Results and prospects from MINOS and MINOS+

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for the MINOS Collaboration

Tufts University

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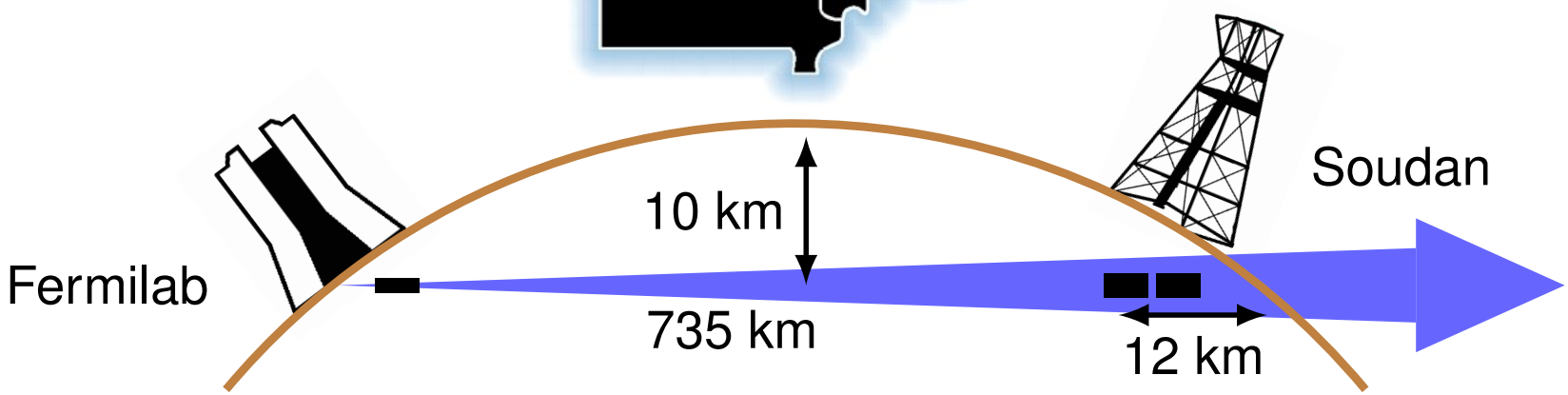
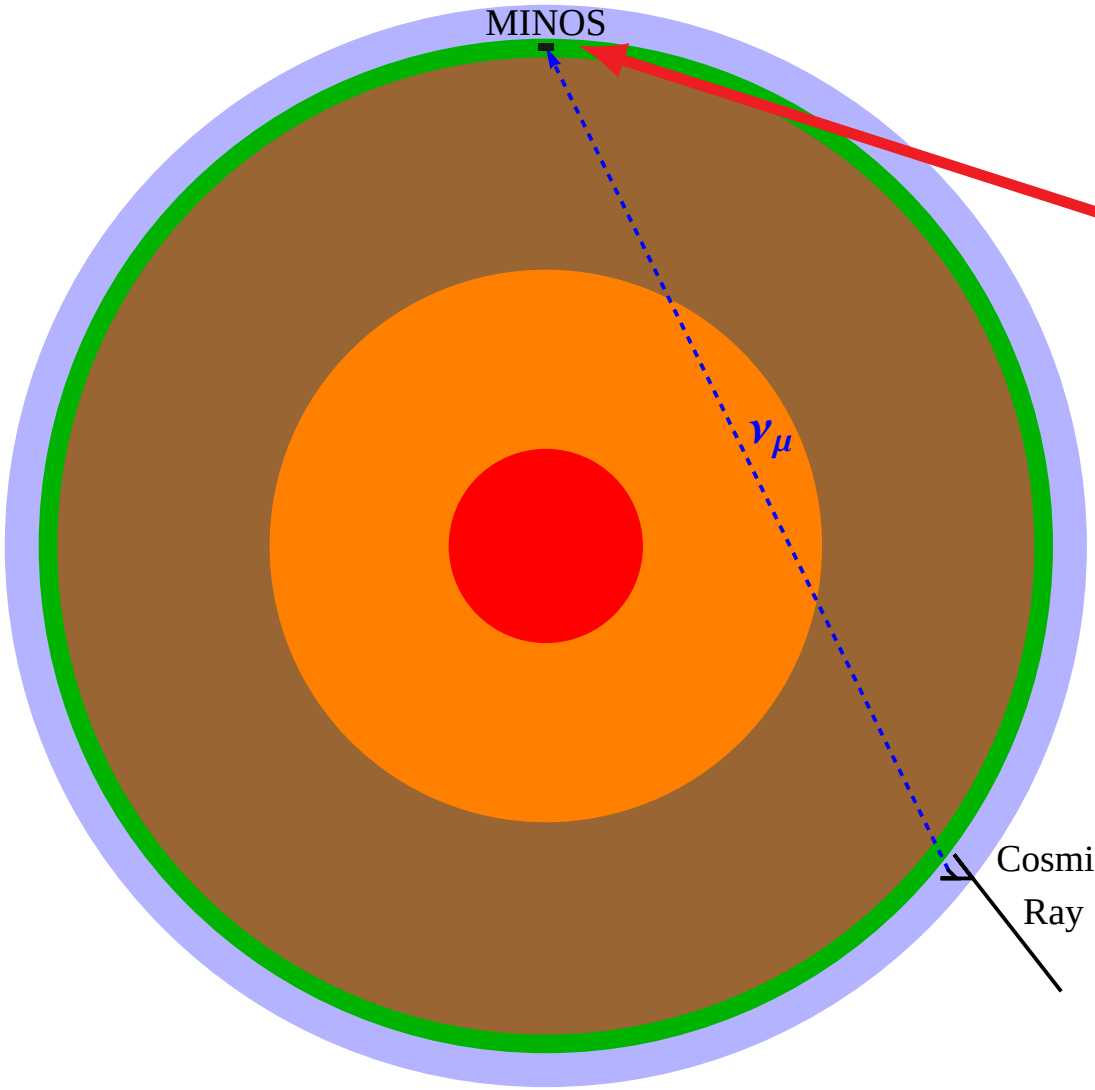
The MINOS experiment

MINOS overview

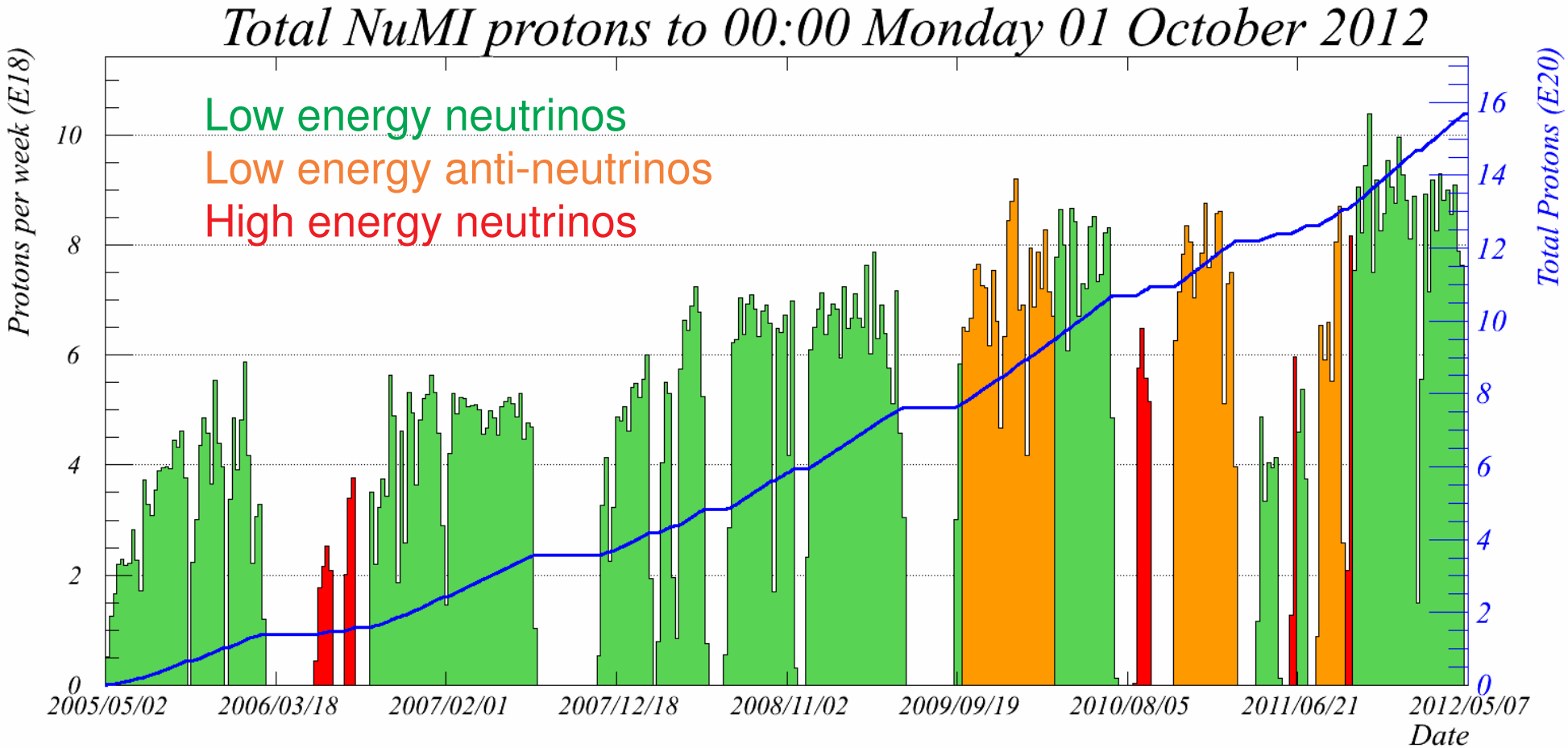


MINOS overview



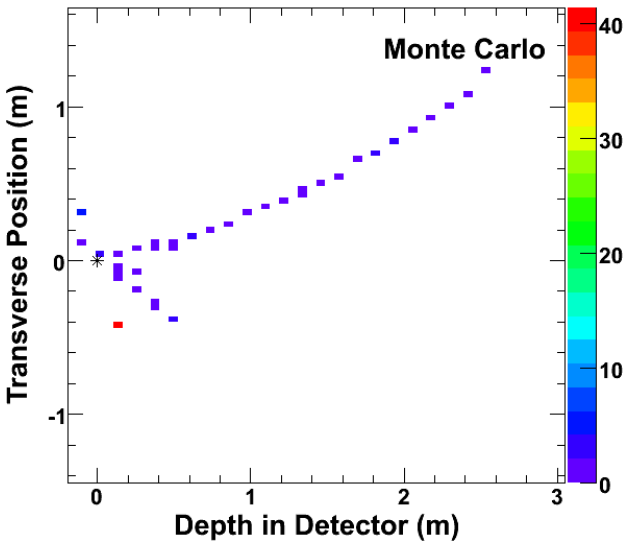
Exposure

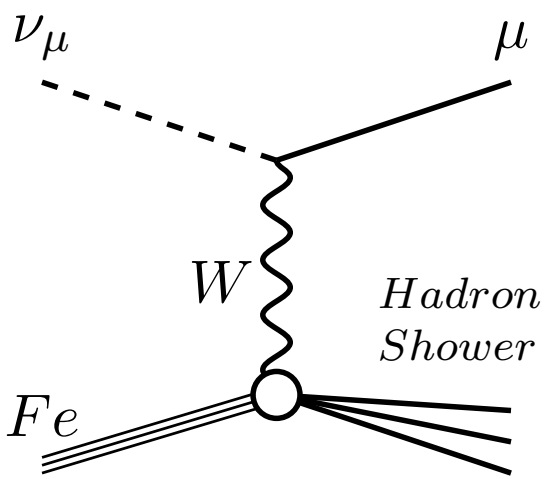
- 15.6×10^{20} protons on target in 7 years of running
- 37.88 kt-year of atmospheric neutrinos since 2003



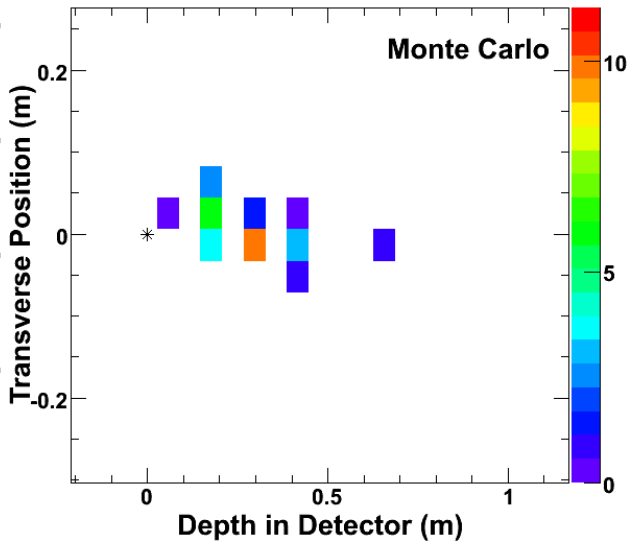
MINOS event topology

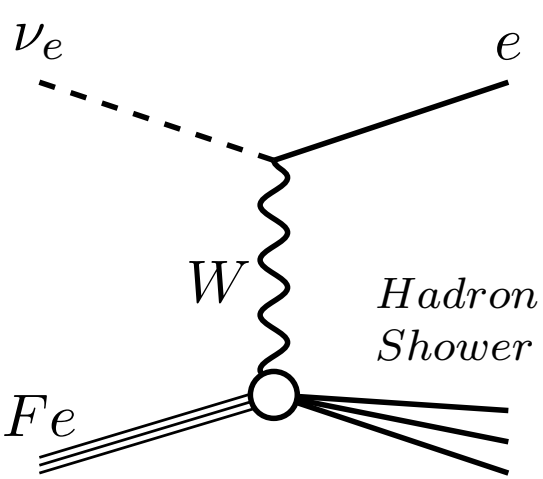
ν_μ-CC event



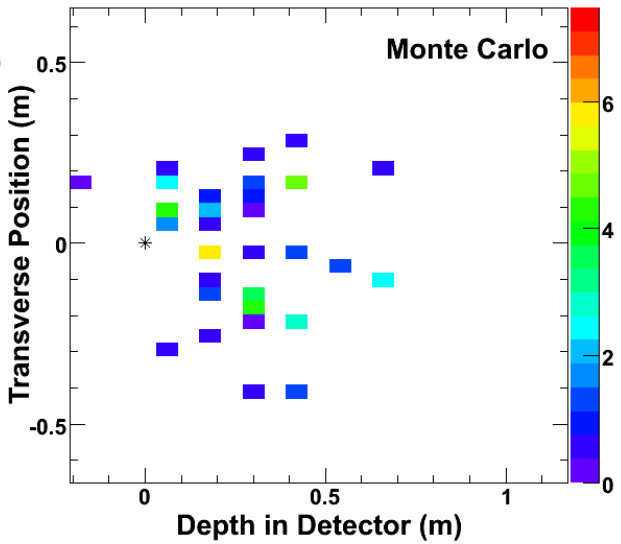


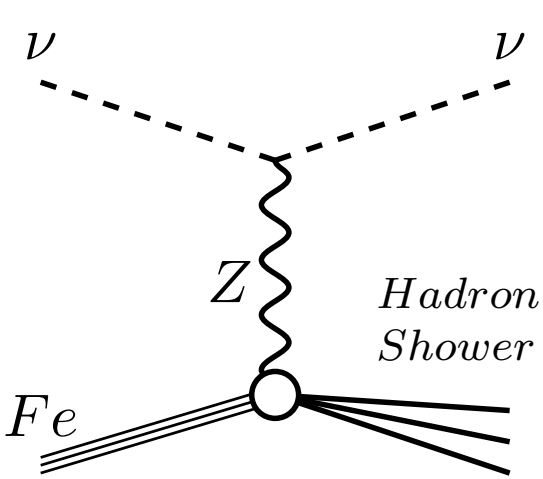
ν_e-CC event





NC event





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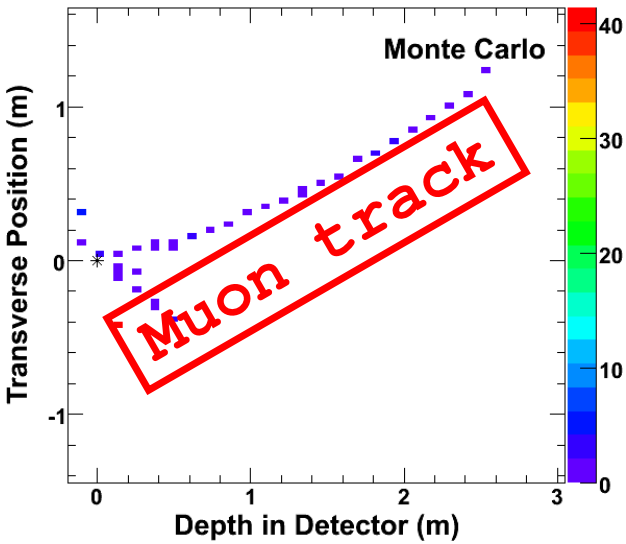
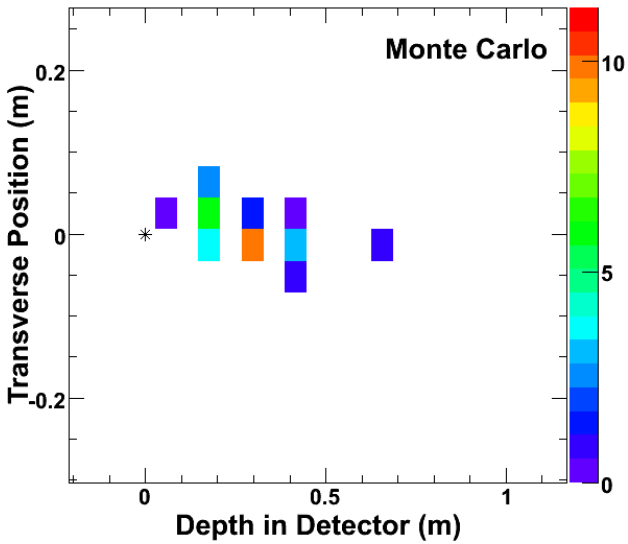


