Latest Results from The MINOS Experiment

Andy Blake, Cambridge University
(for the MINOS collaboration)

International Conference on Topics in Astroparticle and Underground Physics.

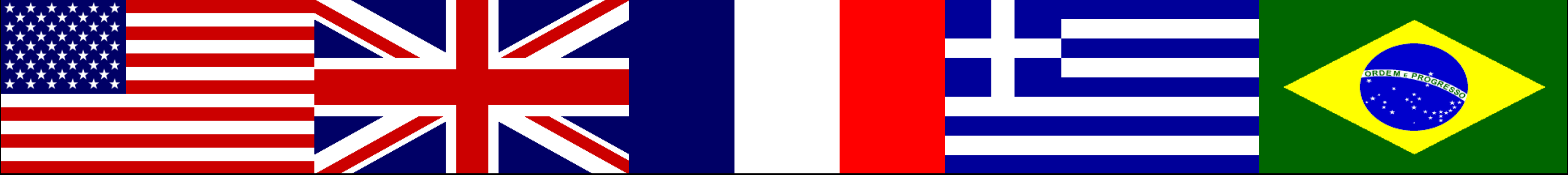
Sendai, Japan – September 2007.

MINOS Physics Goals

- **Precision studies of ν_μ disappearance.**
  - Measure Δm^2_{23} and $\sin^2 2\theta_{23}$ **PRL 97, 191801 (2006).**
  - High statistics constraints on alternative disappearance models. (e.g. neutrino decay, neutrino decoherence, sterile neutrinos …).
- **Search for sub-dominant ν_e appearance.**
  - First observation or improved limit for small mixing angle θ_{13}.
- **Atmospheric neutrino oscillations.**
  - Contained vertex ν_μ CC interactions. **PRD 73, 072002 (2006).**
  - Neutrino-induced upward-going muons. **PRD 75, 092003 (2007).**
- **Cosmic ray physics.**
  - Muon charge ratio at TeV energies. **arXiv/0705.3815 [hep-ex].**

This Talk:

- **New preliminary results on ν_μ disappearance based on exposure of 2.5×10^{20} protons on the NuMI target. arXiv/0708.1495 [hep-ex].**
- **New preliminary atmospheric muon and electron neutrino results.**

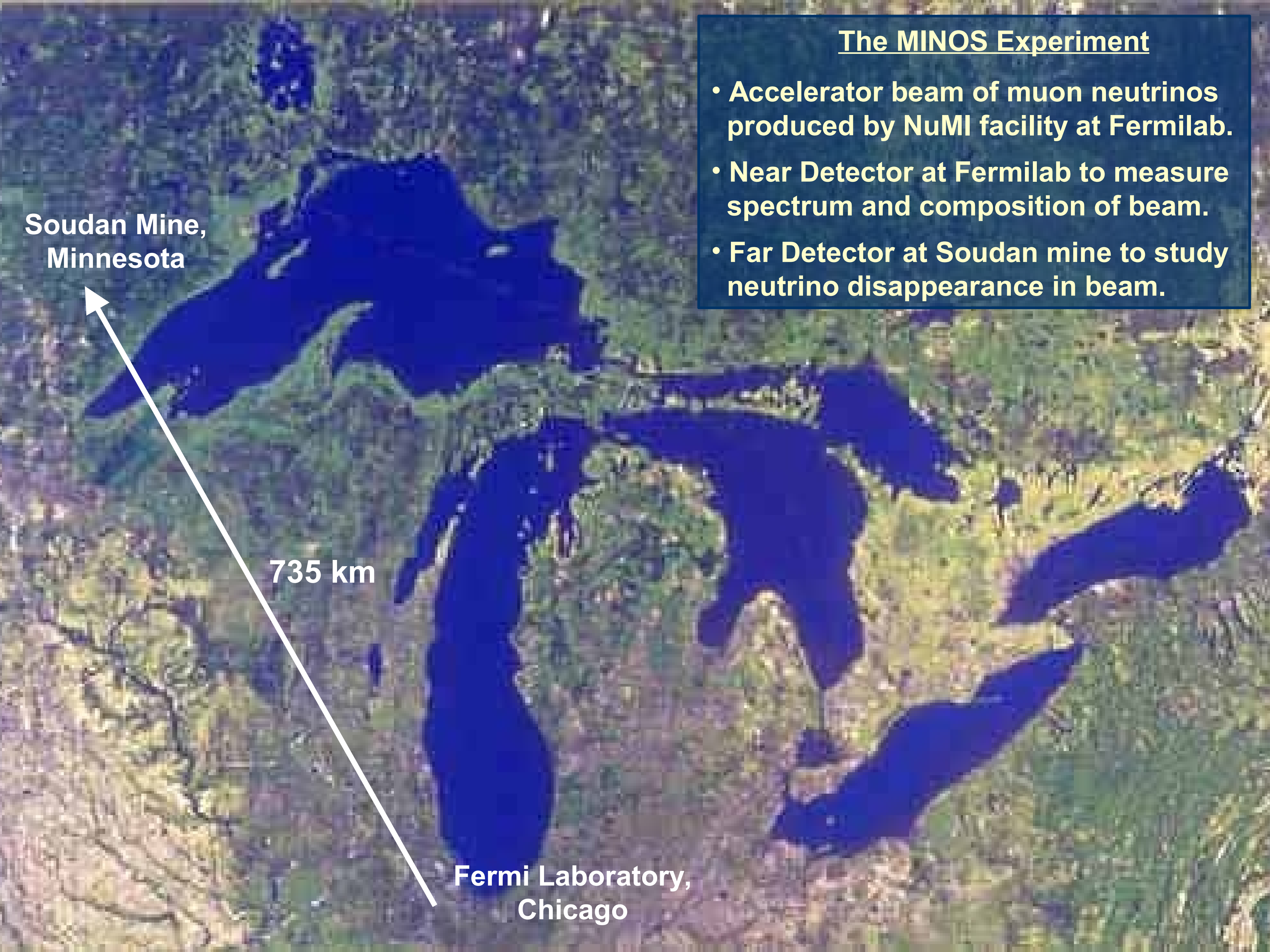


THE MINOS COLLABORATION

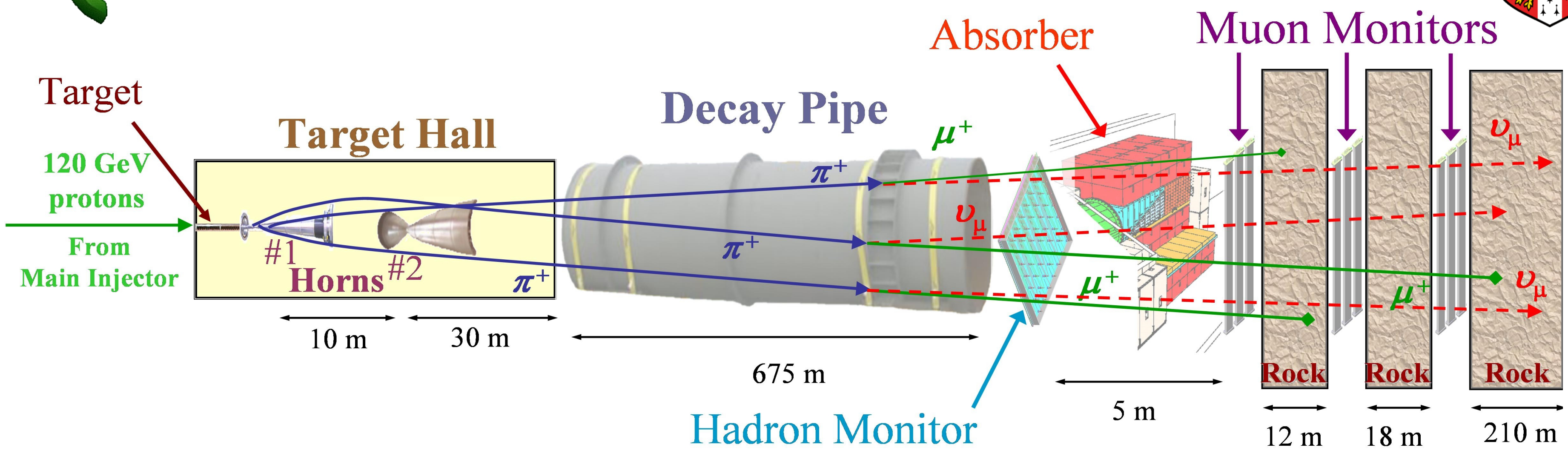
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • College de France
Fermilab • Harvard • IIT • Indiana • Minnesota Duluth • Minnesota Twin Cities • Oxford • Pittsburgh
Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas Austin
Tufts • UCL • William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

The MINOS Experiment

- Accelerator beam of muon neutrinos produced by NuMI facility at Fermilab.
- Near Detector at Fermilab to measure spectrum and composition of beam.
- Far Detector at Soudan mine to study neutrino disappearance in beam.

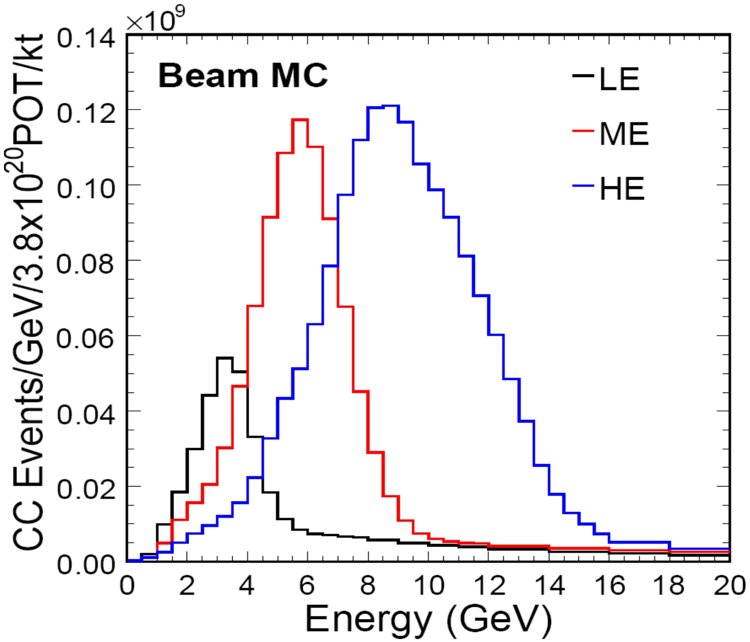


The NuMI Beam

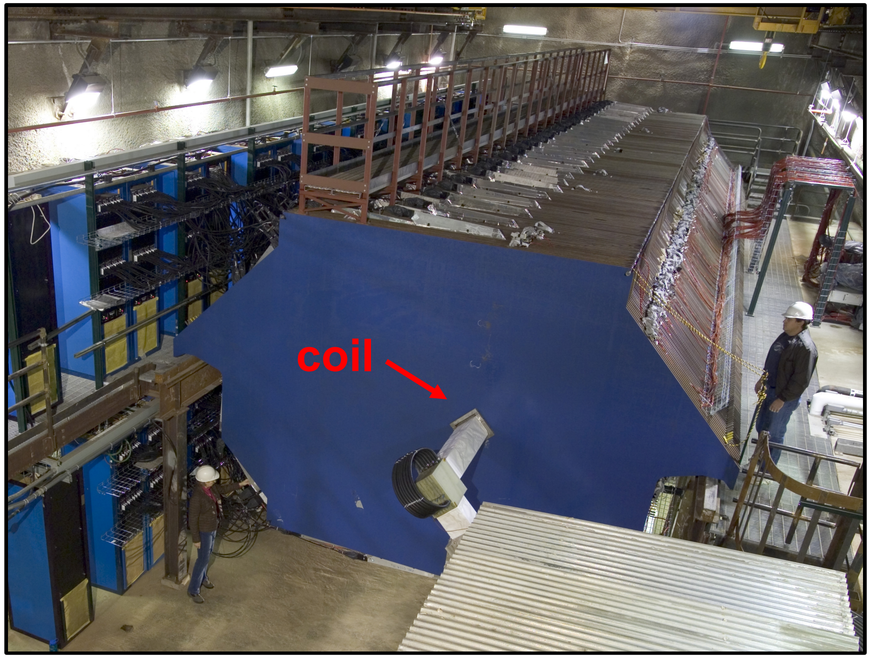


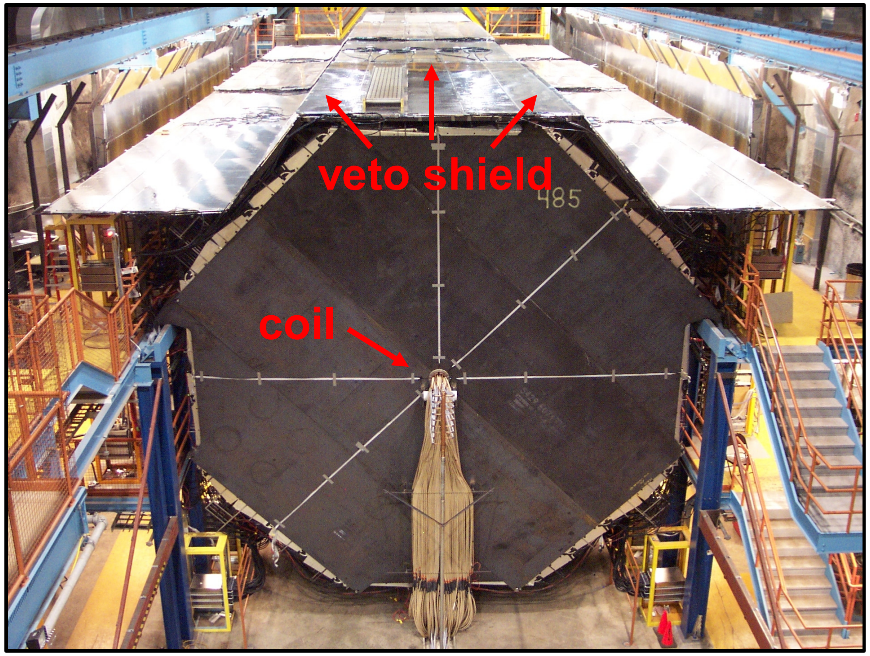
Neutrinos from the Main Injector (NuMI)

- 120 GeV protons from Main Injector directed onto 50g graphite target.
- 10μs spills with 2.4s cycle time.
- 2.5 x 10^{13} protons per pulse.
- Typical beam power ~175 kW.
- Relative target position is moveable, making beam spectrum configurable.
- Majority of running in LE configuration.



The MINOS Detectors





Near Detector

1 kT mass

1 km from target

282 steel planes

153 scintillator planes

100m underground

Functionally Identical Detectors

steel and scintillator sampling calorimeters.

Magnetized steel (B ~1.3T).

GPS time-stamping for synchronization.

