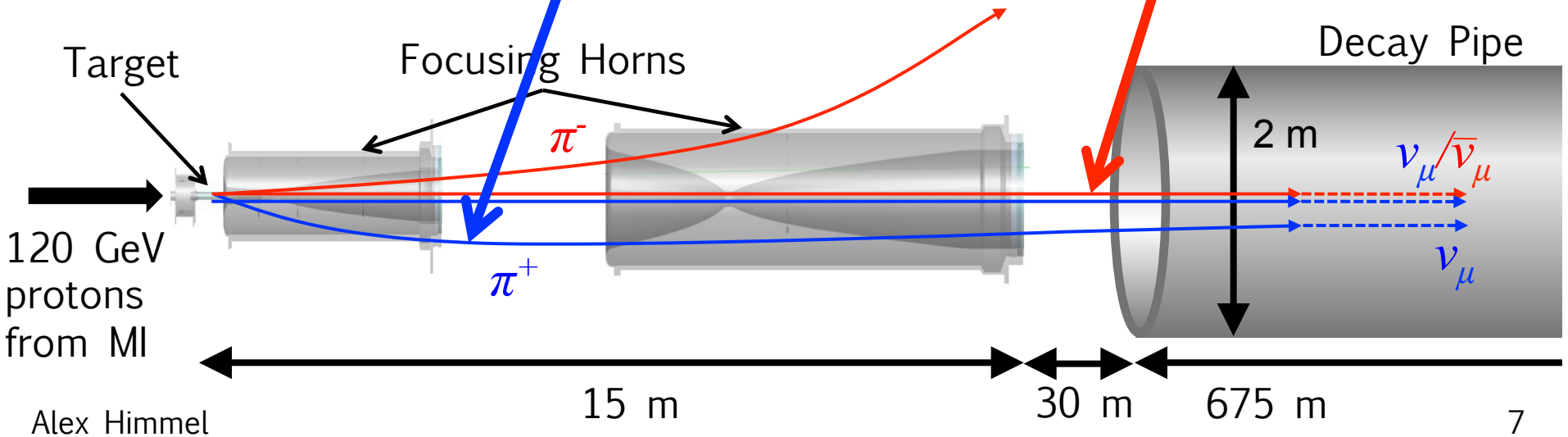


Peak vs. Tail

- $\bar{\nu}_\mu$'s from **low-p_t π^-'s**
  - Pass through horn necks
- ν_μ's from **high-p_t π^+'s**
  - Focused by horns

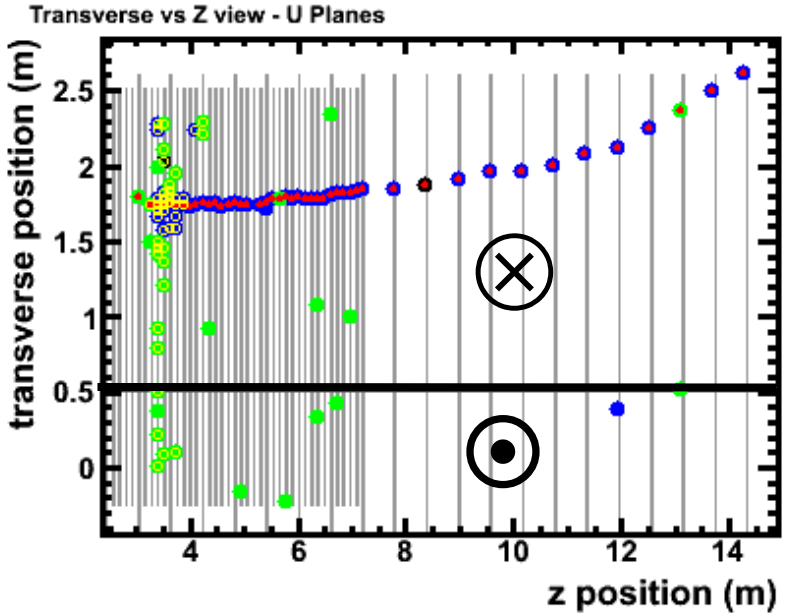




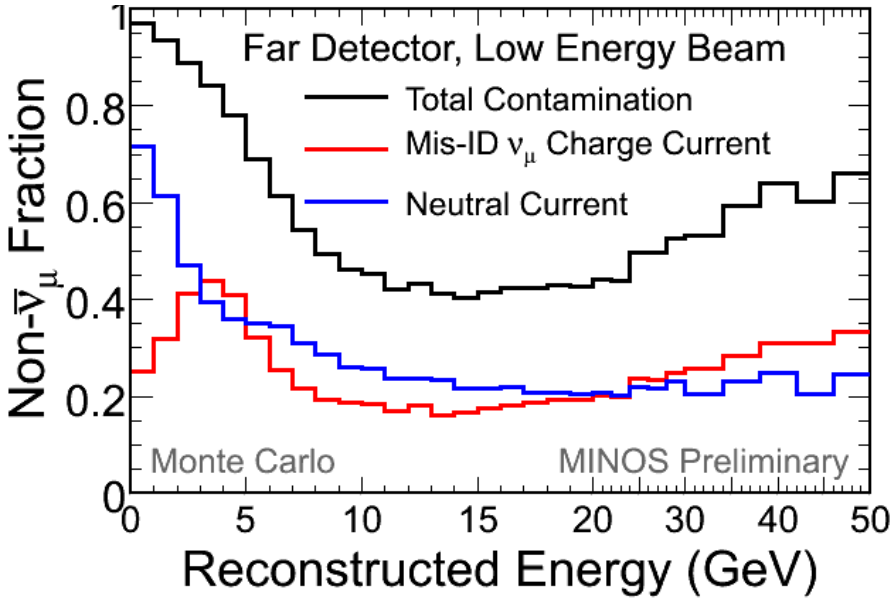


Selection

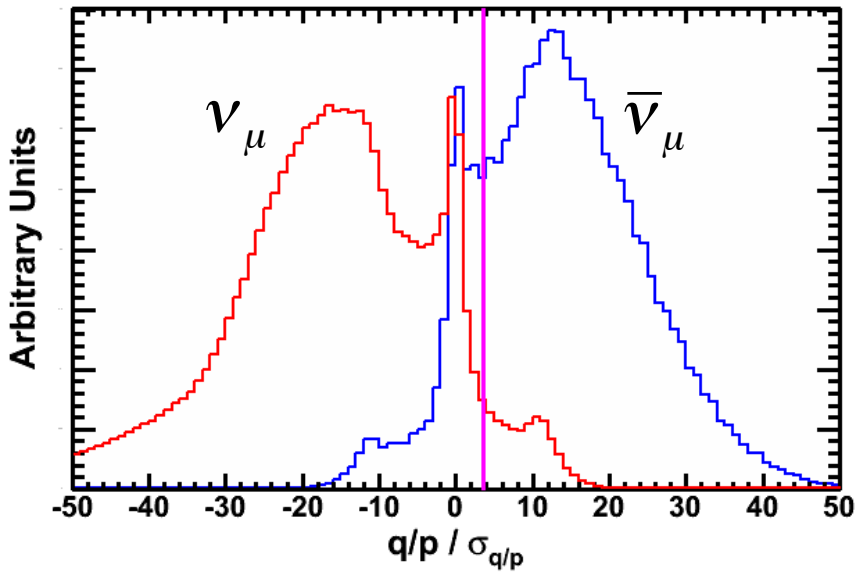
- Antineutrino signature: μ^+
  - Ex: $\bar{\nu}_\mu + p \rightarrow n + \mu^+$
  - Long tracks, curving outwards in the detector



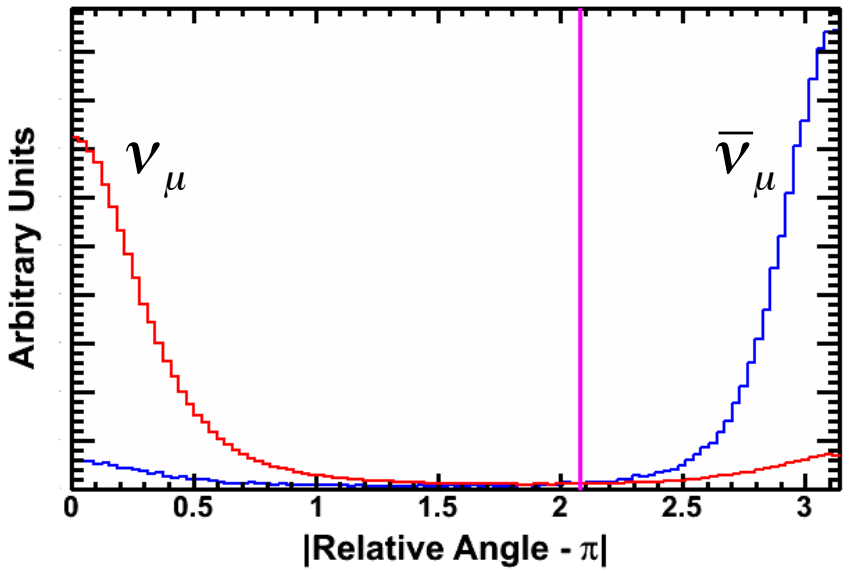
- Just selecting positive events is insufficient



Selection: Charge Sign



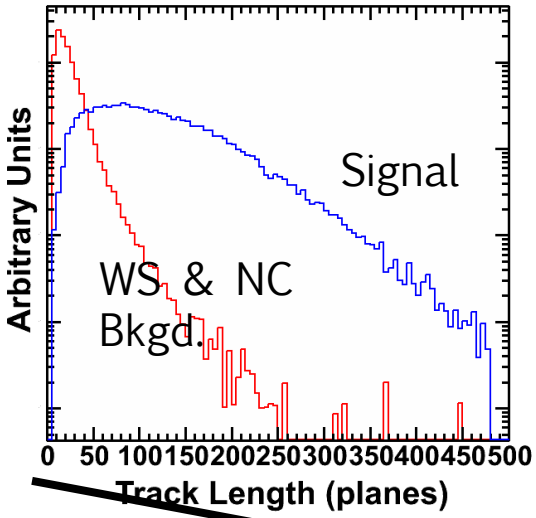
$(q/p) / \sigma_{(q/p)}$

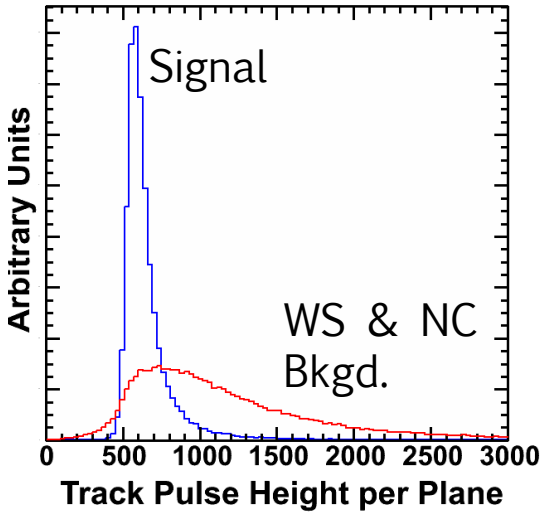


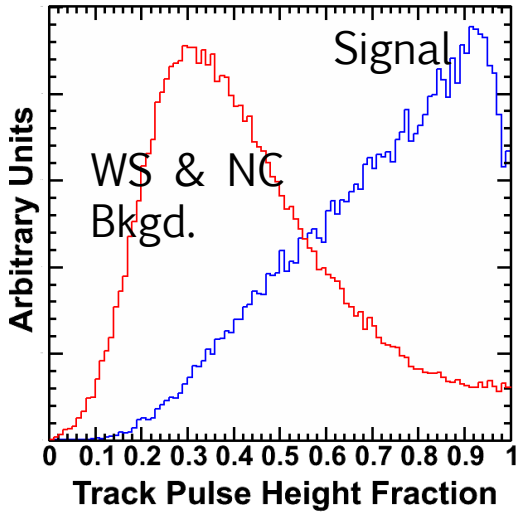
|Relative angle - π|

- Significance of the measured curvature
- Change in angle between the beginning and end of the track.

Selection: CC-NC

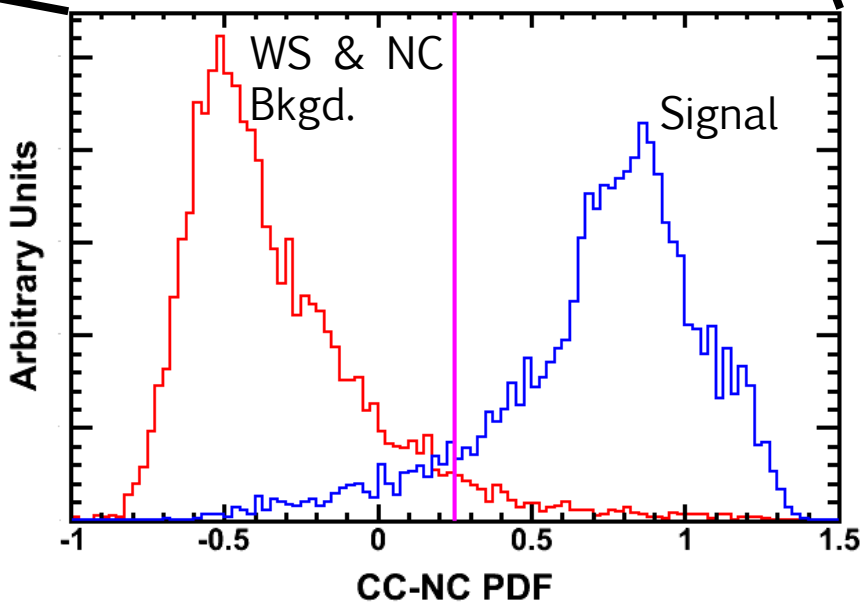




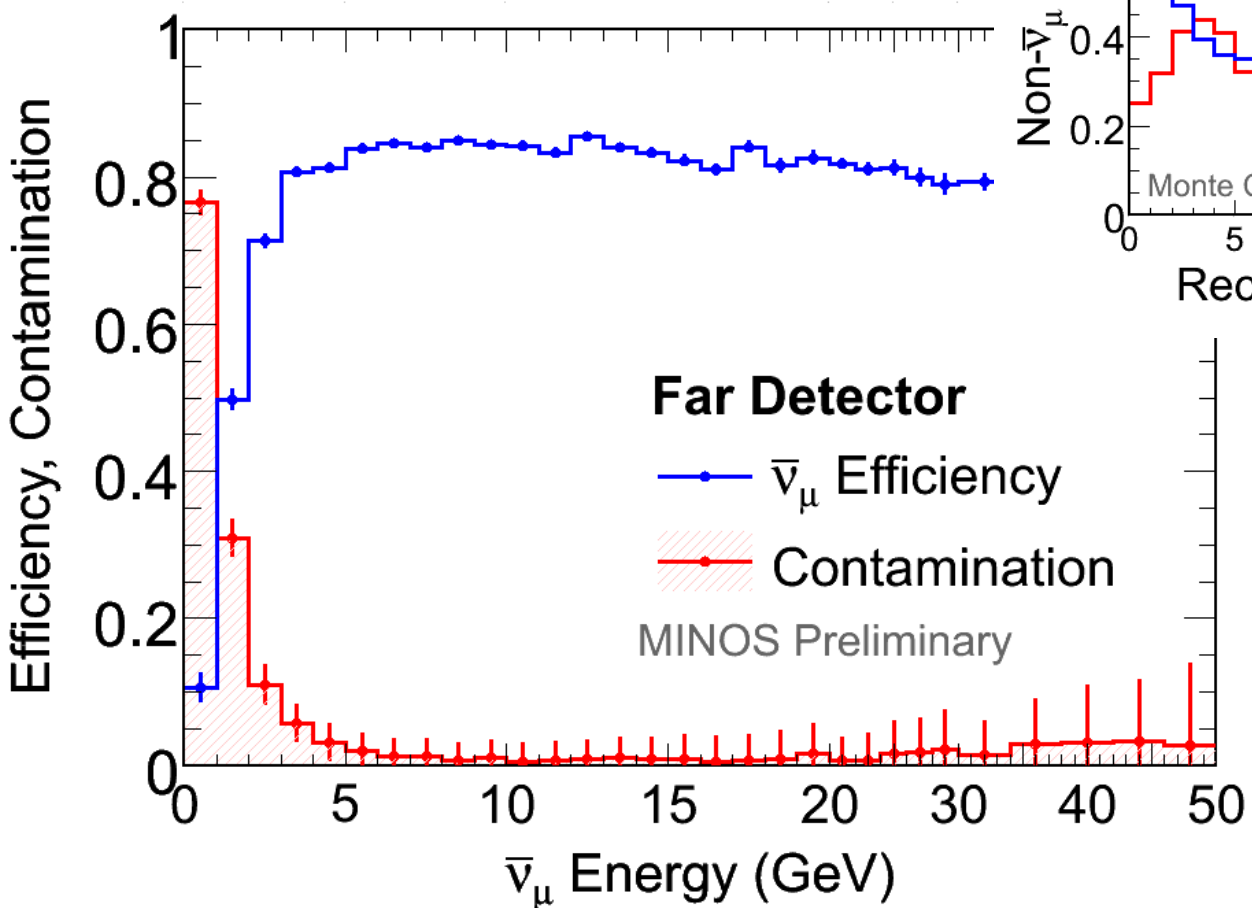


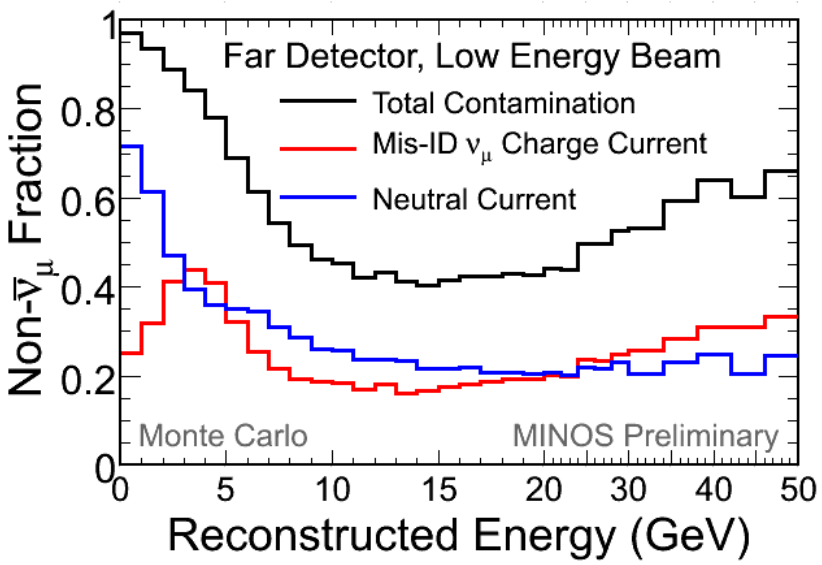
Discriminates on:

