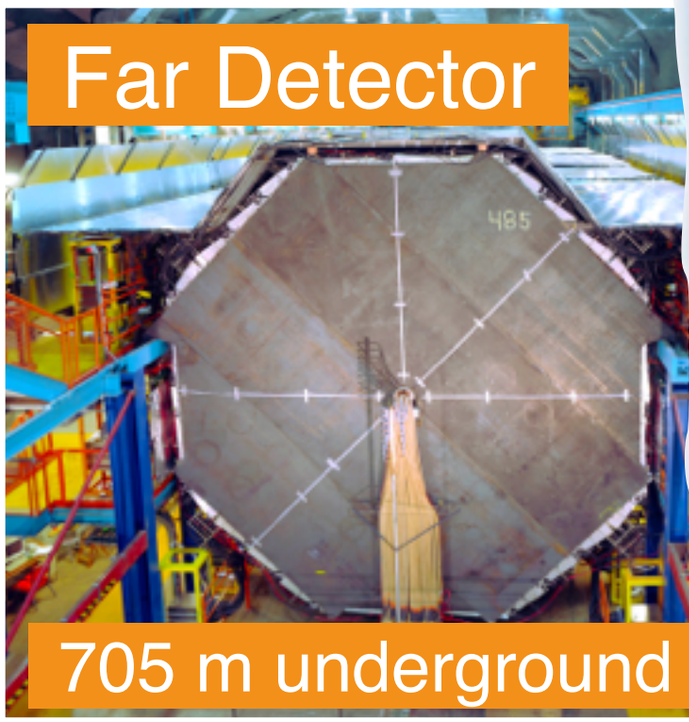
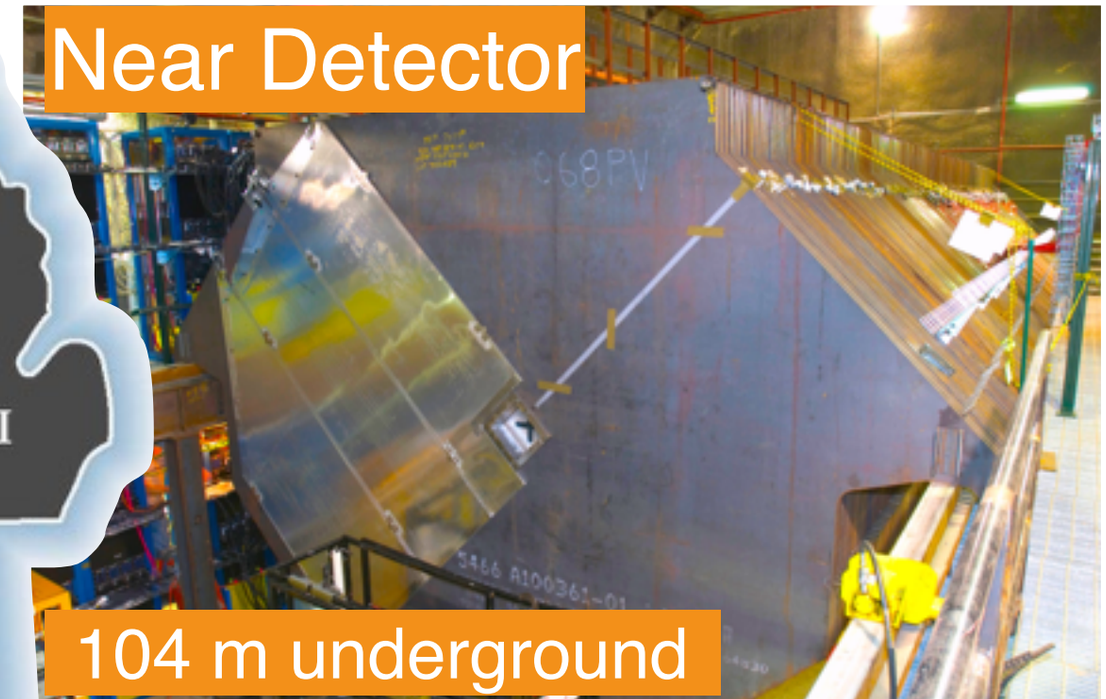
Muon Neutrino Disappearance at MINOS+

Tom Carroll
The University of Texas at Austin
On behalf of the MINOS+ Collaboration

June 6, 2017

MINOS Detectors





- 735 km from target
- 5.4 ktons

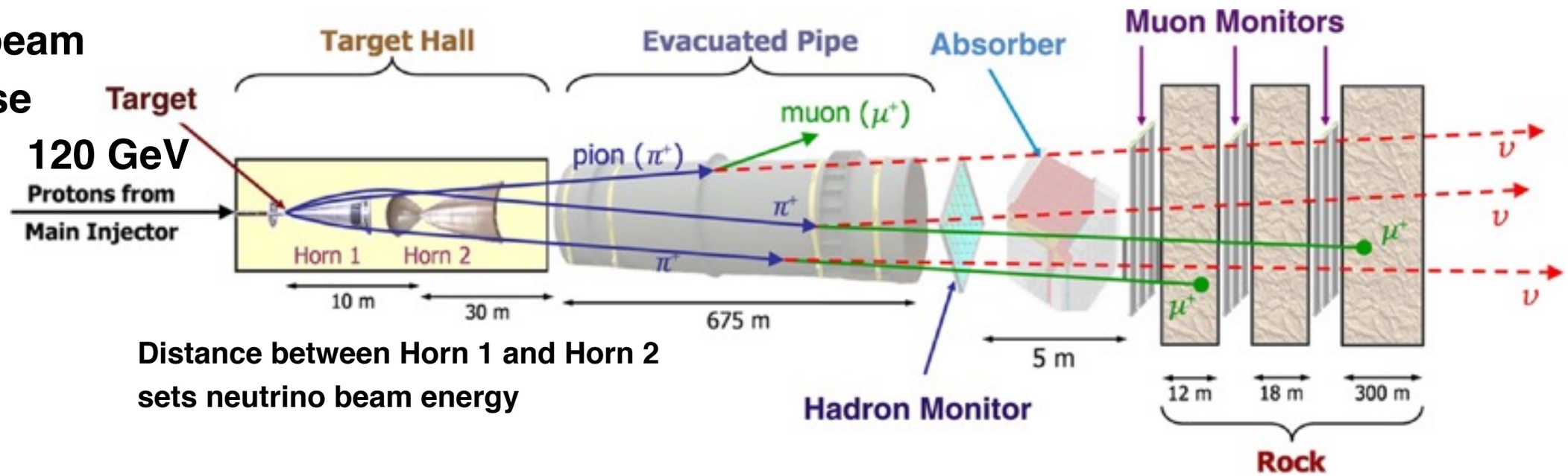
- 1 km from target
- 980 tons

- On-axis long-baseline neutrino oscillation experiment
- Functionally equivalent detectors
- Magnetized steel-scintillator, tracking-sampling calorimeters

