

Recent Results from MINOS

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University of Sussex

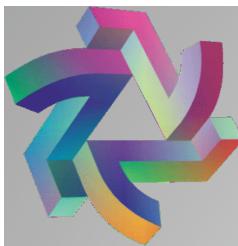
Rencontres de Moriond

6-13 Mars 2010



Outline

- ✓ MINOS
- ✓ NuMI Beam
- ✓ Results
 - ✓ Muon Neutrino Disappearance
 - ✓ Muon Antineutrino Disappearance
 - ✓ Electron Neutrino Appearance
 - ✓ Neutral Current Analysis
- ✓ Conclusion



MINOS

- MINOS (Main Injector Neutrino Oscillation Search)
 - long baseline (735 km) oscillation experiment
 - neutrinos produced using the 120 GeV proton beam at the Fermilab Main Injector (NuMI beam)
- Concept
 - Near Detector at Fermilab to measure the beam composition and the energy spectrum
 - Far Detector in Minnesota to look for and study oscillations



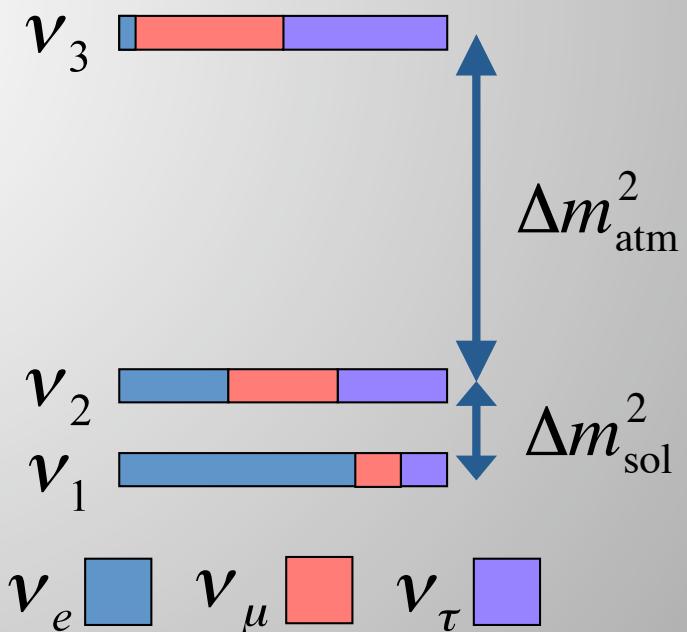


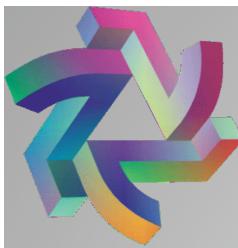
Physics Goals

- Look for ν_μ CC disappearance
 - perform precision measurements of $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$
- Look for $\bar{\nu}_\mu$ CC disappearance
 - test CPT conservation
 - measure $|\Delta \bar{m}^2_{32}|$ and $\sin^2(2\bar{\theta}_{23})$
- Look for ν_e appearance
 - sensitive to θ_{13}
- Look for sterile flavour

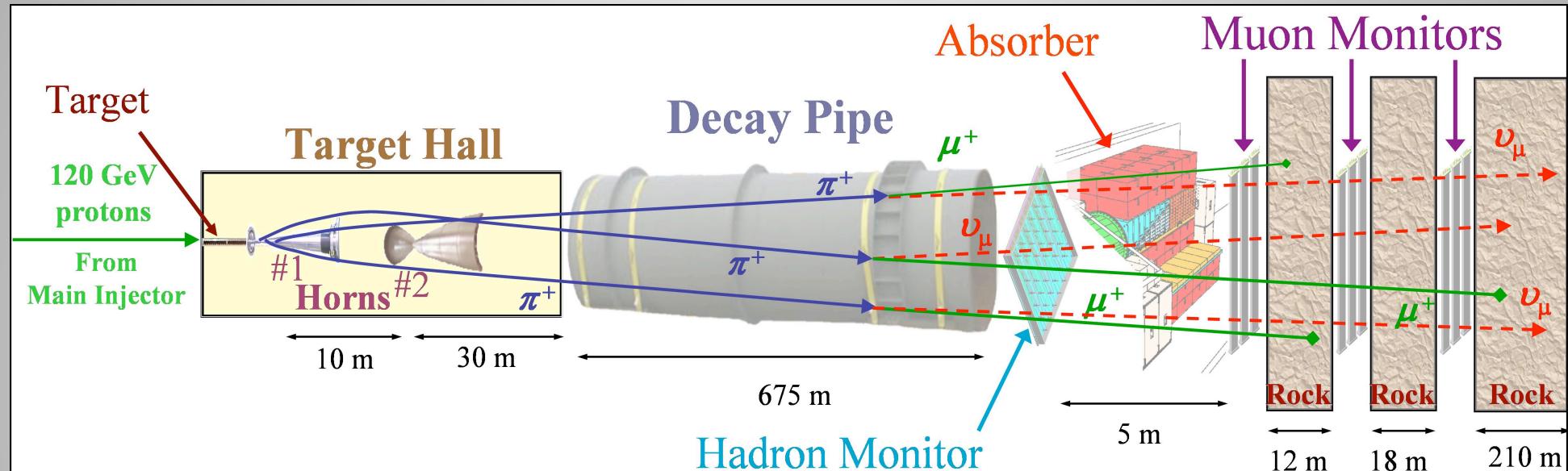
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_e appearance
 ν_μ disappearance

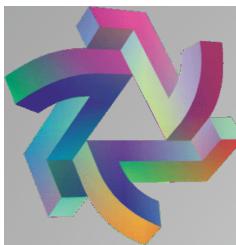




NuMI Neutrino Beam

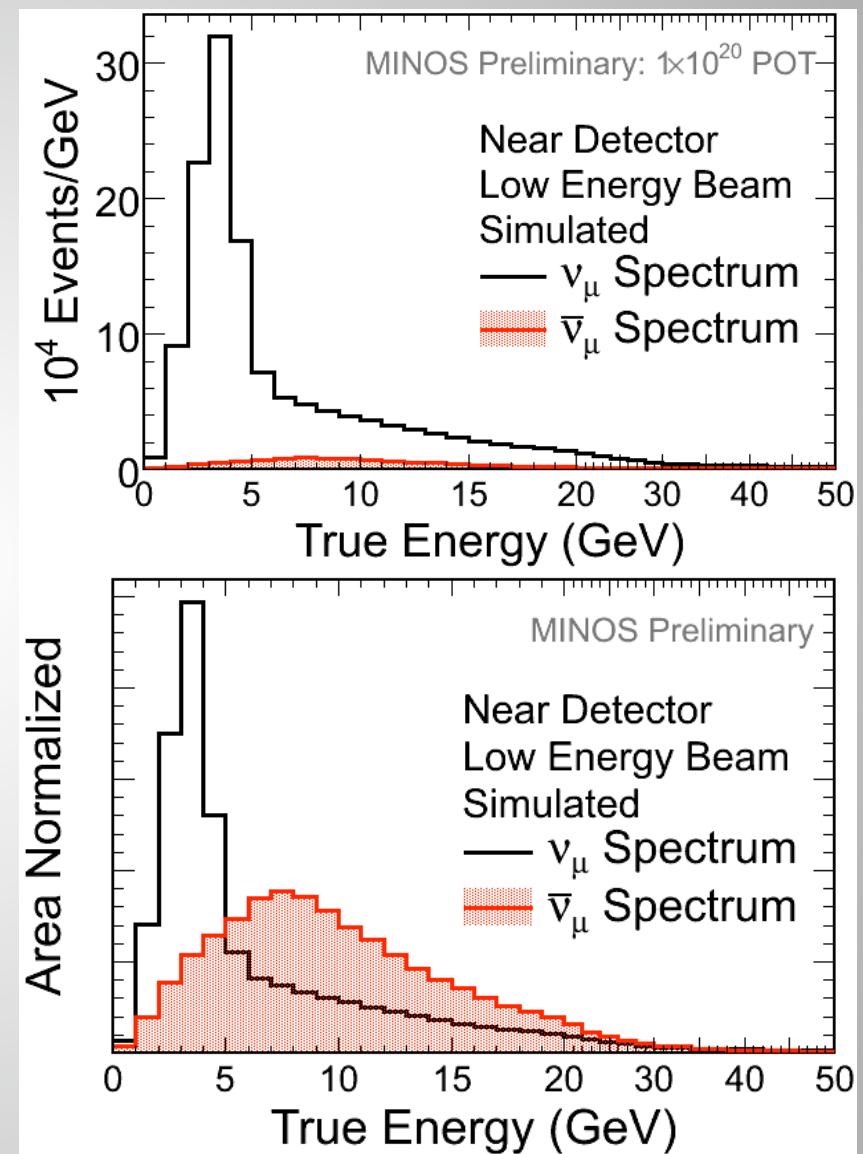


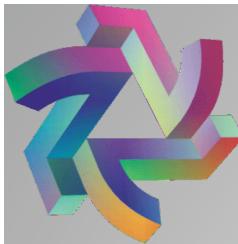
- 120 GeV protons from the Main Injector impinge on a graphite target and produce π s and K s
- Two magnetic horns to focus the π s and K s
- Energy spectrum can be adjusted by varying the relative position of the target and the horns.



