RECENT RESULTS FROM THE MINOS EXPERIMENT

JENNY THOMAS

UCL

PREVIEW

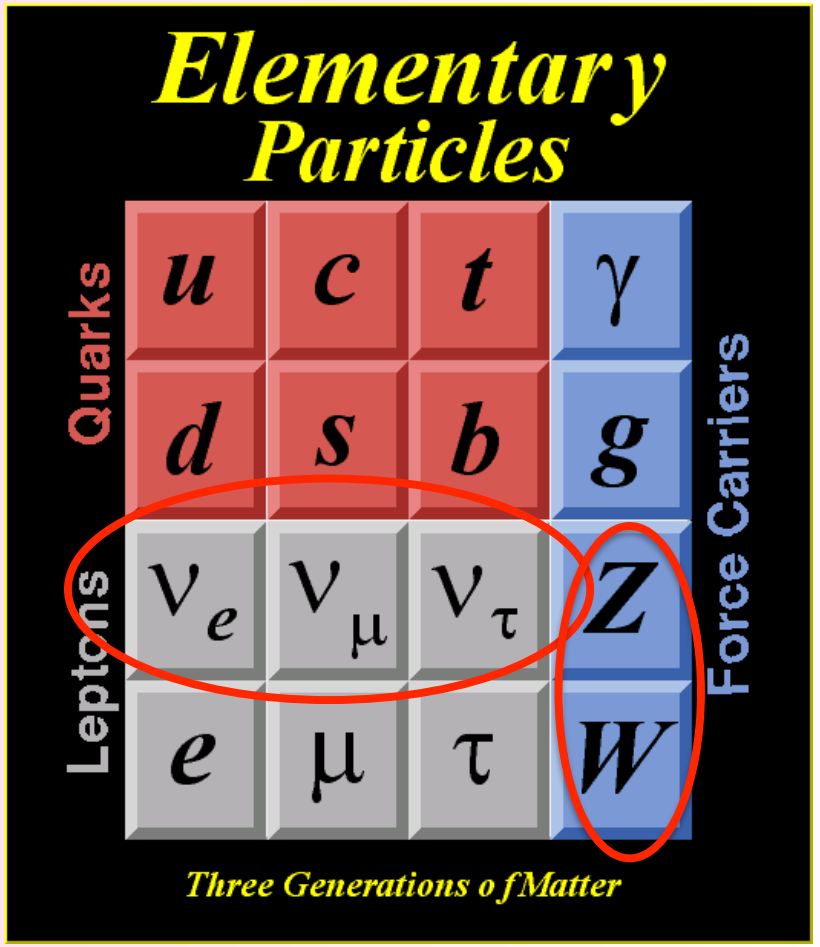
- Whirlwind tour of where we are
  - Introduction to Neutrinos, Oscillations and what the experiments tell us
- Properties of neutrino oscillations
  - Results from MINOS are world's best
- Future plans for MINOS
  - Analysis of new anti-neutrino running
  - MINOS+?
- Summary
  - Lots still to do, picture still missing pieces

INTRODUCTION

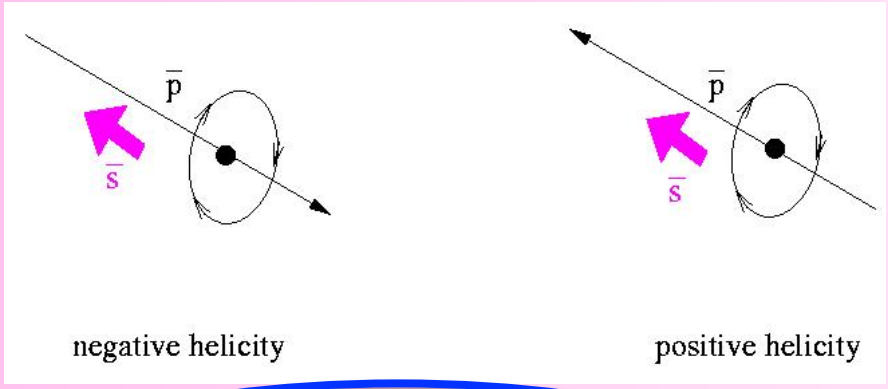
What you all know about neutrinos already

THE STANDARD MODEL

- Quarks, Leptons and Gauge Bosons make up the elementary particles
- Three generations of leptons with $\Delta Q=1$
- Three generations of quarks with $\Delta Q=1$
- Three interactions, weak, EM and strong
- Neutrinos are the only neutral fermion

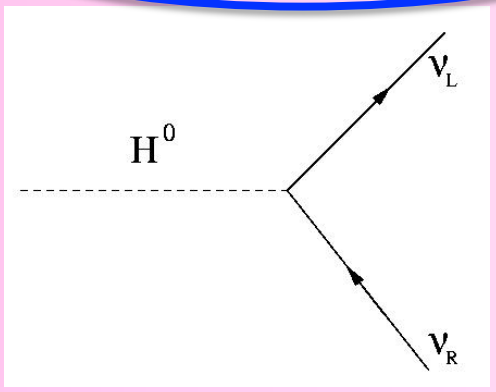


NEUTRINO PROPERTIES



Fermion	Strong	EM	Weak
L.H. Quarks	X	X	X
R.H. Quarks	X	X	
L.H. Charged leptons		X	X
R.H. Charged leptons		X	
L.H. Neutrinos			X
R.H. Neutrinos			

Weak interaction violates parity



- Neutrinos were thought to be exactly massless : SM reproduced the parity violation by **making** them so. Not any more!
- Spin = ½, but left handed only. Not any more!
- It is the mass term which would allow a RH neutrino to exist (coupling to the Higgs in today's parlance)

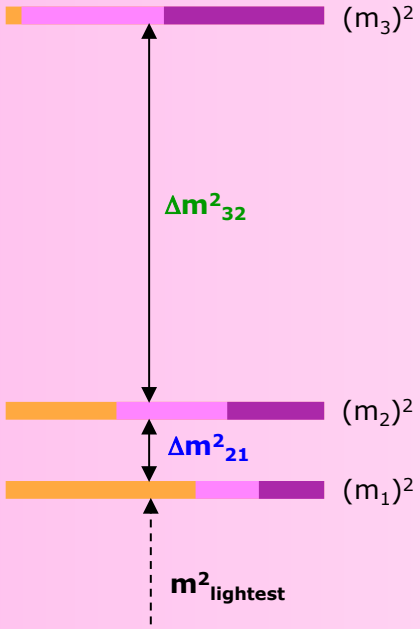
NEUTRINO SECTOR STATUS

Solar&Reactor Atmospheric Reactor/LBL Double Beta

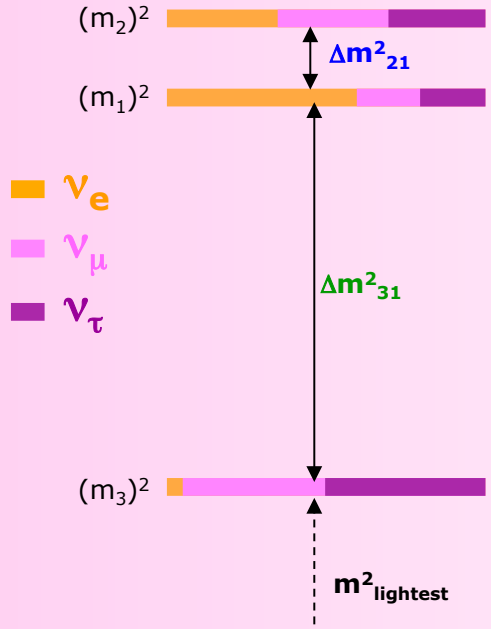
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha/2} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\beta/2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Normal hierarchy



Inverted hierarchy



3 light neutrino flavours: e, μ, τ

Δm^2_{21} : (7.0 - 9.1) × 10^{-5} eV²
TAN²θ_{12} : 0.34 – 0.62

Δm^2_{32} : ($2.23^{+0.11}_{-0.08}$) × 10^{-3} eV²
sin²θ_{23} : >0.91 (@90% C.L.)

SIN²θ_{13} ≤ 0.045
δ: unknown

Hierarchy : unknown

$m_{lightest}$ < 2.2 eV
Dirac or Majorana: unknown

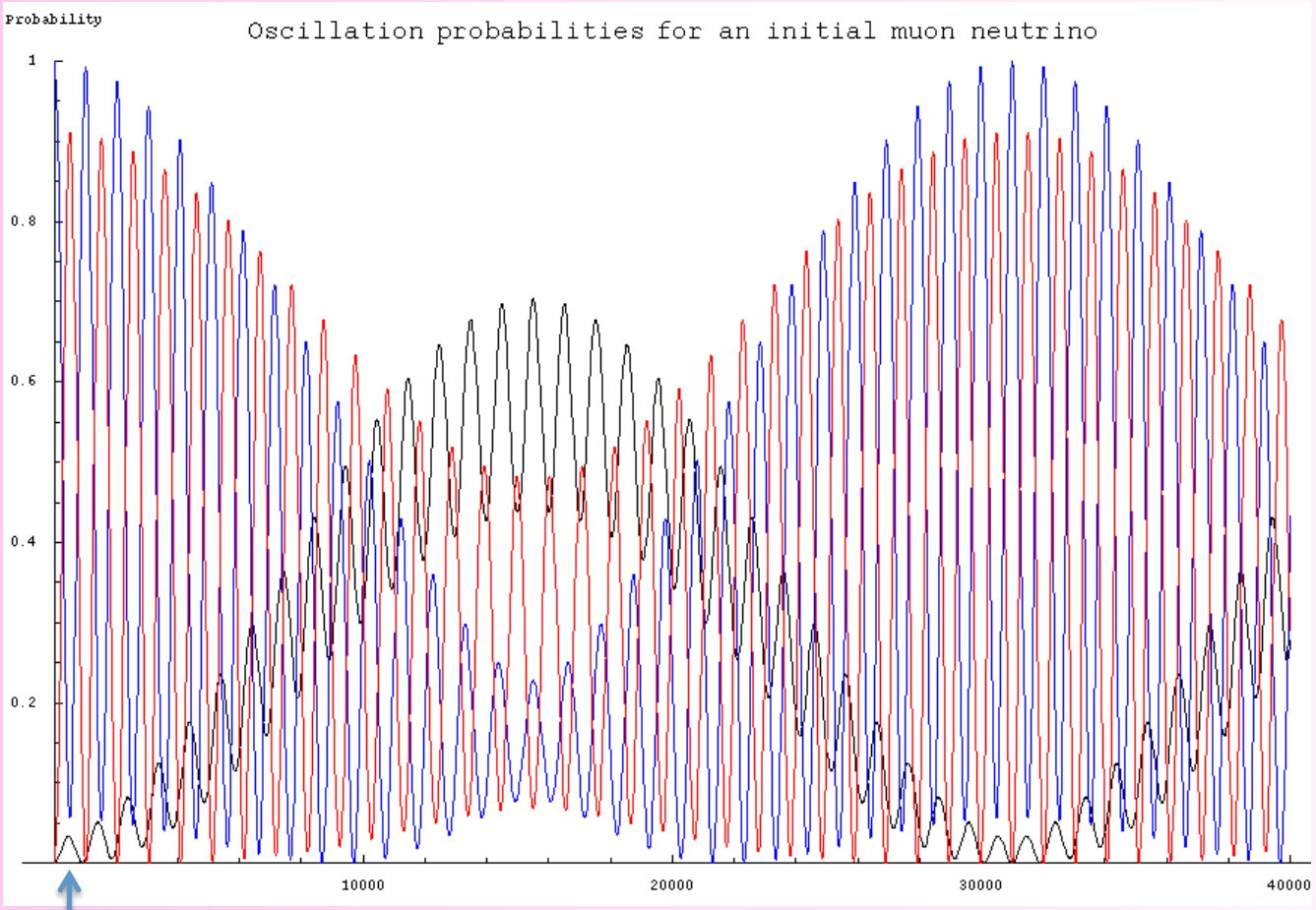
SIMPLE 2-FLAVOUR EXPRESSION

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

(Average L/E is about 500 km/GeV for MINOS)

IN A SNAPSHOT:
WHAT ITS LIKE TO BE A MUON NEUTRINO

ν_e ν_μ ν_τ



L/E (km/GeV)

MINOS

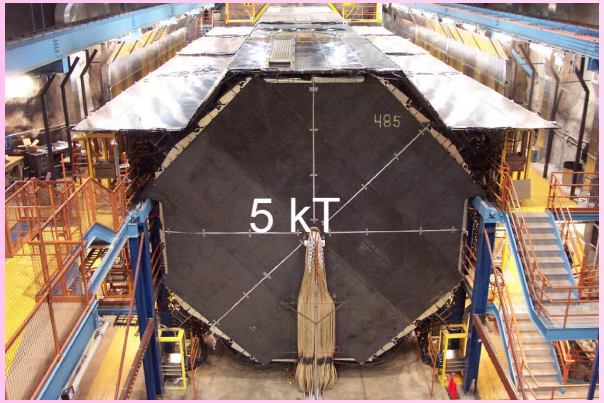
THE MINOS EXPERIMENT

- Given the confusing nature of the neutrino
  - choose a place where you have a big probability of seeing a ν_μ become one of its chums
  - L/E ~ 500 GeV is maximum probability of ν_μ disappearance without too much interference from ν_e (!!!)
  - use a very very massive detector because the neutrino cross section is very very small
- then you can...
  - measure atmospheric oscillation parameters with precision (neutrinos and anti-neutrinos)
  - search for sub-dominant oscillation of $\nu_\mu \rightarrow \nu_e$
  - Search for sterile neutrino flavours
  - And still look at atmospheric neutrinos…..

THE MINOS DETECTOR

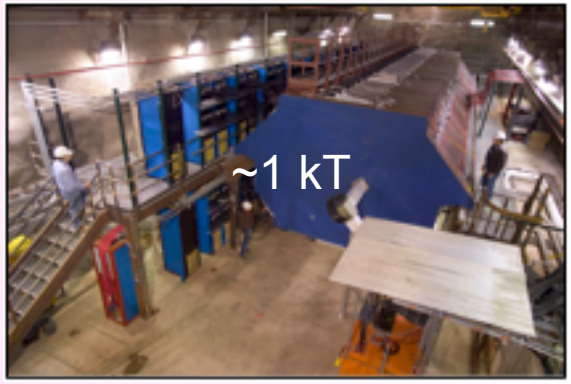
How 5kT of steel can measure the lightest particles

THE MINOS EXPERIMENT



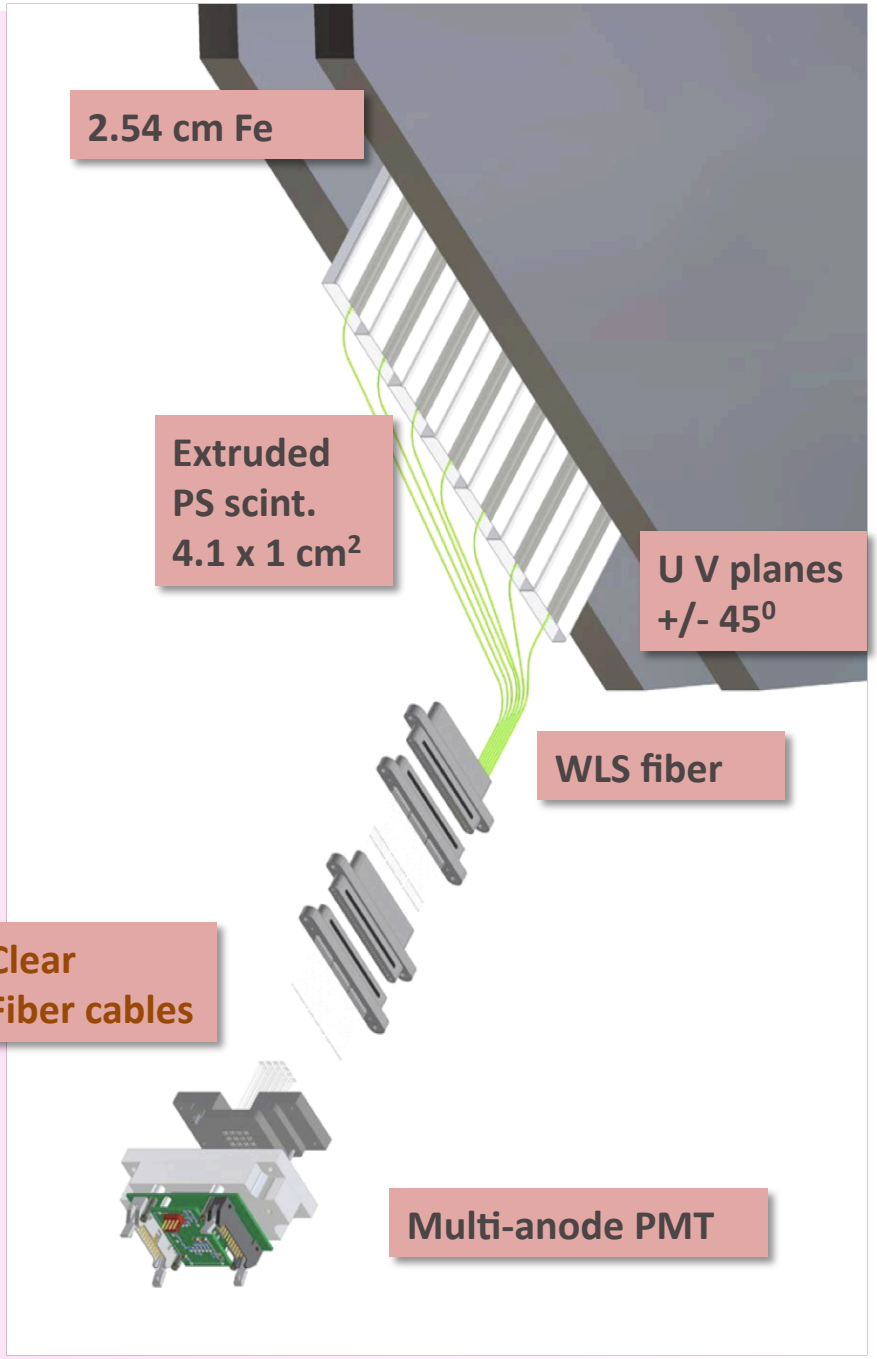
- Long baseline neutrino oscillation experiment
  - Neutrinos from NuMI
  - L=732km, E~1-5GeV
  - L/E ~500 km/GeV
  - Atmospheric neutrino L/E

- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties
- Magnetic field measures charge



DETECTOR TECHNOLOGY

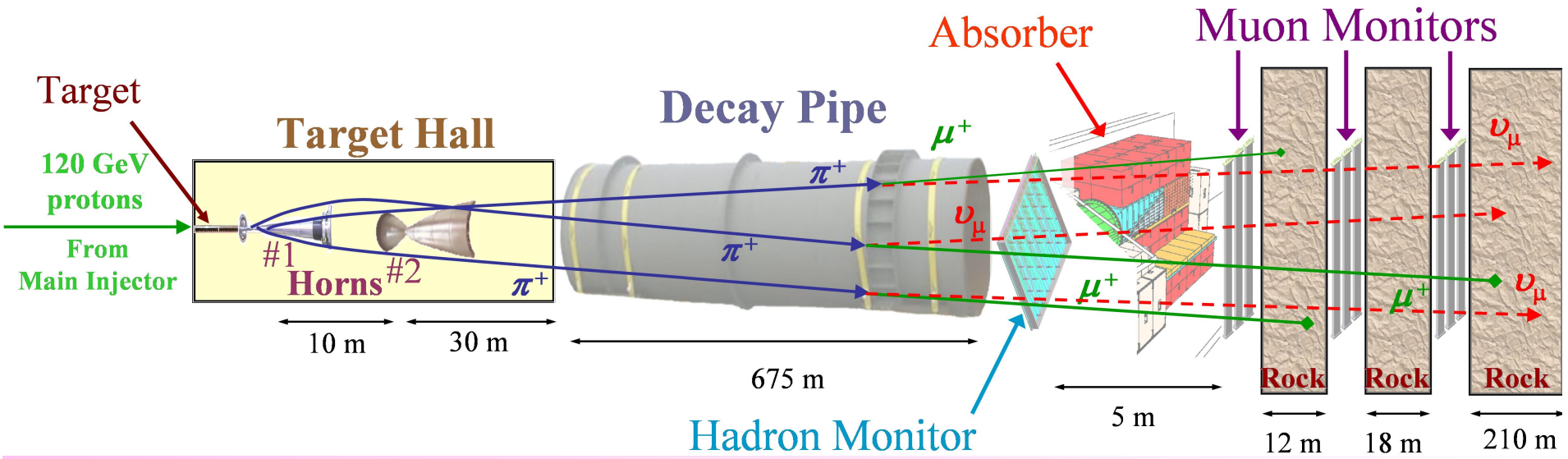
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