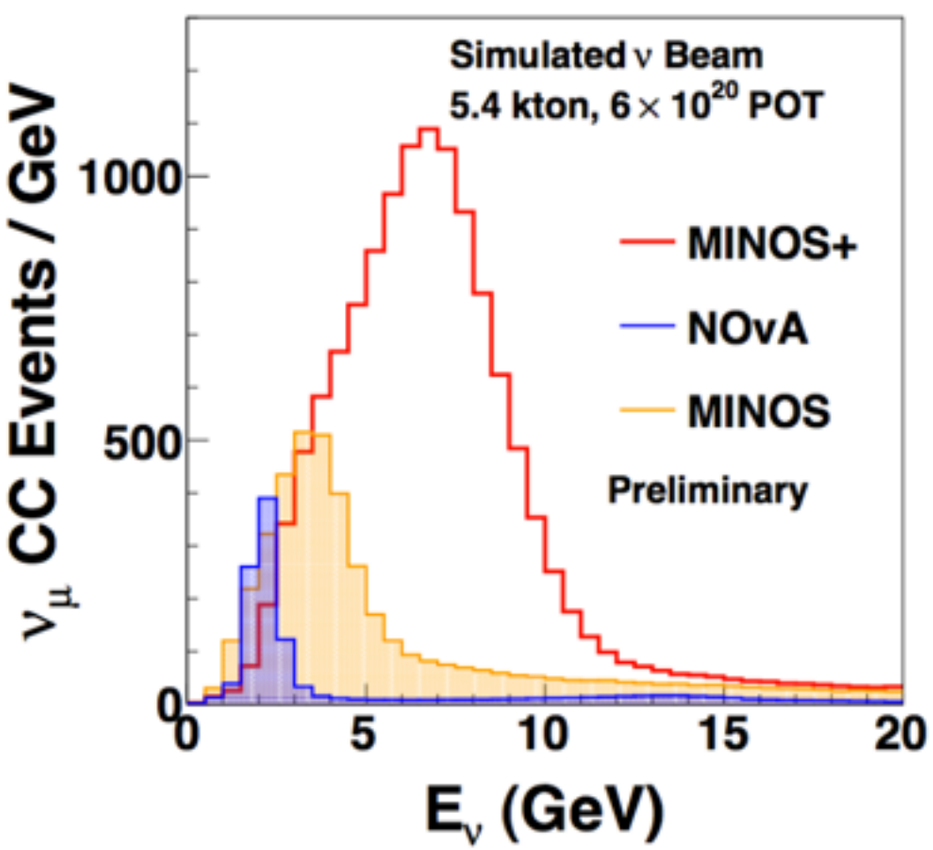
NuMI Beamline

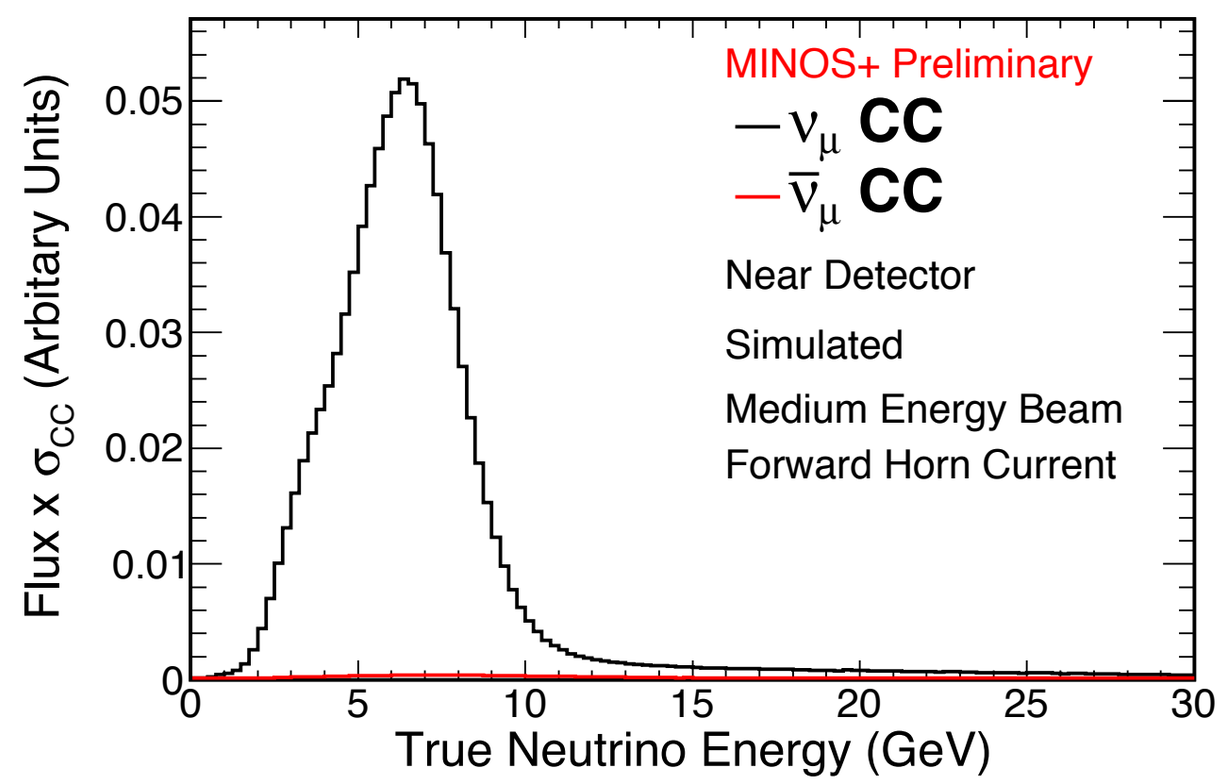
300–500+ kW beam

2–5×10^{13} P/pulse

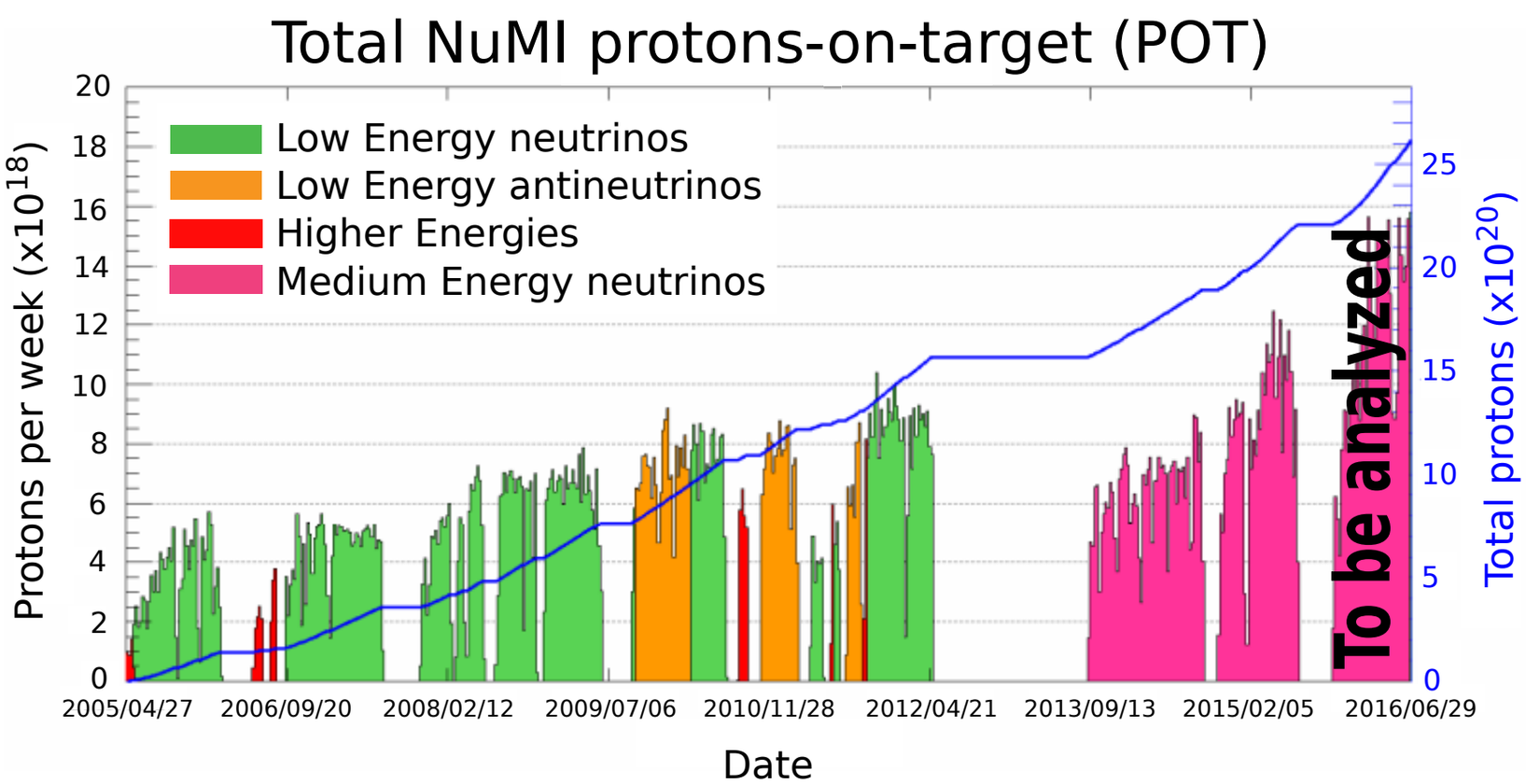


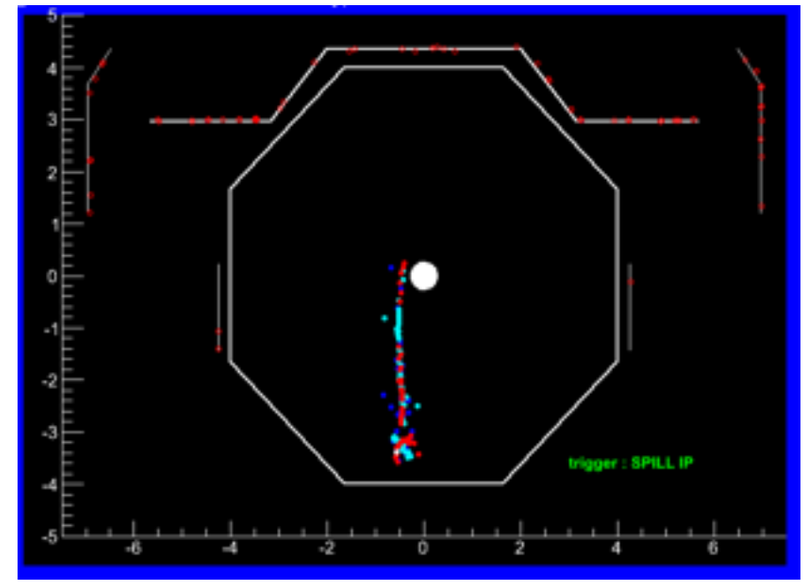
Distance between Horn 1 and Horn 2 sets neutrino beam energy





Data





Last MINOS+ beam event
June 29, 2016

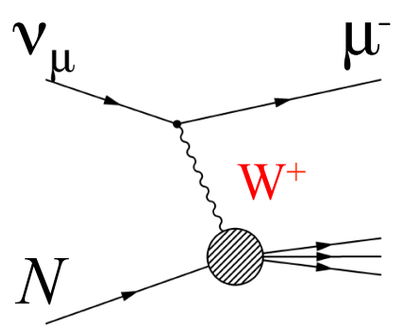
MINOS	MINOS+

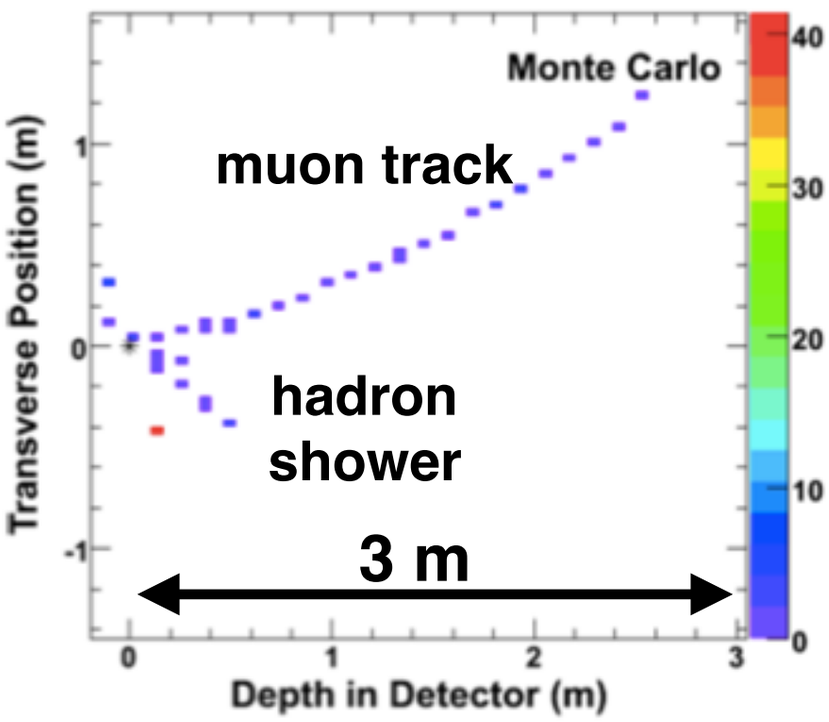
This talk		
10.56×10^{20} POT	3.36×10^{20} POT	5.80×10^{20} POT

+ 48.67 kt-yr atmospheric neutrino exposure

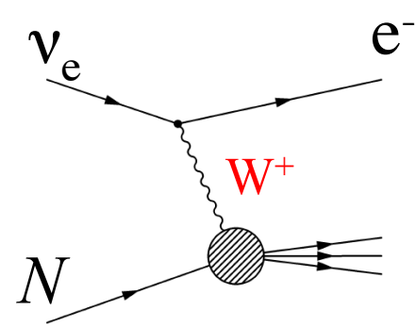
Events

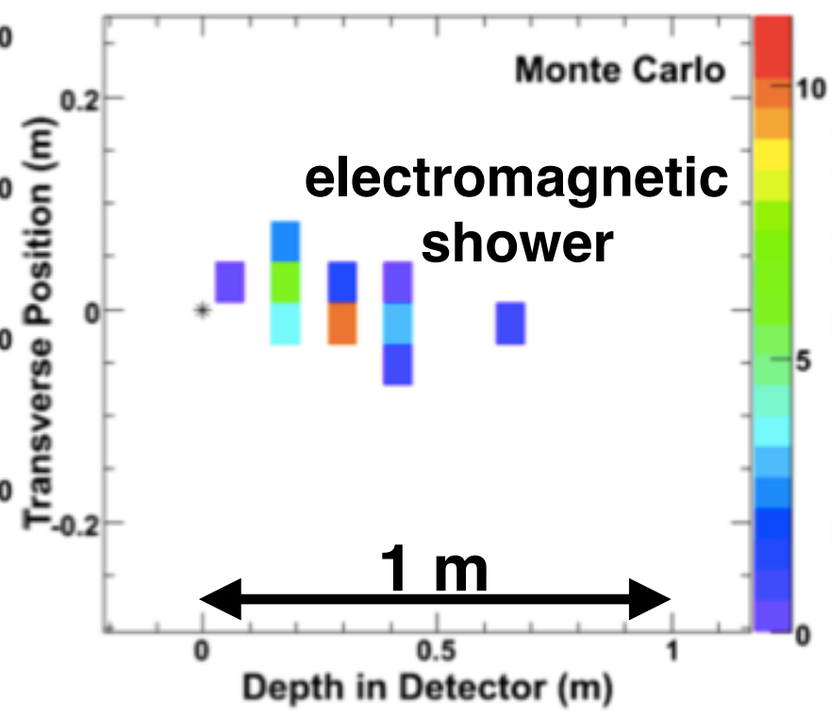
Signal
ν_μ Charged Current (CC)



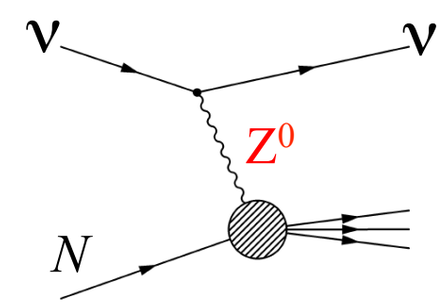


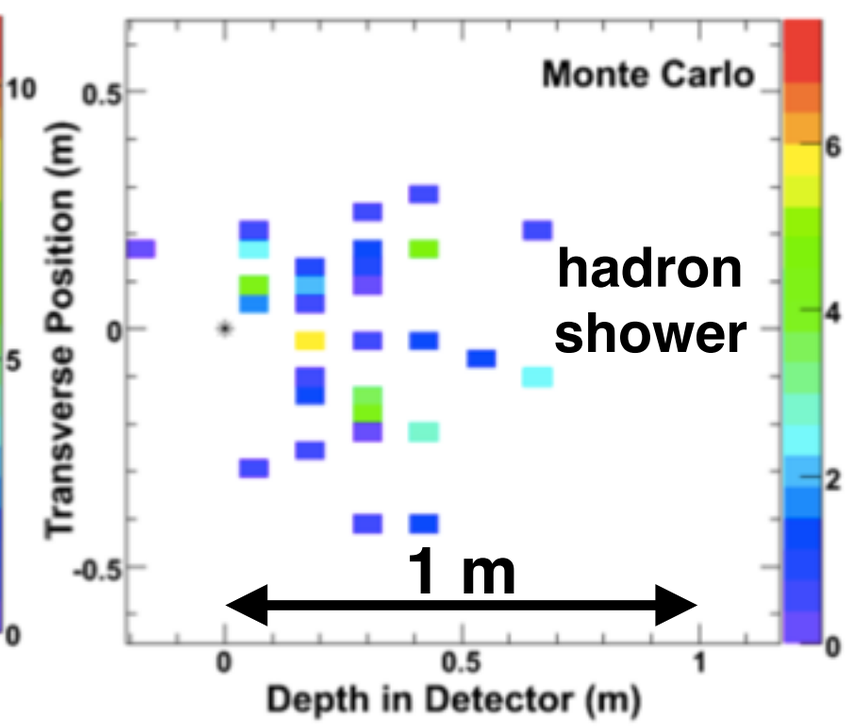
Signal
ν_e Charged Current (CC)



