Recent Results and Future Prospects from MINOS

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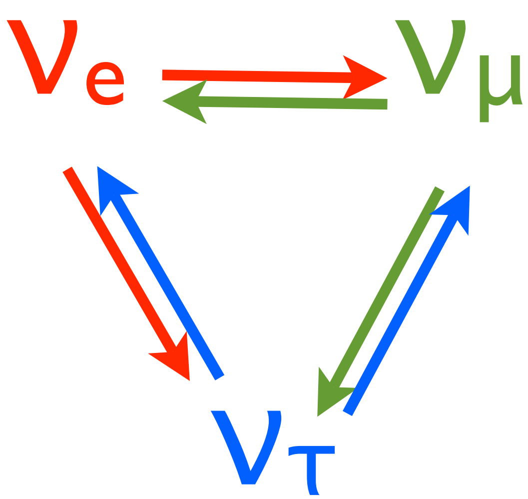
Argonne National Laboratory

Les Rencontes de Physique de la Vallée D'Aoste
La Thuile, March 2, 2010

The MINOS Collaboration

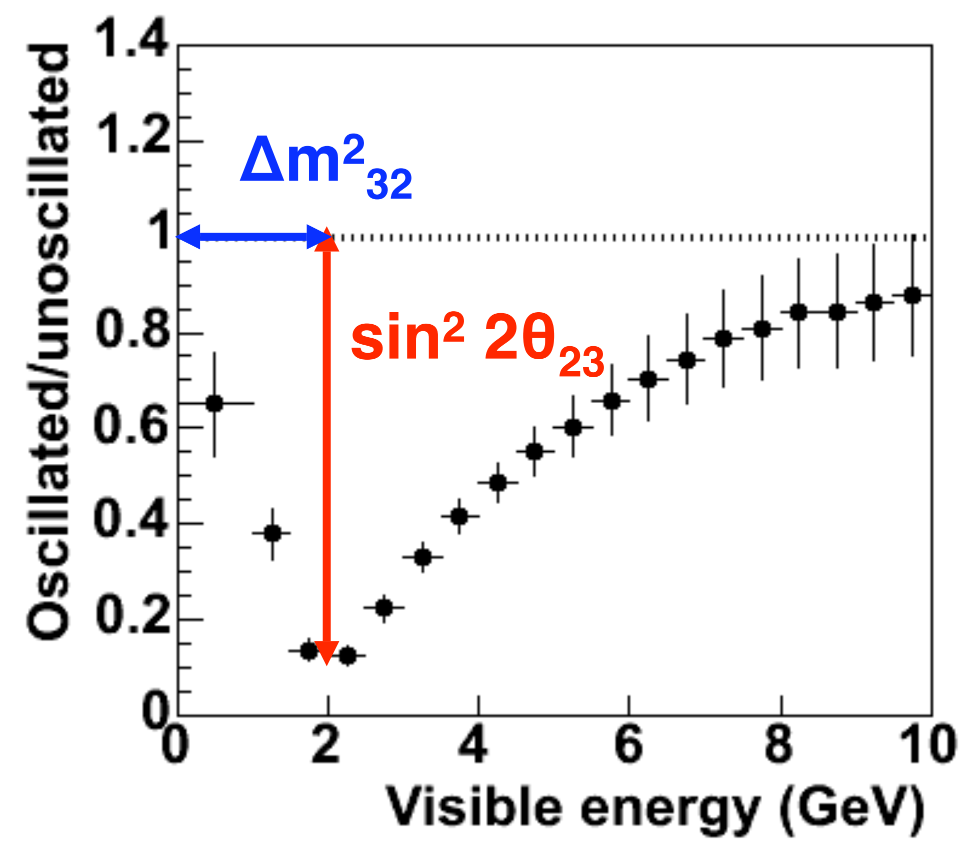
Argonne - Arkansas Tech - Athens - Benedictine - Brookhaven - Caltech - Cambridge - Campinas - Fermilab - Harvard - IIT - Indiana - Minnesota-Twin Cities - Minnesota-Duluth - Oxford - Pittsburgh - Rutherford - São Paulo - South Carolina - Stanford - Sussex - Texam A&M - Texas-Austin - Tufts - UCL - Warsaw - William & Mary

Goals of the MINOS Experiment



* Make precise measurement of Δm^2 and $\sin^2(2\theta)$ via:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2\,L/E)$$



* Secondary goals:
  * Search for sterile neutrinos
  * Search for subdominant $\nu_\mu \rightarrow \nu_e$
  * CPT tests
  * Atmospheric neutrino and cosmic ray studies

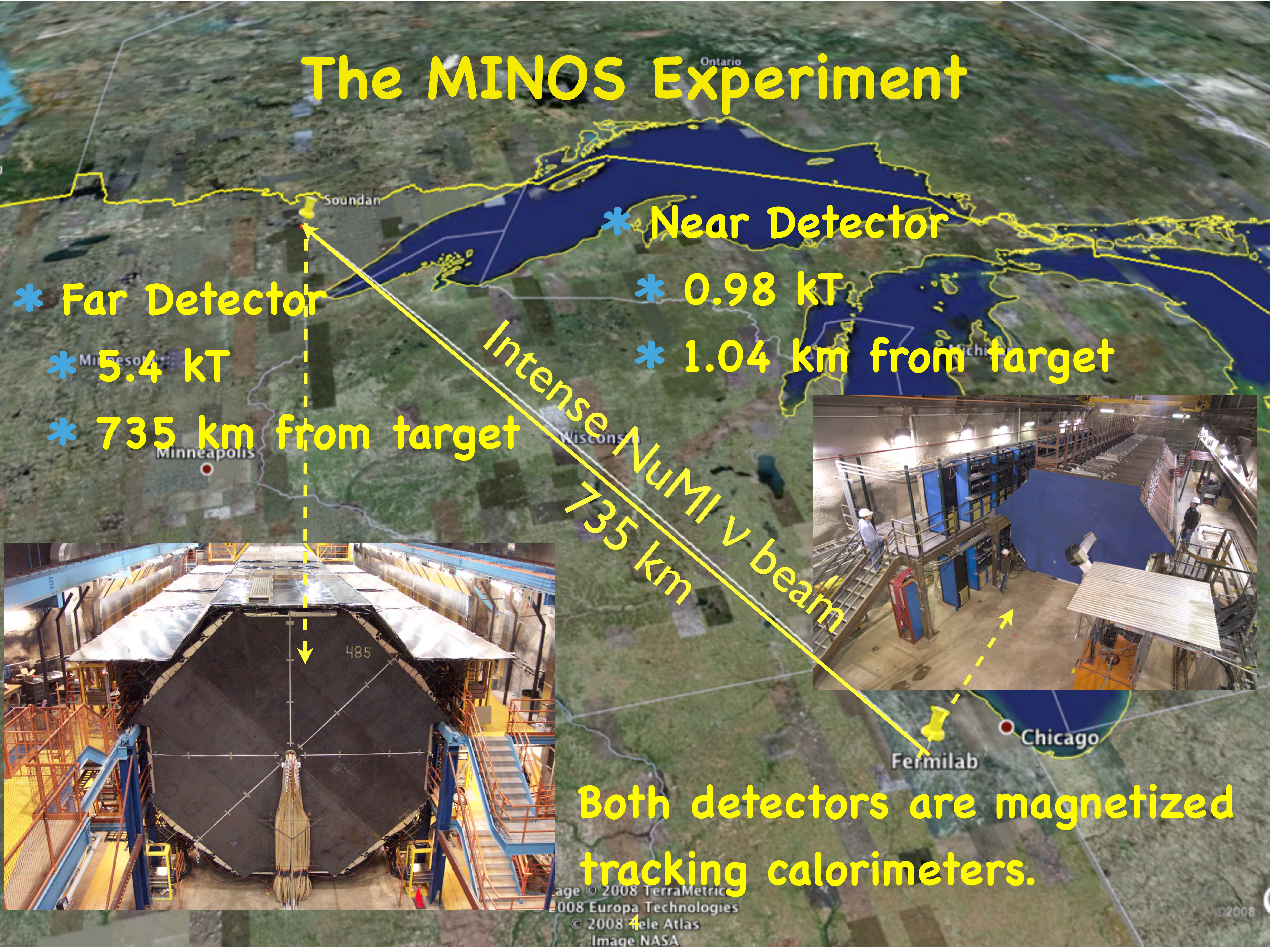

The MINOS Experiment
Ontario
Soundan
* Far Detector
* 5.4 kT
* 735 km from target
Minneapolis
* Near Detector
* 0.98 kT
* 1.04 km from target
Intense NuMI ν beam
735 km
Wisconsin
485
Chicago
Fermilab
Both detectors are magnetized tracking calorimeters.
Image © 2008 TerraMetrics
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Image NASA
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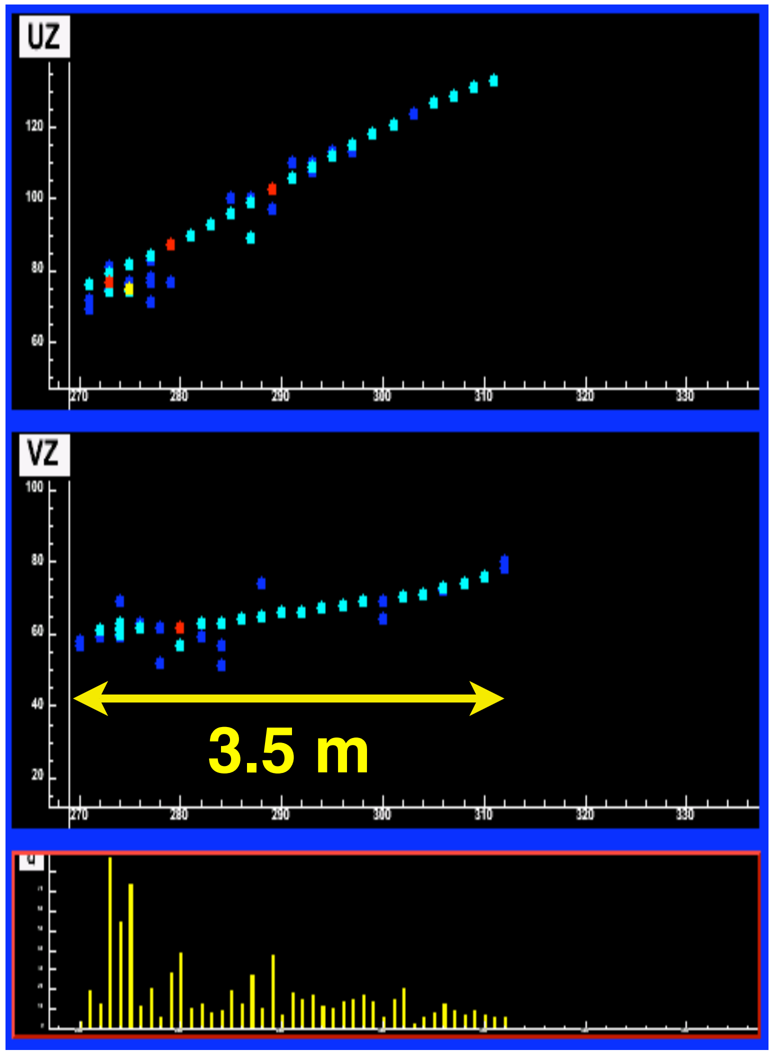
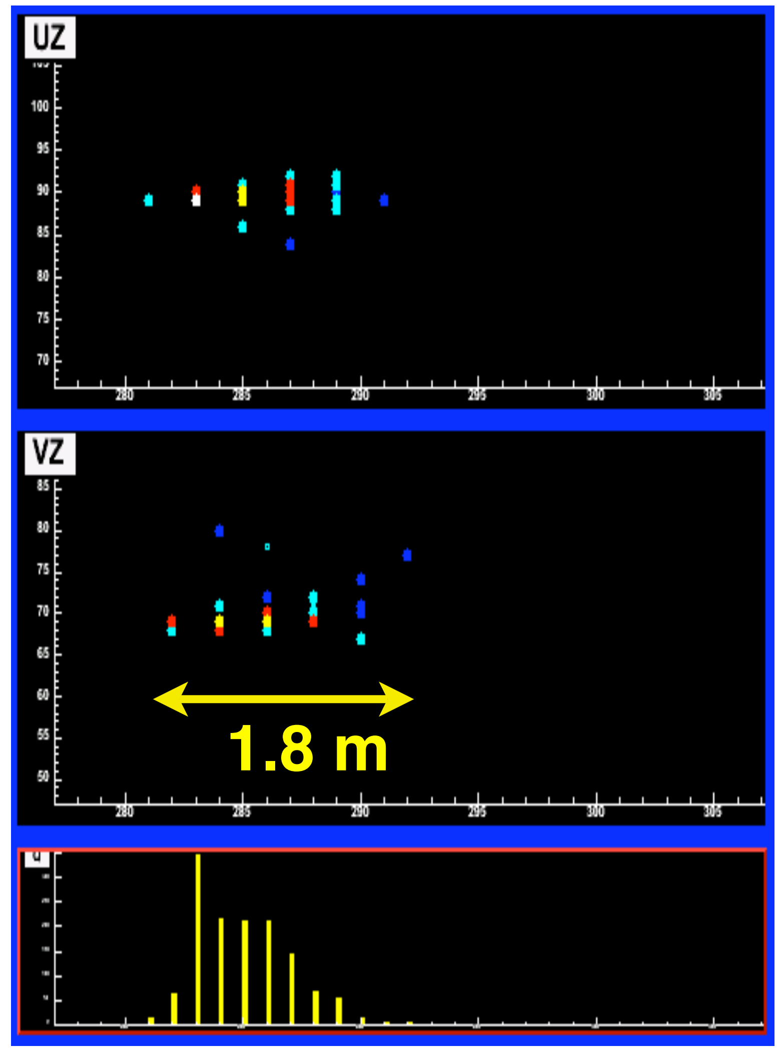
Identifying Events in MINOS

ν_μ CC event



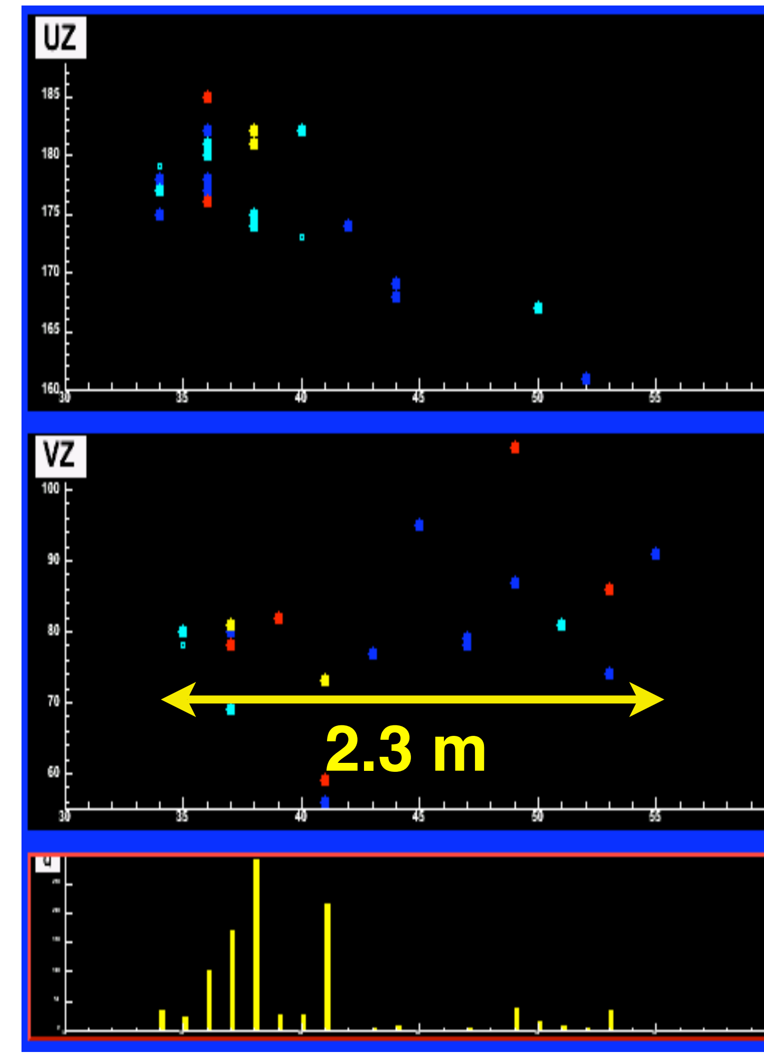
Long μ track + shower at vertex

ν_e CC event



Short event with EM shower profile.

NC event



Short, diffuse event.

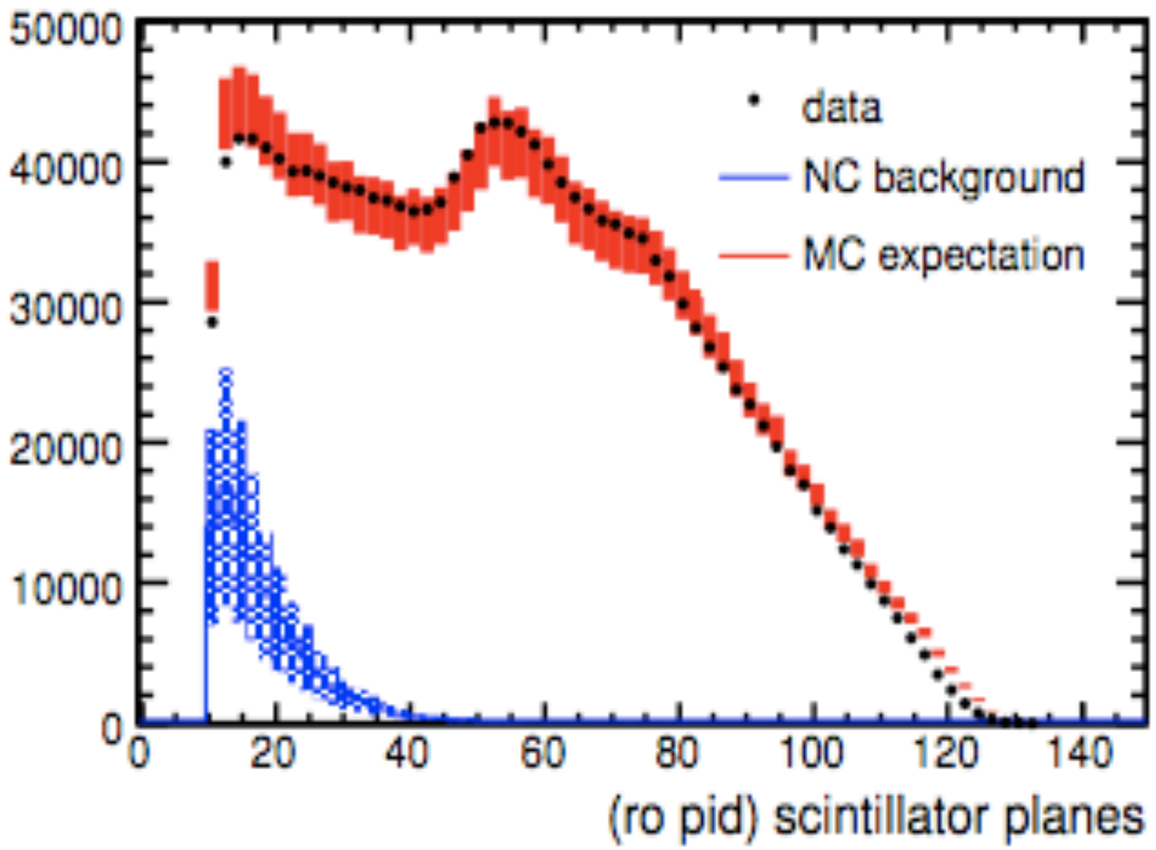
E_μ determined from curvature and/or range,

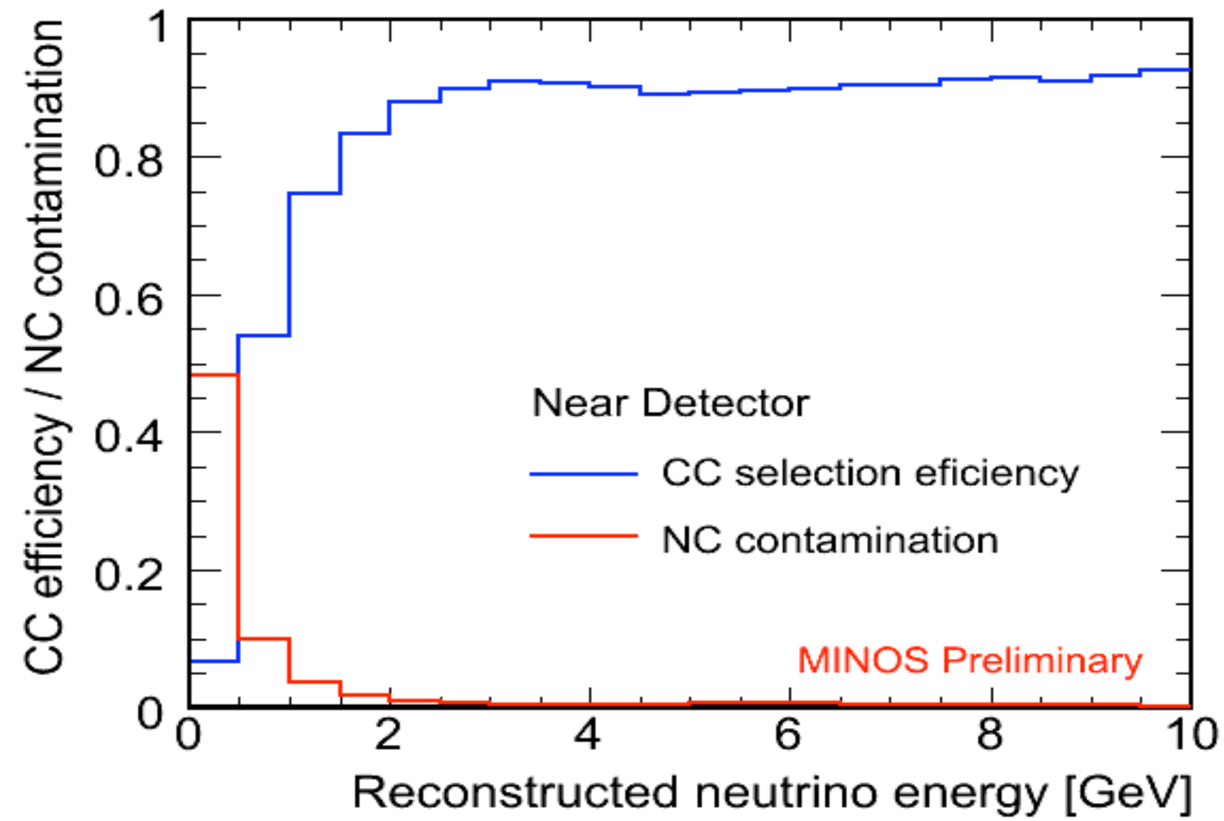
E_{shower} determined from MC tuned to external data.