Far Detector

5.4 kT mass

735 km from target

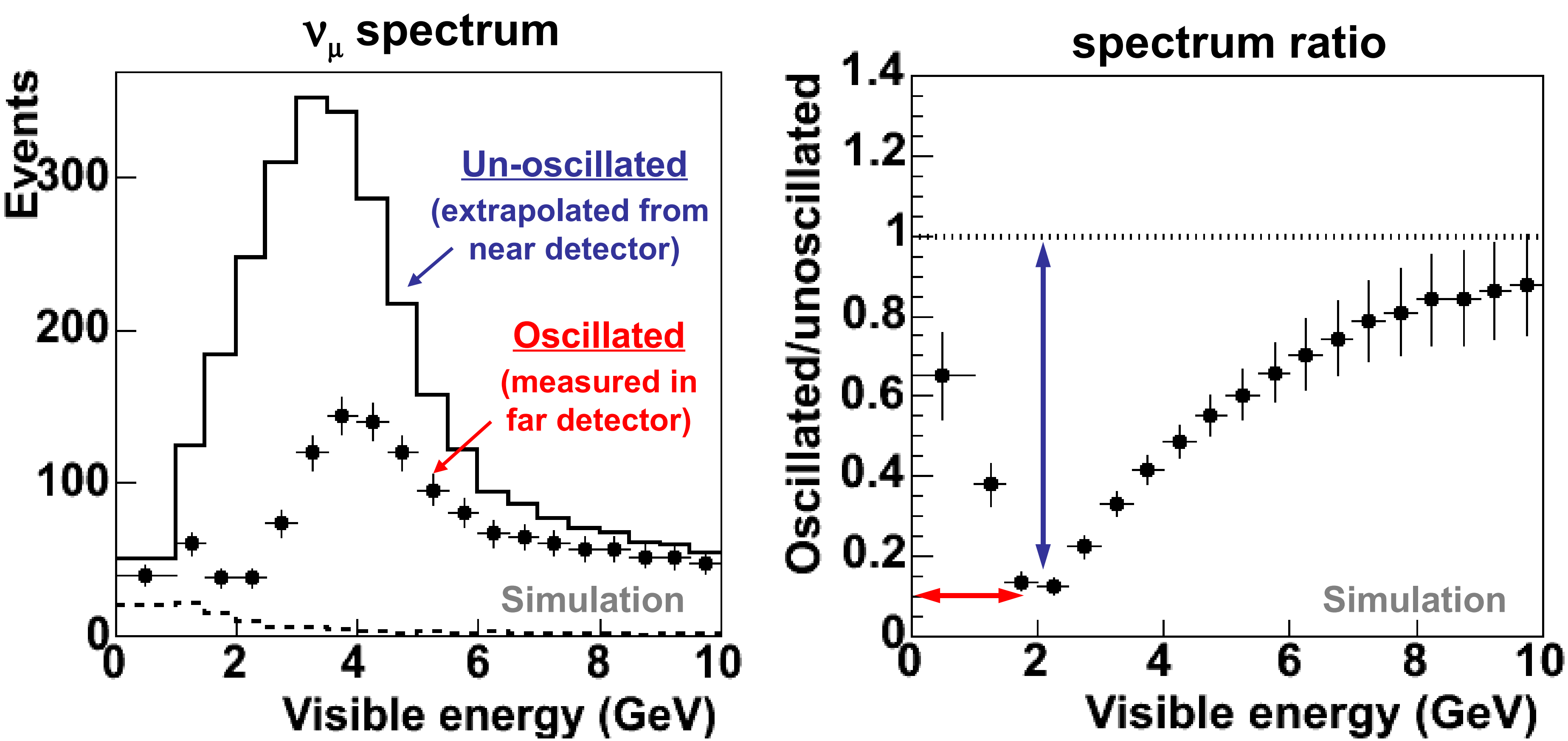
486 steel planes

484 scintillator planes

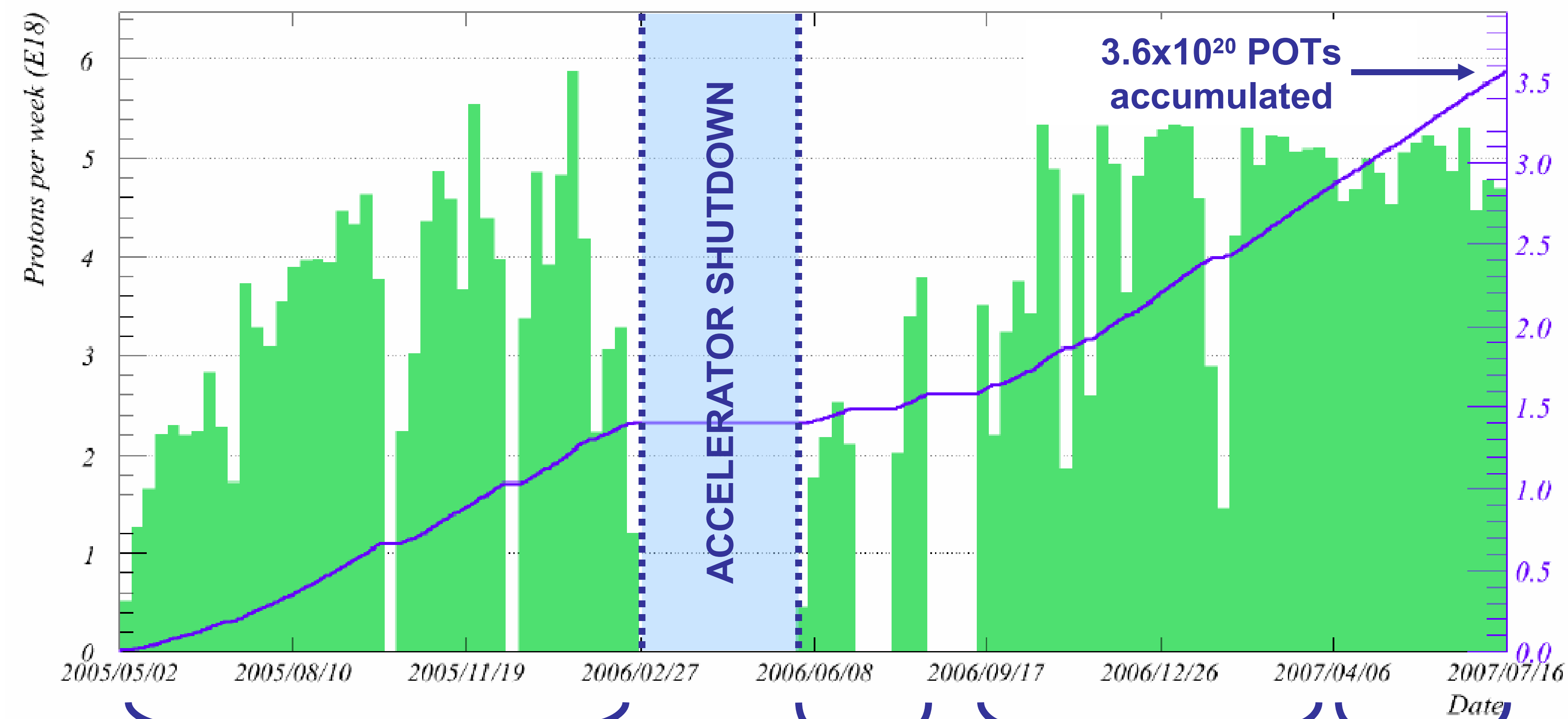
700m underground

ν_μ Disappearance Measurement

Look for ν_μ deficit : $$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E}\right)$$



2+ Years of NuMI Running



RUN I
(1.27x10[20] PoTs)

Higher Energy Runs

RUN IIa
(1.23x10[20] PoTs)

RUN IIb

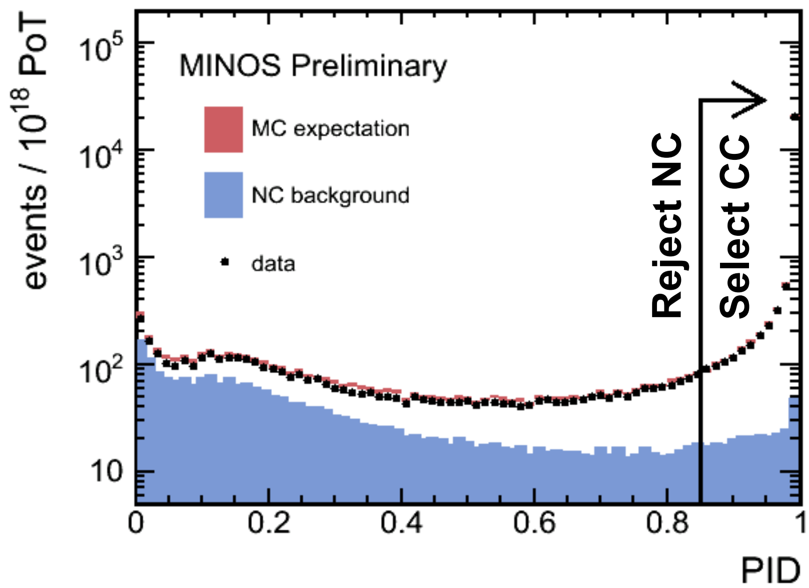
Updated results based on RUN I and RUN IIa (2.5×10^{20} POTs).

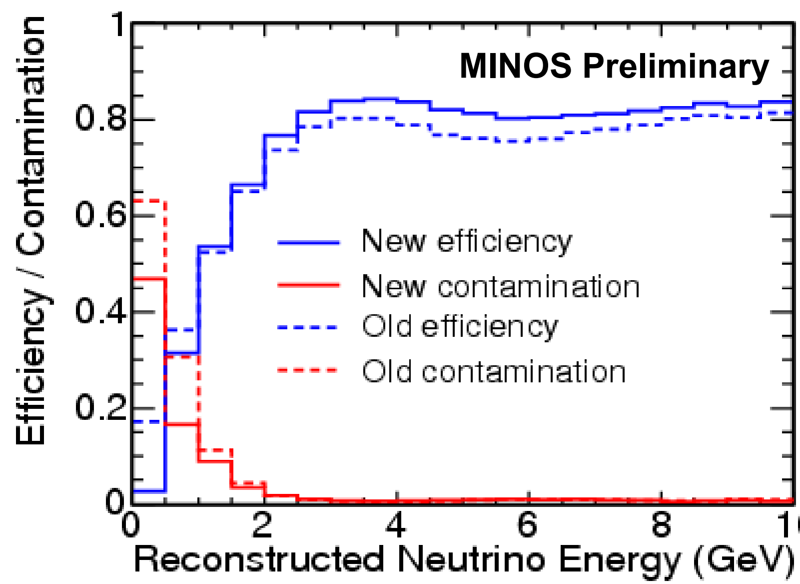
New and Improved Analysis

- **Improvements over 2006 analysis:**
  – Better reconstruction.
  – Improved event selection.
  – Improved shower modelling.
  – New intra-nuclear modelling.
- **CC/NC interactions separated using multivariate 2D likelihood procedure combining information from:**
  – Track observables.
  – Event length.
  – Event kinematics.

Improvement in selection
~1% more CC signal.
~50% less NC background.

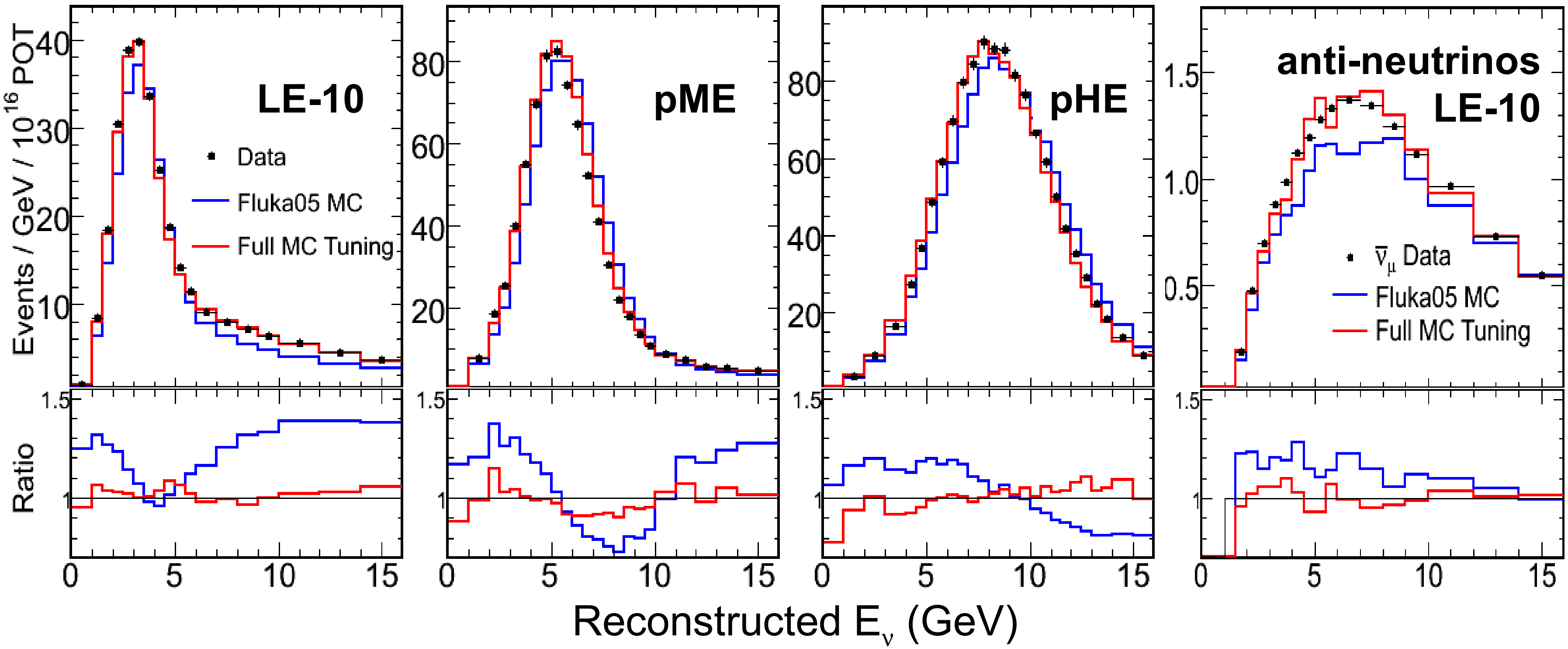
- **Data and Monte Carlo agree well.**





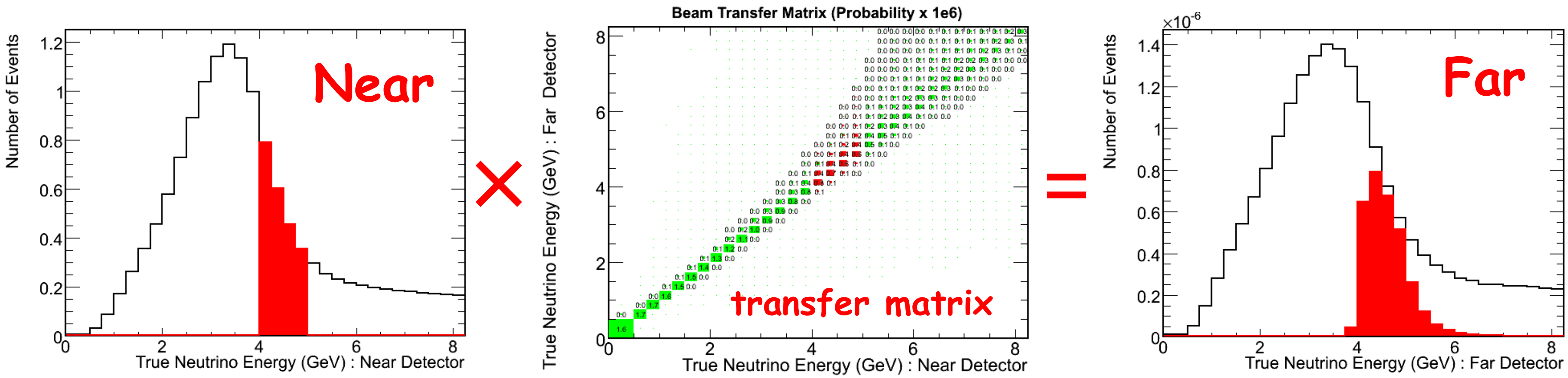
Hadron Production Tuning

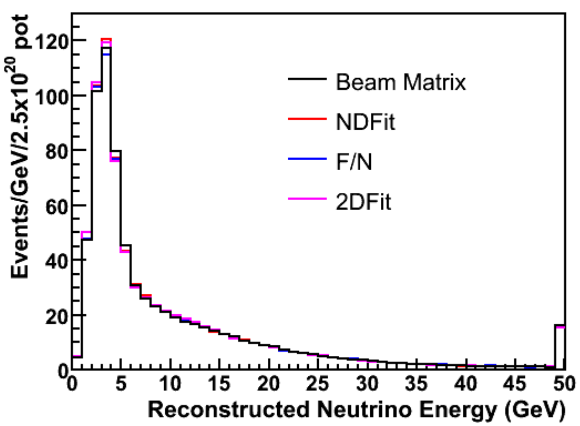
- **Parameterize Fluka 2005 hadron production model as f(x_F,p_T).**
- **Fit to near detector data collected in different beam configurations.**
  - incorporate into the fit: horn focusing current, beam misalignments, cross-sections, neutrino energy scale, neutral current background.
- **Improved agreement between data and MC in all configurations.**

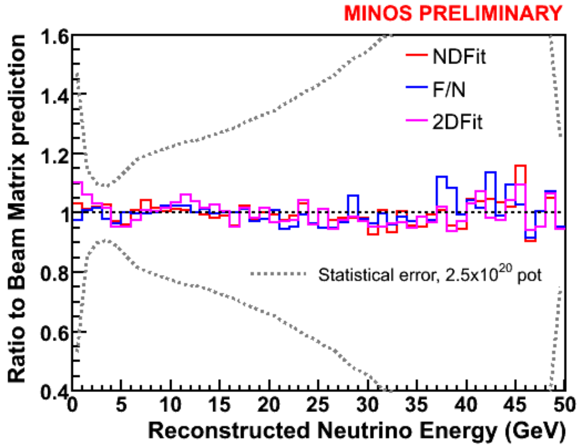


Predicting the Far Spectrum

- **Directly use near detector data to extrapolate from near to far detector.**
  - Use Monte Carlo to correct for energy smearing and detector acceptance.
  - Use a beam transfer matrix derived from the beam simulation to relate neutrino interactions in each detector via their parent hadrons.







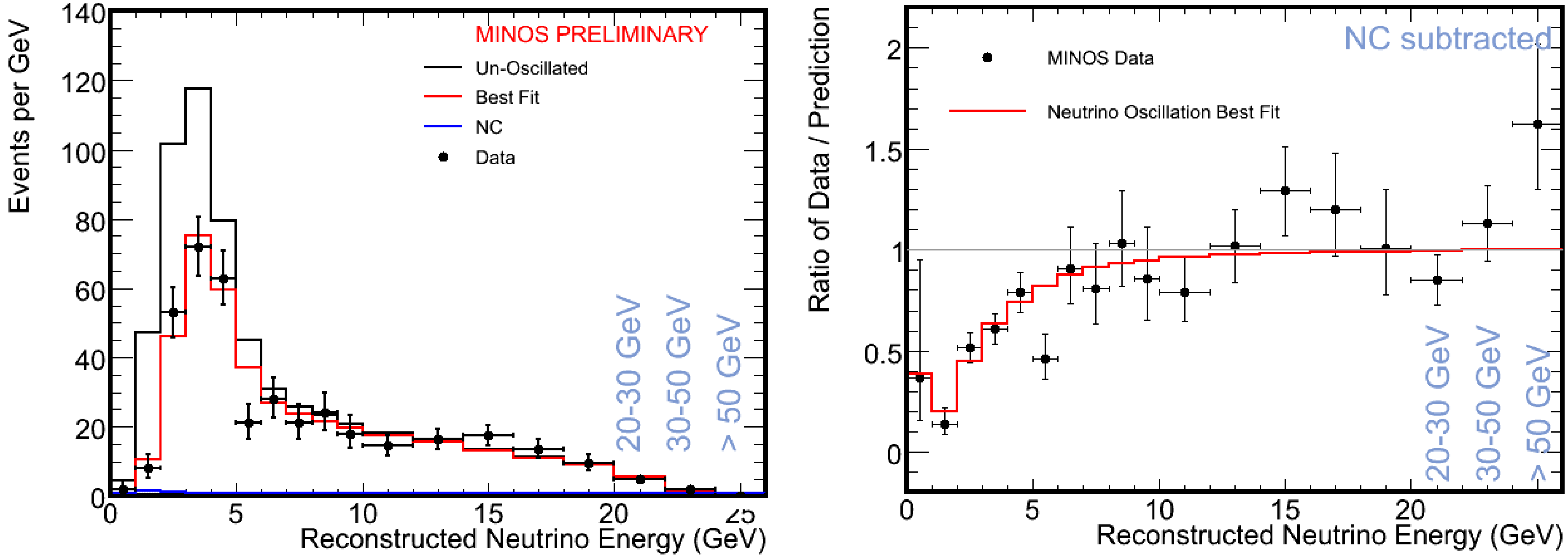
Systematic Uncertainties

- Systematic uncertainties on oscillation parameters evaluated by fitting fake data sets generated from MC with systematic shifts applied.
- The three largest uncertainties identified from this study are included as nuisance parameters in the oscillation analysis.

