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MINOS, NOνA, MINOS+

Overview and Future Prospects

Jeff Hartnell

University of Sussex

XIIIth International Workshop on Neutrino Factories, Super beams and Beta beams

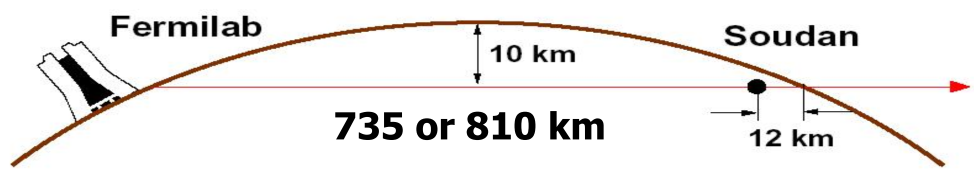
UNIGE & CERN, 1-6th August 2011

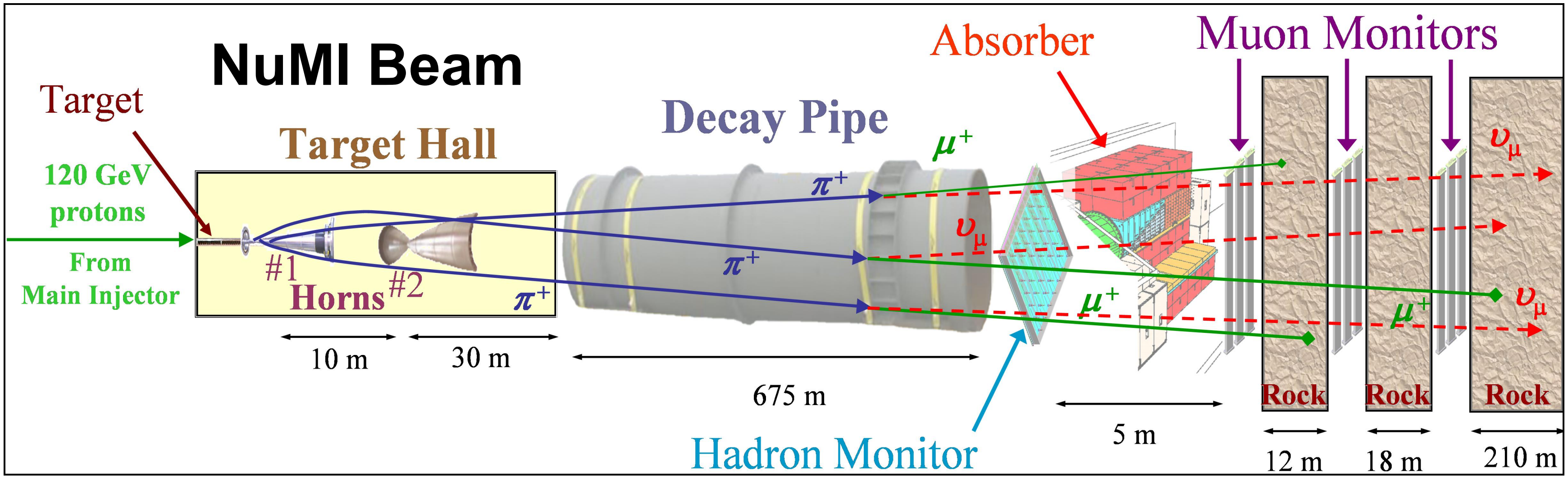
Introduction

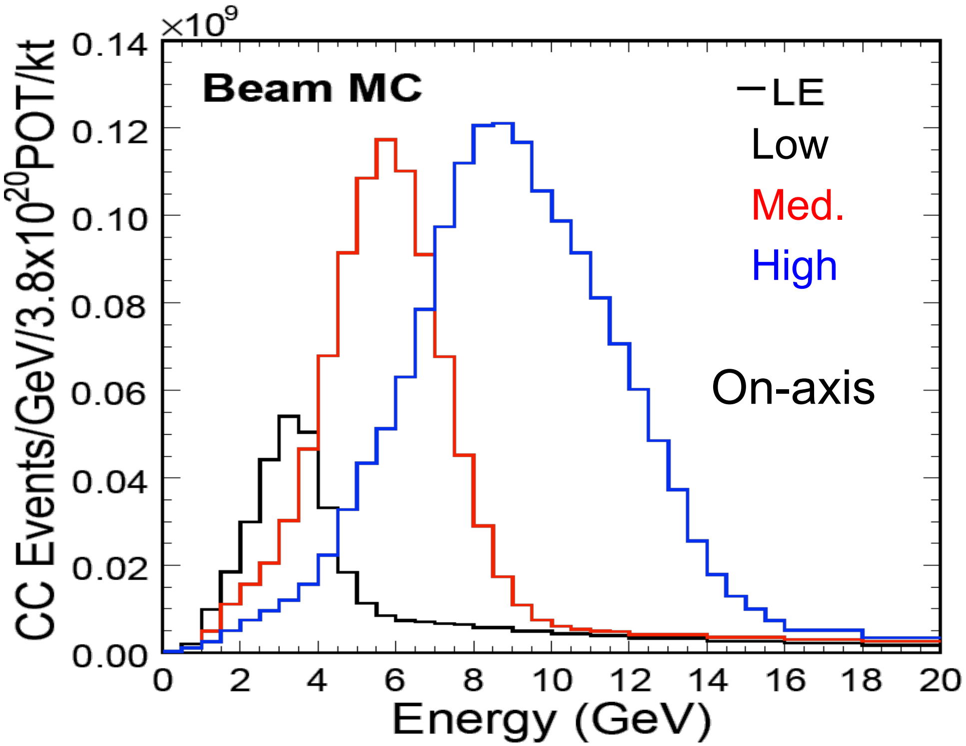
- Overview and the NuMI Beam
- MINOS
  - Muon neutrino and antineutrino disappearance
  - Electron neutrino appearance
- NOvA
  - ND status
  - FD status
  - Physics reach
- MINOS+
  - Searches for new physics

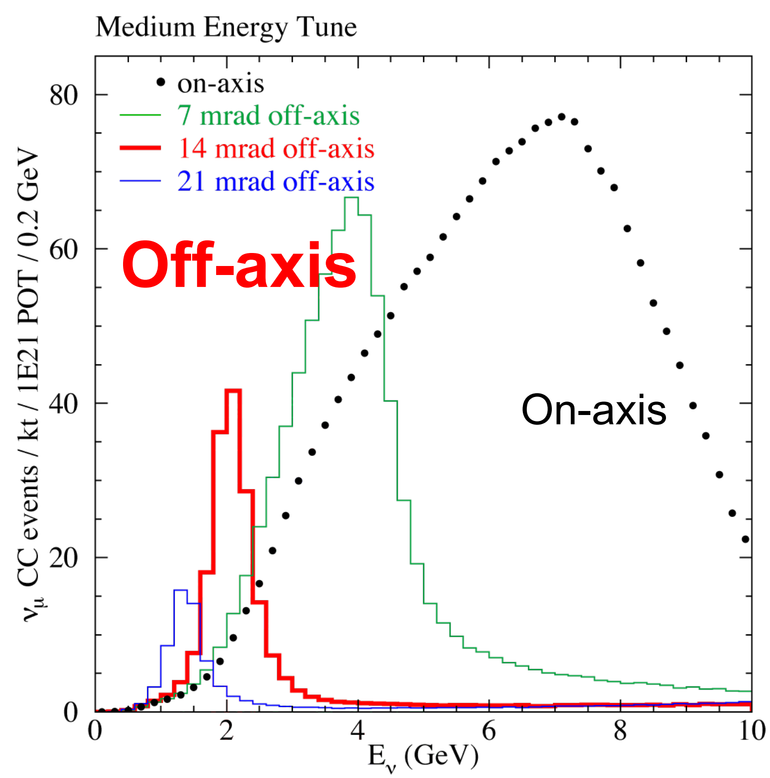
Long-Baseline Overview

- MINOS(+) and NOvA
- Two-detector experiments:
- Near detector at Fermilab
  - measure beam composition
  - energy spectrum
- Far detector in Minnesota
  - measure oscillations and search for new physics





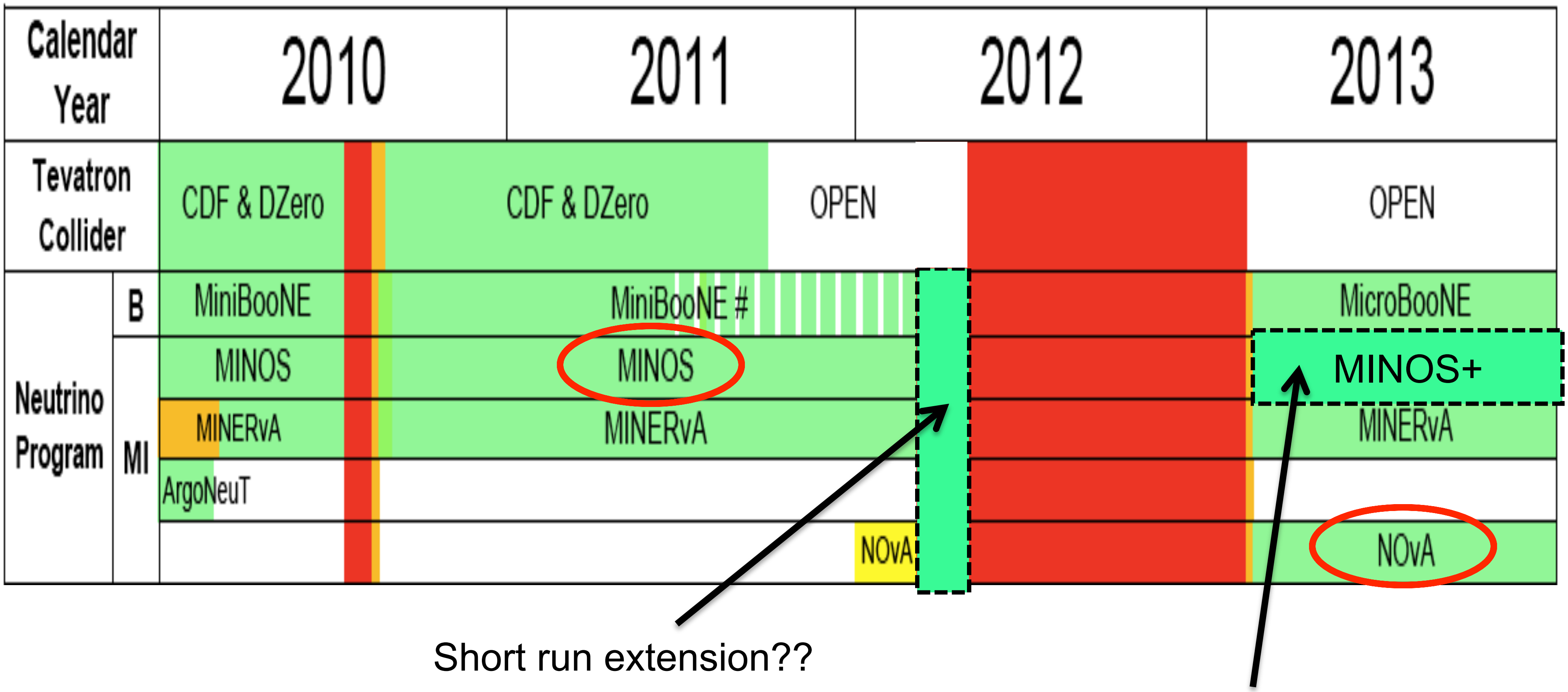




Much more: Jim Strait, Tuesday Plenary

Draft 2010-13 Fermilab Accelerator Experiments' Run Schedule

http://www.fnal.gov/directorate/program_planning/schedule/



Short run extension??

Stage I approval from Fermilab Physics Advisory Committee

The MINOS Collaboration

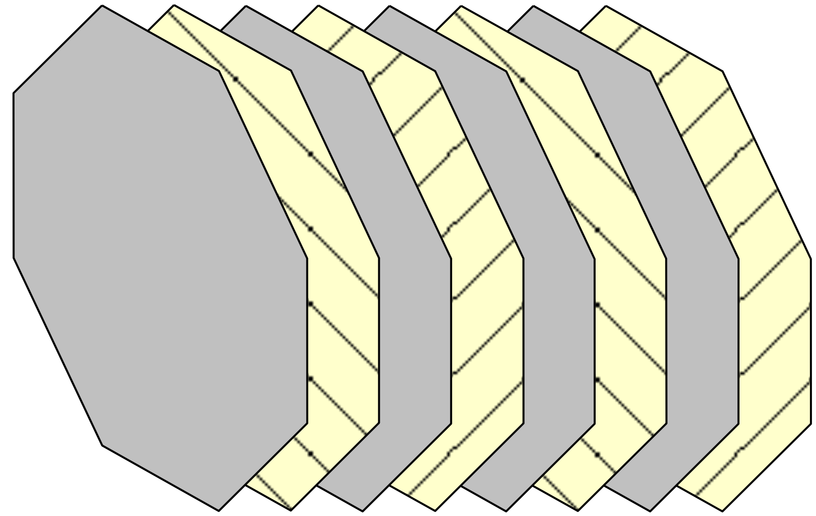
120 scientists
30 institutions

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab Goias • Harvard • Holy Cross • IIT • Indiana • Iowa State • Minnesota-Twin Cities Minnesota-Duluth • Otterbein • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

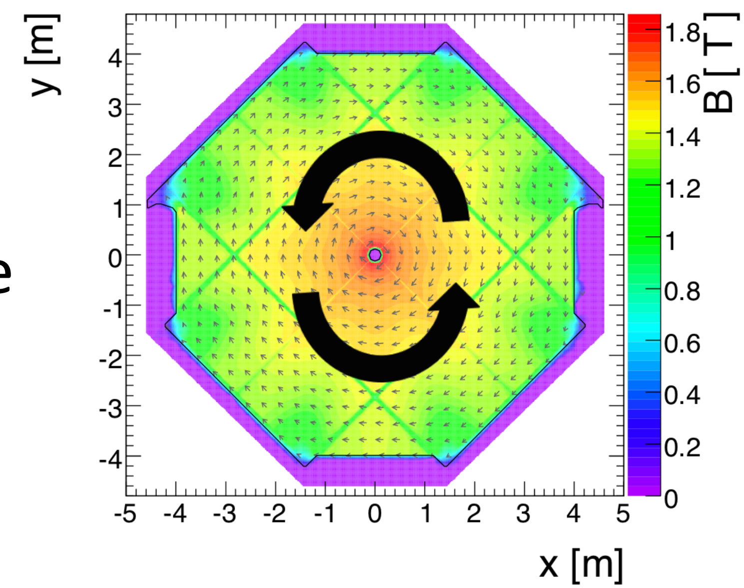
MINOS Physics Goals

- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν ← **Alex Sousa, WG1, Wednesday**
- Search for Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector

MINOS Detectors

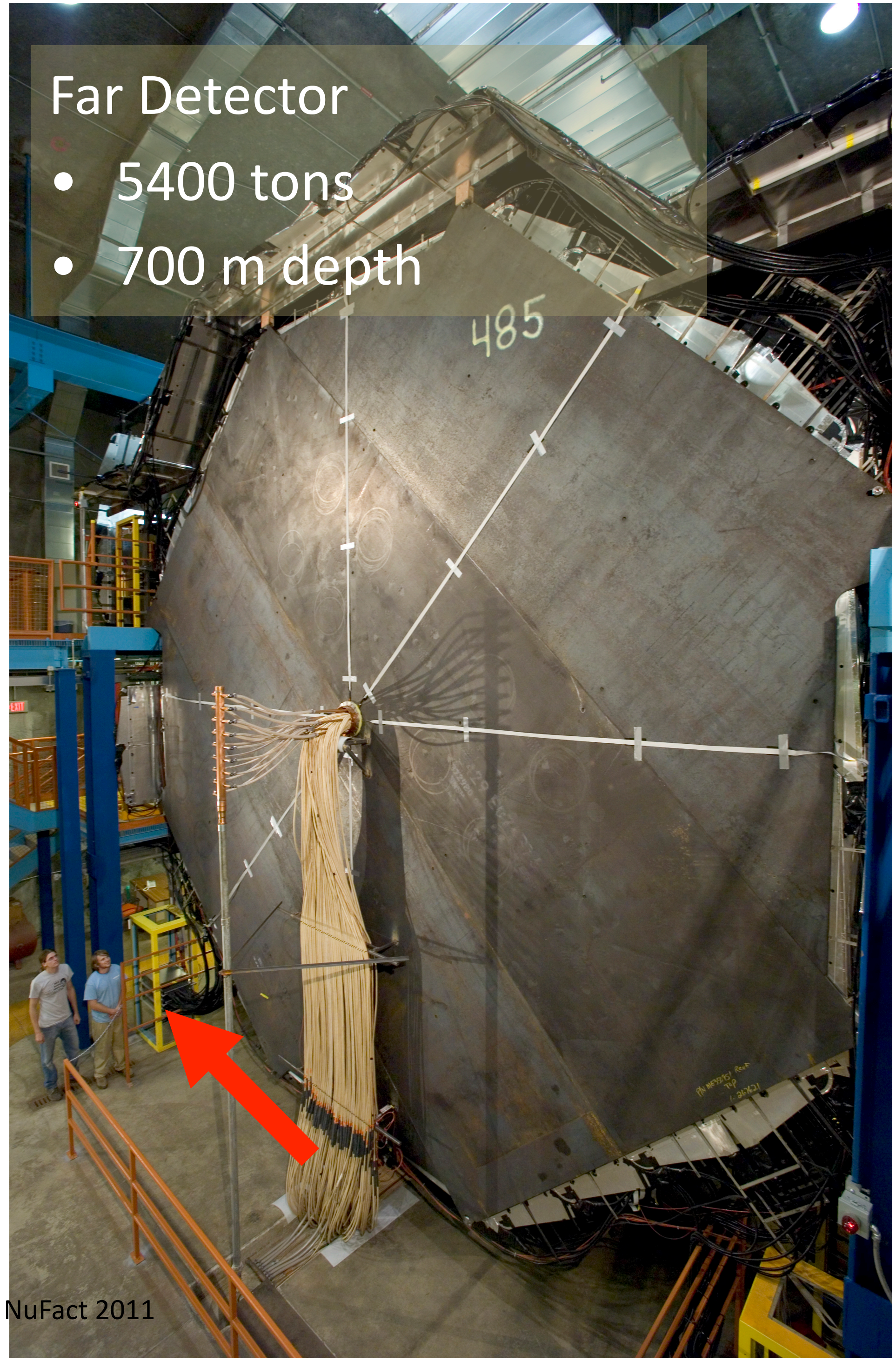


- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick
  - scintillator strips 4.1 cm wide



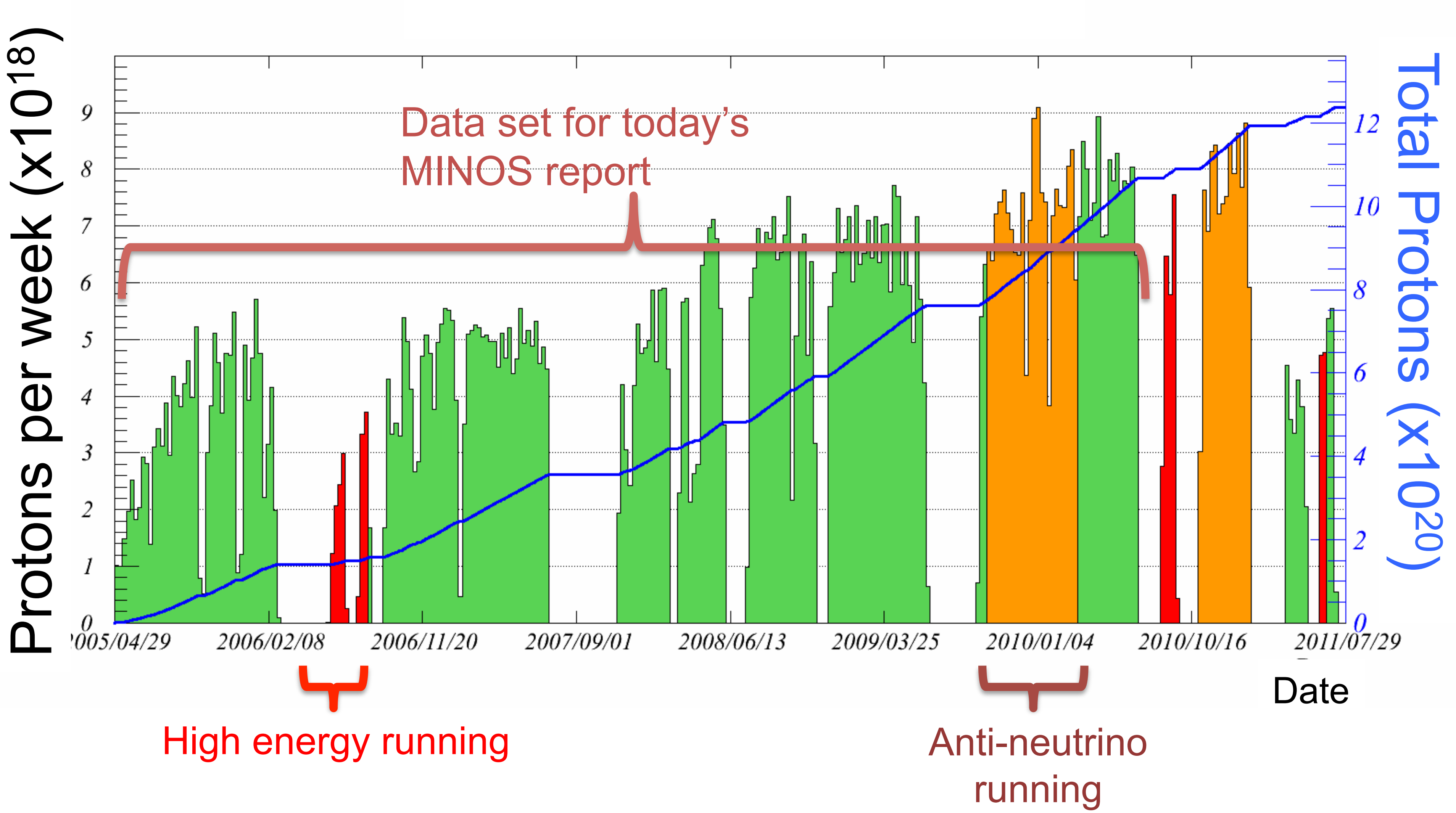
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-

MINOS Detectors

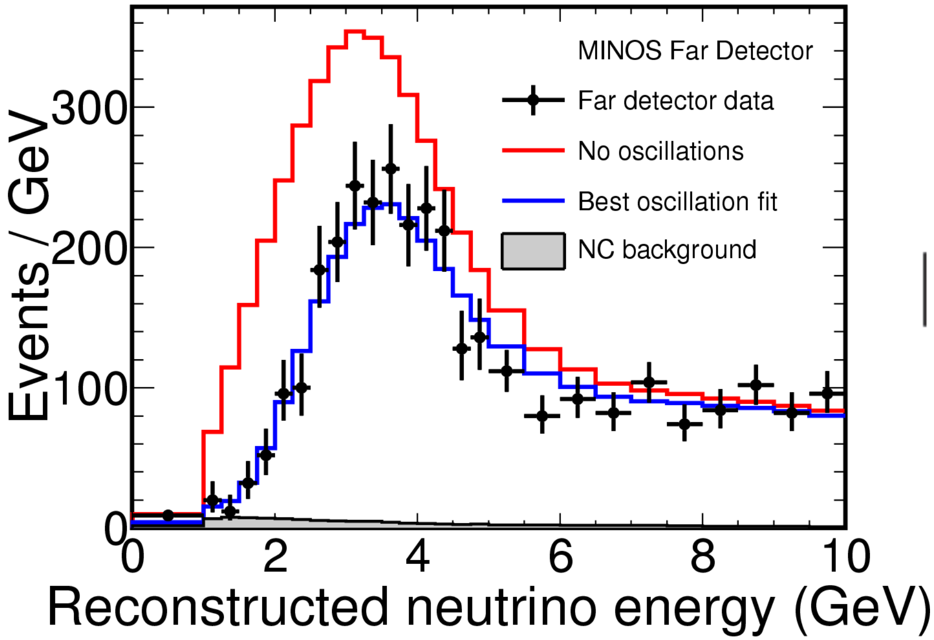


Jeff Hartnell, NuFact 2011

6+ years of NuMI data



Muon Neutrino & Antineutrino Disappearance Results

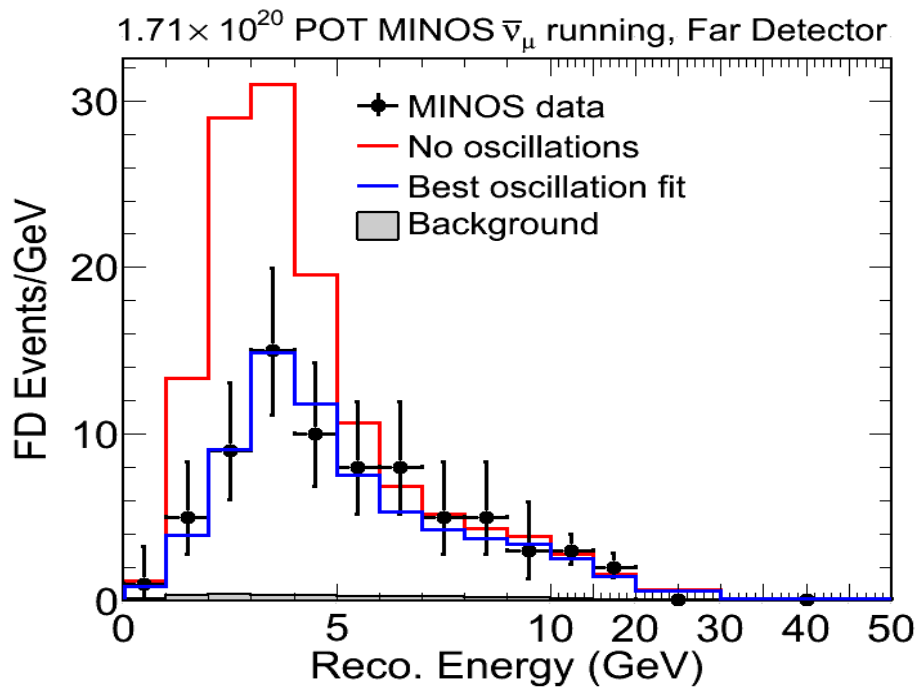


Muon neutrinos

$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2(2\theta) > 0.9 \text{ at 90\% C.L.}$$