- Event length
- ~ dE/dx
- ~ y



Selection

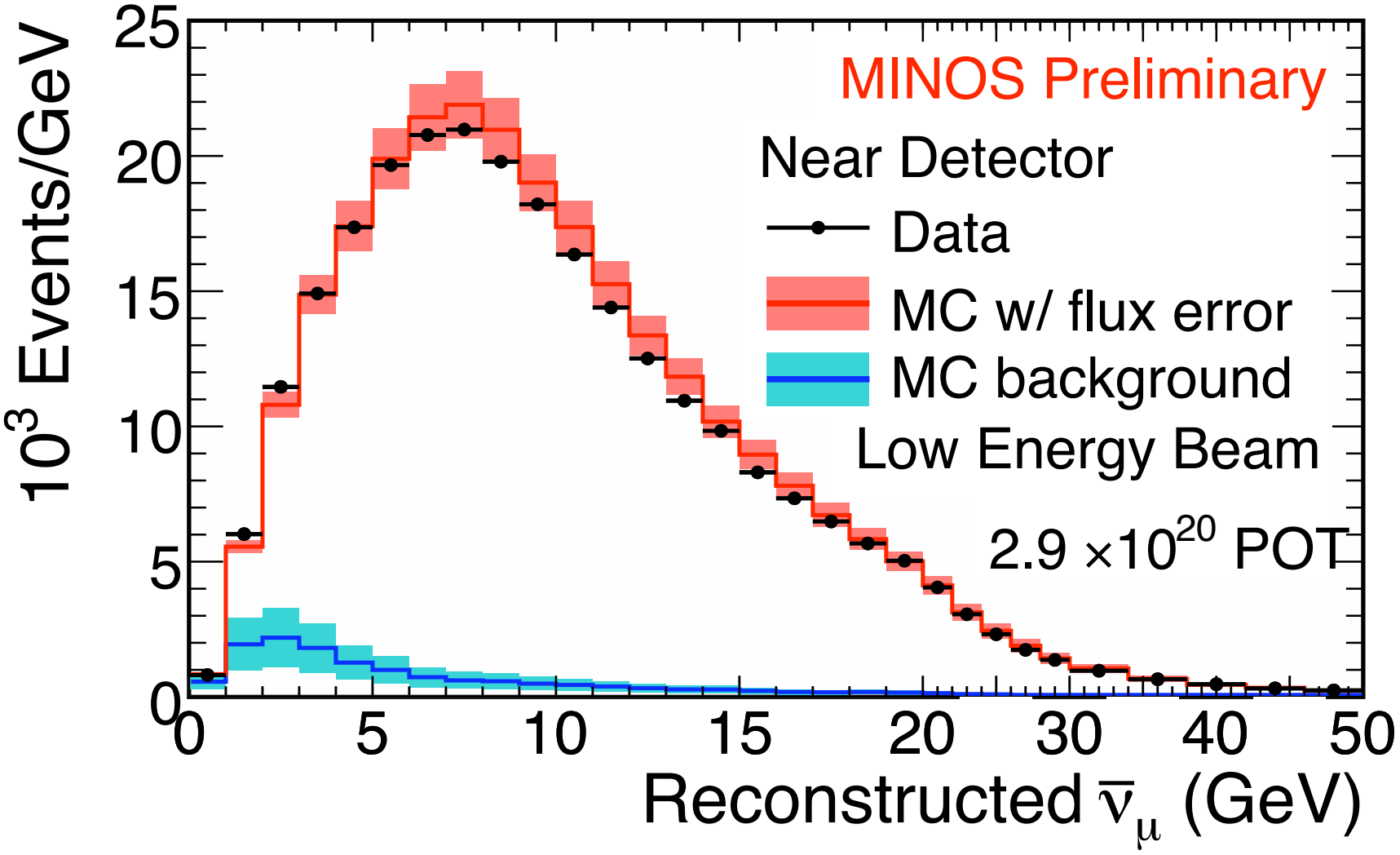




82% efficiency

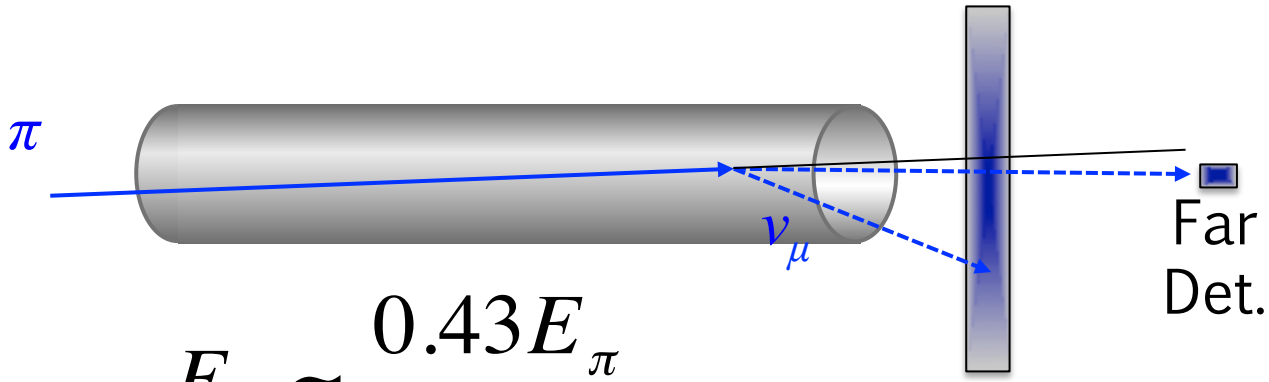
97% purity

Near Detector Spectrum

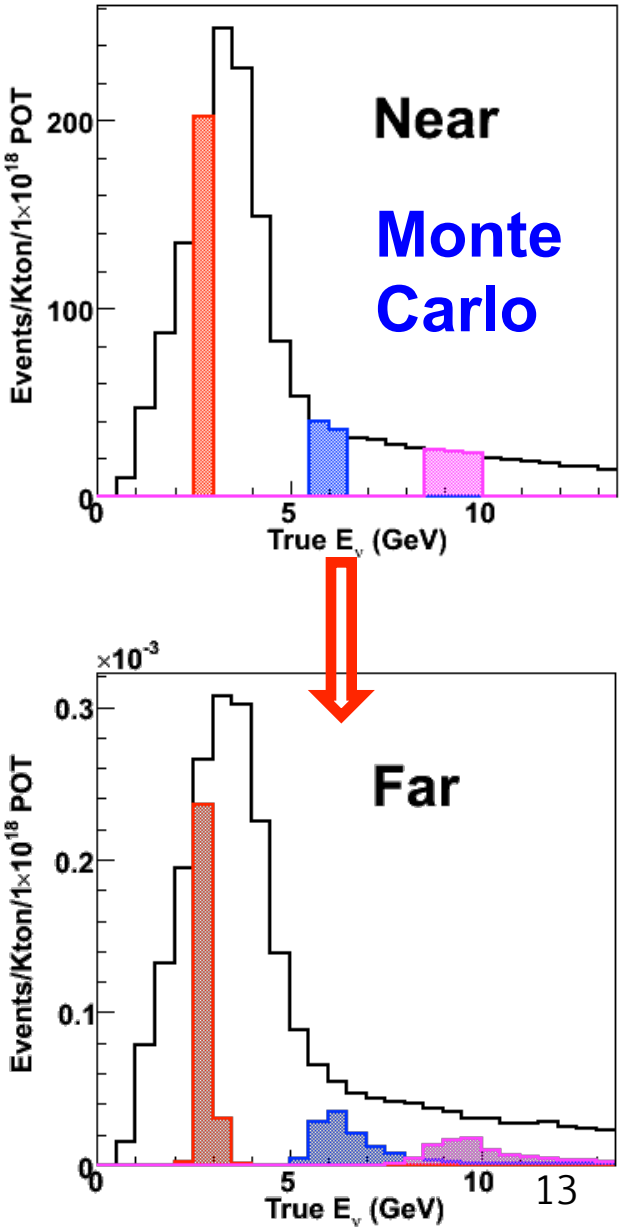


Near-to-Far Extrapolation

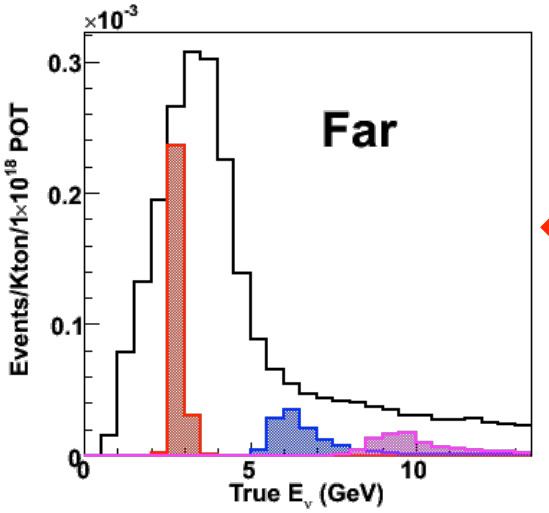
- The Near Detector and Far Detector spectra are not identical.

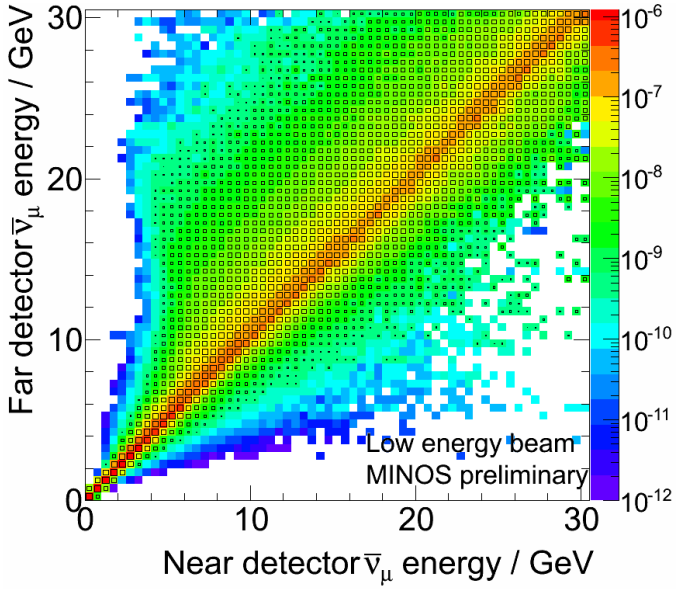


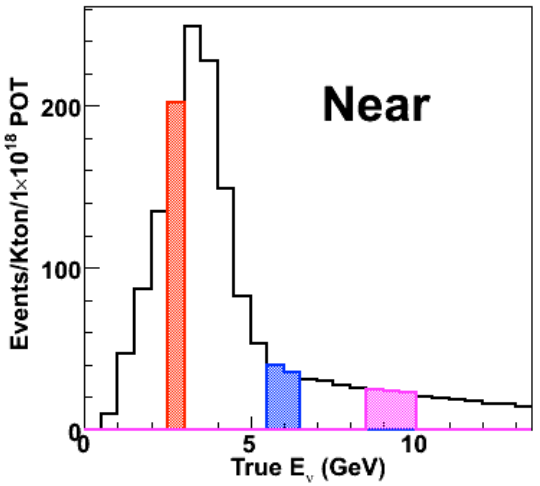
$$E_\nu \approx \frac{0.43 E_\pi}{1 + \gamma_\pi^2 \theta_\nu^2}$$



Beam Matrix Extrapolation



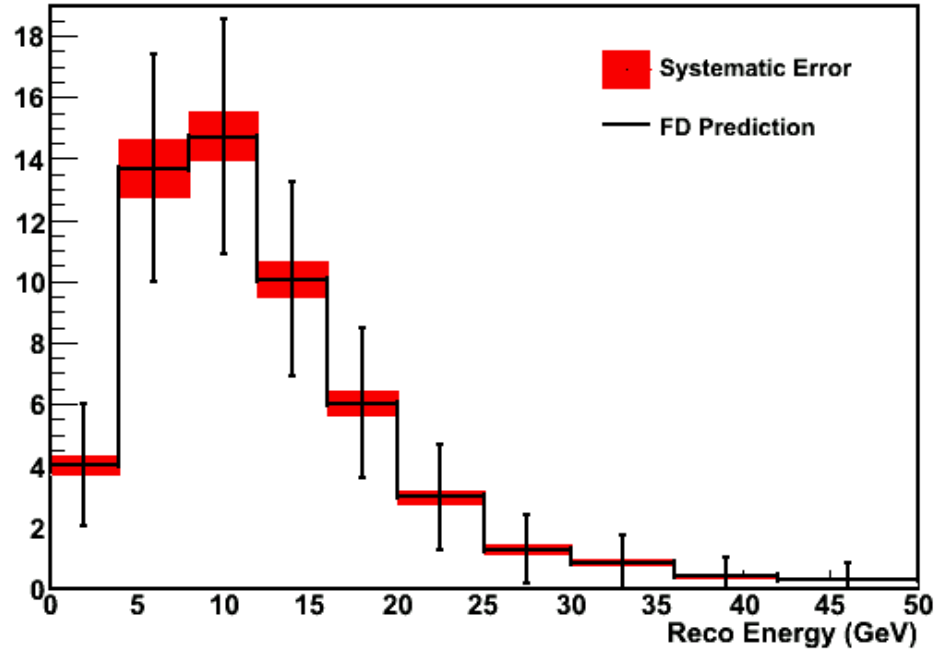


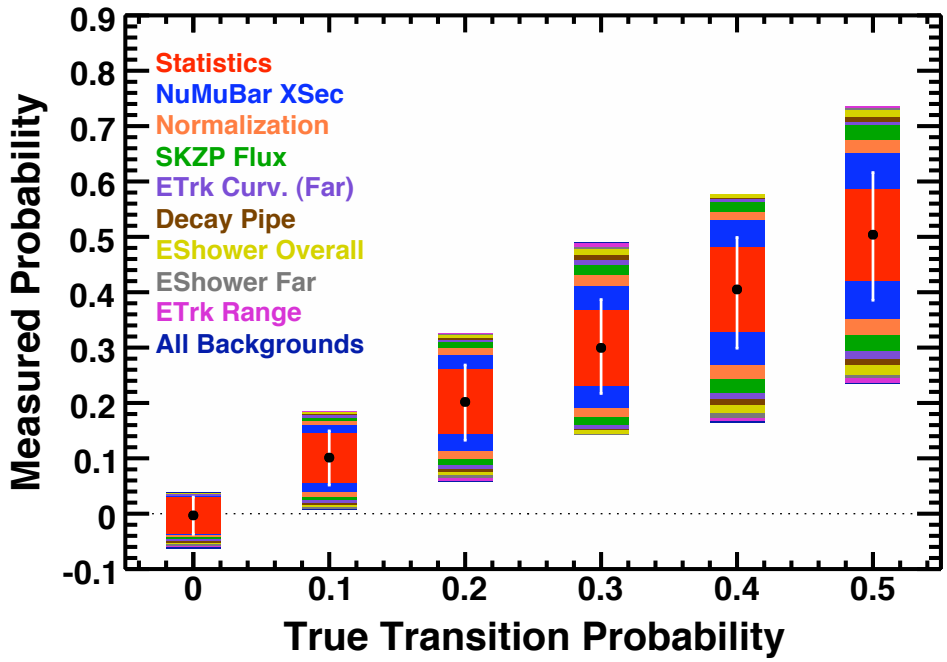


Monte Carlo

- A beam matrix transports measured Near Det. spectrum to the Far Det.
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
- MC used to correct for energy smearing and acceptance

Systematics

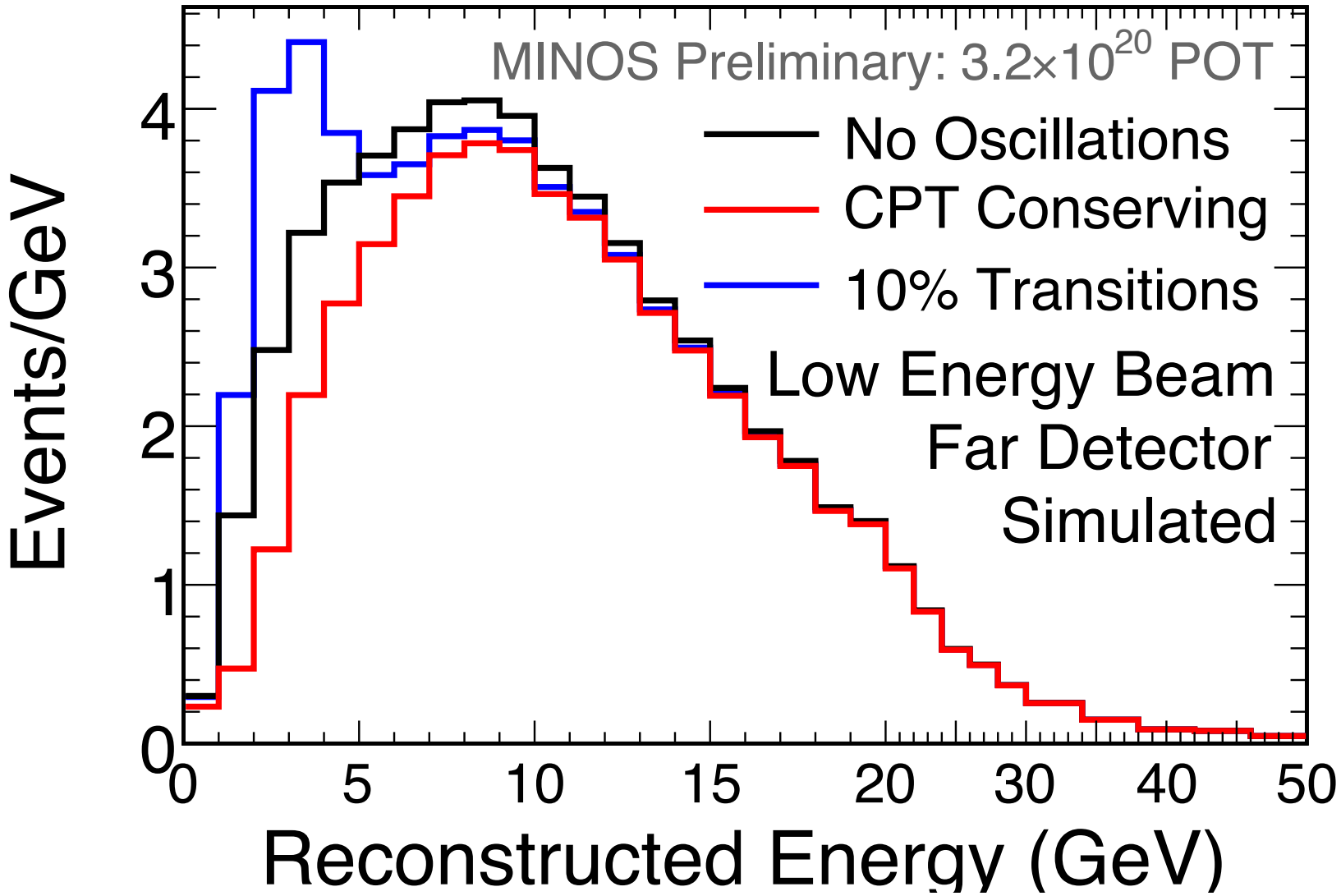




- Systematic errors are much smaller than the statistical uncertainty.

