Recent Results from MINOS

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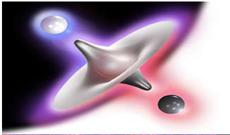
On behalf of the MINOS Collaboration

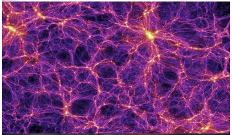
Universidade Estadual de Campinas

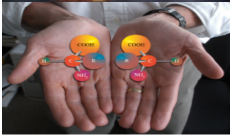
August 01, 2011

Why Neutrinos?

- Neutrinos oscillate
- Neutrino mass is beyond the SM
- Consequences to the history of the universe
  - Matter-Antimatter asymmetry
  - Structure formation
  - Supernova mechanisms
  - Life on Earth?*







***"Supernovae, Neutrinos, and the Chirality of the Amino Acids" arXiv:1106.4330v1**

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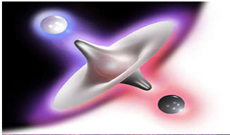

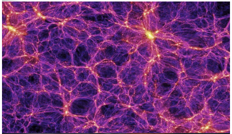

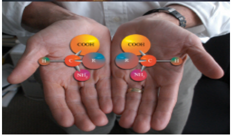

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The MINOS Baseline

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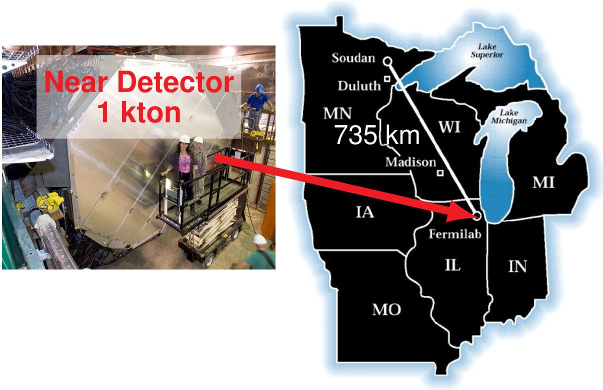

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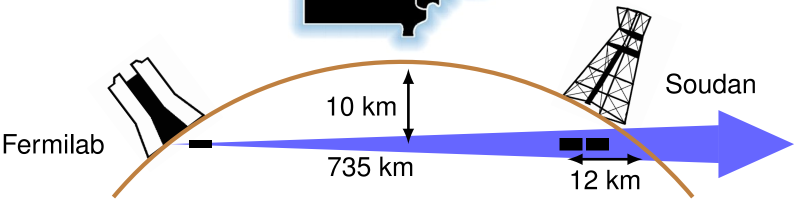
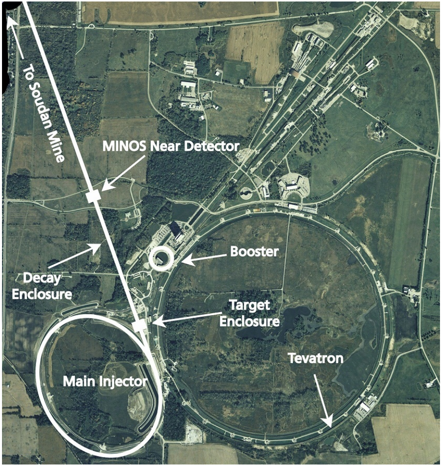
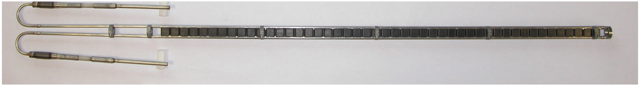


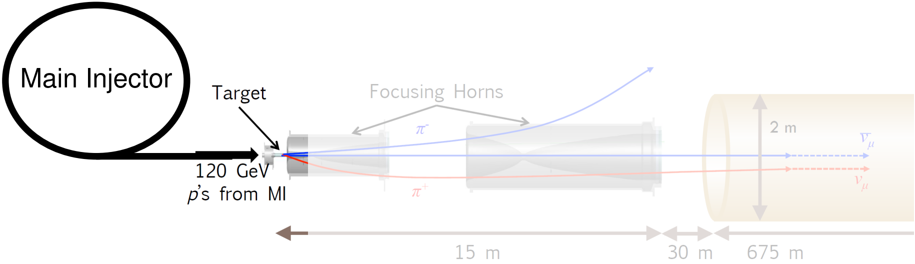
How to Make a Neutrino Beam

Accelerate protons to 120 GeV in the Main Injector



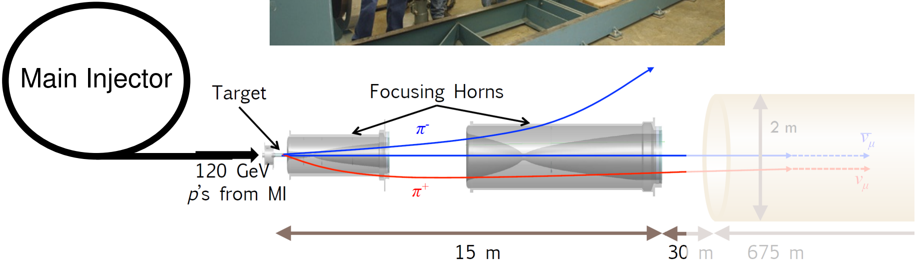
Smash them into a graphite target





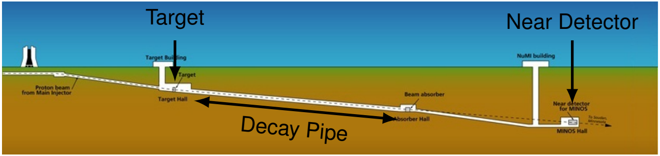
How to Make a Neutrino Beam

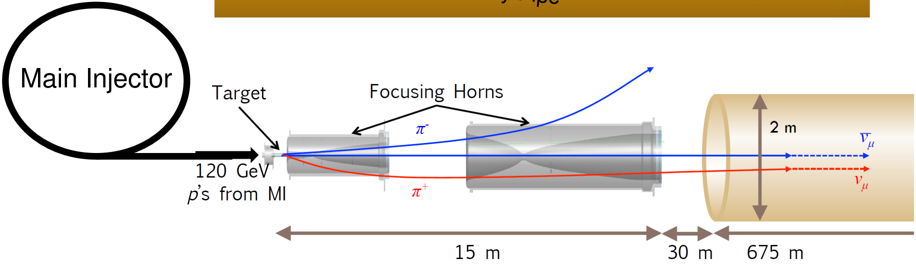
Focus outgoing mesons (π's and K's)



How to Make a Neutrino Beam

Let them decay into neutrinos





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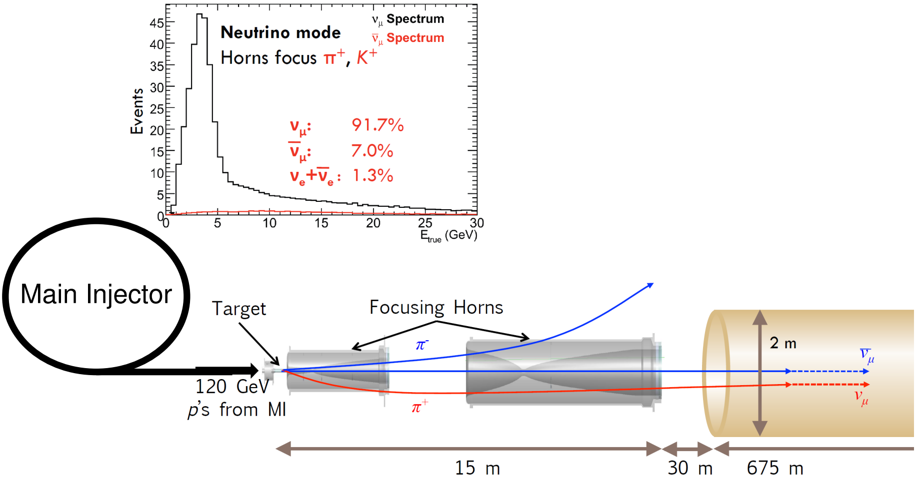