Neutrino Energy Spectrum

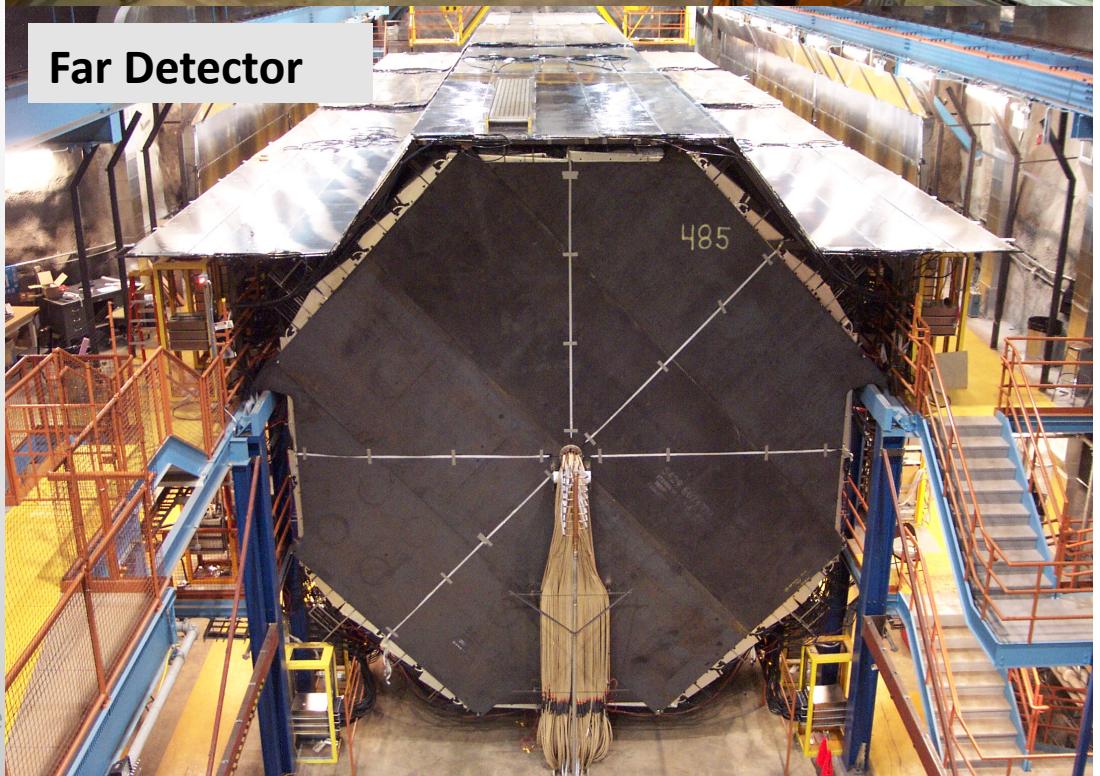
- Optimal beam configuration for $|\Delta m^2_{32}|$ “Low Energy”
- Beam composition in the Near Detector
 - 91.7 % of ν_μ
 - 7.0 % of $\bar{\nu}_\mu$
 - 1.3 % of ν_e and $\bar{\nu}_e$
- Significant difference in energy spectra:
 - ν_μ peaks at 3 GeV
 - $\bar{\nu}_\mu$ peaks at 8 GeV

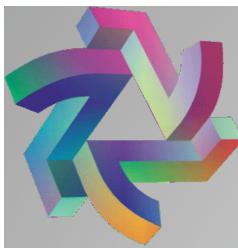




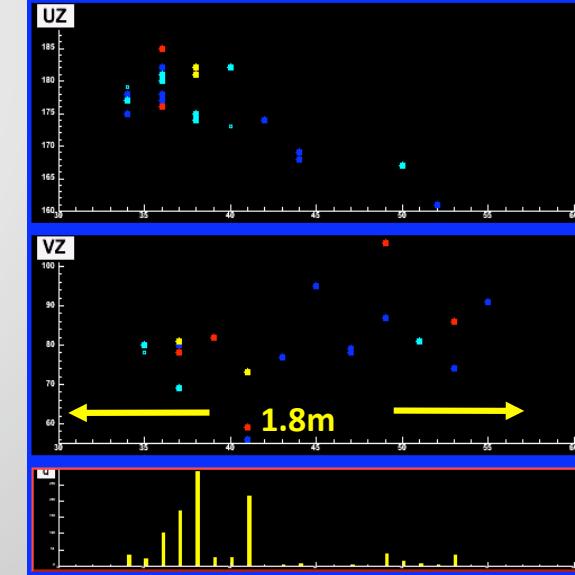
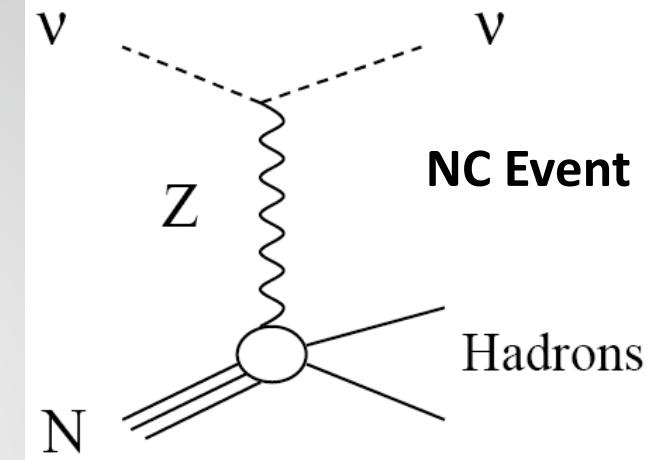
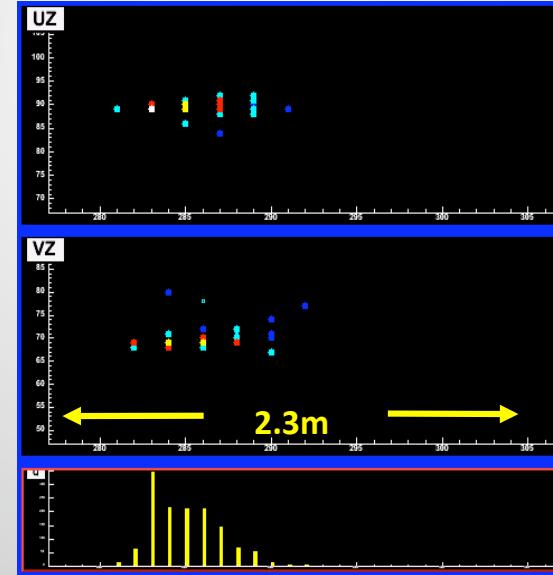
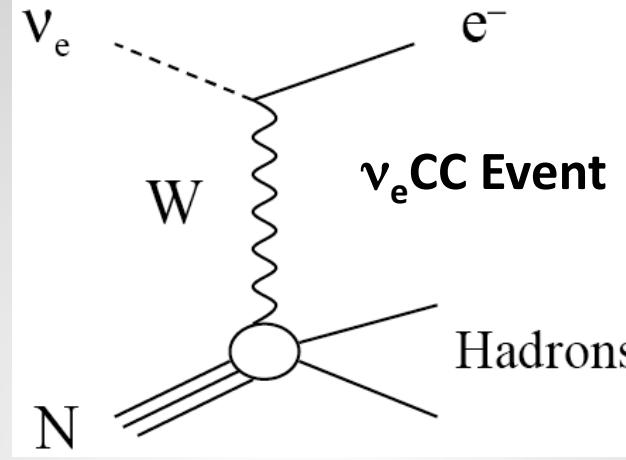
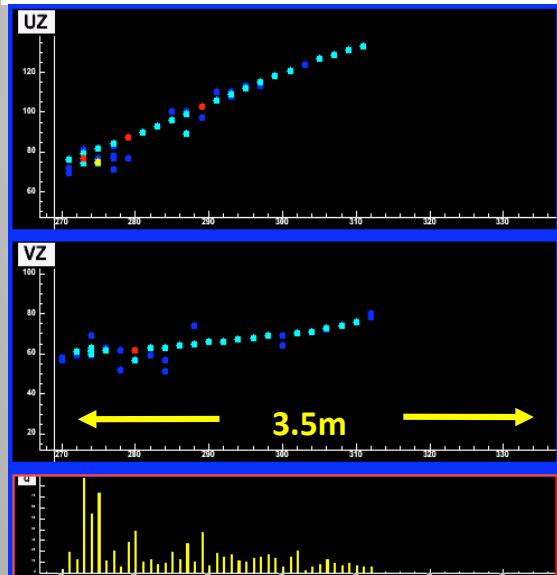
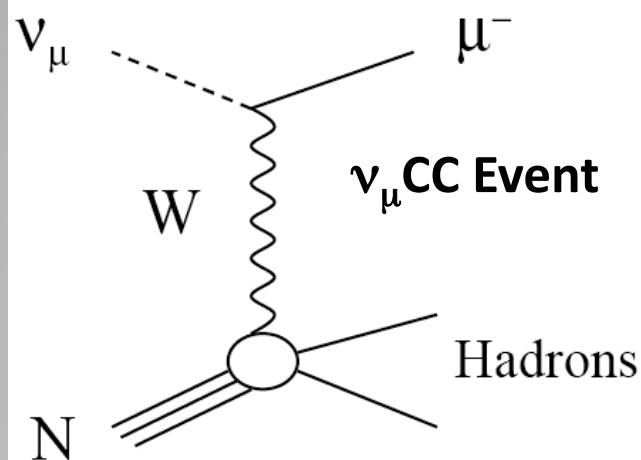
Detectors

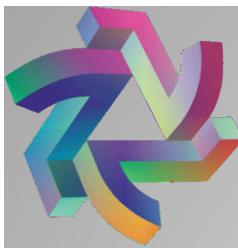
- Massive
 - 0.98 kt (Near Detector)
 - 5.4 kt (Far Detector)
- Magnetised sampling steel & scintillator calorimeters
 - ~ 1.3 T
 - steel 2.5 cm thick
 - scintillator strips 1 cm thick x 4.1 cm wide
- As similar as possible to reduce systematic uncertainties associated with neutrino flux, cross sections, and detector efficiency.



