Initial results for $\nu_\mu \rightarrow \nu_e$ oscillations in MINOS

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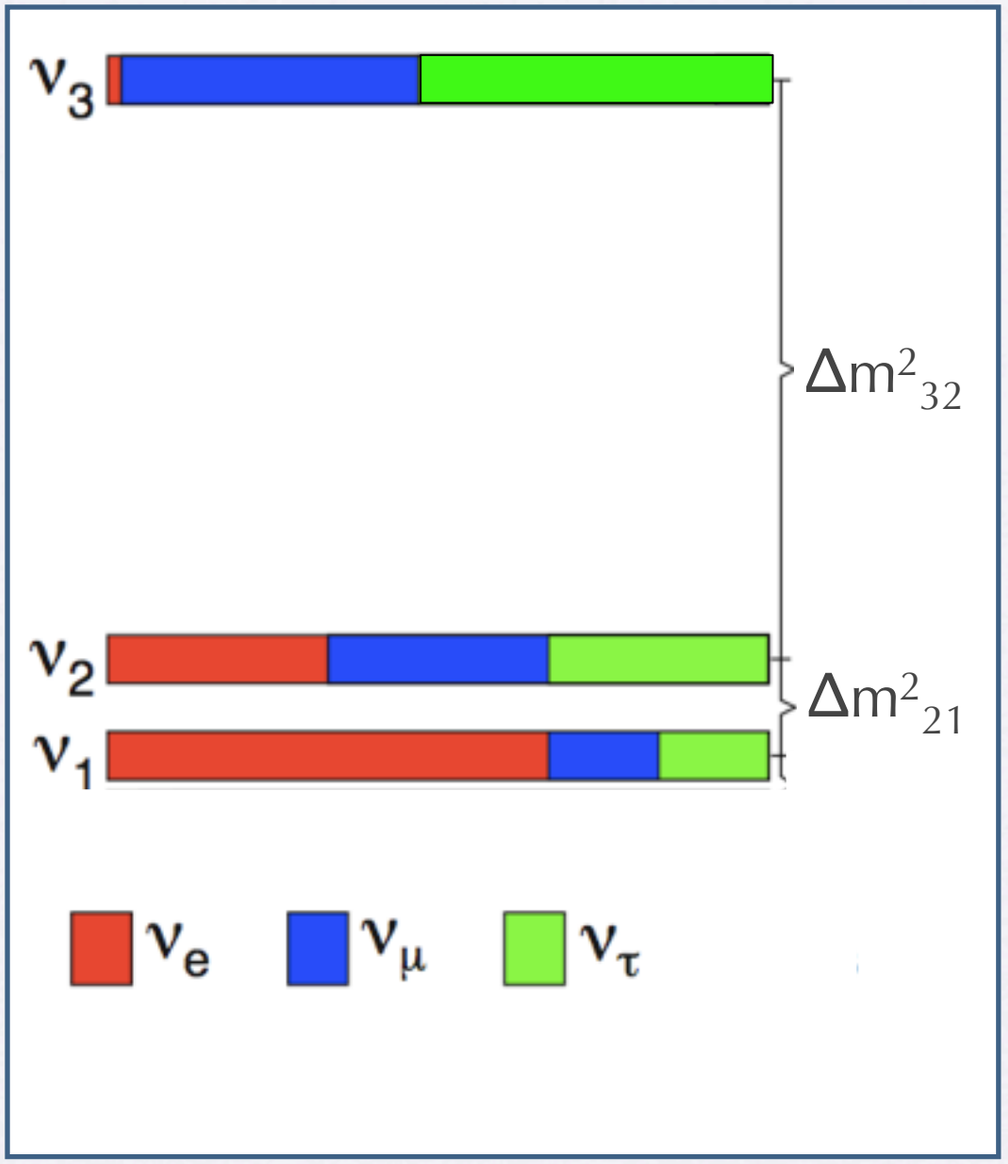
FNAL Wine and Cheese Seminar
February 27, 2009

Overview of this talk

- The MINOS experiment: physics and layout
- The search for ν_e appearance in MINOS:
  - ✦ Select ν_e candidate events
  - ✦ Measure the background in the Near Detector
  - ✦ Extrapolate the background to the Far Detector
  - ✦ Study sidebands in Far Detector data
  - ✦ Results from Far Detector data
- Summary

Neutrino masses and mixing

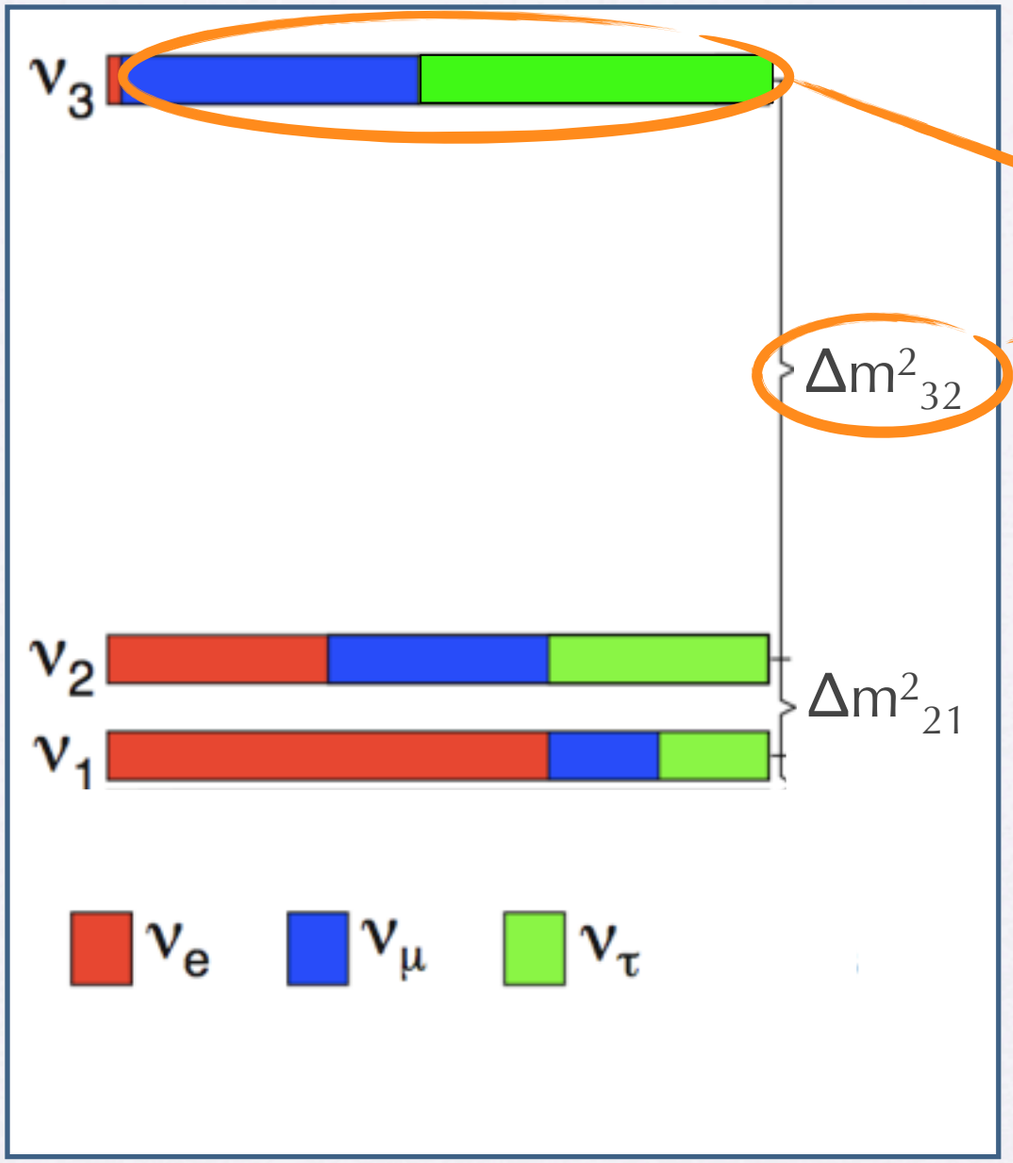
What is the current experimental picture?



- Two mass scales:
  - the atmospheric mass scale: Δm^2_{32}
  - the solar mass scale: Δm^2_{21}
- Large mixing angle for atmospheric neutrino oscillations.
- Solar neutrino oscillations are subject to matter effects. Non maximal mixing angle.
- Mass ordering known for the solar mass scale. Not known for the atmospheric.

MINOS physics goals

study "atmospheric" neutrino oscillation parameters



PRL **101** 131802 (2008)

3.36 x10^{20} protons on target (POT)

- ✓ Study ν_μ disappearance as a function of energy:
  - ✓ Precision measurements of Δm^2_{32} and $\sin^2(2\theta_{23})$.

$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 (68% CL)

$\sin^2 2\theta_{23} > 0.90$ (90% CL)

χ^2/ndf=90/97

Decay: disfavored at 3.7 σ

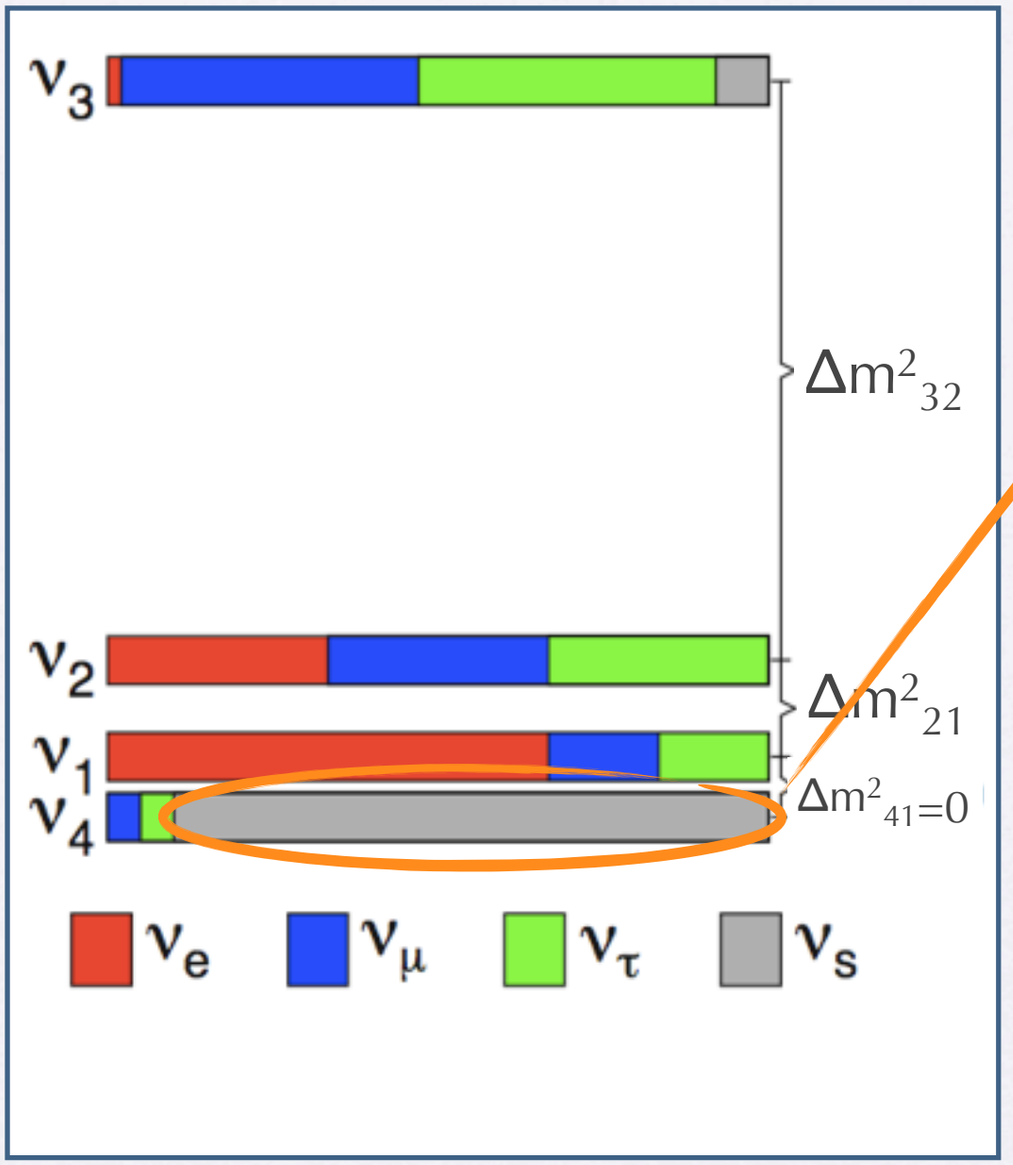
Decoherence: disfavored at 5.7 σ

World's best measurement:

5% in Δm^2_{32}.

MINOS physics goals

study "atmospheric" neutrino oscillation parameters



PRL **101** 221804 (2008)
2.46 x10^{20} POT

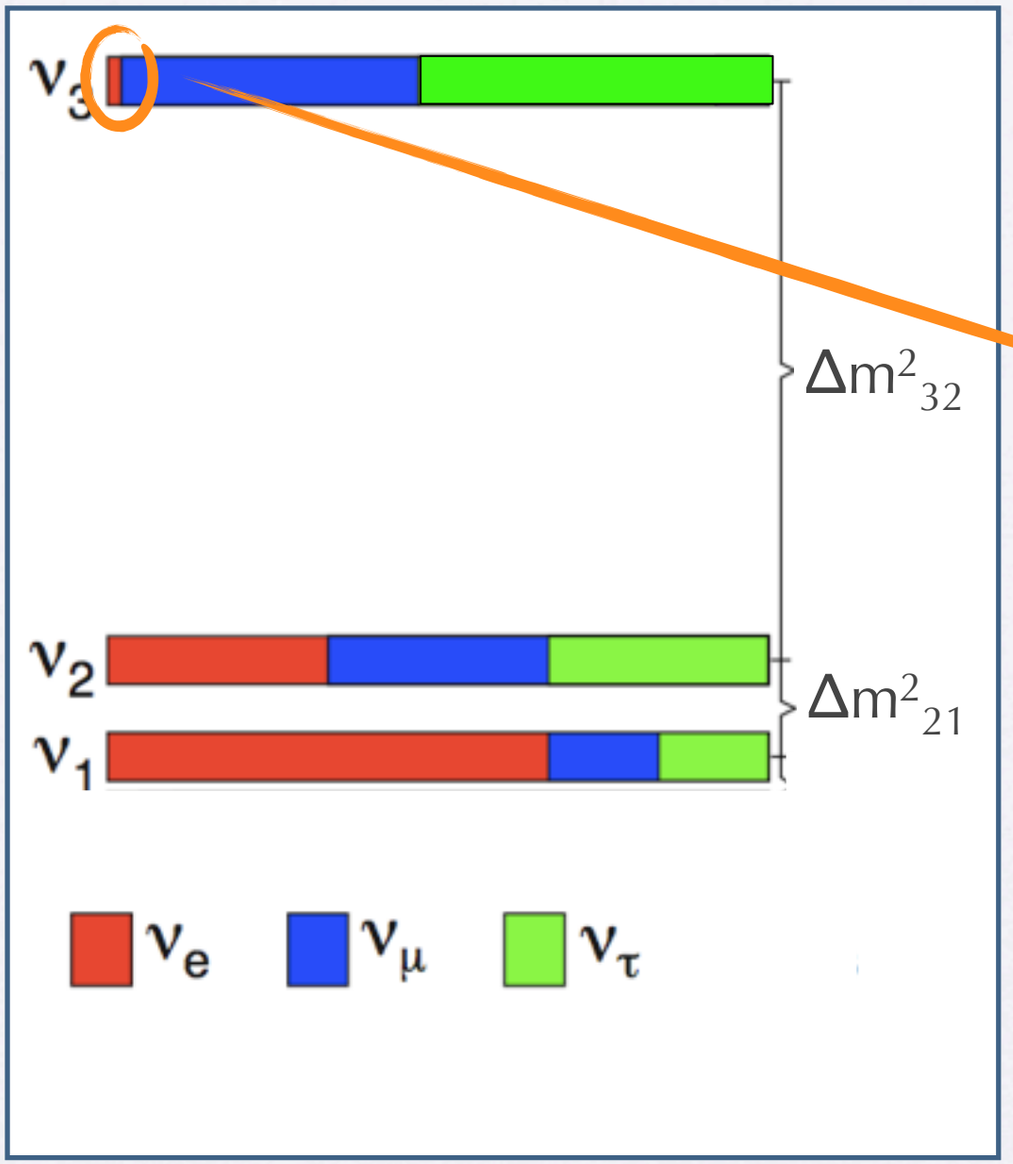
- ✓ Mixing to sterile neutrinos at $\Delta m^2_{34} \sim \Delta m^2_{32}$:
  - ✓ Fraction of neutrinos that oscillate into the sterile state.

Assuming no electron neutrino appearance:
$f_s = 0.28^{+0.25}_{-0.28}$(stat.+syst.)
$f_s < 0.68$ (90% CL)

- Other MINOS Physics:
  - Use magnetized detectors for CPT tests.
  - Studies of cosmic rays and atmospheric neutrinos in the Far Detector.
  - Neutrino interactions studies in the Near Detector.

MINOS physics goals

study "atmospheric" neutrino oscillation parameters



✦ **Search for subdominant oscillations i.e. $\sin^2(2\theta_{13})$.**

✓ **First results to be shown today.**

3.14 x10^{20} POT

Searching for θ_{13}

Missing element in the PNMS neutrino mixing matrix

- **The probability of ν_e appearance in a ν_μ beam:**

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta$$

$$+\alpha\Delta \cos\theta_{13} \sin 2\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \cos\Delta$$

$$-\alpha\Delta \cos\theta_{13} \sin 2\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \sin\Delta$$

no matter effects

- **Searching for ν_e events in MINOS, we can access $\sin^2(2\theta_{13})$.**
- Probability depends not only on θ_{13} but also on δ_{CP} .
  - A non-zero θ_{13} would open the door to a CP violation measurement in the neutrino sector which could reveal the origin of the matter/anti-matter asymmetry of the universe.

Searching for θ_{13}

Adding matter effects

$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

- **The probability of ν_e appearance in a ν_μ beam:**

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \\ & +2\alpha \sin\theta_{13}\cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta \\ & -2\alpha \sin\theta_{13}\sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta \end{aligned}$$

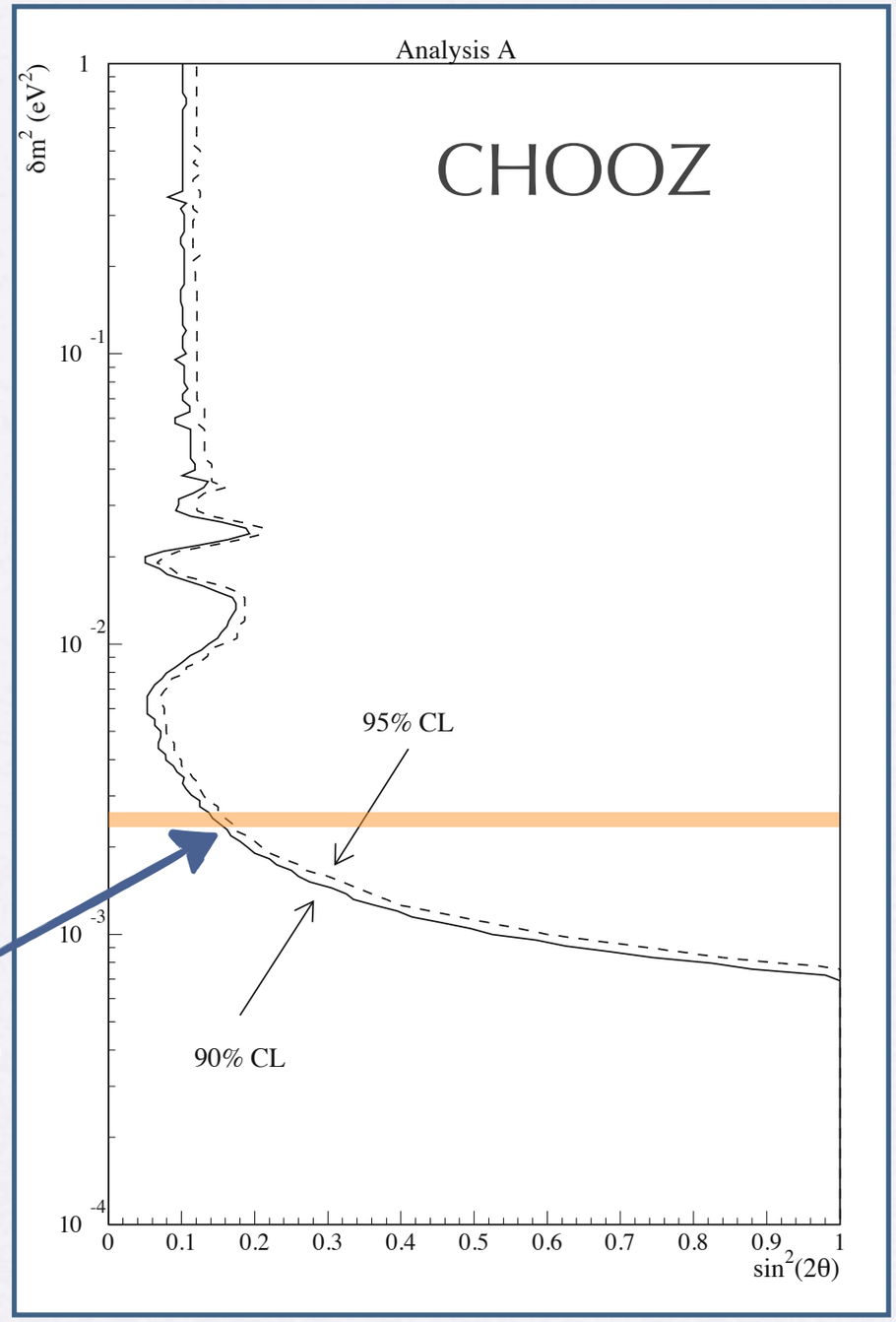
- **Searching for ν_e events in MINOS, we can access $\sin^2(2\theta_{13})$.**
- Probability depends not only on θ_{13} but also on δ_{CP}.
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy i.e. the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$.

Relevant oscillation parameters

- The CHOOZ experiment published a limit in $\sin^2(2\theta_{13})$.
- Note reactor experiments do not have δ_{CP} or mass hierarchy dependence.
- Since then MINOS has measured Δm^2_{32} very precisely.
- Thus for this talk:

MINOS best fit
$|\Delta m^2_{32}| = 2.43 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1.00$

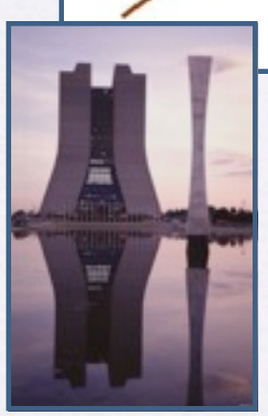
CHOOZ limit (90%CL)
$\sin^2 2\theta_{13} = 0.15$



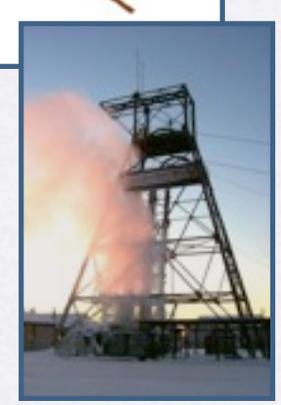
There are no measurements for δ_{CP} or the mass hierarchy.

MINOS in a nutshell

- Produce a high intensity beam of muon neutrinos at Fermilab.
- Measure background at the Near Detector and use it to predict the Far Detector spectrum.
- If neutrinos oscillate we will observe a distortion in the data at the Far Detector in Soudan, 735 km away.



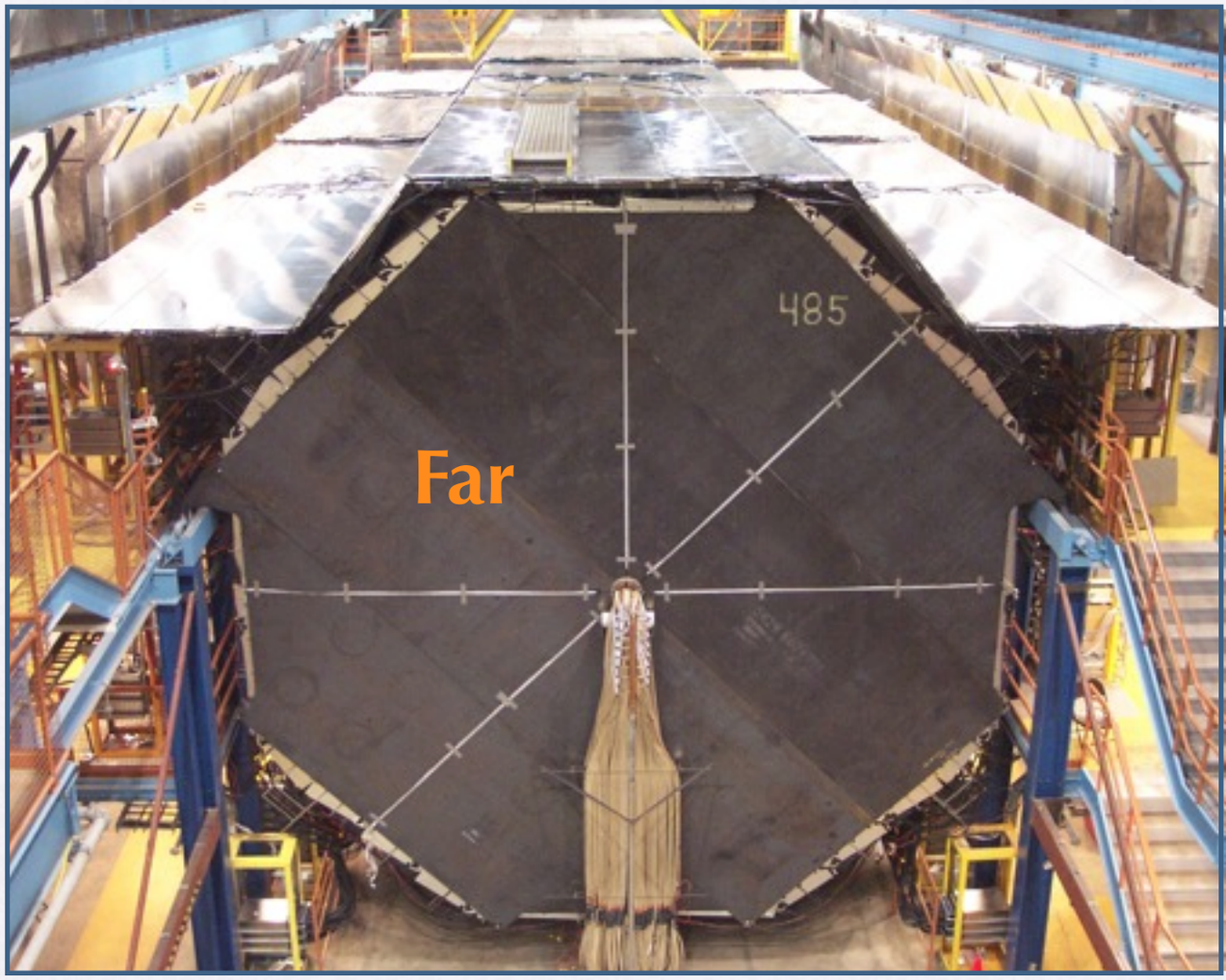
←long baseline→



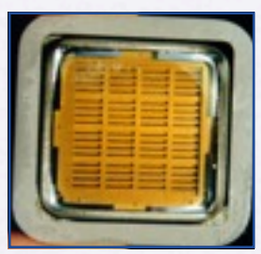
Main **I**njector **N**eutrino **O**scillation **S**earch

The MINOS detectors

- Functionally identical: **Near and Far detectors**
- 1 inch thick octogonal steel planes, alternating with planes of 4.1cm x 1cm scintillator strips, up to 8m long. Magnetized.
  - **Near**: ~ 1kton, 282 steel squashed octagons. Partially instrumented.
  - **Far**: 5.4 kton, 486 (8m/octagon) fully instrumented planes.

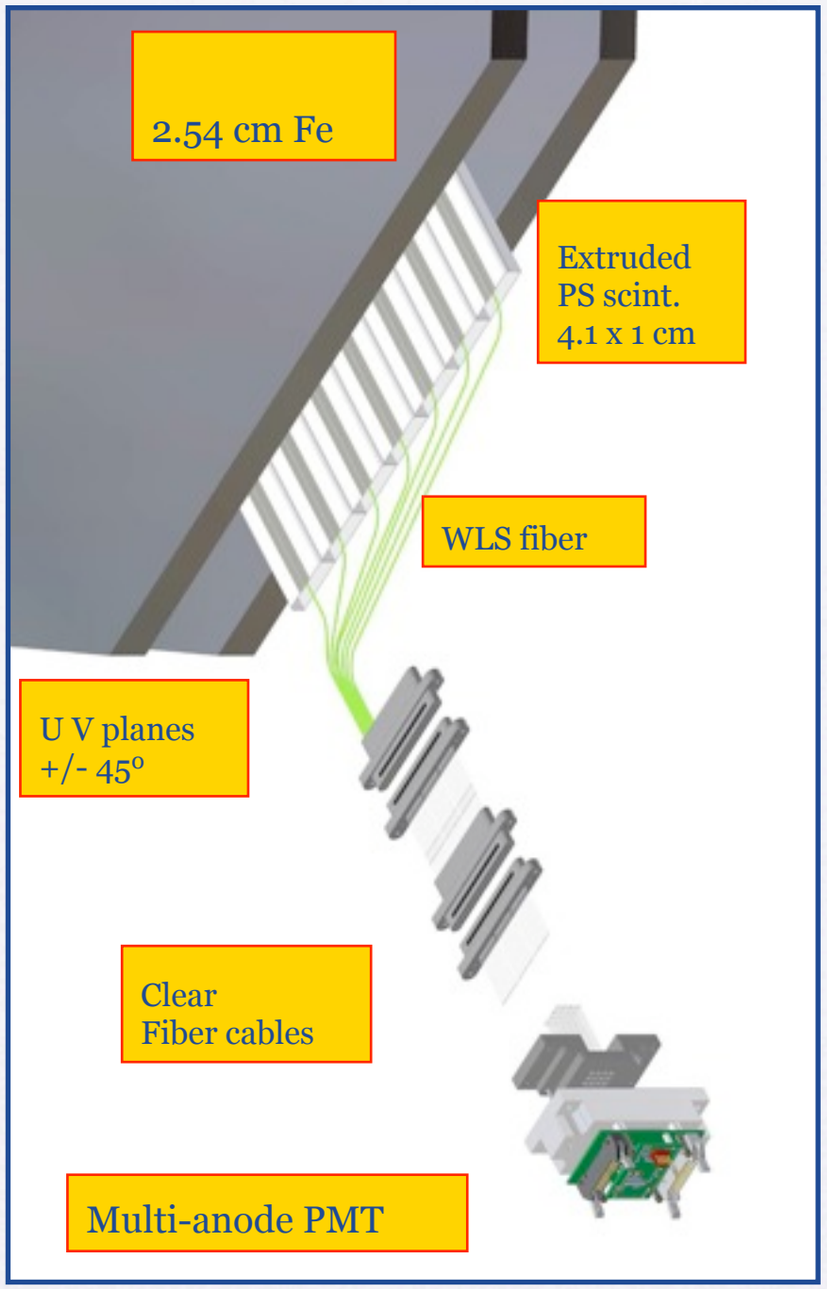


MINOS detector technology

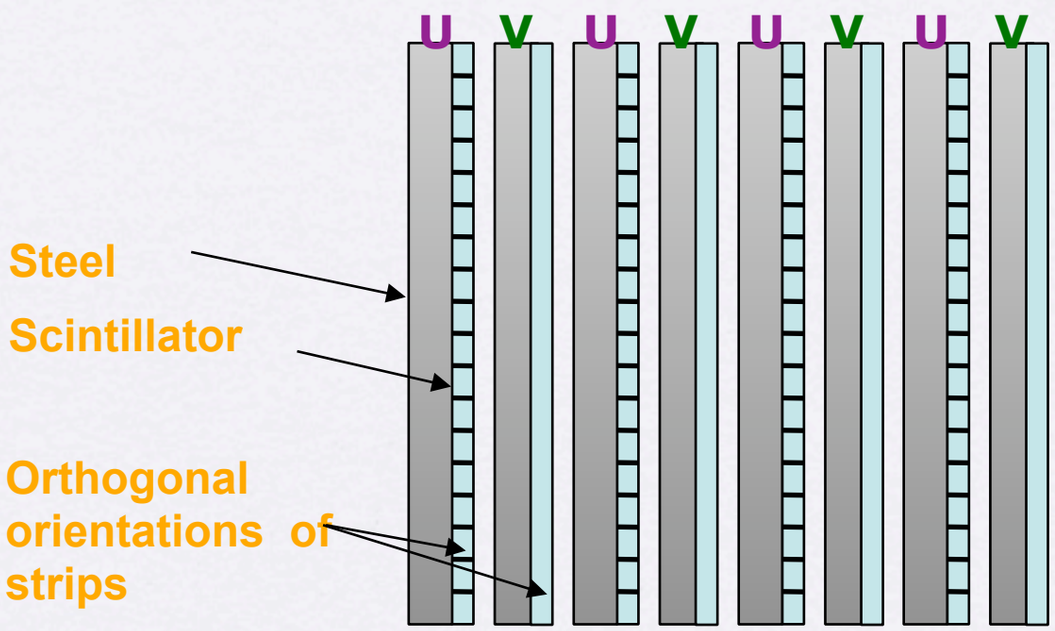


M16

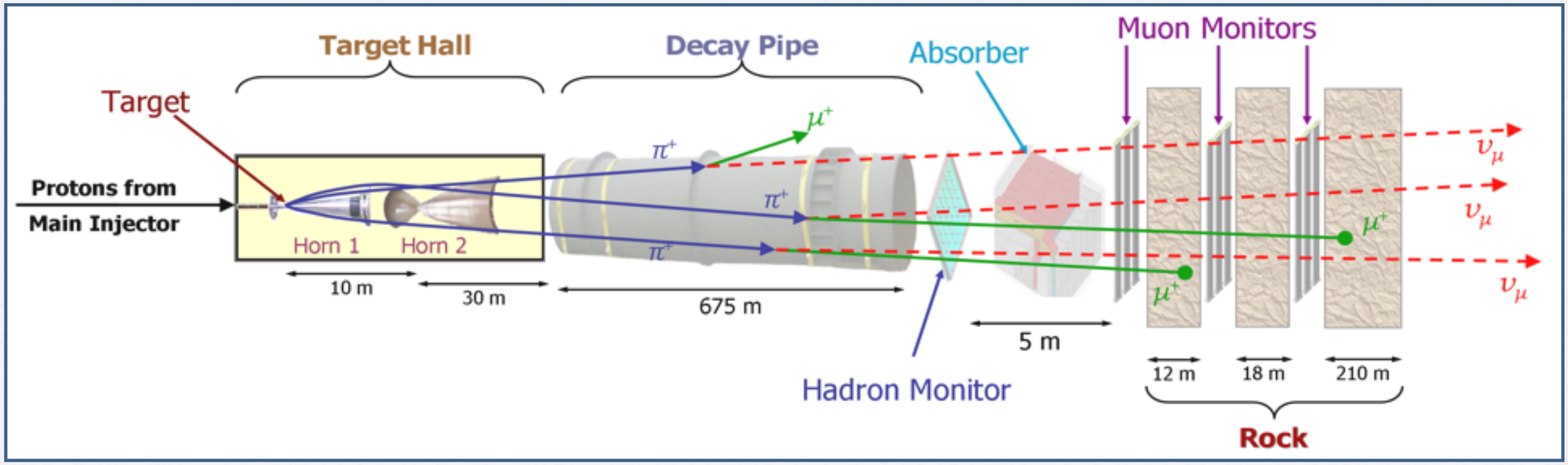
M64



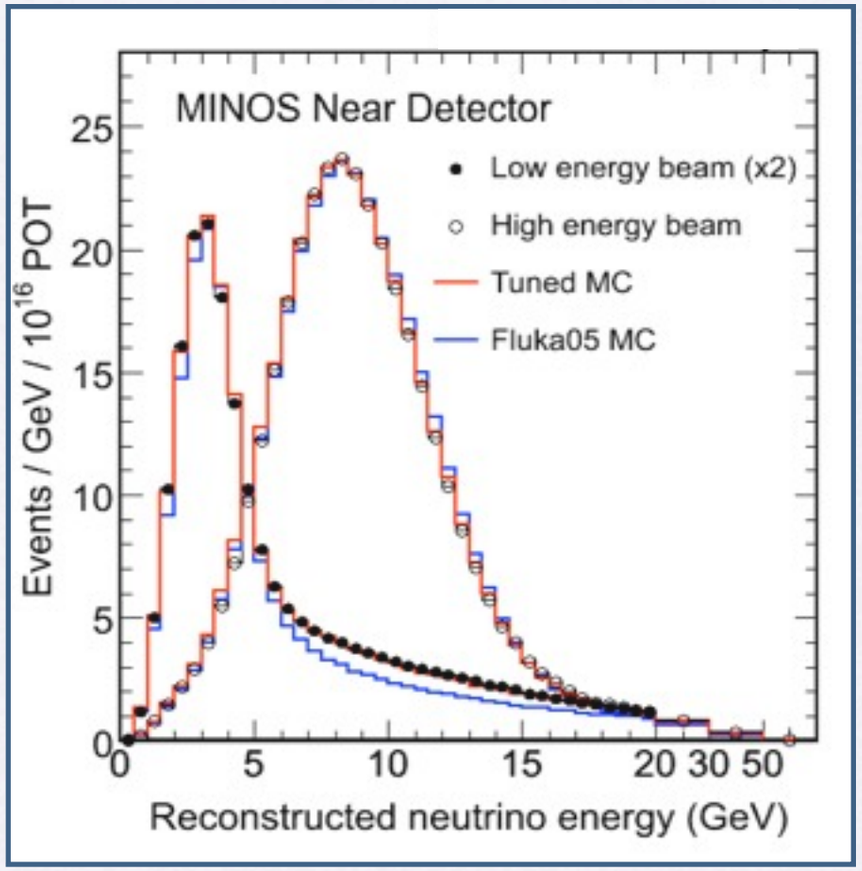
- **In both detectors:**
  - co-extruded polysterene scintillator strips
  - orthogonal orientation on alternate planes - U, V
  - optical fiber readout to multi-anode PMTs (M64 for the ND, M16 for the FD)



Producing neutrinos



- **Ne**u**trinos from the **M**ain **I**njector (NuMI)
- 10 μs spill of 120 GeV protons every 2.2 s
- Currently 275 kW typical beam power
- Currently 3.0 x 10^{13} protons per pulse
- Neutrino spectrum changes with target position.

