RECENT RESULTS FROM THE MINOS EXPERIMENT

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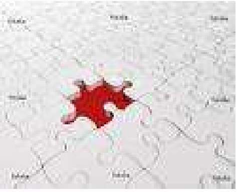
UCL

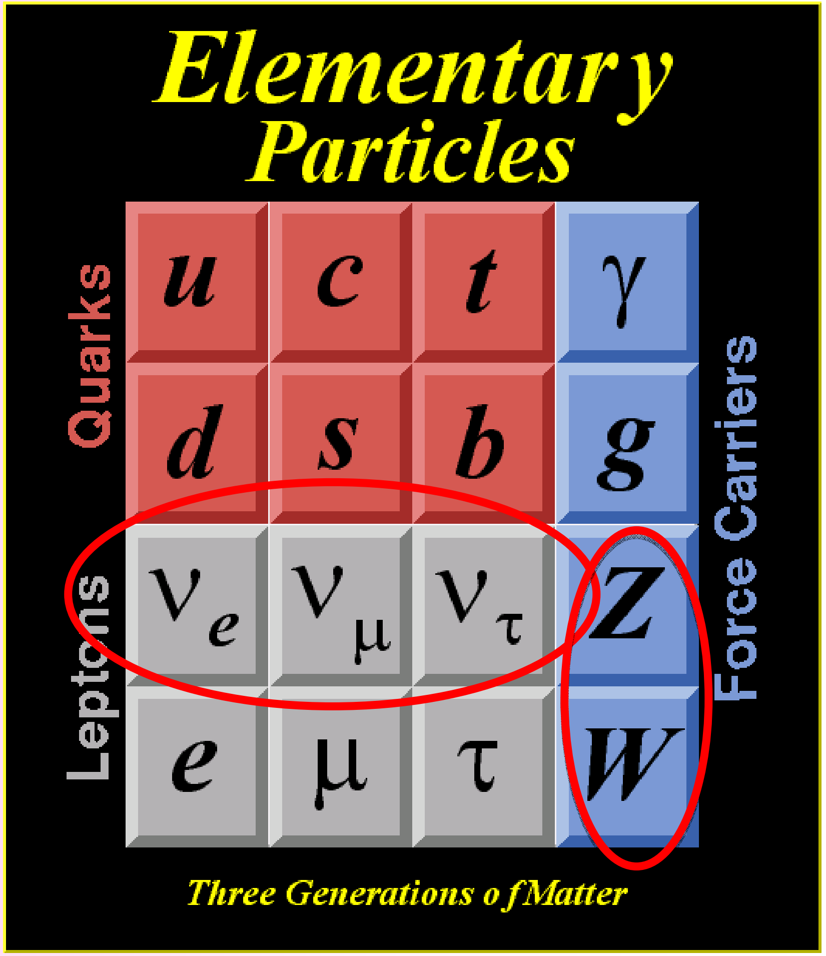
Preview

- **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**
  - Another year of running anti-neutrinos
- **Summary**
  - Lots still to do, picture still missing pieces

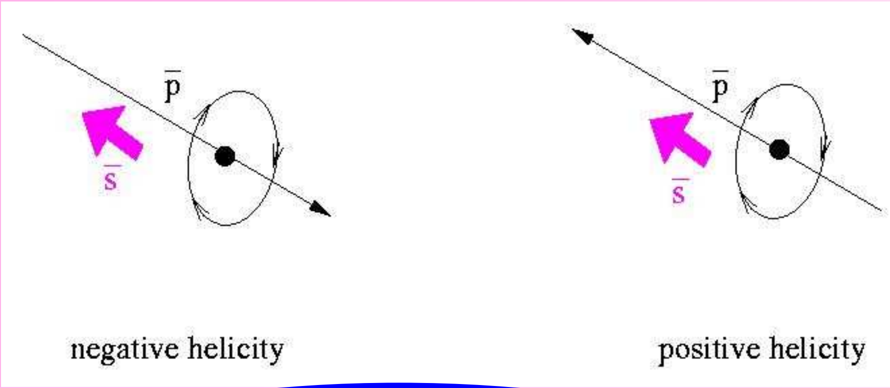


The Standard Model

- Quarks, leptons and gauge bosons make up the elementary particles
- Three generations of leptons with ΔQ=1
- Three generations of quarks with ΔQ=1
- Three interactions, weak, EM and strong
- Neutrinos are the only neutral fermion



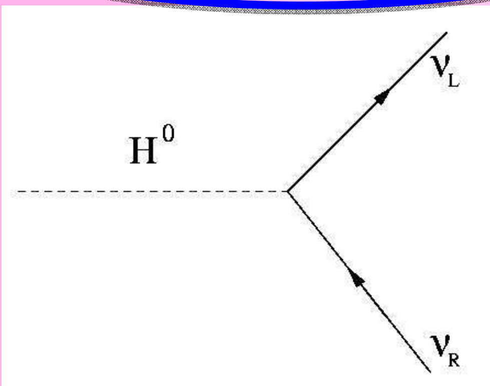
NEUTRINO PROPERTIES



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 !

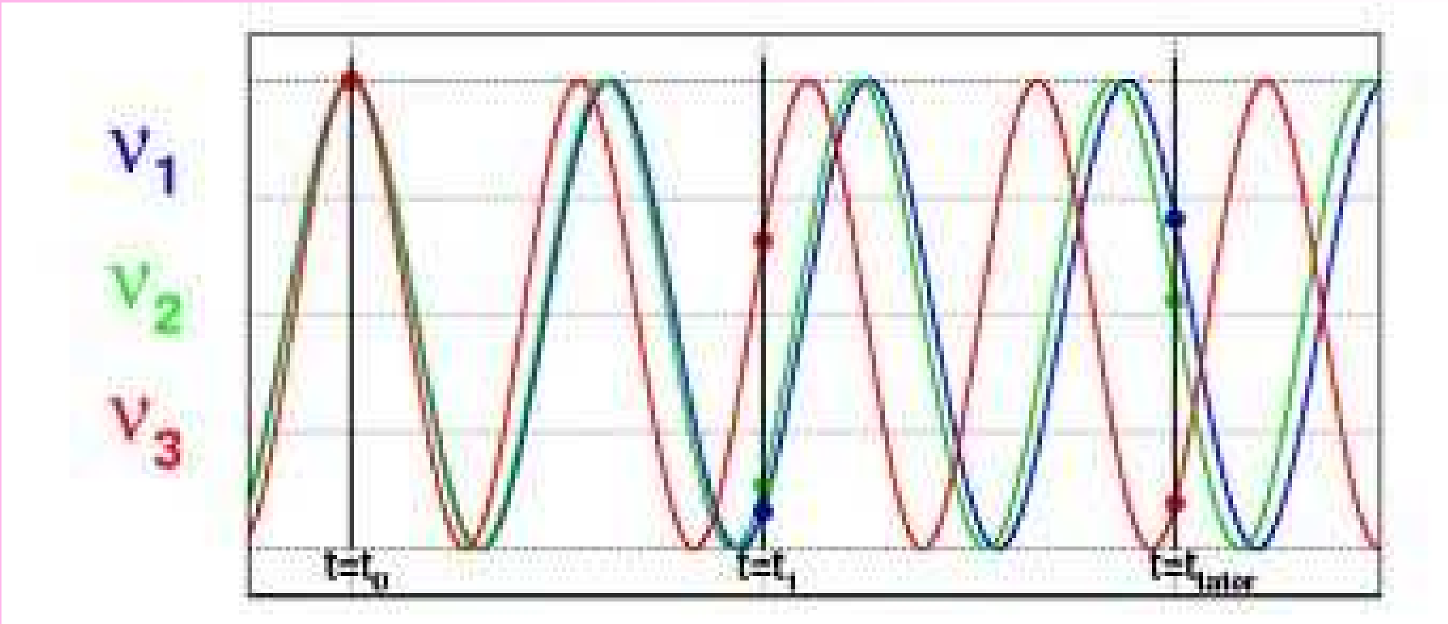
Weak interaction violates parity



- 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)
- This if the neutrinos were DIRAC particles like the other quarks and leptons

NEUTRINO MASS

- IF NEUTRINOS ARE NOT MASSLESS, THEN THEY CAN OSCILLATE BETWEEN THE THREE MASS STATES



ν_μ ν_τ ν_e

NEUTRINO OSCILLATIONS

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

$$|\nu_e(0)\rangle = c_1|\nu_1\rangle + s_1 c_3|\nu_2\rangle + s_1 s_3|\nu_3\rangle$$

$$|\nu_e(t)\rangle = c_1 e^{-iE_1 t}|\nu_1\rangle + s_1 c_3 e^{-iE_2 t}|\nu_2\rangle + s_1 s_3 e^{-iE_3 t}|\nu_3\rangle$$

$$P(\nu_e \to \nu_\mu) = \left|\langle \nu_\mu | \nu_e(t)\rangle\right|^2 \qquad = \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$

$$= 1 - 2c_1^2 s_1^2 c_3^2[1-\cos(E_1-E_2)t] - 2c_1^2 s_1^2 s_3^2[1-\cos(E_1-E_3)t] - 2s_1^4 s_3^2 c_3^2[1-\cos(E_2-E_3)t]$$

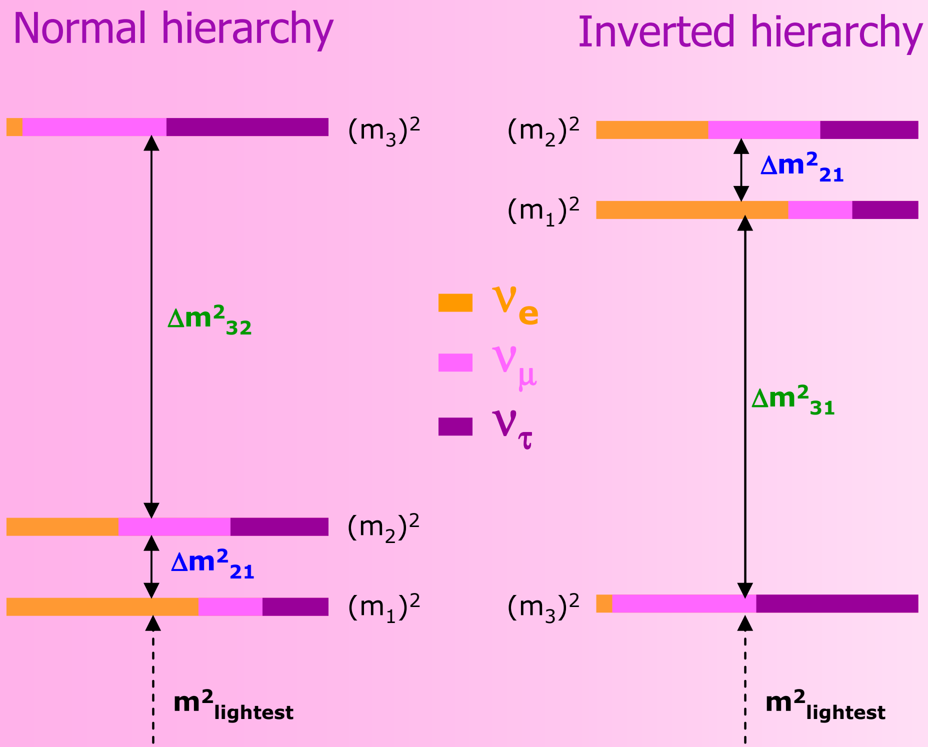
$$E_i = p + \frac{m_i^2}{2p}, E_i - E_j = \frac{(m_i^2 - m_j^2)}{2p}$$

NEUTRINO SECTOR STATUS

Solar&Reactor Atmospheric Reactor/LBL Double Beta

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

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}C_{12}C_{13} & C_{13}S_{12} & S_{13}\\ -C_{23}S_{12}e^{i\delta}-C_{12}S_{13}S_{23} & C_{12}C_{23}e^{i\delta}-S_{12}S_{13}S_{23} & C_{13}S_{23}\\ S_{23}S_{12}e^{i\delta}-C_{12}C_{23}S_{13} & -C_{12}S_{23}e^{i\delta}-C_{23}S_{12}S_{13} & C_{13}C_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



3 light neutrino flavours: e, μ, τ

Δm^2_{21} : (7.0 - 9.1) × 10^{-5} eV^2
TAN$^2\theta_{12}$: 0.34 – 0.62

Δm^2_{32} : ($2.35^{+0.11}_{-0.08}$) × 10^{-3} eV^2
sin$^2\theta_{23}$: >0.91 (@90% C.L.)

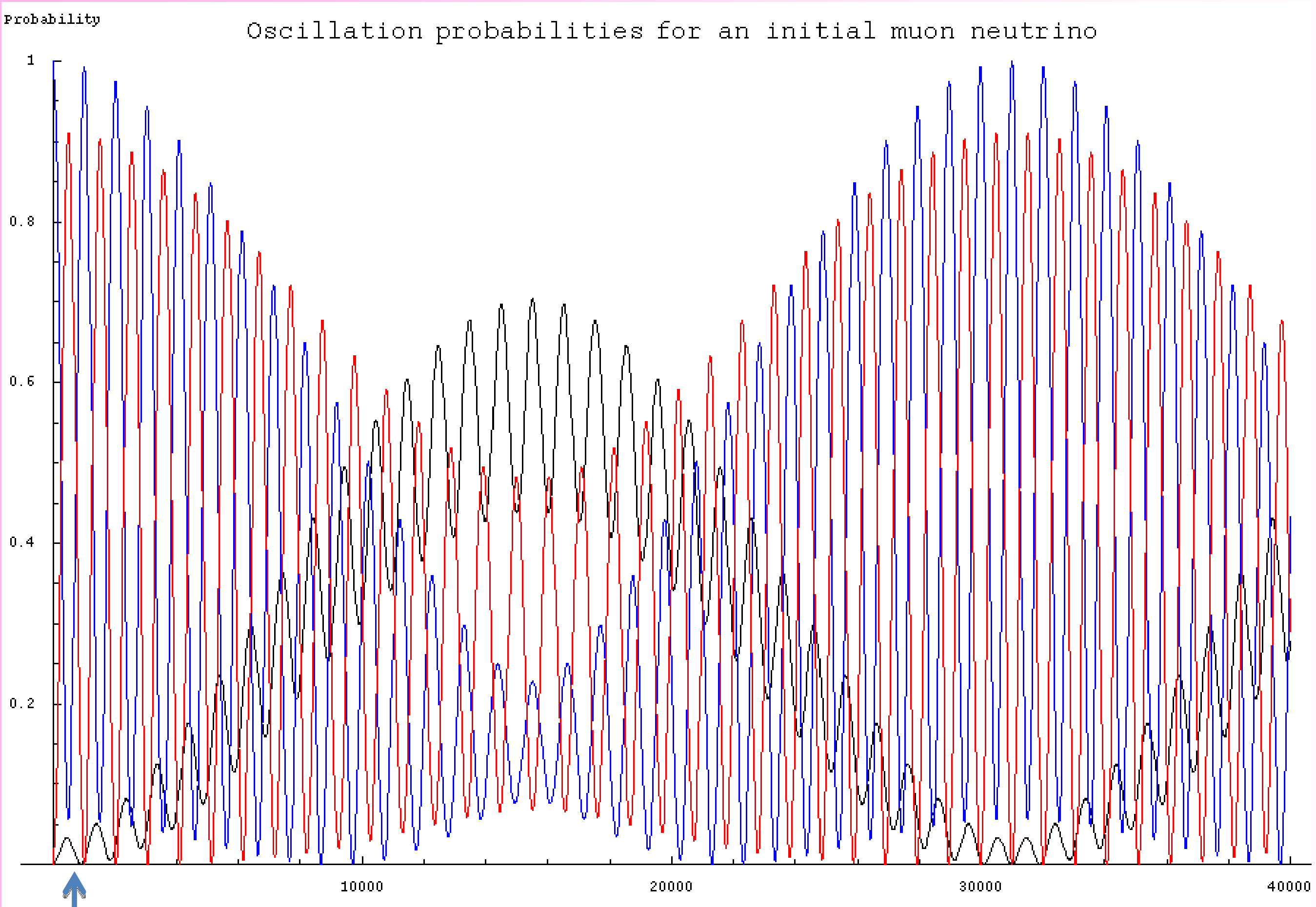
SIN$^2\theta_{13} \leq 0.045$
δ: unknown

Hierarchy **: unknown**

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

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

ν1 ν2 ν3



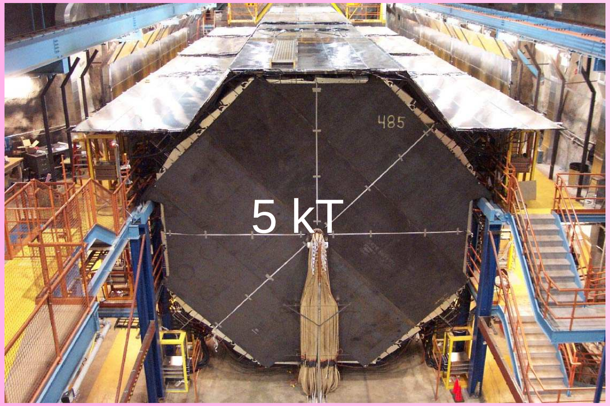
L/E (km/GeV)

MINOS

THE MINOS EXPERIMENT

- **GIVEN THE CONFUSING NATURE OF THE NEUTRINO**
  - choose a place where you have a big probability of seeing a n_m become one of its chums
  - L/E ~ 500 GeV is maximum probability of n_m disappearance without too much interference from n_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 νμ->νe

The MINOS Experiment

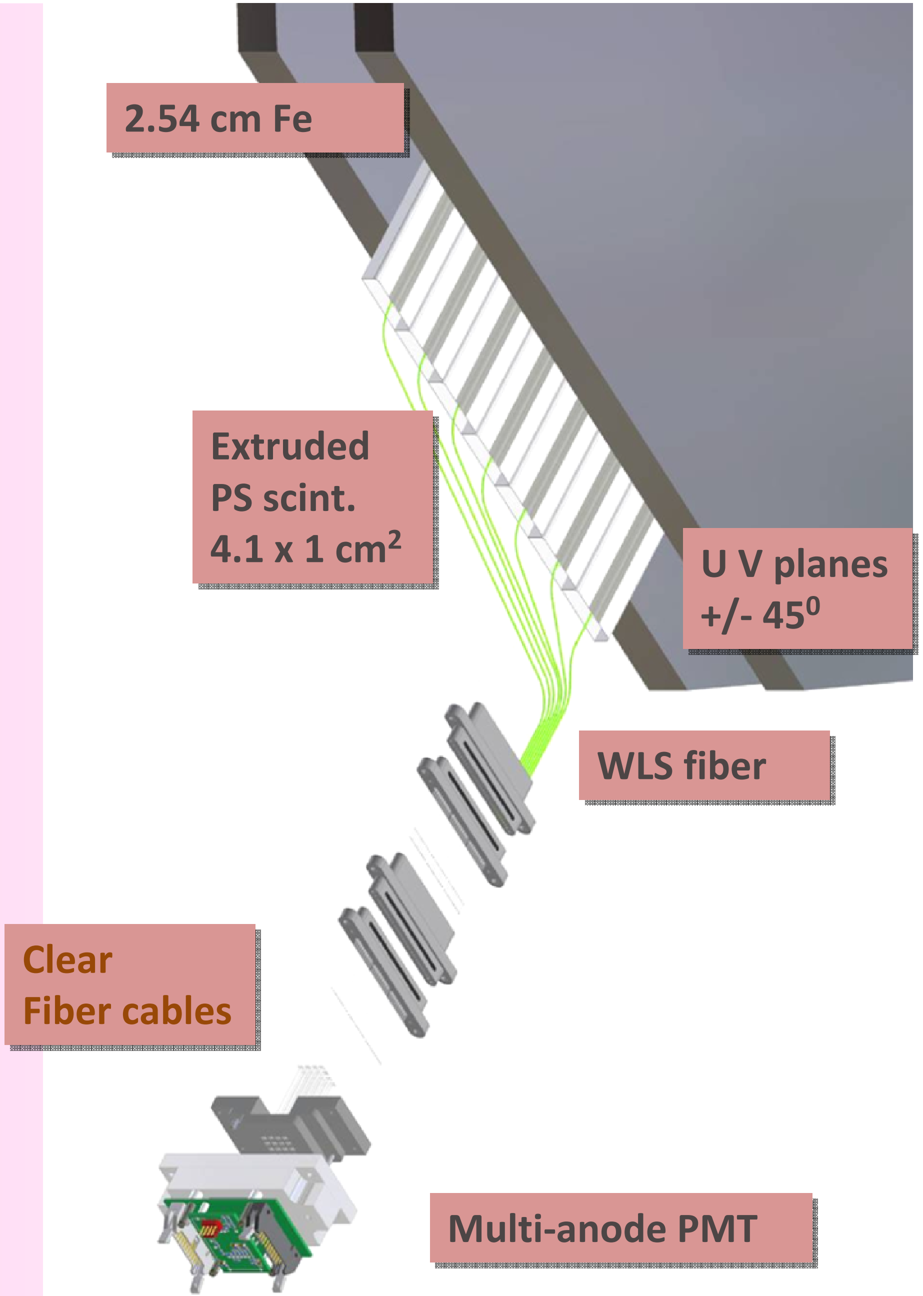


- Long baseline neutrino oscillation experiment
  - Neutrinos from NuMI
  - L/E ~500 km/GeV
  - Atmospheric neutrino L/E

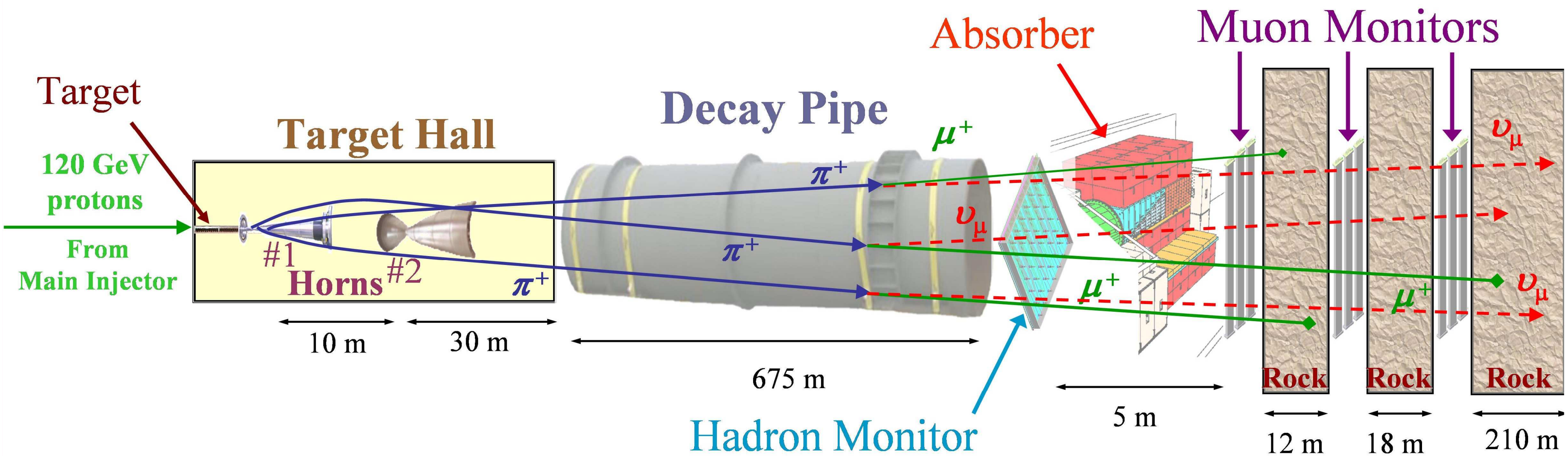
- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties
- Magnetic field measures charge

