Physics at the NuMI Beam

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University of Sussex

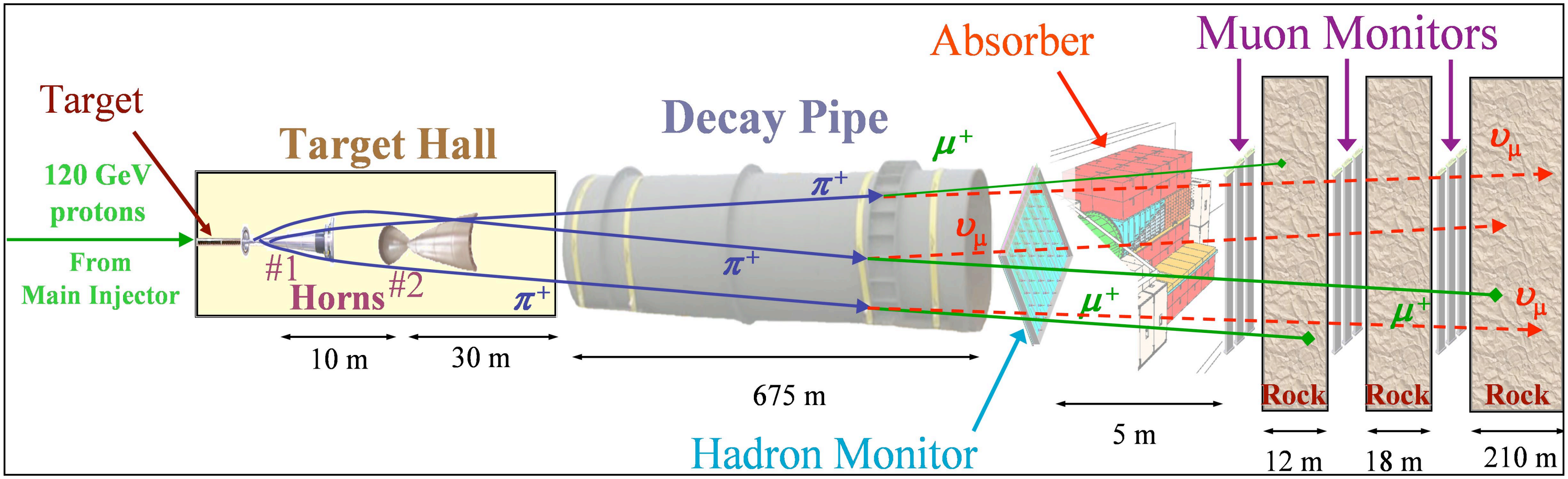
Neutrino Oscillations Workshop

Otranto, 4-11th September 2010

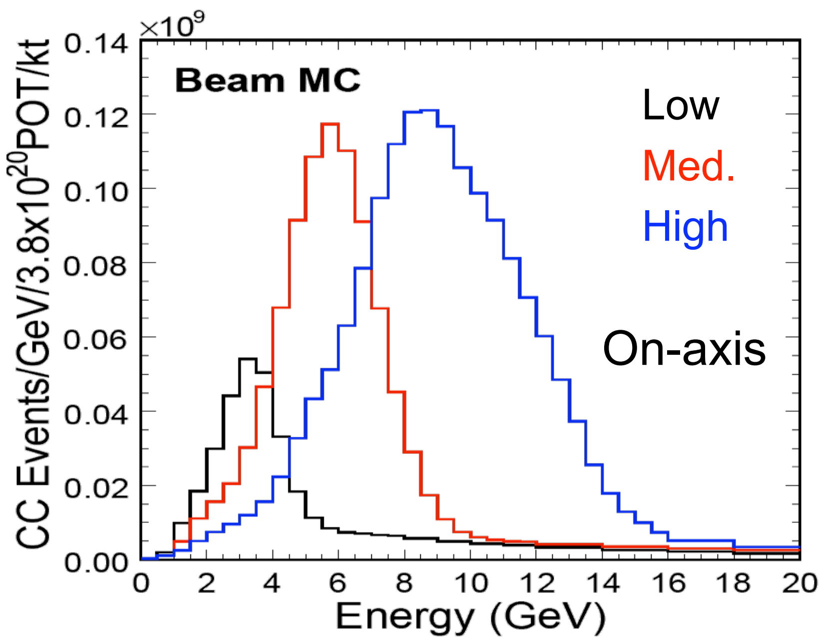
Introduction

- Part I: NuMI beam
  - Present
  - Beam composition
    - Neutrinos/anti-neutrinos/ν_e
  - Future
- Part II: the experiments
  - MINOS
  - NOvA
  - Minerva
  - ArgoNeut

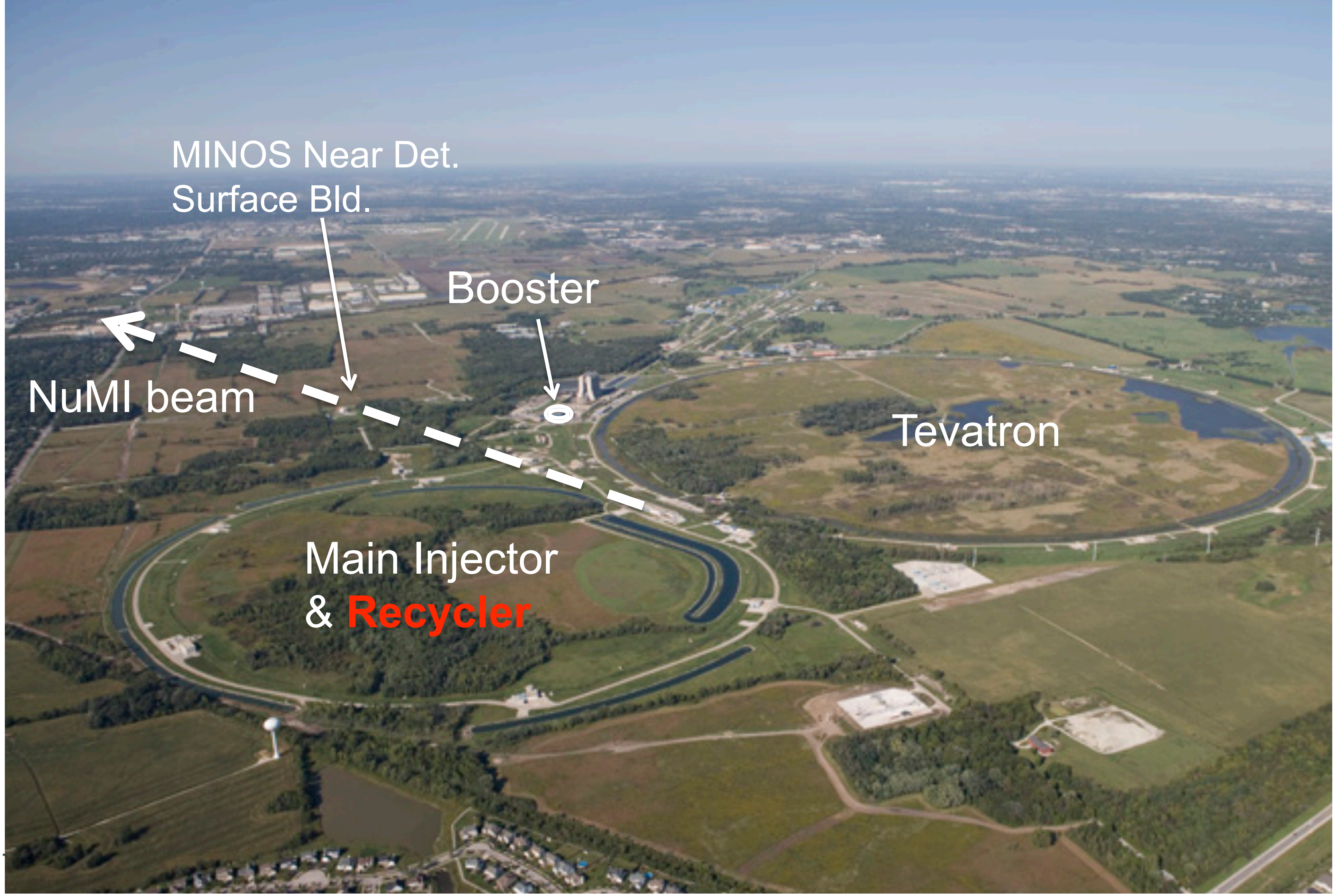
NuMI Neutrino Beam



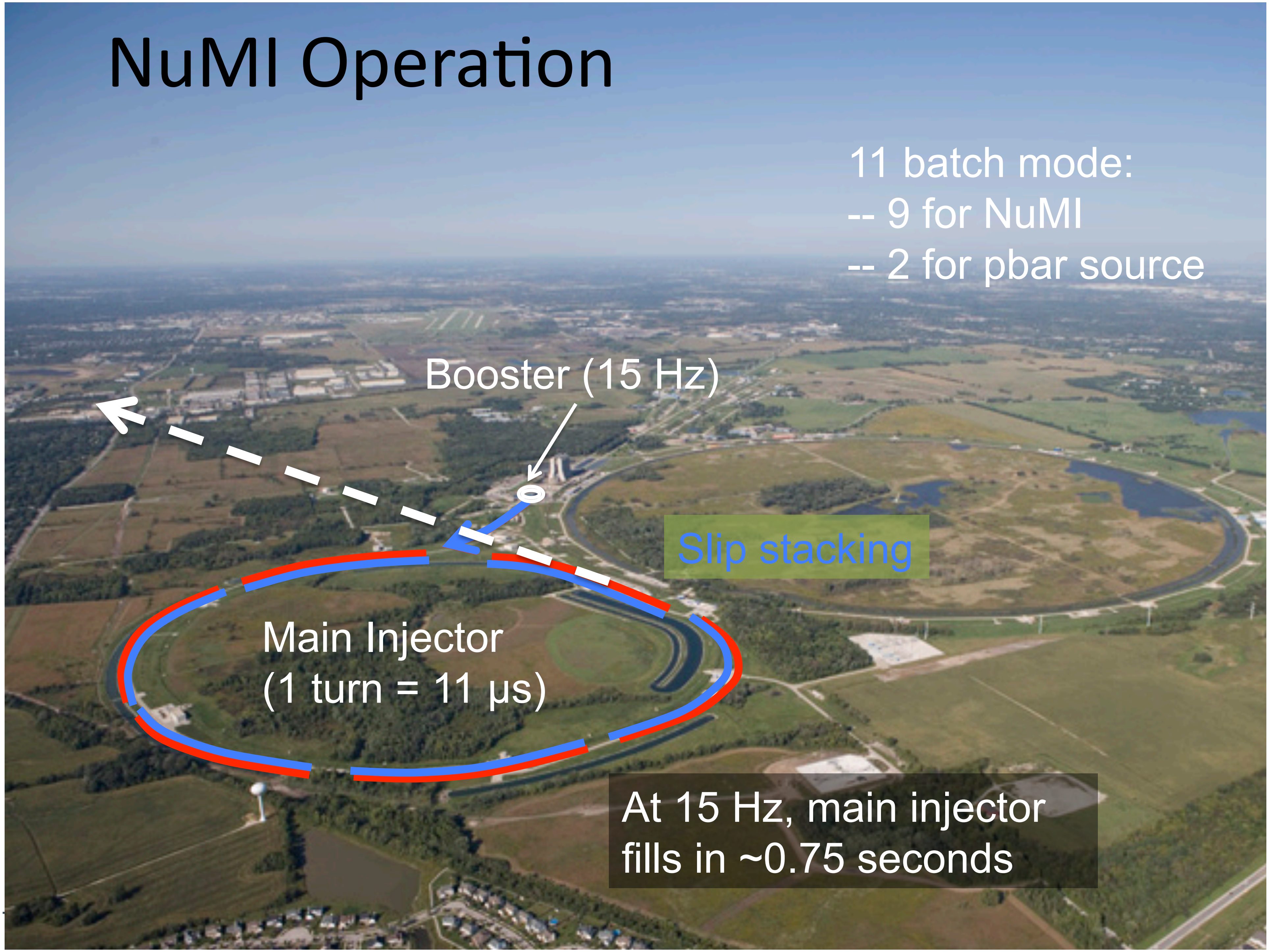
- 120 GeV protons strike target
- 10 μs long pulse of ~3x10^{13} protons every 2.2 seconds 320 kW)
- Two magnetic horns focus secondary π/K
  - decay of π/K produce neutrinos
- Variable neutrino beam energy



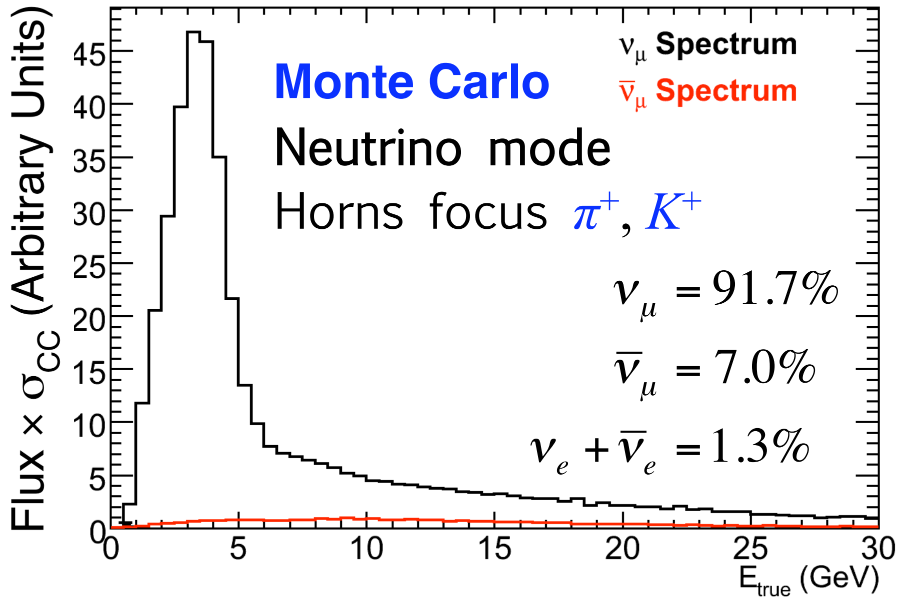
Fermilab Complex

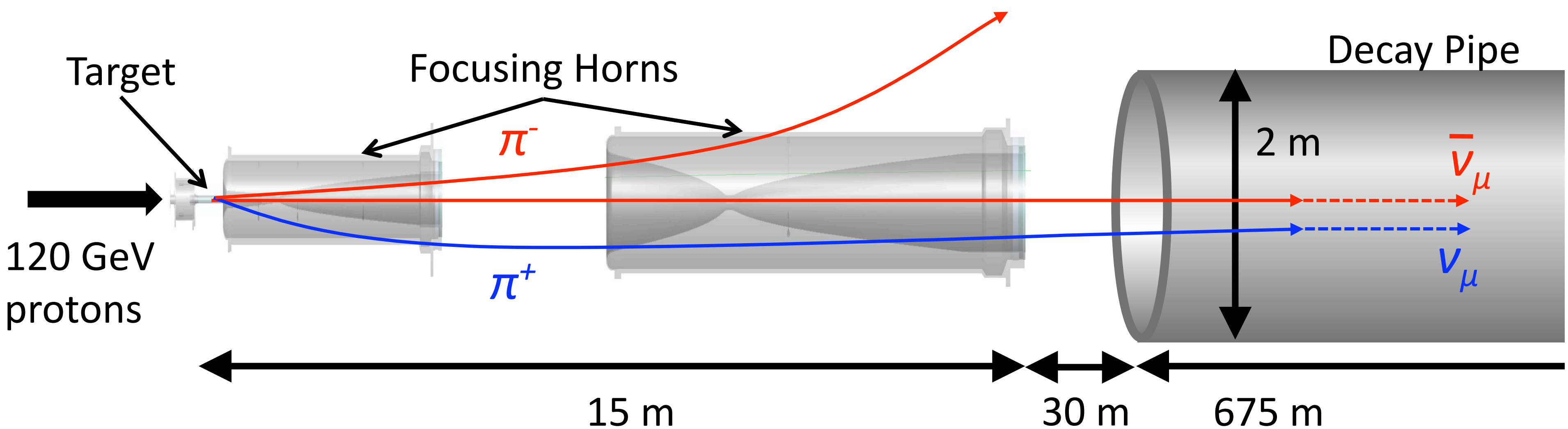


NuMI Operation

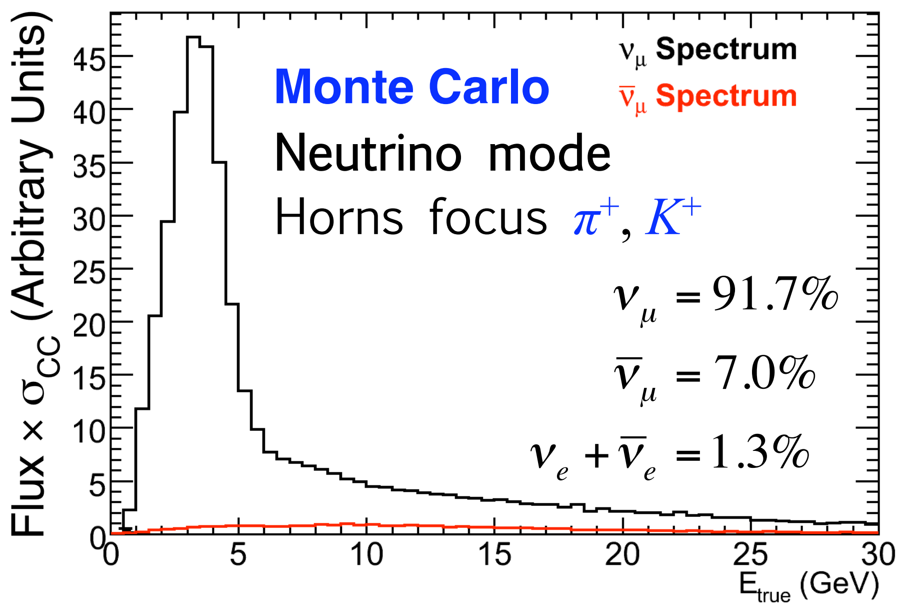


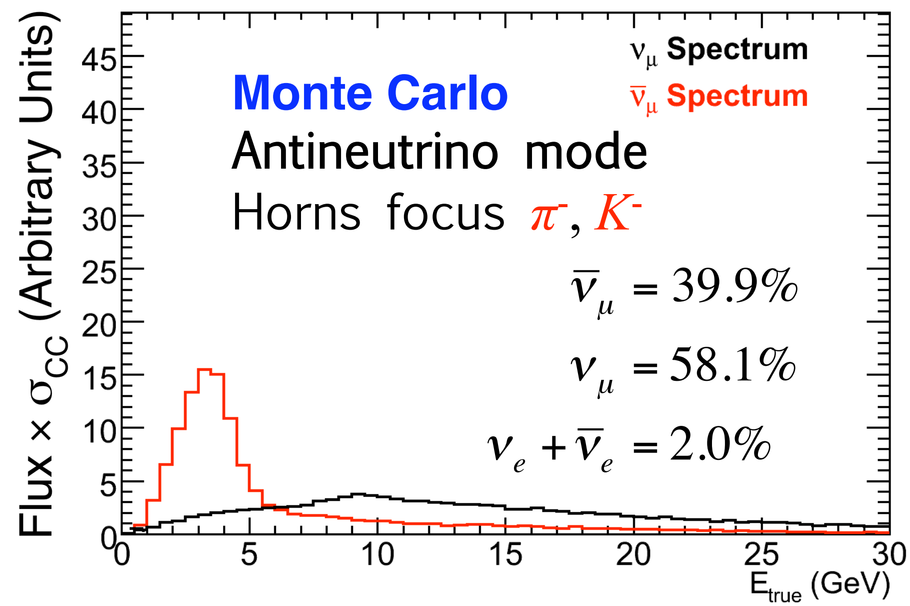
Neutrino Mode (On-axis)

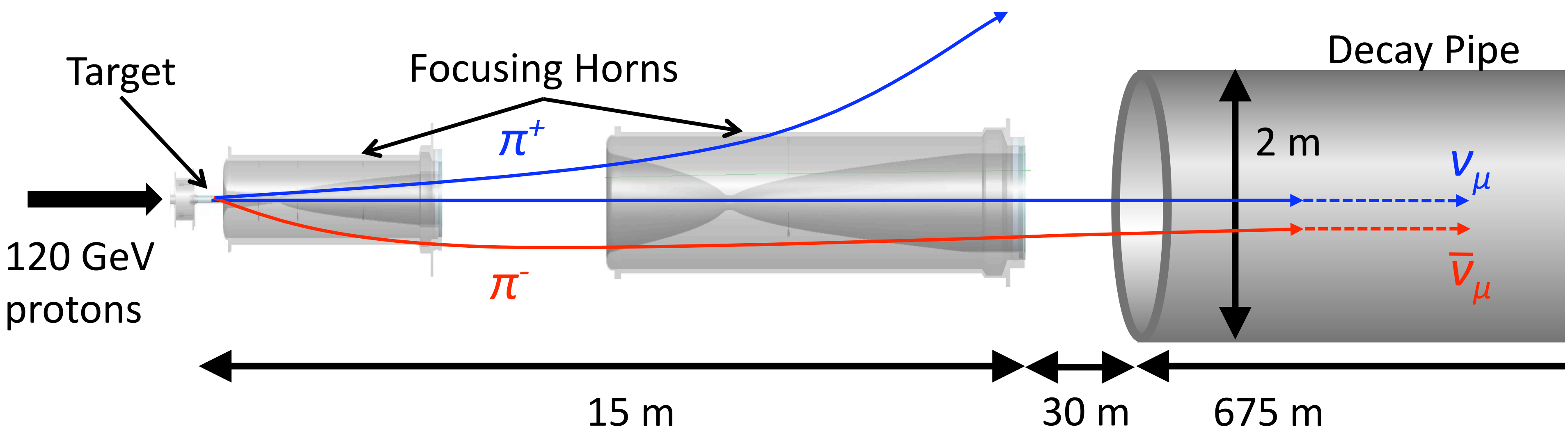




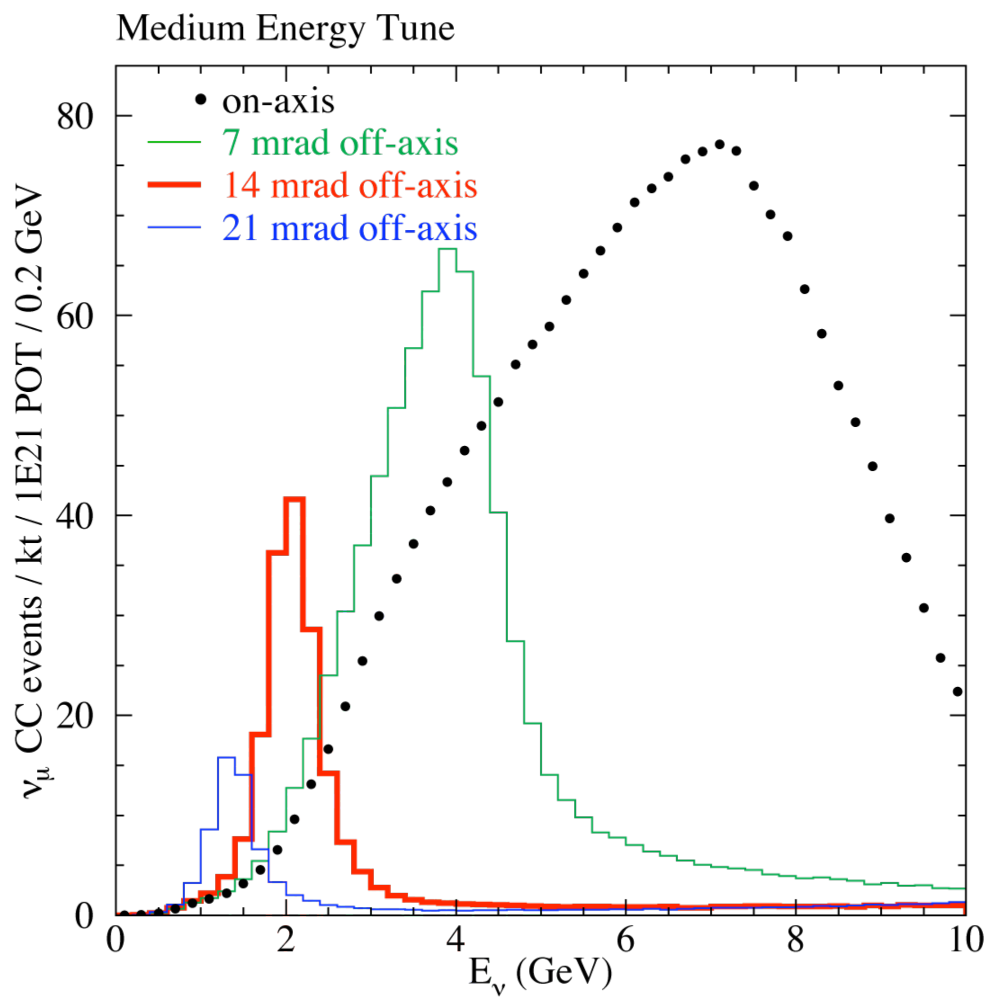
Anti-neutrino Mode (On-axis)







