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

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Joint Experimental-Theoretical Seminar

FNAL

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Absolute neutrino mass?

Unmeasured, but known **small:**

→ **less than ~0.7 eV**

(sum of ν masses inferred from cosmological observations)

→ **less than ~2 eV**

(direct kinematic measurements of ν_e effective mass)

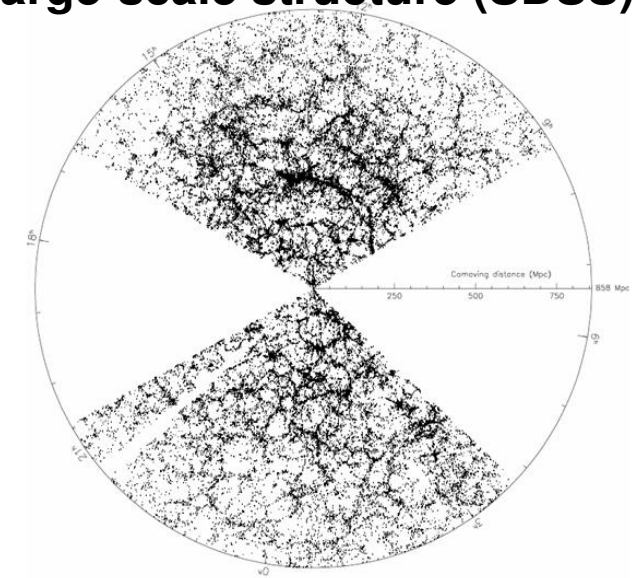
Or, notably: $m_\nu \ll m_{\mathrm{EW}}$

"See-saw" mechanism puts the physical neutrino mass at:

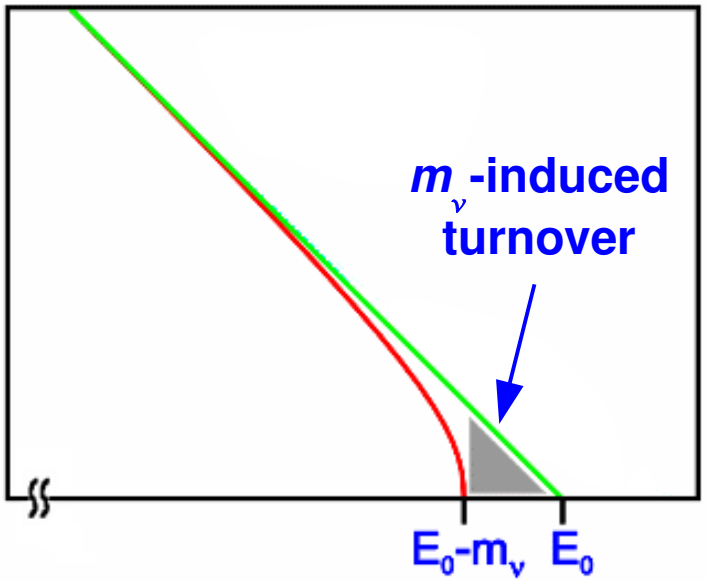
$$m_\nu \sim \frac{m_{\mathrm{EW}}^2}{m_{\mathrm{GUT}}}$$

Neutrino sector may provide a window to new physics

Large-scale structure (SDSS):



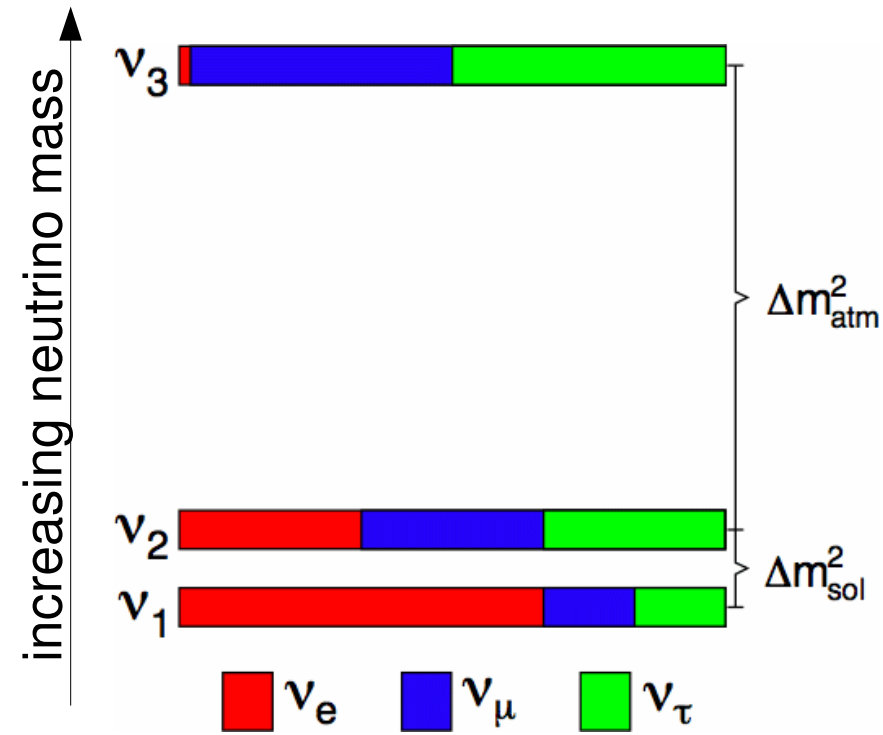
Beta decay endpoint:



Neutrino mixing

mass eigenstates ≠ flavor eigenstates:

$$\underset{\alpha=(e,\mu,\tau)}{|\nu_\alpha\rangle} = \sum_i U^*_{\alpha i}|\nu_i\rangle$$



flavor composition of the neutrino can **change as it propagates:**

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L)\rangle|^2$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}L/E]$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[2.54\Delta m^2_{ij}L/E]$$

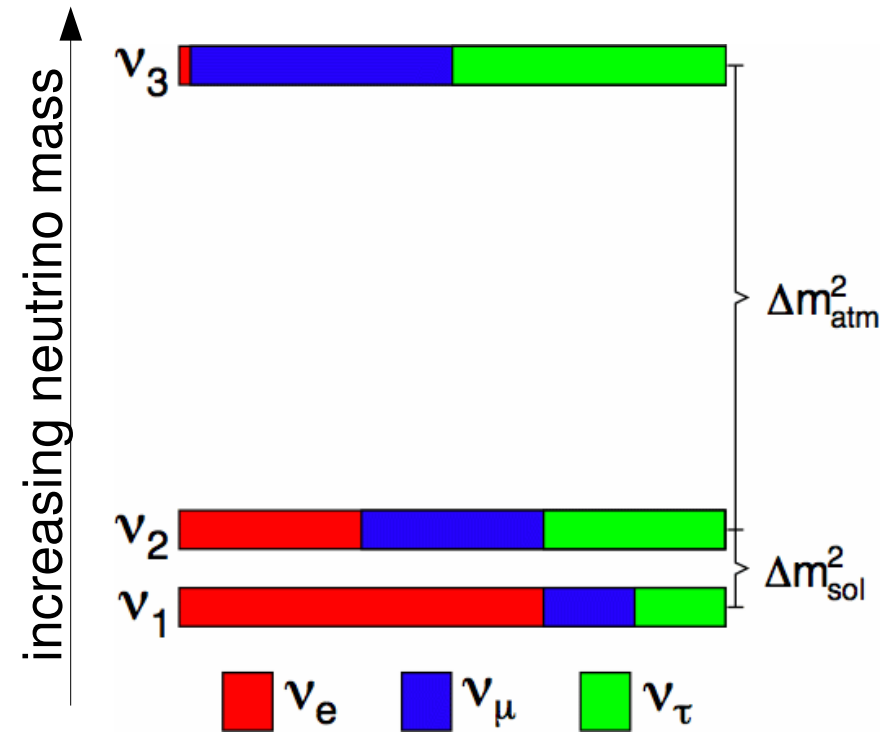
two-neutrino case: $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$

$$\left(1.27,\ 2.54 \text{ in units of } \frac{\mathrm{GeV}c^4}{\mathrm{eV}^2\mathrm{km}}\right)$$

Neutrino mixing

Two oscillation regimes:

- ***solar***, *reactor experiments:*
  $$\Delta m^2_{\rm sol} = (7.6 \pm 0.2) \times 10^{-5}\ {\rm eV}^2$$
- ***atmospheric***, *accelerator experiments:*
  $$\Delta m^2_{\rm atm} = (2.43 \pm 0.13) \times 10^{-3}\ {\rm eV}^2$$



Mixing angles extracted so far...

$$\theta_{12} = 34^\circ \pm 3^\circ$$
$$\theta_{23} = 45^\circ \pm 5^\circ$$
$$\theta_{13} < 11^\circ \quad (90\%\ \text{C.L.})$$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Accessible by MINOS}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar sector}} \times \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana phases}}$$

Many questions

- ➞ Why is θ_{23} near maximal?
- ➞ What is θ_{13} and why is it small?
- ➞ Why so different than quark mixing?

Quarks:

$$U_{\rm CKM} \sim \begin{pmatrix} 1 & 0.2 & 0 \\ 0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

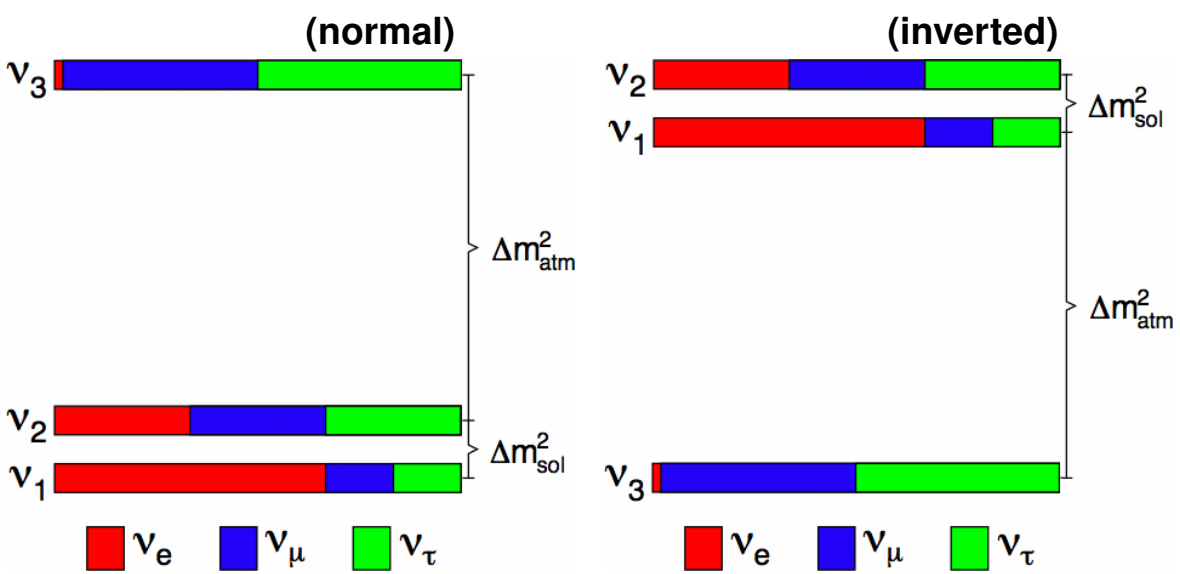
Neutrinos:

$$U_{\rm MNS} \sim \begin{pmatrix} 0.8 & 0.6 & 0 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

underlying symmetries, unification implications...

- ➞ Is CP violation is present?
- ➞ Are neutrinos Majorana?
- ➞ What is the hierarchy of neutrino masses?

leptogenesis, interpreting CMB & LSS observations, $0\nu\beta\beta$



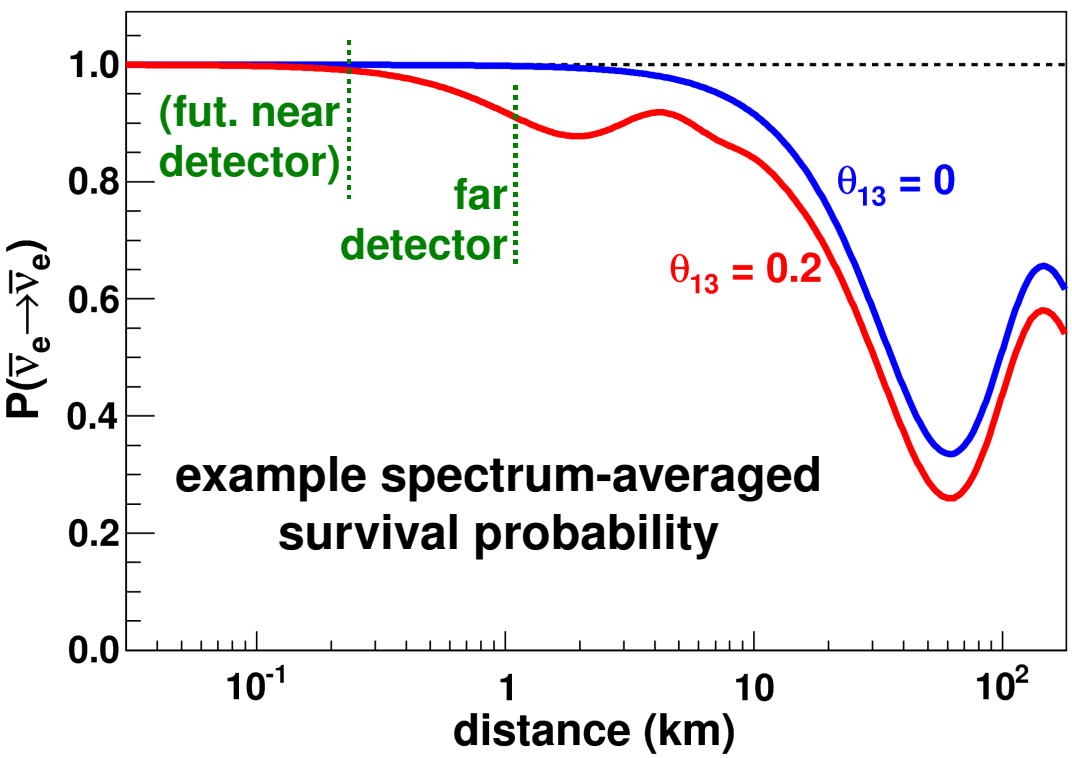
Measuring θ_{13}

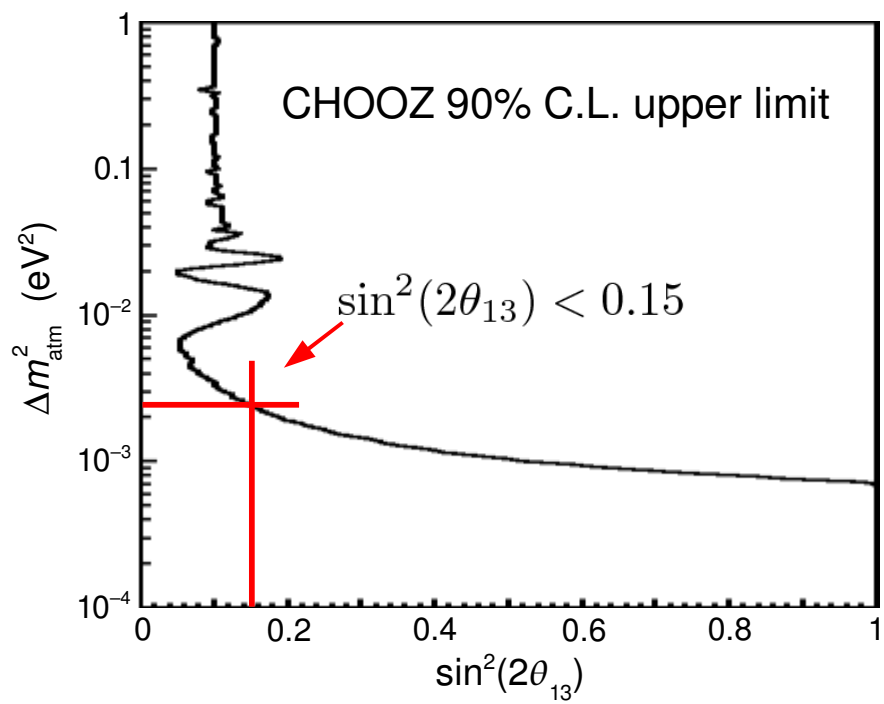
- Need a neutrino source: **accelerators** or **nuclear reactors**
- **CHOOZ reactor experiment** holds best limit
- ***Reactor principle:***

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \underline{\sin^2(2\theta_{13})} \sin^2(1.27\Delta m^2_{\mathrm{atm}} L/E)$$

plus smaller solar term

***L* ≈ 2 km** ***E* ≈ 4 MeV**





Measuring θ_{13}

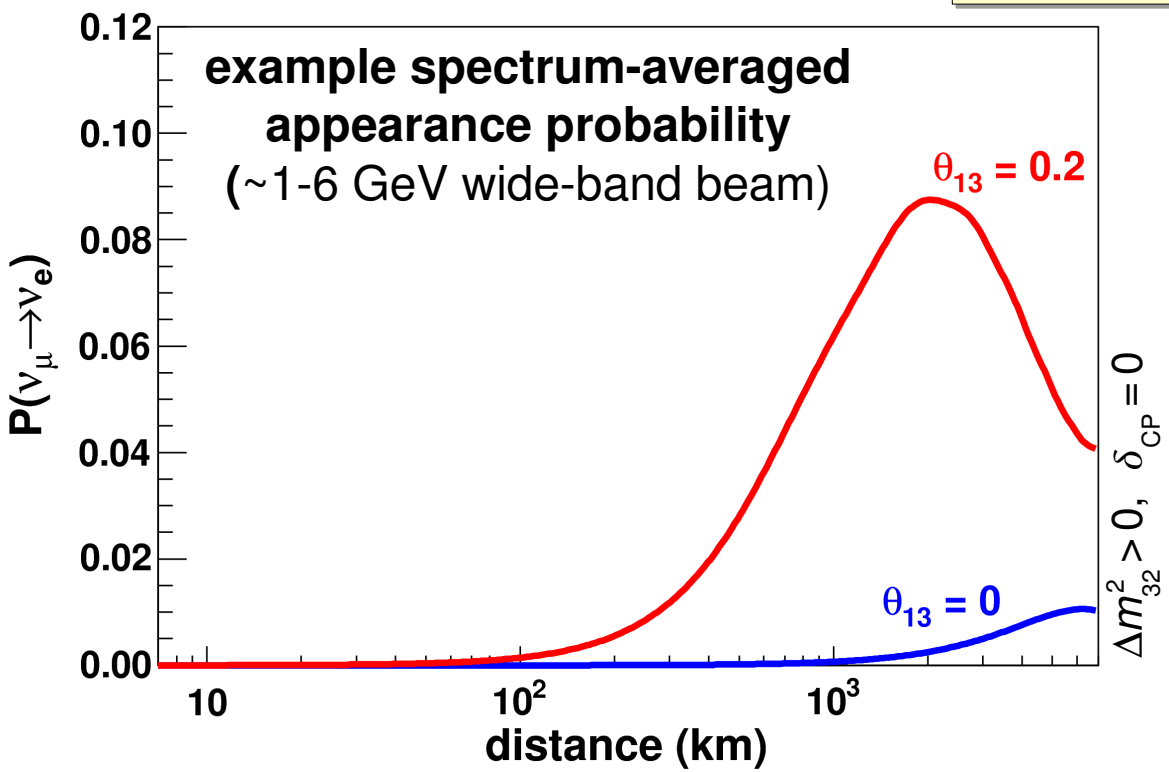
- A conventional **accelerator-based** neutrino source provides ν_μ
- Look for **appearance** of ν_e

$$P(\nu_\mu \to \nu_e) \approx$$
$$2\,\underline{\sin^2(2\theta_{13})}\,\sin^2(\theta_{23})\,\sin^2(1.27\Delta m^2_{\rm atm} L/E)$$

plus ***potentially large modifications*** *(CPv, matter effects)*

250 - 2500 km (L)

0.5 - 5 GeV (E)



Disappearance (reactor):

θ_{13}

Appearance (accelerator):

θ_{13}, θ_{23}, $\not{CP}$, sign(Δm^2_{32})

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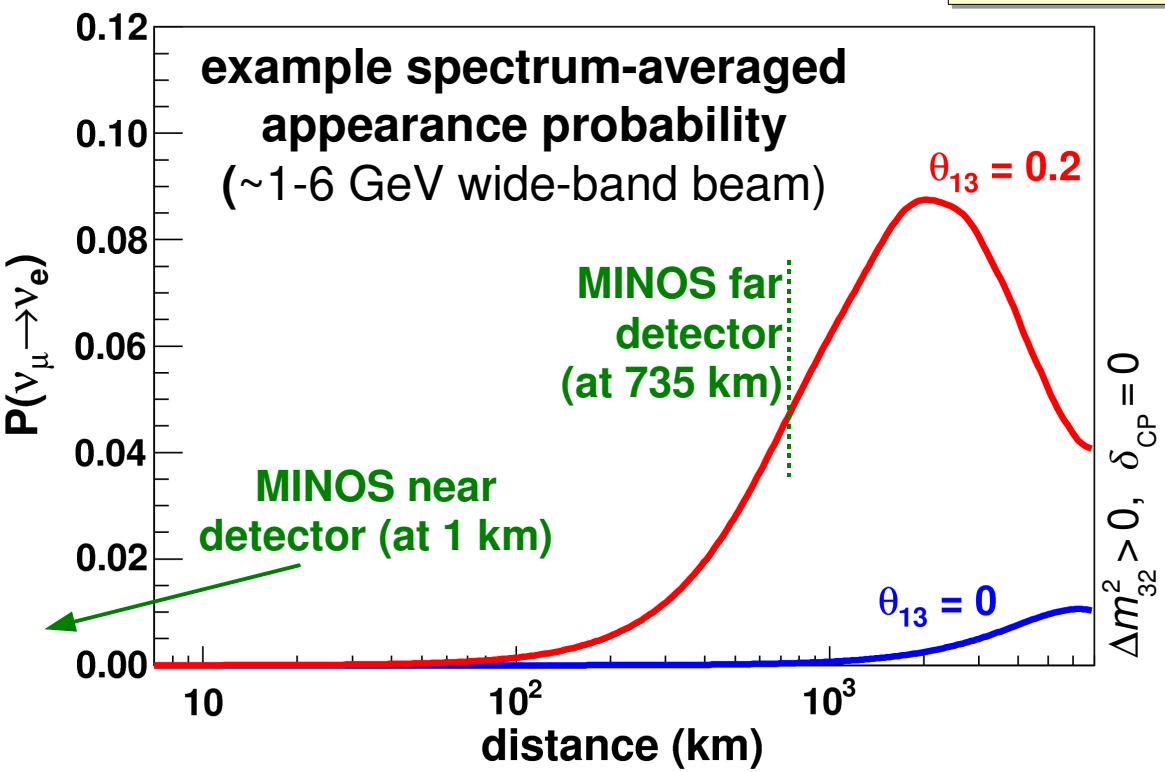

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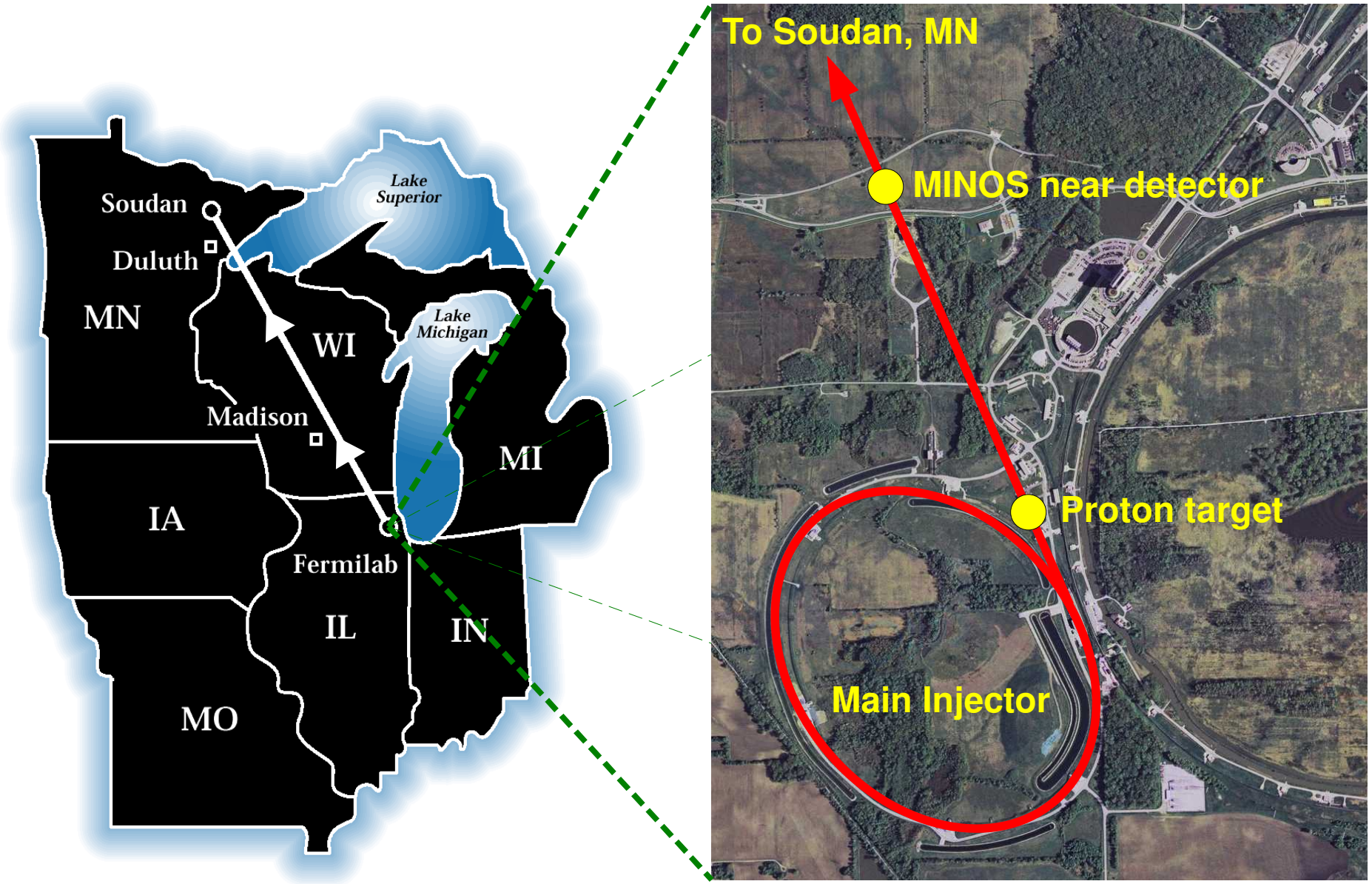
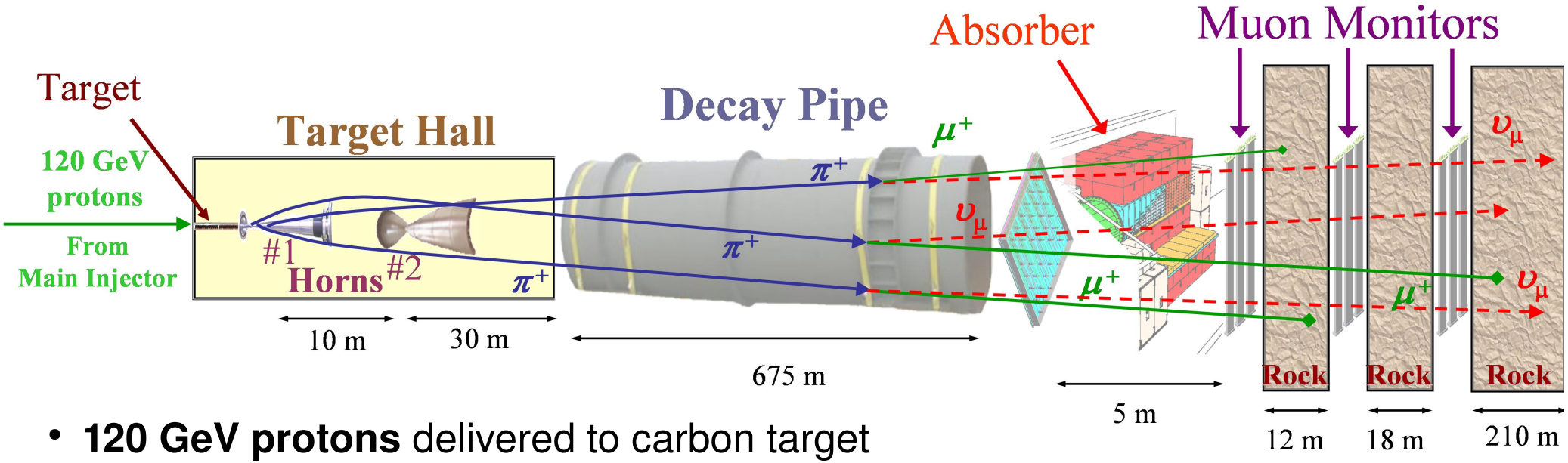
$\nu_\mu \rightarrow \nu_e$ in MINOS

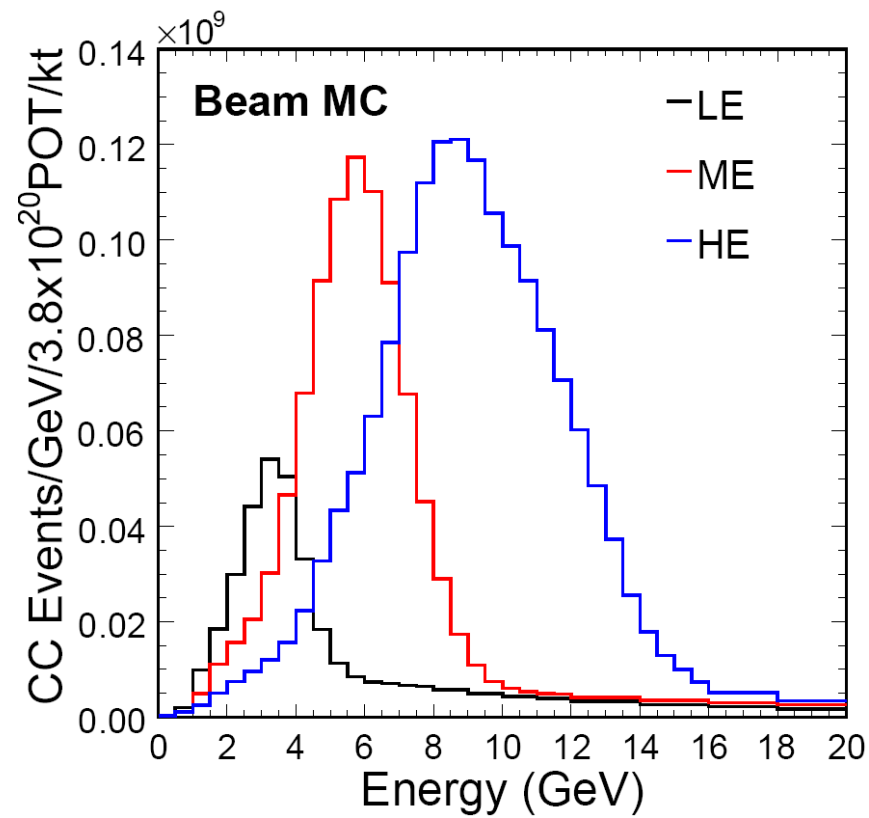
Main Injector Neutrino Oscillation Search (MINOS)

