Measuring Antineutrino Oscillations in MINOS

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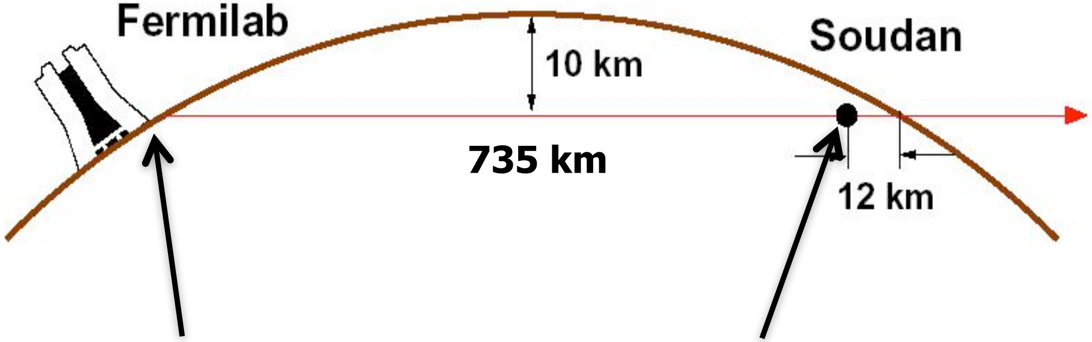
IOP 2010
University College London

Main **I**njector **N**eutrino **O**scillation **S**earch

27 Institutions, 147 Physicists



Neutrinos are produced by the **NuMI beam.** The beams composition and energy are measured by the **Near Detector**

The oscillated neutrino beam is measured by the **Far Detector**, at a mine in Minnesota.

Measurements and limits include:

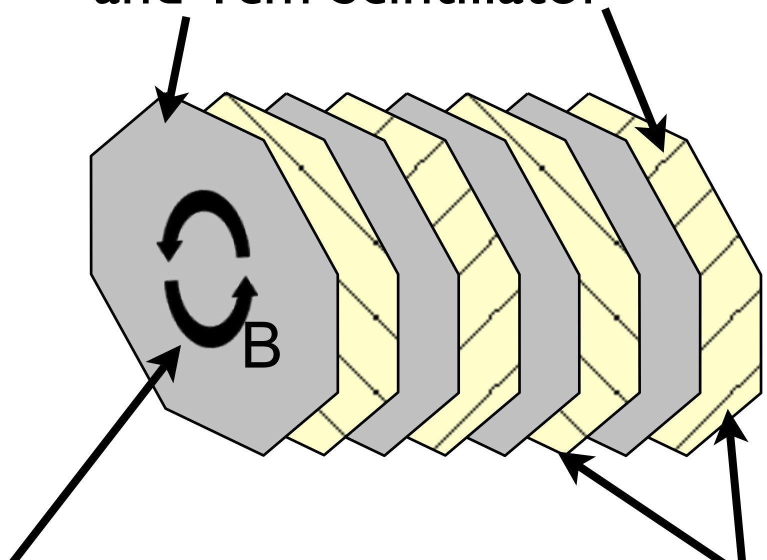
Δm^2_{32}, $\sin^2 2\theta_{32}$, $\Delta\overline{m}^2_{32}$, $\sin^2 2\overline{\theta}_{32}$, θ_{13}, Sterile Neutrinos, CPT conservation, Cross-sections...

MINOS Detectors

Both detectors are functionally equivalent, in order to reduce systematics.

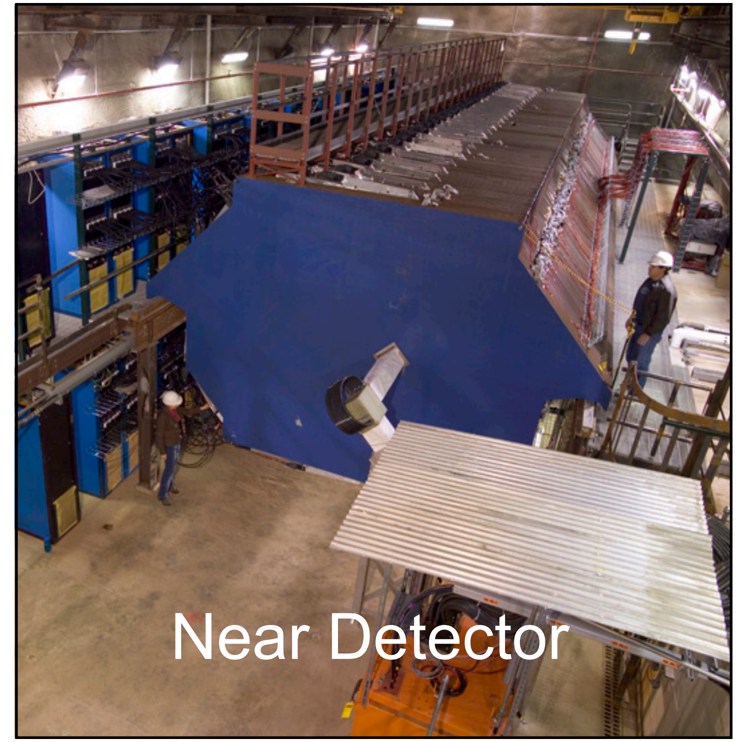
Near Detector	**Far Detector**
‣At Fermilab, IL	‣At Soudan, MN
‣282 Planes	‣486 Planes
‣980 Ton	‣5400 Ton

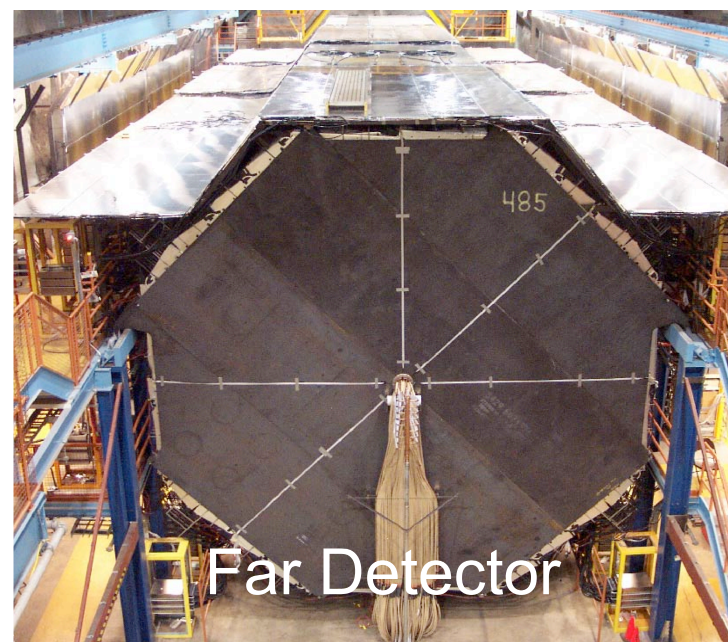
Planes of 2.54cm Steel and 1cm Scintillator



Toroidal magnetic field allows charge sign determination

Alternating scintillator planes in perpendicular directions for 3D event reconstruction

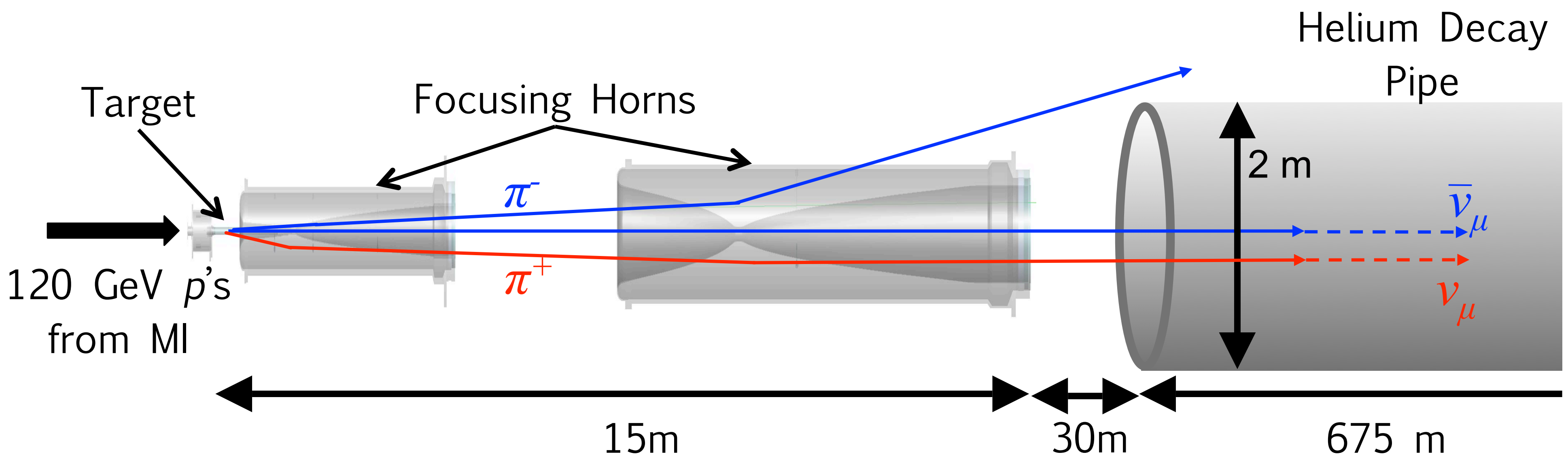




- Neutrinos are provided by the "**N**e**u**trinos at the **M**ain **I**njector" (NuMI) beam at Fermilab

- 120 GeV protons are collided with a graphite target to produce πs and Ks, which decay to produce neutrinos (mainly ν_μ, $\bar{\nu}_\mu$)

- Two magnetic horns focus resultant particles of a *specific charge-sign*, depending on the current direction:
  - Neutrino parents are focused in *Forward Horn Current* (**FHC**) mode
  - Antineutrino parents are focused in *Reverse Horn Current* (**RHC**) mode