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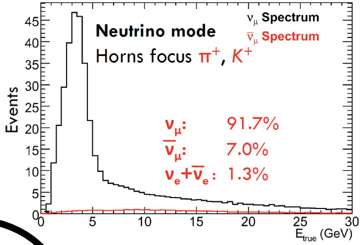
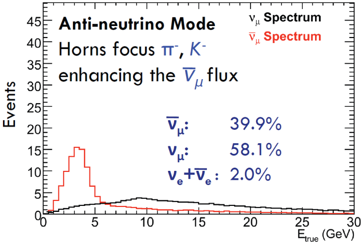
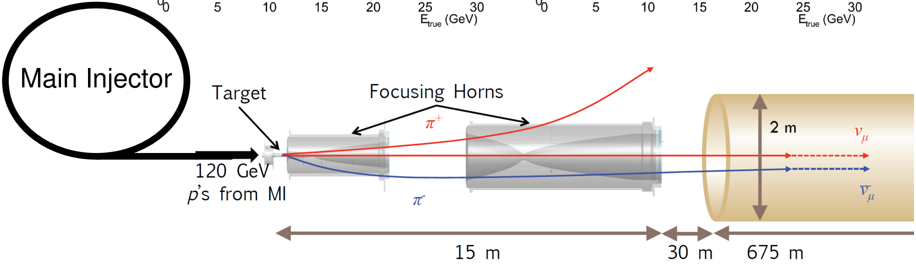
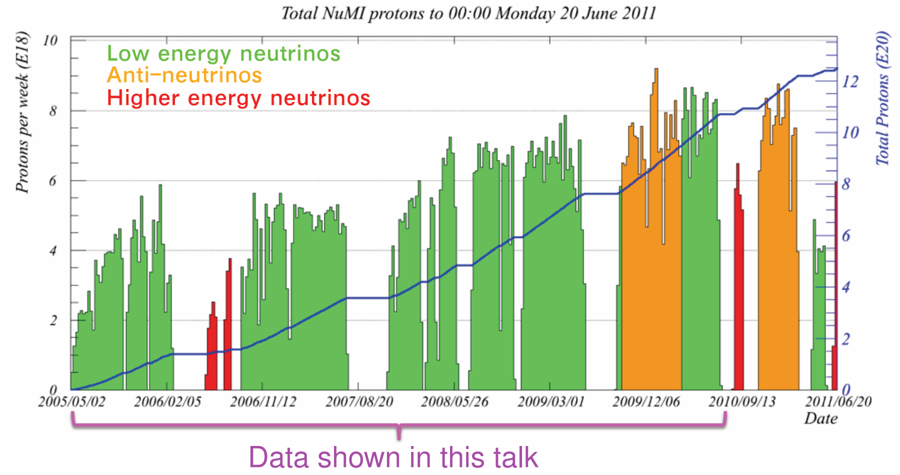






Beam Performance

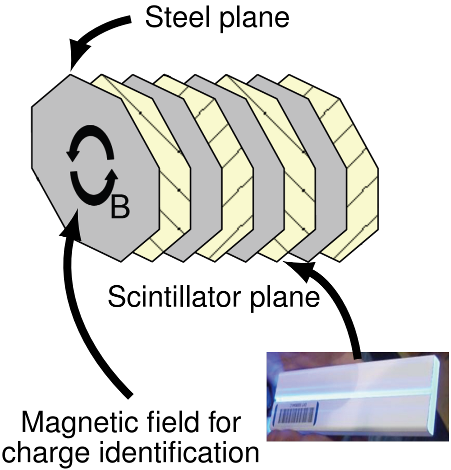
Beam intensity has been increasing

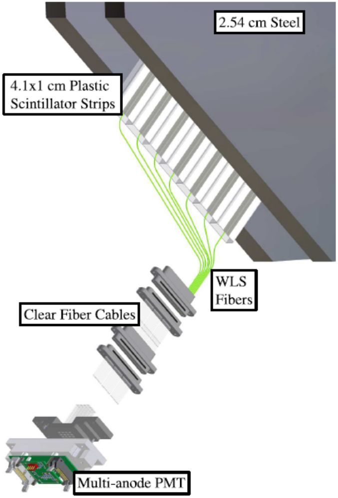


How to Make a Neutrino Detector

Alternate steel and scintillator planes

How to Make a Neutrino Detector





How to Distinguish Events

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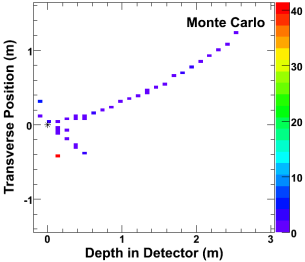

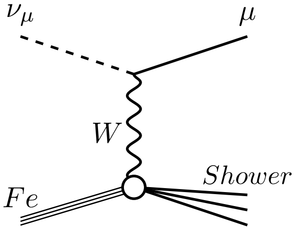

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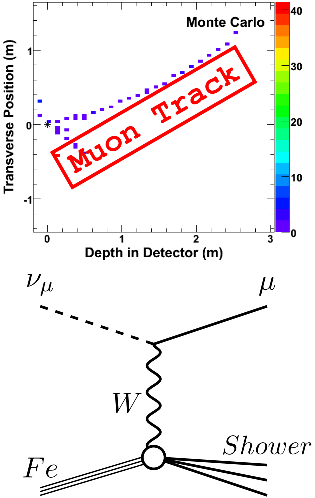

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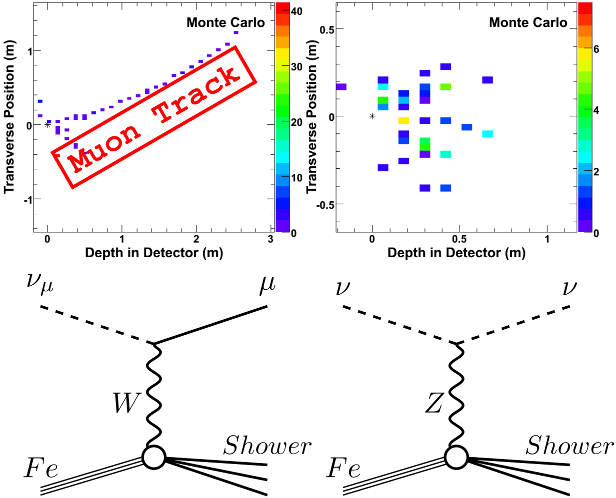

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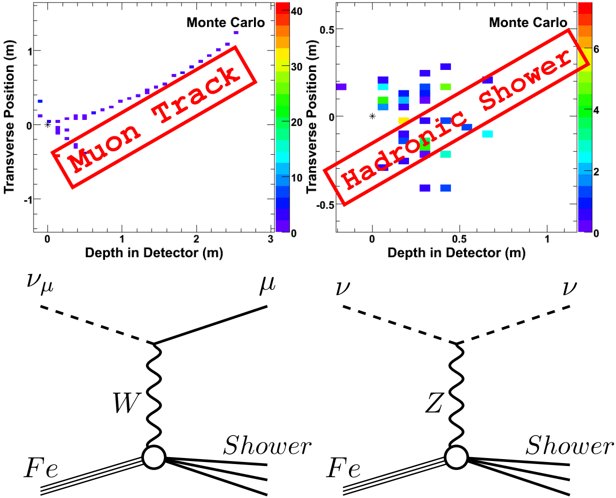