ν_e-CC event



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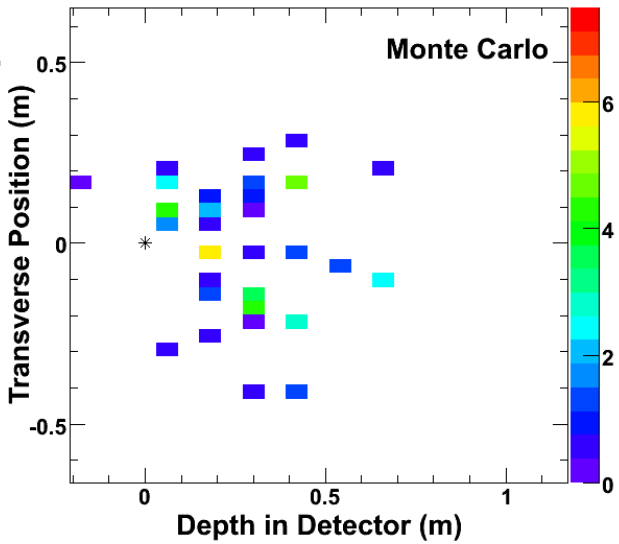
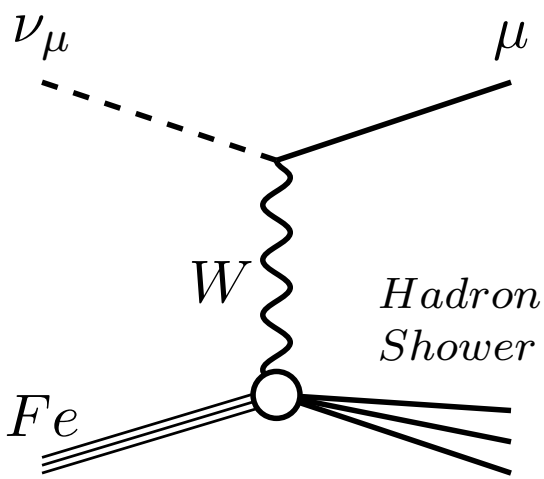
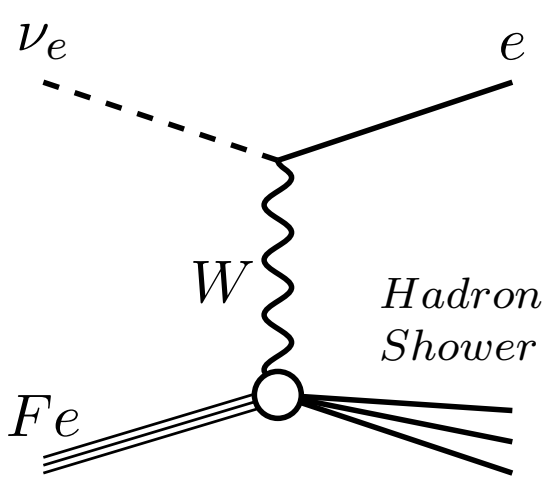
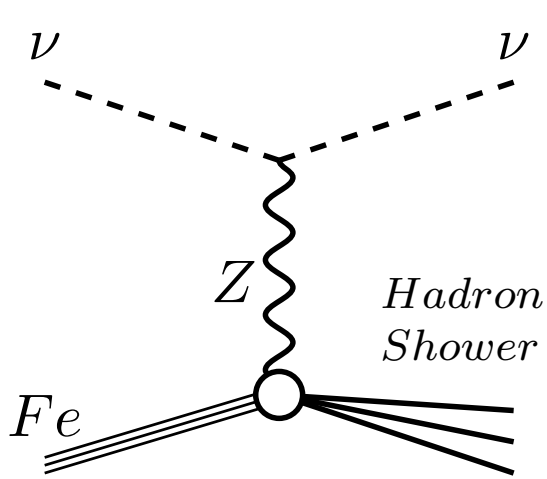


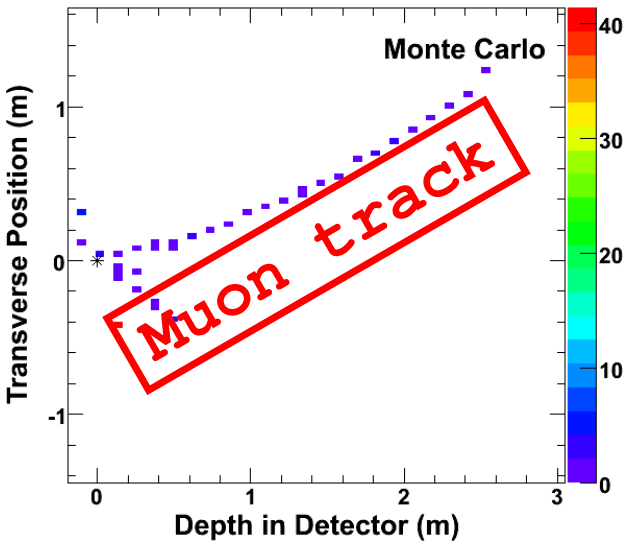




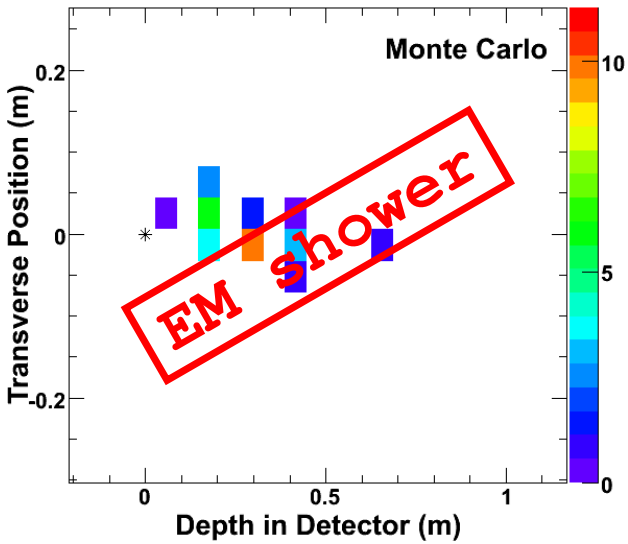


MINOS event topology

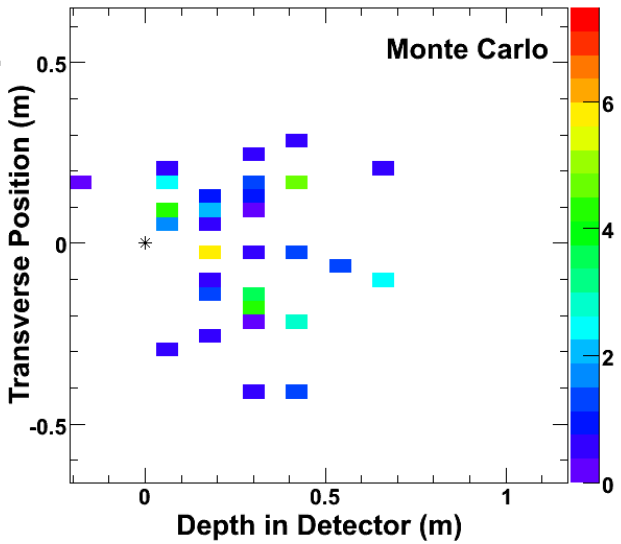
ν_μ-CC event

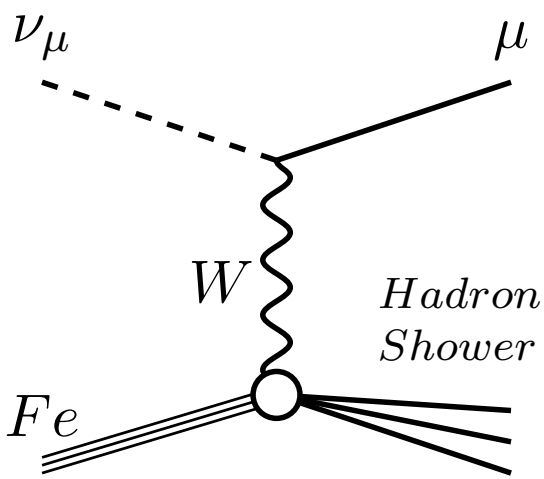


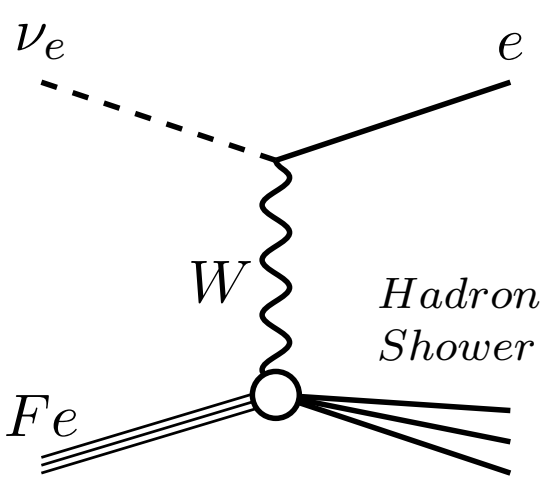
ν_e-CC event

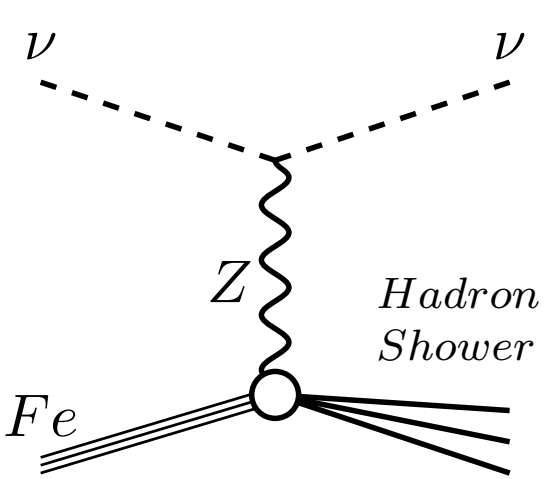


NC event









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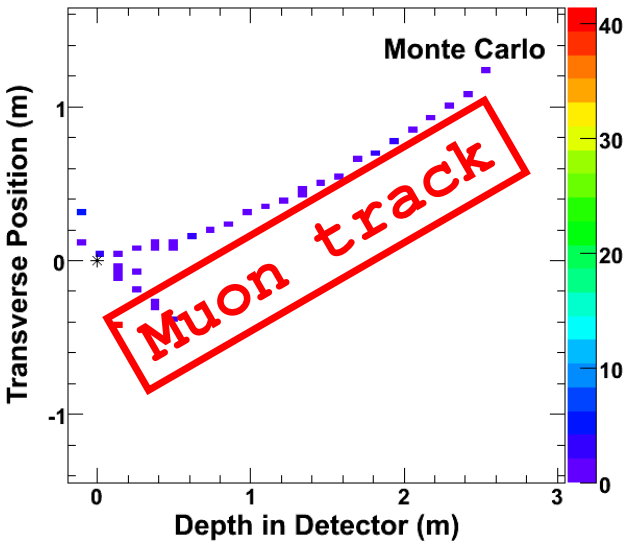

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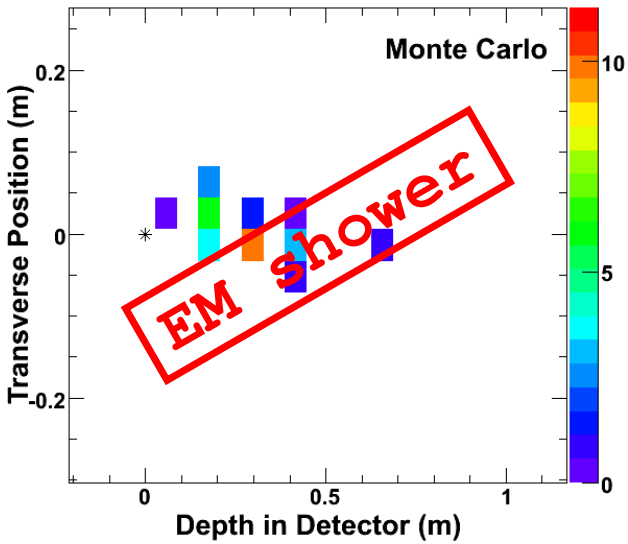

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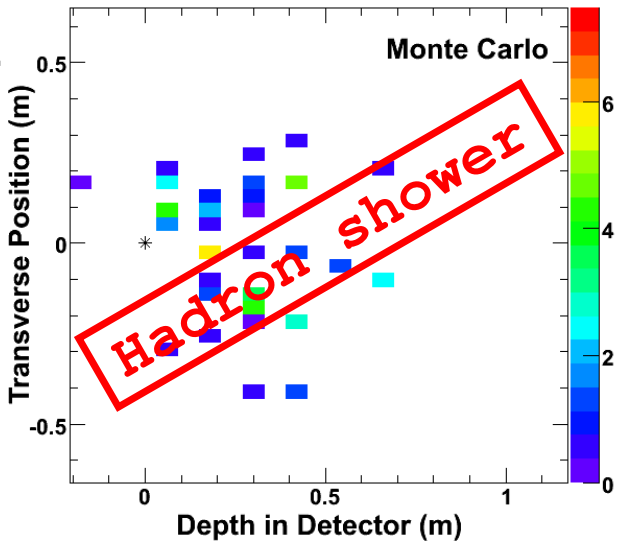
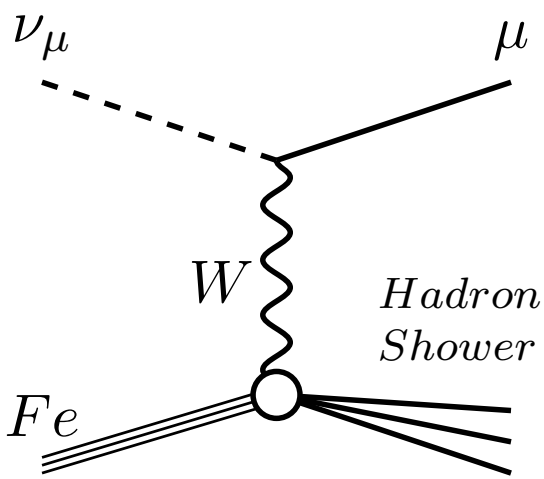
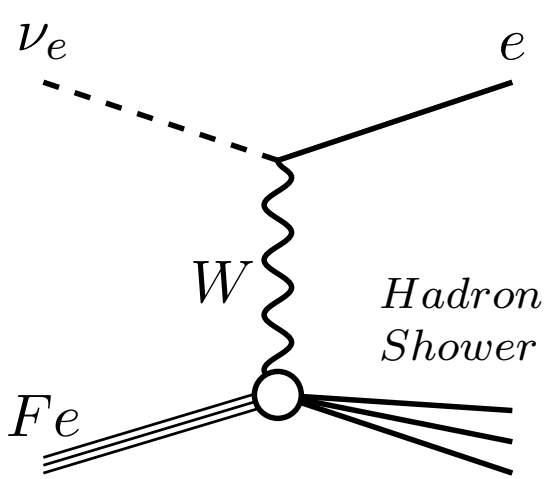
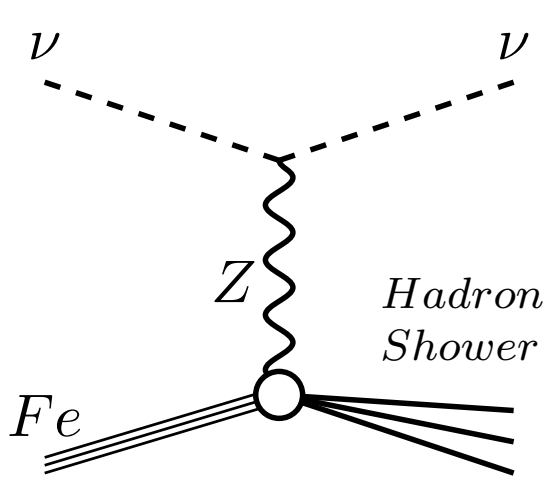
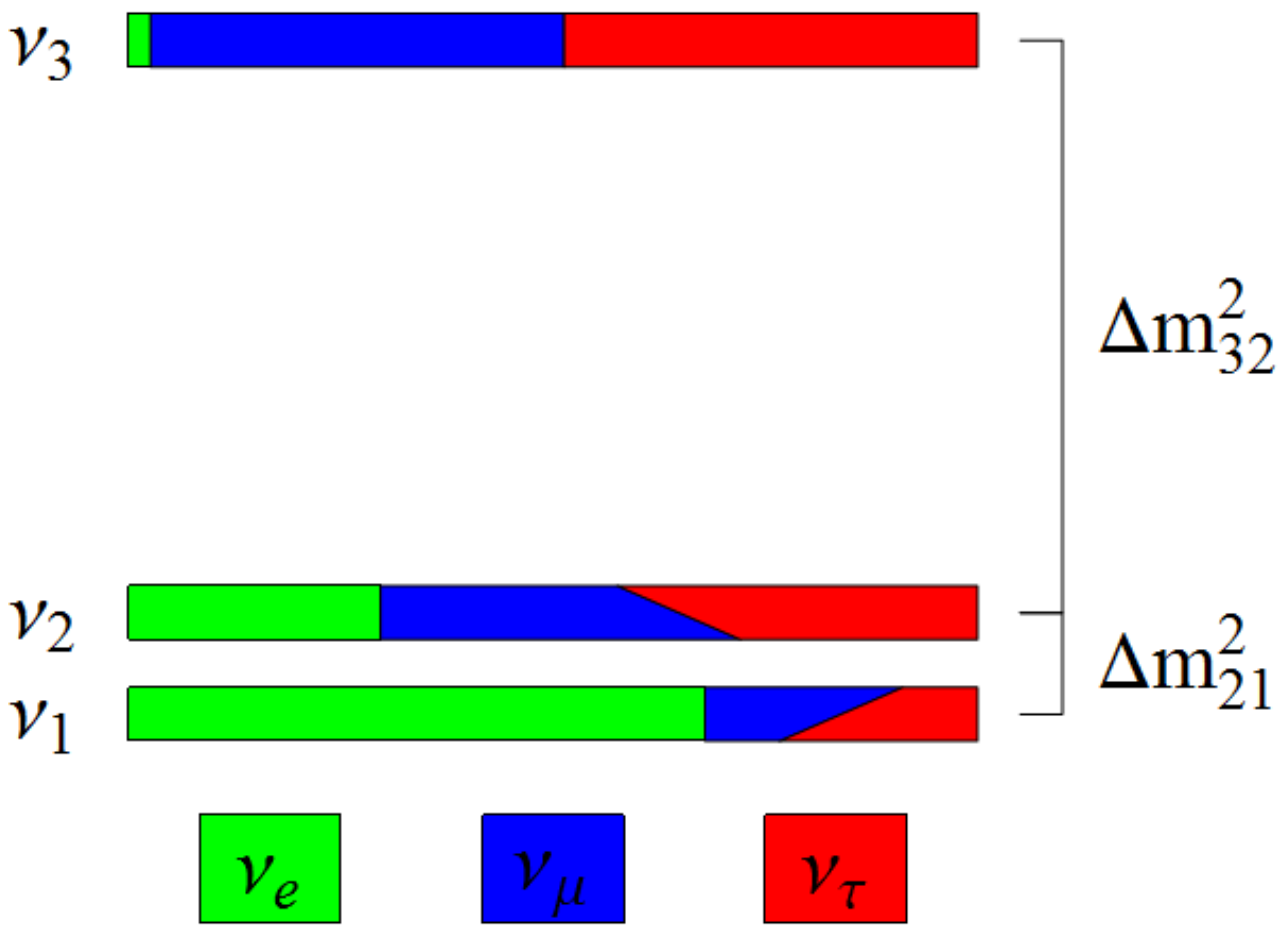