DETECTOR TECHNOLOGY

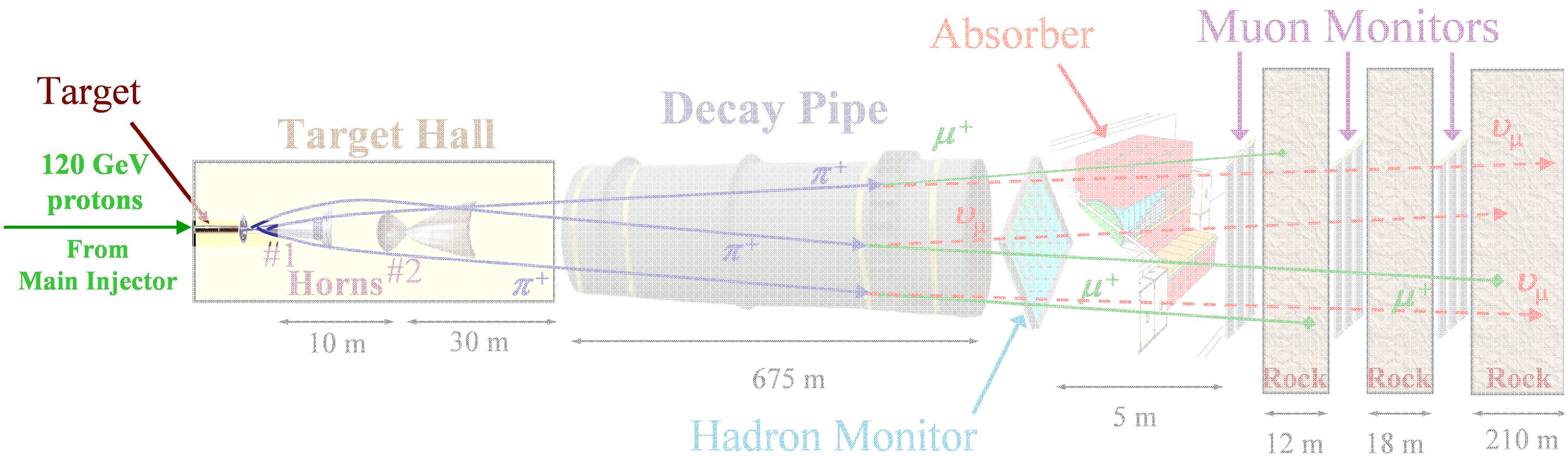
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same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



Making a Neutrino Beam

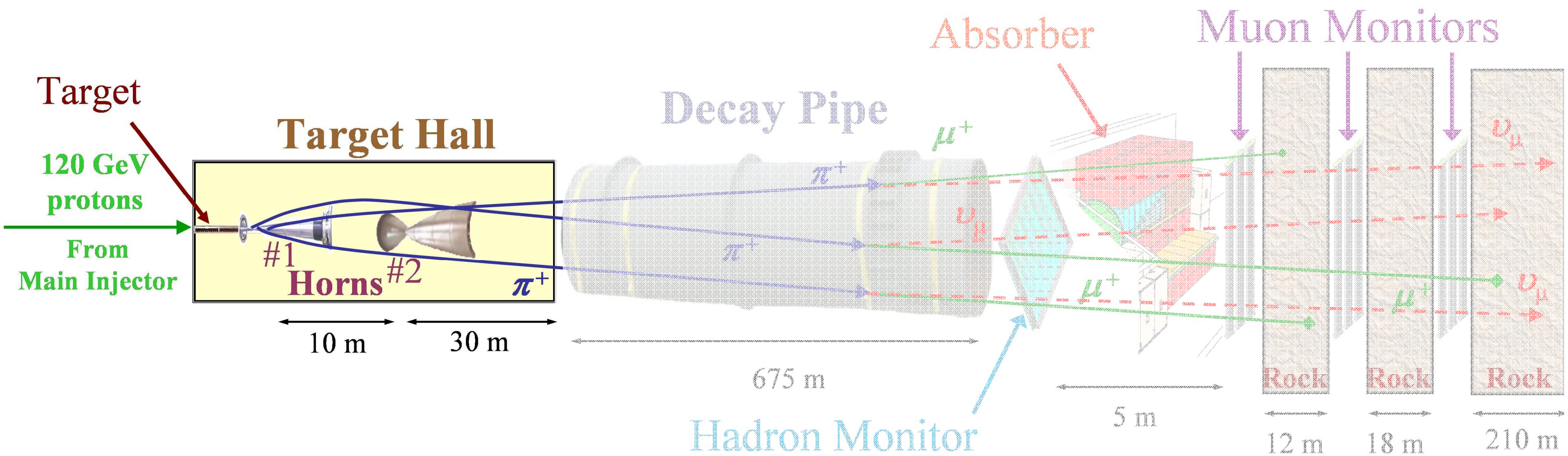


MAKING A NEUTRINO BEAM



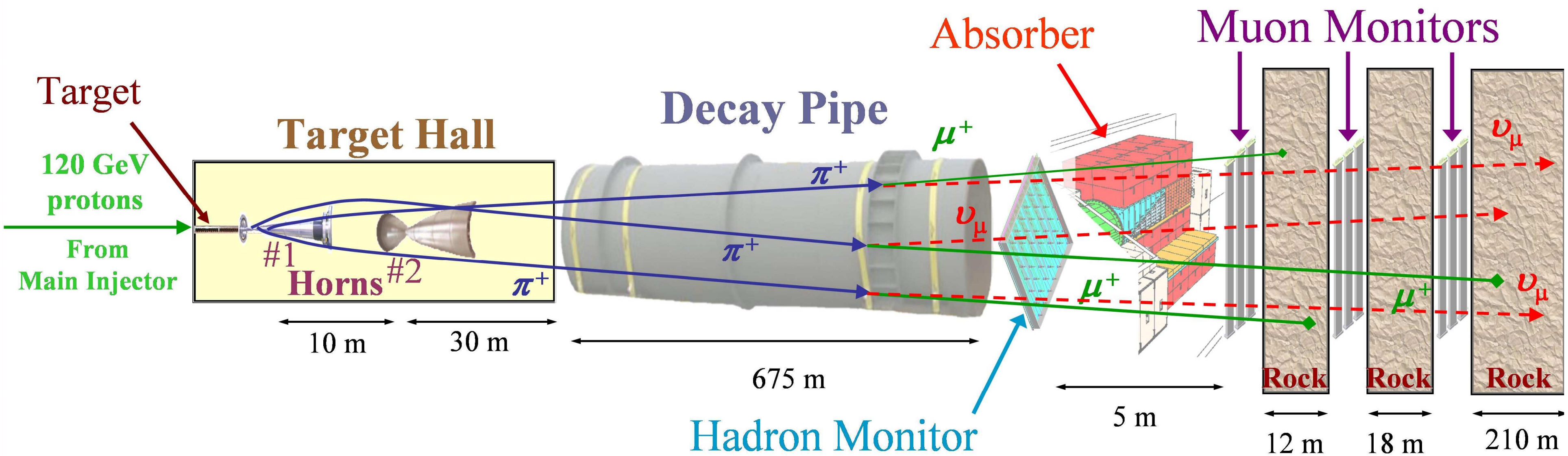
- **HADRON PRODUCTION**
  - bombard graphite target with 120 GeV p^+ from Main Injector
    - 2 interaction lengths
    - 310 kW typical power
  - produce hadrons, mostly π and K

Making a Neutrino Beam



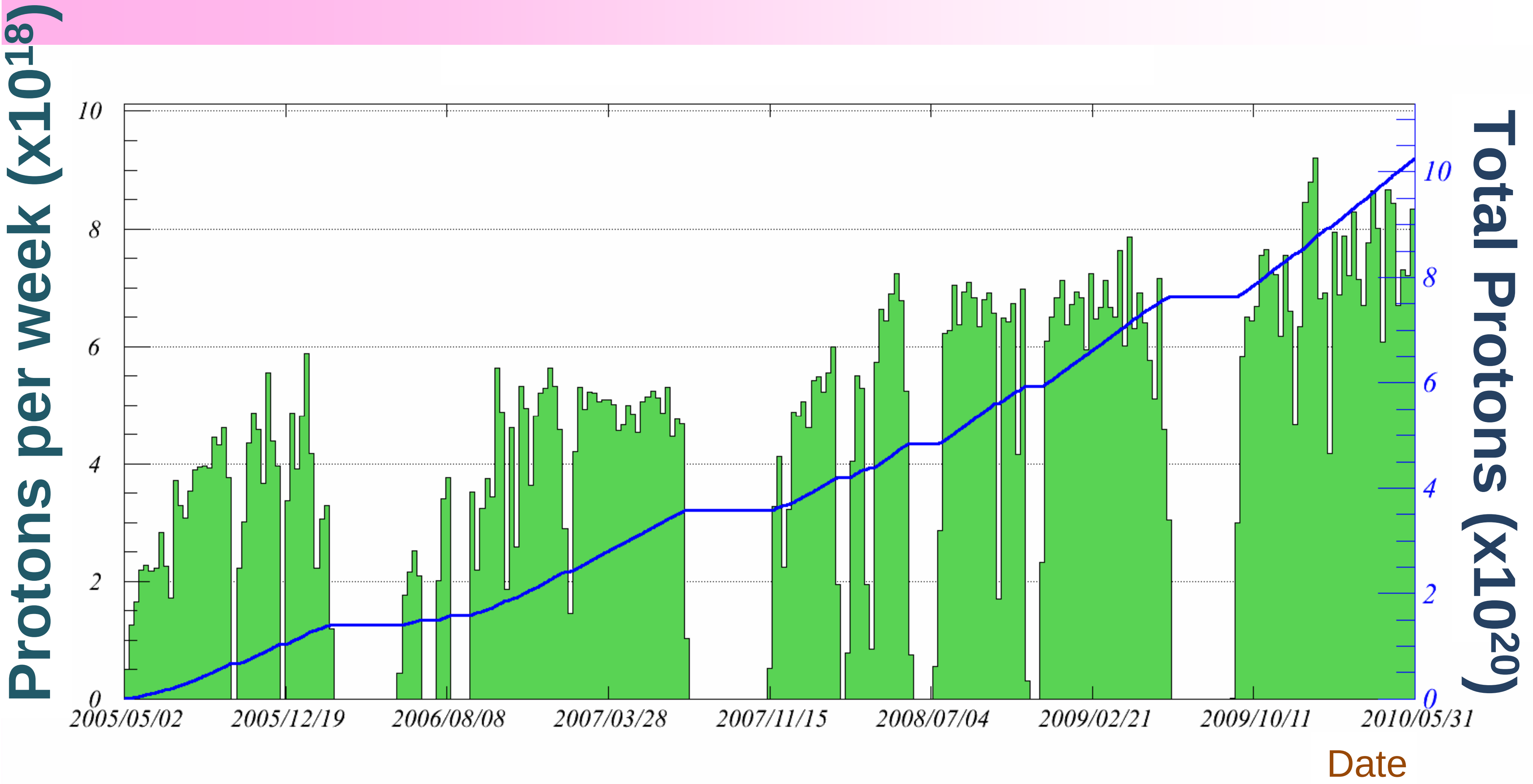
- **Focusing**
  - hadrons focused by 2 magnetic focusing horns
  - sign selected hadrons
    - forward current, (+) for standard neutrino beam runs
    - reverse current, (–) for anti-neutrino beam

Making a Neutrino Beam

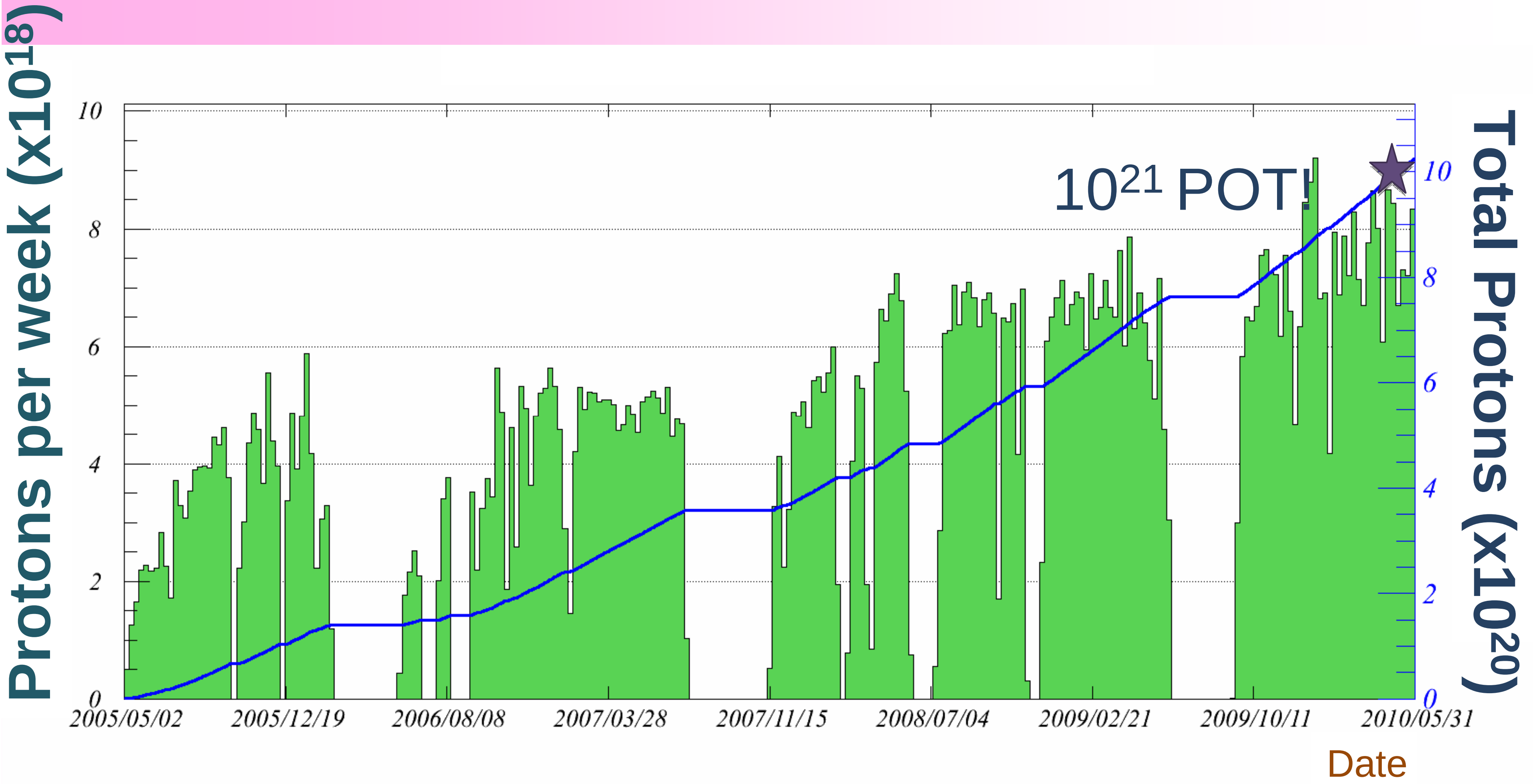


- **Decay**
  - 2 m diameter decay pipe, 660m length
  - result: wide band beam, peak determined by target/horn separation
  - secondary beam monitored