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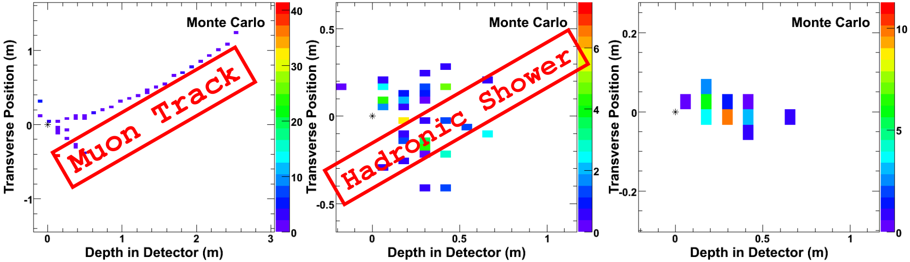

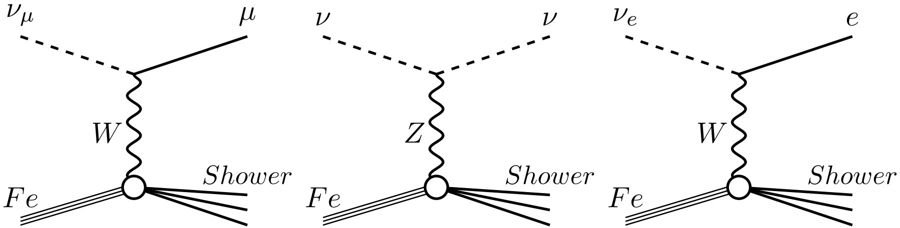

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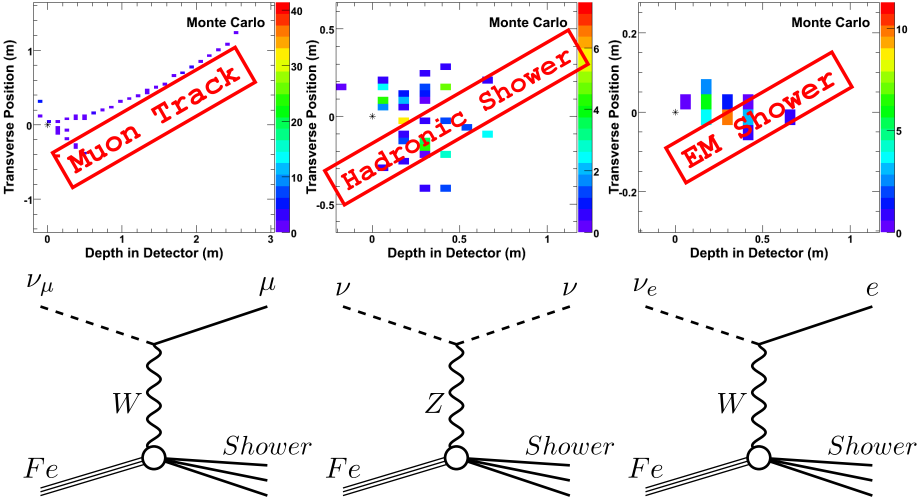
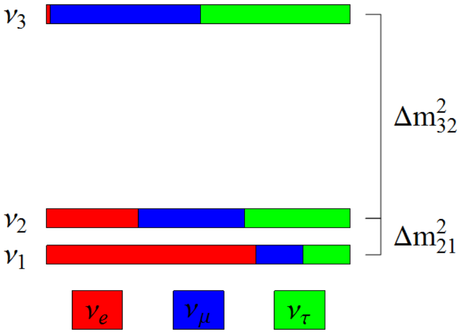


Neutrino Oscillations



Slow Oscillations

- Governed by Δm^2_{21}
- Relevant at $L/E \gtrsim 10^4$ km/GeV
- Not accessible by MINOS

Fast Oscillations

- Governed by Δm^2_{32}
- Relevant at $L/E \gtrsim 300$ km/GeV
- Small ν_e contribution ($\theta_{13} \ll 1$)

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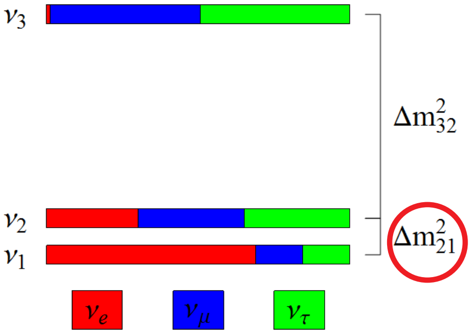

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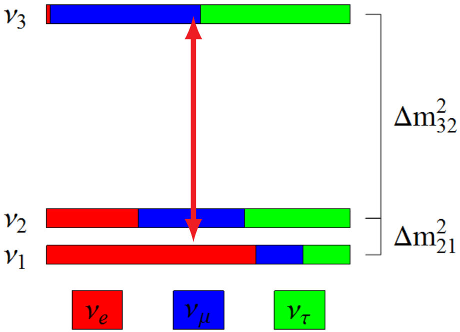

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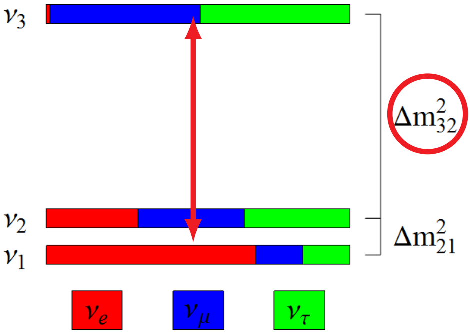

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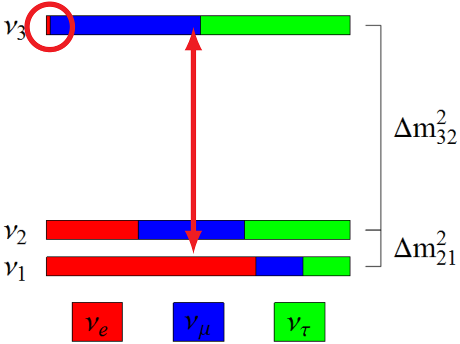

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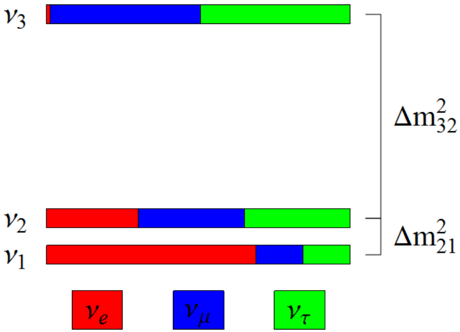
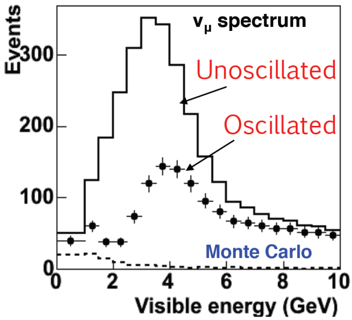
Comparing ν_μ-CC Hits

Are muon neutrinos disappearing?

Comparing ν_μ-CC Hits

$$\mathcal{P}_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2(2\theta_{23}) \sin^2(1.27 \Delta m^2_{32} \frac{L}{E})$$



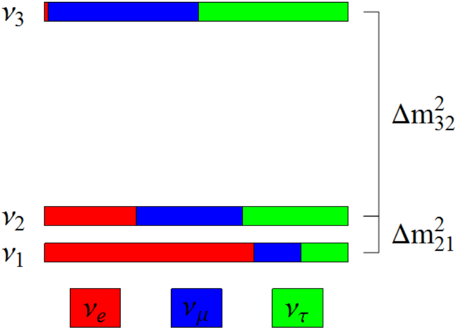


MC Input Parameters

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

$\Delta m^2_{23} = 3.35 \times 10^{-3}$ eV^2

Comparing ν_μ-CC Hits



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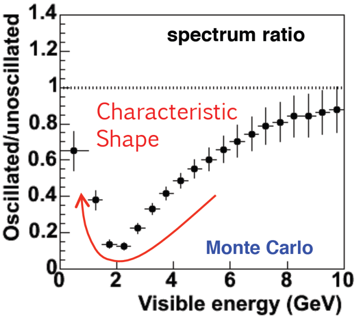