Off-axis beam (NOvA)



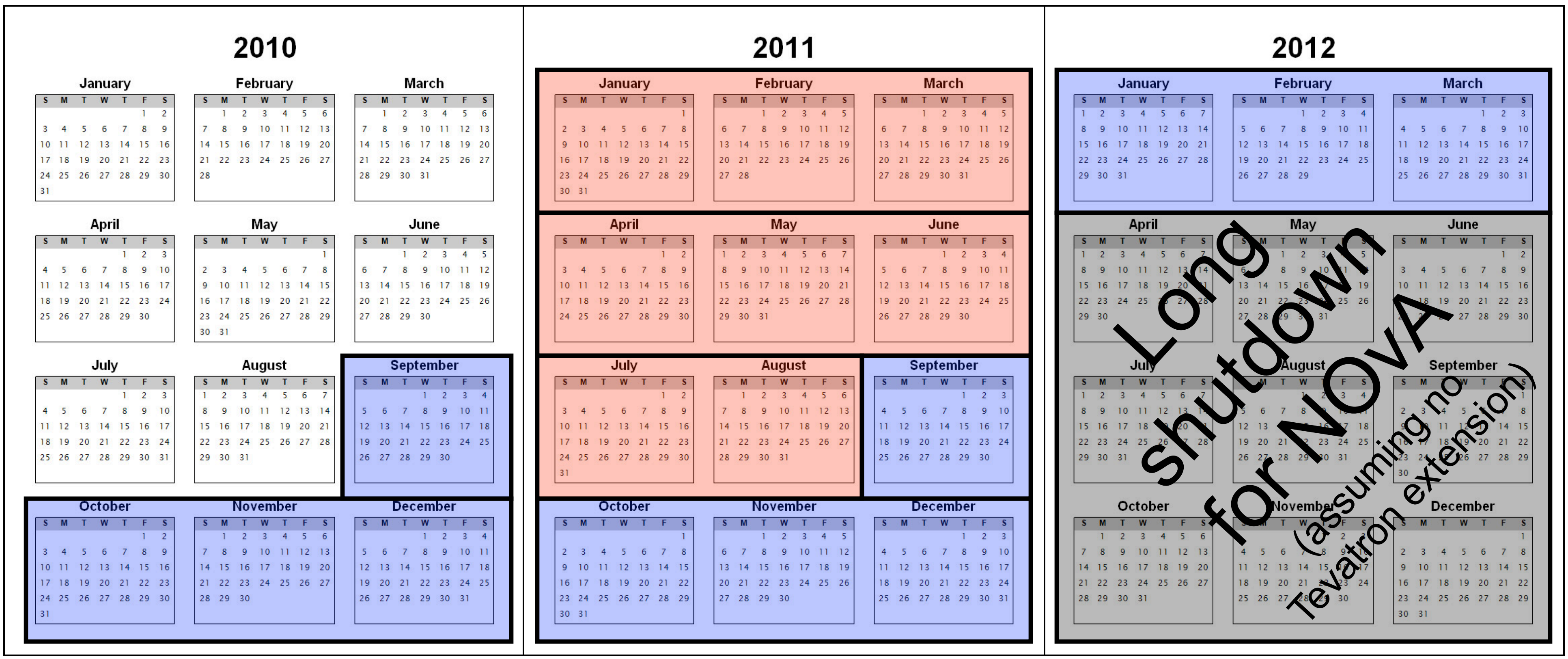
NuMI Near Term Future

MINOS priority

Minerva priority

MINOS will run in anti-neutrino mode

8 months will yield 2.2 x 10^{20} POT
(more than double existing 1.7 x 10^{20} POT of anti-neutrinos)



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}

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)

Potential Tevatron Extension to 2014

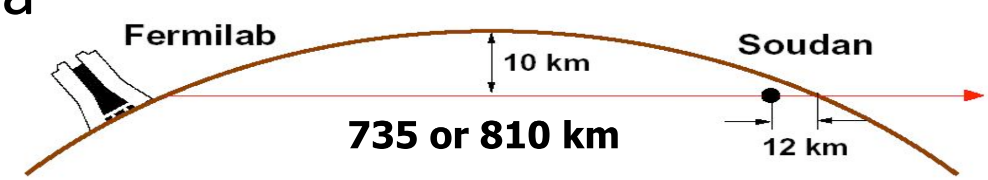
- 27th August: Fermilab PAC strongly recommended a three year extension of the Tevatron to 2014 (final decision O(month)?)
  - CDF+D0 predicted sensitivity is $>3\sigma$ across the interesting Higgs mass region: 114->185 GeV
    - For low mass: H->bb channel different to LHC (H->$\gamma\gamma$)
- Tevatron requires Recycler for pbar cooling
  - also needed for NuMI upgrade to 700 kW (but NuMI can run at 400 kW in parallel w/o Recycler)
- Tevatron extension also has significant impact on other intensity frontier projects

Part II

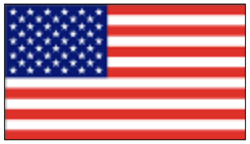
The Experiments

Long-Baseline Overview

- MINOS and NOvA
  - 1st and 2nd generation
- Both (will) have two detectors:
- Near detector at Fermilab
  - measure beam composition
  - energy spectrum
- Far detector in Minnesota
  - search for and study oscillations



The MINOS Collaboration



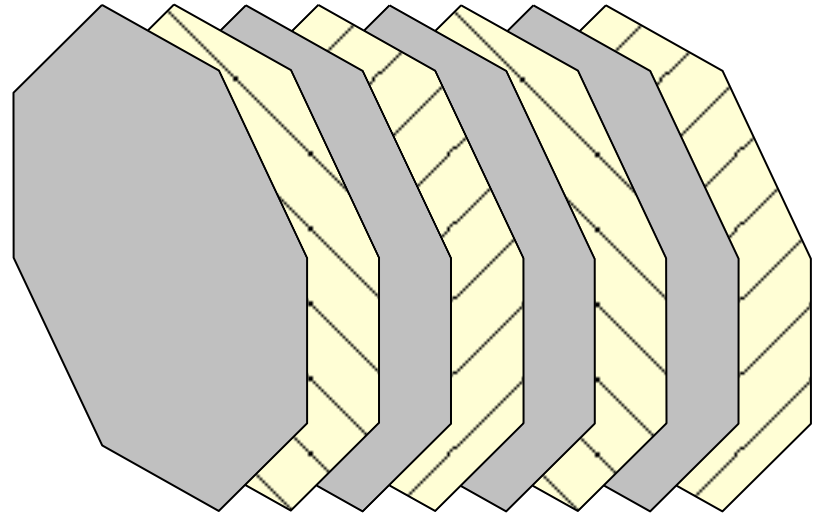
120 scientists
30 institutions

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

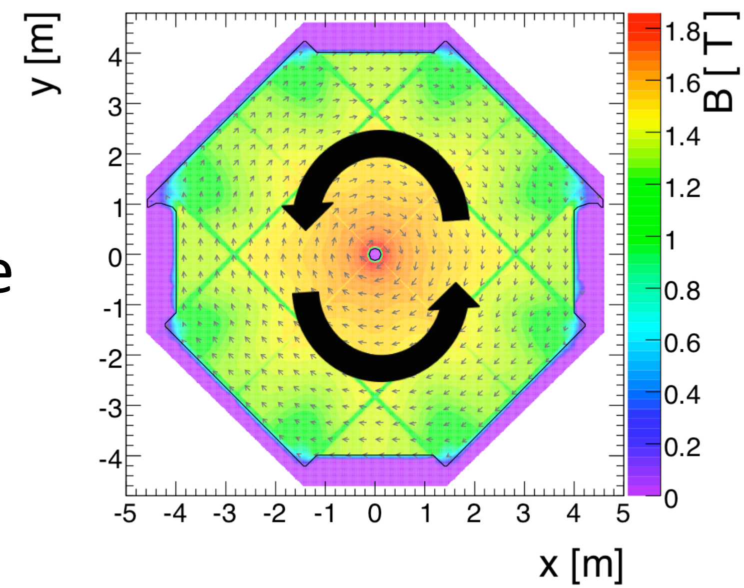
MINOS Physics Goals

- 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 $\nu_\mu \to \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector

MINOS Detectors

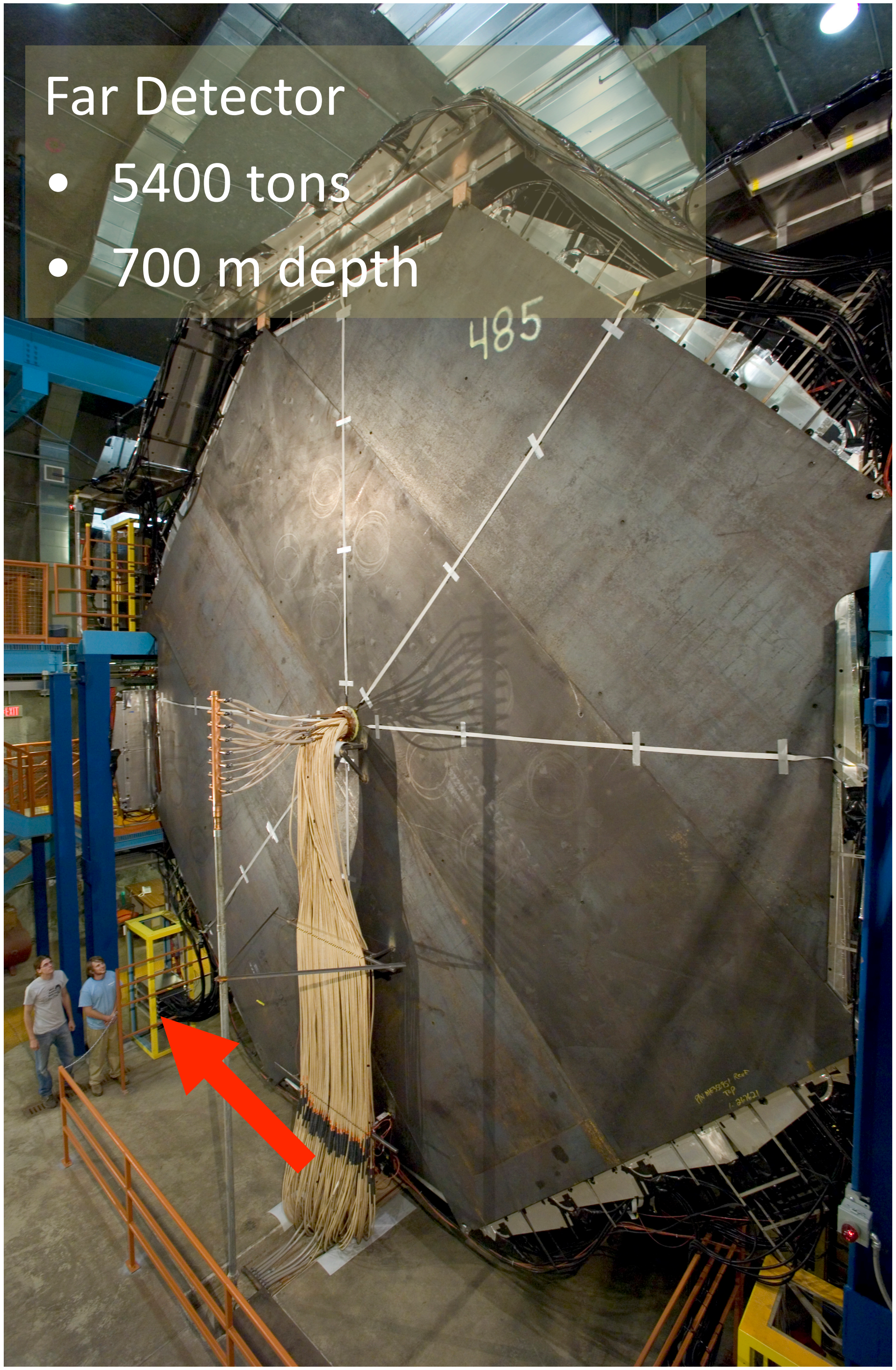


- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick
  - scintillator strips 4.1 cm wide
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-



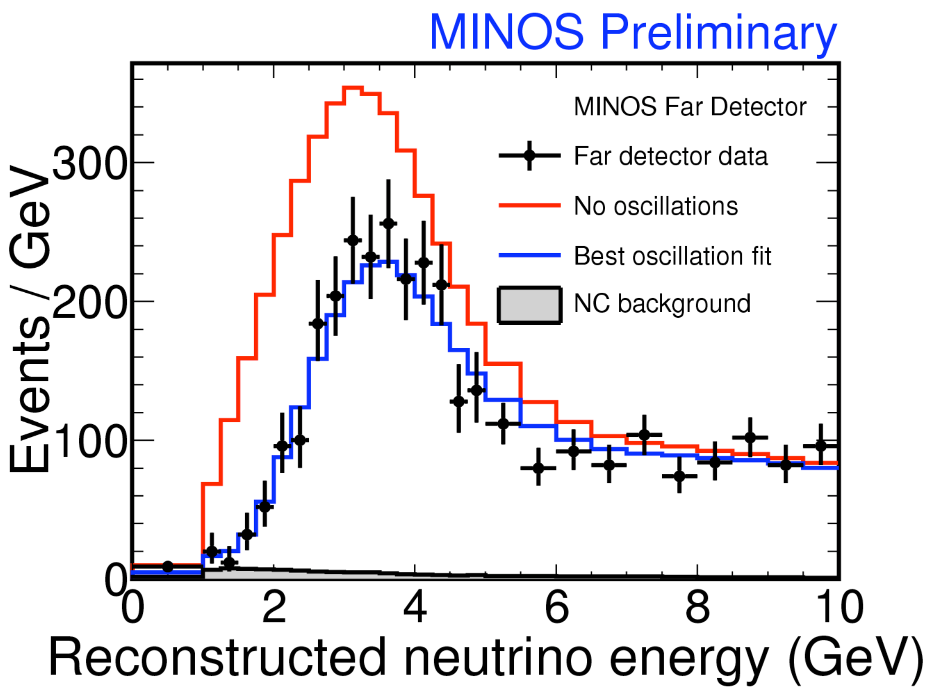
P. Vahle, Neutrino 2010
A. Himmel, FNAL W&C

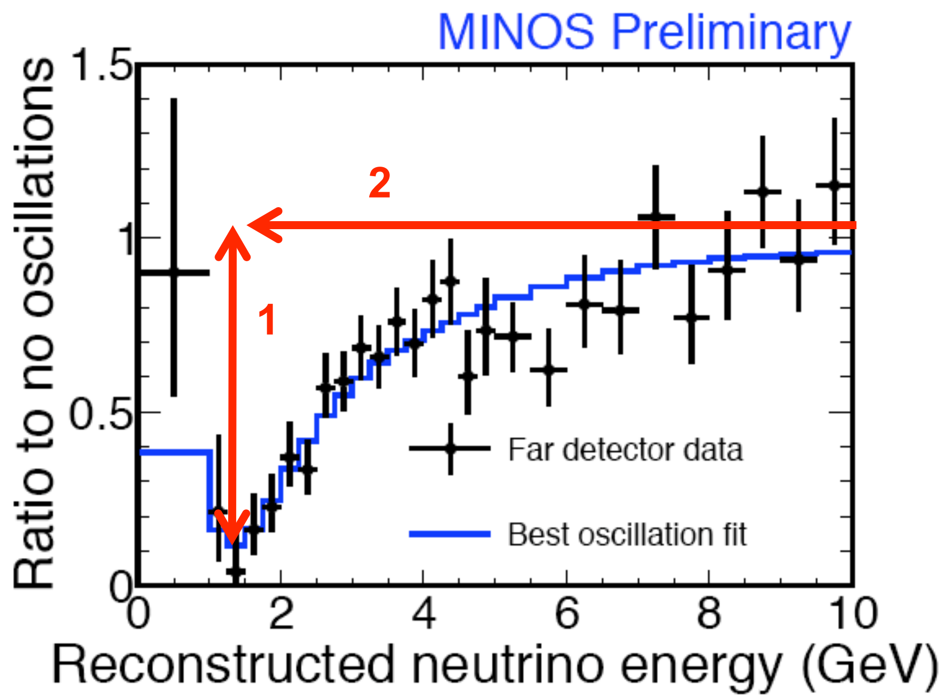
MINOS Detectors



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

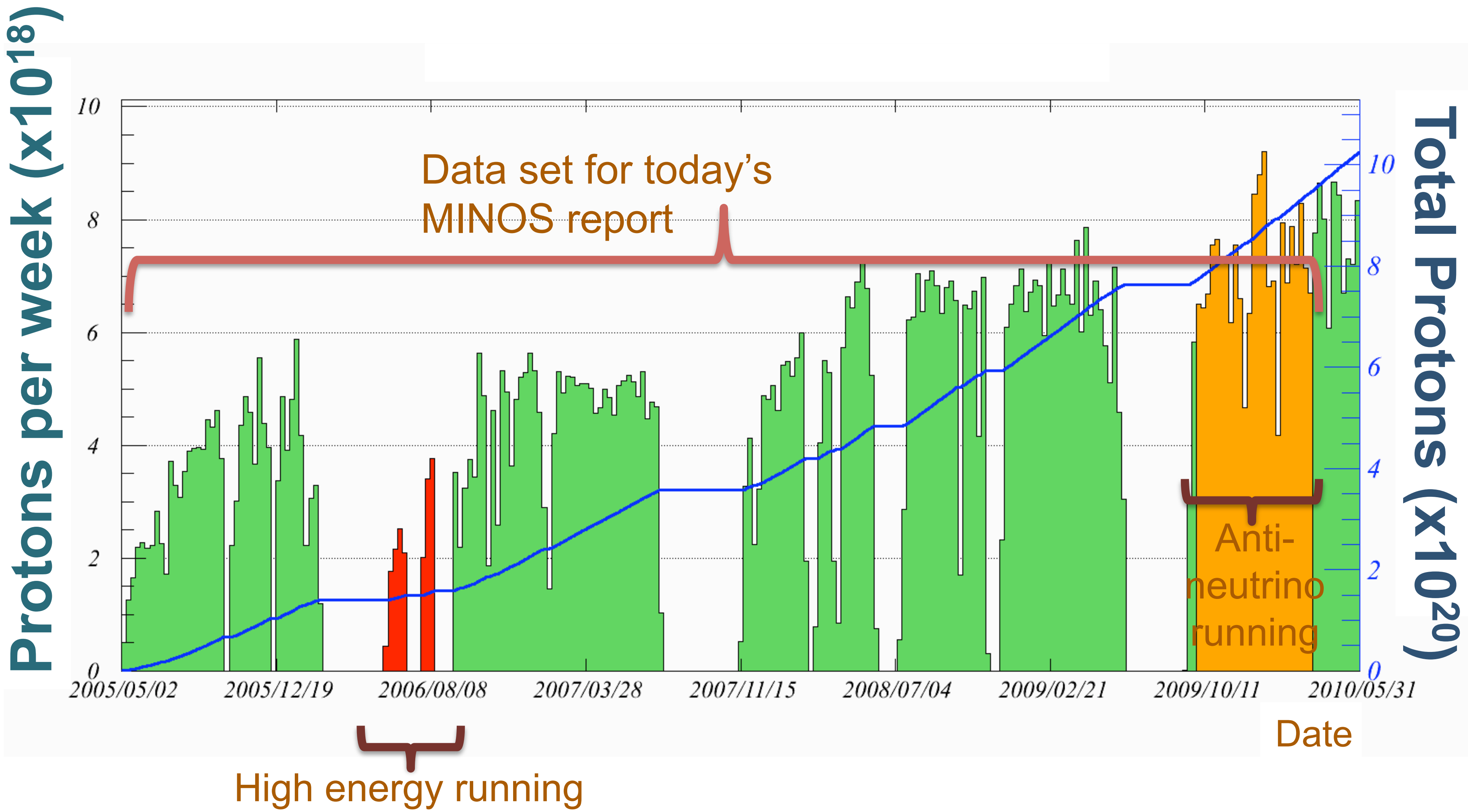




$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \boxed{\sin^2 2\theta}\,\sin^2(1.267\boxed{\Delta m^2}L/E)$$

