MINOS Update

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for the
MINOS Collaboration

Fermilab Users' Meeting

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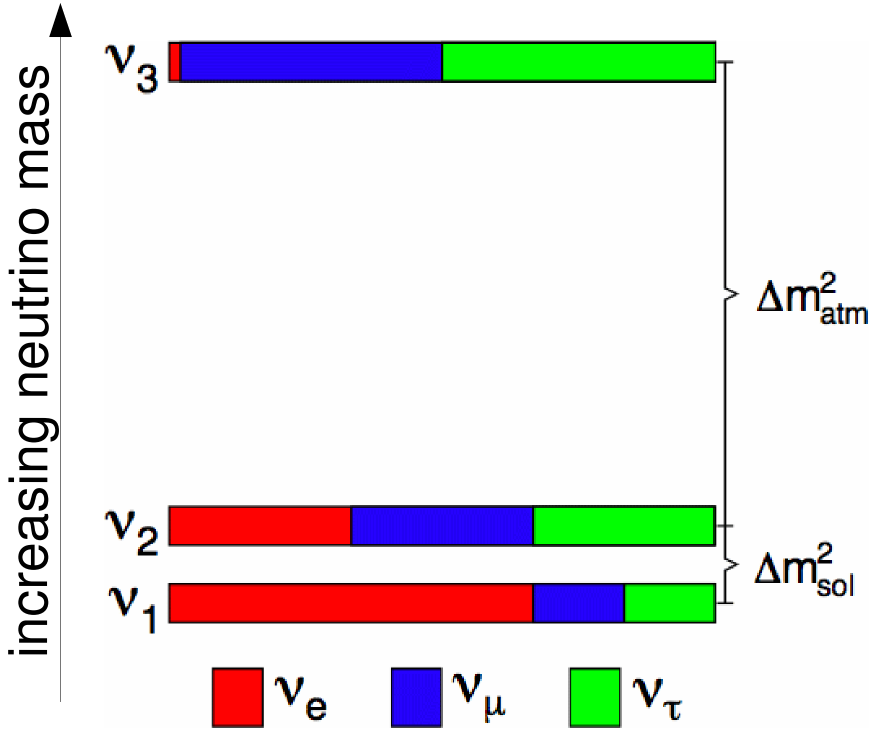
Neutrino mass and mixing

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:*
  $$\Delta m^2_{\rm atm} = (2.32^{+0.12}_{-0.08})\times 10^{-3}\ {\rm eV}^2$$



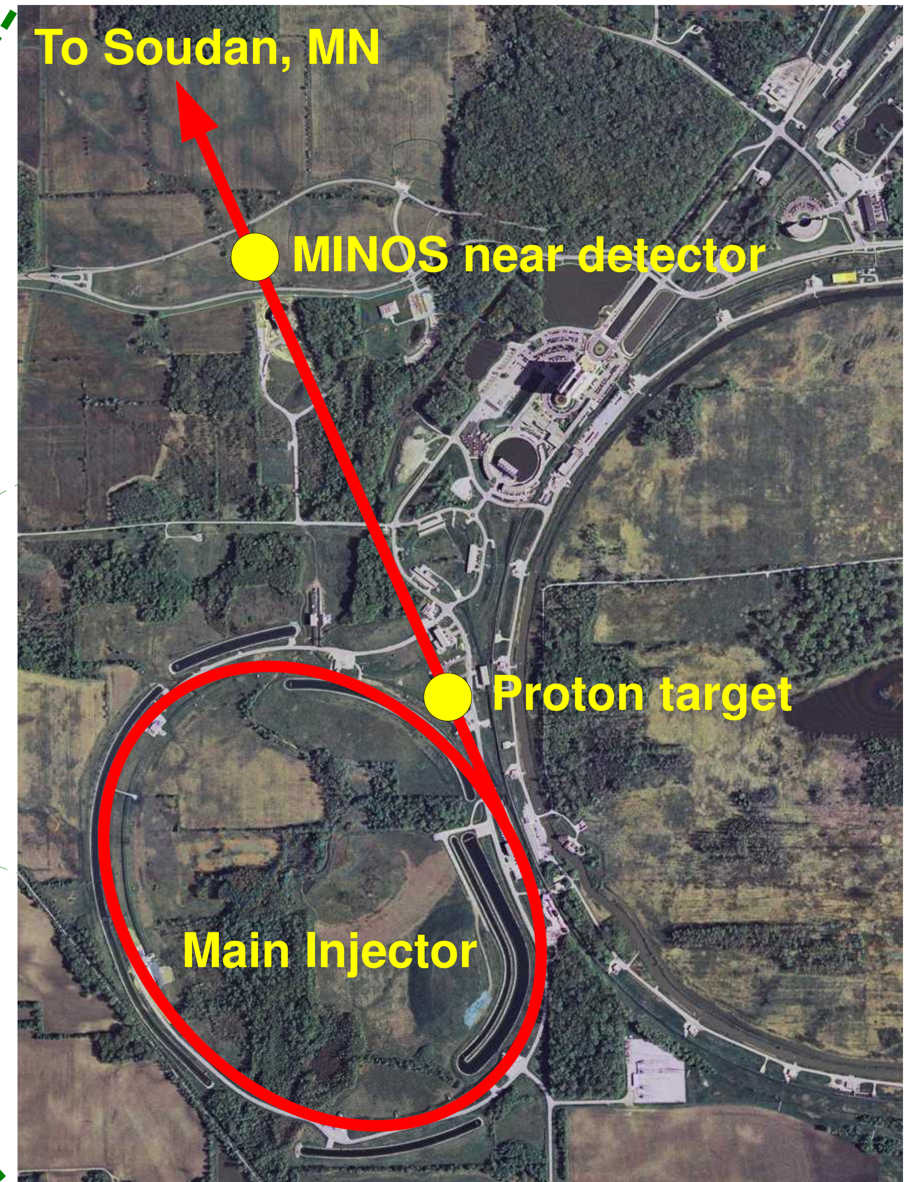
Mixing angles extracted so far...

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

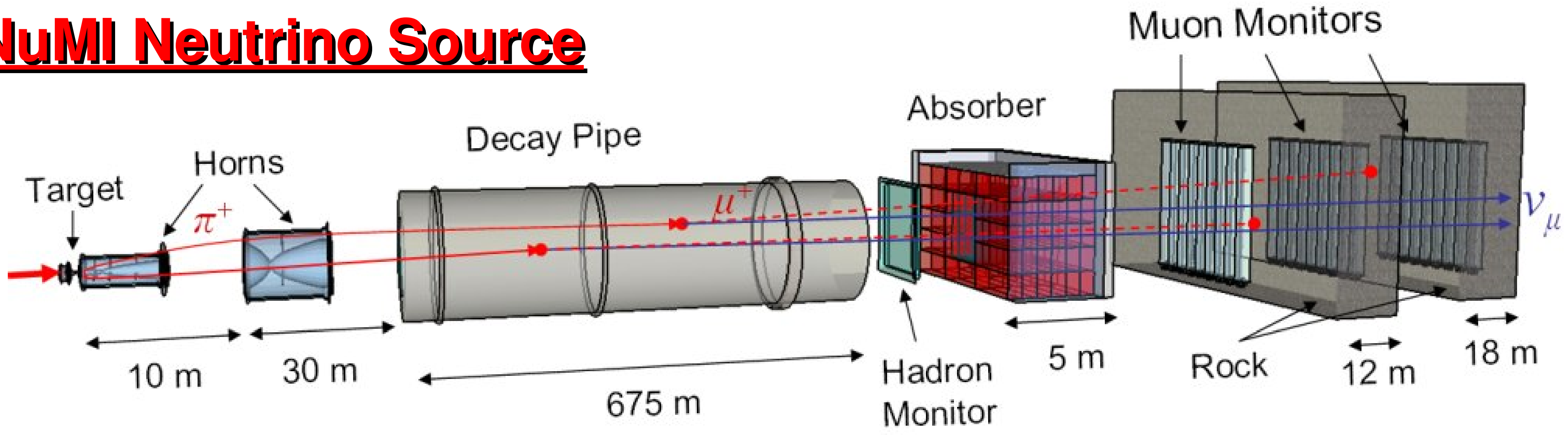
$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Accessible by MINOS}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12}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

Main Injector Neutrino Oscillation Search (MINOS)

735 km to the far detector

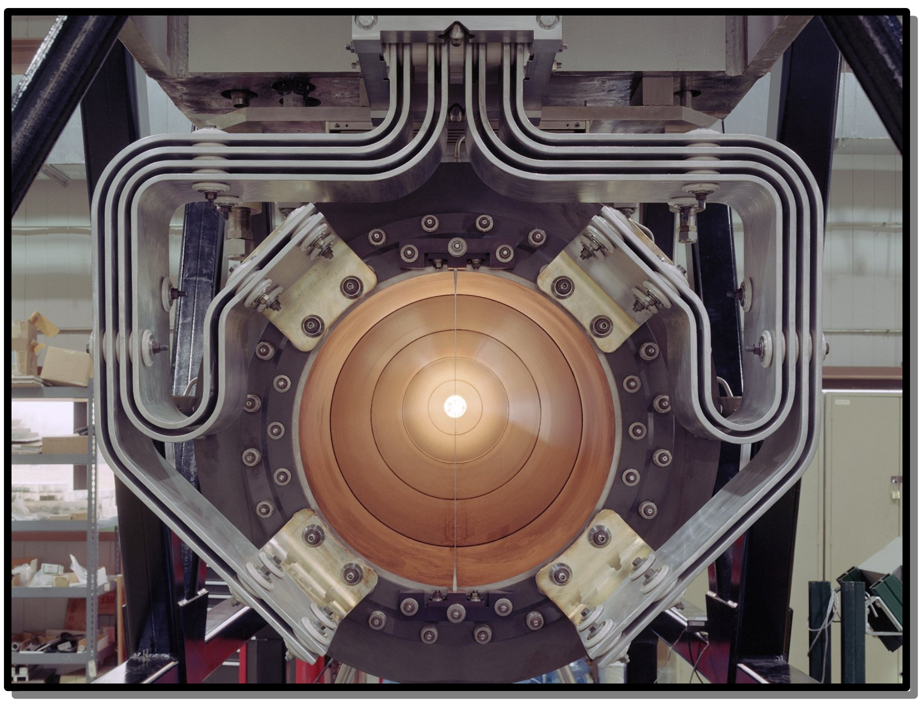


NuMI Neutrino Source



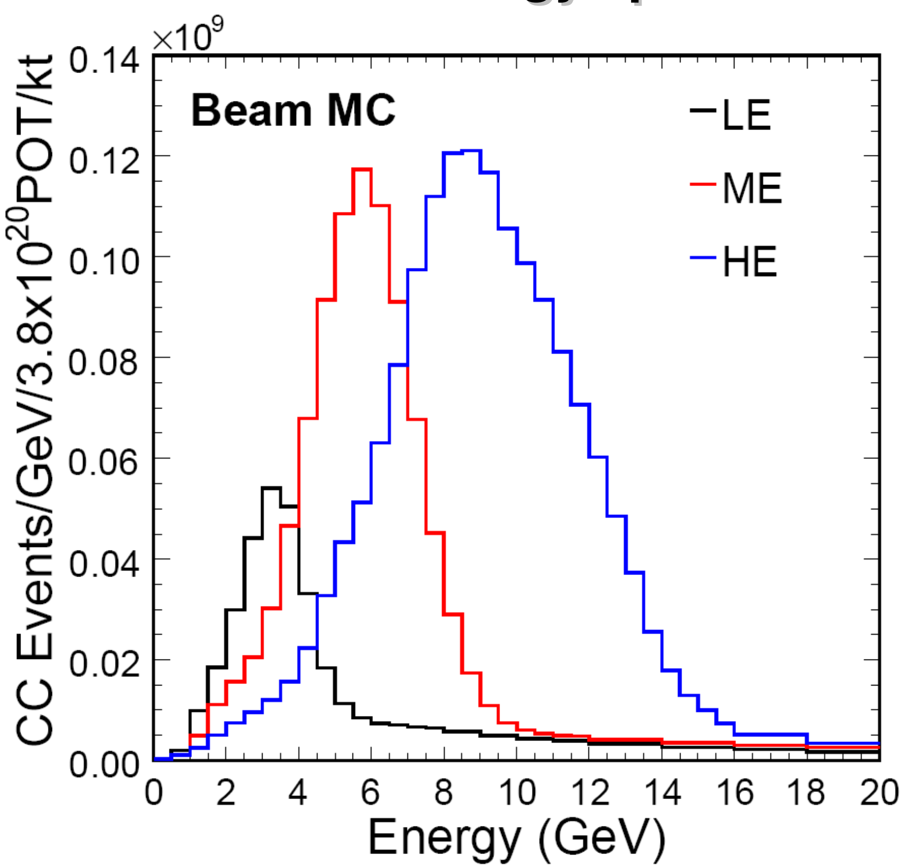
120 GeV protons delivered to carbon target

Magnetic **focusing horns** select positive or negative secondaries (π^+/π^- mostly)

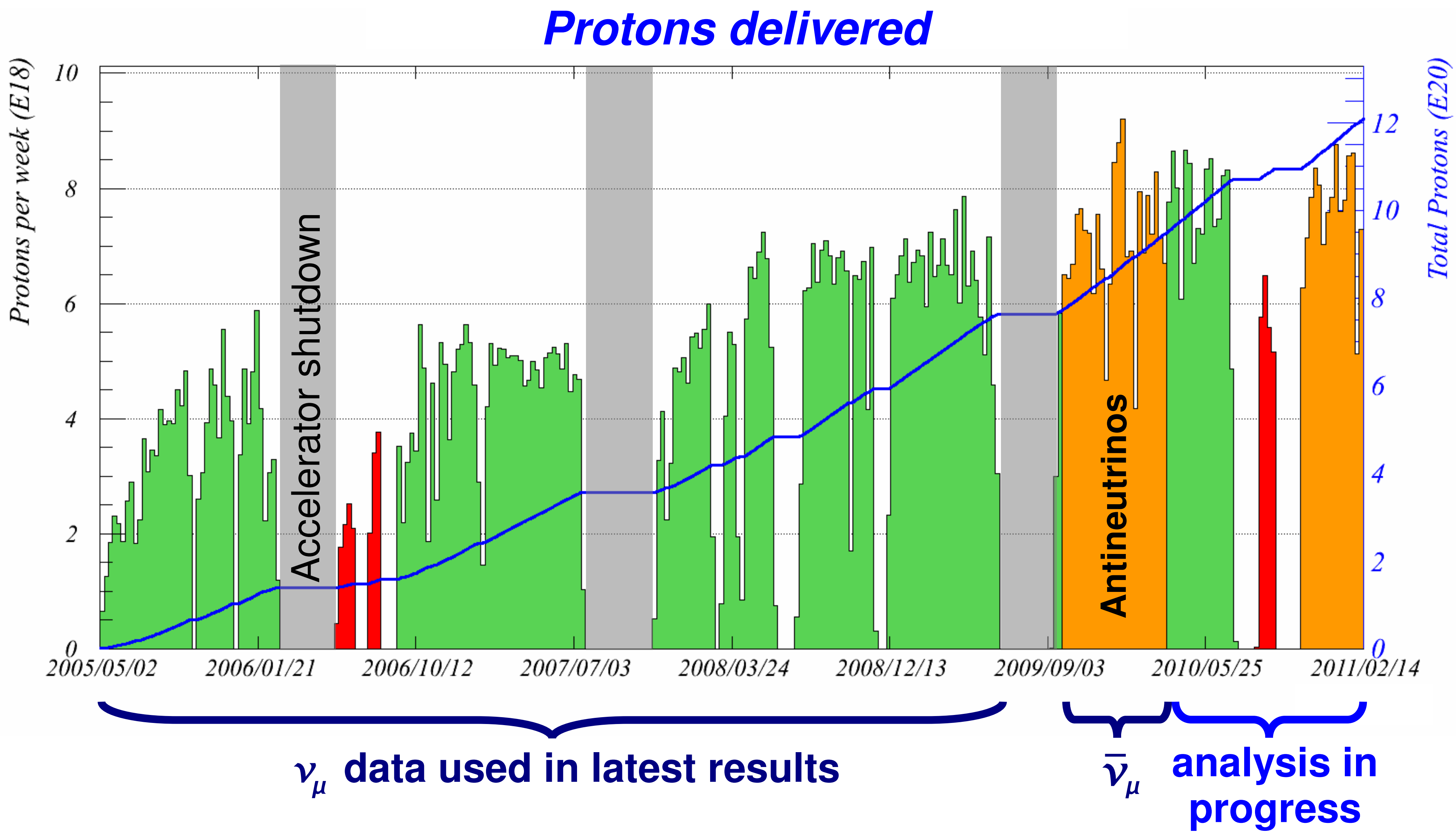


NuMI horn

Tunable energy spectrum

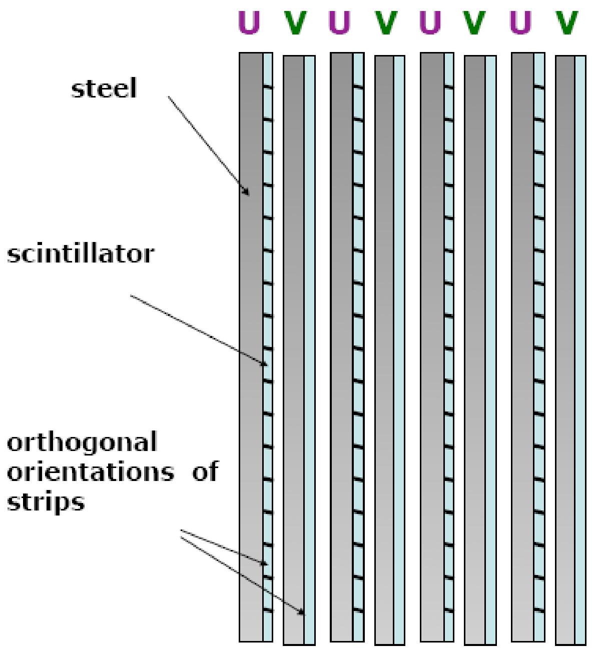


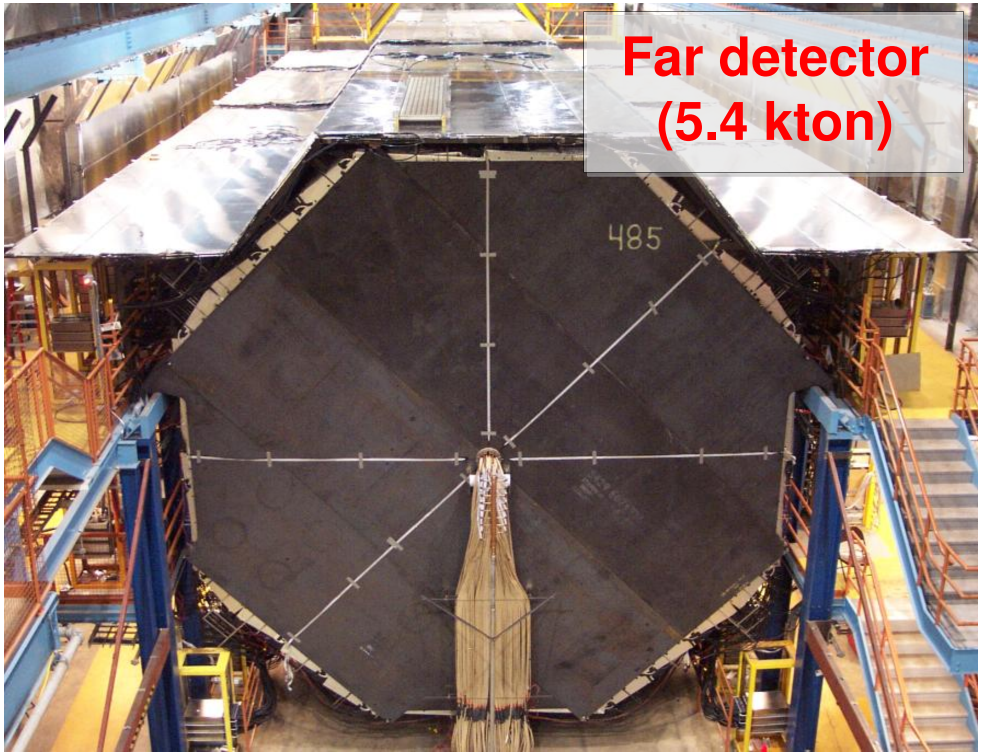
Neutrinos at the Main Injector (NuMI)



MINOS Detectors

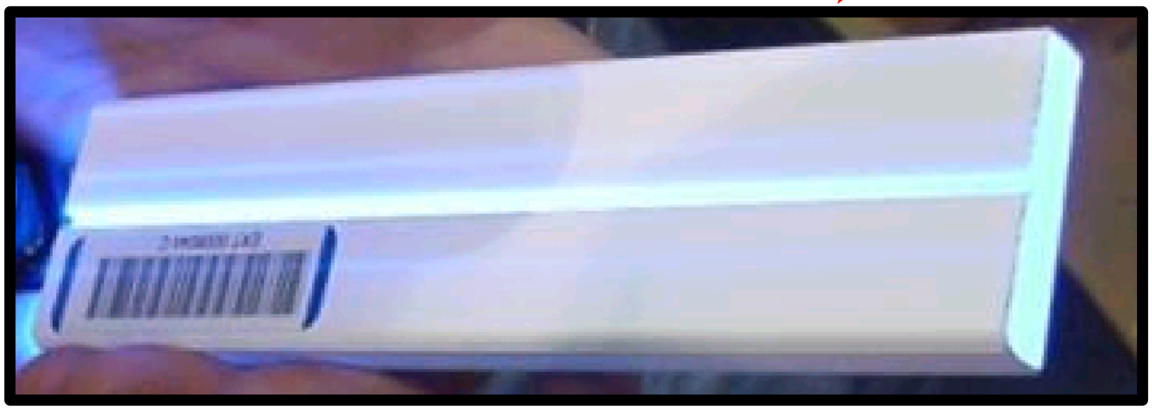
- **Near** and **far detectors:**
  Magnetized tracking calorimeters (~1.3 T field)
- Alternating layers of
  steel (1” thick plates)
  scintillator (1 cm thick, 4.1 cm wide strips)
- Scintillator layers oriented at ±45°