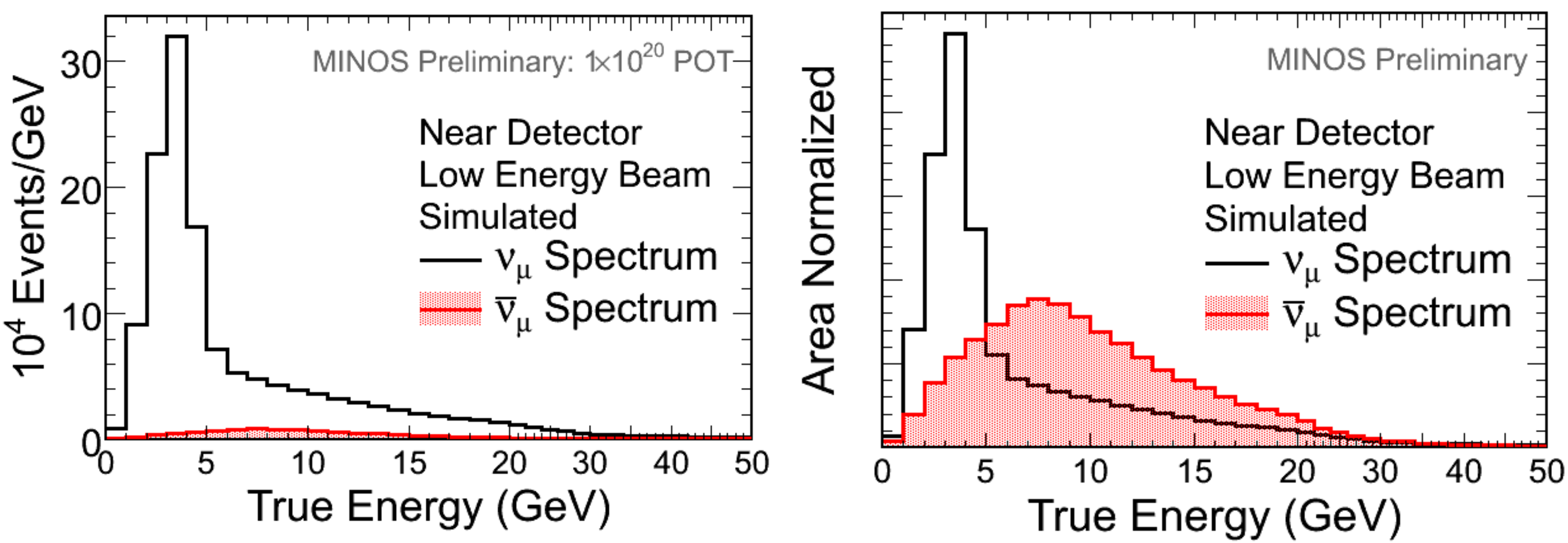


Antineutrinos

When running in neutrino mode, 7% of the beam is 'contaminated' with muon antineutrinos.

Challenges to an analysis of these include:

- Antineutrinos have cross-sections about ~1/3 compared to neutrinos
- Antineutrino parents that pass through the horns in this configuration are on average of a higher energy



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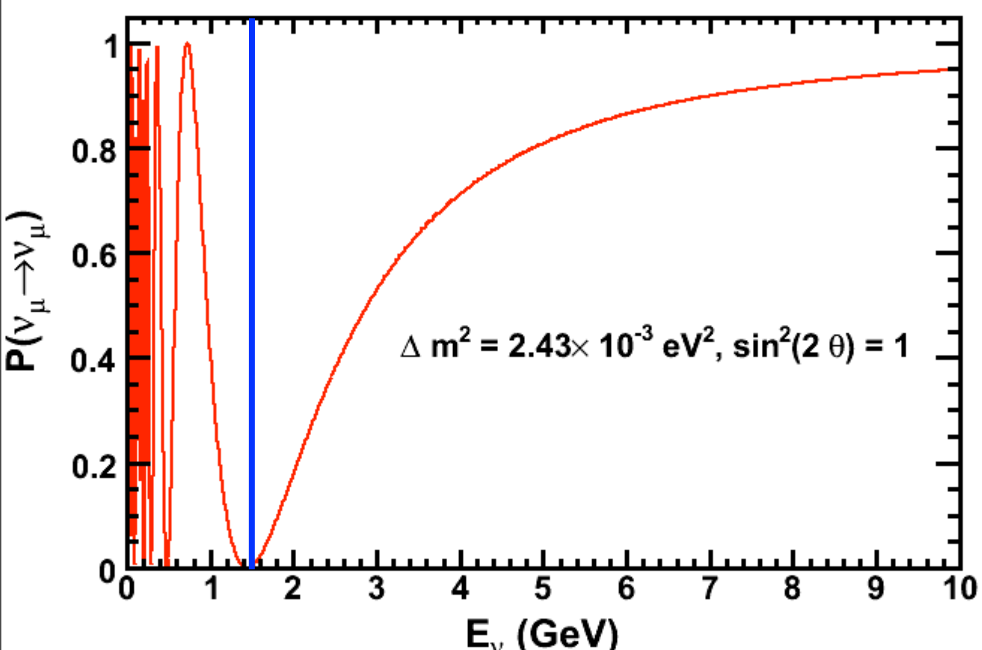
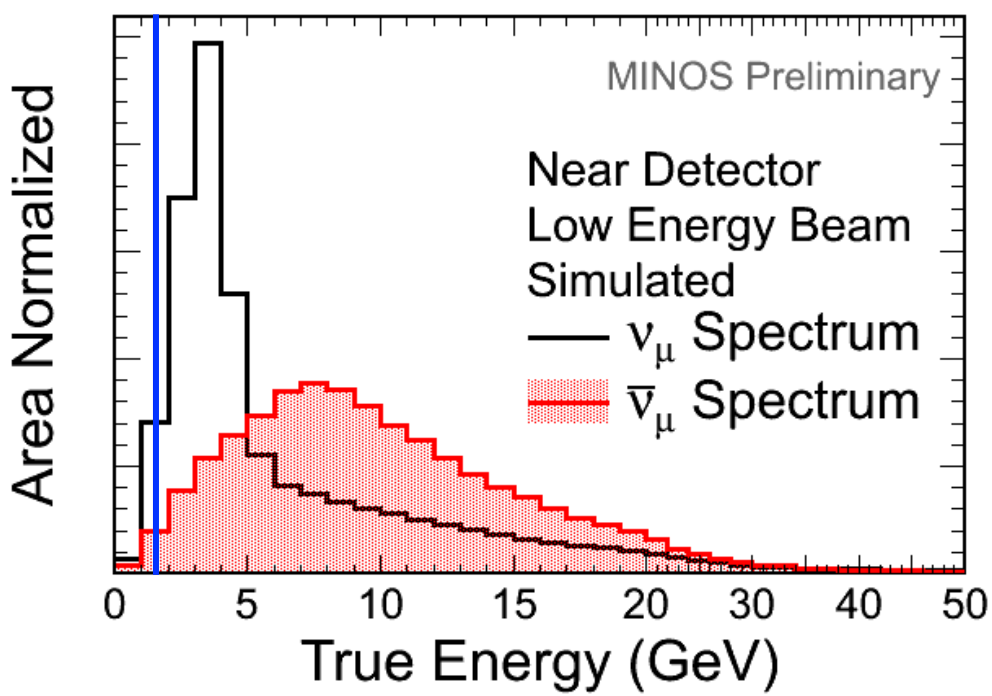


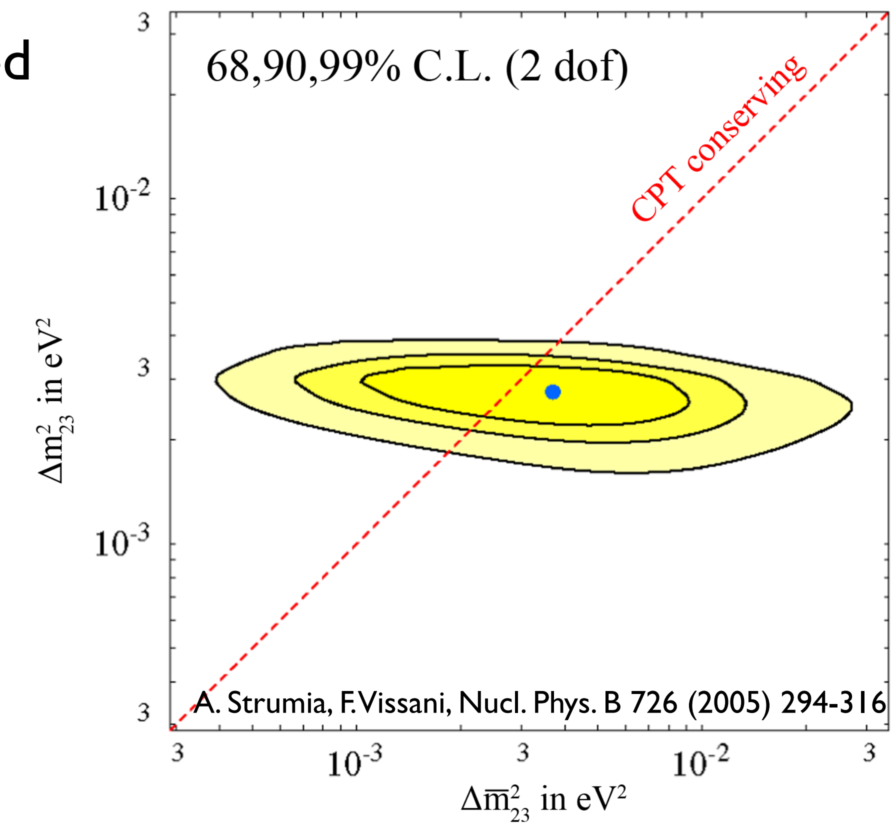


Motivation for measuring Antineutrinos

- We have the only large, underground sign-separating Neutrino detector, and no next-generation detectors with similar capabilities (event-by-event charge separation) are planned

- A possible explanation of LSND
  - M.C. Gonzalez-Garcia et al., Phys. Rev. D 68 (2003) 053007
  - The LSND experiment measured oscillations using antineutrinos and found $0.2\ eV^2 < \Delta m^2 < 2\ eV^2$, much larger than any other measurement
  - One explanation was that LSND's measured $\Delta\overline{m}^2$ was significantly different from Δm^2
  - Constraints from other experiments have made this less likely, but still viable if sterile neutrinos are included.

