New Results From the MINOS Experiment

Hugh Gallagher for the MINOS Collaboration
Tufts University

Neutrino 2008
Christchurch, NZ
May 27, 2008

Outline

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Neutrino 2008
May 27, 2008

1) Introduction

2) The MINOS Experiment and NuMI Facility

3) Analysis of Charged Current Events
   - Precision measurements of Δm^2, $\sin^2(2\theta)$
   - Oscillations vs. alternative hypotheses

4) Analysis of Neutral Current Events
   - Do ν_μ oscillate to sterile neutrinos?

5) ν_e Appearance

6) Conclusion

Published:
Phys.Rev.Lett.97,191801,2006
Phys.Rev.D77:072002,2008
1.27 x 10^{20} POT

This Analysis:
3.36 x 10^{20} POT

The MINOS Collaboration

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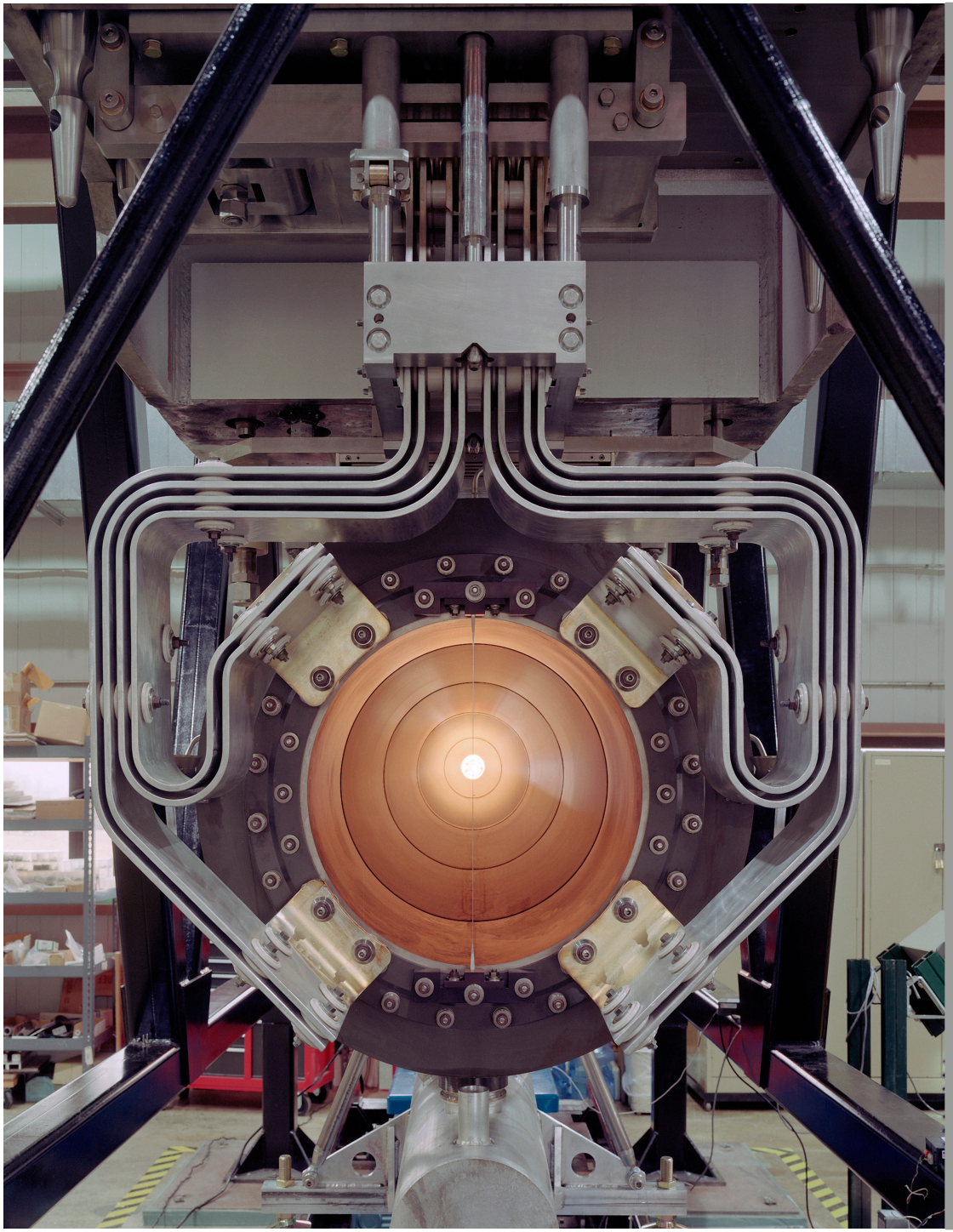

The MINOS Experiment

Physics Goals
The NuMI Beam

The Goals of MINOS

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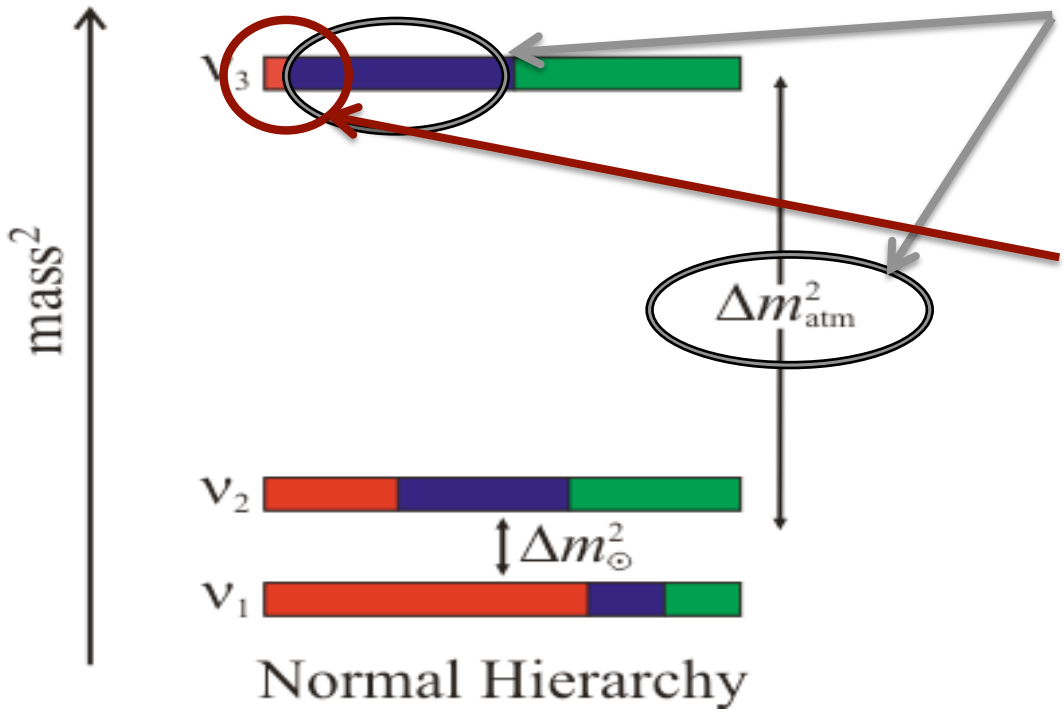

Make precision measurements of the oscillation parameters Δm^2 and $\sin^2(2\theta)$.

Search for subdominant oscillations at Δm^2_{atm}.

One mass scale dominance: $\Delta m^2_{atm} >> \Delta m^2_{\odot}$

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

The Goals of MINOS

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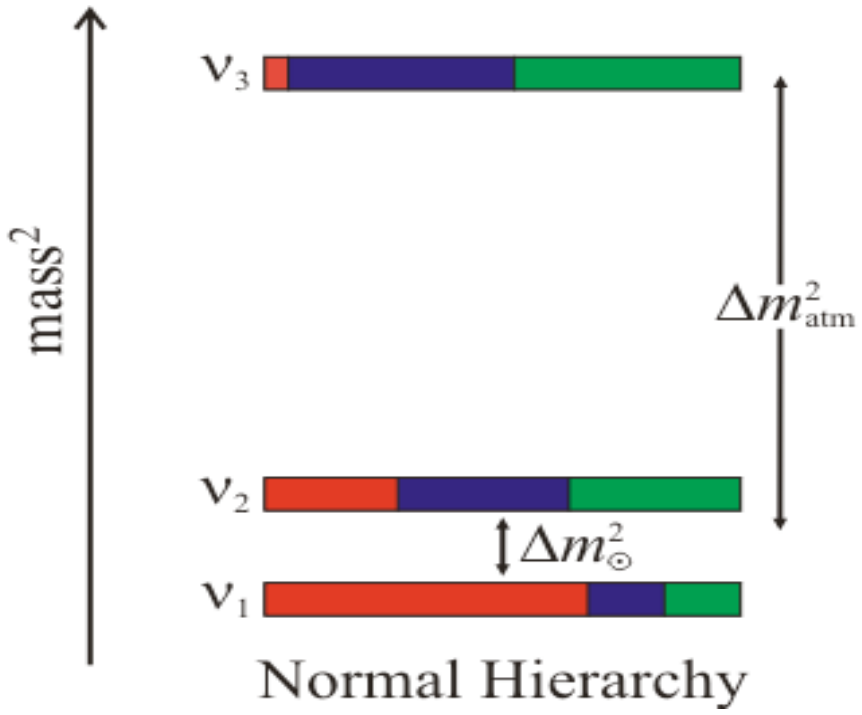

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Confirm oscillations vs. exotic explanations (decay, decoherence).

Mixing to sterile neutrinos?

Use the magnetized detectors to make CPT tests.

The Goals of MINOS

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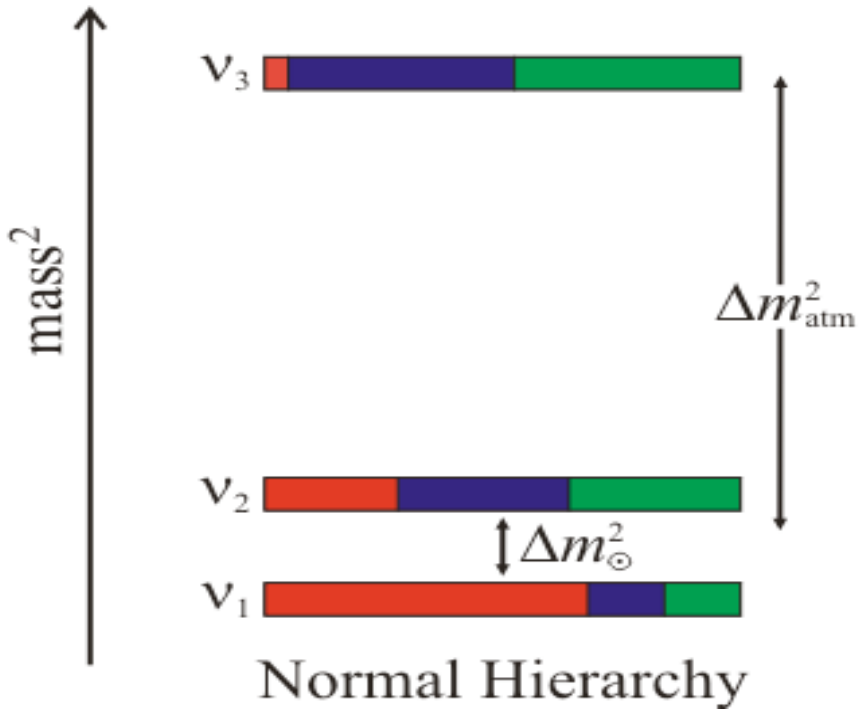

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Make precision measurements of the oscillation parameters Δm^2 and $\sin^2(2\theta)$.

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Confirm oscillations vs. exotic explanations (decay, decoherence).

Mixing to sterile neutrinos?

Use the magnetized detectors to make CPT tests.

Far Detector-only studies of atmospheric neutrinos and cosmic rays.

Near detector-only measurements of neutrino interaction physics.

The MINOS Experiment

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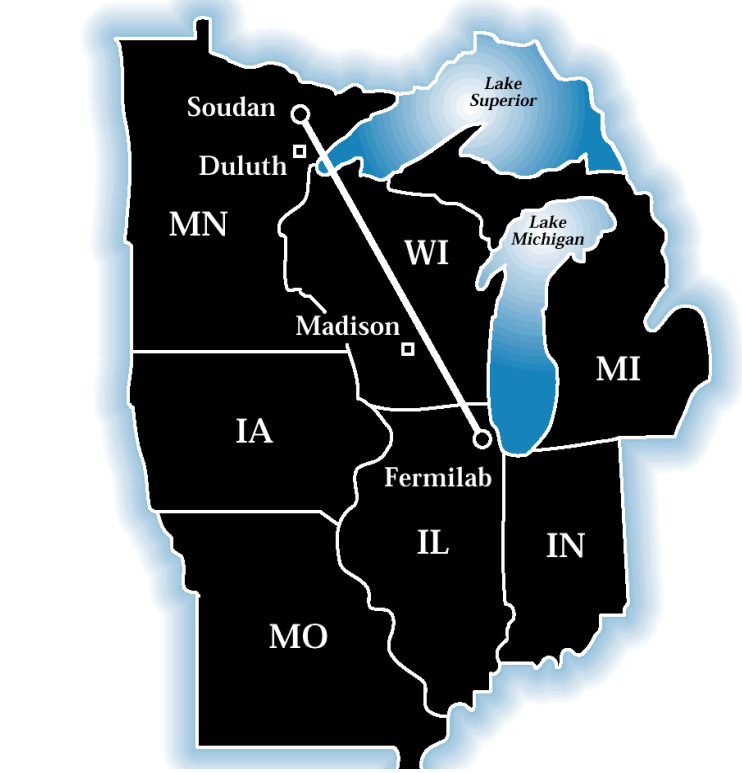
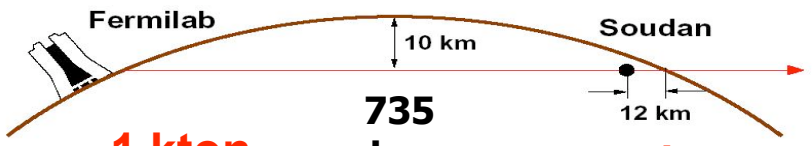
MINOS (Main Injector Neutrino Oscillation Search) – a long baseline neutrino oscillation experiment:

Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.

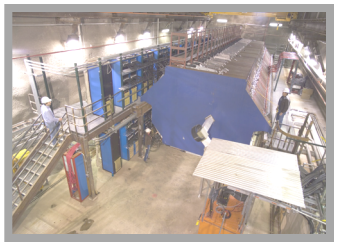
A “Near Detector” at Fermilab to measure the beam composition and energy spectrum.

A “Far Detector” deep underground in the Soudan Mine, Minnesota, to search for evidence of oscillations.

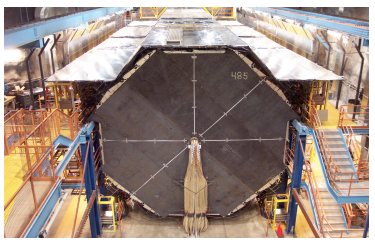




1 kton



5.4 kton



Neutrinos at the Main Injector (NuMI)

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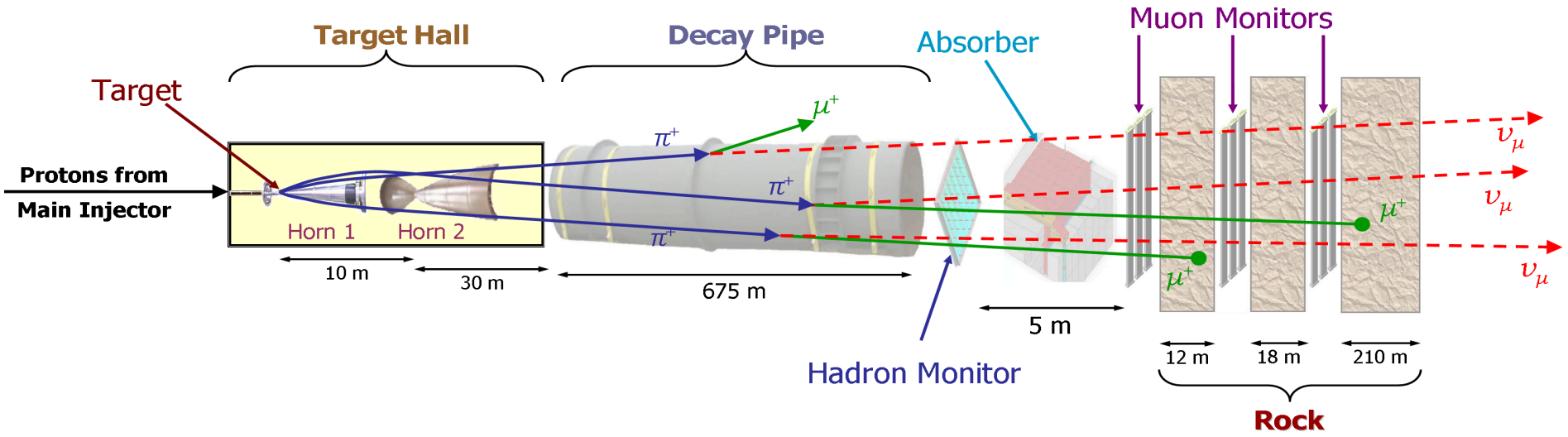


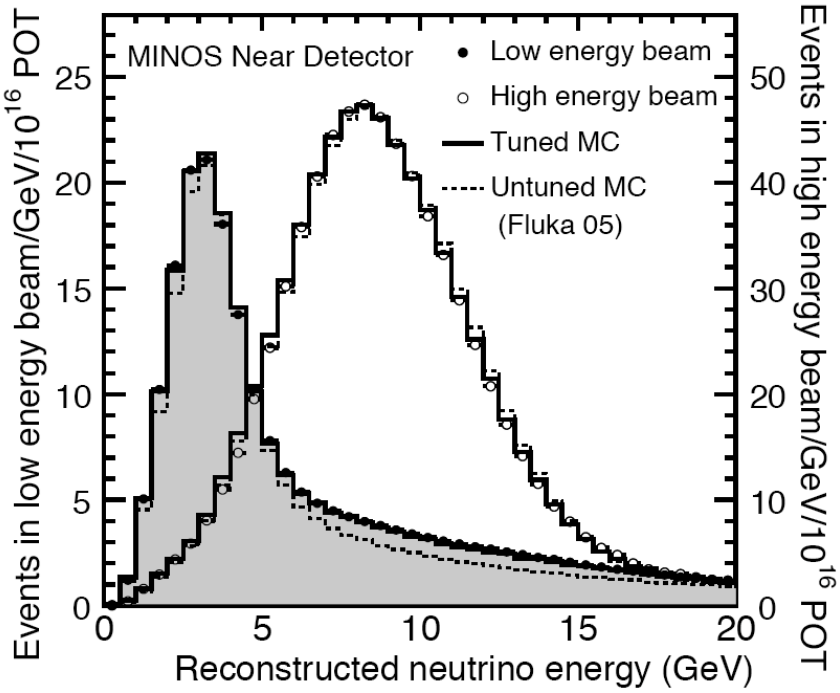
Beam energy spectrum can be tuned by varying the relative positions of target and horns.