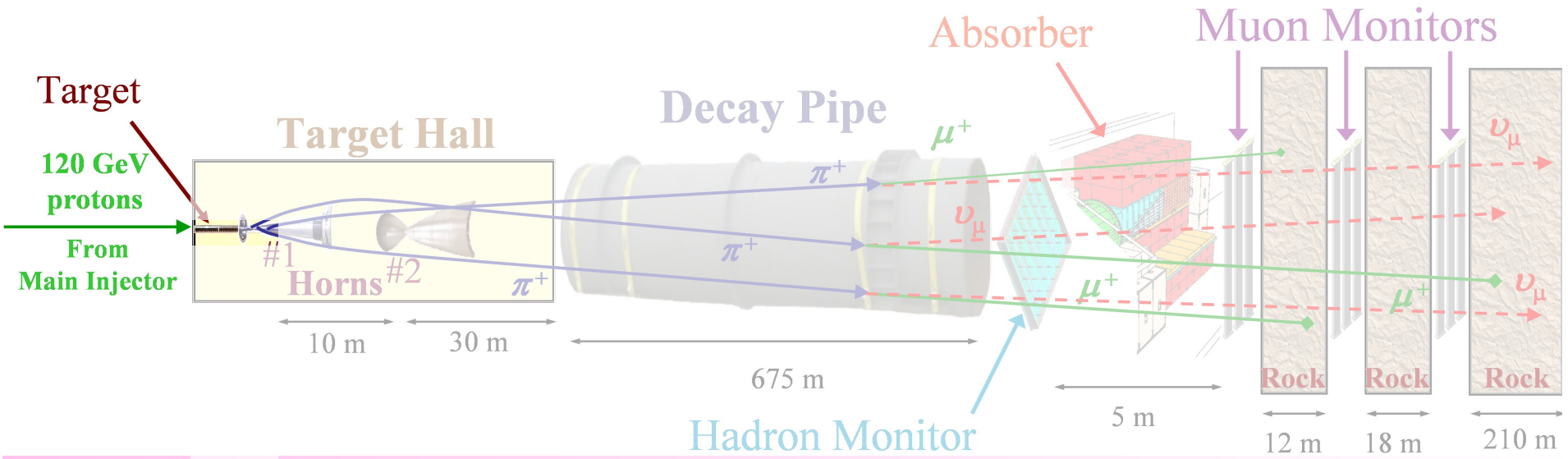
THE NEUTRINO BEAM

And how you make it

MAKING A NEUTRINO BEAM

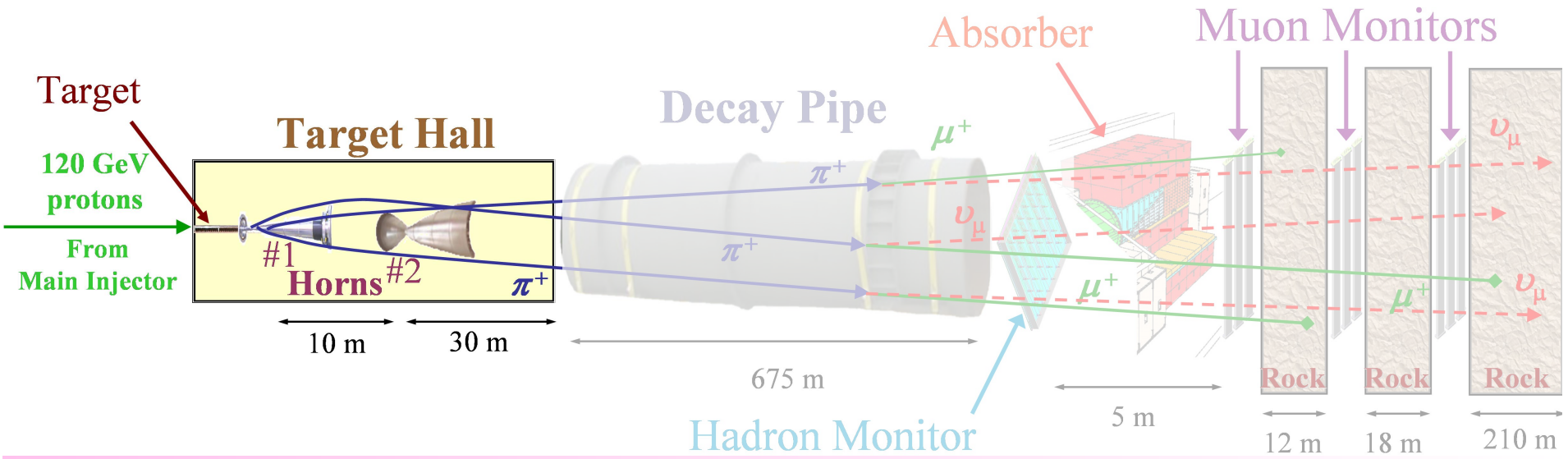


MAKING A NEUTRINO BEAM



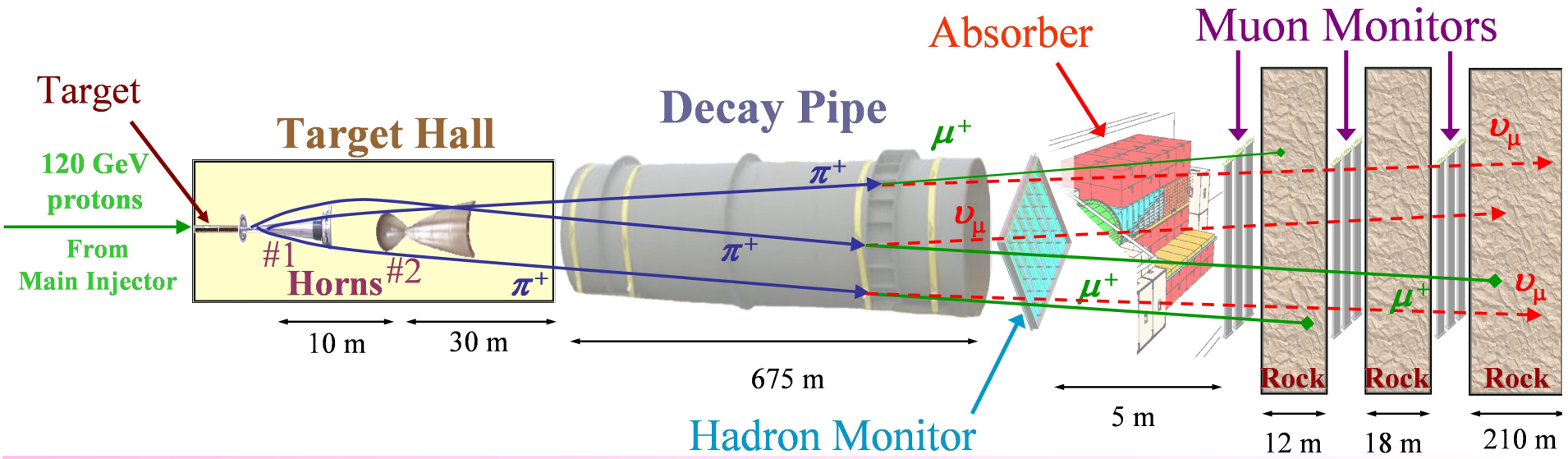
- **Hadron Production**
  - bombard graphite target with 120 GeV p^+ from Main Injector
    - 2 interaction lengths
    - 310 kW typical power
  - produce hadrons, mostly π and K

MAKING A NEUTRINO BEAM



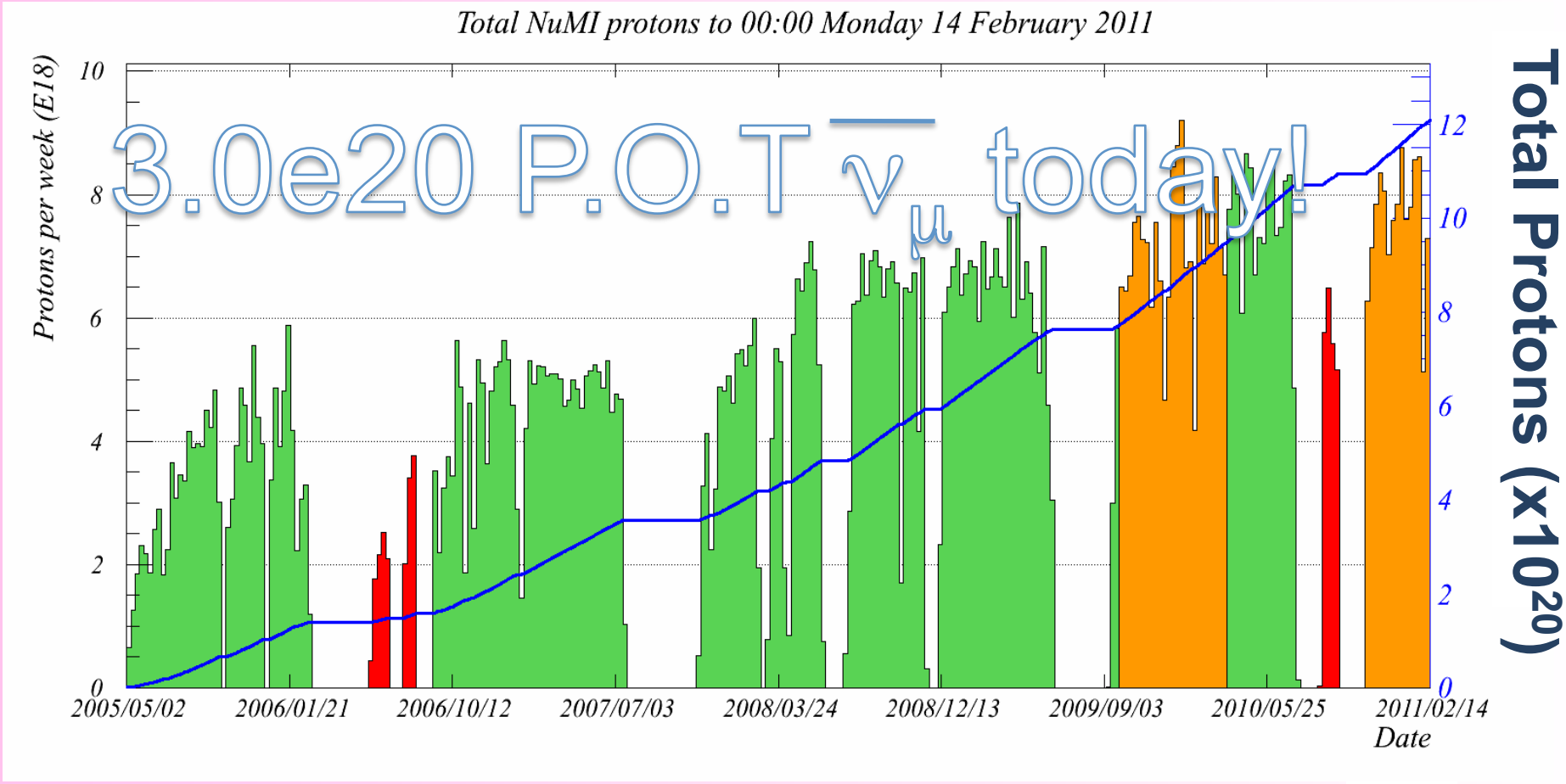
- **Focusing**
  - hadrons focused by 2 magnetic focusing horns
  - sign selected hadrons
    - forward current, (+) for standard neutrino beam runs
    - reverse current, (–) for anti-neutrino beam

MAKING A NEUTRINO BEAM



- **Decay**
  - 2 m diameter decay pipe, 660m length
  - result: wide band beam, peak determined by target/horn separation
  - secondary beam monitored

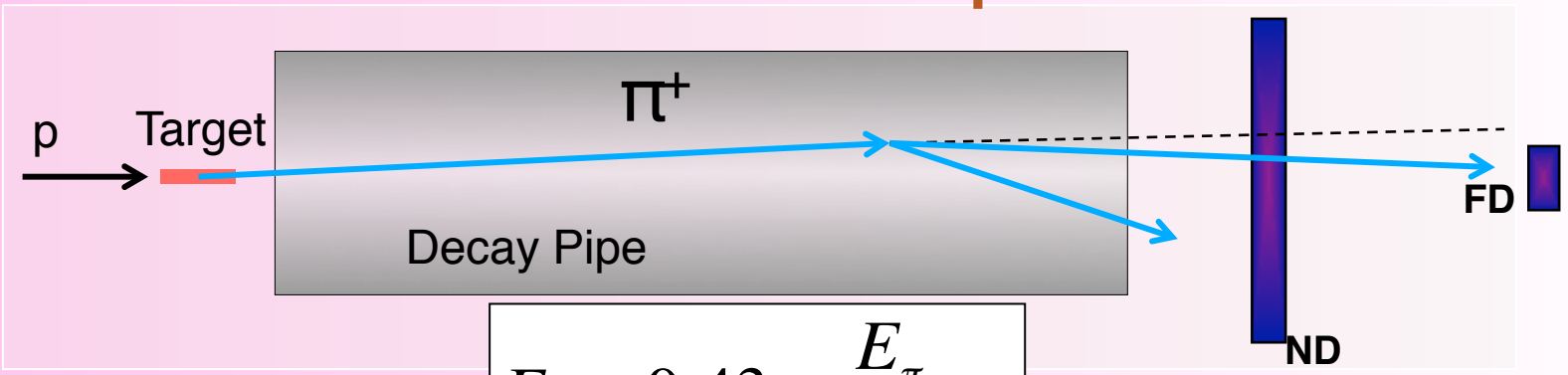
BEAM PERFORMANCE



Date

NEAR TO FAR

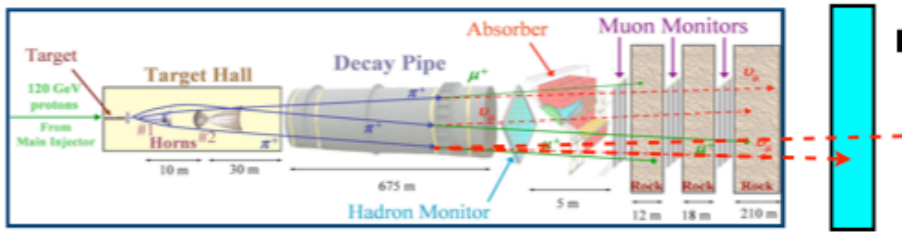
Far spectrum without oscillations is similar, but not identical to the Near spectrum!



$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

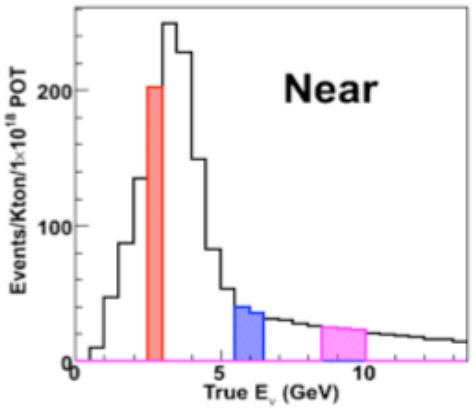
- Neutrino energy depends on angle wrt original pion direction and parent energy
  - higher energy pions decay further along decay pipe
  - angular distributions different between Near and Far

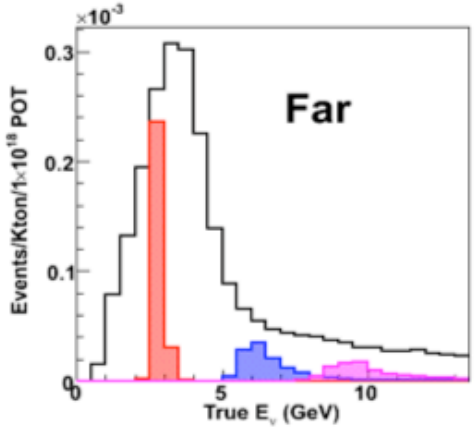
EXTRAPOLATION

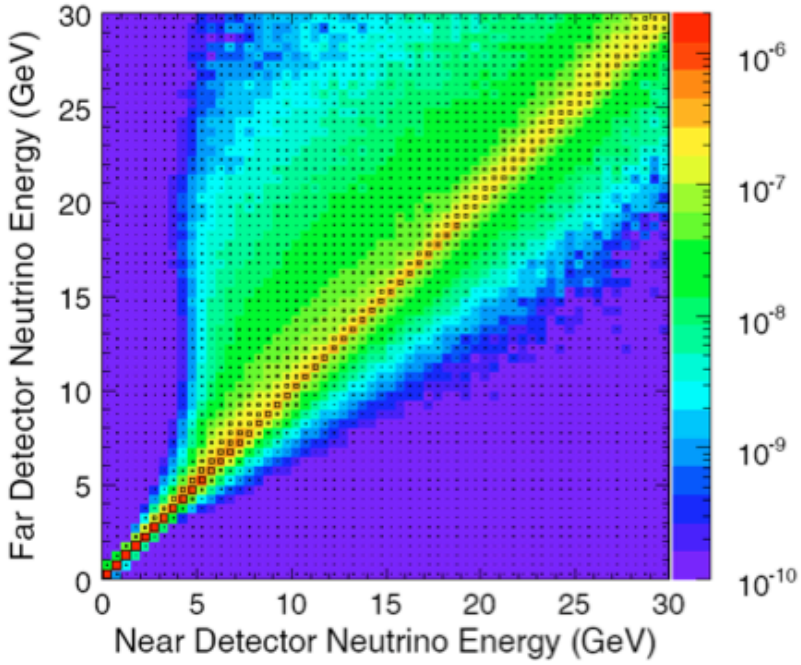


Line Source at ND

Point Source at FD







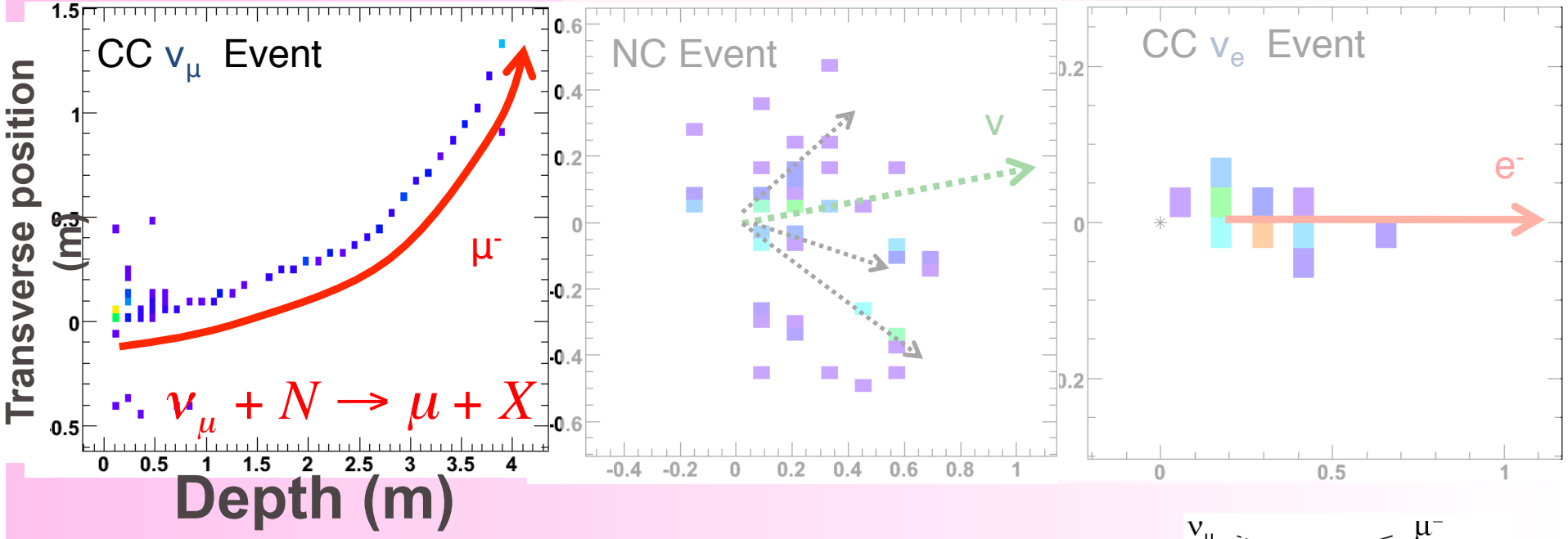
Near Detector energy spectrum extrapolated to Far Detector, using MC to provide energy smearing and correct for detector acceptance

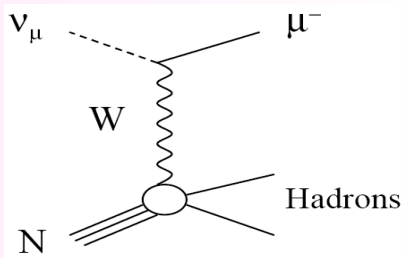
NEUTRINO EVENTS IN MINOS

How easy they are to find and how hard some of them can be to identify

NEUTRINO EVENTS IN MINOS

Simulated Events

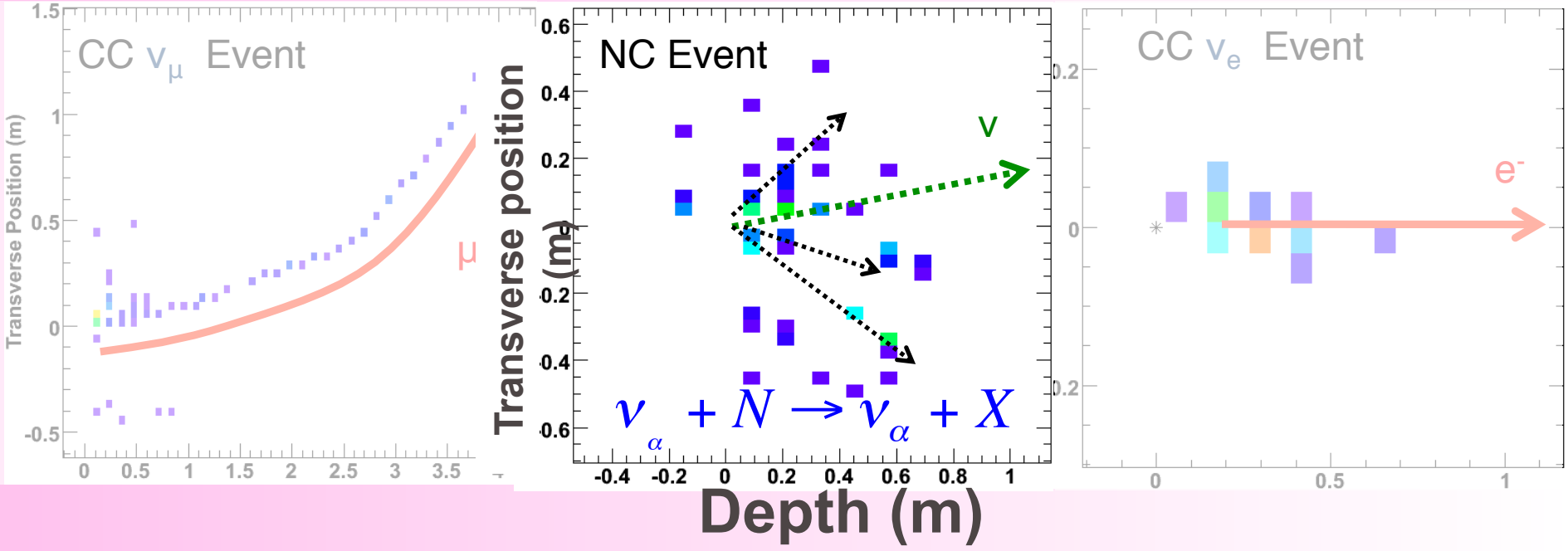




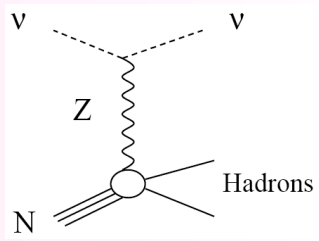
- ν_μ Charged Current events:
  - long μ track, with hadronic activity at vertex
  - neutrino energy from sum of muon energy (range or curvature) and shower energy

