MINOS Experiment

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Outline

- Introduction
  - **The MINOS Experiment & Detectors, NuMI Beam**
  - **The MINOS collaboration & FNAL MINOS group**
- MINOS & NuMI this past year
  - **Performance, uptime, accumulated POT**
- A Selection of Recent Physics Results
  - **CC oscillation analysis**
  - **Cosmic Ray Charged Ratio**
- Physics in the pipeline
  - **NC event analysis**
  - **ν_e appearance analysis**

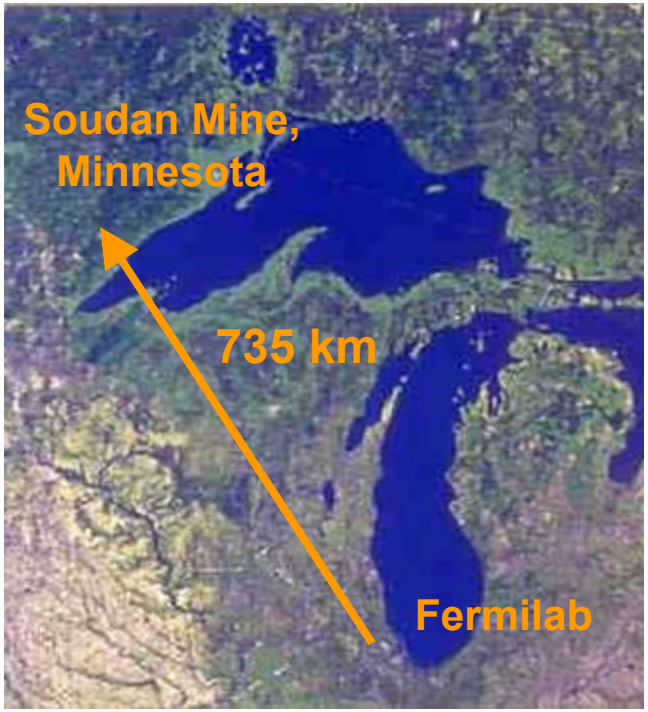
Introduction – MINOS Physics Goals

- 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. PRD 76, no. 5, Sep 20, 2007**

Introduction – MINOS Experiment

Main Injector Neutrino Oscillation Search
a two detector long baseline
ν oscillation experiment.

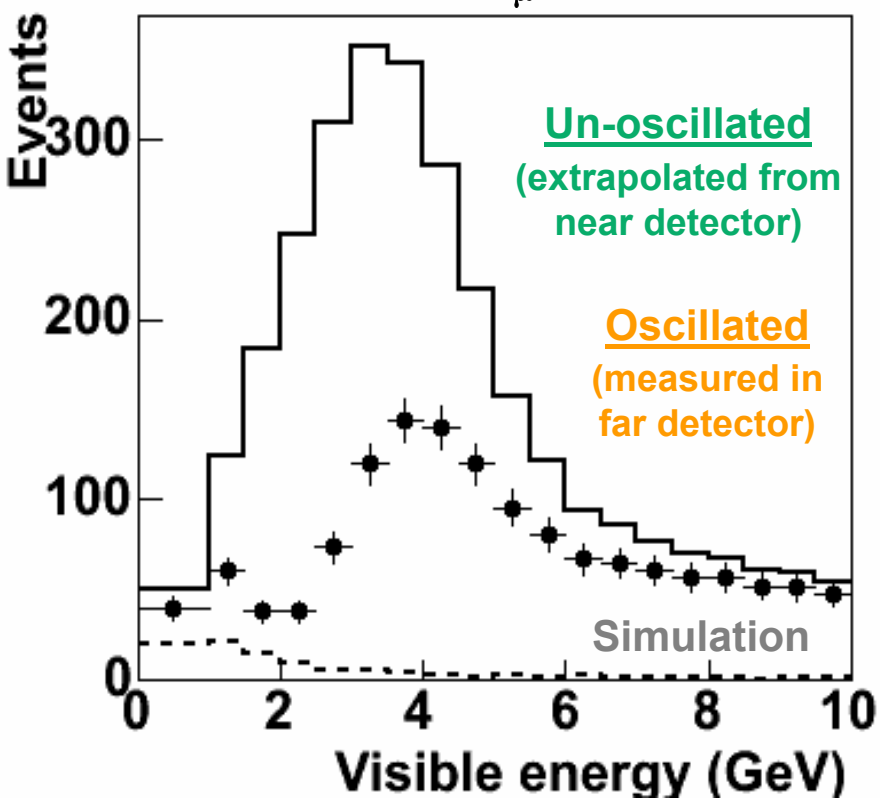
- **Accelerator beam of muon neutrinos, produced by NuMI facility at Fermilab.**
- **Use the Near Detector at Fermilab to measure the spectrum and composition of the neutrino beam. The measured ND spectrum is directly used to predict the Far Detector un-oscillated spectrum.**
- **Use the Far Detector at the Soudan mine to study neutrino disappearance in the beam. Beam production modeling and neutrino cross section uncertainties cancel out between the two Detectors.**