- Limited antineutrino knowledge, world $\Delta\overline{m}^2$ limits are 6 times wider for antineutrinos than for neutrinos.



A. Strumia, F. Vissani, Nucl. Phys. B 726 (2005) 294-316

Latest Antineutrino Results

- Have performed an analysis of antineutrino disappearance with 3.2×10^{20} Protons on Target (POT) in neutrino mode

- Because of low statistics, cannot approximate confidence limits as gaussian in the presence of our physical boundaries

- Have used the Feldman-Cousins technique to determine the correct confidence intervals

    G. Feldman, R. Cousins Phys. Rev. D 57, 3873 - 3889 (1998)

- We can also account for systematics in a very natural way - exactly on each event in the Monte-Carlo, rather than approximating the effects on the spectrum

Feldman-Cousins Method

- With Gaussian statistics, we can draw a contour by tracing round the likelihood surface at a prescribed up-value ($\Delta\chi^2$)

$(1-\alpha)$ (%)	$m=1$	$m=2$
68.27	1.00	2.30
90.	2.71	4.61
95.	3.84	5.99

*C. Amsler et al. (Particle Data Group), Physics Letters **B667**, 1 (2008)*

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- To do this, we generate a large number of real-statistics experiments and fit each one separately

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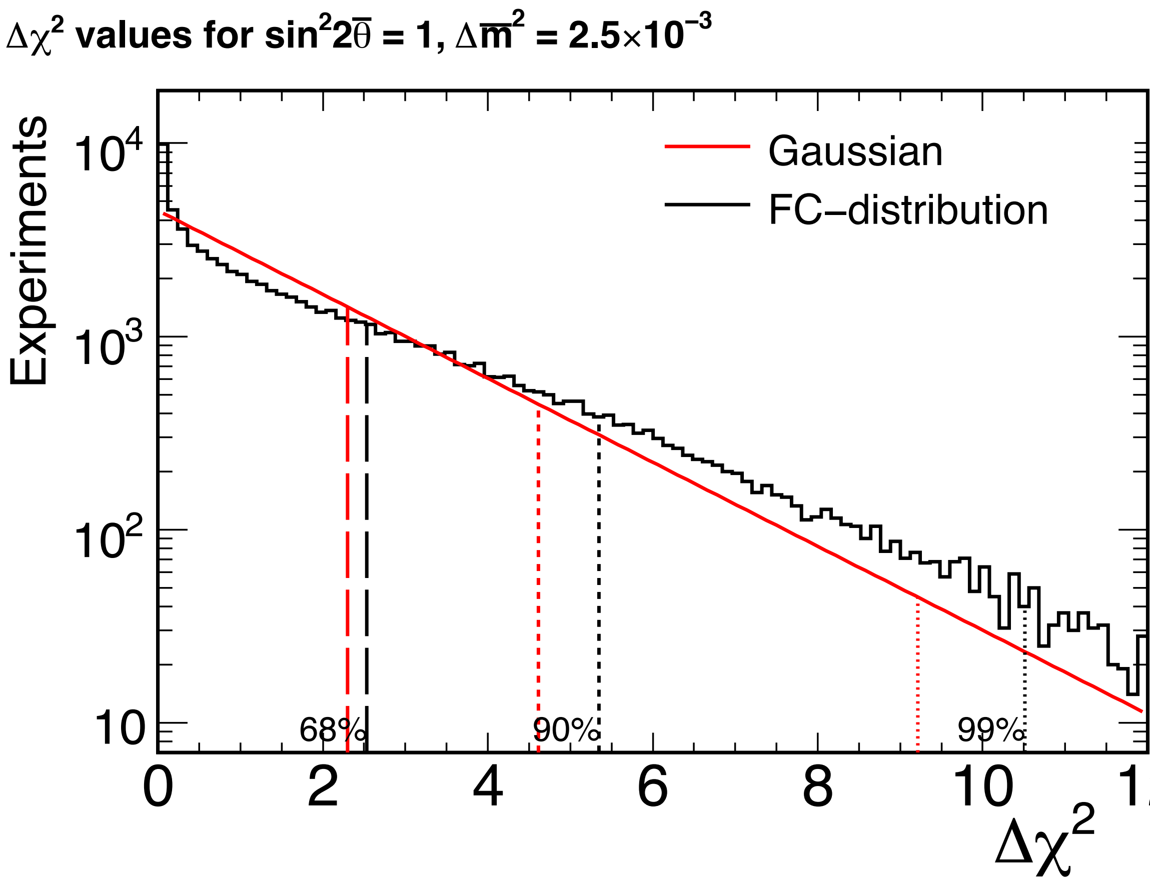
- We can use the results of these fits to create a distribution of likelihood values

- The integral of this distribution to the required coverage gives you the value at which to trace the contour



Coverage Correction

- Each point the contour passes through is corrected separately

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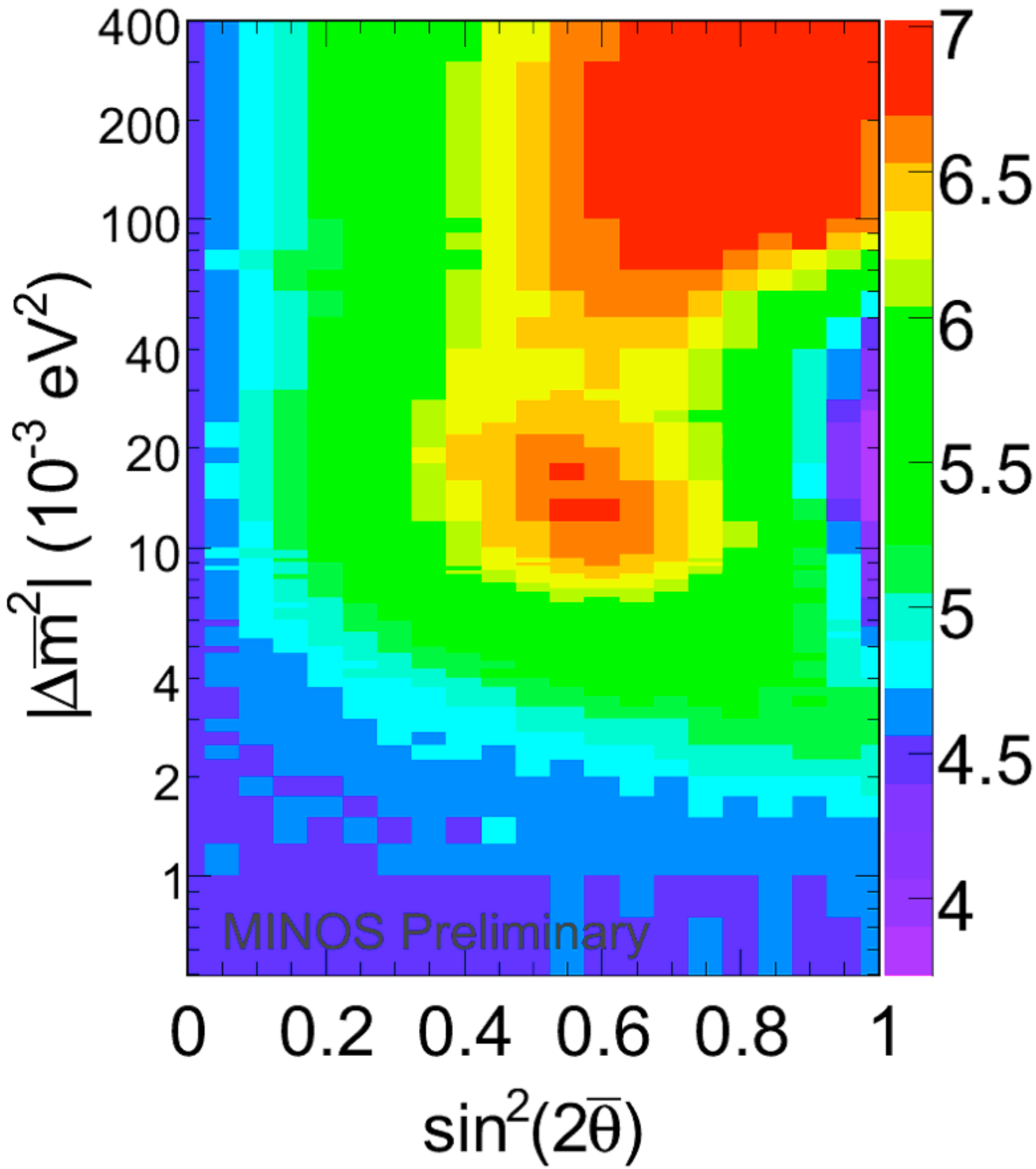
- Each point the contour passes through is corrected separately
- This image shows the grid of $\Delta\chi^2$ values that give 90% coverage
- Once the likelihood surface is generated, any points below the corresponding place on this graph are within 90%
- **This has the ultimate effect of 'pushing' the contour around**
- Confidence limits become exact, not an approximation



