Initial results on ν_e appearance in MINOS

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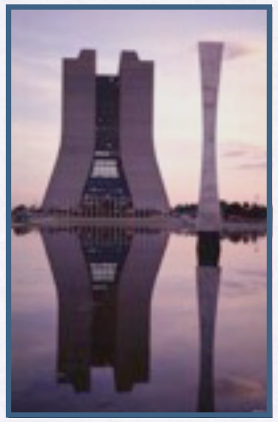
MINOS in a nutshell

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

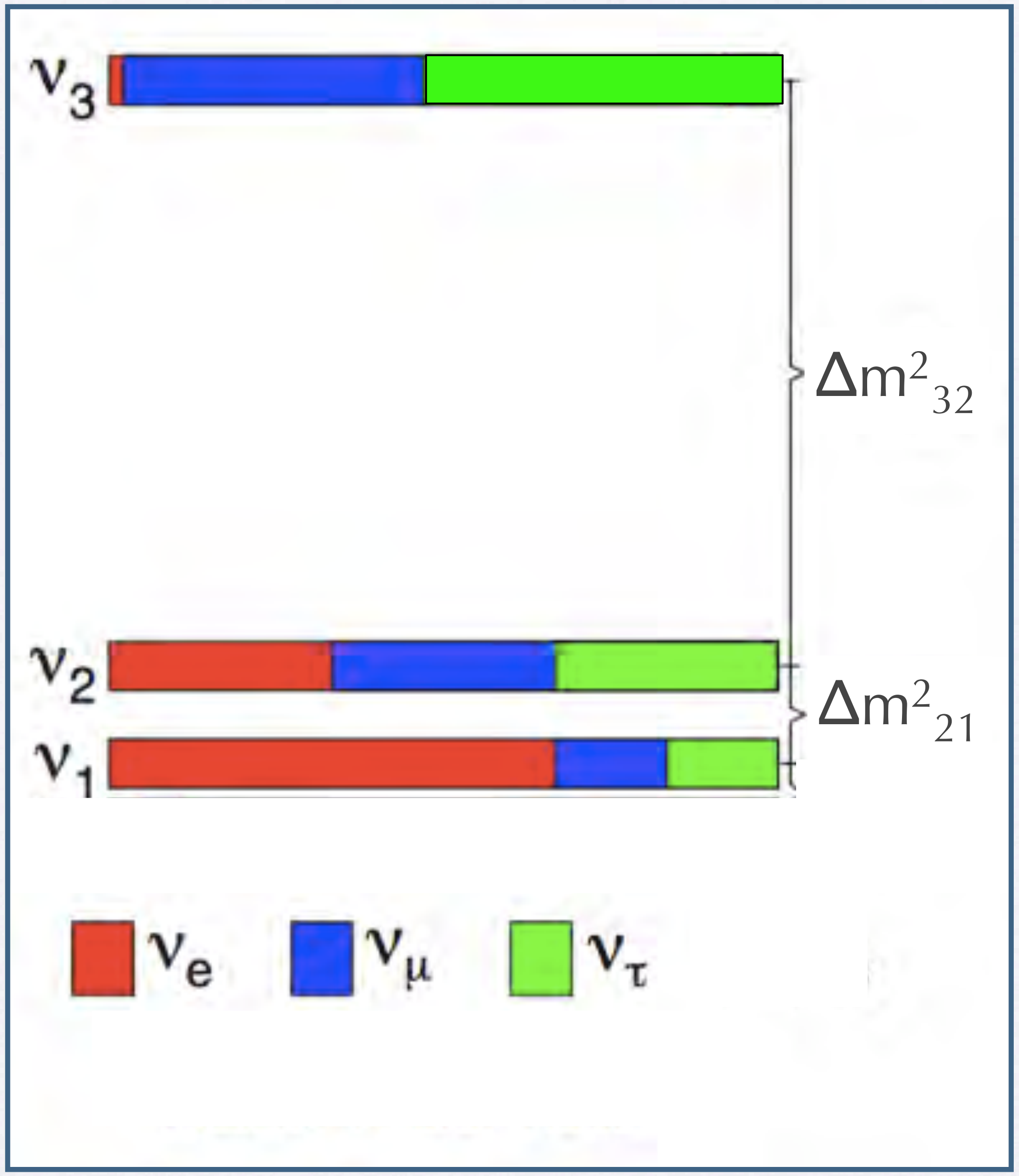
- Produce a high intensity beam of muon neutrinos at Fermilab.
- Measure background at the Near Detector and use it to predict the Far Detector spectrum.
- If neutrinos oscillate we will observe a distortion in the data at the Far Detector in Soudan.



←long baseline→
735 km

Neutrino masses and mixing

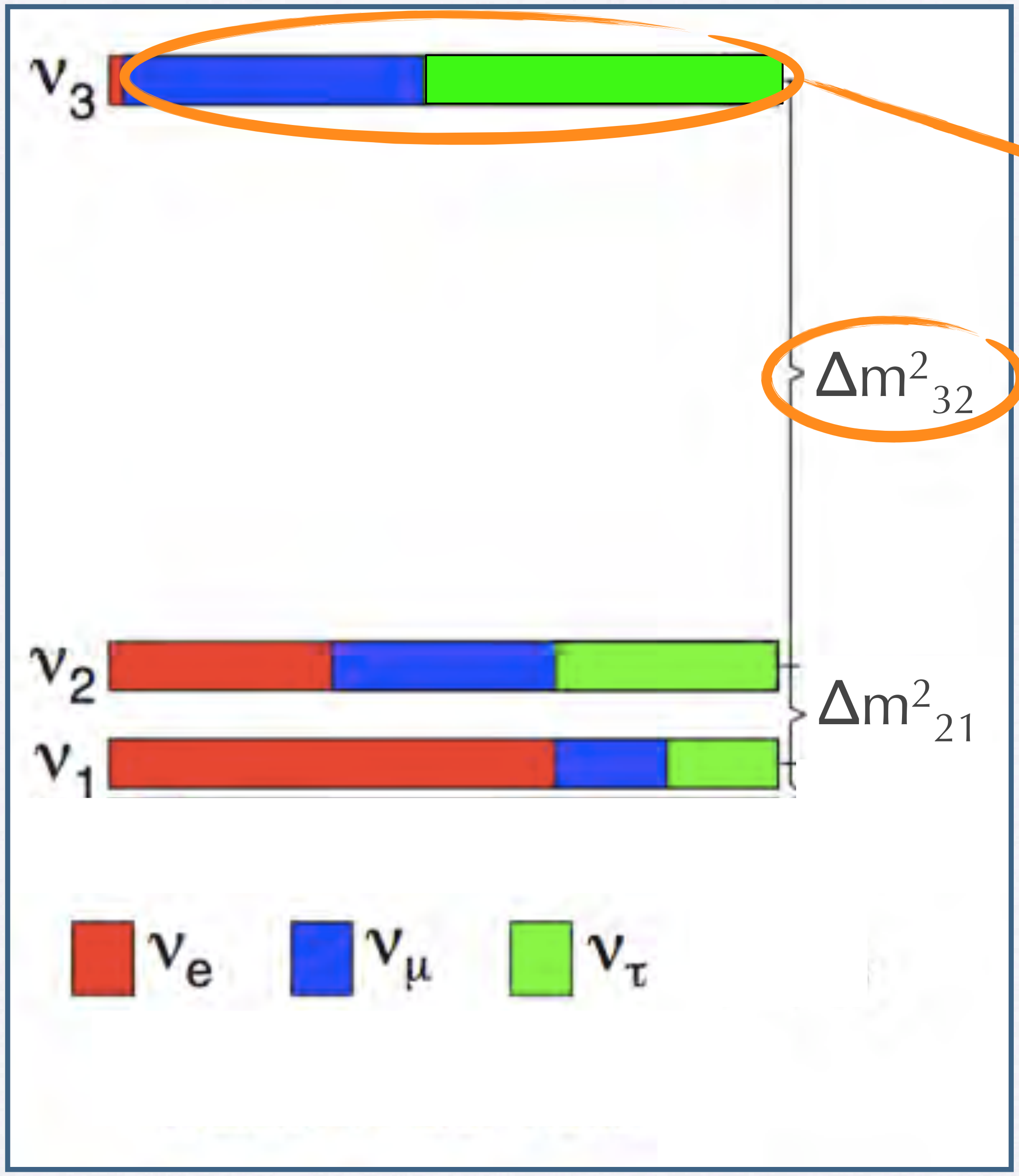
What is the current experimental picture?



