NuMI Muon Antineutrinos in MINOS

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for the MINOS collaboration

Fermilab Joint Experimental-Theoretical Seminar, May 15th 2009

Introduction

- MINOS physics goals
- NuMI neutrino beam
- MINOS detectors
- Selecting muon anti-neutrinos
- Far detector spectrum
- Results
- Future plans

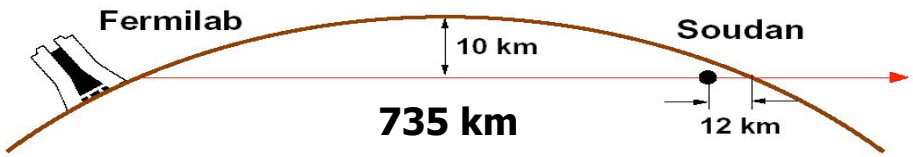
The MINOS Collaboration

140 scientists
28 institutions

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

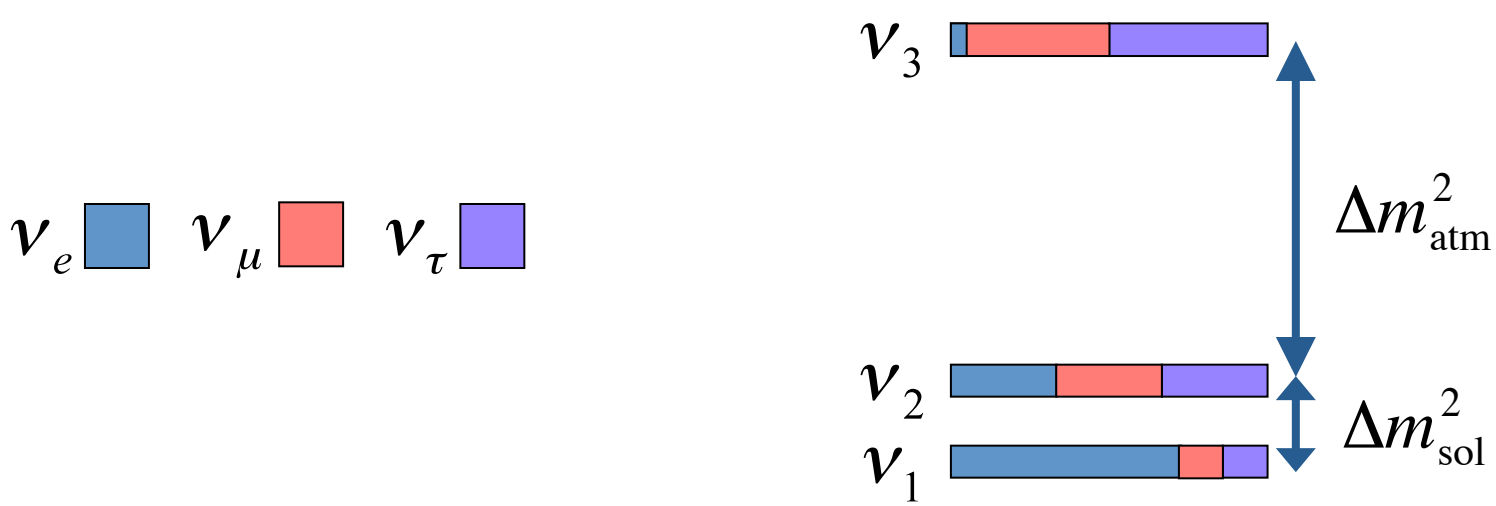
MINOS Overview

- Main Injector Neutrino Oscillation Search
- Neutrinos at the Main Injector (NuMI) beam at Fermilab
- Two detectors:
- Near detector at Fermilab
  - measure beam composition
  - energy spectrum
- Far detector in Minnesota
  - search for and study oscillations



Neutrino Masses and Mixings

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



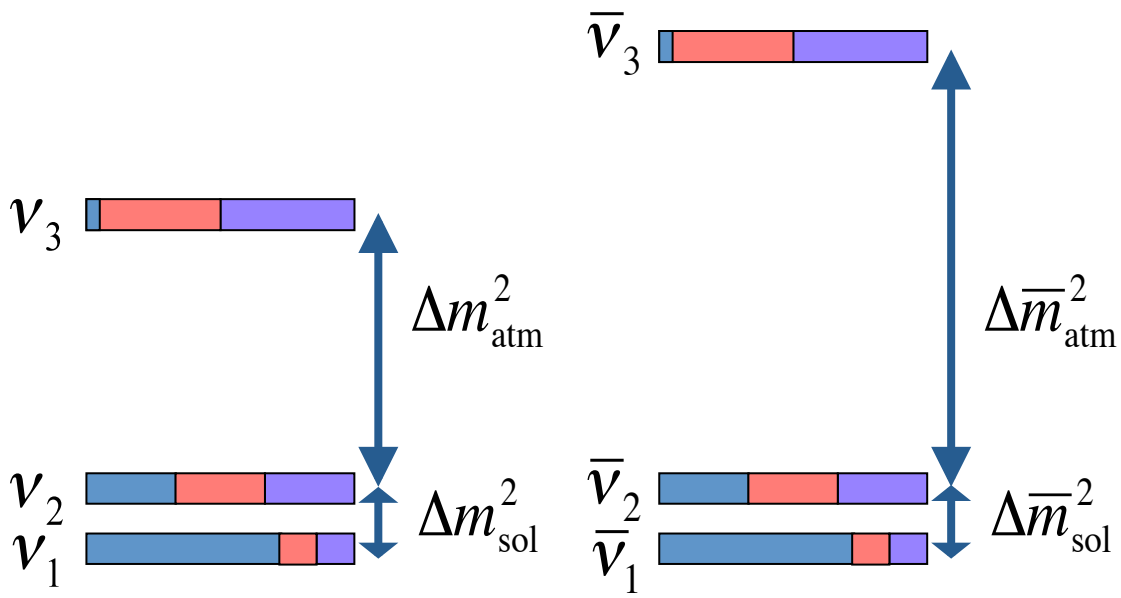
MINOS Physics Goals

- Precise measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector
- Search for both $\bar{\nu}_\mu$ disappearance **AND** appearance
  - test the standard neutrino model

$\bar{\nu}_\mu$ Disappearance

- Do ν_μ and $\bar{\nu}_\mu$ oscillate in the same way?

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



- If not, then could be evidence for CPT violation or non-standard interactions

$\bar{\nu}_\mu$ Appearance

- MINOS has observed the disappearance of 100s of ν_μ
  - Do any of these reappear as $\bar{\nu}_\mu$?
  - Consider an experimentally driven parametrisation:

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

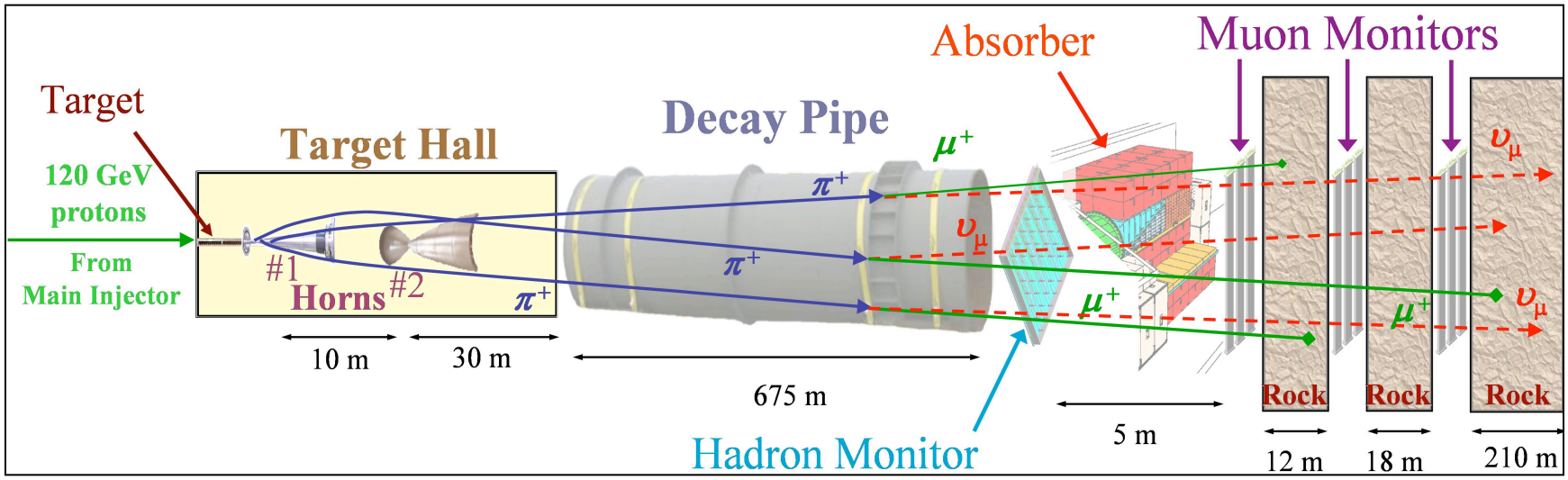
  - where α is the fraction of ν_μ that transition to $\bar{\nu}_\mu$

- $\bar{\nu}_\mu$ appearance predicted by the standard model at the 10^{-18} level if neutrinos are Majorana:

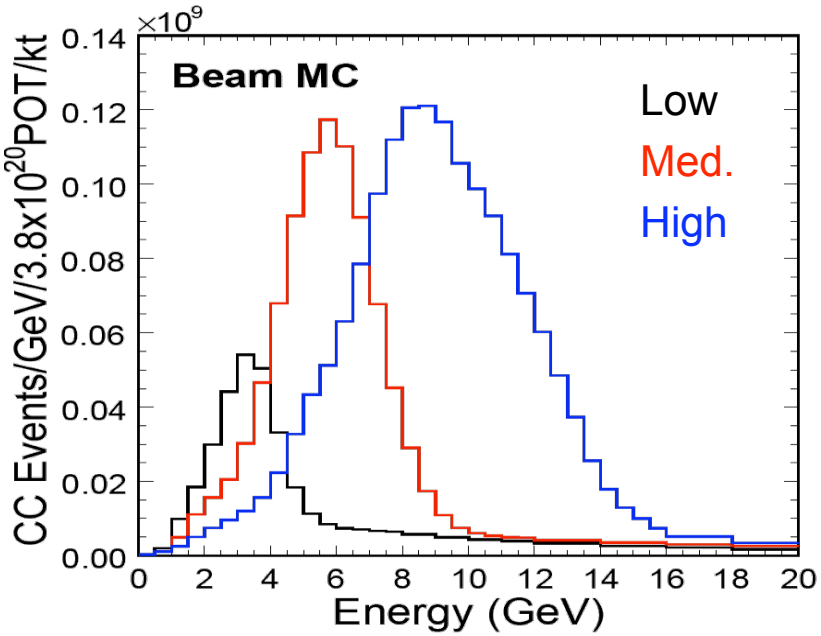
$$P(\nu_\mu \rightarrow \bar{\nu}_\mu) \sim (m_\nu / E_\nu)^2$$

- Also predicted at a very low level by models with a large neutrino magnetic moment, neutrino decay and other exotic processes (*Langacker and Wang, Phys. Rev. D 58:093004)*

NuMI Neutrino Beam

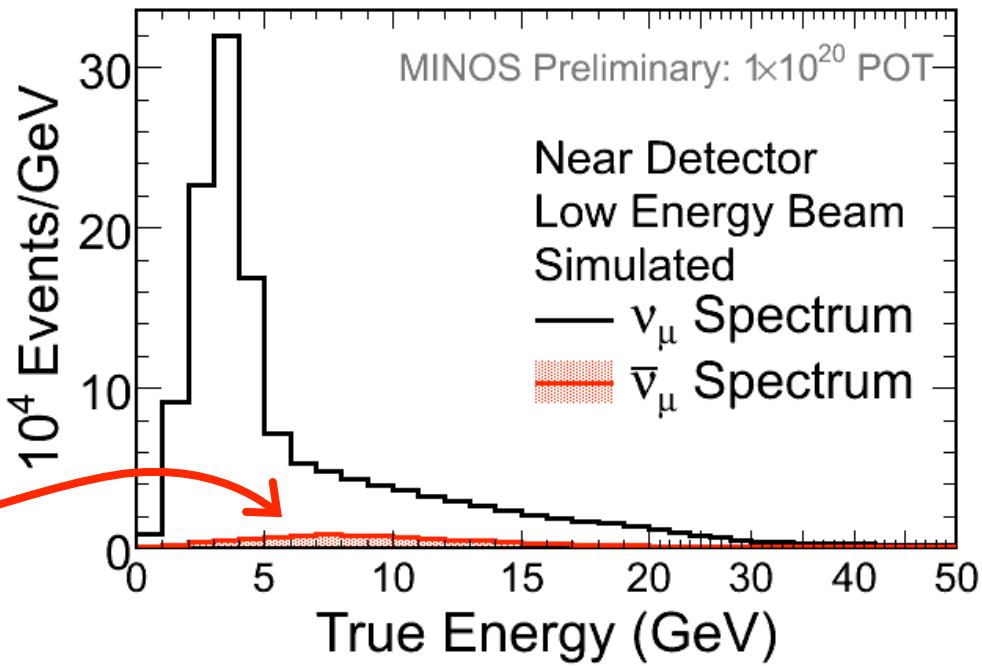


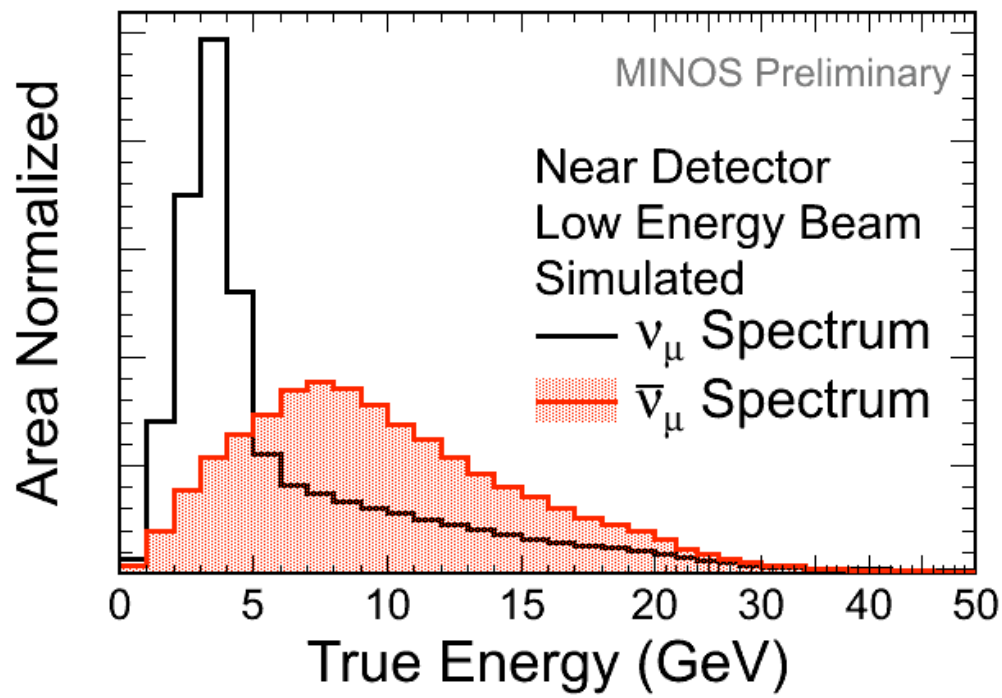
- 120 GeV protons strike target
- 10 μs long pulse of ~3×10^{13} protons every 2.2 seconds (275 kW)
- Two magnetic horns focus secondary π/K
  - decay of π/K produce neutrinos
- Variable neutrino beam energy



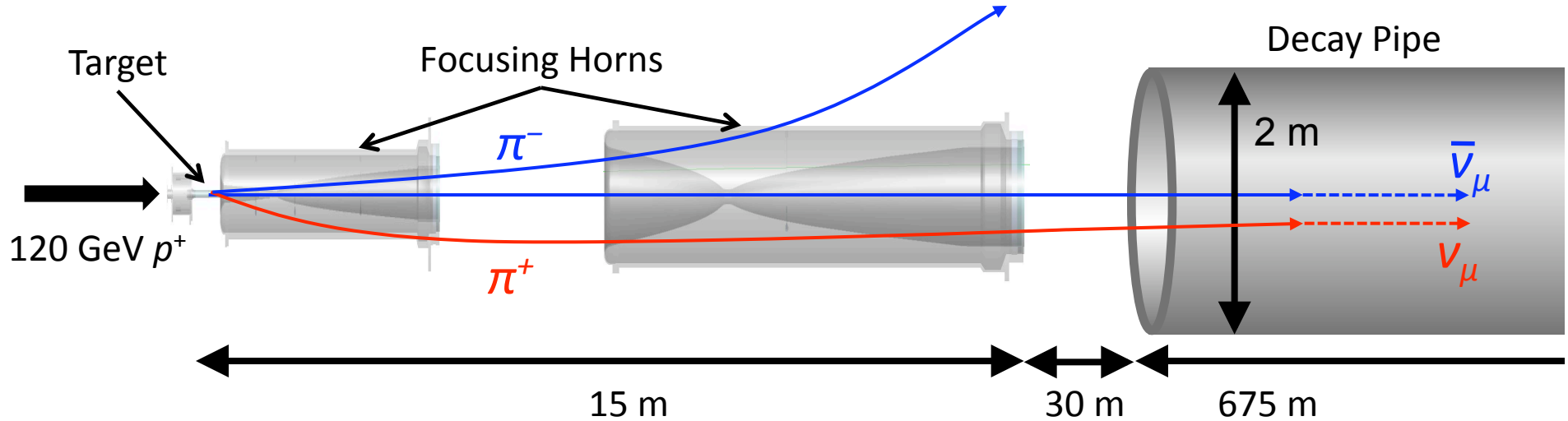
Beam Flavour Composition

- The charged current interactions in the Near detector comprise of:
  - 91.7% ν_μ
  - 7.0% $\bar{\nu}_\mu$
  - 1.3% ν_e and $\bar{\nu}_e$
- Significant difference in the energy spectrum:
  - ν_μ peak at 3 GeV
  - $\bar{\nu}_\mu$ peak at 8 GeV

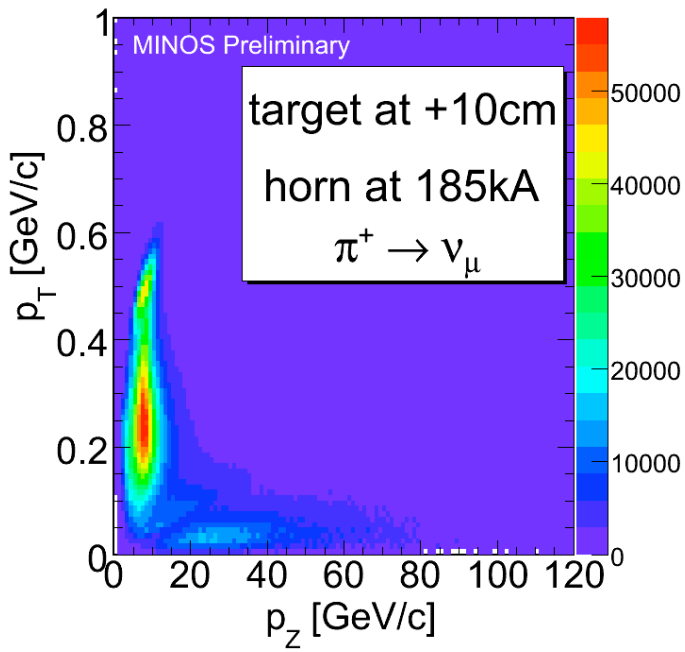


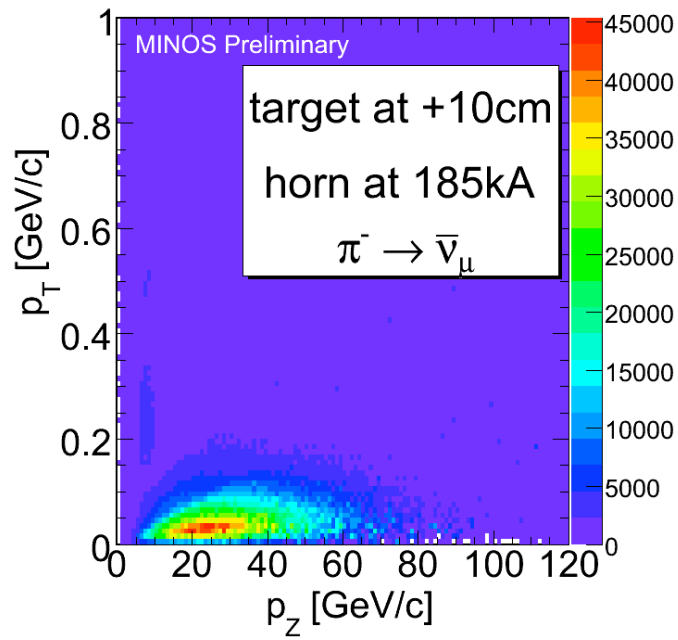


Why are the spectra so different?



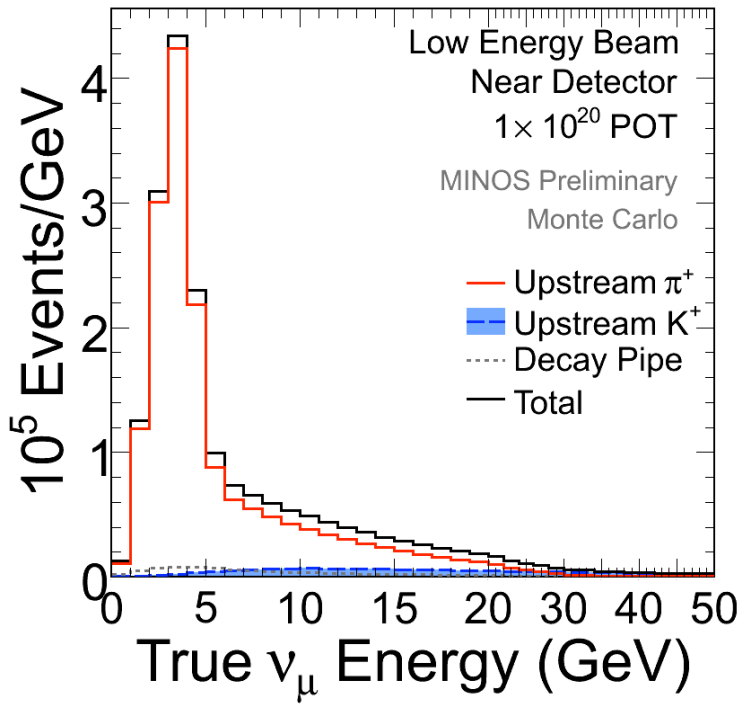
- Majority of $\bar{\nu}_\mu$ come from "neck-to-neck" low-p_T π^- that travel down the centre of the horns where there is zero magnetic field
- ν_μ spectrum dominated by **focused** high-p_T π^+

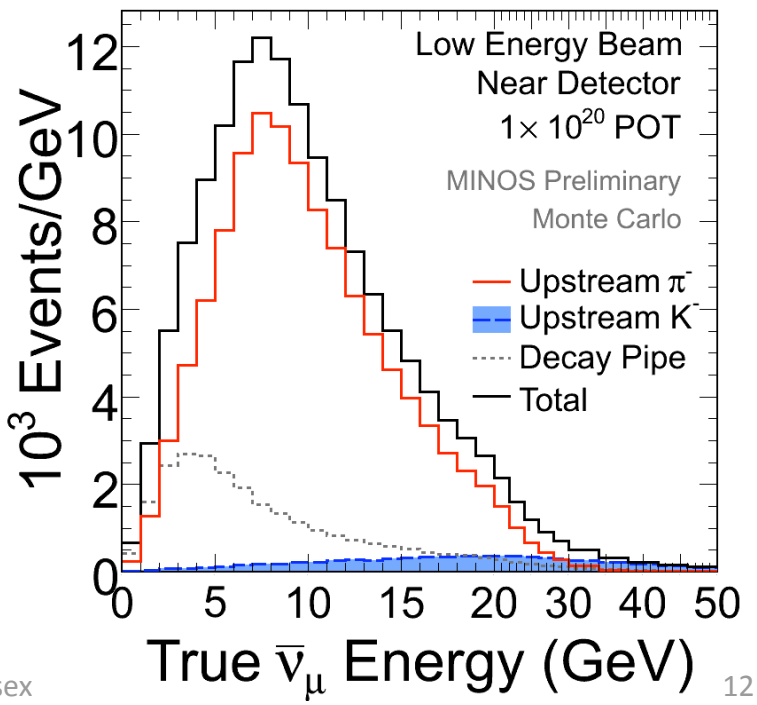




Where do the ν_μ and $\bar{\nu}_\mu$ originate?