ν_μ CC Analysis

Precision measurement of Δm^2 and $\sin^2(2\theta)$

ν_μ CC Event Selection

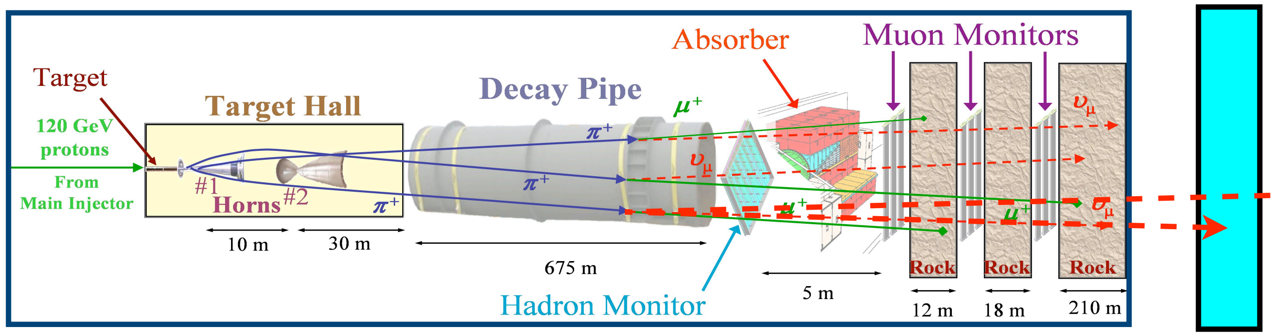


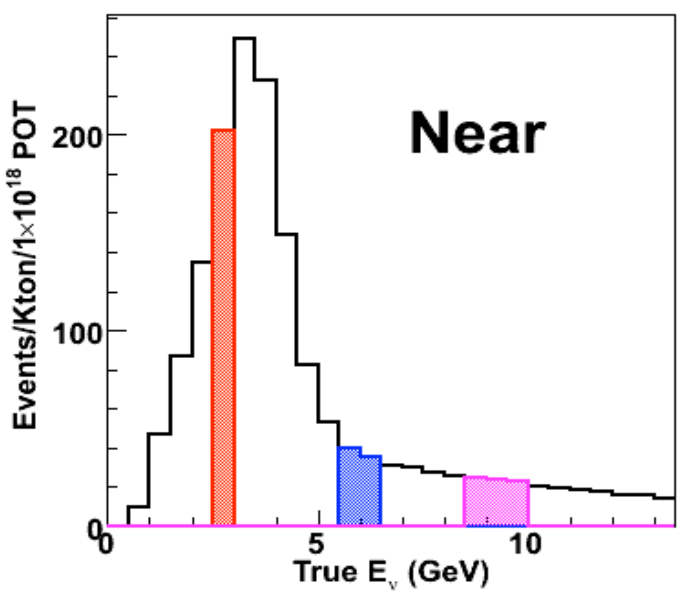


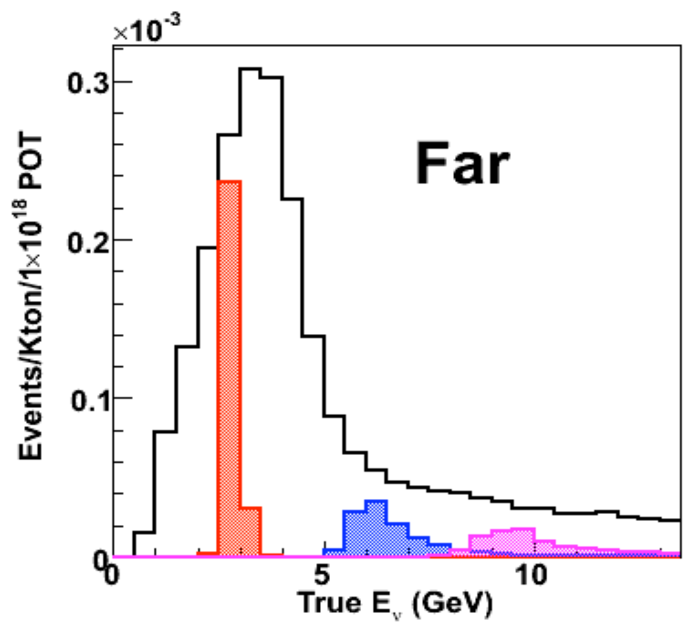
- CC/NC separation achieved via a kNN event selection based on:
  - Track length
  - Mean pulse height
  - Fluctuation in pulse height
  - Transverse track profile

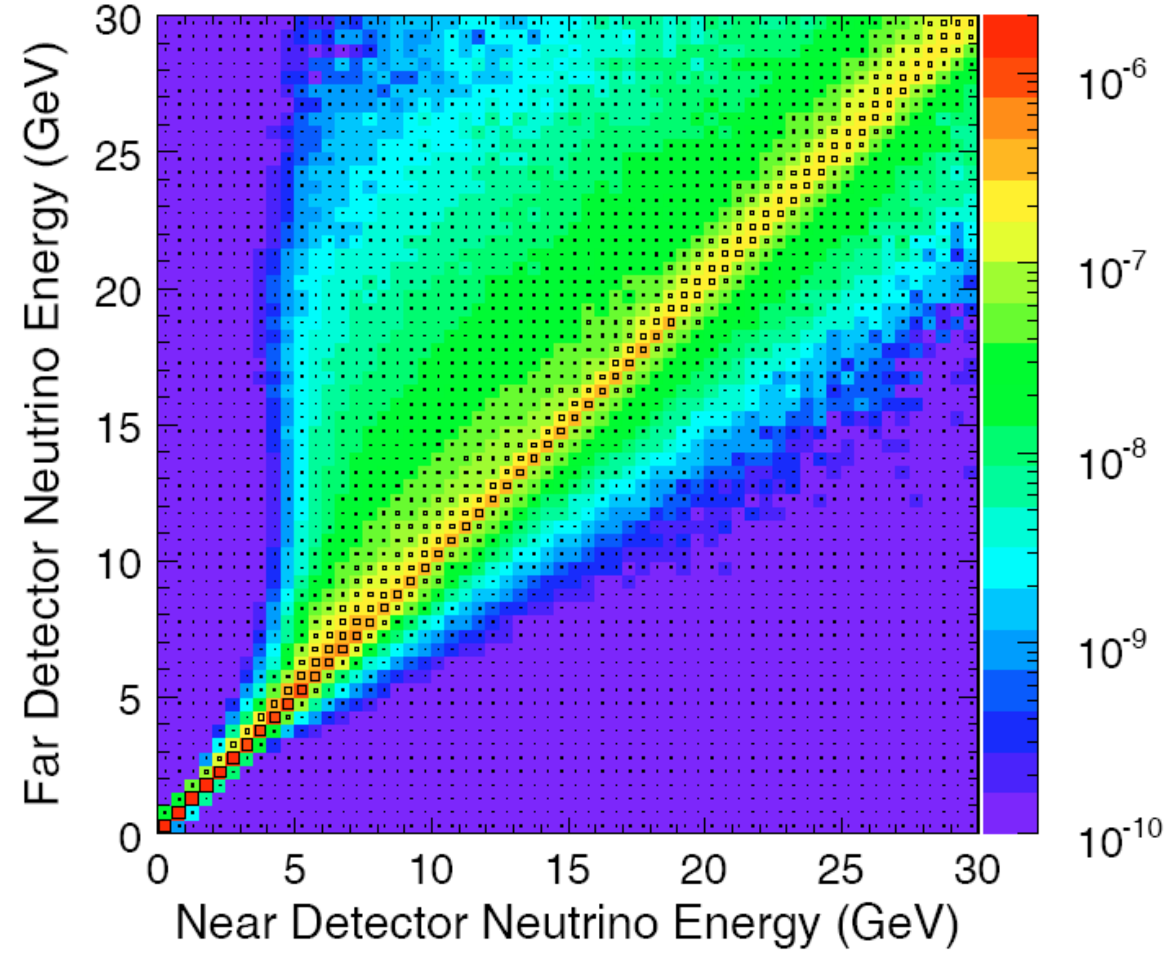
- Cut on separation parameter maximizes CC selection efficiency and minimizes NC background.
- Good agreement between data and MC above the CC/NC separation parameter cut.

Expected Far Detector Spectrum



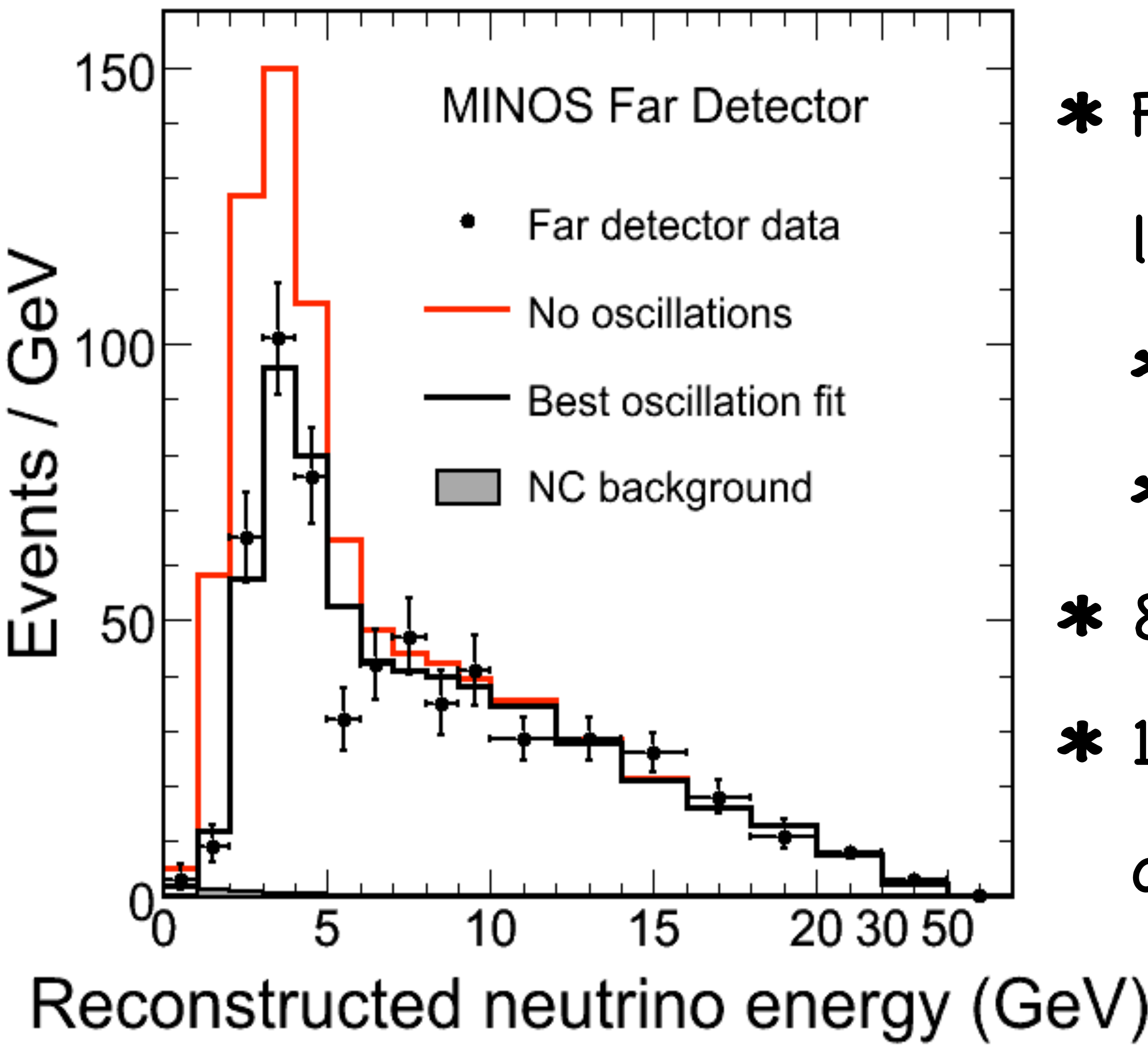






- ✱ Near detector spectrum is extrapolated to the far detector.
- ✱ Use MC to provide energy smearing and acceptance corrections.

FD Energy Spectrum/Performing the Fit

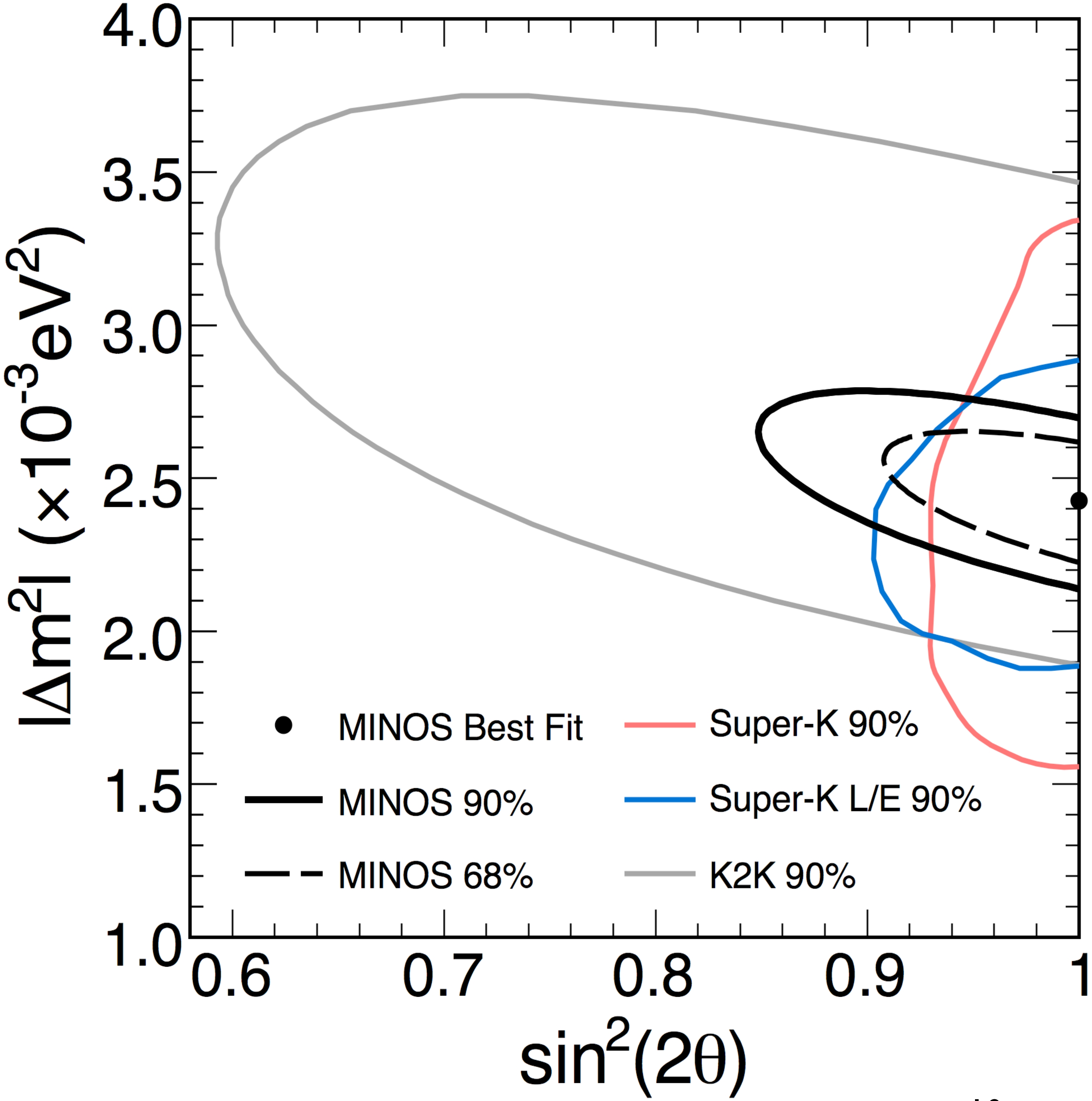


- FD energy spectrum is only looked at after performing:
  - low-level data quality checks
  - procedural checks
- 848 events observed in the FD
- 1065 ± 60 expected with no oscillations

- We fit the energy distribution to the oscillation hypothesis and include nuisance parameters to account for systematics.

Contours

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\,\sin^2(1.27\,\Delta m^2\, L/E)$$



* **Constrained fit:**
  * $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$ (68% CL)
  * $\sin^2(2\theta) > 0.90$ (90% CL)
  * $\chi^2/ndof = 90/97$
* **Unconstrained fit:**
  * $\Delta m^2 = 2.33 \times 10^{-3}\ eV^2$
  * $\sin^2(2\theta) = 1.07$
  * $\Delta\chi^2 = -0.6$

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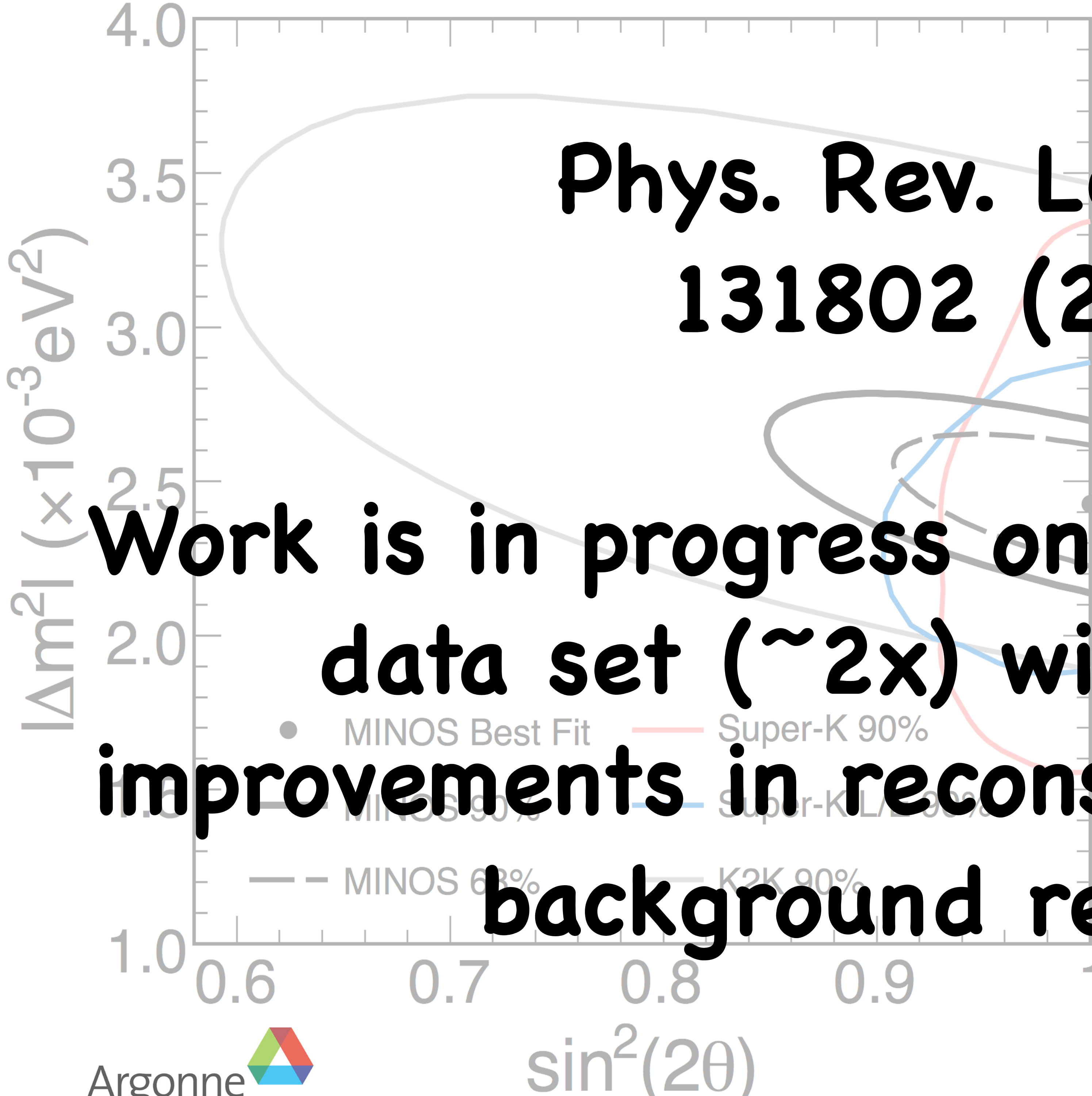
Contours

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\,\sin^2(1.27\,\Delta m^2\,L/E)$$

Details in

Phys. Rev. Lett. 101, 131802 (2008)



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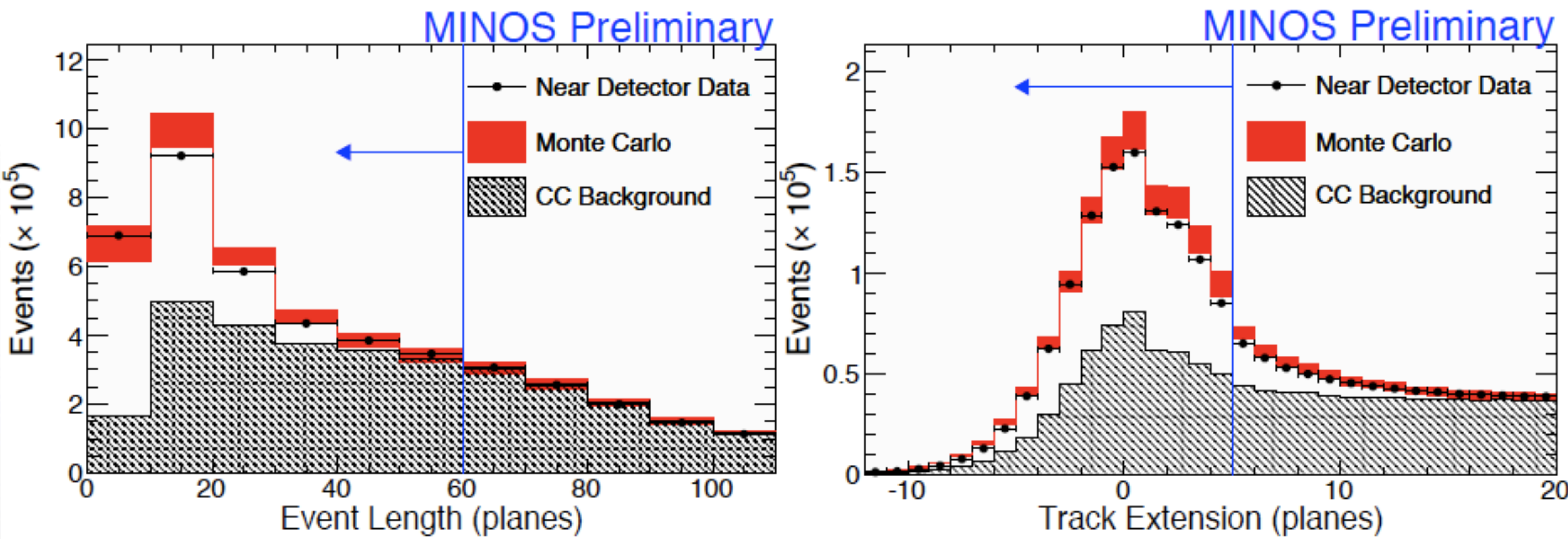
Work is in progress on analysis of larger data set (~2x) with significant improvements in reconstruction, PID and background reductions.

NC Analysis

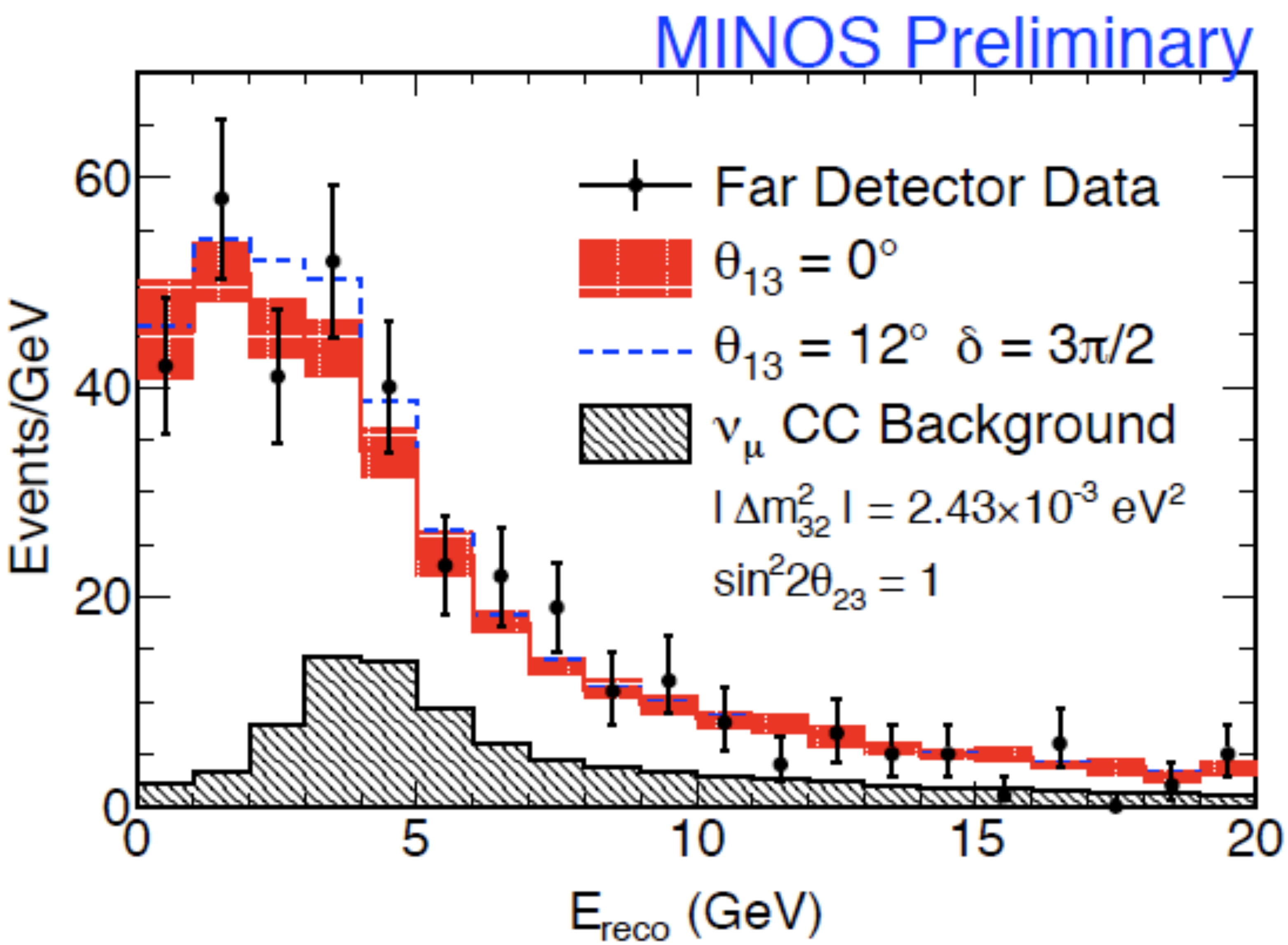
The search for sterile neutrinos

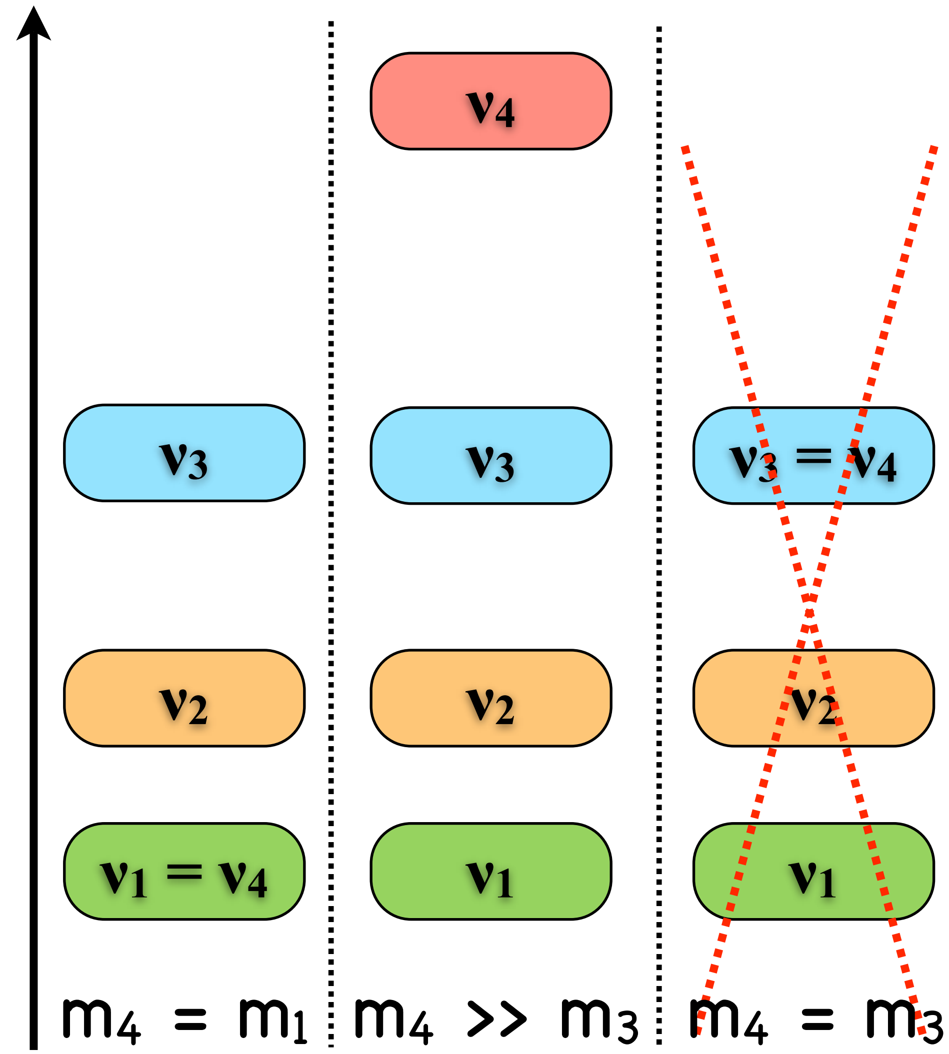
NC Event Selection in the ND



* Since NC events probe active flavors, a depletion of NC events in the FD can only be explained by ν_s.
* We select reconstructed "shower-like" (short) events that fall within a fiducial volume.