- 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 recent results

study "atmospheric" neutrino oscillation parameters



PRL **101** 131802 (2008)
PRL **101** 221804 (2008)

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

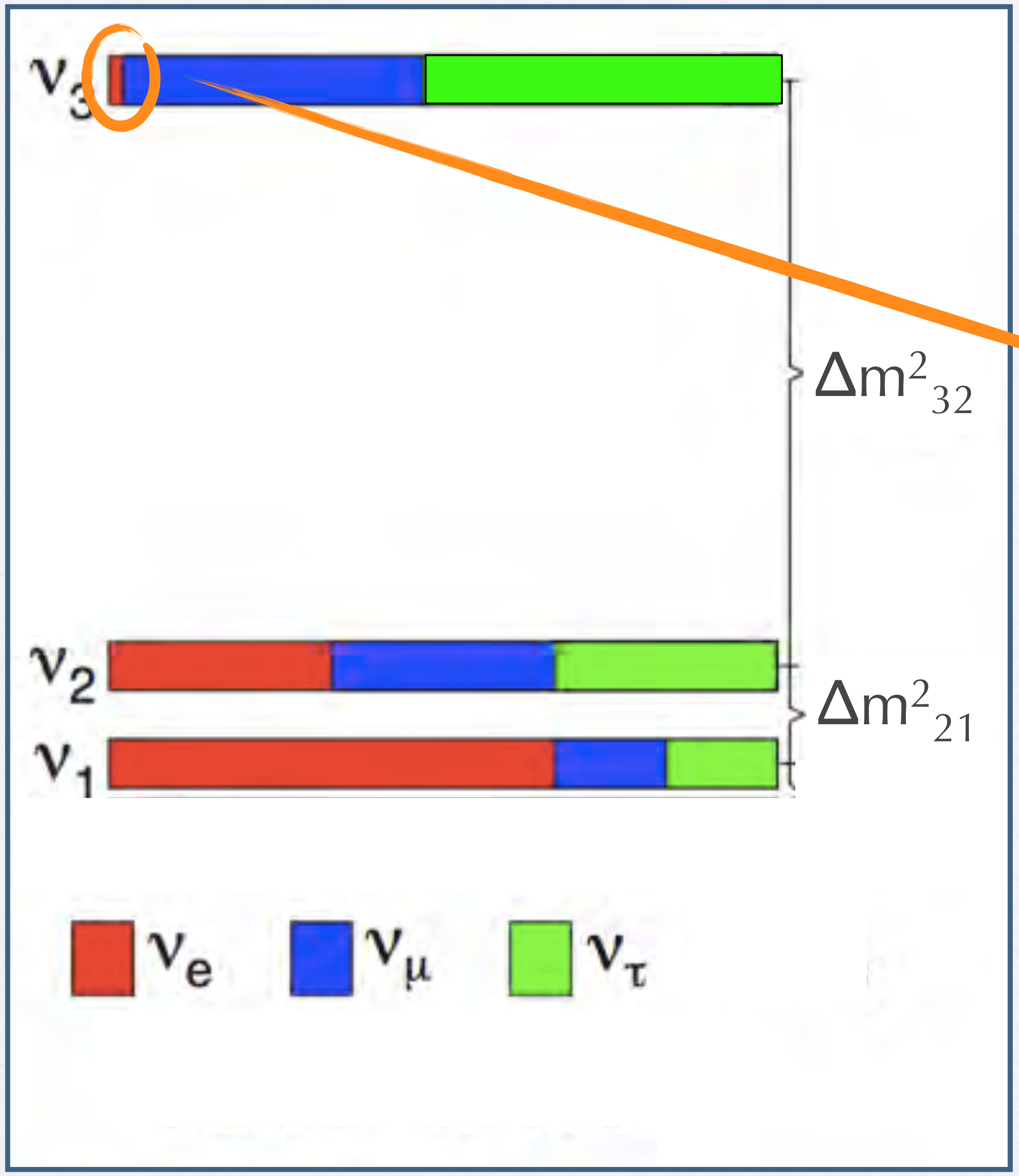
$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3}\ eV^2$ (68% CL)
$\sin^2 2\theta_{23} > 0.90$ (90% CL)
$\chi^2/ndf = 90/97$

- ✓ 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)

MINOS new results

study "atmospheric" neutrino oscillation parameters



- **Search for subdominant oscillations i.e. $\sin^2(2\theta_{13})>0$**

NEW!

Searching for θ_{13} in MINOS

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

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

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

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

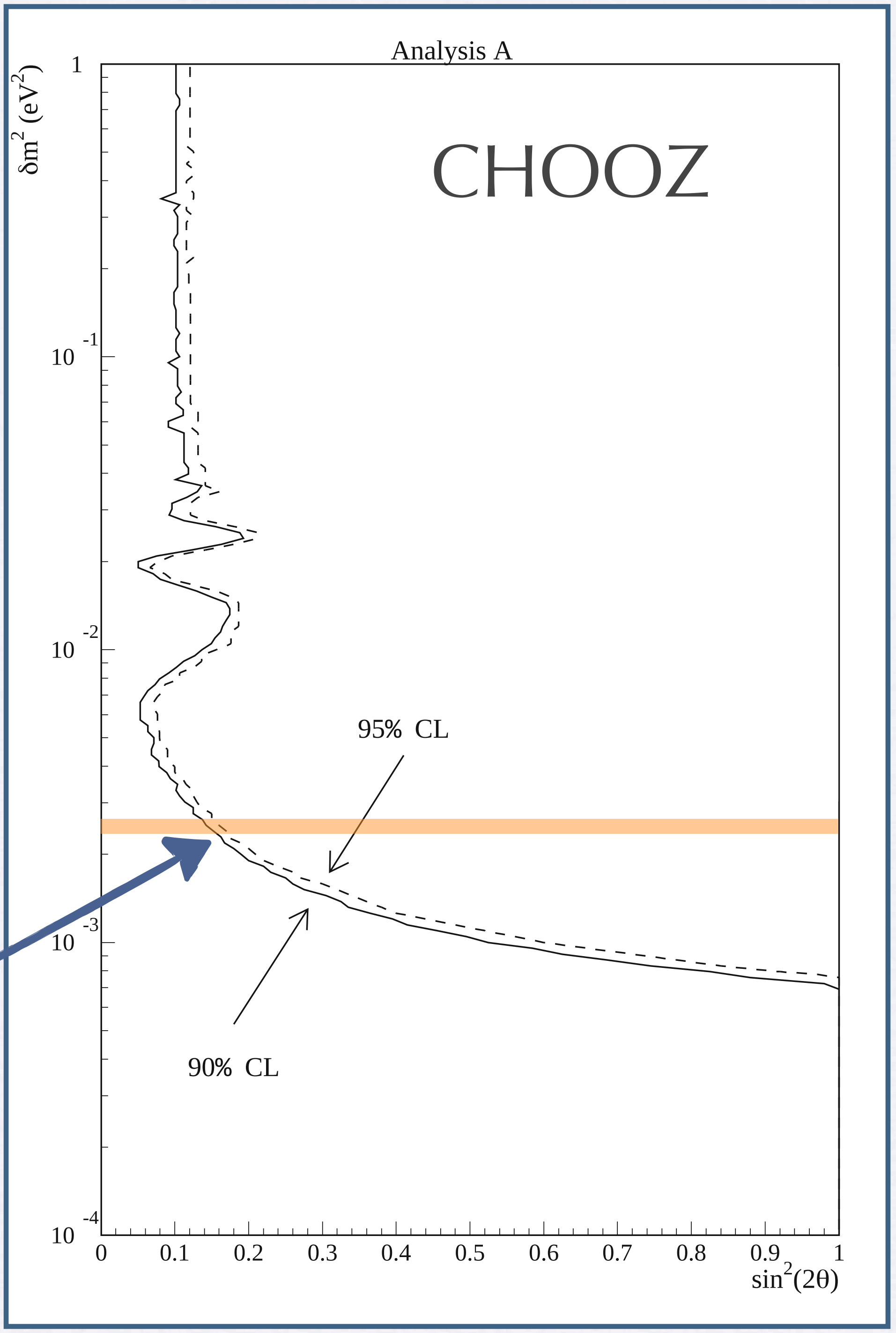
- **Searching for ν_e events in MINOS, we can access $\sin^2(2\theta_{13})$.**
- Probability depends not only on θ_{13} but also on δ_{CP} .
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy i.e. the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$.

Relevant oscillation parameters

- The CHOOZ experiment published a limit in $\sin^2(2\theta_{13})$.
- Since then MINOS has measured Δm^2_{32} very precisely.
- Thus for this talk:

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

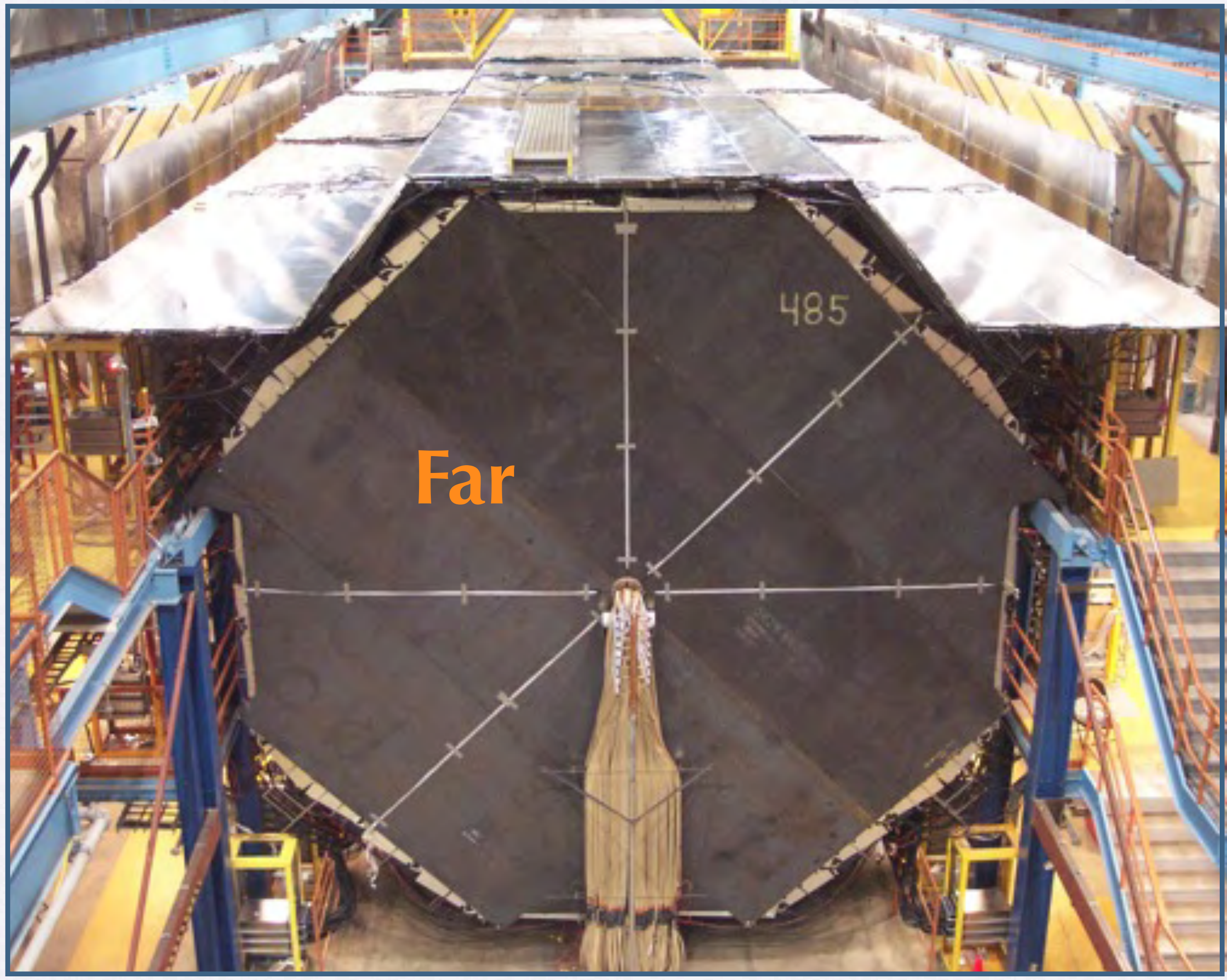
CHOOZ limit (90%CL)
$\sin^2 2\theta_{13} = 0.15$



