Three and four-flavor neutrino oscillation results from MINOS

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for the MINOS Collaboration

Tufts University

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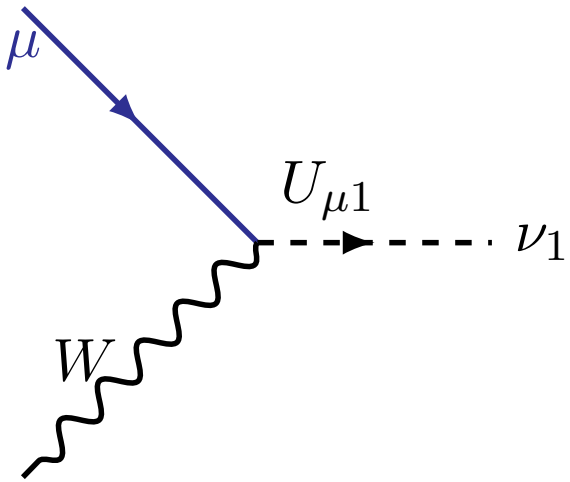
Outline

- ◇ Neutrino oscillations
- ◇ MINOS overview
- ◇ New 3ν results
- ◇ New 4ν results
- ◇ Summary

Neutrino Oscillations



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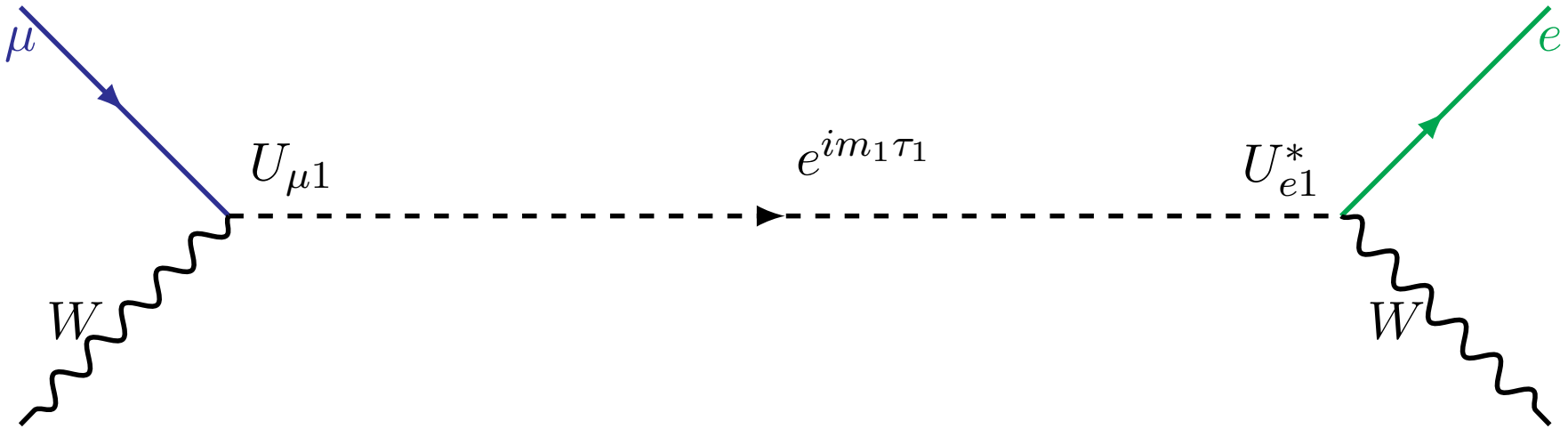

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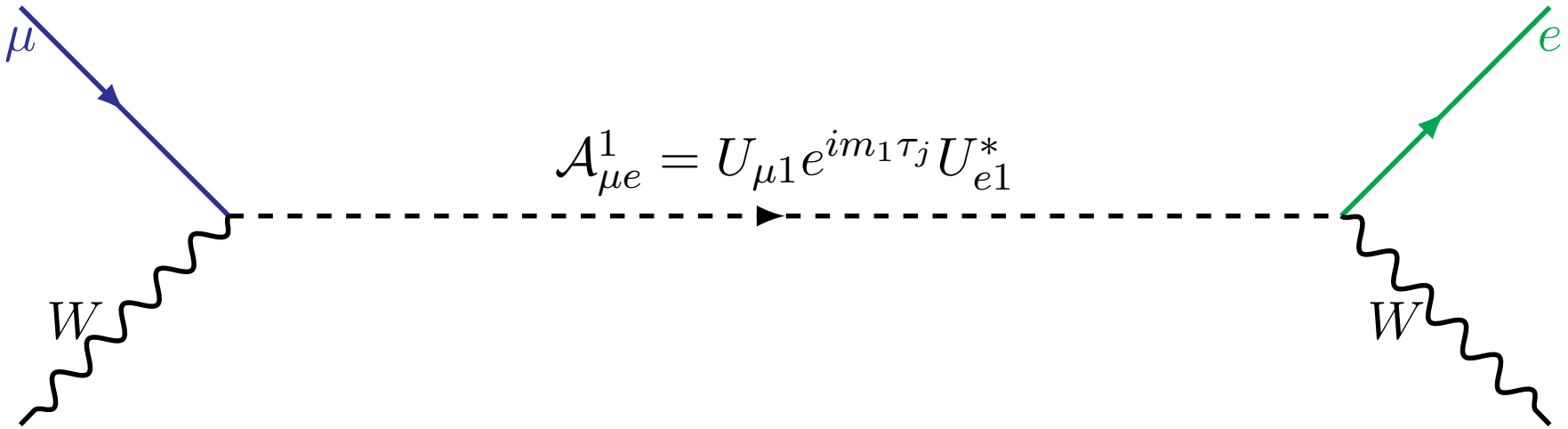

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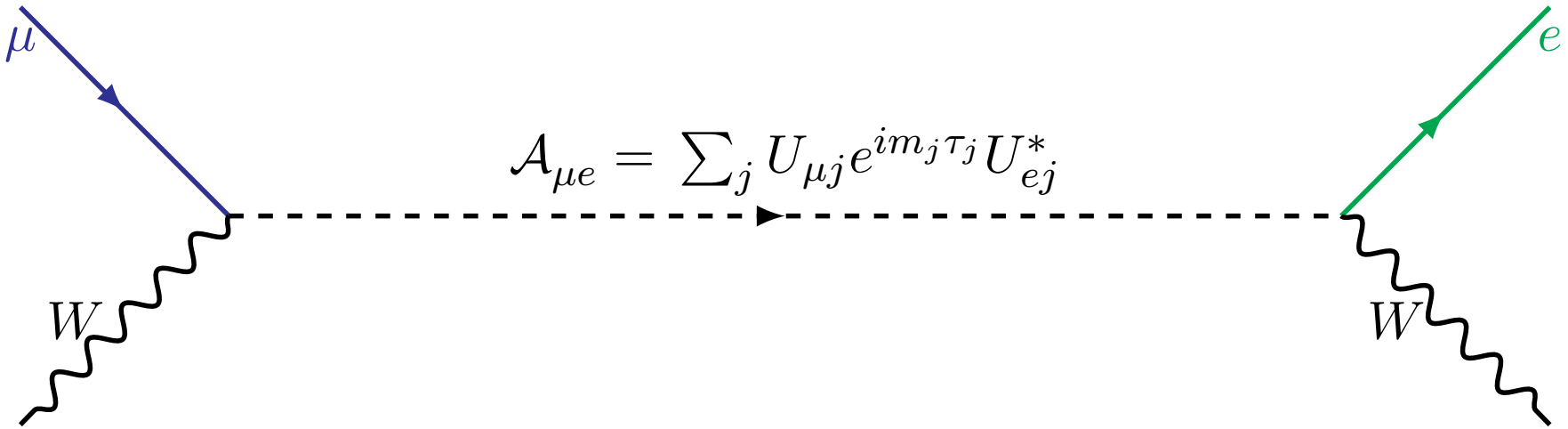

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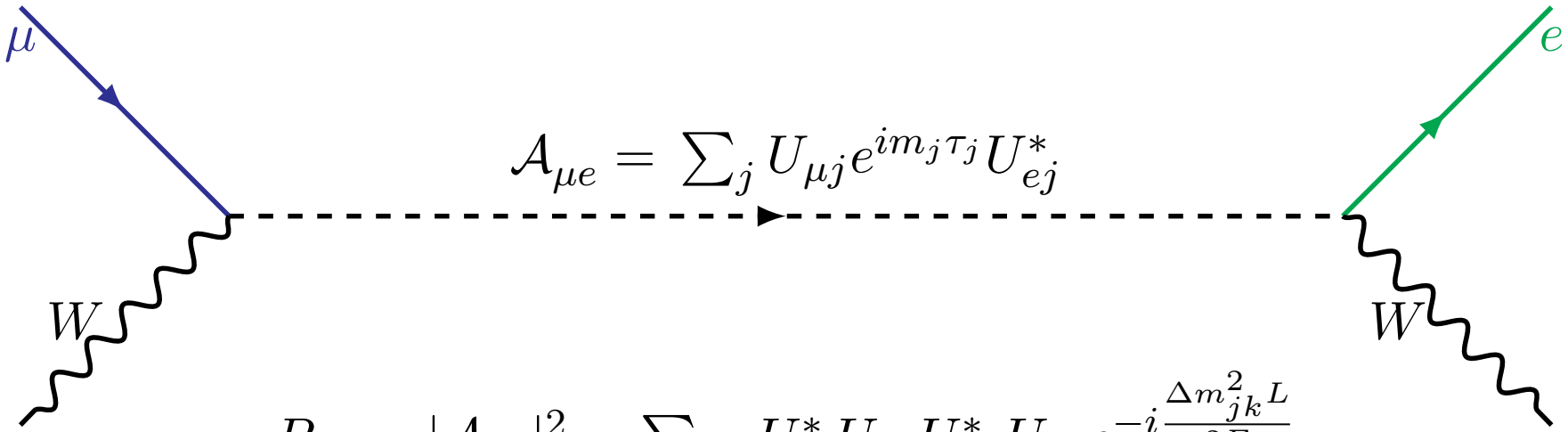
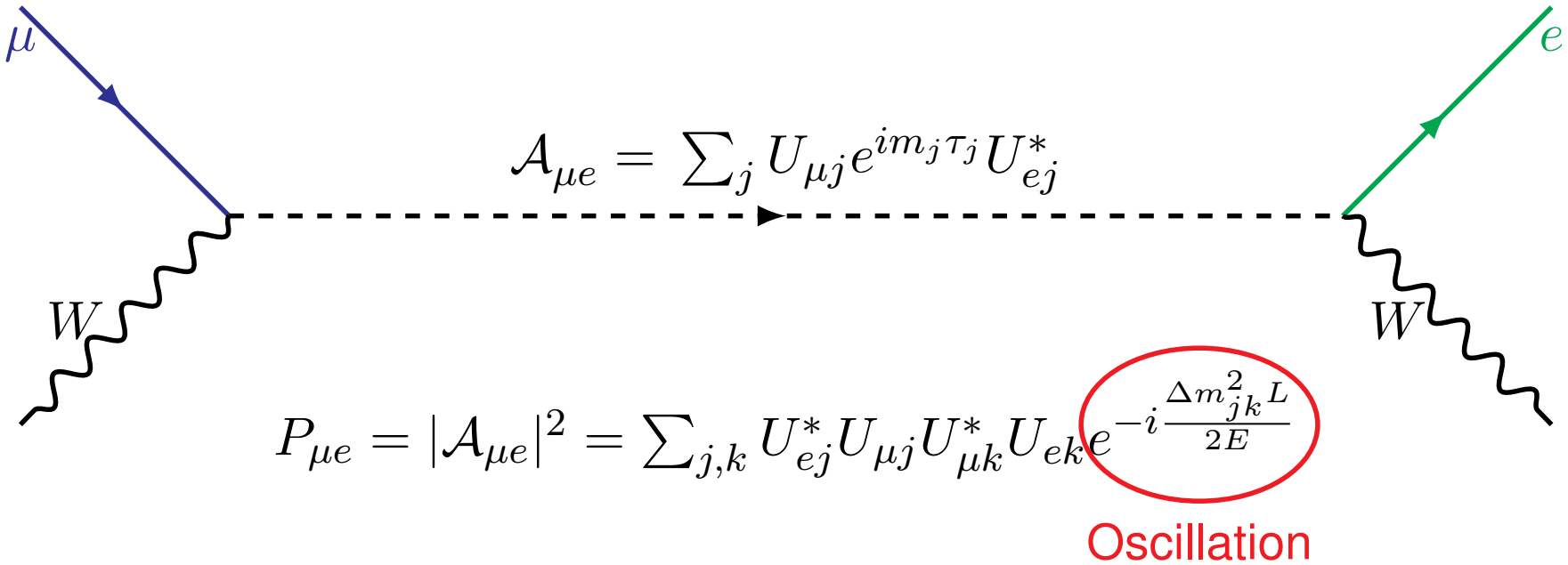


