MINOS Results from the NuMI beam

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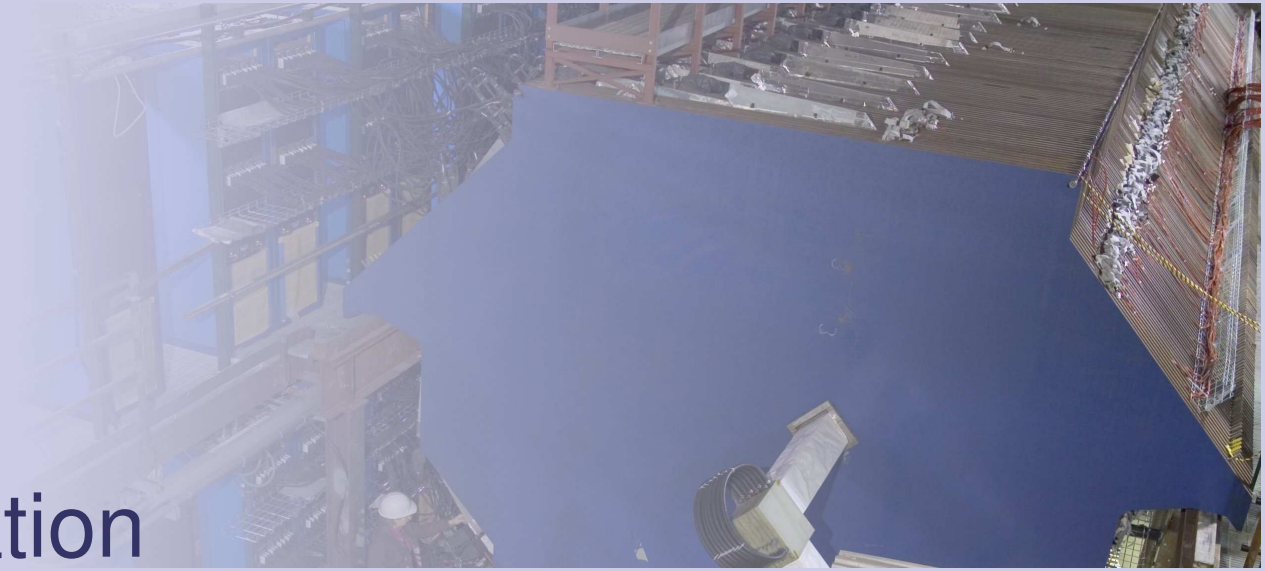

for the

MINOS collaboration

Neutrino Physics

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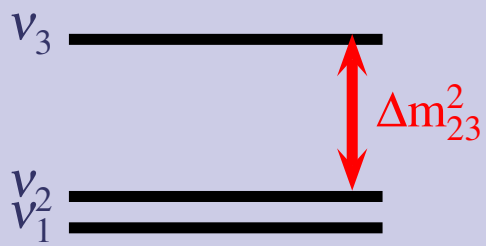
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$\sin^2 2\theta = 4U^2_{\mu 3}(1 - U^2_{\mu 3})$$

- Pontecorvo-Maki-Nakagawa-Sakata matrix
- ν_1 defined as largest part of ν_e
- MSW $\rightarrow$ sign of Δm^2_{12}
- Chooz $\rightarrow U_{e3}$ is small

MINOS will:

- Make a precise (<10%) measurement of Δm^2_{23} and $\sin^2 2\theta$
- Search for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations
- Search for / rule out exotic models
  - $\Rightarrow$ Neutrino decay
  - $\Rightarrow$ Sterile neutrinos
- First measurement of ν vs $\overline{\nu}$ oscillations [atmospheric: Phys.Rev.D73:072002,2006]

MINOS Collaboration

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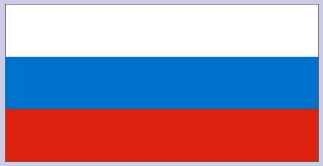
Argonne • Athens • Benedictine
Brookhaven • Caltech • Cambridge
Campinas • Fermilab • College
de France • Harvard • IIT • Indiana
ITEP Moscow • Lebedev
Livermore • Minnesota, Twin Cities
Minnesota, Duluth • Oxford
Pittsburgh • Protvino • Rutherford
Appleton Lab • Sao Paulo
South Carolina • Stanford •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



MINOS overview

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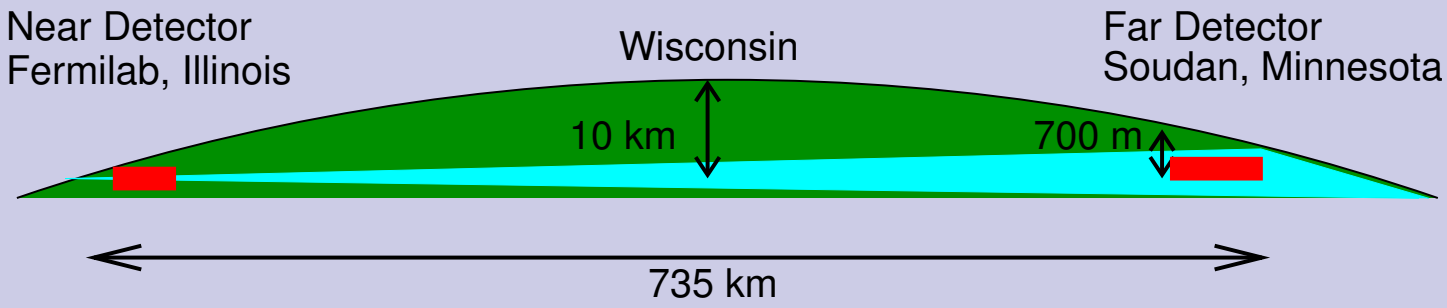
- Main Injector Neutrino Oscillation Search
- Precision measurement of "atmospheric" neutrino oscillation parameters
- Beam of ν_μ from 120 GeV Main Injector protons
- Two detectors:
  - ⇒ Near detector at FNAL—measure initial beam spectrum and composition
  - ⇒ Far detector at Soudan, MN—look for oscillations



Measuring neutrino oscillations

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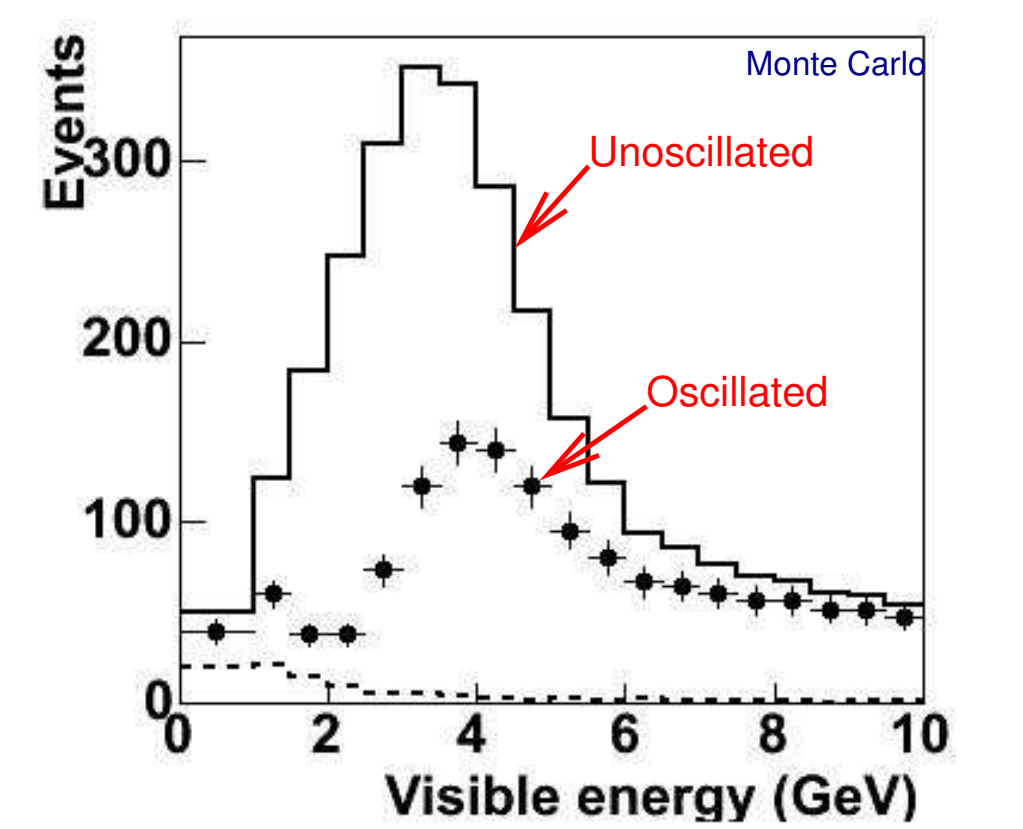
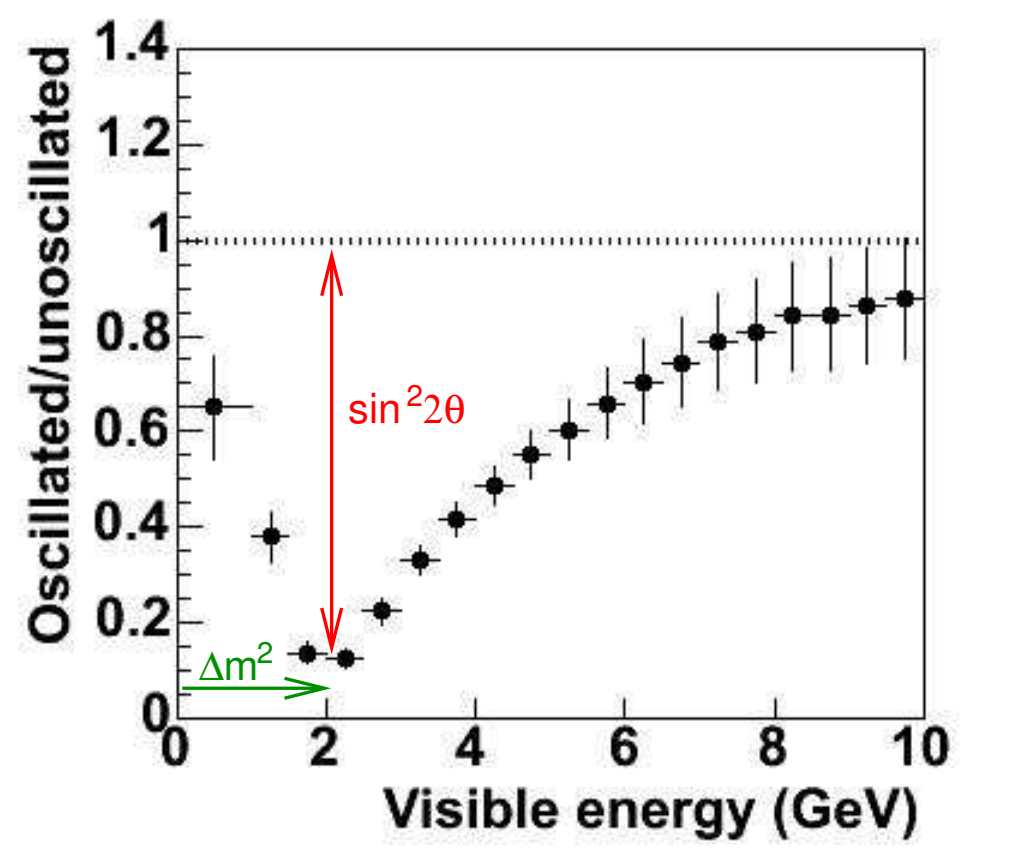
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$