Phys. Rev. Lett. 106, 181801 (2011)



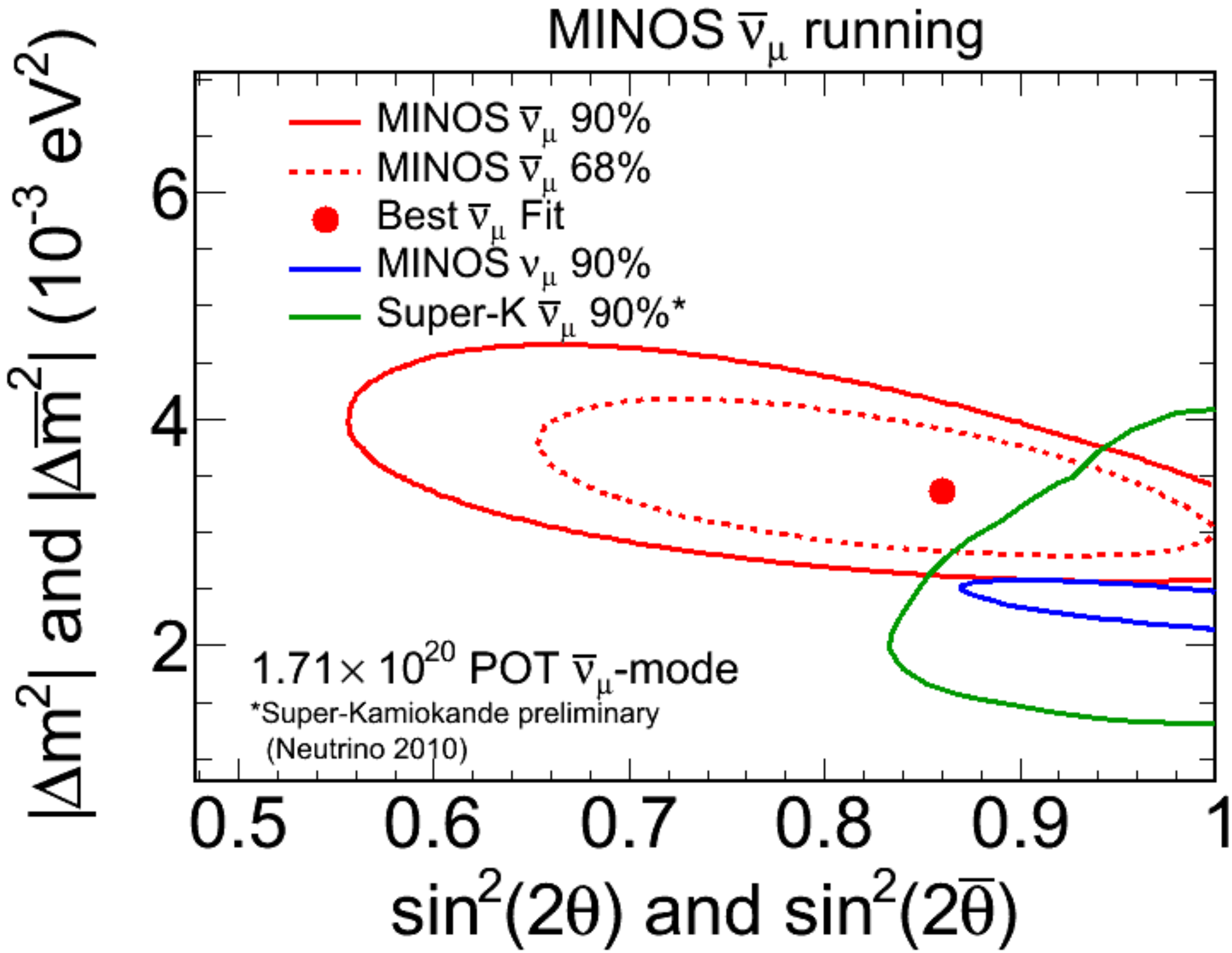
Muon antineutrinos

$$|\Delta \overline{m}^2| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

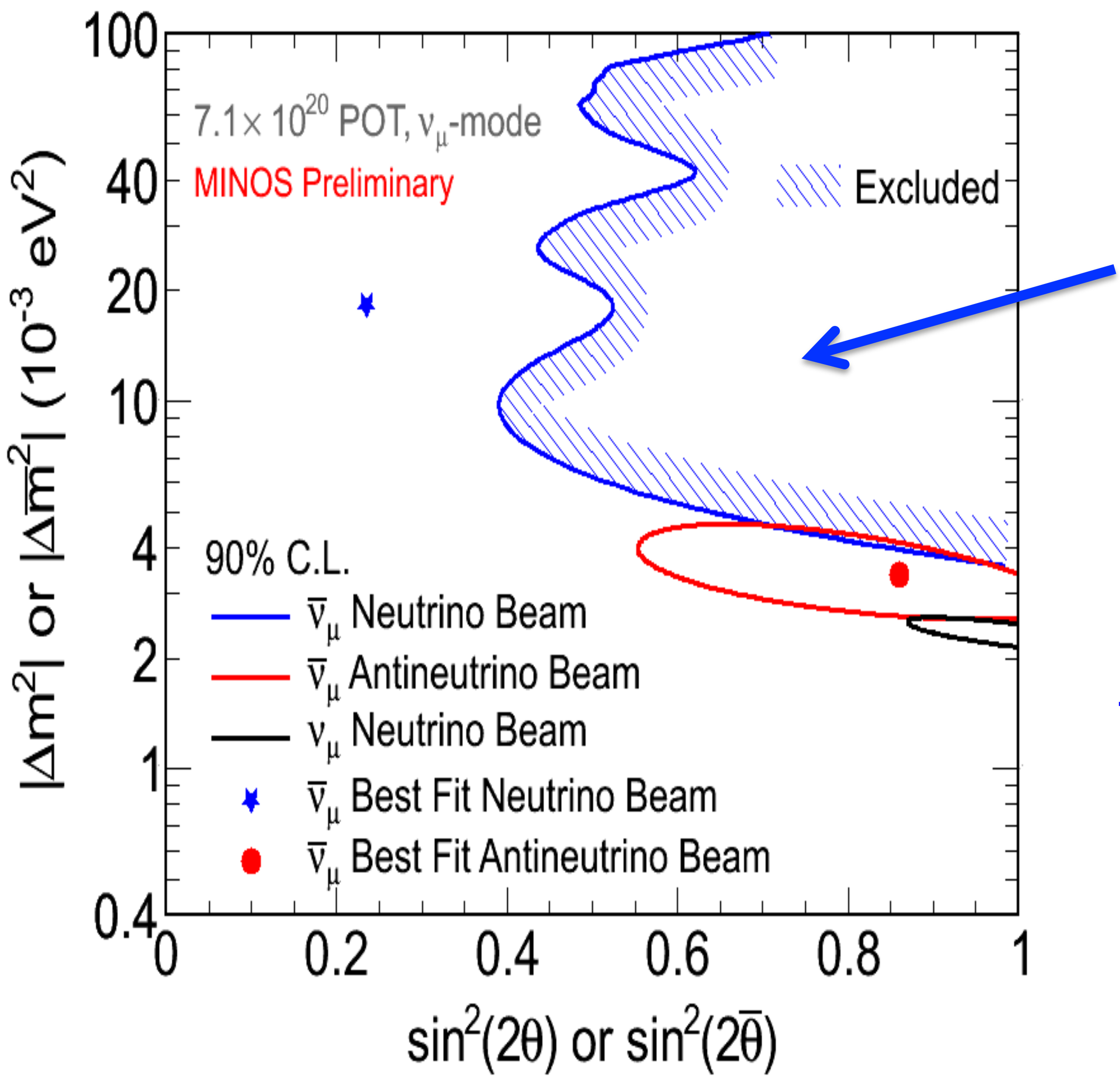
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}$$

Phys. Rev. Lett. 107, 021801 (2011)

Comparisons to Neutrinos



Using “wrong sign” events

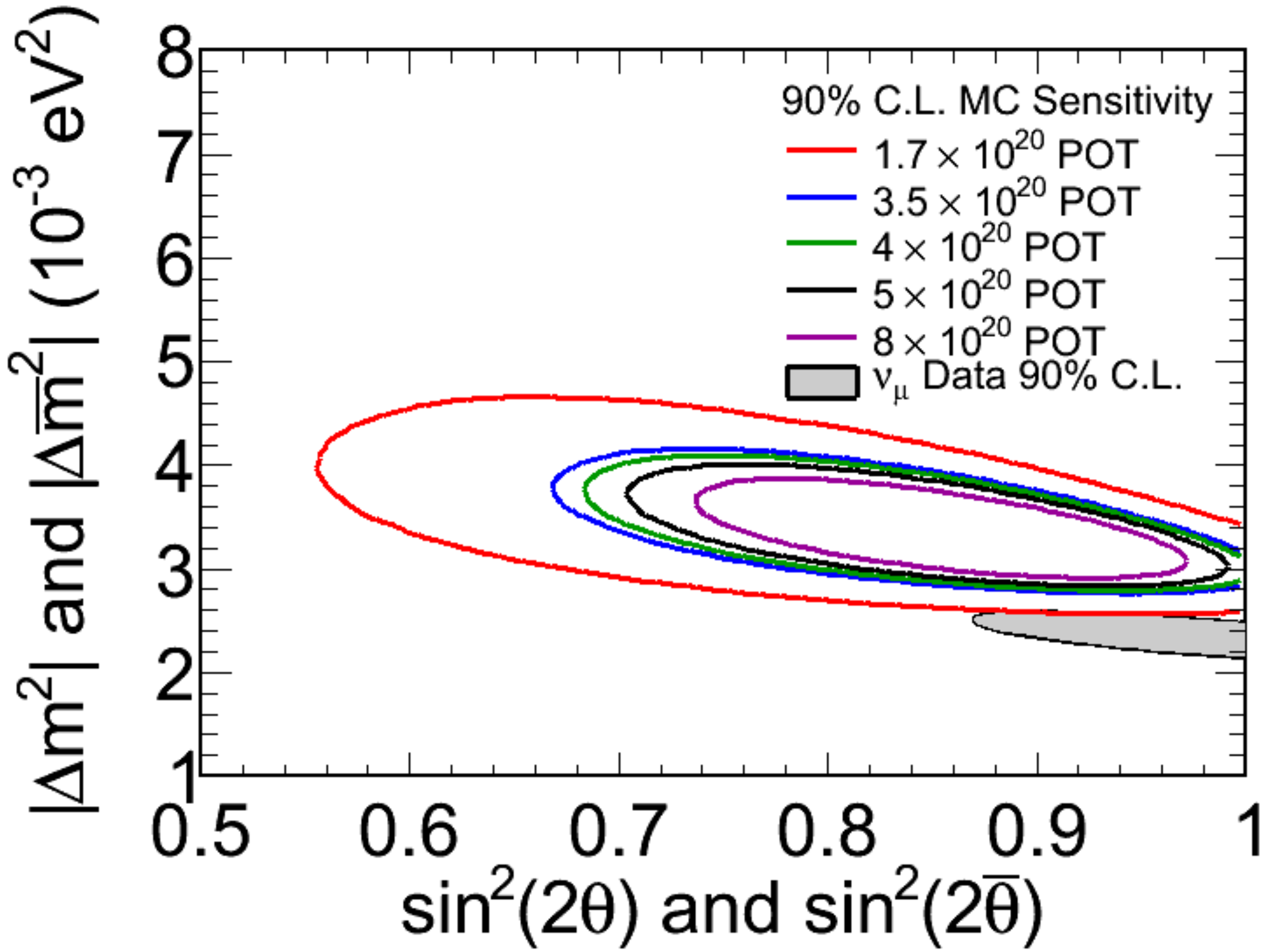


Select 7% antineutrino component of neutrino beam

Complementary information from higher energy events

Paper to hit the arXiv this week

More anti-neutrinos to come…



Updated result expected later in the summer…

Electron Neutrino Appearance Analysis

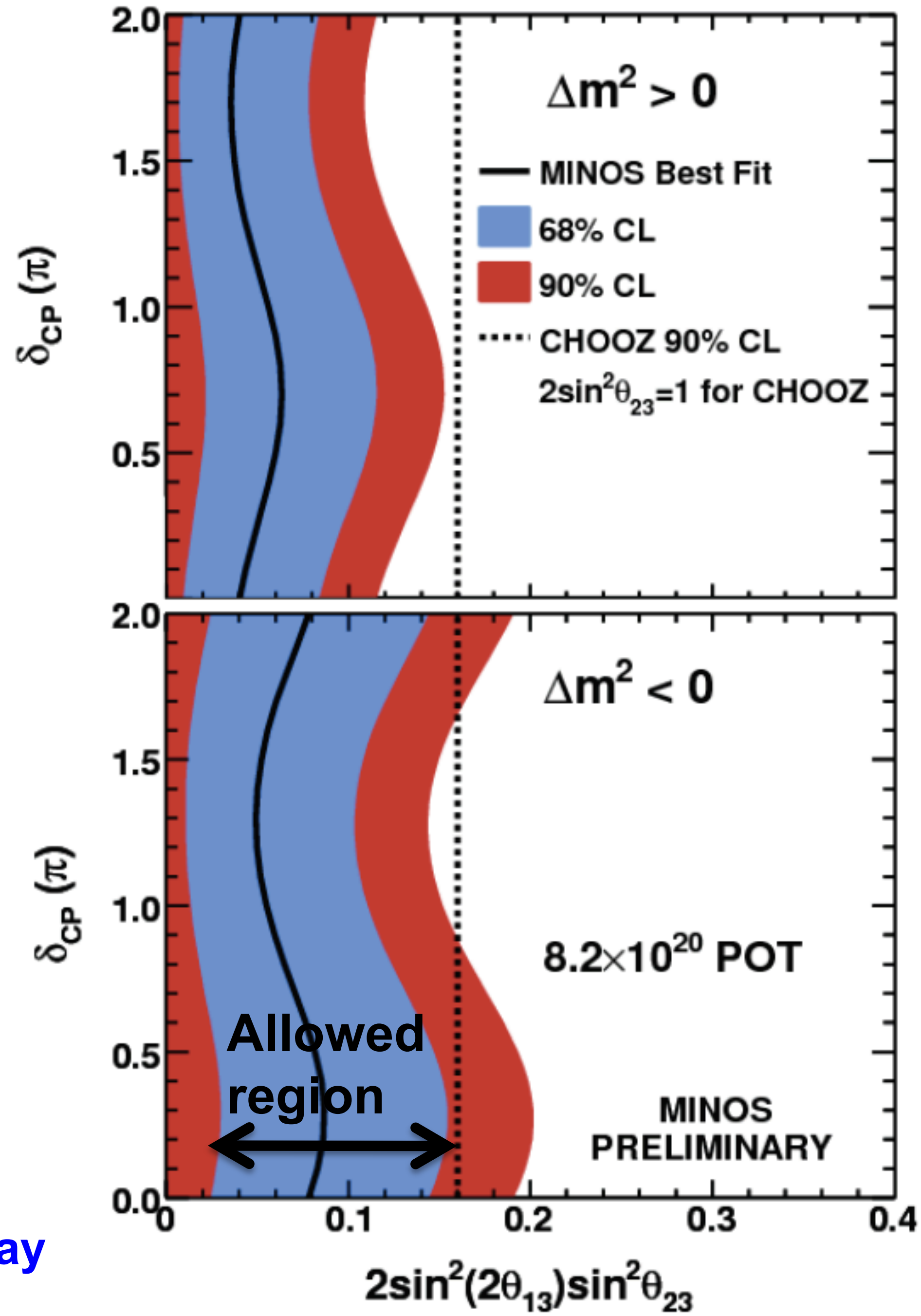
ν_e Appearance Results

- Based on ND data, expect:
  49.6 ± 7.0(stat) ± 2.7(syst)
- Observe: **62** events in the FD

Assuming $\delta_{CP} = 0$, $\theta_{12} = \pi/4$, $|\Delta m^2_{32}| = 2.32 \times 10^{-3}$ eV^2 and normal (inverted) hierarchy:

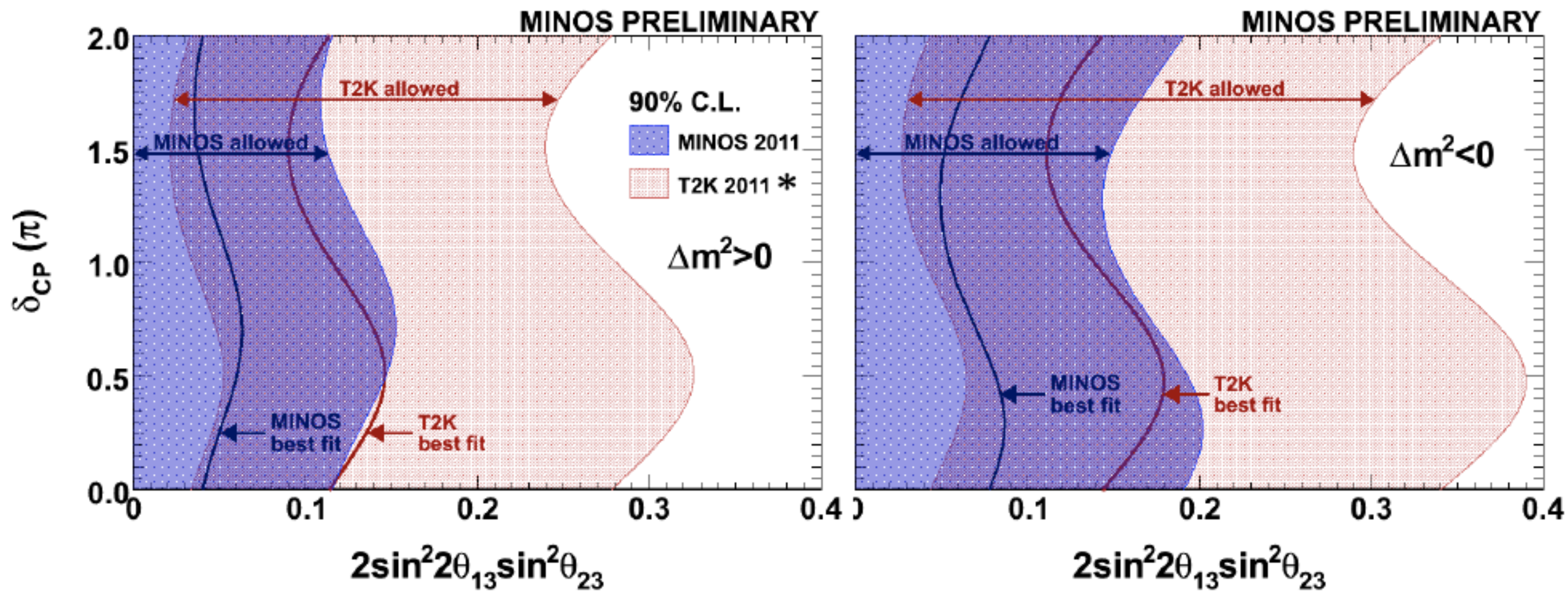
$\sin^2(2\theta_{13}) < 0.12\ (0.19)$ at 90% C.L.

$\sin^2(2\theta_{13}) = 0$ disfavored at 89% C.L.



Much more info: Jeff Nelson, WG1, Friday

Comparing MINOS and T2K



Overlay of MINOS and T2K allowed regions

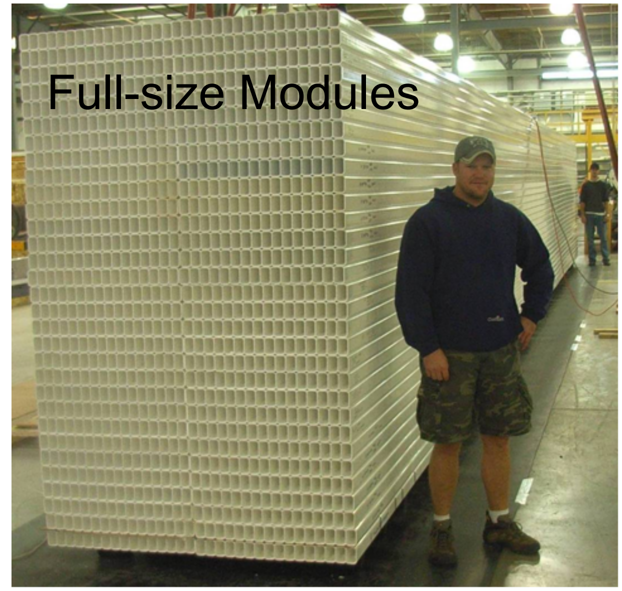
arXiv:1108.0015 (MINOS)
arXiv:1106.2822 (T2K)
Phys. Rev. Lett. 107, 041801 (2011)

NOvA Collaboration

24 Institutions
110 physicists

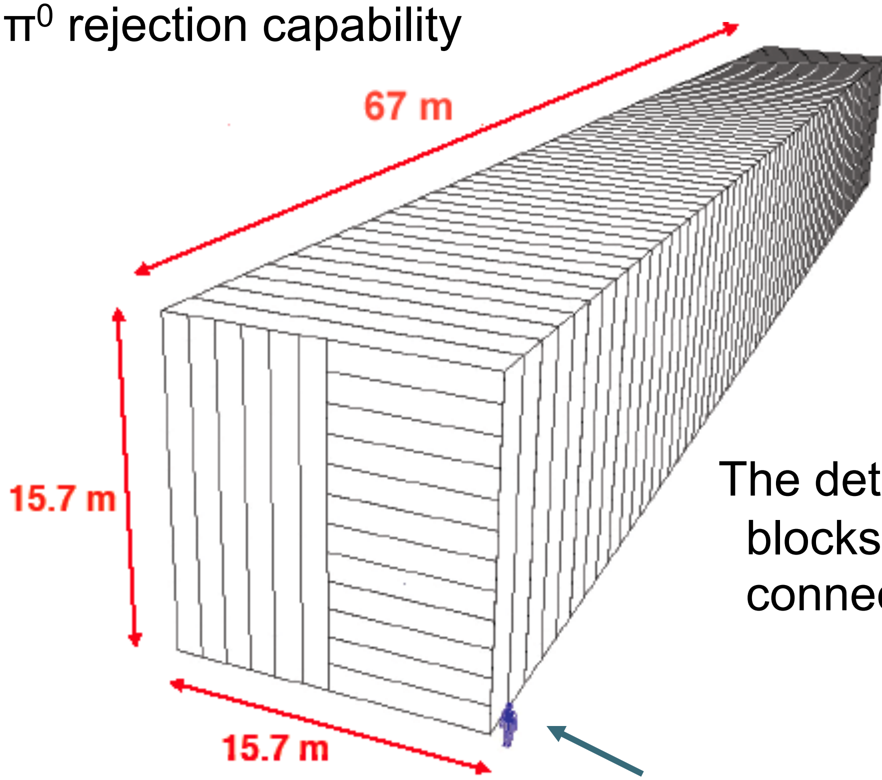
Near detector taking data: Mathew Muether, WG1, Friday

Far Detector



TASD: Totally Active Scintillator Design

Longitudinal sampling is ~0.15 X_0, which gives:
-- excellent μ-*e* separation
-- π^0 rejection capability