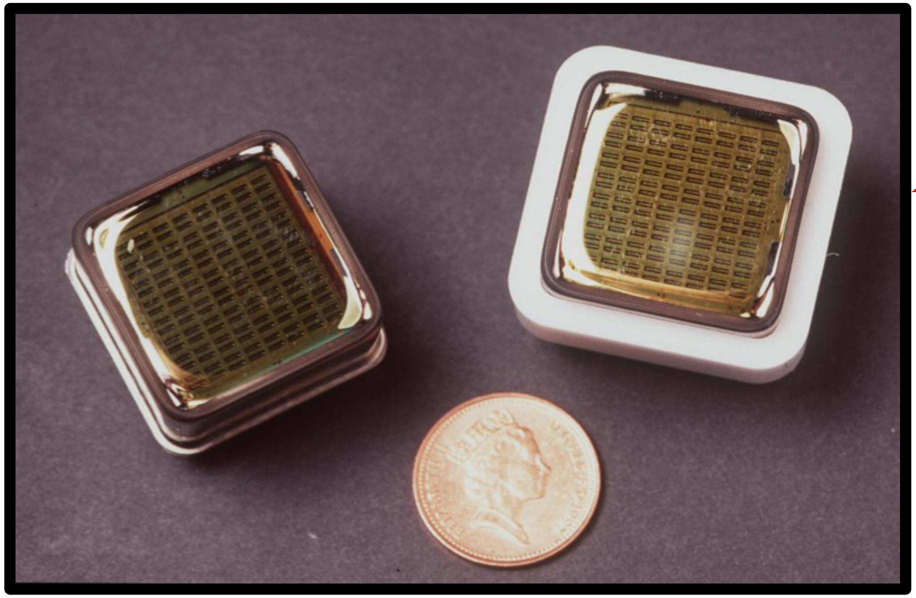


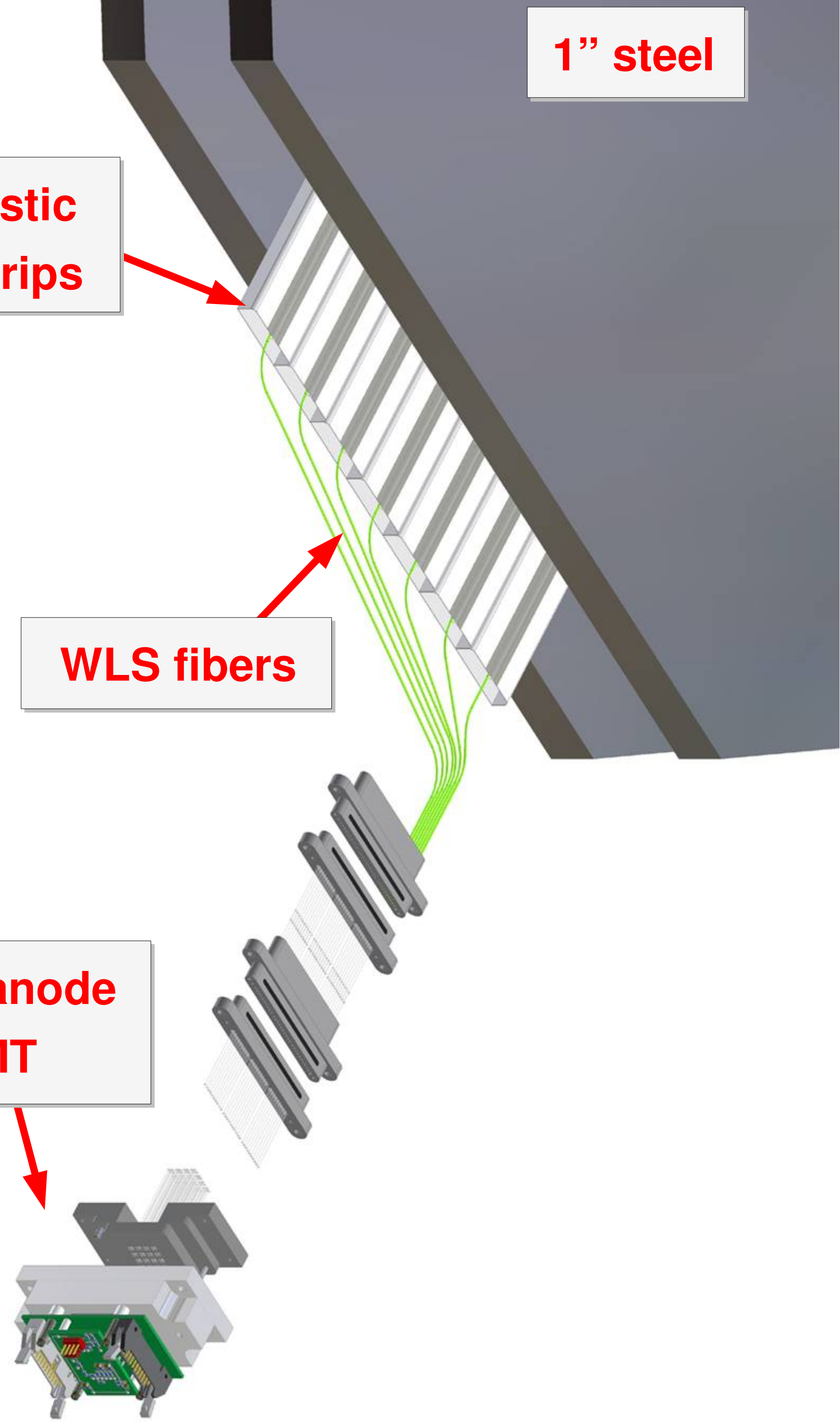
MINOS Detectors

Extruded plastic scintillator strips



Multi-anode PMT



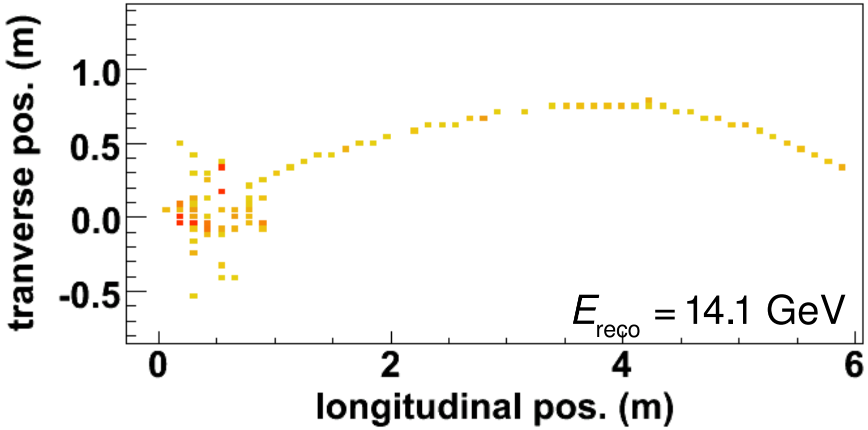


Neutrino events

ν_μ charged current

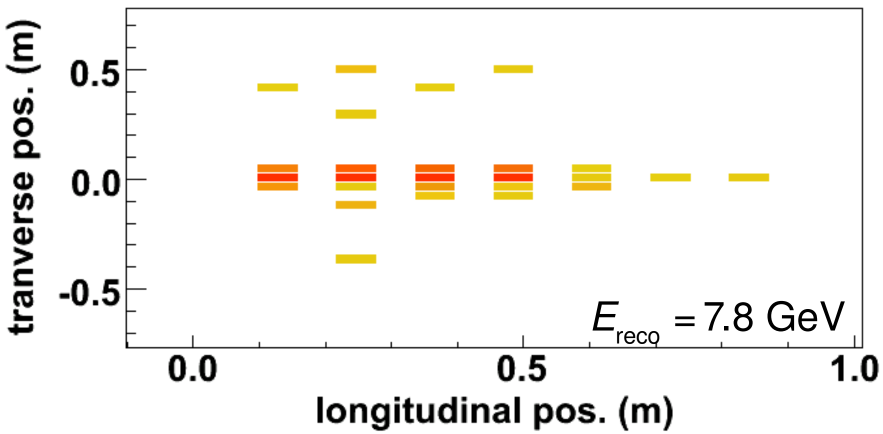
- Clear signature in MINOS: *long track*
- If μ track is very short, event can be mistaken for NC or ν_e CC

(Monte Carlo)



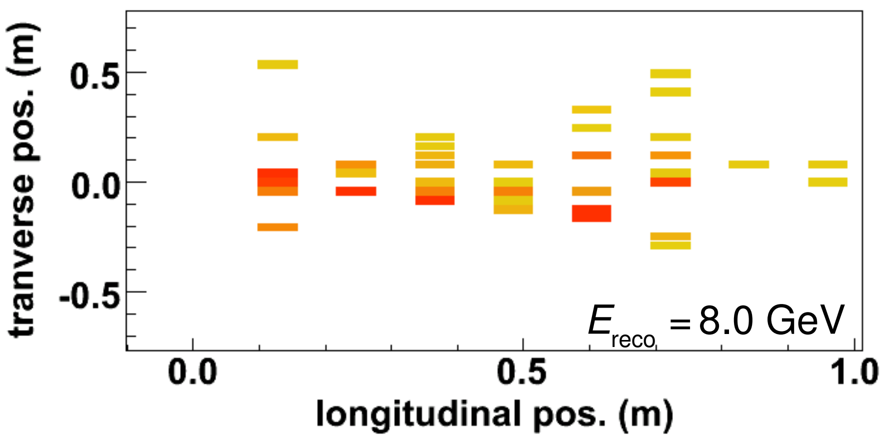
ν_e charged current

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



neutral current

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

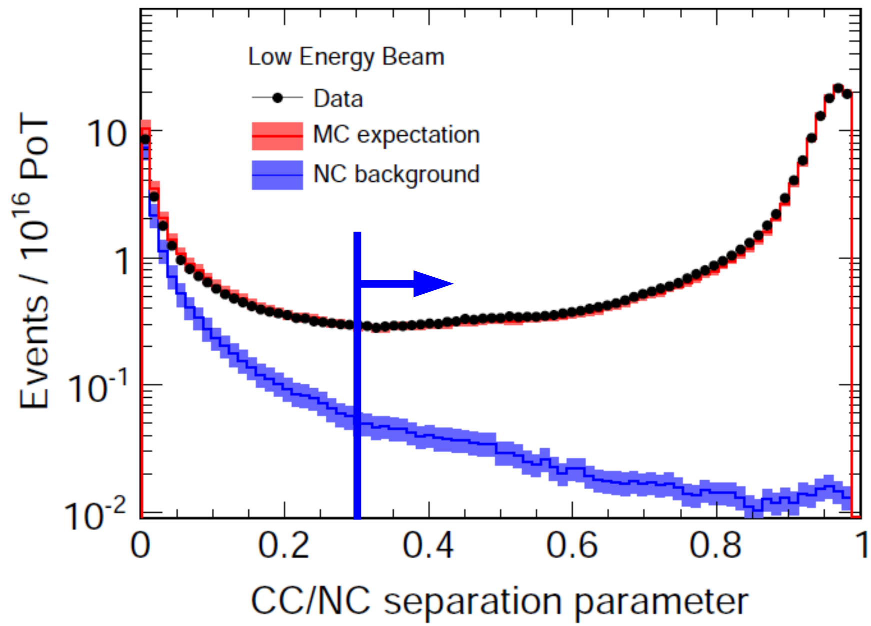


ν_μ disappearance ($\nu_\mu \rightarrow \nu_x$)

Muon neutrino disappearance

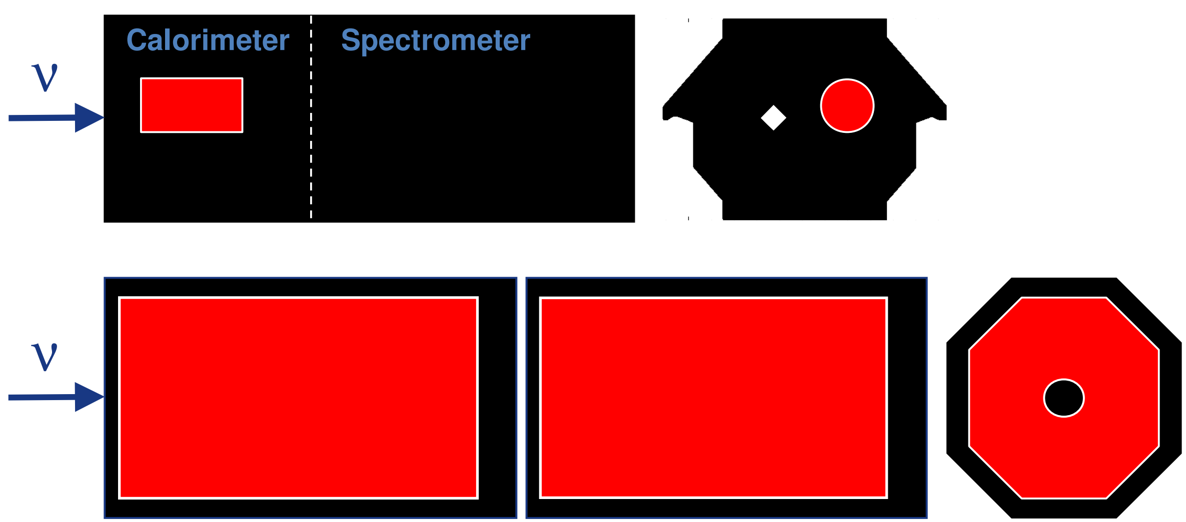
- Start by measuring ν_μ charged current rate in **near detector**
- ***First stage of selection:***
  - ▸ **Fiducial volume** (below)
  - ▸ Beam **timing**, **cosmic** removal
  - ▸ How "**track-like**" is the event? →
- ***New for 2010 analysis:***
  - ▸ Recover **short-track** events
    (second kNN discriminant and no muon charge cut)

kNN **selector**

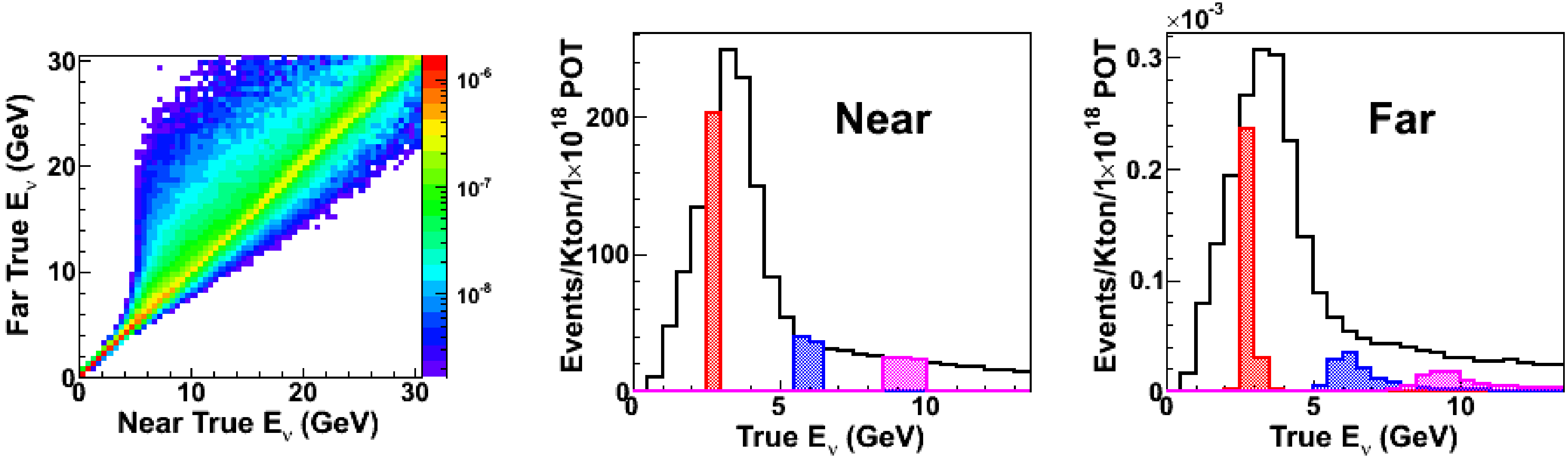


Near det.

Far det.

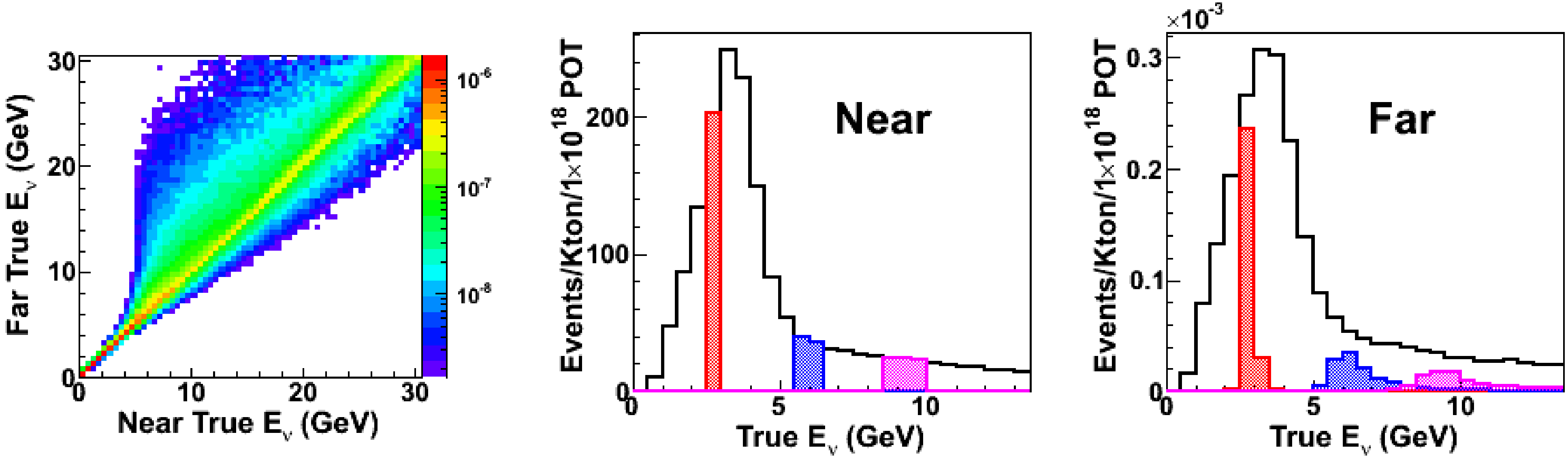


Fiducial regions (in red)



- 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)*

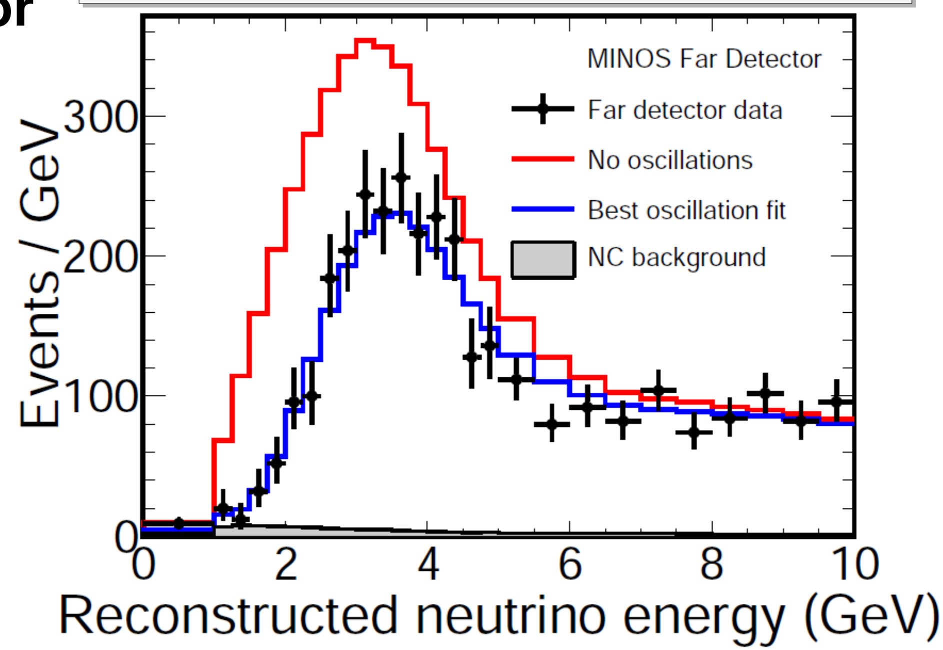


- Convert the measured **near detector energy spectrum** into a prediction for the **far detector**

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

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

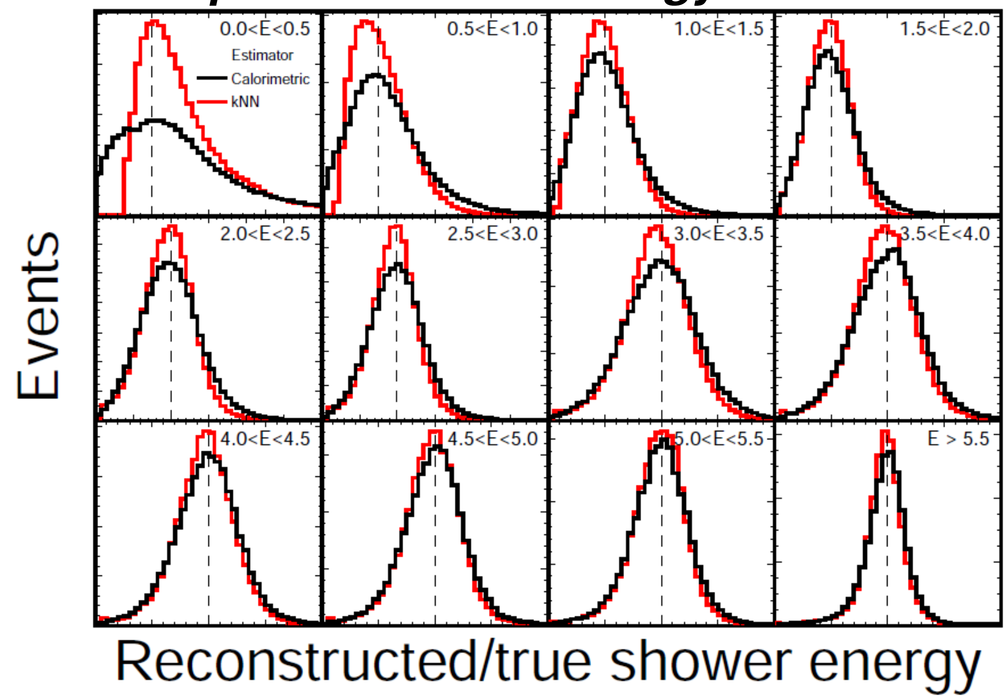
ν_μ disappearance at far detector



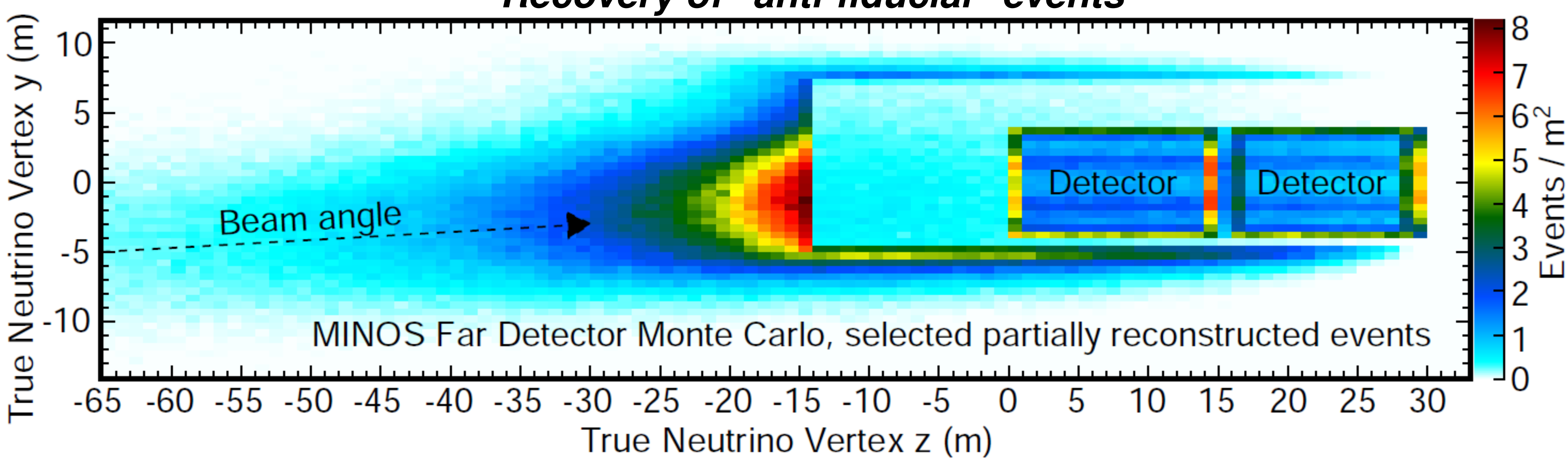
Also new in this result...

