The MINOS Electron Neutrino Appearance Analysis

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MINOS ν_e - Appearance Analysis

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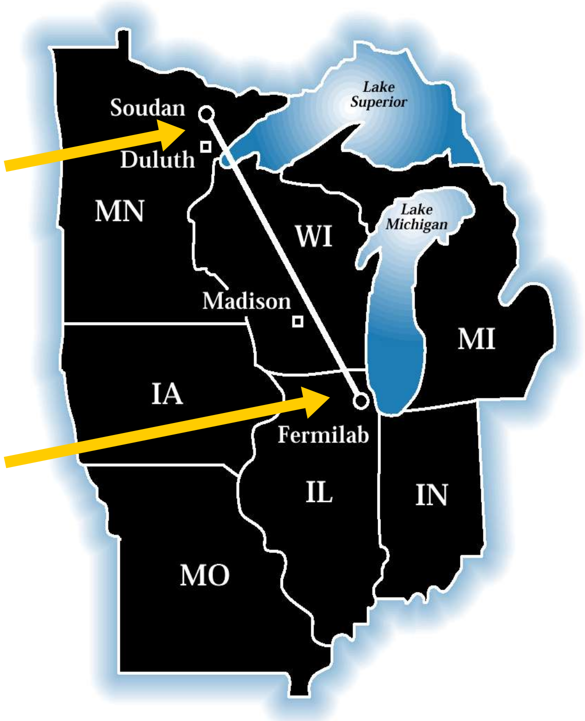
The MINOS Experiment

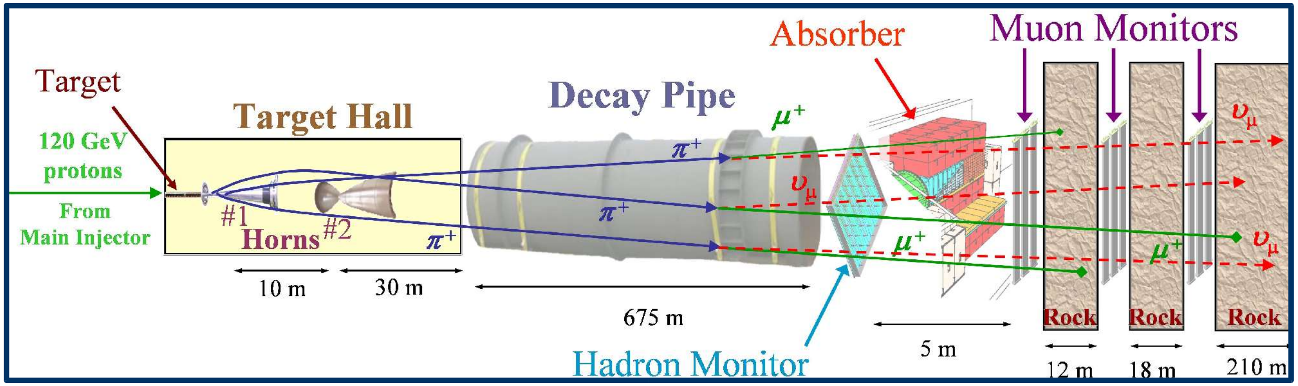
Main Purpose of MINOS

- to measure disappearance of muon neutrinos

MINOS Detectors

- Iron scintillator calorimeters, functionally identical
- Near Detector:
  - 1 kT, 3.8m x 4.8 m x 15m,
  - 282 steel planes, 153 scintillator planes
- Far Detector
  - 5.4 kT, 8m x 8m x 30m,
  - 484 steel/scintillator planes, veto shield





NUMI Beam

- 120 GeV protons from Main Injector
- impact on graphite target
- produces hadrons
- focusing by 2 magnetic horns
- decay into into neutrinos and other particles
- absorber/rock remove heavier particles, leave neutrinos

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Electron Neutrino Appearance

normal mass hierarchy:

$m_3^2 > m_2^2 > m_1^2$

inverted mass hierarchy:

$m_2^2 > m_1^2 > m_3^2$

Neutrino oscillations:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Weak Eigenstates — PMNS Matrix — Mass Eigenstates

The probability that a muon neutrino will oscillate to an electron neutrino is given by:

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{31}^2 L/E)$$

$\nu_\mu \to \nu_\tau$ ➡ dominant oscillation mode;

$\nu_\mu \to \nu_e$ ➡ sub-dominant oscillation mode,

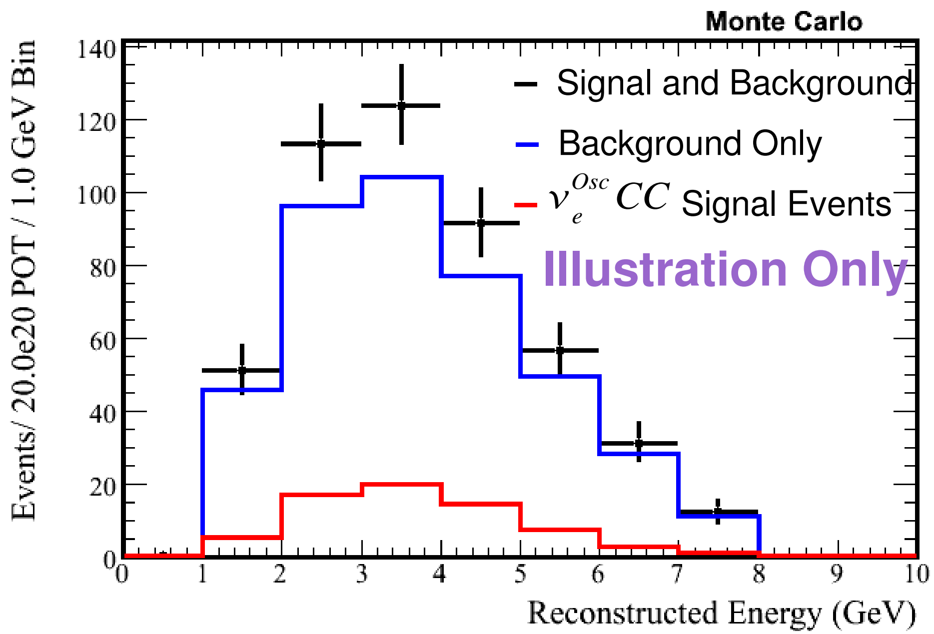
current best limit set by the CHOOZ experiment:

e.g. for $\Delta m_{32}^2 = 2.4\times10^{-3}\, eV^2 \to \sin^2 2\theta_{13} < 0.15$