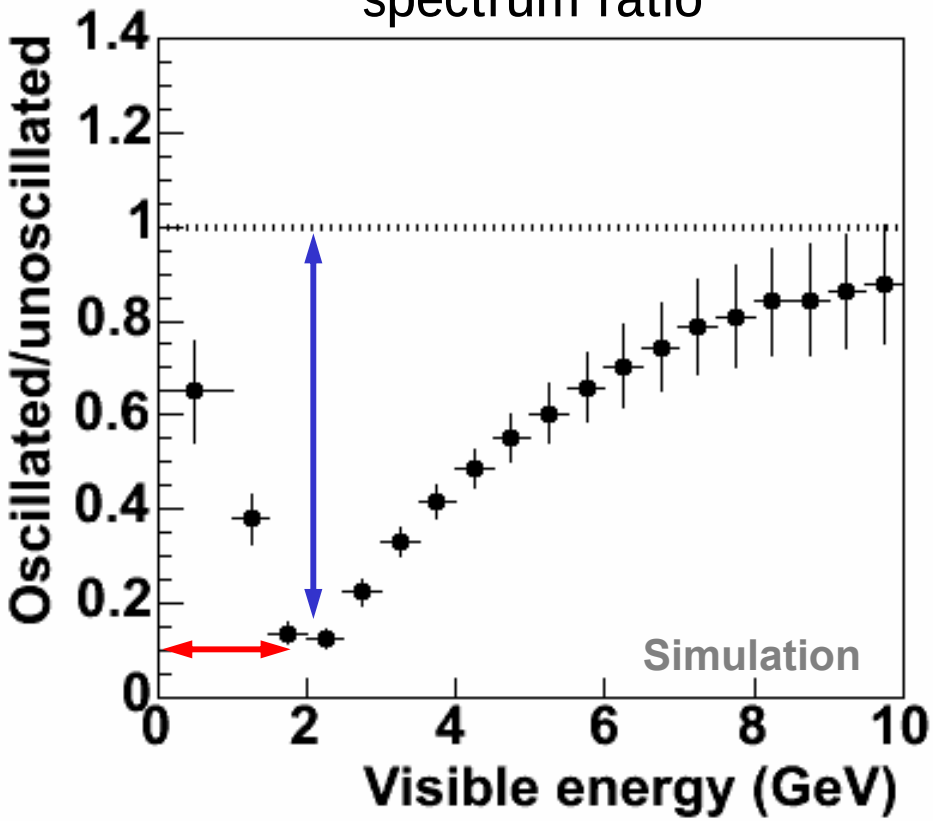
ν_μ Disappearance Measurement

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

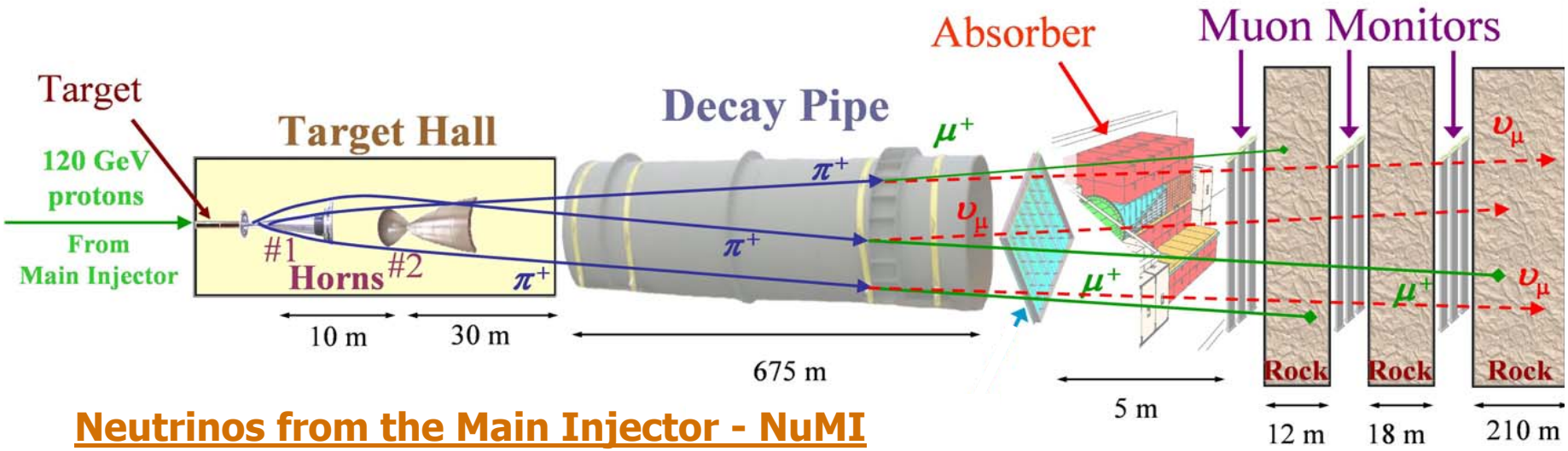
Far Detector ν_μ spectrum



spectrum ratio

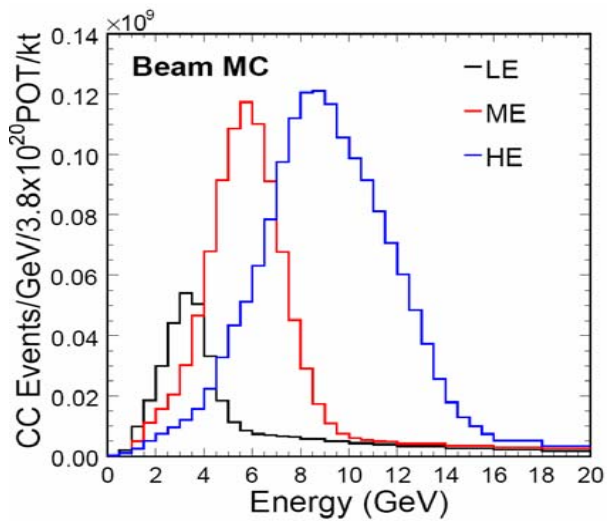


Introduction – NuMI Beam

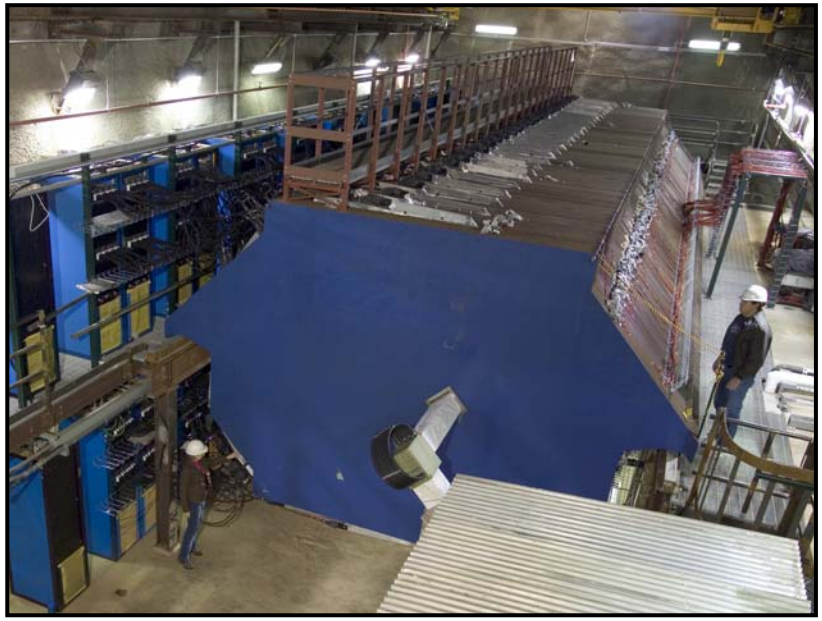


Neutrinos from the Main Injector - NuMI

- **120 GeV protons from Main Injector, directed onto 1λ graphite target**
- **10ms spills with 2.4s cycle time**
- **2.5 x 10^{13} protons per pulse**
- **Typical beam power ~175 kW**
- **Target position wrt focusing horns is moveable, making the beam energy spectrum configurable.**
- **Majority of running in LE configuration**



Introduction – 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 sandwich 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

MINOS Collaboration

30 institutions **175 physicists**

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

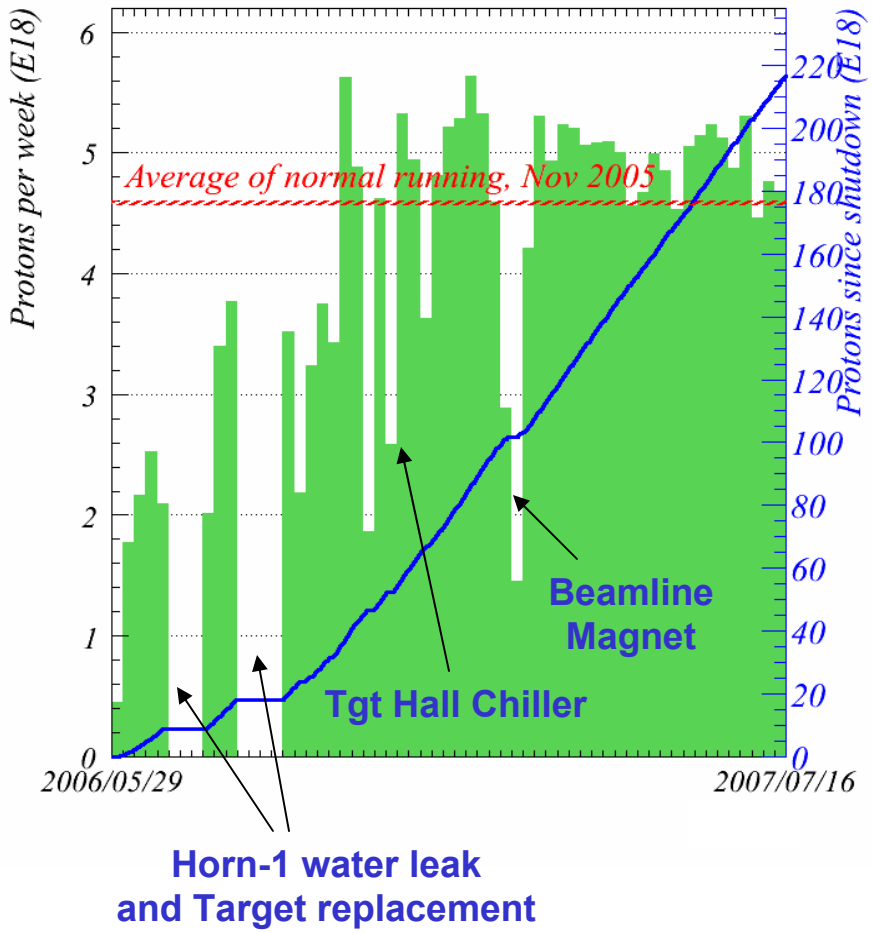
24 PhD theses from MINOS data so far – more on the way
Average since 2003 is 4 per year

FNAL MINOS Group

- 26 MINOS Collaborators in the FNAL group
  - **23 senior staff; 2 RAs; 1 Wilson Fellow**
  - **13 within PPD/Neutrino Department, 2 in other PPD Depts**
    - **3 are co-Convenors of Analysis Working Groups**
    - **Co-Spokesperson**
    - **Run Coordinator for the past 1.5 yrs**
  - **11 within Accelerator Div**
    - **6 cover NuMI Beam operations from the External Beams Dept**
    - **1 in the Main Injector Dept**
    - **4 in other departments**
  - **2 within Computing Div**

NuMI Beam Performance

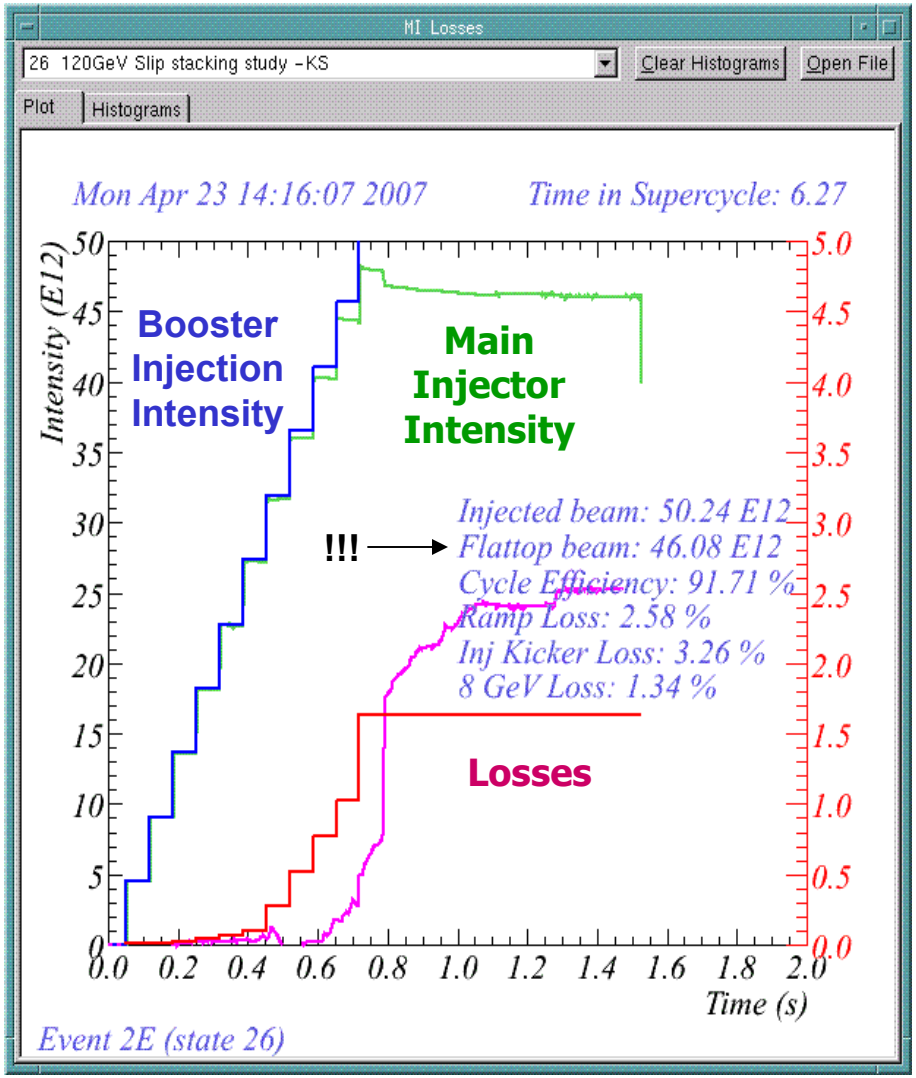
POT per week, June 2007 – July 2007



- **Good beam delivery for most of this past running period, June 1, 2006 through July 17, 2007**
  - **An early start to the Shutdown for the NuMI beam due to a Horn water leak, this time in Horn-2. Repairable.**
  - **Longest downtimes were due to NuMI-specific problems**

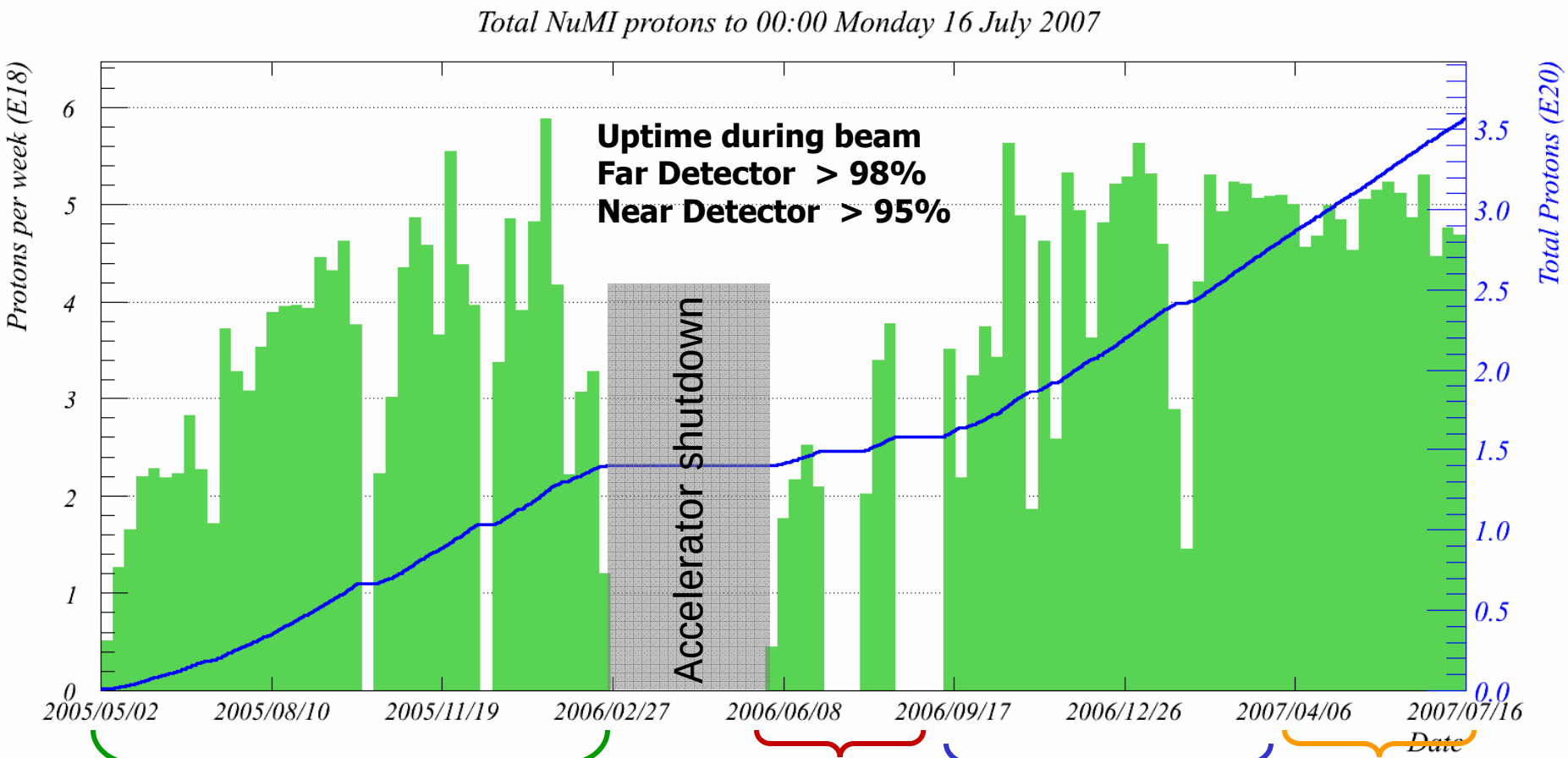
- **Protons on Target**
  - **For the running period - 2.2 E20**
  - **For Fiscal Year 2007 - 1.9 E20**
  - **Since last December -**
    - **Per pulse average 2.3 e13**
    - **Per week average 4.8 e18**