NuMI beam

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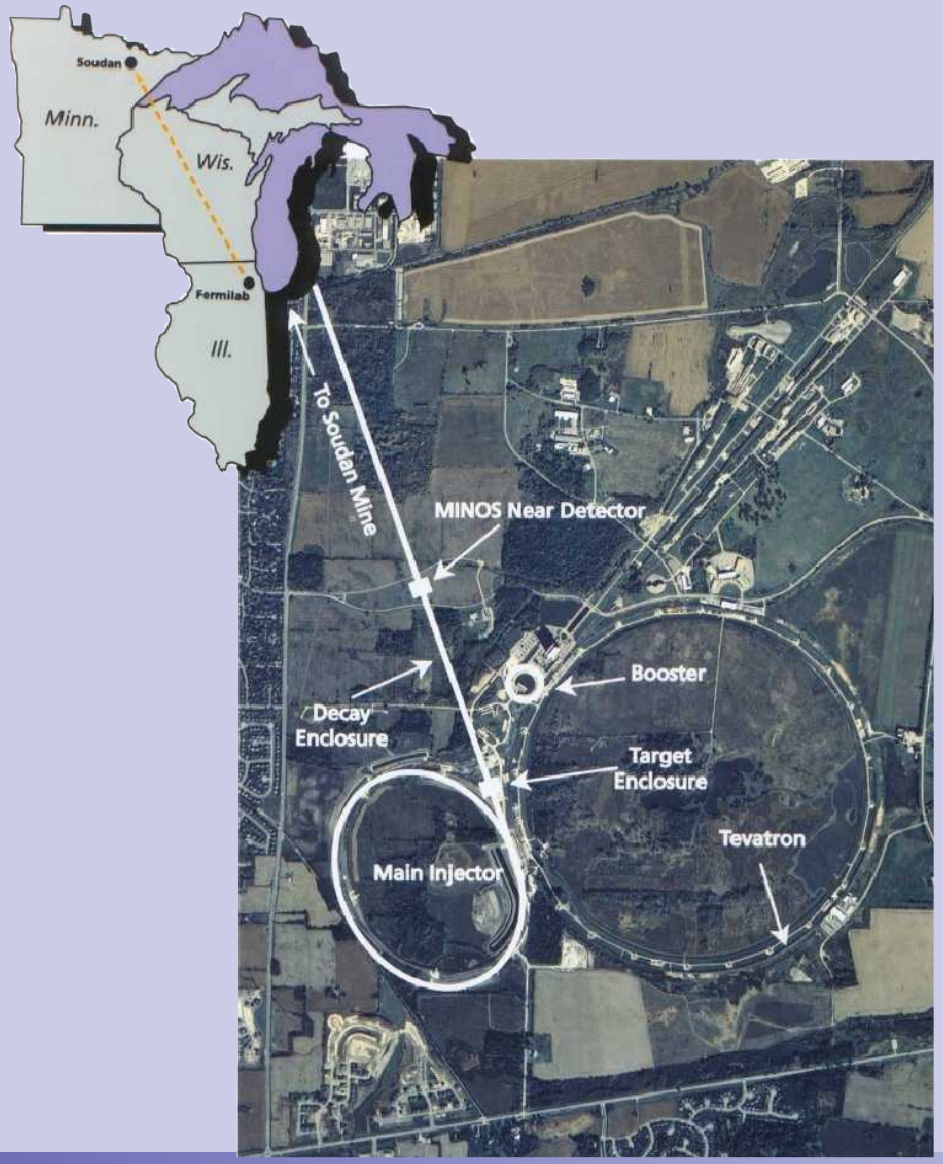

Design Parameters:

- 120 GeV protons from Main Injector (fed by Linac and Booster)
- 10 μs spill (single-turn extraction)
- 1.87s cycle time
- 4×10^{13} protons per pulse
- 0.4 MW

NuMI Beamline

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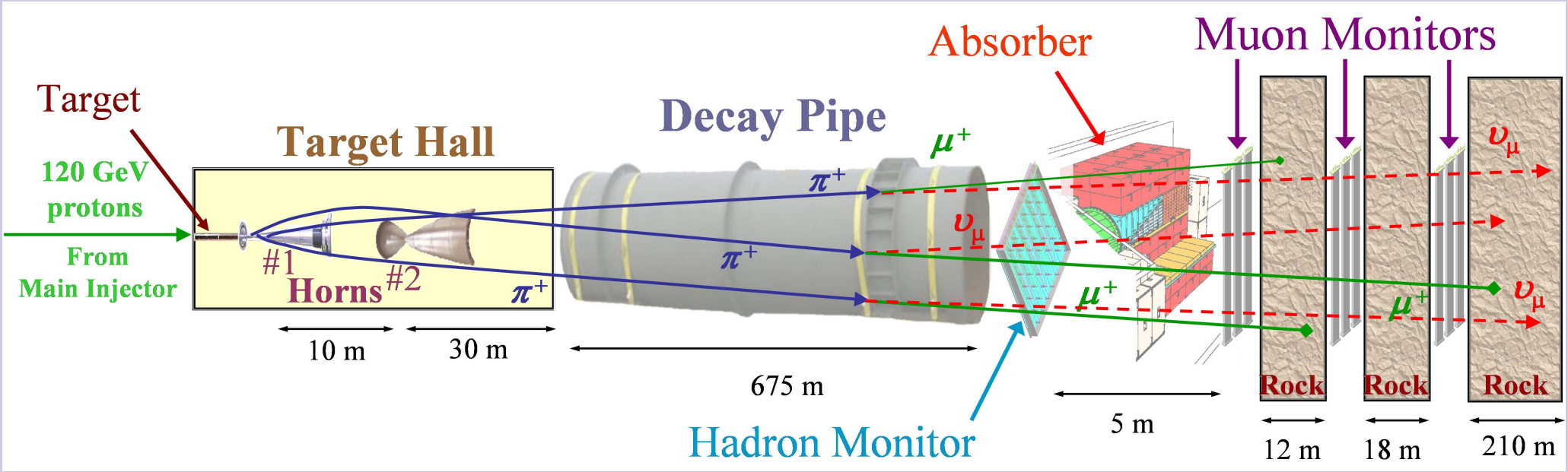

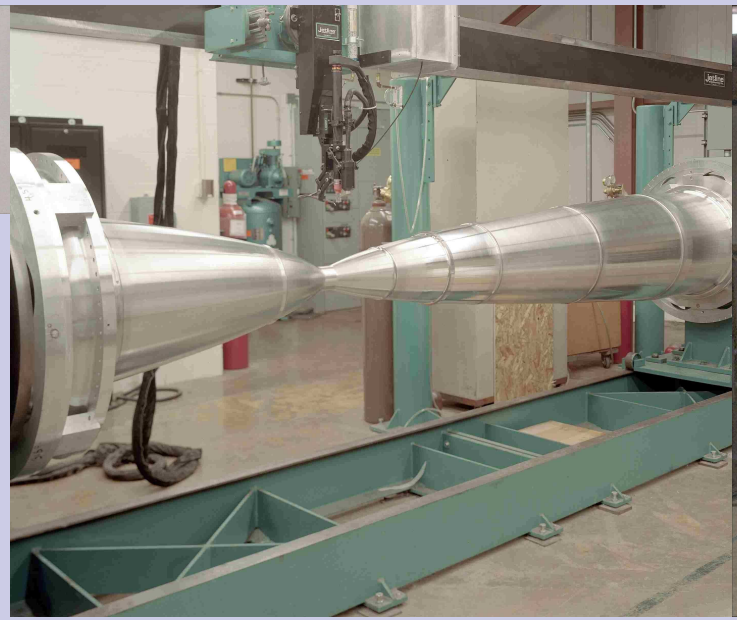

- 1m long graphite target
- Magnetic focusing horns
- Decay pipe to make neutrinos
- Monitors for hadrons and muons

Tunable beam energy

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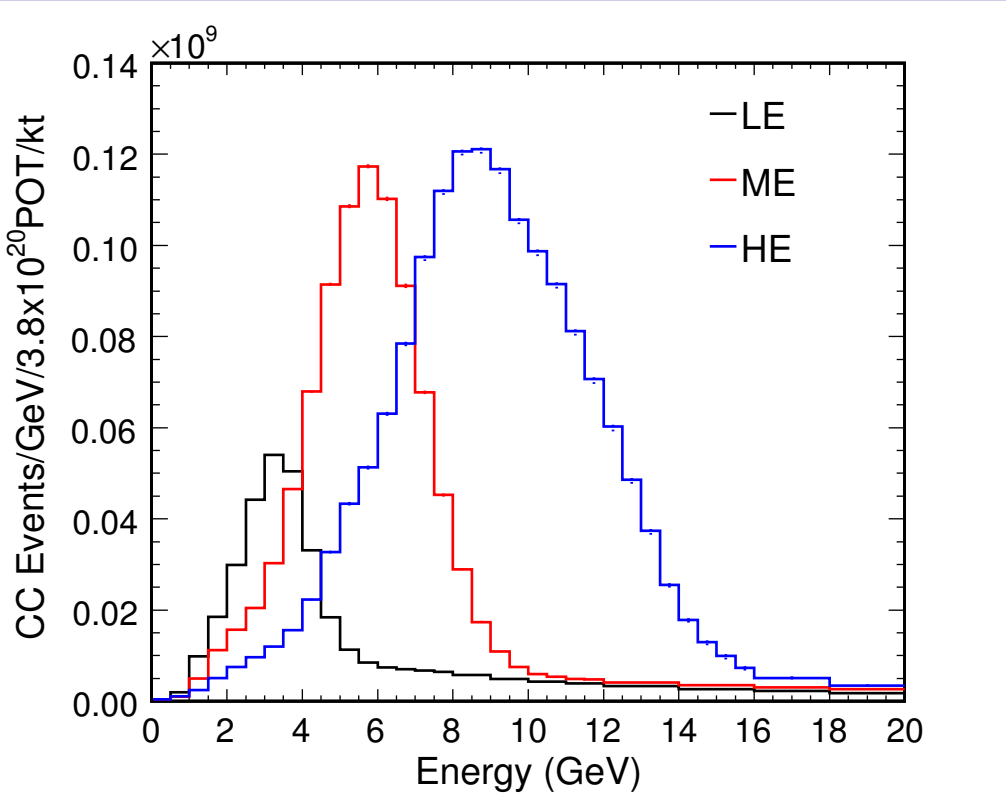

- Move target to select energy
  - ⇒ Continuous range of choices between LE and HE
- $\sim 1.5 \times 10^{19}$ POT early in run in ME and HE positions, for commissioning and systematic studies
- Oscillation dataset all taken in LE position

Proton Counting

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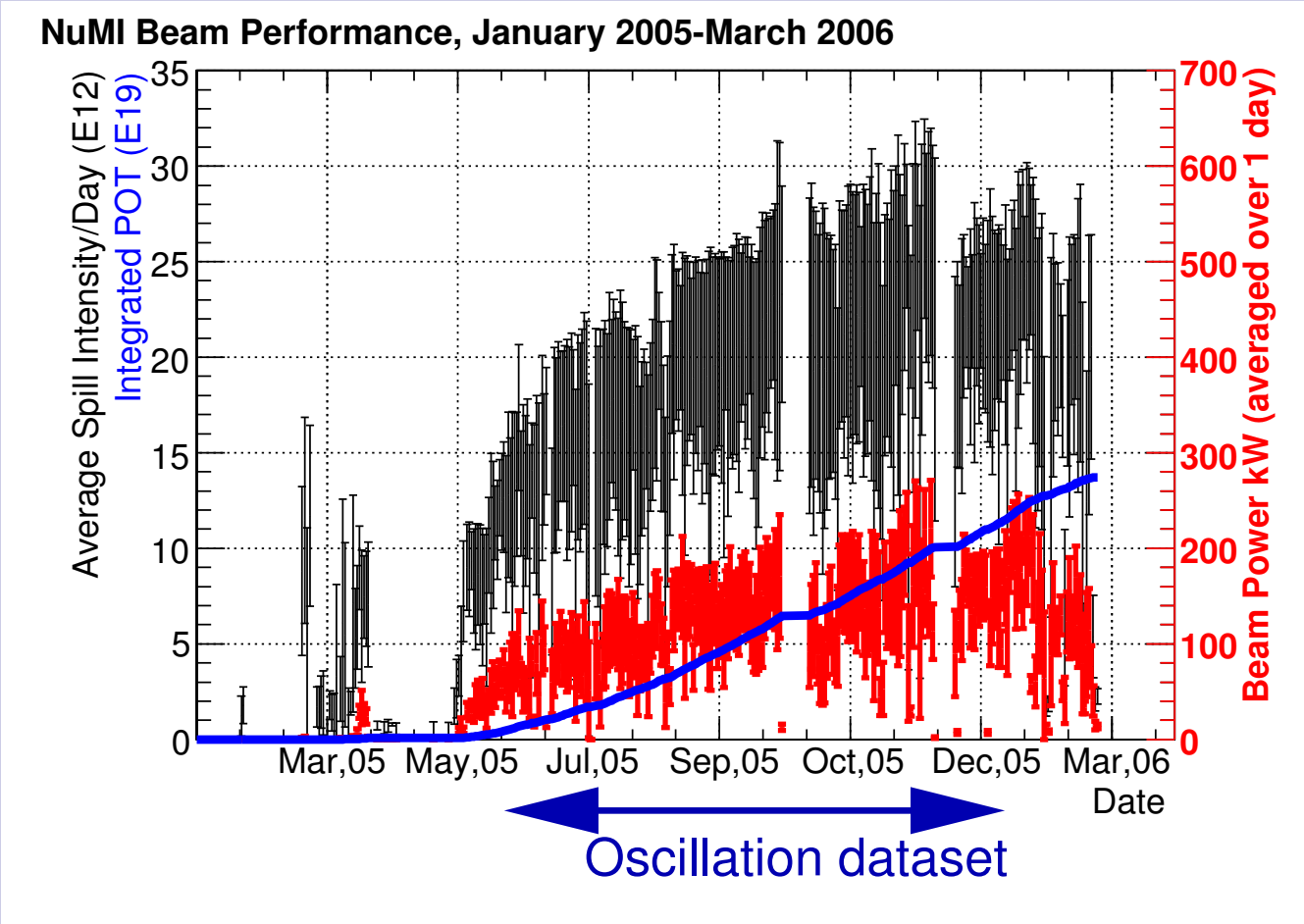