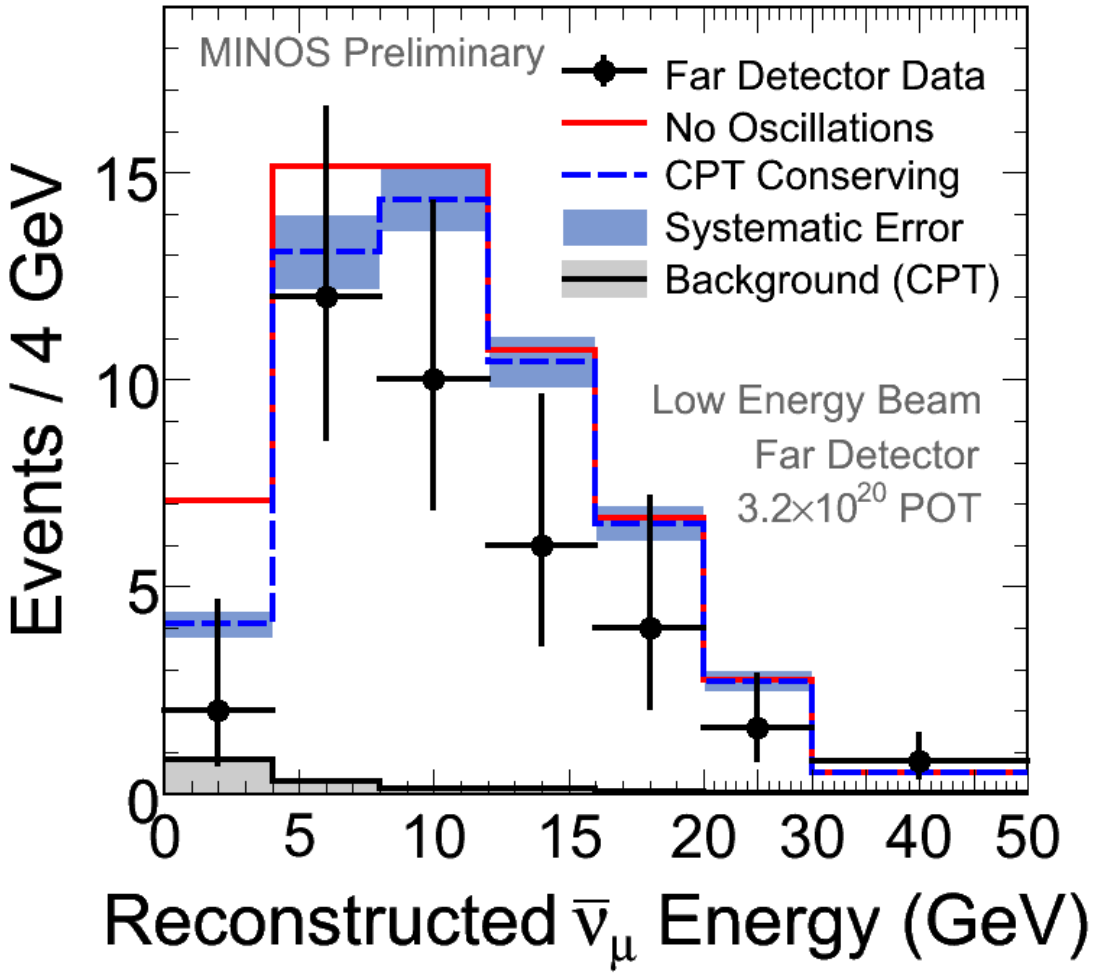
- Systematics are small at low transition probability, comparable to statistics at high.
- The white bars show all errors summed in quadrature.

Neutrino-mode Signals

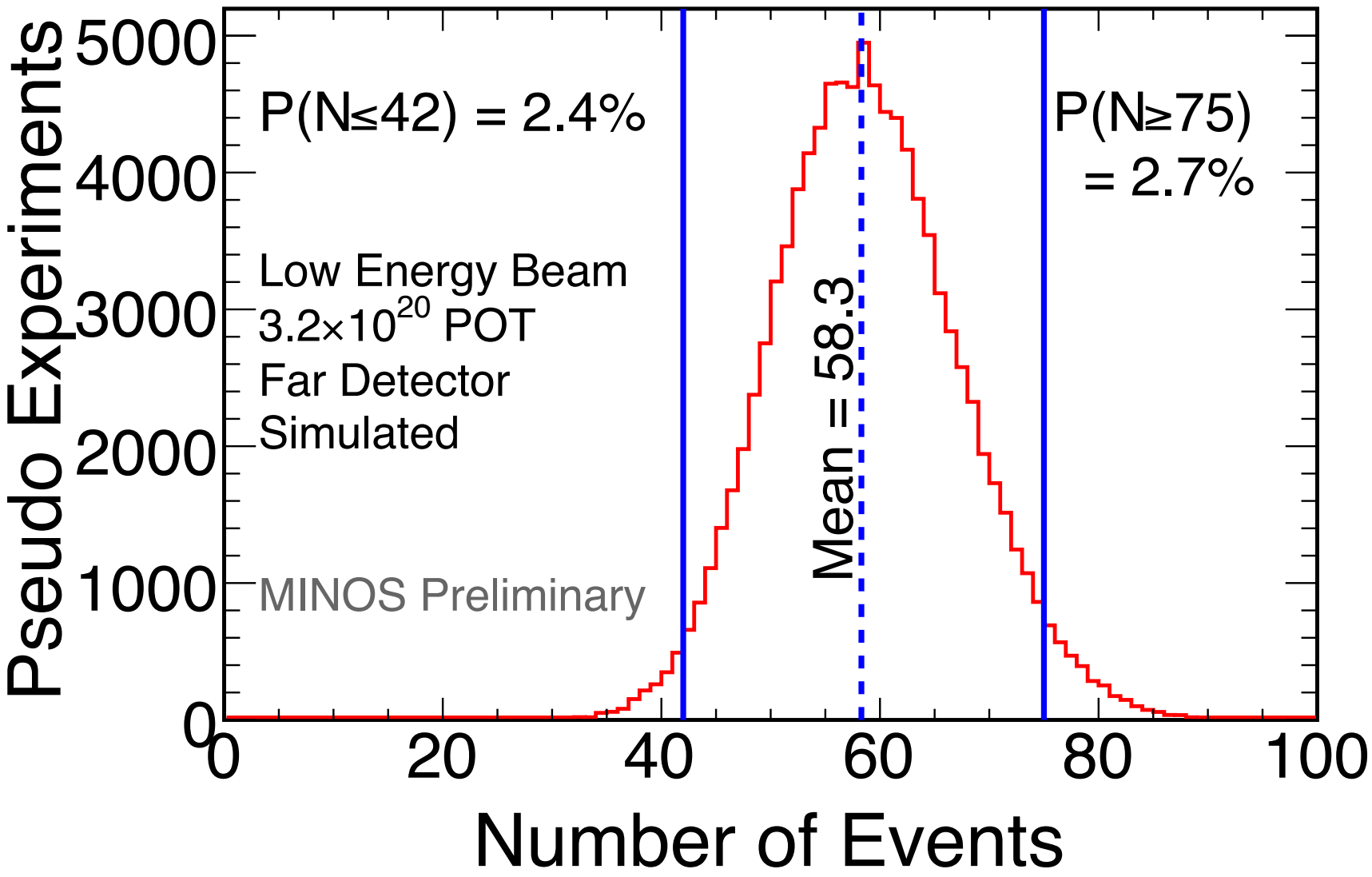


Far Detector Spectrum

- Observe:
  42 events
- CPT Oscillations:
  - 58.3 ± 7.6 (stat.)
    ± 3.6 (syst.)
- No oscillations:
  - 64.6 ± 8.0 (stat.)
    ± 3.9 (syst.)



Event Count


Pseudo Experiments
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
Number of Events
P(N≤42) = 2.4%
P(N≥75)
= 2.7%
Low Energy Beam
3.2×10^20 POT
Far Detector
Simulated
MINOS Preliminary
Mean = 58.3



Fitting for Oscillations



- Fit performed by minimizing a binned -log likelihood

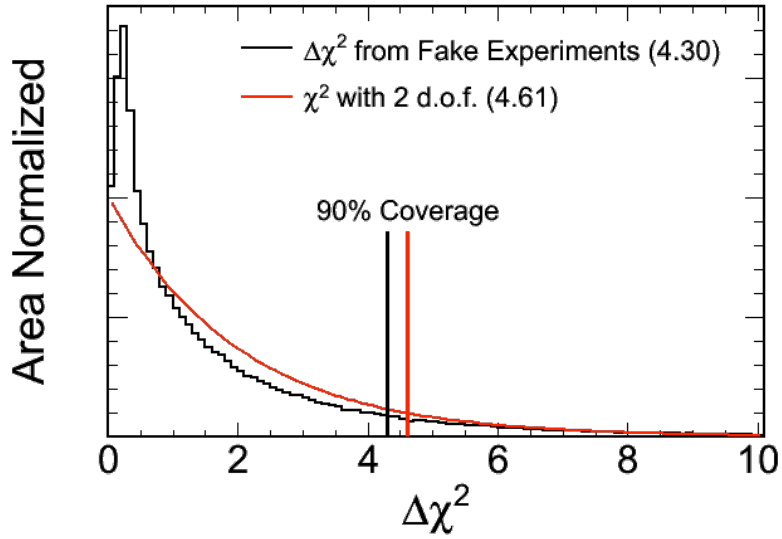
$$-2\ln L(\vec{\alpha}) = 2\sum_i \left[p_i(\vec{\alpha}) - d_i + d_i \ln \frac{d_i}{p_i(\vec{\alpha})} \right]$$

$$\vec{\alpha} = [\Delta\overline{m}^2_{\mathrm{atm}}, \sin^2(2\overline{\theta}_{23})]$$

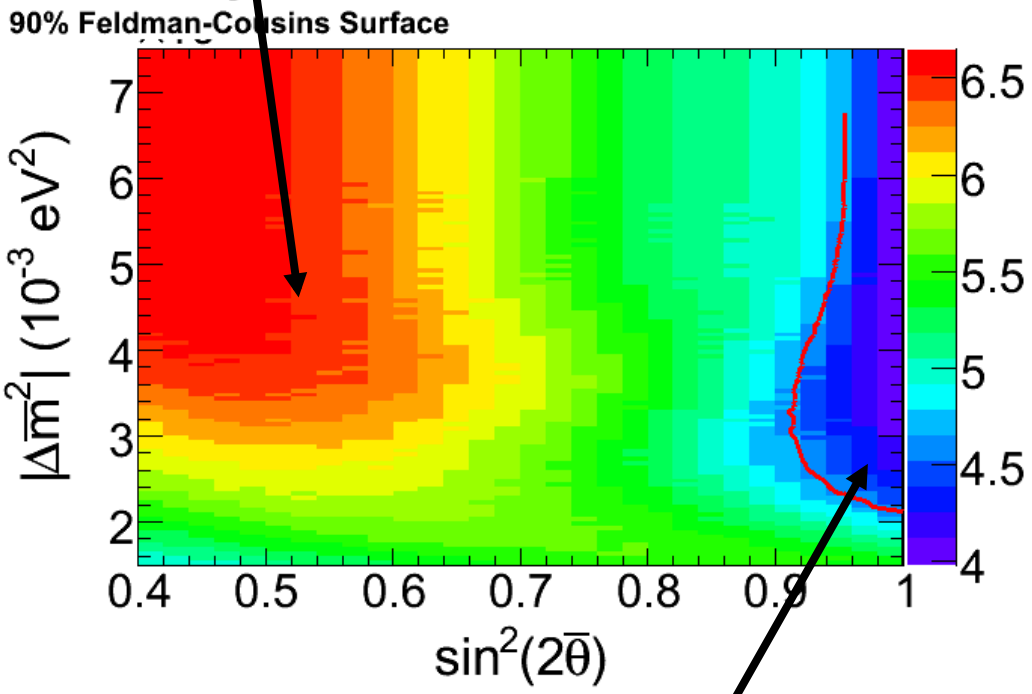
- A Feldman-Cousins approach is used
  - Many fake experiments used create empirical χ^2 distributions as a function of the parameters
  - Systematics included in the fake experiments

Feldman-Cousins

- Each point is the $\Delta\chi^2$ that encompasses 90% of fake experiments
  - A perfectly Gaussian surface would be 4.7 everywhere.



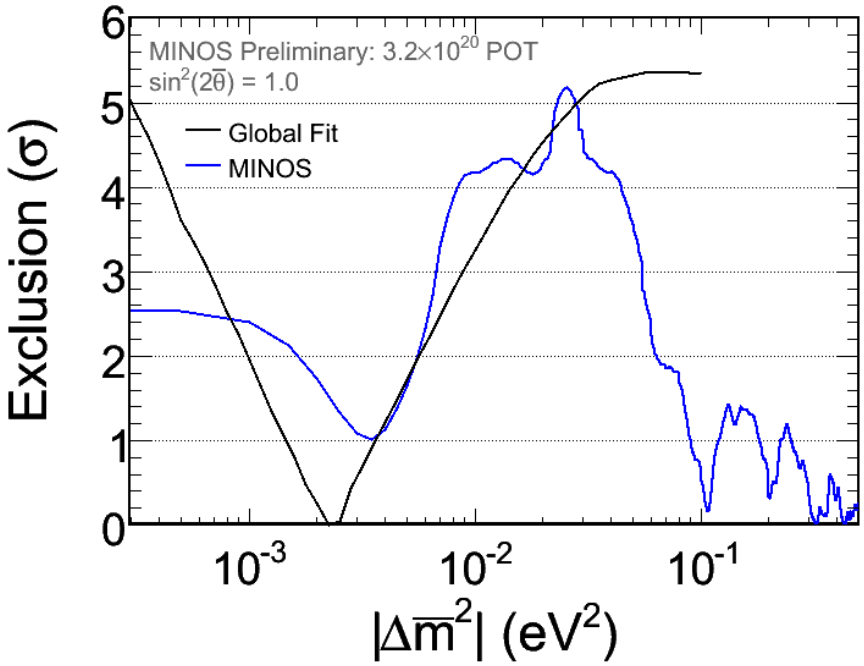
Worse than Gaussian Degeneracy with fast oscillations