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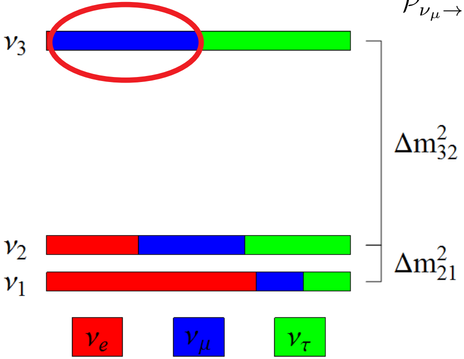

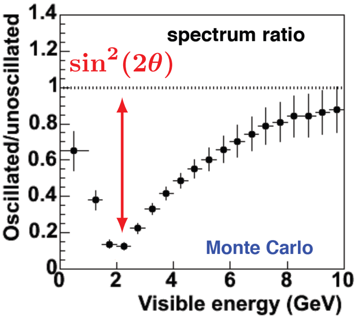

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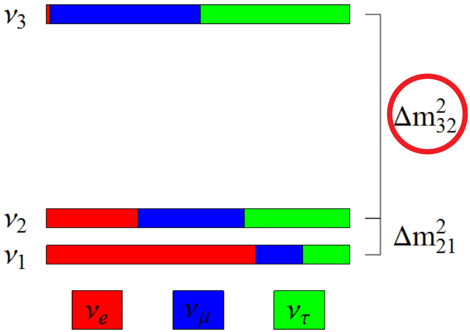

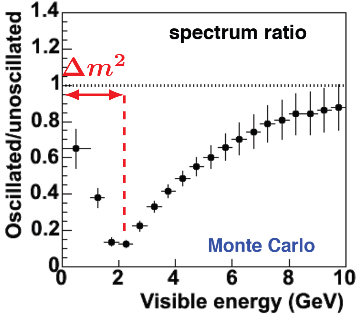

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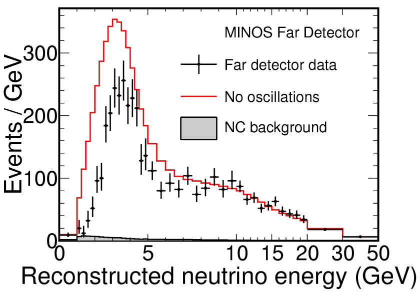
Comparing ν_μ-CC Hits

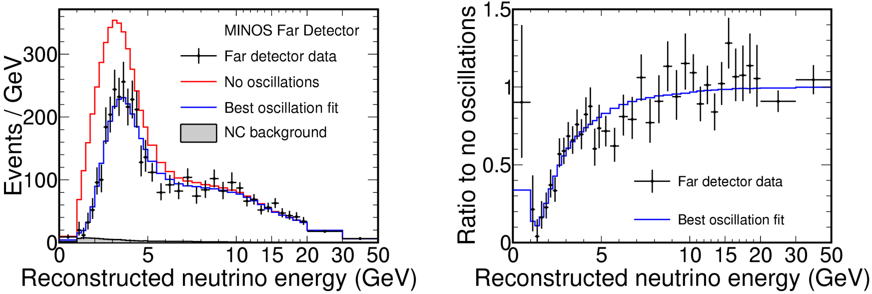
Precision measurements of oscillation parameters



Expected **2451** events with no oscillation.
Observed **1986** events.

Comparing ν_μ-CC Hits

Precision measurements of oscillation parameters



Best fit at $|\Delta m^2| = 2.32 \times 10^{-3}$ eV^2 and $\sin^2(2\theta) = 1.00$

Comparing ν_μ-CC Hits

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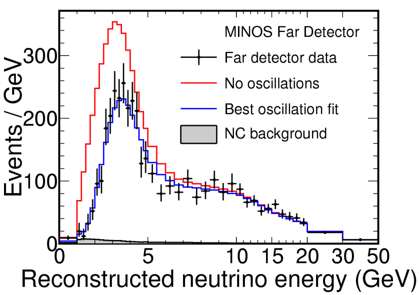


Pure decay† and decoherence‡ excluded at $> 6\sigma$

Searches for possible sub-dominant effects are underway

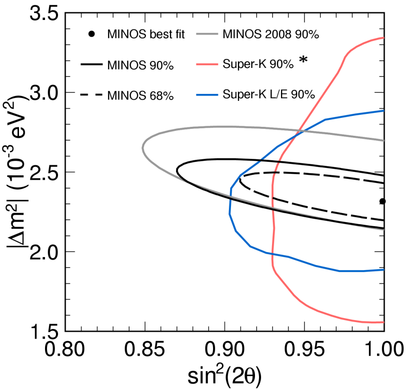
† **Phys. Rev. Lett. 82, 2640 (1999)** ‡ **Phys. Rev. D 67, 093006 (2003)**

Comparing ν_μ-CC Hits

Precision measurements of oscillation parameters

$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$$
$\sin^2(2\theta) > 0.9$ at 90% C.L.

Best measurement of $|\Delta m^2|$

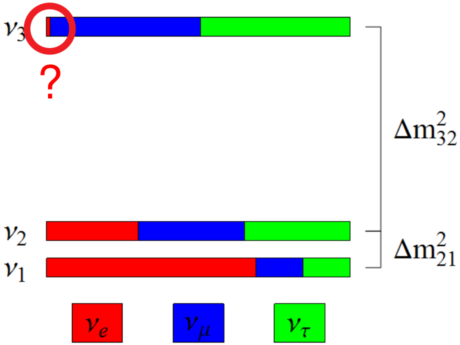


Phys. Rev. Lett. 106, 181801 (2011)

***Phys. Rev. D 74, 032002 (2006)**

Comparing ν_e-CC Hits

How small is the small ν_e contribution?



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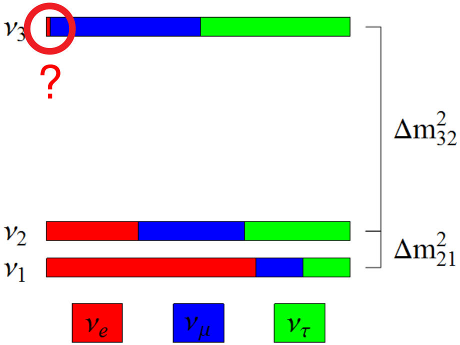

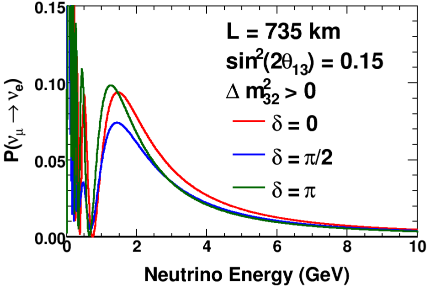

$$\mathcal{P}_{\nu_\mu \to \nu_e} = \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2(1.27 \Delta m^2_{32} \tfrac{L}{E}) + f(\delta_{CP}, \theta_{13}, \ldots) \mathcal{O}(\tfrac{\Delta m^2_{21}}{\Delta m^2_{32}})$$

Comparing ν_e-CC Hits

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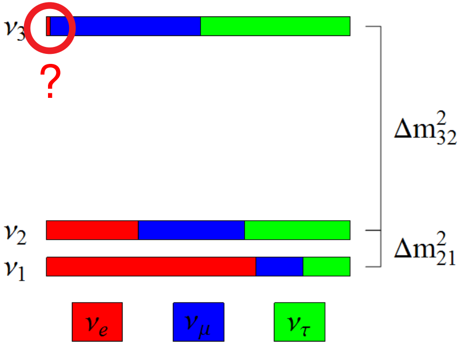

