Use of the Near Detector in the MINOS ν_e appearance measurement

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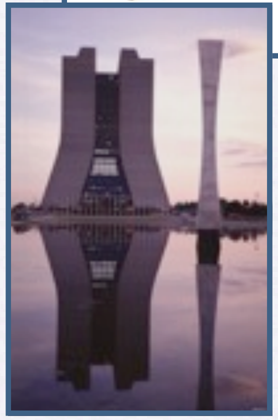
Using the MINOS ND

- Talk with different focus: the analysis experience.
  - Many slides from last Friday's W&C.
- The main analyses in MINOS use the Near Detector for several important things:
  - Relative calibration.
  - Beam uncertainties.
  - Measurement of the signal before oscillations.
- The ν_e appearance analysis is no different except it uses it to measure the background instead of the signal.

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.

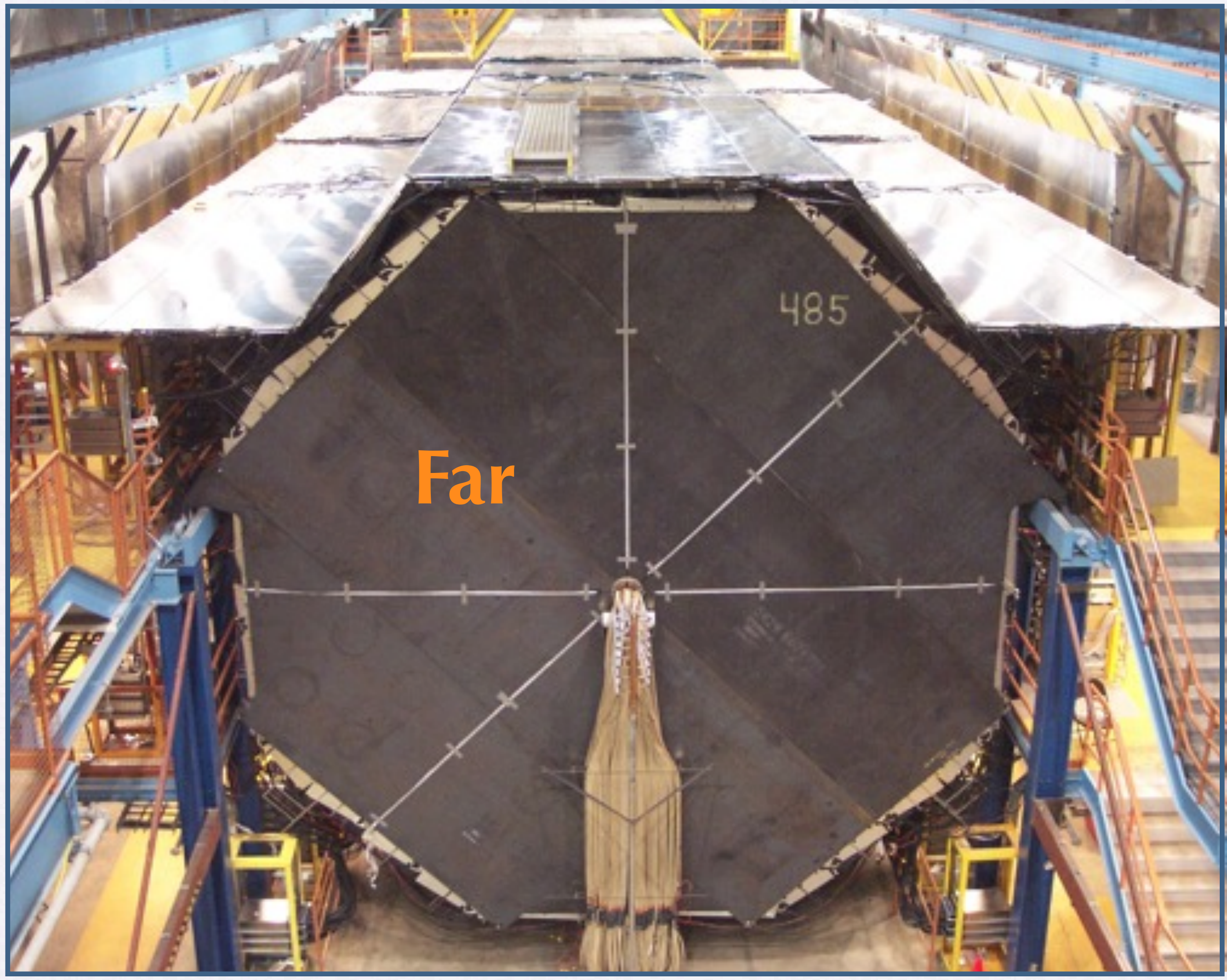


←long baseline→ concept

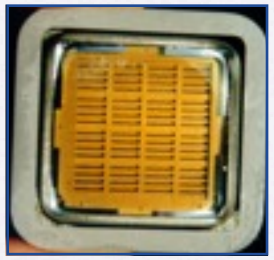
Main **I**njector **N**eutrino **O**scillation **S**earch

The MINOS detectors

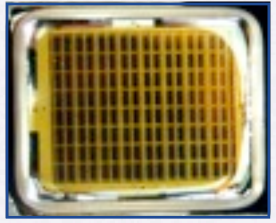
- Functionally identical: **Near and Far detectors**
- 1 inch thick octogonal steel planes, alternating with planes of 4.1cm x 1cm scintillator strips, up to 8m long. Magnetized.
  - **Near**: ~ 1kton, 282 steel squashed octagons. Partially instrumented.
  - **Far**: 5.4 kton, 486 (8m/octagon) fully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