$$\mathcal{A}_{\mu e} = \sum_j U_{\mu j} e^{i m_j \tau_j} U^*_{ej}$$

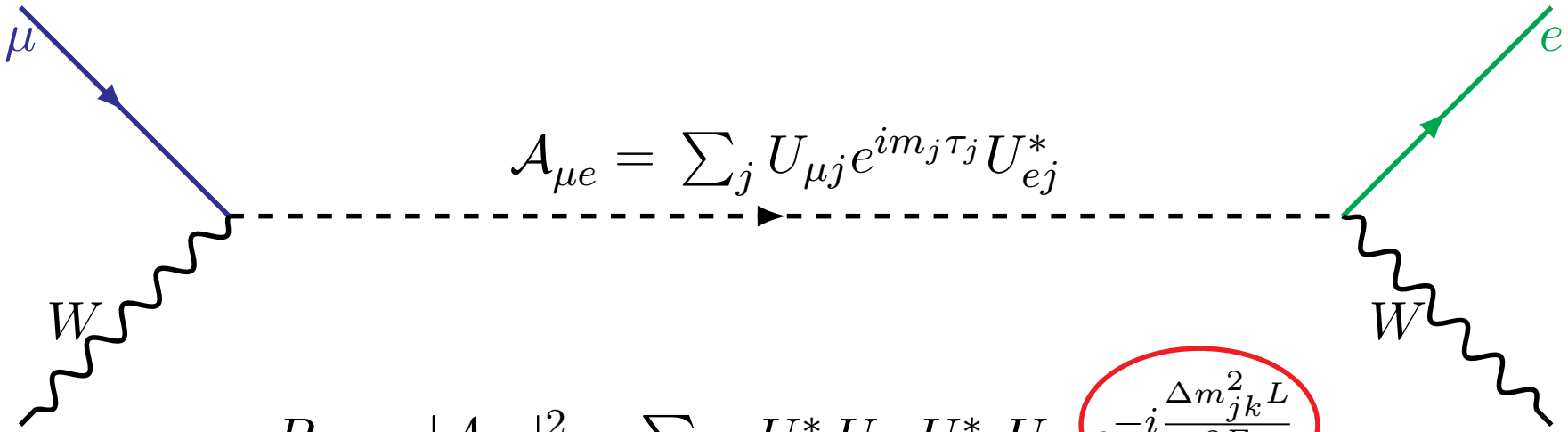
$$P_{\mu e} = |\mathcal{A}_{\mu e}|^2 = \sum_{j,k} U^*_{ej} U_{\mu j} U^*_{\mu k} U_{ek} e^{-i \frac{\Delta m^2_{jk} L}{2E}}$$

Neutrino Oscillations



Neutrino Oscillations

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{23} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



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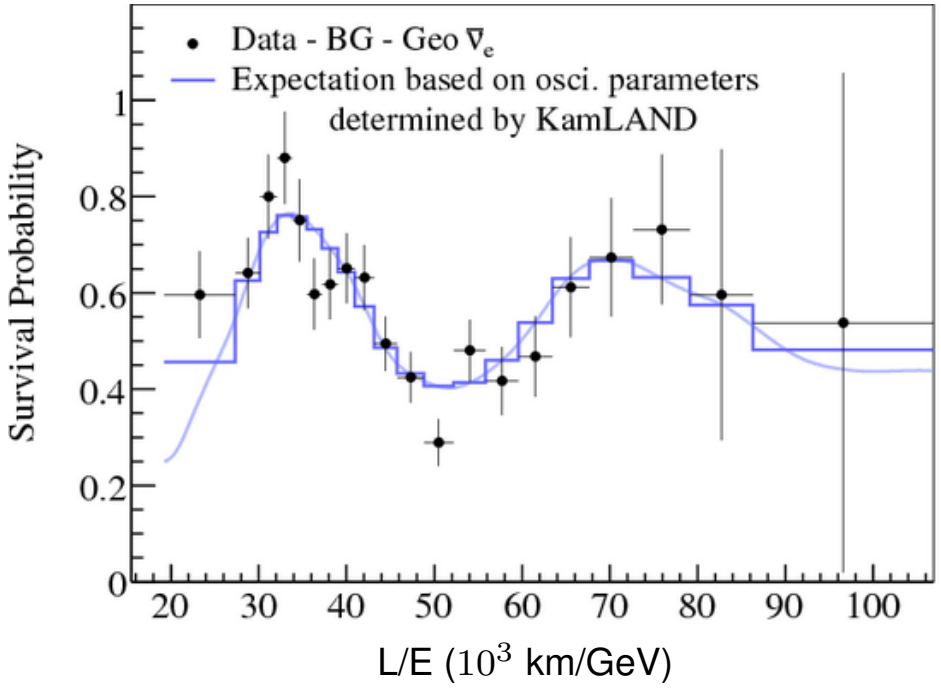
Oscillation

$U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$

In general: $n(n-1)/2$ angles and $(n-1)(n-2)/2$ phases

Two-flavor approximation

Reactor $\overline{\nu}_e$



$$\Delta m^2_{\odot} \sim 7.5 \times 10^{-5} \text{eV}^2$$

Two-flavor approximation

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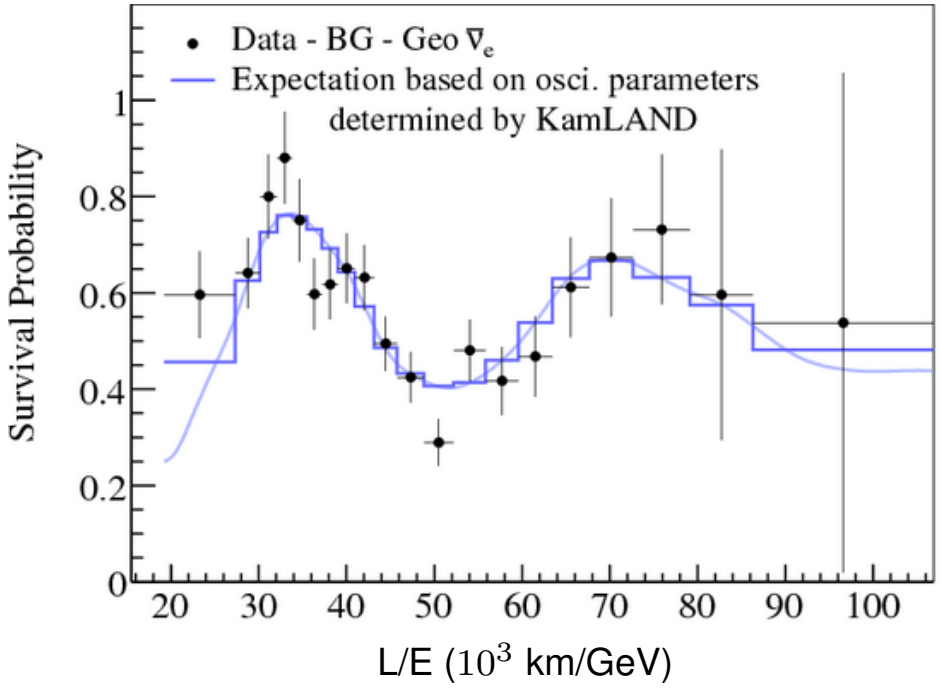
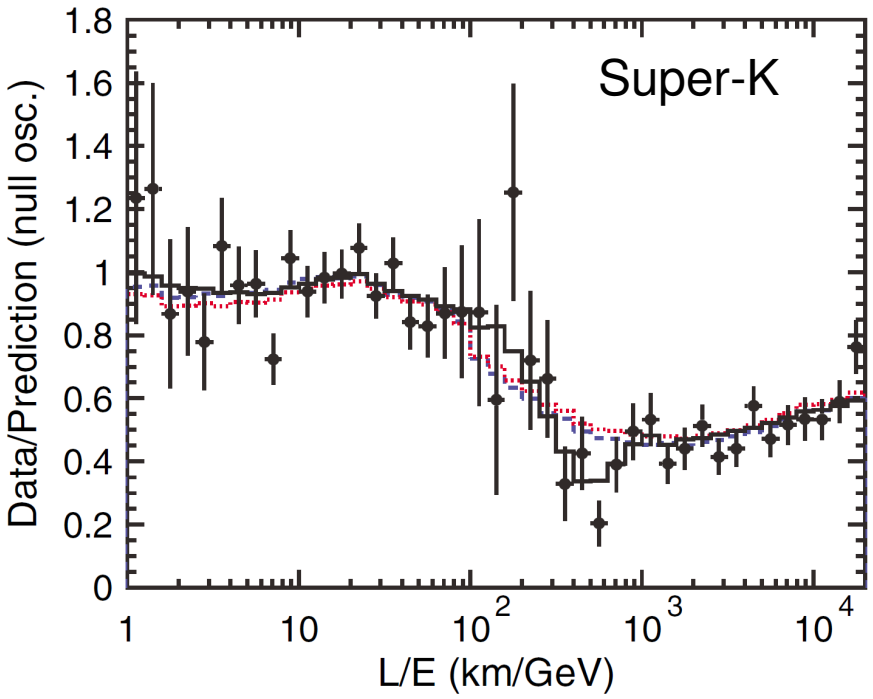


Atmospheric ν_μ



$$\Delta m^2_\odot \sim 7.5 \times 10^{-5}\text{eV}^2$$

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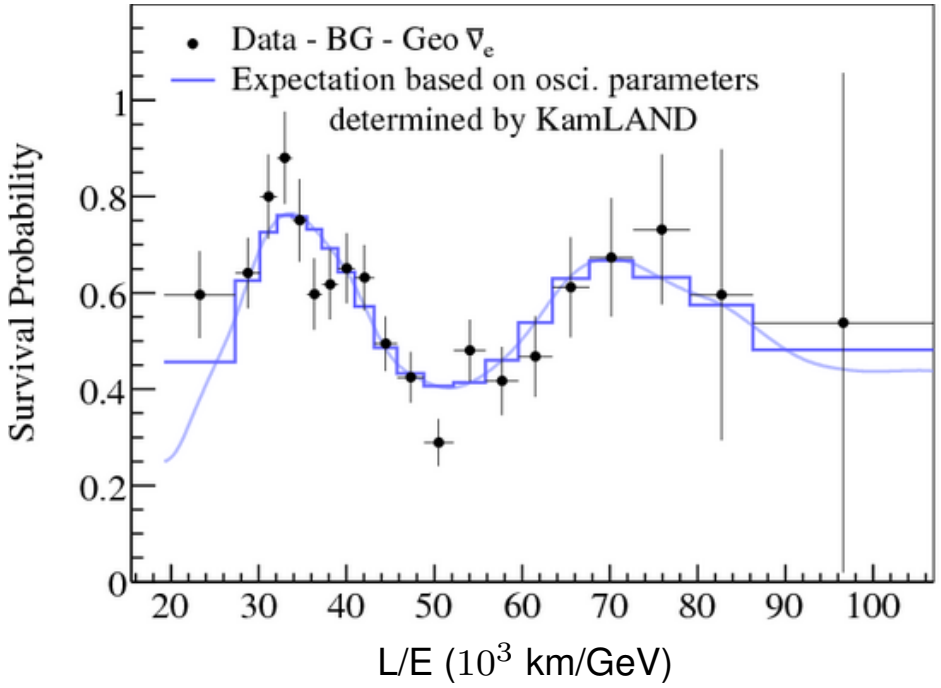