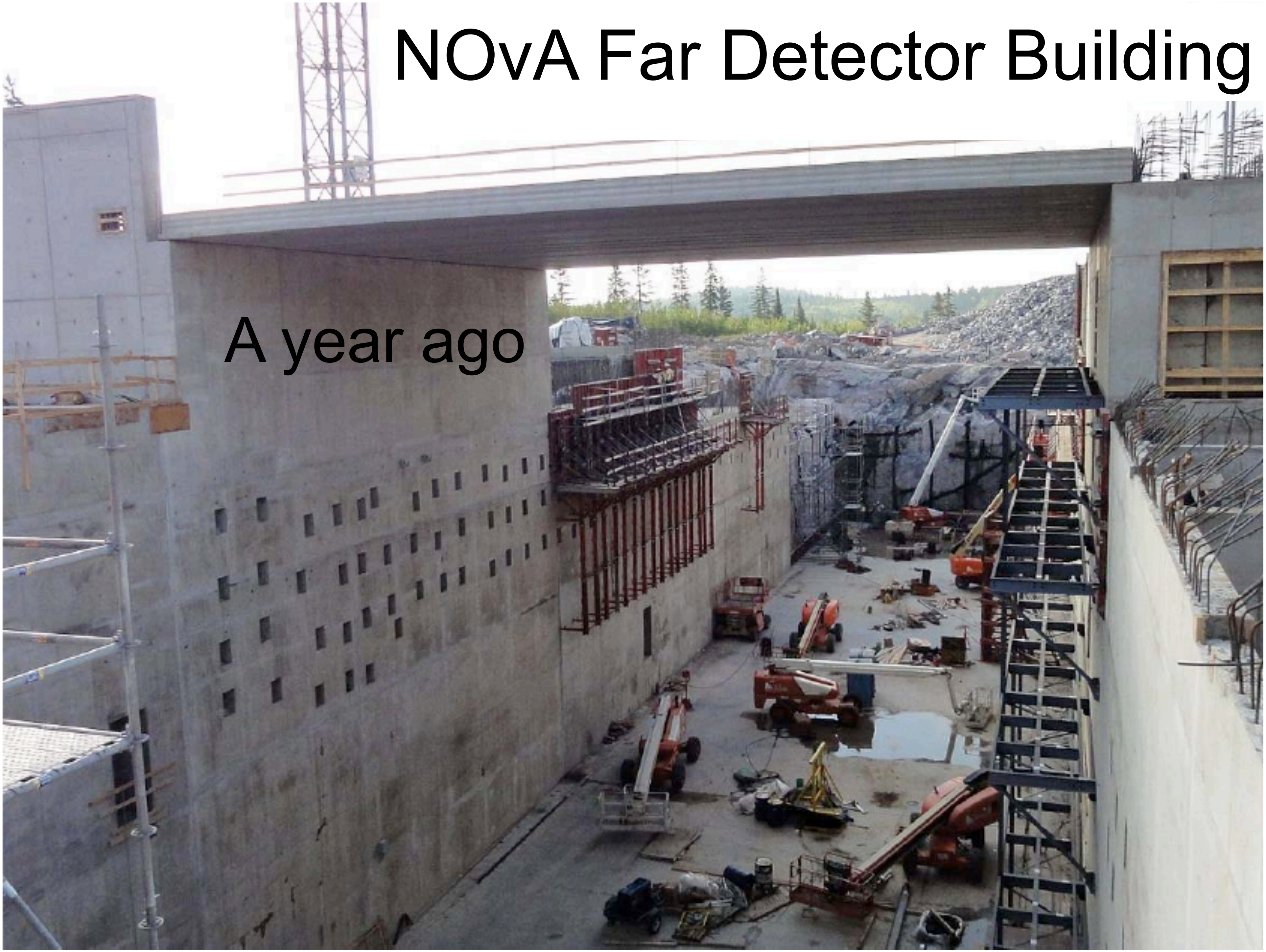


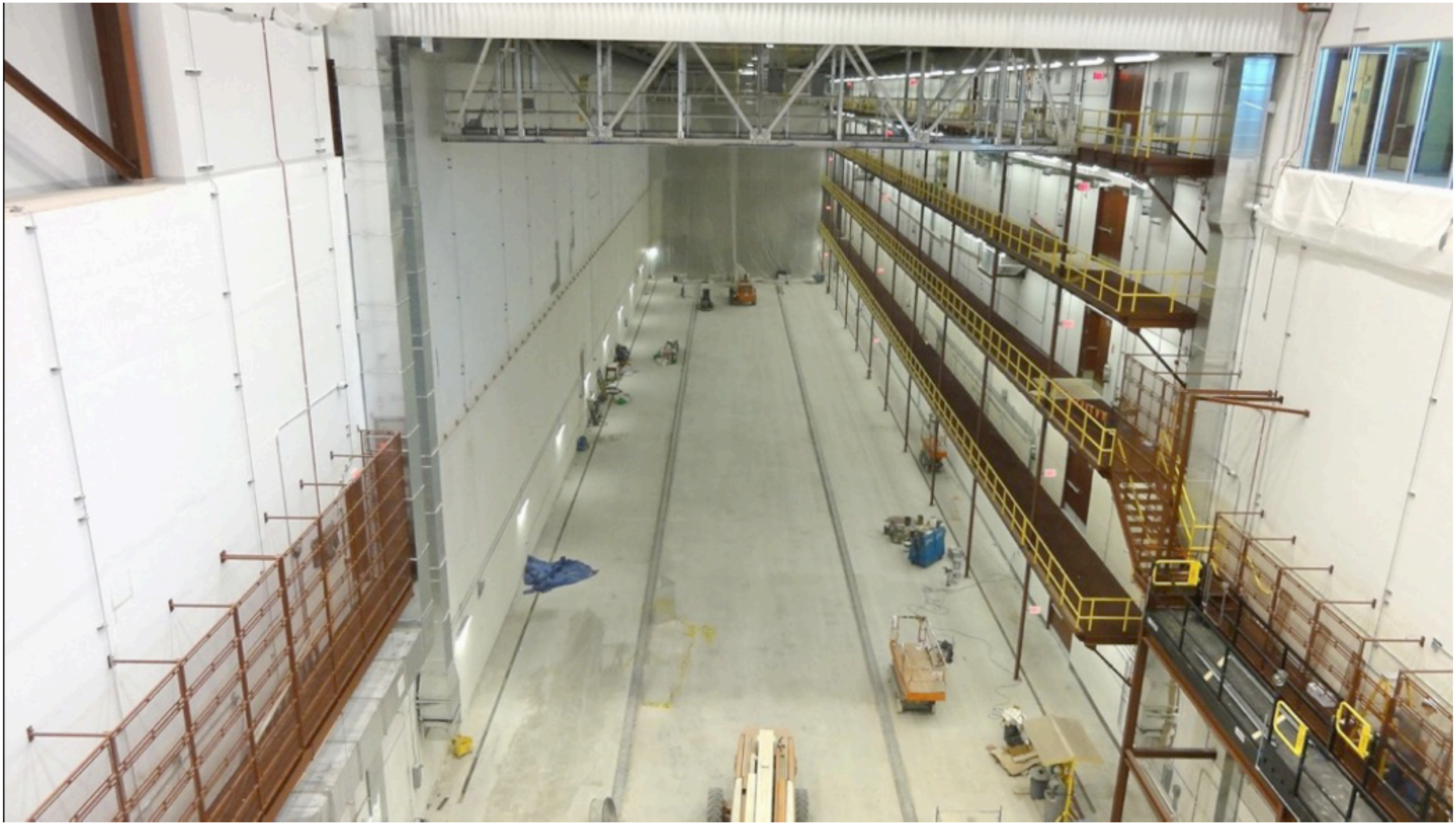
An admirer

Baseline total mass of 14 kT. Enough room in the building for 18 kT

The detector can start taking data as soon as blocks are filled and the electronics connected.

NOvA Far Detector Building

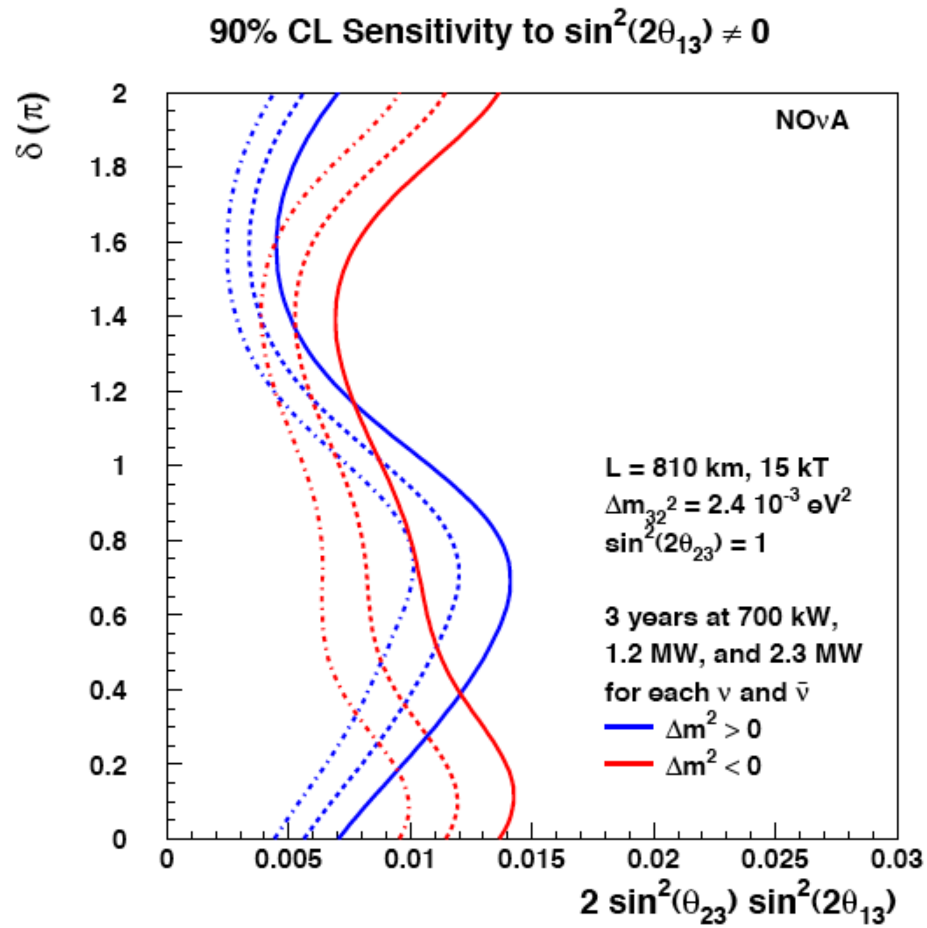




Far detector laboratory complete

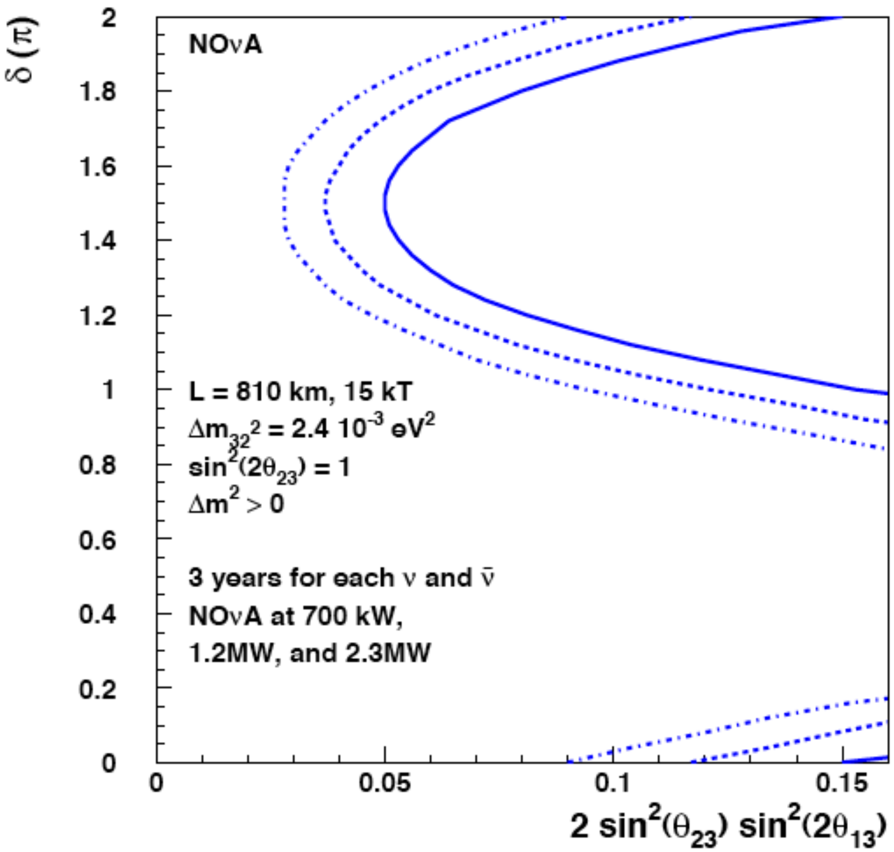
Planning to have first block in place and filled prior to March 2012 shutdown

Sensitivity to $\sin^2(2\theta_{13}) \neq 0$

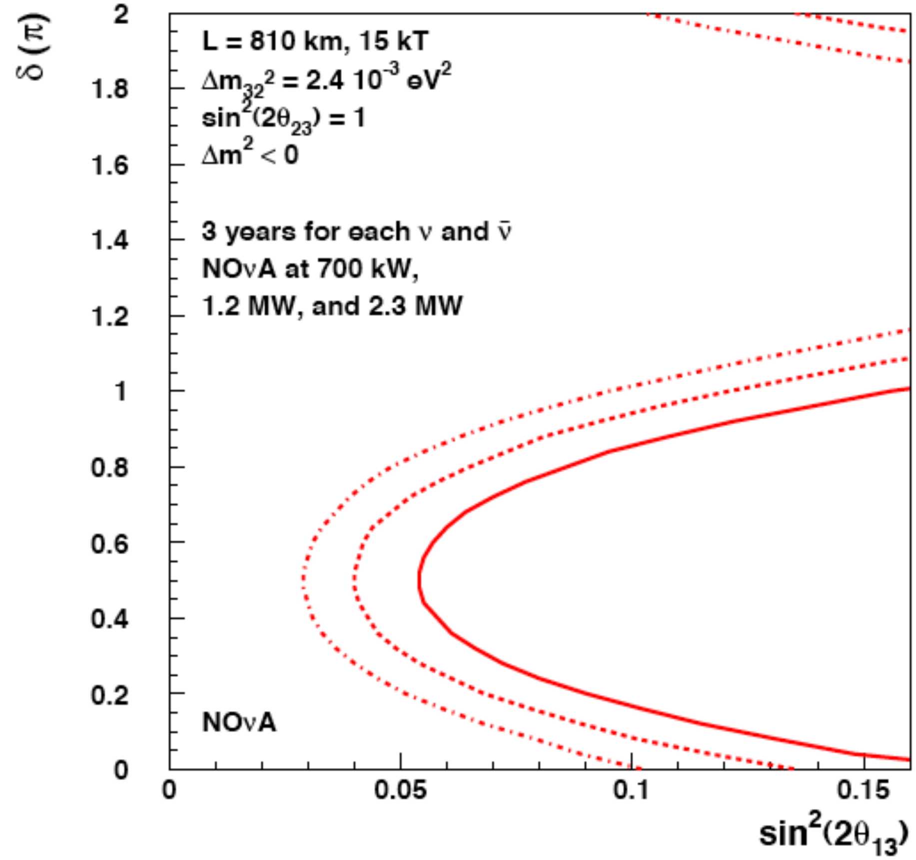


95% CL Resolution of Mass Ordering: NOνA Alone

For relatively large θ_{13}, can determine mass hierarchy
for 50% of possible δ-values



Normal Ordering



Inverted Ordering

How achievable is 700 kW?

- Two main improvements:
  - Reduce cycle time: 2.2 -> 1.3 seconds (1.7x more)
  - Increase 9 -> 12 batches to NuMI (1.3x more)
    - Multiplicative, so **2.2x** more POT overall

320 kW -> 700 kW

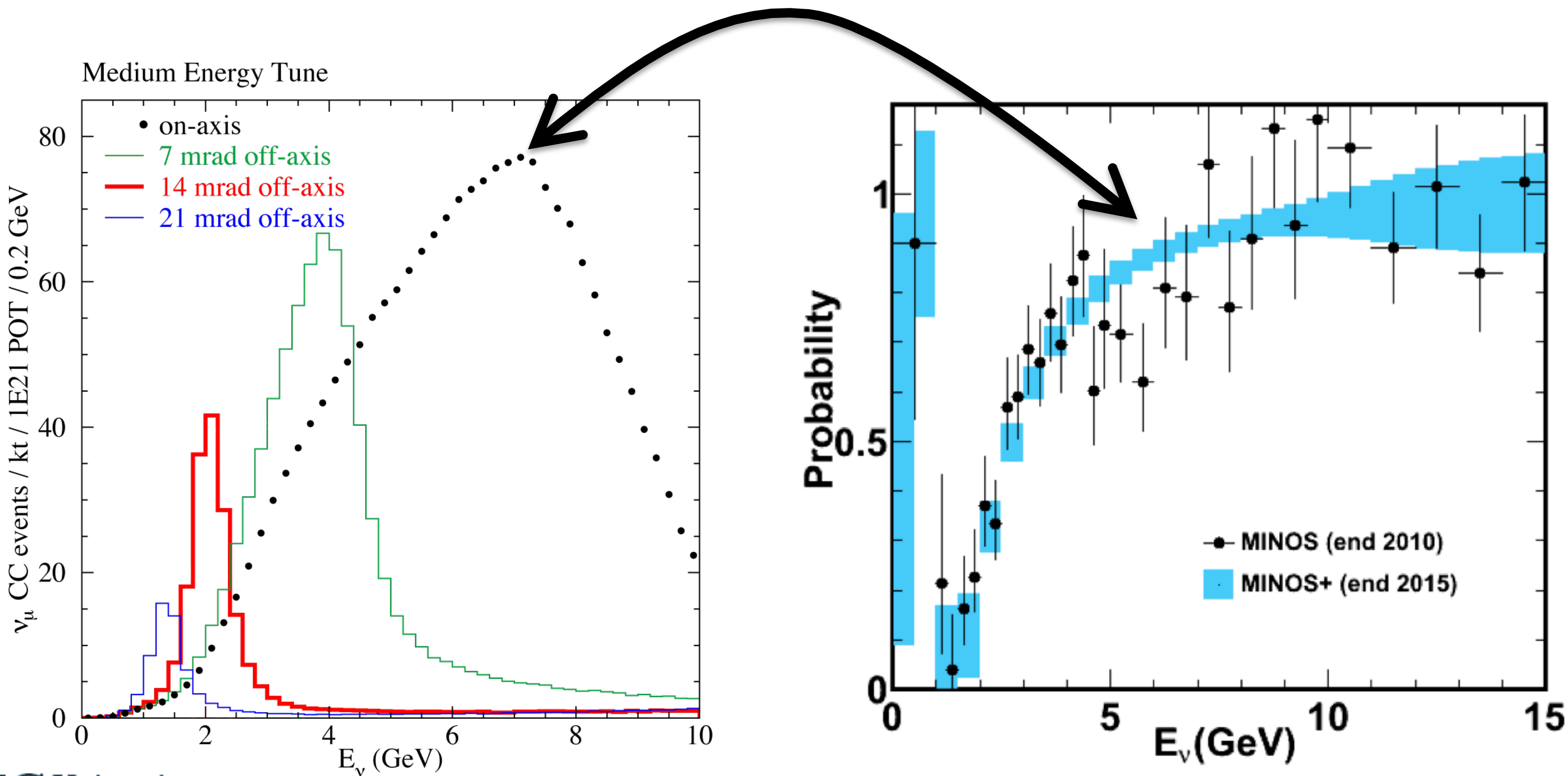
- Already have 11 batches in MI (2 for pbar)
  - space for 1 more
- Fill the Recycler while MI is ramping
    - (Recycler is in MI tunnel, used to cool 8 GeV pbars)
  - save ~0.75 seconds per cycle
  - also ramp slightly faster (~0.15 seconds saved)

Dedicated talk: Phil Adamson, WG3, Tuesday

MINOS+

MINOS+

- Search for new physics in a precision long-baseline neutrino measurement
- Use large on-axis flux in MINOS detector
- Improves hugely on precision in 4-10 GeV range



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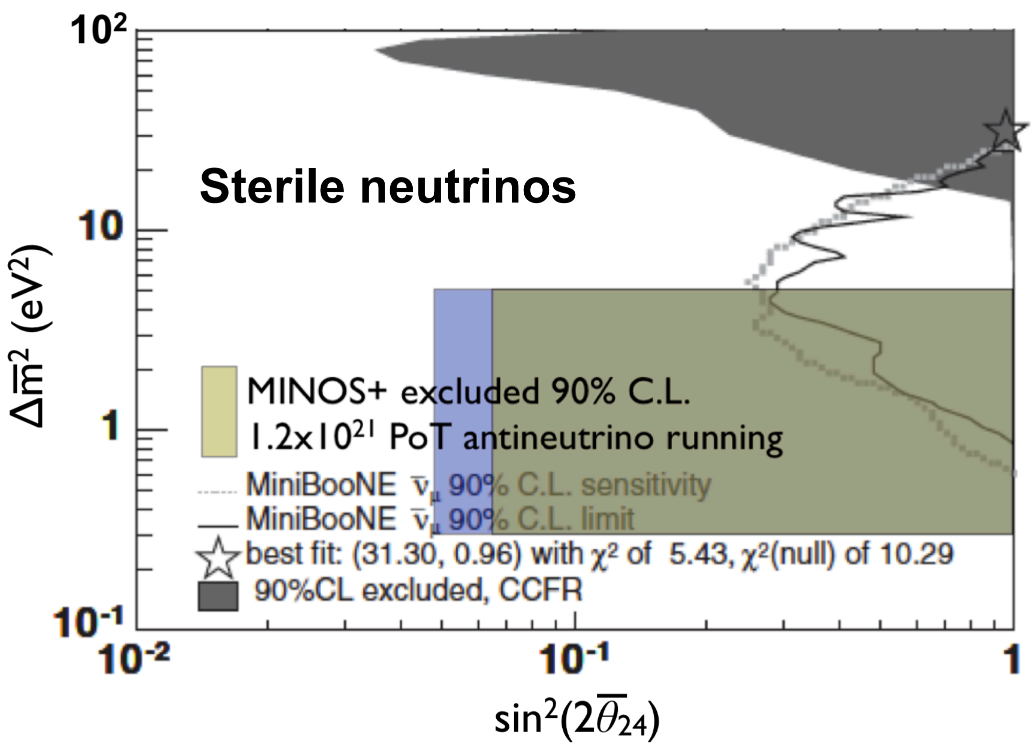
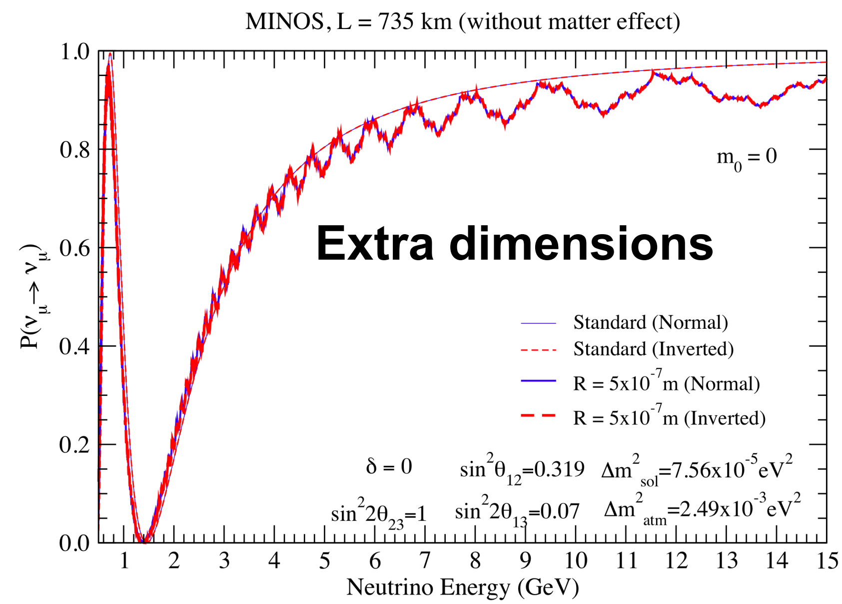
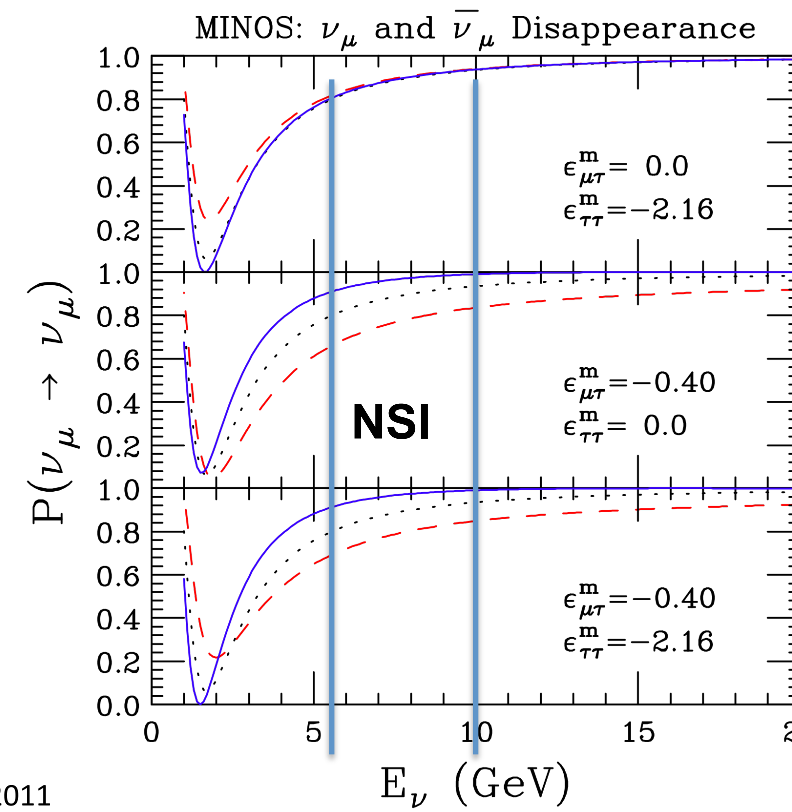
Search for wide range of new physics