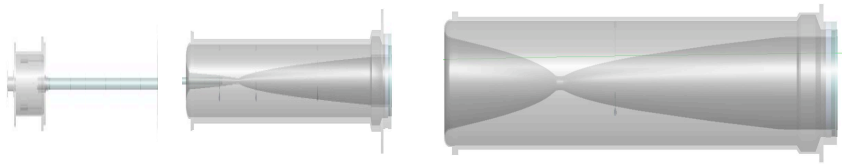
- ν_μ originate almost entirely from π^+ produced upstream of decay pipe
- In contrast, $\bar{\nu}_\mu$ spectrum has significant components that originate from:
  - Upstream produced K^-
    - constrained by external hadron production data
    - K^0 < 1% of total
  - μ^+ from π^+ (small and well constrained)
  - Interaction of primary protons and secondary hadrons downstream
    - Decay pipe production in walls





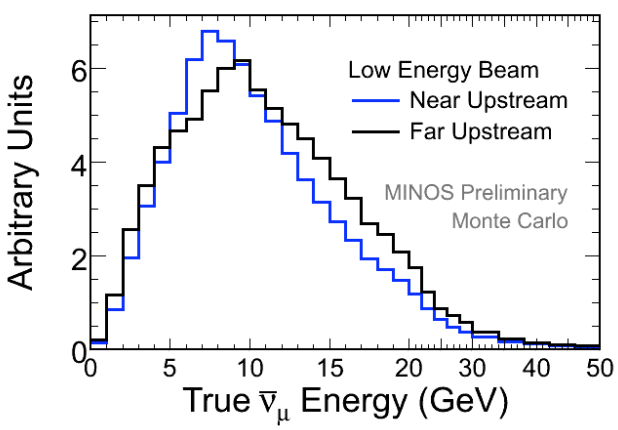
$\bar{\nu}_\mu$ Production Location

- Location in the beamline where $\bar{\nu}_\mu$ are produced affects the relative spectrum in the two detectors
- Decay pipe production of π^- is important
  - Occurs further downstream: projects a larger solid angle to Near detector
- Upstream production gives similar spectra in both detectors

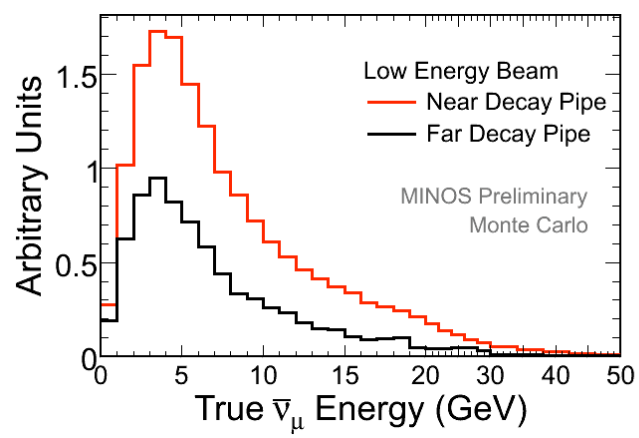


Upstream production

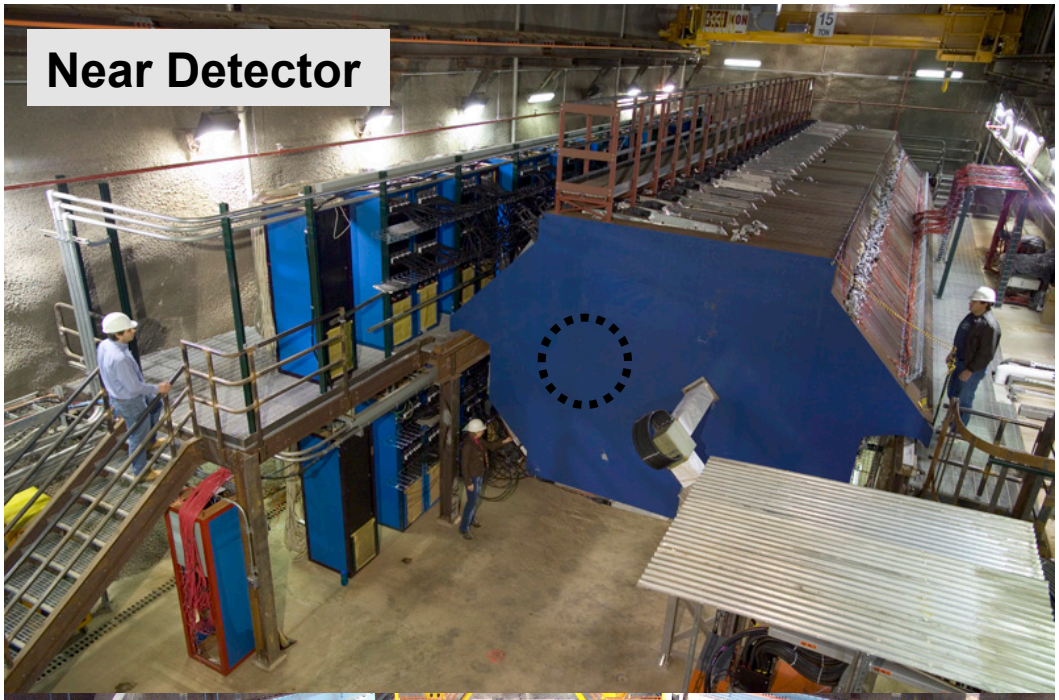
Decay pipe production

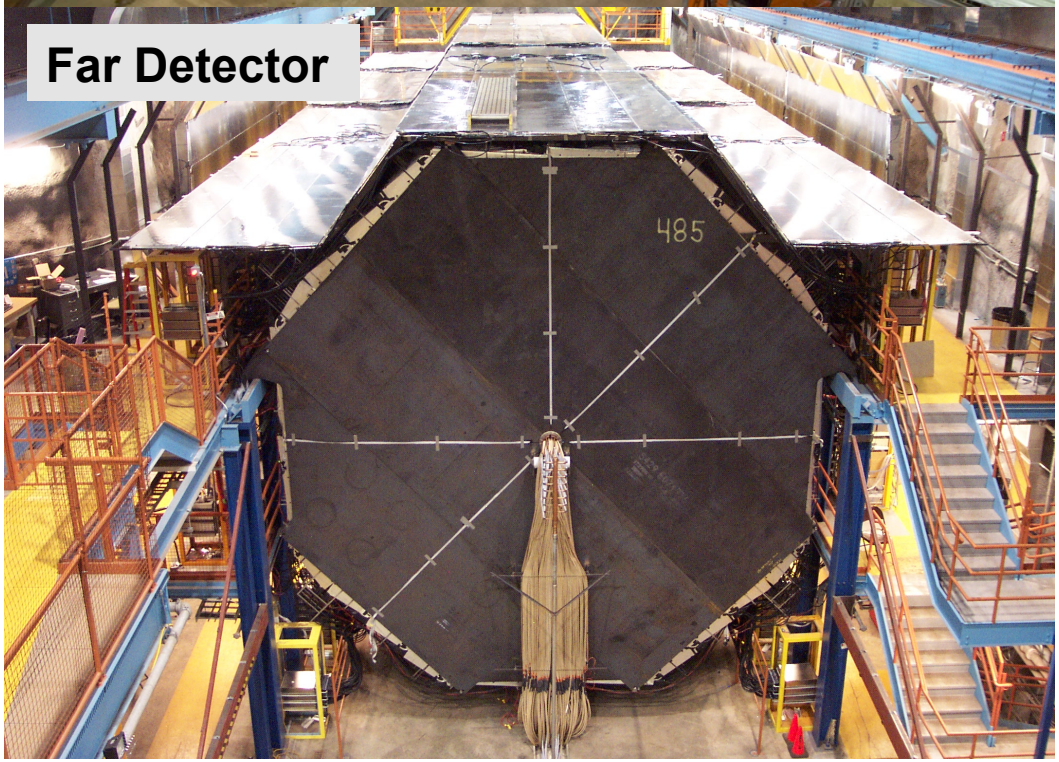


Near 83%
Far 92%



Near 17%
Far 8%

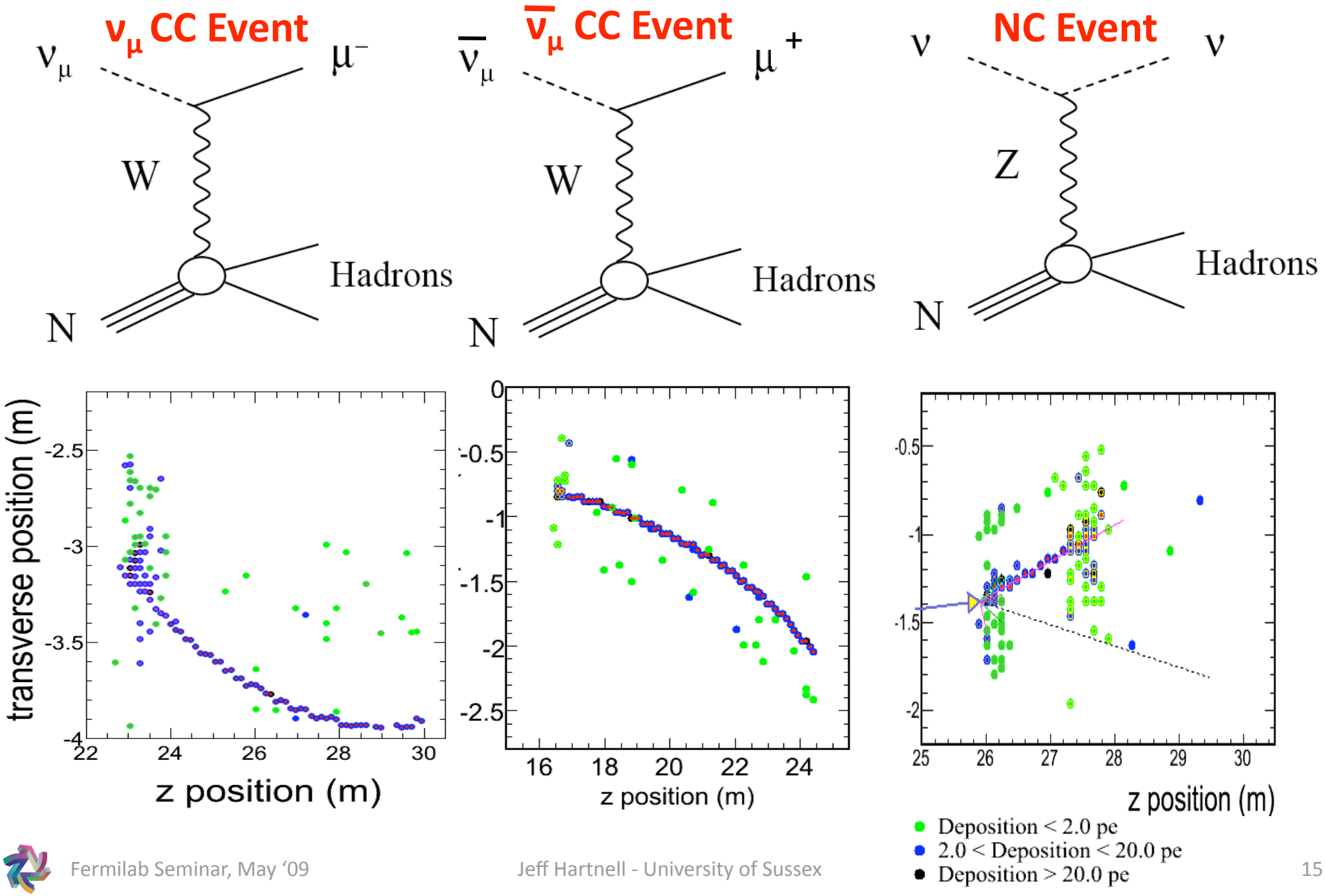




MINOS Detectors

- Massive
  - 1 kt Near detector
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

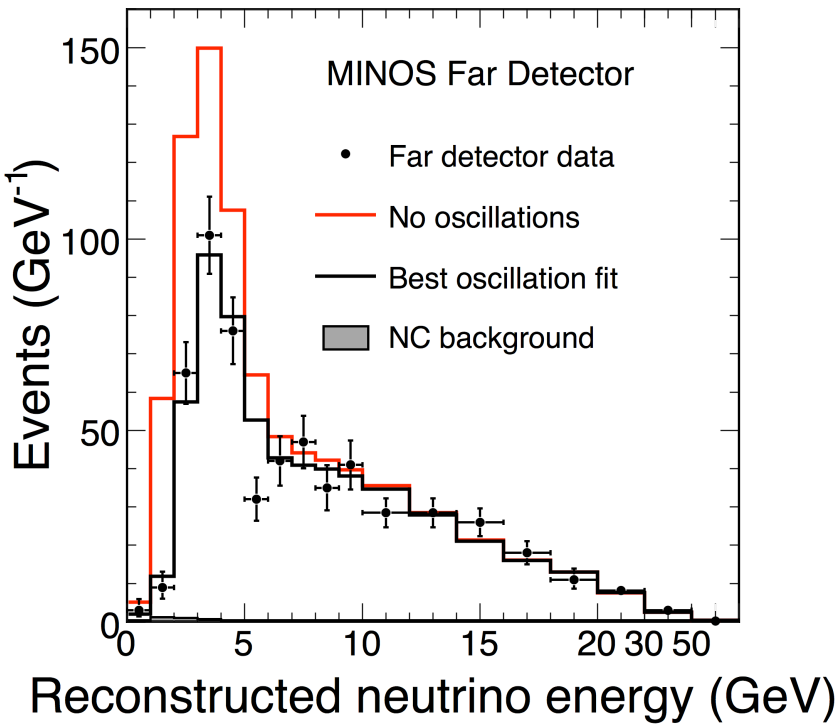
MINOS Event Topologies

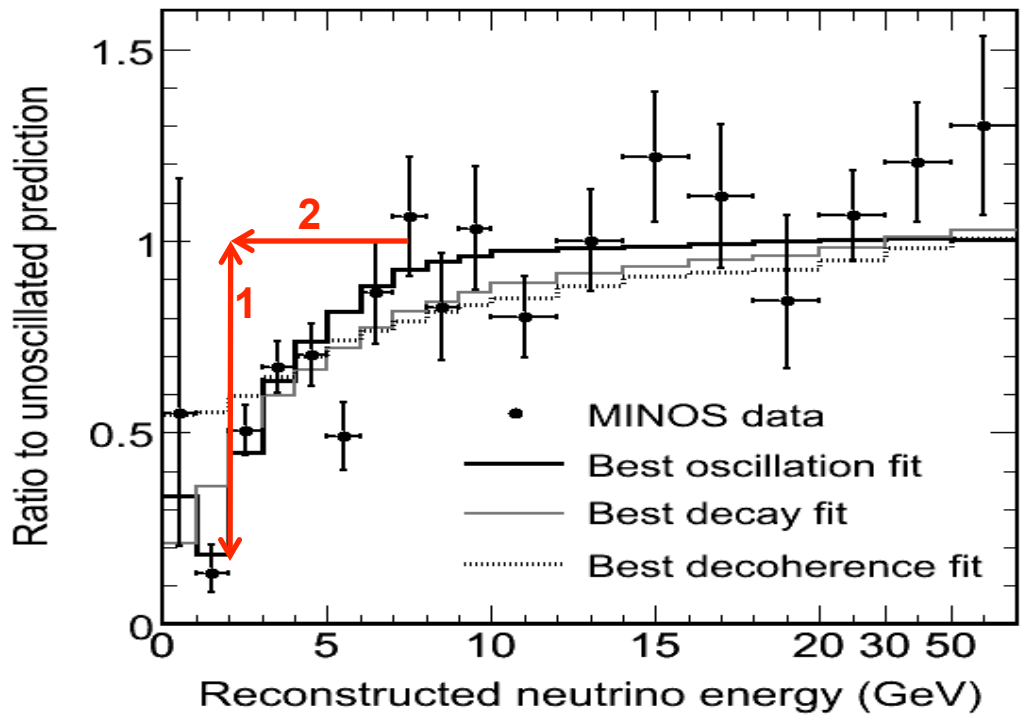


A quick review of the 2008 Muon Neutrino Disappearance Analysis

Experimental Approach

- **Two detector experiment** to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated ν_μ spectrum at Near detector
    - extrapolate using MC
  - Compare to measured spectrum at Far detector





$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \underbrace{\boxed{\sin^2 2\theta}}_{1} \sin^2(1.267 \underbrace{\boxed{\Delta m^2}}_{2} L/E)$$

Allowed Region

- Energy spectrum fit with the oscillation hypothesis:

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

- Results:

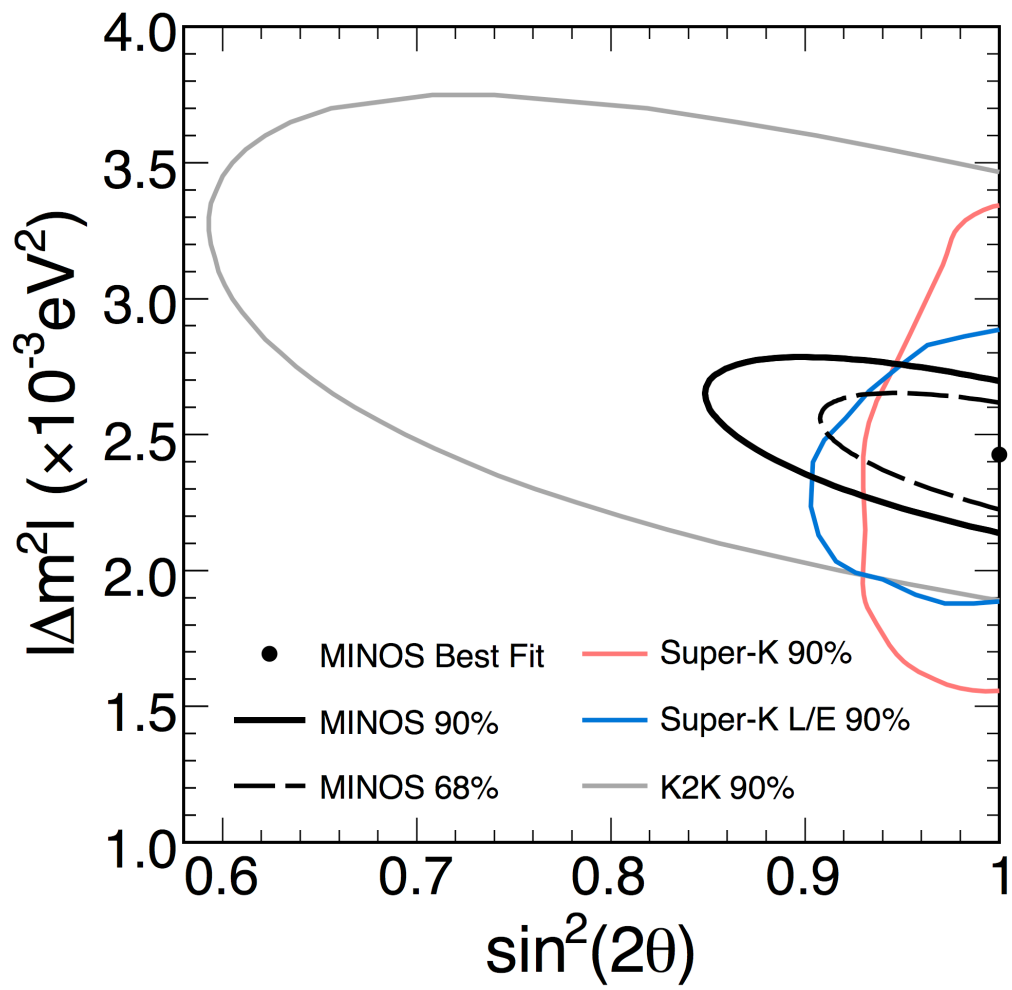
$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$

at 68% C.L.

$\sin^2(2\theta_{23}) > 0.90$

at 90% C.L.

PRL **101** 131802 (2008)



Most precise measurement of $|\Delta m^2_{32}|$ performed to date

What about the Muon **Anti-**Neutrinos…

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons}$$

$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons}$$

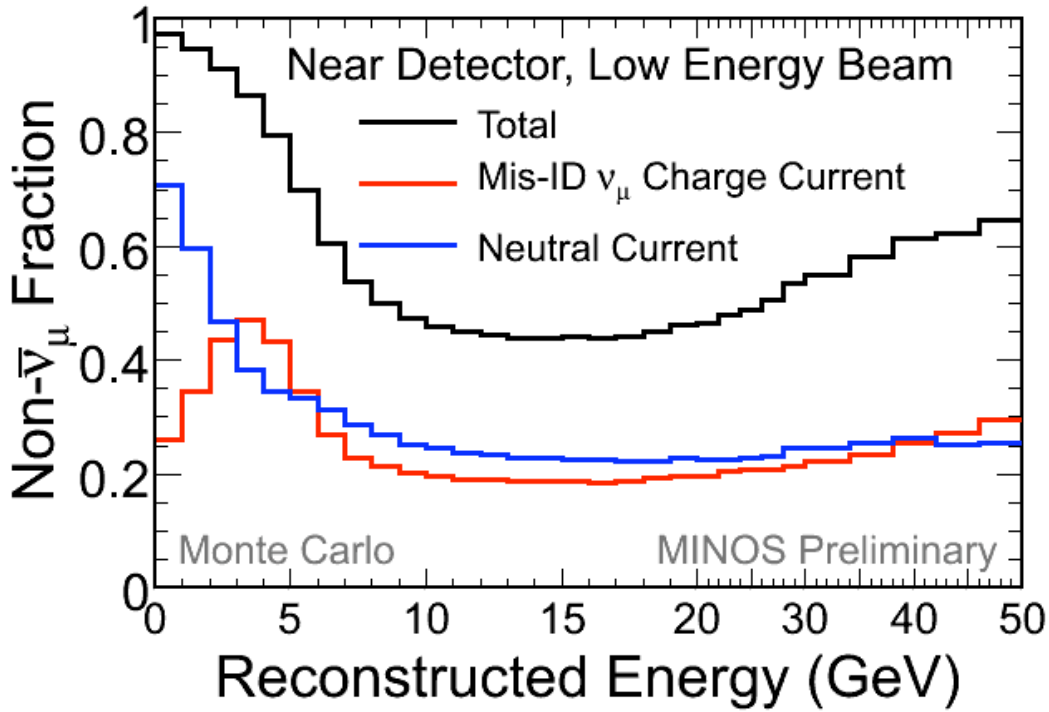
Blind Analysis

- A blinding procedure was followed (as for previous MINOS analyses)
- All selection cuts, data samples, extrapolation techniques, fitting routines and systematic uncertainties were finalised before the Far detector data were looked at
- No changes have been made after box opening

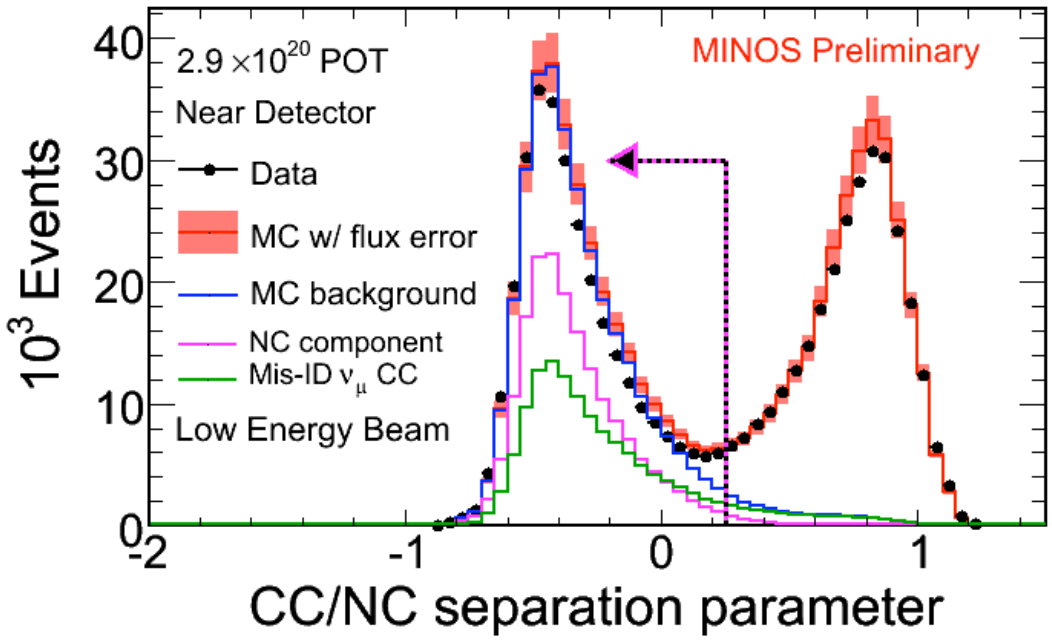
Selecting $\bar{\nu}_\mu$

- $\bar{\nu}_\mu$ CC events are 7% of beam
- Searching for $\bar{\nu}_\mu$ CC amongst a large sample of other events:
  - Mis-identified ν_μ CC where μ charge sign is wrong
  - Neutral Current (NC) events where another particle fakes a μ^+ track
- NC events with a track are ~50:50, positive:negative charge sign
- Develop cuts to remove contamination
  - Cut on 3 additional variables

All events with a positive curvature track



1st Additional Selection Variable



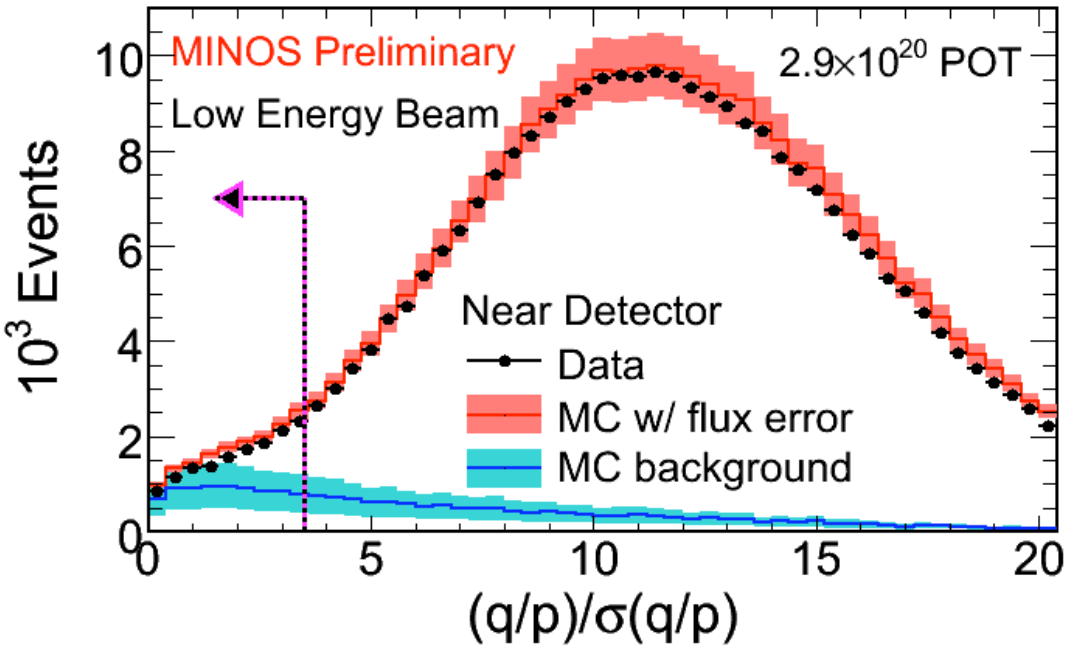
- Likelihood-based with 3 Probability Density Functions:
  - Track length
  - Pulse height fraction in track
  - Pulse height per plane

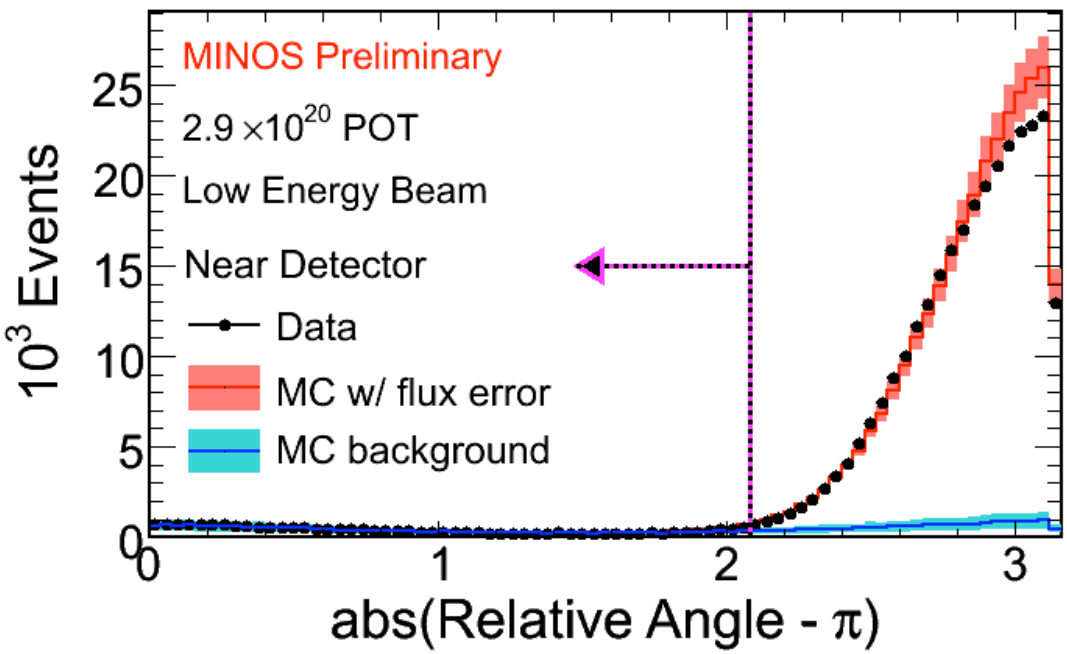
PRL 97 191801 (2006) & PRD 77 072002 (2008)

- Use CC/NC separation parameter developed for previous analyses
  - Cut removes **both** NC and mis-identified ν_μ CC events
- Mis-ID ν_μ CC events tend to be inelastic events where the muon is obscured by a large hadronic shower
  - high-y events
- Cut harder (+0.25) compared to ν_μ analysis (-0.1) due to greater background