EVENTS IN MINOS

Simulated Events

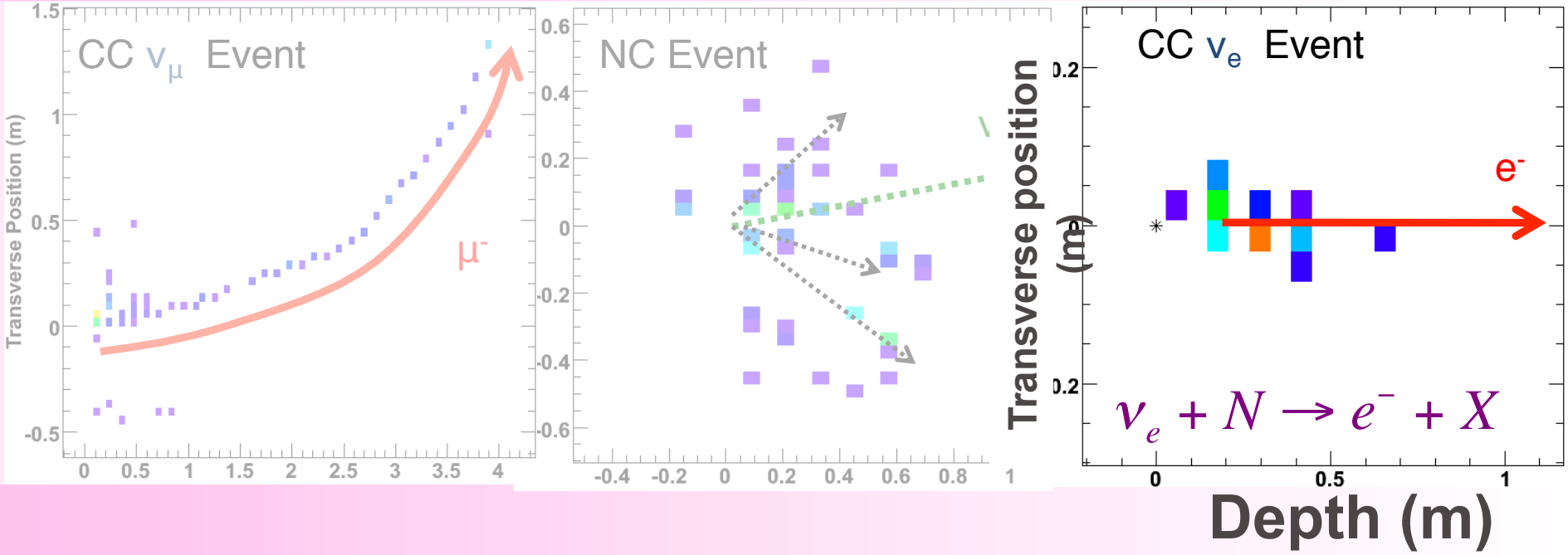


- Neutral Current events:
  - short, diffuse shower event
  - shower energy from calorimetric response

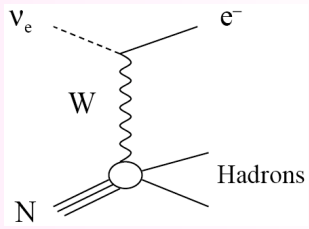


EVENTS IN MINOS

Simulated Events



- ν_e Charged Current events:
  - compact shower event with an EM core
  - neutrino energy from calorimetric response



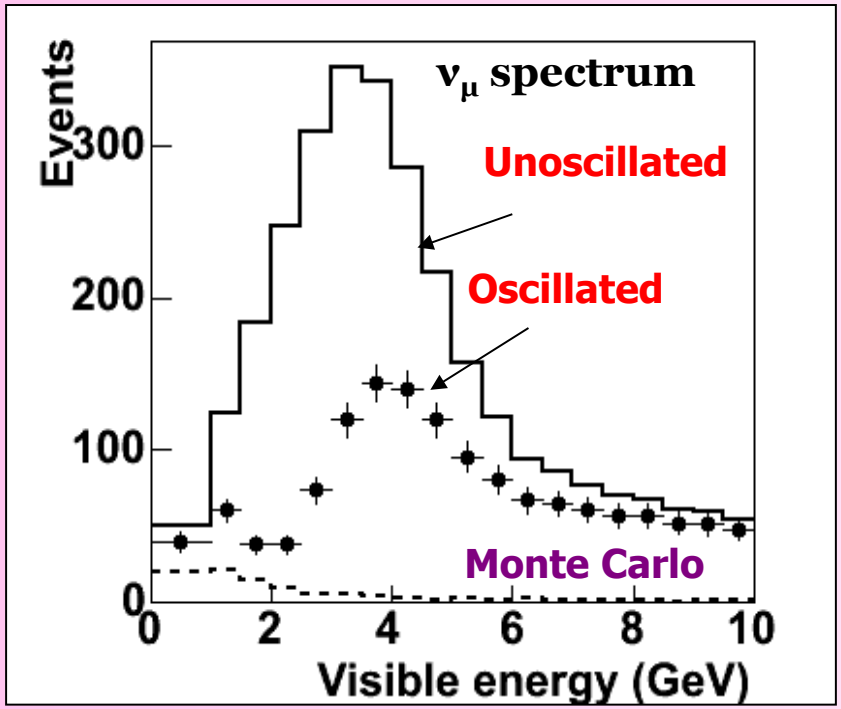
NEUTRINO OSCILLATION MEASUREMENT

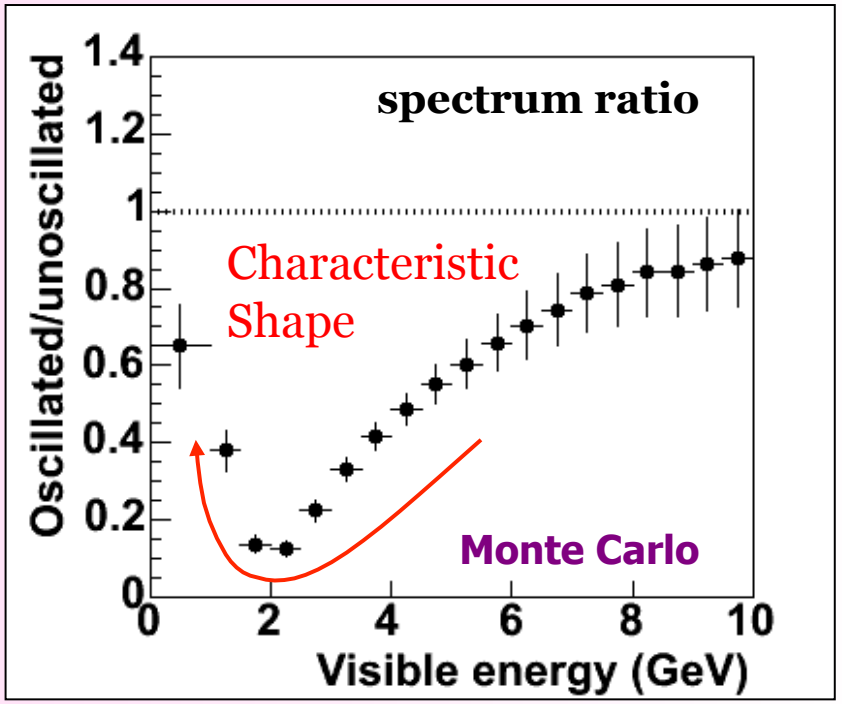
A simple idea

ν_μ DISAPPEARANCE

- Look for ν_μ disappearance as a function of neutrino energy
- Use ND to predict unoscillated spectrum at Far Detector
- Compare with measured spectrum to extract oscillation parameters

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





(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2 **)**

ν_μ DISAPPEARANCE

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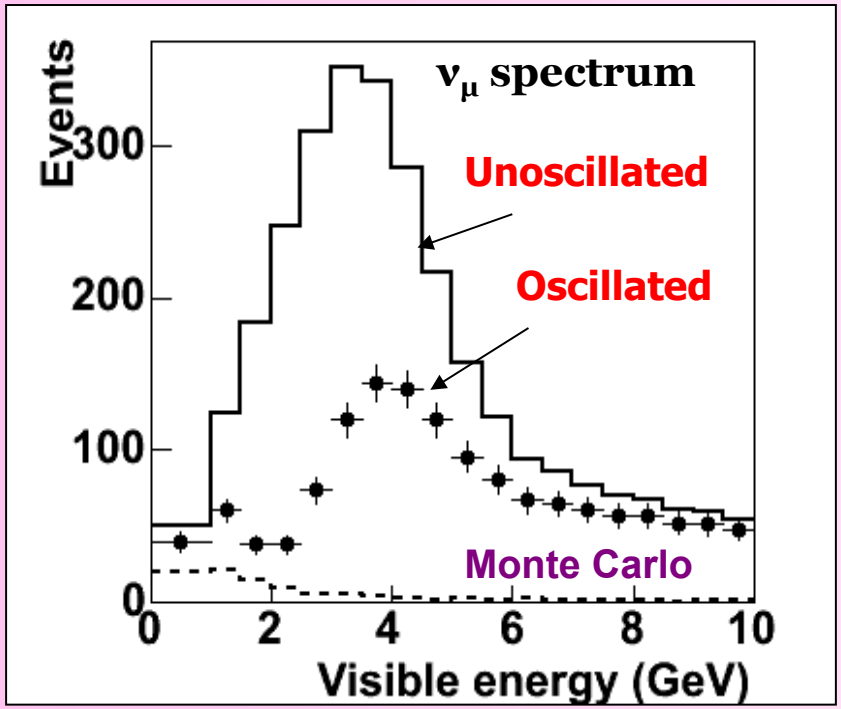
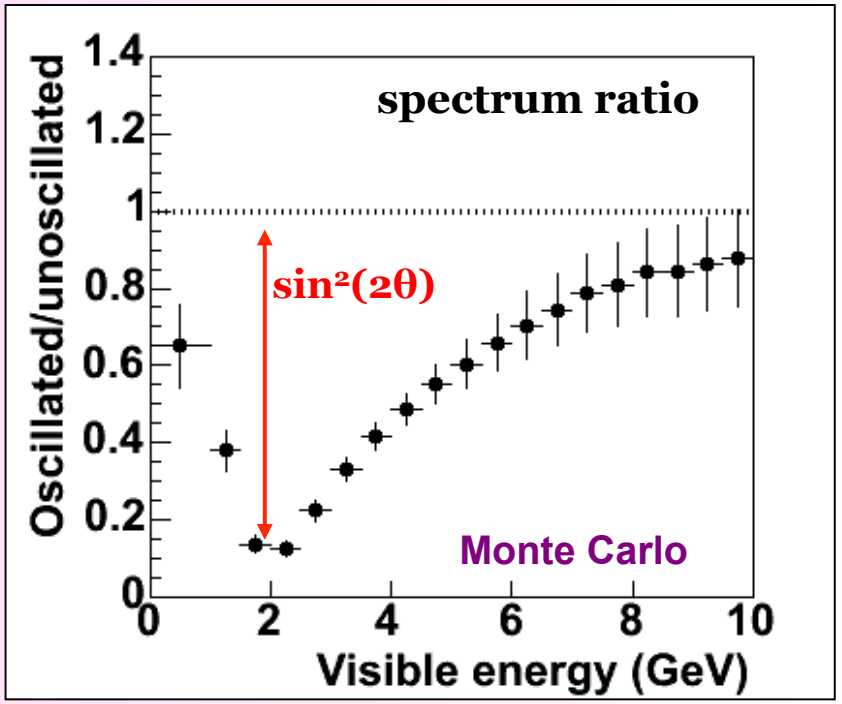


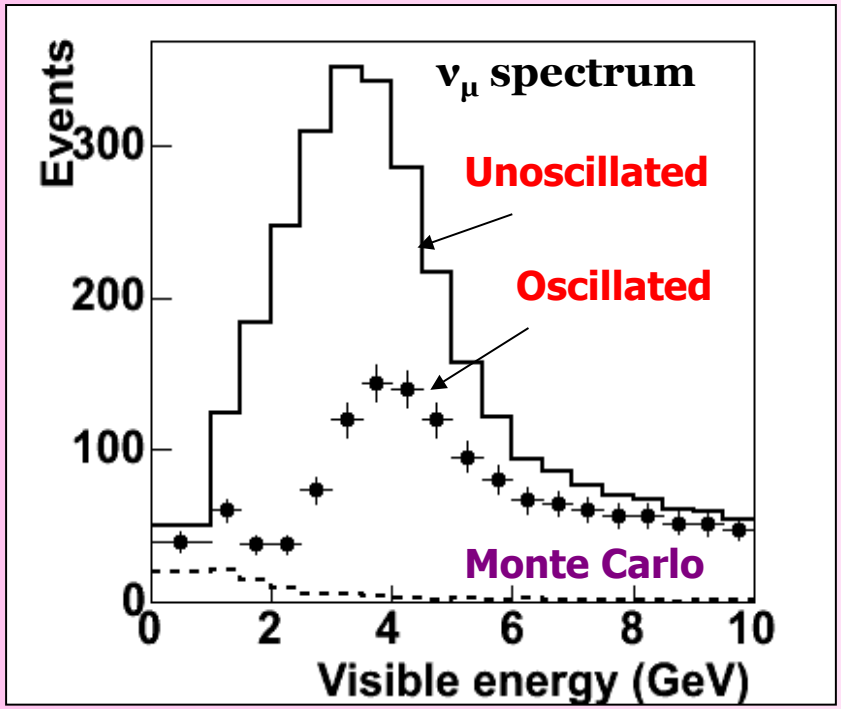


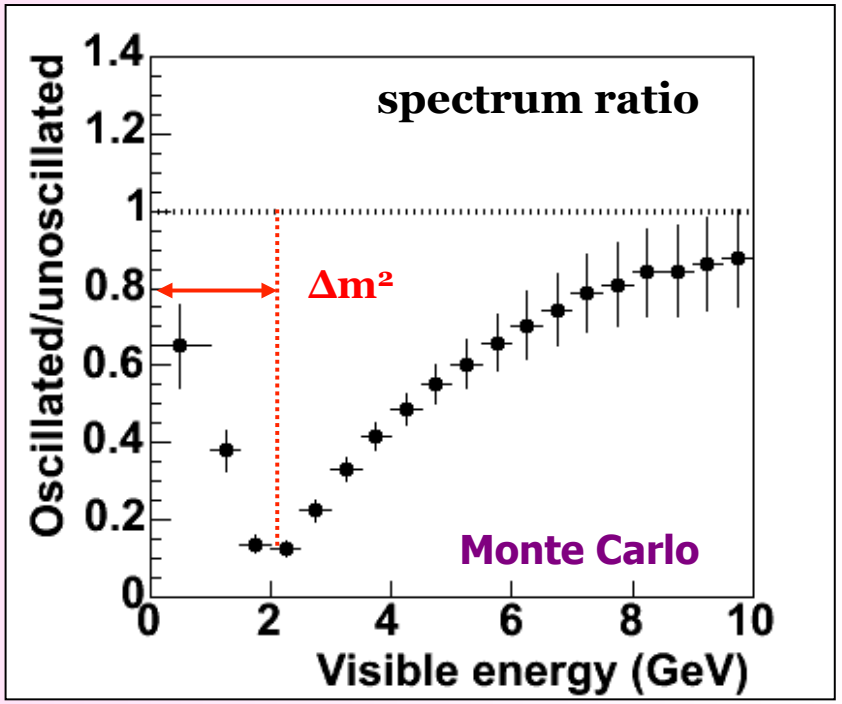
(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2 **)**

ν_μ DISAPPEARANCE

- Long baseline ν_μ disappearance experiment
- Predict unoscillated CC spectrum at Far Detector
- Compare with measured spectrum to extract oscillation parameters

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





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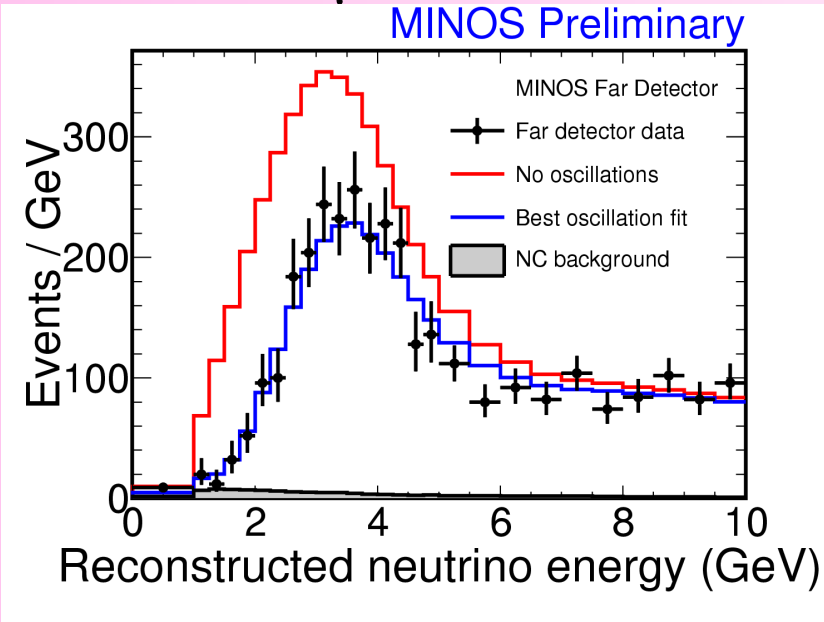
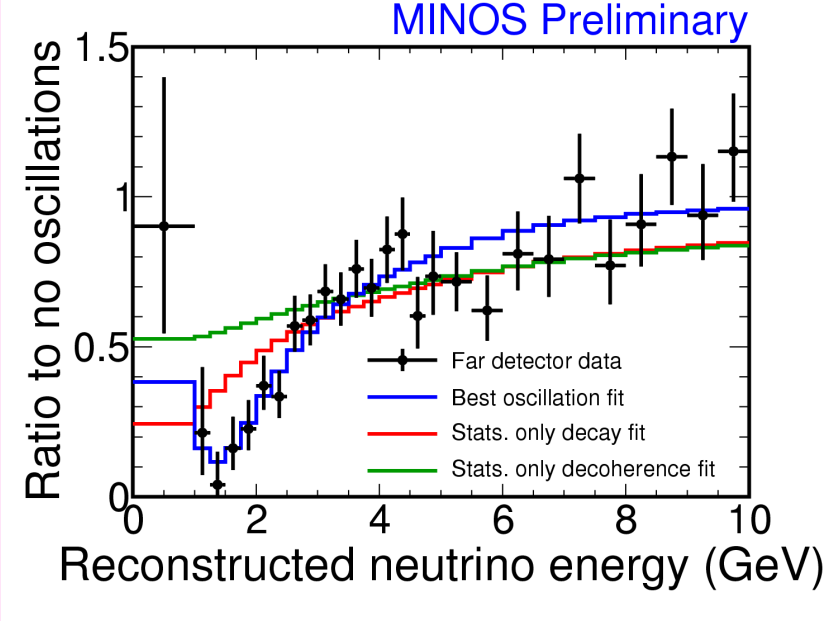
ν_μ DISAPPEARANCE RESULT





No Oscillations:

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

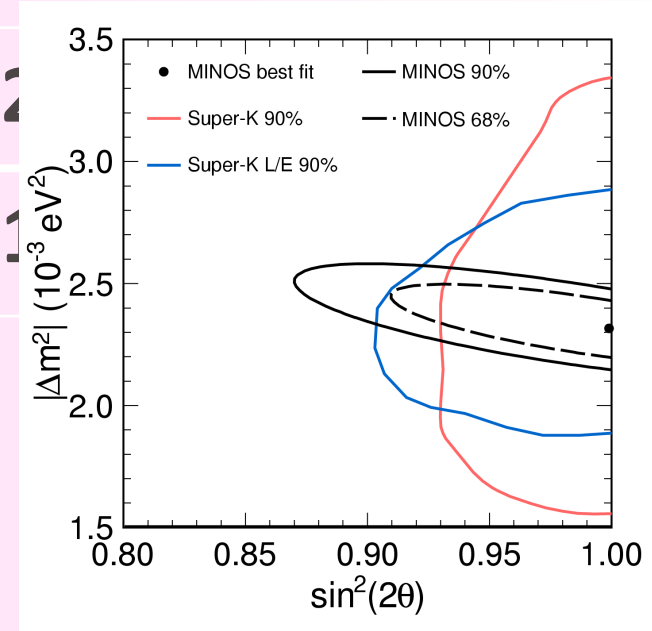
Observation:

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

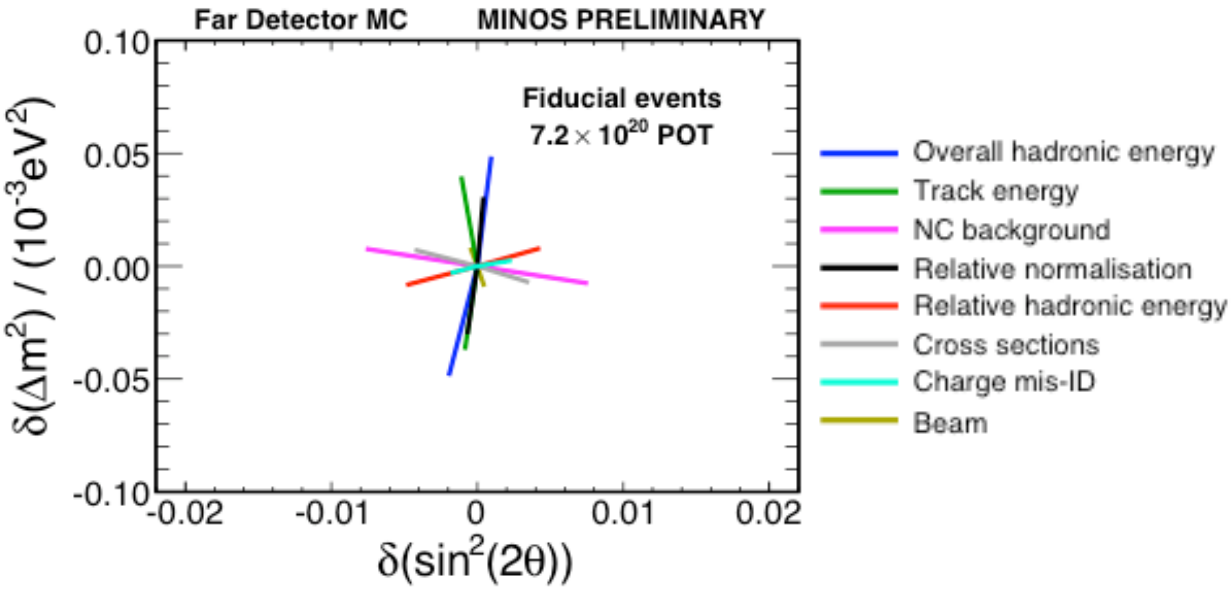
$\sin^2(2\theta) > 0.90\ (90\%\ \mathrm{C.L.})$