NuMI Beam Performance



- Big improvements on the way
  - **Slip-Stacking in the Main Injector works!**
  - **Doubles the per-pulse intensity to NuMI target, from about 2.3 e13 to ~4.0 e13 ppp**
  - **Works in the normal NuMI-PBar Mixed Mode**
  - **Only short tests during the last run, due to losses within MI. Installation of collimators in MI, proceeding now, will allow slip-stacking to be the normal running mode when we start up**

MINOS – data collection



Physics data set used for last year's results

1.27x10^{20} POT Run I

Higher ν beam energy study data

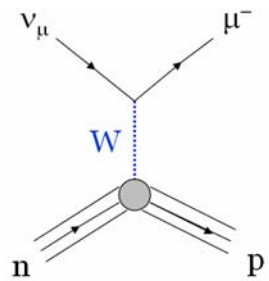
Physics data set added in for current analysis and results

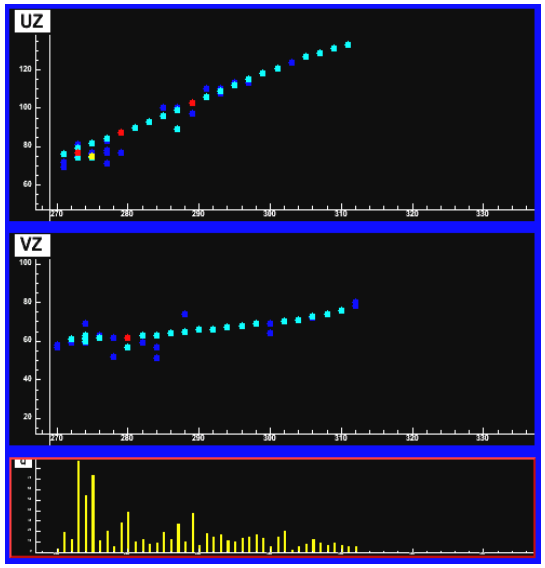
1.23x10^{20} POT Run IIa

RunIIb

Recent Results – CC oscillation analysis
Event Topologies

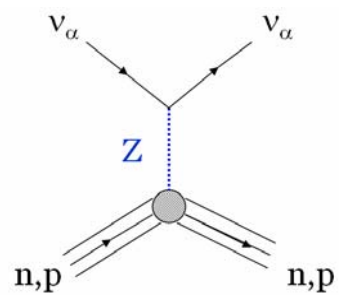
ν_μ CC Event

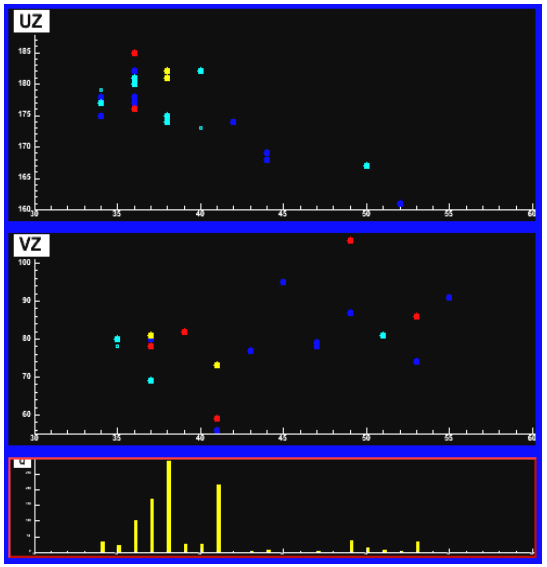




long μ track & hadronic activity at vertex

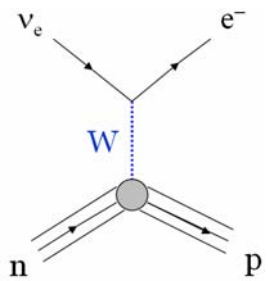
NC Event

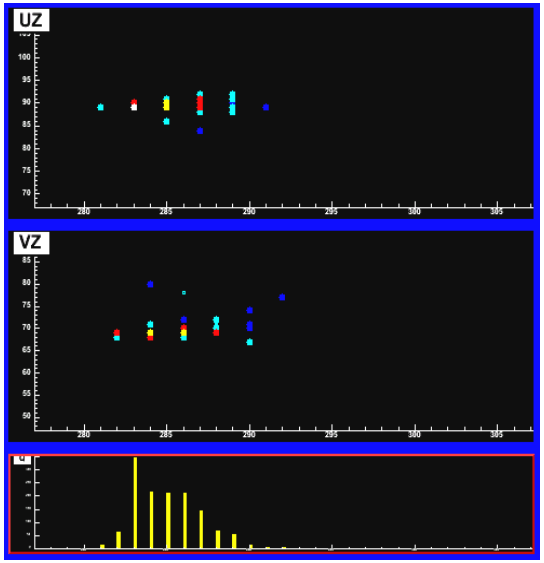




short event, often diffuse

ν_e CC Event



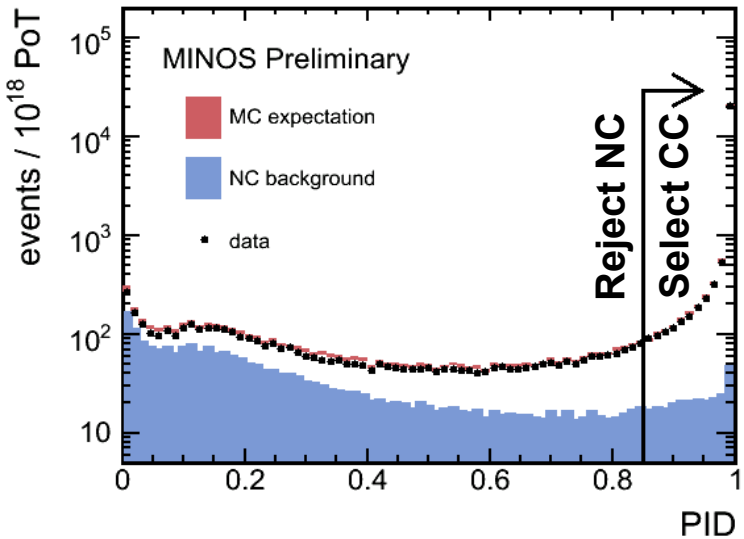


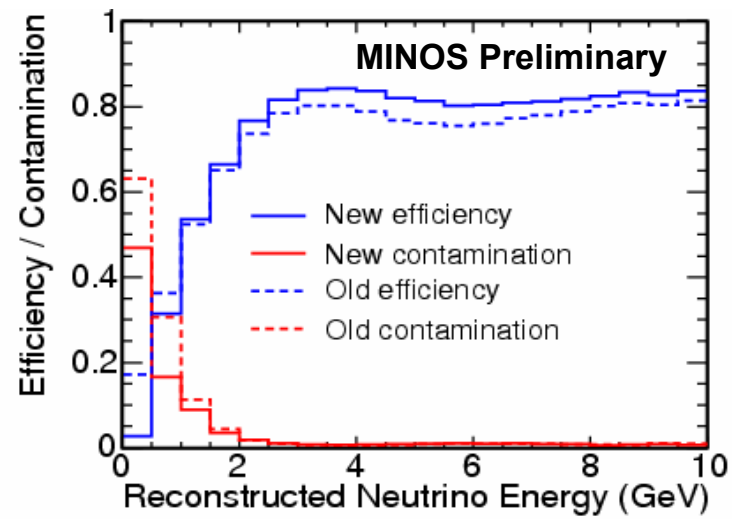
short, with typical EM shower profile

Recent Results – CC oscillation analysis
New and Improved Analysis

- Improvements over 2006 analysis
  - **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**
- Data and Monte Carlo agree well

