MINOS Results and Prospects

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Outline

- **Overview of MINOS**
  - Physics goals
  - Beam & Detectors
- **ν_μ disappearance**
  - Latest results
- **Prospects**
  - ν_μ disappearance
  - ν_e appearance
  - NC analysis
  - Anti-neutrinos
- **Summary**

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

MINOS Physics Goals

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- **Test the ν_μ disappearance hypothesis**
  - Measure $|\Delta m^2_{32}|$ & $\sin^2(2\theta_{23})$ precisely
    PRL 97, 191801 (2006)
  - Provide high statistics discrimination against other disappearance models (neutrino decay… etc).
- **Search for subdominant ν_e appearance**
- **Compare ν, $\bar{\nu}$ oscillations**
  - Test of CPT
- **Neutrino/nucleon interaction physics**
- **Atmospheric neutrino oscillations**
  PRD 75, 092003 (2007)
  PRD 73, 072002 (2006)
- **Cosmic ray physics**
  hep-ex/0705.3815

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

At MINOS baseline:

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2\theta_{23}\sin^2\frac{\Delta m^2_{32}L}{4E}$$

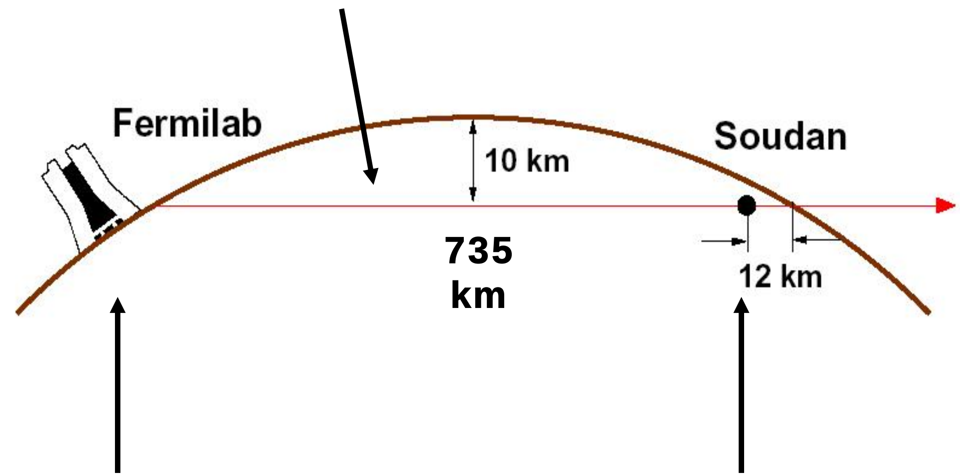
$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\frac{\Delta m^2_{32}L}{4E}$$

The MINOS Experiment

MINOS

- **MINOS (Main Injector Neutrino Oscillation Search)** is a long-baseline neutrino oscillation experiment:

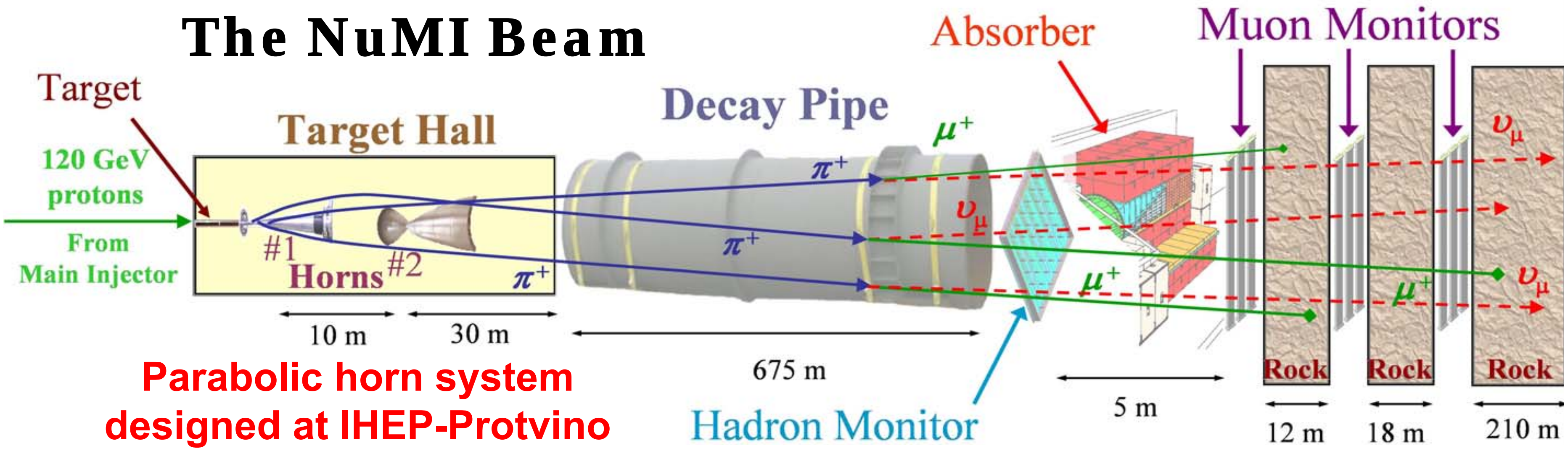
The NuMI neutrino beam provided by 120 GeV protons from the Fermilab Main Injector



A Near detector at Fermilab to measure the beam composition and energy spectrum.

A Far detector at the Soudan Mine in Minnesota to search for neutrino oscillations.

The NuMI Beam

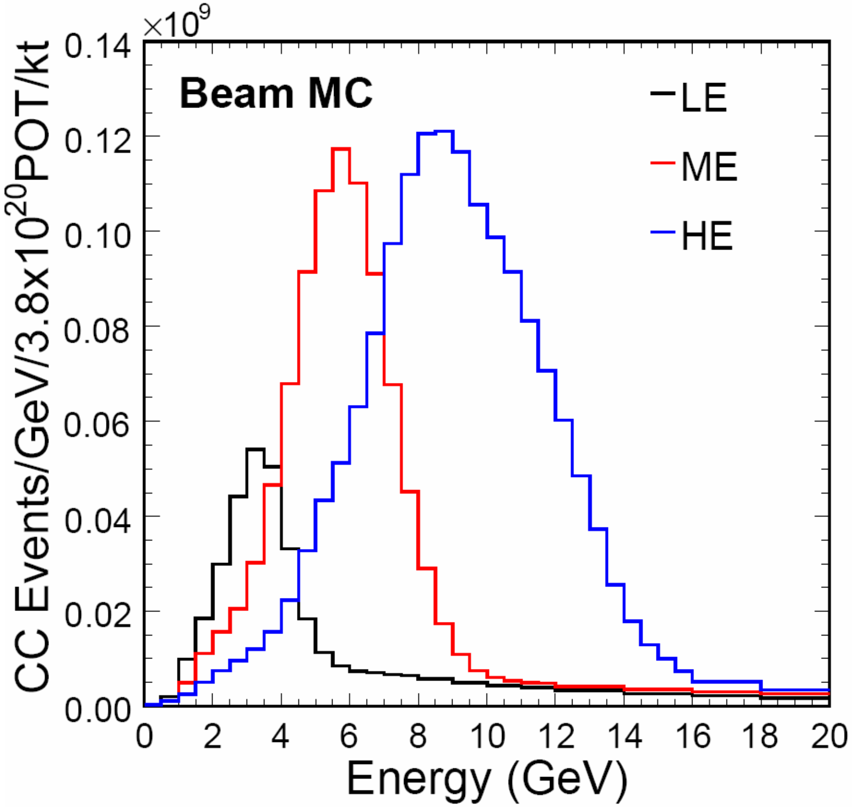


Parabolic horn system designed at IHEP-Protvino

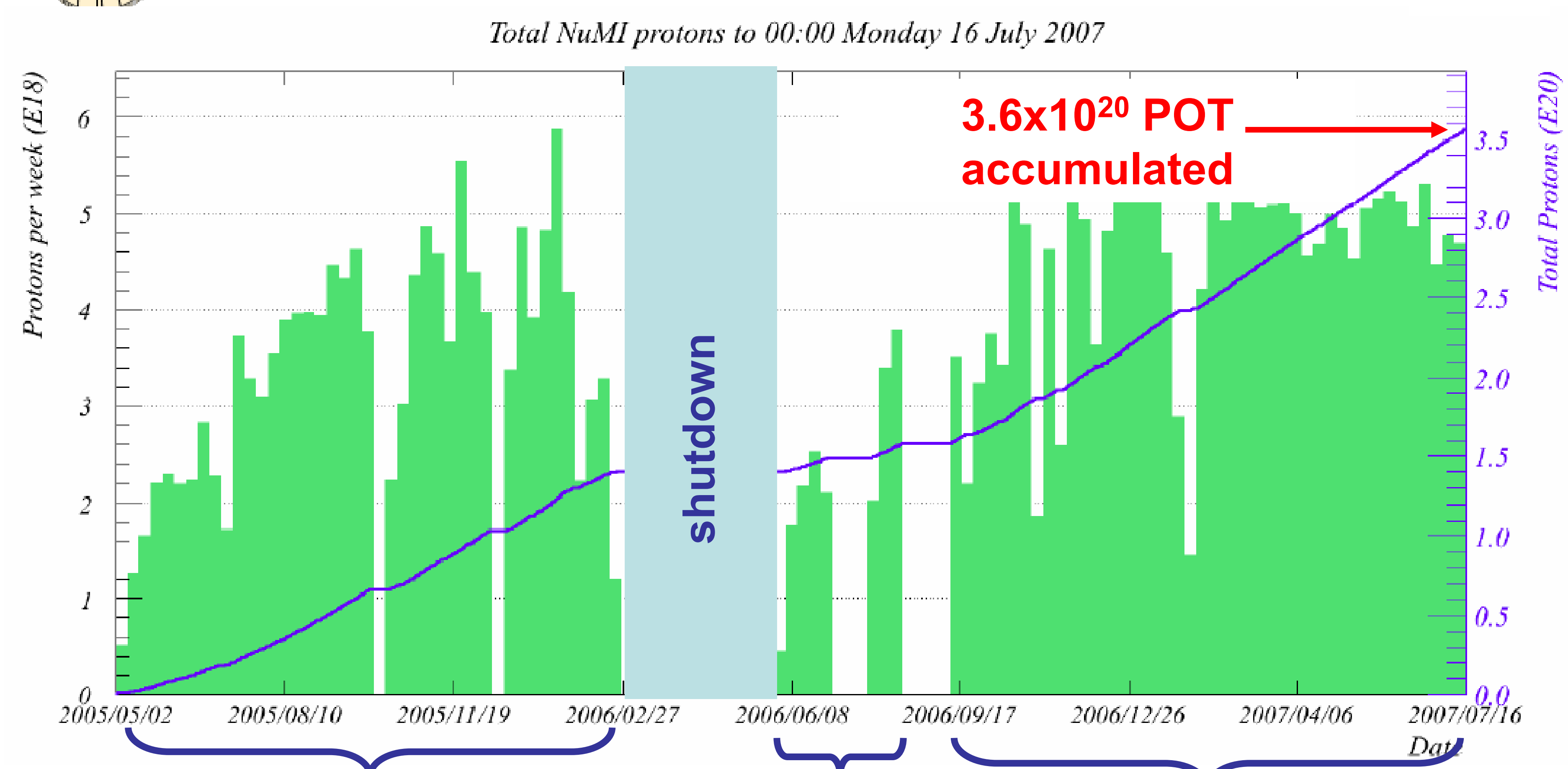
- Moveable target relative to horn 1 allows for different beam configurations.
- Designed for 1.867s cycle time, 4×10^{13} protons/pulse and 0.4MW.

Number of expected CC interactions at the FD (no oscillations)

Beam	Target z position (cm)	FD Events per 1e20 pot
LE-10	-10	390
pME	-100	970
pHE	-250	1340



2+ years of MINOS running



1st year of running
(published dataset: 1.27×10^{20} POTs)

Higher energy runs

2nd year of running
(99+% FD live time!)