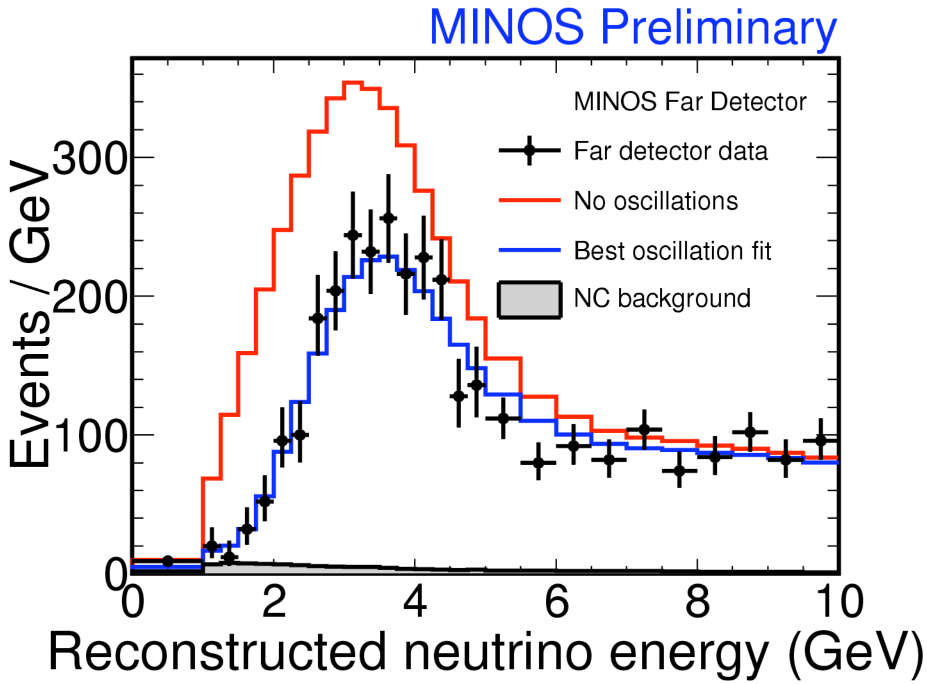
1 2

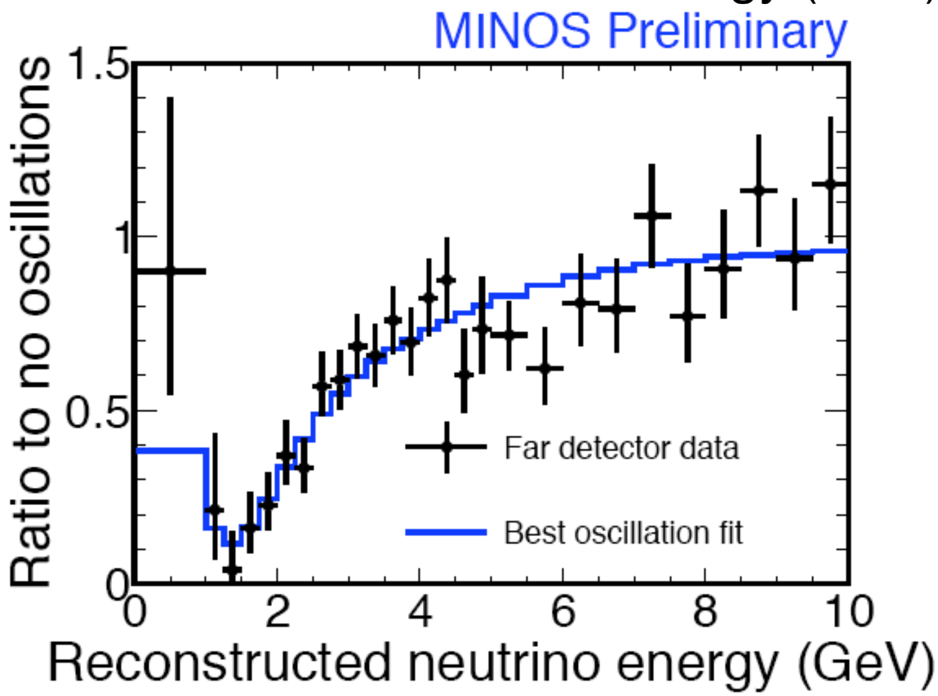
5 years of NuMI data

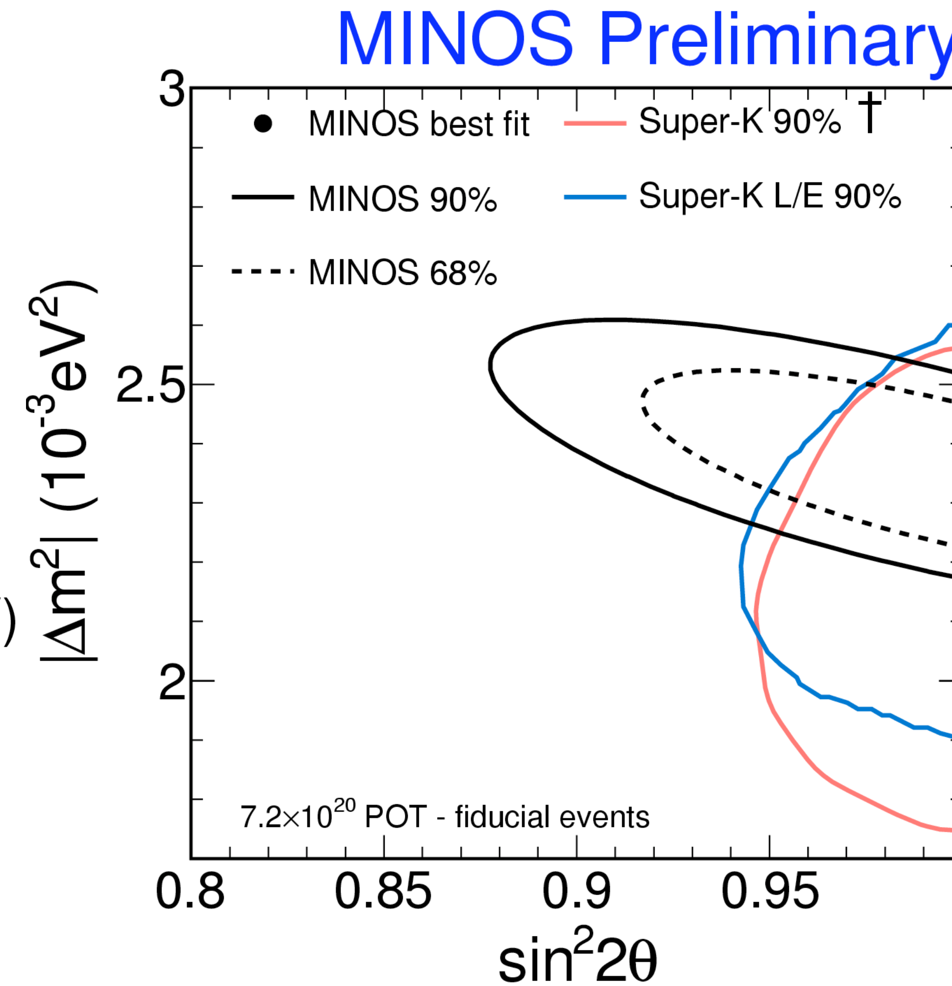


P. Vahle, Neutrino 2010

Neutrino Results







$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

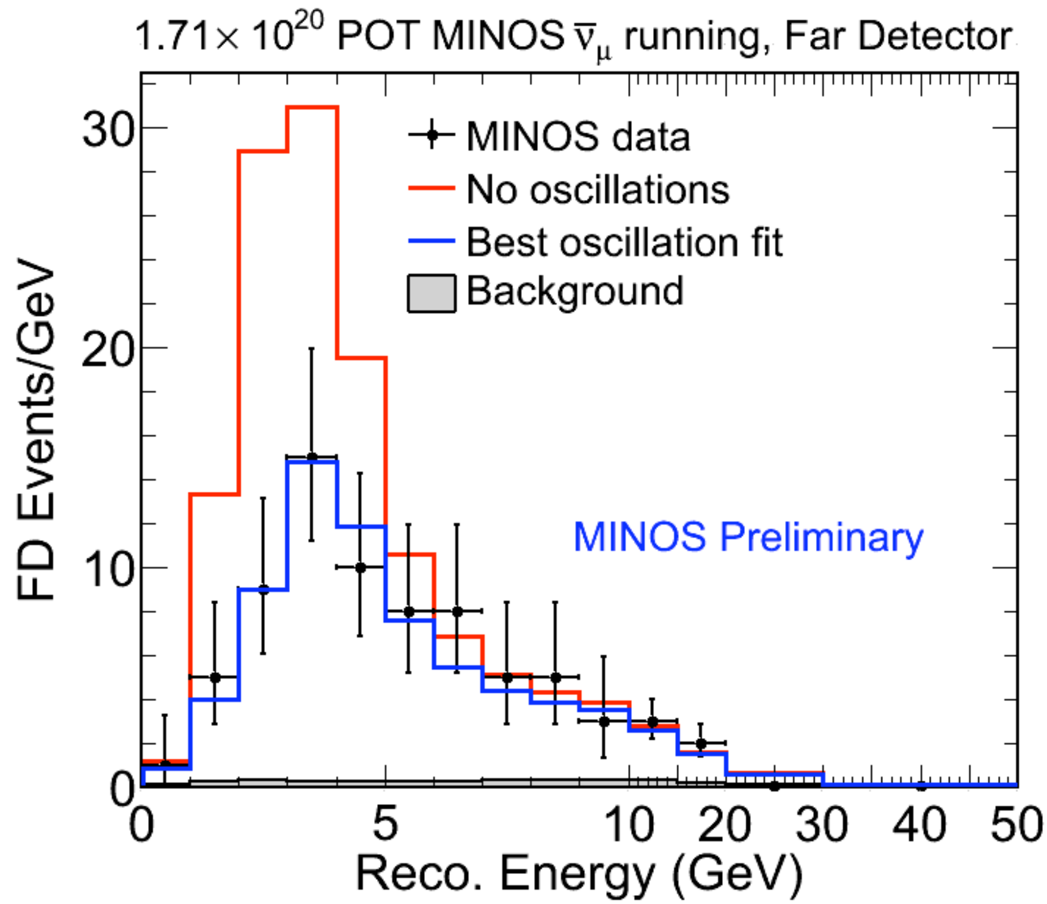
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

†Super-Kamiokande 2-flavour (preliminary)

[Vahle, Nu2010]

Anti-neutrino Results

Far Detector Data

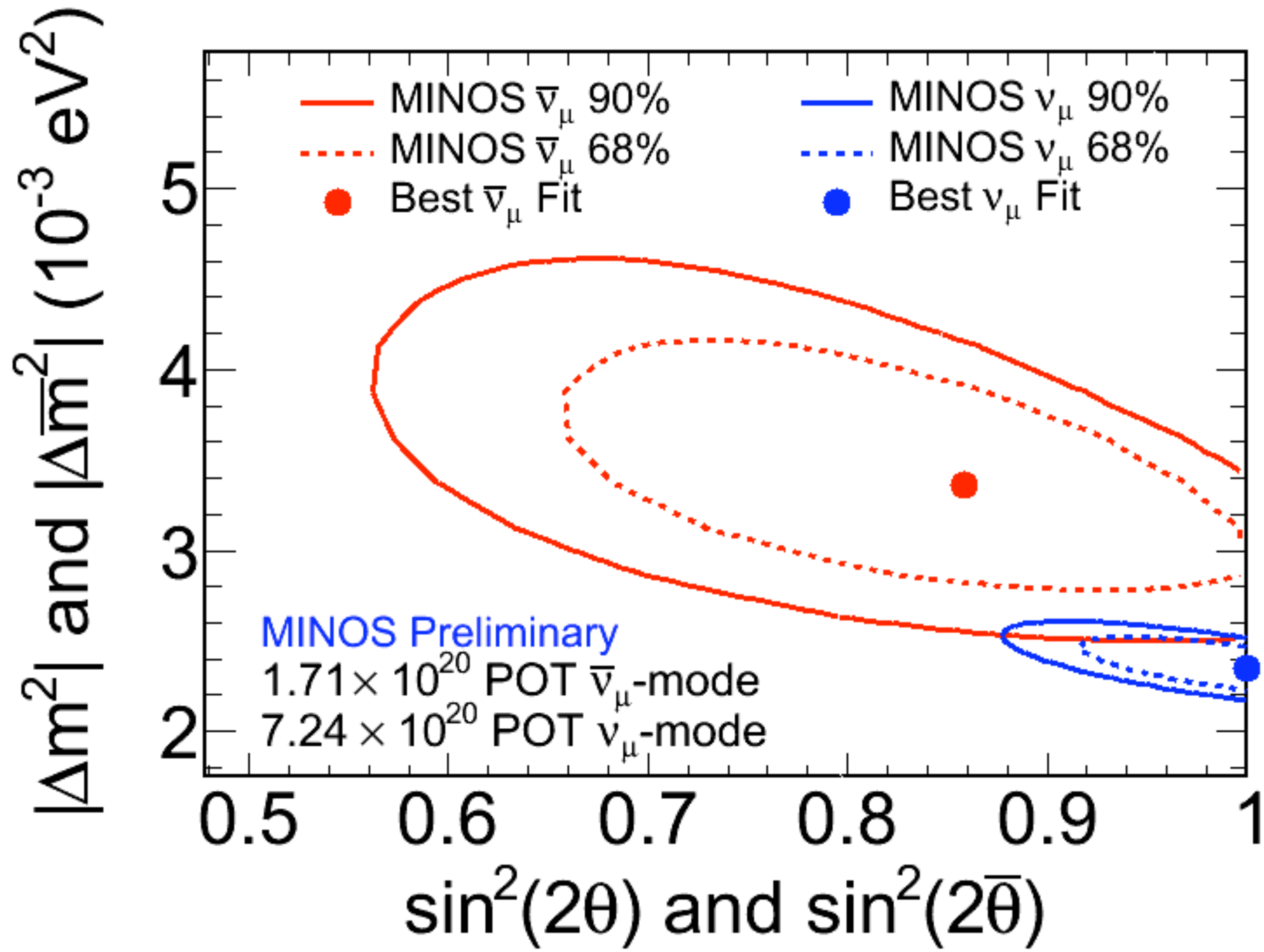


- No oscillation Prediction: **155**
- Observe: **97**
- No oscillations disfavored at 6.3σ

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

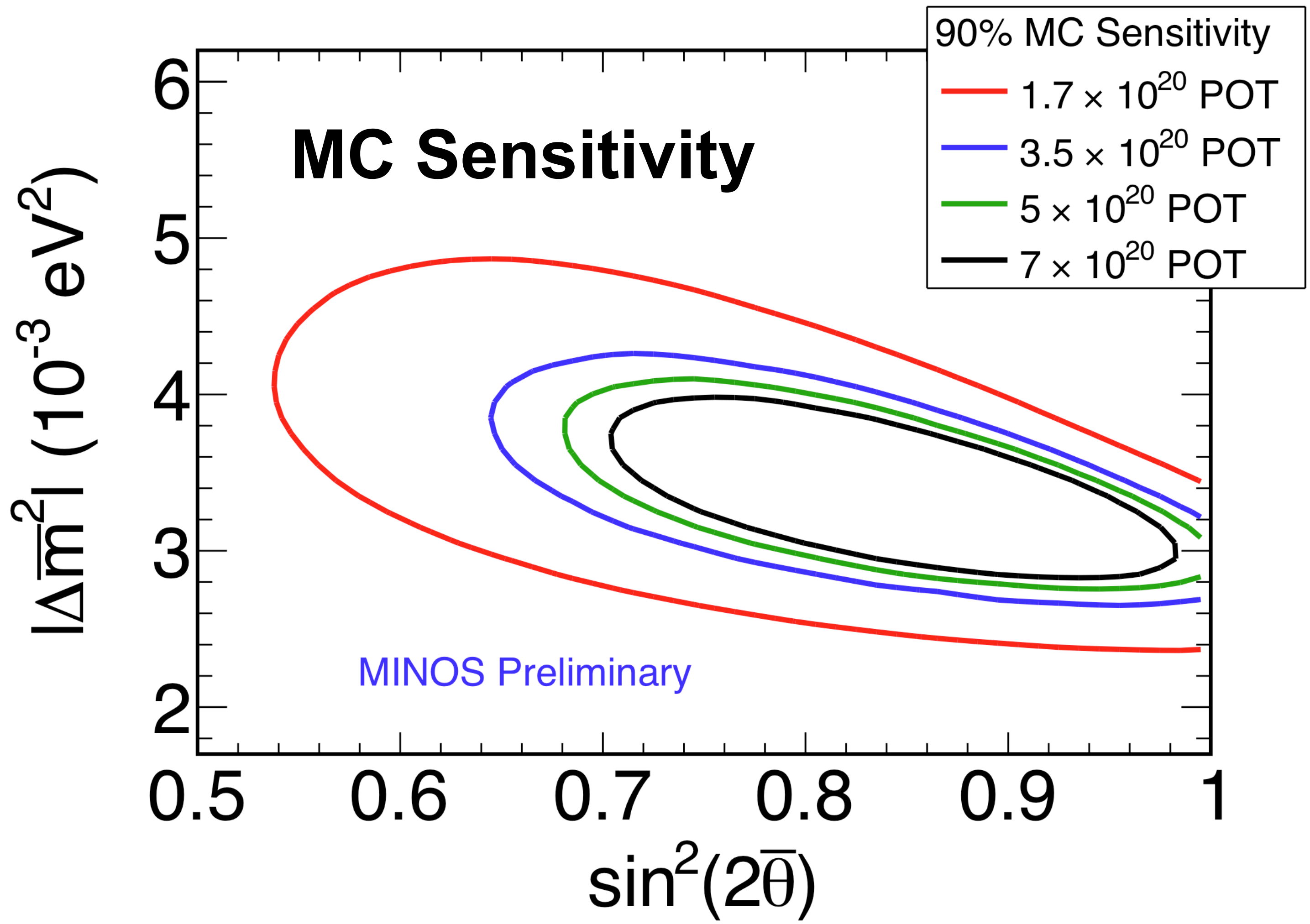
$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

Comparisons to Neutrinos



P. Vahle, Neutrino 2010

More anti-neutrinos to come…



Electron Neutrino Appearance Analysis

ν_e Appearance Results

- Based on ND data, expect:
  49.1±7.0(stat.)±2.7(syst.)
- Observe: **54** events in the FD, a 0.7σ excess

for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

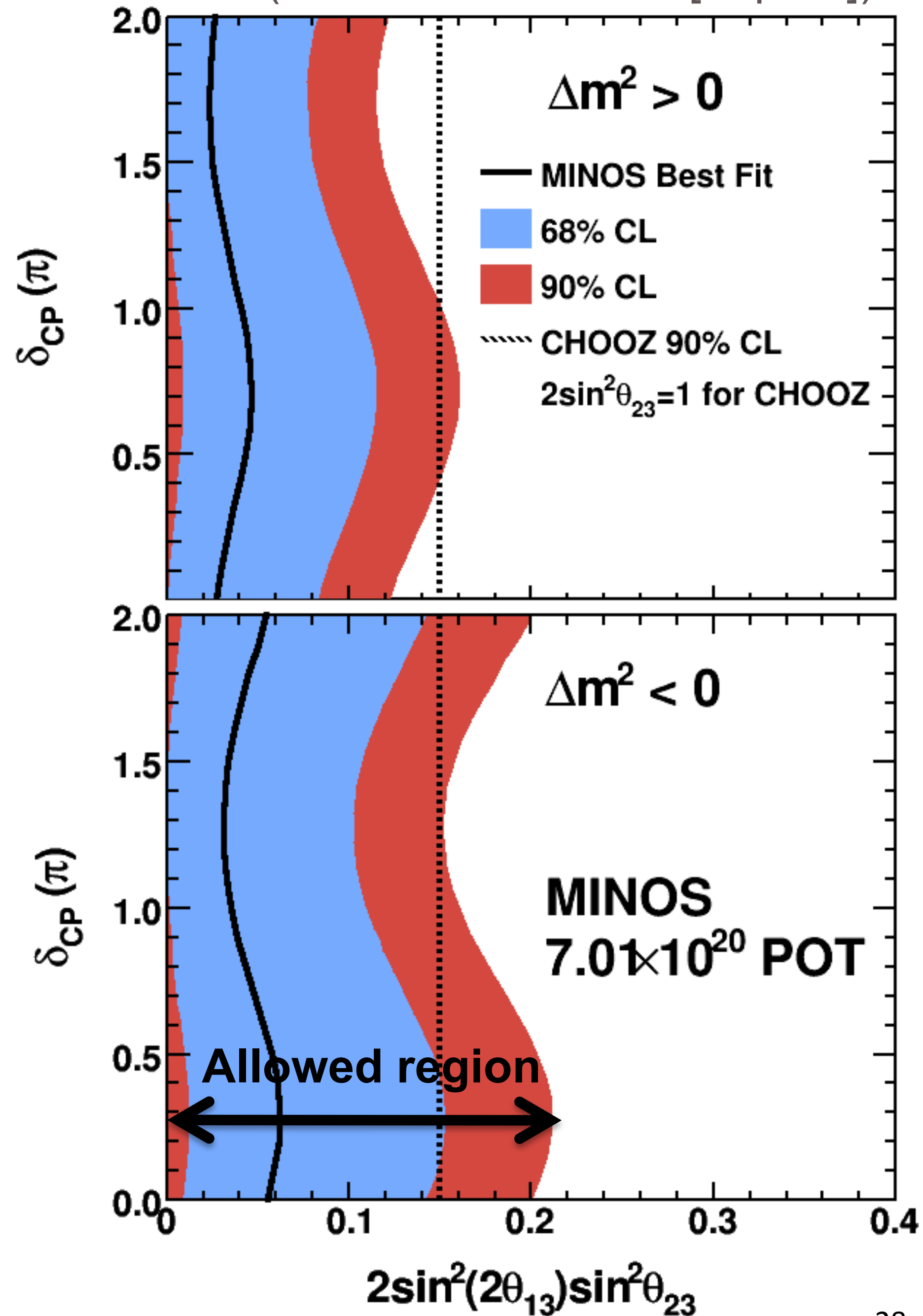
$|\Delta m^2_{32}| = 2.43 \times 10^{-3}\ \text{eV}^2$

$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

$\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

at 90% C.L.

(arXiv:1006.0996v1 [hep-ex])



The NOνA Collaboration

at Argonne National Lab, 25 April 2009

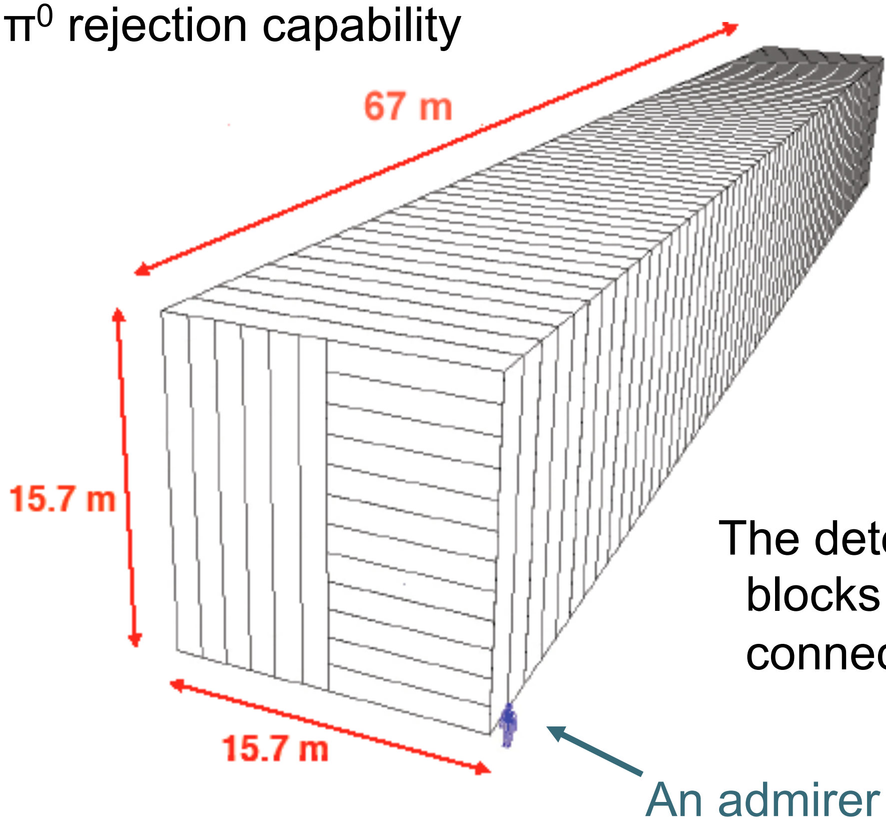
180 Scientists and Engineers from 26 Institutions

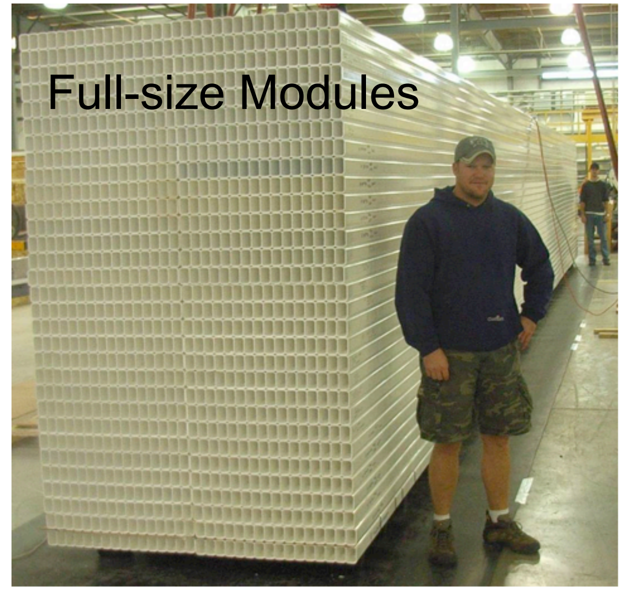
Argonne National Laboratory - University of Athens - California Institute of Technology - University of California, Los Angeles - Fermi National Accelerator Laboratory - Harvard University - Indiana University - Lebedev Physical Institute - Michigan State University - University of Minnesota, Duluth - University of Minnesota, Minneapolis - The Institute for Nuclear Research, Moscow - Technische Universität München, Munich - State University of New York, Stony Brook - Northwestern University - University of South Carolina, Columbia - Southern Methodist University - Stanford University - University of Tennessee - Texas A&M University - University of Texas, Austin - University of Texas, Dallas - Tufts University - University of Virginia, Charlottesville - The College of William and Mary - Wichita State University

Far Detector

TASD: Totally Active Scintillator Design

Longitudinal sampling is ~0.2 X_0, which gives:
-- excellent μ-*e* separation
-- π^0 rejection capability

