Recent Results from the MINOS Experiment

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Brookhaven National Laboratory
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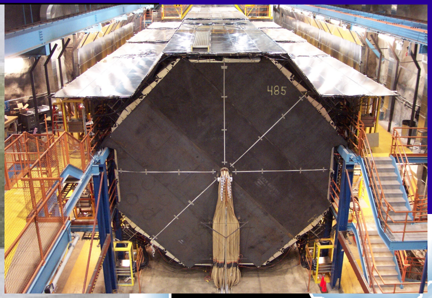
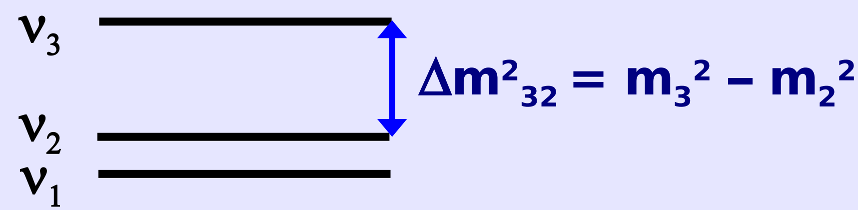


Introduction to the MINOS Experiment

MINOS Physics Goals

- Test $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
  - see talk M. Sanchez
- Search for or constrain exotic phenomena
  - Sterile ν, ν decay
- Compare ν, $\bar{\nu}$ oscillations
  - Test of CPT violation
- Atmospheric neutrino oscillations
  - Phys. Rev. D73, 072002 (2006)

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



Useful Approximations:

ν_μ Disappearance (2 flavors):

$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$

ν_e Appearance:

$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{31} L/E)$

Units: Δm^2_{32} (eV^2), L(km), E(GeV)

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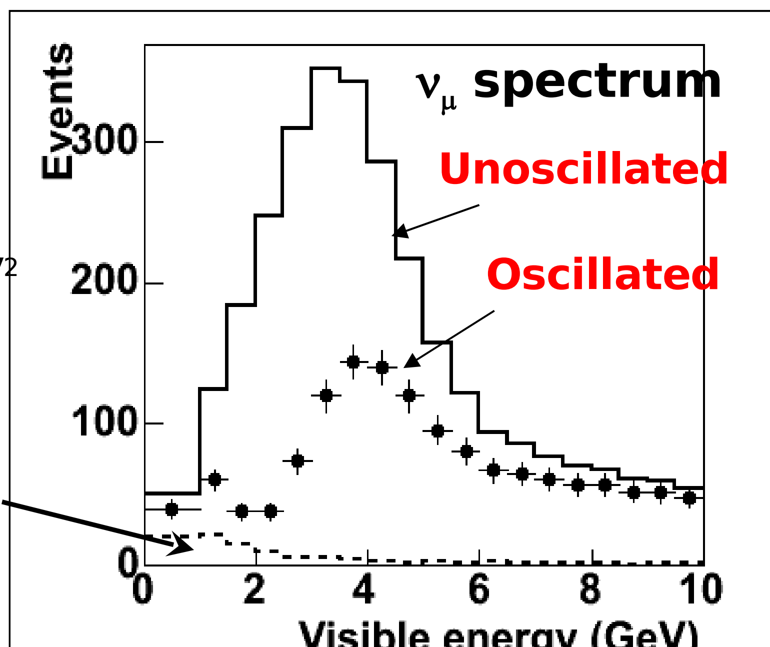
Long Baseline Concept

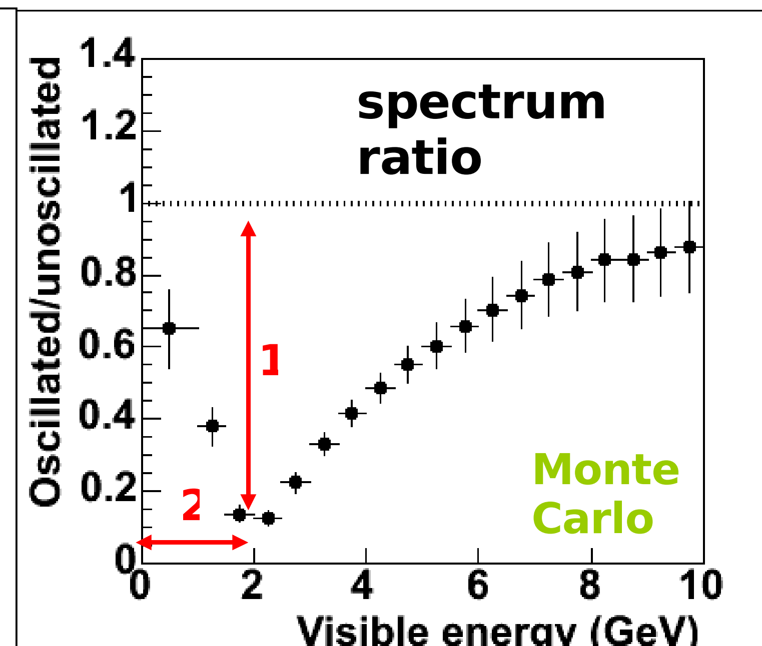
- Generic long baseline ν_μ disappearance experiment
- Predict unoscillated charged current (CC) spectrum at Far Detector (fixed L)
- Compare with measured Energy spectrum to extract oscillation parameters

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

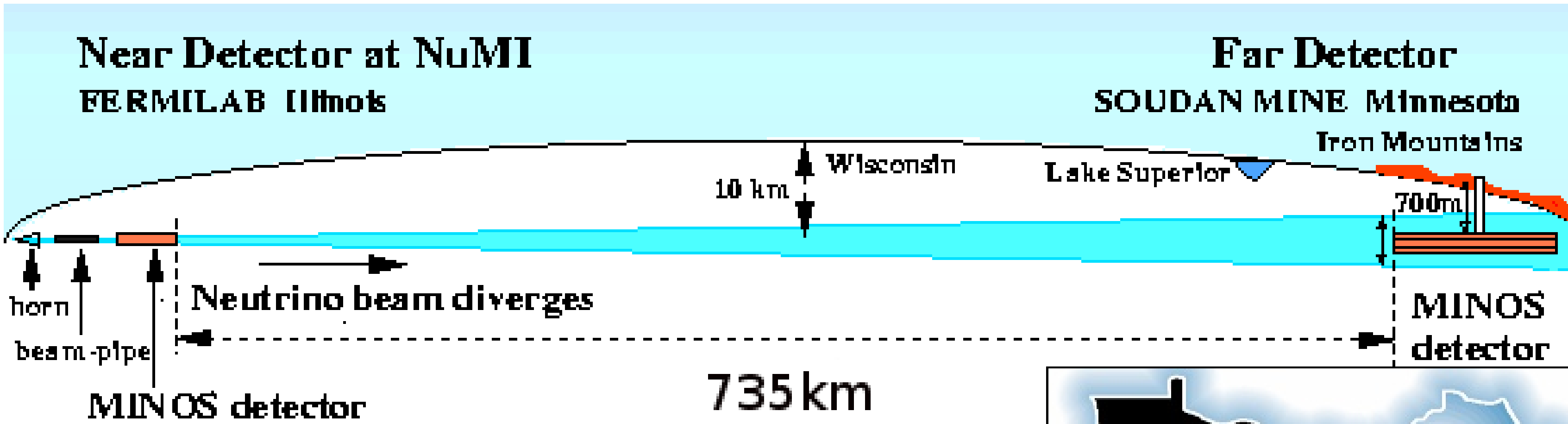
Inputs:
$\sin^2 2\theta = 1.0$
$\Delta m^2 = 3.35 \times 10^{-3}$ eV^2

Neutral current (NC) background





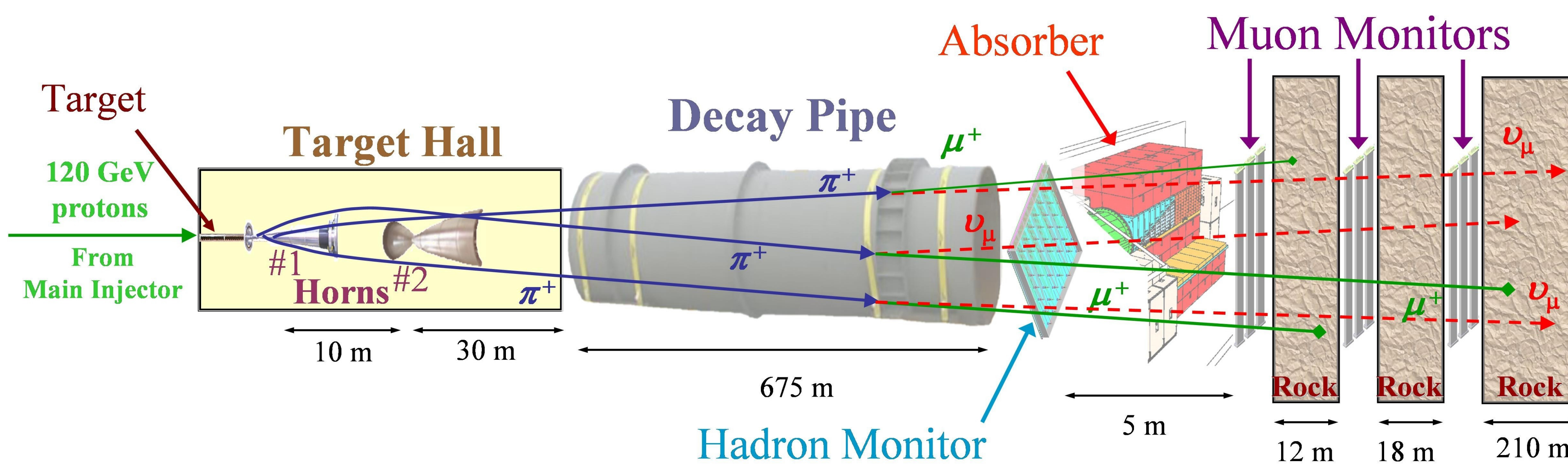
MINOS Experiment



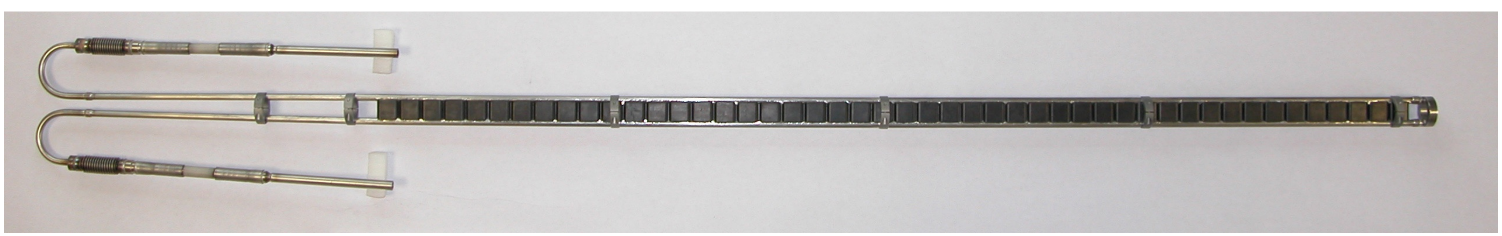
- High intensity ν_μ beam produced by 120 GeV protons from the Main Injector at FNAL

- compare energy spectrum:
  near detector ⇔ far detector
  1km 735km
  unoscillated ⇔ oscillated

NuMI Beamline



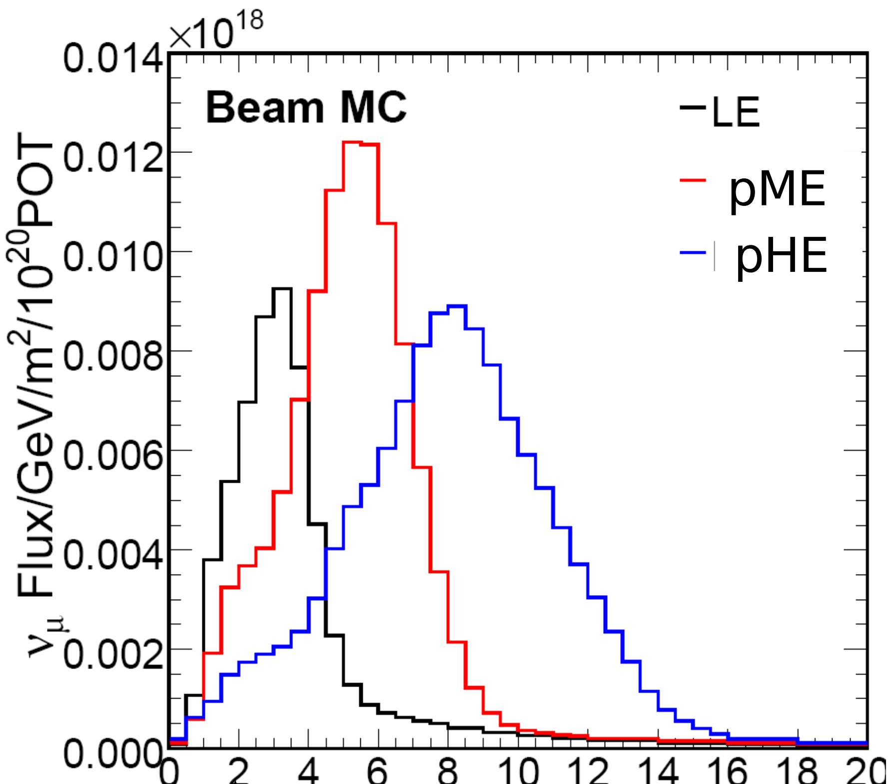
- ✔ movable target ⇒ variable beam energy
  - ➔ graphite, 47 segments, 6.4x15x20mm^3