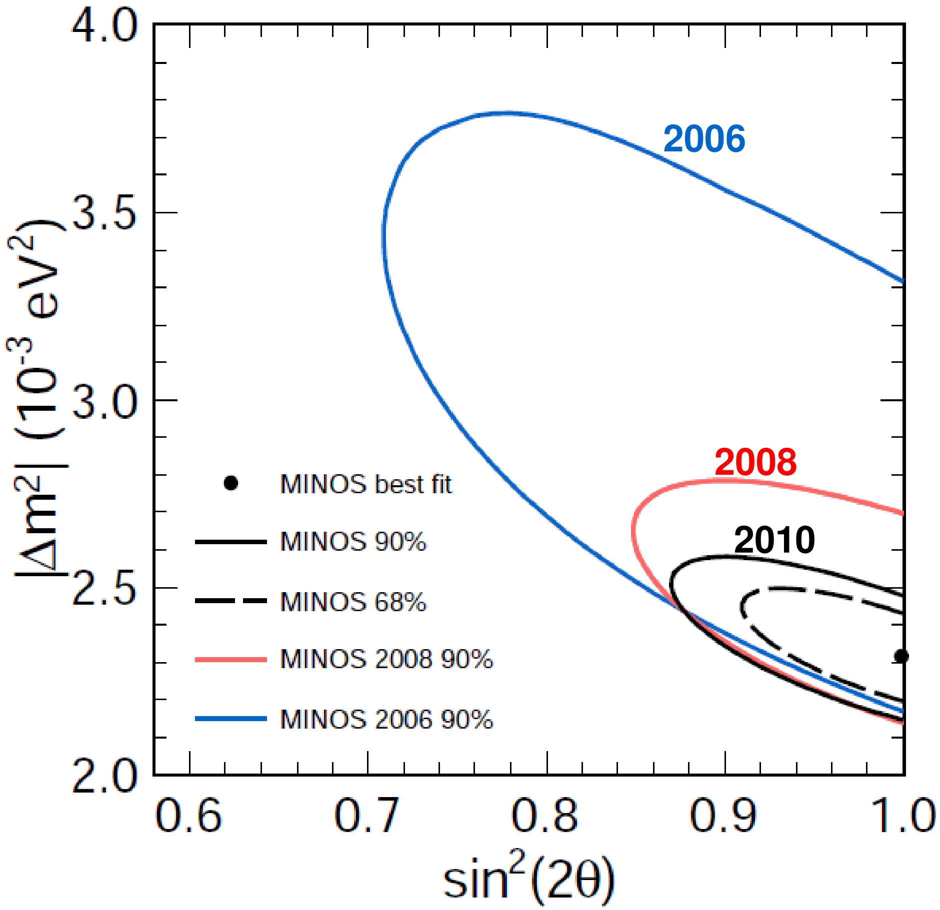
- More than **twice the data** over the 2008 result
- Updated **beamline simulation**
- Fitting in **resolution bins**
- Improved **shower energy estimator**
- Recovery of events starting **outside the detector**

Improved shower energy estimator



Recovery of "anti-fiducial" events





Oscillation interpretation:

- Parameter space shown at left.
- Most precise Δm^2_{atm} measurement:

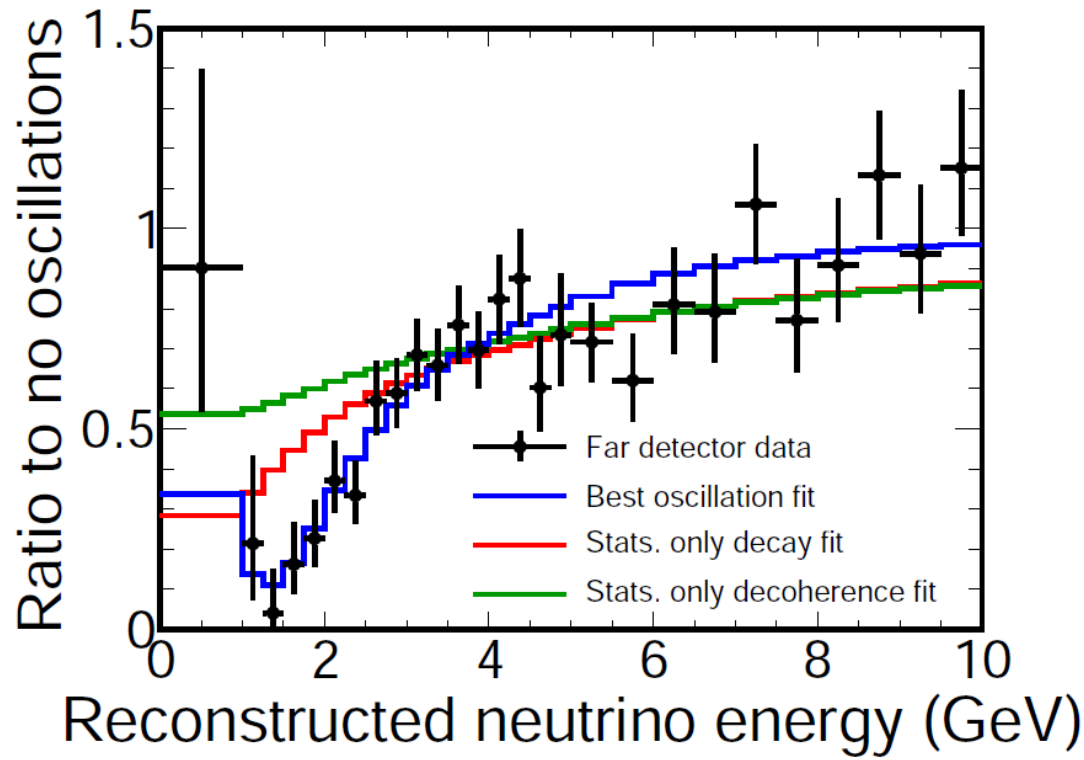
$$\Delta m^2_{\rm atm} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\ {\rm eV}^2$$

MINOS, PRL **106**, 181801 (2011)

Strongly disfavored alternative interpretations:

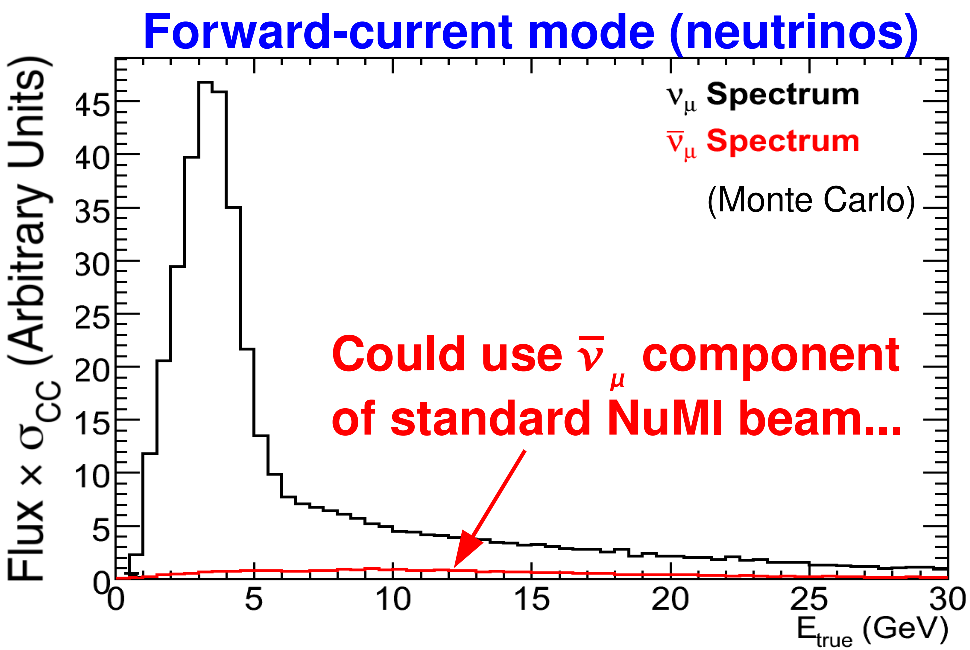
Neutrino decay: $>7\sigma$

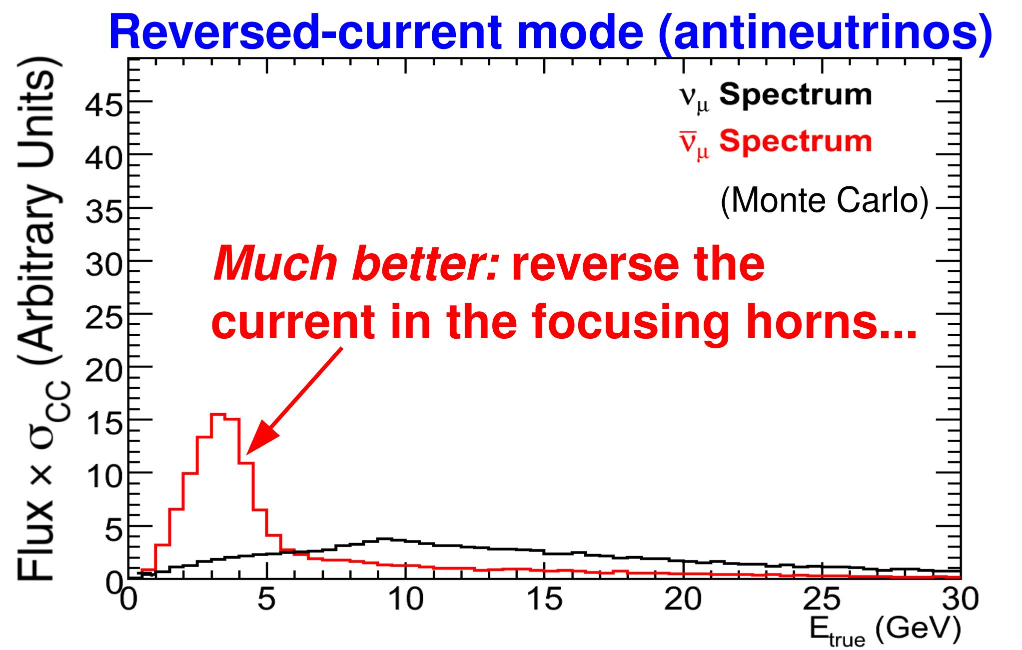
Decoherence: $>9\sigma$



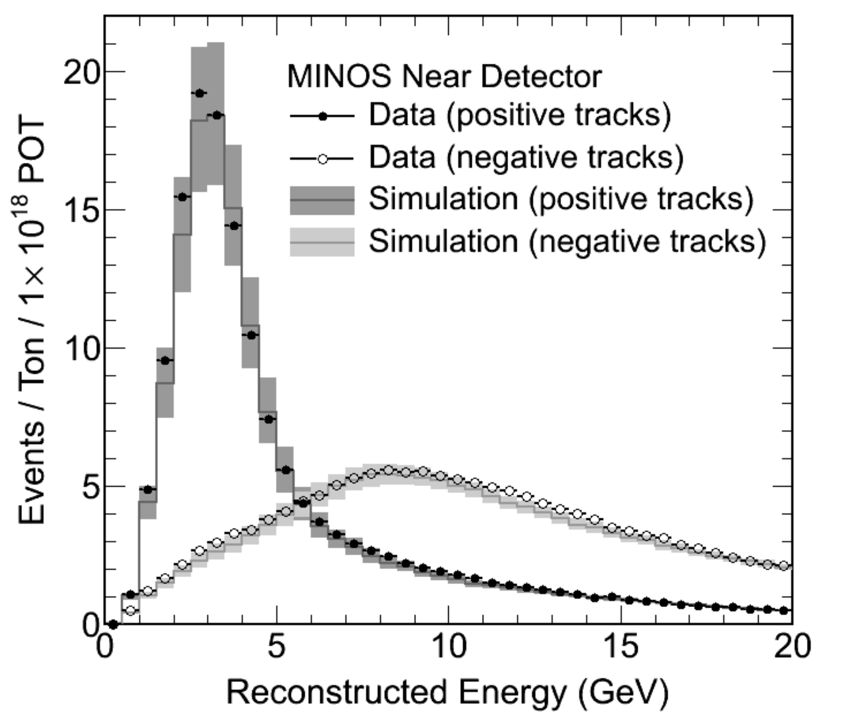
Same for $\bar{\nu}_\mu$?

Antineutrino running

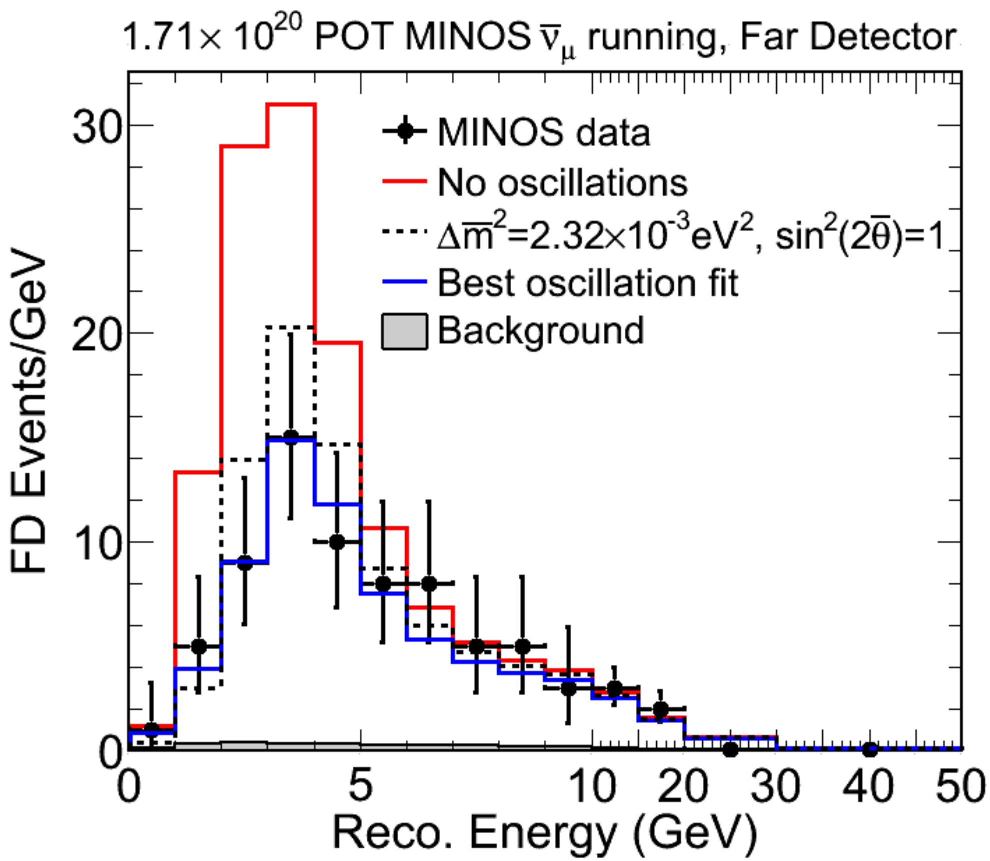


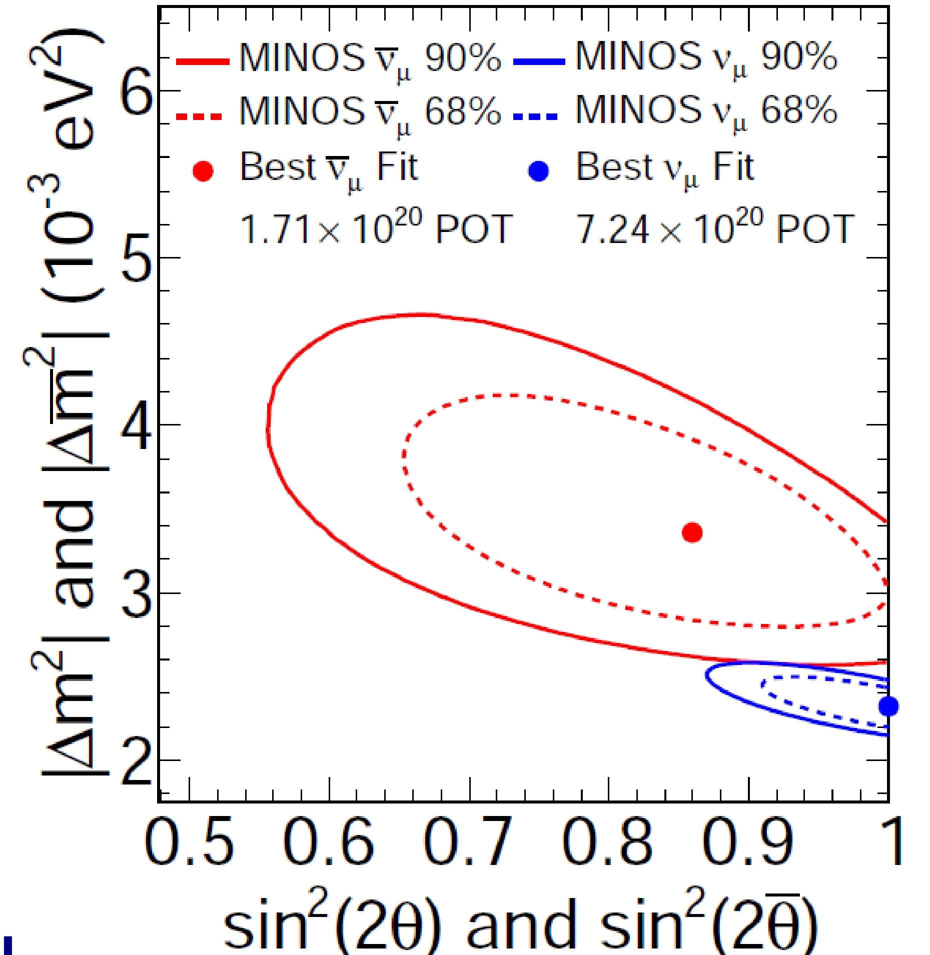


- Reversed horn current running
  → *predominantly **antineutrino flux***
- **Magnetic detectors** allow muon charge selection
- Good $\nu/\bar{\nu}$ separation; well-modeled →



$\overline{\nu}_\mu$ observed in the Far Detector





- $\bar{\nu}_\mu$ **disappearance** observed at **6.3σ C.L.**
- Well described by **flavor oscillations:**

stat. errors dominate

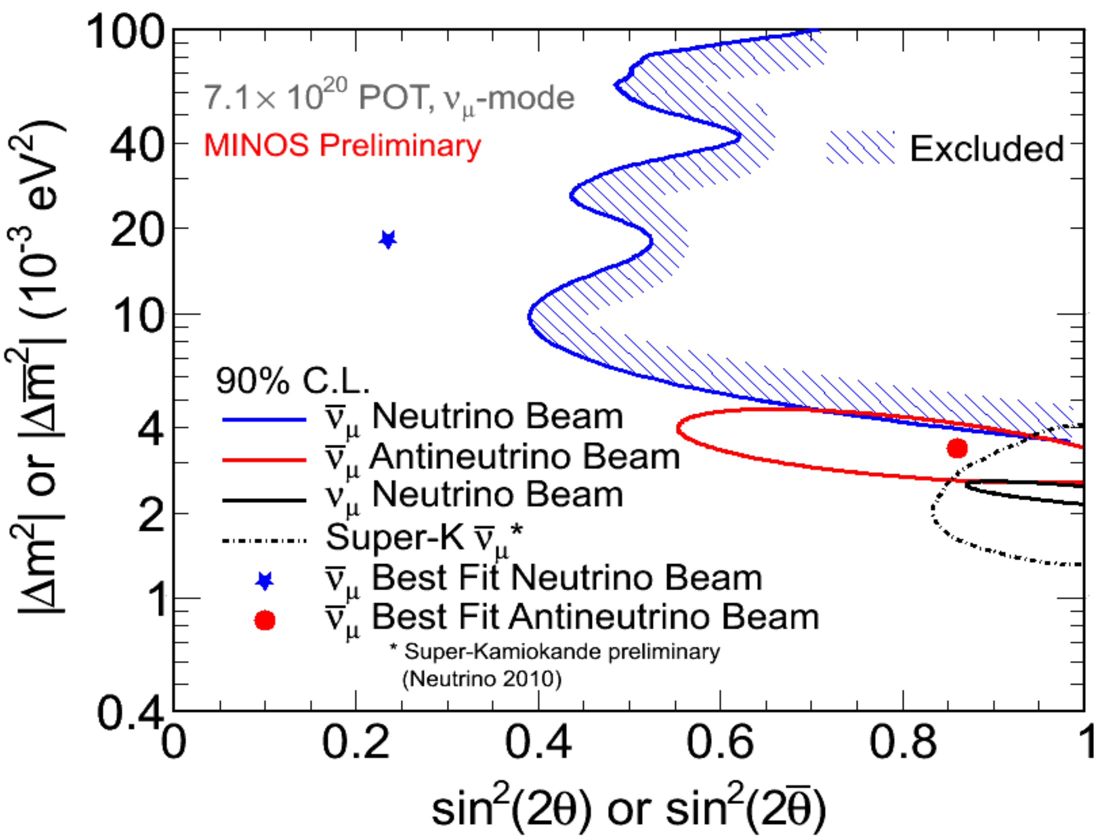
$$\Delta\overline{m}^2_{\rm atm} = (3.36^{+0.46}_{-0.40})\times 10^{-3}\ {\rm eV}^2$$
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}$$

$\nu/\bar{\nu}$ compatibility at only 2% C.L.