2nd & 3rd Additional Selection Variables

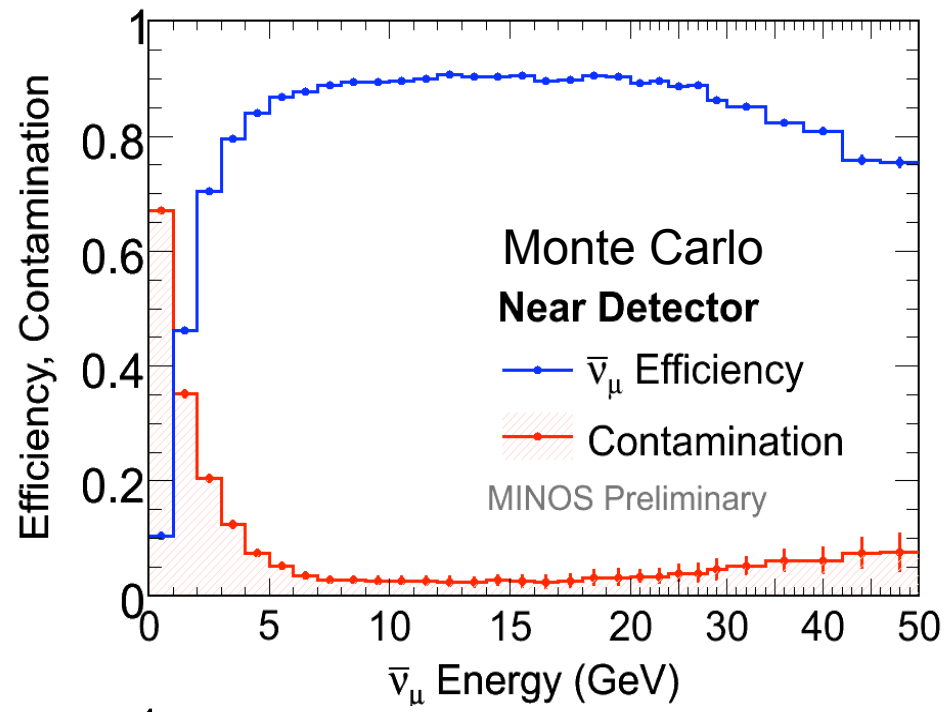
2) Track fit charge sign significance
3) Relative angle
   – measure of whether the track curves towards or away from the magnetic coil hole, relative to its initial direction

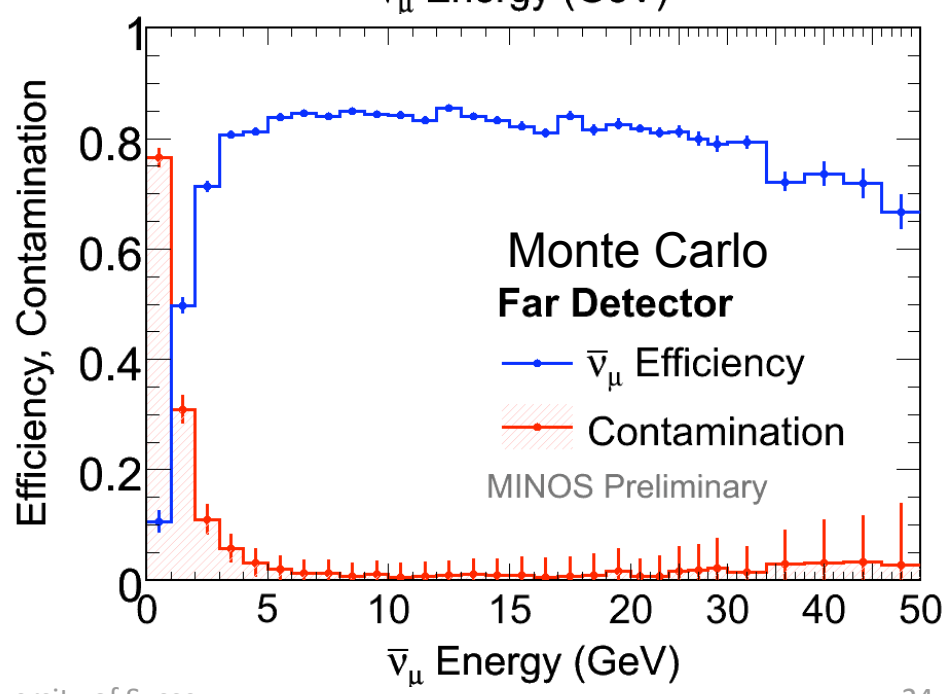




Efficiency and Contamination

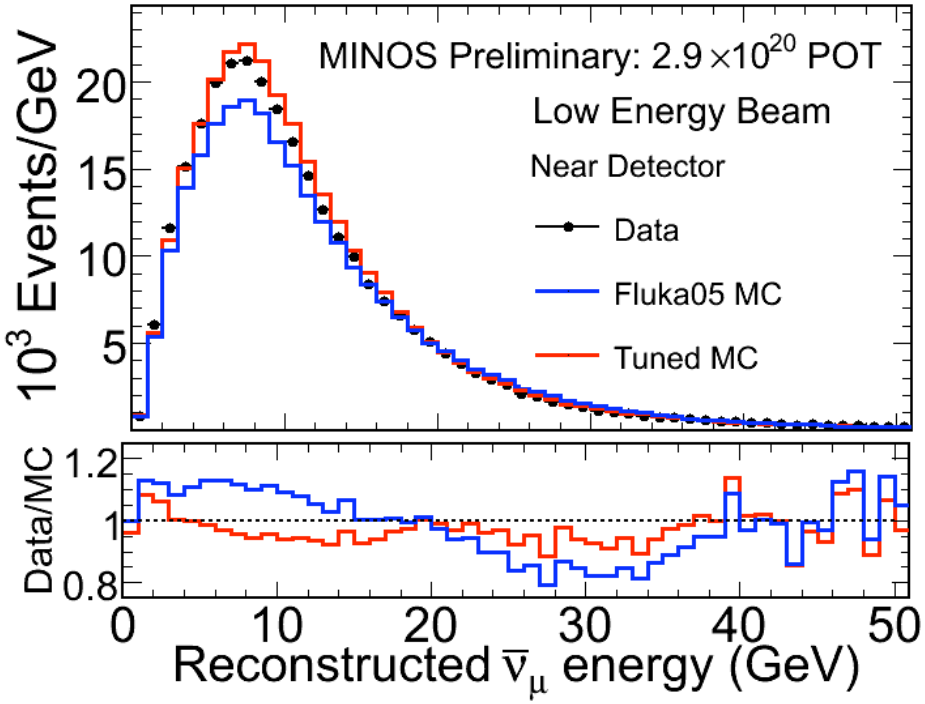
- After all cuts:
  - Near detector
    - Efficiency of 87%
    - Contamination of 5%
  - Far detector
    - Efficiency of 82%
    - Contamination of 3%
- Optimised for physics sensitivity to CPT conserving oscillations
  - lower contamination is possible but at the cost of events

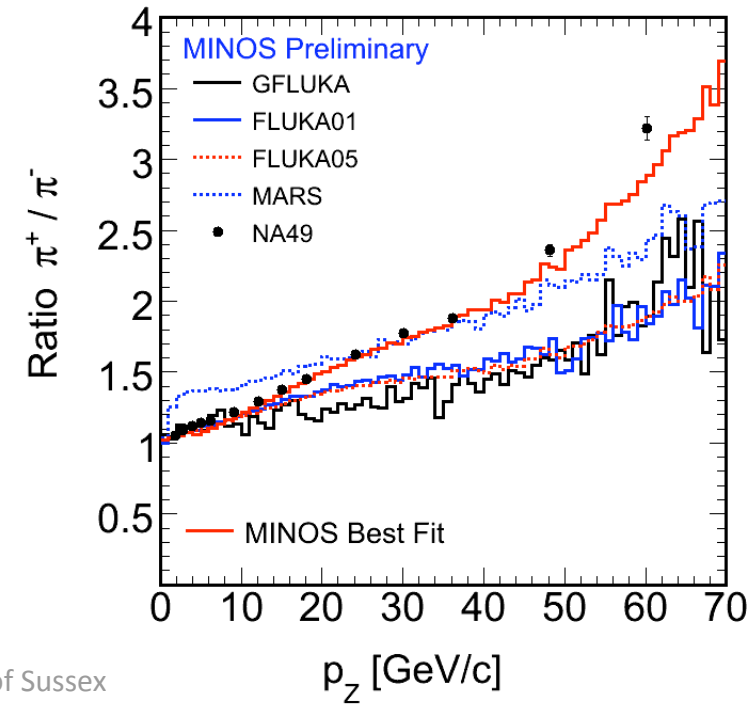




Near Detector $\bar{\nu}_\mu$

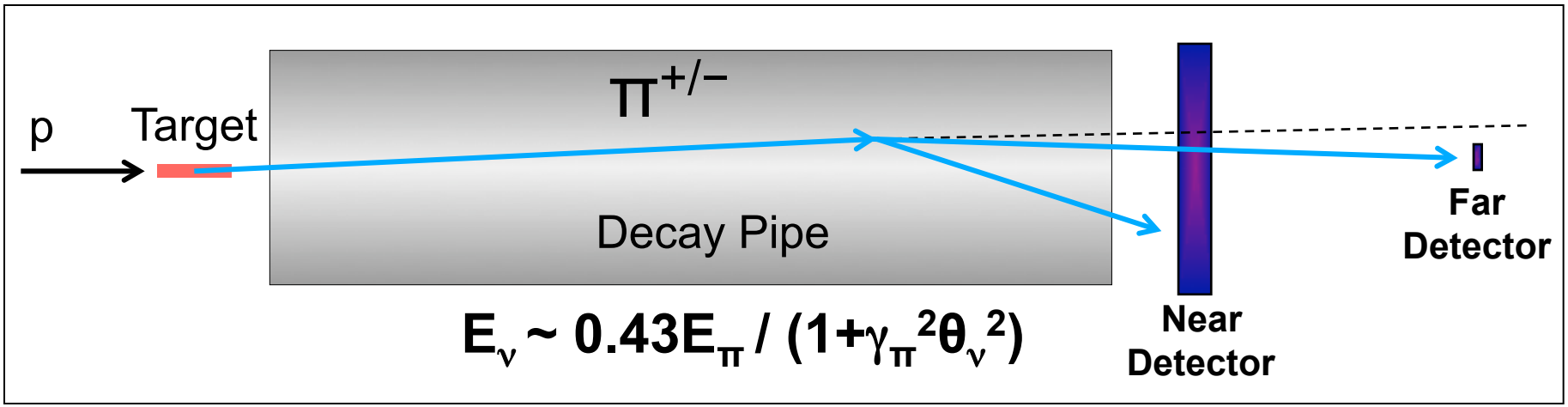
- Unlike for ν_μ moving target or changing horn current does not probe the p_T/p_Z space
  - $\bar{\nu}_\mu$ spectrum is the same to 10% in all beam configurations
- Hadron production in the beam target is modeled by Fluka05
  - Sparse hadron production data
  - Prediction uncertainty is ~20%
- Fit Near detector data to a hadron production model
  - Result for π^+/π^- ratio great success: agrees well with new NA49 data
    - Eur. Phys. J. C 49 897 (2007)
  - Doesn't significantly affect the Far detector prediction





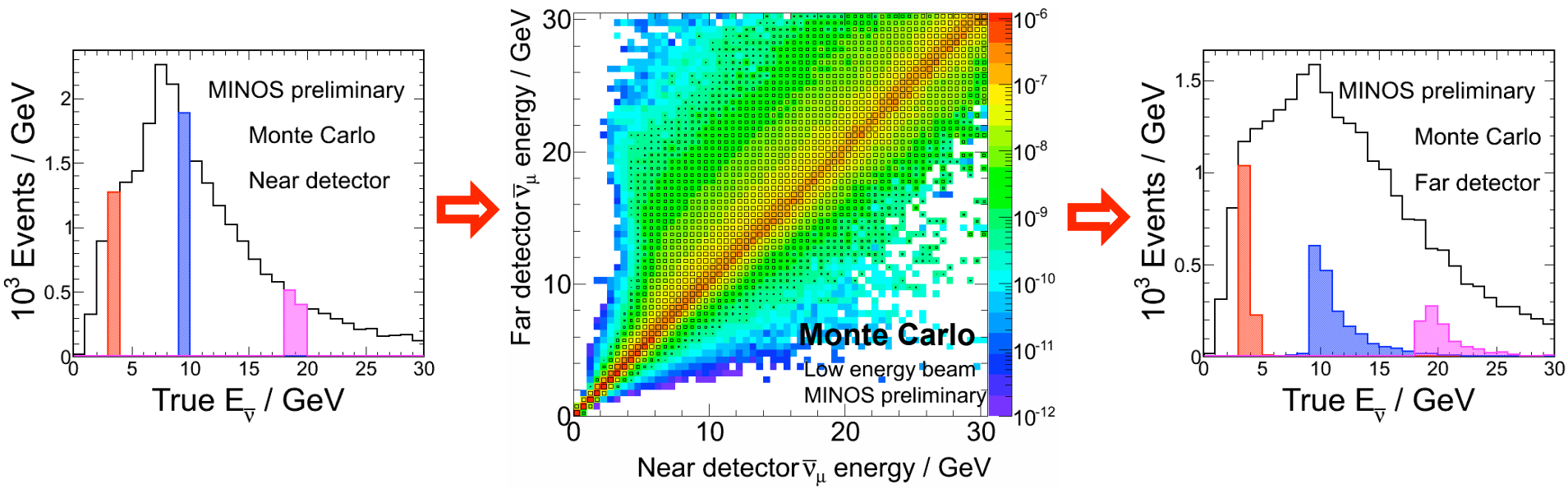
Near to Far Extrapolation

- Near detector spectrum ≠ Far detector
  - Project different solid angles
  - Non-point source for Near detector
  - π/K decay kinematics
    - average neutrino energy varies with angle



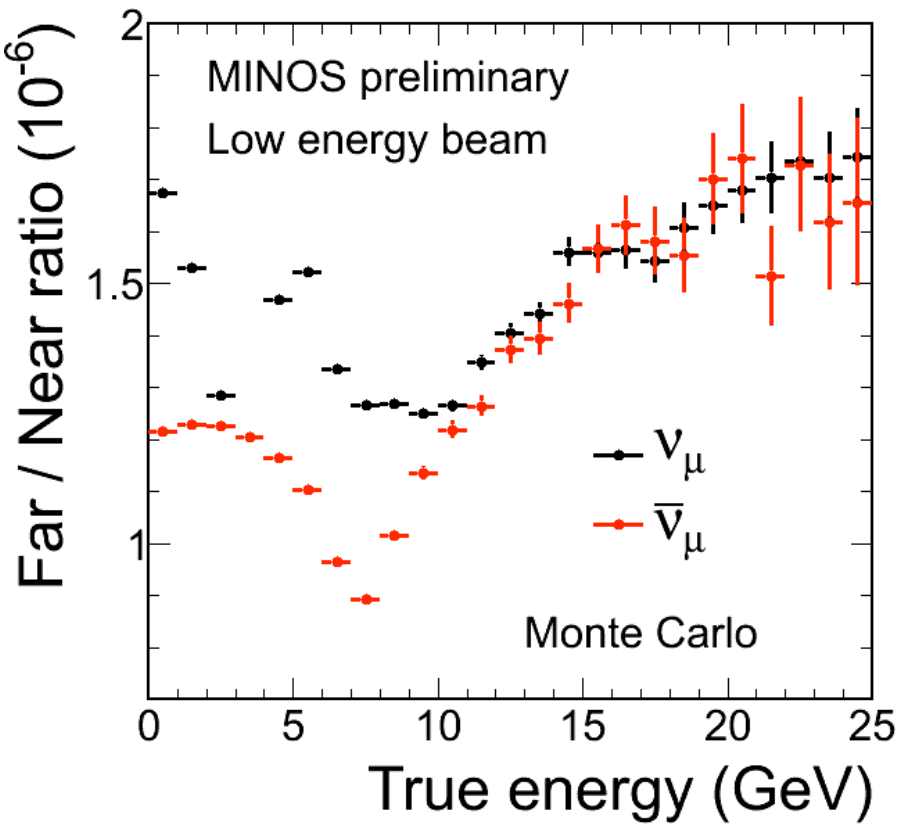
Beam Matrix Extrapolation

- A beam matrix transports measured Near spectrum to Far
  - ν_μ and $\bar{\nu}_\mu$ are extrapolated independently
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
  - Matrix element M_{ij} reflects the probability of obtaining a Far event with energy E_j given the observation of a Near event with energy E_i
- MC used to correct for energy smearing and acceptance



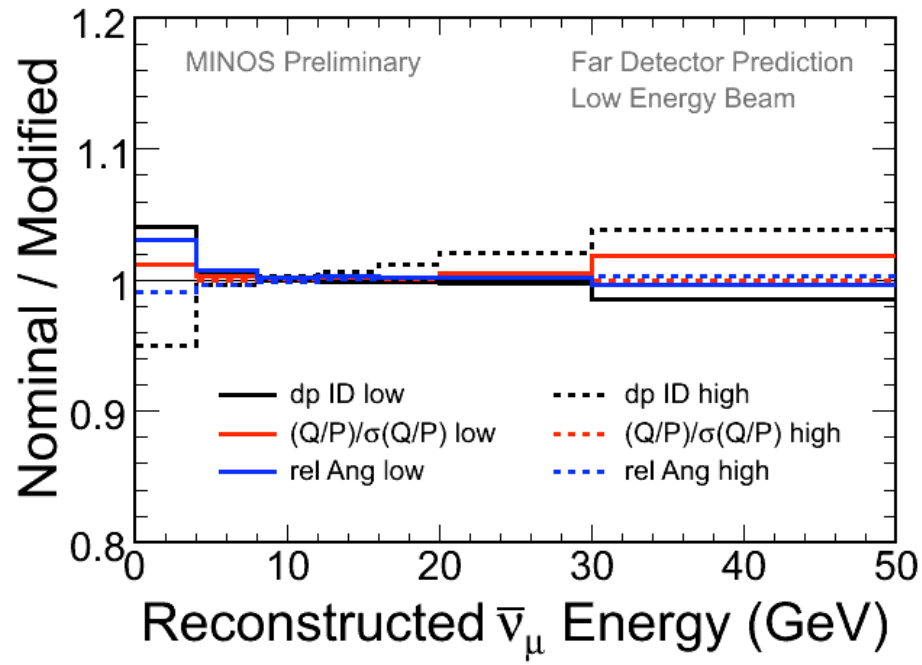
Data-Driven Hadroproduction Study

- Do we correctly model divergence of $\bar{\nu}_\mu$ in the beam?
- Use ν_μ observed in Far detector to cross check the $\bar{\nu}_\mu$ predicted spectrum
  - ν_μ high-energy tail (>10 GeV) extrapolates almost identically to $\bar{\nu}_\mu$
- Data-driven cross check:
  - ν_μ high energy tail agrees with prediction
  - Constrains $\bar{\nu}_\mu$ prediction >10 GeV to ±10%



Data/MC Tests

- Procedure: change the value of cuts in **Near** detector data & MC then extrapolate
  - If data/MC agreement is perfect then no change in Far detector prediction will be observed
- Example: set CC/NC separation parameter cut to 0.1(low) and 0.45(high)
  - contamination changes by factor 3
  - efficiency changes by ~8%
- Large change in contamination and Far prediction changes by <5%

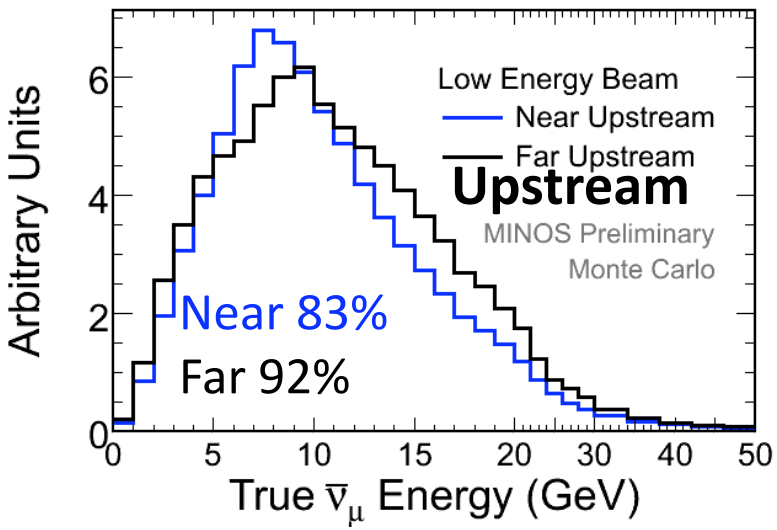


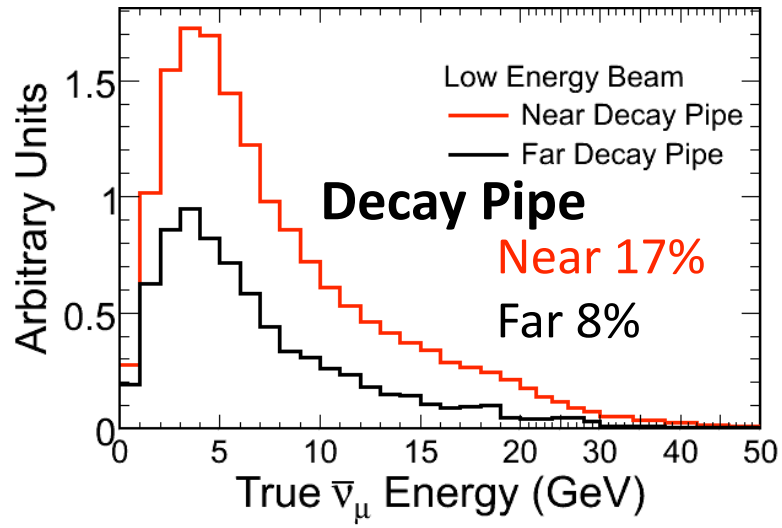
Systematic Uncertainties

- Errors that are the same as the ν_μ analysis
  - **Normalisation:** ±4%
    - Relative reconstruction eff., detector livetime and mass
  - **Muon energy:** range ±2%, curvature ±4%
    - (Error from curvature increased slightly due to exiting tracks)
  - **Beam extrapolation:** 1σ error band from beam fit
  - **Relative shower energy:** ±3%
  - **Absolute shower energy:** ±10%

- Errors that are specific for this analysis
  - **Decay pipe production:** ±40%
  - **Background:** ±50%

Decay Pipe Production Uncertainty

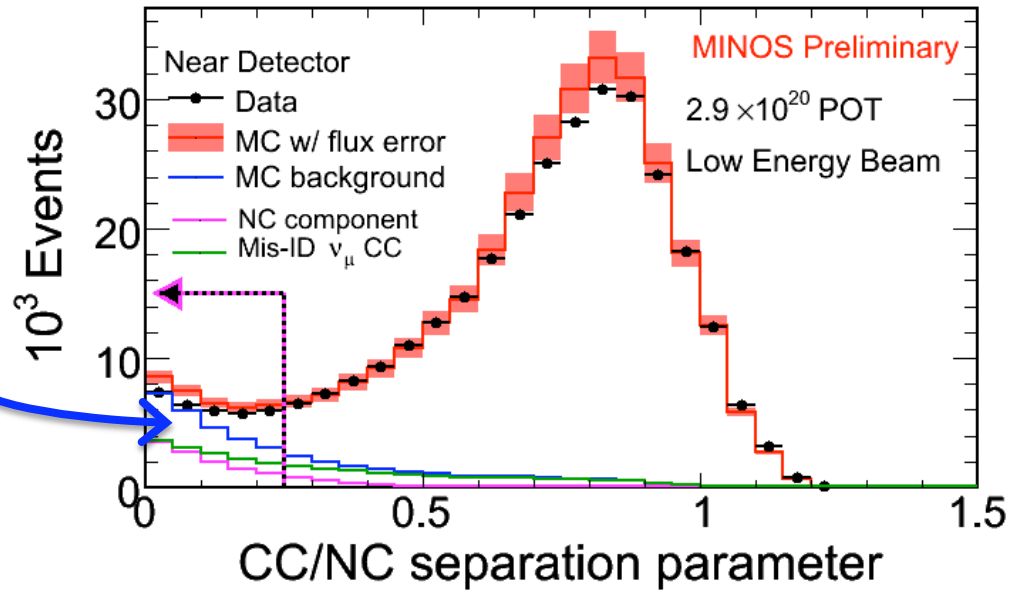




- Decay pipe component extrapolates differently
- Hadroproduction fitting procedure does not directly tune the decay pipe component: benefits from independent estimate
- Recently added helium to previously evacuated decay pipe
  - Extra downstream material increases production
- Compare Near detector spectra w/ and w/o helium
  - Fit for the decay pipe production
  - Result: 10% increase required in MC Decay Pipe production - 30% precision
- Take a conservative error of 40%: gives 4% Far detector rate change

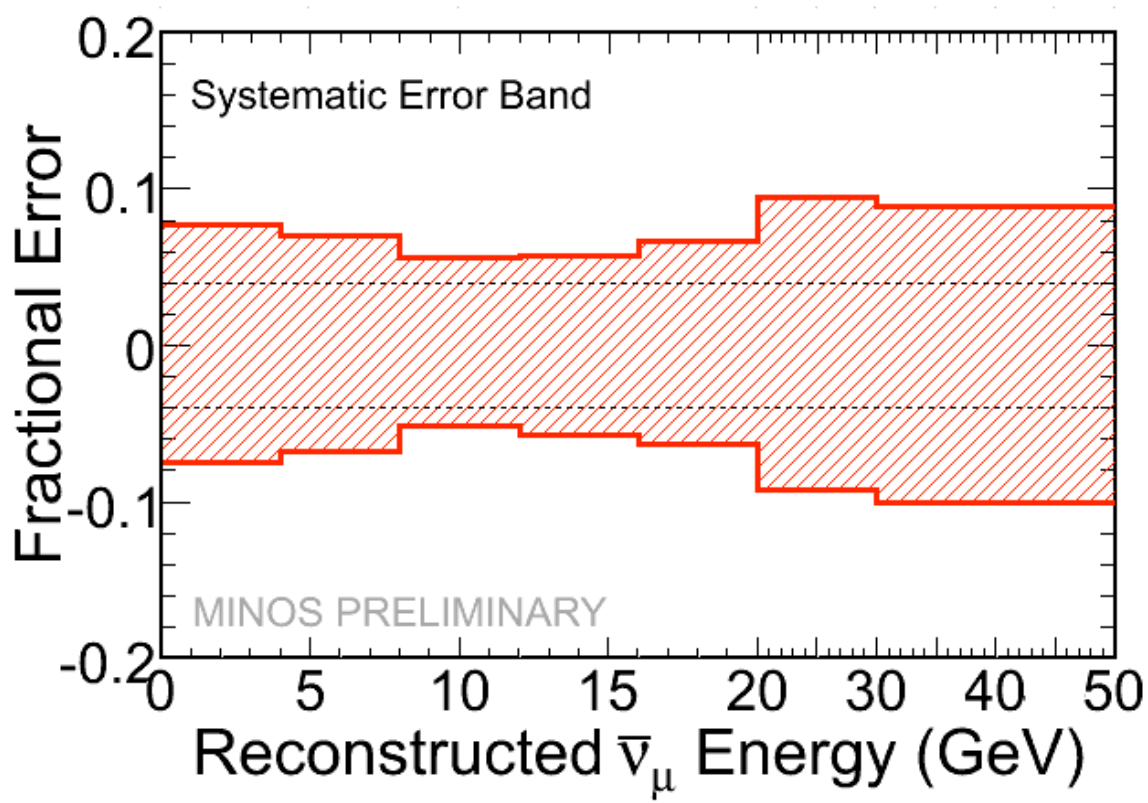
Background Systematic Uncertainty

- Consider the events that fall just below the cut on CC/NC separation parameter
  - 0.0 -> 0.25
- Scale NC and mis-ID ν_μ CC events (separately) in each energy bin to make data/MC agree
- The largest scale factor is 50% so take this as a conservative estimate of the error