In the LE configuration, interactions are:

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

Performance (Week of 5/12):

- 10μs spill of 120 GeV protons every 2.2s
- Intensity: 3.0×10^{13} POT/spill
- 0.275 MW beam power
- 10^{18} POT /day



NuMI Beam Performance

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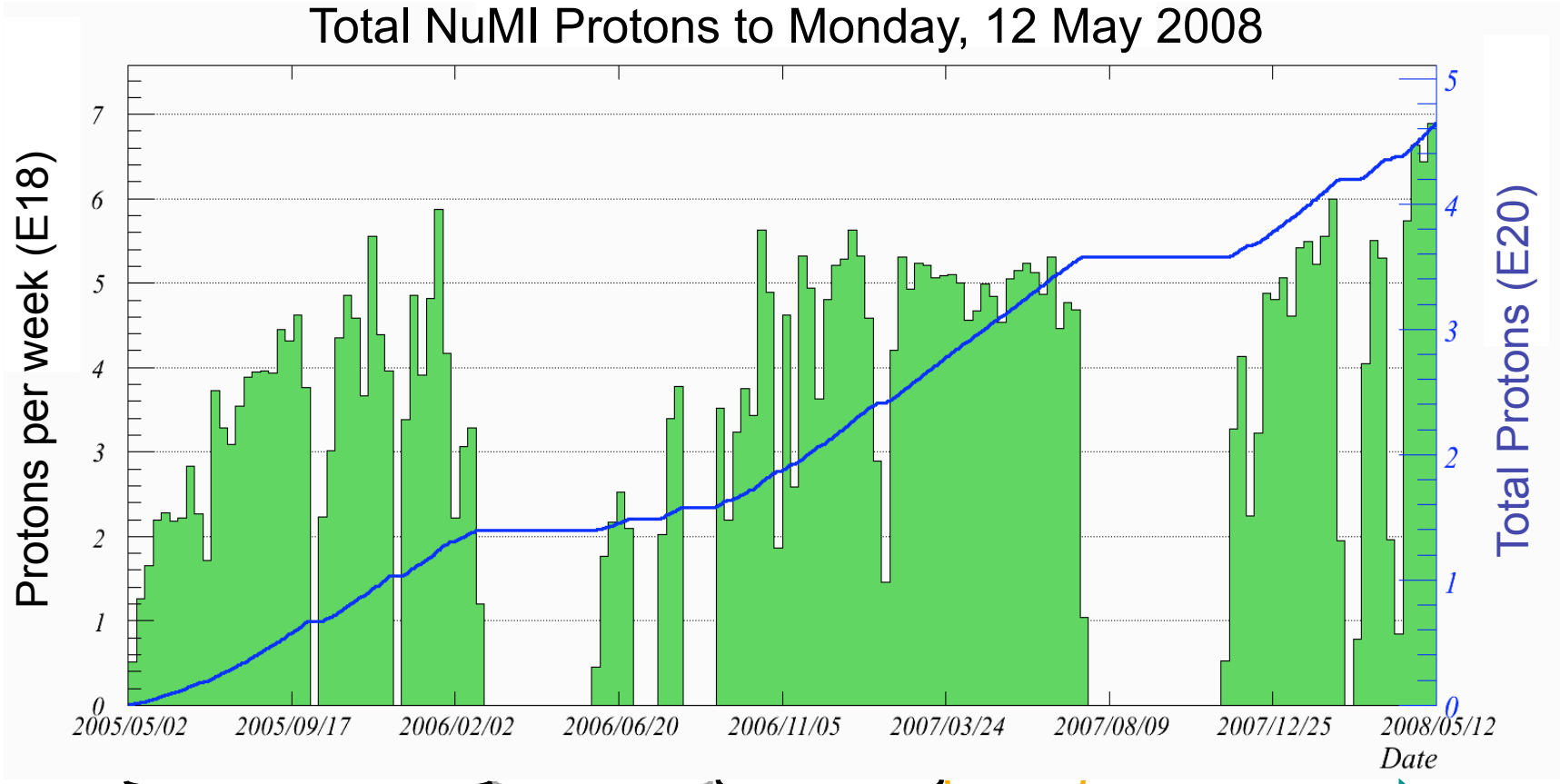

Many thanks to Fermilab's Accelerator Division

NuMI Beam Performance

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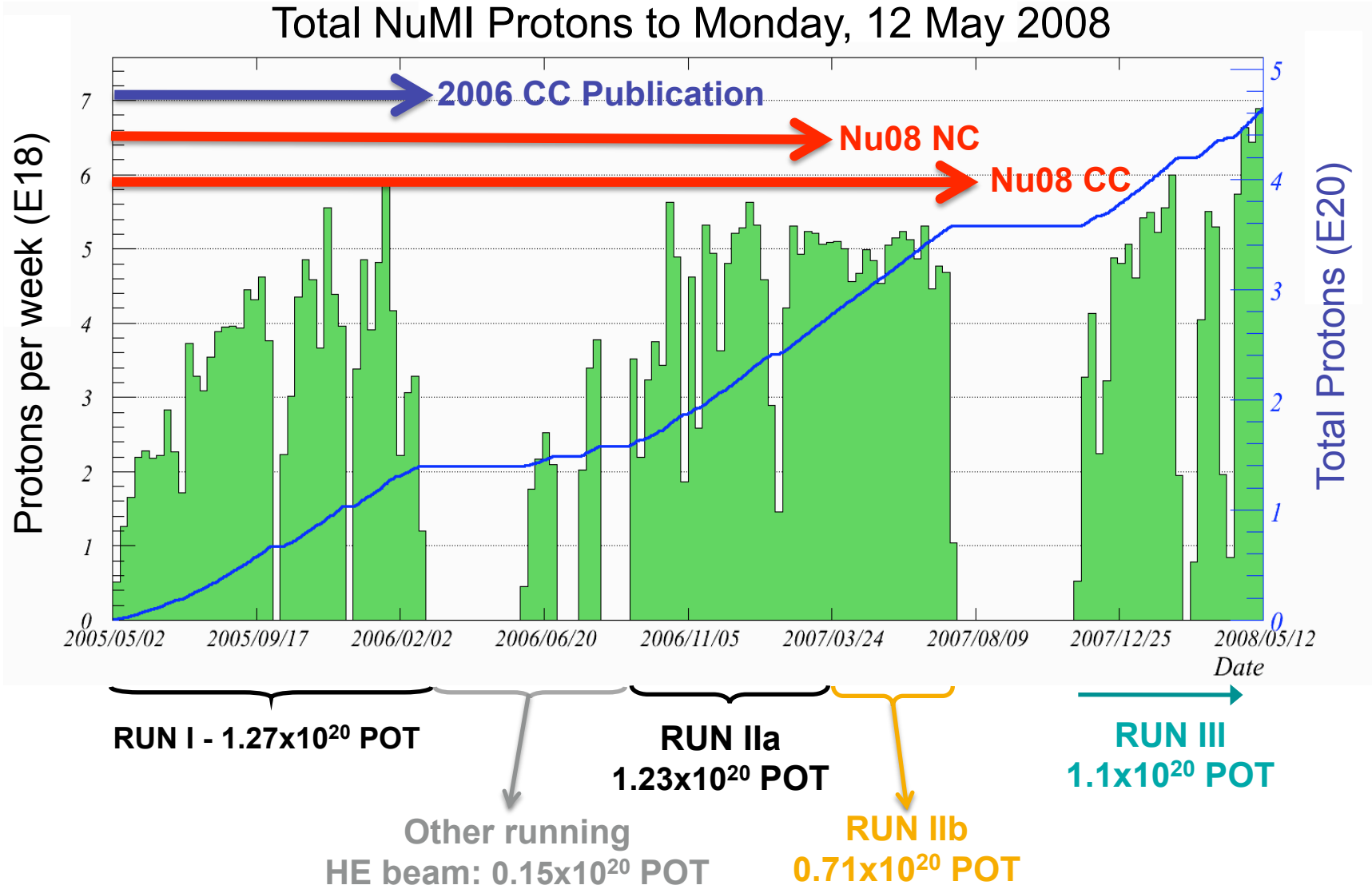

Event Topologies

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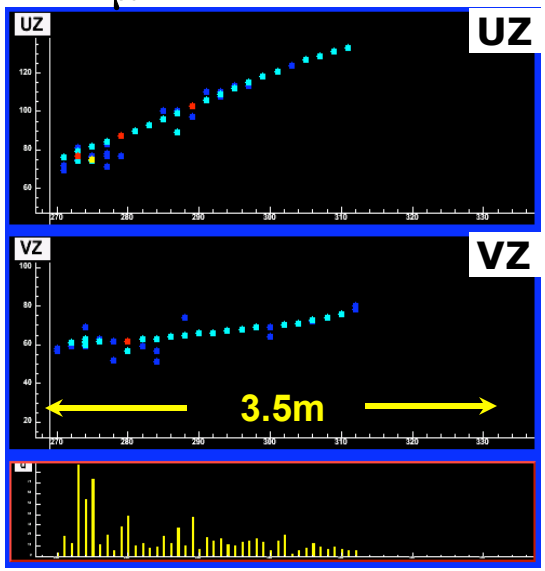
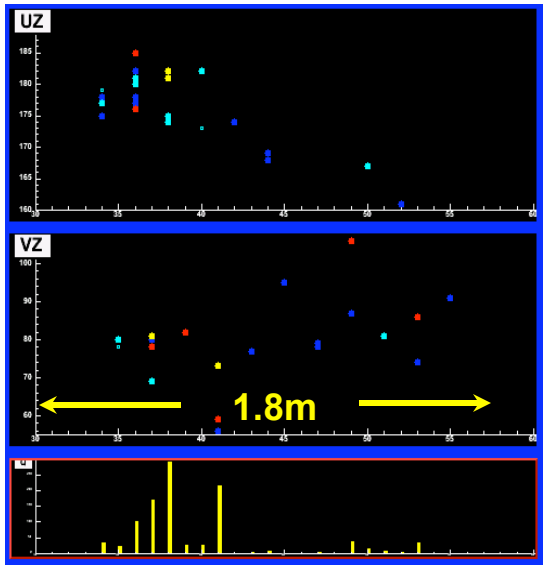
Monte Carlo

ν_μ CC Event



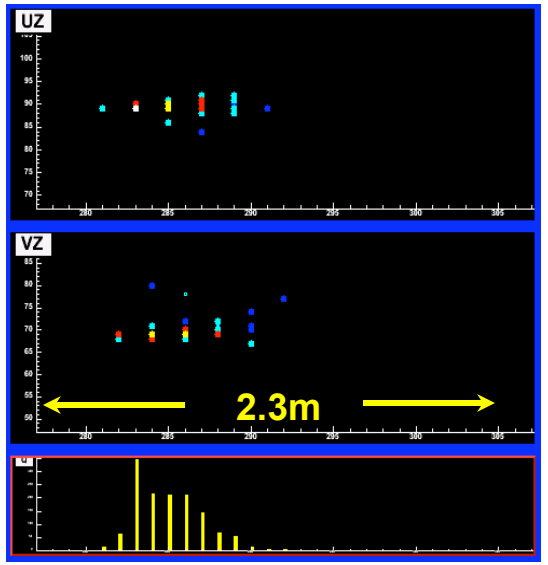
•long μ track+ hadronic activity at vertex

NC Event



• short event, often diffuse

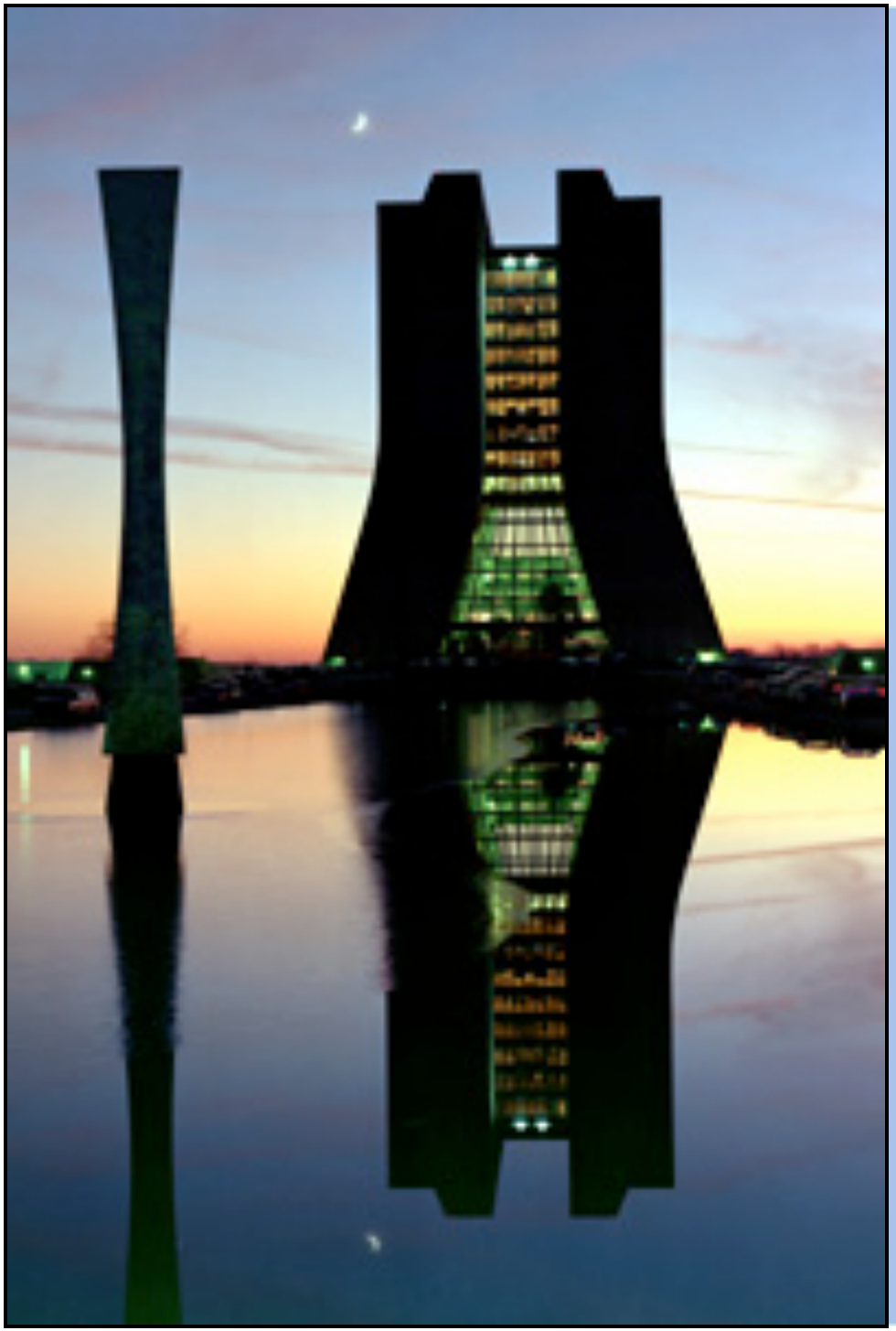
ν_e CC Event



• short, with typical EM shower profile

$$E_\nu = E_{shower} + P_\mu$$

55%/√E 6% range, 10% curvature



Charged Current Analysis

Precision measurement of Δm^2 and $\sin^2(2\theta)$

Testing the oscillation hypothesis

CC Event Selection

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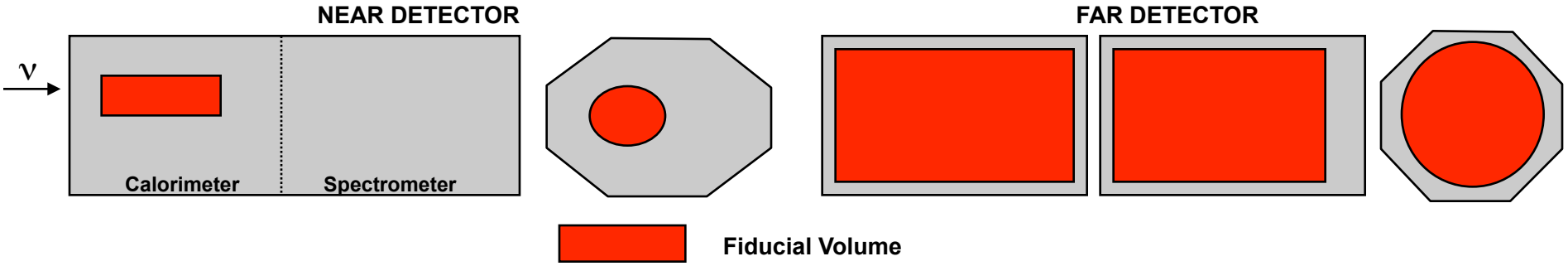
ν_μ CC-like events are selected in the following way:

Event must contain at least one good reconstructed track

The reconstructed track vertex should be within the fiducial volume of the detector:



Coil hole cut

The fitted track should have negative charge (selects ν_μ)

Cut on kNN-based Particle ID parameter which is used to separate CC and NC events.