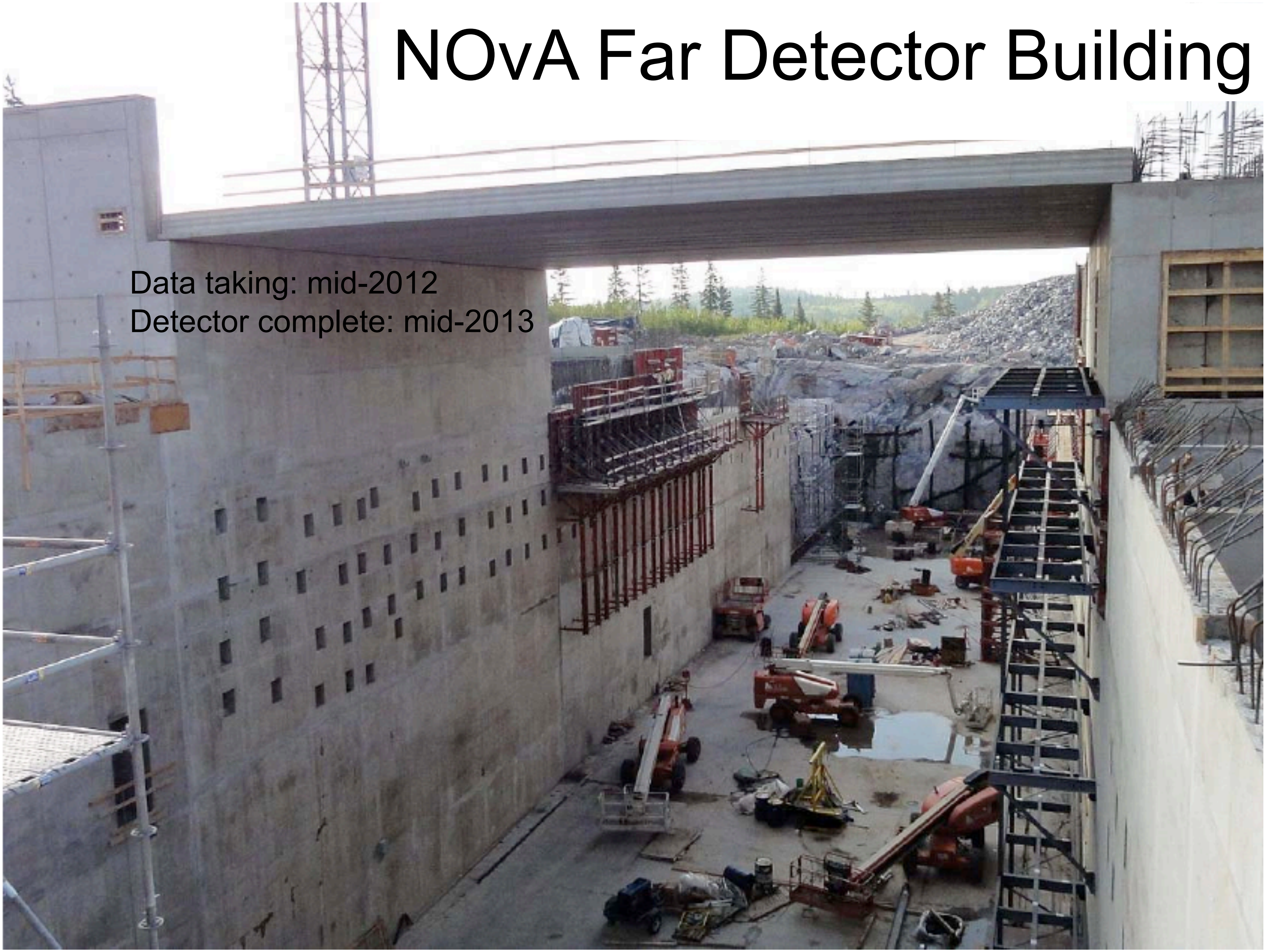




There are 1003 planes, for a total mass of 15 kT. There is enough room in the building for 18 kT

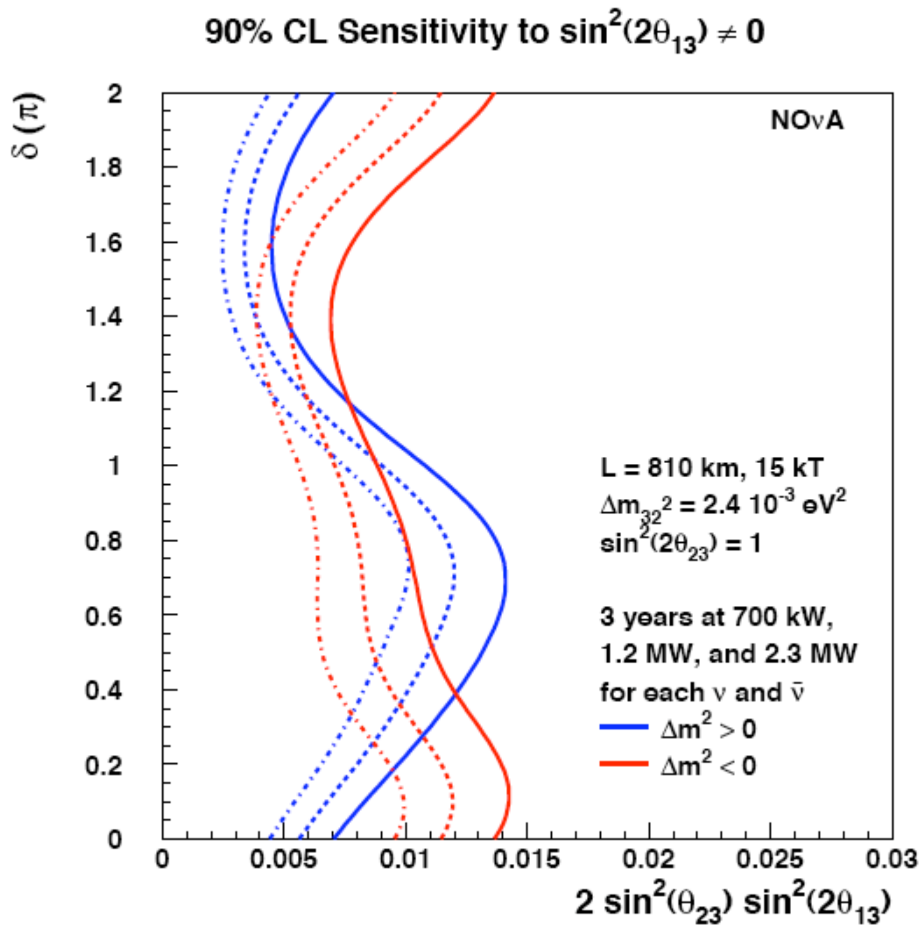
The detector can start taking data as soon as blocks are filled and the electronics connected.

NOvA Far Detector Building



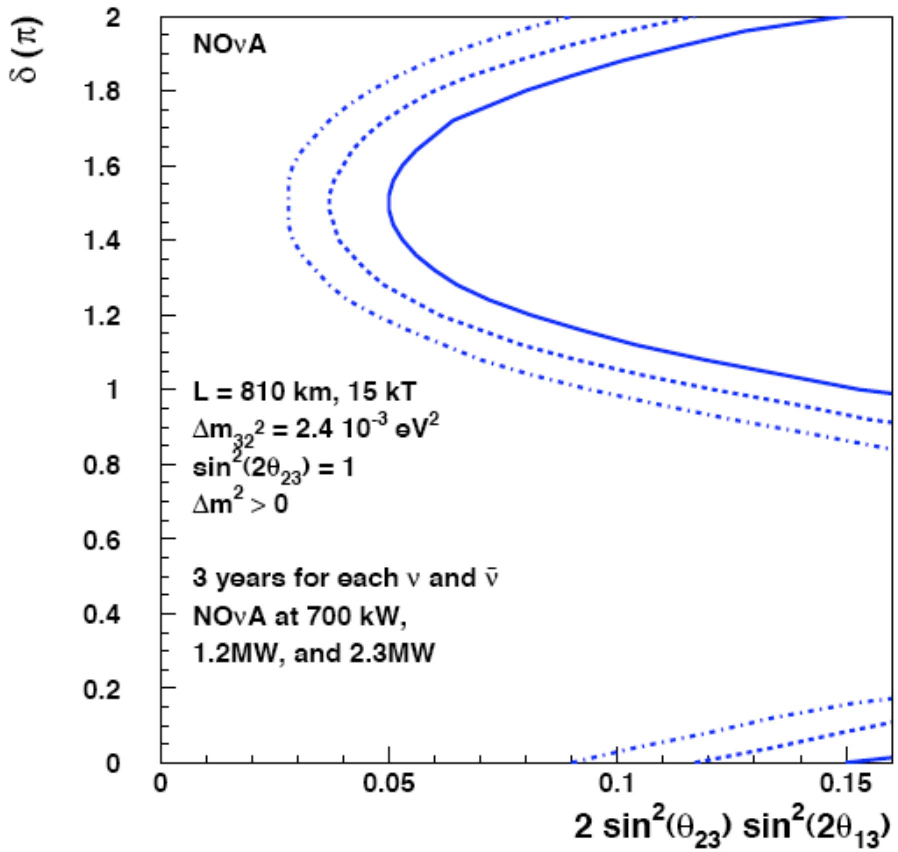
Data taking: mid-2012
Detector complete: mid-2013

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

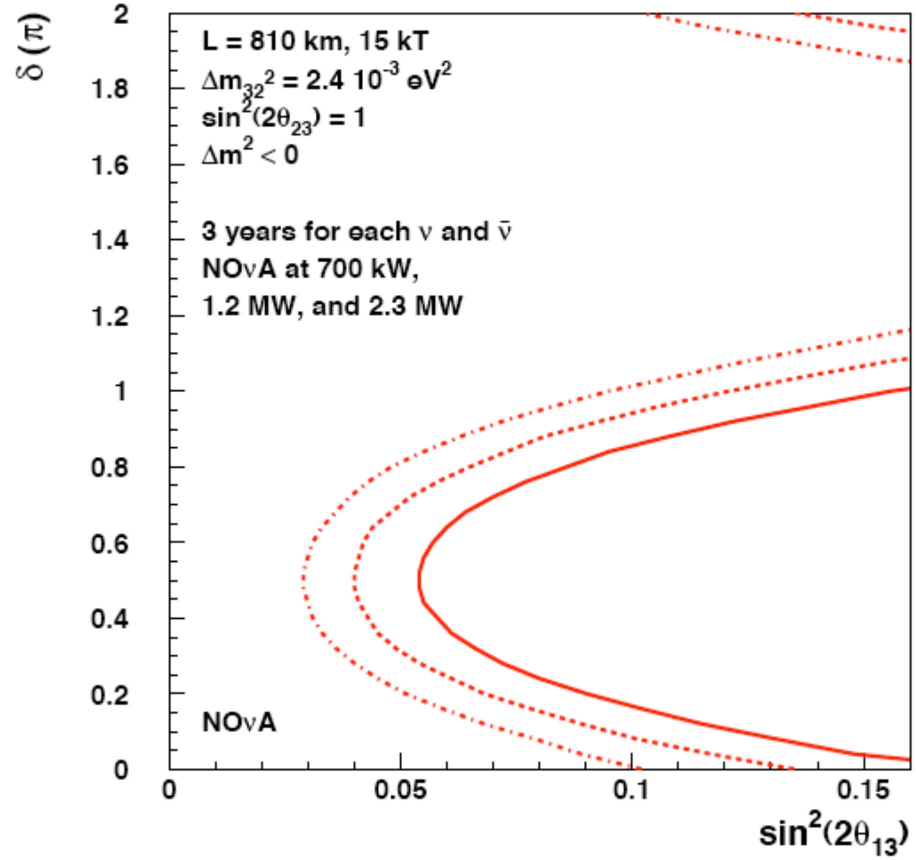


95% CL Resolution of Mass Ordering: NOνA Alone

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



Normal Ordering



Inverted Ordering

ArgoNeut

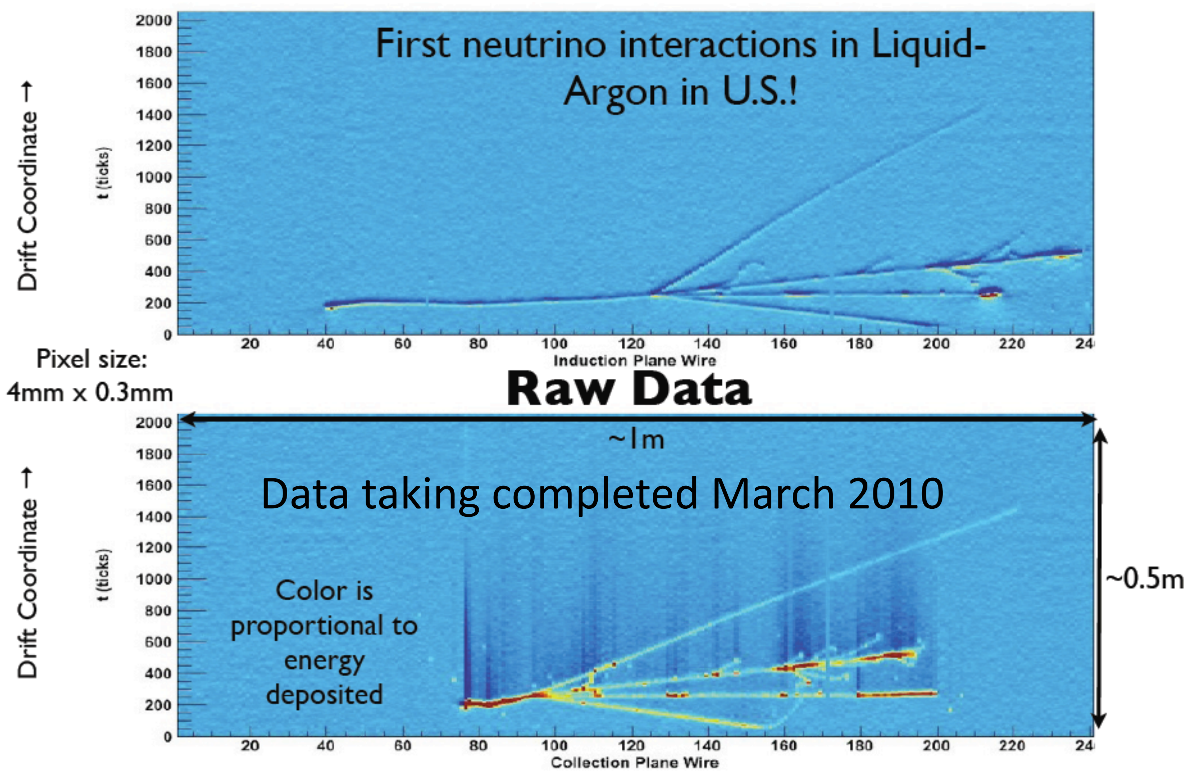
&

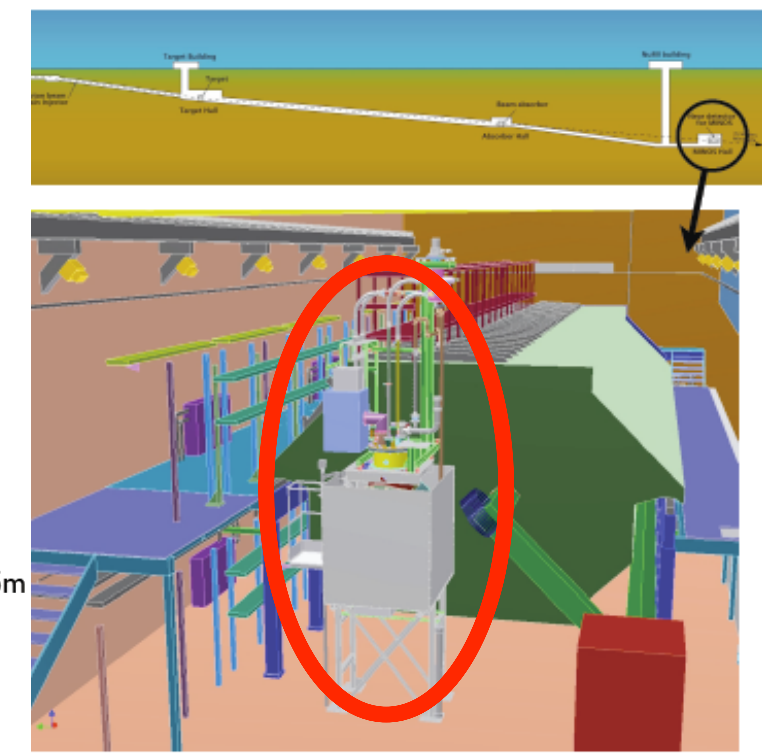
Minerva

ArgoNeuT

Ornella Palamara (Tues. Parallel)

- Test project to operate LArTPC in neutrino beam with goals to:
  - Gain experience building/running LArTPC in a neutrino beam
  - Accumulate neutrino/antineutrino events (1st time in US, 1st time in low-energy beam)
  - Develop simulation and reconstruction for LArTPCs, and compare MC with data





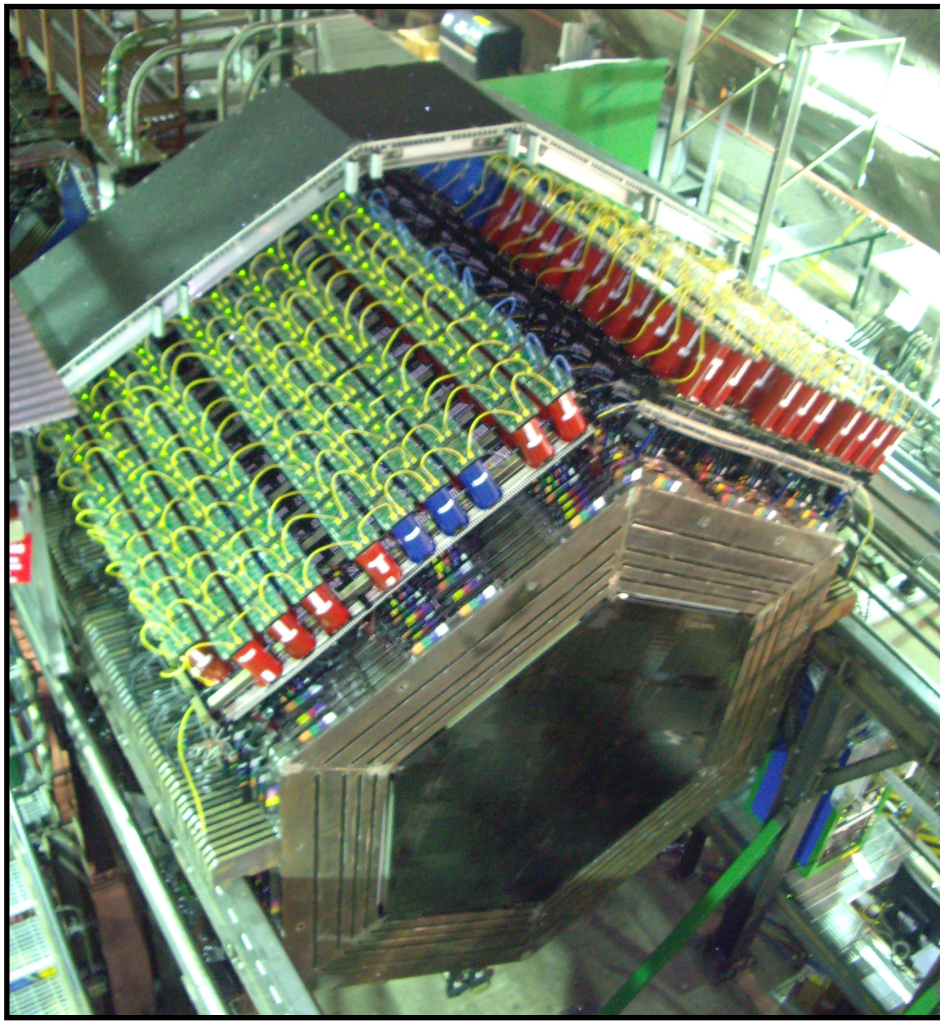
MINOS Hall at Fermilab

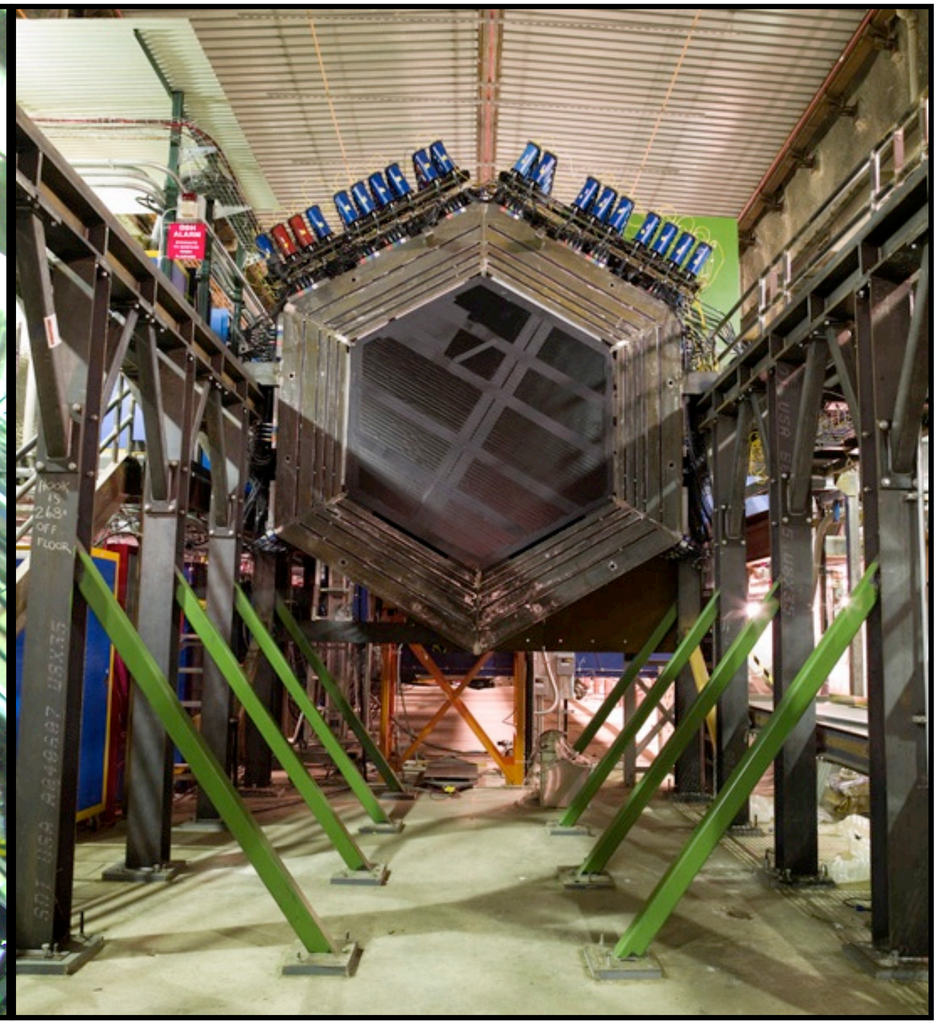
M. Soderburg, Nu2010

Steven Manly (Friday parallel)

MINERνA

A dedicated neutrino scattering experiment



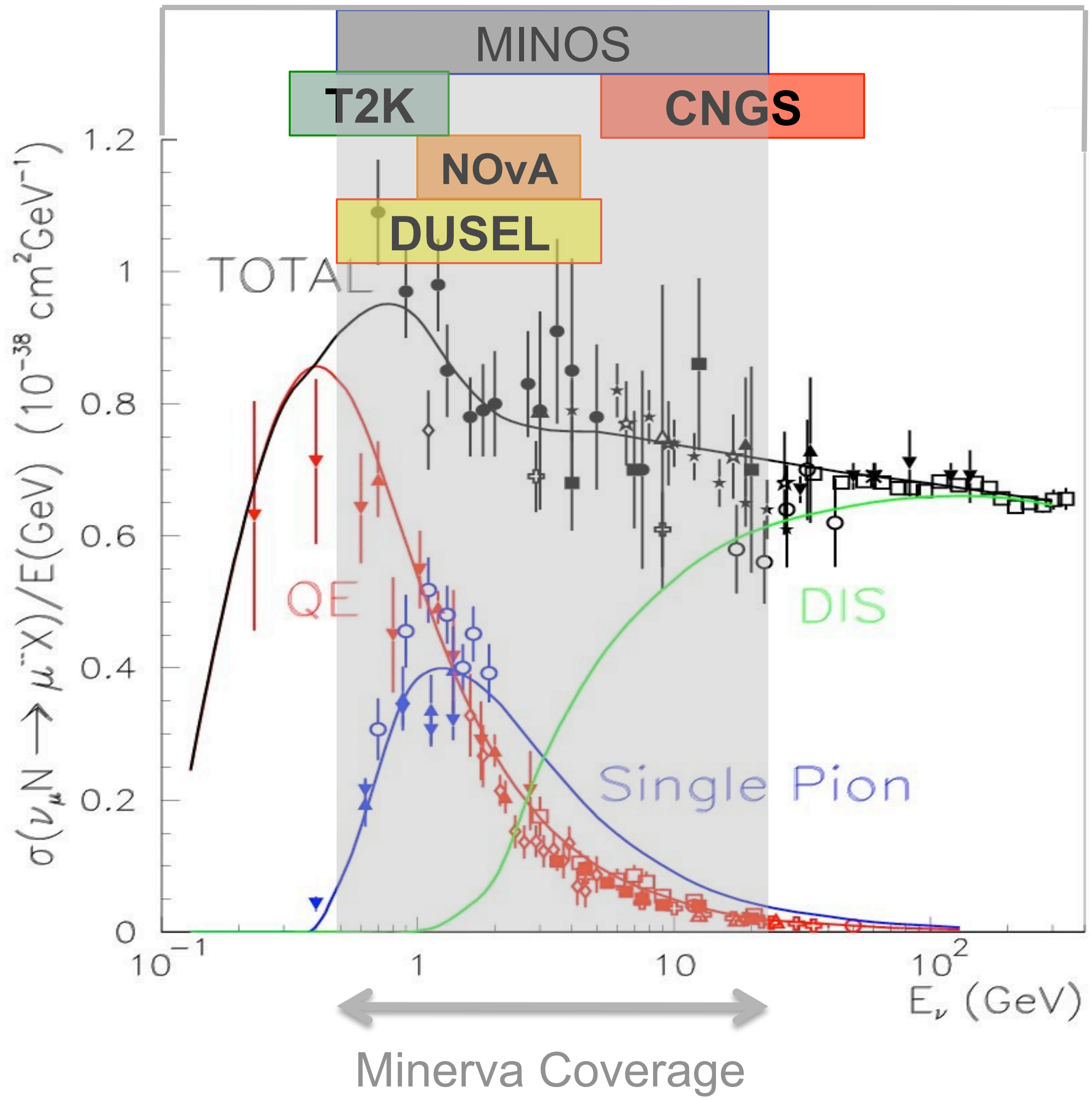


Minerva and Neutrino Oscillations

- Neutrino energy ranges and detector target materials affect neutrino cross-sections strongly
  - Dominant **interaction channels** change rapidly
  - Many **resonances** to consider
  - **Nuclear effects** complicated and not well known
- Goal: map out and study the physics of neutrino-nucleus interaction

  (0.5->20 GeV)

ν_μ charged-current cross-sections



Minerva Status

- Detector constructed (except for water and He targets)
  - 1st data set was during NuMI anti-neutrino run
  - 2nd data set collected this year in neutrino mode
- Analyses underway
- Everything on track for a useful and interesting set of measurements in near future

Conclusions

- Much exciting physics from the NuMI beam already with MINOS (NuMI at 320kW)
  - Most precise measurement of Δm^2_{atm}
    - $\Delta m^2_{atm} = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ eV^2$
  - Limits on ν_e appearance
  - Anomaly with anti-neutrino disappearance
    - NuMI will switch back in Jan/11 (will more than double data set)
- Second phase getting underway
  - Minerva is taking neutrino scattering data
  - Straightforward NuMI upgrade to 700 kW in 2012
    - (initially 400 kW if Tevatron extension approved)
  - NOvA detectors' construction underway
- Exciting future with NuMI: stay tuned!