Three-flavor oscillations



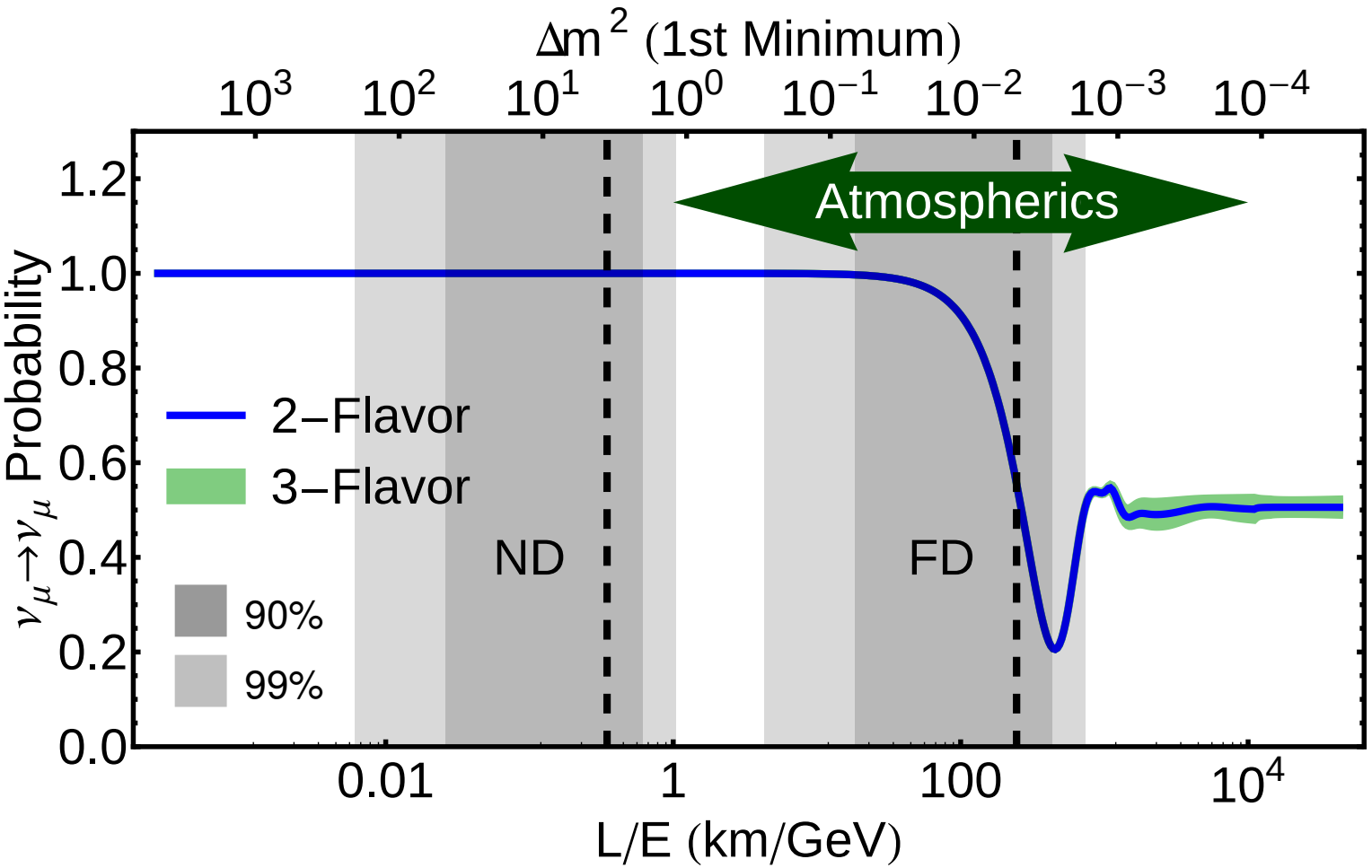
Beyond two flavors

- $L/E \ll 10^4$ km/GeV:
  $\mathcal{P}_{\alpha\beta} = \delta_{\alpha\beta} \pm \sin^2(2\theta^{\oplus}_{\alpha\beta}) \sin^2(1.27\Delta m^2_{\alpha\beta} L/E) + \mathcal{O}(\Delta m^2_{\odot} L/E)^2$

- Two degeneracies:
  - Mass hierarchy
  - Octant of $\theta^{\oplus}_{\alpha\beta}$

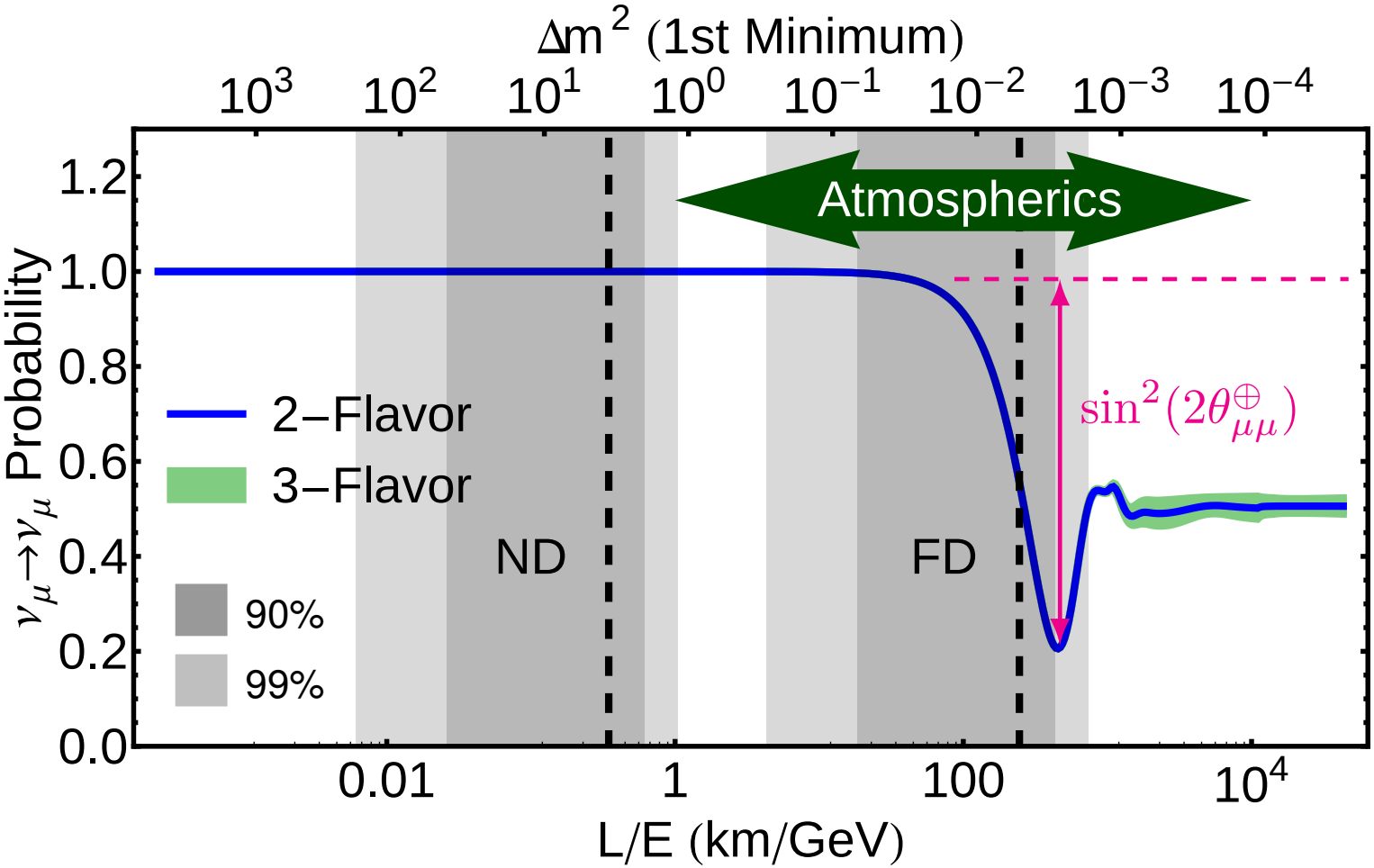
- Three solutions:
  - Three-flavor terms ($\mathcal{O}(\Delta m^2_{\odot} L/E)$)
  - Matter effects ($\Delta m^2_{32} \sim \sqrt{2} G_F n_e E$)
  - Multiple channels ($\theta^{\oplus}_{\mu\mu} \neq \theta^{\oplus}_{\mu e} \neq \theta^{\oplus}_{ee}$)

Survival probability



$$\mathcal{P}_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2(2\theta^{\oplus}_{\mu\mu}) \sin^2(1.27 \Delta m^2_{\mu\mu} \frac{L}{E}) + \mathcal{O}(\Delta m^2_{\odot} \frac{L}{E})^2$$

Survival probability



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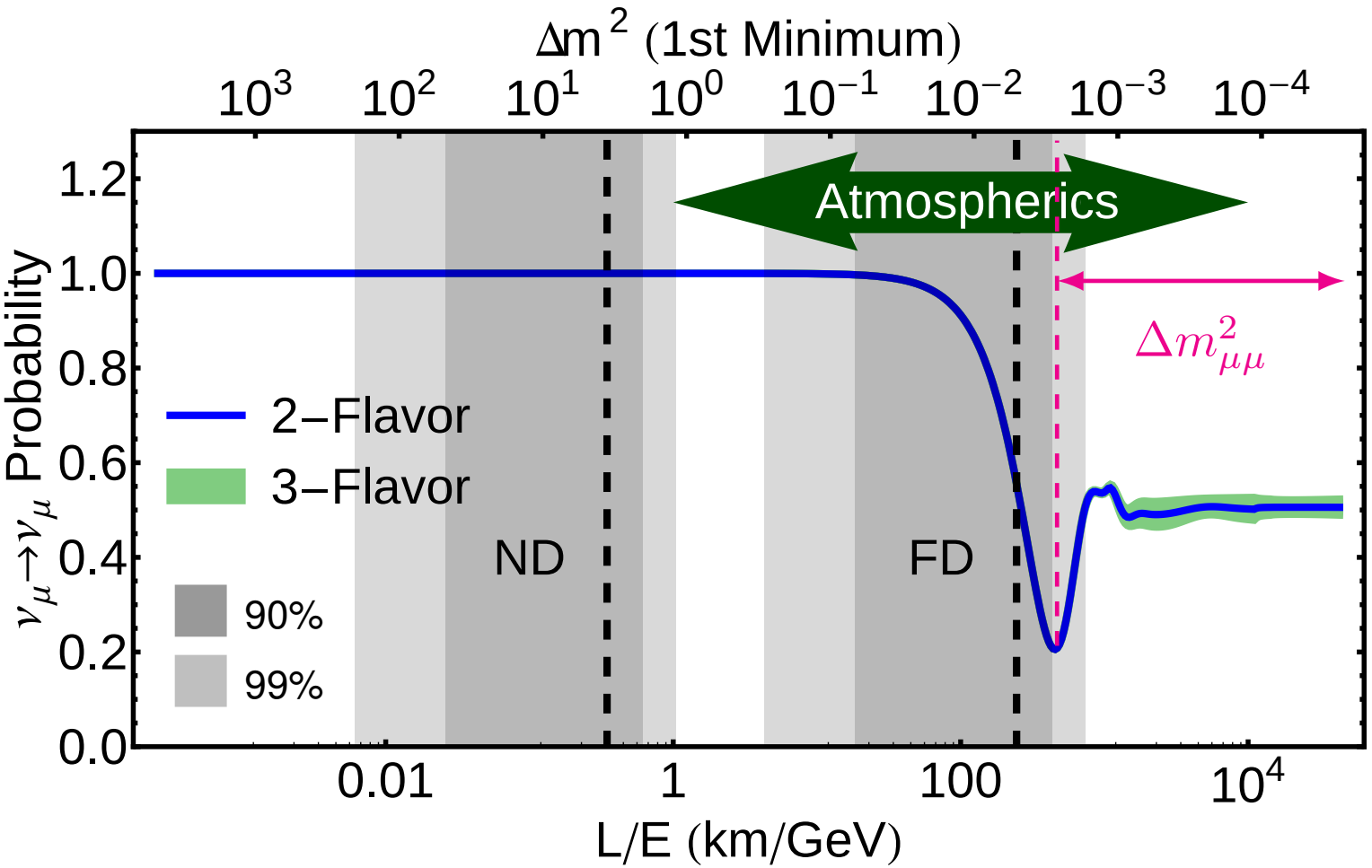

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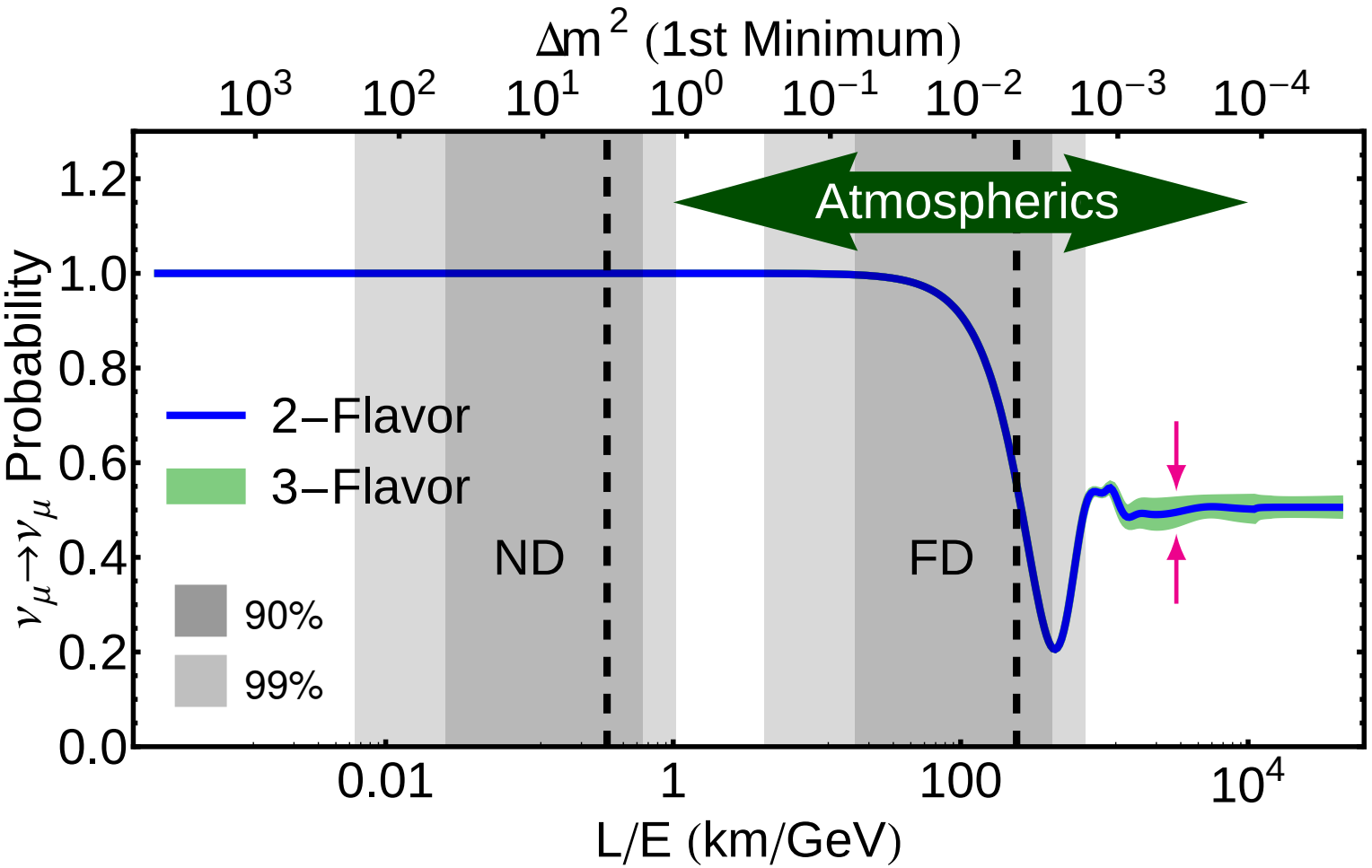