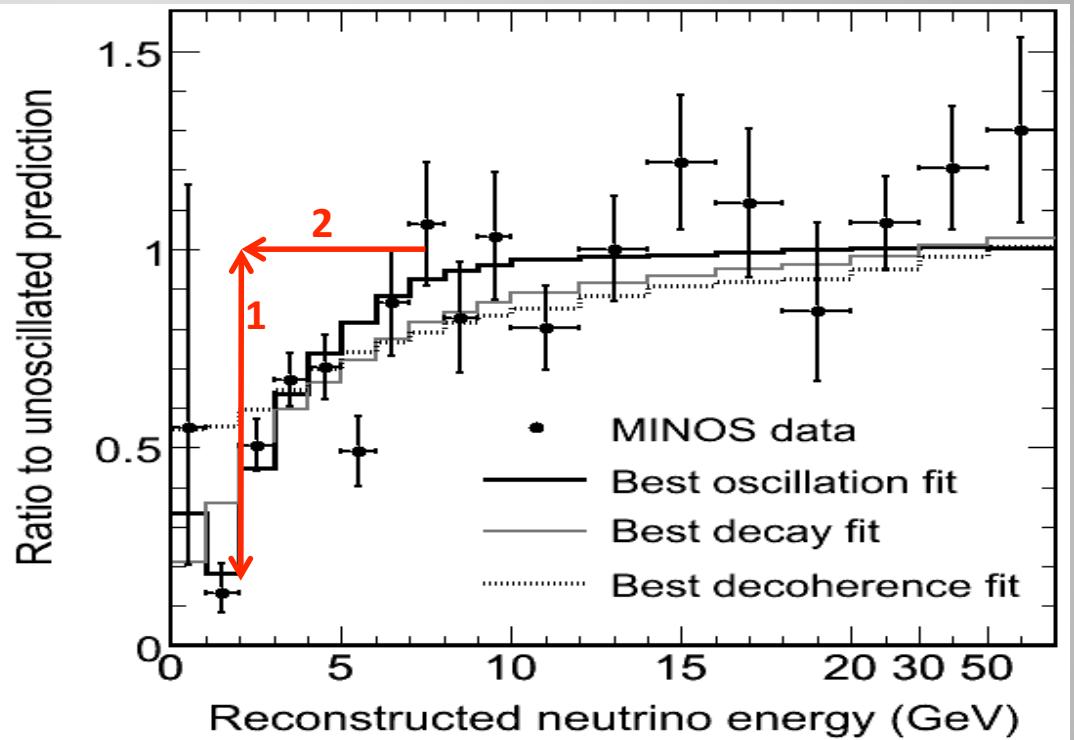
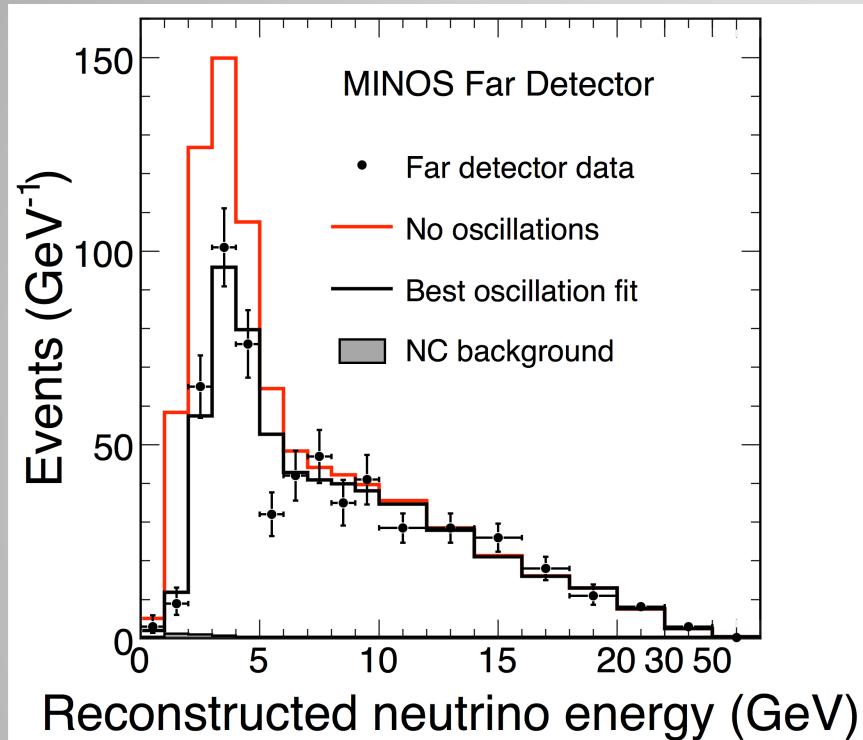


Event Topologies





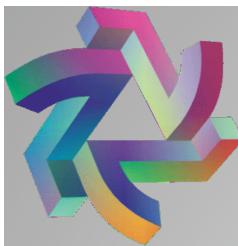
ν_μ Disappearance



- Predict unoscillated spectrum at the Far Detector by extrapolating the Near Detector spectrum using MC
- Compare with the measured spectrum to extract the oscillation parameters
- Test the hypothesis $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \boxed{\sin^2 2\theta} \sin^2(1.267 \boxed{\Delta m^2} L / E)$

1

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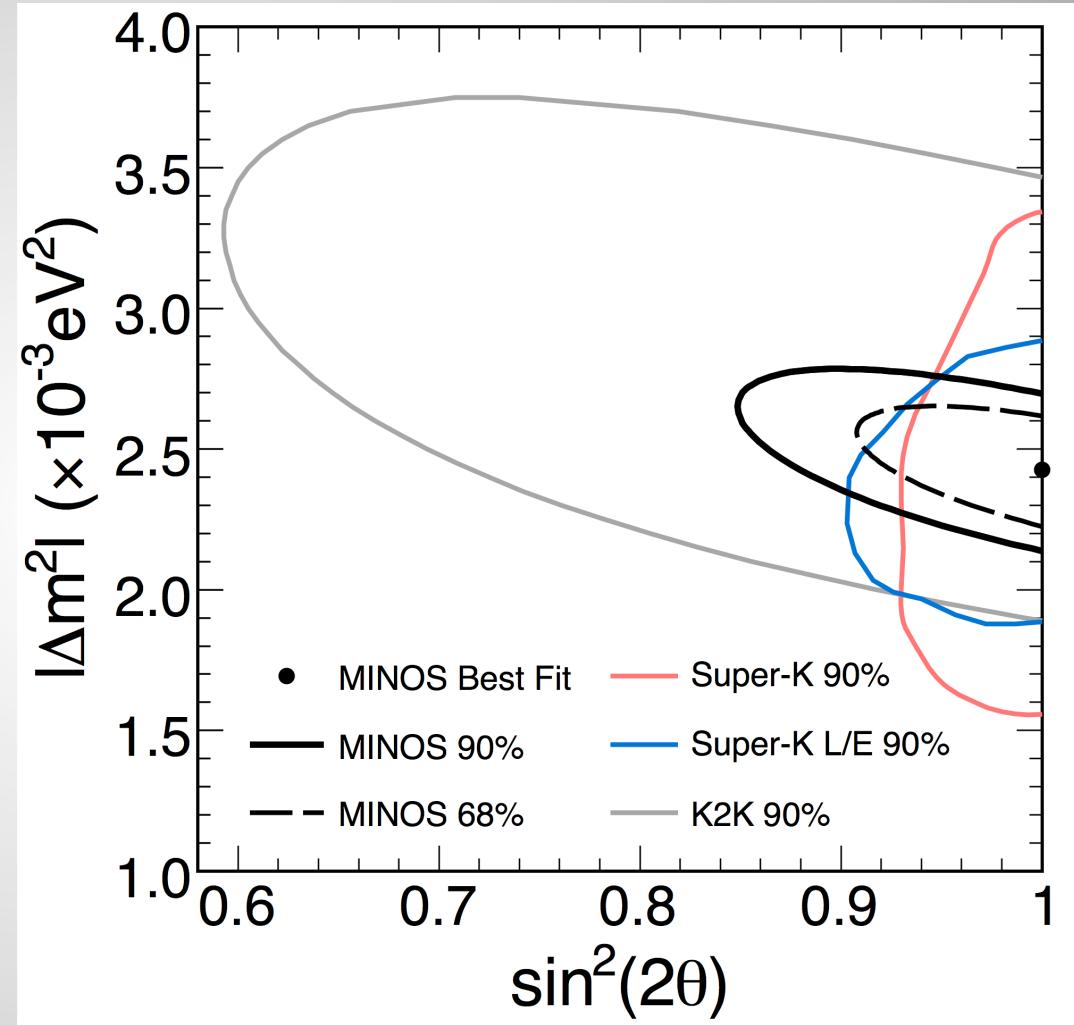


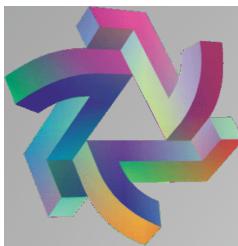
ν_μ Disappearance

$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2$
at 68% C.L.