Total Systematic Uncertainty on Far Detector Prediction

- Added systematic uncertainties in quadrature
- Overall uncertainty is <10% across all energies
  - significantly less than statistical error
- Dashed line shows the 4% normalisation uncertainty



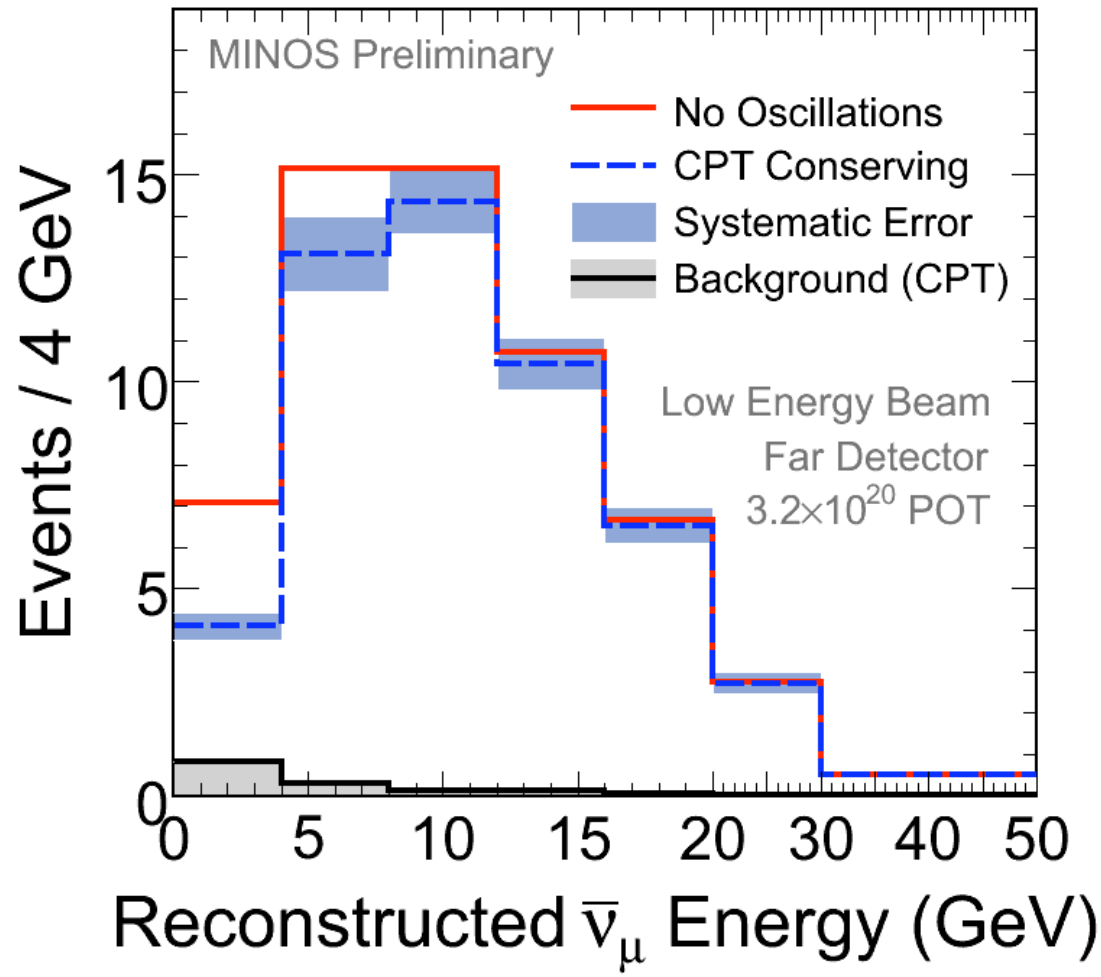
Extensive Independent Checks Performed

- Performed the entire analysis with a secondary event selection
  - 3 different selection variables
- Used two additional extrapolation methods
- Used a second independent track fitter to determine the muon charge sign
- All other analyses done as checks give very similar answer (not presented today)
- Extensive scanning of events by eye

The Far Detector…

Predicted Far Detector Spectrum

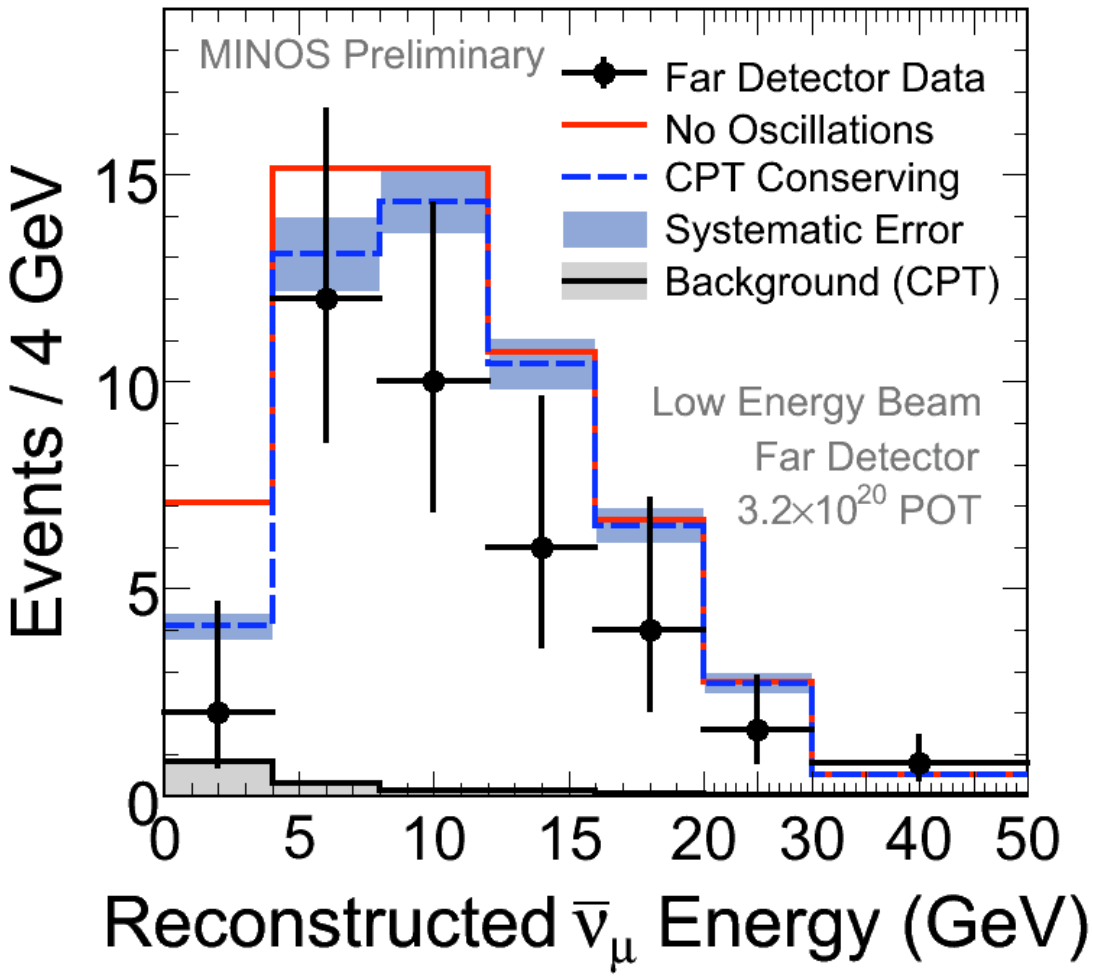
- Predicted events with CPT conserving oscillations:
  - 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - 64.6 ± 8.0 (stat.) ± 3.9 (syst.)



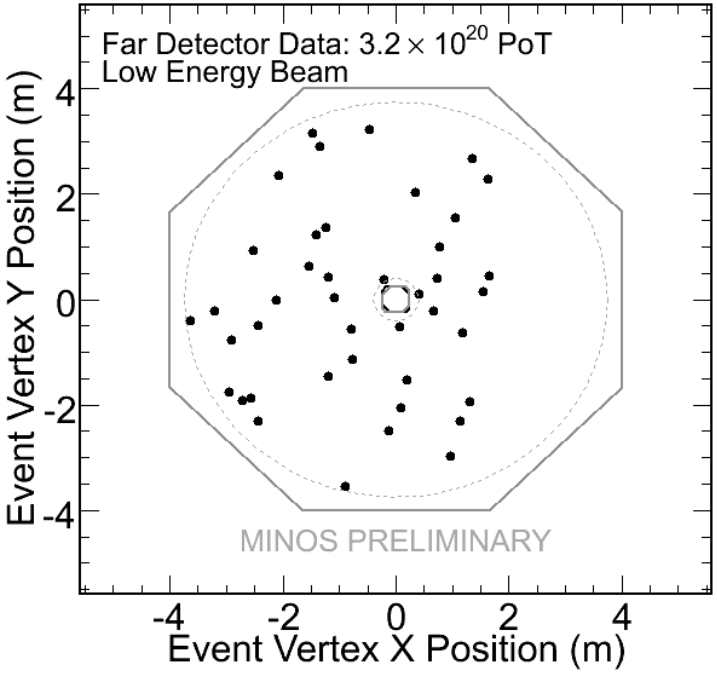
Far Detector Spectrum

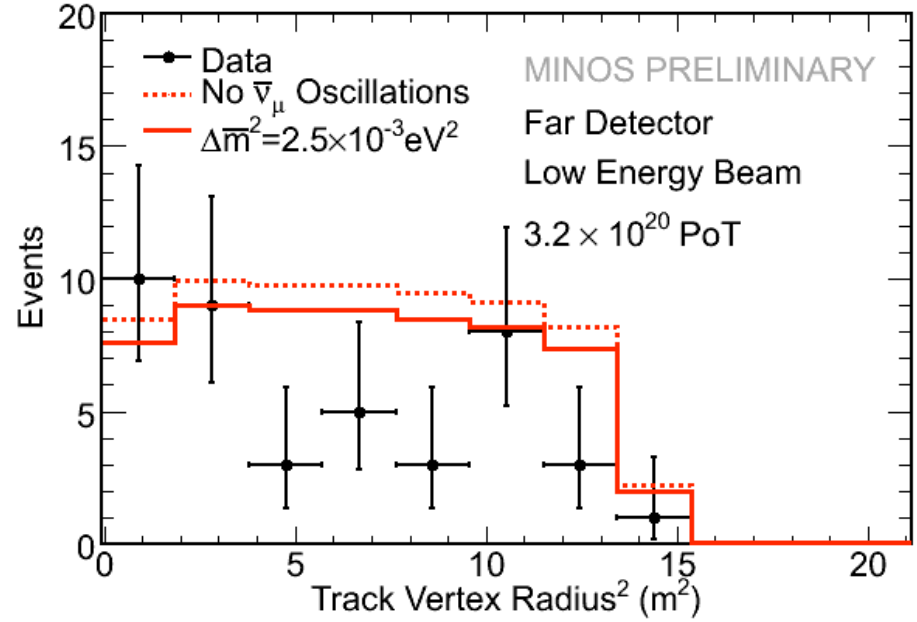
- Observe **42 events** in the Far detector
- First direct observation of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment

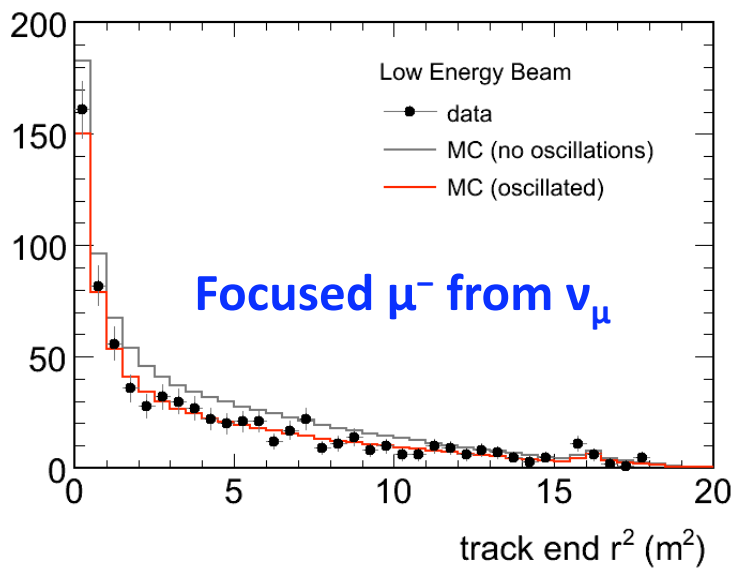
- Predicted events with CPT conserving oscillations:
  - 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - 64.6 ± 8.0 (stat.) ± 3.9 (syst.)

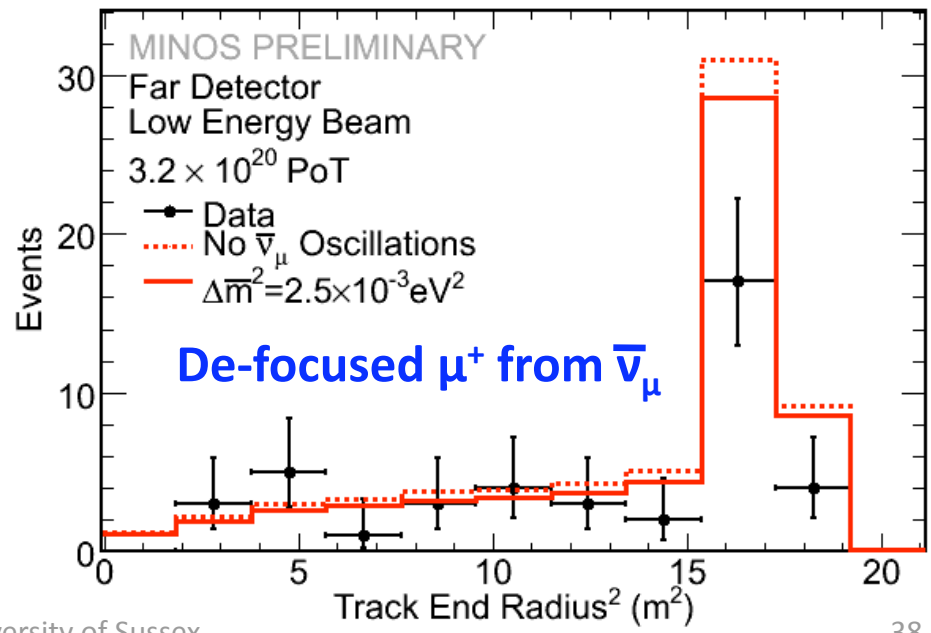


Far Detector Distributions



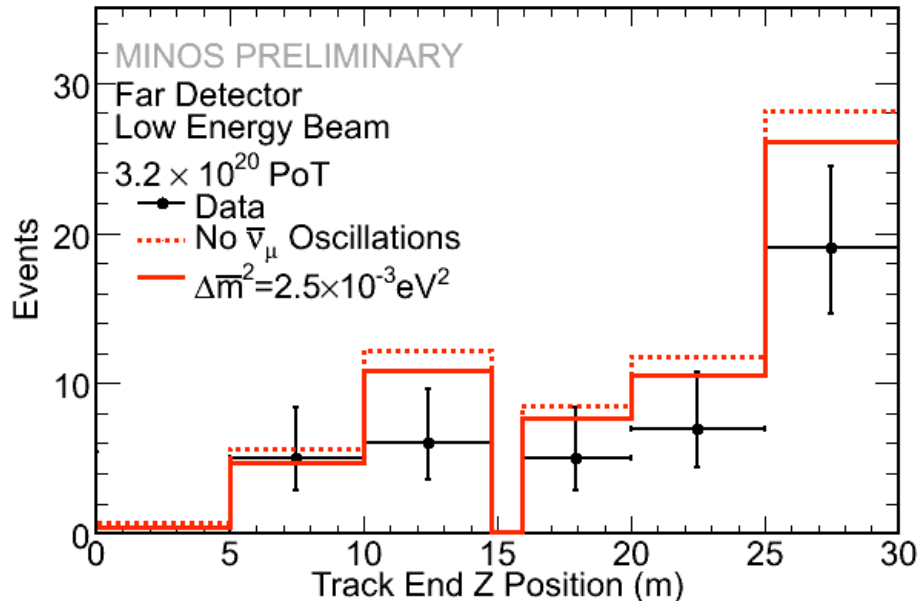


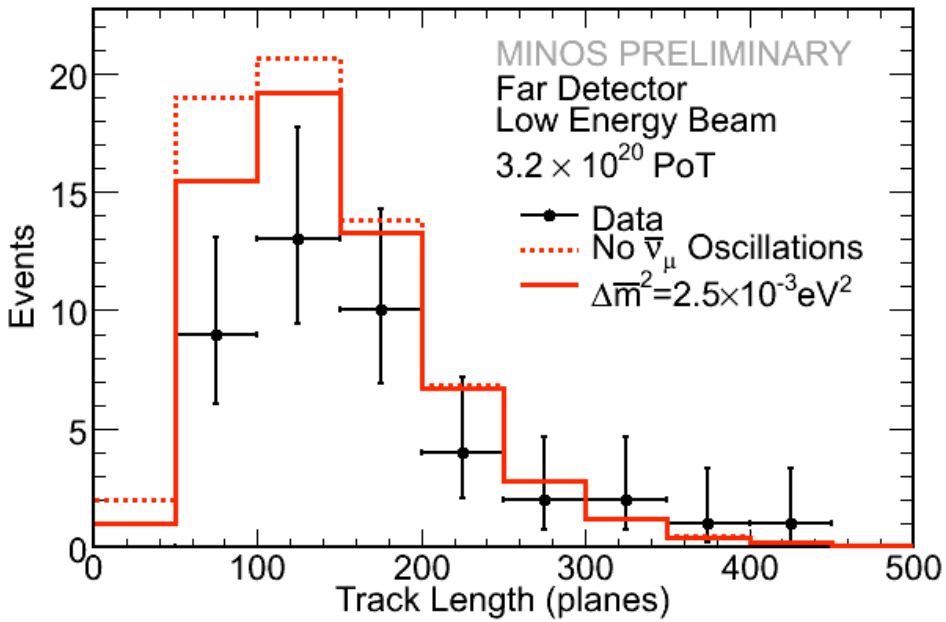


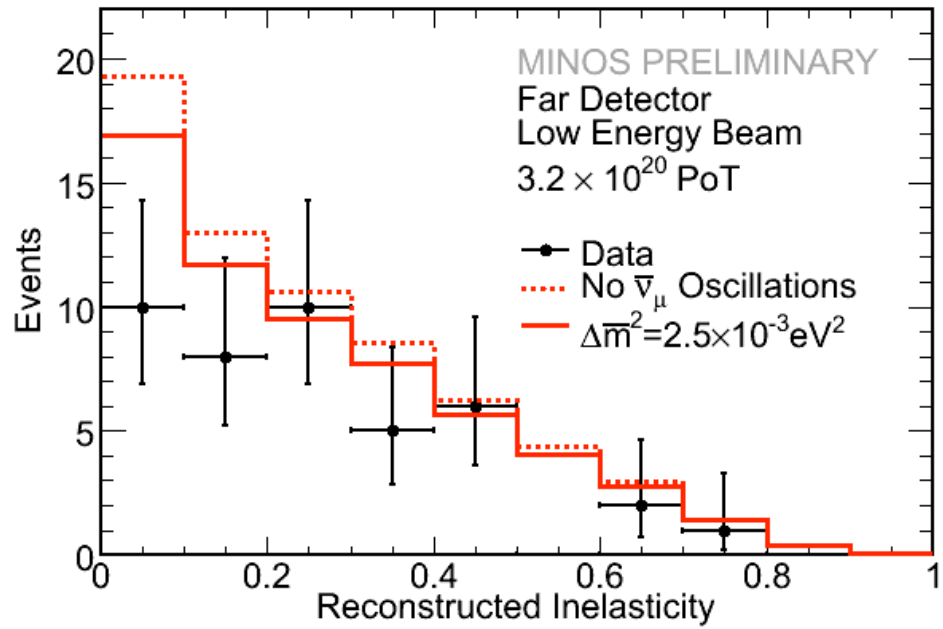


Far Detector Event Properties

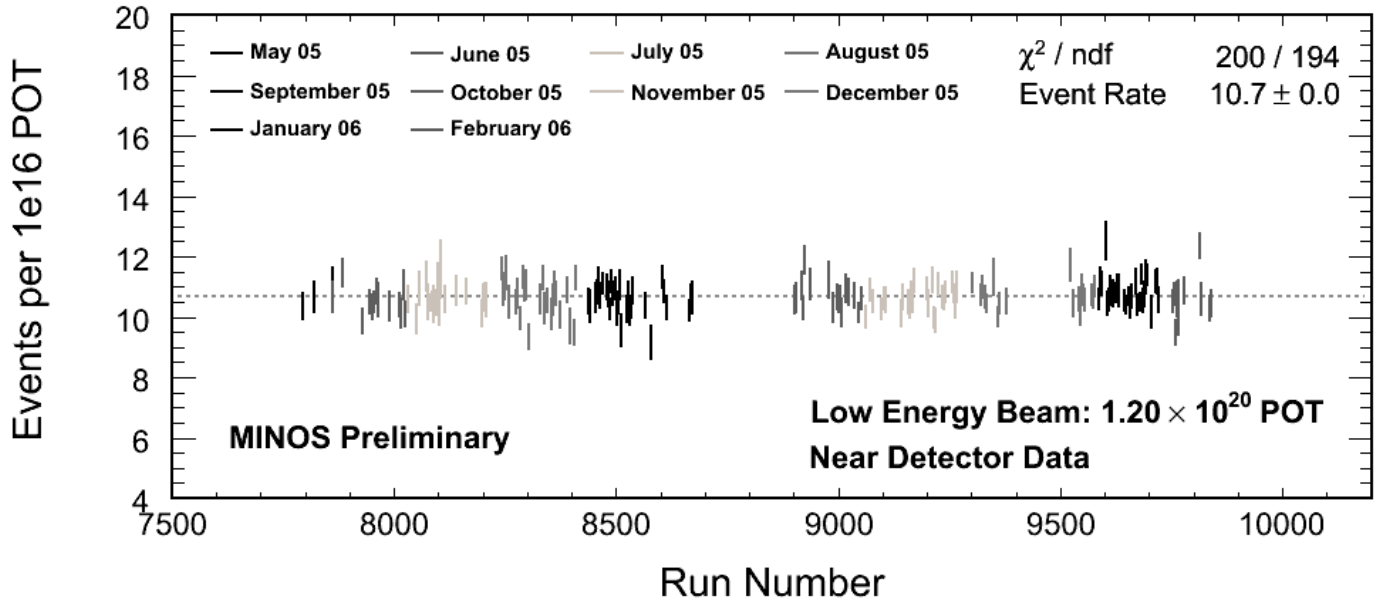
- The higher average energy of $\bar{\nu}_\mu$ mean that a large fraction exit the back of the detector
- Events are typically 100-200 planes long
- Shapes of distributions consistent with 42 events



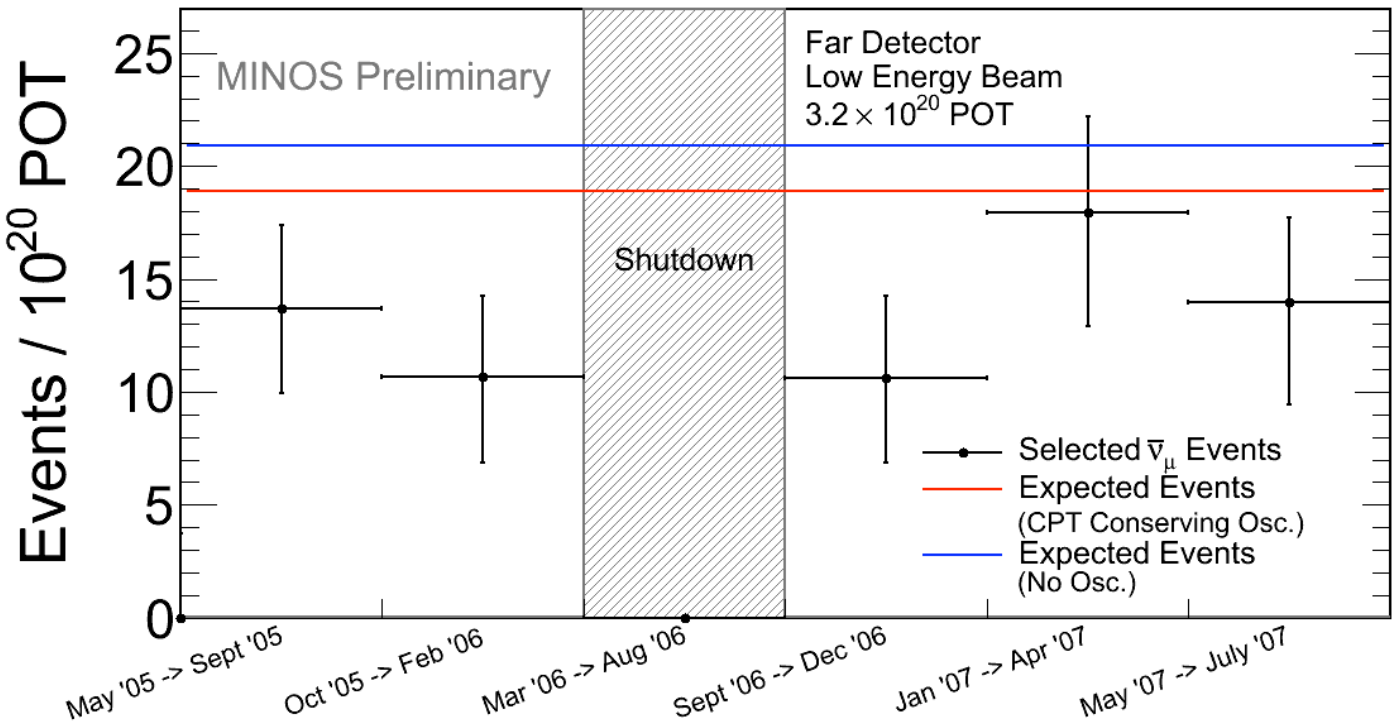




Near Detector Events vs. Time

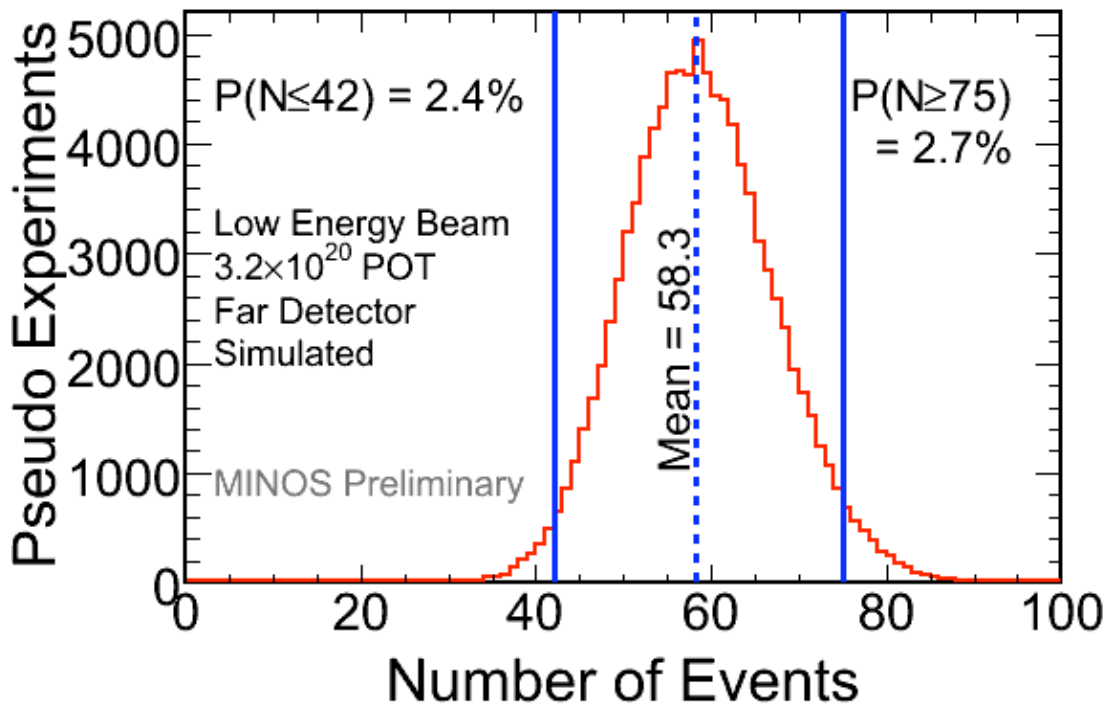


Far Detector Events vs. Time



Statistical Context

- Compared to the CPT-conserving oscillation hypothesis we have a deficit of 16.3 events
- Using normalisation 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