CC Event Selection

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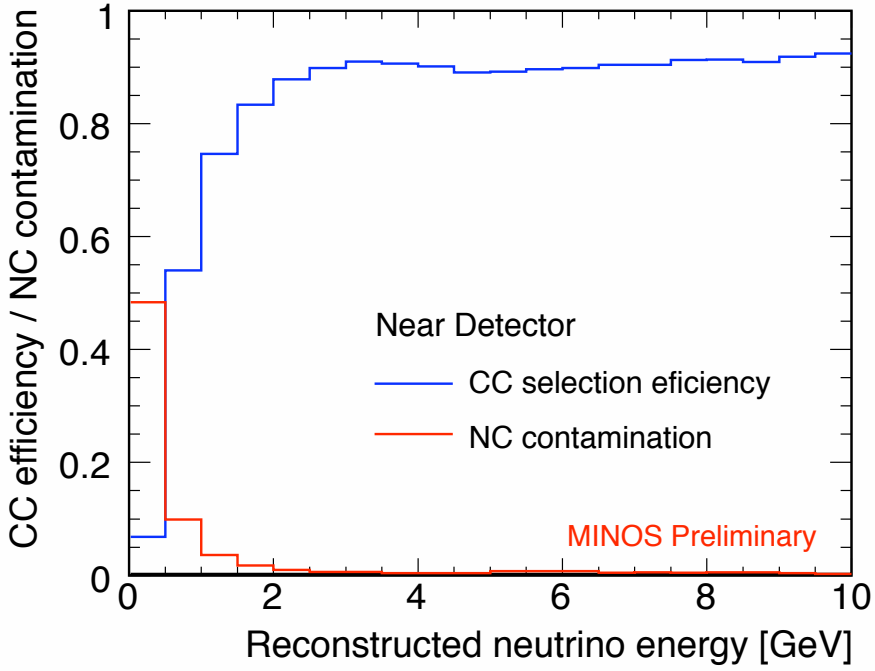
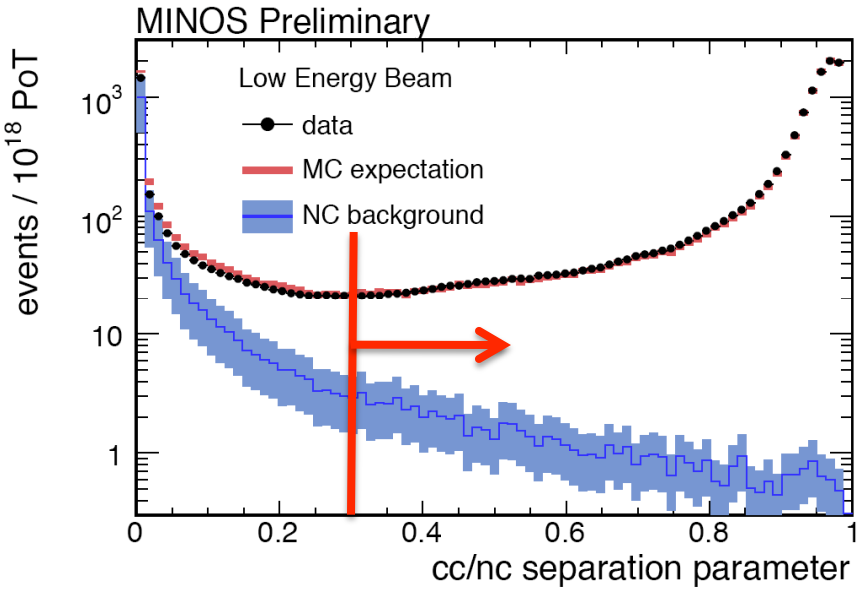
CC / NC Event classification is performed with a new k-nearest neighbor (kNN) based algorithm with four inputs:

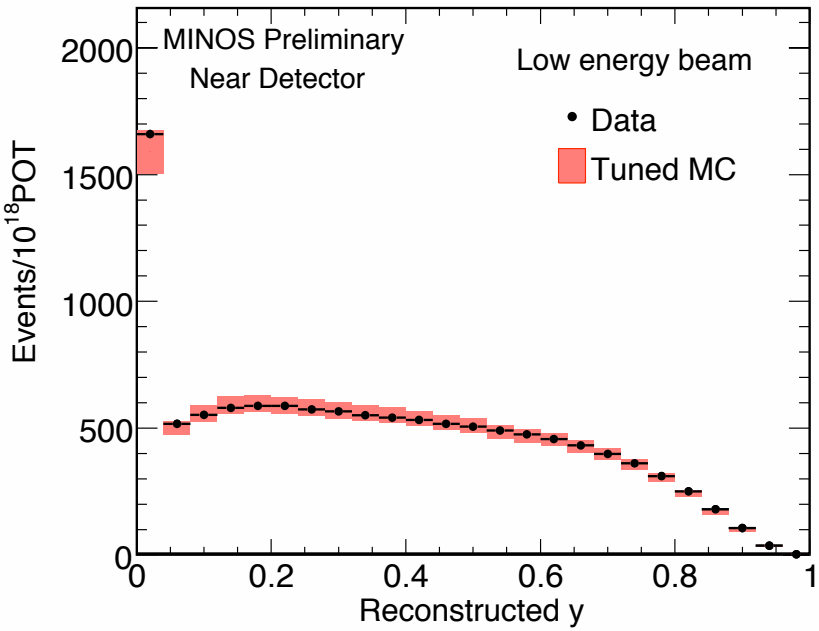
1. Track length (planes)

For hits on the track:

2. Mean pulse height
3. Fluctuation in pulse height
4. Transverse track profile







Near to Far Extrapolation

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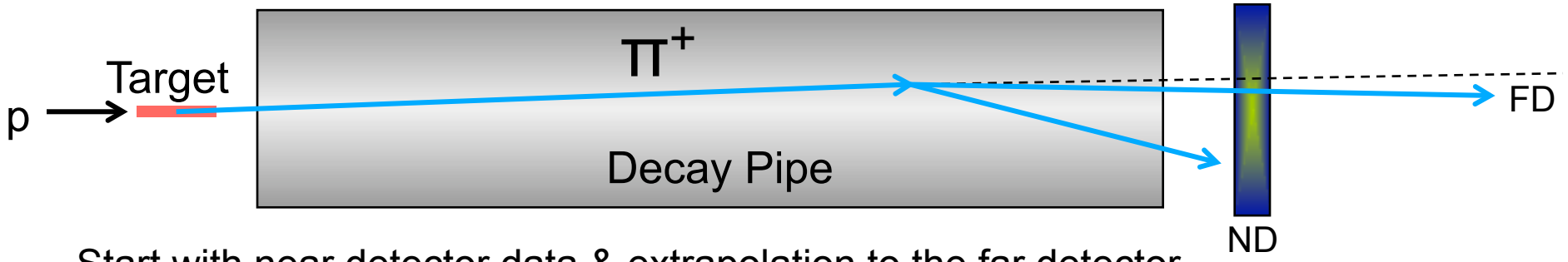
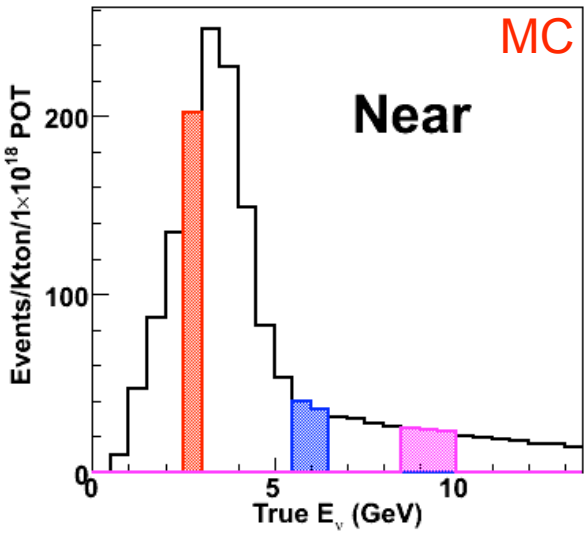
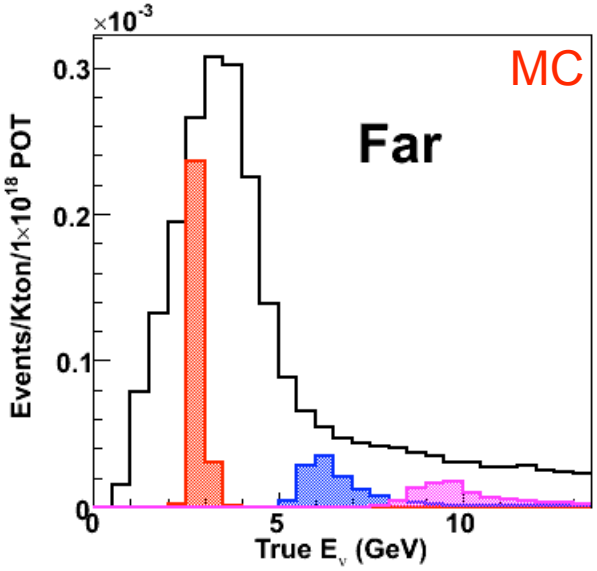
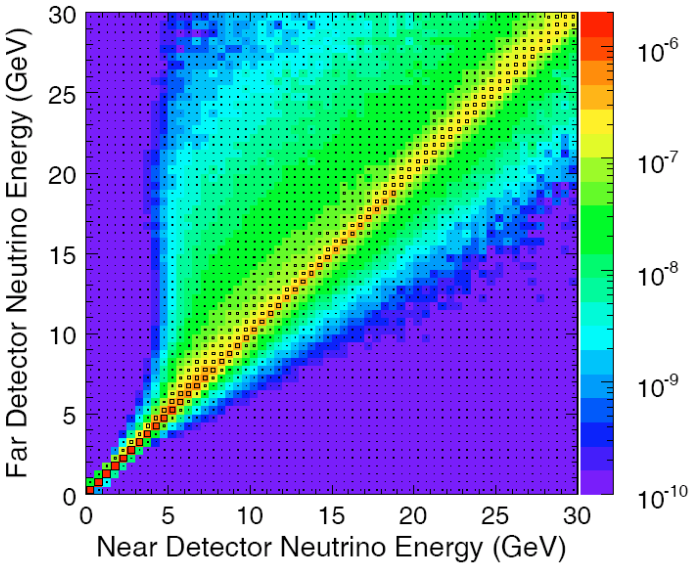


Start with near detector data & extrapolation to the far detector

- Use Monte Carlo to provide corrections due to energy smearing and acceptance
- Encode pion decay kinematics & the geometry of the beamline into a matrix used to transform the ND spectrum into the FD energy spectrum







Far Detector Data Quality - LE

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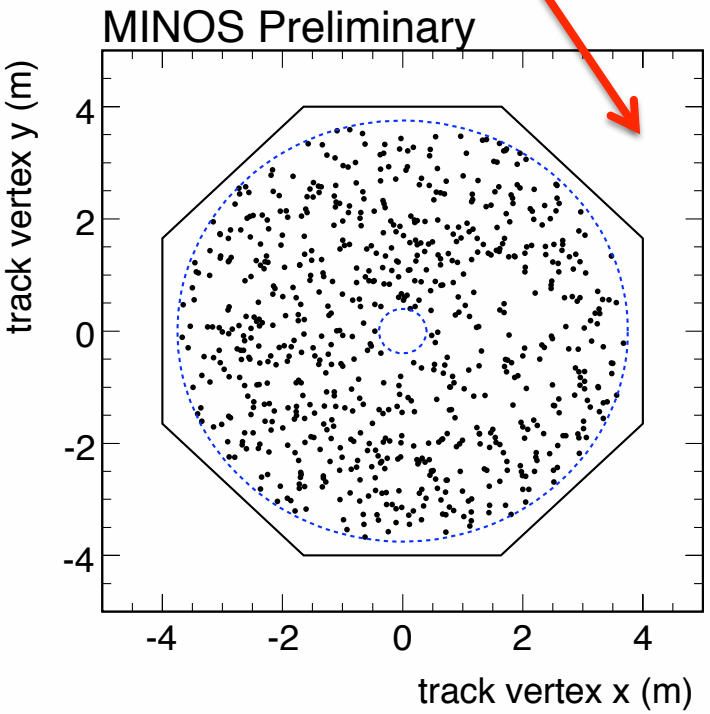
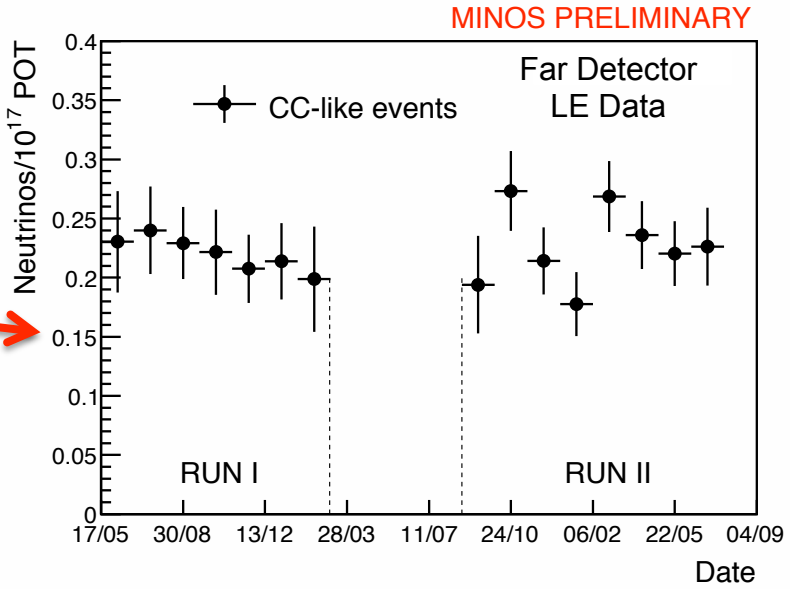
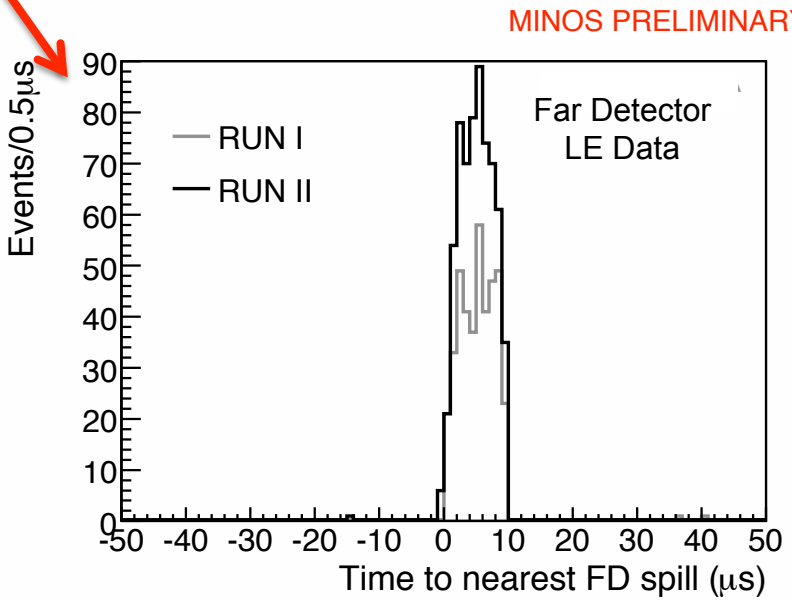
848 events observed in the FD
1065±60 (syst) expected without oscillations

Data are well described by MC:
Events/POT over this exposure
Event time
Spatial vertex distributions







Far Detector Distributions - LE

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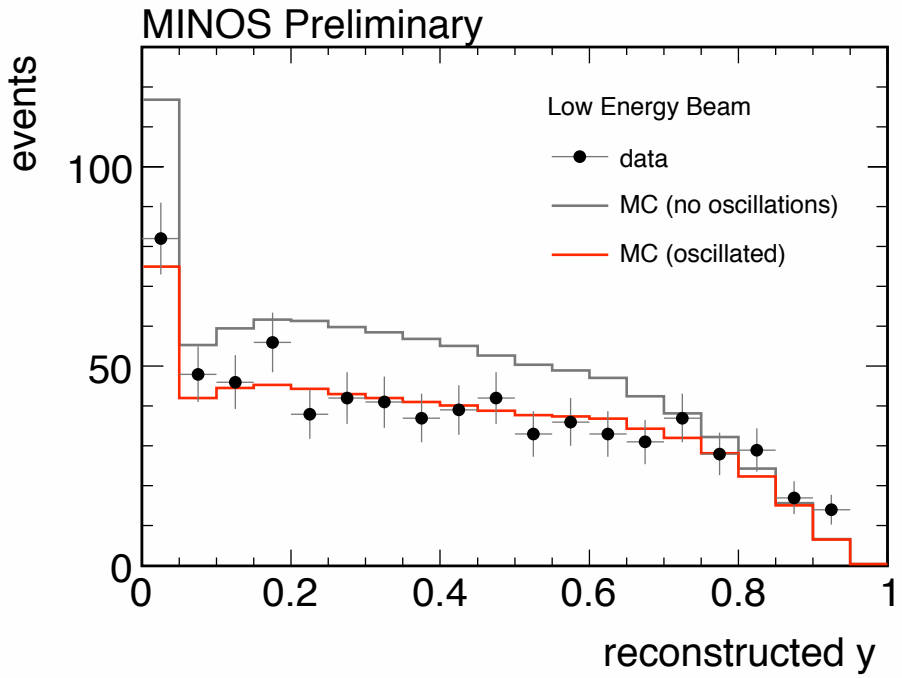
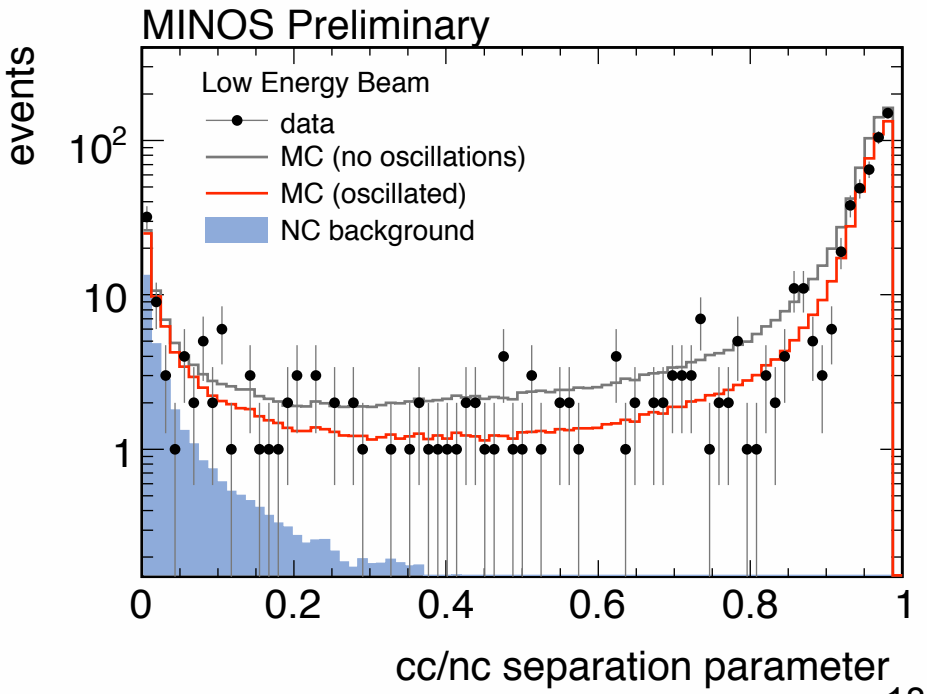


Good agreement is also seen in reconstructed quantities.