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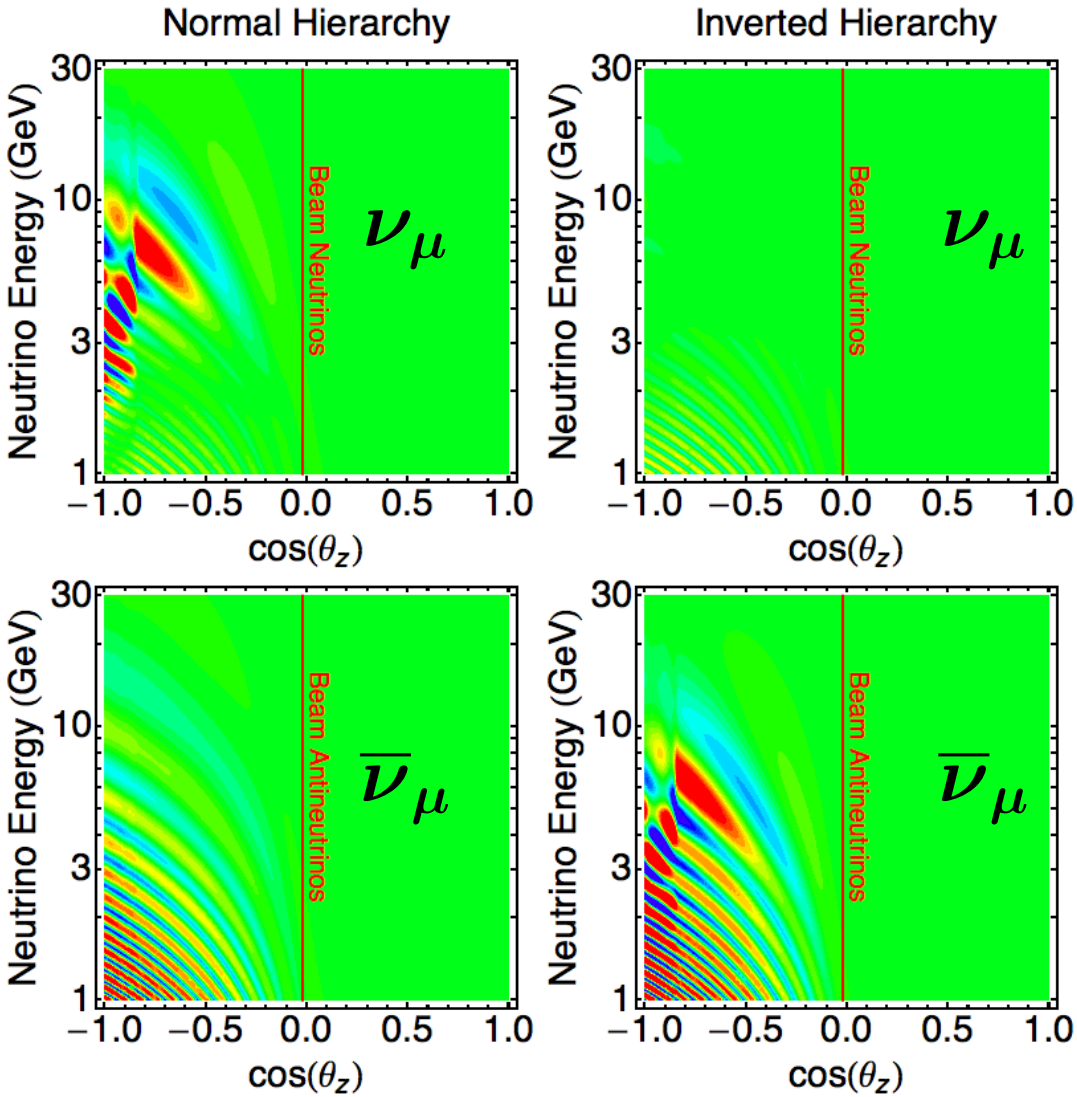
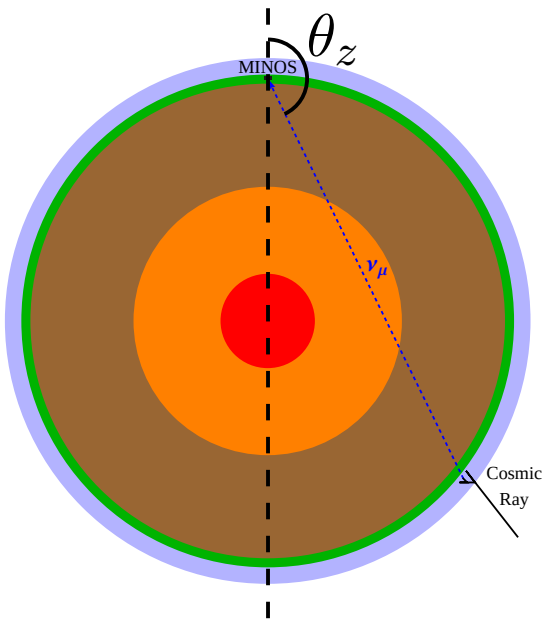
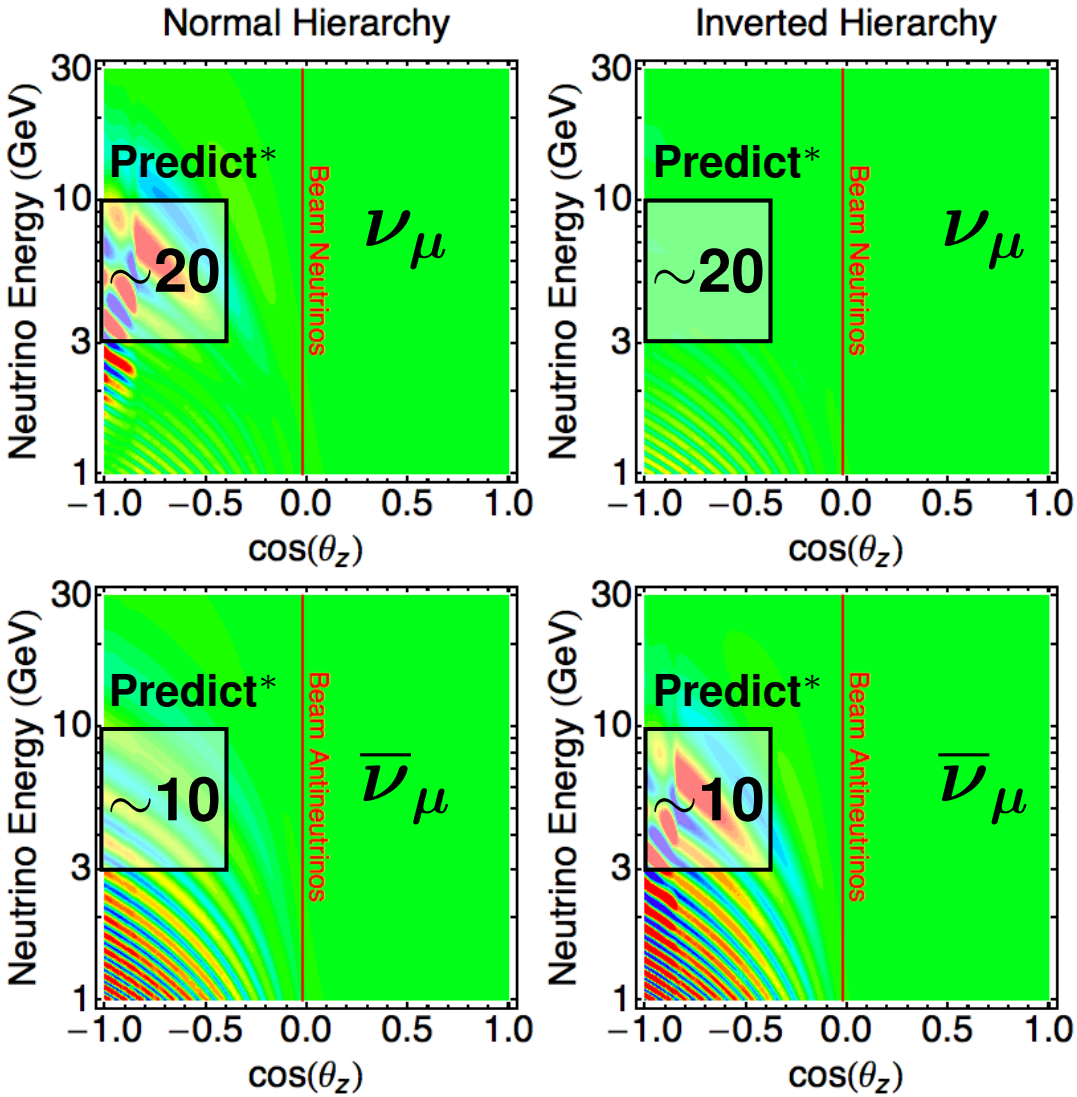
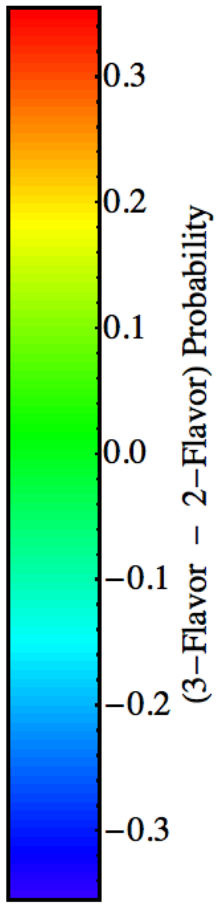
Mantle Resonance

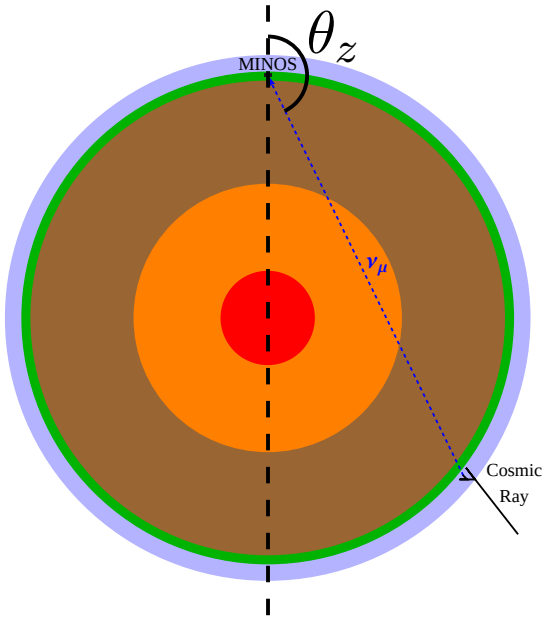




Mantle Resonance







*Contained-vertex events

Analysis Overview

- Extended version of the 2ν result[†]
- New binning in $\cos(\theta_z)$ and energy to exploit resonance effects
- Improved algorithm for calculating 3ν probabilities
- Fit in 4D parameter space: $(\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta_{CP})$
- Include 15 systematics as nuisance parameters in the fit
- External constraint from average of reactor experiments:
  - $\sin^2\theta_{13} = 0.0242 \pm 0.0025$ ($\theta_{13} = 8.95°$)
- Solar parameters fixed to global average:[*]
  - $\Delta m^2_{21} = 7.54 \times 10^{-5}$ eV^2
  - $\sin^2\theta_{12} = 0.307$

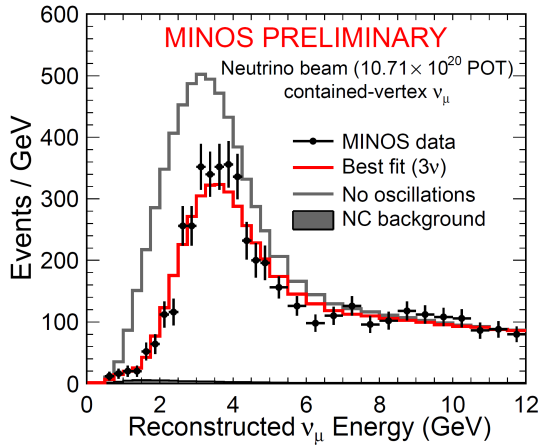
[†] Phys. Rev. Lett. 110, 251801 (2013)

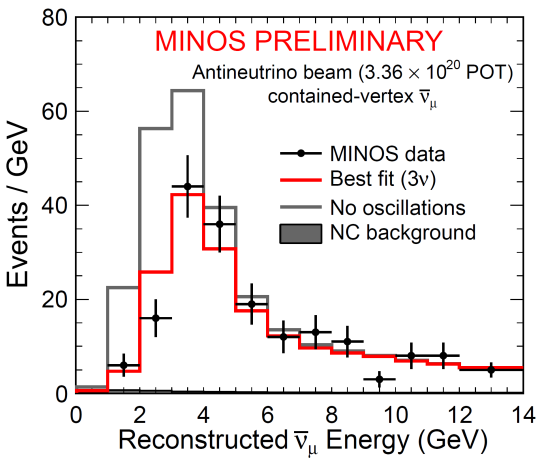
[*] Fogli et al., Phys. Rev. D 86, 013012 (2012)

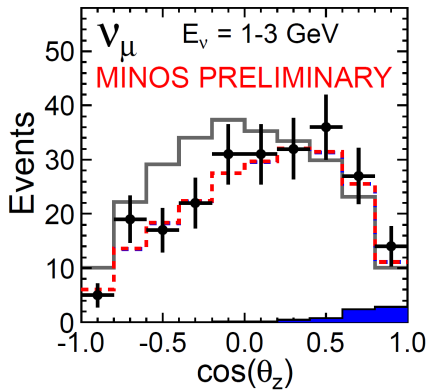
Data Samples

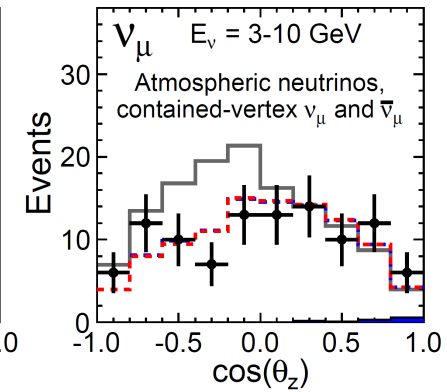
- Uses the same data samples as the 2ν result
- Full beam exposure:
  - 10.71×10^{20} POT taken in neutrino mode
    - Select ν_μ-CC interactions
    - Select $\overline{\nu}_\mu$-CC interactions
  - 3.36×10^{20} POT taken in anti-neutrino mode
    - Select $\overline{\nu}_\mu$-CC interactions
- 37.88 kt-years of atmospheric neutrinos
  - Select ν_μ-CC interactions
  - Select $\overline{\nu}_\mu$-CC interactions