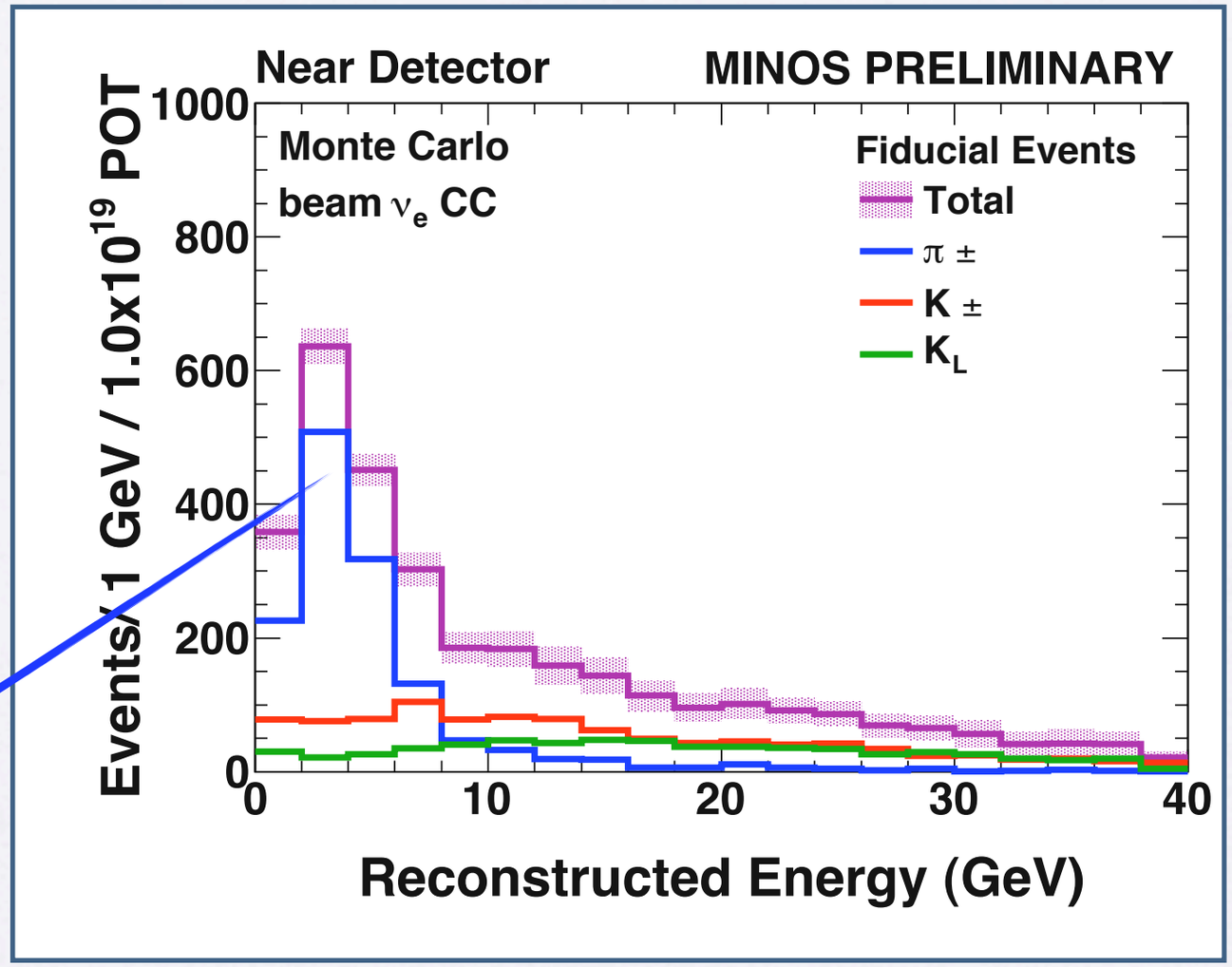


Beam ν_e component

- Neutrino beam has 1.3% of ν_e contamination from pion and kaon decays.

- Region of interest for the ν_e oscillation analysis, 1-8GeV, dominated by events from secondary muon decays:

$$\pi^+ \rightarrow \mu^+\nu_\mu$$
$$\hookrightarrow e^+\bar{\nu}_\mu\nu_e$$

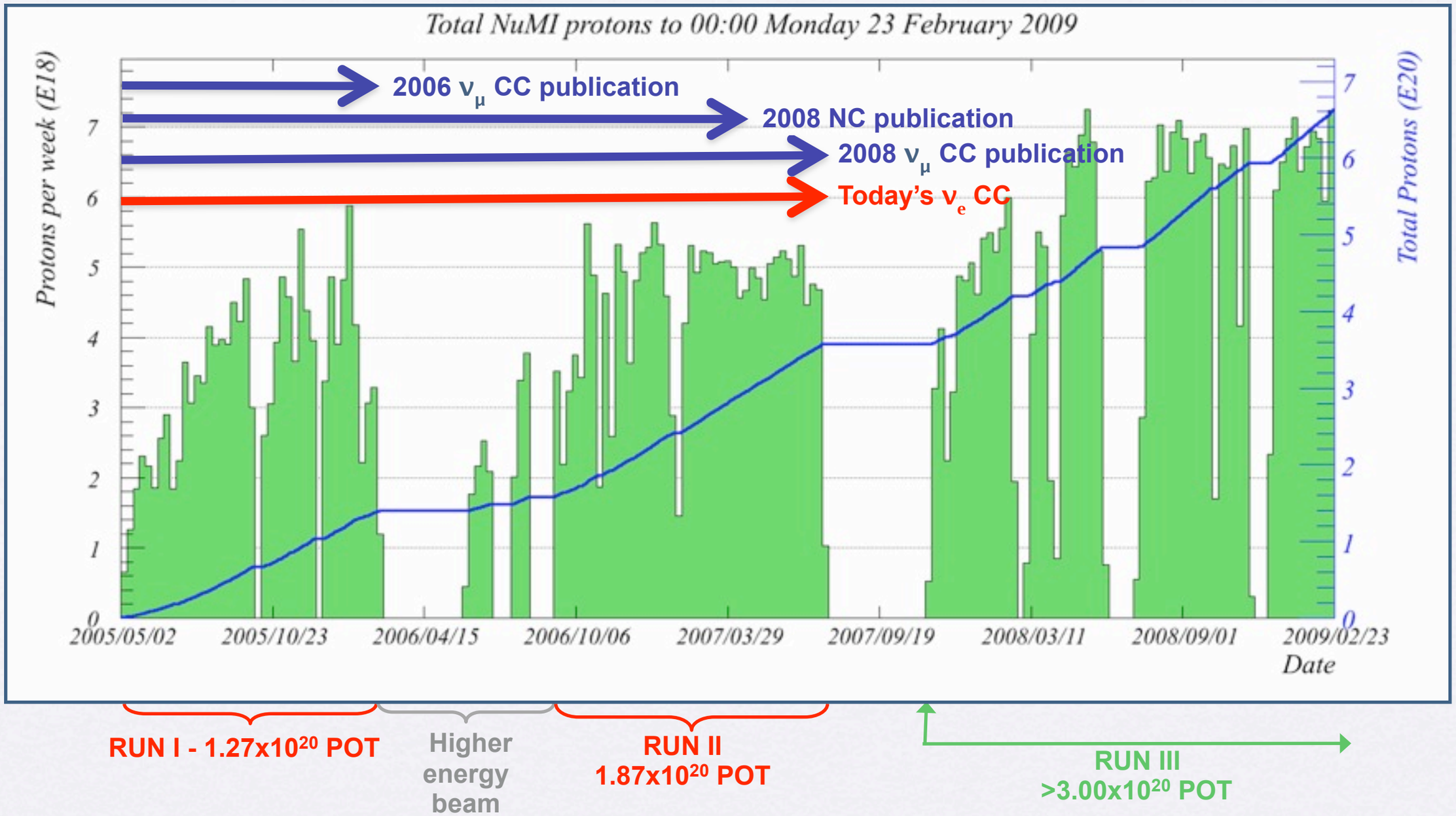


- Near and Far beam ν_e spectra are constrained by using ν_μ events from several beam configurations.

- Uncertainties on the flux in the region of interest are ~10%.

The Beam: NuMI protons

Current results on data through Run II



Results shown for run I+II - 3.14 x 10^{20} POT

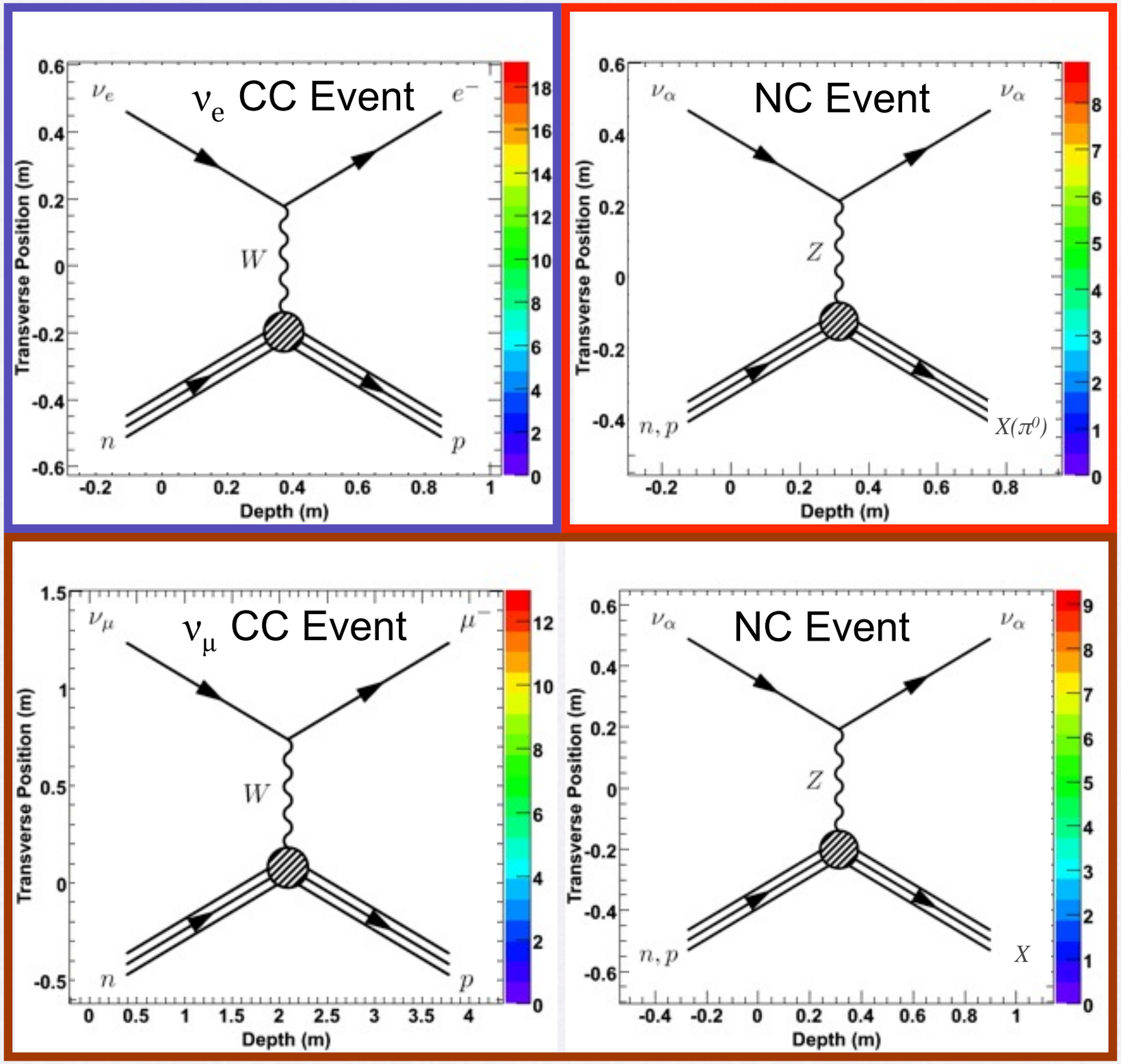
Search for ν_e appearance:

Results using Run I+II

3.14×10^{20} POT

Neutrino Event Topologies

To select ν_e CC we focus on finding compact showers.



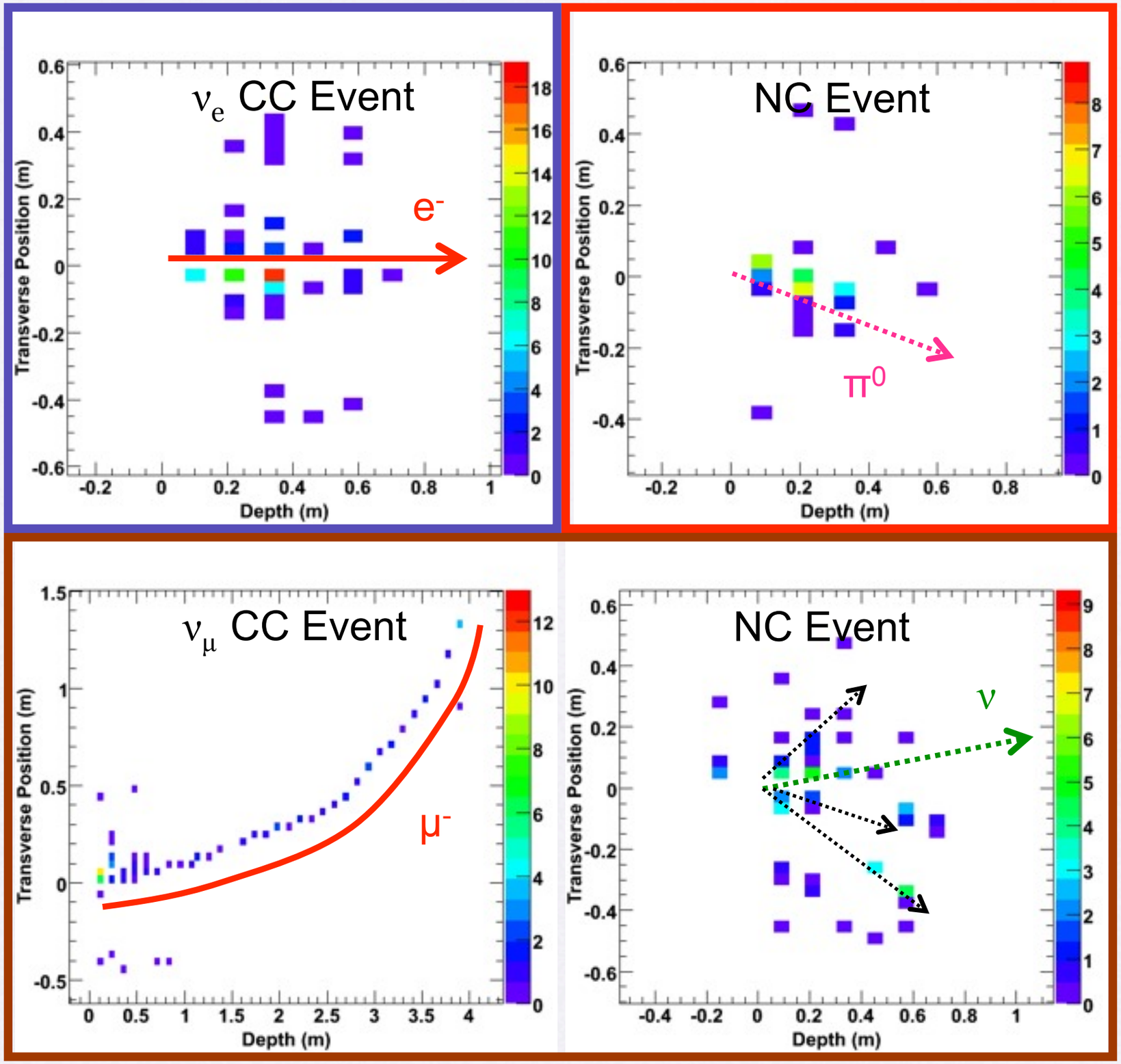
Neutrino Event Topologies

To select ν_e CC we focus on finding compact showers.

Signal

Irreducible Background

Reducible Background

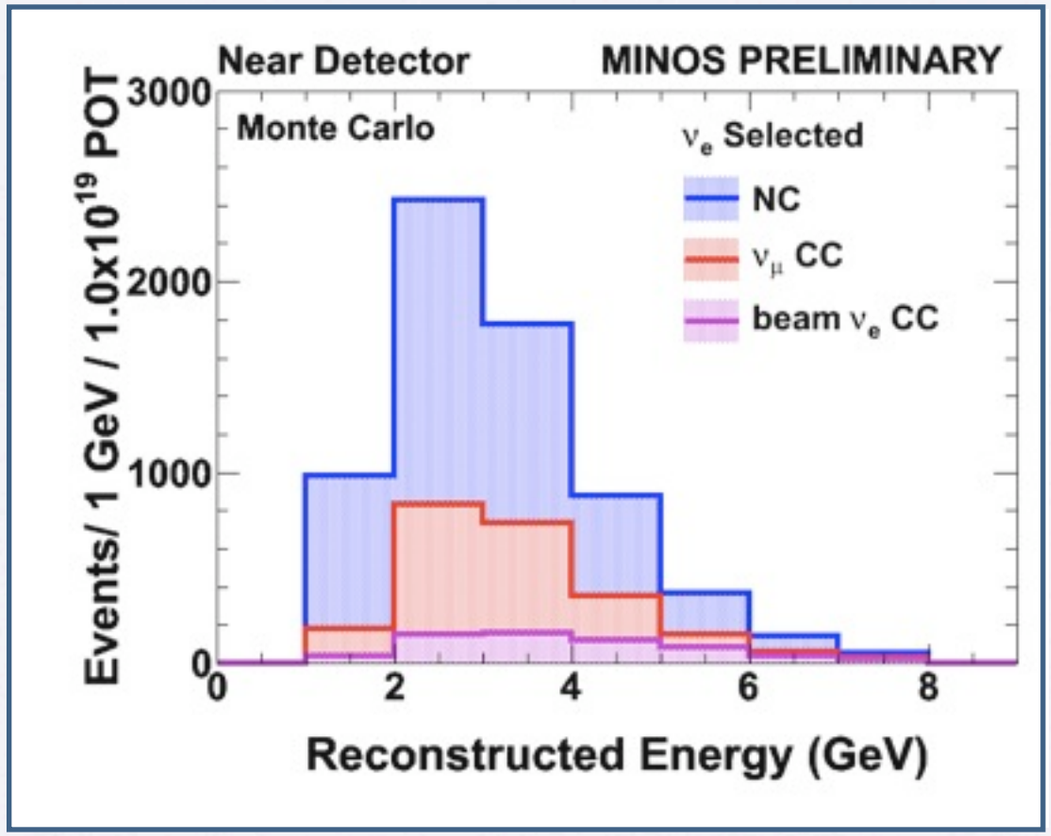


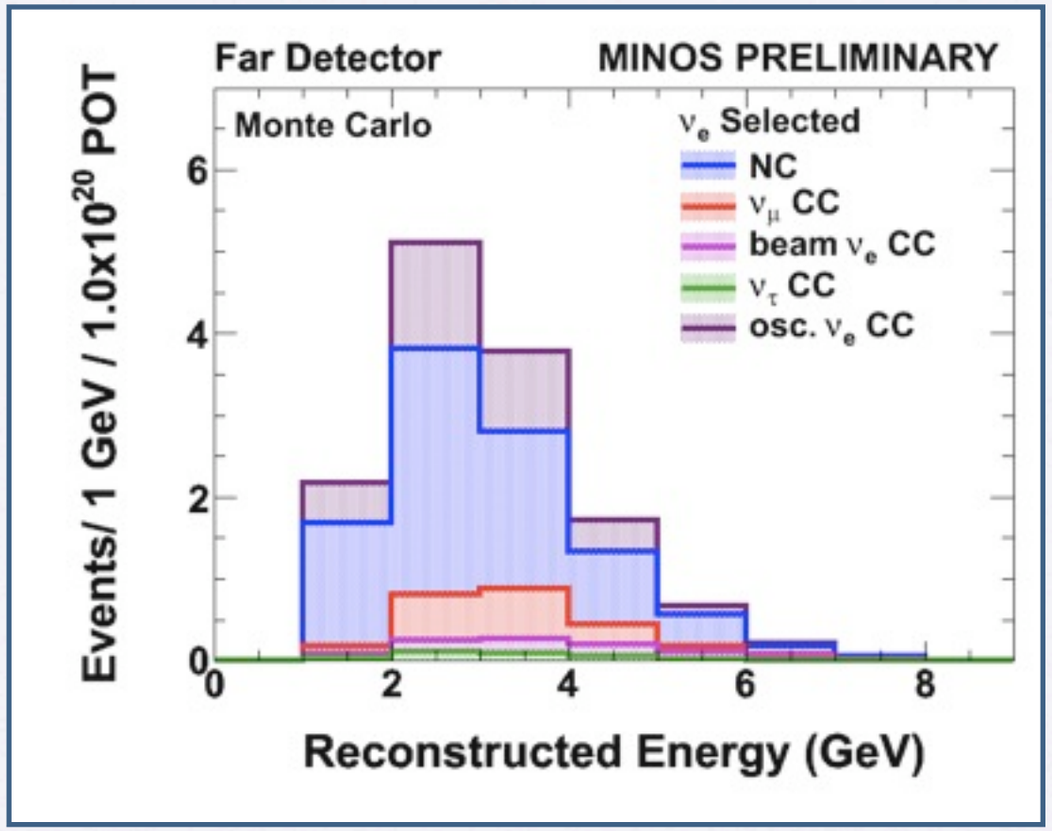
Monte Carlo events

ν_e appearance in MINOS

- **Select ν_e events** by finding electron candidates in the MINOS Detectors.
- **Measure the background** from events passing ν_e selection in the Near Detector.
- **Extrapolate the number of background events** to the Far Detector taking into account ν_μ to ν_τ oscillations.
- **Look for an excess of ν_e events** in the Far Detector data. Cut and count events.

ν_e appearance in MINOS



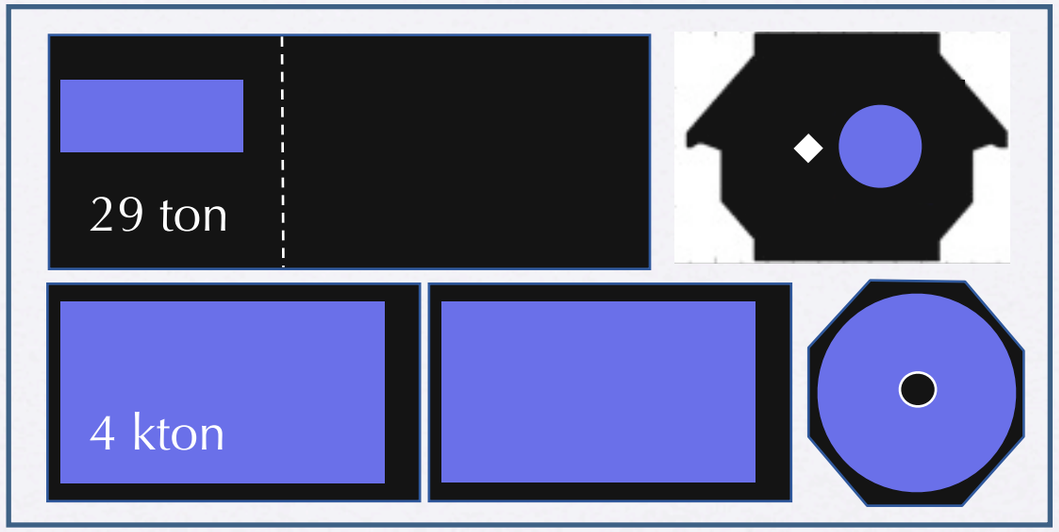


- When **selecting ν_e event candidates** in the Near Detector we will have a mix of components that do not extrapolate in the same way to the Far Detector.
- We need to **separate the main background components** NC, ν_μ CC and beam ν_e CC events, in the Near Detector.
- Then **extrapolate the background in the Far Detector** by extrapolating the components, oscillating the ν_μ CC component and calculating the ν_τ CC.
- Then **look for the ν_e excess** arising from ν_μ to ν_e oscillations in the Far Detector.

Selecting ν_e events

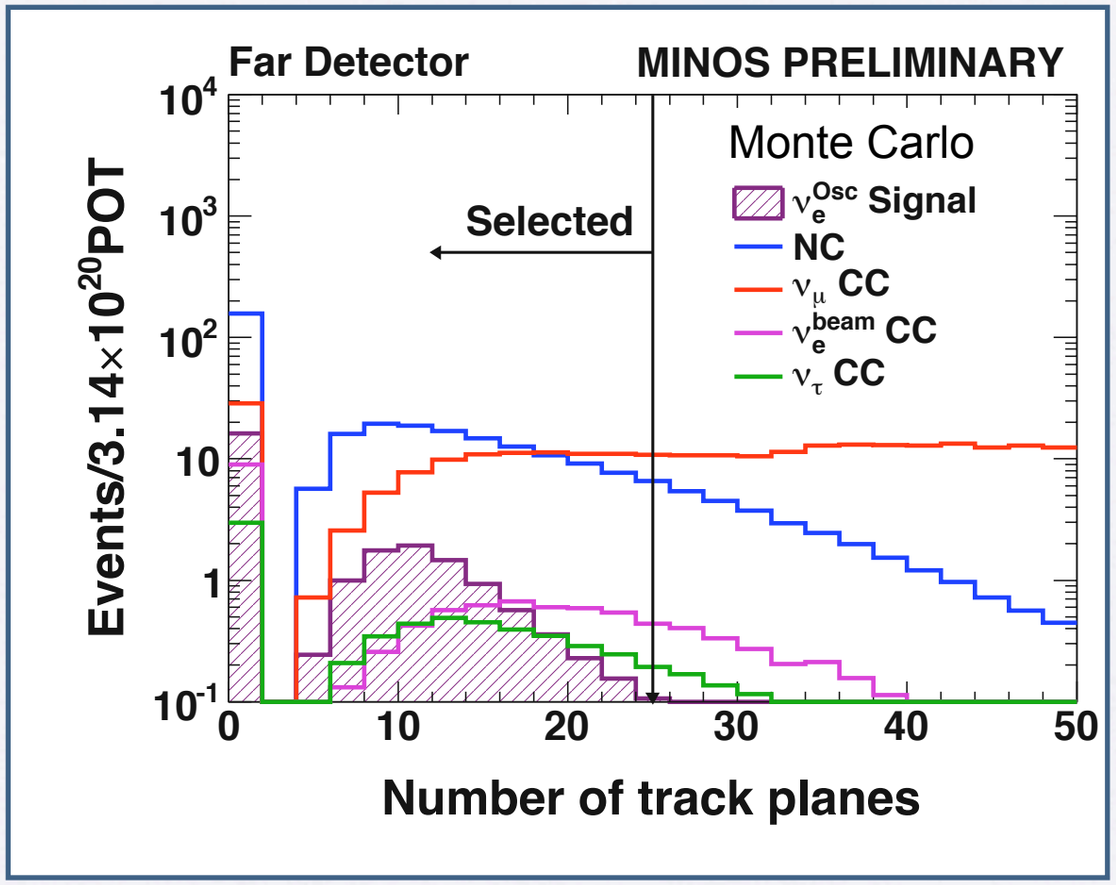
Selecting ν_e events

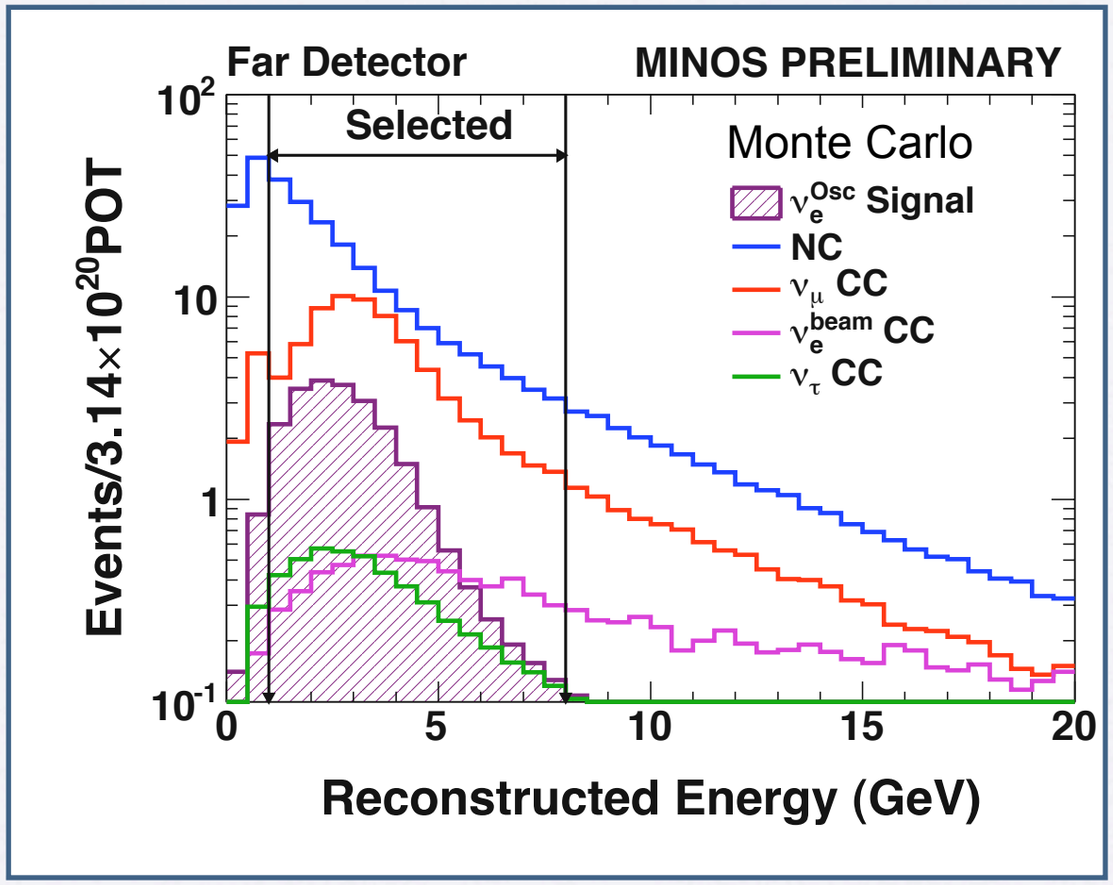
- **Basic cuts** to ensure data quality:
  - Beam quality and detector quality cuts.
  - Fiducial volume cuts:
    - Near Detector:
      1m < z < 5m , r < 0.8m
    - Far Detector:
      0.5 m < z < 14.3 or 16.3m < z < 28m,
      0.5m < r < 3.7m



  - Cosmic rejection cuts based on steepness.
- **ν_e preselection cuts** to reduce background.
- **ν_e selection cuts** based on shower topology.

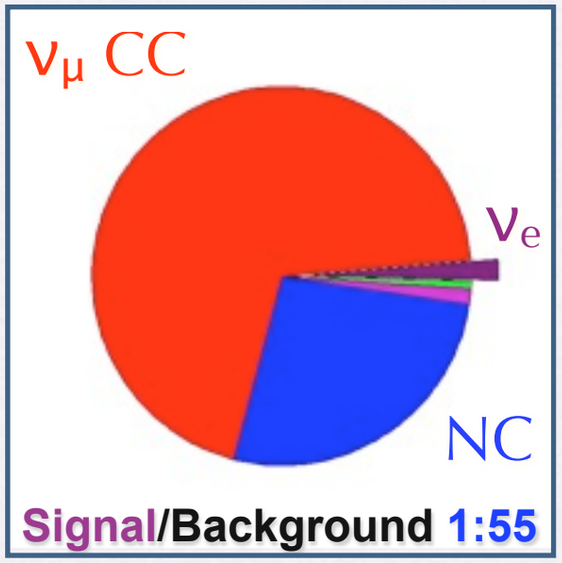
ν_e Preselection cuts



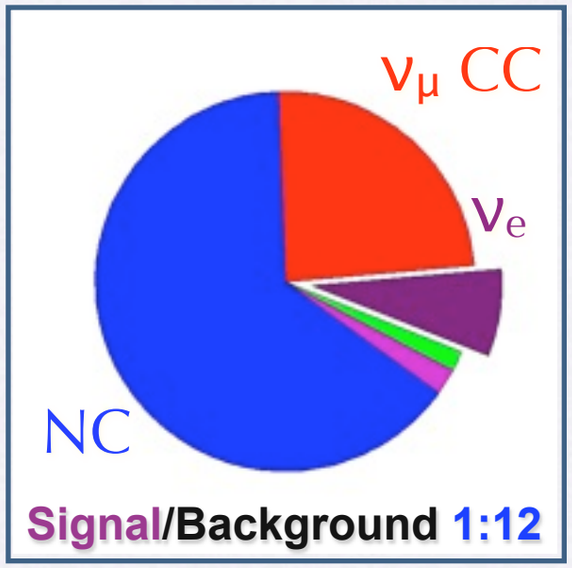


signal at CHOOZ limit

- Preselection requirements:
  - Track length < 25 planes.
  - Track like length < 16 planes.
  - Reconstructed energy 1-8 GeV.
  - At least one shower and 4 contiguous planes with > 0.5 MIP energy units.