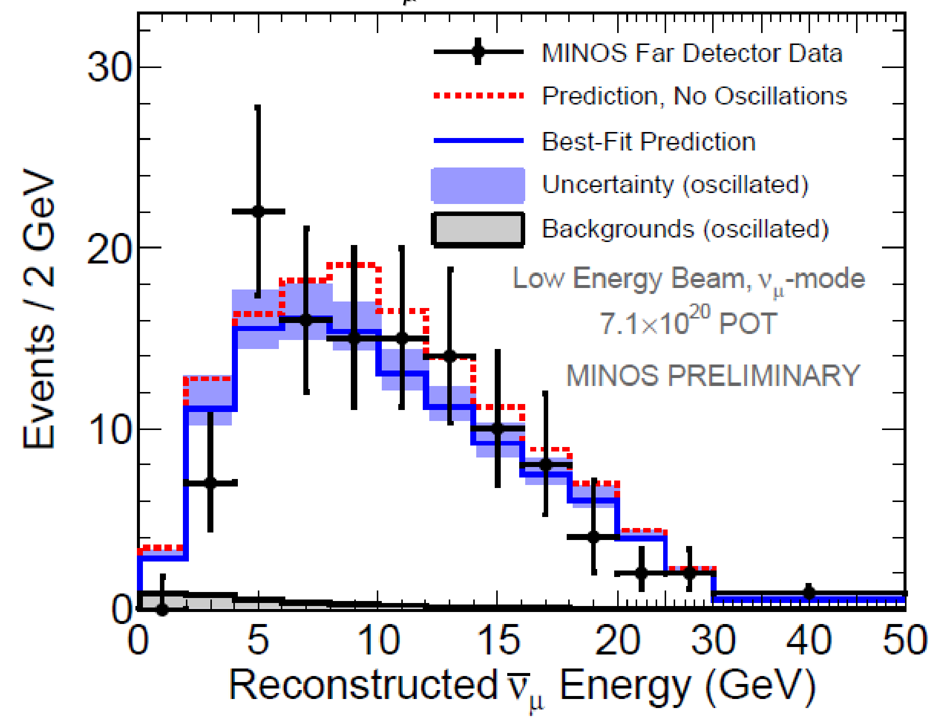
MINOS, arXiv:1104.0344 (2011)

$\bar{\nu}_\mu$ observed in the Far Detector (in ν-mode)

- Large exposure in **forward-current (neutrino) mode**, but with **higher-energy spectrum**
- Results **consistent** with reversed-current (antineutrino) mode measurement



FD $\bar{\nu}_\mu$ data (ν-mode running)



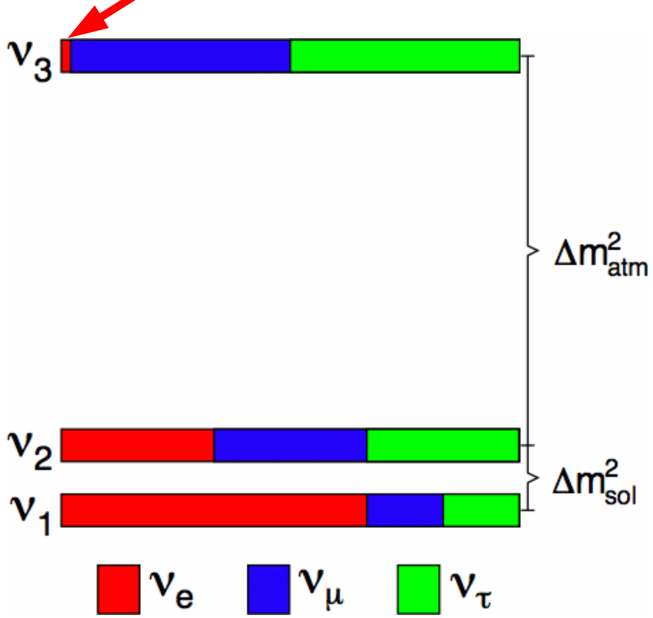
Reversed-mode data sample now nearly doubled, from **1.7×10^{20} p.o.t.** to **3.0×10^{20} p.o.t.**

Updated antineutrino results this summer.

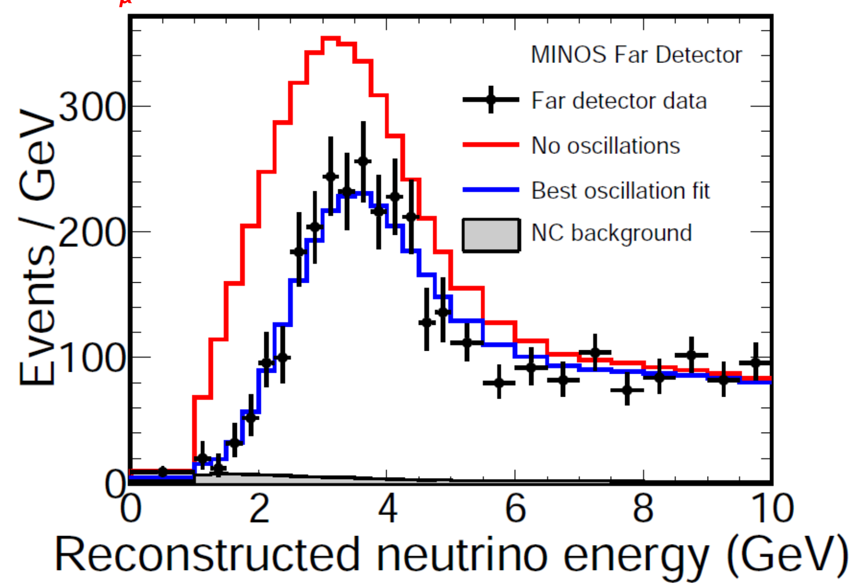
What do the “lost” ν_μ become?

In the standard picture...

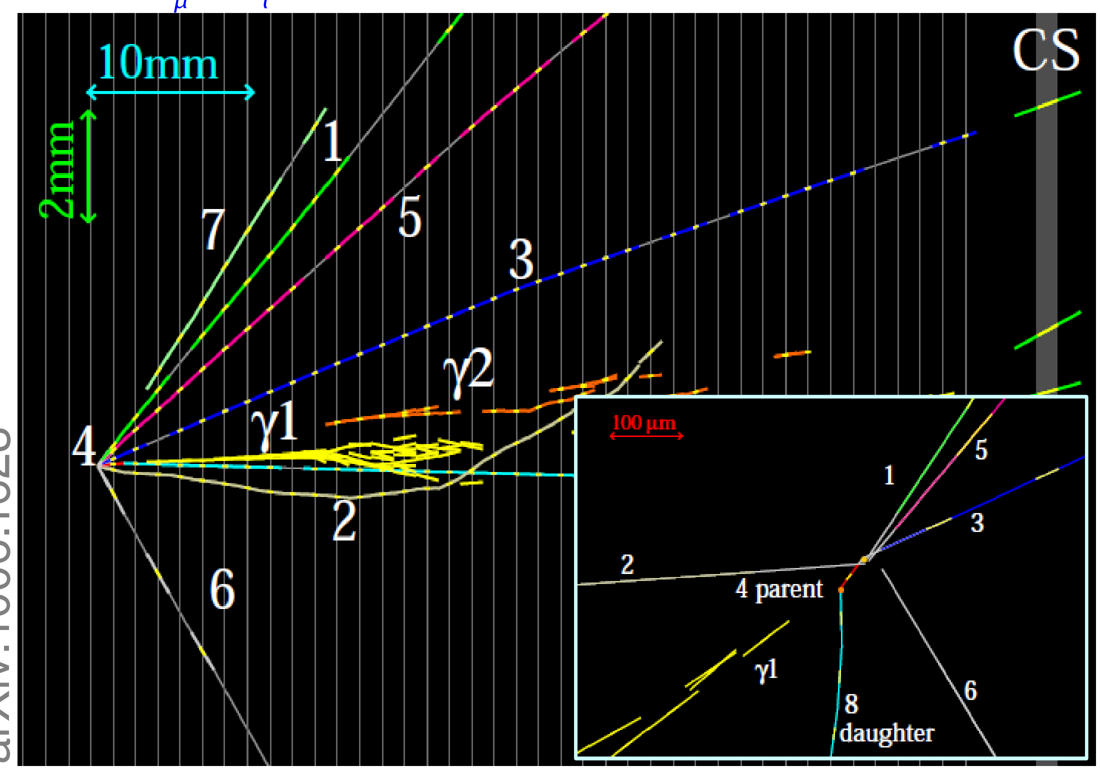
- Barring new physics, the original muon neutrinos have become superpositions of ν_e, ν_μ, ν_τ
- The proportion of ν_e is governed by the **mixing angle θ_{13}**, known to be small



ν_μ disappearance at the far detector



$\nu_\mu \rightarrow \nu_\tau$ candidate, OPERA collaboration



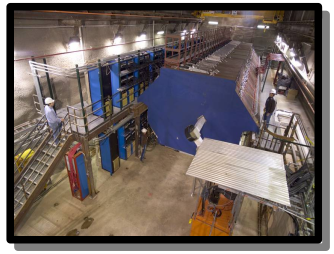
arXiv:1006.1623

98.7% ν_μ

1.3% ν_e

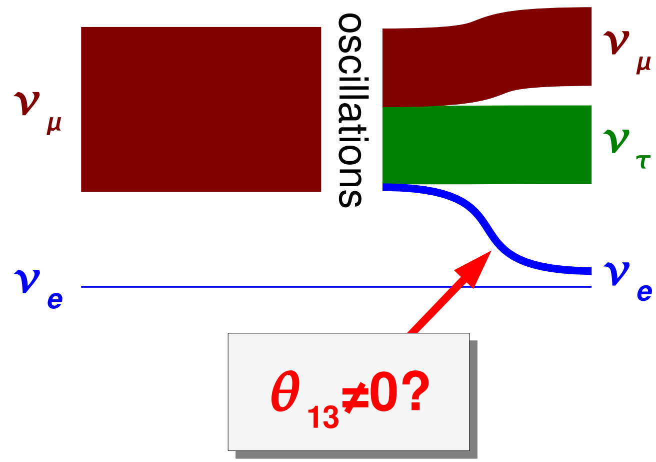
(and $\overline{\nu}$)

near detector

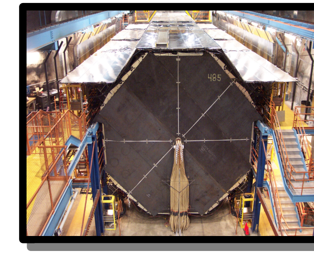


millions of ν events

→ *travel 735 km* →



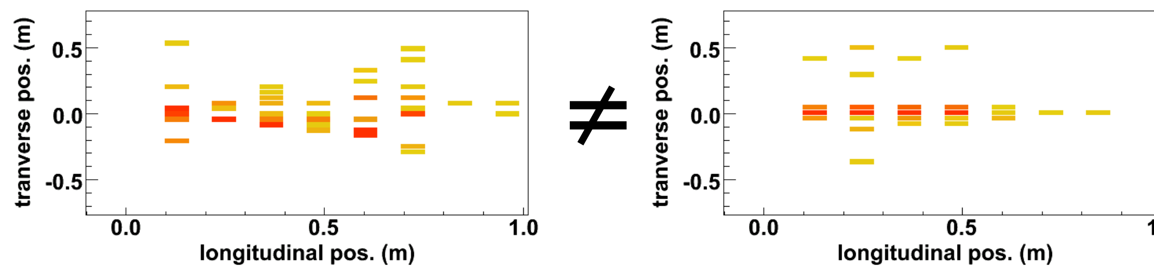
far detector



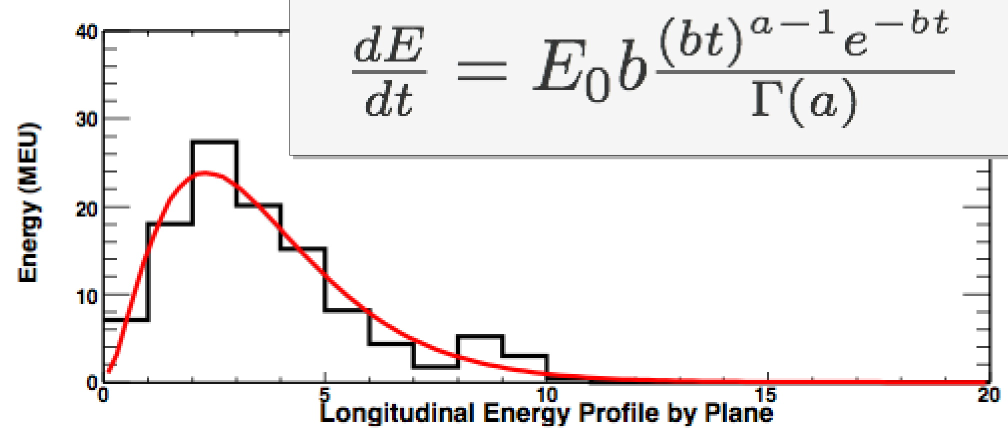
thousands of ν events

ν_e appearance:

- Being with **shower-like** (non-track-like) events
- Classify shower topology with an **ANN** to select ν_e events
- 11 variables derived from longitudinal and transverse **energy deposition profiles**
- *Examples:* longitudinal shower fit parameters; shower width metrics



Example EM shower profile



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

ν_e appearance result (2010)

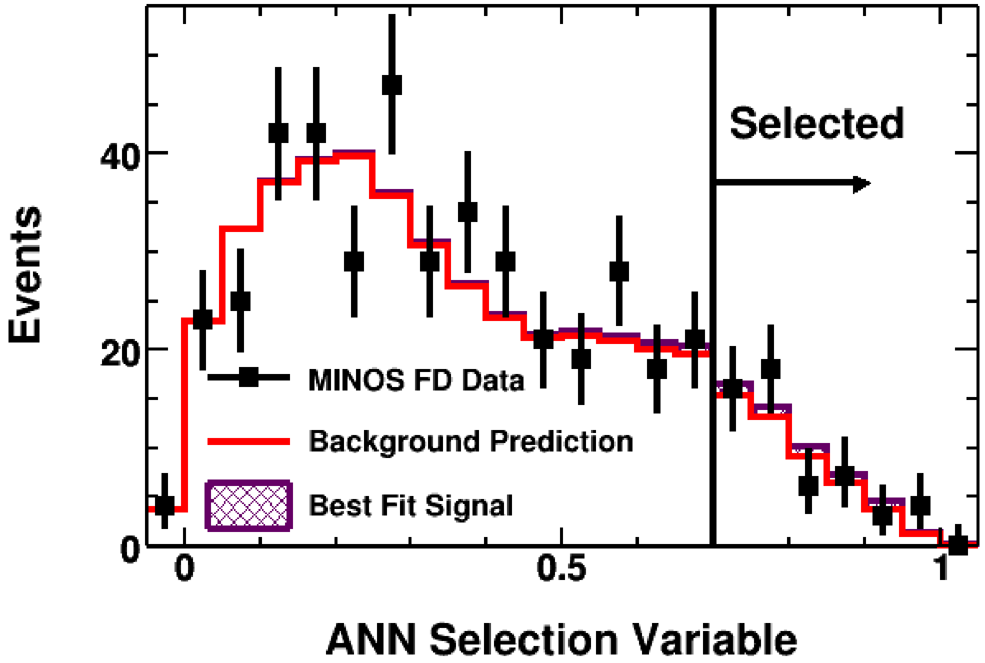
With 7×10^{20} protons-on-target

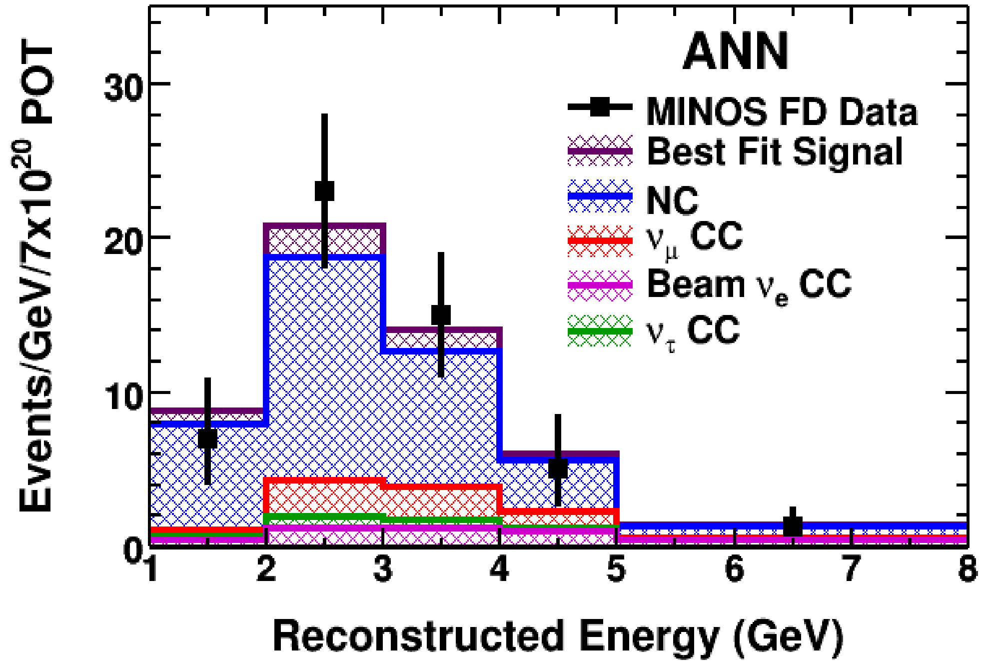
ν_e charged current candidate events:

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

observed: **54**

(0.7σ excess)

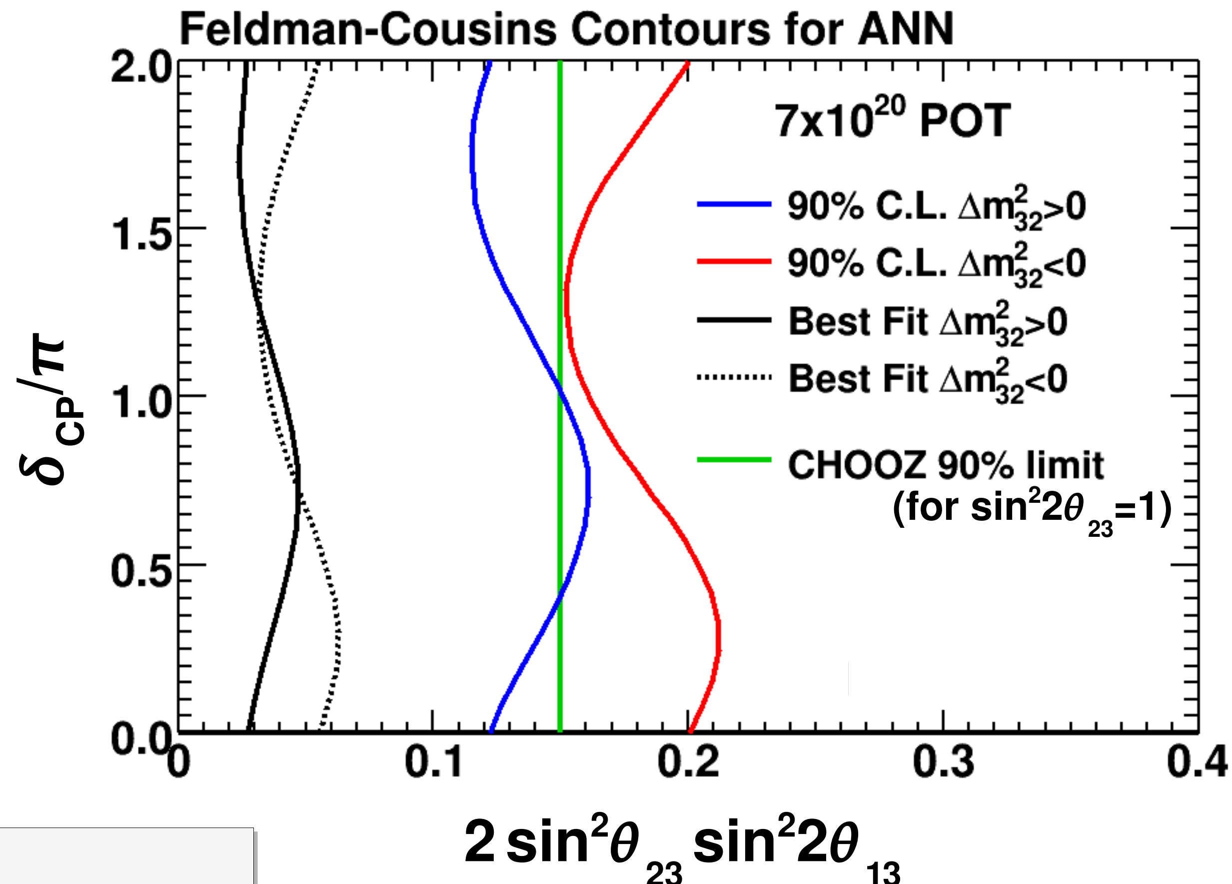




Oscillation interpretation of the data (2010)

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

90% C.L. allowed ranges →



MINOS, PRD **82**, 051102 (2010)

Representative 90% C.L. limits:

→ *put* $\delta_{CP}=0$, $\theta_{23}=\pi/4$

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

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

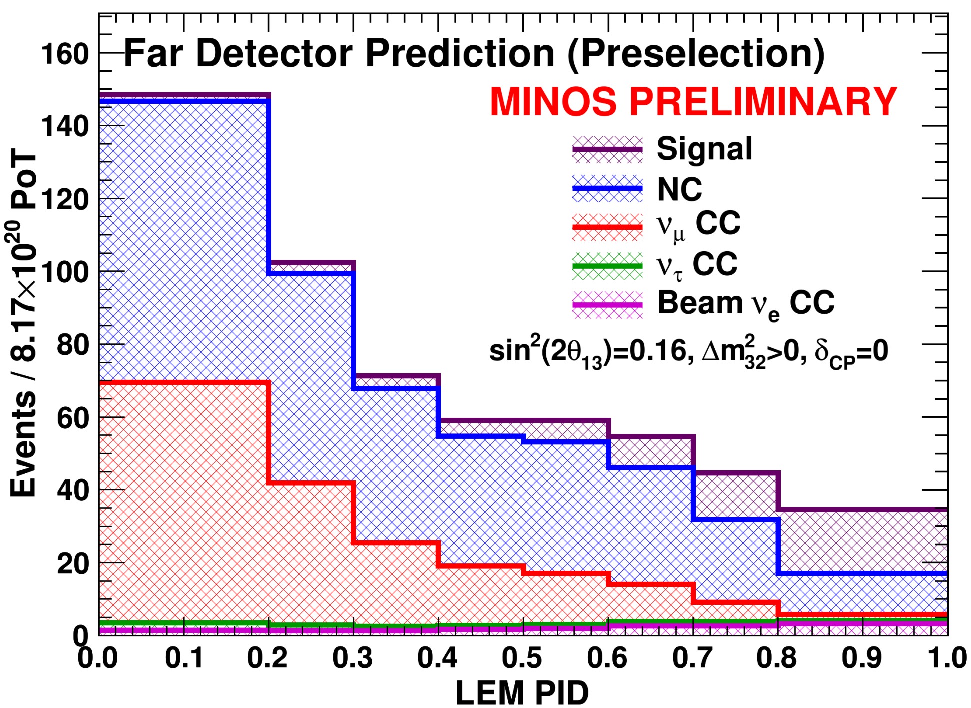
(other oscillation parameters' uncertainties taken into account)

New for 2011 analysis

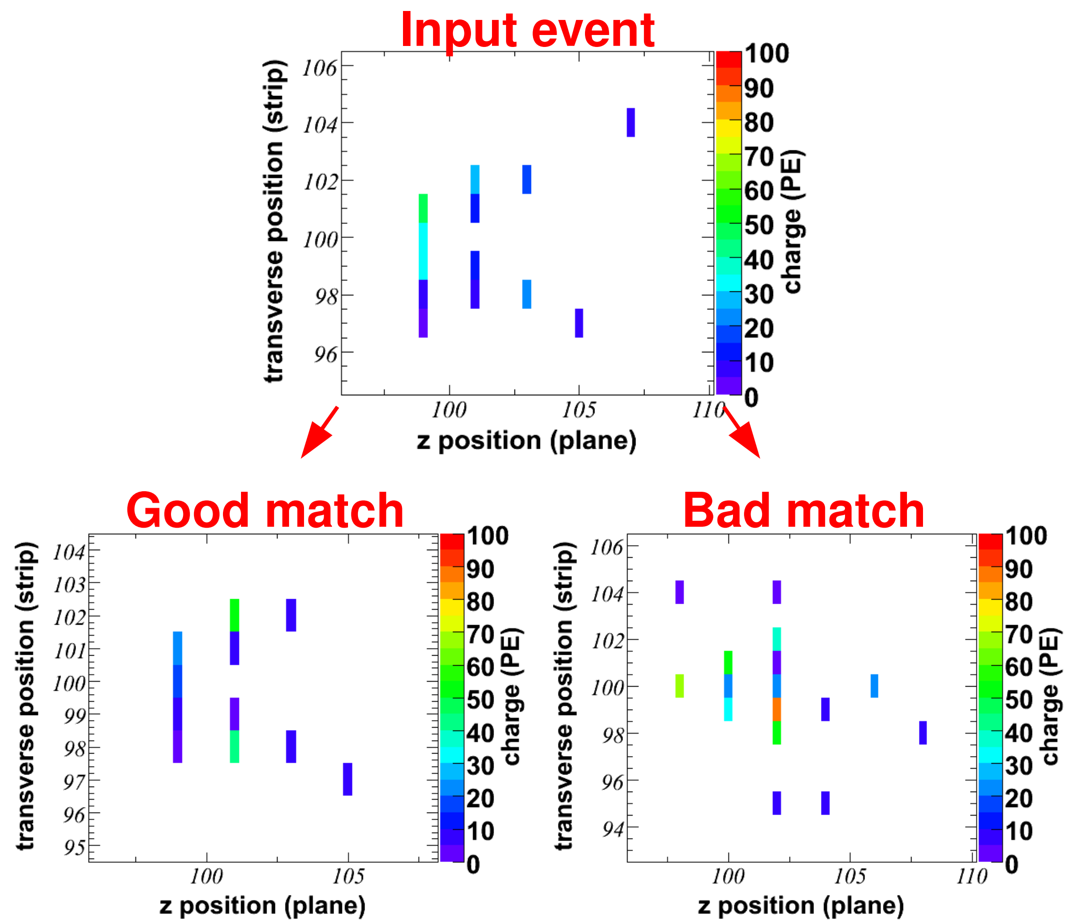
- **A bit more data:**
  7.0×10^{20} p.o.t. $\rightarrow$ 8.2×10^{20} p.o.t.