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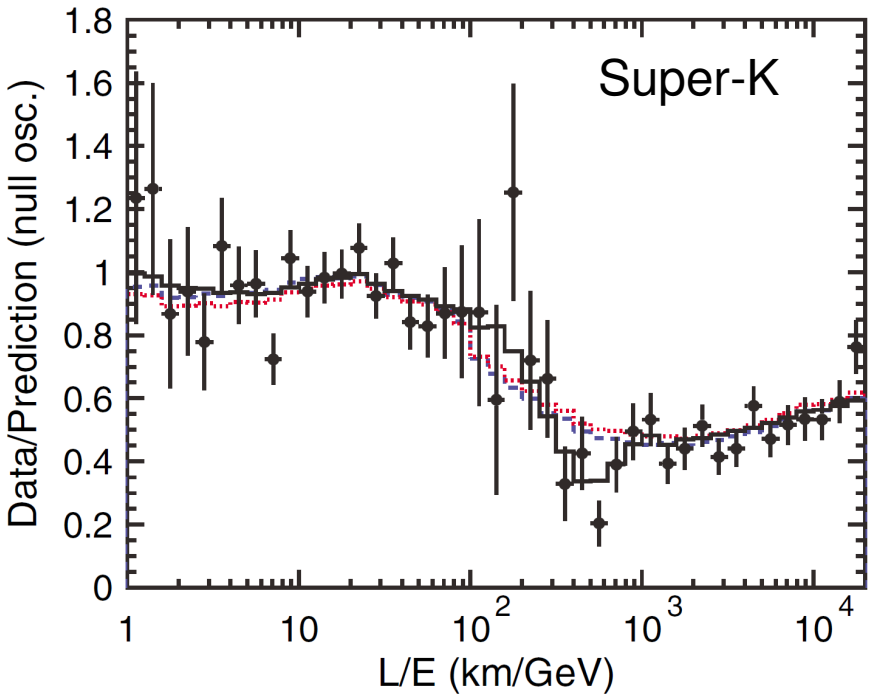

$$\Delta m^2_\odot \sim 7.5 \times 10^{-5}\text{eV}^2 \qquad \Delta m^2_\oplus \sim 2.5 \times 10^{-3}\text{eV}^2$$

$$L/E \ll 10^4 \text{ km/GeV}$$

$$\mathcal{P}_{\alpha\beta} = \delta_{\alpha\beta} \pm \sin^2(2\theta^\oplus_{\alpha\beta}) \sin^2(1.27\Delta m^2_{\alpha\beta} L/E) + \mathcal{O}(\Delta m^2_\odot L/E)^2$$

Two-flavor approximation

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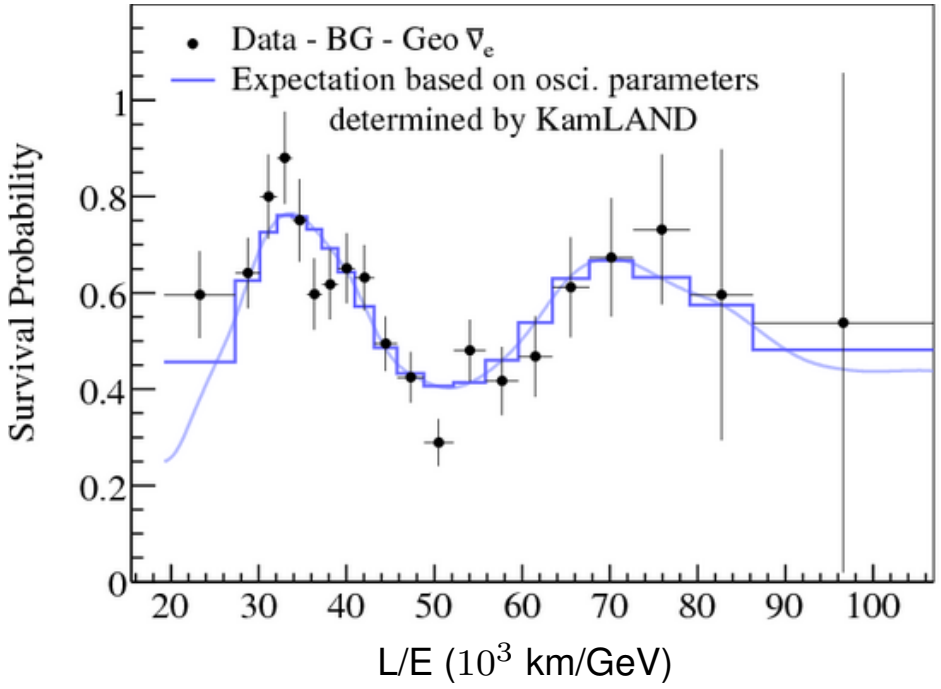

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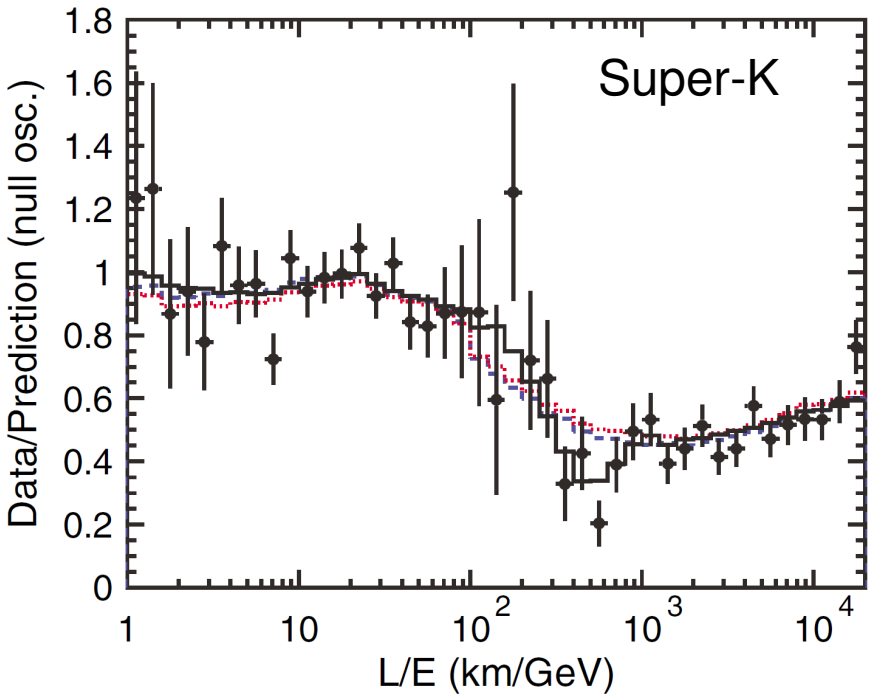

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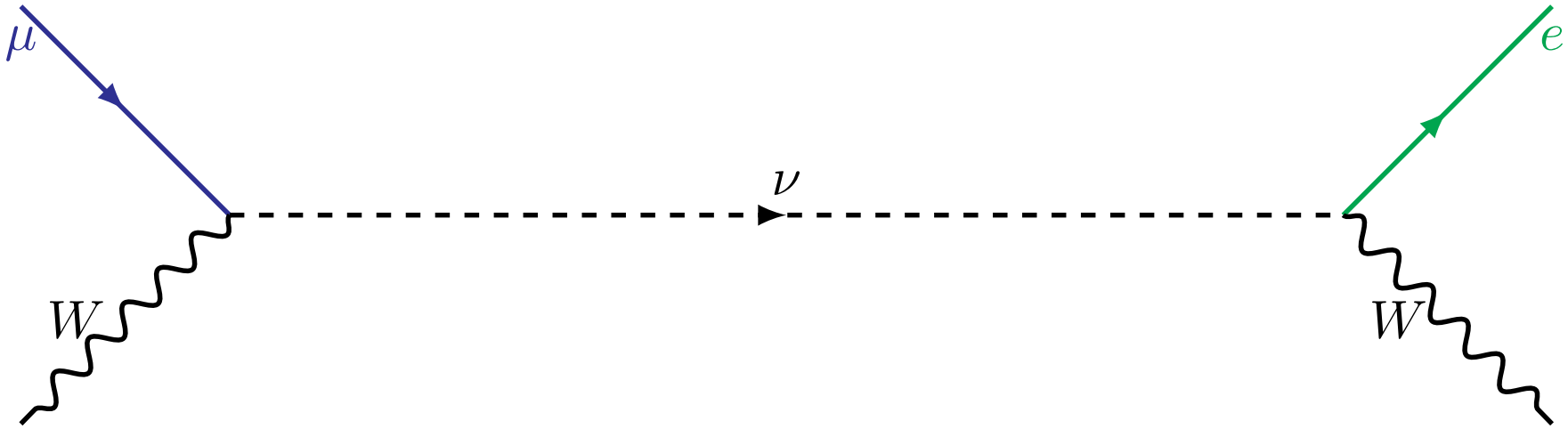
$$L/E \gtrsim 10^4 \text{ km/GeV}$$

$$\mathcal{P}_{\alpha\beta} \approx \delta_{\alpha\beta} \pm [\mathcal{C}^{\oplus}_{\alpha\beta} + \sin^2(2\theta^{\odot}_{\alpha\beta})\sin^2(1.27\Delta m^2_\odot L/E)]$$

Matter Effects



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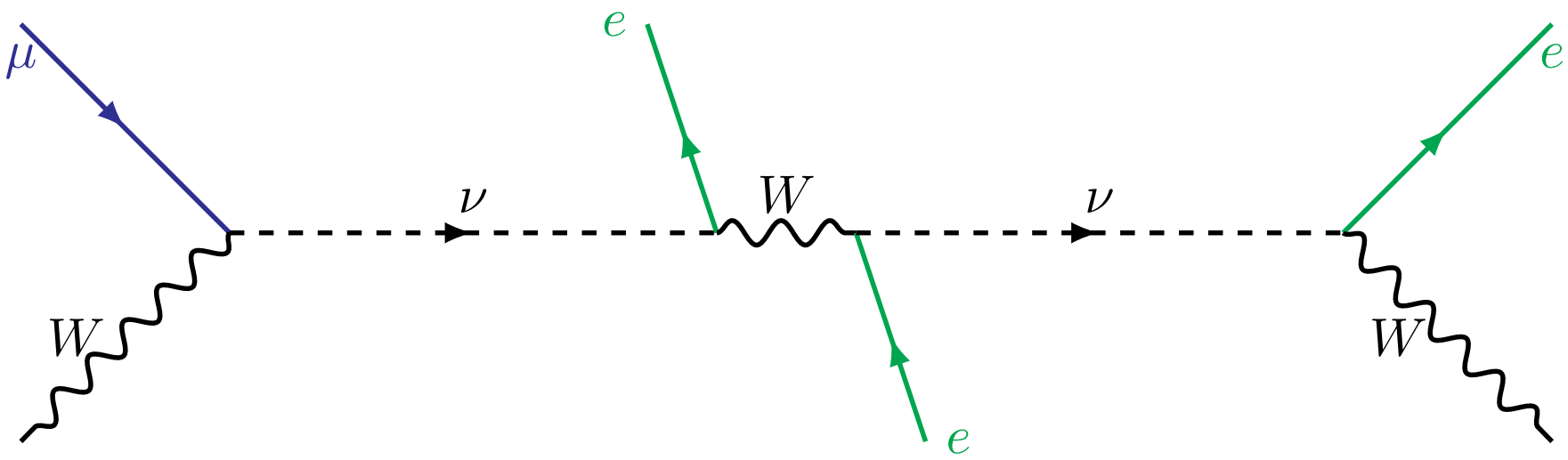
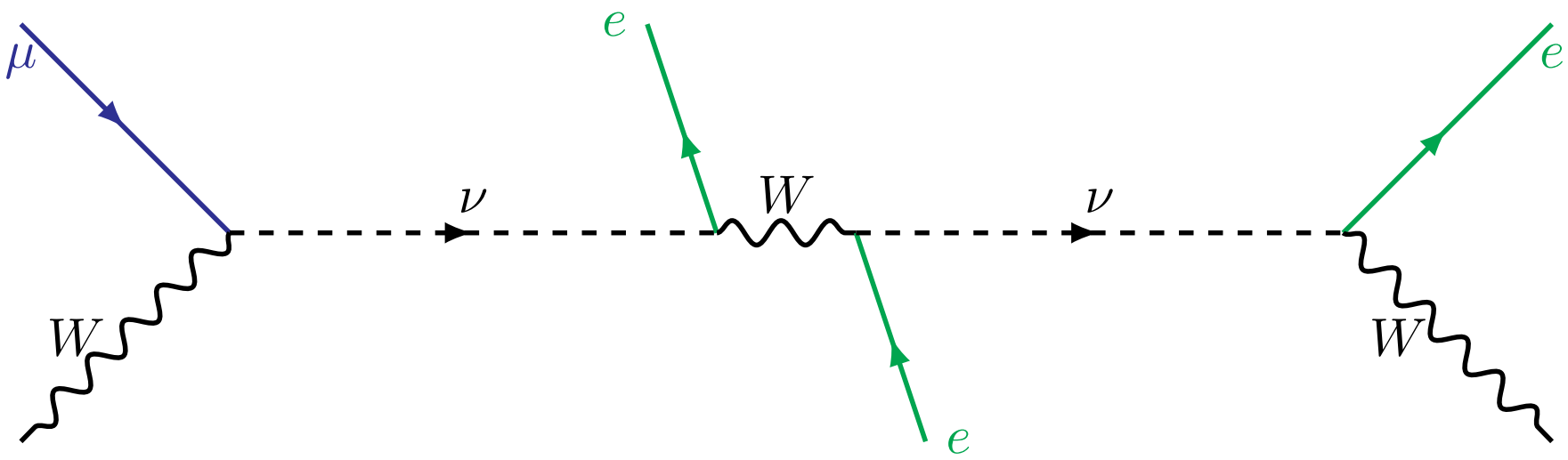