Before

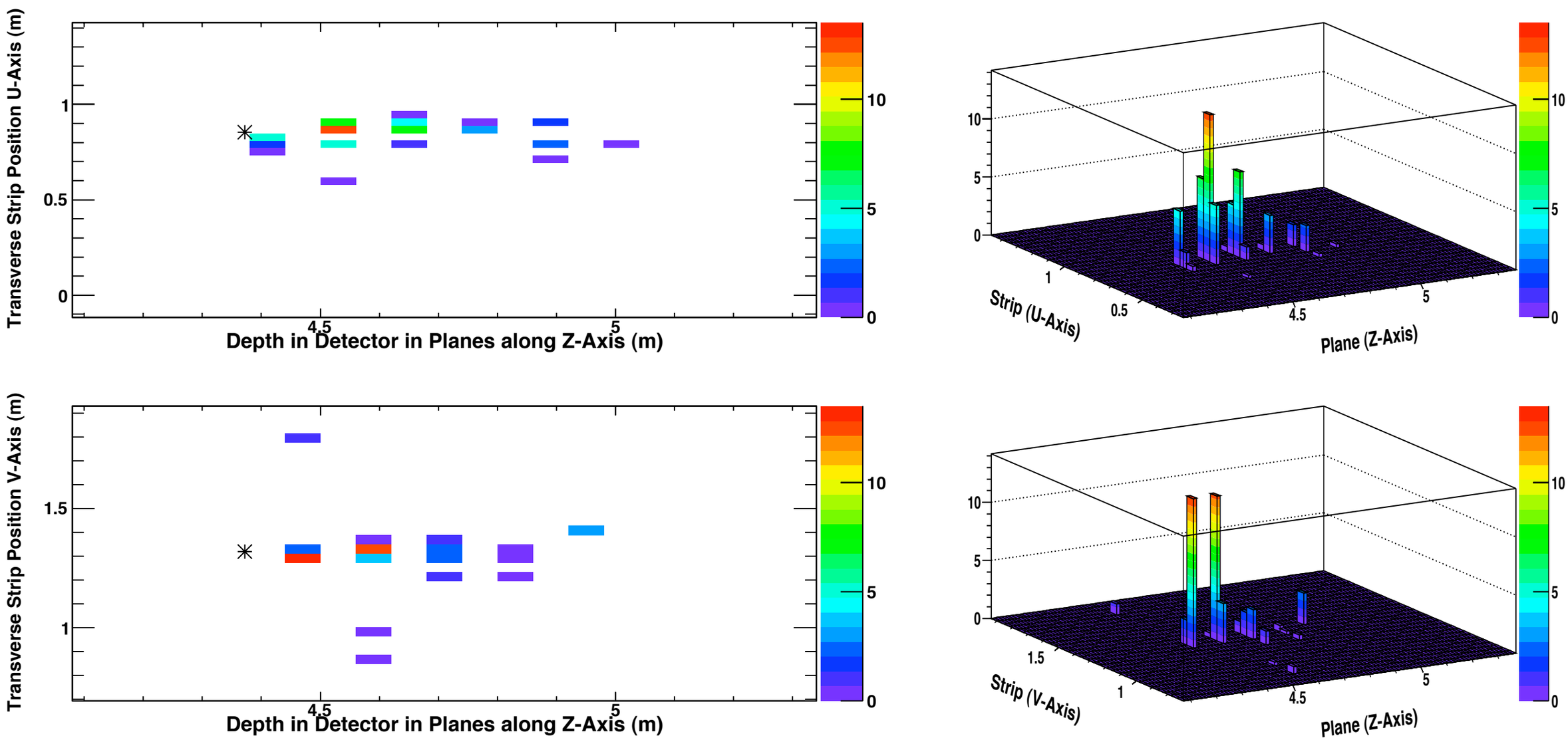


After

Candidate ν_e in the FD data

- Typical EM shower characteristics:
  - steel thickness: 2.54cm ~$1.44X_0$
  - strip width: 4.12cm (Moliere rad ~3.7cm)

Run: 32687 Snarl: 90343
Reco Energy: 4.6 GeV

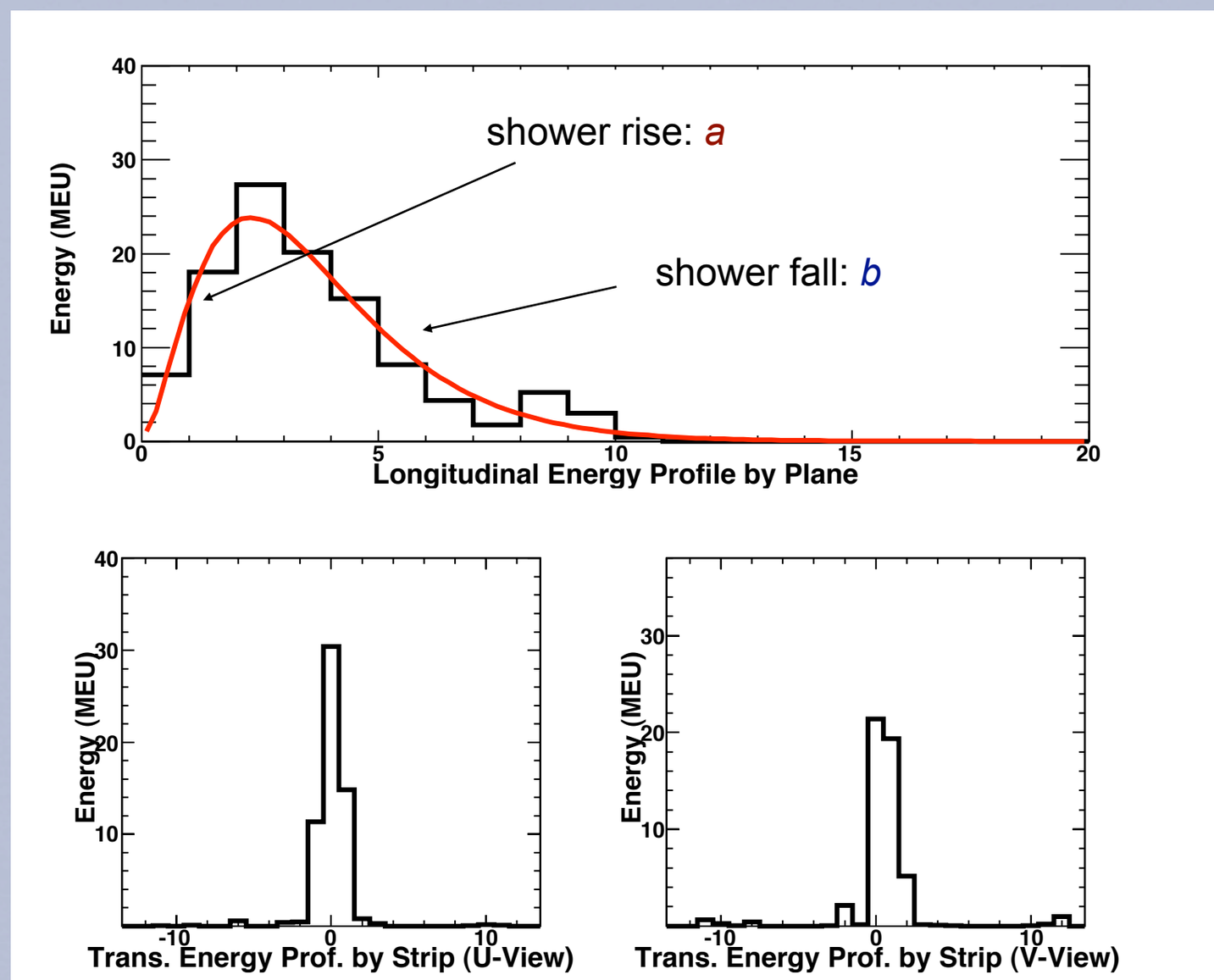


Event Characterization

Input to Artificial Neural Network (ANN)

Candidates must contain a compact shower and exhibit characteristic EM profile.

Run: 32687 Snarl: 90343
Reco Energy: 4.6 GeV



longitudinal:

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- fraction of energy deposited within 2,4,6 planes
- longitudinal energy projection

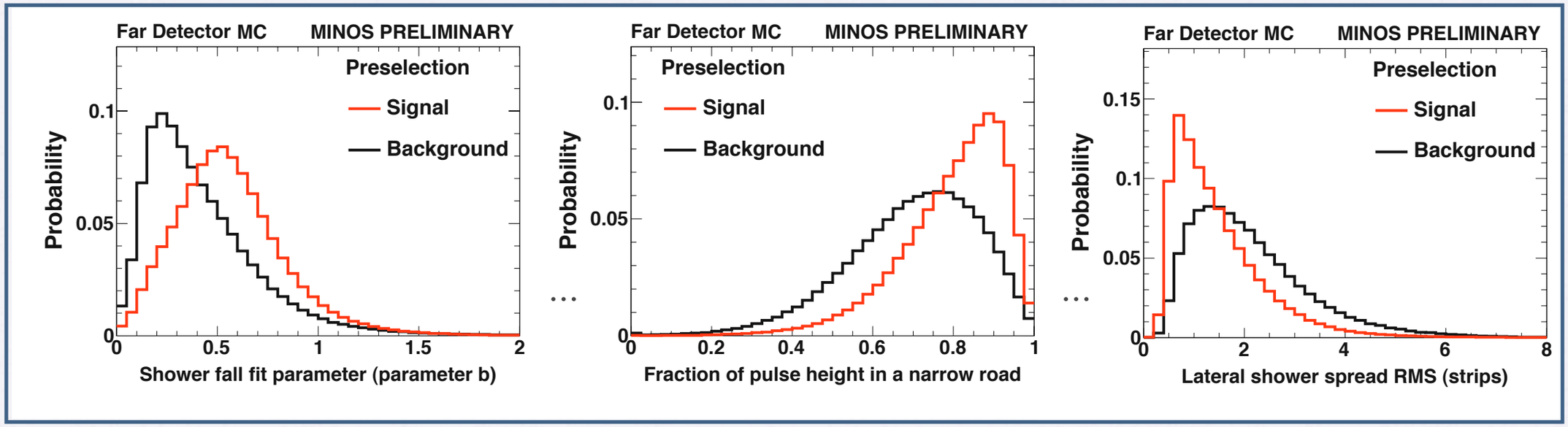
transverse:

- 90% containment radius
- lateral shower spread (RMS)
- fraction of energy deposited within 3 strips along shower axis

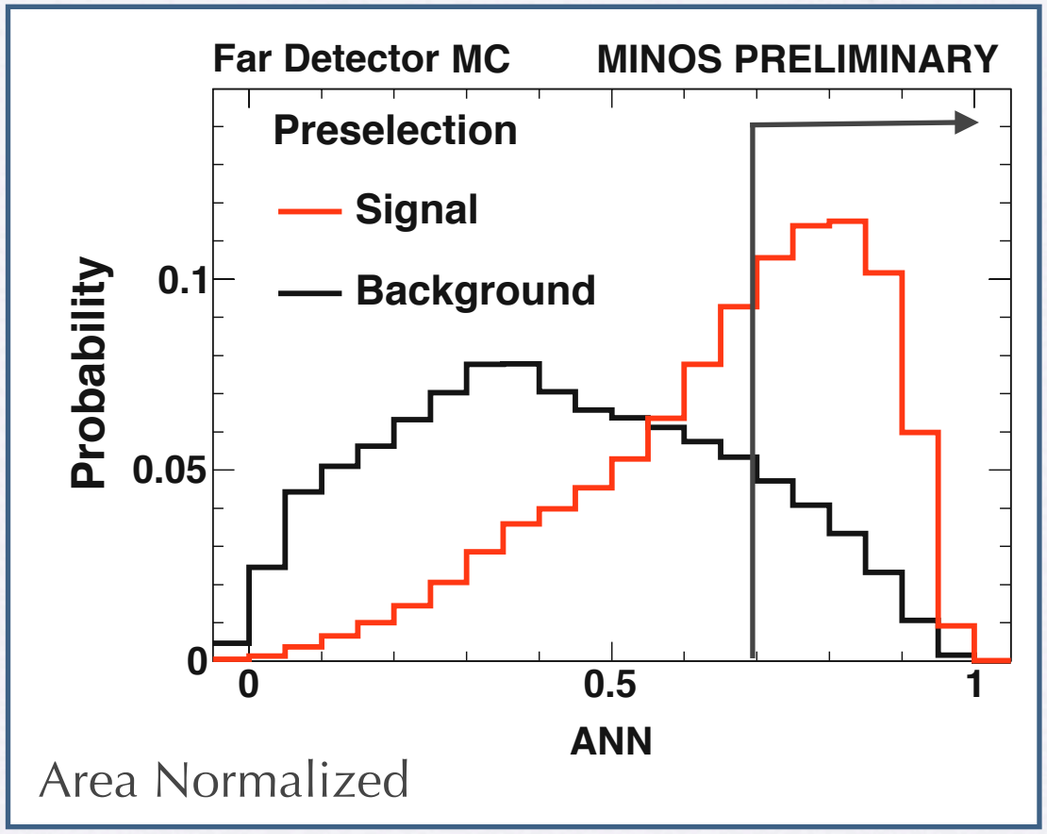
Selecting ν_e events with ANN

event characterization in length, width and shower shape

Examples



- 11 variables chosen describing length, width and shower shape.
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - CC rejection >99.4%
  - signal/background 1:4



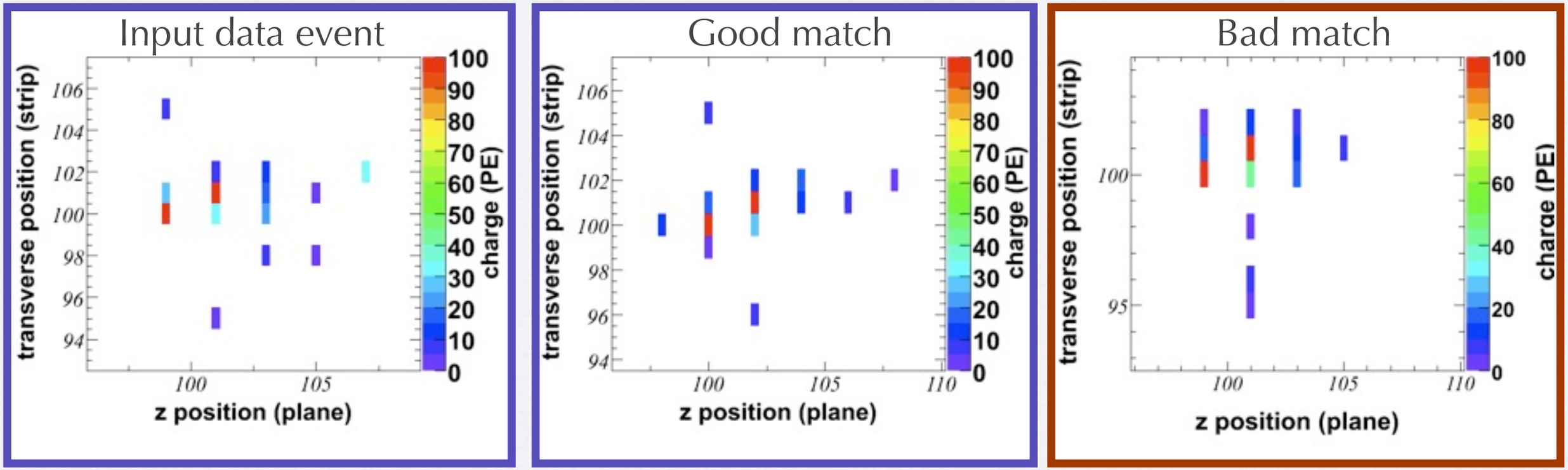
$\Delta m^2_{32}=0.0024\ eV^2$, $\sin^2\theta_{23}=1.0$

Primary selection method

Alternative selection algorithm

Library Event Matching (LEM)

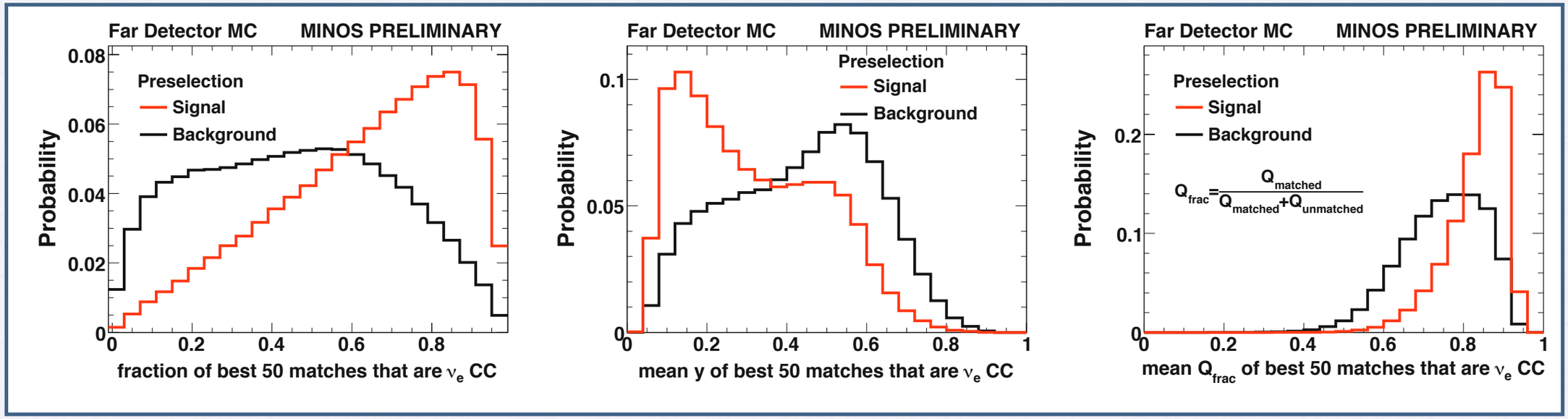
What is the likelihood that two events come from the same hit pattern at the photomultiplier level?



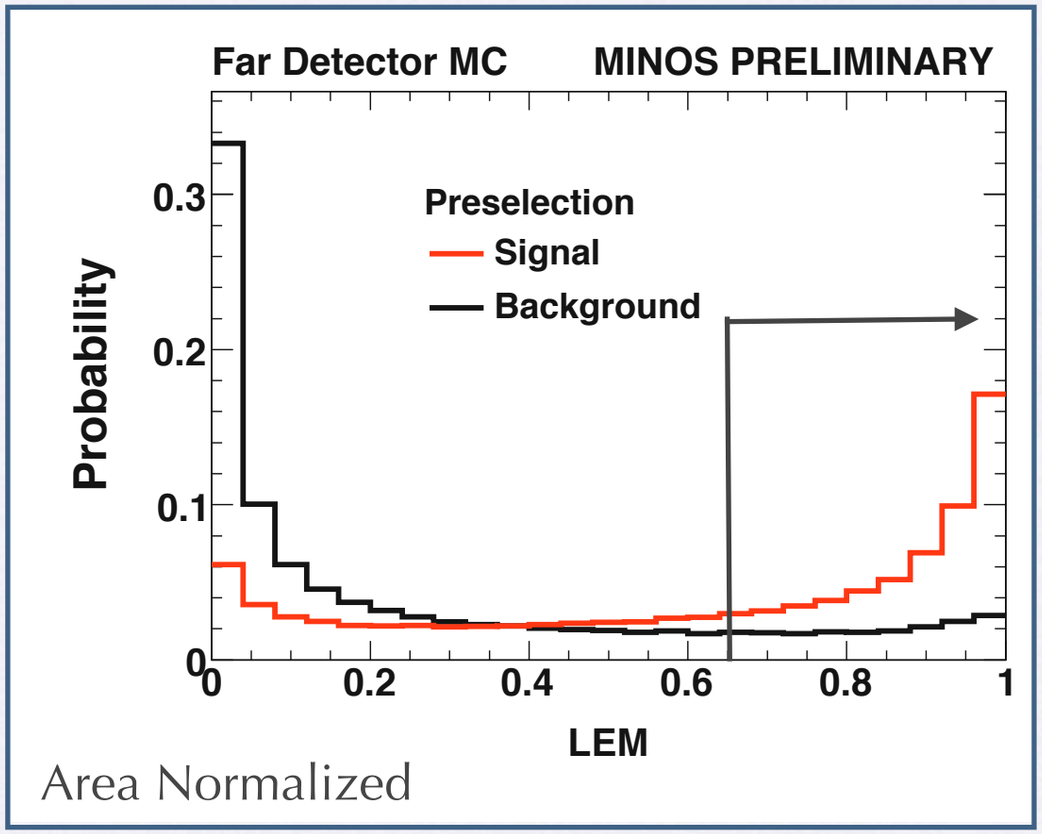
- Compare each input event to large library of MC ν_e CC and NC events.
- Select 50 best matches according to the likelihood that two events have the same hit pattern in position and energy deposition.
- Construct discriminant variables from the properties of the 50 best matches, eg. fraction of the 50 best matches that are ν_e CC.

Selecting ν_e events with LEM

fraction of electron neutrino events in 50 best matches



- 3 variables combined in a likelihood as a function of energy.
- LEM algorithm has better signal efficiency and background rejection.
- Sidebands may indicate an unexplained Far/Near difference to which this method would be more sensitive.



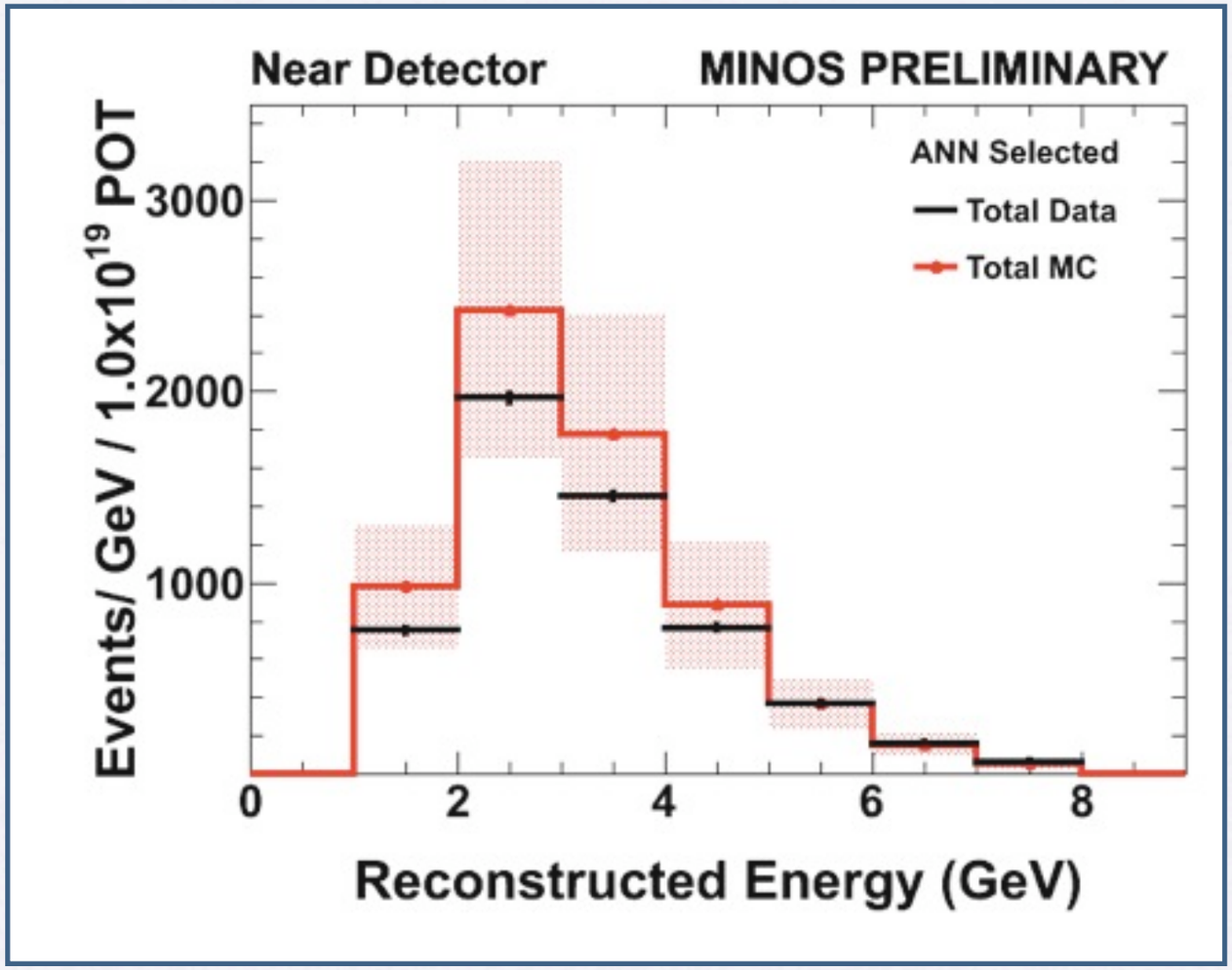
$\Delta m^2_{32}=0.0024\ eV^2$, $\sin^2\theta_{23}=1.0$

Secondary selection method

Determining the background for the ν_e selection

ν_e selected Near Detector data

- MC tuned to external bubble chamber data for hadronization models.
  - External data sparse in our kinematic range.
  - Strong background rejection leaves just tails of distributions.
- It is not surprising that the data/MC shows disagreement with the model.
- Discrepancy is within the large uncertainties of the model.
- We have developed **two data-driven methods** to correct the model to match the data.

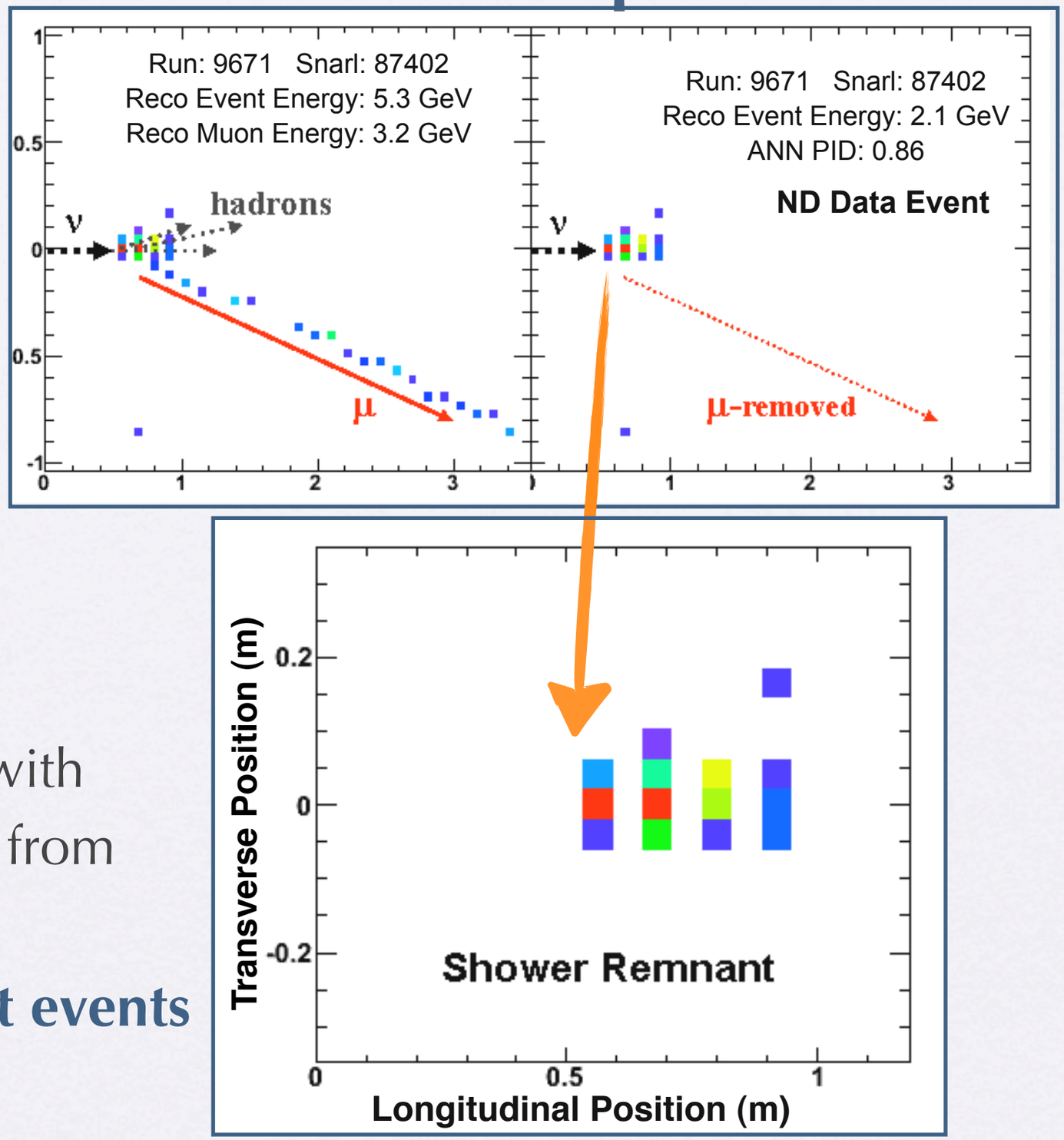


- The MRCC method uses muon removed ν_μ CC to study the hadronic showers and correct MC.
- The **Horn on/off method** uses the difference in background composition of the two horn configurations.

Studying hadronic showers using muon removal technique

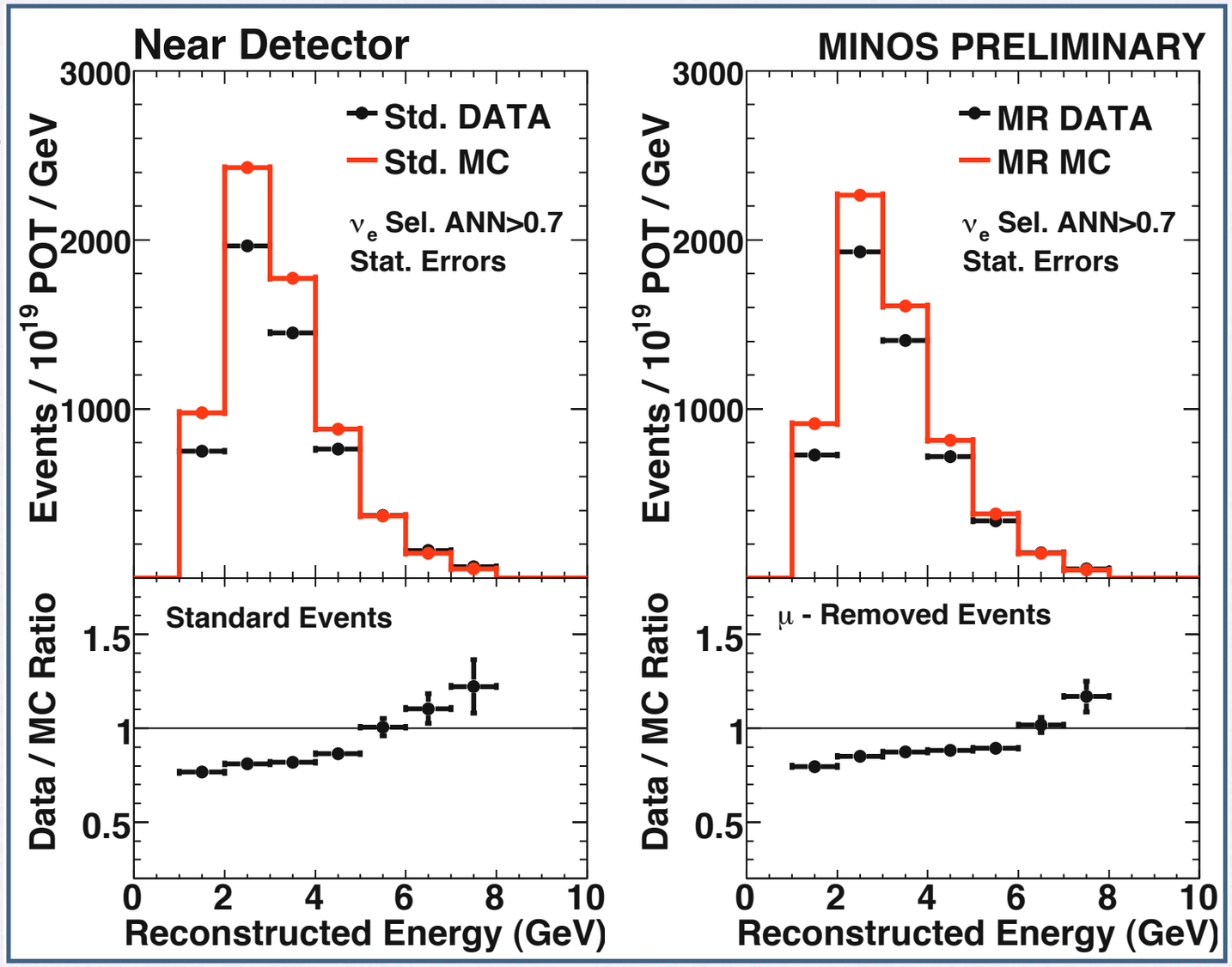
- Remove the muon track in a selected ν_μ CC event and use the rest as a hadronic shower only event.
- We use events that pass our ν_μ Charged Current event selection, i.e. that have a well defined track.
- Well understood ν_μ CC spectra, with well known efficiency and purity from the ν_μ disappearance analysis.

Muon Removed Charged Current events ⇒ MRCC events



Hadronic shower modeling in the ν_e selected data and muon-removed data

- We apply the ν_e selection to the standard data and MC as well as to the Muon Removed data and MC.
- Discrepancy with the model shows the same trend not only in energy but in shower topology for both sets.
- Thus modeling of the hadronic shower is a major contribution to the disagreement.
- As the MRCC sample is independent, we can use it to obtain a **data-driven correction** to the model.



Overall disagreement:
- 16.6% data/MC
- 13.8% MR data/MC

Hadronic shower modeling in the ν_e selected data and muon-removed data

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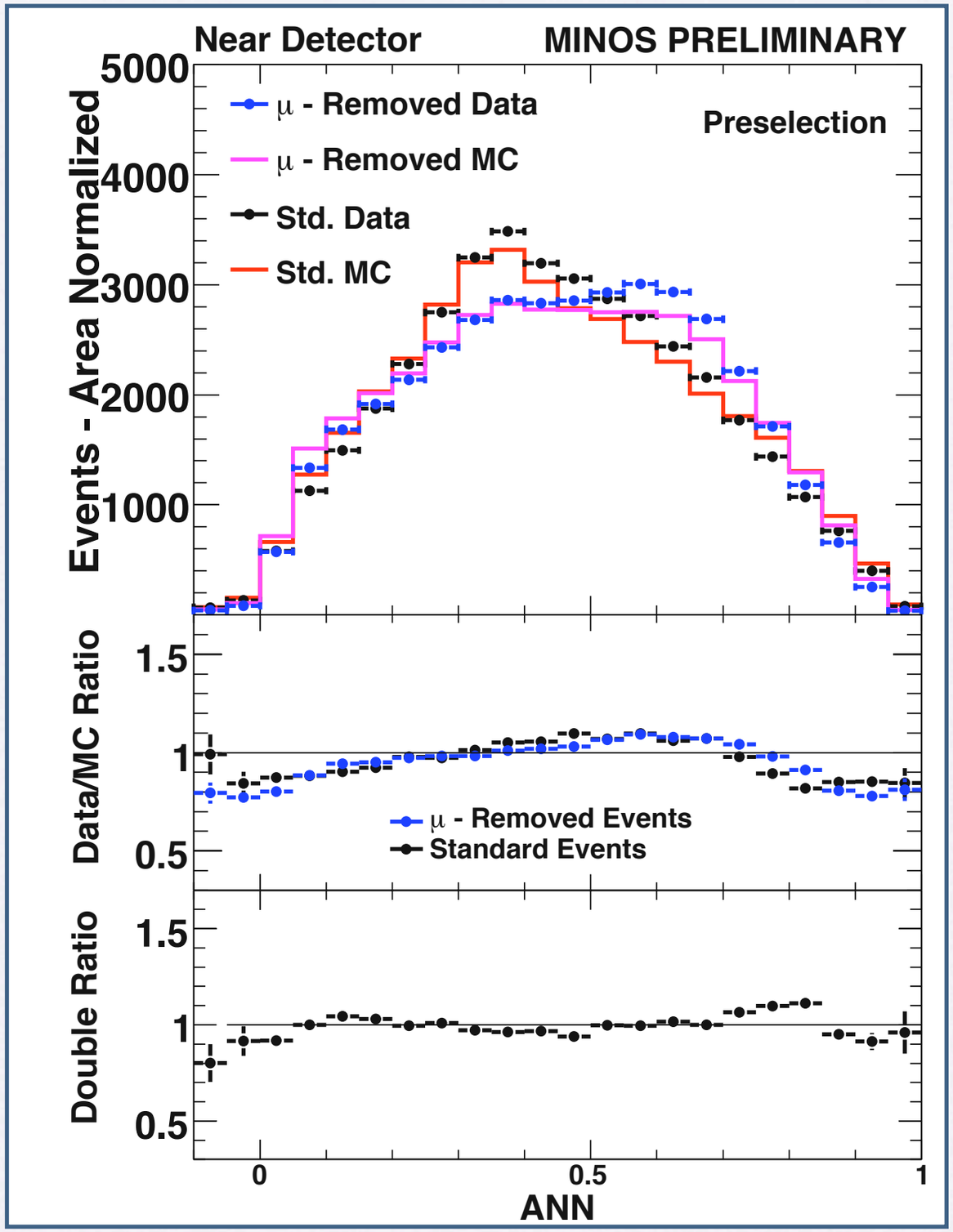
- Discrepancy with the model shows the same trend not only in energy but in shower topology for both sets.
- Thus modeling of the hadronic shower is a major contribution to the disagreement.
- As the MRCC sample is independent, we can use it to obtain a **data-driven correction** to the model.