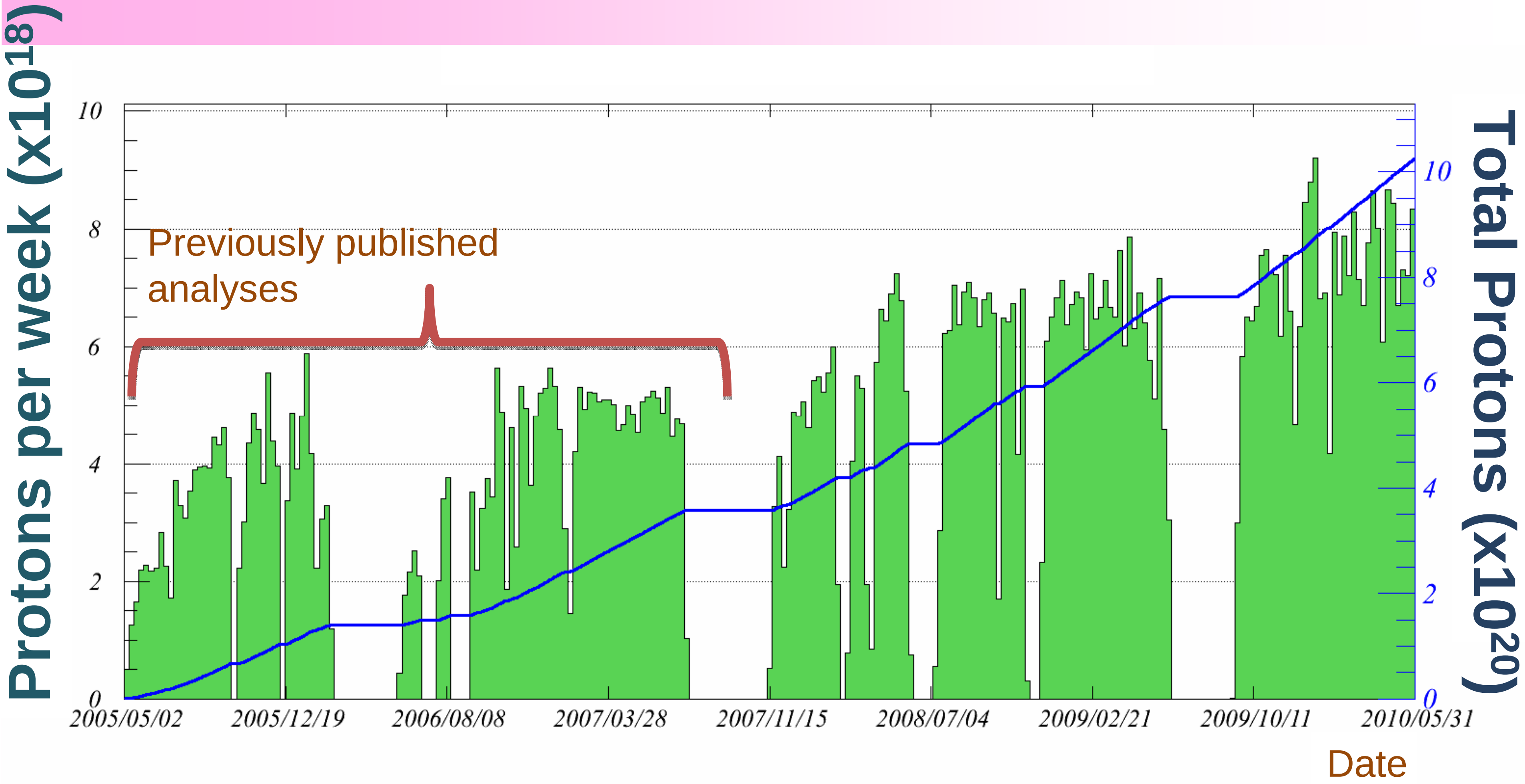
BEAM PERFORMANCE



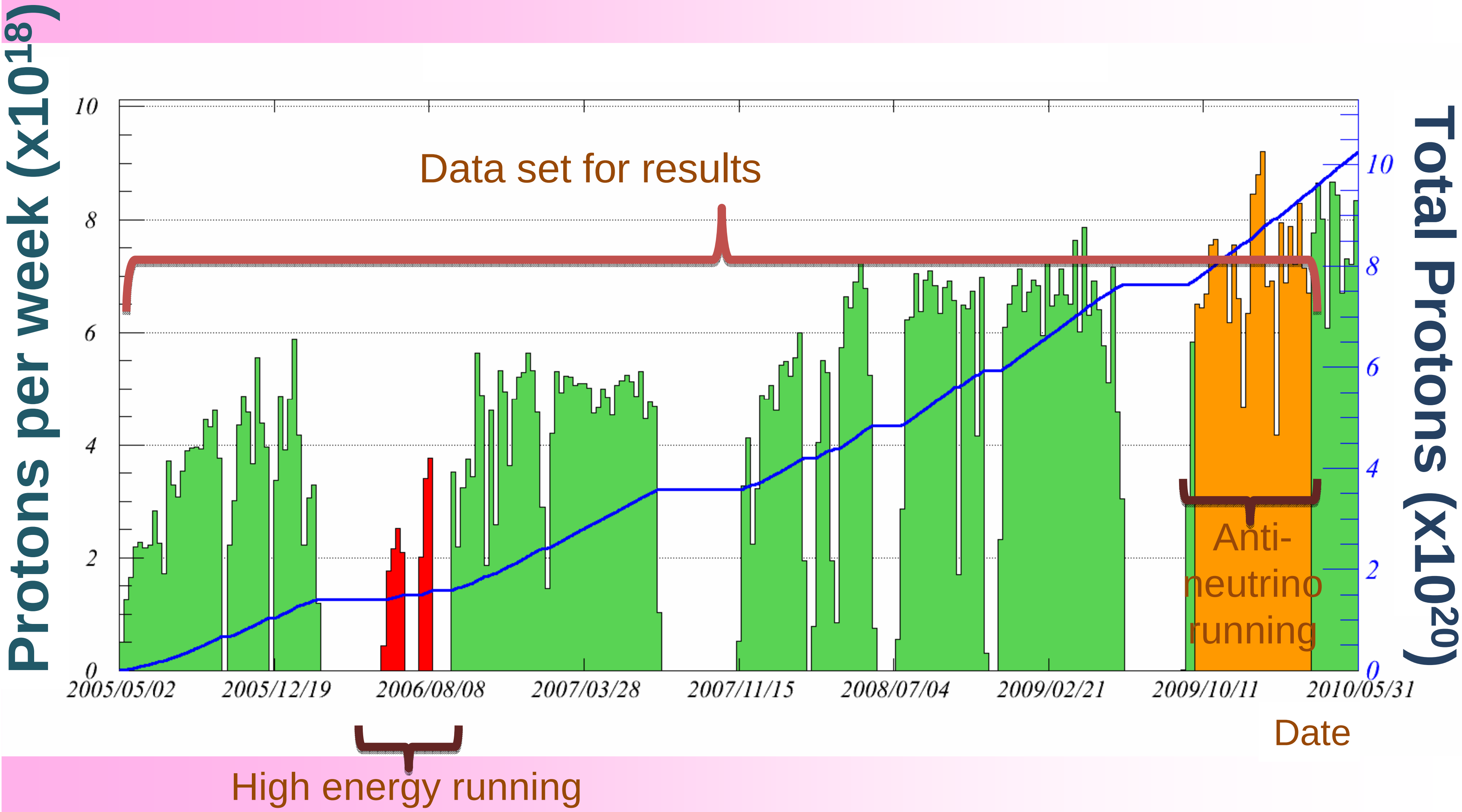
BEAM PERFORMANCE



BEAM PERFORMANCE

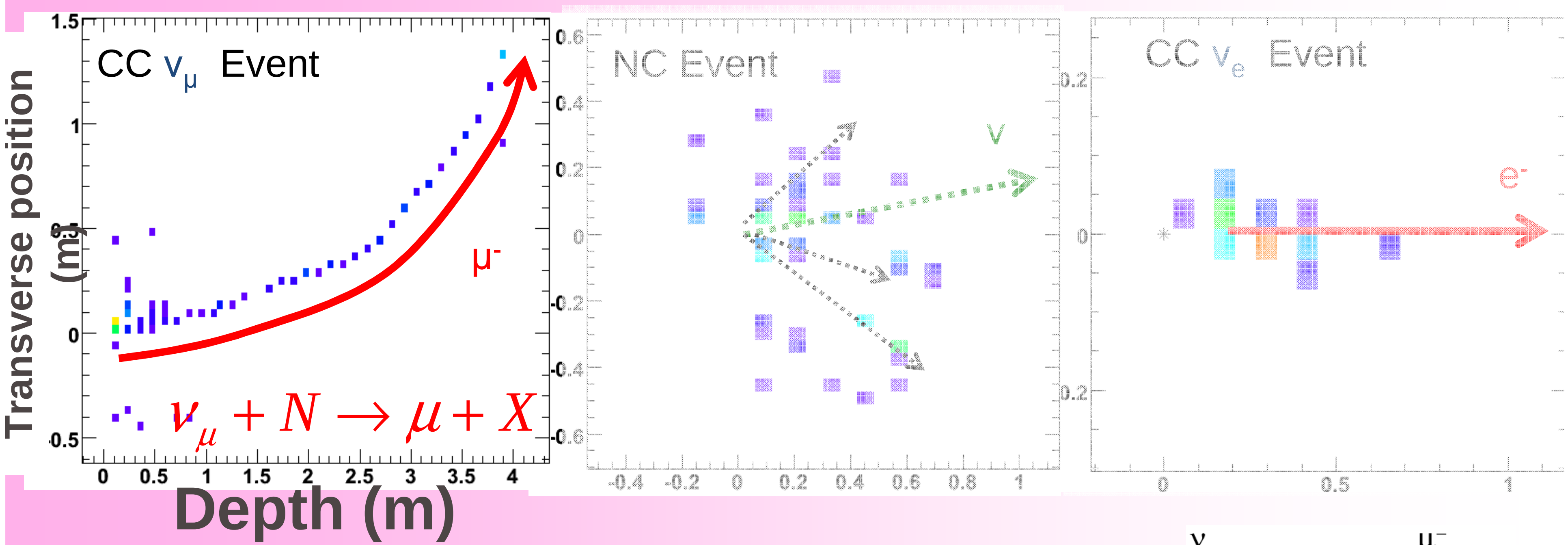


BEAM PERFORMANCE

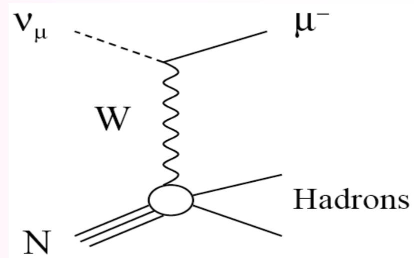


NEUTRINO EVENTS IN MINOS

Simulated Event



- 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

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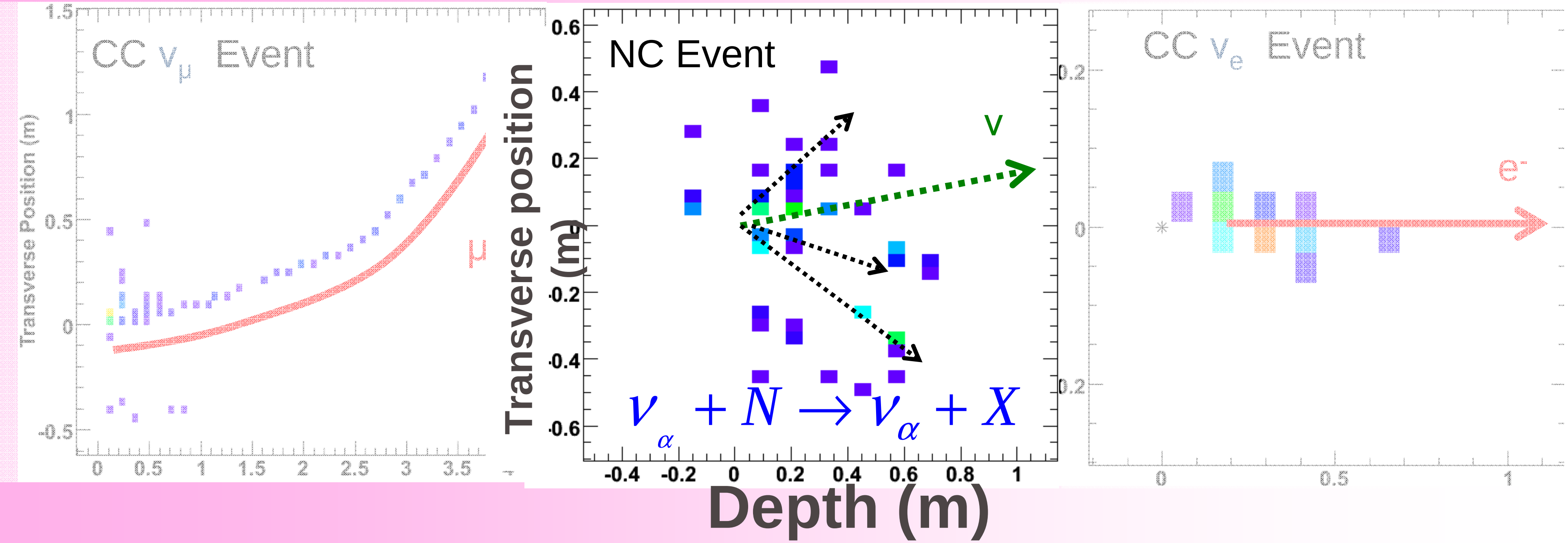
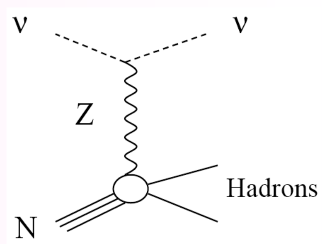
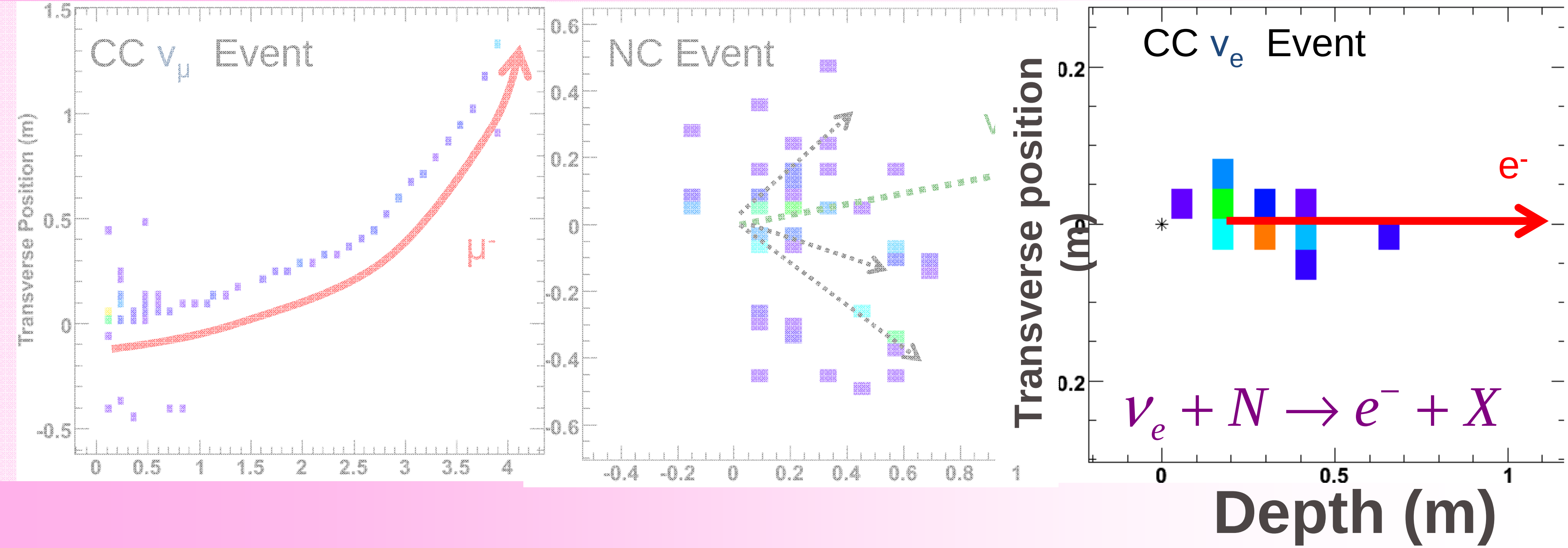


- **NEUTRAL CURRENT EVENTS:**
  - short, diffuse shower event
  - shower energy from calorimetric response

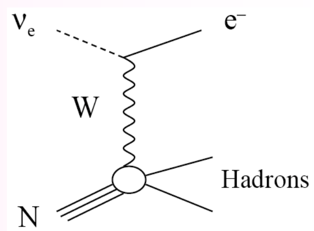


Events in MINOS

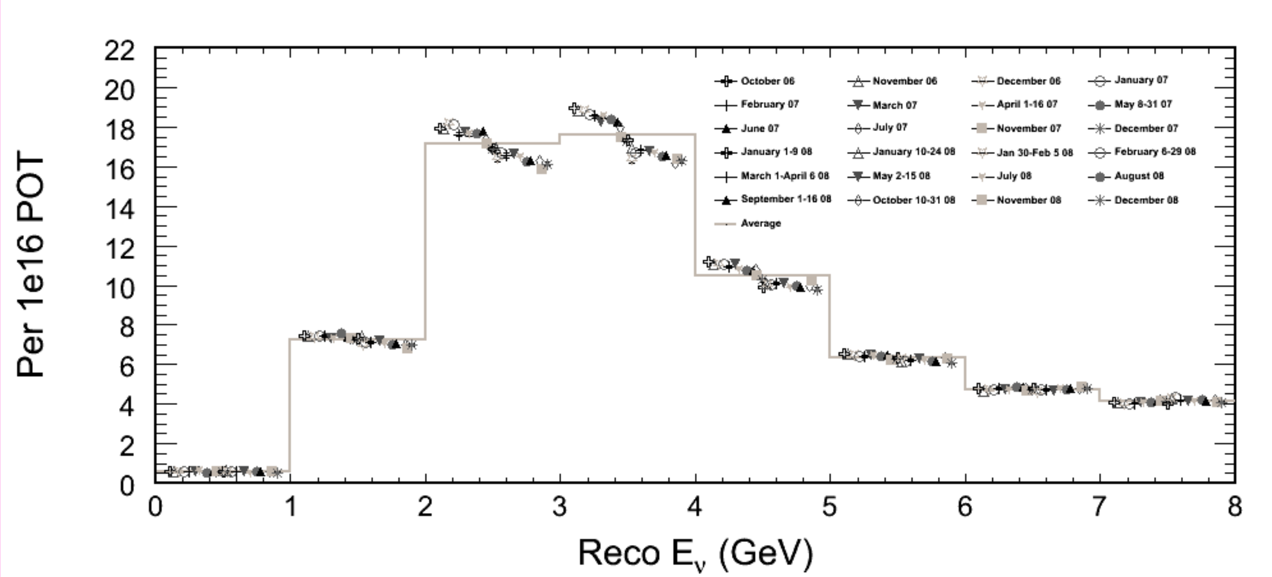
Simulated Events



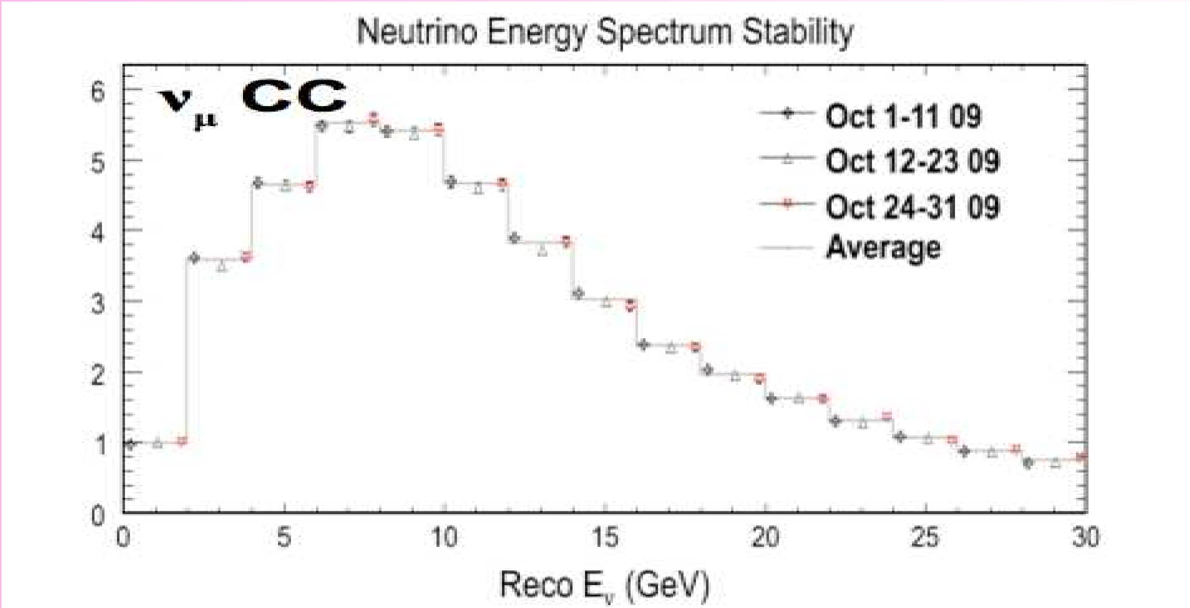
- ν_e **Charged Current Events:**
  - compact shower event with an EM core
  - neutrino energy from calorimetric response



NUMI TARGET



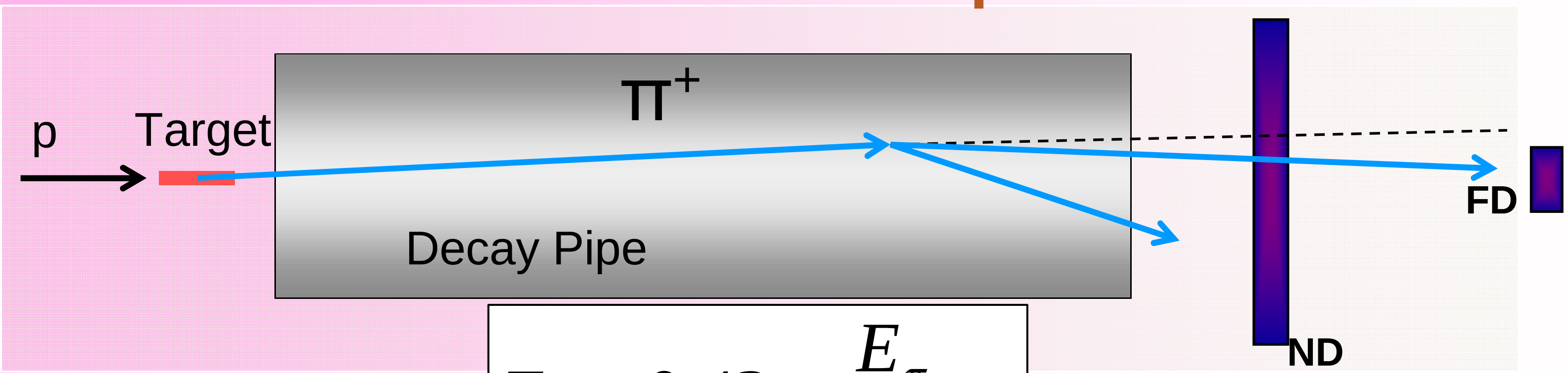
OLD



NEW

NEAR TO FAR

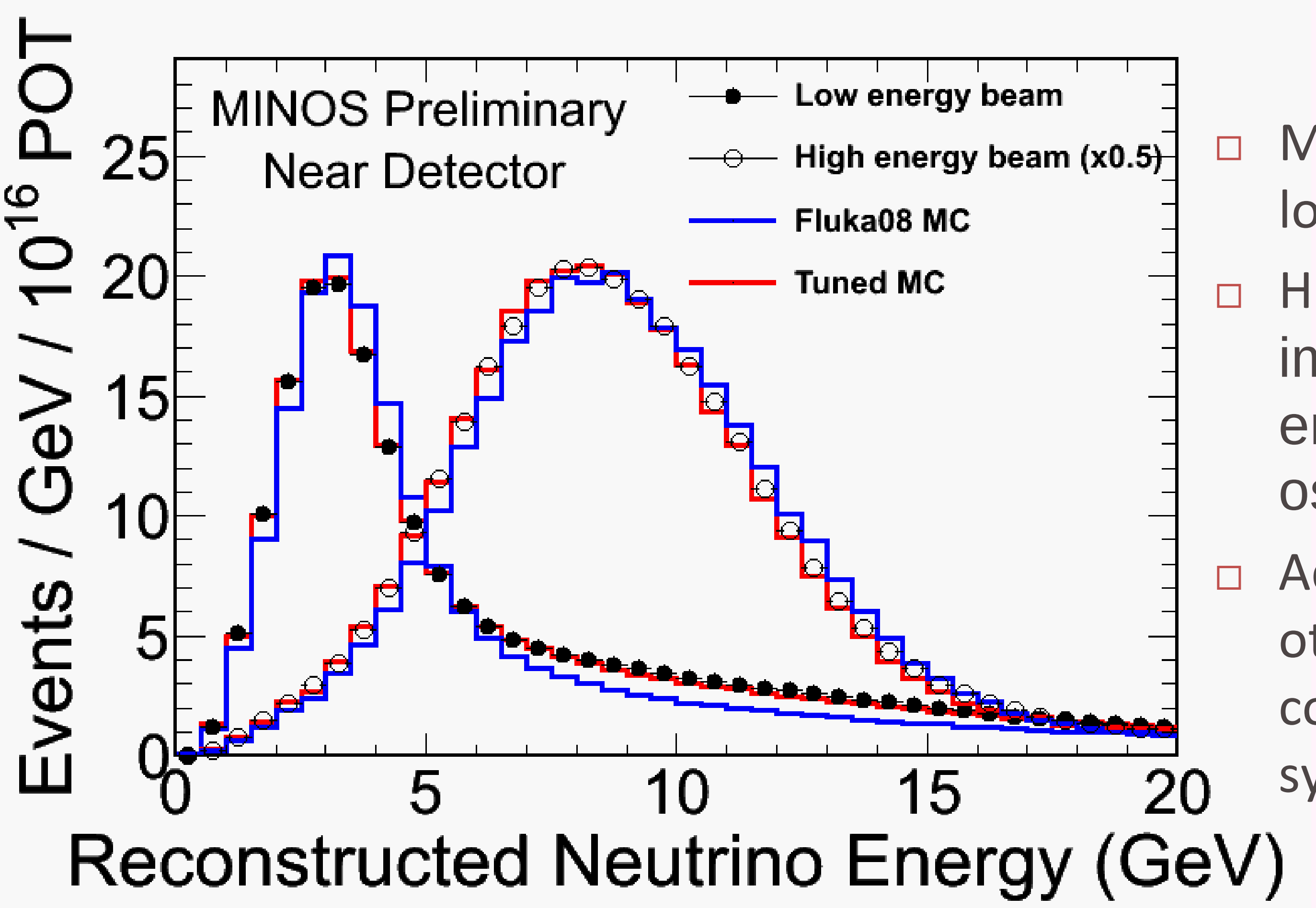
Far spectrum without oscillations is similar, but not identical to the Near spectrum!