- Numbers of tracks/showers
- Track energies
- Shower energies
- Kinematic distributions



Oscillation fit data:

Run I LE data: 1.27 x 10^{20} POT
Run II LE data: 1.94 x 10^{20} POT
Run II HE data: 0.15 x 10^{20} POT

Systematic Uncertainties

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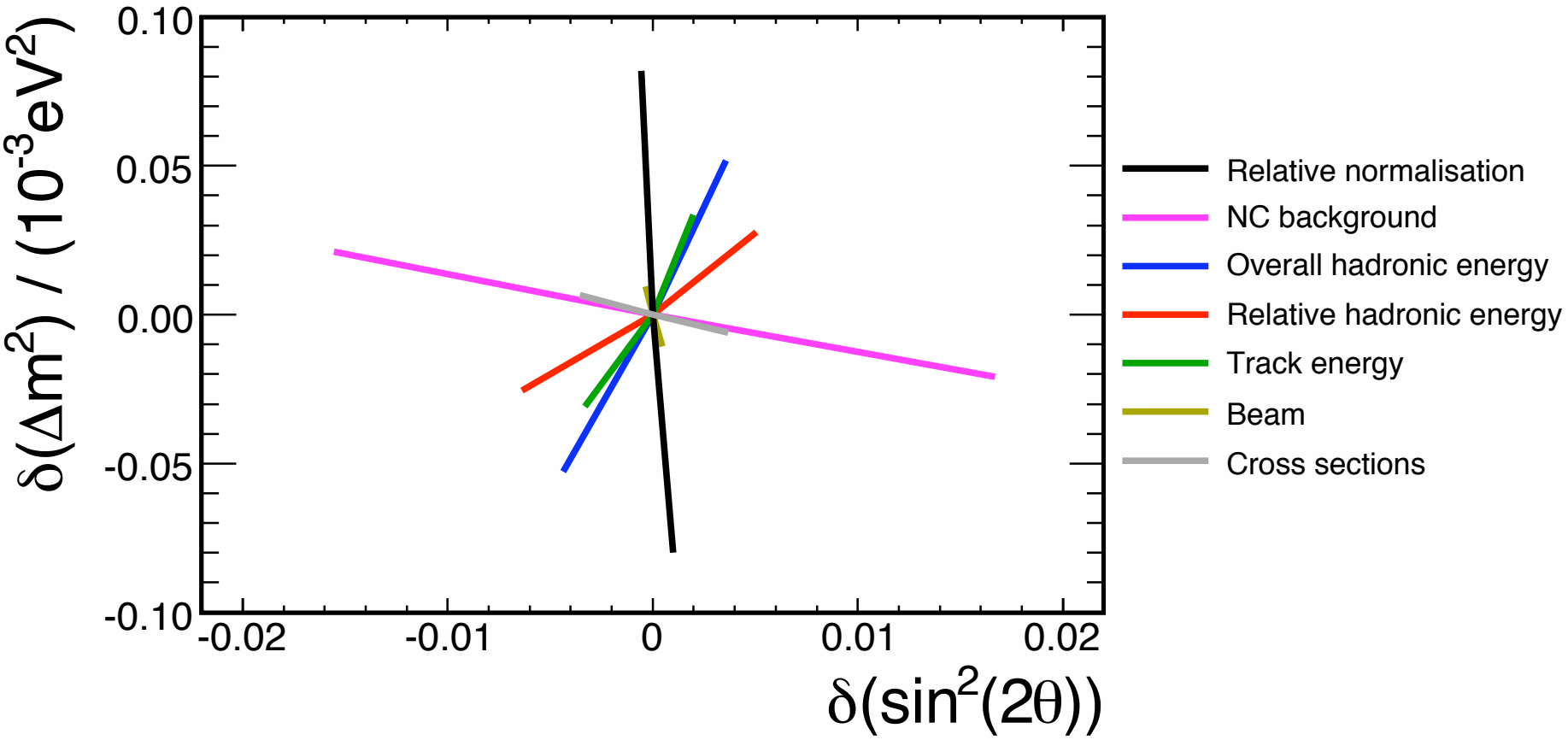
The impact of different sources of systematic uncertainty were evaluated by fitting modified MC in place of the data:



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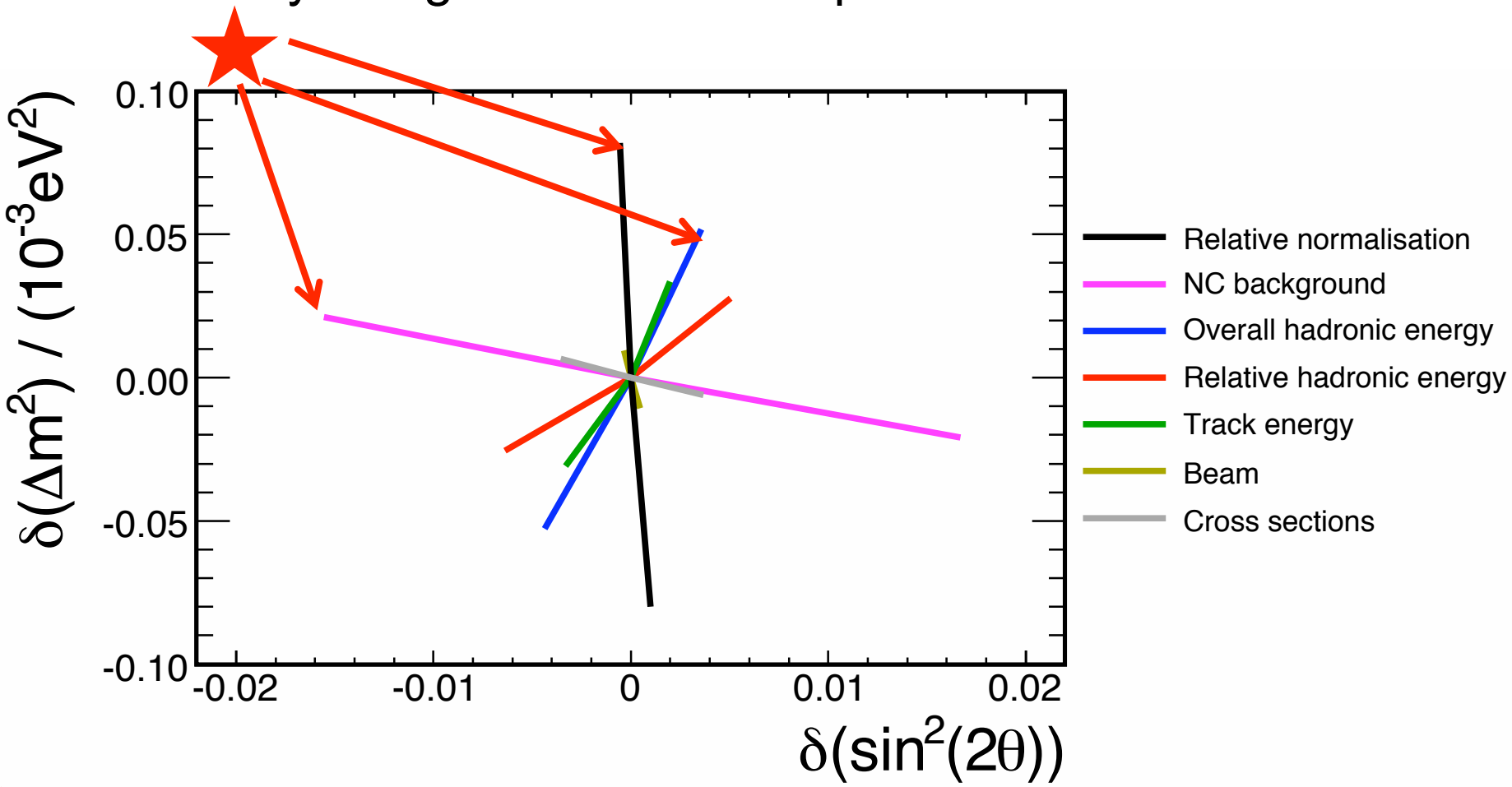

The three largest will be included as nuisance parameters in the oscillation fit.

Energy Spectrum

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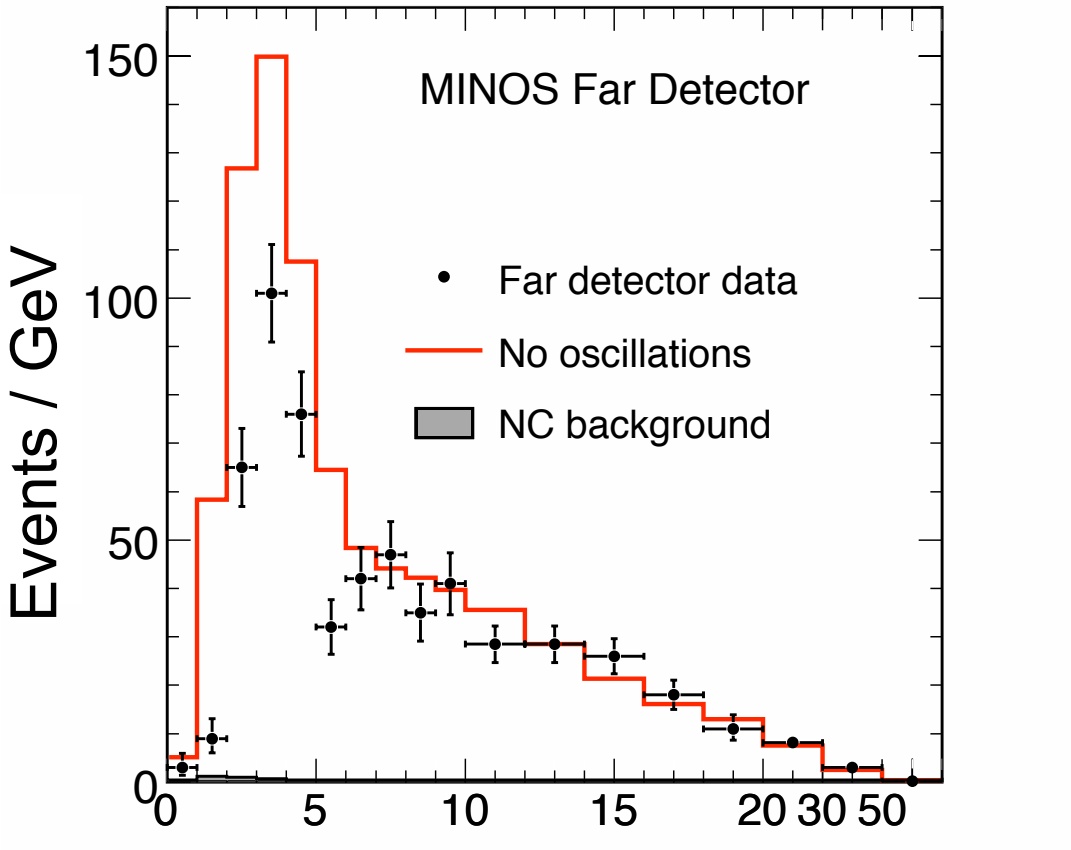

$$\chi^2 = \sum_{nbins} (2(e_i - o_i) + 2\, o_i \ln(o_i / e_i)) + \sum_{nsys} \frac{\Delta s_j^2}{\sigma_{s_j}^2}$$

Fit the energy distribution to the oscillation hypothesis:

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

Including the three largest sources of systematic uncertainty as nuisance parameters:

- Absolute hadronic energy scale: 10.3%
- Normalization: 4%
- NC contamination: 50%

Energy Spectrum

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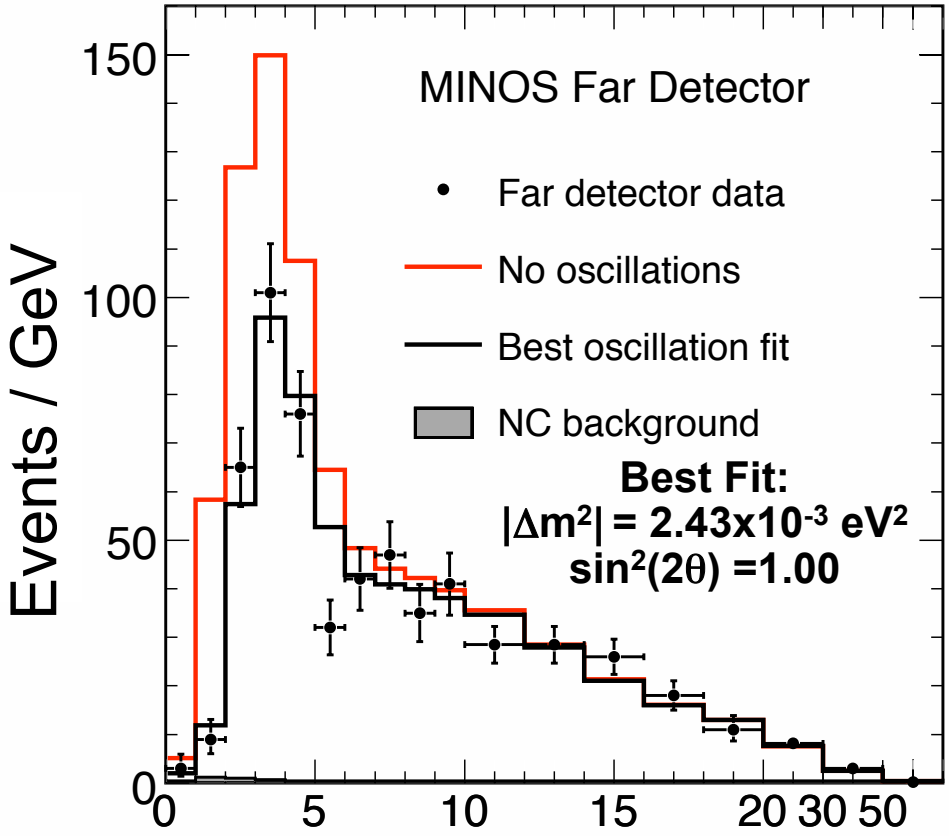

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χ^2/ndof = 90/97

Allowed Region

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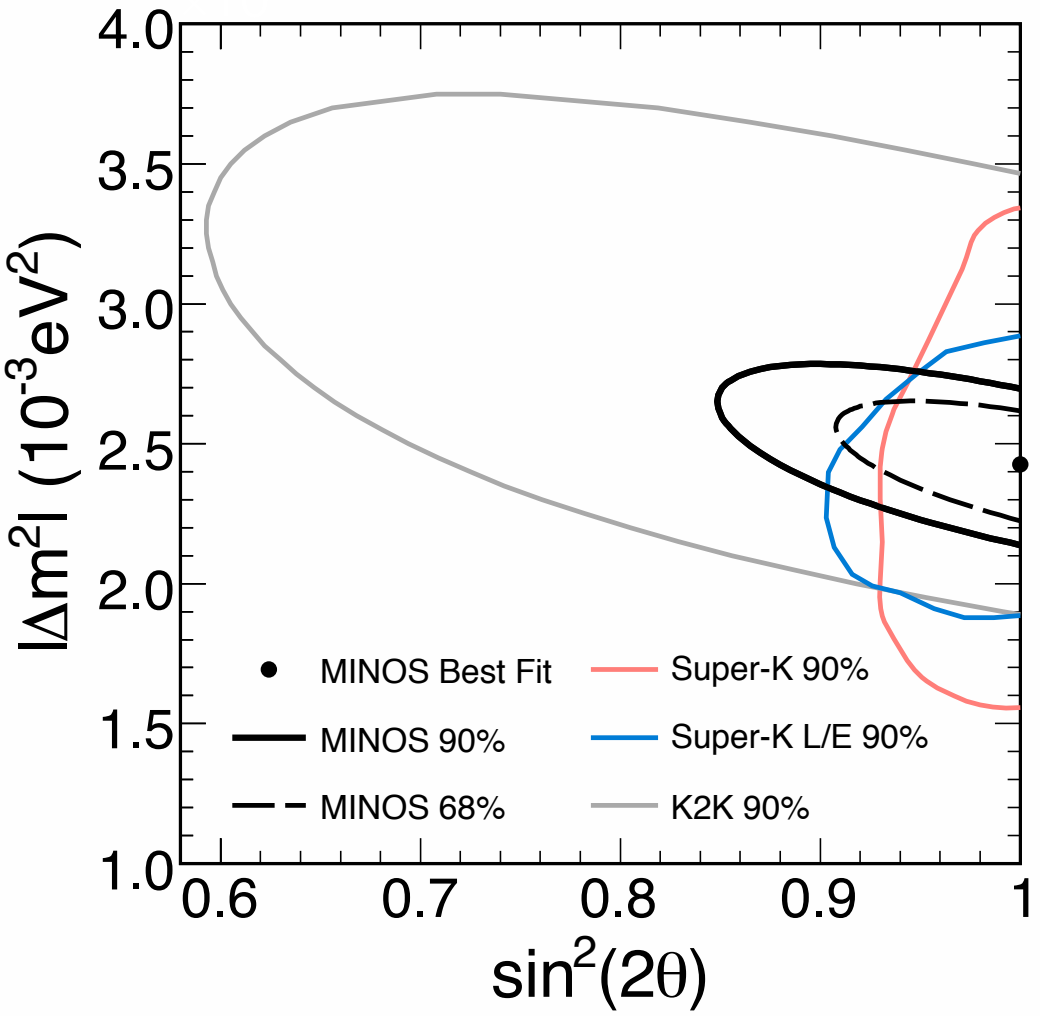

$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% C.L.)

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

χ^2/ndof = 90/97

Fit is constrained to the physical region.

Unconstrained:

$|\Delta m|^2 = 2.33 \times 10^{-3}$ eV^2

$\sin^2(2\theta)=1.07$

$\Delta\chi^2=-0.6$

Alternative Hypotheses

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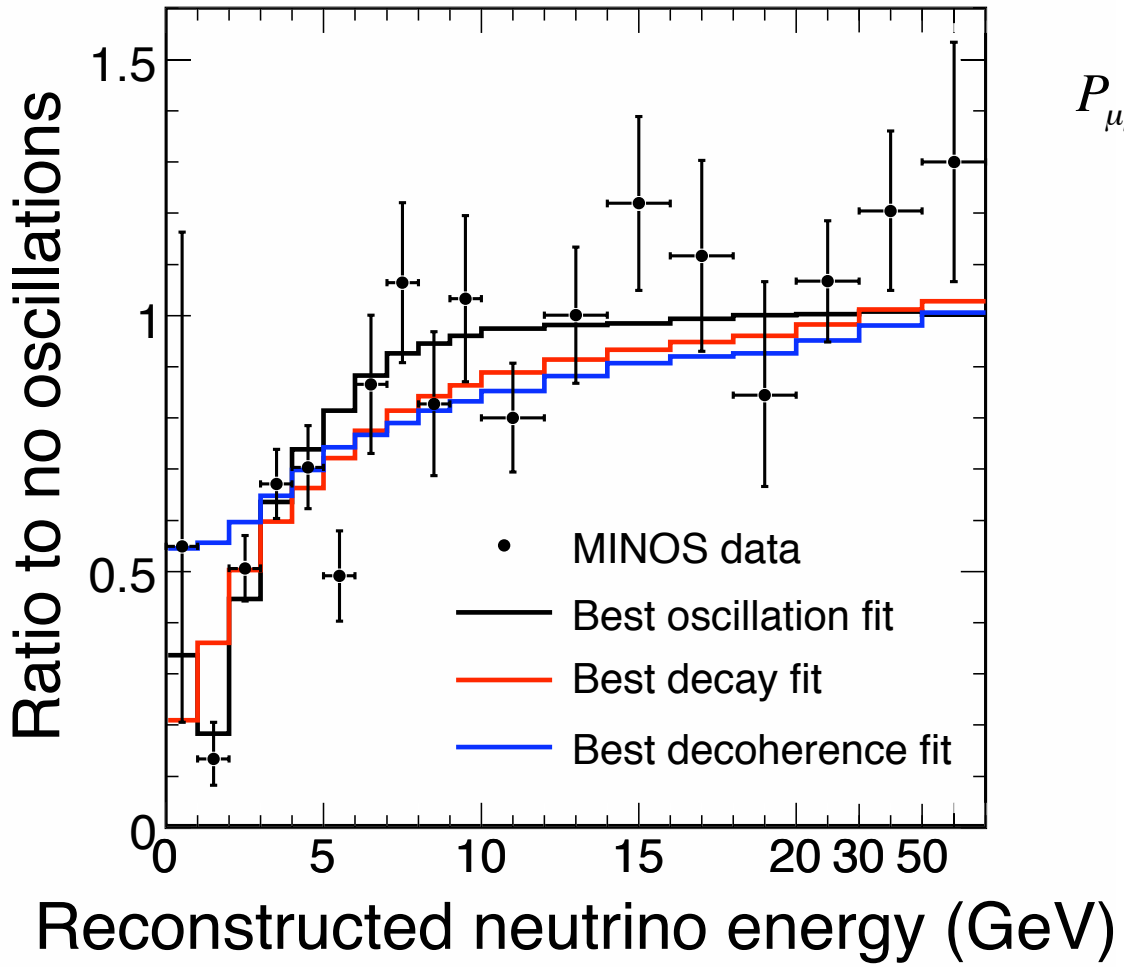

Decay:

$$P_{\mu\mu} = (\sin^2\theta + \cos^2\theta \ \exp(-\alpha L/2E))^2$$

V. Barger *et al.*, PRL82:2640(1999)

χ^2/ndof = 104/97

$\Delta\chi^2$ = 14

disfavored at 3.7σ

Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006 (2003)