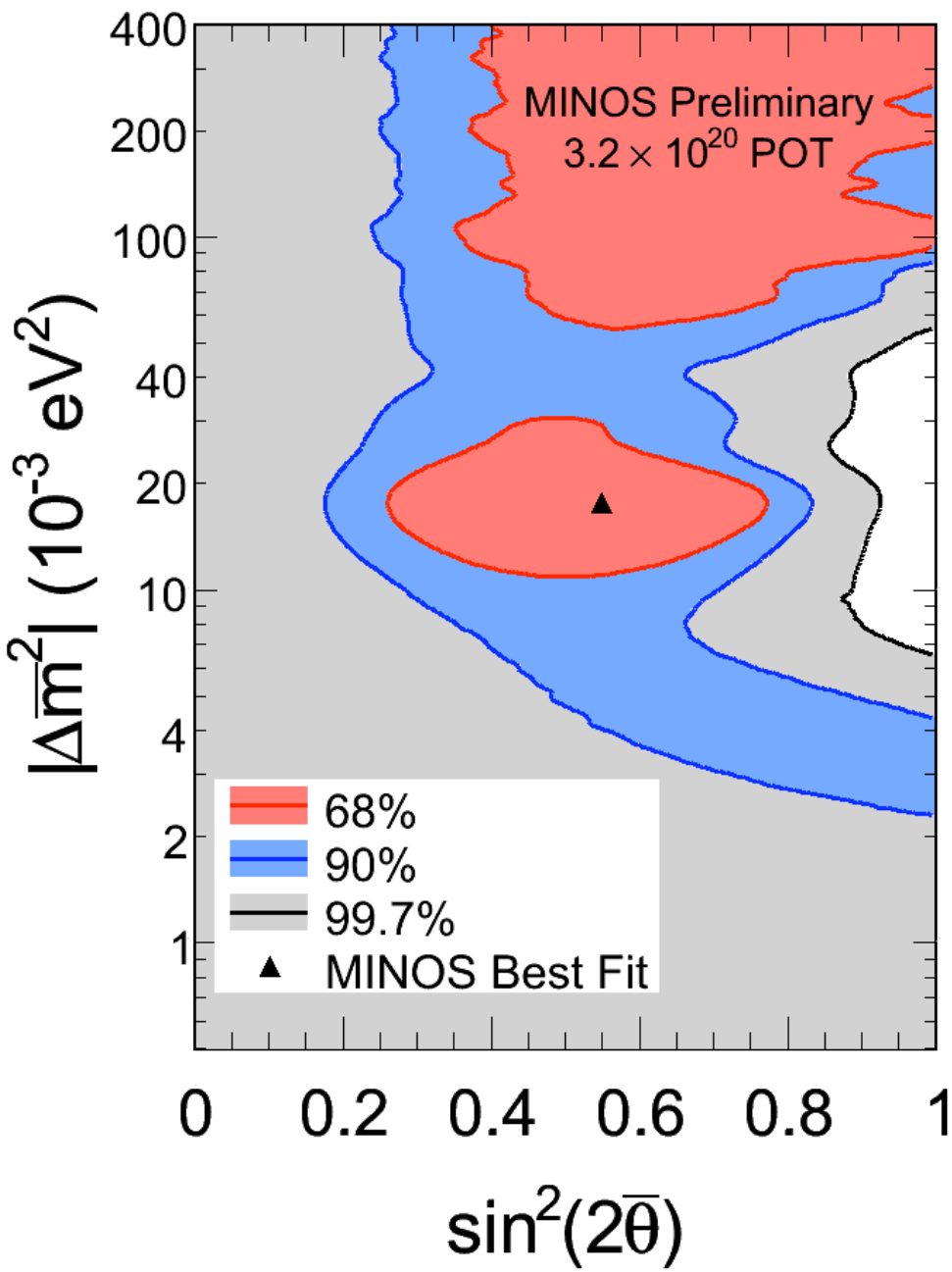
Results of fits

1.) **Disappearance: oscillation model**

2.) Appearance: fraction of events transitioning from ν_μ to $\bar{\nu}_\mu$

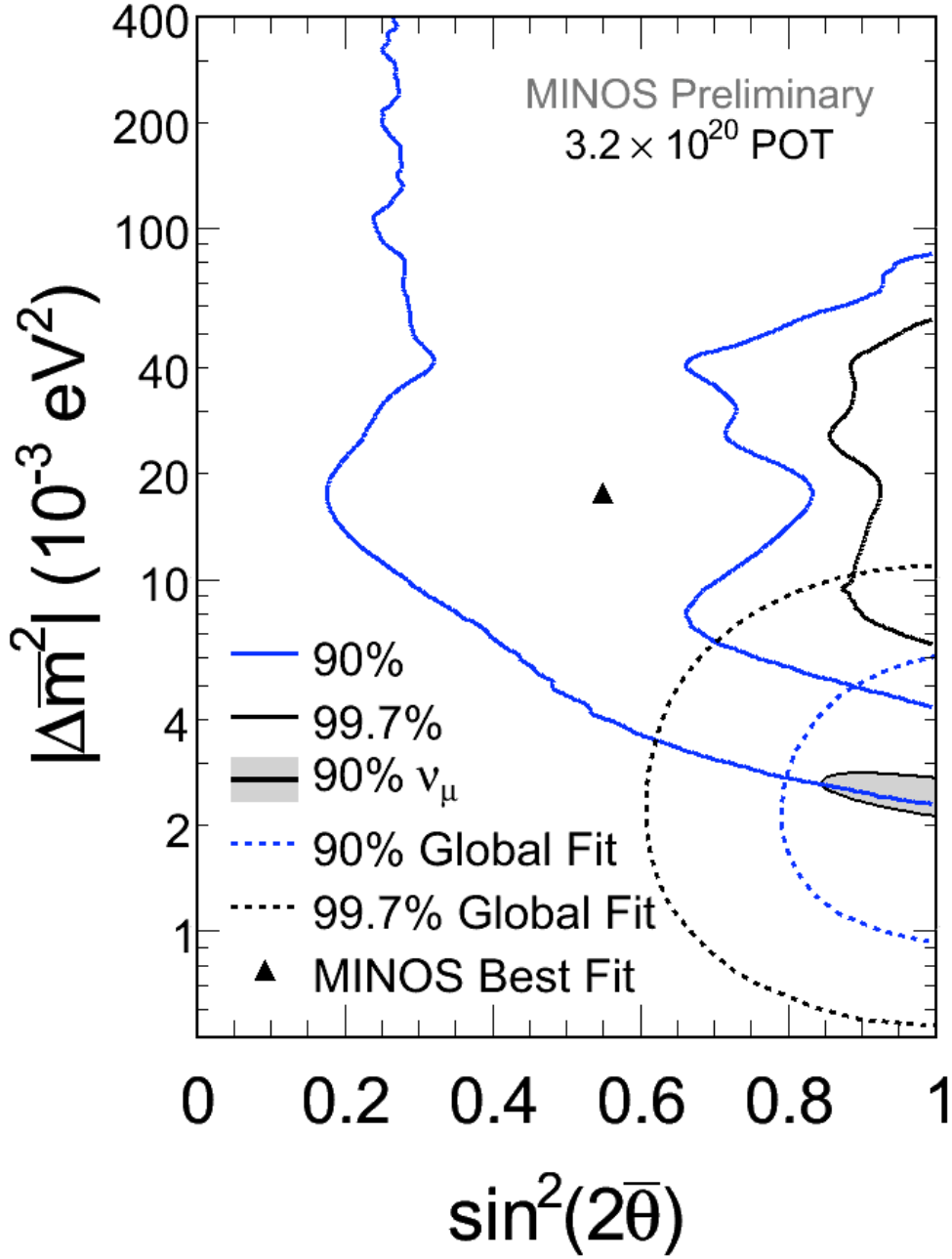
Allowed Region

- Contours obtained using Feldman-Cousins technique, including systematics
- Null oscillation hypothesis excluded at 99%
- CPT conserving point from the MINOS neutrino analysis is within 90% contour
- $\bar{\nu}_\mu$ best fit is at high value, due to deficit at high energy
- Unshaded region around maximal mixing is excluded at 99.7% C.L.



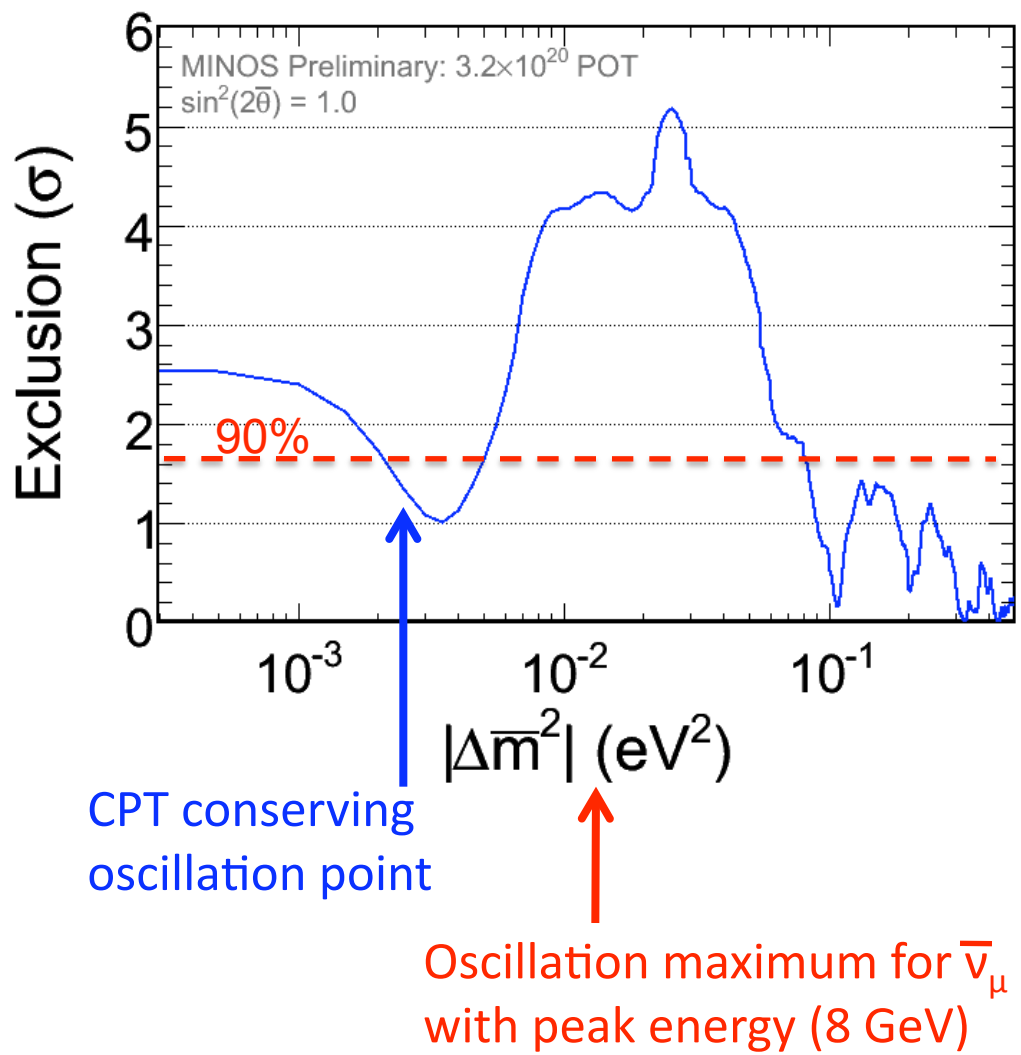
Comparison to Global Fit

- Global fit to previous data
  - Super-Kamiokande dominates
  - Includes SK-I and SK-II data
  - M. C. Gonzalez-Garcia & Michele Maltoni, Phys. Rept. 460 (2008)
- MINOS data excludes previously allowed CPT violating regions of parameter space, particularly near maximal mixing



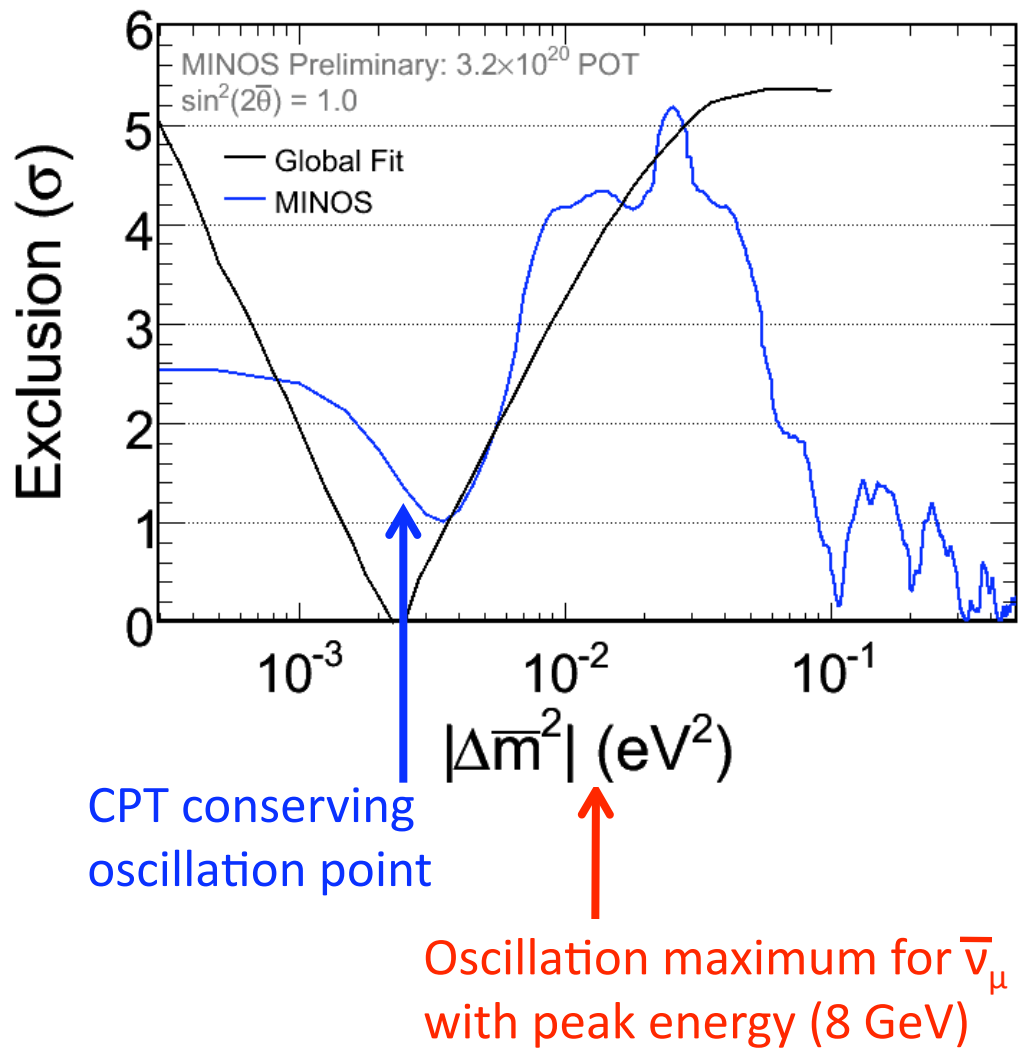
1-Parameter Fit at Maximal Mixing

- Low statistics data set doesn't constrain mixing angle well
- Gain best sensitivity to $\Delta\overline{m}^2$ by performing a 1-parameter fit at maximal mixing
  - Reasonable assumption, global fit constrains:
    - $\sin^2(2\overline{\theta}_{23}) > 0.92$ (68% C.L.)
- MINOS **excludes** at maximal mixing:
  - $(5.0 < \Delta\overline{m}^2 < 81)\times10^{-3}$ eV^2 (90% C.L.)
- Similarly at 3σ C.L.:
  - $(6.7 < \Delta\overline{m}^2 < 55)\times10^{-3}$ eV^2 (3σ C.L.)



Results at maximal mixing w/ Global Fit

- Can clearly see that MINOS data excludes previously allowed CPT violating regions of parameter space
  - both above and below the global fit minimum



Results of fits

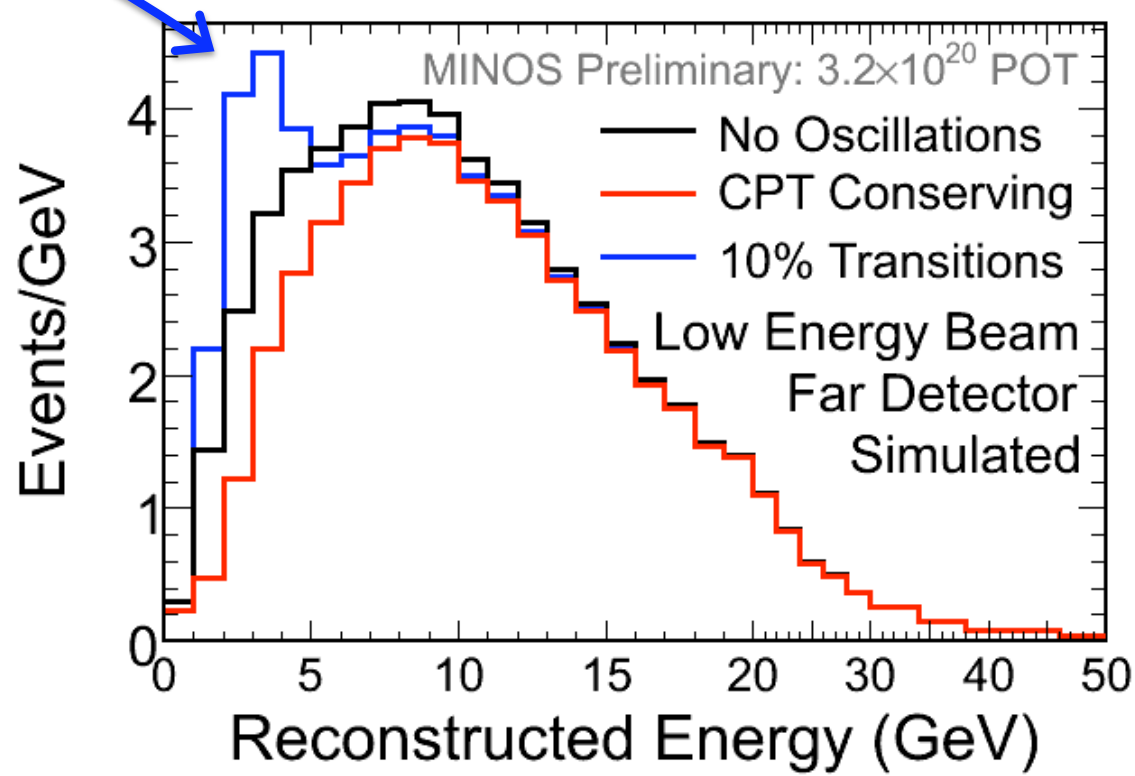
1.) Disappearance: oscillation model

2.) **Appearance: fraction of events transitioning from ν_μ to $\bar{\nu}_\mu$**

Predicted Far Detector Spectrum with 10% $\bar{\nu}_\mu$ Appearance

- If 10% of ν_μ transitioned to $\bar{\nu}_\mu$ we would see this experimental signature

- The intrinsic $\bar{\nu}_\mu$ in the NuMI beam are effectively the background to a search for $\bar{\nu}_\mu$ appearance



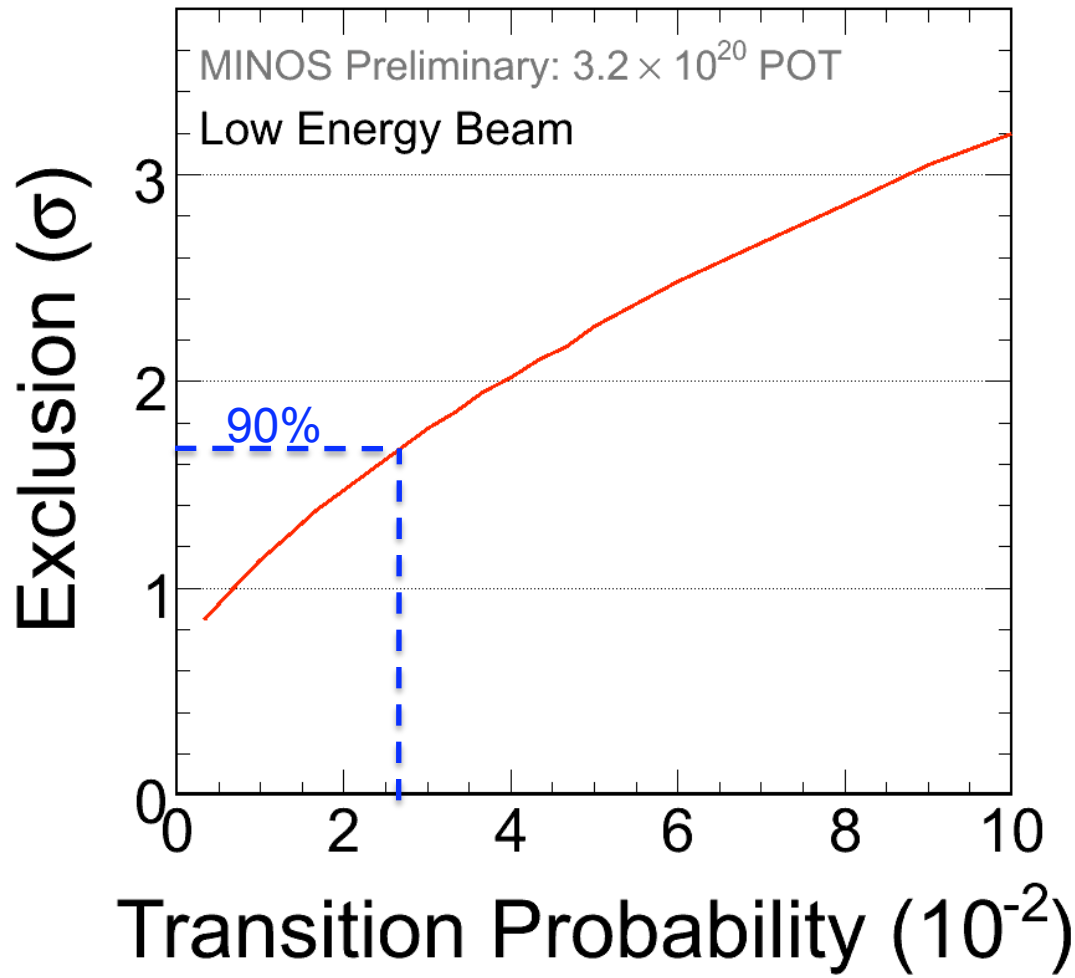
Results of Search for $\bar{\nu}_\mu$ Appearance

- MINOS observes **no appearance** of $\bar{\nu}_\mu$ in the NuMI beam
- 1-parameter fit for α using simple parameterisation

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

(θ and Δm^2 set to CPT conserving case)

- Uncertainty from $\bar{\nu}_\mu/\nu_\mu$ cross section ratio
- Result: limit fraction, α, of events transitioning from ν_μ to $\bar{\nu}_\mu$:
  - $\alpha < 0.026$ (90% C.L.)