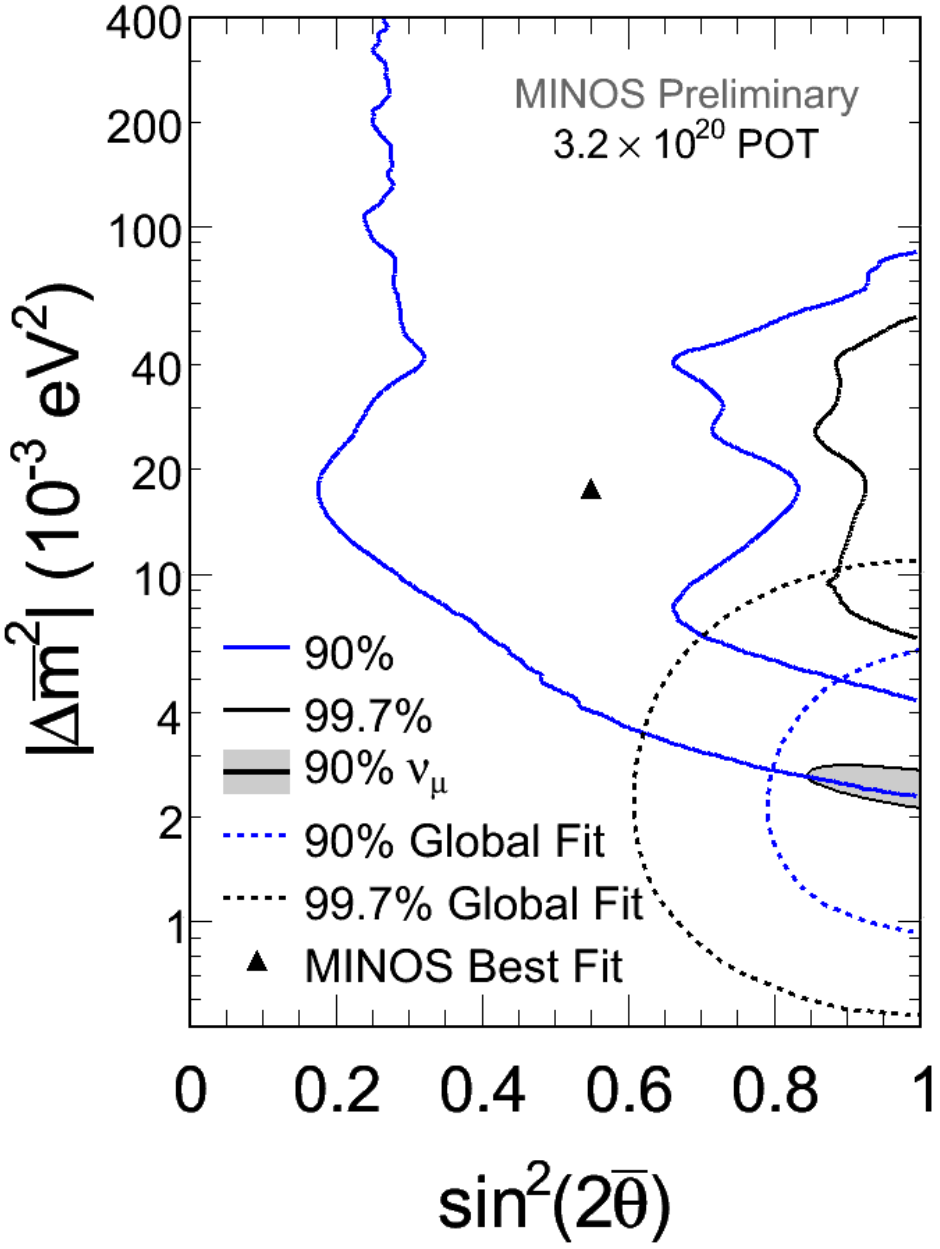


Better than Gaussian Physical boundary gives extra information

Oscillations Result

- Sensitivity limited due to:
  - Low statistics
  - Few low-energy events



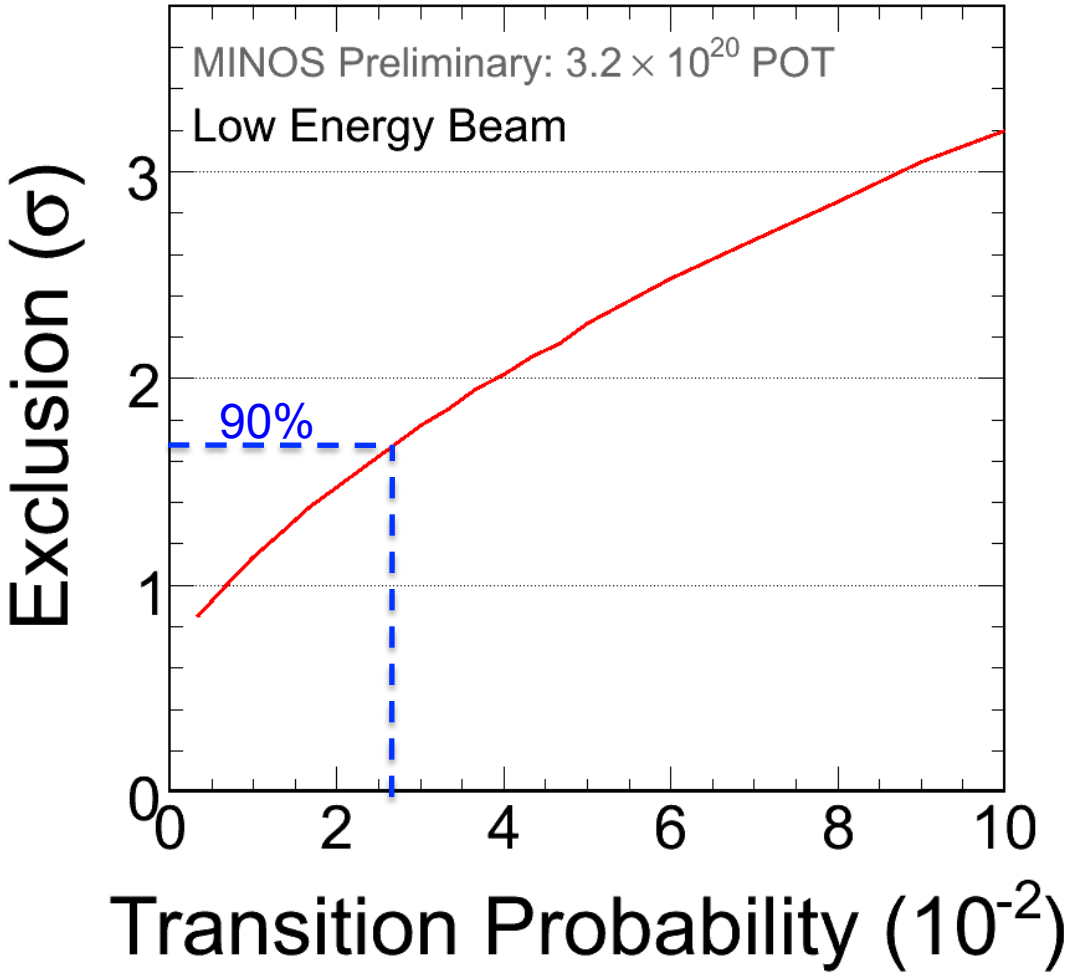


Appearance Result

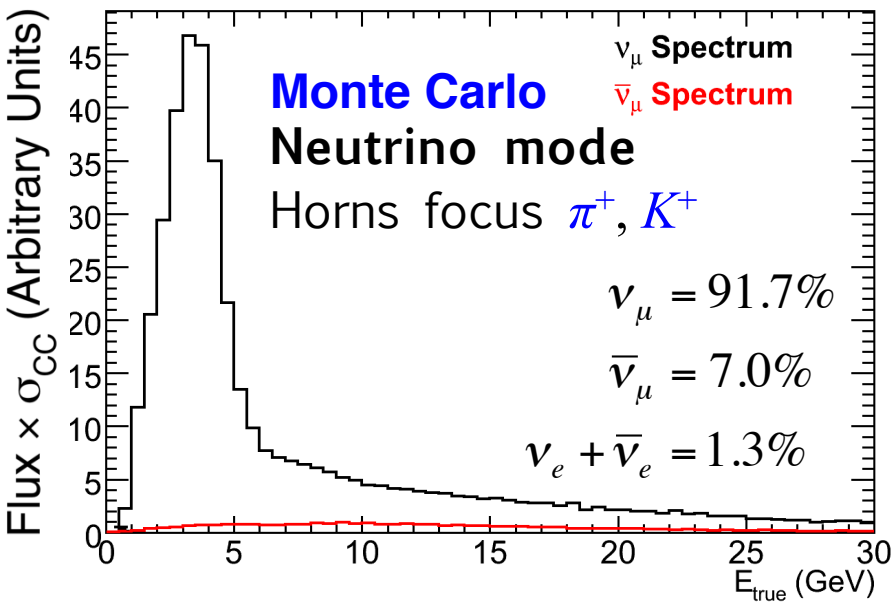
$$P(\nu_\mu \rightarrow \bar{\nu}_\mu) = \alpha \sin^2(2\theta) \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

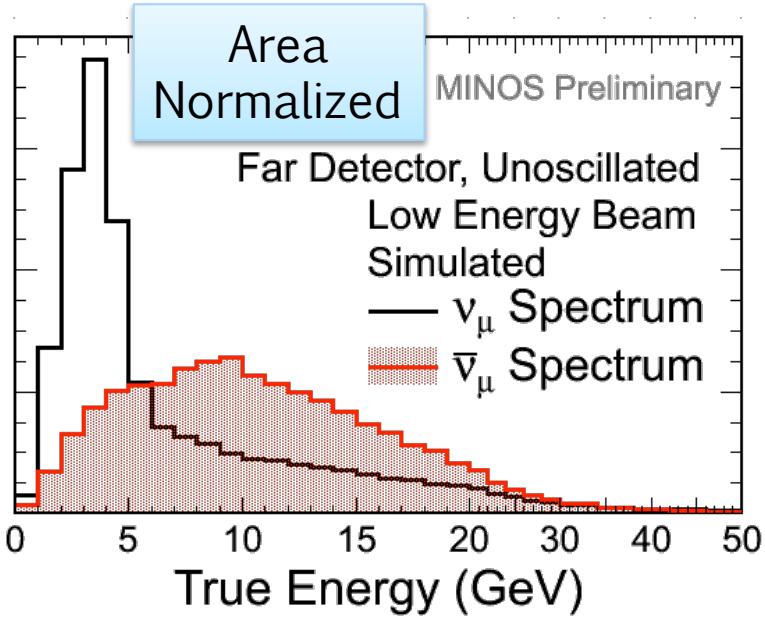
- MINOS observes
  no appearance of $\bar{\nu}_\mu$
  in the NuMI beam

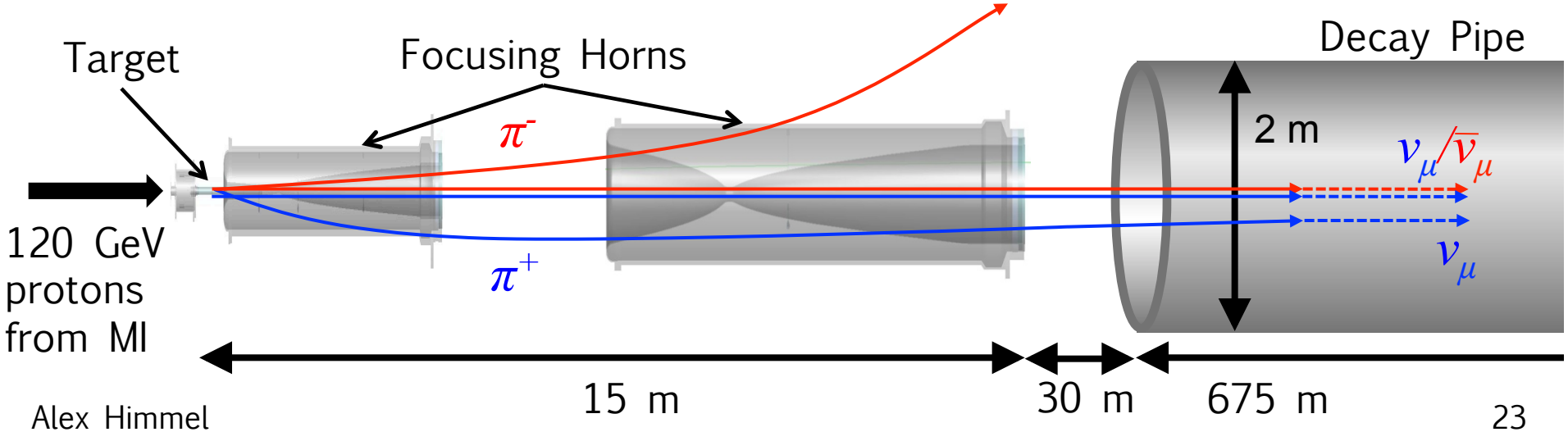
- We limit the fraction, α, of events transitioning from ν_μ to $\bar{\nu}_\mu$:
  $\alpha < 0.026$ (90% C.L.)



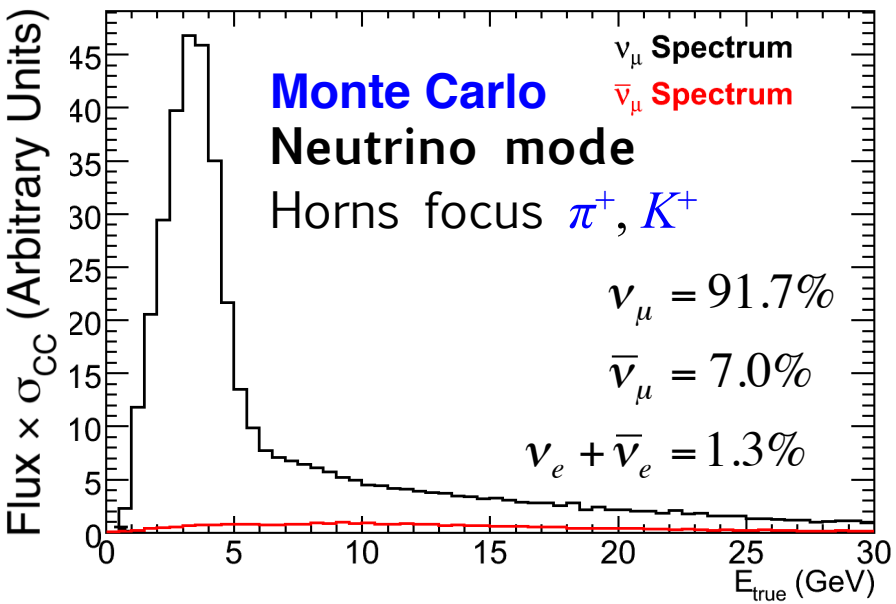
Neutrino Mode

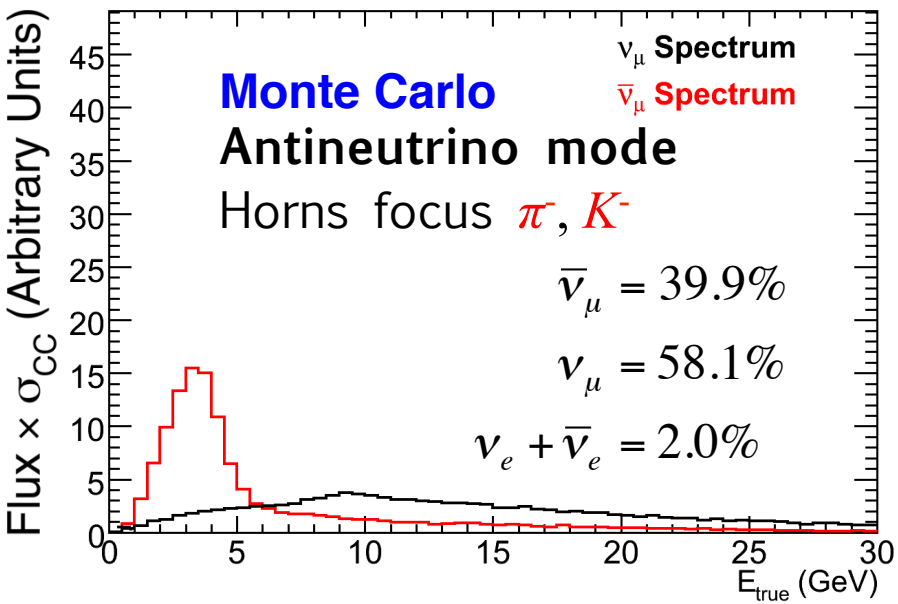


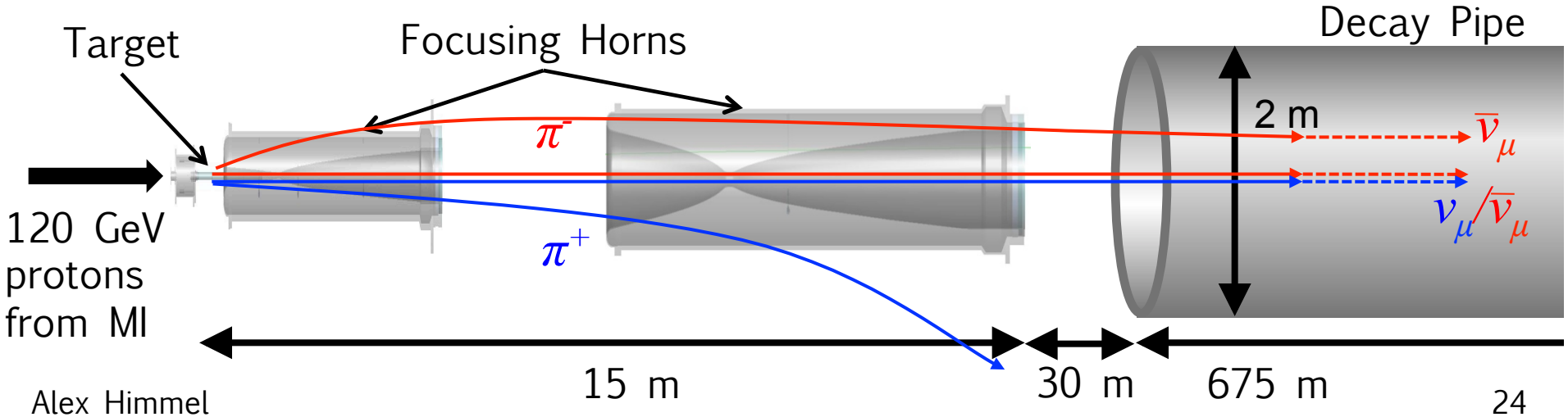




Antineutrino Mode

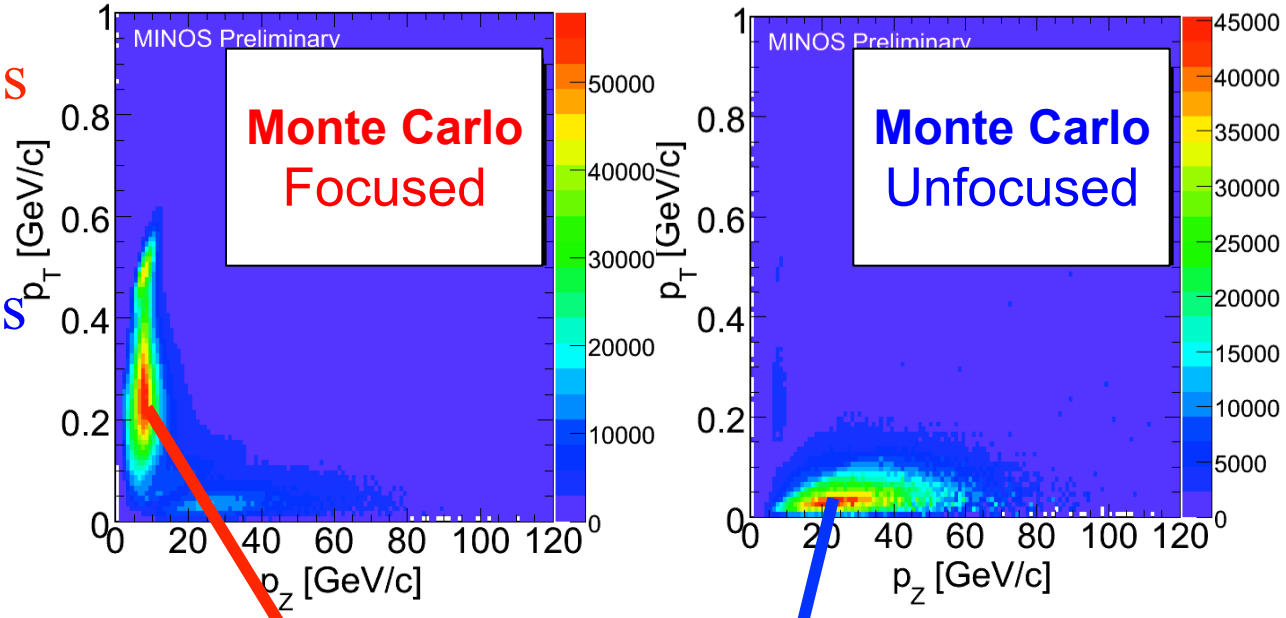


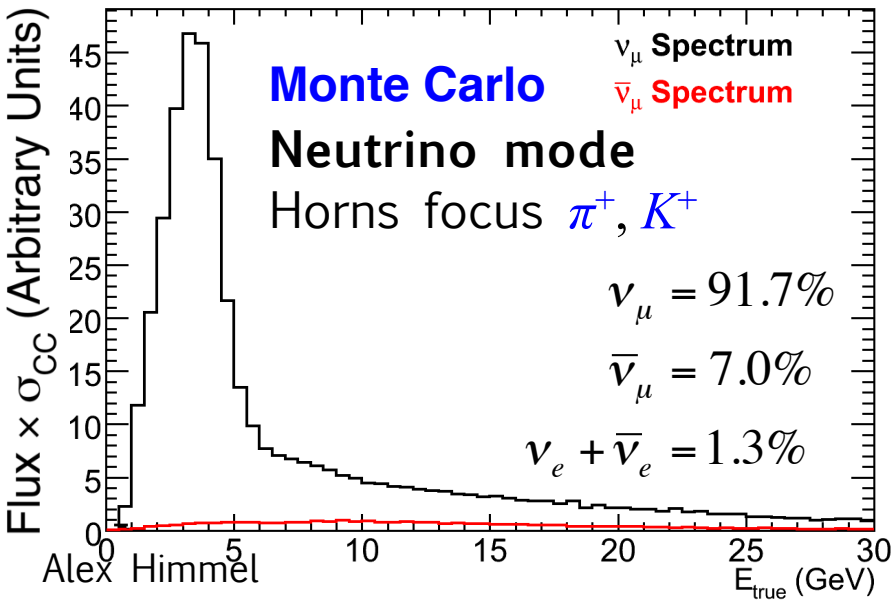


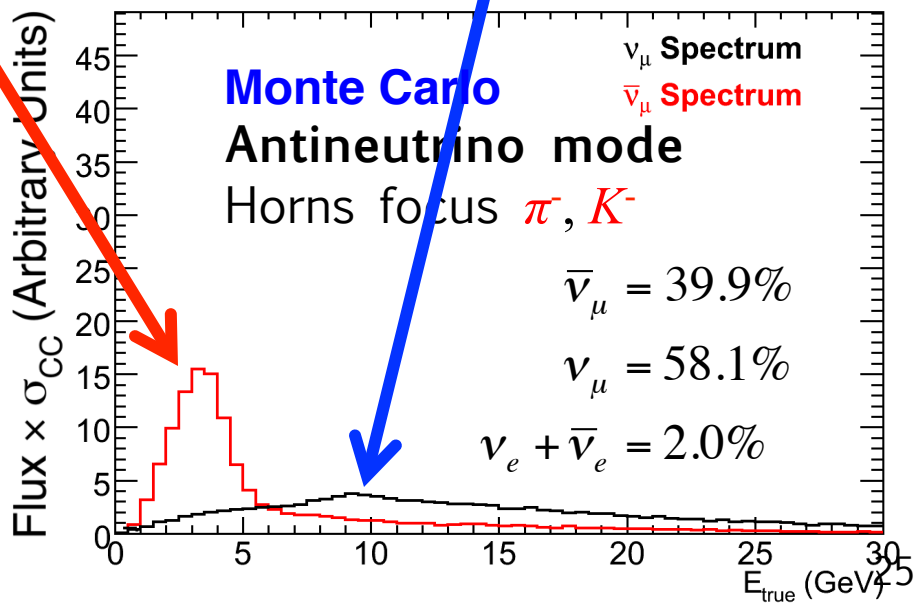


Peak vs. Tail

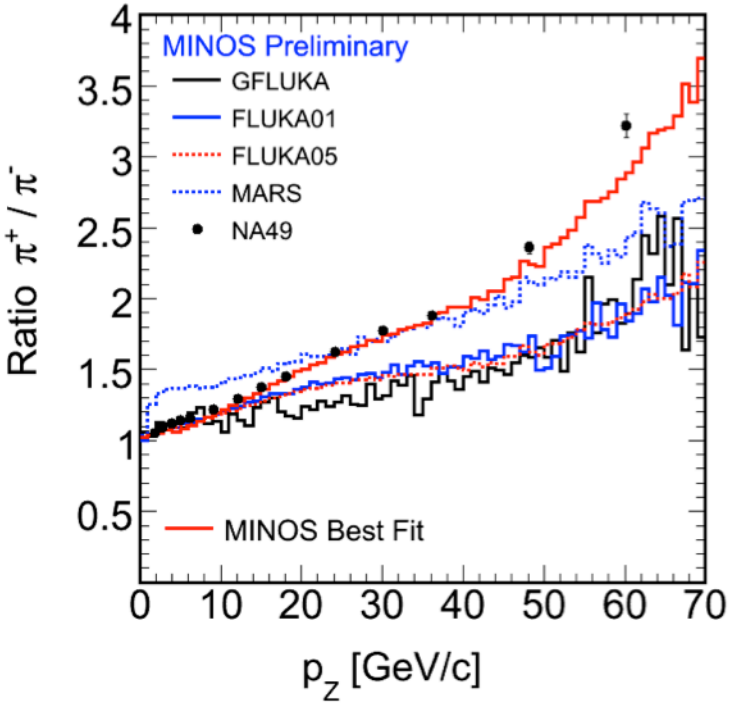
- ν_μ's from **low-p_t π^-'s**
  - Focused by horns
- ν_μ's from **high-p_t π^+'s**
  - Pass through horn center