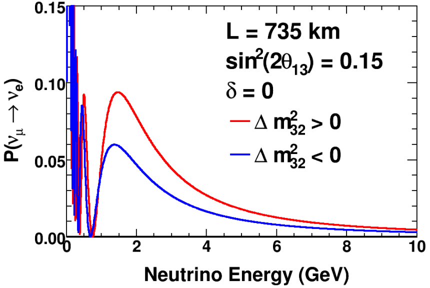

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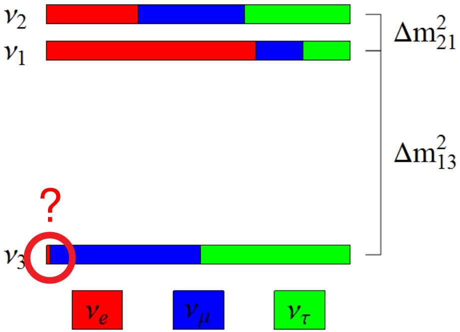

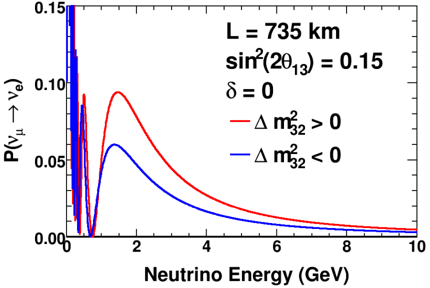

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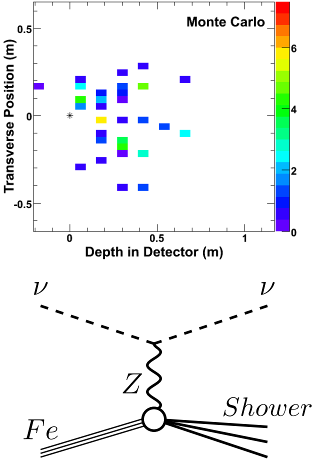
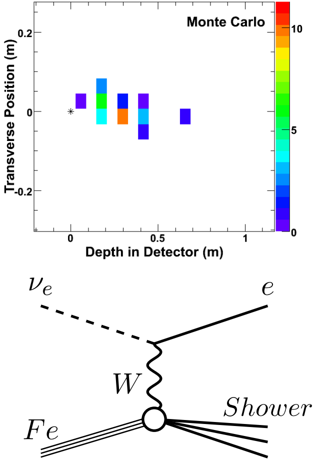
Comparing ν_e-CC Hits

Difficult to distinguish NC and ν_e-CC events





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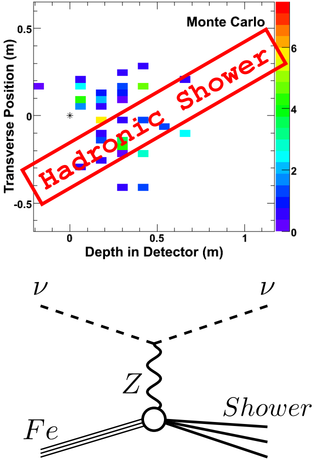
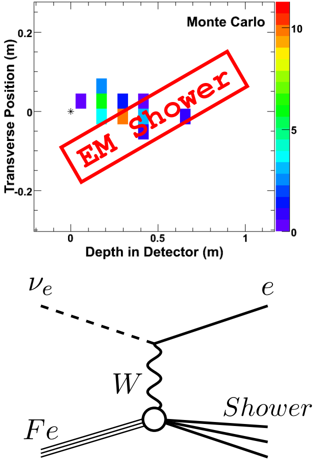
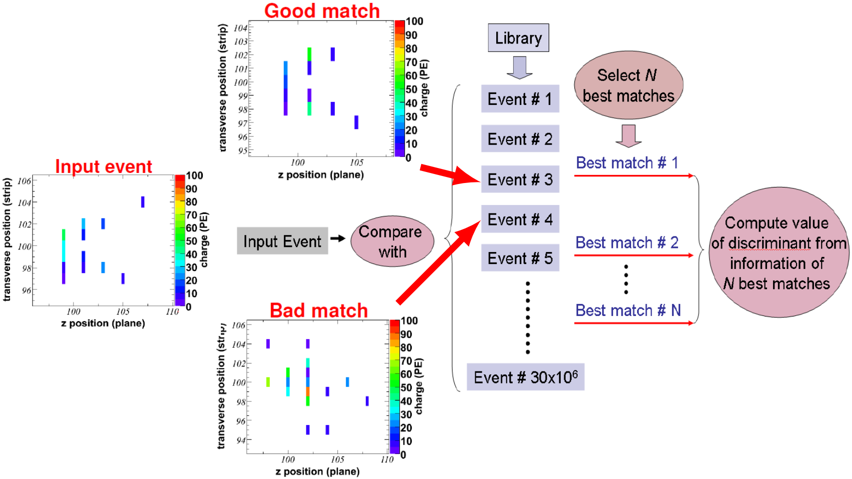




Comparing ν_e-CC Hits

Library Event Matching (LEM)



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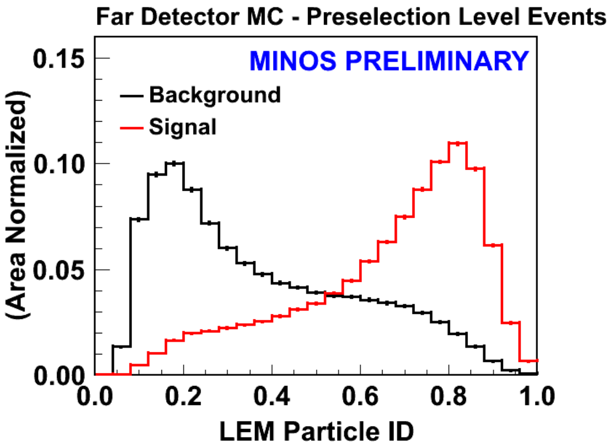
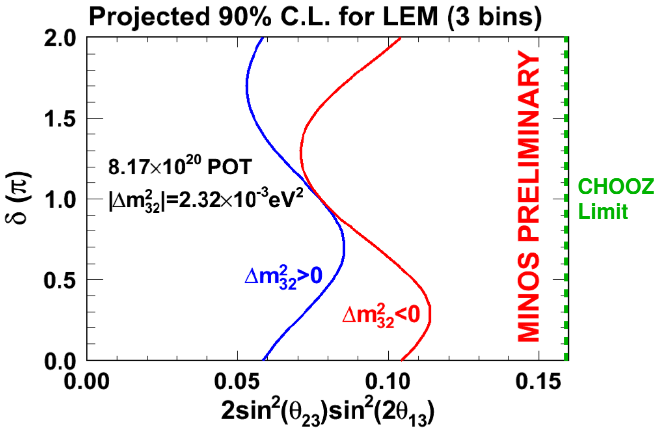
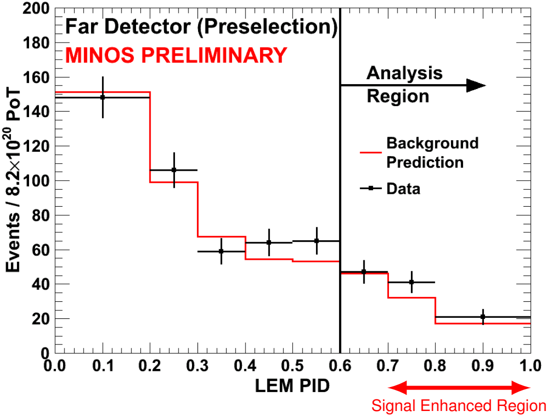


Comparing ν_e-CC Hits

Most sensitive θ_{13} measurement to date



Comparing ν_e-CC Hits

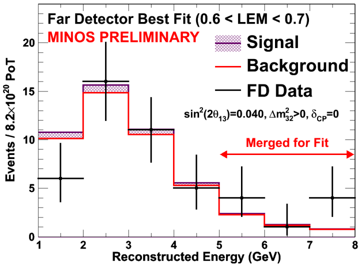


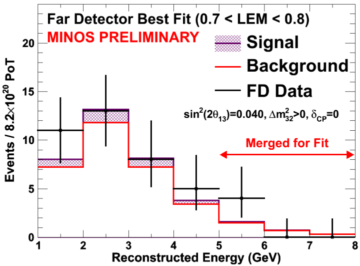
In signal enhanced region (LEM>0.7):