$\sin^2(2\theta_{23}) > 0.90$
at 90% C.L.

World leading measurement of
 $|\Delta m^2_{32}|$
PRL 101 131802 (2008)





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

Large background (NC events and mis-identified ν_μ events)

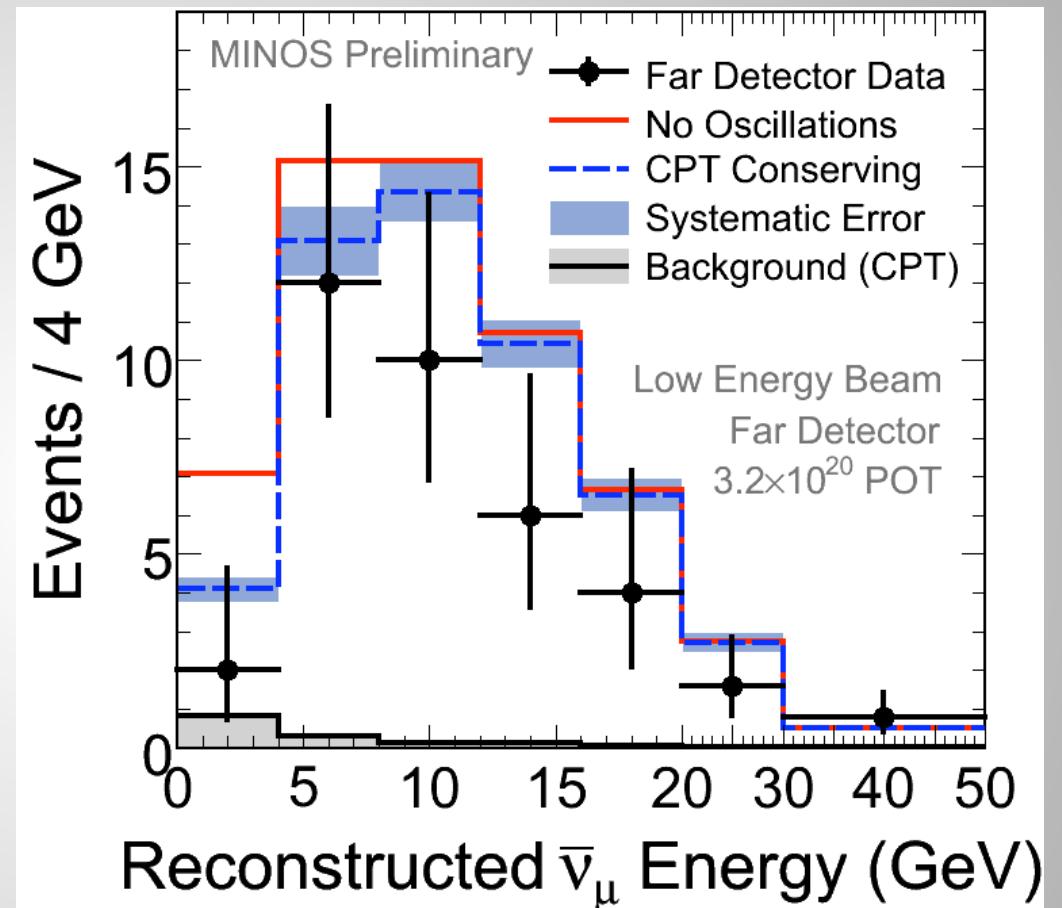
Predicted events with CPT conserving oscillations:

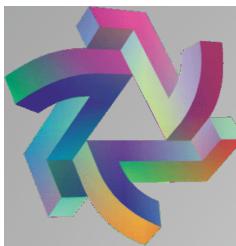
$58.3 \pm 7.6 \text{ (stat.)} \pm 3.6 \text{ (syst.)}$

Predicted events with null oscillations:

$64.6 \pm 8.0 \text{ (stat.)} \pm 3.9 \text{ (syst.)}$

Observed: **42**
(1.9σ deficit)

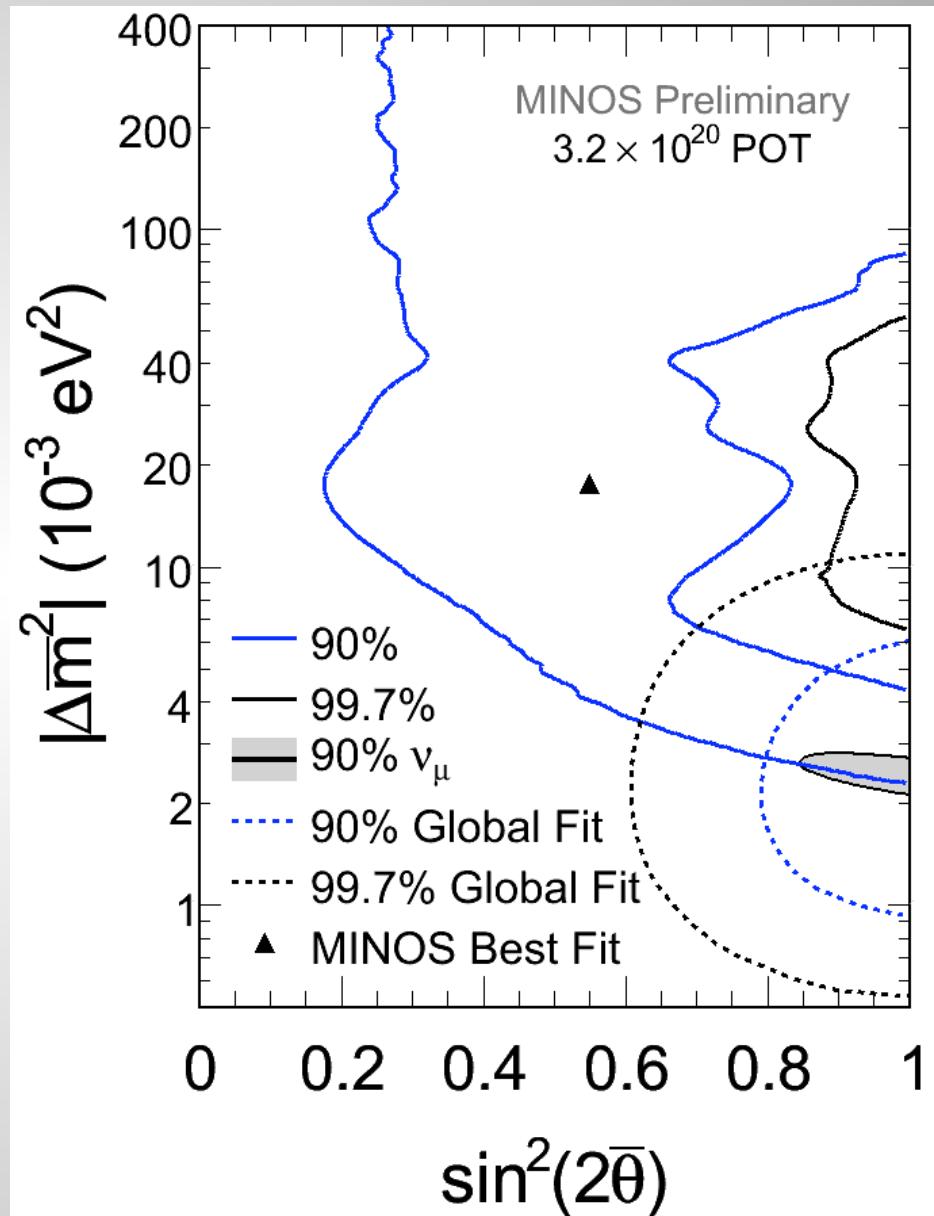


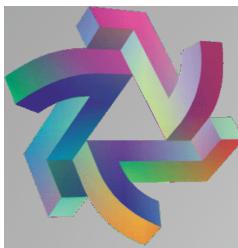


$\overline{\nu}_\mu$ Disappearance

- $\overline{\nu}_\mu$ best fit is at high value, due to deficit at high energy
- CPT conserving point from the MINOS neutrino analysis is within 90% contour
- Null oscillation hypothesis excluded at 99%
- At maximal mixing **exclude**:
 $(5.0 < \Delta\bar{m}^2 < 81) \times 10^{-3} \text{ eV}^2$ (90% C.L.)
- Dashed lines show global fit to previous data, Super-Kamiokande dominates (SK-I and SK-II)