- A **new selection** method ("*Library Event Matching*")

  Compares input event to large library of simulated events, finding those that are the most similar



<u>Library Event Matching (LEM) Example</u>

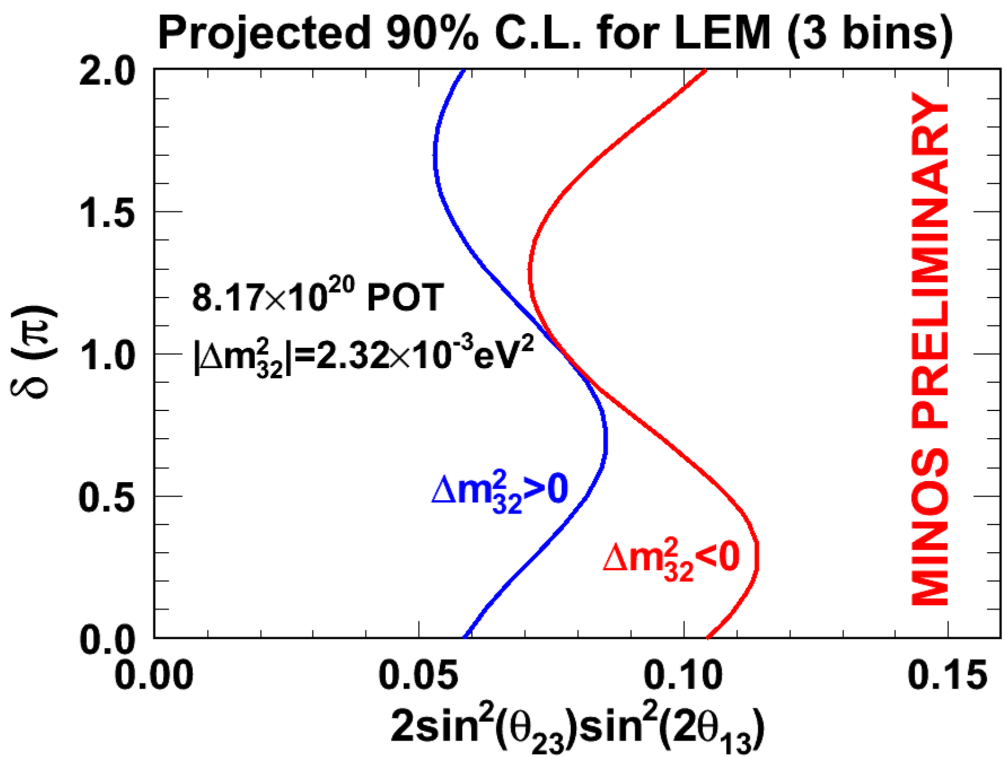


- Move from just counting events to **fitting** (*e.g.*, LEM PID distribution)

- *At left:* predicted **FD distribution** for the **LEM** discriminant

New for 2011 analysis

- **30% improvement** in $\sin^2(2\theta_{13})$ sensitivity over 2010 result
- 24% improvement from the **analysis upgrades** alone
  (roughly half from new selector, half from fitting)
- ***Below:*** **preliminary 90% C.L. sensitivity** for 8.17×10^{20} p.o.t. analysis

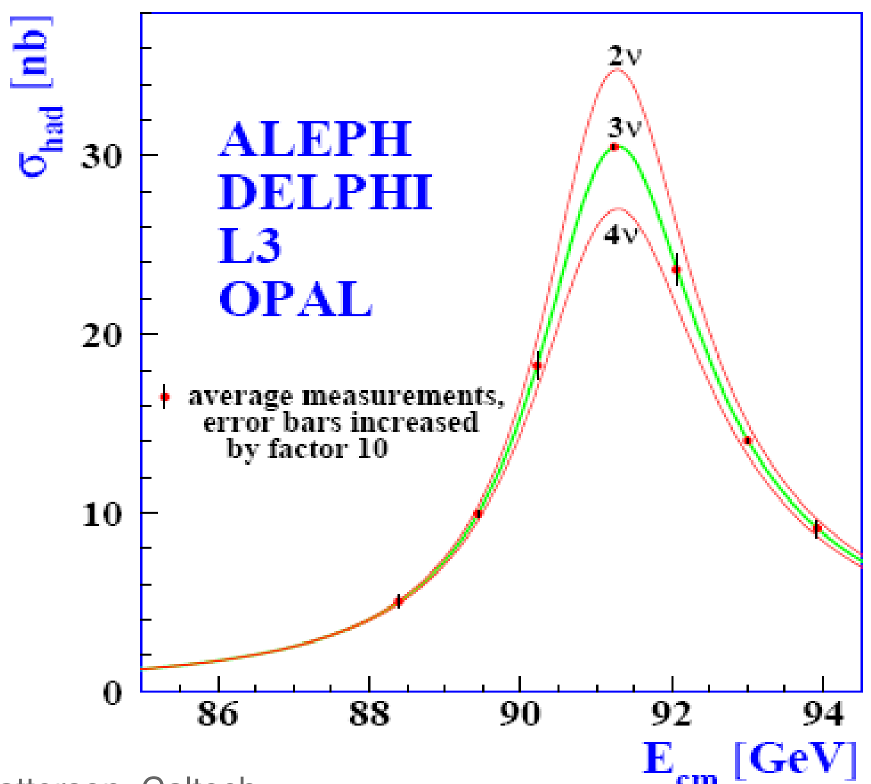


Look for a new θ_{13} result this summer.

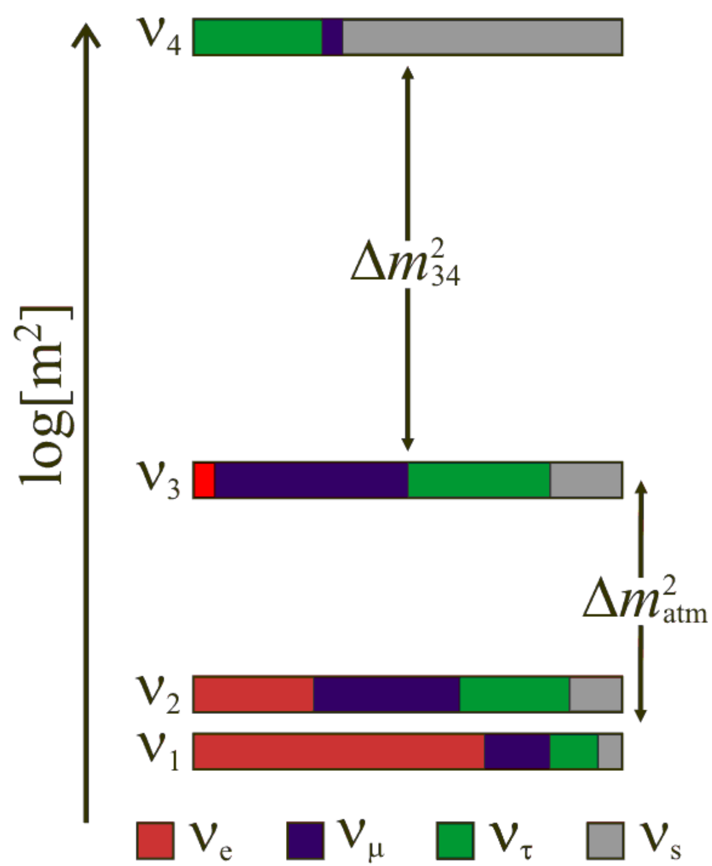
Sterile neutrinos? ($\nu_\mu \to \nu_s$)

Sterile neutrinos? ($\nu_\mu \rightarrow \nu_s$)

- If other light neutrinos exist, they must be **sterile** *(LEP Z^0 measurements)*
- Sterile & active neutrinos could still mix:
  Sterile mixing would reduce the rate of neutral current events at the far detector

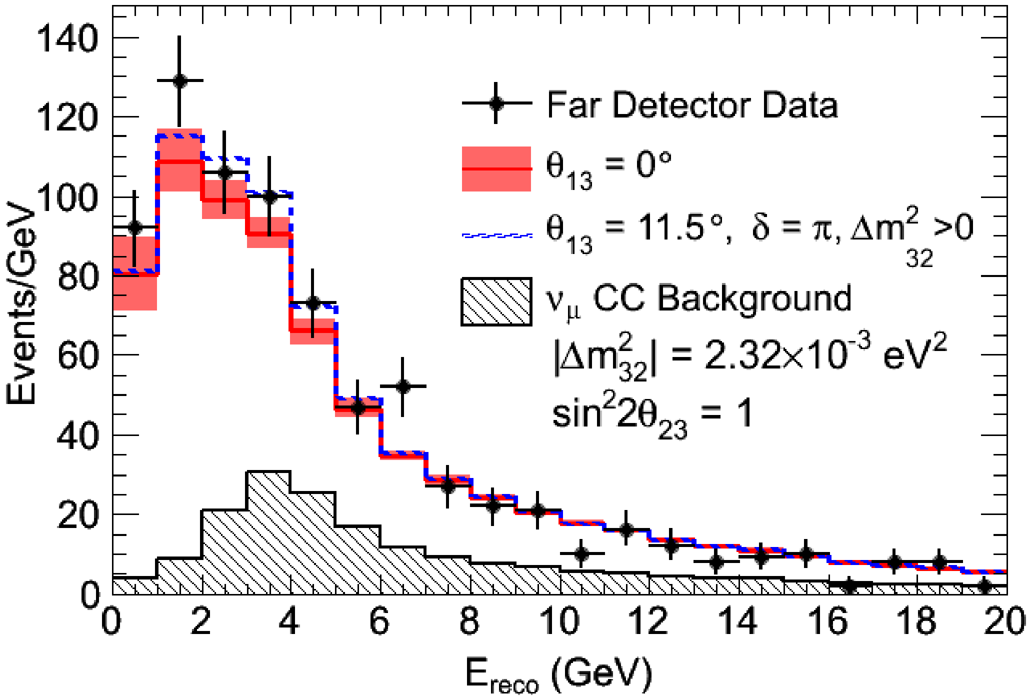


Example masses/mixings with a single sterile state



MINOS neutral current sample

MINOS, arXiv:1104.3922 (2011)



- Select events *without* muon track *(i.e., neutral-current-like)*

  Observed far det. spectrum →

- Possibility of θ_{13}-driven ν_e appearance adds uncertainty

- Data consistent with **no sterile mixing**

No evidence of deficit →

Can convert into limits on model parameters, or summarize with:

$$f_s = \frac{P(\nu_\mu \to \nu_s)}{P(\nu_\mu \to \nu_{e,\tau,s})}$$

$$< 0.22 \ (90\% \text{ C.L.})$$

if no ν_e appearance

$$R = \frac{\text{(observed)} - \text{(expected CC bg)}}{\text{expected NC}}$$

0-120 GeV:

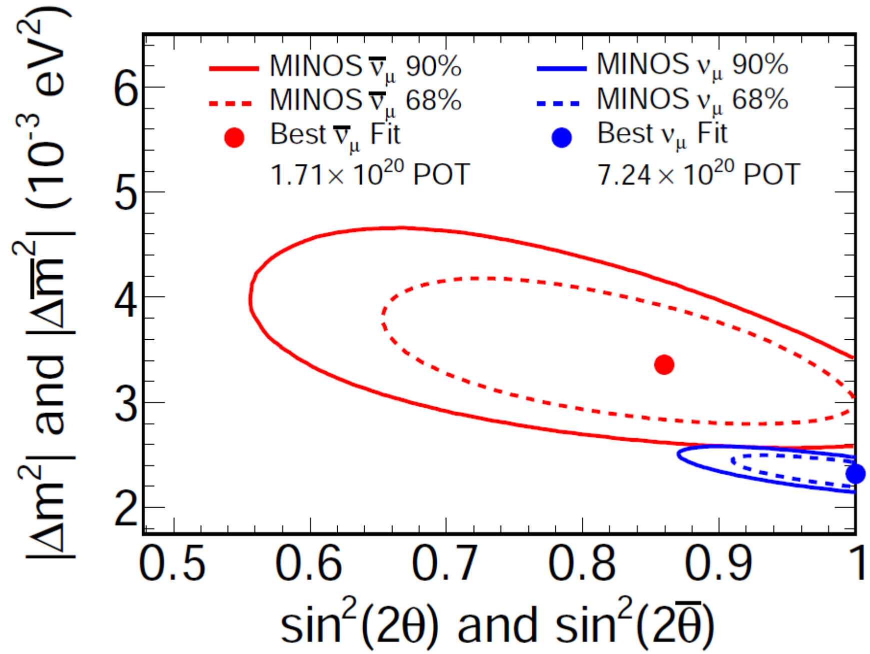
$$\mathbf{R = 1.09 \pm 0.06_{stat} \pm 0.05_{syst} - 0.08_{\nu_e}}$$

0-3 GeV:

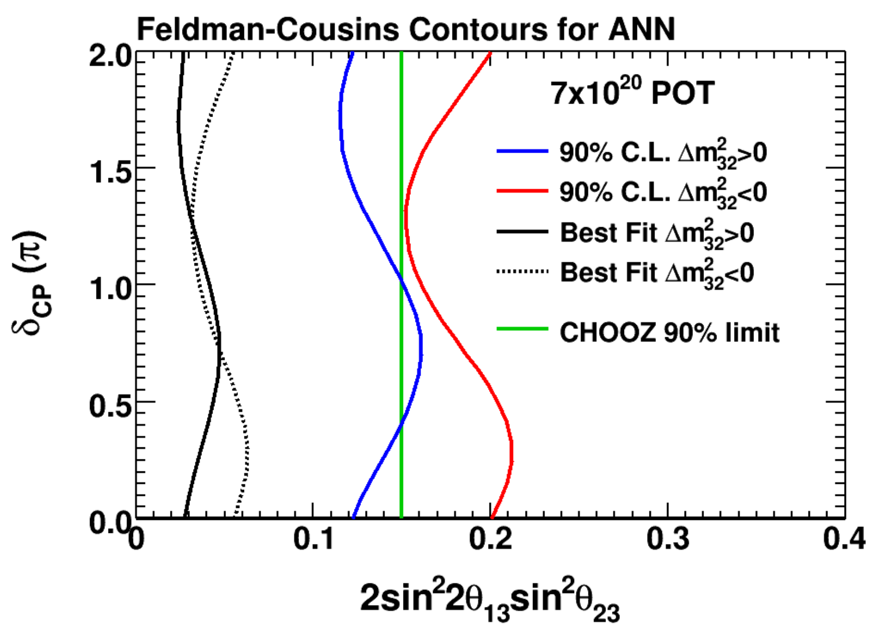
$$\mathbf{R = 1.16 \pm 0.07_{stat} \pm 0.08_{syst} - 0.08_{\nu_e}}$$

MINOS Summary

- **New ν_μ disappearance result**
  - ➡ *precision mass-splitting measurement:*
    $$\Delta m^2_{\rm atm} = (2.32^{+0.12}_{-0.08})\times 10^{-3}\ {\rm eV}^2$$



- **High-purity $\bar{\nu}_\mu$ measurement**
  - ➡ *some tension (2% C.L. agreement w/ ν_μ)*
  - ➡ *updated result this summer*
- **New $\sin^2(\theta_{13})$ limits**
  - ➡ *improved sensitivity this summer*



- **No evidence for sterile mixing:**
  - ➡ $f_s < 0.22$ (90% C.L.; θ_{13}=0)
- ***Did not cover...***
  - physics with atmo. neutrinos, cosmic rays
  - neutrino/antineutrino cross sections
  - other BSM physics searches
- **MINOS+ proposed** to collect large sample of 4–10 GeV ν and anti-ν interactions parasitically during NOνA running

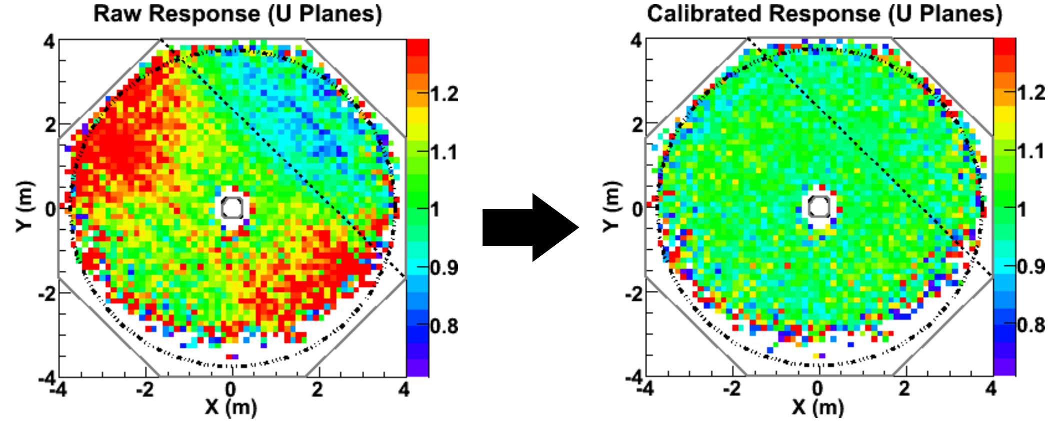
Extra slides

Calibration

Cosmic ray muons:

measure & remove **spatial variations**

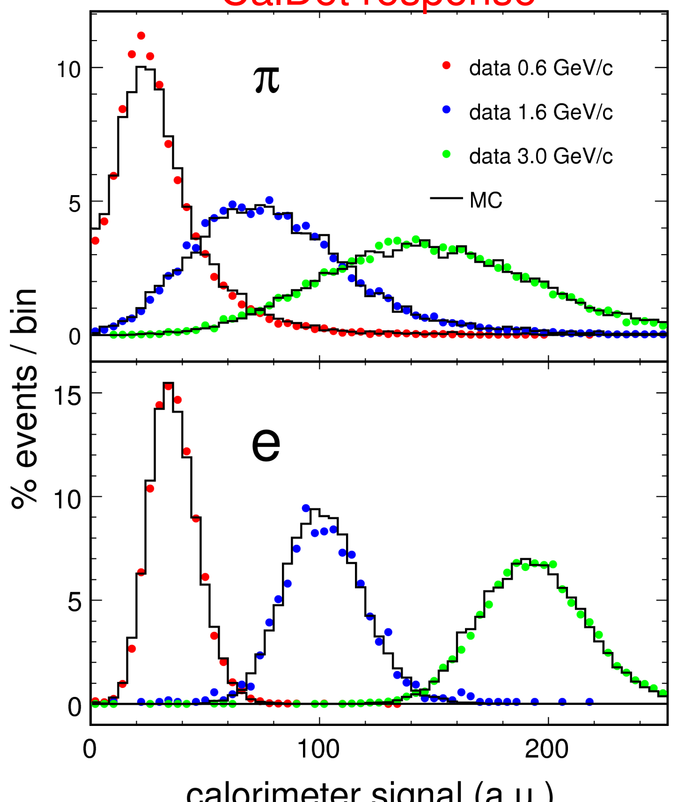
(channel differences, attenuation)



MINOS Calibration Detector (CalDet): *E* scale

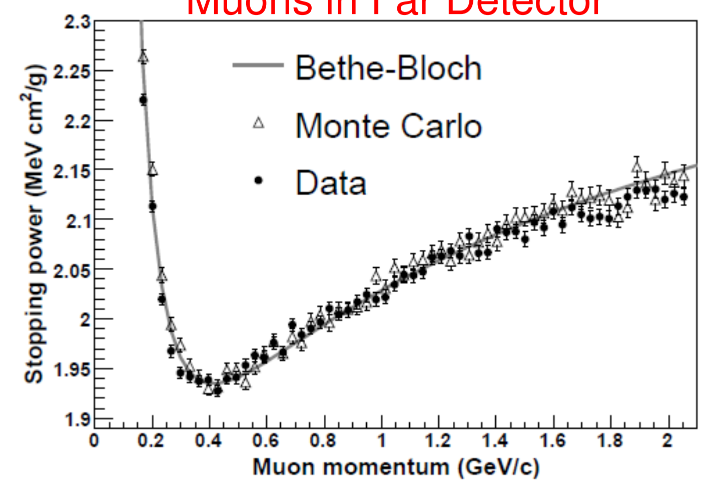
- Exposed to **0.2–10 GeV** *p*, *e*, μ, π at CERN
- 60 planes, 1 m x 1 m