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

The MINOS detectors

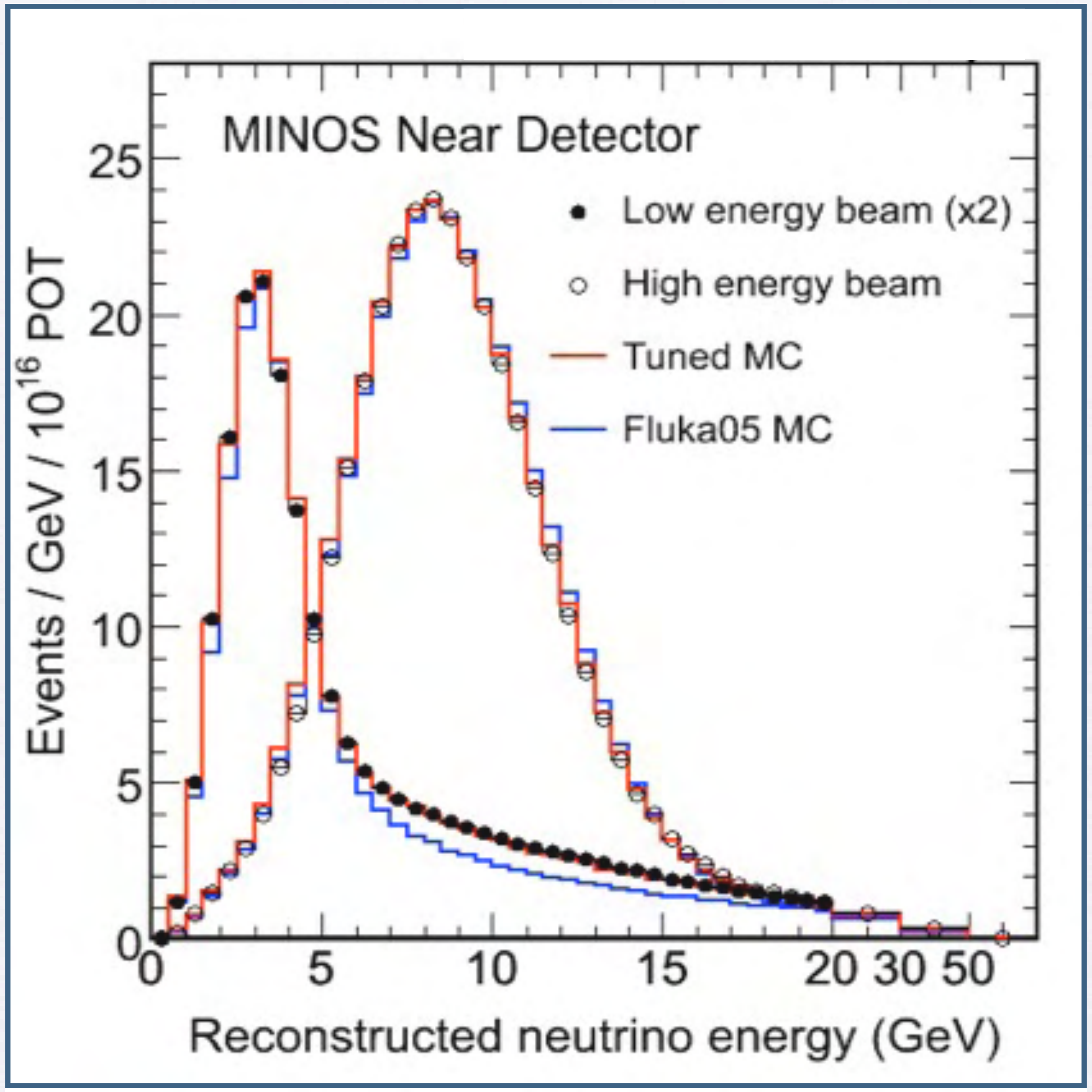
- Functionally identical: **Near and Far detectors**
- Octogonal steel planes (2.54cm thick ~1.44X_0)
- Alternating with planes of scintillator strips (4.12cm wide, Moliere rad ~3.7cm).
  - **Near (ND)**: ~ 1kton, 282 steel squashed octagons. Partially instrumented.
  - **Far (FD)**: 5.4 kton, 486 (8m/octagon) fully instrumented planes.



The NuMI Beam

- NuMI is primarily a ν_μ beam.
  - 1.3% of ν_e contamination from pion and kaon decays.
- Neutrino spectrum changes with target position with respect to focusing horns.
  - We use ν_μ CC events in ND to constrain flux.
- Region of interest dominated by events from secondary muon decays,
  - Constrained by ν_μ CC spectra.
- Uncertainties on the beam ν_e flux in the region of interest are ~10%.

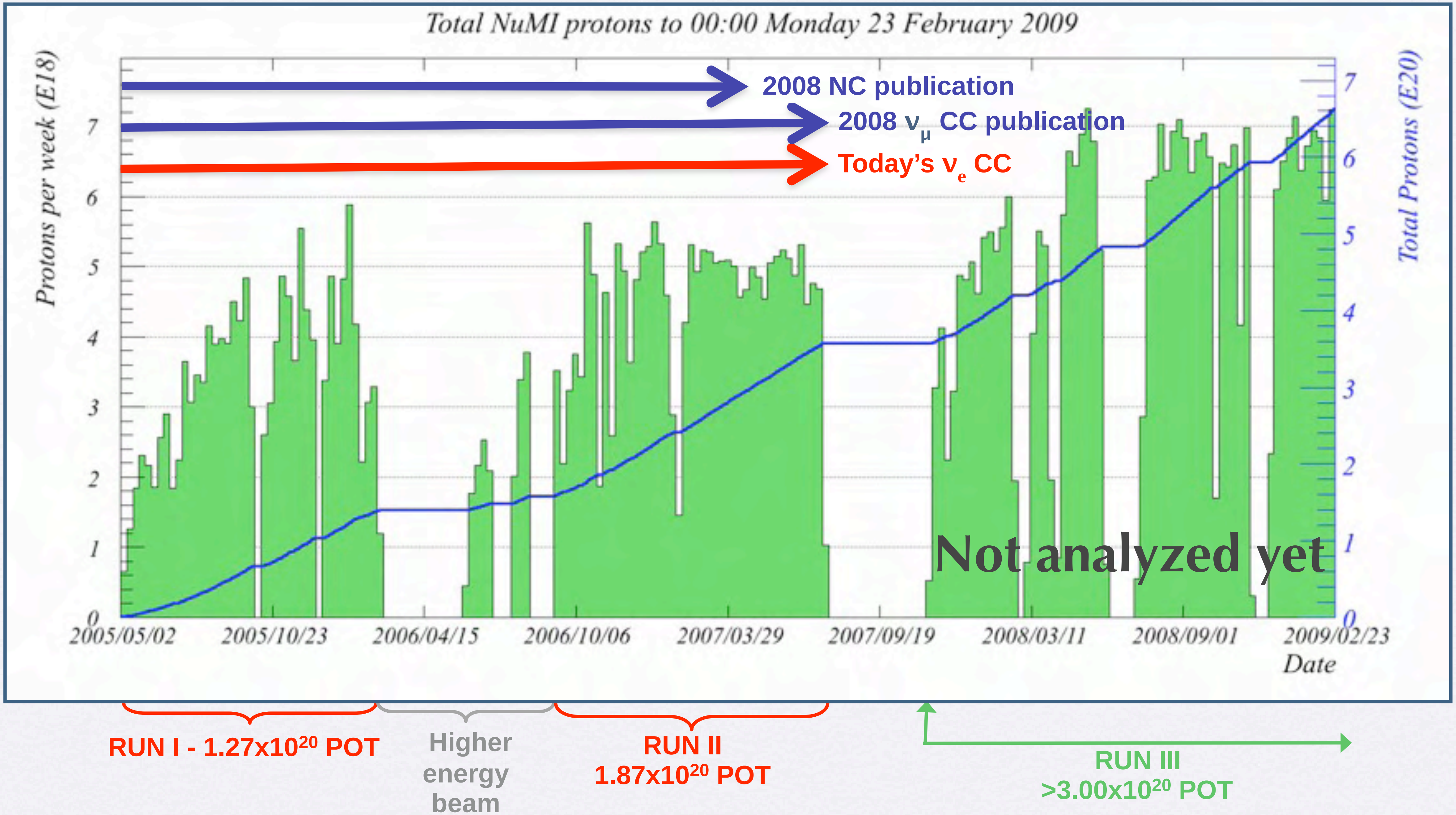
Ne**U**trinos from the **M**ain **I**njector