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

- 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

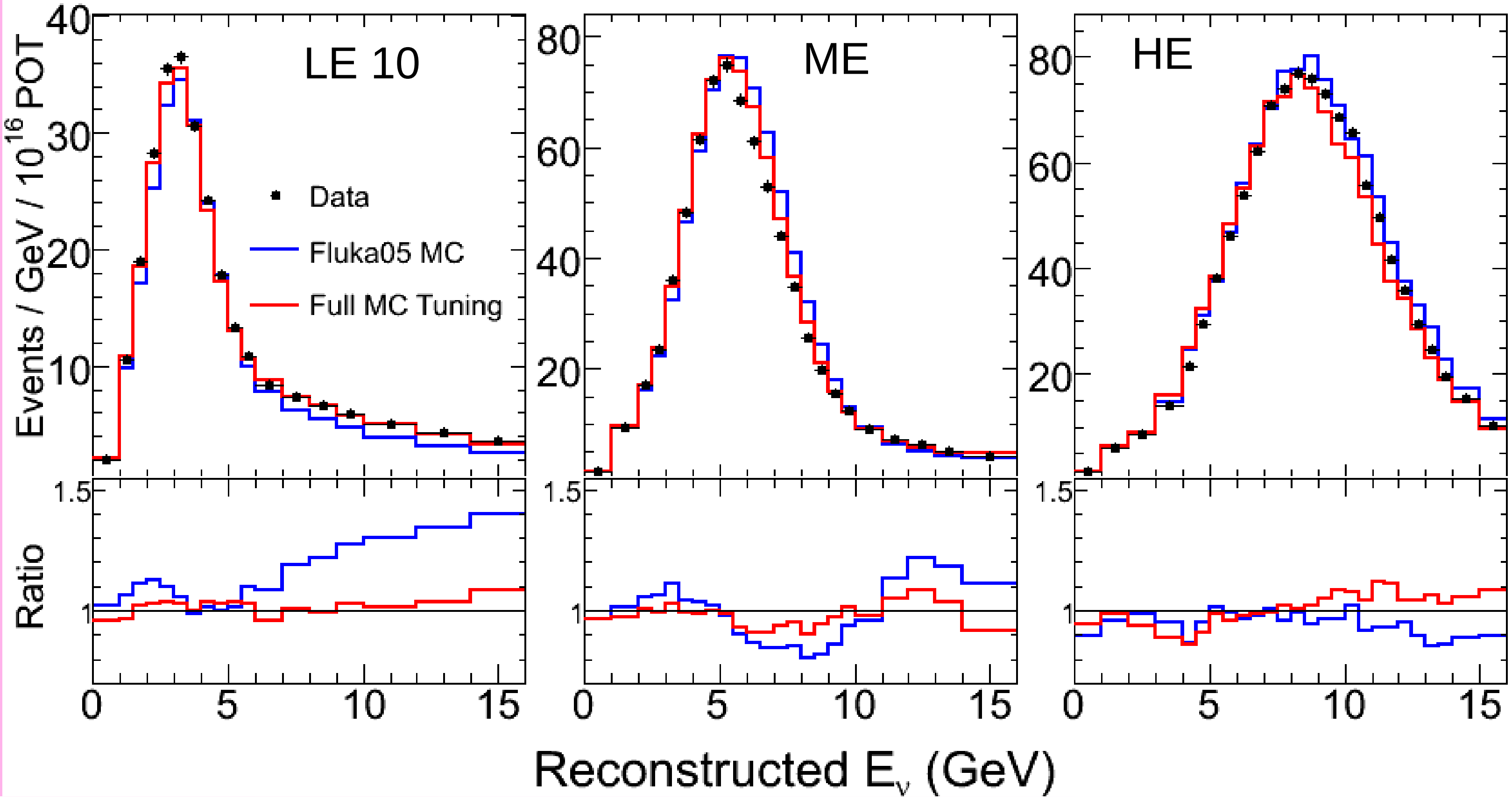
CC Events in the Near Detector



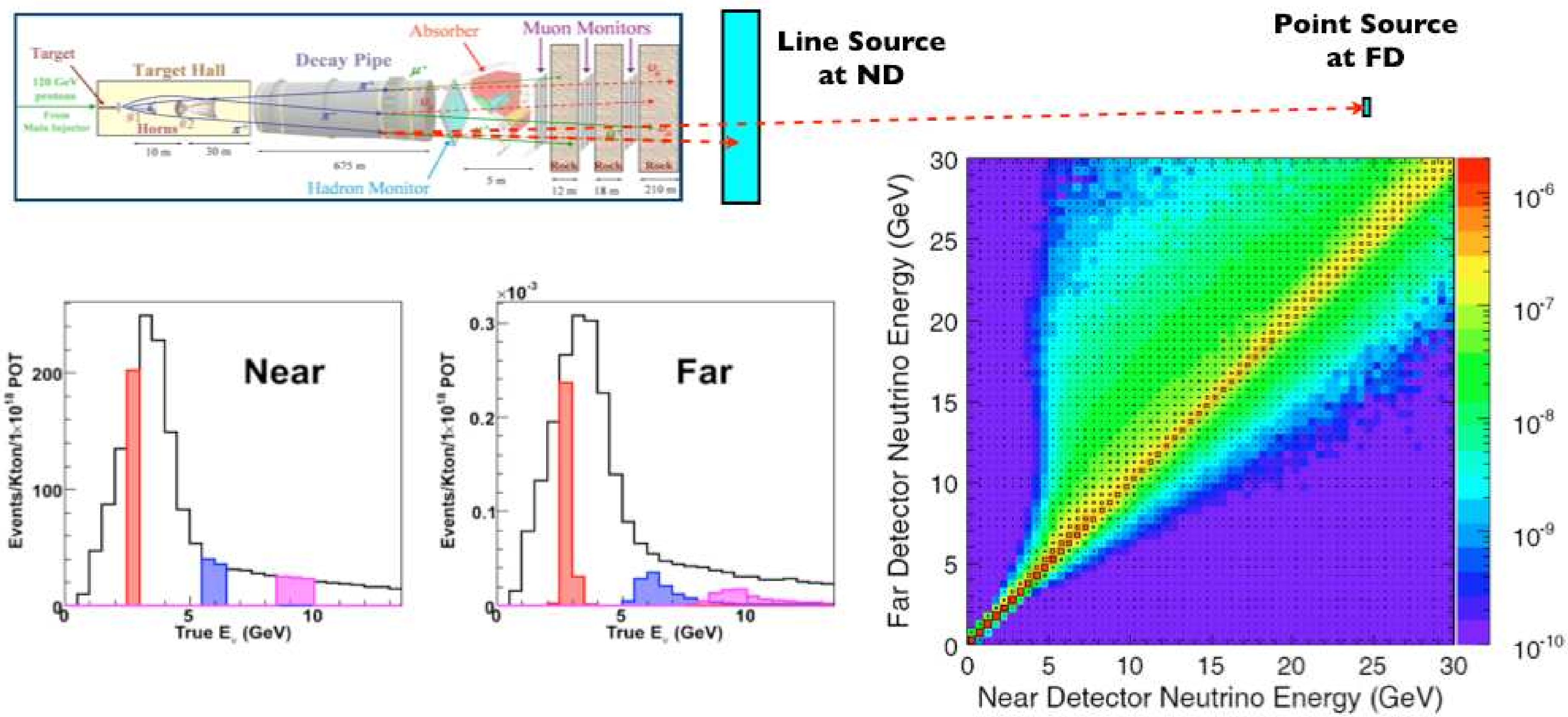
- Majority of data from low energy beam
- High energy beam improves statistics in energy range above oscillation dip
- Additional exposure in other configurations for commissioning and systematics studies

NEUTRINO SPECTRUM

- Use flexibility of beam line to constrain hadron production, reduce uncertainties due to neutrino flux



EXTRAPOLATION

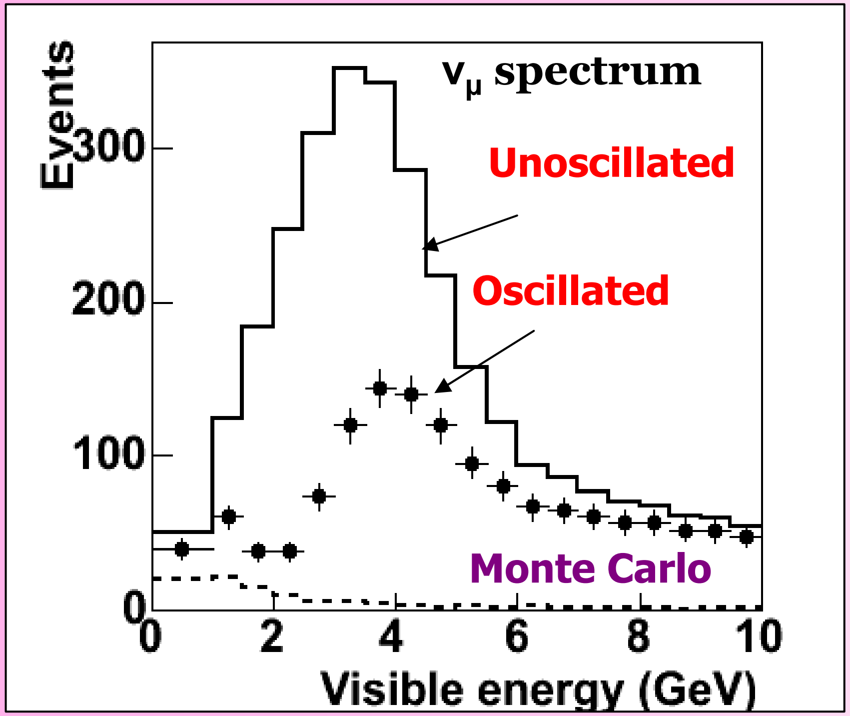


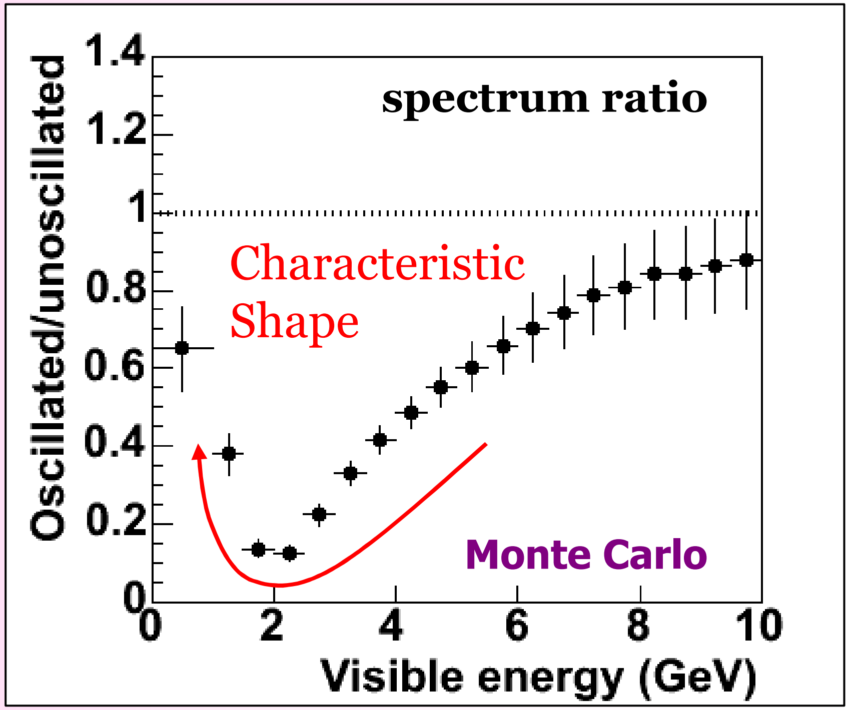
Near Detector energy spectrum extrapolated to Far Detector, using MC to provide energy smearing and correct for detector acceptance

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

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



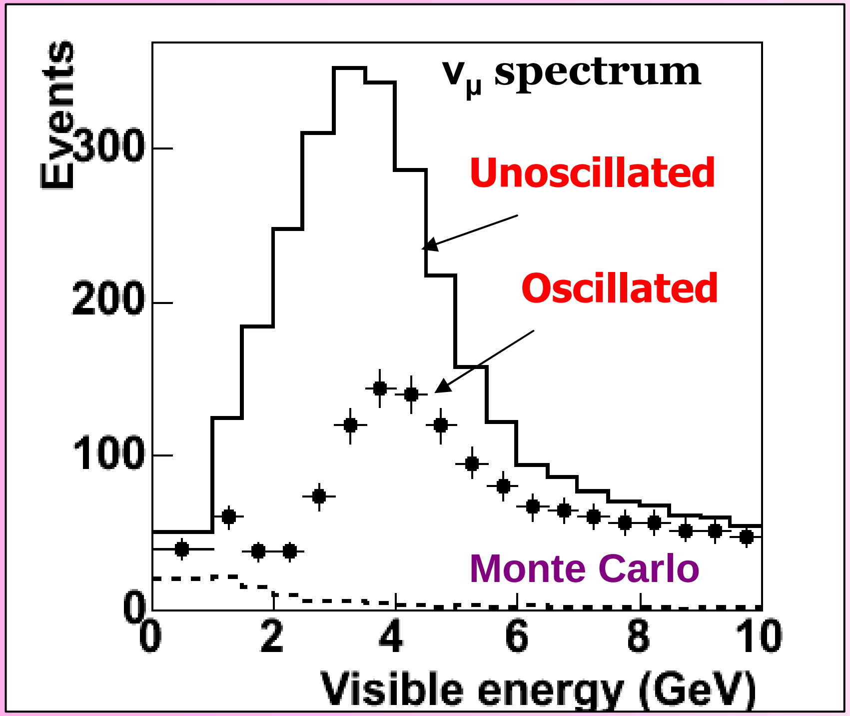


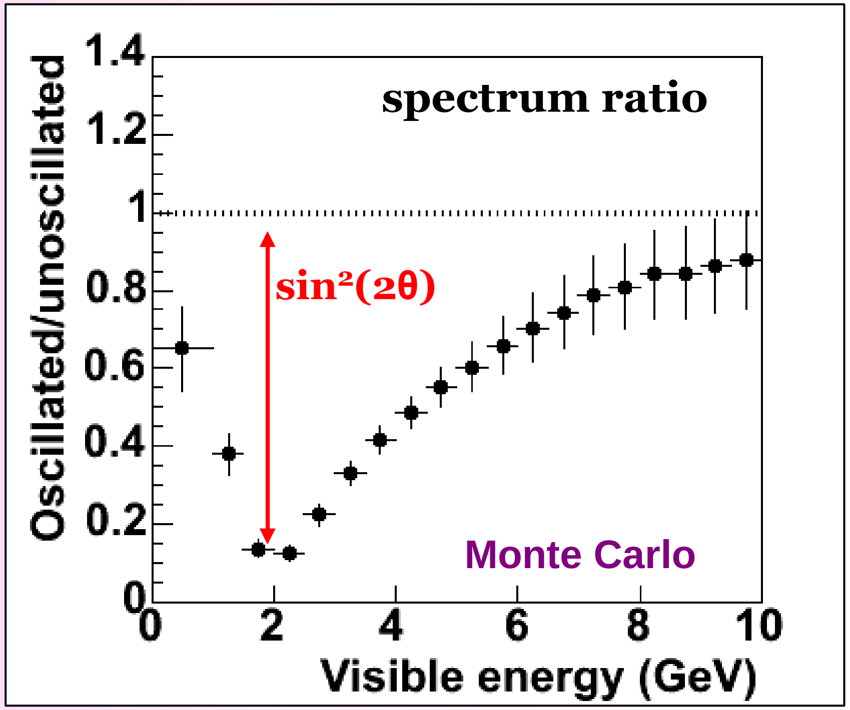
(**Input parameters:** $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2)

ν_μ DISAPPEARANCE

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

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





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ν_μ Disappearance

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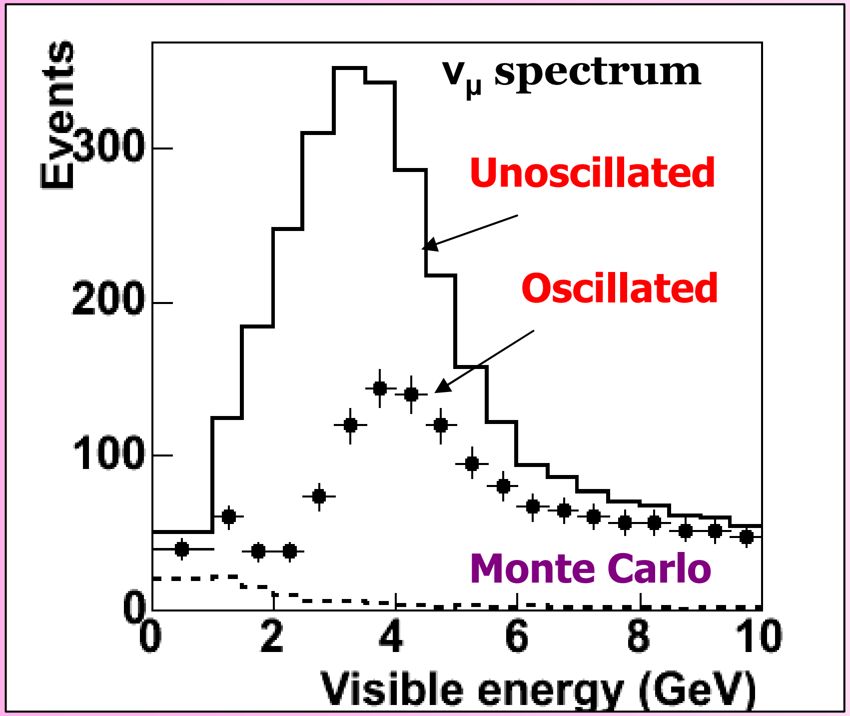

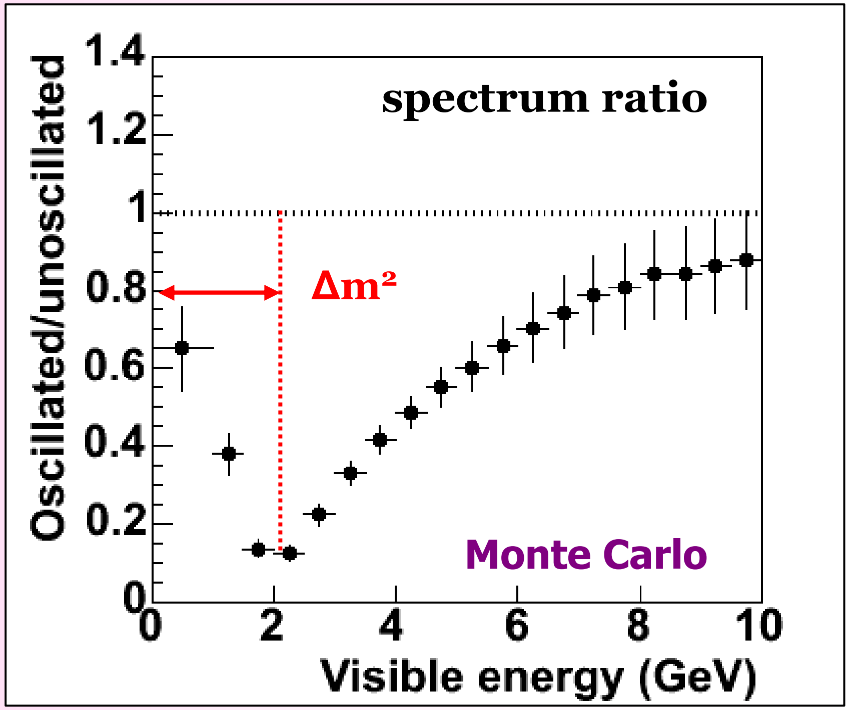

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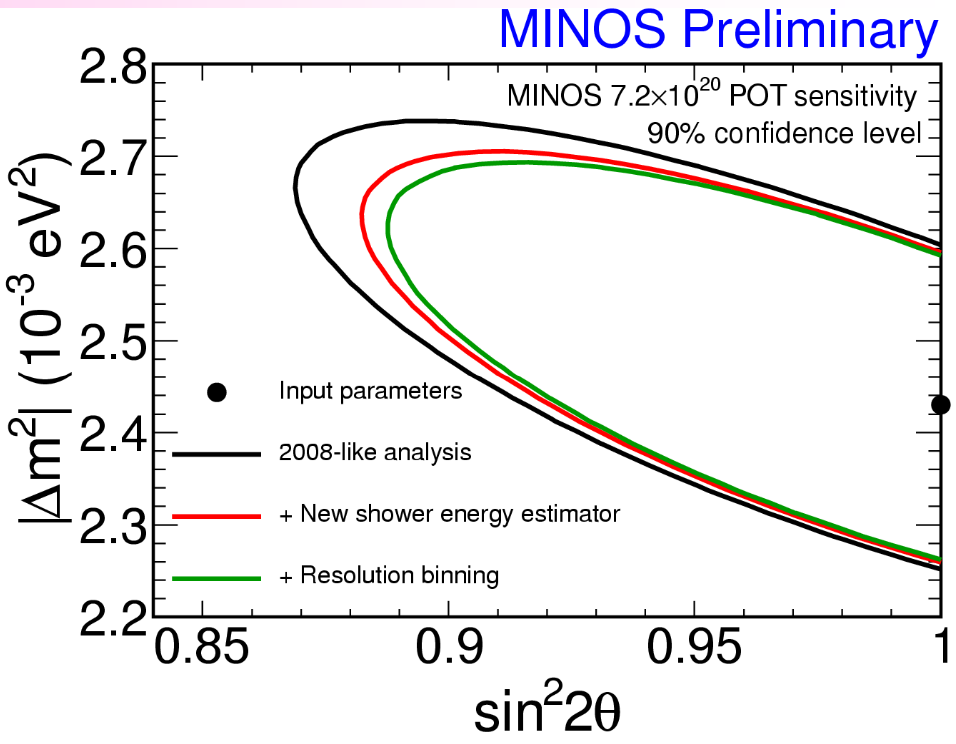
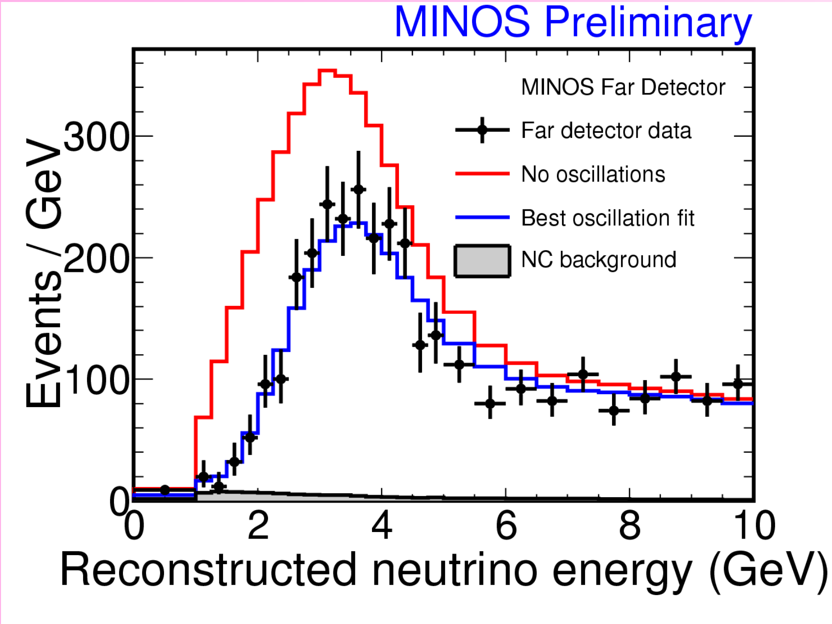
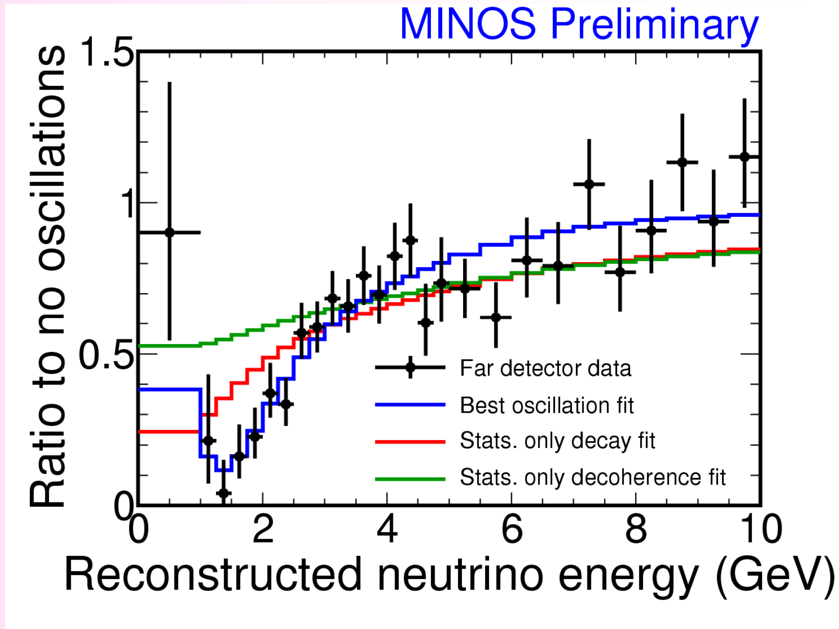
ANALYSIS IMPROVEMENTS

- Since PRL 101:131802, 2008
  - $3.4 \times 10^{20} \rightarrow 7.2 \times 10^{20}$ POT
- Analysis improvements
  - updated reconstruction and simulation
  - new selection with increased efficiency
  - no charge sign cut
  - improved shower energy resolution
  - separate fits in bins of energy resolution
  - smaller systematic uncertainties