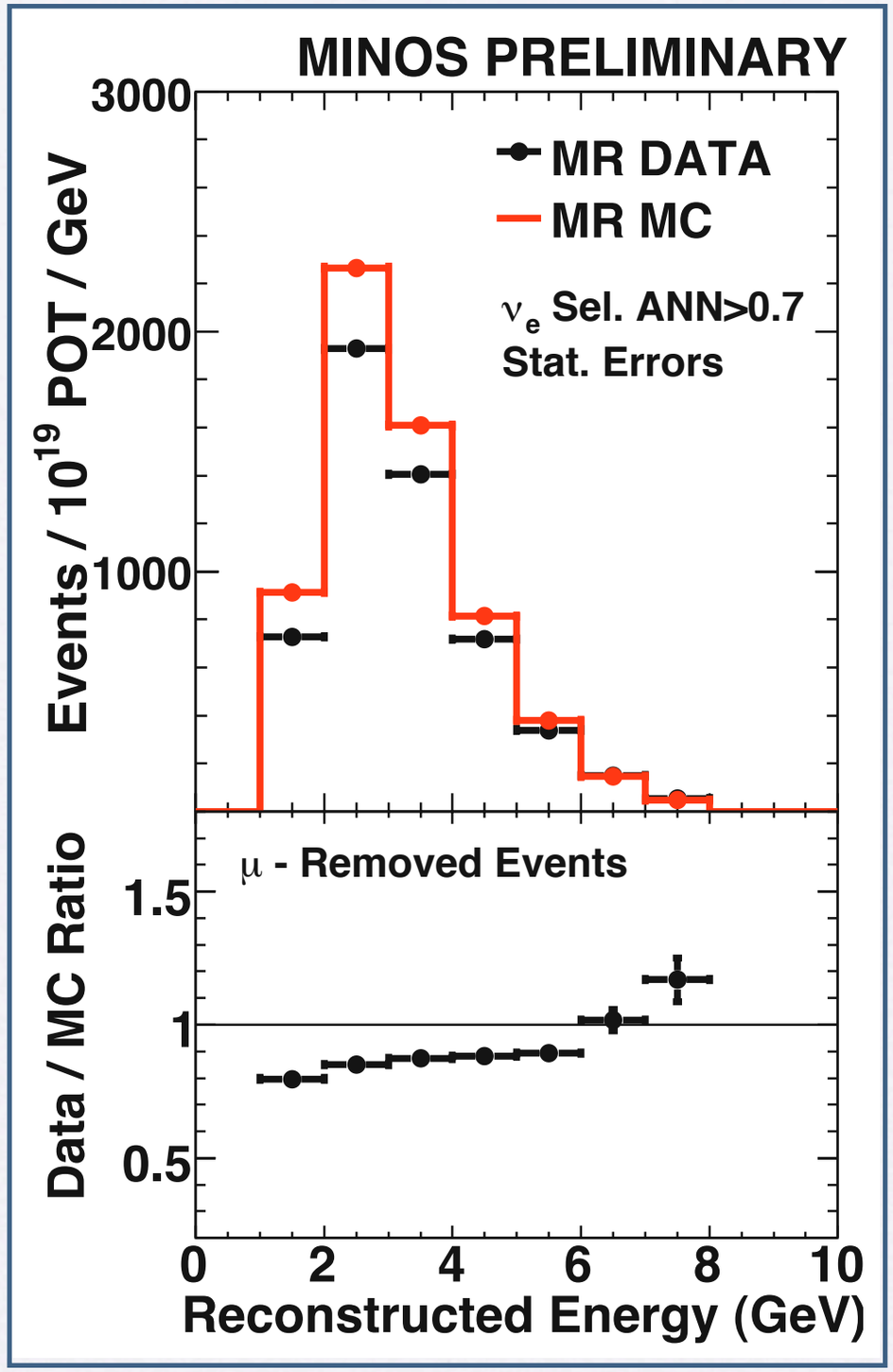


Using MRCC as a data-driven correction

- We use the data/MC ratio from MRCC to obtain a **data-driven correction** that is applied to the standard NC events as a function of energy.

$$NC_i^{corr} = \frac{MRCC_i^{data}}{MRCC_i^{MC}} \times NC_i^{MC}$$

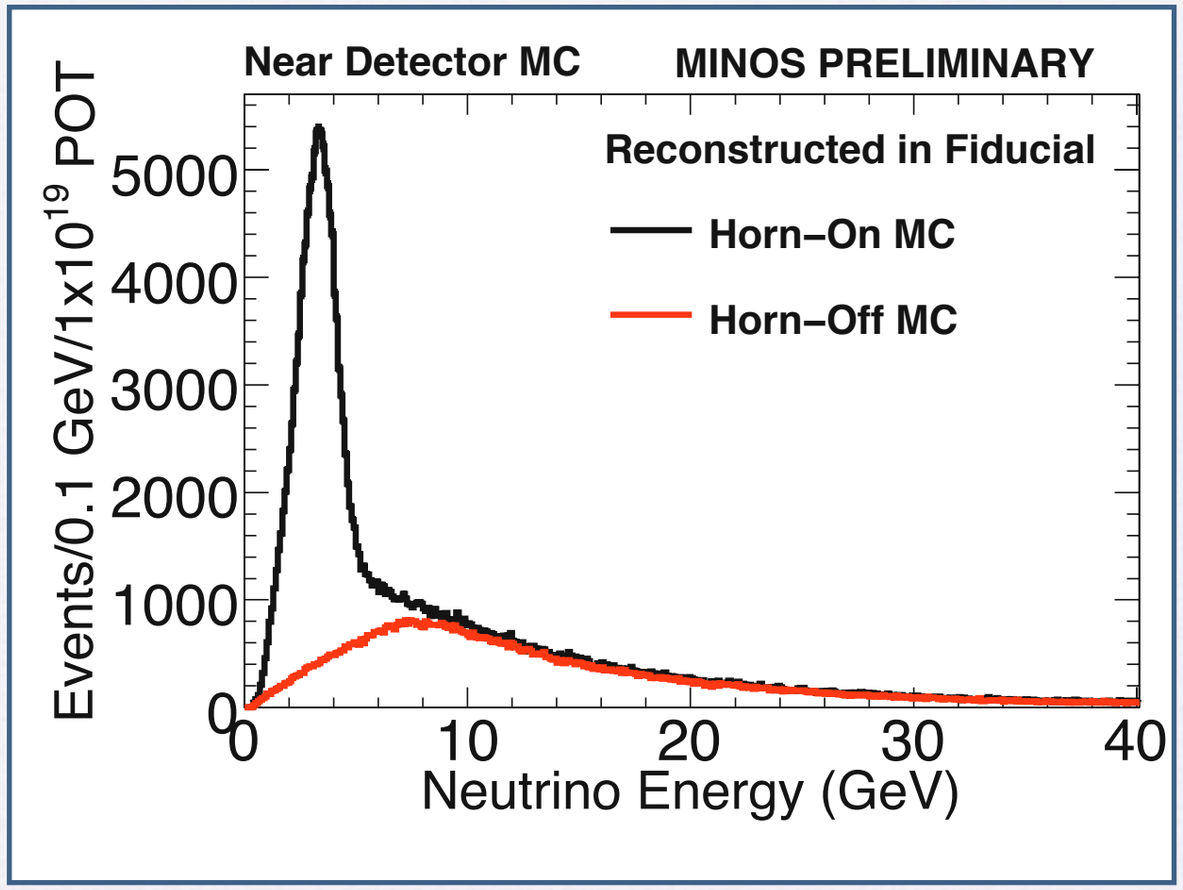
- The number of ν_μ CC events is taken from the number of events in the data minus the corrected NC and beam ν_e events.
- Differences between NC and MRCC showers introduces a systematic error that is difficult to quantify.



Secondary separation method

Estimating the background using horn on and horn off data

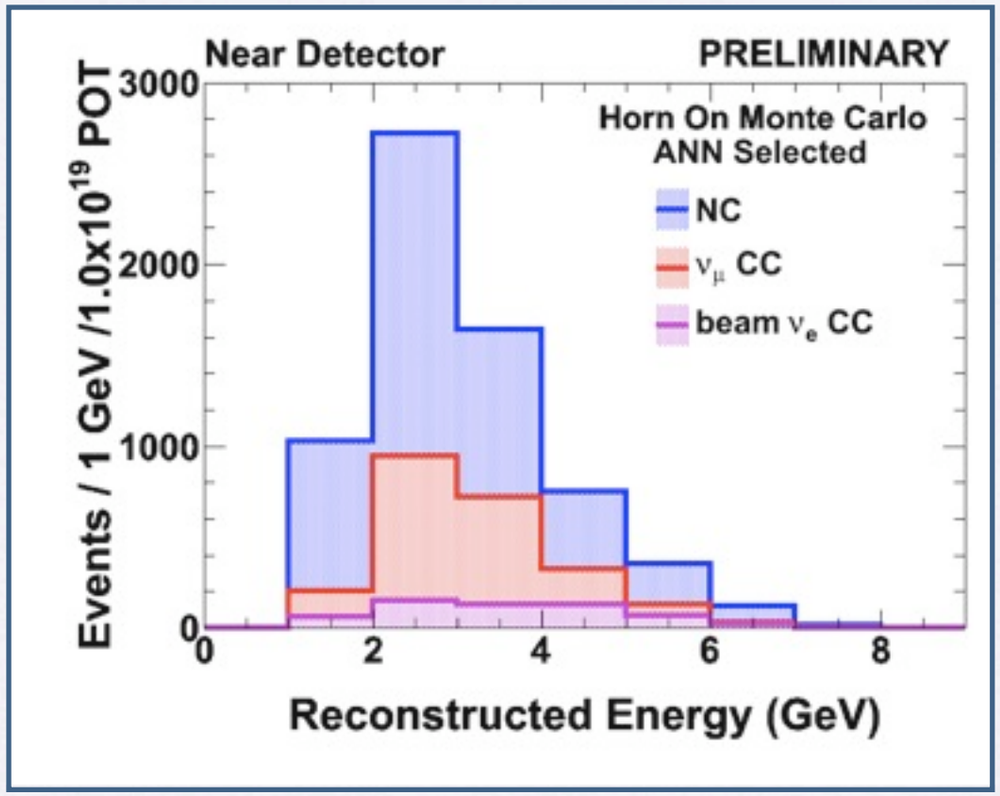
- When beam horns are turned off, the parent pions do not get focused, resulting in the disappearance of the low energy peak in the neutrino energy spectrum.

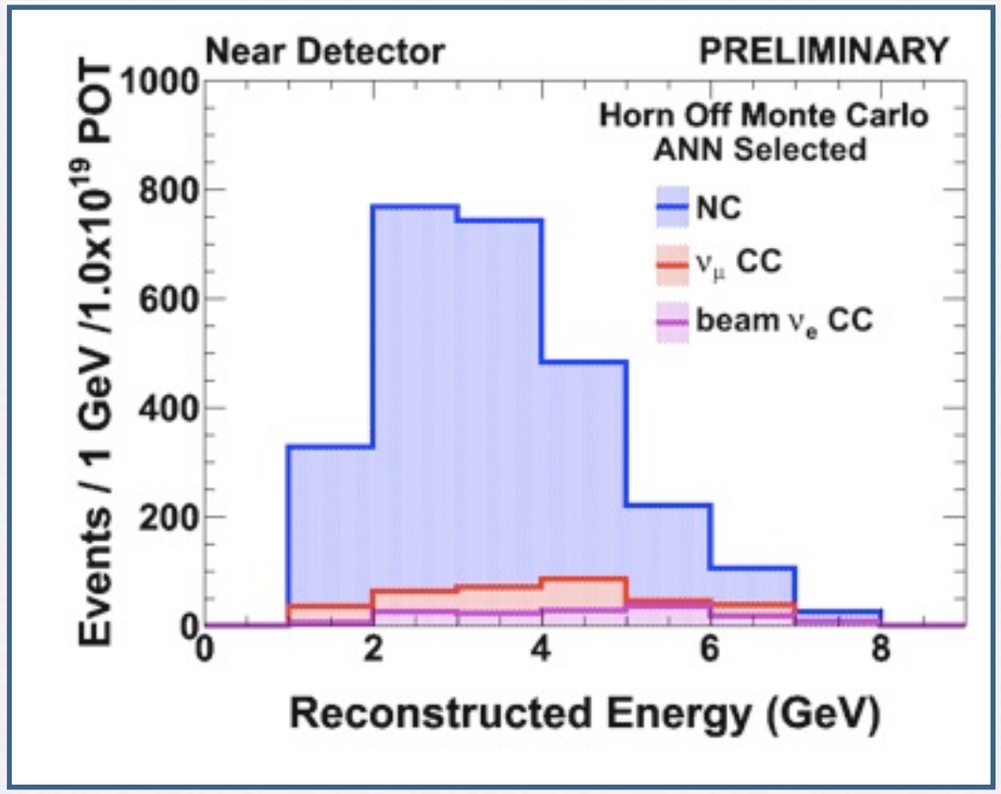


- The consequence is a spectrum dominated by NC arising from the long tail in true neutrino energy that gets measured in our region of interest in visible energy.

Estimating the background using horn on and horn off data

- After applying the ν_e selection cuts to the ND data, the composition of the selected events is thus very different with the NuMI horns on or off.





- Using the horn off spectrum which is dominated by NC, we can measure that component with better precision than in the horn on beam.

Estimating the background using horn on and horn off data

- The **beam ν_e flux** is obtained from the ν_μ CC flux which is constrained by data in the different beam configurations.
- The two main background components can be estimated using the number of data events in the horn on and horn off configurations: $\mathbf{N^{on}}$ and $\mathbf{N^{off}}$.

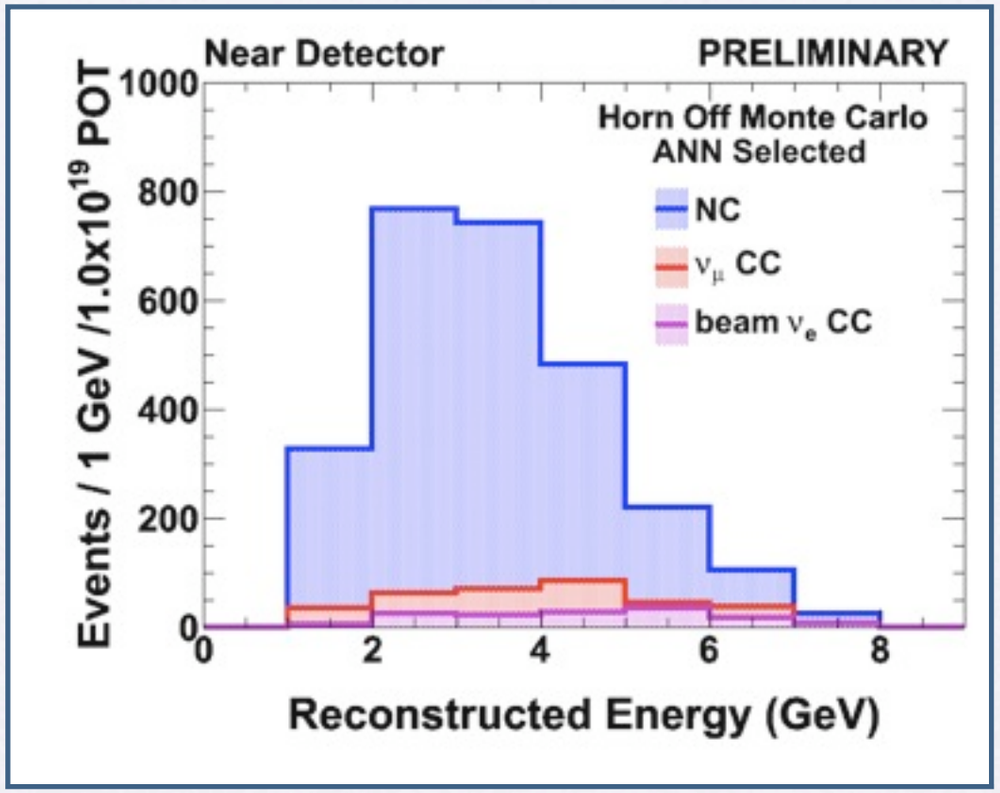
$$\mathbf{N^{on}} = N_{NC} + N_{CC} + N_e \qquad (1)$$

$$\mathbf{N^{off}} = r_{NC}*N_{NC} + r_{CC}*N_{CC} + r_e*N_e \qquad (2)$$

from MC:

$$r_{NC(CC,e)} = N_{NC(CC,e)}^{off}/N_{NC(CC,e)}$$

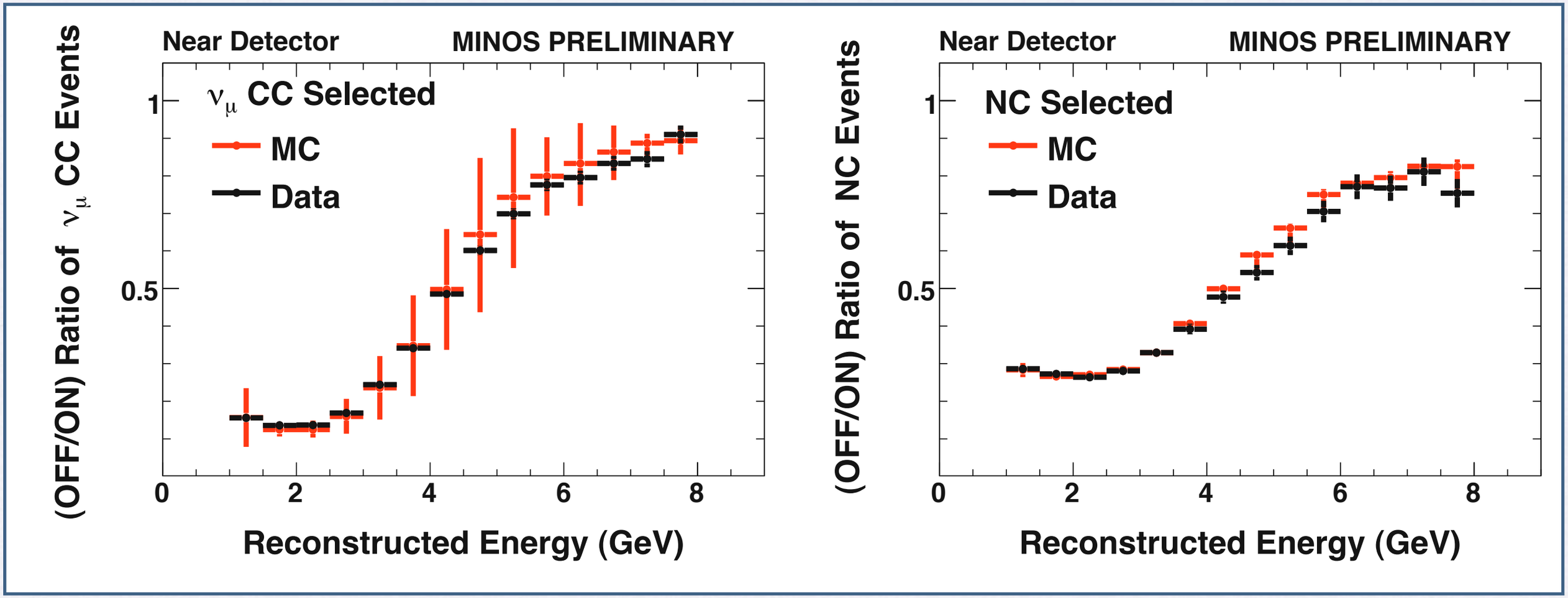
The key is to use the **Horn off/on ratios** for each component to solve.



- Producing **data-driven predictions** for NC and ν_μ CC background for the horn on configuration.

Estimating the background using horn on and horn off data

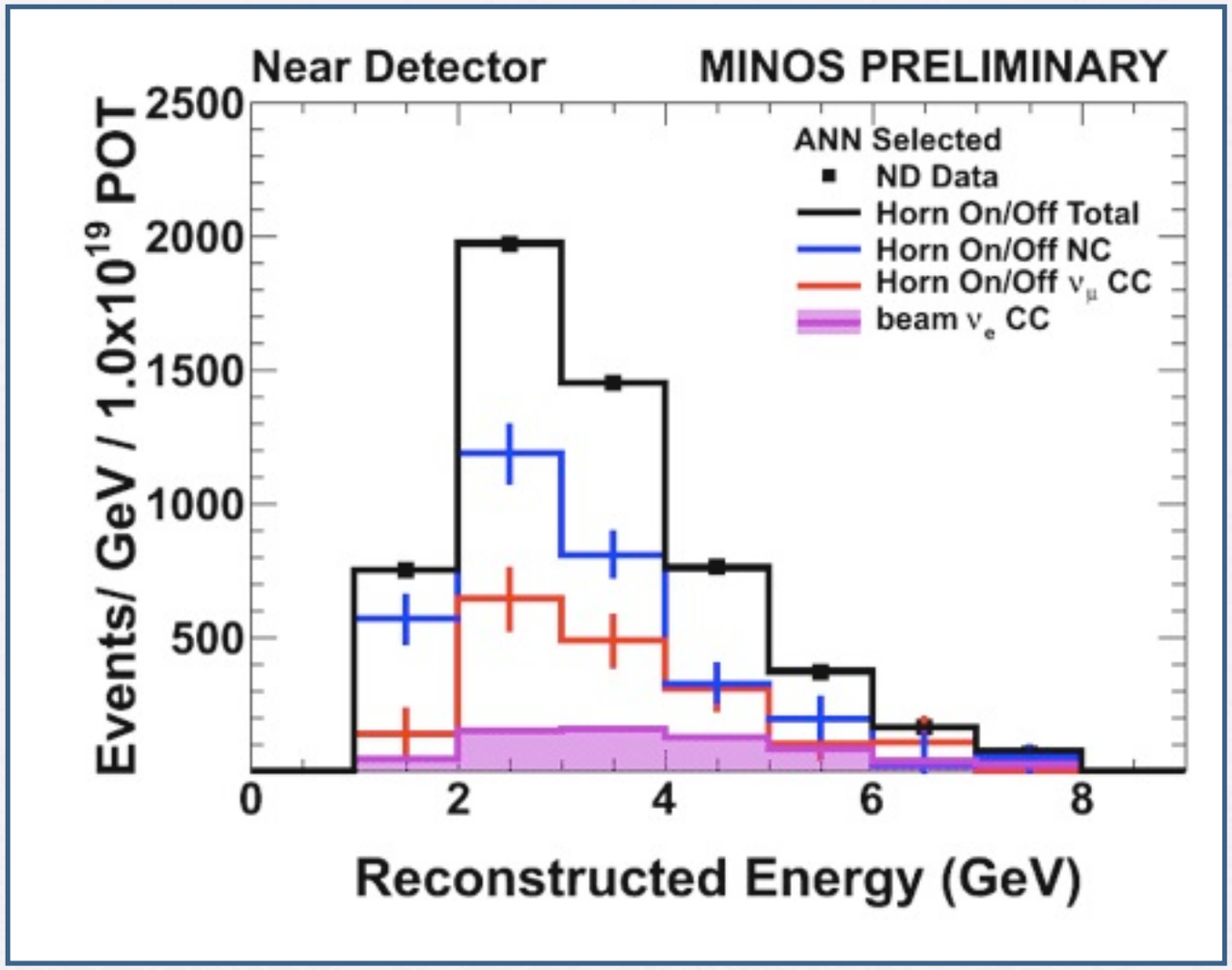
- Horn off/on ratios for ν_μ CC and NC selected events match well between data and MC after fiducial volume cuts.
- Similar ratios are used to solve the horn on/off equations.



MC error statistical plus systematic.

ND data-driven background

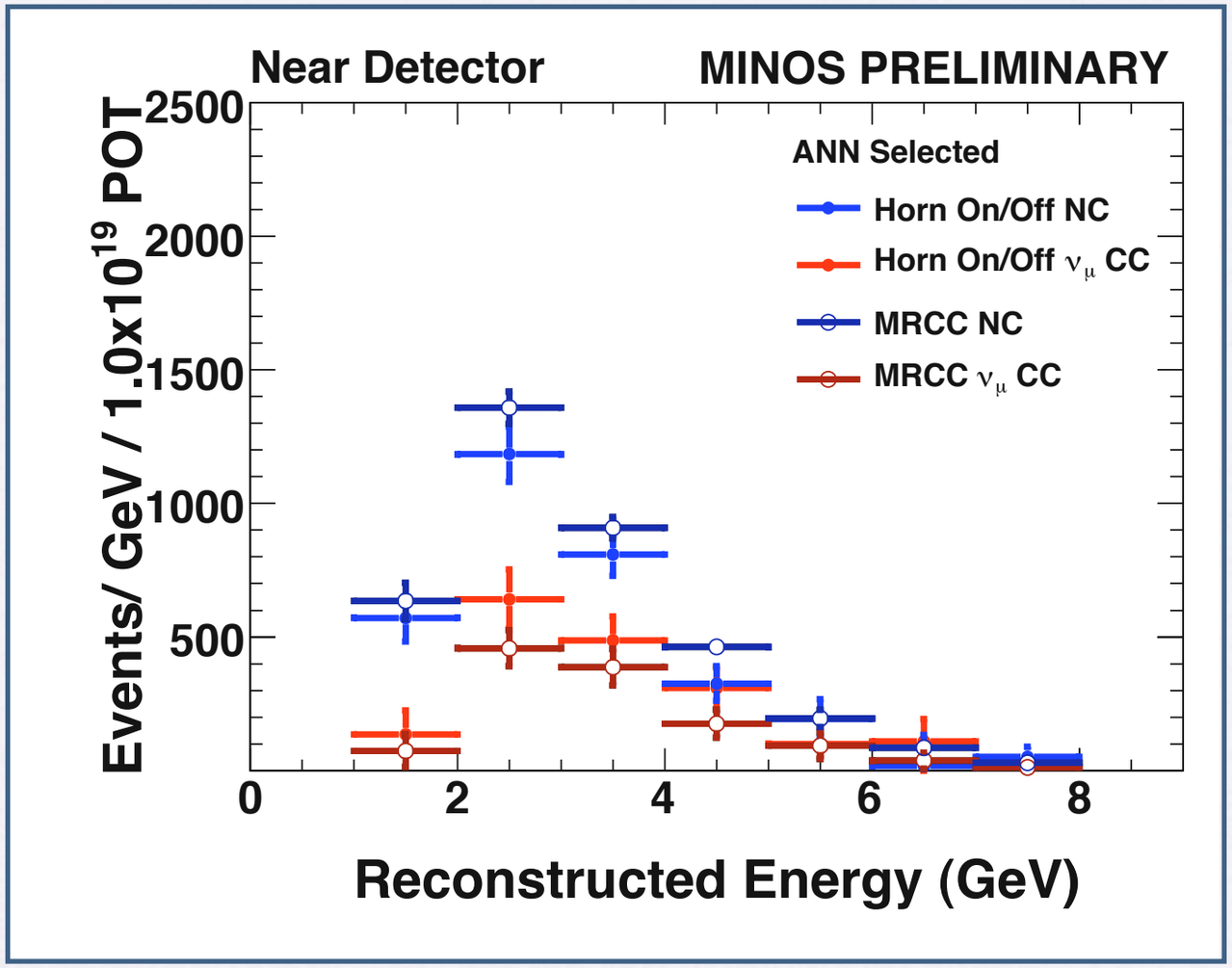
Results from the Horn on/off method



- The NC and ν_μ CC components for the the standard beam configuration are simultaneously solved in the horn on/off method and are by definition equal to the data after beam ν_e subtraction.

ND data-driven background

Results from the both methods

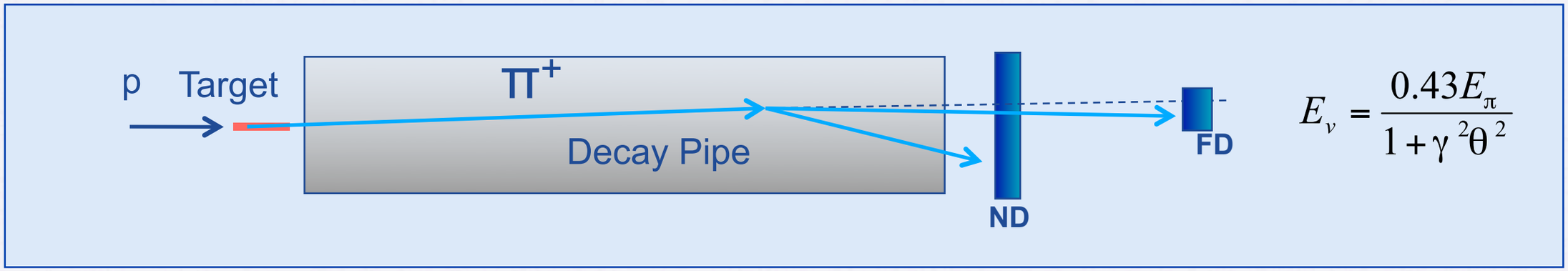


- The **two data-driven methods**, Horn on/off and MRCC, are in good agreement in the Near Detector NC and ν_μ CC background for the ν_e analysis.
- Each background is then <u>extrapolated to the Far Detector</u>.

Predicting the Far Detector background and signal

Predicting the FD background

- Use Near Detector data to predict Far Detector spectrum.
- We expect the Far Detector spectrum to be similar to $1/R^2$ scaled Near Detector spectrum, but not identical.



- Predict the event rate at each energy bin by correcting the expected Monte Carlo rate using the ratio of data to Monte Carlo in the Near Detector:

$$FD_i^{predicted} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{Data}$$

- The Monte Carlo provides necessary corrections due to energy smearing and acceptance.

Other Far/Near differences

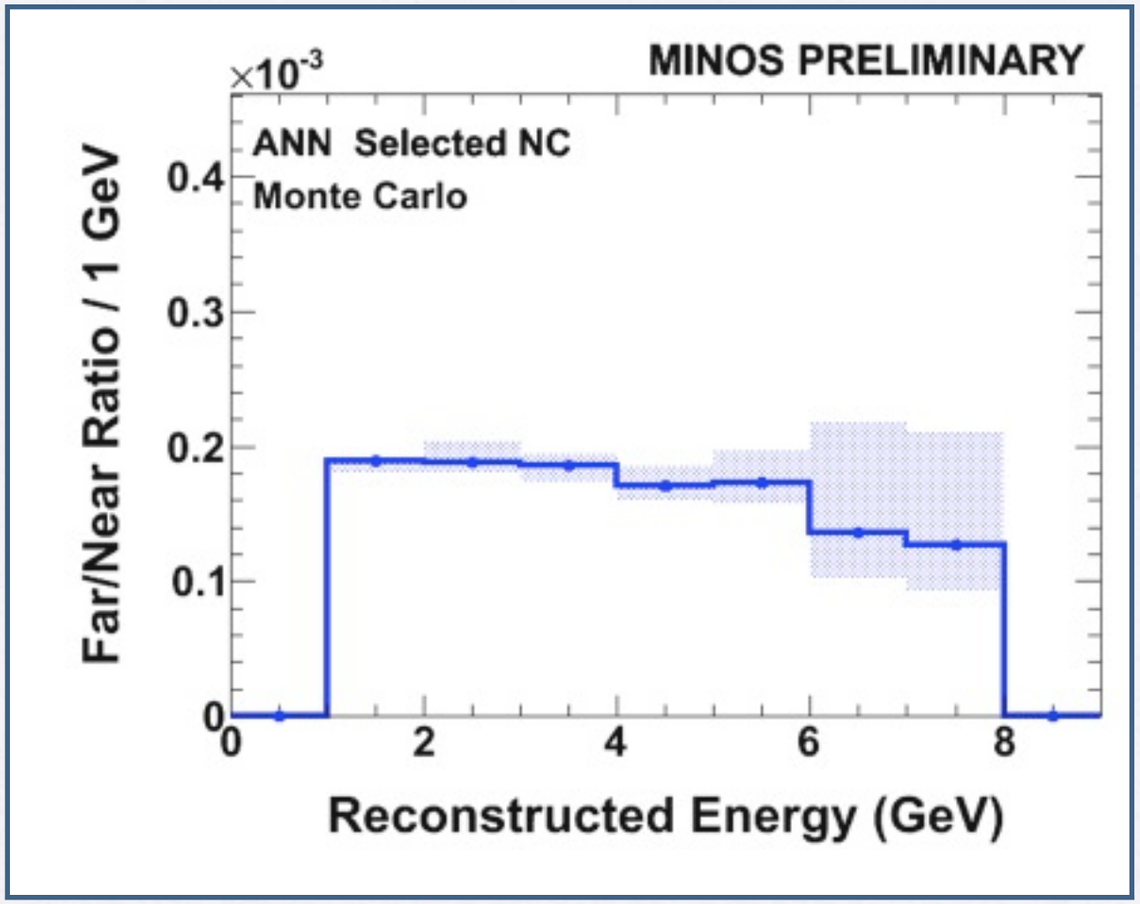
MINOS detectors are very similar, however there are small differences:

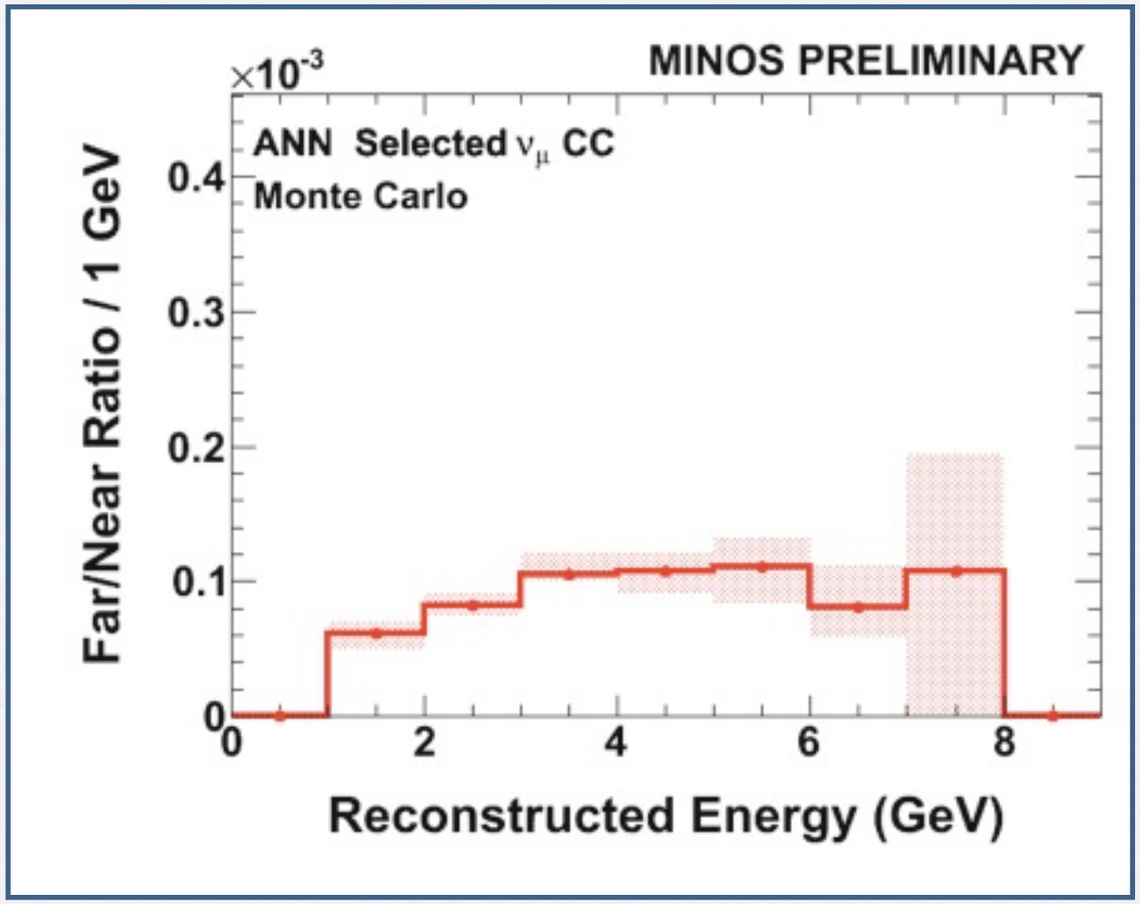
- Far/Near spectrum different due to **beamline geometry and oscillations** in the Far.
- **Readout patterns:**
  - Light level differences due to differences in fiber length.
  - Multiplexing in the Far (8 fibers per PMT pixel).
  - Partial (one-sided) readout in the Near.
- **Photomultipliers (M64 in Near Detector, M16 in Far):**
  - Different gains/front end electronics.
  - Different crosstalk patterns (also related to readout patterns).
- **Neutrino intensity:**
  - higher rates in the Near Detector thus faster readout.
- **Relative energy calibration.**

These considerations **affect the Far/Near ratio** and are considered in the extrapolation uncertainties

Predicting the FD background

- The Near Detector ν_e selected **NC** and $\boldsymbol{\nu_\mu}$ **CC** background components are corrected by the Far/Near MC ratios:

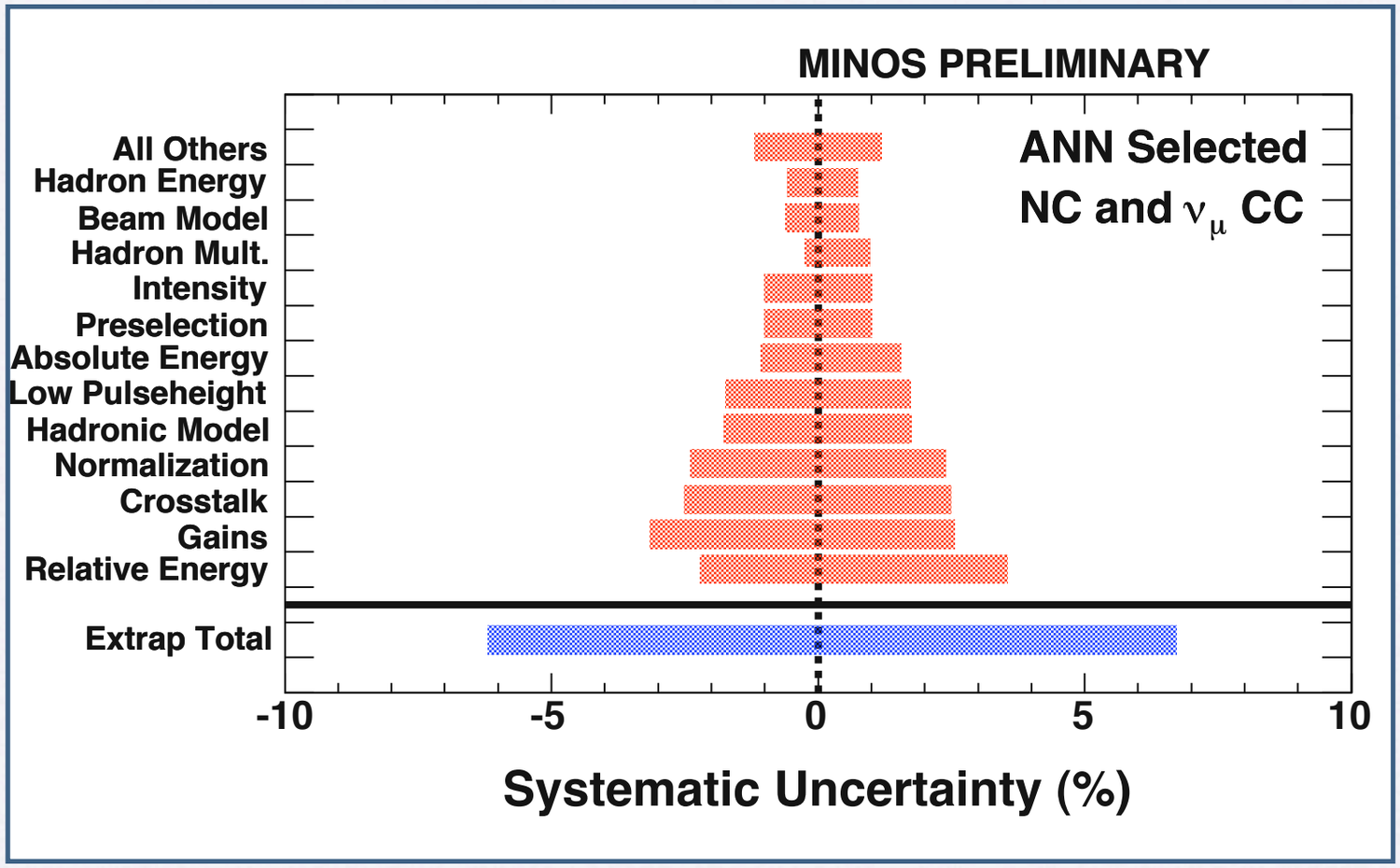




- Far/Near ratio accounts for geometry, fiducial volume ratio, intensity, other detector effects and oscillations.
- The **signal** $\boldsymbol{\nu_e}$ and the $\boldsymbol{\nu_\tau}$ **CC** from ν_μ oscillations are corrected using the extrapolation of the ν_μ CC spectrum.
- The **beam** $\boldsymbol{\nu_e}$ in the Far Detector are taken from the MC.

FD background systematic errors

Extrapolation errors



- For most systematic errors, we generated special MC with the modified parameter in Near and Far. Used this modified MC for extrapolation and calculated the difference with the standard results.
- For the main background components the larger systematics are **relative energy, gains, crosstalk and relative normalization**.

FD background systematic errors

Total errors

Preliminary Uncertainties	Horn On/Off
(1) Extrapolation	6.4%
(2) Systematic (separation method)	2.7%
(3) Statistical (separation method)	2.3%
Total (sum in quadrature)	7.3%
Statistical error (data)	**19%**

Systematic uncertainties are dominated by error in the extrapolation.
Statistical uncertainties dominate.