Uncertainty	Δm^2 (10^{-3} eV^2)	$\sin^2 2\theta$
Near/far normalization (4%)	0.065	<0.005
Abs. shower energy scale (10%)	0.075	<0.005
NC normalization (50%)	0.010	0.008
All other systematics	0.040	<0.005
Total uncertainty (quad. sum)	0.11	0.008
Statistical uncertainty	0.17	0.080

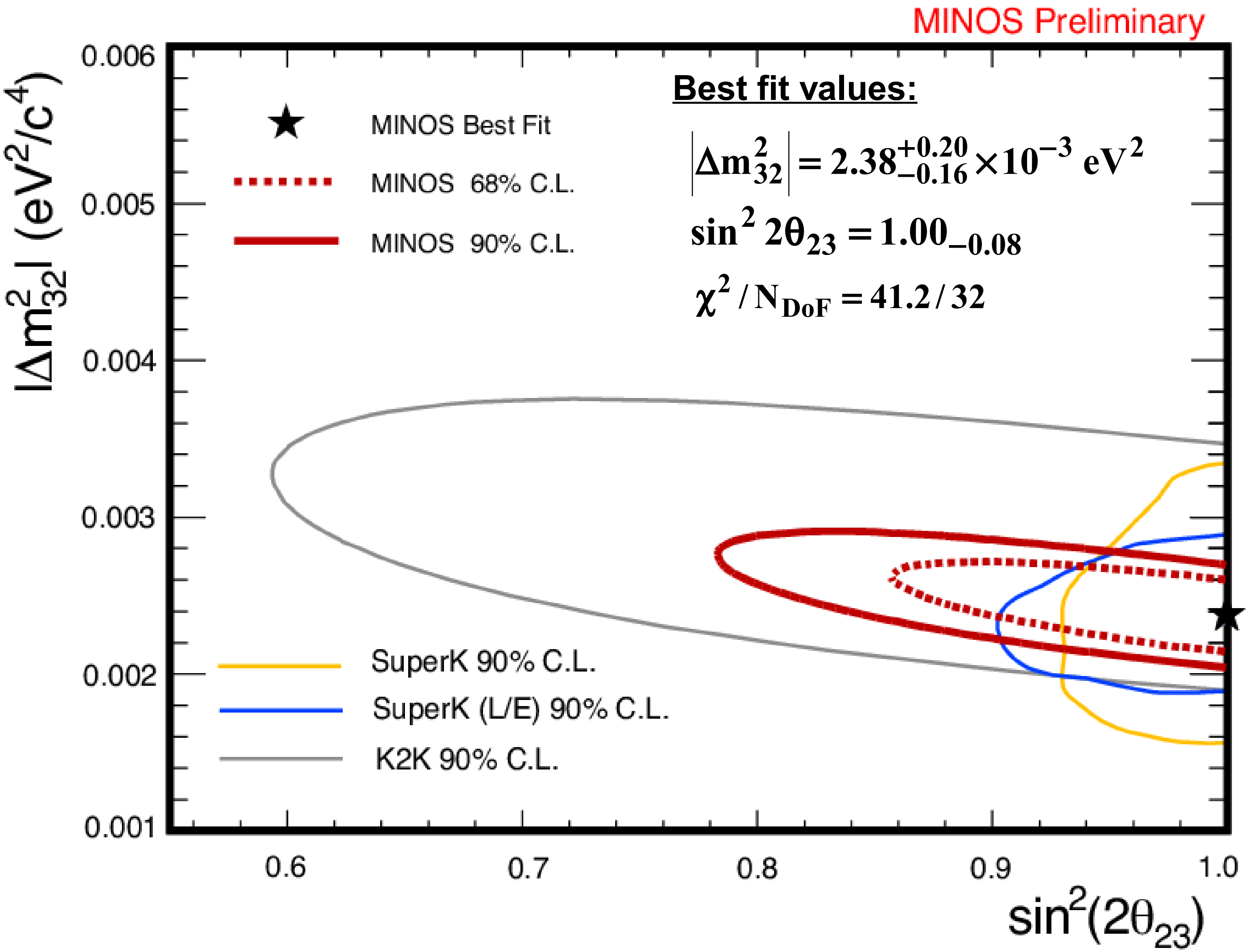
Oscillation Analysis

PRELIMINARY OSCILLATION RESULTS FOR 2.5x10[20] POTs DATA.



Data sample	Observed	Expected (no osc.)	Observed / Expected
ν_μ (all E)	563	738 ± 30	0.74 (4.4σ)
ν_μ (<10 GeV)	310	496 ± 20	0.62 (6.2σ)
ν_μ (<5 GeV)	198	350 ± 14	0.57 (6.5σ)

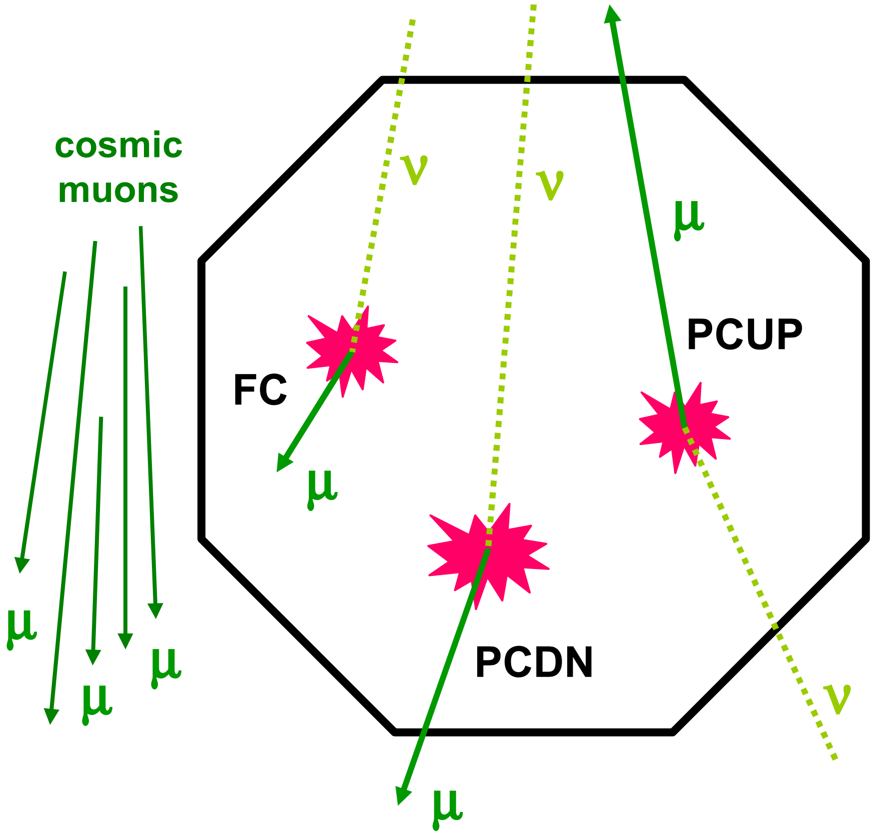
Allowed Parameter Space



Atmospheric Neutrinos at MINOS

- **MINOS far detector can be used to study atmospheric neutrinos.**
  - 5.4 kT mass generates high rate of atmospheric neutrino interactions.
  - 700m depth provides shielding against cosmic muon background.
  - magnetic field enables separation of neutrino and anti-neutrino events.
  - Calorimeter detector design enables measurement of total energy.

- **Atmospheric neutrino analyses:**
  - contained vertex interactions.
    PRD 73, 072002 (2006).
  - neutrino-induced up-going muons.
    PRD 75, 092003 (2007).
  - Reported here are new preliminary contained vertex muon and electron atmospheric neutrino results.



Contained vertex events classified as follows:
- **Fully Contained (FC).**
- **Down-Going Partially Contained (PCDN).**
- **Up-Going Partially Contained (PCUP).**

Atmospheric Muon Neutrinos

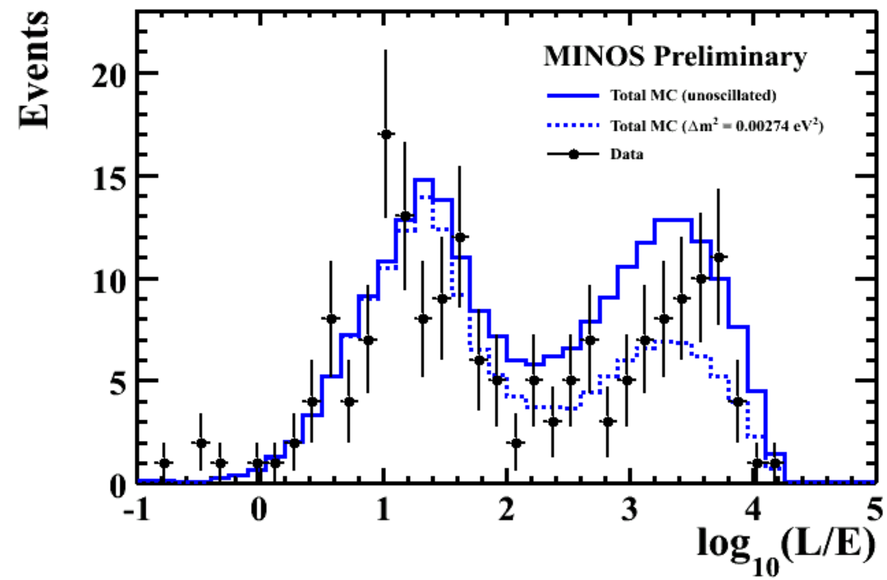
- Updated contained vertex ν_μ analysis based on exposure of 12.23 kT-Yrs.
- Observe 277 events, with expectation of 354 ± 47 in absence of oscillations.
- Select events with well-measured muon direction based on timing information.
  - 105 downward-going, 77 upward-going.

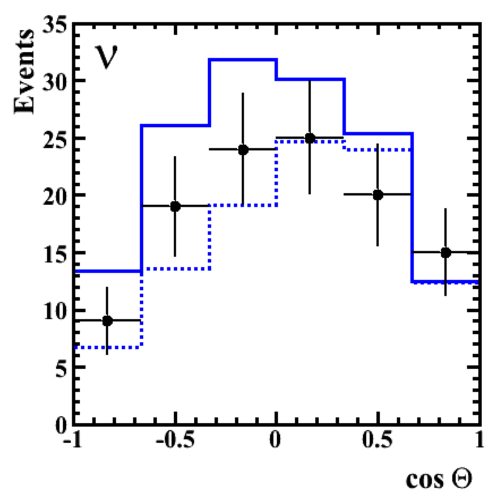
$$R^{data}_{up/down} / R^{MC}_{up/down} = 0.72^{+0.13}_{-0.11}(stat) \pm 0.04(sys)$$

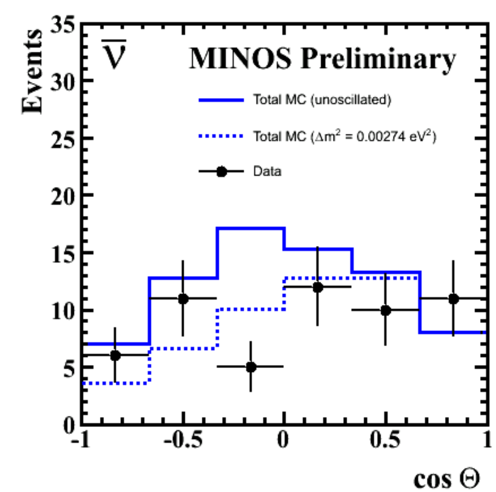
- Select events with well-measured muon charge based on curvature in B-field.
  - 112 neutrinos, 55 anti-neutrinos.

$$R^{data}_{\bar{\nu}/\nu} / R^{MC}_{\bar{\nu}/\nu} = 0.93^{+0.19}_{-0.15}(stat) \pm 0.12(sys)$$

- Oscillation analysis carried out by binning events according to their Bayesian *L/E* resolution.







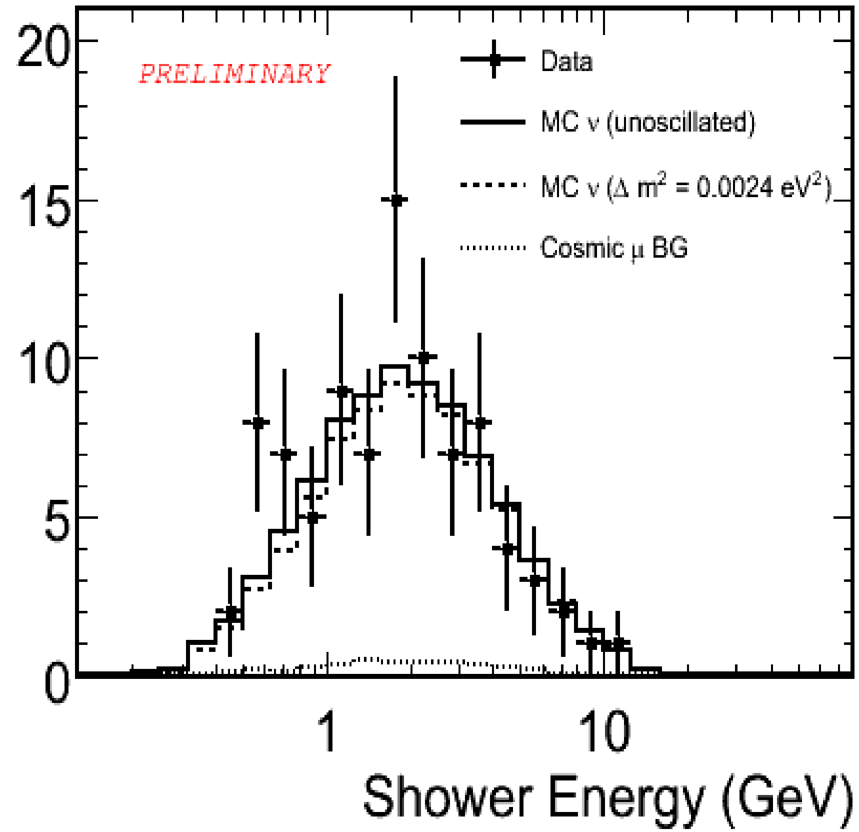
Atmospheric Electron Neutrinos

- **Preliminary MINOS atmospheric ν_e results based on exposure of 6.18 kT-Yrs.**
  - Identify ν_e events as contained vertex electromagnetic showers.
  - Observe 89 candidate ν_e events with expectation of 89 ± 17 events.
  - Observe 113 candidate ν_μ events with expectation of 150 ± 30 events.

$$R^{data}_{\mu/e} / R^{MC}_{\mu/e} = 0.74^{+0.12}_{-0.10}(stat) \pm 0.05(sys)$$

- **Use selected ν_e event sample to measure atmospheric neutrino flux normalization relative to *Bartol04* flux model.**
  - account for oscillations of true ν_μ events in selected ν_e event sample.

$$S_{atm} = 1.07 \pm 0.12(stat) \pm 0.08(sys)$$



Summary

- **MINOS has had a successful second year of beam running.**
  - 3.6×10^{20} PoTs have now been accumulated after two years.
- **Updated oscillation measurement based on 2.5×10^{20} PoTs.**