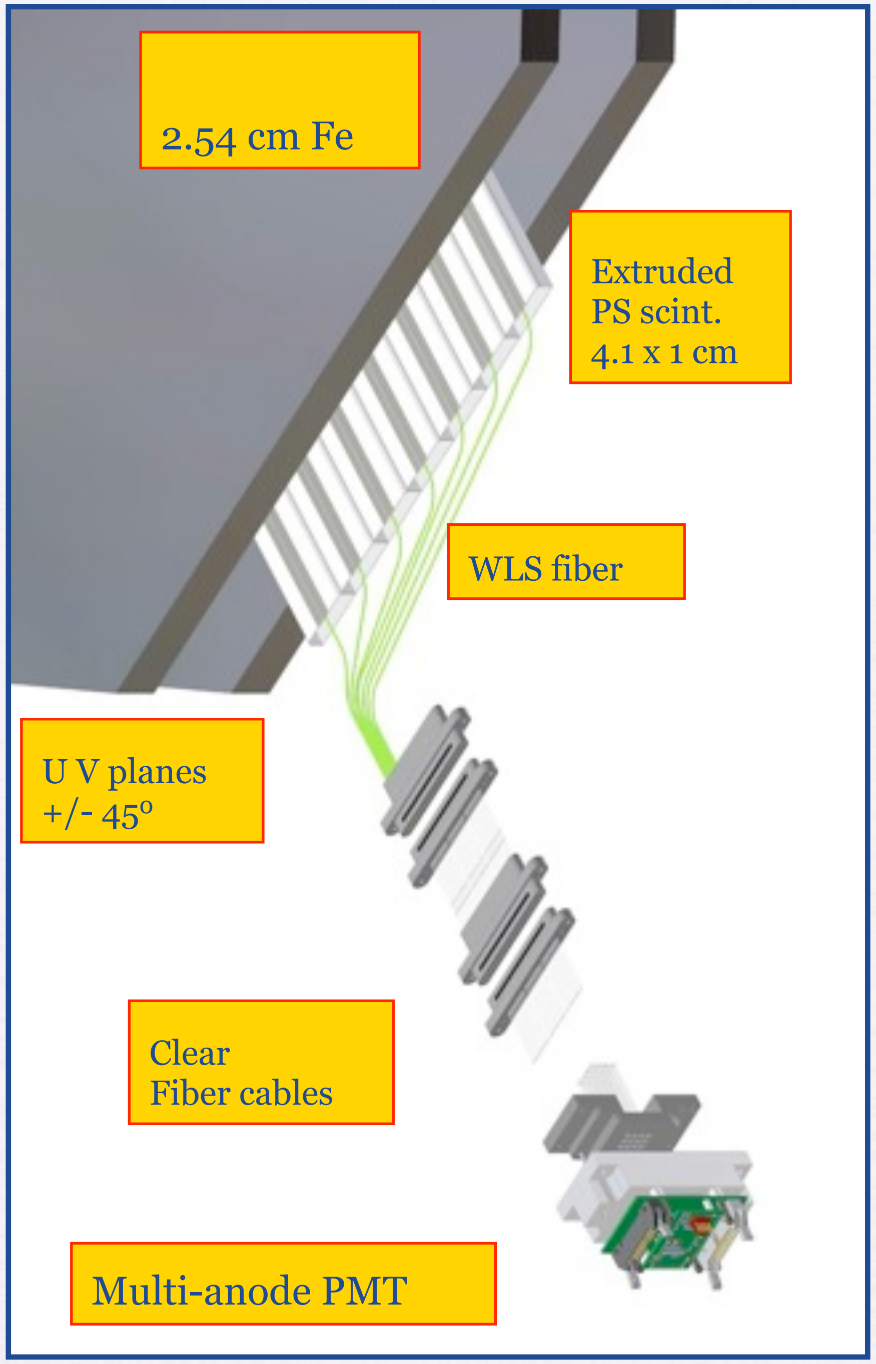
MINOS detector technology



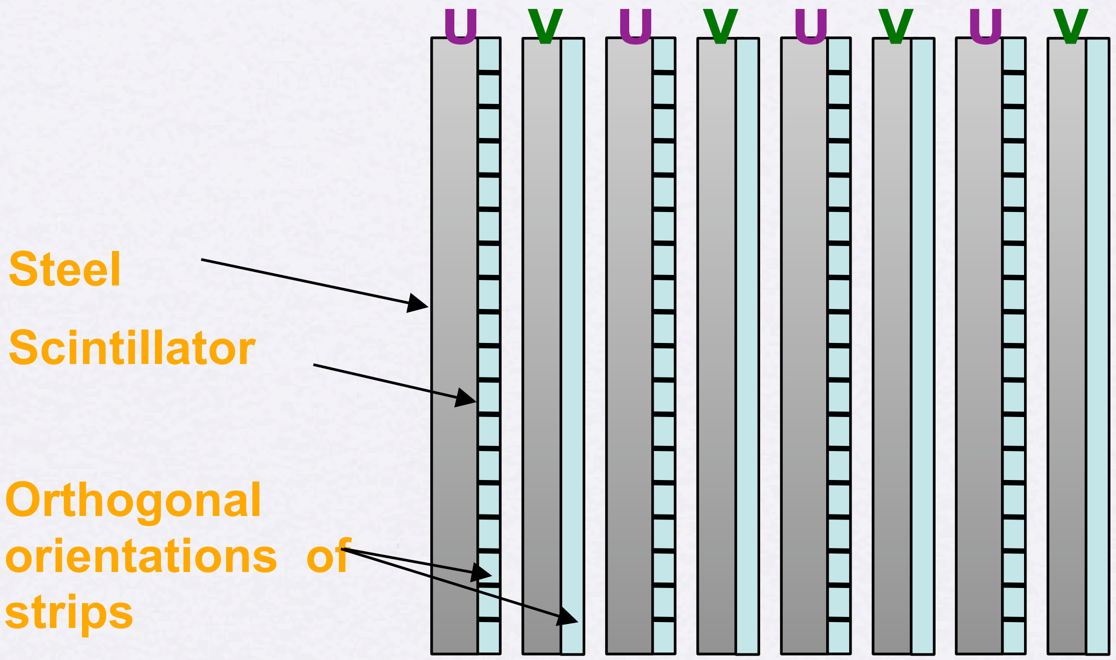
M16



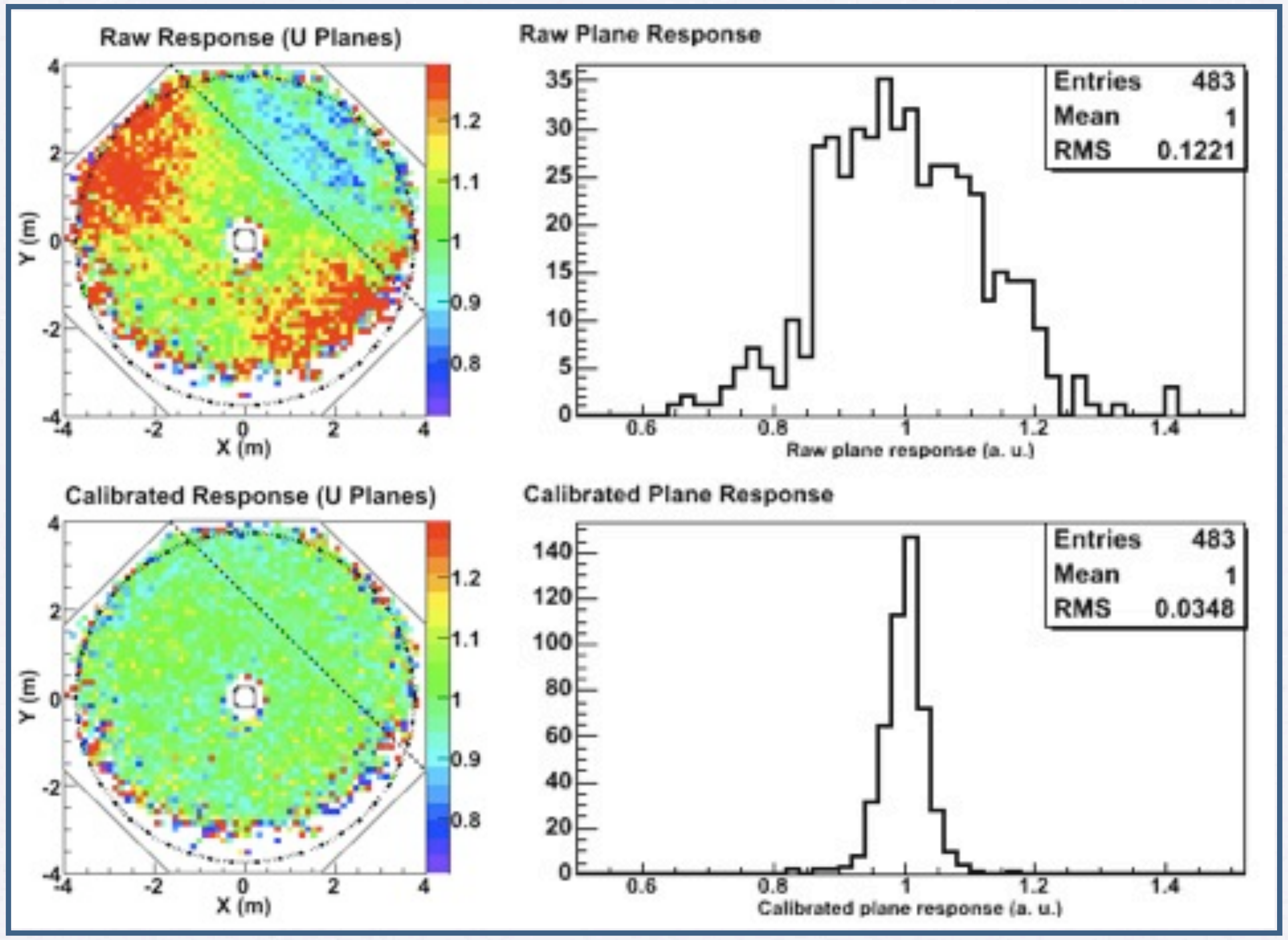
M64

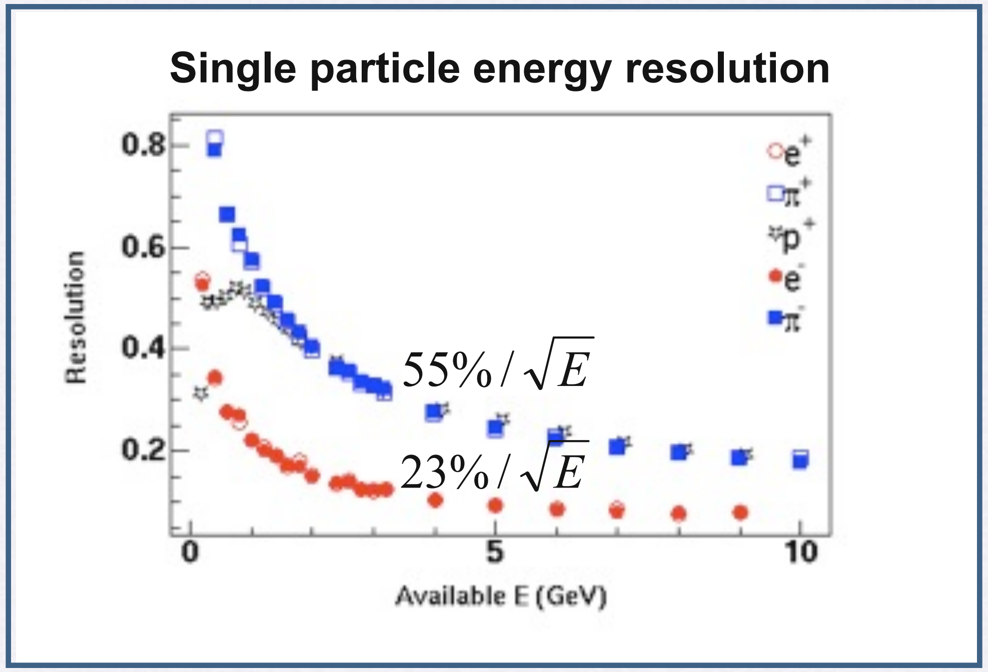


- **In both detectors:**
  - co-extruded polysterene scintillator strips
  - orthogonal orientation on alternate planes - U, V
  - optical fiber readout to multi-anode PMTs (M64 for the ND, M16 for the FD)



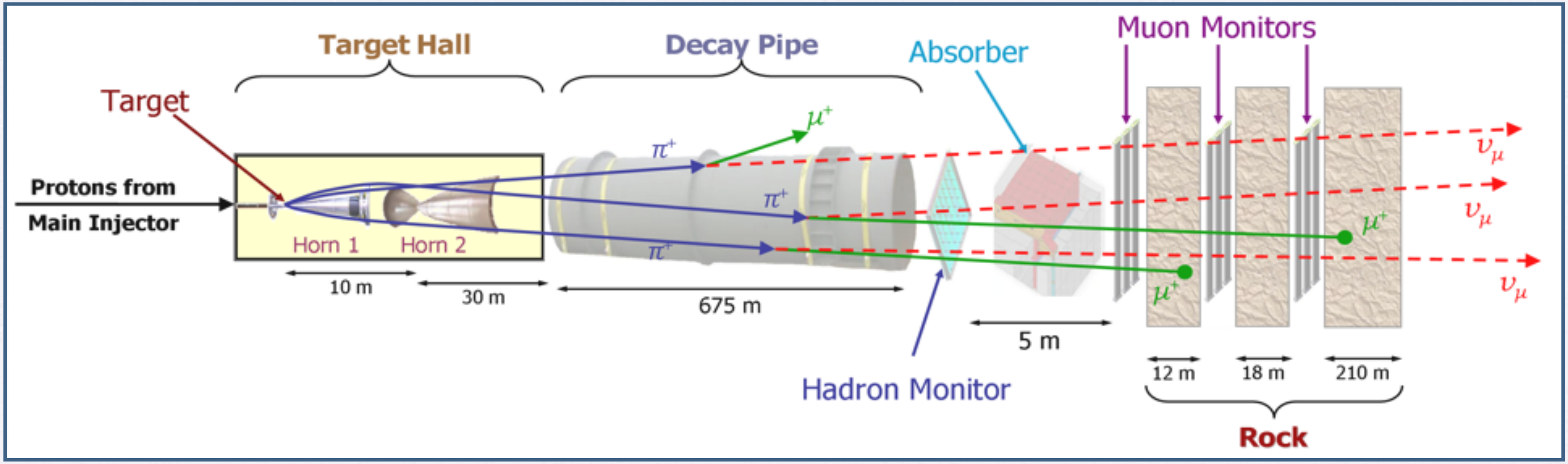
MINOS calibration system



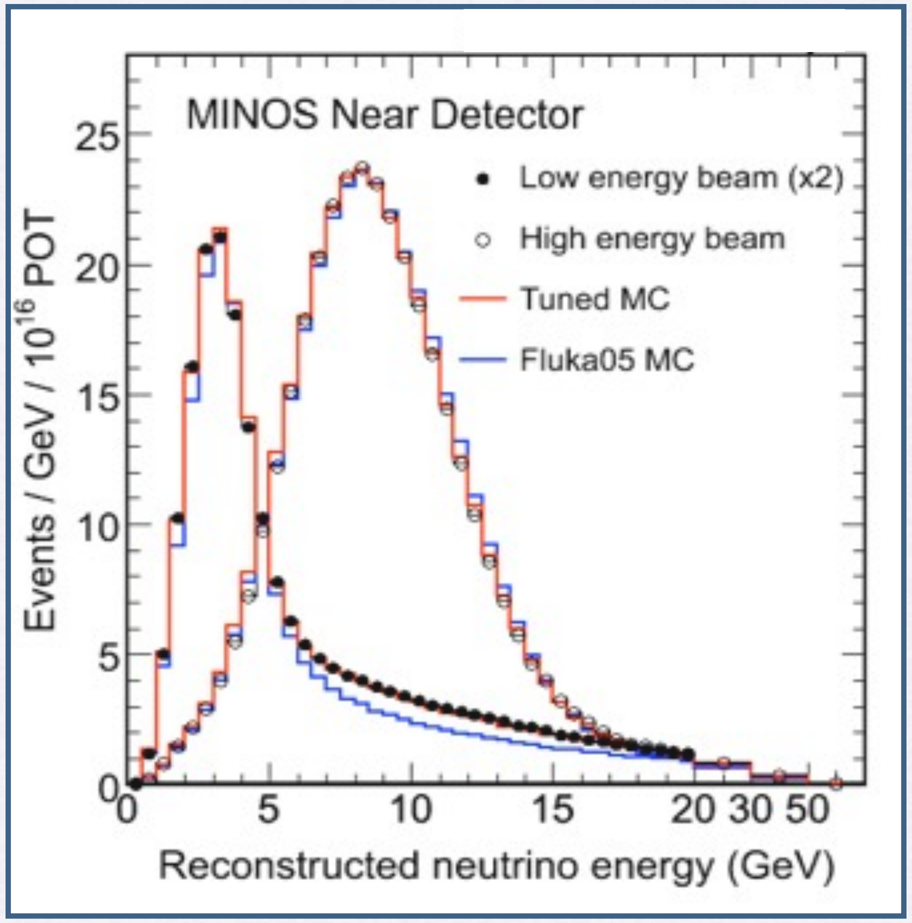


- Calibration of ND and FD response using:
  - Light Injection system (PMT gain)
  - Cosmic ray muons (strip to strip and detector-to-detector)
  - Calibration detector (overall energy scale)
    - mini-Minos in a CERN test beam (CalDet)
- Energy scale calibration:
  - 3.1% relative error in ND
  - 2.3% relative error in FD
  - ND-FD relative: 3.8%

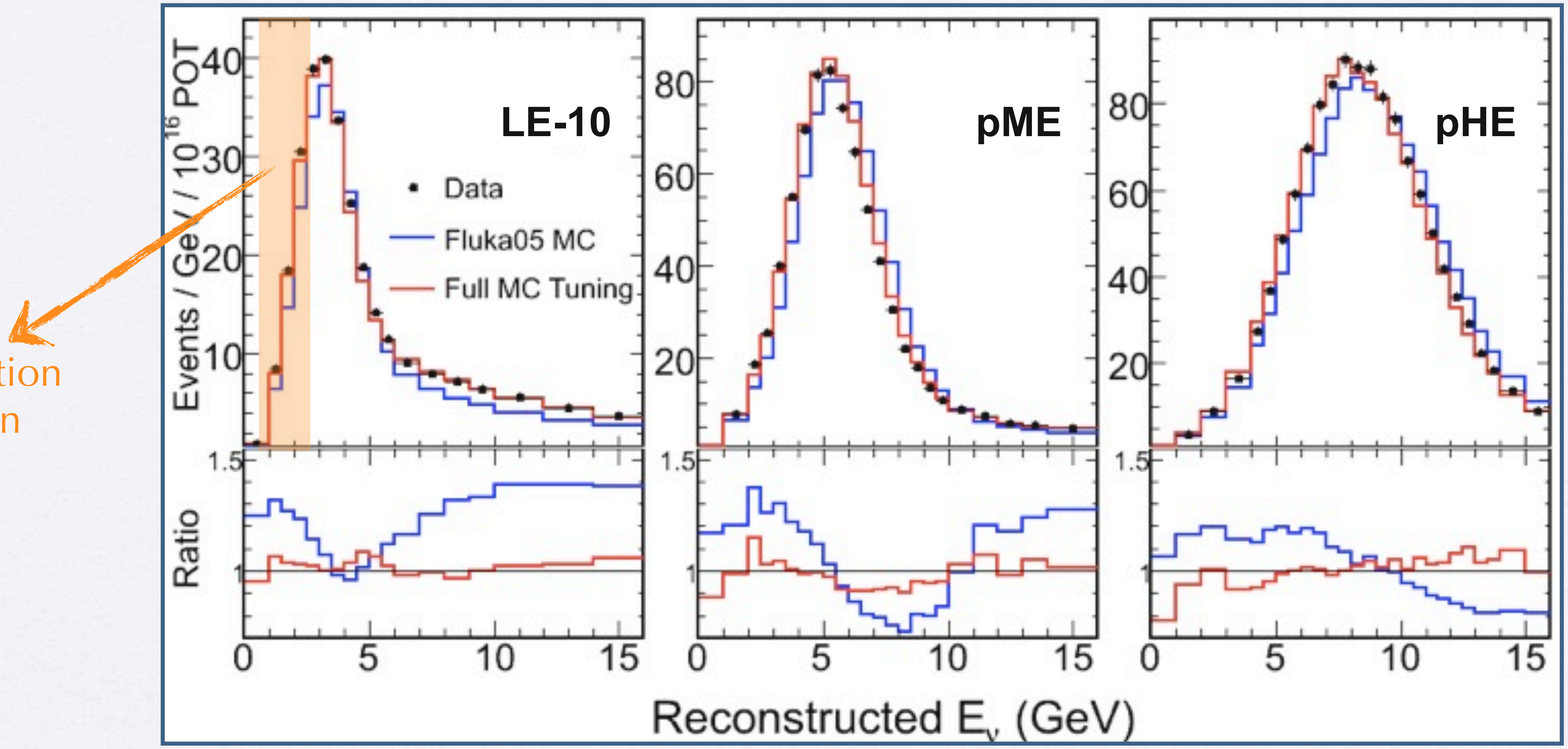
Producing neutrinos



- **Neu**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.



Reconstructed Beam Spectrum



Oscillation region

-10 cm, 185 kA

-100 cm, 200 kA

-250 cm, 200 kA

Discrepancies between data and Fluka05 Beam MC vary with beam setting: so source is due to beam modeling uncertainties rather than cross-section uncertainties.

MC tuned by fitting to hadronic x_F and p_T over 7 beam configurations (3 shown here).

LE-10 Data/tuned MC agree to ~5%.

Worse agreement for higher energy beams.

See Zarko's talk for details

on this tuning and errors.

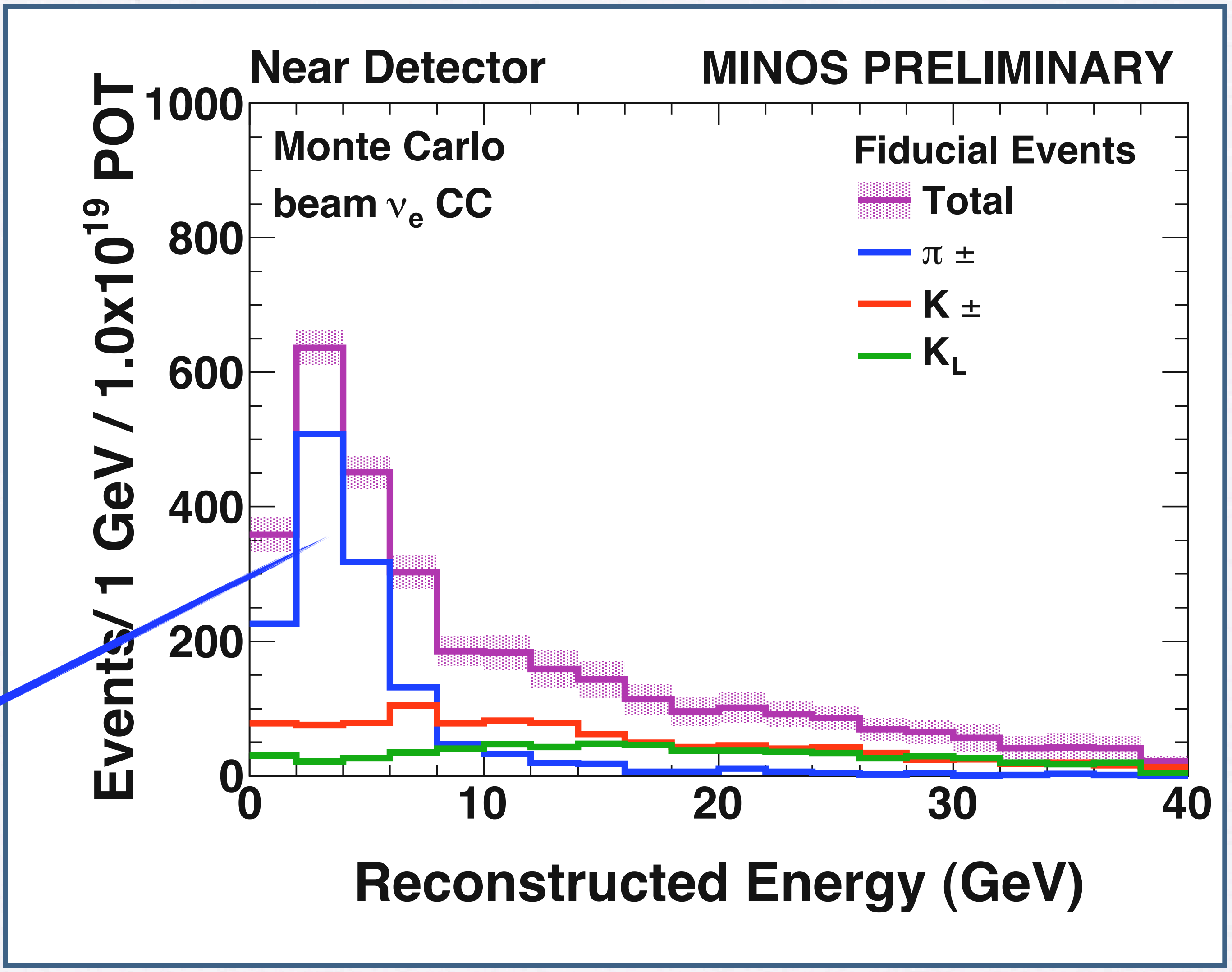
- **Lesson: LE better understood, increase your flux below 1GeV.**

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:

$$\begin{aligned}\pi^+ \quad &\rightarrow \quad \mu^+\nu_\mu \\ &\quad\ \hookrightarrow e^+\bar{\nu}_\mu\nu_e\end{aligned}$$

- 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%. After nue selection 9% in the Near, 13% in the Far.