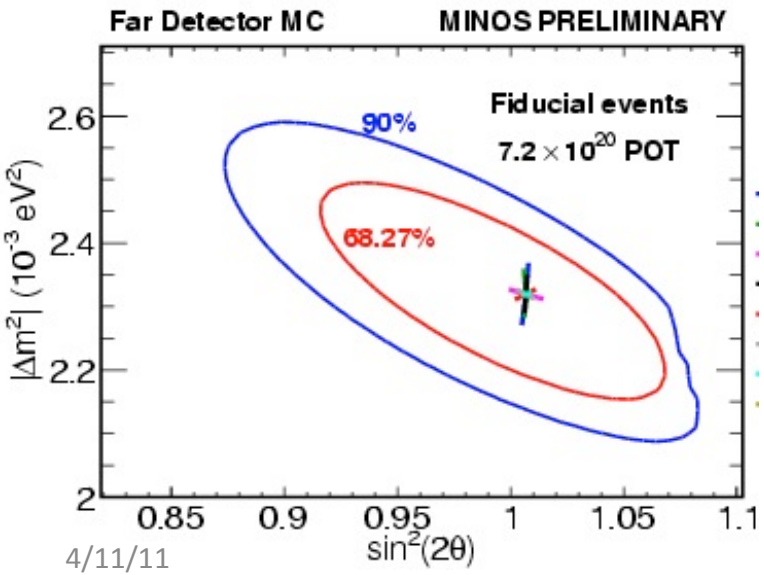
$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$

Super-K latest contour, uses full 3 flavour mixing



CC ν_μ systematic uncertainties



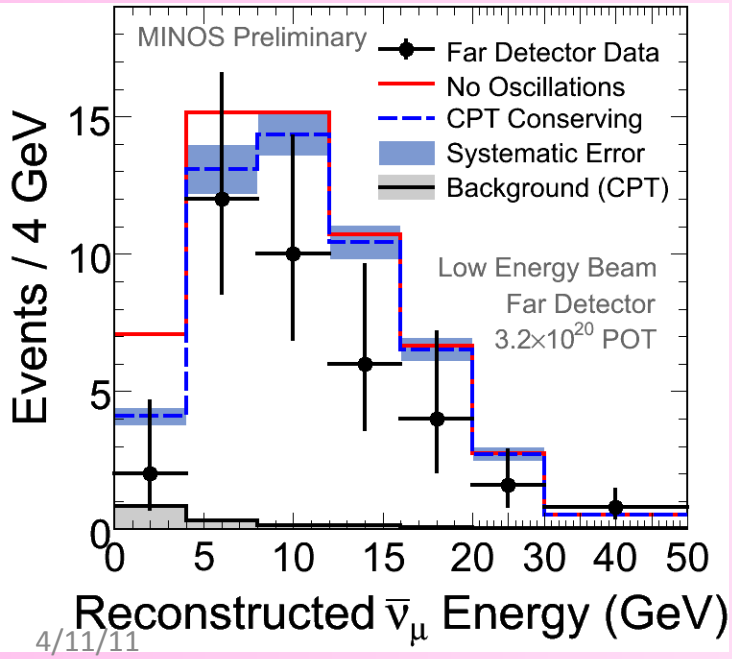


Dominant systematic uncertainties:

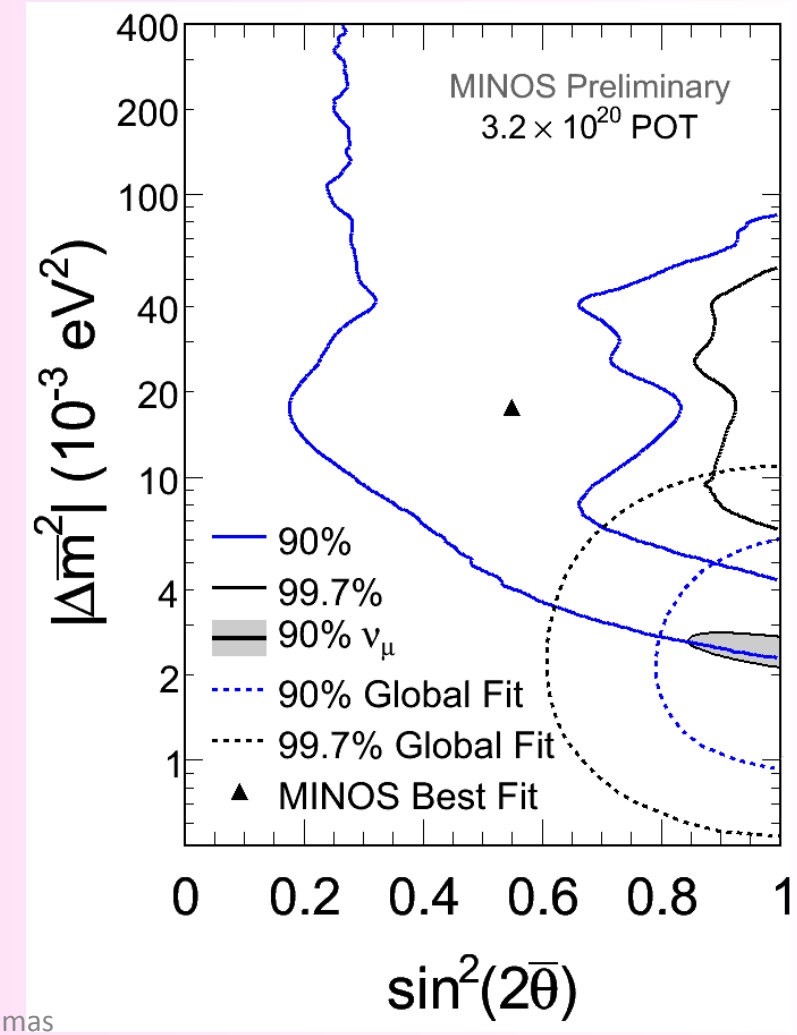
- Hadronic energy calibration
- Track energy calibration
- NC background
- Relative Near to Far normalization

ANTINEUTRINO RESULTS

- 42 events observed
  - No oscillations
    - $64.6 \pm 8.0_{stat} \pm 3.9_{syst}$
  - conserving
    - $58.3 \pm 7.6_{stat} \pm 3.6_{syst}$
- Deficit is 1.9σ
- Consistent with the ν_μ parameters at 90% c.l.
-



Global fit from Gonzalez-Garcia & Maltoni, *Phys. Rept.* 460 (2008), SK data dominates

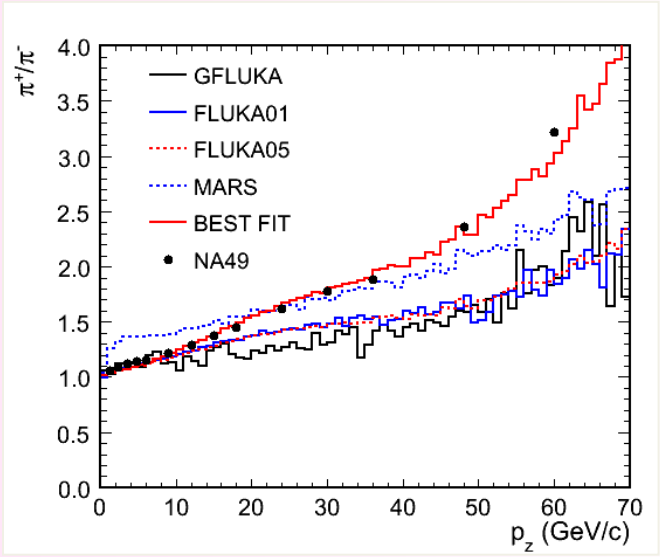


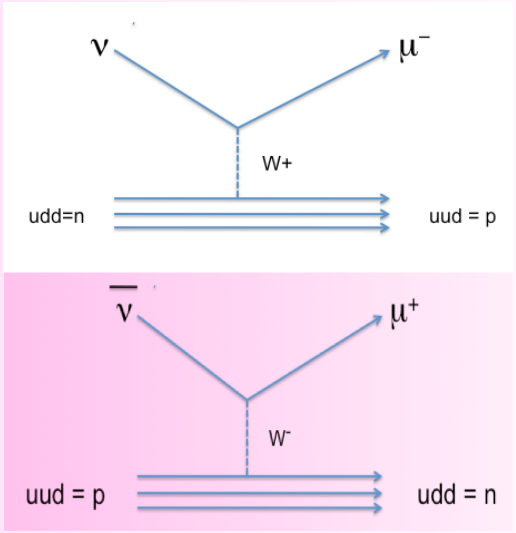
THE ANTI-NEUTRINO BEAM

How you make it and why it isn't really

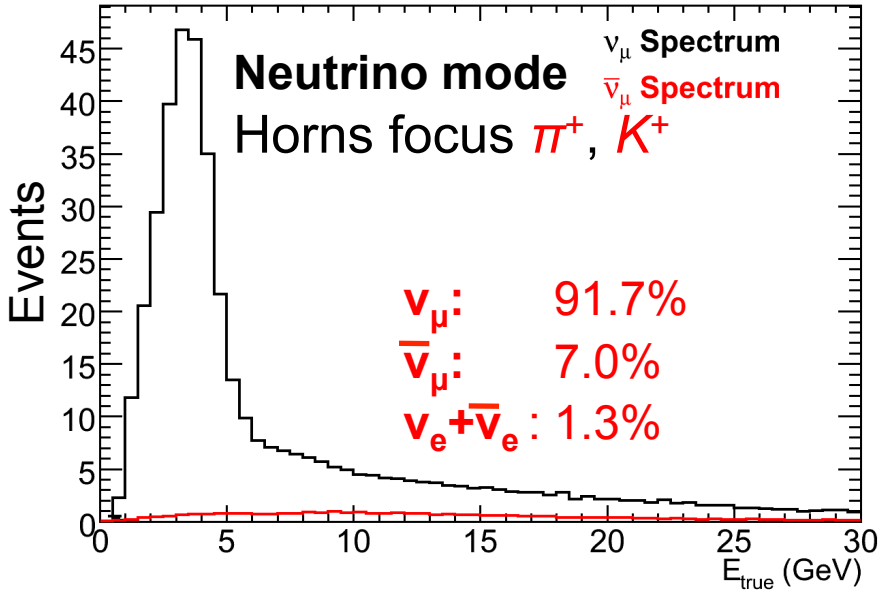
MAKING AN ANTI-NEUTRINO BEAM

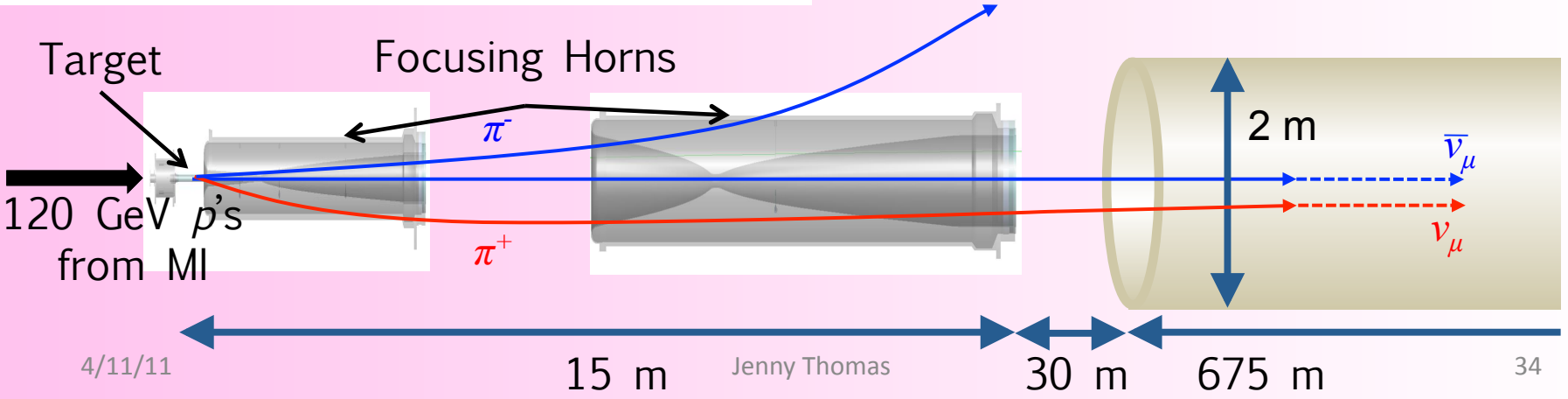
- **Several issues contribute to lower anti-neutrino rate**
  - $\pi+\pi-$ production ratio at target favours $\pi-$ at level of ~1.3-1.5 (approx 30%)
  - Ratio of n to p in iron gives ~30% in cross section
  - Vector boson exchange has a sign (~30%)
  - ν x-section larger at low energies by 30-50%
- **All results in about a factor 3 lower yield of anti-neutrinos**



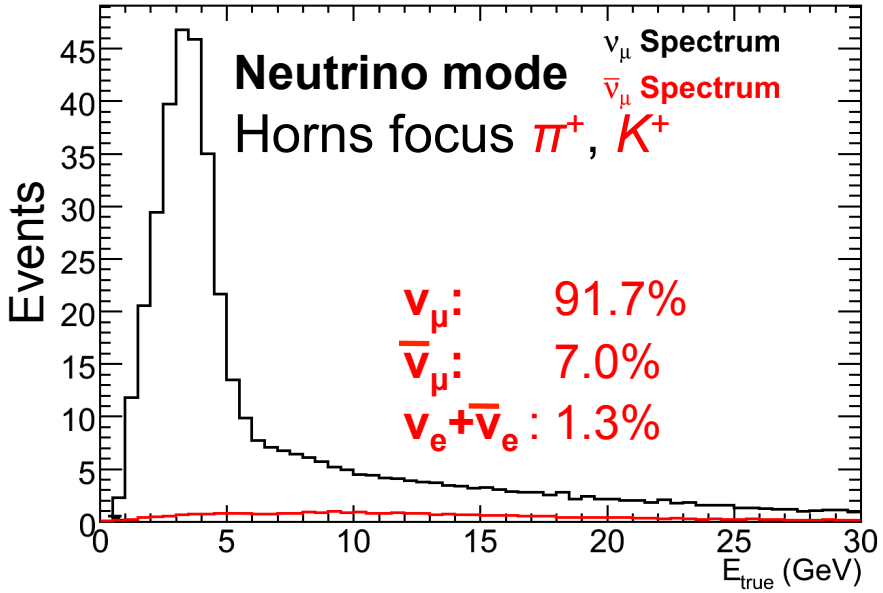


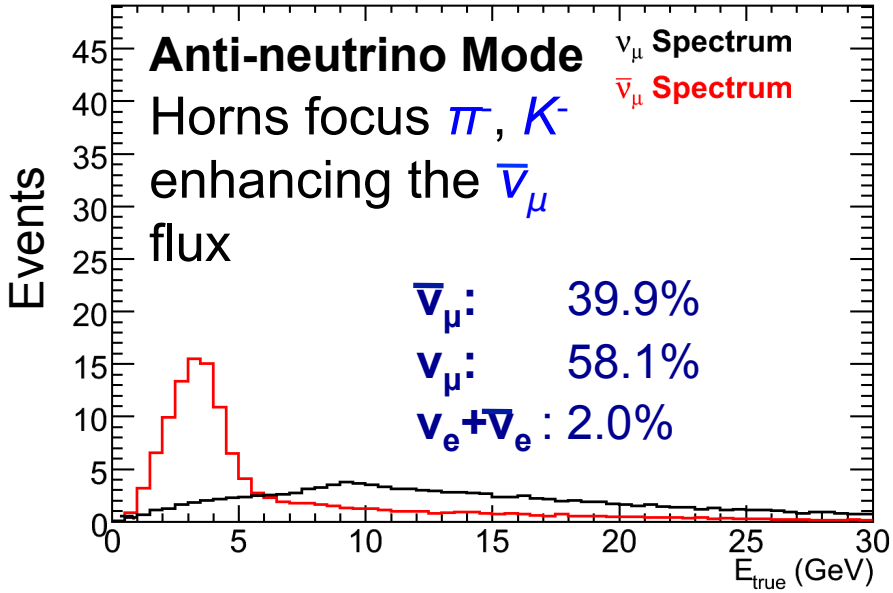
MAKING AN ANTI-NEUTRINO BEAM

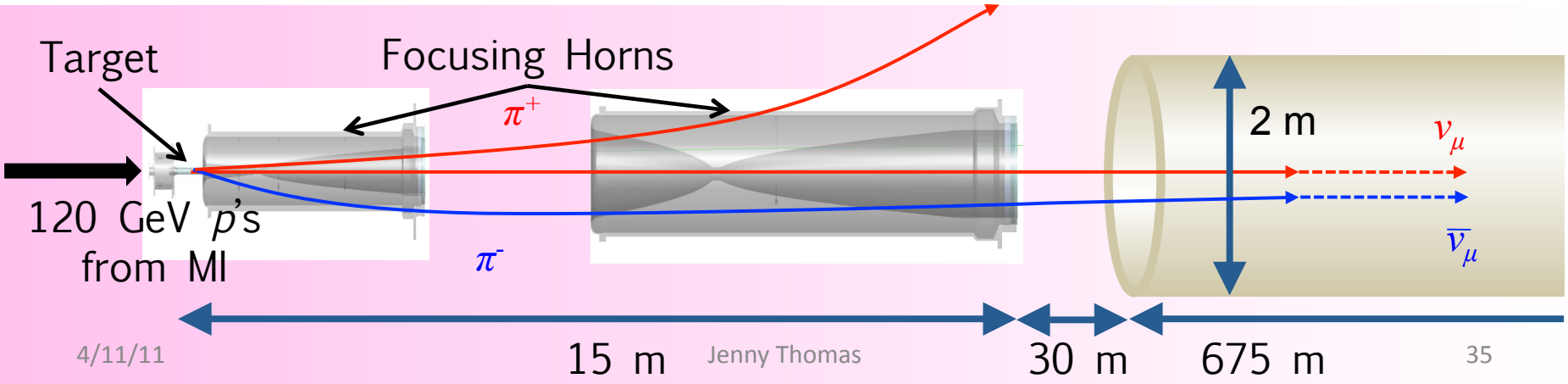




MAKING AN ANTI-NEUTRINO BEAM





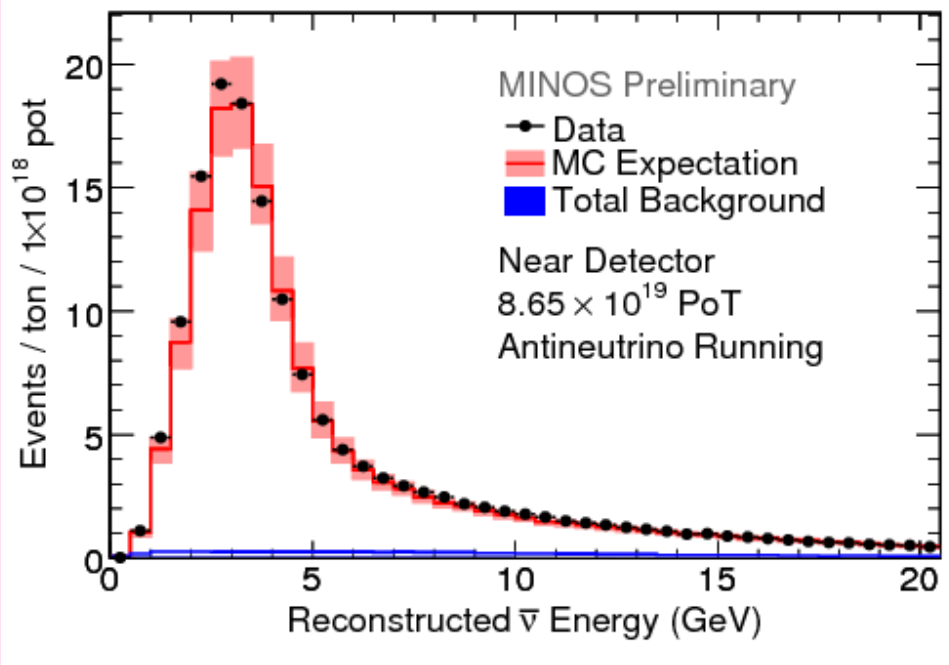


ANTI-NEUTRINO OSCILLATIONS

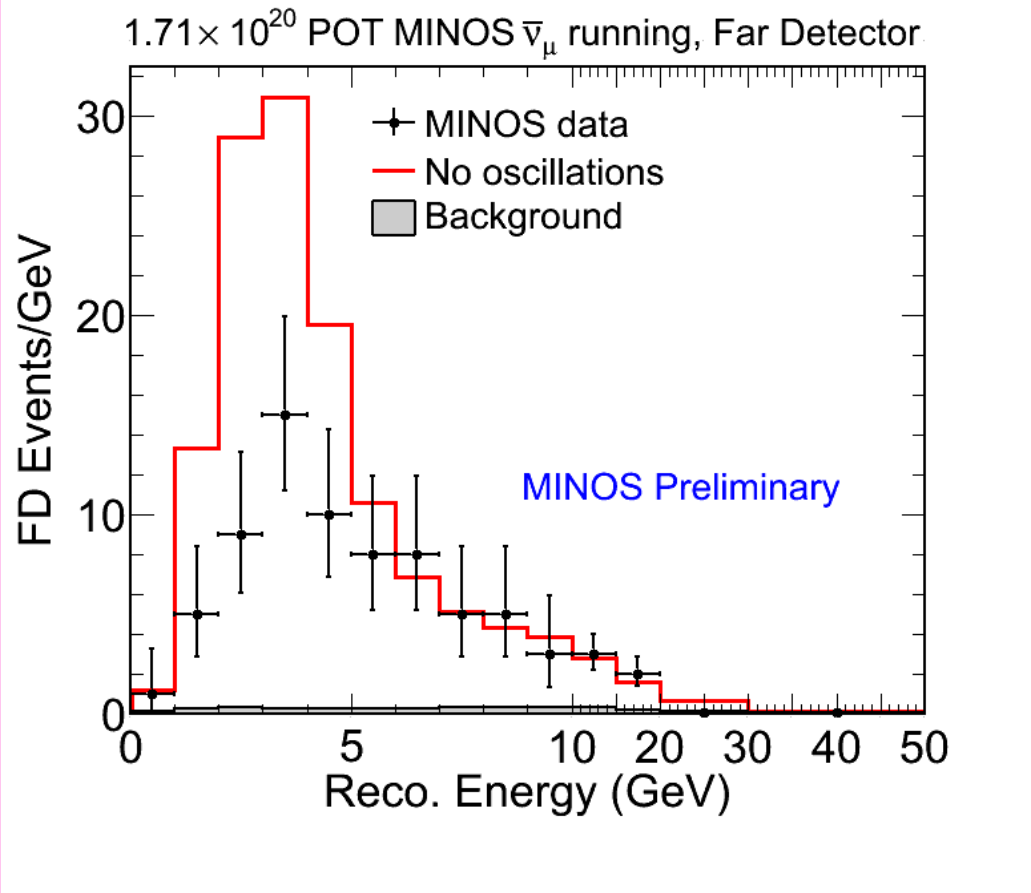
Measured in the same way,
comparison of ND with FD

ND ANTI-NEUTRINO SELECTION

- **Focus and select positive muons**
  - purity 94.3% after charge sign cut
  - purity 98% < 6GeV
- **Data/MC agreement comparable to neutrino running**
  - different average kinematic distributions
  - More low y events (more hard muons)