χ^2/ndof = 123/97

$\Delta\chi^2$ = 33

disfavored at 5.7σ

Data Sensitivity

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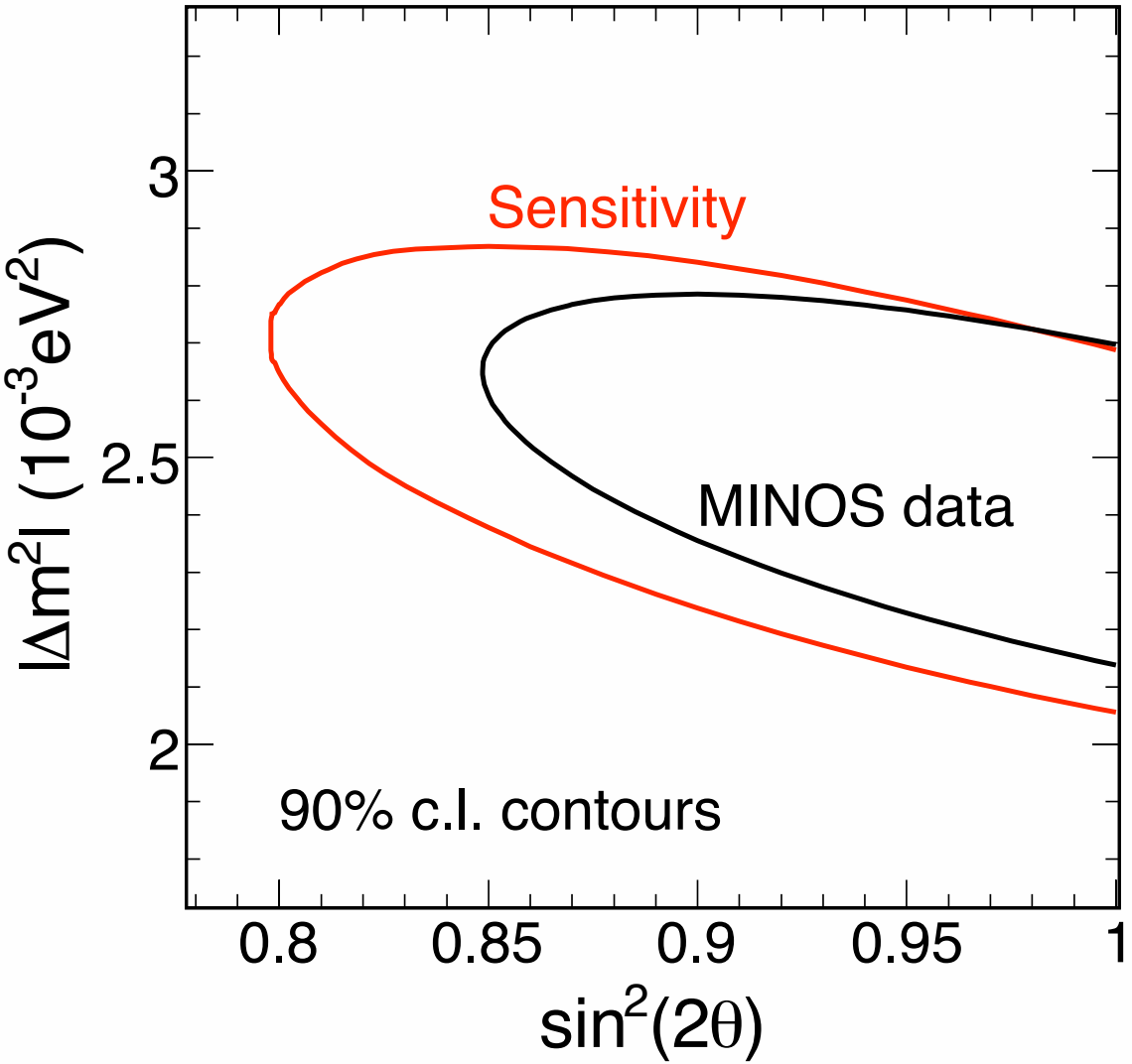

For a true value at the best fit point of:

$|\Delta m^2| = 2.43 \times 10^{-3}$ eV^2
$\sin^2(2\theta) = 1.00$,

26.5% of unconstrained fits have a fit value of $\sin^2(2\theta) \geq 1.07$.

Neutral Current Analysis

Searching for evidence of oscillations to sterile neutrinos.

Motivation

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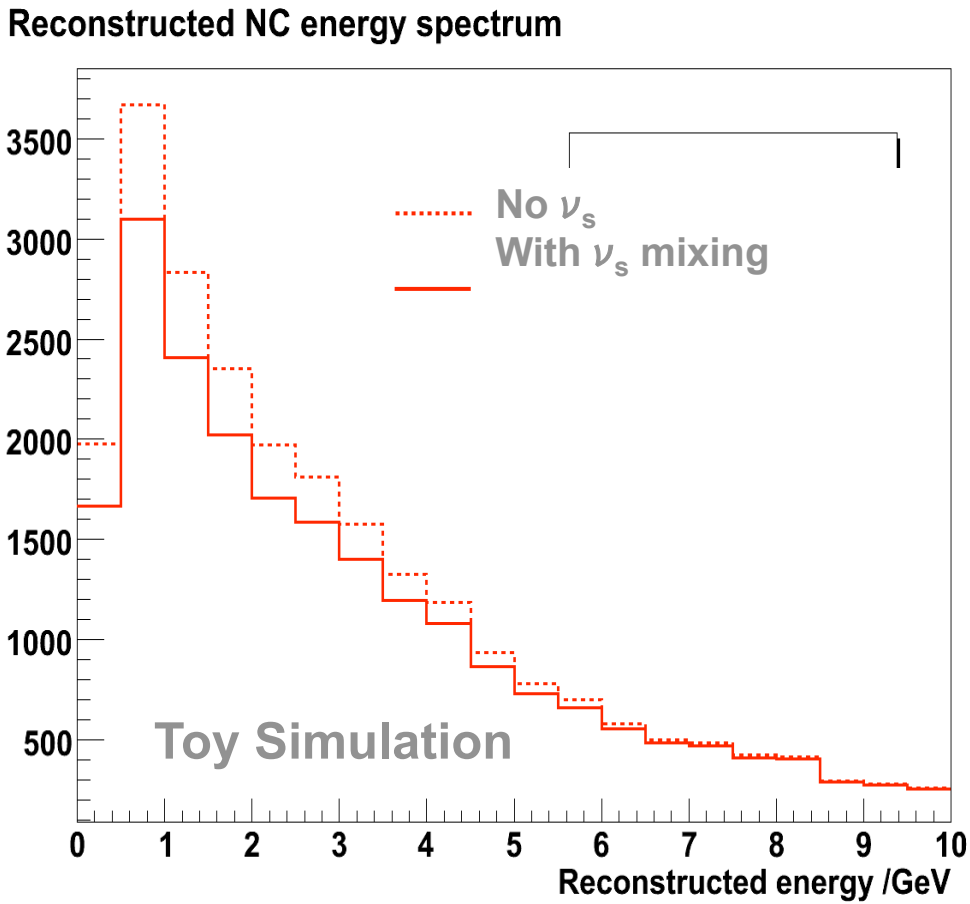
In the standard 3-flavor picture neutrinos are oscillating between ν_e, ν_μ, ν_τ.

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

Alexandre Sousa and Tobias Raufer, "Neutral Current Interactions in MINOS – A Search for Sterile Neutrinos"



Near Detector NC Selection

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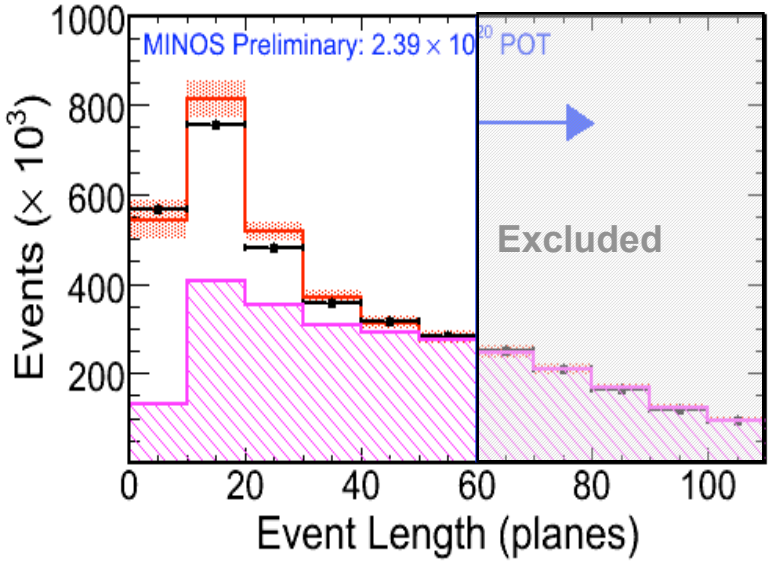

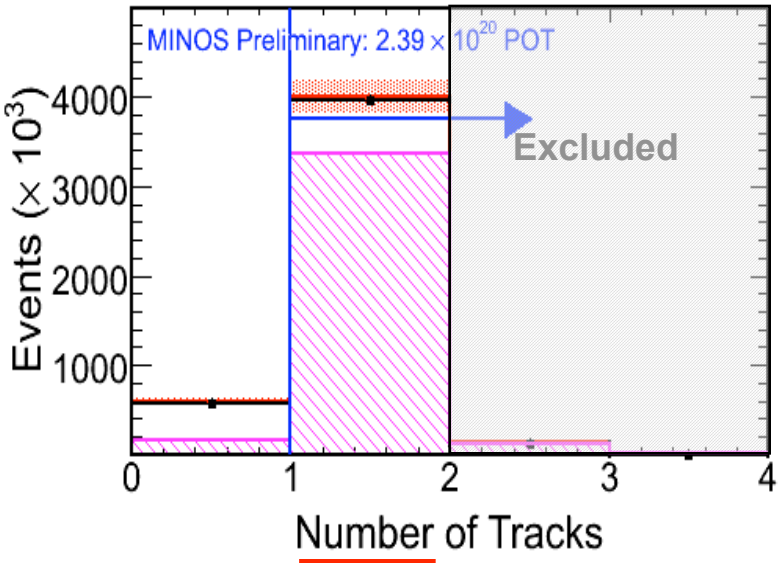

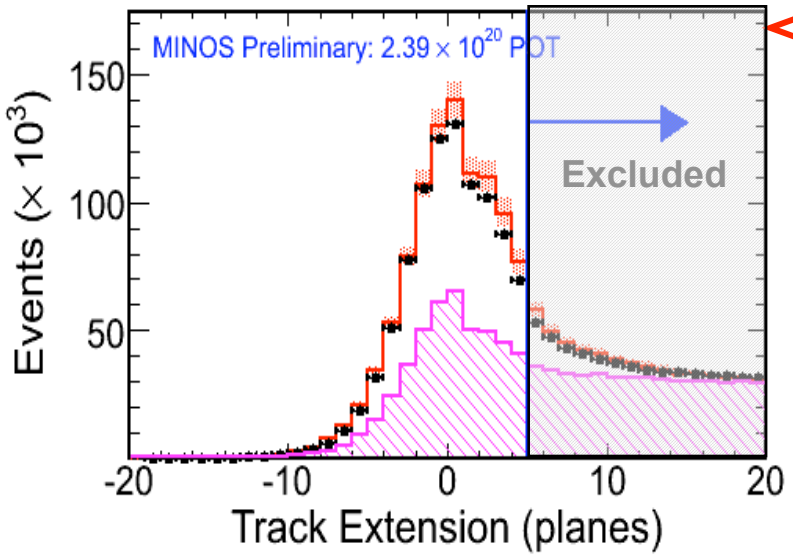

Near Detector Data

Monte Carlo

Monte Carlo CC Background

NC Energy Spectrum

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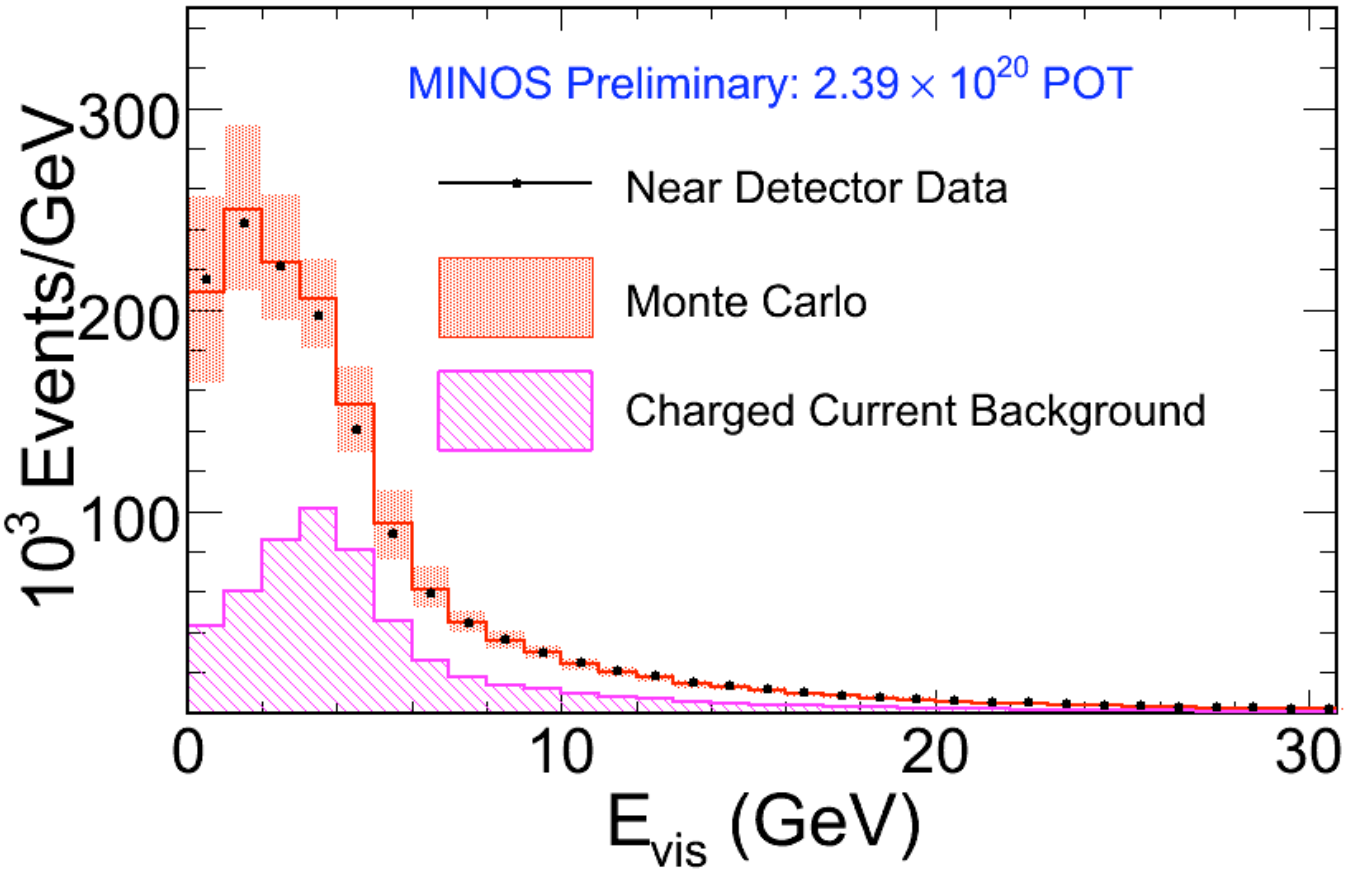
NC selected Data and MC energy spectra for Near Detector



NC events are selected with 90% efficiency and 60% purity

Far Detector NC Selection

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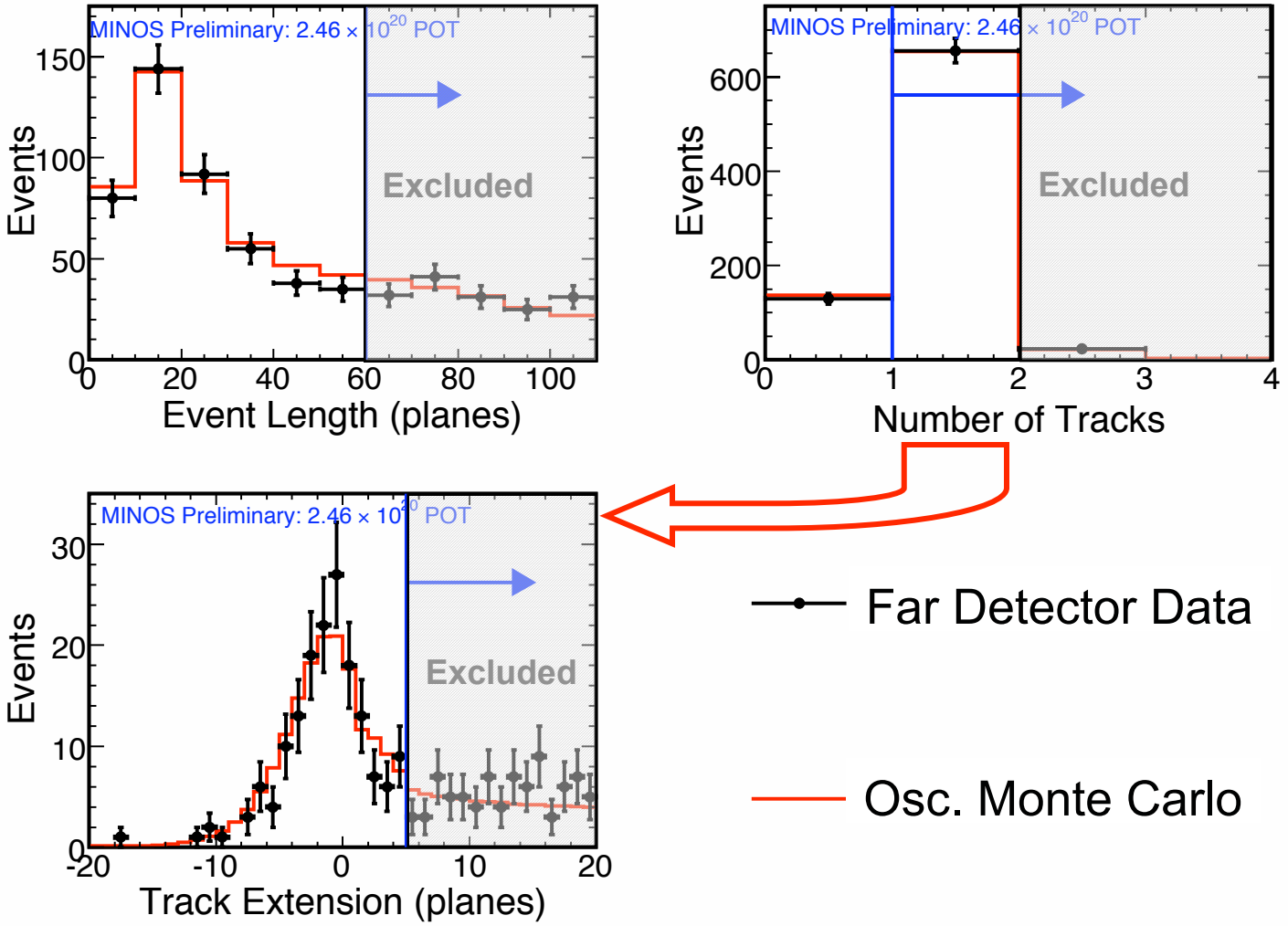
The FD selection uses the same variables as the ND selection, with identical cut values

MC oscillated with 2007 MINOS CC best fit: $\Delta m^2 = 2.38 \times 10^{-3}$ eV^2, $\sin^2(2\theta)=1$



3 Flavor Analysis

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Compare the NC energy spectrum with the expectation of standard 3-flavor oscillation physics.