Matter Effects

$$H_{eff} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger \pm \sqrt{2} G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



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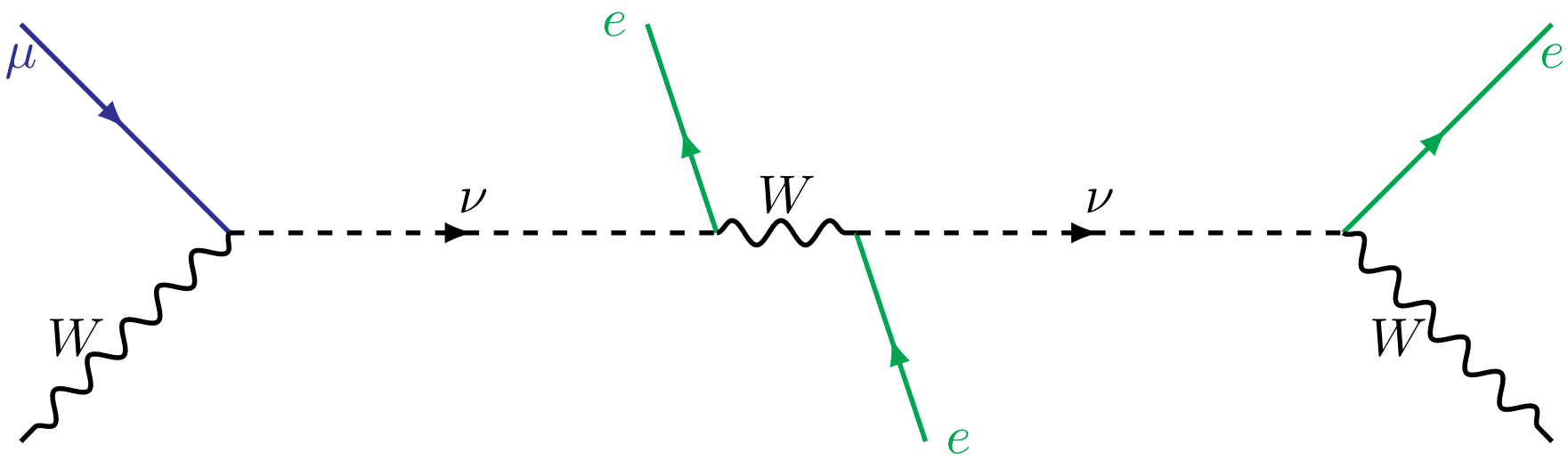
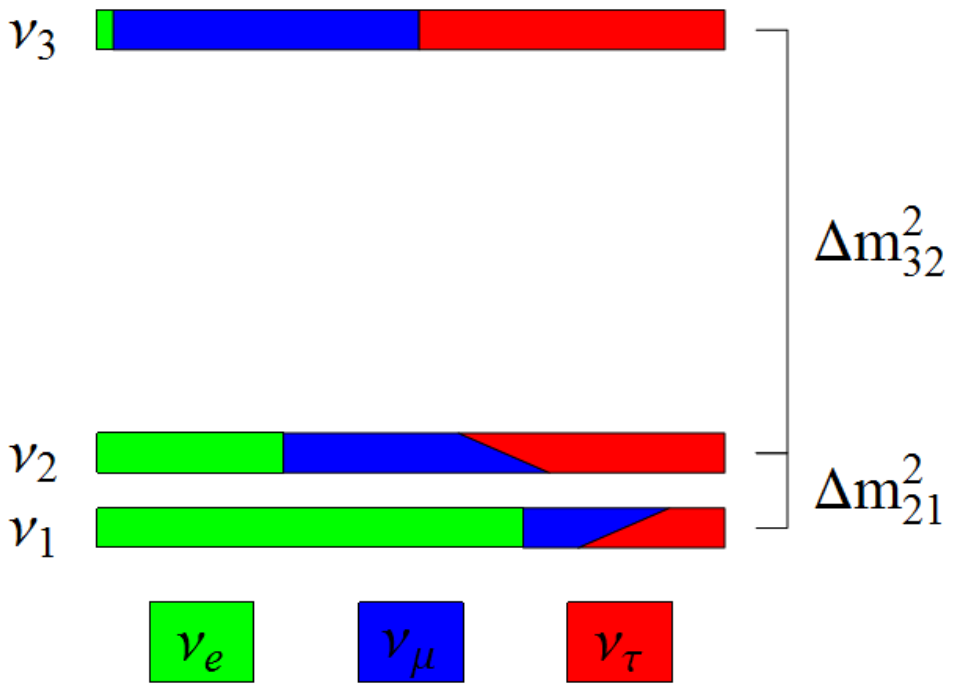


- Relevant when $\sqrt{2} G_F N_e \gtrsim \frac{\Delta m^2}{2E}$
- In Earth, $\sqrt{2} G_F N_e \sim 1/(1500 \pm 500$ km$)$
- Comparable to $\frac{\Delta m^2_{31}}{2E}$ for $E \sim 10$GeV

What we know



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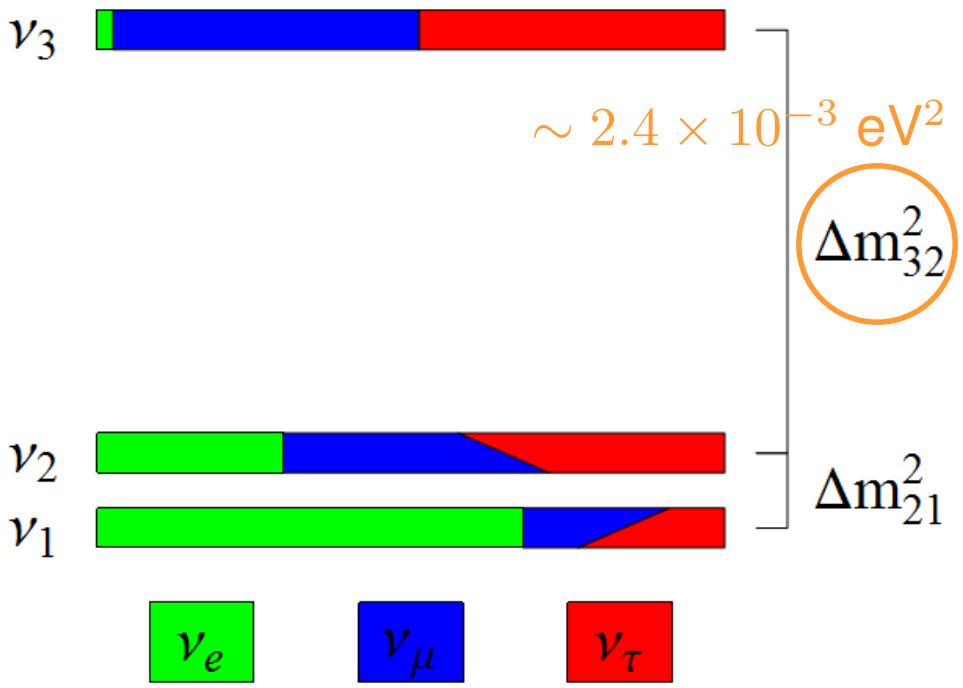

MINOS 2ν:
$|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3}$ eV^2

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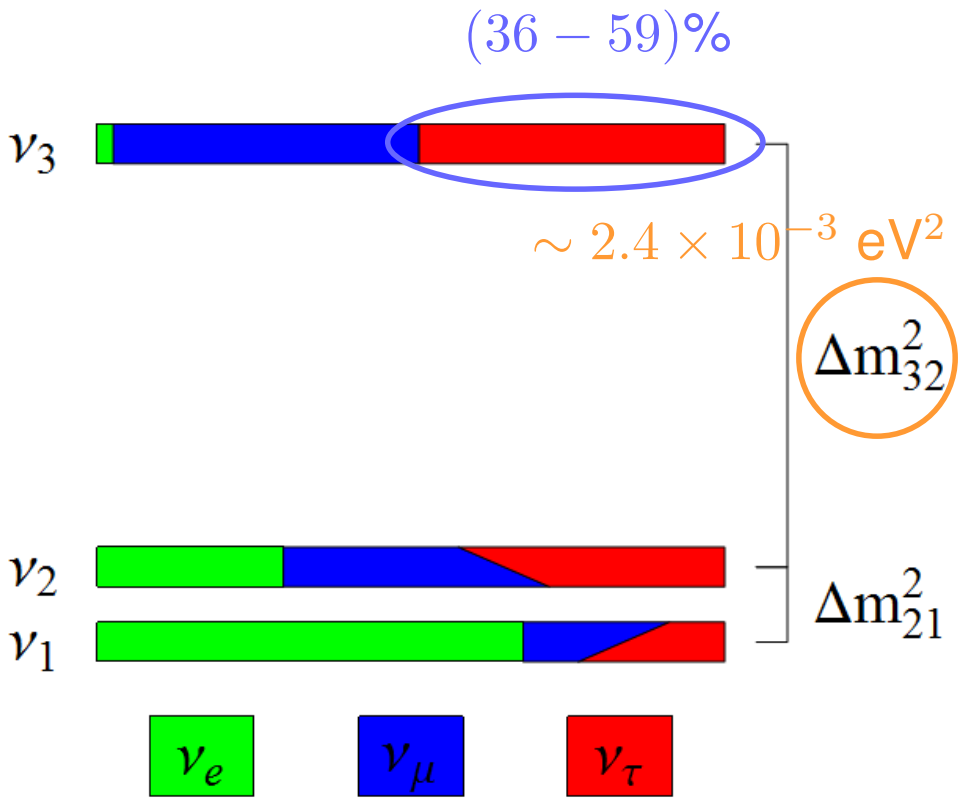

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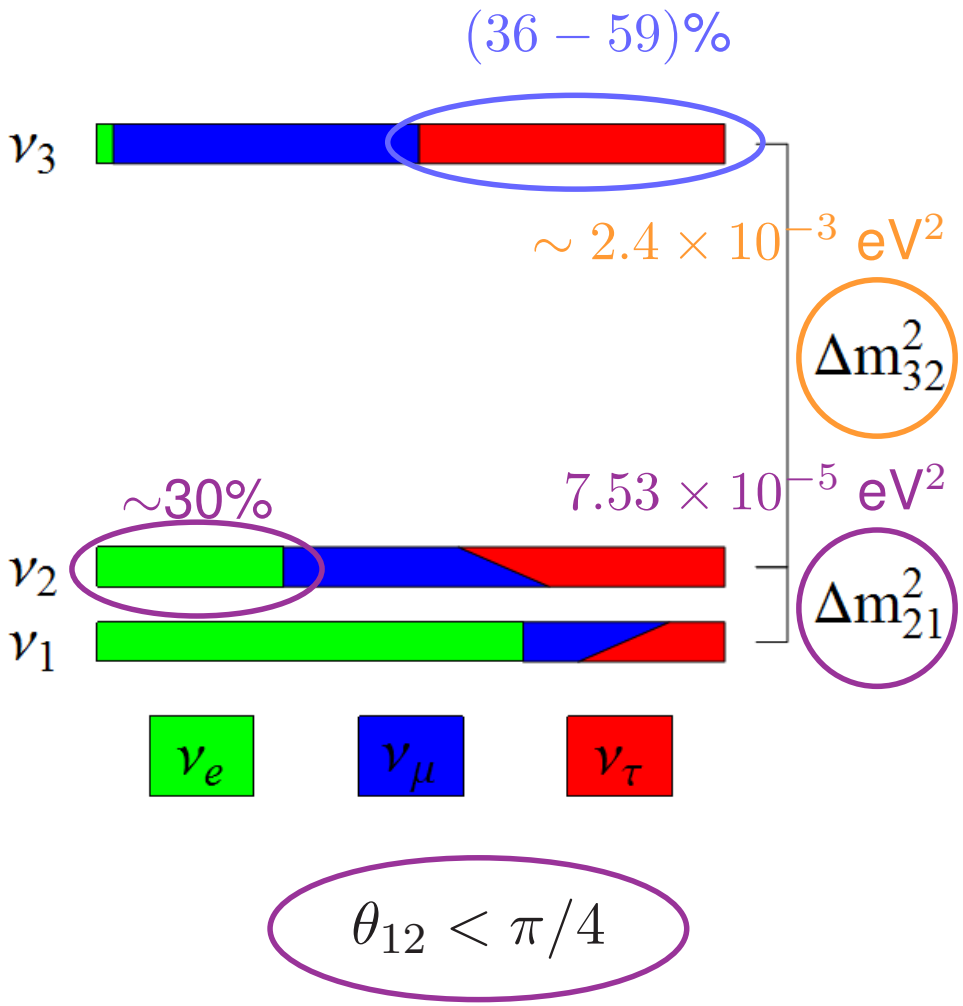
Super-Kamiokande:
$0.393 < \sin^2(\theta_{23}) < 0.630$
at 90% C.L.