Measured ν_μ CC events

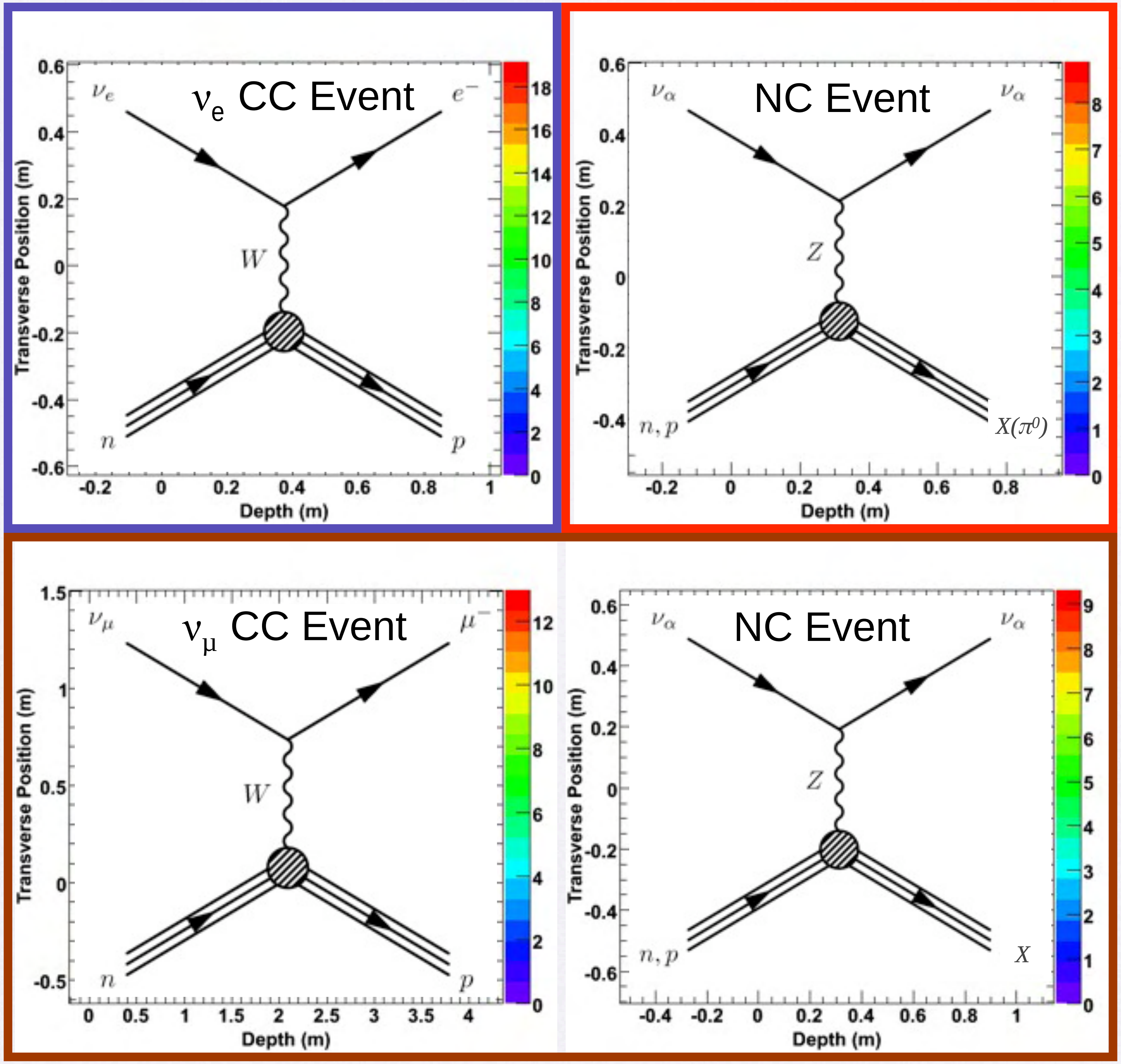
MINOS data

Current results on data through Run II



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

Neutrino Event Topologies



Neutrino Event Topologies

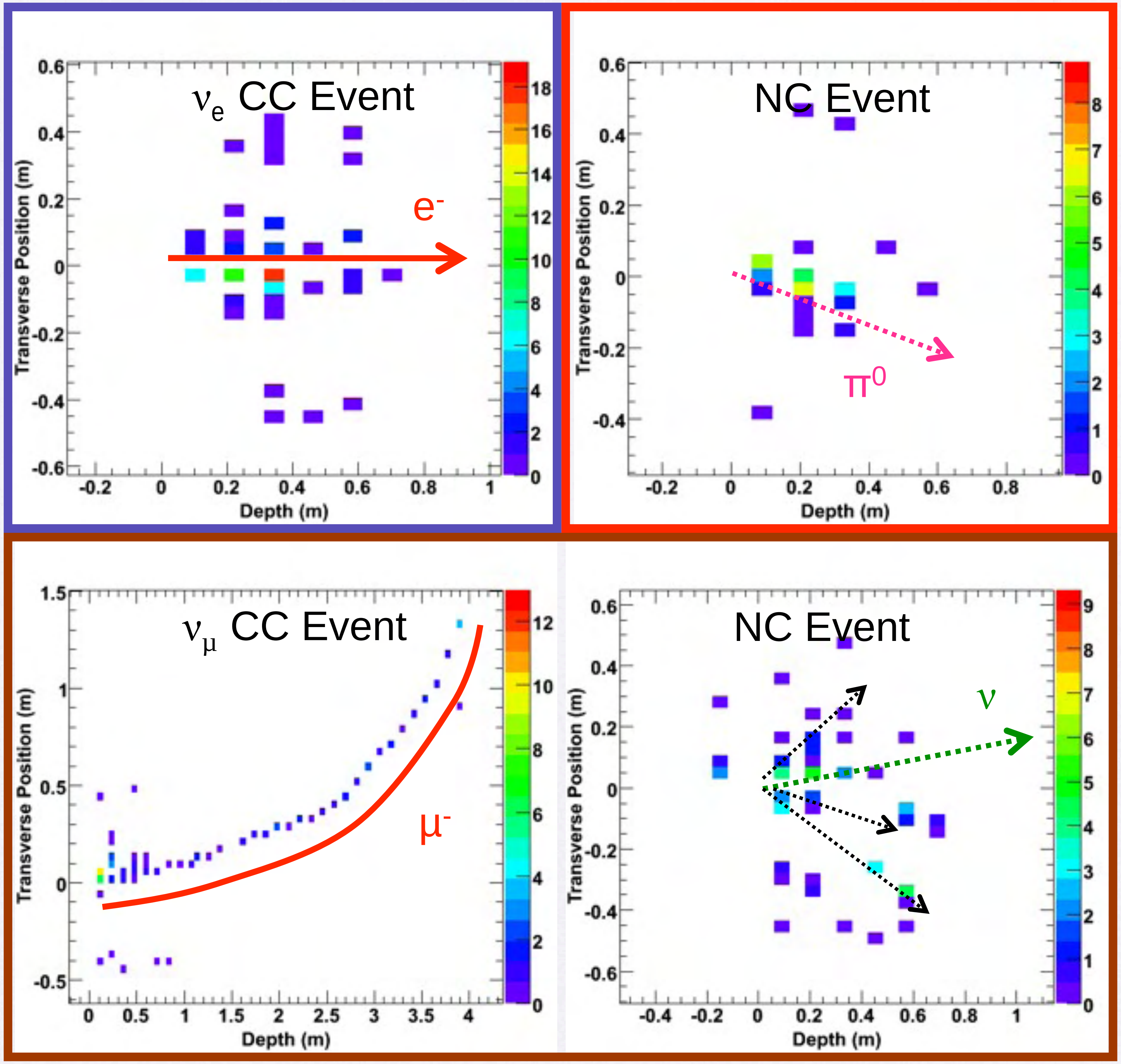
To select ν_e CC we focus on finding compact showers.