ν_μ DISAPPEARANCE RESULT



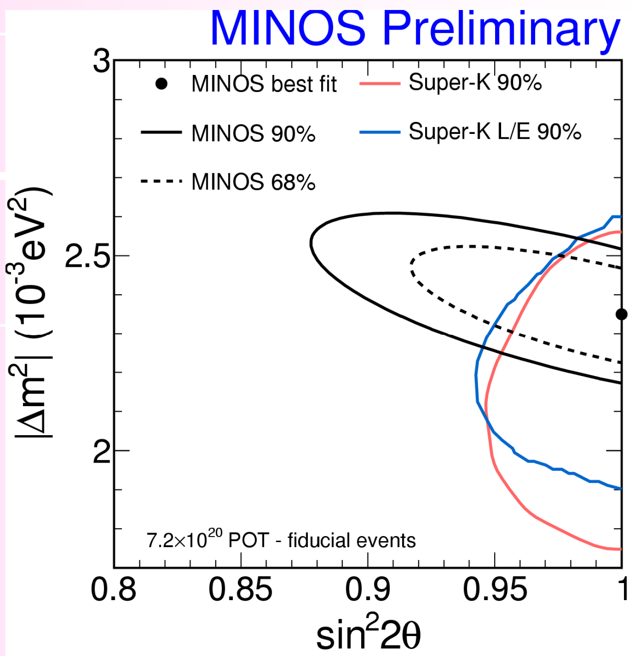


No Oscillations:

Observation:

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

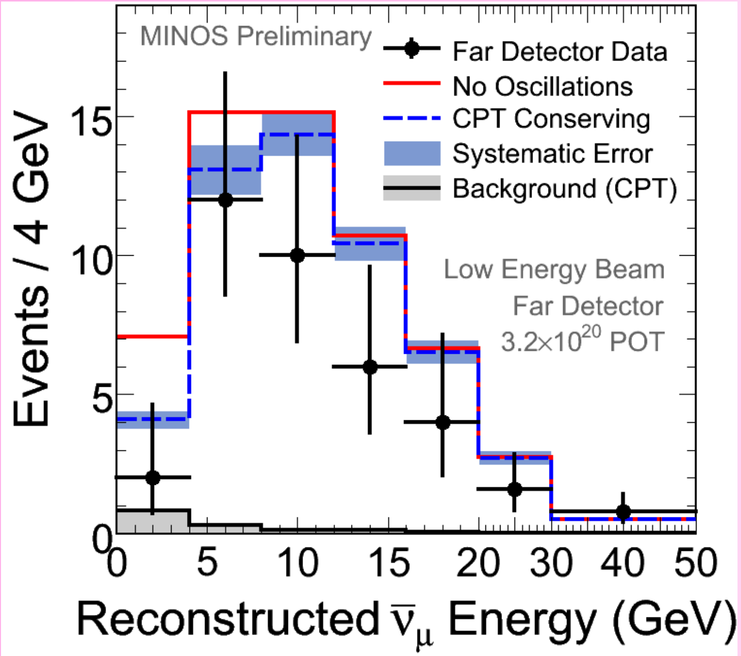
$$\sin^2(2\theta) > 0.91\,(90\%\,\mathrm{C.L.})$$



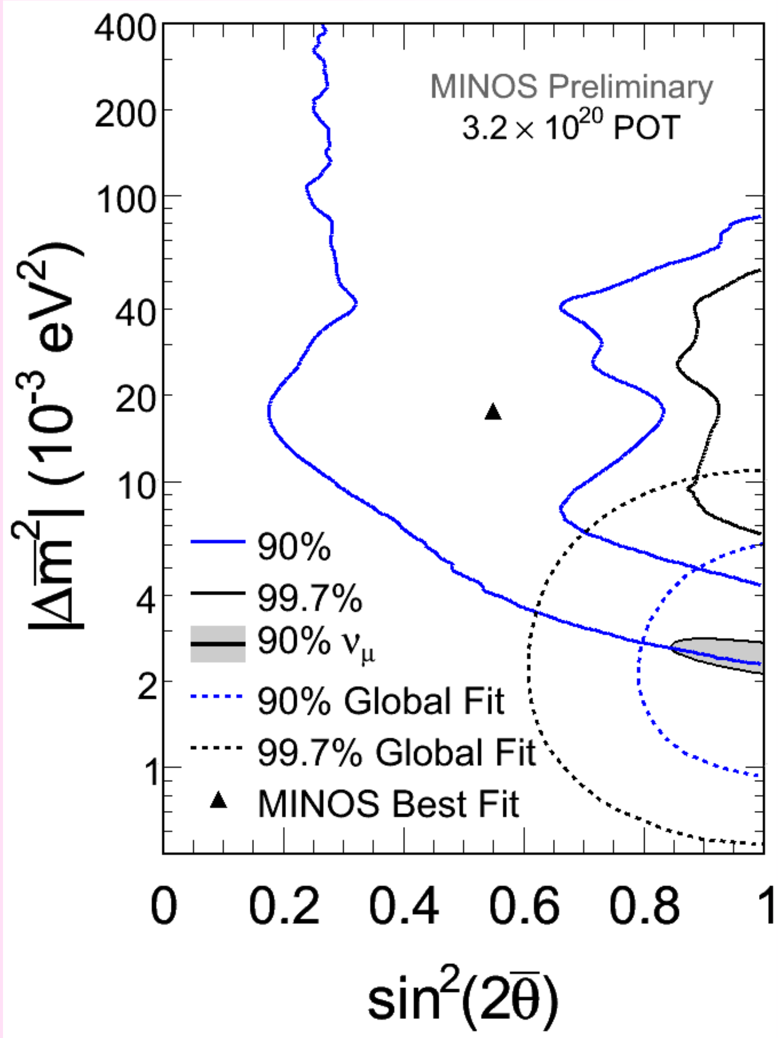
Super-K latest contour, uses full 3 flavour mixing

Antineutrino Results

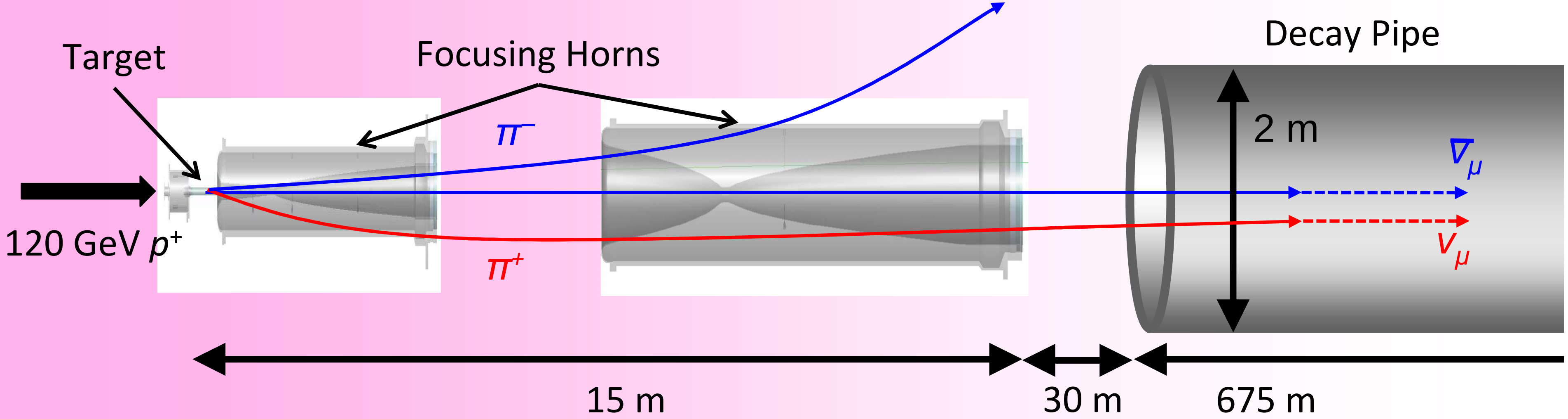
- 42 events observed
  - No oscillations
    - $64.6 \pm 8.0_{stat} \pm 3.9_{syst}$
  - conserving
    - $58.3 \pm 7.6_{stat} \pm 3.6_{syst}$
- Deficit is 1.9σ
- Consistent with the ν_μ parameters at 90% c.l.
-

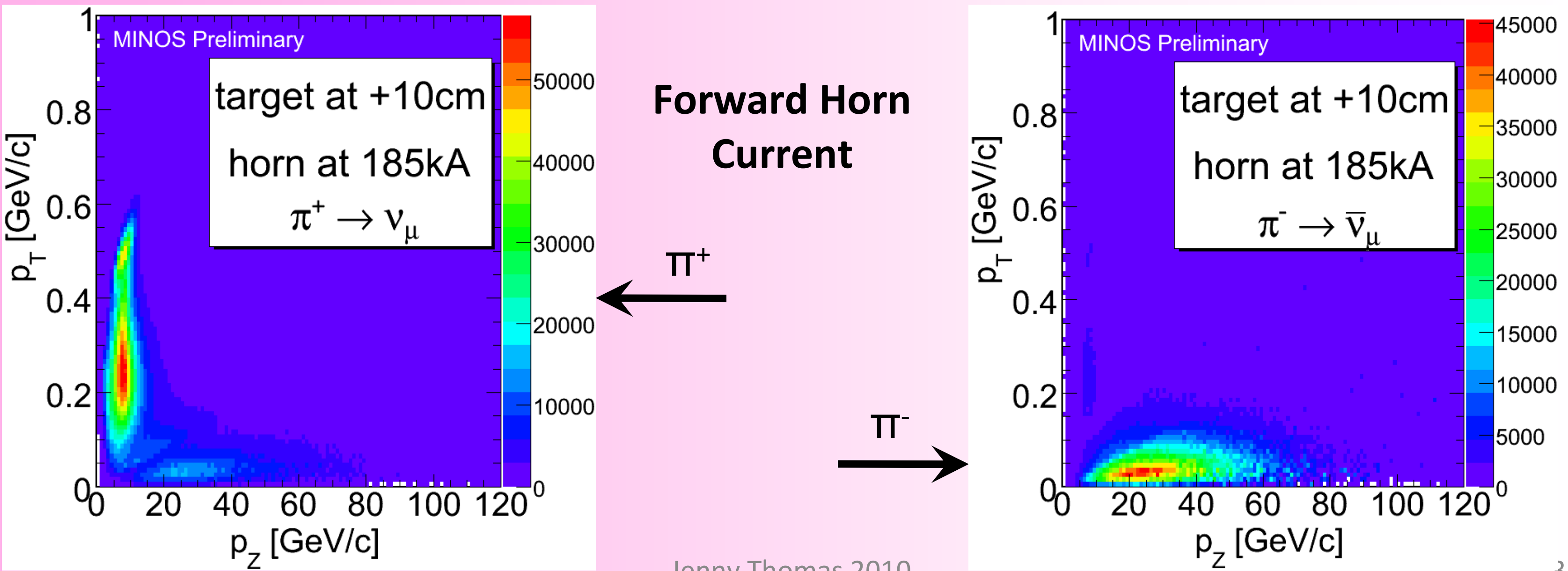


Global fit from Gonzalez-Garcia & Maltoni, *Phys. Rept.* 460 (2008), SK data dominates



WHY ARE THE ν_μ AND ν_μ SPECTRA SO DIFFERENT ?

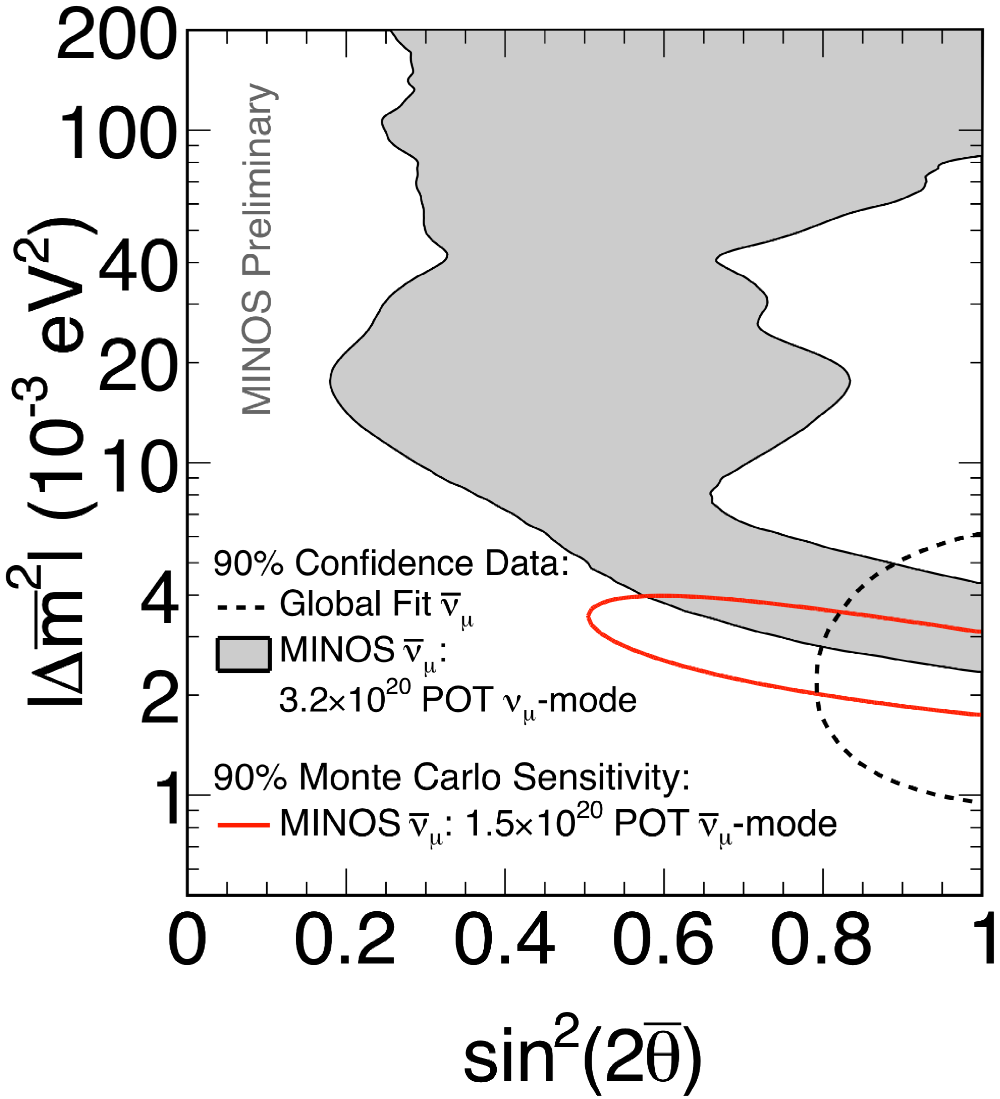




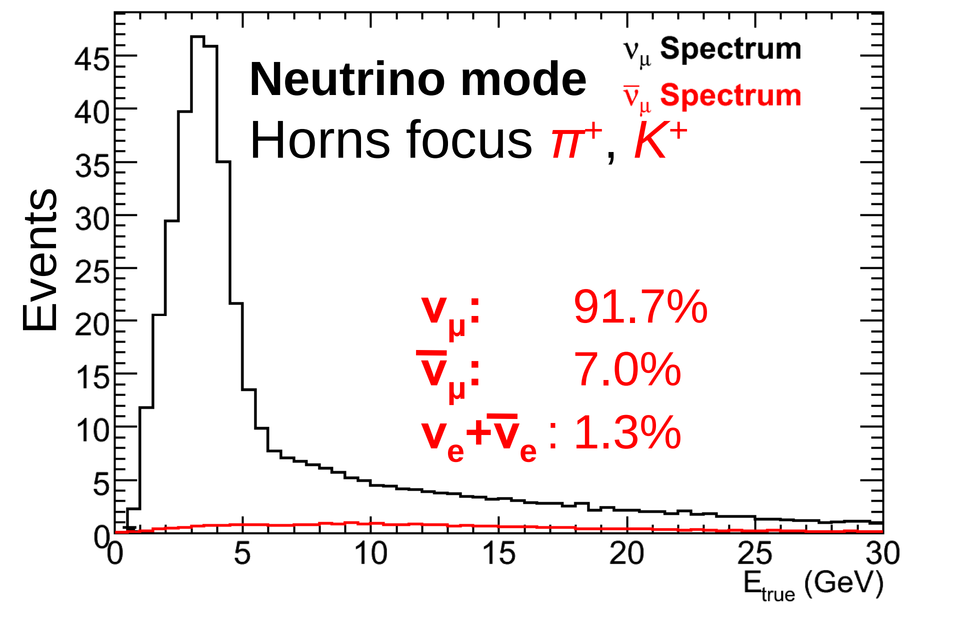
$\bar{\nu}_\mu$ DISAPPEARANCE

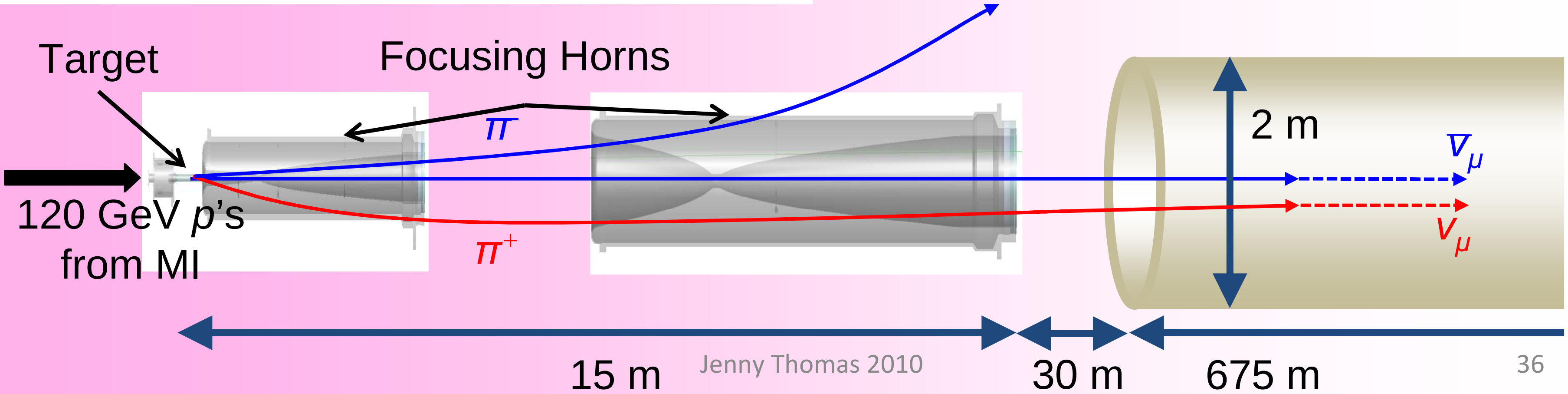
DEDICATED $\bar{\nu}_\mu$ RUN

- Reverse horn current to focus π^-'s and K^-'s
- ~ 1.5 x 10^{20} PoT accumulated in 6 months
- 4x reduction on $\Delta\bar{m}^2_{23}$ uncertainty