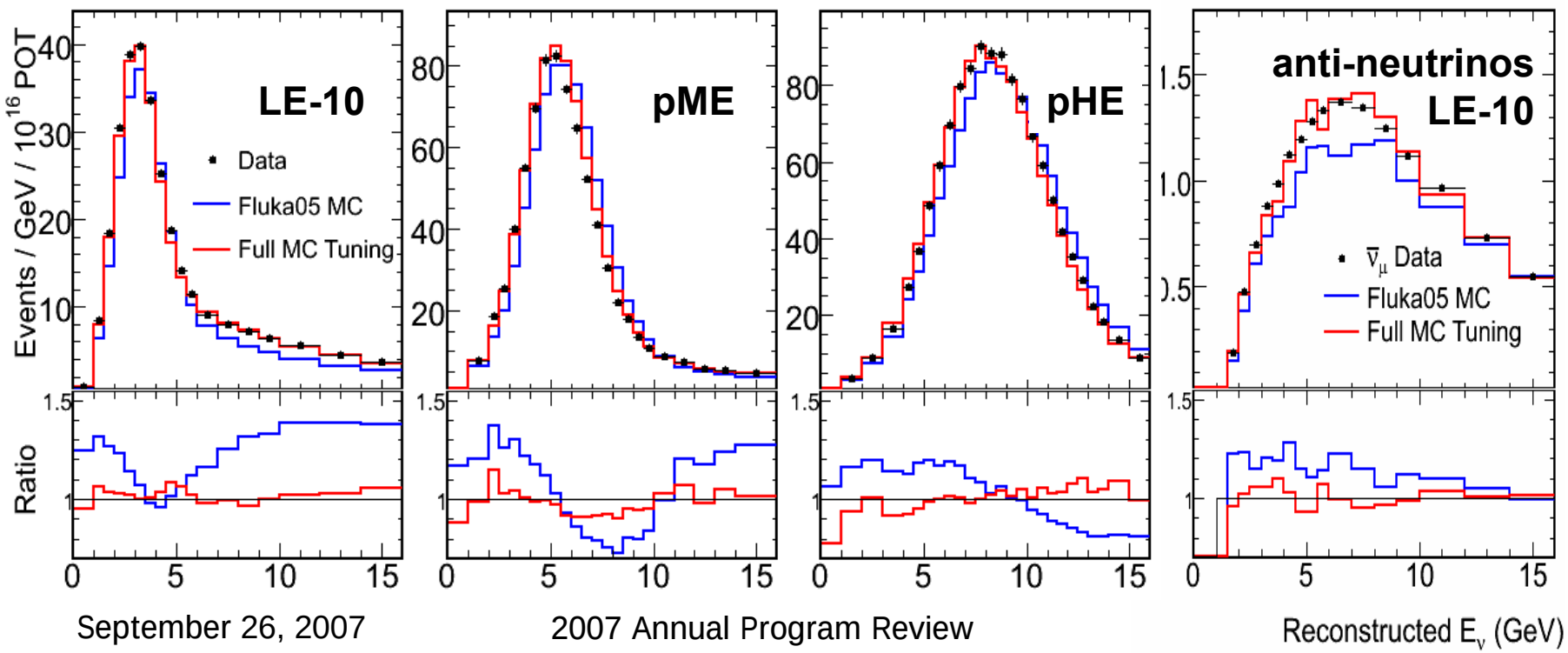
Improvement in selection
~1% more CC signal.
~50% less NC background.





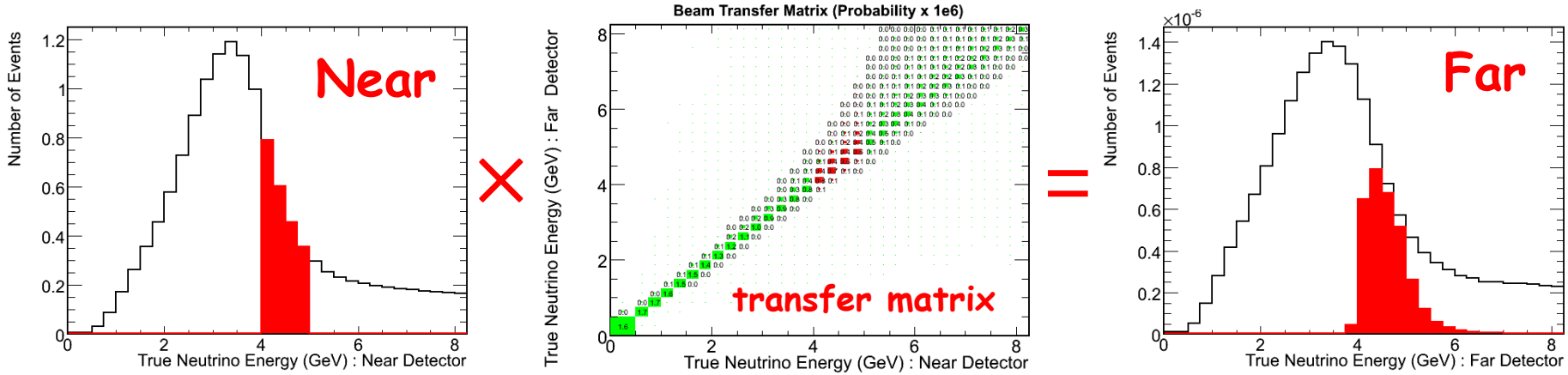
Recent Results – CC oscillation analysis
Hadron Production Tuning

- 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.



Recent Results – CC oscillation analysis
Predicting the Far spectrum

- **Directly use near detector data to extrapolate from near to far detector.**
  - **Use detector 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.**
  - **Beam Matrices that correspond to different hadron production models are very similar (spread in each column determined primarily by the geometry of the beamline)**



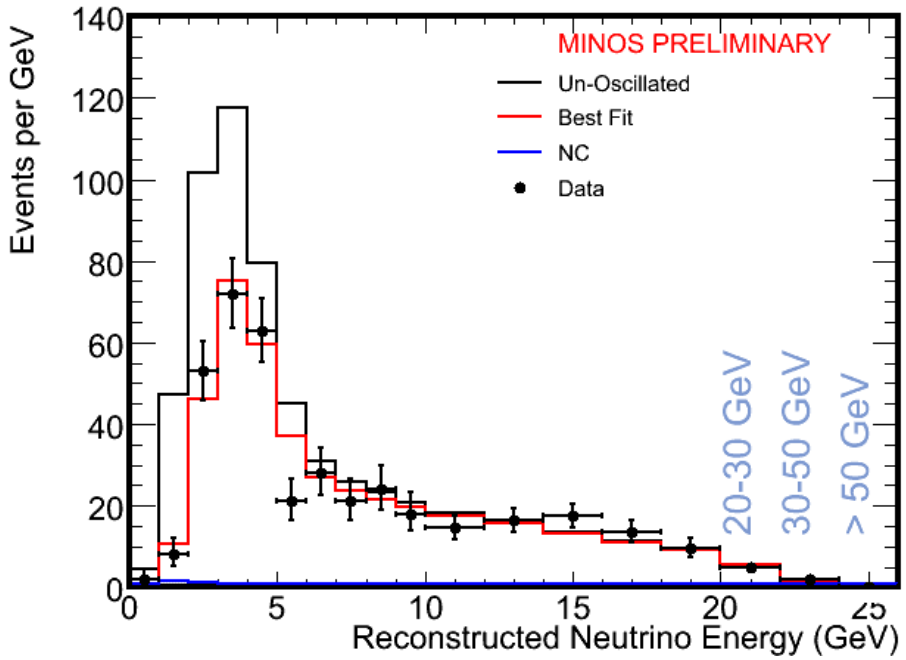
Recent Results – CC oscillation analysis
Systematic Uncertainties

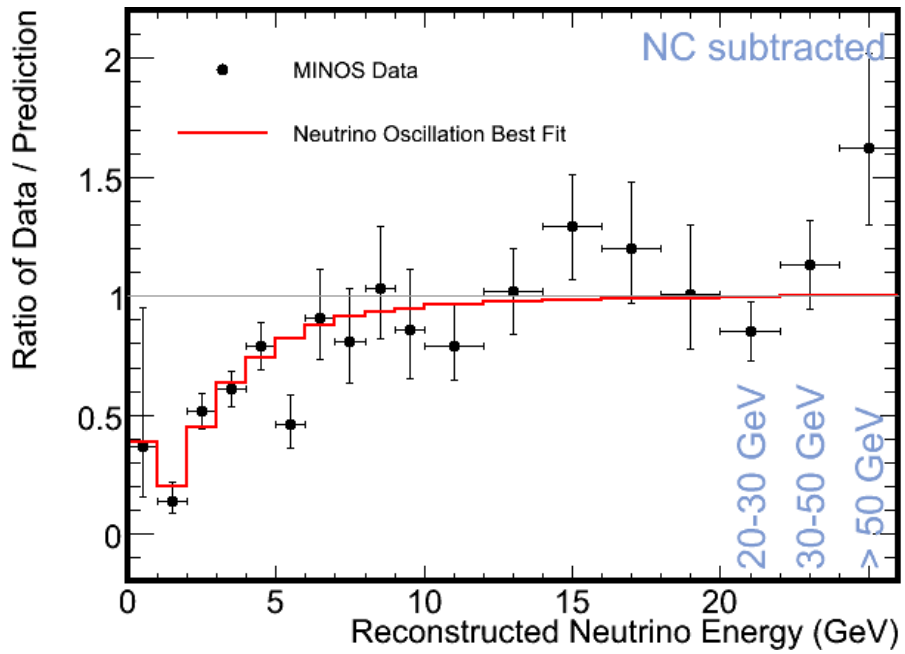
- Systematic uncertainties on oscillation parameters are evaluated by fitting fake data sets generated from MC with systematic shifts applied.
- The three largest uncertainties identified from this study are included as nuisance parameters in the oscillation analysis.

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

Recent Results – CC oscillation analysis

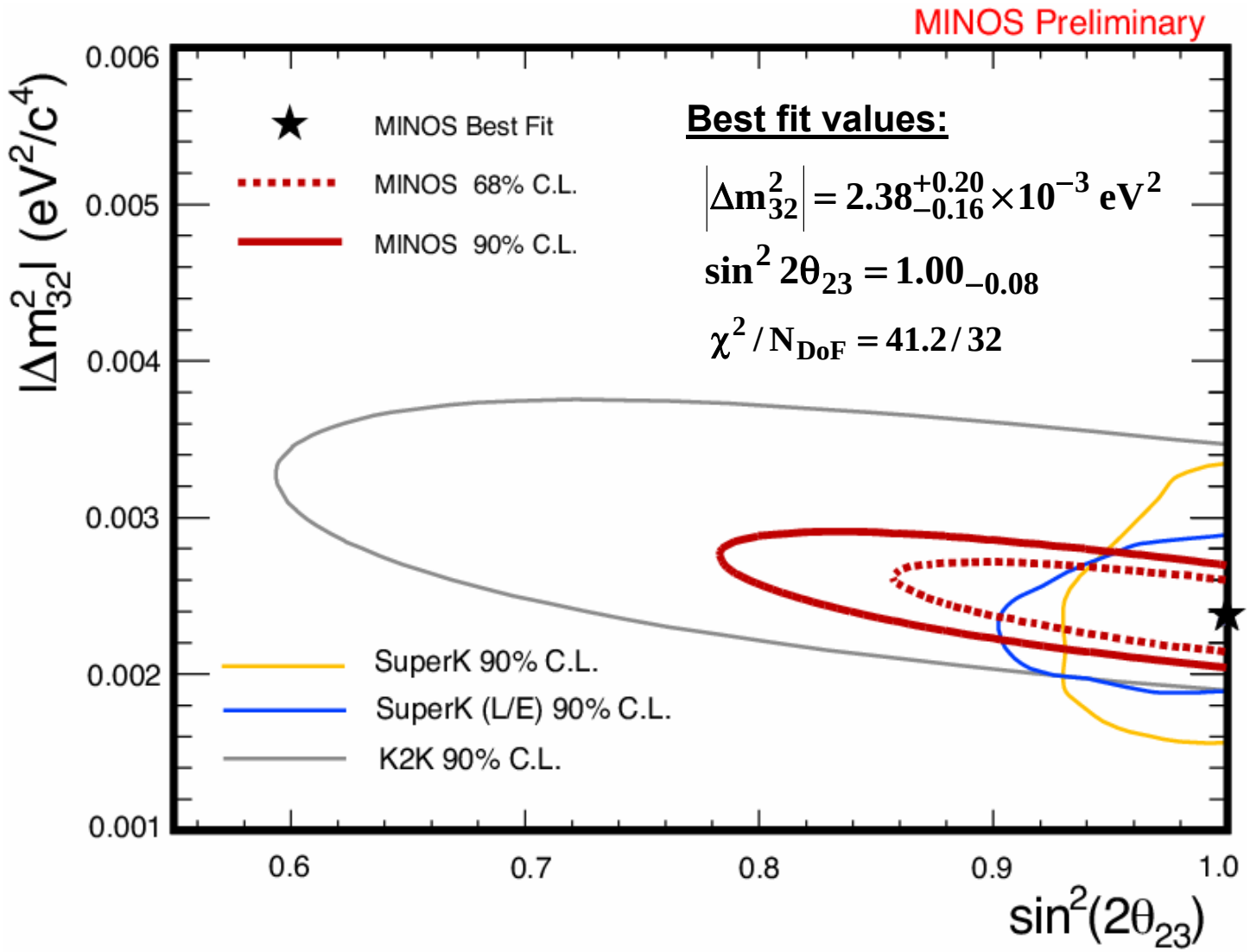
PRELIMINARY OSCILLATION RESULTS FOR 2.5x10^{20} POTs DATA.