MC events

Signal

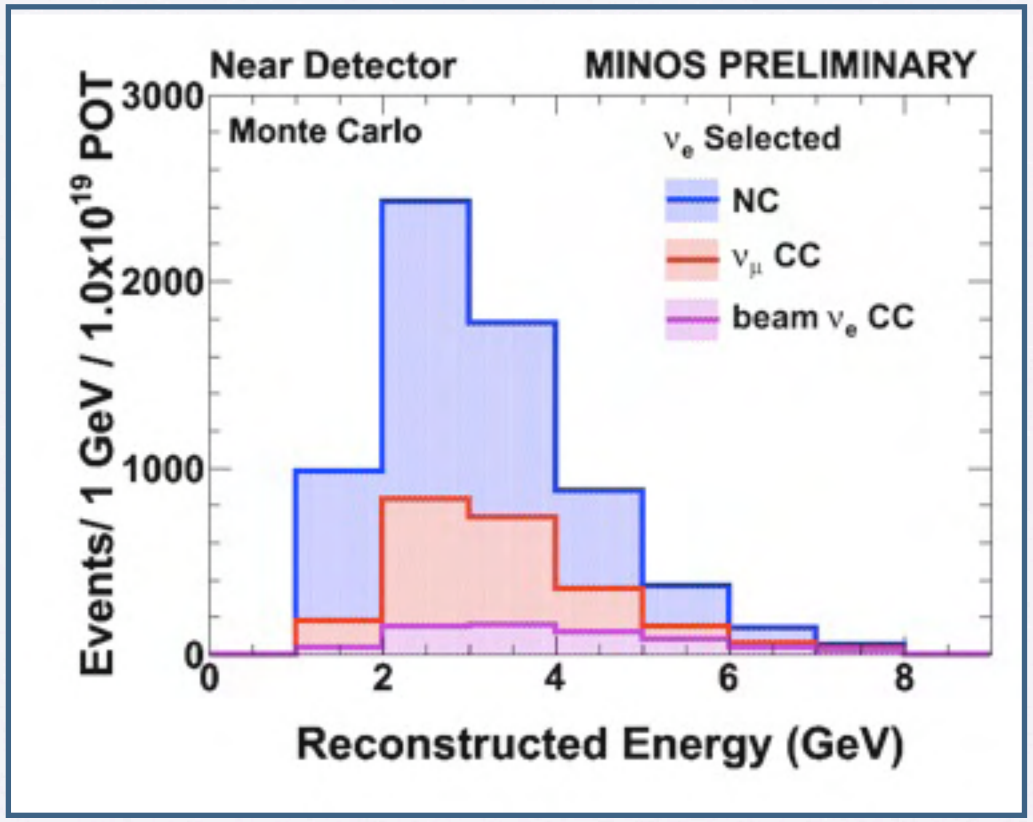
"Irreducible" Background

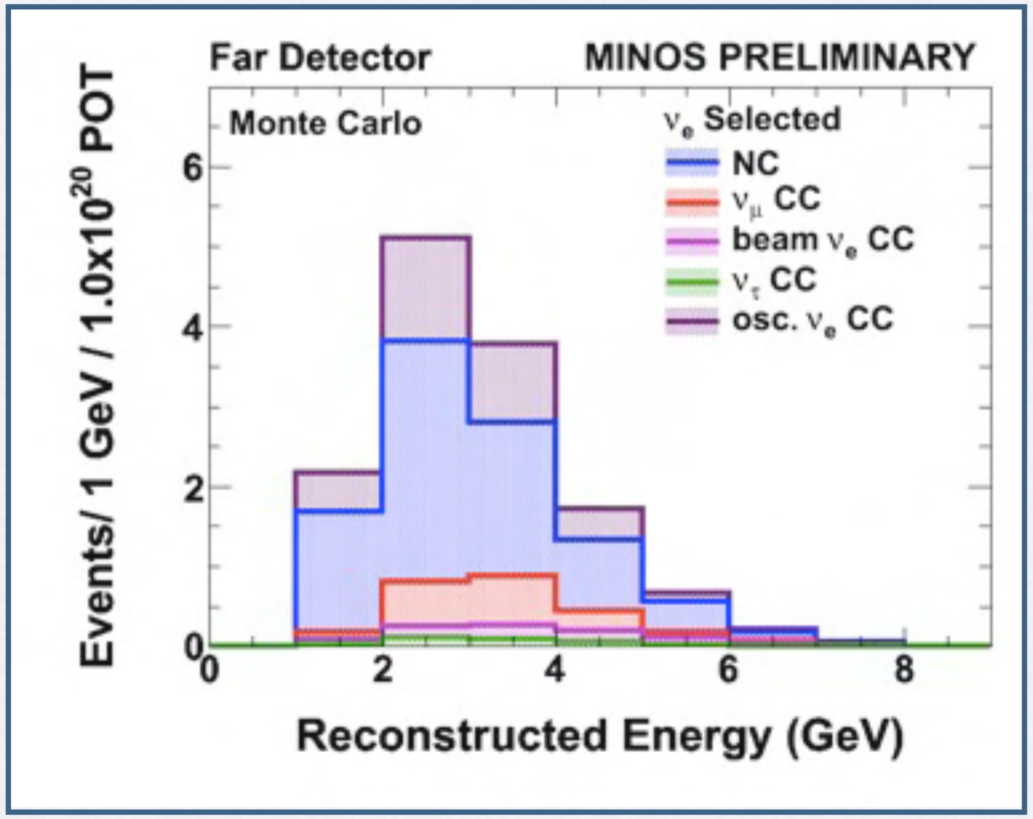
Reducible Background



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.
  - **Separate the main background components** NC, ν_μ CC and beam ν_e CC since they extrapolate differently.
- **Extrapolate each background type** 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.