- **Note off-axis beam would be dominated by kaons, less well known.**
- **Lessons:**
- **use same axis for the ND if you want to measure your beam ν_e.**
- **if kaons are dominant you will need to constrain them separately, miniboone high?**

Looking for ν_e

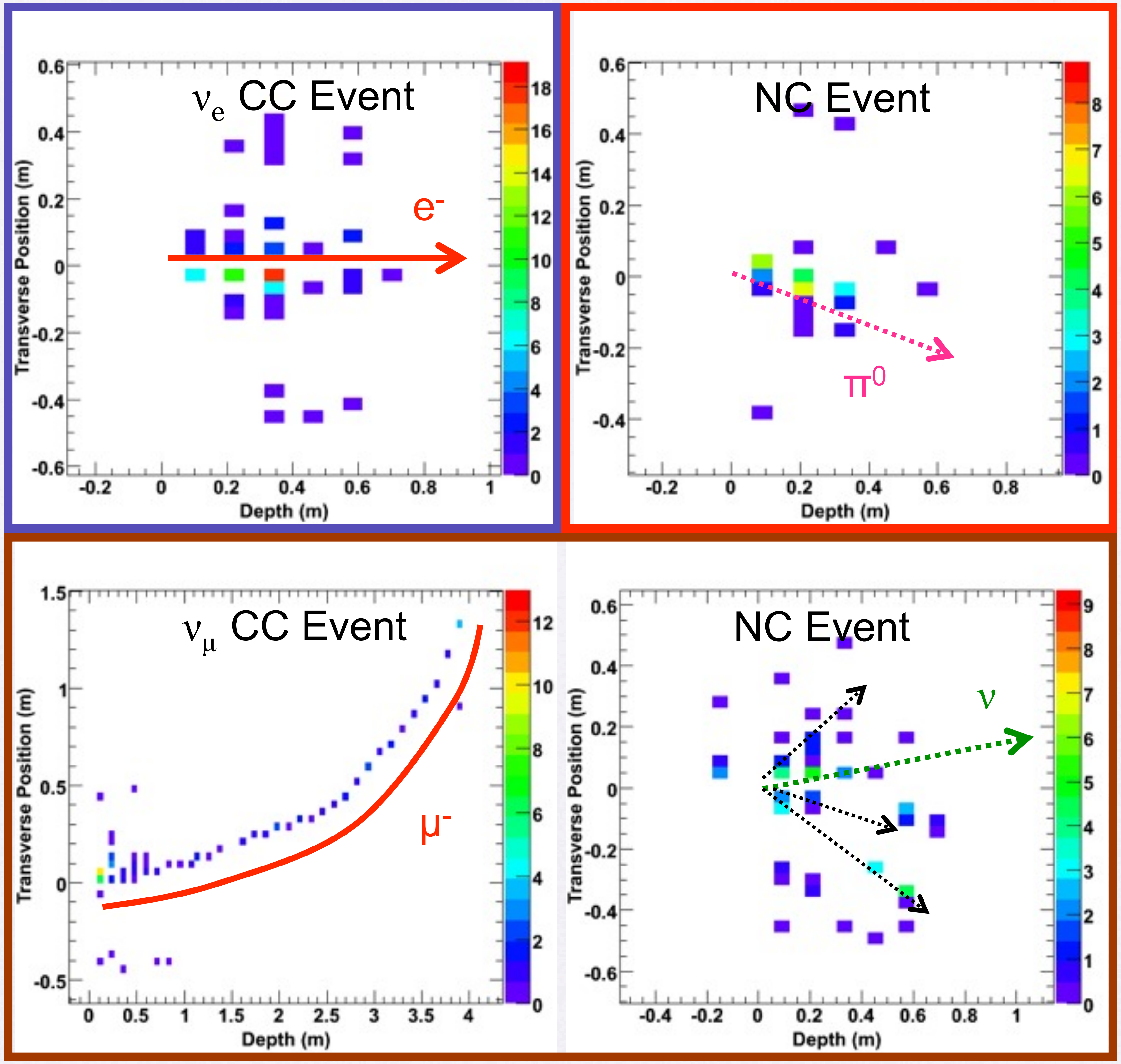
To select ν_e CC we focus on finding compact showers.

Signal

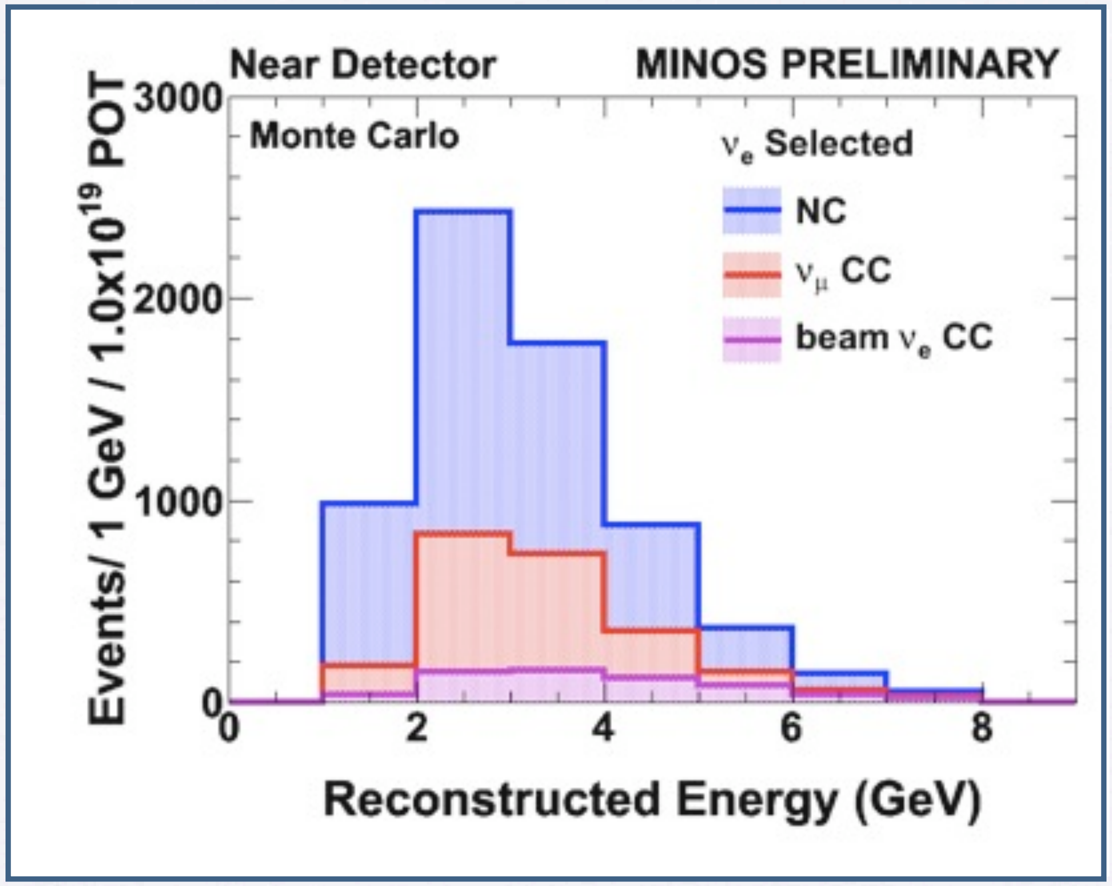
Irreducible Background

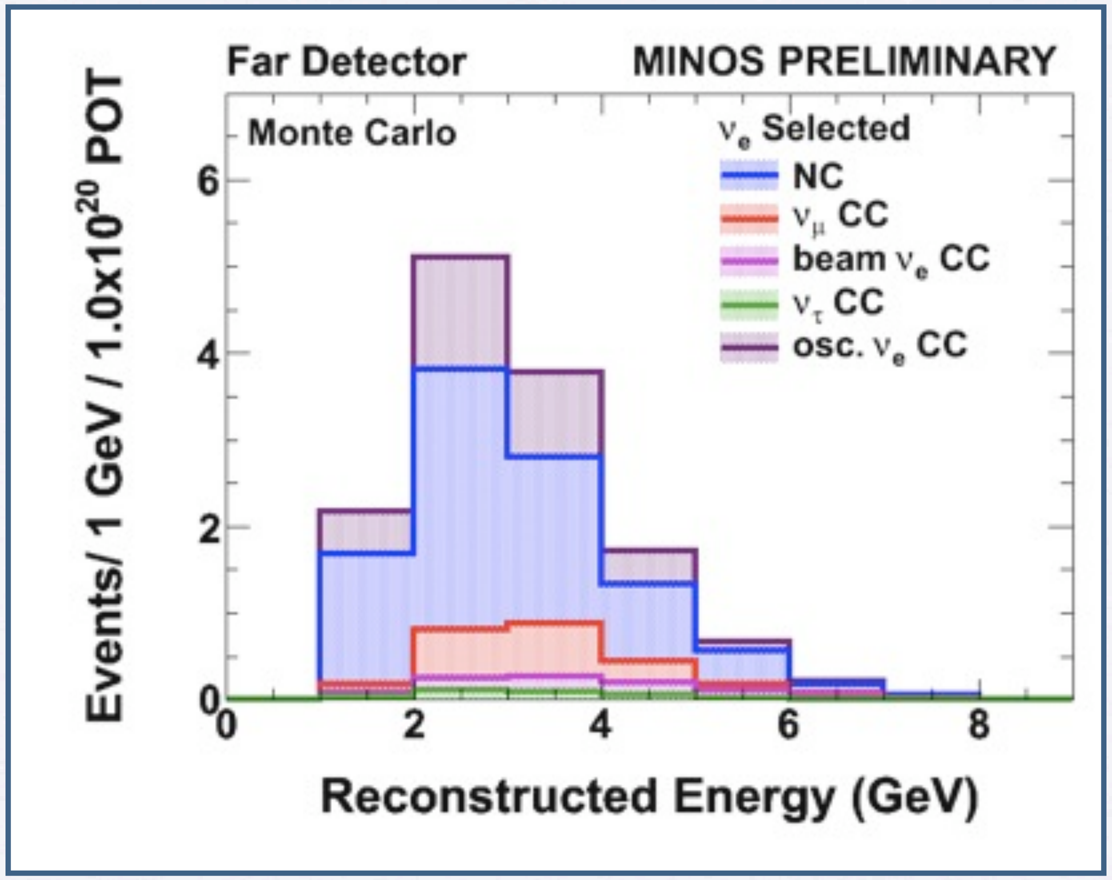
Reducible Background

Monte Carlo events



ν_e appearance in MINOS

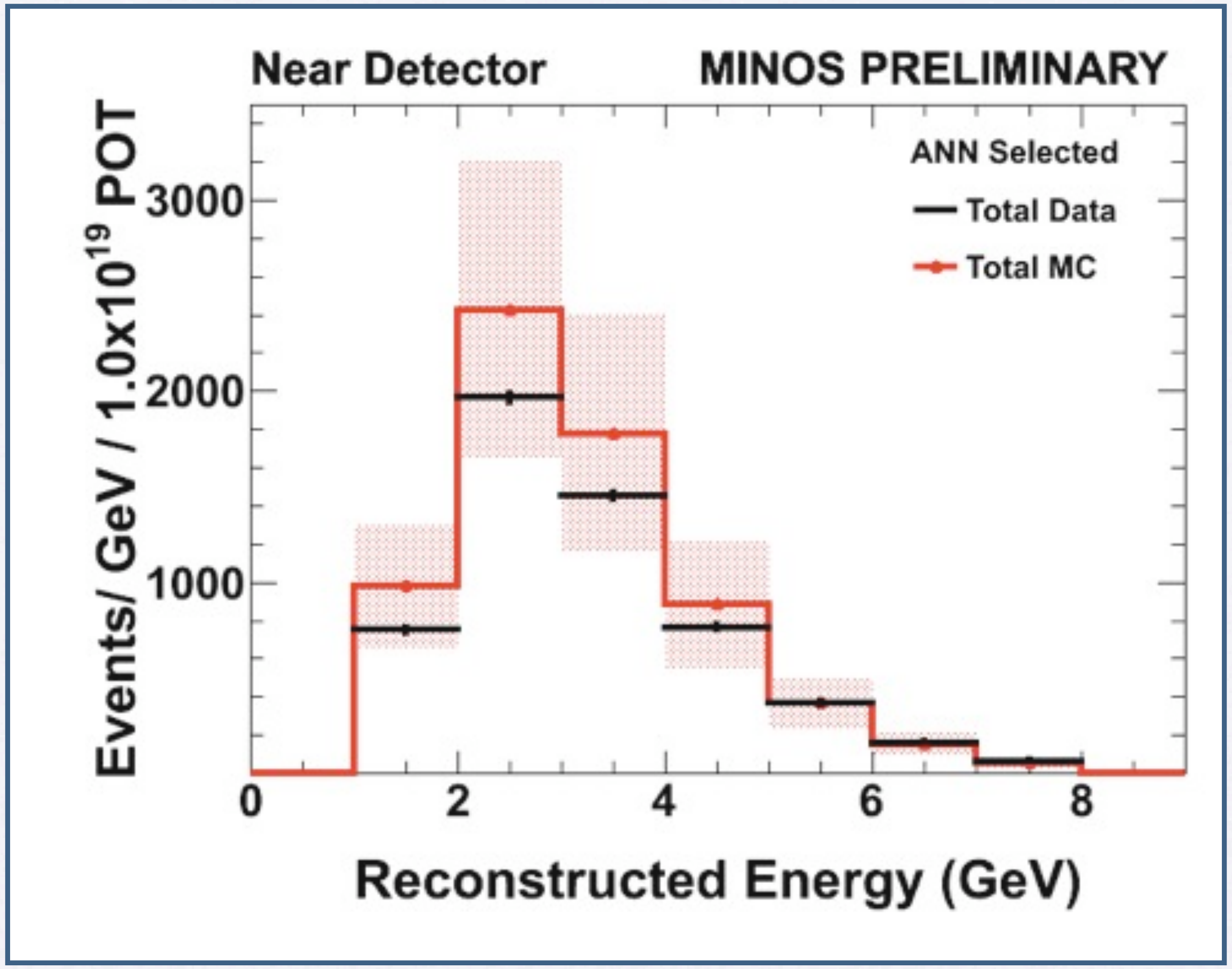




- When **selecting ν_e event candidates** in the Near Detector we will have a mix of components that do not extrapolate in the same way to the Far Detector.
- We need to **separate the main background components** NC, ν_μ CC and beam ν_e CC events, in the Near Detector.
- Then **extrapolate the background 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.
  - **Lesson: use same target mass, minimize Far/Near differences.**