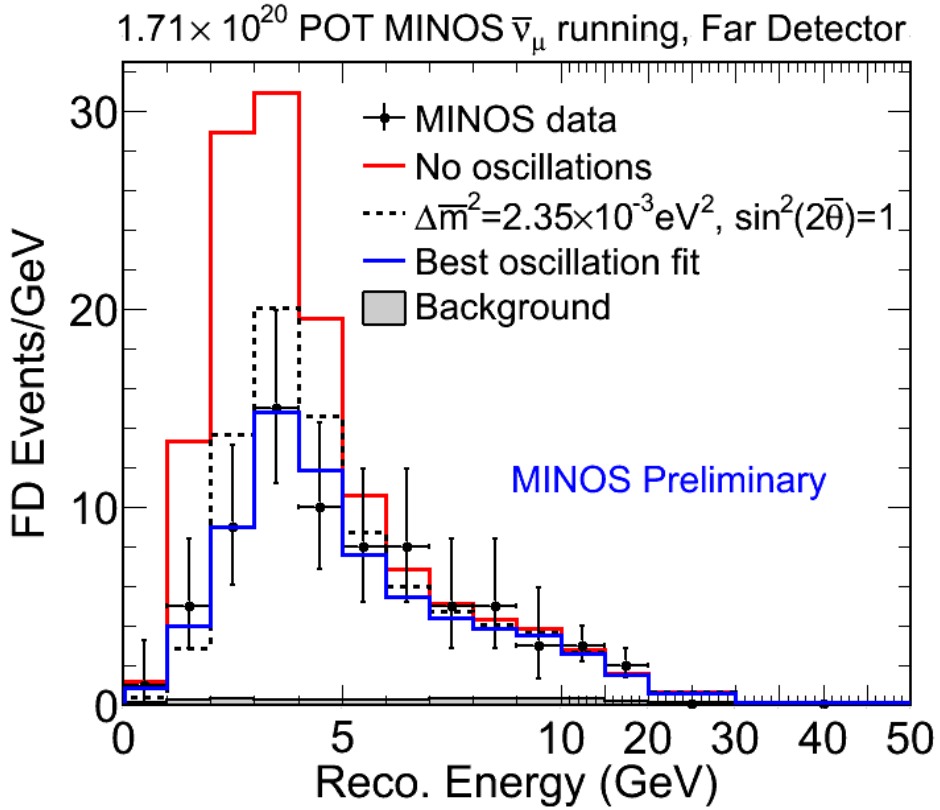


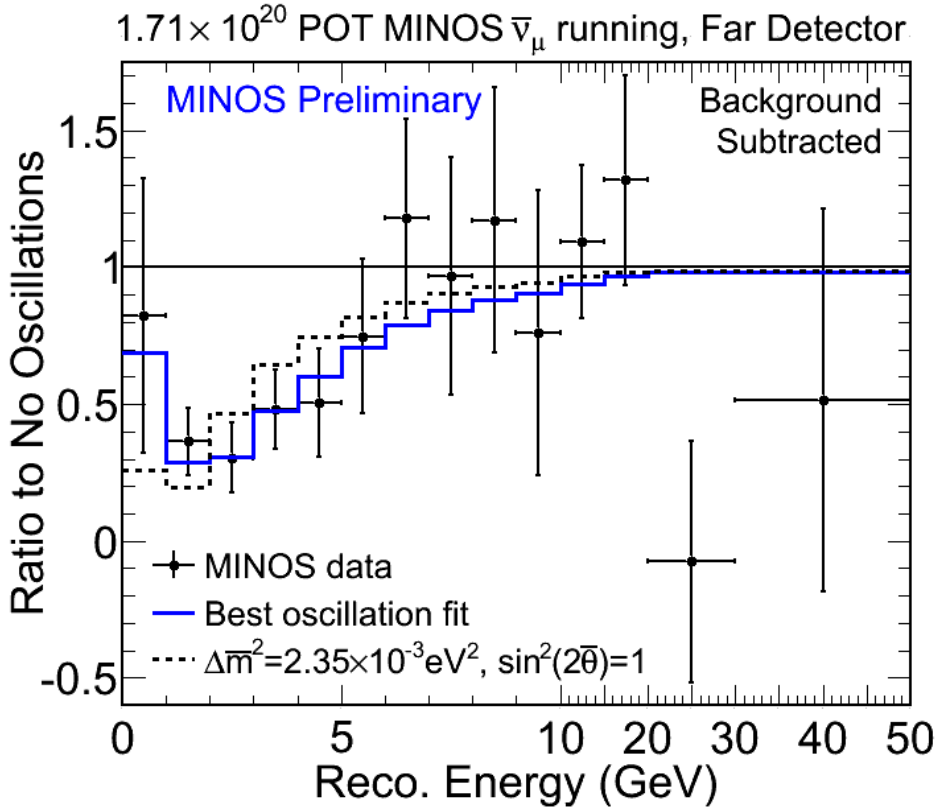
FAR DETECTOR DATA



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

COMPARISON TO NEUTRINO OSCILLATION PARAMETERS

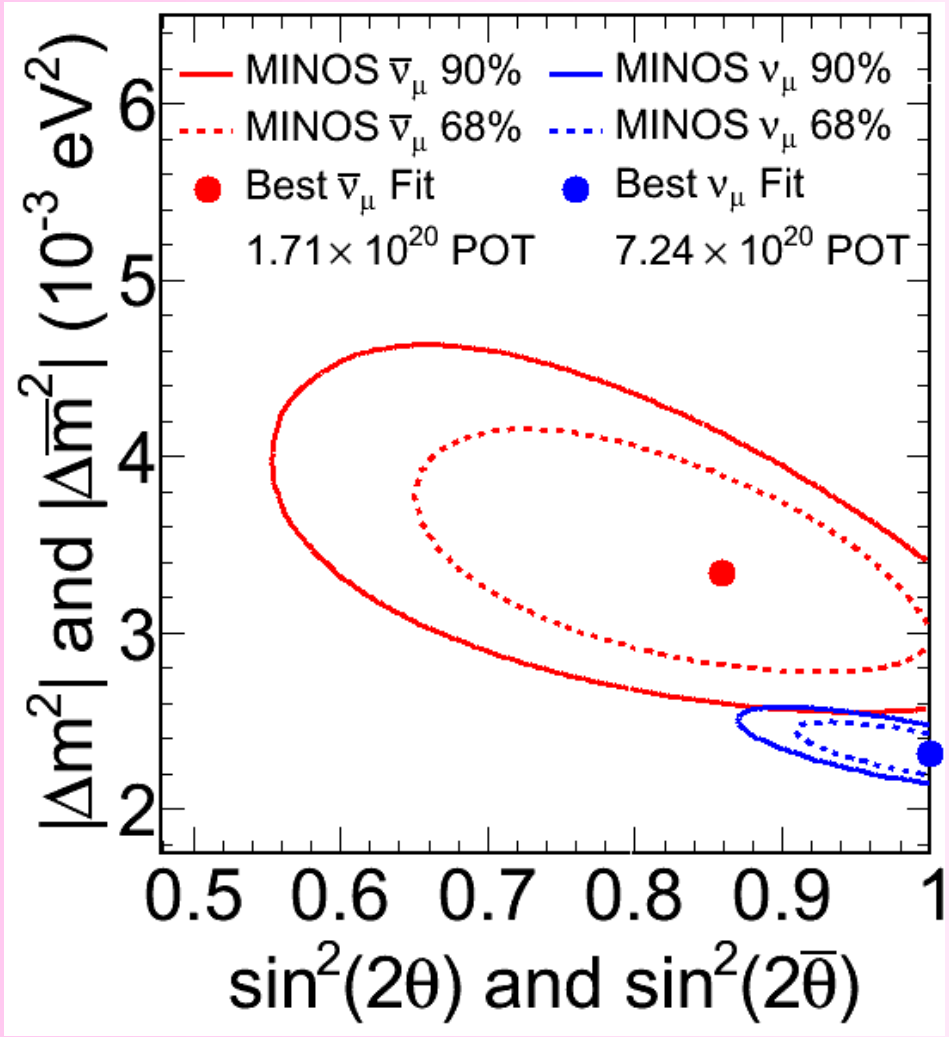




$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

COMPARISON TO NEUTRINOS

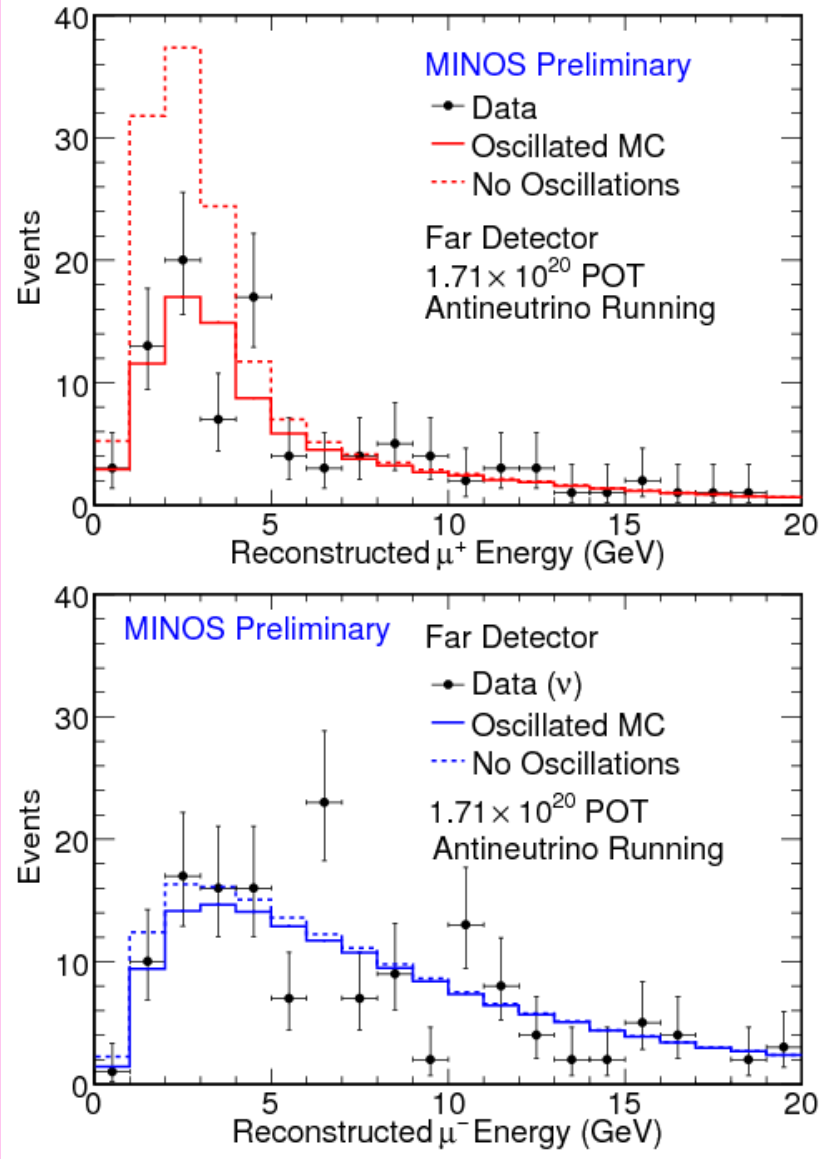


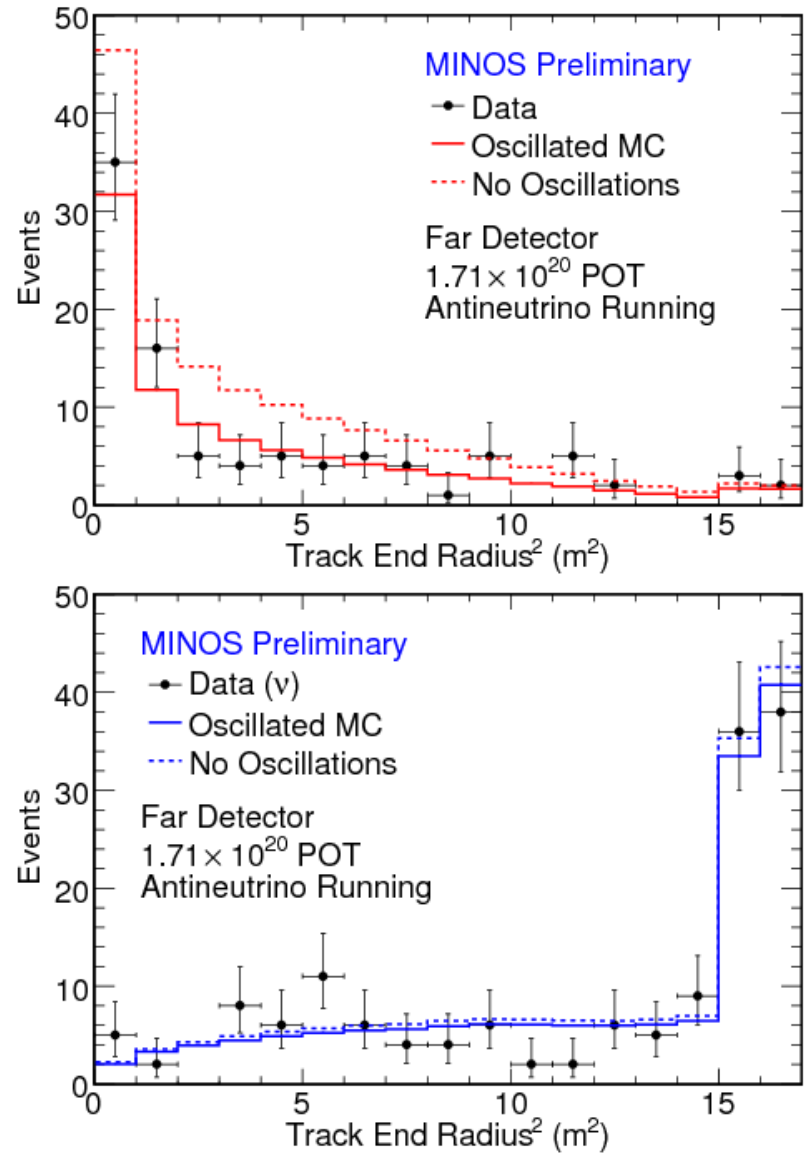
More anti-neutrino running expected soon

- Contour includes effects of dominant systematic uncertainties
  - normalization
  - NC background
  - shower energy
  - track energy

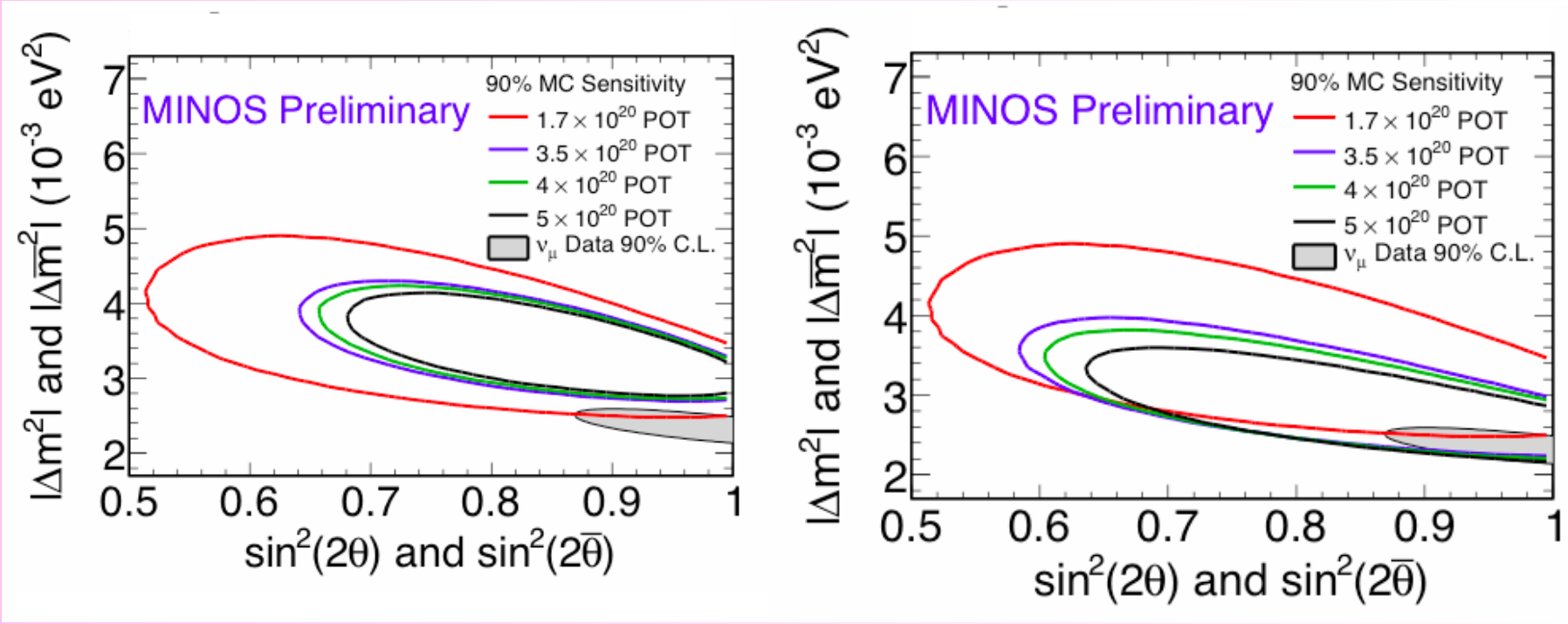
< 2% probability of same parameters

FD DATA


MINOS Preliminary
Data
Oscillated MC
No Oscillations
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Reconstructed μ+ Energy (GeV)
MINOS Preliminary
Far Detector
Data (ν)
Oscillated MC
No Oscillations
1.71× 10^20 POT
Antineutrino Running
Events
Reconstructed μ− Energy (GeV)


MINOS Preliminary
Data
Oscillated MC
No Oscillations
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Track End Radius² (m²)
MINOS Preliminary
Data (ν)
Oscillated MC
No Oscillations
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Track End Radius² (m²)

FUTURE SENSITIVITY



1.7e20 existing anti-ν data + Additional data with same anti-ν parameters

1.7e20 existing anti-ν data + additional data with CC-ν_μ parameters

SEARCH FOR ν_e

Brief overview of the world status and the MINOS present limits

MINOS: SEARCHING FOR θ_{13}

- **The probability of ν_e appearance in a ν_μ beam:**

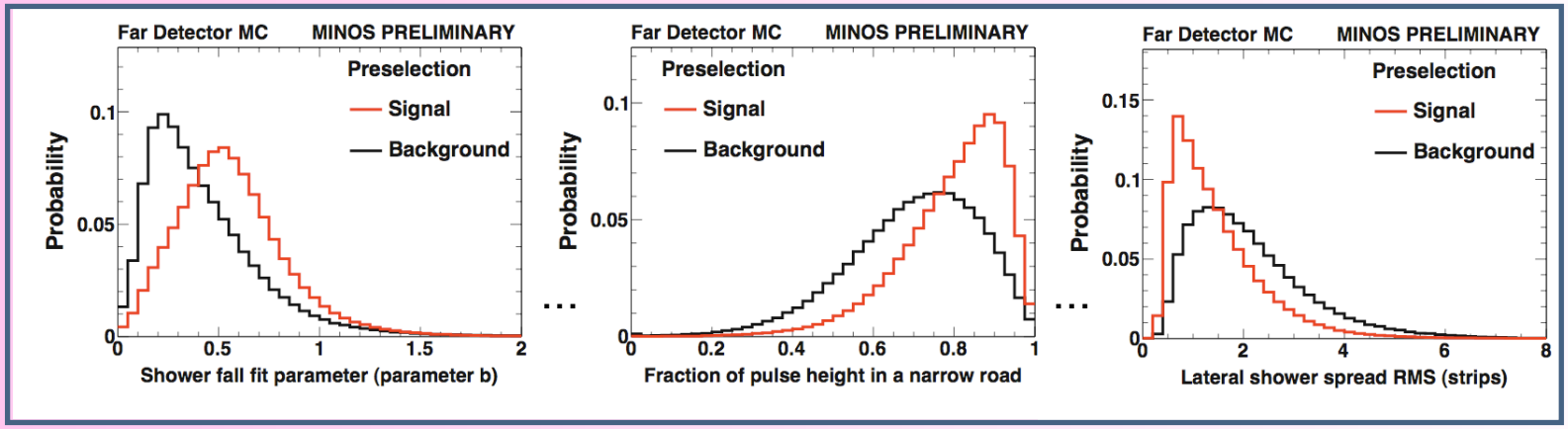
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})[\sin^2(1.27\ \Delta m^2_{32} L/E)]$$
$$\mp O(\sin(\theta_{13})\sin(\delta_{cp}))$$

- **Searching for ν_e events in MINOS, we can access $\sin^2(2\theta_{13})$.**
- **Probability depends not only on θ_{13} but also on δ_{CP}**
  - A non-zero θ_{13} would open the door to a CP violation measurement in the neutrino sector which could reveal the origin of the matter/anti-matter asymmetry of the universe.