Currently in shutdown until October 2007

The MINOS detectors

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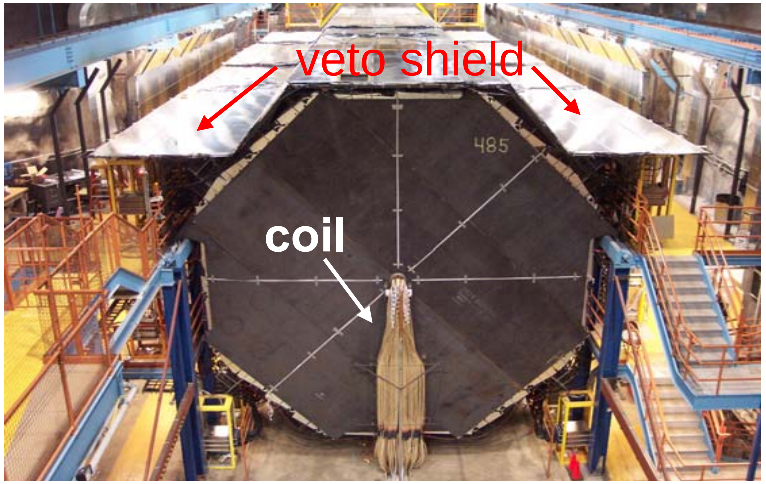
NEAR DETECTOR

1 kton mass
282 steel and 182 scintillator planes

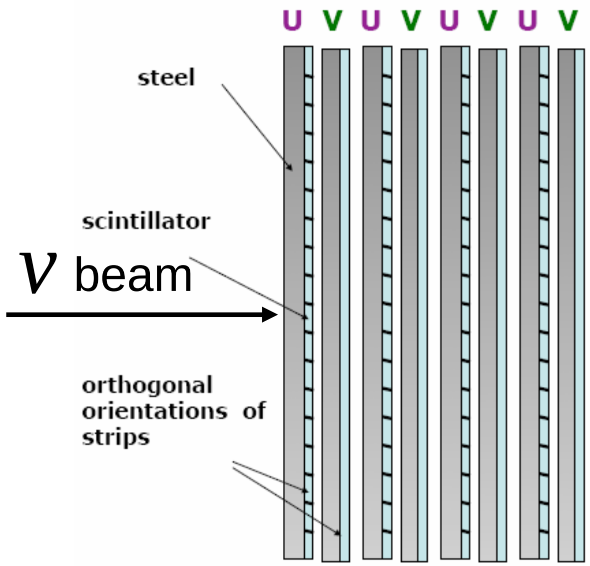
FAR DETECTOR



5.4 kton mass
484 scintillator/steel planes

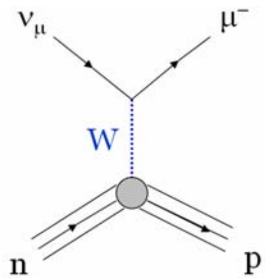
❖ **Functionally identical detectors:**

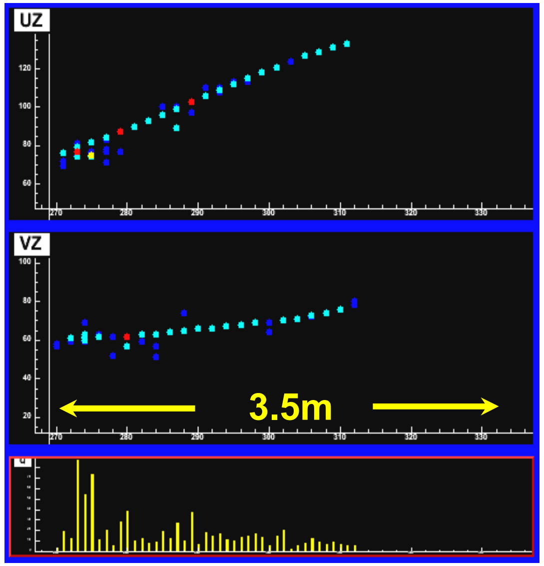
- Iron-scintillator sampling calorimeters.
- Magnetized steel planes B ≈ 1.2T
- GPS time stamping to synchronize FD with ND/beam.



Event topology in MINOS

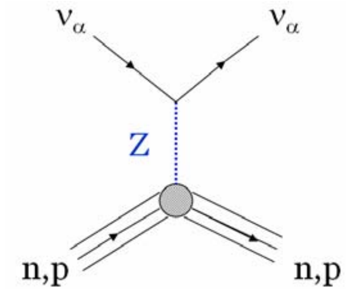
ν_μ CC Event

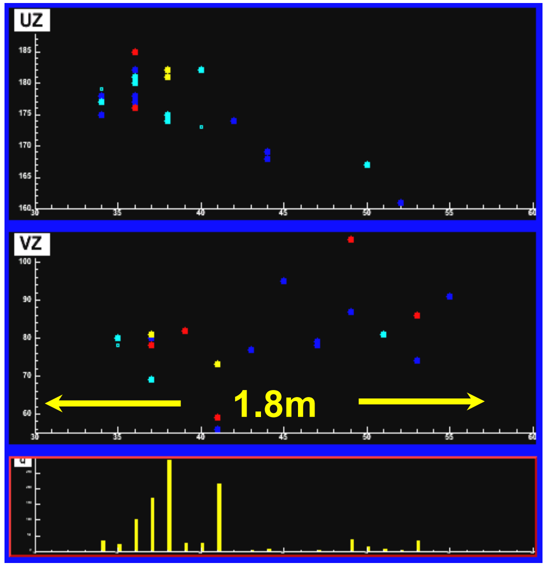




long μ track & hadronic activity at vertex

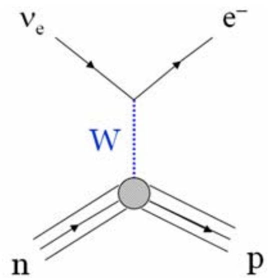
NC Event

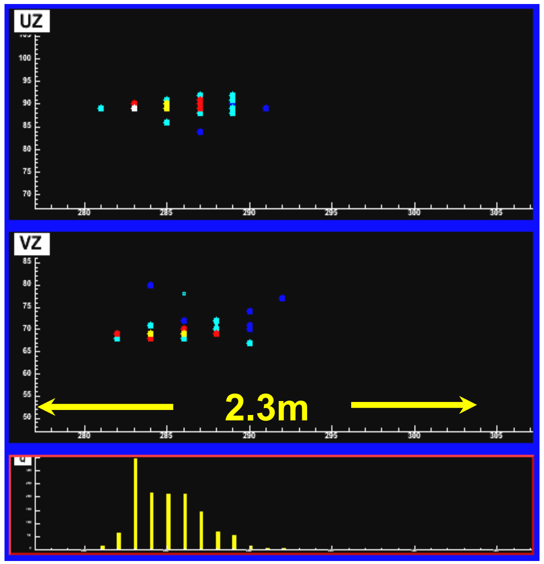




short event, often diffuse

ν_e CC Event





short, with typical EM shower profile

- Challenging to distinguish NC from ν_e CC.
- Very clear signature for ν_μ CC events: $E_\nu = E_{shower} + P_\mu$

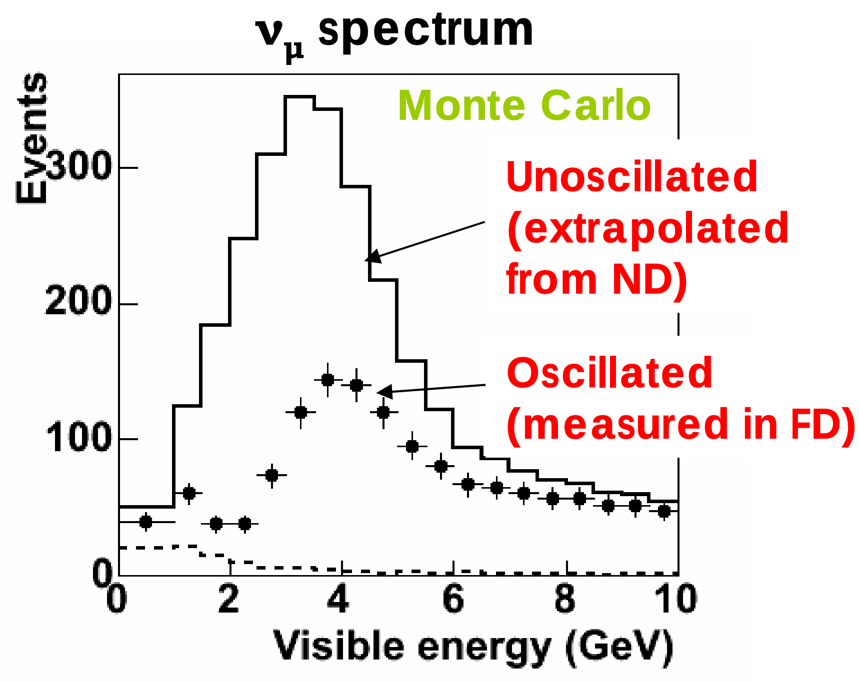
55%/√E (GeV)