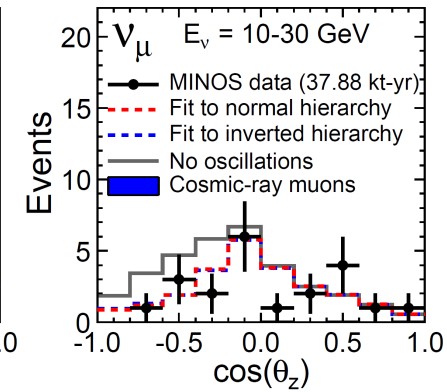
Disappearance Data

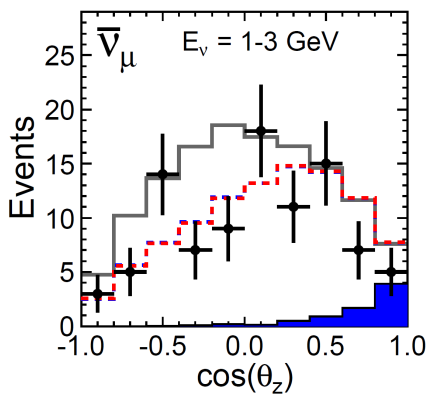


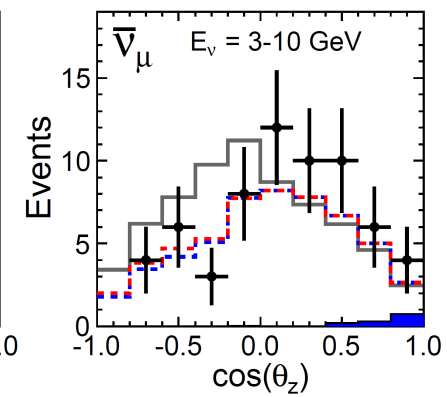


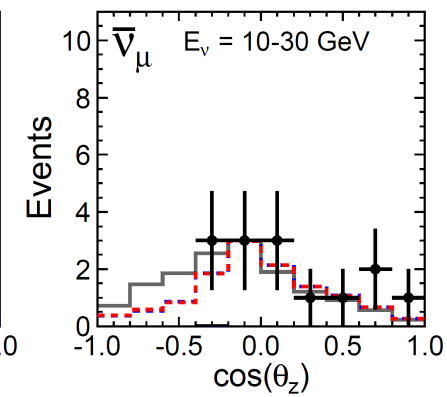






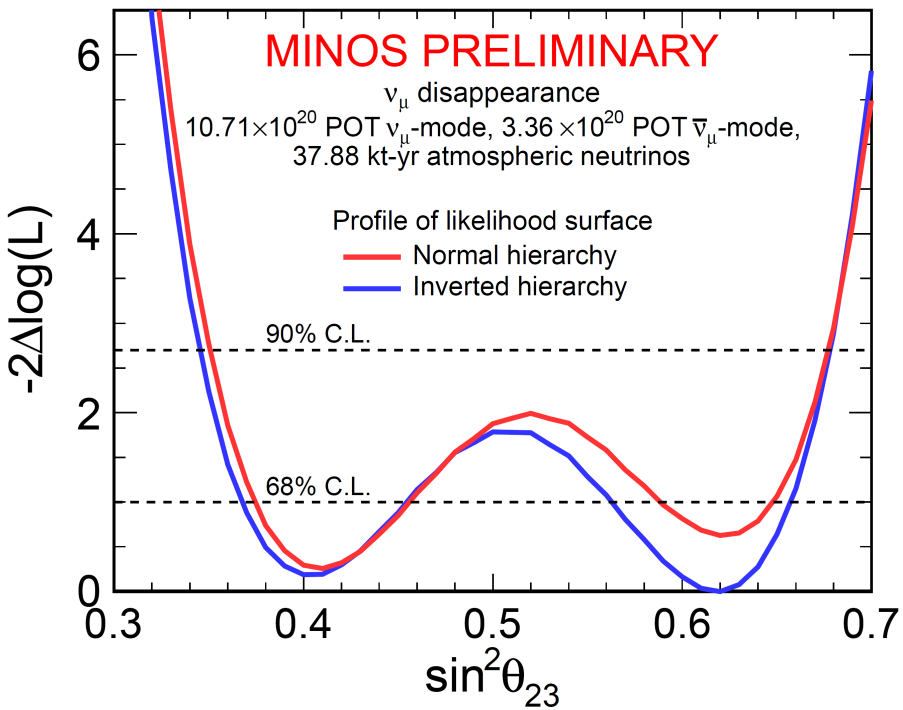


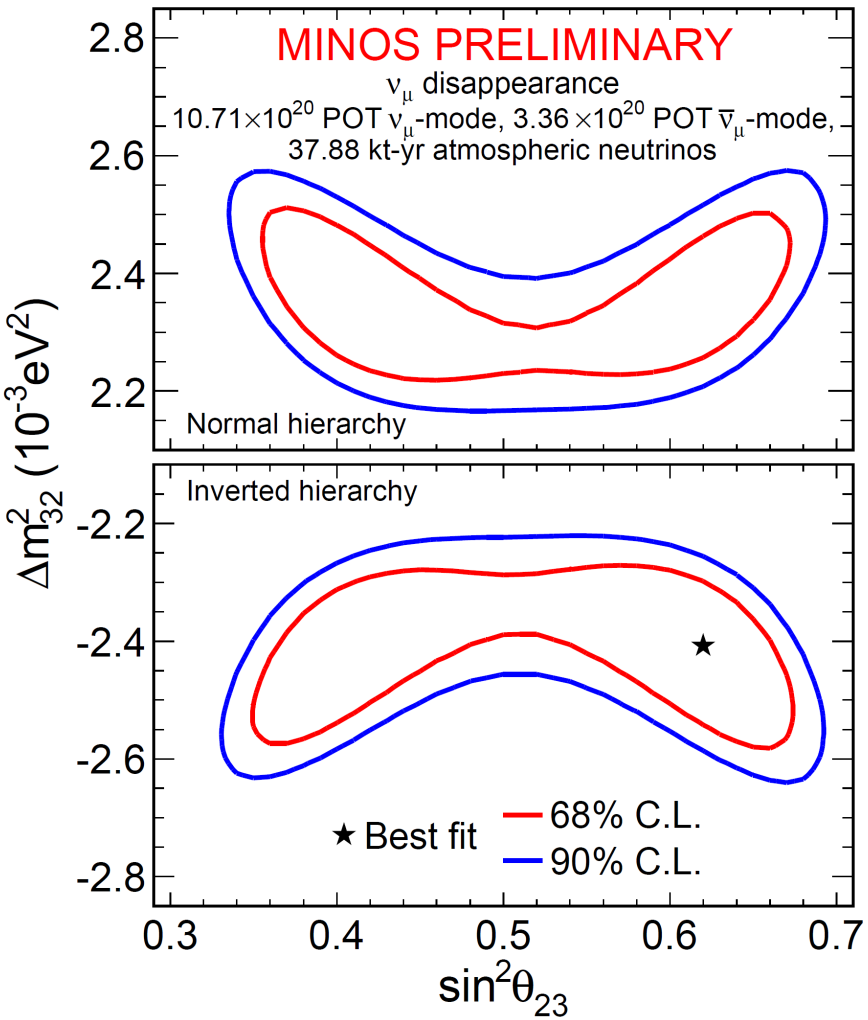




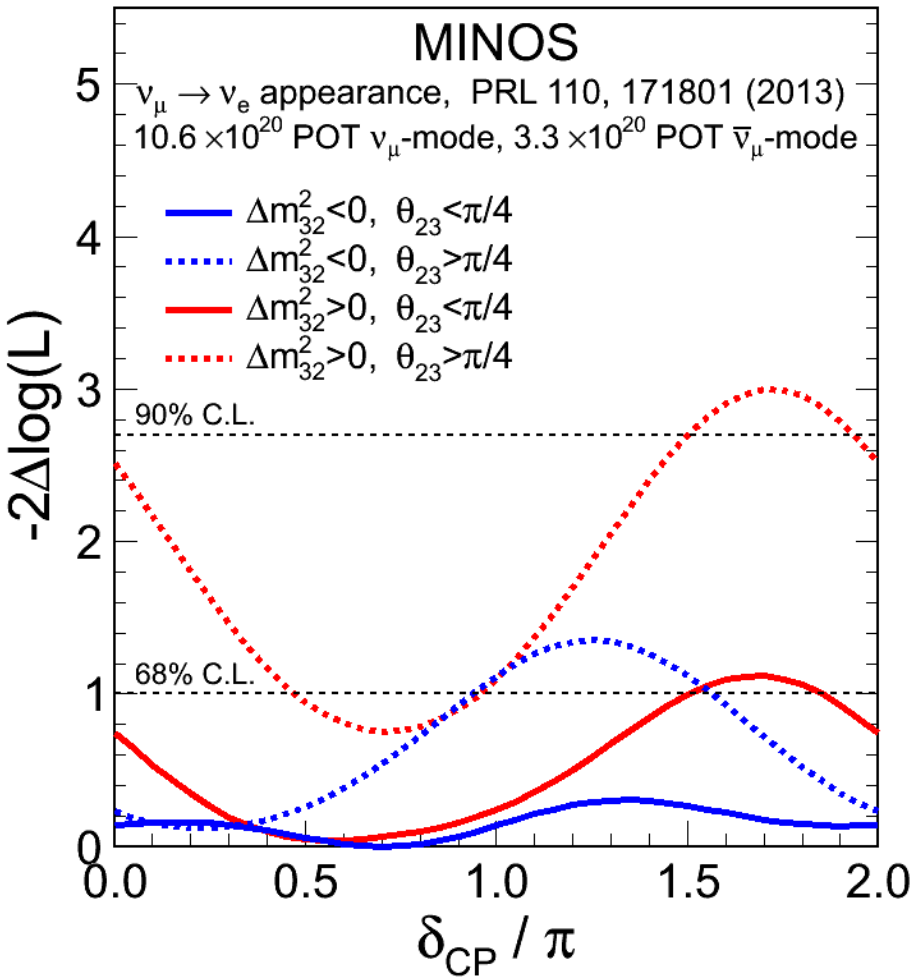
Disappearance Results

- Marginal preference for inverted hierarchy and upper octant



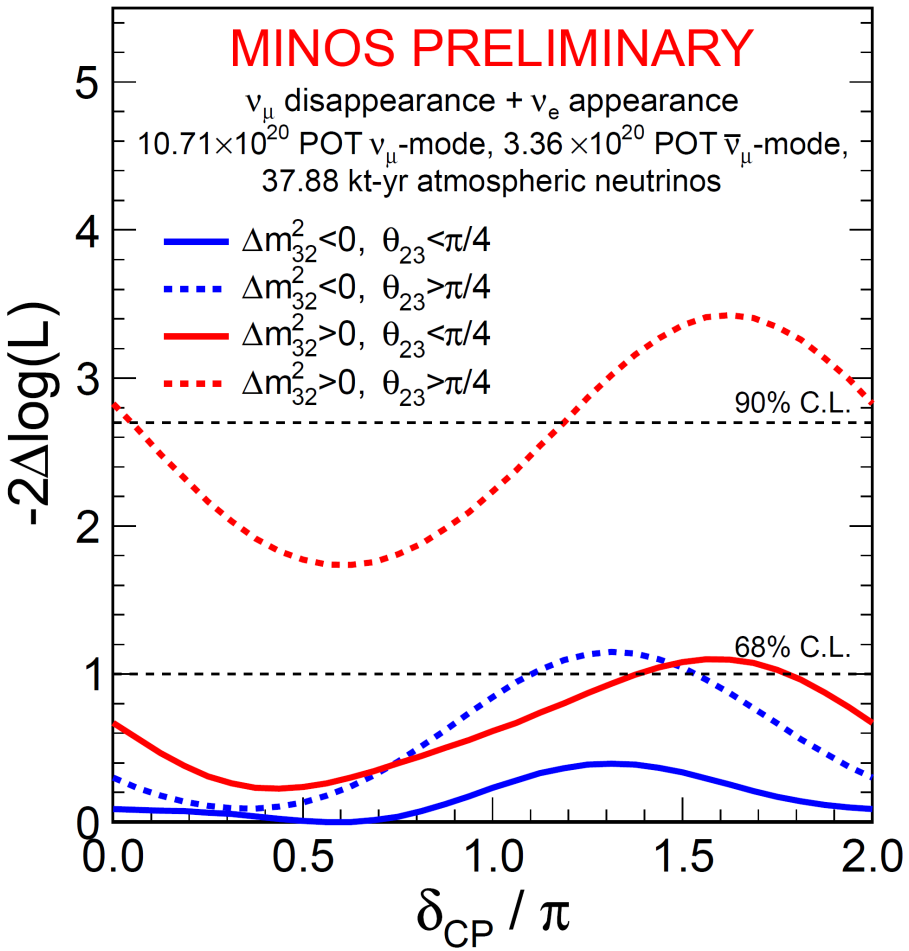


Combining with ν_e Appearance



- Appearance result also probes 3-flavor oscillations

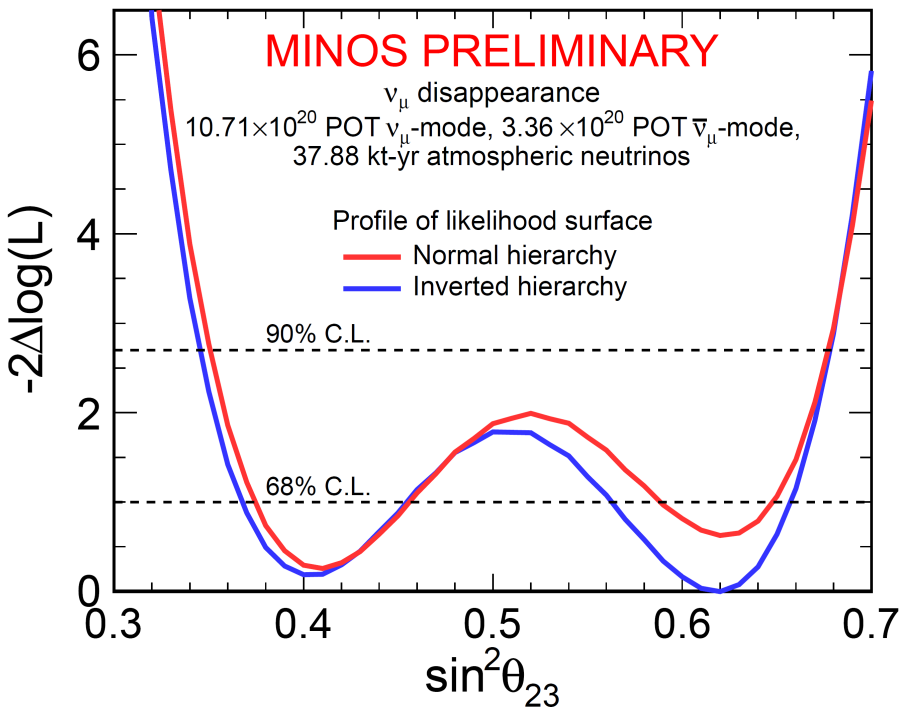
Combining with ν_e Appearance

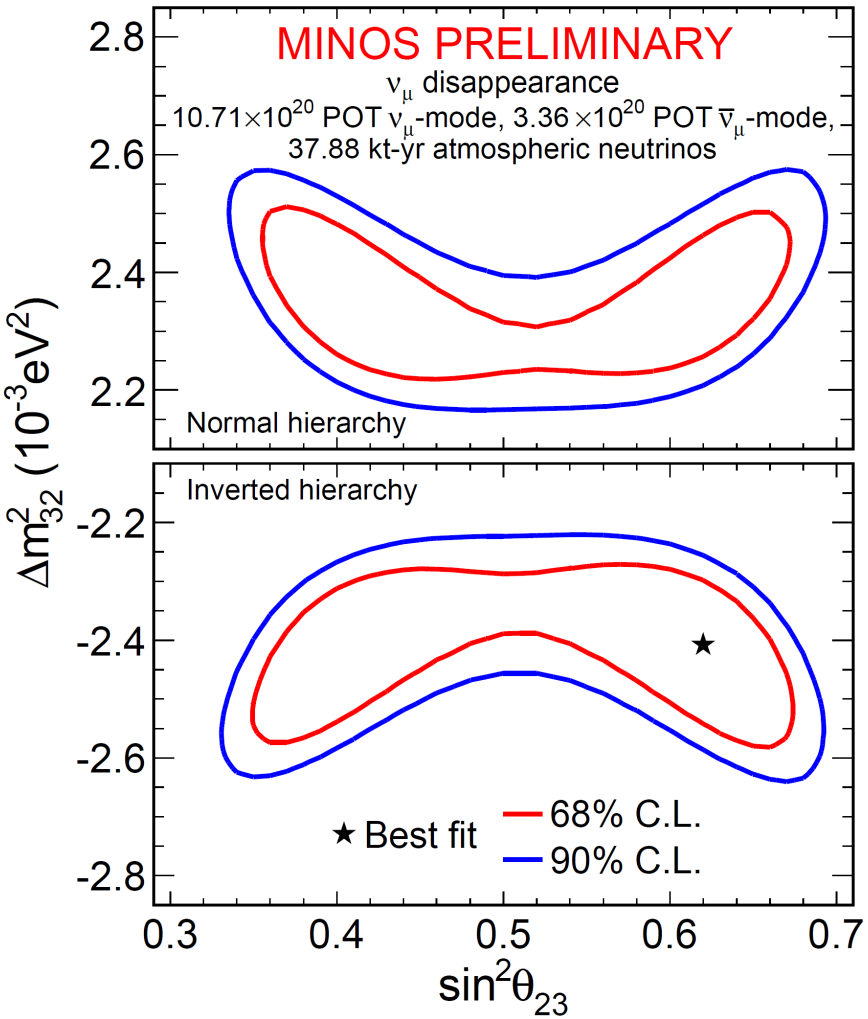


- Appearance result also probes 3-flavor oscillations
- Performed a preliminary combined fit of appearance and disappearance data
- Add 4D likelihood surfaces: $(\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta_{CP})$
- Systematics are taken to be uncorrelated between analyses
- Normal hierarchy and upper octant disfavored at 81% C.L.

Disappearance Results

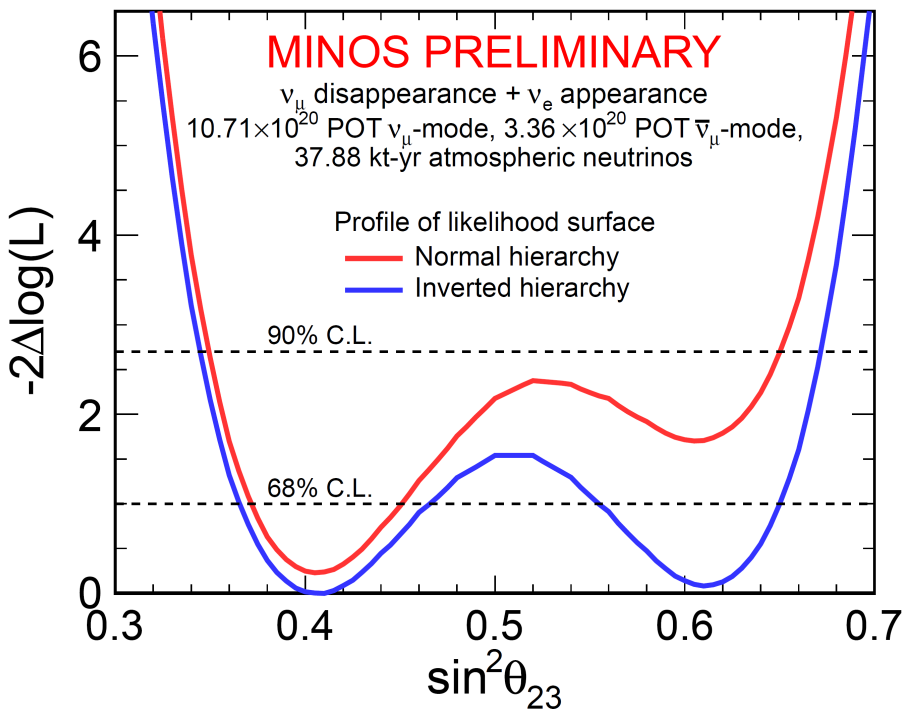
- Marginal preference for inverted hierarchy and upper octant

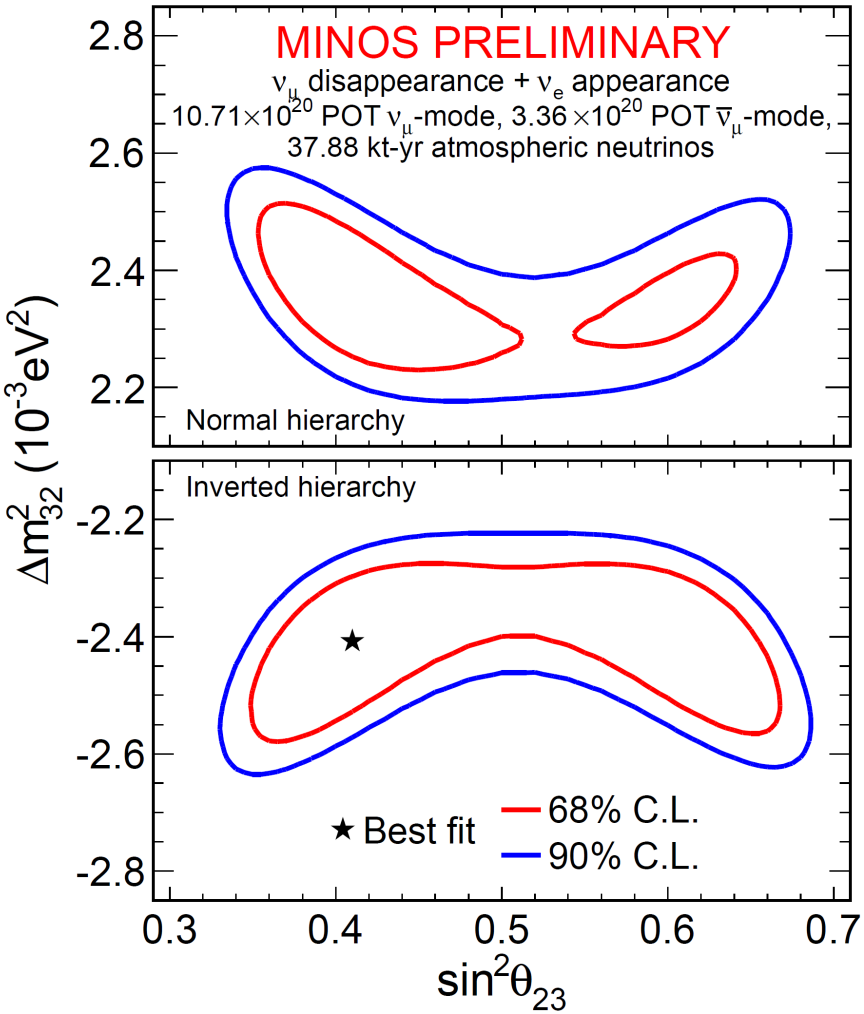




Combined Results

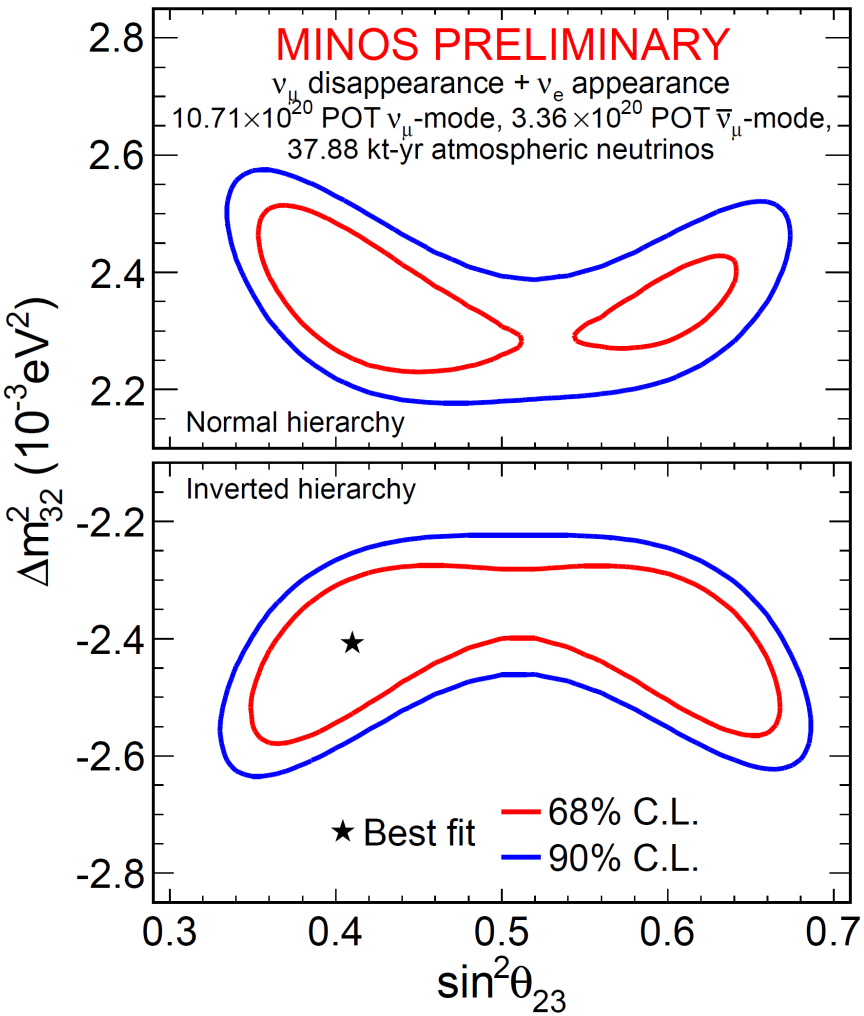
- Marginal preference for inverted hierarchy and lower octant