- ✔ 2 magnetic focusing horns ⇒ ν or $\bar{\nu}$ beam
  - ➔ parabolic, pulsed, 200kA, 3T field

NuMI Neutrino Beam

- LE-10 configuration is most favorable for oscillation analysis and constitutes ~95% of total exposure
  - ➔ Data in 5 other configurations for systematic studies
- LE-10 event composition: 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, 1.3% ν_e / $\overline{\nu}_e$



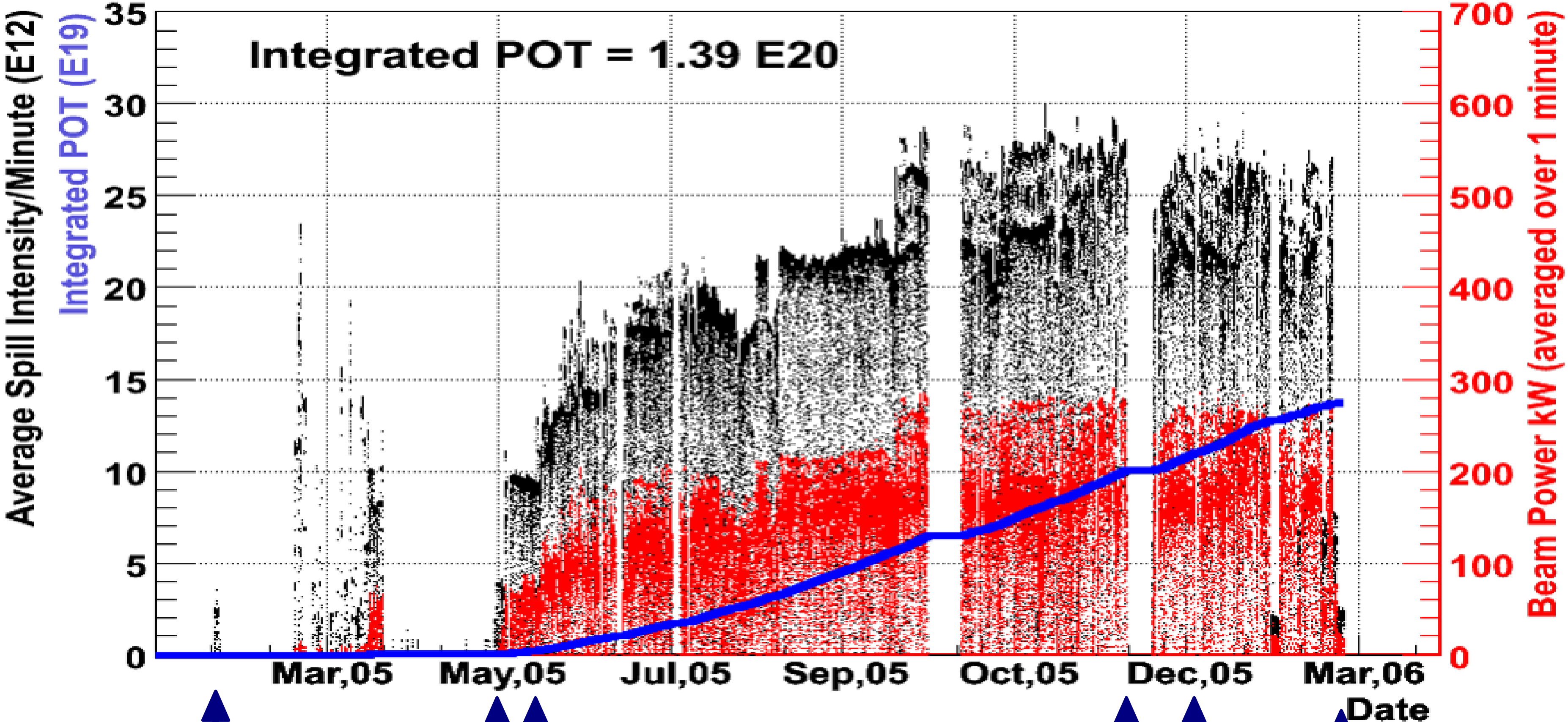
Position of oscillation maximum
(Δm^2=0.00335eV^2,L=735km)

expected unoscillated FD events* per 10^{20} pot**

	target position (cm)	
LE-10	-10	390
pME	-100	970
pHE	-250	1340

*Events in fiducial volume
**pot=Protons-on-target

1st year of NuMI Running



First neutrinos in ND

Start of LE running

Integrated 10^{20} POT

First Analysis Data Set
(0.93×10^{20} POT)

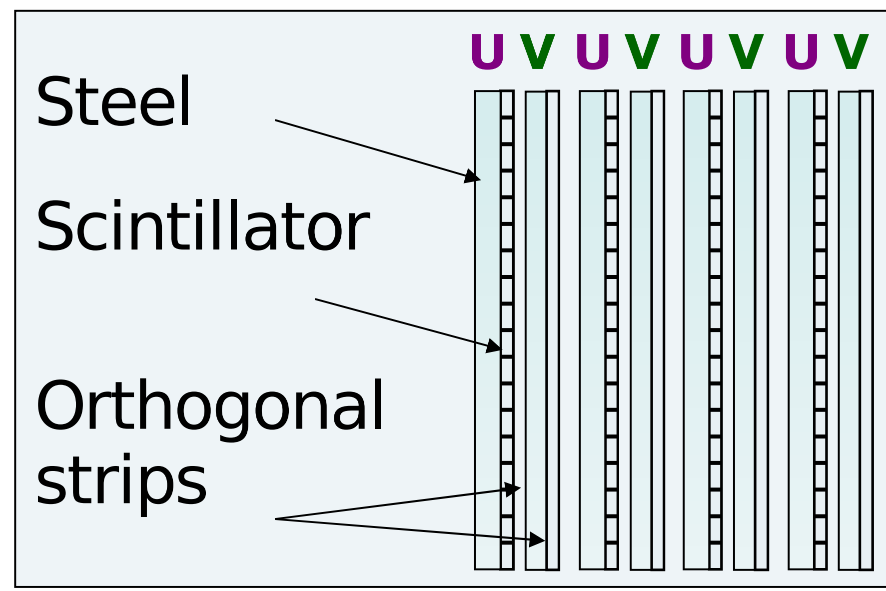
Main Injector Shutdown

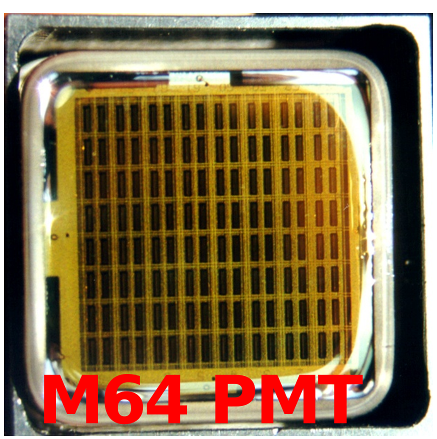
Final Analysis Data Set
(1.27×10^{20} POT)

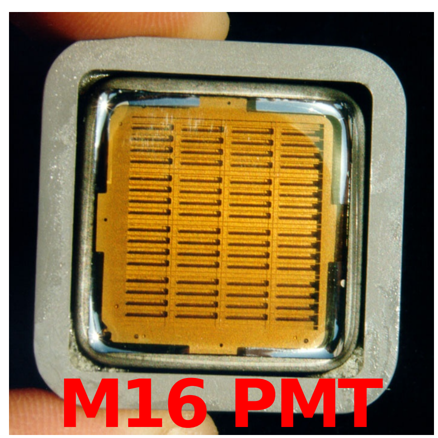
Detector Technology

Near and Far detector functionally identical:

- ✔ 2.54cm magnetized steel plates, <B>=1.2T field
- ✔ 4.1x1cm^2 scintillator strips
- ✔ consecutive planes have orthogonal strips
- ✔ optical readout: multi-channel PMTs
- ✔ GPS timestamps





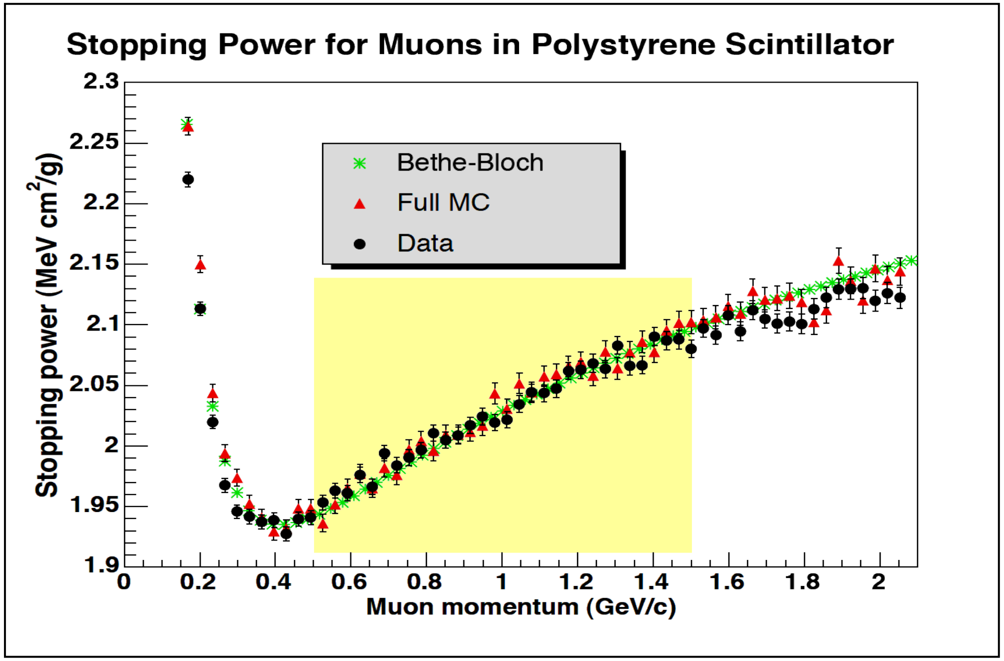


MINOS Detectors

1	mass (kt)	5.4
3.8x4.8	plane size (m^2)	8x8
282/153	# steel/scint pl.	486/484
front: all pl. instrumented back: 1/5 pl. instrumented fast QIE electronics	specifics	veto shield for cosmics 8x optical multiplexing

Calibration

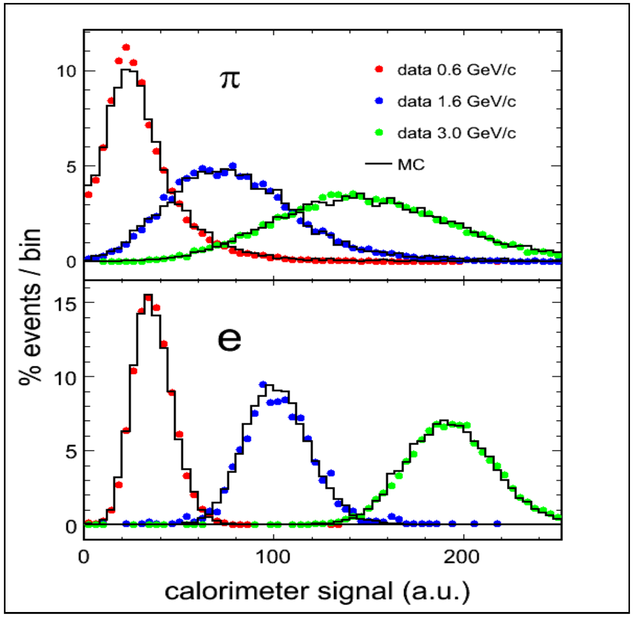
- ✔ Light injection: PMT gain
- ✔ cosmic ray μ:
  - strip-to-strip,
  - inter-detector
- ✔ calibration detector: overall energy scale
  - ➔ 'mini-MINOS' at CERN test beam
  - ➔ measured e/μ/π/p response