- Towards end of run:
  - ⇒ Mean power 170 kW
  - ⇒ Peak power 270 kW
  - ⇒ Difference is effect of pbar source / collider operations

MINOS detectors

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Functionally identical tracking calorimeters
Magnetised to 1.2 T
GPS timestamping to synchronise detectors and beam

- 735 km from target
- 5.4 kton
- 484 steel / scintillator planes

- 1 km from target
- 1 kton
- 282 steel planes
- 153 scintillator planes

Event topology

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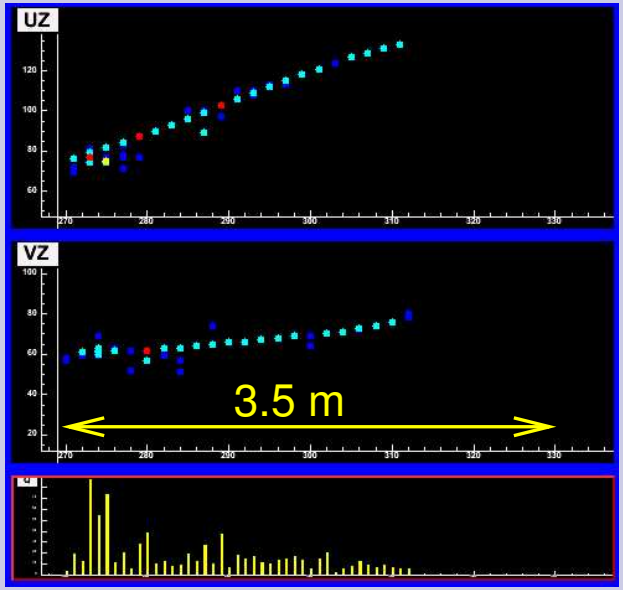

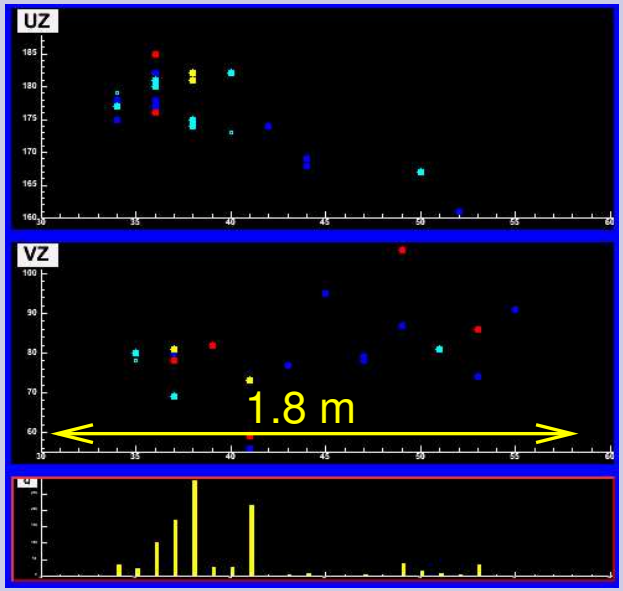

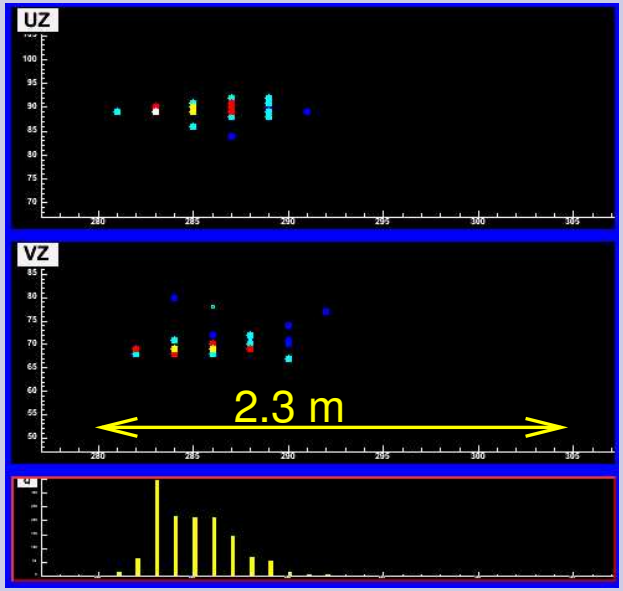

- ν_μ CC event
  - ⇒ Long muon track
  - ⇒ Hadronic shower at vertex
- NC event
  - ⇒ Short, often diffuse event
- ν_e CC event
  - ⇒ Short, compact EM shower

Event selection cuts

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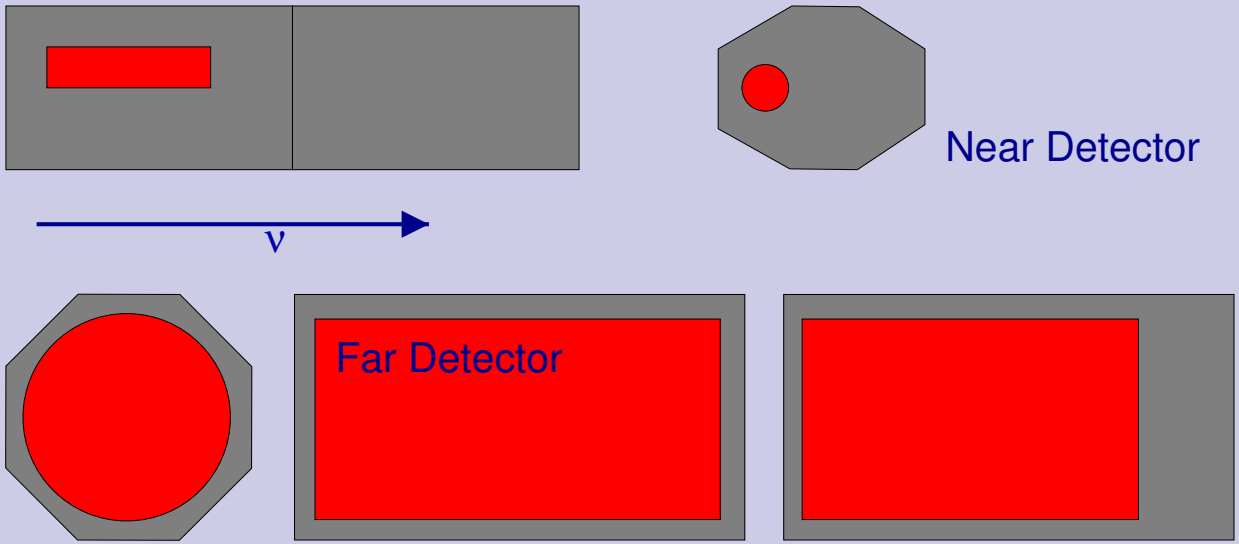

Fiducial cut on vertex position:

- Near Detector:
  - ⇒ 1m<z<5m (z measured from detector front face)
  - ⇒ r<1m from beam centre
- Far Detector:
  - ⇒ z>50cm from front face, >2m from rear face
  - ⇒ r<3.7m from detector centre

- Event must contain at least one good reconstructed track
- Track should have negative charge (selects ν_μ)
- Likelihood-based particle ID favours being a CC event

CC event selection

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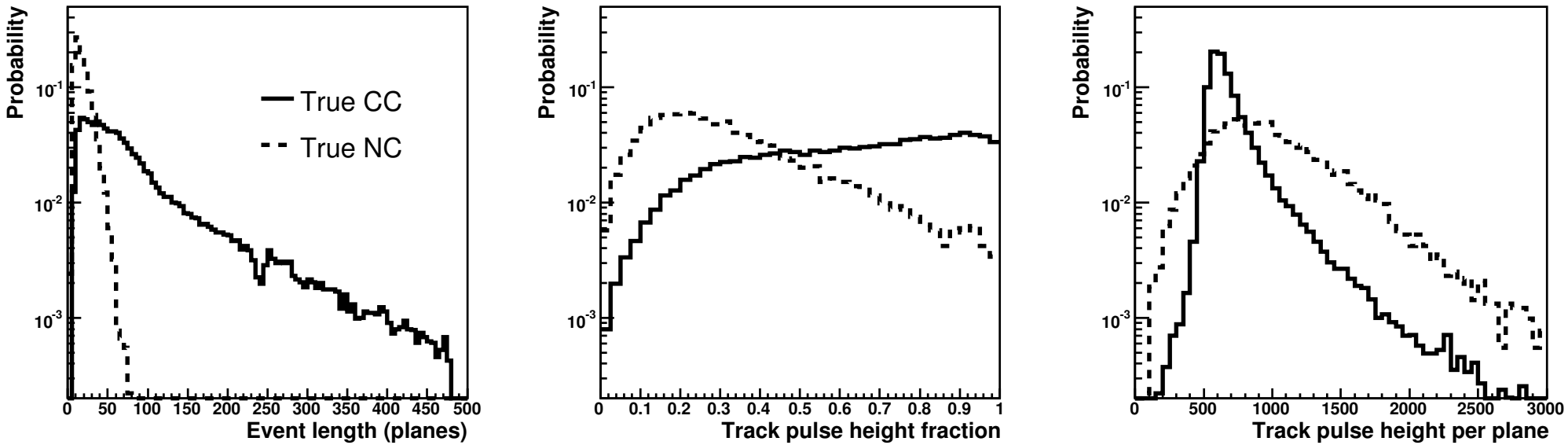
Input variables for PDF-based event selection



- Events selected with likelihood procedure with input PDFs:
  - ⇒ Event length in planes
  - ⇒ Fraction of event pulse height reconstructed in track
  - ⇒ Average track pulse height per plane
- Define P_μ (P_{NC}) as the product of the three CC (NC) PDFs at the values of the three variables for the event

CC Particle ID

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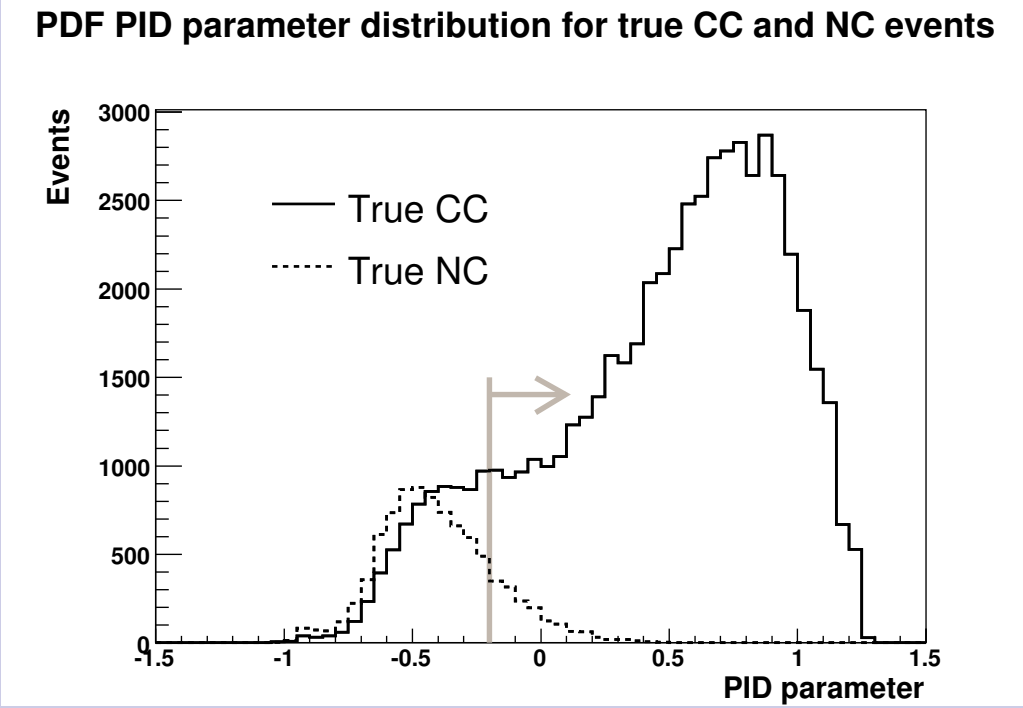