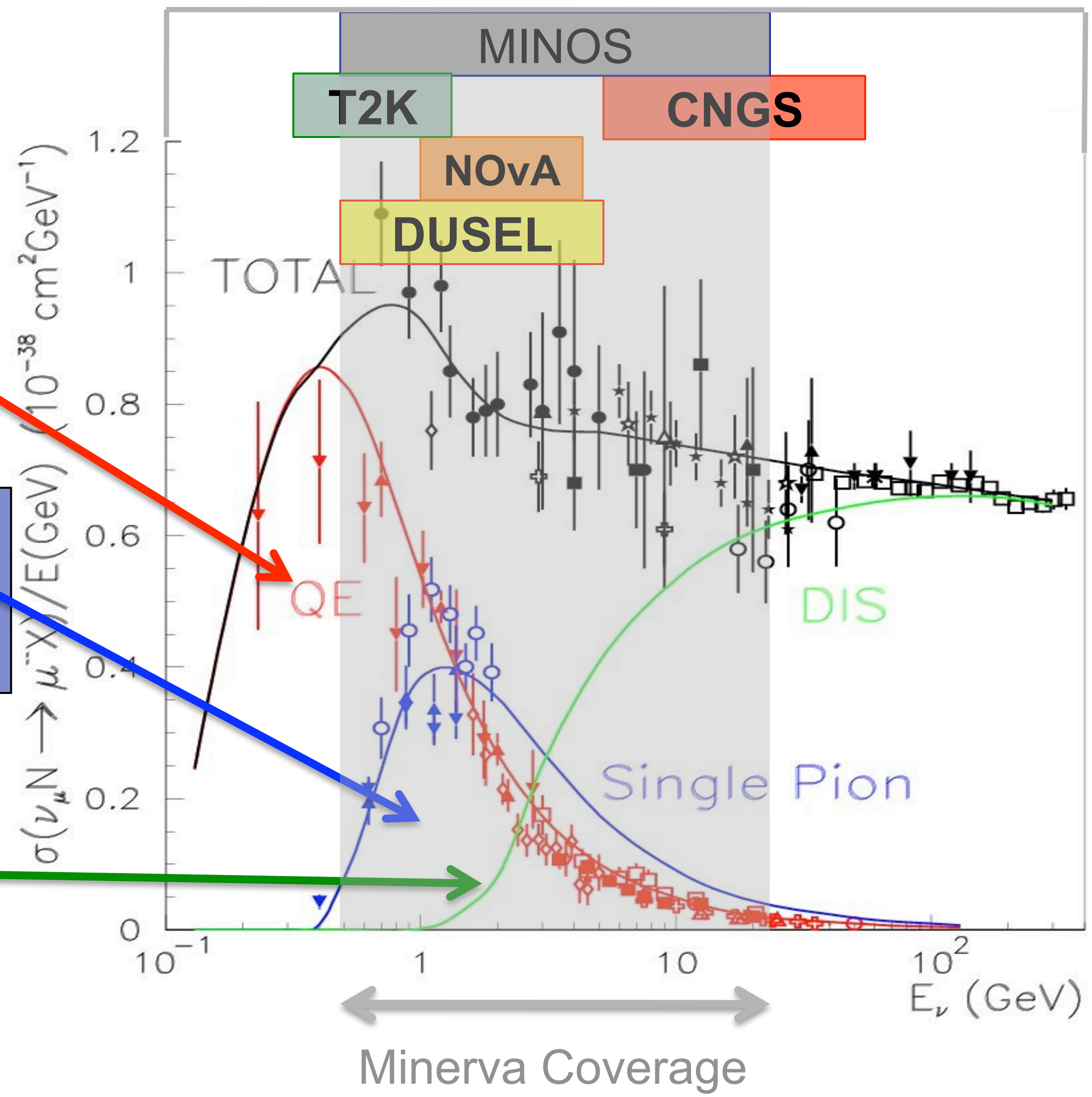
Backup slides

ν_μ charged-current cross-sections

Quasi-Elastic
signal channel in LBL oscillation experiments

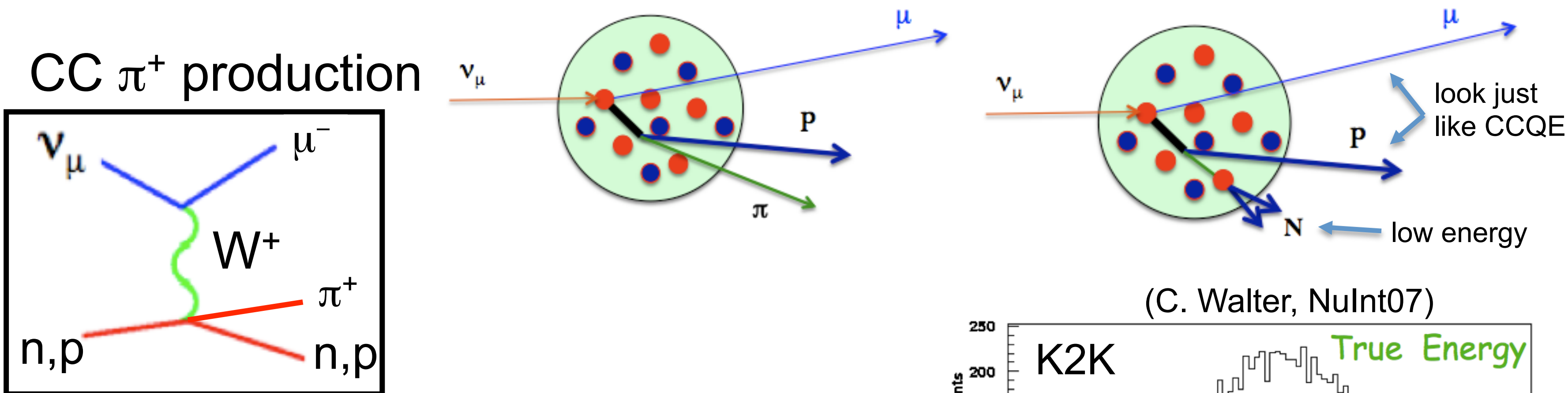
NC π^0	**CC π^+**
background for ν_e appearance	background for ν_μ disappearance

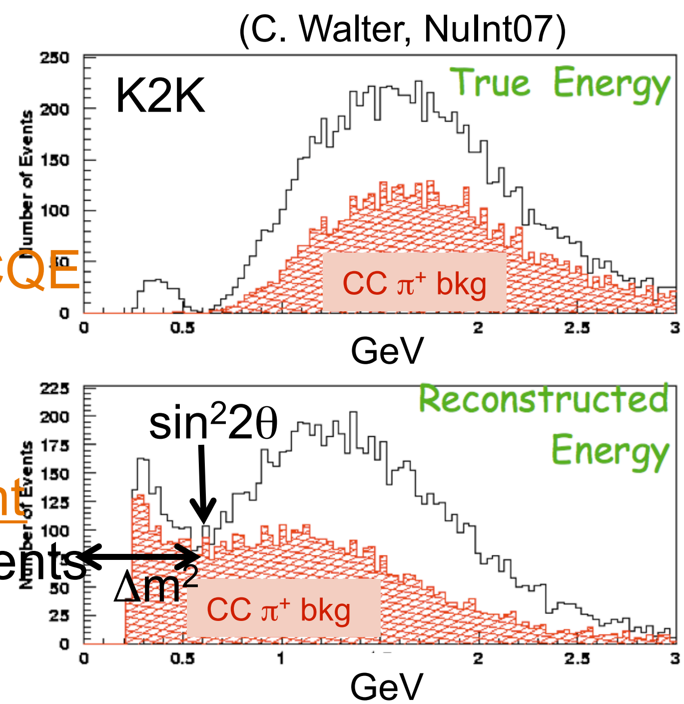
DIS
need to extrapolate into low energy region



Minerva example

- Single Pion Production





- Pion absorption creates irreducible bkgd to CCQE
- Pion re-interaction σ is large (30-40%) at these energies
- Pion absorption causes missing energy in event reconstruction – affects oscillation measurements
- **Nuclear effects strike again…**

Dave Schmitz, Fermilab

Prospects for Higgs Evidence

~16 fb^{-1} :

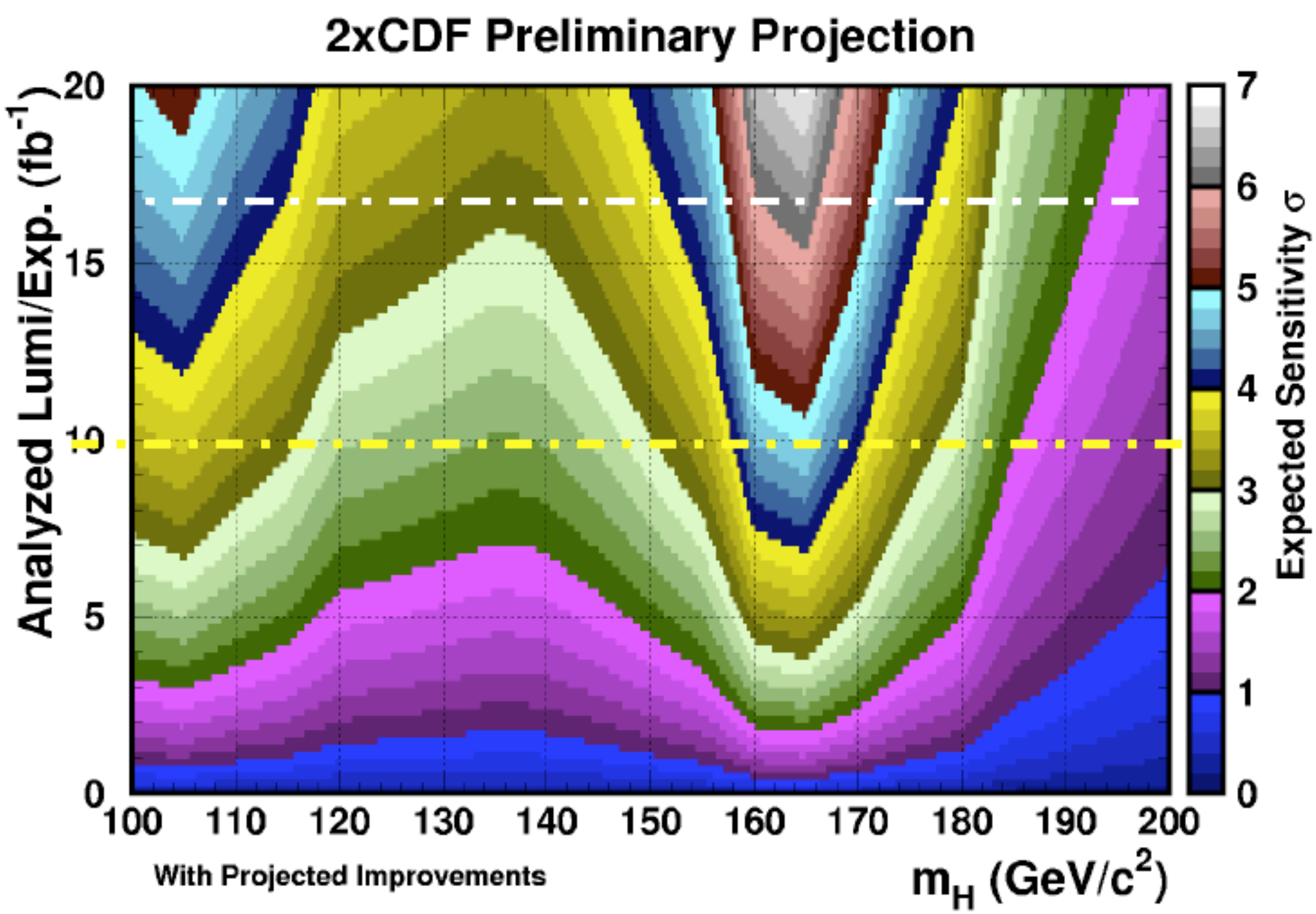
> 3 σ expected sensitivity from 100 – 180 GeV

>4 σ @ 115 GeV

>6 σ @ 165 GeV

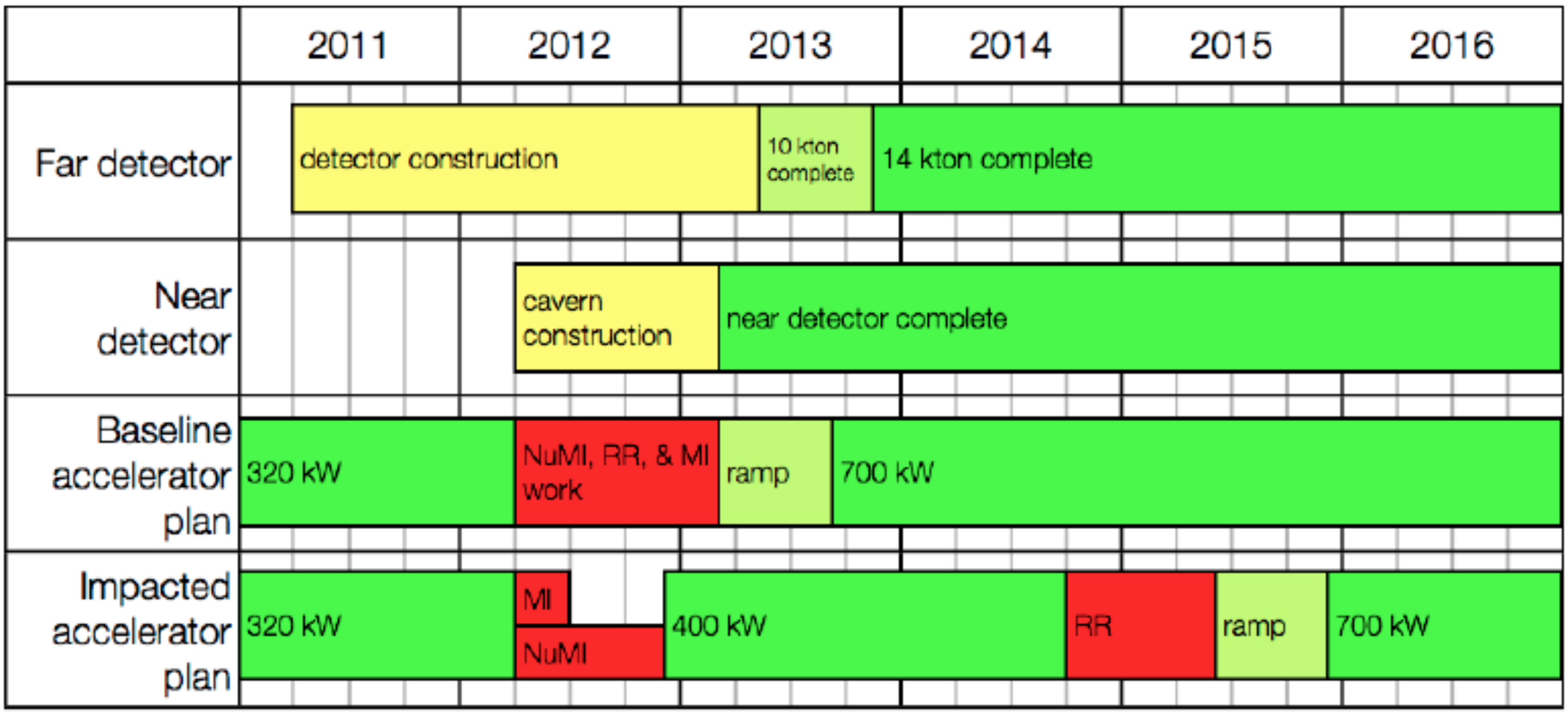
End of 2011:

> 2.4 σ expected sensitivity across mass range

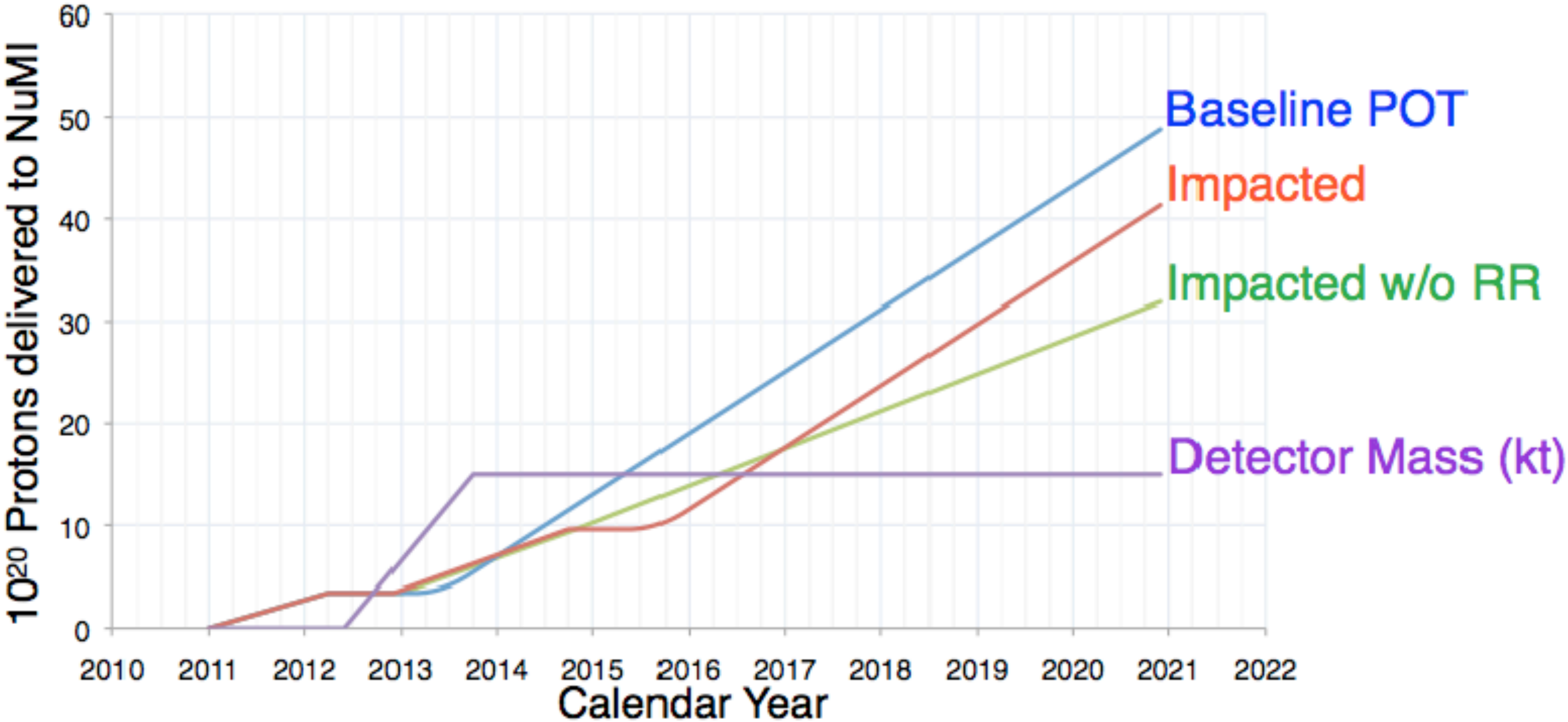


Fermilab

Scenarios


2011
2012
2013
2014
2015
2016
Far detector
detector construction
10 kton complete
14 kton complete
Near detector
cavern construction
near detector complete
Baseline accelerator plan
320 kW
NuMI, RR, & MI work
ramp
700 kW
Impacted accelerator plan
320 kW
MI
NuMI
400 kW
RR
ramp
700 kW

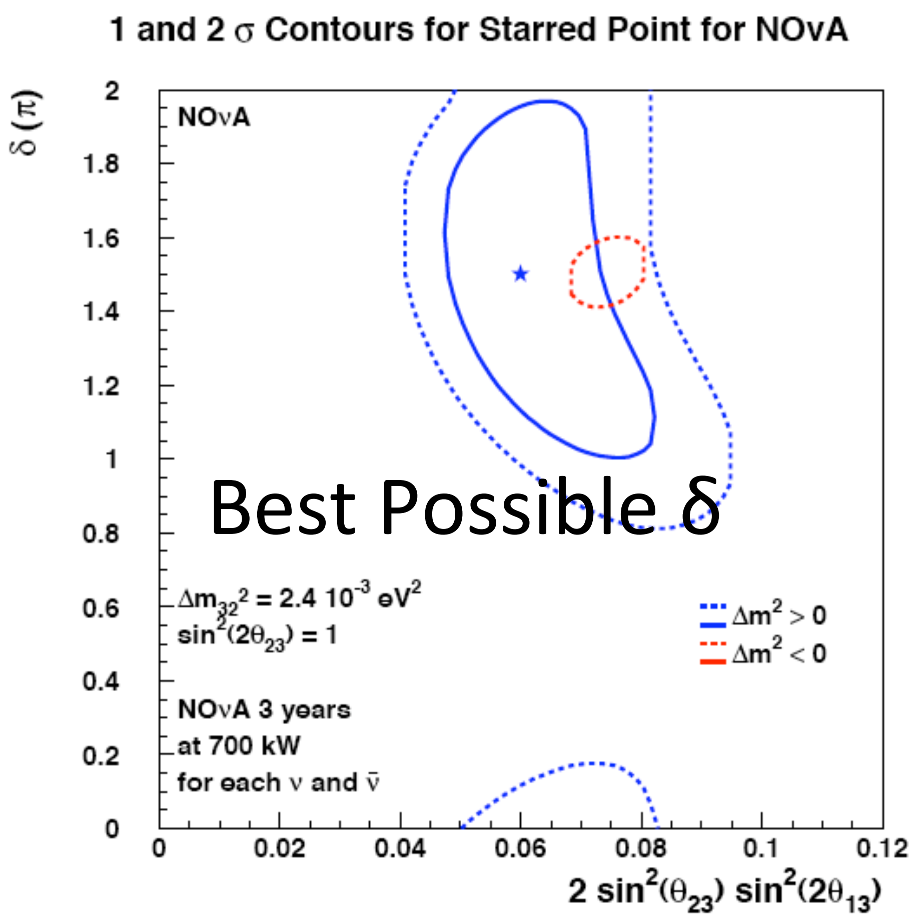
Integrated POT & Detector Mass

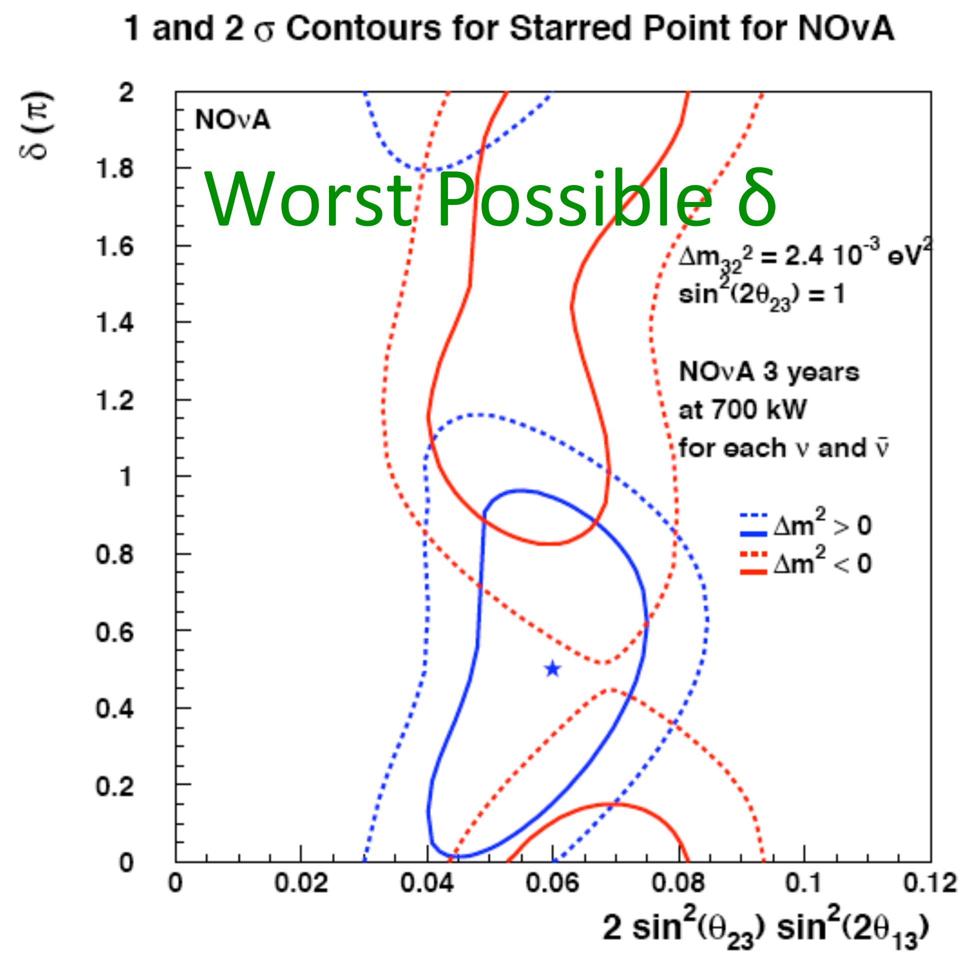


Impact Summary

- Impact of Tevatron 2014 on NOνA:
  - Reduce the NOνA data set by roughly a factor of 2 in the 2015-2016 time period.
  - Delay first results on ν_μ antineutrino oscillations by 2 years.
  - Delay first results on mass ordering and the CP-violating phase by 2 years.
  - Delay the final results by 1.5 years.
  - Add an additional 3.7 M$ to the cost of the project.