Results: Far detector Data

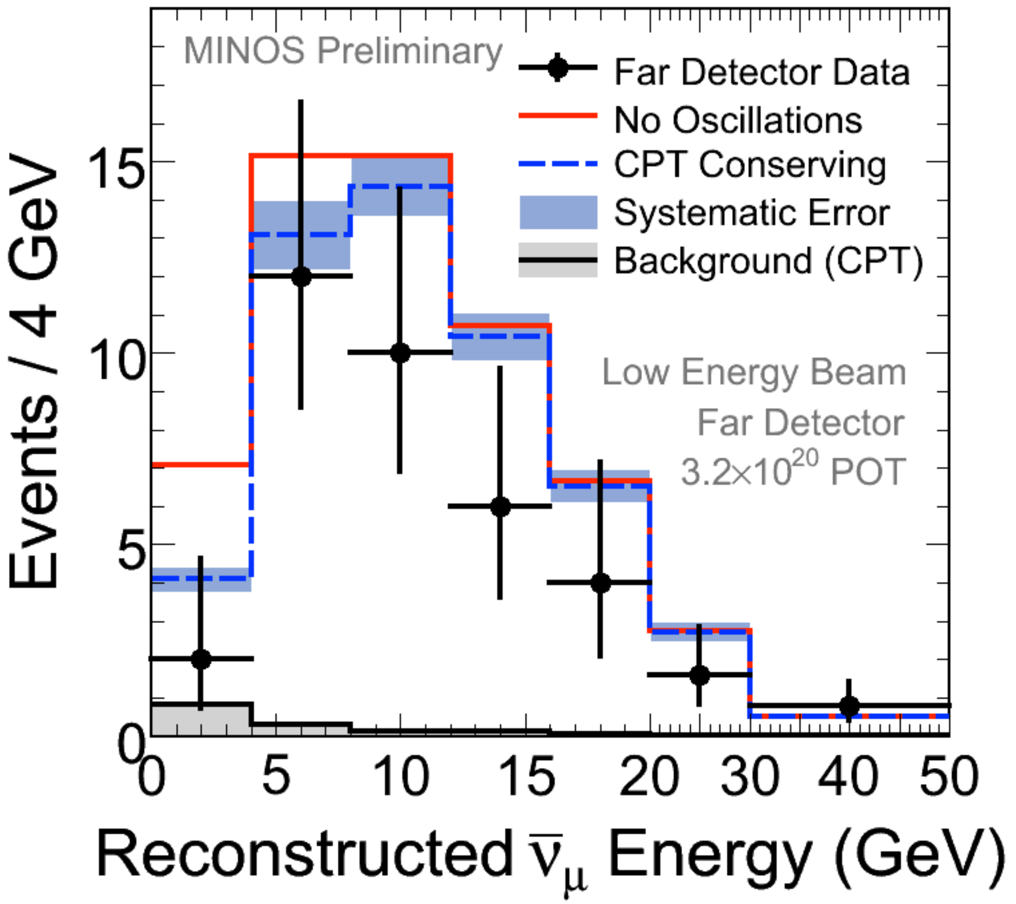
- Predicted events with CPT conserving Oscillations:

  58.3 ± 7.6 (stat) ± 3.6 (syst.)

- Predicted events for null oscillations:

  64.6 ± 8.0 (stat) ± 3.9 (syst.)

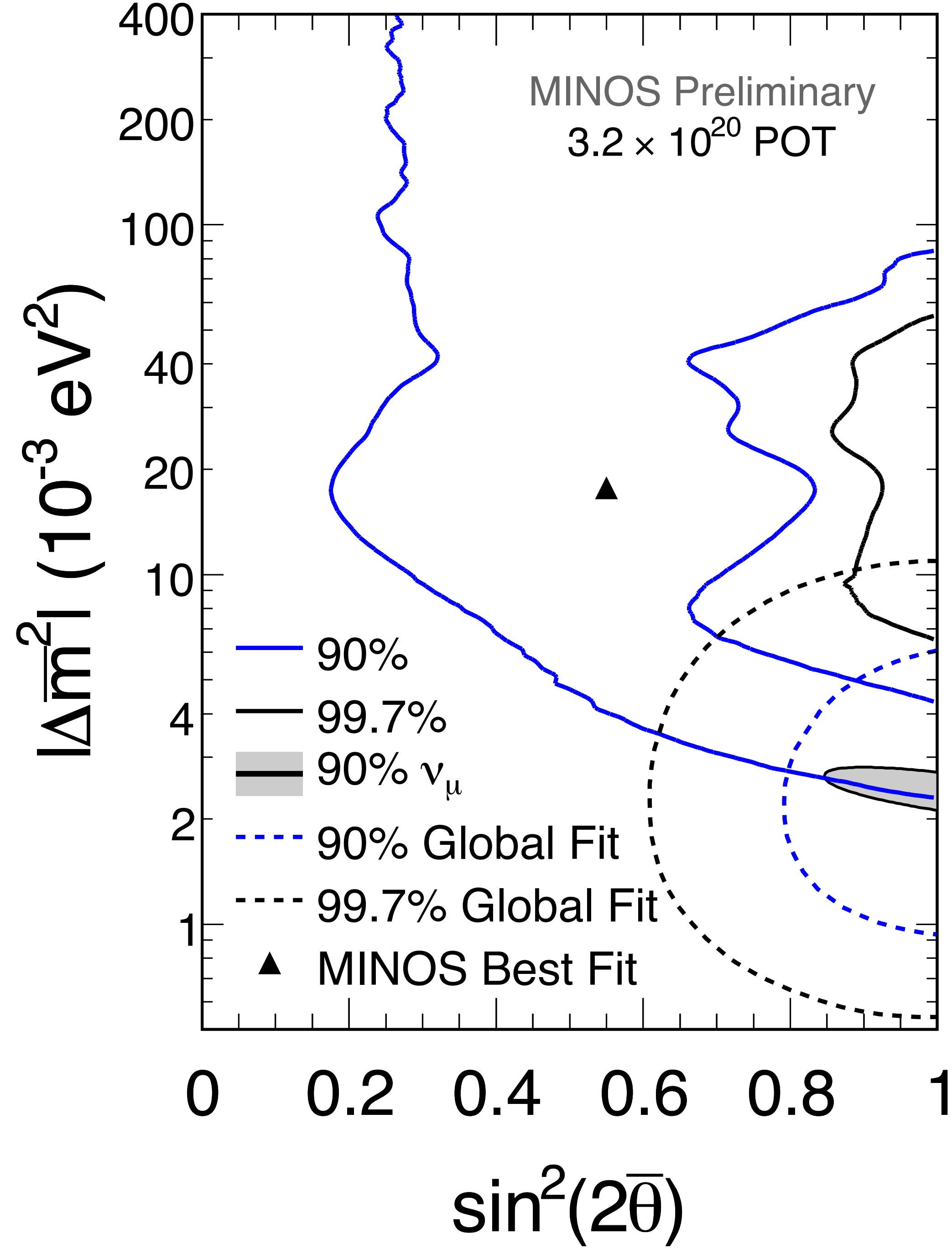
- Observed: **42 Events**
  - 1.9σ deficit
  - At high energy, where oscillation signature is not expected



- Feldman-Cousins corrected contour *including* systematics
- Best fit is at high value, due to deficit at high energy
- CPT conserving point from the MINOS neutrino analysis is within the 90% contour
- Null oscillation hypothesis excluded at 99%
- At maximal mixing **exclude**:

  $(5.0 < \Delta\bar{m}^2 < 81)\times 10^{-3}\ \mathrm{eV}^2$

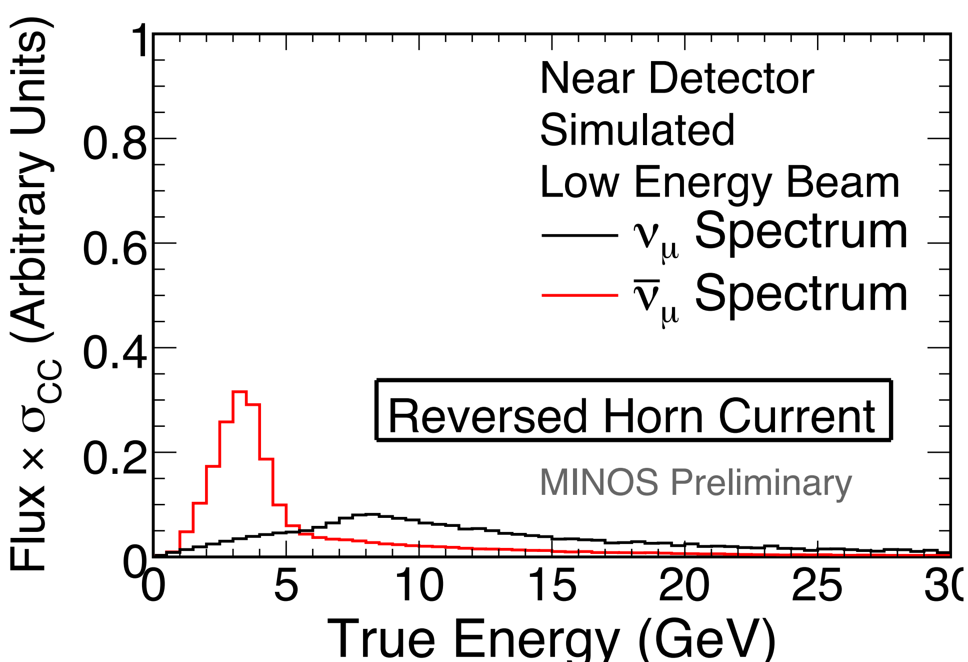
- Dashed lines show global fit to previous data, Super-Kamiokande dominates (SK-I and SK-II)