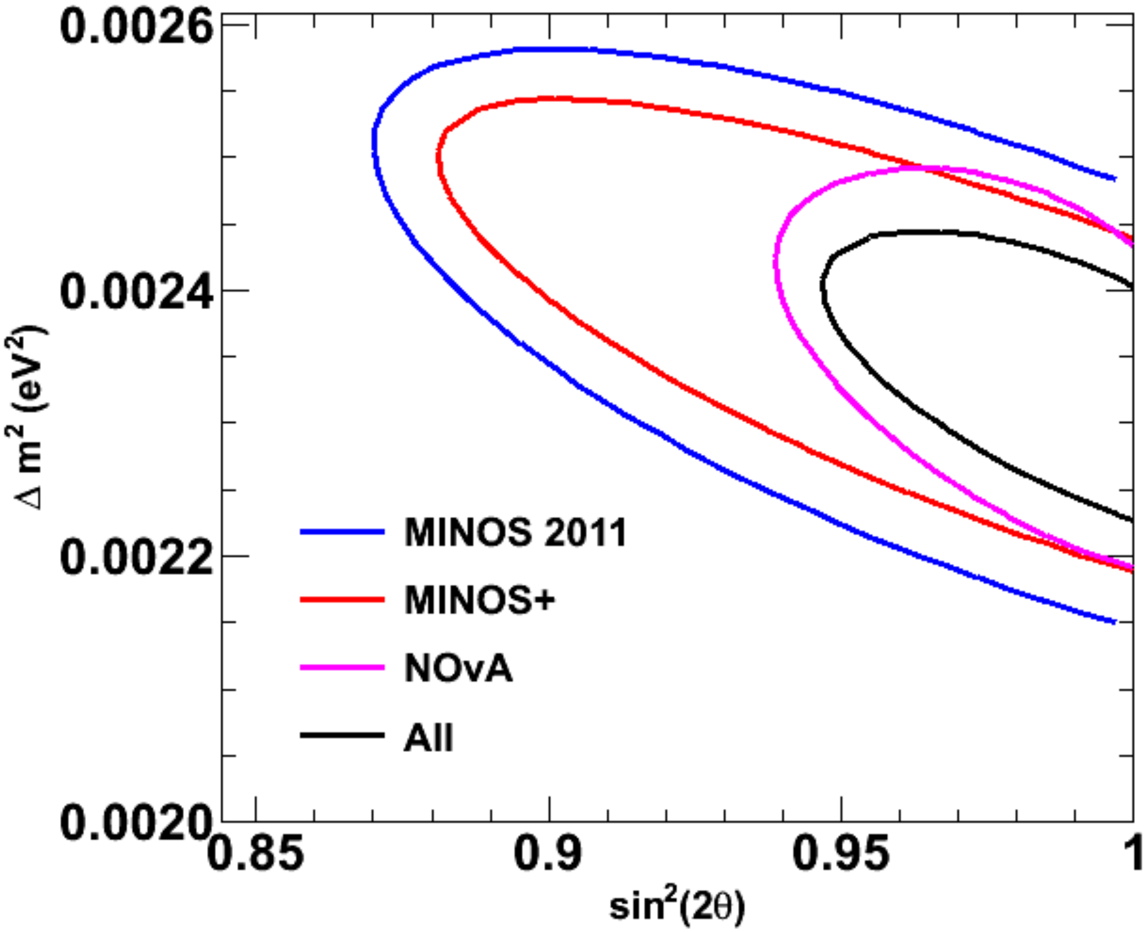






If new physics here, MINOS+ will be able to unravel it with the energy spectrum giving model discrimination (hard for off-axis experiments)

MINOS and MINOS+



- After 1 year MINOS+ continues to improve Δm^2 measurement

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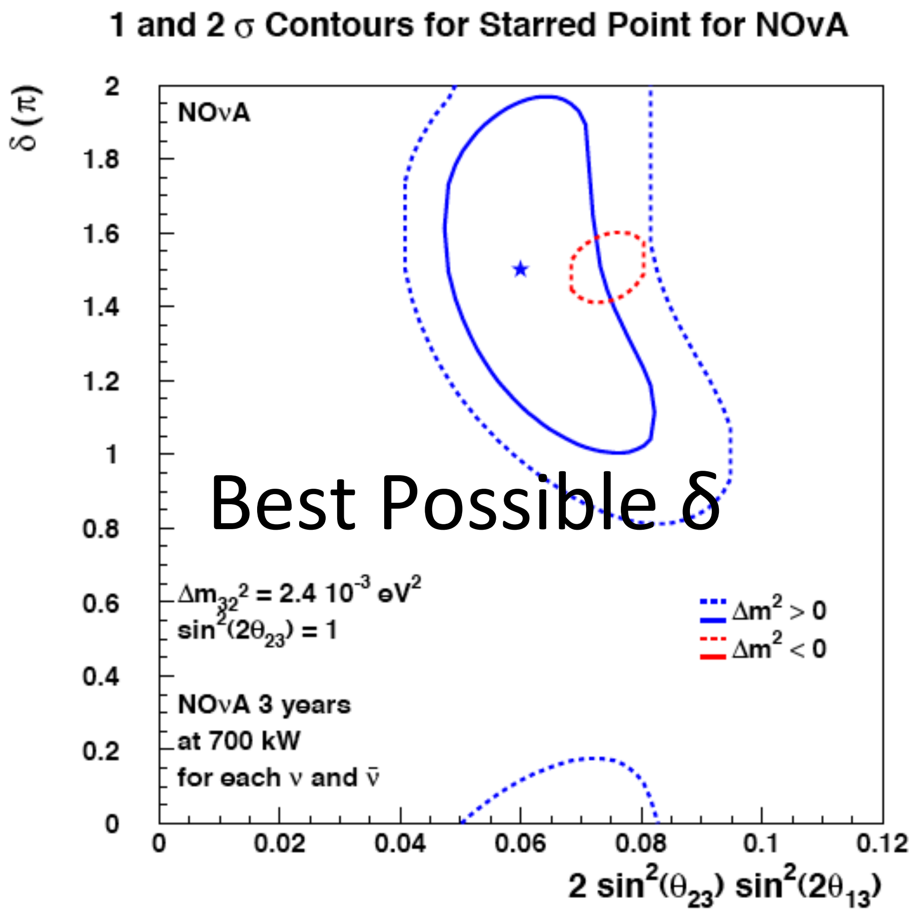
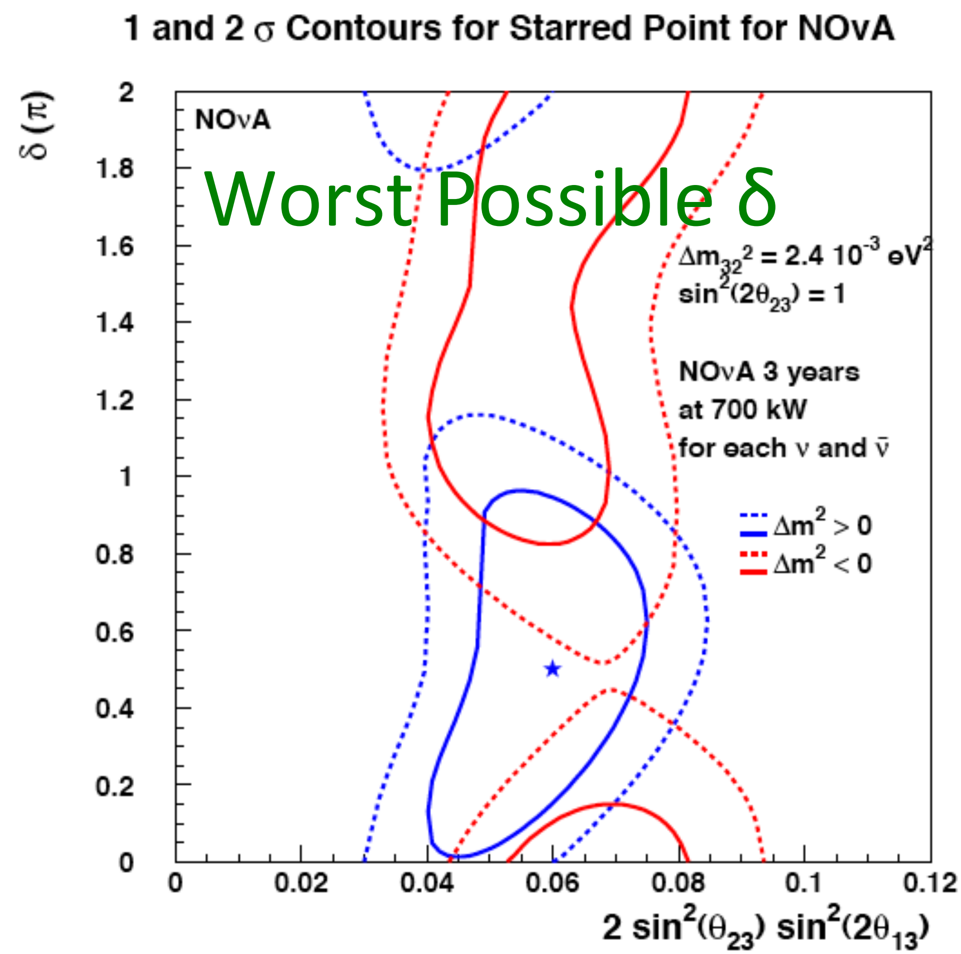
Conclusions

- Much exciting physics from MINOS (NuMI at 320kW)
  - Most precise measurement of Δm^2_{atm}
    - $\Delta m^2_{atm} = 2.32^{+0.12}_{-0.08} \times 10^{-3}$ eV^2
  - ν_e appearance hint
  - Anomaly with antineutrino disappearance
- Second phase getting underway with a straightforward NuMI upgrade to 700 kW in 2012
  - NOvA ND is taking neutrino data
  - NOvA FD detector construction starts very soon
  - Sensitivity to mass hierarchy if θ_{13} is large
  - MINOS+ will search for new physics
    - Combines high precision with wide energy spectrum
- Exciting future: stay tuned!

Backup slides

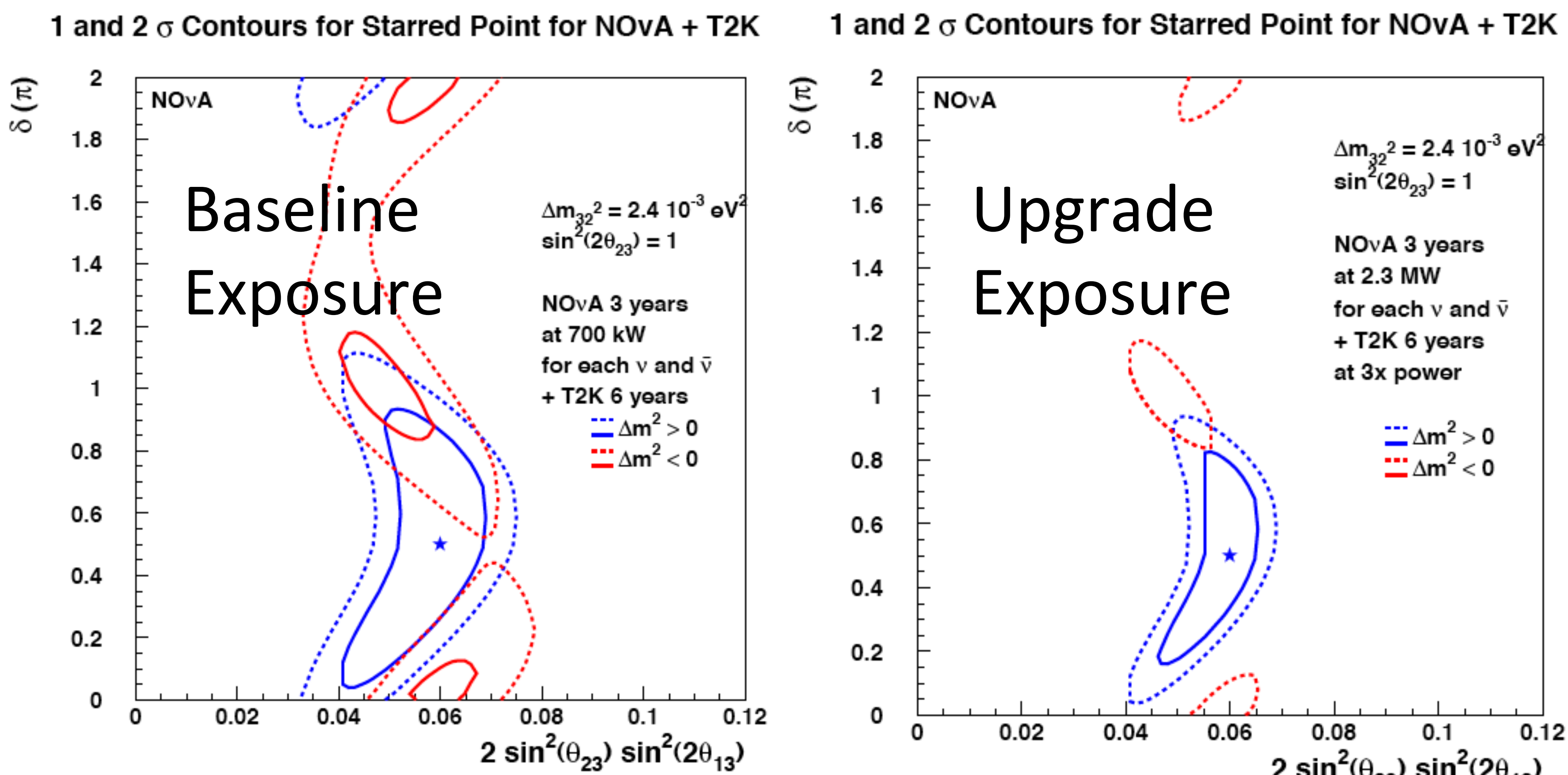
δ vs. θ_{13} Sensitivity Contours





Synergy by combining with T2K

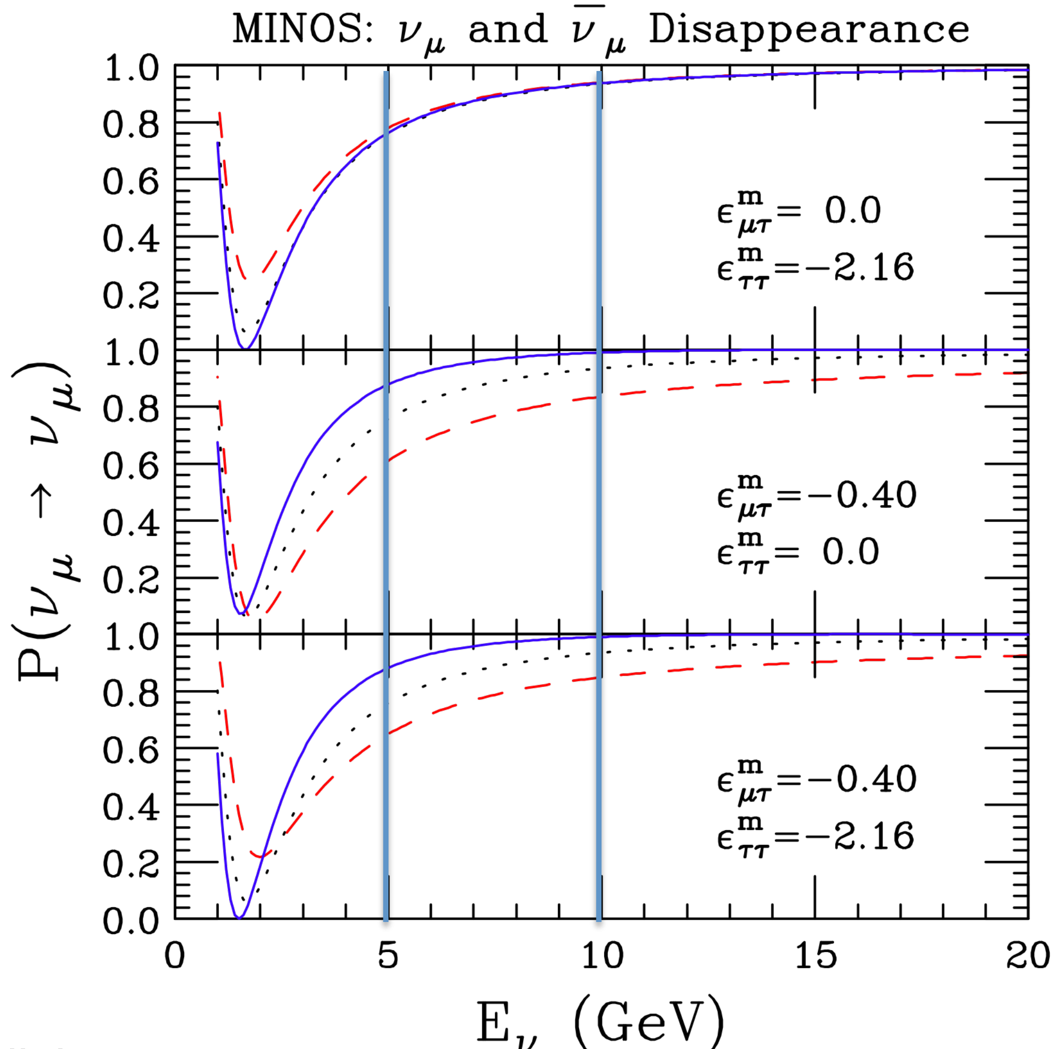
δ vs. θ_{13} Contours: Worst Possible δ
T2K and NOvA Combined



MINOS+

Non Standard Interactions*

- Our anti-neutrino result has motivated some work from other theorists*
- Note the NSI has a measurable effect in neutrinos as well as antineutrinos
- Comparison of low energy to high energy behavior could disentangle this without anti-nu running

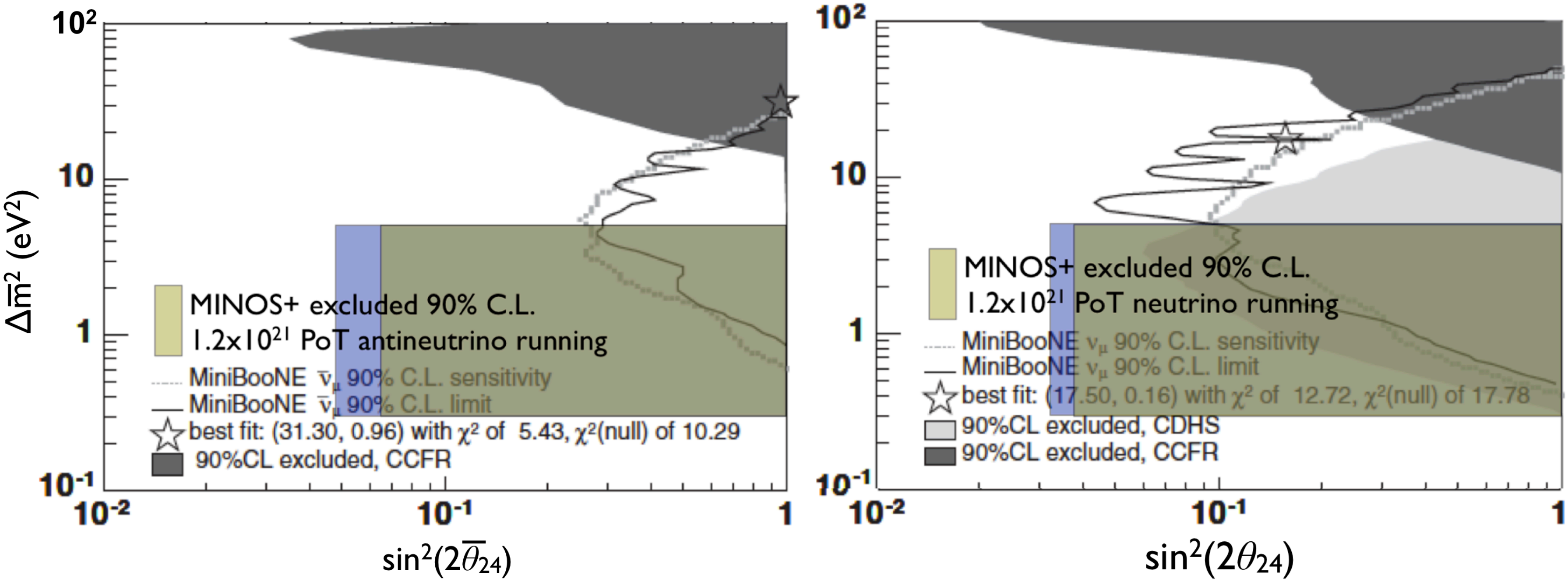


* Alexander Friedland , Cecilia Lunardini, Phys.Rev.D74:033012,2006.

* J. Kopp, P.A.N. Machado and S.Parke, Phys.Rev.D82:113002 (2010).

MINOS+ : $\nu_\mu \rightarrow \nu_s$

- Using CC disappearance

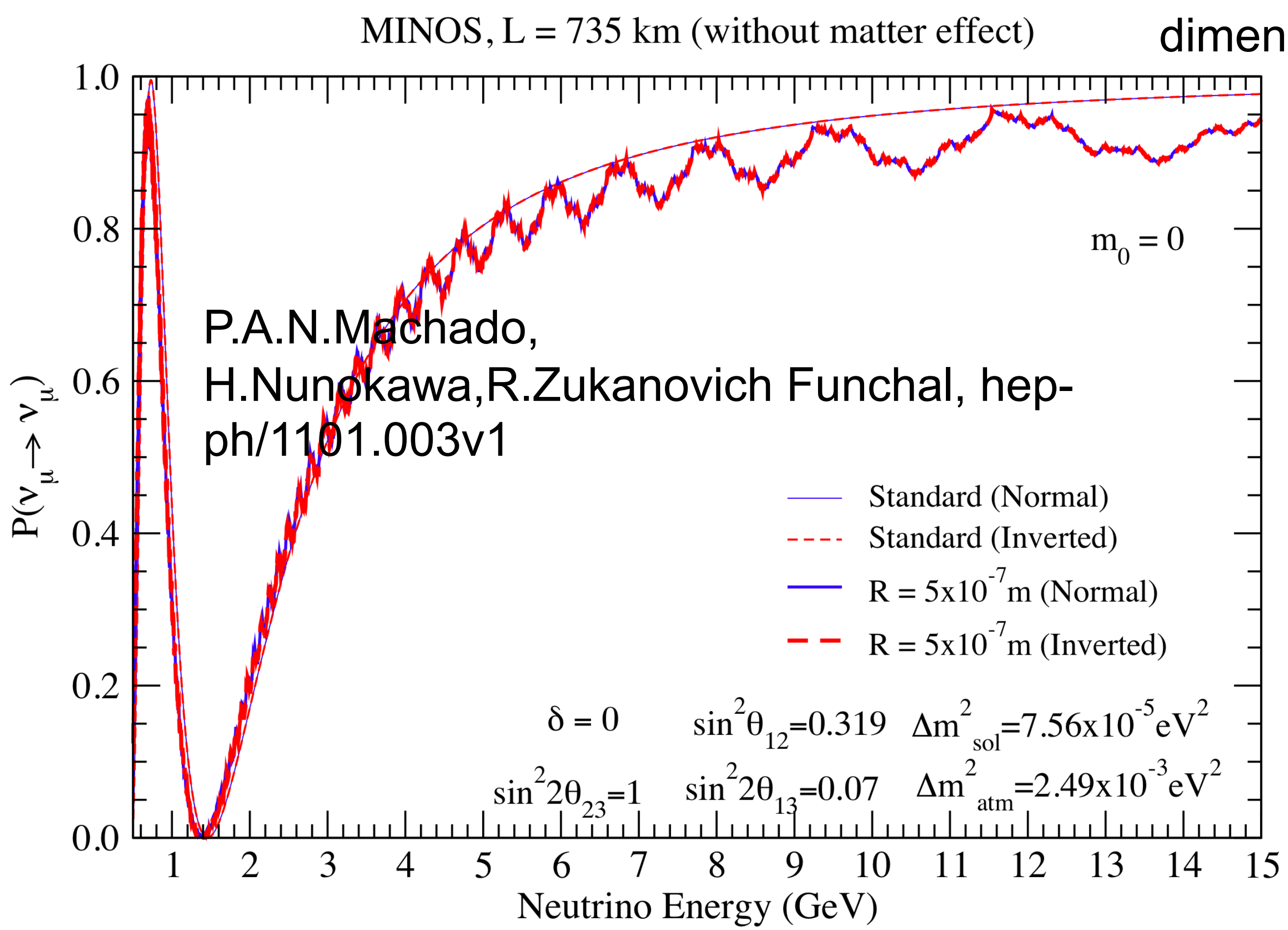


- Including NC and CC disappearance probes mixture of $\theta_{24}+\theta_{34}$

More info from Alex Sousa, WG1, Wednesday

Extra Dimensions

Assumes heavy RH (sterile) neutrino + extra dimensions!