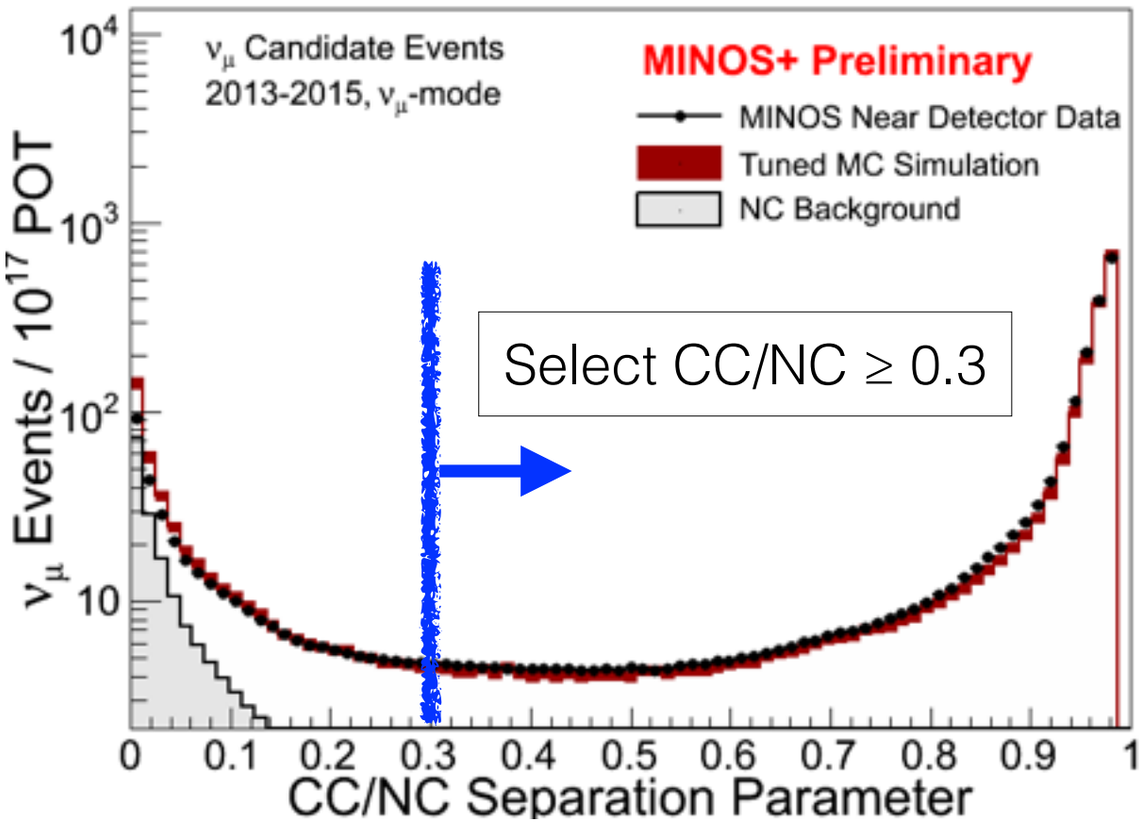


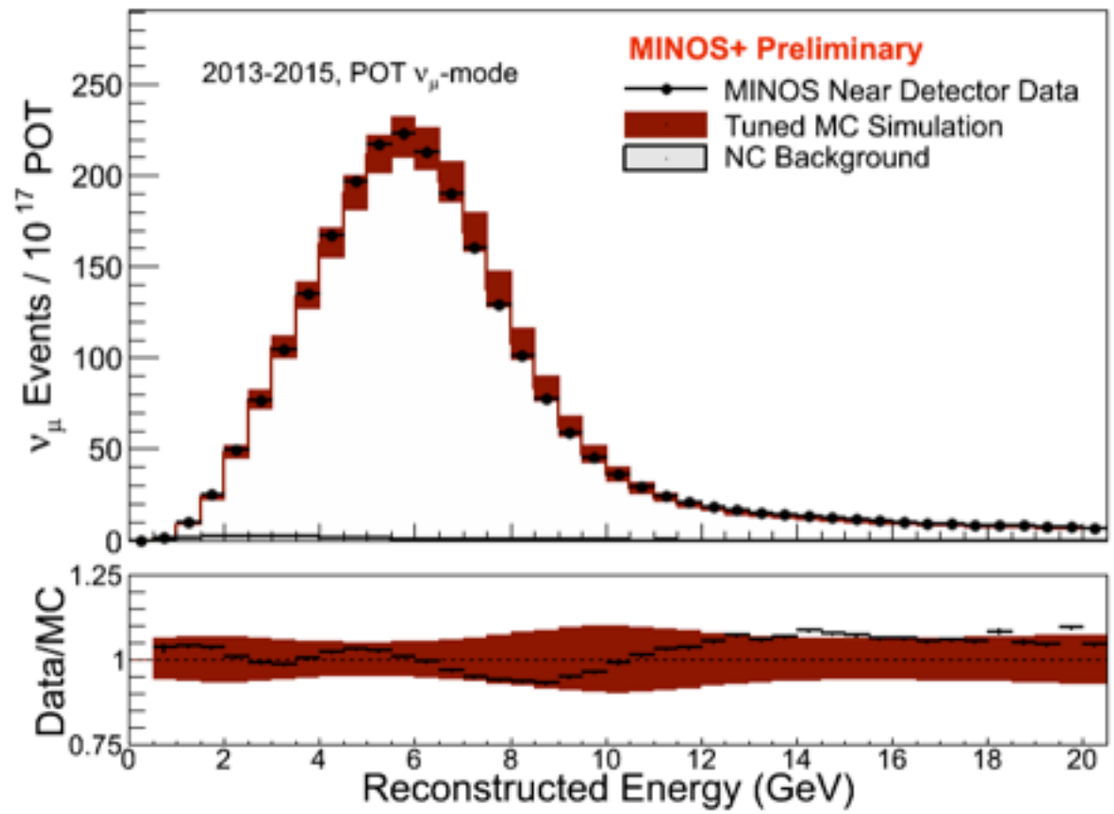
Background
Neutral Current (NC)





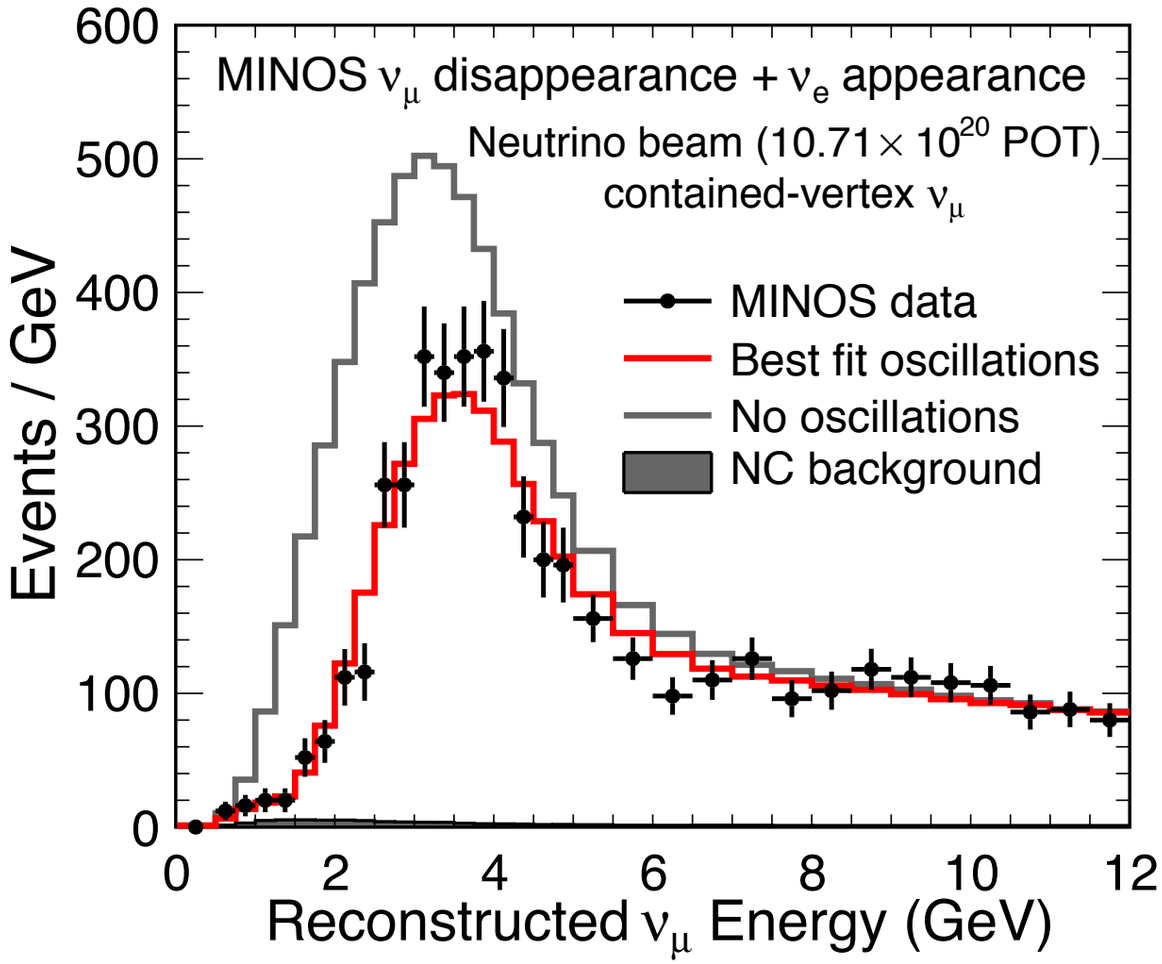
Event Selection

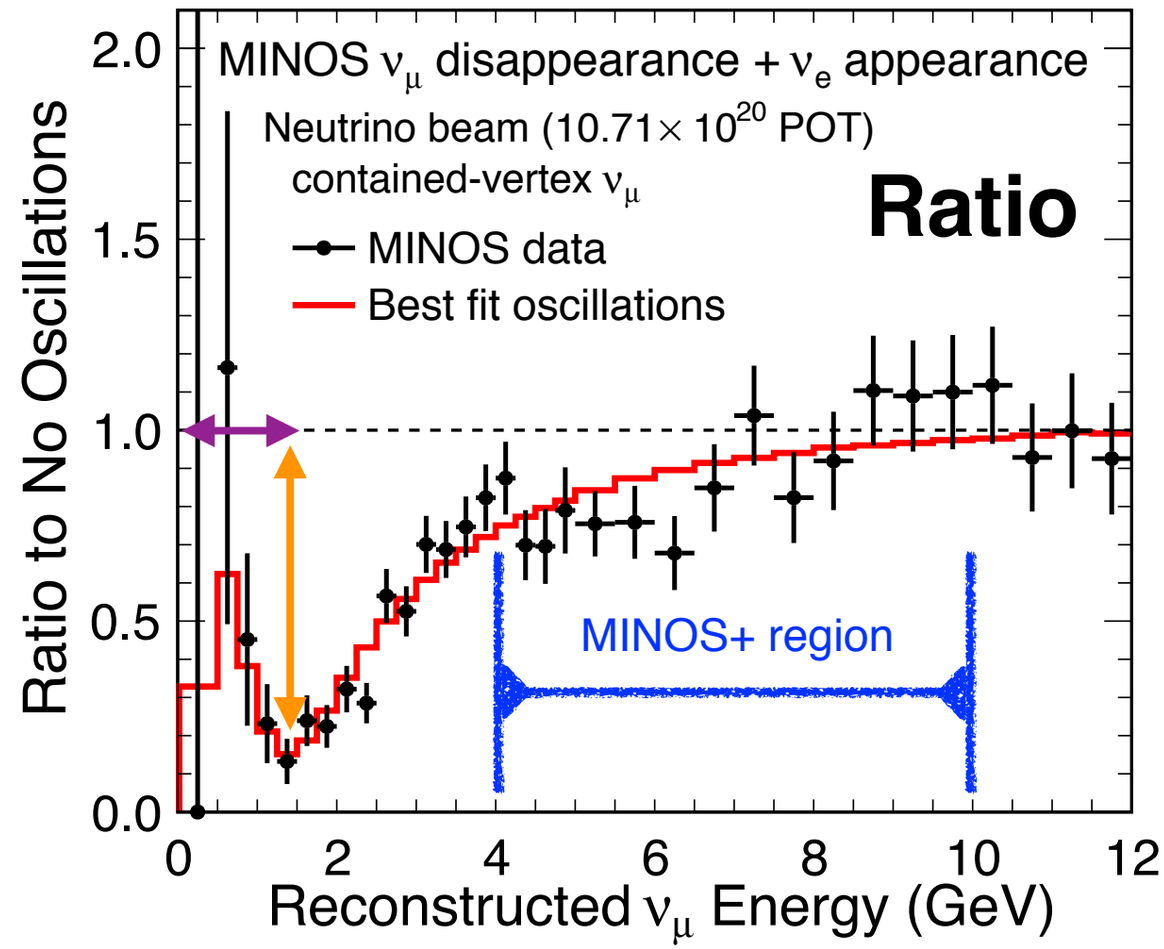




Use muon track features in a k-Nearest Neighbors classification algorithm

MINOS ν_μ Disappearance





$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

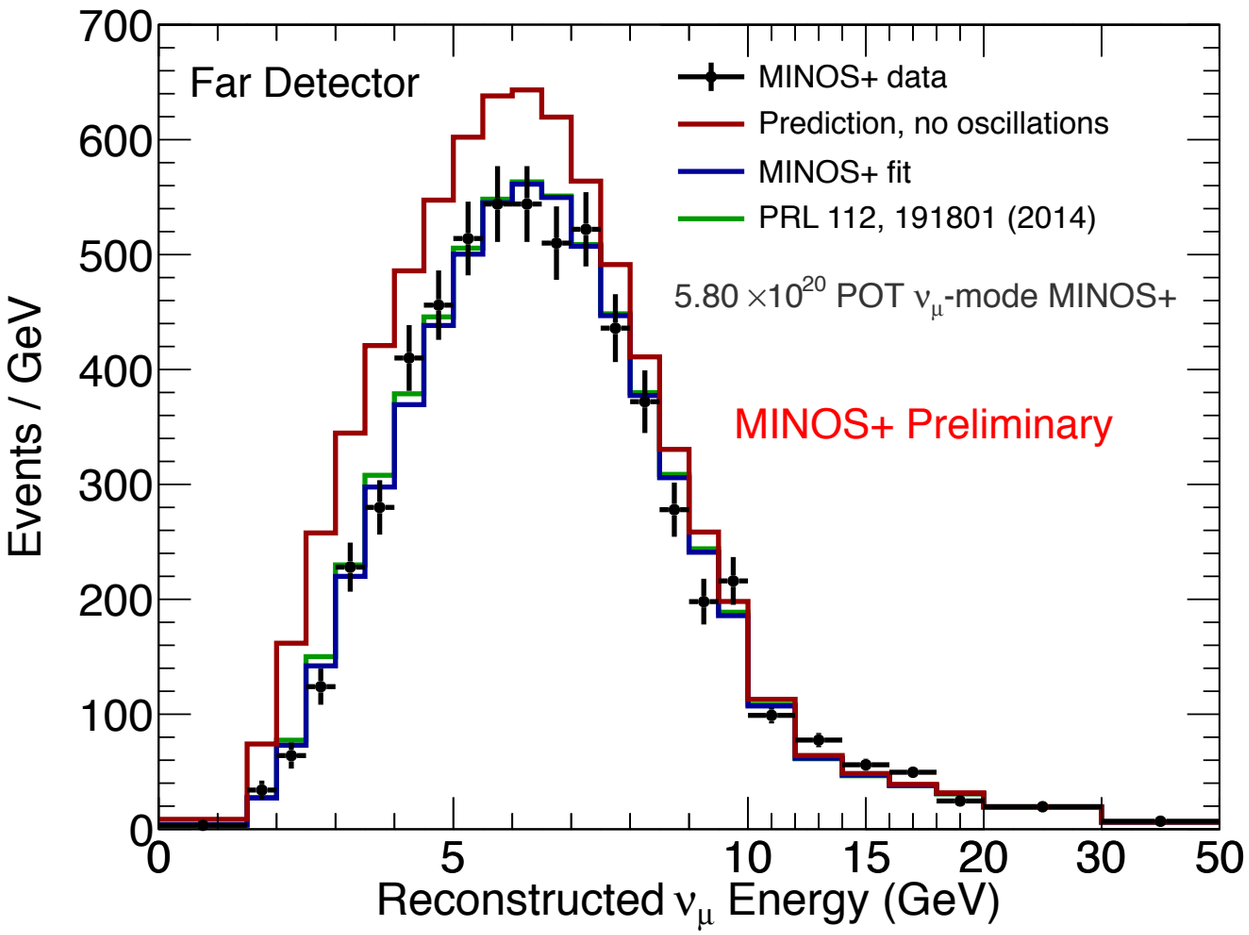
$$\sin^2 2\theta = 4\sin^2\theta_{23}\cos^2\theta_M\left(1-\sin^2\theta_{23}\cos^2\theta_M\right)$$