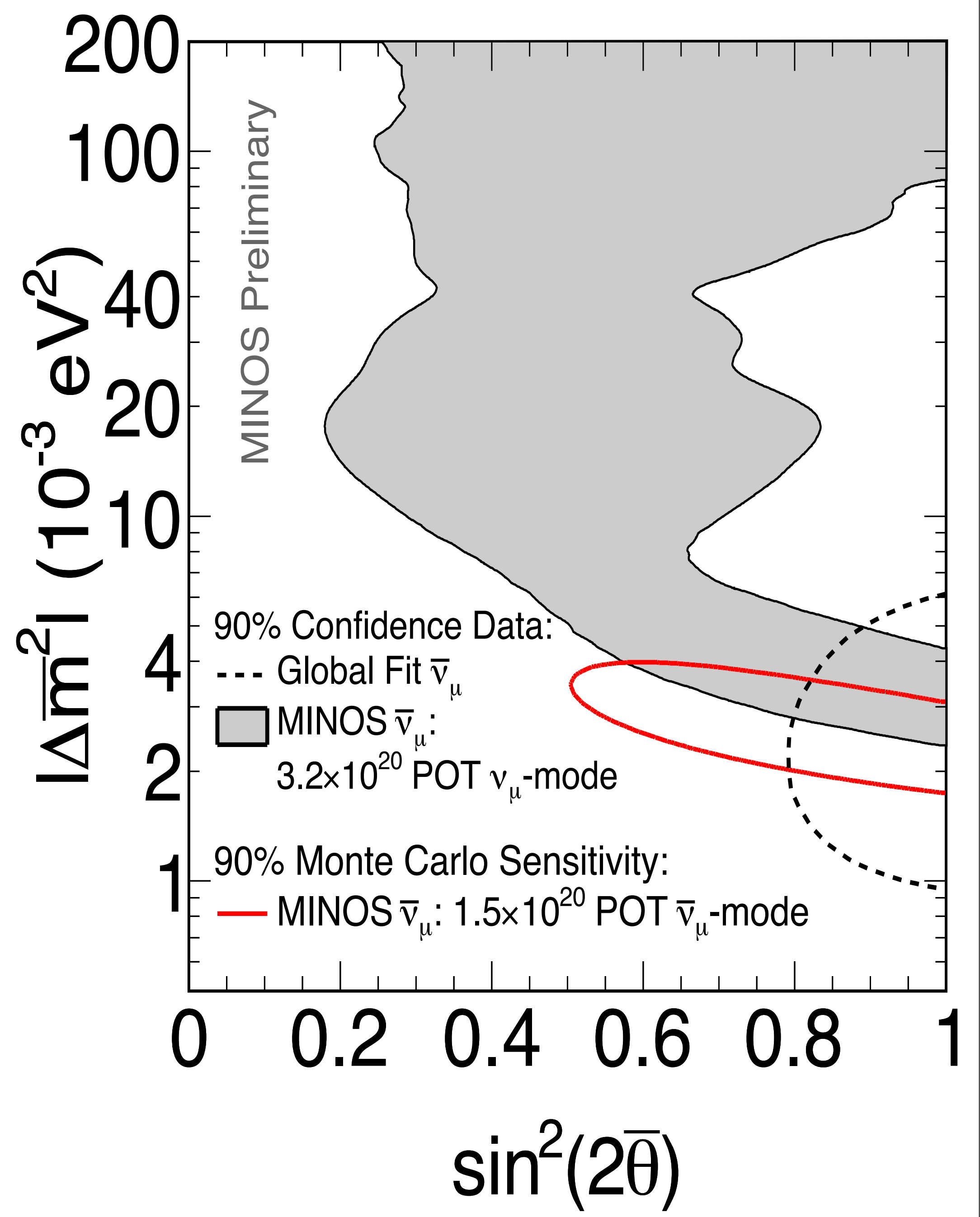


M. C. Gonzalez-Garcia & M. Maltoni, Phys. Rept. 460 (2008)

Future Analysis: Reversed Horn Current

- In October we started taking data with the beam in antineutrino mode
- Have accumulated 1.76×10^{20} POT in this configuration
- Antineutrino spectrum is lower energy, and dominant
- First results this summer!



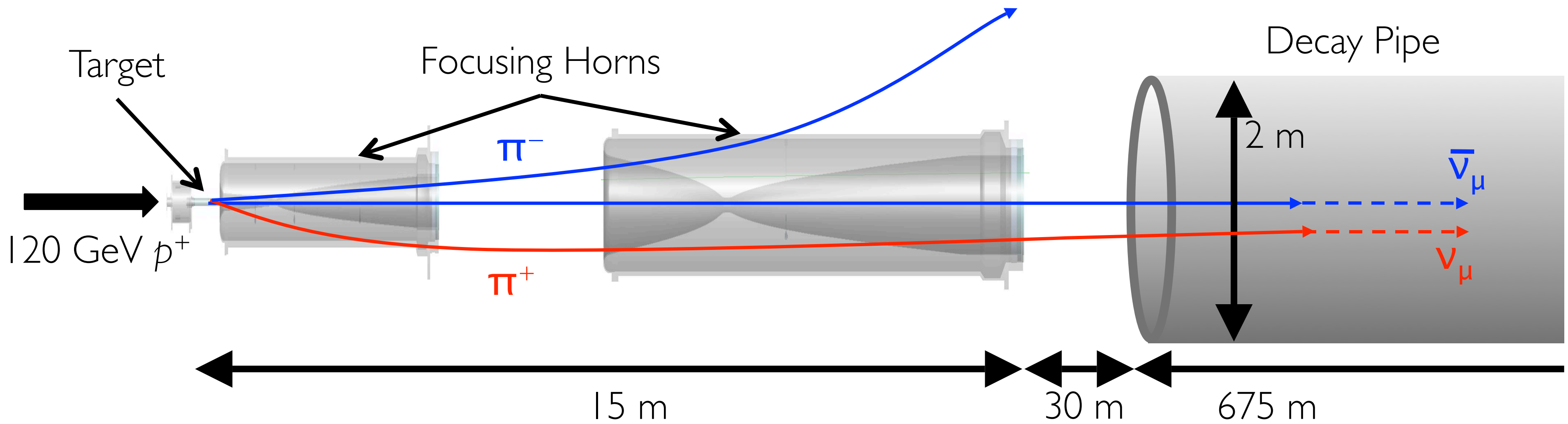


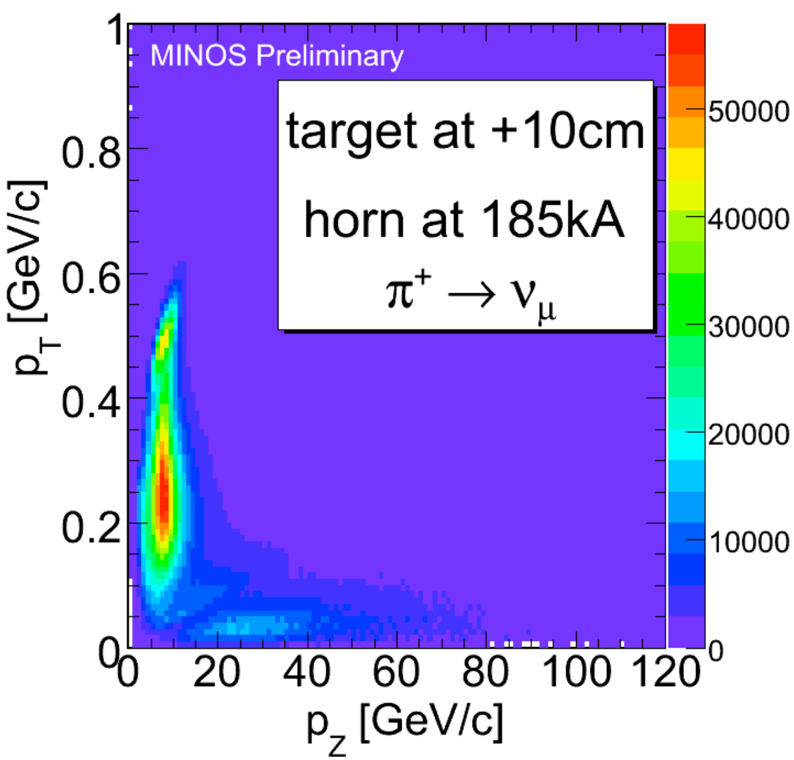
Summary

- MINOS is a mature and flexible experiment that has measured many facets of neutrino properties
- Presented data of the first direct observation of $\bar{\nu}_\mu$ in a long-baseline experiment
- The Feldman-cousins technique was used to correctly calculate the confidence intervals
- Data from NuMI in antineutrino result will be presented this summer

Backup Slides

Why are the spectra so different?