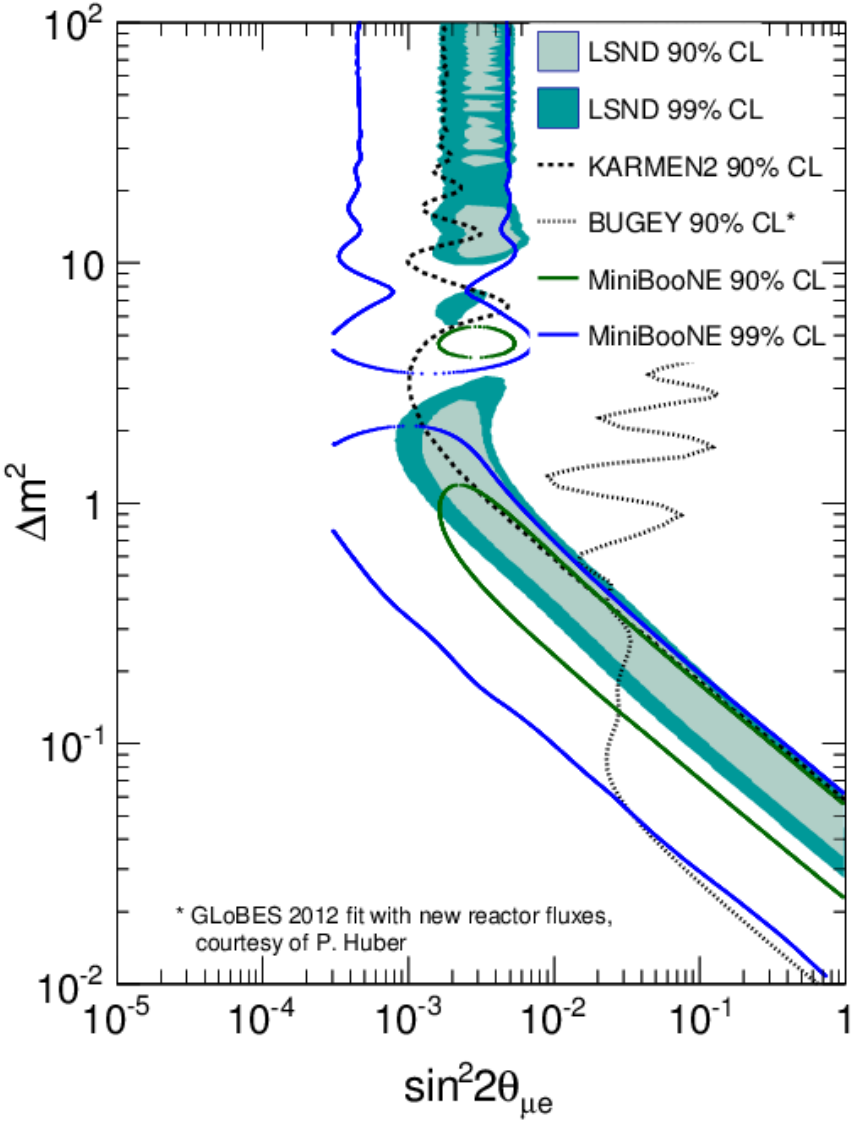


Combined Results

- Marginal preference for inverted hierarchy and lower octant
- Normal Hierarchy
  - $|\Delta m^2_{32}| = 2.37^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$
  - $0.35 < \sin^2\theta_{23} < 0.65$ at 90% C.L.
- Inverted Hierarchy
  - $|\Delta m^2_{32}| = 2.41^{+0.12}_{-0.09} \times 10^{-3}\text{eV}^2$
  - $0.34 < \sin^2\theta_{23} < 0.67$ at 90% C.L.



Sterile Neutrino Controversy



- LSND and MiniBooNE have seen $\nu_\mu \to \nu_e$ signals with $> 3\sigma$ at $L/E \sim 1$ km/GeV
- Possibly due to sterile neutrinos
- New mass splitting $\Delta m^2_{\oslash} \sim 1$ eV^2
- Conflicting with other experiments
- 4-flavor model:
  - $\sin^2(2\theta^{\oslash}_{\mu e}) \sim \sin^2(2\theta_{14}) \sin^2\theta_{24}$
  - $\sin^2(2\theta^{\oslash}_{ee}) \sim \sin^2(2\theta_{14})$
  - $\sin^2(2\theta^{\oslash}_{\mu\mu}) \sim \sin^2(2\theta_{24})$
- See Zarko's talk on Friday

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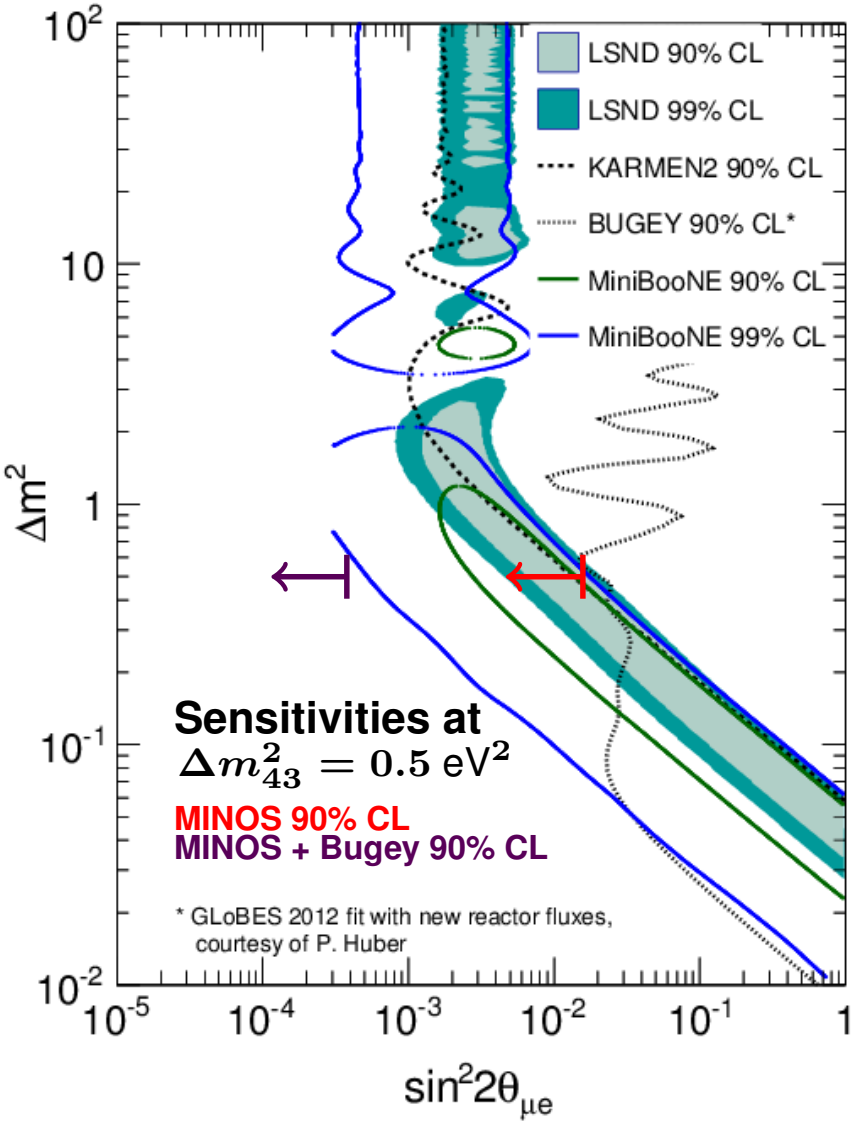

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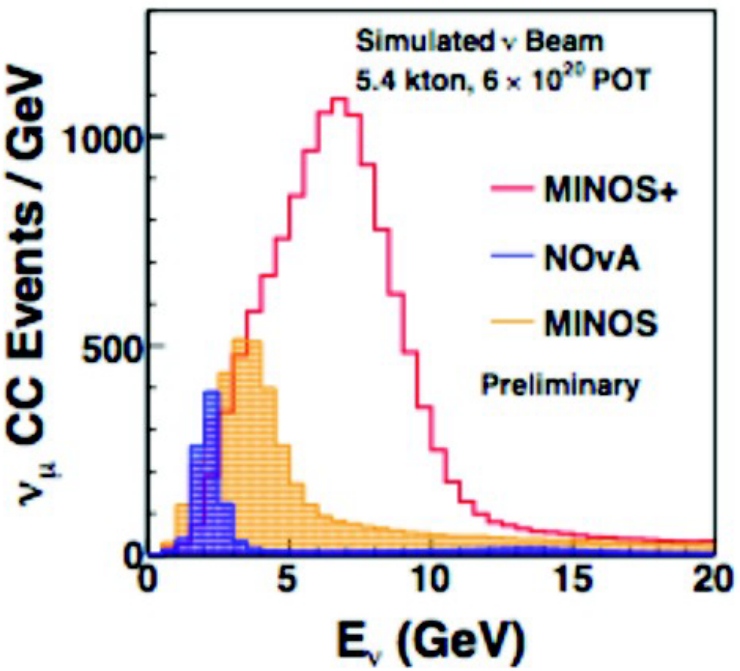
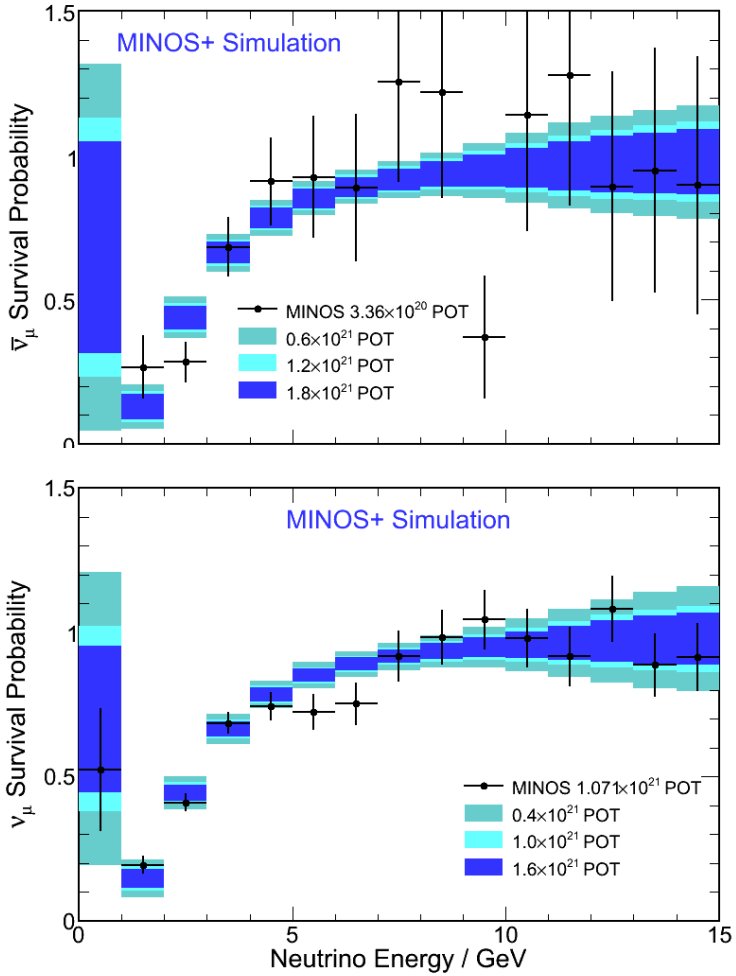
MINOS+



3000 events/year between 4-10 GeV

- **Higher energy neutrinos**
- **Broad spectrum to test three-flavor paradigm**
- More statistics, different energy, different systematics
- High statistics with neutrinos and anti-neutrinos
- Improved sensitivity to:
  - Sterile neutrinos
  - Extra-dimensions
  - Non-standard interactions
  - Decoherence
  - Decay

MINOS+



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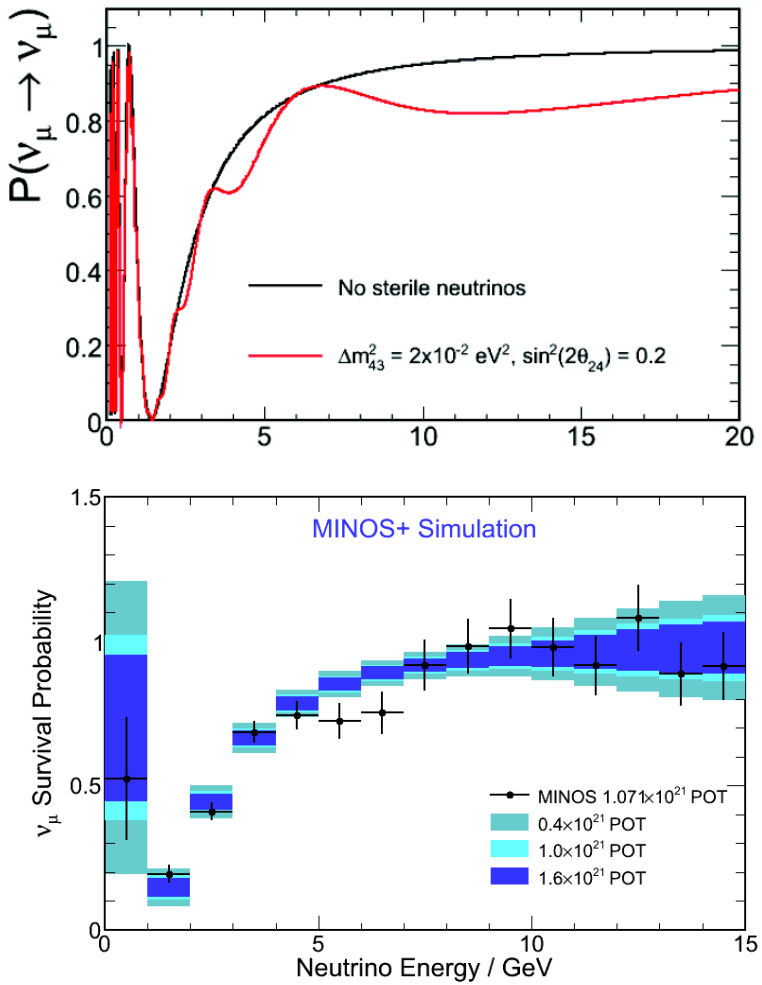

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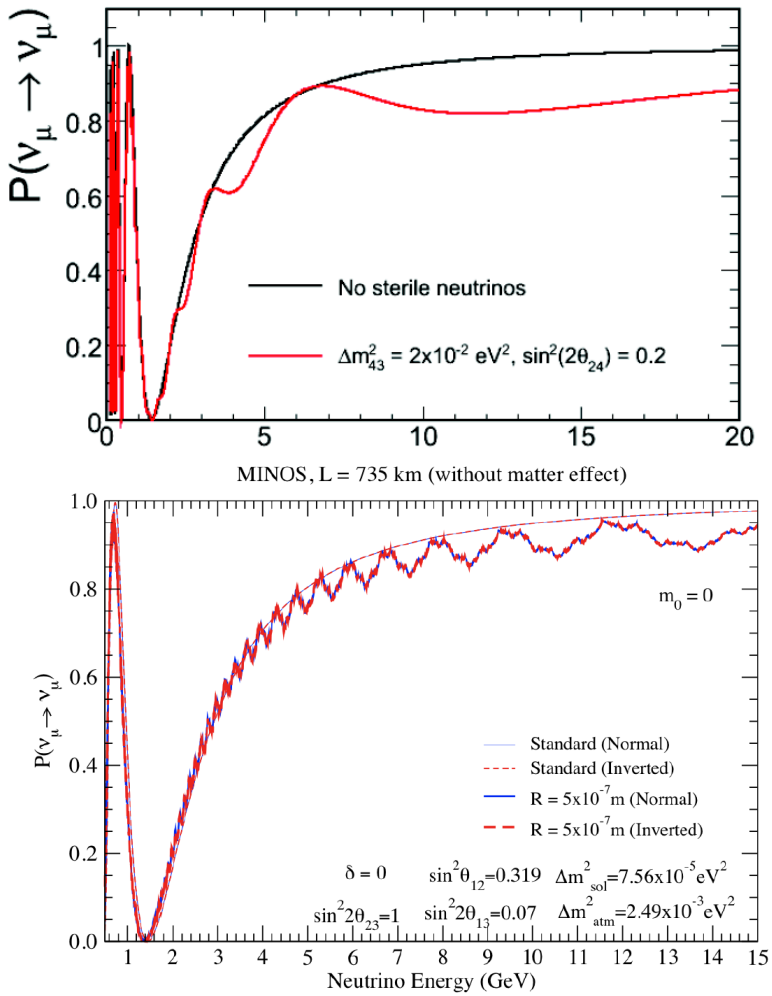