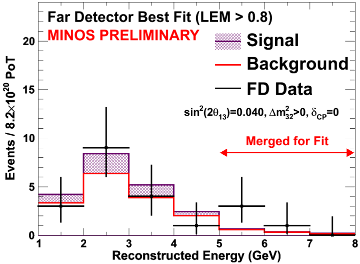
Expected with $\theta_{13} = 0$: **49.6 $\pm$ 7.0(stat) $\pm$ 2.7(syst)**

Obseved: **62**

Comparing ν_e-CC Hits







Fit in 3 LEM bins x 5 energy bins

Best fit at $\sin^2(2\theta_{13}) = 0.04^{+0.05}_{-0.03}$

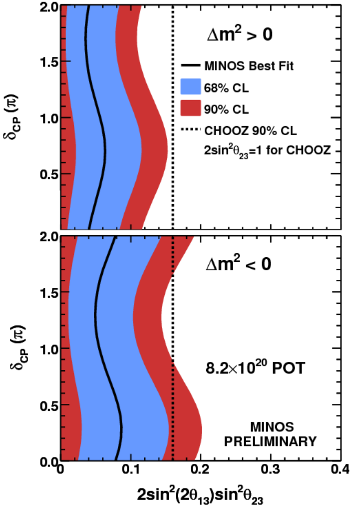
Assuming normal hierarchy, $|\Delta m^2_{32}| = 2.32 \times 10^{-3}$ eV^2, $\delta_{CP} = 0$ and $\theta_{12} = \pi/4$

Comparing ν_e-CC Hits

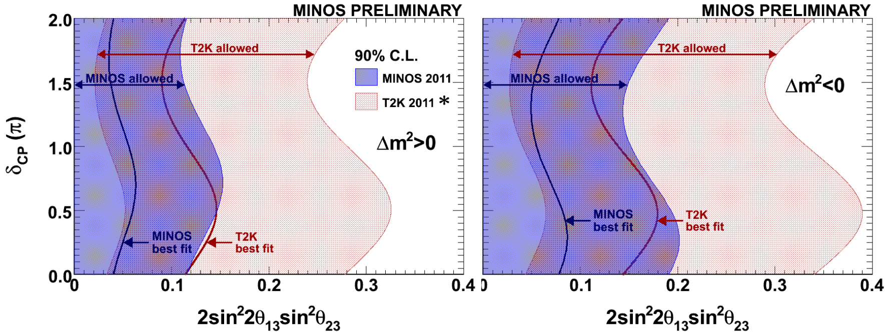
Assuming $\delta_{CP} = 0$, $\theta_{12} = \pi/4$, $|\Delta m^2_{32}| = 2.32 \times 10^{-3}$ eV^2 and normal (inverted) hierarchy:

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

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



Comparing MINOS and T2K

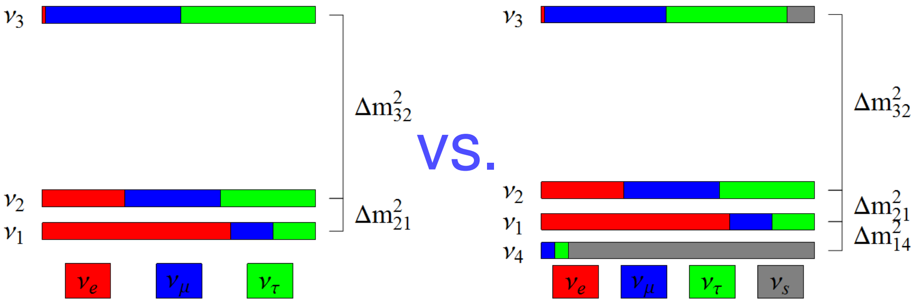


Overlay of MINOS and T2K allowed regions

*arXiv:1106.2822

Comparing NC Hits

Test of the 3 neutrino oscillation model

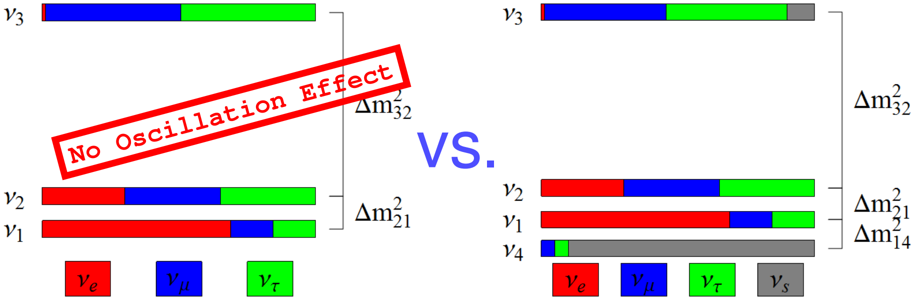


NC interaction is not sensitive to flavor

Only 3 light active neutrinos from LEP

Comparing NC Hits

Test of the 3 neutrino oscillation model



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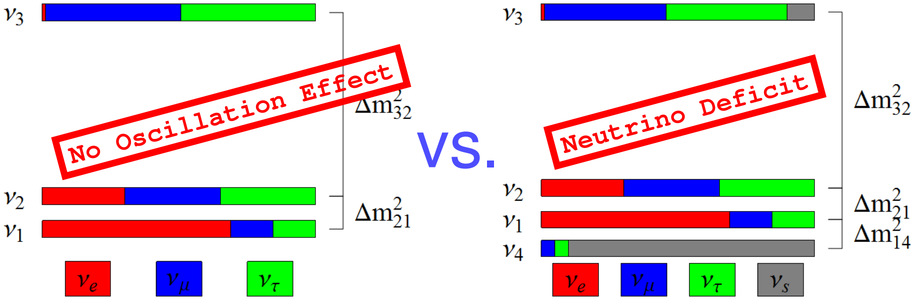
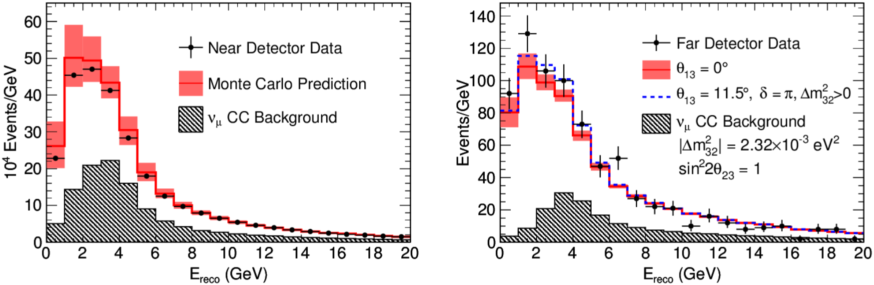


NC interaction is not sensitive to flavor

Only 3 light active neutrinos from LEP

No evidence of deficit in NC events



Expected **754 (795)** events for $\theta_{13} = 0° \ (11.5°)$. Observed **802** events.

$$f_s = \frac{\mathcal{P}_{\nu_\mu \to \nu_s}}{1 - \mathcal{P}_{\nu_\mu \to \nu_\mu}} < \mathbf{0.22} \ (\mathbf{0.40})$$ at 90% C.L. with $\theta_{13} = 0° \ (11.5°)$

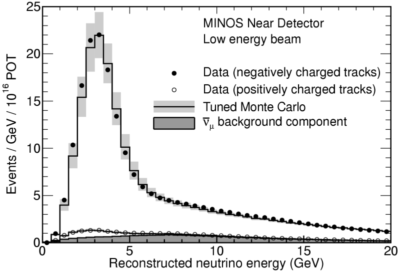
Phys. Rev. Lett. 107, 011802 (2011)

Comparing $\overline{\nu}_\mu$-CC Hits

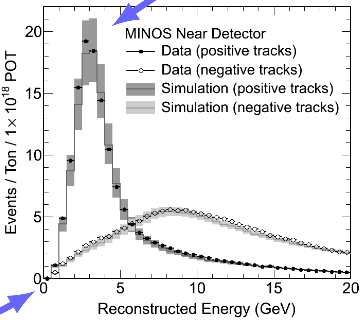
Are antineutrino oscillations the same?