FD NC Energy Spectrum + Fit Models





SNO results

Model	θ_{13}	χ^2/D.O.F.	θ_{23}	θ_{24}	θ_{34}	f_s
$m_4 = m_1$	0	47.5/39	$45.0^{+9.0}_{-8.9}$	-	$0.1^{+28.7}_{-0.1}$	0.51
	12	46.2/39	$47.1^{+8.8}_{-11.0}$	-	$23.0^{+22.6}_{-24.1}$	0.55
$m_4 \gg m_3$	0	47.5/38	$45.0^{+9.0}_{-8.9}$	$0.0^{+7.2}_{-0.0}$	$0.1^{+28.7}_{-0.1}$	0.52
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$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}}$$

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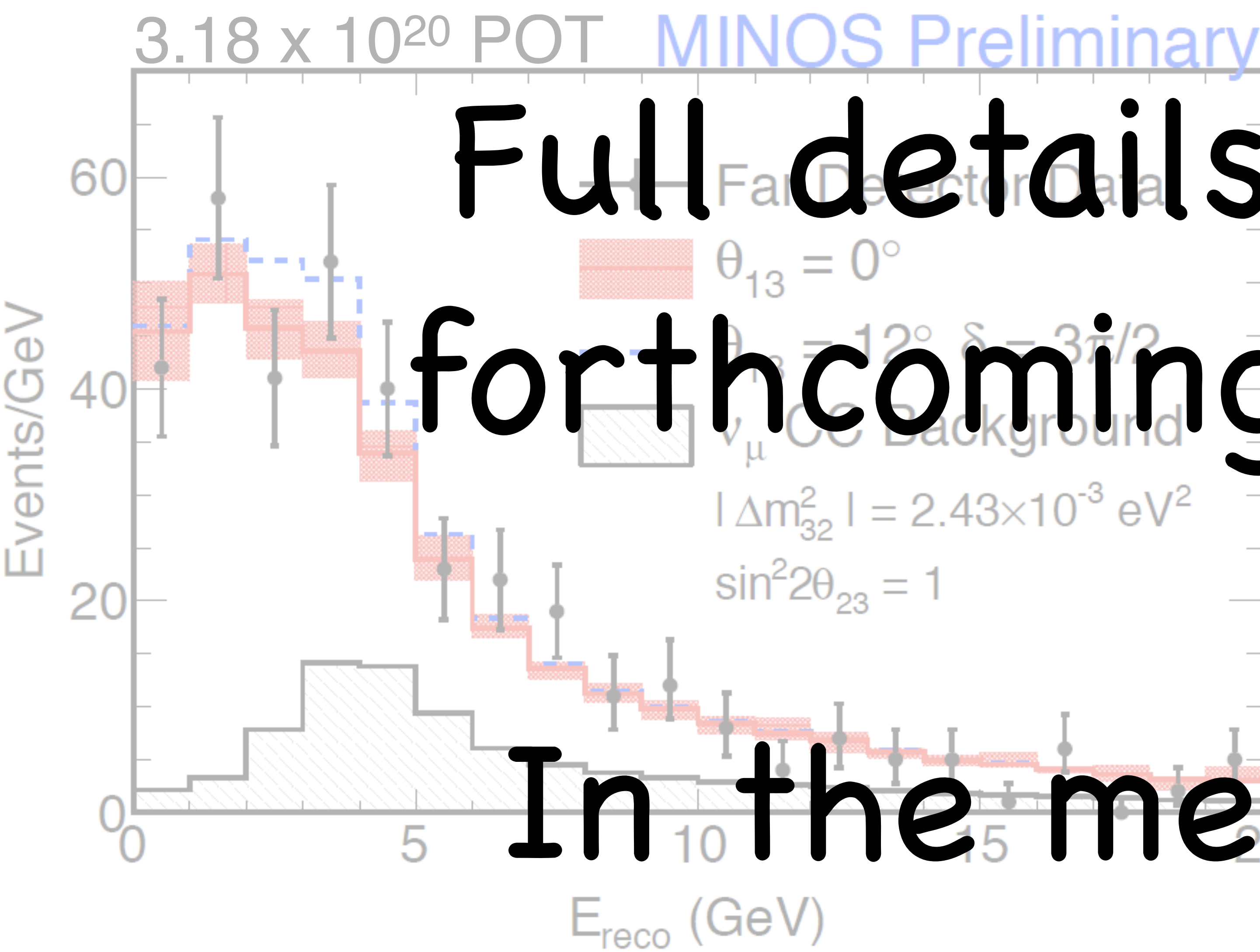
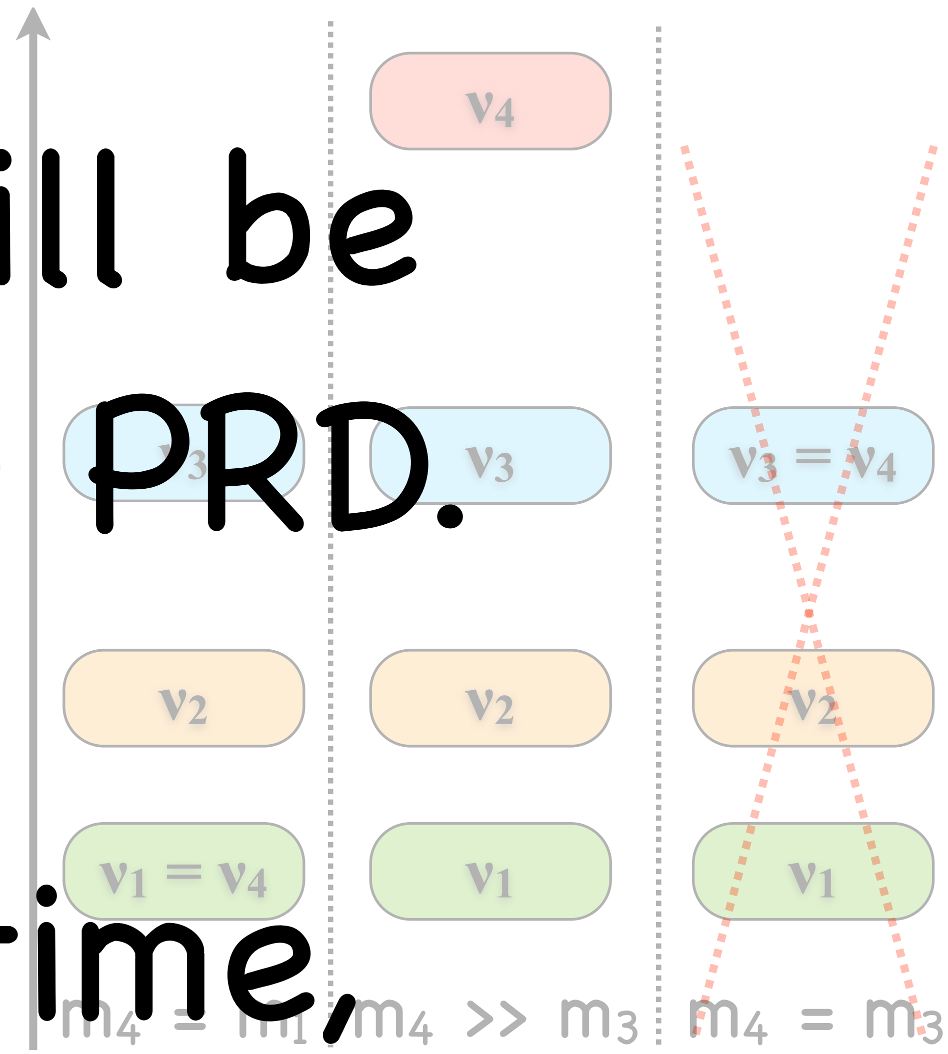
FD NC Energy Spectrum + Fit Models





SNO results

Full details will be forthcoming in PRD.

In the meantime, see hep-ex 1001.0336

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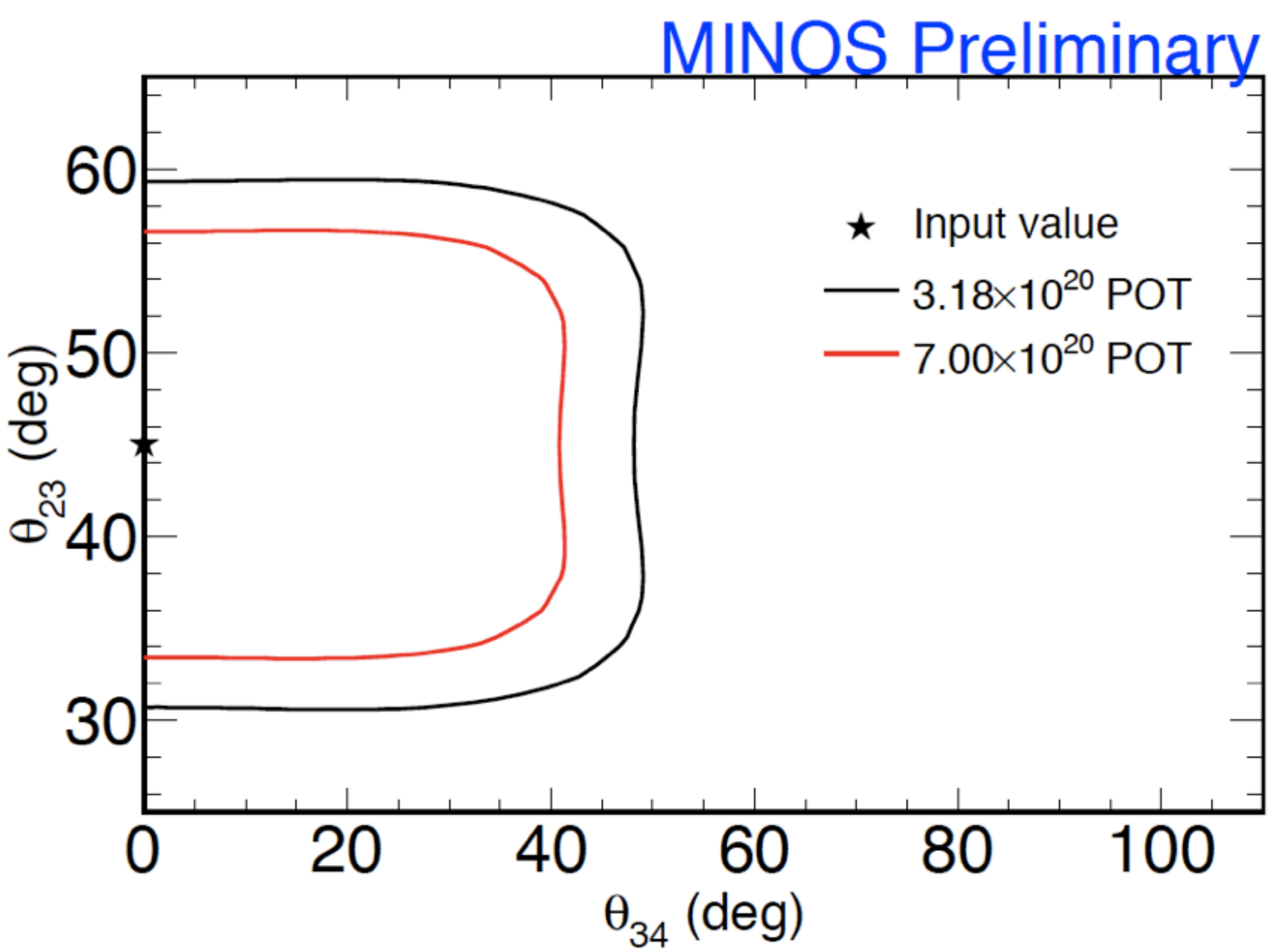
$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}}$$

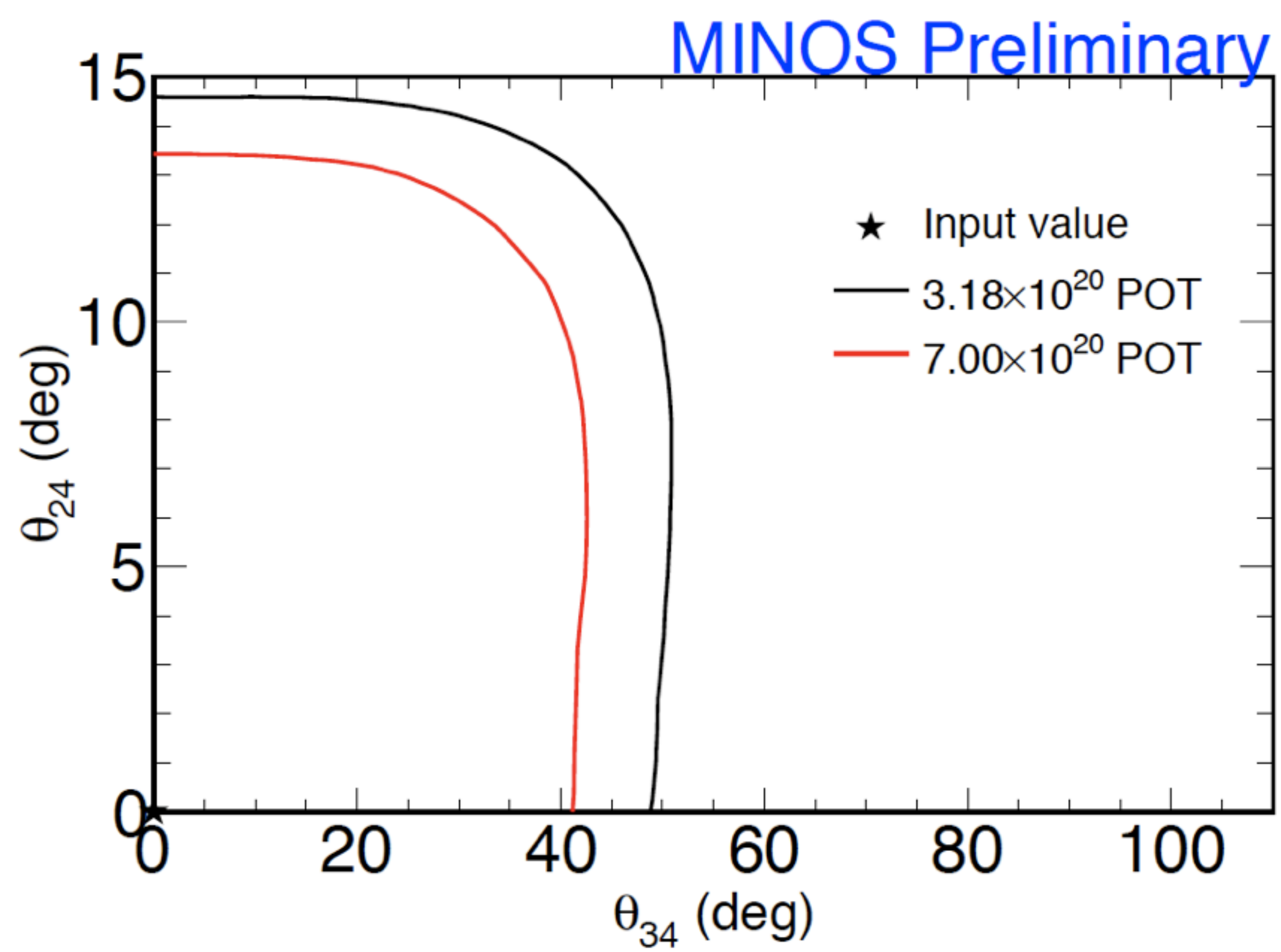
Future Prospects of ν_s Analysis

* A ~2x larger data set (7 x 10^{20} POT) is currently being analyzed, and improvements in several systematics are expected.

$m_4 \equiv m_1$ model



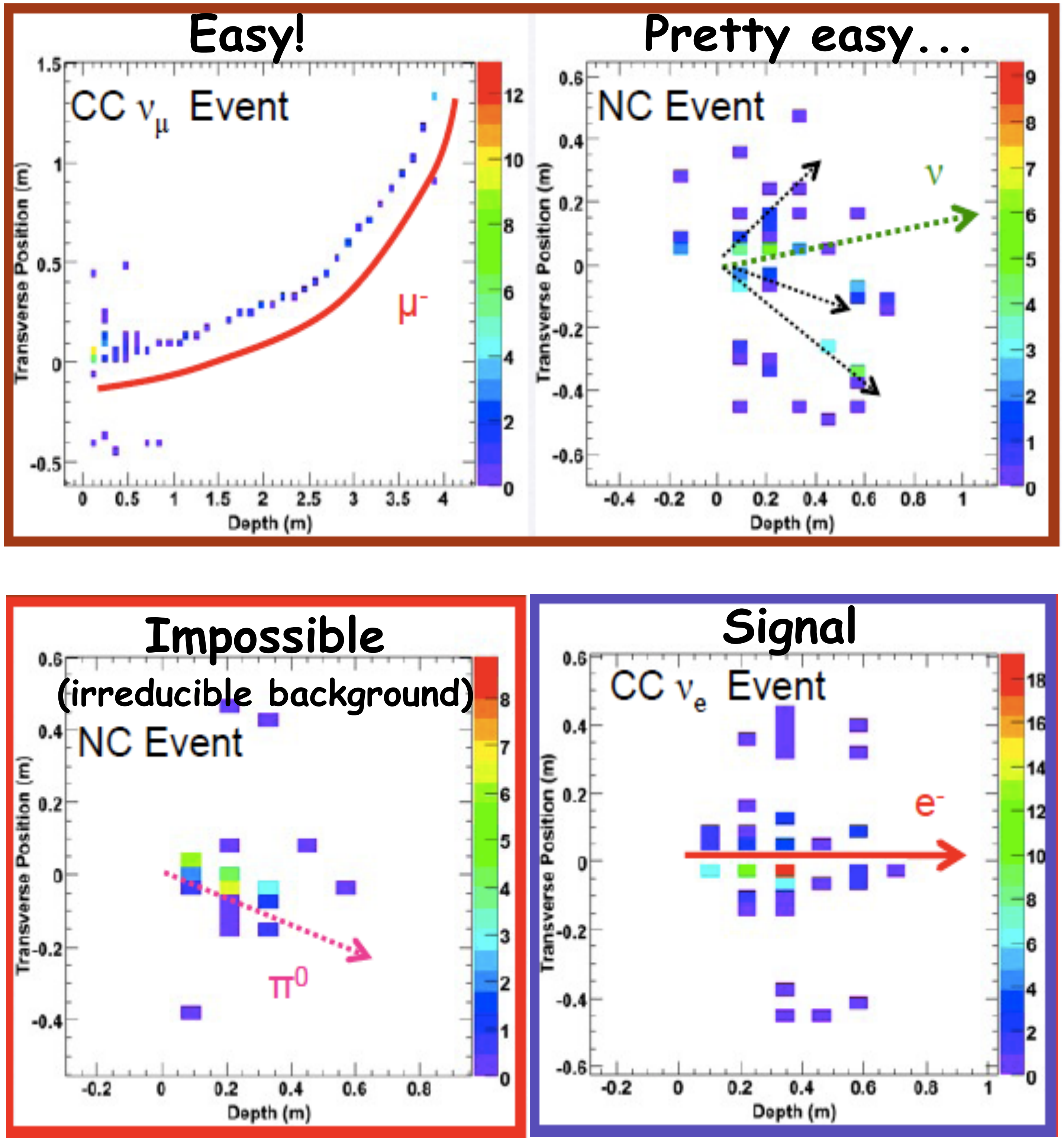
$m_4 \gg m_3$ model individual contours



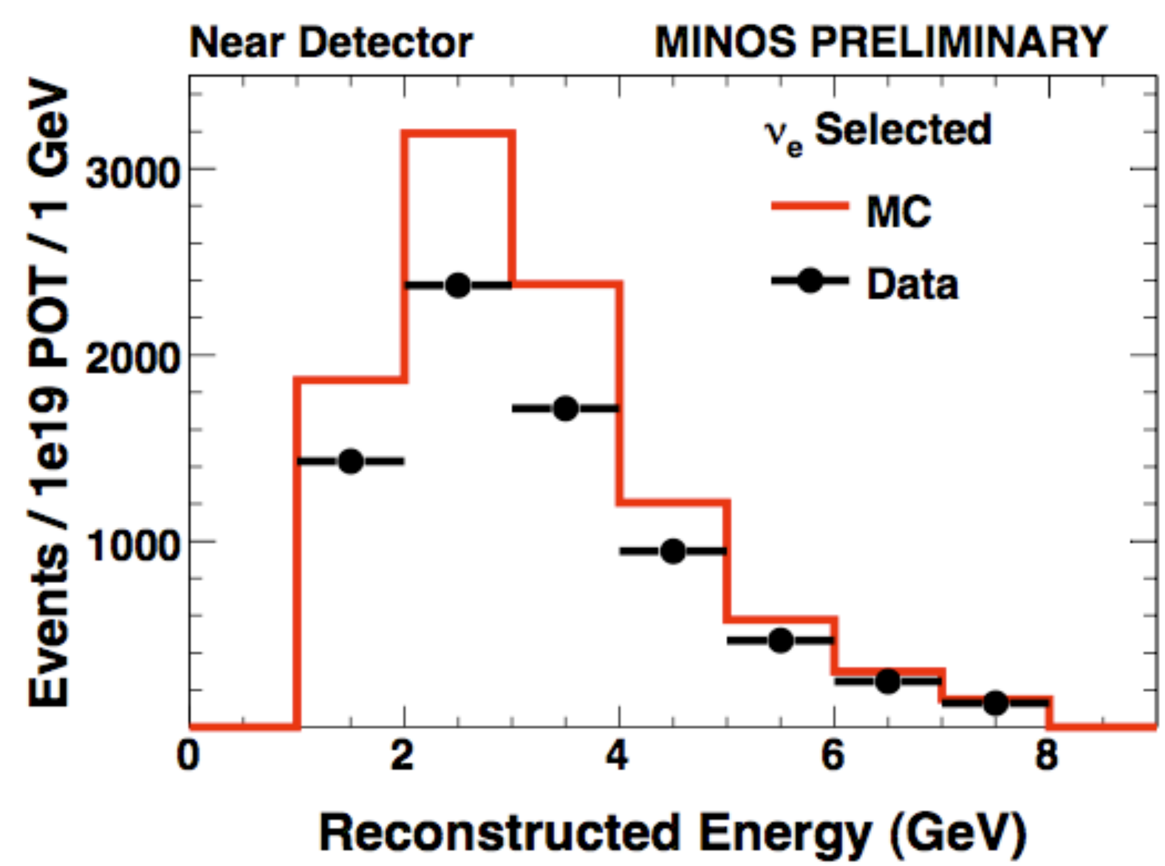
ν_e CC Analysis

The search for ν_e appearance

ν_e Appearance – Challenging Analysis!



* Measurement dominated NC and ν_μ CC backgrounds.
* We see a very large discrepancy between selected ν_e ND MC and data events.
* Two data-driven methods have been developed to resolve the MC/data difference.