P.A.N.Machado, H.Nunokawa,R.Zukanovich Funchal, hep-ph/1101.003v1

- MINOS data has already put limit on extra dimensions at about 1 micron level.
- This is just an example of the breadth of subjects which can be studied in the long baseline neutrino beam at higher energy

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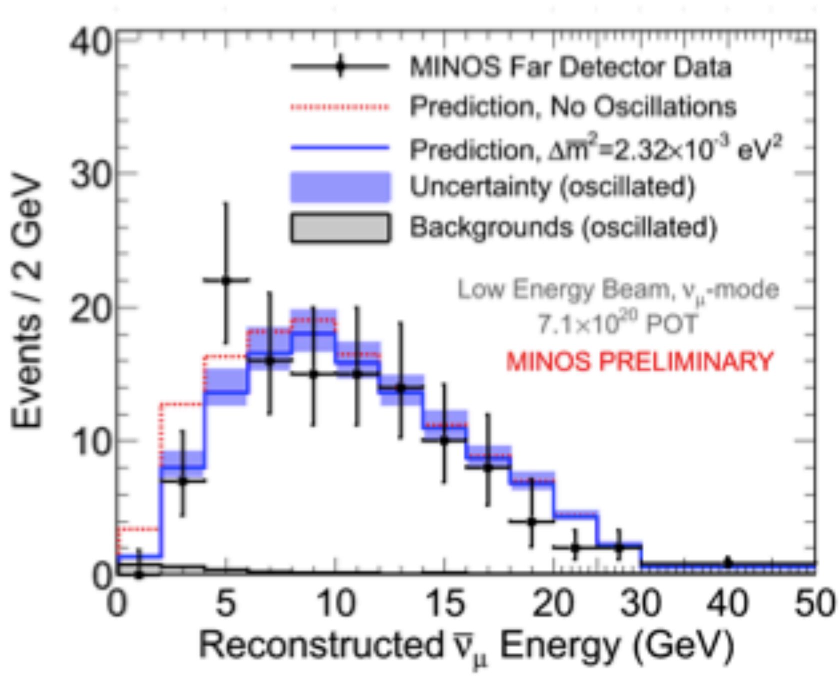
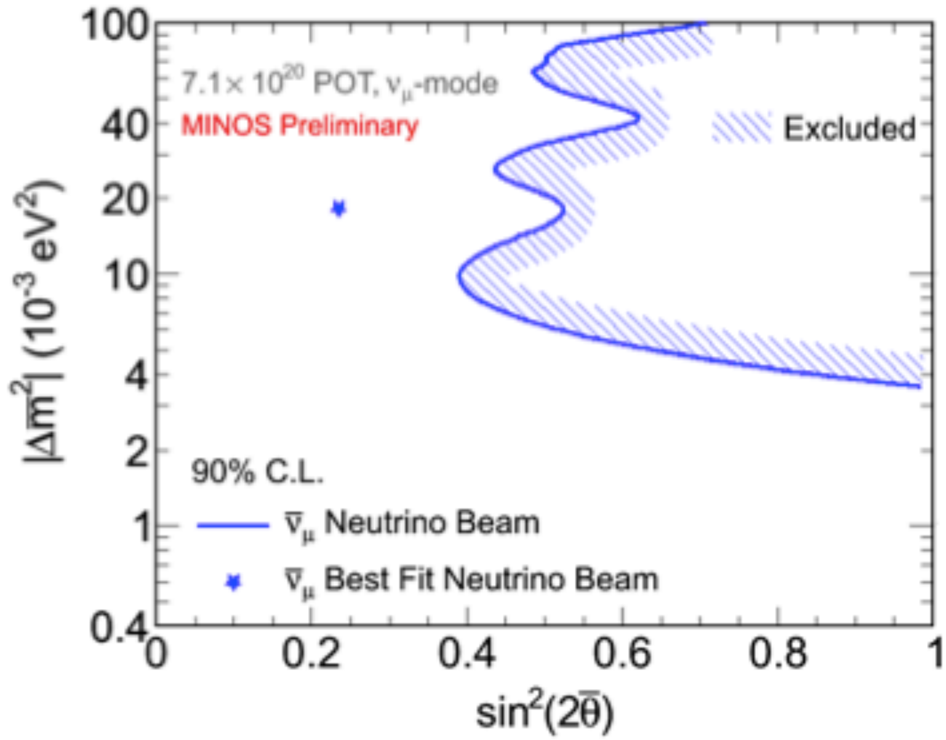
MINOS

Anti-neutrino Disappearance

30





No Oscillations: $150.3^{+16.3}_{-18.2}$

With Oscillations: $136.4^{+15.2}_{-14.9}$

Observed: 130

at $\sin^2(2\bar{\theta}_{23}) = 1$

$|\Delta\bar{m}^2| < 3.37 \times 10^{-3}\ \mathrm{eV}^2$ (90% C.L.)

P. Vahle, INFO 2011

Soudan Fire

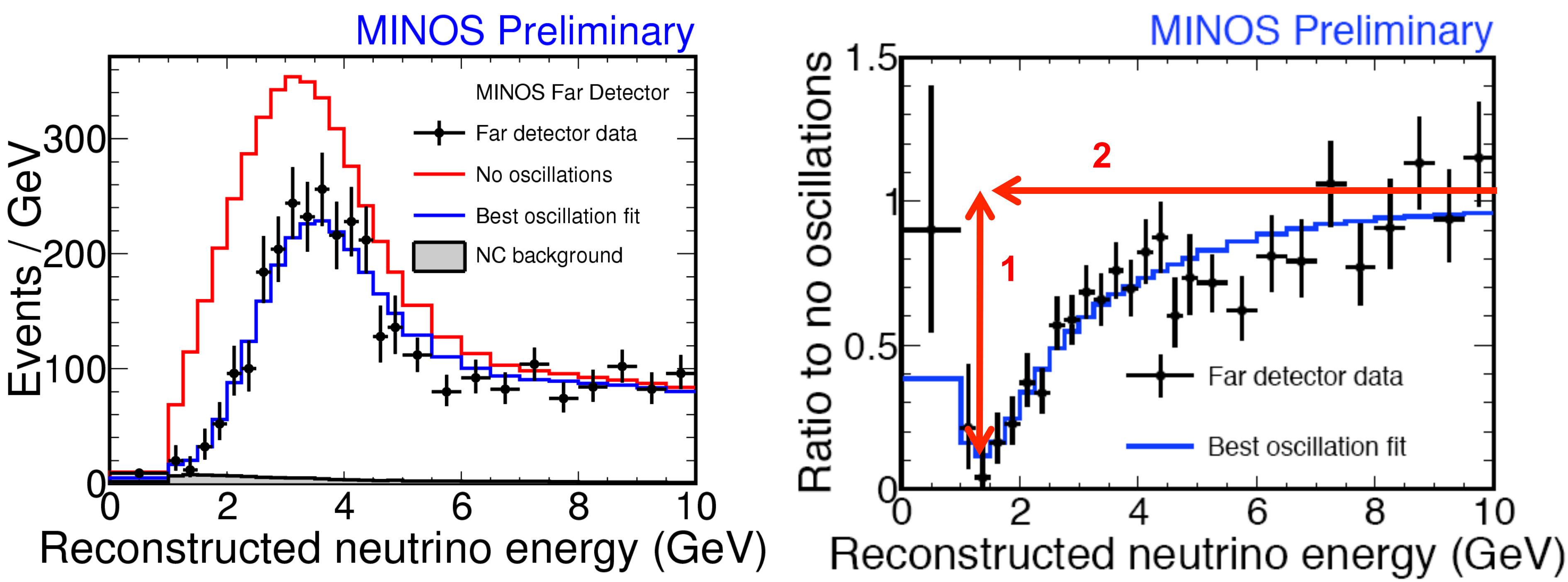
11

- March 17, smoke detected in FD hall due to a fire in the shaft
- Power to the lab shut off automatically
- Foam pumped in to extinguish the fire
- No damage to the MINOS detector
- Detector returned to full operations May 19

P. Vahle, INFO 2011

Experimental Approach

- **Two detector experiment** to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated ν_μ spectrum at Near detector
    - extrapolate using MC
  - Compare to measured spectrum at Far detector



$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \boxed{\sin^2 2\theta}\sin^2(1.267\boxed{\Delta m^2}L/E)$$

1 2

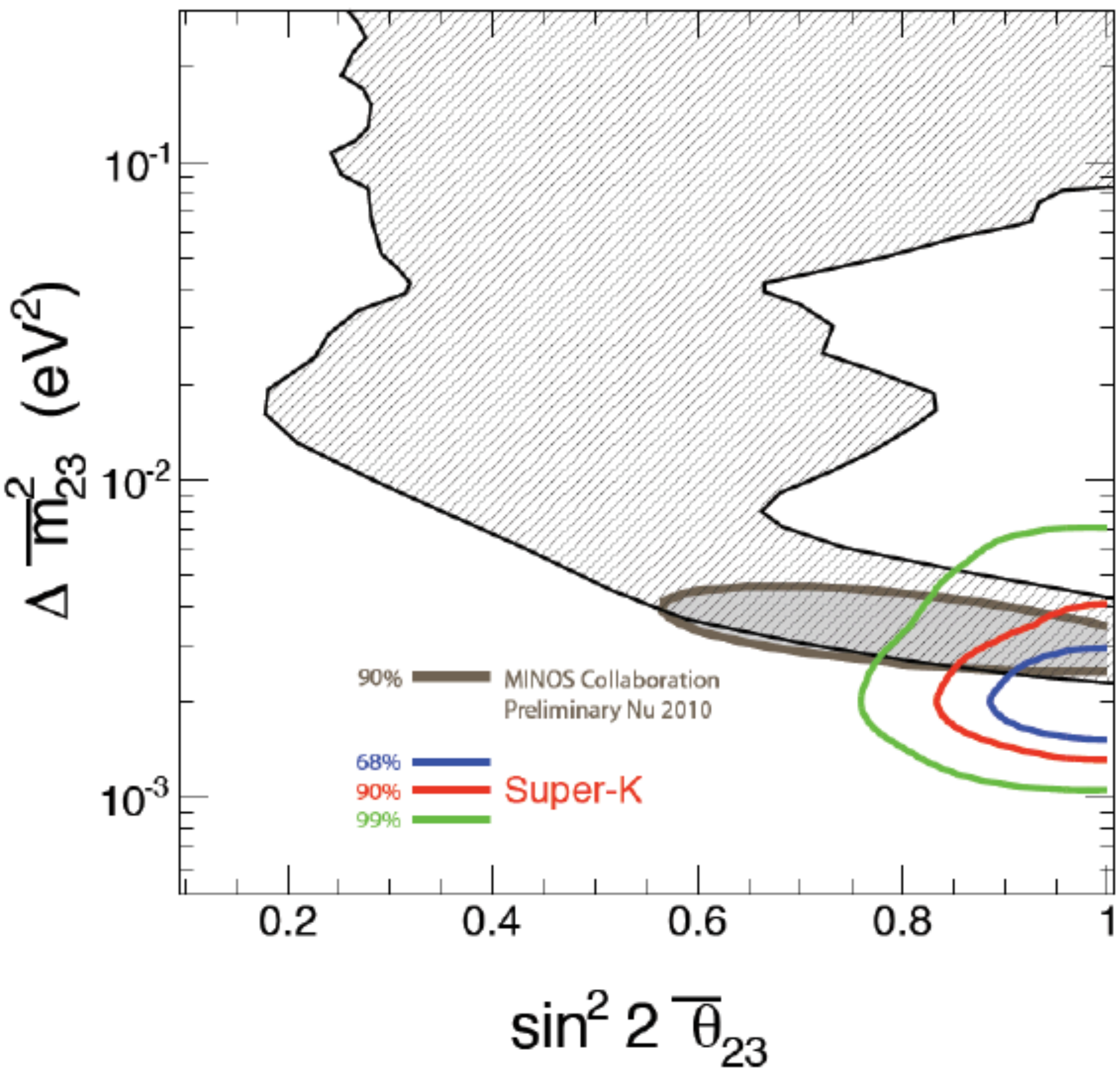
Search for CPT violation in atm. ν

Jun 2009

- Under the CPT theorem, $P(\nu \rightarrow \nu)$ and $P(\bar{\nu} \rightarrow \bar{\nu})$ should be same.
- Test ν oscillation or $\bar{\nu}$ oscillation separately.

SK-I+II+III

Preliminary



Neutrino:

$\Delta m_{23}^2 = 2.2 \times 10^{-3}$ eV^2

$\sin^2 2\theta_{23} = 1.0$

Anti-neutrino:

$\Delta \overline{m}_{23}^2 = 2.0 \times 10^{-3}$ eV^2

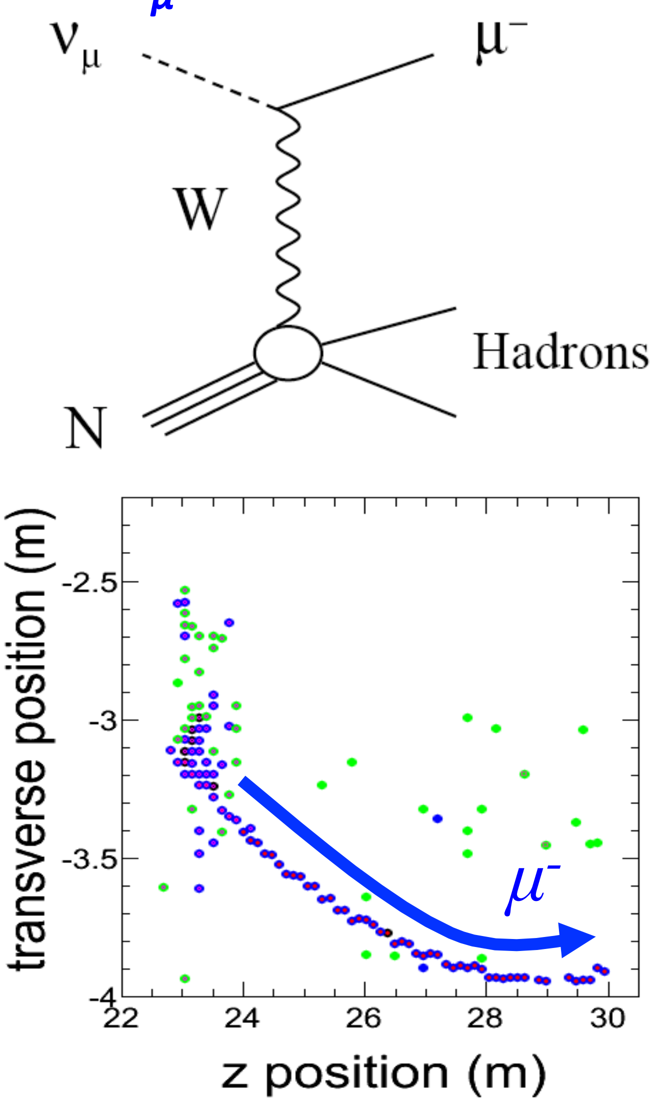
$\sin^2 2\overline{\theta}_{23} = 1.0$

No evidence for CPT violating oscillations is found

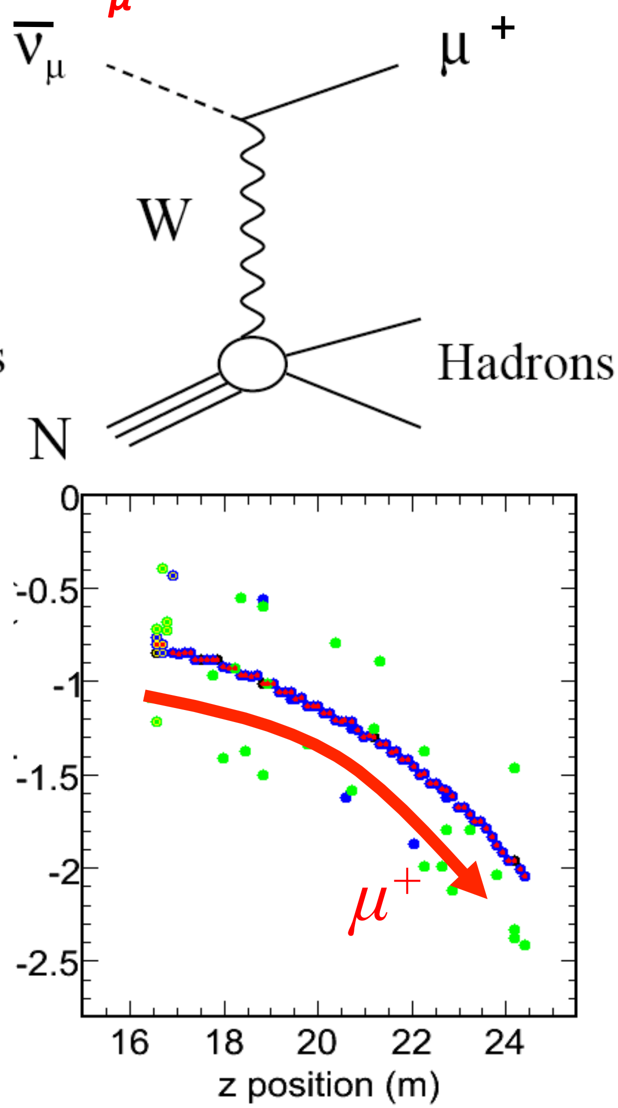
Poster-79 by Roger Wendell

MINOS Event Topologies

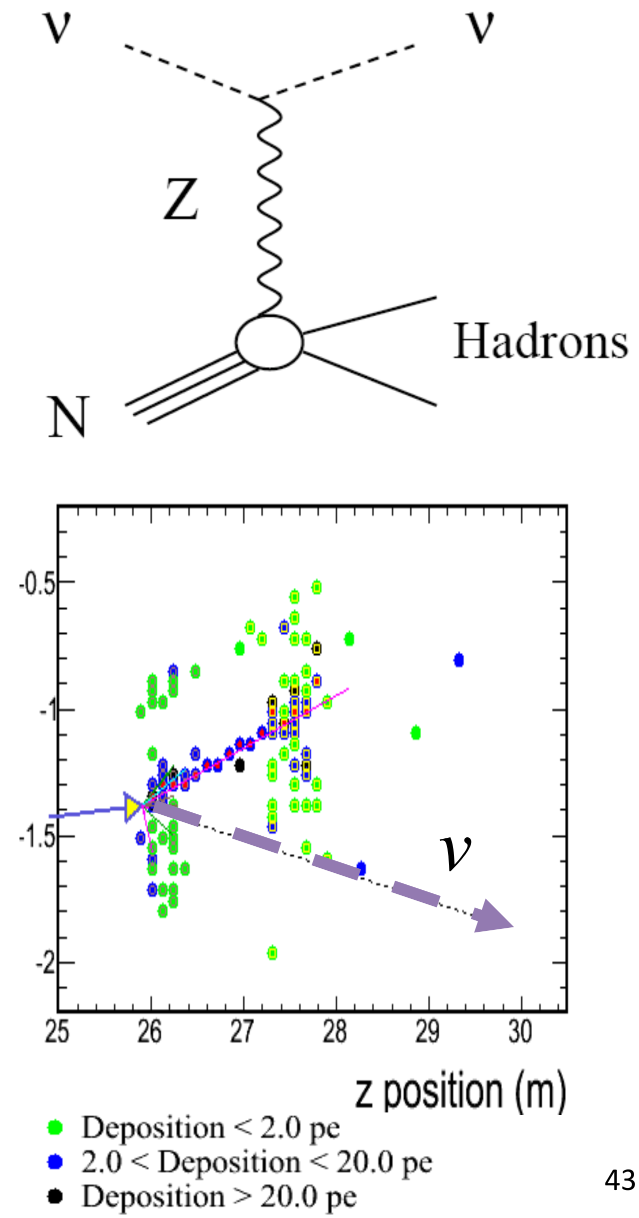
ν_μ CC Event



$\bar{\nu}_\mu$ CC Event



NC Event

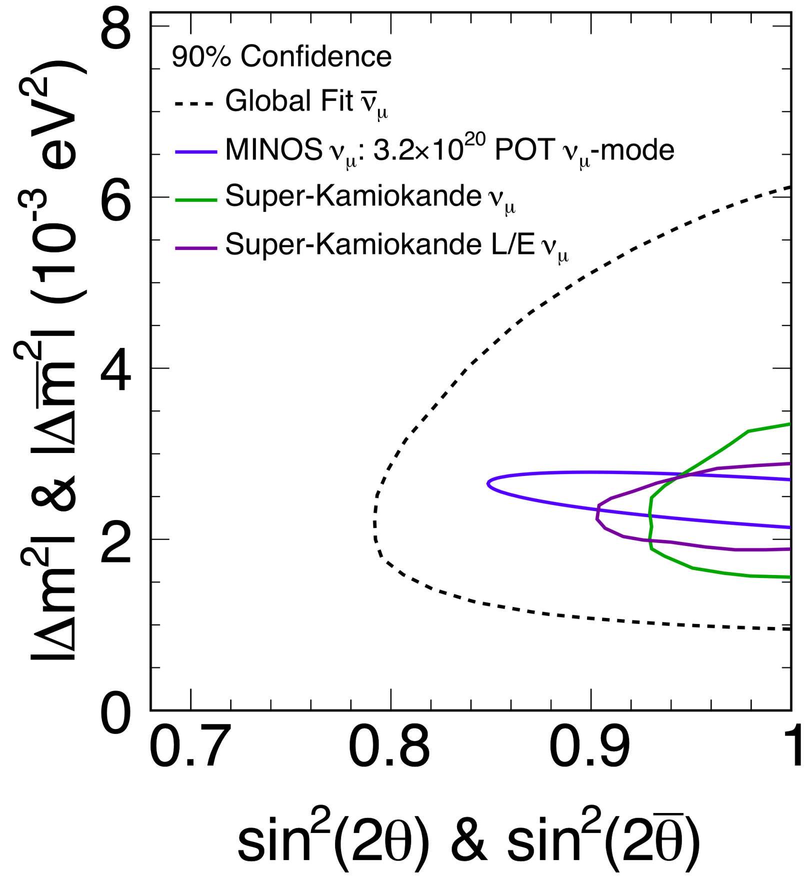


Simulated Events

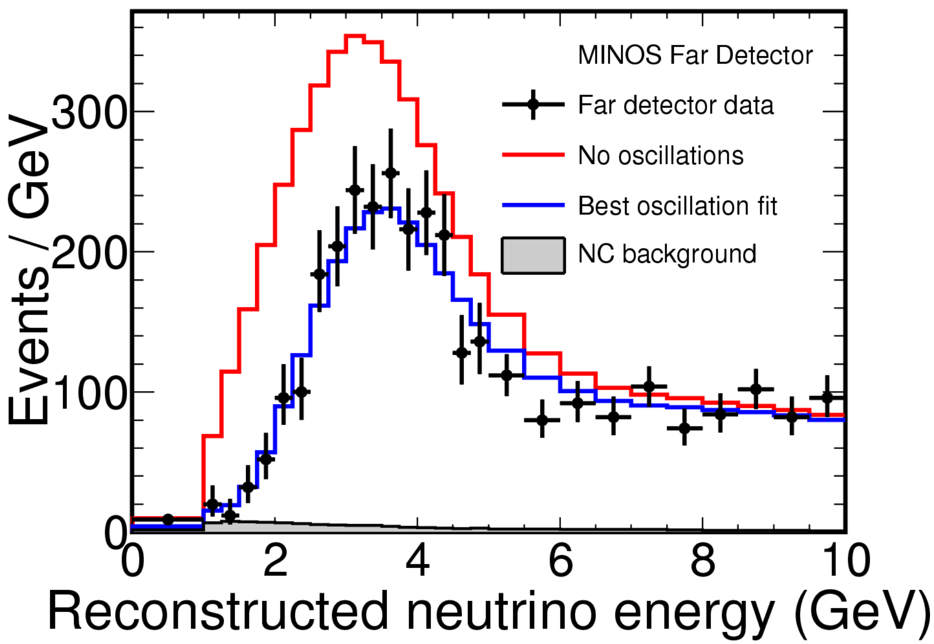
Why study ν_μ and $\overline{\nu}_\mu$?

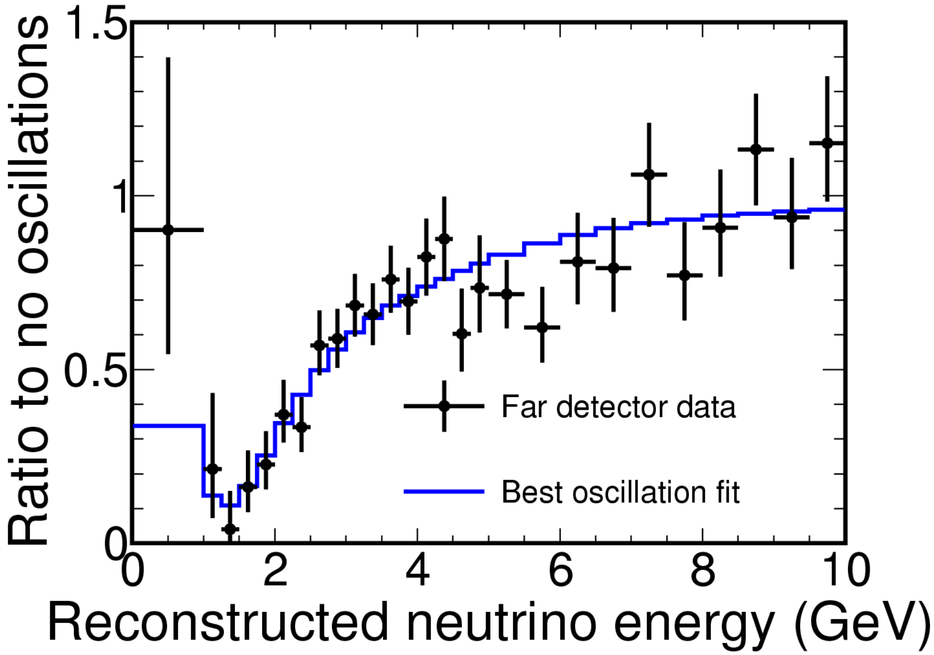
$$P(\nu_\mu \rightarrow \nu_\mu) \stackrel{?}{=} P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu)$$

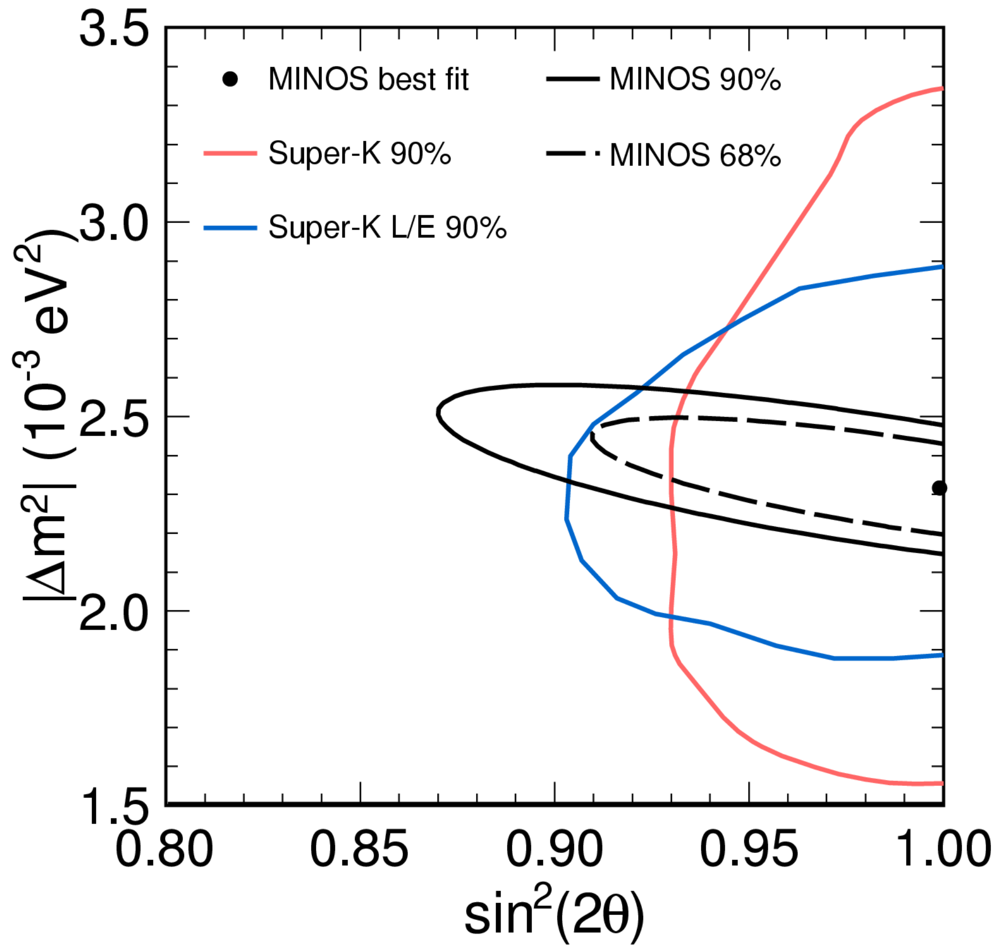
- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation



- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.