Comparing $\overline{\nu}_\mu$-CC Hits

Neutrino Running



Select positive tracks

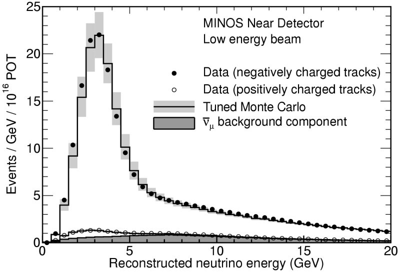


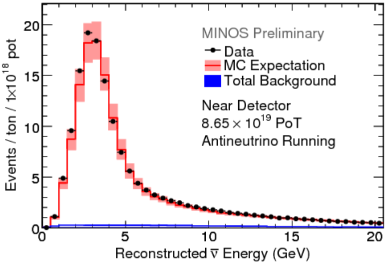
Reverse Horn Current

Antineutrino Running

Comparing $\overline{\nu}_{\mu}$-CC Hits

Neutrino Running

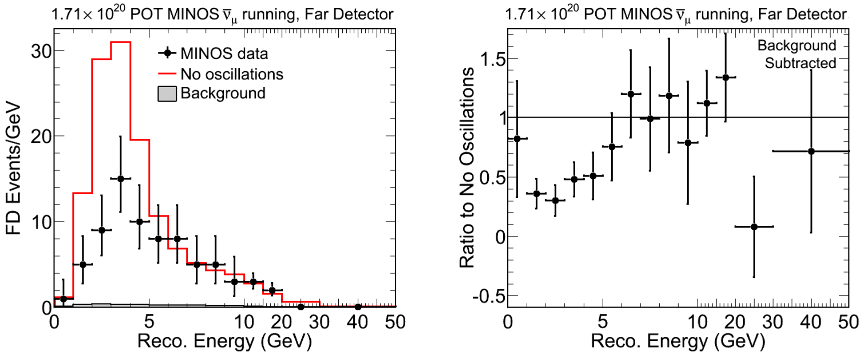




Reverse Horn Current

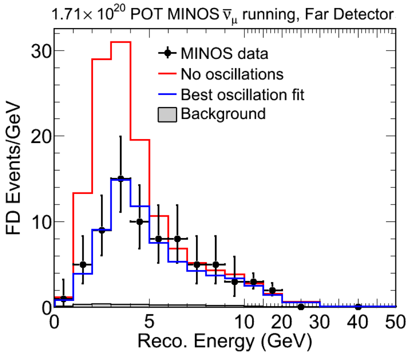
Antineutrino Running

Comparing $\overline{\nu}_{\mu}$-CC Hits



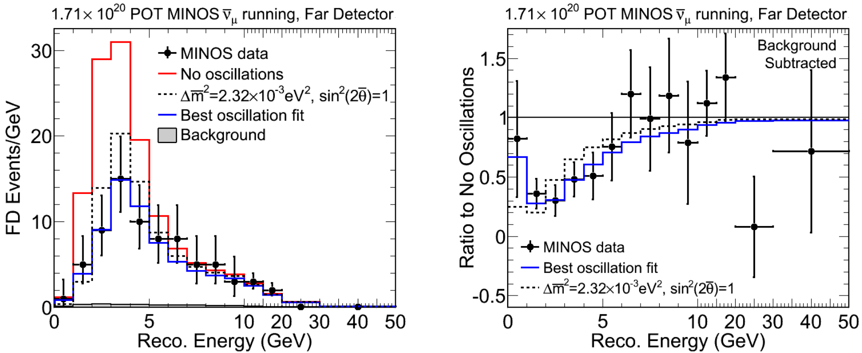
Expected **156** events with no oscillation.
Observed **97** events.

Comparing $\overline{\nu}_\mu$-CC Hits



Best fit at $|\Delta\overline{m}^2| = \mathbf{3.36 \times 10^{-3}}$ **eV²** and $\sin^2(2\overline{\theta}) = \mathbf{0.86}$

Comparing $\overline{\nu}_\mu$-CC Hits



How do neutrinos and antineutrinos compare?

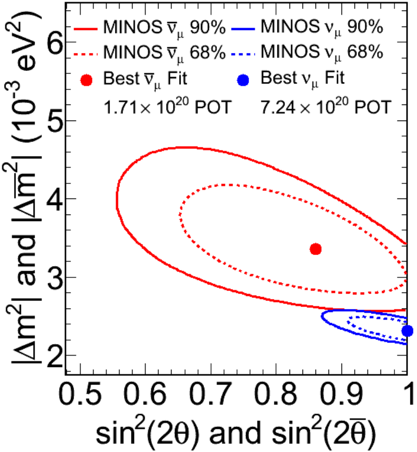
Comparing $\overline{\nu}_\mu$-CC Hits

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

$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2$$
$$\sin^2(2\theta) > 0.9 \text{ at 90\% C.L.}$$

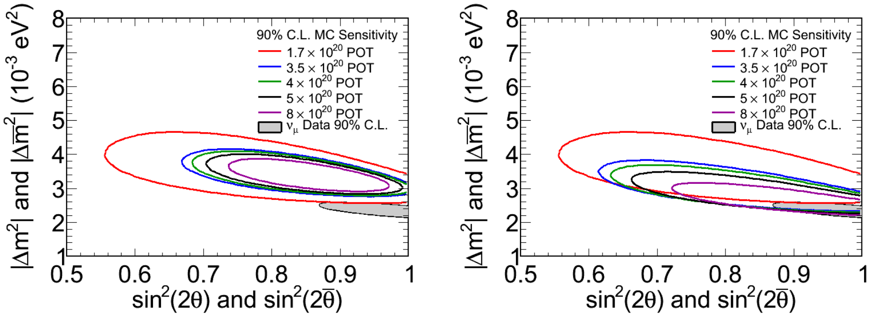
2% chance of observing this, given identical ν_μ and $\overline{\nu}_\mu$ oscillation parameters.

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



Comparing $\overline{\nu}_\mu$-CC Hits

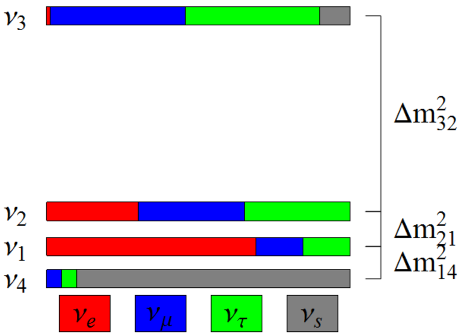
What to expect with more statistics?



$$\mathcal{P}_{\overline{\nu}_\mu\to\overline{\nu}_\mu} \neq \mathcal{P}_{\nu_\mu\to\nu_\mu} \qquad \mathcal{P}_{\overline{\nu}_\mu\to\overline{\nu}_\mu} = \mathcal{P}_{\nu_\mu\to\nu_\mu}$$

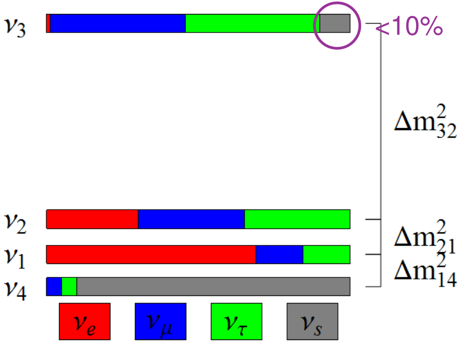
New results with 2.95×10^{20} POT exposure expected this summer

Summary



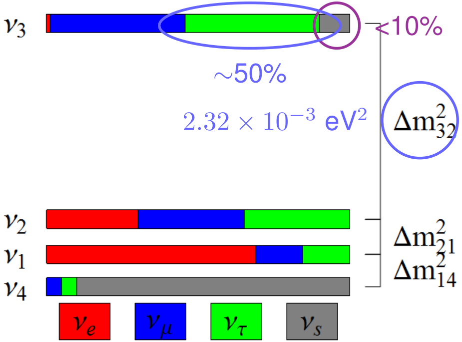
ν_3
Δm^2_{32}
ν_2
Δm^2_{21}
ν_1
Δm^2_{14}
ν_4
ν_e
ν_μ
ν_τ
ν_s

Summary



NC analysis:
$f_s < 0.22\ (0.40)$
at 90% C.L.