Pick the oscillation parameter values

- $\sin^2 2\Theta_{23} = 1$
- $\Delta m^2_{32} = 2.38 \times 10^{-3}$ eV^2
- $\Delta m^2_{21} = 7.59 \times 10^{-5}$ eV^2, $\Theta_{12} = 0.61$ from KamLAND+SNO
- $\Theta_{13} = 0$ or 0.21 (normal MH, $\delta = 3\pi/2$) from CHOOZ Limit
- Note that CC ν_e are classified as NC by the analysis

Make comparison in terms of number of events in different energy ranges

- 0-3 GeV
- 0-5 GeV
- All events (0-120 GeV)

Result is #σ (dis-)agreement

Energy Distribution

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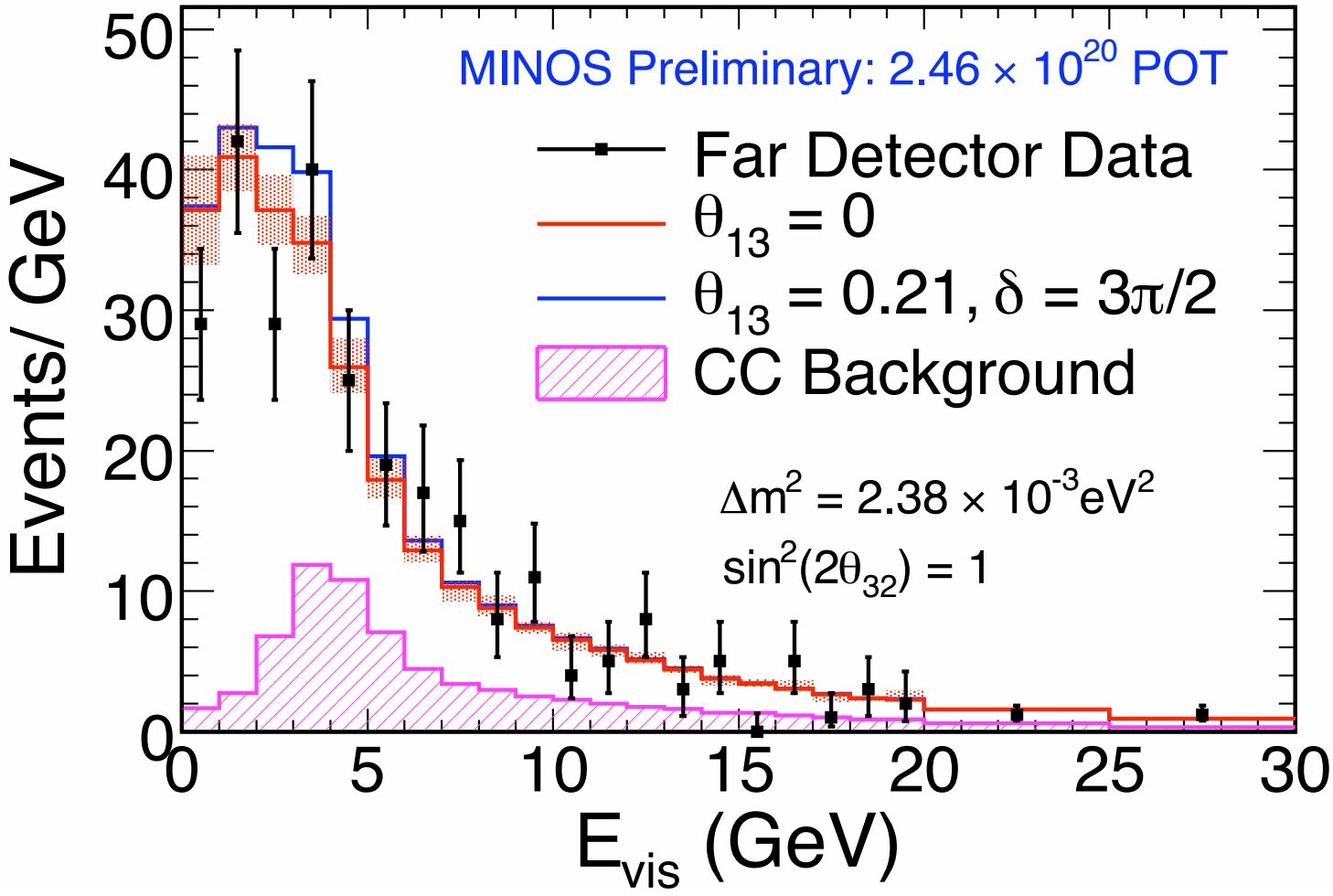
Far Detector reconstructed energy spectra for NC-like events.

Oscillation parameters are fixed. MC predictions with Θ_{13}=0 and Θ_{13} at the CHOOZ limit are shown.



Results and Significance

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Comparisons between observed Data and MC Prediction (for θ_{13}=0)

Energy Range (GeV)	Data	MC	Significance (σ)
0-3	100	115.16 ± 7.67	1.15
0-5	165	175.92 ± 10.42	0.65
0-120	291	292.63 ± 15.02	0.10

The data-MC difference is slightly larger for θ_{13} at the Chooz limit.

For E_{vis}< 3 GeV the fraction of neutral current events that disappear is less than 35% at 90% CL.

For E_{vis}< 120 GeV the fraction of neutral current events that disappear is less than 17% at 90% CL.

ν_e Appearance Future Prospects

ν_e Appearance

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Search for ν_e appearance in a beam that is 98.7% ν_μ.

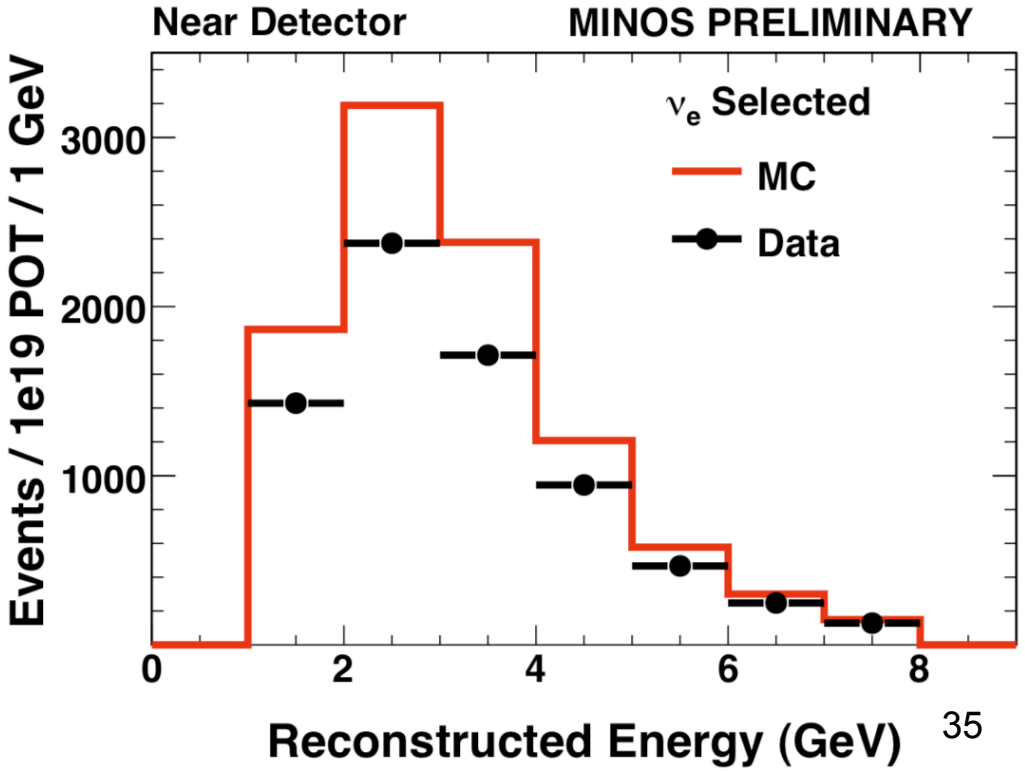
Select ν_e CC in the near and far detector with a neural network.

ND measures a mix of beam ν_e, NC and ν_μ CC events.

Solution: use two independent data driven methods to estimate NC and CC ν_μ backgrounds

Josh Boehm, "Electron Neutrino Appearance in the MINOS Experiment"

J. Pedro Ochoa, "Electron Neutrino Background Analysis with the MINOS Near Detector"



ν_e Sensitivity

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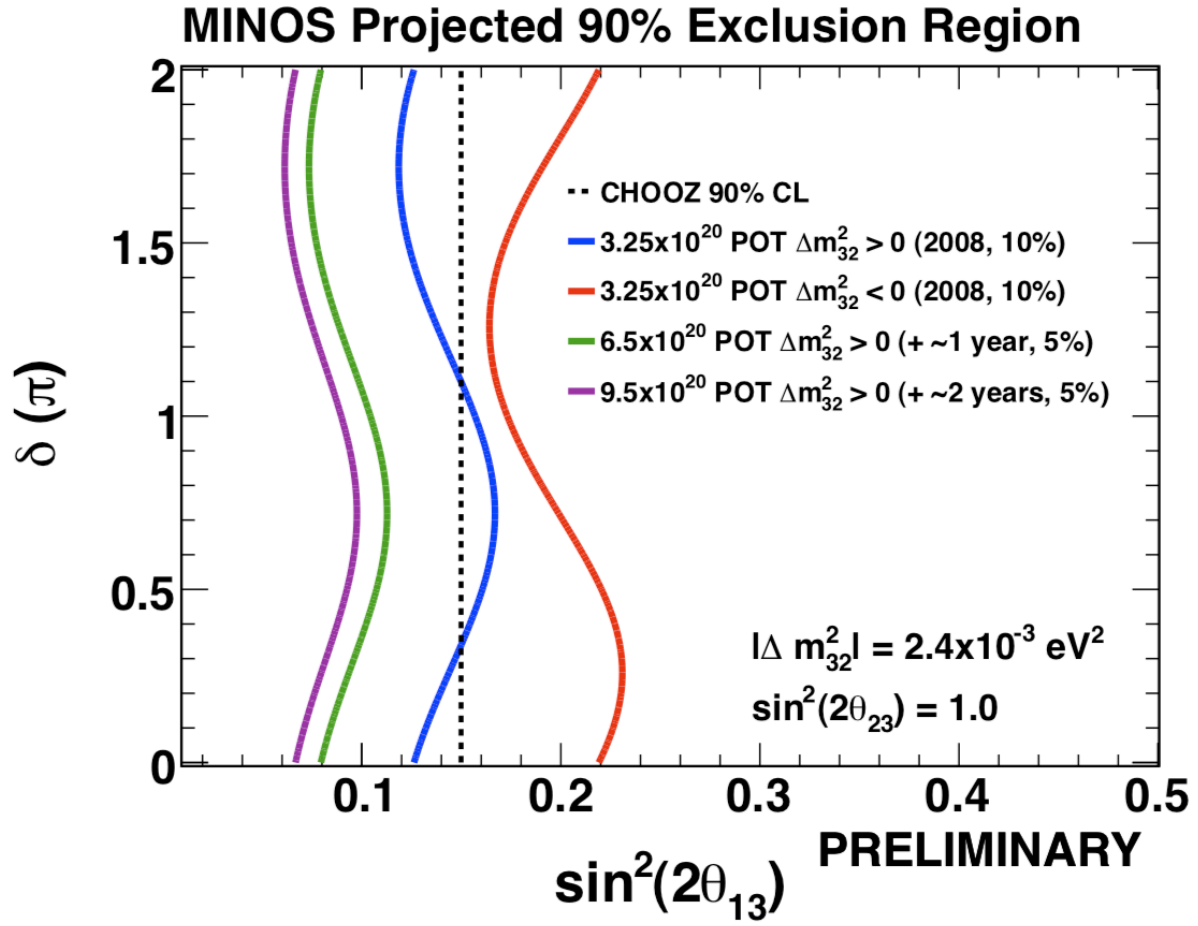

At CHOOZ limit expect 12 ν_e signal events and 42 background events with 3.25×10^{20} protons.

Use sidebands to study predicted far detector backgrounds.

Other Analyses

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Neutrino Interaction physics measurements in ND:

- m_A extraction from quasi-elastic events
- Inclusive CC cross section and structure functions
- NC coherent scattering on iron

Anti-neutrino oscillation measurements

Lorentz violation measurements in ND

Atmospheric neutrinos

Cosmic rays → Alec Habig, "Cosmic Ray Studies with the MINOS Detectors"

Conclusions

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The MINOS Experiment has made a new measurement of the atmospheric neutrino oscillation parameters for 3.36 x10^{20} POT:

$$|\Delta m|^2 = (2.43 \pm 0.13) \times 10^{-3}\ eV^2 \quad (68\%\ C.L.)$$
$$\sin^2(2\theta) > 0.90 \quad (90\%\ C.L.)$$

From an analysis of CC events, decay and decoherence are **disfavored at 3.7 and 5.7 standard deviations**, respectively.

From an analysis of neutral current events in the Far Detector for an exposure of 2.46×10^{20} POT, **the fraction of NC events that disappear is less than 0.17 at 90% CL**.

First results on ν_e appearance are expected later this year and have sensitivity below the Chooz limit. Other ND-only results expected later this year also.

Acknowledgments

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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 and to the crew of the Soudan Underground Laboratory for their efforts.

We also gratefully acknowledge financial support from the US DOE and NSF; the UK STFC; the State and University of Minnesota; the University of Athens, Greece and Brazil's FAPESP and CNPq.

EXTRAS

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The MINOS Detectors

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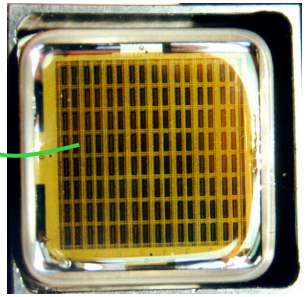
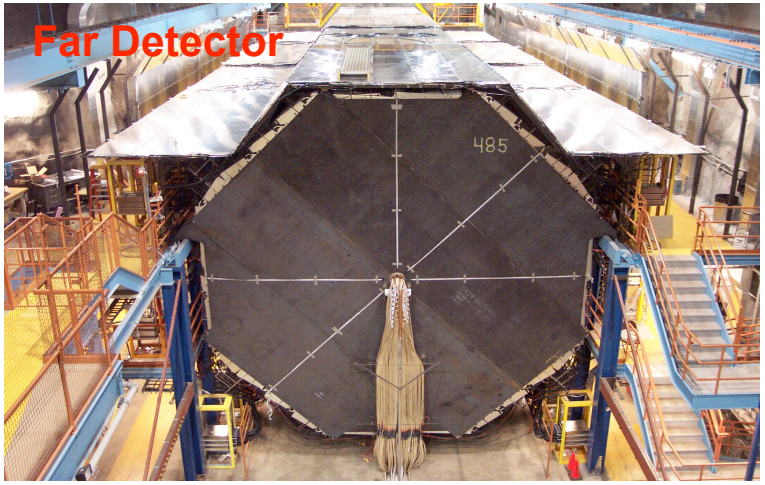
Functionally equivalent detectors:

- 2.54 cm thick magnetized steel plates
- 4.1 x 1 cm co-extruded scintillator strips (MINOS developed technology)
- optical fiber readout to multi-anode PMTs

Hamamatsu M-64





- 5.4 kton
- 8 x 8 x 30 m
- 484 steel/scintillator planes
- M16 PMT, x8 multiplexing
- VA electronics

- 1 kton
- 3.8 x 4.8 x 15 m
- 282 steel, 153 scintillator planes
- M64 PMT
- Fast QIE electronics

Hadron Production Tuning

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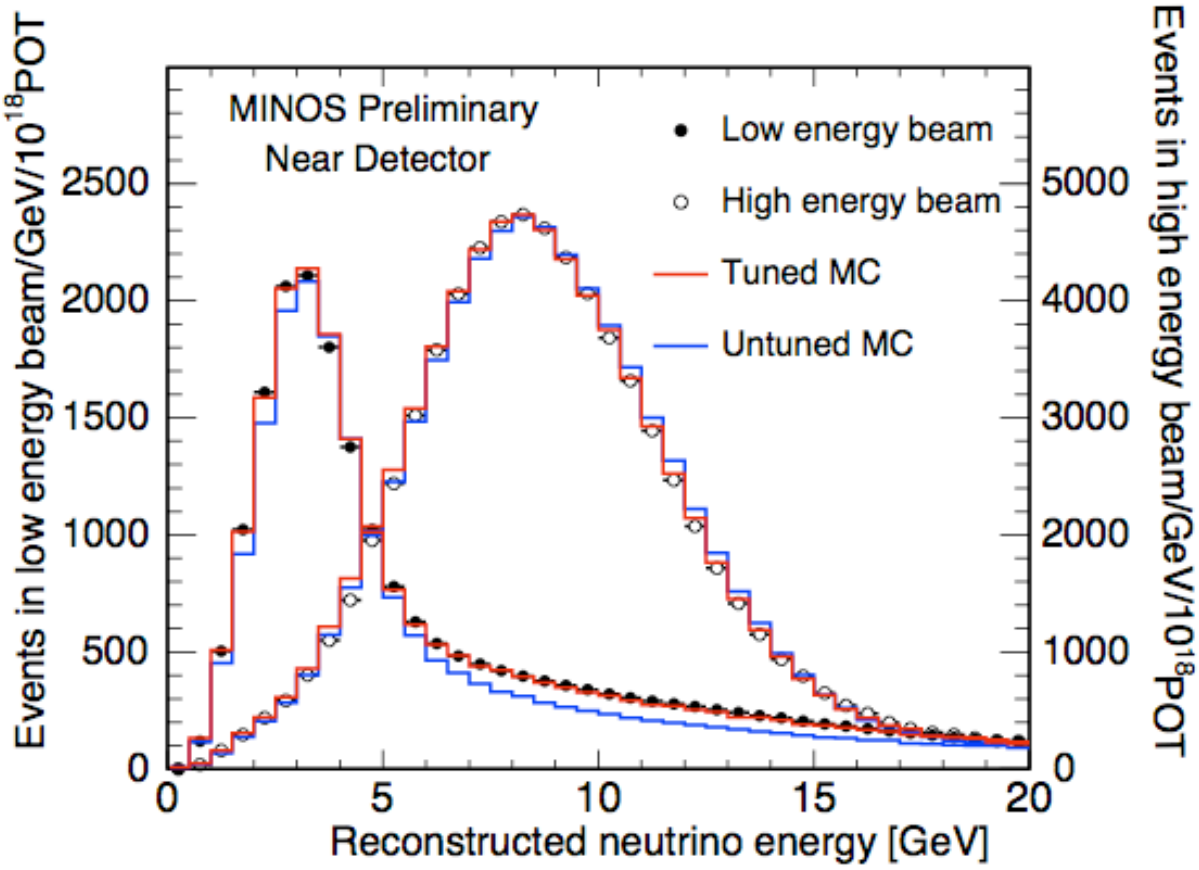
Hadron production from the NuMI target has substantial uncertainties.

Fit CC data taken in nine different beam configurations (target position / horn current) to improve the hadron production model.



This fit reweights events based on a parametrization of the Fluka2005 prediction as a function of hadron x_F and p_T.

This procedure reduces uncertainties in the flux prediction at the Far Detector.