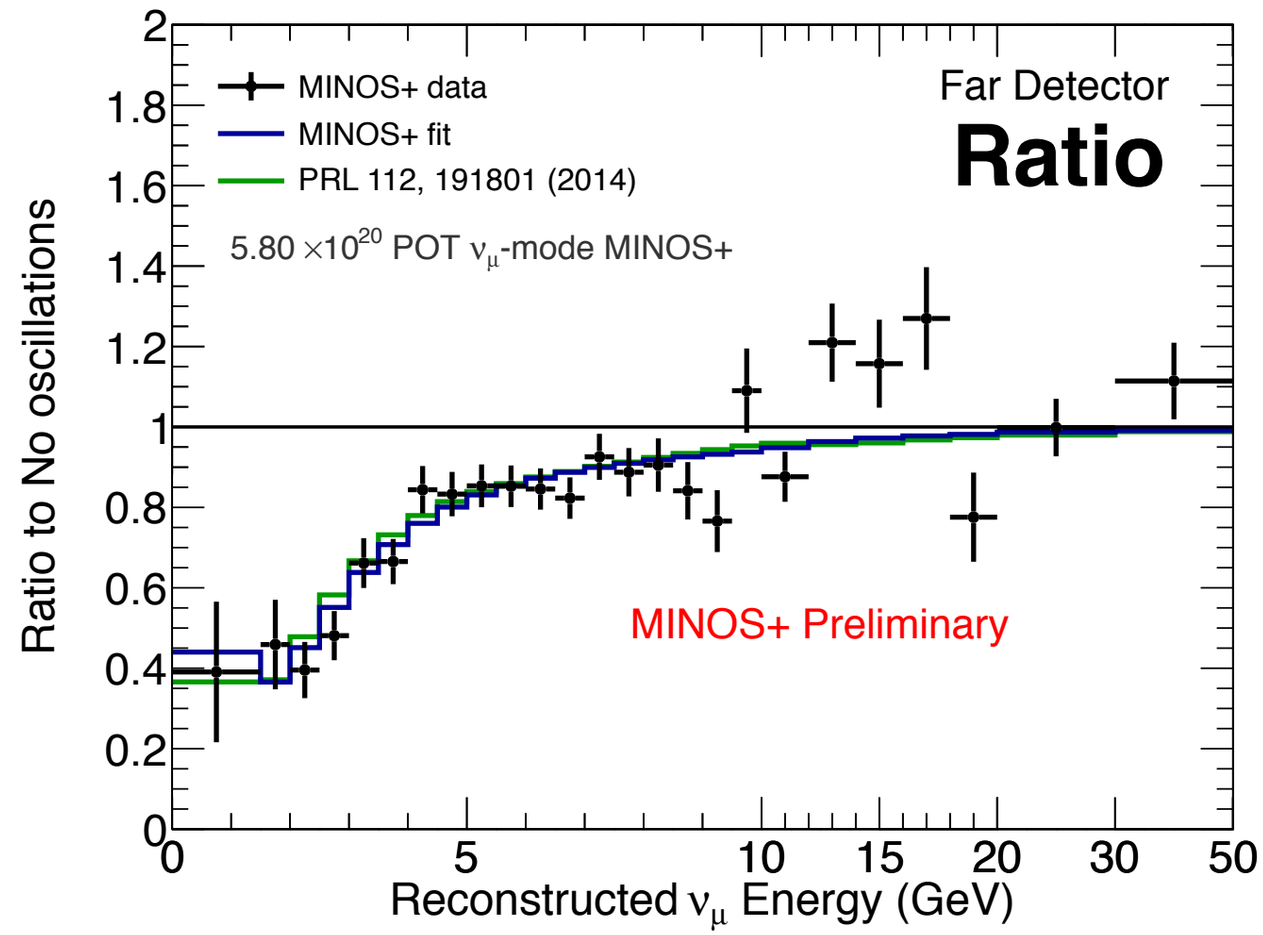
$$\Delta m^2 = \Delta m^2_{32} + \Delta m^2_{21}\sin^2\theta_{12} + \Delta m^2_{21}\cos\delta_{CP}\sin\theta_M\tan\theta_{23}\sin 2\theta_{12}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left(A - \cos 2\theta_{13}\right)^2}$$

PRL 112, 191801 (2014)