ν_e selected Near Detector data

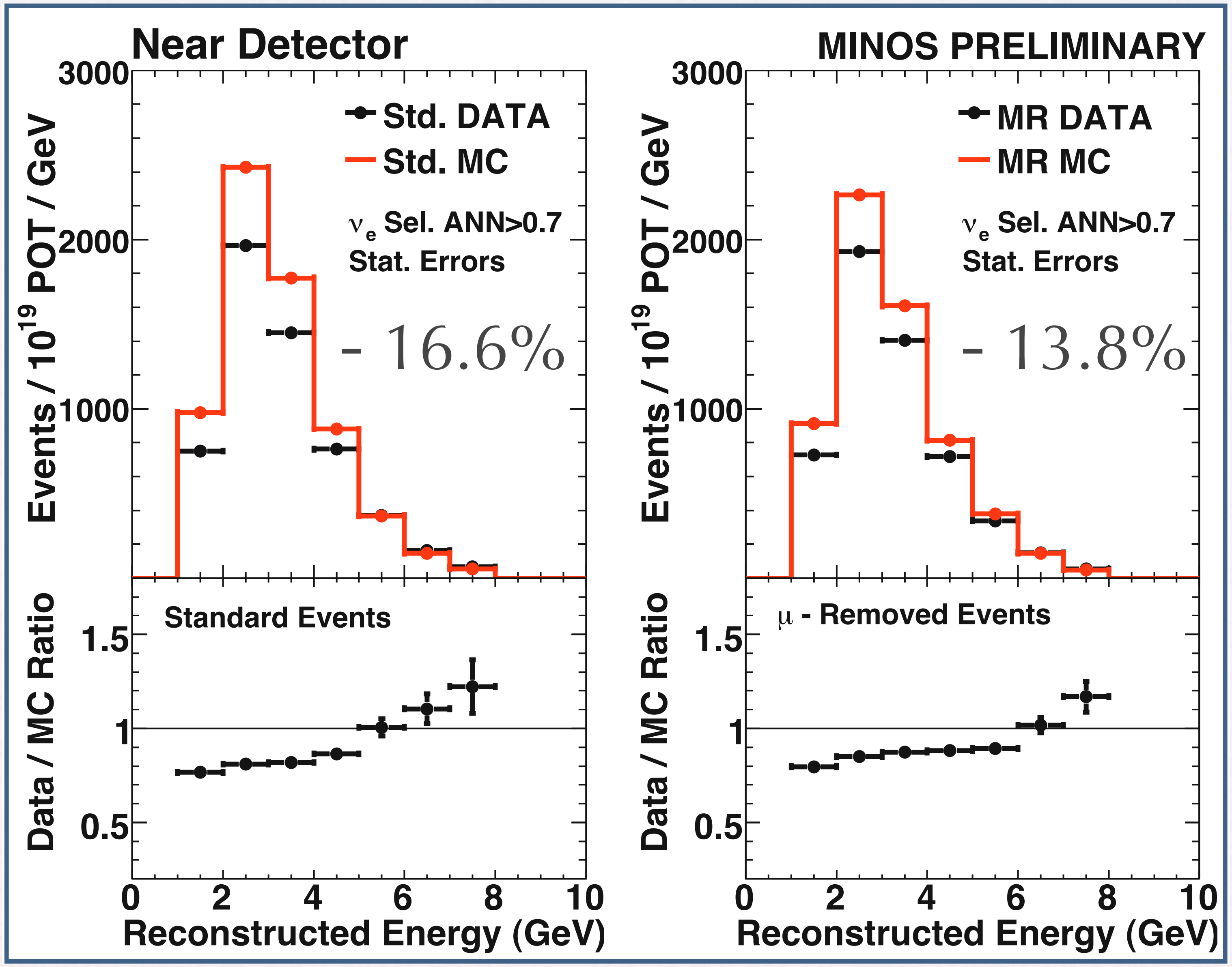
- MC tuned to external bubble chamber data for hadronization models.
  - External data sparse in our kinematic range.
  - Strong background rejection leaves just tails of distributions.
- It is not surprising that the data/MC shows disagreement with the model.
- Discrepancy is within the large uncertainties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



- **Lesson: Measure your background with same target mass, don't trust the MC.**

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

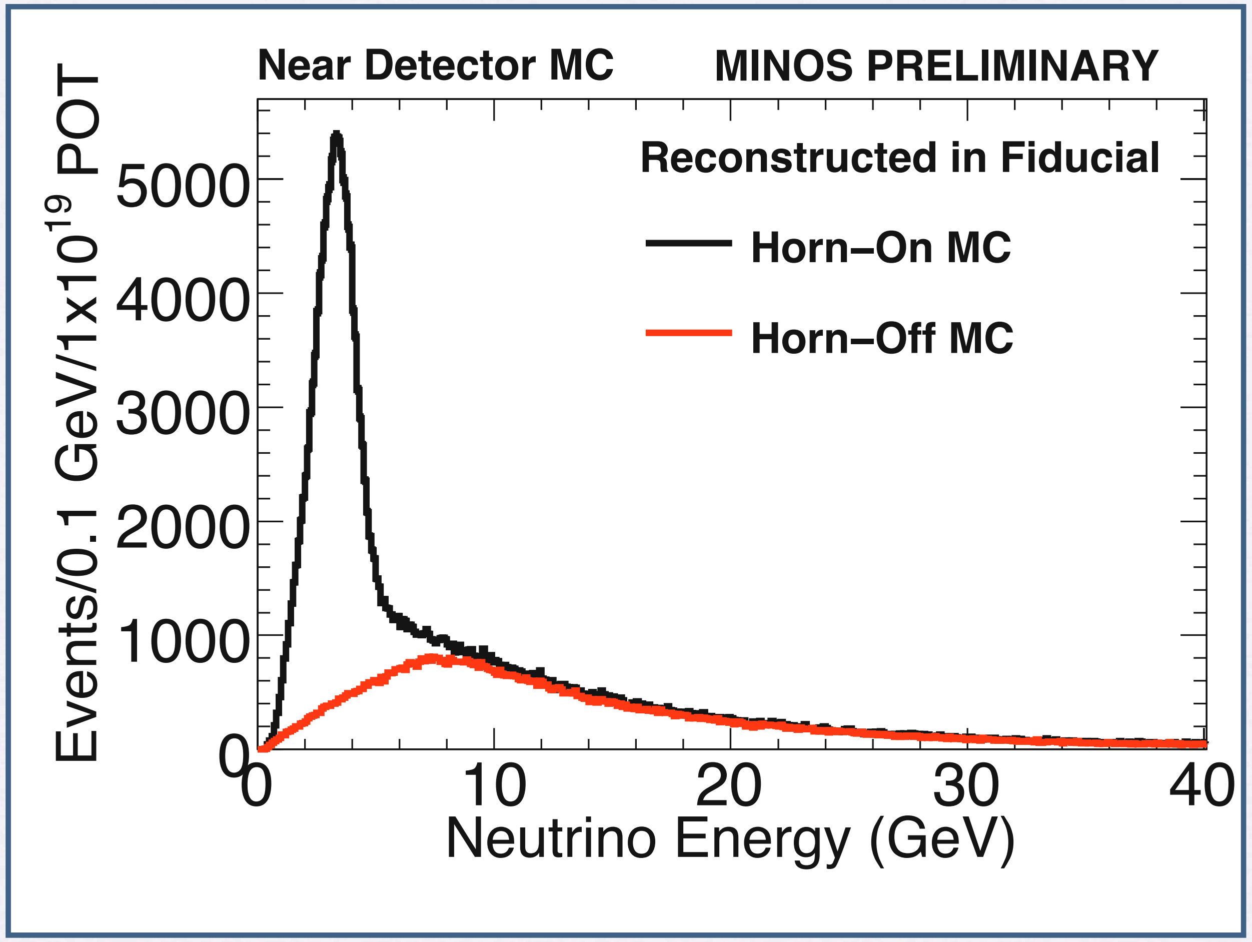
- We apply the ν_e selection to the standard data and MC as well as to the Muon Removed data and MC.
- Discrepancy with the model shows the same trend not only in energy but in shower topology for both sets.
- Thus modeling of the hadronic shower is a major contribution to the disagreement.
- As the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



Lesson: use the data creatively.
Note a relevant technique for a Water Cerenkov Detector or for a high resolution detector.

Estimating the background using horn on and horn off data

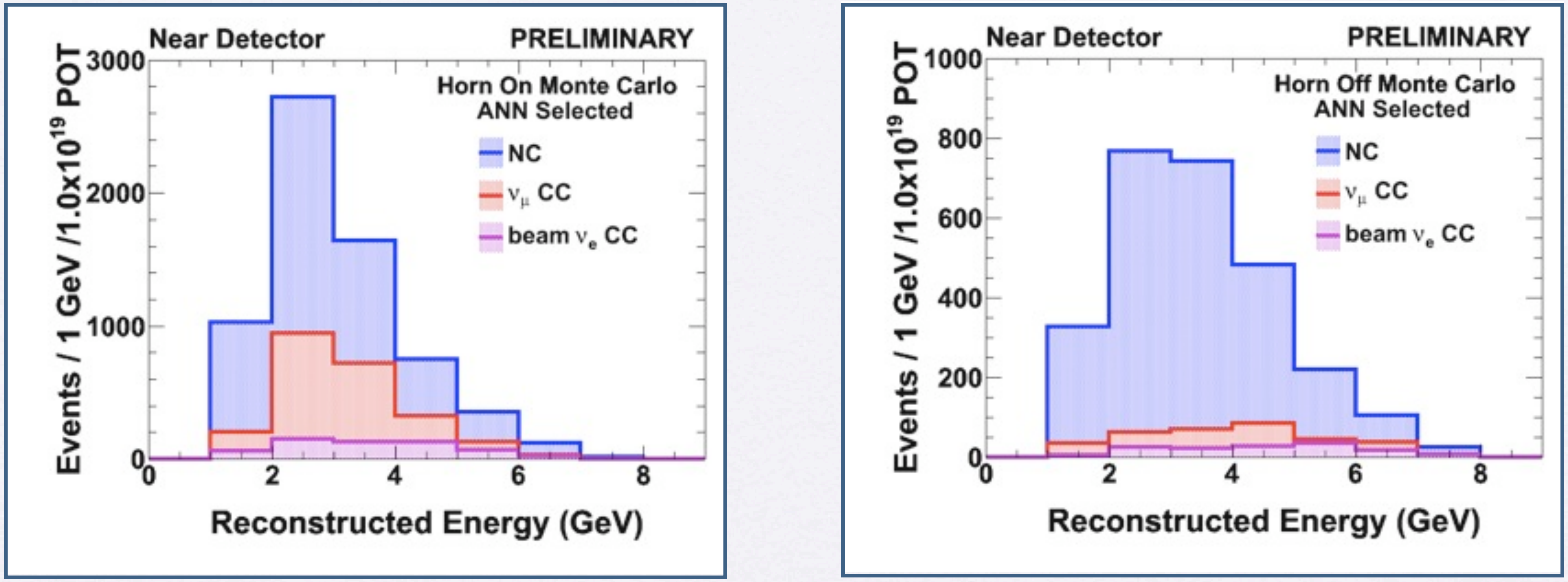
- When beam horns are turned off, the parent pions do not get focused, resulting in the disappearance of the low energy peak in the neutrino energy spectrum.



- 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.
  - **Lesson: Might be specific to MINOS resolution that we can do this, ie not sensitive to angular distribution of the showers.**

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 $\mathbf{N^{off}}$.