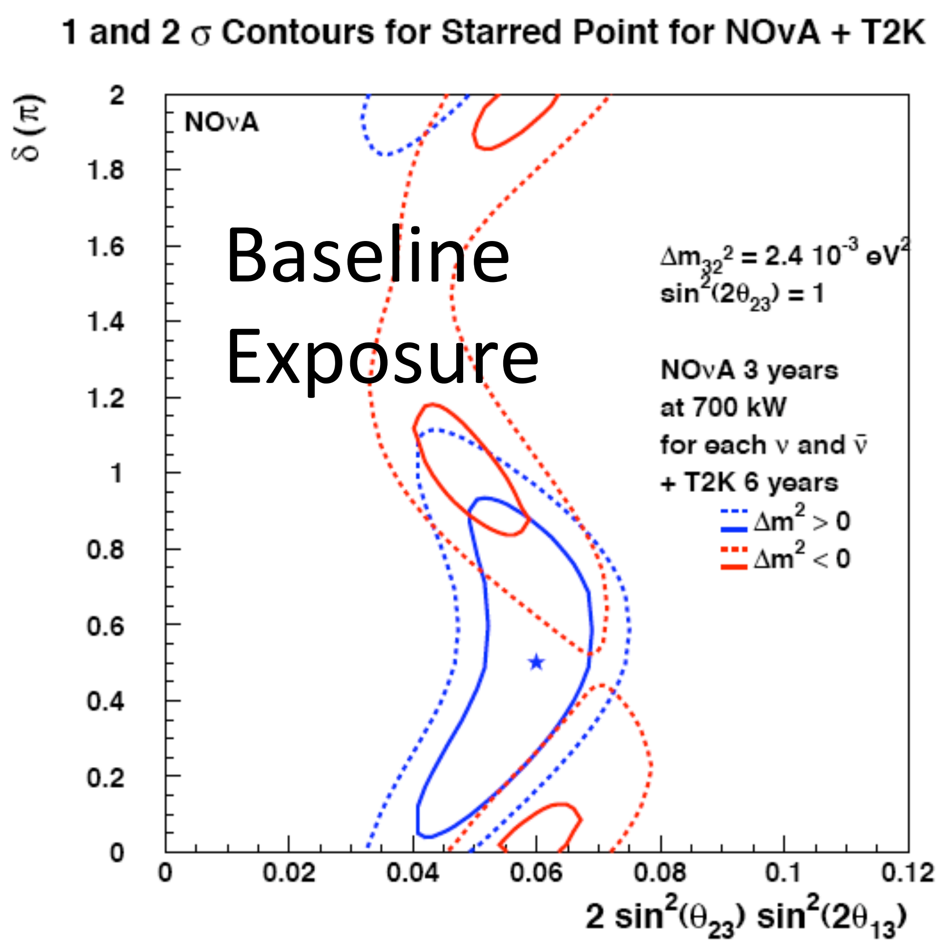
δ vs. θ_{13} Sensitivity Contours

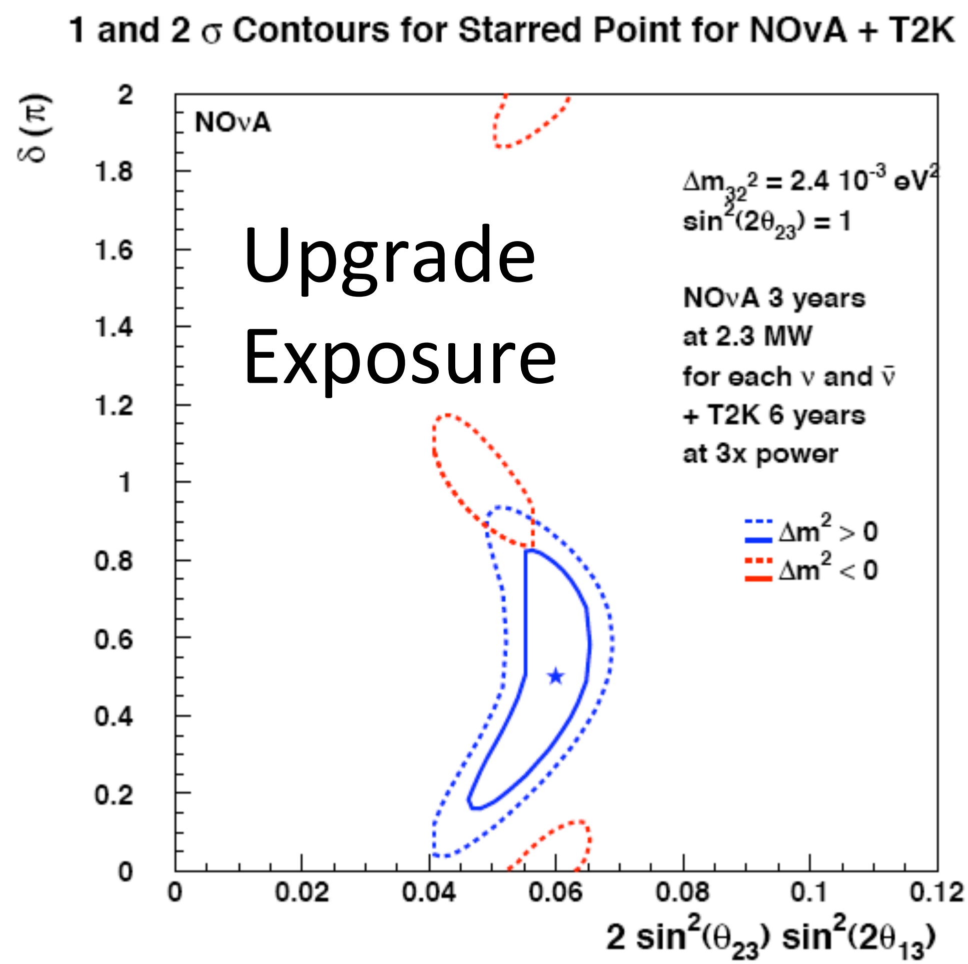




Synergy by combining with T2K

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

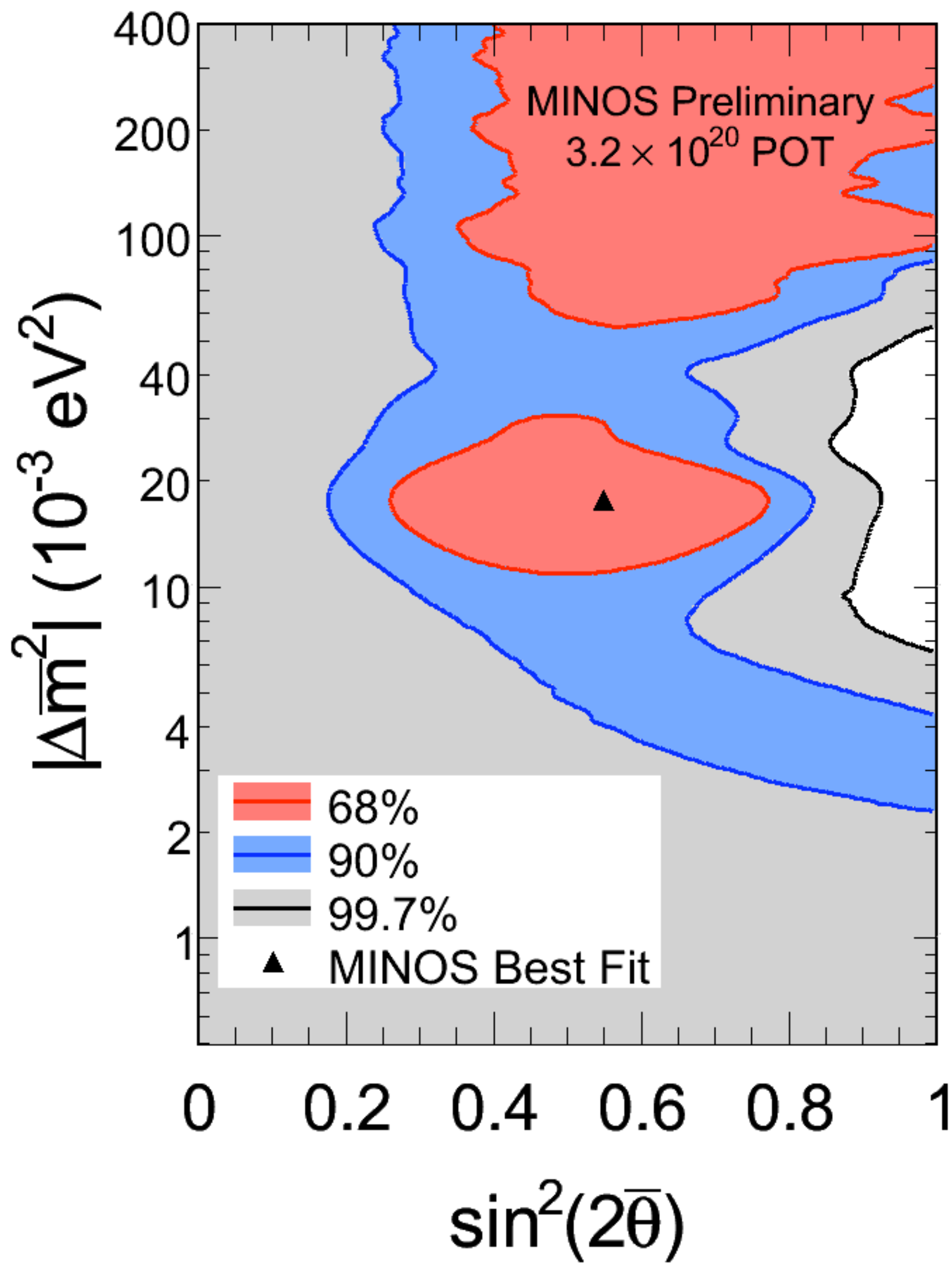




MINOS

Allowed Region

- Contours obtained using Feldman-Cousins technique, including systematics
- Null oscillation hypothesis excluded at 99%
- CPT conserving point from the MINOS neutrino analysis is within 90% contour
- $\bar{\nu}_{\mu}$ best fit is at high value, due to deficit at high energy
- Unshaded region around maximal mixing is excluded at 99.7% C.L.



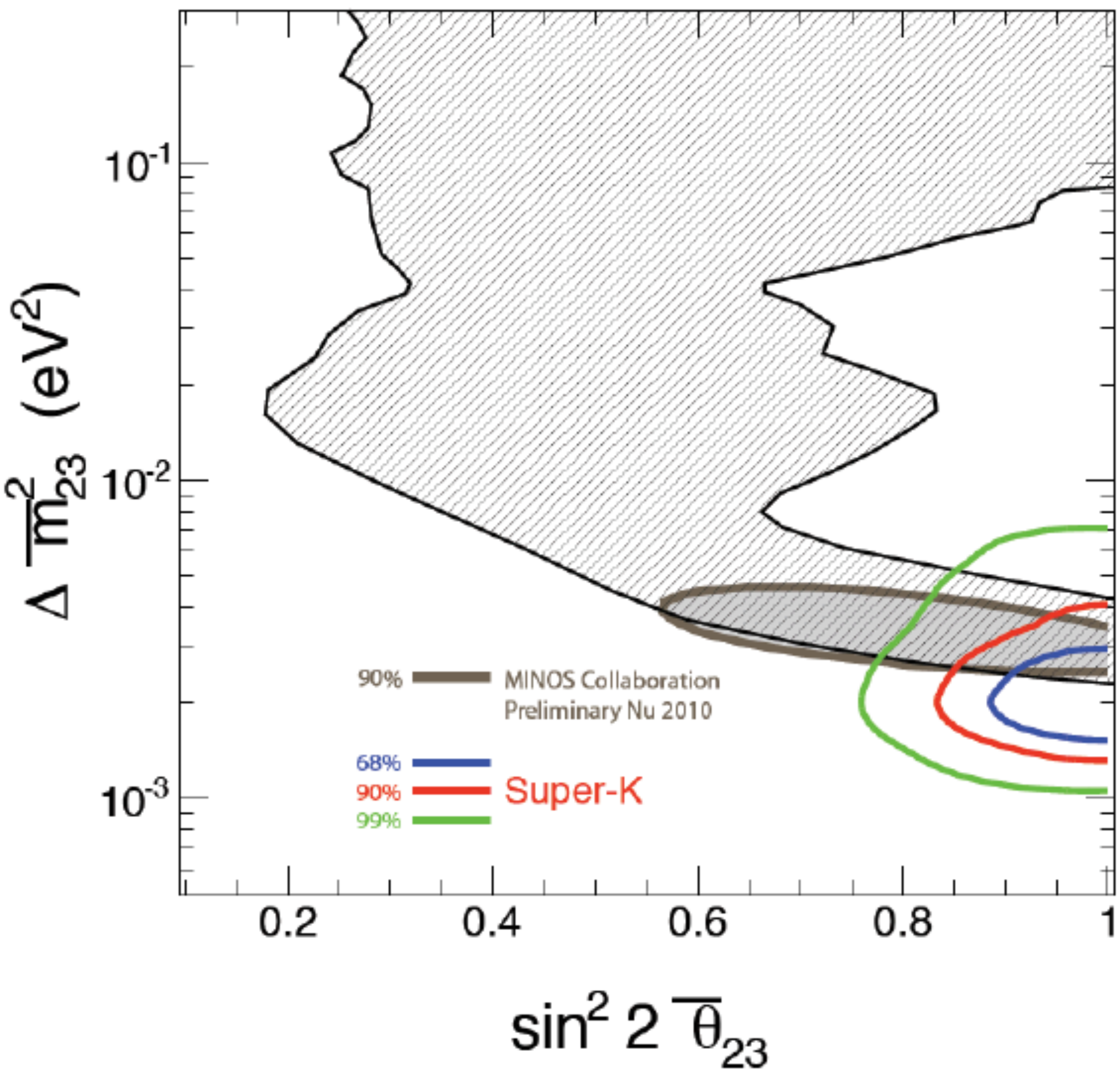
Search for CPT violation in atm. ν

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:

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

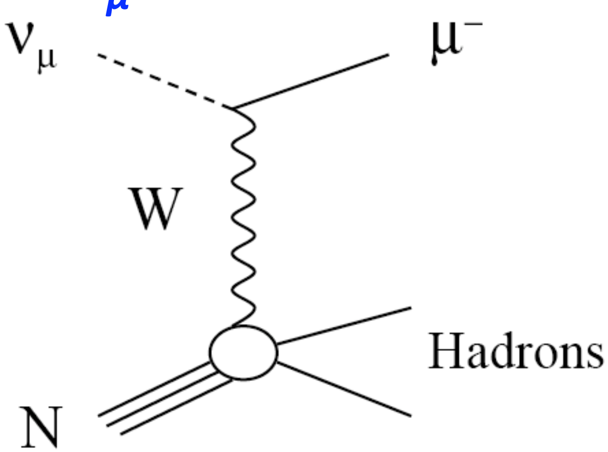
$\sin^2 2\overline{\theta}_{23} = 1.0$

No evidence for CPT violating oscillations is found

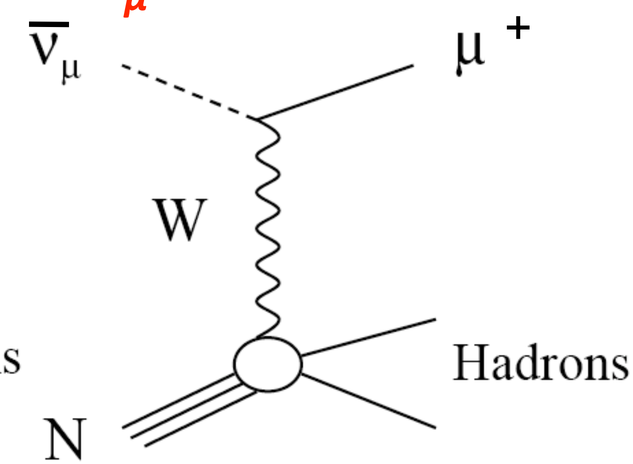
Poster-79 by Roger Wendell

MINOS Event Topologies

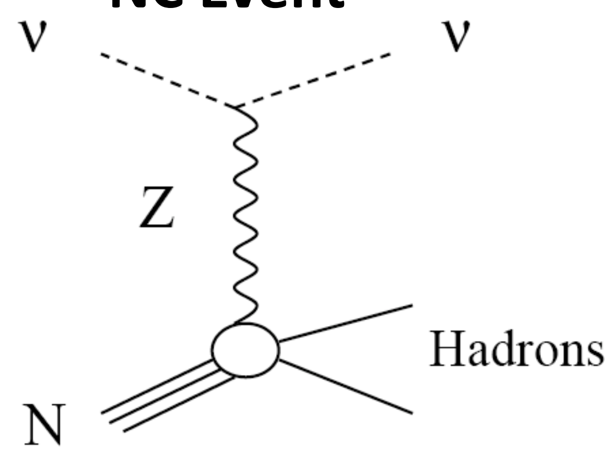
ν_μ CC Event

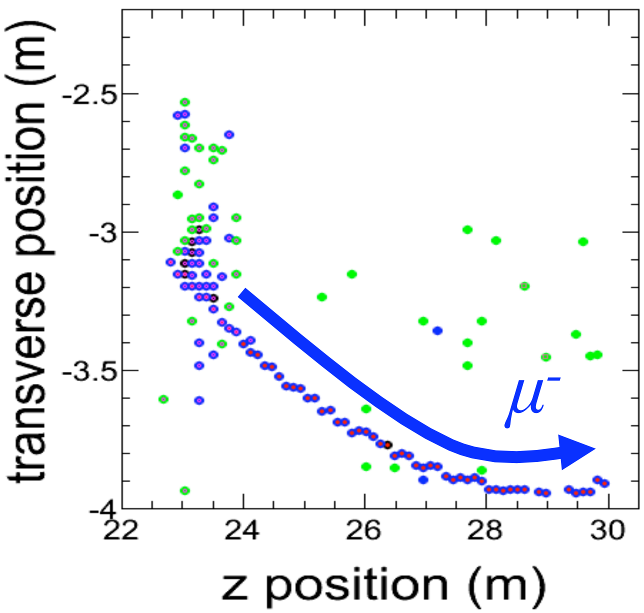


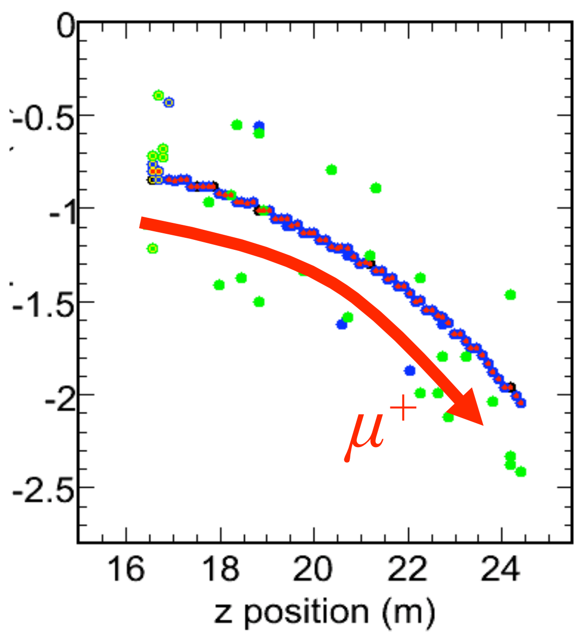
$\bar{\nu}_\mu$ CC Event

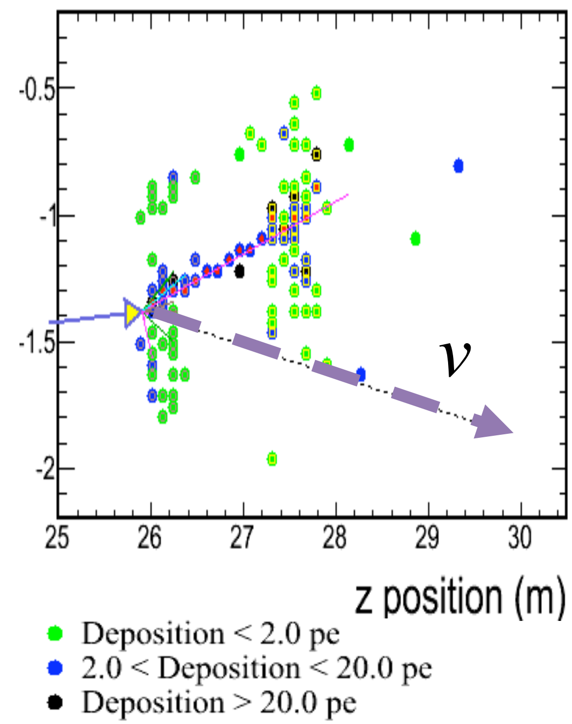


NC Event





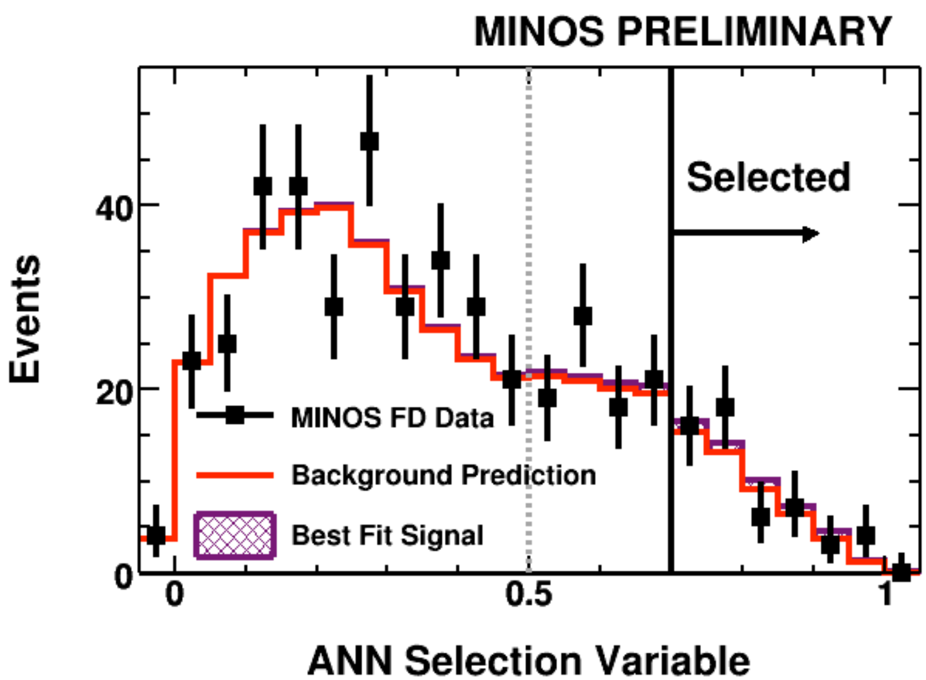


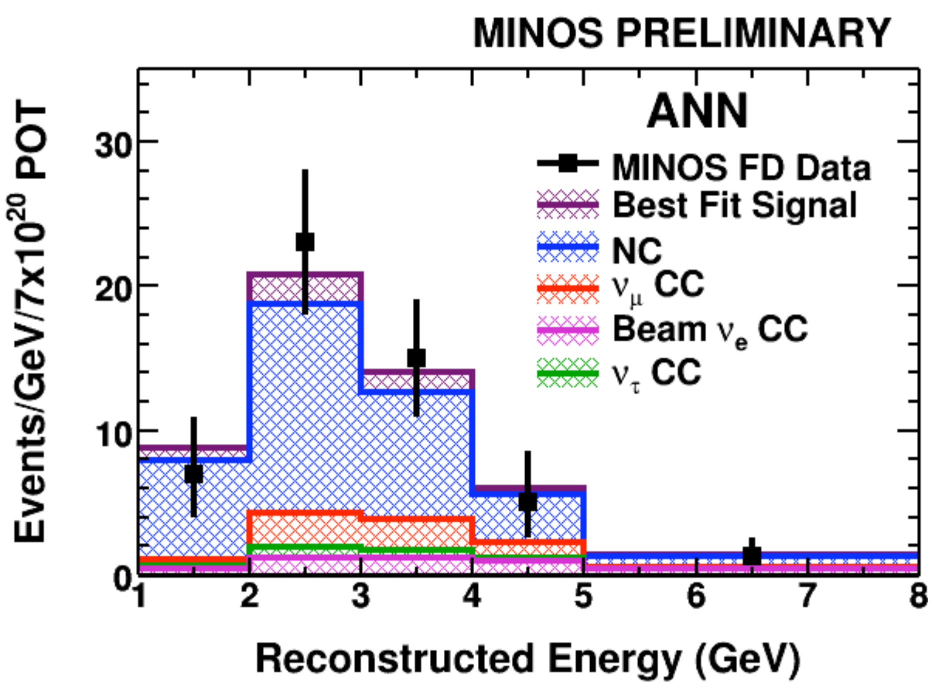


Simulated Events

ν_e Appearance Results

- Based on ND data, expect: **49.1±7.0(stat.)±2.7(syst.)**
- Observe: **54** events in the FD, a 0.7σ excess