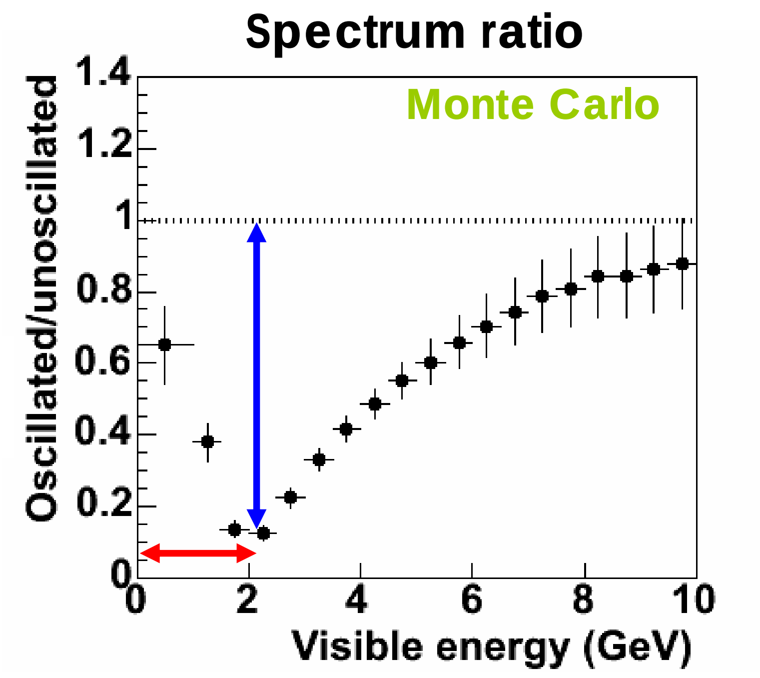
6% range, 13% curvature

ν_μ disappearance

- **Principle of the measurement:**

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



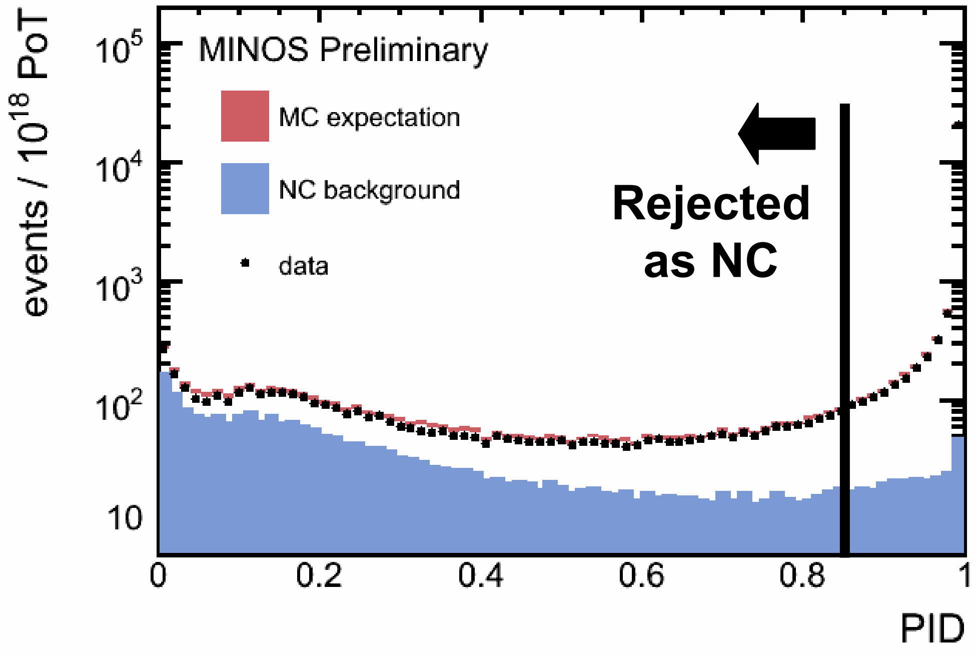


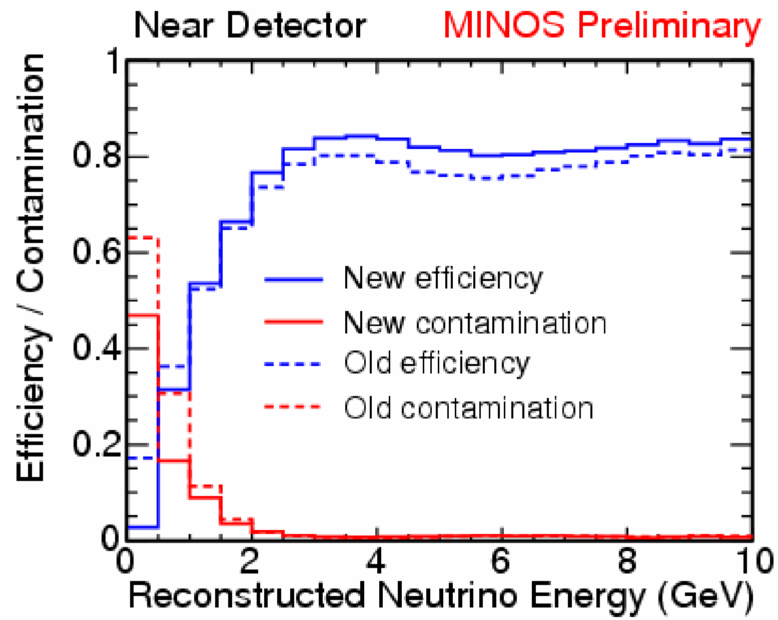
- **Improvements** over previous analysis (PRL 97, 191801 2006) :
  - ✓ Better reconstruction
  - ✓ Improved event selection
  - ✓ New intra-nuclear modeling
  - ✓ Improved shower modeling

+ twice the data (2.5x10^{20} POT total)

Improved ν_μ CC event selection

- Events are classified into charged current (CC) and neutral current (NC).
- Multivariate likelihood-based PID based on:
  - Track properties
  - Event length
  - Event kinematics
- Data-MC agree very well.





Hadron production tuning

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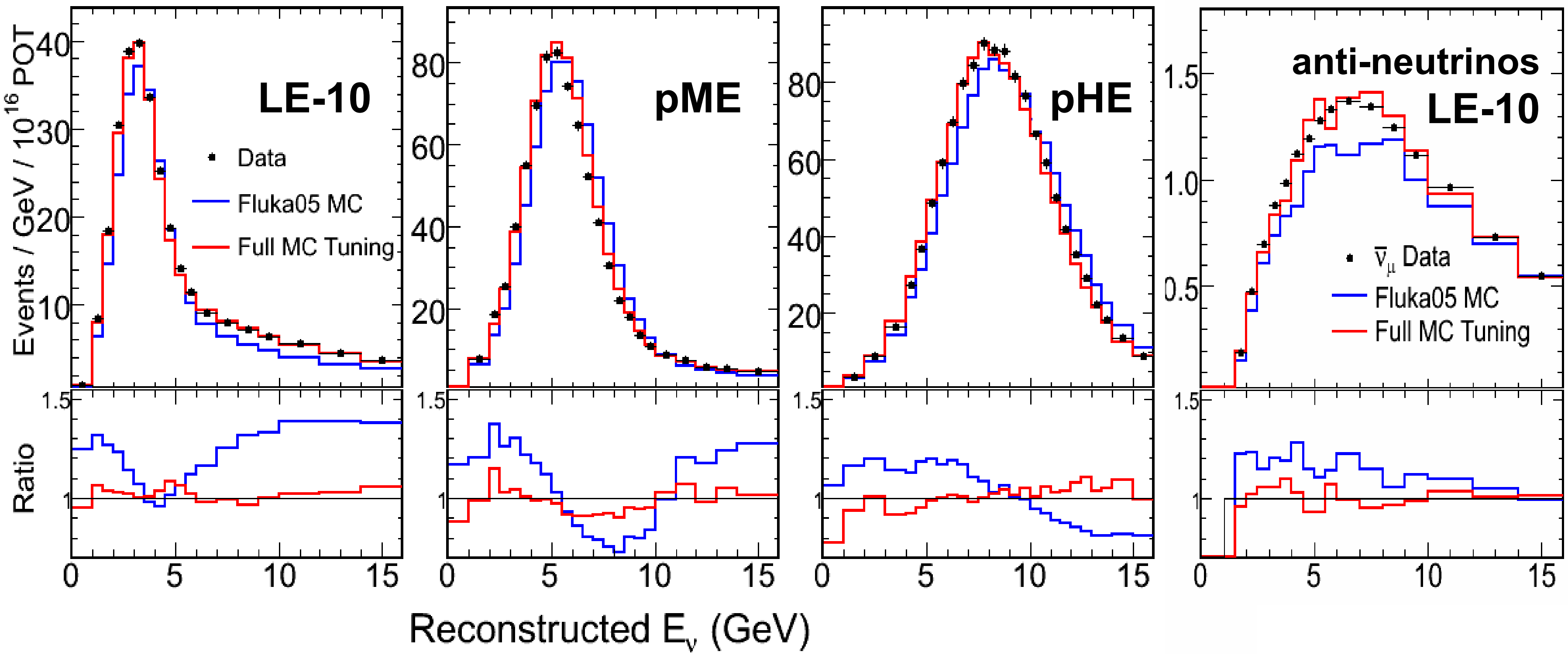
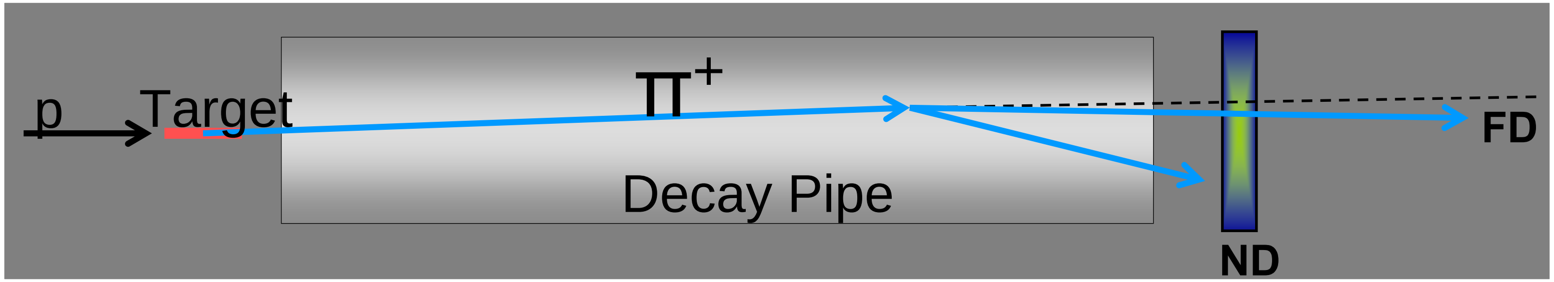
- Data-MC agree very well but situation **can be improved**.
- Parameterize Fluka 2005 hadron production as $f(x_f, p_t)$ and fit using ND data taken in different energy configurations.
- Horn focusing, beam misalignments, energy scale, cross section and NC background are included in fit.
  - **Improved agreement obtained in all energy configurations !**

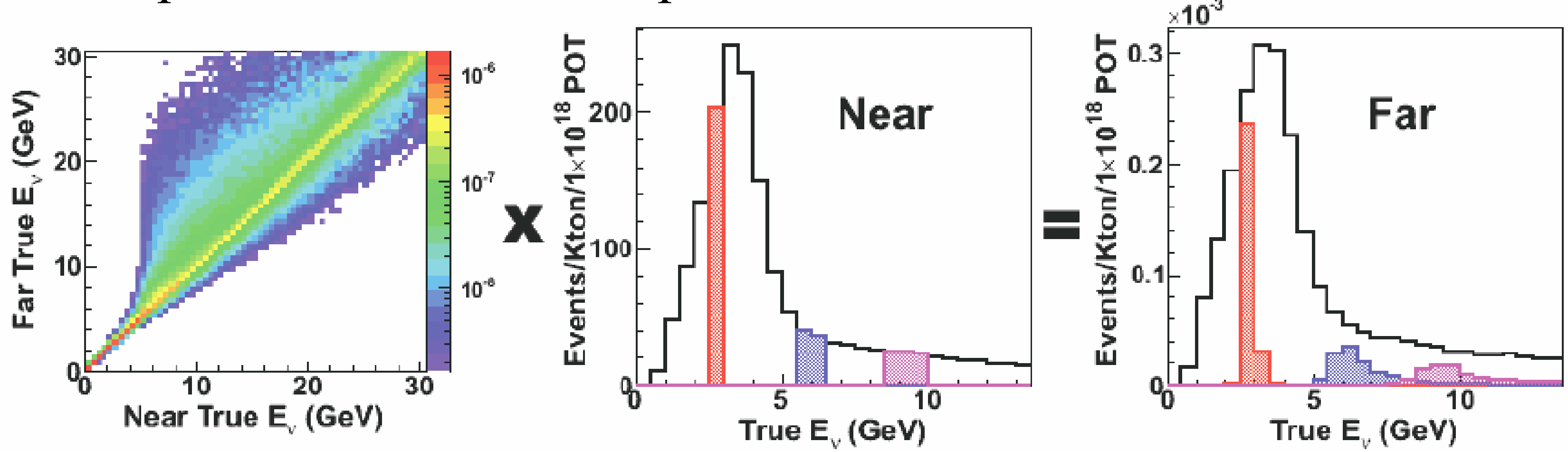


Predicting the FD spectrum

- **Directly use ND data to perform extrapolation.**
- Use MC to provide necessary corrections for acceptance and energy smearing.
- Use knowledge of pion decay kinematics and geometry to predict FD spectrum from measured ND spectrum:



- Encapsulate ND→FD transport in "Beam Matrix":



Systematic uncertainties

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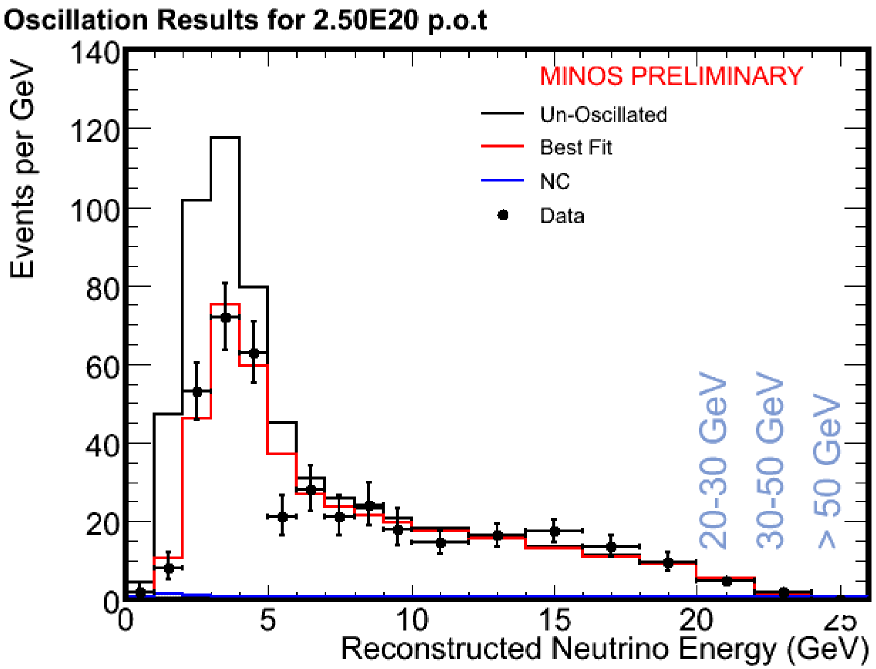
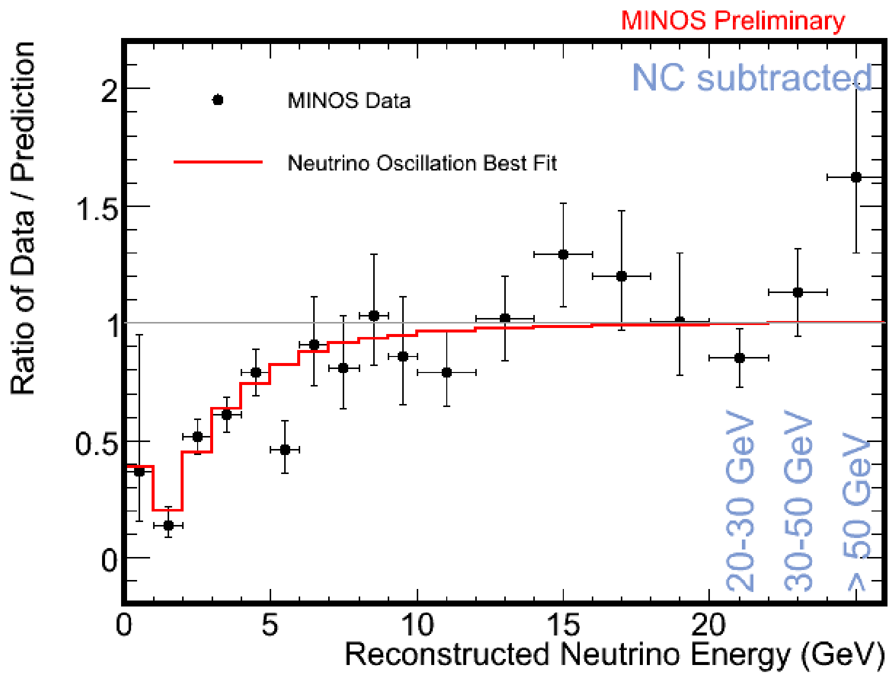
- Systematic uncertainties obtained by generating MC with the following systematic shifts and using it as “fake data”, with standard oscillation parameters.
- The three largest uncertainties were included as nuisance parameters in the oscillation fit.