What we know



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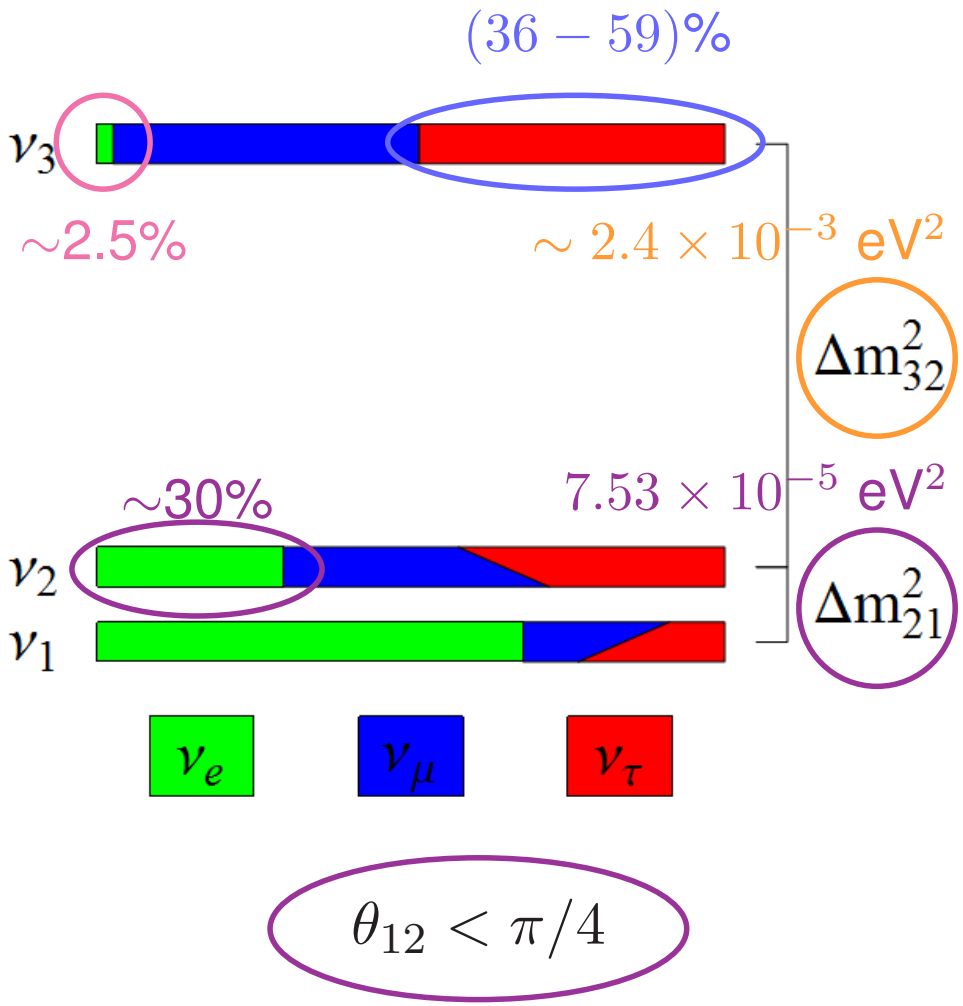
Solar+KamLAND:
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{12}) = 0.304^{+0.014}_{-0.012}$

What we know



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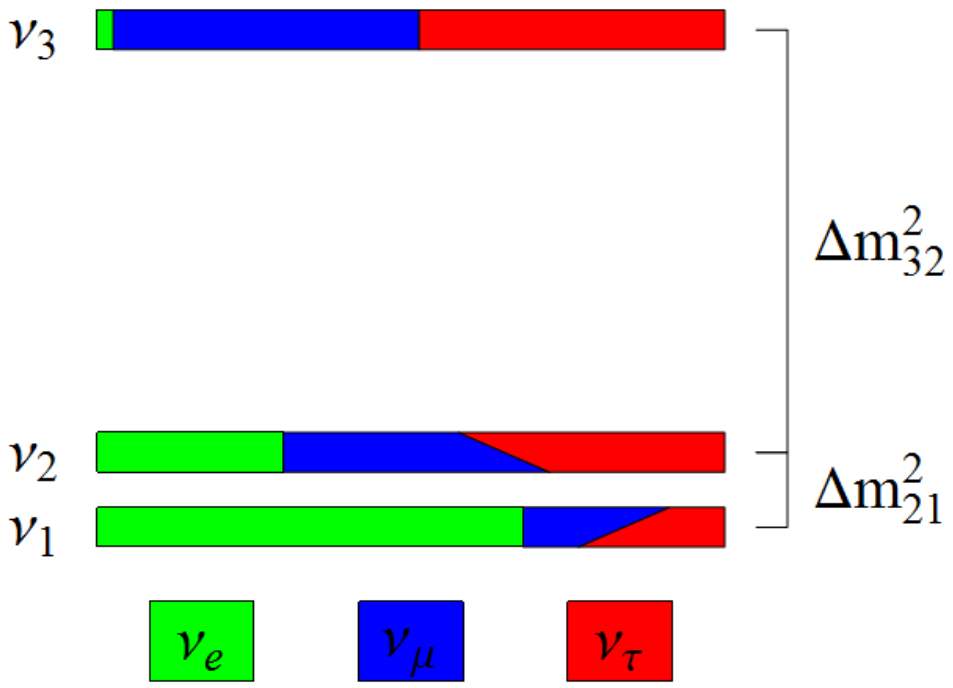
Daya Bay+RENO+DC:
$\sin^2(\theta_{13}) = 0.0251 \pm 0.0034$

What we don't know



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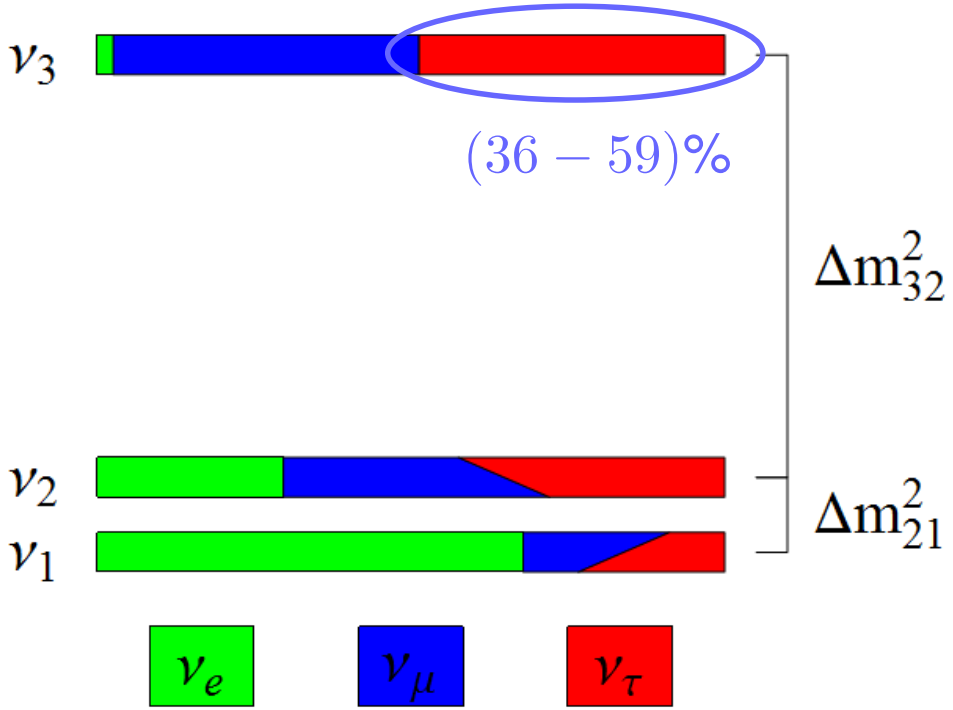
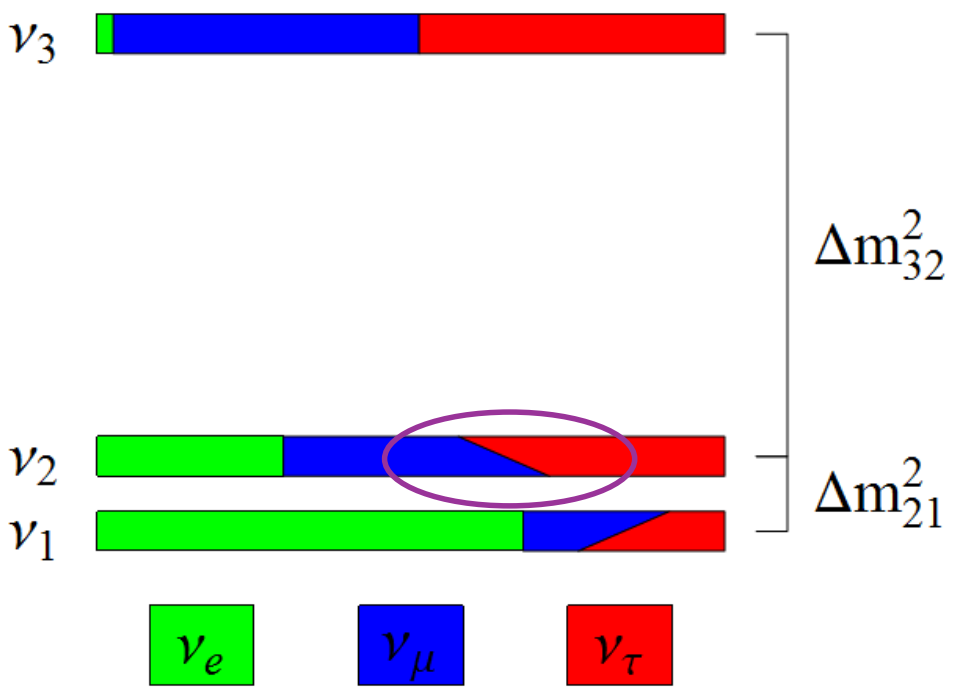


Is θ_{23} maximal?
What is the octant of θ_{23}?

What we don't know



Is θ_{23} maximal?
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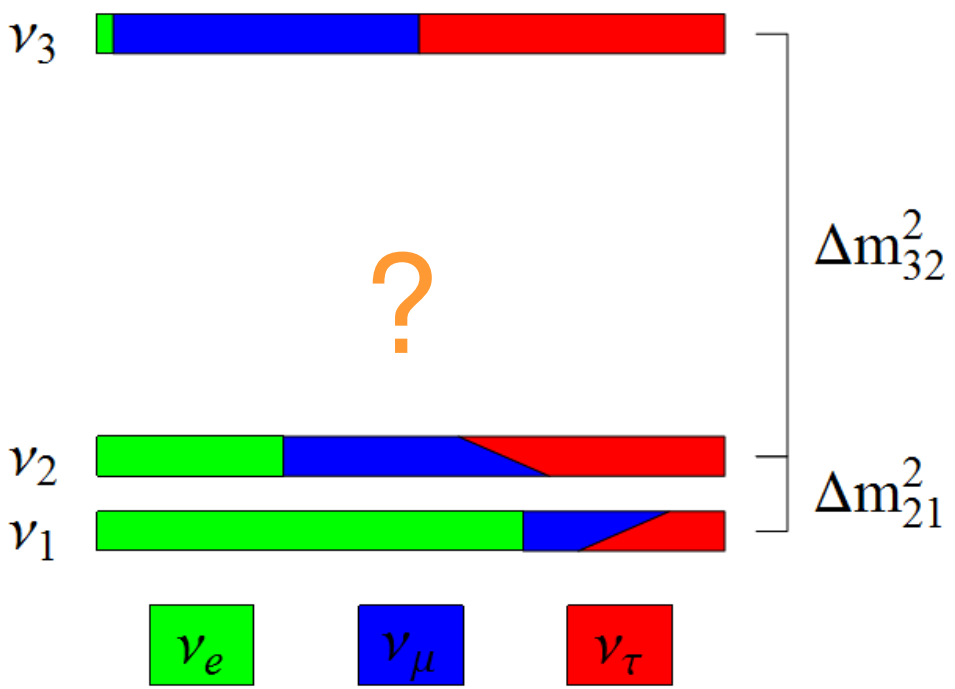
Do neutrinos violate CP?
What is the value of δ_{CP}?