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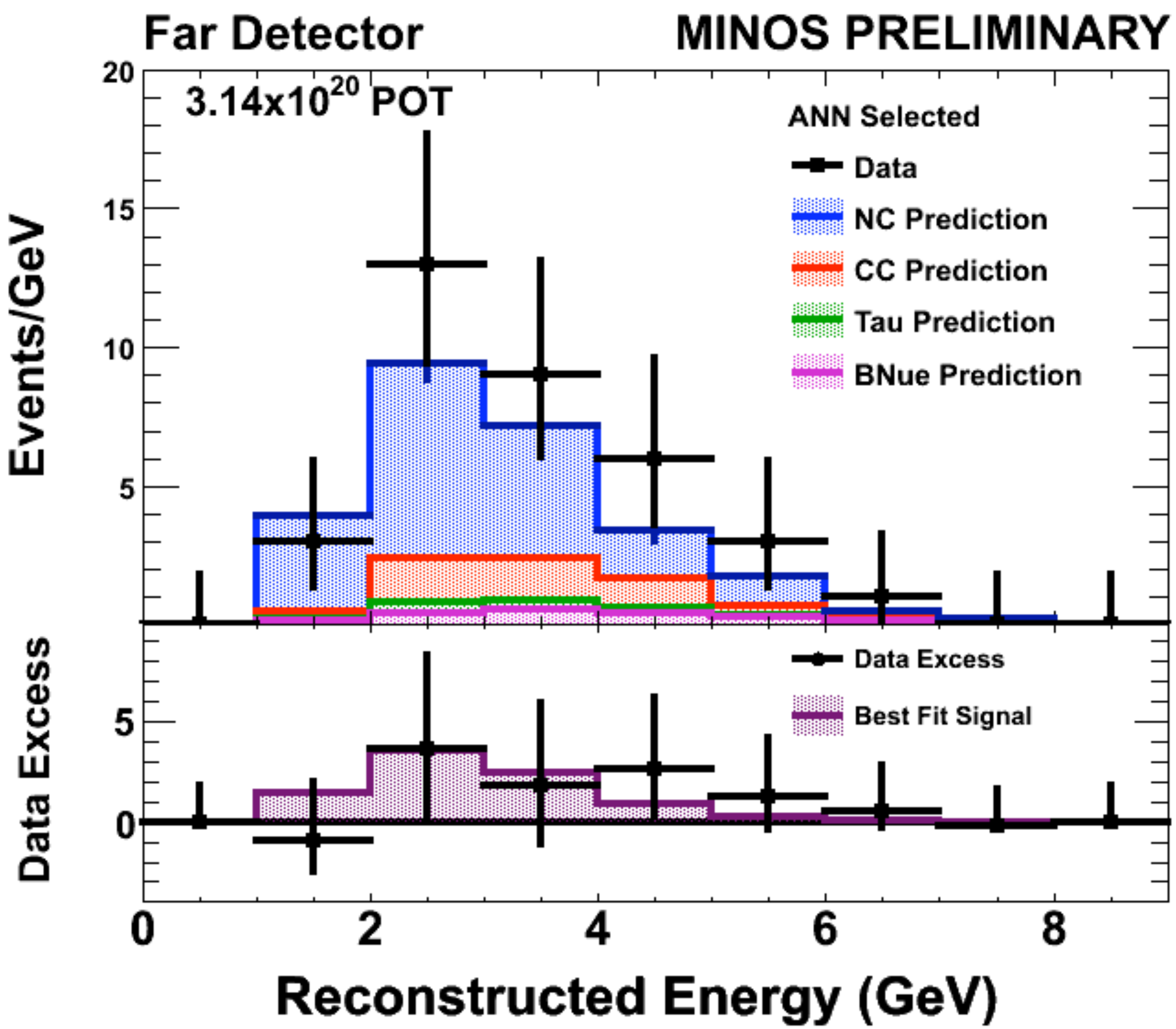
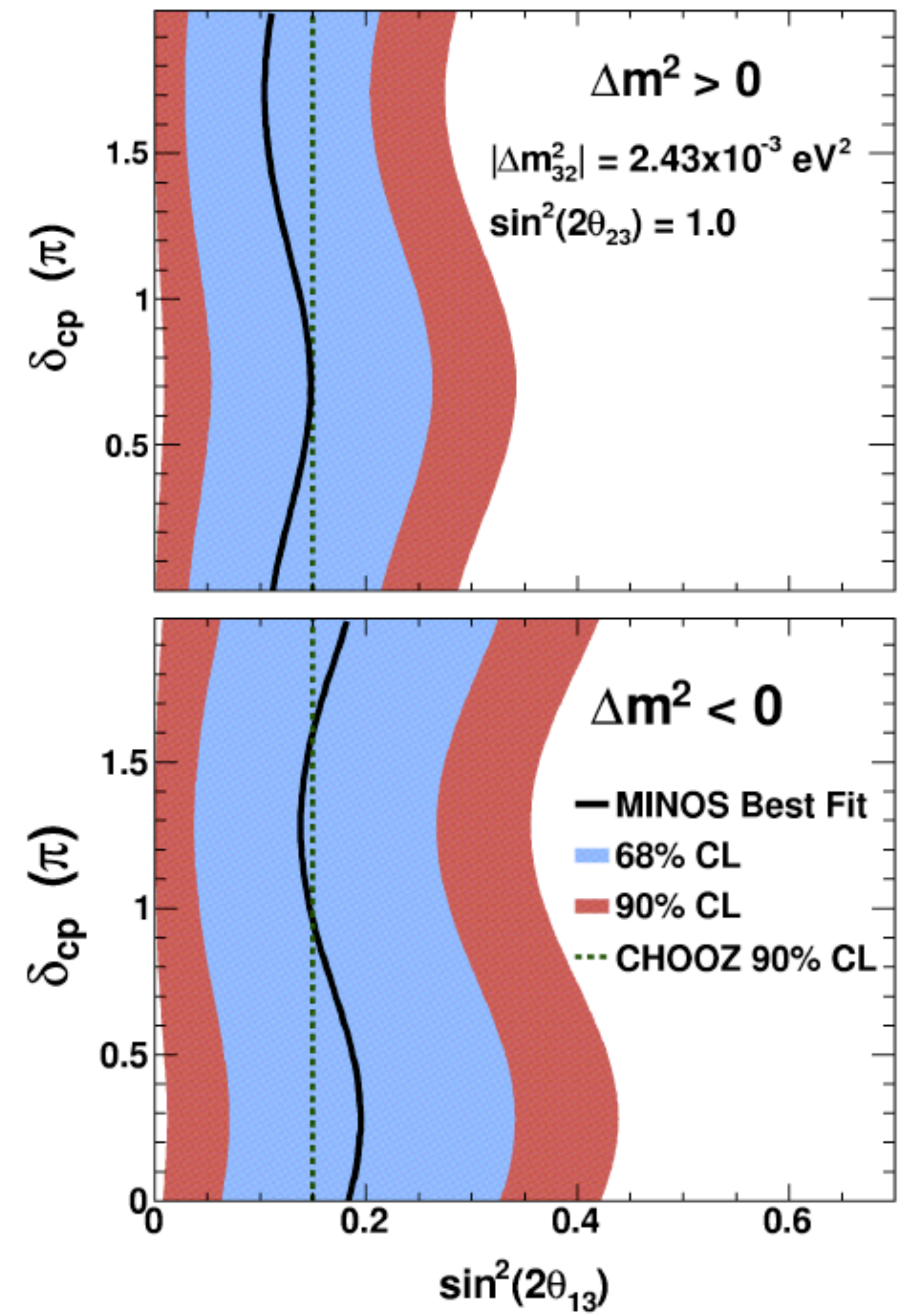
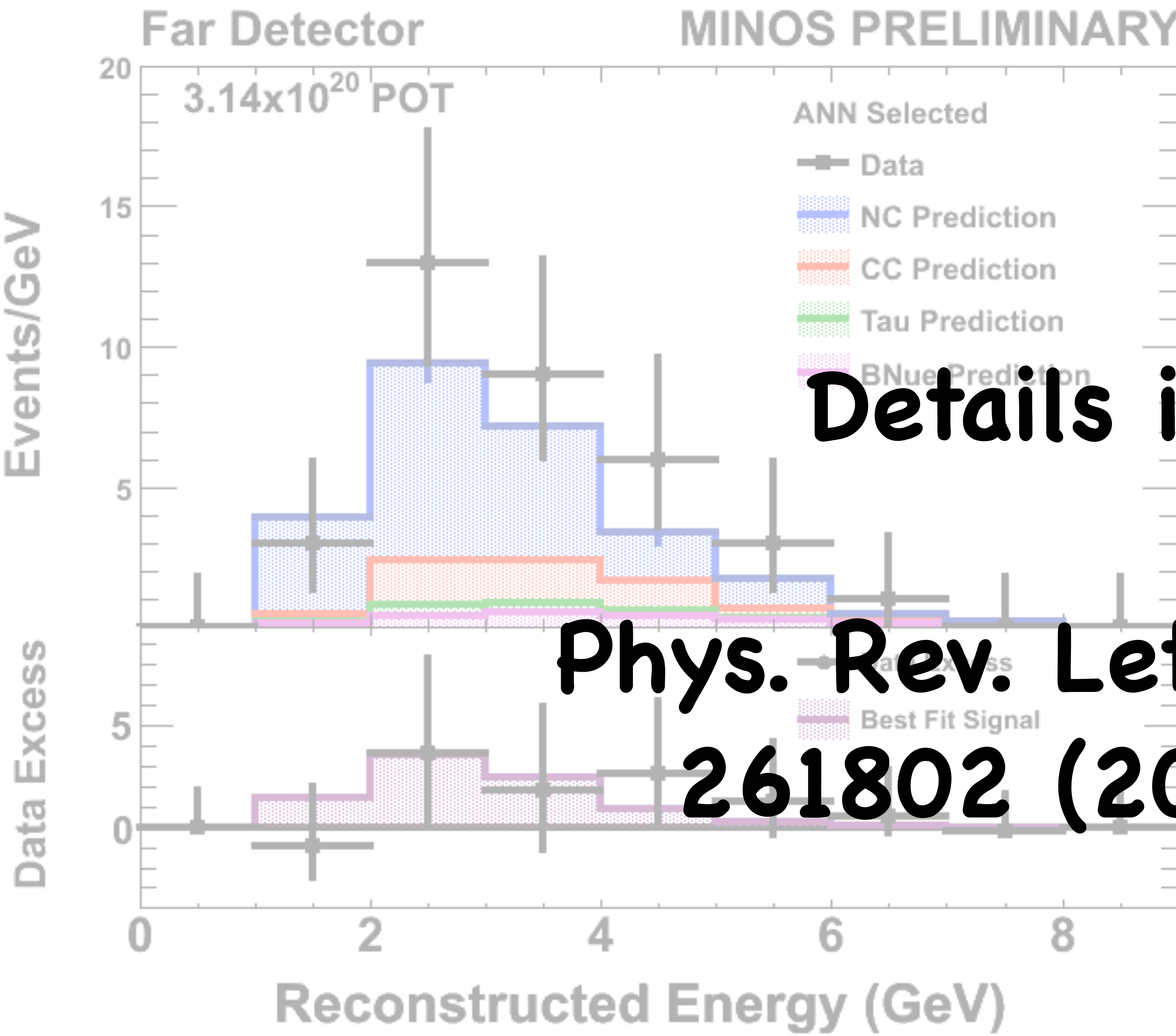
ν_e 3x10^{20} POT Results

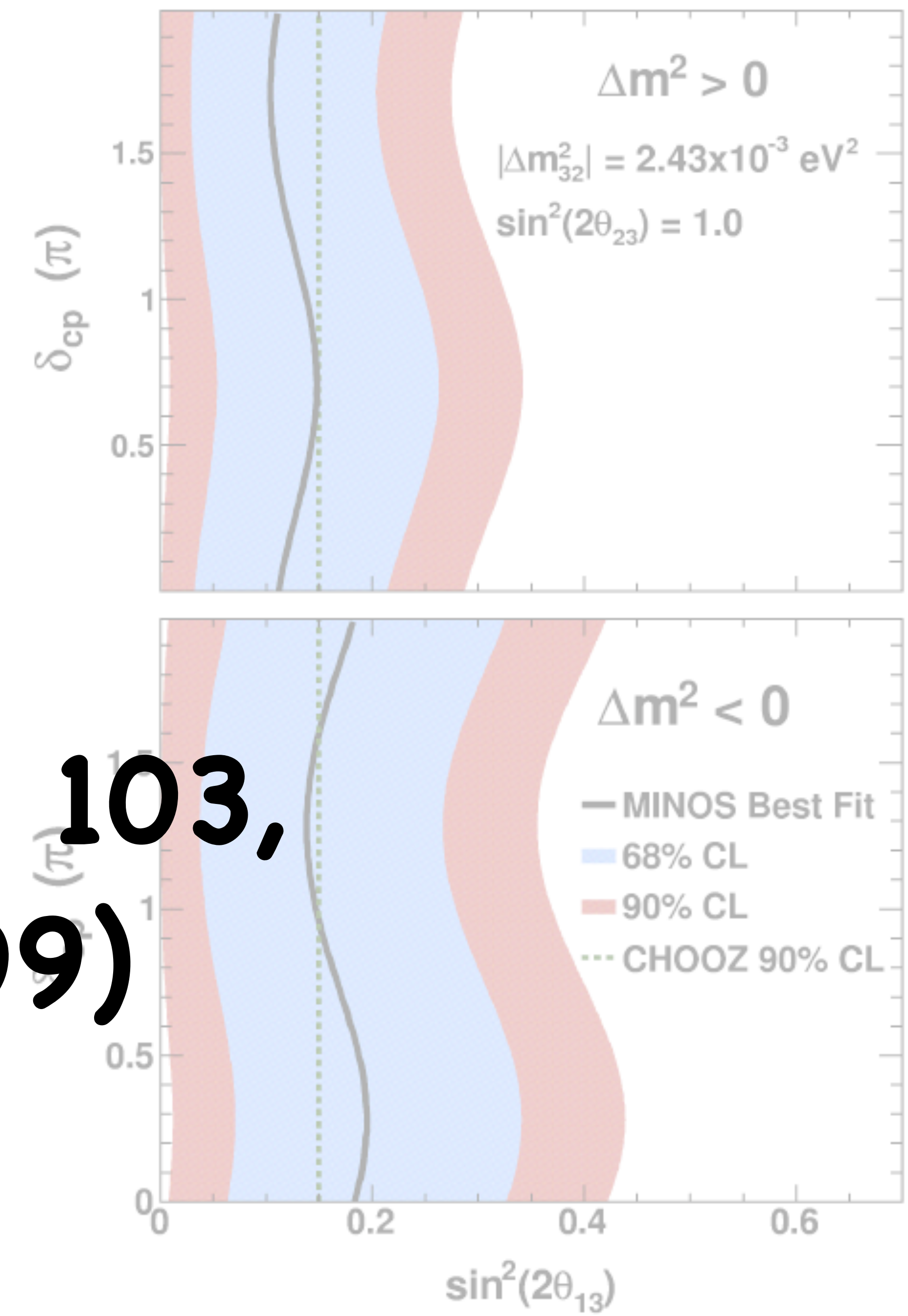




- We observe 35 events, and expect 27 ± 5 (stat) ± 2 (syst) events.
- Results are 1.5 σ high; $\sin^2(2\theta_{13})$=0 is included at the 92% level.

ν_e 3×10^{20} POT Results



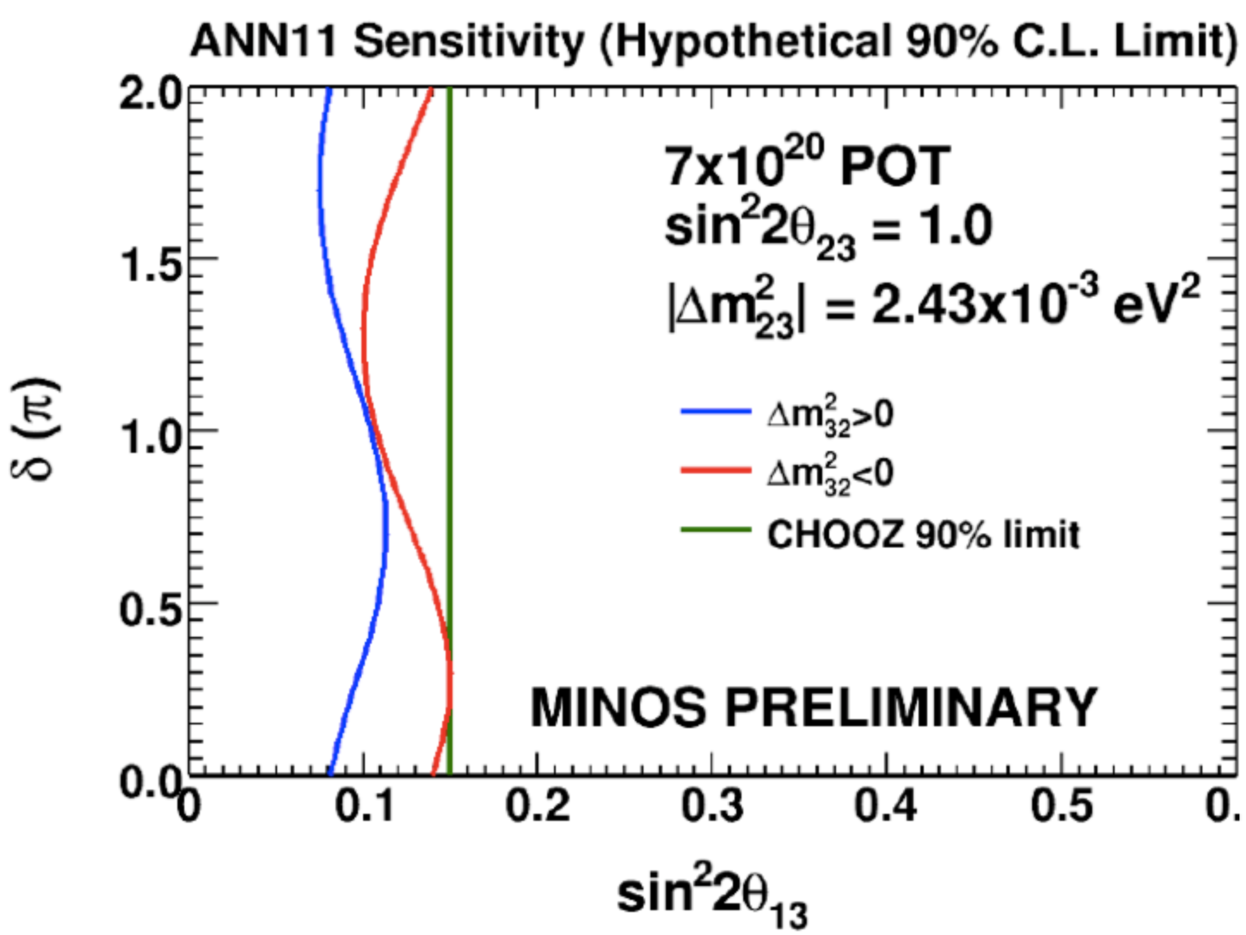


Details in

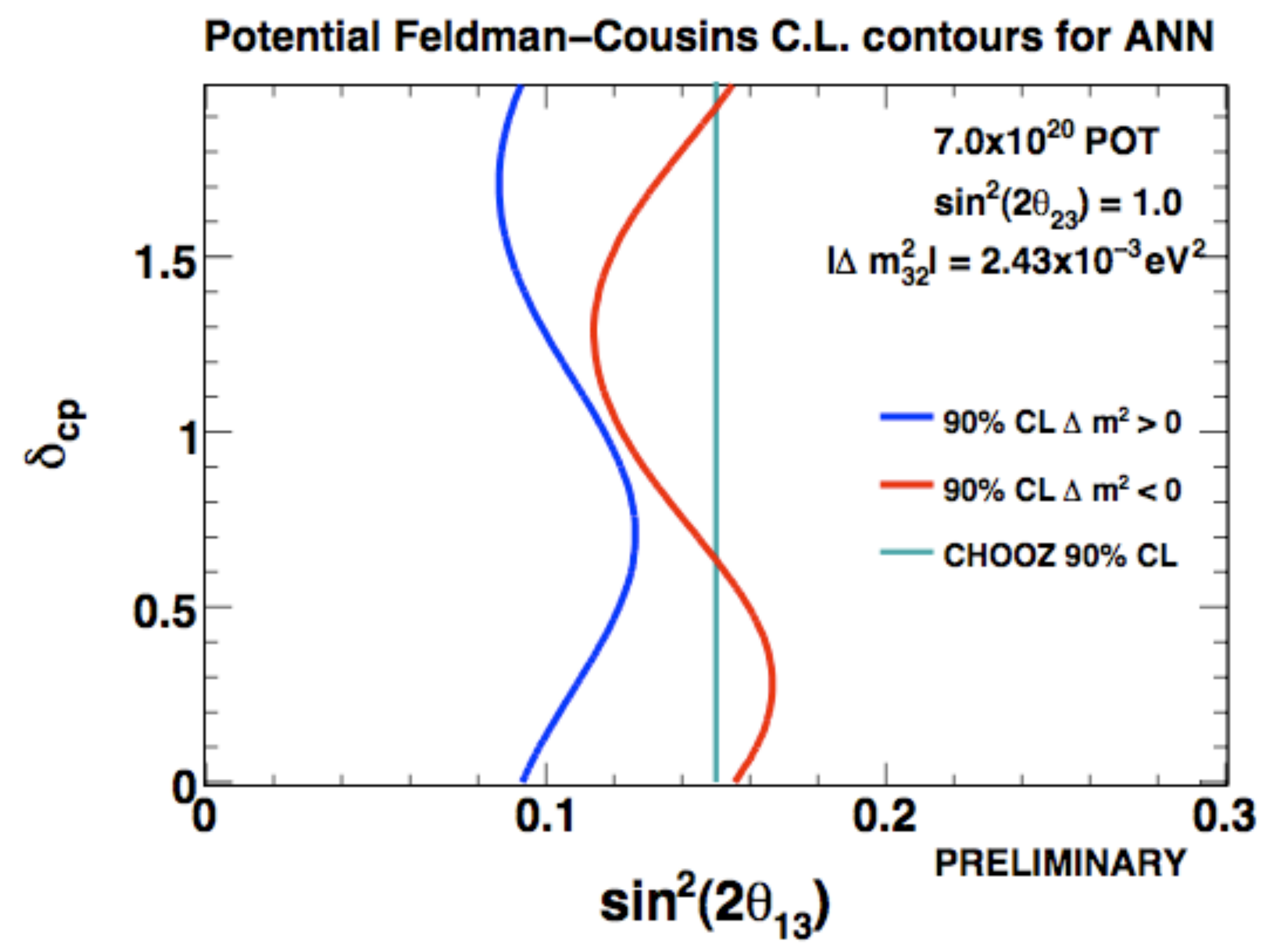
Phys. Rev. Lett. 103, 261802 (2009)

* We observe 35 events, and expect 27 ± 5 (stat) ± 2 (syst) events.
* Results are 1.5 σ high: $\sin^2(2\theta_{13})=0$ is included at the 92% level.

Forthcoming Updated ν_e Results



If we observe exactly our BG prediction.



If the data excess vanishes...

* Improved analysis of larger data set is now complete:
  * ~2x larger data set
  * Systematics reduced from 10% to 5%
* Results will be presented in April.