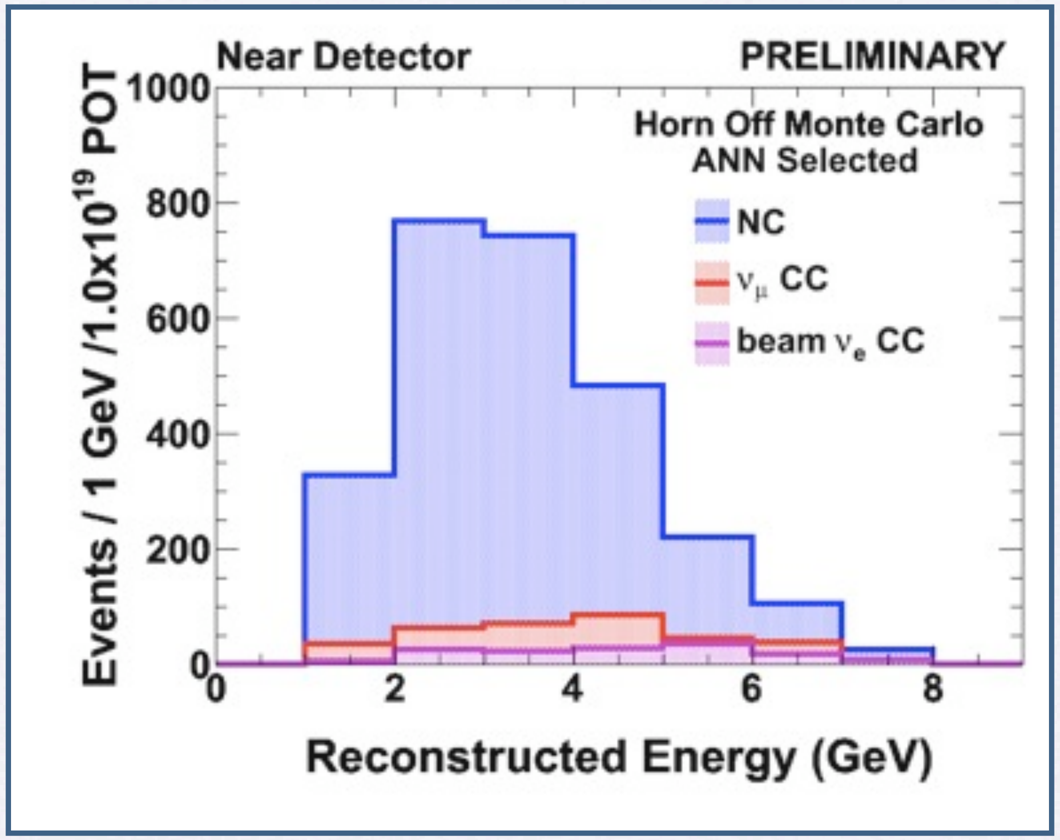
$$N^{on} = N_{NC} + N_{CC} + N_e \quad (1)$$

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

from MC:

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

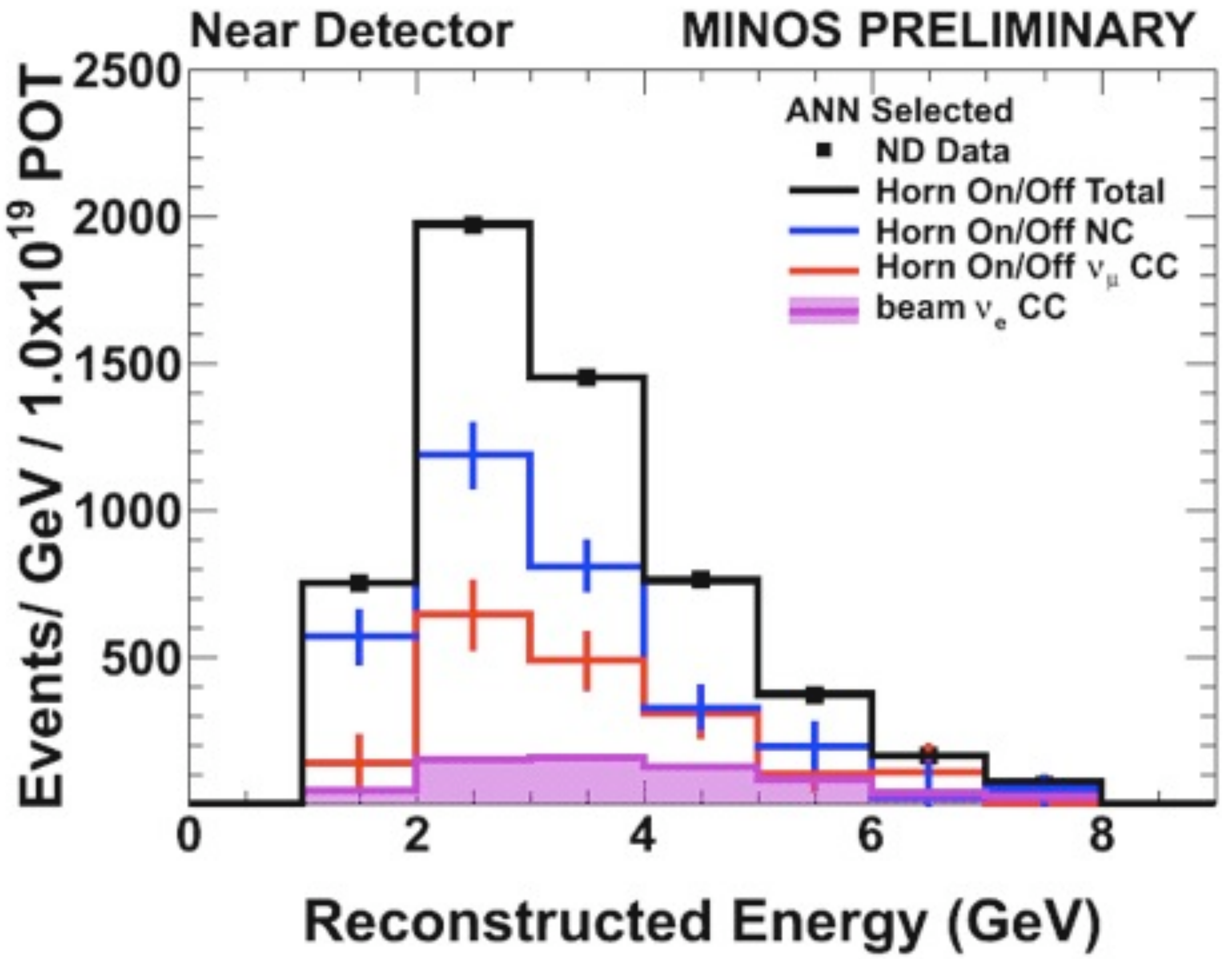
The key is to use the **Horn off/on ratios** for each component to solve:



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

ND data-driven background

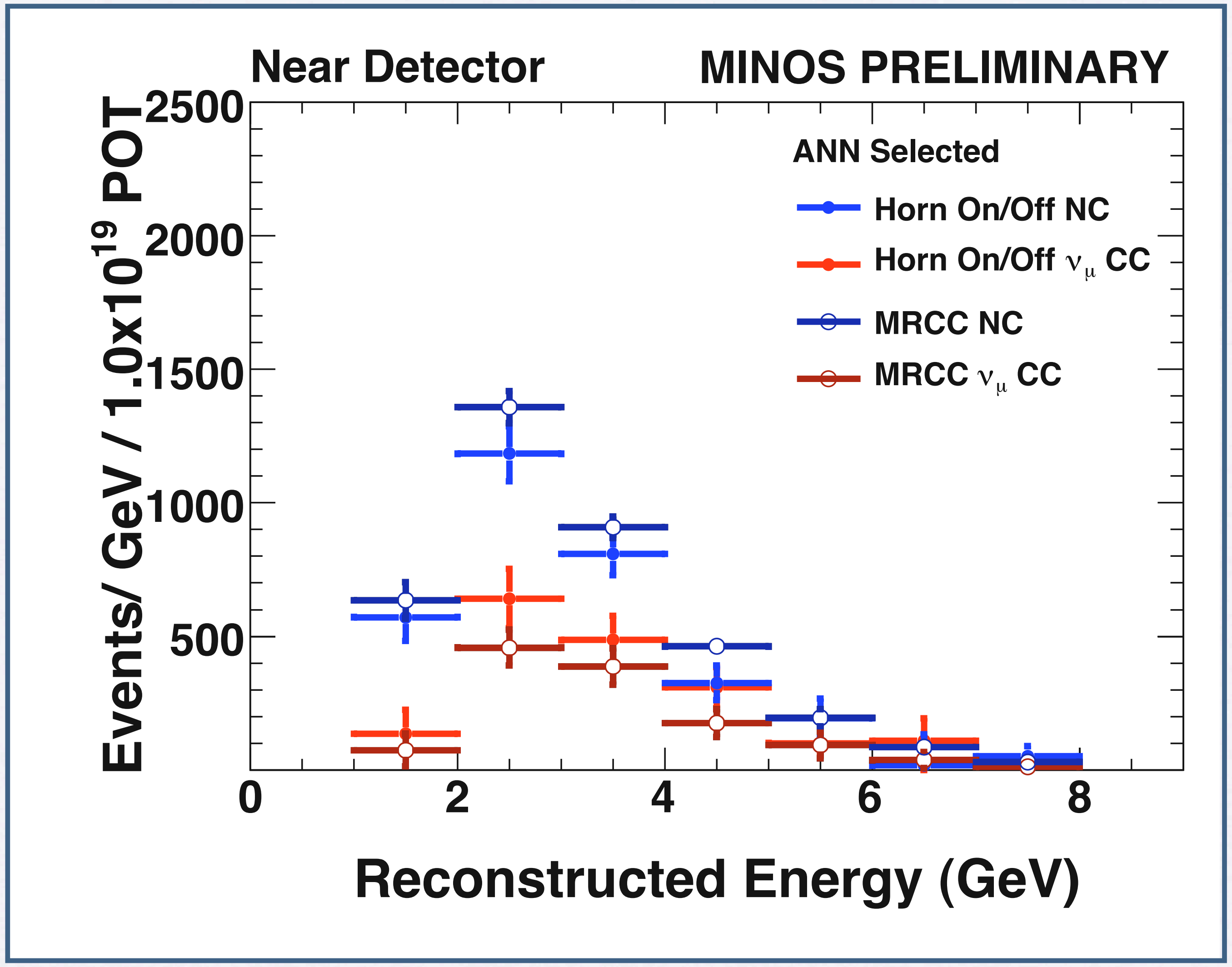
Results from the Horn on/off method



- 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 extrapolated to the Far Detector.

ND data-driven background

Integral number of events selected

	Total	NC	ν_μ CC	ν_e beam
MC	6764	4429	1742	593
Horn on/off	5524±35	3150^{+292}_{-273}	1781^{+366}_{-302}	593±178
MRCC		3674±190	1236±274	614±186

scaled to 1.0 x10^{19} POT

- 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 extrapolated to the Far Detector.

ND data-driven background

Horn off beam corrections

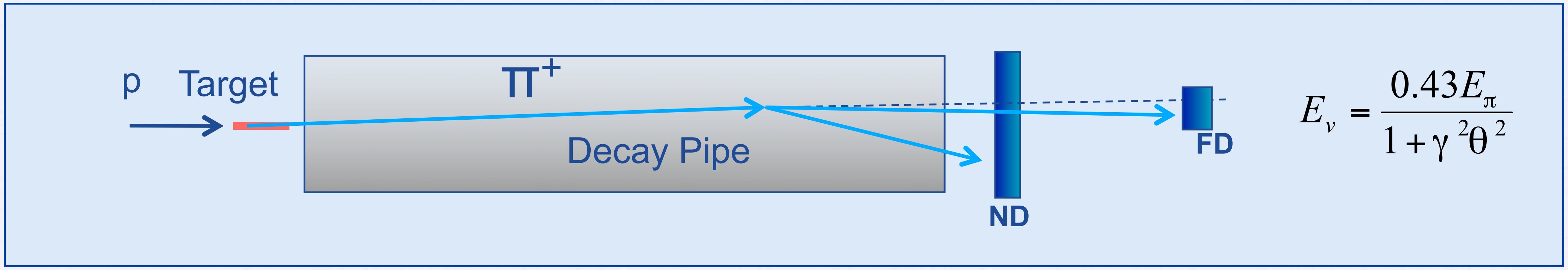
	Total	NC	ν_μ CC	ν_e beam
MC	2680	2338	205	137
Horn off	2105±62	1691^{+199}_{-182}	276^{+216}_{-148}	137±42

scaled to 1.0 x10^{19} POT

- NC (horn off)/NC (horn on) = 0.54±0.08
- NC corrected by 28% for horn off, 29% for horn on.

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.



$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

- 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:

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

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

Other Far/Near differences

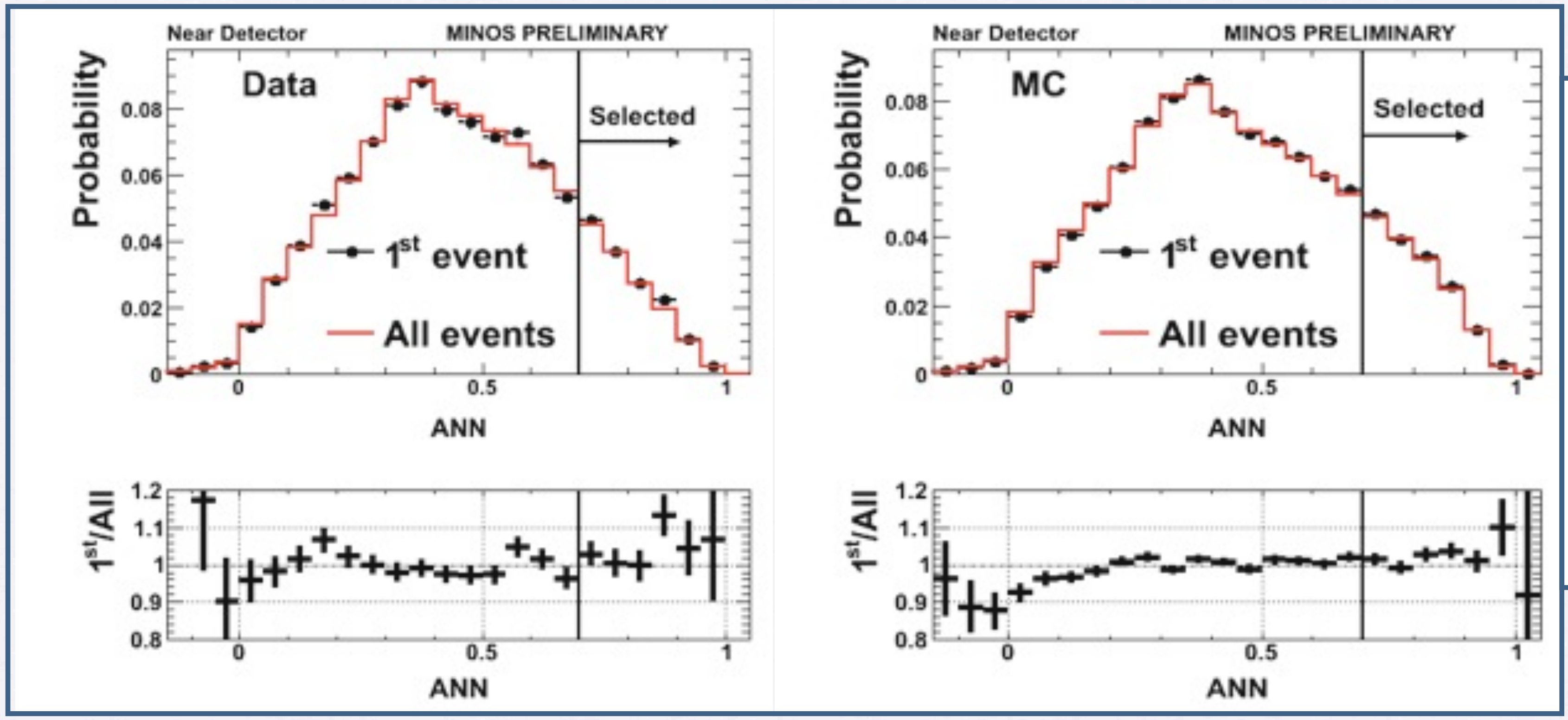
MINOS detectors are very similar, however there are small differences:

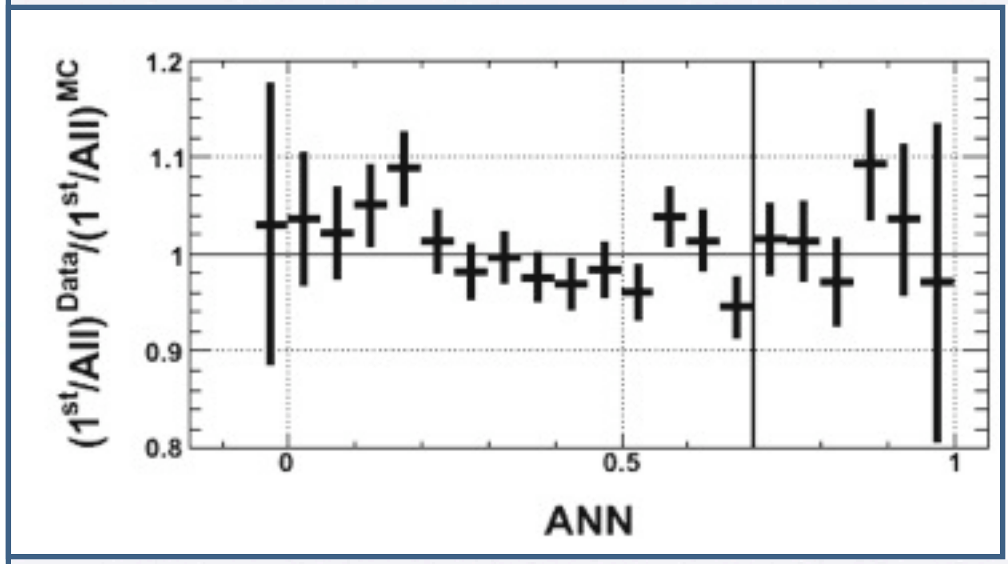
- Far/Near spectrum different due to **beamline geometry and oscillations** in the Far.
- **Readout patterns:**
  - Light level differences due to differences in fiber length.
  - Multiplexing in the Far (8 fibers per PMT pixel).
  - Partial (one-sided) readout in the Near.
- **Photomultipliers (M64 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 result in systematic errors.