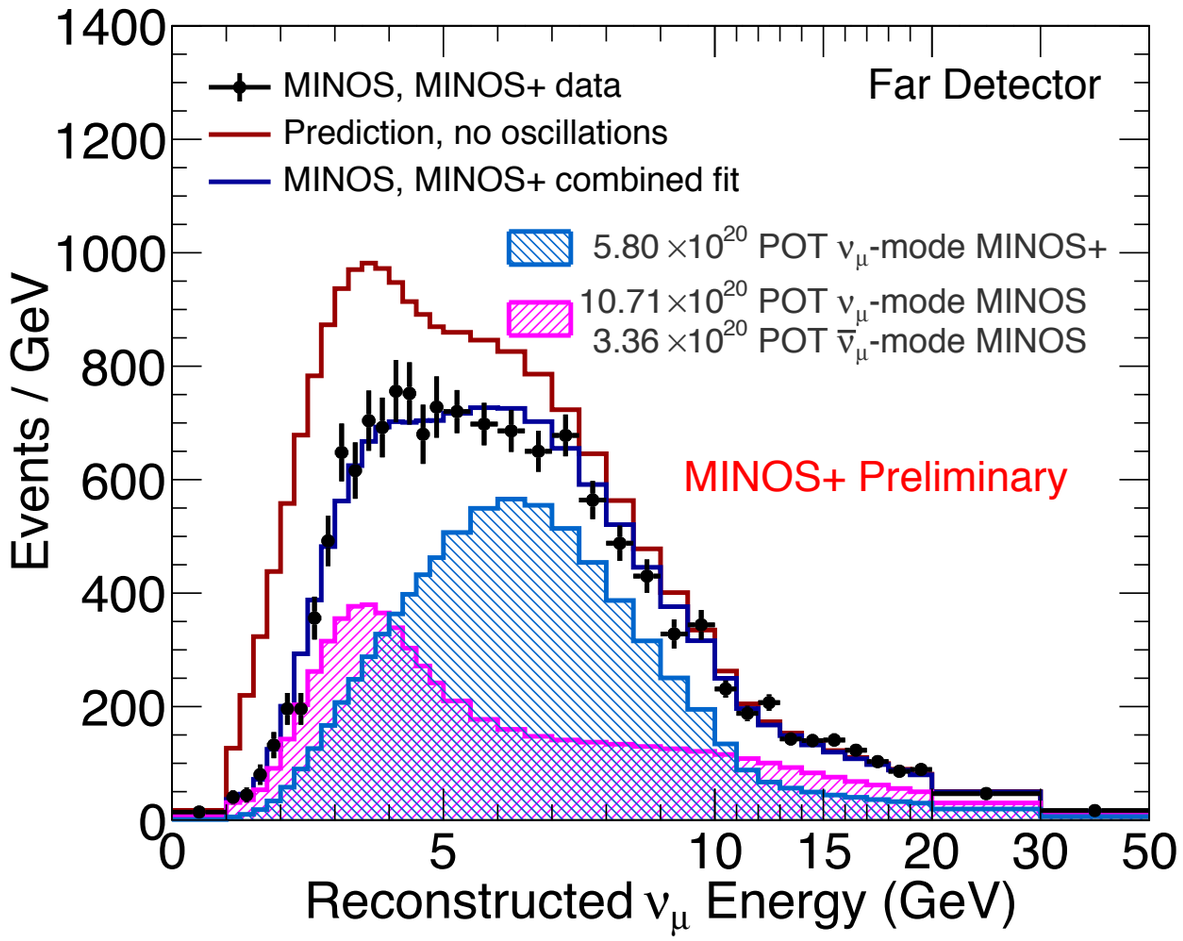
MINOS+ ν_μ Disappearance

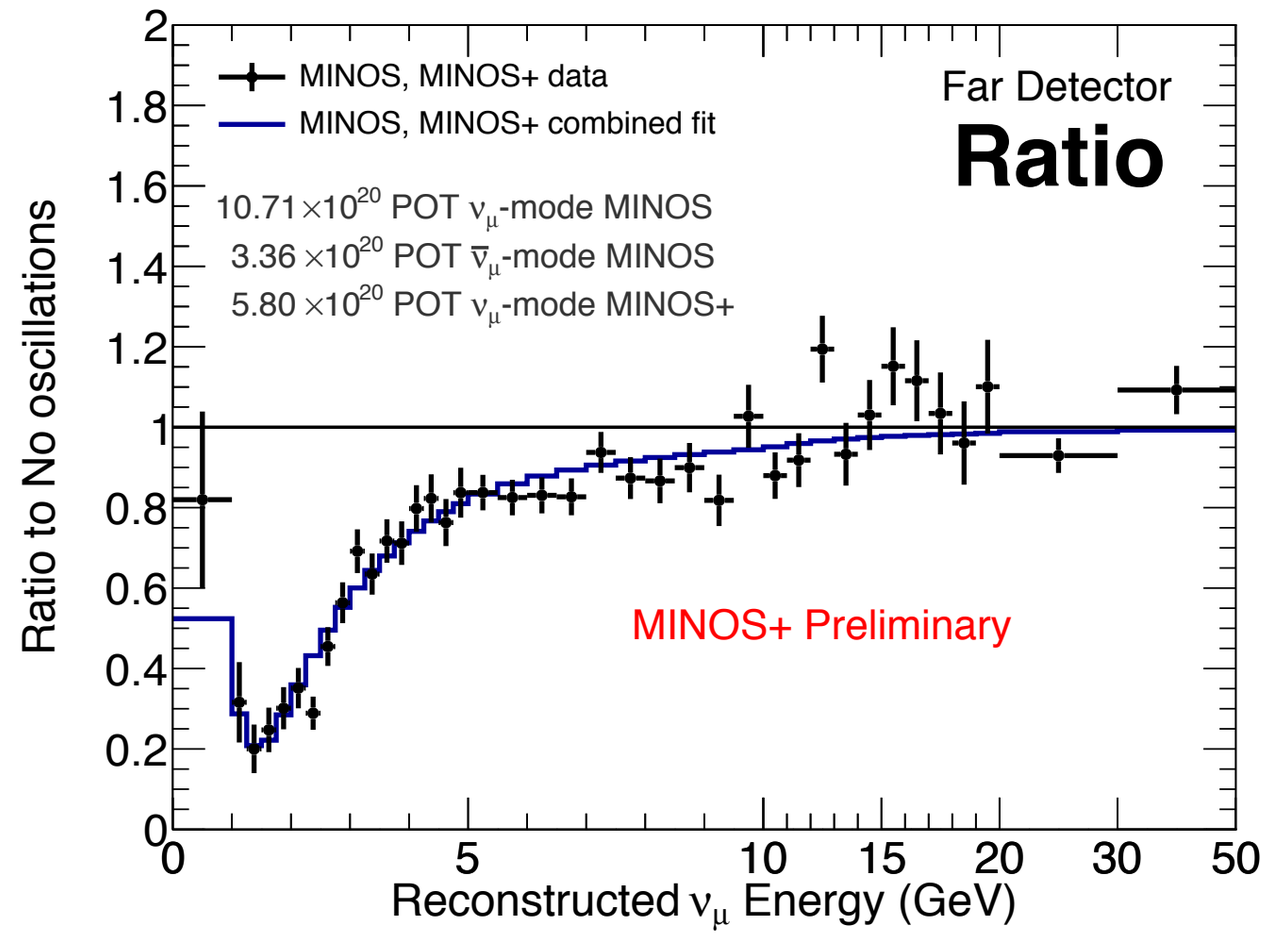




MINOS+ (2013–2015) fit consistent with MINOS

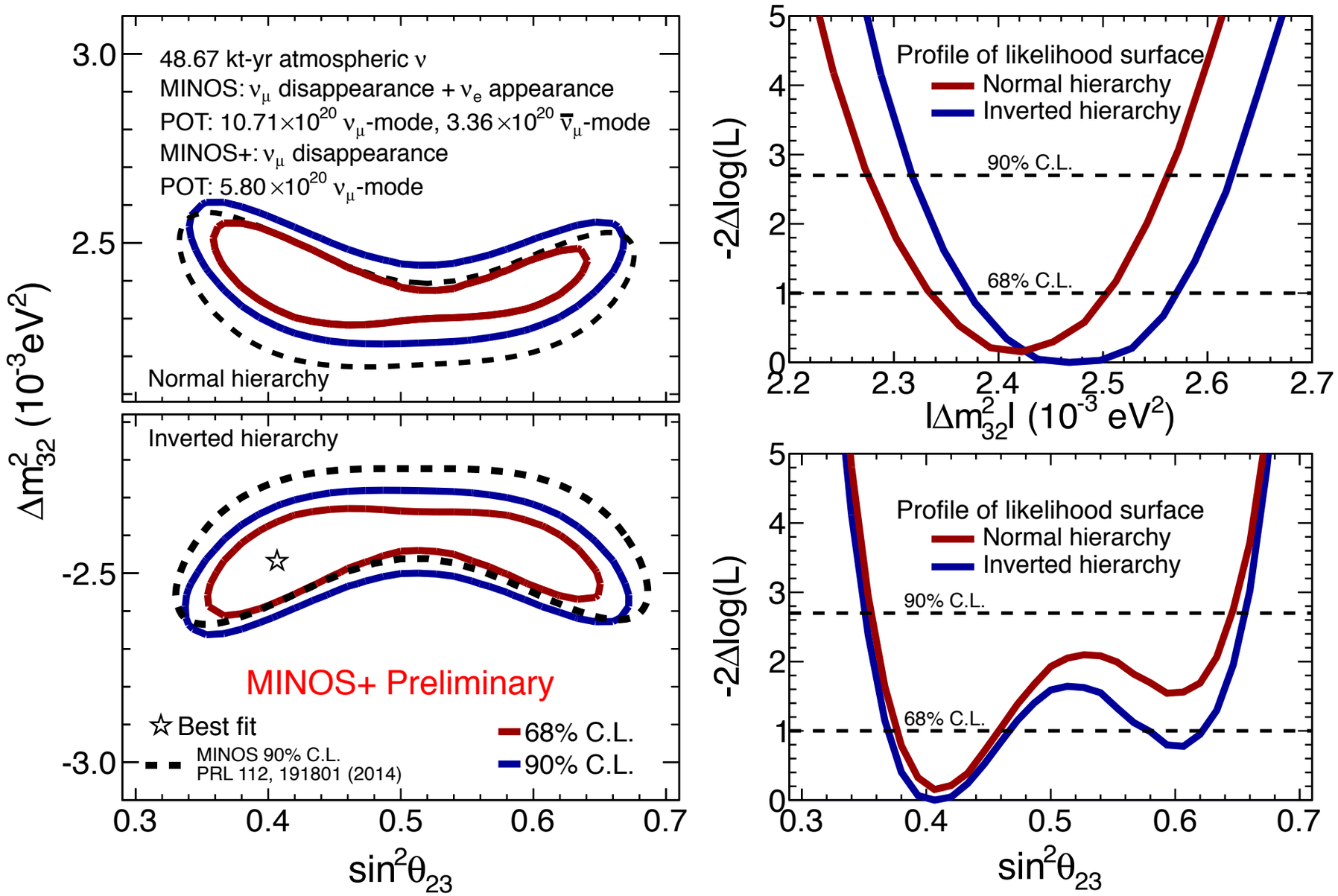
MINOS, MINOS+ ν_μ Disappearance





Event Type	MINOS (2005—2013)	MINOS+ (2013—2015)
ν_μ	2579	3692
$\bar{\nu}_\mu$	538	179

Combined Confidence Intervals



Normal Hierarchy

$$\Delta m^2_{32} = 2.42 \pm 0.09 \times 10^{-3}\ \text{eV}^2\ (68\%\ \text{C.L.})$$

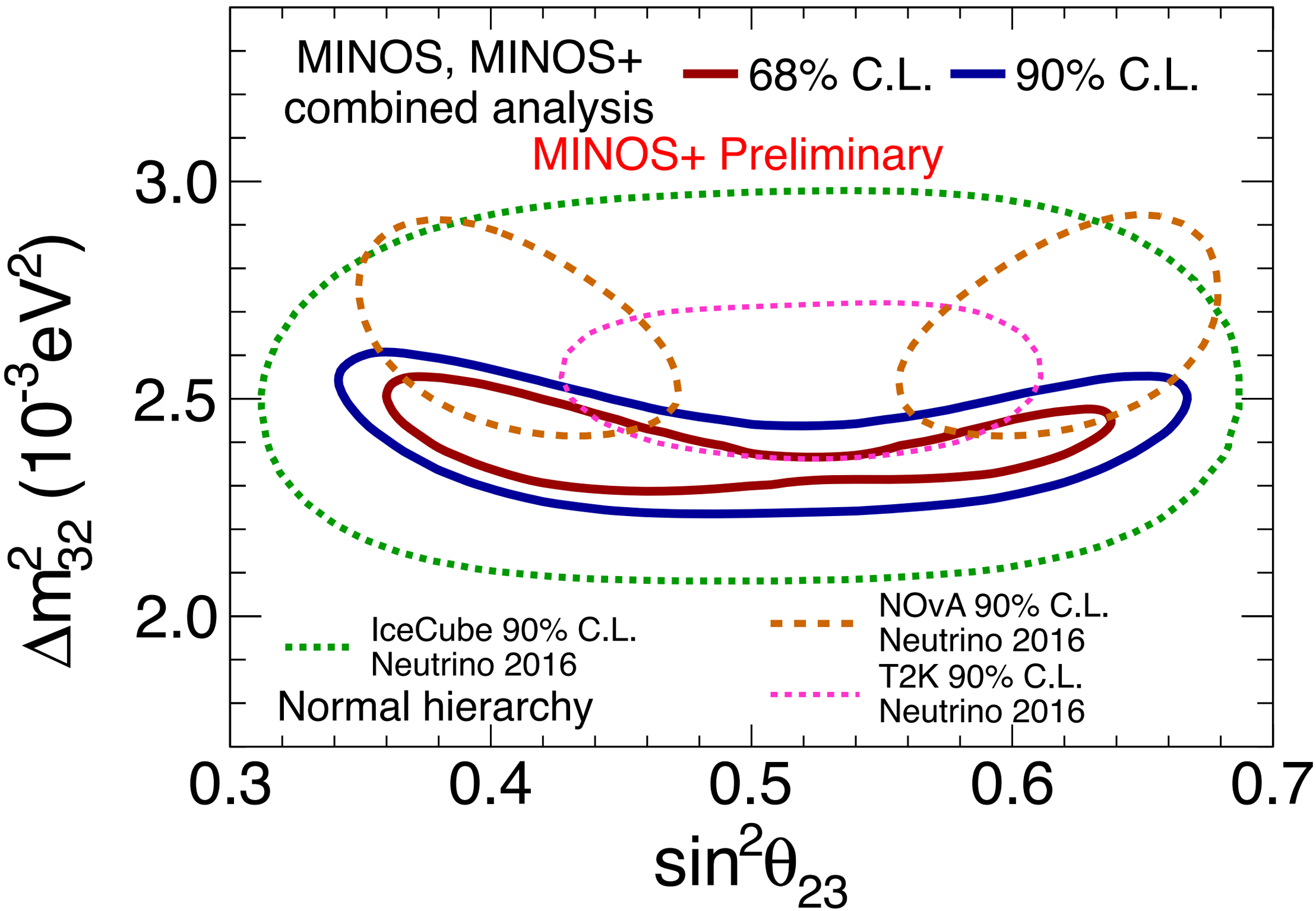
$$\sin^2\theta_{23} = 0.41^{+0.24}_{-0.06}\ (90\%\ \text{C.L.})$$

Inverted Hierarchy

$$\Delta m^2_{32} = 2.48^{+0.09}_{-0.11} \times 10^{-3}\ \text{eV}^2\ (68\%\ \text{C.L.})$$

$$\sin^2\theta_{23} = 0.41^{+0.25}_{-0.06}\ (90\%\ \text{C.L.})$$

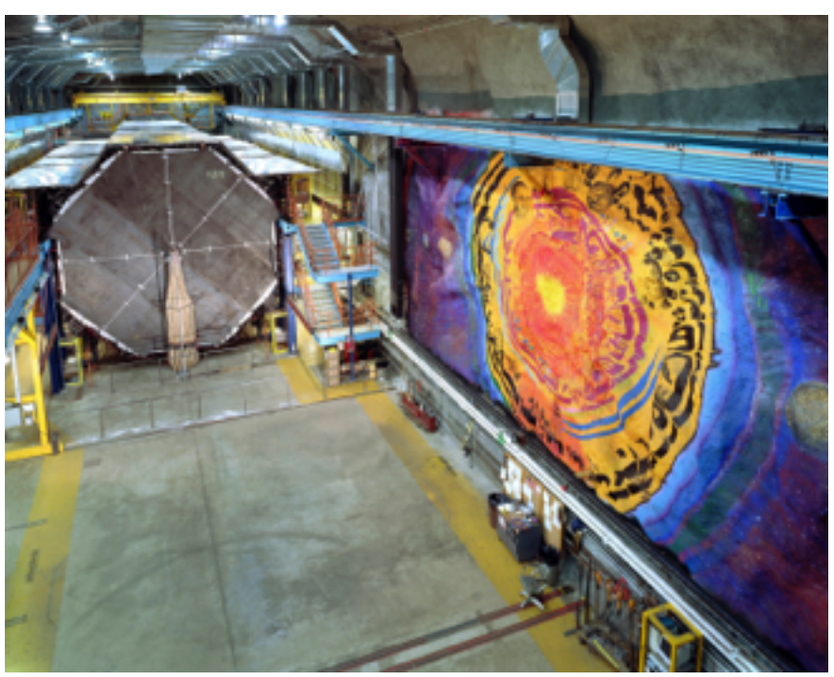
Comparison to Other Experiments

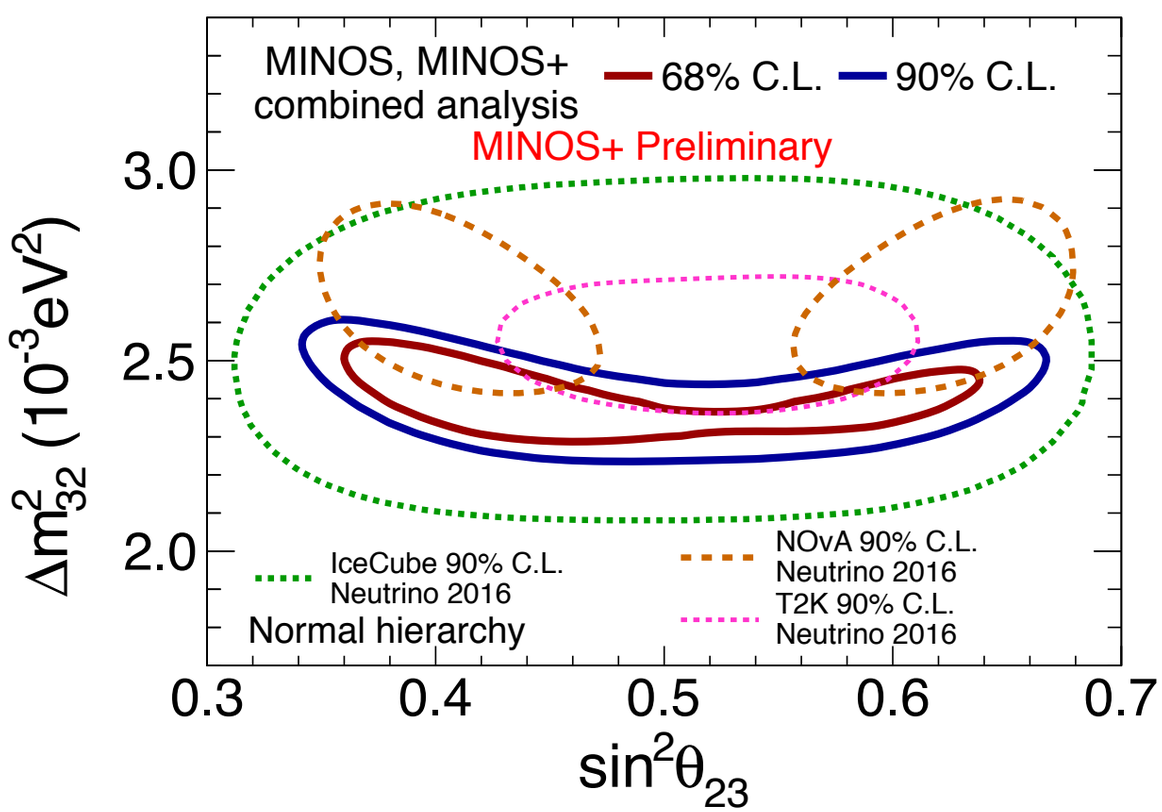


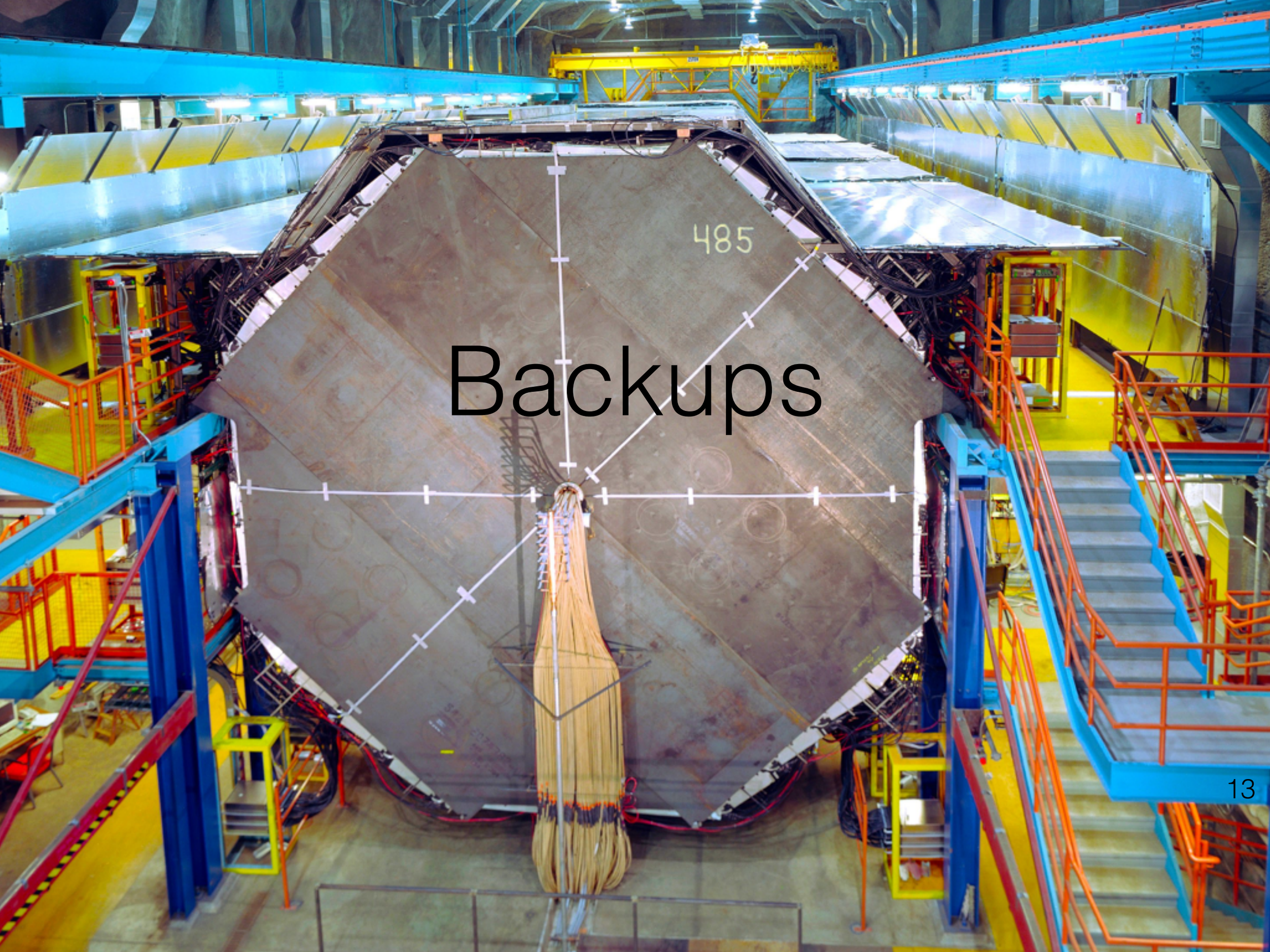
Conclusion

- MINOS+ is testing the three-flavor paradigm with 5.80x10^{20} PoT
- MINOS+ is doing exotic searches:
  - Sterile neutrinos
  - Large extra dimensions
  - Non-standard interactions

Hierarchy	Parameter	Best fit	Confidence limits
Normal	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.42	2.33 - 2.51 (68% C.L.)
	$\sin^2\theta_{23}$	0.41	0.37 - 0.46 (68% C.L.)
			0.35 - 0.65 (90% C.L.)
Inverted	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.48	2.37 - 2.57 (68% C.L.)
	$\sin^2\theta_{23}$	0.41	0.37 - 0.58 (68% C.L.)
			0.35 - 0.66 (90% C.L.)