Conclusions

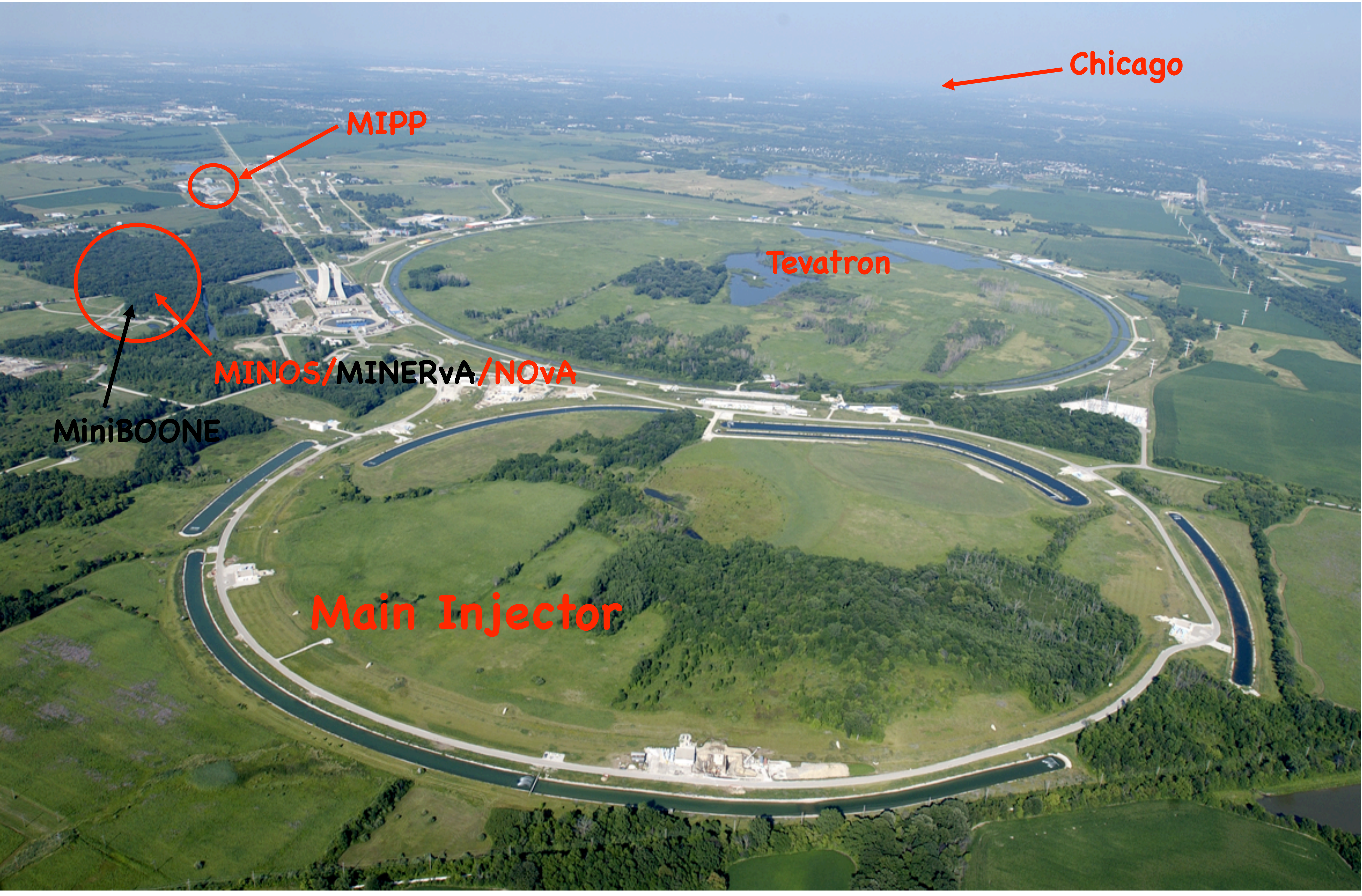
- Latest ν_μ CC analysis results (3.36×10^{20} POT) provide world's best determination of Δm^2_{atm}:
  - $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$ (68% CL),
  - $\sin^2(2\theta) > 0.90$ (90% CL)
- Sterile neutrino analysis results (3.18×10^{20} POT) indicate no strong hint of a fourth, inactive neutrino.
- Results of search for ν_e appearance via θ_{13} (3.14×10^{20} POT) are consistent with Chooz limit.
- Updated results based on improved statistics (x2) and reduced systematics will be forthcoming from MINOS within the next few months - stay tuned!

Future Outlook for Fermilab

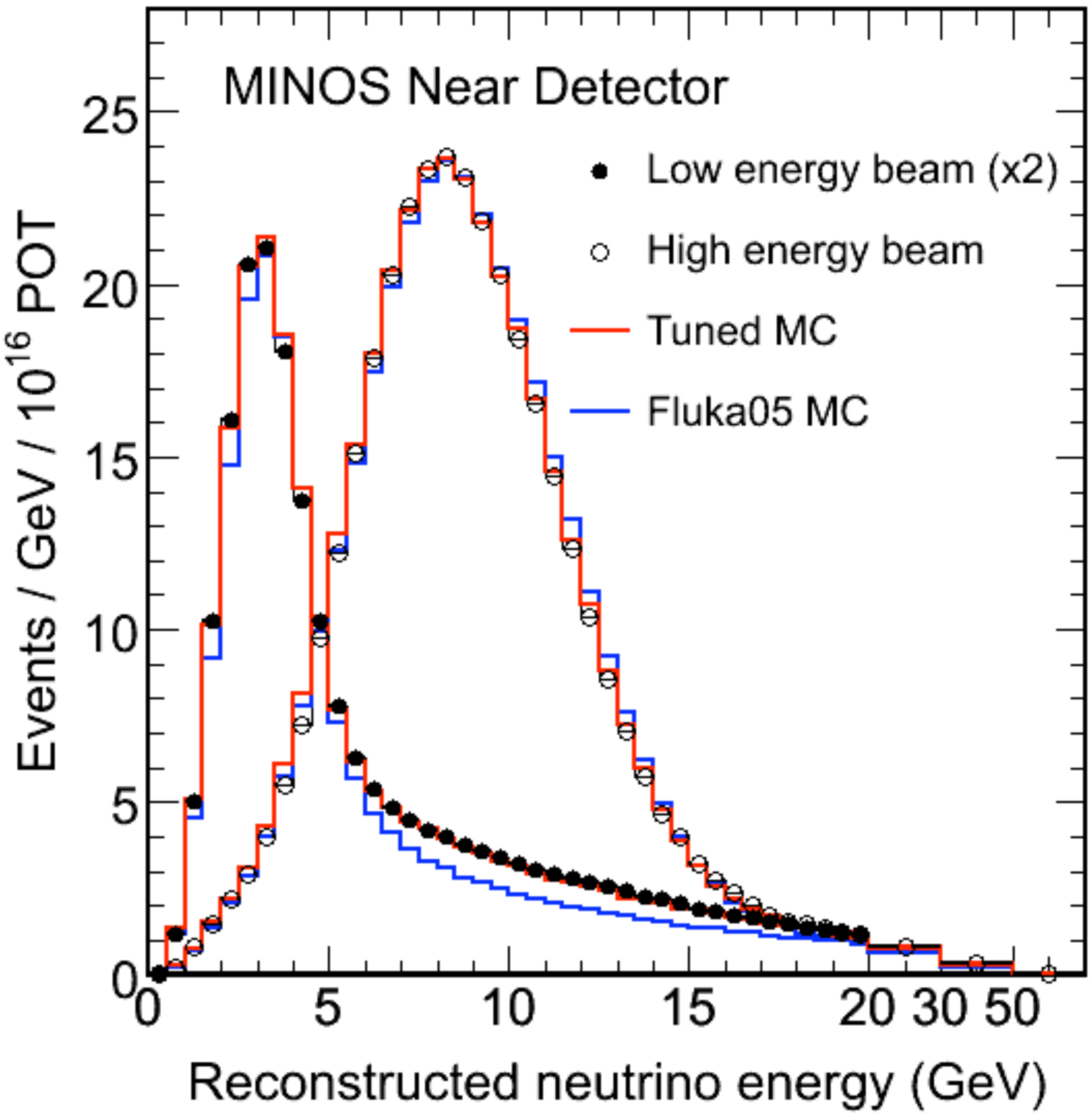
* Lots going on!
* MINERvA
    * precision neutrino cross-sections
    * running, construction complete
* Liquid Argon Program:
    * ArgoNeut (small scale R&D), already seen beautiful neutrino events
    * MicroBooNE (170 ton LAr TPC, construction complete ~2012)
* NOvA
    * off-axis long-baseline experiment, θ_{13}, δ_{CP} & mass-hierarchy
    * construction of FD to begin later this year
    * prototype detector to be built this summer
    * data in 2013, after 700 kW accelerator upgrade
* Long-baseline Neutrino to DUSEL (1300 km, first stage approval from DOE)
* Muon & Kaon Program:
    * Mu2e (comparable sensitivity to COMET, first stage approval from DOE)
    * $(g-2)_\mu$/EDM under consideration
    * $K \rightarrow \pi^+ \nu\nu$

Backup Slides

Neutrino Program at FNAL

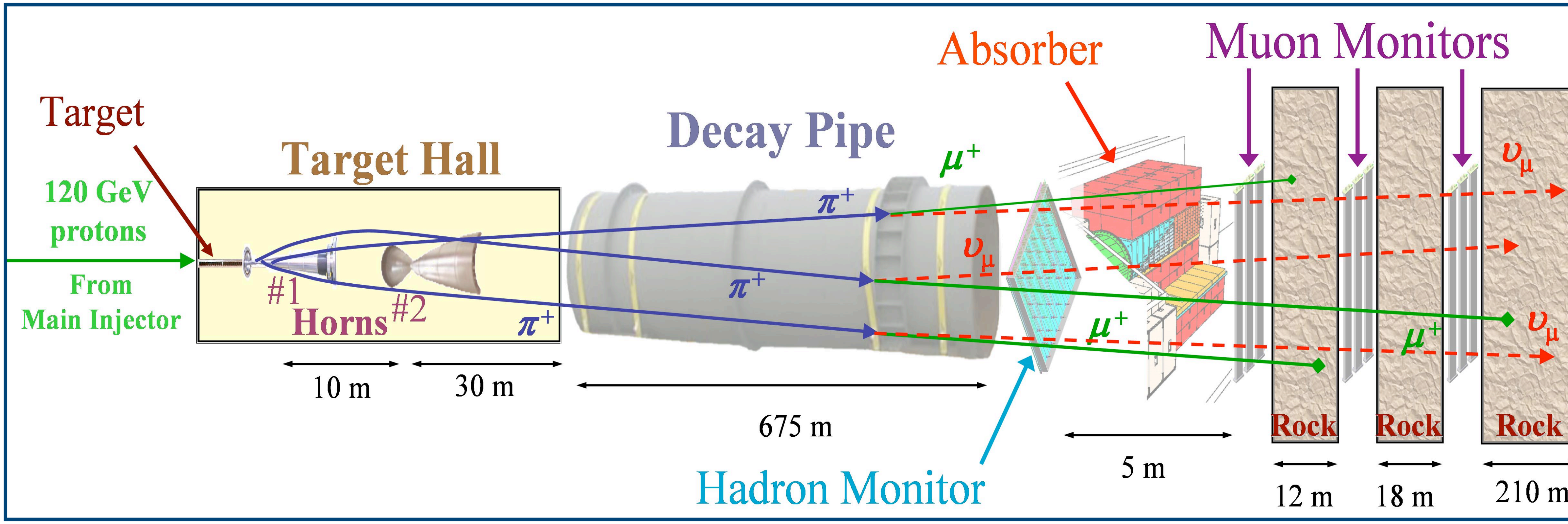


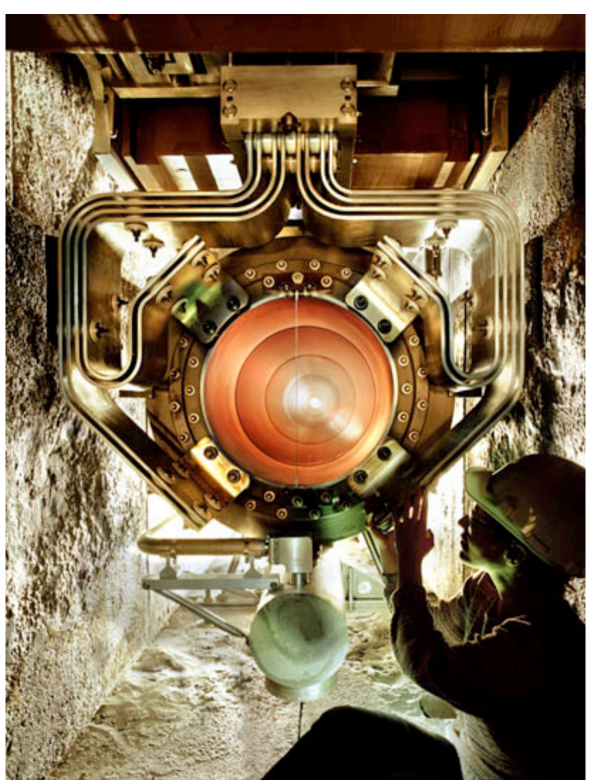
Predicting the Flux



- MINOS uses Fluka MC to predict the ν flux.
- Uncertainty on flux is ~30% due to lack of hadron production data.
- To improve our data-to-MC agreement, we tune the Fluka MC to ND energy spectra of different beam configurations.
- These beam-reweighted spectra are used in all analyses discussed today.

Producing Neutrinos at the Main Injector





- Neutrinos are produced from secondary mesons created in 120 GeV/c p + graphite target interactions.
- The secondary mesons are focused by two magnetic horns; ν beam energy is tunable by moving target position longitudinally w.r.t. the horn positions.
- In LE beam configuration, beam is composed of 92.9% ν_μ, 5.8% $\bar{\nu}_\mu$, and 1.3% ν_e and $\bar{\nu}_e$.

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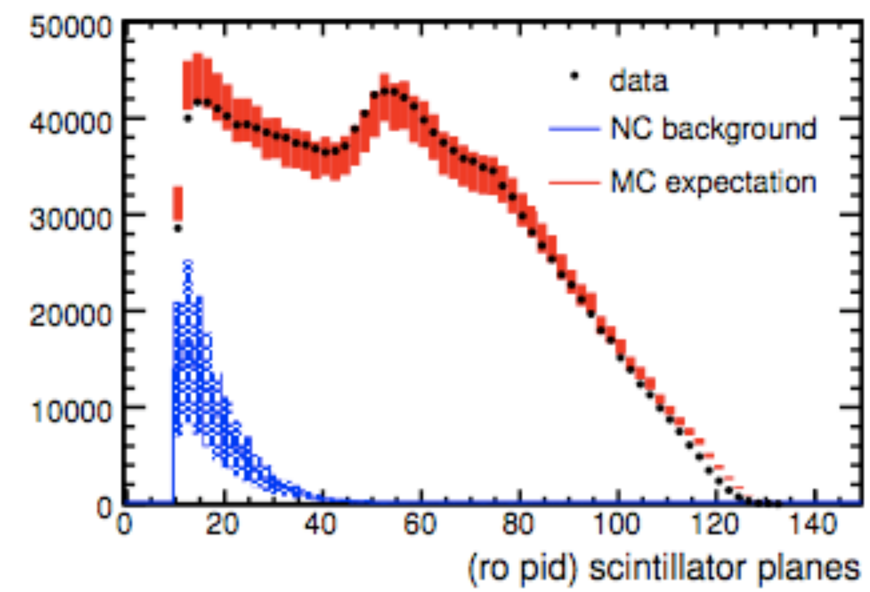
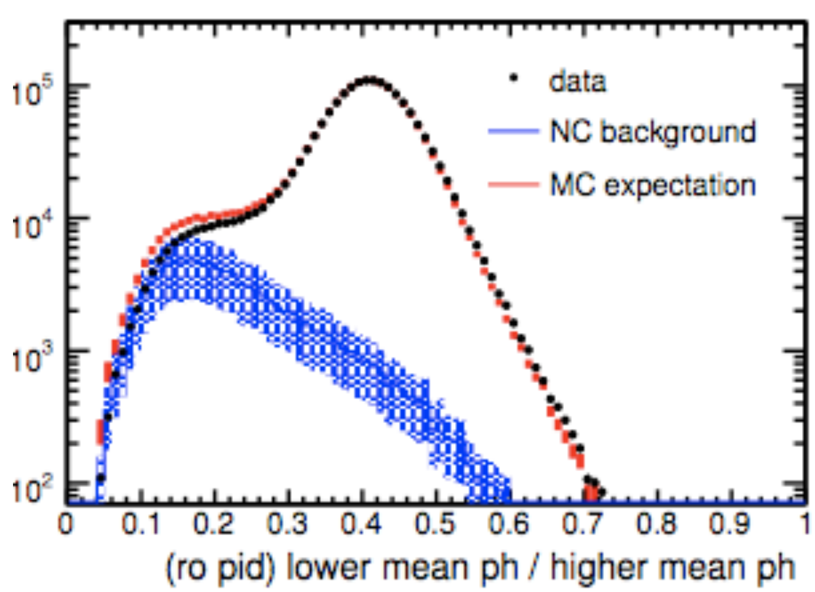
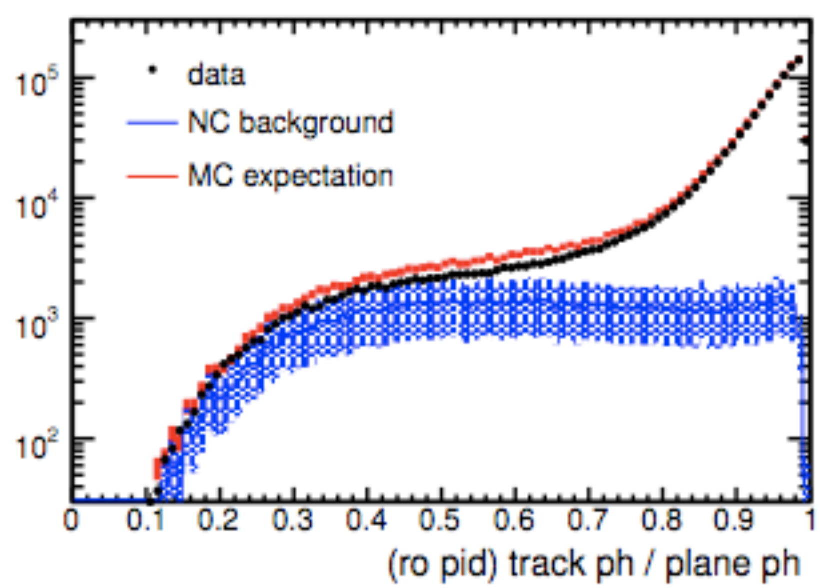
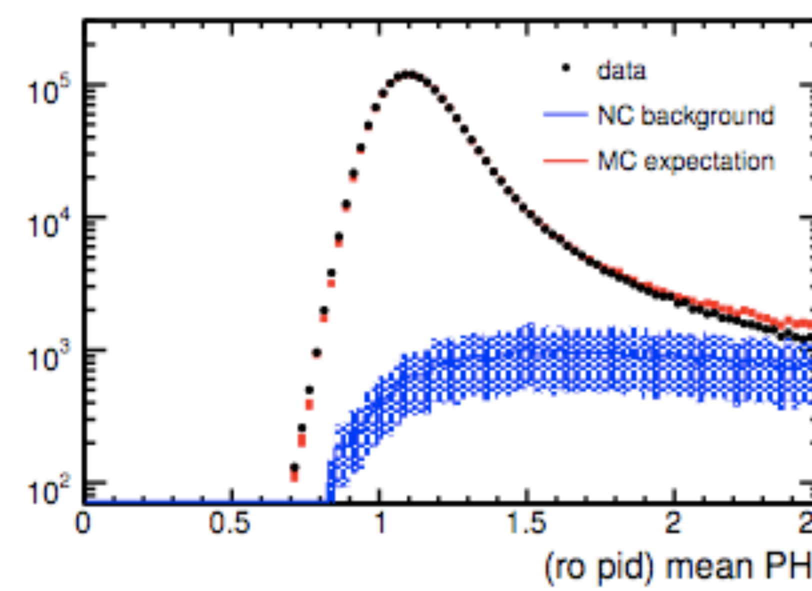
ν_μ CC/NC Separation

* CC/NC separation achieved via a kNN event selection based on:
  * Track length
  * Mean pulse height
  * Fluctuation in pulse height
  * Transverse track profile