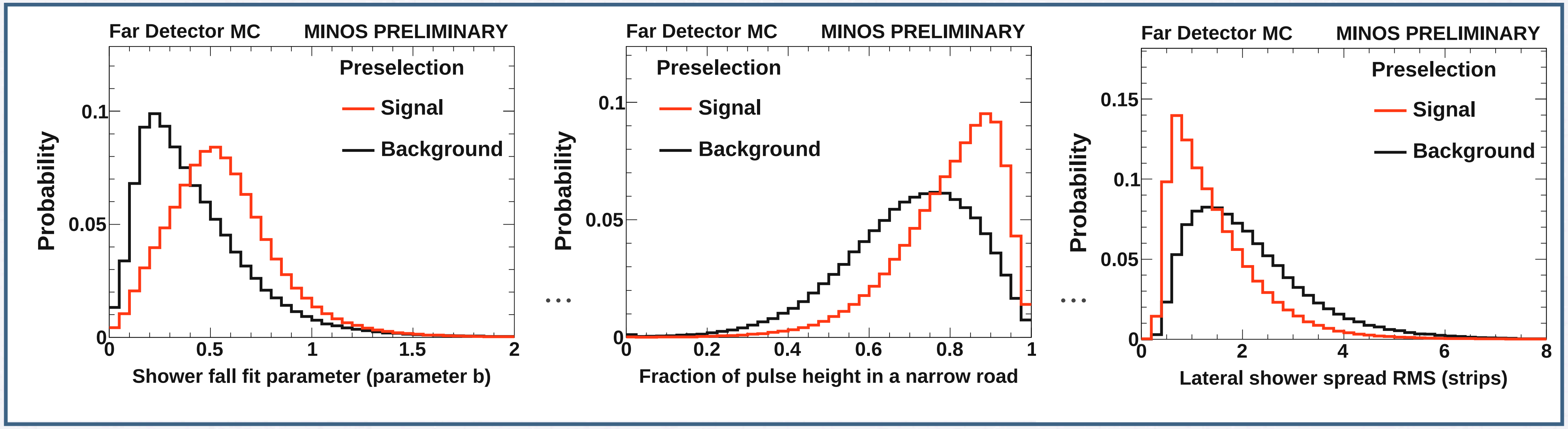




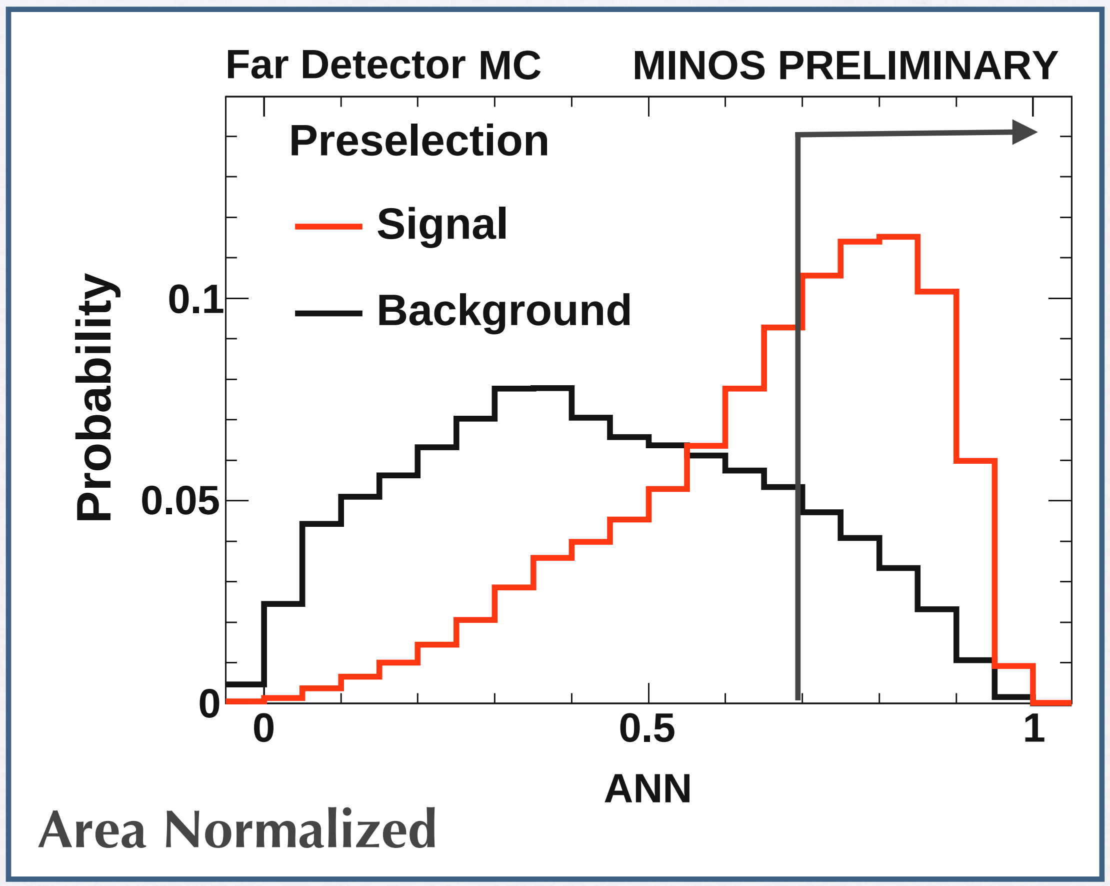
Selecting ν_e events

After selecting a shower dominated sample in signal energy region

Examples



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

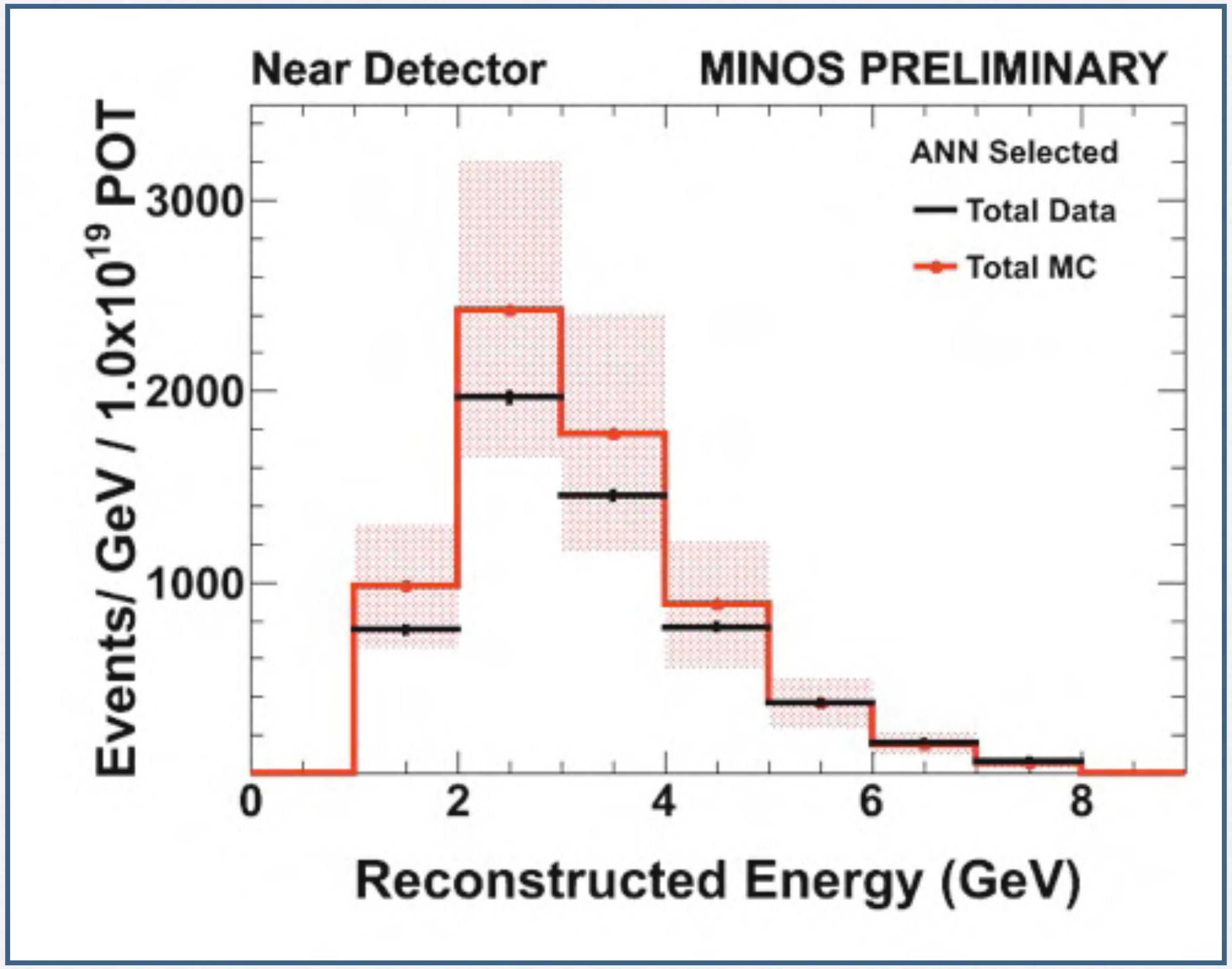


Secondary selection also studied. Better signal efficiency and background rejection. Different systematics.

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

Estimating the background in Near Detector data

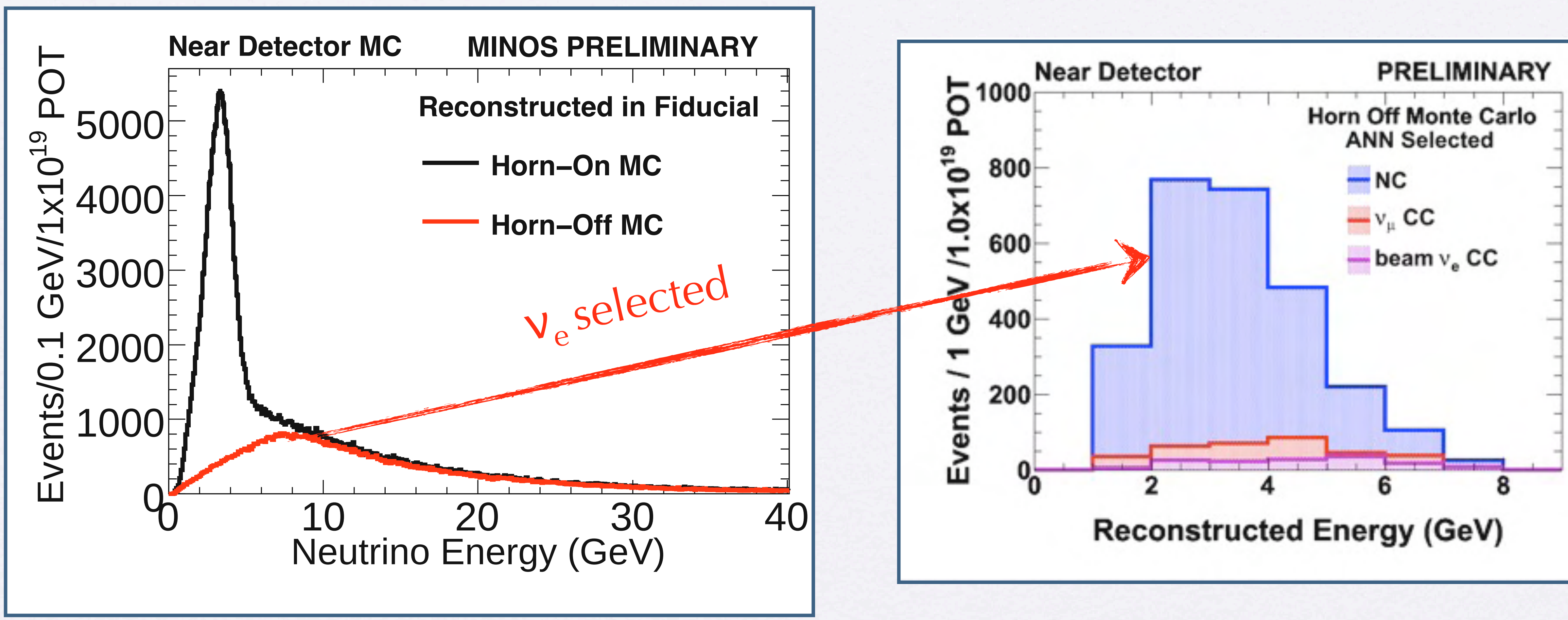
- Disagreement is within the large uncertainties of the model.
  - Mostly due to modeling of hadronic shower.
- We have developed **two data-driven methods.**
  - To measure the different background contributions in the Near Detector.



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

Separate background components NC vs CC

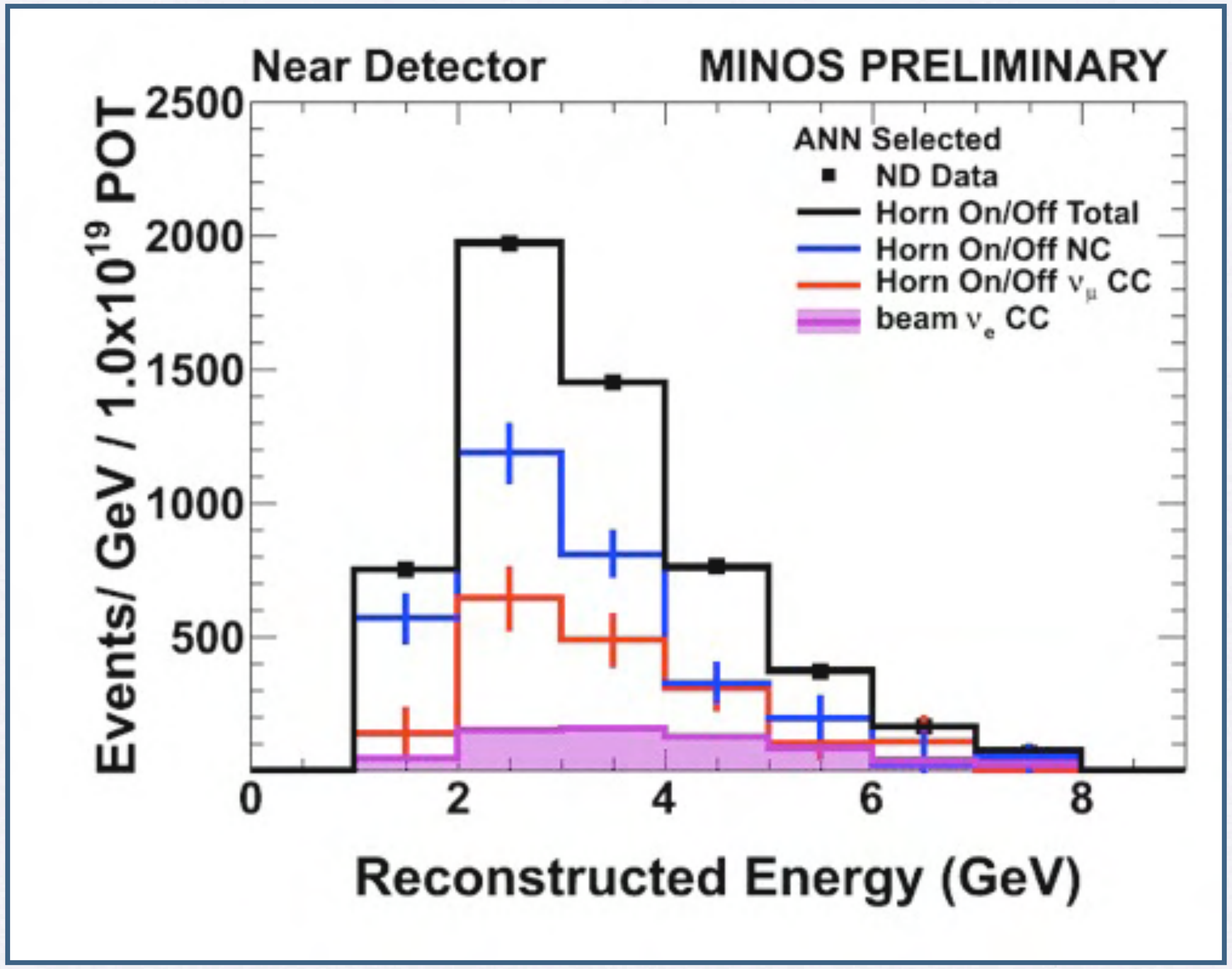
- Normal beam configuration has a peak which is focused by the horns.
- When beam horns are turned off, the parent pions do not get focused result in no peak.