Lesson: Make your detectors as similar as possible.

Intensity systematic

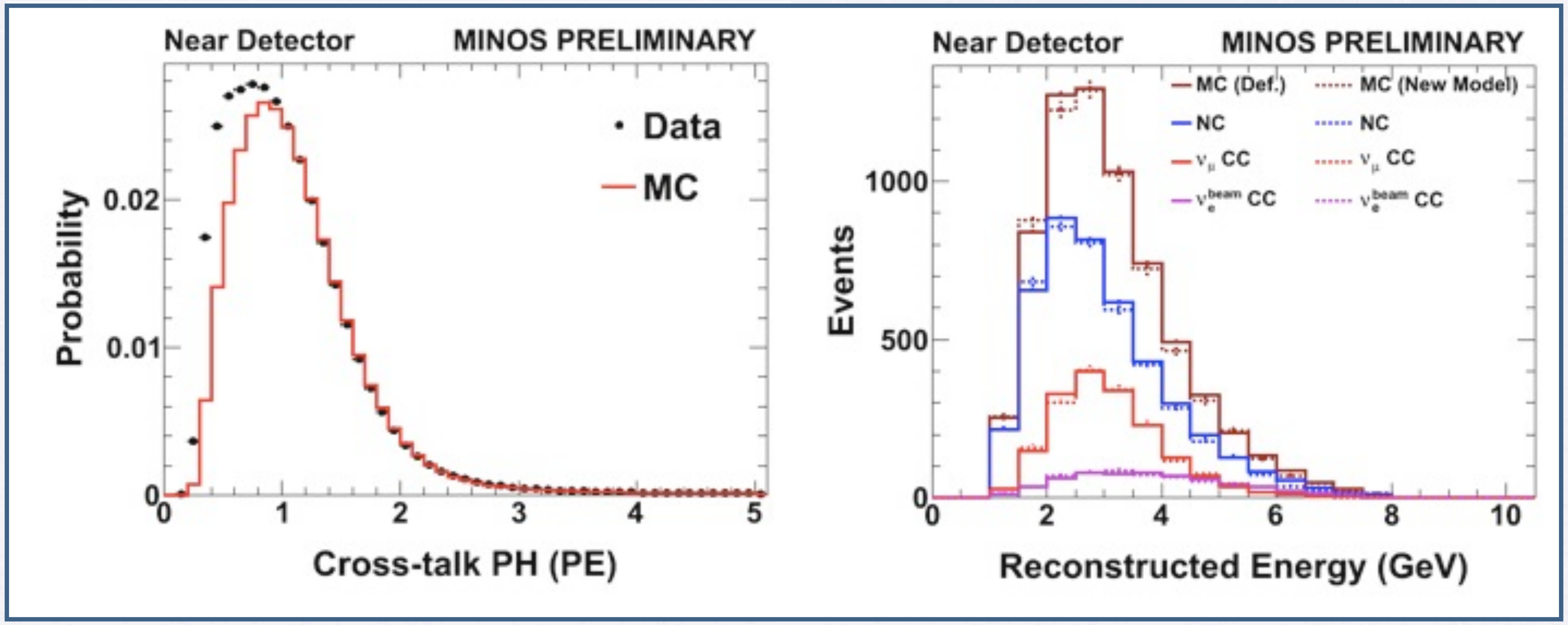




- Different rates at two detectors: ~8 events in 10μs spill window in ND and ~1 event per day in FD.
- First event in each ND spill is unaffected by late activities of other events. We compare the 1st event to all other events to understand potential systematic effects.
- Difference in relative efficiencies between data and MC is taken as systematic error for the integral above the cut resulting in a 1% systematic error.

- **Lesson: Intensity will be more important for the water cerenkov detectors, move detector farther away? see 2km detector for T2k.**

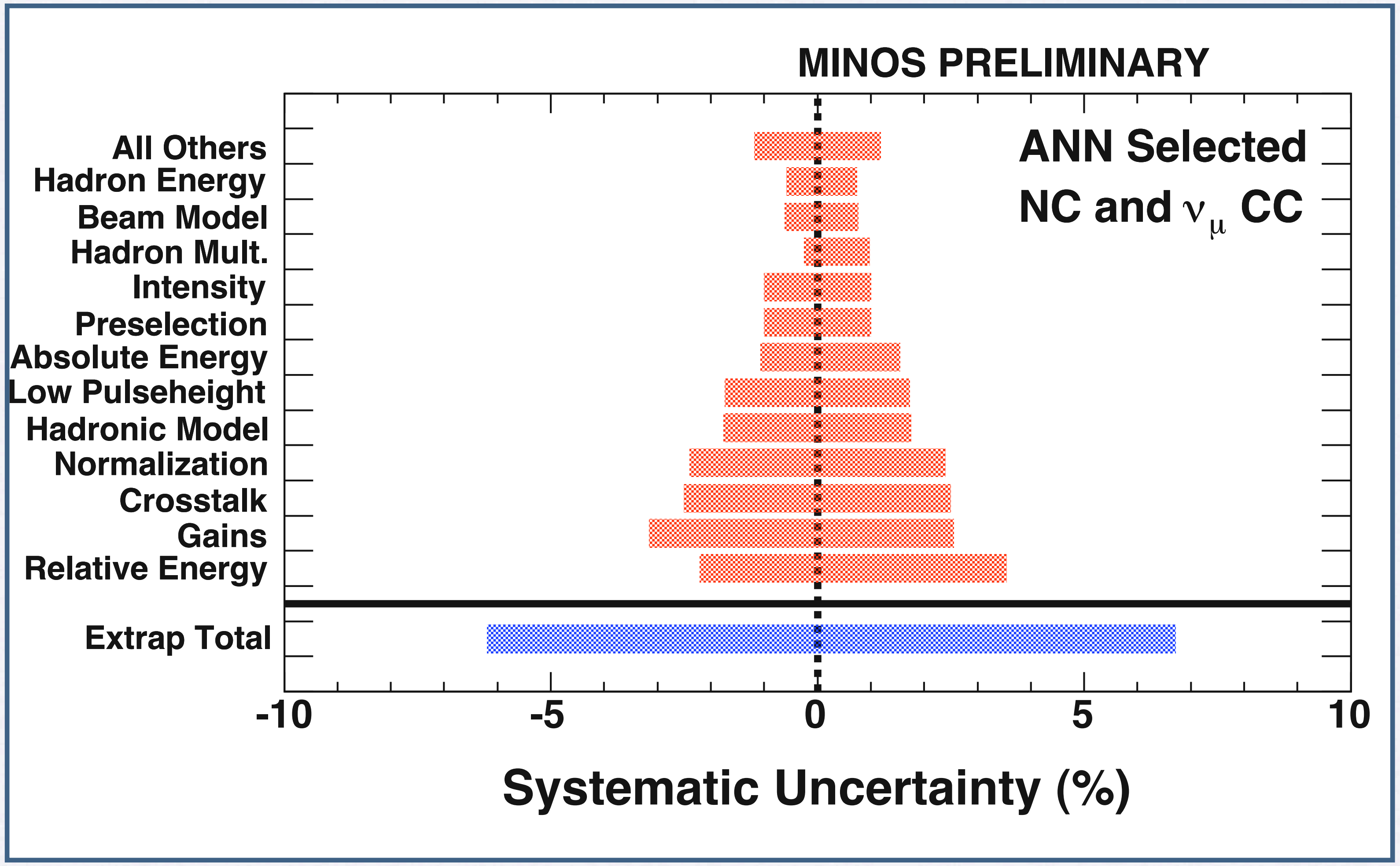
Crosstalk systematic



- PMT crosstalk is not well modeled in the Monte Carlo.
- Input variables to selections were constructed to avoid this problem by using hits greater than 2PE.
- The crosstalk model was improved by using cosmic ray muons.
- The difference between number of events selected in the current vs to the improved model was used as a systematic error.
- **Lesson: Use identical photodetectors, but you can't. Just as in MINOS there are limitations, need better pixelation.**

FD background systematic errors

Extrapolation errors



- For the main background components the larger systematics are **relative energy, gains, crosstalk and relative normalization**.
- **Lesson: If everything is made equal, the only relevant parameters are the distance to both detectors, the mass and the efficiency at each of the detectors.**

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%**

Lesson: We can obtain a 7% systematic uncertainty because we have two similar detectors.

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)

ν_e appearance result:

MINOS PRELIMINARY

In case you missed it!

Lesson: We want more statistics!

ν_e appearance result:

Observation 35 events

Expected Background 27±5(stat)±2(sys)

for 3.14×10^{20} POT

MINOS PRELIMINARY

In case you missed it!

Lesson: We want more statistics!

Summary

- Having similar detectors provides invaluable measurement of the background when looking for electron neutrino appearance.
- Goal should be:
  - same target mass
  - similar intensity
  - similar photodetectors
- Any differences will be paid in systematic errors.