M. C. Gonzalez-Garcia & M. Maltoni, Phys. Rept.
460 (2008)

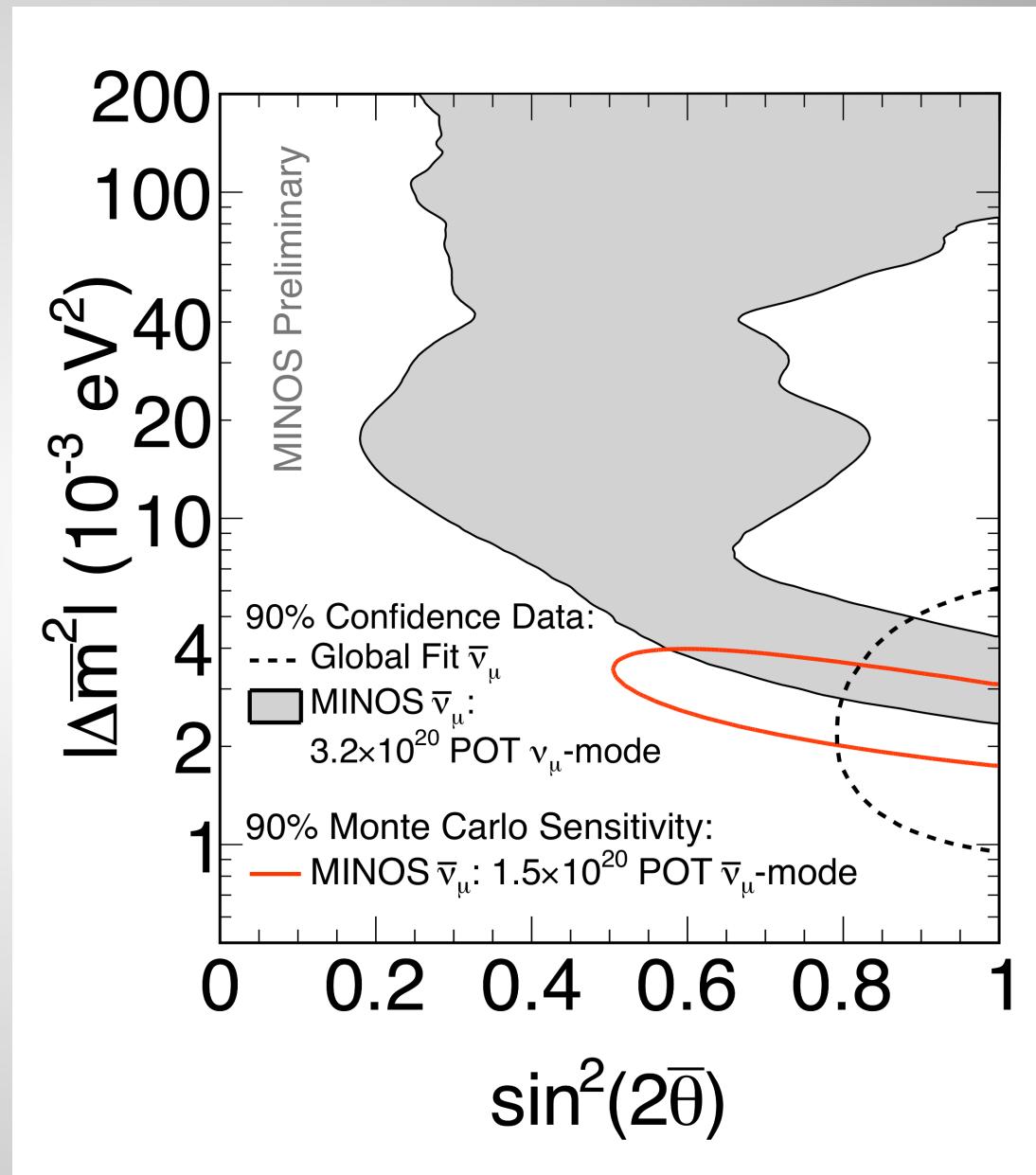


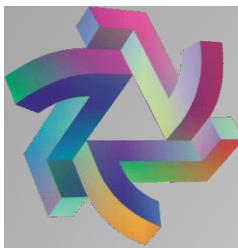


$\bar{\nu}_\mu$ Disappearance

Dedicated $\bar{\nu}_\mu$ run

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





ν_e Appearance

Sub-dominant neutrino oscillations

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(1.27 \Delta m_{31}^2 L/E)$$

(also CPV and matter effects: not shown here but included in fit)

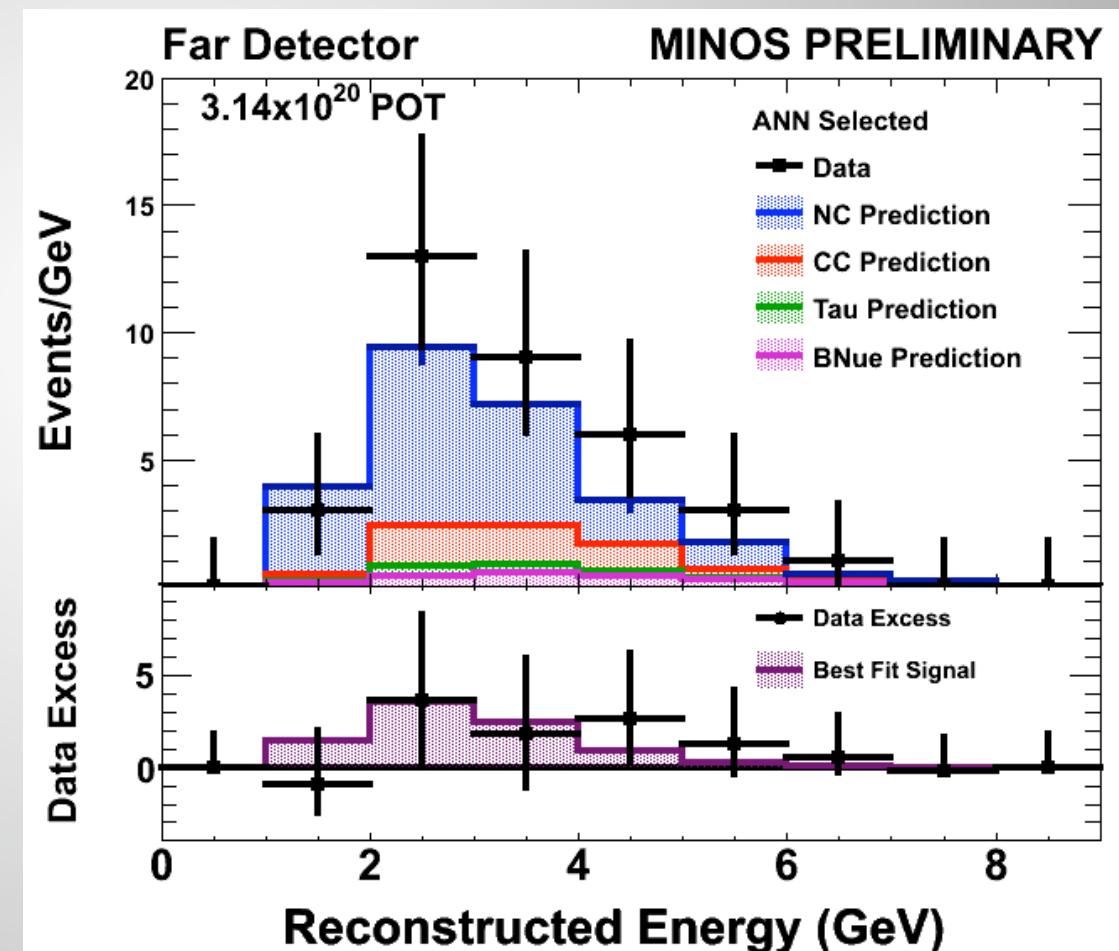
Select events w/ compact shower,
typical EM profile

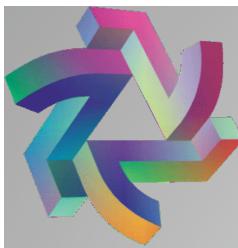
Measurement dominated by NC and
 ν_μ CC backgrounds.