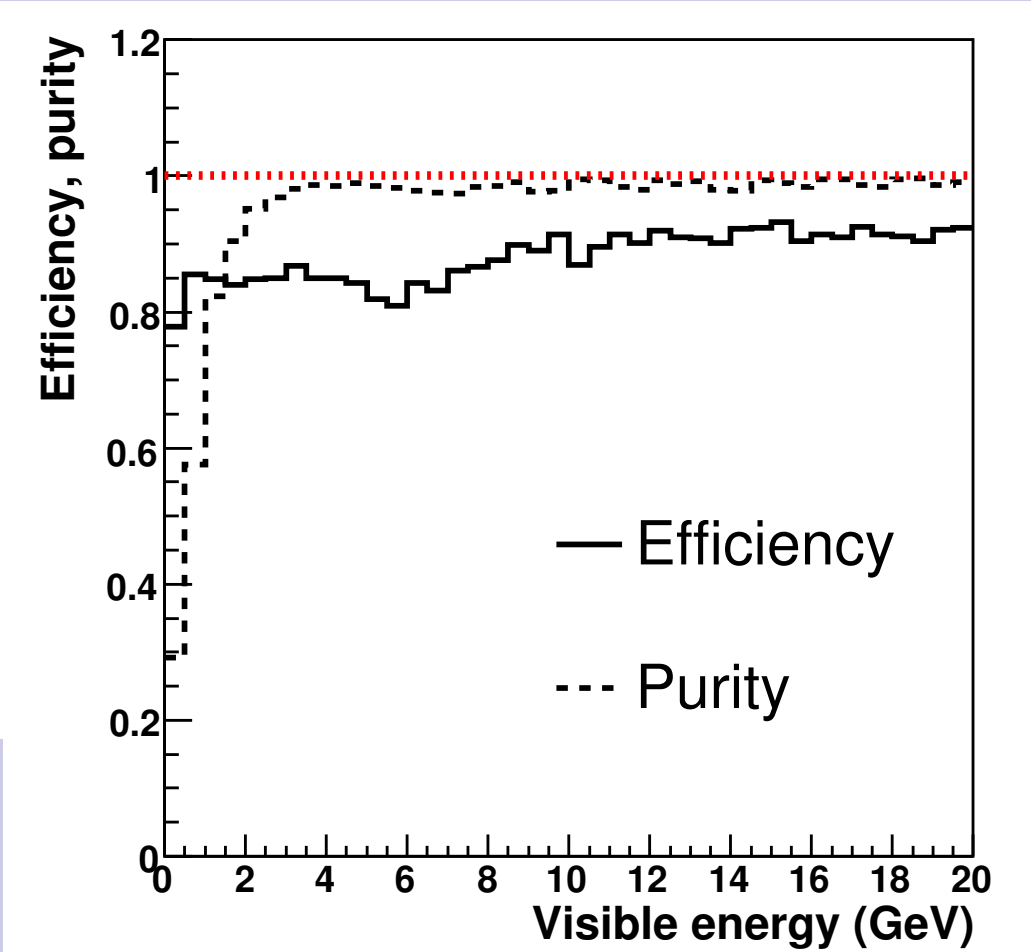

- PID $= -\left(\sqrt{-\log P_\mu} - \sqrt{-\log P_{\mathrm{NC}}}\right)$
- CC-like events $PID > -0.2$ in Far detector (> 0.1 in near)
- NC contamination limited to lowest energy bins

- Efficiency 87%
- Purity 97%

Hadron model tuning

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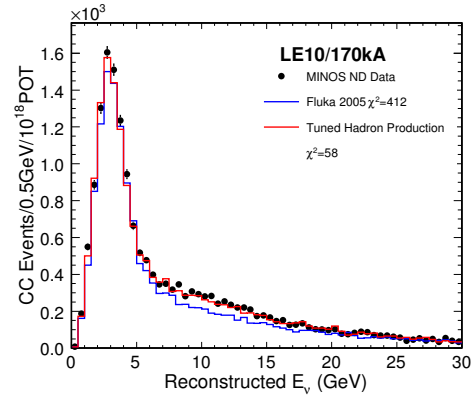

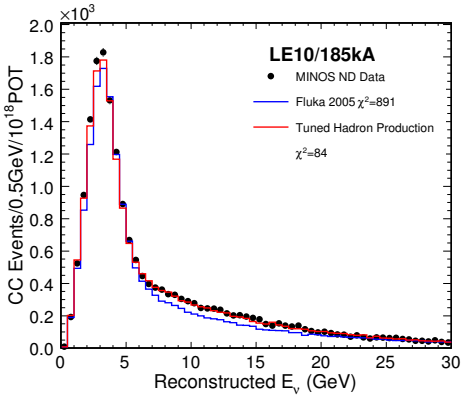

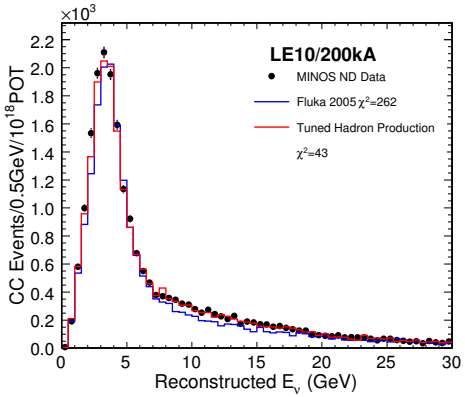

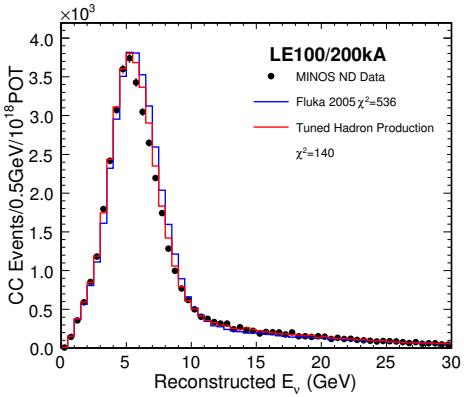

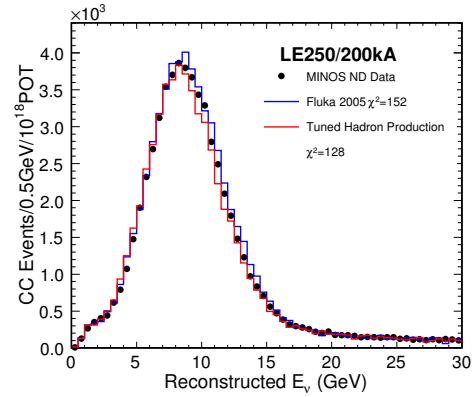

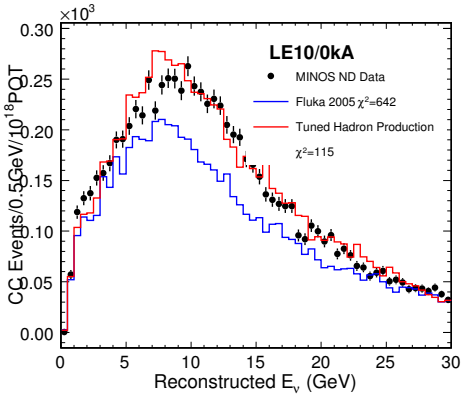

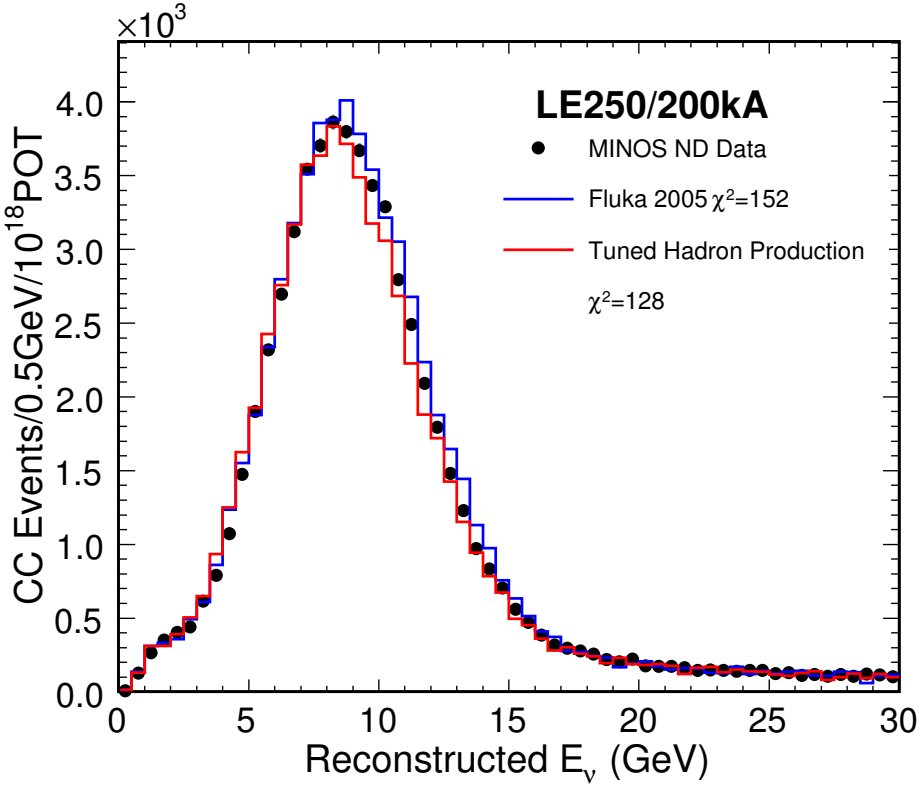

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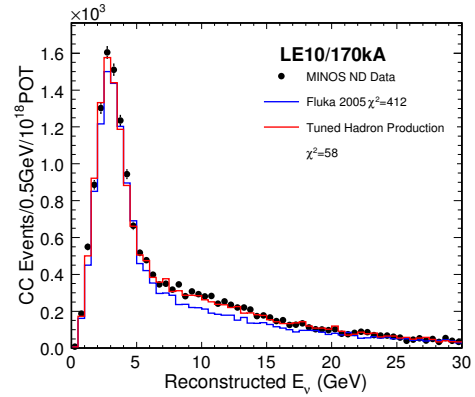