Example - 8 signal events expected for:

$\sin^2 2\theta_{23} = 1.0,\ \Delta m_{23}^2 = 2.4\times10^{-3}\, eV^2,\ \sin^2 2\theta_{13} = 0.1$

Spectrum With/Without Signal for Selected Candidate Events



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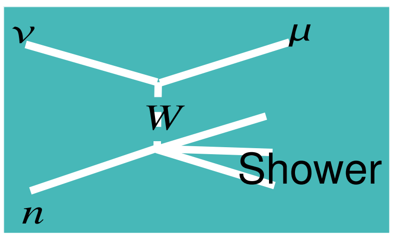
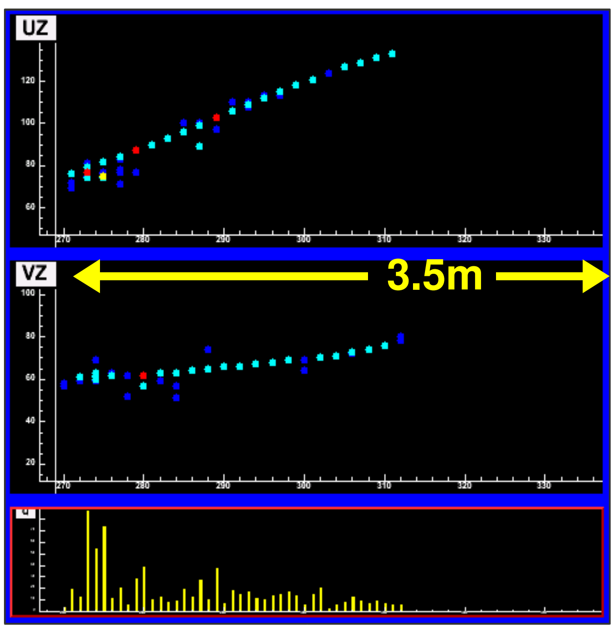
MINOS identifies electron neutrino interactions by shower topology (track for muon neutrinos).