<u>Energy resolution: (E in GeV)</u>

Hadrons: 56% / √E ⊕ 2%

Electrons: 21% / √E ⊕ 4% / E



➔ see poster J. de Jong

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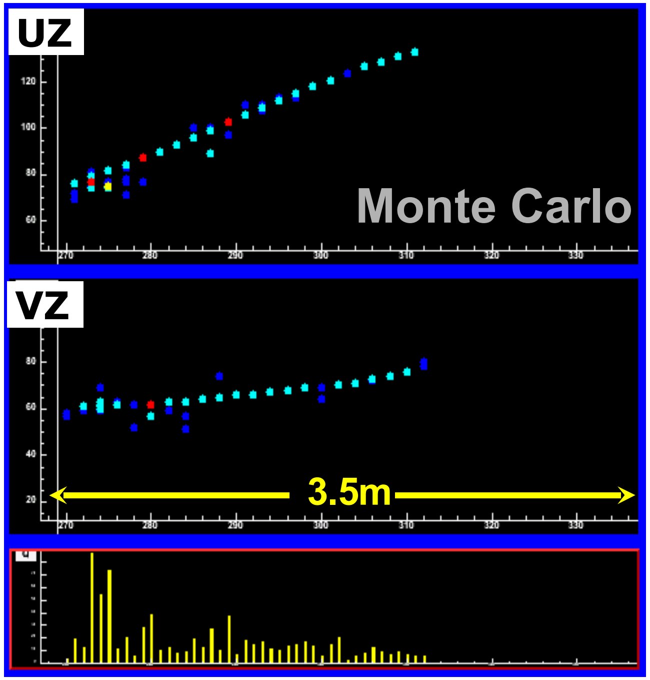
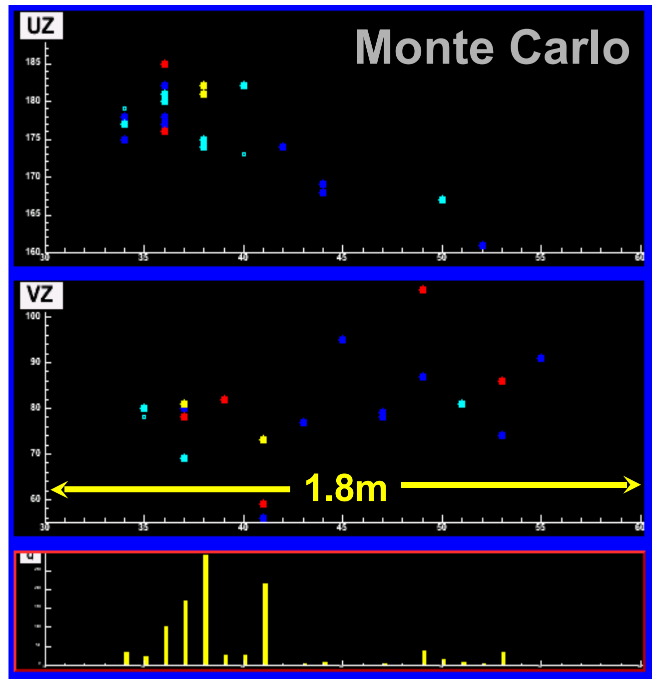
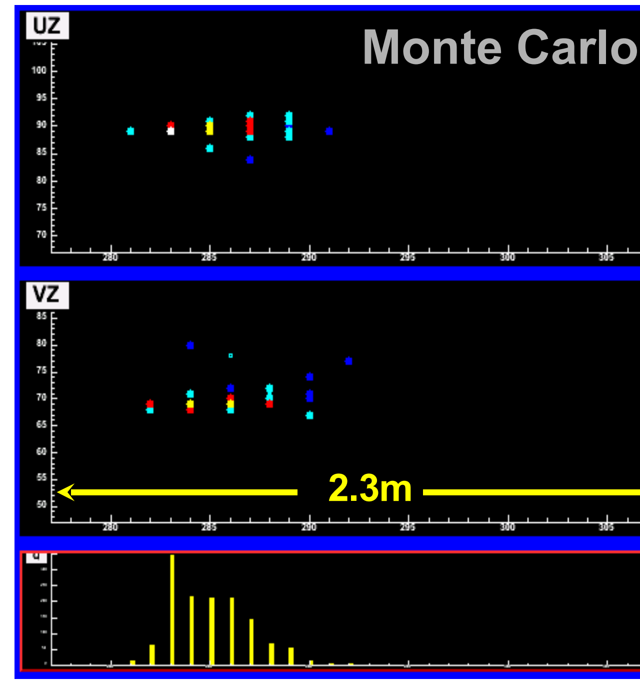
ν_μ Charged Current Event Selection

Event Topologies

ν_μ CC	ν_x NC	ν_e CC







ν_μ CC:
- ✓ long track (μ)
- ✓ hadronic activity near vertex

ν_x NC:
- ✓ short event
- ✓ often diffuse

ν_e CC:
- ✓ short event
- ✓ EM shower profile

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

$\sigma(E_{shower})$: 55%/√E

$\sigma(P_\mu)$: 6% range; 13% curvature

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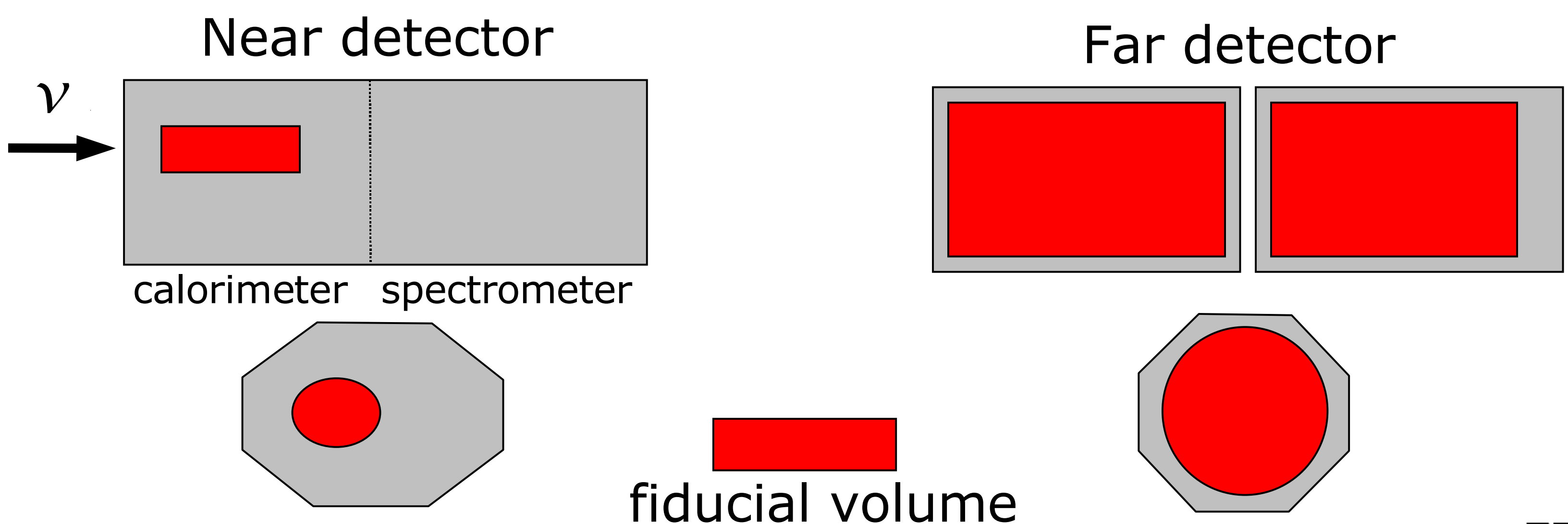
Pre-selecting ν_μ CC Events

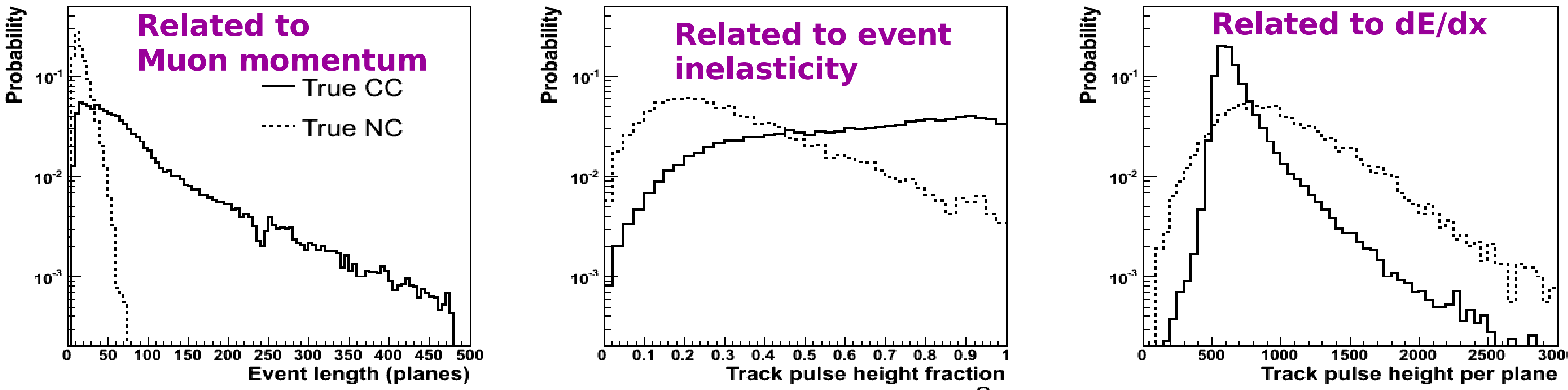
- beam and detector monitoring quality cuts
- pre-selection:
  - at least one good reconstructed track
  - only select fitted tracks with negative charge
  - fiducial volume cuts on vertex:
    - ND: 1m < z < 5m; r < 1m w.r.t. beam center
    - FD: z > 50cm from edge, z>2m from end; r < 3.7m



Selecting ν_μ CC Events

Input variables for PDF-based event selection

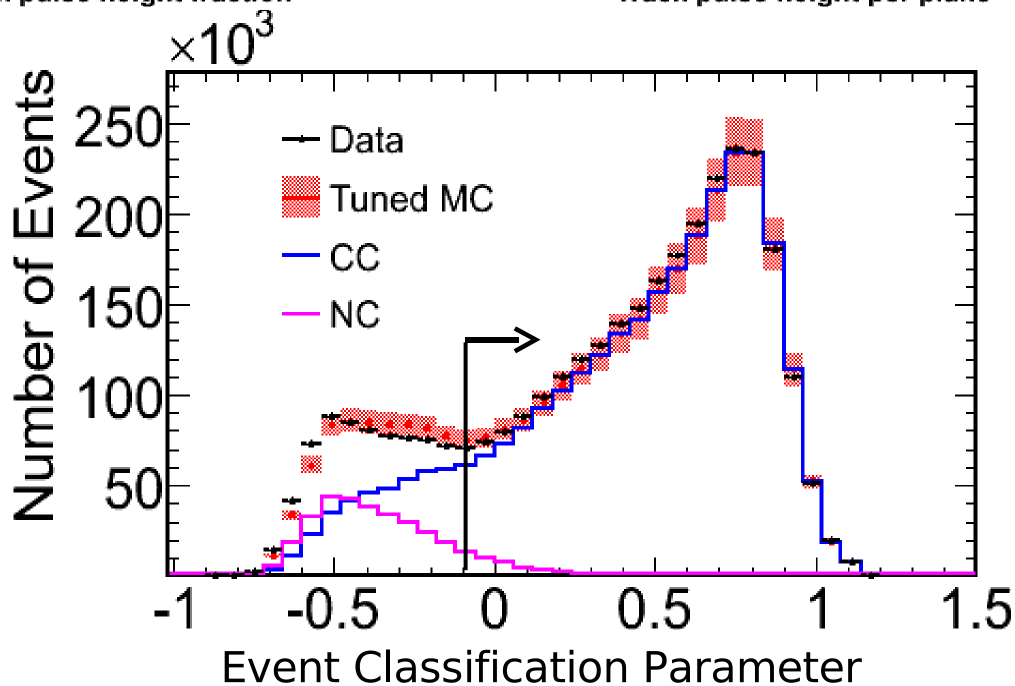
Monte Carlo



- Event classification parameter defined as:

$$PID = -\sqrt{-\log P_{CC}} + \sqrt{-\log P_{NC}}$$

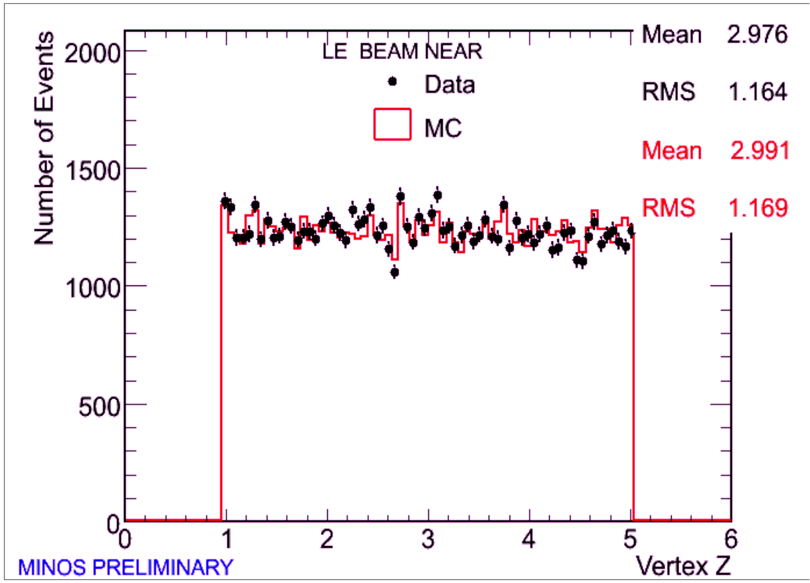
- Select CC-like events:
  - PID>-0.2 in FD
  - PID>-0.1 in ND