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)

Recent Results – CC oscillation analysis
Allowed Parameter space



Best fit values:

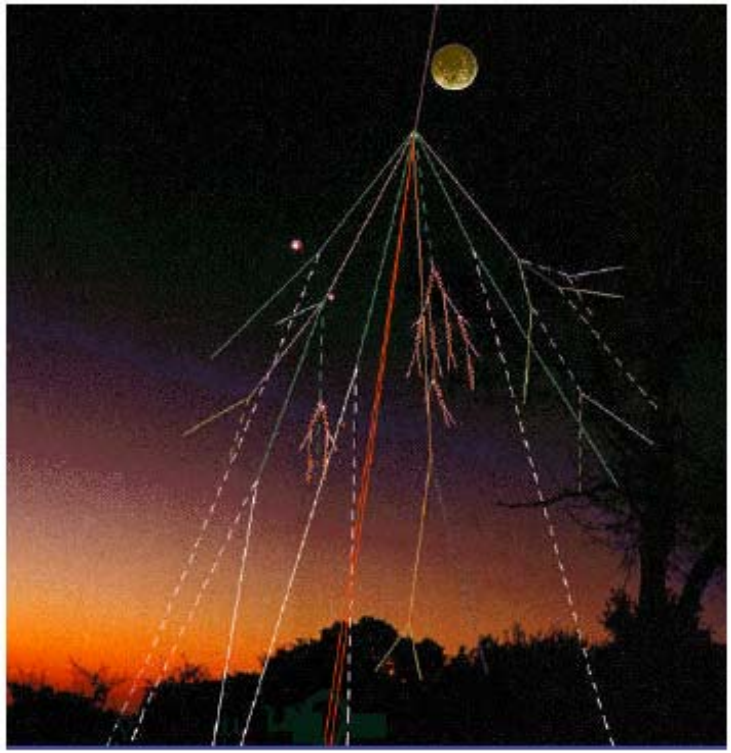
$$\left|\Delta m^2_{32}\right| = 2.38^{+0.20}_{-0.16} \times 10^{-3}\ \mathrm{eV}^2$$

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

$$\chi^2 / N_{DoF} = 41.2/32$$

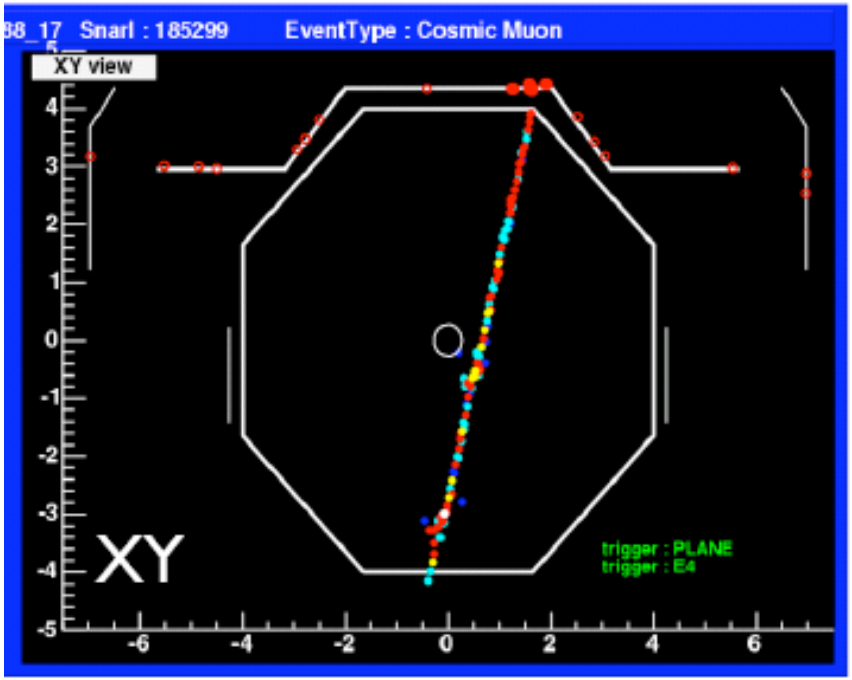
Recent Results – Cosmic Ray Charge Ratio

- **Cosmic ray muons are produced by primaries interacting in the upper atmosphere**
  - Cosmic ray primaries have positive charge – more positive pions and kaons are produced than negative
  - Charge ratio R of muons will be > 1
- **Charge ratio is important for modeling cosmic ray interactions. It also constrains atmospheric neutrino flux models and the ratio of neutrinos to anti-neutrinos**
  - Increasing importance of kaons leads to increased ration with increasing energy
  - Larger role from heavy elements leads to decreased ratio with increasing energy
  - Increase in charm production leads to decreased ratio with increasing energy



$$R = \frac{N_{\mu^+}}{N_{\mu^-}}$$

Recent Results – Cosmic Ray Charge Ratio



- **It can seem easy to pick out cosmic ray muons in the Far Detector, but it can be harder to determine the charge of the track.**
  - **High energy muons from cosmics don't bend much as they pass through**
  - **Fiducial volume is chosen where the B field is best known and strongest**
  - **Selected events have to come in with some angle so as to pass through multiple planes, see more Bdl**

- **With a set of selected events with measured charge and energy, one gets the muon charge ratio <u>underground</u>**
- **To get the charge ratio at the surface, one has to project these events back to the surface, through a column of rock, and calculate their energy loss in the rock to obtain their energy at the surface**
  - **Involves a knowledge of the local geology**

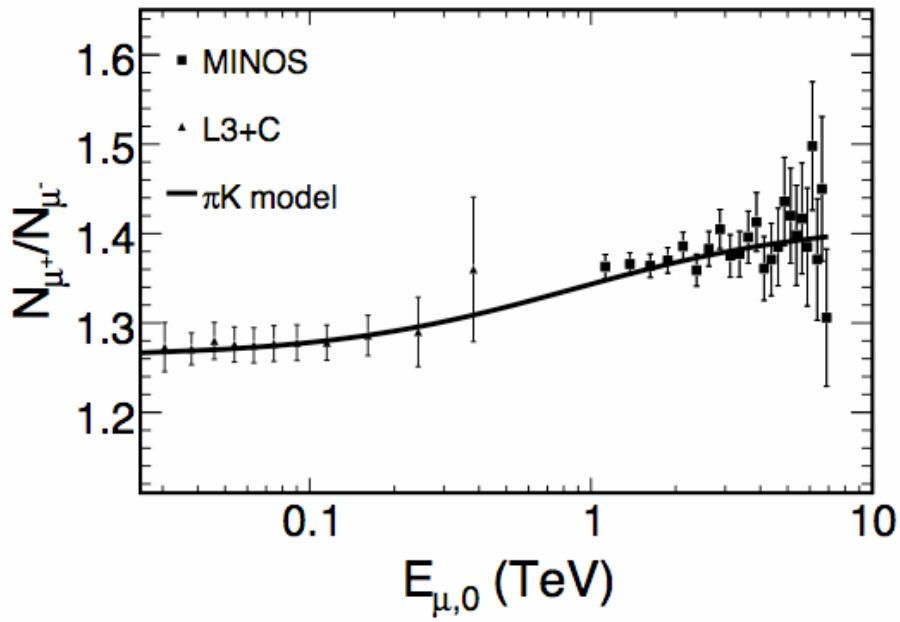
Recent Results – Cosmic Ray Charge Ratio

Charge ratio measured by MINOS over the data's energy range

1.371 ± 0.003(stat) + 0.012 - 0.010(sys)

A larger value than measured by CERN L3, but also a different energy range

Make a qualitative model, using ratios of +/- pions and +/- kaons which change as a function of energy, to fit the data, shown by the line in the plot

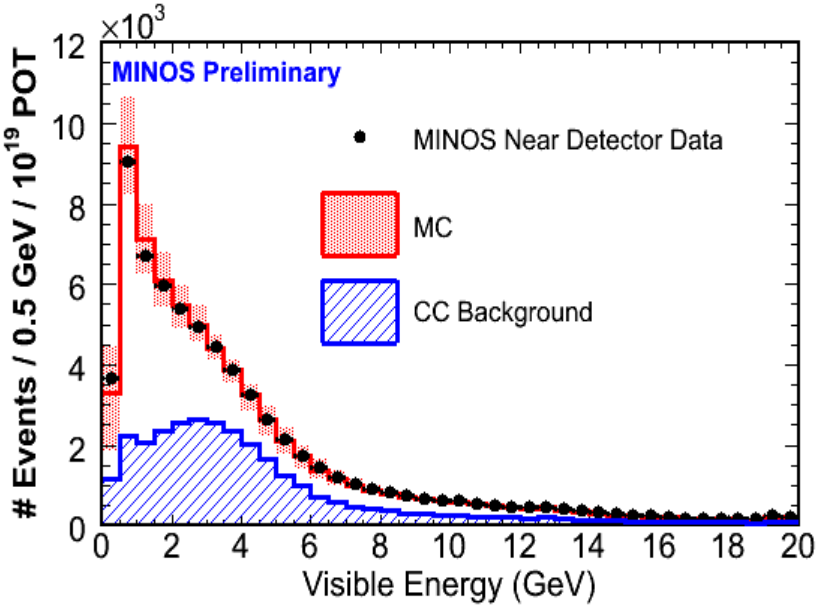


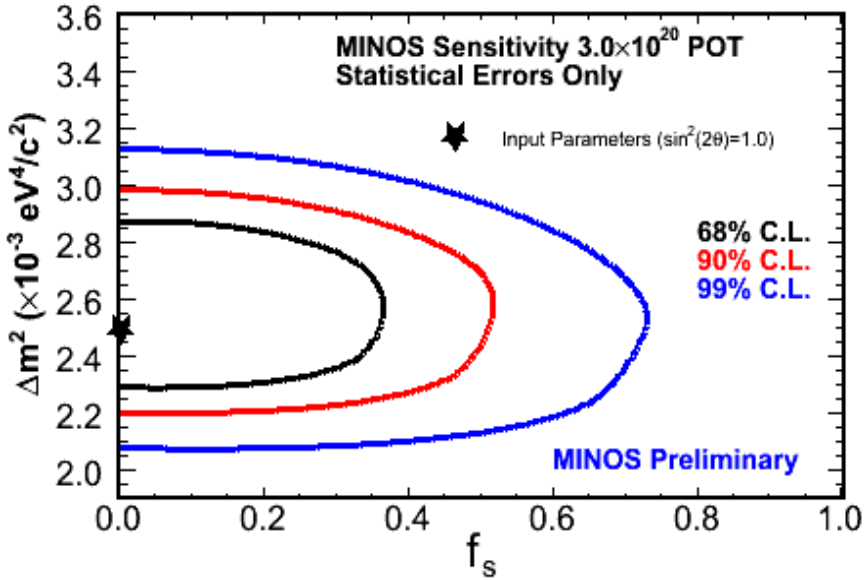
This result was a highlight of this year's Cosmic Ray conference in Mexico And was also featured in last week's TAUP2007 conference in Japan