FD data-driven background

Data-driven Methods	Total	NC	ν_μ CC	ν_τ CC	ν_e beam
Horn on/ off	**27**	**18.2**	**5.1**	**1.1**	**2.2**
MRCC	28	21.1	3.6		

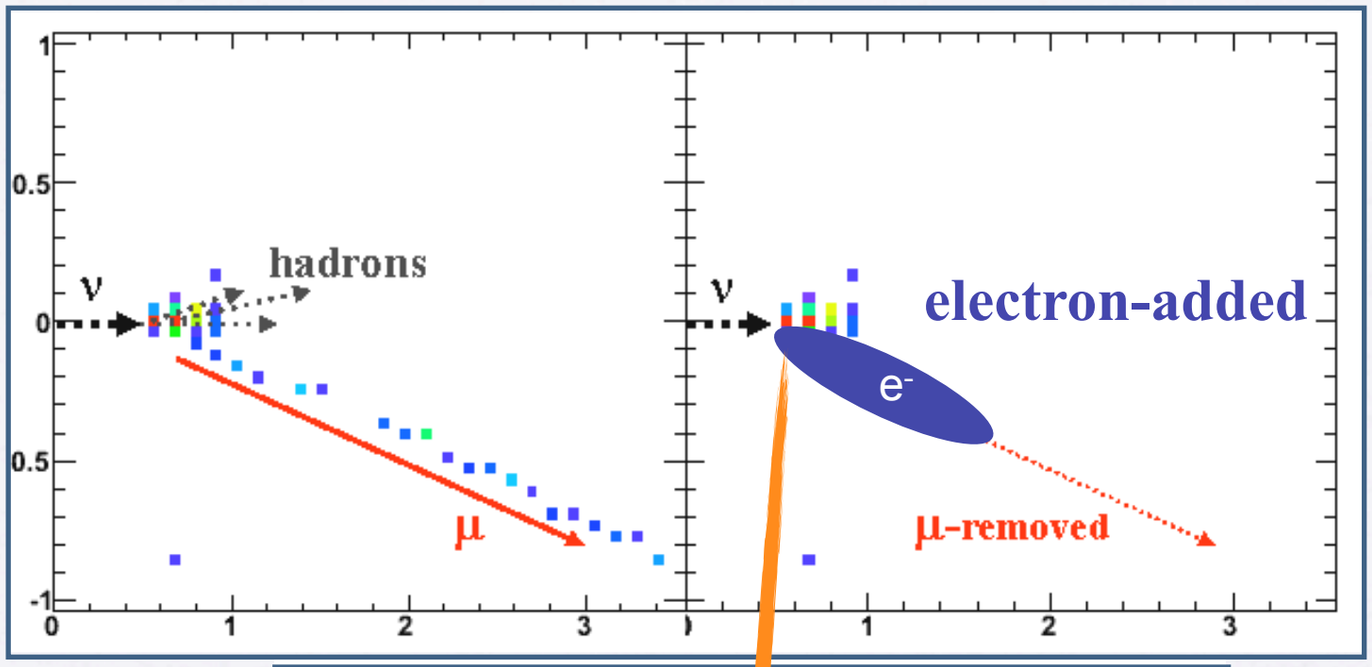
scaled to 3.14 x10^{20} POT

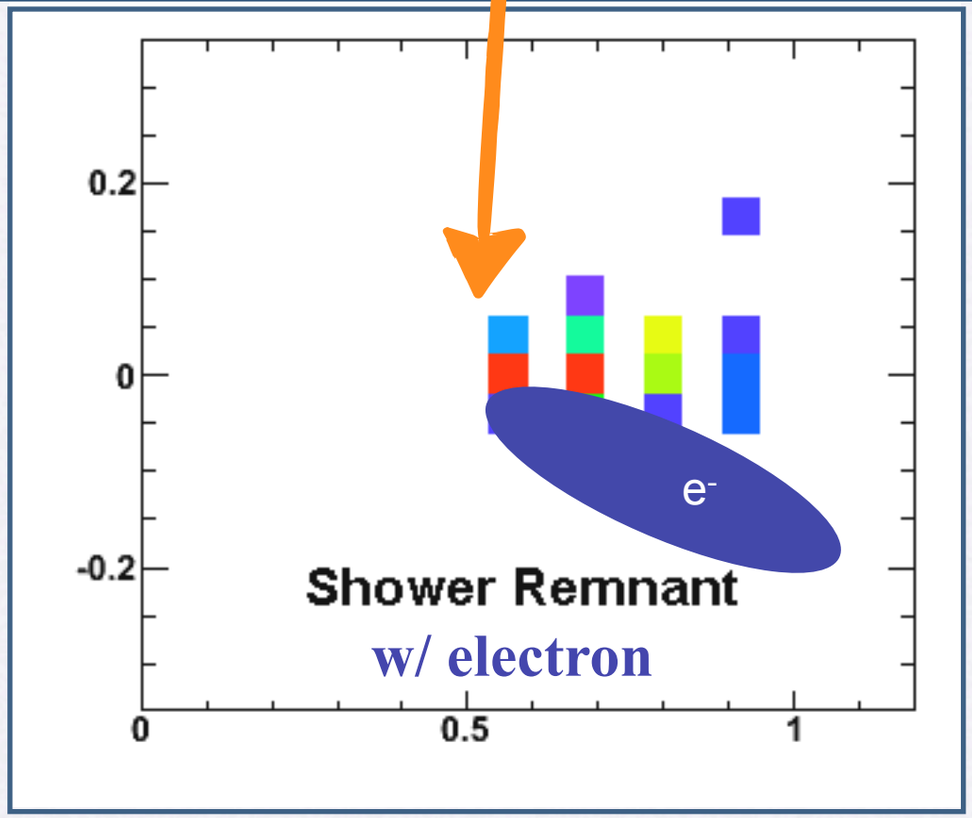
- The two data-driven methods, Horn on/off and MRCC, are in excellent agreement in the Far Detector.
- ~1 event difference is well within errors.
- The horn on/off is the primary separation method.

The background prediction at 3.14 x10^{20} POT is:
27±5(stat)±2(sys)

Estimating the signal efficiency

- After removing the muon track in selected ν_μ CC events, we replace the lepton with a MC electron.
- This simulates a DIS signal event using the hadronic shower from the data.
- Simulation of electrons benchmarked against test beam data.
  - Agreed better than 3%.



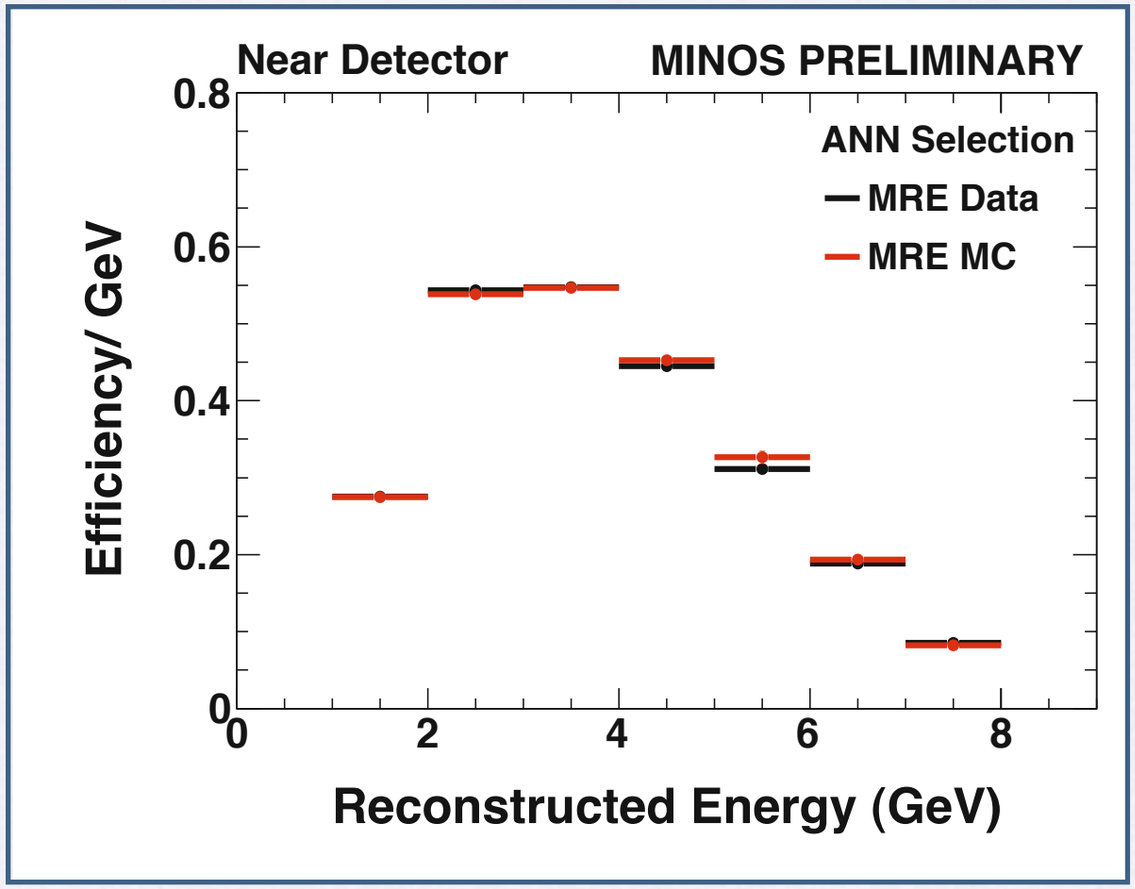


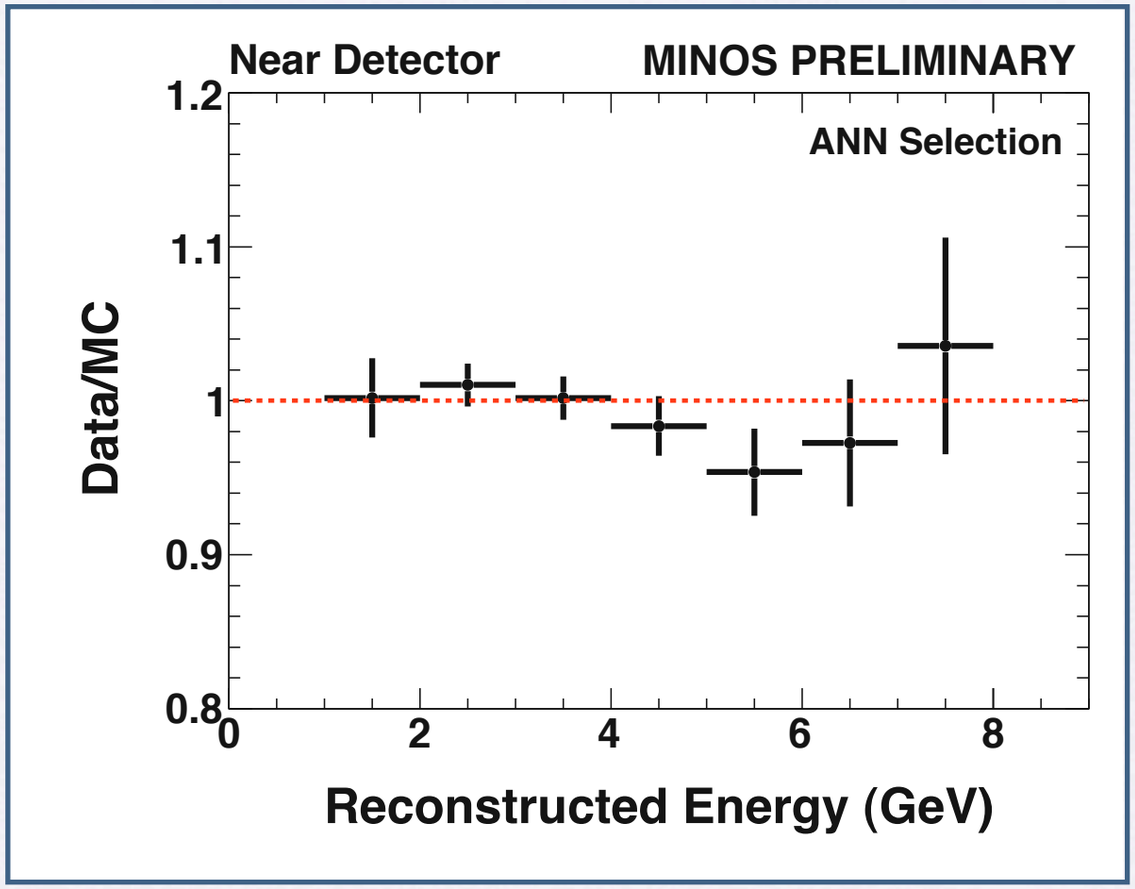
Muon Removed w/ electron added
⇒ MRE events

Estimating the signal efficiency

- The ν_e selection is applied to the MRE data and MC.
- The ratio of data/MC is applied as a correction to the signal efficiency.
- Expected signal depends on δ_{CP} and the mass hierarchy.

The signal prediction at the CHOOZ limit (3.14 x10^{20} POT) ranges from: 6 to 12 events.





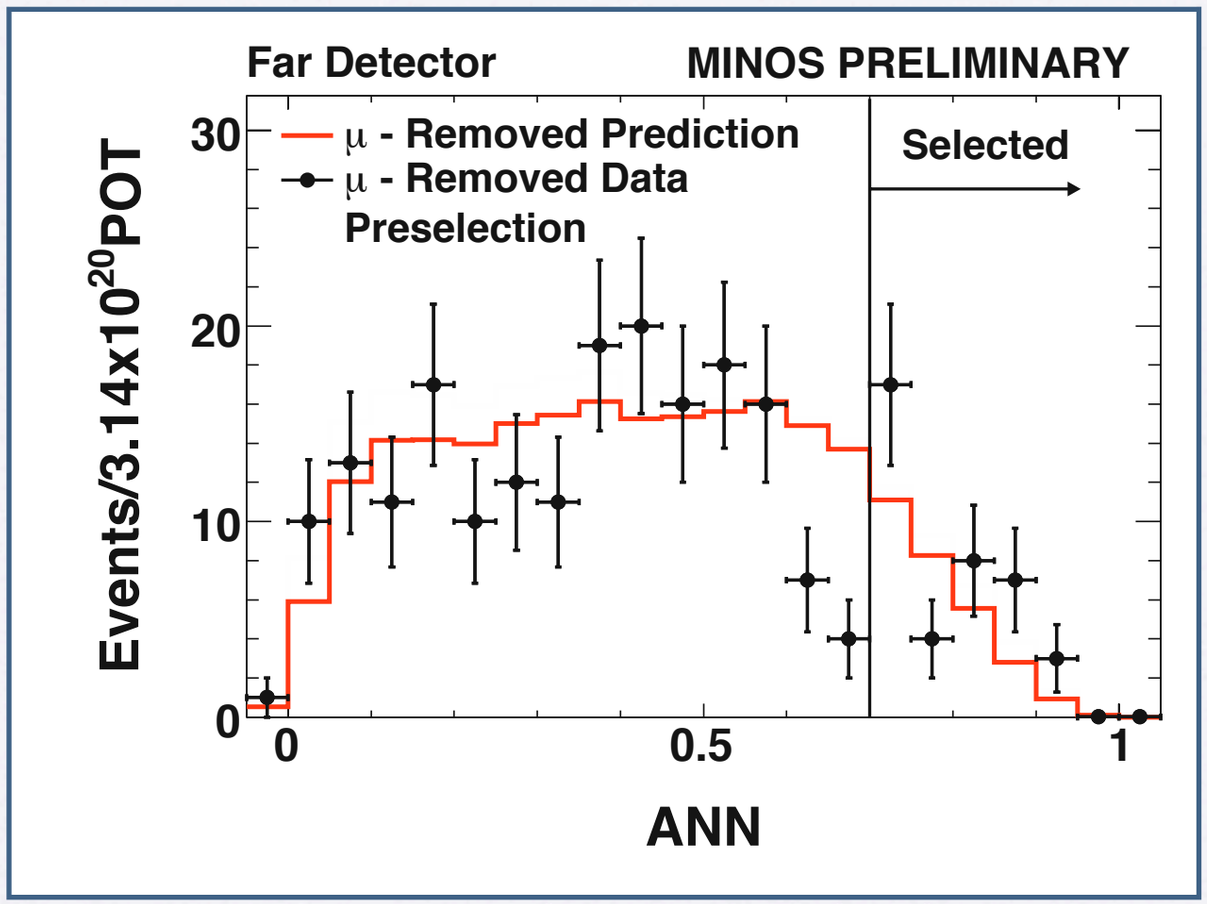
Blind Analysis

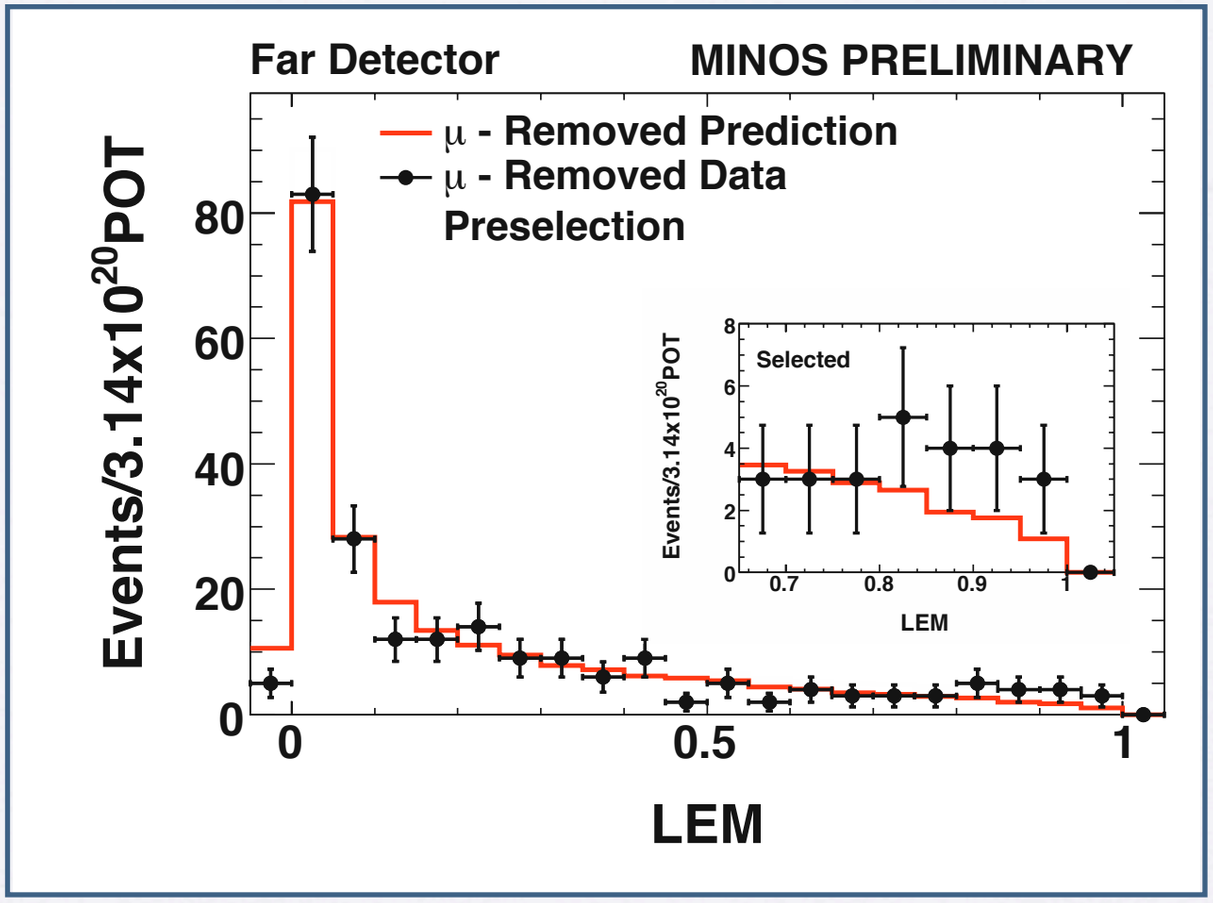
- We have performed a **blind analysis**.
- Before using any Far Detector data in the signal region all background and signal predictions were finalized.
  - including systematic errors
- We also studied 3 sidebands available:
  - Far Detector Muon Removed events.
  - Far Detector Muon Removed w/ electron events.
  - ν_e selection region below the signal cut.

Far Detector Sidebands

3.14×10^{20} POT

Muon removed sideband





Primary selection method

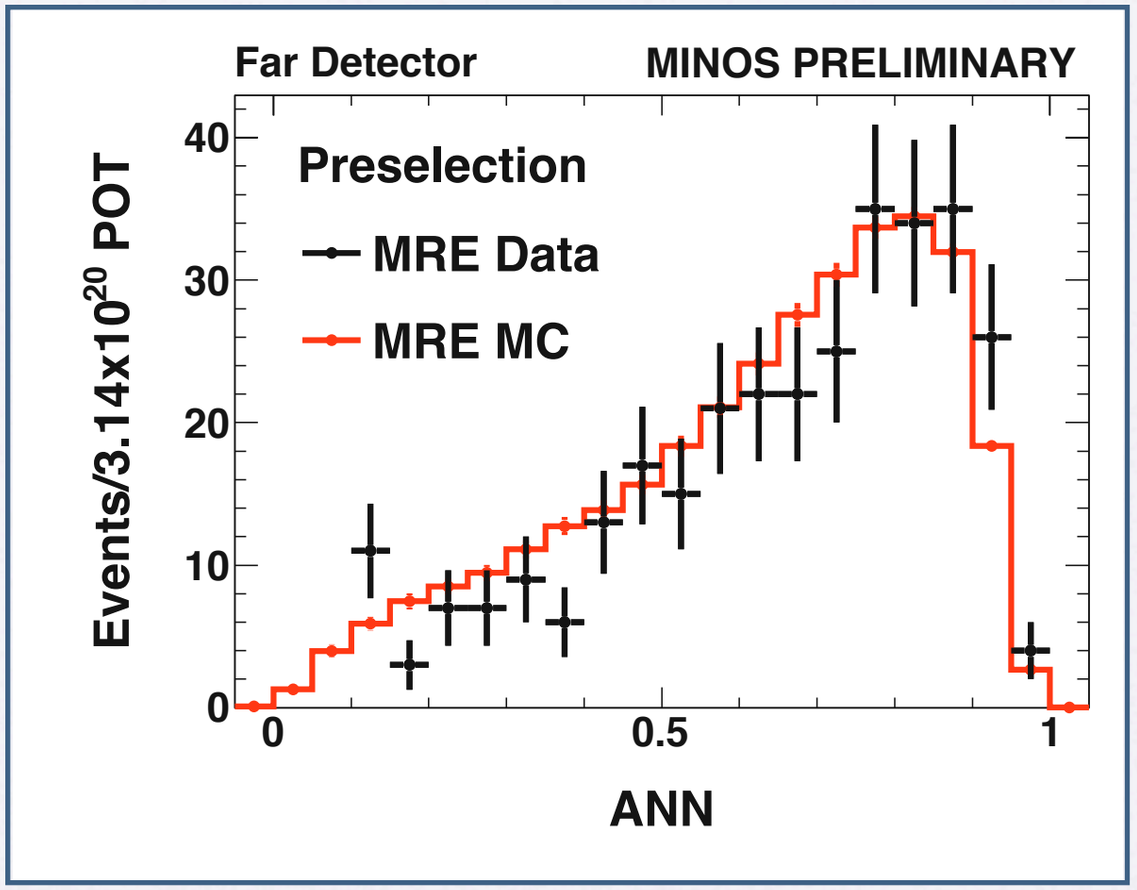
- **We observe a total of 39 events.**
- **We expect 29±5(stat)±2(sys) events.**

- We observe a total of 25 events.
- We expect 17±4(stat)±2(sys) events.

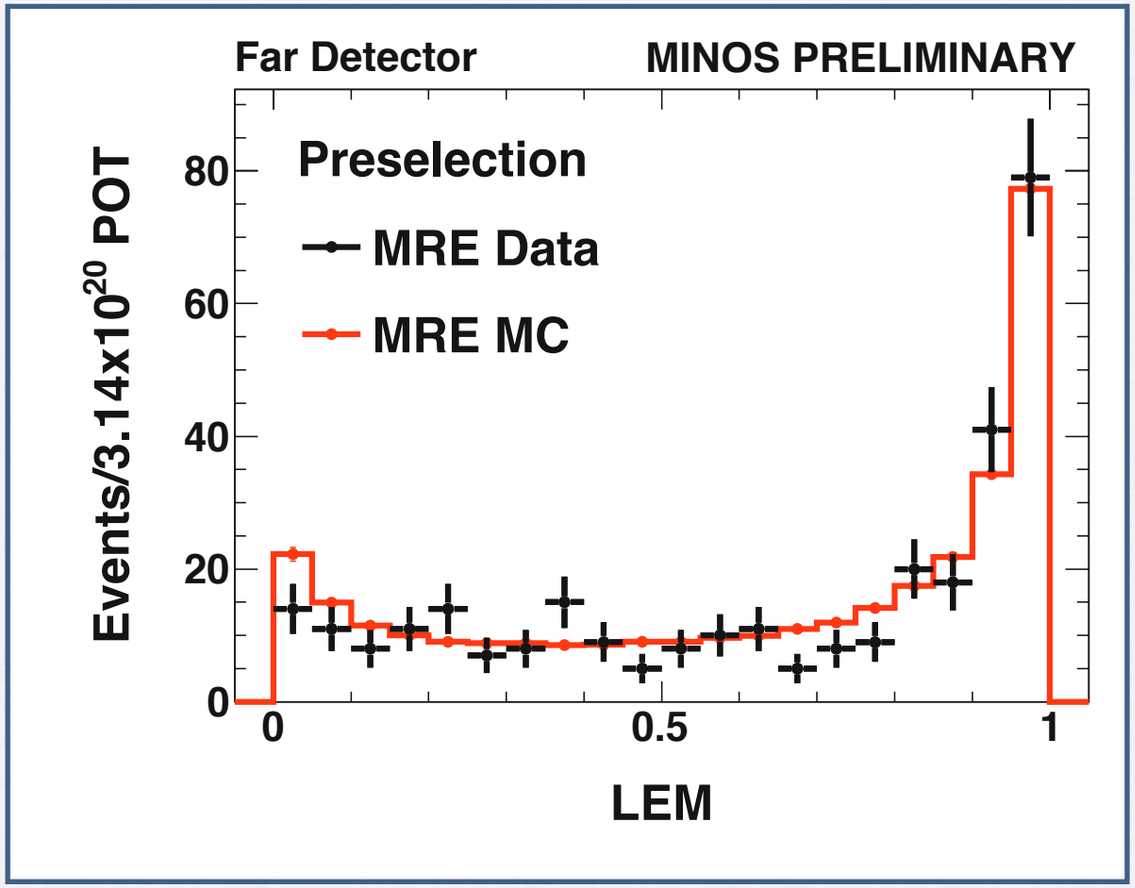
- Results are consistent within 2 σ for both selections.
- It is possible this is a statistical fluctuation or it might hint to an unexplained Far/Near difference.

Muon removed w/electron sideband

- Adding the electron to the muon removed events, present good agreement in PID.



Primary selection method



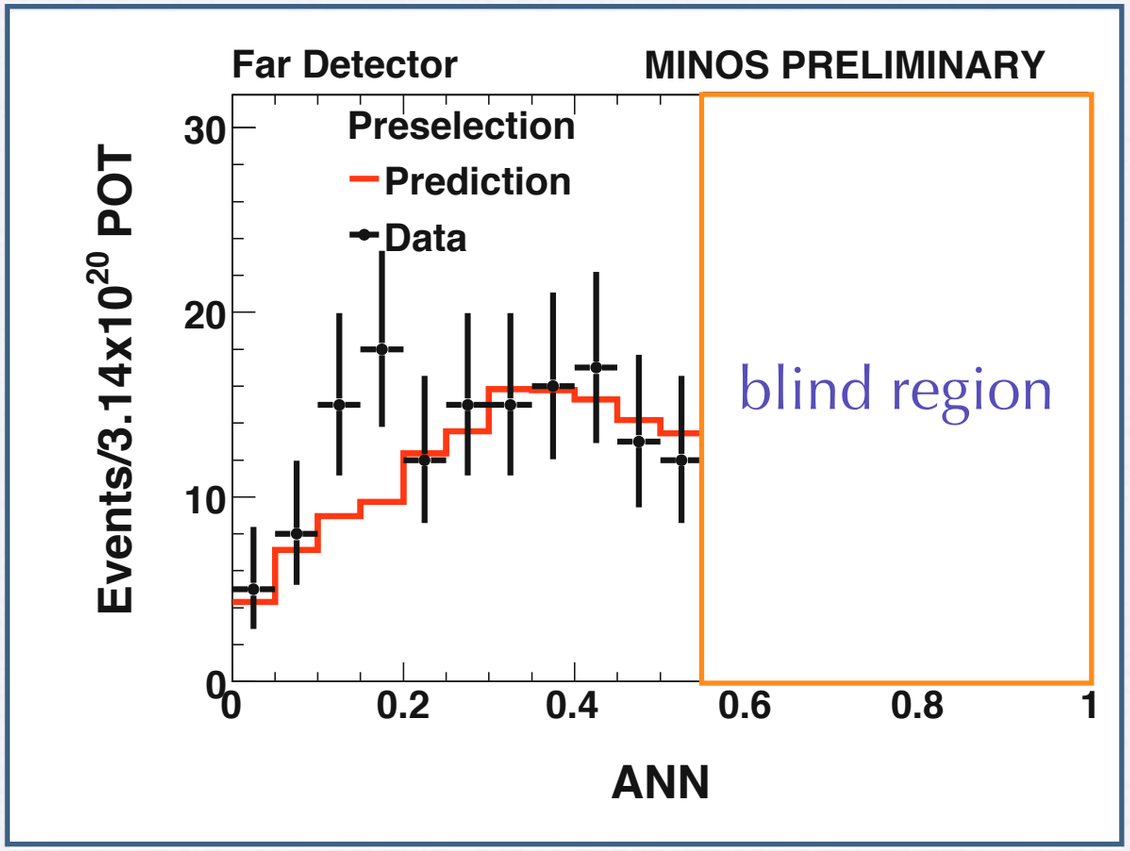
- **We observe a total of 159 events.**
- **We expect 152±13(stat)±12(sys) events.**

- We observe a total of 180 events.
- We expect 176±13(stat)±16(sys) events.

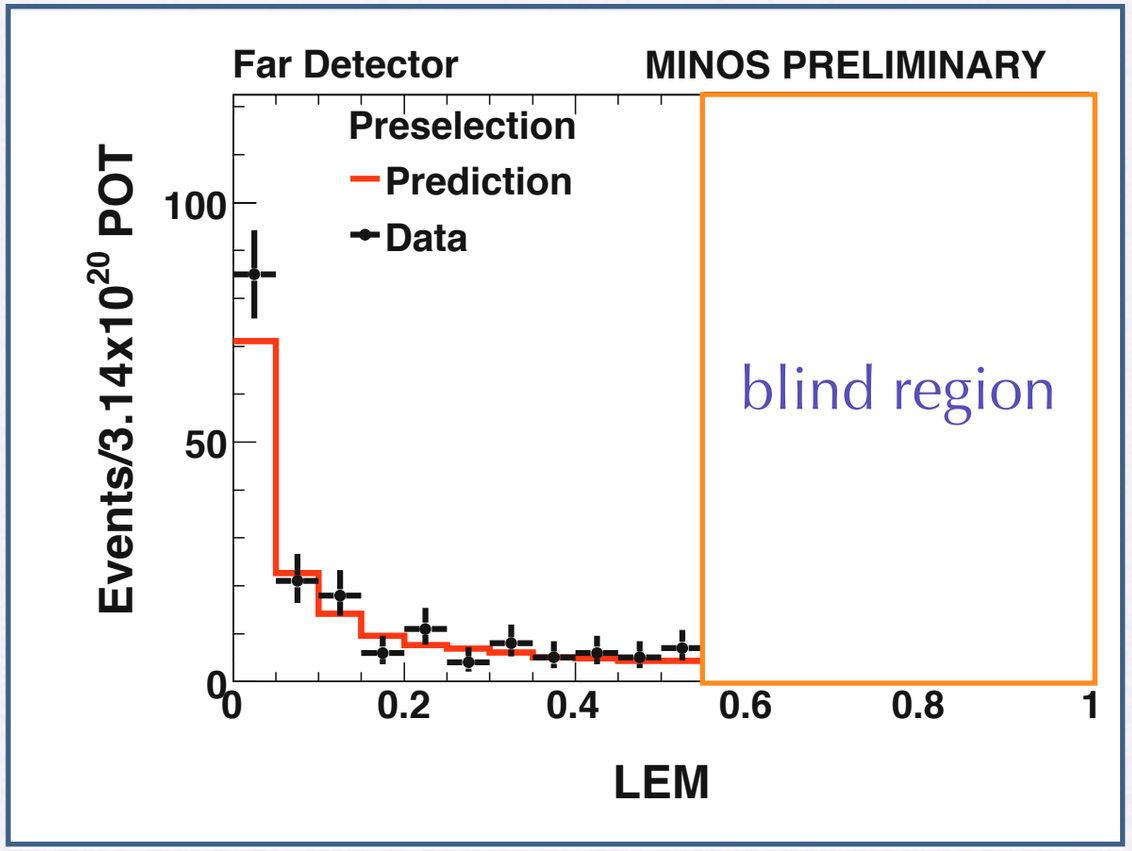
Results are consistent within 0.5 σ for both selections.

Lower PID region

- We also looked in the lower PID region. Finding no obvious disagreement.



Primary selection method



- **We observe a total of 146 events.**
- **We expect 132±12(stat)±8(sys) events.**

- We observe a total of 176 events.
- We expect 157±13(stat)±3(sys) events.

Note results are ~1σ above expectation for both selections.

ν_e appearance result:

MINOS PRELIMINARY

ν_e appearance result:

Observation 35 events

Expected Background 27±5(stat)±2(sys)

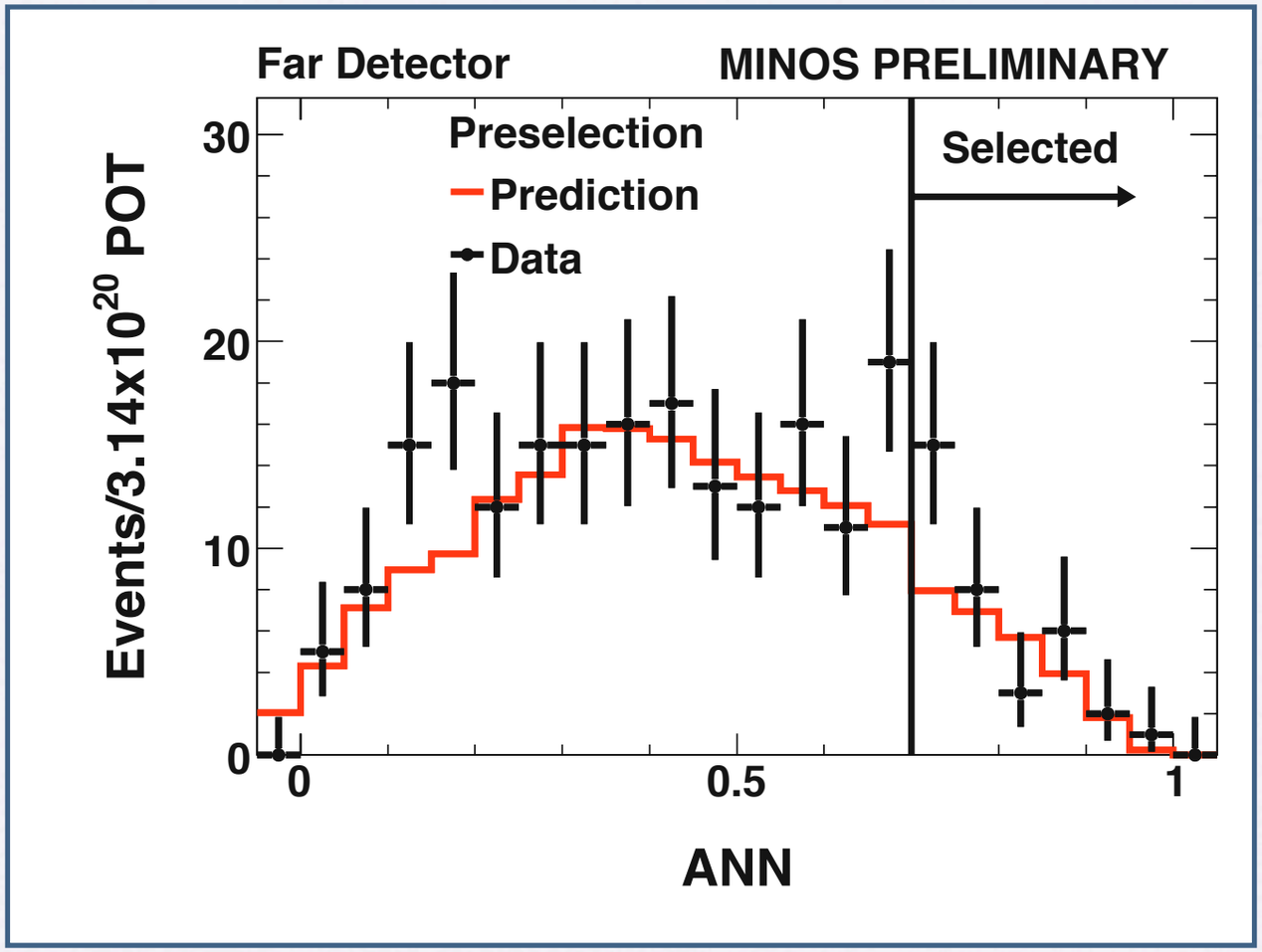
for 3.14×10^{20} POT

MINOS PRELIMINARY

ν_e Selected Far Detector Data

Primary selection method

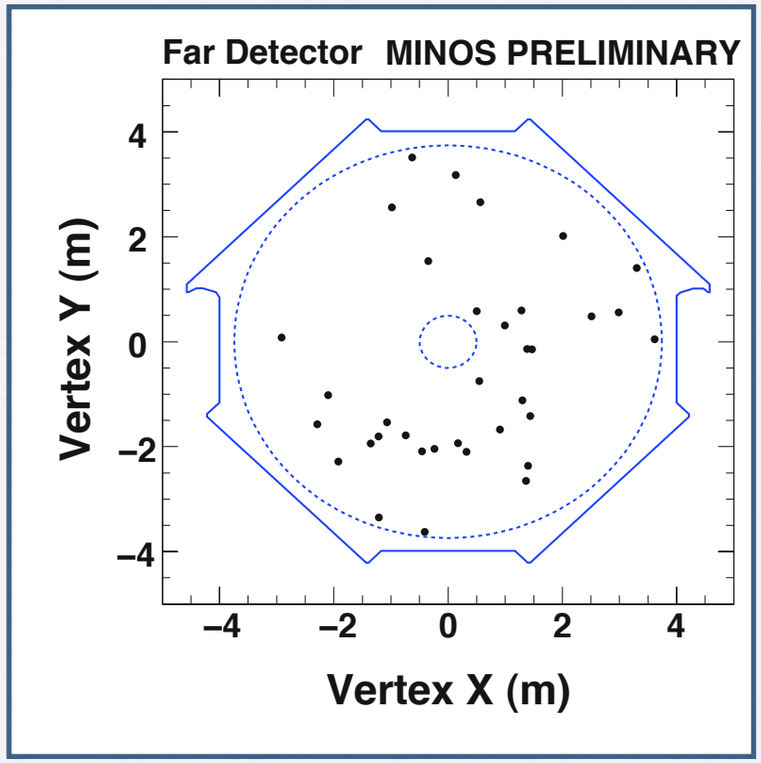
- Preselected data in the FD as a function of PID compared to the corrected MC.