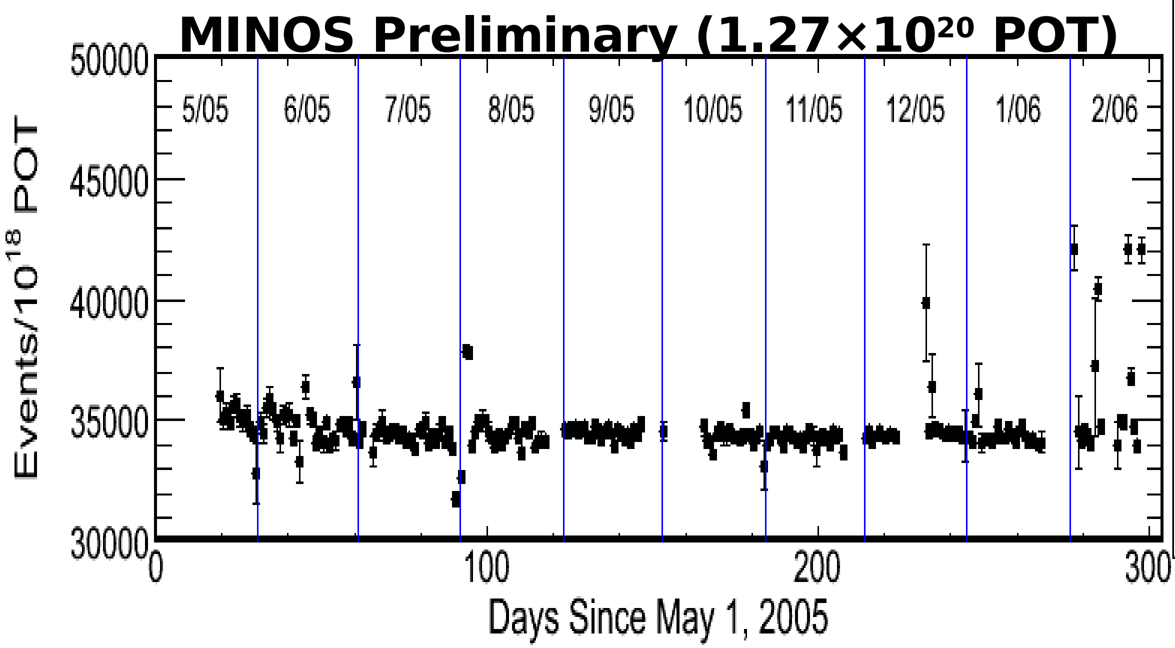


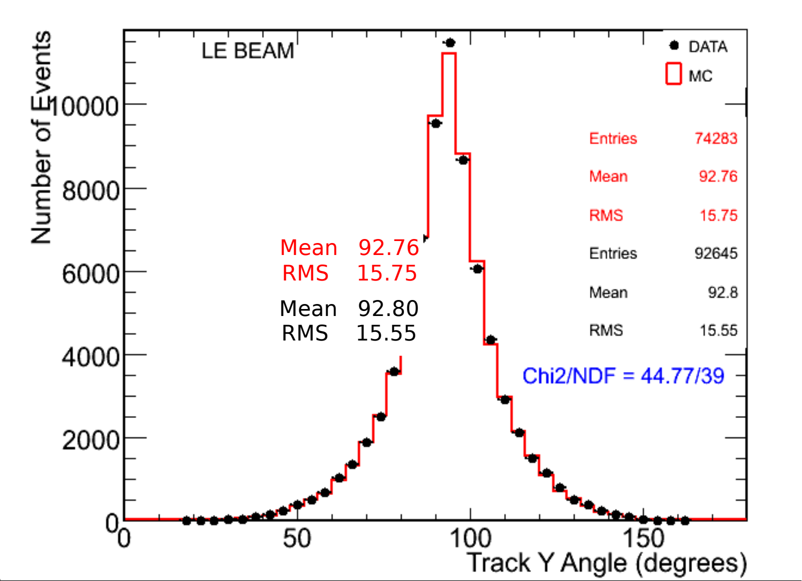
Near Detector Distributions

- ✔ event rate flat over time
  - ✗ deviations due to different running conditions
- ✔ distributions well reproduced by Monte Carlo

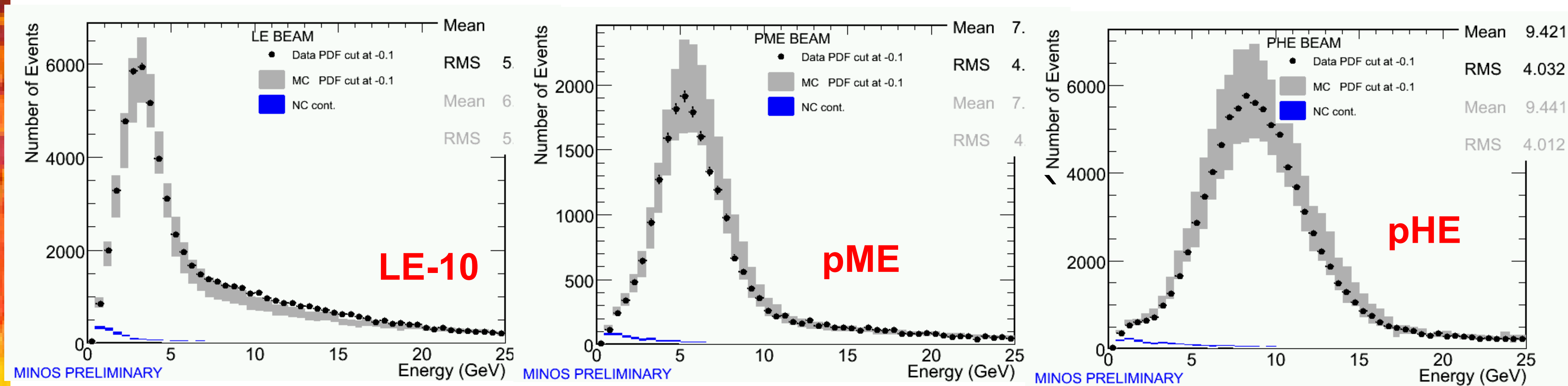
➔ see D. Naples talk on ND physics



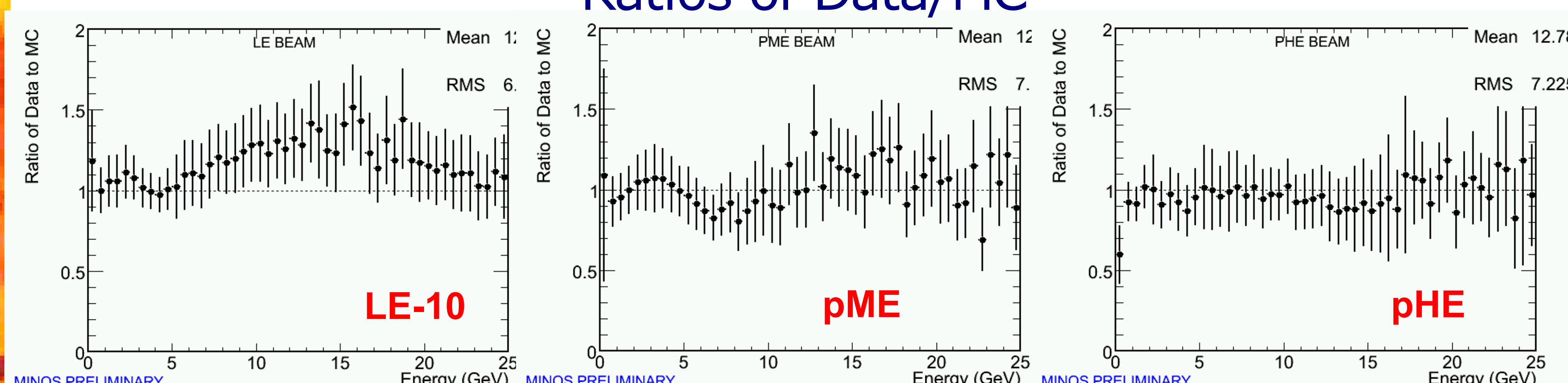




Near Detector Energy Spectra



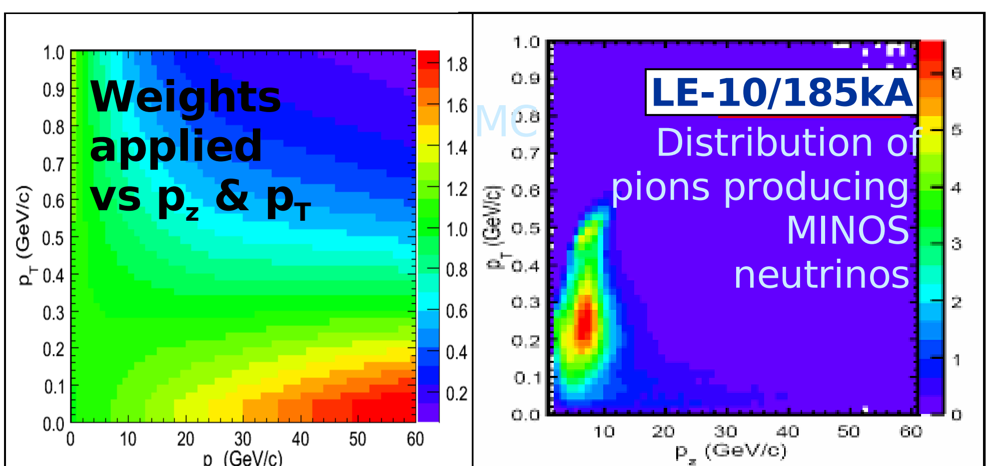
Ratios of Data/MC

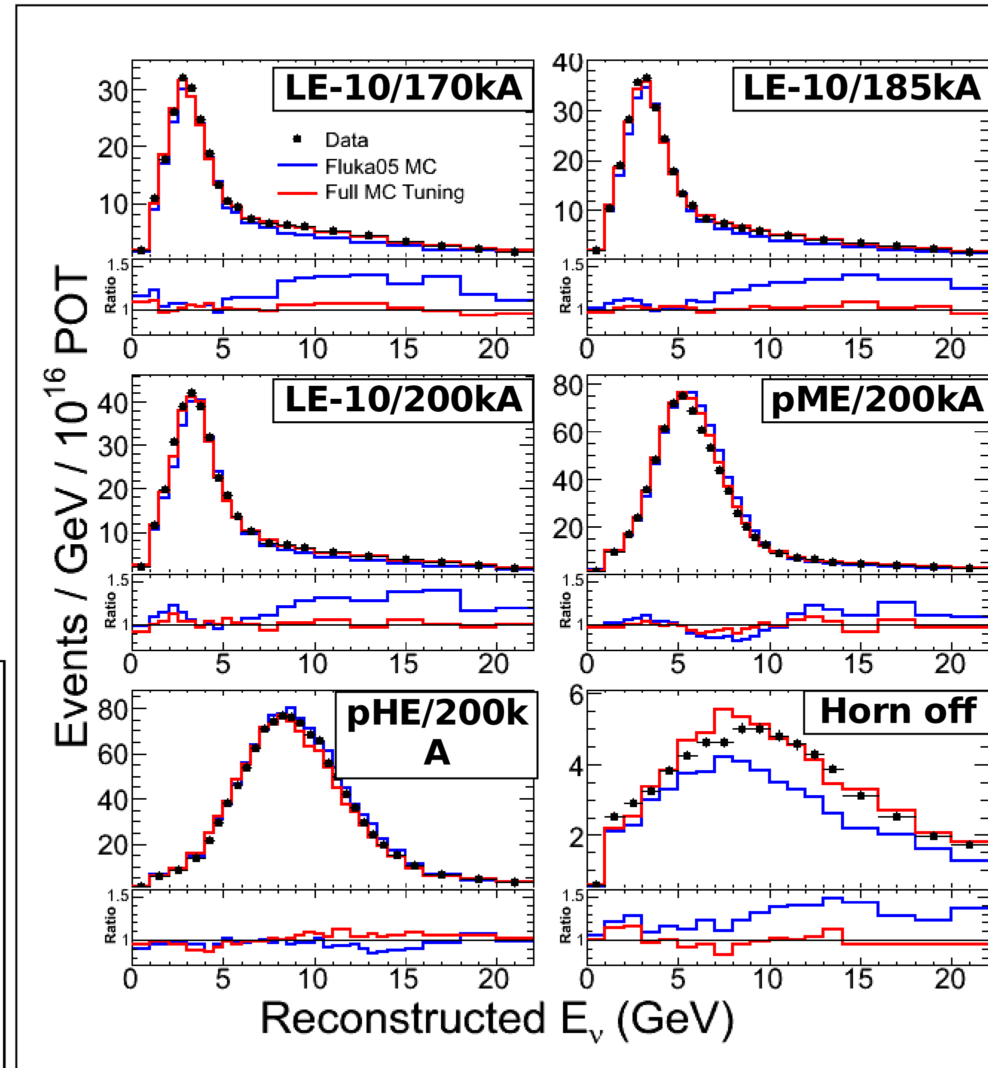


Error envelopes shown reflect uncertainties due to cross-section modelling, beam modelling and calibration uncertainties