CalDet response



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

Muons in Far Detector

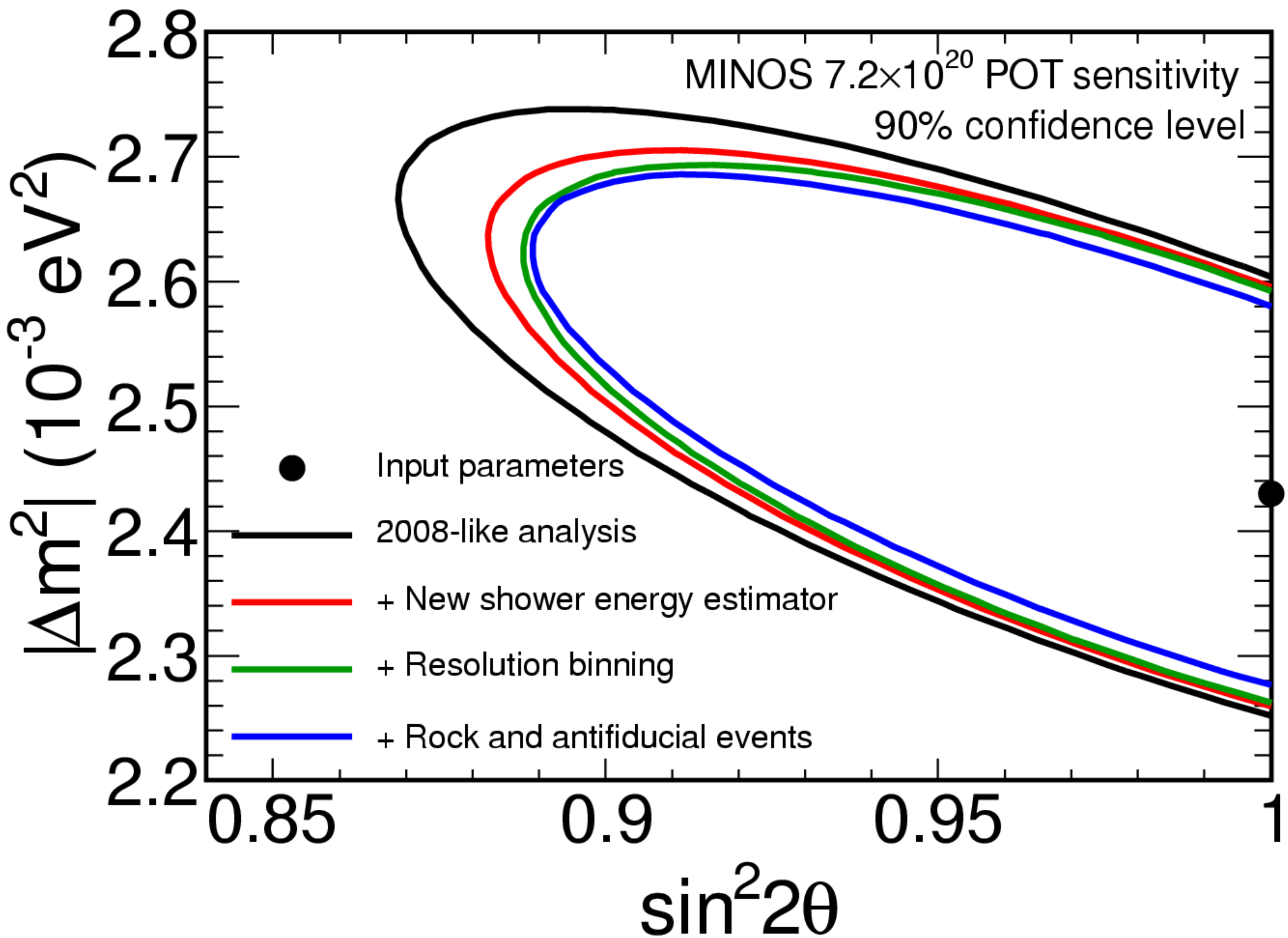


MINOS calorimetry good to:

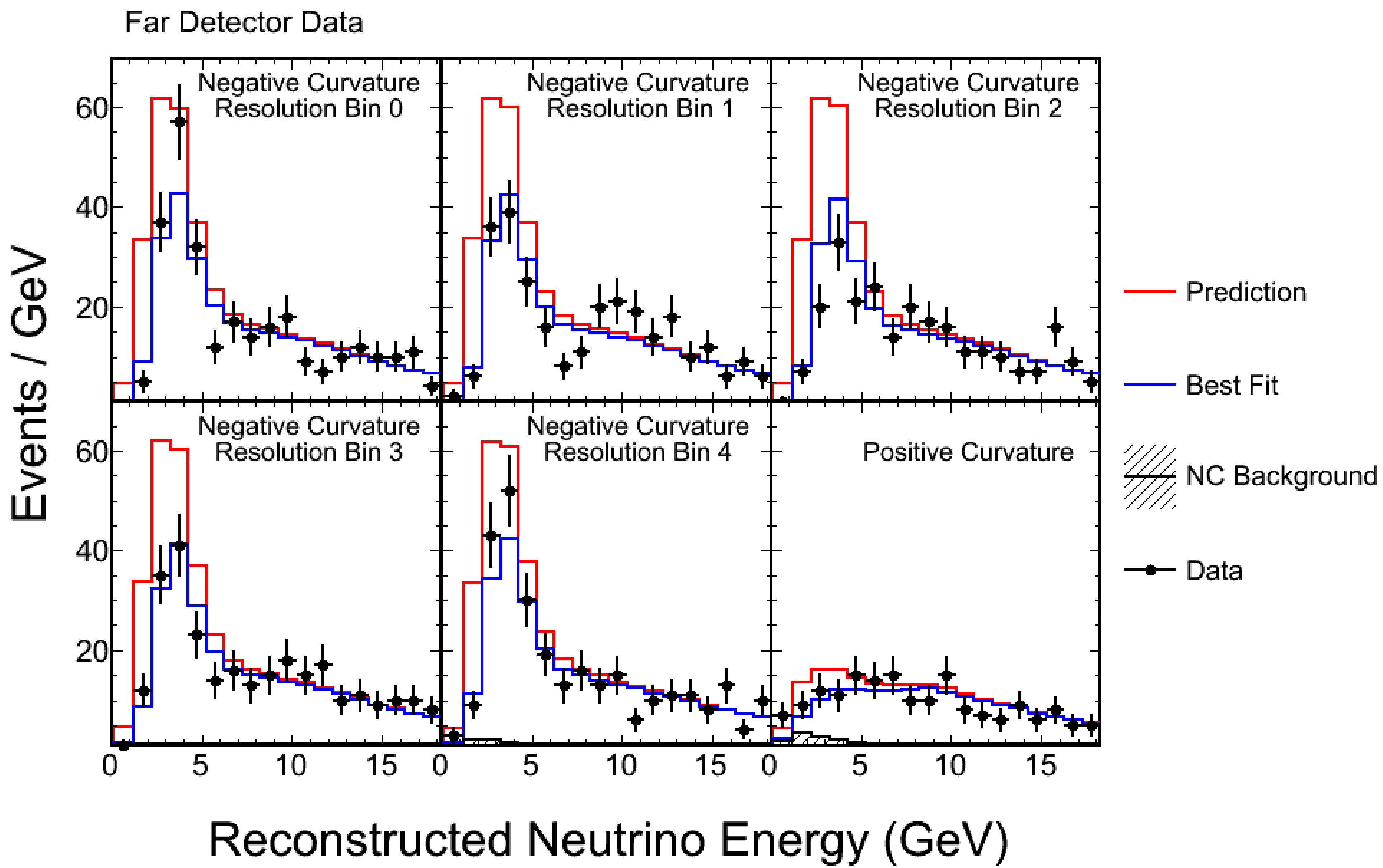
6% (absolute)

2% (relative near/far)

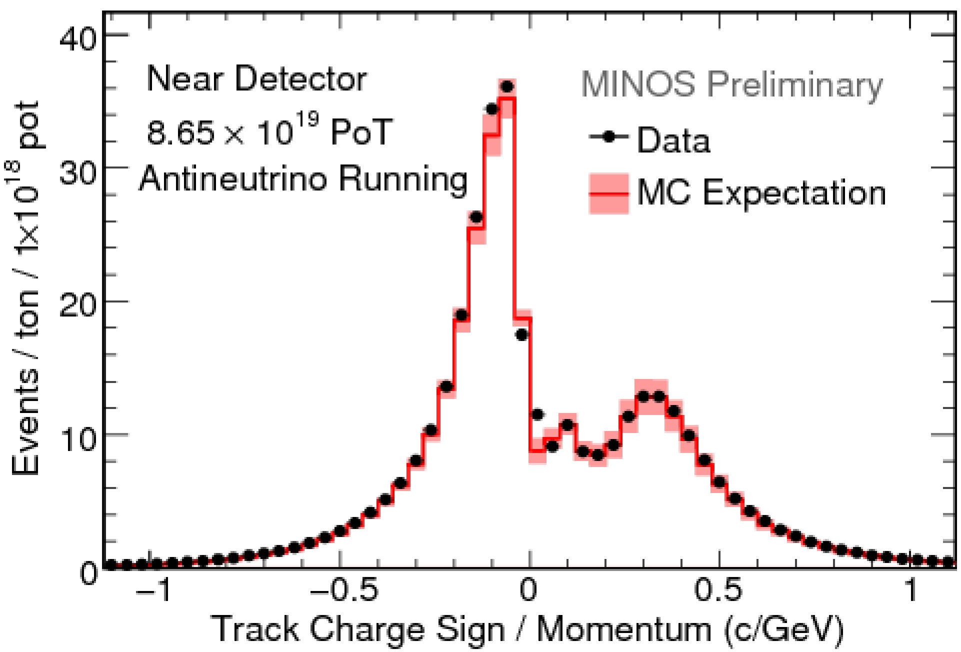
Analysis improvements, 2010 ν_μ CC analysis

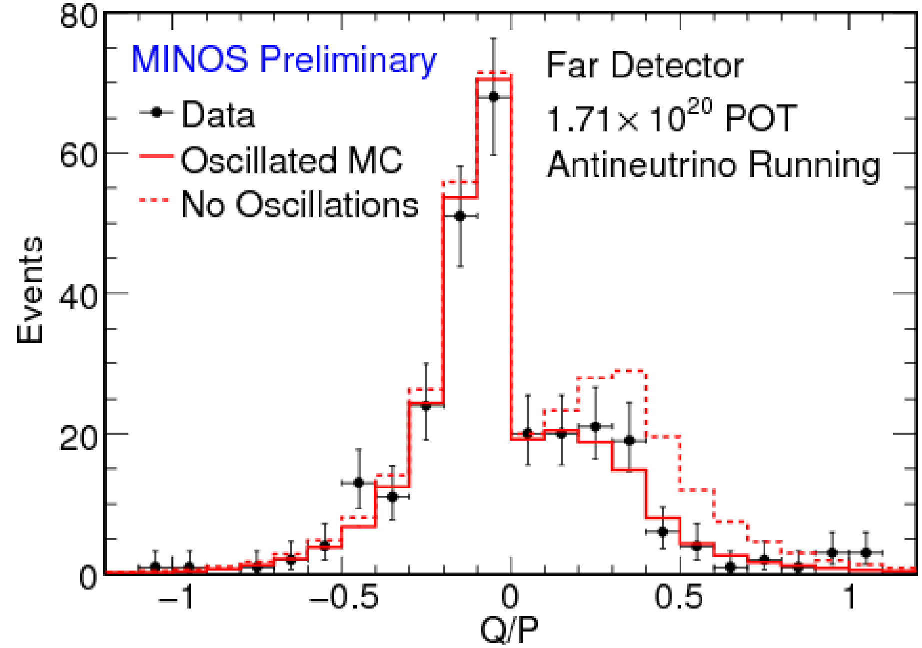


FD data in resolution bins, 2010 ν_μ CC analysis

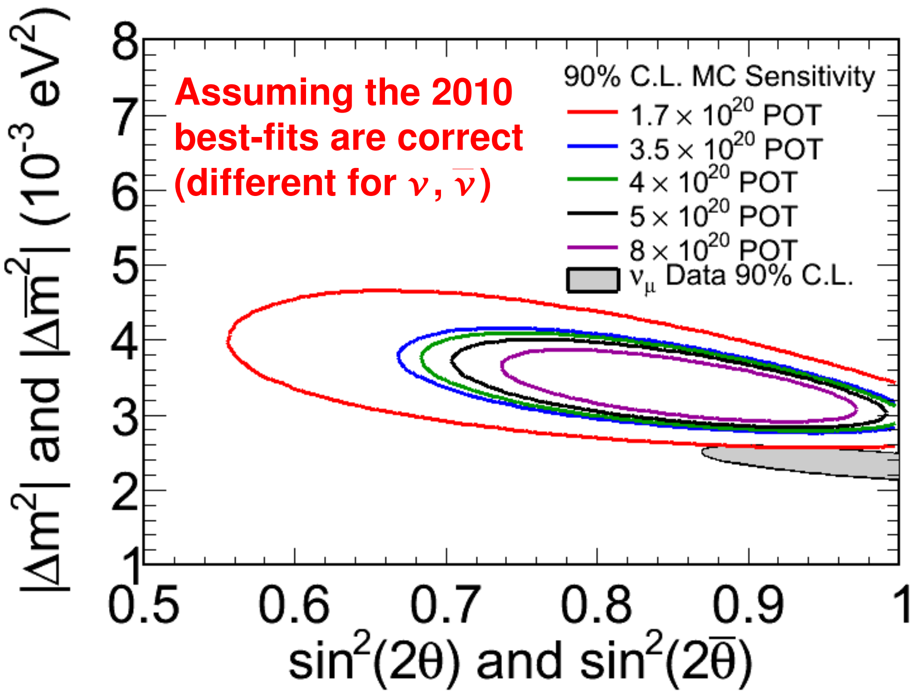


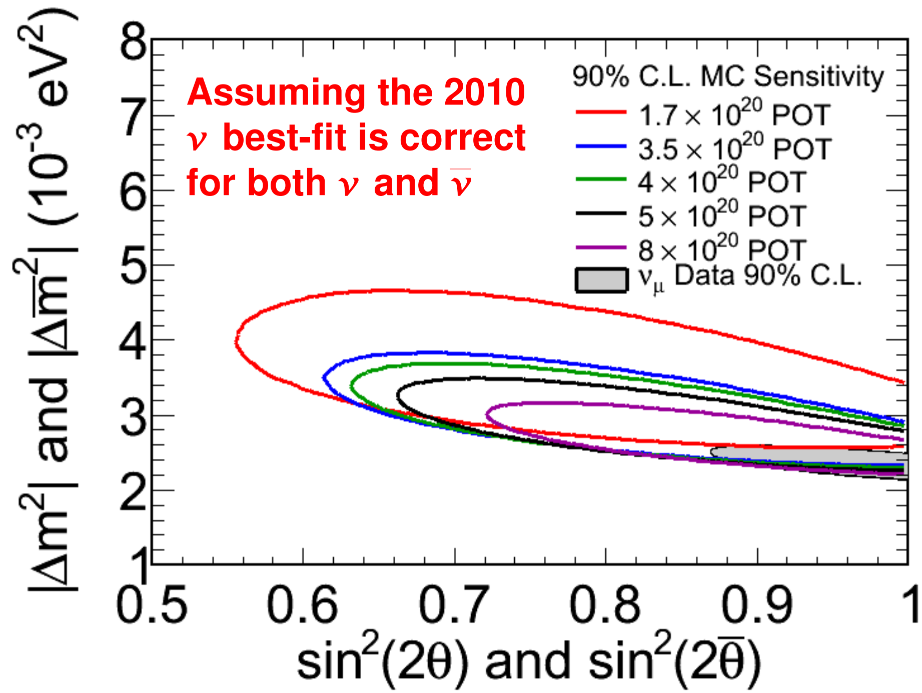
ND and FD data and prediction, *q/p*
2010 antineutrino analysis

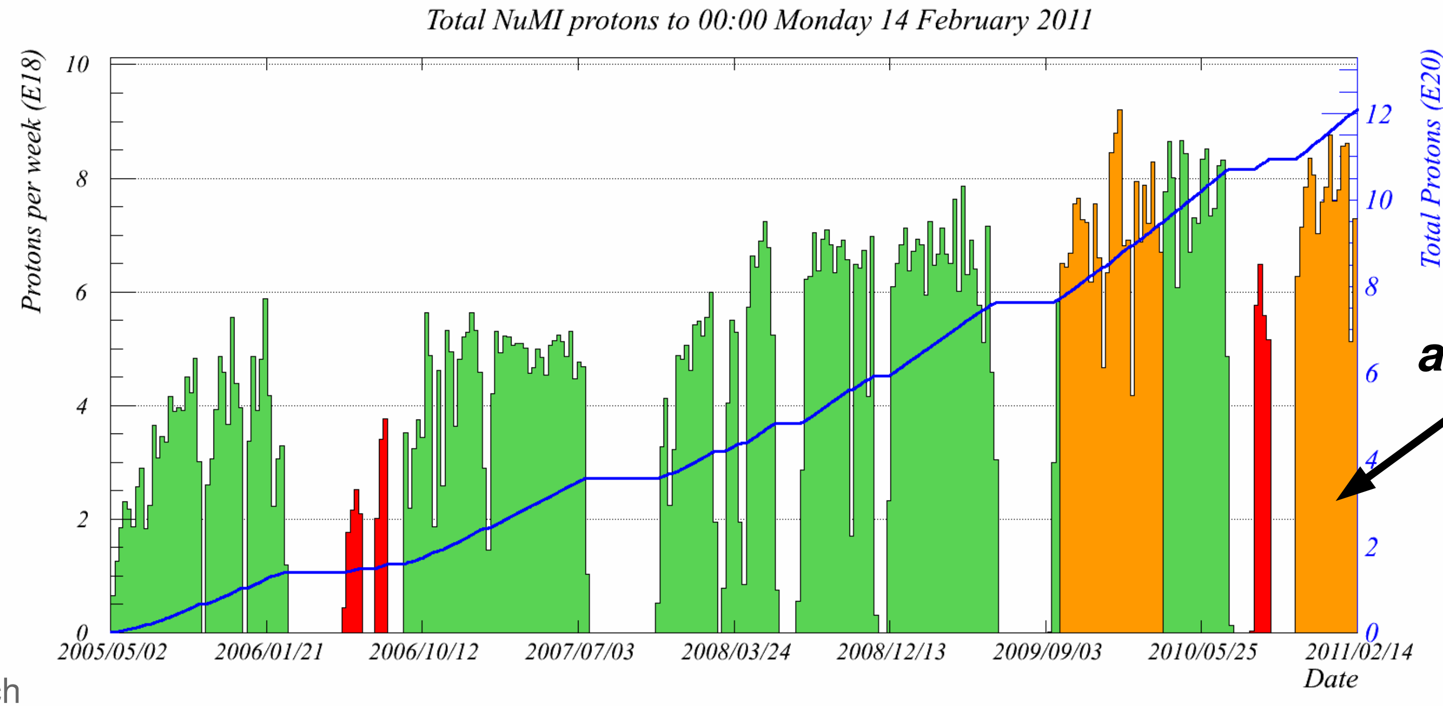




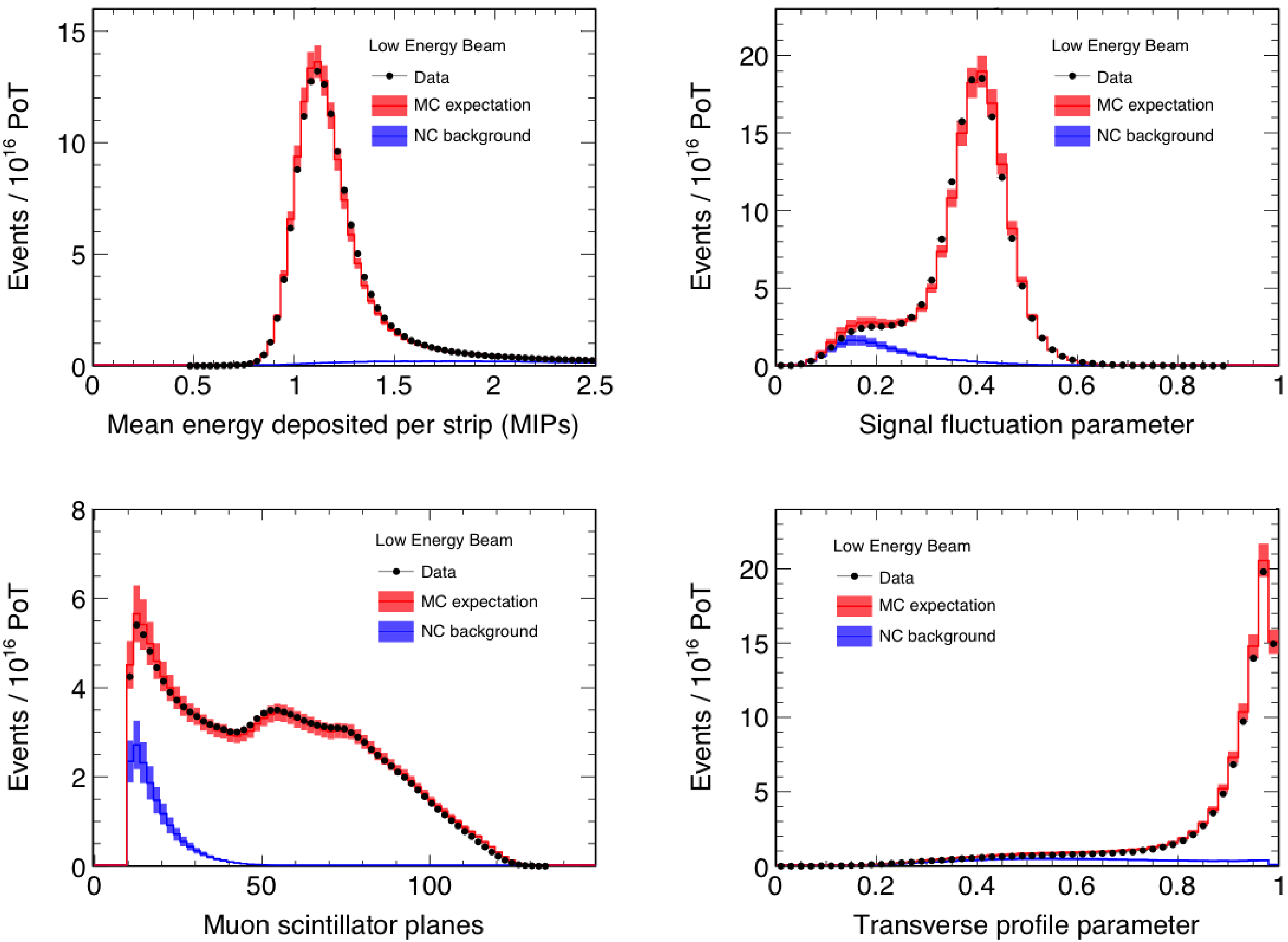
Potential evolution of antineutrino disappearance result