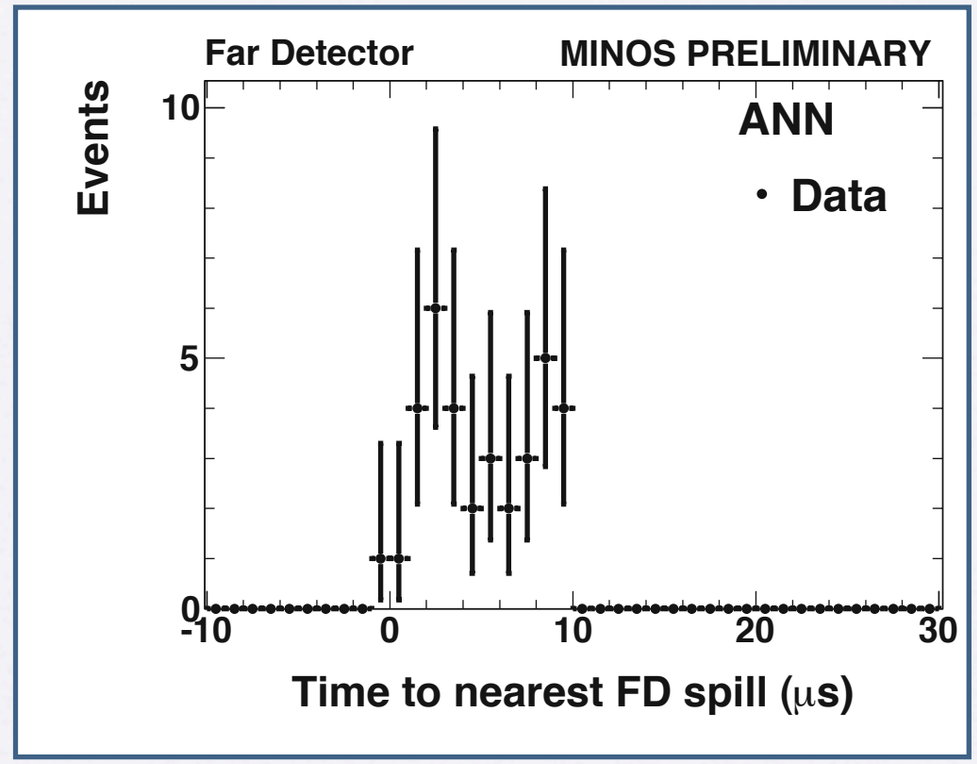


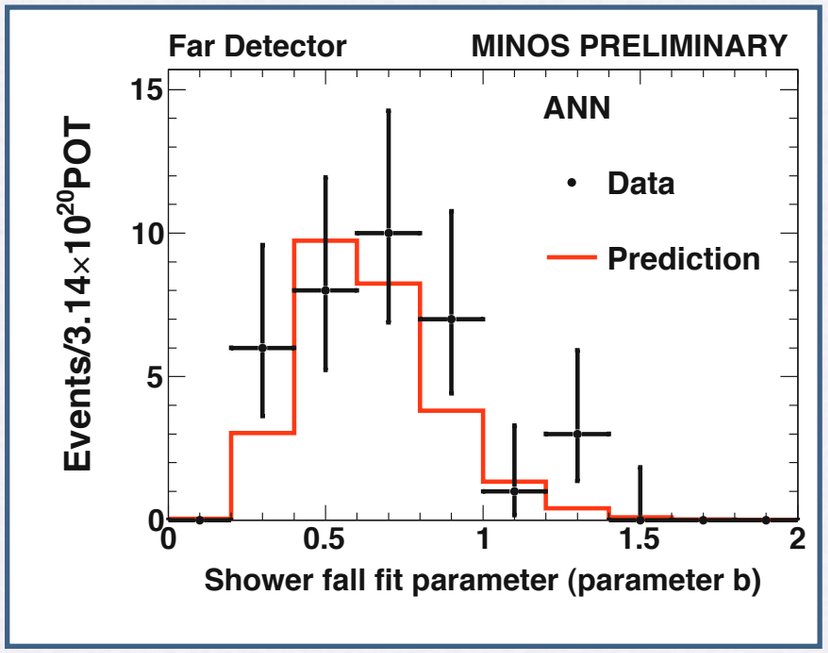
- **We observe a total of 35 events.**
- **We expect 27±5(stat)±2(sys) background events.**

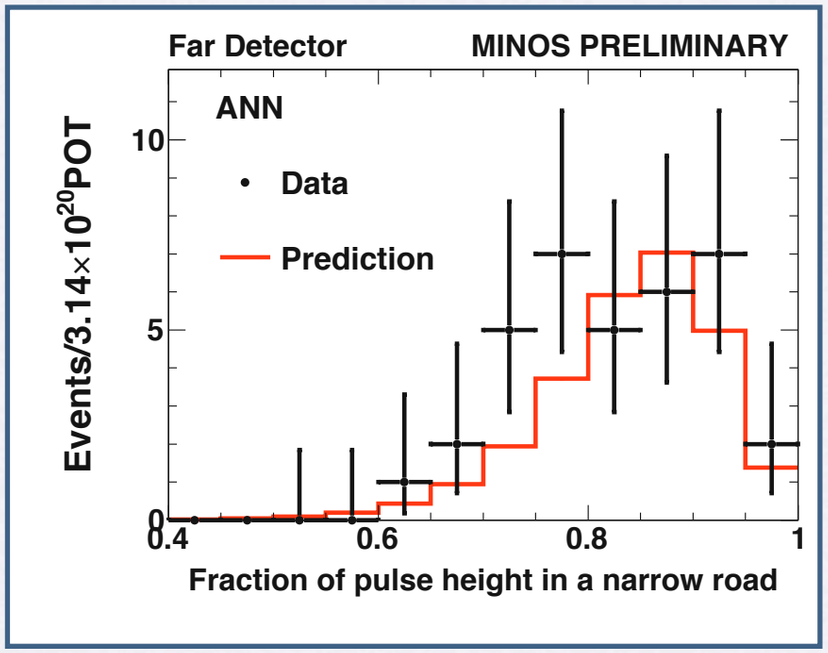
Results are 1.5 σ above expected background.

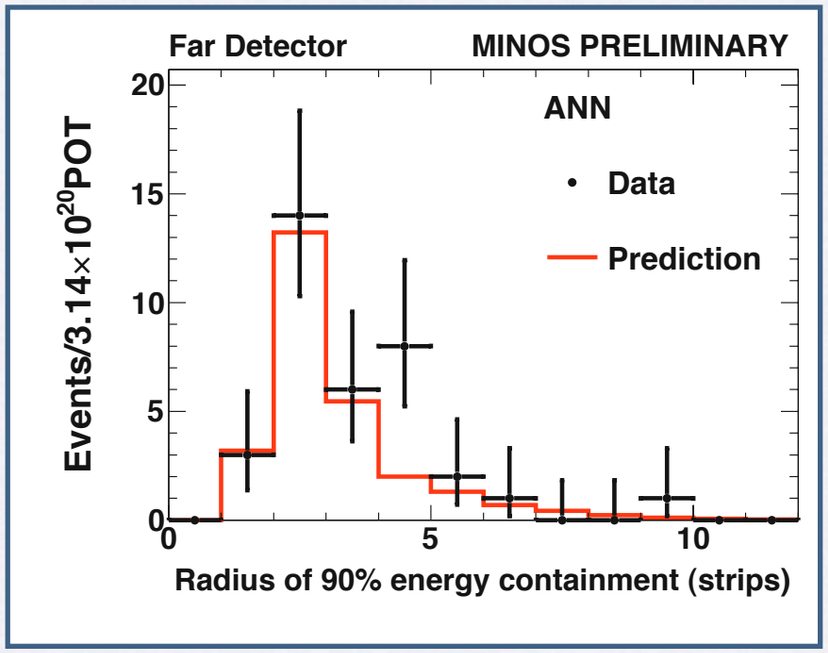
Far Data ν_e selected distributions







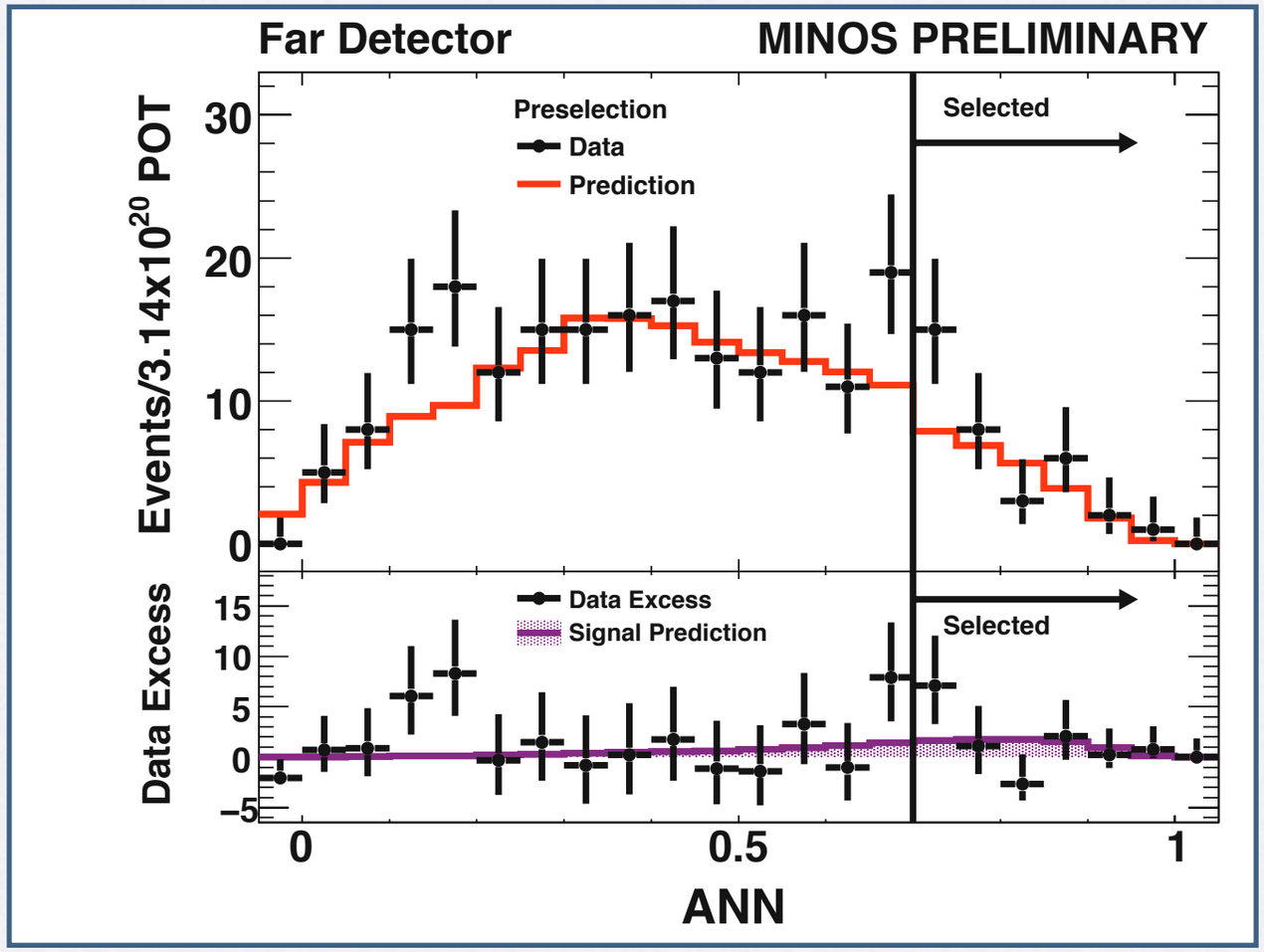


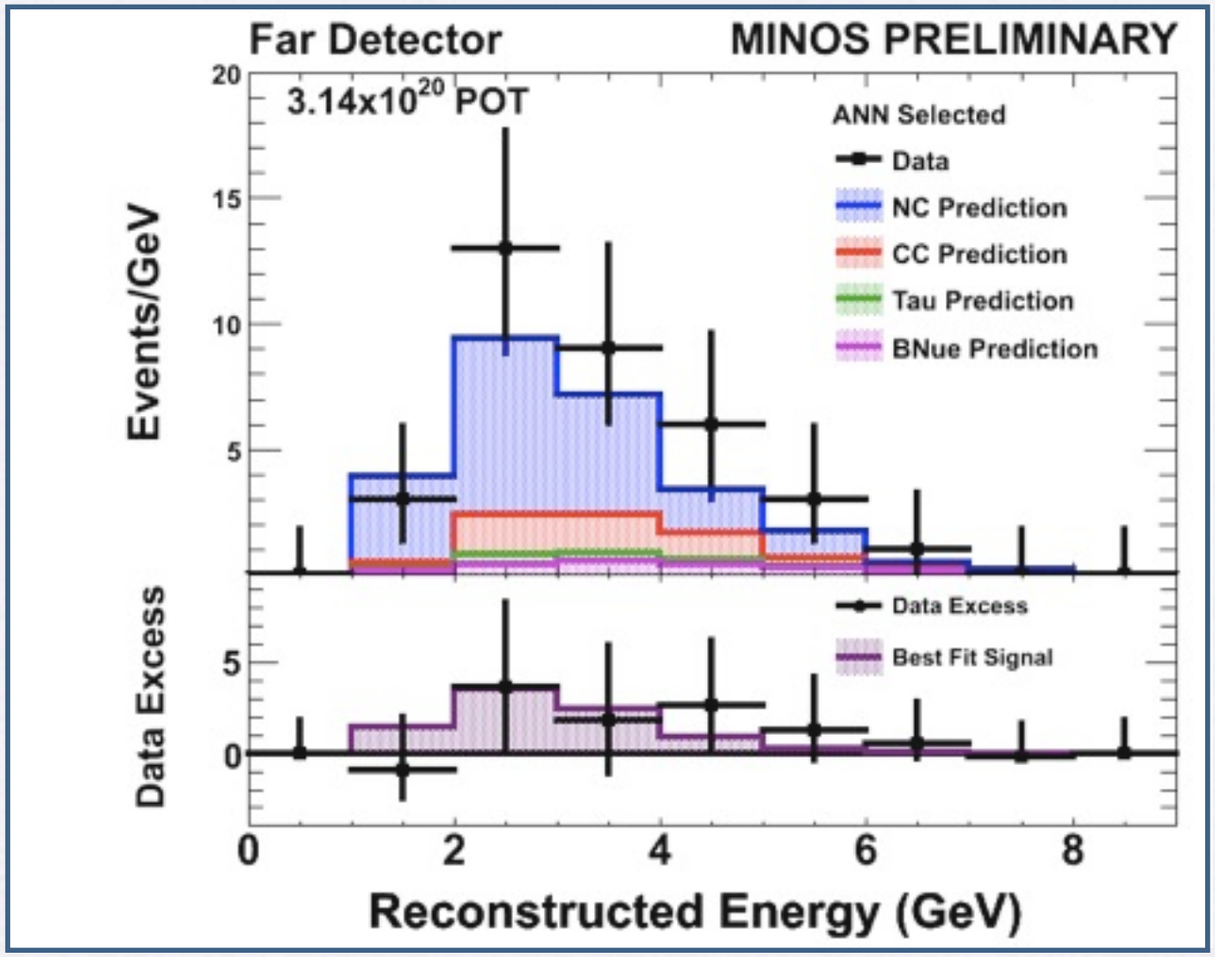


ν_e Selected Far Detector Data

Primary selection method

- **We observe a total of 35 events in this sample.**
- **We expect 27±5(stat)±2(sys) background events.**



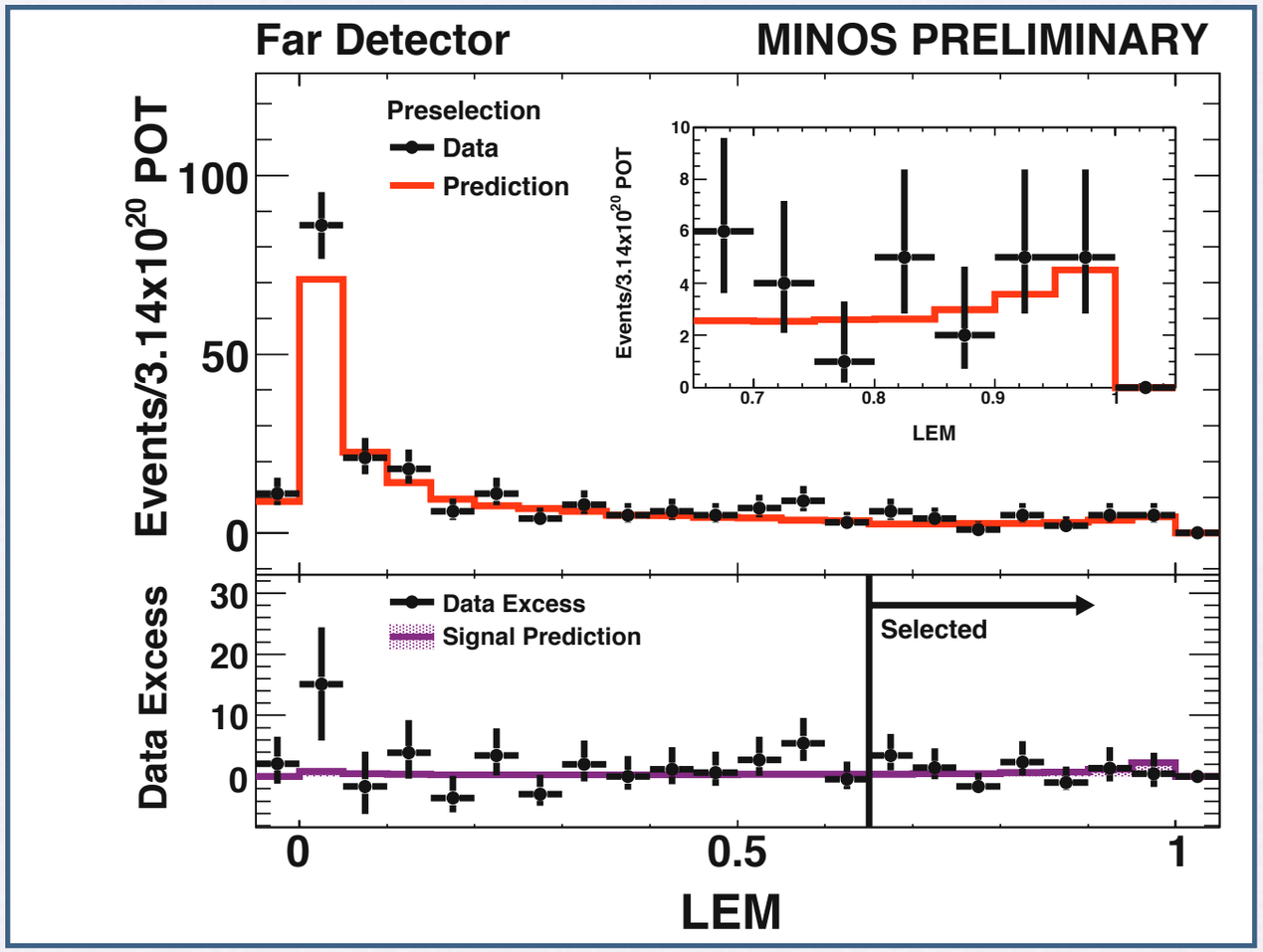


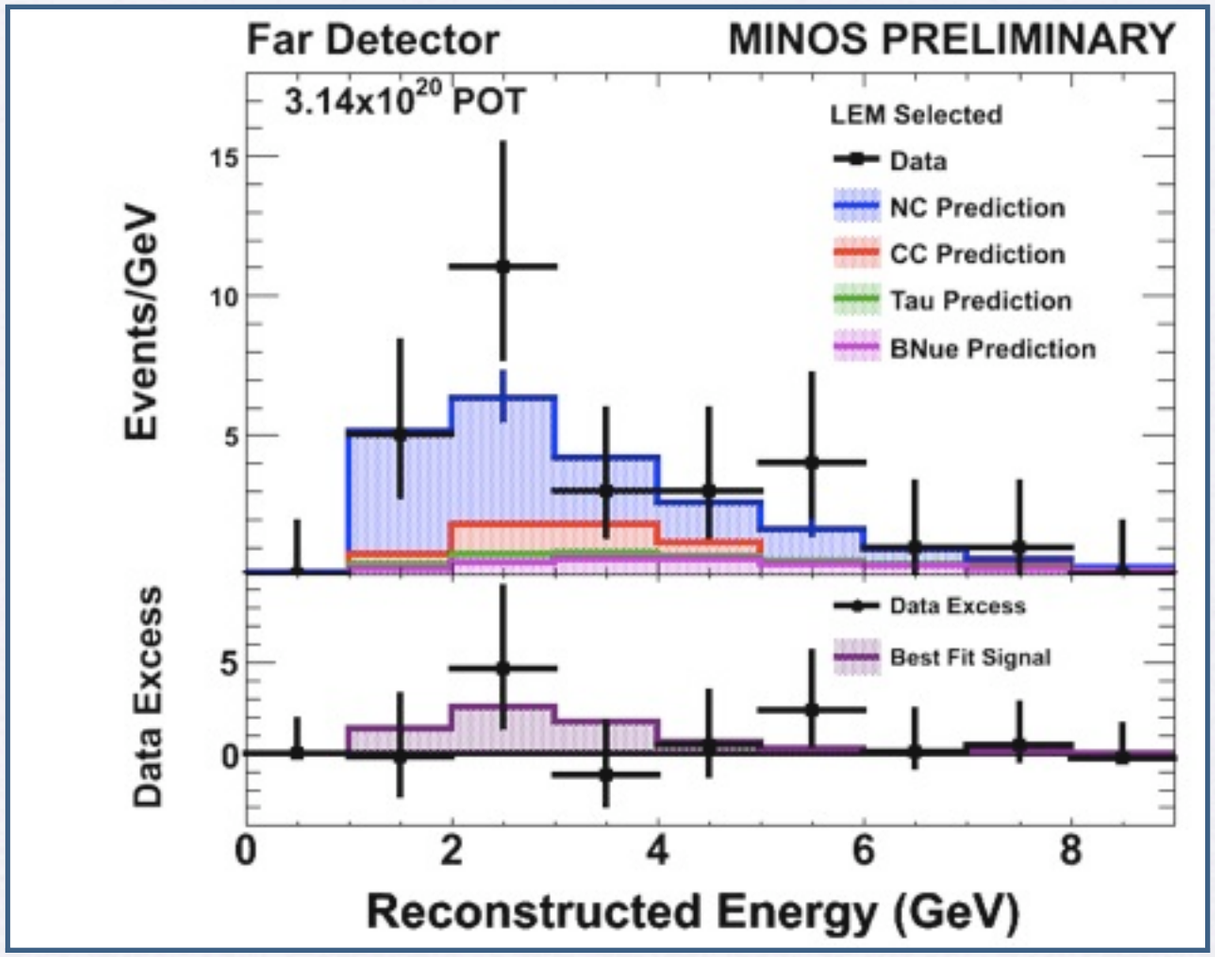
- If we fit the oscillation hypothesis to data, we can obtain the signal prediction for the best fit point.

ν_e Selected Far Detector Data

Secondary selection method

- **We observe a total of 28 events in this sample.**
- **We expect 22±5(stat)±3(sys) background events.**



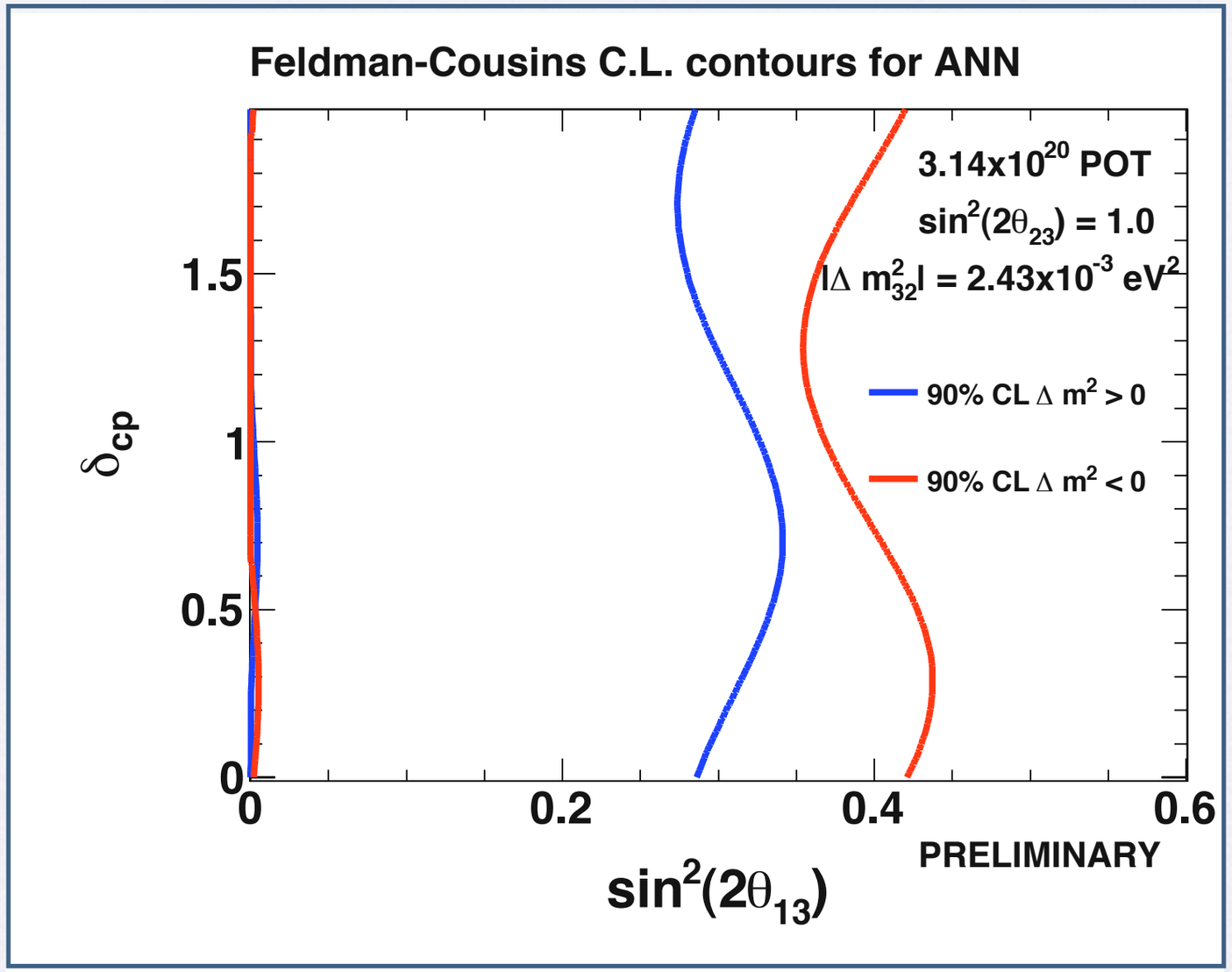


- If we fit the oscillation hypothesis to data, we can obtain the signal prediction for the best fit point.

MINOS 90% CL in $\sin^2 2\theta_{13}$

Fitting the oscillation hypothesis to our data

- Plot shows 90% limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
  - shown at the MINOS best fit value for Δm^2_{32} and $\sin^2 2\theta_{23}$.
  - for both mass hierarchies
- A Feldman-Cousins method was used.
- Results are for primary selection and primary separation method.



MINOS 90% CL in $\sin^2 2\theta_{13}$

Fitting the oscillation hypothesis to our data

- Plot shows 90% limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
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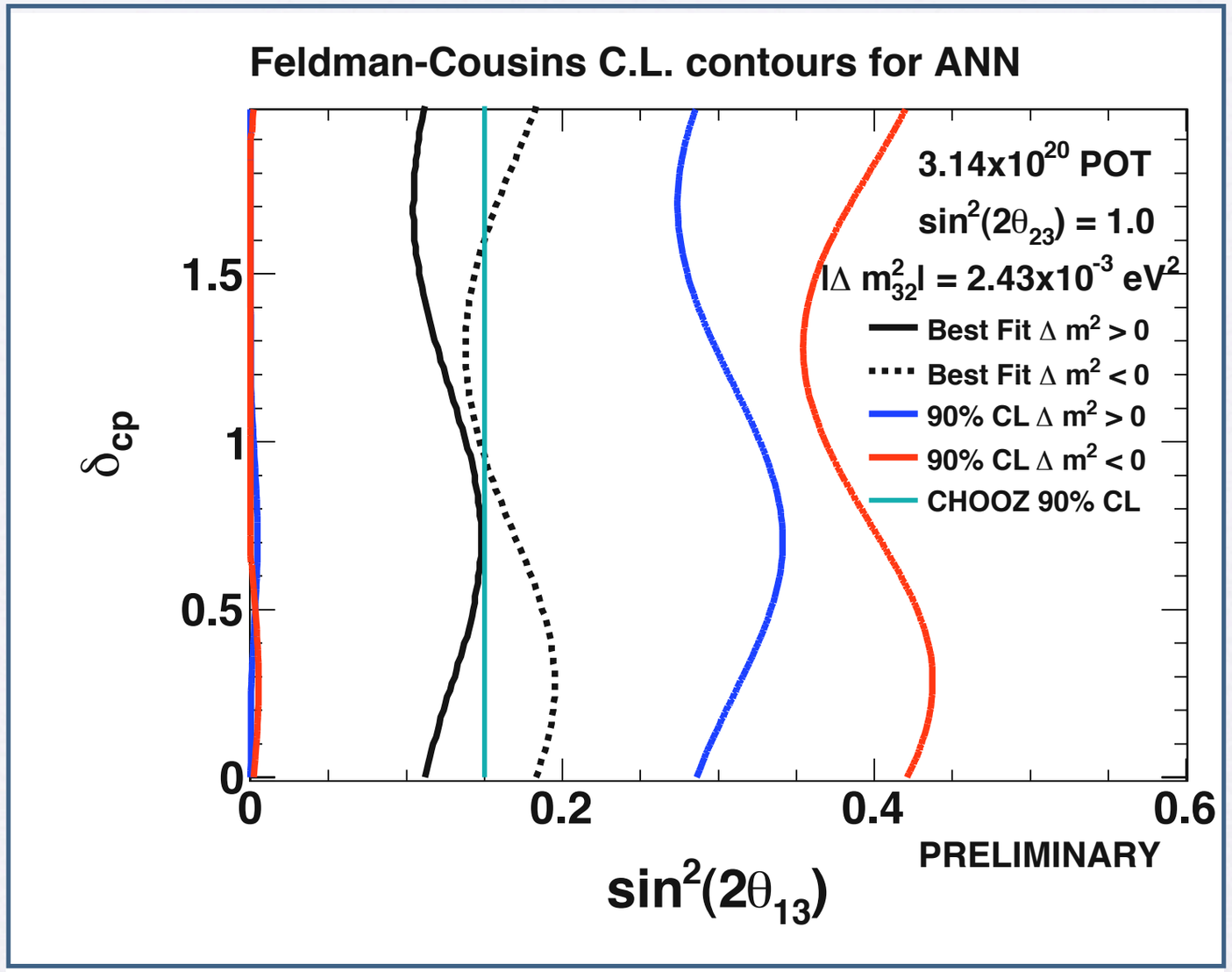
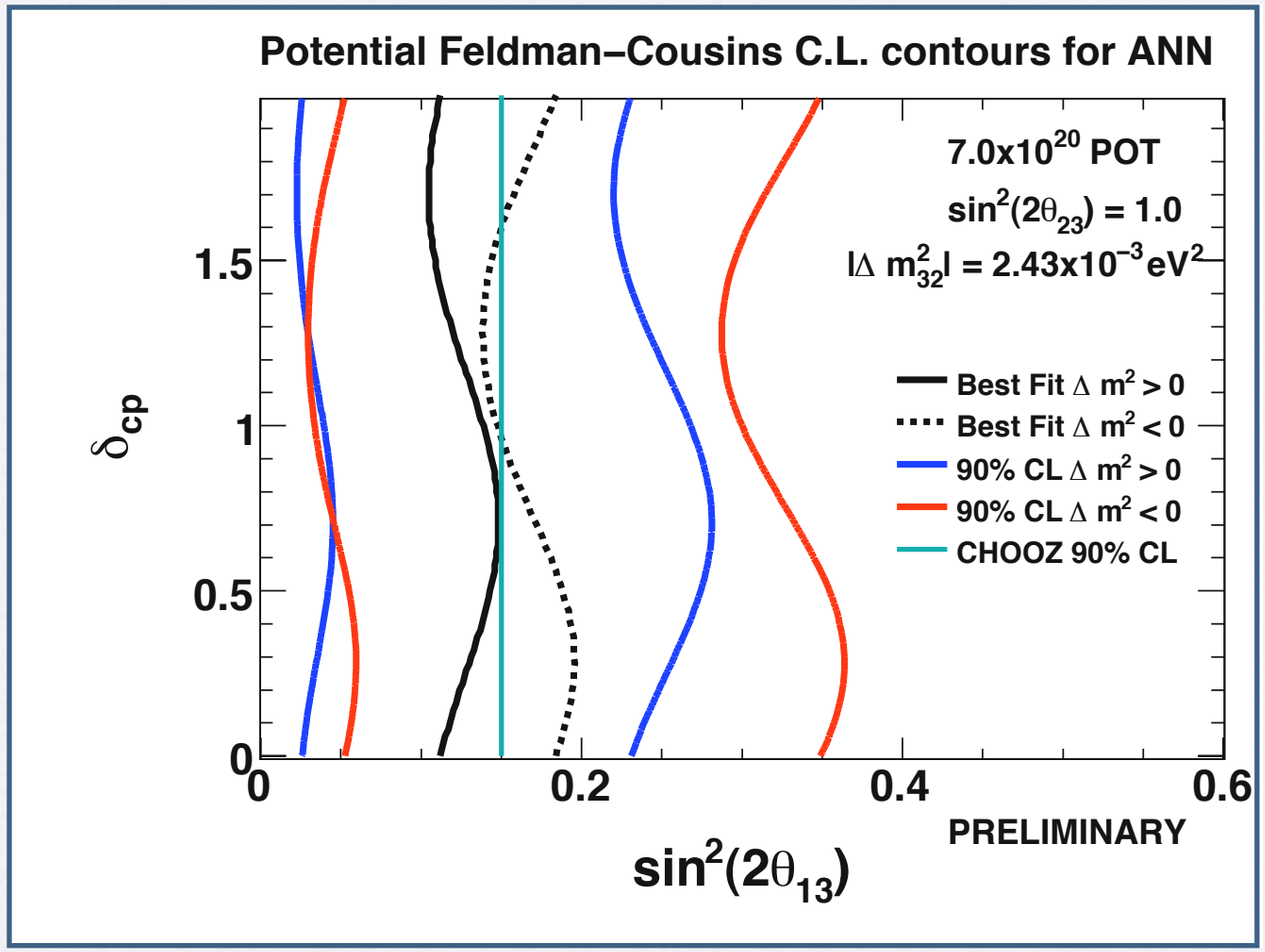
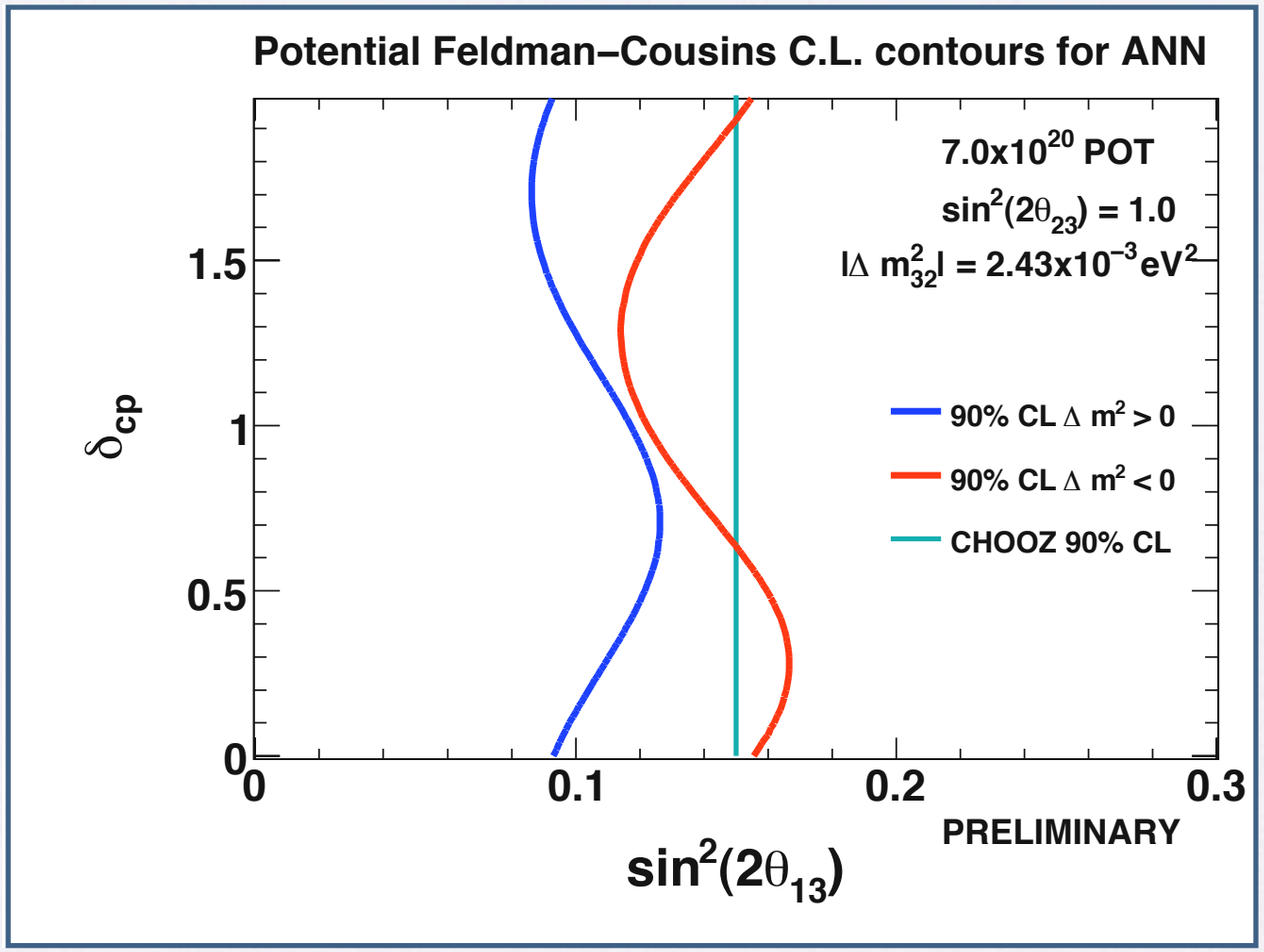


Future 90% CL contours

7.0 x10^{20} POT





Future measurement if data excess persists.