Hadron Production Tuning

- Parametrize Fluka2005 as a function of ν parent x_F and p_T
- Perform fit which reweights parent x_F and p_T to improve data/MC agreement
- Horn focusing, beam misalignments included as nuisance parameters in fits
- Small changes in x-section, neutrino energy scale, NC background also allowed





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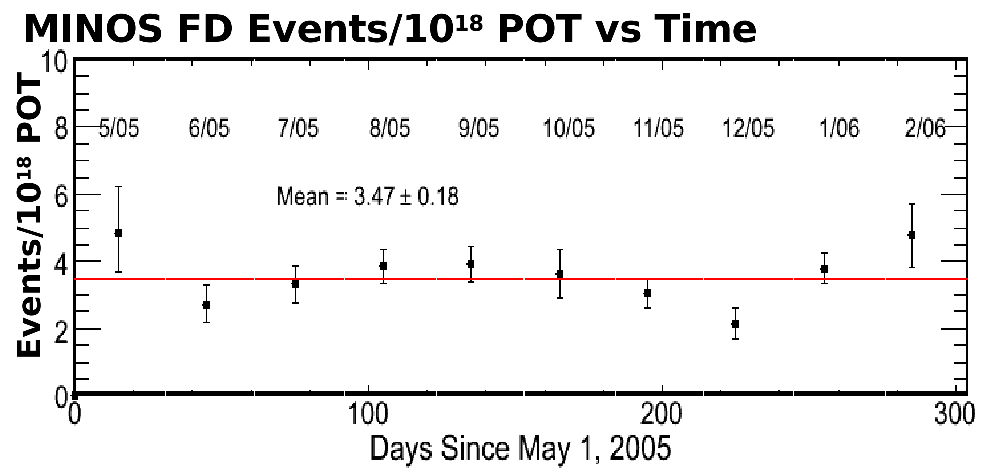
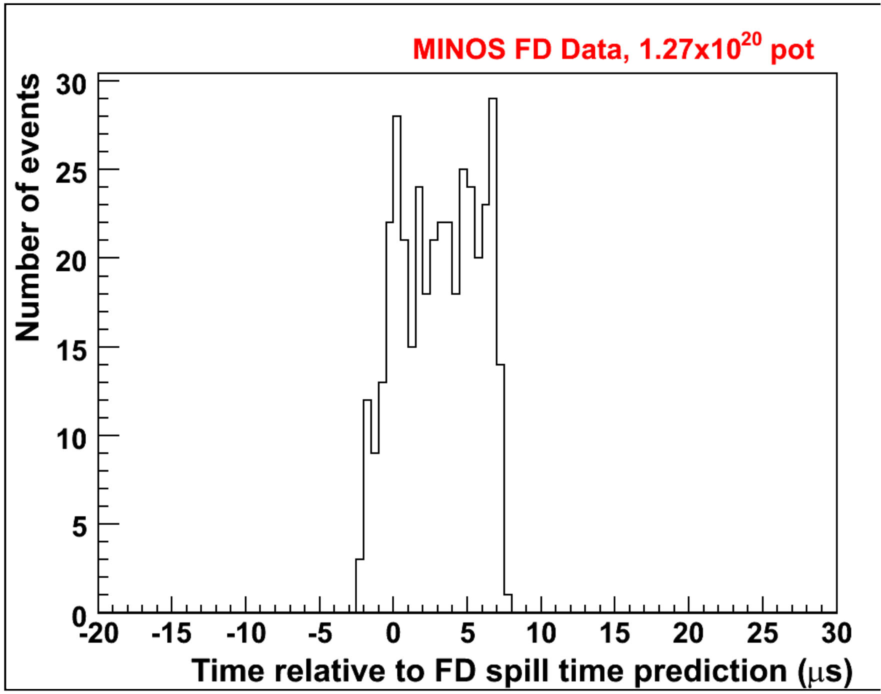
Selecting Far Detector Beam Events

- LE-10 data sample
  - ➔Total POT: 1.27×10^{20}
  - ➔FD live time: 98.9%
- Beam spill trigger reads out all activity in 100μs around spill signal (10μs)
- event rate constant over time
- event time consistent with spill
- additional 53° cut around beam axis to reject cosmics
- cosmic background estimated using sidebands outside timing cut and fake spills in anti-coincidence with beam spills: upper limit < 0.5 events





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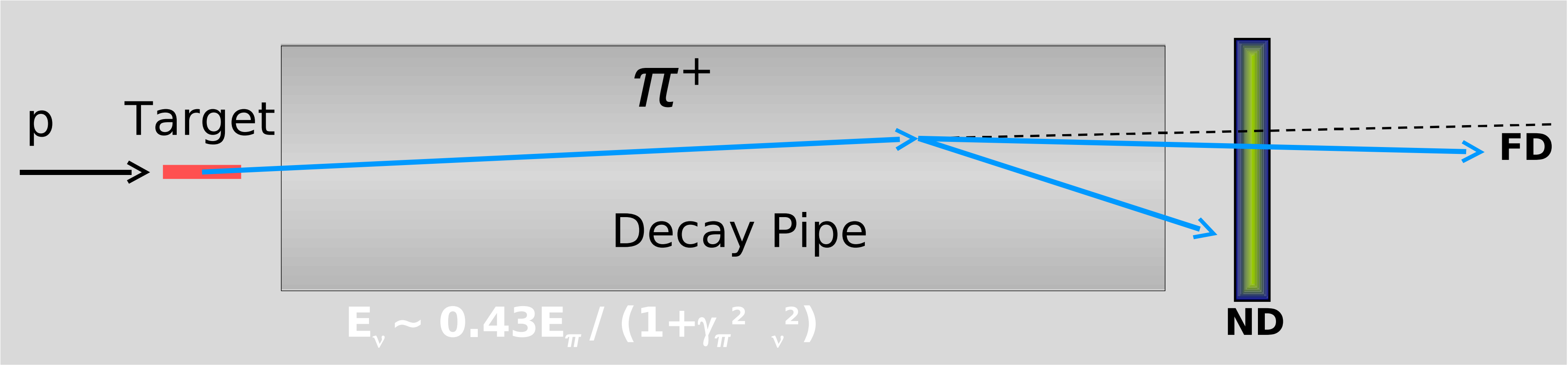
Far Detector Oscillation Analysis

Predicting unoscillated FD Spectrum

- Near and far detector see different decay angles of the neutrinos ⇒ different energy spectra



- Several methods developed for extrapolation
- Primary method is ‘matrix method’:
  - ➔contains info of pion 2-body decay kinematics and beamline geometry
  - ➔MC used to correct energy resolution and acceptance
  - ➔See talk N. Saoulidou

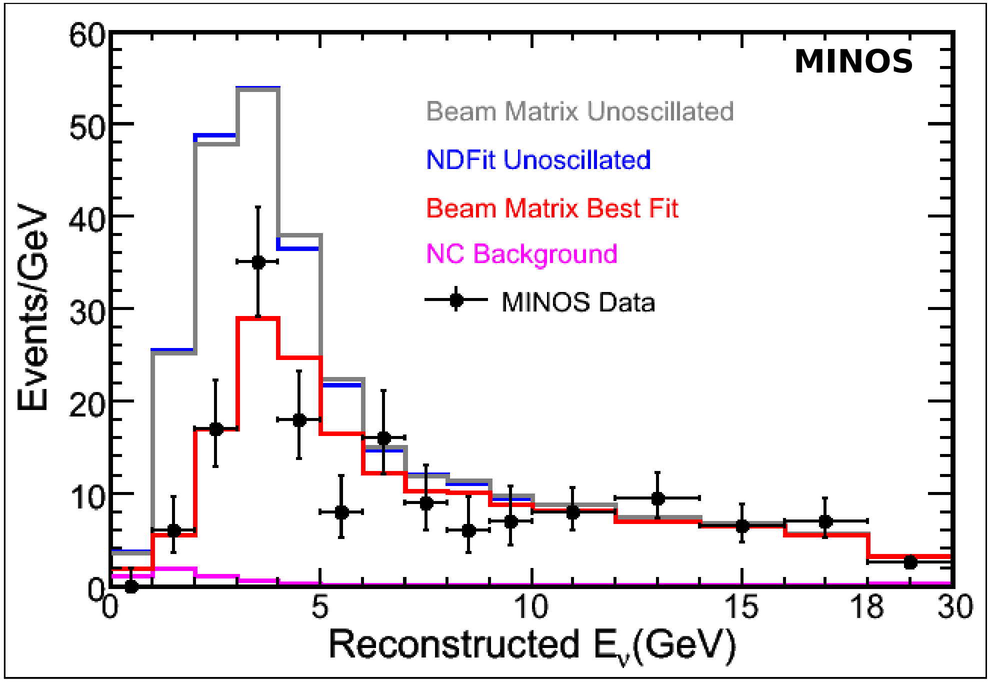
Observed vs. Expected Event Rate

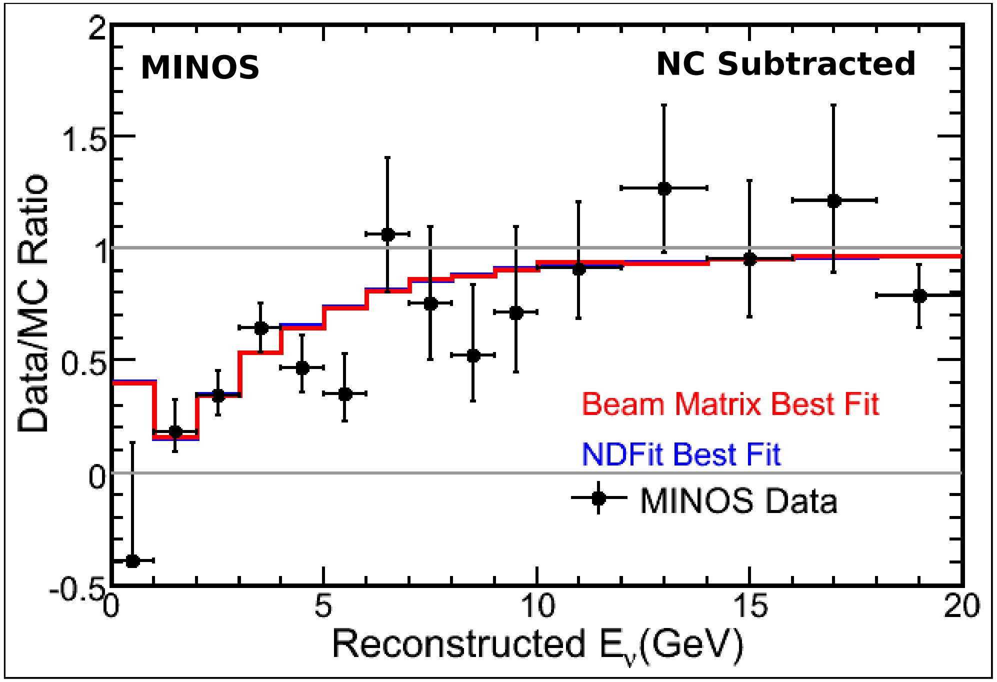
Data sample (ν_μ only)	observed	expected	ratio
E_ν < 30 GeV	215	336.0±14.4	0.64±0.05
E_ν < 10 GeV	122	238.7±10.7	0.51±0.05
E_ν < 5 GeV	76	168±8.8	0.45±0.06