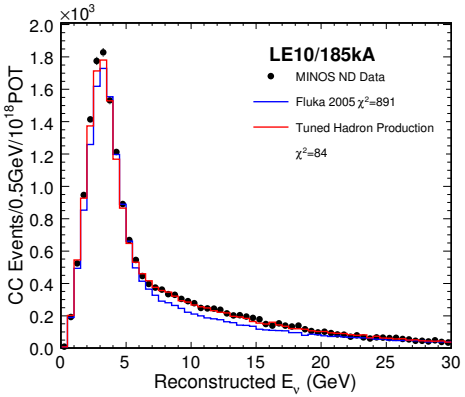

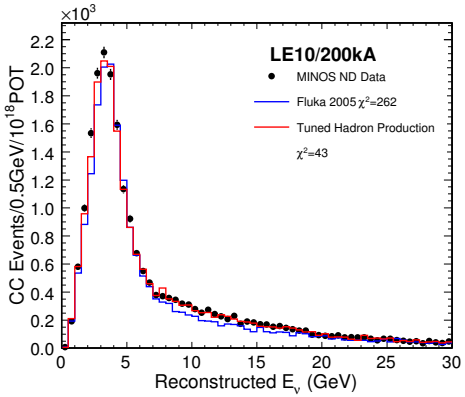

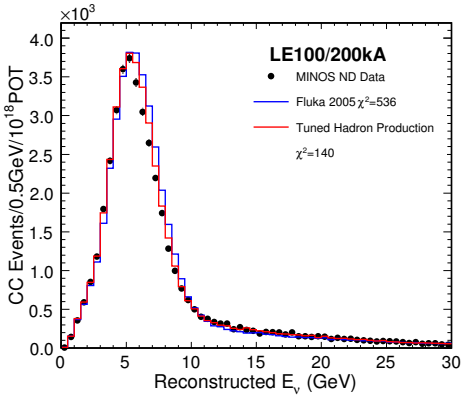

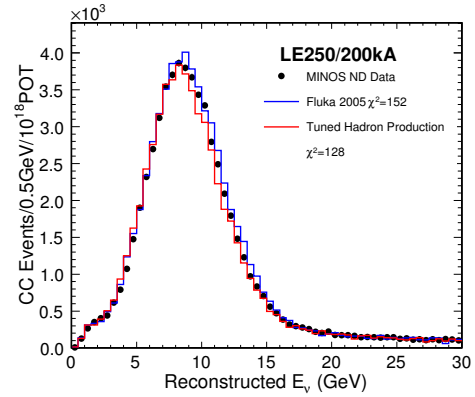

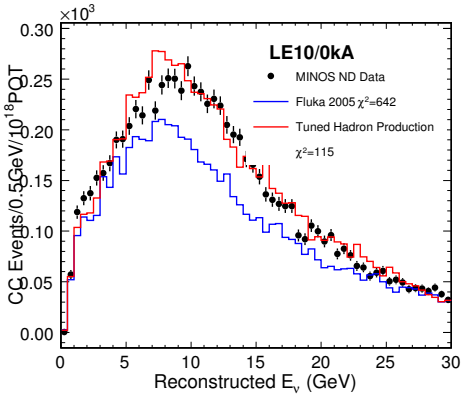

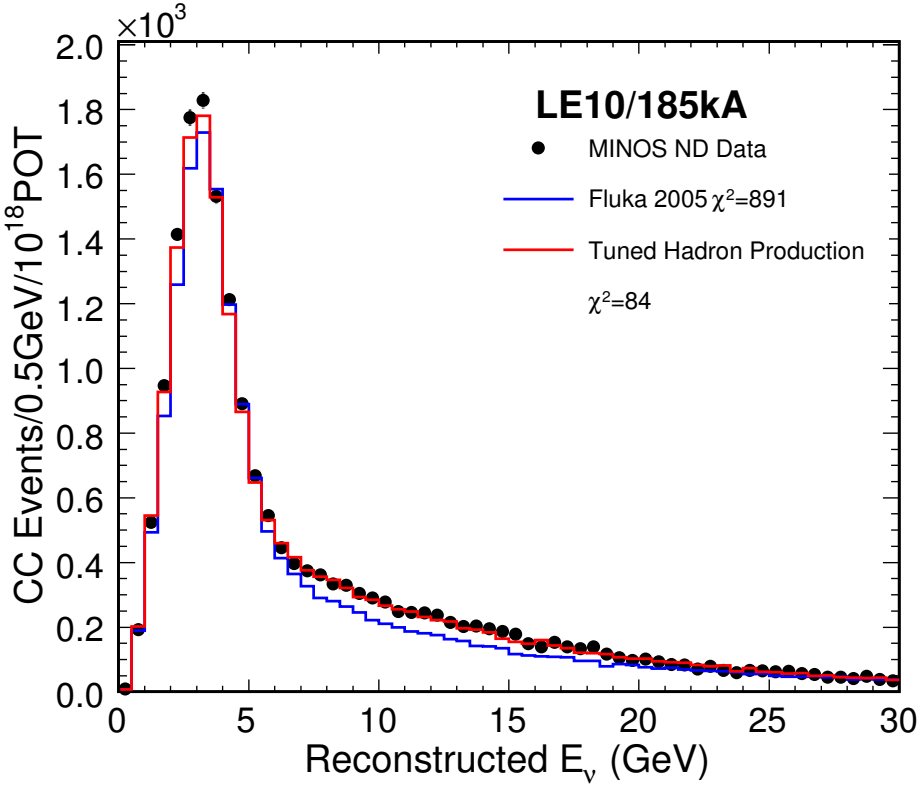

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Hadron model tuning

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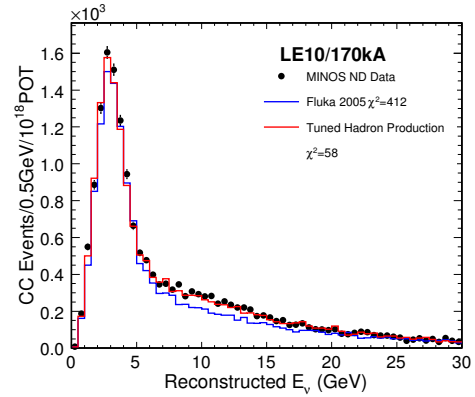

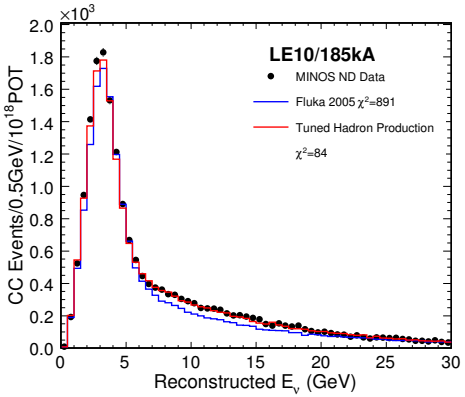

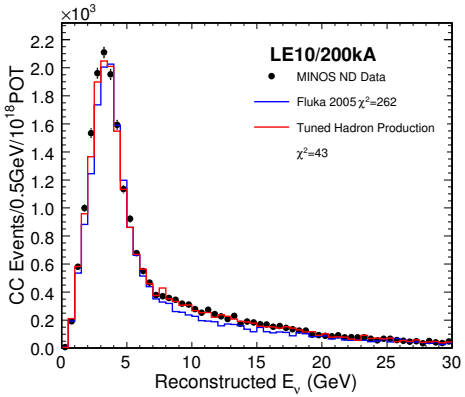

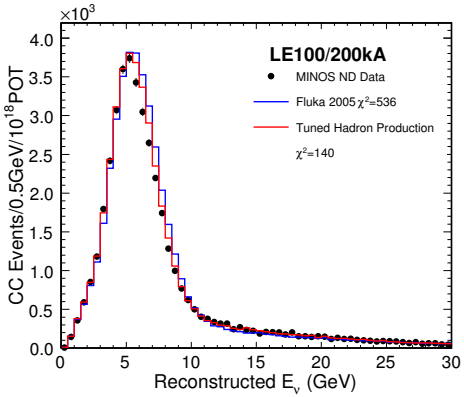

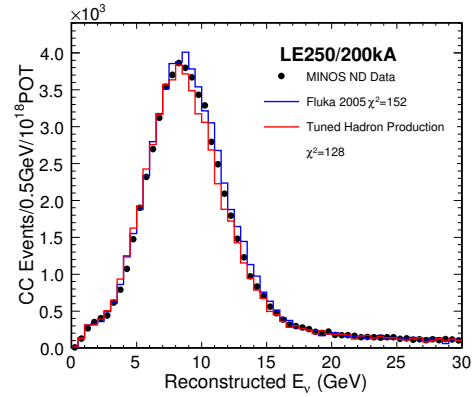

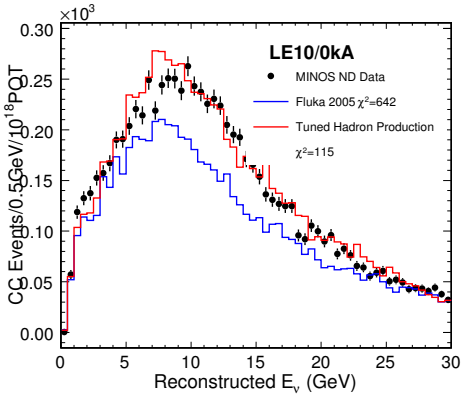

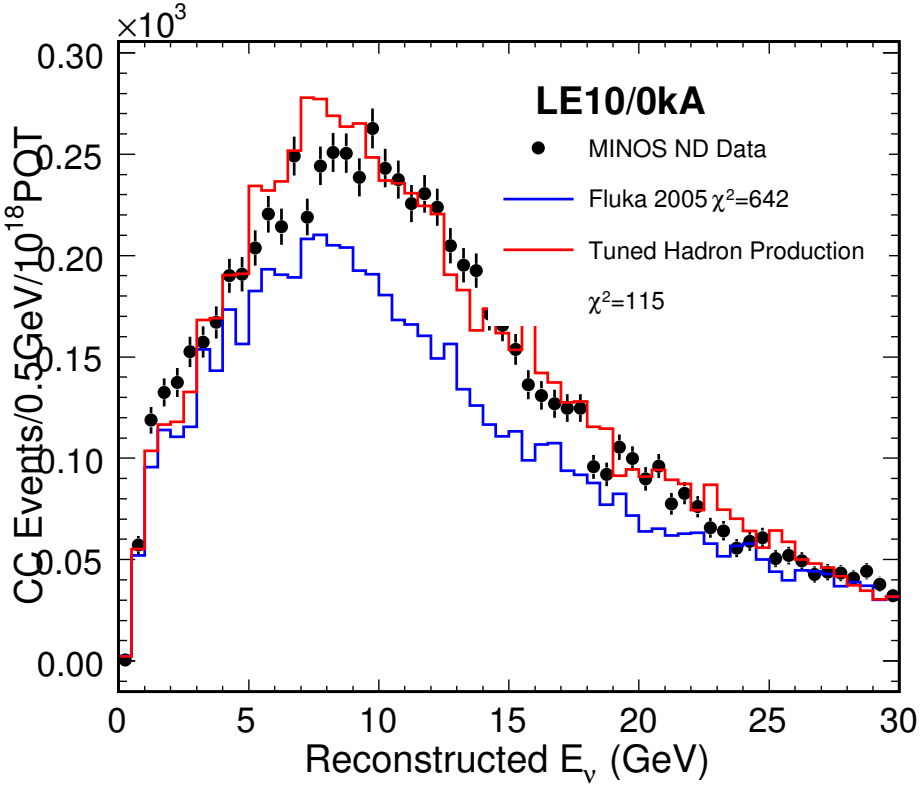

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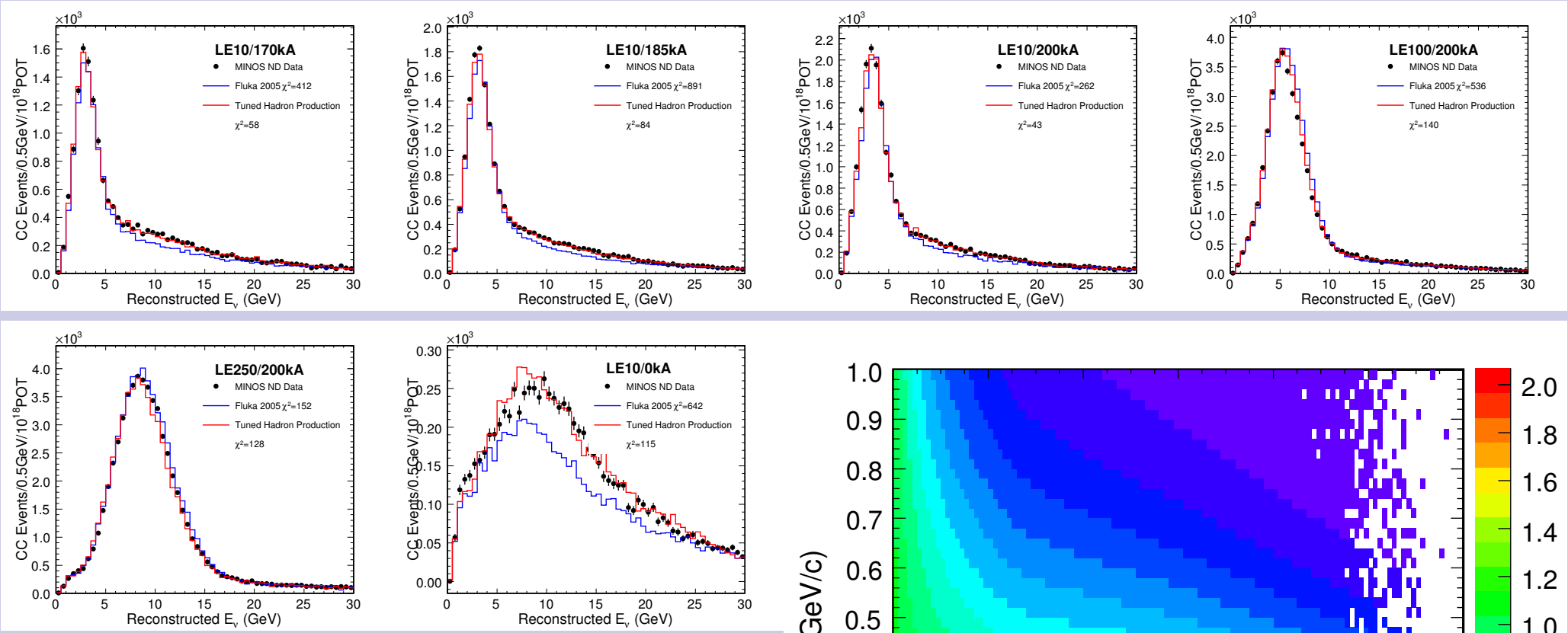