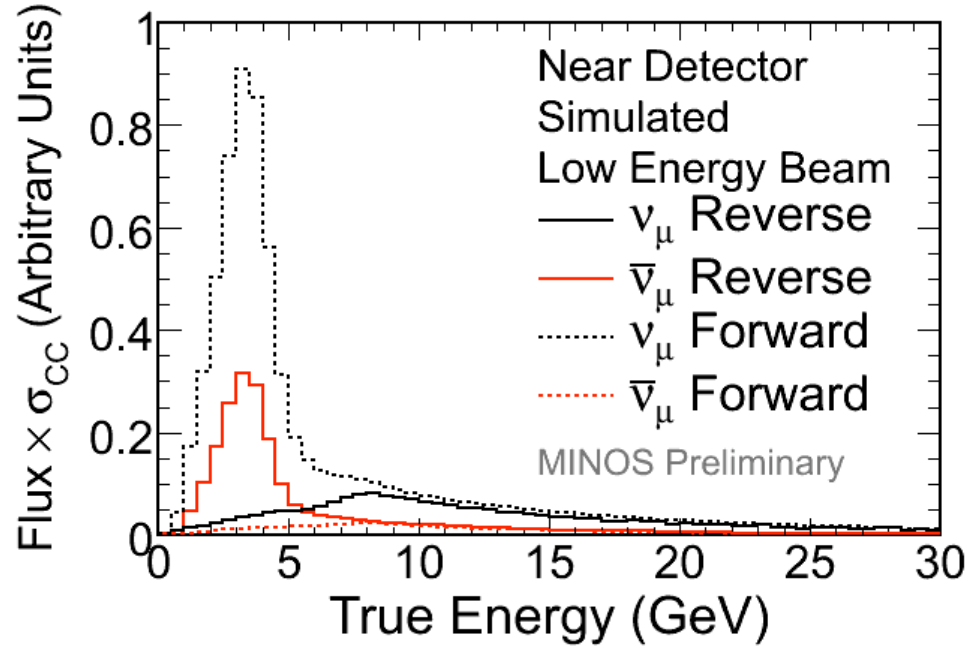
Future plans

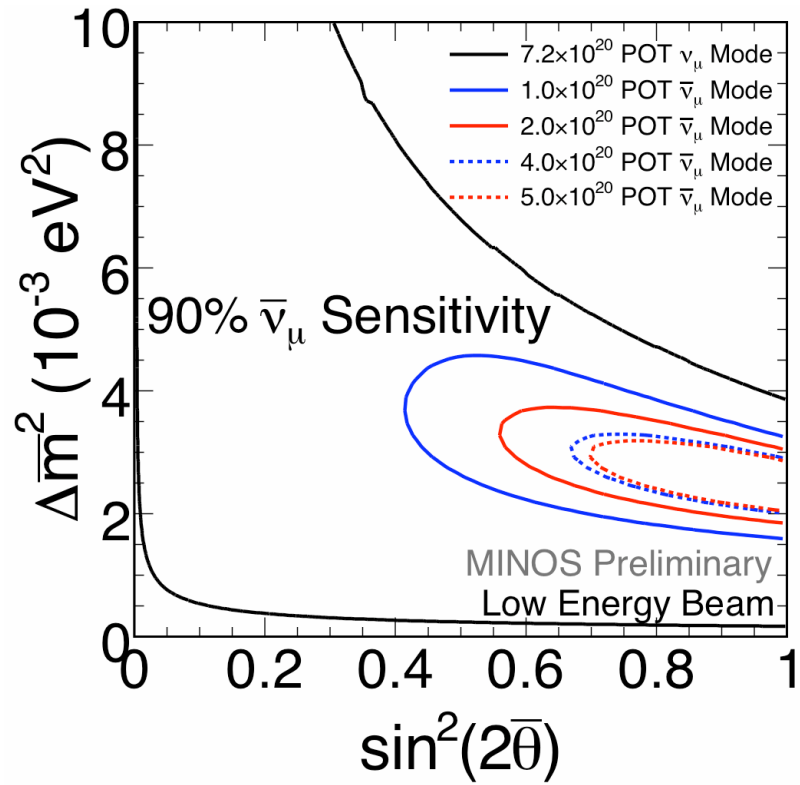
a.) Update analysis with more than double the data set

b.) Dedicated $\bar{\nu}_\mu$ run

Dedicated $\bar{\nu}_\mu$ Running

- Plan to reverse current in NuMI magnetic horns to focus π^- from September
  - create a $\bar{\nu}_\mu$ beam
- MINOS can directly observe $\bar{\nu}_\mu$ disappearance at 7σ with 5×10^{20} POT
  - rapidly reduce the uncertainty on $\Delta\bar{m}^2_{32}$





Conclusions

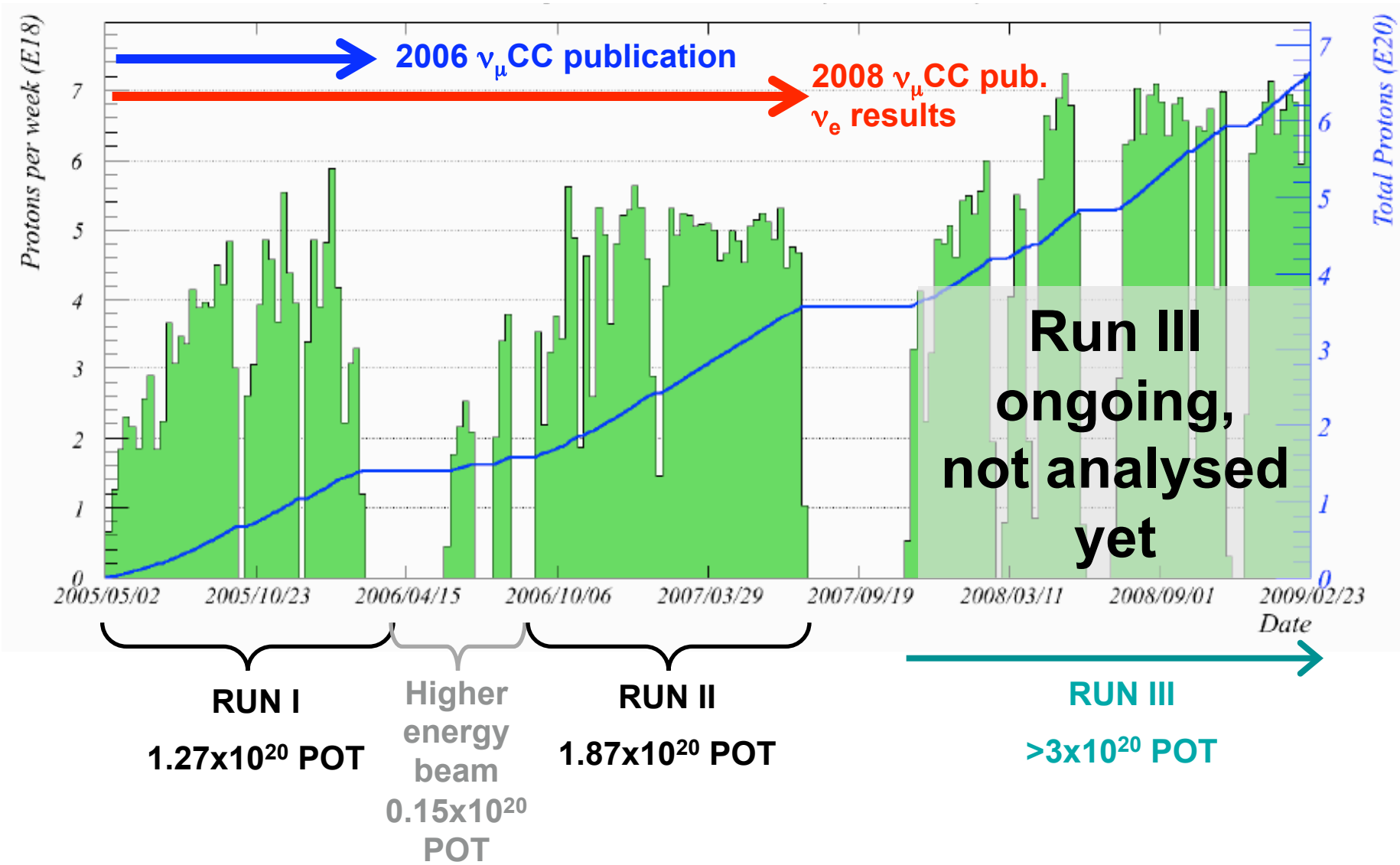
- These data are the first direct observation of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment
- The magnetic field in the 5.4 kton iron Far detector was used to separate μ^+ from μ^- and NC events
- CPT-conserving oscillations point is within the 90% contour
- MINOS **excludes** oscillations at maximal mixing with:
  - $(5.0 < \Delta\bar{m}^2 < 81) \times 10^{-3}$ eV^2 (90% C.L.)
- MINOS observes **no appearance** of $\bar{\nu}_\mu$ in the NuMI beam
  - constrain the fraction, α, of ν_μ that transition to $\bar{\nu}_\mu$
  - $\alpha < 0.026$ (90% C.L.)
- Exciting future for this measurement:
  - Results from double the data set soon
  - Dedicated $\bar{\nu}_\mu$ run to commence in September

Acknowledgements

- On behalf of the MINOS Collaboration, I would like to express our gratitude to the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment
- We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us

Backup slides

Accumulated Beam Data



The muon anti-neutrino analysis presented today uses Run I + Run II

Far Detector Left/Right Asymmetry

- In addition to studies using ν_μ and cosmic rays we also studied our new data from Run-III
- To avoid unblinding the new data we just looked at the left/right event asymmetry:

$$A = (L - R) / (L + R)$$

- In the present data set (3.2×10^{20} POT):

  $A = -0.190$

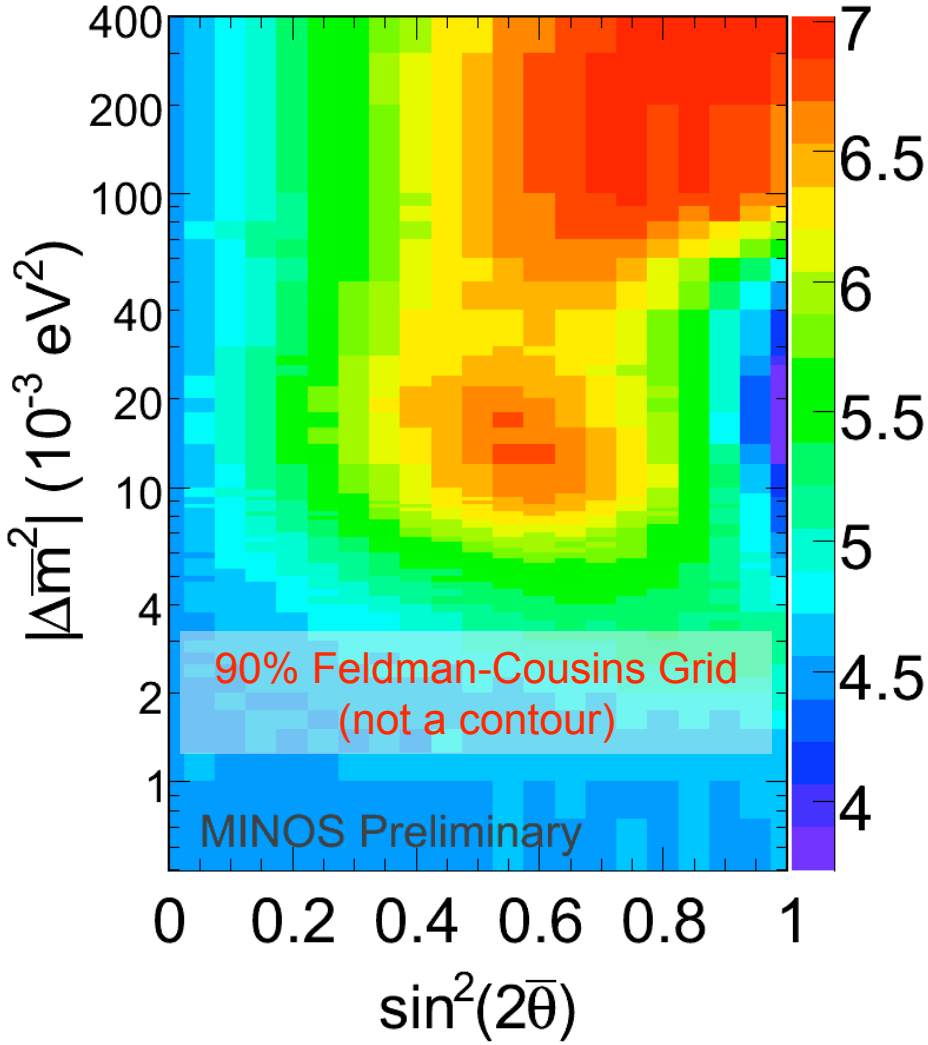
- In the new Run-III data set:

  $A = +0.065$

- Conclusion: the observed asymmetry is not present in the Run-III data

Feldman-Cousins Technique

- The presence of physical boundaries in the parameter space and the low statistics event sample requires a Feldman-Cousins approach to determine the correct contour
- Generate and fit 35,000 mock experiments at each grid point
  - Randomly shift events within systematic uncertainties
  - Calculate the $\Delta\chi^2$ between the best fit and the true oscillation parameters for each mock expt.
  - Determine the $\Delta\chi^2$ required to cover 68%, 90%, etc of experiments



$\Delta\chi^2$ required at each grid point to cover 90% of simulated mock experiments
Gaussian expectation: $\Delta\chi^2 = 4.6$

Results of Fit to the Oscillation Model

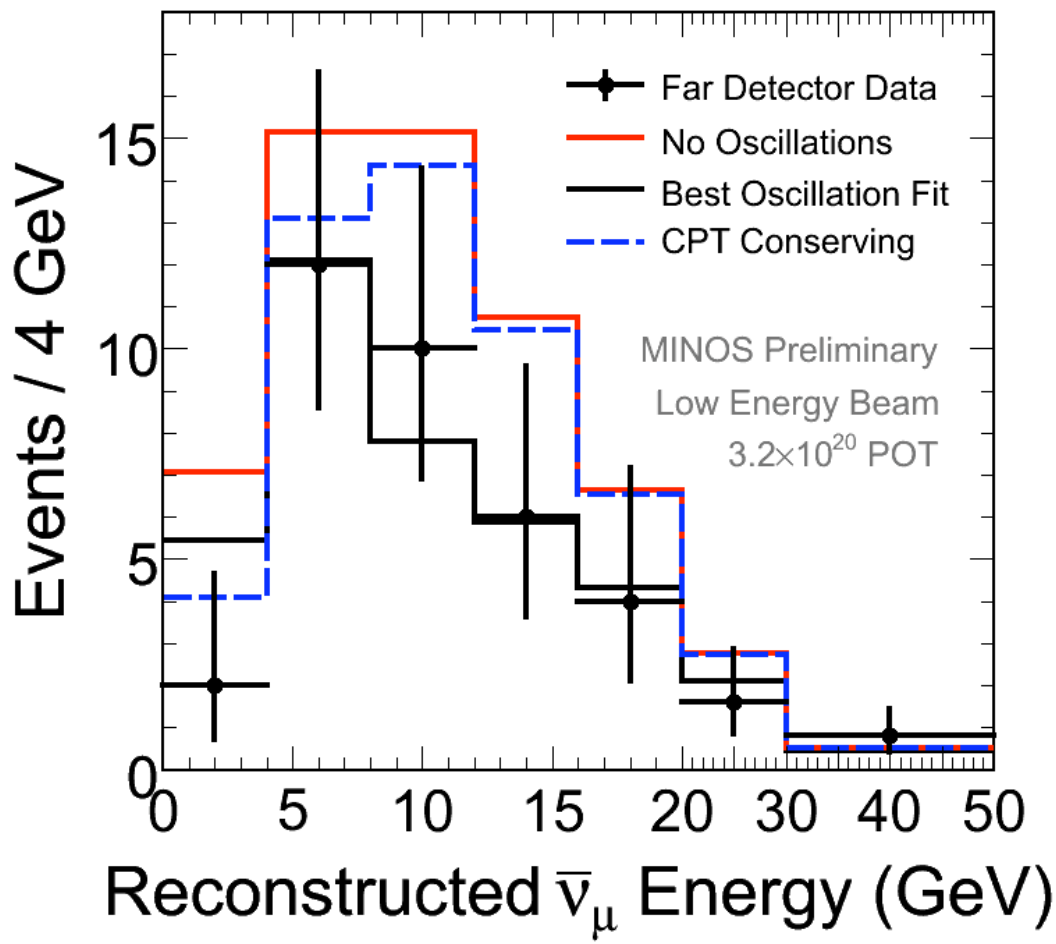
- Fit to a two anti-neutrino oscillation hypothesis

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

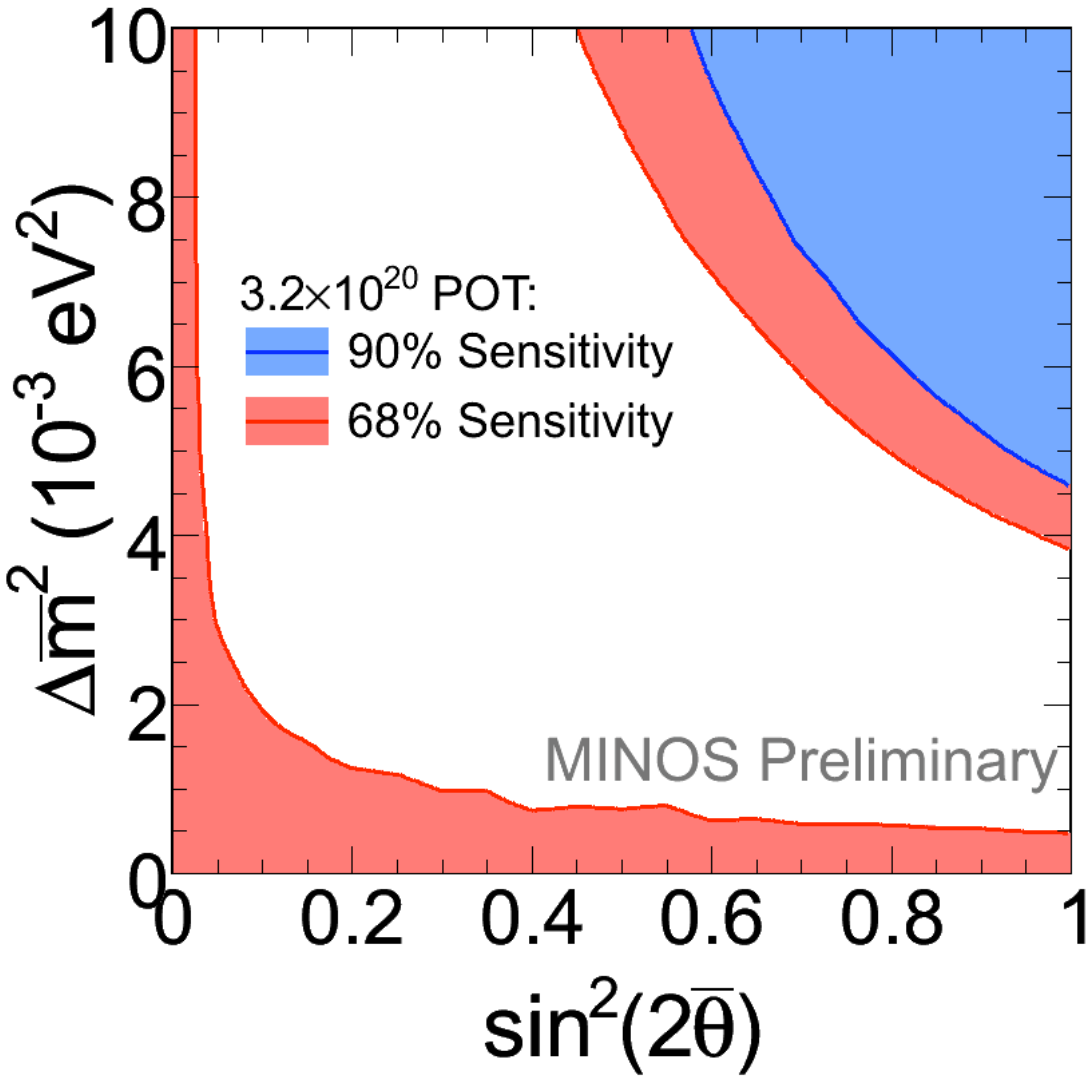
- Use a finely binned maximum loglikelihood fit

$$-2\ln\lambda(\mathbf{p}) = 2\sum_{i=0}^{Nbins}\left[e_i(\mathbf{p}) - o_i + o_i \ln\frac{e_i(\mathbf{p})}{o_i}\right],$$

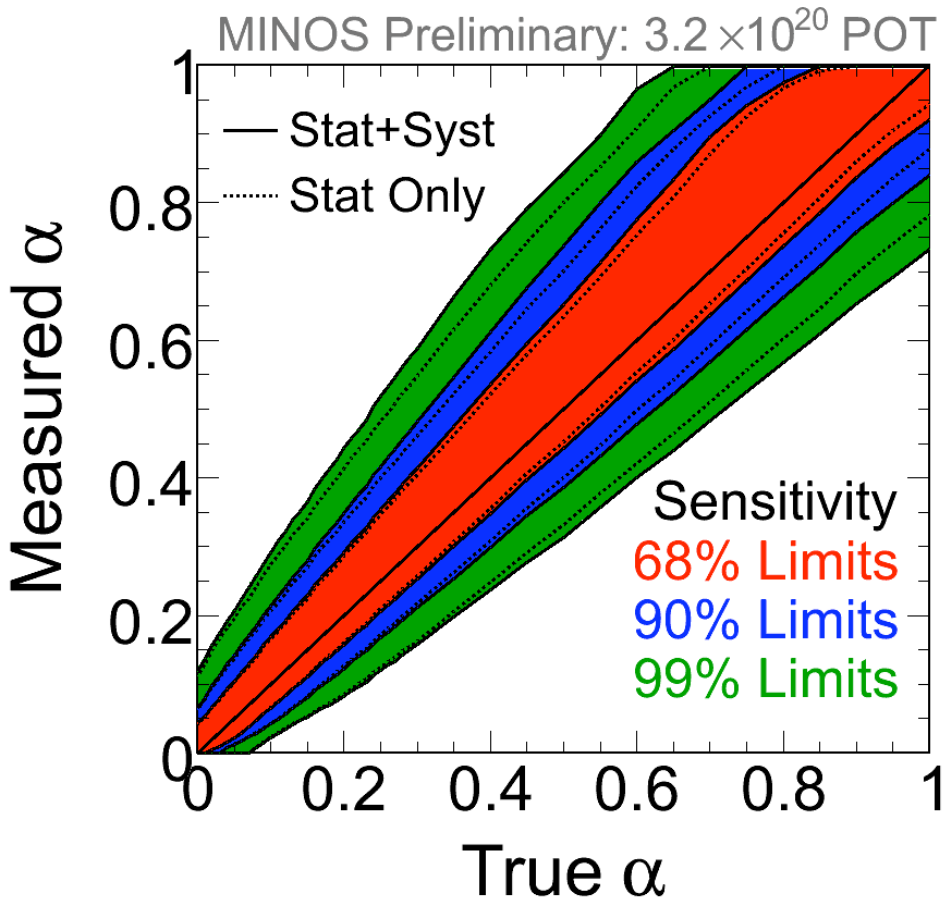
$$\mathbf{p} = \left\{\Delta m^2, \sin^2(2\theta)\right\}, \{\alpha\}$$

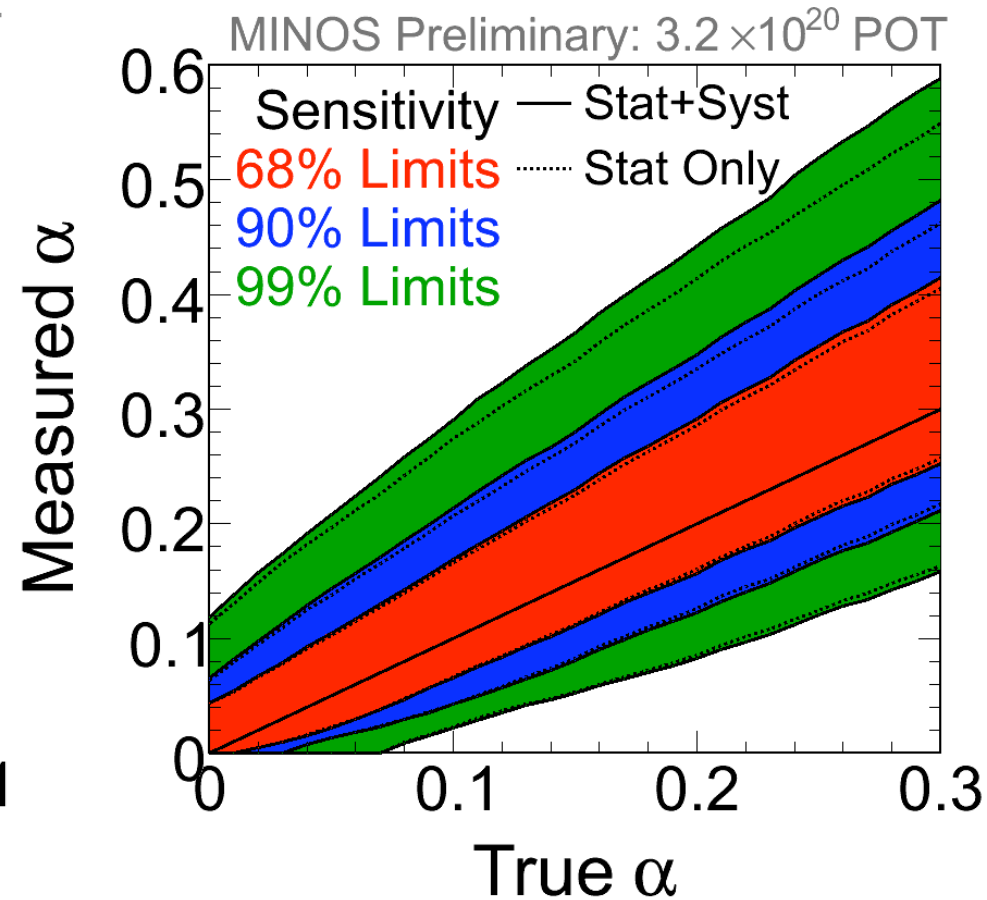


Oscillations Sensitivity



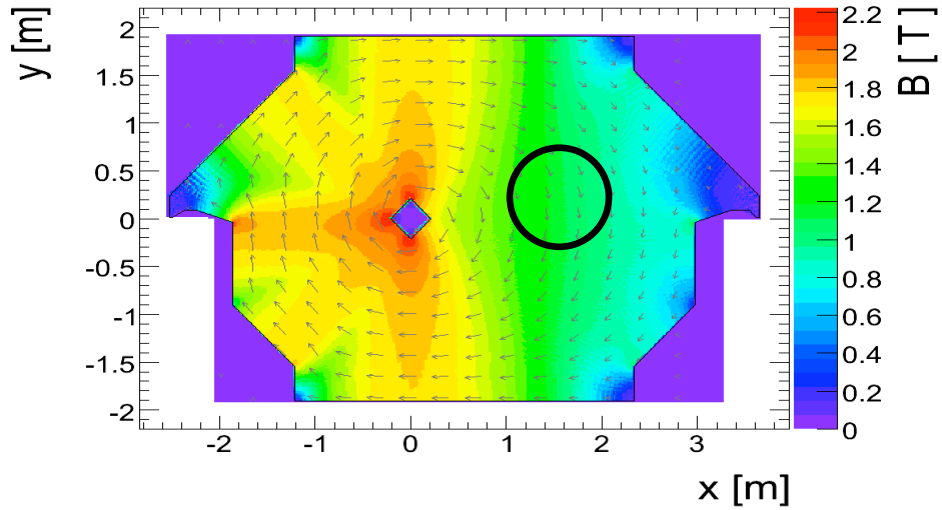
Transitions Sensitivity

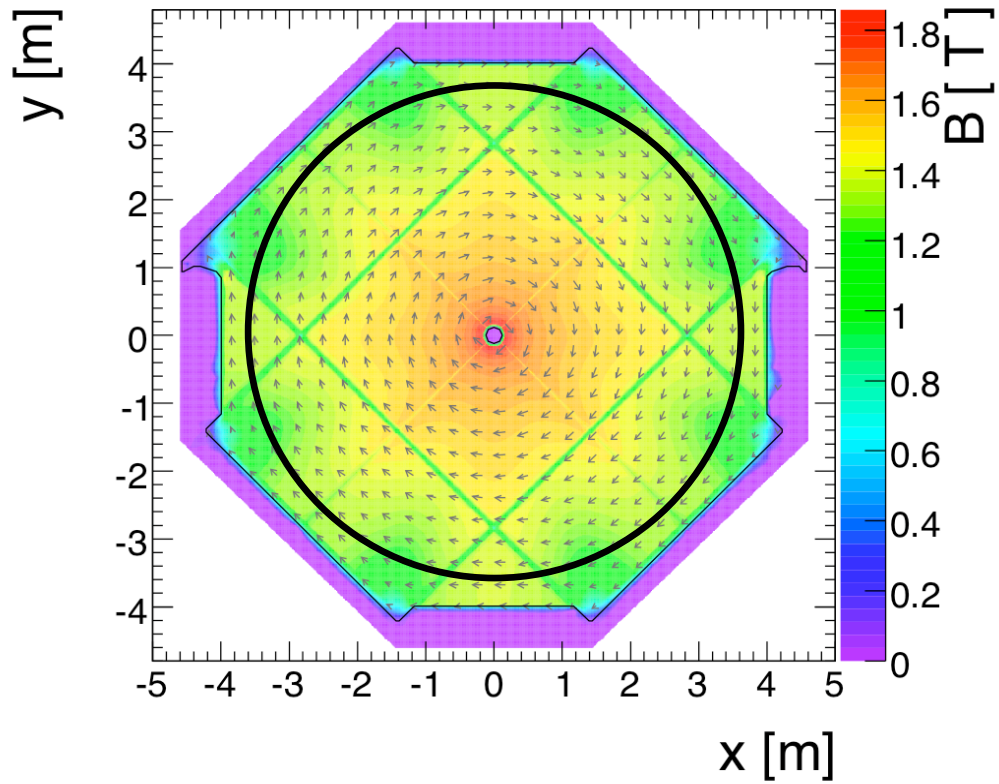




Magnetic Field

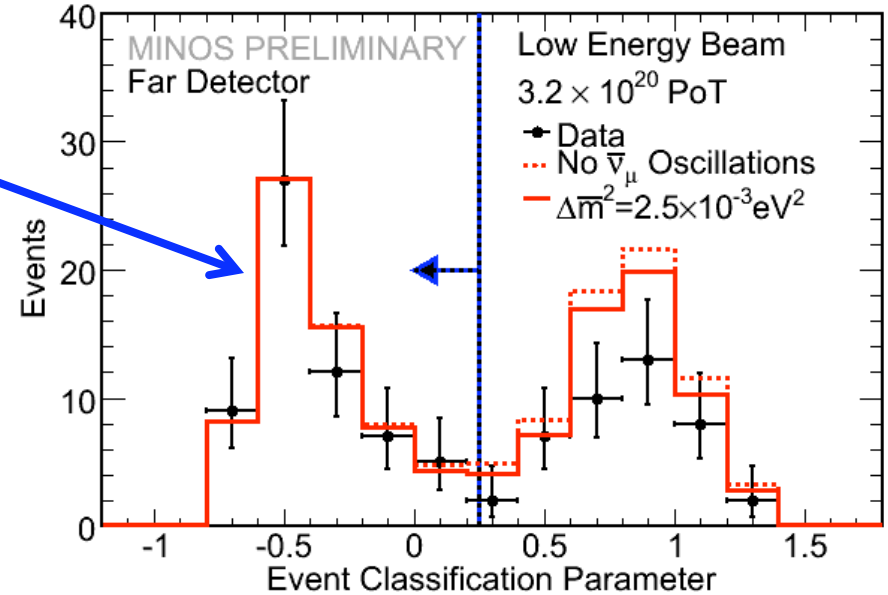
- Magnetic coil runs down the detector centre and back along the bottom
  - Produces a "toroidal" field
  - Fiducial volume has <B> = 1.3 T
- **Magnetic field separates μ^- from μ^+**
  - Focused μ's typically follow an "S" shaped path: bending towards, then crossing the coil
  - De-focused μ's are bent outwards to the detector edges, typically exiting
- Coil current polarity is "forward" to focus μ^- from ν_μ towards the coil