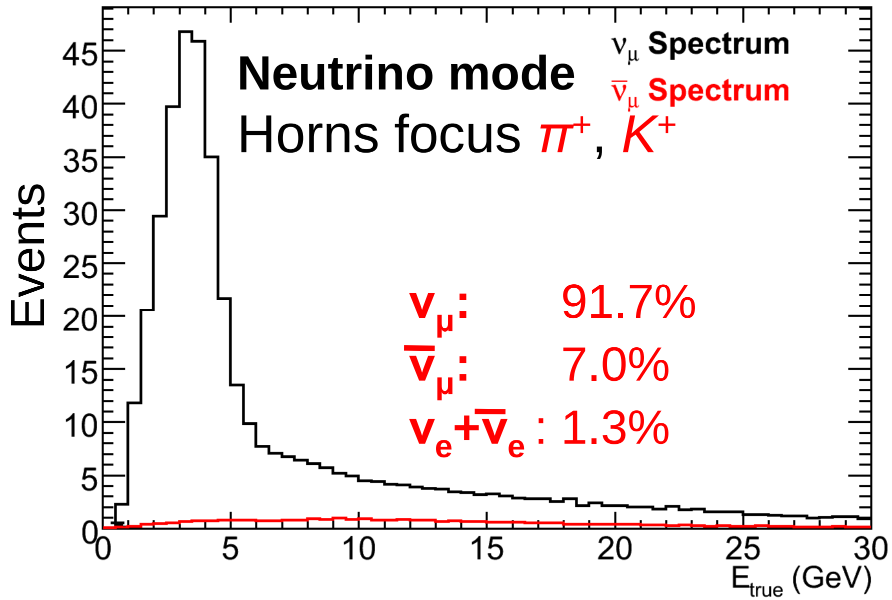


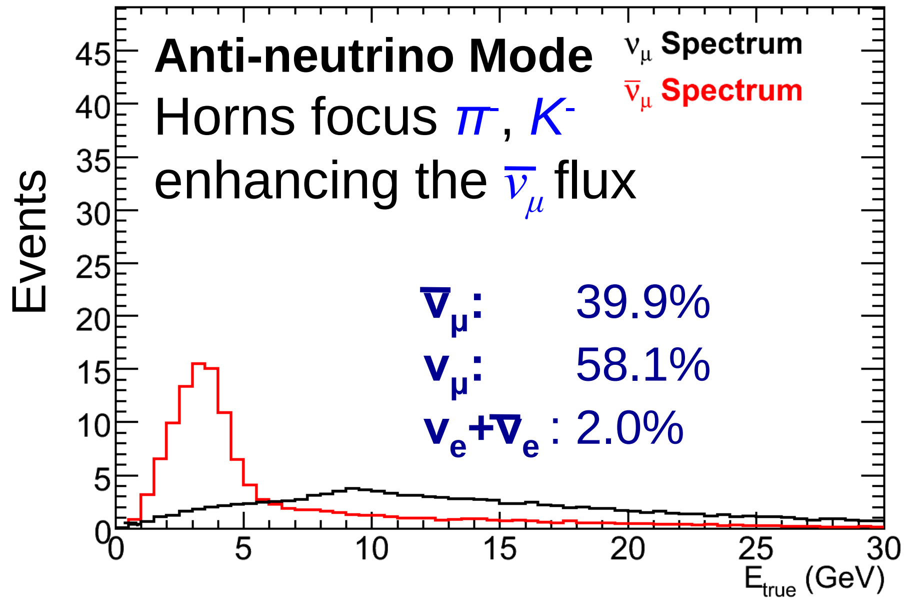
Making an Anti-Neutrino Beam

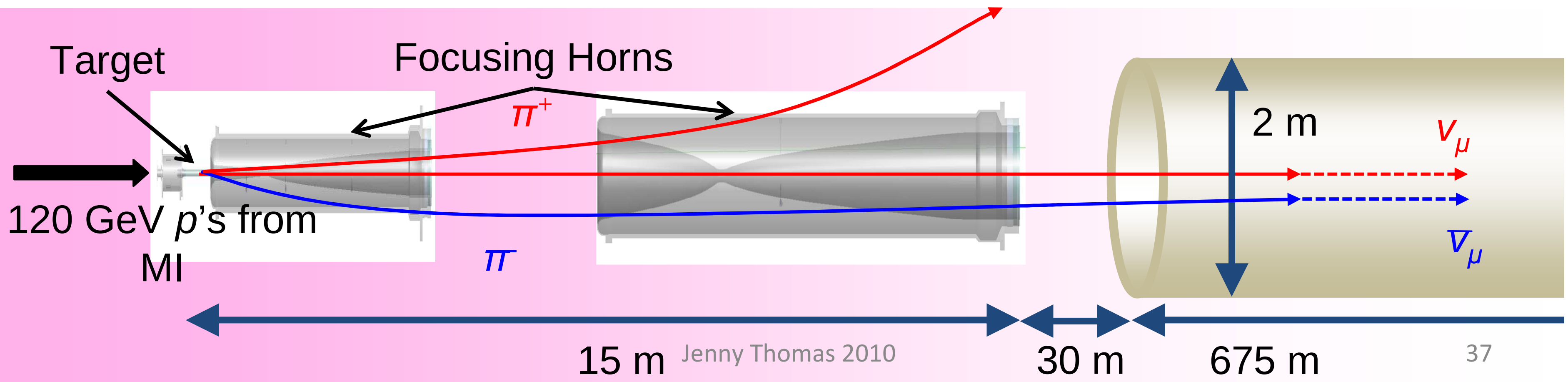




MAKING AN ANTI-NEUTRINO BEAM

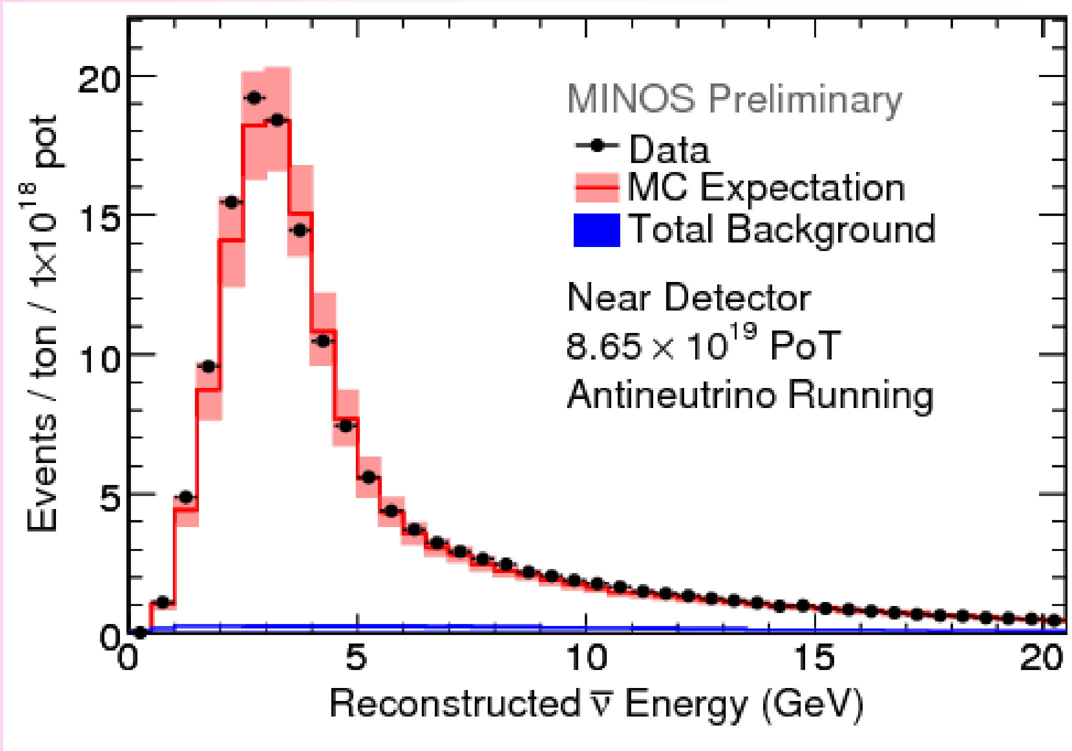




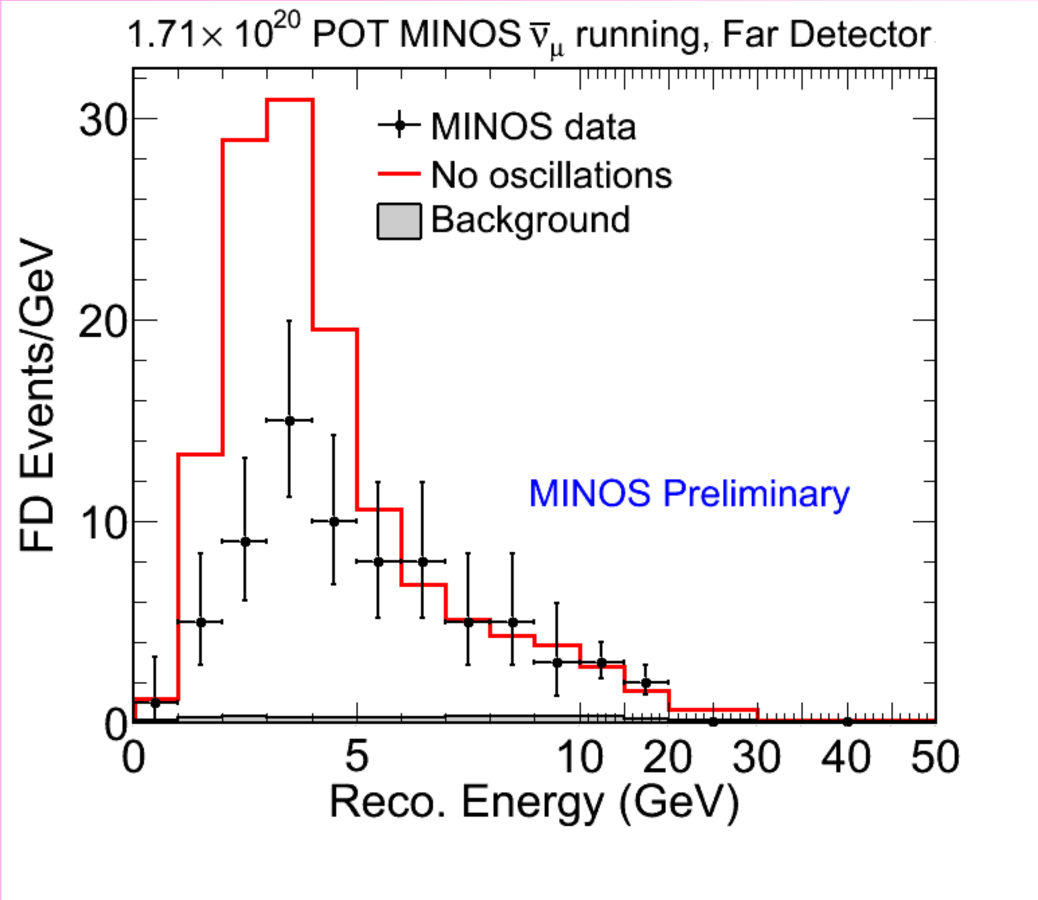


ND Anti-Neutrino Data

- **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 forward muons

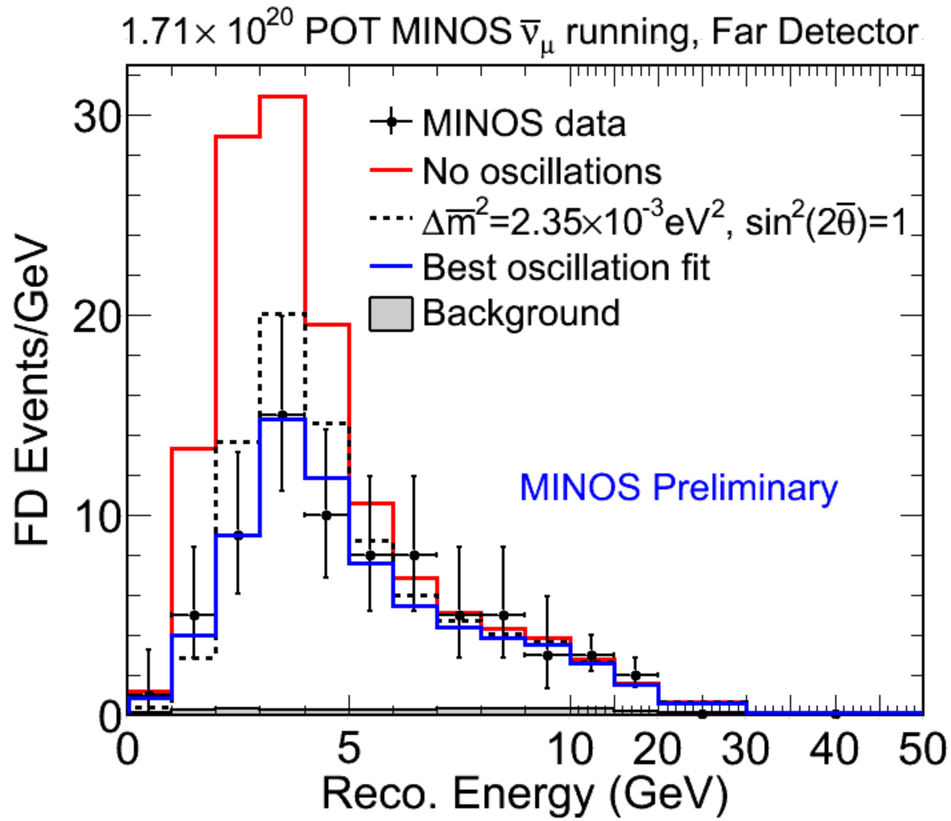


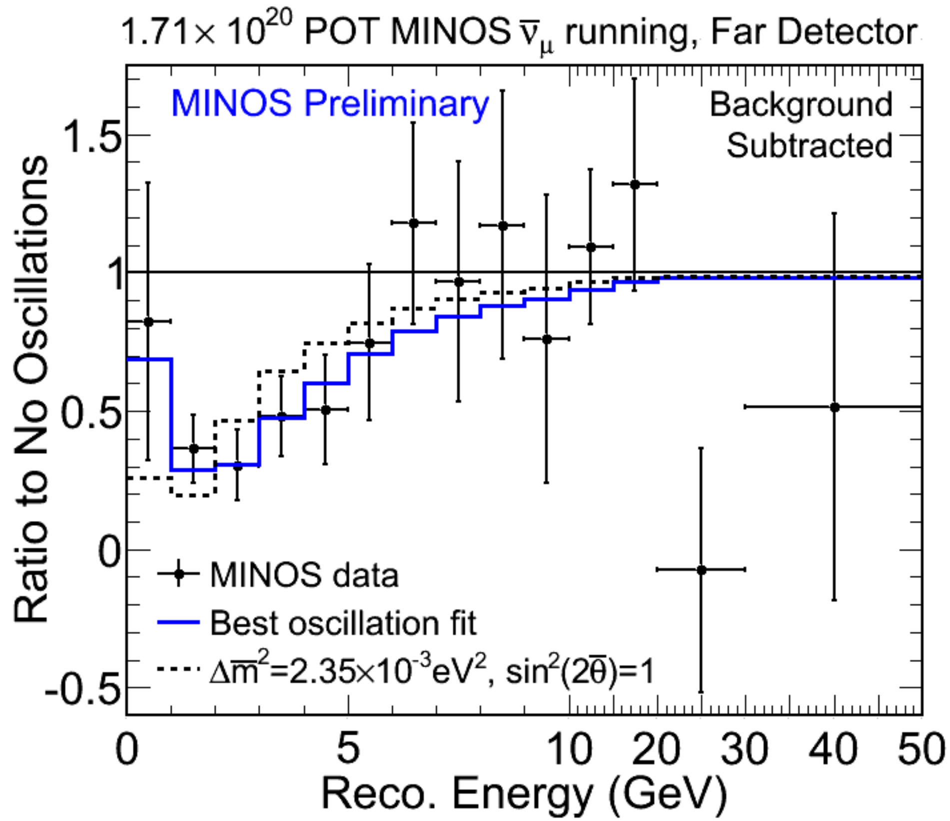
FAR DETECTOR DATA



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

Comparison to Neutrino Oscillation Parameters

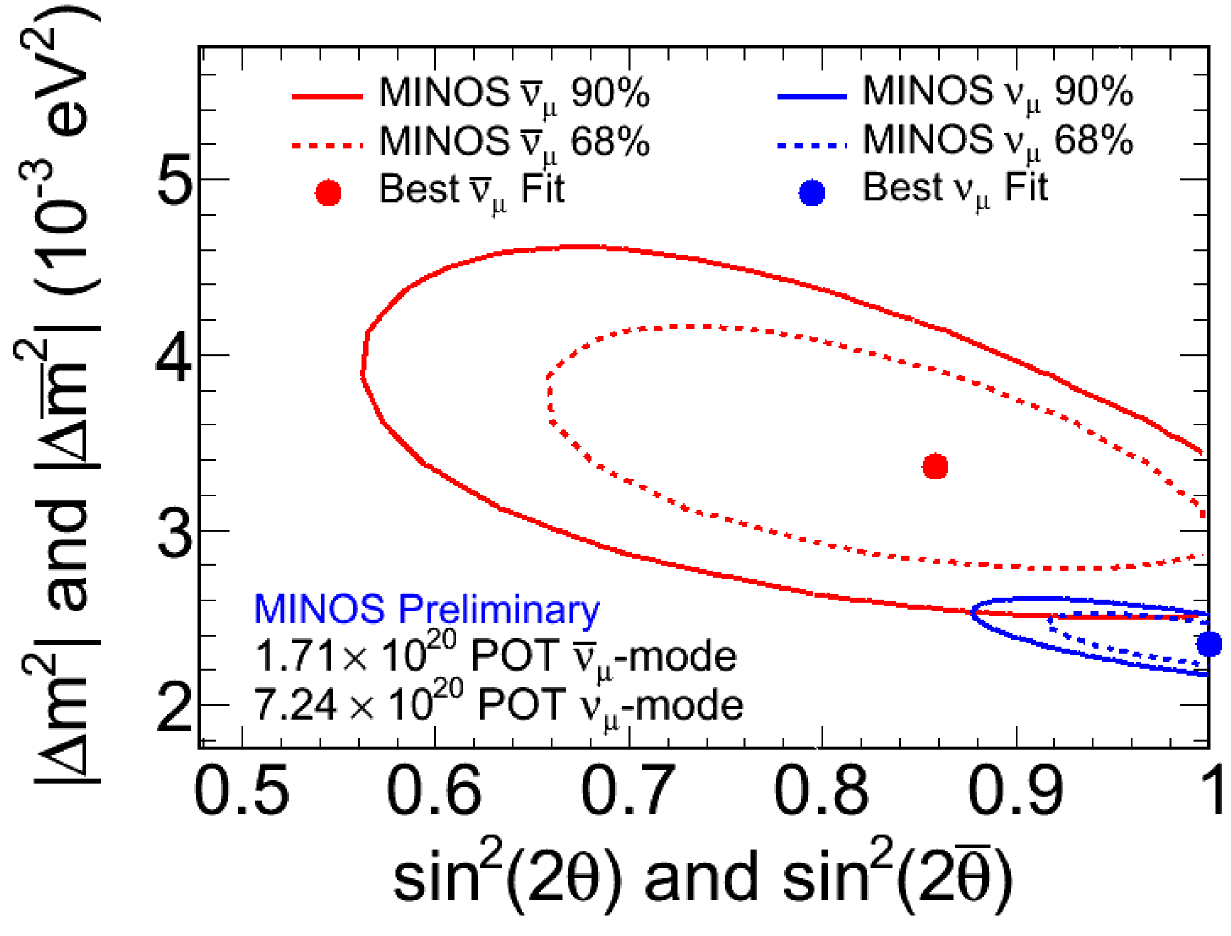




$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

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

COMPARISONS TO NEUTRINOS



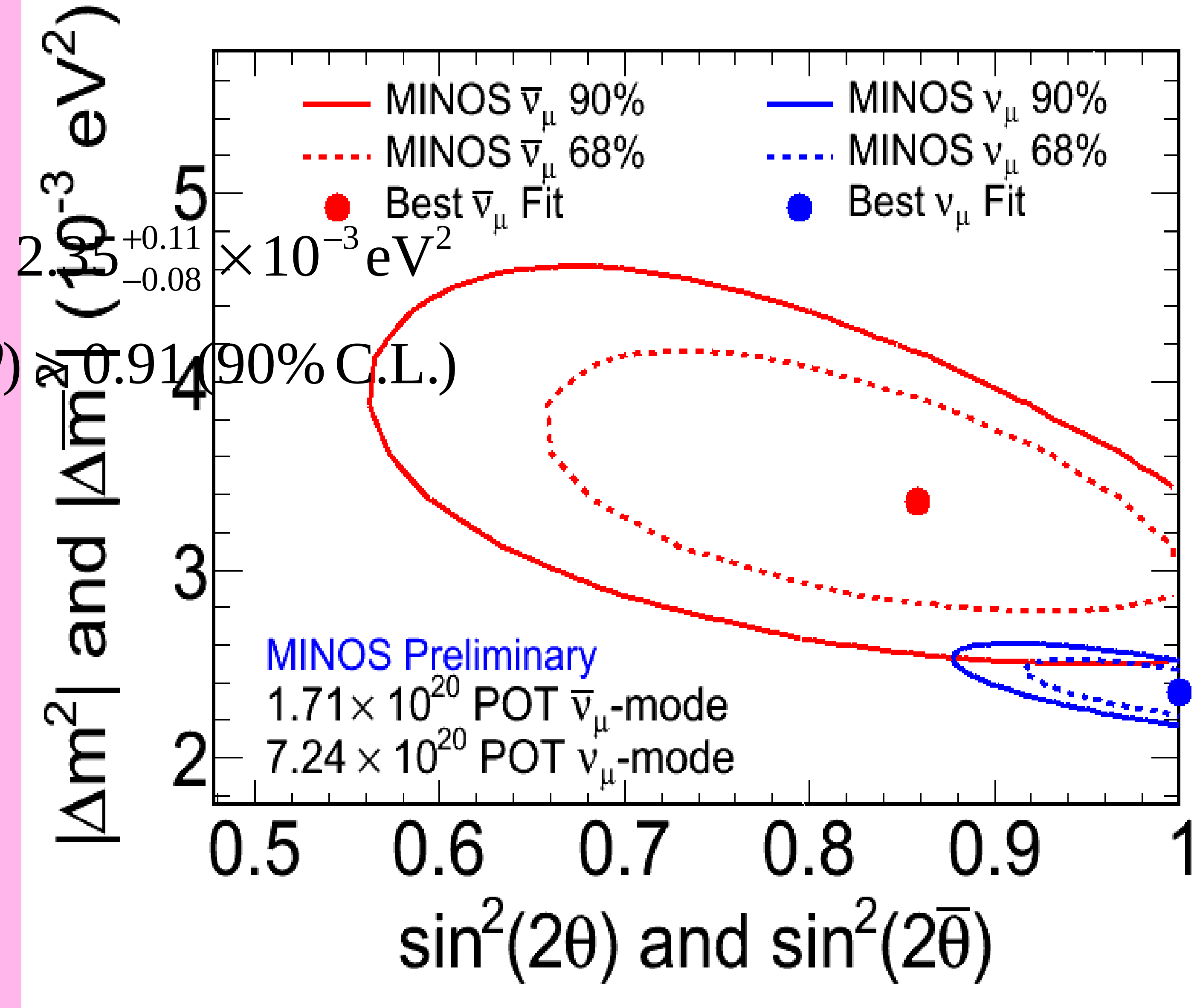
More neutrino running expected at the end of this year

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

< 5% probability of same parameters

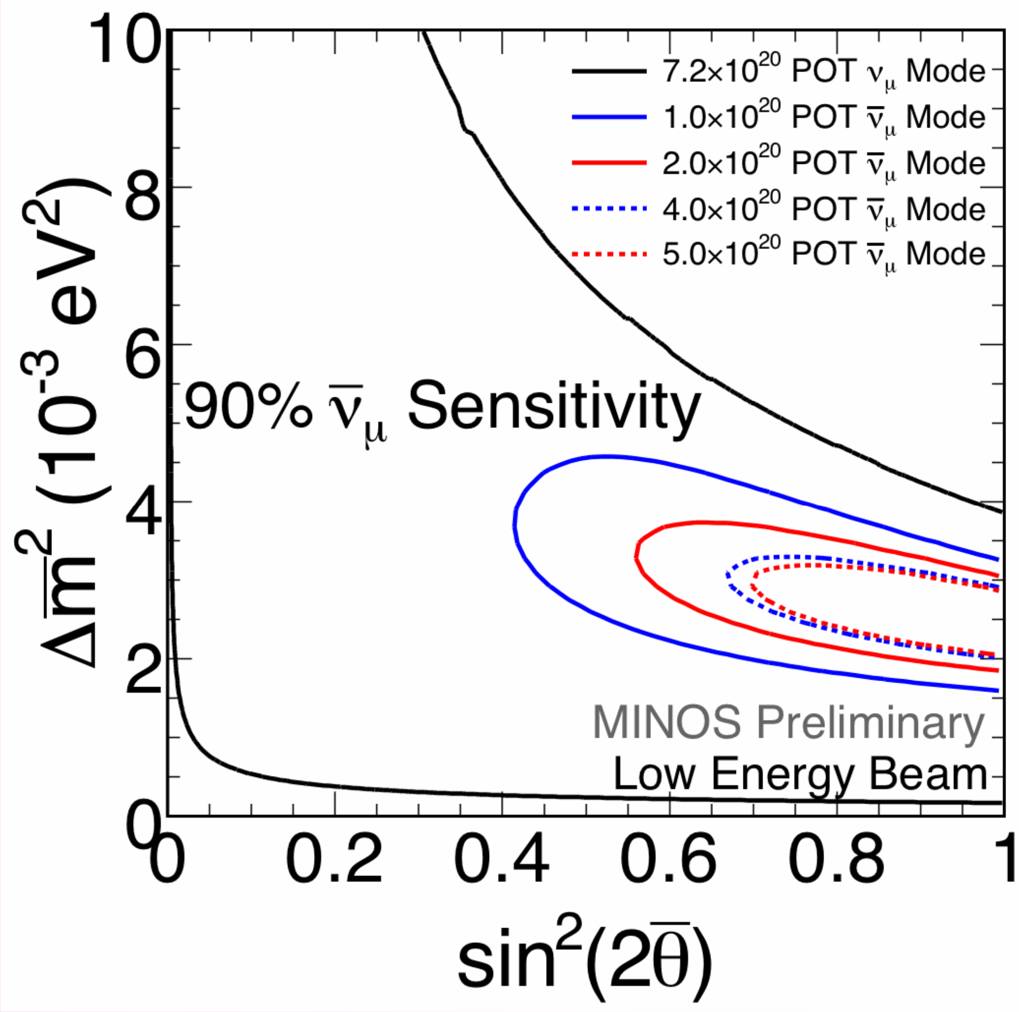
$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