735 km to the far detector



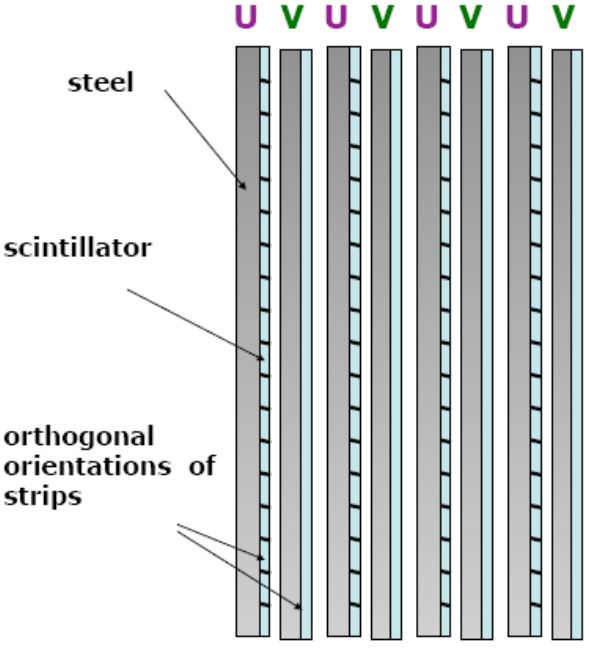


- **120 GeV protons** delivered to carbon target
- Magnetic **focusing horns** send positive secondaries (π^+ mostly) down **decay pipe**
- Target and horn positions are adjustable: ***tunable neutrino energy spectrum*** →

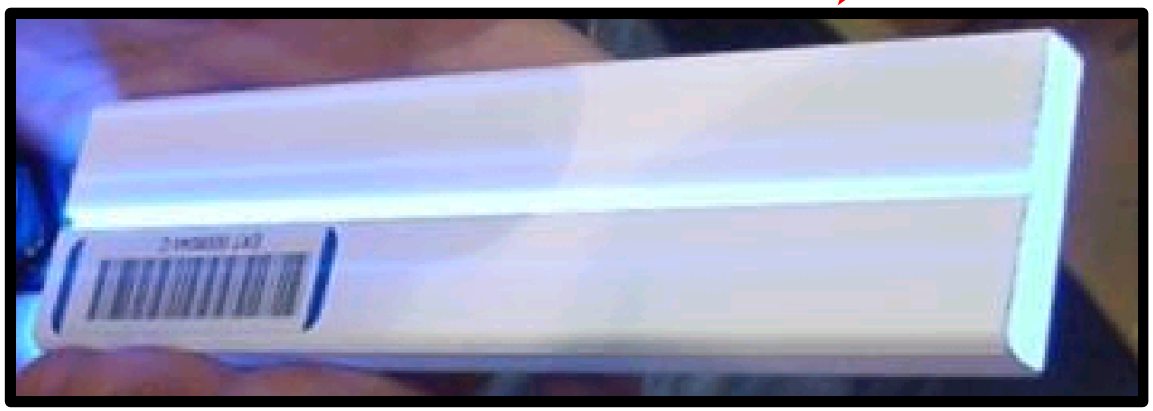


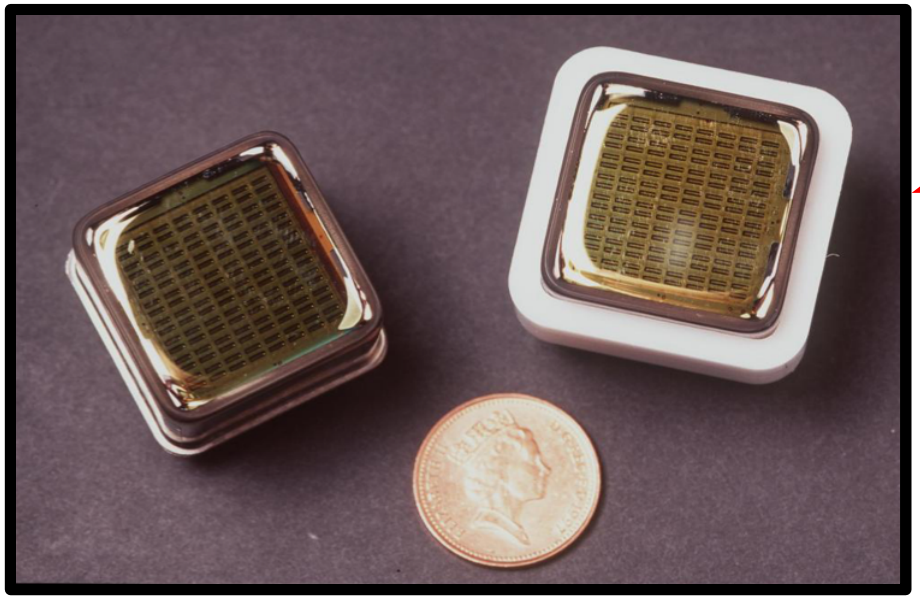
MINOS Detectors

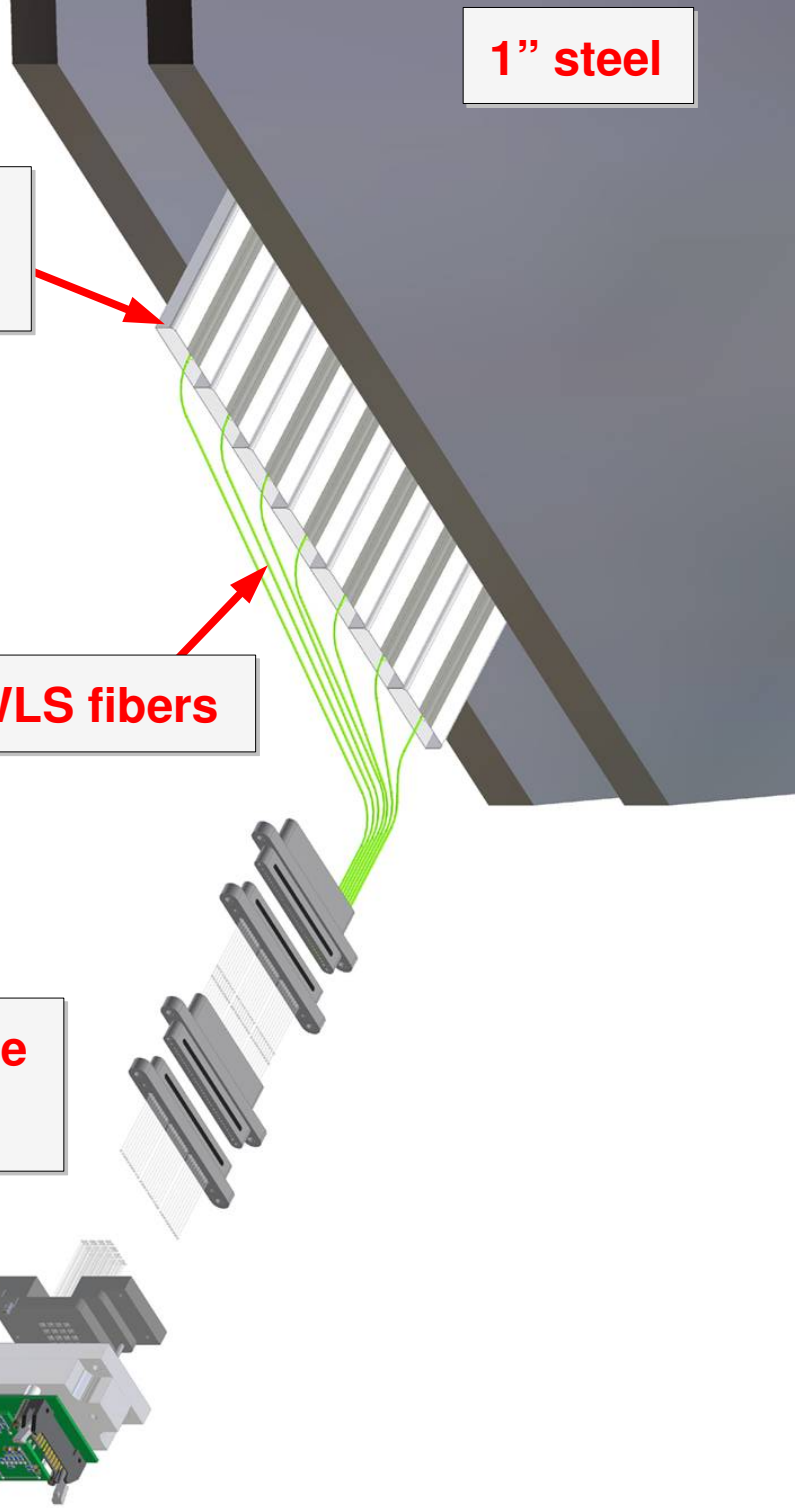
- **Near** and **far detectors:**
  Magnetized tracking calorimeters (~1.3 T field)
- Alternating layers of
  steel (1” thick plates)
  scintillator (1 cm thick, 4.1 cm wide strips)
- Scintillator layers oriented at ±45°



MINOS Detectors





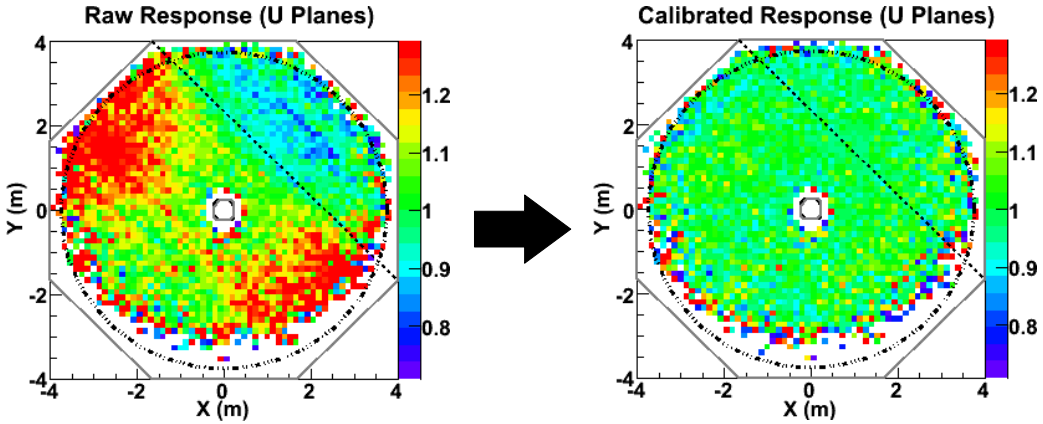


Calibration

Cosmic ray muons:

measure & remove **spatial variations**

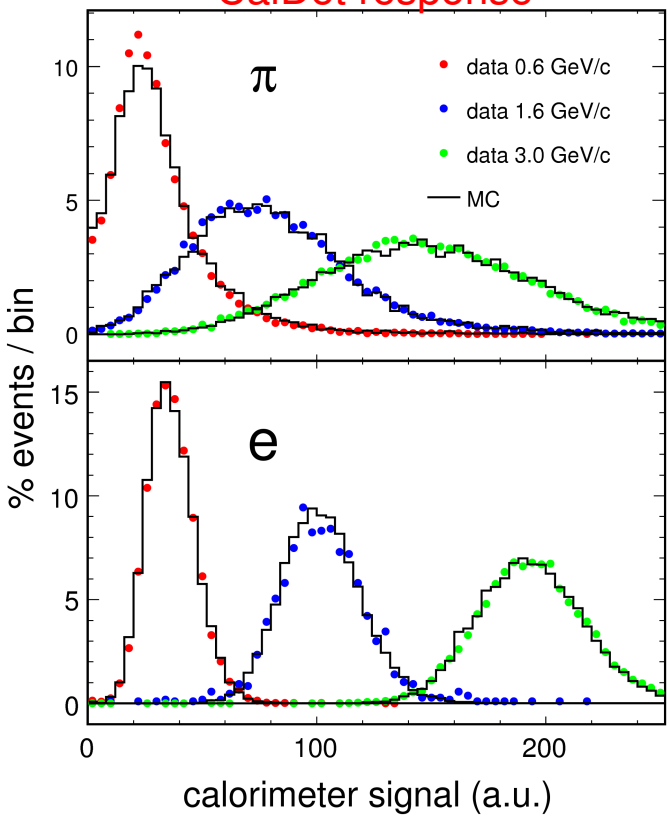
(channel differences, attenuation)



MINOS Calibration Detector (CalDet): *E* scale

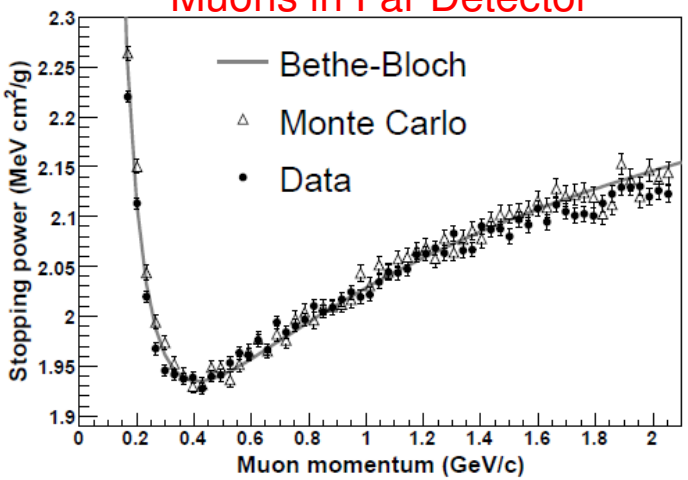
- Exposed to **0.2–10 GeV** *p*, *e*, *μ*, *π* at CERN
- 60 planes, 1 m x 1 m

CalDet response



Everything **tied together** with **stopping muons:**

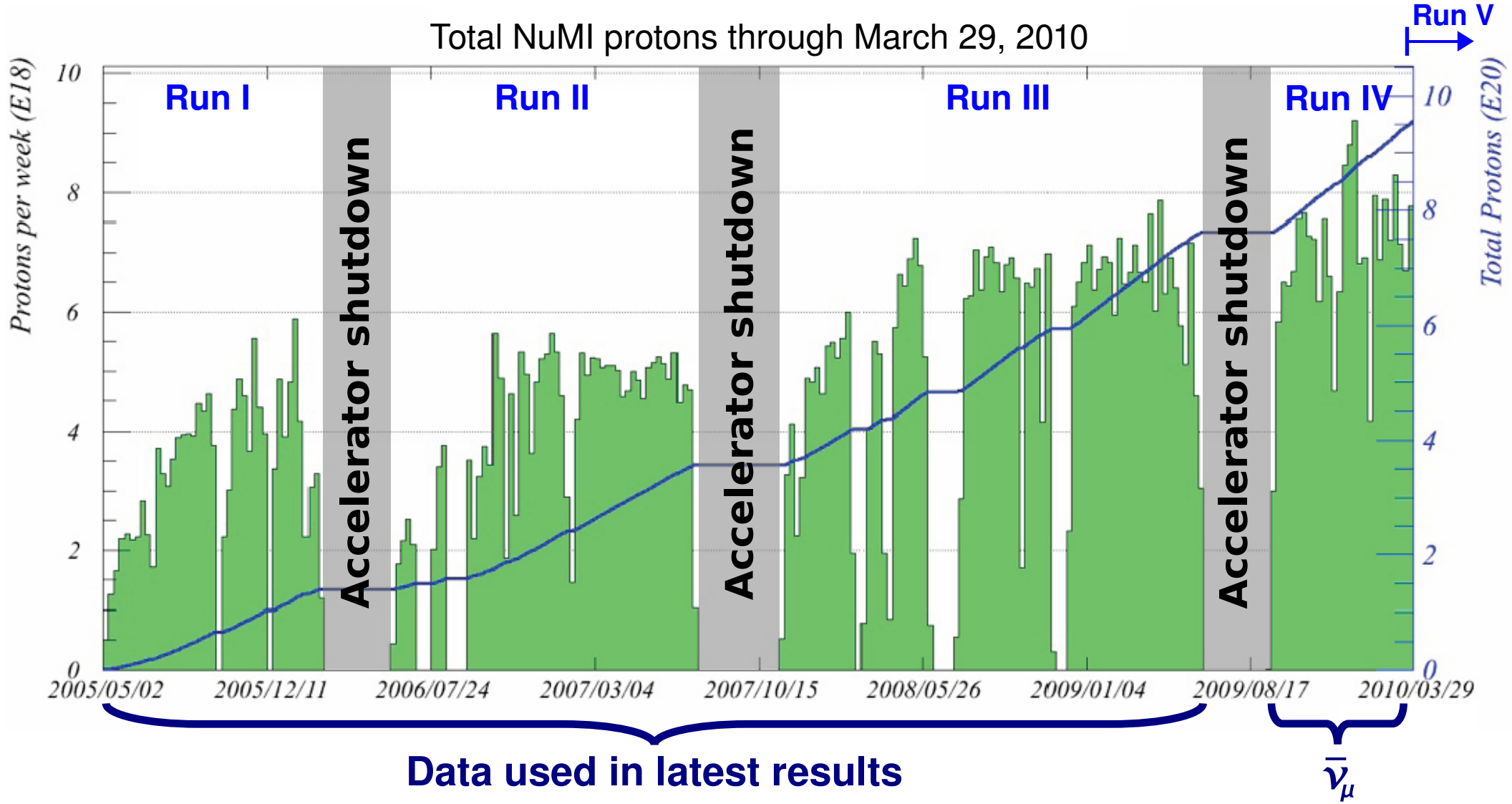
Muons in Far Detector



MINOS calorimetry good to:

6% (absolute)

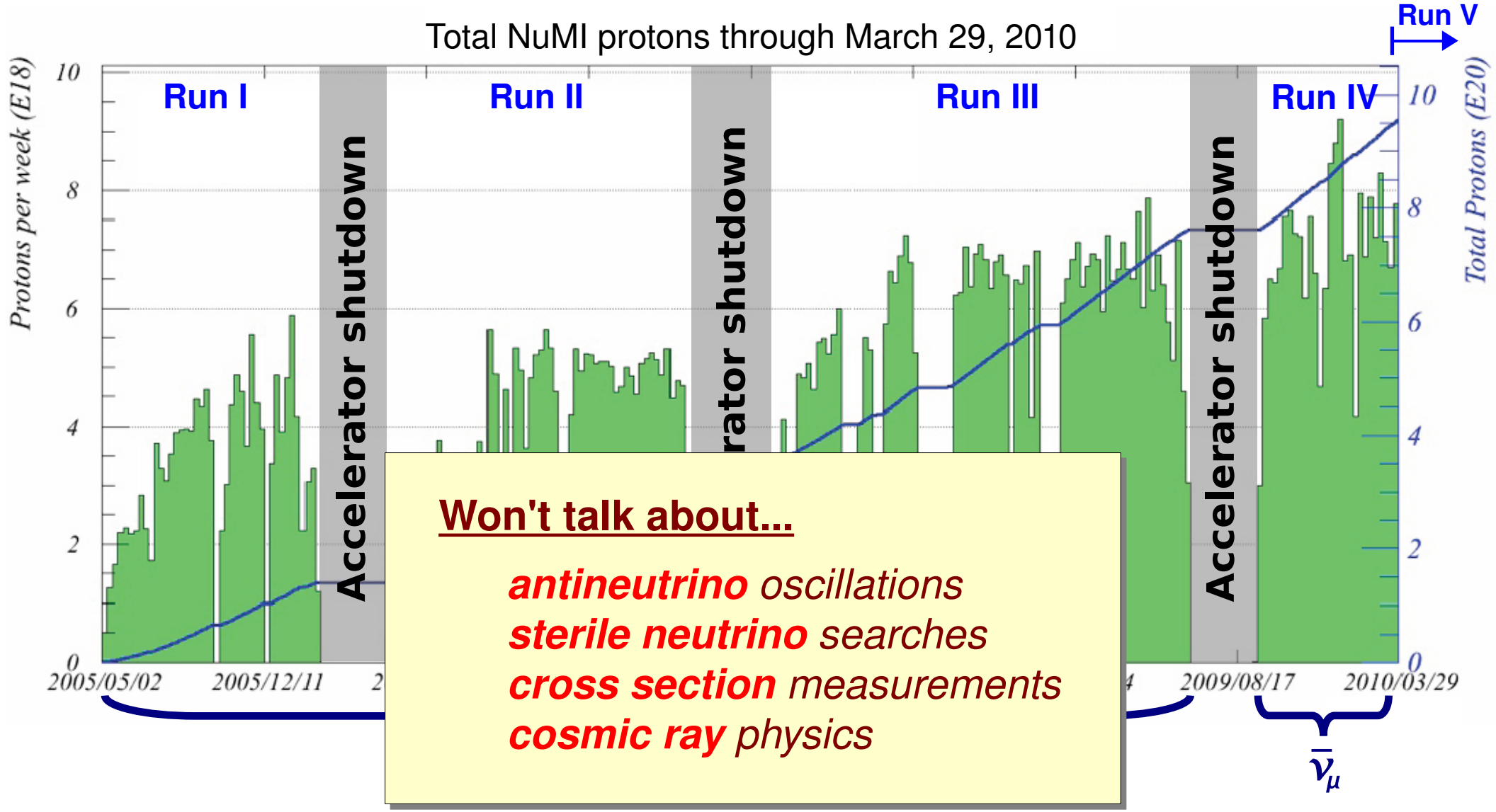
2% (relative near/far)



Excellent NuMI intensity over past two years

ν_e **appearance** results through Run III (~**7×10^{20} p.o.t.**)

Total NuMI protons through March 29, 2010



Won't talk about...

antineutrino *oscillations*
sterile neutrino *searches*
cross section *measurements*
cosmic ray *physics*

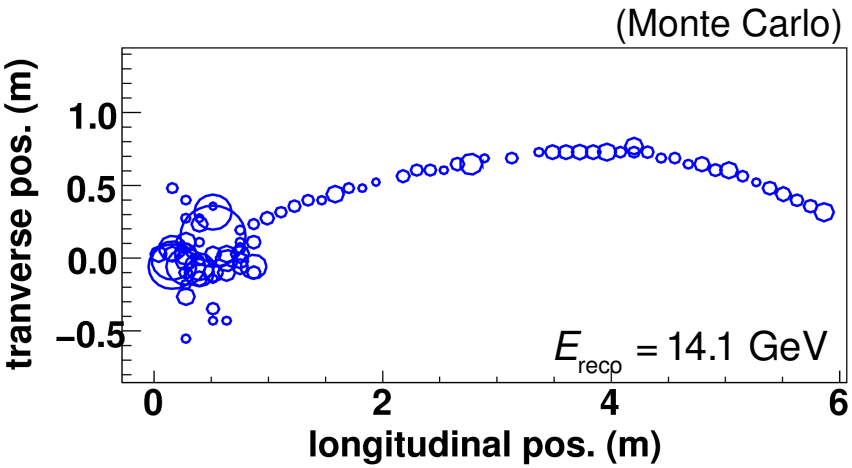
Excellent NuMI intensity over past two years

ν_e **appearance** results through Run III (~**7×10^{20} p.o.t.**)

Neutrino events

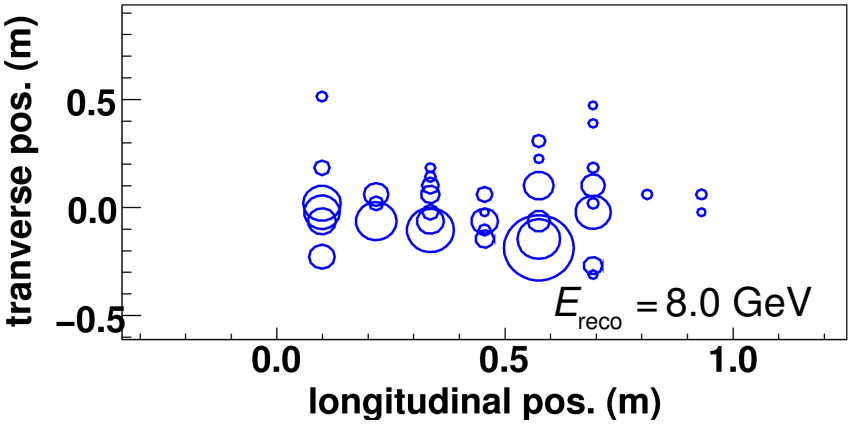
ν_μ charged current

- Clear signature in MINOS: *long track*
- If μ track is very short, event can be mistaken for ν_e CC



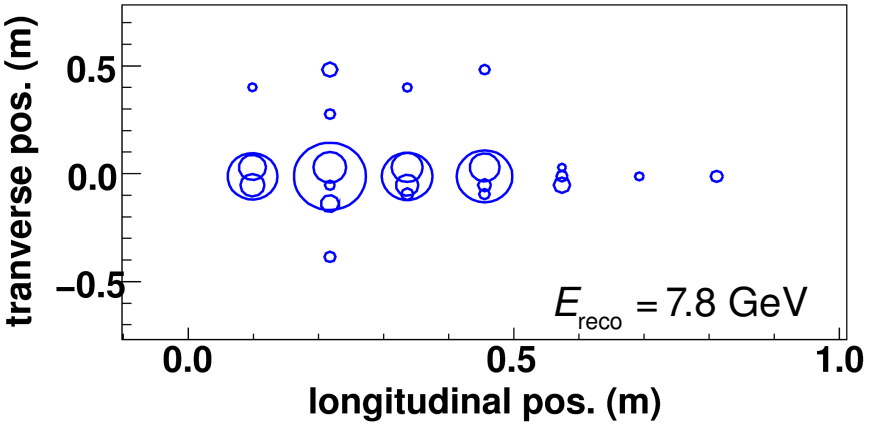
neutral current

- Esp. with π^0, hard to distinguish from ν_e CC
- Energy more transversely distributed



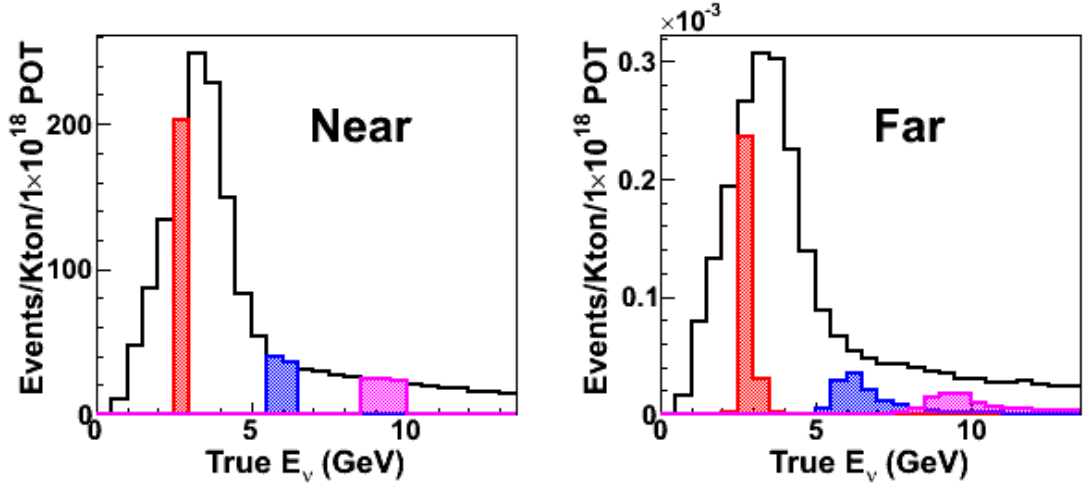
ν_e charged current [signal]

- ν_e is small component of initial flux
- Electron leaves characteristic deposition pattern (**compact shower**)