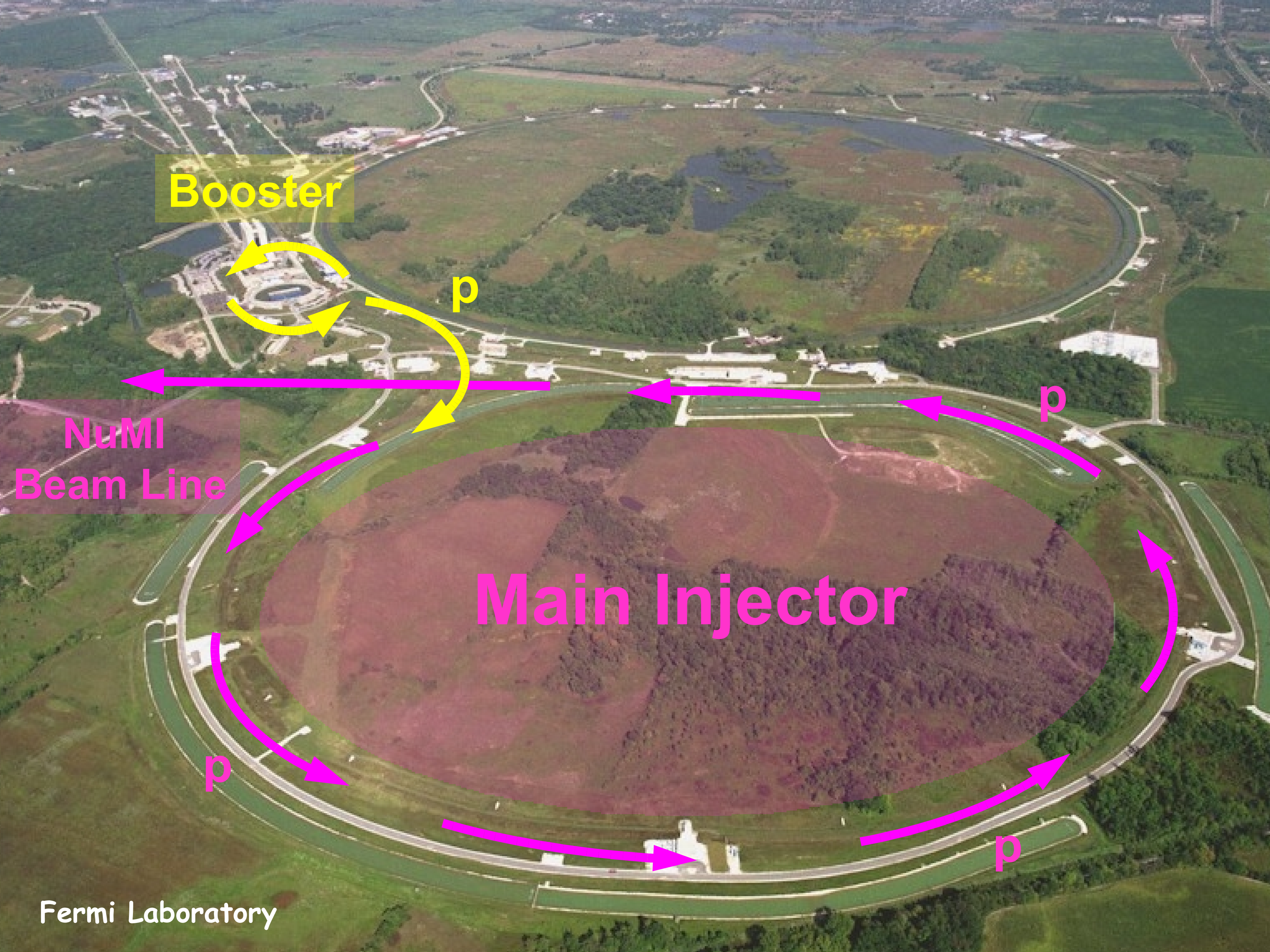
$$\left|\Delta m^2_{32}\right| = 2.38^{+0.20}_{-0.16} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.08}$$

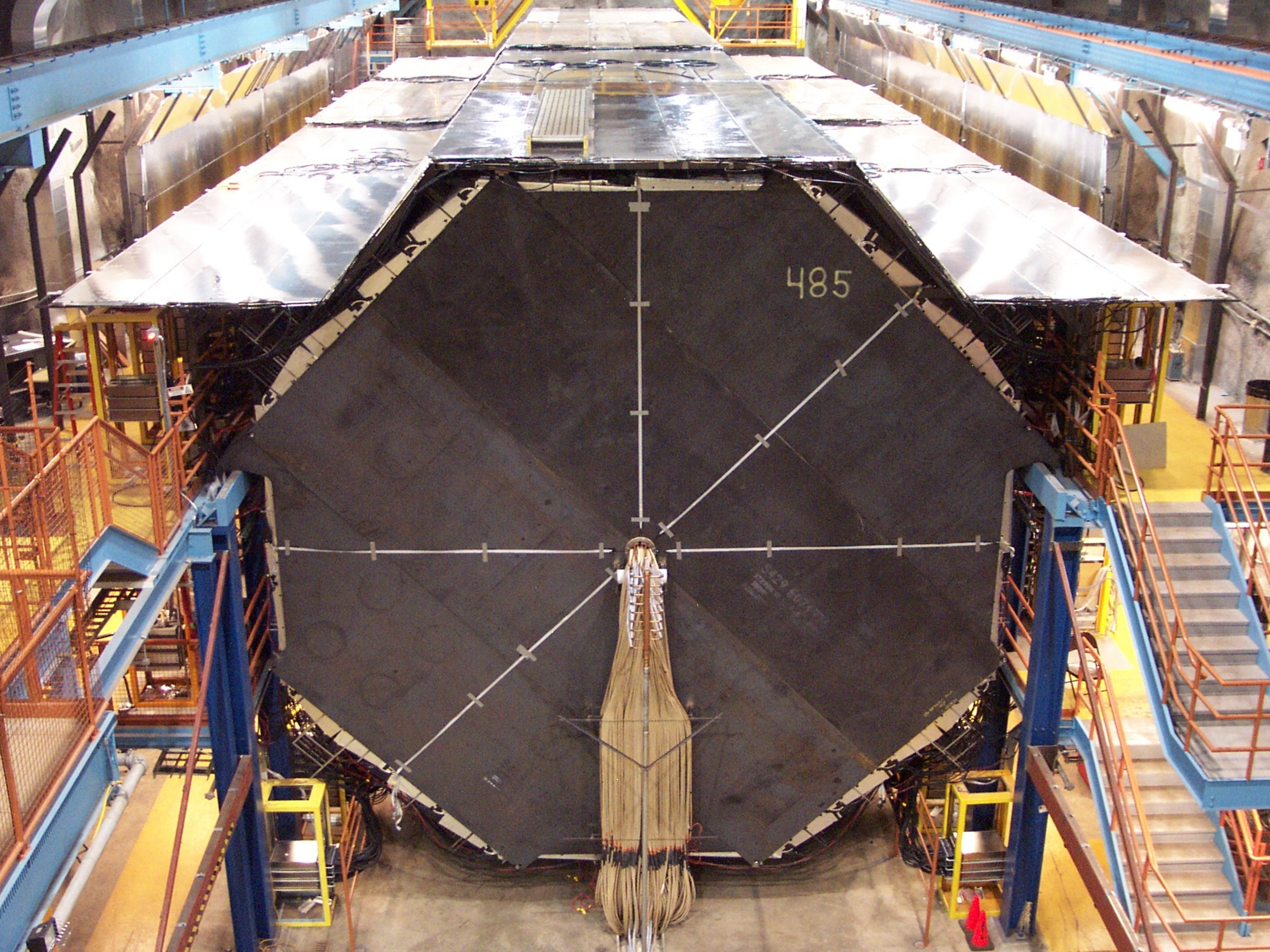
- **Other oscillation analyses using beam data are progressing.**
  - ν_e appearance, anti-ν_μ disappearance, sterile neutrinos…
- **Updated atmospheric muon and electron neutrino results.**
  - developing combined analysis of all MINOS atmospheric neutrino data.

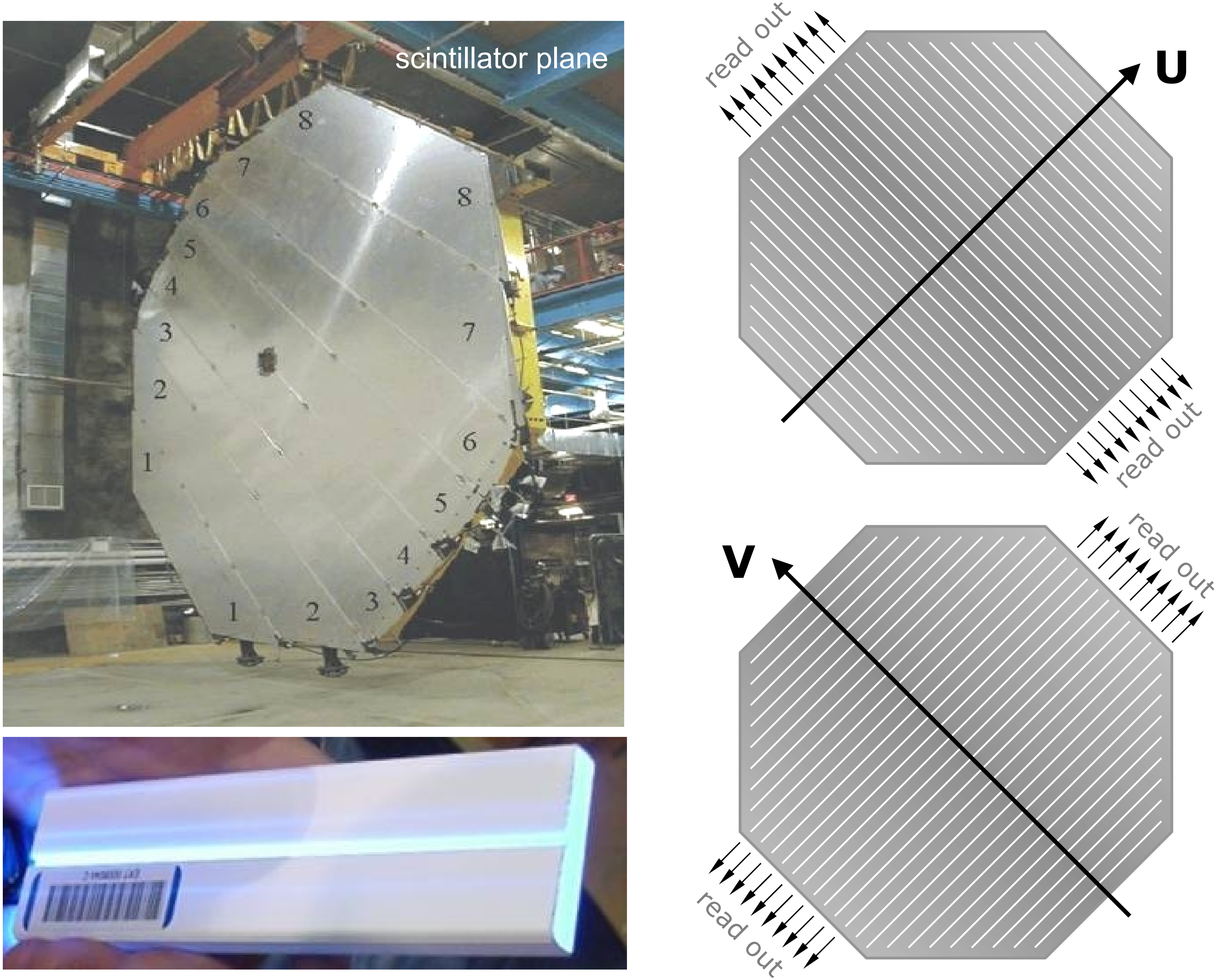
See poster session for more information on latest MINOS results

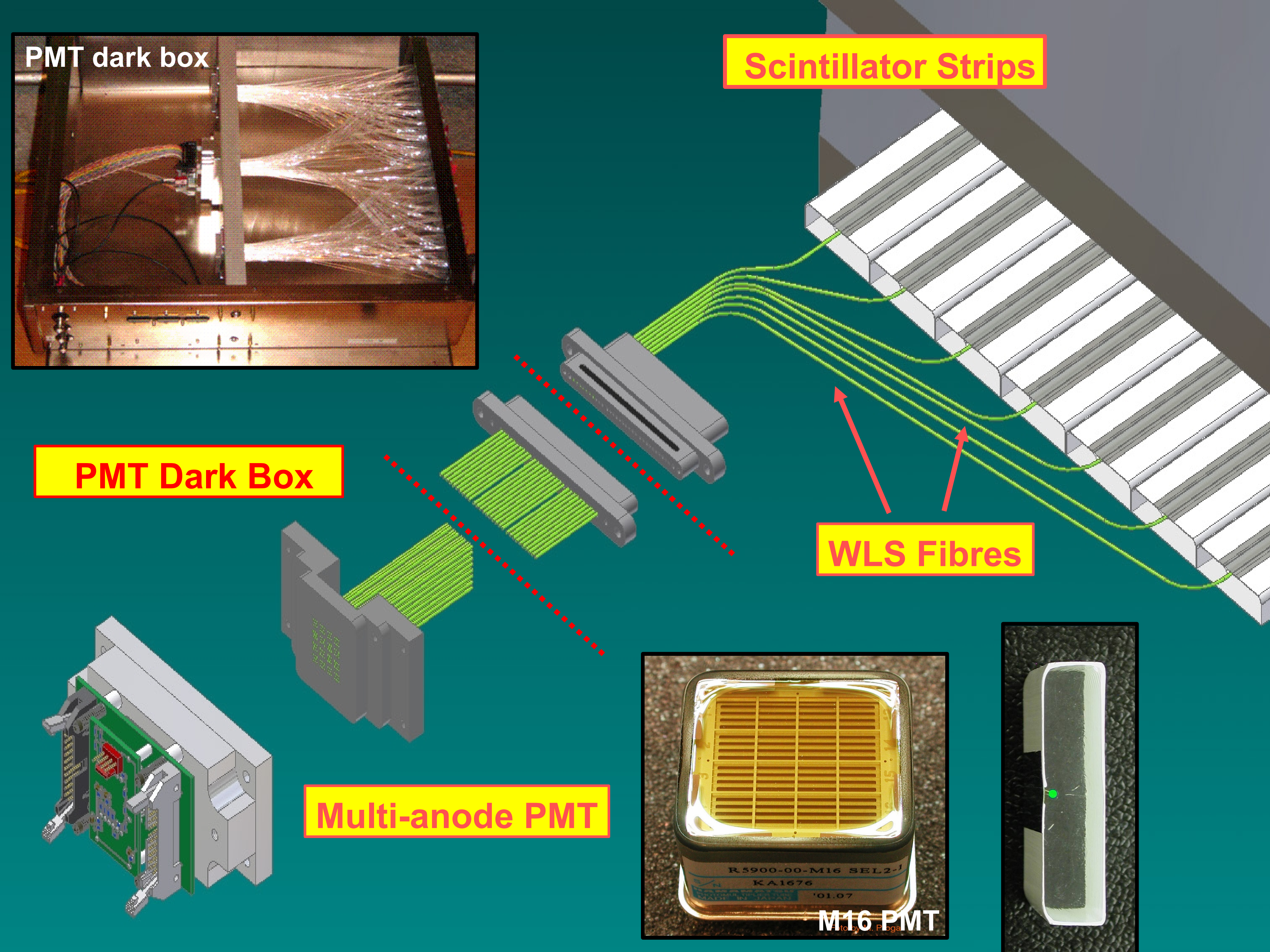
Backup Slides



Booster
p
NuMI
Beam Line
p
Main Injector
p
p
Fermi Laboratory

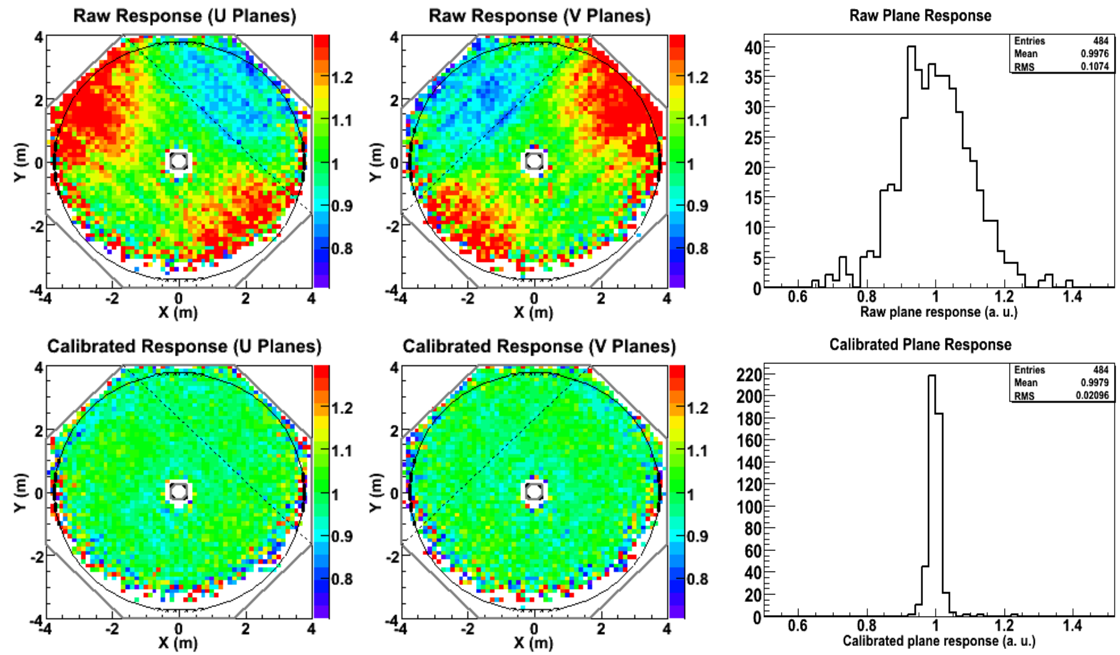

485


scintillator plane
8
7
6
5
4
3
2
1
8
7
6
5
4
1
2
3
read out
U
read out
V
read out
read out


PMT dark box
Scintillator Strips
PMT Dark Box
WLS Fibres
Multi-anode PMT
R5900-00-M16 SEL2-1
KA1676
'01.07
M16 PMT

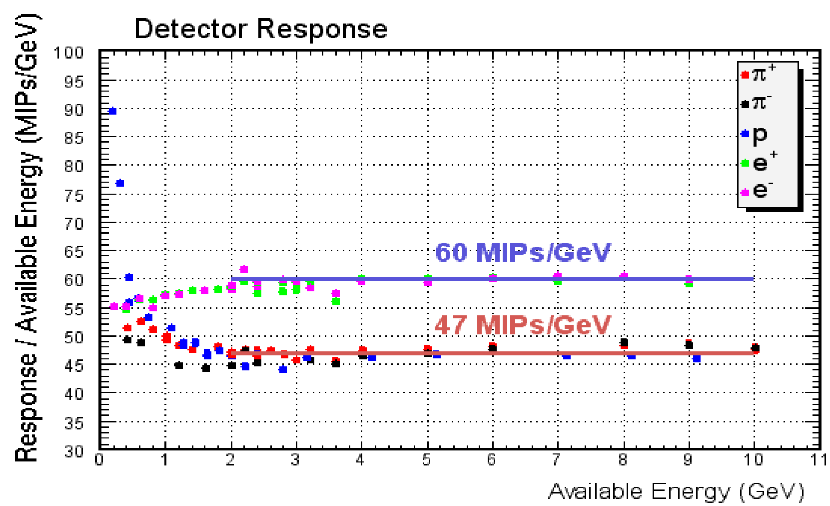
MINOS Calibration

- **Light injection system:**
  - PMT gain and linearity.
- **Cosmic ray muons:**
  - relative strip calibration.
  - intra-detector calibration.