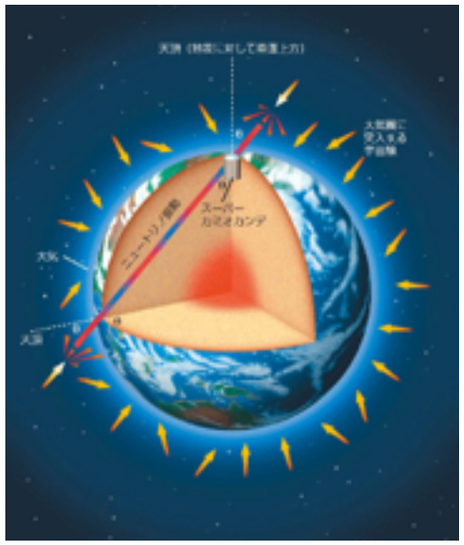




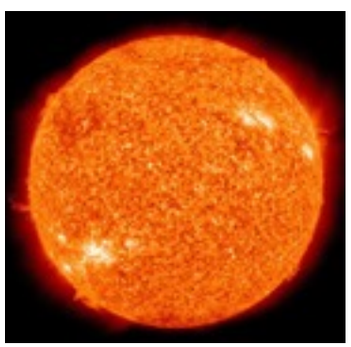
Backups

Neutrinos Oscillate

- atmospheric neutrino anomaly
  - $N(\nu_\mu):N(\nu_e) \neq 2$
  - $\nu_\mu \longrightarrow \nu_\tau$ (Super-Kamiokande 1998)

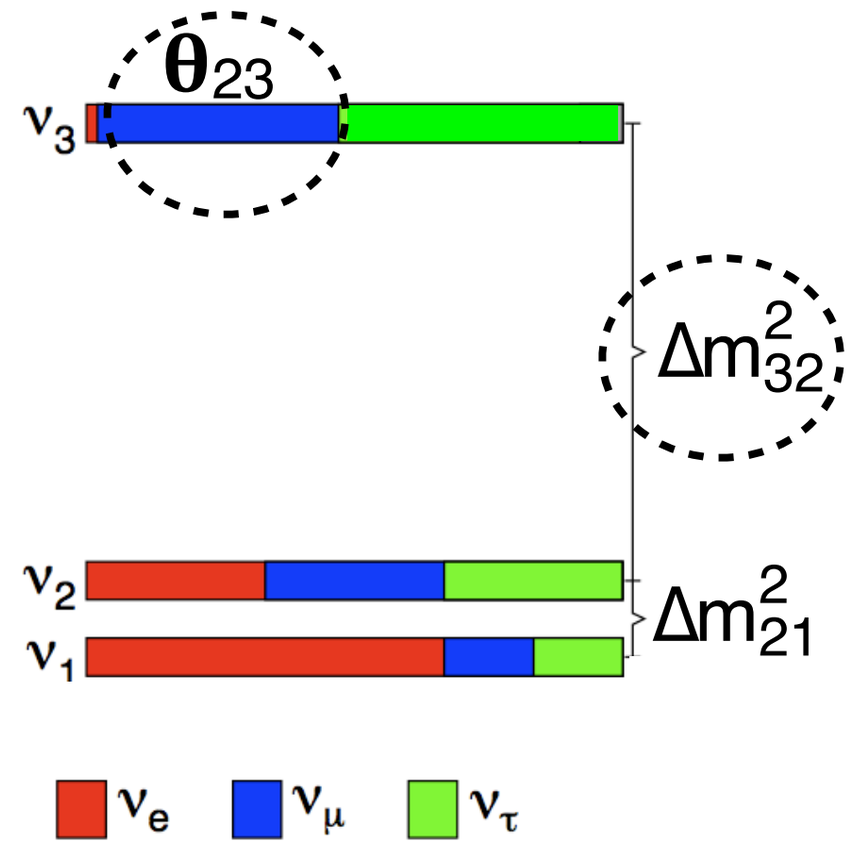


- solar neutrino deficit
  - $N(\nu_e)$ < predicted
  - $\nu_e \longrightarrow \nu_{\mu,\tau}$ (SNO 2001)



Three-flavor model:

- 2 mass squared differences
- 3 mixing angles
- 1 phase



Neutrino Mixing and Oscillations

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ \sin\theta_{13}e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric, accelerator reactor, accelerator reactor, solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^\dagger \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

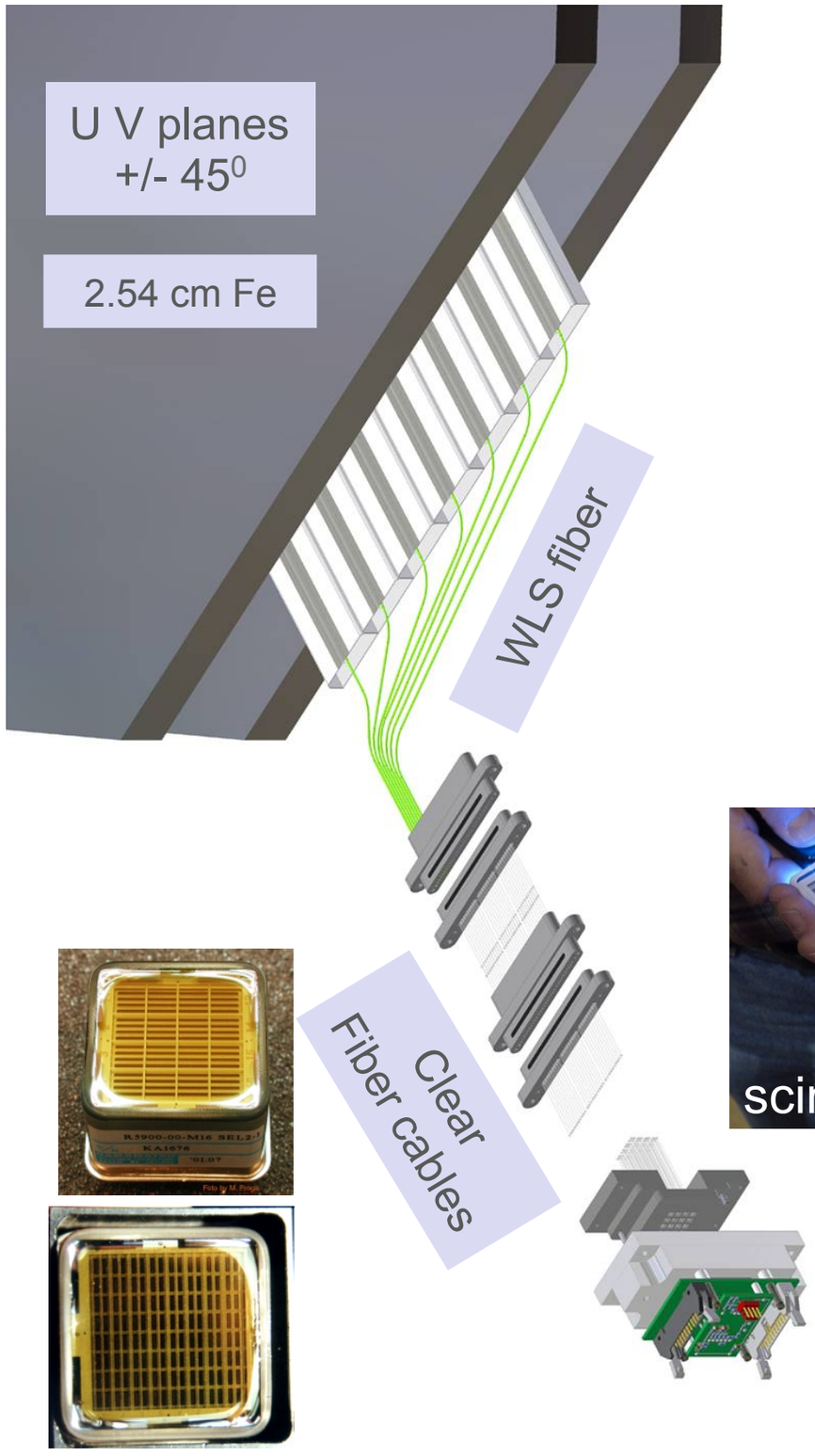
- Plane-wave approximation:

$$\begin{cases} |\nu_\alpha\rangle = \sum_{j=1}^{3} U^*_{\alpha j} |\nu_j\rangle \\ |\nu_j(t,\vec{x})\rangle = e^{-i(E_j t - \vec{p}_j \cdot \vec{x}_j)} \end{cases}$$

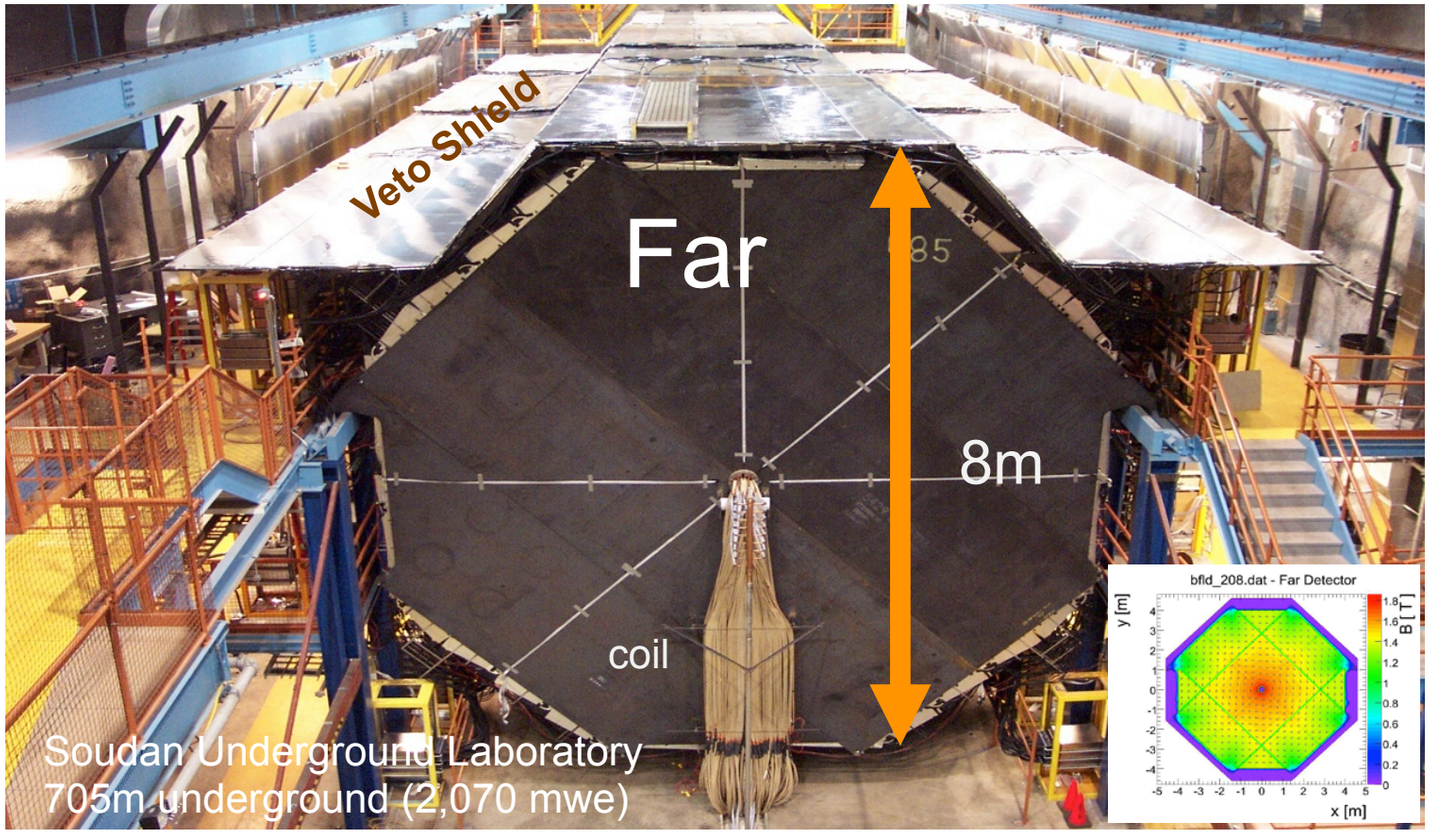
$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta | \nu_\alpha(t,\vec{x}) \rangle \right|^2 = f(\Delta m^2_{kj} \frac{L}{E}, \vec{\theta}, \delta_{CP})$$