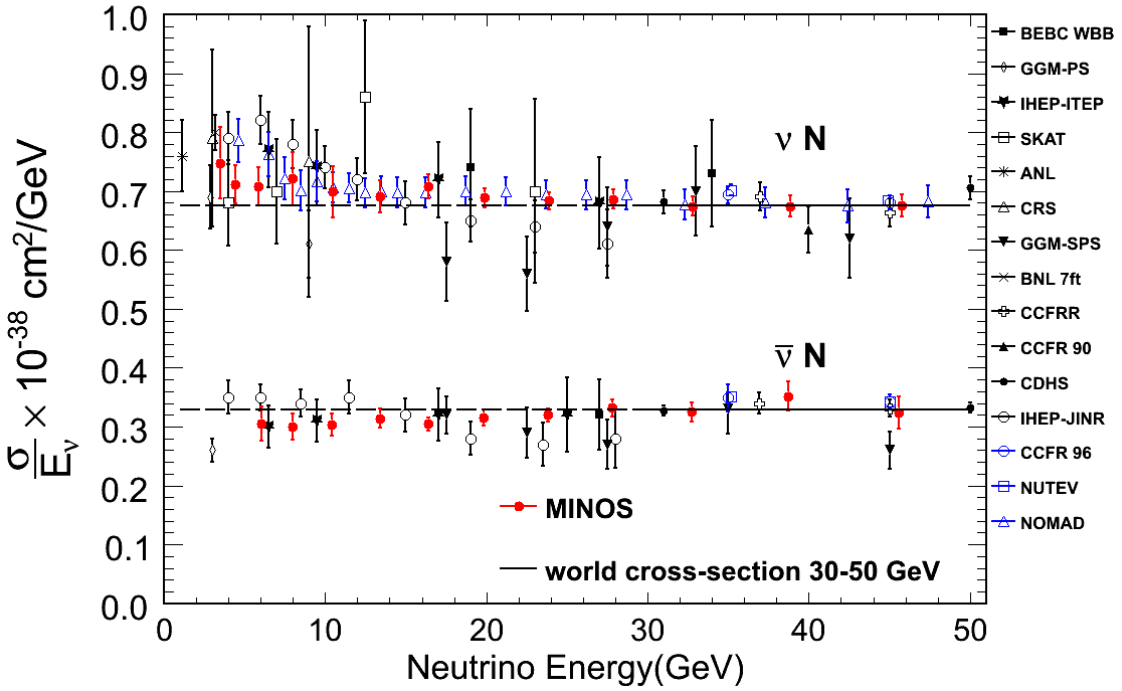




Antineutrino Cross-section



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

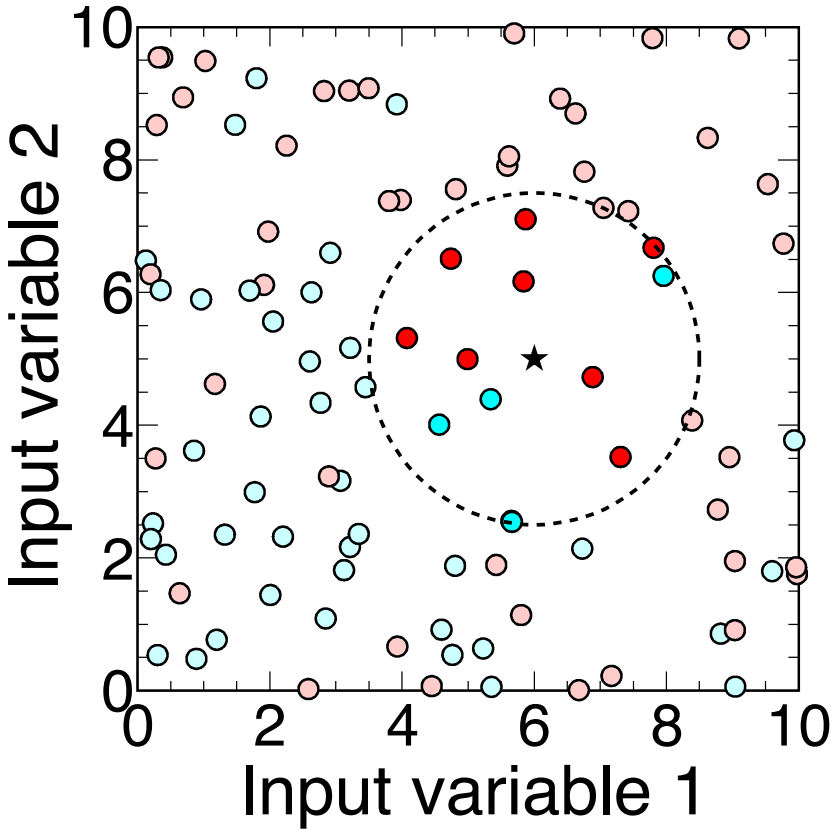


Phys. Rev. D 81 072002 (2010)

- x1.3 lower π^- production
- x2.3 lower interaction cross-section

Selecting Charged Currents

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to Monte Carlo events
  - Fraction of signal in *k* most similar events is the discriminant



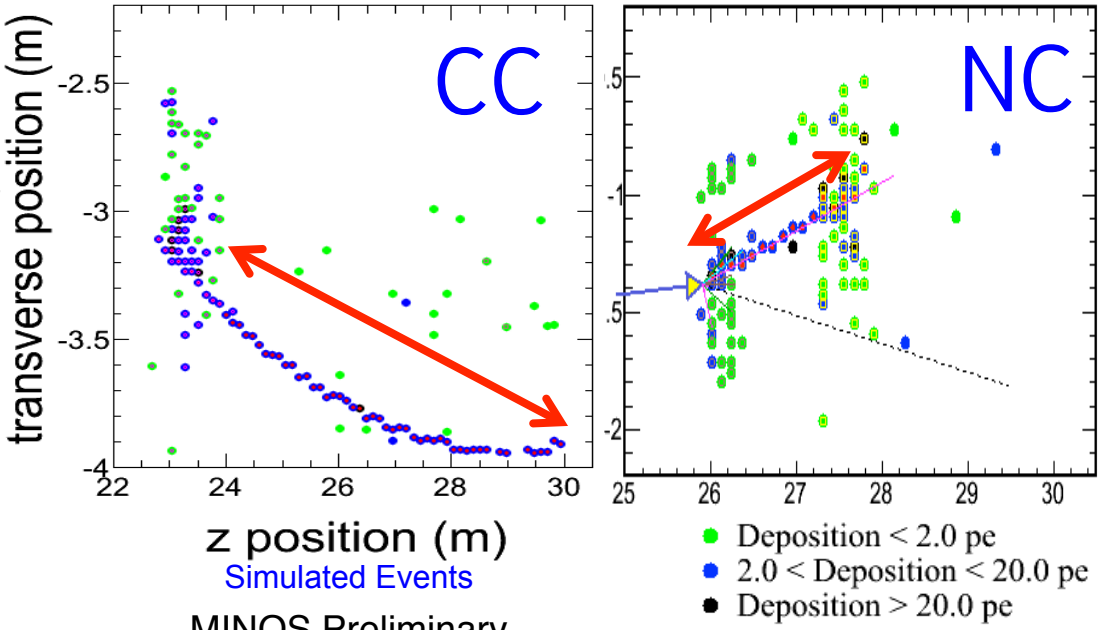
k-Nearest Neighbors

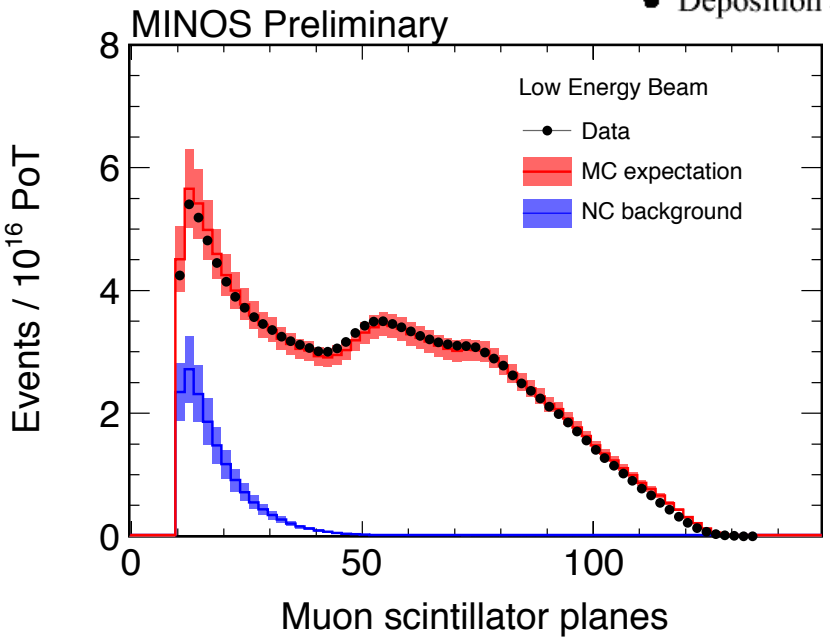
"kNN"

Selecting Charged Currents

- CC/NC separation using a kNN algorithm

- 4-parameter comparison
  - Track length
  - Transverse energy profile
  - Energy deposited per plane
  - Energy fluctuations along the track

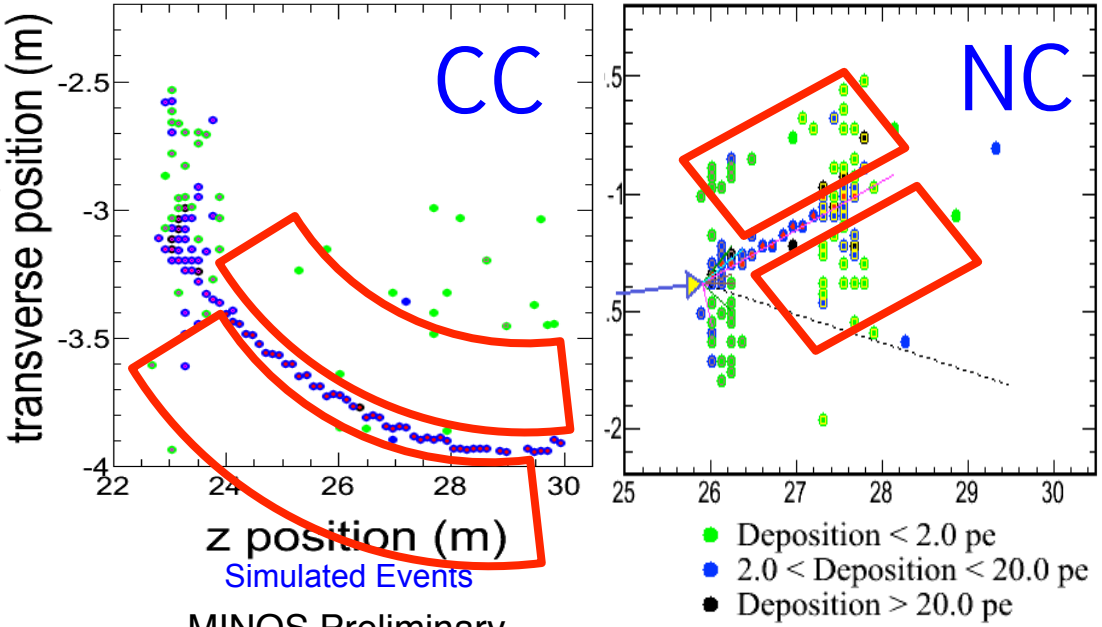


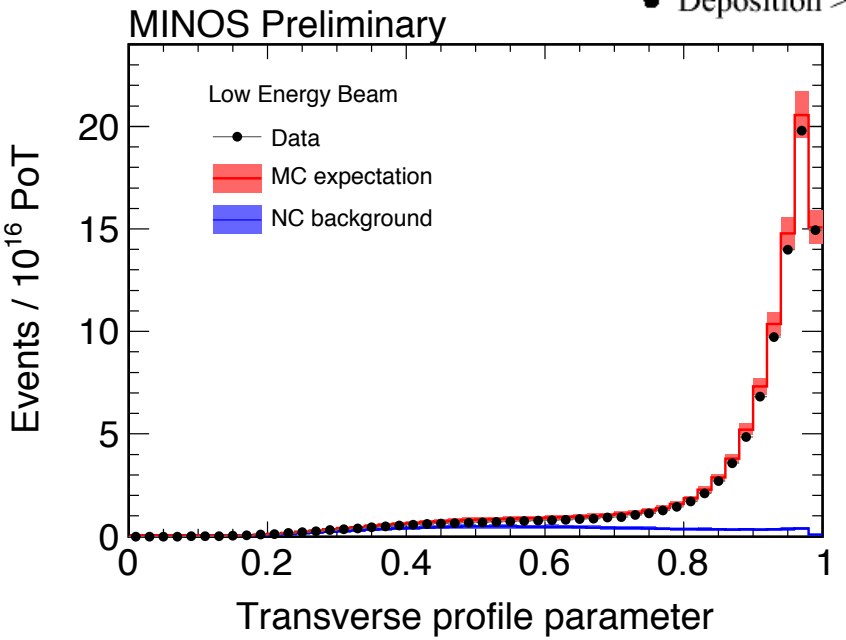


Selecting Charged Currents

- CC/NC separation using a kNN algorithm

- 4-parameter comparison
  - Track length
  - Transverse energy profile
  - Energy deposited per plane
  - Energy fluctuations along the track





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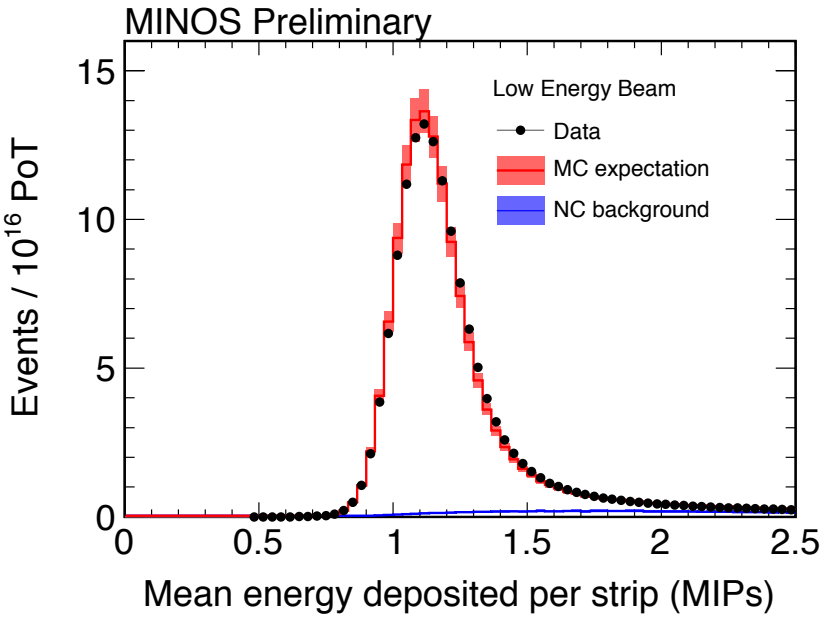
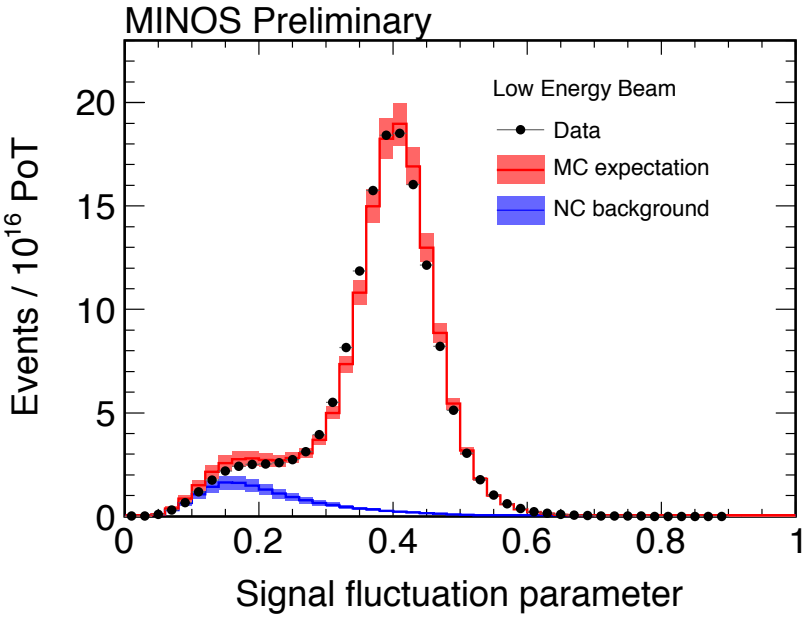
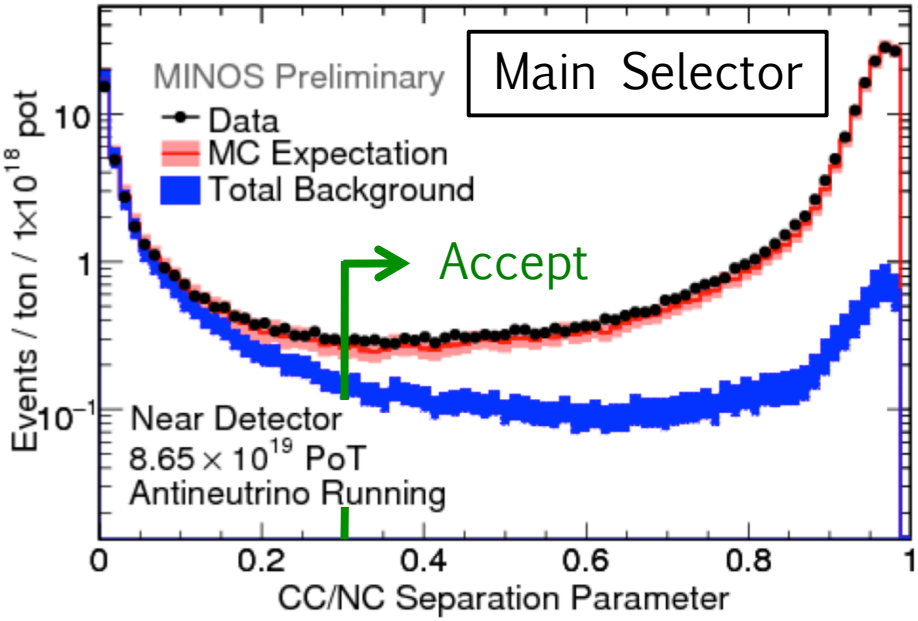
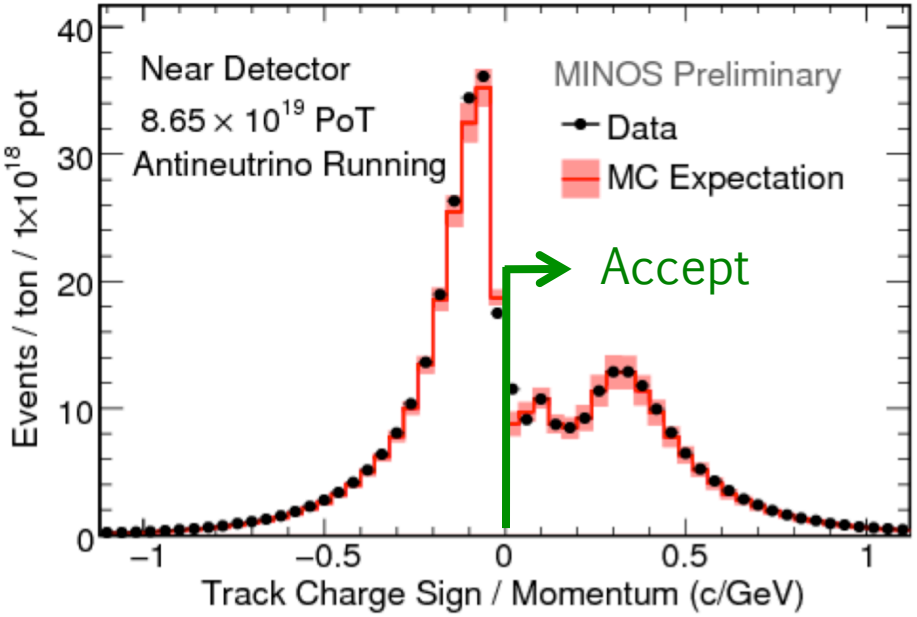