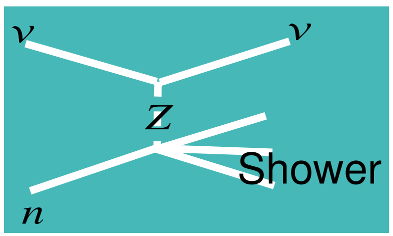
Charged Current Muon Neutrino Event

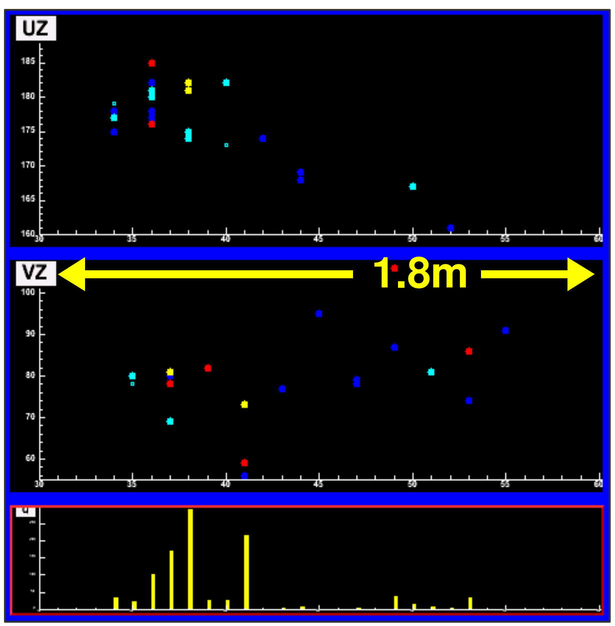




Muon track and hadronic shower at vertex

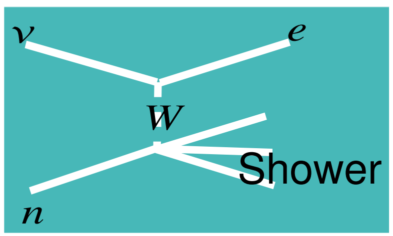
Neutral Current Event

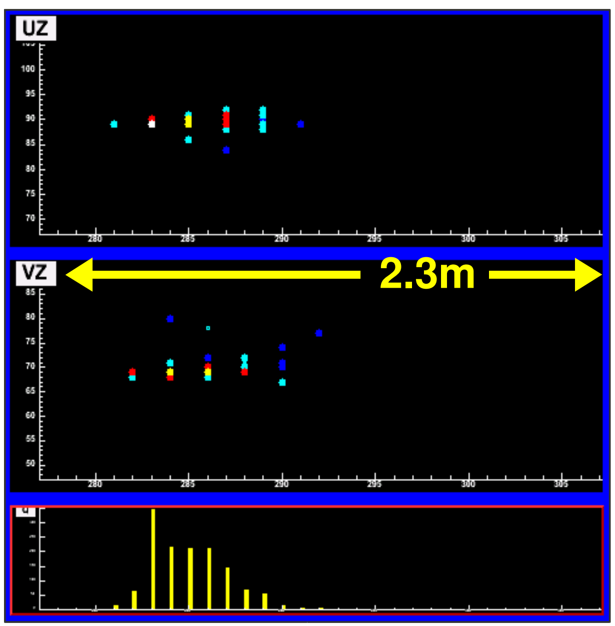




Shorter event, mostly shower hits

Charged Current Electron Neutrino Event





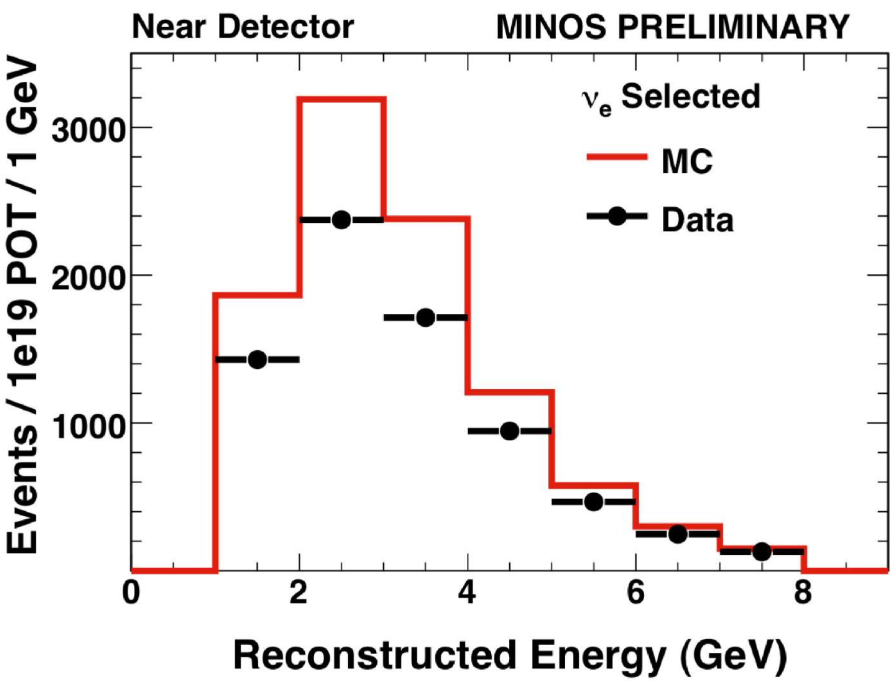
EM shower, often similar topology to NC event

Near Detector Spectrum

Due to granularity of detectors, charged current ν_e events are eclipsed by a variety of backgrounds:

- mainly **neutral current** events (NC)
- additionally **muon neutrino charged current events** with a very short track (CC ν_μ)
- **beam electron neutrino charged current events** (beam CC ν_e)
- **tau neutrino charged current events** (Far Detector only – CC ν_τ)

- MINOS neutrino interactions occur in a **kinematic region where little experimental data** available
- particle **showers** in MINOS detectors **hard to model => Data / MC disagreement not unexpected**
- developed **2 data-driven methods** to correct our Near Detector MC to match the Data and to split out the different background components (separate extrapolation)
- One of those two methods is the **Muon Removed Charged Current method** (MRCC)



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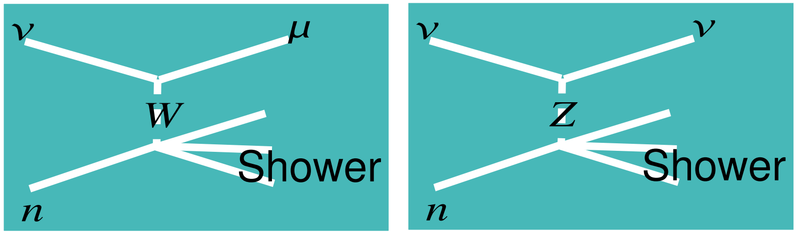
Muon Removed Charge Current Method

- To first order, in the MINOS detectors, CC ν_μ and NC showers are similar
- Can identify muon CC ν_μ events very well, so can create an independent shower sample to correct our MC.

CC ν_μ :   NC:



For both MC and Data, take muon neutrino charged current events and remove the muon track

↓

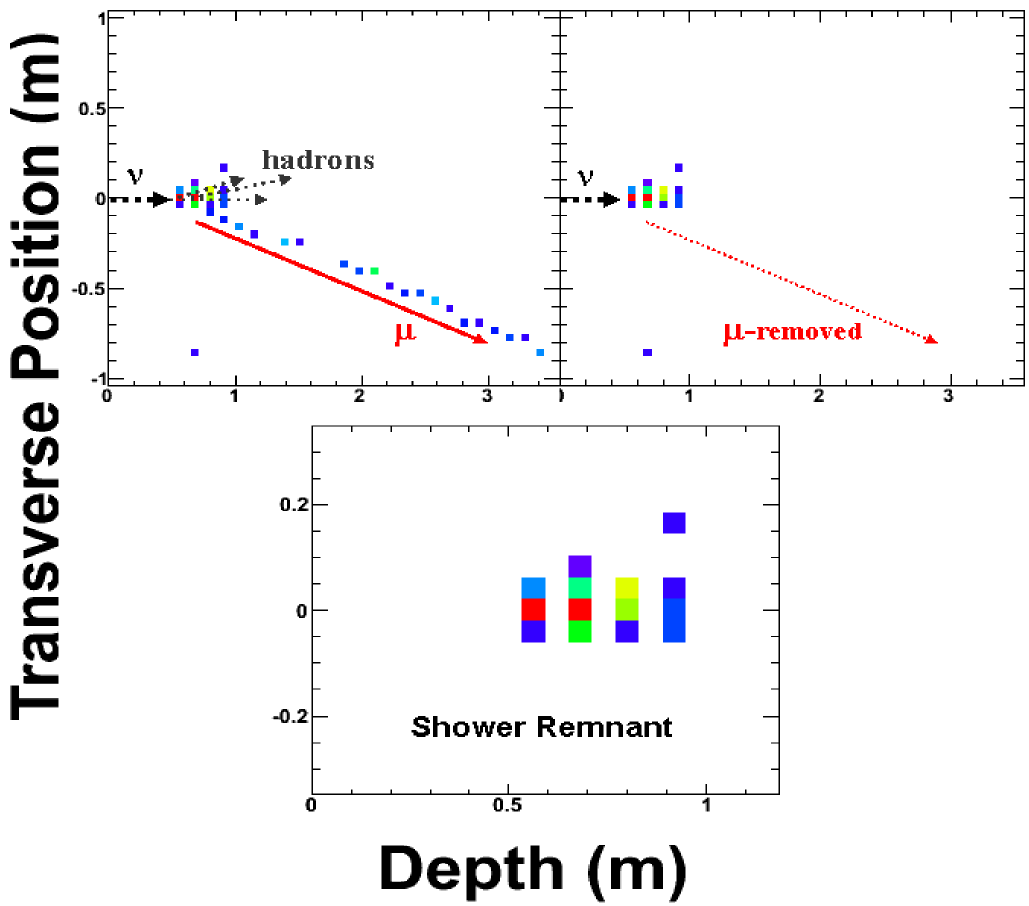
Re-reconstruct, so as to simulate the behaviour of normal neutral current events

↓

Select a pure sample of muon-removed events that were originally charged current muon neutrino events

↓

Apply analysis selection cuts to both MC and Data, then take the Data / MC ratio to provide an ad-hoc correction factor to MC neutral current events