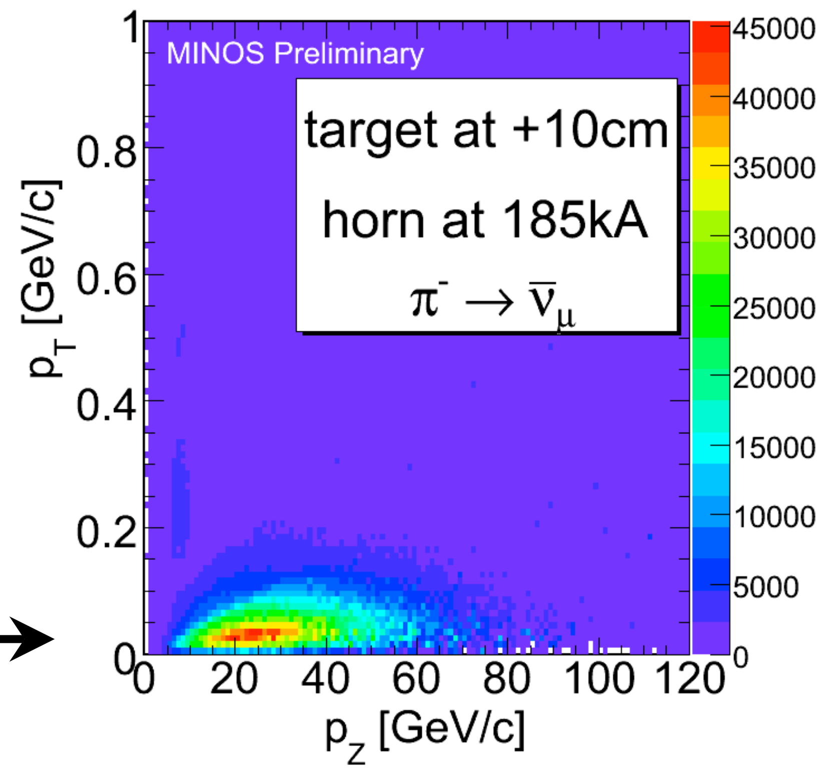




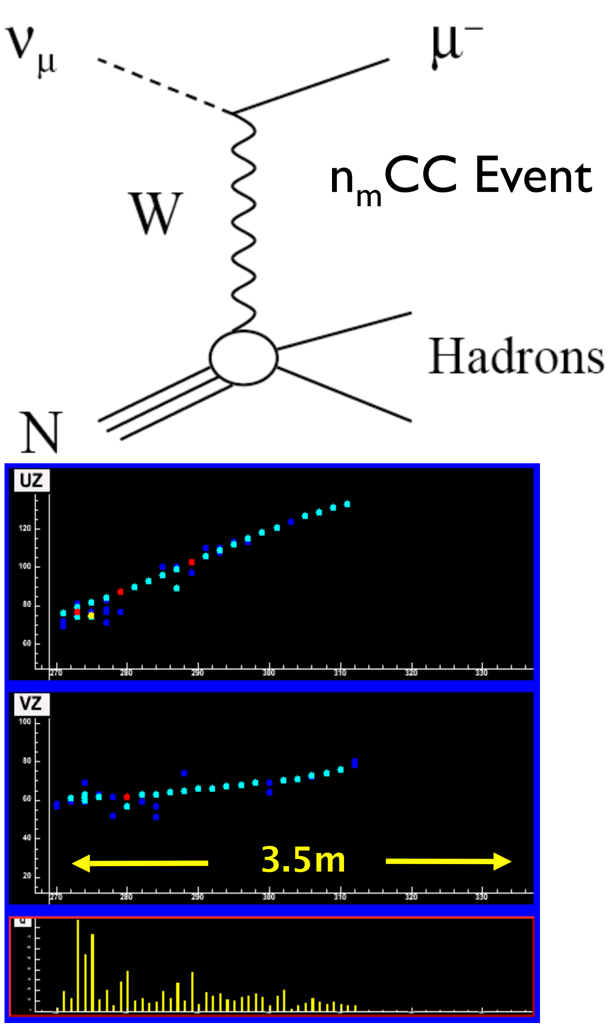
Forward Horn Current

π^+

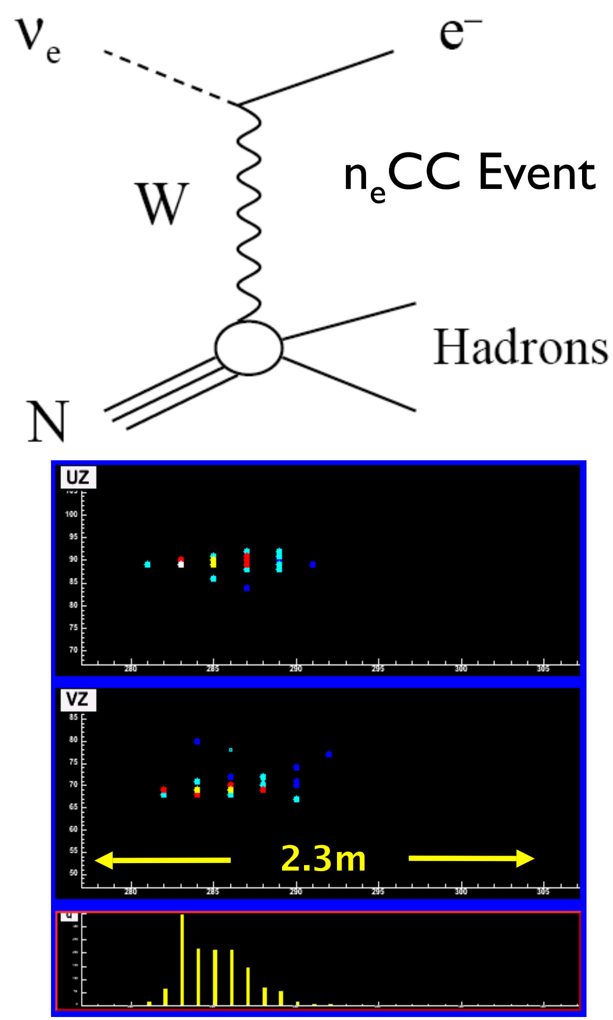
π^-



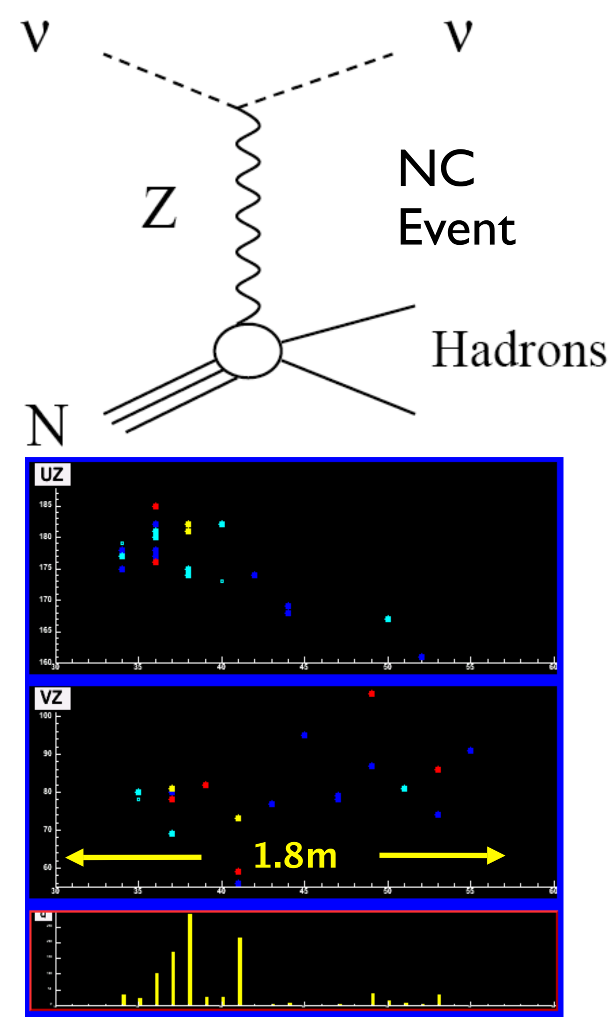
Event Topologies



long μ track+ hadronic activity at vertex



short, with typical EM shower profile



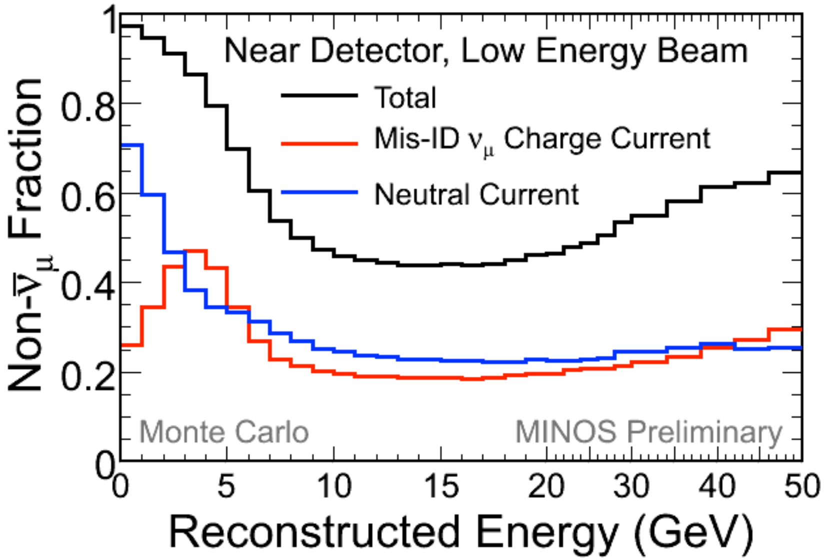
short event, often diffuse

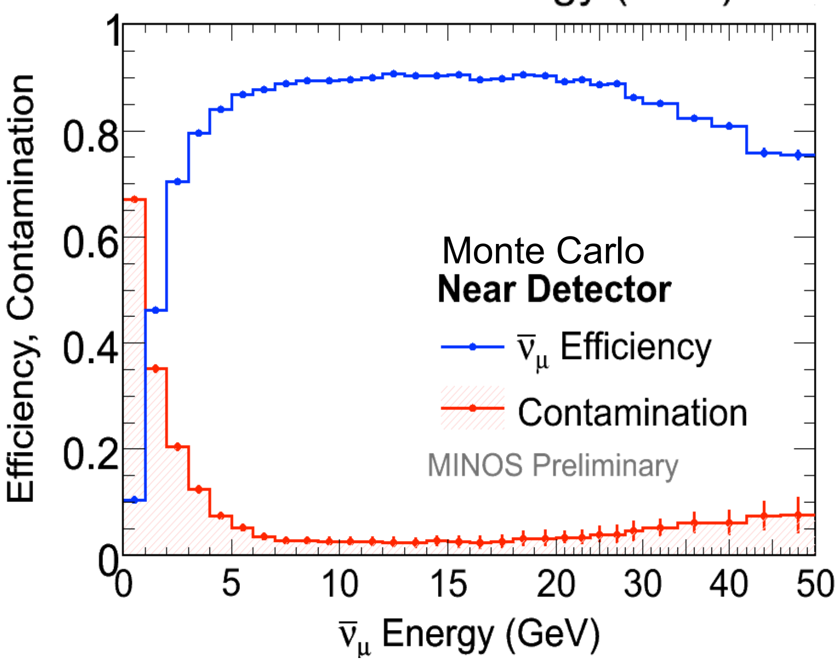
Selection: Backgrounds

- Large background:
  - mis-identified ν_μ events with wrong track sign (8%)
  - NC events faking a muon track (50%)

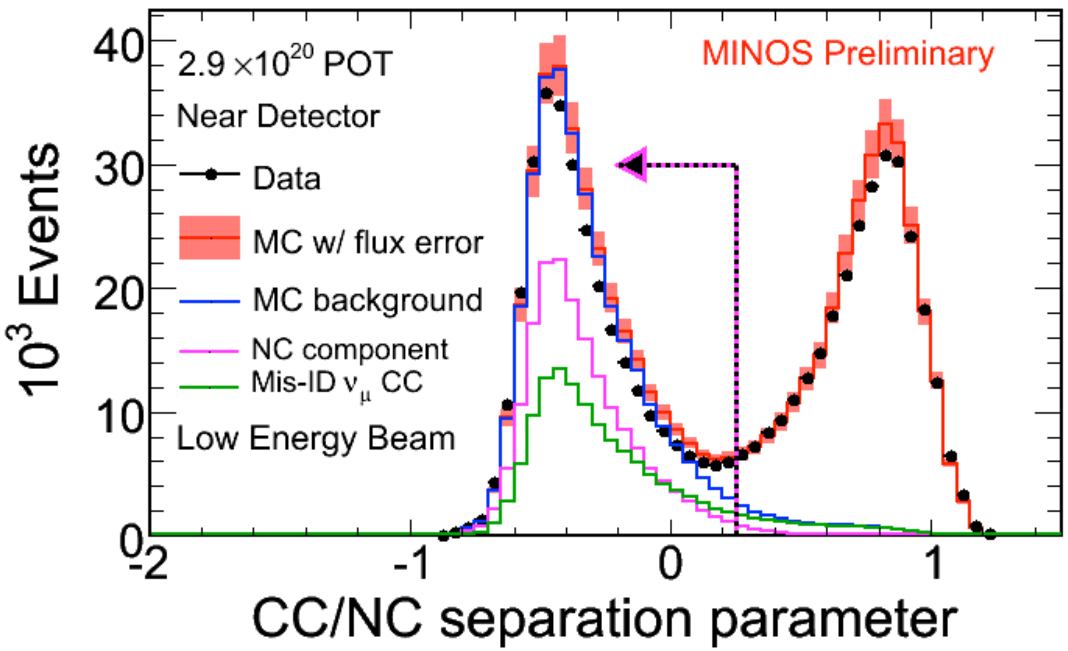
- Additional selection cuts:
  - Significance of charge sign determination
  - Relative angle (does the track curve towards or away from the magnetic coil hole relative to its initial direction)
  - Likelihood based on track length and pulse height for CC/NC separation