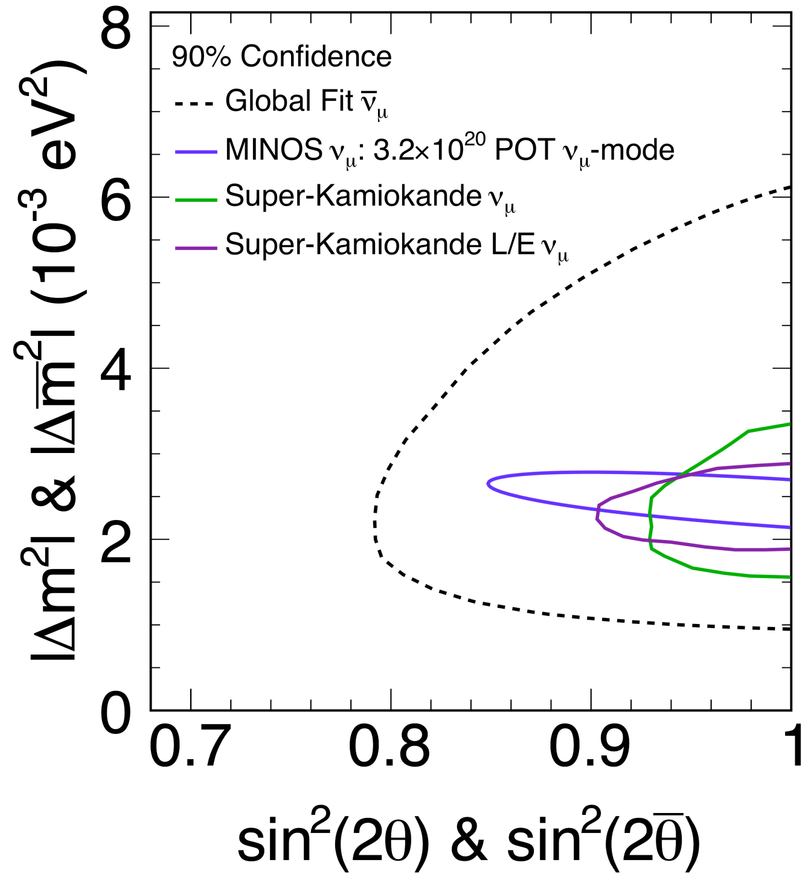




Why study ν_μ and $\overline{\nu}_\mu$?

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

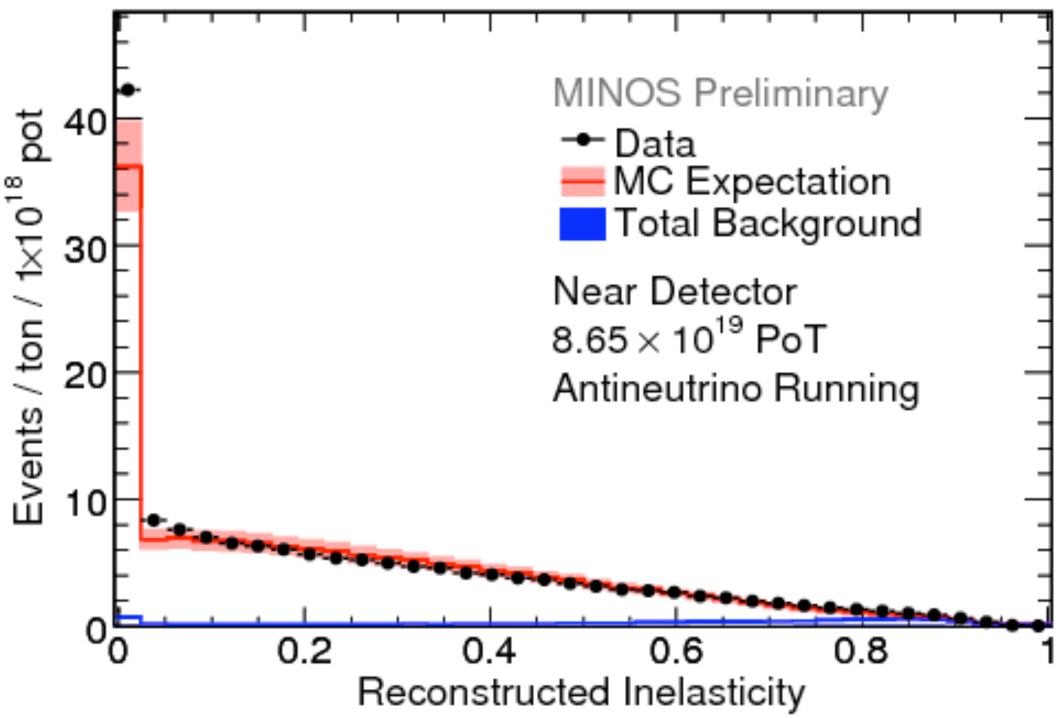
- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation



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

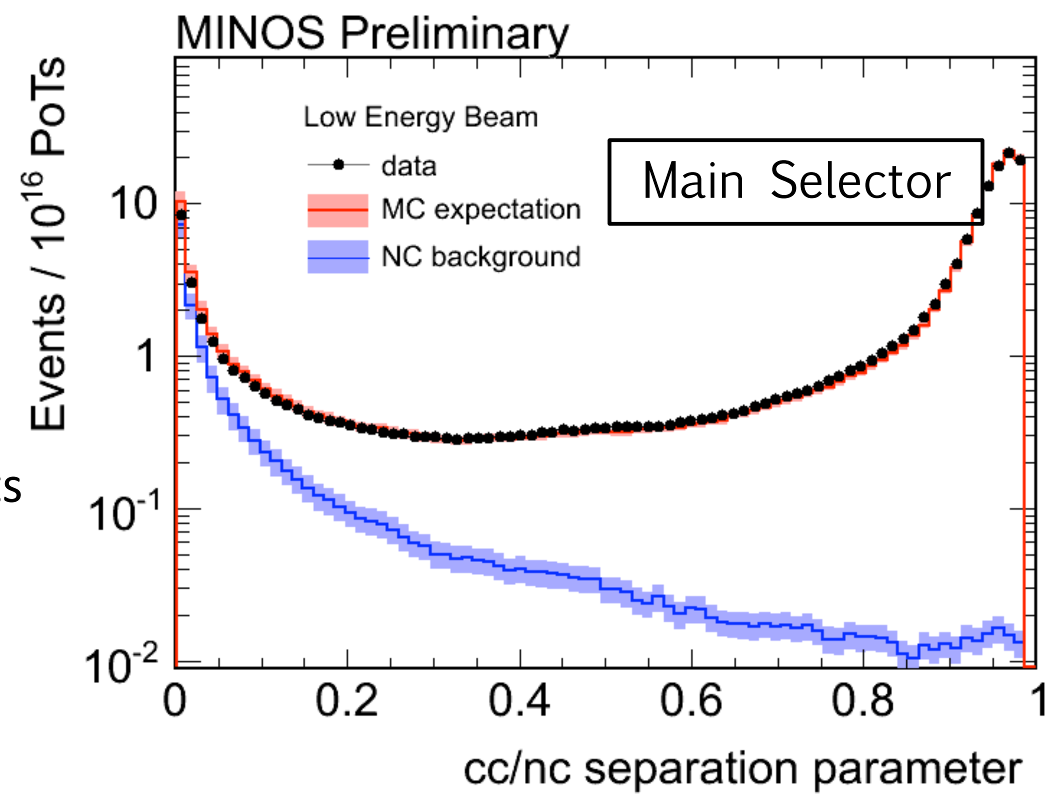
The Anti-neutrino Analysis

- 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

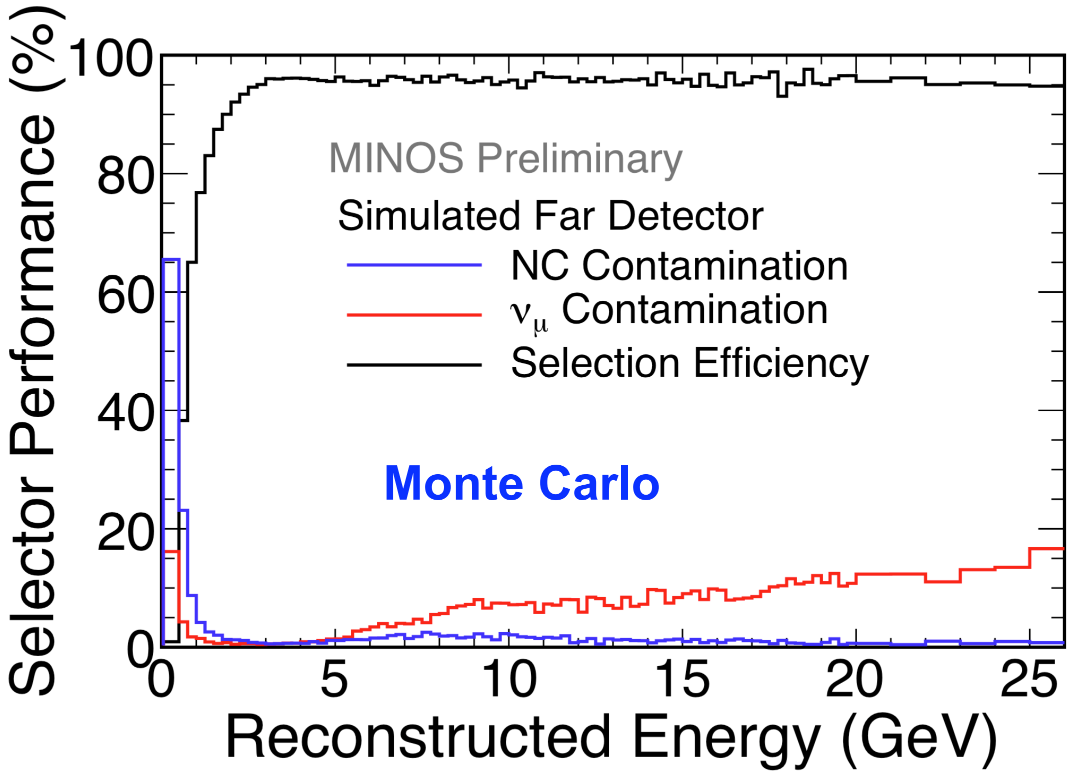


Common Selection

- 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



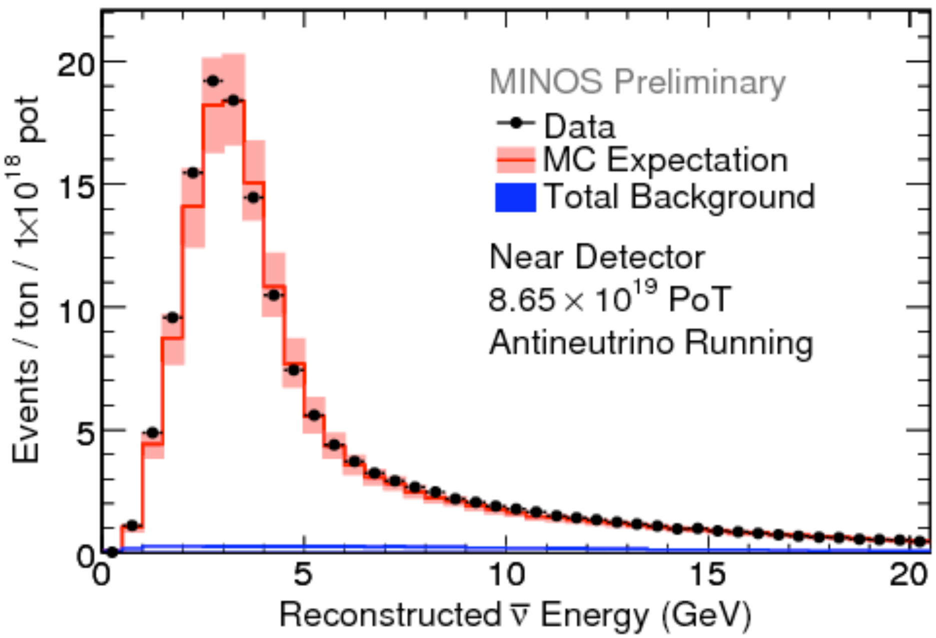
Antineutrino Efficiency & Purity

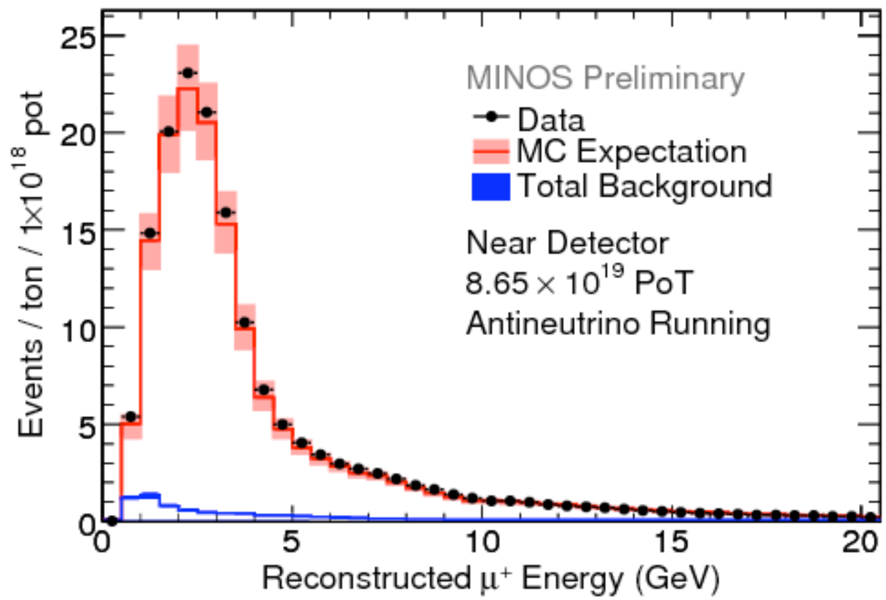


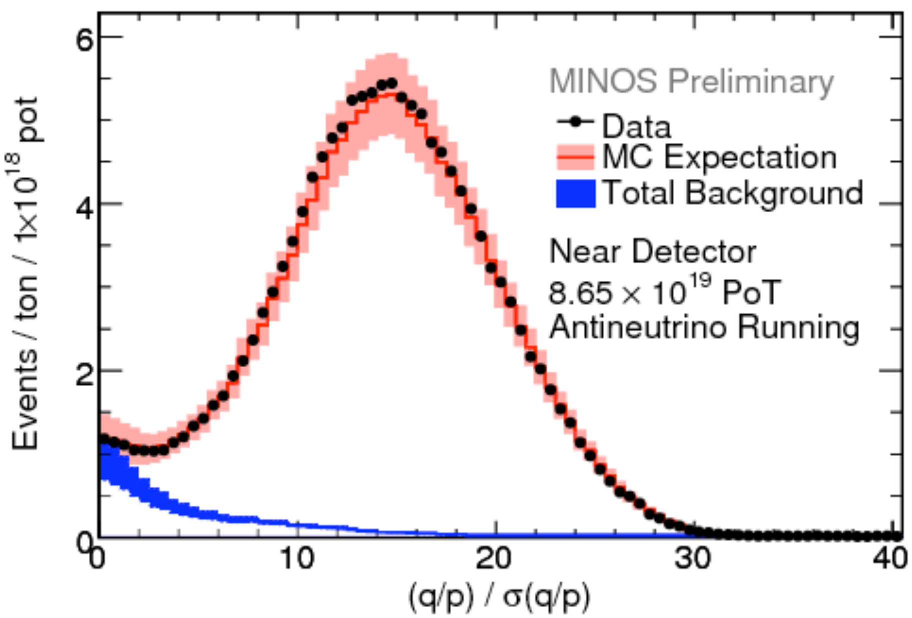
	Signal	Bkgd.
0-6 GeV	106	1.9
6-20 GeV	38	4.3
> 20 GeV	8	3.0

High energy ν_μ contamination does not affect the oscillation result

Near Detector Data





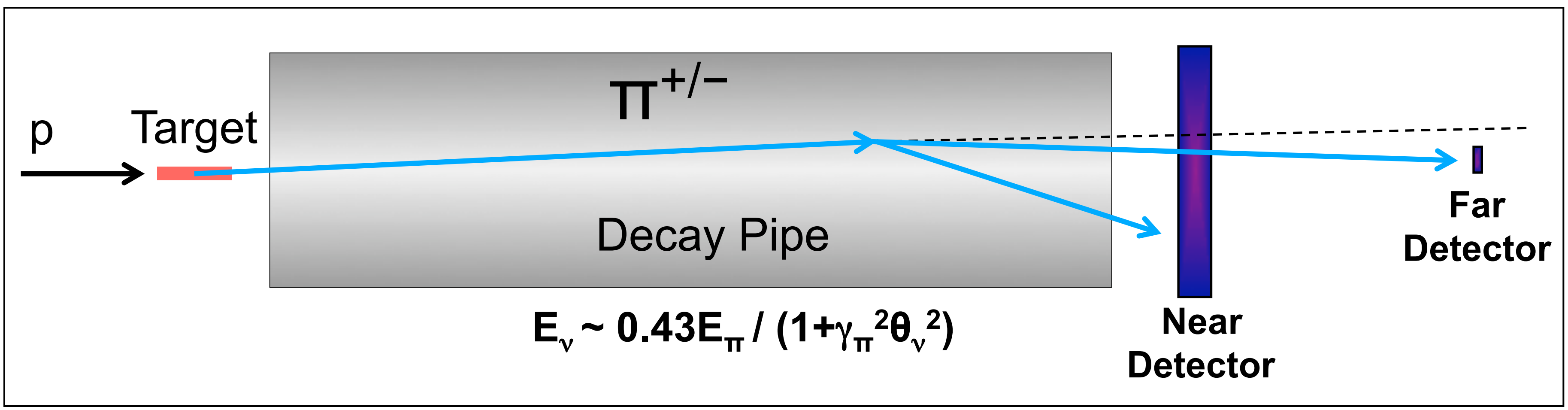


- Data/MC agreement comparable to neutrino running

P. Vahle, Neutrino 2010

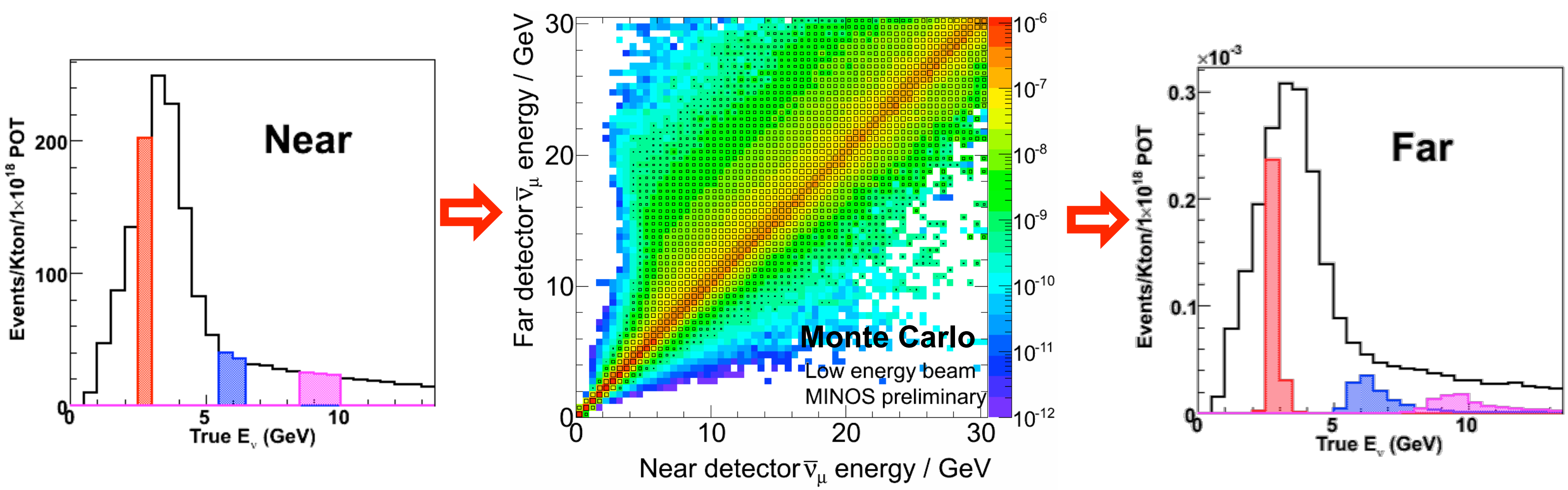
Near to Far Extrapolation

- 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

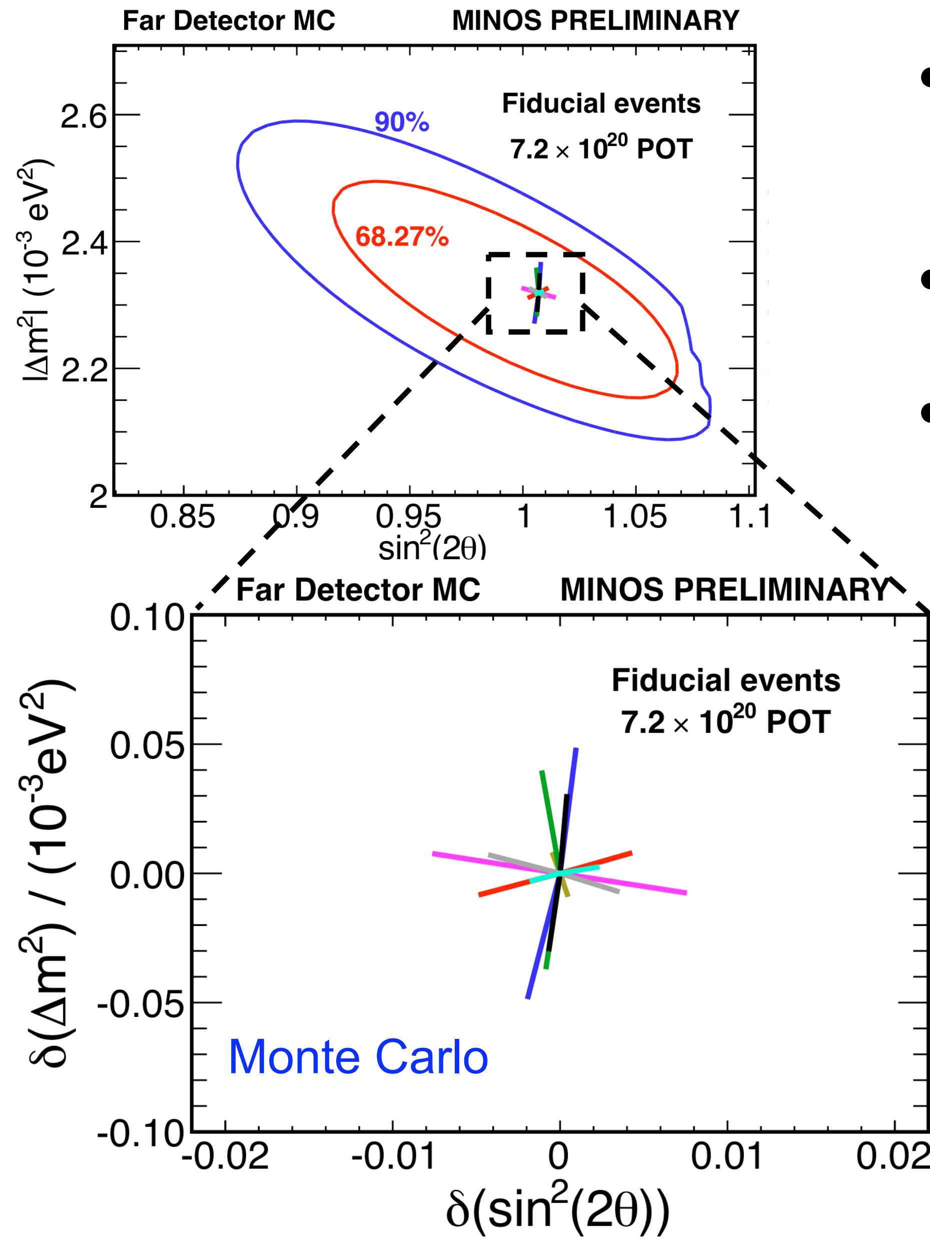


Beam Matrix Extrapolation

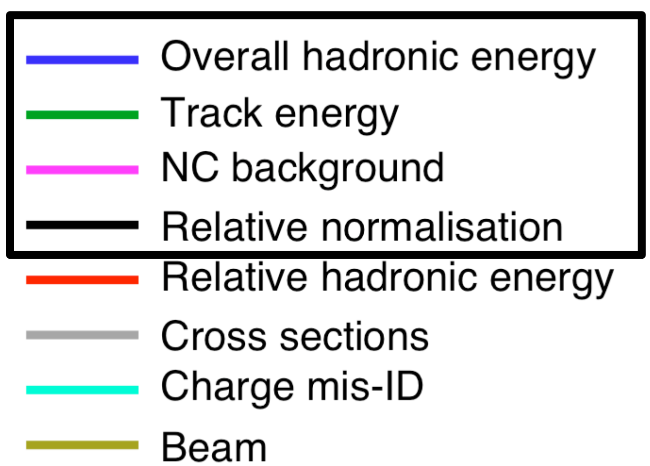
- A beam matrix transports measured Near spectrum to Far
  - ν_μ and $\bar{\nu}_\mu$ are extrapolated independently
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
  - Matrix element M_{ij} reflects the probability of obtaining a Far event with energy E_j given the observation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