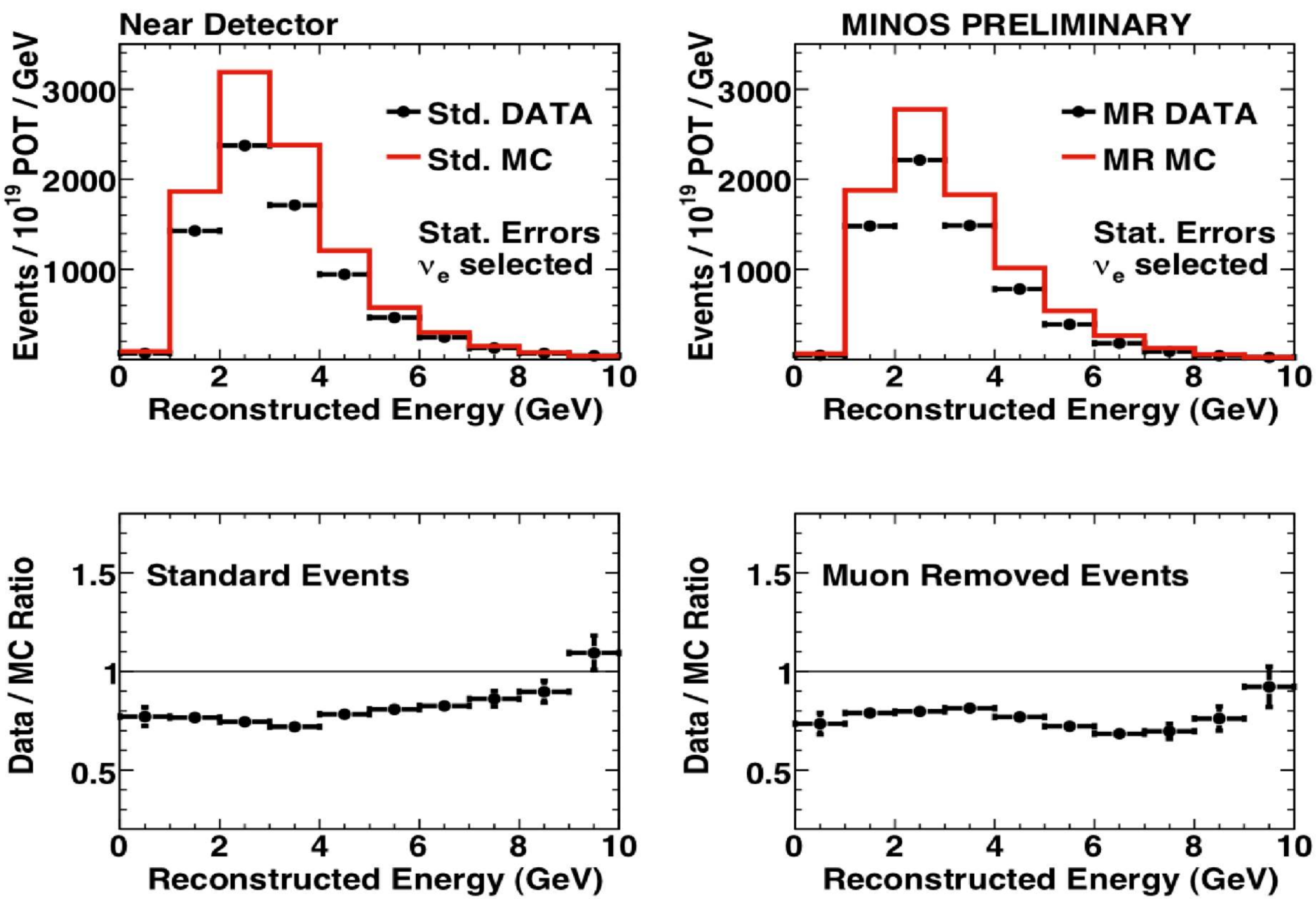


Standard Near Detector Events and Muon Removed Events Comparison

Near Detector CC ν_e selected standard events show **similar data-MC disagreement** to muon removed events

=> the similarity in the data-MC comparisons points to **imperfect shower modelling** as the source of the discrepancy

=> the similarity is also present for **shower topology variables**



Muon Removed Correction:

$$NC^{MRcorr.} = NC_{Std.MC}\left(DATA_{MR}/MC_{MR}\right)$$

$$CC\,\nu_{\mu}^{corr.} = Data - NC^{MRcorr.} - Beam\,\nu_{e}$$

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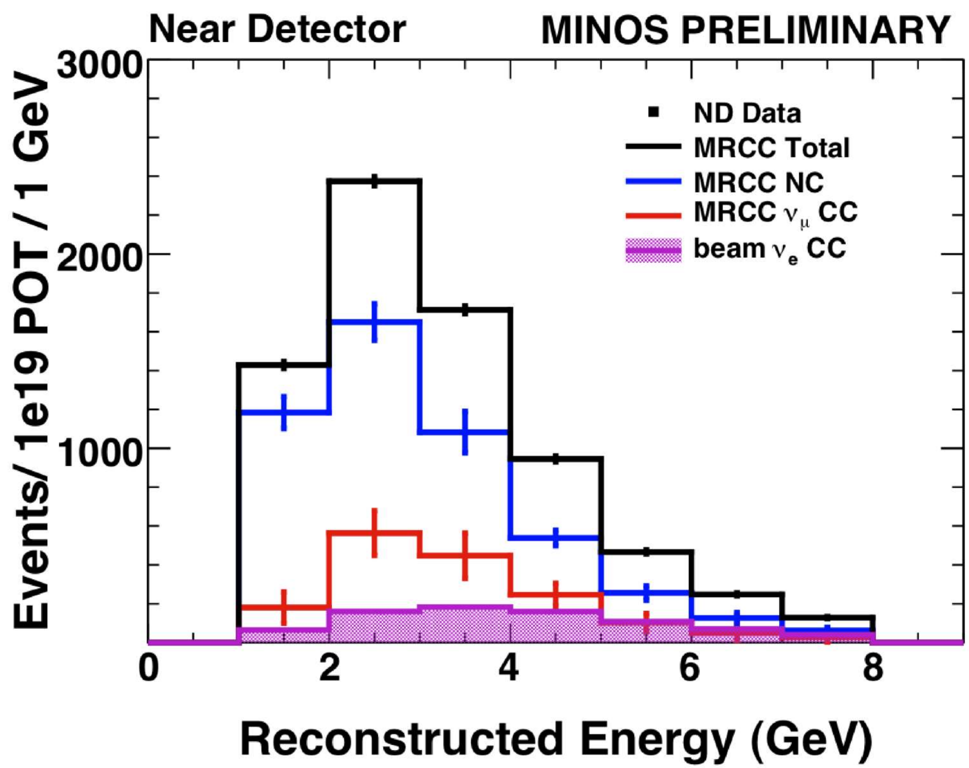
Near Detector Results from Data-Driven Background Estimation Methods



- MRCC method **agrees with data** by design.
- Second method is independent and depends on beam description. The **two data-driven methods agree** with each other.
- Obtained **backgrounds** are then **ready to be extrapolated to the Far Detector** and data-driven sensitivity limits can be obtained.