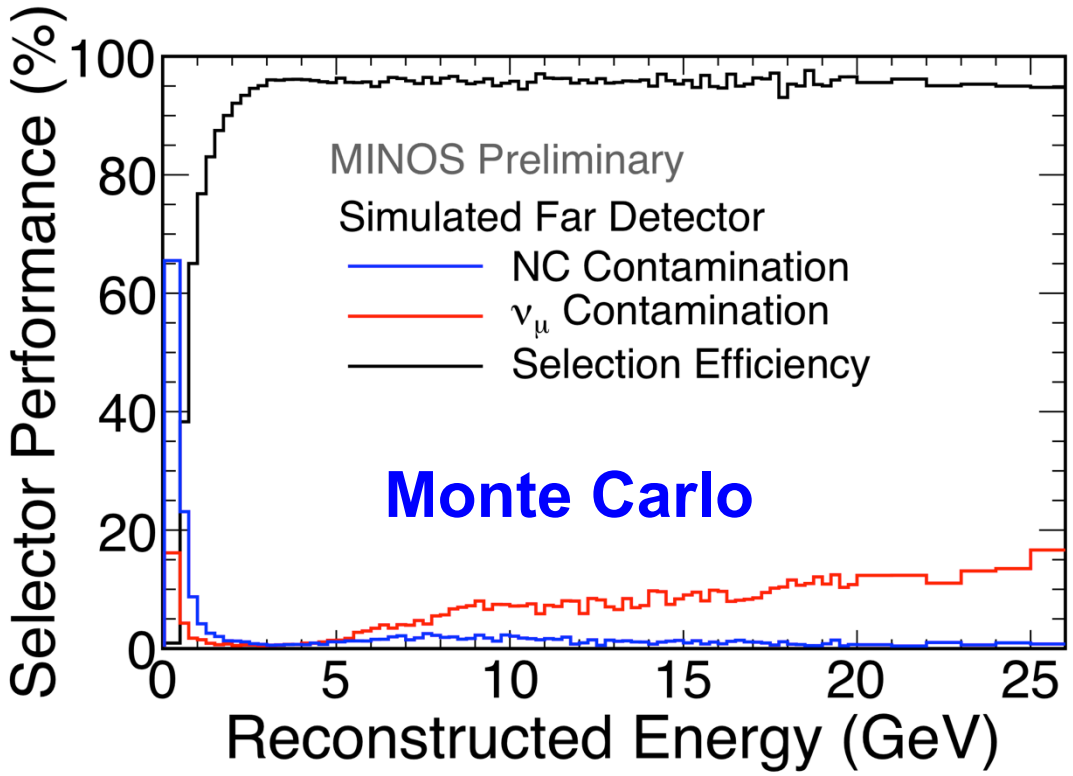
Selecting CC Antineutrinos

- Use the CC/NC Selector
  - Removes NC and high-y CC interactions
- Accept only events with positive reconstructed charge





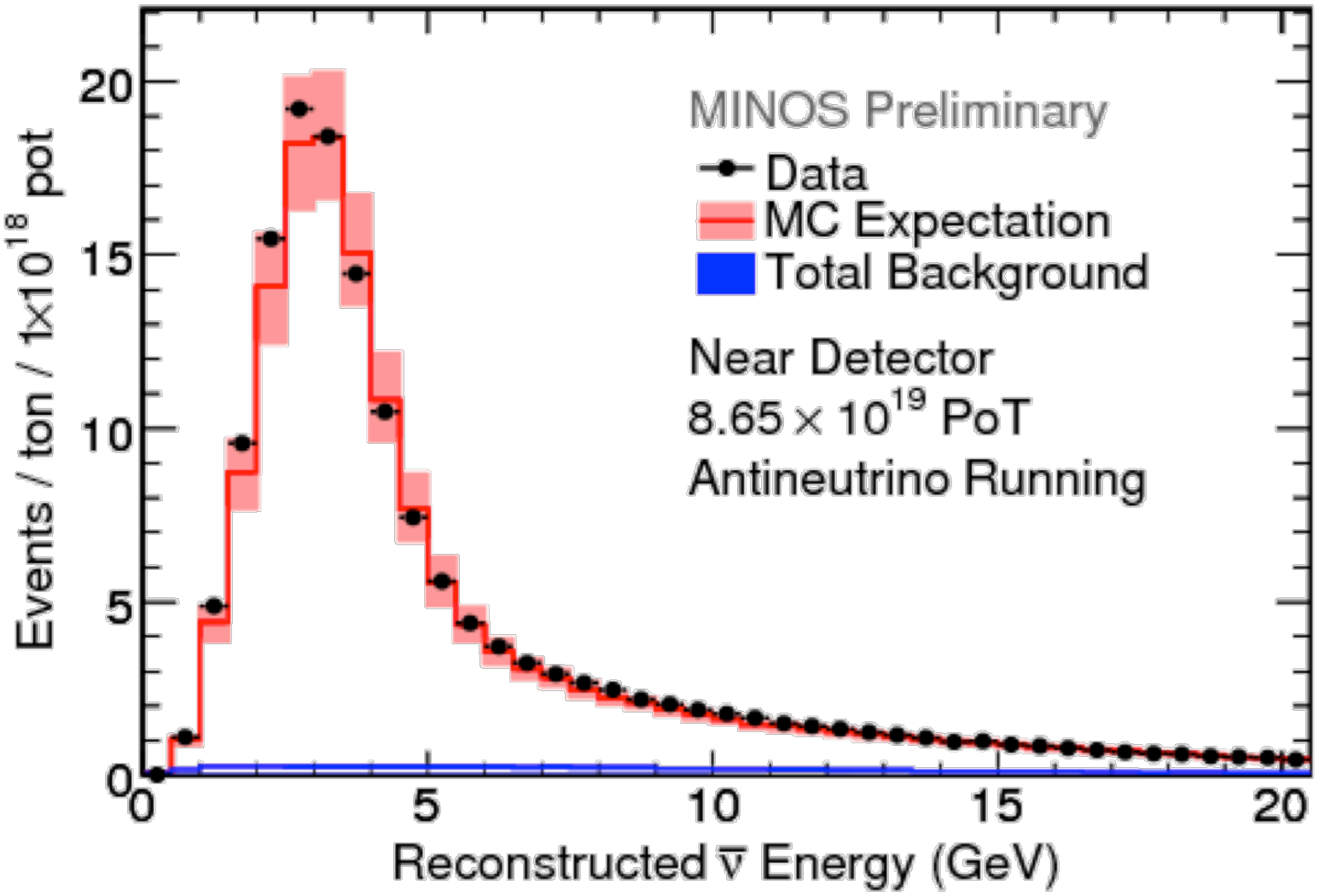
Efficiency & Purity



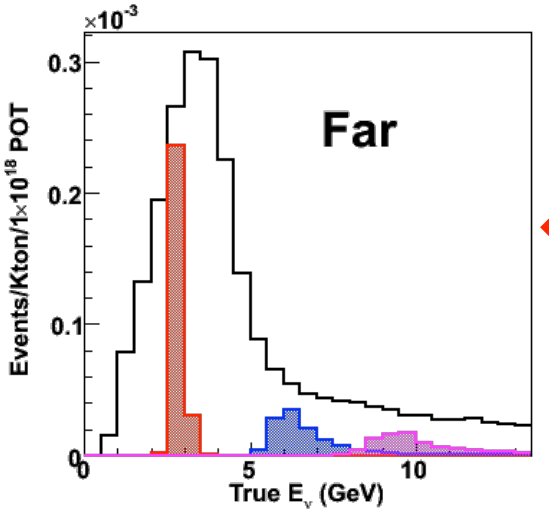
	Signal	Bkgd.
0-6 GeV	106	1.9
6-20 GeV	38	4.3
> 20 GeV	8	3.0

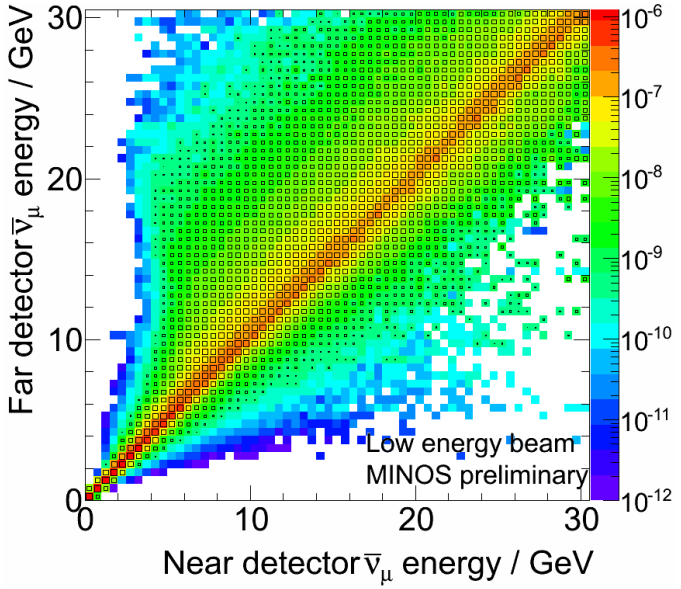
High energy ν_μ contamination does not affect the oscillation result

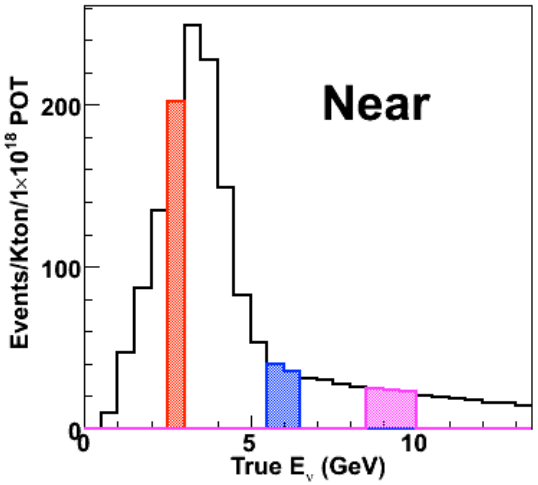
Near Detector Spectrum



Beam Matrix Extrapolation



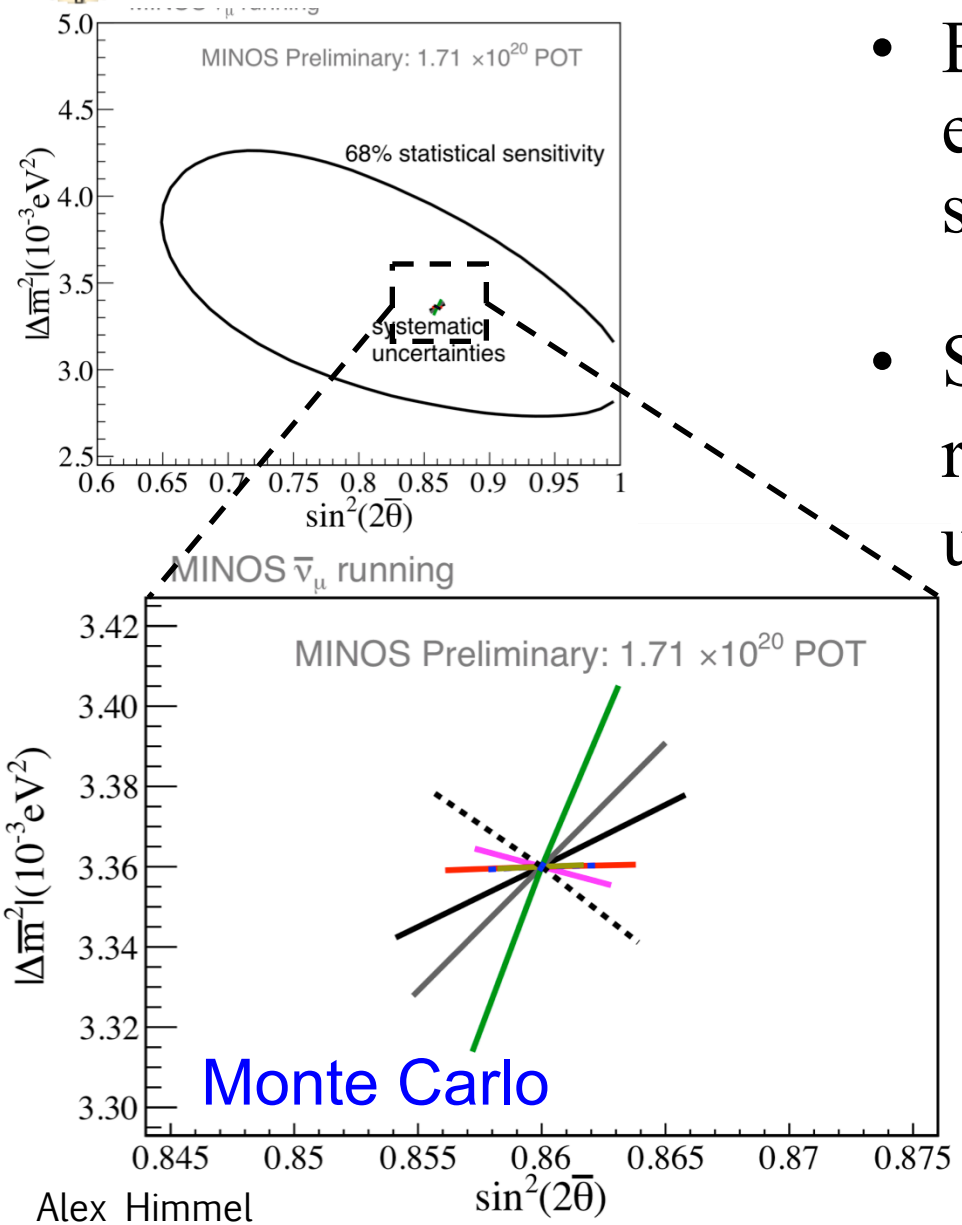




Monte Carlo

- A beam matrix transports measured Near Det. spectrum to the Far Det.
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
- MC used to correct for energy smearing and acceptance

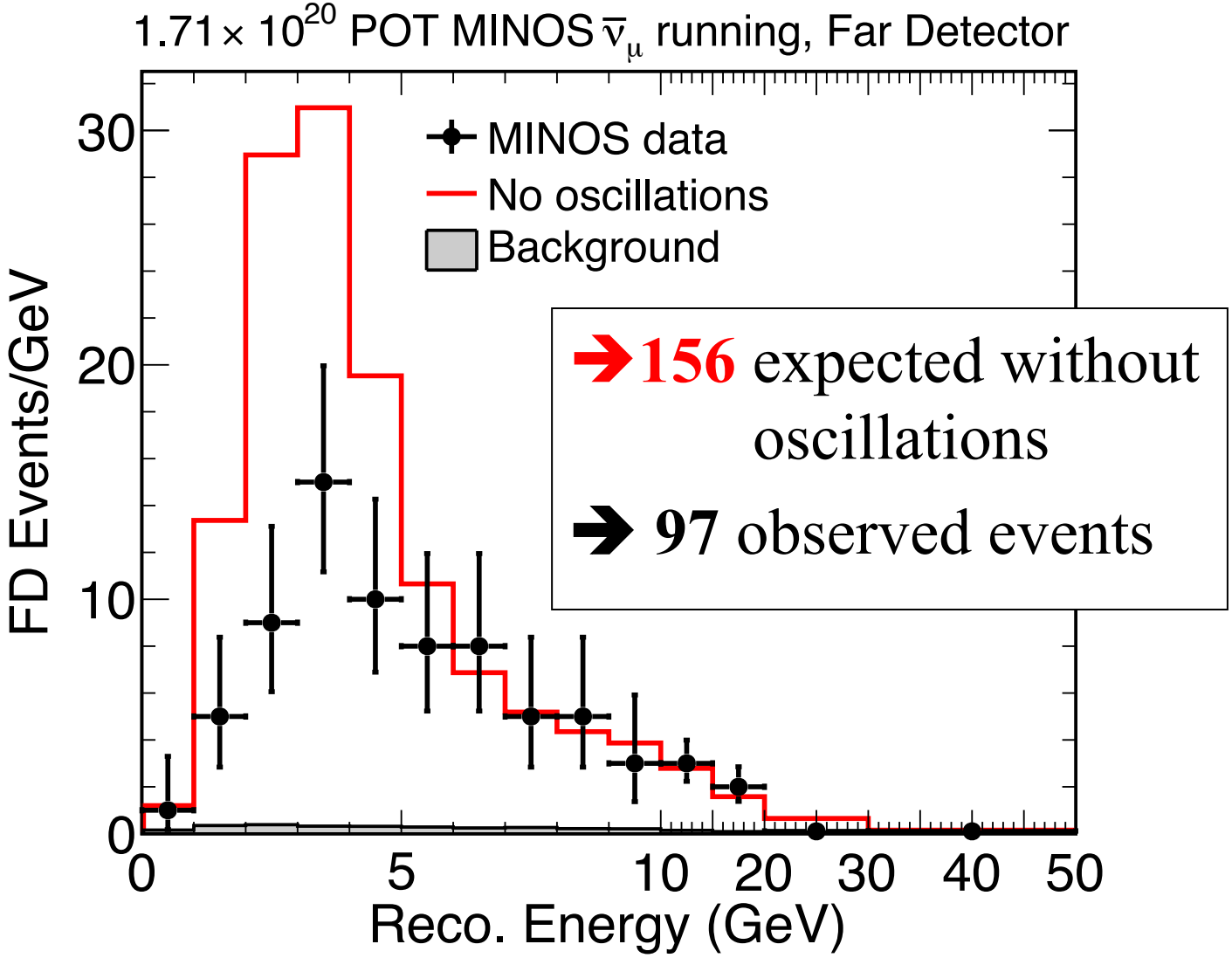
Systematics



- Effect of uncertainties estimated by fitting systematically shifted MC
- Systematics are very small relative to the statistical uncertainty