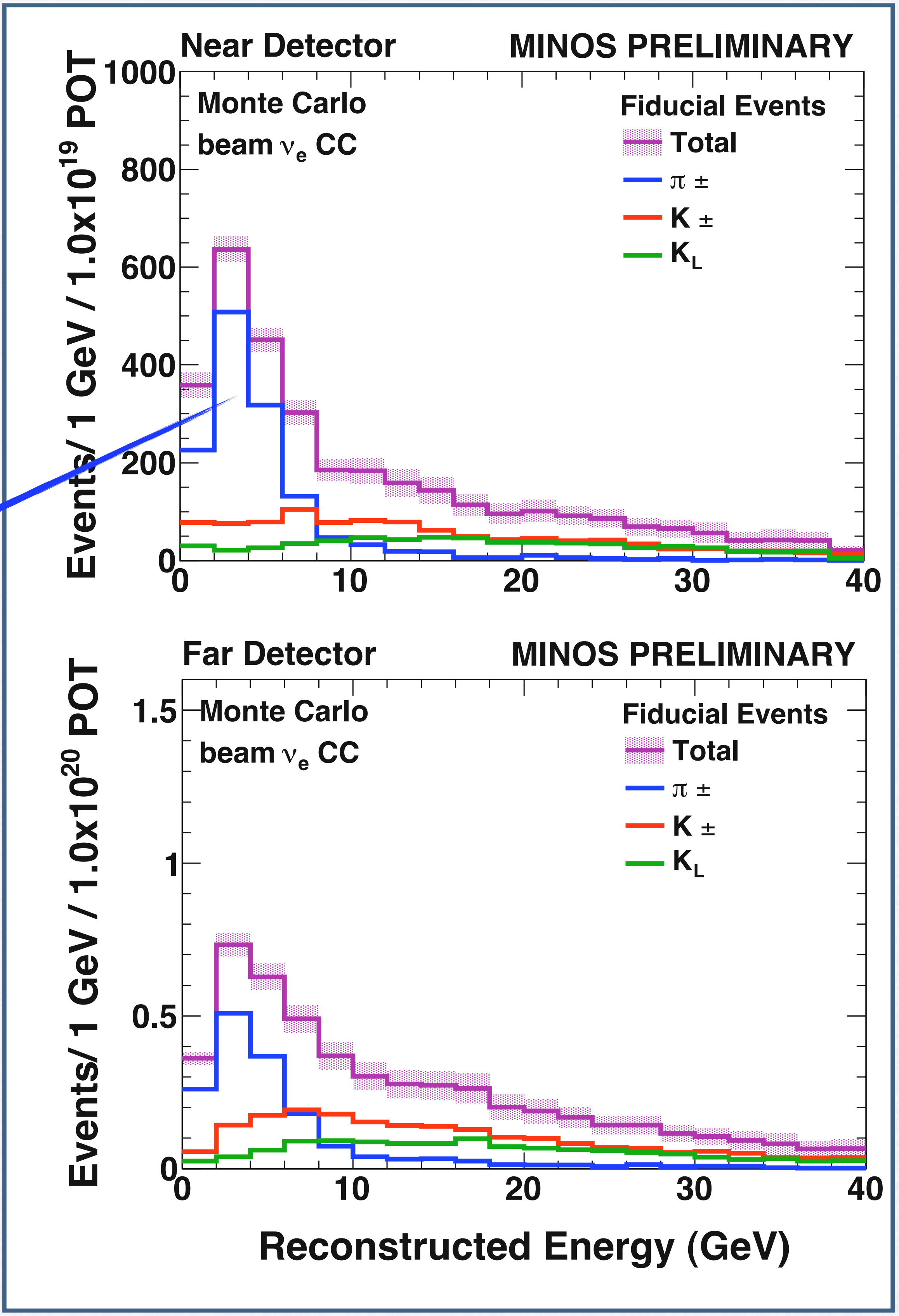
Backup

Beam ν_e component

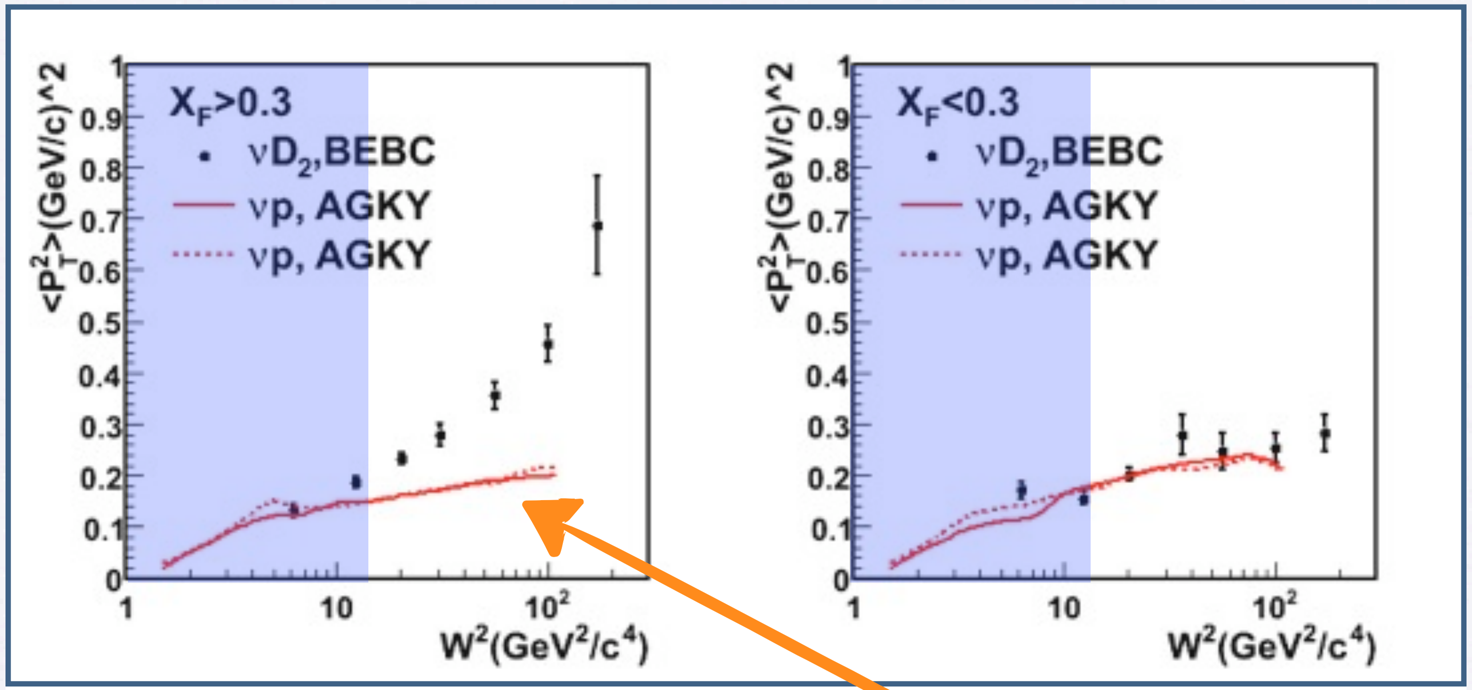
- Neutrino beam has 1.3% of ν_e contamination from pion and kaon decays.
- Region of interest for the ν_e oscillation analysis, 1-8GeV, dominated by events from secondary muon decays:

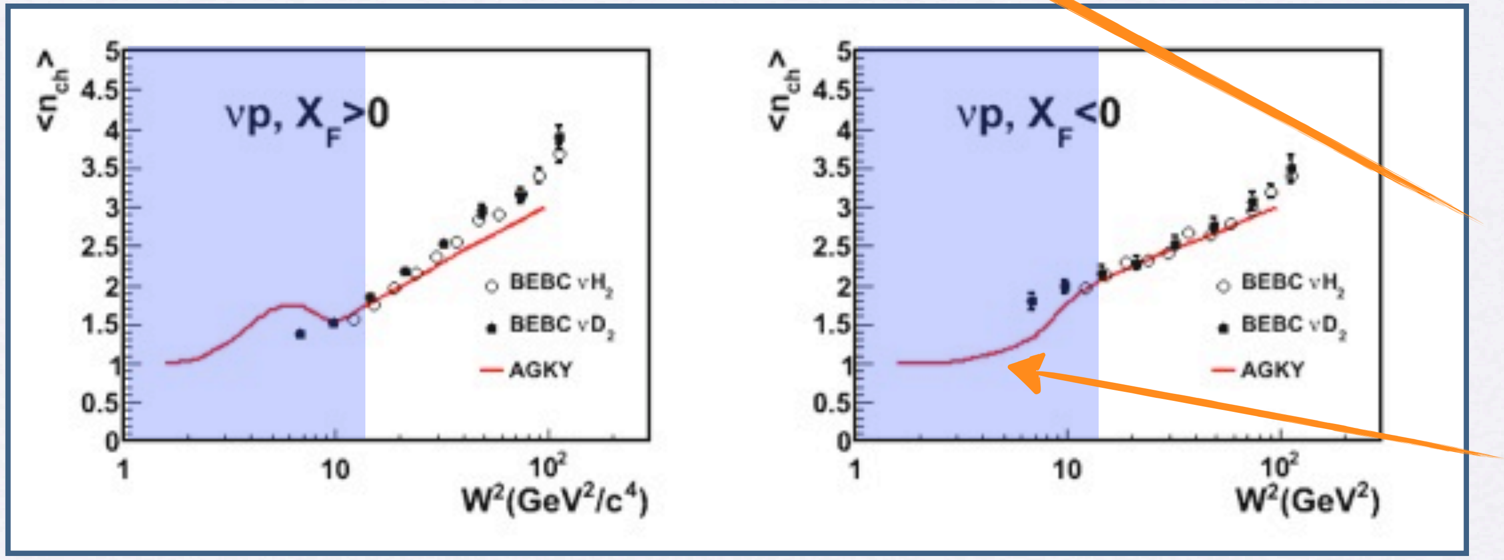
$$\begin{aligned} \pi^+ &\rightarrow \mu^+ \nu_\mu \\ &\quad\hookrightarrow e^+ \bar{\nu}_\mu \nu_e \end{aligned}$$

- Near and Far beam ν_e spectra are constrained by using ν_μ events with different beam configurations.
- Errors from these fits after ν_e selection are ~9% in the Near and ~13% in the Far Detector.



MINOS Monte Carlo





Region of interest: 1 - 15 GeV^2 in W^2

- MC tuned to external bubble chamber data for hadronization models.
- 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.
- Model at lower W^2 is an extrapolation.

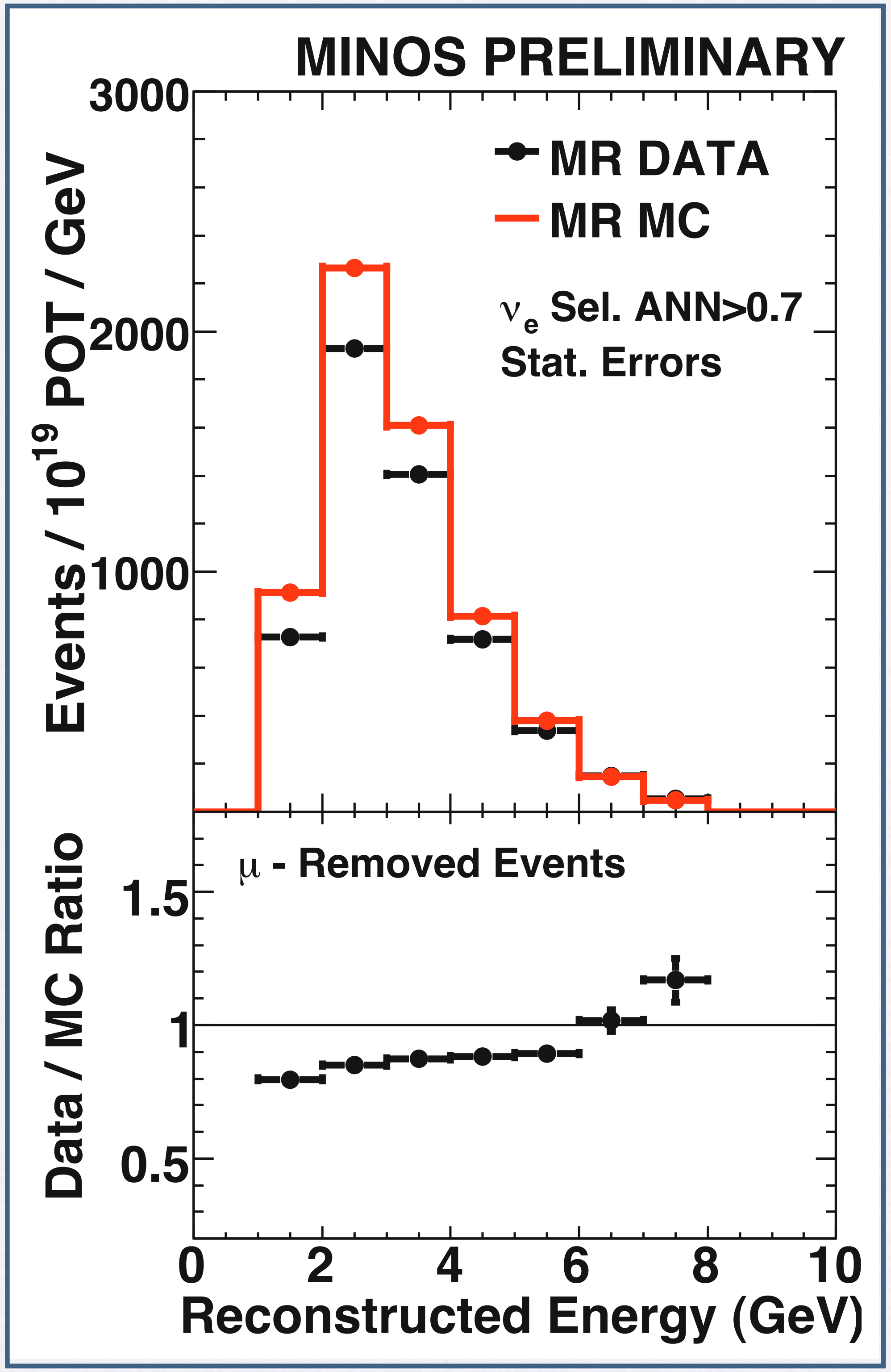
We need to use more information from our own data in the Near Detector.

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.