Uncertainty	Δm^2 (10^{-3} eV^2)	$\sin^2(2\theta_{23})$
Near/far normalisation (4%)	0.065	<0.005
Abs. shower energy scale (10%)	0.075	<0.005
NC normalisation (50%)	0.010	0.008
All other	0.040	<0.005
Total sys. (quad. sum)	**0.11**	**0.008**
Statistical	**0.17**	**0.080**

Oscillation Fit

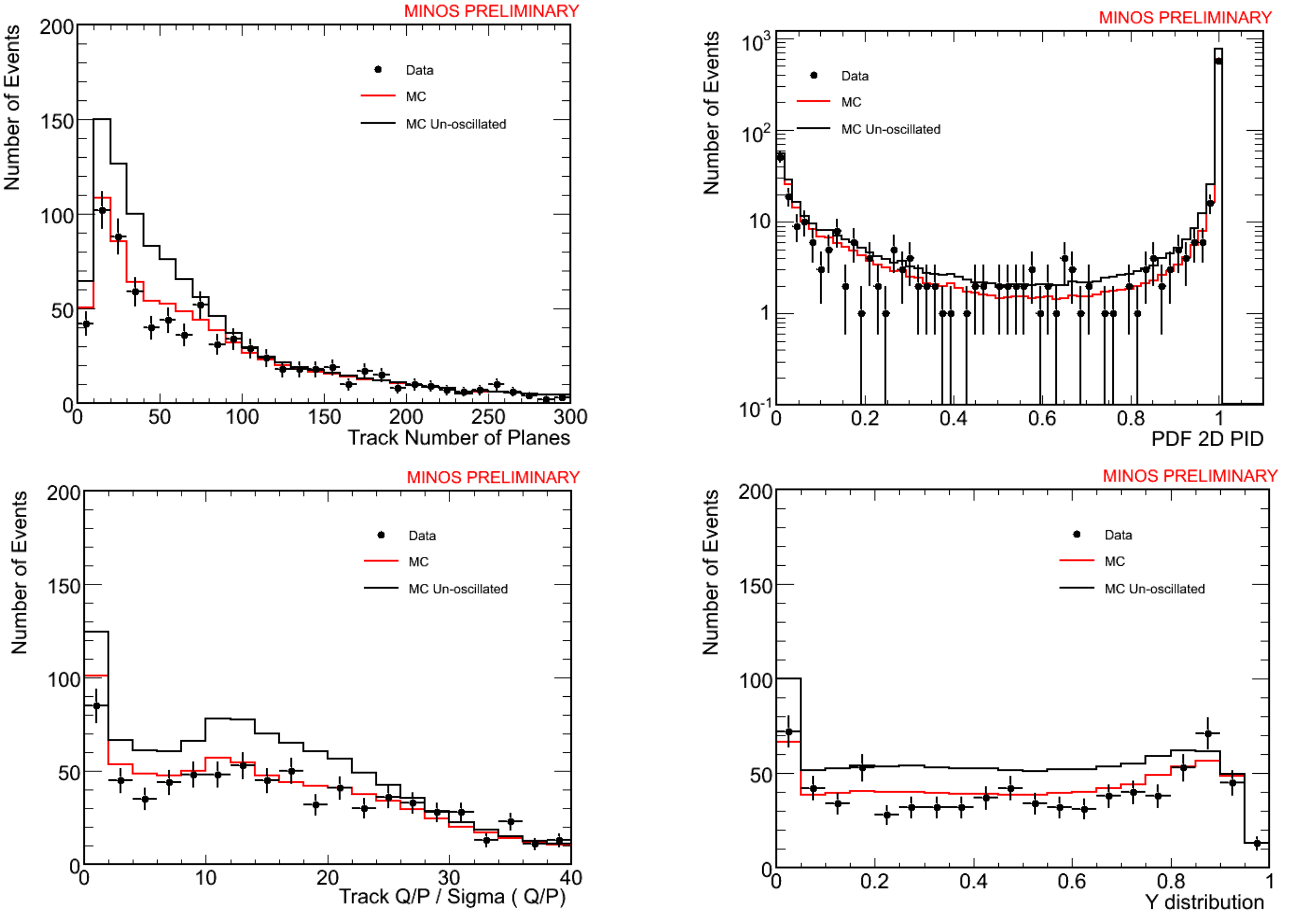




Data sample	Observed	Expected (no osc.)	Observed /expected
ν_μ (all E)	563	738 ± 30	0.74 (4.4σ)
ν_μ (<10 GeV)	310	496 ± 20	0.62 (6.2σ)
ν_μ (<5 GeV)	198	350 ± 14	0.57 (6.5σ)

Far Detector data & MC comparison

❖ Data is well described by oscillation best fit:



Allowed parameter space

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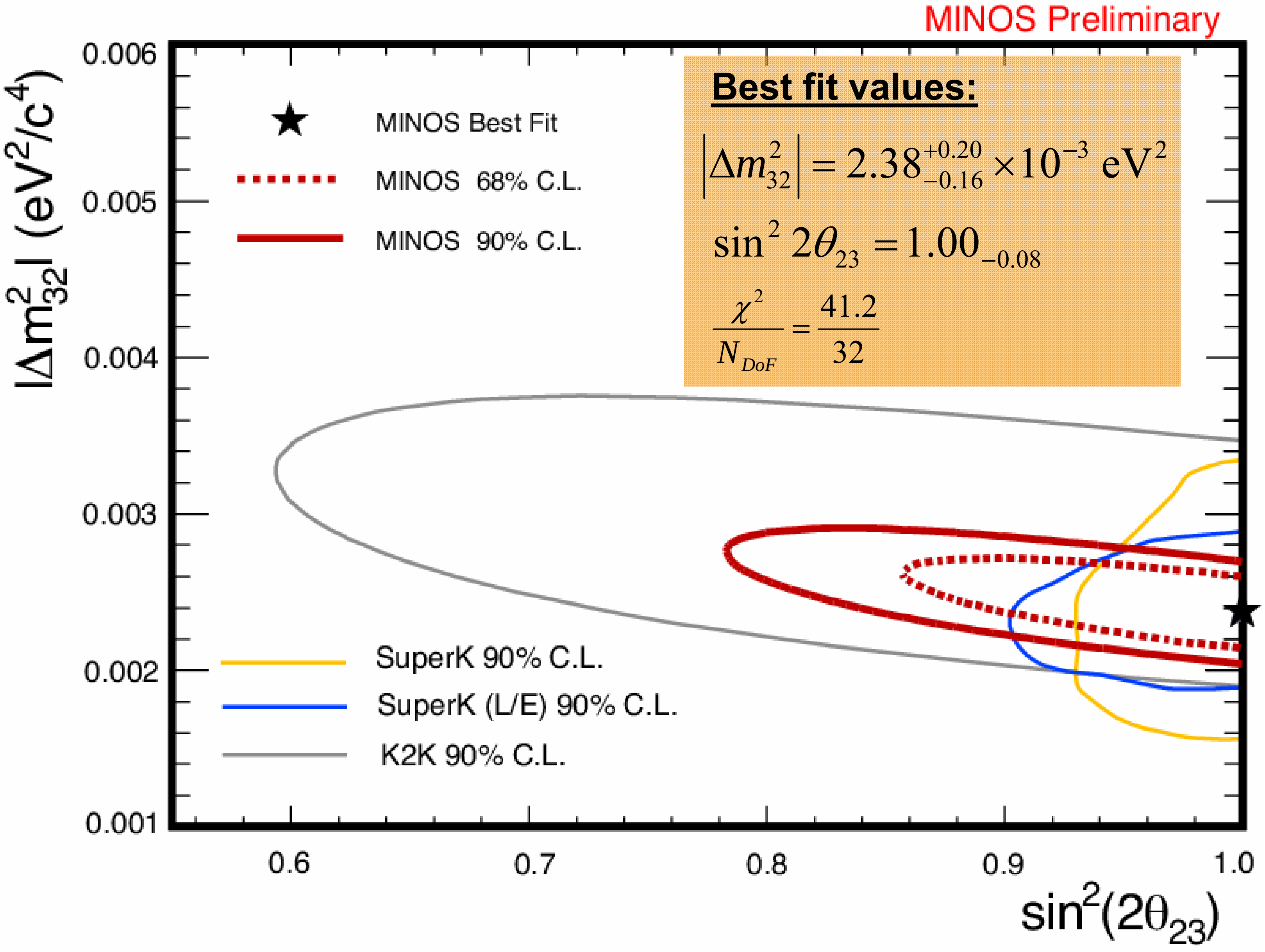


Best fit values:

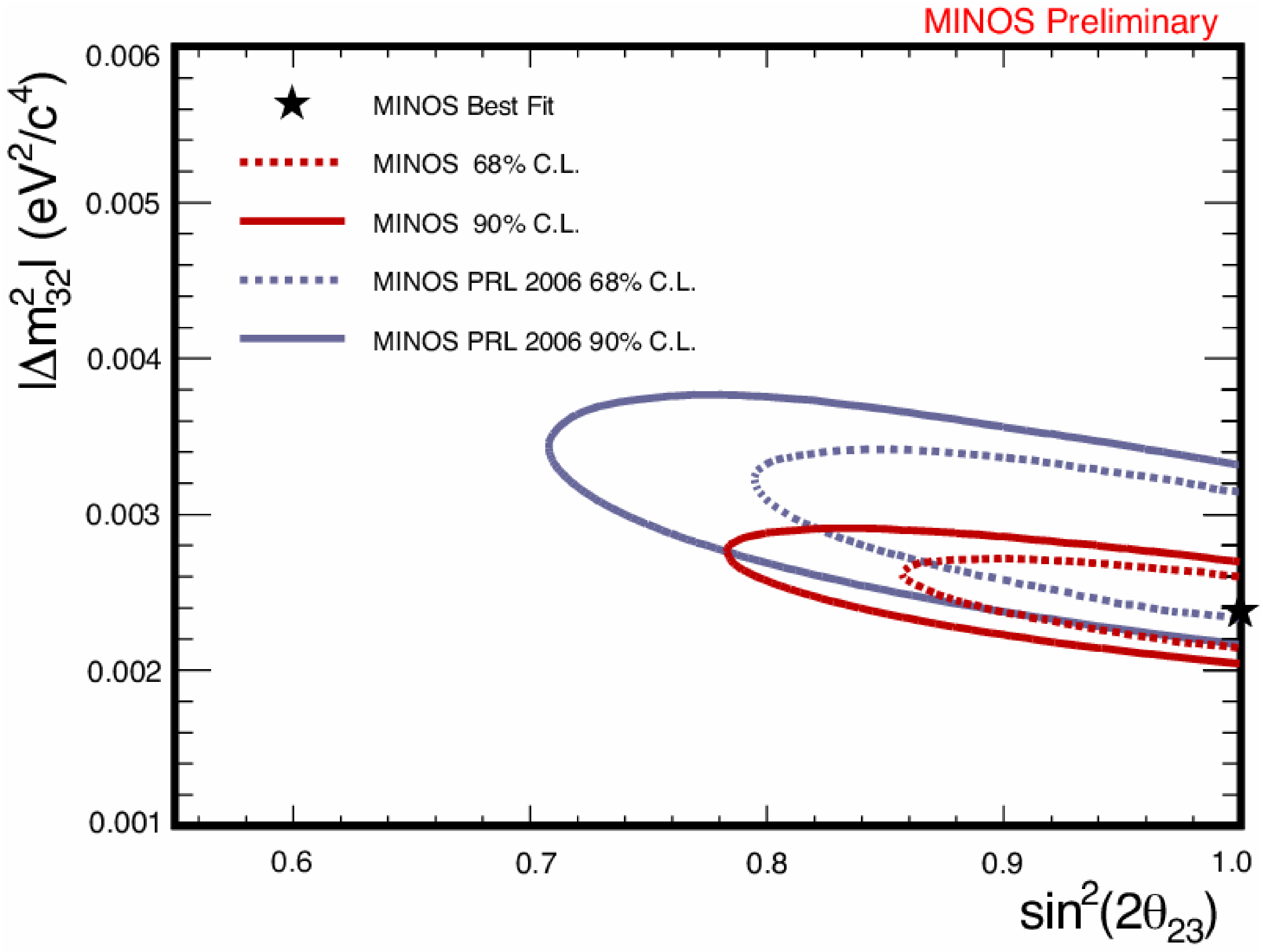
$$\left|\Delta m^2_{32}\right| = 2.38^{+0.20}_{-0.16} \times 10^{-3}\ \mathrm{eV}^2$$