Just published this week - PRD 76 Num 5, Sep 20 2007

Results in the pipeline - 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.**

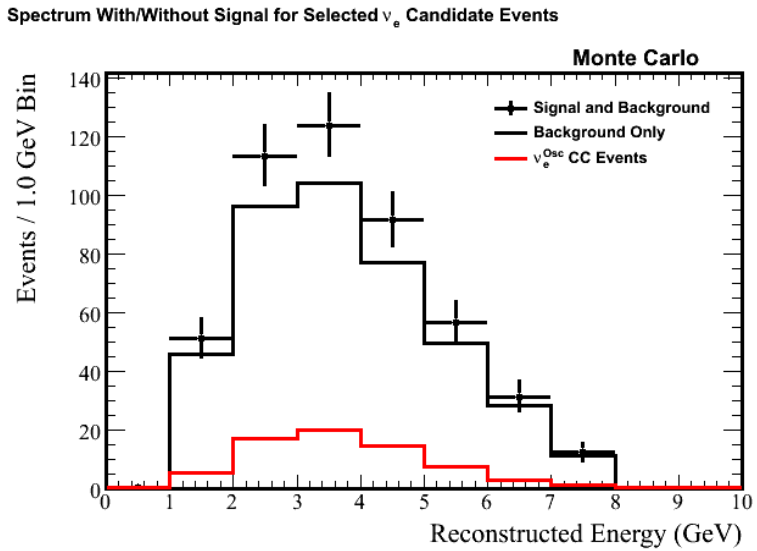


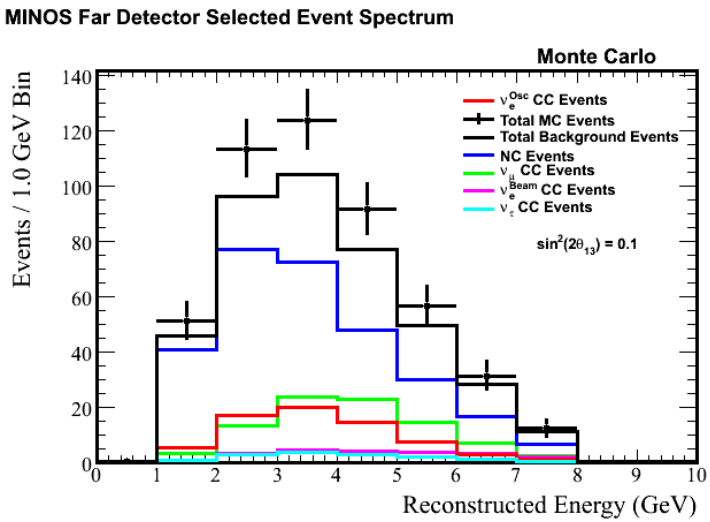


- **Similar style of event selection to the CC analysis, but opposite emphasis**
- **Far detector data for this analysis currently blinded – discussion on the un-blinding process TBD at this week's collaboration meeting.**

Results in the Pipeline - ν_e Appearance Analysis

- **MINOS can constrain or measure θ_{13}, near current limits, by looking for ν_e appearance.**
  - **Challenges are to separate signal and understand background, dominated by NC events**
  - **Much effort has gone into developing techniques for distinguishing between electromagnetic and hadronic showers.**
- **Near Detector events are extrapolated to predict the background rate in the Far Detector, and the prediction compared with the data.**
- **If there is a signal this will provide a measurement of θ_{13}.**

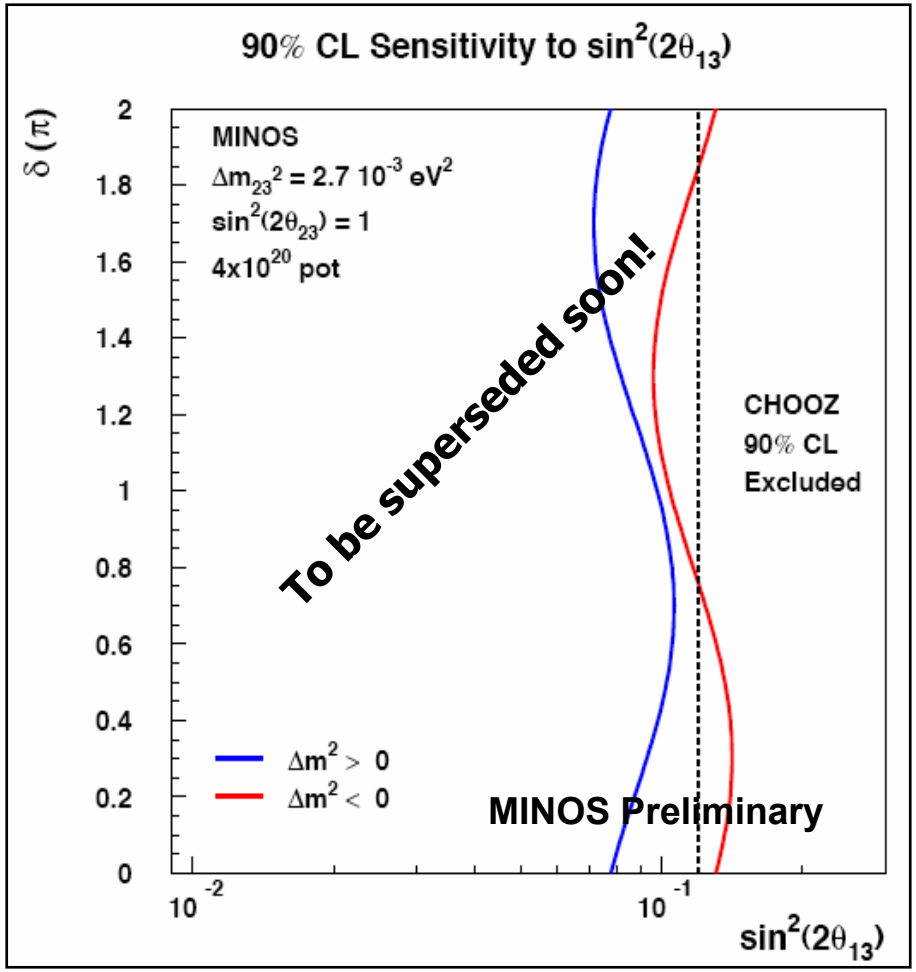




Results in the Pipeline - ν_e Appearance Analysis

- **The analysis group expects to "open the box" by the end of this year and have a result whose reach is comparable to the current Chooz limit.**
- **Plot shows δ_{CP} vs. $\sin^2 2\theta_{13}$ for both hierarchies for MINOS best fit value at 4×10^{20} POT.**
  - **Plot is based on early Monte Carlo that is being superseded by a data driven sensitivity method using the latest MC version**