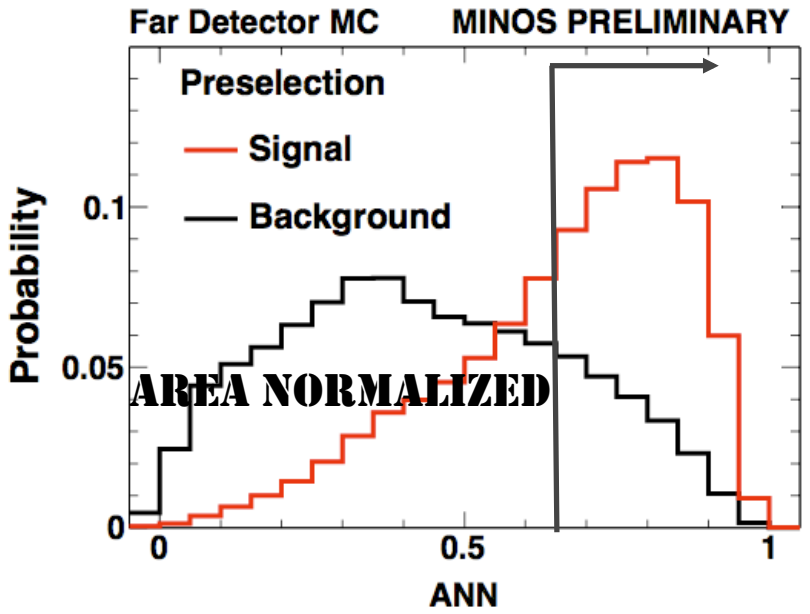
SELECTING ν_e EVENTS WITH ANN

EVENT CHARACTERIZATION IN LENGTH, WIDTH AND SHOWER SHAPE

EXAMPLE



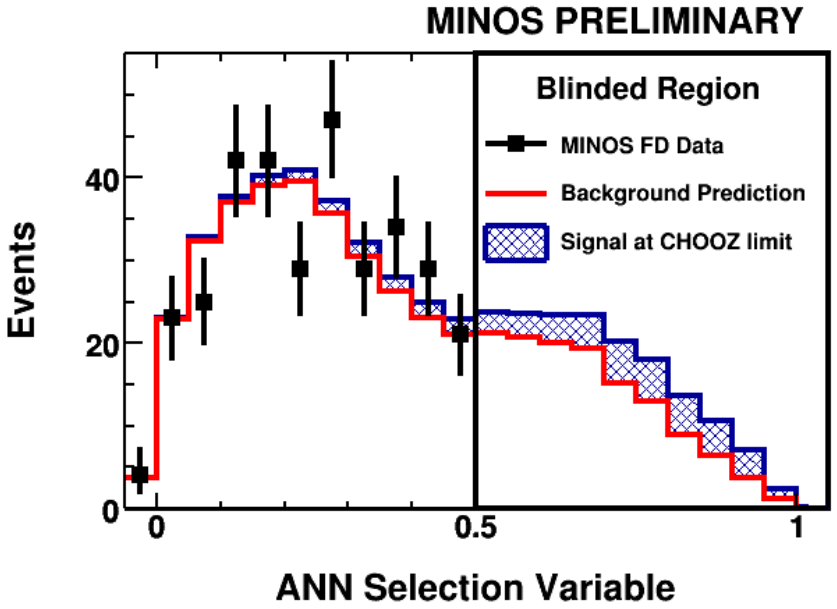
- 11 variables chosen describing length, width and shower shape.
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - CC rejection >99.4%
  - signal/background 1:4



$\Delta m^2_{32}=0.0024\ eV^2$, $\sin^2\theta_{23}=1.0$

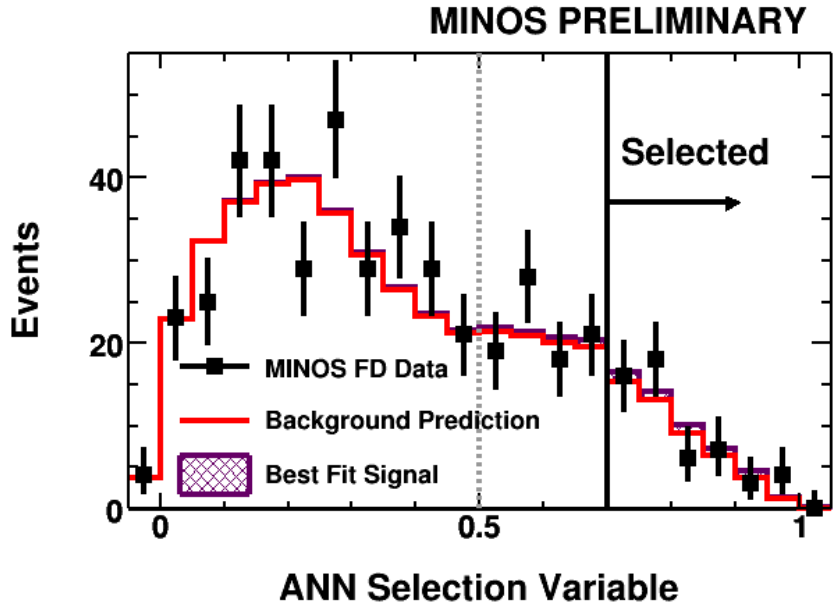
FD DATA

sideband



- OBSERVE A TOTAL OF 327 EVENTS.
- EXPECT 314±18(STAT)
- DIFFERENCE OF 13 EVENTS ALSO CONSISTENT WITH CHOOZ LIMIT
- 0.75 SIGMA EXCESS

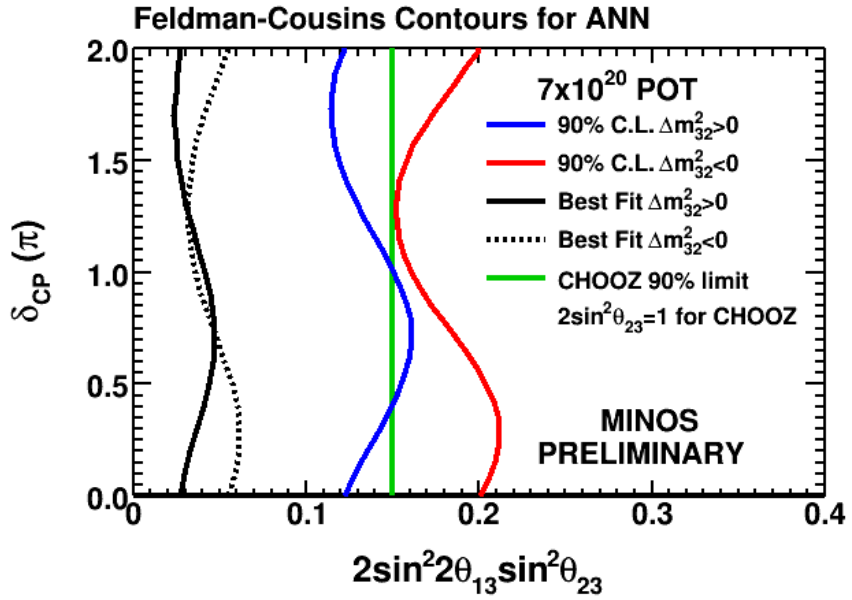
selected

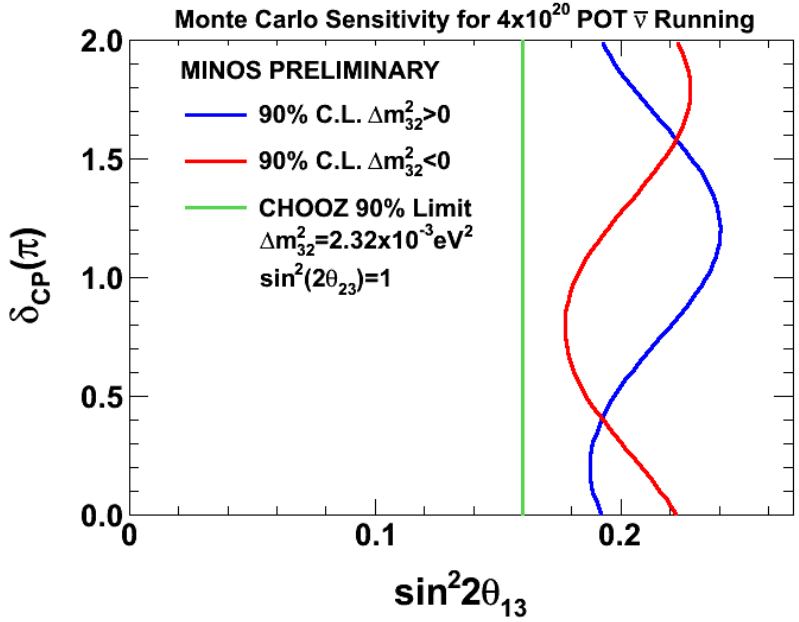


- OBSERVE A TOTAL OF 54 EVENTS
- EXPECT 49.1±7(STAT)±2.7(SYS) BACKGROUND EVENTS
- DIFFERENCE OF 4.9 EVENTS
- 0.7SIGMA EXCESS

MINOS 90% C.L. FOR SIN^{2}2θ_{13}

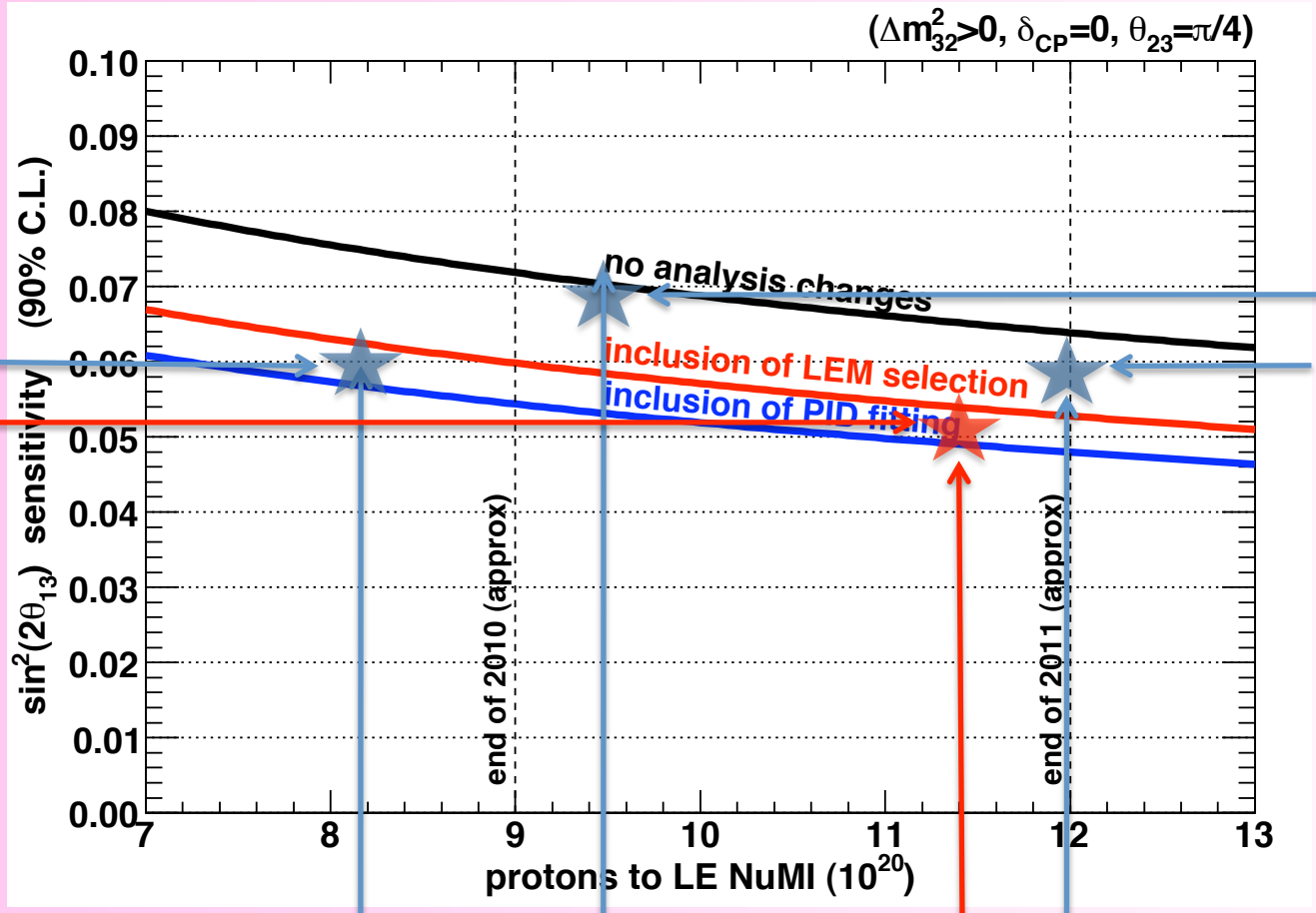
$\sin^2(2\theta_{13}) < 0.12\ (0.20)$ at 90% C.L.





Anti-neutrino reach

SENSITIVITY



MINOS

MINOS?

T2K

Double Chooz

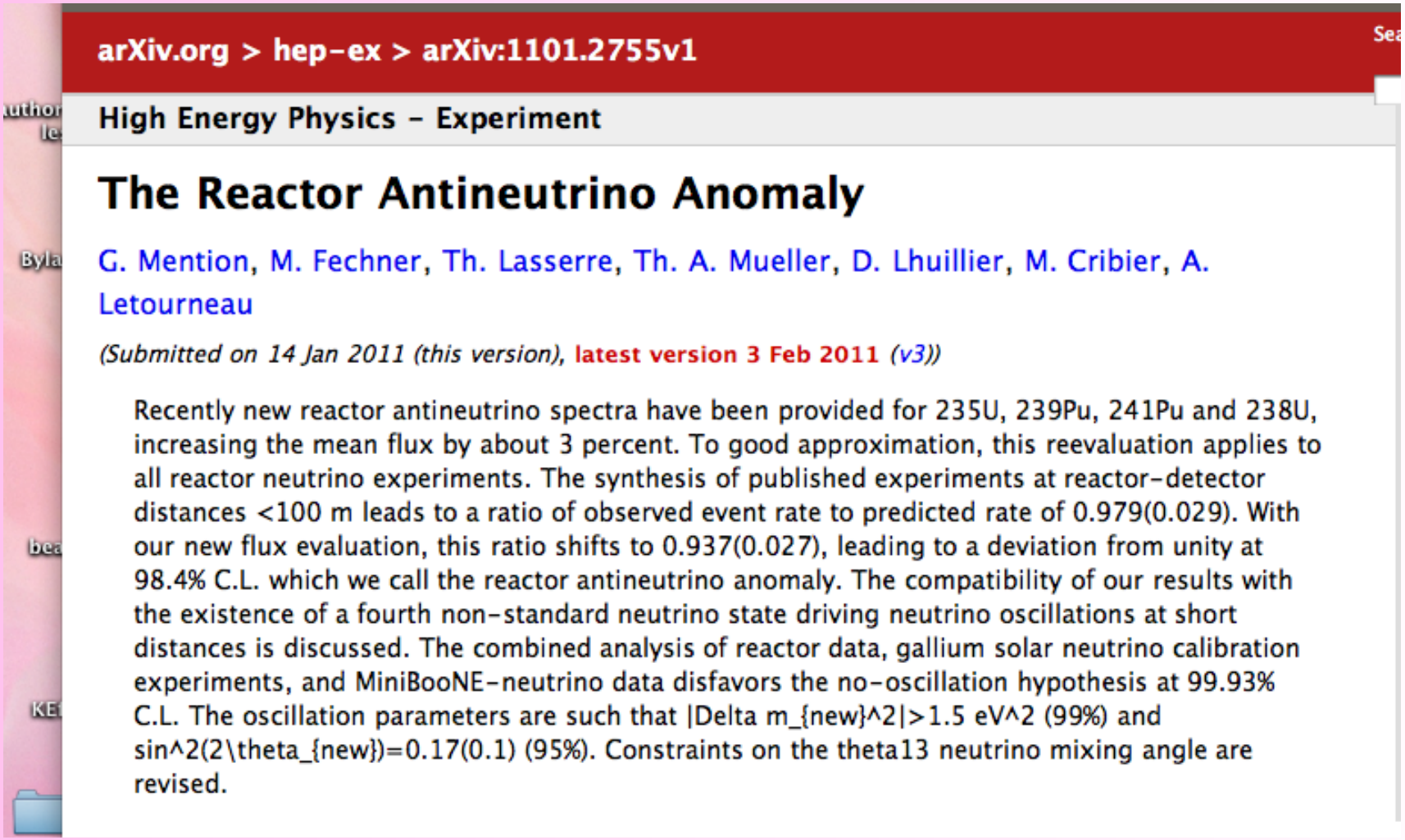
this summer

RESULTS AVAILABLE → 1 month from now

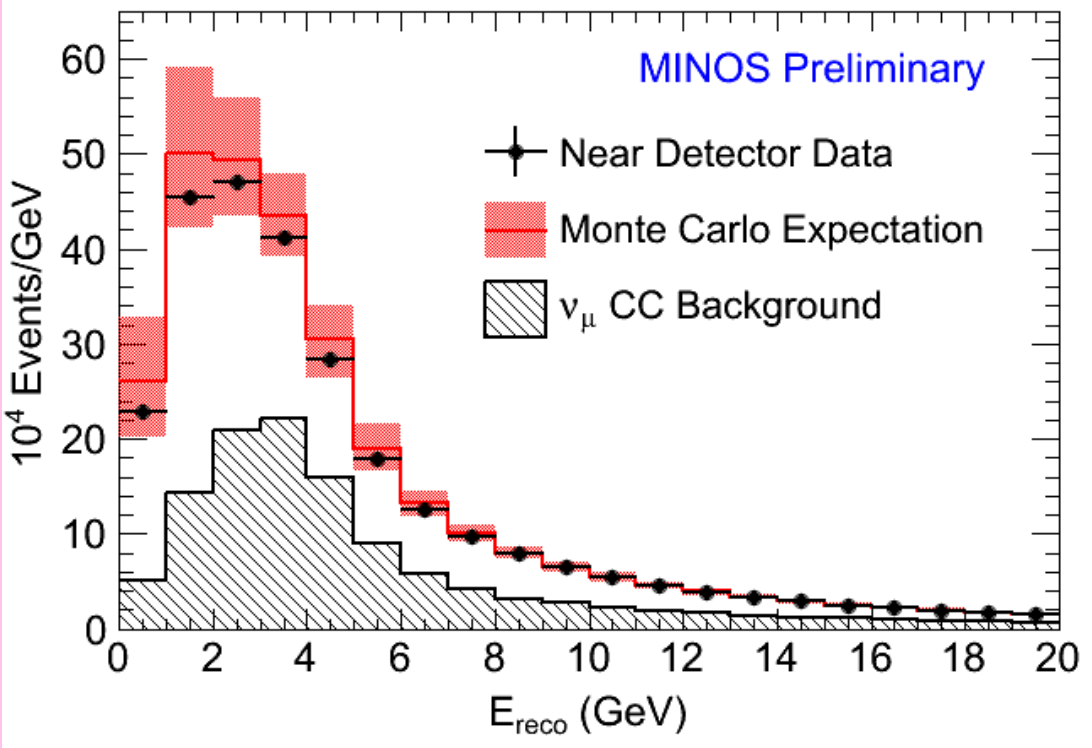
2.0 years

1.0 year

SEARCH FOR STERILE NEUTRINOS

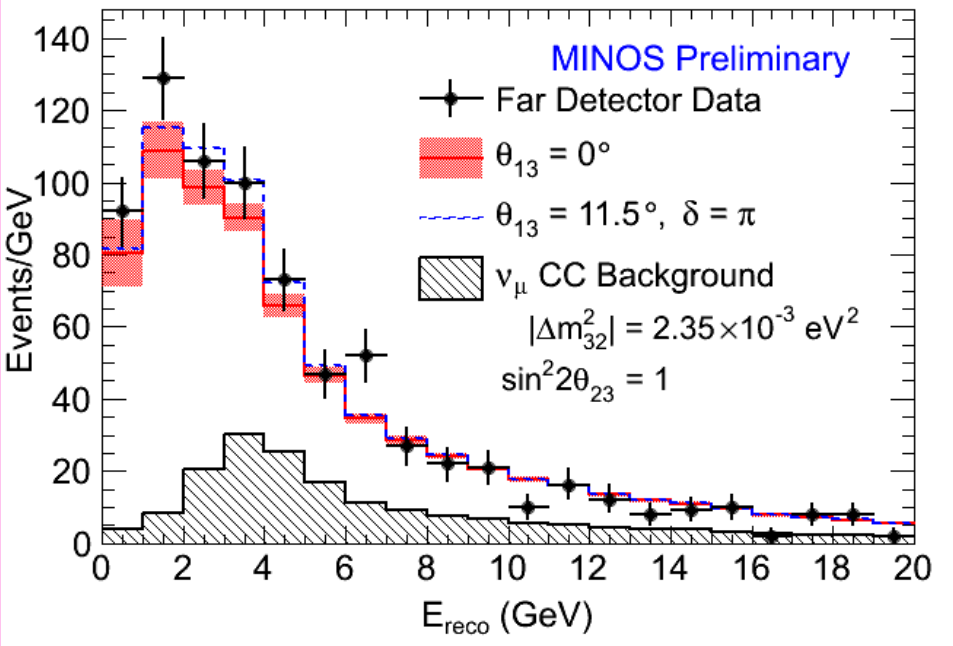

arXiv.org > hep-ex > arXiv:1101.2755v1
High Energy Physics - Experiment
The Reactor Antineutrino Anomaly
G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau
(Submitted on 14 Jan 2011 (this version), latest version 3 Feb 2011 (v3))
Recently new reactor antineutrino spectra have been provided for 235U, 239Pu, 241Pu and 238U, increasing the mean flux by about 3 percent. To good approximation, this reevaluation applies to all reactor neutrino experiments. The synthesis of published experiments at reactor-detector distances <100 m leads to a ratio of observed event rate to predicted rate of 0.979(0.029). With our new flux evaluation, this ratio shifts to 0.937(0.027), leading to a deviation from unity at 98.4% C.L. which we call the reactor antineutrino anomaly. The compatibility of our results with the existence of a fourth non-standard neutrino state driving neutrino oscillations at short distances is discussed. The combined analysis of reactor data, gallium solar neutrino calibration experiments, and MiniBooNE-neutrino data disfavors the no-oscillation hypothesis at 99.93% C.L. The oscillation parameters are such that |Delta m_{new}^2|>1.5 eV^2 (99%) and sin^2(2\theta_{new})=0.17(0.1) (95%). Constraints on the theta13 neutrino mixing angle are revised.

NEUTRAL CURRENT NEAR EVENT RATES



- Neutral Current event rate should not change in standard 3 flavor oscillations
- A deficit in the Far event rate could indicate mixing to sterile neutrinos
- ν_e CC events would be included in NC sample, results depend on the possibility of ν_e appearance

NEUTRAL CURRENTS IN THE FAR DETECTOR

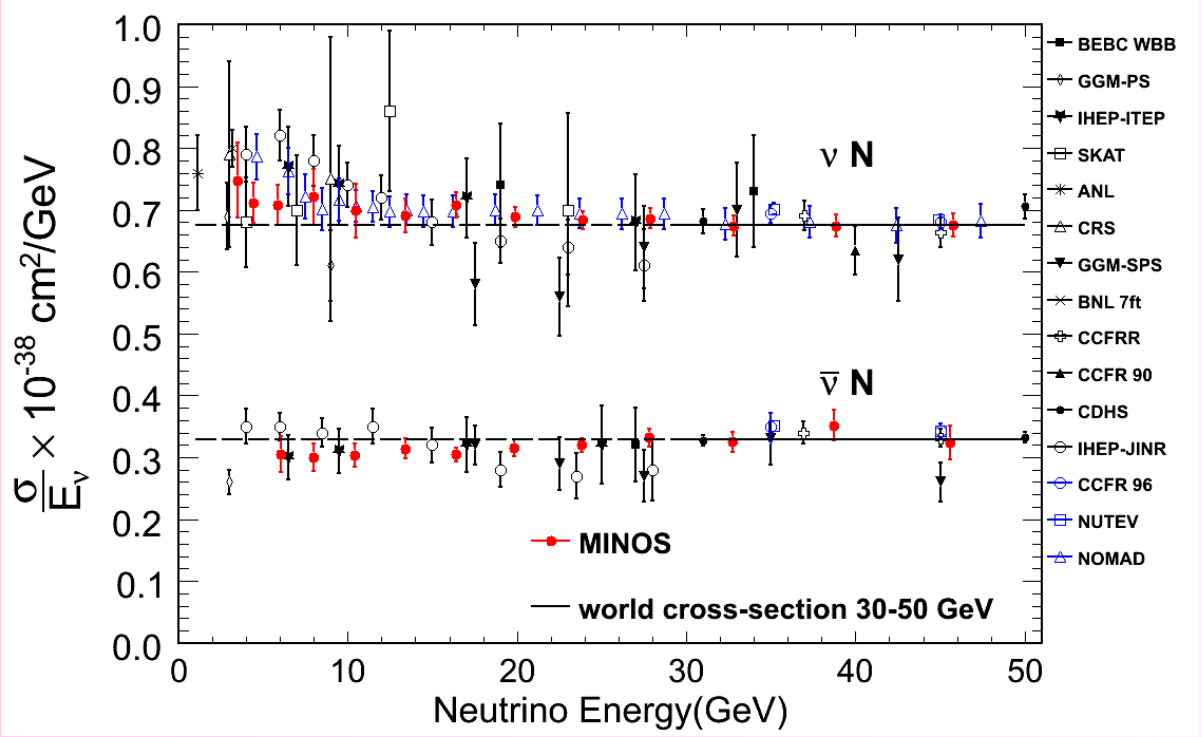


$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ (0.40) \text{ at } 90\% \text{ C.L.}$$

- Expect: **757** events
- Observe: **802** events
- No deficit of NC events
- Rules out sterile neutrinos between about $0.4eV^2$ and $5eV^2$, and with probability >~ 0.04
- Anti-neutrinos???