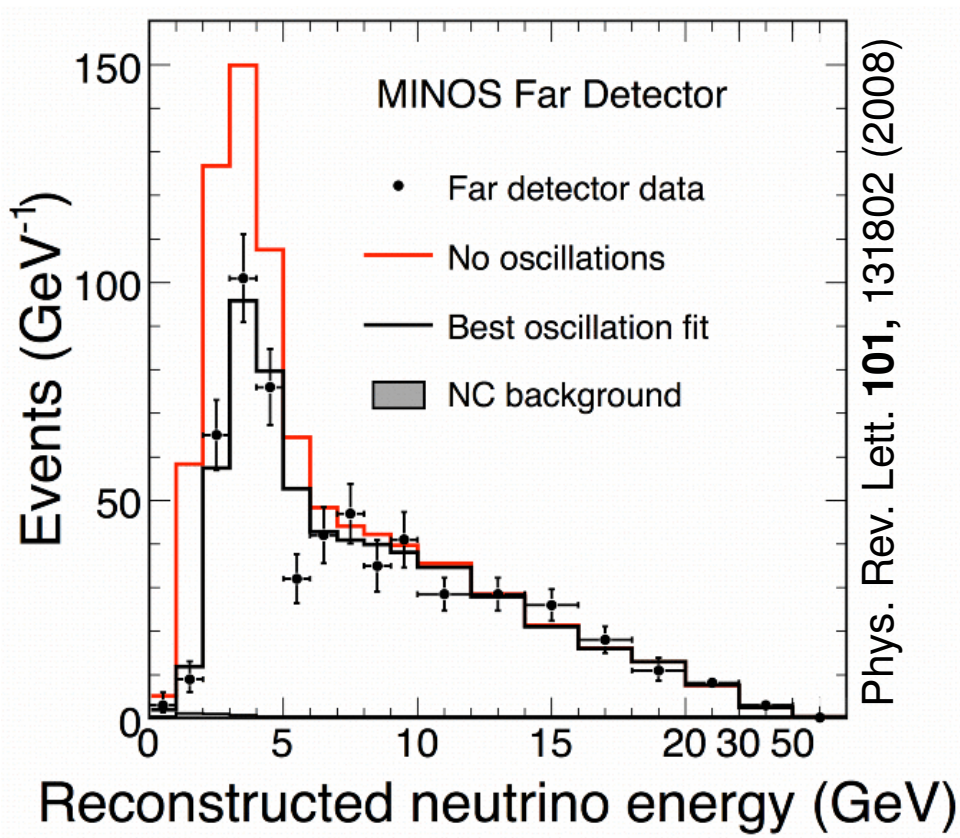


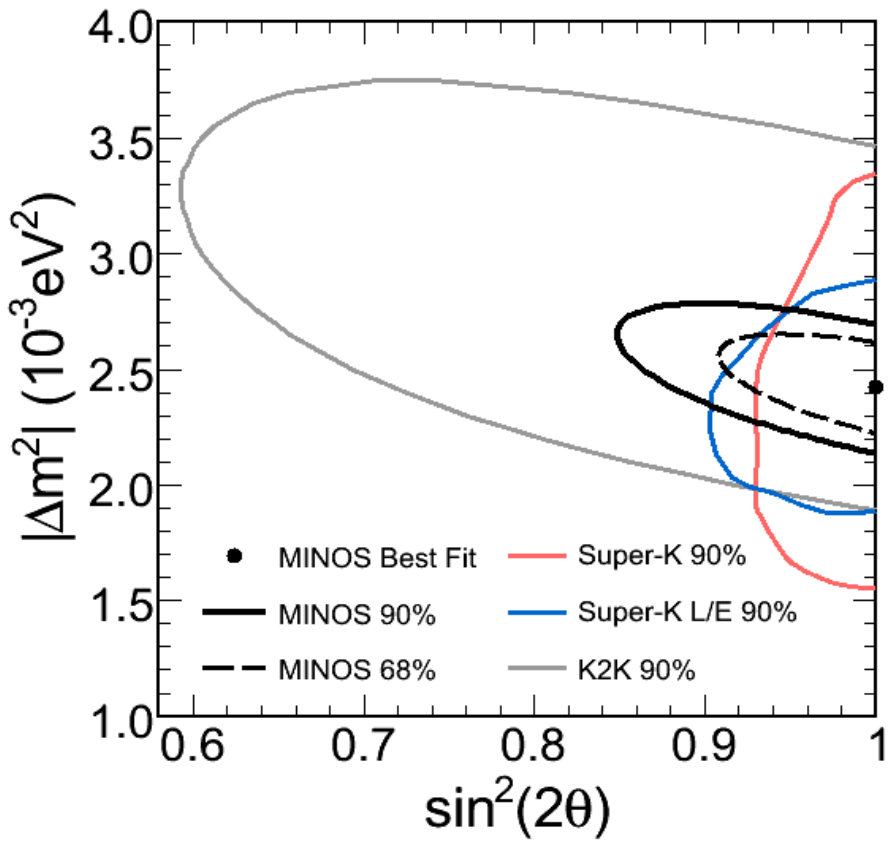
First, ν_μ survival

- Measure ν_μ **CC interactions** in the **near detector**
- **Transport** observed spectrum to create far detector **prediction**



- **Energy-dependent deficit** in far detector data ⇒ θ_{23}, $|\Delta m^2_{32}|$



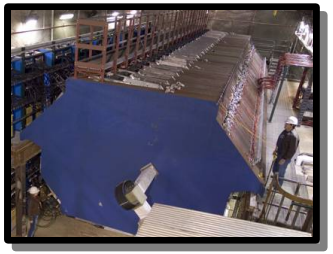


ν_e appearance

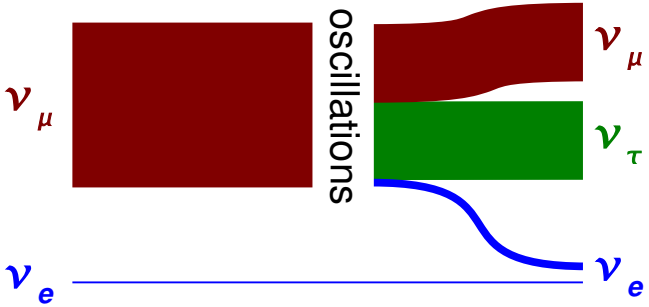
→ *travel 735 km* →

98.7% ν_μ
1.3% ν_e
(and $\bar{\nu}$)

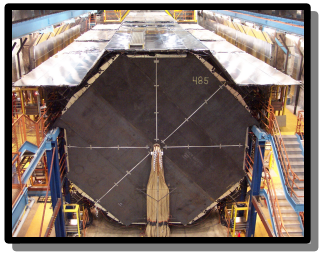
near detector



millions of ν events



far detector



thousands of ν events

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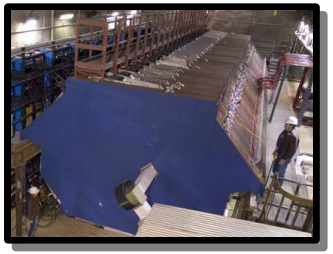

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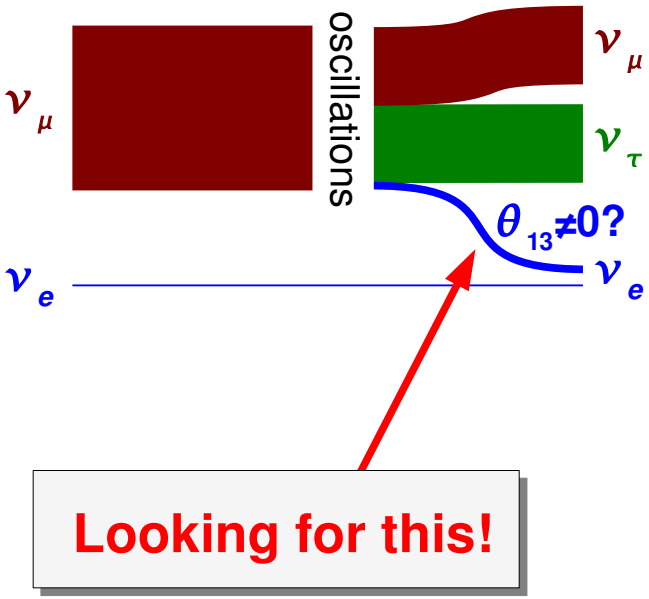
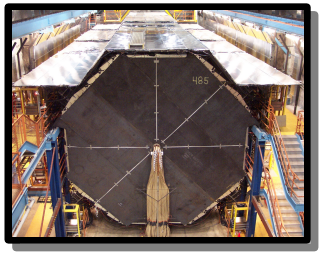


Looking for this!

far detector



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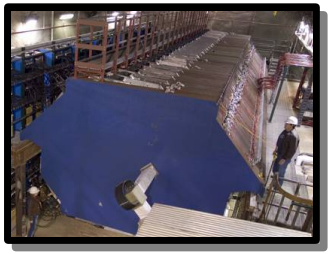
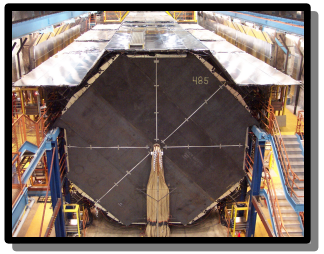


millions of ν events

apply ν_e selection

thousands of ν_e candidates

far detector



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FD data!

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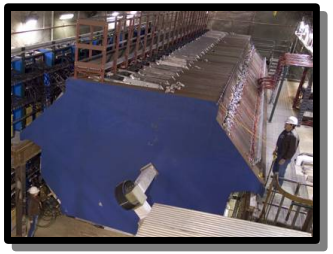


millions of ν events

apply ν_e selection

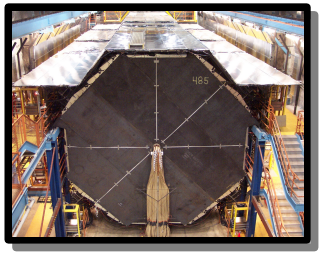
thousands of ν_e candidates

decompose the sample

measured background components:

ν_x **NC**
ν_μ **CC**
ν_e **CC**

far detector



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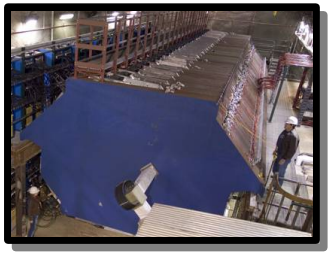

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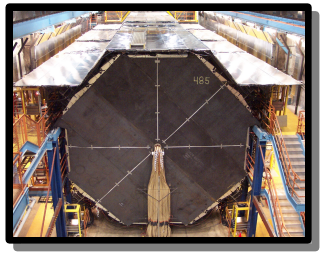

thousands of ν events

apply ν_e selection

apply ν_e selection

FD data!

thousands of ν_e candidates

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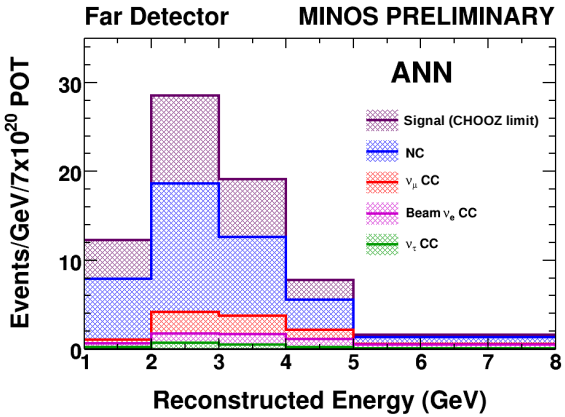
ν_x **NC**
ν_μ **CC**
ν_e **CC**

predict FD bkgnd.

FD prediction!



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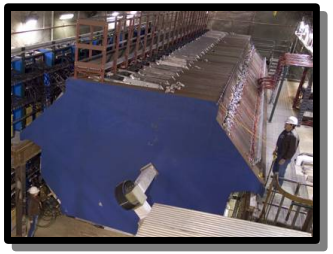
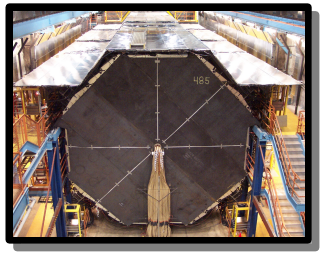


far detector



millions of ν events

thousands of ν events

apply ν_e selection

apply ν_e selection

FD data!

thousands of ν_e candidates

Compare

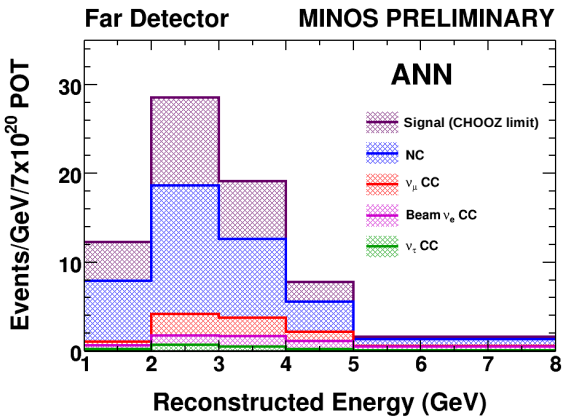
decompose the sample

FD prediction!

measured background components:

ν_x **NC**
ν_μ **CC**
ν_e **CC**

predict FD bkgnd.

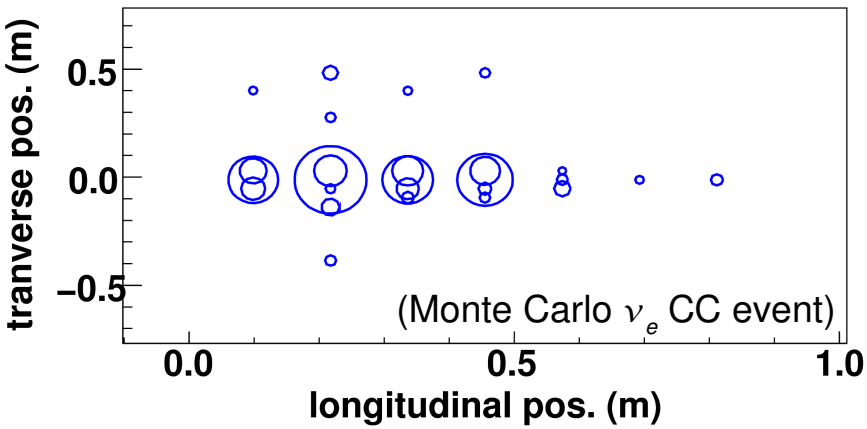


Preliminary cuts

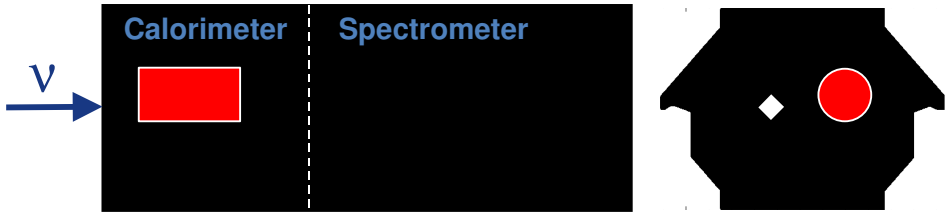
- Selecting ν_e **CC candidates**: *start with some* ***preliminary cuts****...*

1. Cleanly contained event vertex

- Tell-tale tracks can be seen
- Ensure reasonable calorimetry

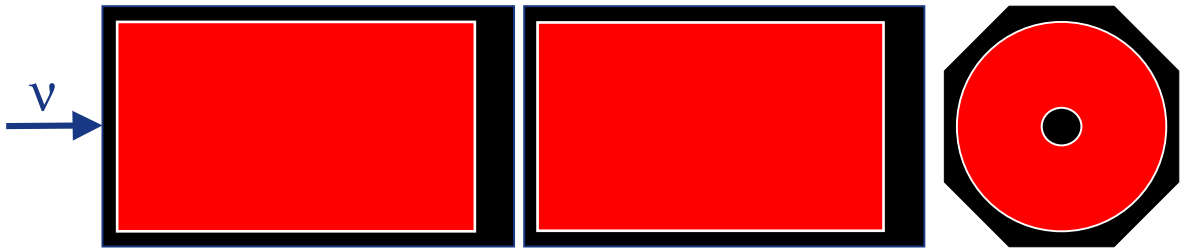


Near det.



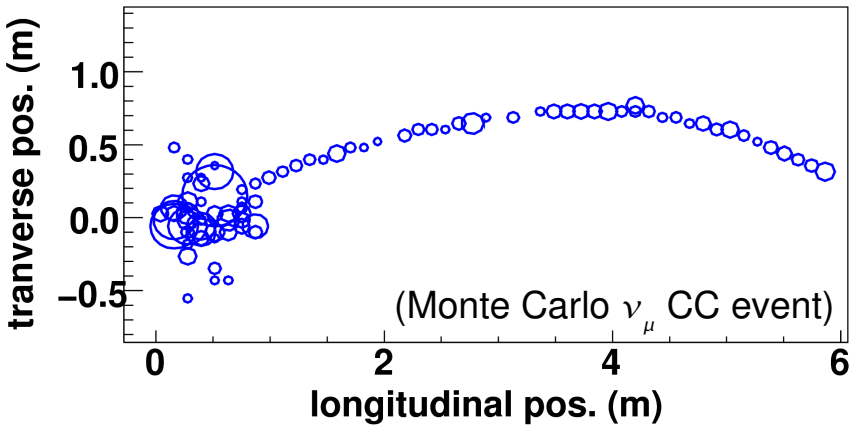
Fiducial regions in red

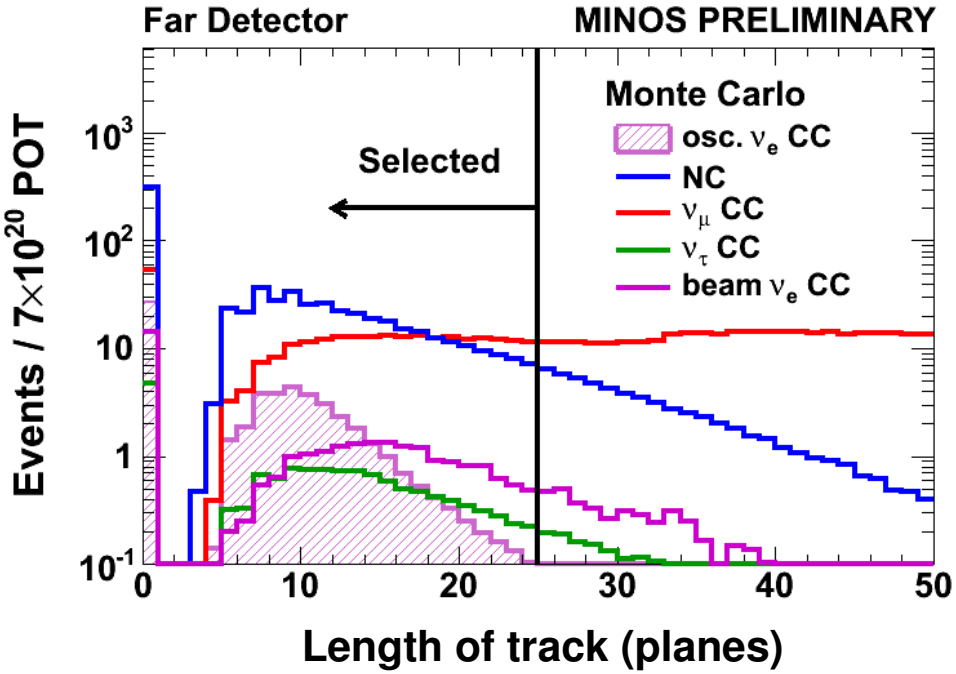
Far det.



2. No long tracks

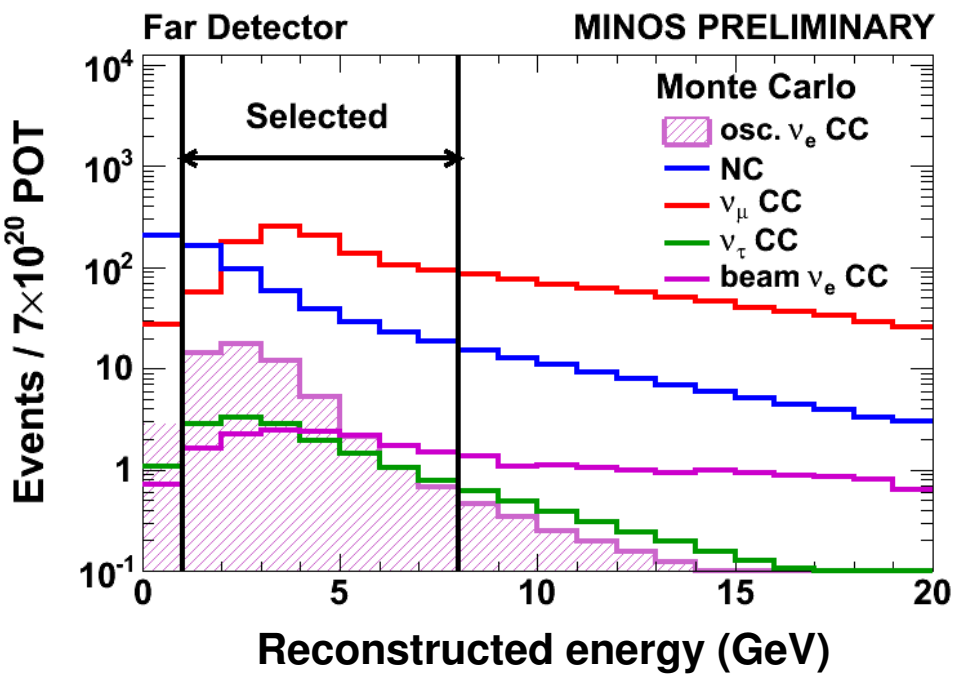
- Removes majority of ν_μ CC events



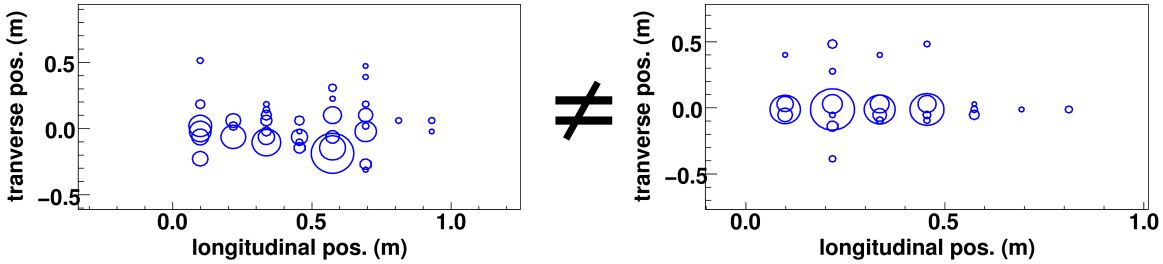


3. Appropriate energy

- No signal expected above 8 GeV
- Minimal signal and lots of NC background below 1 GeV

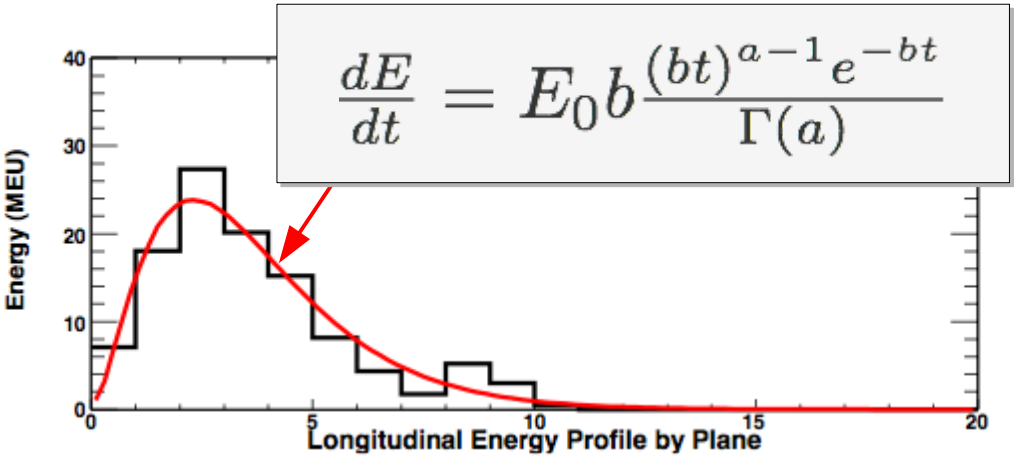


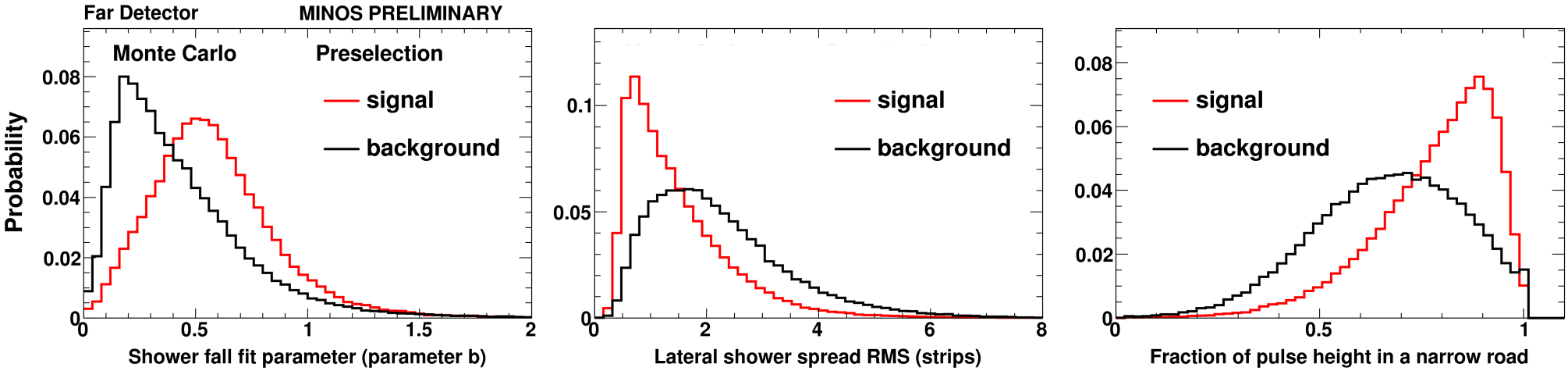
Shower identification



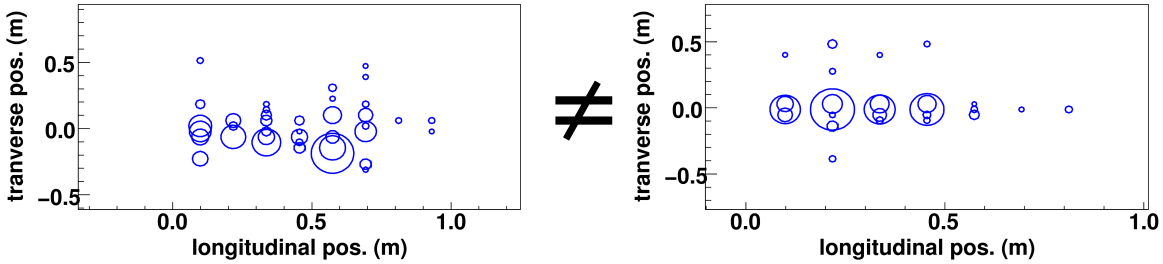
- Classify shower topology with an **ANN**
- 11 discriminant variables derived from longitudinal and transverse **profiles of energy deposition**
- *Examples:* shower fall off (parameter *b*), shower width metrics

Example EM shower profile





Shower identification



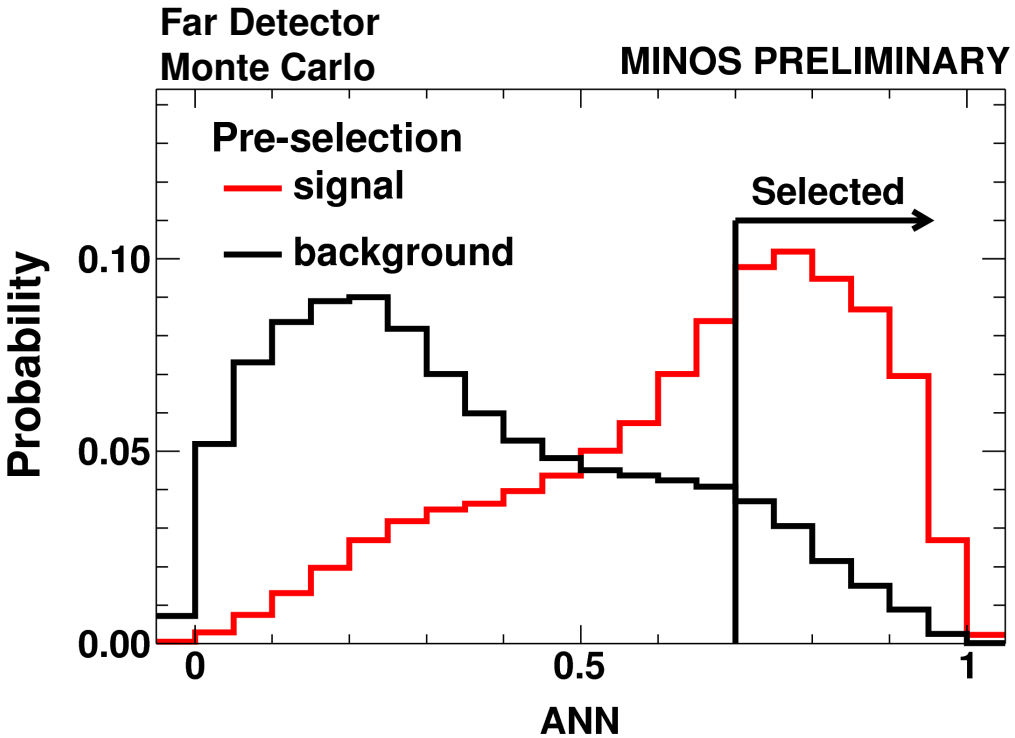
- Classify shower topology with an **ANN**
- 11 discriminant variables derived from longitudinal and transverse **profiles of energy deposition**
- *Examples:* shower fall off (parameter *b*), shower width metrics

Selection efficiencies (presel.+ANN):

signal ***42%***

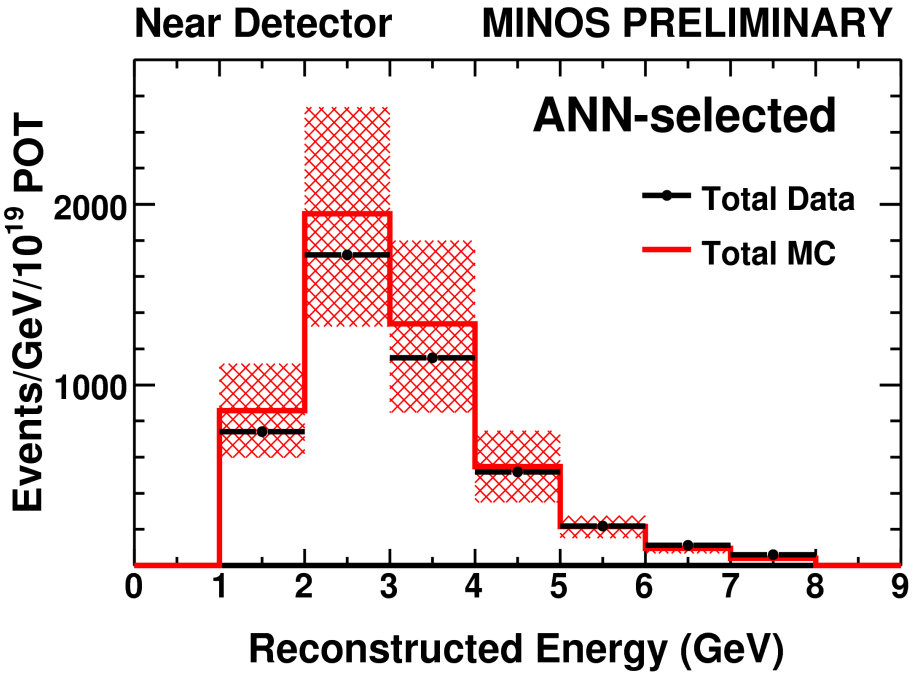
NC ***5.4%***
CC ***0.4%***
} ***(i.e., mis-ID rates)***

Resulting ANN discriminant:



Near detector events

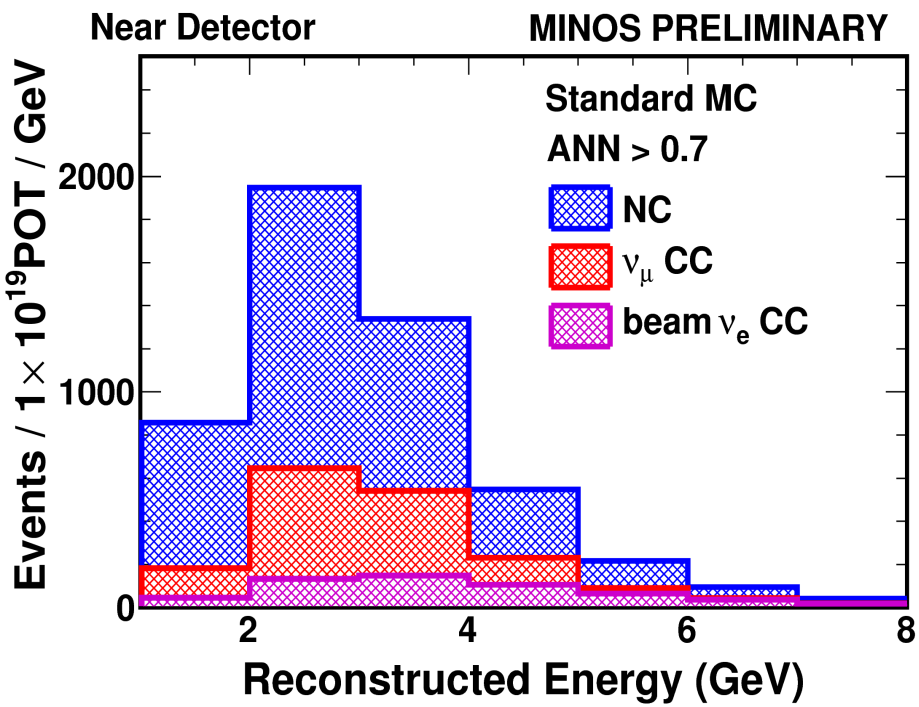
ν_e **candidates** in the **near detector** (ANN selection)



- Data and MC differ by up to 15%, but...
- ... are consistent given the large hadronic model uncertainties (*red error band*)

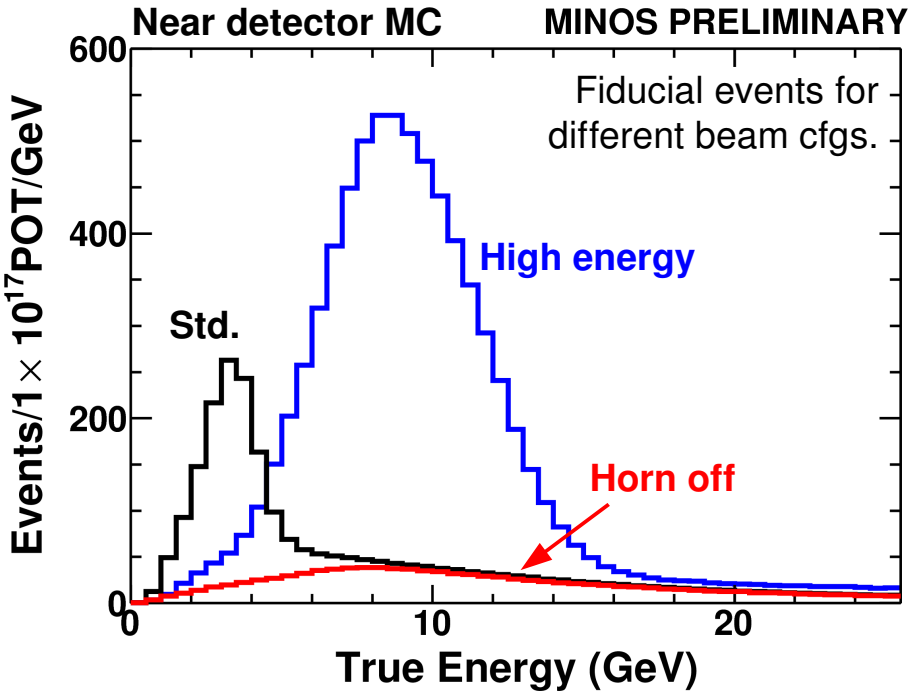
We need not rely on the simulation of the primary backgrounds *(neither raw production nor selection efficiencies)*

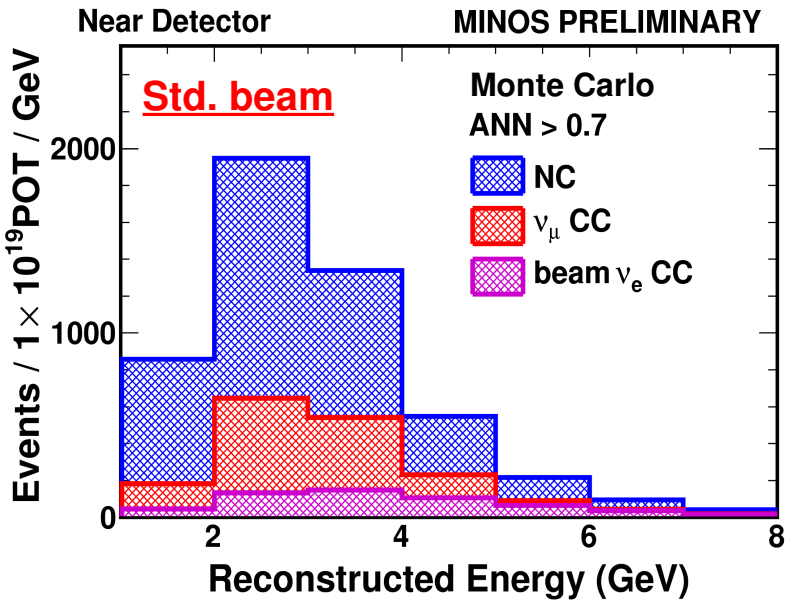
- Observed **near** detector rate is converted to a **far** detector prediction



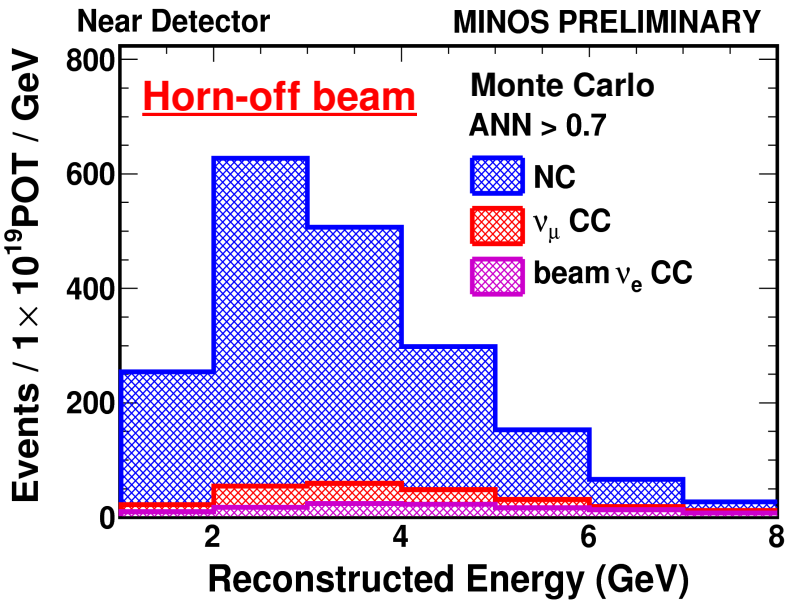
Background decomposition

- Transport of **CC components** to far det. requires application of $P_{osc}(\nu_\mu \rightarrow \nu_x)$
- Could use MC to estimate fraction of background that is ν_μ and ν_e CC
- *Better:* **measure NC, CC components** by adjusting horn focusing, modifying NC / CC fraction



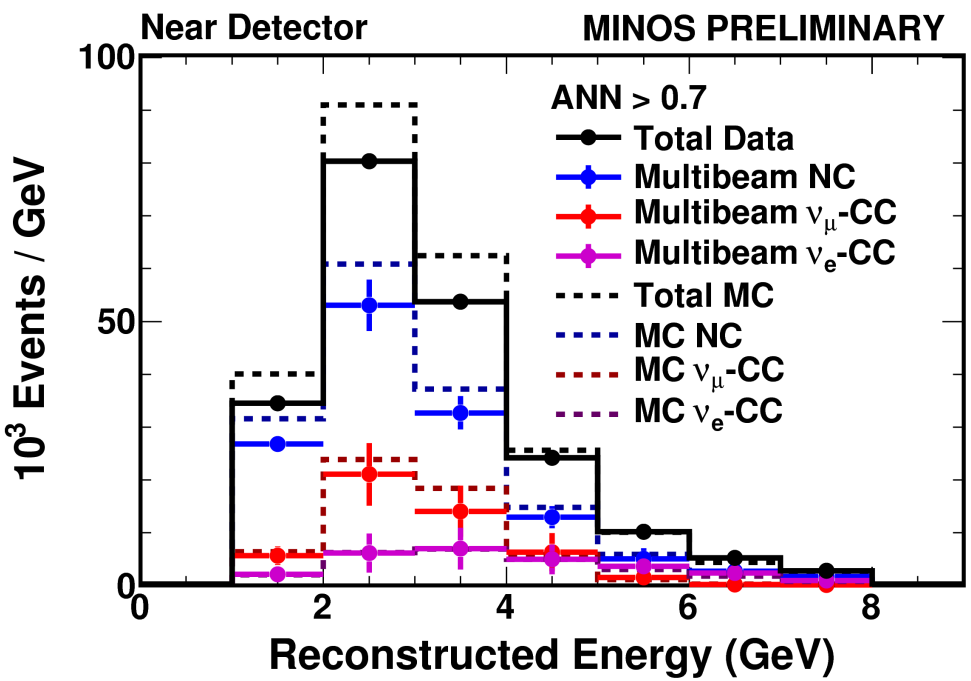


Turn off focusing horn

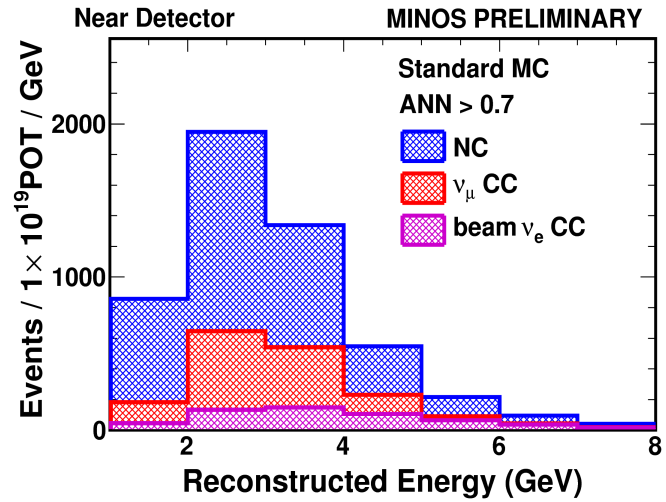


- *Approximately...*
  - **horn-off** and **high-*E*** ⇒ **NC**
  - **tuned MC** ⇒ ν_e **CC**
  - **unitarity** ⇒ ν_μ **CC**

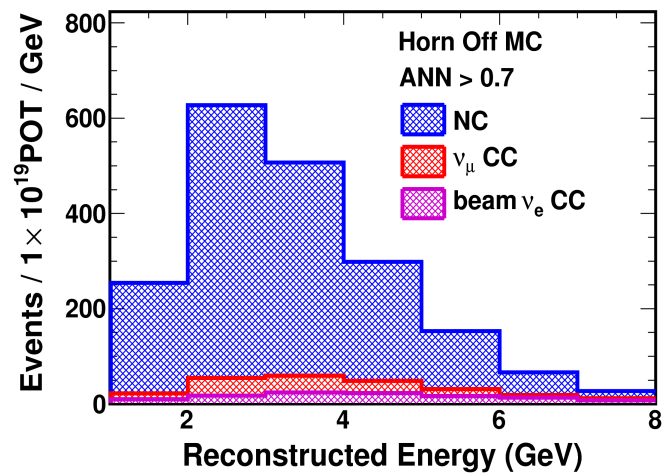
- *Actually...*
  - Solve the full **linear system**
    (3 beam configurations and 3 background components)
  - ...with injected MC ν_e **constraint**



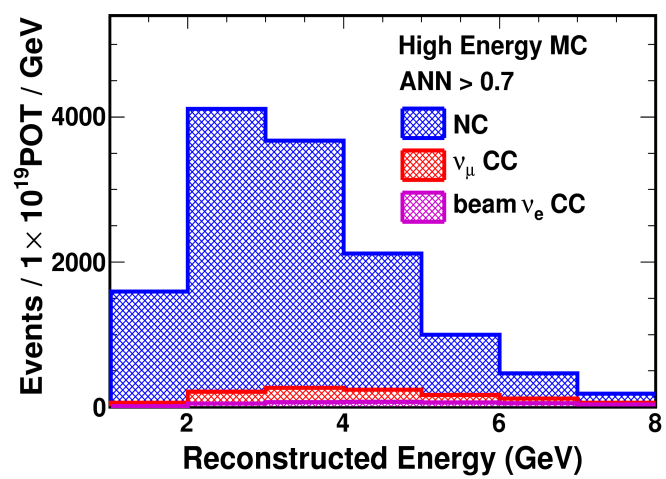
Standard



Horn off



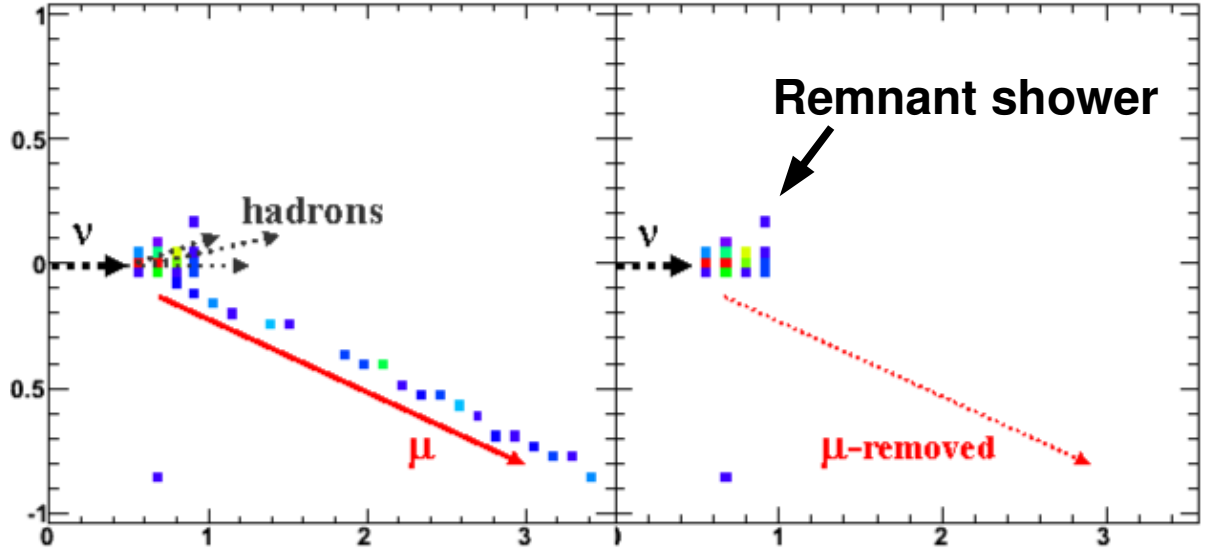
High energy



A cross check...

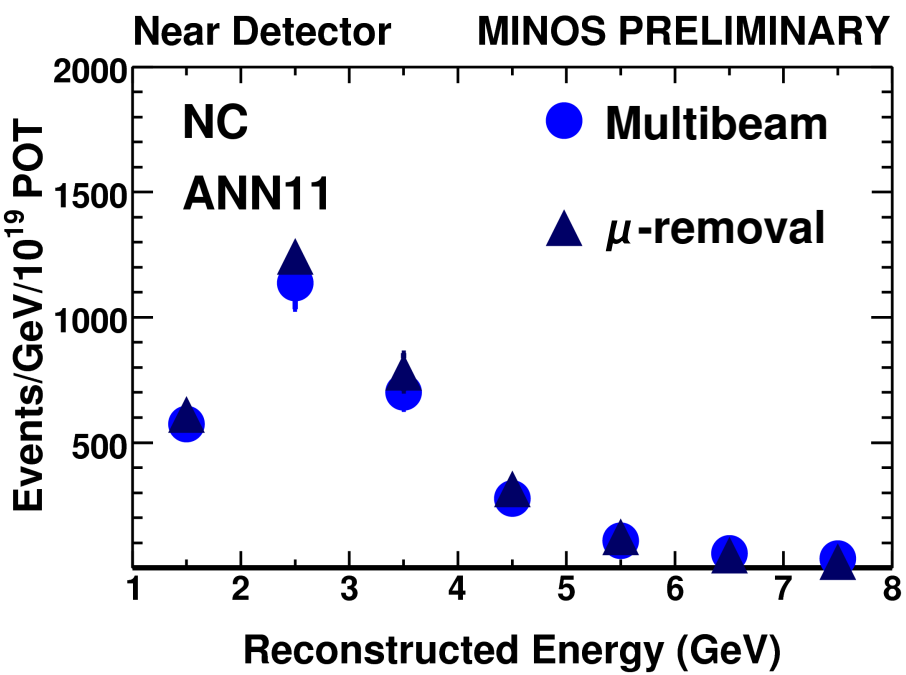
Alternatively

Use **mock NC events** to measure **NC acceptance**



Remove the hits from μ tracks in ν_μ CC events

Apply ν_e selection to the remnants (*mock NC events*)



Data/MC ratio with mock NC events

⇒ **correction** for real NC events

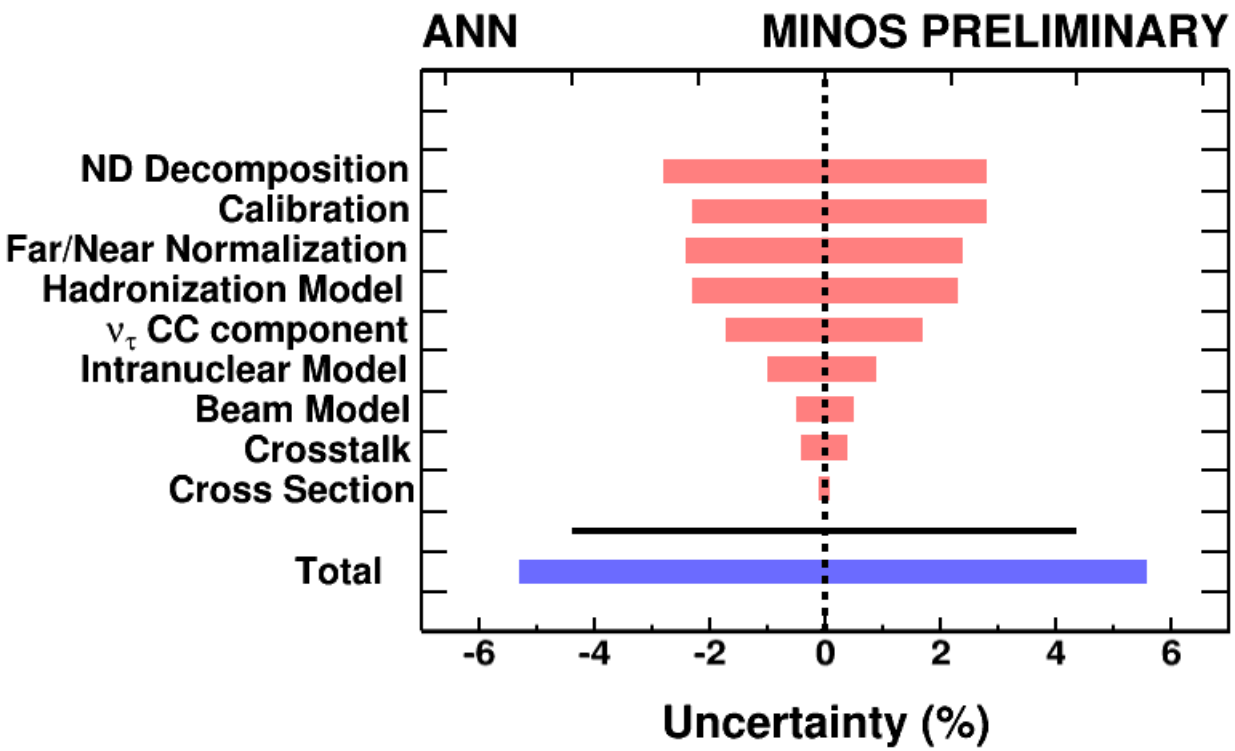
Resulting "measured" NC component agrees between the two methods

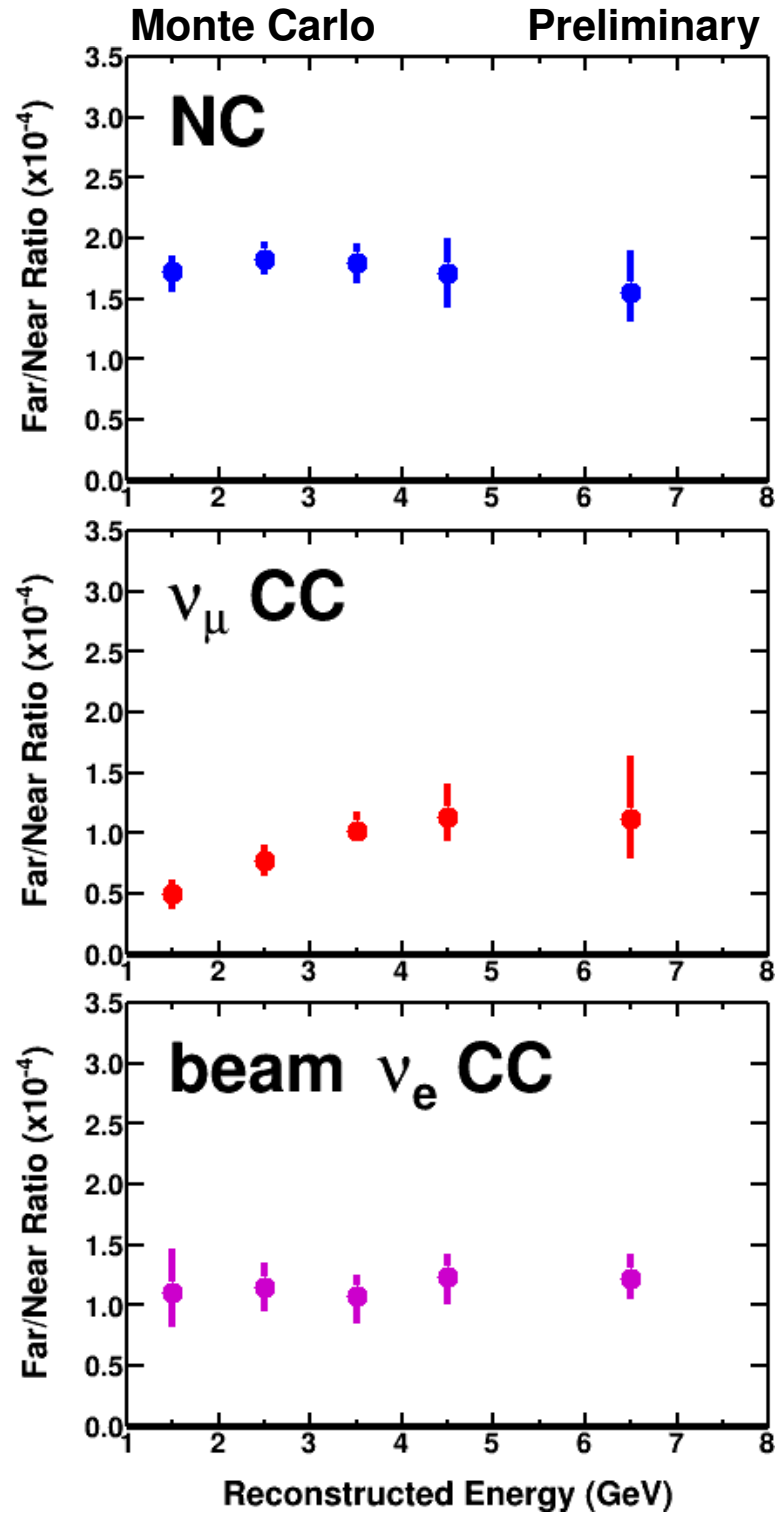
From near data to far prediction

Far/near ratios in bins of energy →

Detector differences lead to systematic errors in **far/near ratio**

attenuation, readout (single vs. double), PMT design, crosstalk, ...



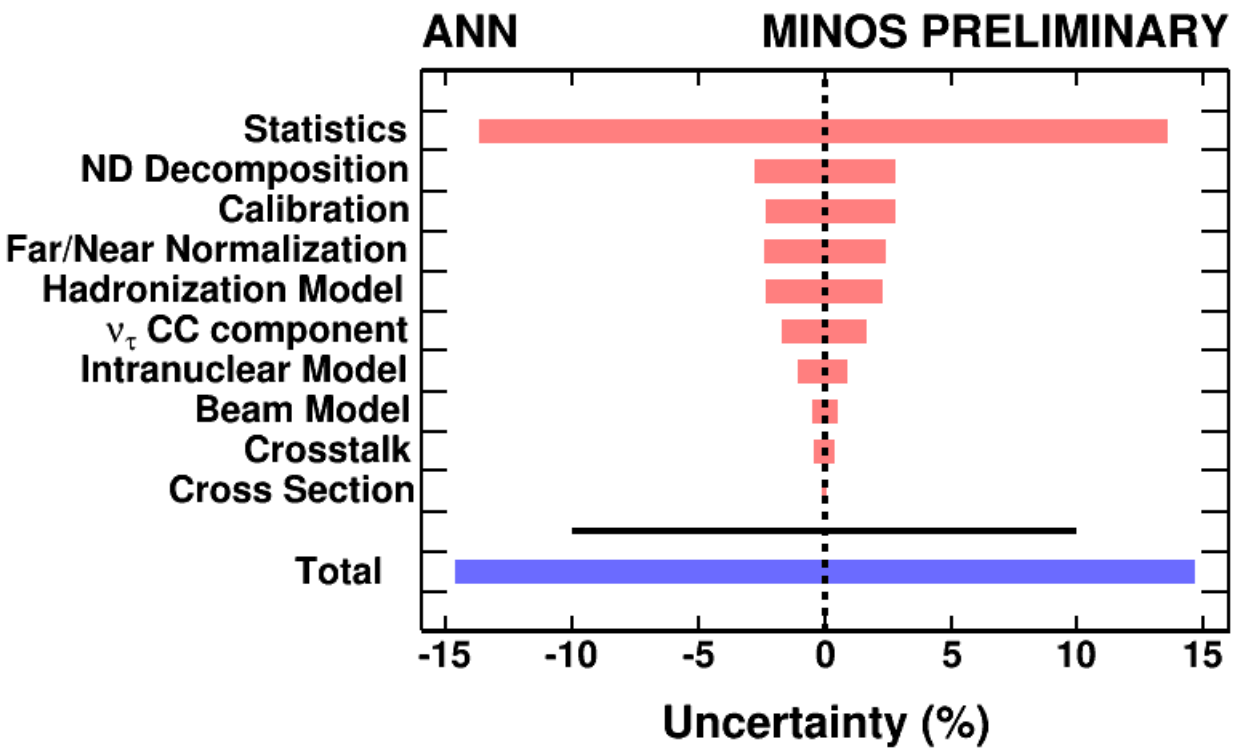


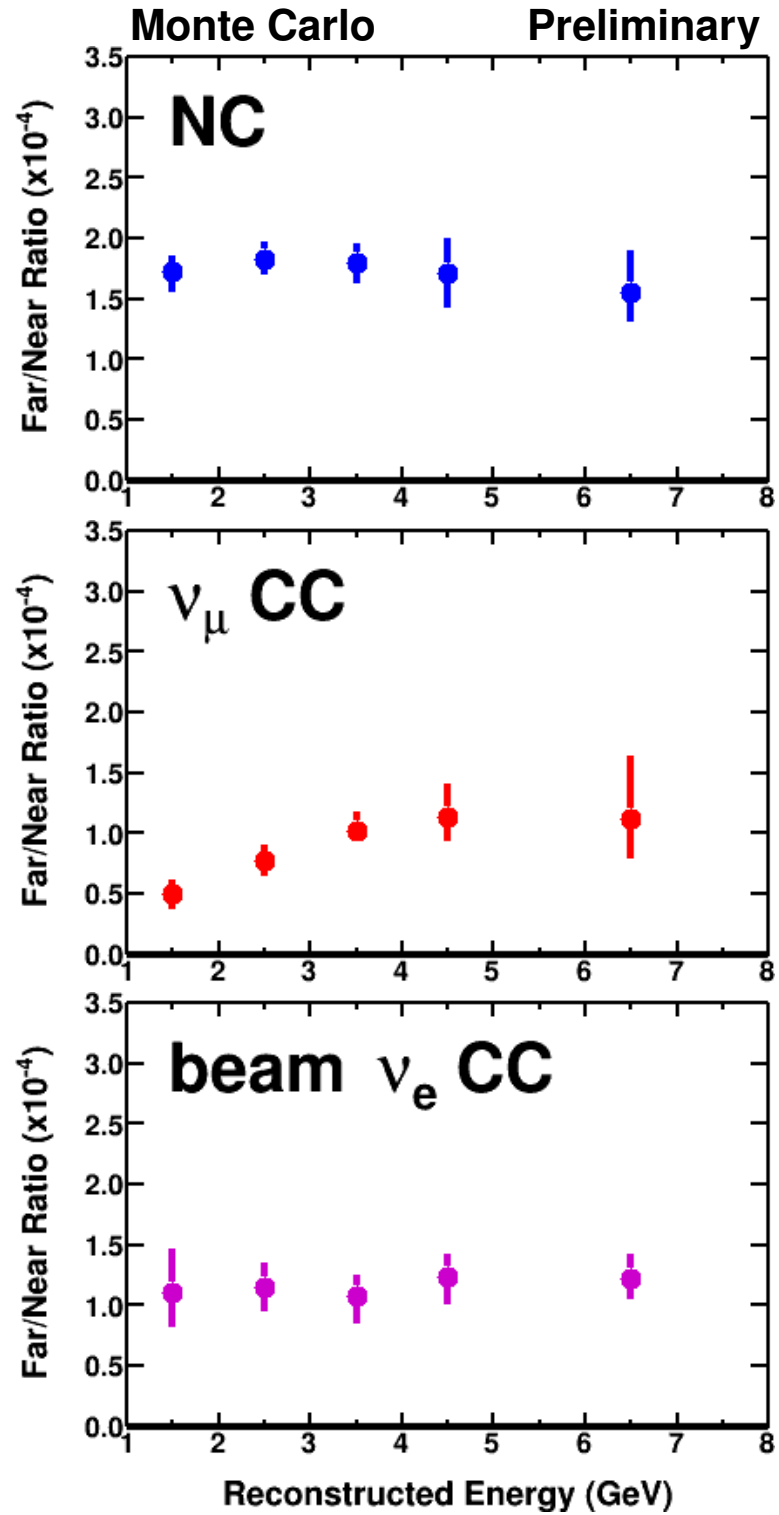
From near data to far prediction

Far/near ratios in bins of energy →

Detector differences lead to systematic errors in **far/near ratio**

attenuation, readout (single vs. double), PMT design, crosstalk, ...