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

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

Comparison with 2006 MINOS result
(PRL 97, 191801 2006)

MINOS

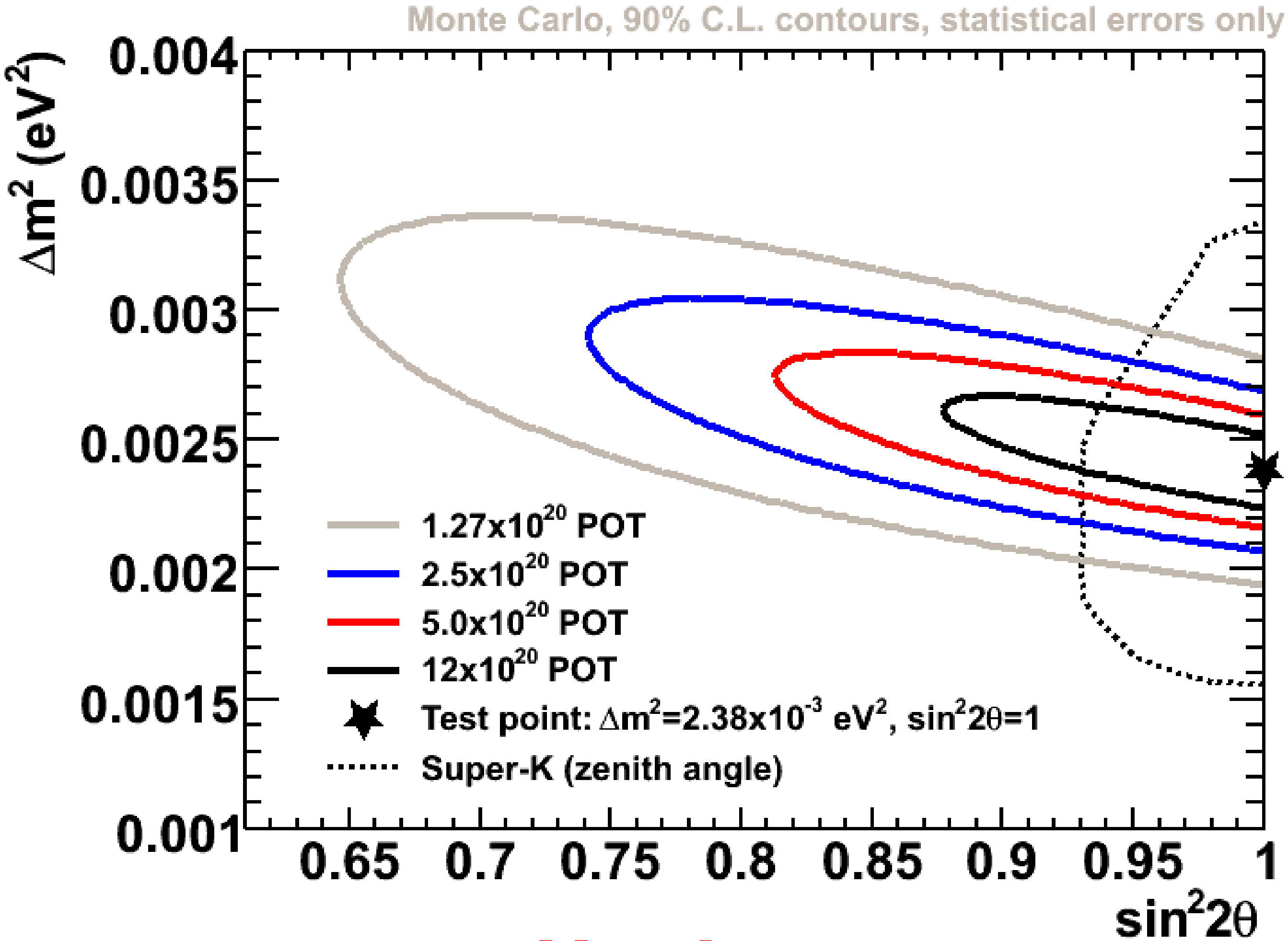


Prospects: ν_μ disappearance

MINOS

❖ **Outlook is very positive:**

MINOS Sensitivity as a function of Integrated POT



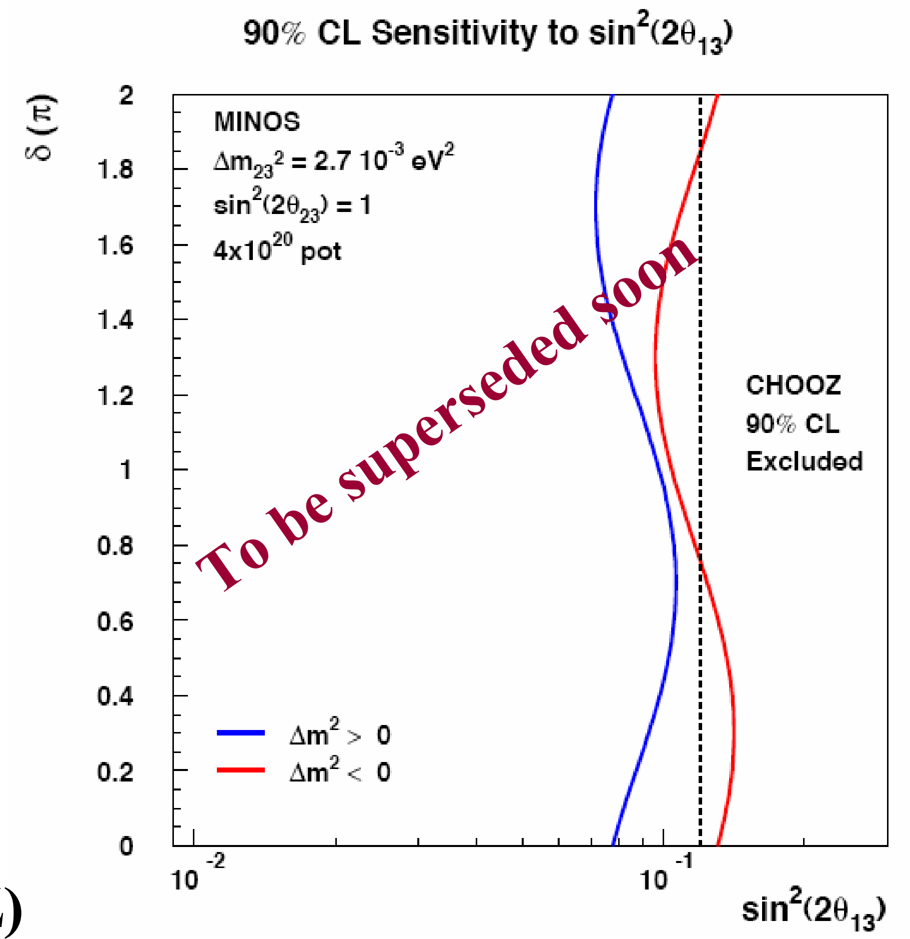
+ add rock muons

ν_e appearance

- **MINOS could make the first non-zero measurement of θ_{13}.**

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{23} L}{4E}$$

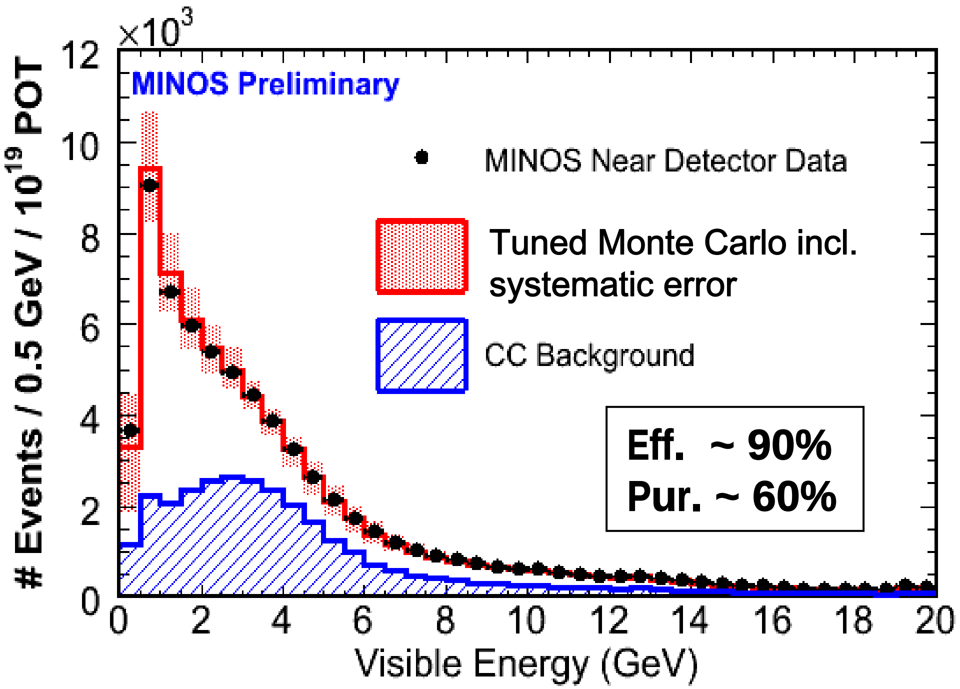
- Challenge lies in signal & background separation:
  - NC events are the dominant background
  - Much effort went into devising techniques that discriminate between EM and hadronic showers.