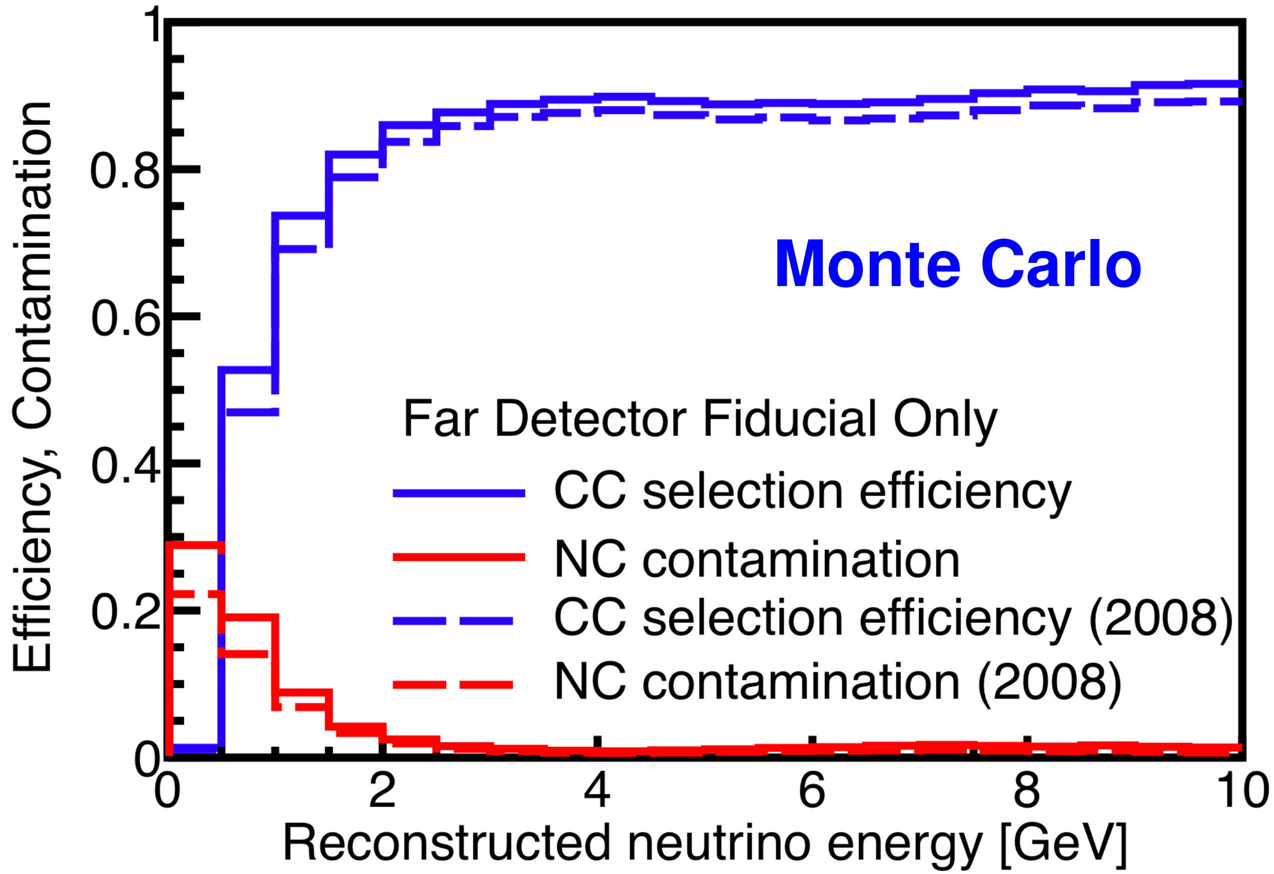




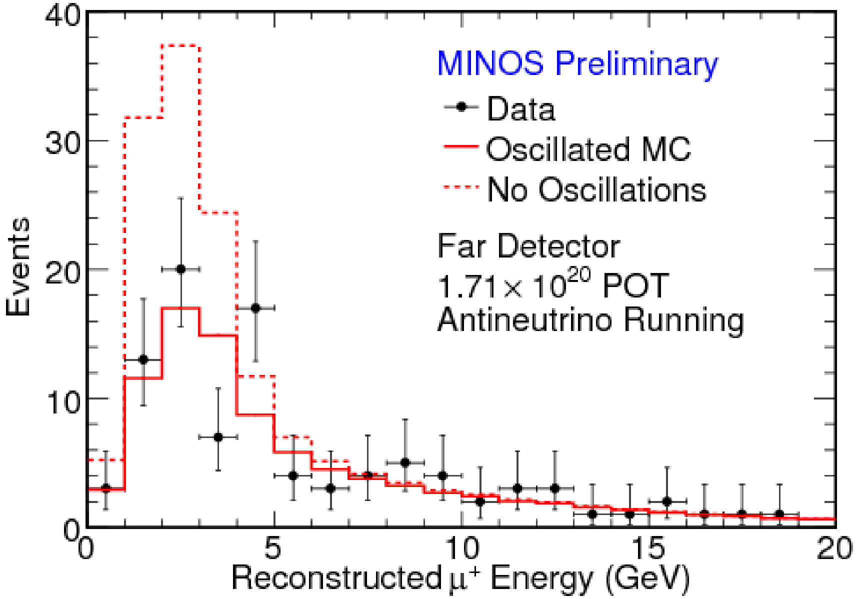
ND data and MC distributions for variables feeding 2010 ν_μ CC analysis's CC/NC separator

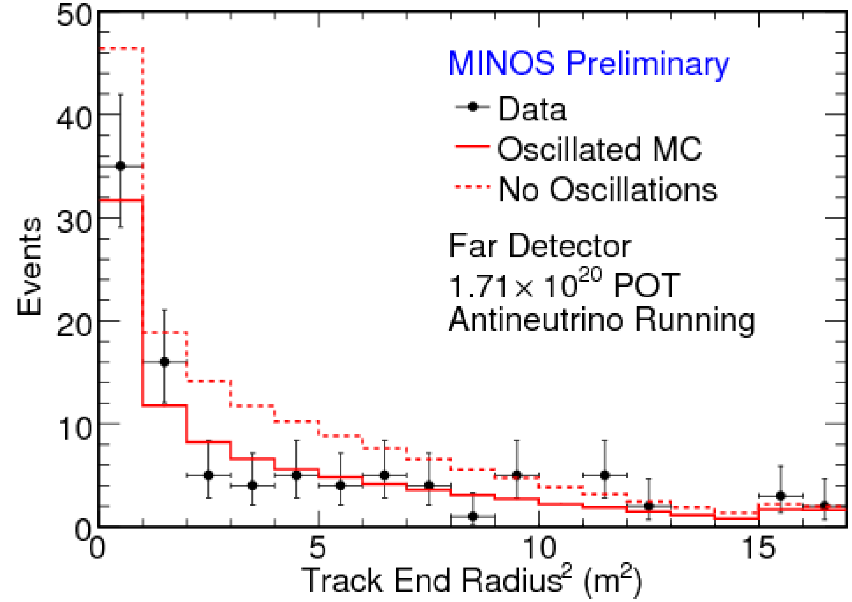


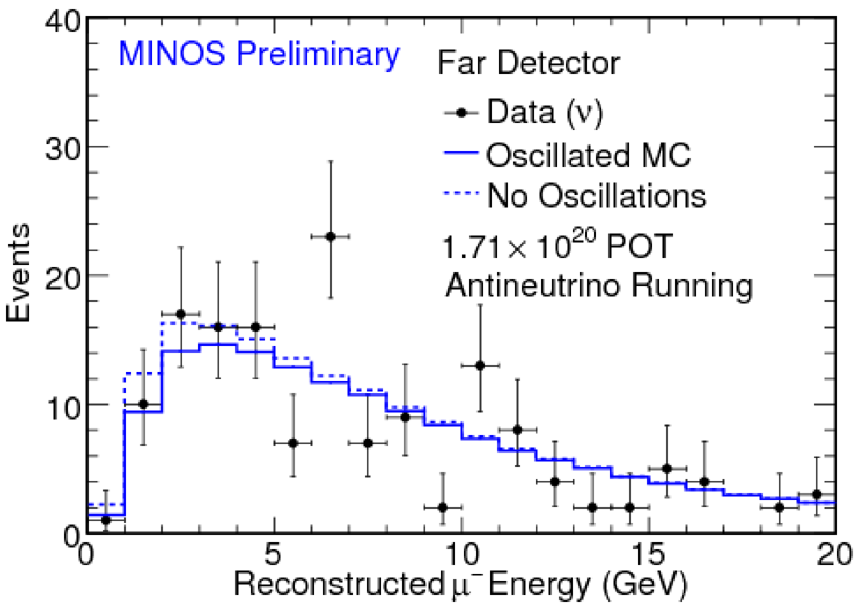
2010 ν_μ CC analysis selection vs. 2008 version

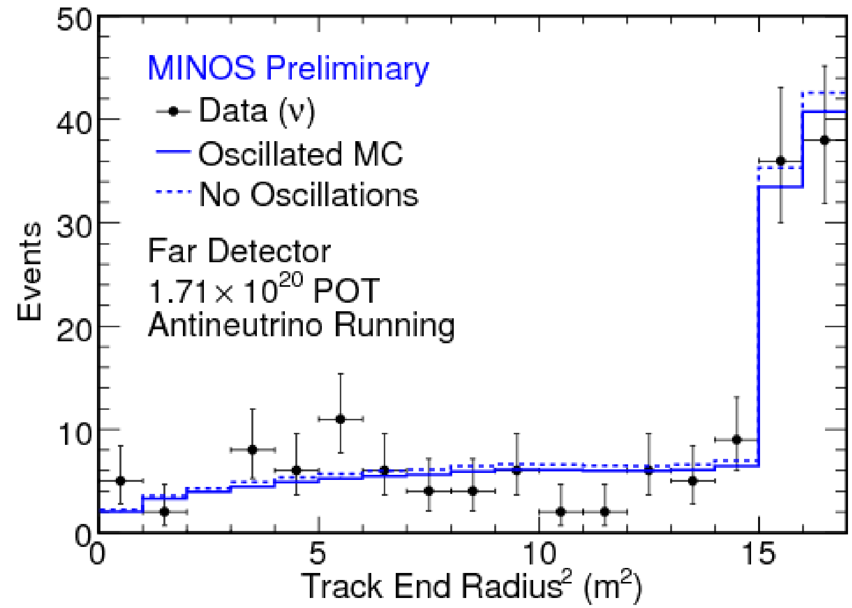


Far detector data in antineutrino-mode running

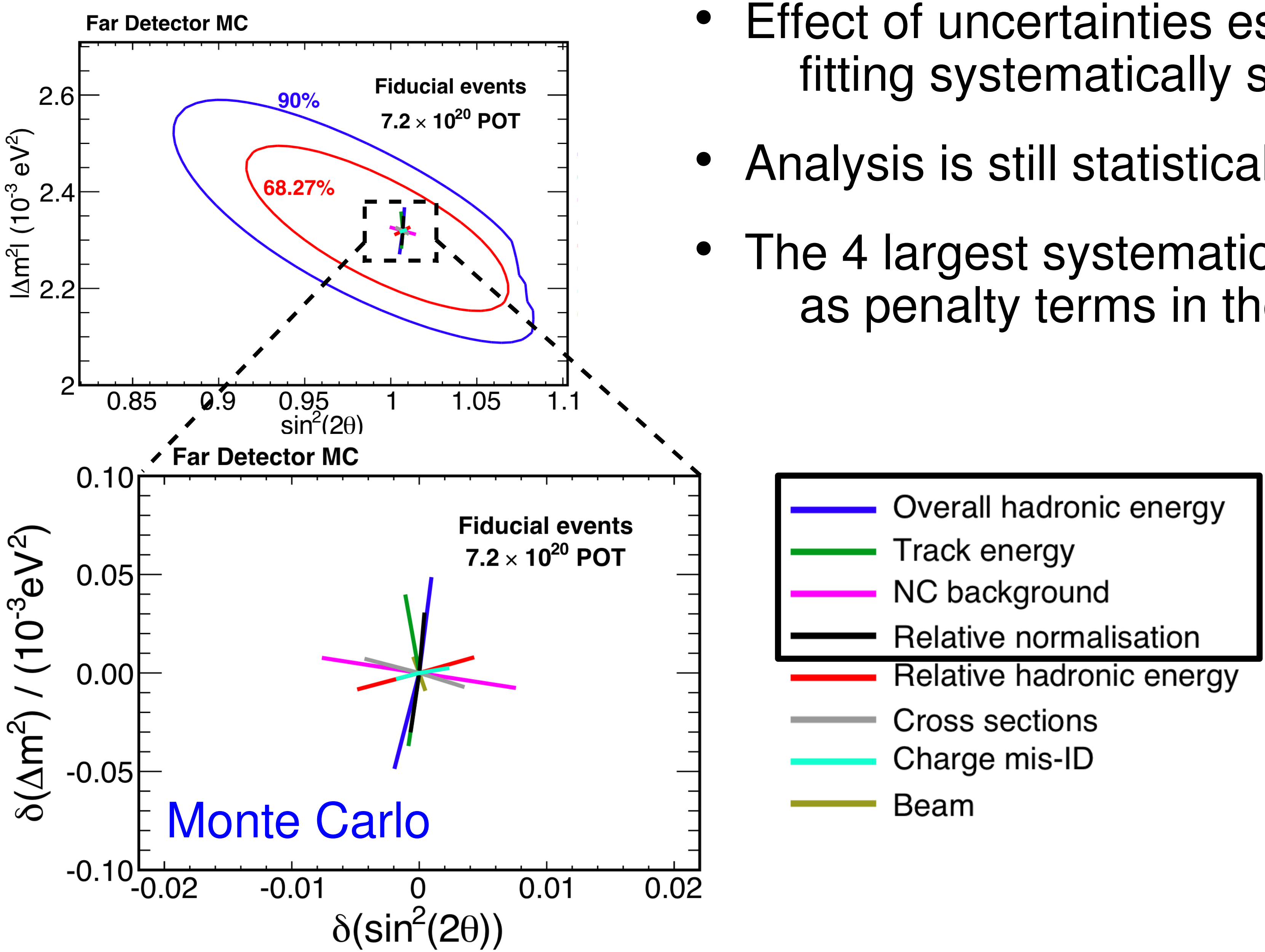






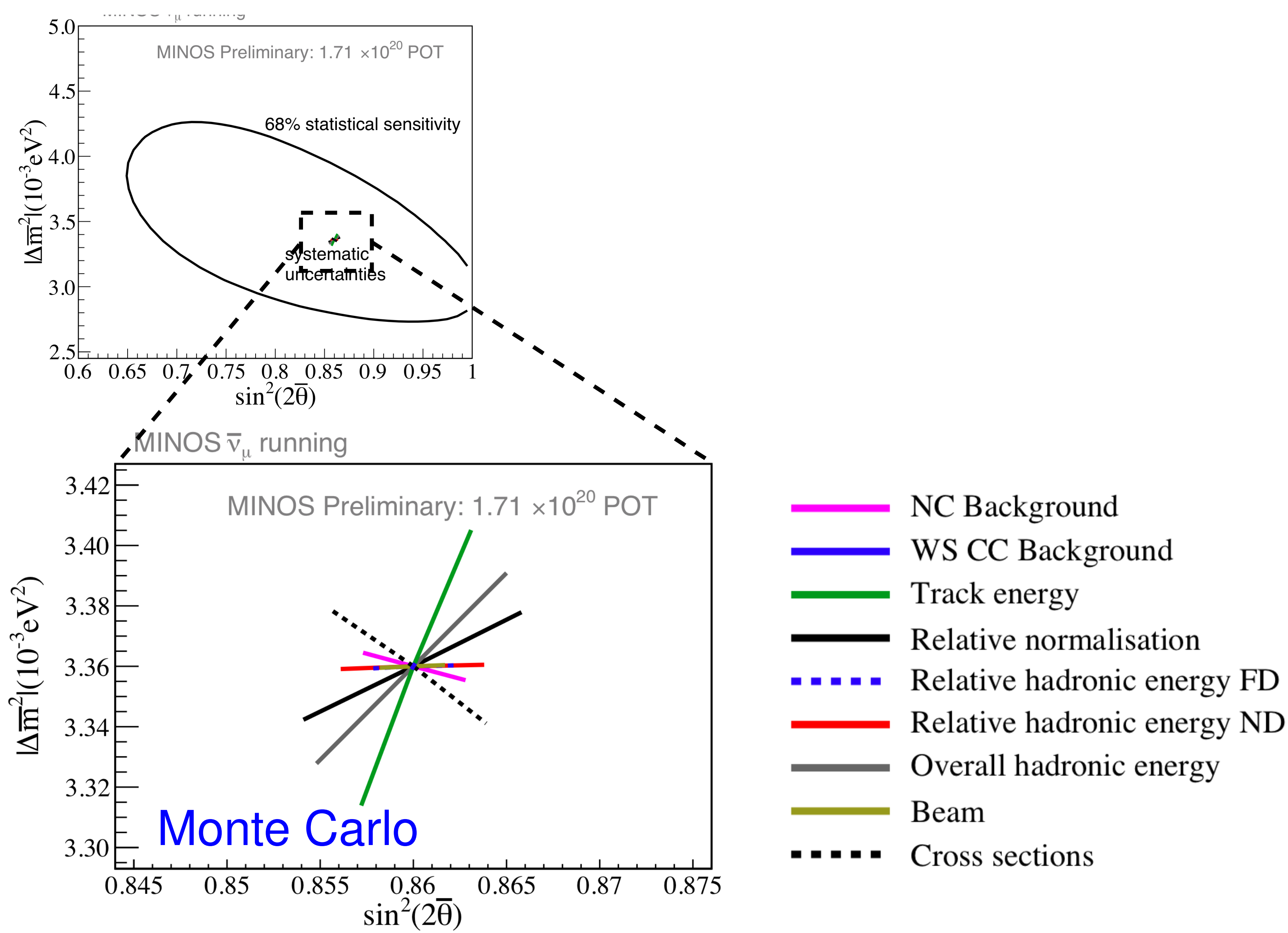


Systematics on ν_μ disappearance measurement



- Effect of uncertainties estimated by fitting systematically shifted MC
- Analysis is still statistically limited
- The 4 largest systematics are included as penalty terms in the fit.

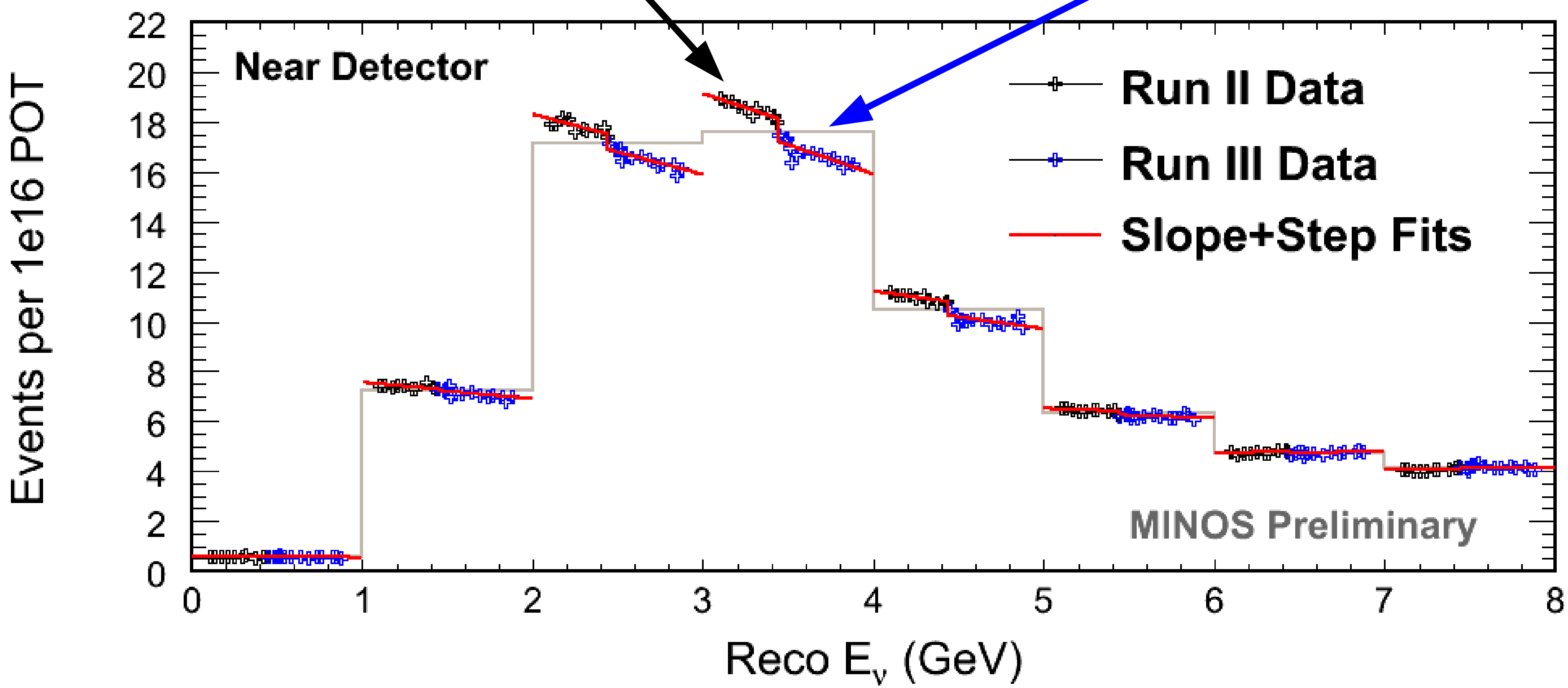
Systematics on anti-ν_μ disappearance measurement