ν_e physics reach of MINOS



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.**

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

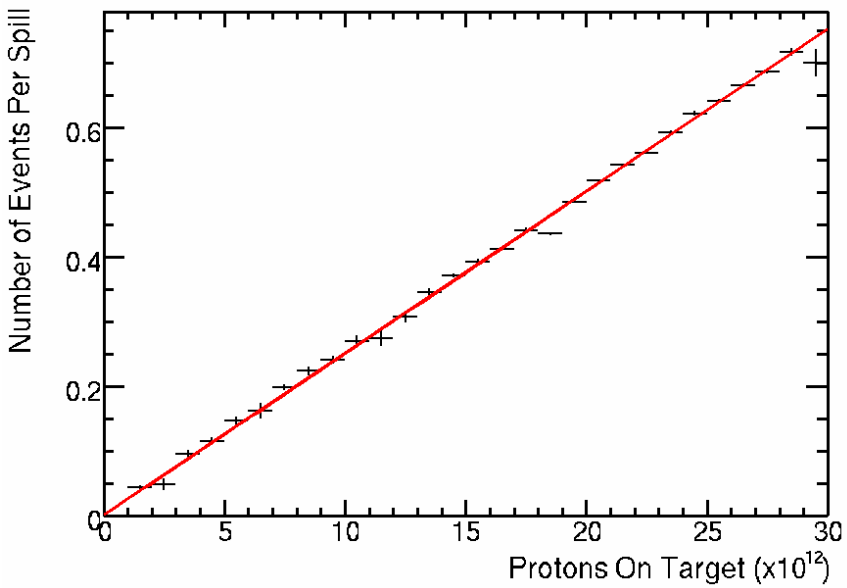
$$\sin^2 2\theta_{23} = 1.00_{-0.08}$$

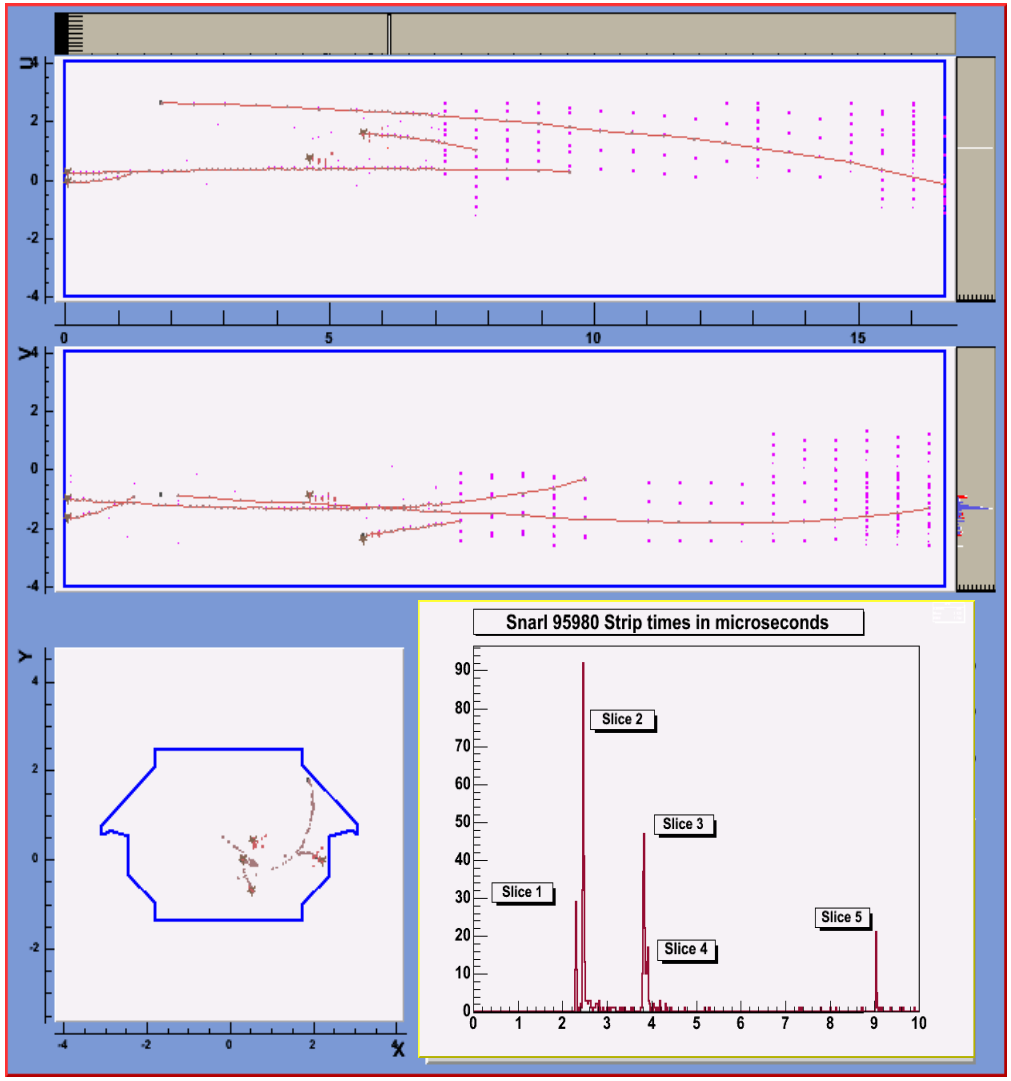
- **Other oscillation analyses using beam data are progressing.**
  - **ν_e appearance, anti-ν_μ disappearance, sterile neutrinos…**
- **Updated atmospheric and cosmic ray results.**
  - **developing combined analysis of all MINOS atmospheric neutrino data.**

Backup Slides

Near Detector Events

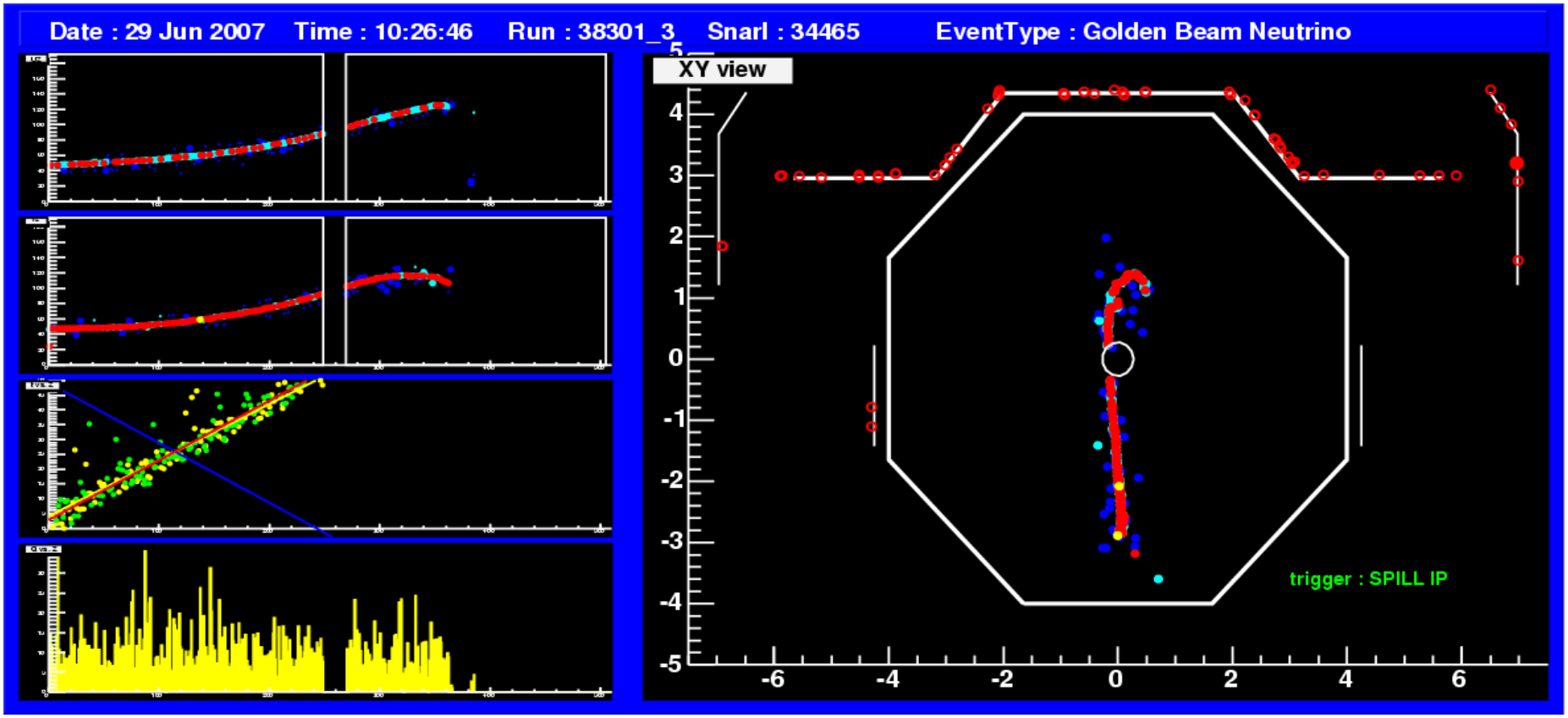
- **High event rate in near detector.**
  - Multiple interactions per spill.
- **Events separated based on topology and timing.**
  - Timing resolution ~20 ns
  - Spatial resolution ~4 cm
- **No significant bias in event rate.**





Far Detector beam neutrino ID

- **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.

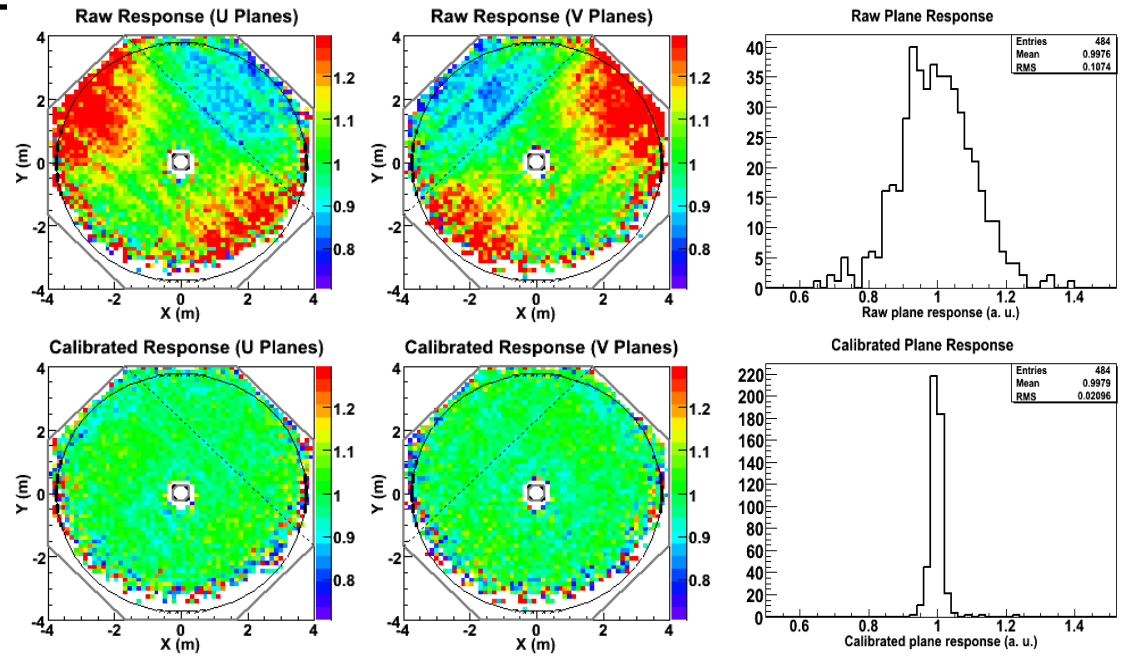


MINOS Detector Calibration

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

Calibration Error:

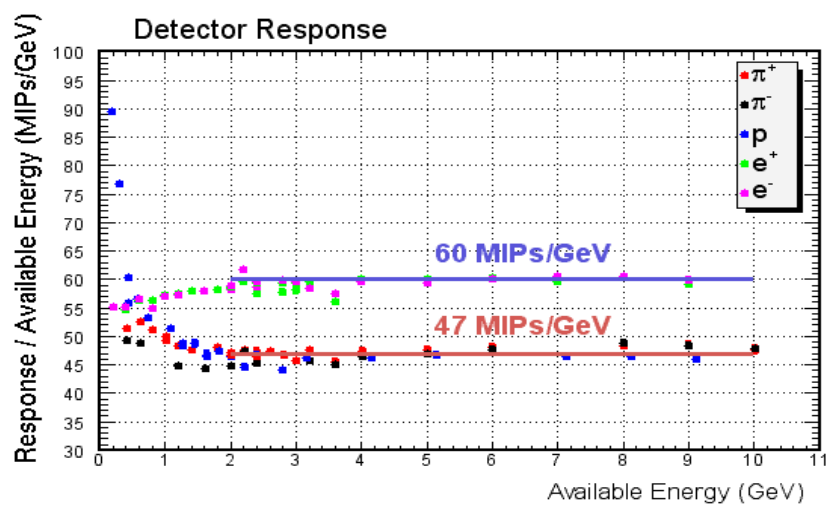
- ND calibration: 3.1%
- FD calibration: 2.3%
- ND/FD calibration: 3.8%