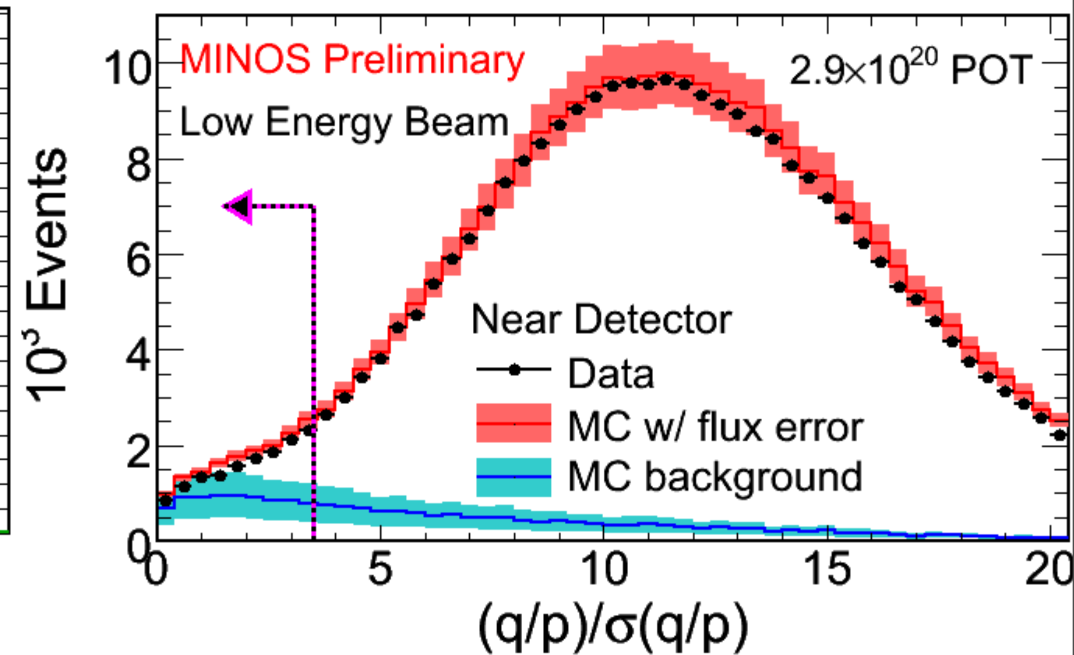
- Near Detector: 87% efficiency, 5% contamination



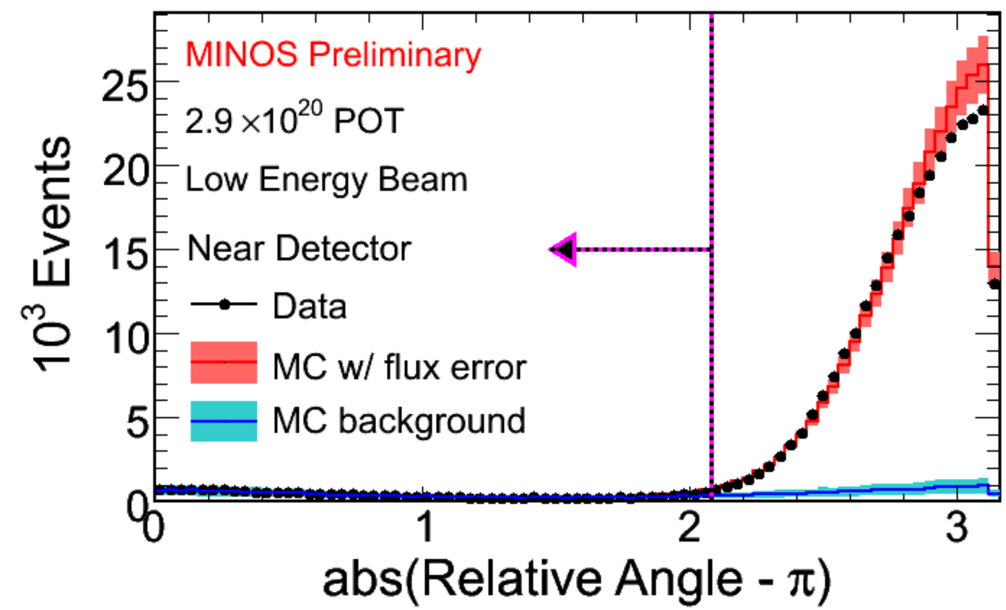


Selection Variables

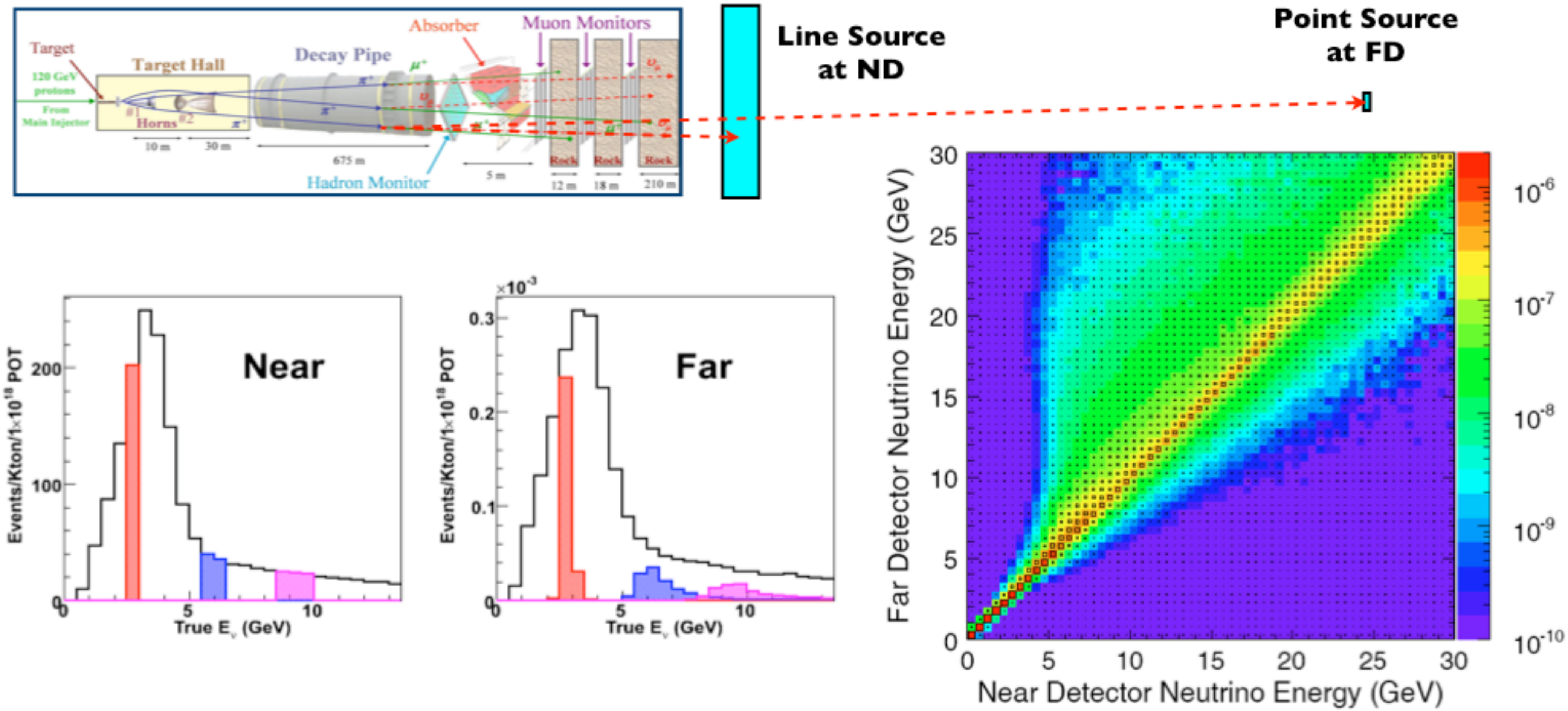




- Likelihood based CC/NC separation (developed for previous analyses, removes both NC and mis-id'd CC)
- Track fit charge significance
- Relative angle (direction of the track in the magnetic field)