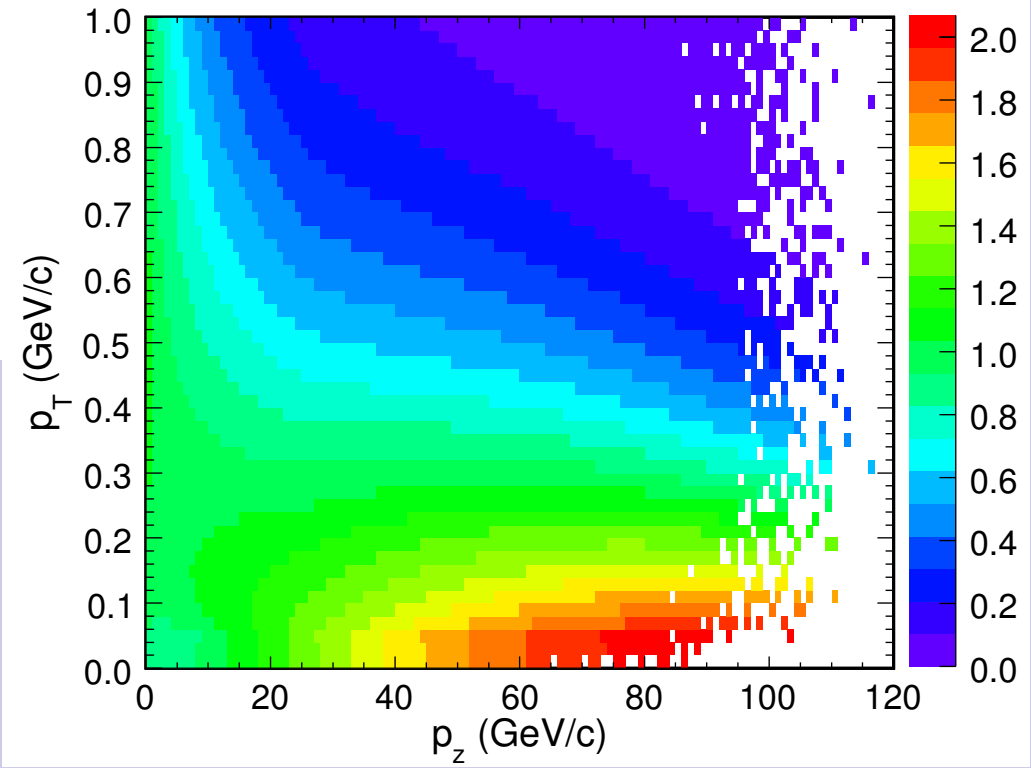

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Beam Stability

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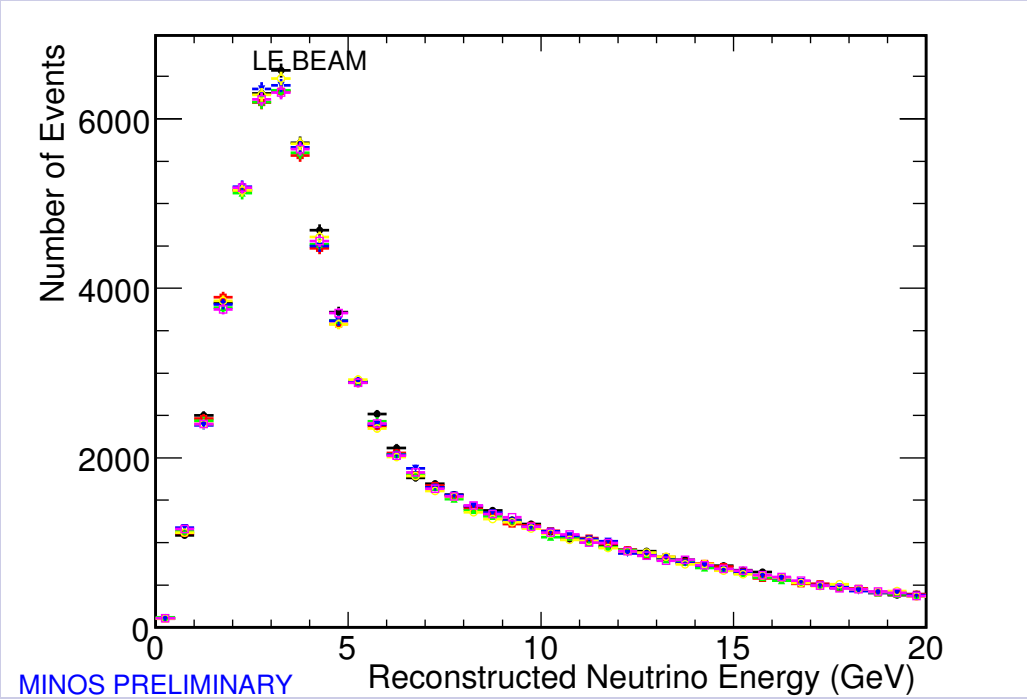
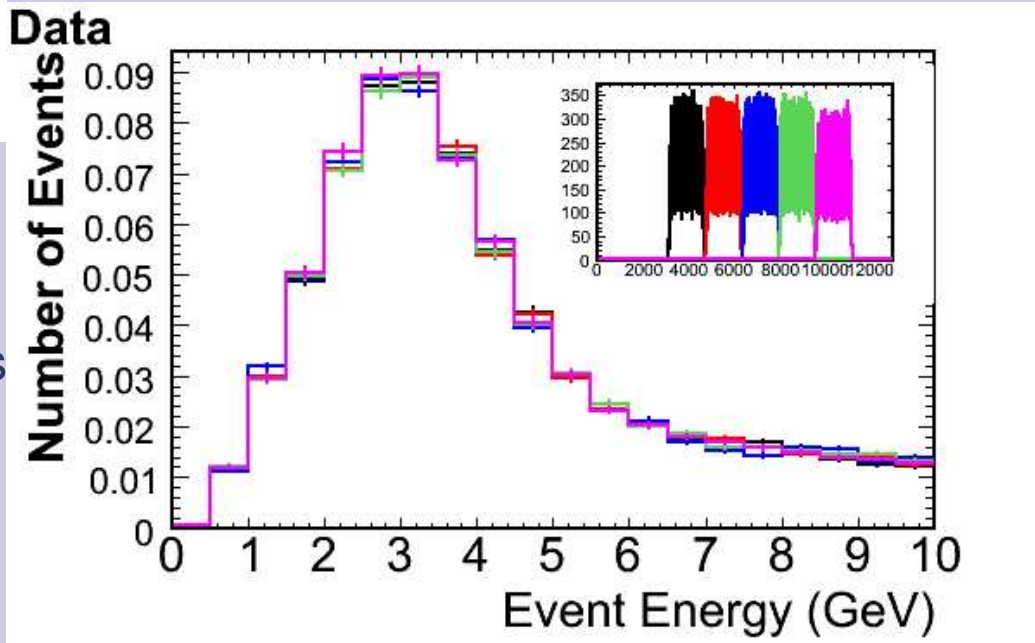


- On the left, the Near Detector reconstructed energy spectrum
- Each colour is a different month (May to November 2005)

- Each beam pulse comes in 5 (or 6) batches
- Accelerator effects give different batches slightly different trajectories down beamline
- No effect on neutrino spectrum



A blind analysis

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- Analysis performed on data taken in the LE beam configuration from 20 May to 6 December 2005
  - ⇒ 0.93×10^{20} POT
  - ⇒ 98.9% POT-weighted Far Detector livetime
- Blind analysis
  - ⇒ Unknown energy- and event length-dependent fraction of events hidden
  - ⇒ "Open" set examined to verify that data is understood (reconstruction, MC)
  - ⇒ Oscillation analyses defined and cuts tuned on MC
  - ⇒ Box opened—full data set analysed
  - ⇒ No re-tuning of cuts allowed

Far Detector Data

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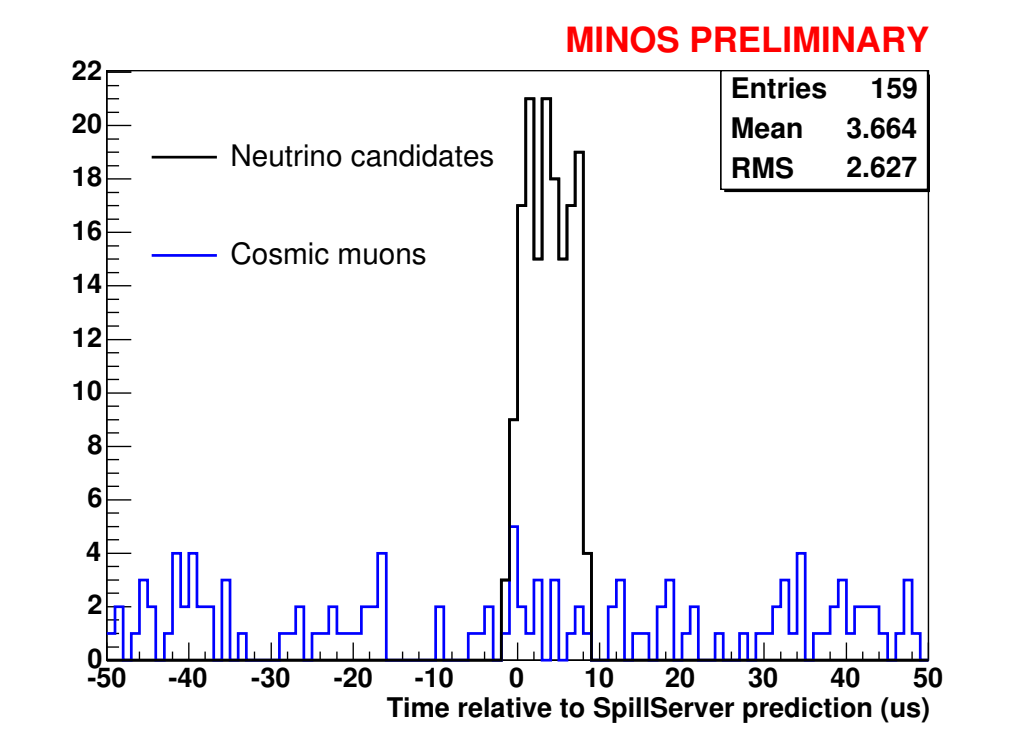
- Beam trigger reads out data 100 μs around spill
- Beam event candidates all come in time with spill
- Backgrounds estimated by generating fake triggers in absence of beam
  - ⇒ 2.6 million fake triggers, 0 events passed selection cuts. Upper limit on background in dataset is 1.7 events (90% CL)