LAST BUT NOT LEAST

- MINOS has the biggest collection of neutrino data in the world
- ND is the first neutrino experiment not to be statistics limited!!
- In the ND, cross sections have been measured



MOST PRECISE DATA IN THE WORLD ACROSS A LARGE ENERGY REGION

MINOS+

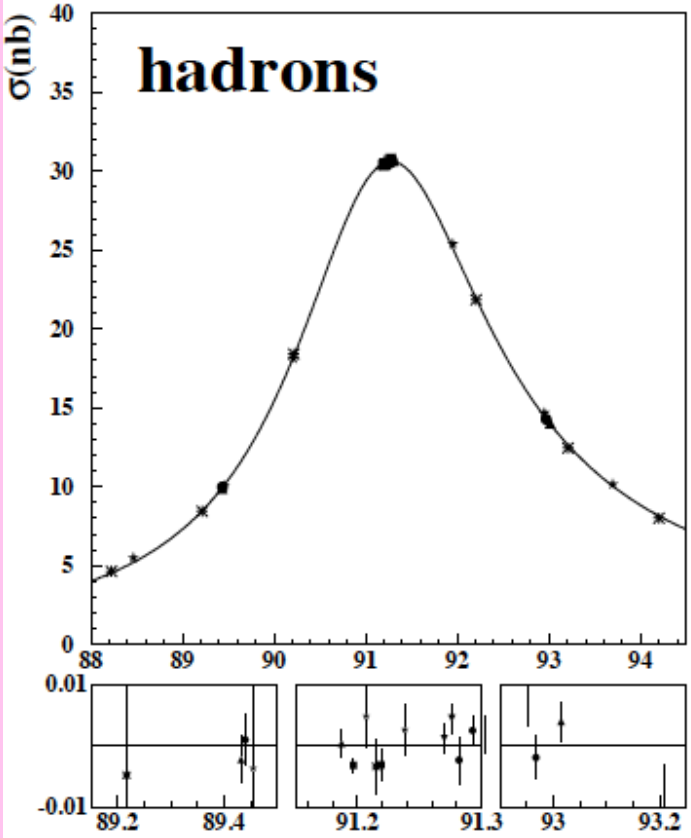
What can MINOS contribute to the neutrino knowledge in the future

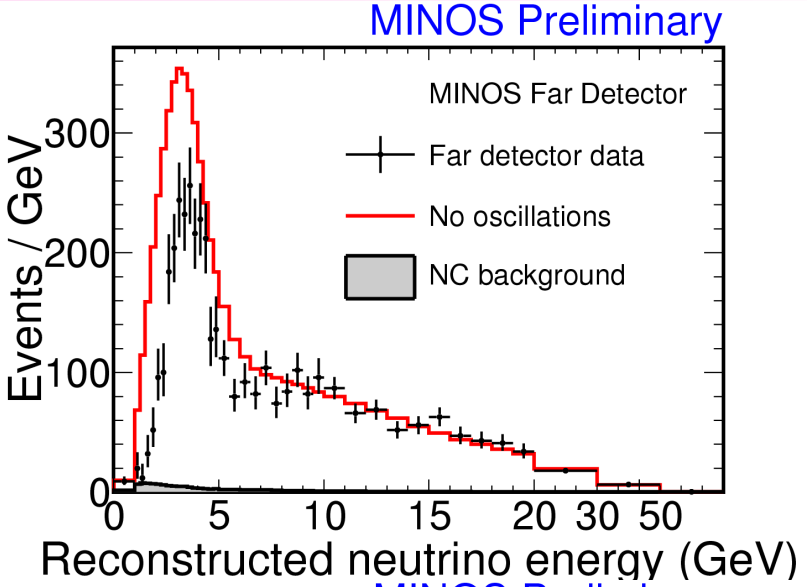
WHAT DO WE KNOW

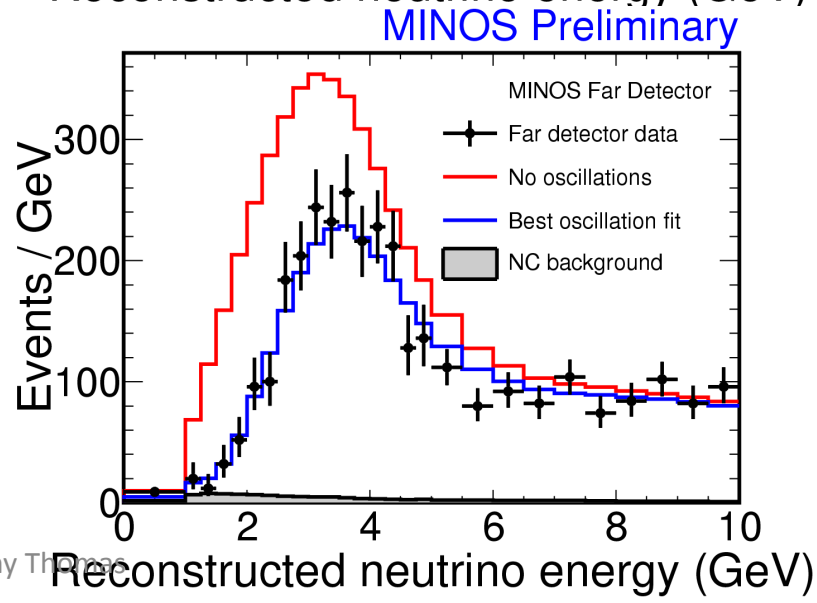
- Neutrino Oscillations have been discovered?
  - Non conservation of CC event rate over distance
- Precision measurement of oscillation parameters has been made by MINOS/SK?
  - 5-10% errors on parameters of the MODEL!
- This has convinced everyone that the first matrix to be written down is correct
  - Throw away all the rest of the information to focus on one parameter of this matrix, θ_{13}

PRECISION MEASUREMENT?

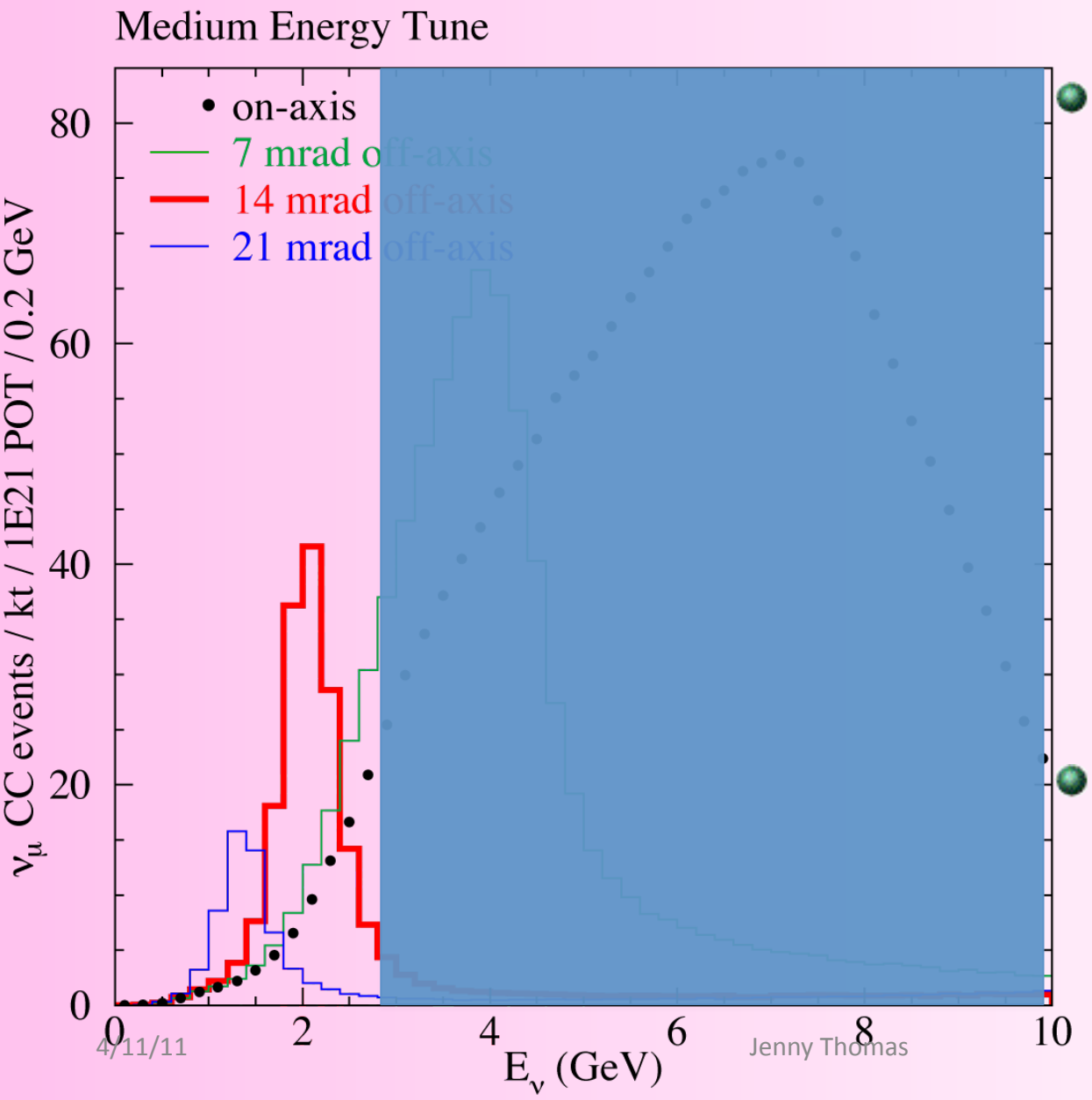
Z LINE-SHAPE FROM ALEPH







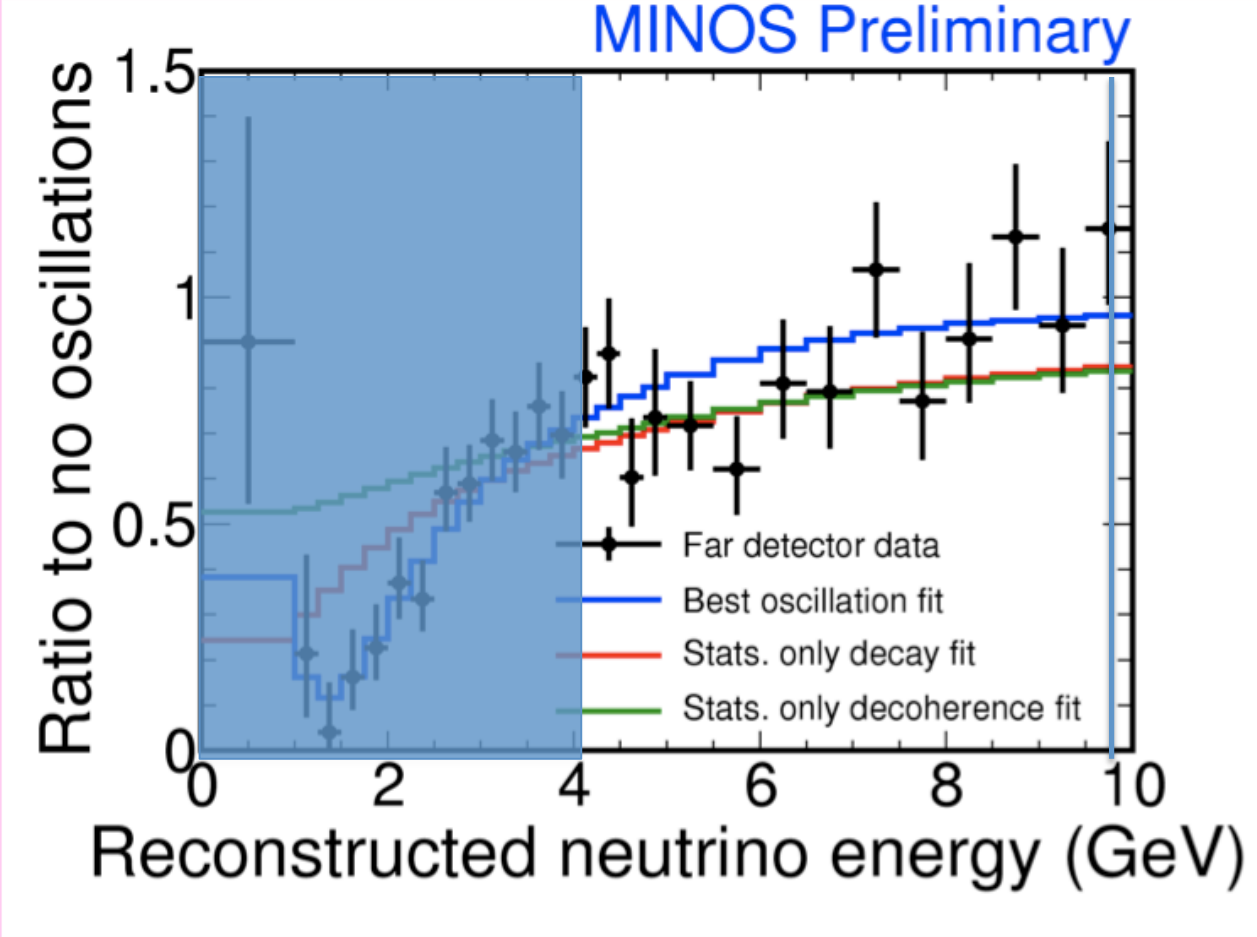
PRECISION MEASUREMENT



In fact this precision measurement is so convincing that we have decided (world wide) to throw away all the other information: area under the black points will be lost!

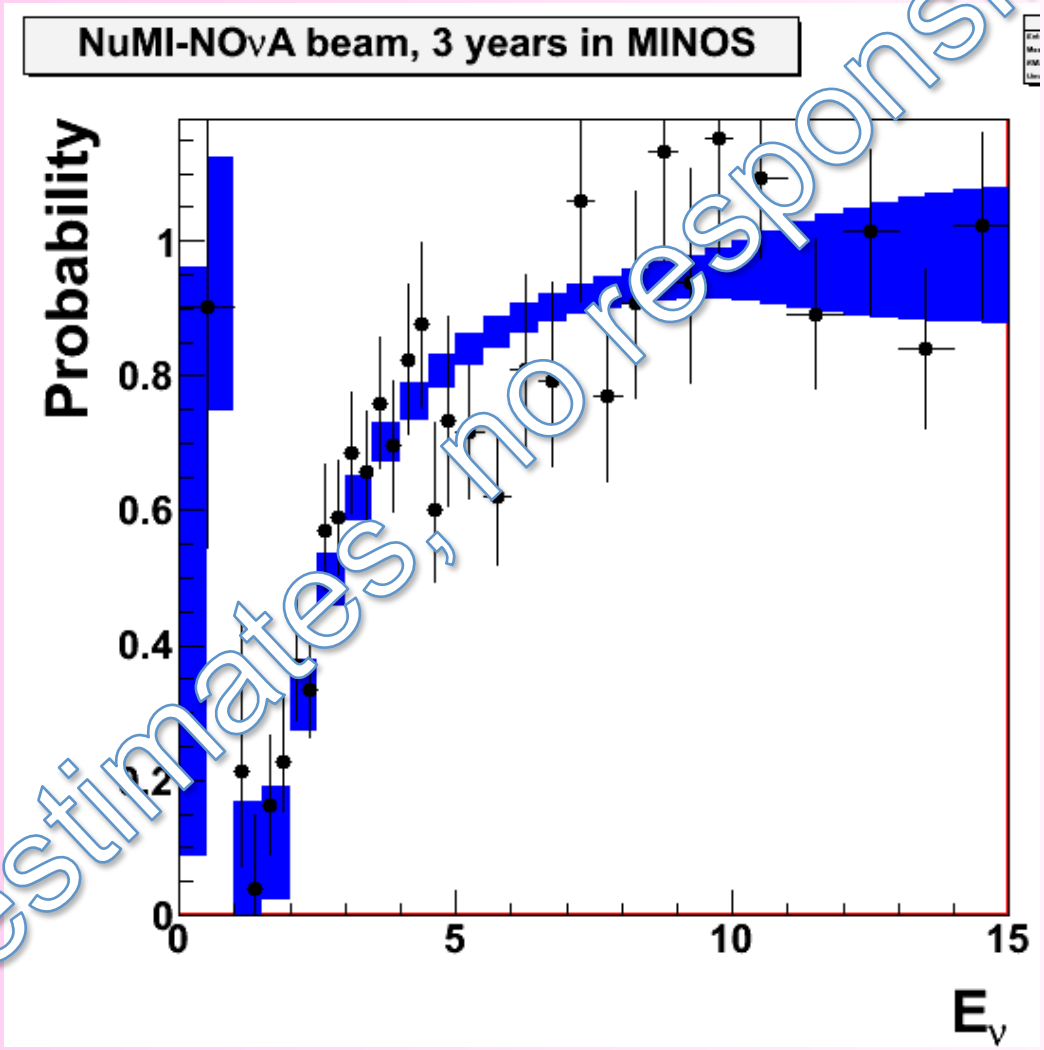
~4000 events/year between 4-10GeV

PRECISION MEASUREMENT?

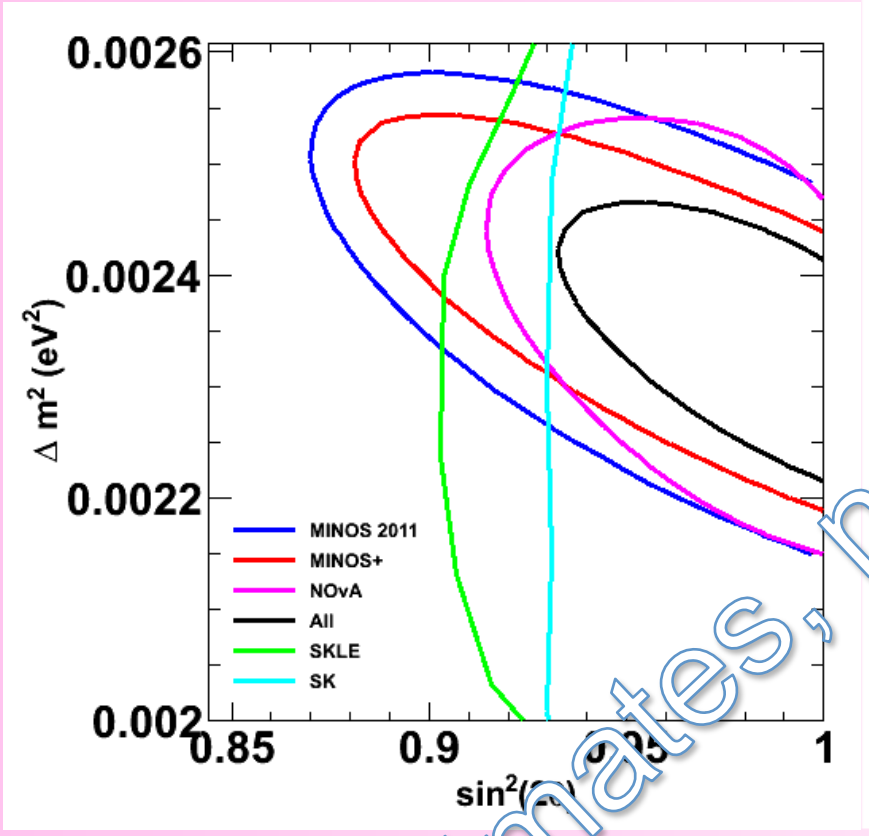


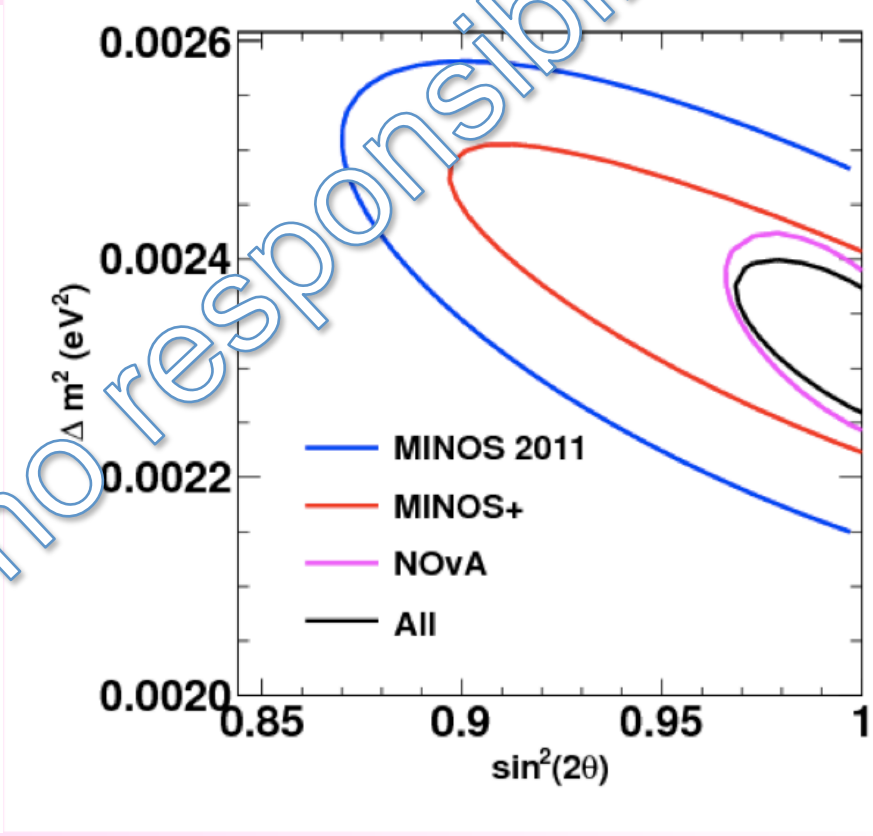
- Initial estimates give ~3000 events in this region in one year of Nova running (about 2x what we have in the LE peak region after ~5 years running)
- In 4-10 GeV region error bars go from 25%/GeV to ~5%/0.5GeV after 2 years