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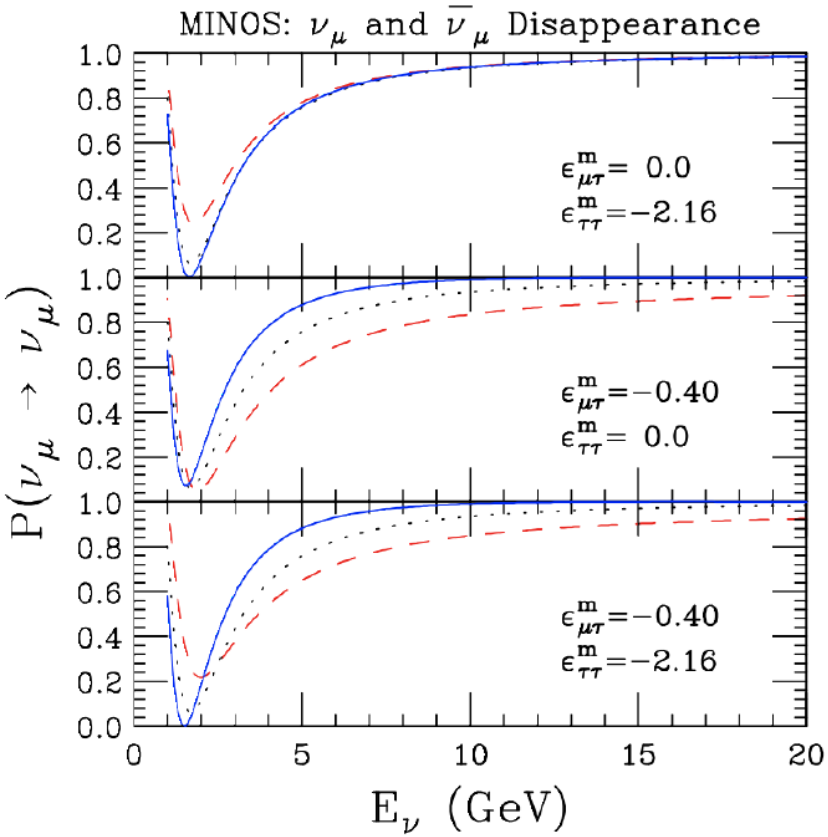

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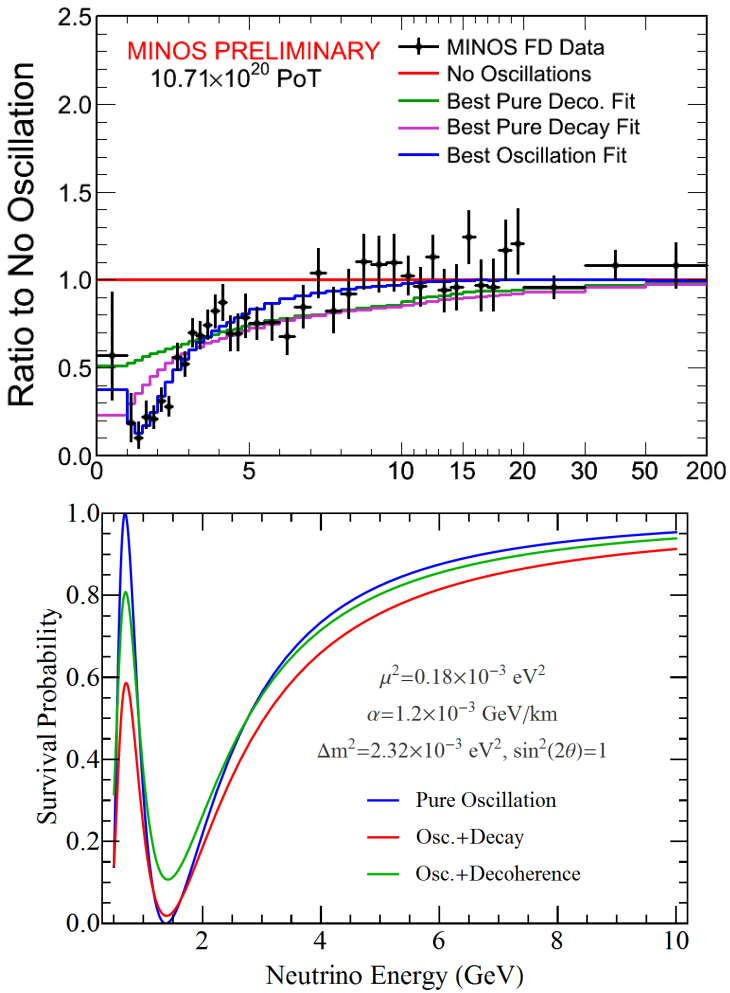

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Summary

- Updated results with full 3-flavor framework

	Parameter	Best fit	Confidence limits
Normal hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}\text{eV}^2$	2.37	$2.28 - 2.46$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.35 - 0.65$ (90% C.L.)
Inverted hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}\text{eV}^2$	2.41	$2.32 - 2.53$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.34 - 0.67$ (90% C.L.)

Preference for inverted hierarchy: $-2\Delta \log L = 0.23$

Preference for lower octant: $-2\Delta \log L = 0.09$

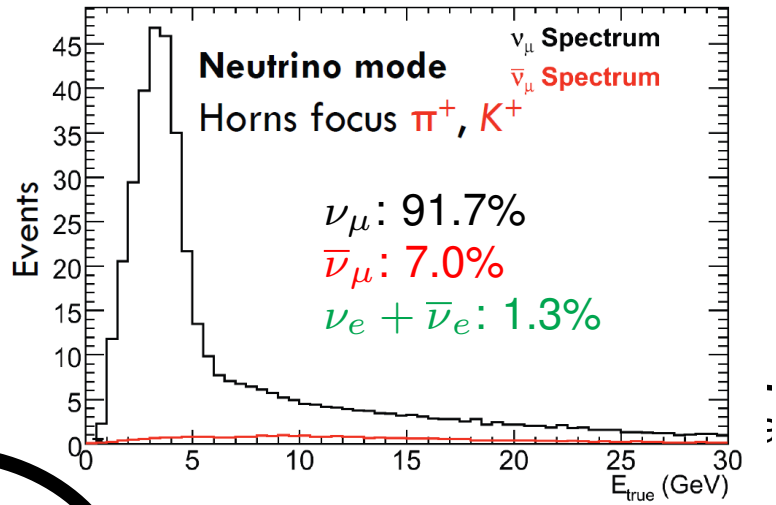
Exclusion of maximal mixing: $-2\Delta \log L = 1.54$ ($\Rightarrow$ 79% C.L.)

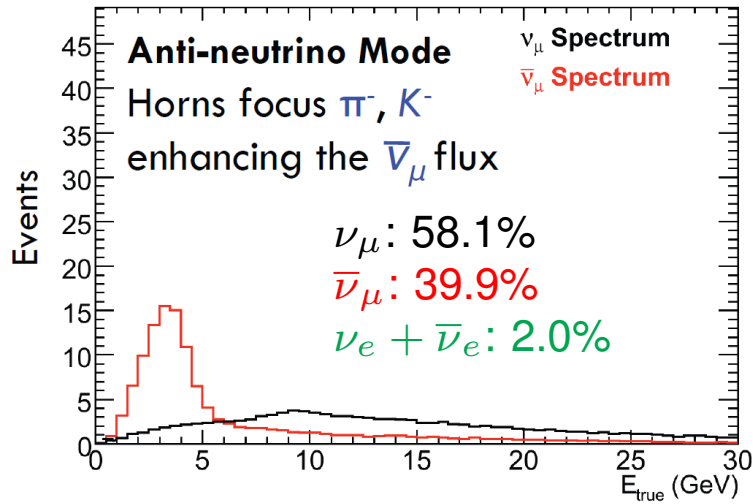
- MINOS+ will continue to test 3-flavor paradigm
- Sensitivity to alternative models in a broad range of energies
- With great statistics comes great responsibility

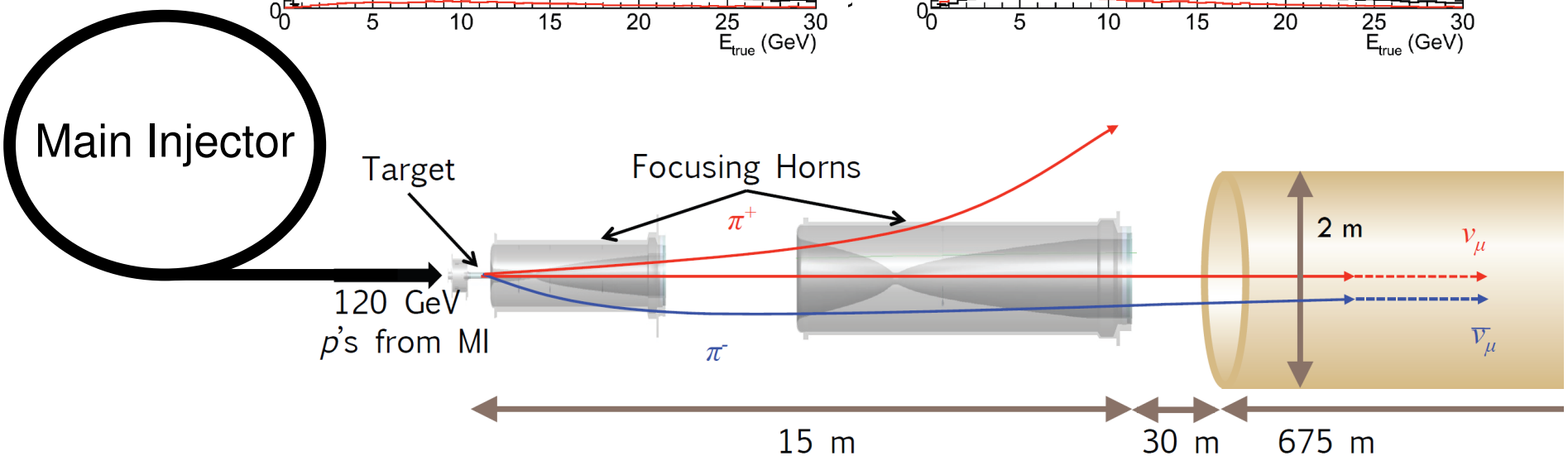
Thank you!

Backup Slides

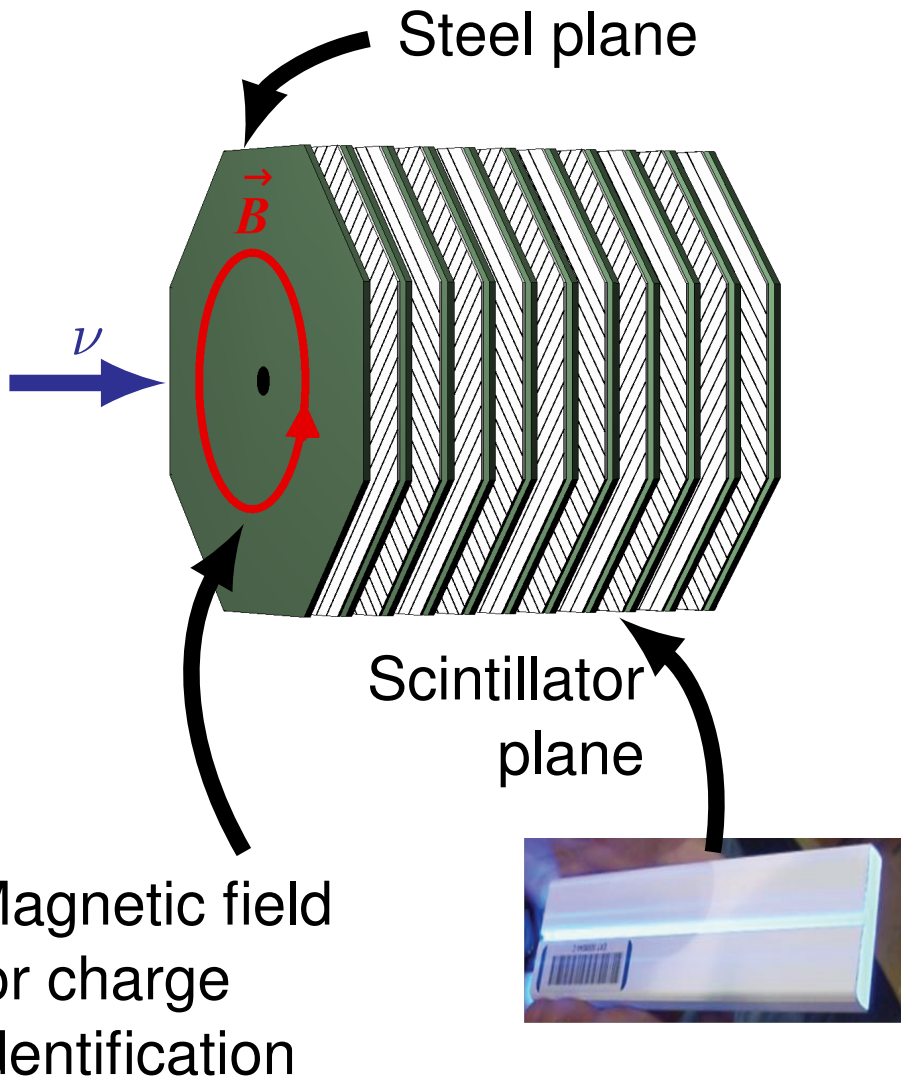
The NuMI beam

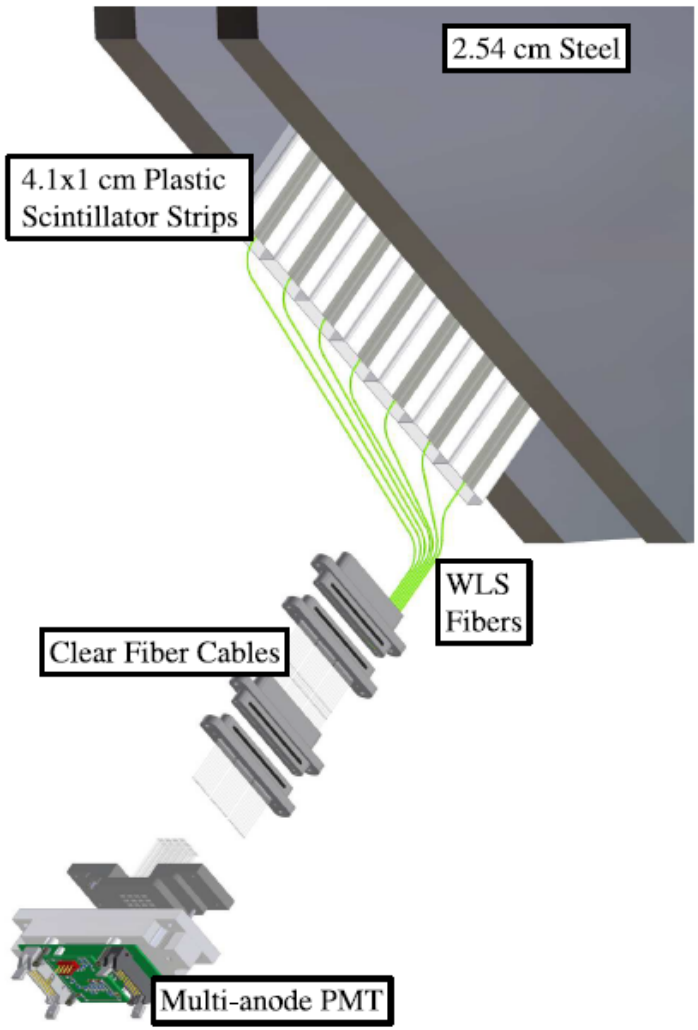






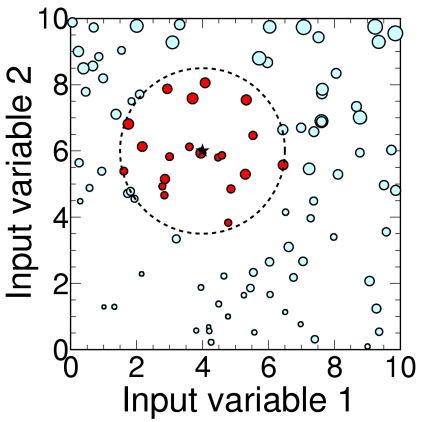
The MINOS detectors

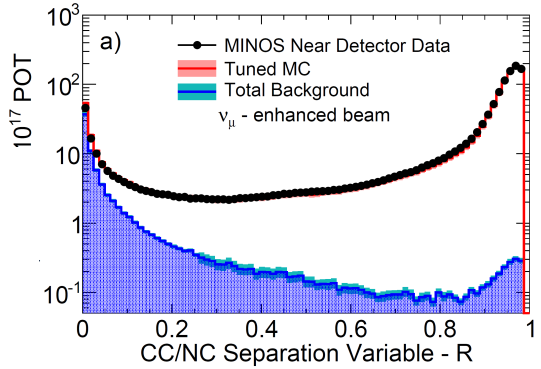


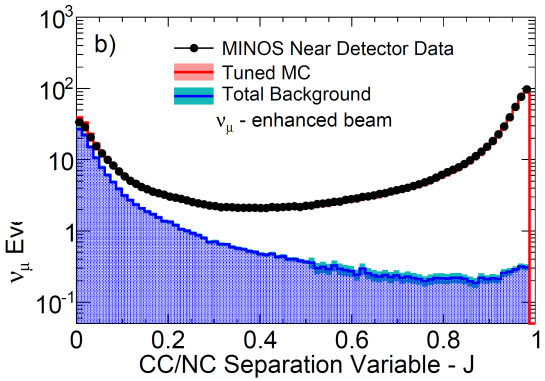


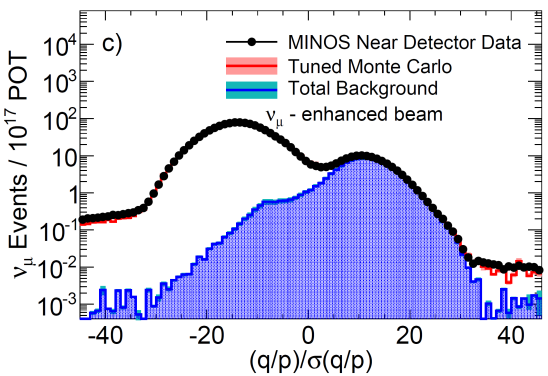
Beam ν_μ-CC selection

- R input variables
  - # of active planes
  - Mean PH per plane
  - PH fluctuation
  - Transverse profile
- J input variables
  - # of active planes
  - Track end PH
  - Scattering
- Select if $J > 0.5 \;||\; R > 0.25$
- Charge determined by curvature