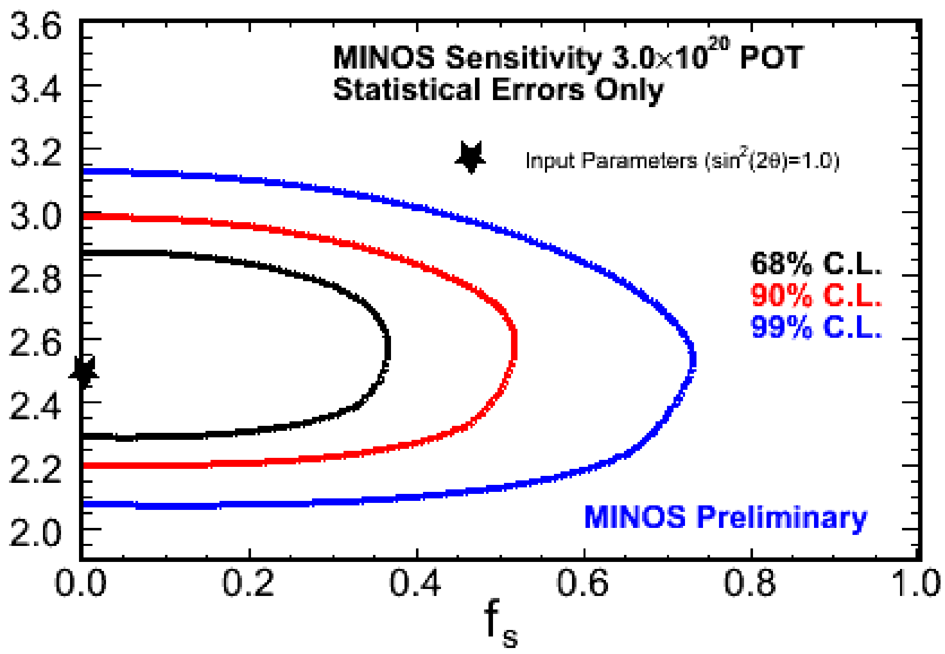


- **By the end of this year sensitivity will be comparable to the world's current best limit (CHOOZ)**

Neutral currents

- Neutral current events are unaffected by standard oscillations:
  → **Can test for oscillations to sterile neutrino(s).**
- Define "fraction of sterile mixing" $\mathbf{f_s}$ to be fraction of disappearing ν_μ's that oscillate to sterile neutrino(s):





- Far Detector data for this analysis is blinded. Analysis is in progress.

Anti-neutrinos

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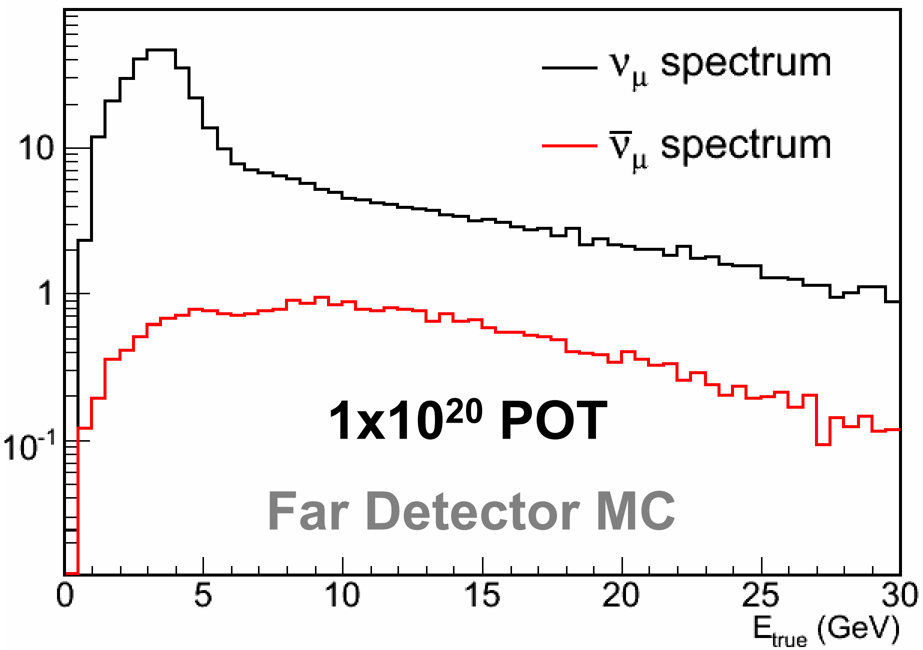
- About ~6% of our beam is made of muon anti-neutrinos:



Magnetic field allows us to separate neutrinos and anti-neutrinos on an event by event basis !

- Can perform an **anti-neutrino oscillation** analysis:
  - CPT violating region for $\Delta\bar{m}^2_{32}$ still **largely unexplored**
  - Could reverse the horn current to get antineutrino beam.

- Can look for $\nu \rightarrow \bar{\nu}$ transitions:
  - Predicted by some models beyond the SM.

Summary

MINOS

- We had a successful year of data collection.
- Results from improved ν_μ disappearance analysis with twice the data have just been released:

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

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

→ The world's best measurement of $|\Delta m^2_{32}|$!

- New analyses continue in other areas such as ν_μ disappearance, ν_e appearance, sterile neutrino search, anti-neutrinos… among many others.
- **Stay tuned for many other exciting measurements and discoveries !**

MINOS

Backup

Changes from previous result

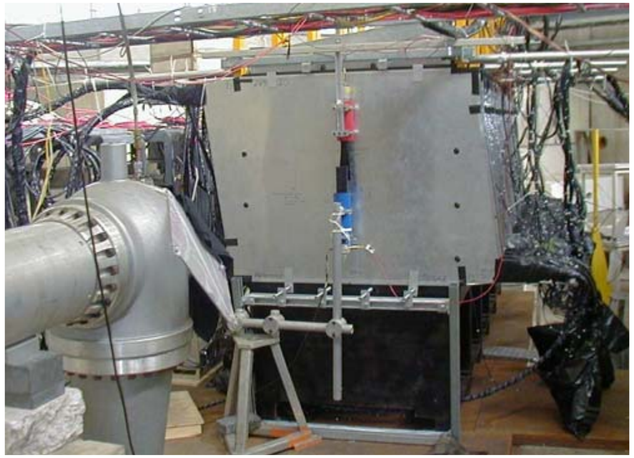
Improvements:
- reco & selection
- shower modelling

Data sets:
- Pre-shutdown
- Post-shutdown

Calibration

MINOS

- **Overall energy scale set by Calibration Detector CALDET:**
  - Mini-MINOS detector at CERN
  - Measured e/μ/π/p response



- **In addition,**
  - Light injection system (PMT gain)
  - Cosmic rays (strip to strip and inter-detector)

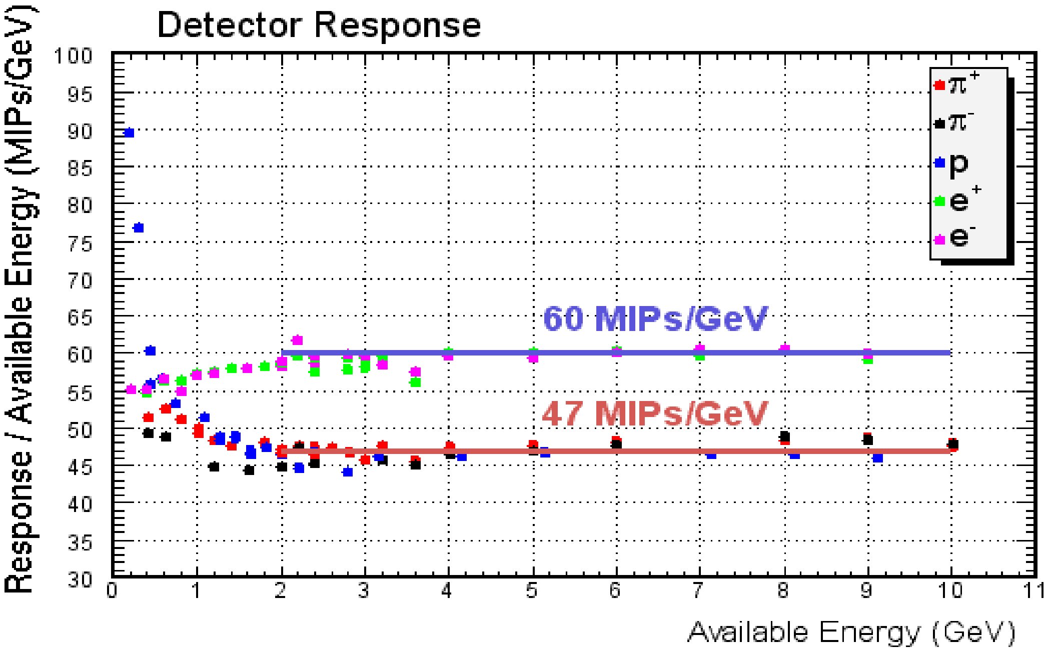
Energy resolution: (E in GeV)

Hadrons:

56% / √E ⊕ 2%

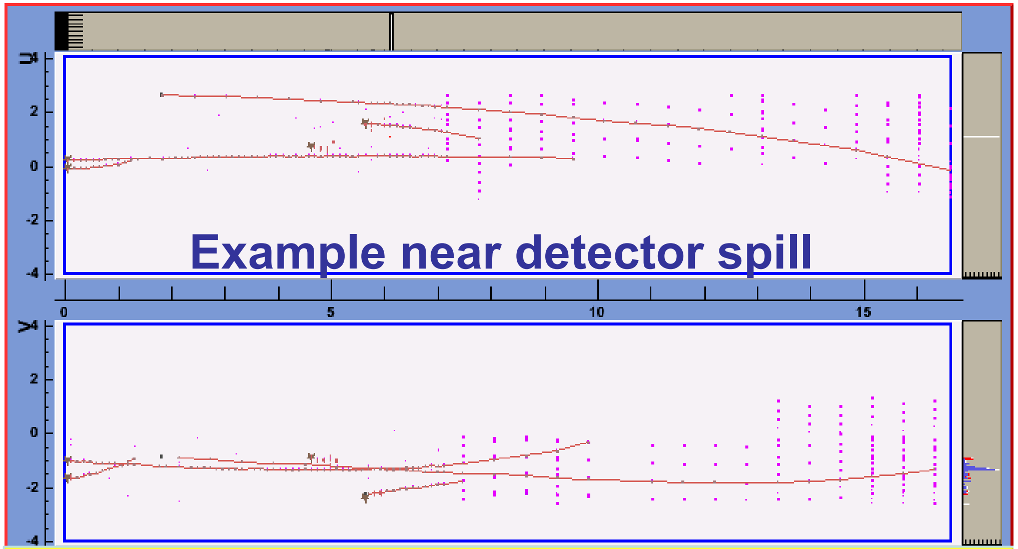
Electrons:

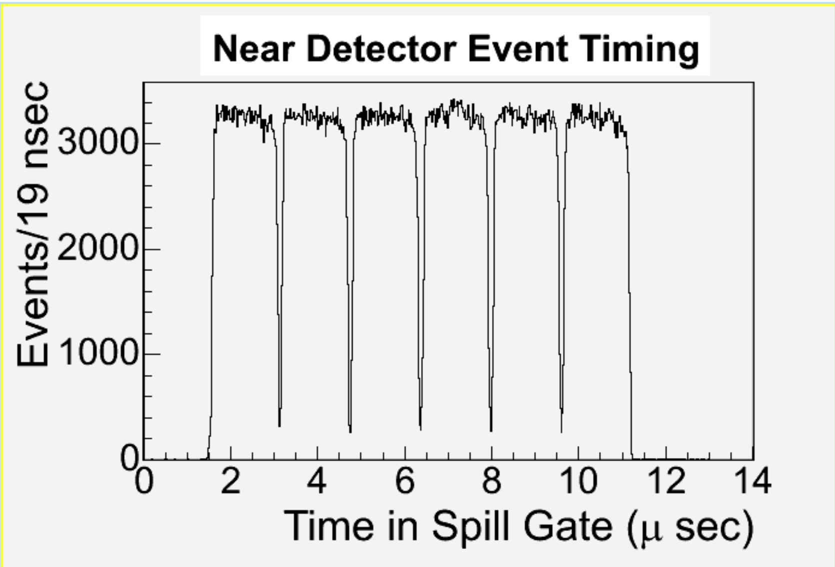
21% / √E ⊕ 4% / E

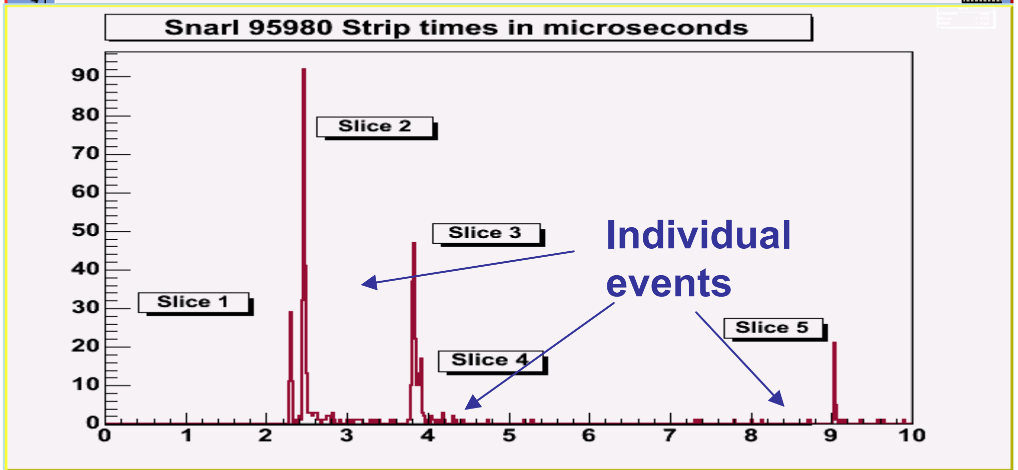


Near Detector Events

- Multiple neutrino interactions per MI spill
- Events are separated based on topology and time information.







time (μs)

← Batch structure clearly seen!