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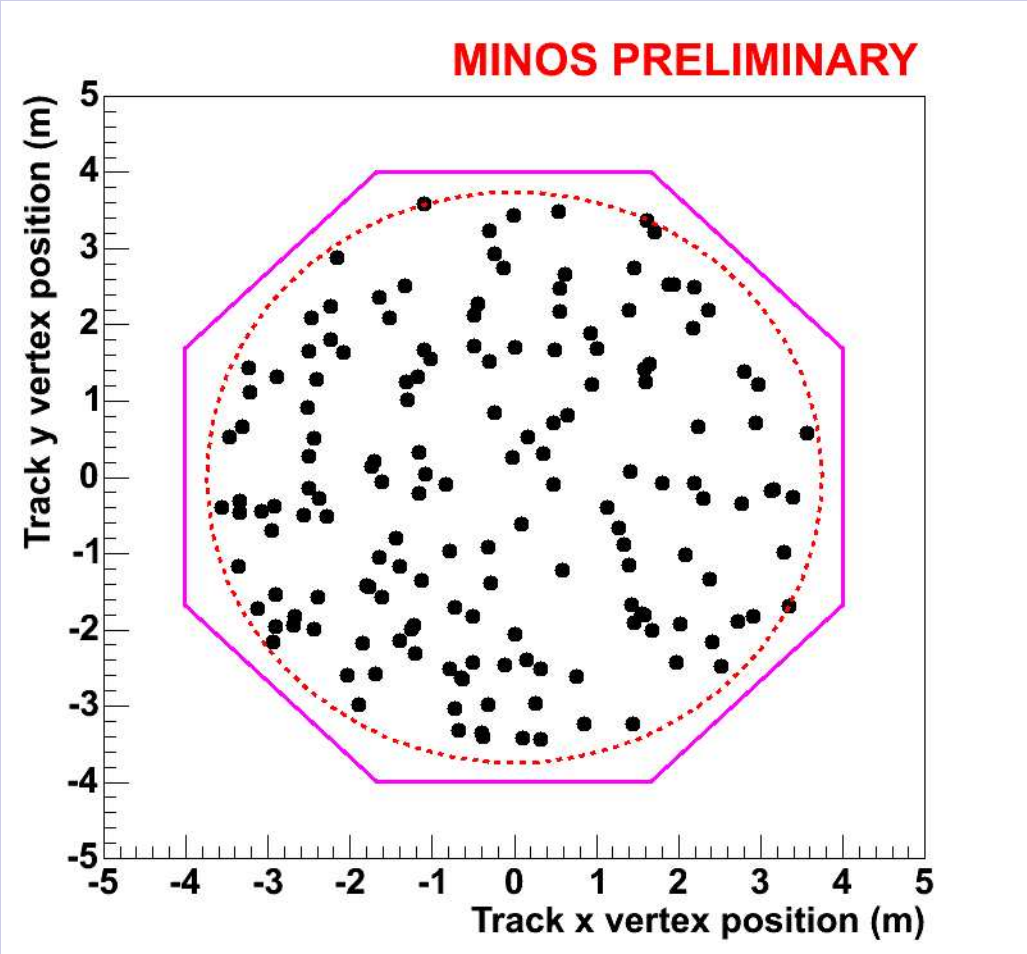

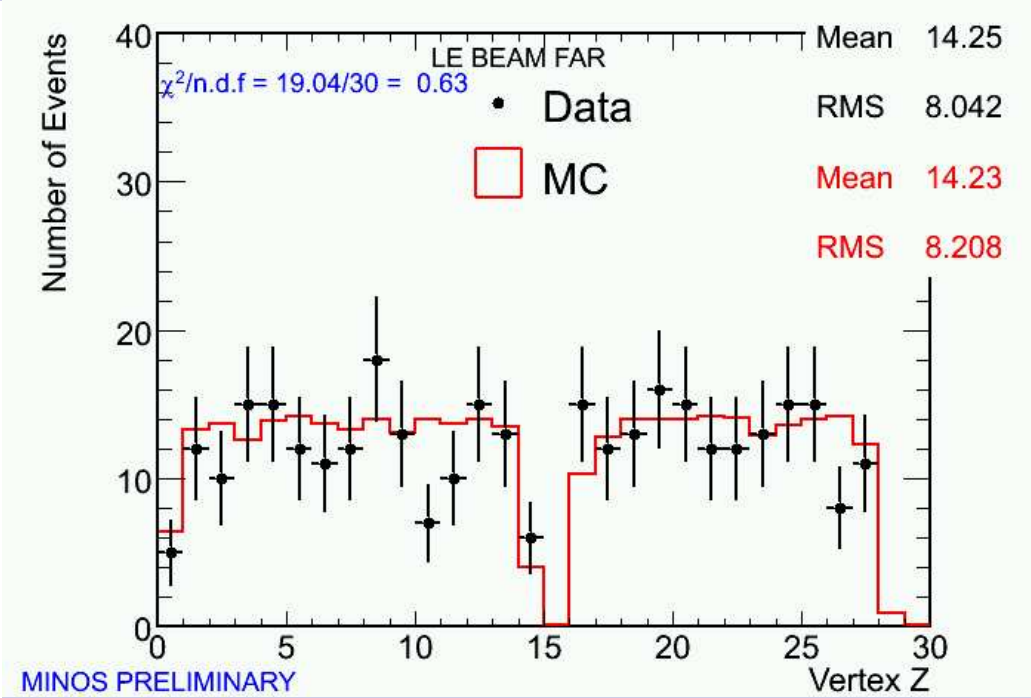

- Candidate neutrino events distributed evenly in Far Detector

Predicting Far spectrum

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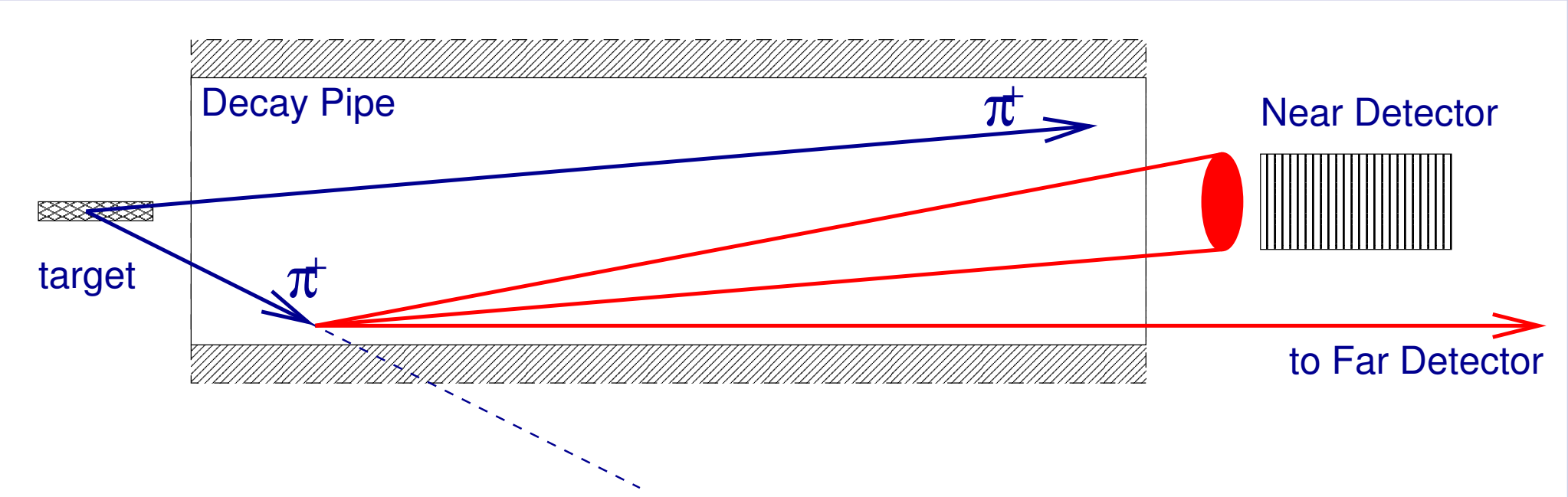

- Use the measured Near detector spectrum to predict the expected spectrum at the Far detector
- Far detector “sees” a point source with a point detector
- Near detector “sees” an extended source with a finite-size detector
  - ⇒ High-angle decays at end of decay pipe

Beam Matrix

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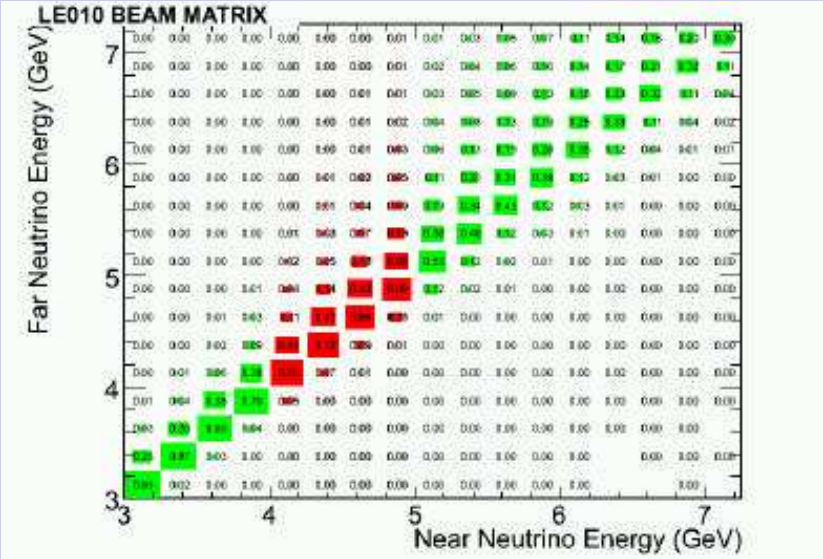

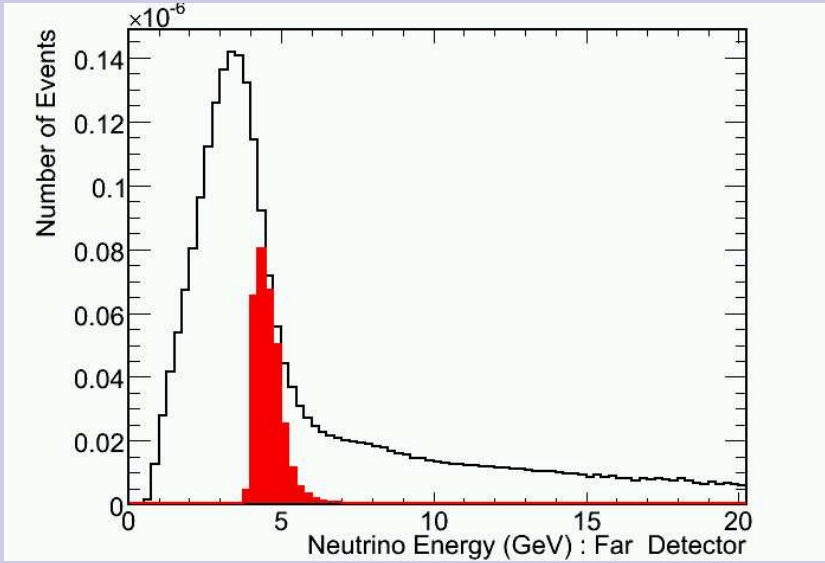

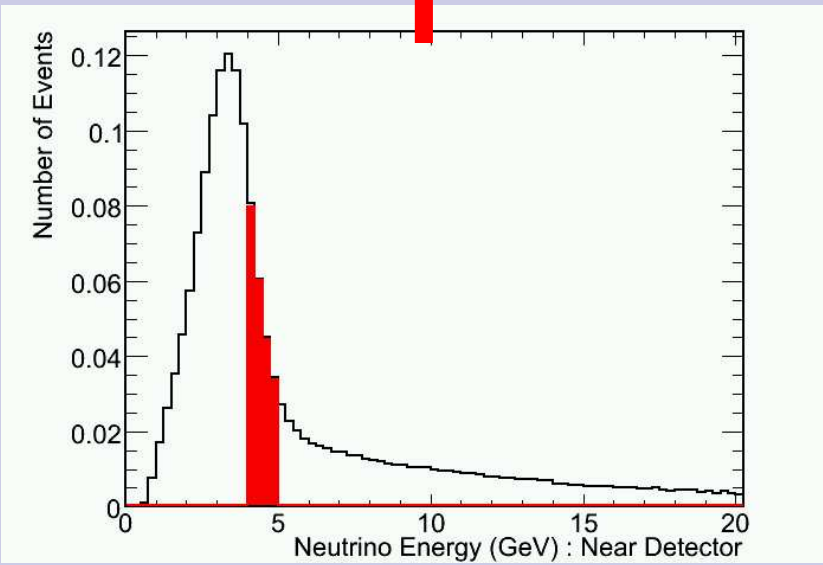

- Beam matrix holds knowledge of pion kinematics
- ND reco → true (detector MC)
- Matrix projects spectrum to Soudan
- (Insert oscillations)
- FD true → reco (detector MC)