NC Background
WS CC Background
Track energy
Relative normalisation
Relative hadronic energy FD
Relative hadronic energy ND
Overall hadronic energy
Beam
Cross sections

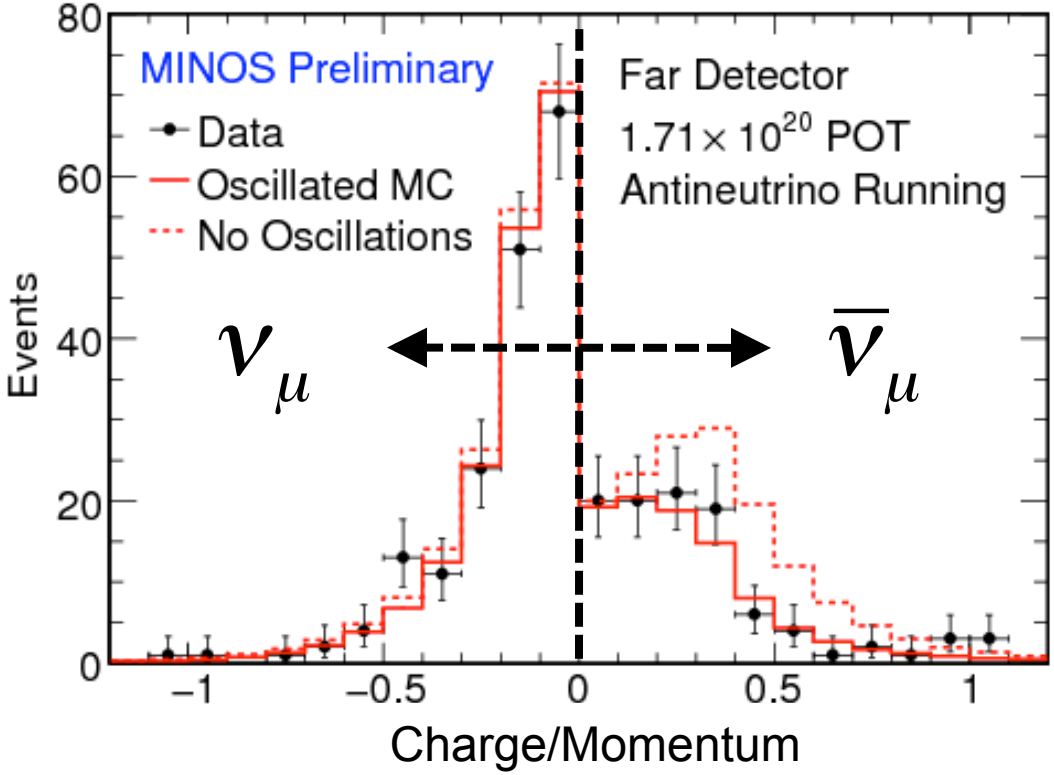
Far Detector Data

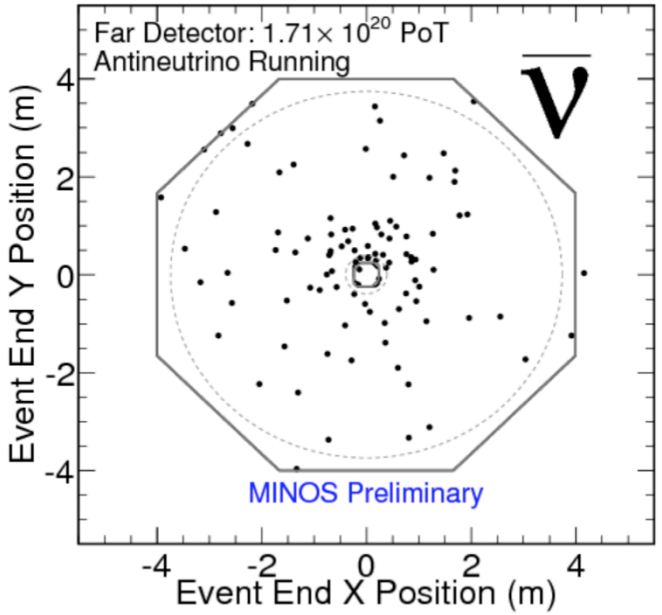


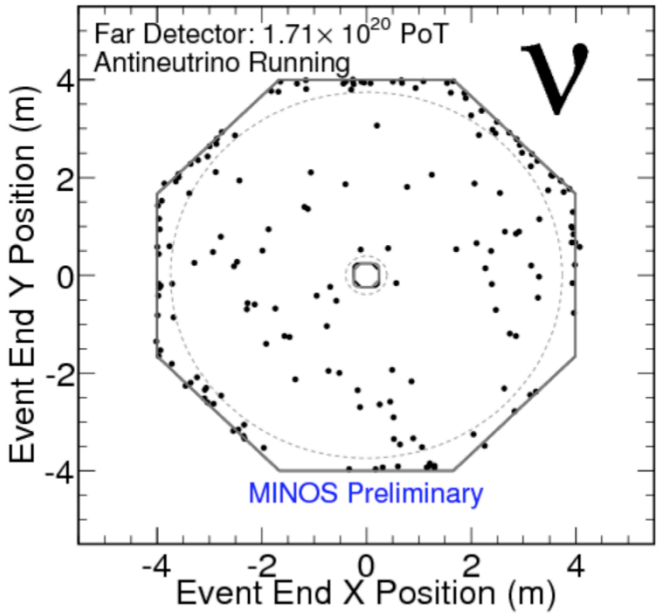
➔**156** expected without oscillations

➔ **97** observed events

Far Detector Data

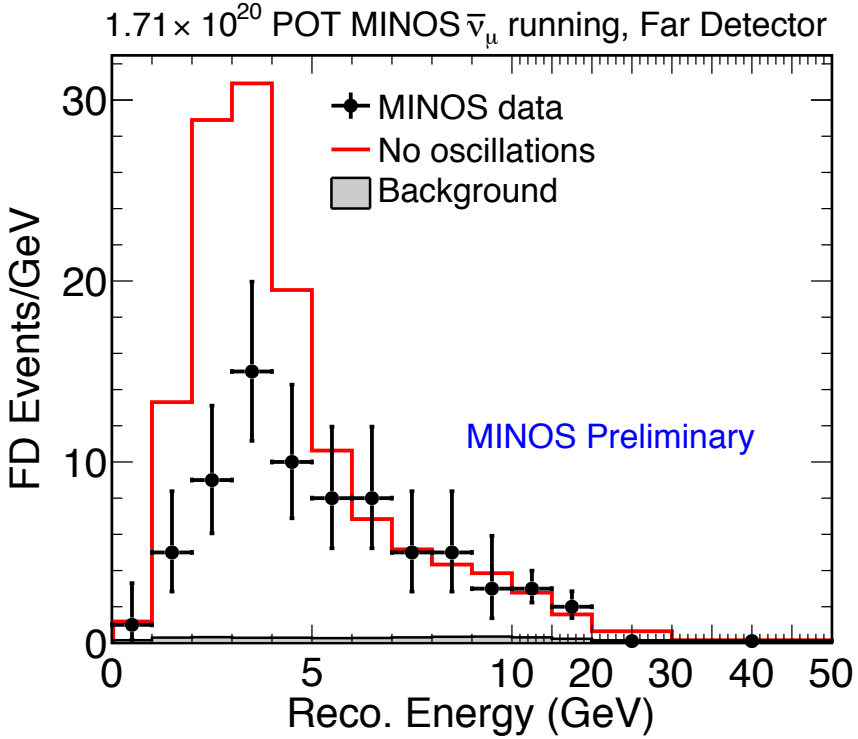


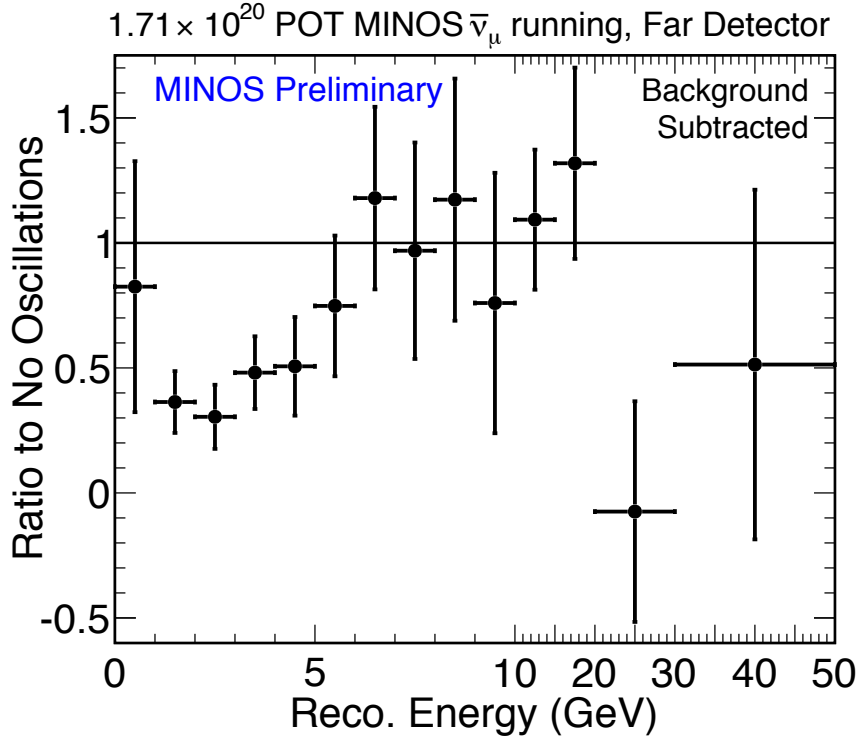




- Good data/mc agreement in charge/momentum
- Antineutrinos focused inwards
- Neutrinos defocused outwards

Far Detector Data





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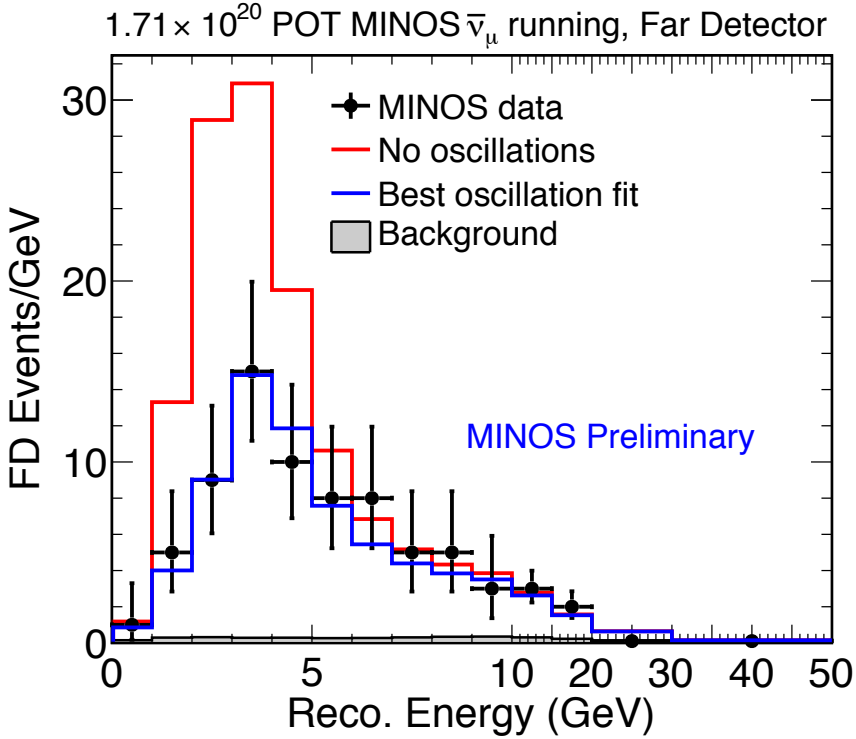

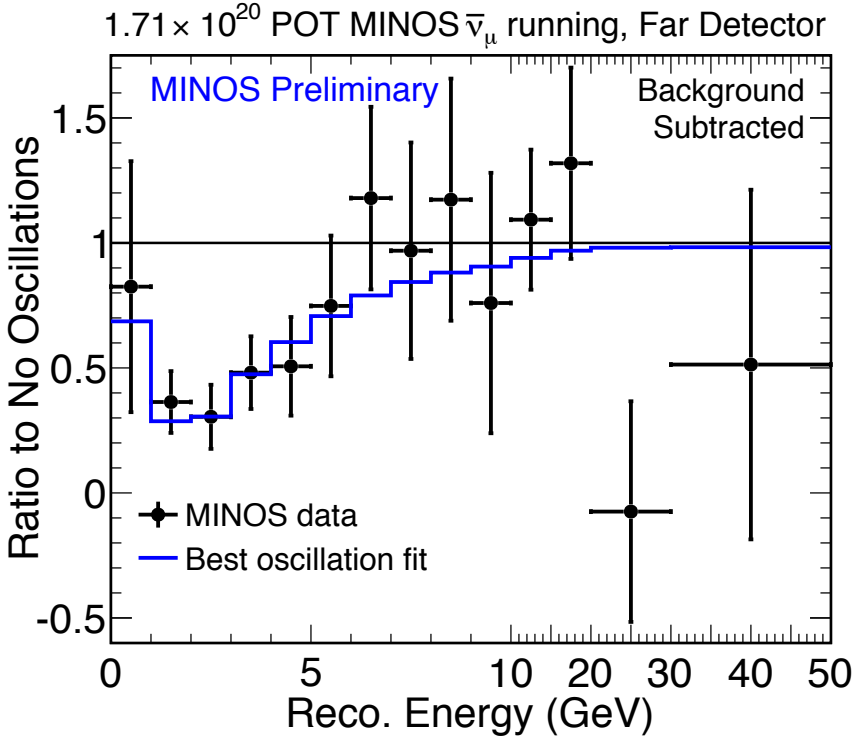

➔ **156** expected without oscillations

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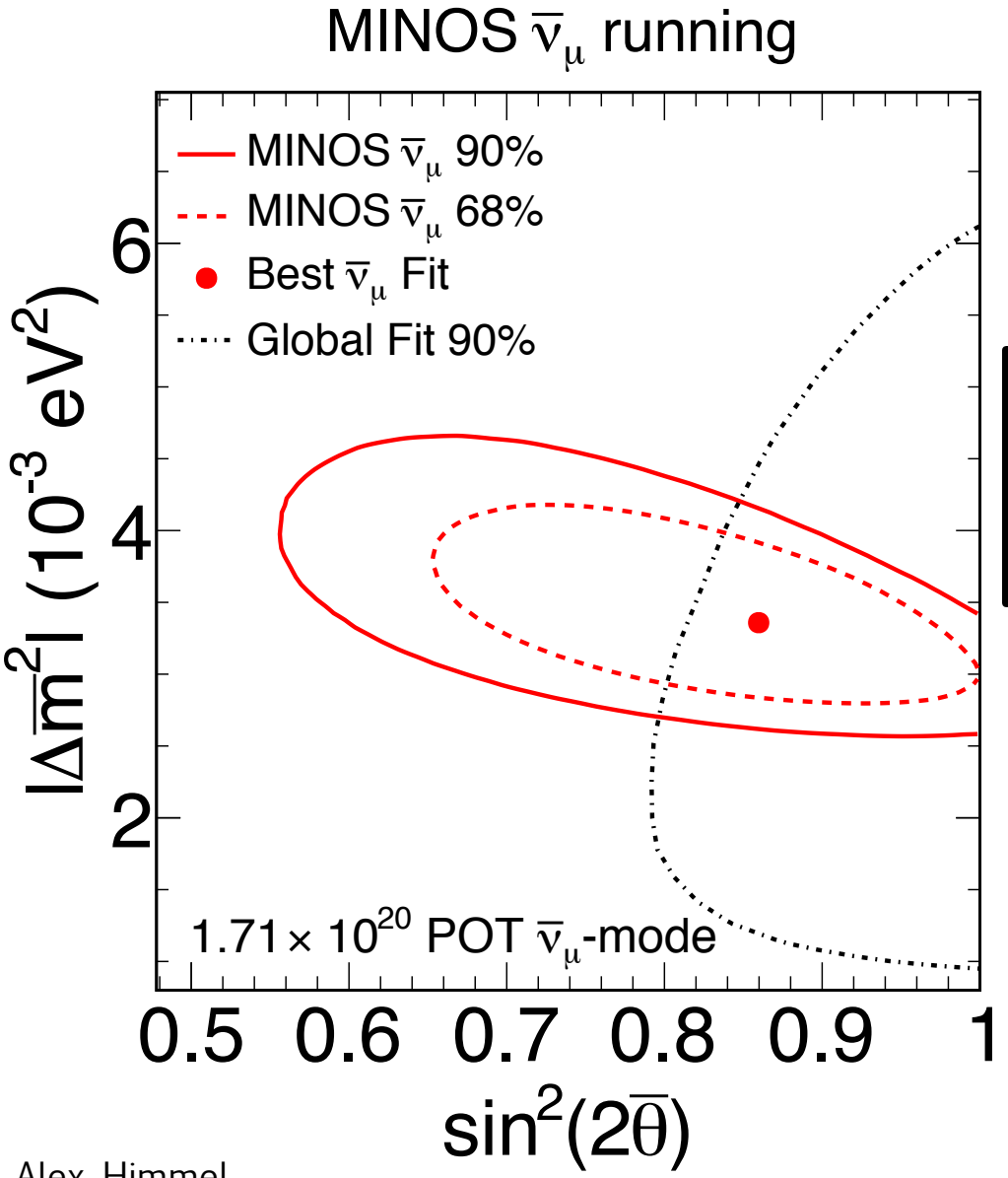
No-oscillations hypothesis is disfavored at **6.3σ**