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

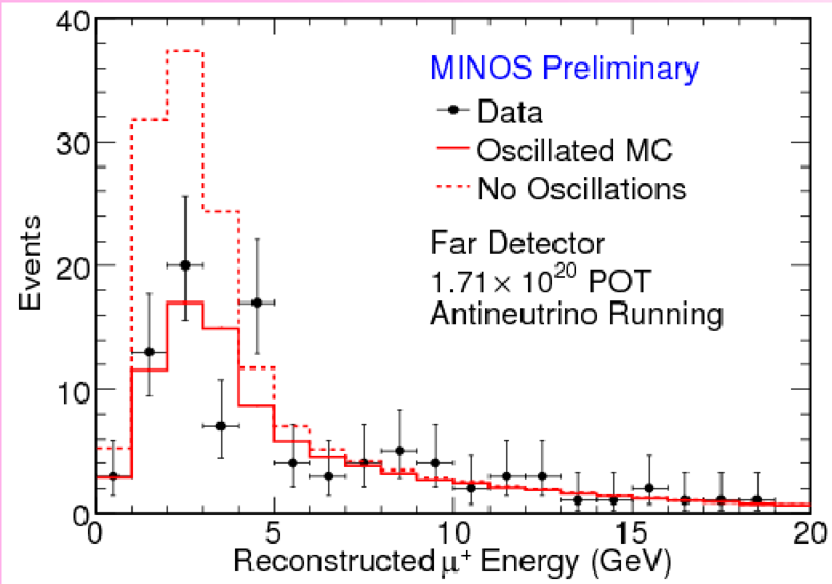


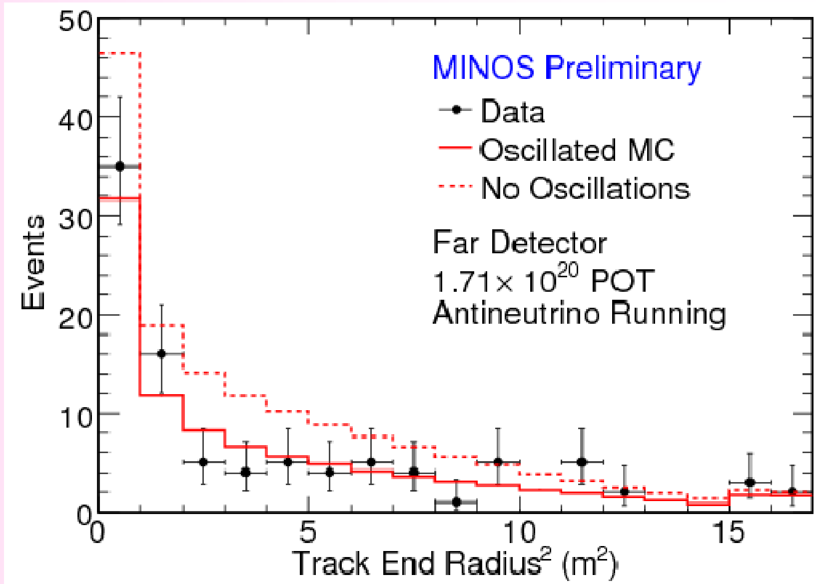
FUTURE SENSITIVITY

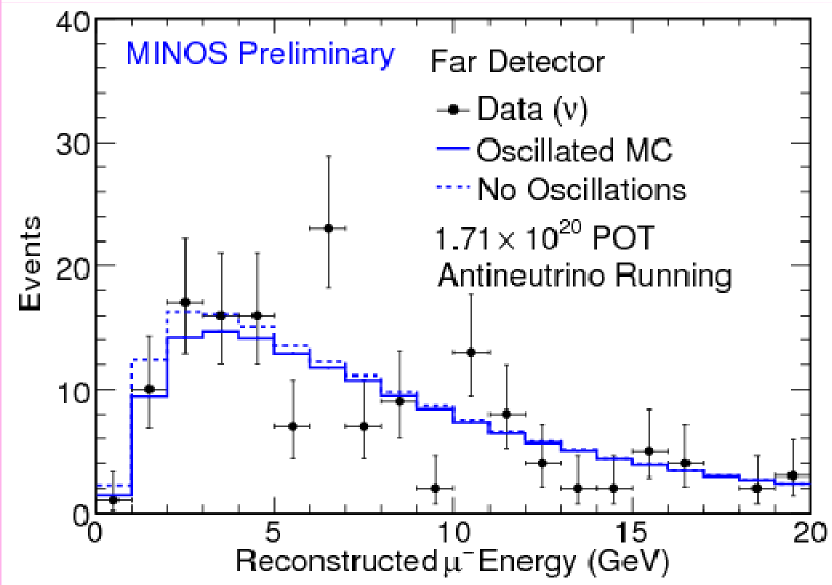
- Predicted sensitivity

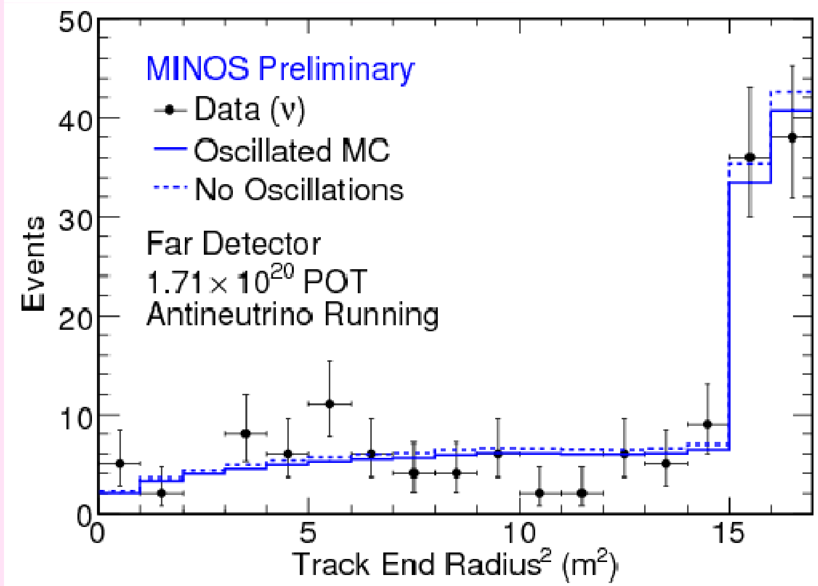


FD DATA


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


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


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

MINOS: SEARCHING FOR θ_{13}

MISSING ELEMENT IN THE PNMS NEUTRINO MIXING MATRIX

- 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.

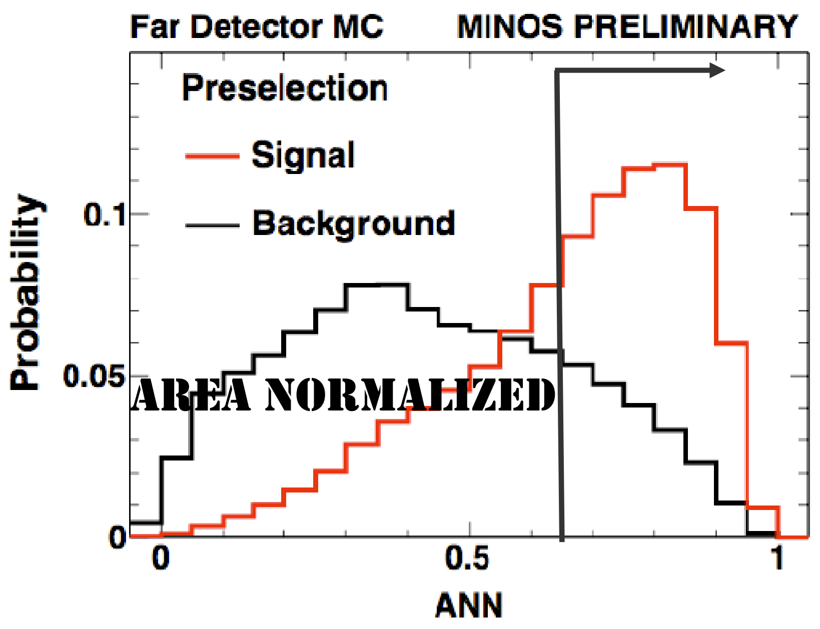
SELECTING ν_e EVENTS WITH ANN

EVENT CHARACTERIZATION IN LENGTH, WIDTH AND SHOWER SHAPE

EXAMPLE

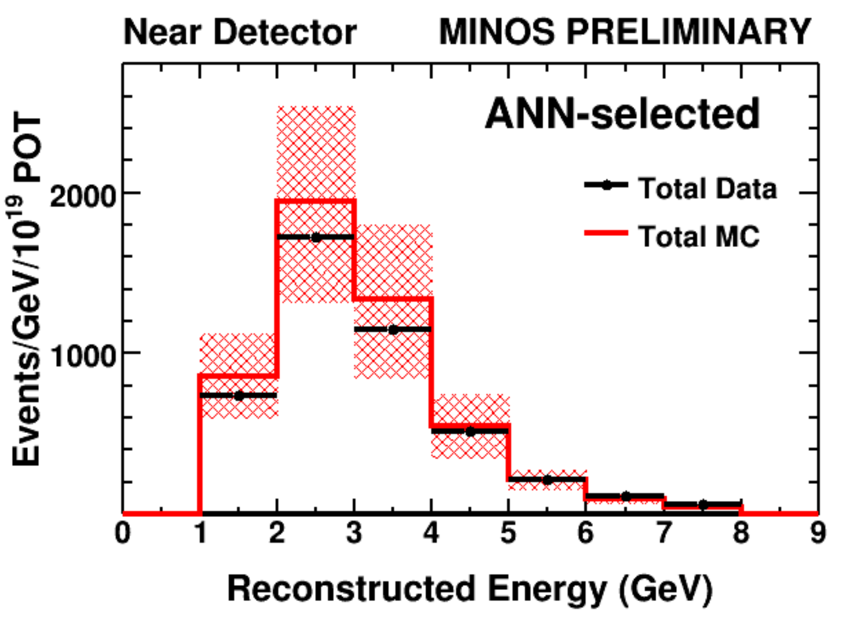
... ...

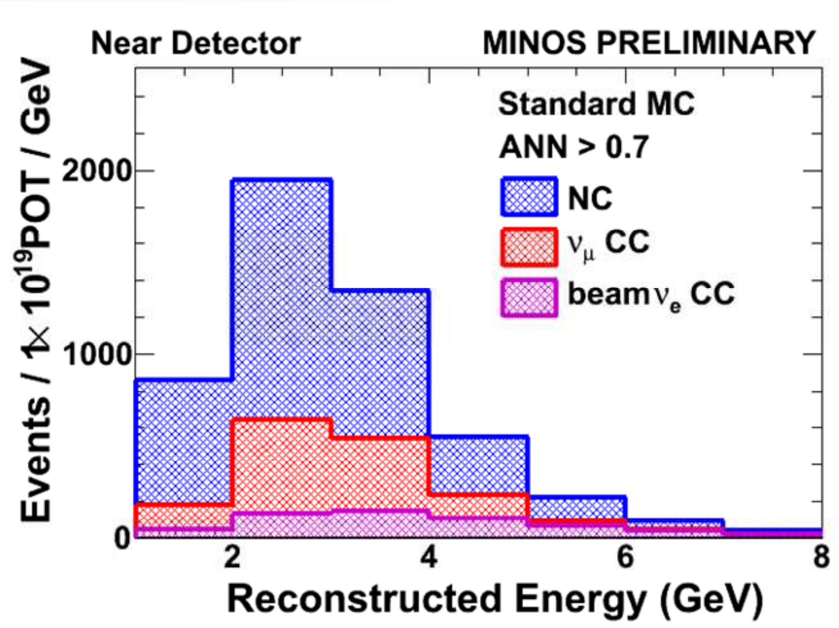
- 7 variables chosen describing length, width and shower shape.
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - CC rejection >99.4%
  - signal/background 1:4



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

ν_e APPEARANCE IN MINOS

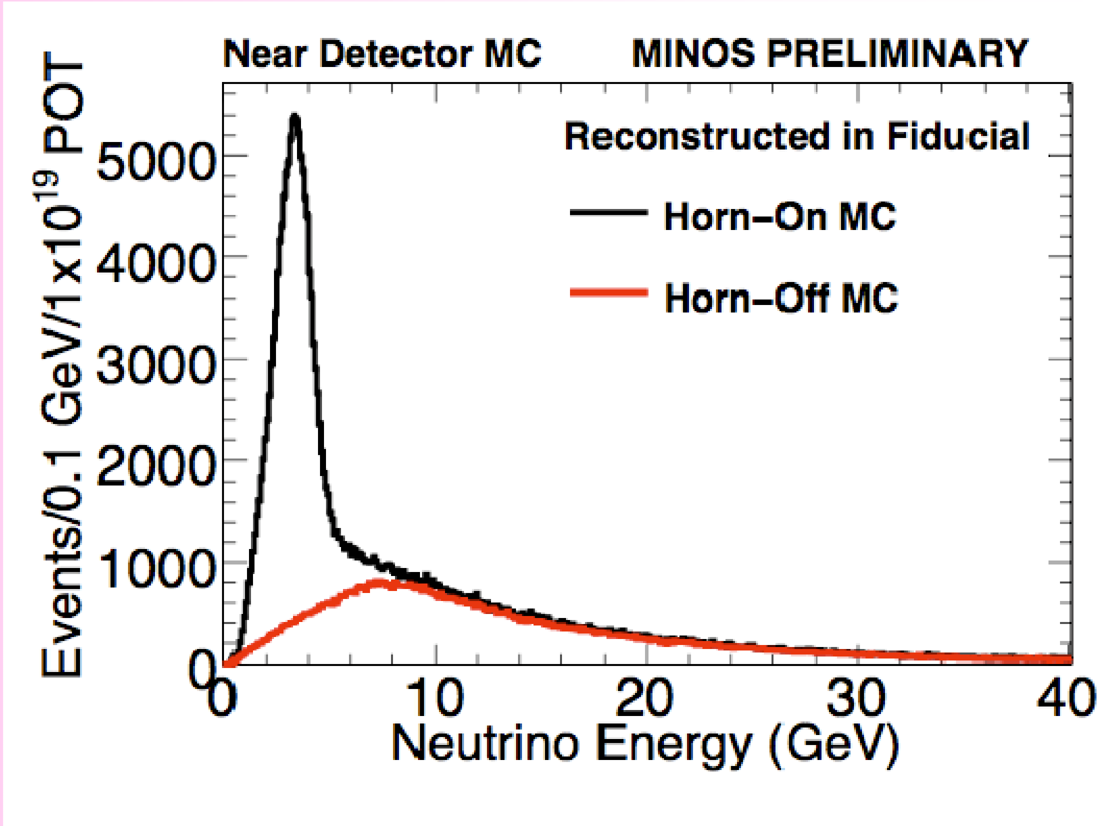




- When **selecting ν_e event candidates** in the Near Detector we will have a mix of components that do not extrapolate in the same way to the Far Detector.
- We need to **separate the main background components** NC, ν_μ CC and beam ν_e CC events, in the Near Detector.
- Then **extrapolate the background to the Far Detector** by extrapolating the components, oscillating the ν_μ CC component and calculating the ν_τ CC.
- Then **look for the ν_e excess** arising from ν_μ to ν_e oscillations in the Far Detector.

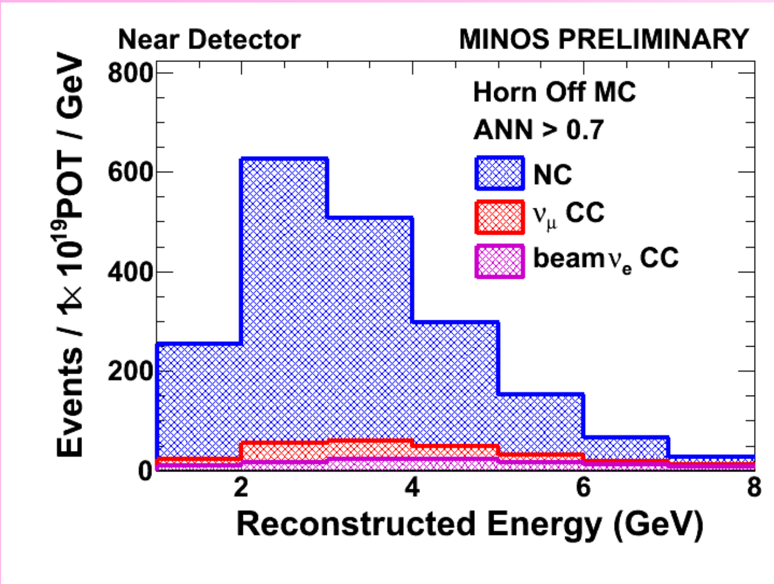
Estimating the Background Using Horn On and Horn Off Data

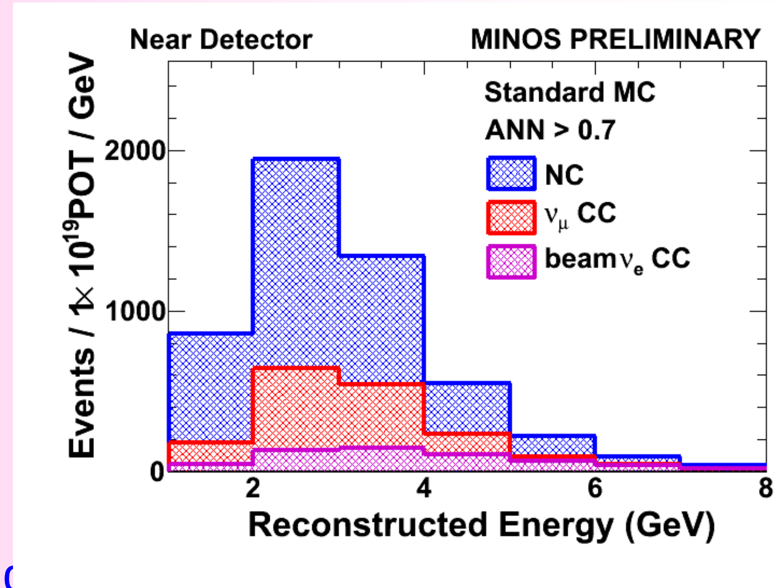
- When beam horns are turned off, the parent pions do not get focused, resulting in the disappearance of the low energy peak in the neutrino energy spectrum.
- Consequence is a spectrum dominated by NC arising from the long tail in true neutrino energy that gets measured in our region of interest in visible energy.



Estimating the background using horn on and horn off data

- After applying the ν_e selection cuts to the ND data, the composition of the selected events is thus very different with the NuMI horns on or off.





…ch is … that component with better precision than in the horn on beam.

$$N^{on} = N_{NC} + N_{CC} + N_e \quad (1)$$

$$N^{off} = r_{NC} * N_{NC} + r_{CC} * N_{CC} + r_e * N_e \quad (2)$$

from MC:

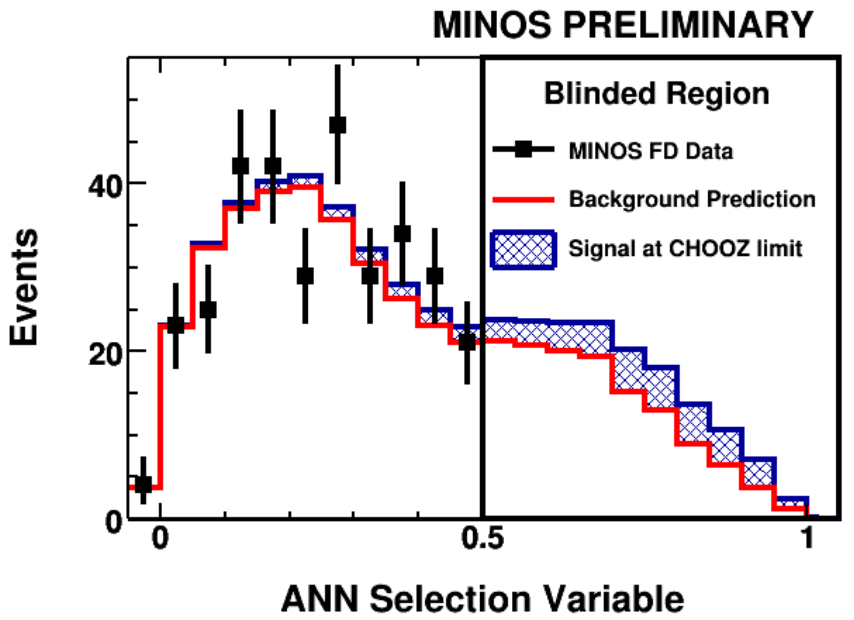
$r_{NC(CC,e)} = N_{NC(CC,e)}^{off} / N_{NC(CC,e)}$

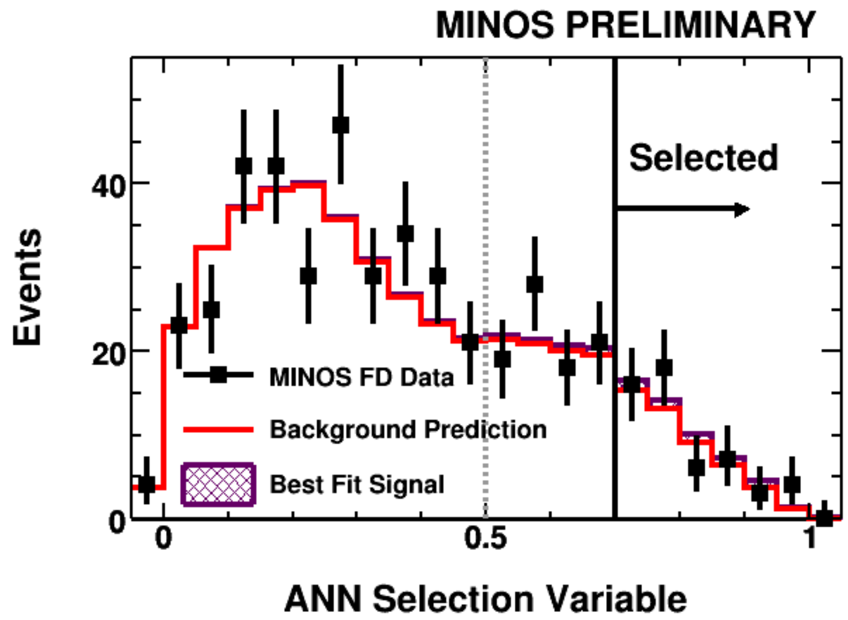
Estimating the Background using Horn On and Horn Off Data

- Horn off/on ratios for ν_μ CC and NC selected events match well between data and MC
- Similar ratios are used to solve the horn on/off equations

MC error statistical plus systematic.