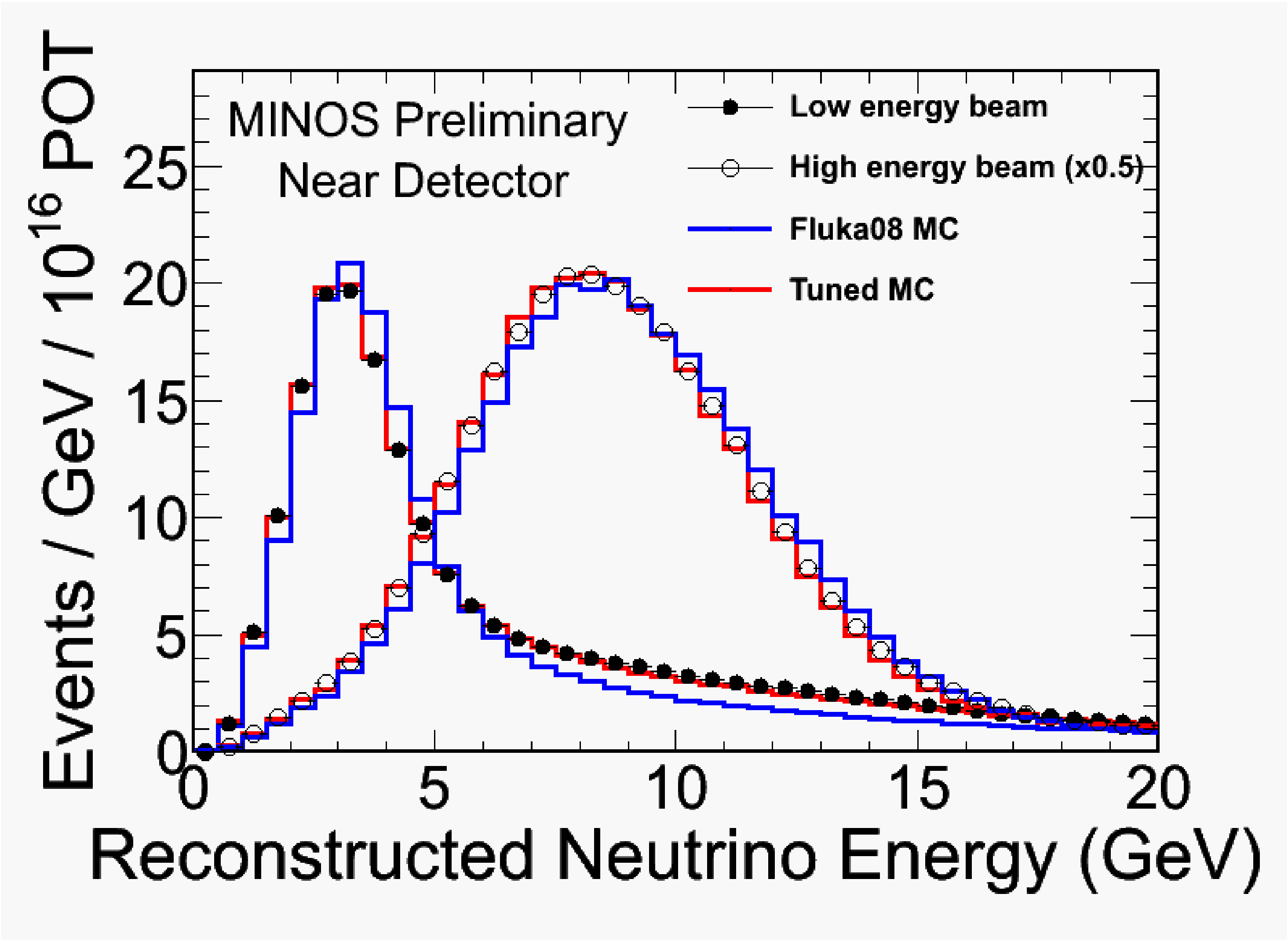
Target degradation

Gradual slope due to radiation damage

Step caused by adding helium to decay pipe



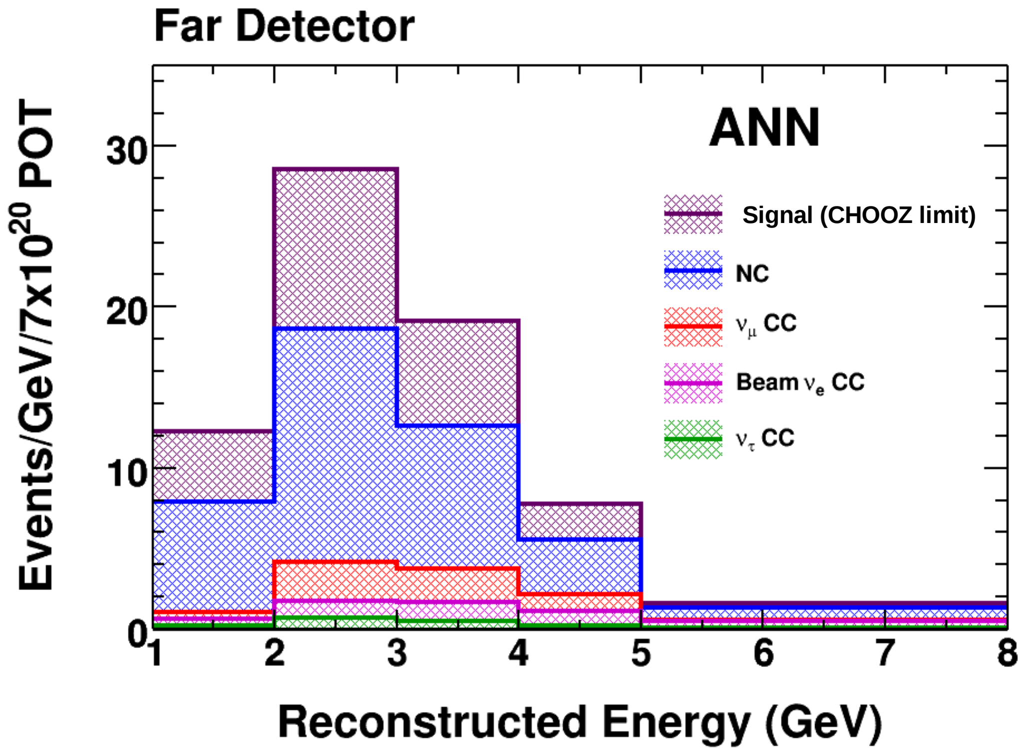
Flux prediction tuning

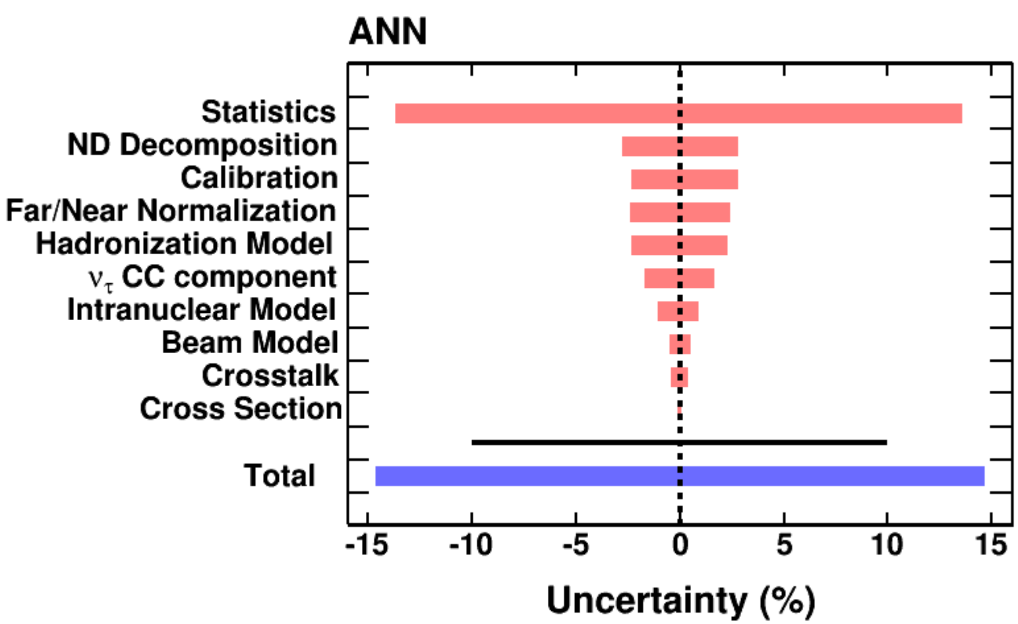


FD prediction for ν_e candidates (2010 analysis)

Detector differences lead to systematic errors when converting **near det. observations** into **far det. prediction**

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





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

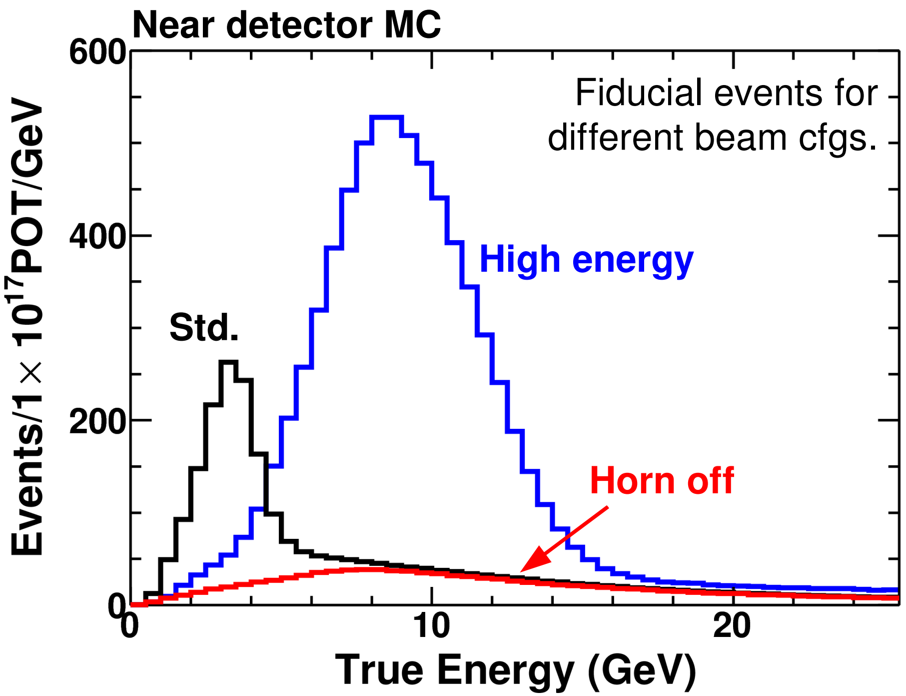
Backgrounds:		**Signal (CHOOZ limit):**	
Total	**49.1**	**ν_e CC**	**24**
NC	35.8		
ν_μ CC	6.3	*(stat. + syst. error on*	
ν_e CC	5.0	*total BG is 7.4 events)*	
ν_τ CC	2.0		

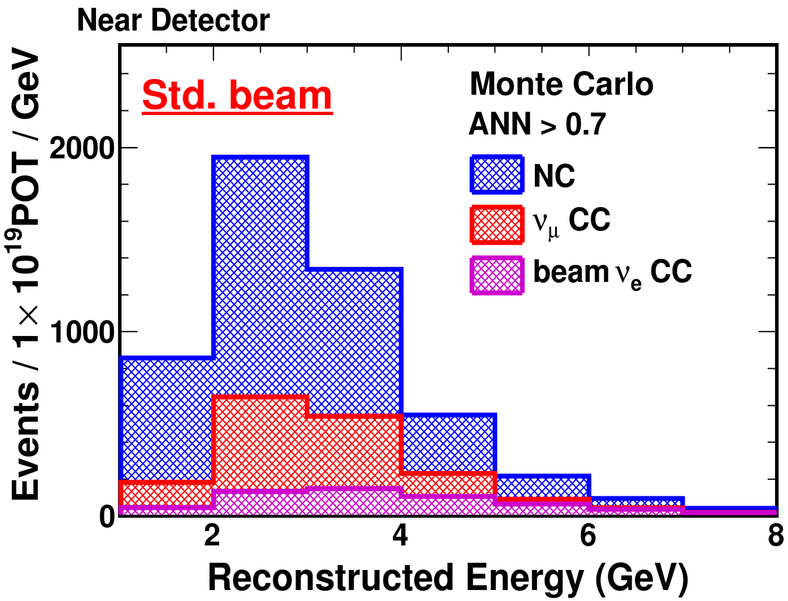
Signal: Δm^2_{32} = 2.43x10^{-3} eV^2 $\sin^2(2\theta_{23})$ = 1.0

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

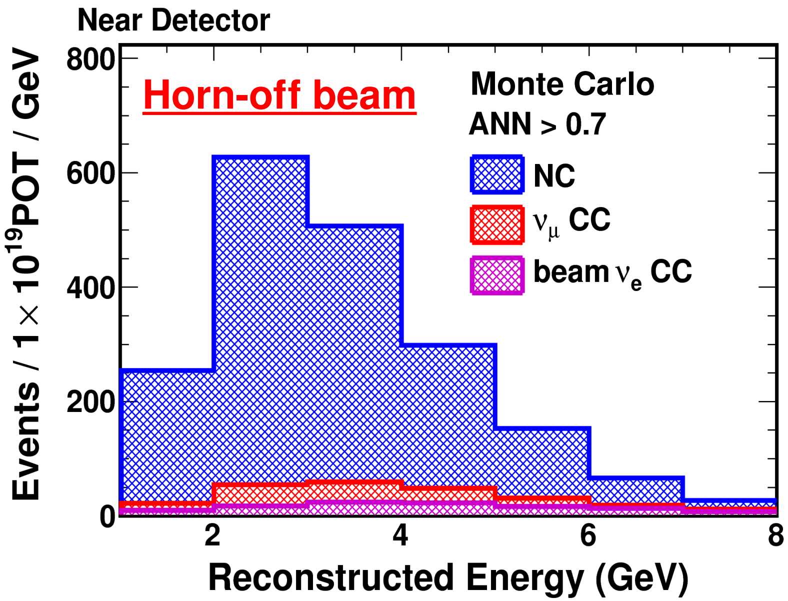
ν_e background decomposition (2010 analysis)

- Transport of **CC components** to far det. requires application of $P_{osc}(\nu_\mu \to \nu_x)$
- 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

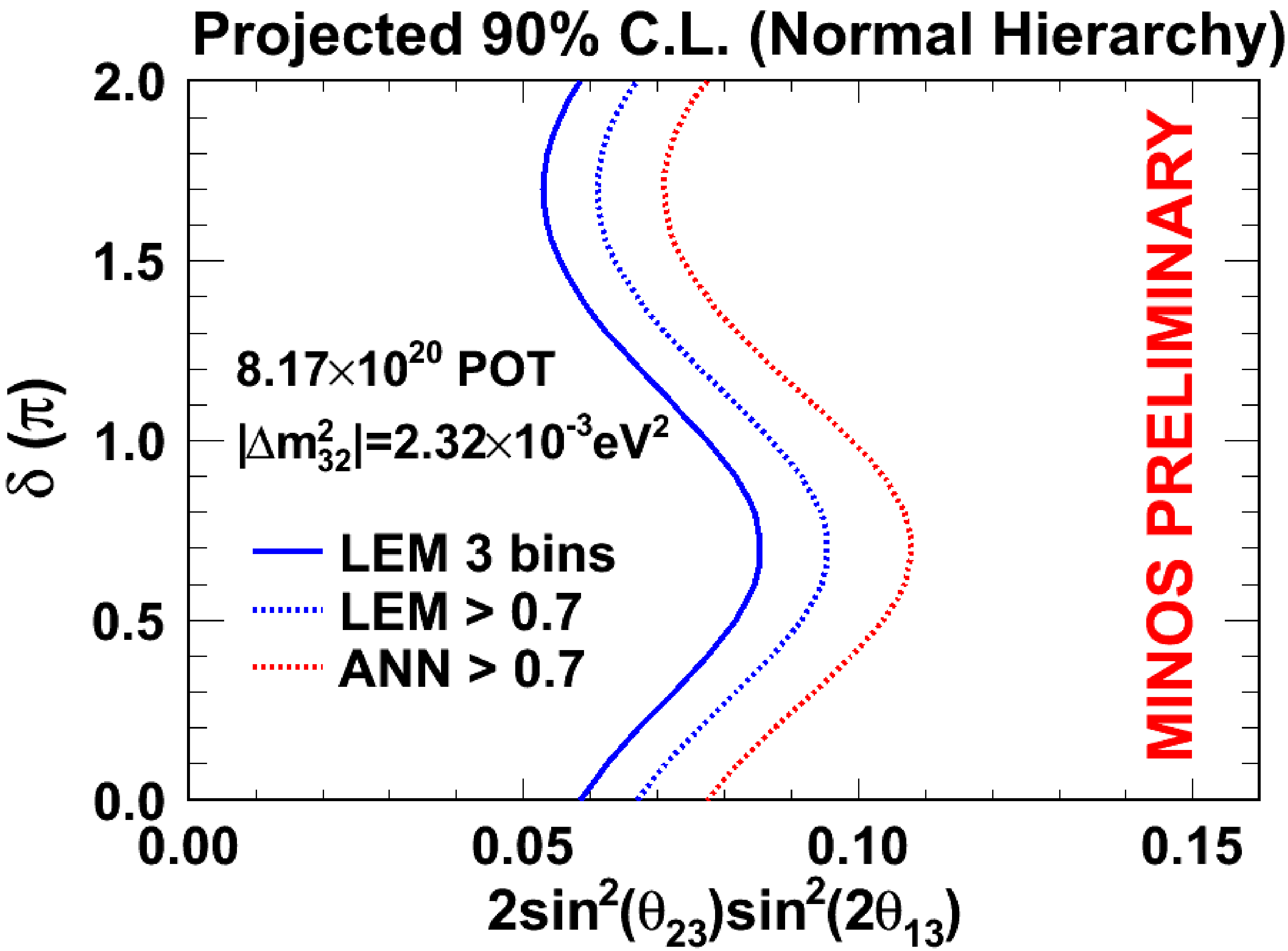




Turn off focusing horn



2011 ν_e appearance analysis improvements' effects on sensitivity



2011 ν_e appearance projected event counts and systematic errors (*preliminary*)

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

expect 49.8 events above LEM=0.7

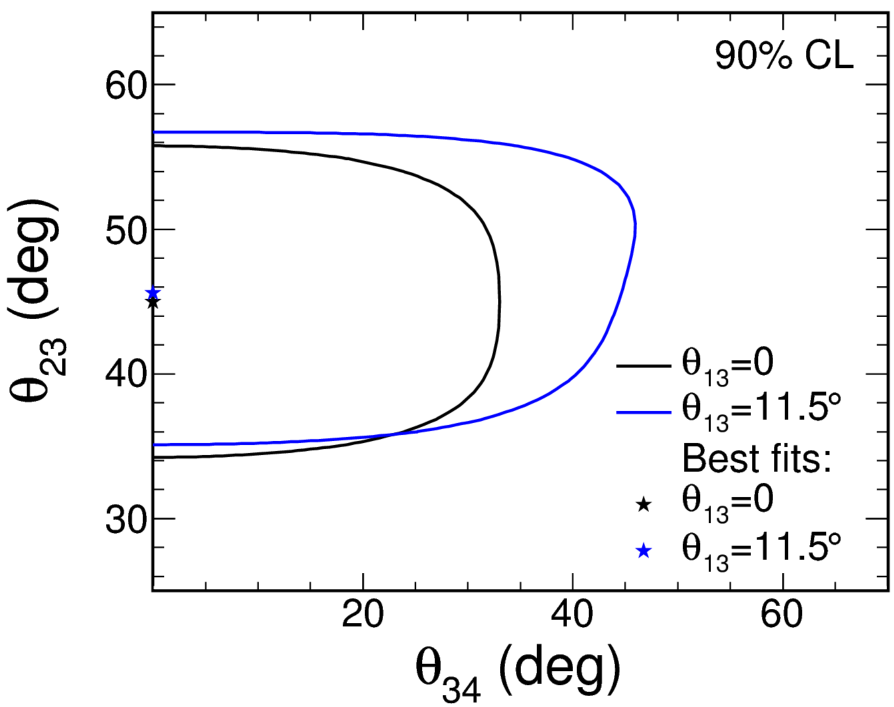
$\sin^2(2\theta_{13})$=0.16

expect 79.4 events above LEM=0.7

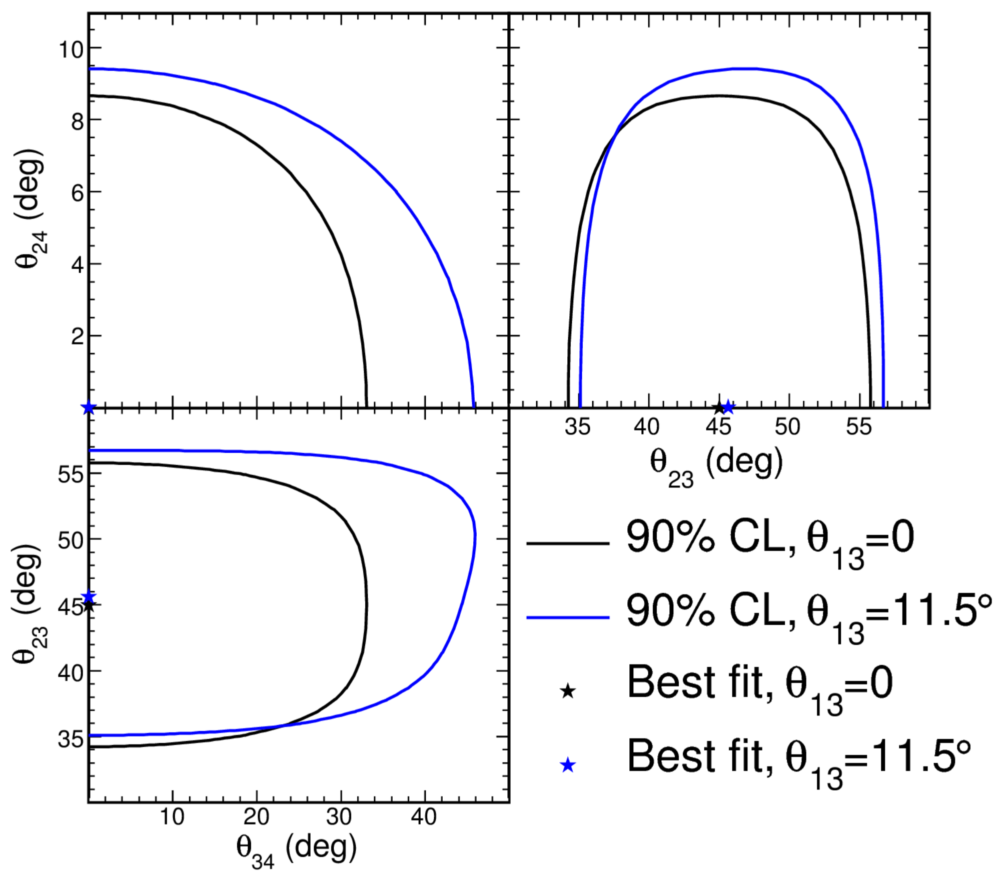
Systematic	
Calibration	± 4.2%
Cross talk	± 2.0%
Normalization	± 1.9%
Hadronic Errors	± 0.8%
Cross Section and Intranuclear Model	± 0.7%
Beam Model	± 0.7%
Total Far/Near Ratio	**± 5.3%**
ν_τ CC Uncertainties	± 2.1%
ND Decomposition Error	**± 0.3%**
Total MC Systematic Uncertainty	**± 5.7%**

Allowed parameter regions for 3+1 sterile models given the MINOS neutral current data

$(m_4^2 - m_3^2) \approx (m_1^2 - m_3^2)$



$(m_4^2 - m_3^2) \gg (m_1^2 - m_3^2)$



NOνA-era event rates at various off-axis locations