42

Near Detector

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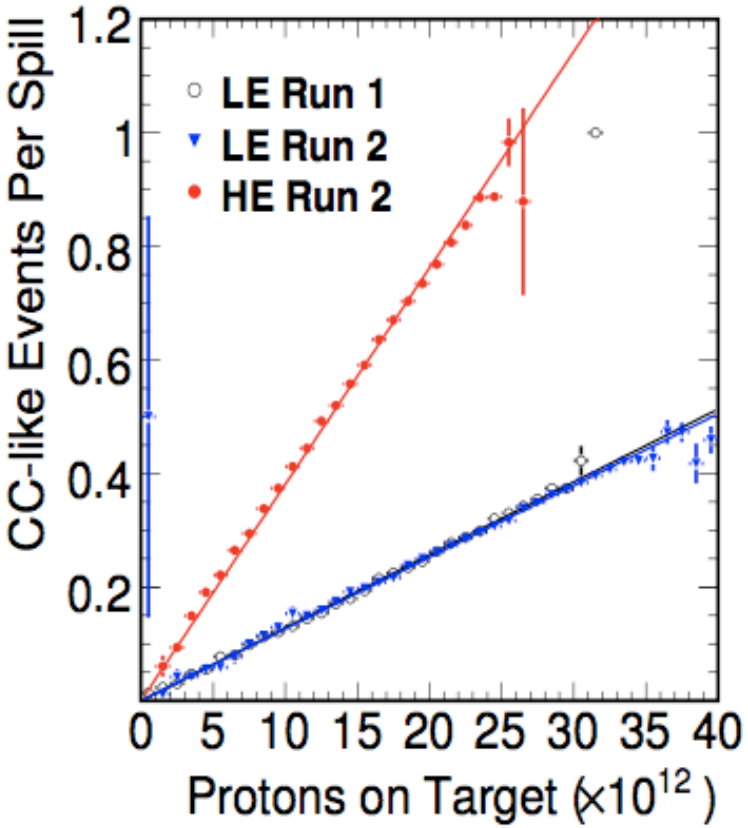
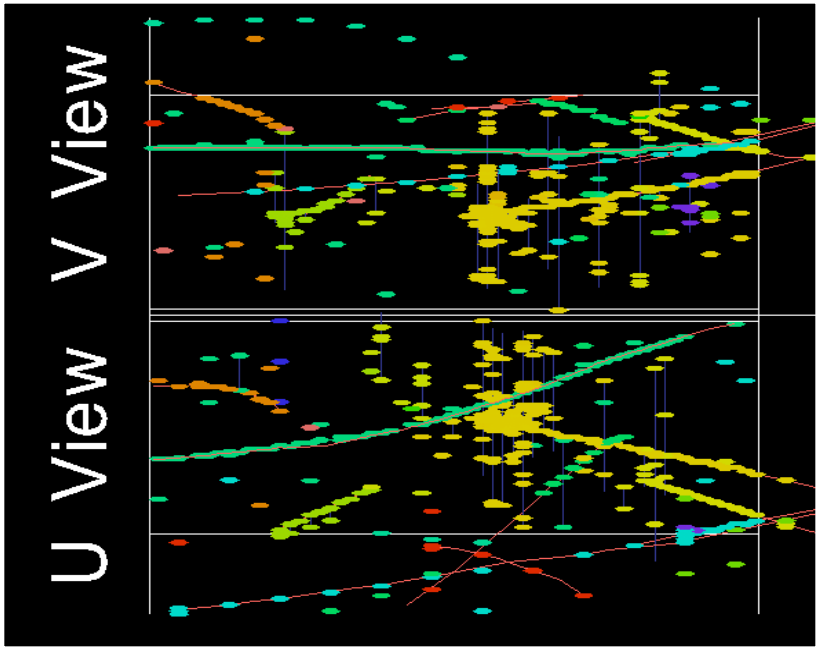
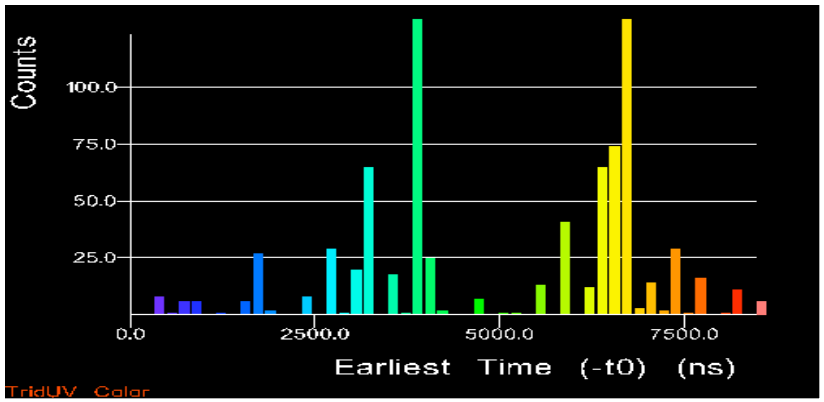
Multiple events per spill are separated based on topology and timing.







CC Event Selection

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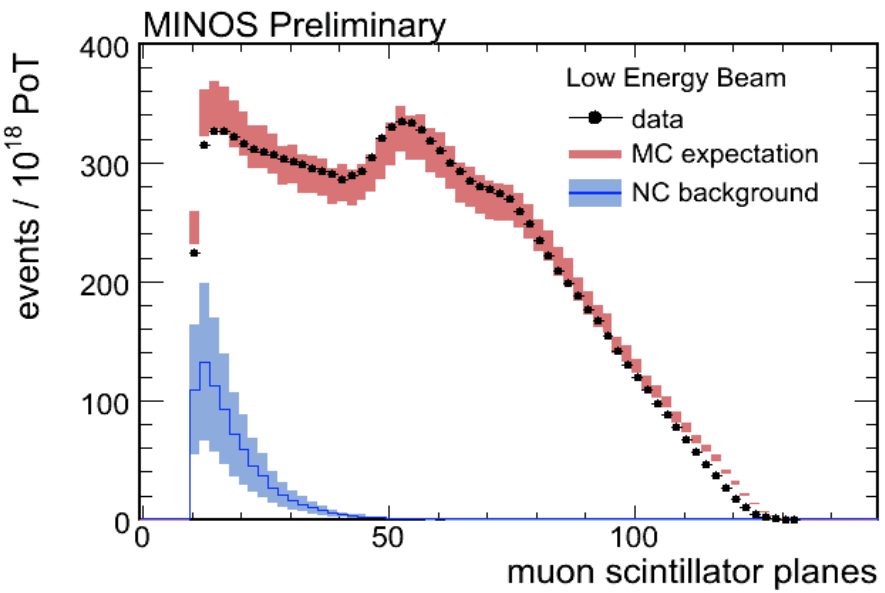

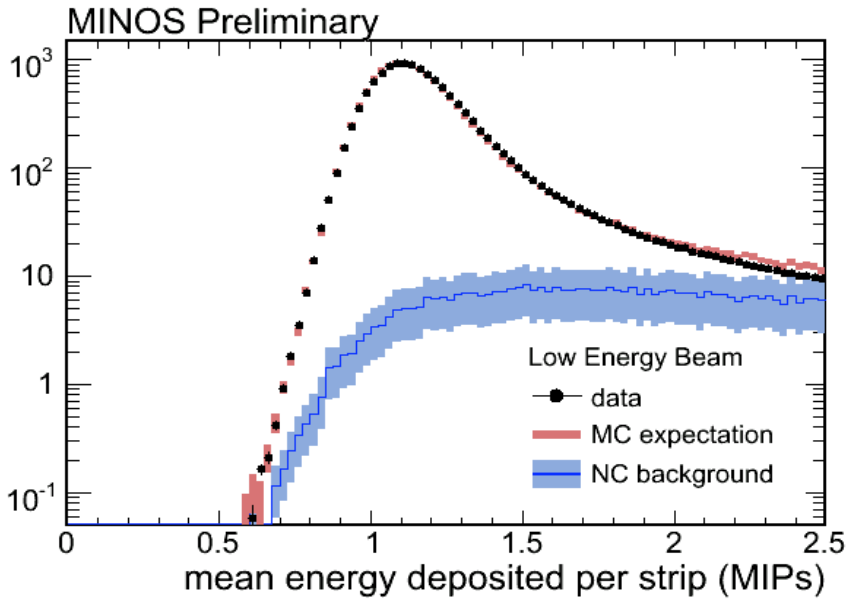

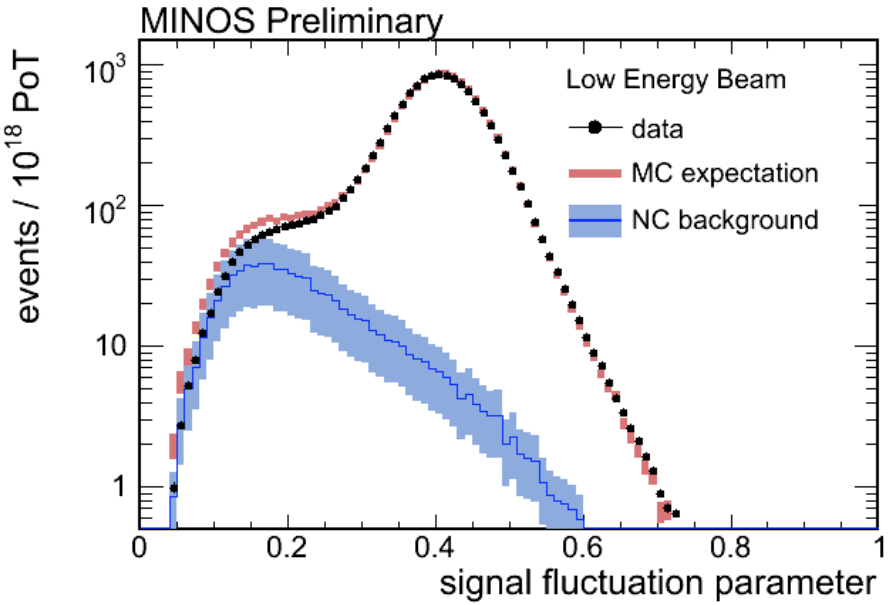

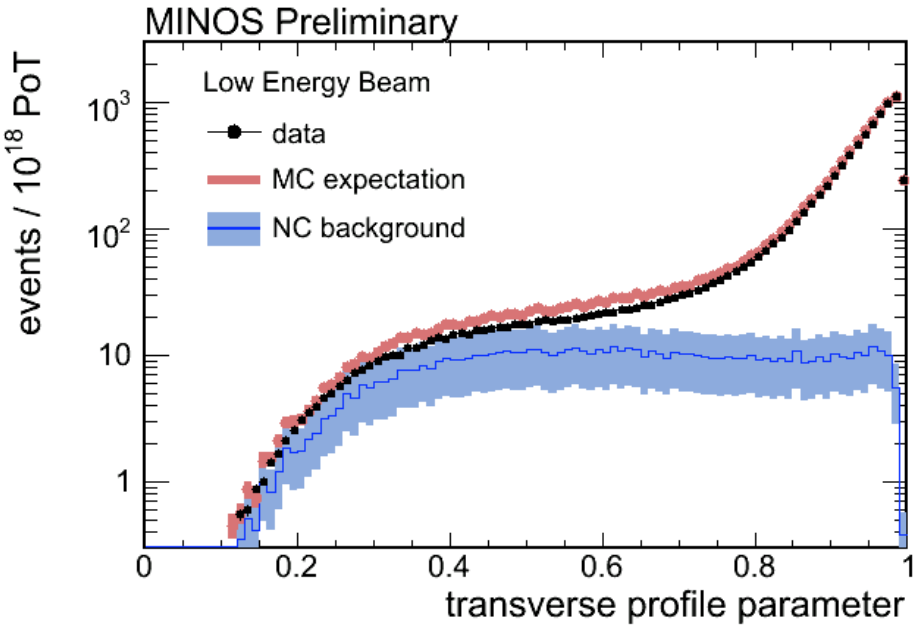

Far Detector NC Data Quality

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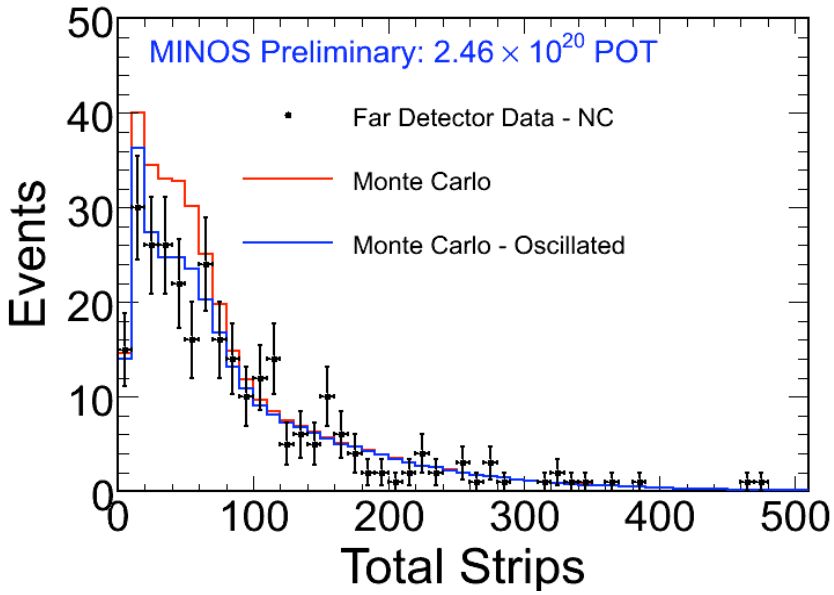

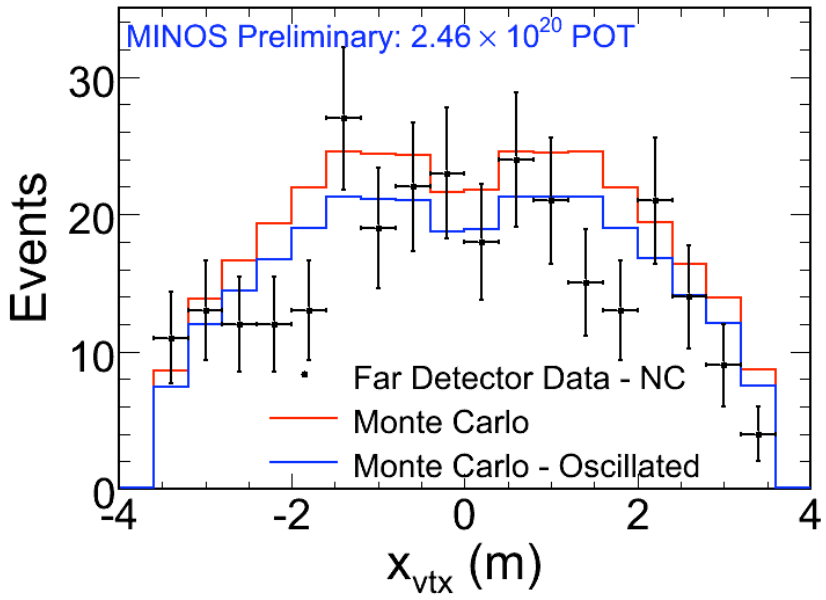

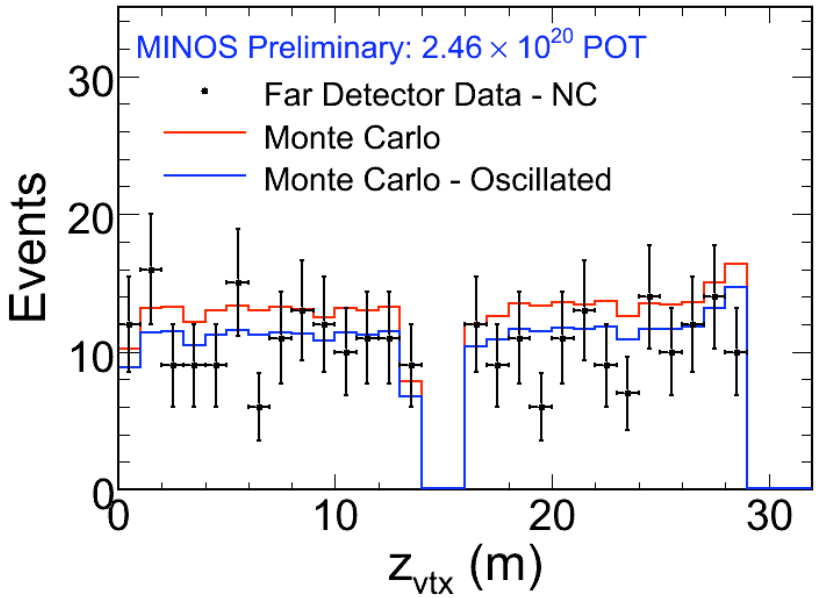

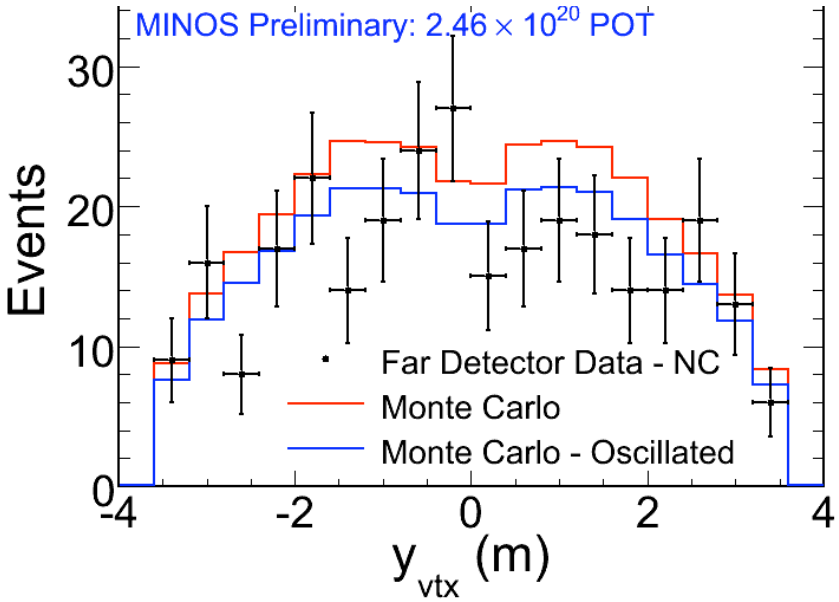

Comparison with 2006 Result

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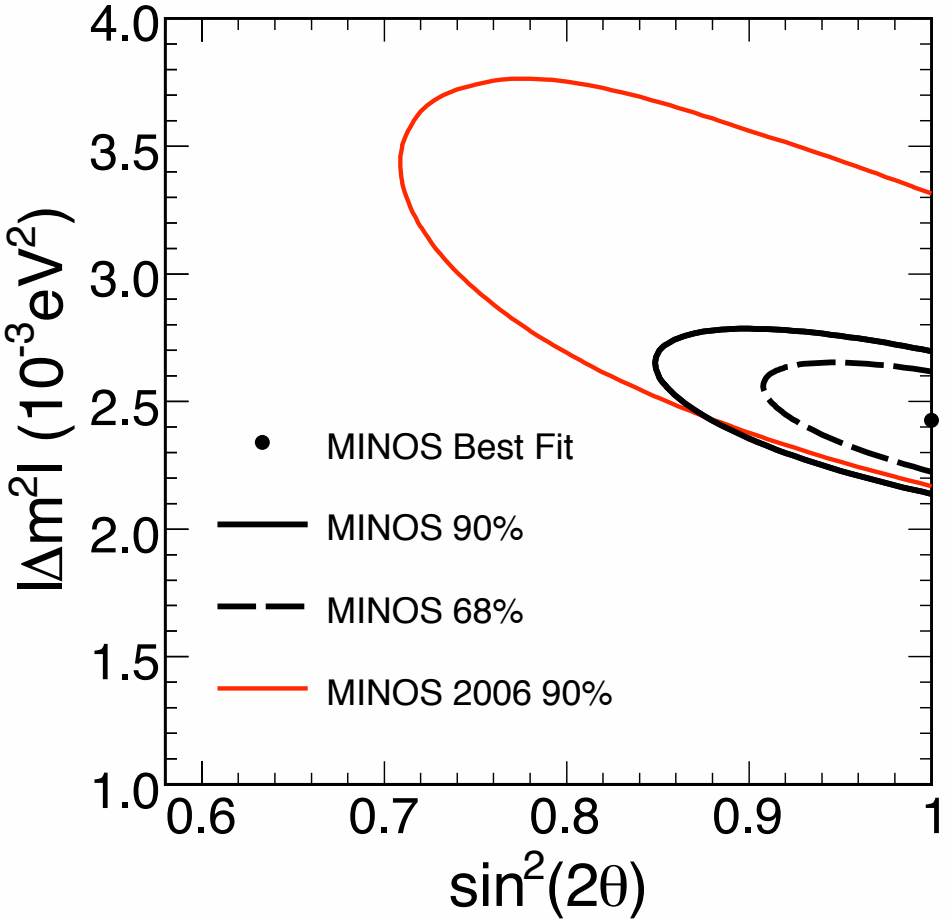