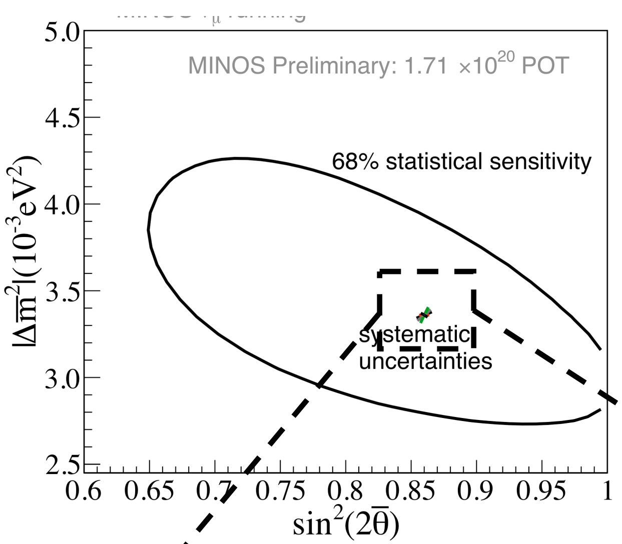
Neutrino Systematics



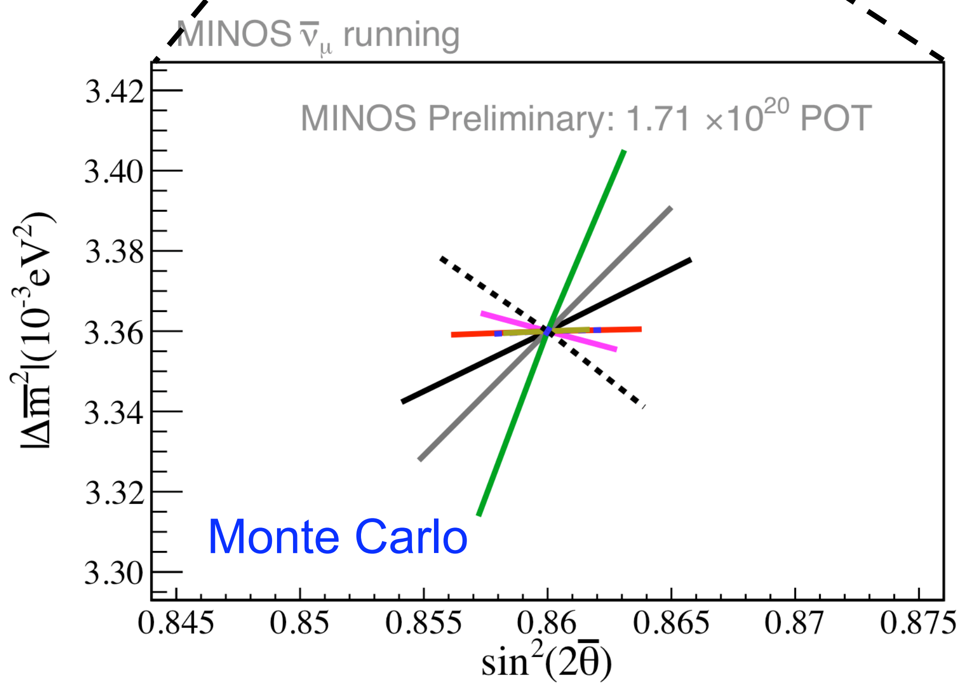
- Effect of uncertainties estimated by fitting systematically shifted MC
- Analysis is still statistically limited
- The 4 largest systematics are included as penalty terms in the fit.

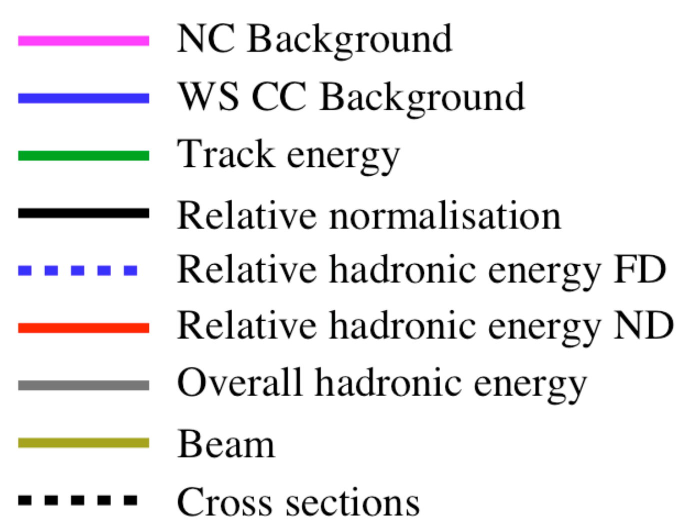


Anti-neutrino Systematics

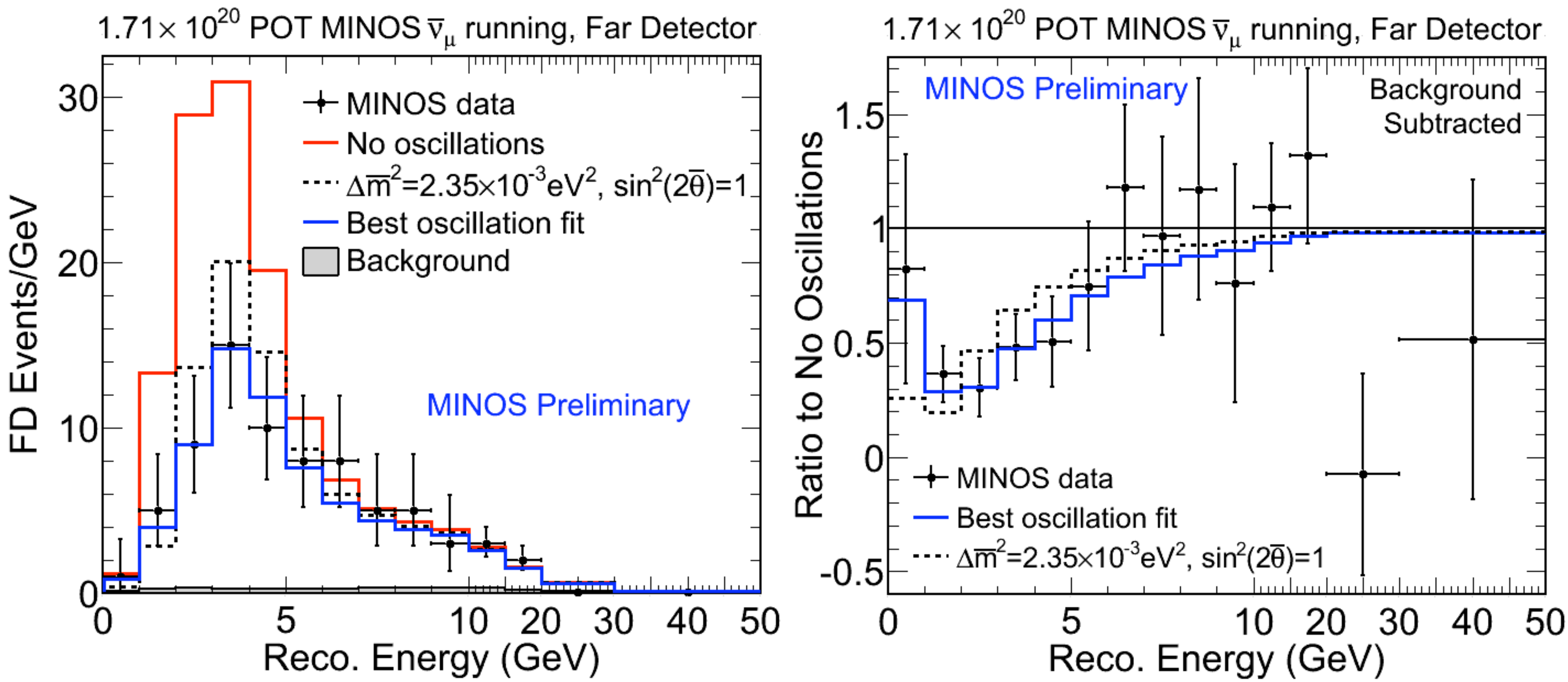


- The antineutrino analysis is even more statistically limited.
- The two analyses have very similar systematics
  - Though sizes of the effects are not the same.

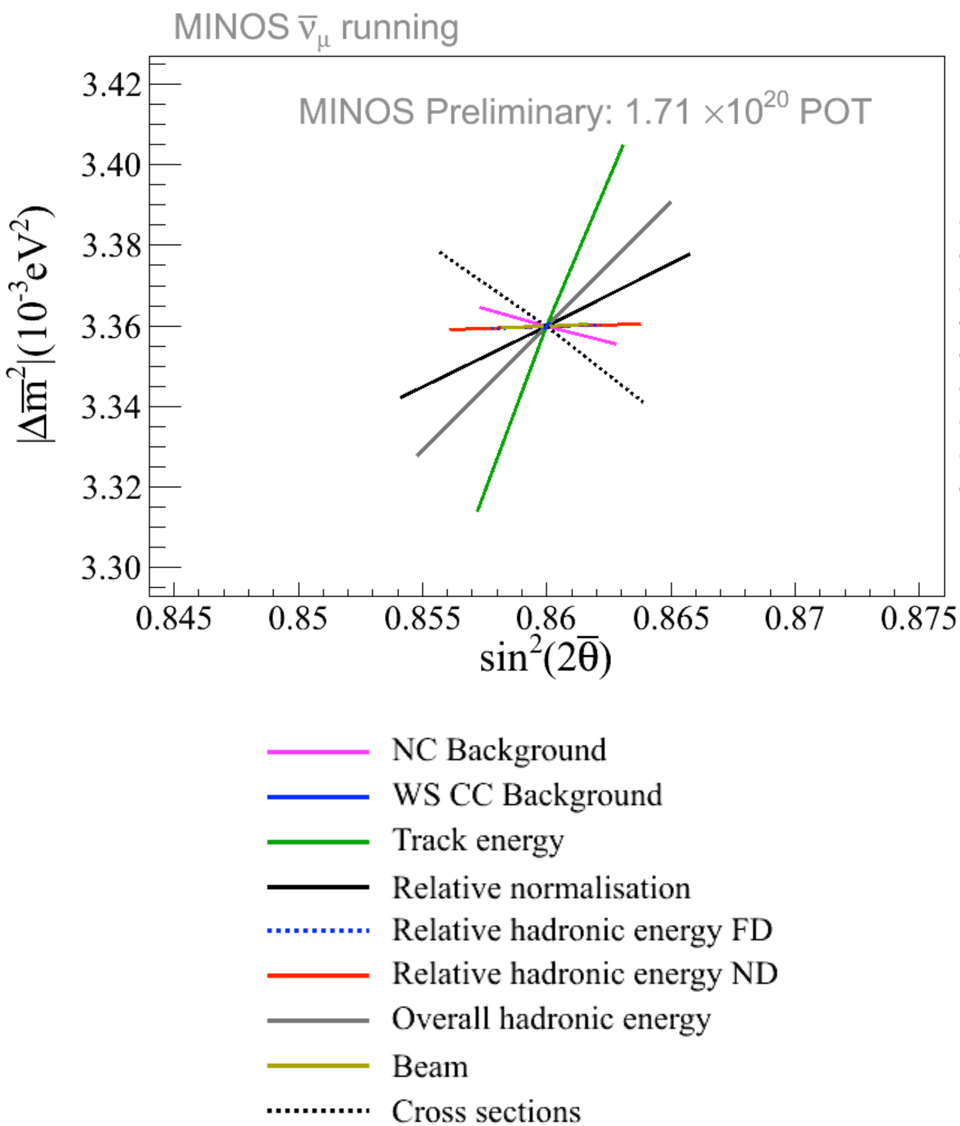


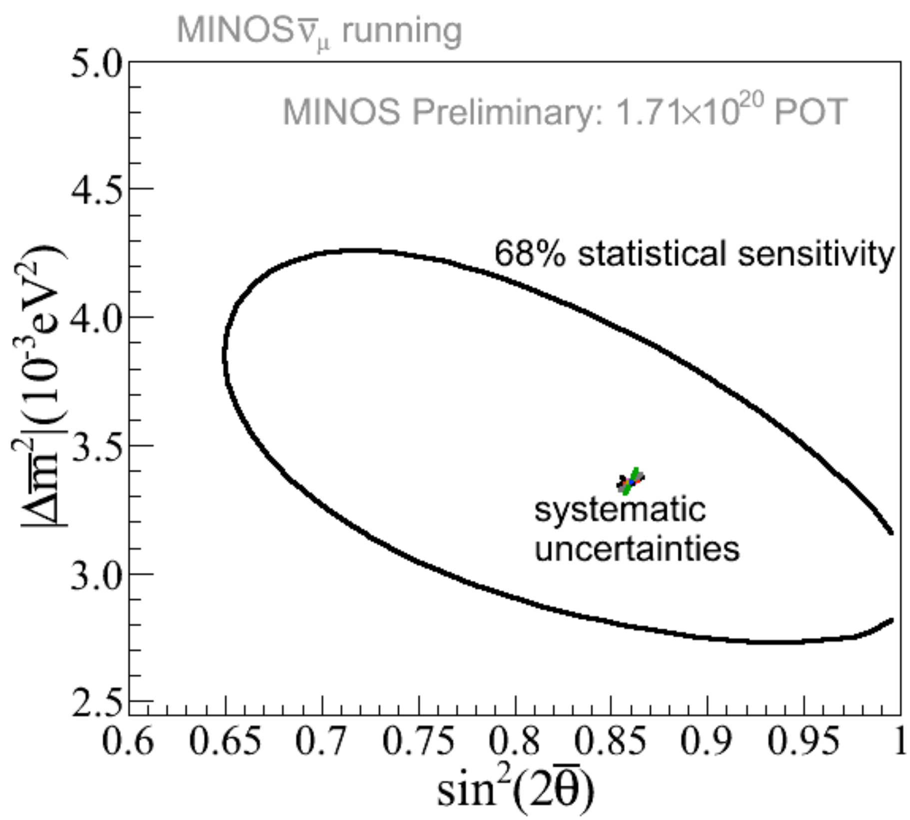


Comparisons to Neutrinos

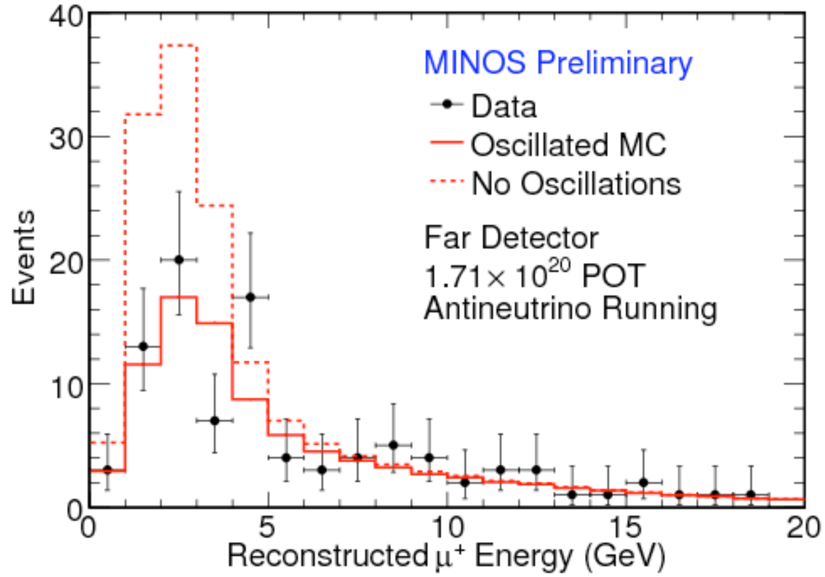


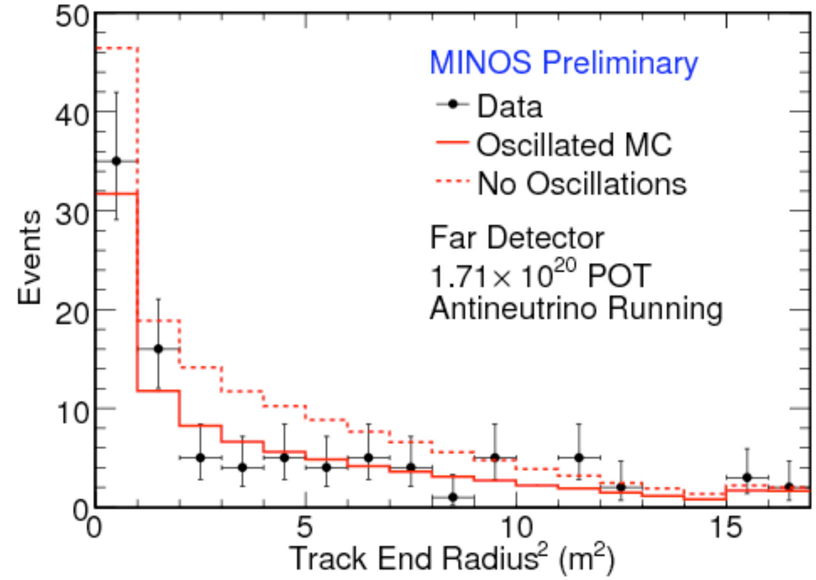
P. Vahle, Neutrino 2010

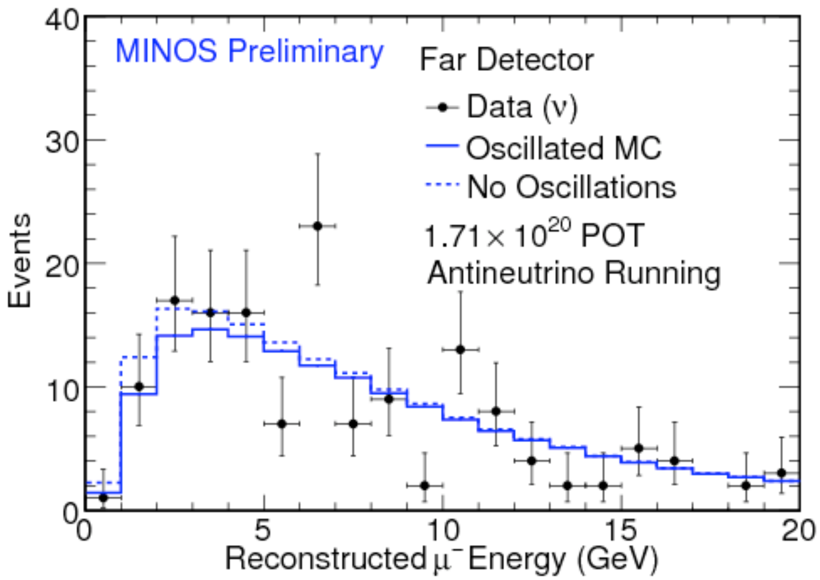

MINOS ν̄μ running
MINOS Preliminary: 1.71 ×10^20 POT
3.42
3.40
3.38
3.36
3.34
3.32
3.30
|Δm̄²|(10⁻³eV²)
0.845
0.85
0.855
0.86
0.865
0.87
0.875
sin²(2θ̄)
NC Background
WS CC Background
Track energy
Relative normalisation
Relative hadronic energy FD
Relative hadronic energy ND
Overall hadronic energy
Beam
Cross sections

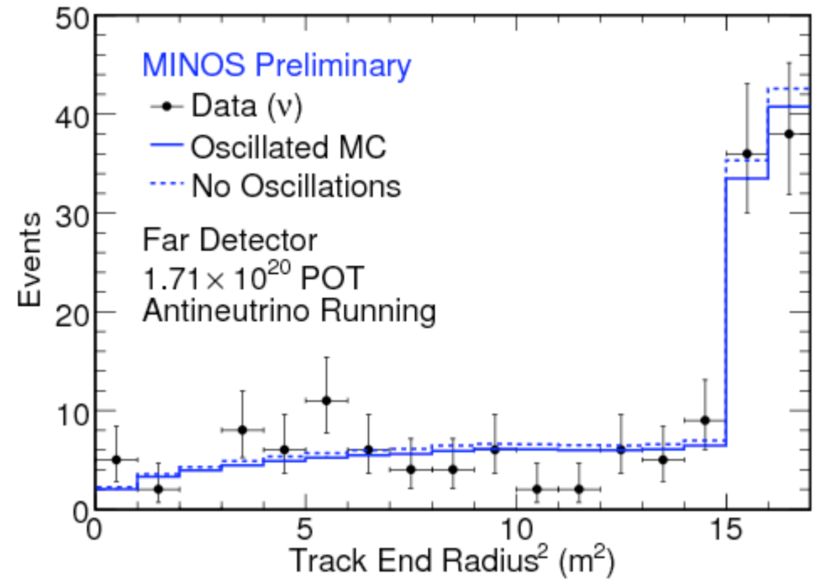

MINOS ν̄μ running
MINOS Preliminary: 1.71×10^20 POT
68% statistical sensitivity
systematic uncertainties
5.0
4.5
4.0
3.5
3.0
2.5
|Δm̄²|(10⁻³eV²)
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
sin²(2θ̄)

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

Slip stacking details