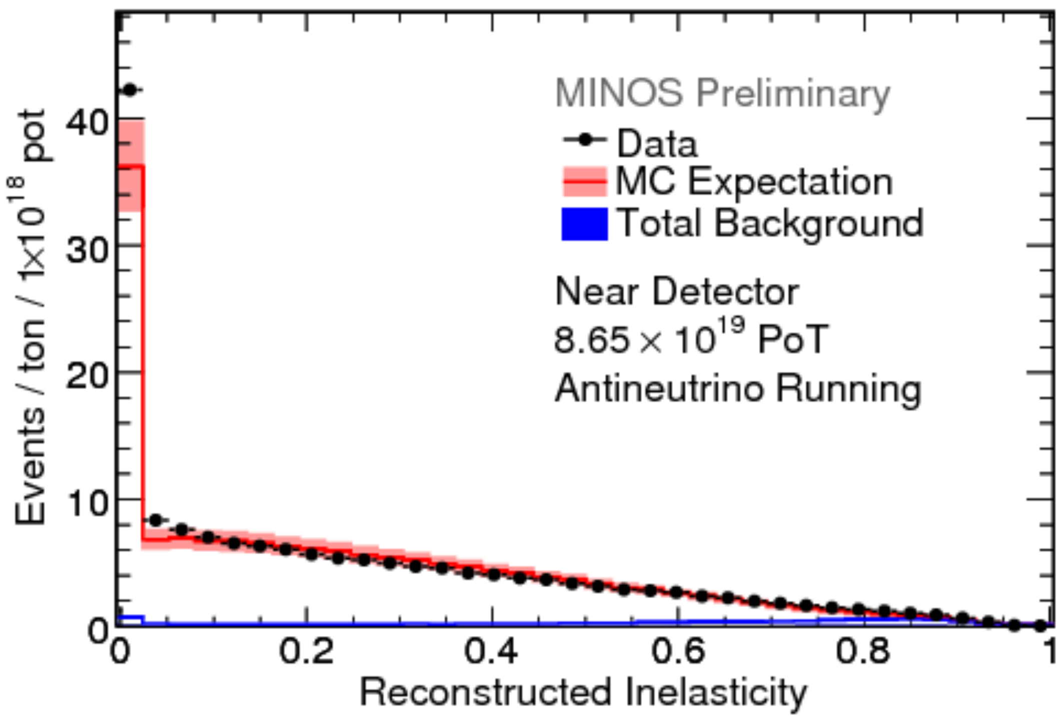
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) > 0.9 \text{ at 90\% C.L.}$$

Phys. Rev. Lett. 106, 181801 (2011)

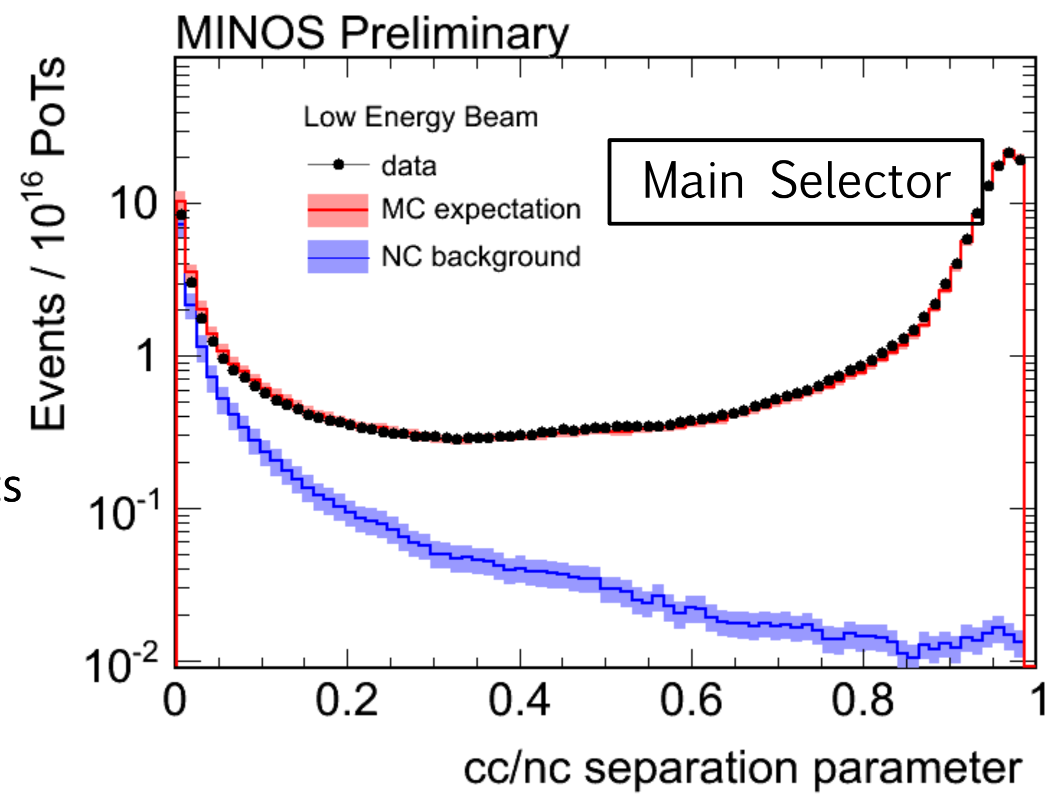
The Anti-neutrino Analysis

- Essentially the neutrino analysis of 2008
  - No resolution binning, shower estimator, new selector
  - Only stopped taking antineutrino data on March 22nd
- What's different with antineutrinos?
  - Lower statistics ~1/12th events
  - Larger wrong-sign component
  - Interactions are less hadronic

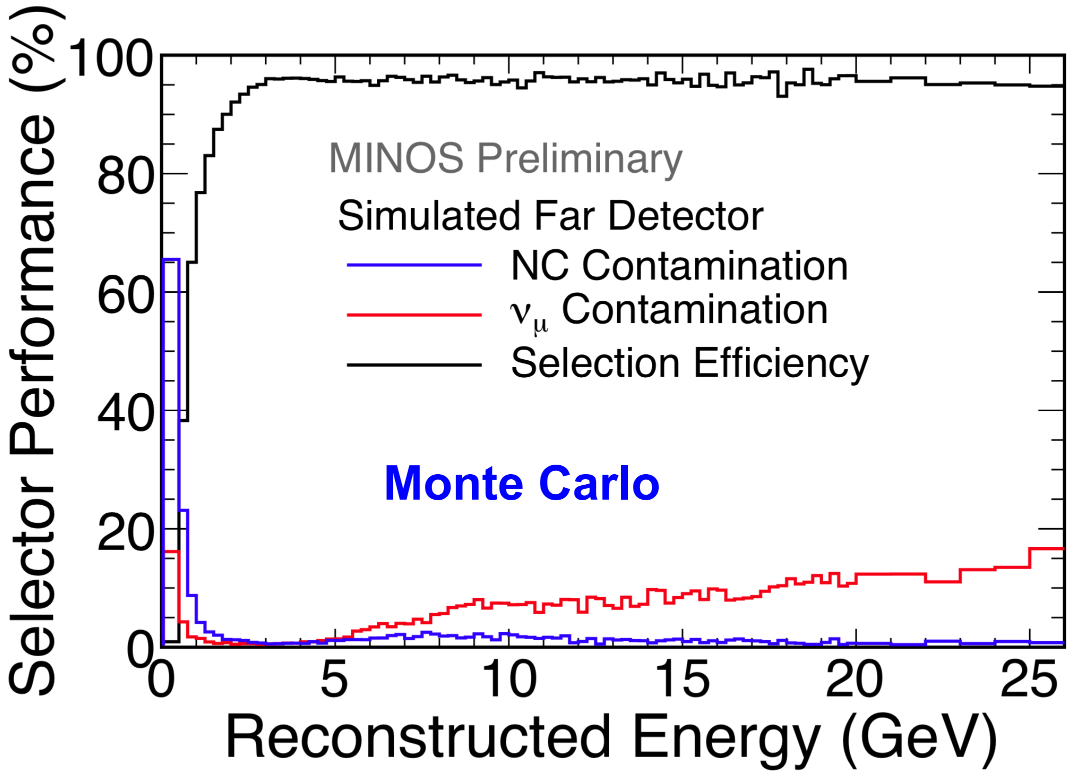


Common Selection

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile



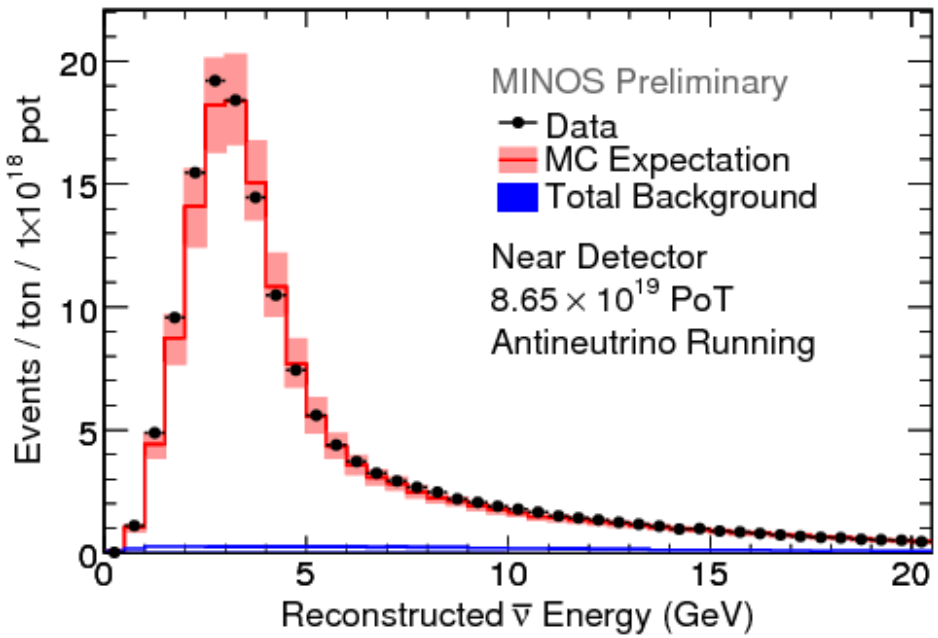
Antineutrino Efficiency & Purity

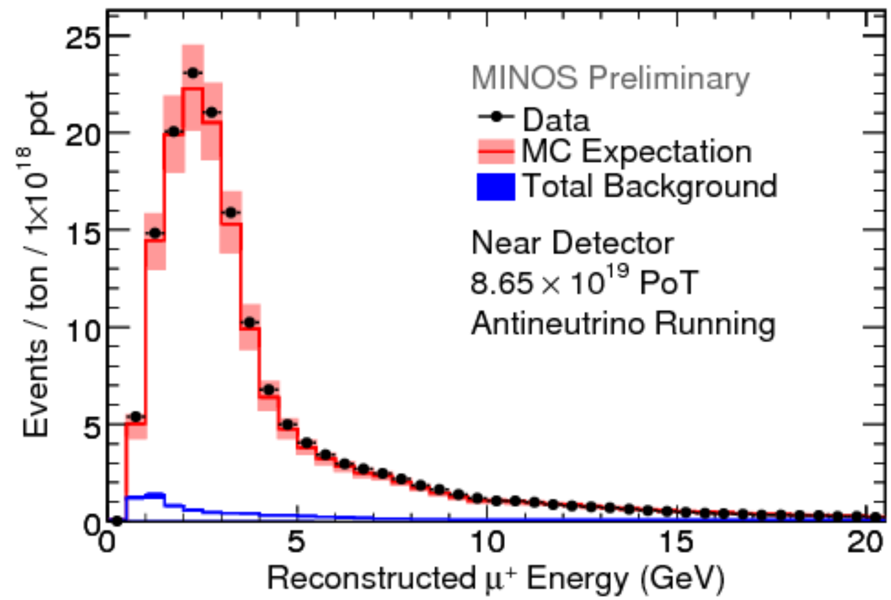


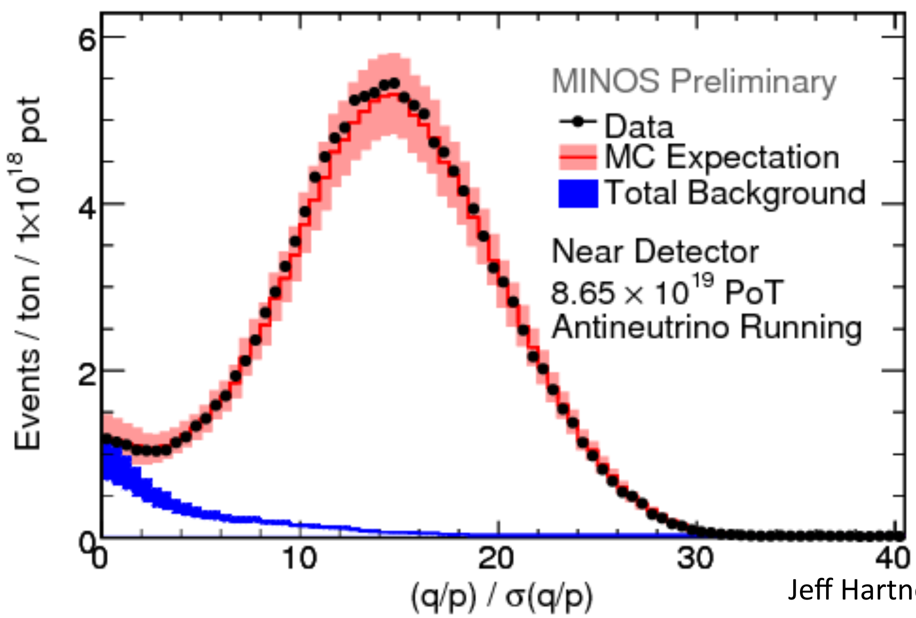
	Signal	Bkgd.
0-6 GeV	106	1.9
6-20 GeV	38	4.3
> 20 GeV	8	3.0

High energy ν_μ contamination does not affect the oscillation result

Near Detector Data



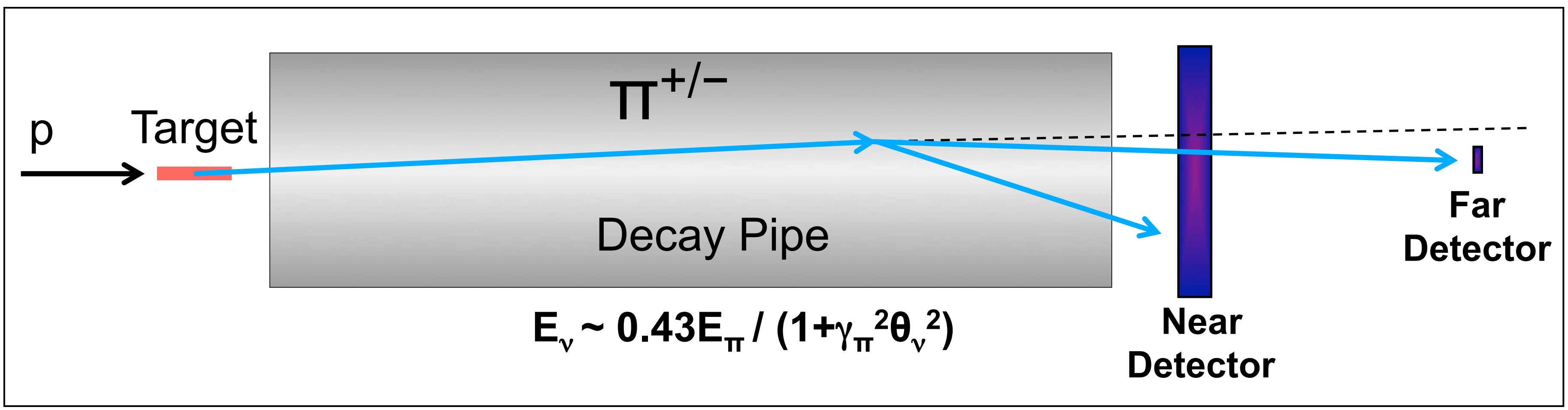




- Data/MC agreement comparable to neutrino running

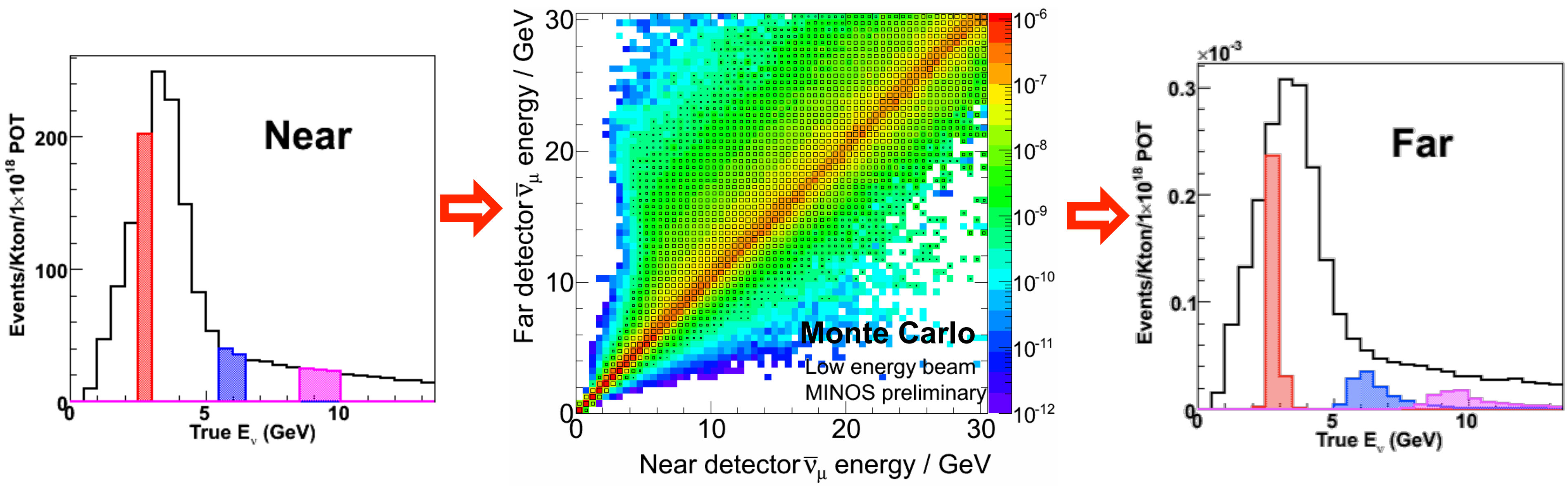
Near to Far Extrapolation

- Near detector spectrum ≠ Far detector
  - Project different solid angles
  - Non-point source for Near detector
  - π/K decay kinematics
    - average neutrino energy varies with angle

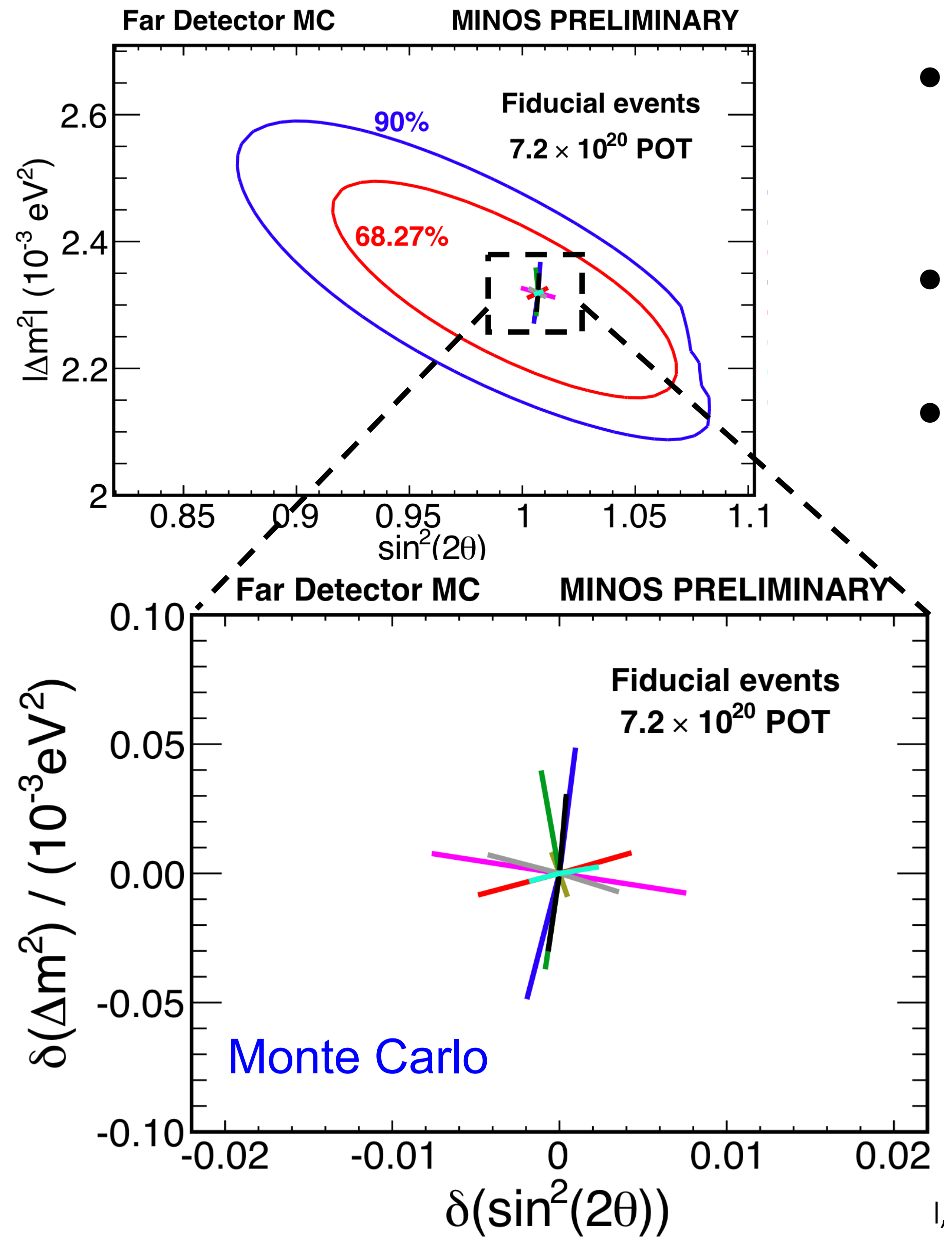


Beam Matrix Extrapolation

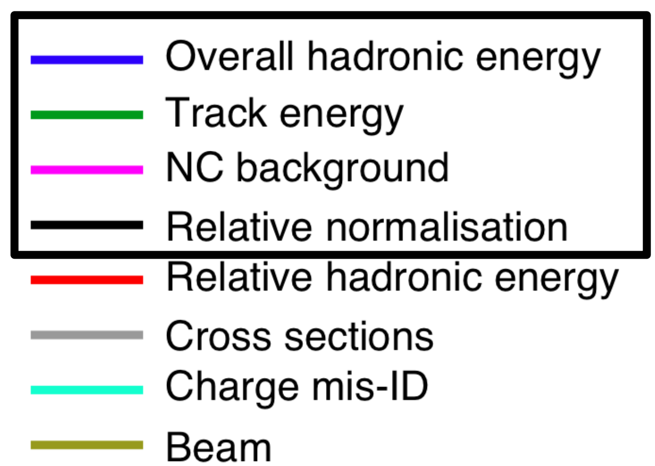
- A beam matrix transports measured Near spectrum to Far
  - ν_μ and $\bar{\nu}_\mu$ are extrapolated independently
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
  - Matrix element M_{ij} reflects the probability of obtaining a Far event with energy E_j given the observation of a Near event with energy E_i
- MC used to correct for energy smearing and acceptance