What we don't know



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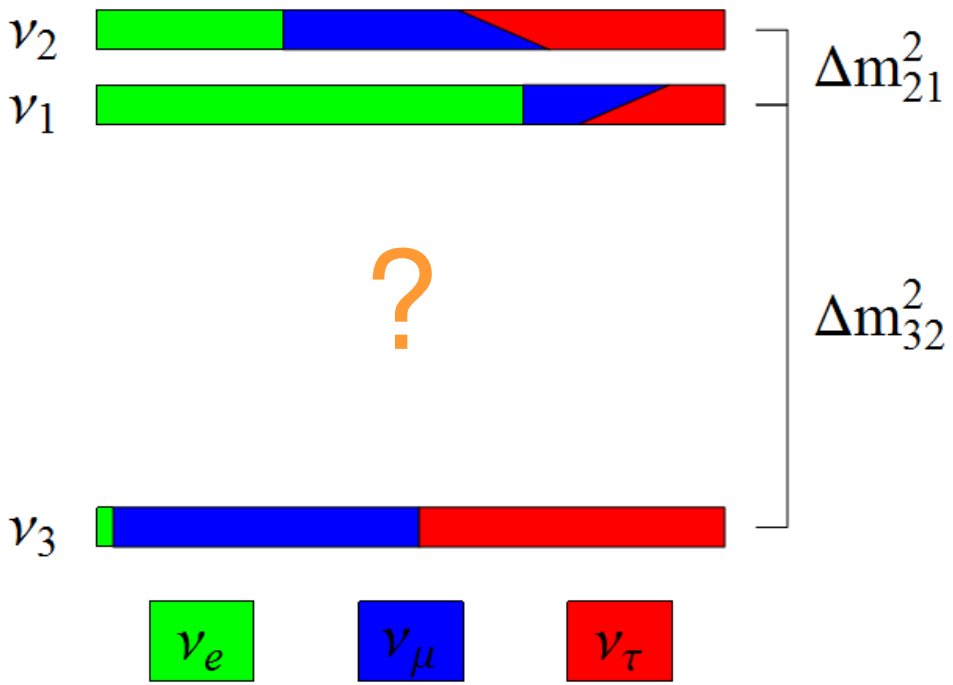

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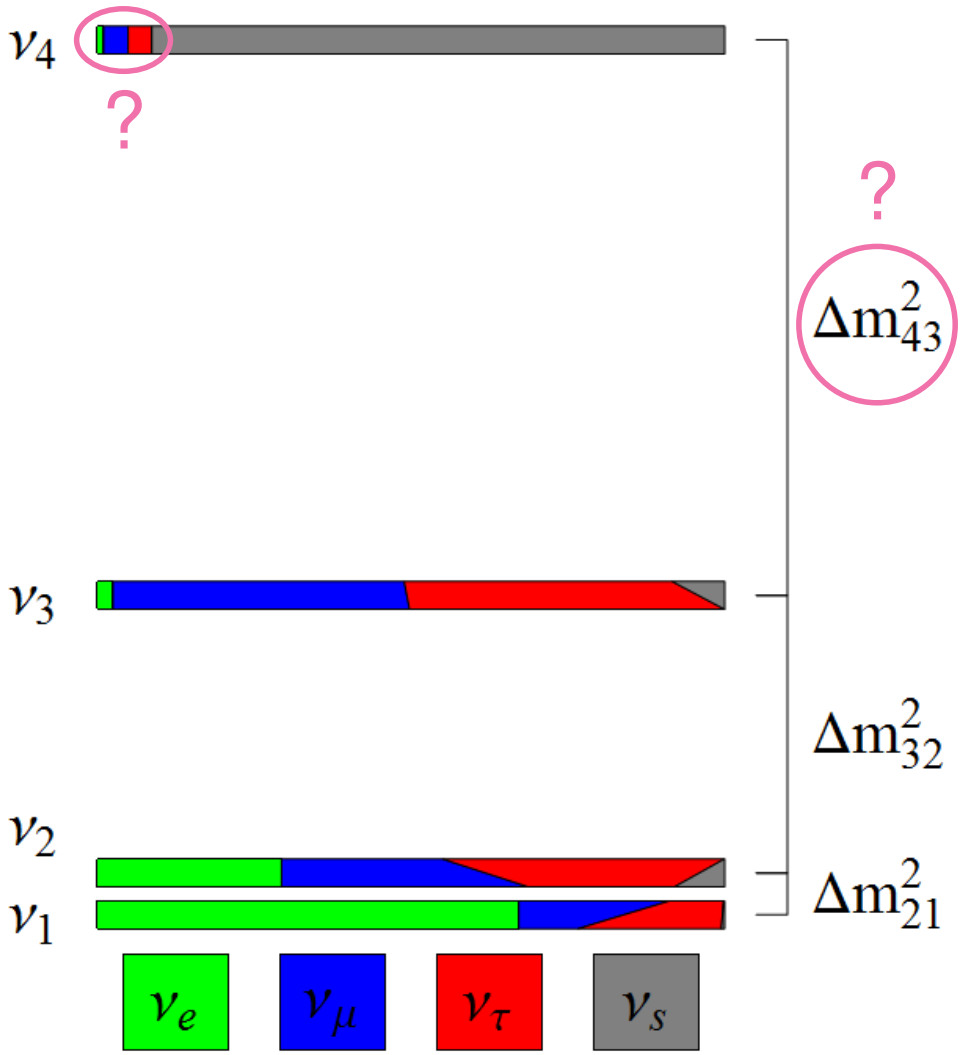

Is θ_{23} maximal?
What is the octant of θ_{23}?

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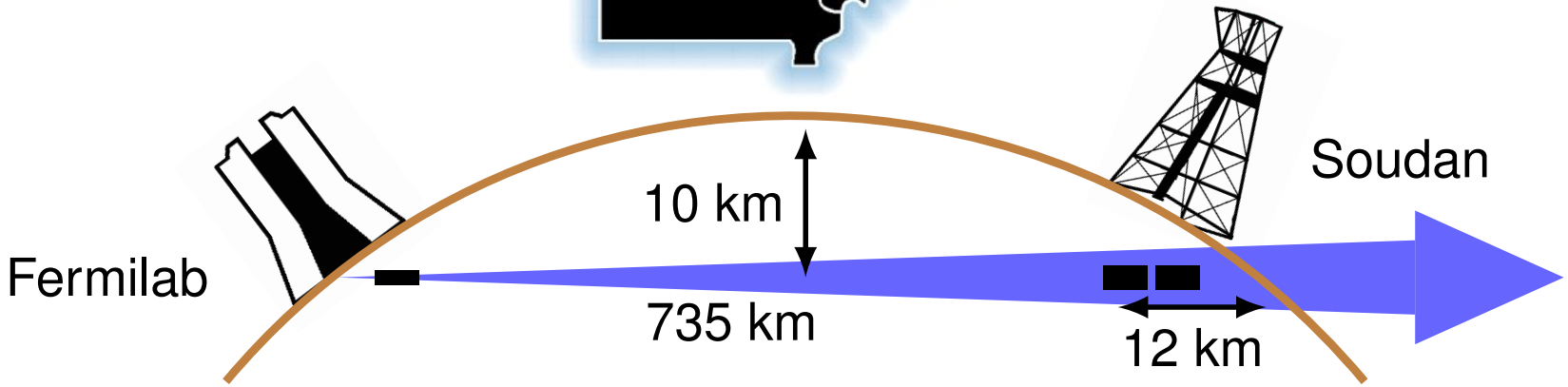
What is the neutrino mass hierarchy?

Are there sterile neutrinos?
Do they mix with active neutrinos?

The MINOS experiment

MINOS overview



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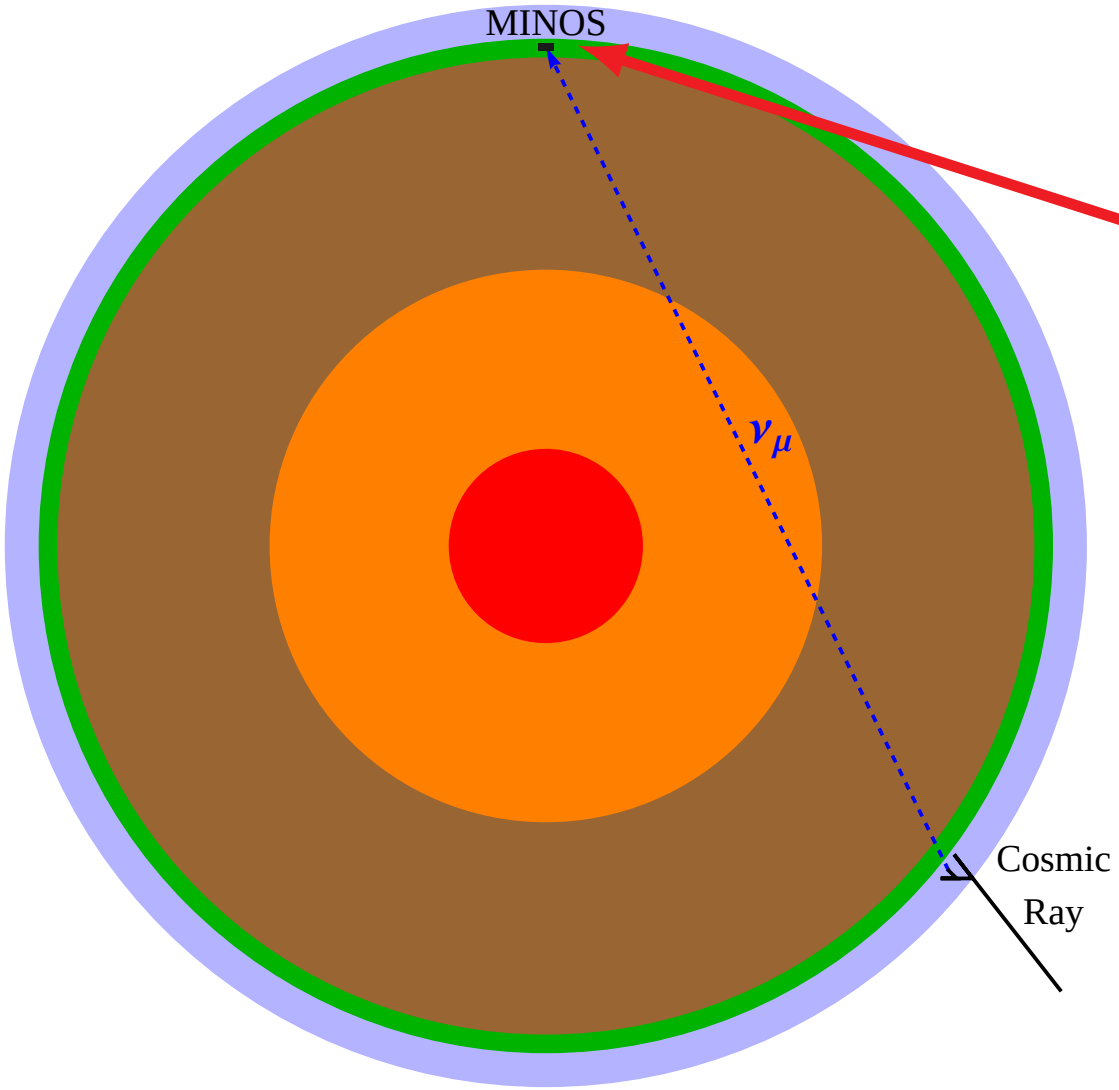
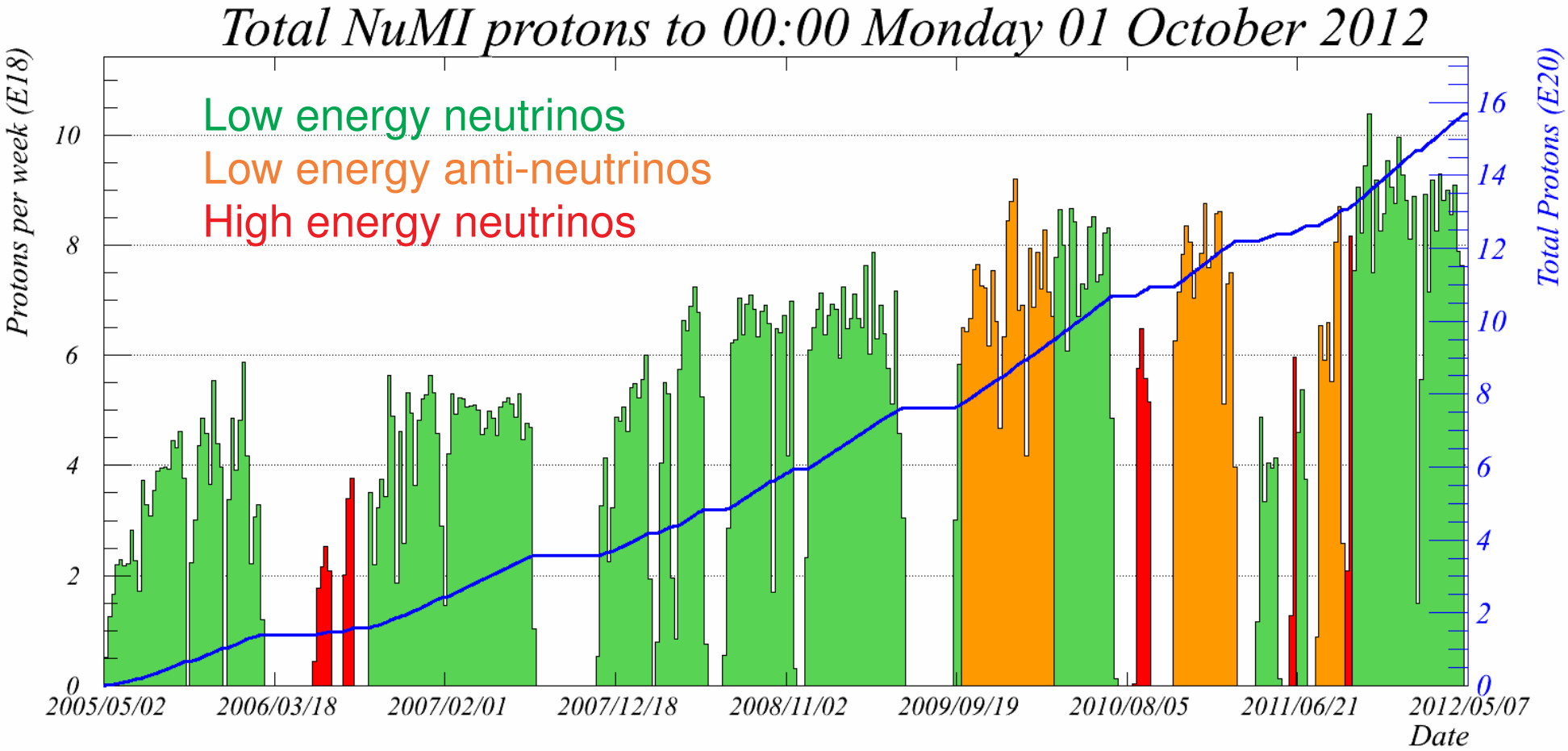