Future limit if excess cancels with more data.

We are close to doubling the data in current running!

Summary

- We have completed an **initial search for ν_e appearance** in the MINOS data.
- We developed two ν_e selections that have a rejection of >92% for NC and >99% for ν_μ CC, the main background components for this analysis.
- We used **two data-driven techniques** to estimate the background in the Far Detector.
- We studied **sideband** Far Detector data to check the extrapolation techniques:
  - Sidebands show adequate agreement, with an excess of 1-2 σ.
  - Observed excess could be a statistical fluctuation or a hint of a Far/Near difference.

More data will clarify these issues.

Summary

- We observe a total of **35 events** and expect **27±5(stat)±2(sys)** background events for 3.14×10^{20} POT.
- If fitted to a oscillation hypothesis we obtain the limits at the MINOS best fit for Δm^2_{32} and $\sin^2(2\theta_{23})$:
  - normal hierarchy, $\delta_{CP} = 0$: **$\sin^2(2\theta_{13}) < 0.29$ (90% CL)**
  - inverted hierarchy, $\delta_{CP} = 0$: **$\sin^2(2\theta_{13}) < 0.42$ (90% CL)**

We are close to doubling these data in current running!
Expect next result with $> 7 \times 10^{20}$ POT

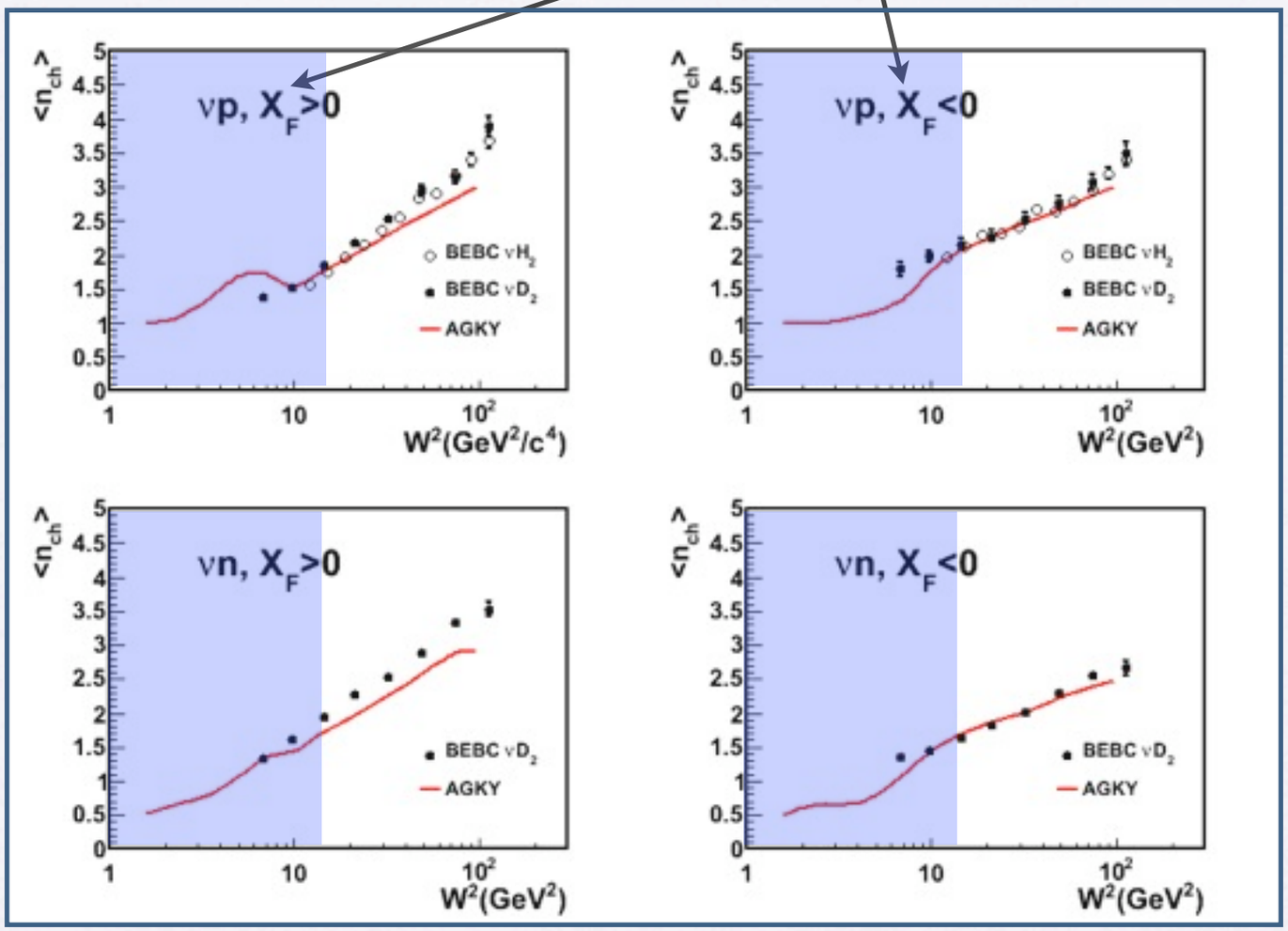
Acknowledgements

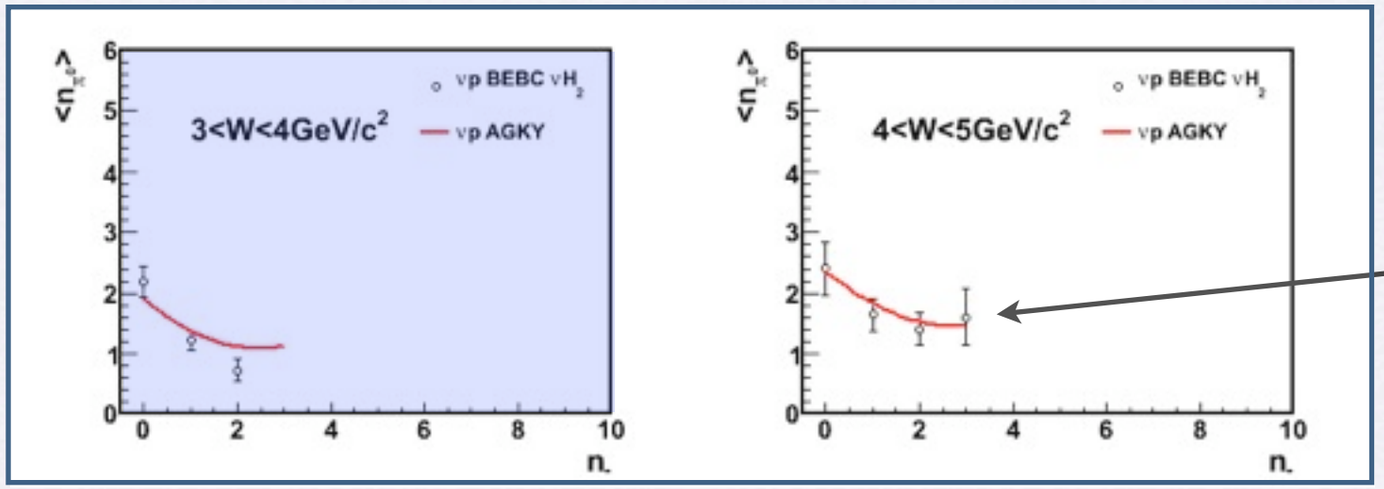
- On behalf of the MINOS Collaboration, I would like to thank the many Fermilab groups who provided the technical expertise and support in the design, the construction, installation and operation of the MINOS experiment.
  - In particular to the Accelerator Division for providing the neutrinos!
- We also like to acknowledge the financial support from DOE; NSF; STFC(UK); the University of Athens, Greece; and Brazil's FAPESP and CNPq.
- We are grateful to the University of Minnesota and the Minnesota DNR for hosting us.

MINOS Monte Carlo

- MC tuned to external bubble chamber data for hadronization (or fragmentation) models.
- Region of interest in mass of hadronic system: 1 - 15 GeV^2 in W^2 or 1 - 4 GeV in W.
- However, data available is for relatively higher energy than the region of interest for this analysis.

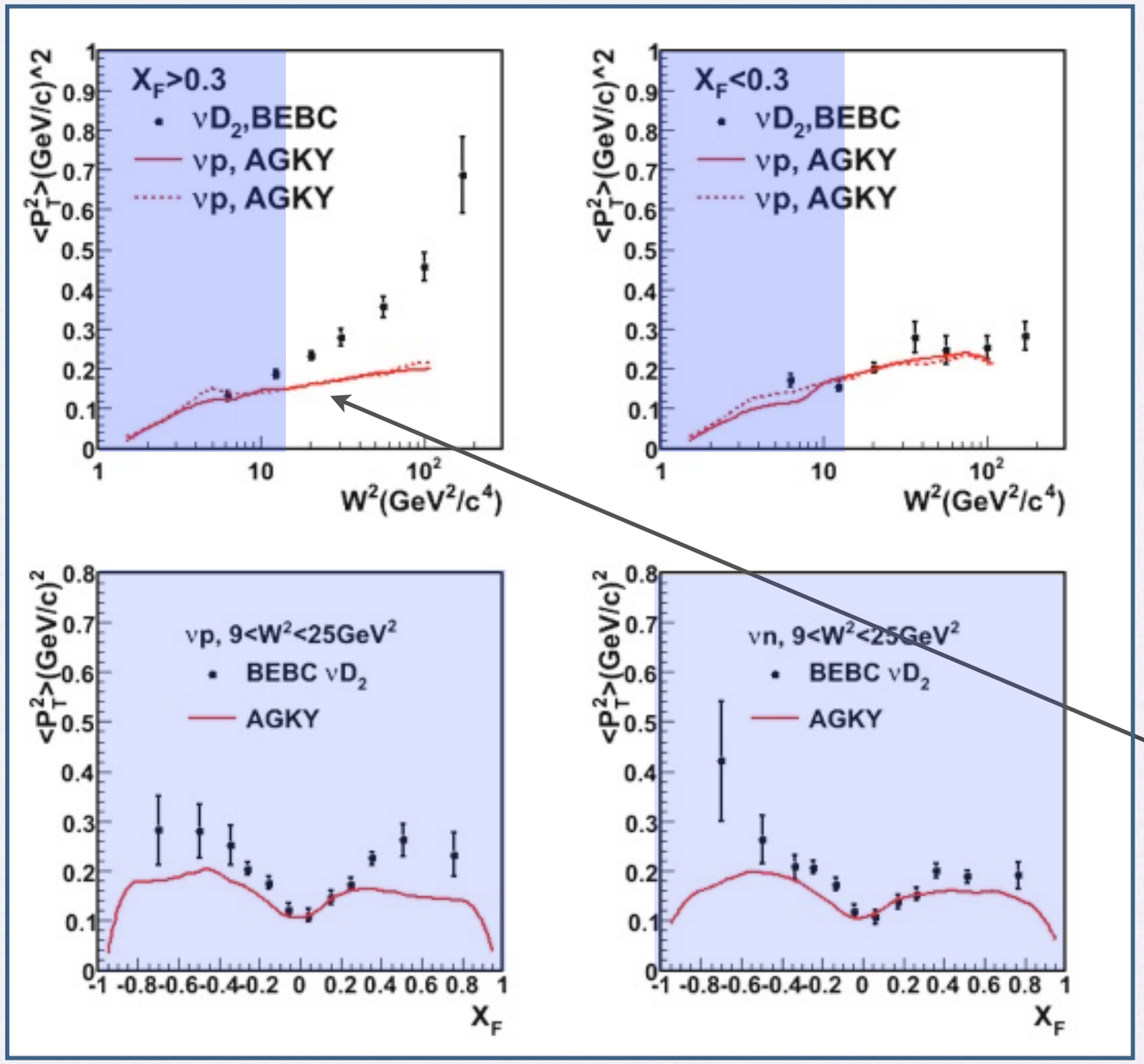
Good agreement in W^2 for forward and backward hemispheres





Also agreement for π_0 vs charged hadron multiplicities for different W^2

MINOS Monte Carlo

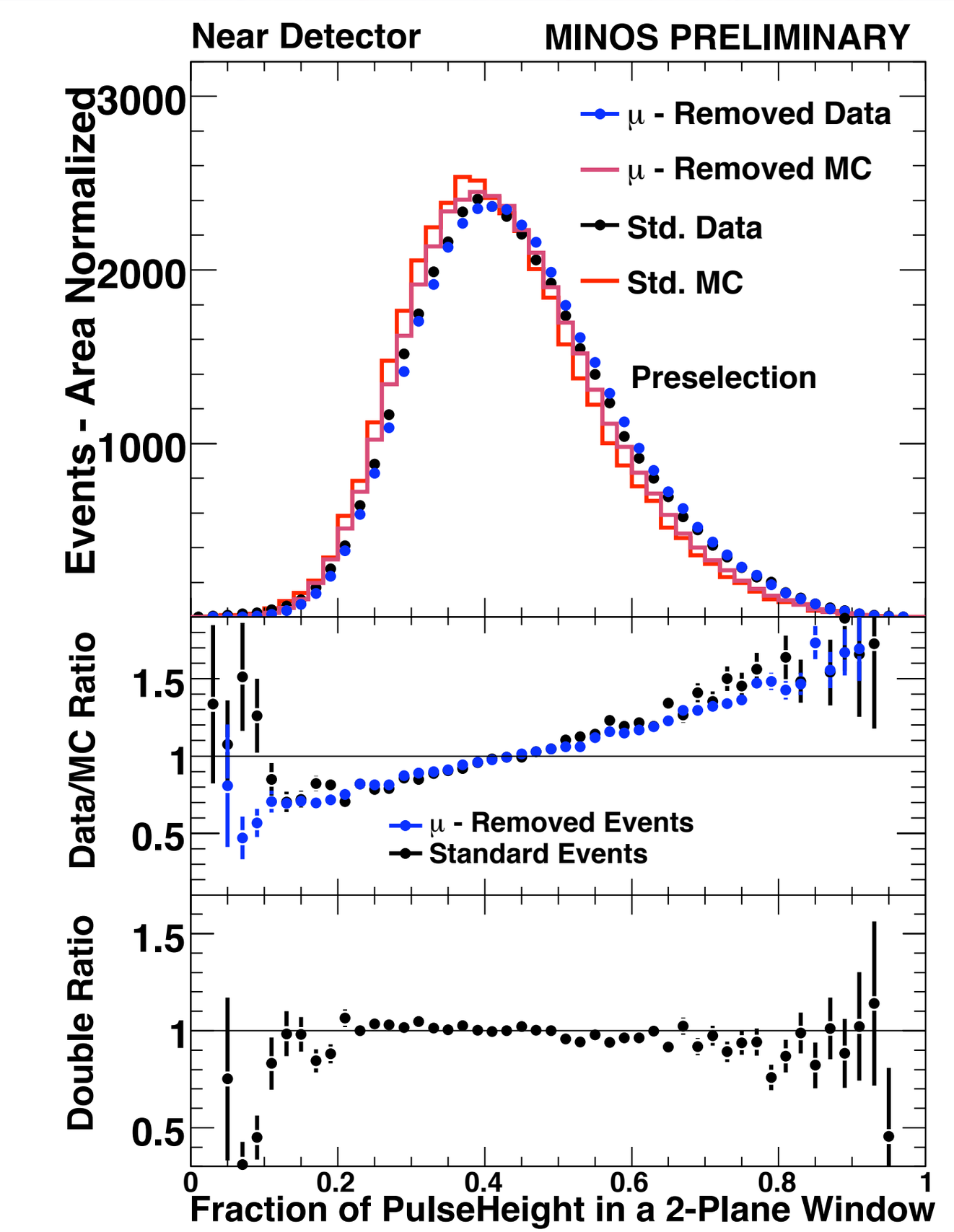


- Tuning focused in the following quantities:
  - Charged/neutral pion multiplicity and dispersion.
  - Forward/backward fragments.
  - Fragmentation functions.
  - Transverse momentum.
- Transverse momentum still too low in forward hemisphere, and model at lower W^2 is an extrapolation.

We need to use more information from our own data in the Near Detector.

Shower Topology

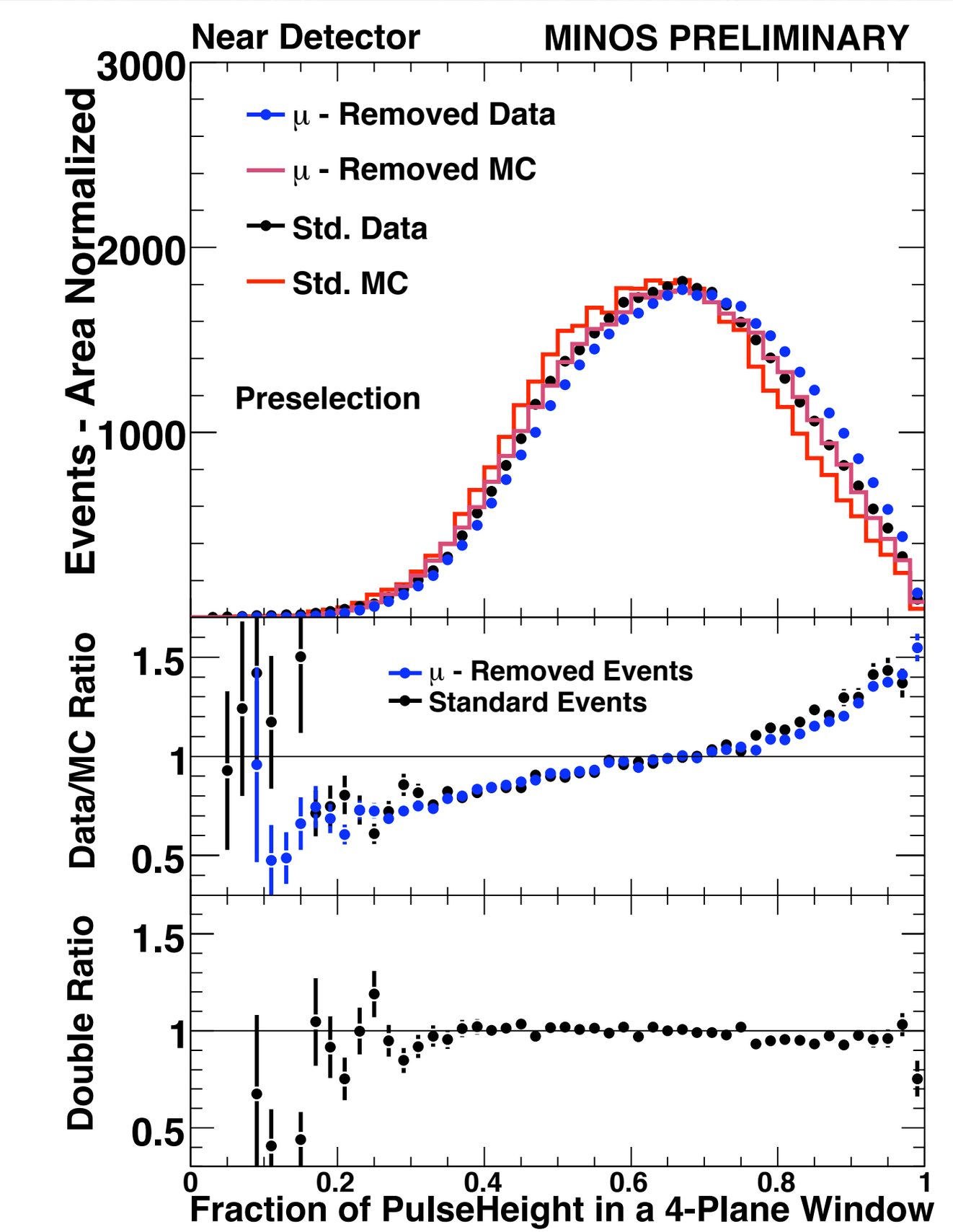
Longitudinal shape



- Fraction of pulse height in a 2-plane window for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

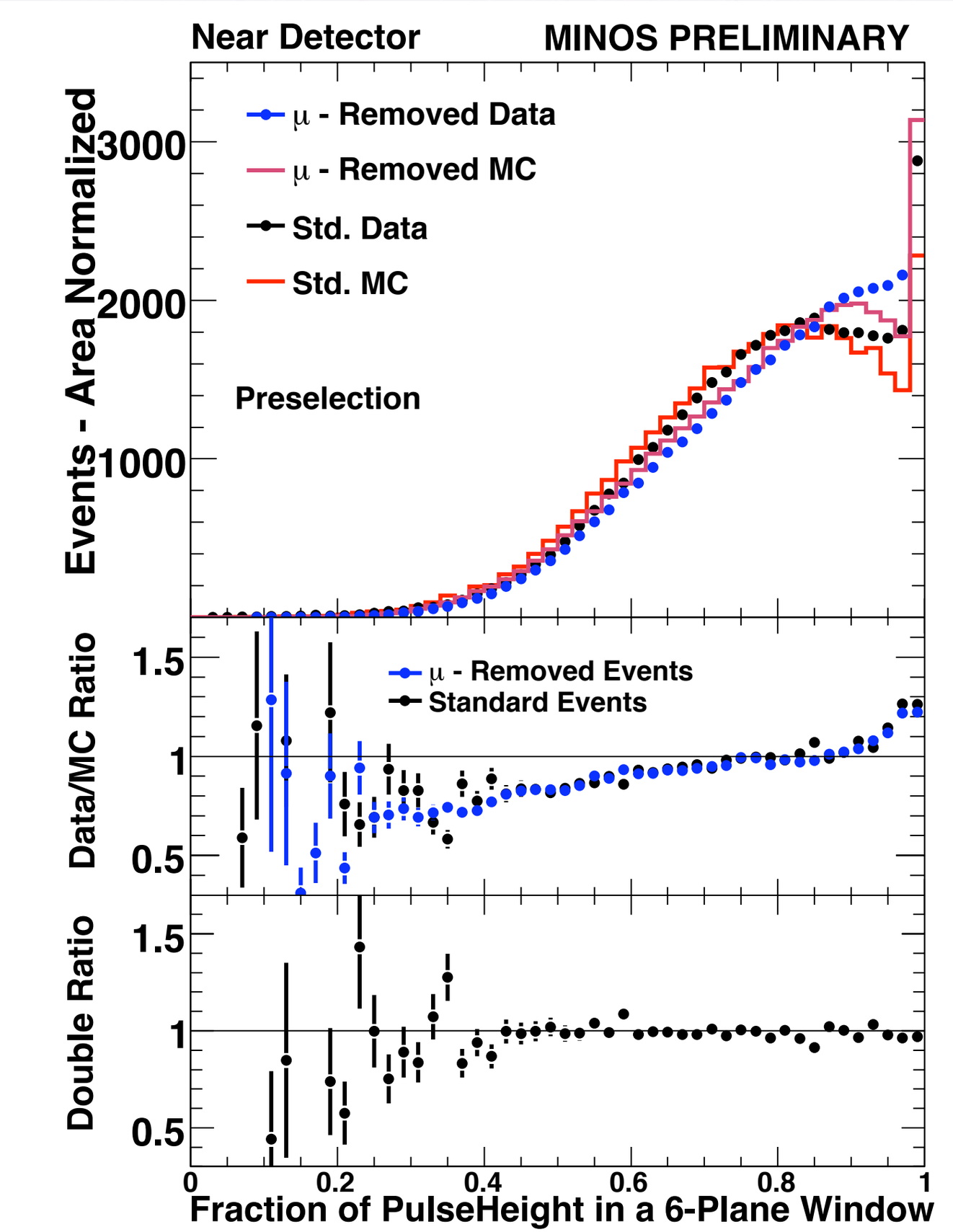
Longitudinal shape



- Fraction of pulse height in a 4-plane window for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

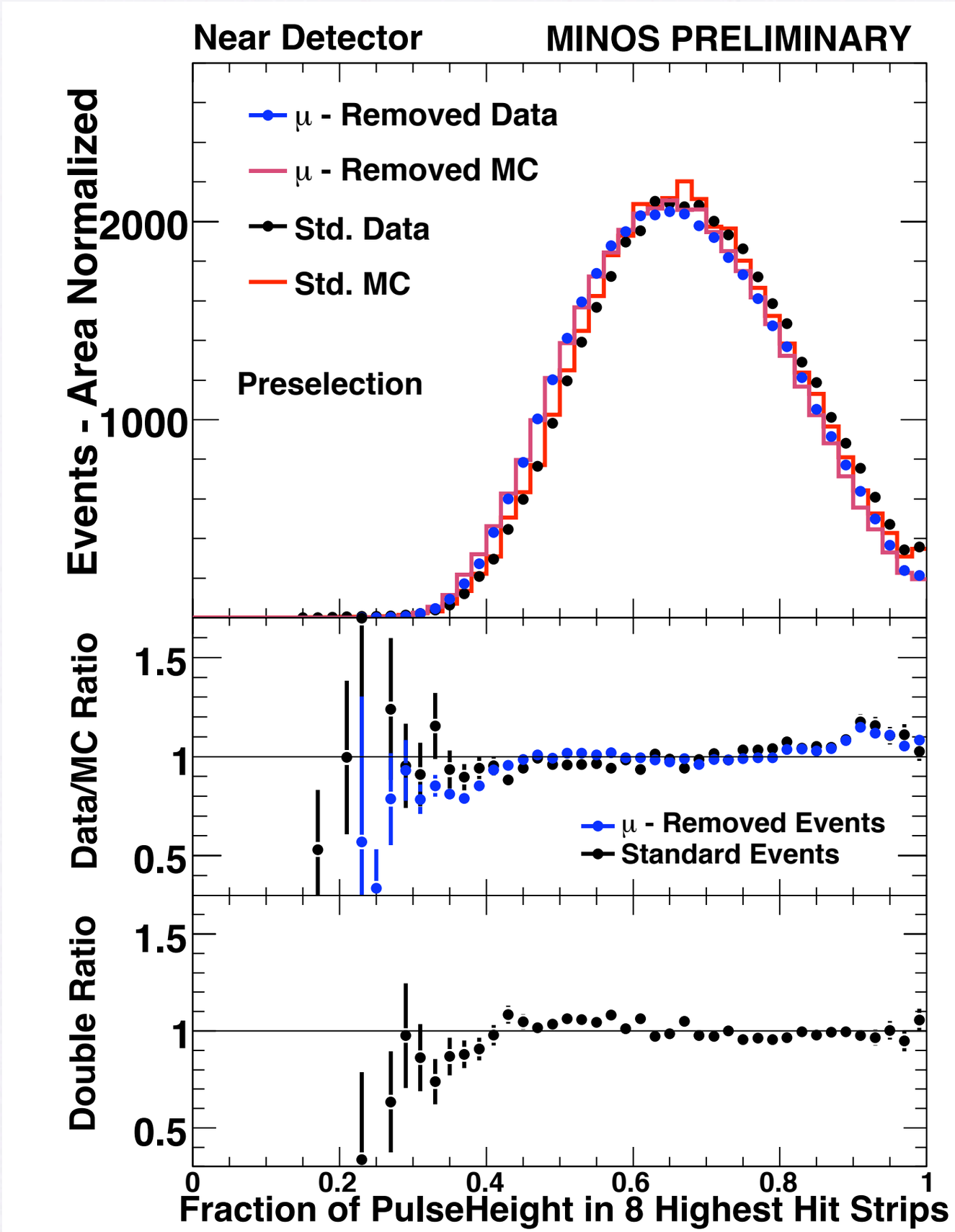
Longitudinal shape



- Fraction of pulse height in a 6-plane window for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

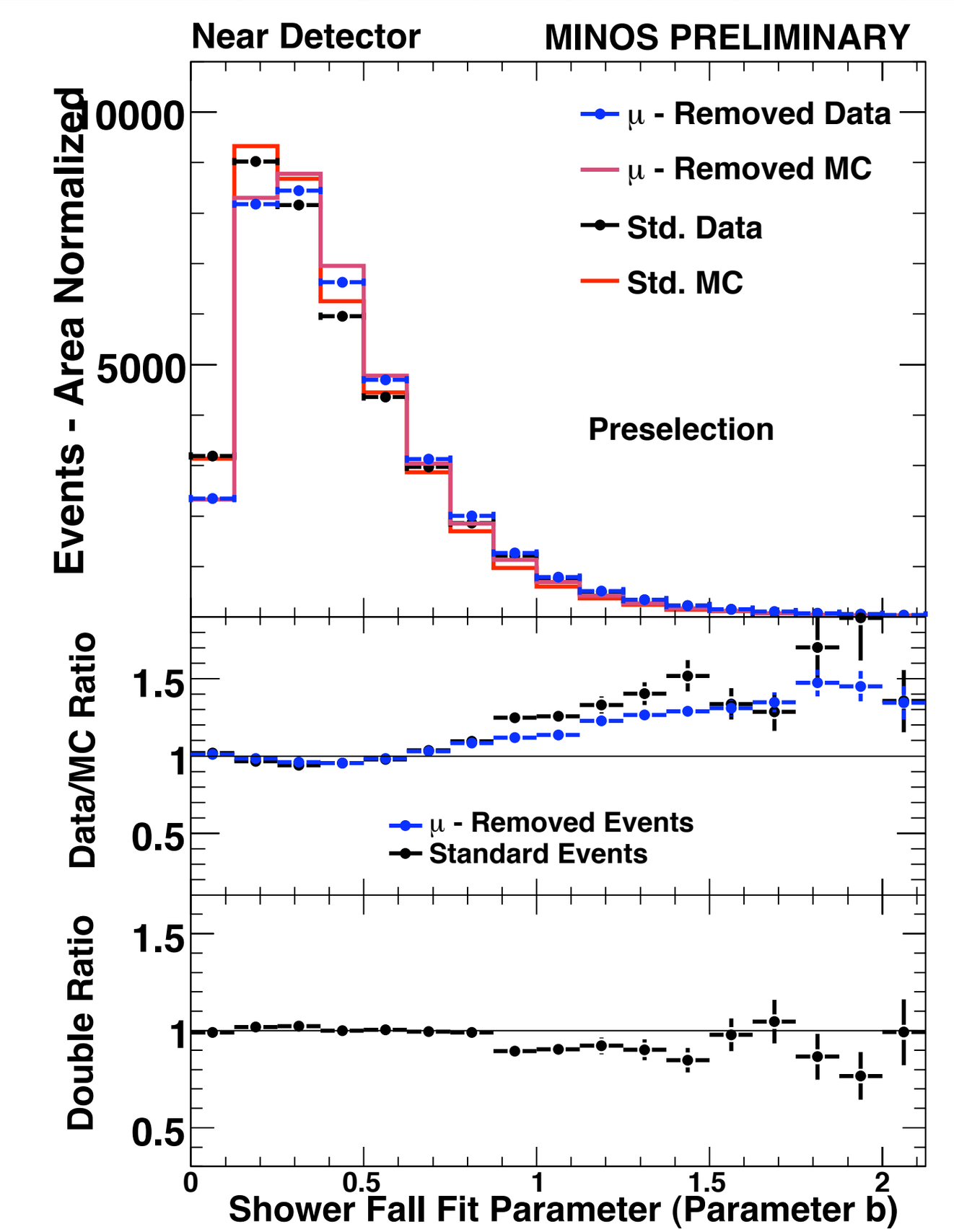
Longitudinal shape



- Fraction of pulse height in the 8 hottest hit strips for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

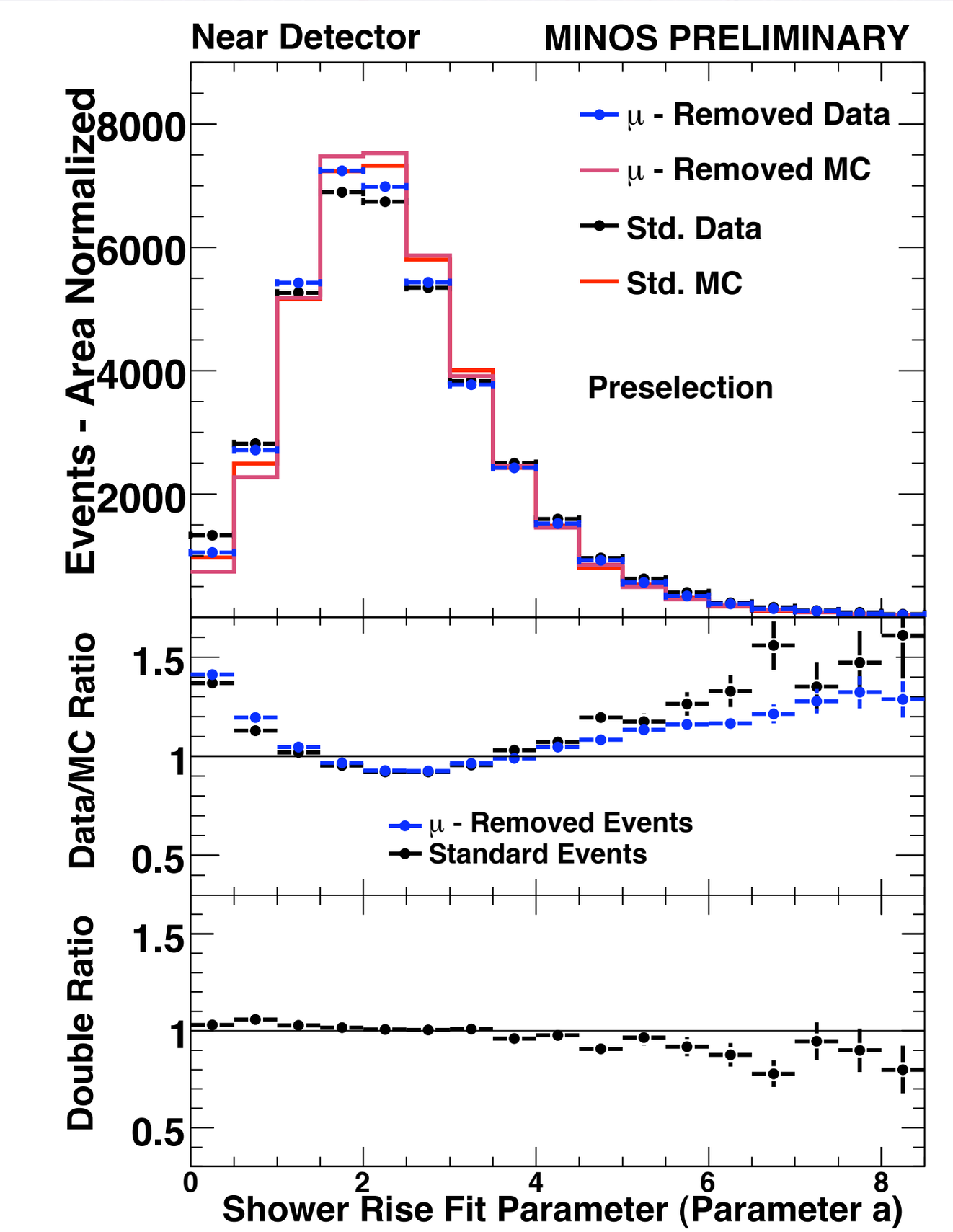
Longitudinal shape



- Parameter b from the longitudinal shower fit standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