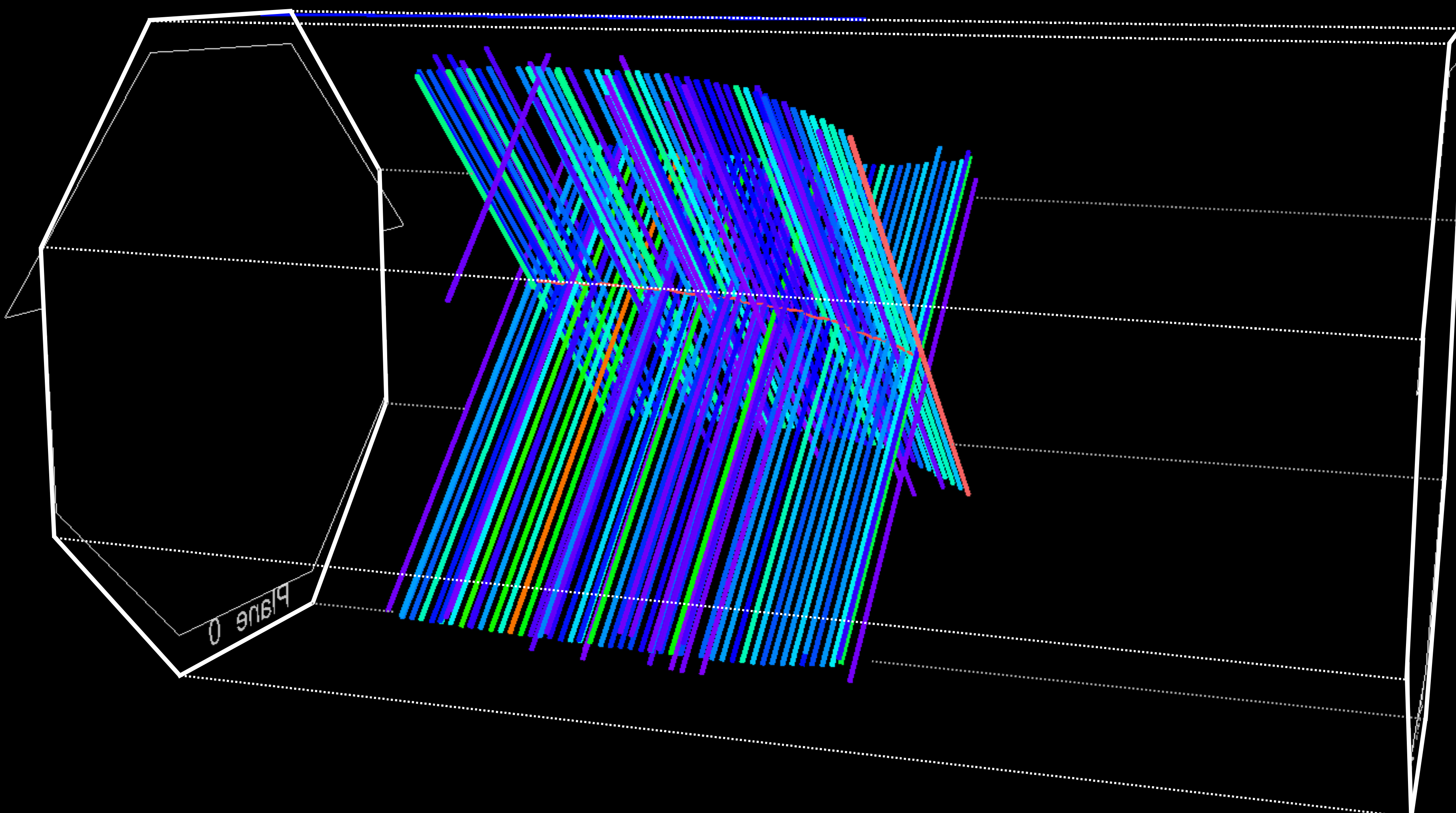
Calibration Error:
- ND calibration: 3.1%
- FD calibration: 2.3%
- ND/FD calibration: 3.8%

- **Overall Energy Scale:**
  - Calibration detector at CERN measured e/μ/π/p response.

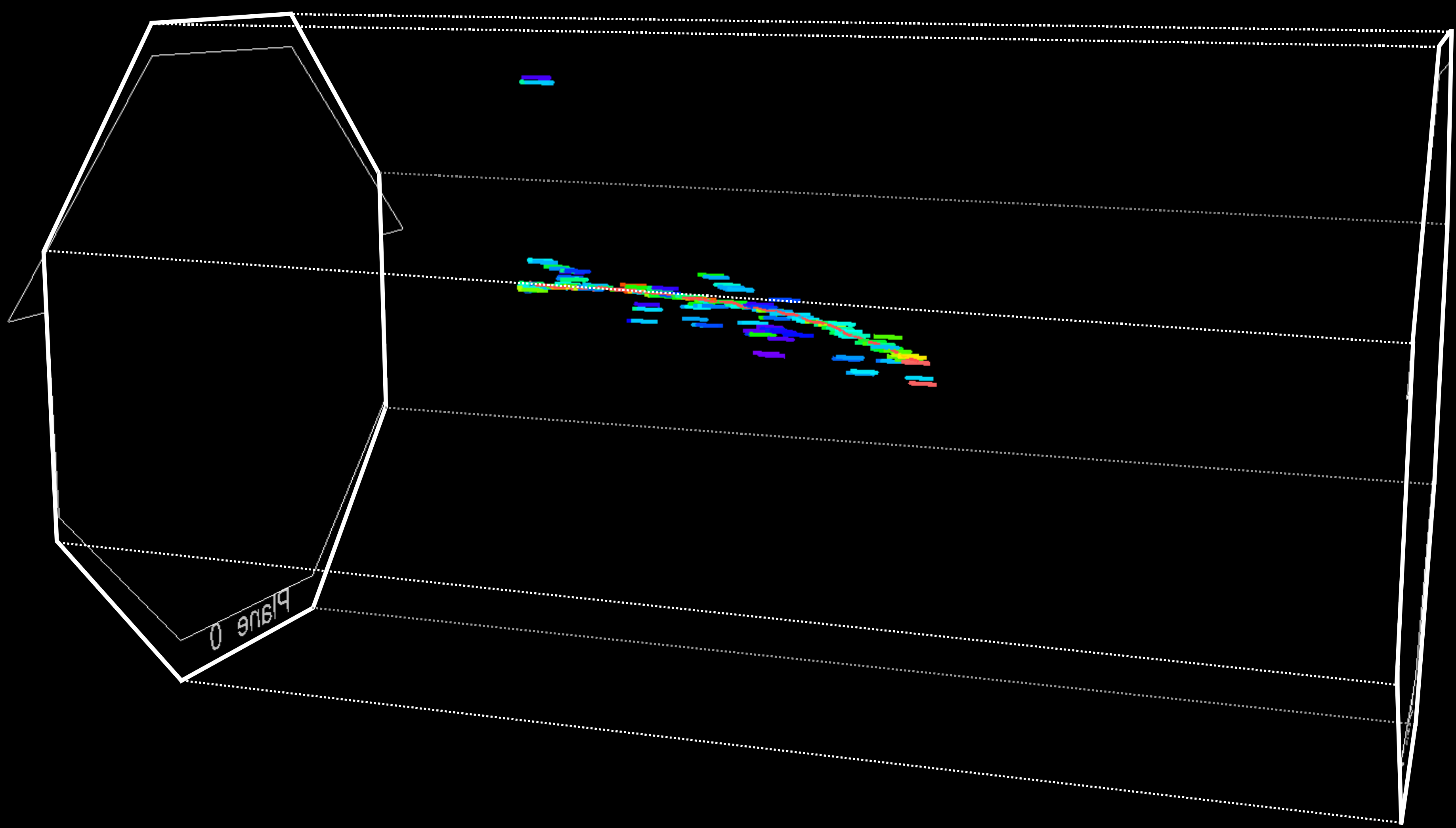


Energy Resolution (E in GeV):
- Hadrons: $56\%/\sqrt{E} \oplus 2\%$
- Electrons: $21\%/\sqrt{E} \oplus 4\%/E$

Reconstruction of a MINOS Event

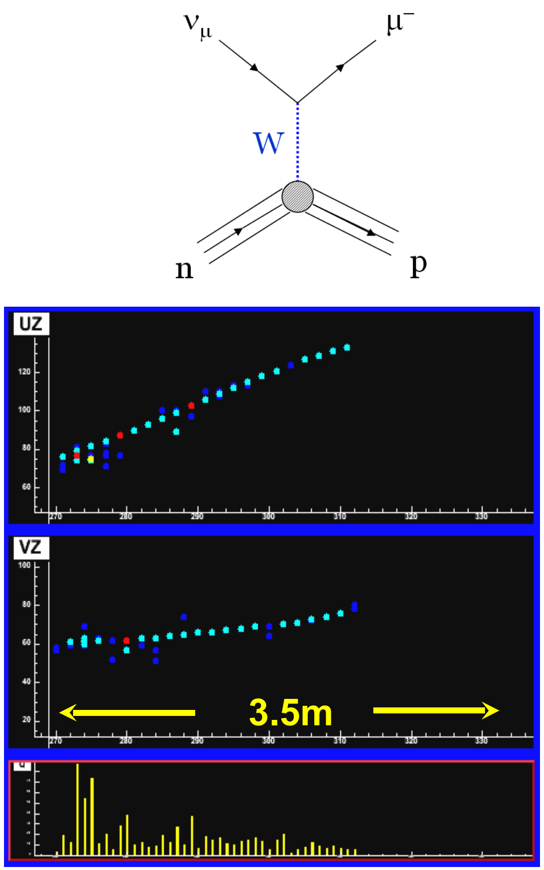


Reconstruction of a MINOS Event



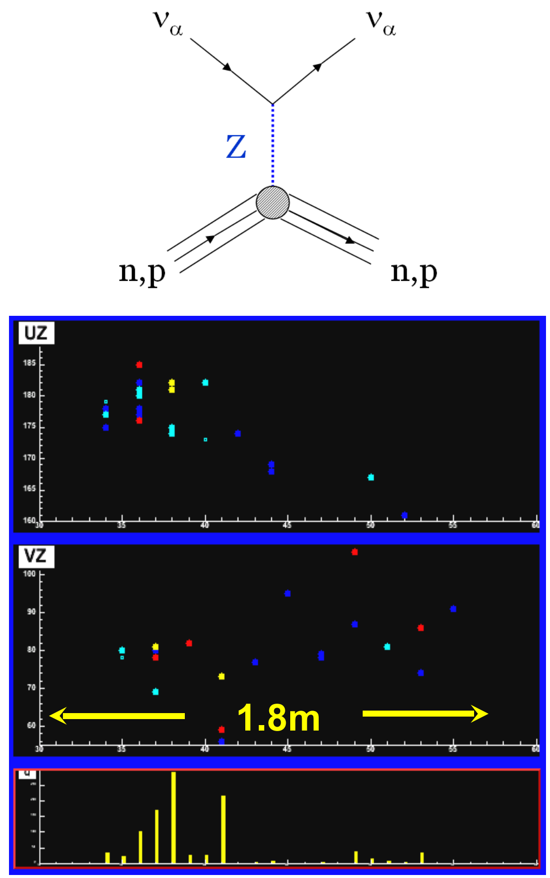
Event Topologies in MINOS

ν_μ CC Event



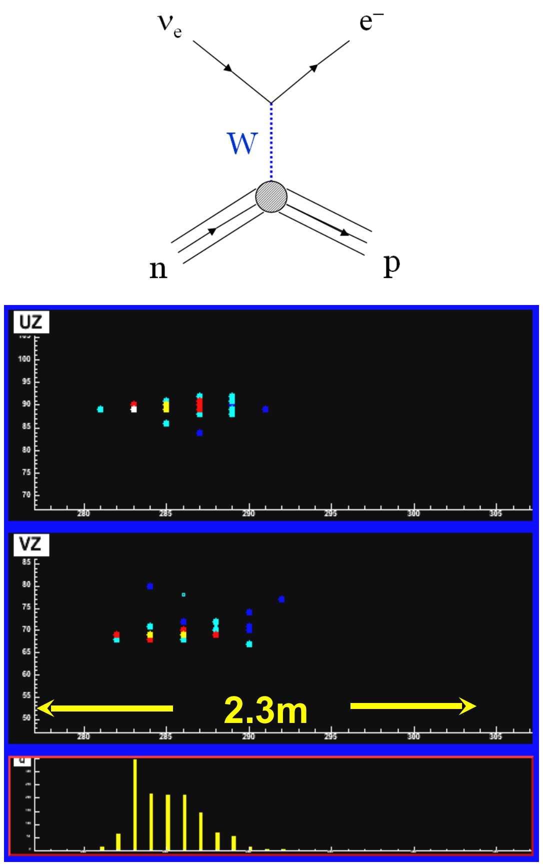
long μ track & hadronic activity at vertex

NC Event



short event, often diffuse

ν_e CC Event



short, with typical EM shower profile

Selecting ν_μ CC Interactions

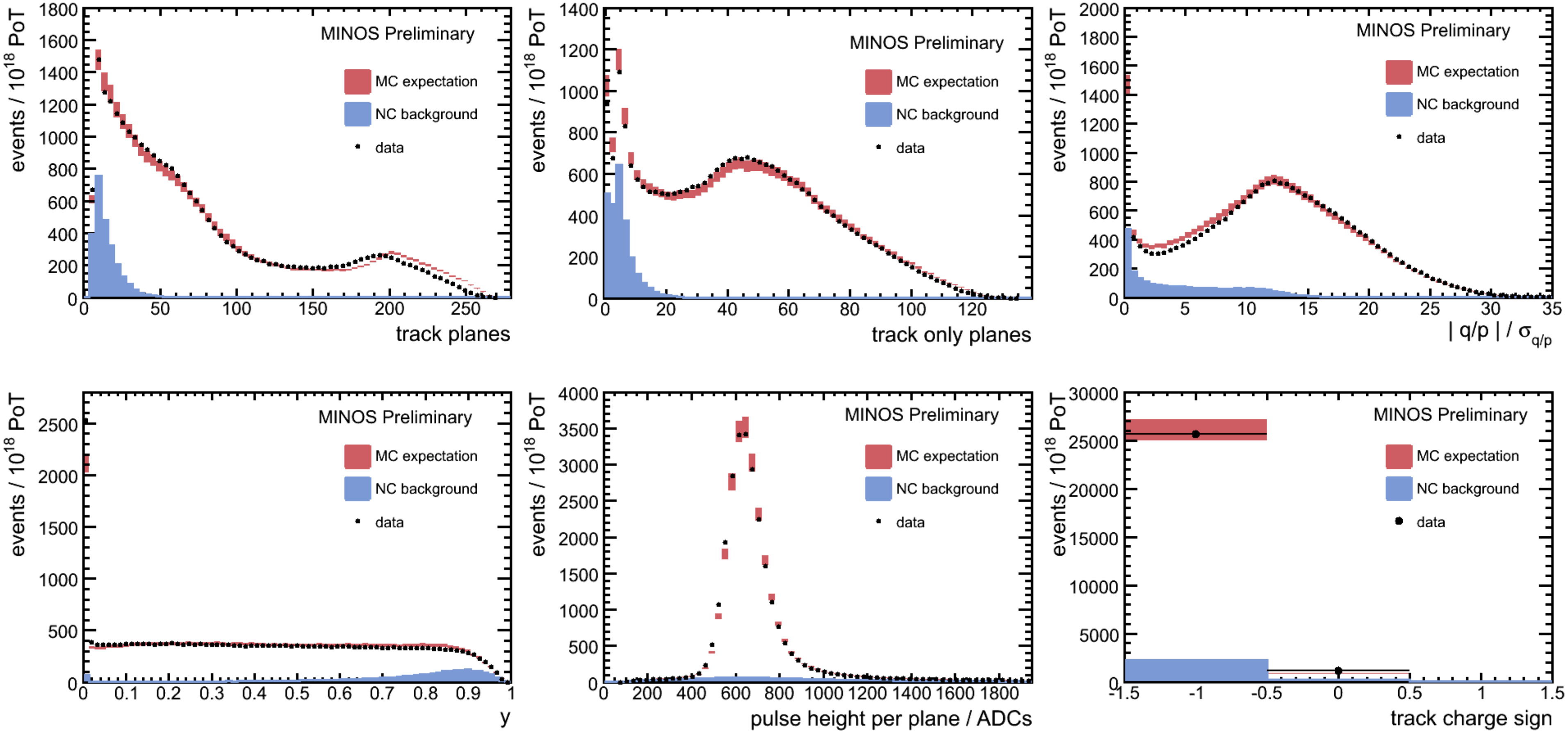
- **CC events selected using a likelihood based procedure with six input PDFs that show discrimminating power between true CC and NC interactions:**
  - Number of track planes.
  - Number of track only planes.
  - Track pulse height per plane.
  - Goodness of muon track fit.
  - Reconstructed muon charge.
  - Reconstructed y (E_{shw}/E_ν).
- **2D PDFs are used to take account of correlations with event length.**
- **The discrimminant variable (PID) is defined as follows:**