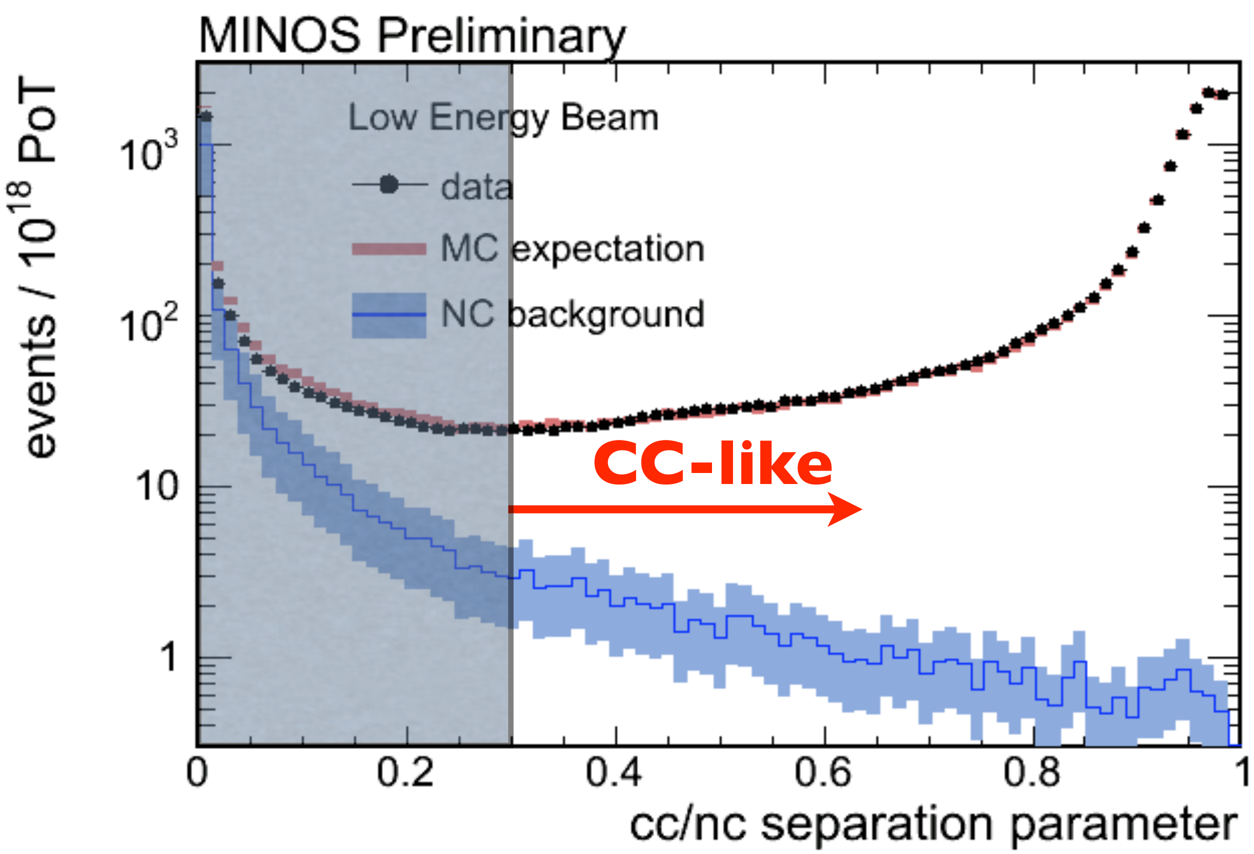


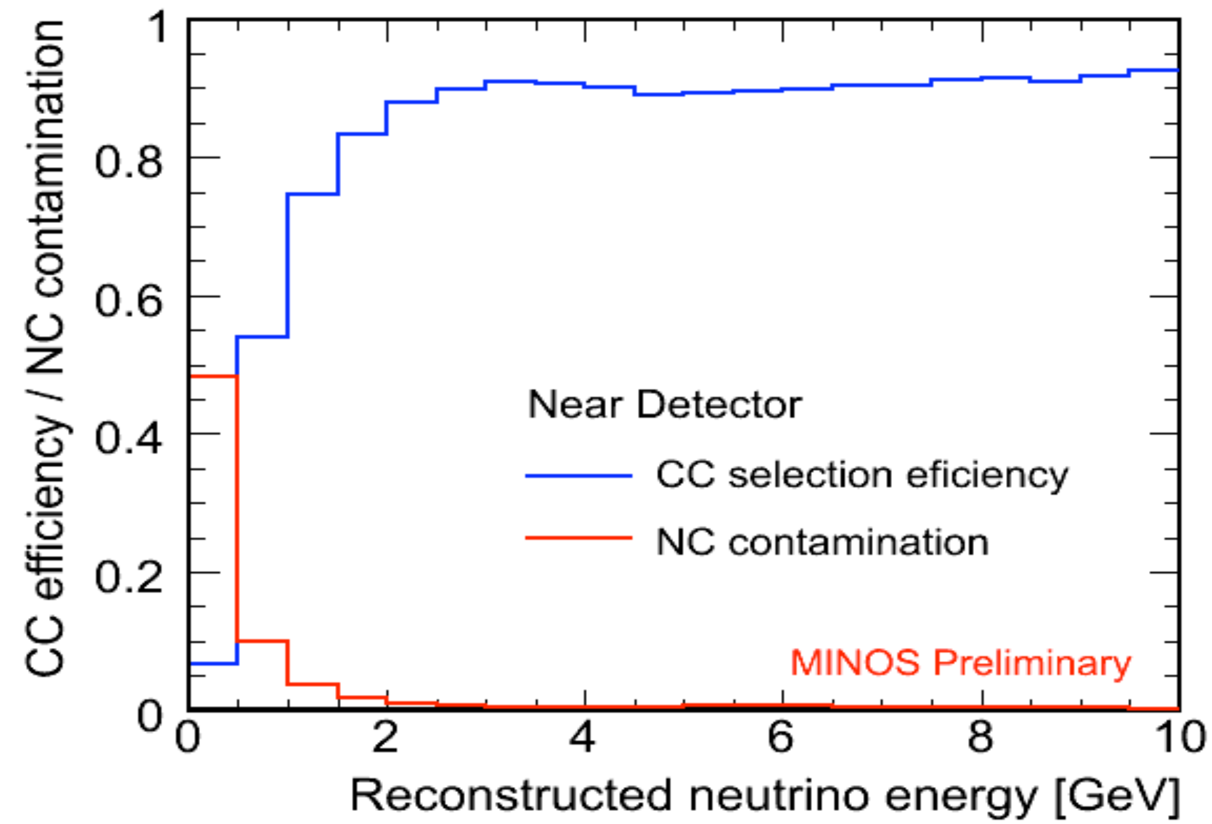






ν_μ CC Event Selection

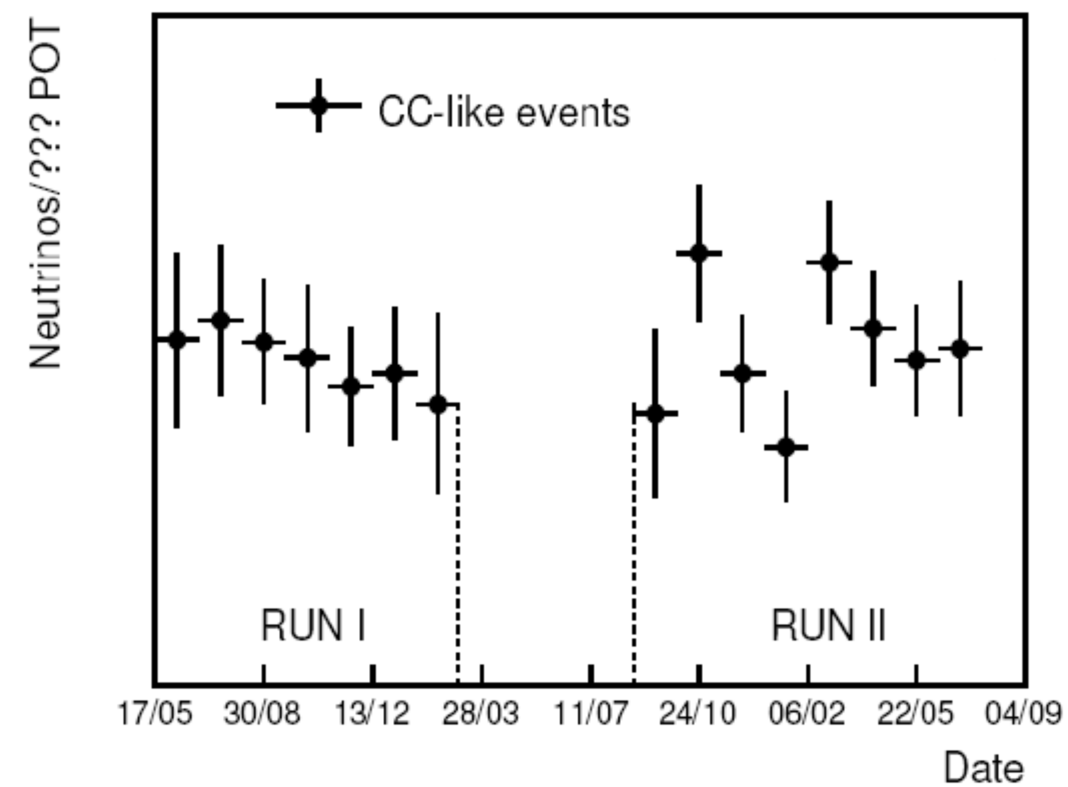


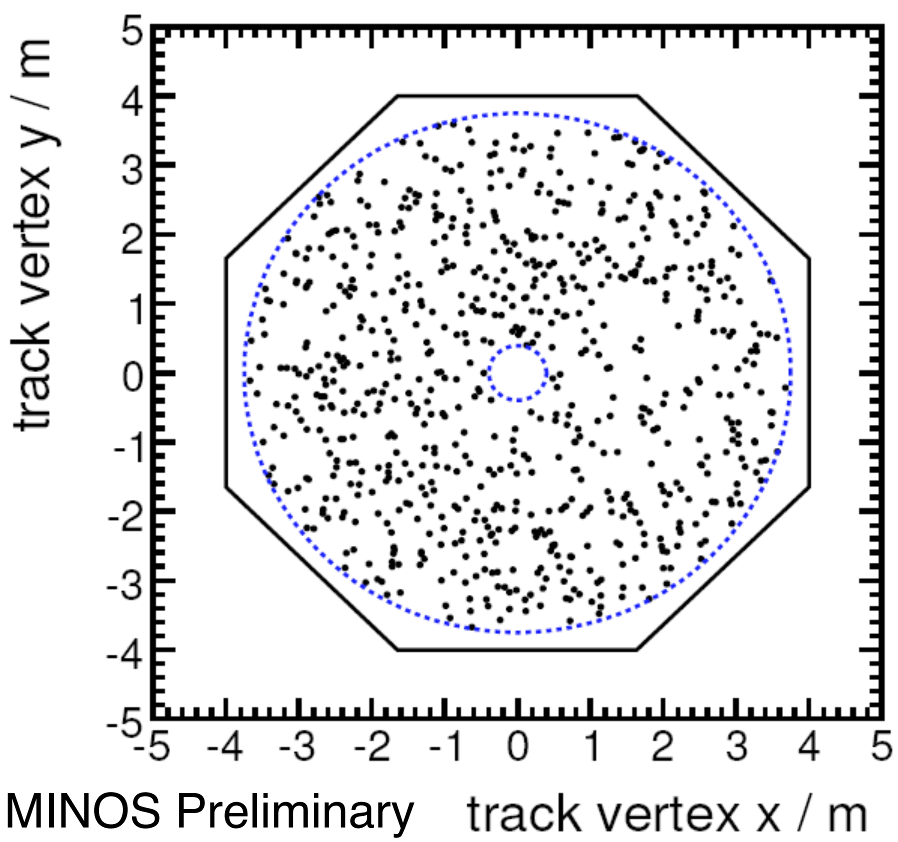


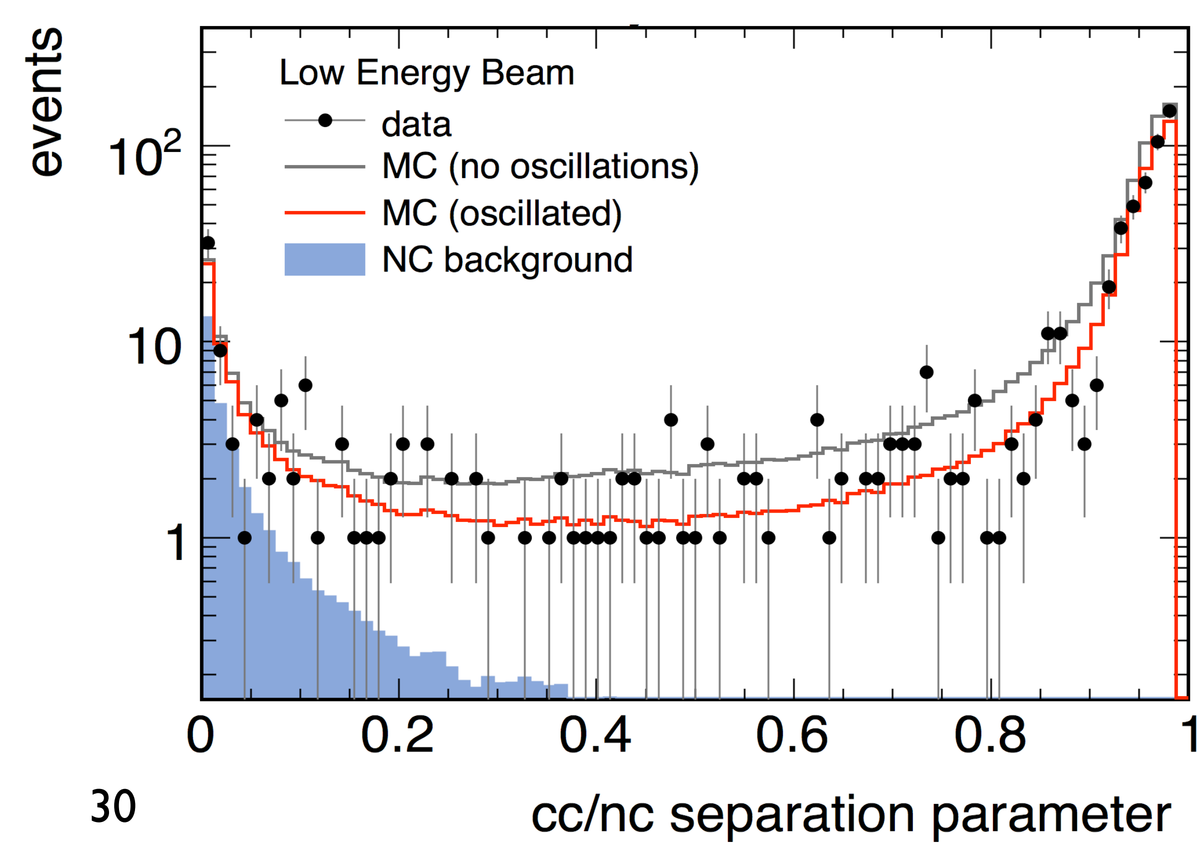
- Cut on separation parameter maximizes CC selection efficiency and minimizes NC background.
- Good agreement between data and MC above the CC/NC separation parameter cut.

Far Detector Low-level Data Quality Checks

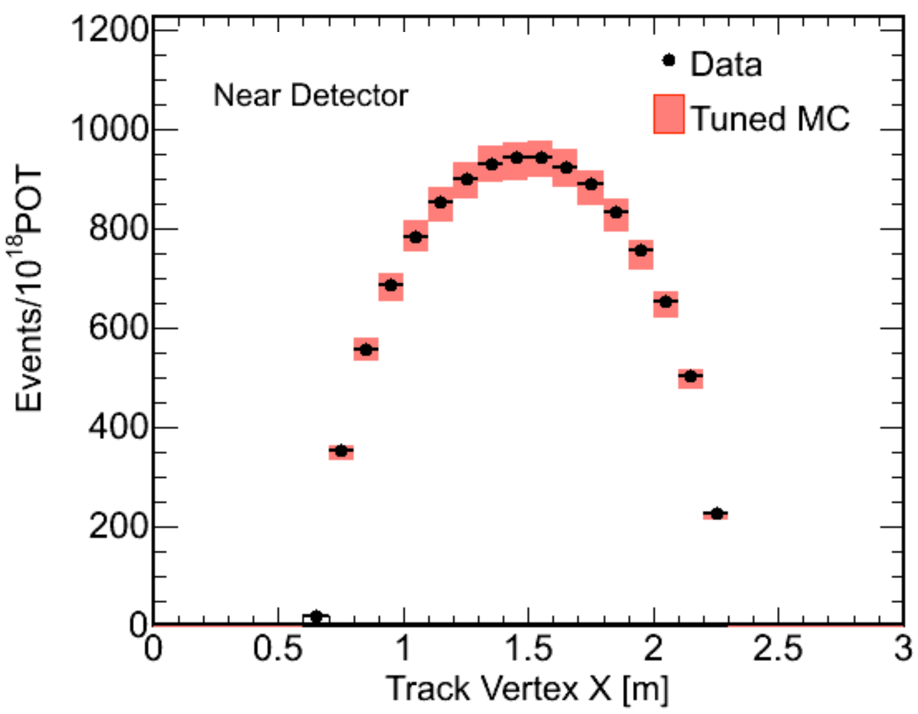
* FD energy spectrum is only looked at after performing:
  * low-level data quality checks
  * procedural checks

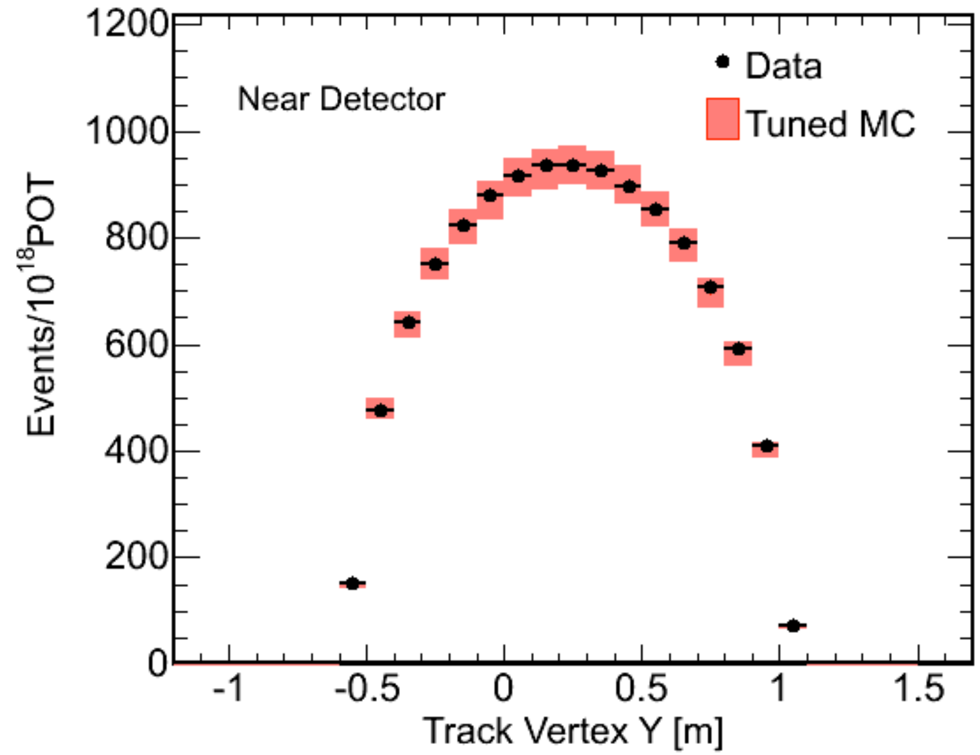


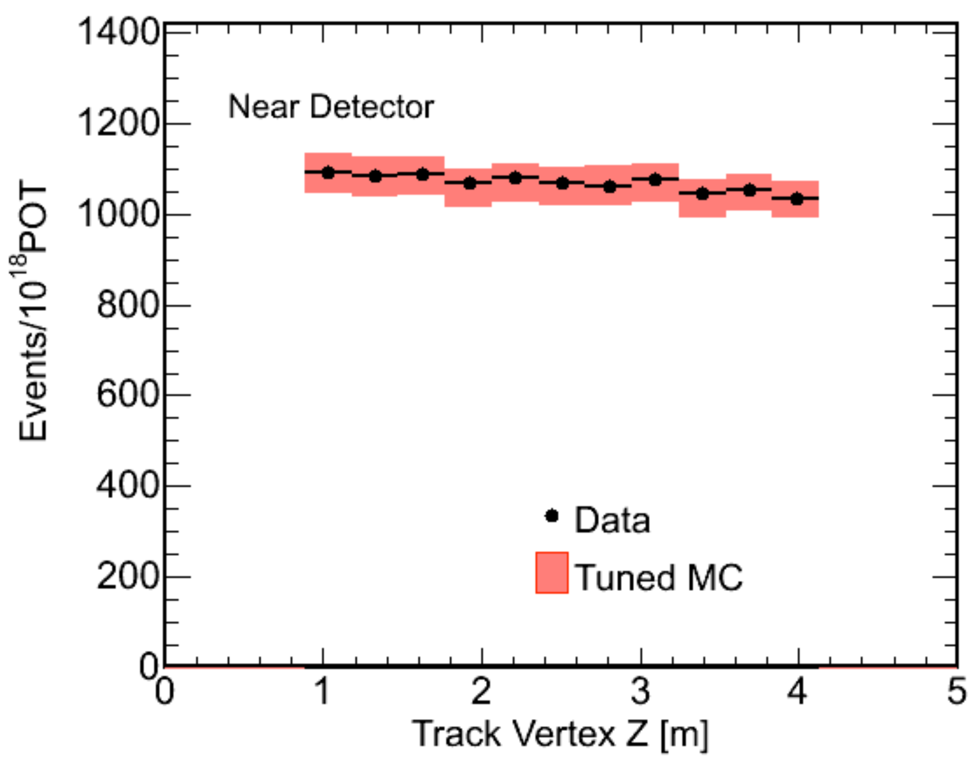




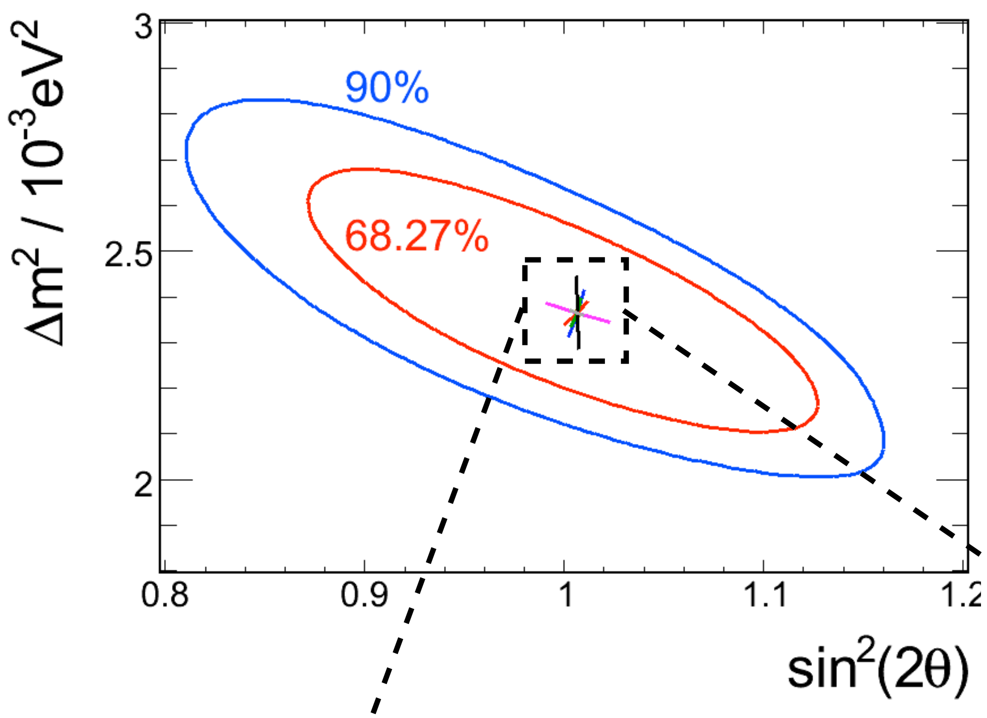
ND Distributions After Making PID Cut



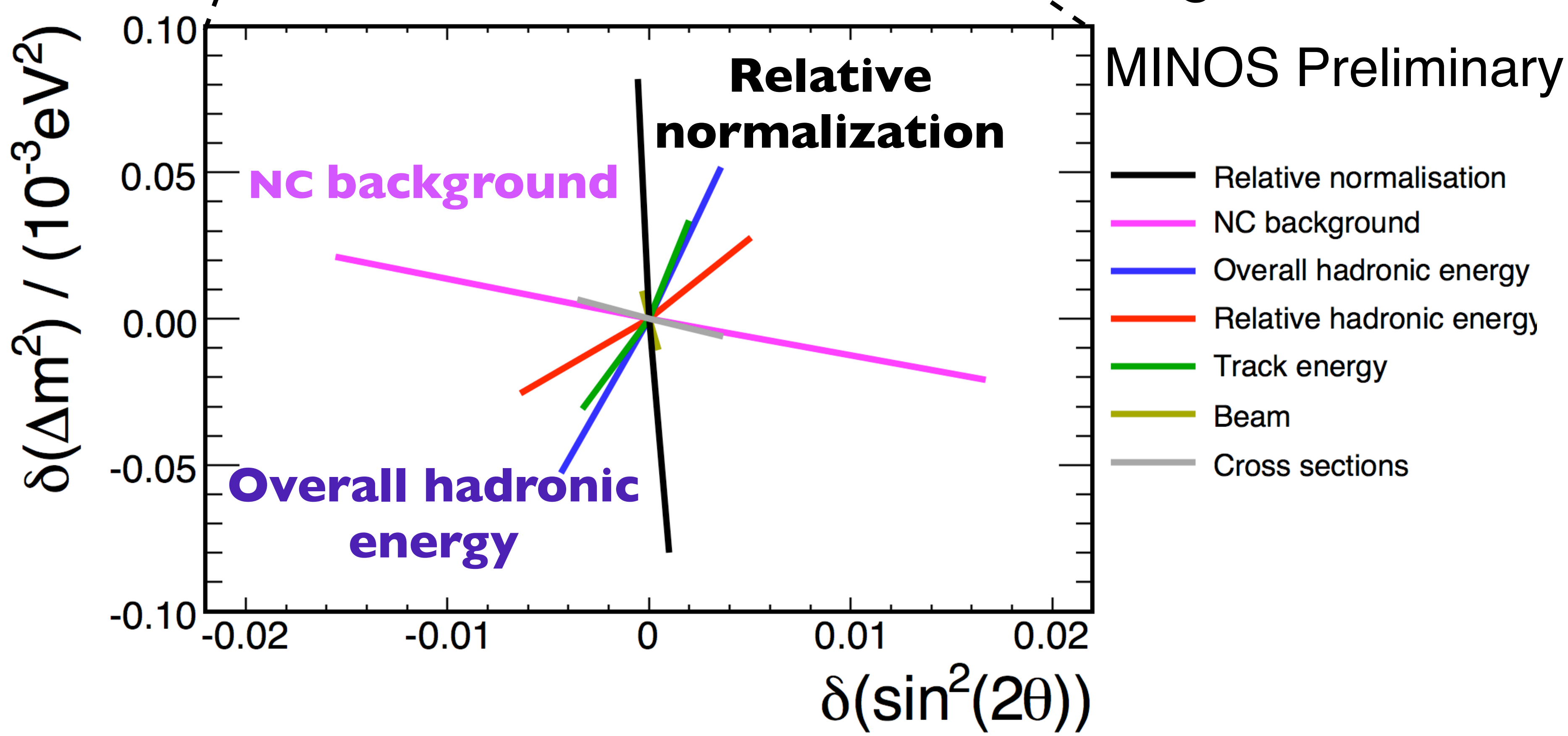




Systematic Uncertainties



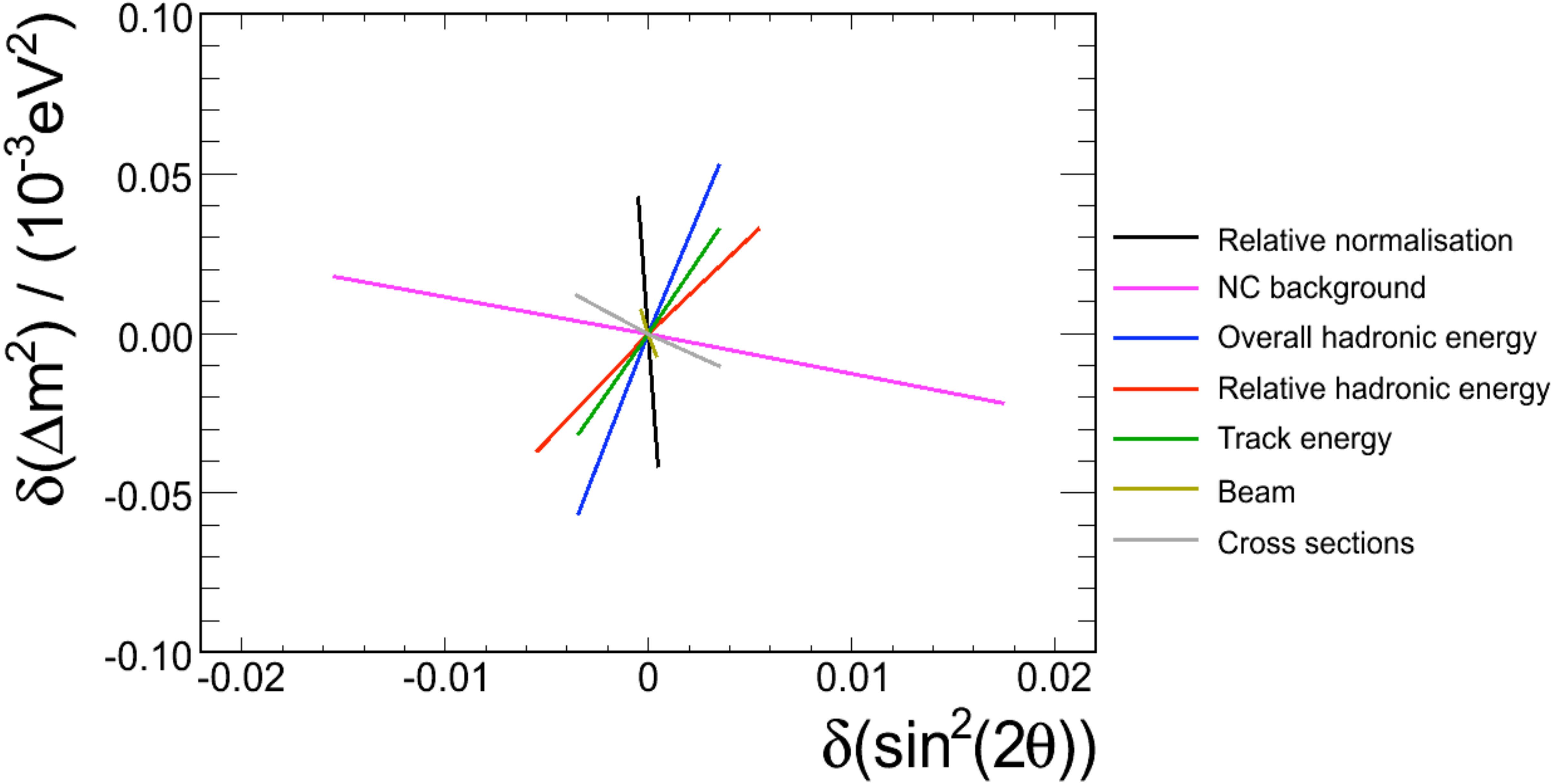
* Systematic uncertainties estimated by fitting modified MC in place of data.
* ν_μ CC measurement is statistics limited.
* Dominant uncertainties are:
  * ND/FD relative normalization (Δm^2)
  * Overall hadronic energy calibration (Δm^2)
  * NC background ($\sin^2(2\theta)$)



* These three systematic effects are included in the final fit as nuisance parameters.