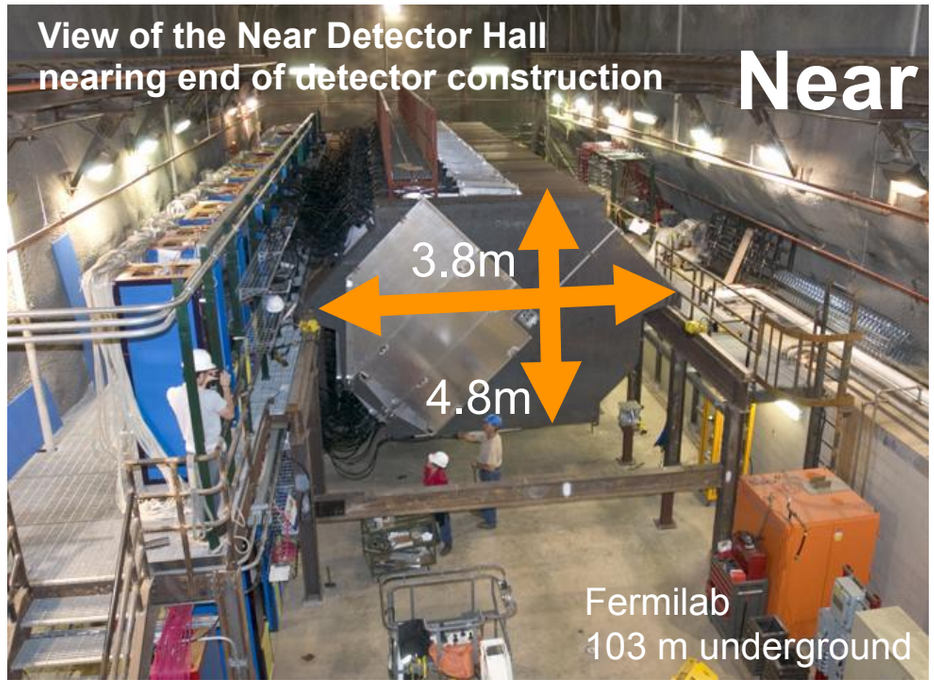
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \Delta m^2_{32} \frac{L}{E}\right)$$

MINOS

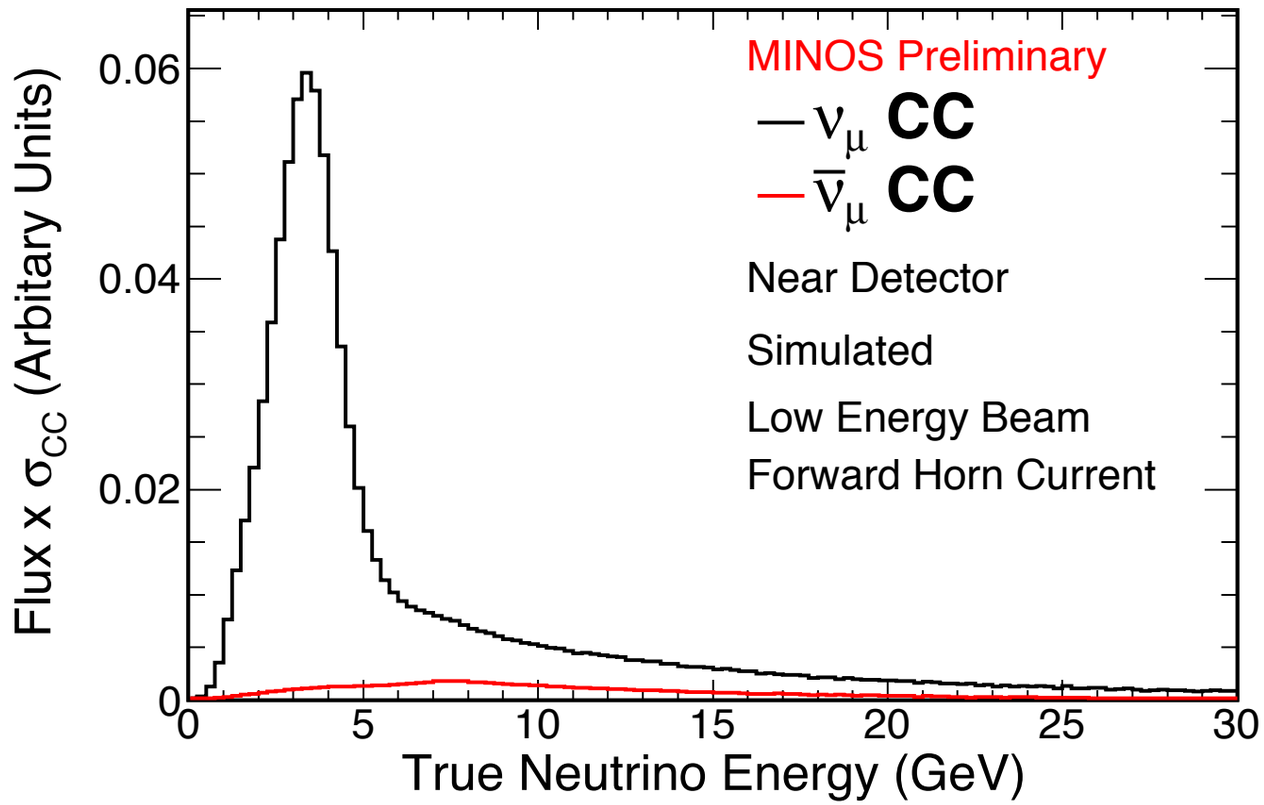

U V planes
+/- 45⁰
2.54 cm Fe
WLS fiber
Clear
Fiber cables

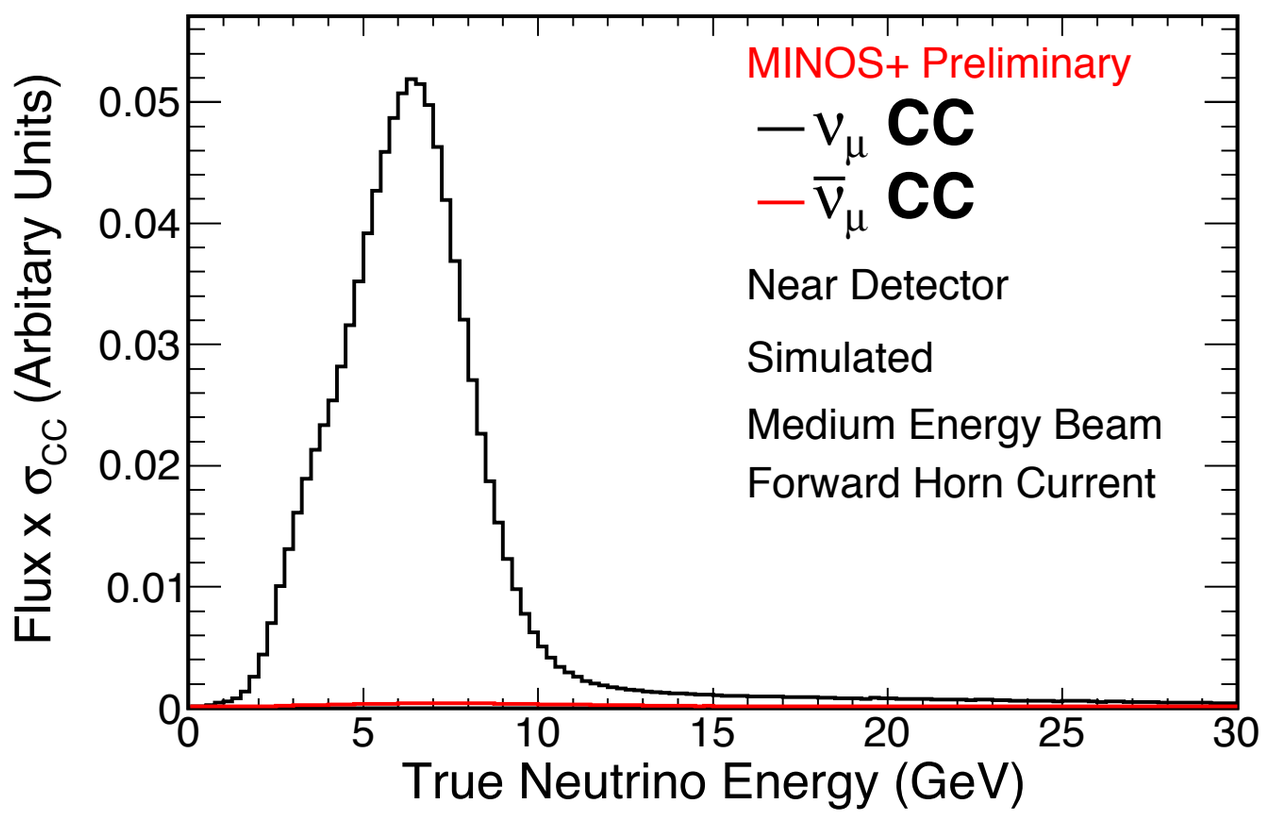
scintillator


Veto Shield
Far
8m
coil
Soudan Underground Laboratory
705m underground (2,070 mwe)
bfld_208.dat - Far Detector
y [m]
x [m]
B [T]

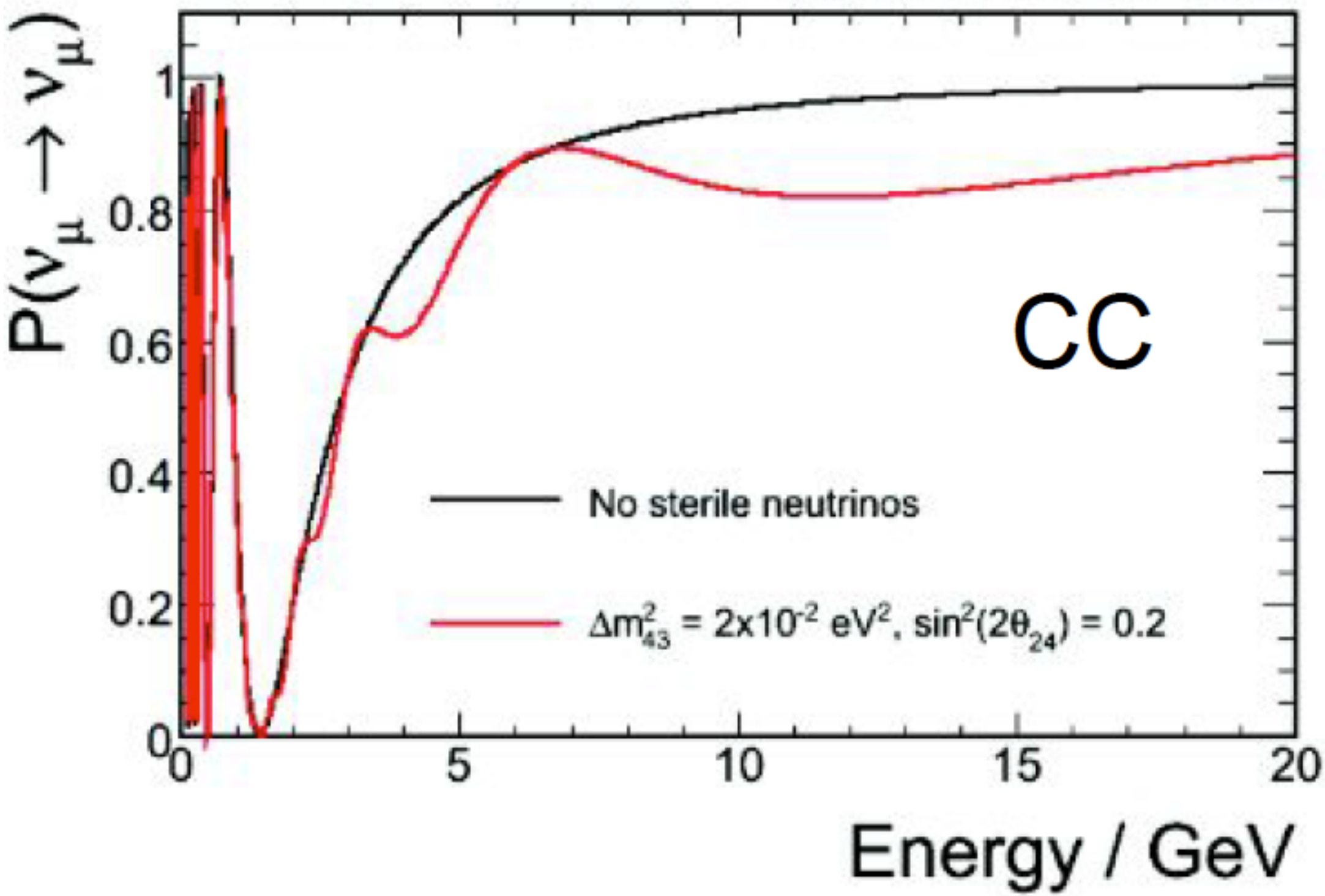

View of the Near Detector Hall
nearing end of detector construction
Near
3.8m
4.8m
Fermilab
103 m underground