$$P_{CC}(X,Y,Z,...) = P(X|CC)\ P(Y|CC)\ P(Z|CC)\ ...\ P(CC)$$

$$P_{NC}(X,Y,Z,...) = P(X|NC)\ P(Y|NC)\ P(Z|NC)\ ...\ P(NC)$$

$$\boxed{PID = \frac{P_{CC}}{P_{CC} + P_{NC}}}$$

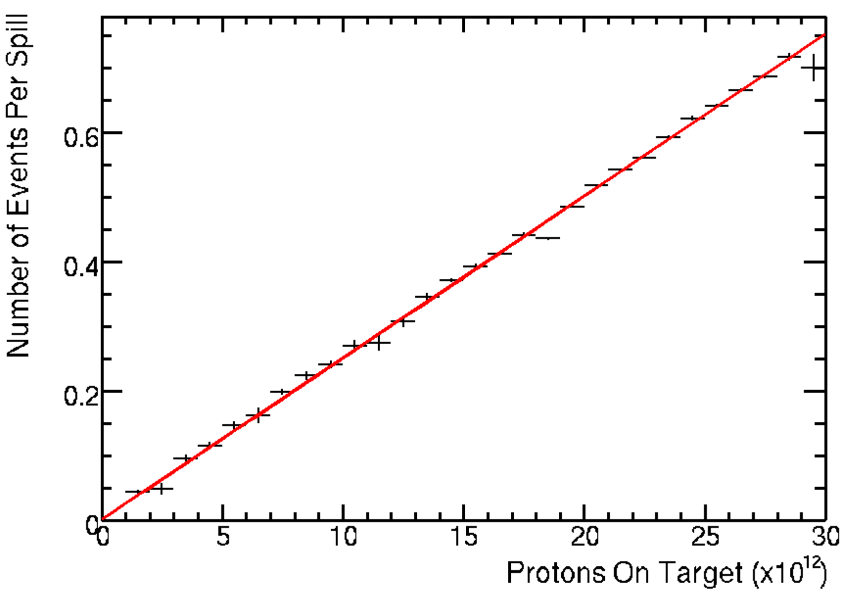
Selecting ν_μ CC Interactions

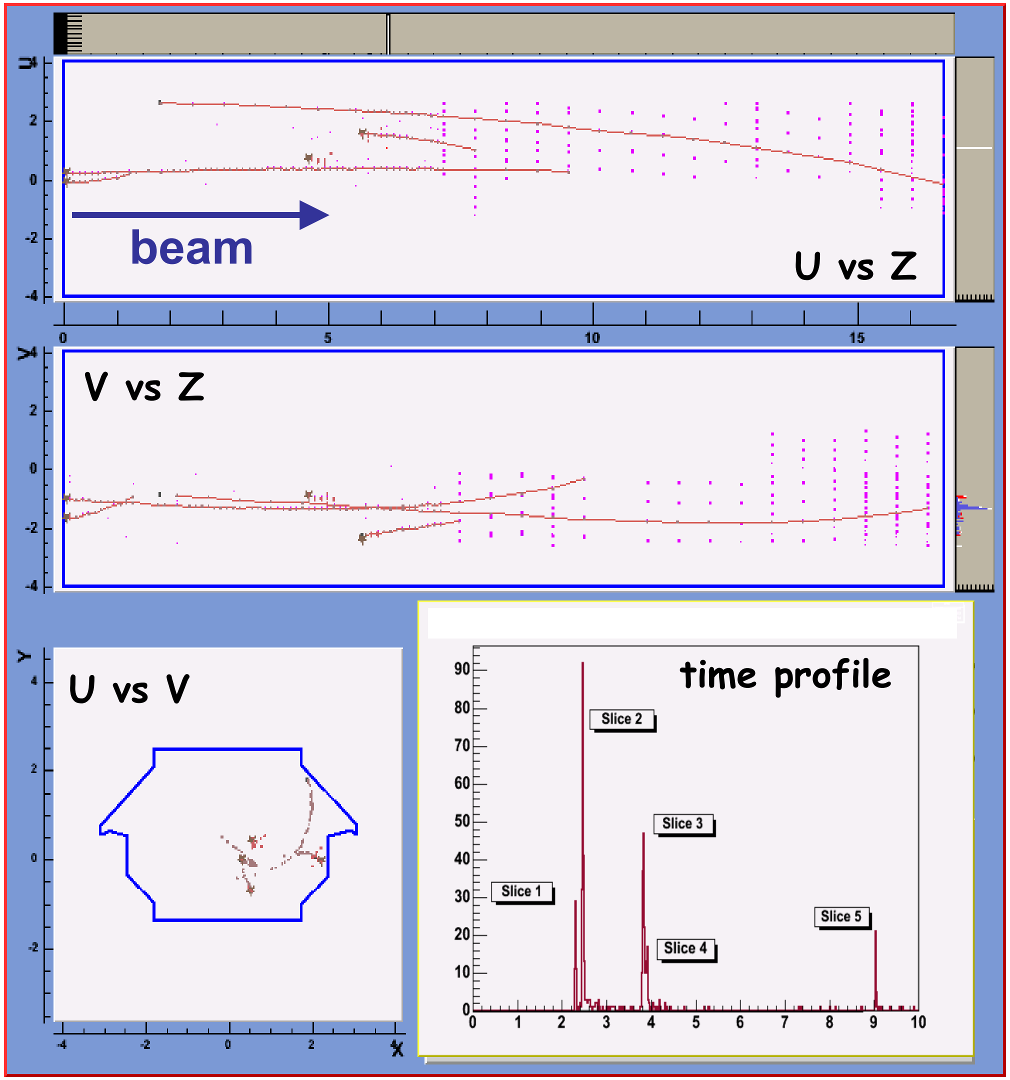


Good agreement between data and Monte Carlo observed for these variables.

Near Detector Interactions

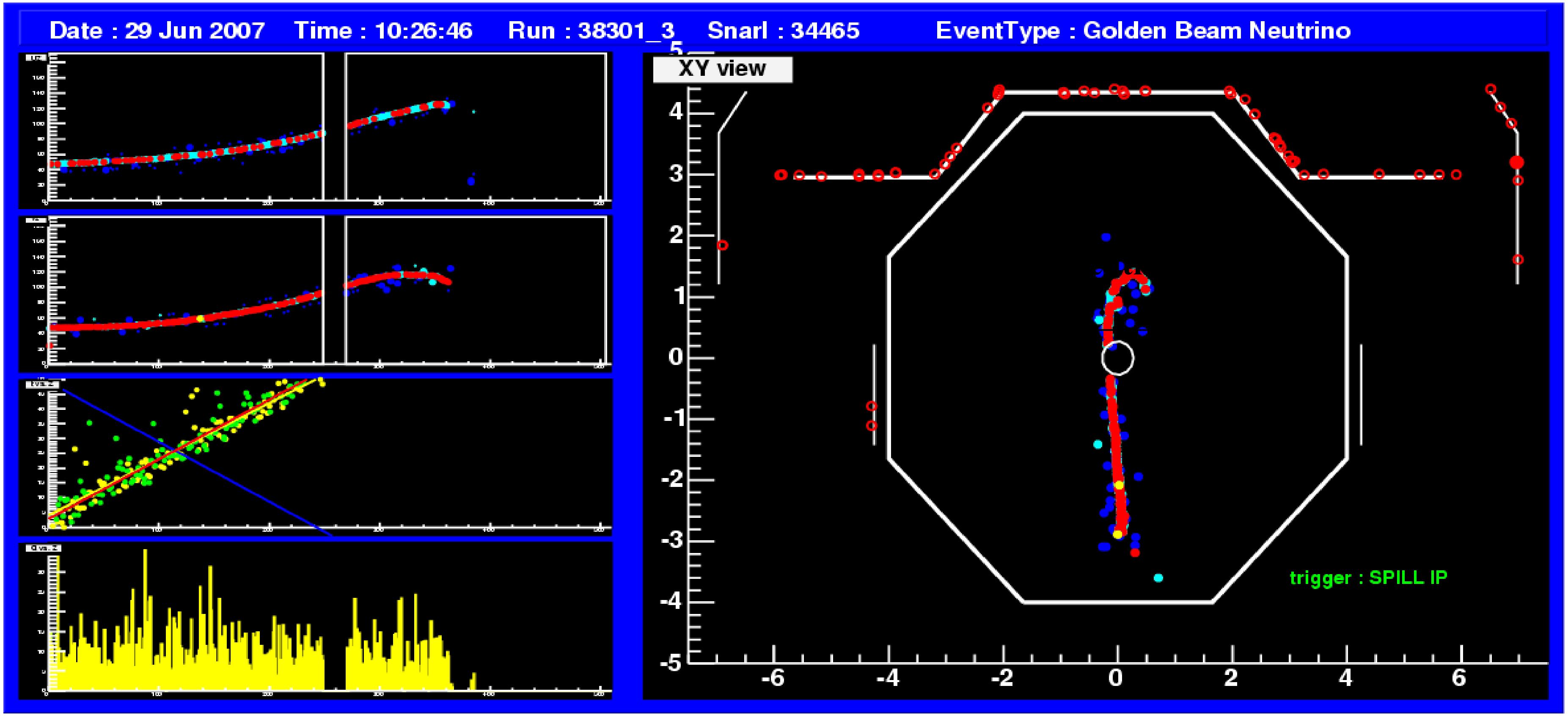
- **High event rate in near detector.**
  - Multiple interactions per spill.
- **Events separated based on topology and timing.**
  - Timing resolution ~20 ns
  - Spatial resolution ~4 cm
- **No significant bias in event rate.**



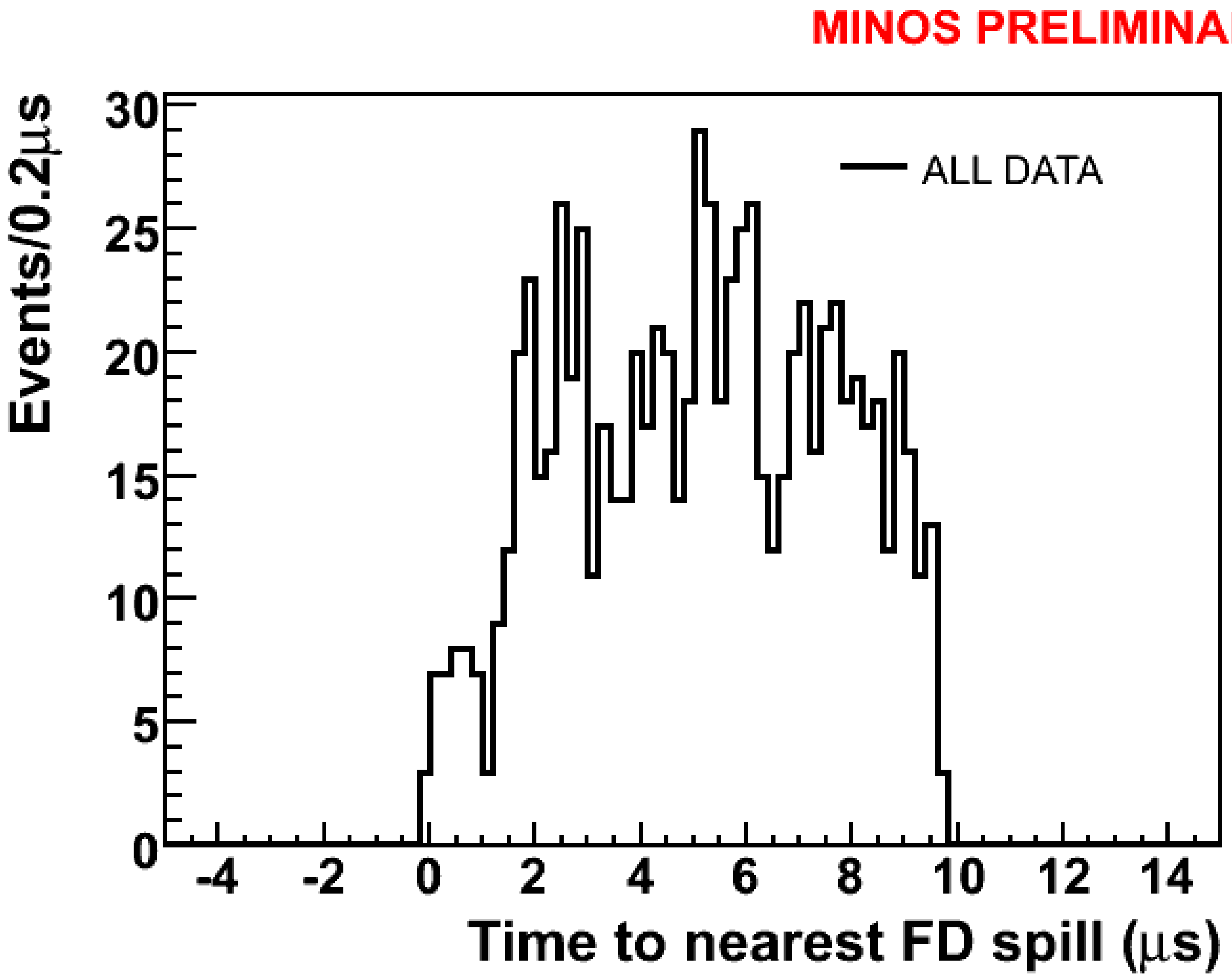


Far Detector Interactions

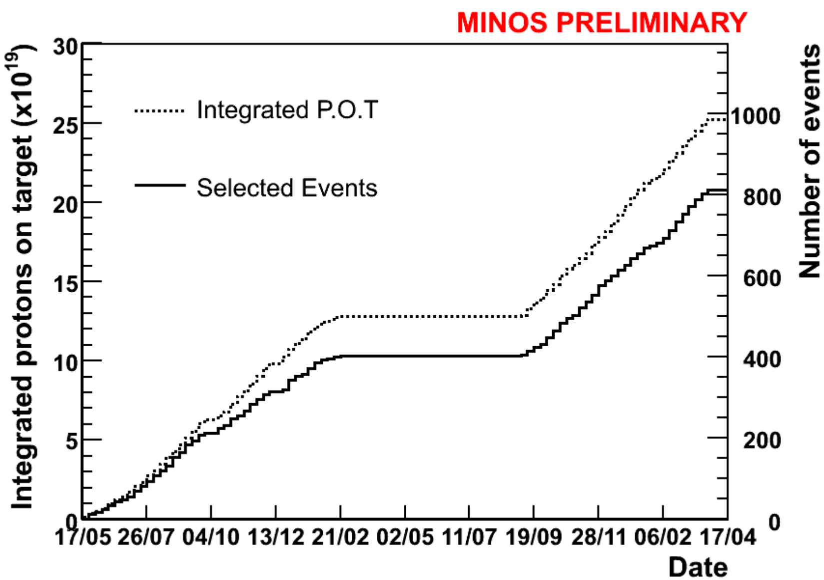
- **Beam interactions identifiable with "spill trigger".**
  - GPS spill time is sent via internet from near to far detector.
  - Events within ±50μs of spill written out by far detector DAQ.