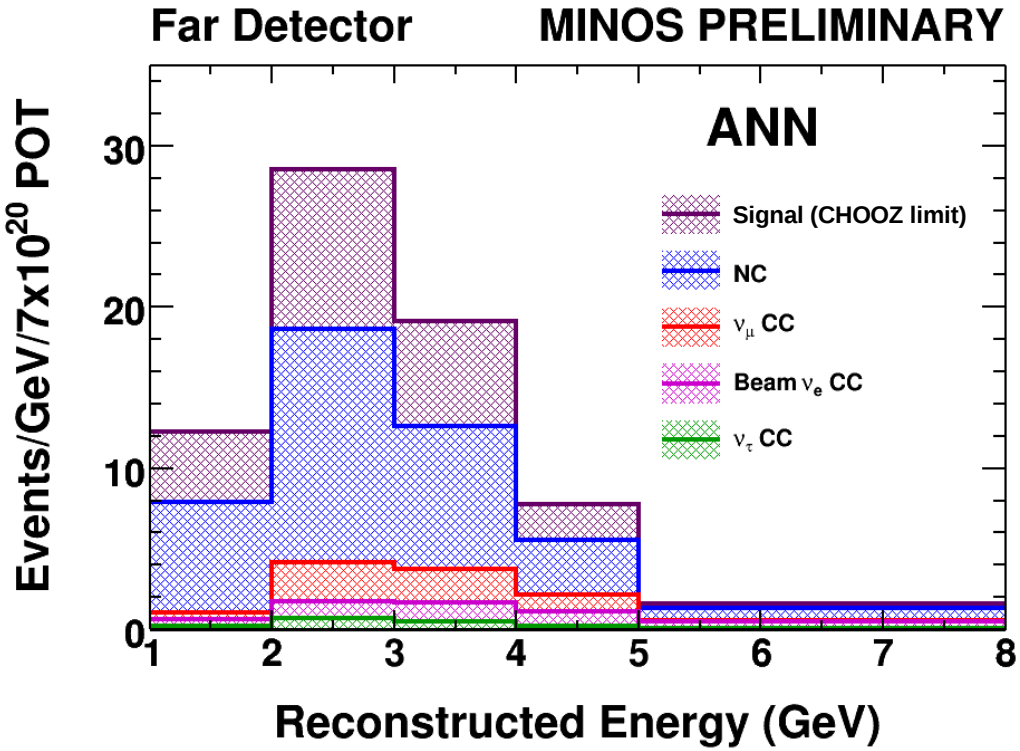




Far detector prediction

Small ν_τ **CC** background (*from* $\nu_\mu \rightarrow \nu_\tau$ *oscillations)* estimated from the Monte Carlo

(with knowledge of ν_μ disappearance)

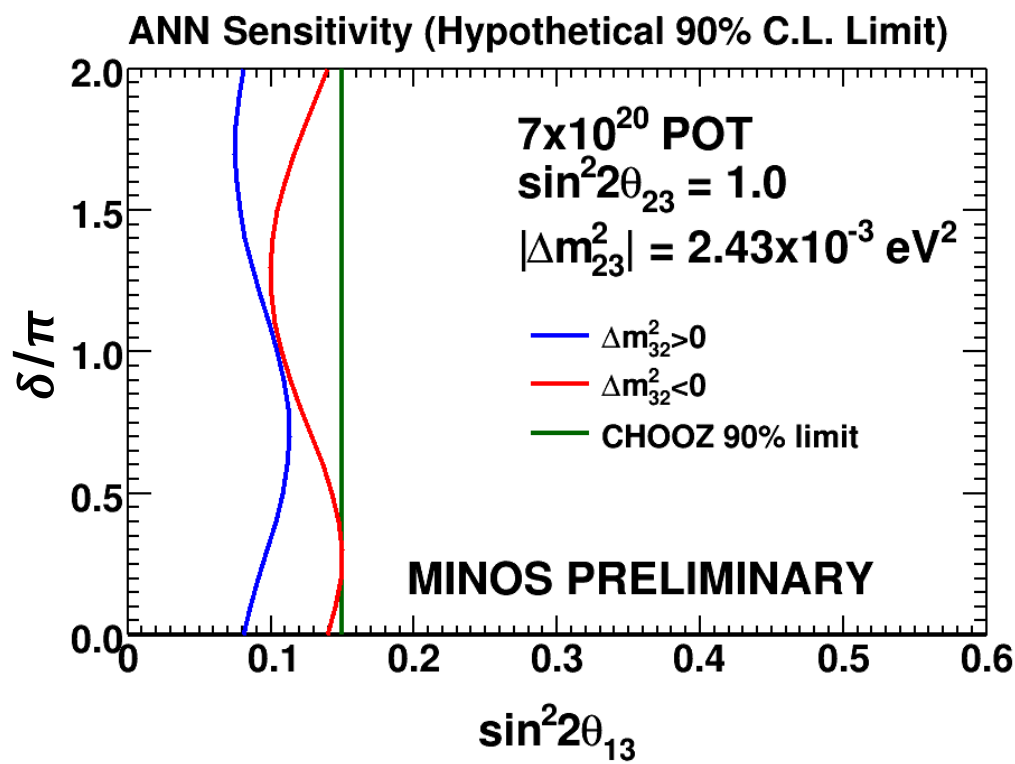


7x10^{20} p.o.t. predicted event counts:

Backgrounds:		**Signal (CHOOZ limit):**	
Total	**49.1**	ν_e **CC**	**24**
NC	35.8		
ν_μ CC	6.3	*(stat. + syst. error on*	
ν_e CC	5.0	*total BG is 7.4 events)*	
ν_τ CC	2.0		

Signal: $\Delta m^2_{32} = 2.43\text{x}10^{-3}$ eV^2 $\sin^2(2\theta_{23}) = 1.0$

$\sin^2(2\theta_{13}) = 0.15$ $\delta_{CP} = 0$



Blind analysis checks

Check of the analysis – *invert the cut*

Perform ***the full analysis*** *with one modification:*

→ **invert the cut** on the ν_e discriminant: **ANN<0.5** rather than **ANN>0.7**

Expected events for ANN<0.5

For $\sin^2(2\theta_{13}) = 0$

Total	**314**
NC	186
ν_μ CC	117
ν_e CC	5
ν_τ CC	6

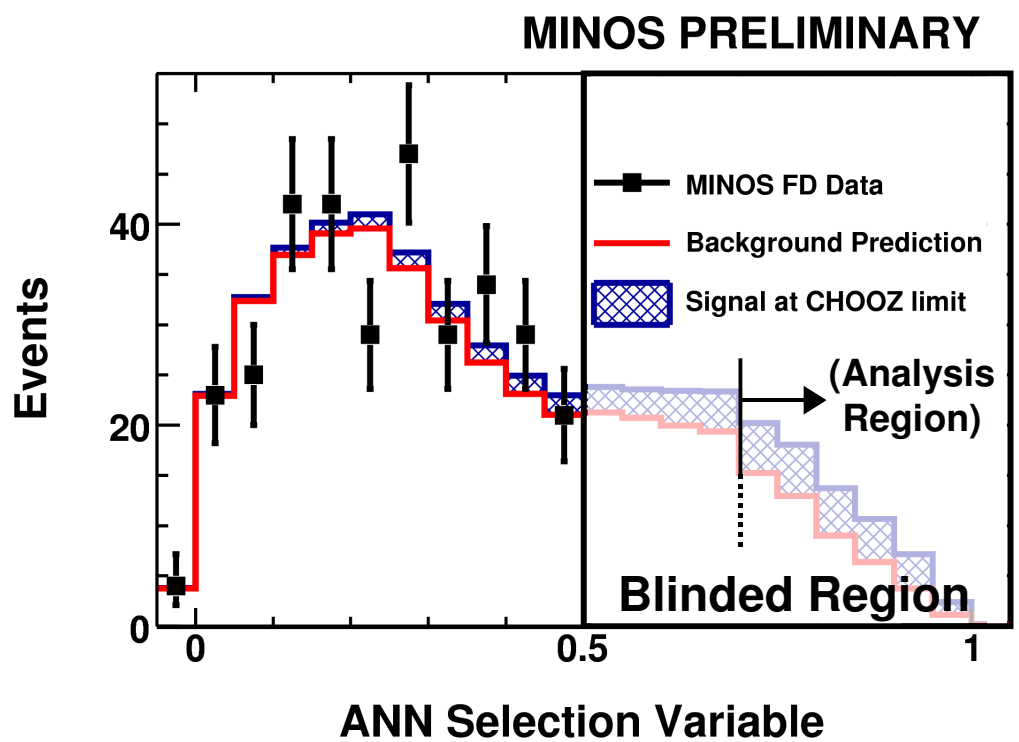
For $\sin^2(2\theta_{13}) = 0.15$

Total	**314 + 13**

Observed for ANN<0.5:

327 events

(0.75σ excess if $\sin^2(2\theta_{13})=0$)



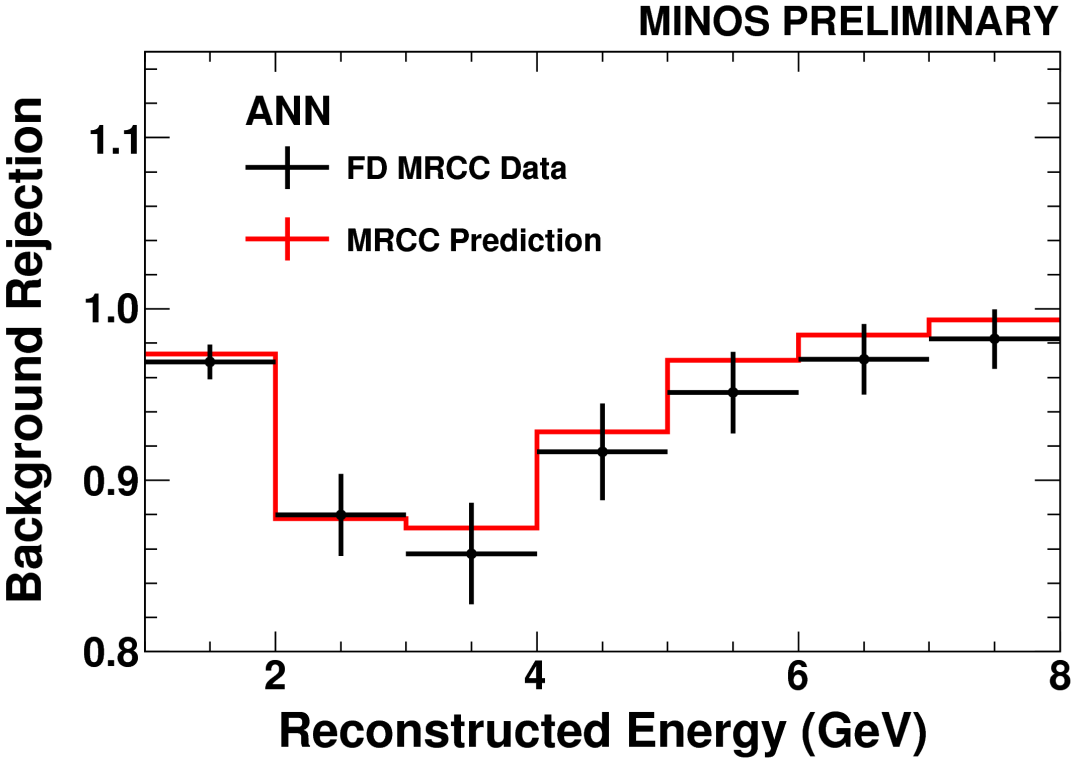
(uncertainty in this test) ≈ 0.4×(uncertainty in main analysis)

Check of the analysis – *verify NC shower mis-ID*

Revisit the **muon-removed events** *(mock NC events)*

→ *Measure **selection efficiency** for these showers in **Far Detector data***
→ *Compare with **Near-Detector-driven** prediction*

Predicted and **measured efficiencies** (vs. energy) **agree**



Mis-ID rate for μ-removed events:

data: (7.2 ± 0.9)%

pred: (6.42 ± 0.05)%

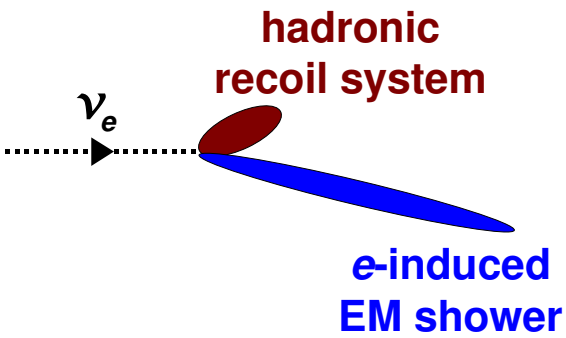
[stat. errors only]

⇒ compatible at 0.86σ

(uncertainty in this test) ≈ (uncertainty in main analysis)

Check of the analysis – *verify signal efficiency*

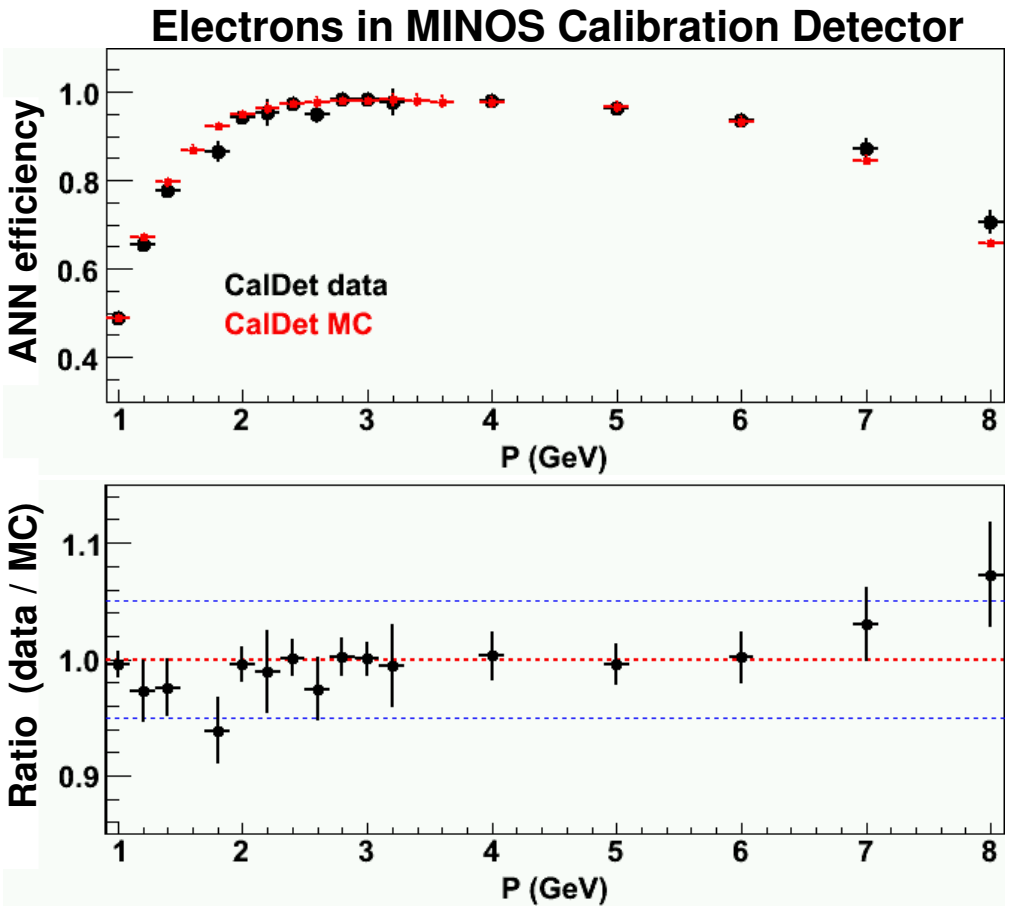
ν_e CC events: **EM shower** + **hadronic shower**



1st: Test selection on **pure EM showers** from **CalDet**

*Efficiency understood to **better than 3%***

Apply a systematic error based on the limits of this comparison



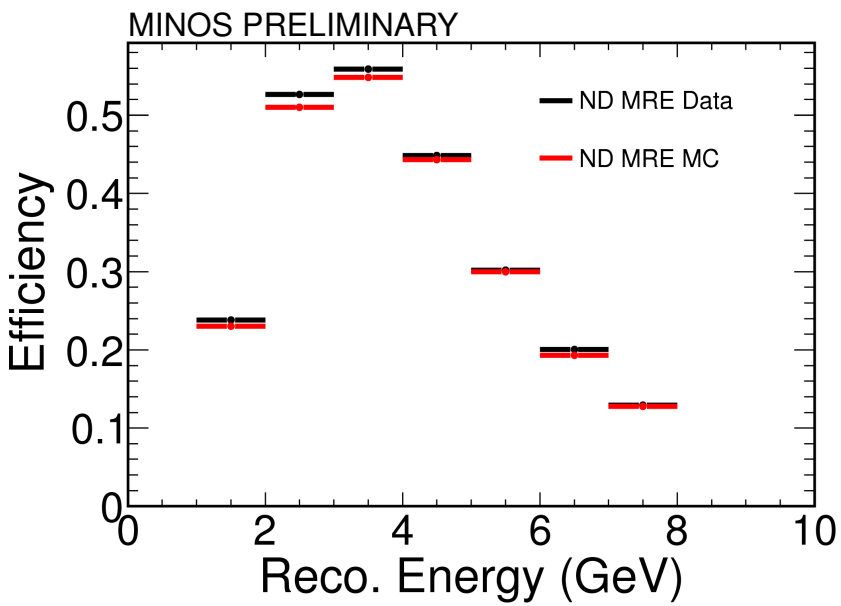
2nd: Test importance of **hadronic shower** modeling:

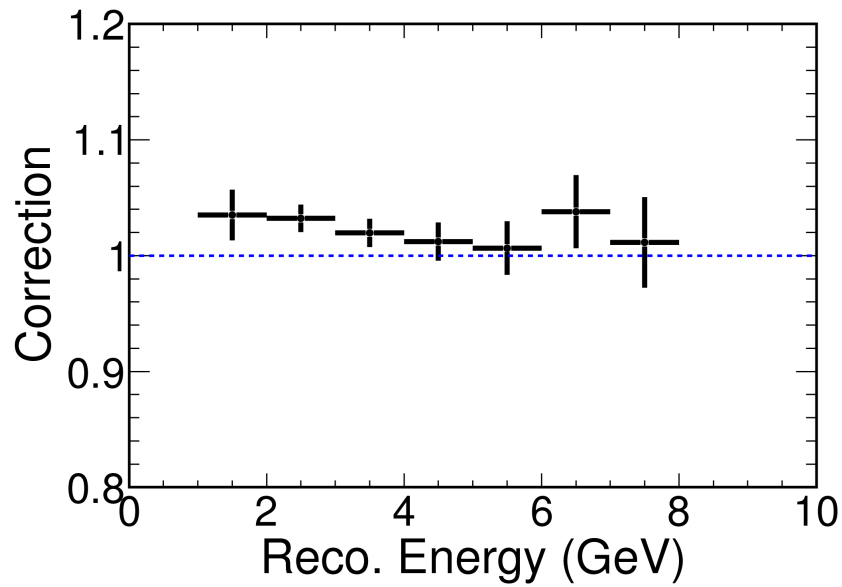
→ *use **μ-removed sample** to get **hadronic showers** from data or MC*

Data *or* MC

Apply ν_e selection to the "merged" events...

Small efficiency difference (~3%) taken as a correction





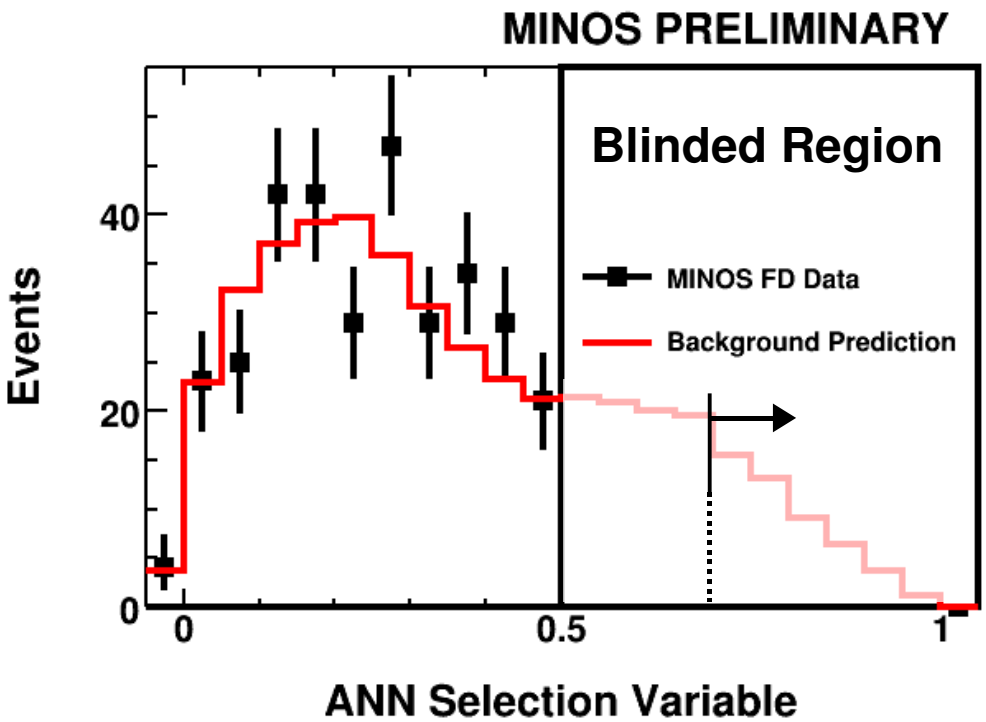
Results

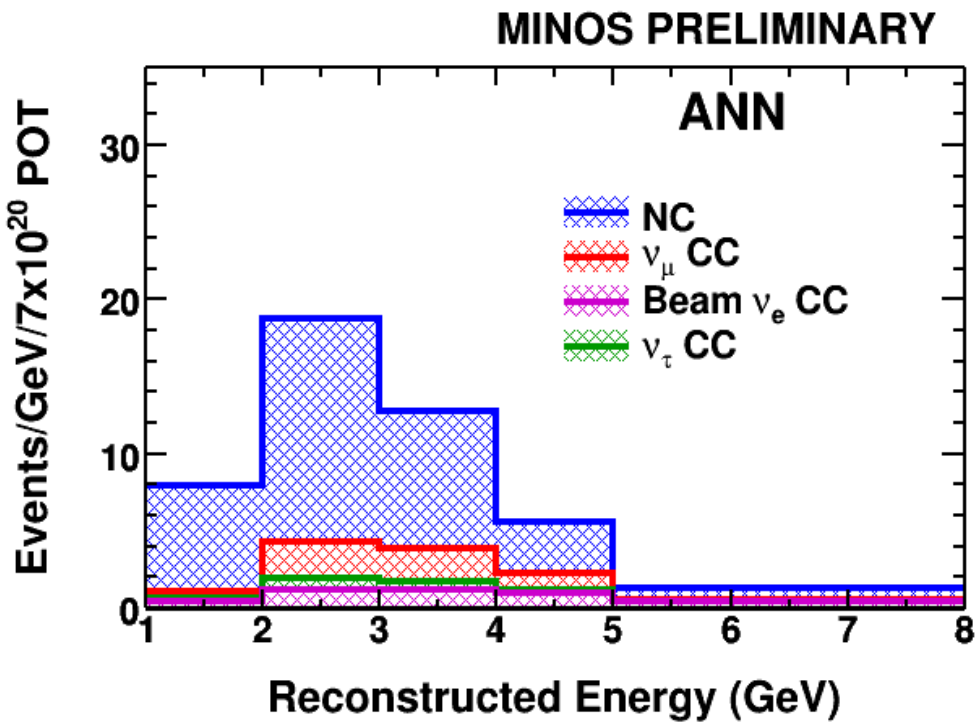
ν_e appearance result

With 7×10^{20} protons on the NuMI target

ν_e charged current candidate events:

background expectation: **49.1 ± 7.0(stat.) ± 2.7(syst.)**





ν_e appearance result

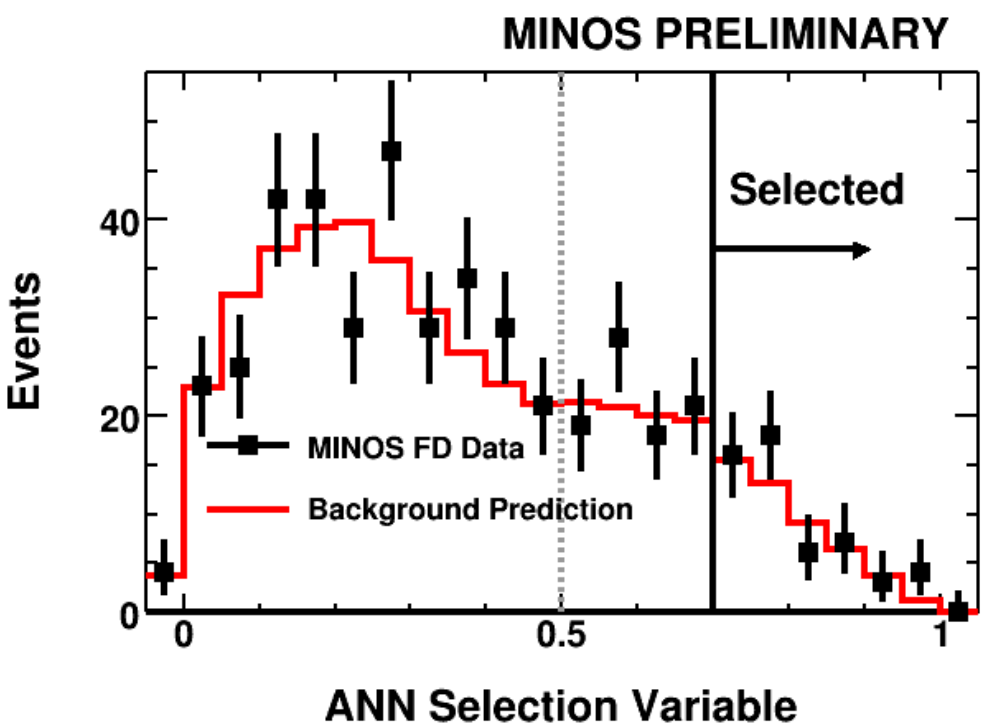
With 7×10^{20} protons on the NuMI target

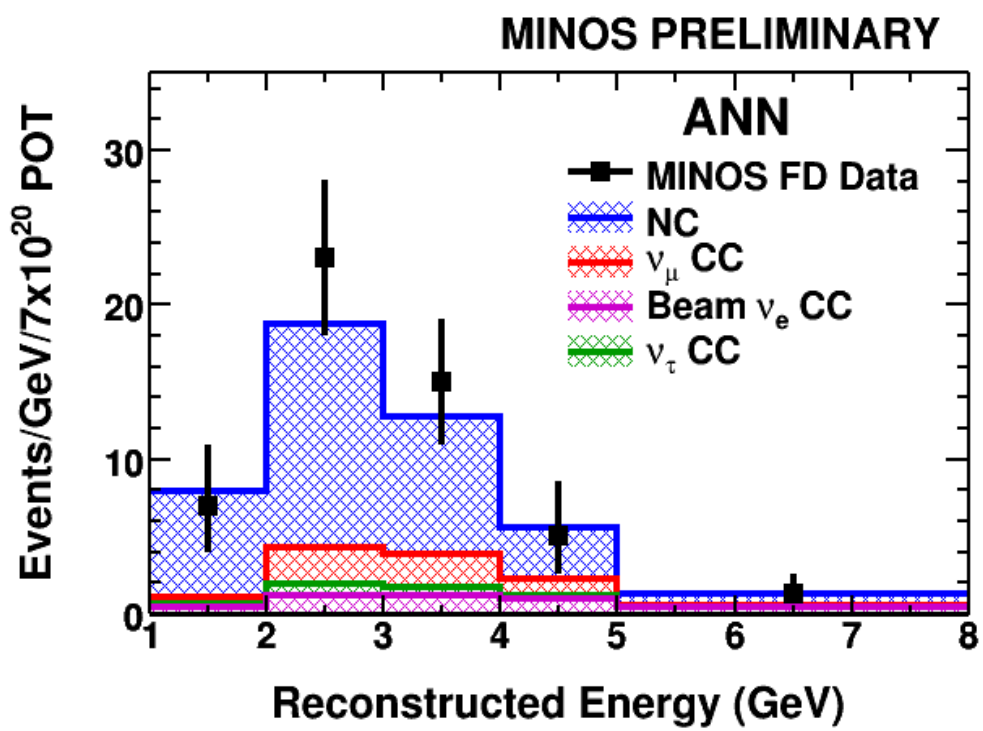
ν_e charged current candidate events:

background expectation: **49.1 ± 7.0(stat.) ± 2.7(syst.)**

observed: **54**

(0.7σ excess)





ν_e appearance result

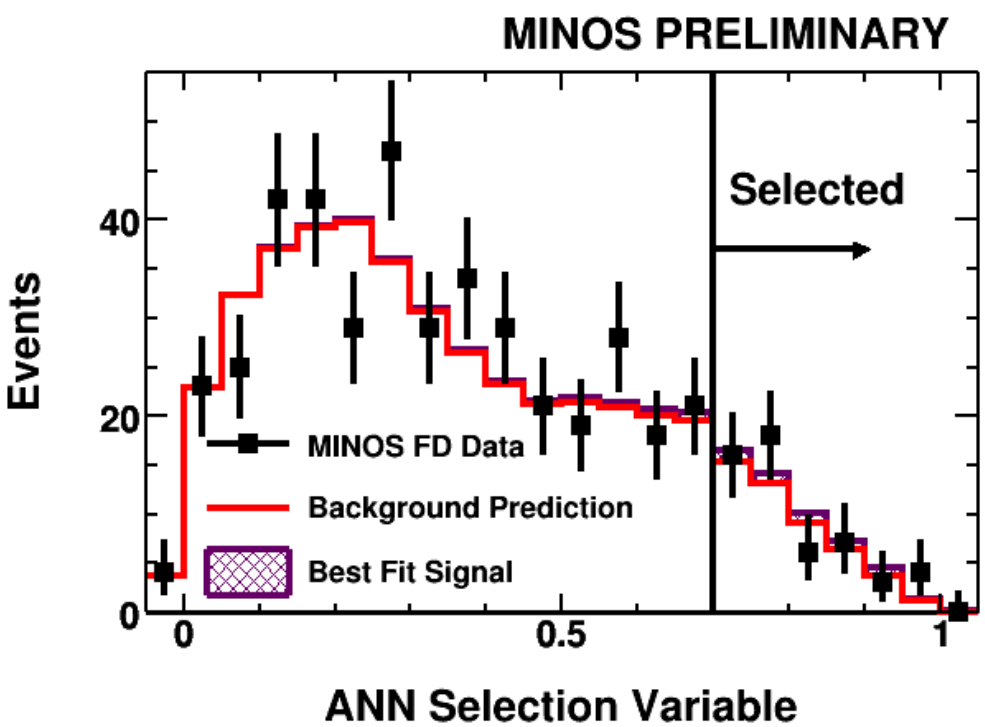
With 7×10^{20} protons on the NuMI target