Best oscillation fit

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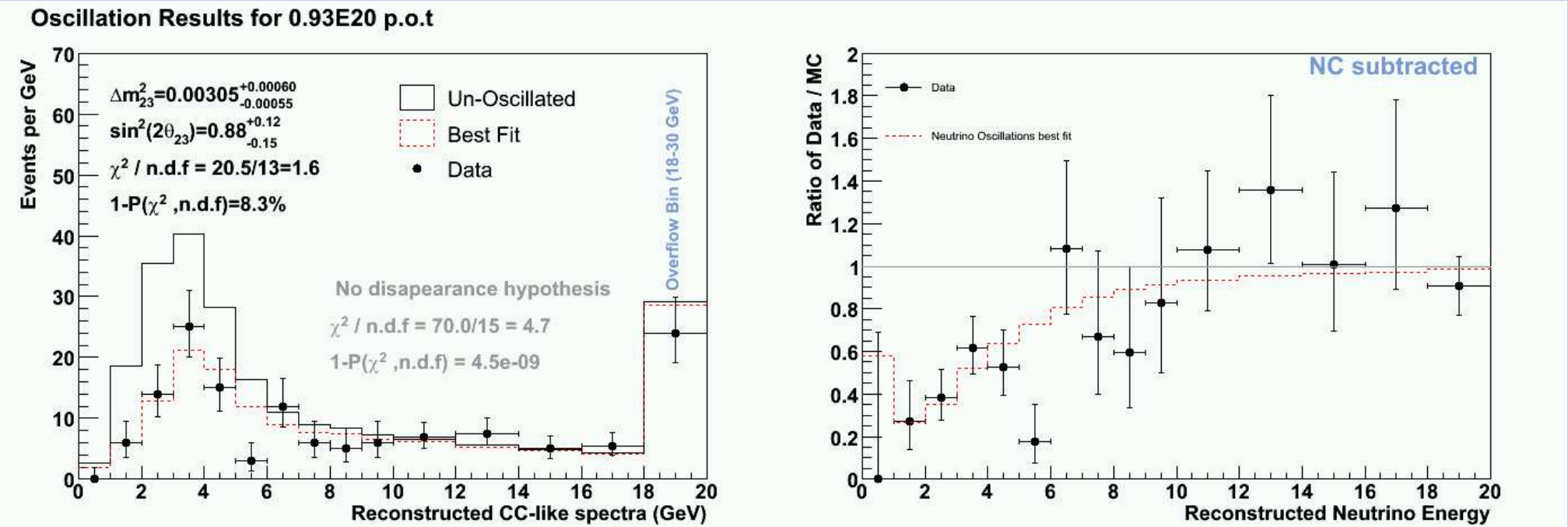

$$\Delta m^2_{23} = 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)$$

- “No oscillation” hypothesis disfavoured at $> 5\sigma$

Allowed regions

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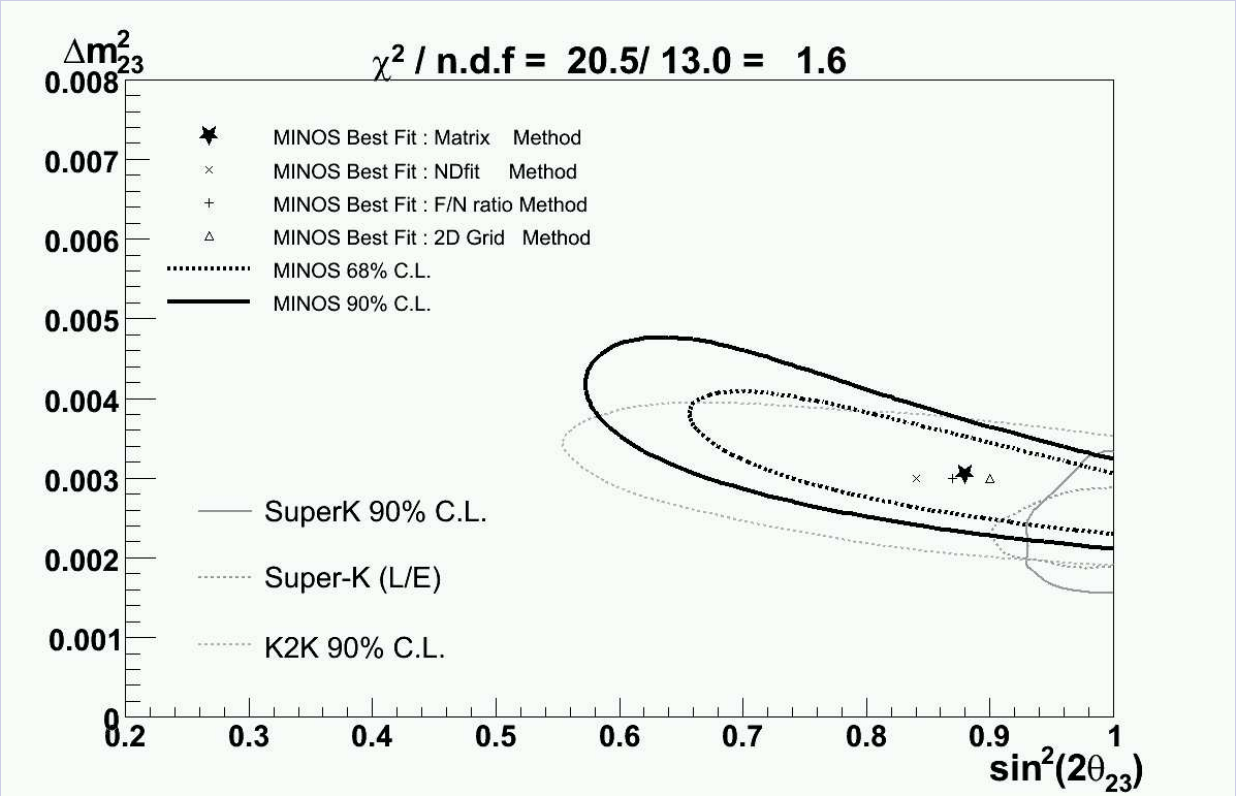

- Four different methods:
  - ⇒ Matrix
  - ⇒ N/F ratio
  - ⇒ NDFit
  - ⇒ 2D Grid Fit
- Systematics different, but results in very good agreement

Systematics

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Systematic shifts in the fitted parameters have been computed with MC "fake data" samples for $\Delta m^2 = 0.003 eV^2$, $\sin^2 2\theta = 0.9$ for the following uncertainties:

Uncertainty	Δm^2 shift (eV^2)	$\sin^2 2\theta$ shift
Normalisation $\pm$ 4%	0.63e-4	0.025
Muon energy scale +/- 2%	0.14e-4	0.020
Relative Shower energy scale +/- 3%	0.27e-4	0.020
NC contamination +/- 30%	0.77e-4	0.035
CC cross-section uncertainties	0.50e-4	0.016
Beam uncertainty	0.13e-4	0.012
Intranuclear re-scattering	0.27e-4	0.030
Total (sum in quadrature)	1.19e-4	0.063
Statistical error (data)	6.4e-4	0.15

Outlook

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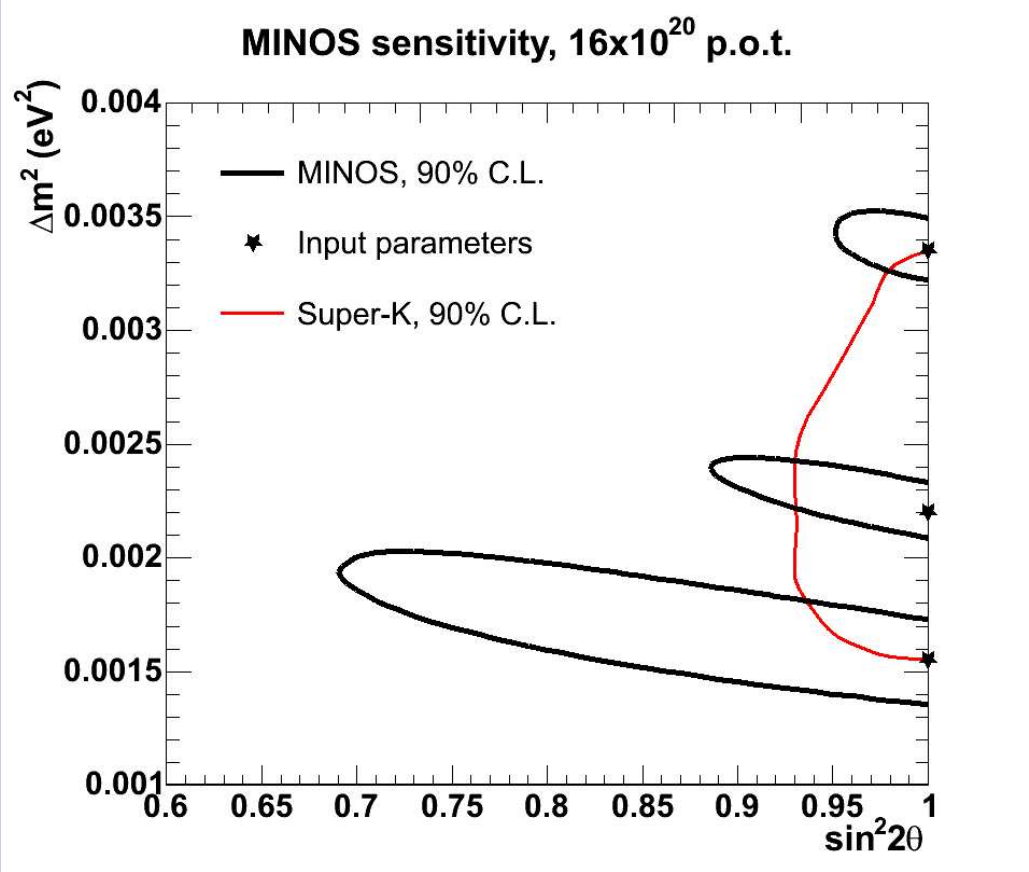
ν_μ disappearance



- Current run plan extends to 2009
- Increase beam intensity (beamline design allows increase of 50% in pulse intensity, 130% in mean power)
- Precise measurement of Δm^2_{23}
- Decrease Chooz limit on $\sin^2 2\theta_{13}$ by a factor of ~ 2
- Rule out neutrino decay, sterile neutrinos etc.

Summary

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- First accelerator neutrino oscillation results from MINOS presented
- "No oscillation" hypothesis disfavoured at 5σ
- Data well described by neutrino oscillations with

$$\Delta m^2_{23} = 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)$$

- If we fix $\sin^2 2\theta_{23} = 1$

$$\Delta m^2_{23} = 2.70^{+0.263}_{-0.305} \times 10^{-3}\,\mathrm{eV}^2$$

- Systematic uncertainties well under control
- Analysis of 1.3×10^{20} POT dataset (up to shutdown) in progress
- Much more data to come, many more results

MINOS Results from the NuMI beam

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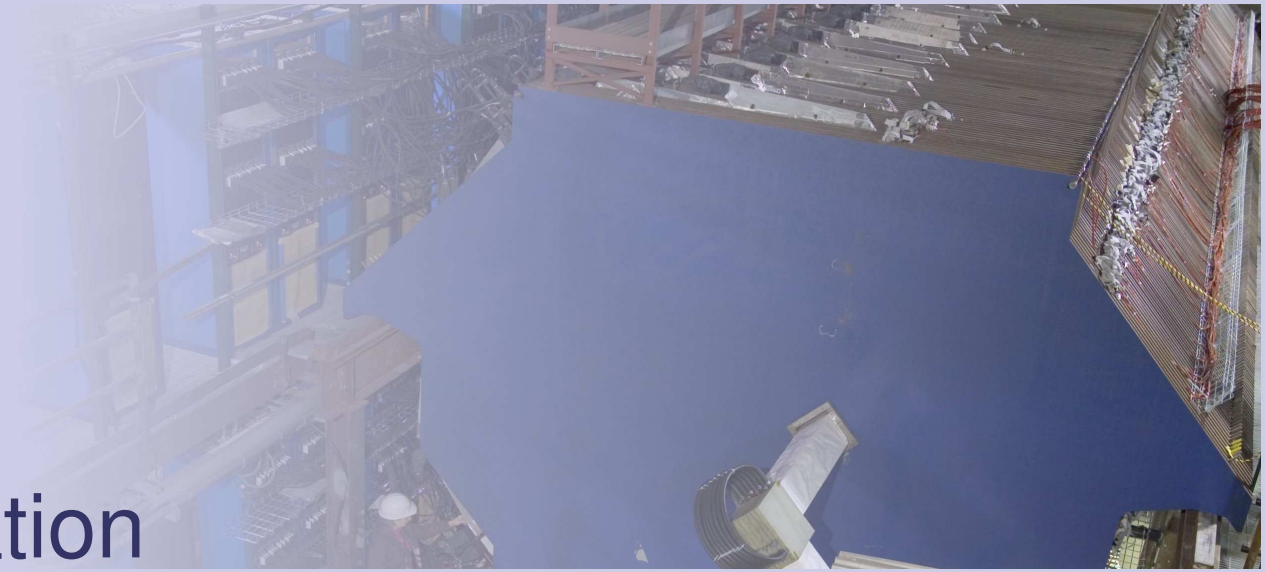

for the

MINOS collaboration