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

Separate background components NC vs CC

- We calculate the NC and ν_μ CC fractions by correcting the measurement using the horn off/on ratios for each components.
  - These ratios agree well with the data.



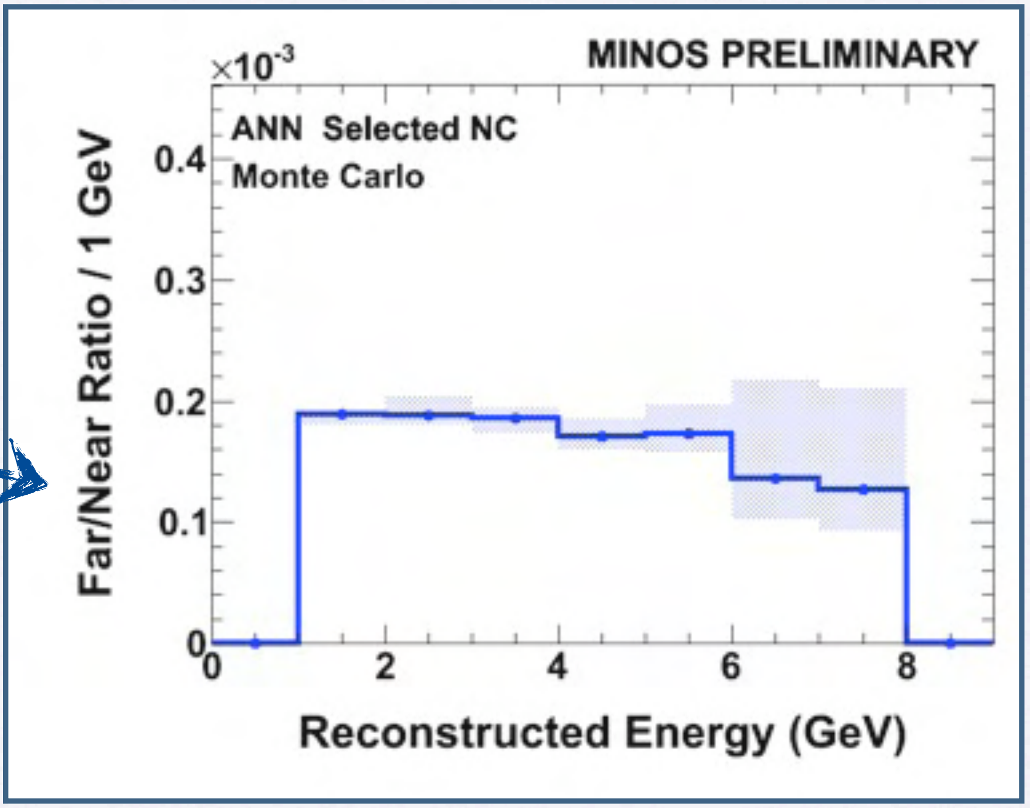
The two data-driven methods are in excellent agreement.

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 ratio.

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

~10^{-4} expected from geometry and fiducial volume ratio alone



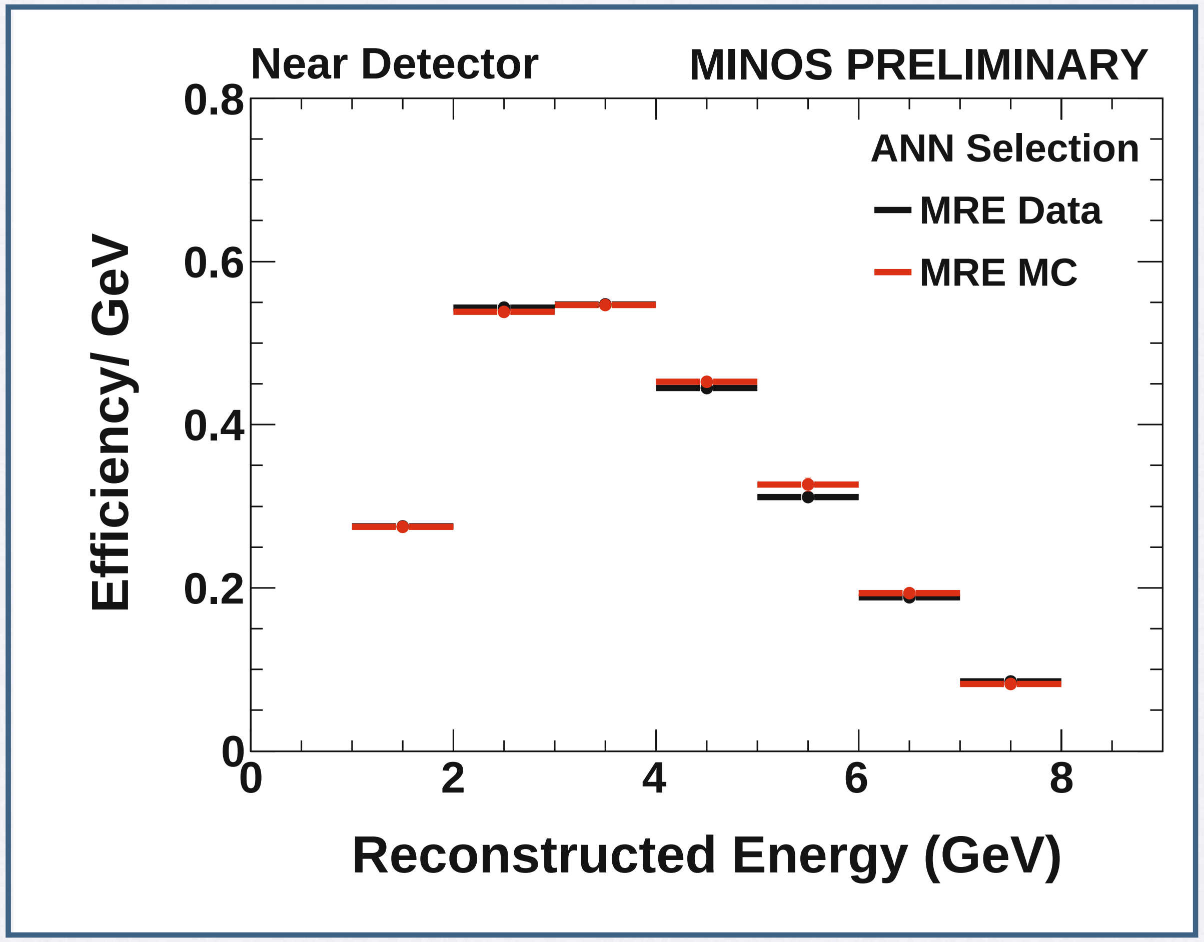
- Far/Near ratio accounts for geometry, fiducial volume ratio, intensity, detector differences and oscillations.
- The **signal** $\boldsymbol{\nu_e}$ and the $\boldsymbol{\nu_\tau}$ **CC** from ν_μ oscillations are corrected using the extrapolation of the ν_μ CC spectrum. The **beam** $\boldsymbol{\nu_e}$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

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

Estimating the signal efficiency

- The ν_e selection is applied to muon removed ν_μ CC with electron added 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 $\times 10^{20}$ POT) ranges from: 6 to 12 events.



ν_e appearance result:

MINOS PRELIMINARY

ν_e appearance result:

Observation 35 events

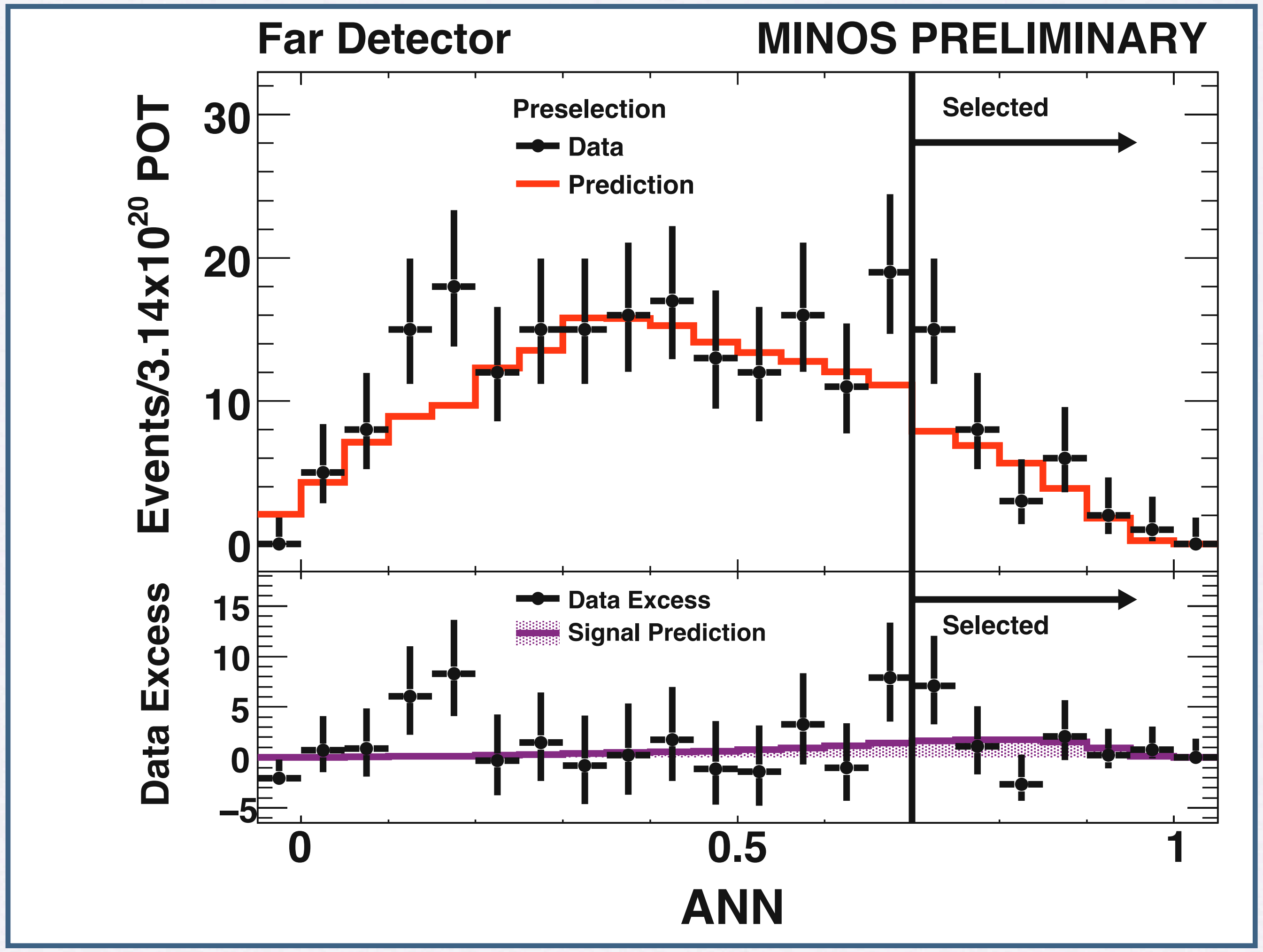
Expected Background 27±5(stat)±2(sys)