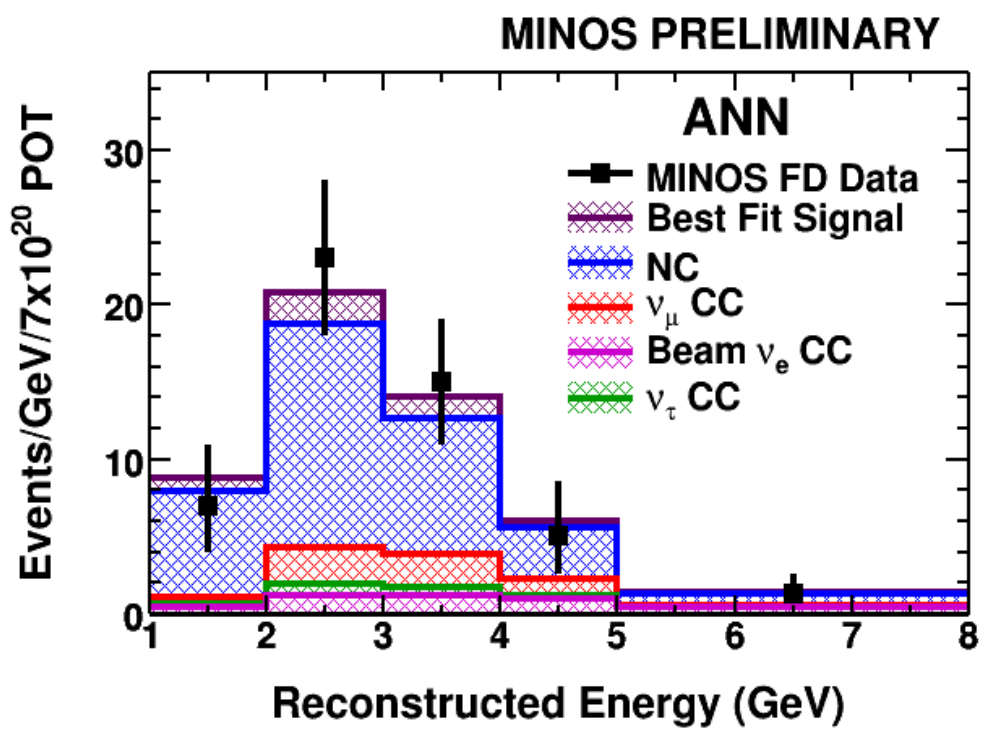
ν_e charged current candidate events:

background expectation: **49.1 ± 7.0(stat.) ± 2.7(syst.)**

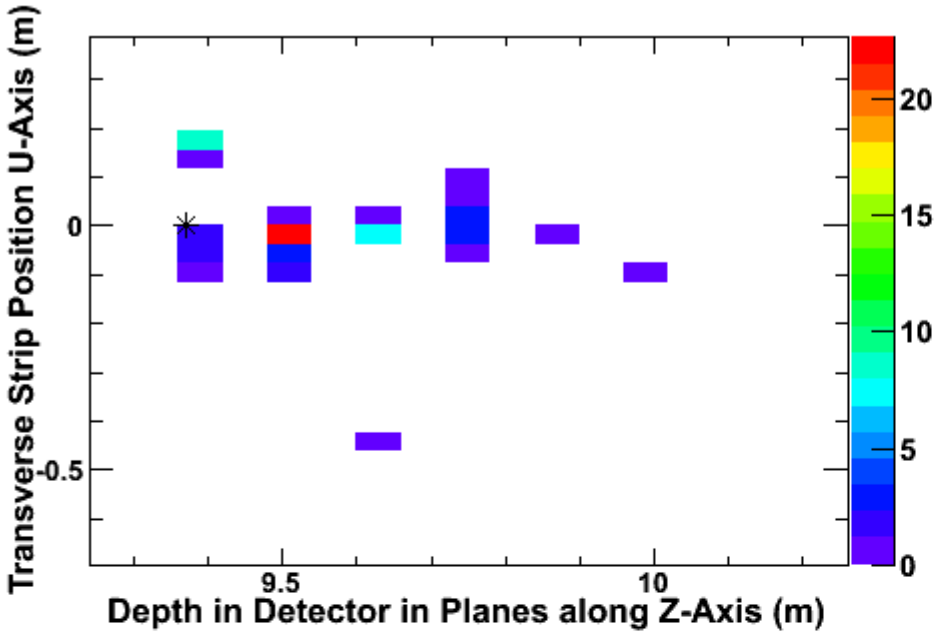
observed: **54**

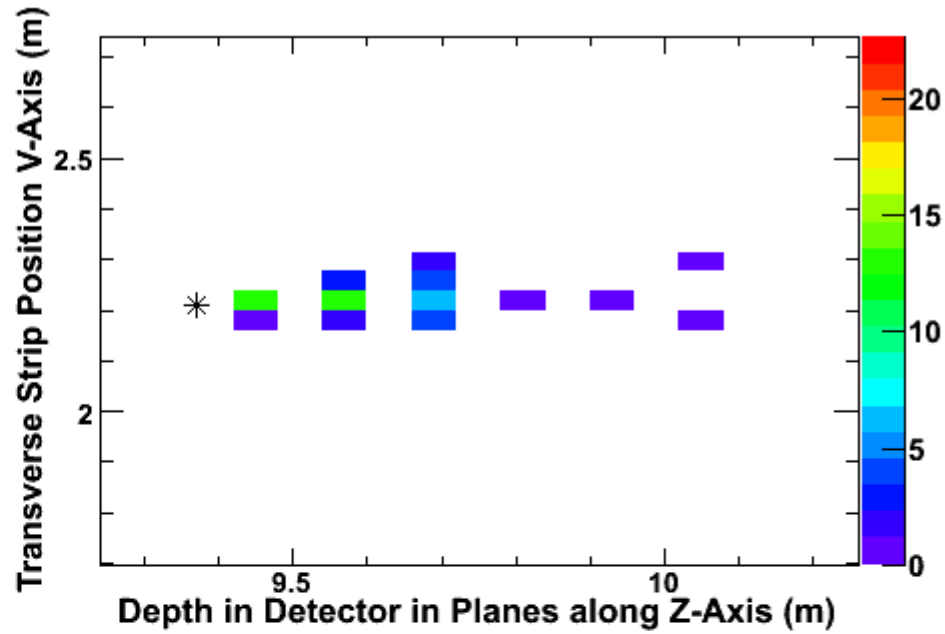
(0.7σ excess)

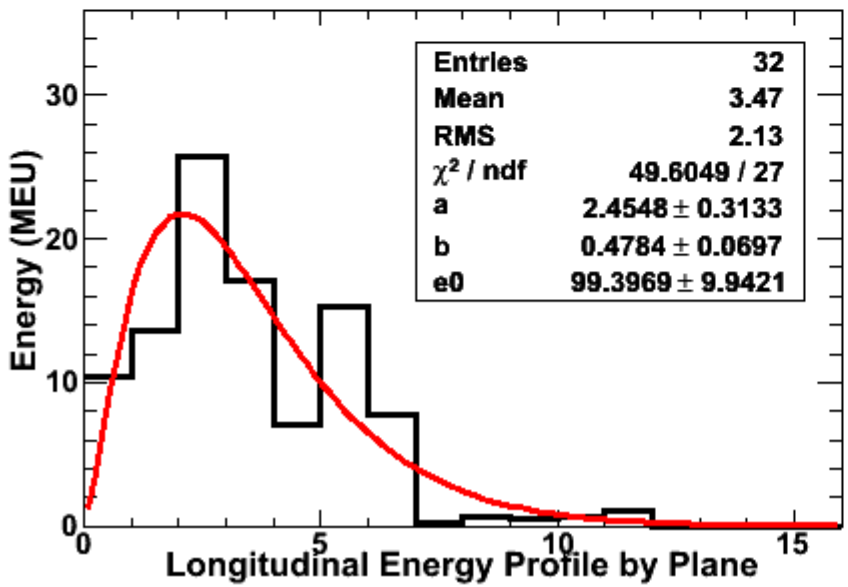


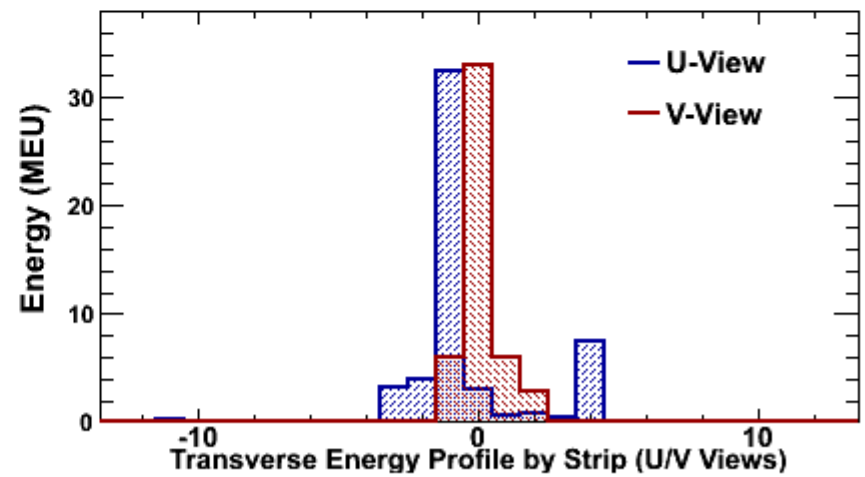


ν_e CC candidate event in the far detector...





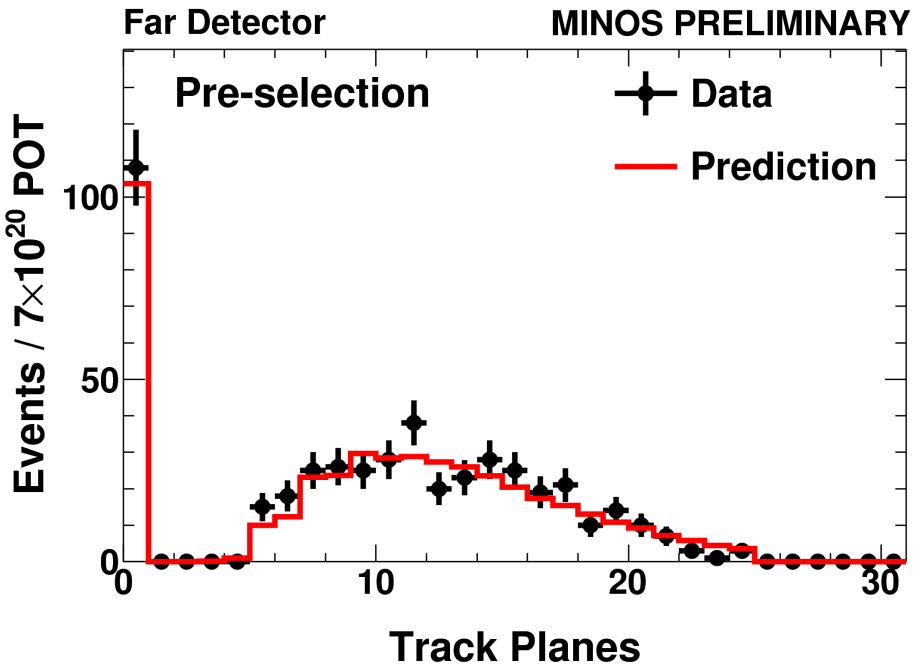


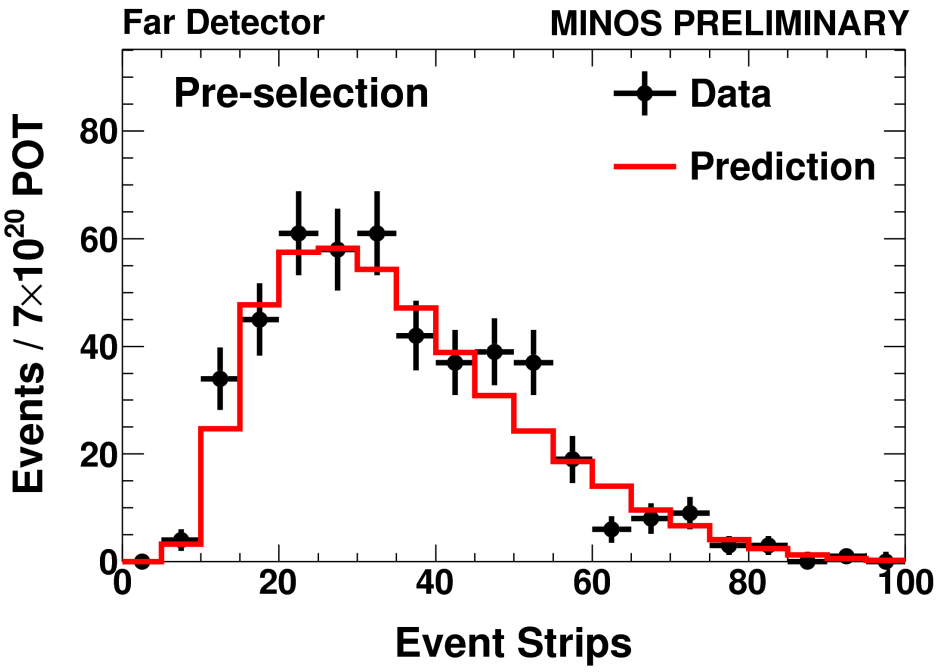


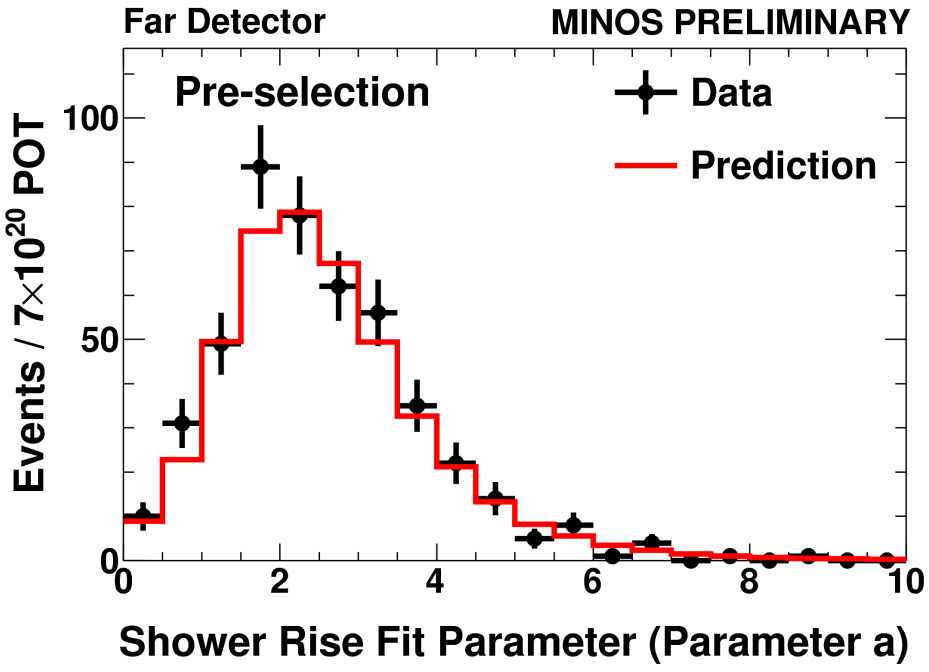
FD RUN = 43563
EVENT ID = 95374
Reco. Energy = 4.35 GeV

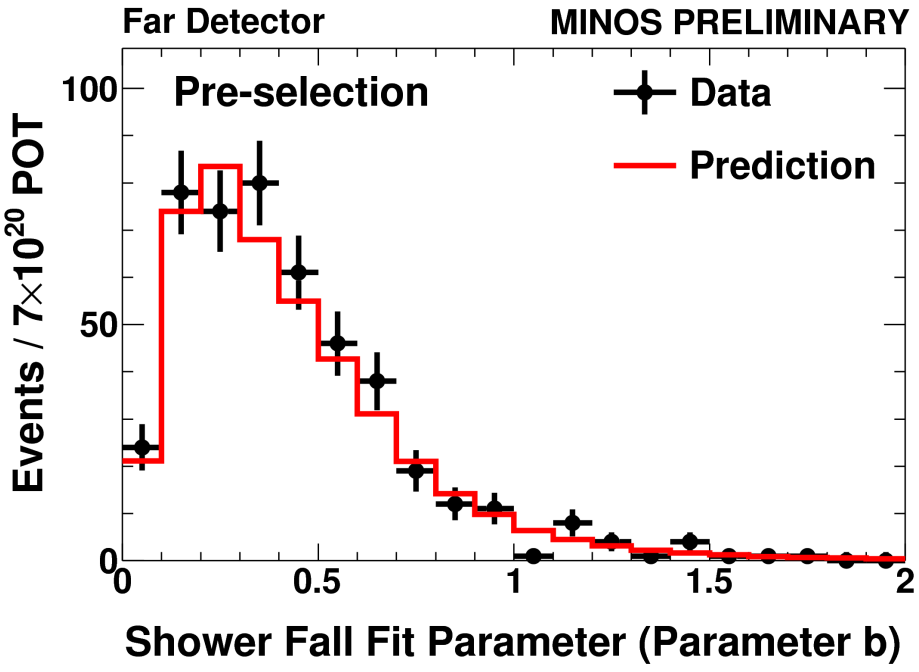
ANN11 PID = 0.81
PAR PID = 0.85
ANN14 PID = 0.86

Event shapes in the far detector: *Data and expectations match*

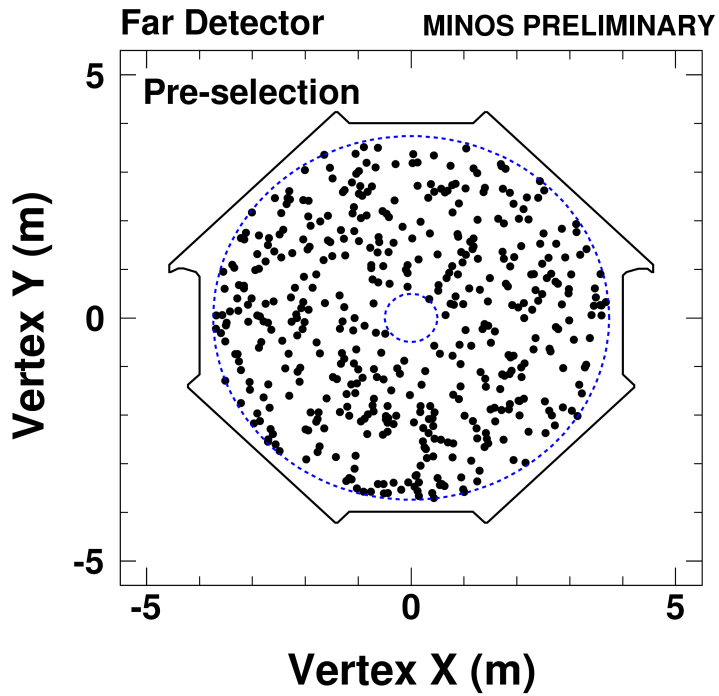


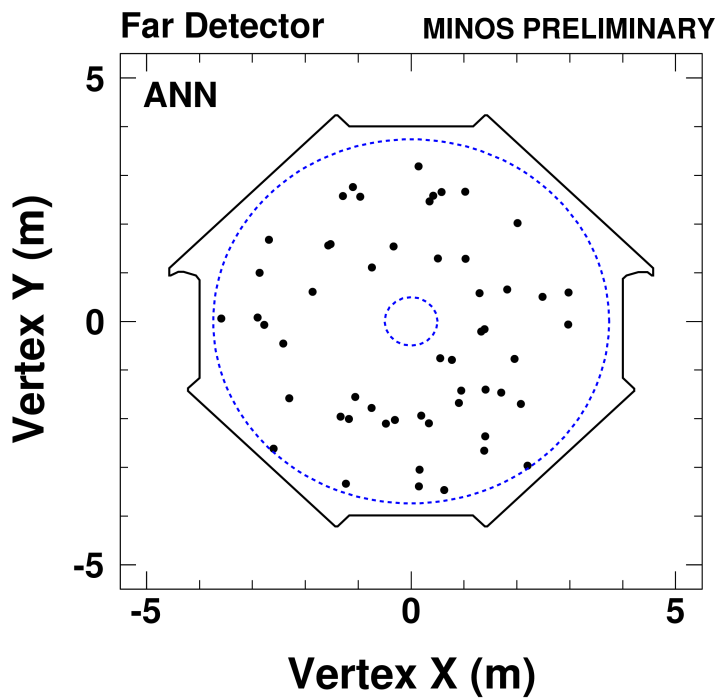


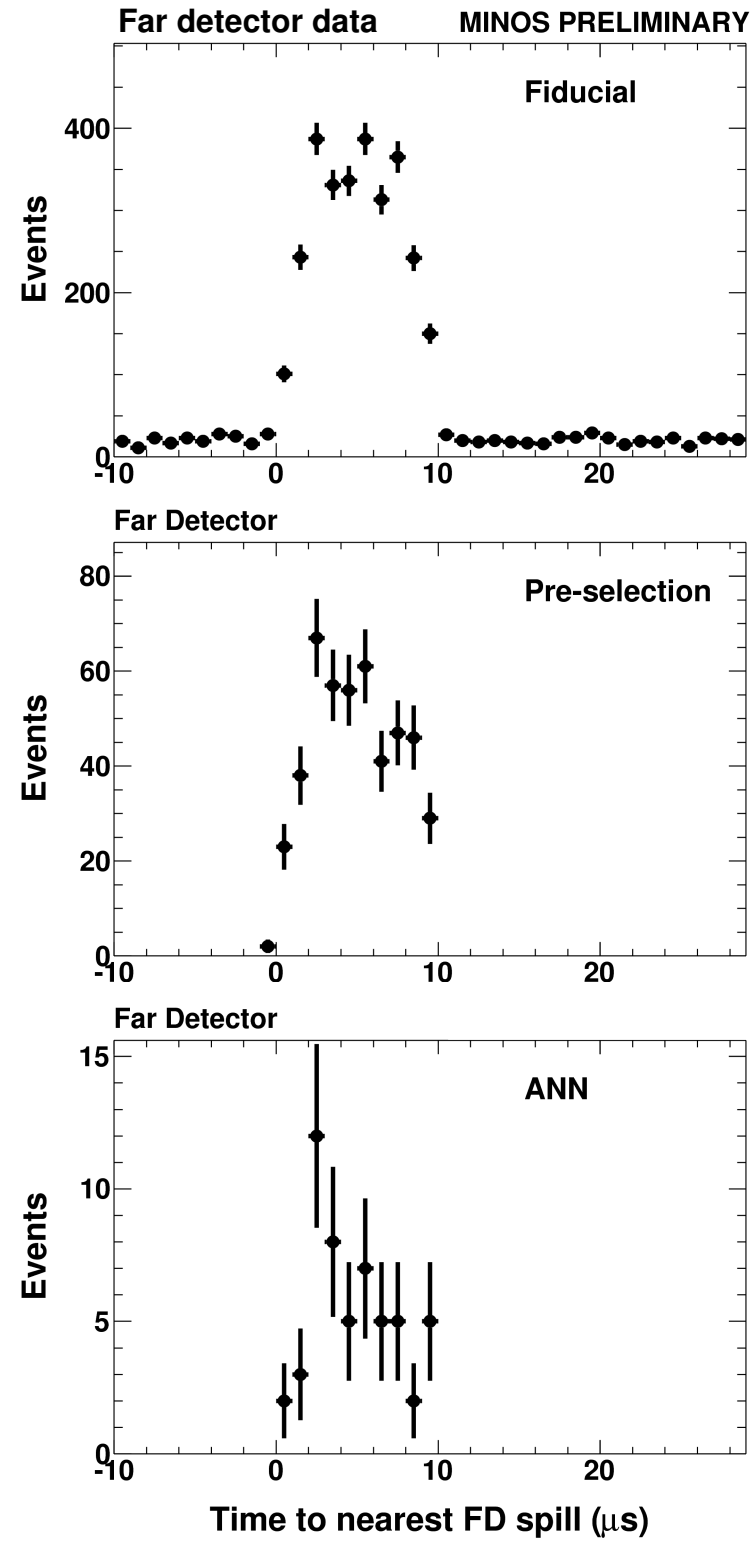




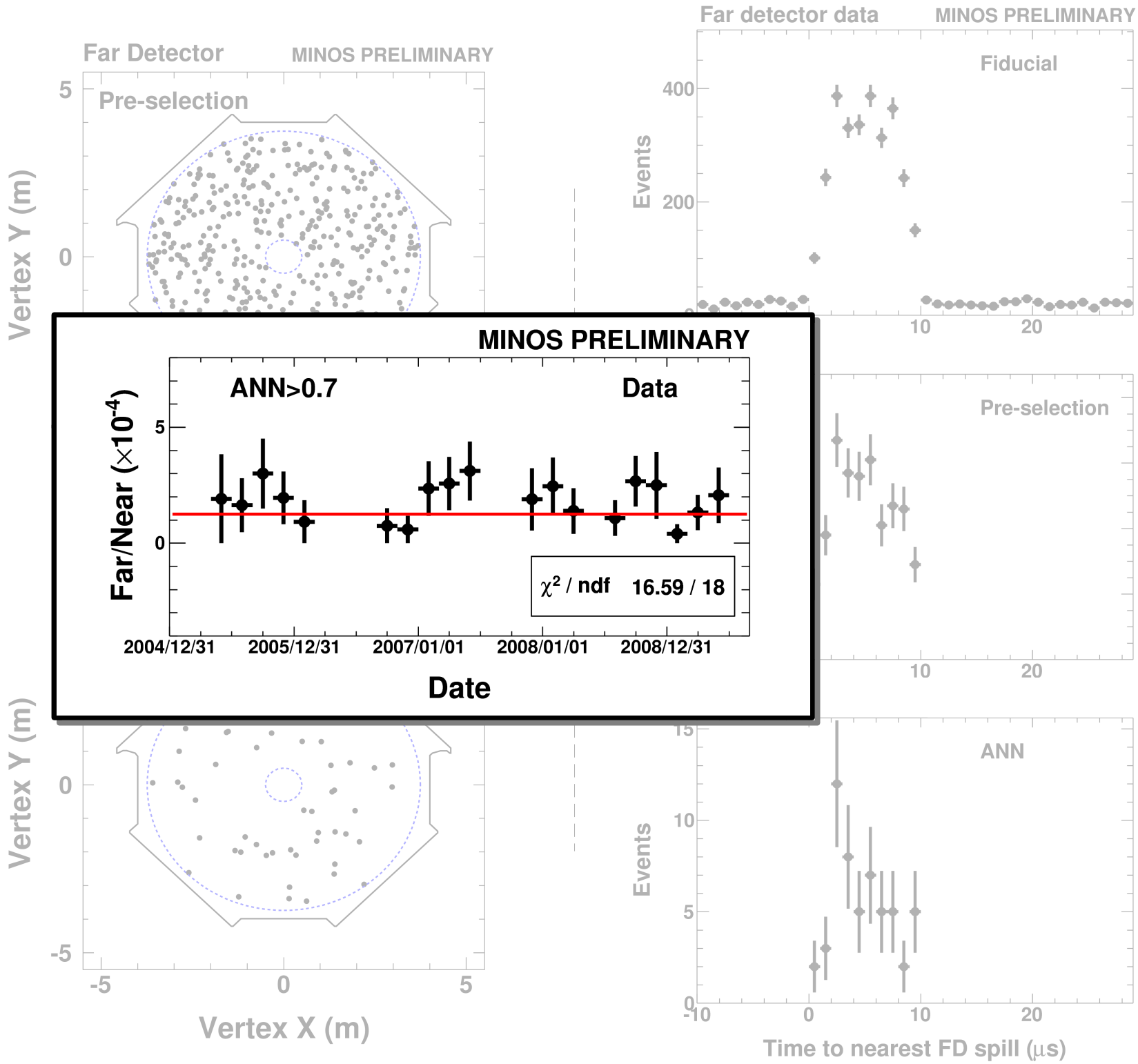
Positions and **times** of events







Positions and **times** of events

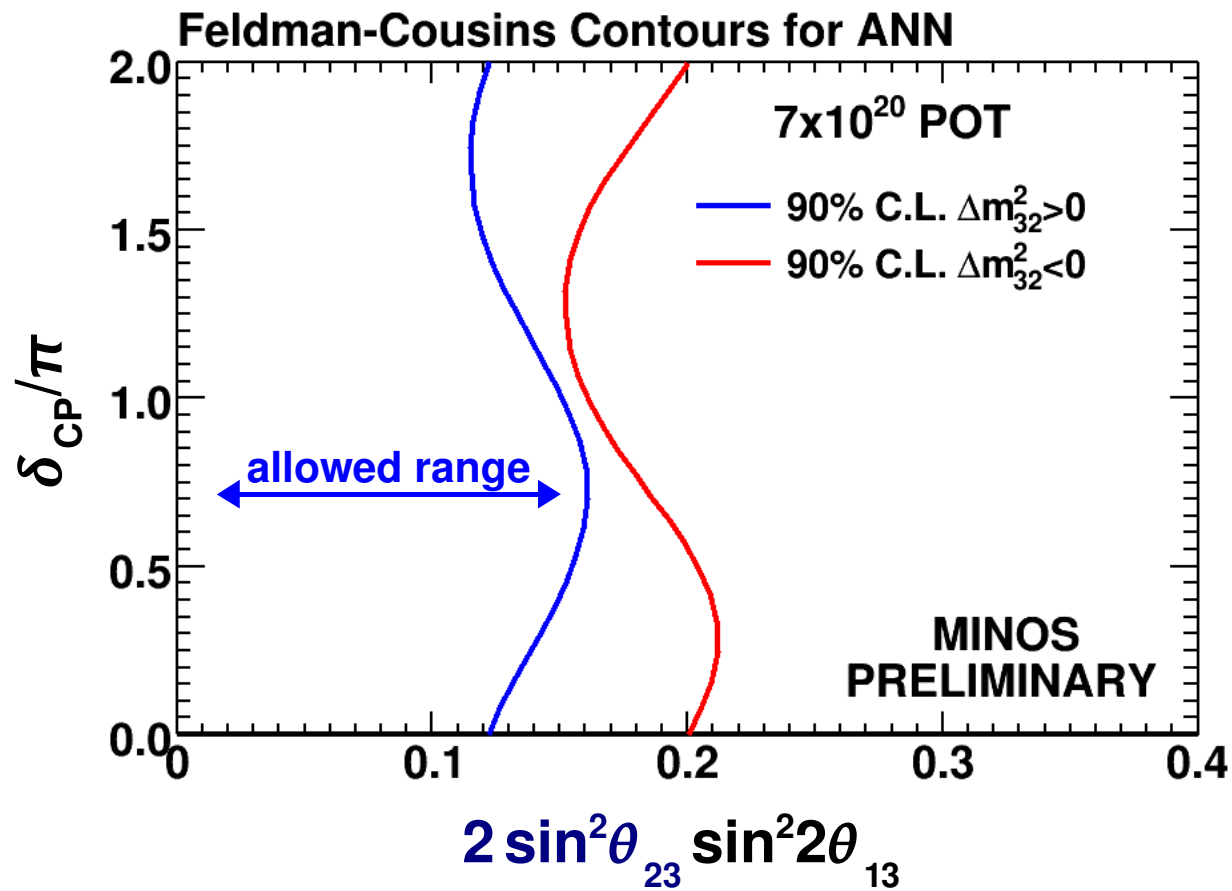


Oscillation interpretation of the data

$\sin^2(2\theta_{13})$ allowed range depends on **CP-phase δ** and **mass hierarchy** [sign(Δm^2)]