Two data-driven methods have been
developed to resolve the MC/data
difference

- Use ND data to constrain the
backgrounds

PRL 103 261802 (2009)





ν_e Appearance

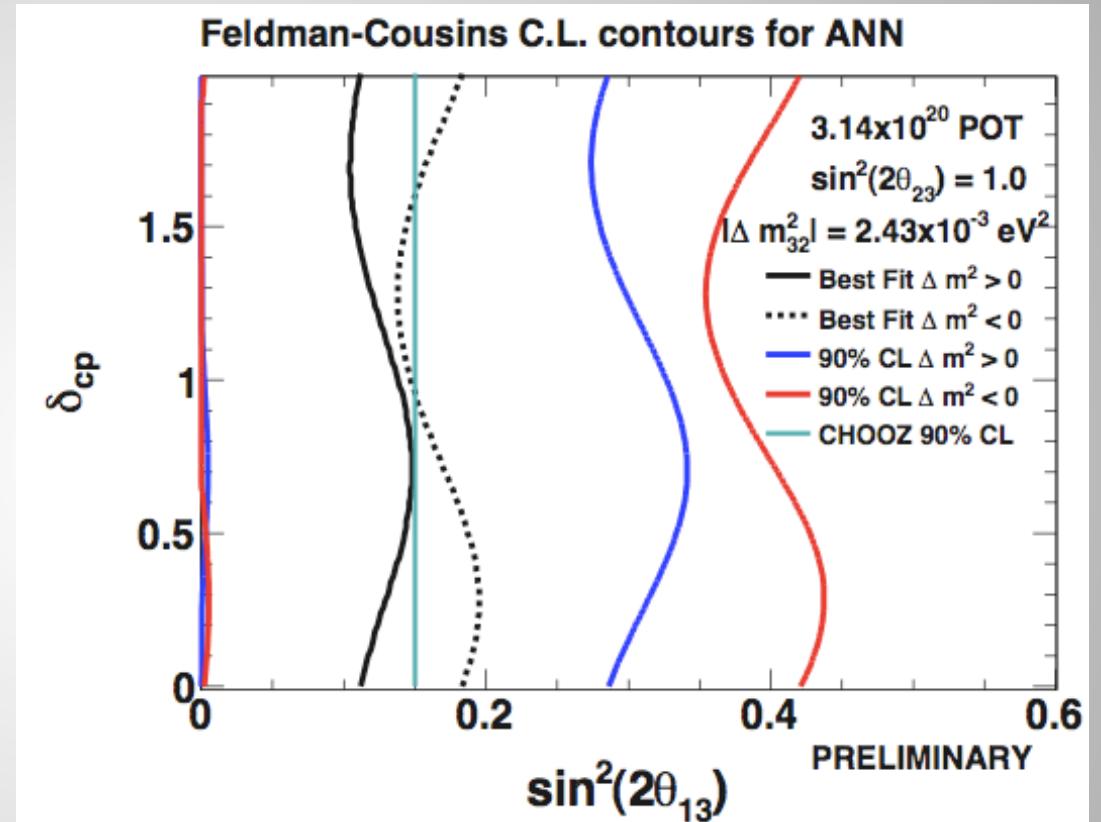
Observe **35** events,
Expect **27 ± 5 (stat) ± 2 (syst)**.

Results are 1.5σ high:
 $\sin^2(2\theta_{13})=0$ is included at the 92%
level.

Box opened on improved analysis:
~2x larger data set

Systematics reduced from 10% to 5%

Results will be presented in April.





Search for Sterile Neutrinos

- Search for a deficit in NC events
- all active flavours participate in NC interaction
 - deficit is a signature of mixing with a sterile flavour ν_s

Assume 1 sterile flavour and mixing with ν_μ and ν_τ at one Δm^2

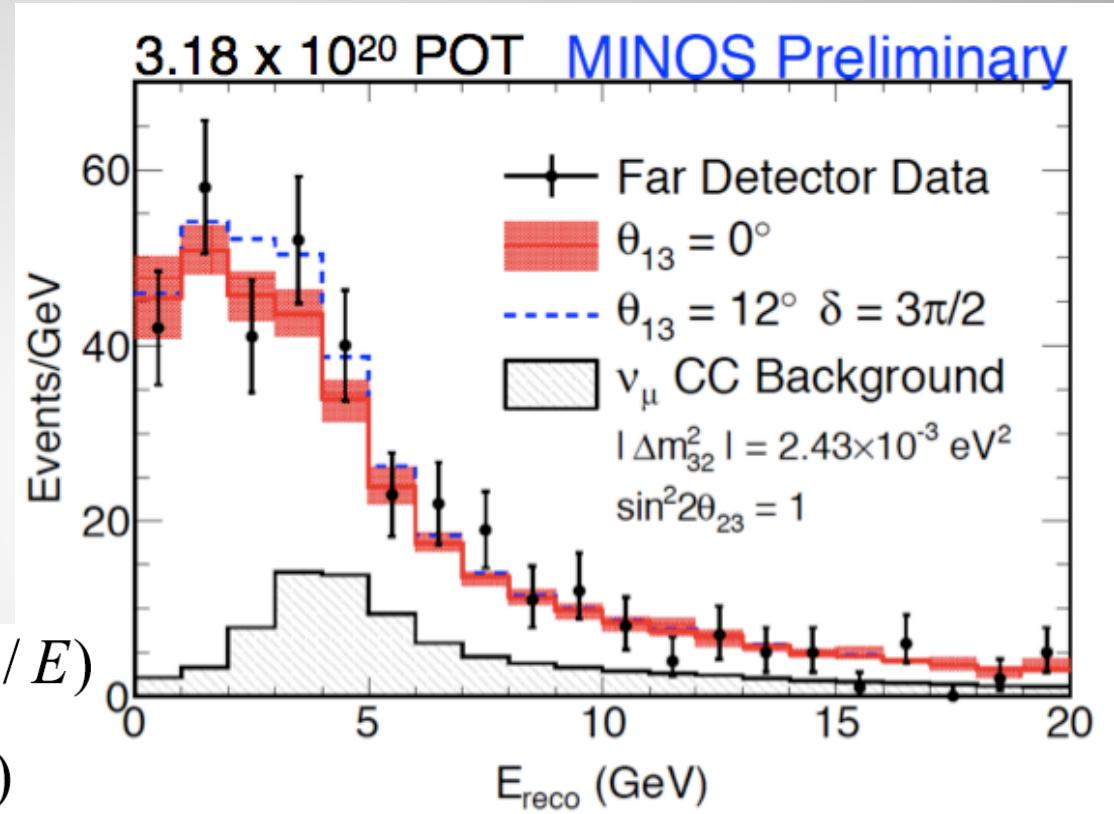
Survival and mixing probabilities:

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

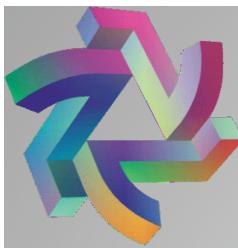
$$P(\nu_\mu - \nu_s) = \alpha_s \sin^2(1.27 \Delta m^2 L / E)$$

(α_μ and α_s fractions)

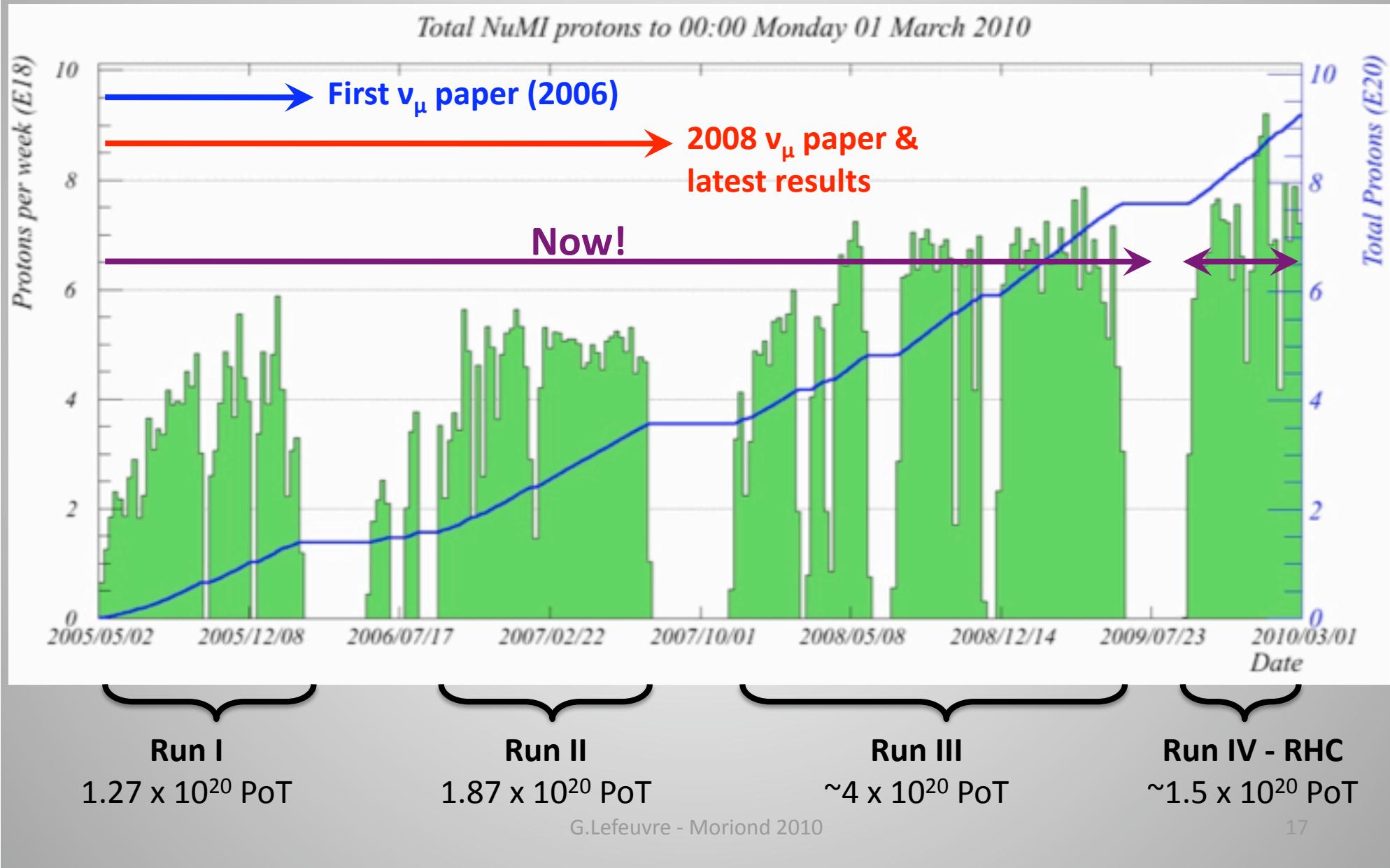
$$f_s = \frac{P(\nu_\mu \rightarrow \nu_s)}{1 - P(\nu_\mu \rightarrow \nu_\mu)} \quad f_s < 0.55 \text{ (90% C.L.)}$$