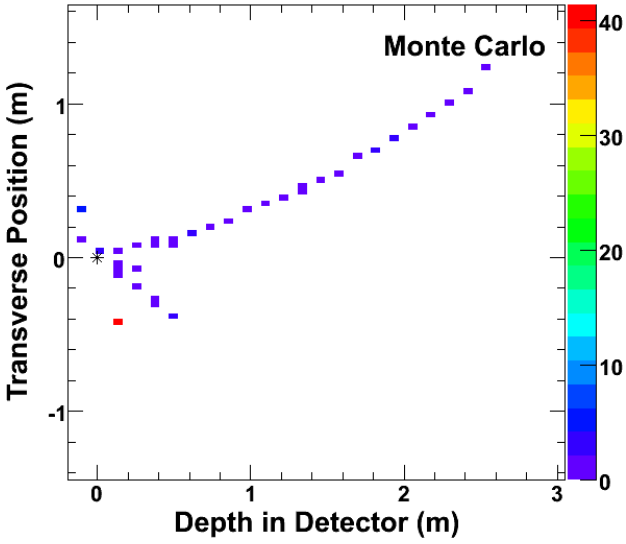
Exposure

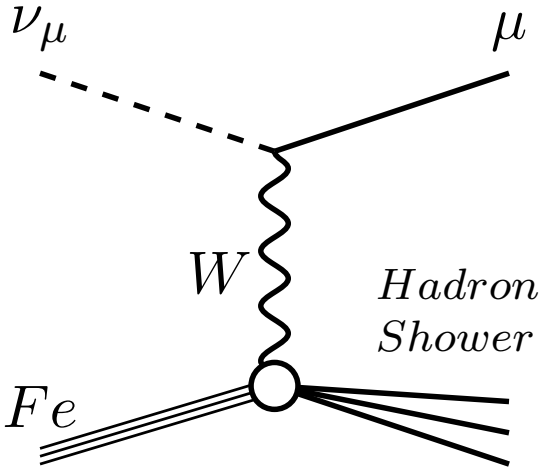
- 15.6×10^{20} protons on target in 7 years of running
- 37.88 kt-year of atmospheric neutrinos since 2003



MINOS event topology

ν_μ-CC event





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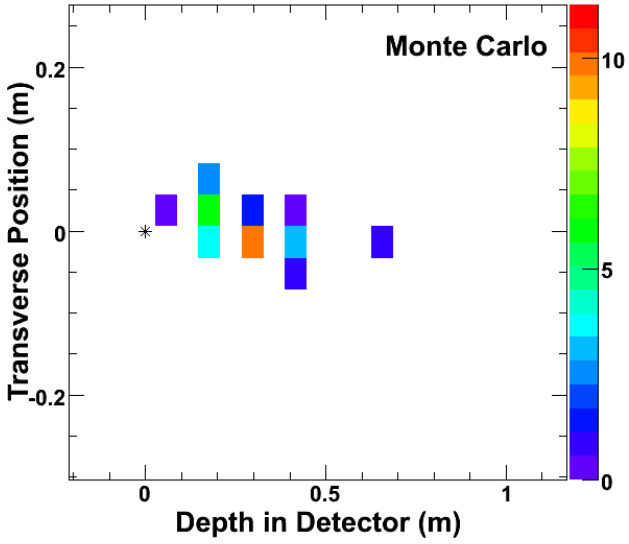
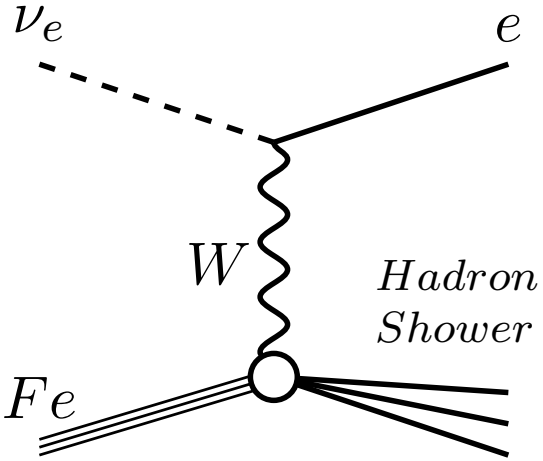
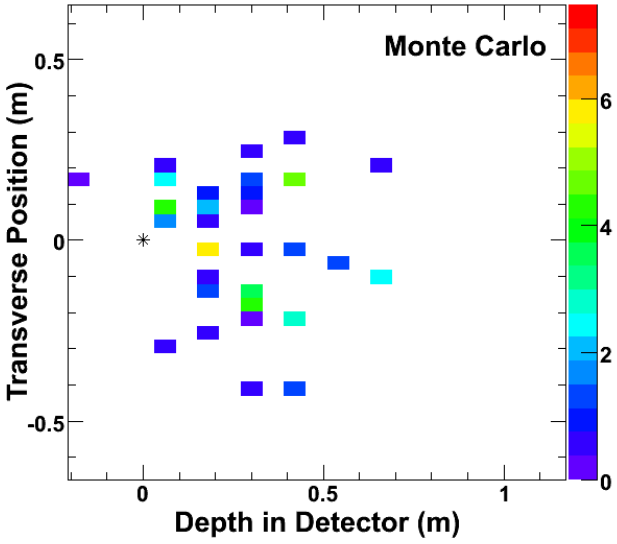
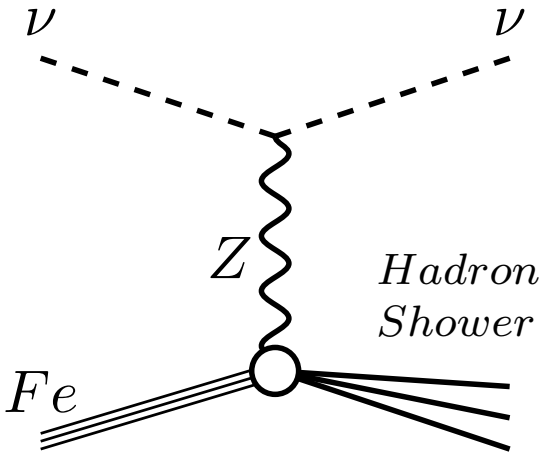




NC event





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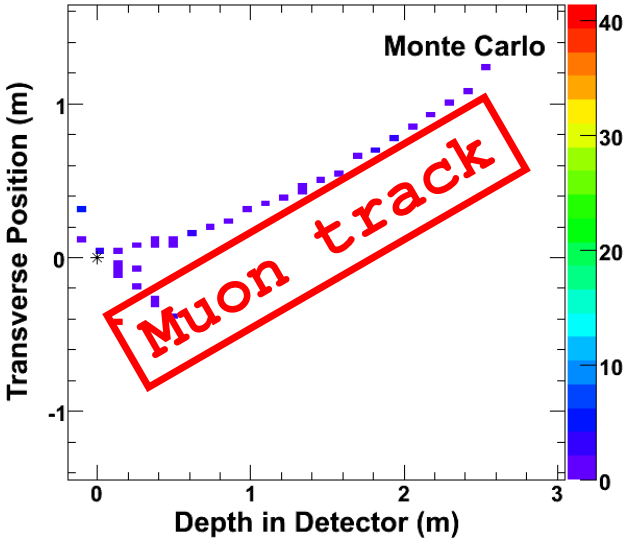

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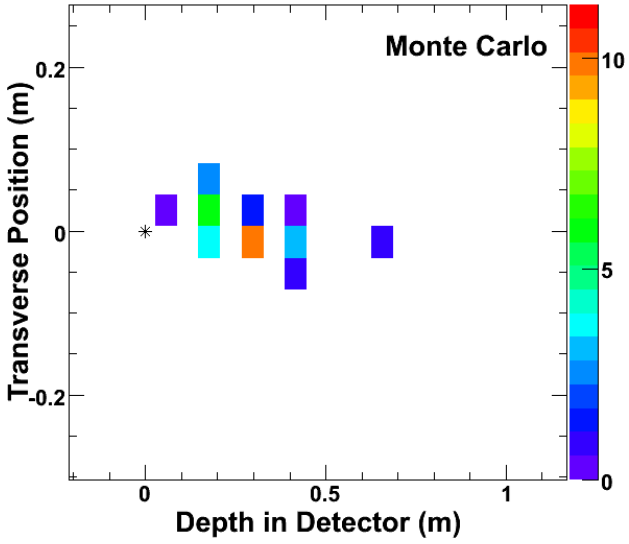

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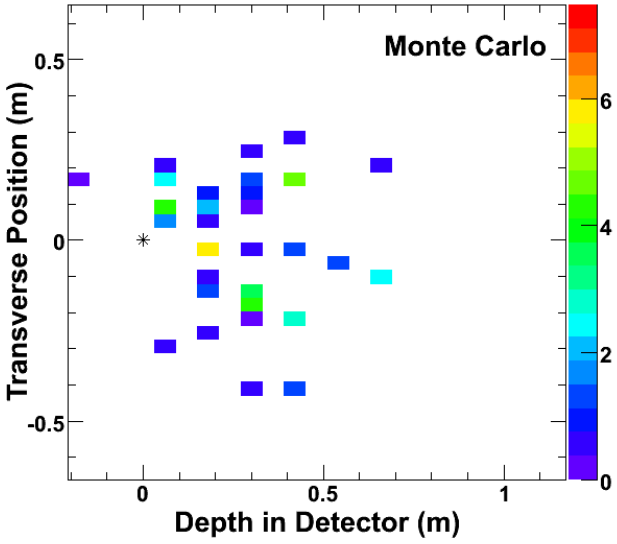