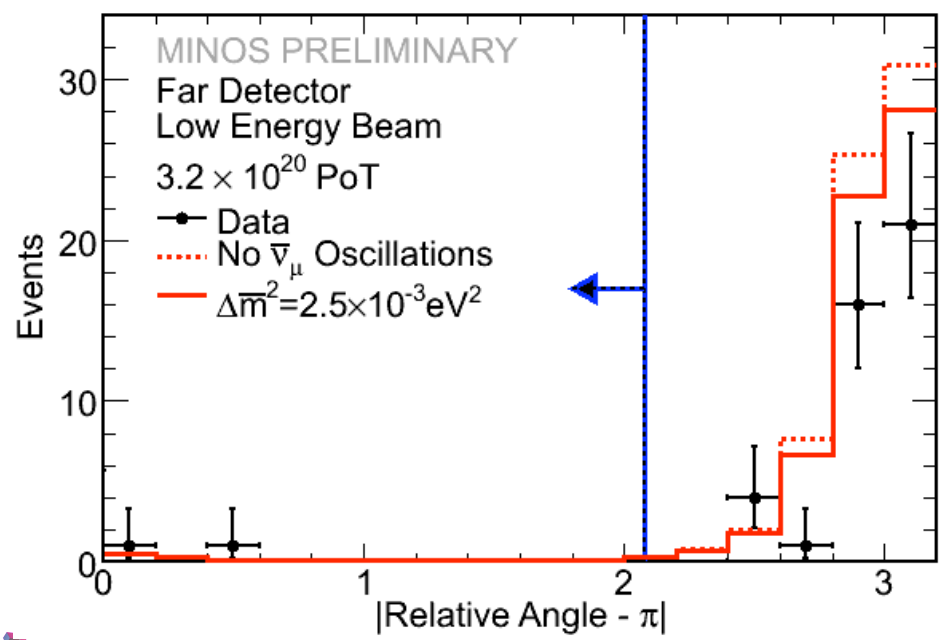


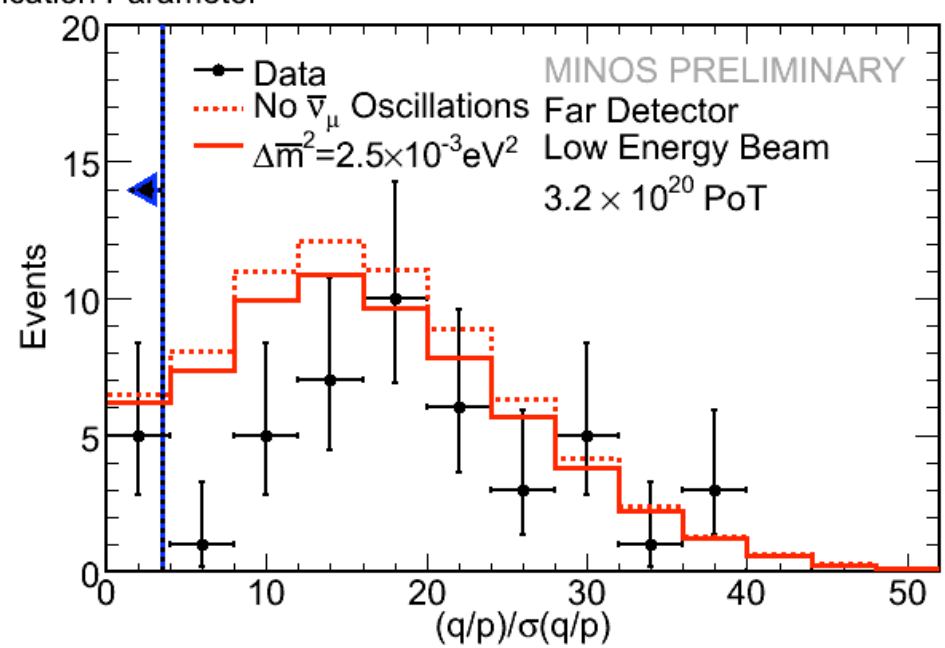


Additional Selection Variables

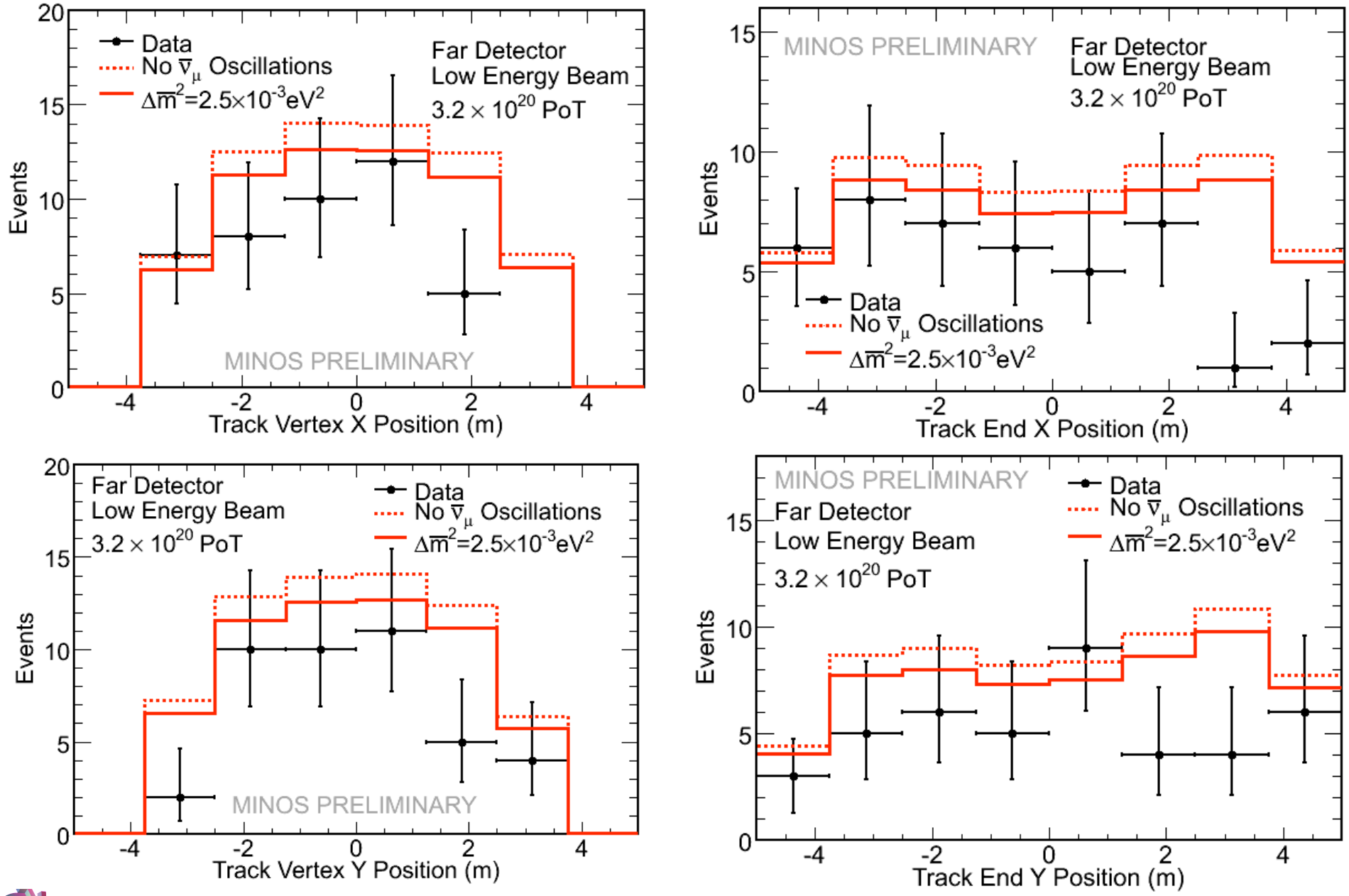
- The backgrounds are well described by the MC



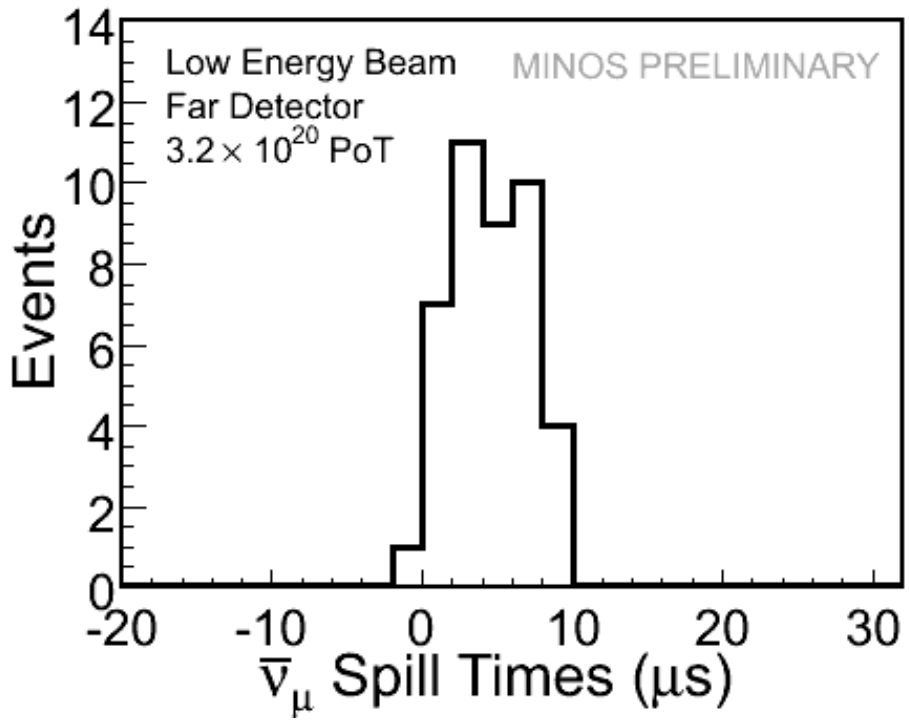




Far Detector Distributions

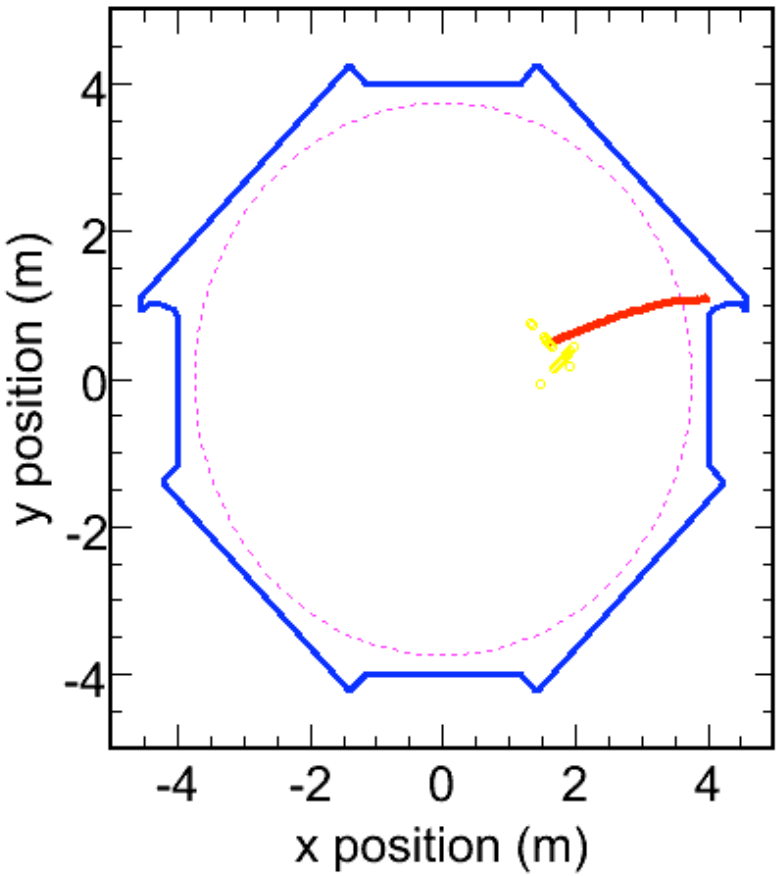


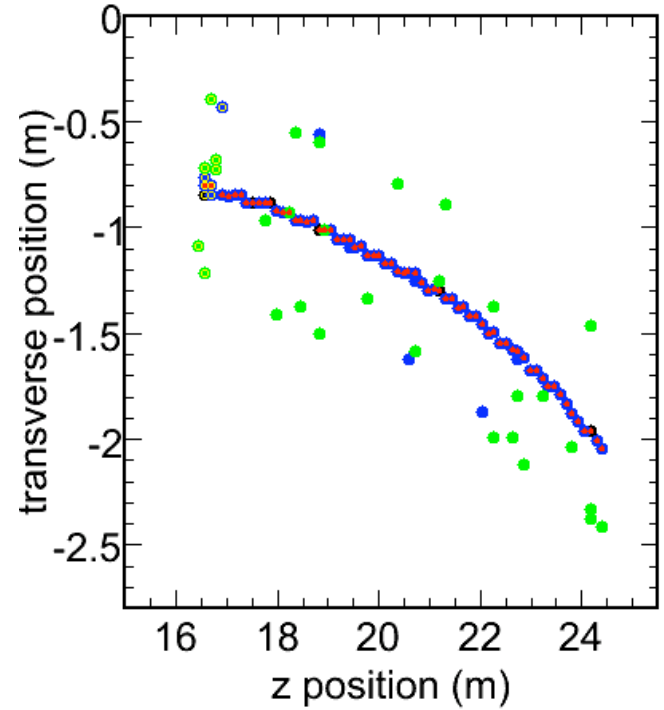
Far Detector Distributions

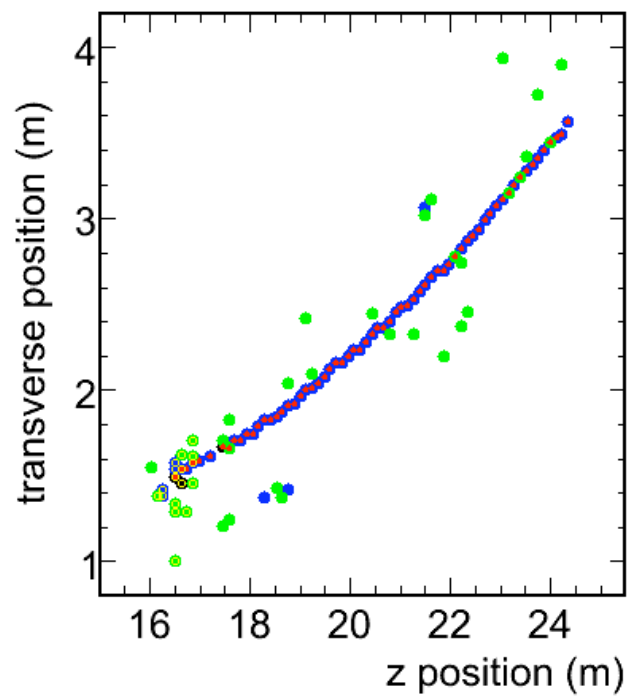


Far Detector Event (1)

- Observe clear curvature in both longitudinal (z-axis) projections and in the X-Y plane
- The muon is bent outwards away from the magnetic coil and exits the detector

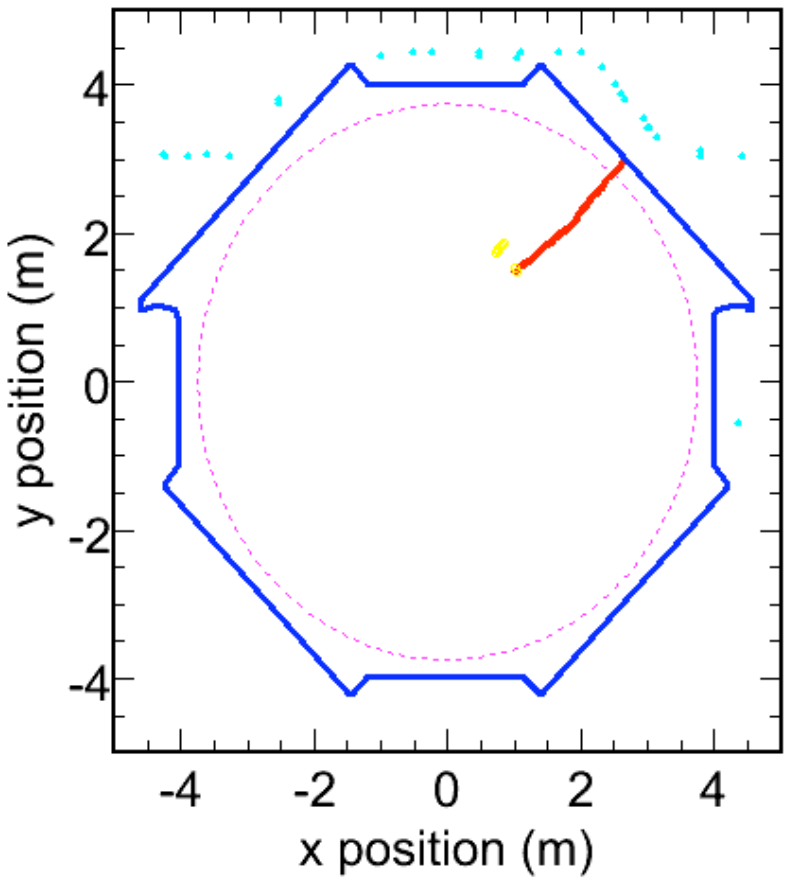


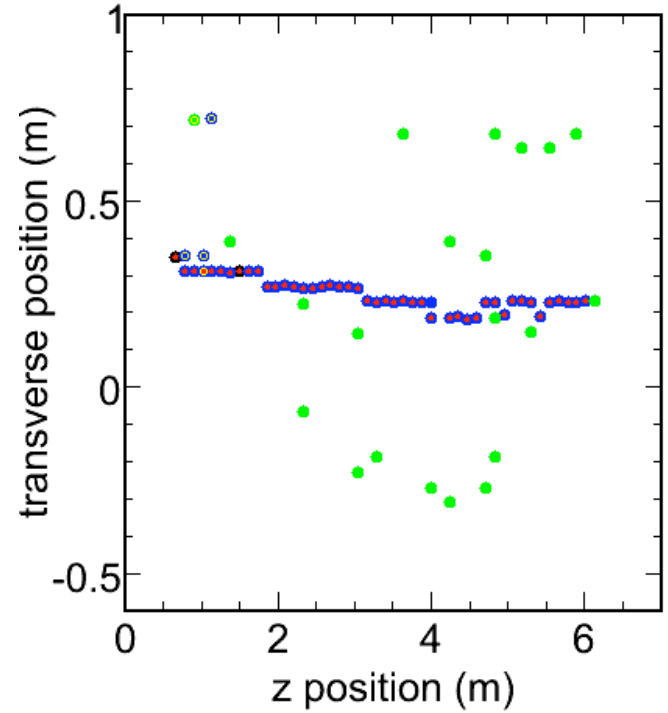


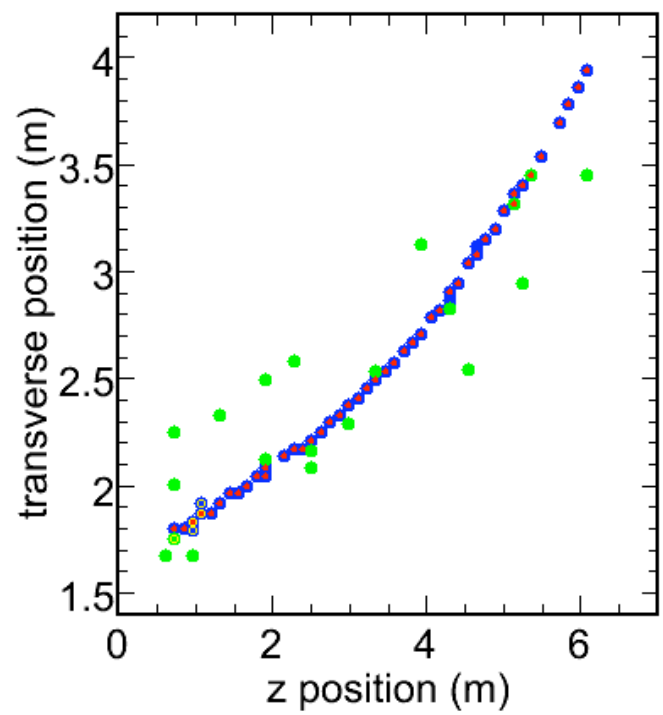


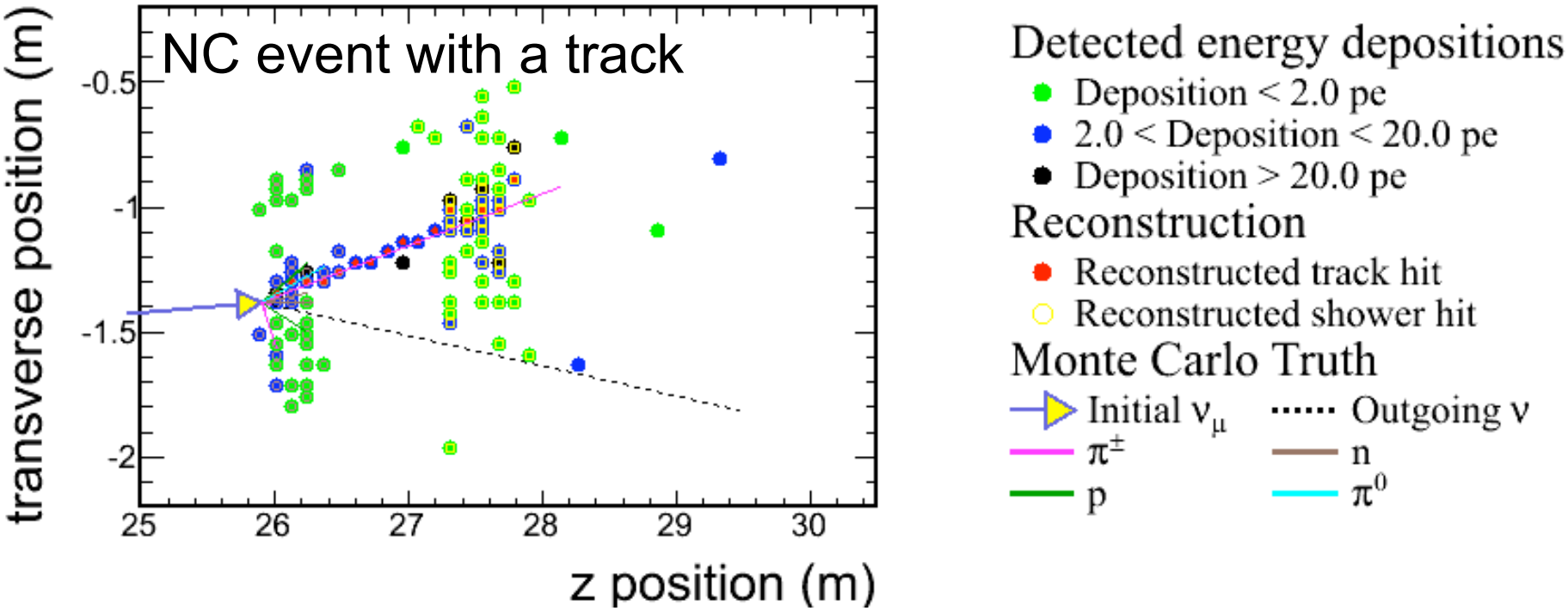
Far Detector Event (2)

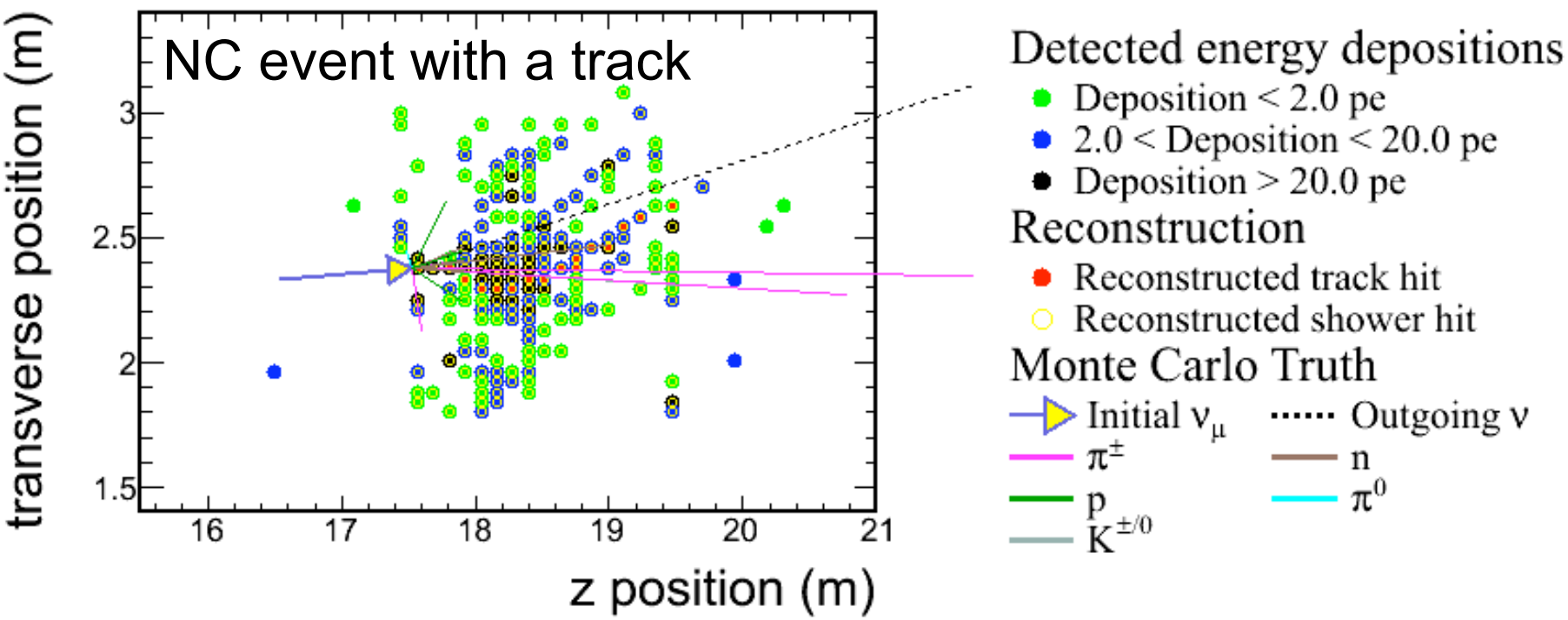
- Observe clear curvature in both longitudinal (z-axis) projections and in the X-Y plane
- The muon is bent outwards away from the magnetic coil and exits the detector