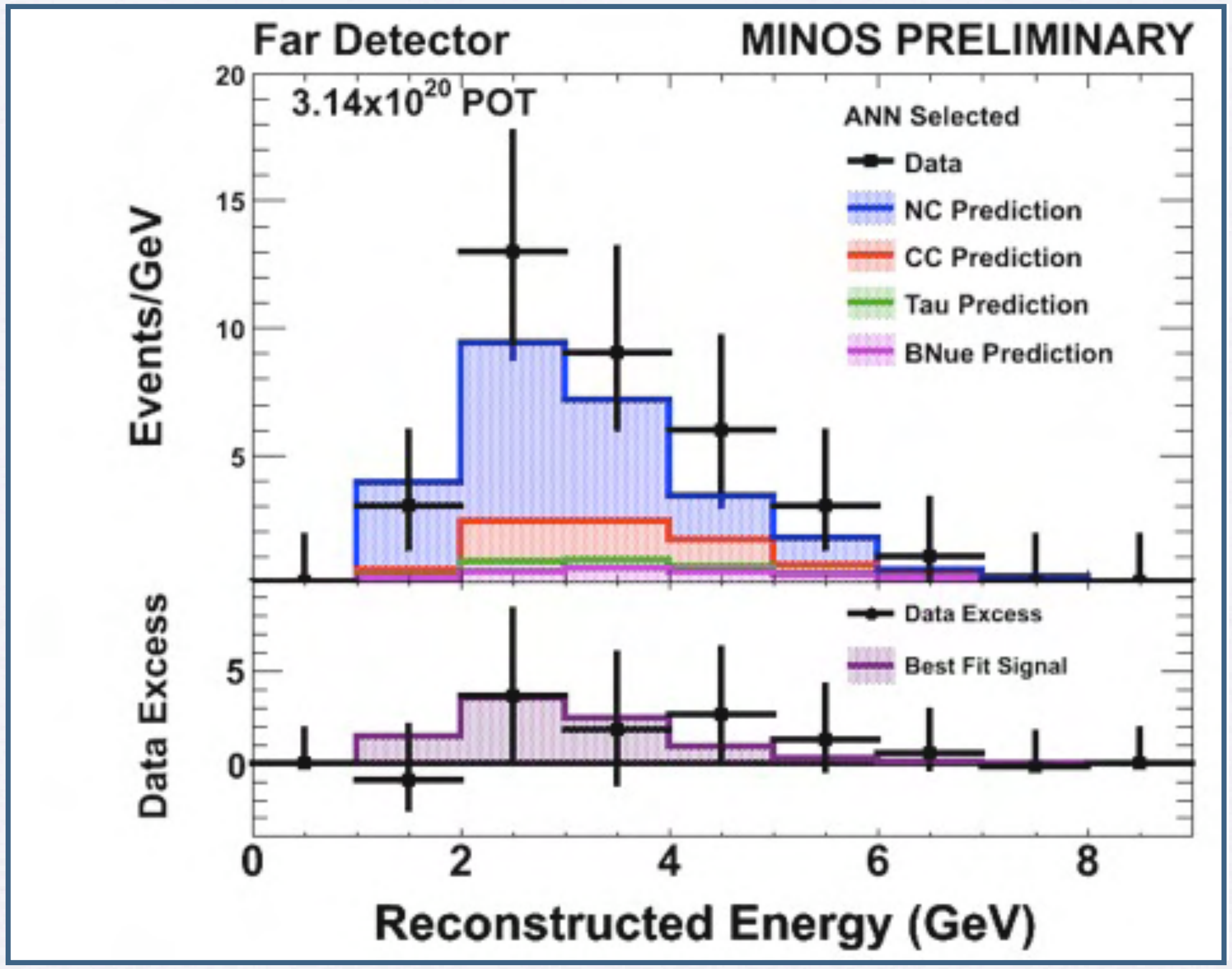
for 3.14×10^{20} POT

MINOS PRELIMINARY

ν_e Selected Far Detector Data

- Blind analysis done. Background/signal predictions and systematic errors finalized before looking at data in Far Detector.



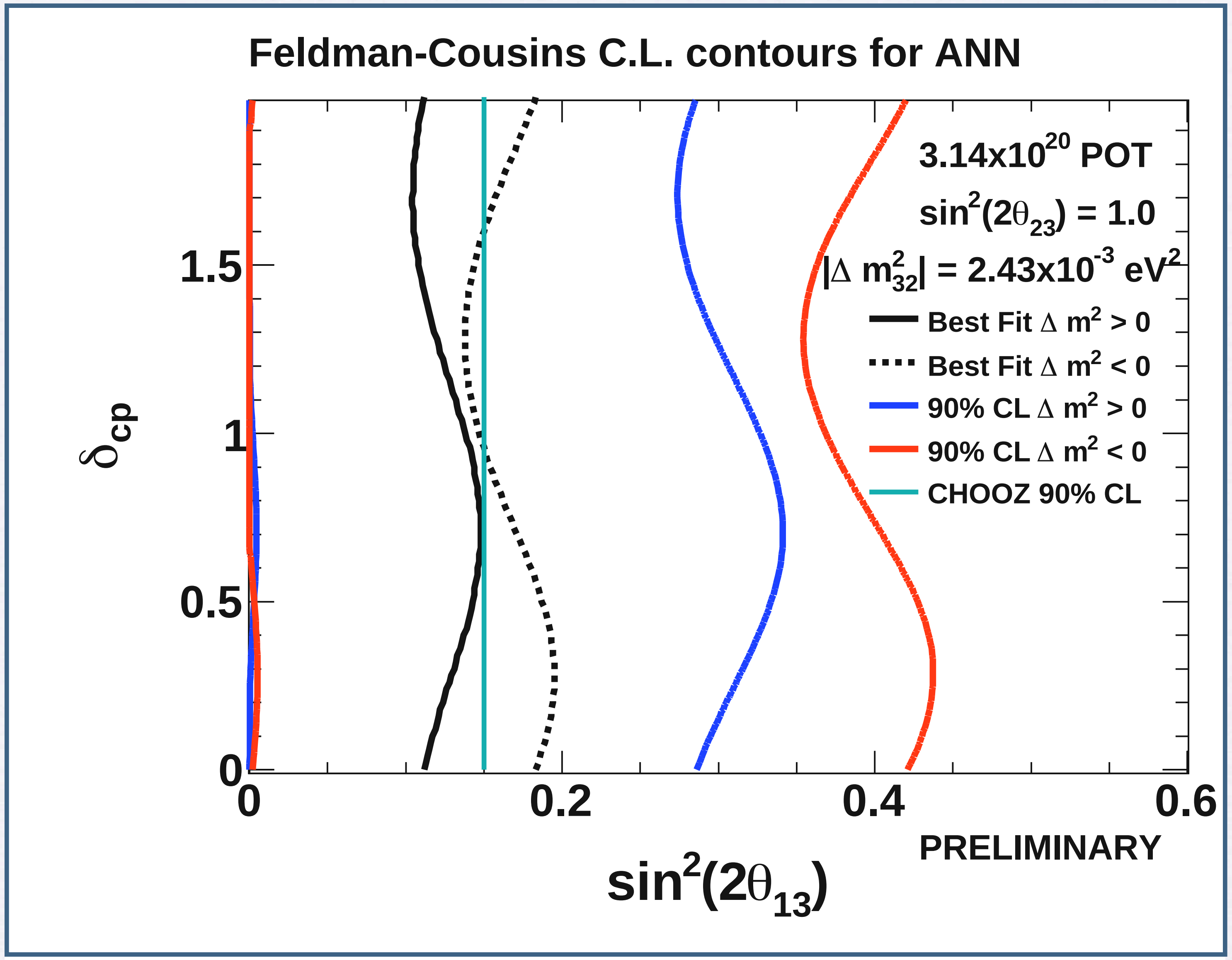


- Sidebands studied in Far Detector: muon removed and below signal region samples. Both consistent within 1-2 σ.

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

Fitting the oscillation hypothesis to our data

- Plot shows 90% CL 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.



Results are consistent with secondary selection and secondary separation method

Summary

- We have completed an **initial search for ν_e appearance** in the MINOS data.
    - Developed two ν_e selections and two data-driven background estimates.
- 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, $\delta_{CP} = 0$: $\mathbf{\sin^2(2\theta_{13}) < 0.29}$ **(90% CL)**
    - inverted hierarchy, $\delta_{CP} = 0$: $\mathbf{\sin^2(2\theta_{13}) < 0.42}$ **(90% CL)**

We are close to doubling these data in current running!
Expect next results with ~ 7×10^{20} POT