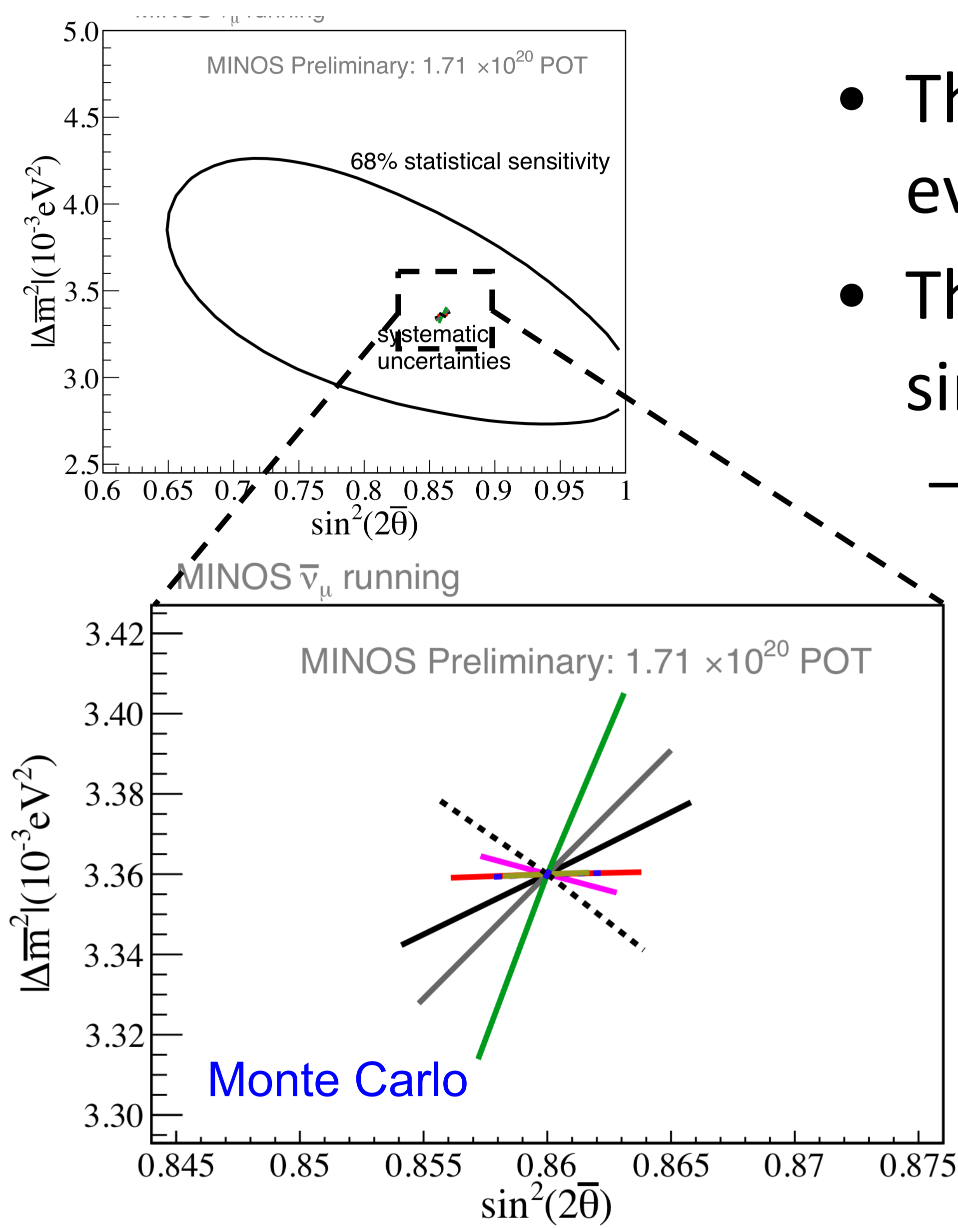
Neutrino Systematics



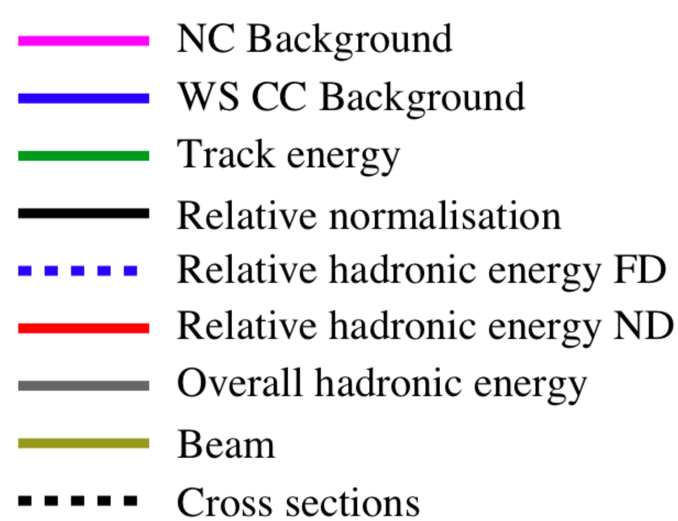
- Effect of uncertainties estimated by fitting systematically shifted MC
- Analysis is still statistically limited
- The 4 largest systematics are included as penalty terms in the fit.



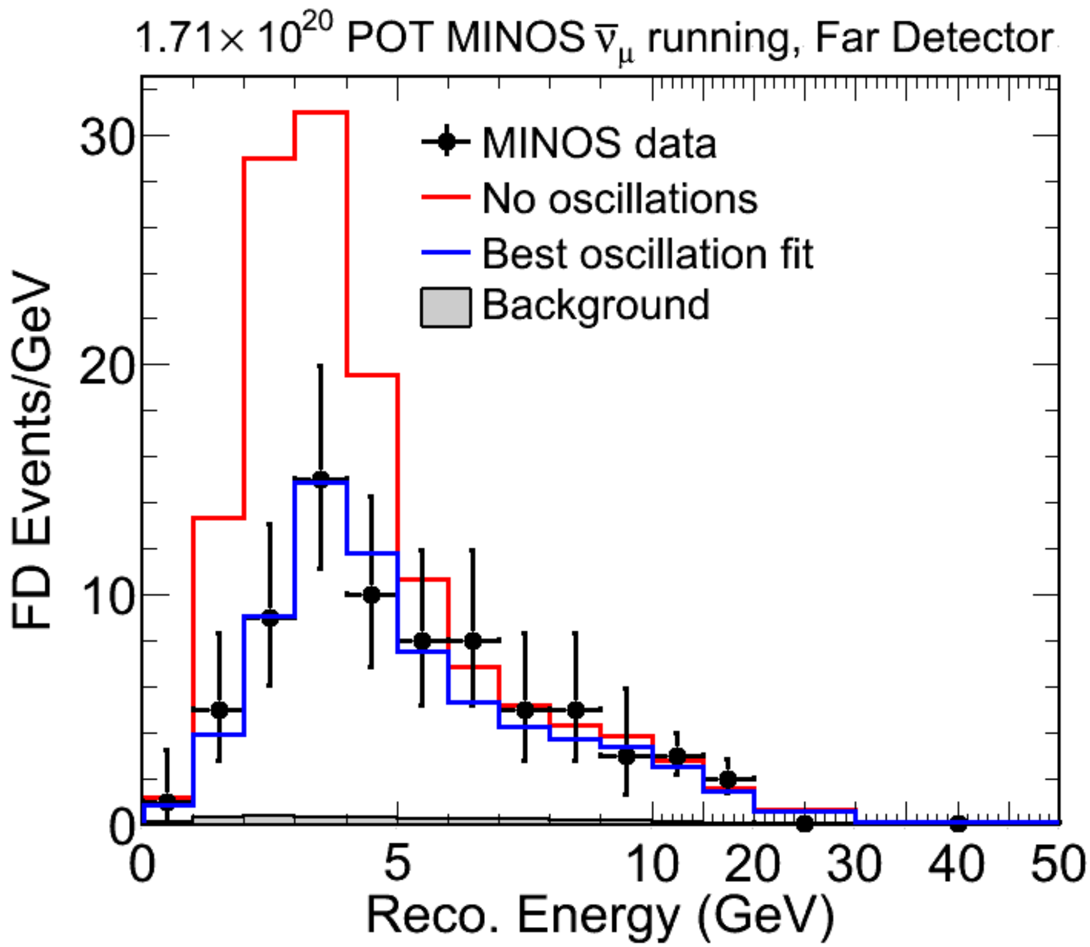
Anti-neutrino Systematics



- The antineutrino analysis is even more statistically limited.
- The two analyses have very similar systematics
  - Though sizes of the effects are not the same.



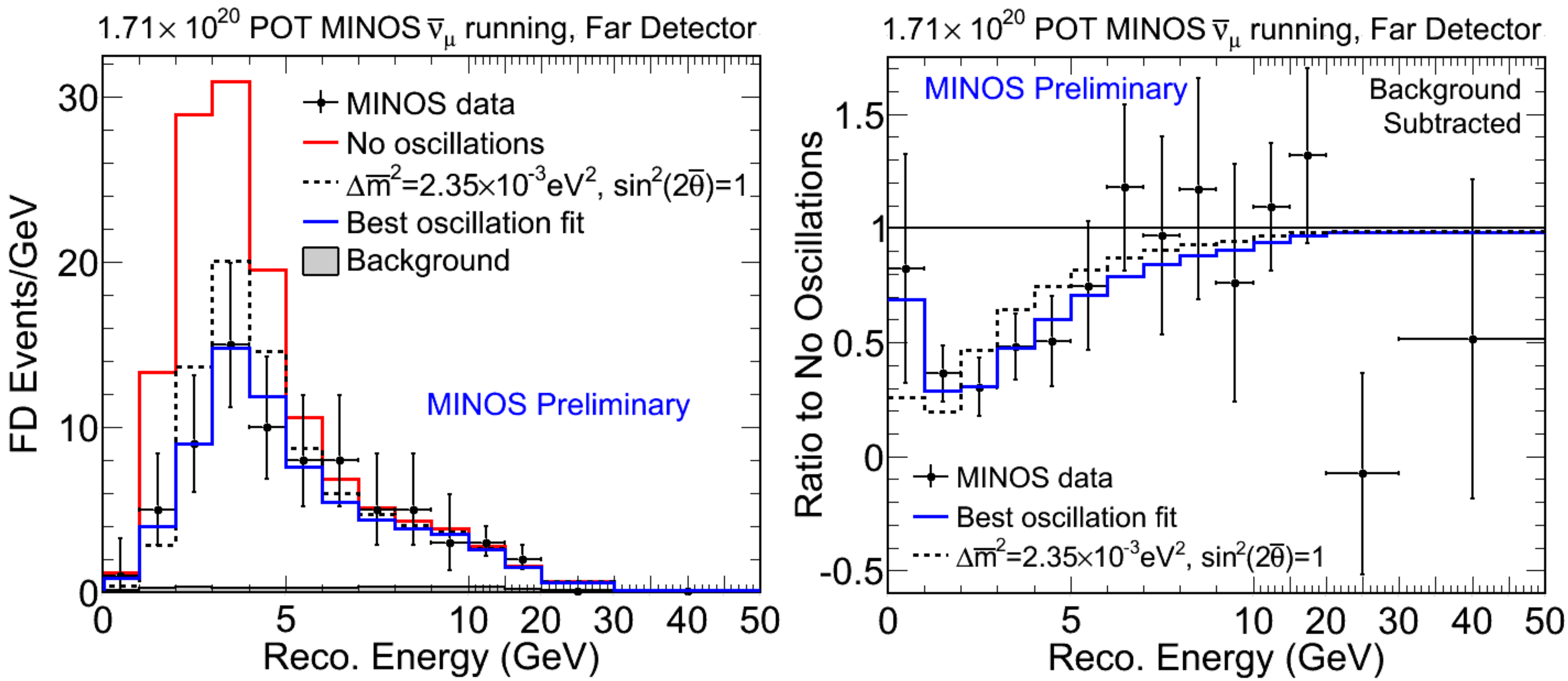
Far Detector Data

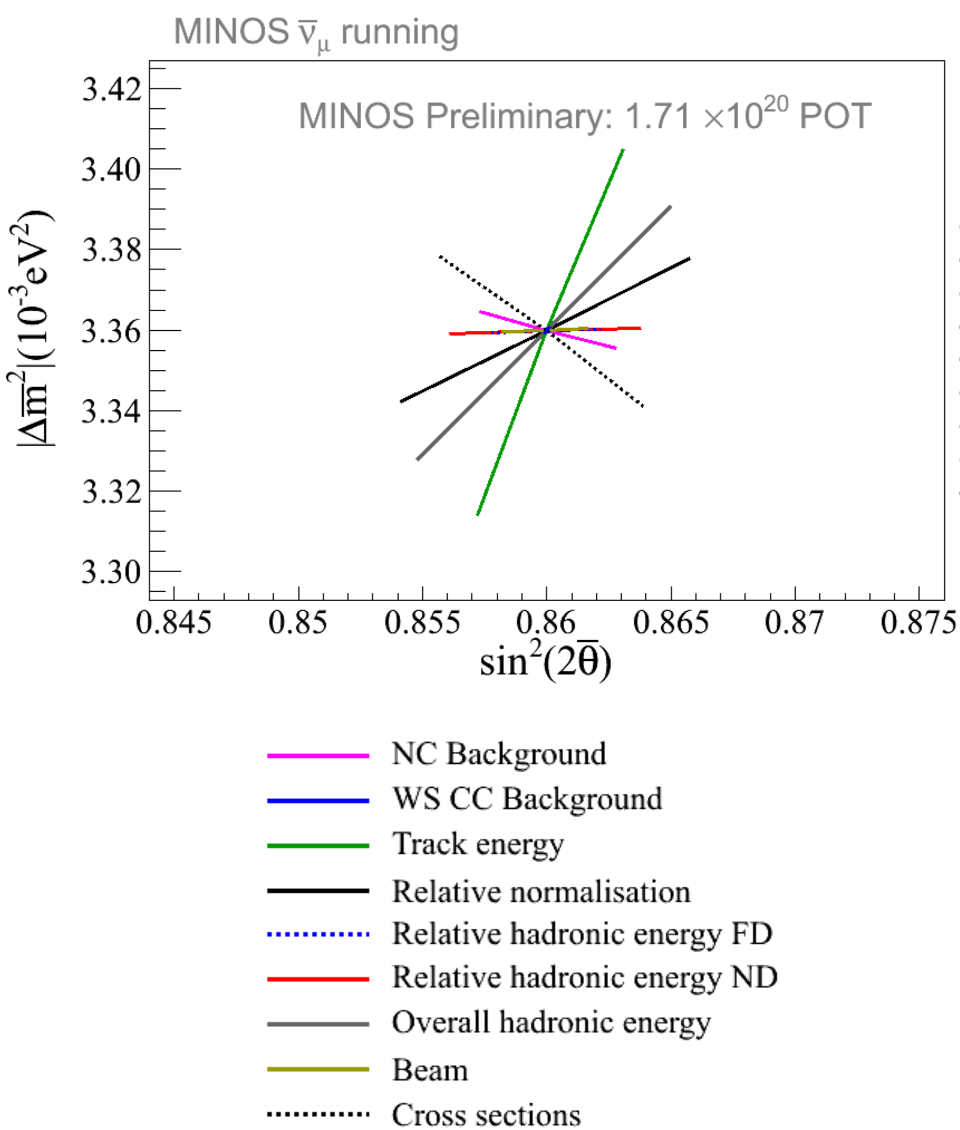


- No oscillation Prediction: **156**
- Observe: **97**
- No oscillations disfavored at 6.3σ

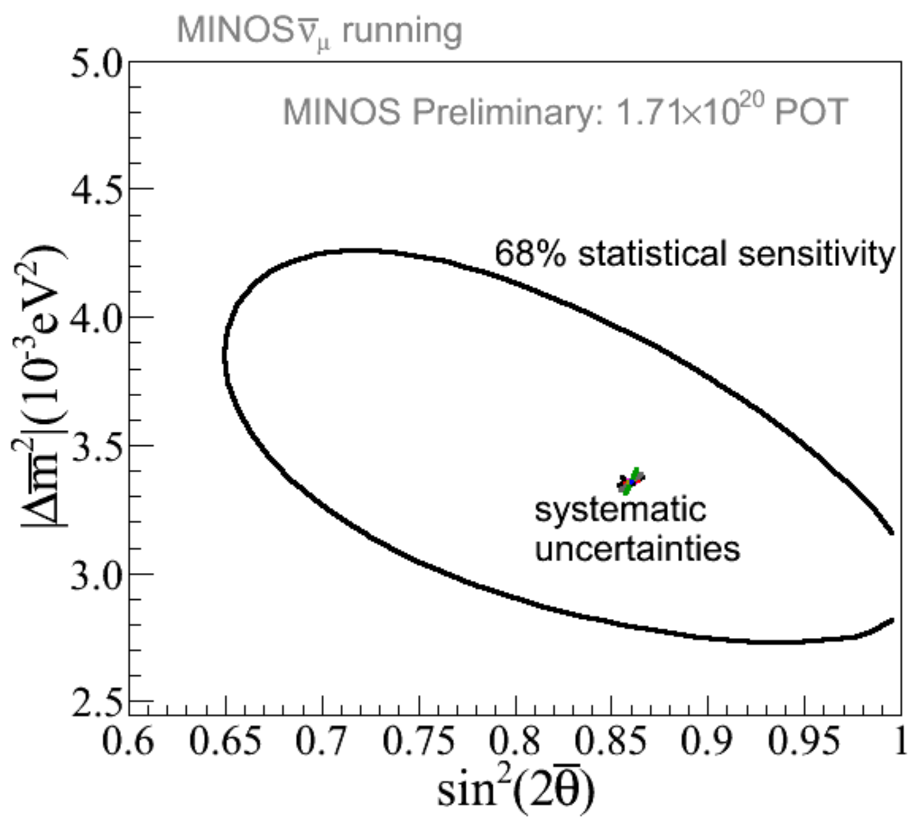
$$|\Delta\overline{m}^2| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\ \text{eV}^2$$
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}$$

Comparisons to Neutrinos



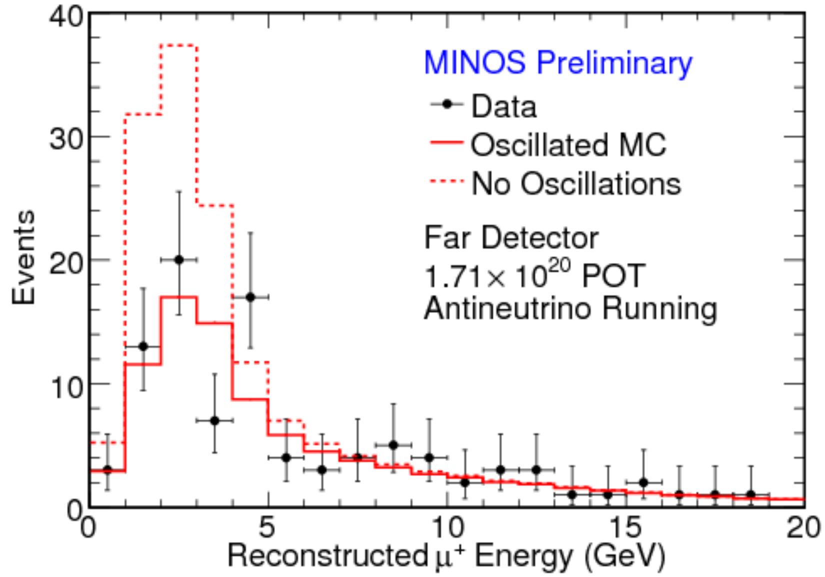


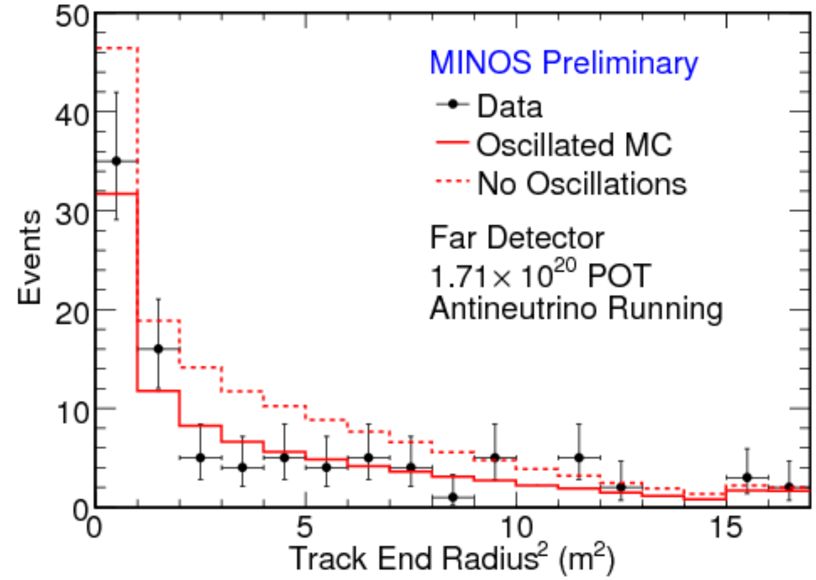
MINOS $\overline{\nu}_\mu$ running
MINOS Preliminary: 1.71 ×10^20 POT
3.42
3.40
3.38
3.36
3.34
3.32
3.30
$|\Delta\overline{m}^2|(10^{-3}eV^2)$
0.845
0.85
0.855
0.86
0.865
0.87
0.875
$\sin^2(2\overline{\theta})$
NC Background
WS CC Background
Track energy
Relative normalisation
Relative hadronic energy FD
Relative hadronic energy ND
Overall hadronic energy
Beam
Cross sections

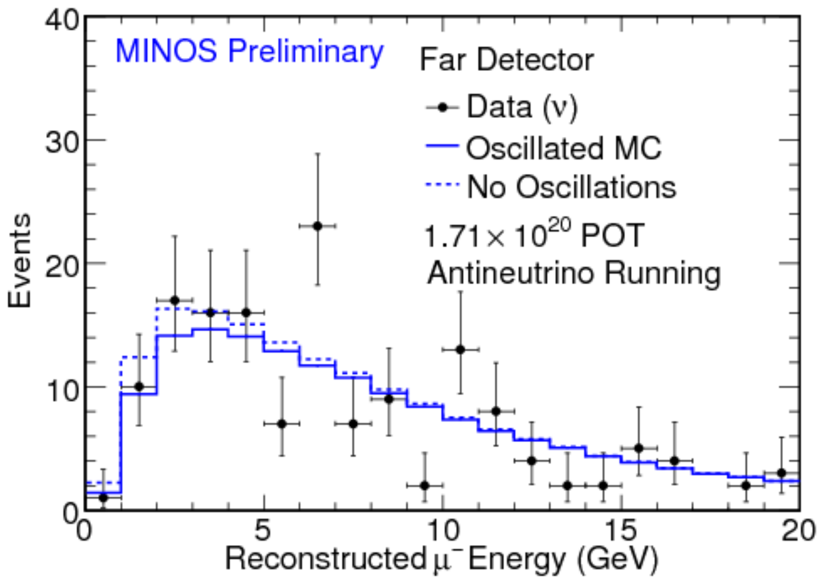


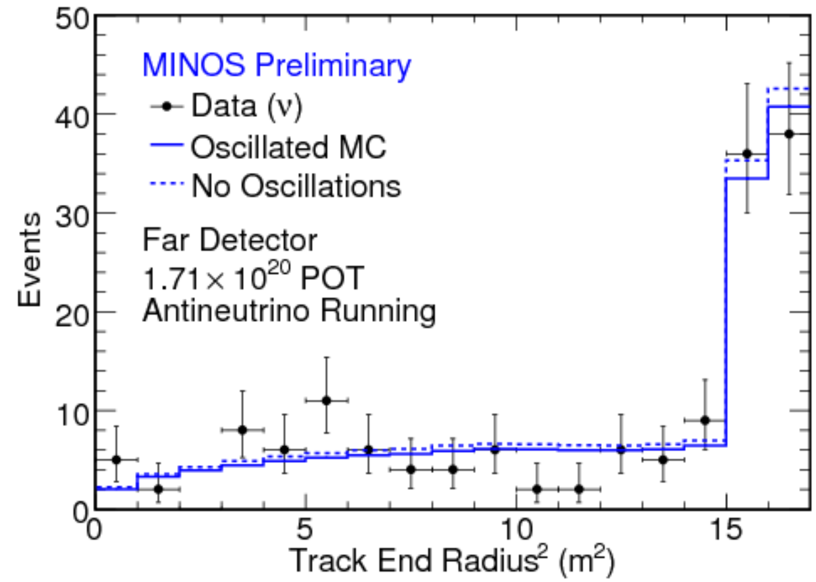
MINOS $\overline{\nu}_\mu$ running
MINOS Preliminary: 1.71×10^20 POT
68% statistical sensitivity
systematic
uncertainties
5.0
4.5
4.0
3.5
3.0
2.5
$|\Delta\overline{m}^2|(10^{-3}eV^2)$
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
$\sin^2(2\overline{\theta})$