Previous result:
PRL **101** 221804 (2008)
Soon in PRD:
hep-ex/1001.0336



Conclusion

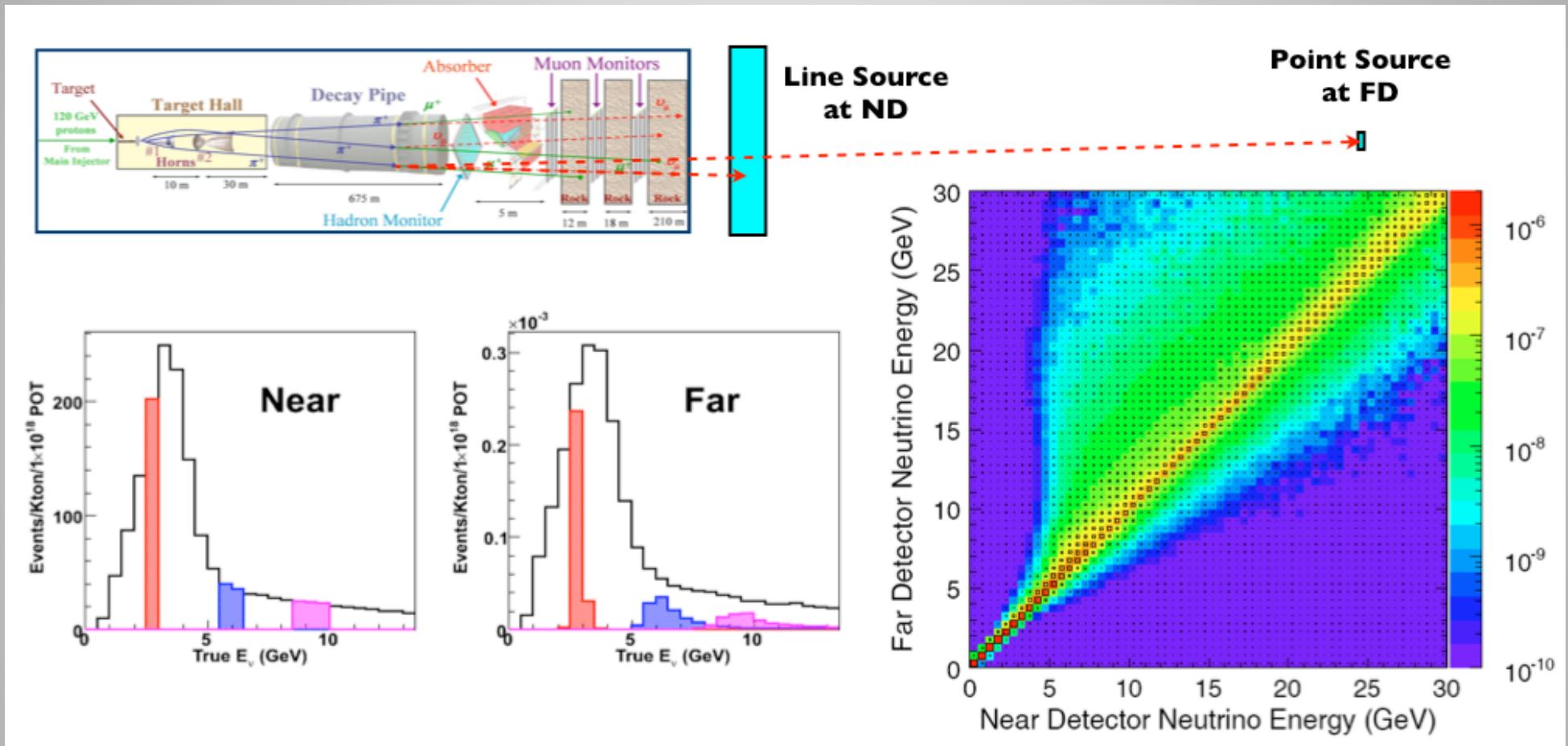




Backup



Extrapolation

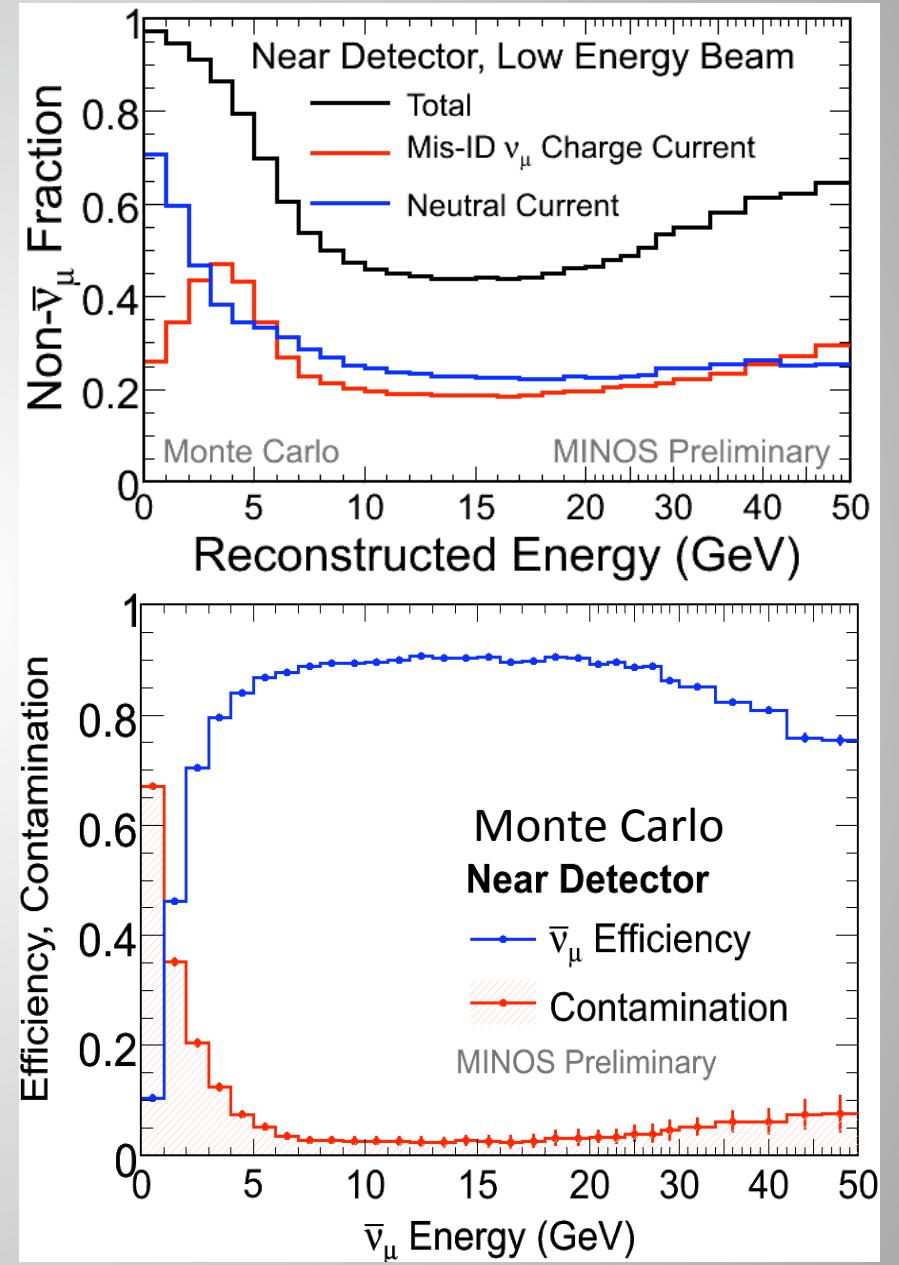


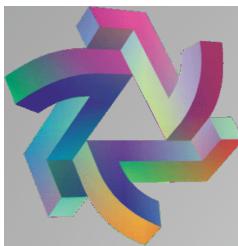
Near Detector energy spectrum extrapolated to Far Detector, using MC to provide energy smearing and correct for detector acceptance