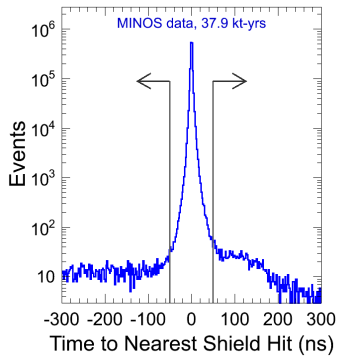


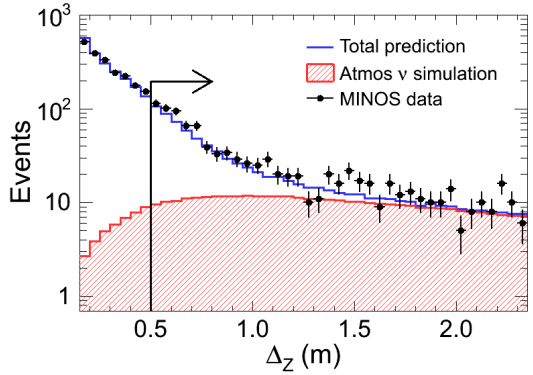


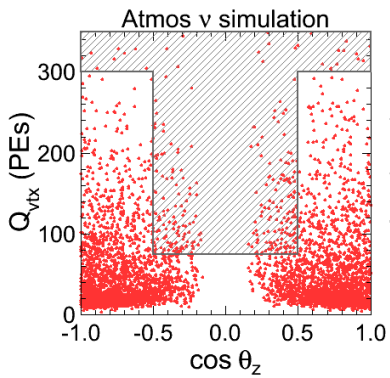
Atmospheric selection

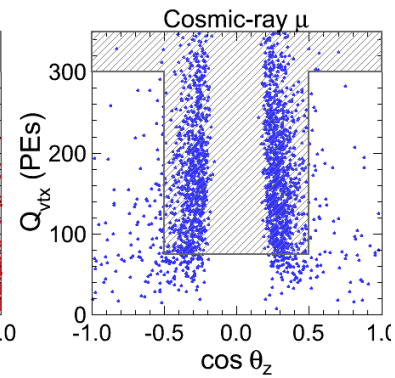
- Contained-vertex selection:
- Select events with long tracks (>8 planes)
- Use timing, direction and topology to remove cosmic rays
- Background reduced by a factor of 10^7

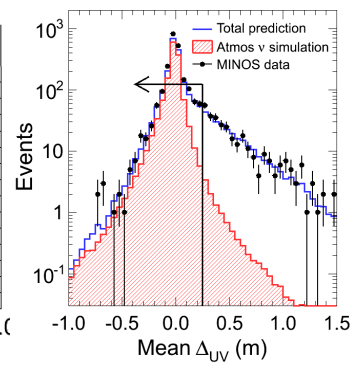
- Also included samples of shower-like events and rock-induced events from up-going and horizontal muons

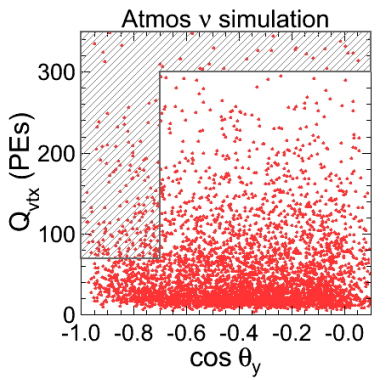


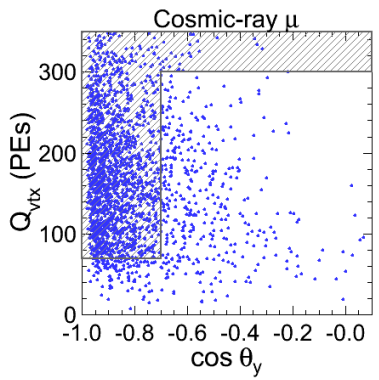


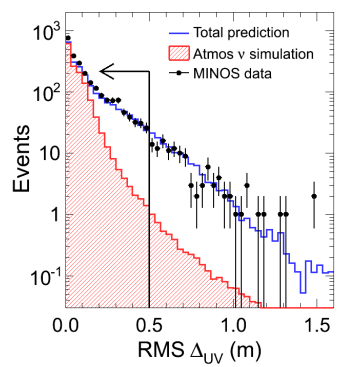








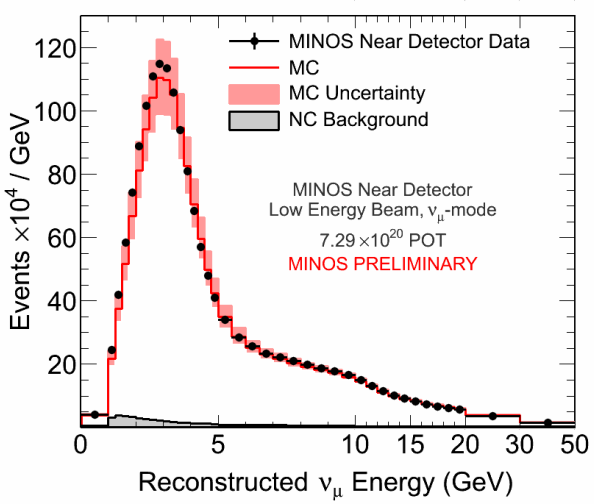


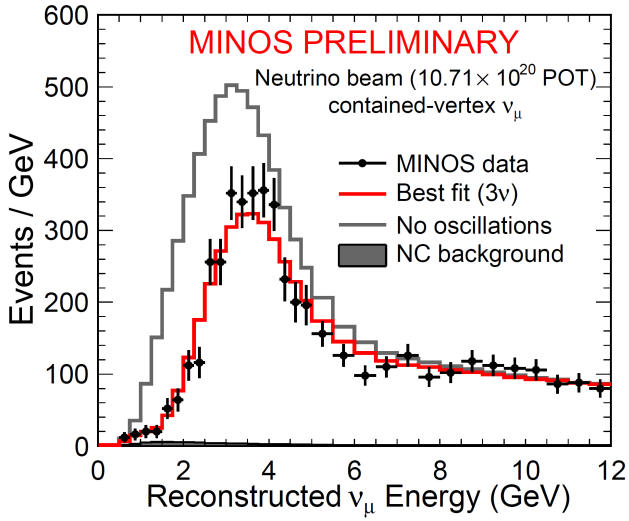


Disappearance Event Samples

Data Set	Simulation No osc.	Simulation With osc.	Events Observed
ν_μ from ν_μ beam	3201	2543	2579
$\bar{\nu}_\mu$ from ν_μ beam	363	324	312
Non-fiducial μ from ν_μ beam	3197	2862	2911
$\bar{\nu}_\mu$ from $\bar{\nu}_\mu$ beam	313	227	226
Atm. contained-vertex $\nu_\mu + \bar{\nu}_\mu$	1100	881	905
Atm. non-fiducial $\mu^- + \mu^+$	570	467	466
Atm. showers	727	724	701

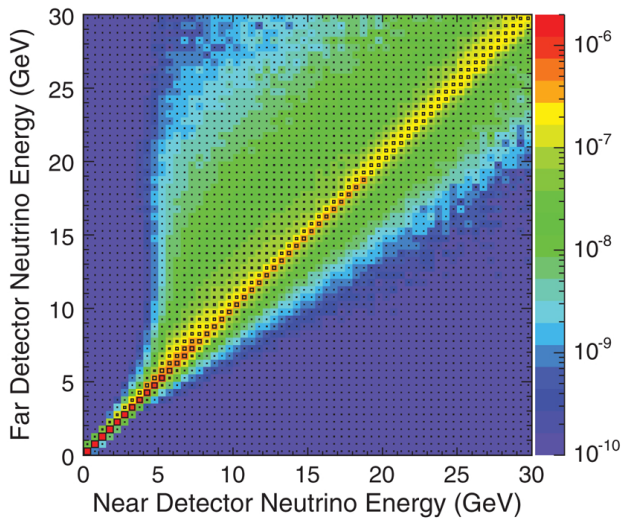
Extrapolation





Unfold

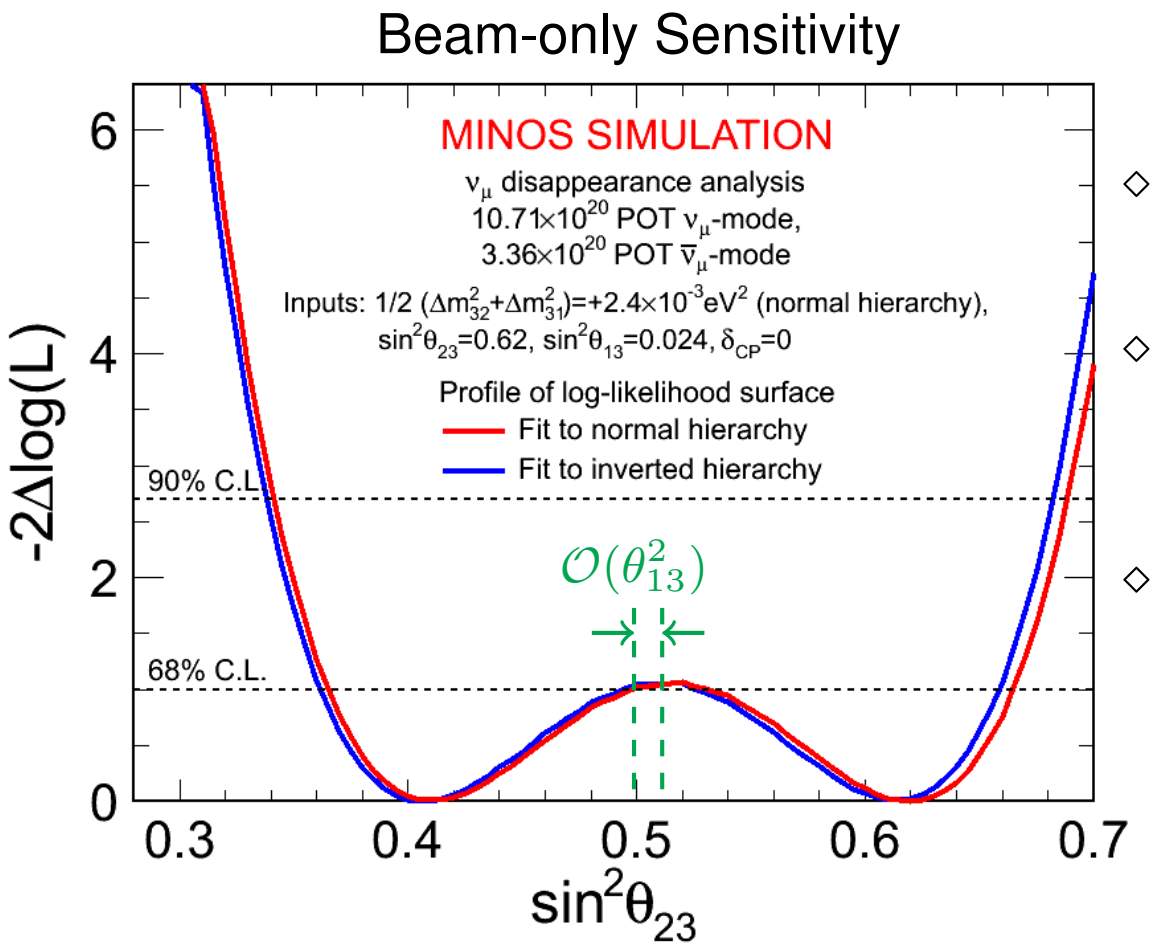
ND flux



Fold

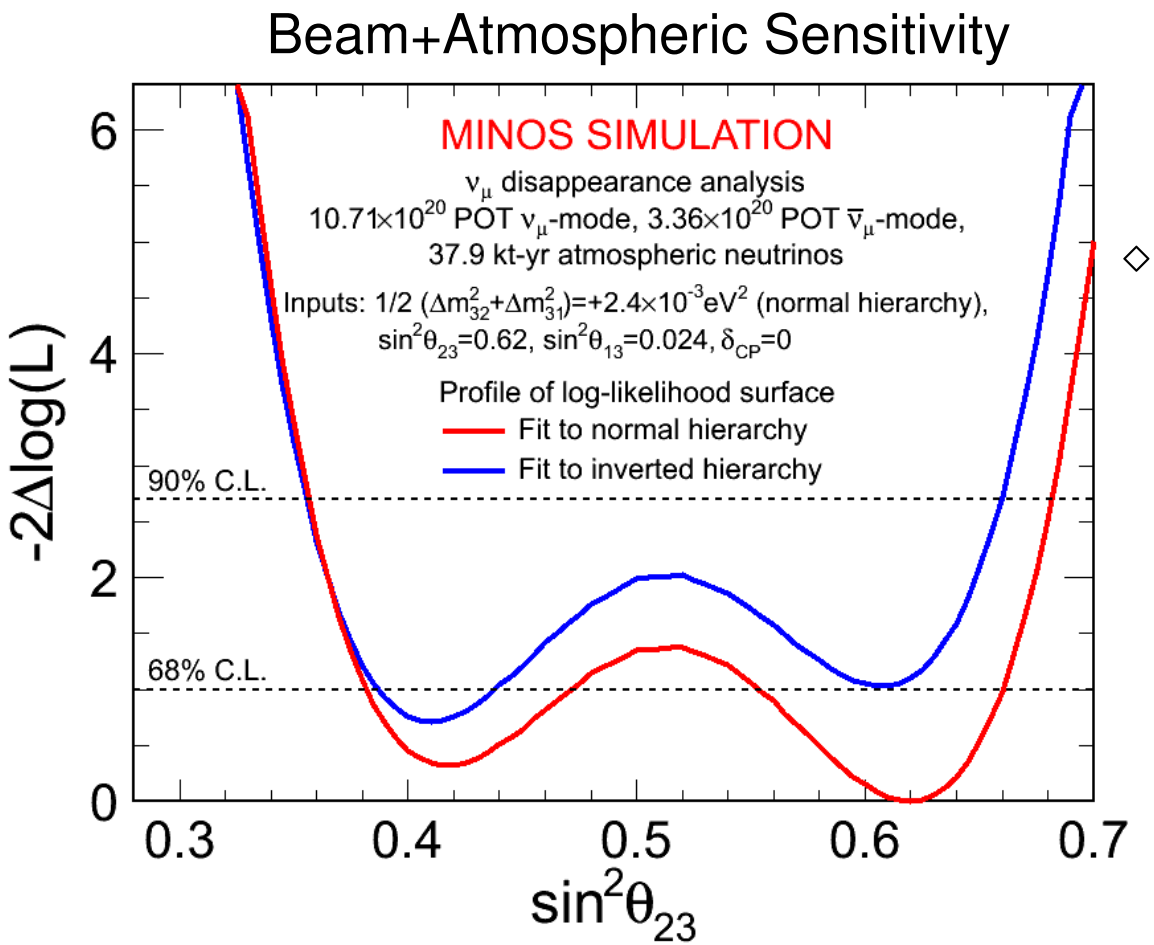
FD flux prediction

Sensitivities



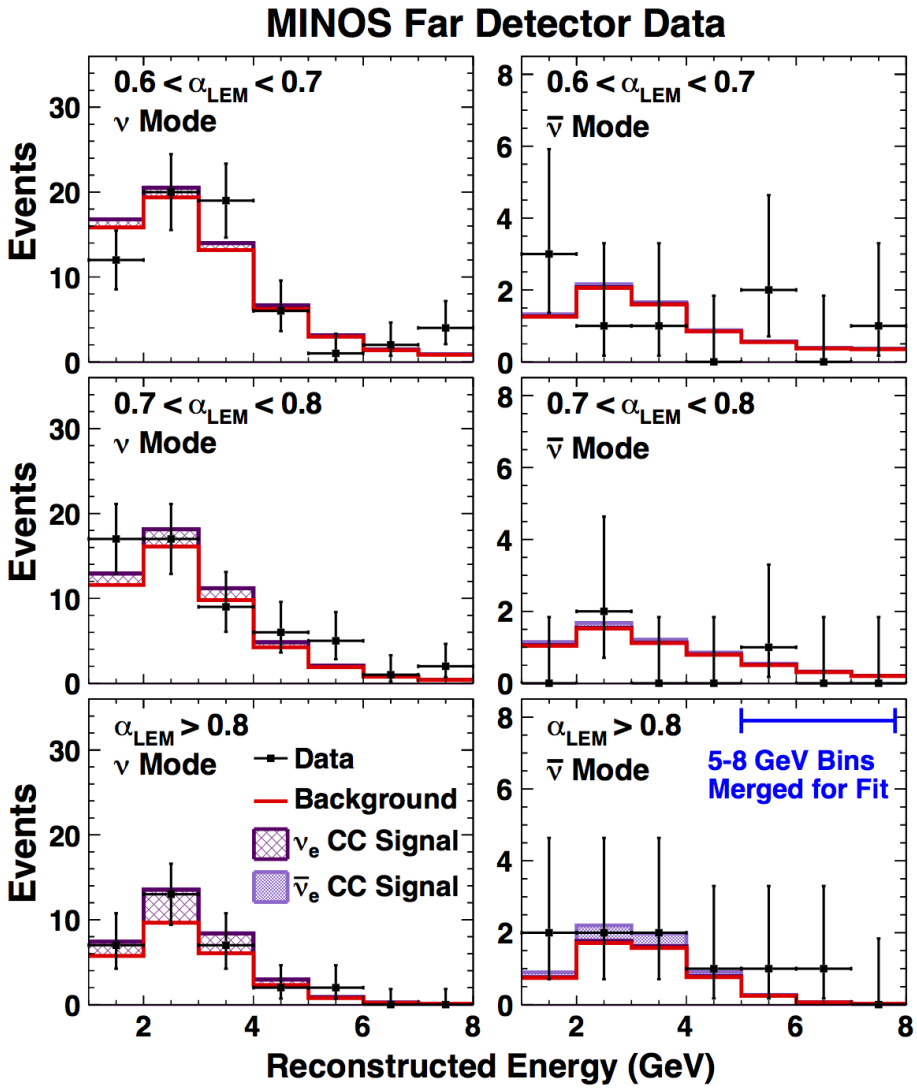
- $\sin^2\theta_{\mu\mu} = \sin^2\theta_{23}\cos^2\theta_{13}$
- Oscillation maximum: $\theta_{\mu\mu} = \pi/4 \neq \theta_{23}$
- No octant discrimination from beam neutrinos

Sensitivities



- Some sensitivity to octant and mass hierarchy by including atmospheric neutrinos

Appearance Spectra



Systematics