- ✔ A large energy dependent deficit
- ✔ Below 10 GeV a 49% deficit is observed
- ✔ Significance is 6.2 (stat+syst)

FD Spectrum / Oscillations Fit

- ✔ Best-fit spectrum for 1.27×10^{20} POT





$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\times10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$

$$\mathrm{Normalization} = 0.98$$

Errors are at 68% C.L.
statistical + systematic

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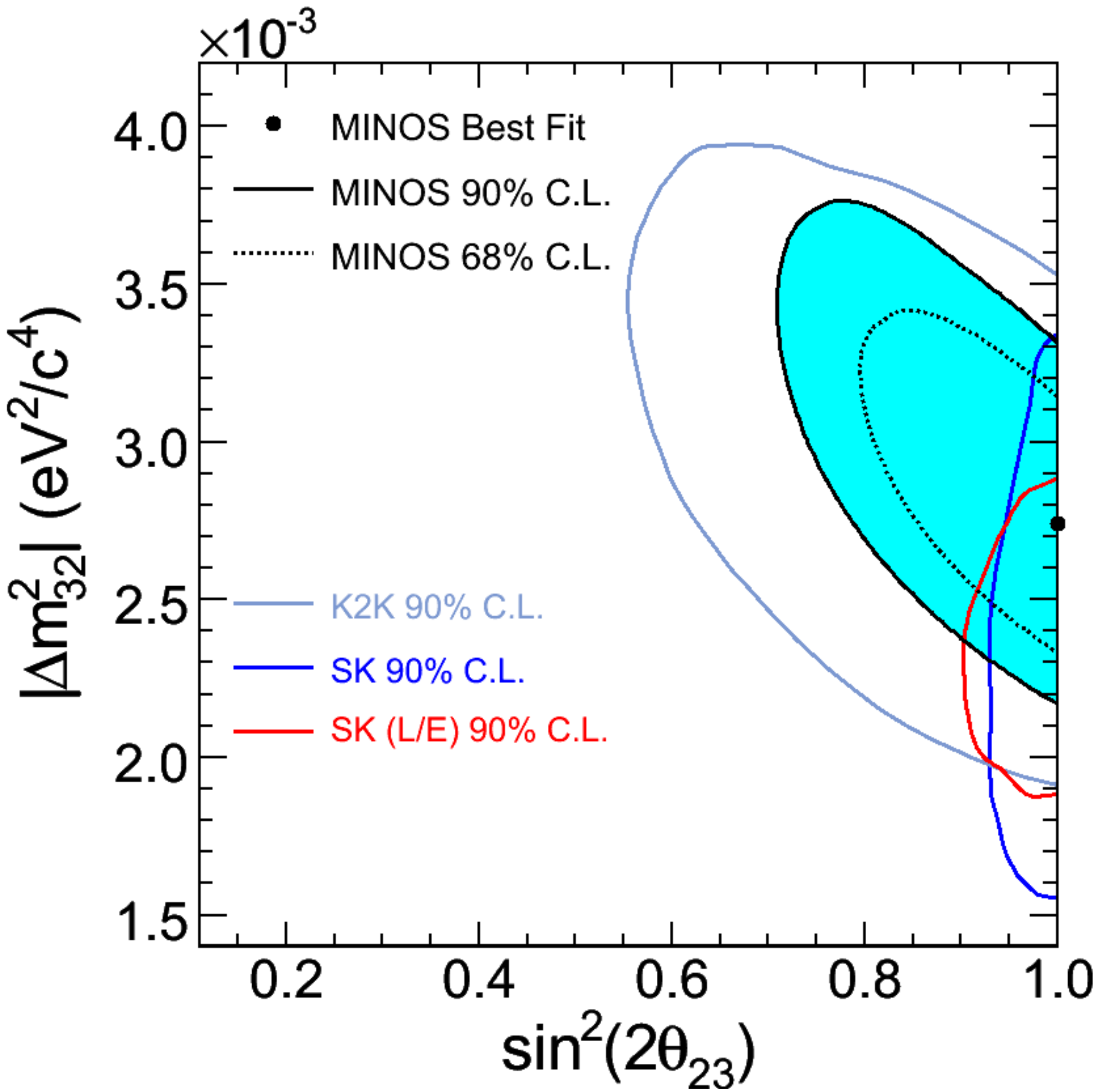
Allowed Region

- ✔ Fit includes penalty terms for three main systematic uncertainties
- ✔ Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$

$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$



Systematic Uncertainties

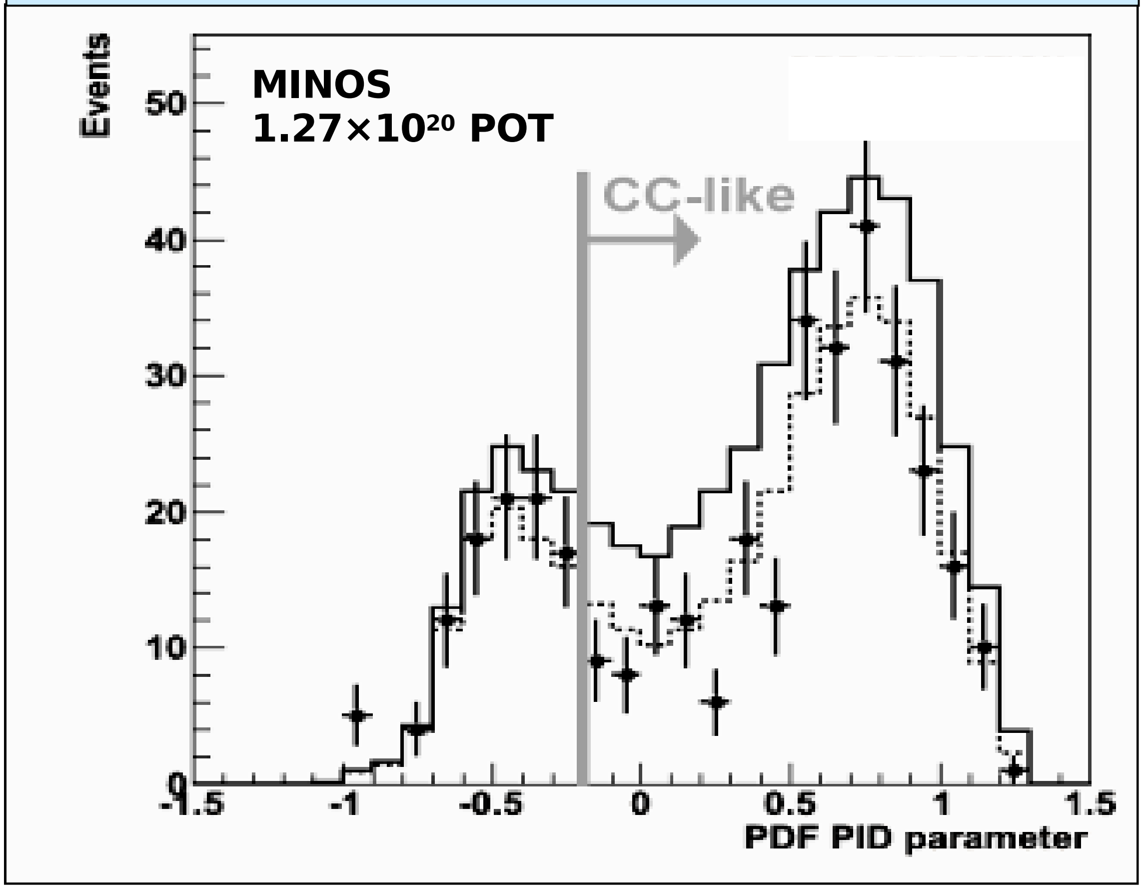
uncertainty	Δm_{32}^2 (10^{-3} eV^2)	$\sin^2 2\theta_{23}$
near/far normalization ±4%	0.050	0.005
abs. hadr. shower energy scale ±5%	0.060	0.048
NC contamination ±50%	0.090	0.050
all other uncertainties	0.040	0.011
total systematic uncertainty	0.13	0.07
statistical uncertainty	0.36	0.12

- ✔ Systematic shifts computed using MC "fake data" samples for $\Delta m^2=2.7\times10^{-3}$ eV^2 and $\sin^2 2\theta=1.0$
- ✔ Δm^2 systematic is ~40% of statistical uncertainty
- ✔ Several systematic uncertainties are data driven → improve with more data and study

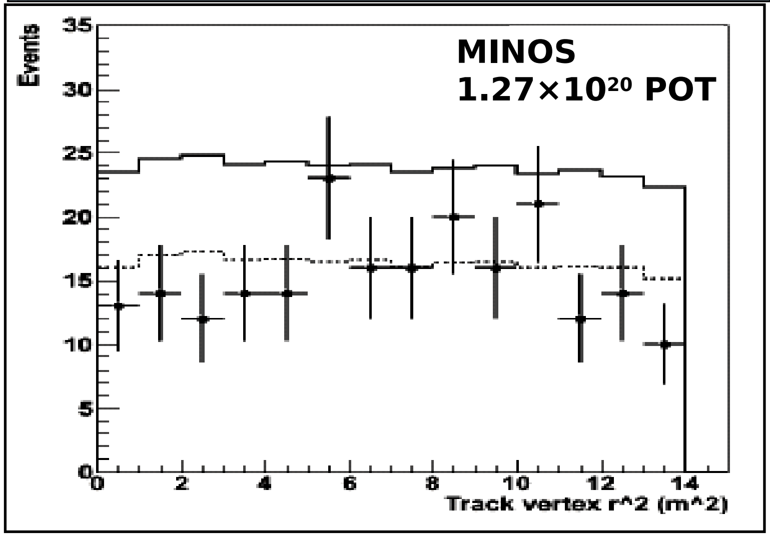
Far Detector Distributions

- ✔ Predicted no oscillations (solid)
- ✔ Best fit (dashed)

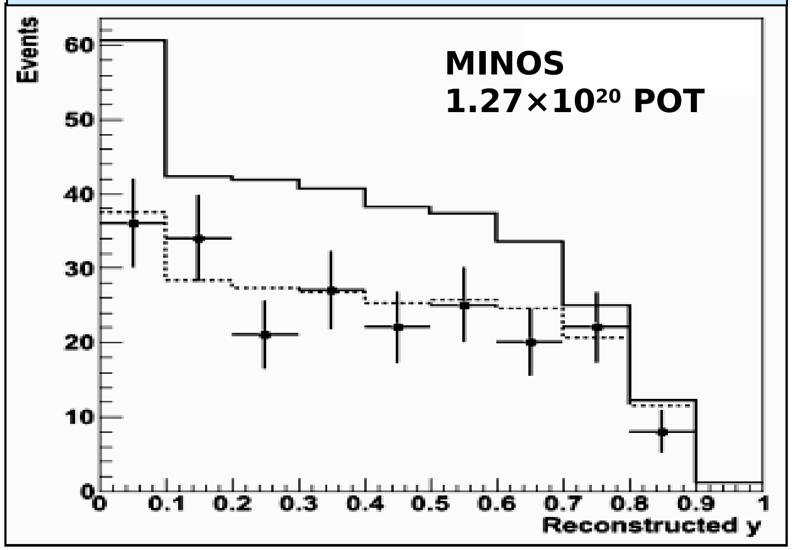
Event Classification Parameter



Track Vertex r^2 (m^2)