Low and Medium Energy Beams

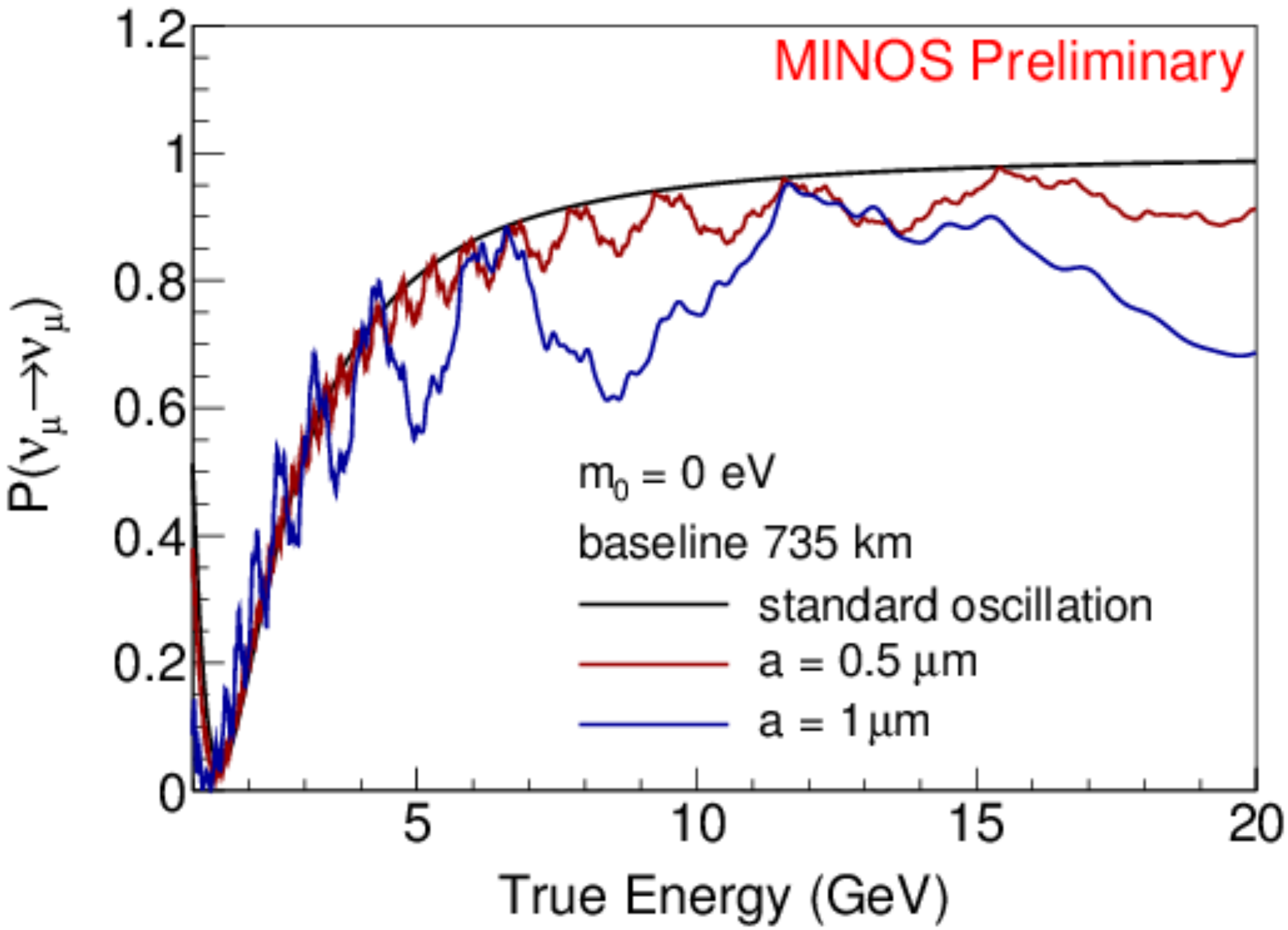
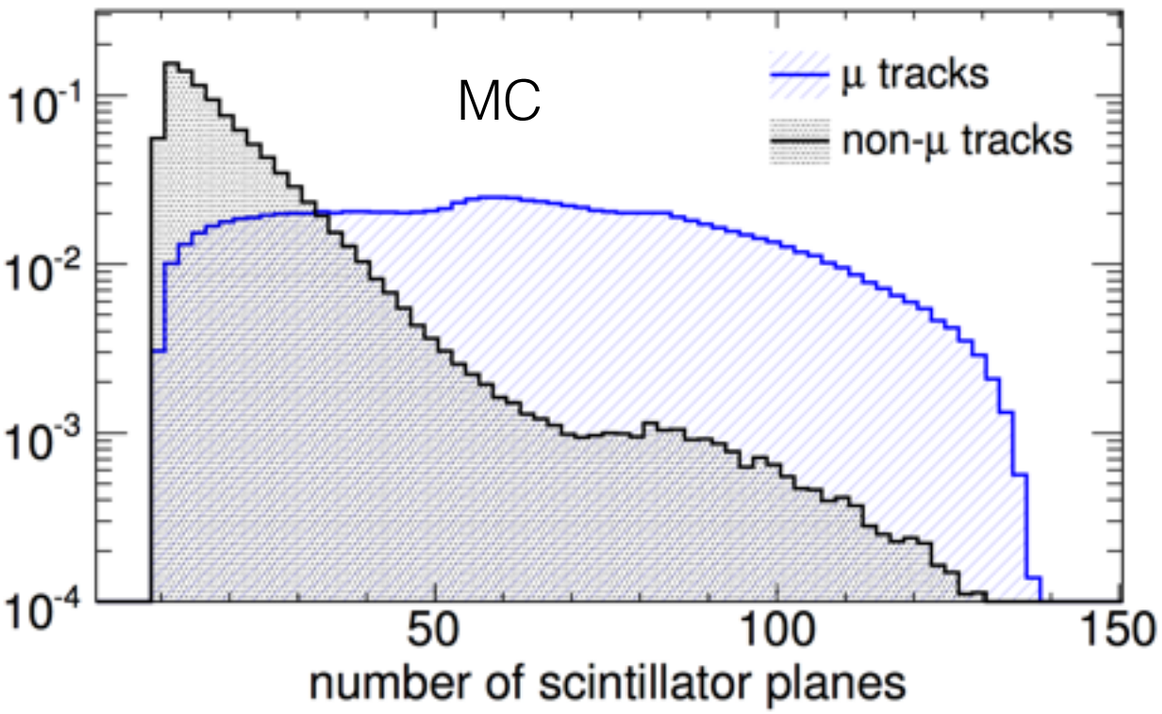
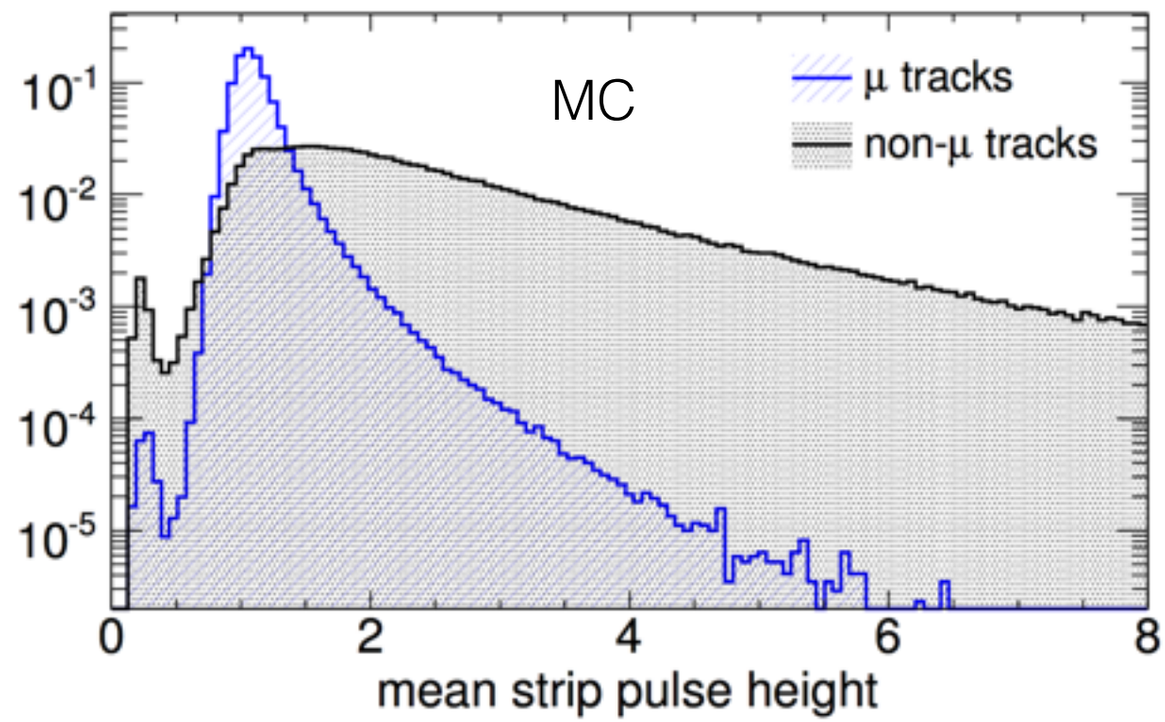
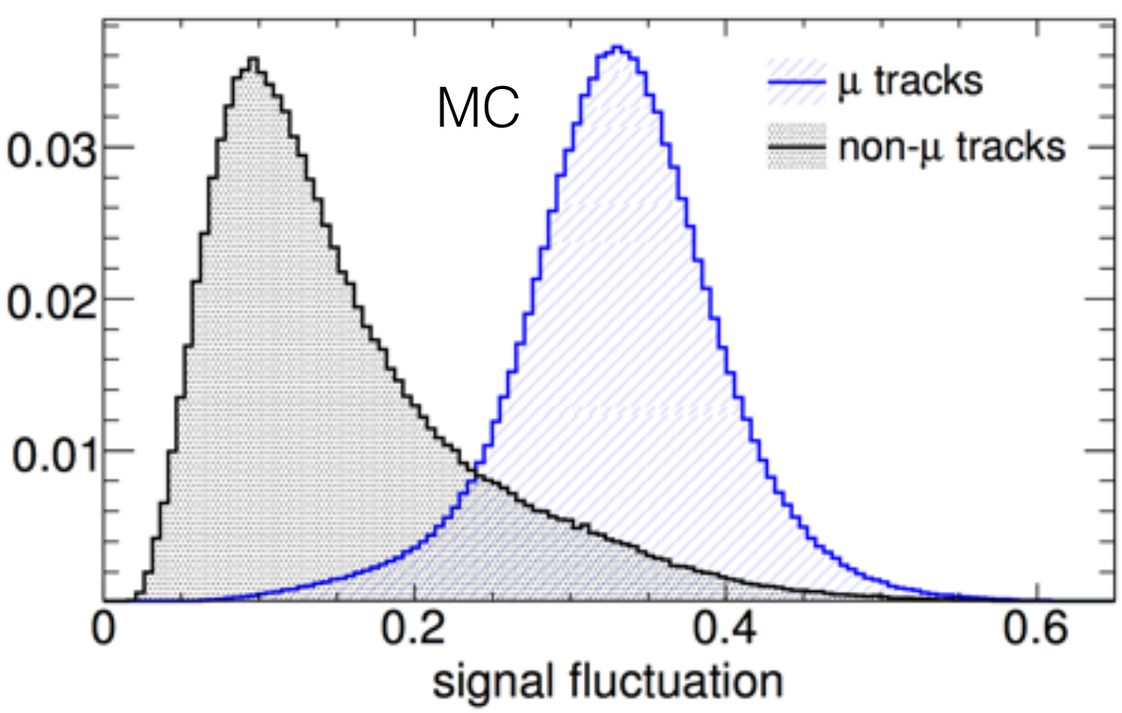
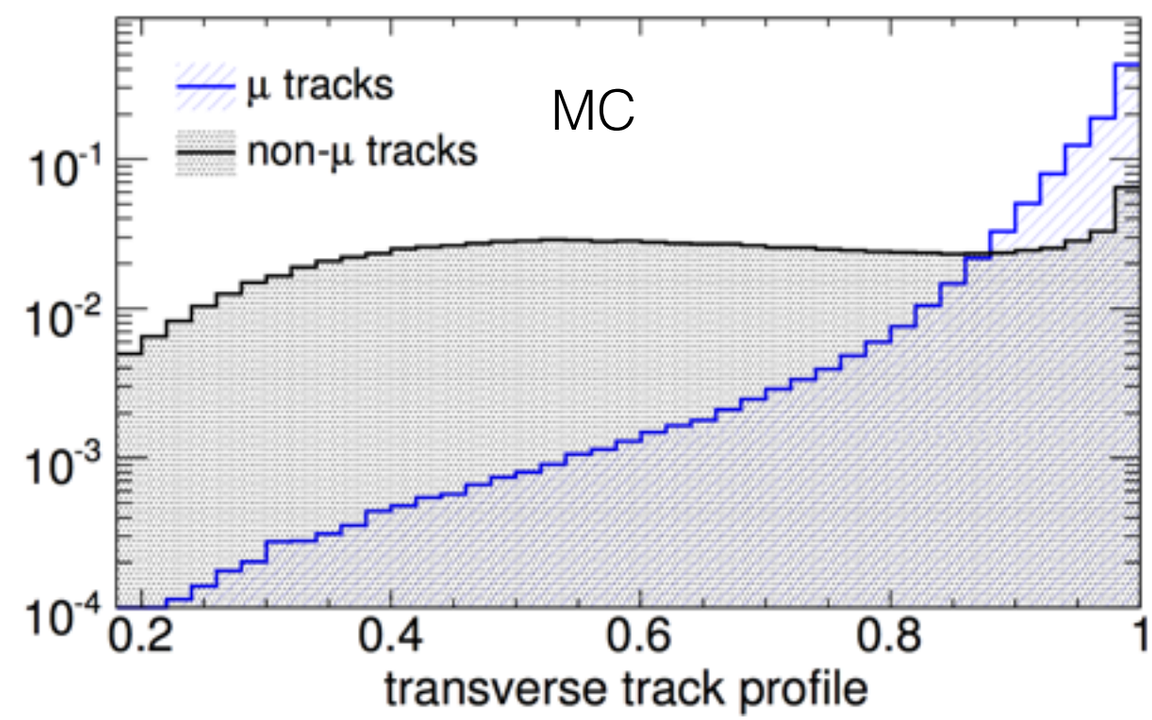




Sterile Neutrinos



Large Extra Dimensions



Muon Track Features