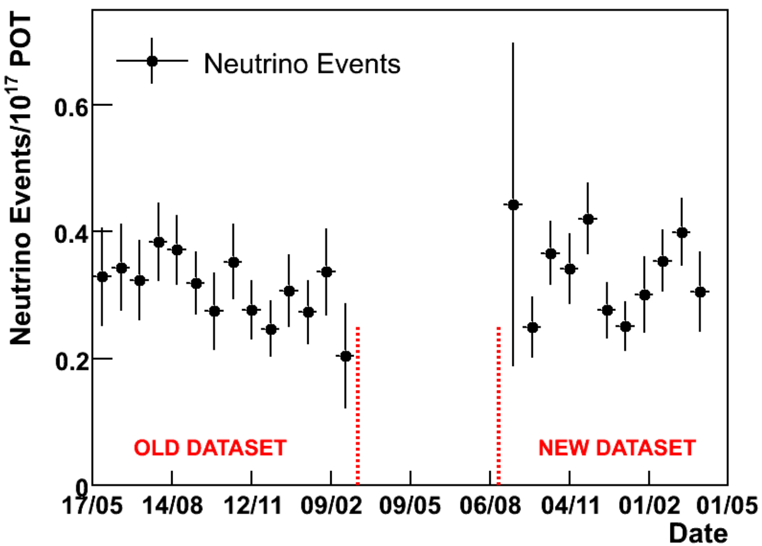


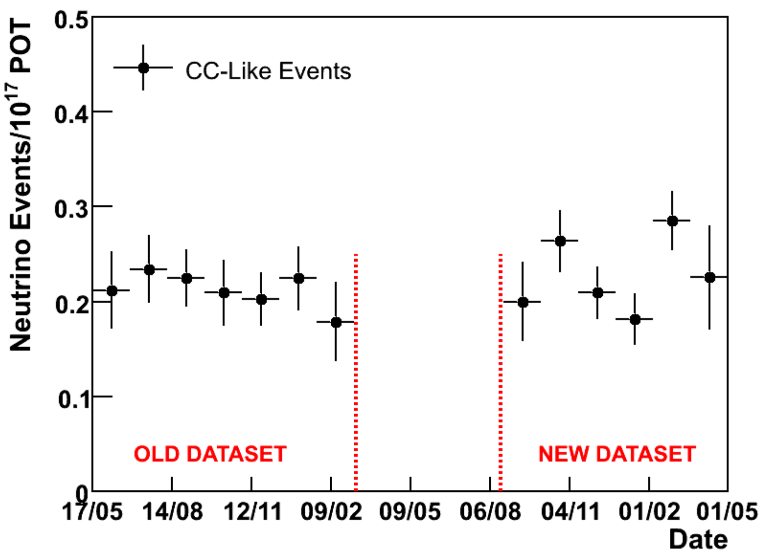
Far Detector Timing



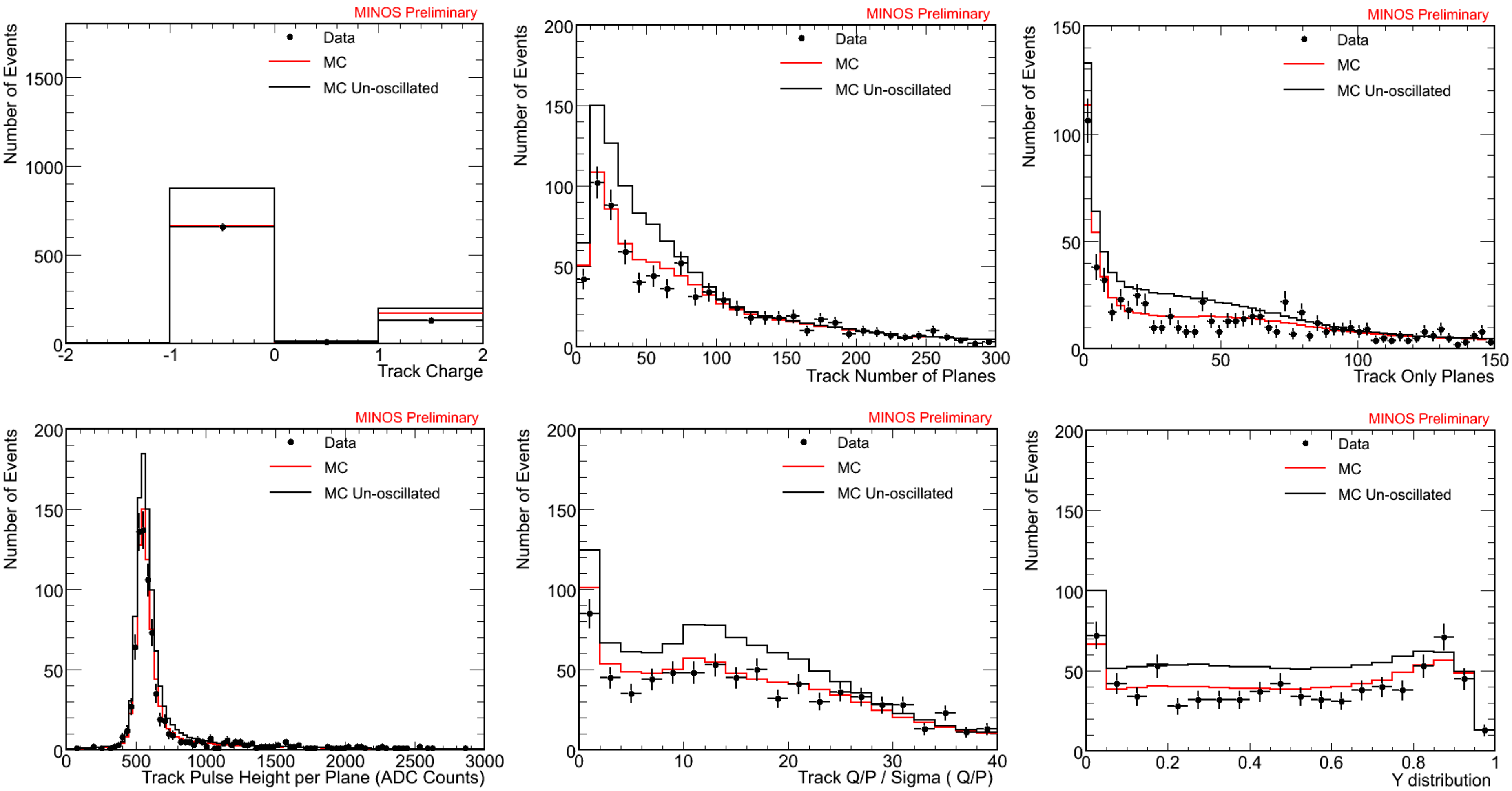
Far Detector Event Rates





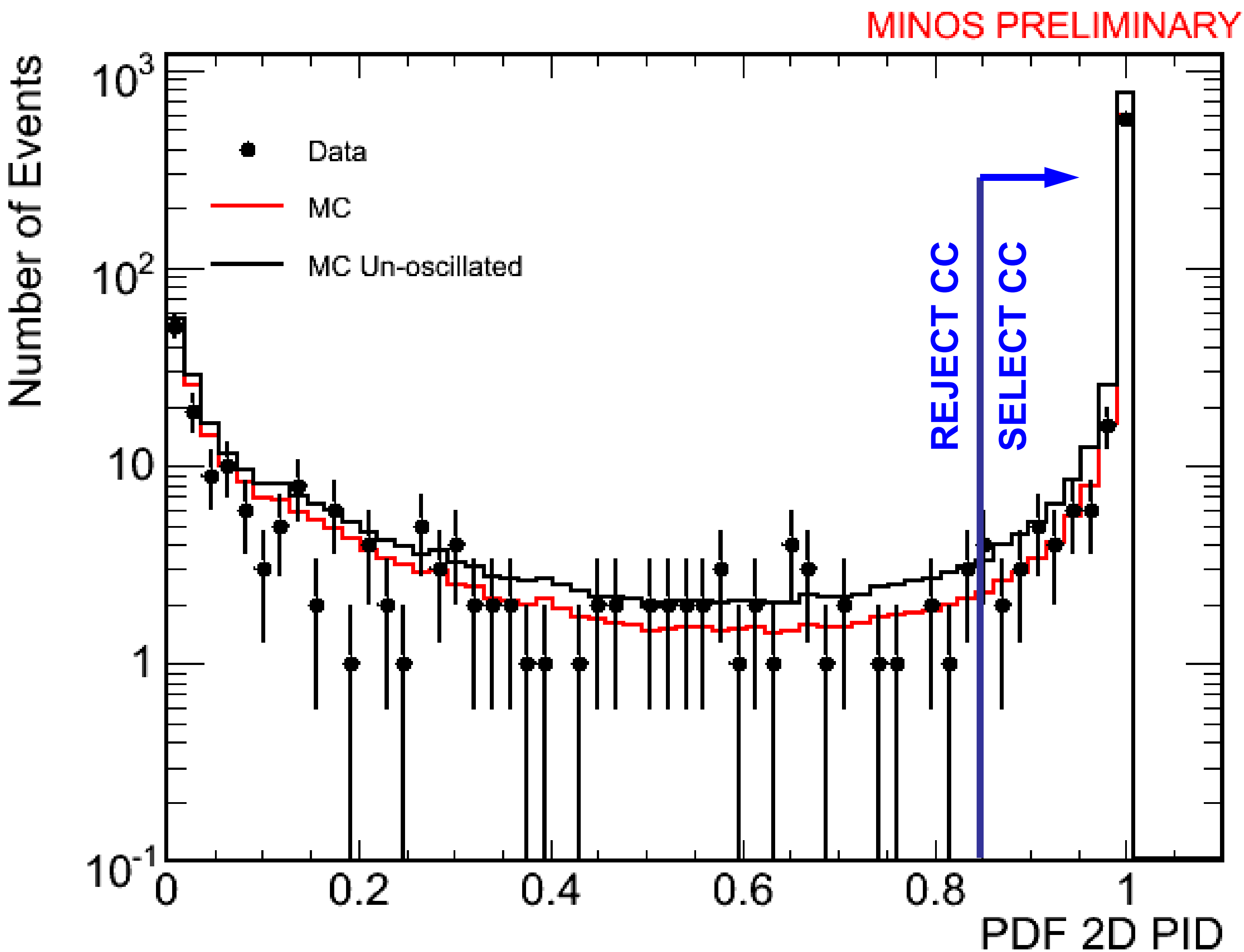


Far Detector Distributions

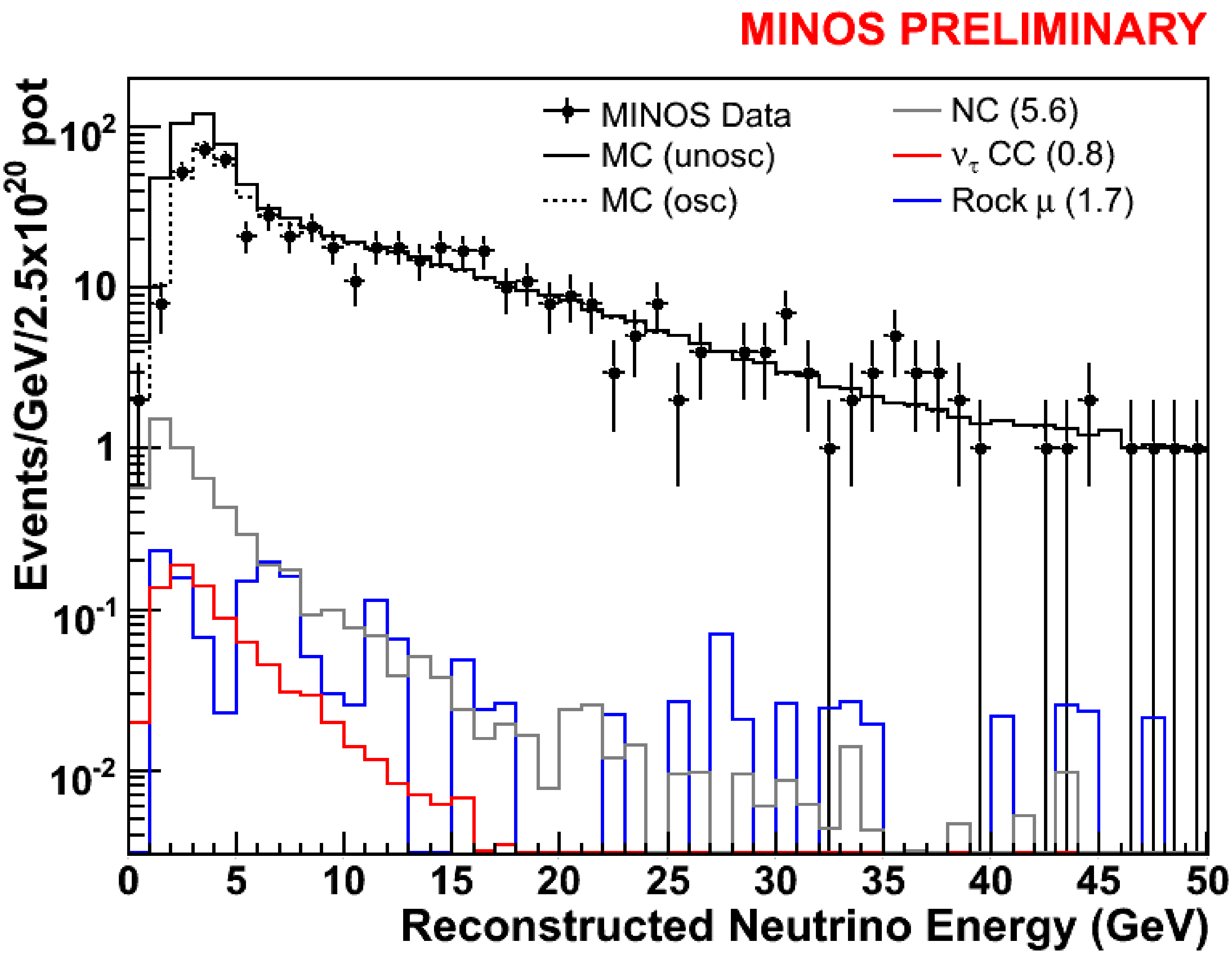


Far detector data is well described by oscillation best fit

Far Detector Distributions

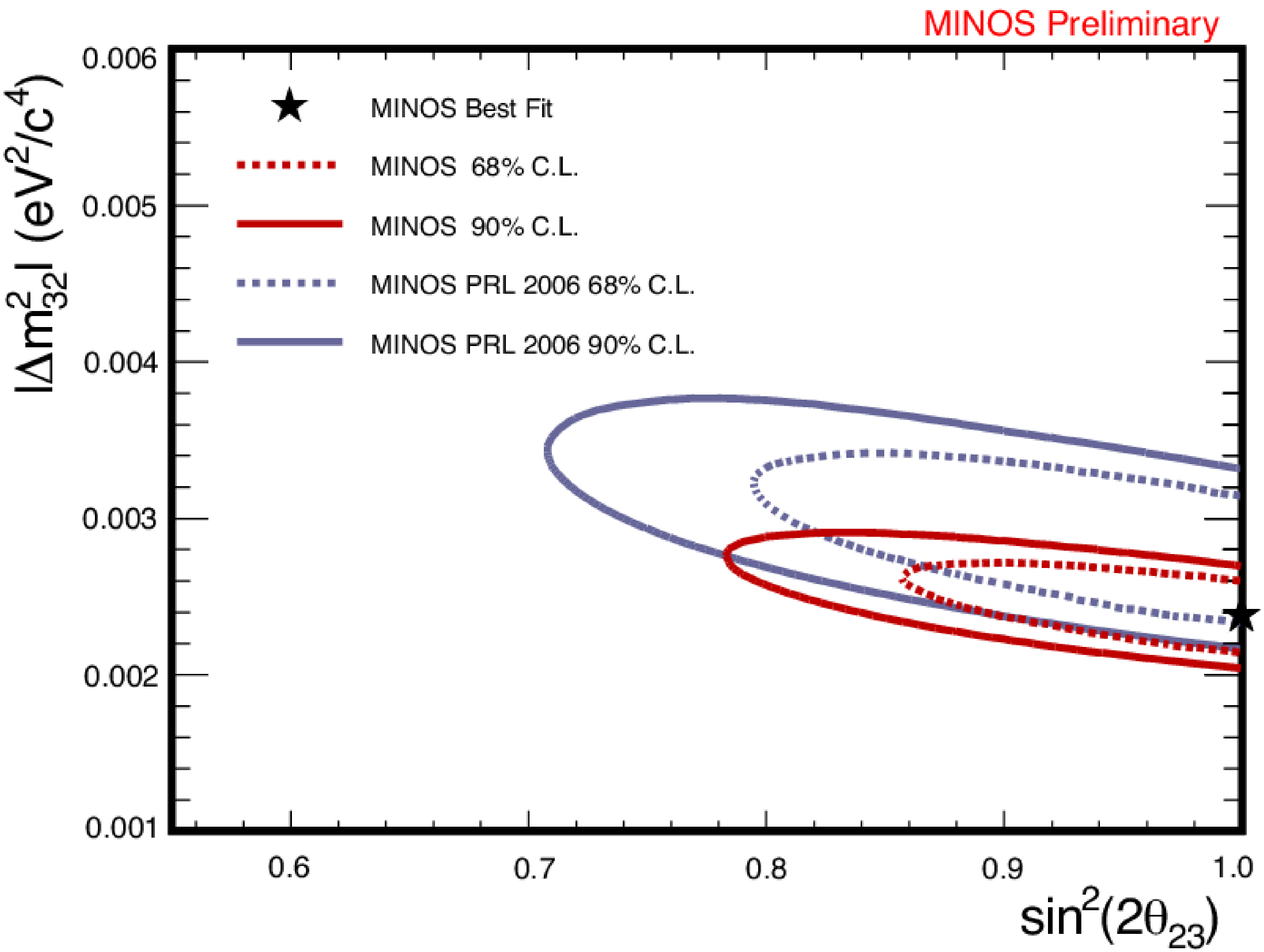


Far Detector Backgrounds



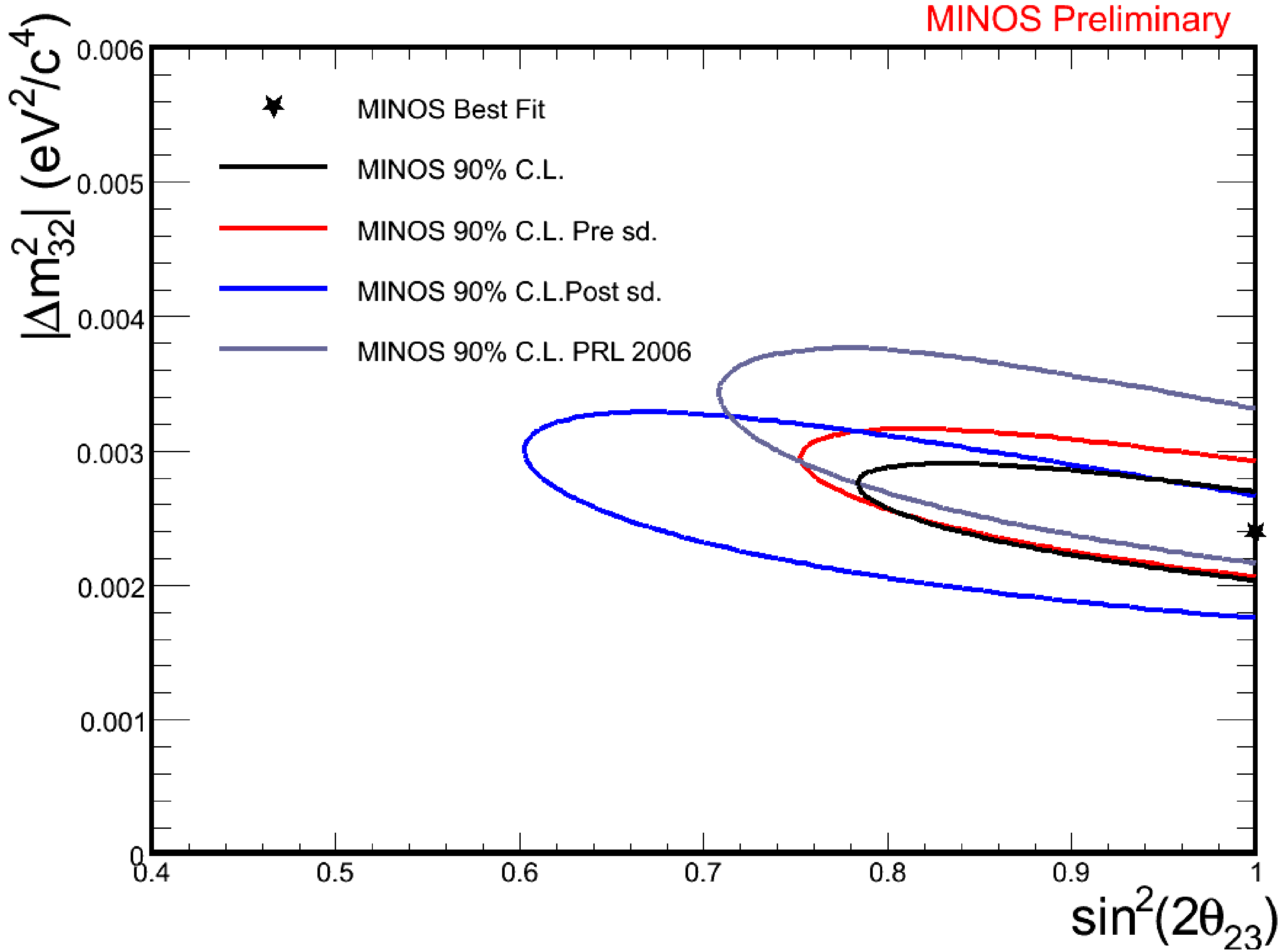
Comparison with 2006 Result

(PRL 97, 191801)