90% C.L. allowed ranges →

(other oscillation parameters taken with current experimental uncertainties)



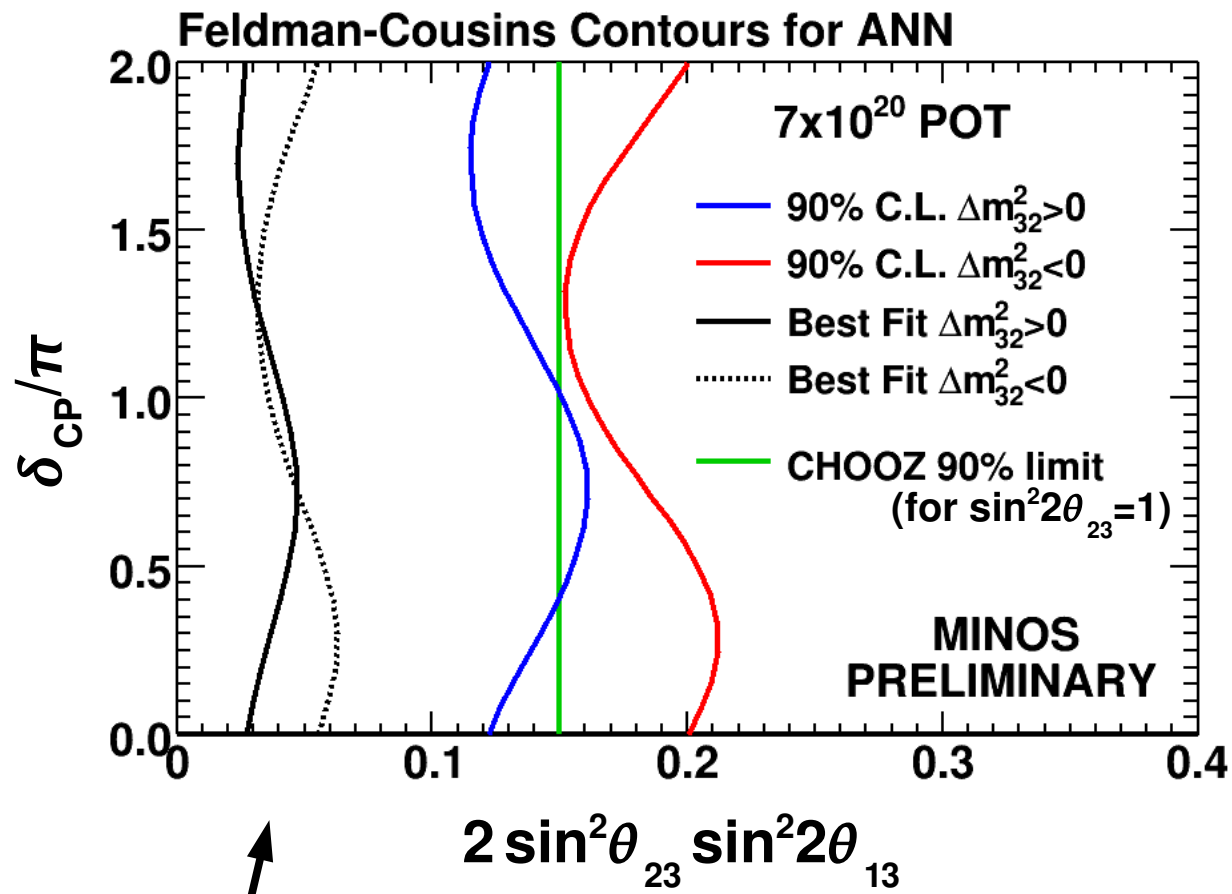
(unity if $\theta_{23} = \pi/4$)

Oscillation interpretation of the data

$\sin^2(2\theta_{13})$ allowed range depends on **CP-phase δ** and **mass hierarchy** [sign(Δm^2)]

90% C.L. allowed ranges →

(other oscillation parameters taken with current experimental uncertainties)



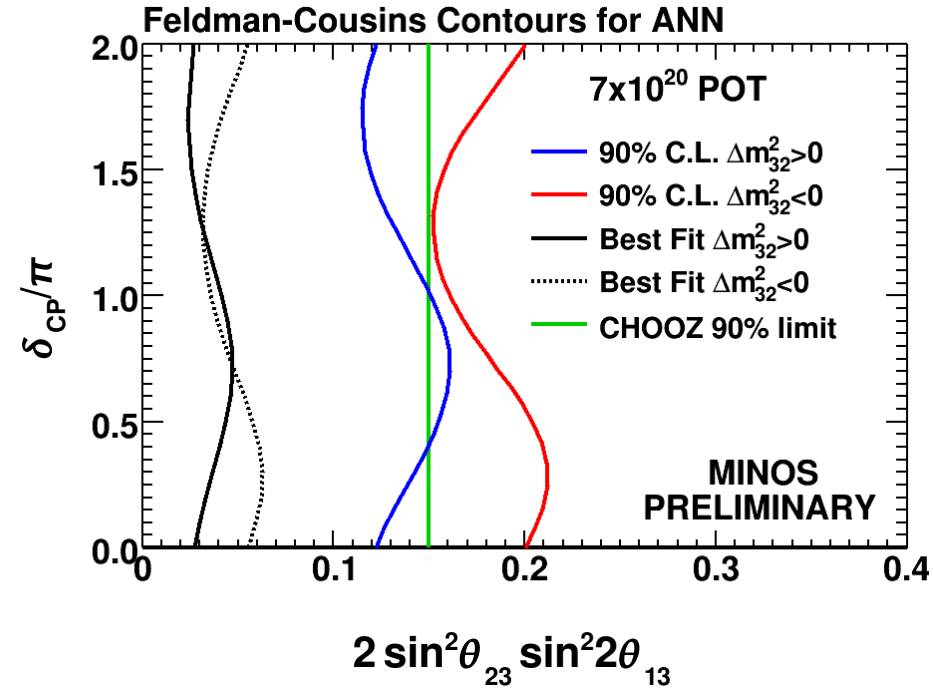
MINOS best-fit [**black curves**] along with CHOOZ upper limit (for $\theta_{23} = \pi/4$) [**green line**].

Summary

- **No significant excess of candidate ν_e CC events:**

  expected bg: **$49.1 \pm 7.0_{stat} \pm 2.7_{syst}$**

  events obs'd: **54**



- **Consistent results obtained with two additional event selectors** *(not shown here)*

Representative 90% C.L. limits: *put* $\delta_{CP}=0$, $\theta_{23}=\pi/4$

normal hier. $\Rightarrow$ $\sin^2 2\theta_{13} < 0.12$

inverted hier. $\Rightarrow$ $\sin^2 2\theta_{13} < 0.20$

- ***For the near future:***

  additional **neutrino data** and **significant new analysis techniques**

  $\Rightarrow$ **potentially large sensitivity gains**

Acknowledgments

The MINOS Collaboration would like to thank the **many Fermilab groups** who provided **technical expertise and support** in the design, construction, installation and operation of the MINOS experiment.

Thanks to the **Accelerator Division** for the neutrinos!

We also acknowledge the financial support from DOE; NSF; STFC(UK); the University of Athens, Greece; Brazil's FAPESP, CNPq, and CAPES.

We are grateful to the **University of Minnesota** and the Minnesota **Department of Natural Resources** for hosting us.

Extra slides

Other selection methods

All consistent

Official selector (ANN11):

Observed: **54**
BG expected: **49 ± 7(stat.) ± 3(syst.)**
Difference: **0.67σ**

Alternate selector (ANN14):

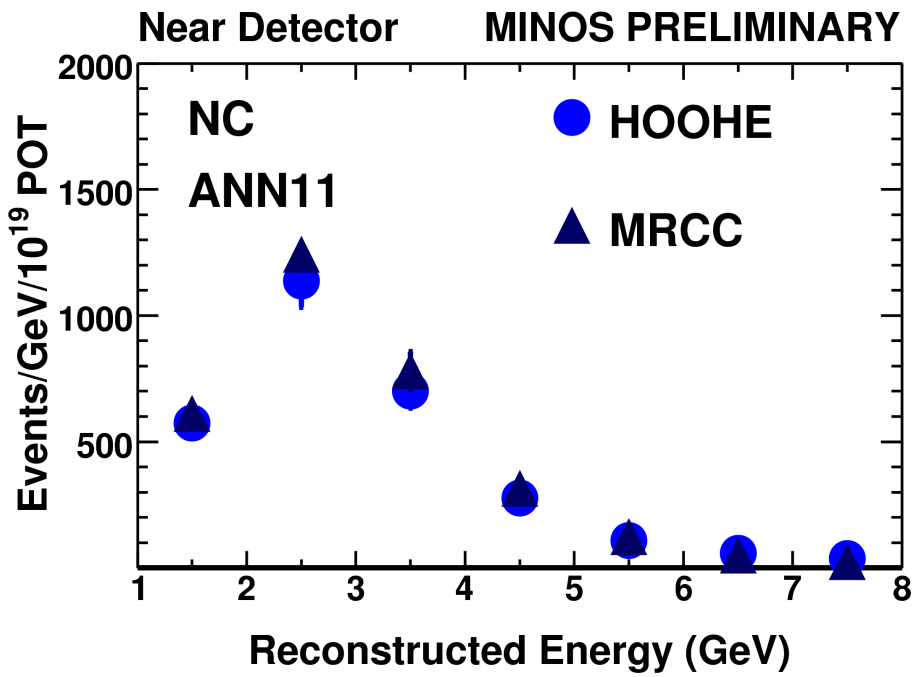
Observed: **36**
BG expected: **34 ± 6(stat.) ± 2(syst.)**
Difference: **0.35σ**

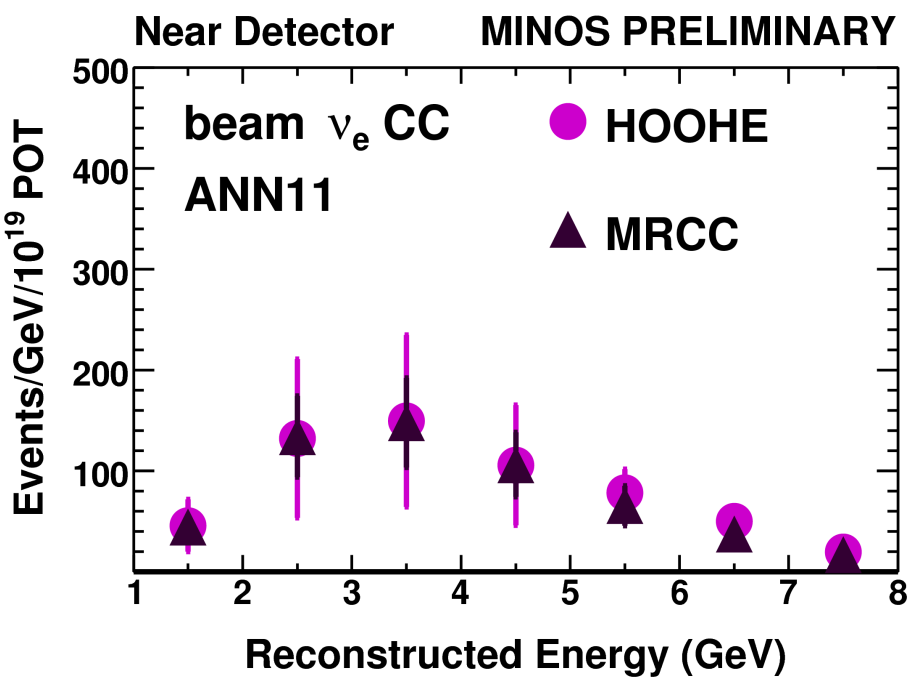
Alternate selector (PAR):

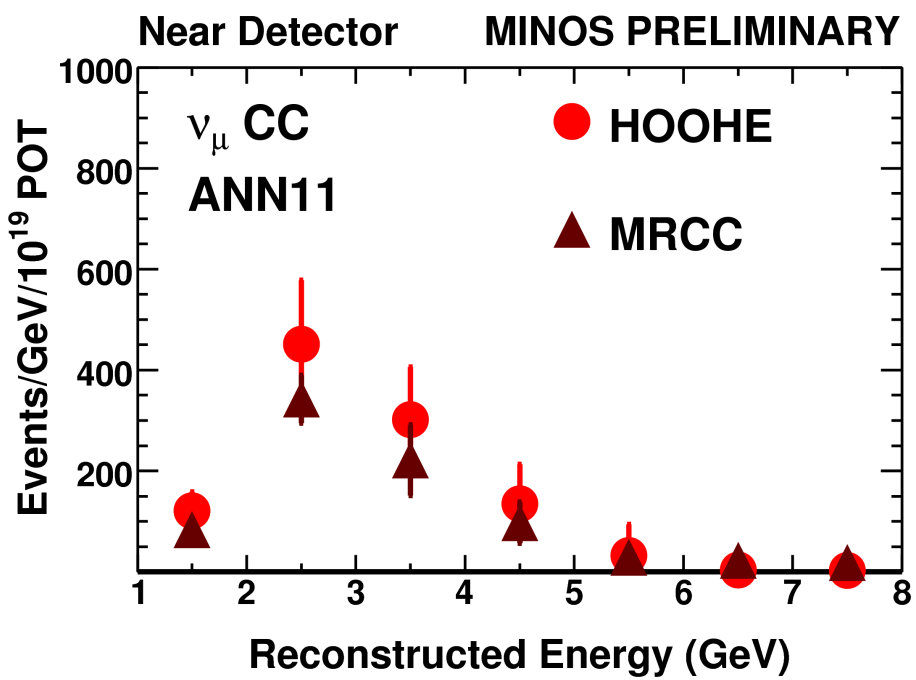
Observed: **59**
BG expected: **54 ± 7(stat.) ± 3(syst.)**
Difference: **0.64σ**

Near detector data decomposed into components by two methods:

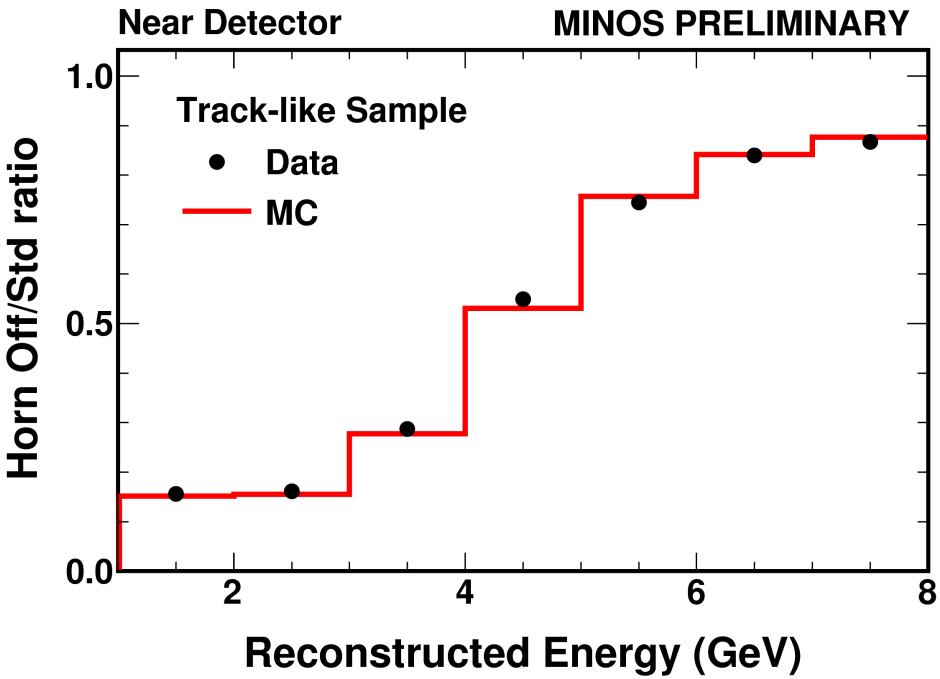
Horn-on/High-*E* (HOOHE)
Muon-removal (MRCC)

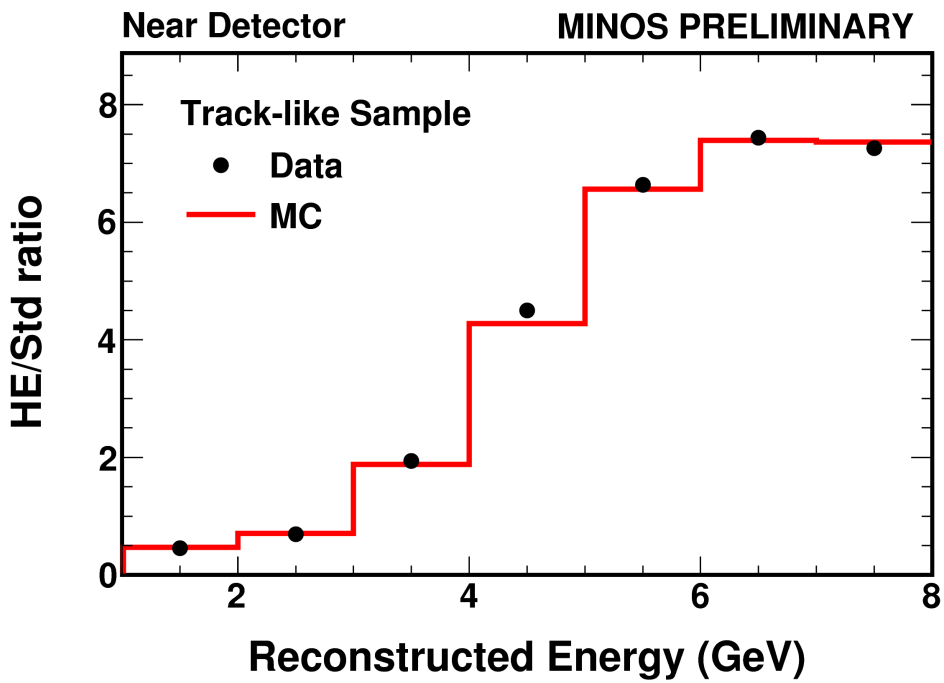


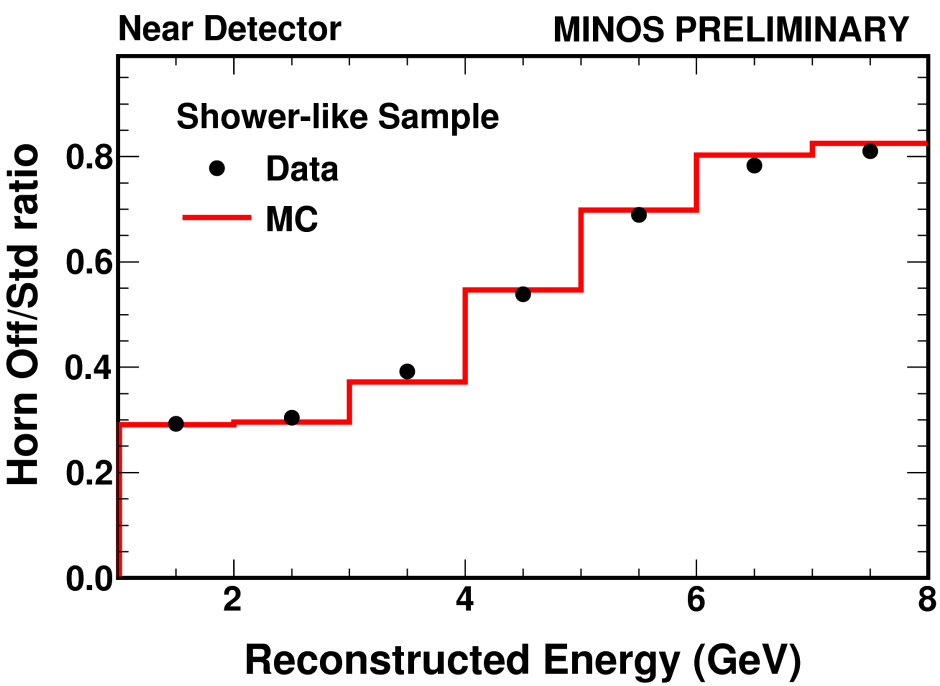


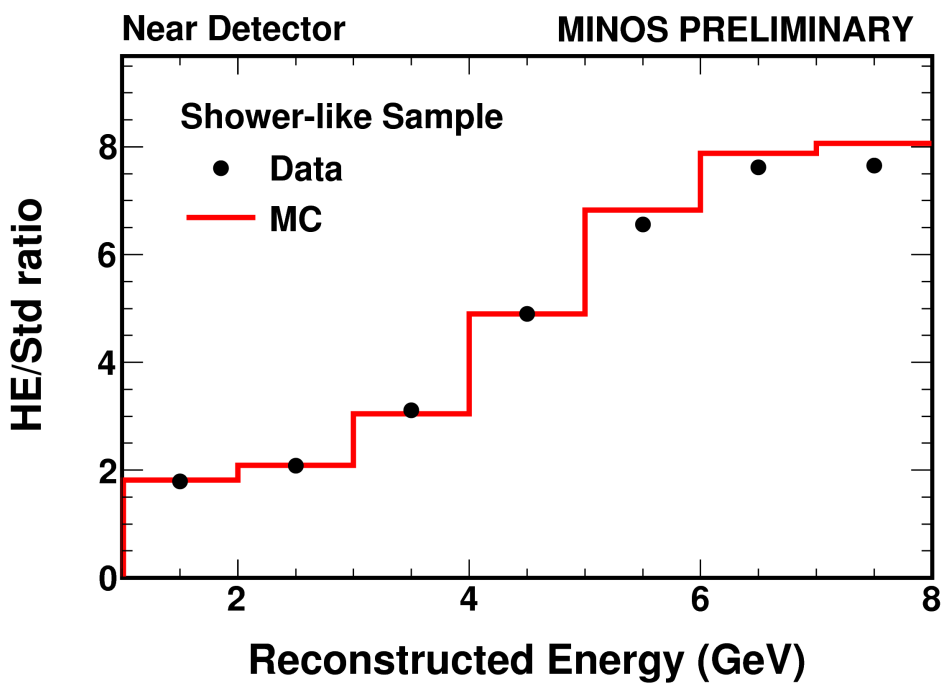


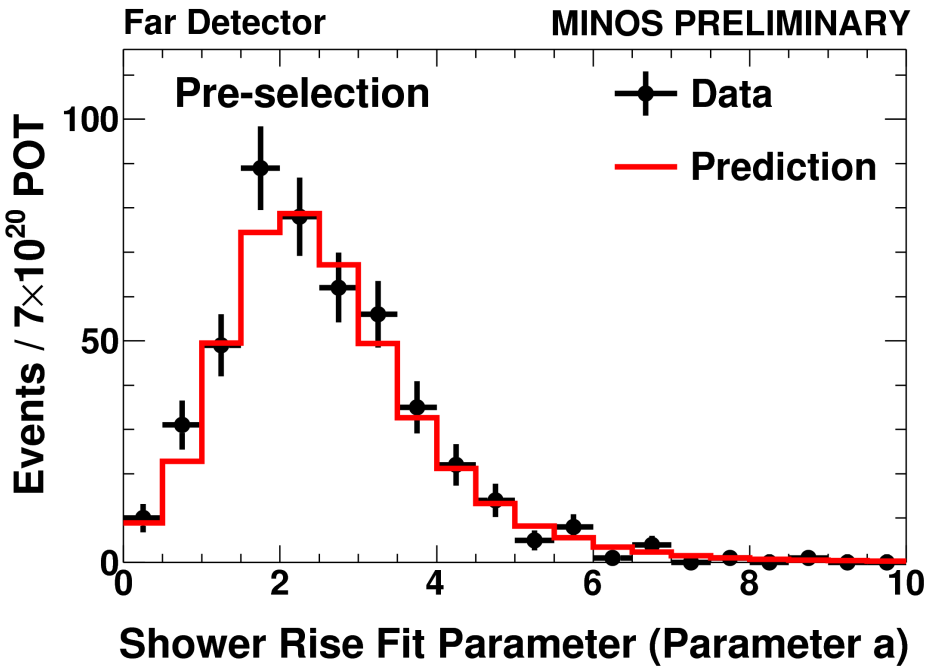
Ratios of CC (or NC) event rates between two beam configurations

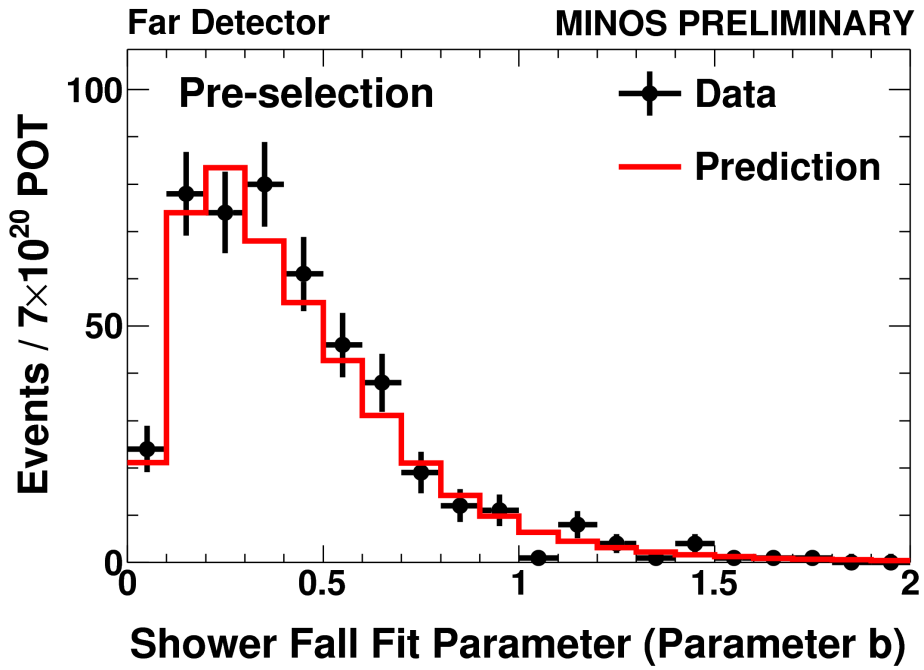









Far Detector
MINOS PRELIMINARY
Pre-selection
Data
Prediction
Events / 7×10^20 POT
Shower Rise Fit Parameter (Parameter a)