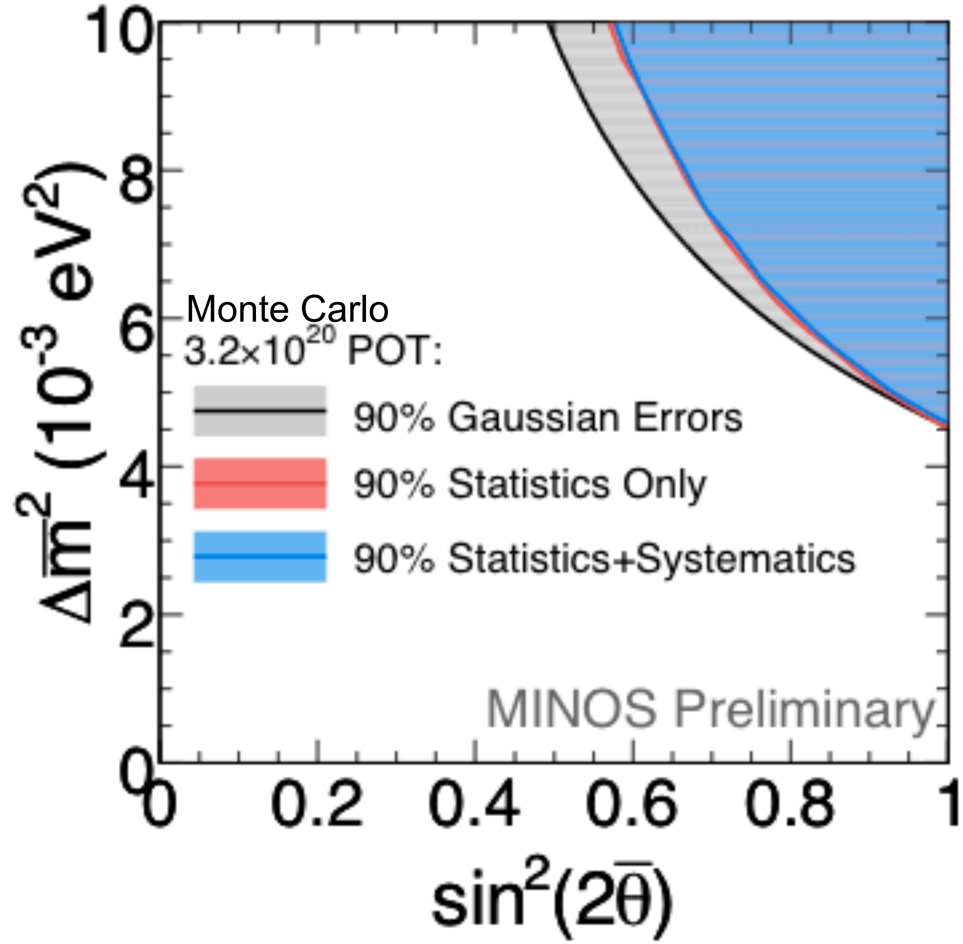
Extrapolation



- Near detector energy spectrum extrapolated to Far Detector, using MC to provide energy smearing and correct for detector acceptance

Sensitivity

- This plot shows the sensitivity of our analysis
- This is the coverage contour we would get in the 'Average' experiment
- The contribution from the Feldman-Cousins corrections are shown



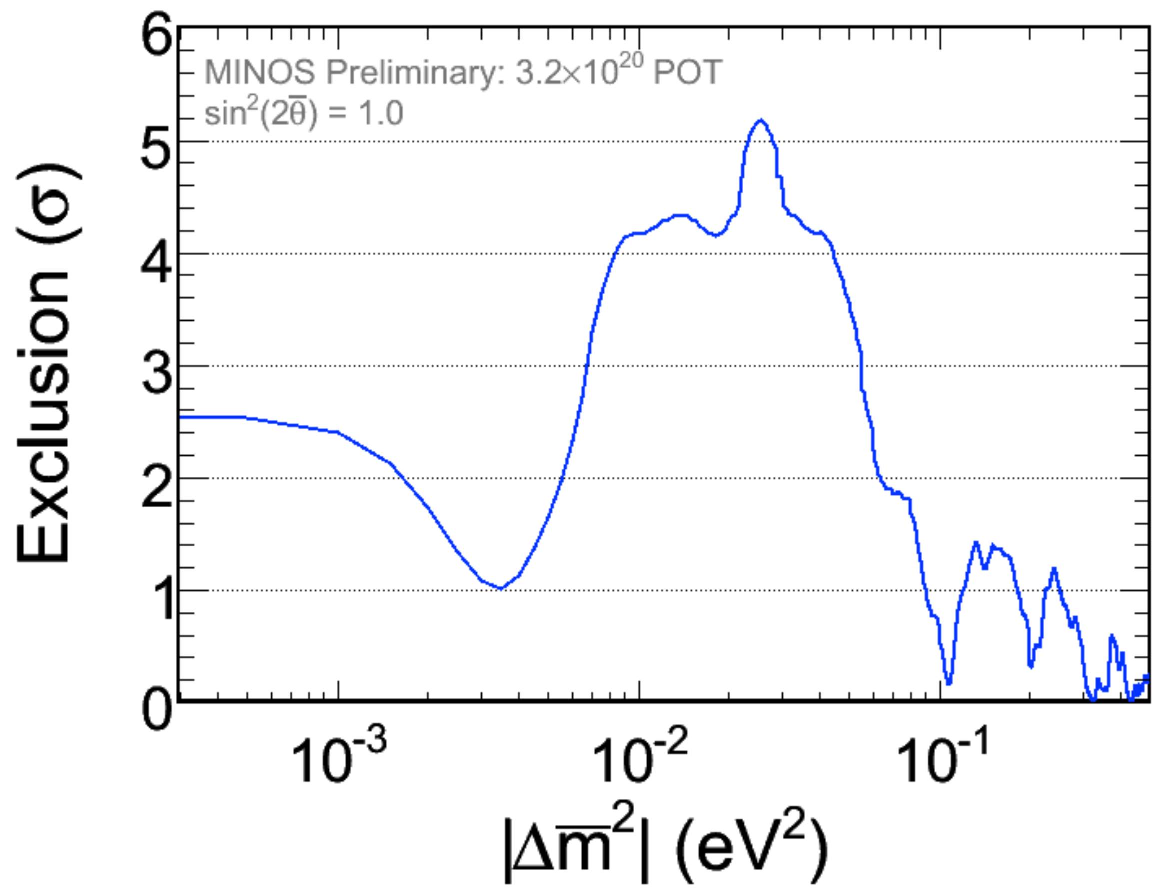
One parameter Fit at Maximal Mixing

- Dataset doesn't constrain mixing angle well.
- Perform one parameter fit at maximal mixing.
- MINOS excludes at maximal mixing:

$(5.0 < \Delta m^2 < 81)\times10^{-3}$ eV^2 (90% C.L.)

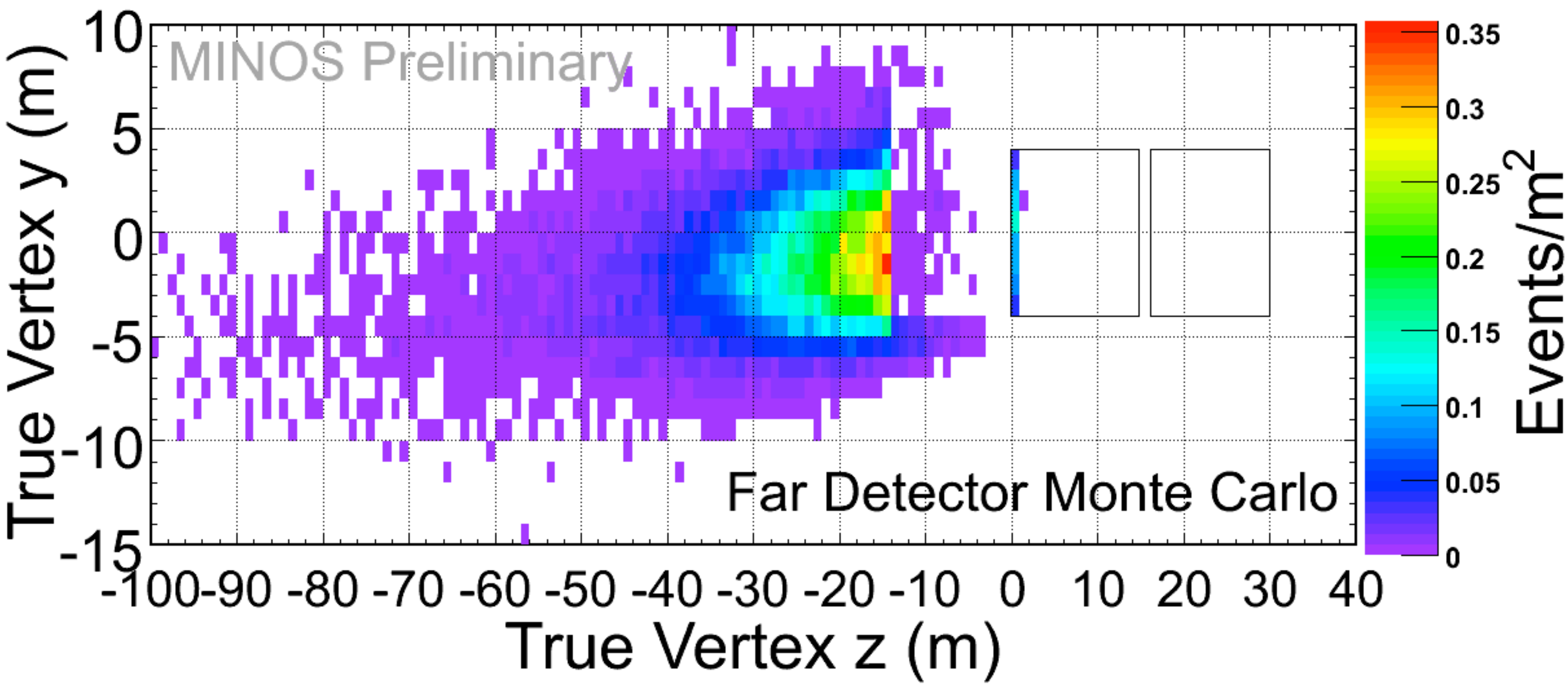
- Similarly at 3σ C.L.:

$(6.7 < \Delta m^2 < 55)\times10^{-3}$ eV^2 (3σ C.L.)



Antineutrino 3.2E20 Cross-Checks

- The deficit is consistent with statistical fluctuations
- Extensive cross checks were performed
- An independent sample of **rock muons** was studied
    - Sample about half the size of the fiducial sample
    - Found a ~1 sigma excess



Statistical Context

- Compared to the CPT-conserving oscillation hypothesis we have a deficit of 16.3 events
- Using normalization information alone this is a 1.9 sigma effect
- A study using 100,000 fake experiments including systematics gave the probabilities in accordance with expectations