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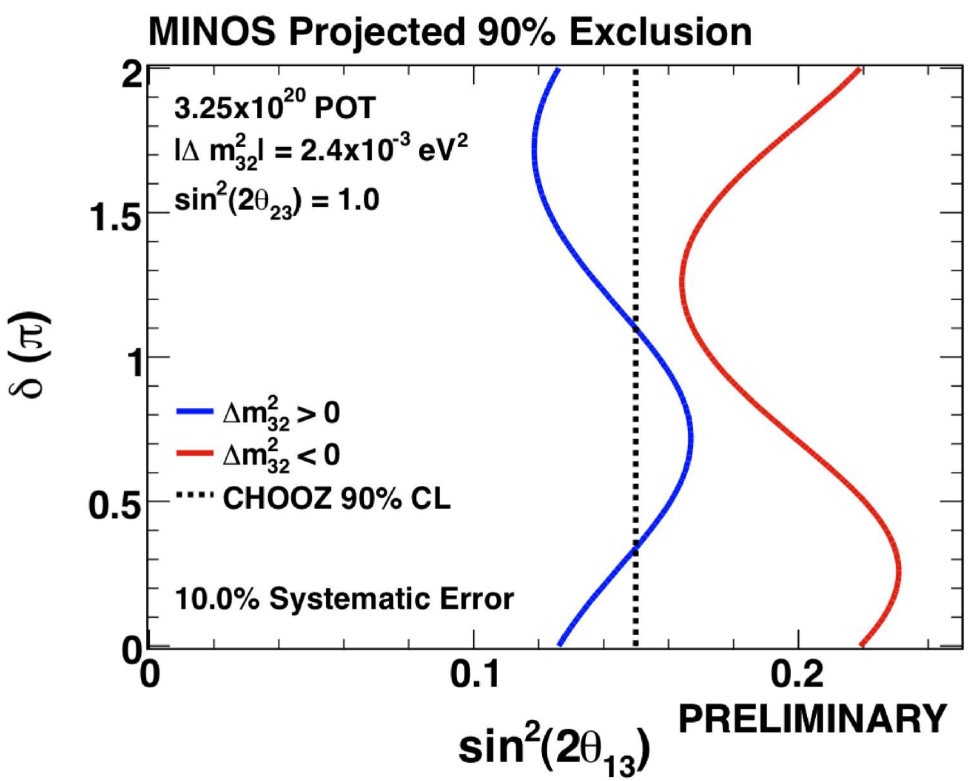
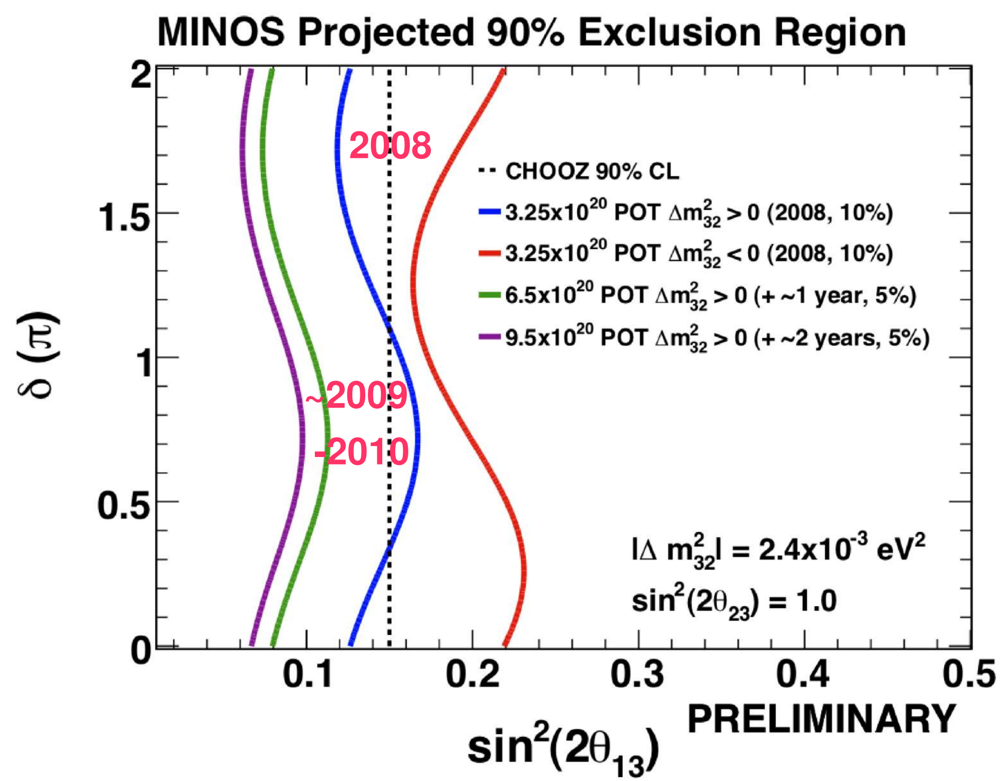
Our preliminary expectation is **42-43 background events** in the Far Detector based on the two data-driven Near Detector methods. **Signal depends on oscillation parameters**.