Run I: $|\Delta m^2| = (2.57^{+0.19}_{-0.20}) \times 10^{-3}$ eV^2, $\sin^2(2\theta) = 1.0$

Run II: $|\Delta m^2| = (2.32^{+0.15}_{-0.16}) \times 10^{-3}$ eV^2, $\sin^2(2\theta) = 1.0$

Improved:
- Reconstruction
- Monte Carlo
- Analysis

CC Systematics

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Uncertainty	Δm^2 (10^{-4} eV^2)	$\sin^2 2\theta$
Near/Far normalization ± 4%	**0.43**	**0.004**
Muon momentum scale (range ± 2%, curvature ± 3%)	0.32	0.004
Absolute hadronic energy scale (±10.3%)	**0.67**	**0.003**
Near/Far shower energy scale ± 3.3%	0.35	0.006
NC contamination ± 50%	**0.20**	**0.017**
CC cross-section uncertainties	0.12	0.004
Beam uncertainties	0.25	0.005
Total Systematic (summed in quadrature)	0.96	0.019
Expected Statistical sensitivity	1.9	0.09

NC Disappearance Fraction

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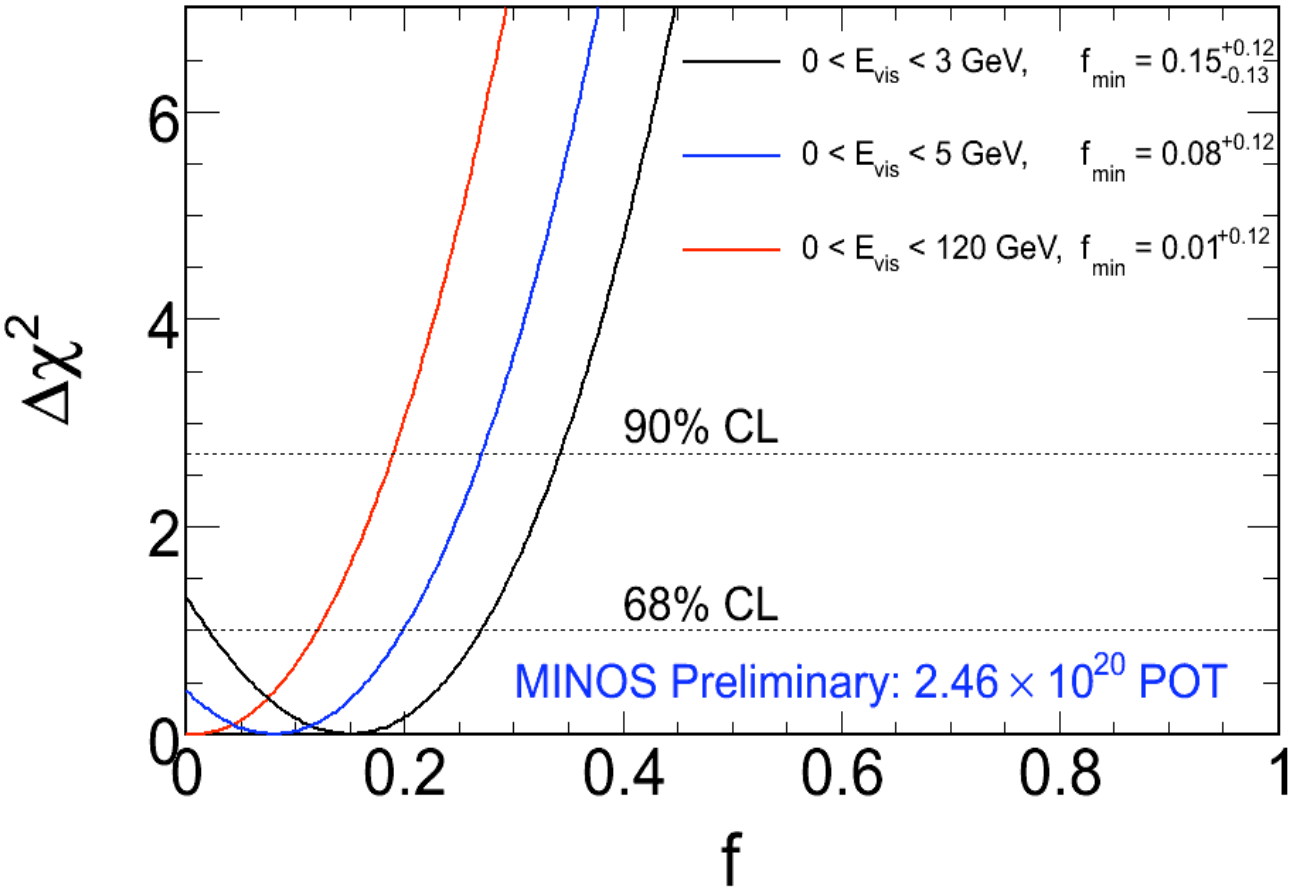
The expected total number of events is given by

$$MC = NC\,(1 - \boldsymbol{f}) + CC\,\nu_\mu + CC\,\nu_e + CC\,\nu_\tau\,,$$

where ***f*** is the fraction of total neutral current events that disappear

Calculate χ^2 for values of ***f*** between 0 and 1 (fixed $\Theta_{13} = 0$)



For E_{vis} < 3 GeV:
f < 0.35, 90% C.L.

For E_{vis} < 120 GeV:
f < 0.17, 90% C.L.

Calibration

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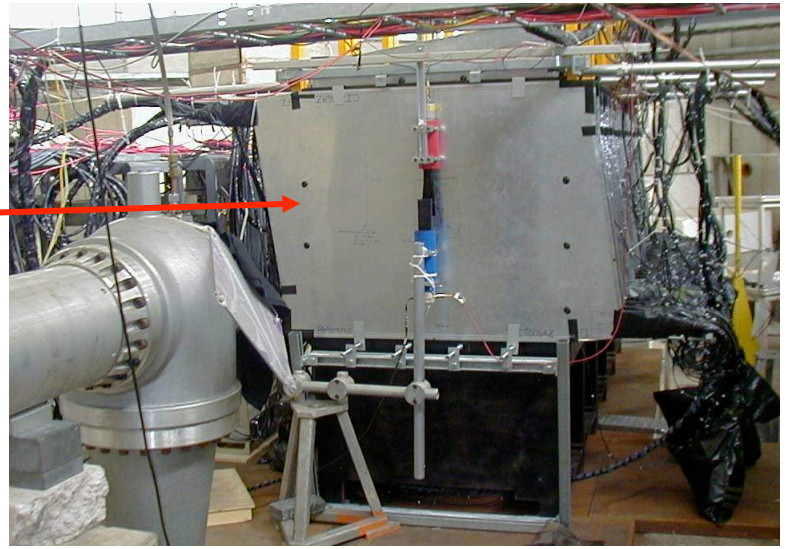
- Help understand energy response to reconstruct E_ν

$$E_\nu = p_\mu + E_{had}$$

- Measured in a CERN test beam with a "mini-Minos"
  - operated in both Near and Far configurations
  - Study e/μ/hadron response of detector
  - Test MC simulation of low energy interactions
  - **Provides absolute energy scale for calibration**



Calibration of ND and FD response using:

Light Injection system (PMT gain)

Cosmic ray muons (strip to strip and detector to detector)

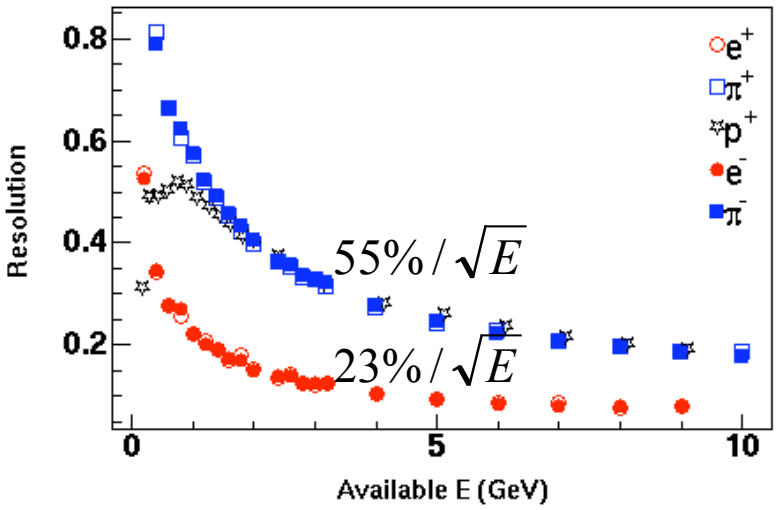
Calibration detector (overall energy scale)

Energy scale calibration:

2% error on relative N/F calibration

5.7% absolute energy calibration

Single particle energy resolution



NC Systematic Errors

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- **Normalization**: ±4%
  - POT counting, Near/Far reconstruction efficiency, fiducial mass
- **Relative Hadronic Calibration:** ±3%
  - Inter-Detector calibration uncertainty
- **Absolute Hadronic Calibration:** ±11%
  - Hadronic Shower Energy Scale(±6%), Intranuclear rescattering(±10%)
- **Muon energy scale:** ±2%
  - Uncertainty in dE/dX in MC
- **CC Contamination of NC-like sample:** ±15%
- **NC contamination of CC-like sample:** ±25%
- **Cross-section uncertainties:**
  - m_A (qe) and m_A (res): ±15%
  - KNO scaling: ±33%
- **Poorly reconstructed events:** ±10%
- **Near Detector NC Selection:** ±8% in 0-1 GeV bin
- **Far Detector NC Selection:** ±4% if E < 1 GeV, <1.6% if E > 1 GeV
- **Beam uncertainty:** 1σ error band around beam fit results

Event Rate/Spectrum Stability

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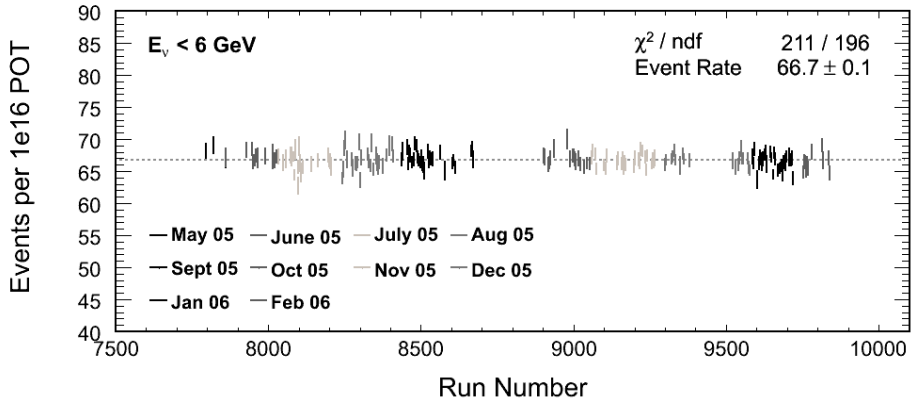
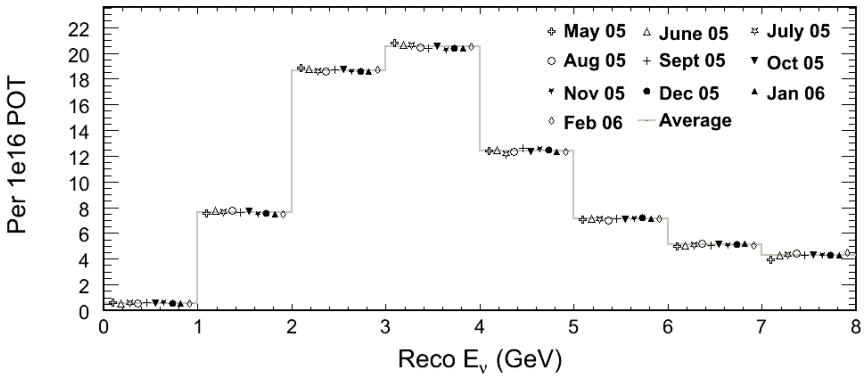
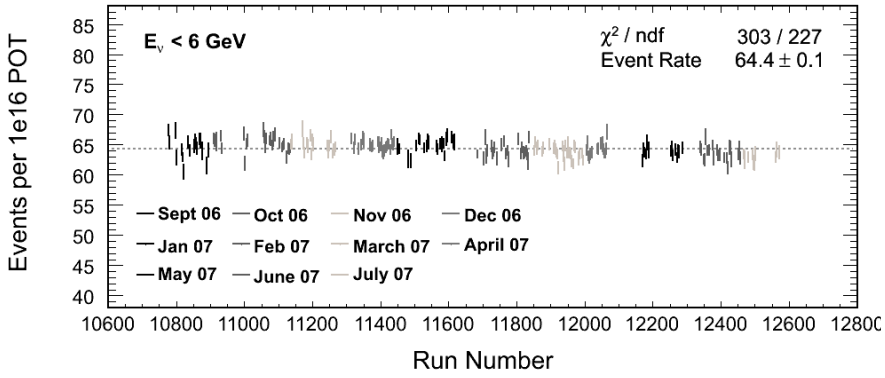
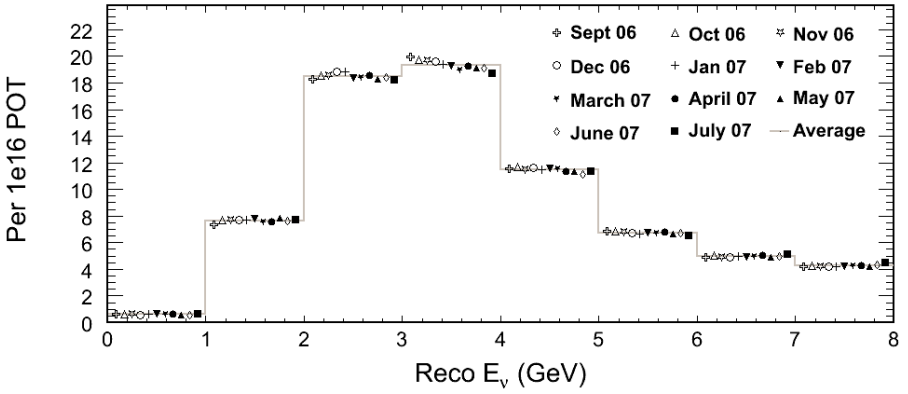
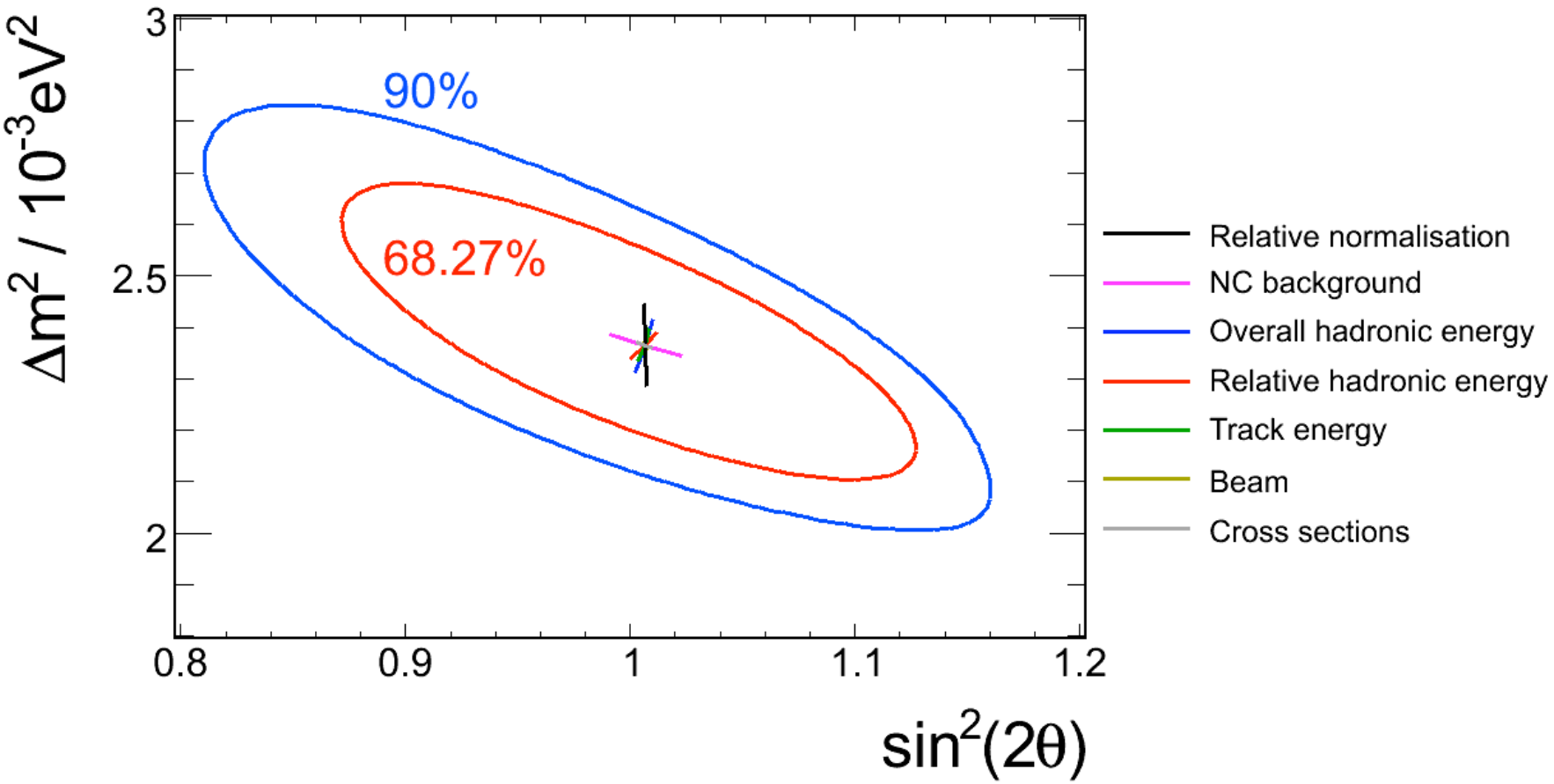








Systematic errors on statistical sensitivity

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