Summary



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$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}$ eV^2
$\sin^2(2\theta) > 0.9$ at 90% C.L.

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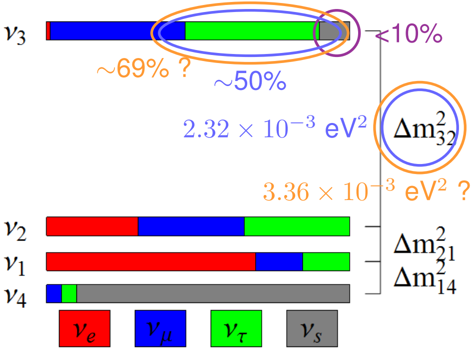

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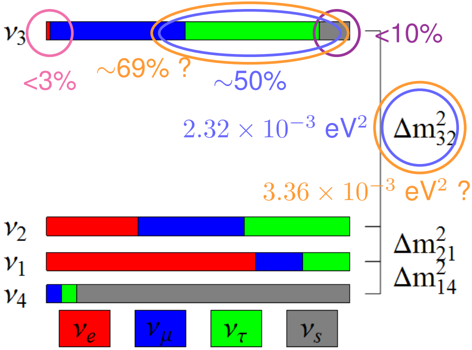

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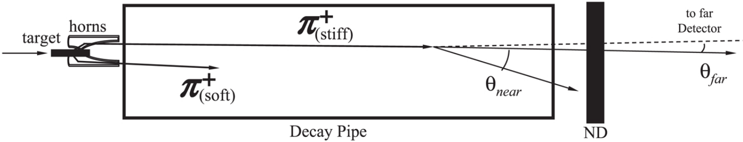
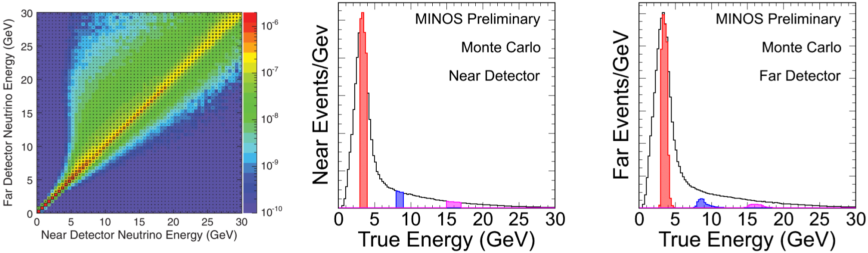
ν_e-CC analysis:
$\sin^2(2\theta_{13}) < 0.12\ (0.20)$
at 90% C.L.

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

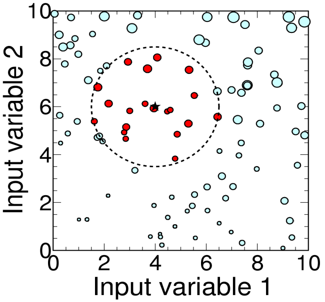
Backup Slides

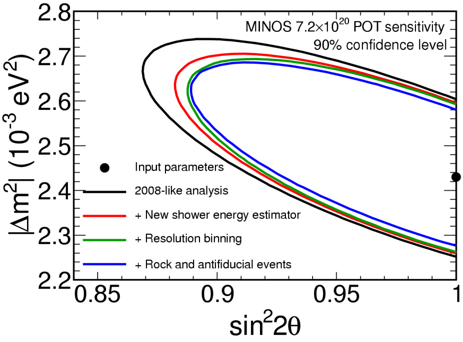
Flux Differences

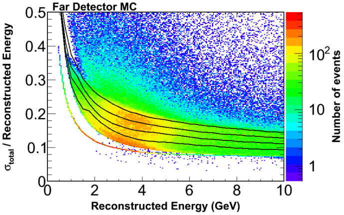


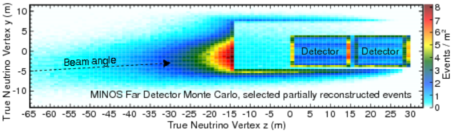


ν_μ-CC Analysis Improvements





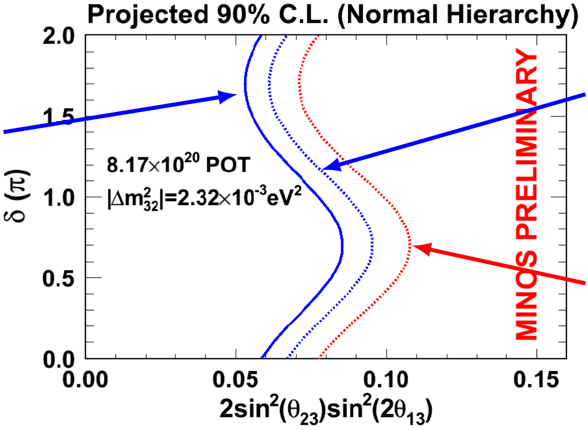




ν_e-CC Analysis Improvements

Analysis improvements since 2010

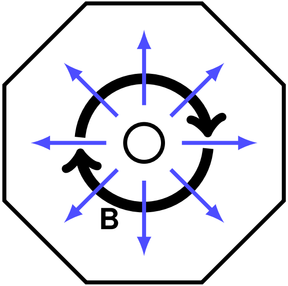
Shape fit and new selection algorithm



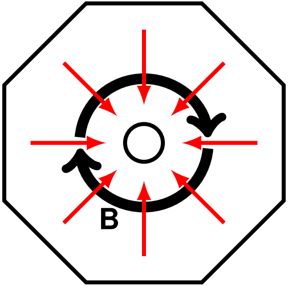
Rate-only with new selection algorithm

2010 style analysis with new data

Charge Identification



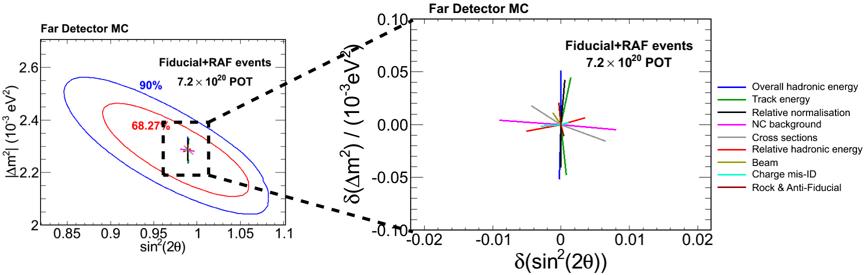
Negative Tracks



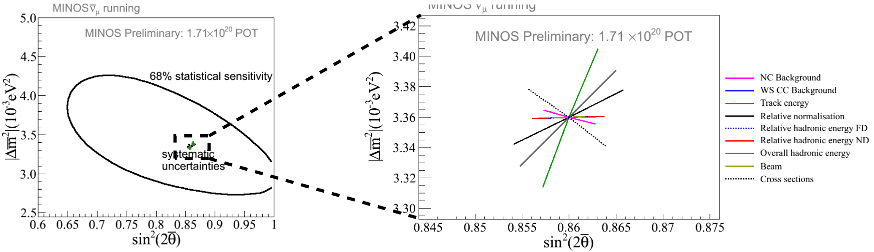
Positive Tracks

Systematic Uncertainties

Neutrinos



Antineutrinos



ν_μ and $\overline{\nu}_\mu$ Contours