Far Detector Data





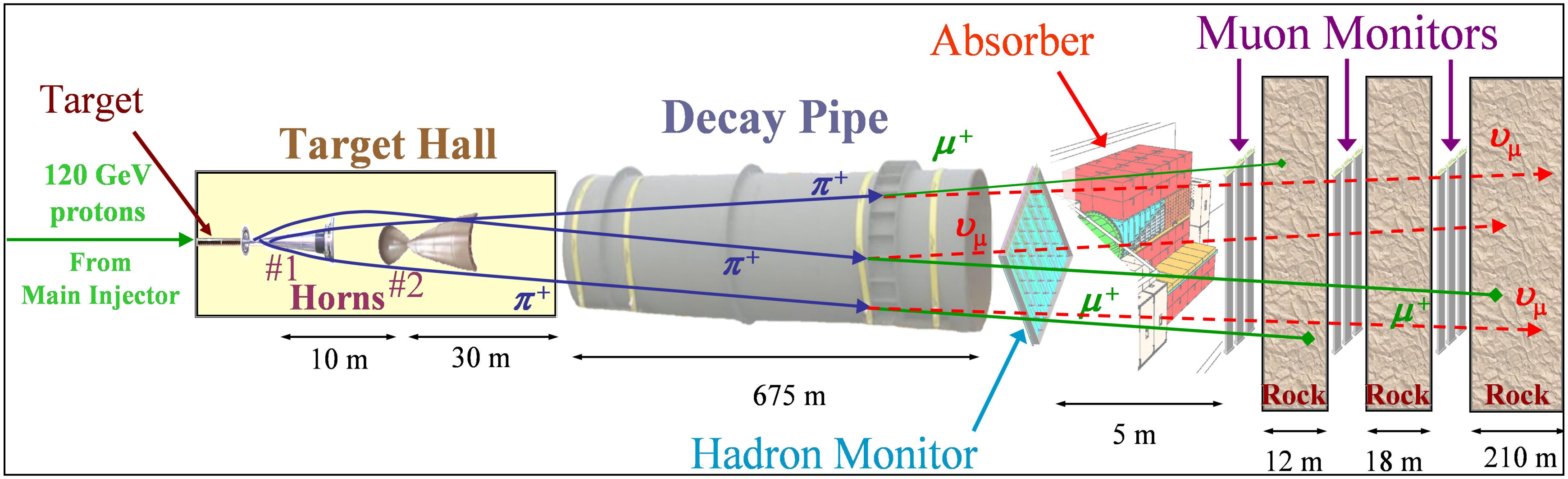




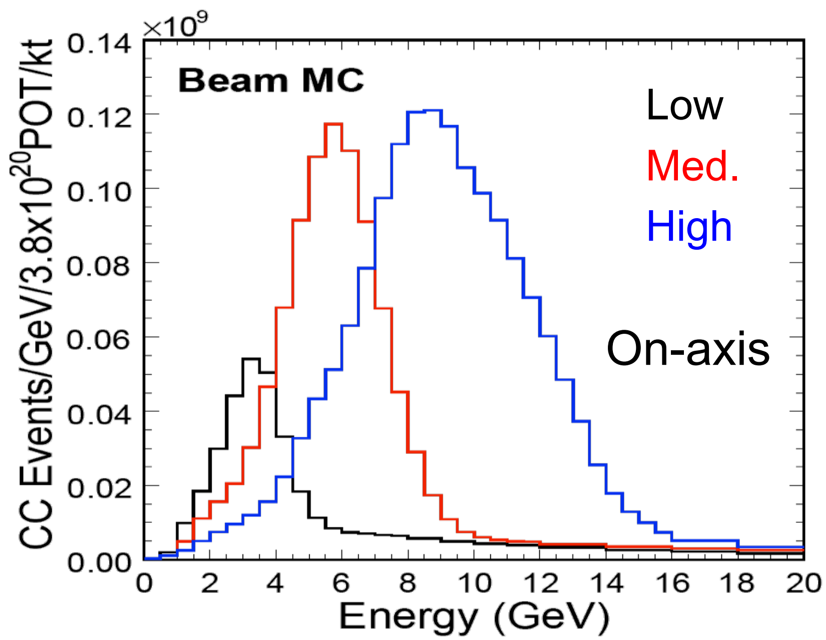
$\nu_\mu \rightarrow \nu_e$ Oscillation Search Overview

- Sub-dominant neutrino oscillations
  - Look for ν_e appearance at Far detector
    - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$
      - also CPv and matter effects: not shown here but included in fit
  - Electron neutrino events only 2% of total (at Chooz limit)
- Select events w/ compact shower, typical EM profile
  - MINOS optimised for ν_μ
  - ν_e signal selection is harder
    - Steel thickness 2.5 cm = 1.4 X_0
    - Strip width 4.1cm ~ Molière radius (3.7cm)
- Use the Near detector to determine the background

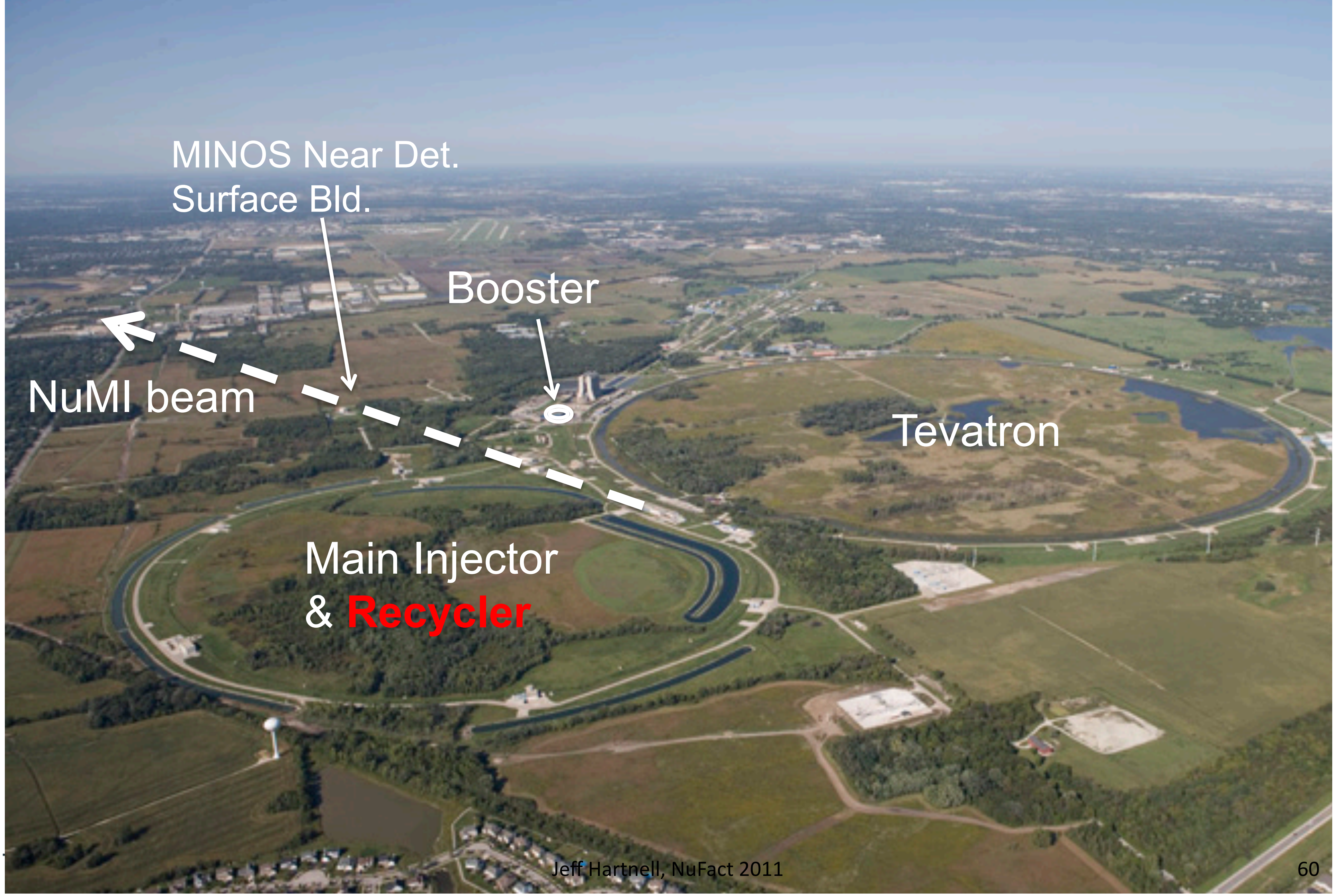
NuMI Neutrino Beam



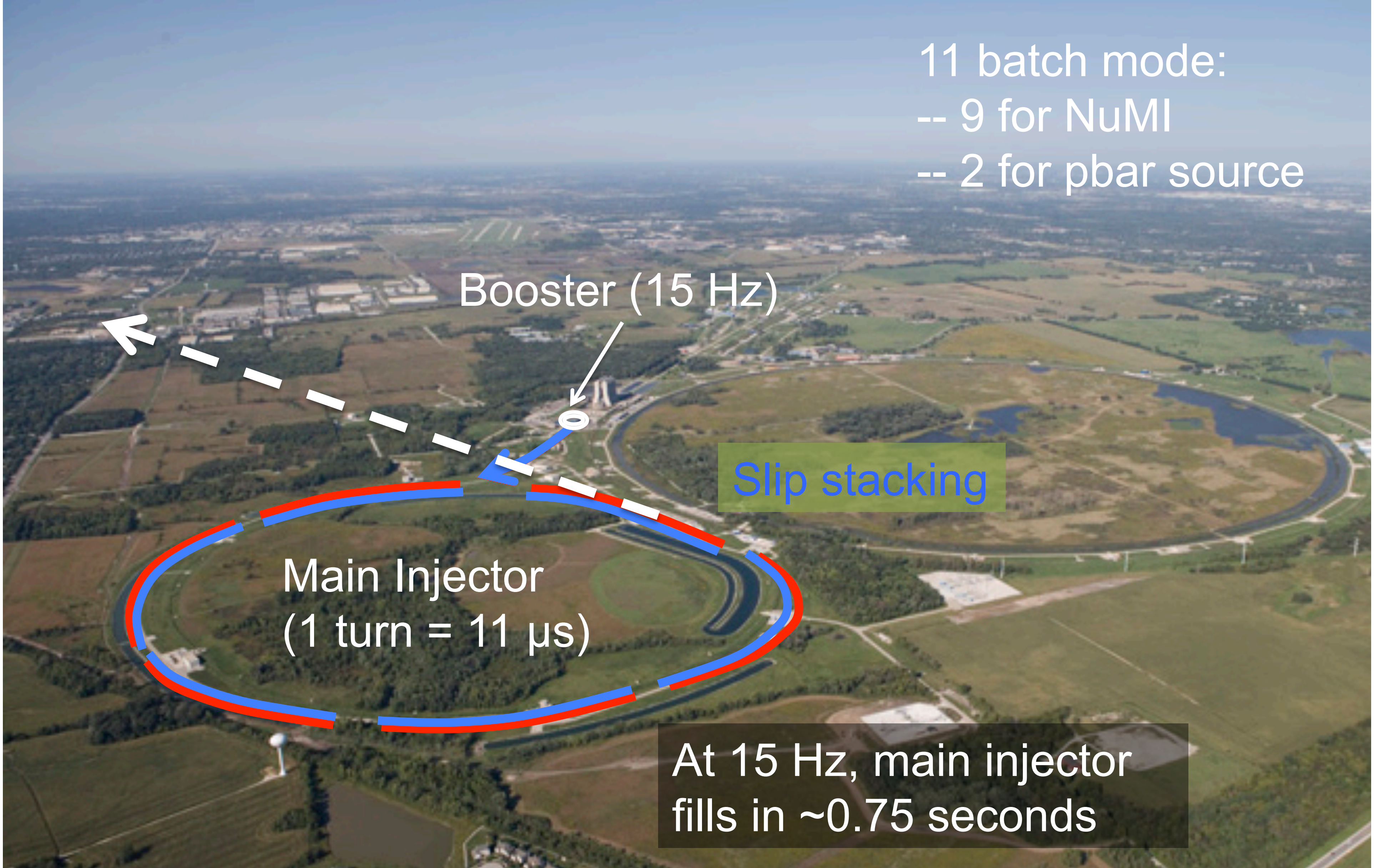
- 120 GeV protons strike target
- 10 μs long pulse of ~3x10^{13} protons every 2.2 seconds 320 kW)
- Two magnetic horns focus secondary π/K
  - decay of π/K produce neutrinos
- Variable neutrino beam energy



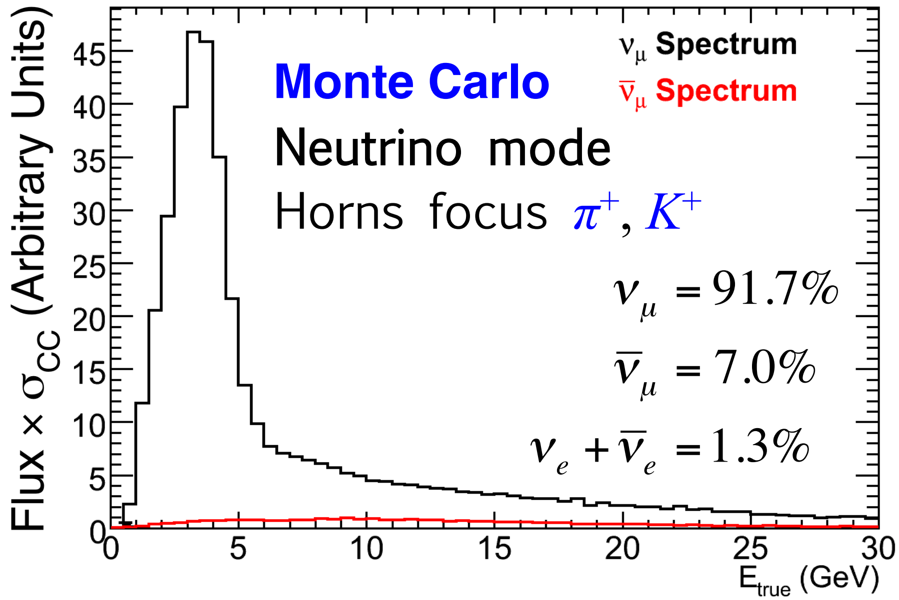
Fermilab Complex

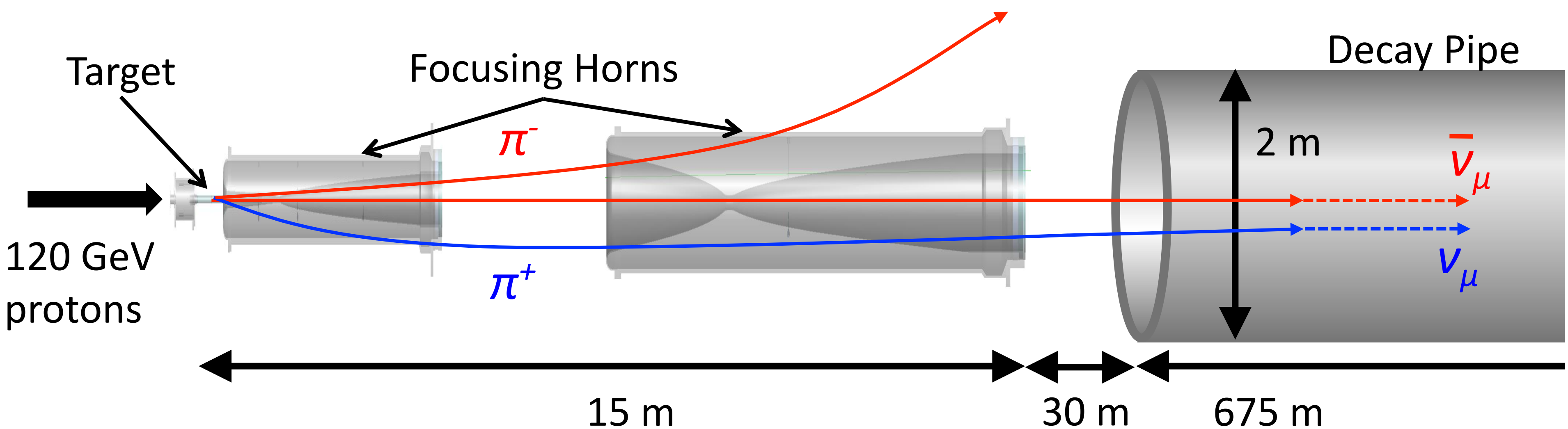


NuMI Operation

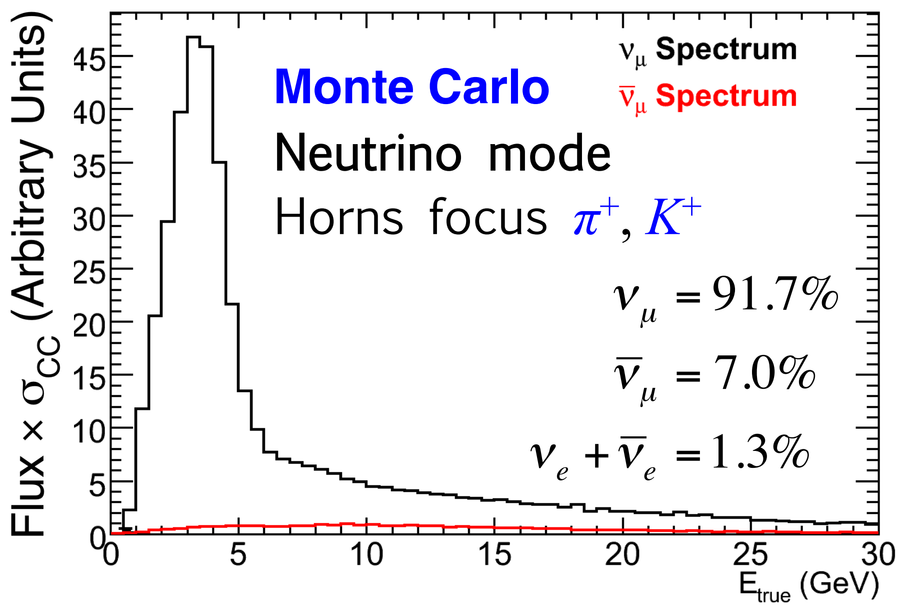


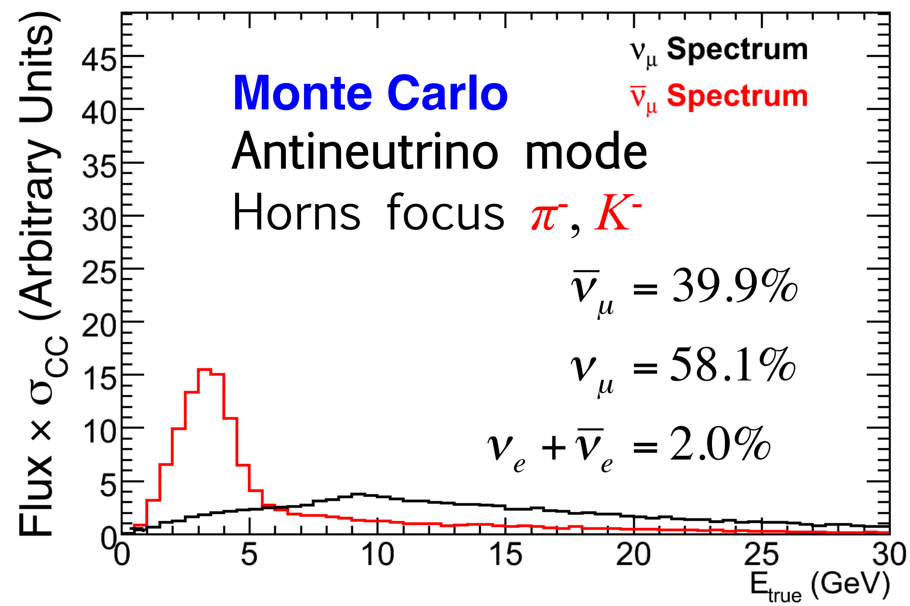
Neutrino Mode (On-axis)

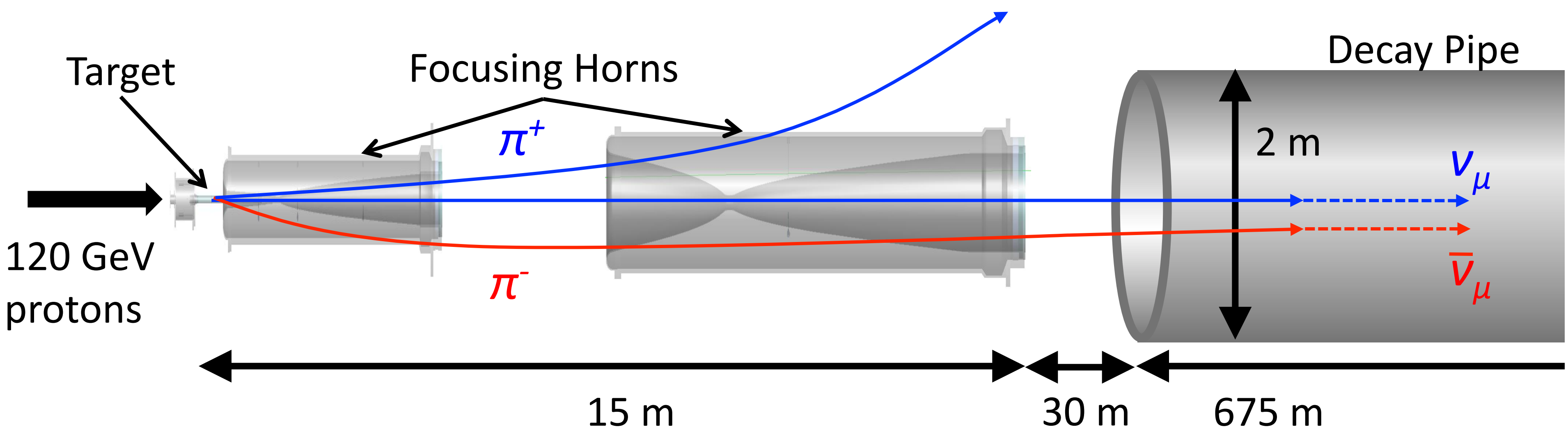




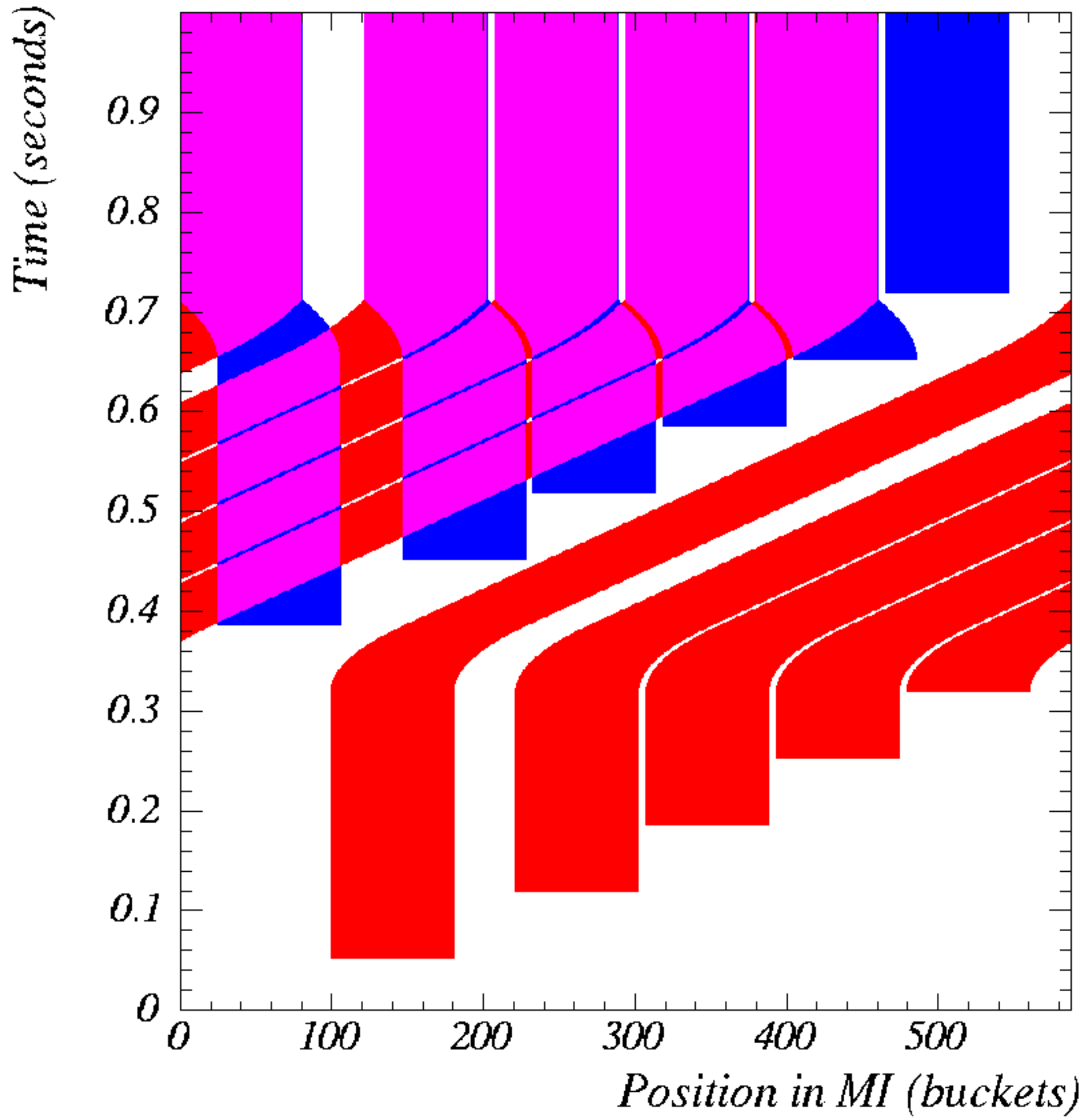
Anti-neutrino Mode (On-axis)







Slip stacking details



NuMI Upgrades

Present — Baseline for future — Future possibilities

	Proton Plan Multi-batch Slip-stacking in MI	NOνA Multi-batch Slip-stacking in Recycler	Conceptual SNuMI Accumulator Momentum Stacking	Conceptual Project X linear accelerator
8 GeV Intensity (p/Batch)	4.3×10^{12}	**4.3×10^{12}**	4.5×10^{12}	5.6×10^{13}
Number of 8 GeV Batches to NuMI	9	**12**	18	3
MI Cycle Time (sec)	2.2	**1.3**	1.3	1.4
MI Intensity (protons per pulse or ppp)	4.5×10^{13}	**4.9×10^{13}**	8.3×10^{13}	1.6×10^{14}
MI to NuMI (ppp)	3.7×10^{13}	**4.9×10^{13}**	8.3×10^{13}	1.6×10^{14}
NuMI Beam Power (kW)	0.3 MW	0.7 MW	1.2 MW	2.3 MW
Protons/year to NuMI	3×10^{20}	**6×10^{20}**	10×10^{20}	20×10^{20}
MI Protons/hour	7.3×10^{16}	**1.3×10^{17}**	2.2×10^{17}	1.0×10^{18}