Far Detector Events

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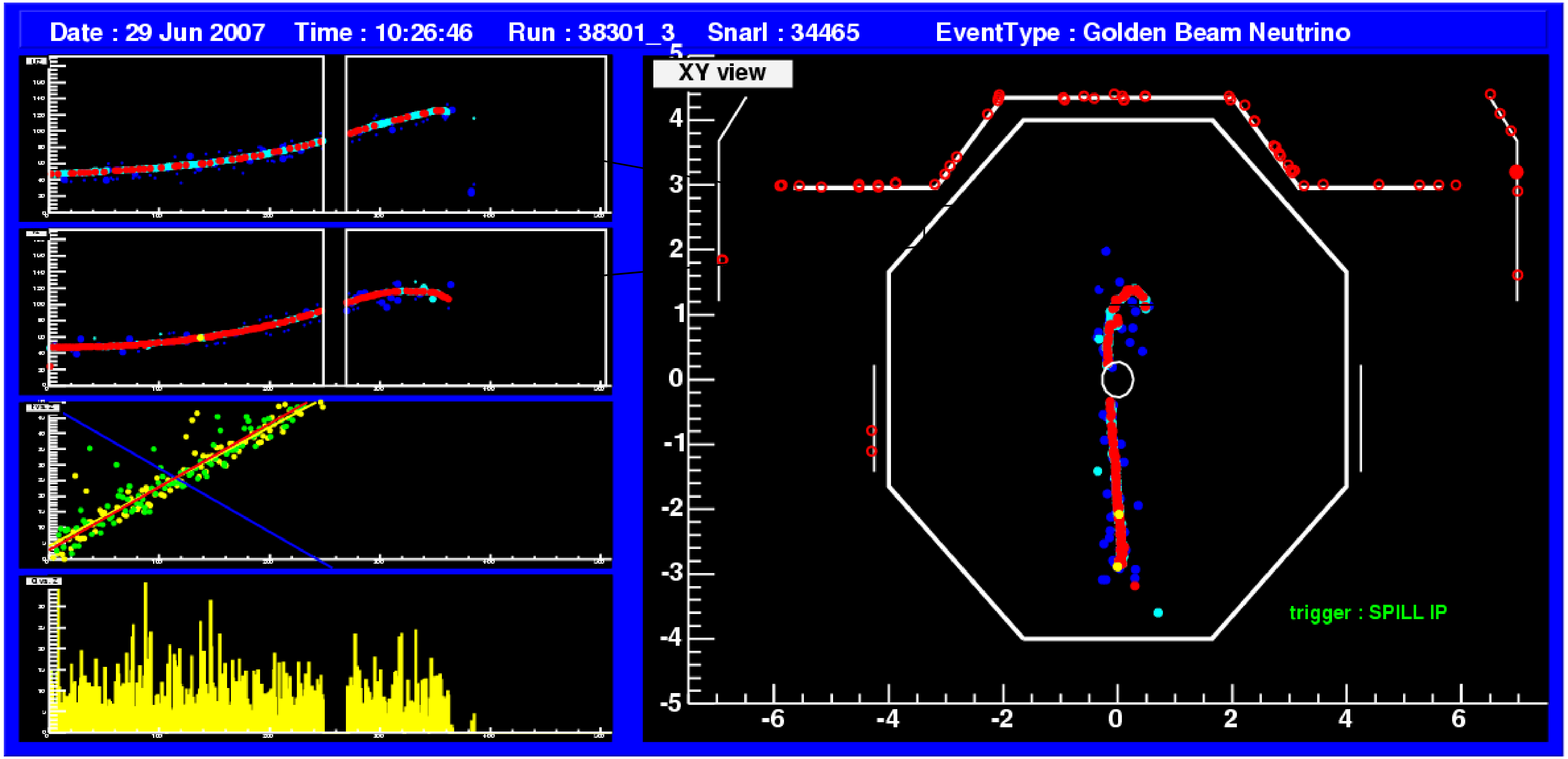
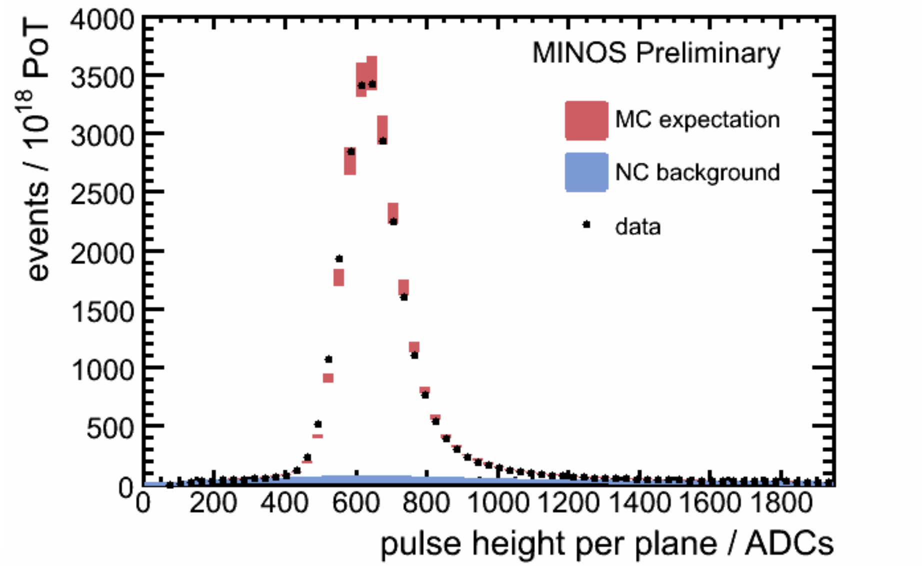
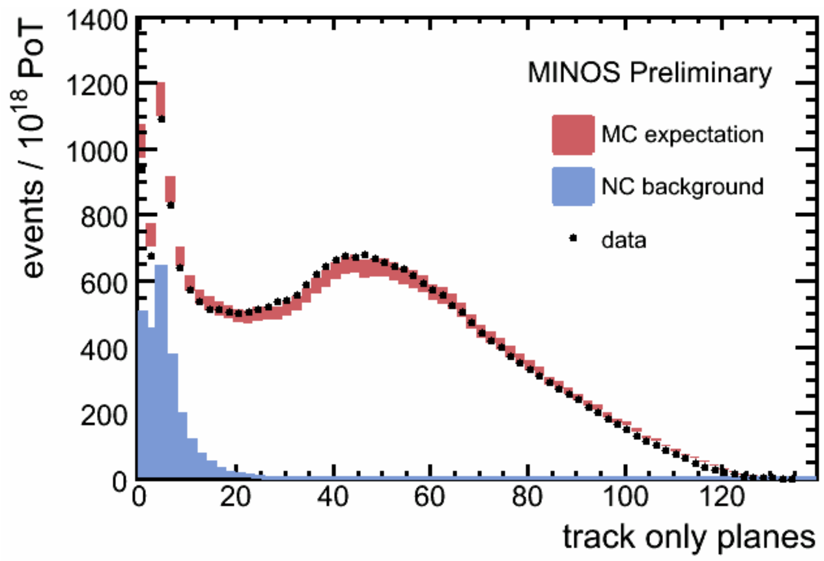
- Beam neutrino interaction rate is ~10^{-6} that of the near detector
- Beam events are identifiable in time with the spill trigger supplied from NuMI