RATIO OF OSCILLATED TO NON-OSCILLATED



MINOS, MINOS+ AND NOνA

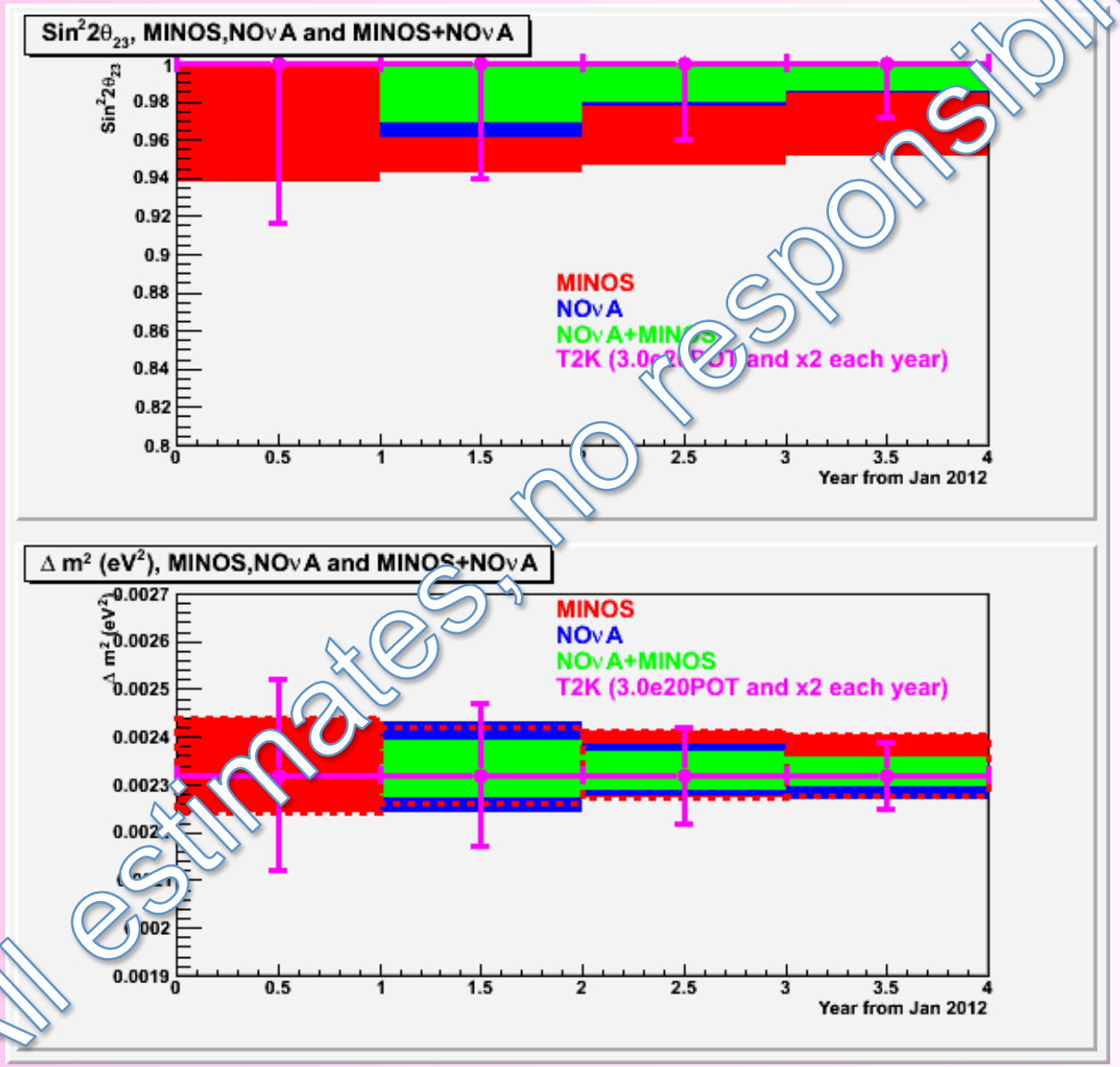




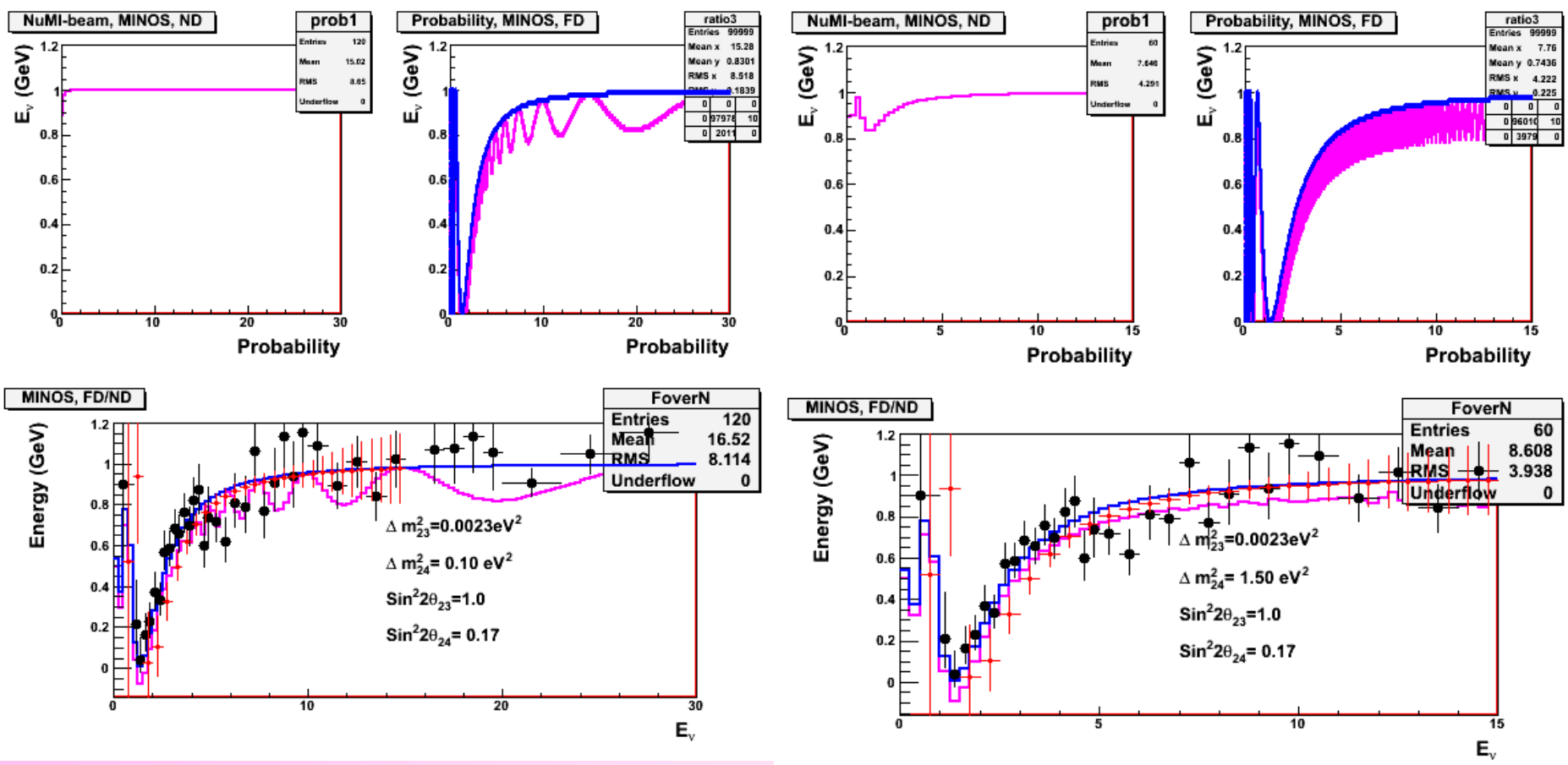
- One year of MINOS+
- MINOS continues to dominate Δm^2 measurement
- NOνA 50% complete

- Three years of MINOS+
- NOνA complete after first 18 months
- Significant improvements to parameters' accuracy over 3 years period due to MINOS+

SUMMARY OF PRECISION



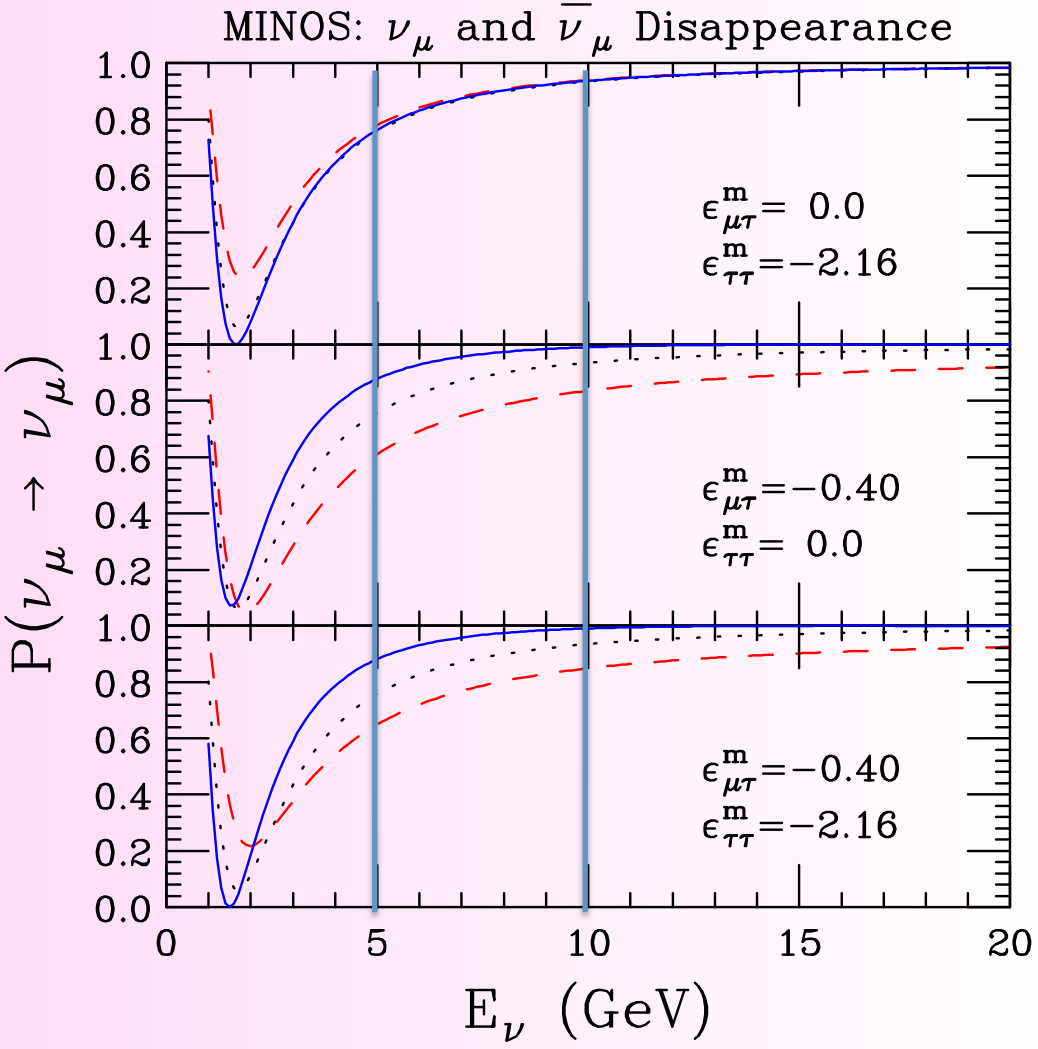
STERILE NEUTRINOS



- Structure could be resolved (smaller Δm^2_{24})
- Just rate comparison across 4-10 GeV will be precise measurement for larger Δm^2_{24}
- Could be augmented by ND measurements if beam flux was better known

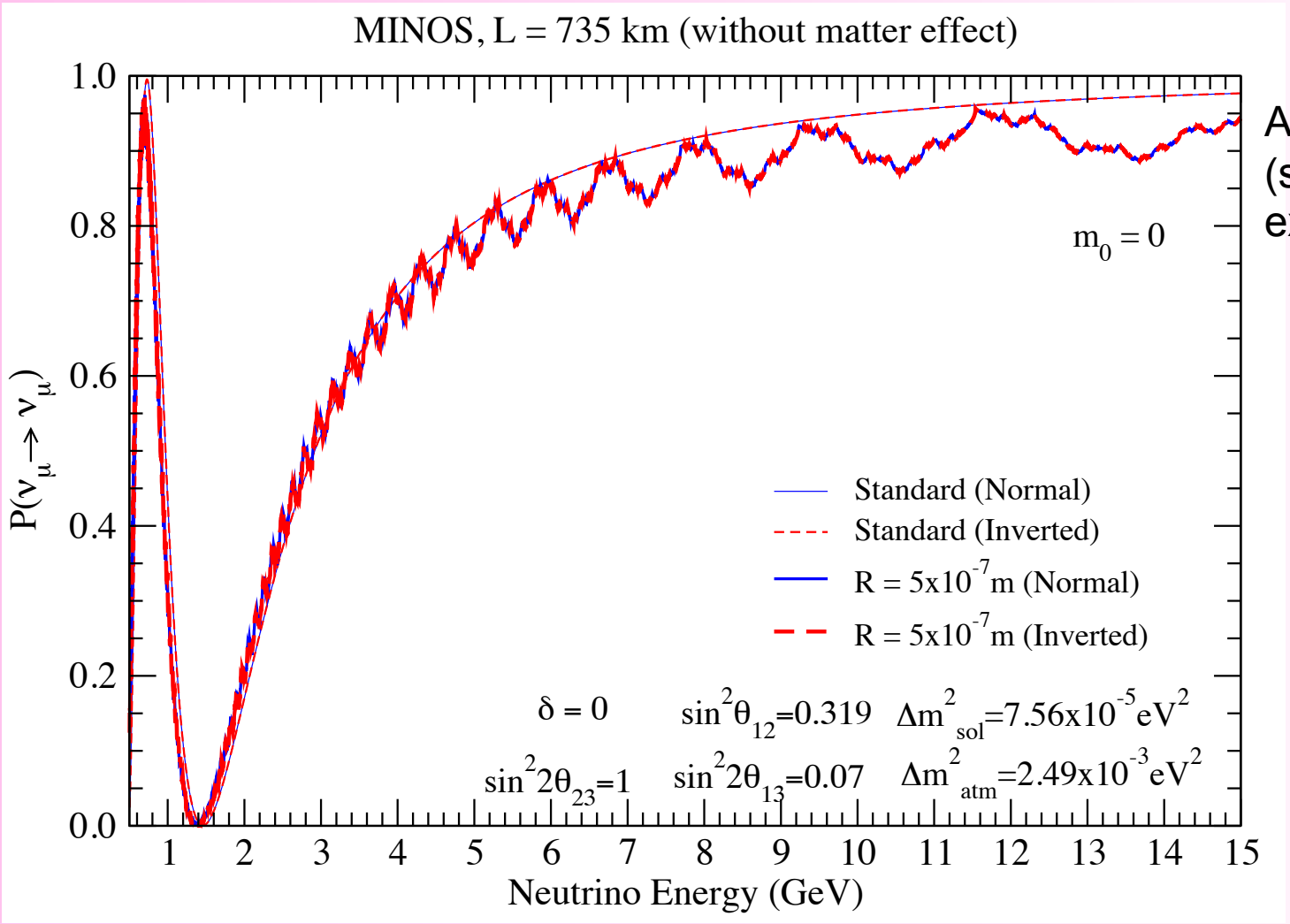
NON STANDARD INTERACTIONS

- Our anti-neutrino result has at least motivated some work from the theorists
- Note the NSI has a measurable effect in neutrinos as well as antineutrinos
- Comparison of low energy to high energy behaviour could disentangle this without anti-nu running
- *J. Kopp, P.A.N. Machado and S.Parke, Phys.Rev.D82:113002,2010*



EXTRA DIMENSIONS

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

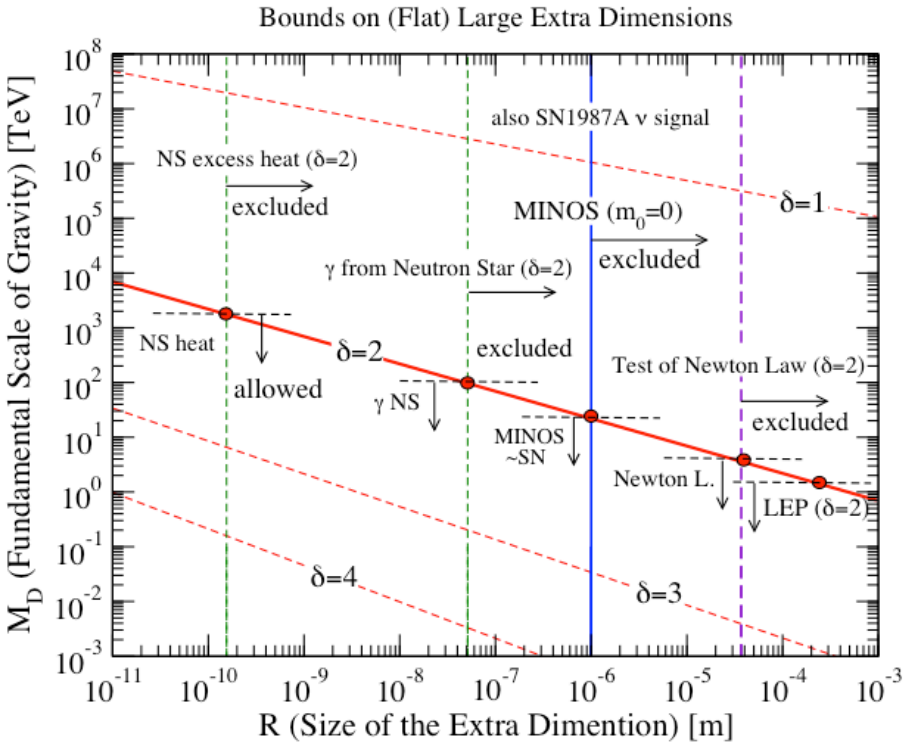


Assumes RH (sterile) neutrino + extra dimensions!

After 1 year post nova running

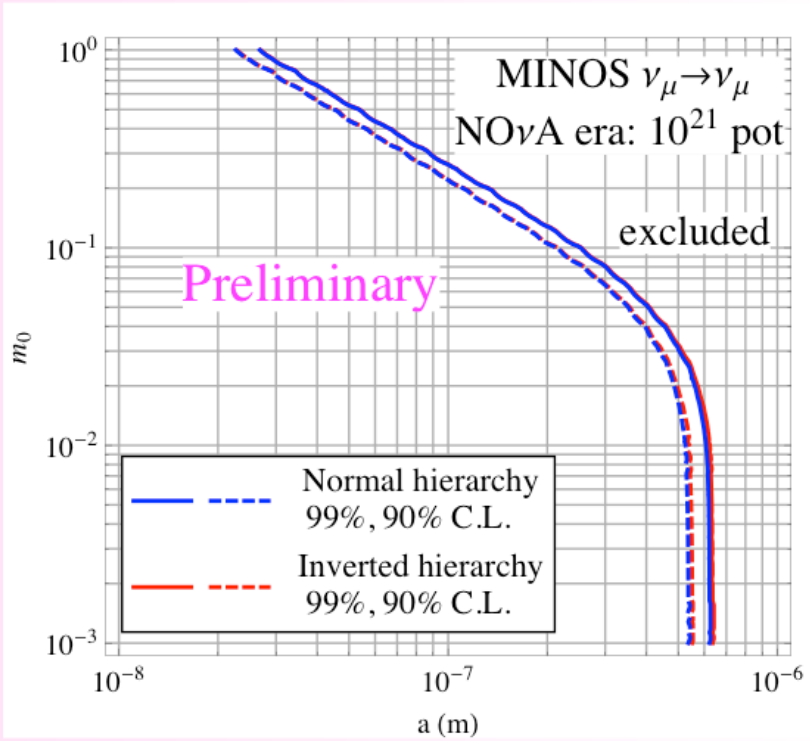
EXTRA DIMENSIONS

P.A.N.Machado,H.Nunokawa,R.Zukanovich



Refs. Giudice and Wells, PDG2010, JPG37, 075021 (2010), p1354
Hannestad and Raffelt, PRD67, 125008 (2003) [Erratum, PRD69, 029901 (2004)]

$\overline{M}_{Pl}{}^2 = \overline{M}_D{}^{2+\delta} (2\pi R)^\delta$, $M_D = (2\pi)^{\delta/(2+\delta)} \overline{M}_D$, $\overline{M}_{Pl} = M_{Pl}/(2\pi)^{1/2}$



BEAM

- Off axis Nova ND
- On Axis MINOS ND
- Electron component Minerva
- A good flux measurement helps everyone
  - We do not have precision on this yet!
  - Expectation of < 5% per 0.5 GeV bin

NEUTRINO MASS

- It is arguable that the fact of neutrino mass does tell us that there is physics at the GUT scale
- The massive RH-Majorana neutrinos which seem to be there naturally via the see-saw mechanism are the favored explanation as to why neutrino mass is so small
- We should look everywhere for this evidence, not just in $\nu_\mu \rightarrow \nu_e$
- The NuMI/MINOS/Nova facility will be unique in the world
  - No other wide band/narrow band beam facility exists now

CONCLUSION

- MINOS has made a step change in our understanding of neutrino oscillation parameters and cross sections using accelerator generated neutrinos
- Some interesting measurements still to be made in the neutrino oscillation field
  - MINOS: ν_e, anti-neutrinos
  - Nova and T2K: θ_{13}
  - MINOS+ intermediate energies
  - OPERA : more tau events
- The new understanding of neutrino oscillations puts a search for fundamental neutrino type (Majorana or Dirac) into the forefront, and into a window of experimental opportunity

LETS NOT BE ARROGANT ABOUT WHAT WE EXPECT TO SEE: NO REASON FOR STANDARD HIERARCHY, OR DIRAC NEUTRINOS