Systematics After the Fit

Relative sizes of systematic effects after nuisance-parameter fit.

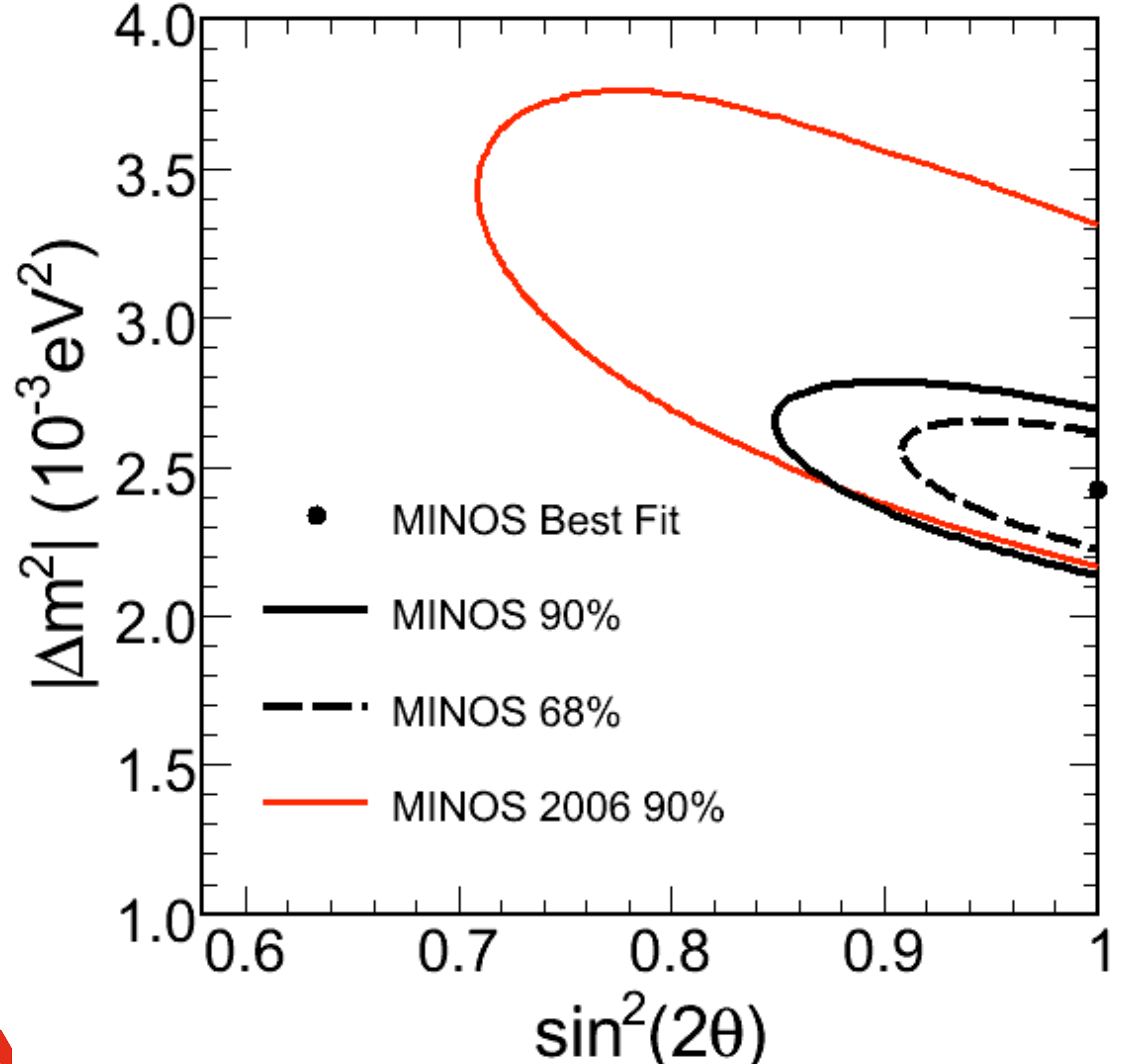


- Normalization: +1.6%
- NC background: -7%
- E_{shower}: -4%

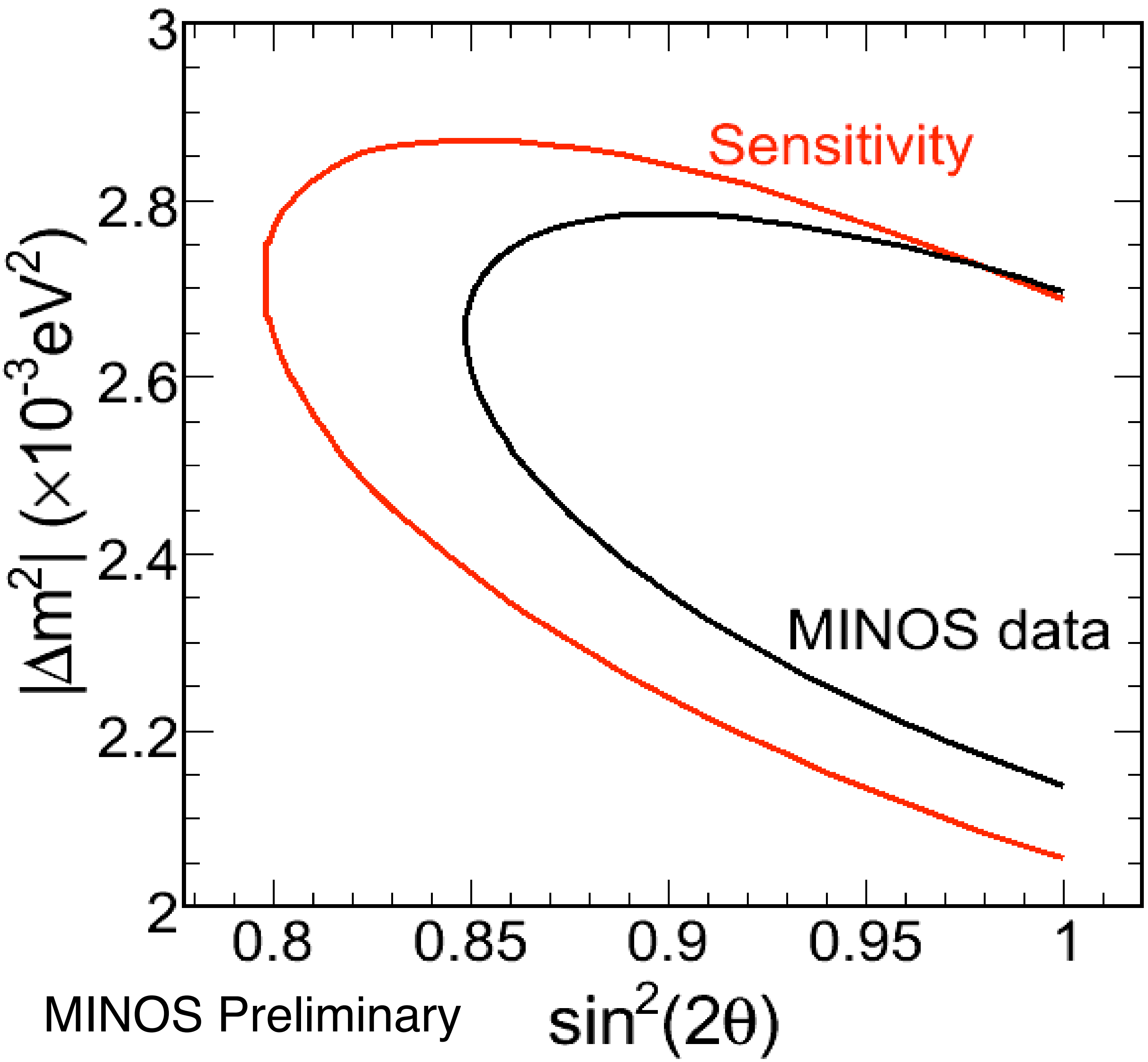
		Best fit		Shift from nominal best fit	
Systematic	Shift	Δm^2_{atm} $/10^{-3}eV^2$	$\sin^2(2\theta_{23})$	Δm^2_{atm} $/10^{-3}eV^2$	$\sin^2(2\theta_{23})$
Nominal	—	2.385	1.000	—	—
Far detector normalisation	−4%	2.465	1.000	+0.080	0.000
	+4%	2.305	1.000	−0.080	0.000
NC background	−50%	2.390	1.000	+0.005	0.000
	+50%	2.385	0.996	0.000	−0.004
Overall shower energy scale	−10%	2.315	1.000	−0.070	0.000
	+10%	2.450	1.000	+0.065	0.000
Relative shower energy scale	−2.2%	2.395	1.000	+0.010	0.000
	+2.2%	2.375	1.000	−0.010	0.000
Track energy from range	−2%	2.355	1.000	−0.030	0.000
	+2%	2.415	1.000	+0.030	0.000
FD Track energy from curvature	−4%	2.370	1.000	−0.015	0.000
	+4%	2.400	1.000	+0.015	0.000
SKZP beam errors	-1σ	2.375	1.000	−0.010	0.000
	$+1\sigma$	2.390	1.000	+0.005	0.000
Total ν_μ CC cross section	−3.5%	2.385	1.000	0.000	0.000
	+3.5%	2.385	1.000	0.000	0.000

Table 4: The best fits to sets of systematically shifted data (the fit constrained to $\sin^2(2\theta_{23}) \leq 1.0$), and the shifts of the best fit parameters from the unshifted case.

2006-2008 Comparison

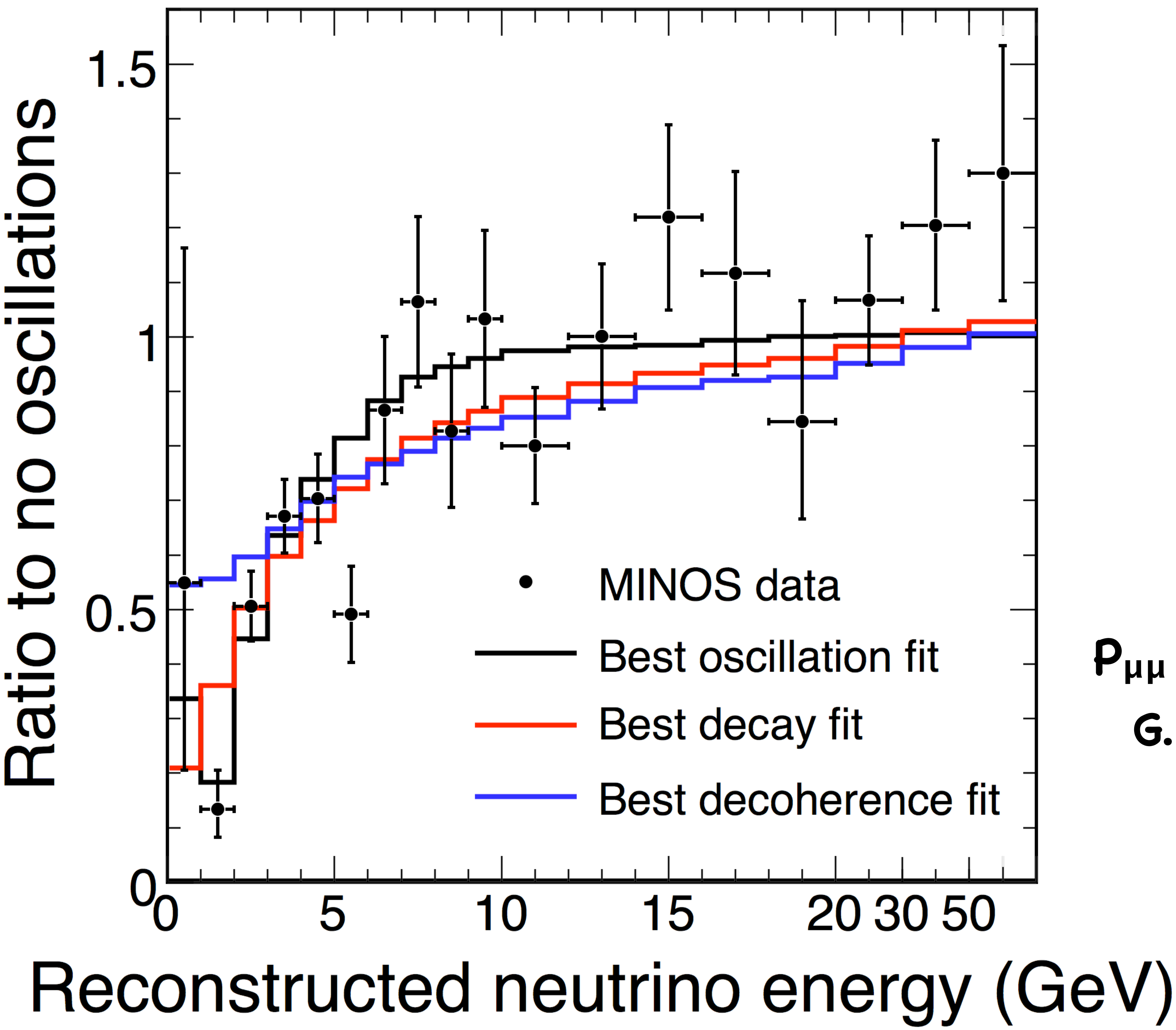


Sensitivity



* Final contour is a bit smaller than the predicted sensitivity because $\sin^2(2\theta)$ falls in the unphysical region.
* A study shows that 26.5% of unconstrained fits have a fit value of $\sin^2(2\theta) \geq 1.07$
* Feldman-Cousins study indicates that our contours are slightly conservative.

Alternative Hypotheses



Decay:

$P_{\mu\mu} = (\sin^2\theta + \cos^2\theta \exp(-\alpha L/E))^2$

V. Barget et. al., PRL82:2640 (1999)

$\chi^2/\text{ndof} = 104/97$

$\Delta\chi^2 = 14$

Disfavored at 3.7 σ

Decoherence:

$P_{\mu\mu} = 1 - ½ \sin^2(2\theta) (1 - \exp(-\mu^2 L/2E))$

G.L. Fogli, et. al., PRD67:093006 (2003)

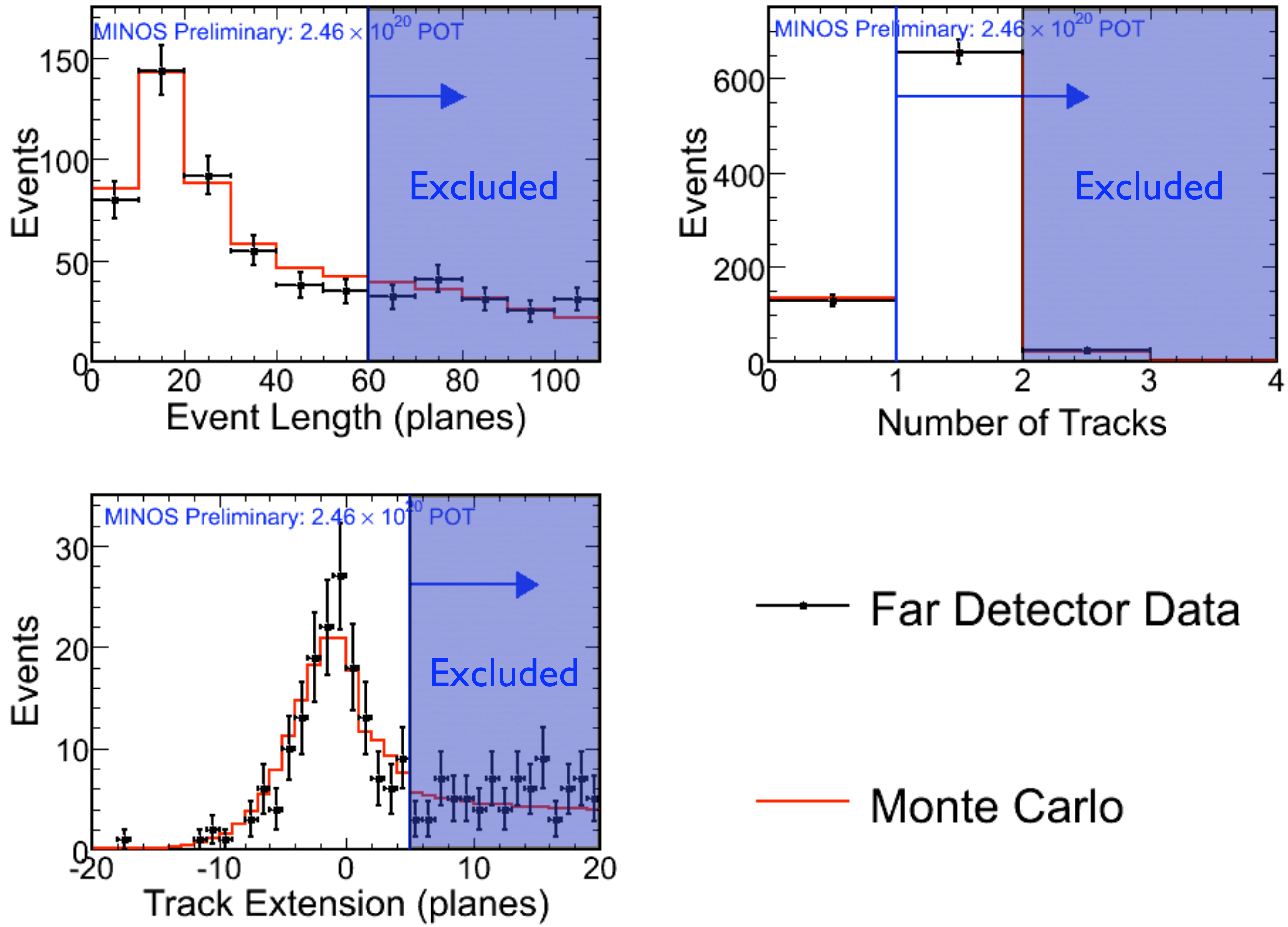
$\chi^2/\text{ndof} = 123/97$

$\Delta\chi^2 = 33$

Disfavored at 5.7 σ

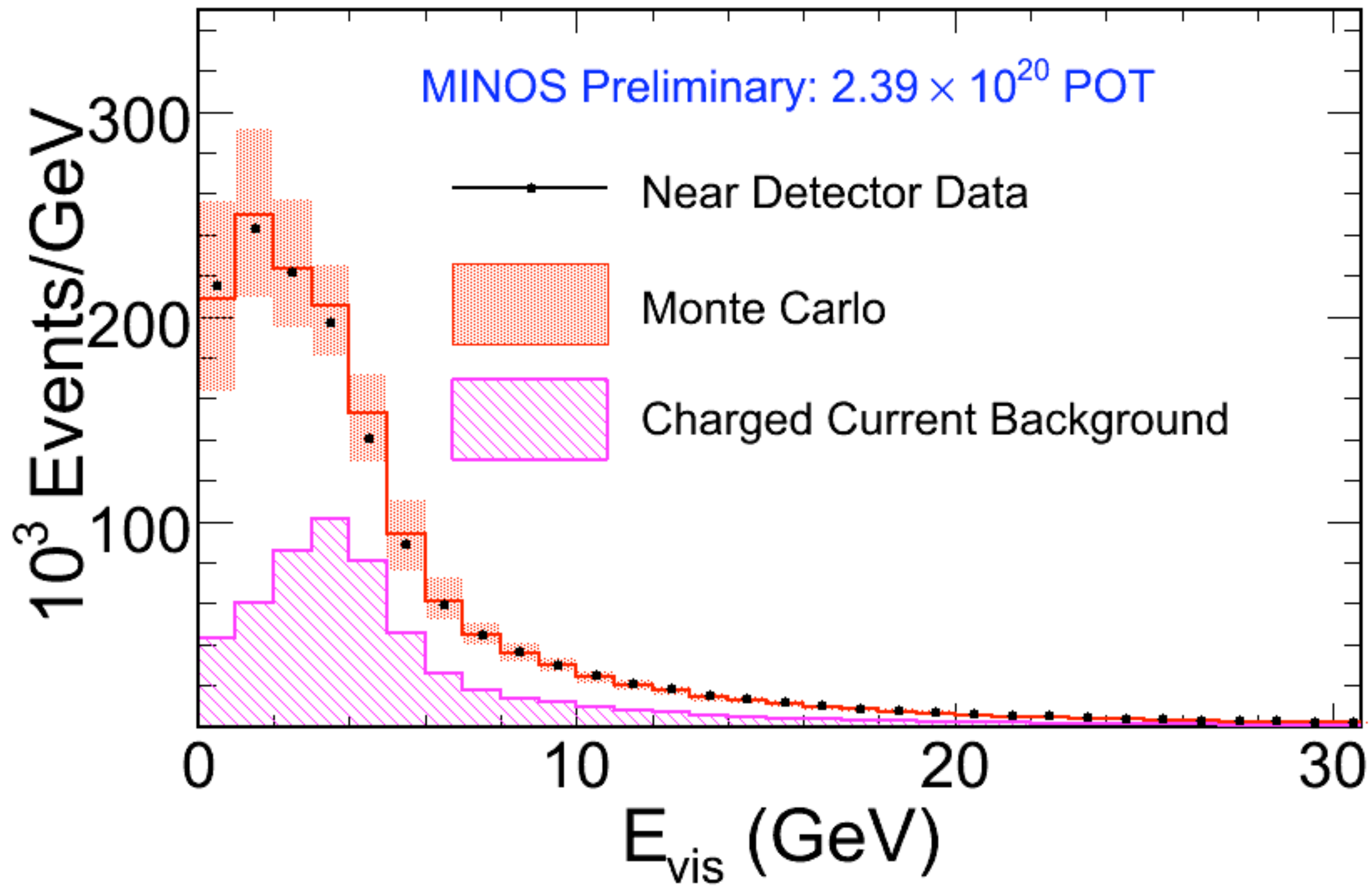
NC Event Selection in the FD

* Identical cuts are made in FD as in ND.
* MC oscillated with 2007 MINOS CC best fit values of Δm^2 = 2.38



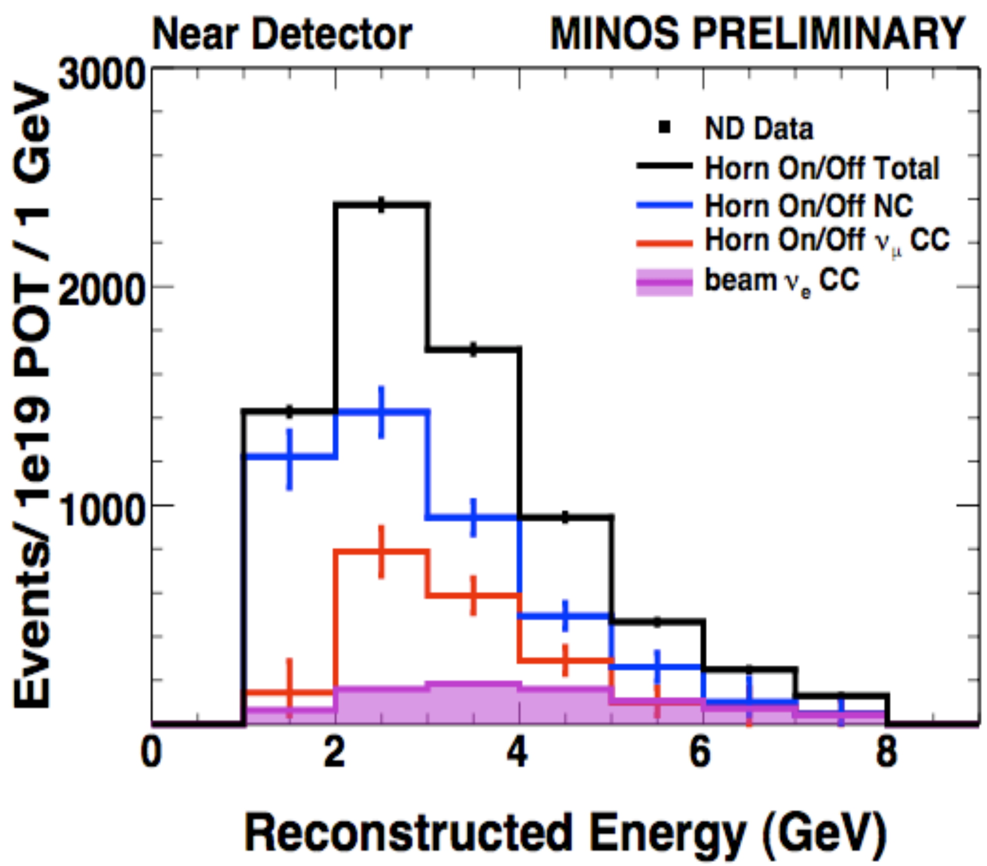
Jonathan M. Paley, Argonne National Laboratory

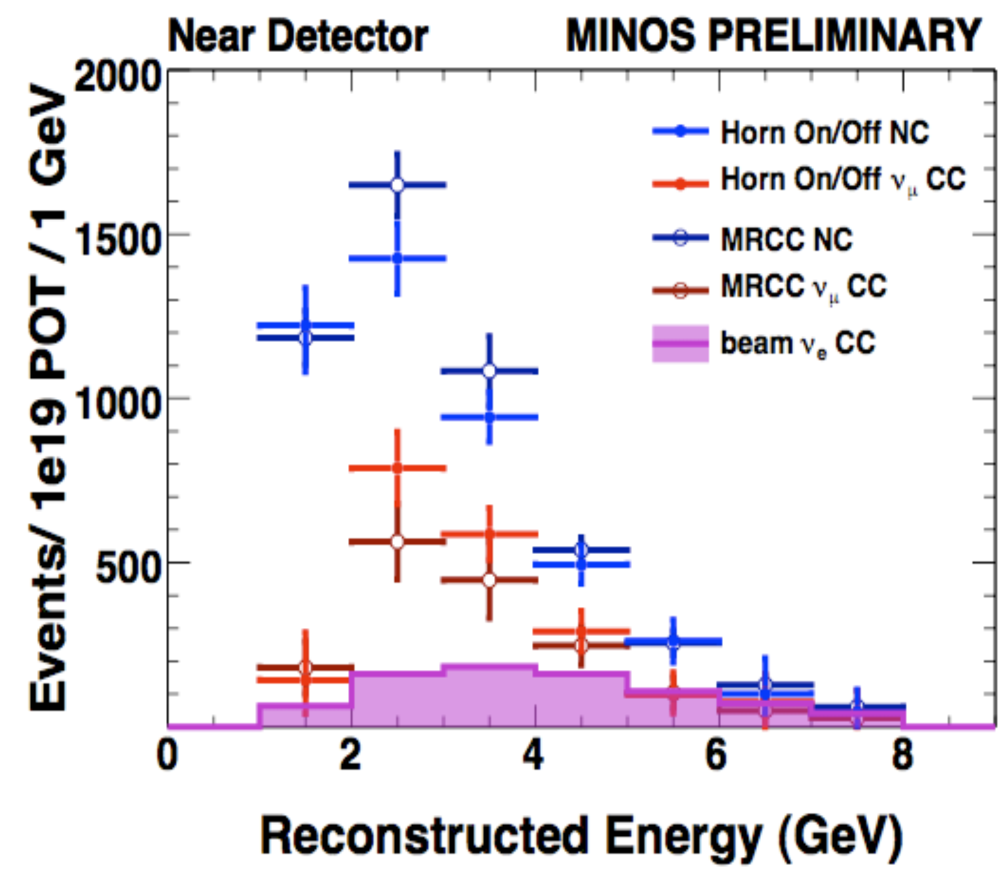
Measured Near Detector Spectrum



NC event selection efficiency is 90%, purity is 60%.