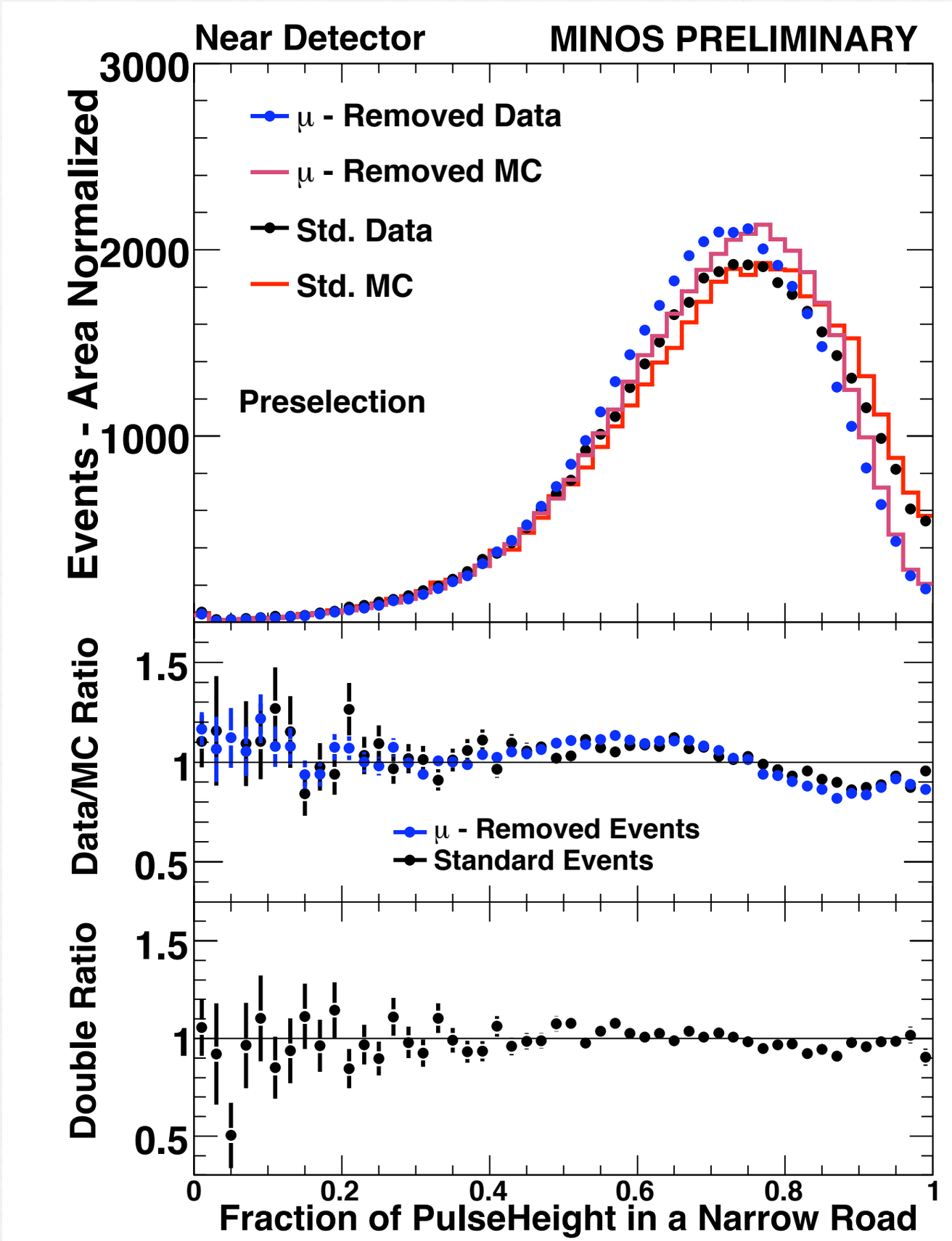
Longitudinal shape



- Parameter a from the longitudinal shower fit standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

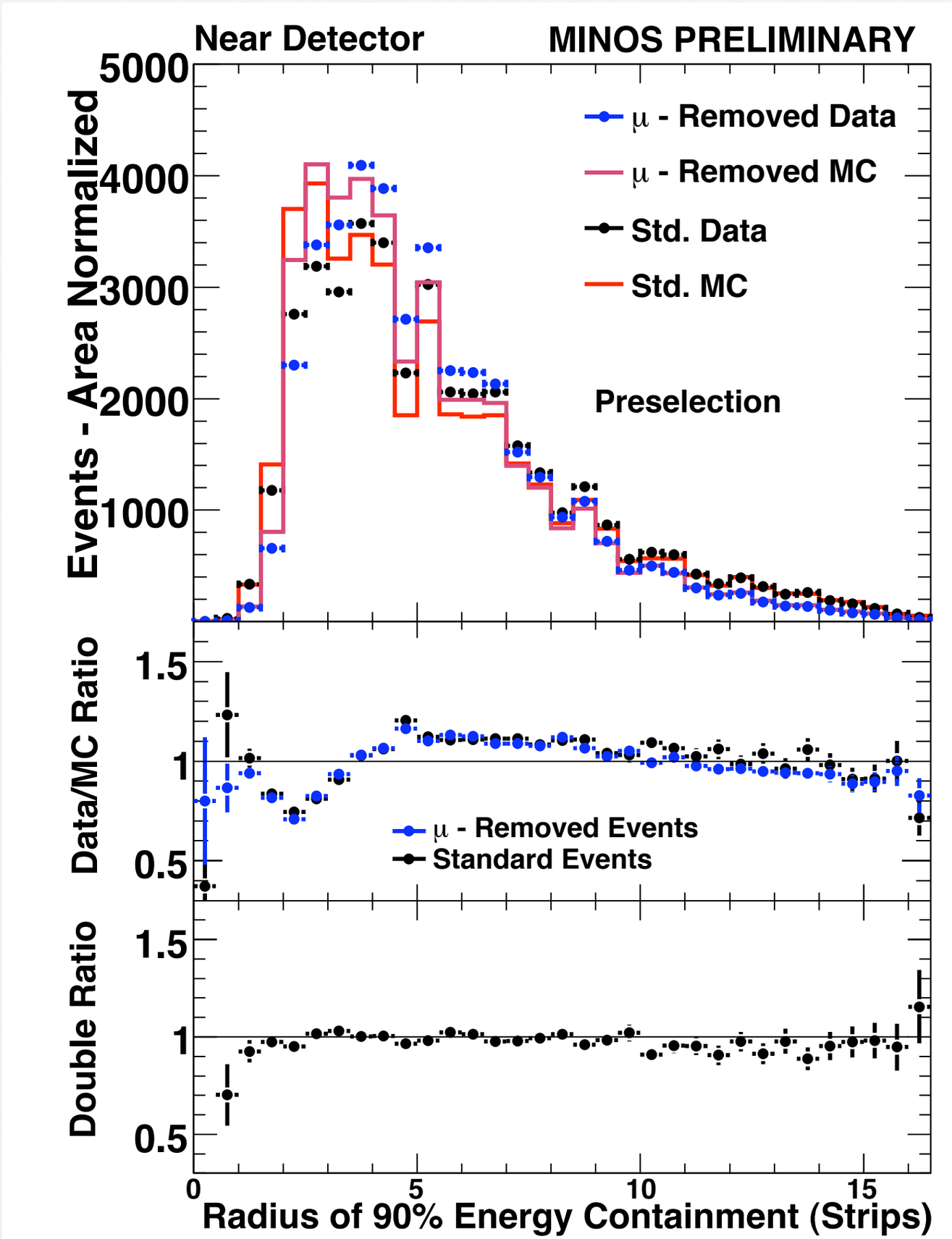
Transverse shape



- Fraction of pulse height in a narrow road for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

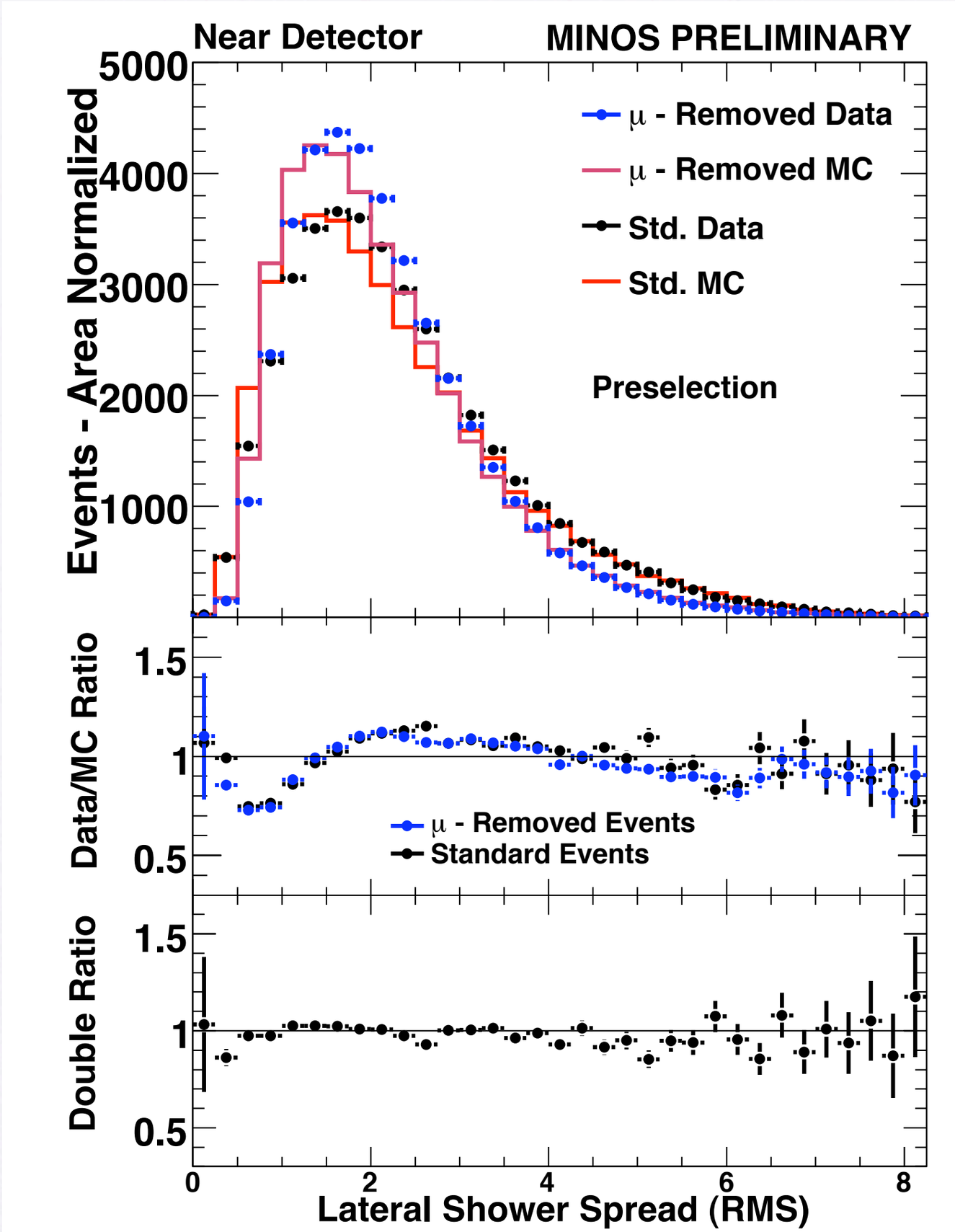
Transverse shape



- Radius of 90% energy containment in number of strips for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

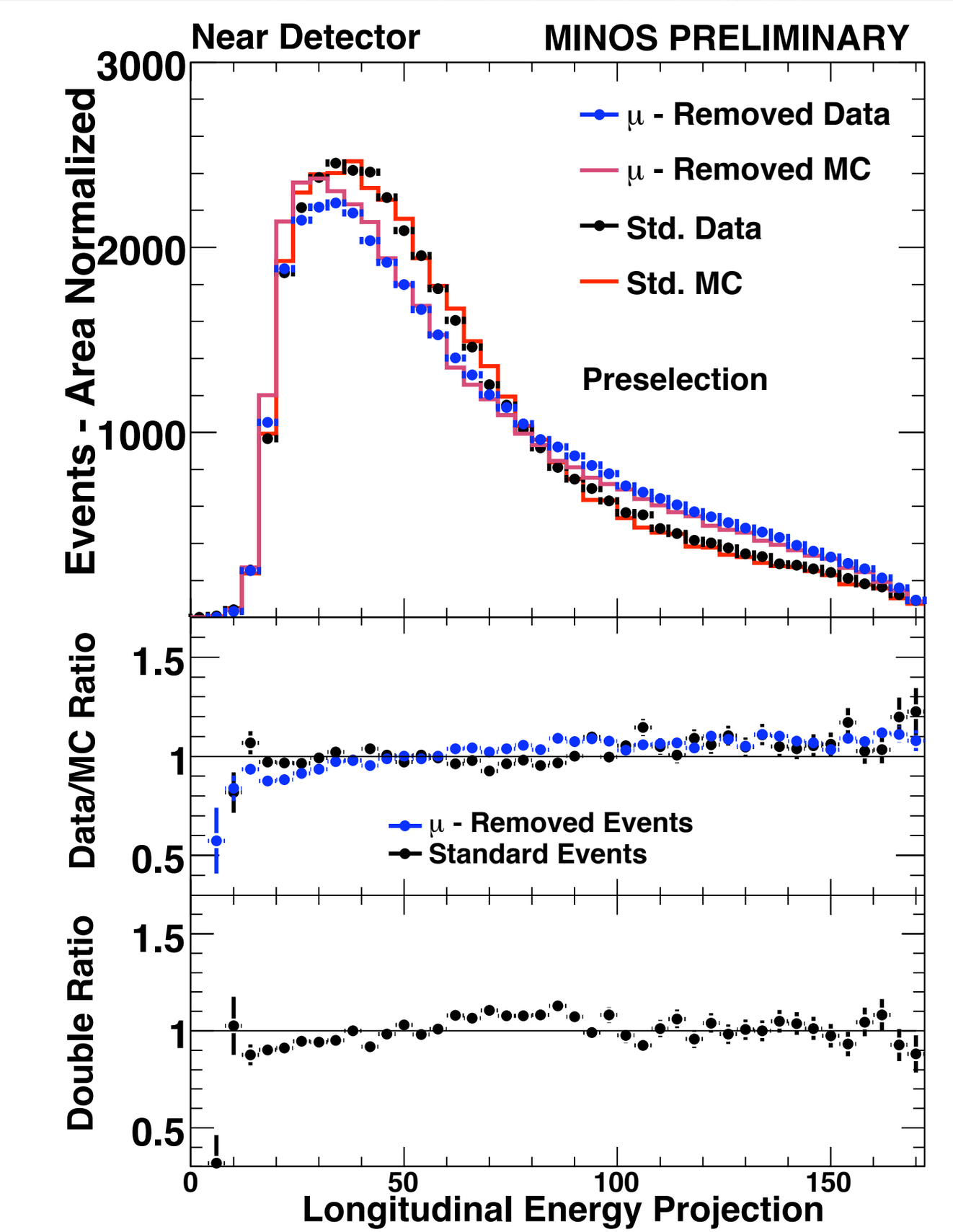
Transverse shape



- RMS in the U and V views combined for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

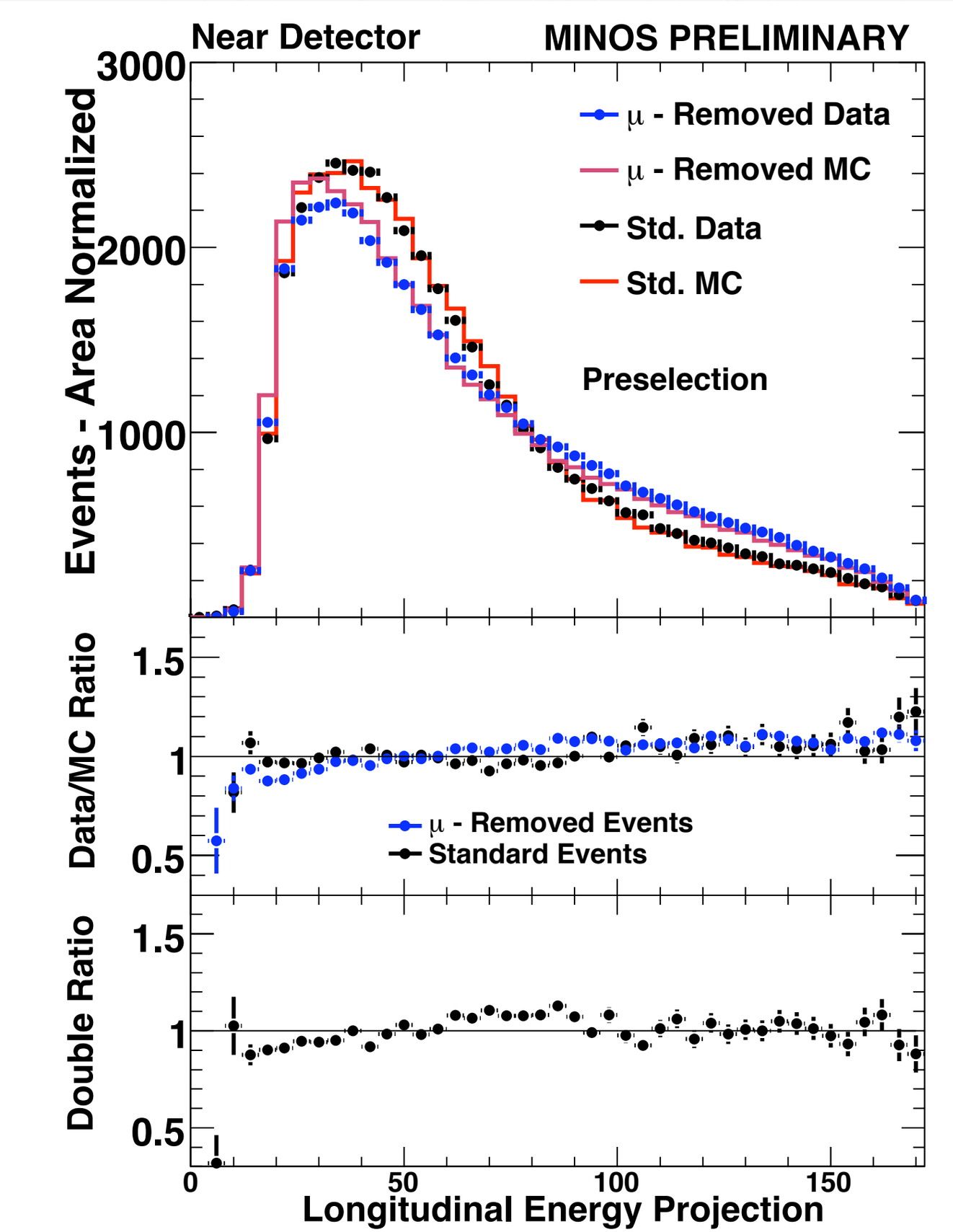
Overall shape/energy



- Energy weighted sum of the distance of each to the z-axis for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

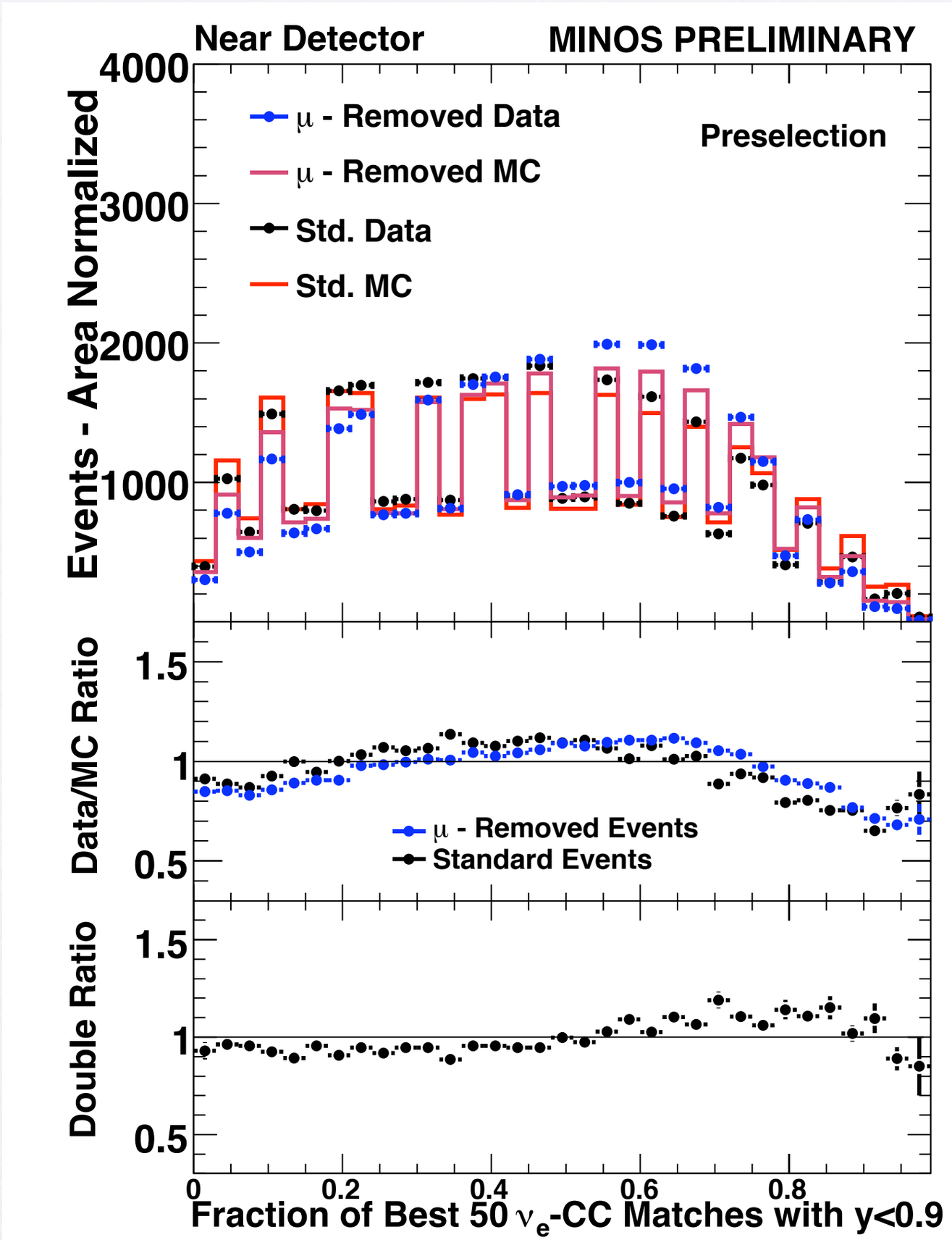
Overall shape/energy



- Sum of the minimum distances of larger than average hits for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

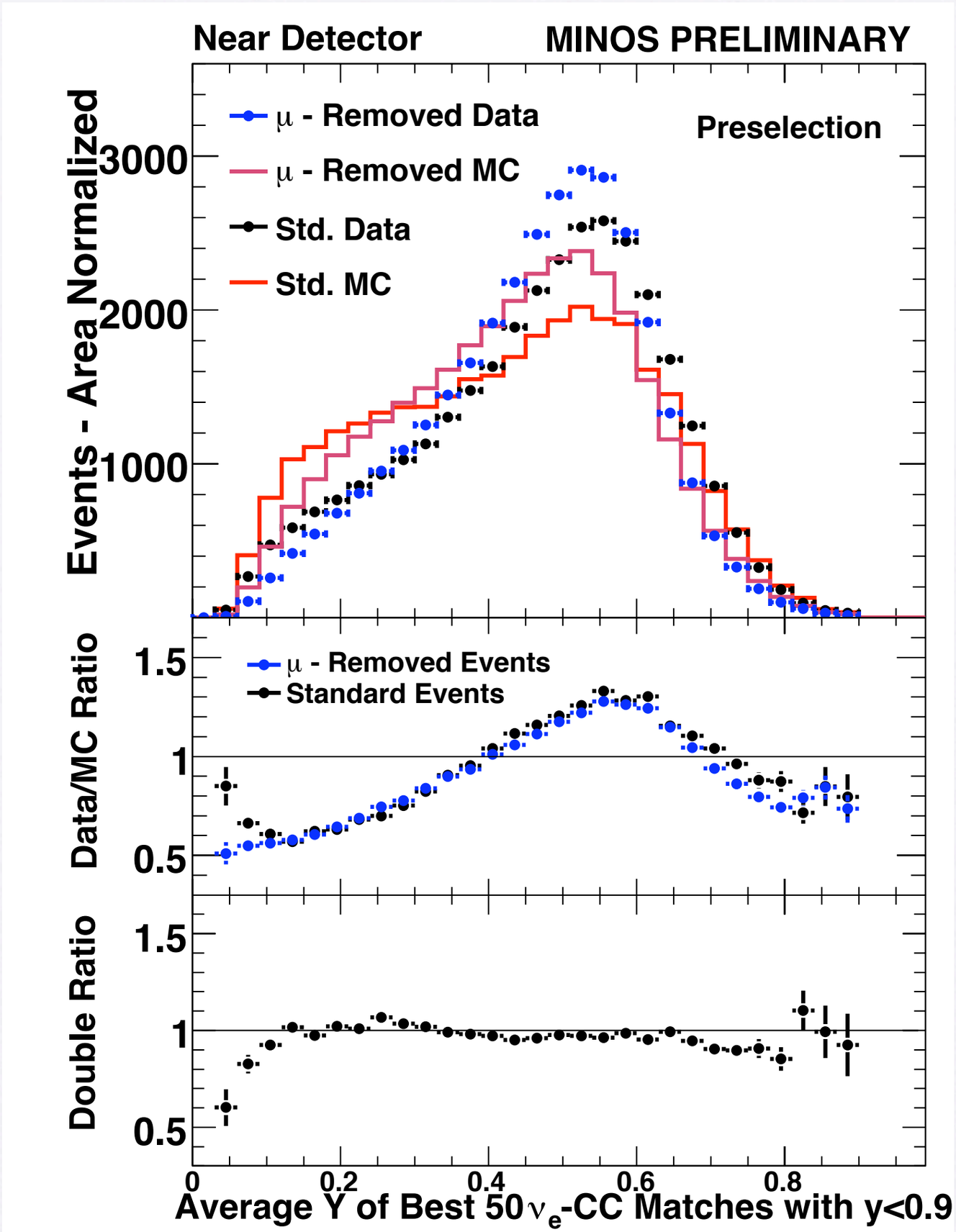
LEM input variable



- Fraction of the best 50 ν_e-CC matches with y<0.9 for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

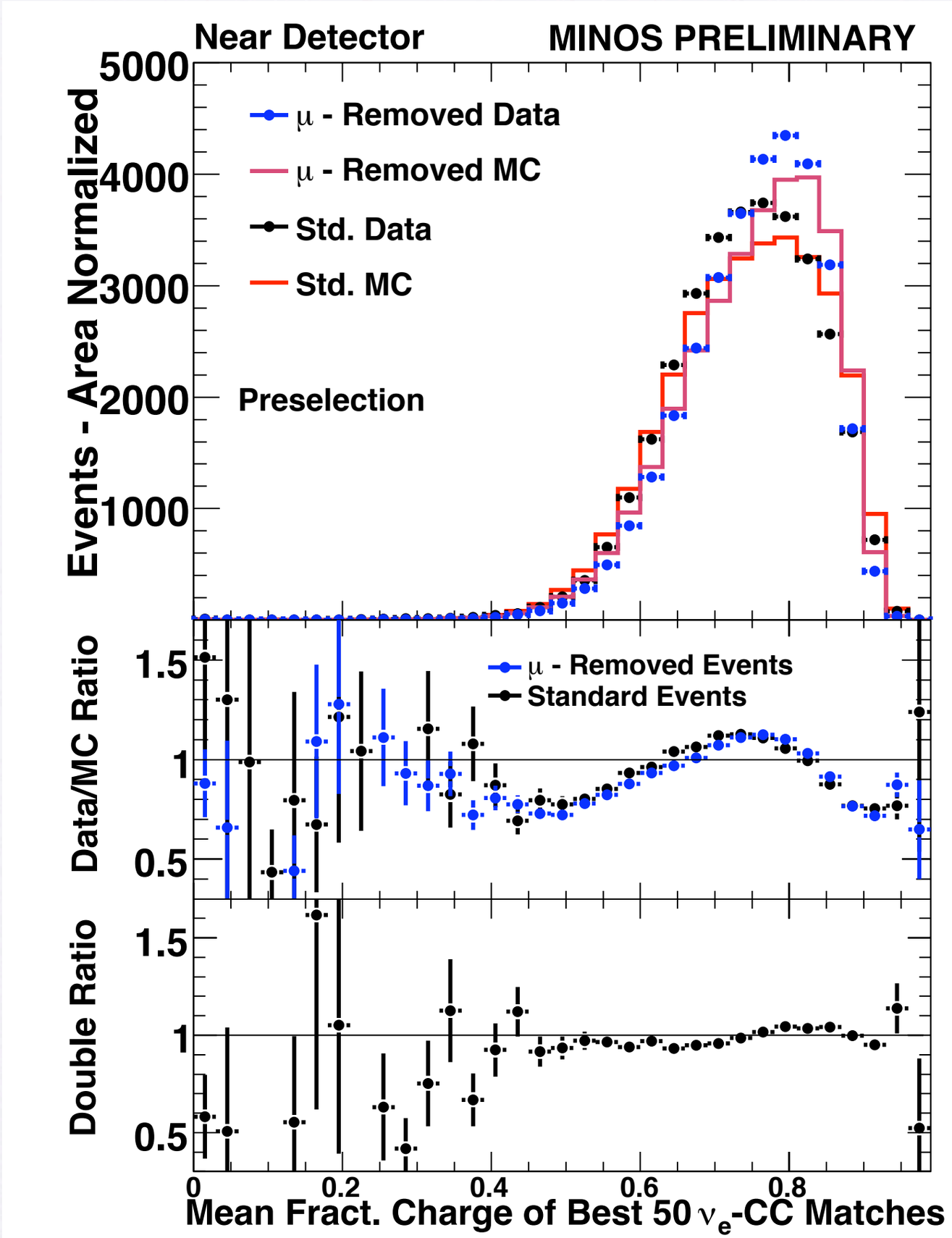
LEM input variable



- Average of the y of the best 50 ν_e-CC matches with y<0.9 for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Shower Topology

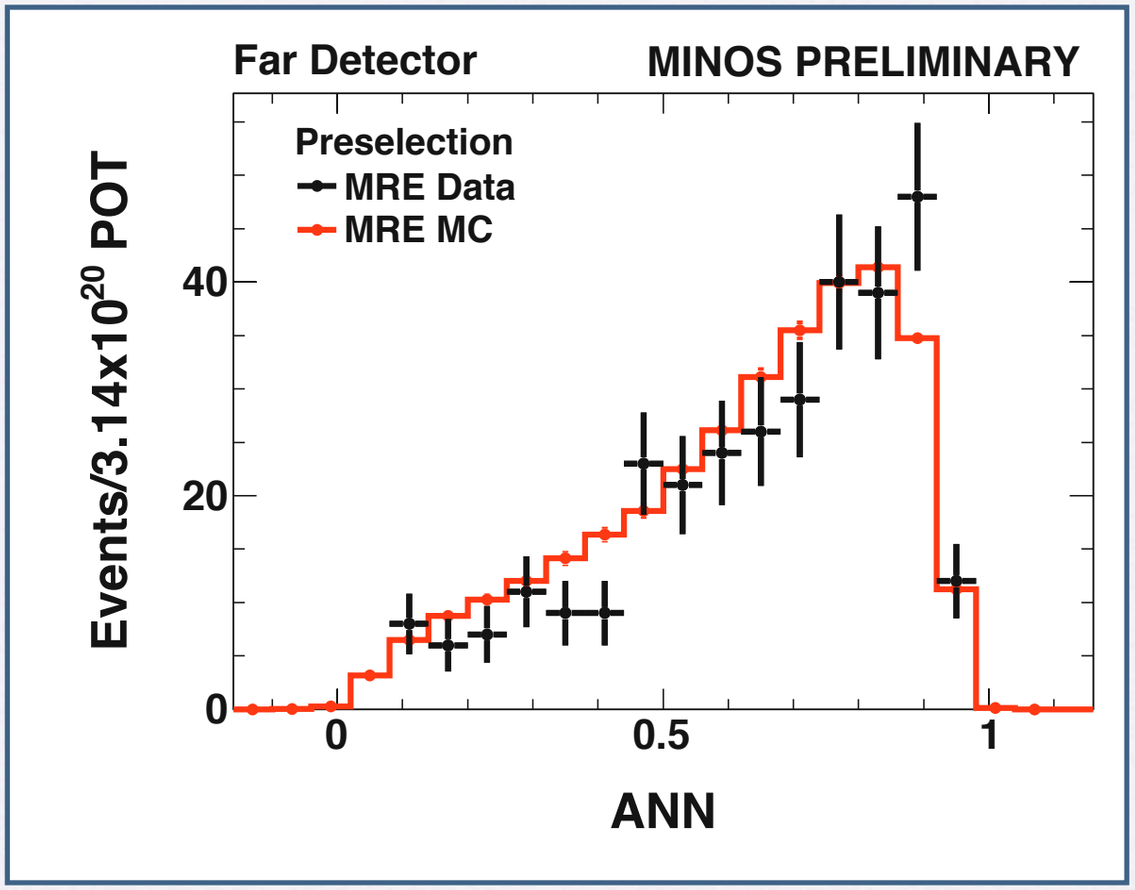
LEM input variable

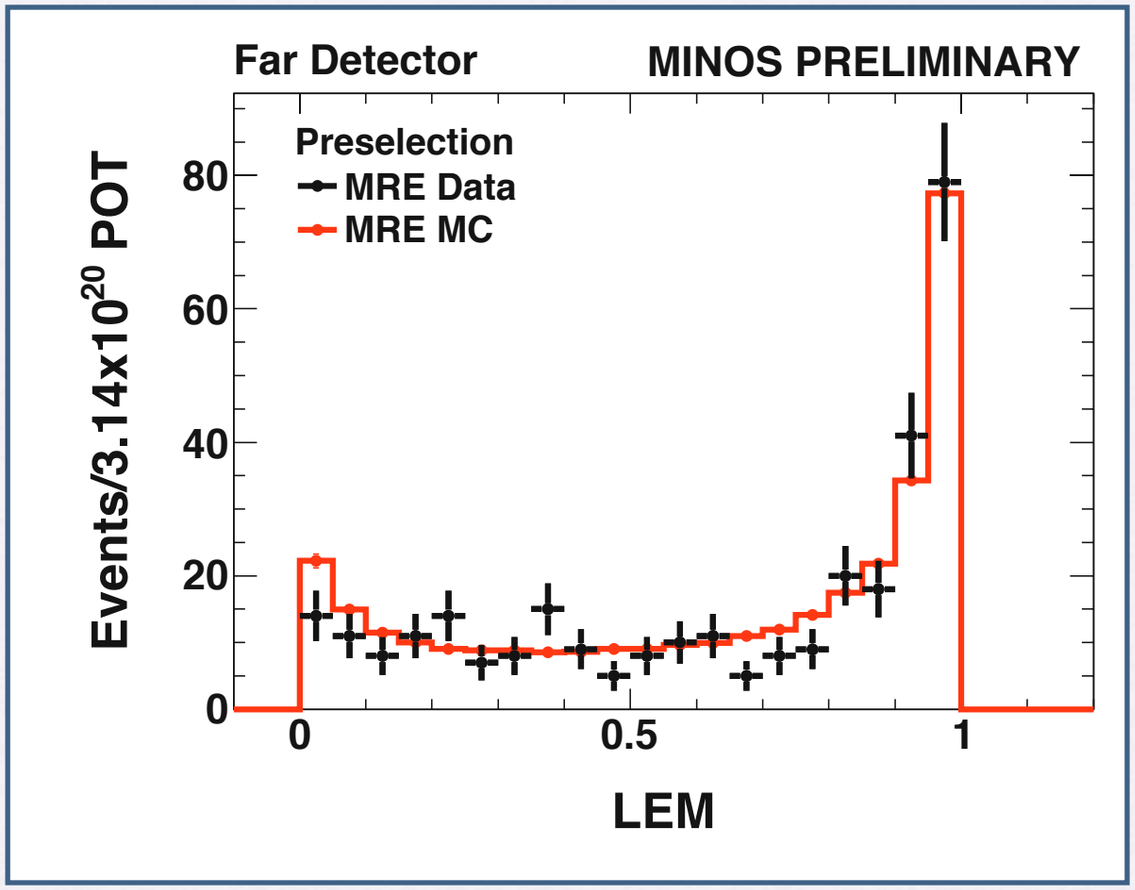


- Mean fractional charge of the best 50 ν_e-CC matches with y<0.9 for the standard ν_e selected data and the MRCC ν_e selected data and MC.
- The ratios of data/MC show the same trends particularly at the peak of the distributions.
- The double ratio shows the level of agreement.

Muon removed w/electron sideband

- Adding the electron to the muon removed events, present good agreement in PID, within 1σ.





	data	pred.	stat	sys	σ Diff
ANN>0.7	159	151	13	12	0.5
LEM>0.65	180	176	13	16	0.2

Region below signal cut

	data	pred.	stat	sys	σ Diff
ANN<0.55	146	132	12	8	1.0
0.55<ANN<0.7	46	38	6	2	1.4
LEM<0.55	176	157	13	3	1.1
0.55<LEM<0.65	12	7	3	0	1.8

MC scaled to 3.14 $\times 10^{20}$ POT

- Predictions are shown using the Horn on/off method. Results from MRCC very similar.
- Both PIDs are consistent within 1σ for the low PID region, and within 2σ for the intermediate PID region.