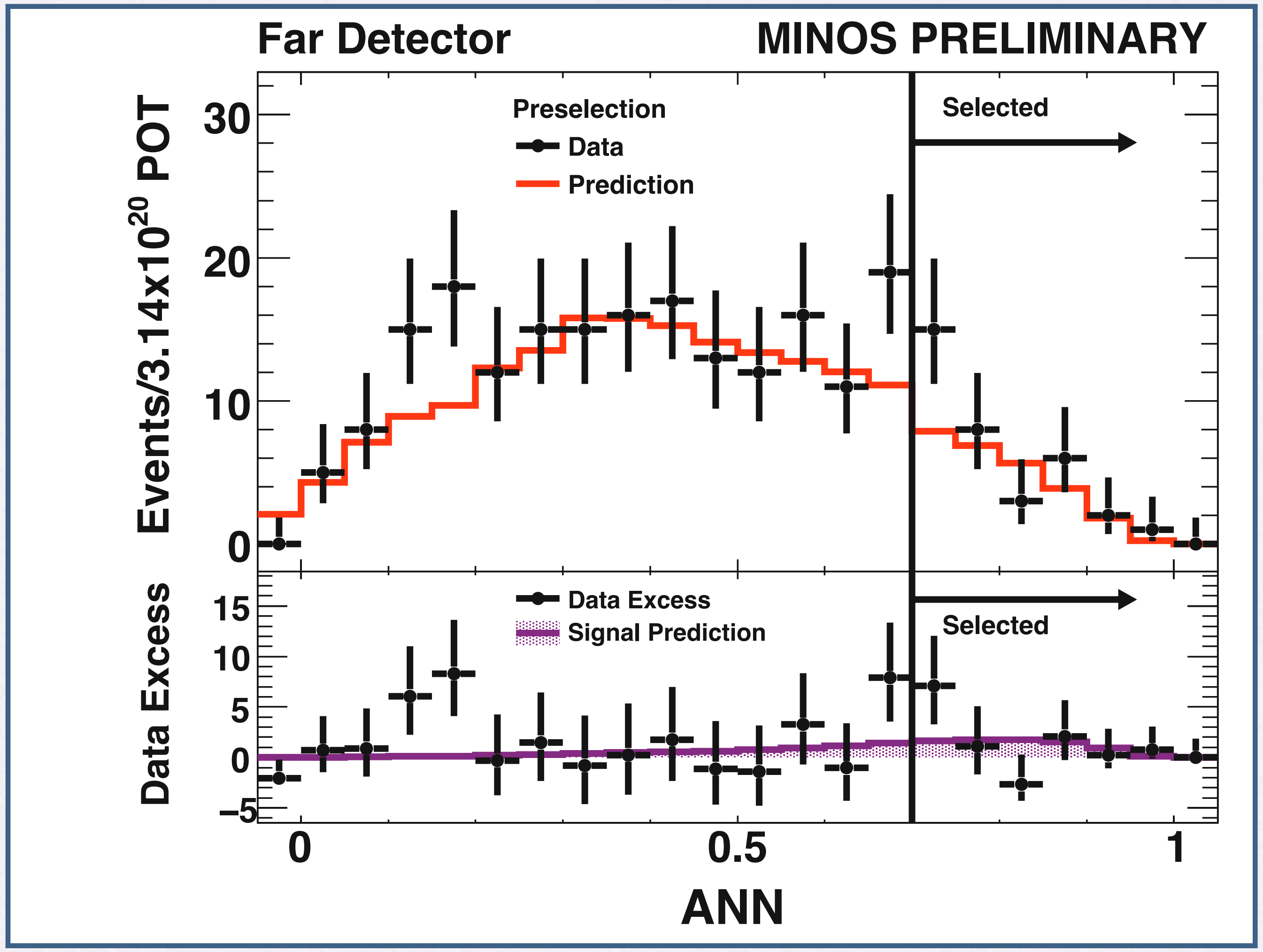


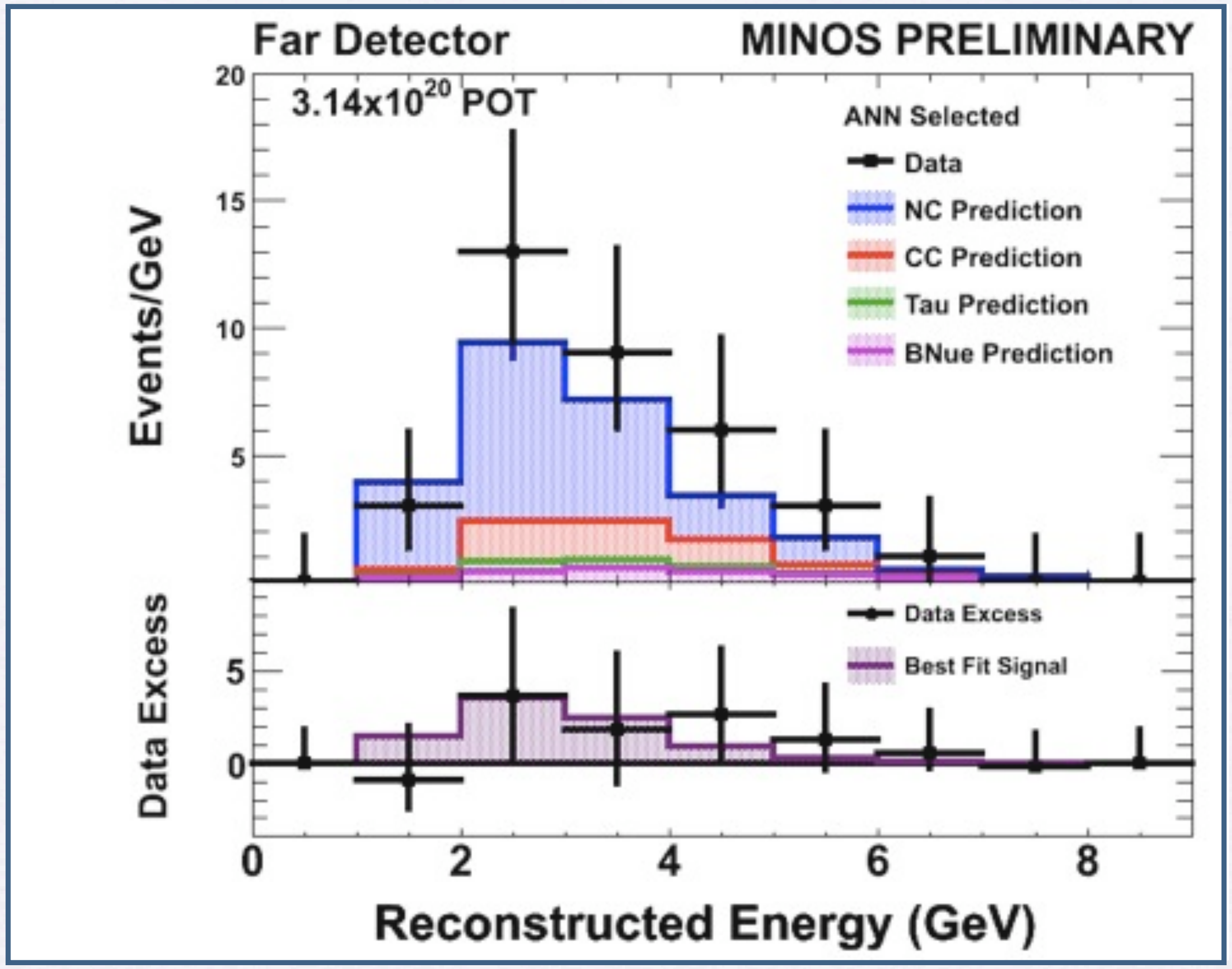
Secondary separation method

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.**



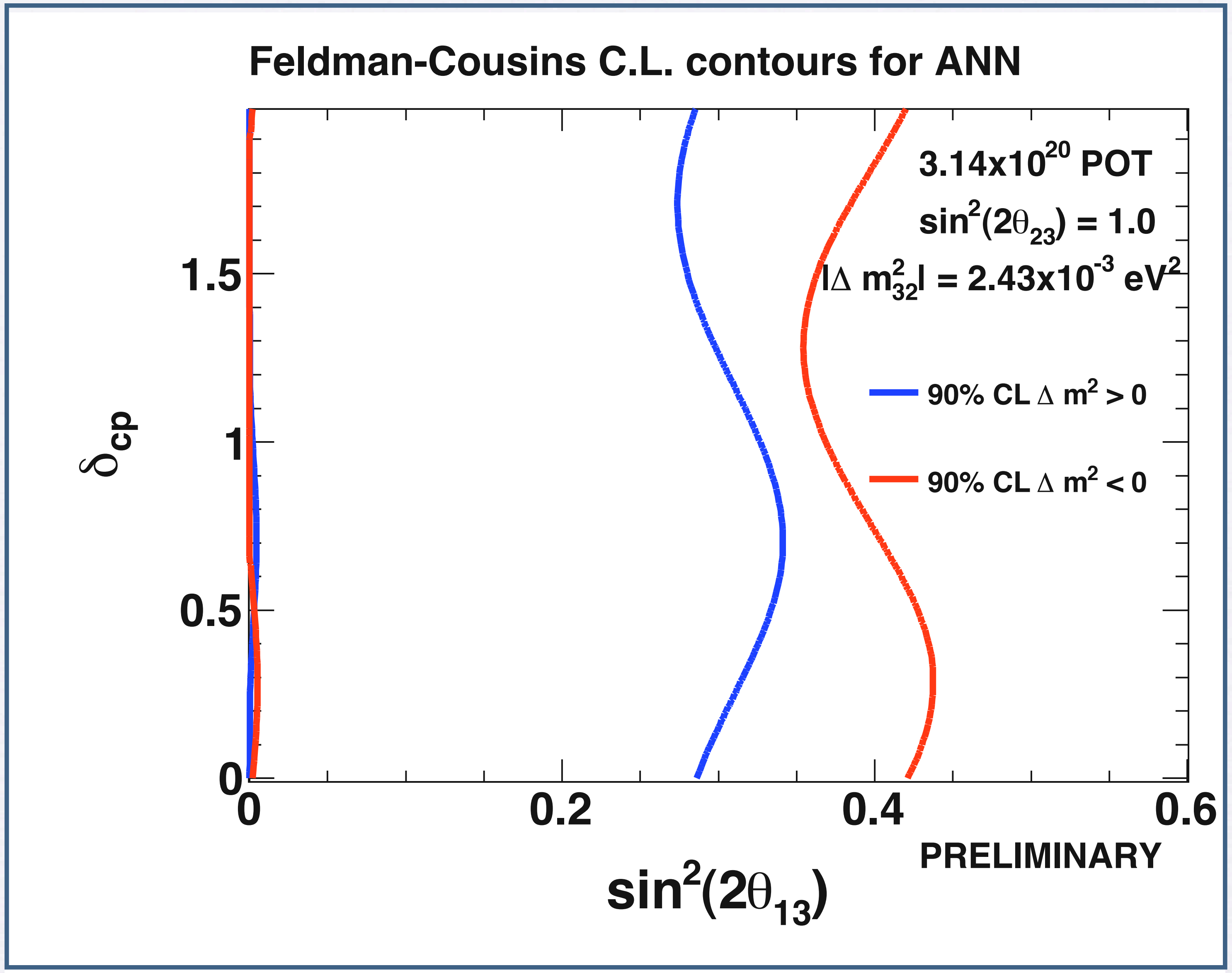


- If we fit the oscillation hypothesis to data, we can obtain the signal prediction for the best fit point.

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.



Searching for θ_{13}

Missing element in the PNMS neutrino mixing matrix

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

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

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

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

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

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

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:**

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

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

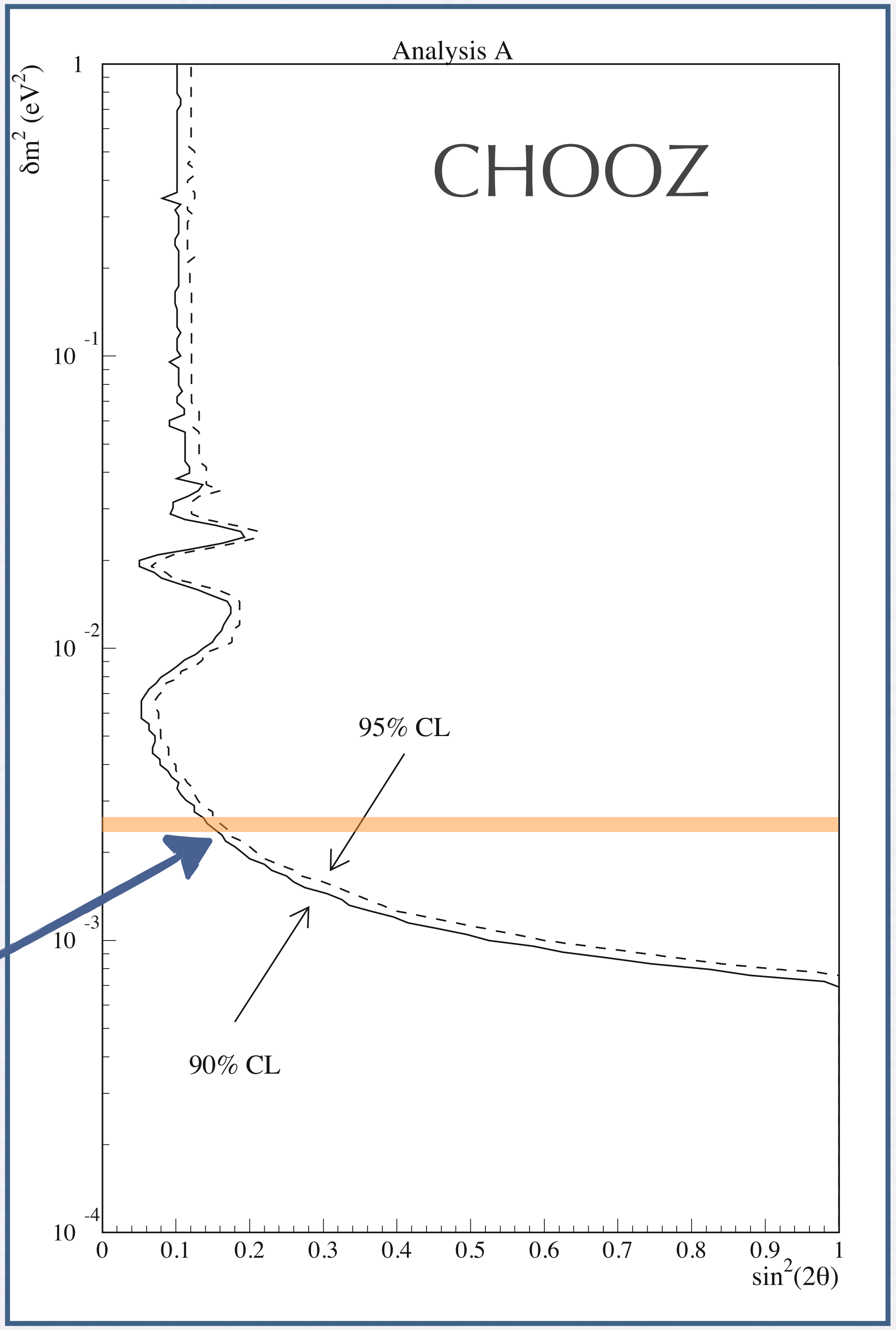
- **Searching for ν_e events in MINOS, we can access $\sin^2(2\theta_{13})$.**
- Probability depends not only on θ_{13} but also on δ_{CP} .
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy i.e. the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$.

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.

Searching for θ$_{13}$

Missing element in the PNMS neutrino mixing matrix

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

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

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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

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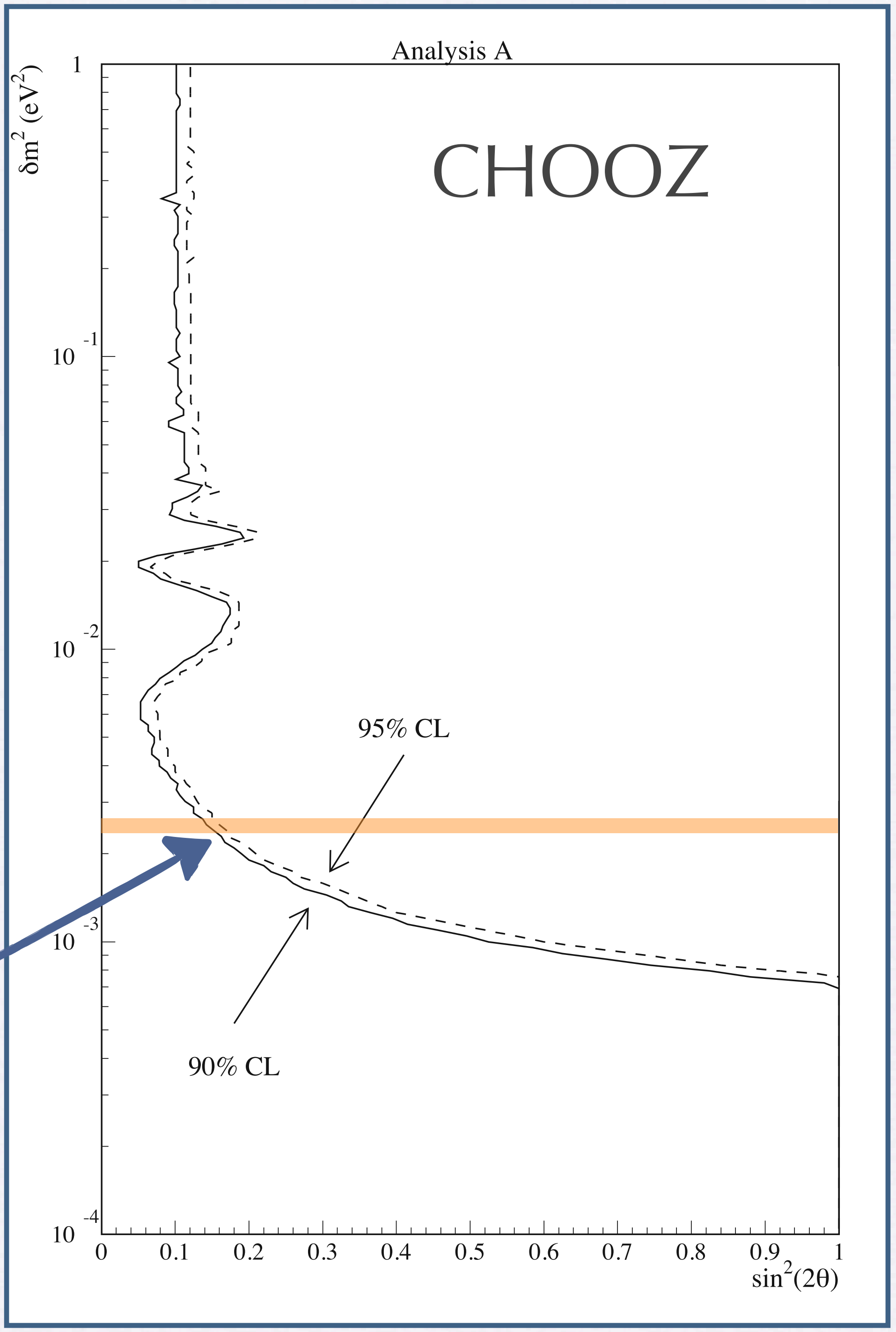

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