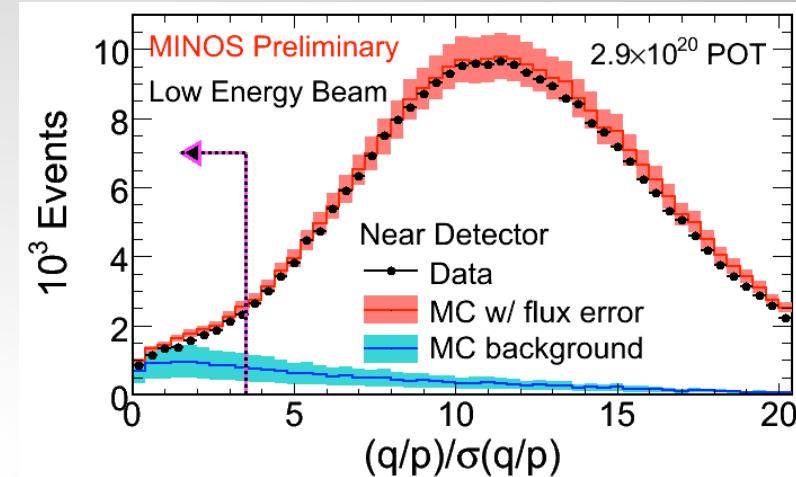
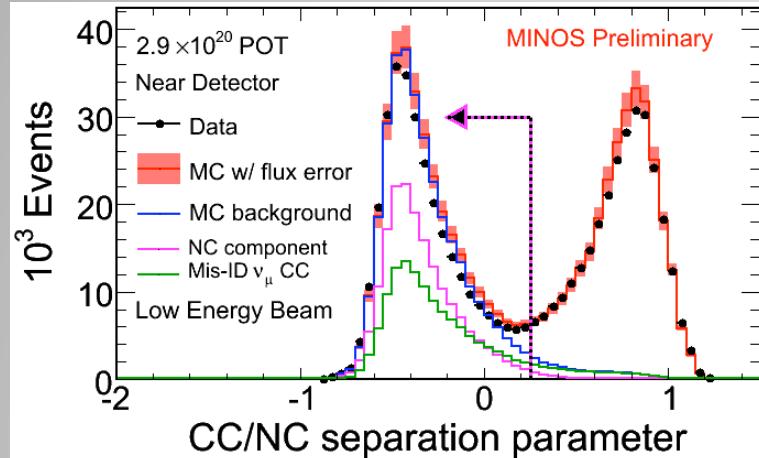
$\bar{\nu}_\mu$ Disappearance

- **Large background:**
 - mis-identified ν_μ events with wrong track sign (8%)
 - NC events faking a muon track (50%)
- **Additional selection cuts:**
 - significance of charge sign determination
 - relative angle (does the track curve towards or away from the magnetic coil hole relative to its initial direction)
 - likelihood based on track length and pulse height for CC/NC separation
- Near Detector: 87% efficiency, 5% contamination

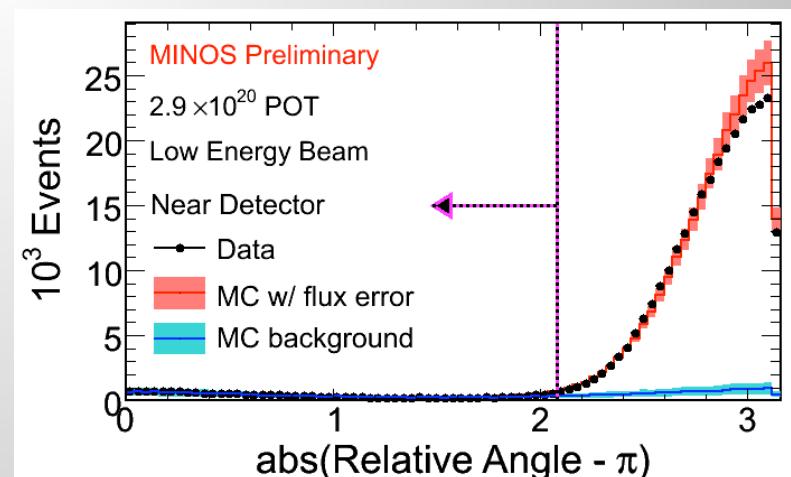


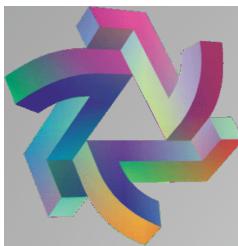


$\bar{\nu}_\mu$ Selection Variables

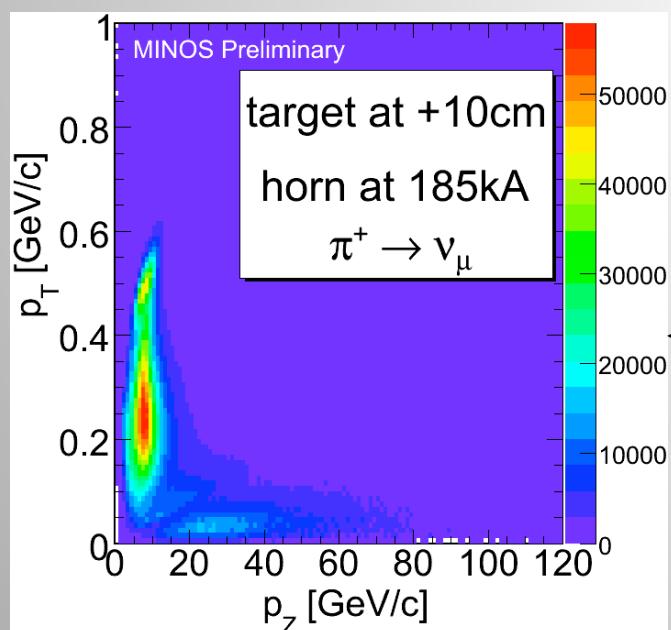
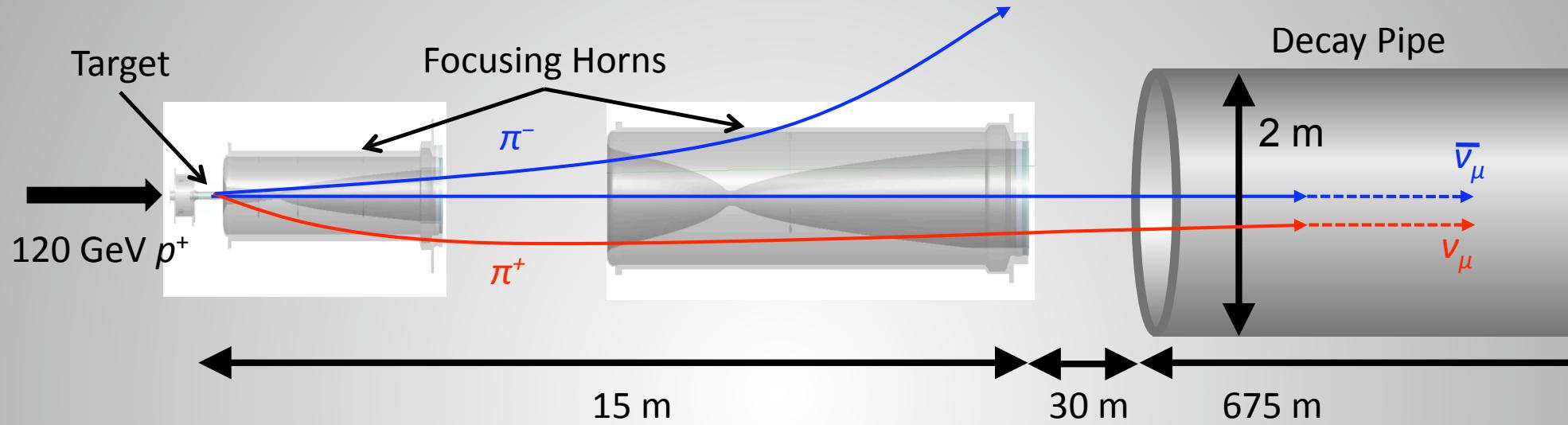


- likelihood based CC/NC separation (developped for previous analyses, removes both NC and mis-id'd CC)
- track fit charge significance
- relative angle (direction of the track in the magnetic field)





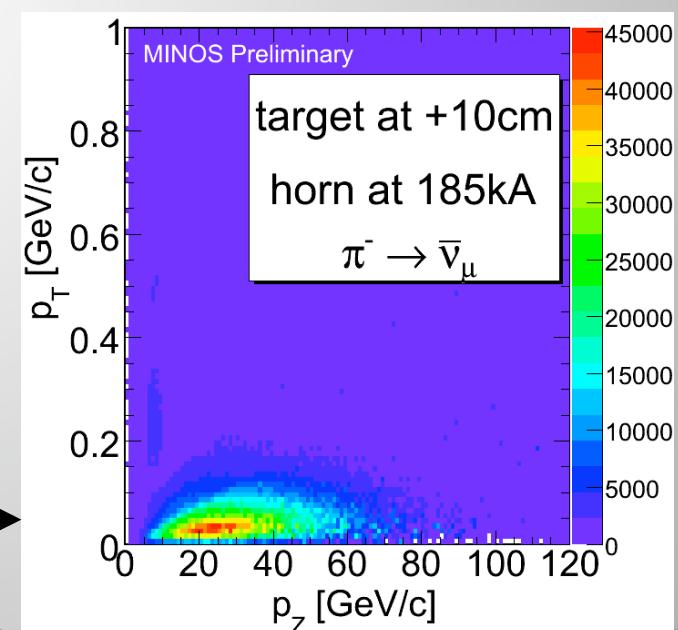
Why are the ν_μ and $\bar{\nu}_\mu$ spectra so different?



Forward Horn Current

π^-

G.Lefèuvre - Moriond 2010



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