$y = E_{shw}/(E_{shw}+P_\mu)$



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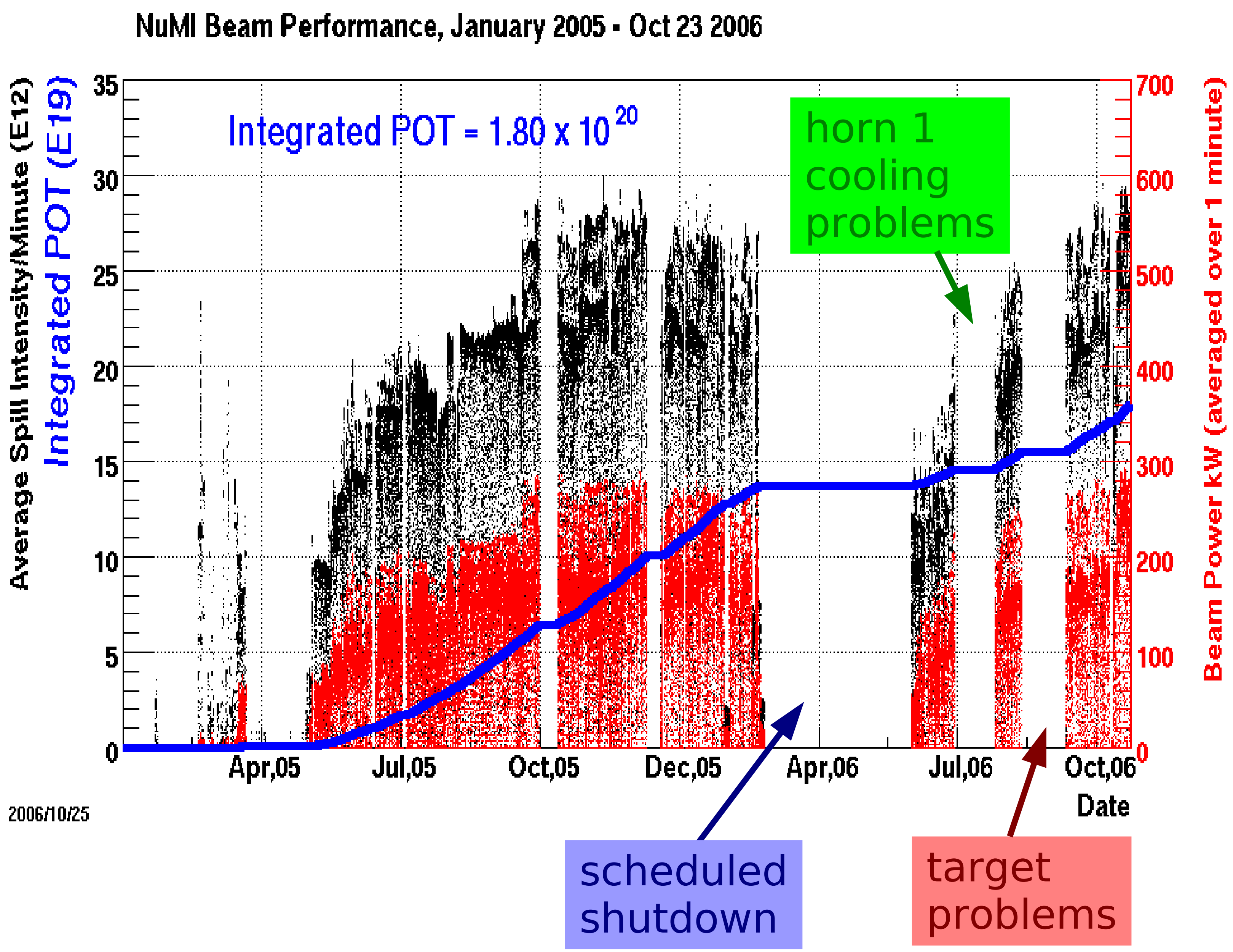
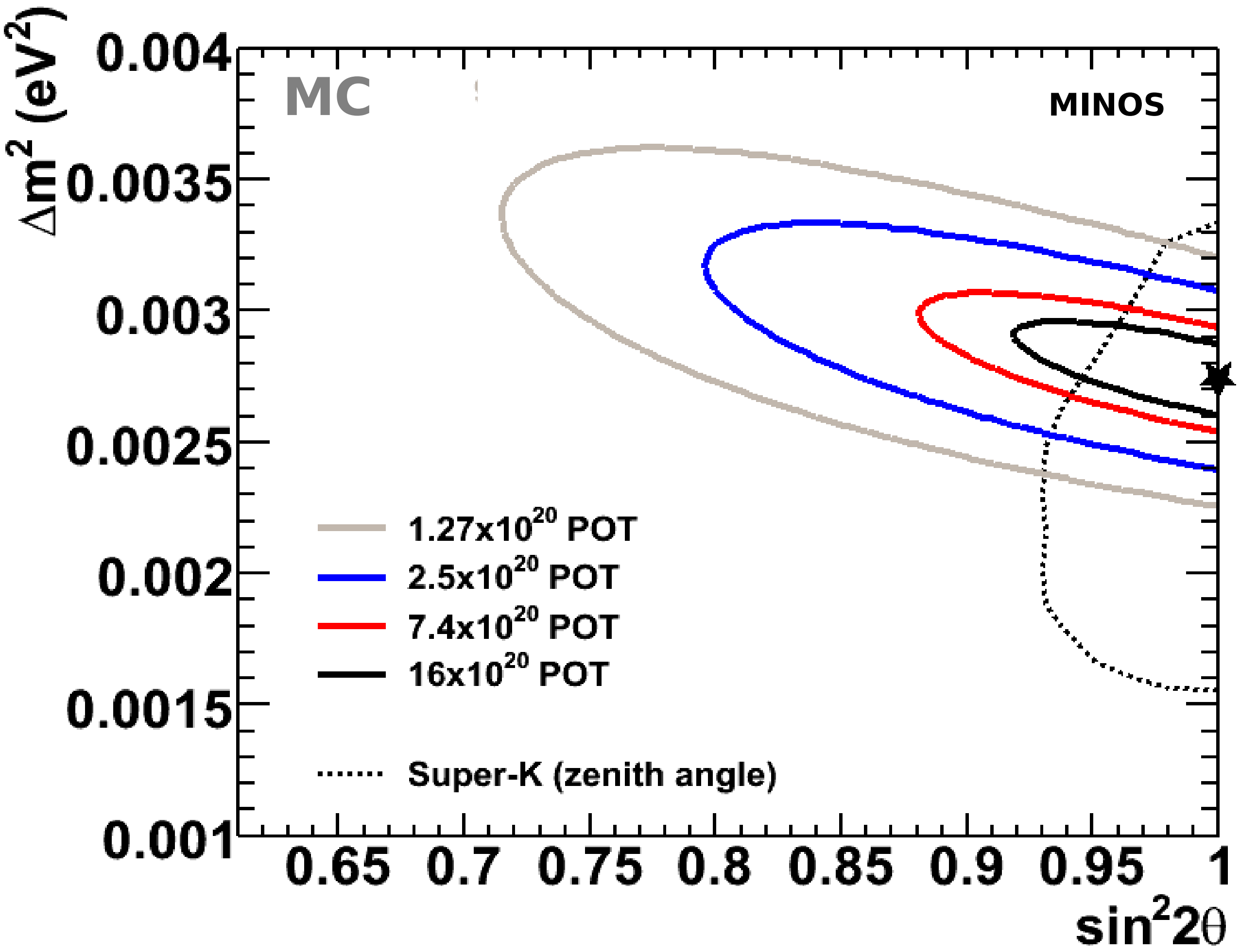
Future Prospects

2nd year of NuMI Running



Projected Sensitivities

- MINOS ν_μ disappearance sensitivities for different POT
- Best fit values used as input



$\Delta m^2_{32} = 2.74 \times 10^{-3}$ eV^2

$\sin^2 2\theta_{23} = 1.00$

- Contours are 90% C.L. statistical errors only

Conclusions

- MINOS has completed a ν_μ disappearance analysis of the first year of NuMI beam data
  - ➔ Exposure used in analysis: 1.27×10^{20} POT
  - ➔ No disappearance excluded at 6.2σ from event rates only
  - ➔ Results consistent with oscillation hypothesis:

$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\times10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$

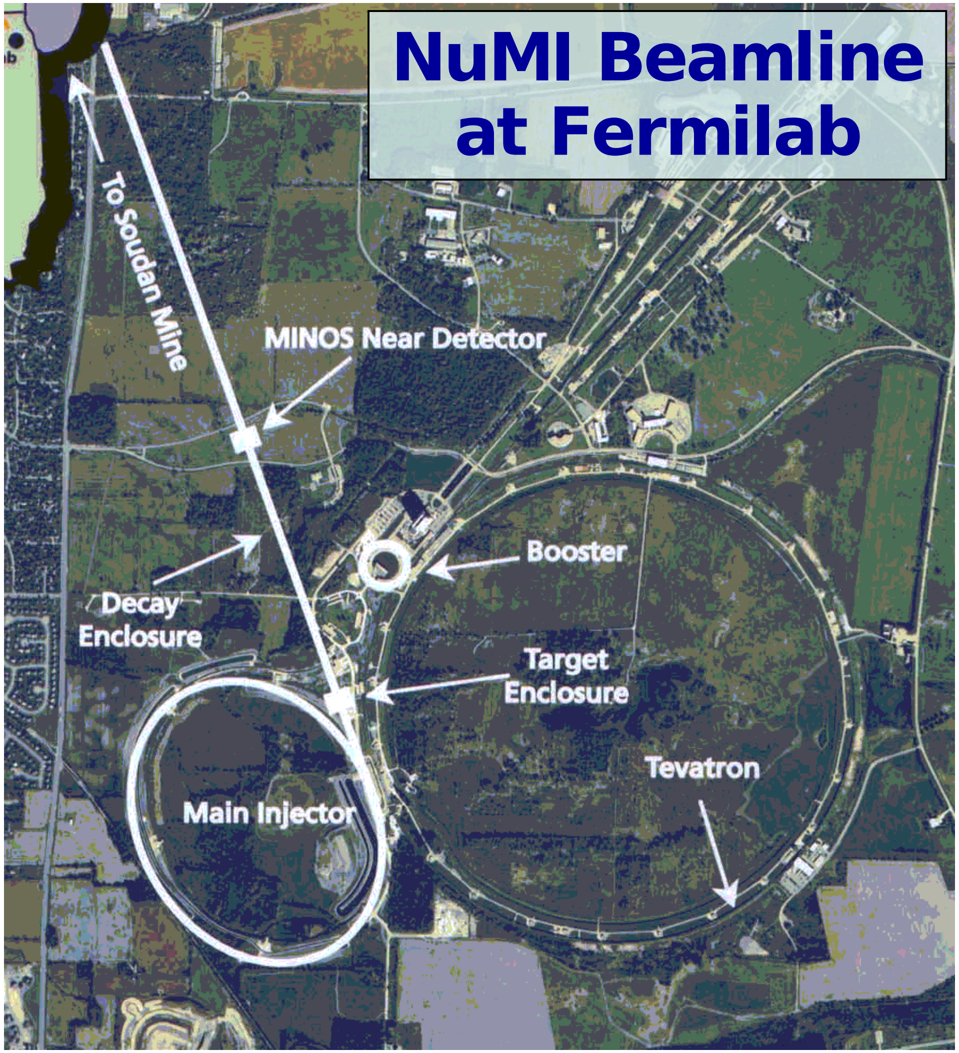
  - ➔ Constraining $\sin^2 2\theta_{23} = 1$ yields: $\left|\Delta m^2_{32}\right| = 2.74\pm0.28\times10^{-3}\,\mathrm{eV}^2$
- Systematic uncertainties under control
  - ➔ significant improvements expected with data driven studies & more statistics
- **Accepted for publication in PRL (hep-ex 0607088)**
- Second year of running underway. Stay tuned for new results

Extras

NuMI Facility

NuMI Design Parameters:

- 120 GeV protons from the Main Injector (MI)
- Single turn extraction ~10 μs spill
- MI accepts up to 6 batches from Booster
  - Either 5 or 6 for NuMI
- 1.9 second cycle time
- 4×10^{13} protons/spill
- 0.4MW



Performance Averages:

(for period: Oct 15 – Jan 31)

- 2.2 second cycle time
- 2.3×10^{13} protons/spill
- 0.17MW

Performance Records:

- 2.0 second cycle time
- 3.0×10^{13} protons/spill
- 0.29MW

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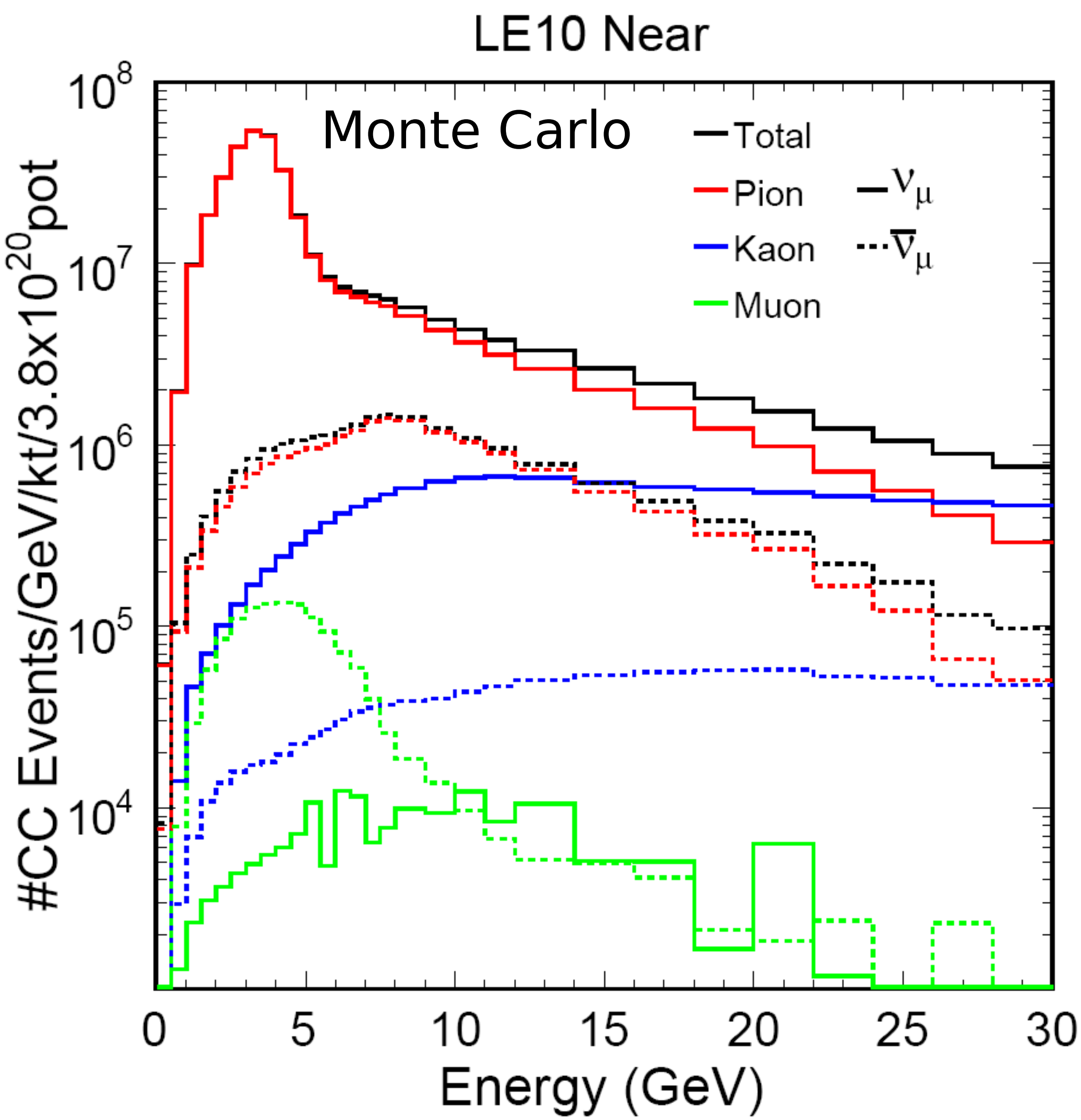
Beam Composition

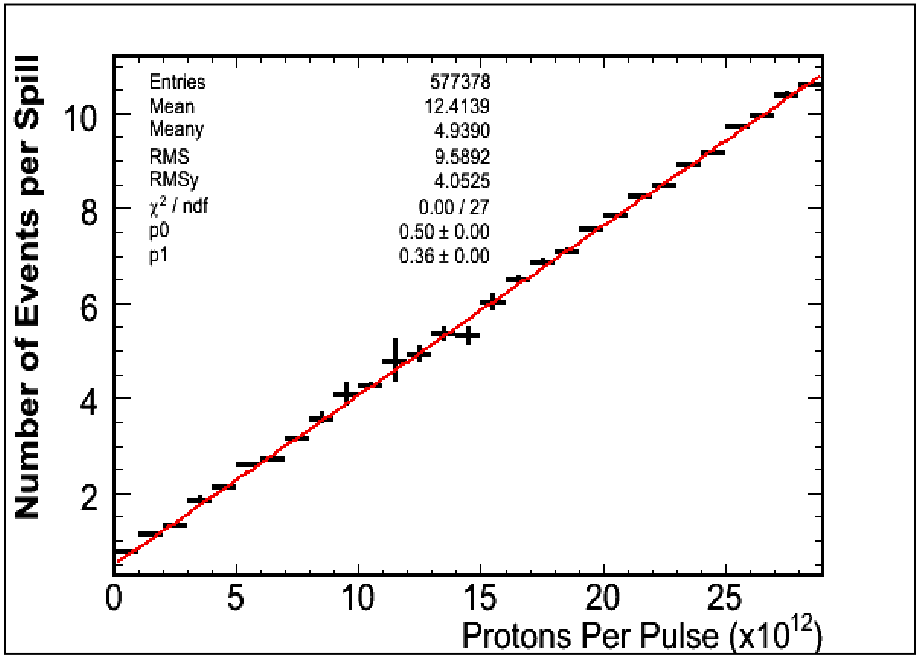


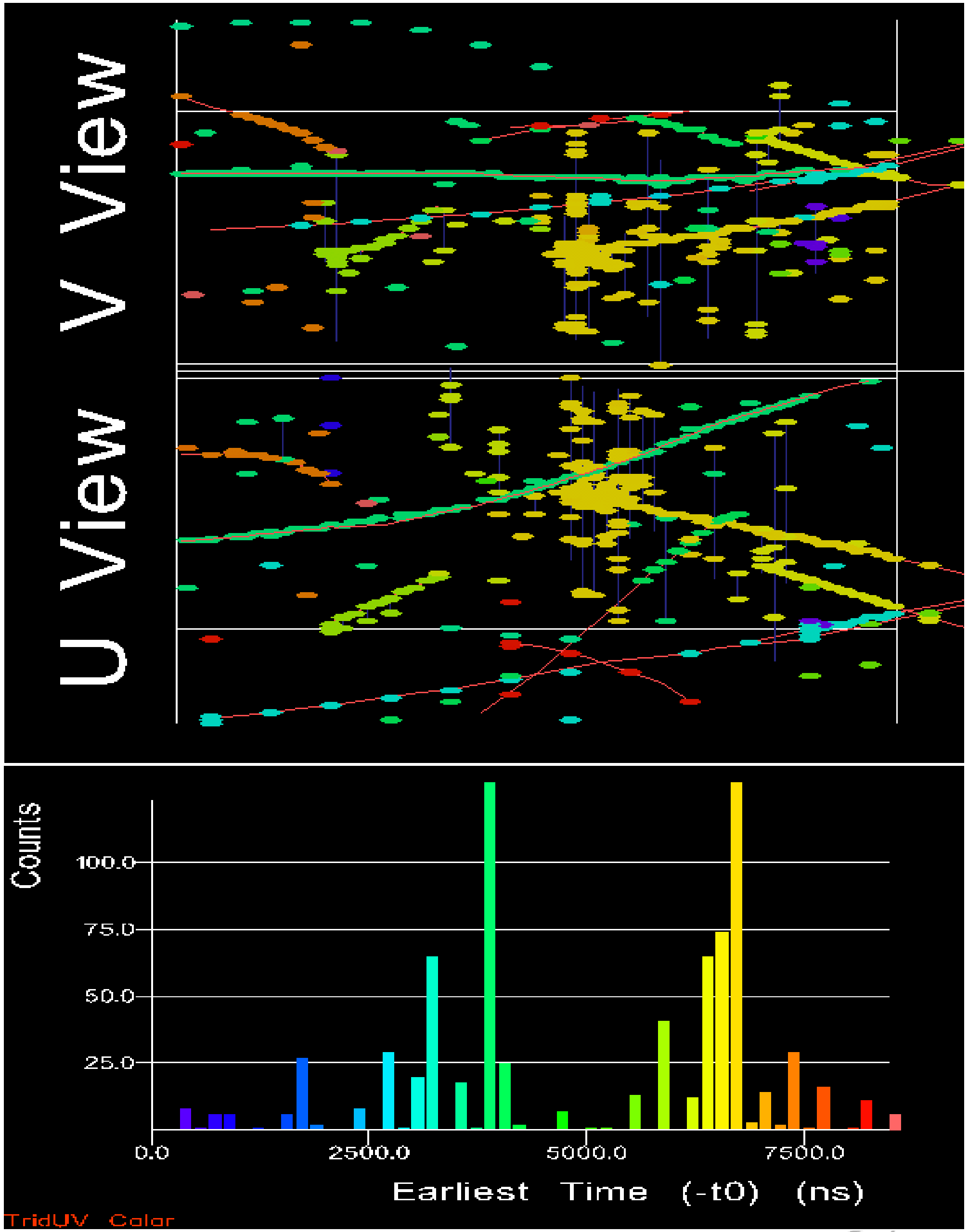
Composition of Charged-Current (CC) Events:

- 92.9% ν_μ
- 5.8% $\bar{\nu}_\mu$
- 1.2% ν_e
- 0.1% $\bar{\nu}_e$

Near Detector Spill

- Multiple events in ND per spill
  - Over 1x10[7] fiducial events collected
- Events separated using topology and timing
  - Color in display indicates time (blue: early, red: late)
- No rate effects observed
  - Linear increase in event rate with beam intensity





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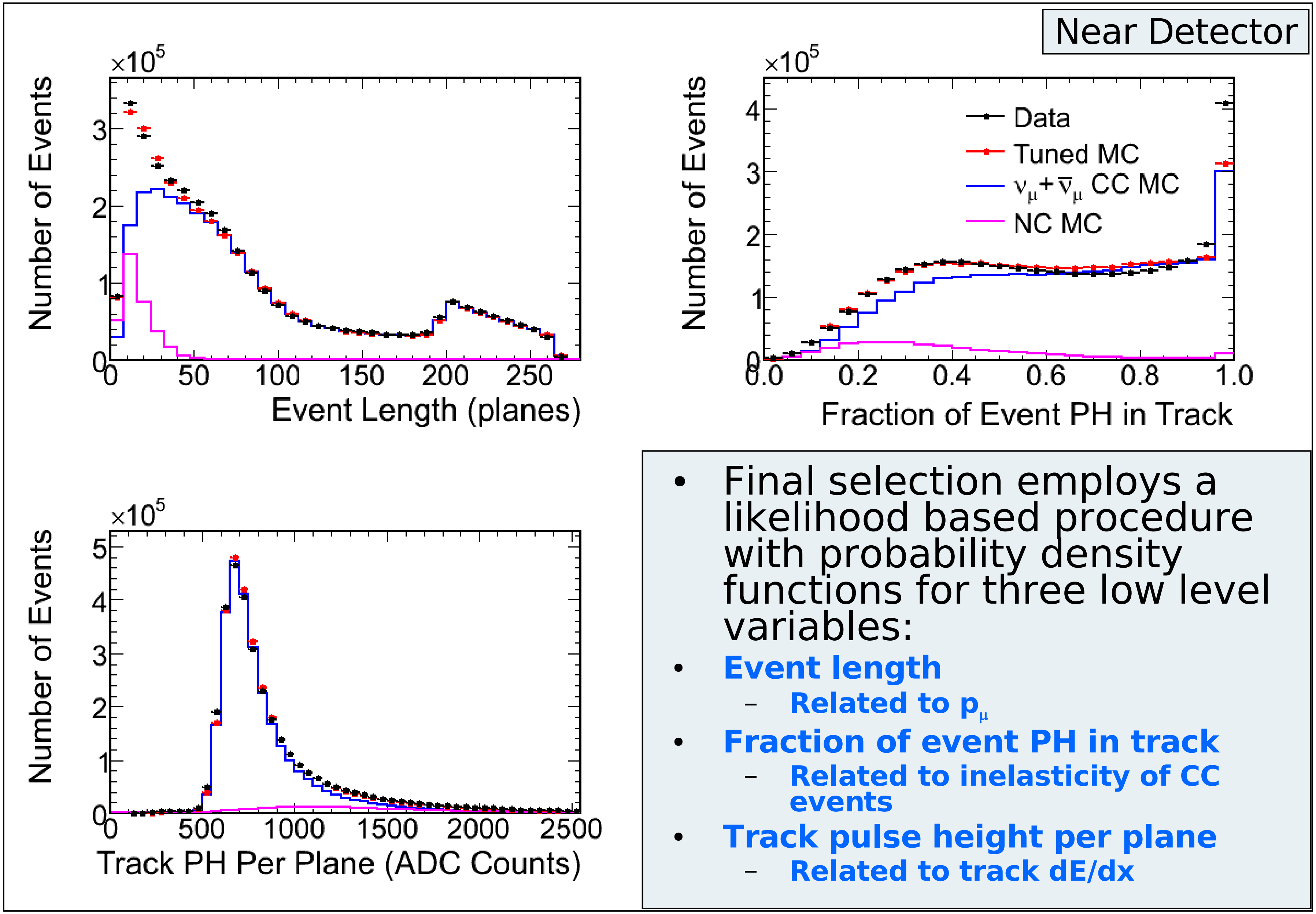
ν_μ CC Event Selection



- Final selection employs a likelihood based procedure with probability density functions for three low level variables:
- **Event length**
  - **Related to p_μ**
- **Fraction of event PH in track**
  - **Related to inelasticity of CC events**
- **Track pulse height per plane**
  - **Related to track dE/dx**

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ND ν_μ CC Efficiencies/Purities