ν_e Data-Driven Background Studies





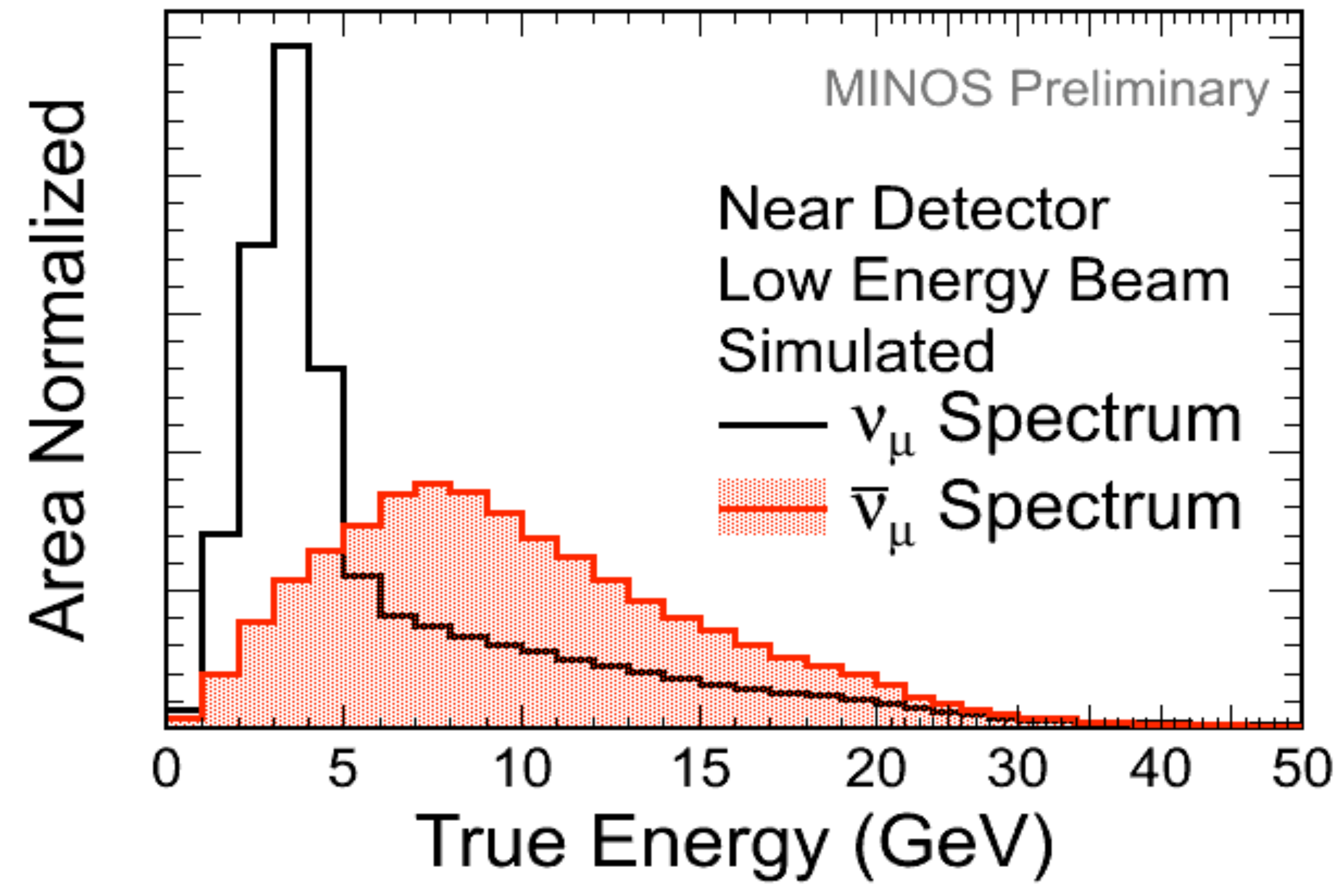
Estimate	Signal ν_e	Total BG	NC	ν_μ CC	Beam ν_e	ν_τ CC
Horn On/Off	12	42	29	8	3	2
MRCC	12	43	32	6	3	2

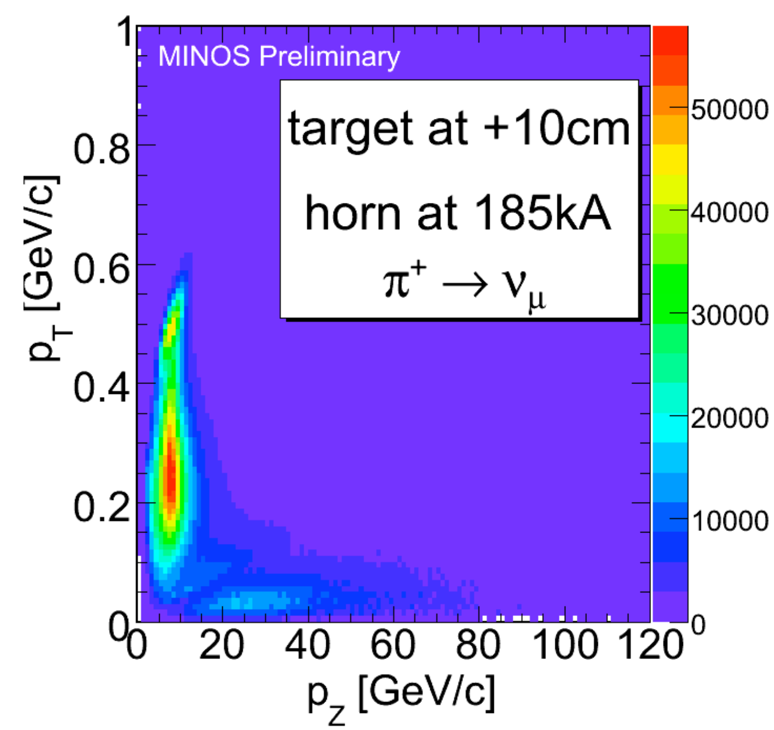
→ $\sin^2(2\theta_{23}) = 1.0$
$\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2
$\sin^2(2\theta_{13}) = 0.15$
no matter effects
3.25×10^{20} POT

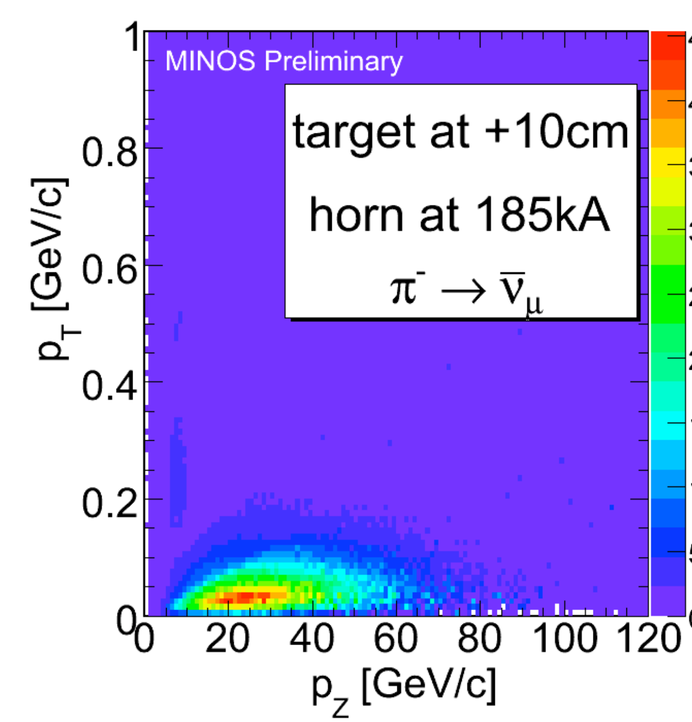
* Horn On/Off - constrain the relative ratios of NC and ν_μ CC background events in two different beam configurations.
* Muon removed hadron showers from ν_μ CC (MRCC).

MINOS Antineutrino Analysis

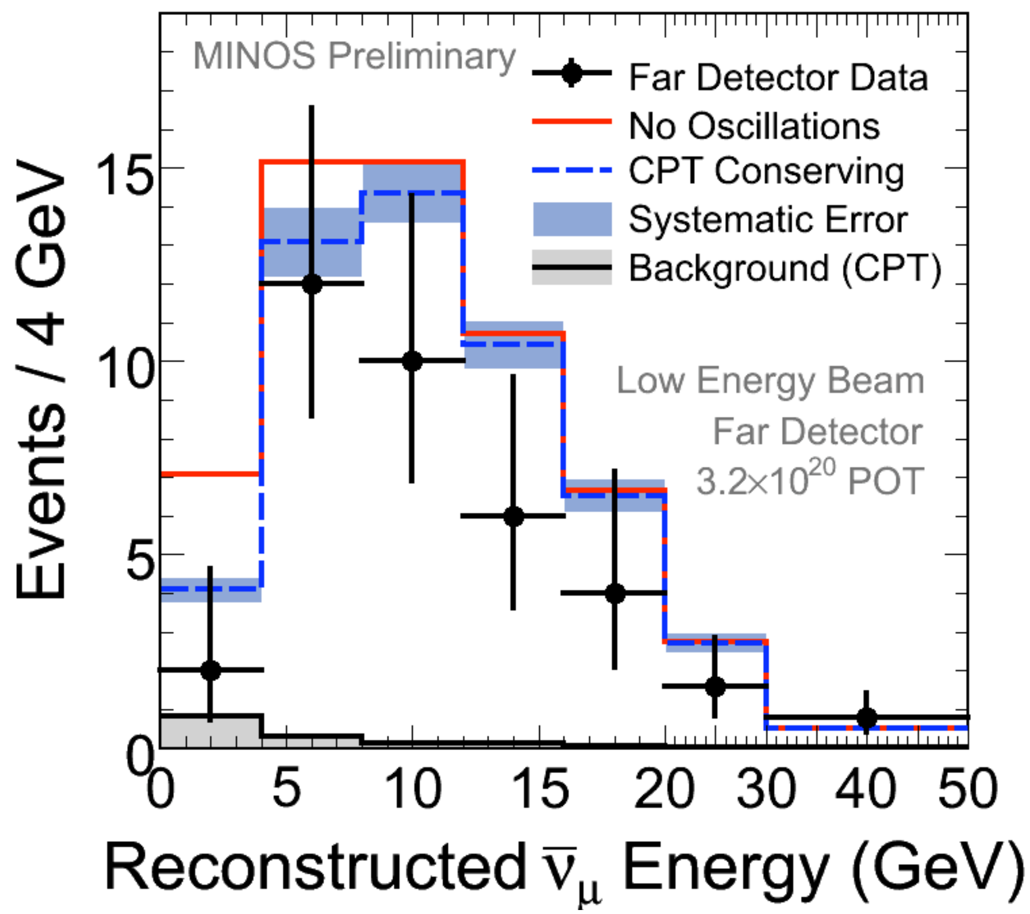
- MINOS is unique in its ability to separate ν_μ from ν_μ events.
- Do ν_μ and ν_μ oscillate the same way? Test of CPT.
- Do ν_μ oscillate to ν_μ ? Possible via some exotic beyond-SM processes and/or Majorana nature of neutrinos.
- NuMI beam consists of ~7% ν_μ.
- Most ν_μ are higher energy and come from low p_T π^-'s that travel straight through the focusing horns; all other π^-'s are defocused and don't reach the decay pipe.







MINOS Antineutrino Results

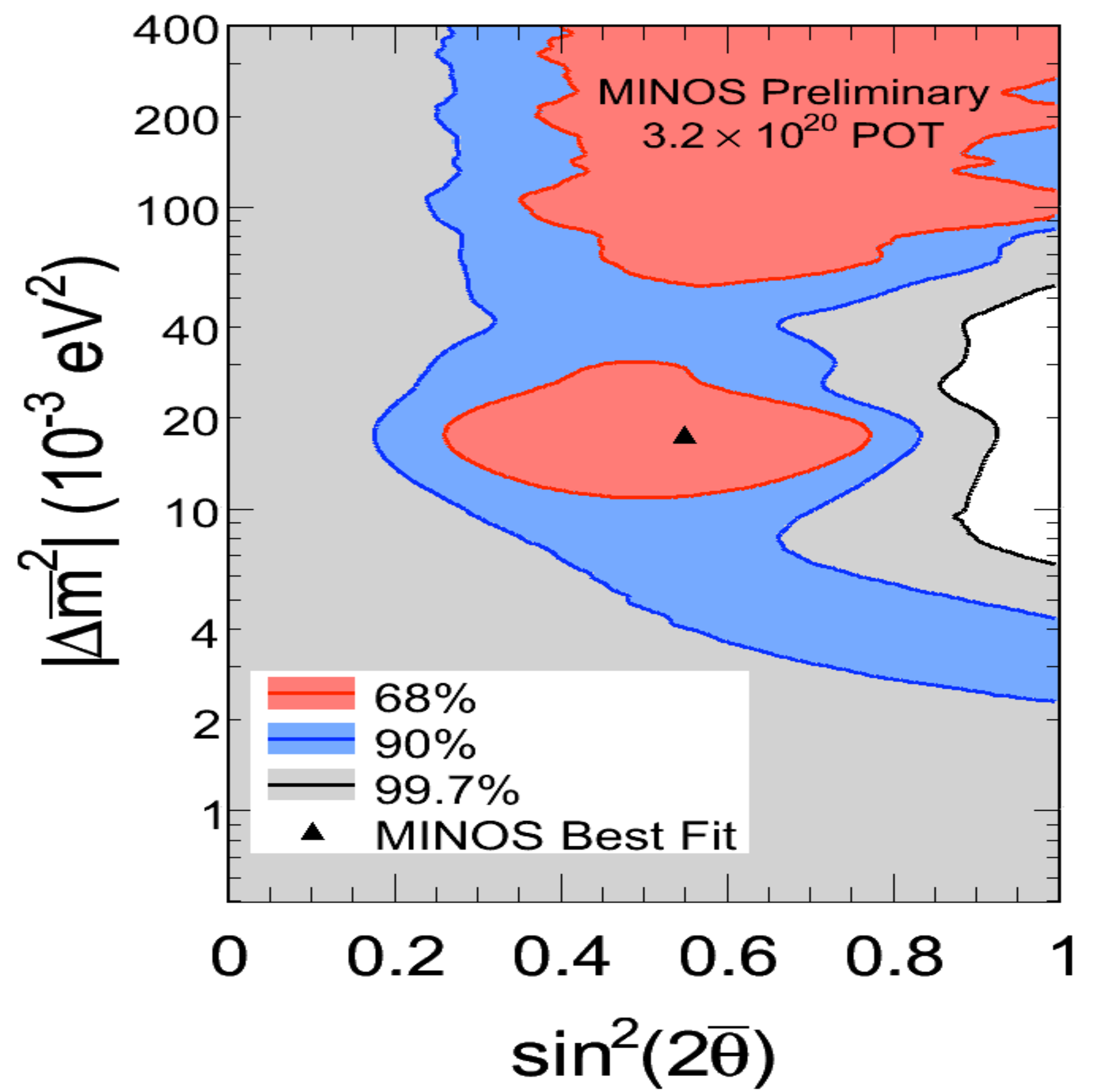


* MINOS excludes at maximal mixing: $(5.0 < \Delta m^2 < 81)\times10^{-3}$ eV^2 (90% CL)
* Null oscillation hypothesis excluded at 99%.
* CPT conserving point from ν_μ analysis falls within 90% contour.

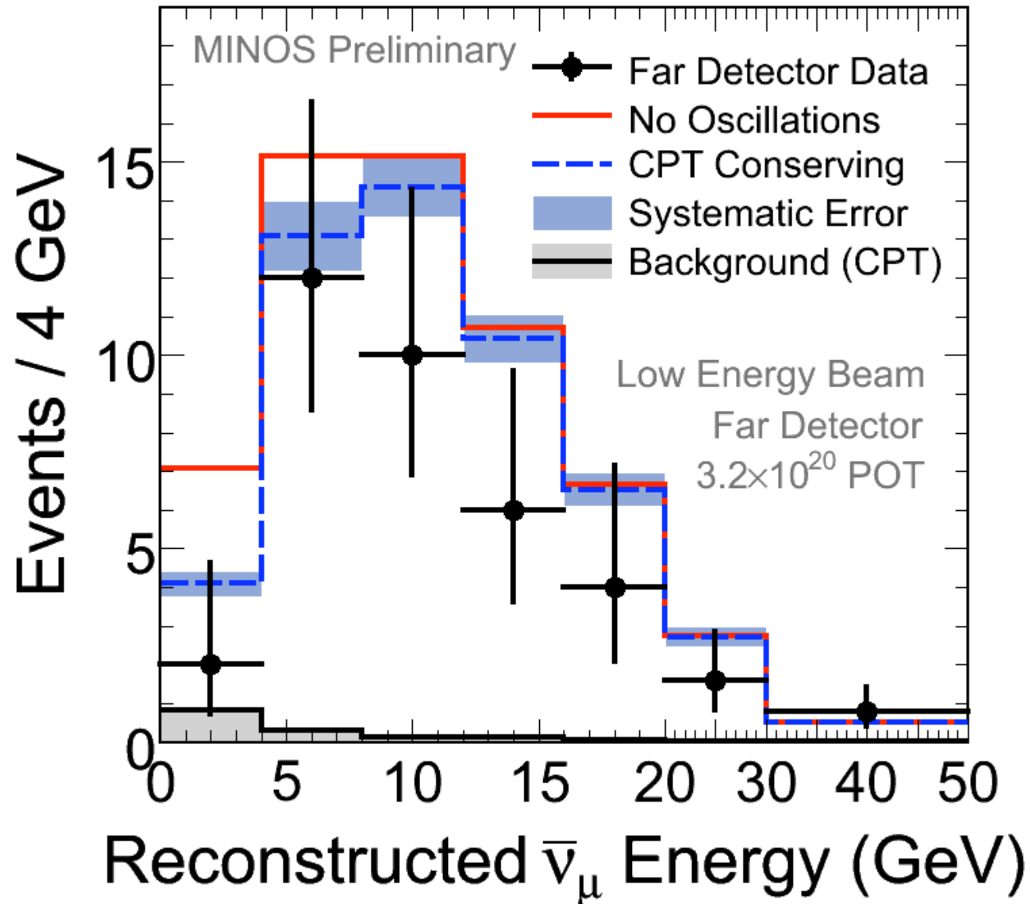
* Events are selected based on track length, pulse height fraction in track, pulse height per plane, track fit charge sign significance, and track curvature.
* Observe 42 events in the FD
* Predicted w/ CPT conserving oscillations:

  58.3 ±7.6 (stat) ±3.6 (syst.)
* Predicted w/ no oscillations:

  64.6 ± 8.0 (stat) ± 3.9 (syst.)



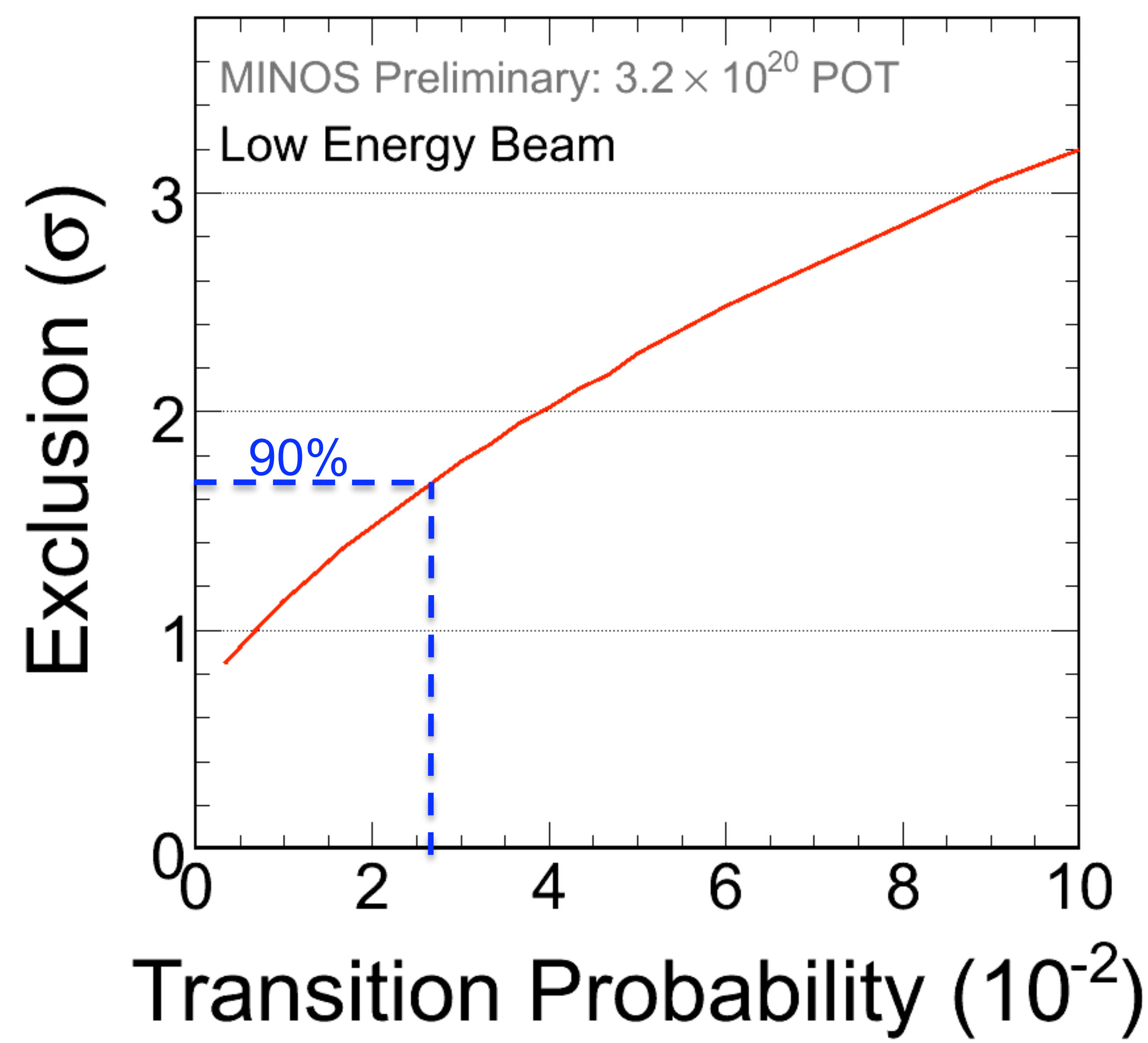
MINOS Antineutrino Results



- MINOS observes **no** excess of ν_μ events in the FD.
- 1-parameter fit for α

$$P(\nu_\mu \rightarrow \overline{\nu_\mu}) = \alpha \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

gives limit: α< 0.026 (90% CL)



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Other Finalized Analyses

* **"Sudden stratospheric warmings seen in MINOS deep underground muon data"**: High-energy cosmic muon rate is strongly correlated to temperature changes in the upper atmosphere. MINOS has shown that (under)ground-based high statistics cosmic muon measurements are a new tool to be used in tracking meteorological phenomena in the upper atmosphere.
* "**Testing Lorentz Invariance and CPT Conservation with MINOS Near Detector Neutrinos**": search for a sidereal signal in the MINOS ND. Upper limits set on individual SME Lorentz and CPT violating terms.
* "**Observation of deficit in NuMI neutrino-induced rock and non-fiducial muons in MINOS far detector and measurement of neutrino oscillation parameters**"