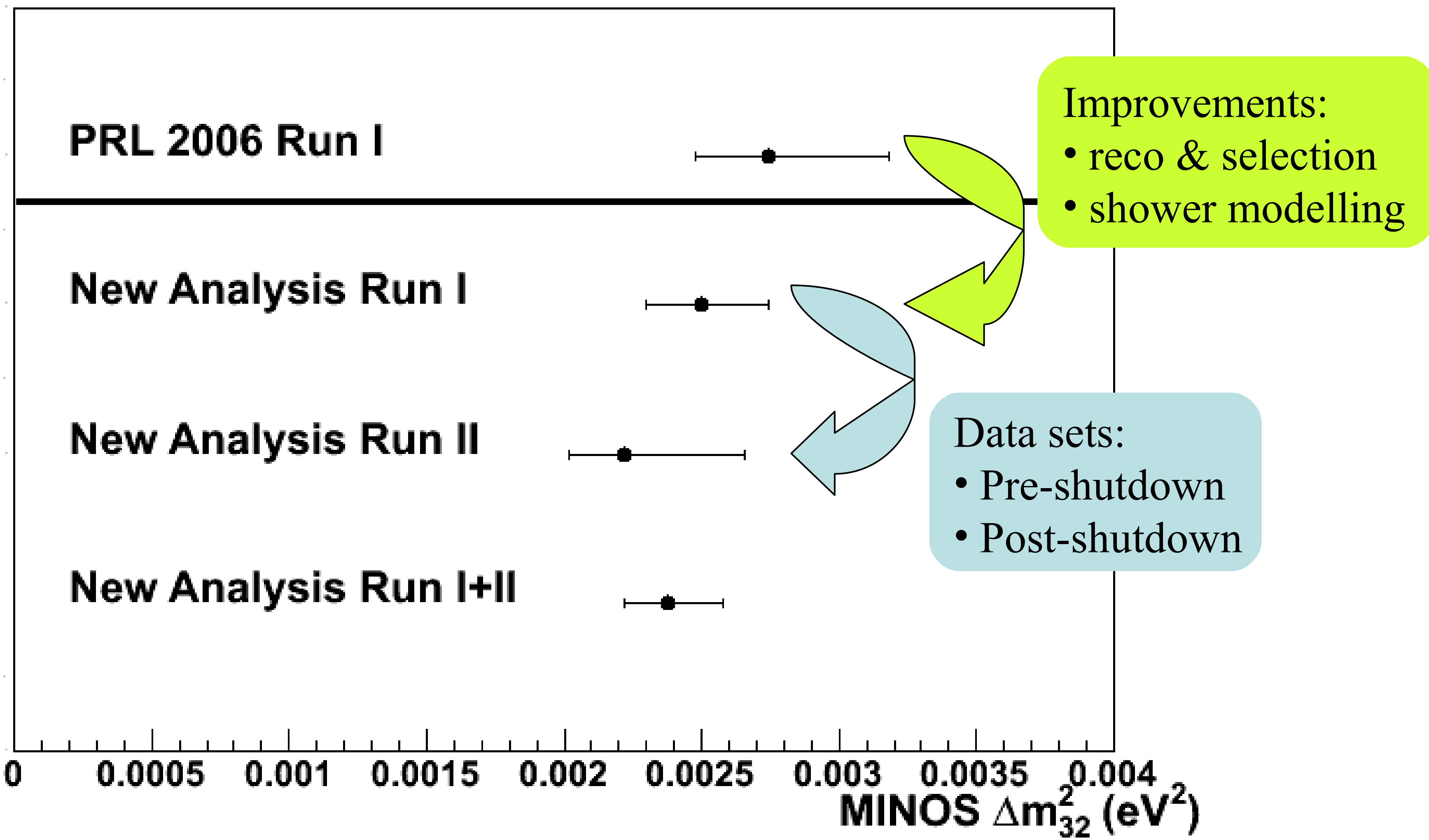
Comparison with 2006 Result

(PRL 97, 191801)

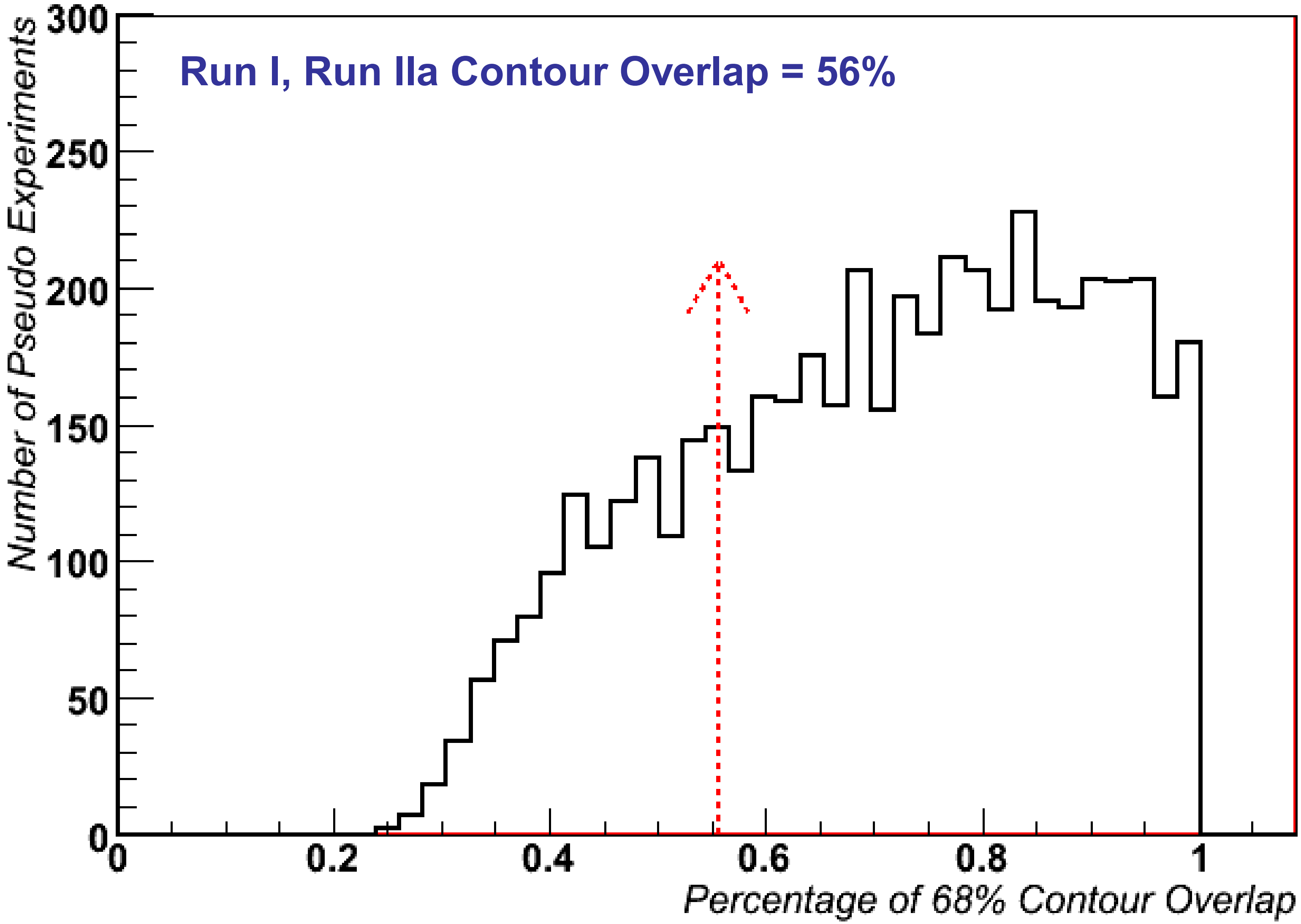


Changes from 2006 Result

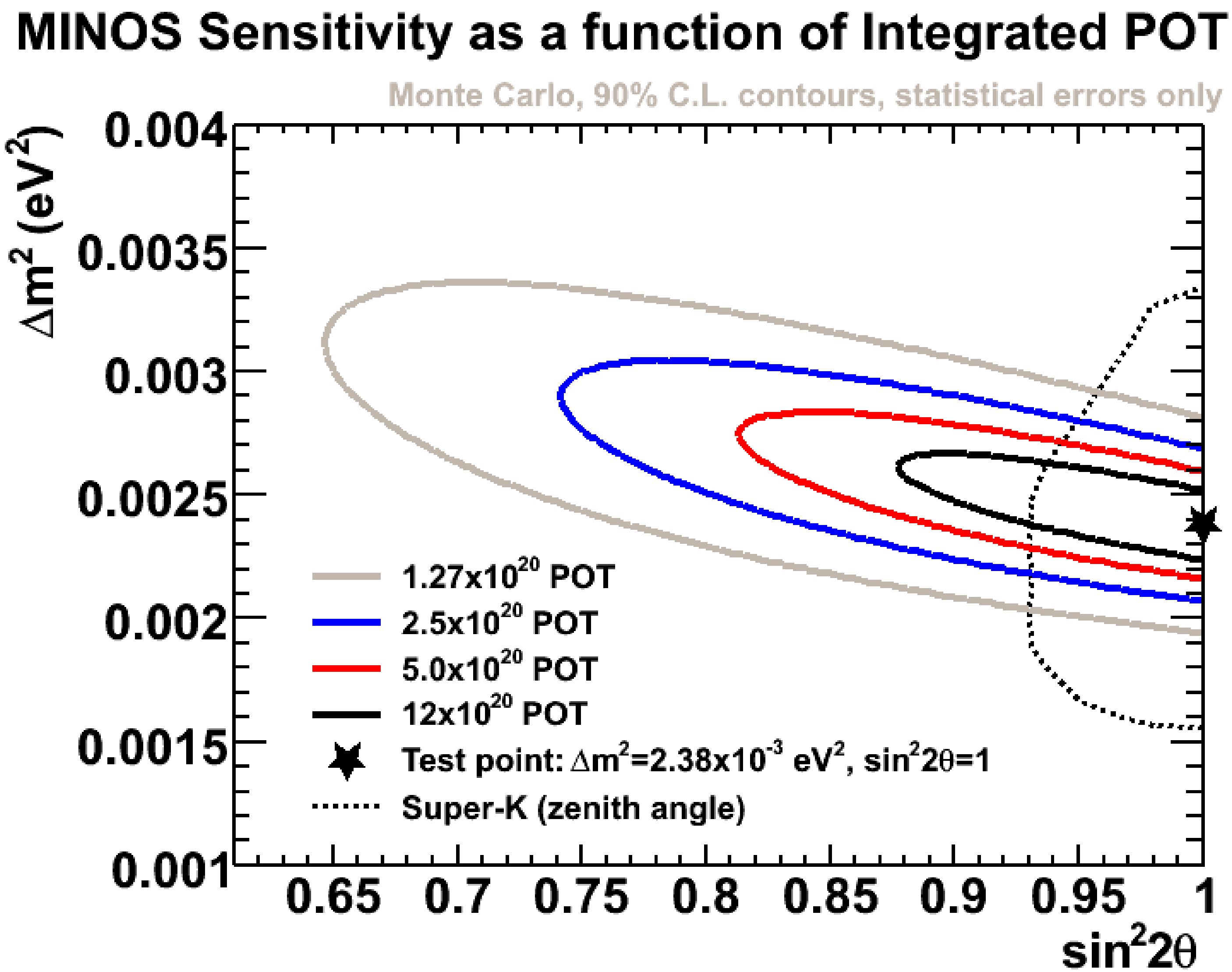
(PRL 97, 191801)



Comparison of Runs I and IIa

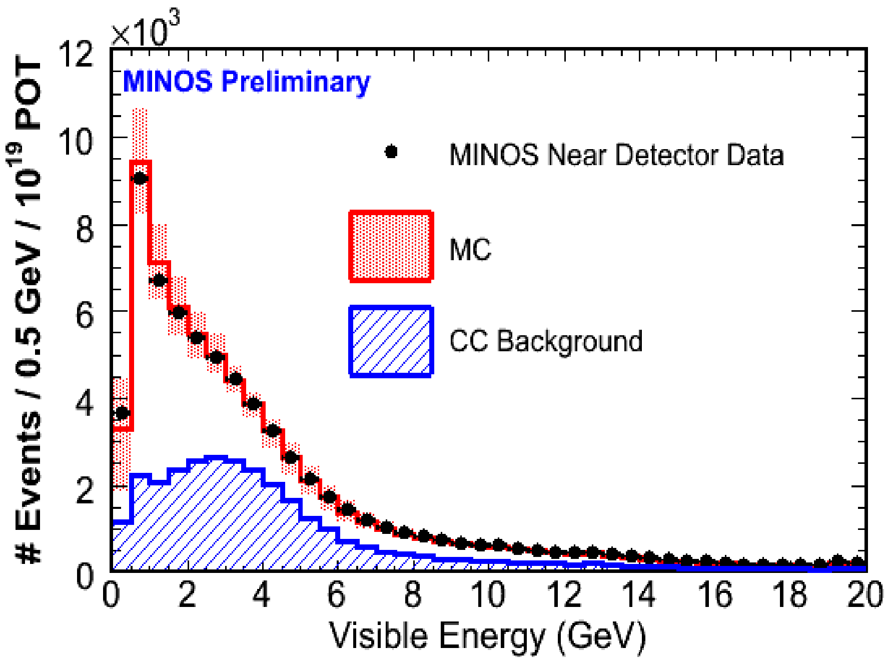


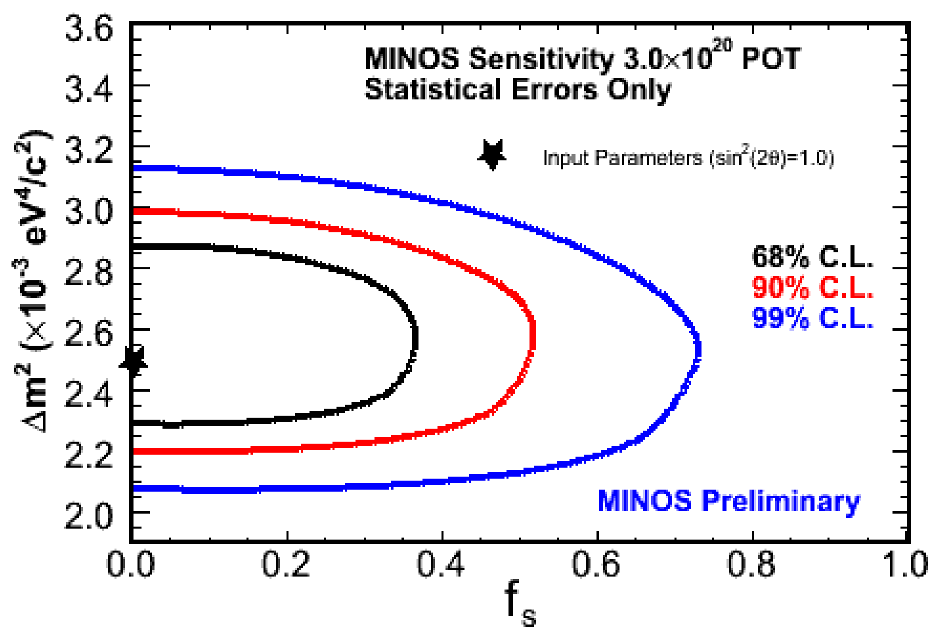
ν_μ Disappearance



NC Analysis

- Neutral current interactions are unaffected by standard oscillations, so can be used to constrain oscillations into sterile neutrinos.
- Define sterile mixing parameter f_s as the fraction of disappearing muon neutrinos that oscillate into sterile neutrinos.





- Far detector data for this analysis currently blinded – analysis in progress.

ν_e Appearance

- **MINOS can constrain or measure θ_{13} by searching for ν_e appearance.**
- **Challenges are to separate signal and understand background.**
  - NC events form dominant background.
  - Much effort has gone into developing techniques for distinguishing between electromagnetic and hadronic showers.
  - Data-driven techniques for background determination also in development.
- **MINOS sensitivity will soon be comparable with the current world best limit (CHOOZ).**