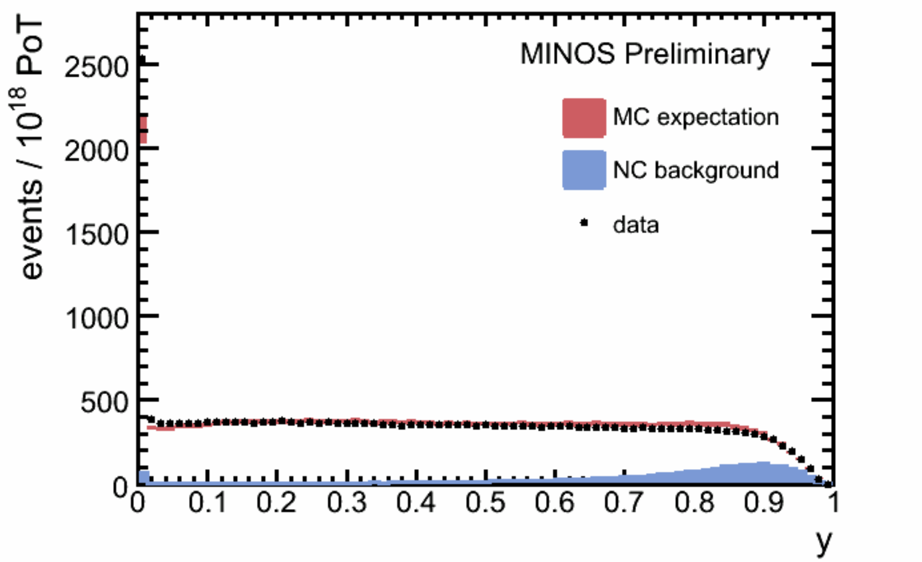


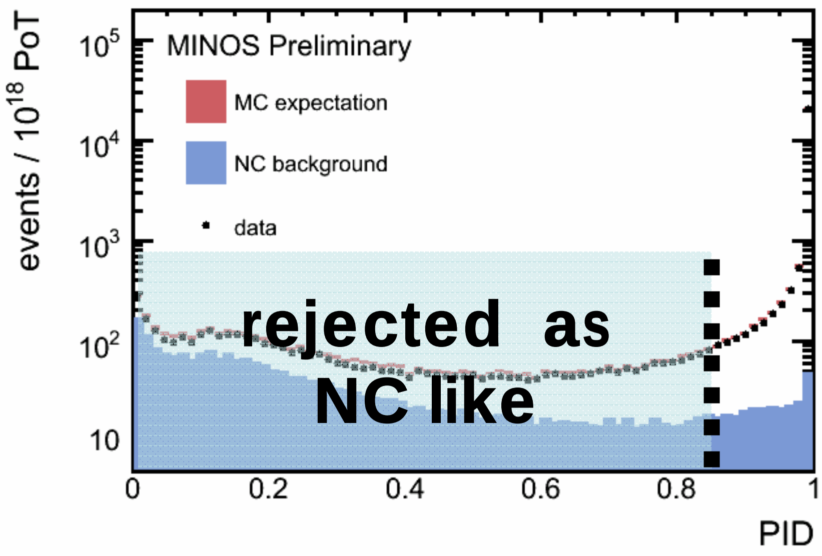
ND data/MC comparison

MINOS









Far Detector Timing Distribution

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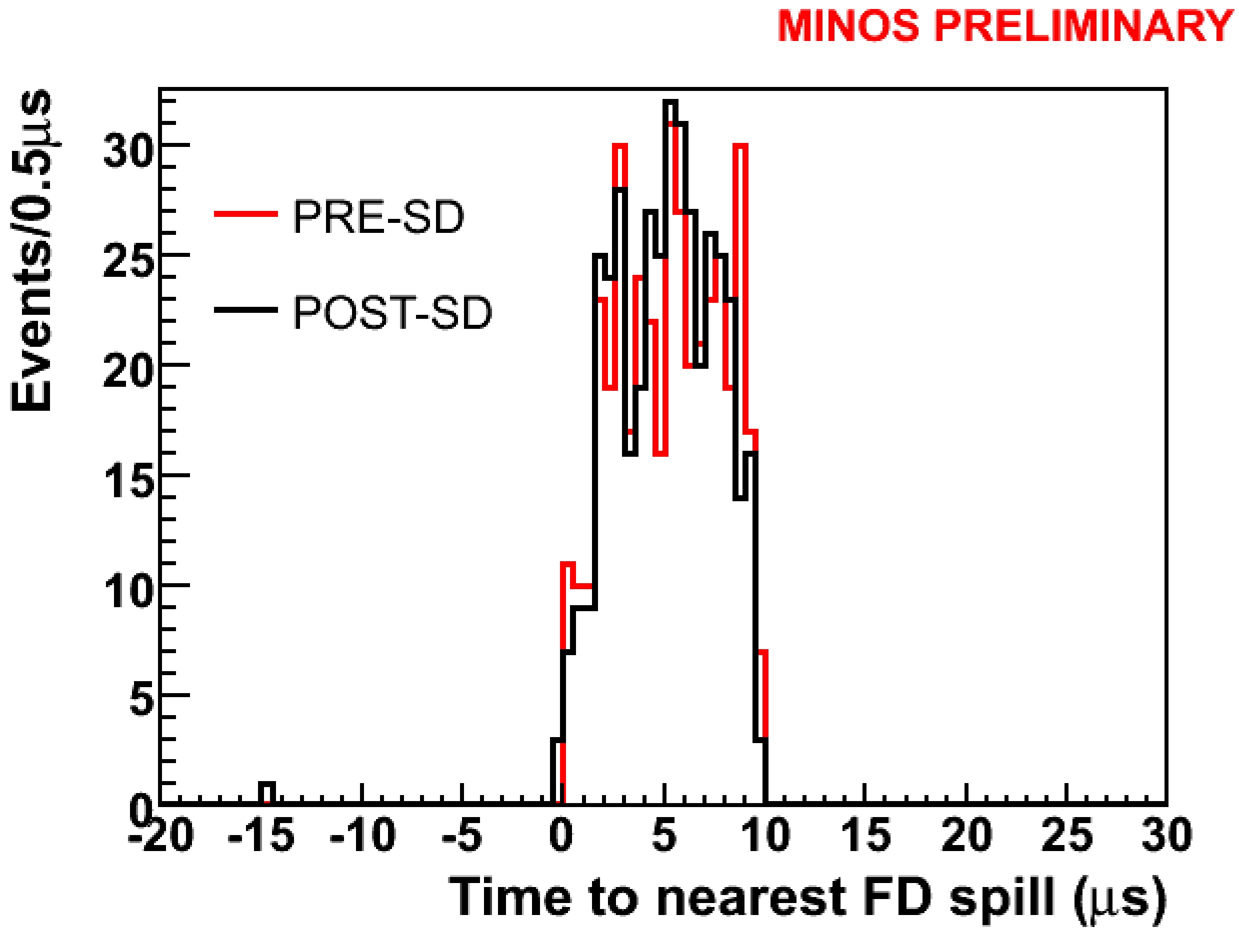
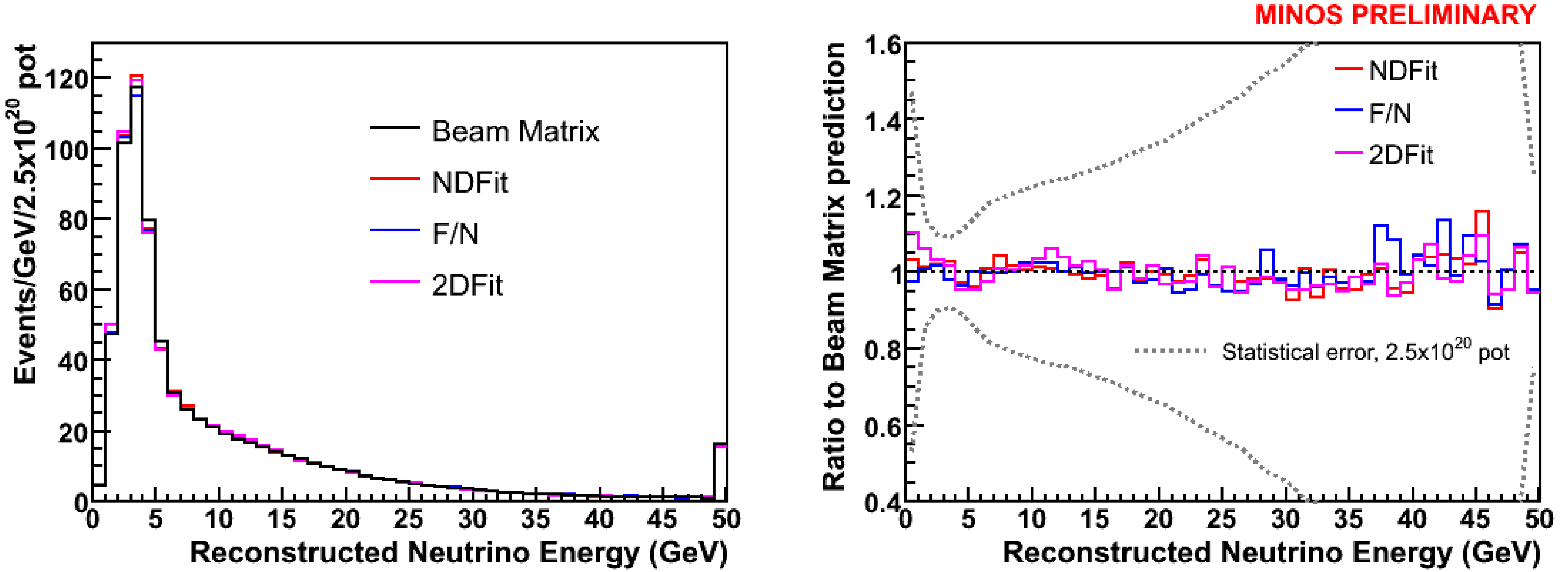
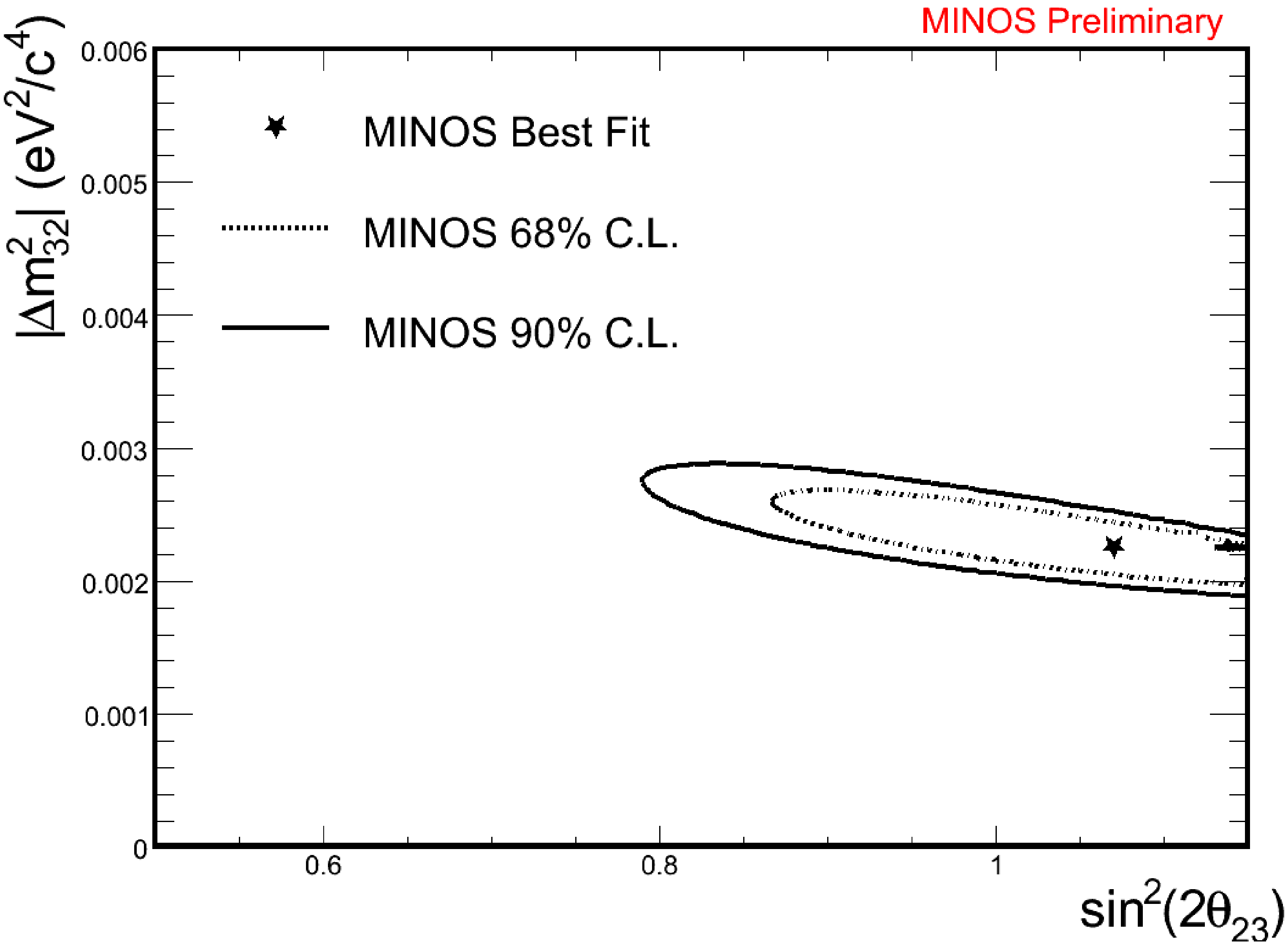


Different predictions of FD unoscillated spectrum

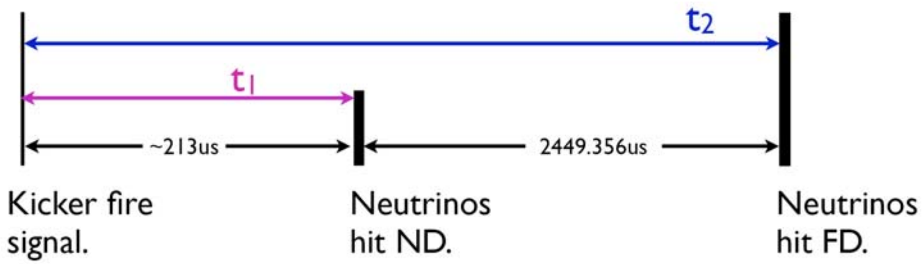


Unconstrained fit

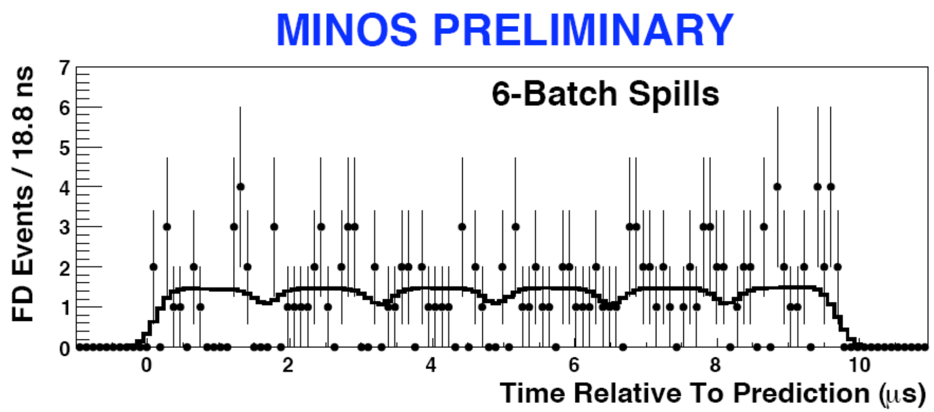


Measuring the speed of neutrinos

MINOS



Measure time of flight as $t_2 - t_1$



arXiv:0706.0437 [hep-ex]

- Time of flight for 734,298.6 m ± 0.7 m:
  $\tau_{nominal}$ = 2,449,356 ns
  τ_{MINOS} = 2,449,228 ns ± 32 ns (stat) ± 64 ns (sys)
- Neutrino Velocity:
  $(v-c)/c = (5.1 \pm 2.9) \times 10^{-5}$ (all at 68% C.L.)

Measuring the mass of neutrinos

MINOS

- Can use arrival time distribution of ν_μ CC events to derive mass limits for the neutrino:

$$T_{m_\nu}(E_\nu) = \frac{\tau}{\sqrt{1 - \left(\frac{m_\nu c^2}{E_\nu}\right)^2}}$$

- **Best fit: m_ν=17MeV**
- **99% C.L. : m_ν < 50MeV**