Far Detector
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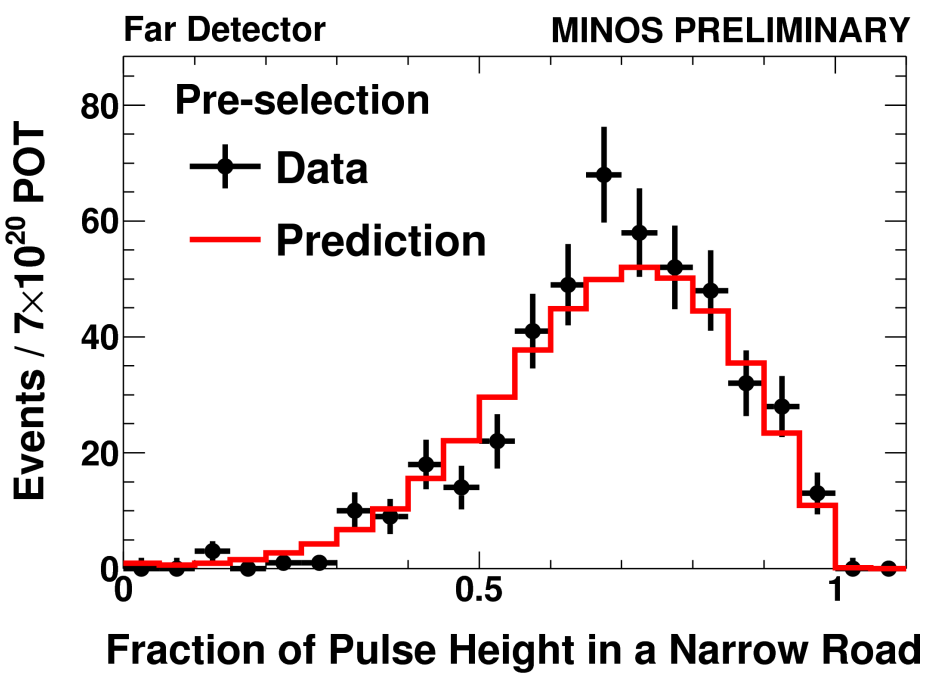
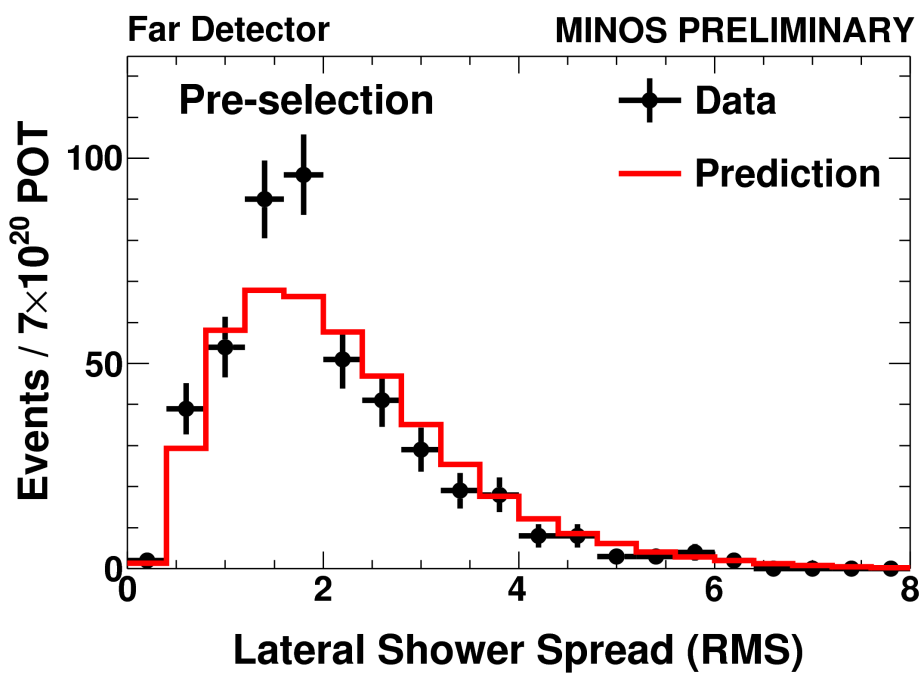
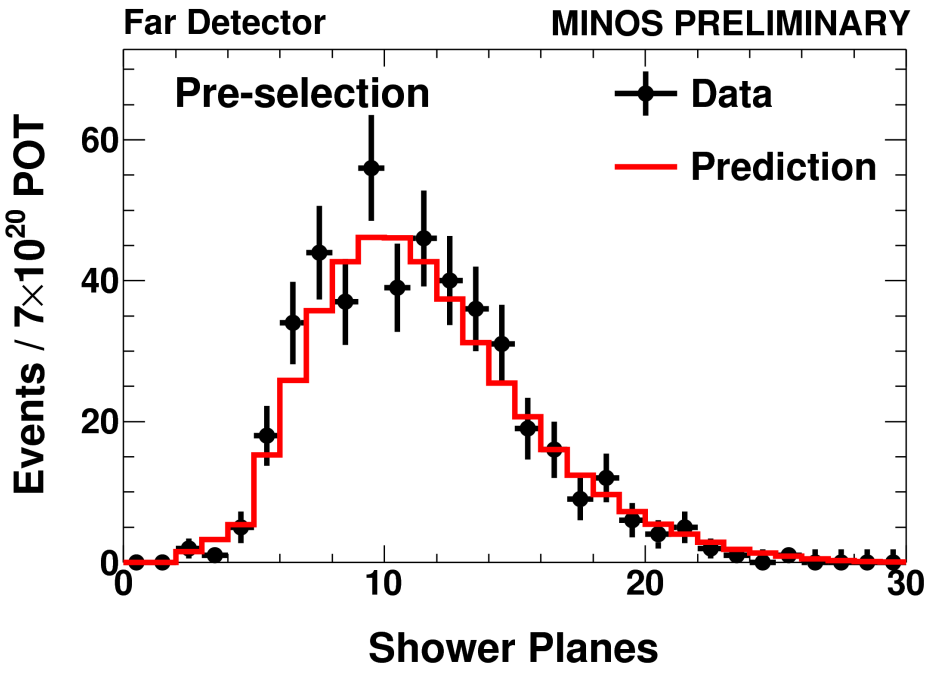
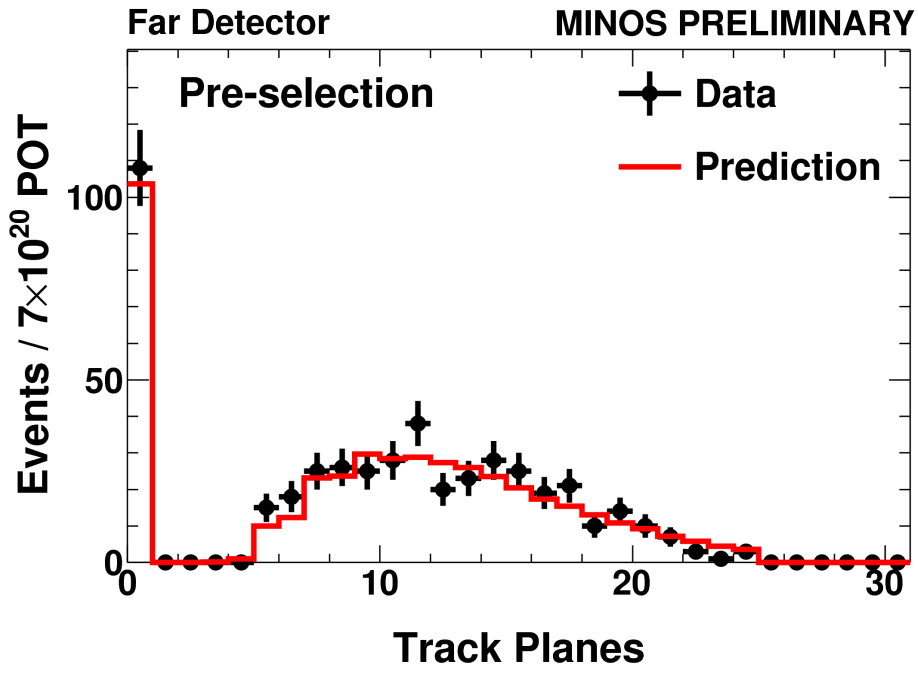
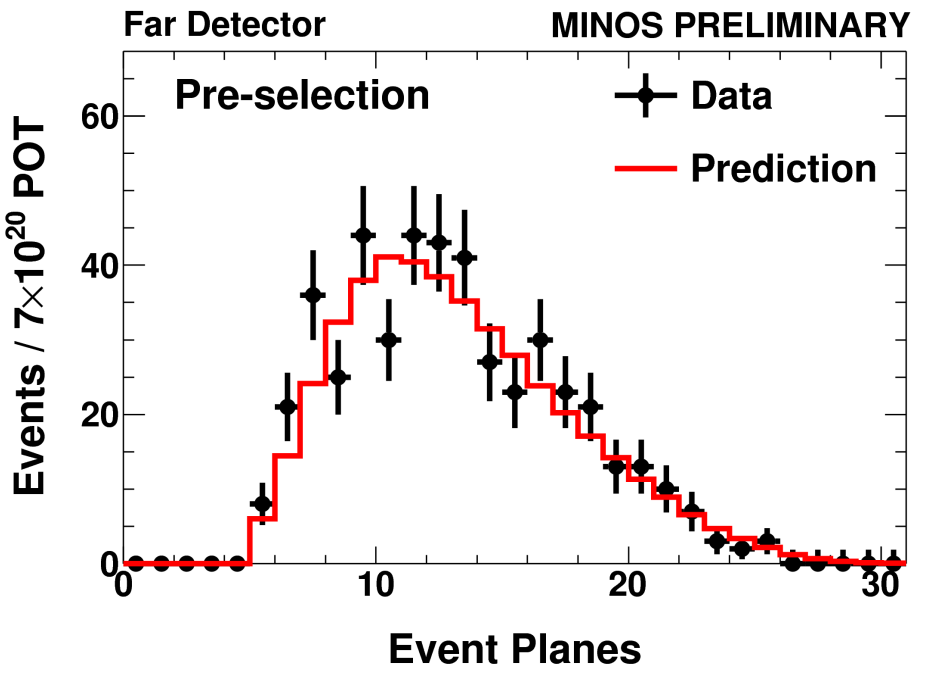
Pre-selection
Data
Prediction
Events / 7×10^20 POT
Shower Fall Fit Parameter (Parameter b)

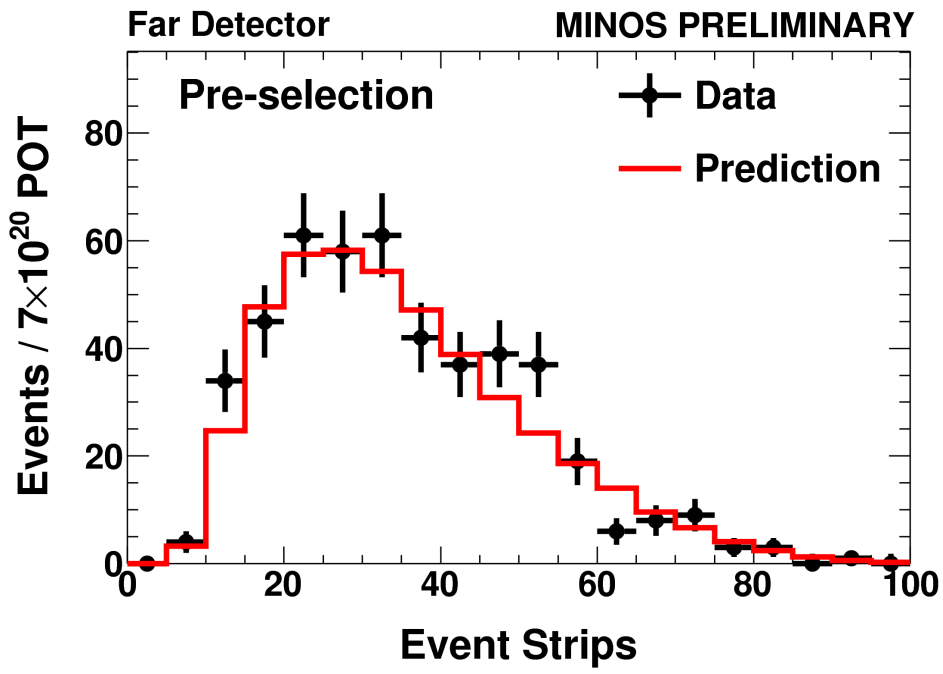

Far Detector
MINOS PRELIMINARY
Pre-selection
Data
Prediction
Events / 7×10^20 POT
Fraction of Pulse Height in a Narrow Road


Far Detector
MINOS PRELIMINARY
Pre-selection
Data
Prediction
Events / 7×10^20 POT
Lateral Shower Spread (RMS)

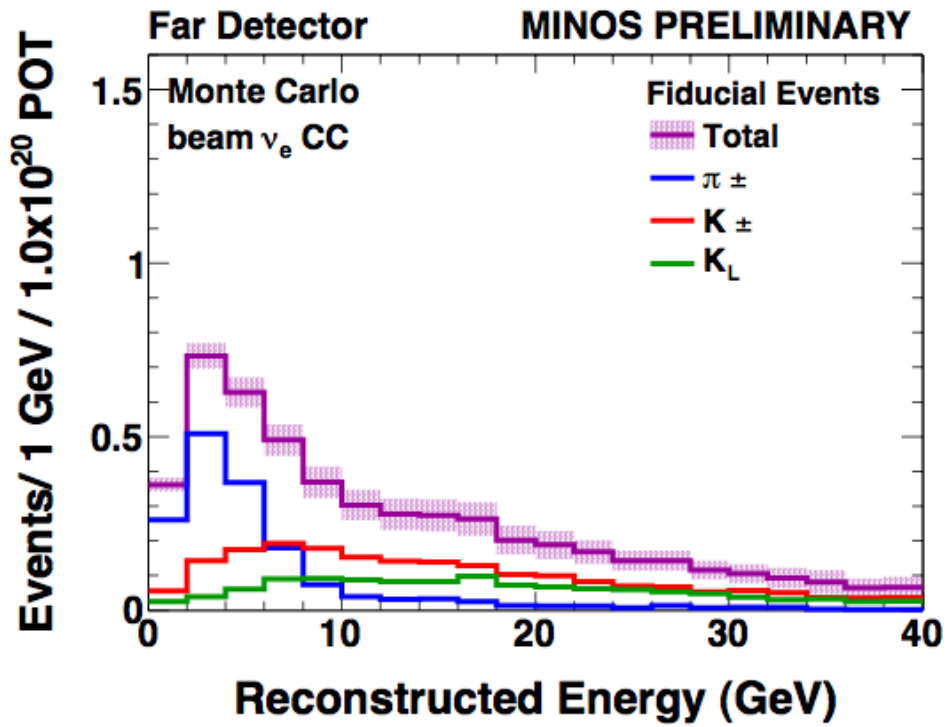

Far Detector
MINOS PRELIMINARY
Pre-selection
Data
Prediction
Events / 7×10^20 POT
Shower Planes

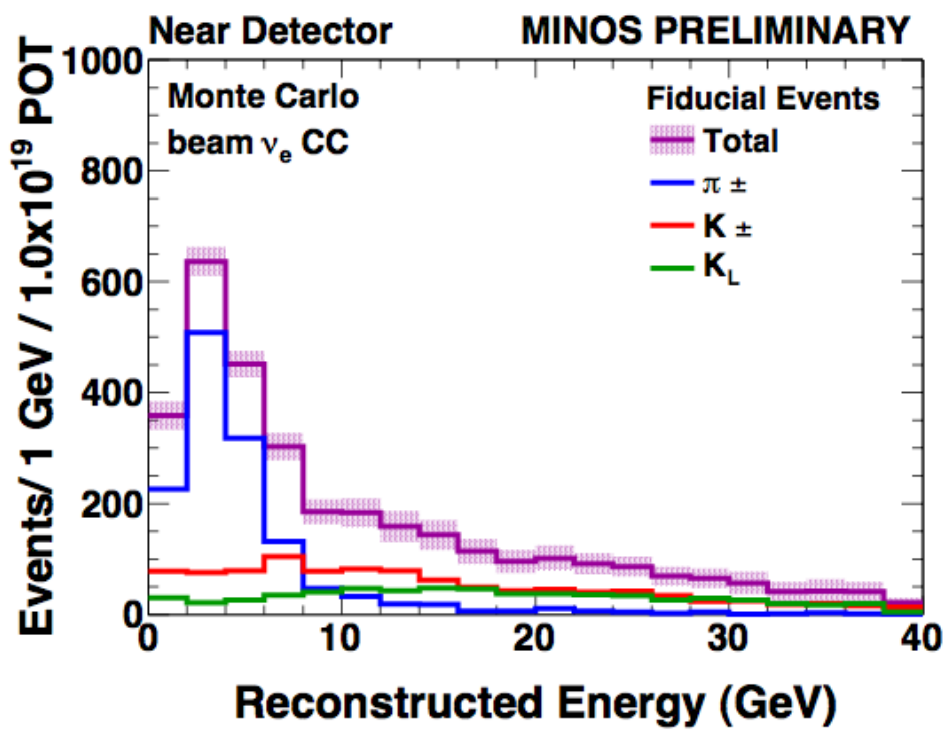

Far Detector
MINOS PRELIMINARY
Pre-selection
Data
Prediction
Events / 7×10^20 POT
Track Planes


Far Detector
MINOS PRELIMINARY
Pre-selection
Data
Prediction
Events / 7×10^20 POT
Event Planes


Far Detector
MINOS PRELIMINARY
Pre-selection
Data
Prediction
Events / 7×10^20 POT
Event Strips

Intrinsic beam ν_e at far and near detectors





ANN variables

Fraction of pulseheight in a n-plane window (n=2,4,6): the fraction of energy deposited in sliding window of n planes divided by the event energy.

Fraction of pulseheight in a narrow road: fraction of total visible energy deposited in a 3 strip window along the shower axis.

Lateral shower spread (RMS): the RMS of the transverse energy deposition profile, where the RMS is computed over a 9 strip window around the pulseheight weighted center of the event.

Radius of 90% energy containment (strips): the number of strips away from the peak of the transverse energy distribution to contain 90% of the energy deposited in a 9 strip window around the pulseheight weighted center of the event.

Shower fit raise and fall parameters (a and b): parameters from the fit to the longitudinal profile of the energy deposition of an event.

Longitudinal energy projection: the energy weighted sum of the distance to each strip projected along the detector z axis.

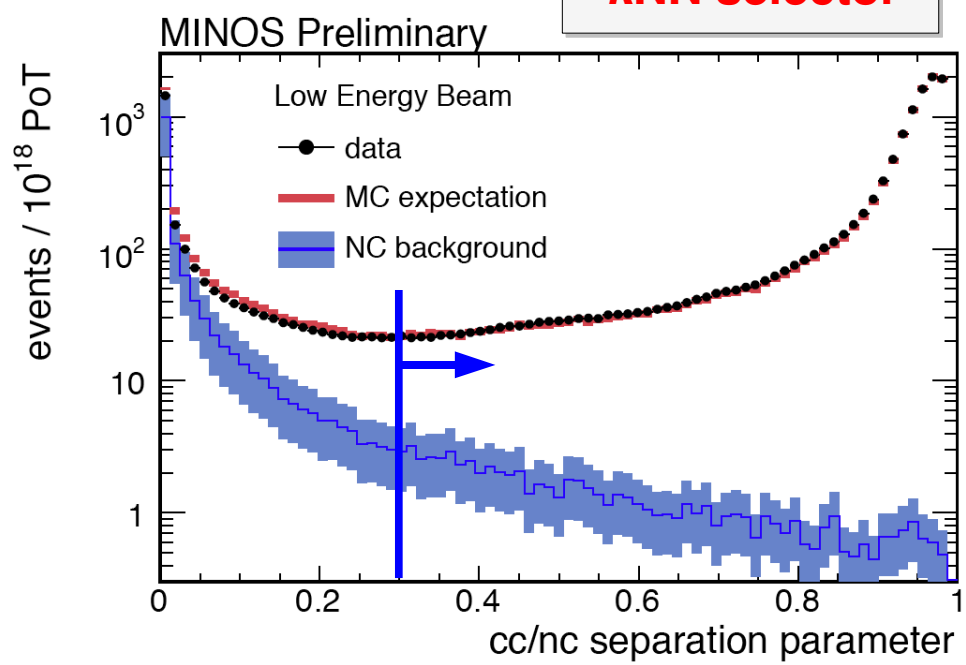
Minimal spanning tree summed weight: the sum of the minimum distances that join the hits of larger than average pulseheight hits in an event.

Fraction of pulseheight in 8 highest PH strips: the fraction of pulseheight in the highest 8 strips divided by the event energy.

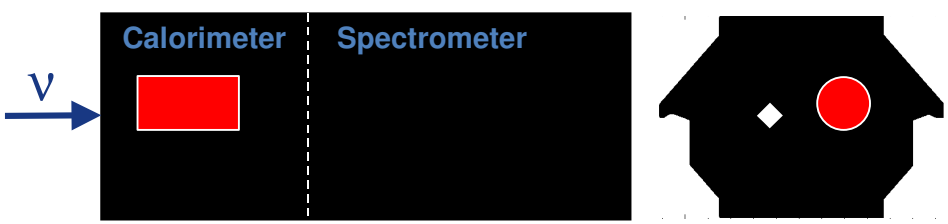
Muon neutrino disappearance

- Start by measuring ν_μ charged current rate in **near detector**
- *Selection:*
  - **Fiducial volume** (below)
  - Beam **timing**, **cosmic** removal
  - How **"track-like"** is the event? – a ***k*-nearest-neighbors** algorithm using:
    track length
    mean pulse height in each place
    fluctuation in pulse heights
    transverse track profile

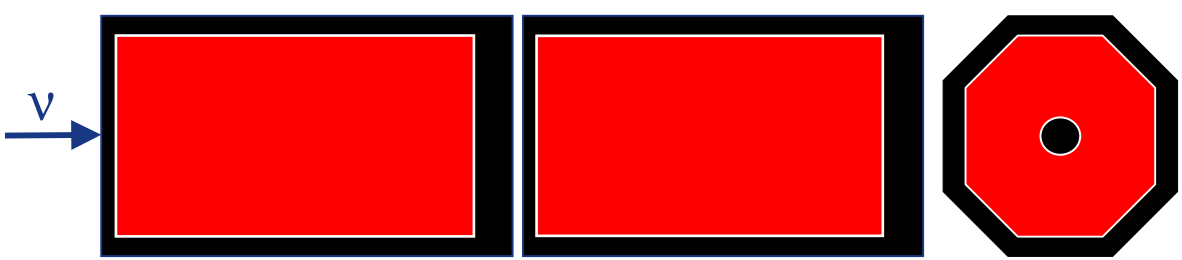
***k*NN selector**



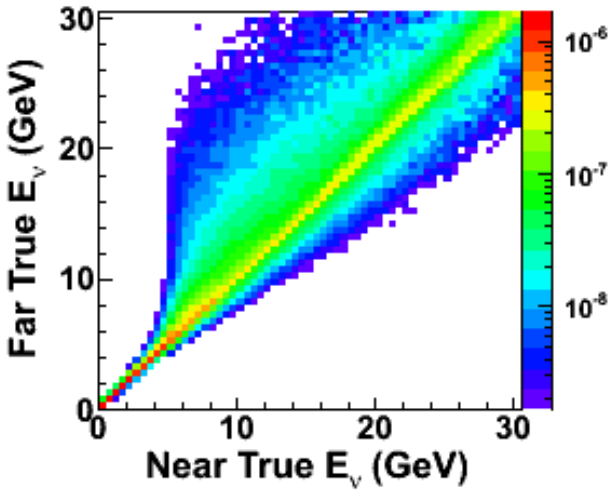
Near det.

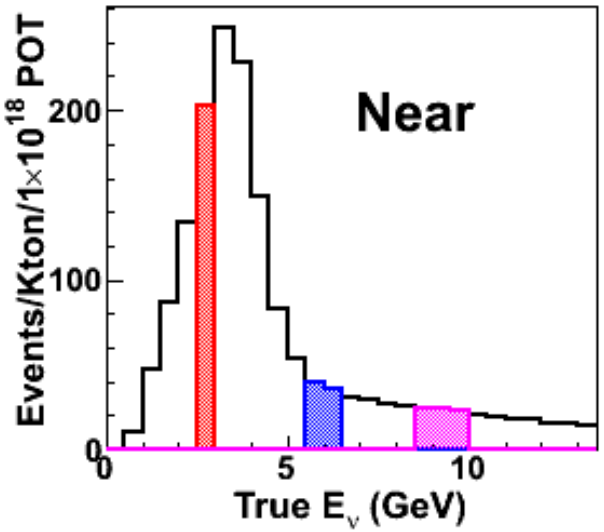


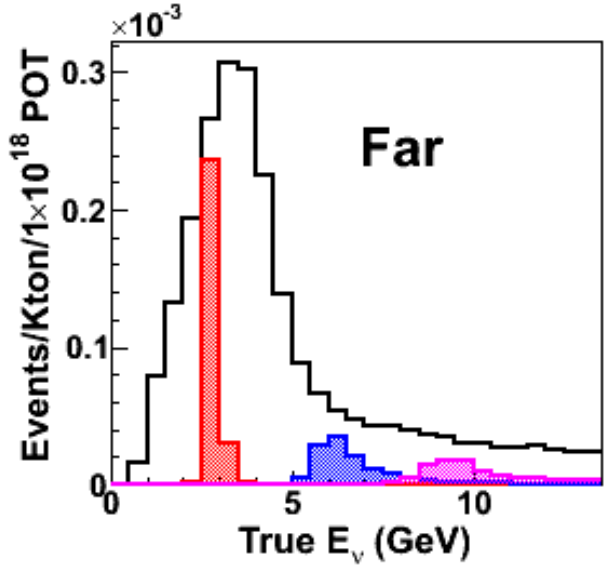
Far det.



Fiducial regions (in red)





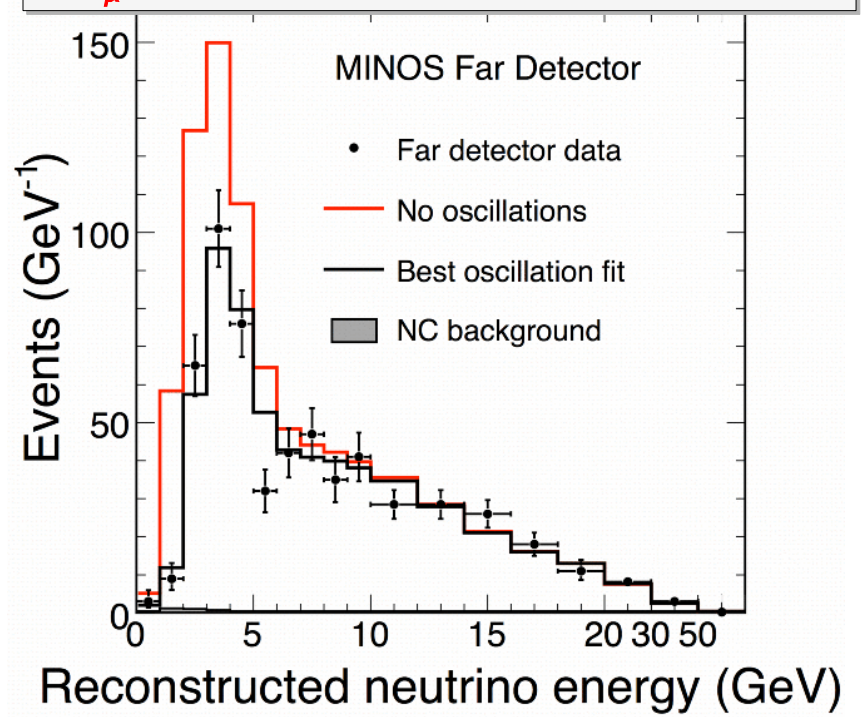


- Convert the measured **near detector energy spectrum** into a prediction for the **far detector**

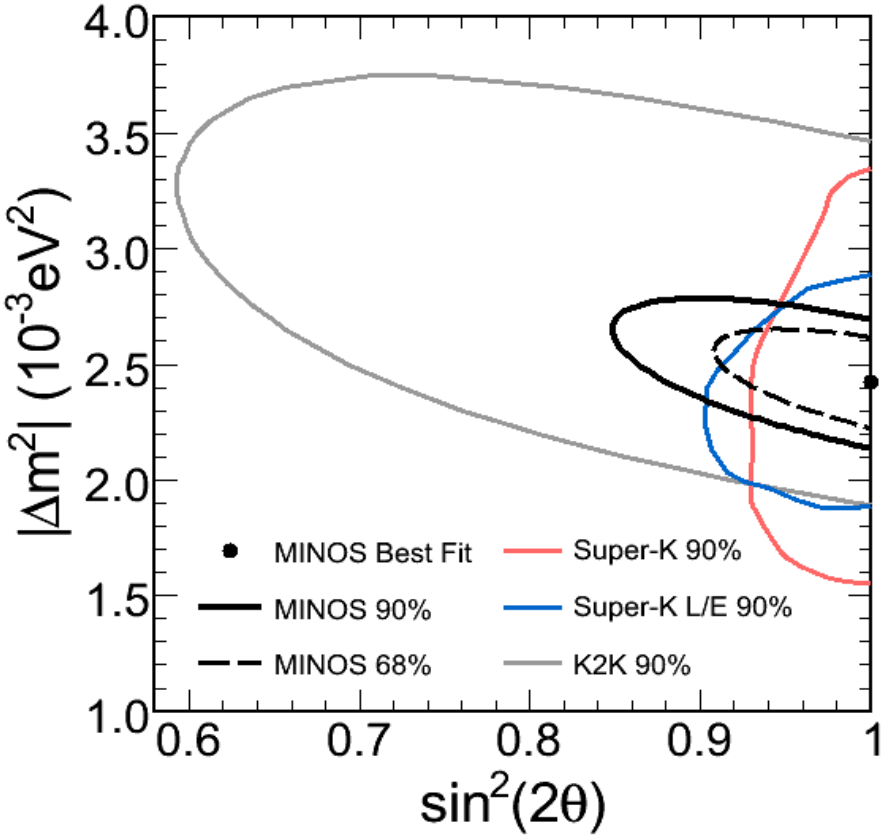
- Monte Carlo used for this, incorporating:
  beamline geometry
  detector solid angles
  readout differences (near vs. far)

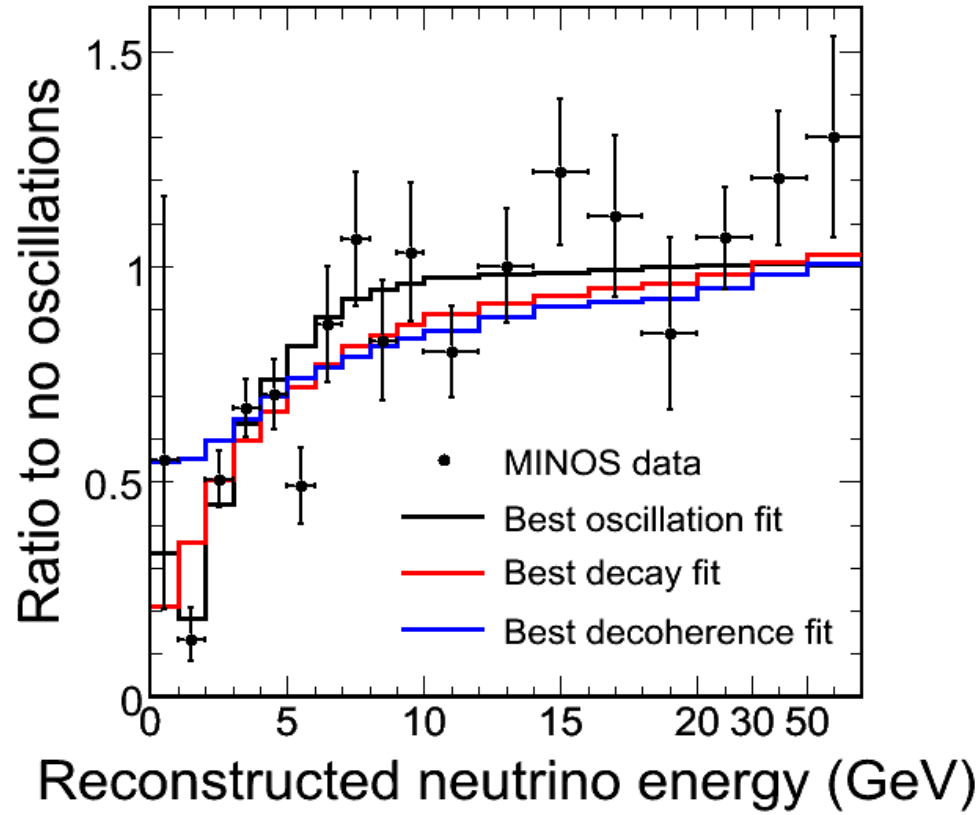
- **Clear deficit seen at far detector** →

ν_μ disappearance at far detector



[Phys. Rev. Lett. **101,** 131802 (2008)]





Oscillation interpretation:

- Parameter space shown above.
- Most precise Δm_{atm}^2 measurement:

$$\Delta m_{atm}^2 = (2.43 \pm 0.13) \times 10^{-3}\ \text{eV}$$

(Uses 3.36 protons-on-target. More than twice this has been collected.)

Strongly disfavored alternative interpretations:

- Neutrino decay: 3.7σ
  (5.4σ with NC sample)
- Decoherence: 5.7σ