Antineutrino Contour



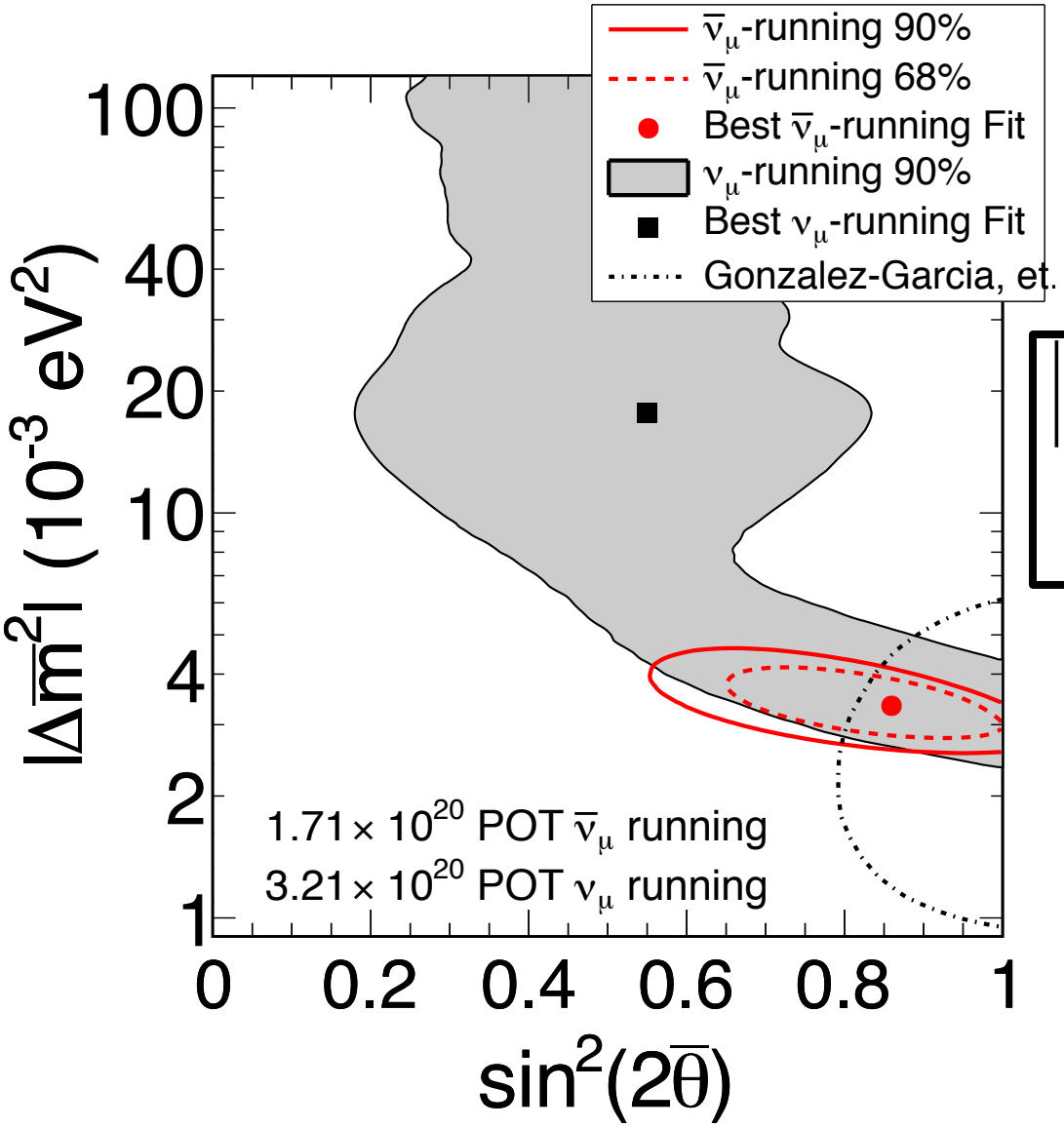
$$\left|\Delta\bar{m}^2_{\text{atm}}\right| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

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

Dot-dash line is a fit to all non-MINOS data

M.C. Gonzalez-Garcia and M. Maltoni Phys. Rept. 460, 2008

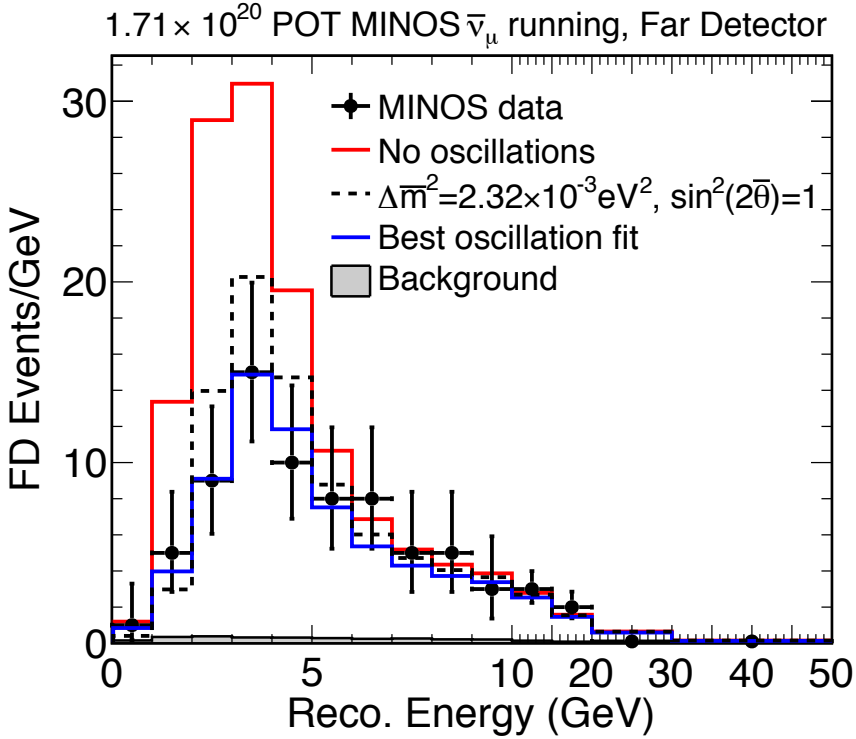
Antineutrino Contour

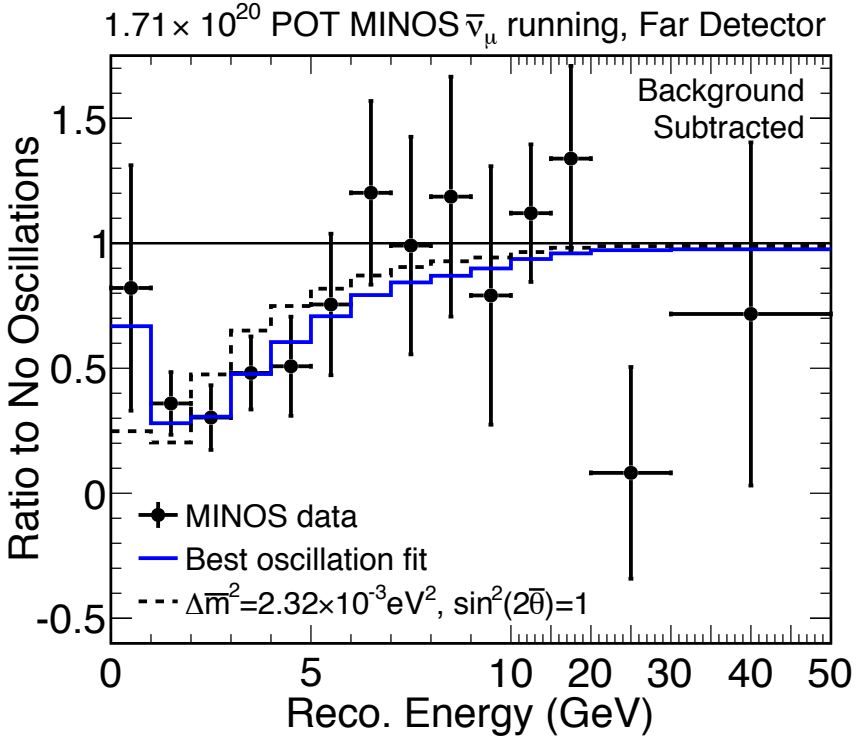


$$\left|\Delta\bar{m}^2_{\text{atm}}\right| = 3.36^{+0.46}_{-0.40}\times10^{-3}\ \text{eV}^2$$

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

Neutrinos and Antineutrinos





- Dashed line shows the antineutrino prediction at the neutrino best fit point.

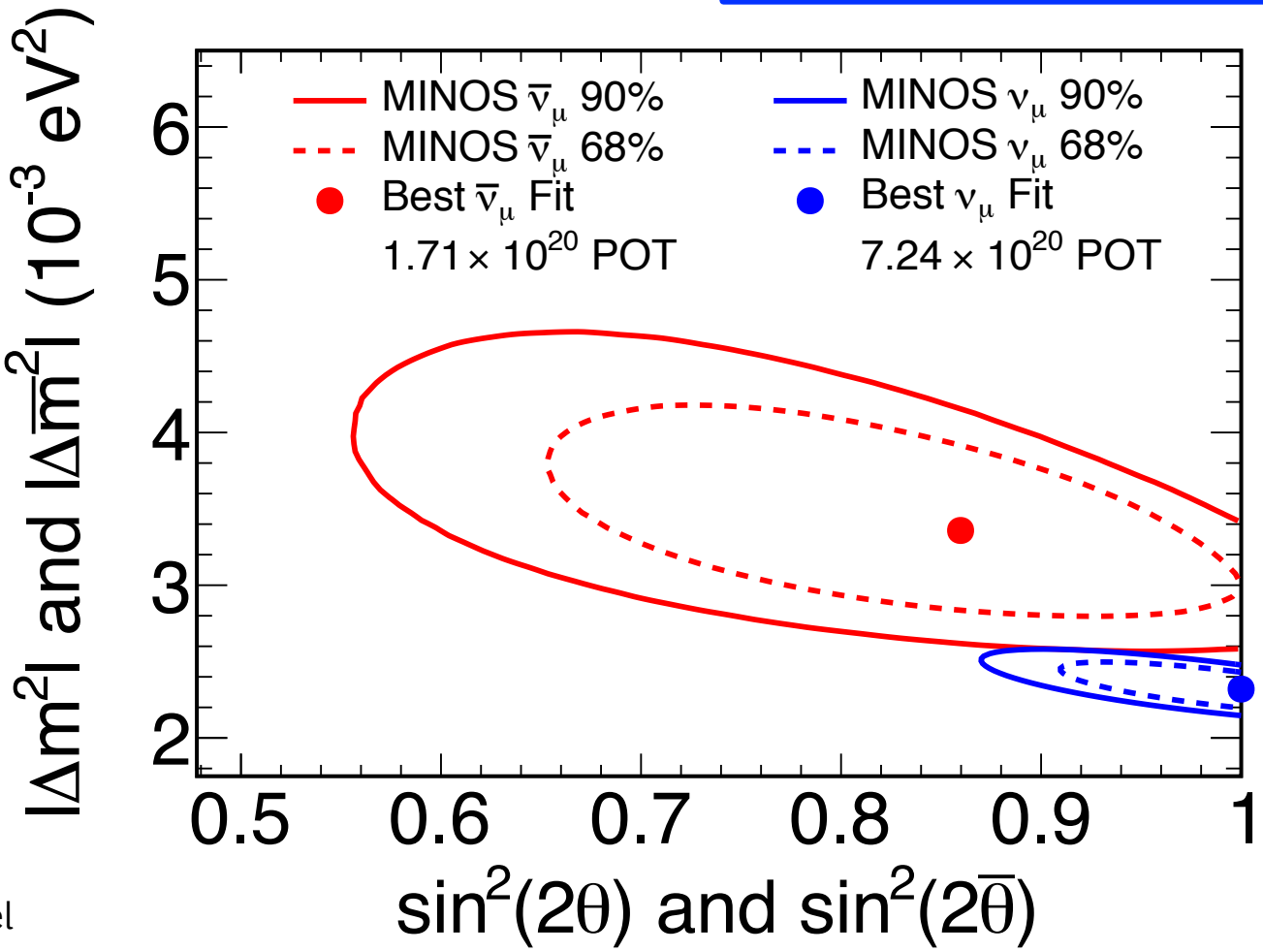
Neutrinos and Antineutrinos

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

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

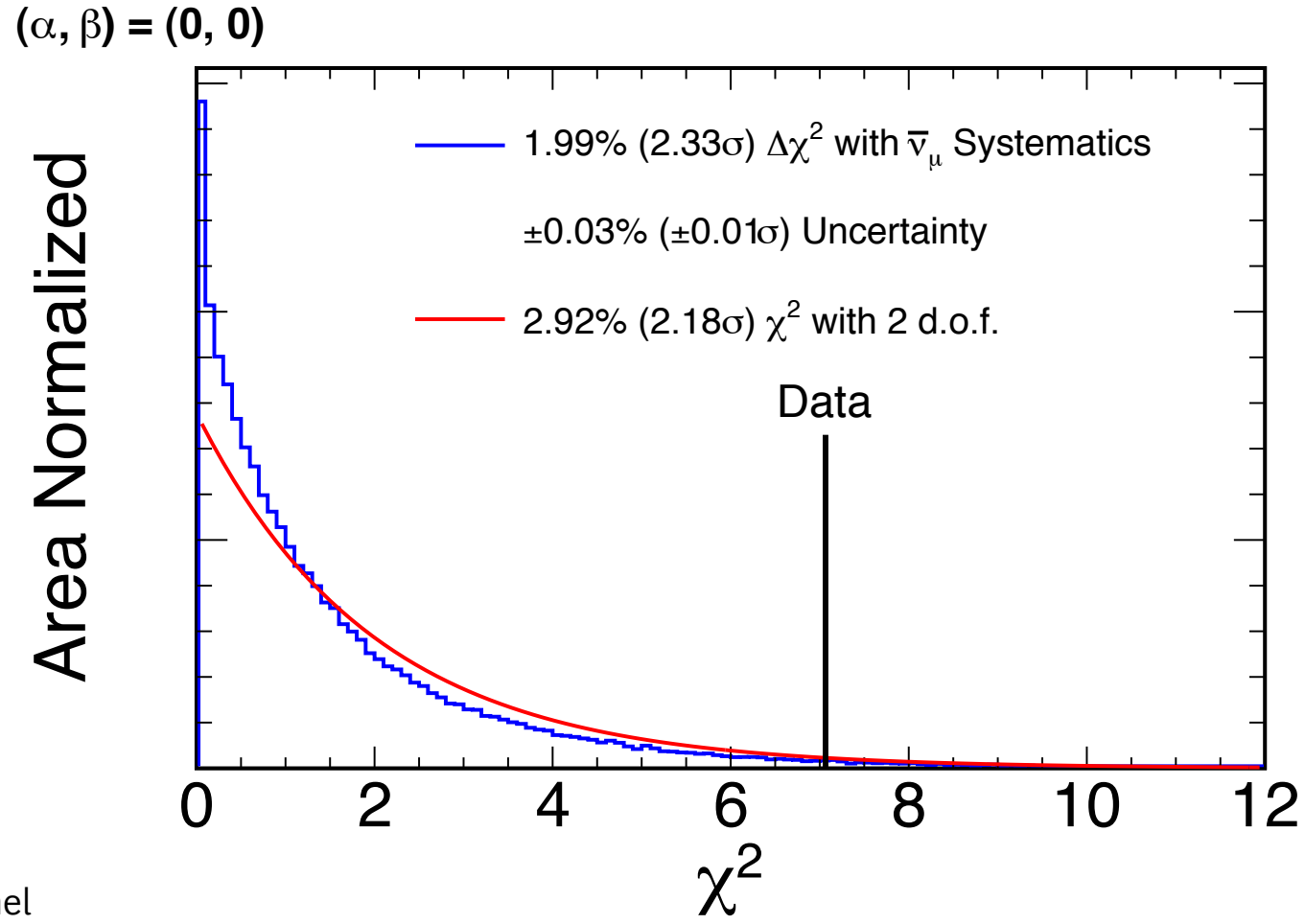
$$\left|\Delta m^2_{\text{atm}}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2$$

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

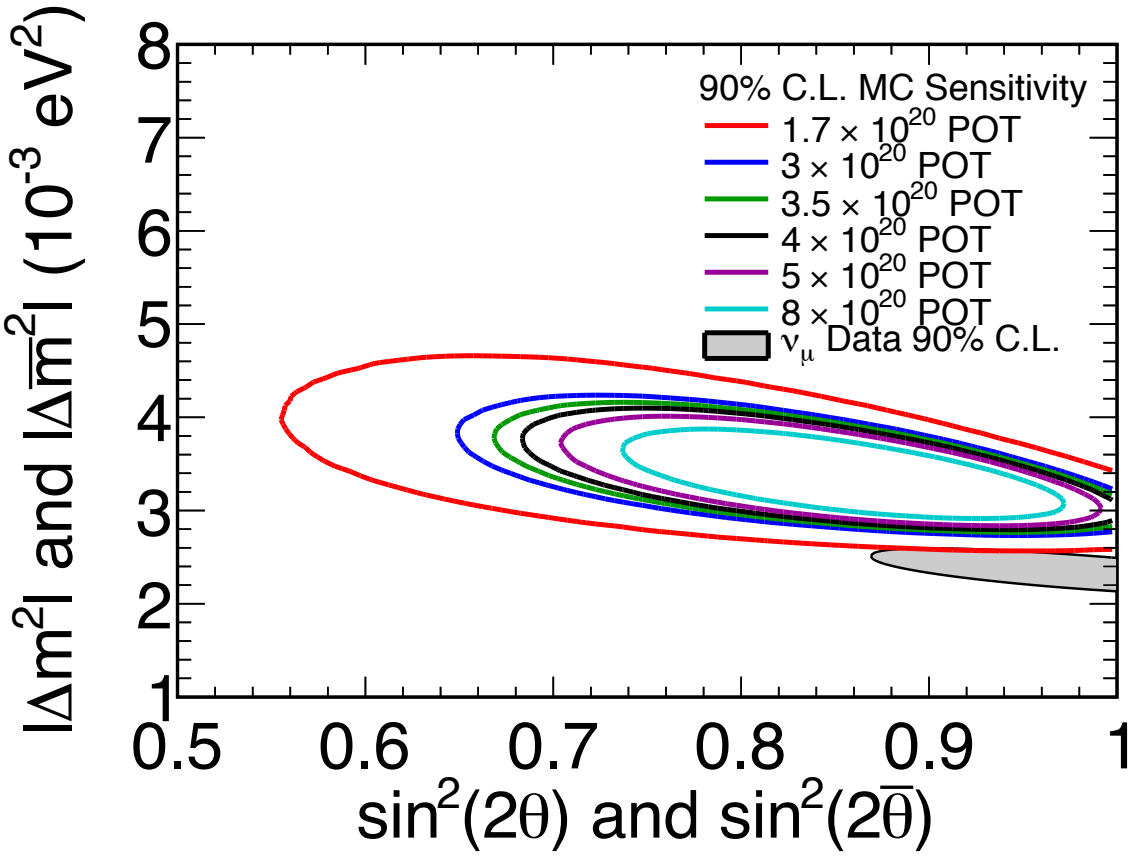


Combined Significance

- Probability of having the same underlying parameters for neutrinos and antineutrinos: 2%



With More Antineutrinos...



- NuMI has begun accumulating another ~2x10^{20} POT (fingers crossed) of antineutrino running.
  - More than double the dataset
  - Can reduce Δm^2 error by more than 30%



Conclusion



- MINOS made the first observation $\overline{\nu}_\mu$ in a neutrino beam
- MINOS has the first direct, precision measurement $|\Delta\overline{m}^2_{\text{atm}}|$

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

$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

- Measured with a dedicated antineutrino run
- There is a 2% probability that the antineutrinos and neutrinos have the same underlying oscillation parameters
- With more antineutrino beam we can rapidly improve the precision on the antineutrino oscillation parameters