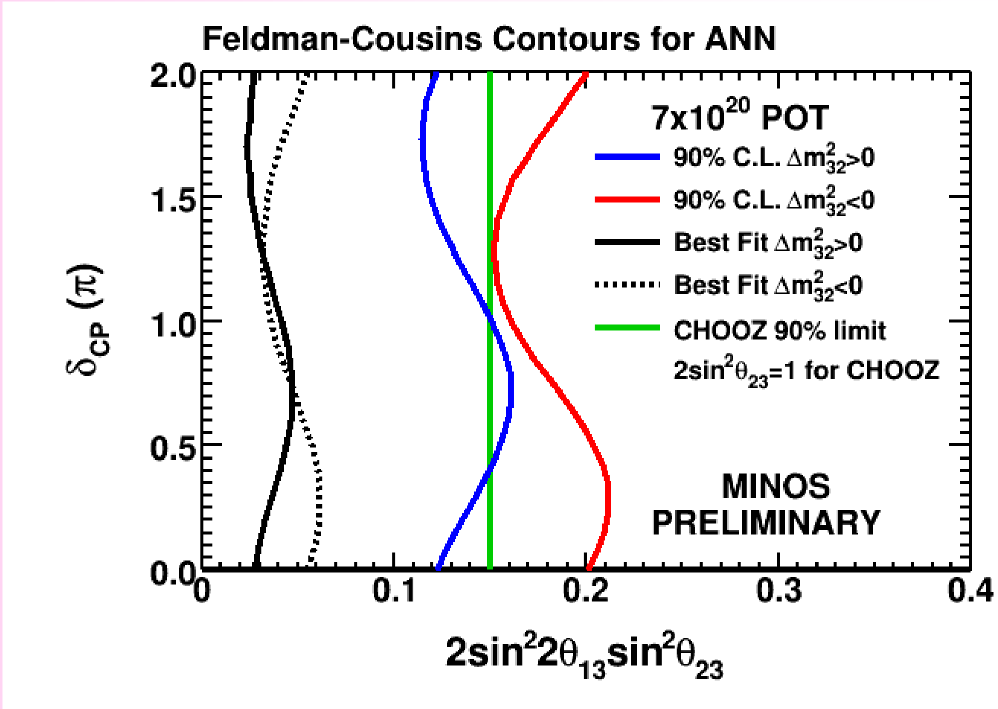
FD DATA

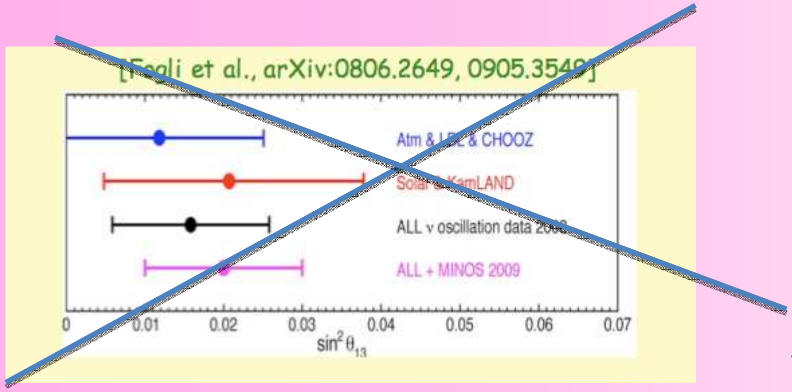

MINOS PRELIMINARY
Blinded Region
MINOS FD Data
Background Prediction
Signal at CHOOZ limit
Events
40
20
0
0
0.5
1
ANN Selection Variable


MINOS PRELIMINARY
Selected
MINOS FD Data
Background Prediction
Best Fit Signal
Events
40
20
0
0
0.5
1
ANN Selection Variable

MINOS 90% C.L. FOR $\sin^2 2\theta_{13}$

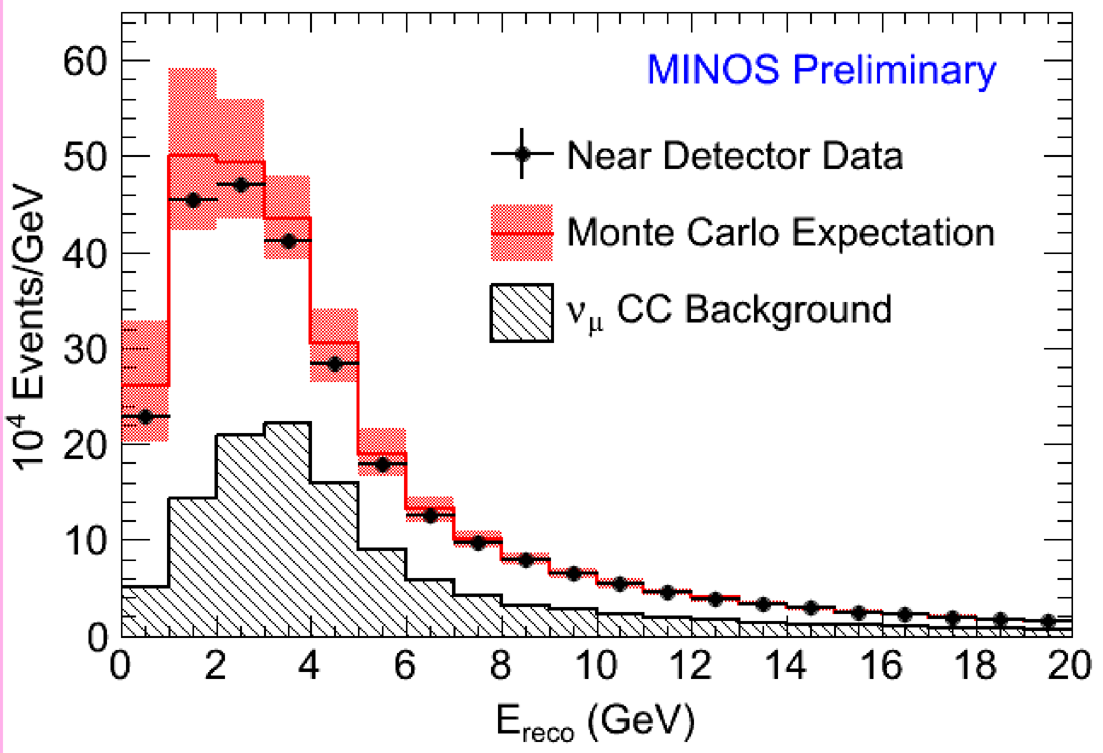
- Plot shows 90% limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
  - shown at the MINOS best fit value for Δm^2_{32} and $\sin^2 2\theta_{23}$.
  - for both mass hierarchies
  - With 7e20 and new analysis, Chooz limit would have been seen with >3σ





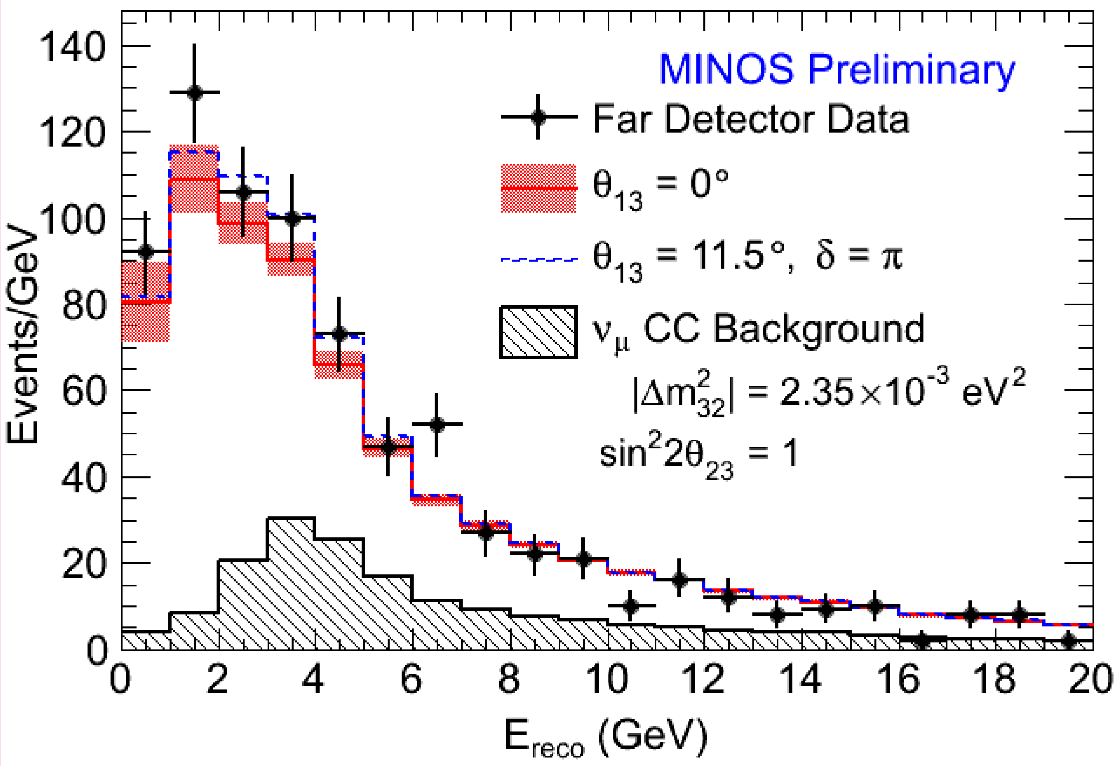
$$\sin^2(2\theta_{13}) < 0.12\ (0.20) \text{ at } 90\% \text{ C.L.}$$

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
- v_e CC events would be included in NC sample, results depend on the possibility of v_e appearance

NEUTRAL CURRENTS IN THE FAR DETECTOR



- Expect: **757** events
- Observe: **802** events
- No deficit of NC events

$$R = \frac{N_{data} - BG}{S_{NC}}$$

$1.09 \pm 0.06\,(\text{stat.}) \pm 0.05\,(\text{syst.})$ (no ν_e appearance)

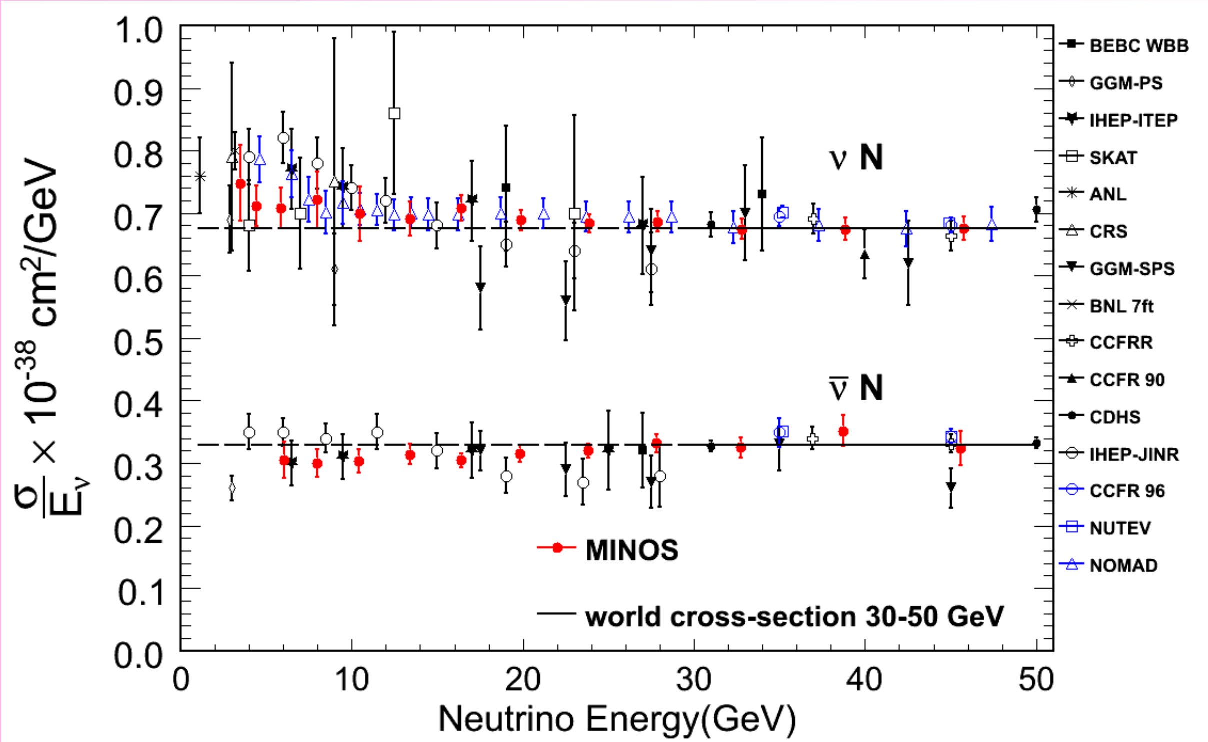
$1.01 \pm 0.06\,(\text{stat.}) \pm 0.05\,(\text{syst.})$ (with ν_e appearance)

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

no (with) ν_e appearance

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

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:
    - anti-neutrinos, double data set by summer 2011
    - θ_{13} improvement in analysis should give us 20% improvement including extra 1.2e20 POT coming soon!!
  - Nova and T2K: θ_{13}
  - OPERA : more tau events
- The new understanding of neutrino oscillations puts a search for fundamental neutrino type 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

BACKUP SLIDES

then after time t we have for the time evolution of the flavour states

$$\begin{aligned} \nu_\alpha(t) &= \cos\theta\, e^{-iE_1 t}\nu_1 + \sin\theta\, e^{-iE_2 t}\nu_2 \\ \nu_\beta(t) &= -\sin\theta\, e^{-iE_1 t}\nu_1 + \cos\theta\, e^{-iE_2 t}\nu_2 \end{aligned} \quad (6)$$

Hence after time t we have the amplitude:

$$\begin{aligned} A_{\alpha\to\beta} &= \langle \nu_\beta | \nu_\alpha(t)\rangle \\ &= (\cos\theta\,\nu_1 + \sin\theta\,\nu_2)(-\sin\theta\, e^{-iE_1 t}\nu_1 + \cos\theta\, e^{-iE_2 t}\nu_2) \\ &= -\cos\theta\sin\theta\, e^{-iE_1 t}\nu_1\nu_1 + \cos^2\theta\, e^{-iE_2 t}\nu_1\nu_2 \\ &\quad - \sin^2\theta\, e^{-iE_1 t}\nu_2\nu_1 + \sin\theta\cos\theta\, e^{-iE_2 t}\nu_2\nu_2 \\ &= -\cos\theta\sin\theta\, e^{-iE_1 t} + \sin\theta\cos\theta\, e^{-iE_2 t} \\ &= \frac{\sin 2\theta}{2}\left(-e^{-iE_1 t} + e^{-iE_2 t}\right) \end{aligned} \quad (7)$$

The probability that the neutrino will be found in state β after time t is then:

$$\begin{aligned} P_{\alpha\to\beta} &= |A_{\alpha\to\beta}|^2 \\ &= \frac{\sin^2 2\theta}{4}\left(-e^{iE_1 t} + e^{iE_2 t}\right)\left(-e^{-iE_1 t} + e^{-iE_2 t}\right) \\ &= \frac{\sin^2 2\theta}{4}\left(1 - e^{iE_2 t}e^{-iE_1 t} - e^{iE_1 t}e^{-iE_2 t} + 1\right) \\ &= \frac{\sin^2 2\theta}{4}\left(2 - e^{i(E_2 - E_1)t} - e^{-i(E_2 - E_1)t}\right) \\ &= \frac{\sin^2 2\theta}{4}\Big\{2 - \cos(t(E_2 - E_1)) - i\sin(t(E_2 - E_1)) \\ &\quad - \cos(-t(E_2 - E_1)) - i\sin(-t(E_2 - E_1))\Big\} \\ &= \frac{\sin^2 2\theta}{4}\left\{2 - 2\cos(t(E_2 - E_1))\right\} \\ &= \frac{\sin^2 2\theta}{2}\left\{1 - \cos(t(E_2 - E_1))\right\} \end{aligned} \quad (8)$$

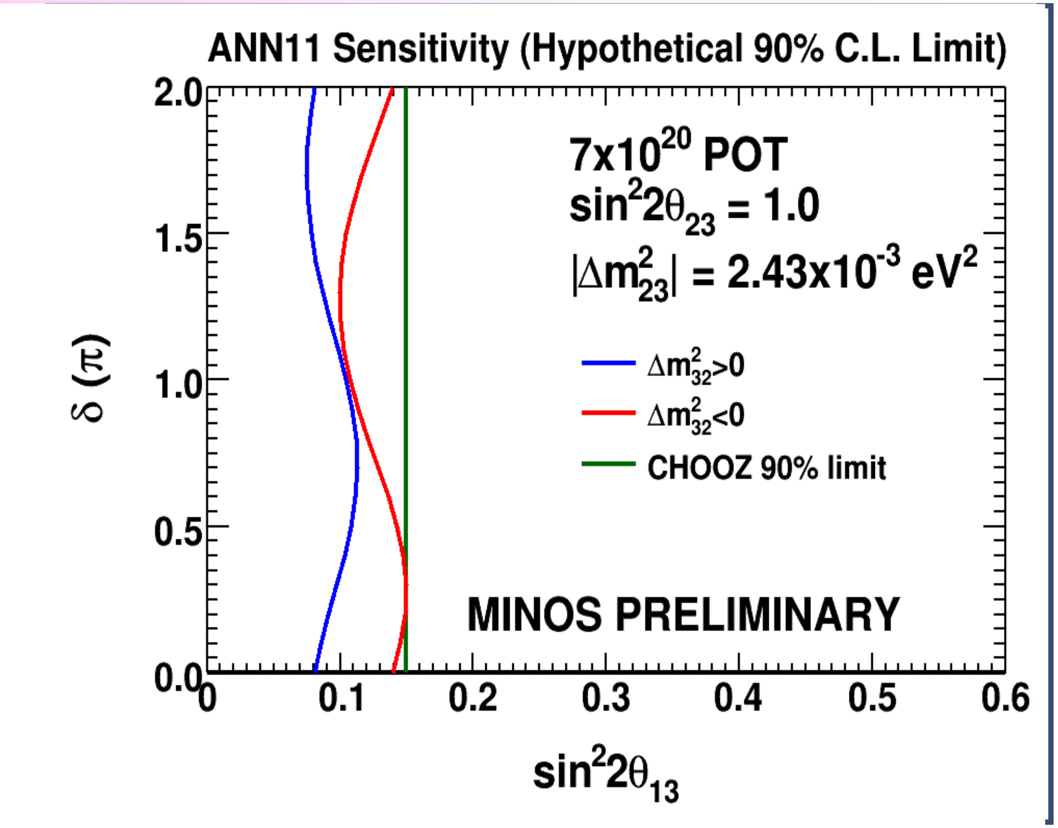
Now, in the relativistic limit, $|\vec{p}_i| = p \gg m_i$. Hence we have:

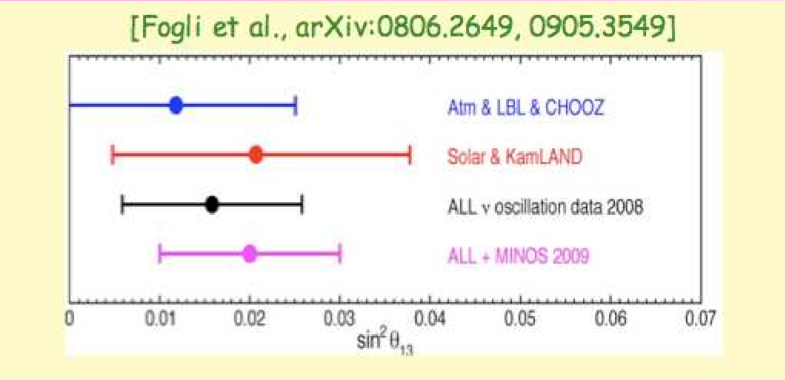
$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq E + \frac{m_i^2}{2E} \quad (9)$$

MINOS 90% CL in $\sin^2 2\theta_{13}$

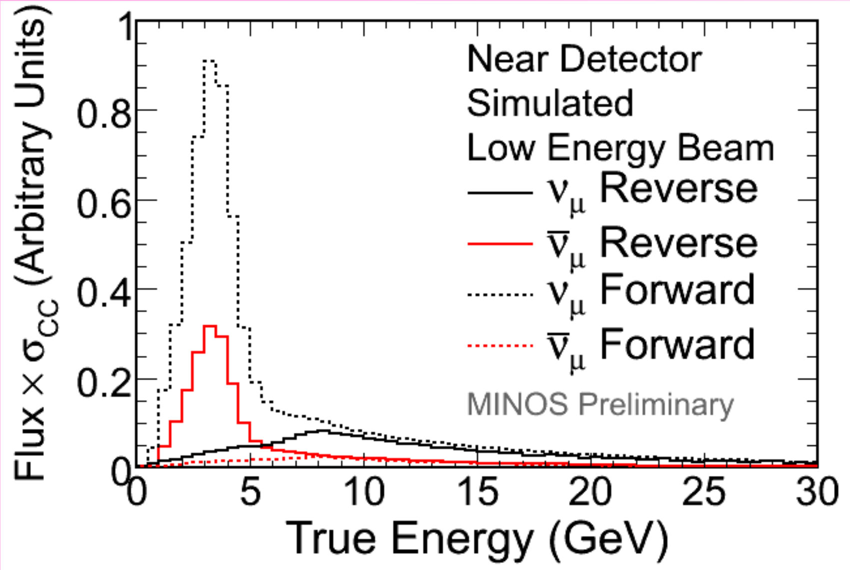
Fitting the oscillation hypothesis to our data

- Plot shows 90% limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
  - shown at the MINOS best fit value for Δm^2_{32} and $\sin^2 2\theta_{23}$.
  - for both mass hierarchies
  - With 7e20 and new analysis, Chooz limit would be seen with >3 σ





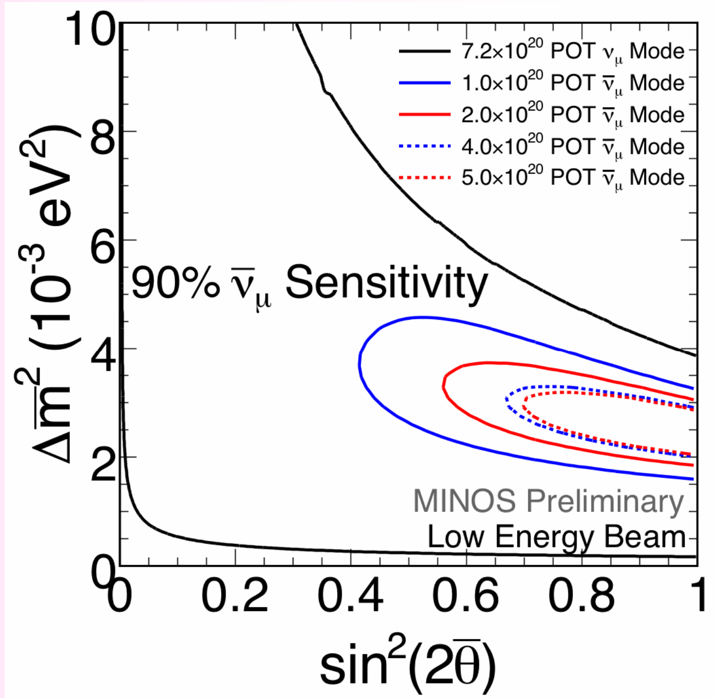
Dedicated $\overline{\nu}_\mu$ Running



By reversing the current in the NuMI focusing horns MINOS can run with a dedicated antineutrino beam

- Obtain a greatly enhanced $\overline{\nu}_\mu$ sample around the oscillation maximum

Data-taking will begin in September 2009



Will allow us to make the first ever precision measurement of the atmospheric-regime $\overline{\nu}_\mu$ oscillation parameters

After one year of running

- Can make a 5σ observation of antineutrino oscillations

BACKUP SLIDES