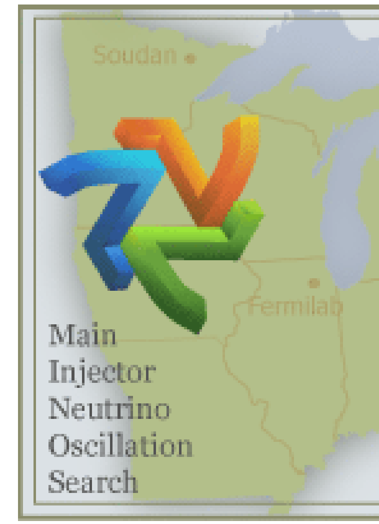
MINOS projected sensitivity for **3.25e20 POT** (data statistics available now) and for a systematic error of 10%:



MINOS projected sensitivity for increased exposure and reduced, but achievable systematic errors:



Summary



- The MINOS **electron neutrino appearance analysis** is **difficult** due to the shower resolution of the detectors (optimized to detect CC ν_μ interactions characterised by long muon tracks)
- Despite this, MINOS's **two detectors** allow us to predict the **Far Detector background** using the Near Detector selected spectrum
- We have developed **2 data-driven methods** to **separate out** the various Near Detector **background components** in order to propagate them to the Far Detector
- **MINOS is close to carrying out its first electron neutrino appearance analysis!**

Back-Up Slides

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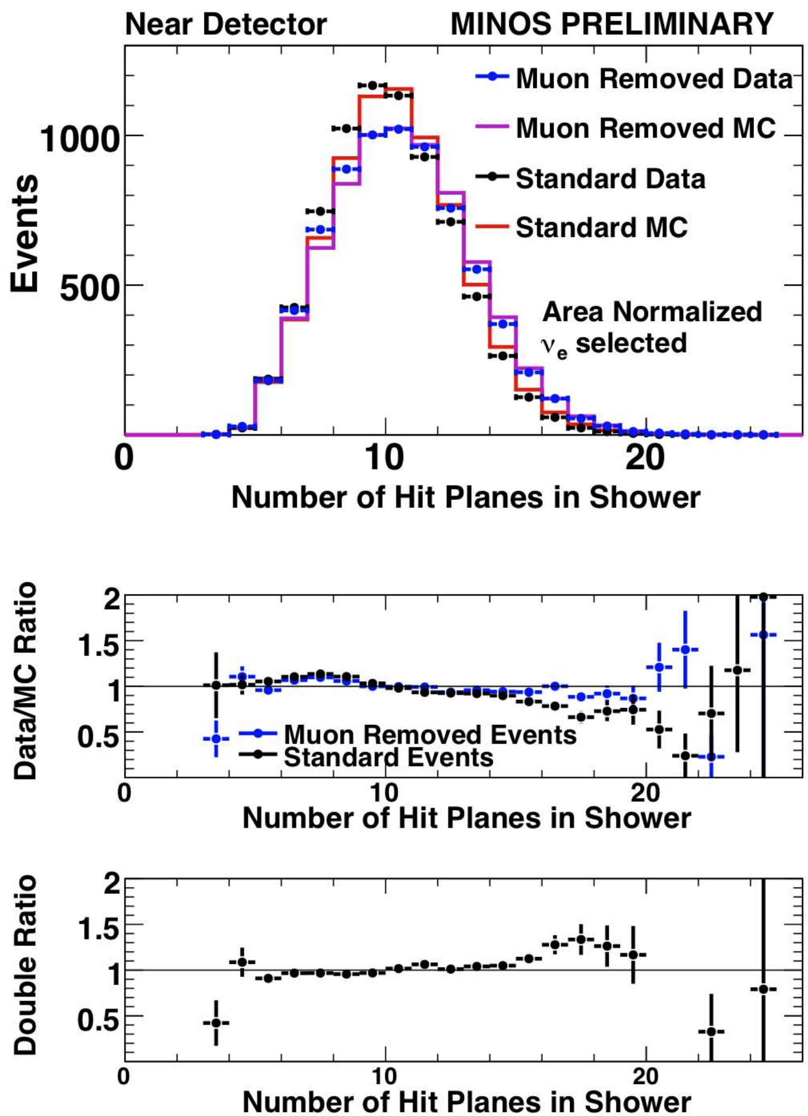
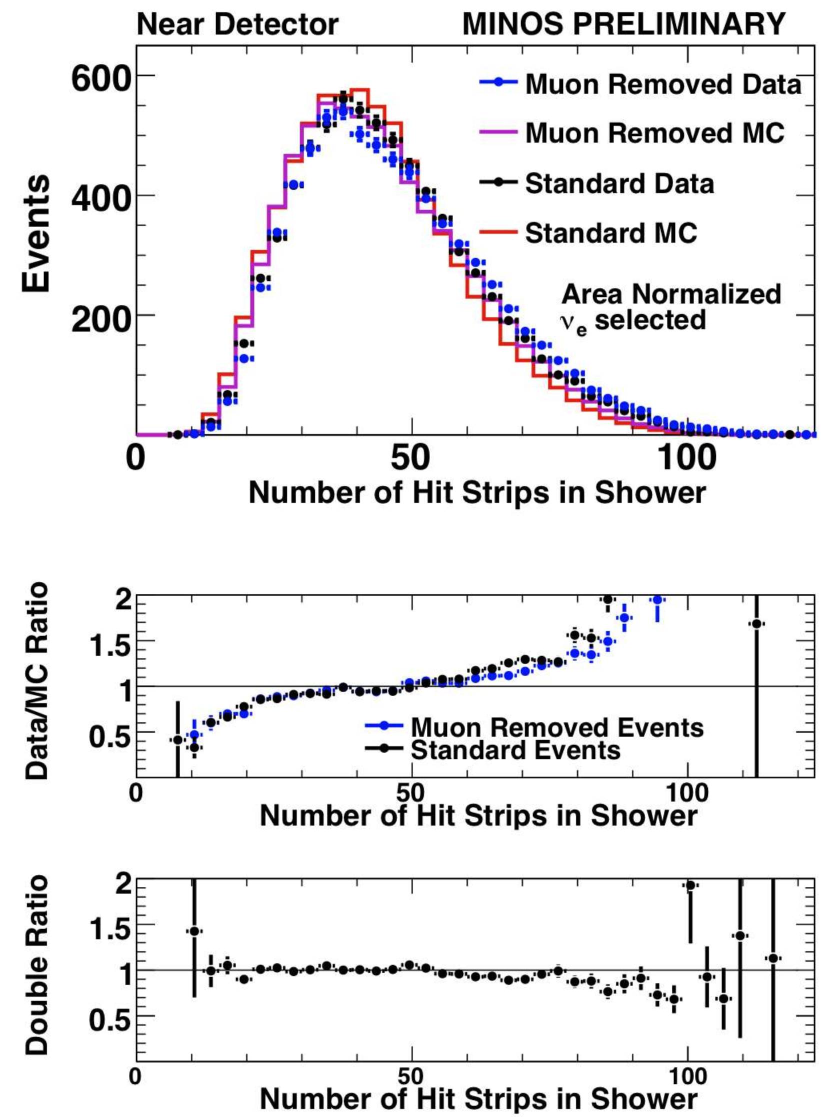
Standard samples versus Muon Removed samples shower topology comparisons:





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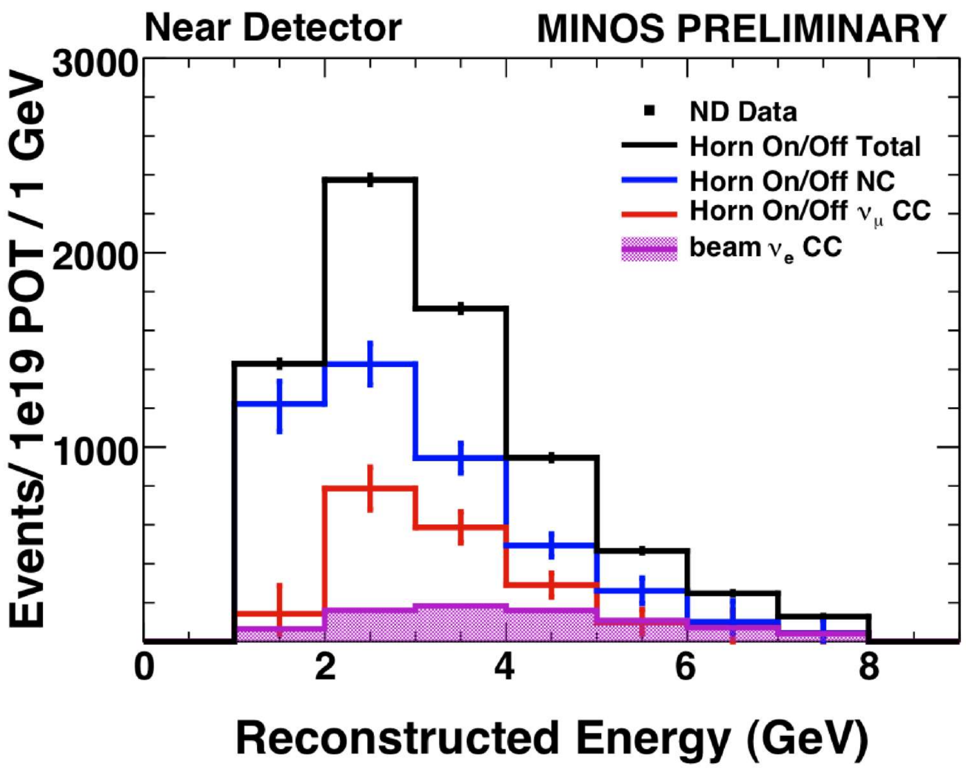
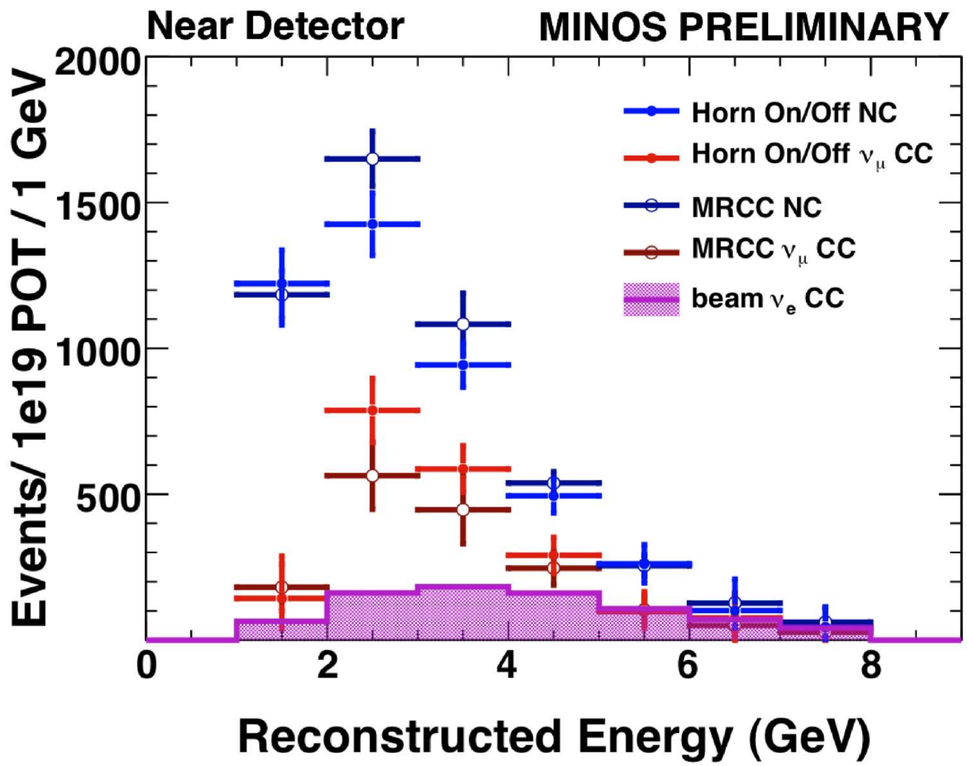
Horn On/Off Method Results:





The 2 methods agree within errors.

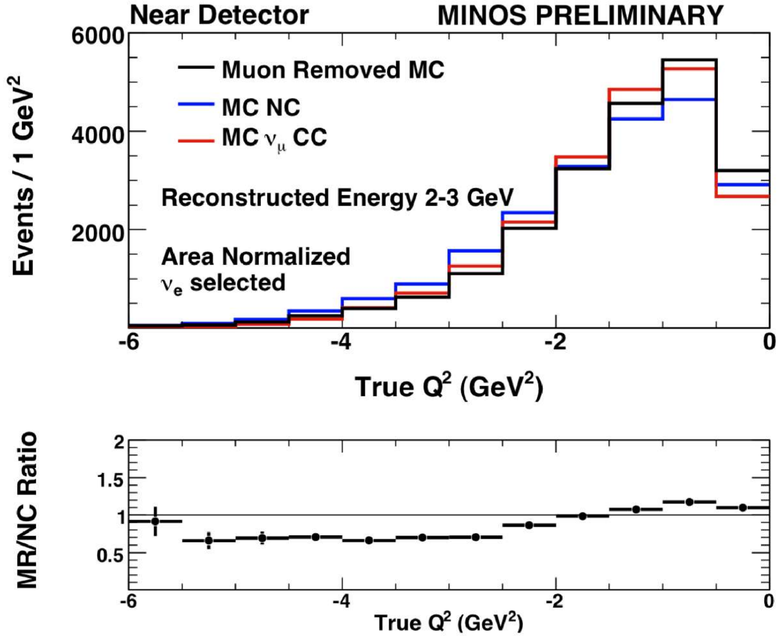
Near Detector Numbers:

PRELIMINARY	Total	NC	ν_μ CC	ν_e CC – Beam
Data-Driven MRCC	7303	4899	1617	788
Data-Driven HOO	7303	4491	2025	788
Monte Carlo	9668	6230	2651	788

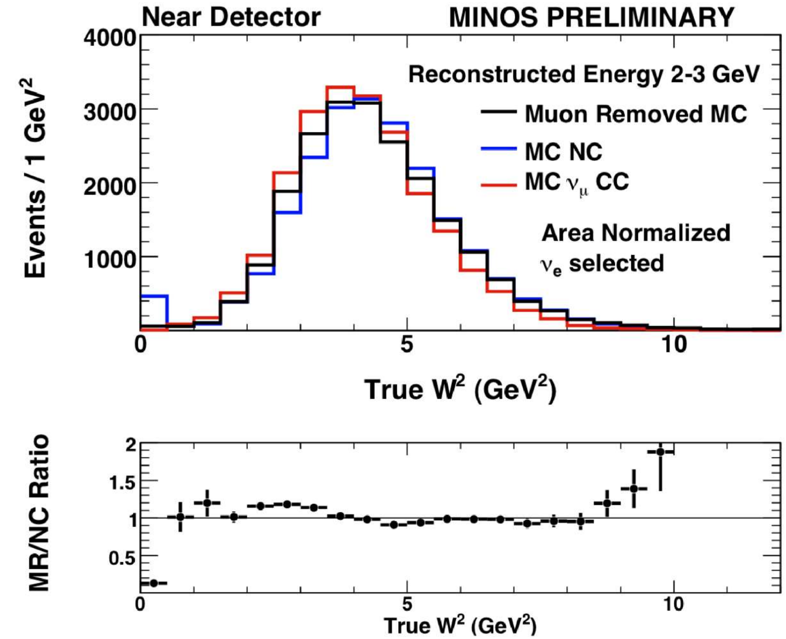
Far Detector Numbers:

PRELIMINARY	Total	NC	ν_μ CC	ν_e CC – Beam	CC
Data-Driven MRCC	**43**	32	6	3	2
Data-Driven HOO	**42**	29	8	3	2

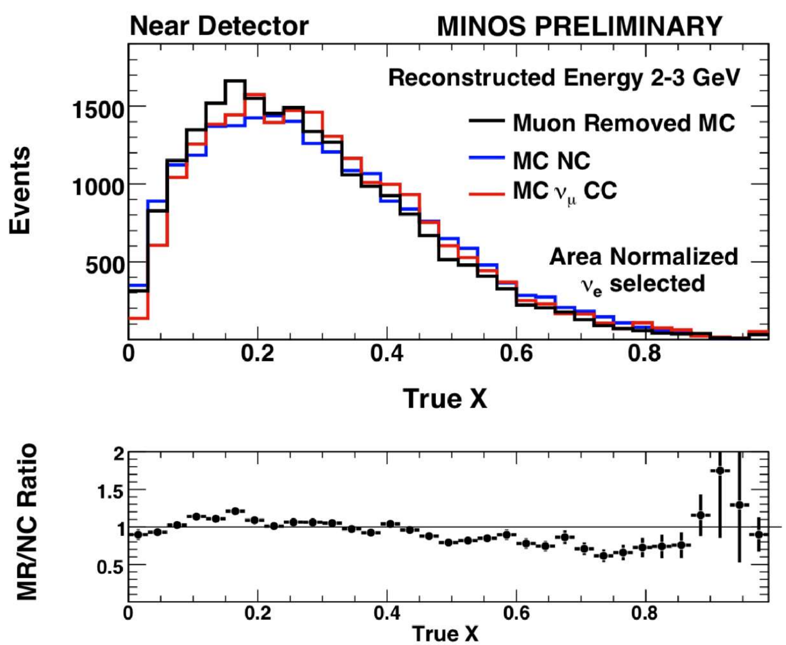
Kinematic variables:



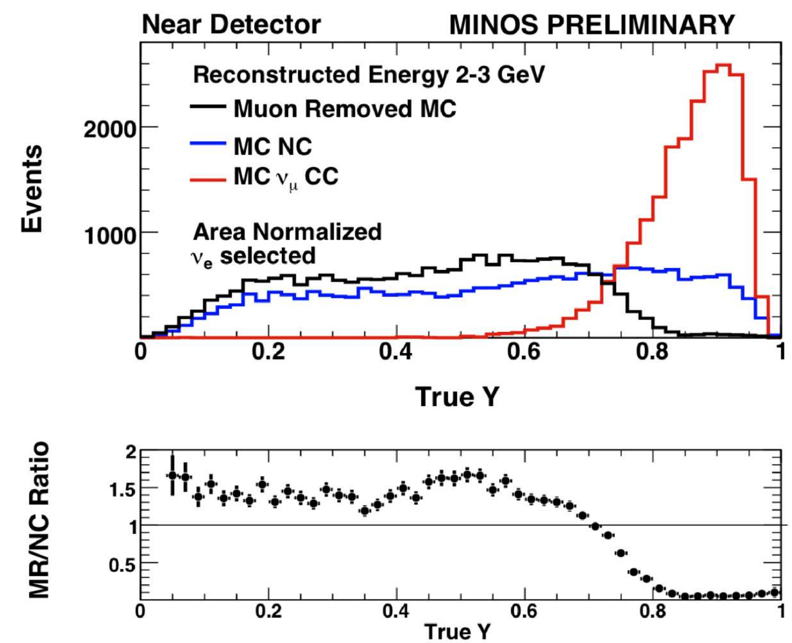
True Q^2 – true four-momentum squared transferred by the neutrino to the nucleon



True W^2 – true mass squared of the system recoiling against the scattered neutrino



True X – true fraction of the nucleon's momentum carried by the struck quark



True Y – true fraction of the neutrino's energy lost in the struck nucleon's rest frame

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Neutrino oscillations:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}=\begin{pmatrix}c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Weak Eigenstates | **PMNS Matrix** | **Mass Eigenstates**

where $s_{ij}=\sin\theta_{ij}$ and $c_{ij}=\cos\theta_{ij}$