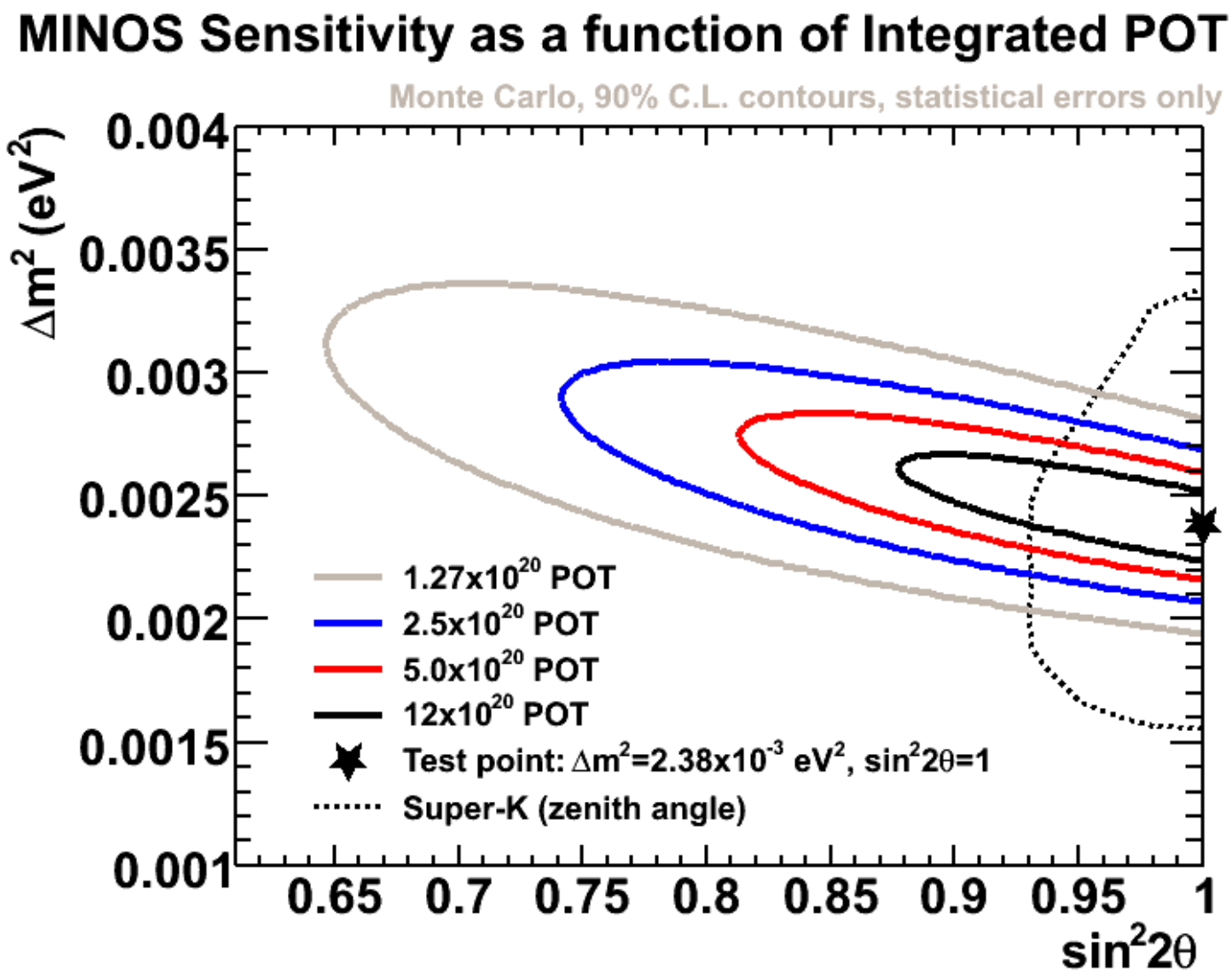
- **Overall Energy Scale:**
  - Calibration detector at CERN measured e/μ/π/p response.

Energy Resolution (E in GeV):

- Hadrons: $56\%/\sqrt{E} \oplus 2\%$
- Electrons: $21\%/\sqrt{E} \oplus 4\%/E$



ν_μ Disappearance

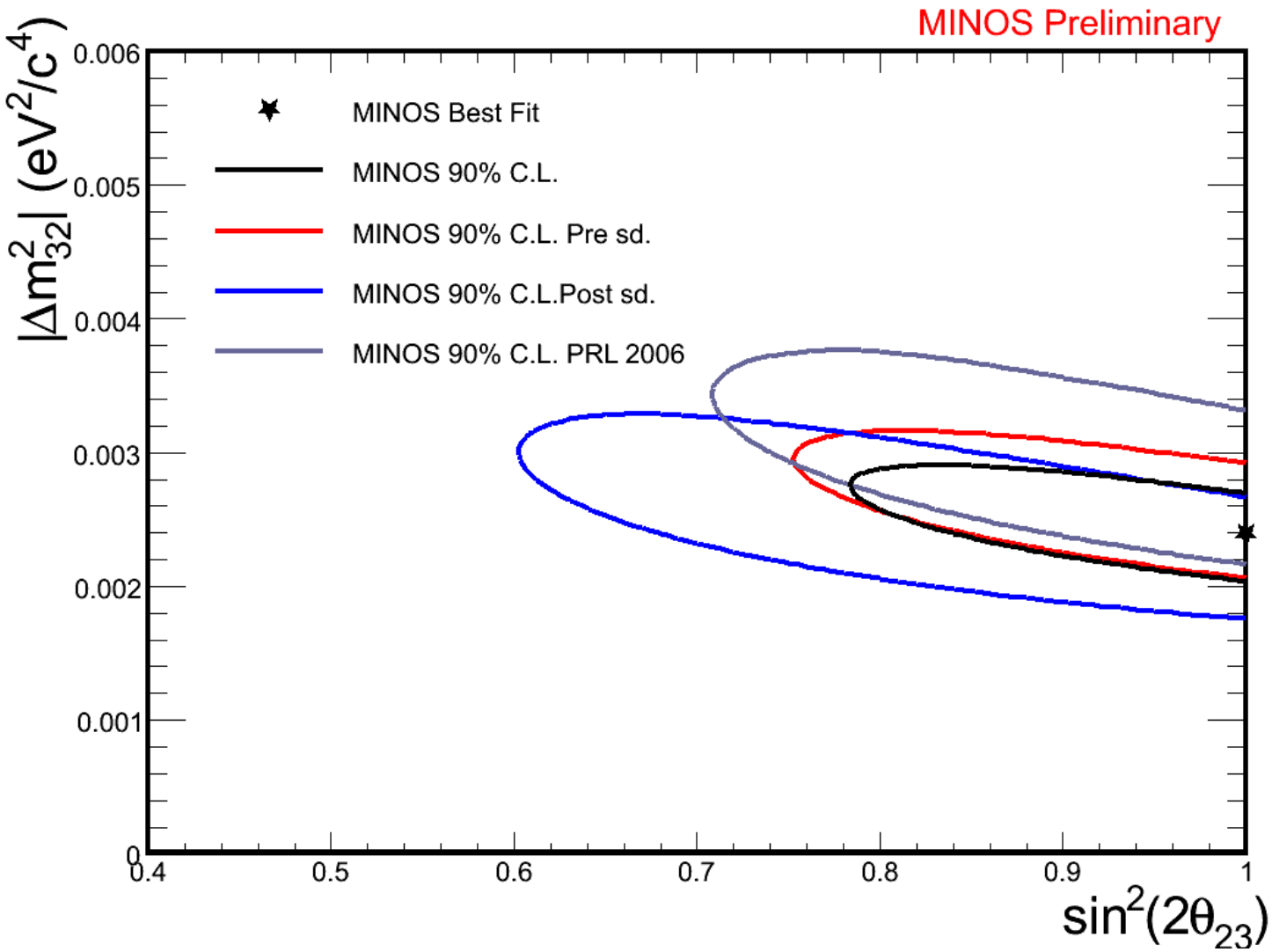


Changes from 2006 Result (PRL 97, 191801)

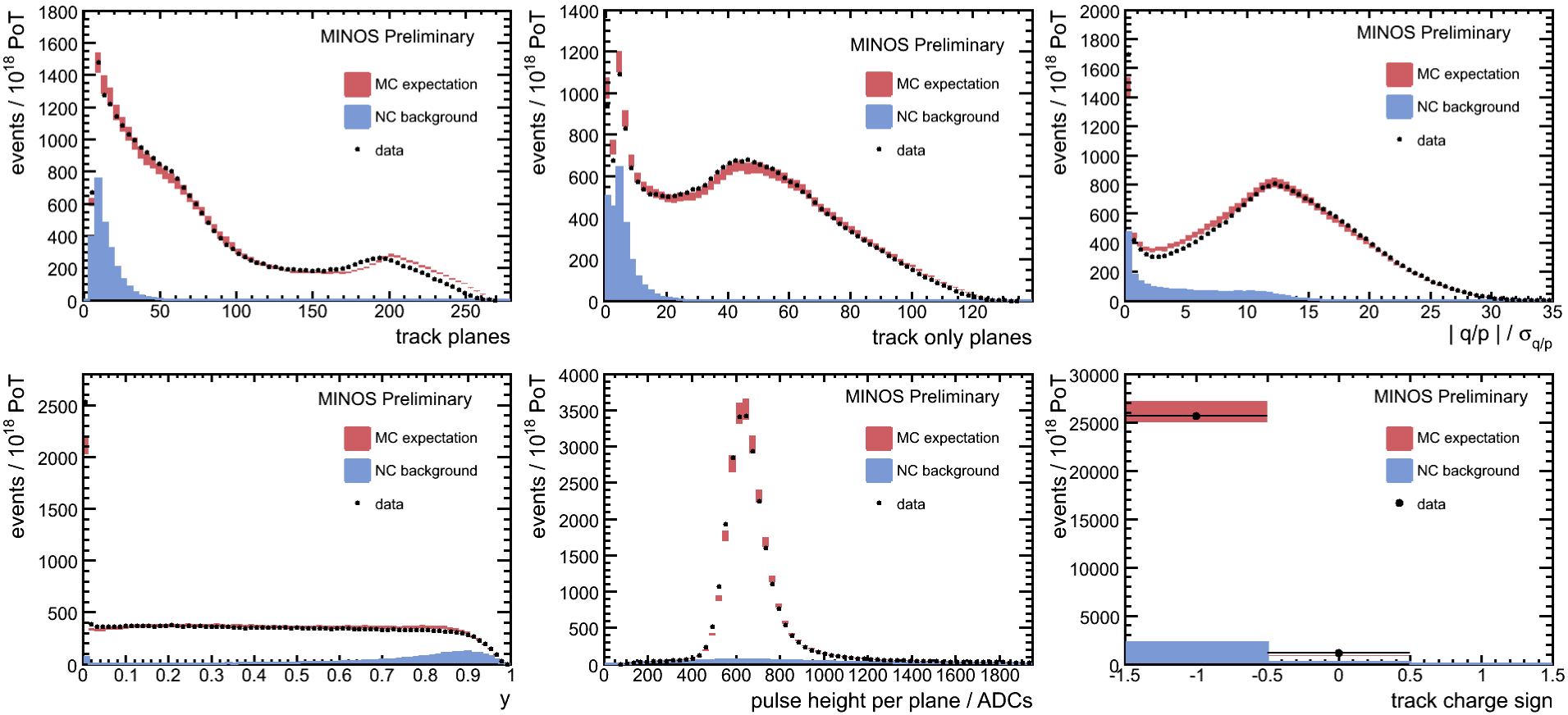
Improvements:
- reco & selection
- shower modelling

Data sets:
- Pre-shutdown
- Post-shutdown

Comparison with 2006 Result (PRL 97, 191801)



Selecting ν_μ CC Interactions



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