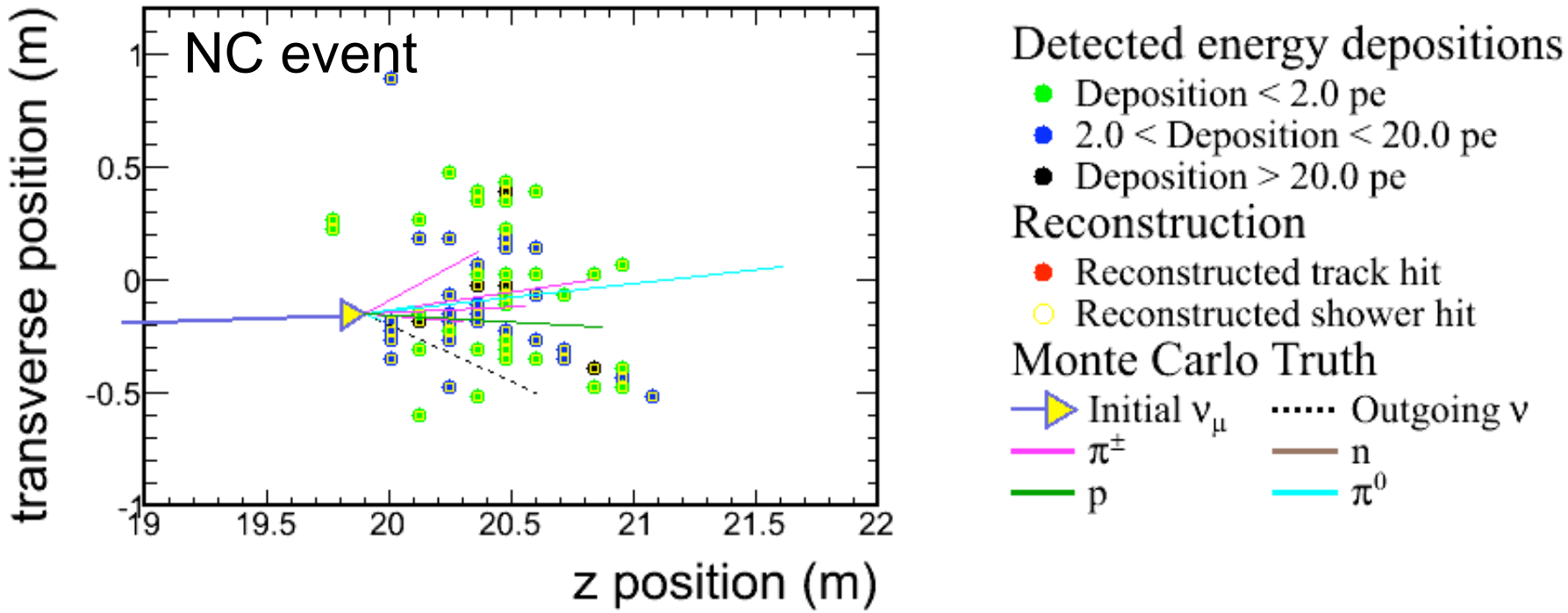


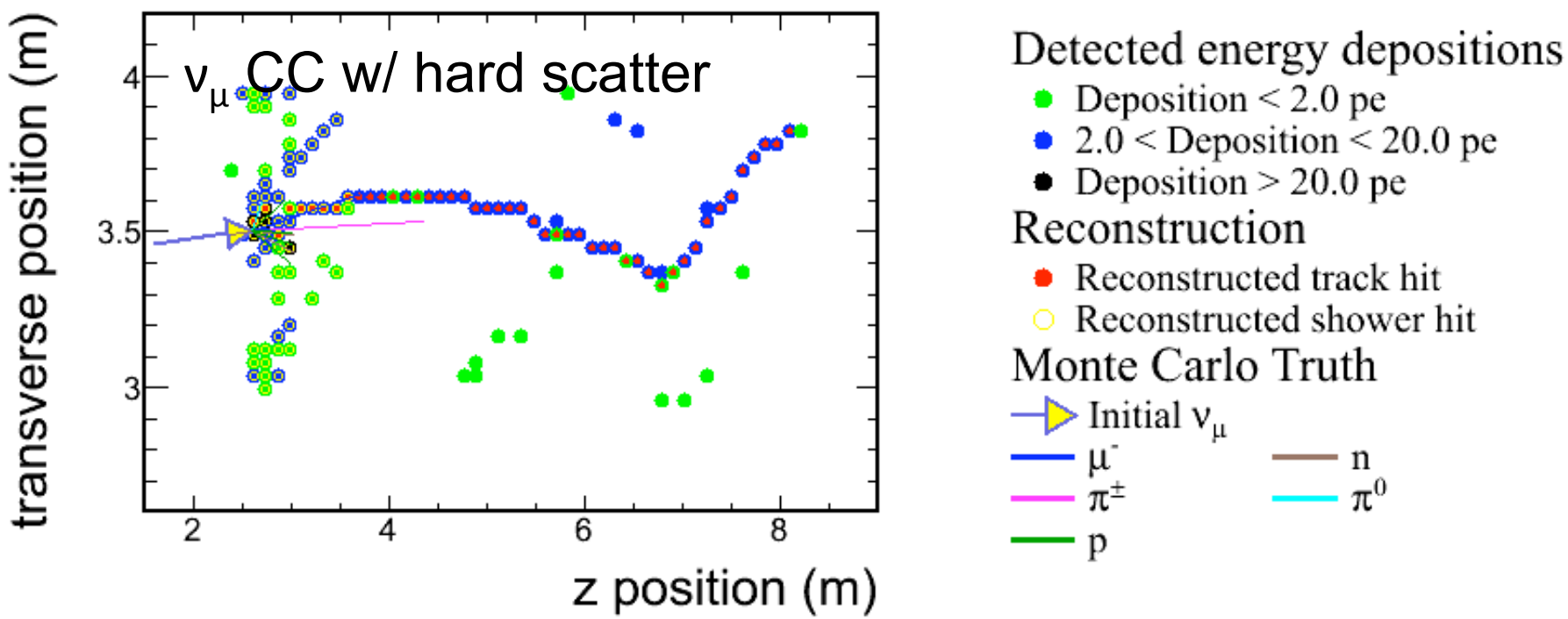


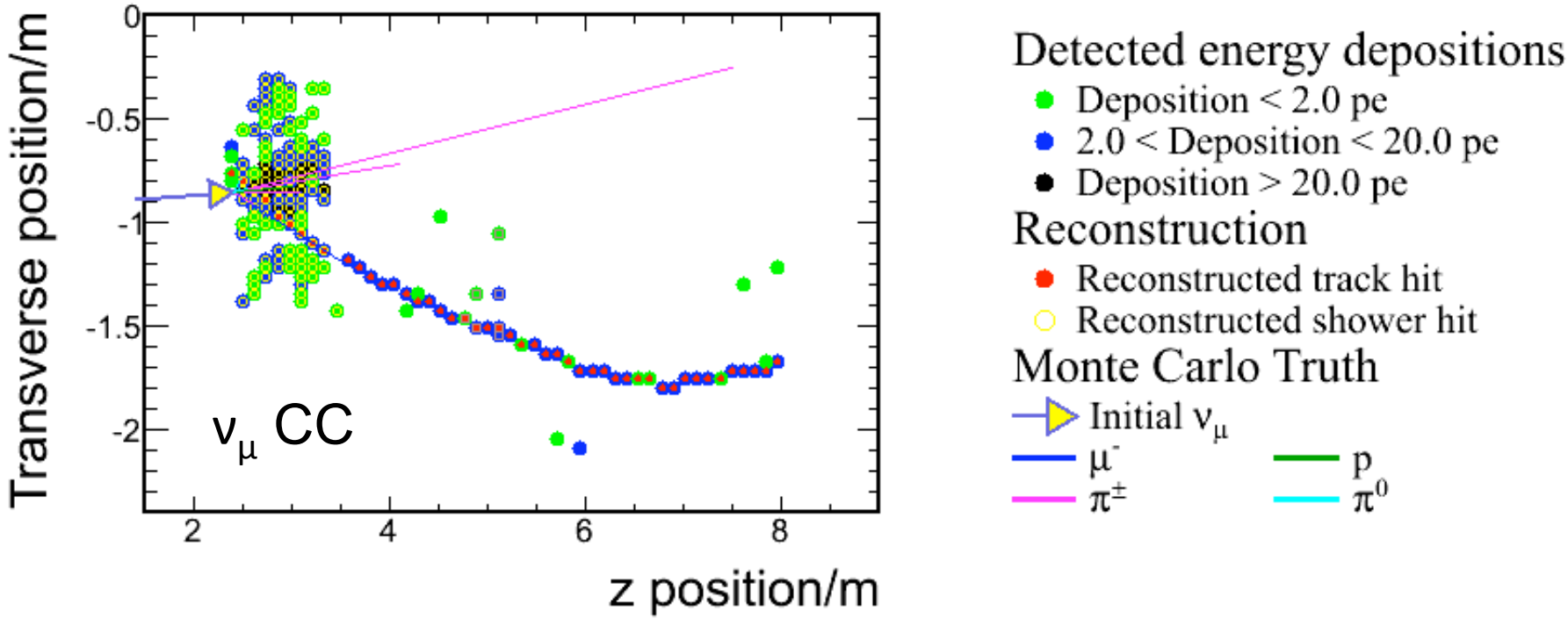


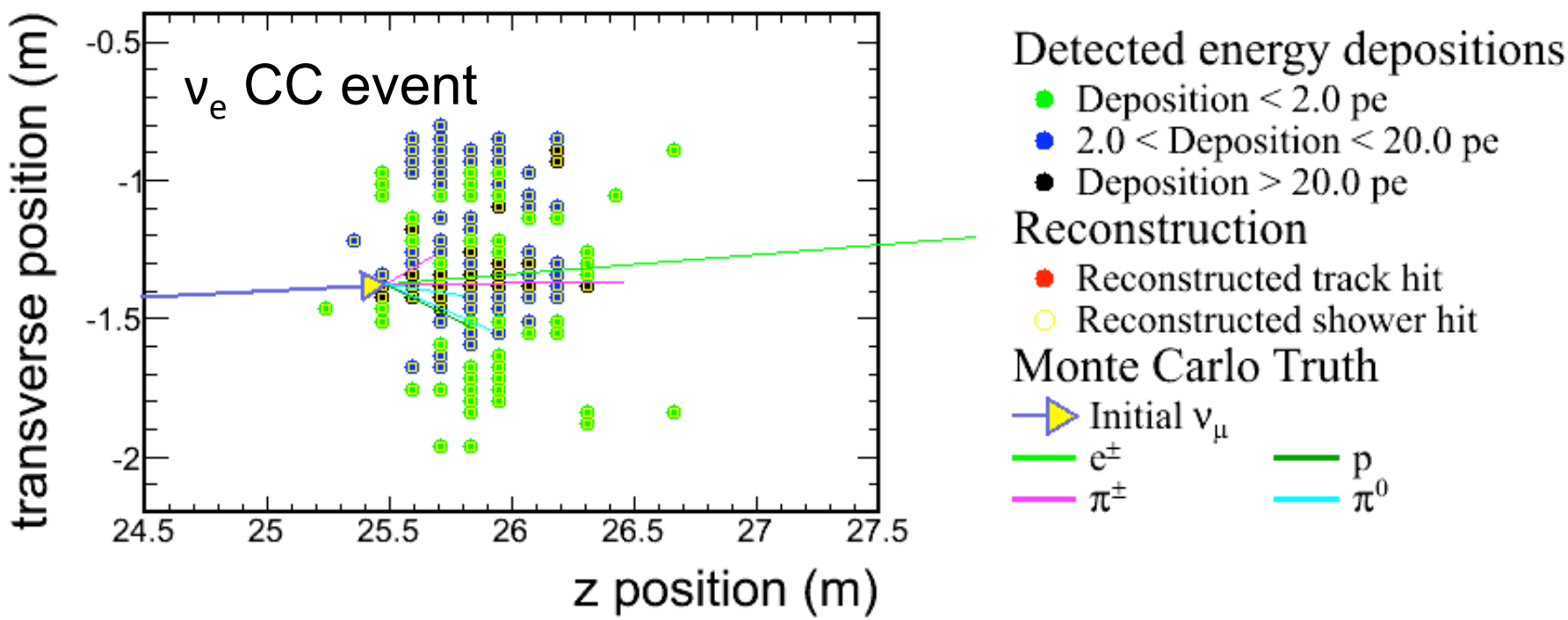

NC event with a track
transverse position (m)
z position (m)
-0.5
-1
-1.5
-2
25
26
27
28
29
30
Detected energy depositions
Deposition < 2.0 pe
2.0 < Deposition < 20.0 pe
Deposition > 20.0 pe
Reconstruction
Reconstructed track hit
Reconstructed shower hit
Monte Carlo Truth
Initial ν_μ
Outgoing ν
$\pi^\pm$
n
p
π^0


NC event with a track
transverse position (m)
z position (m)
3
2.5
2
1.5
16
17
18
19
20
21
Detected energy depositions
Deposition < 2.0 pe
2.0 < Deposition < 20.0 pe
Deposition > 20.0 pe
Reconstruction
Reconstructed track hit
Reconstructed shower hit
Monte Carlo Truth
Initial ν_μ
Outgoing ν
$\pi^\pm$
n
p
π^0
$K^{\pm/0}$


NC event
transverse position (m)
z position (m)
1
0.5
0
-0.5
-1
19
19.5
20
20.5
21
21.5
22
Detected energy depositions
Deposition < 2.0 pe
2.0 < Deposition < 20.0 pe
Deposition > 20.0 pe
Reconstruction
Reconstructed track hit
Reconstructed shower hit
Monte Carlo Truth
Initial ν_μ
Outgoing ν
$\pi^\pm$
n
p
π^0

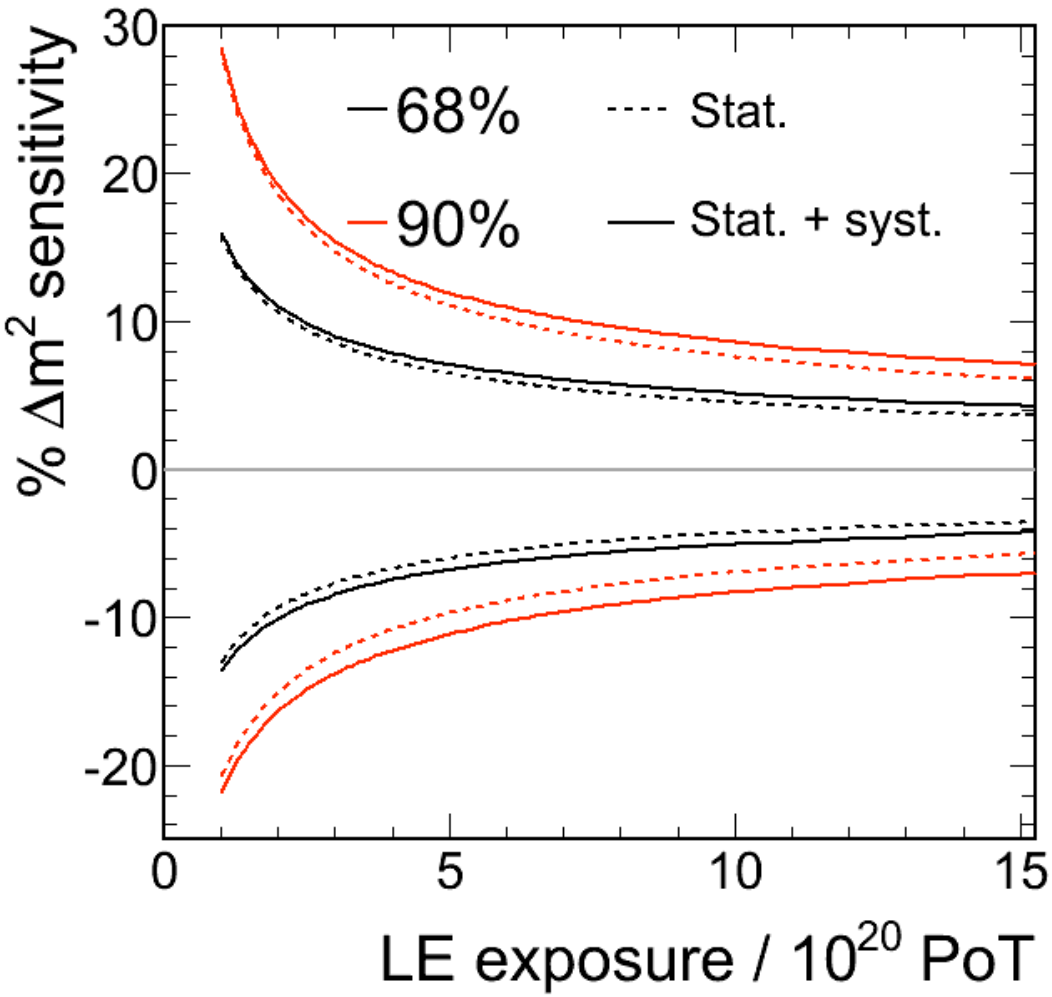

ν_μ CC w/ hard scatter
transverse position (m)
z position (m)
4
3.5
3
2
4
6
8
Detected energy depositions
Deposition < 2.0 pe
2.0 < Deposition < 20.0 pe
Deposition > 20.0 pe
Reconstruction
Reconstructed track hit
Reconstructed shower hit
Monte Carlo Truth
Initial ν_μ
μ^-
n
$\pi^\pm$
π^0
p


Transverse position/m
z position/m
ν_μ CC
Detected energy depositions
Deposition < 2.0 pe
2.0 < Deposition < 20.0 pe
Deposition > 20.0 pe
Reconstruction
Reconstructed track hit
Reconstructed shower hit
Monte Carlo Truth
Initial ν_μ
μ^-
p
$\pi^\pm$
π^0


transverse position (m)
z position (m)
ν_e CC event
Detected energy depositions
Deposition < 2.0 pe
2.0 < Deposition < 20.0 pe
Deposition > 20.0 pe
Reconstruction
Reconstructed track hit
Reconstructed shower hit
Monte Carlo Truth
Initial ν_μ
$e^\pm$
p
$\pi^\pm$
π^0

Neutrino Δm^2 sensitivity evolution

- Neutrino Δm^2_{32} measurement will reach the point of diminishing returns after next result (without accelerator/ beam upgrade)

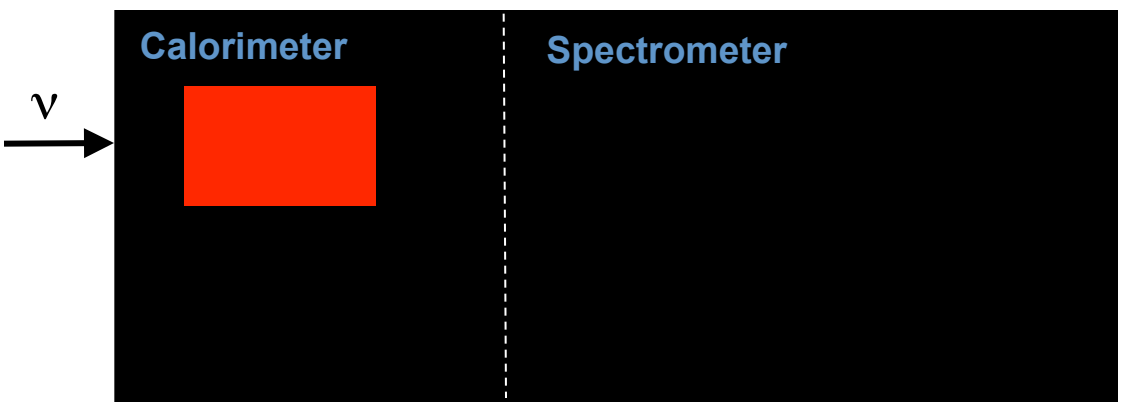


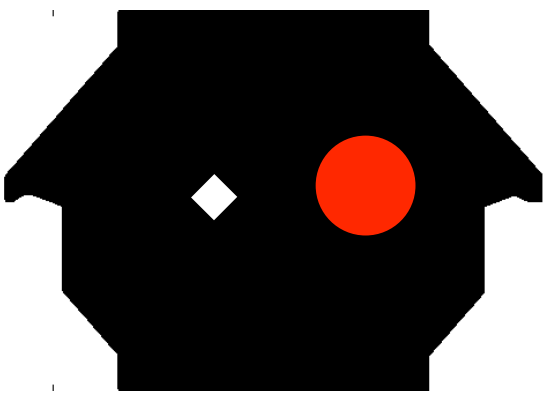
Event Scanning

- Every far detector event has been scanned by eye and detailed comparisons with MC of event reconstruction have been performed at the 1-2% level
- For this analysis further detailed scans were performed of all events with a positive track and all events with tracks ending towards the detector edge (a search for defocused μ^+ reconstructed as μ^-)
  - no problems were found

Event Pre-Selection Cuts

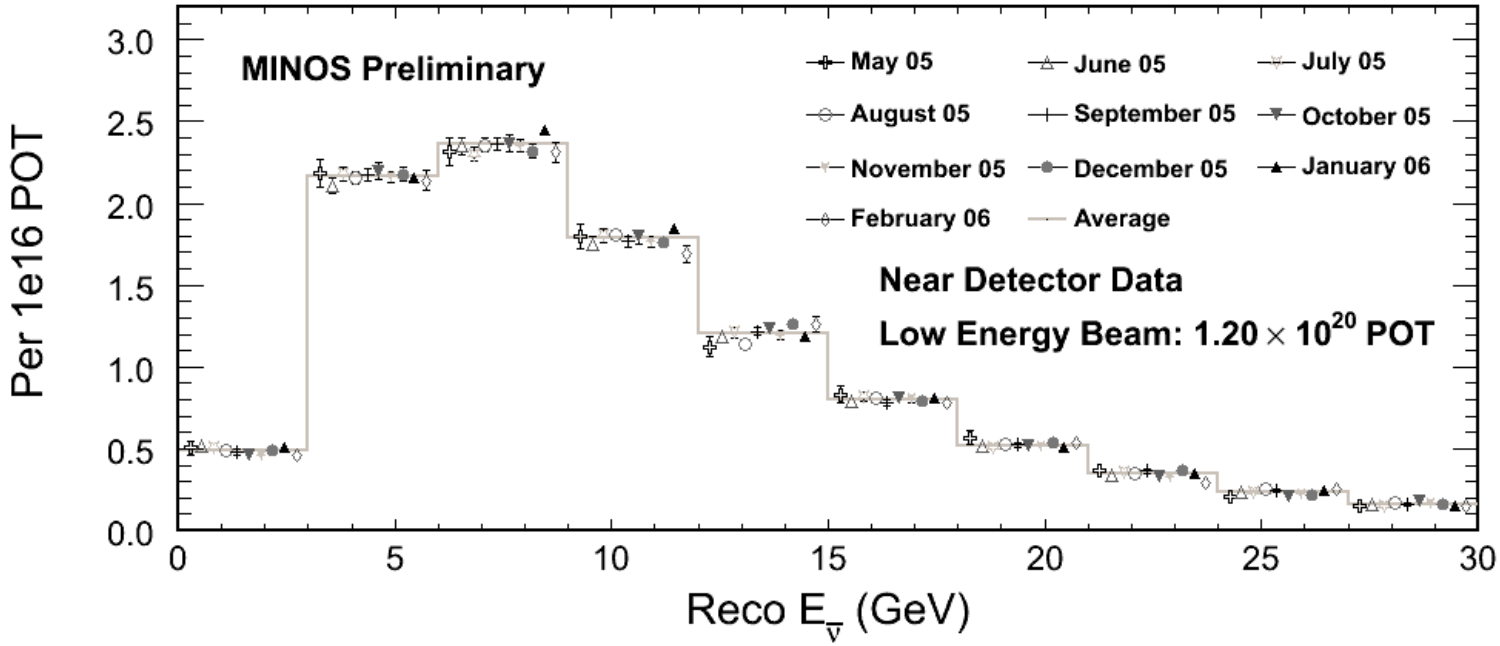
- Exactly the same as 2008 neutrino disappearance analysis
- Beam quality and detector quality cuts
  - Beam positioning, magnetic horns energized, detector running within operational parameters
- Event vertex reconstructed within the fiducial volume of the detector

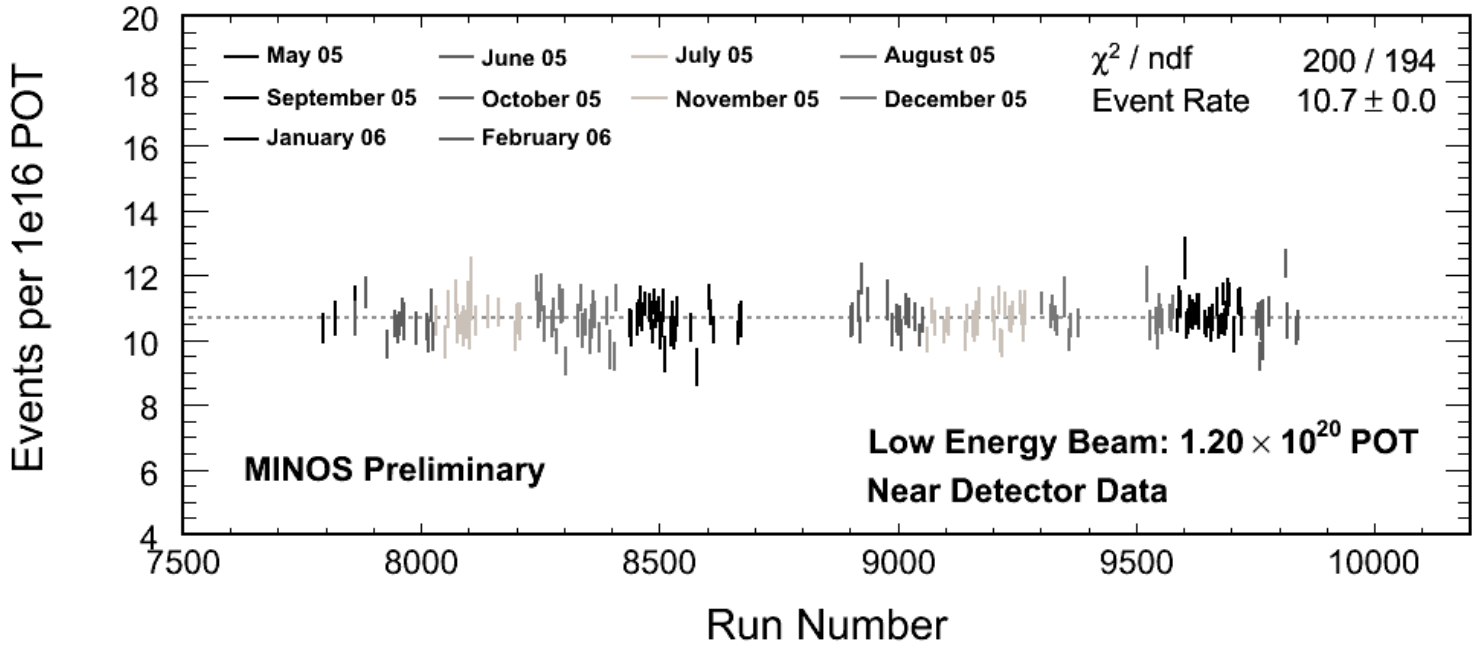




Near Detector

Near detector beam stability





Run-II looks very similar