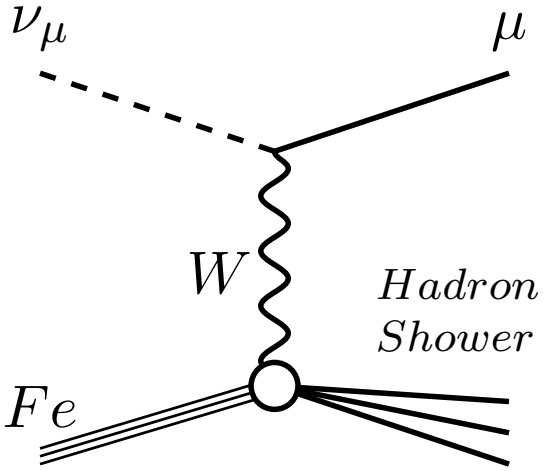

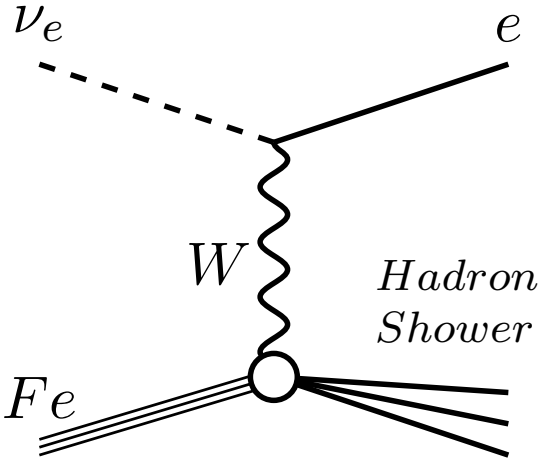

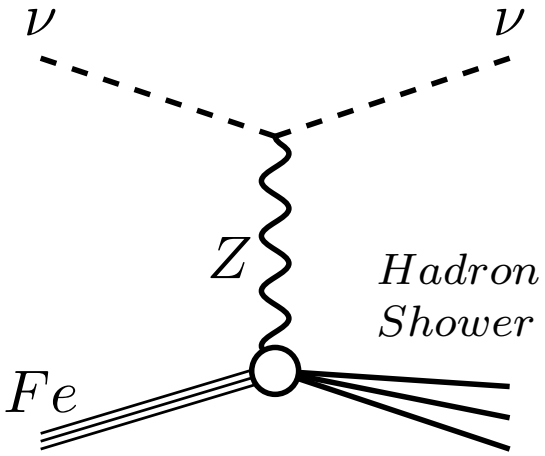

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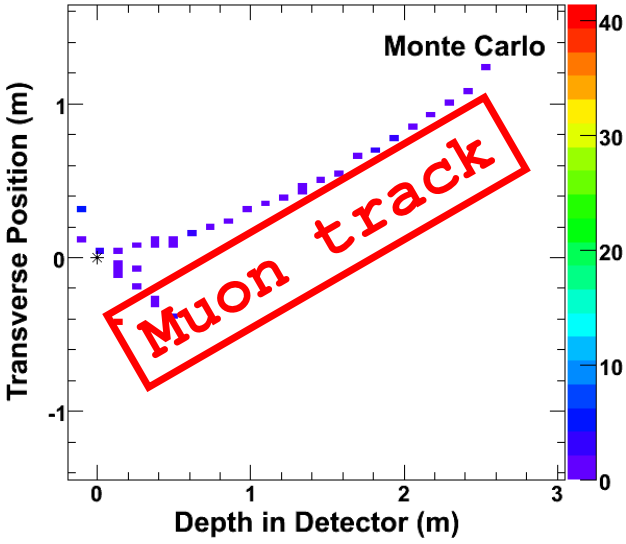

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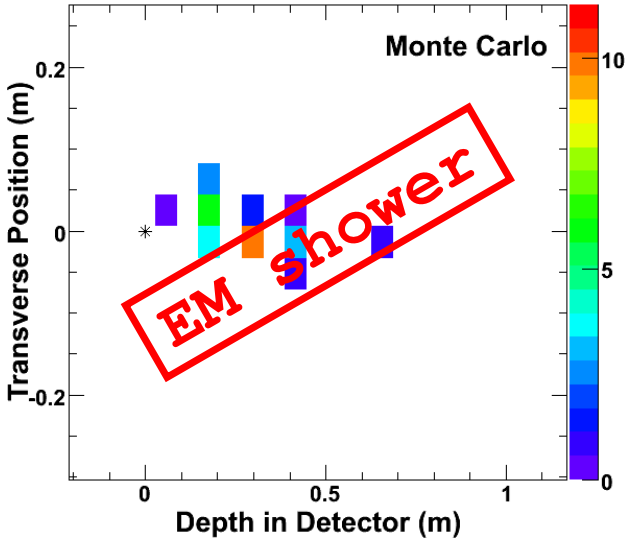
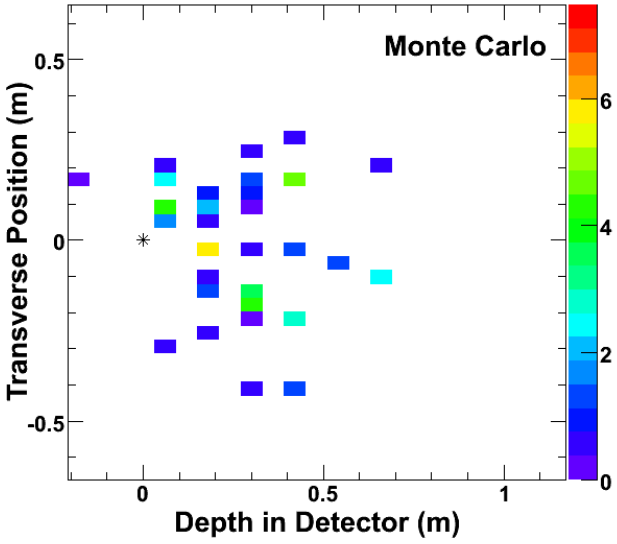
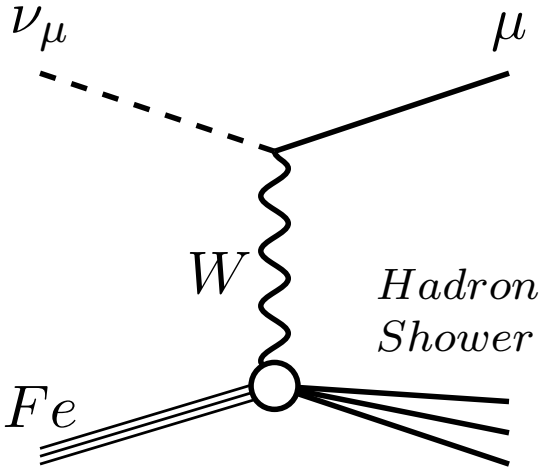
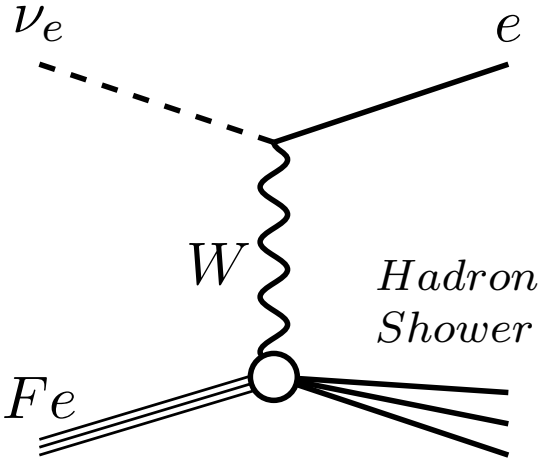
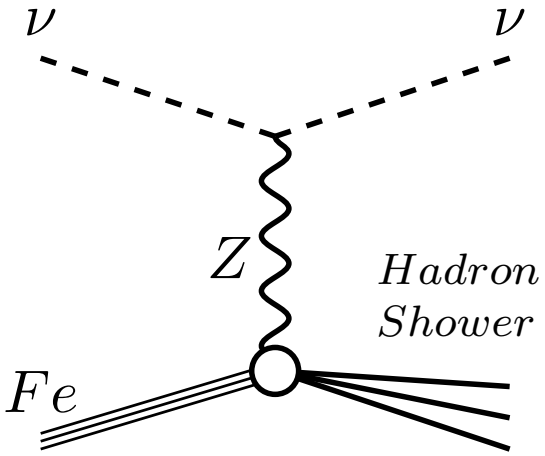


NC event



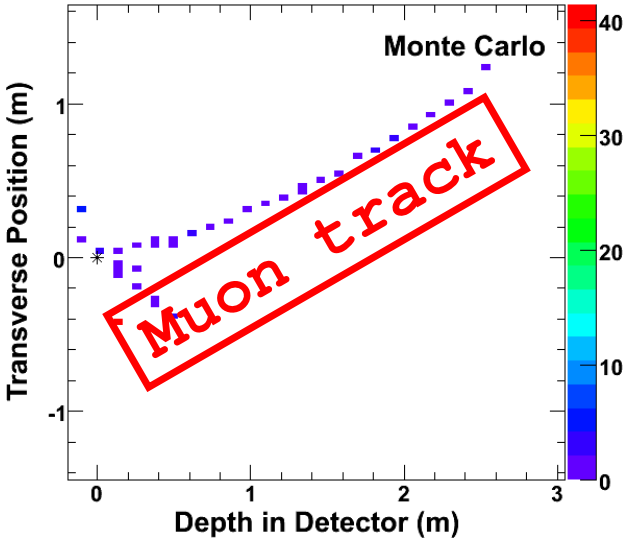


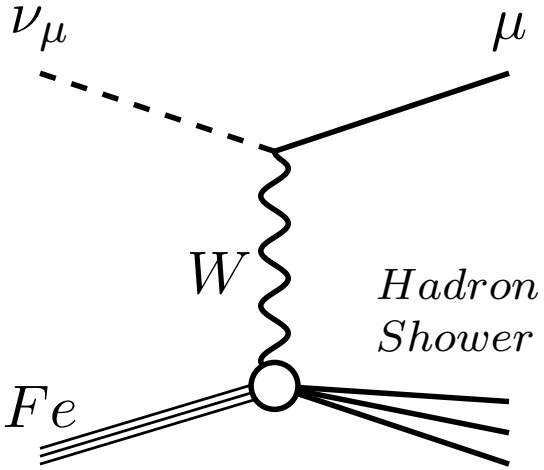




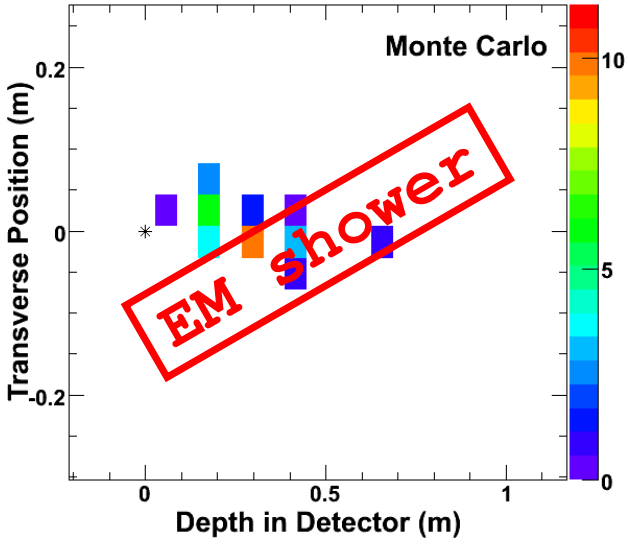
MINOS event topology

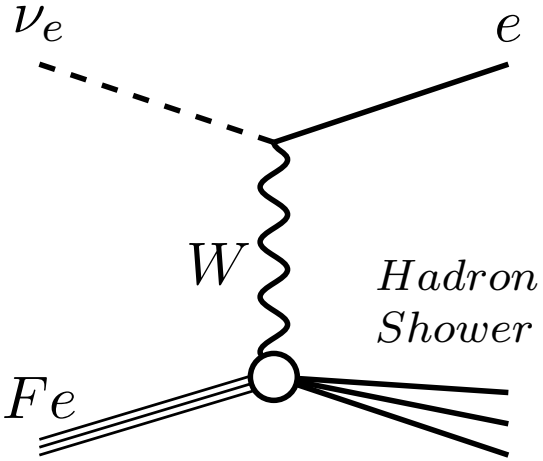
ν_μ-CC event



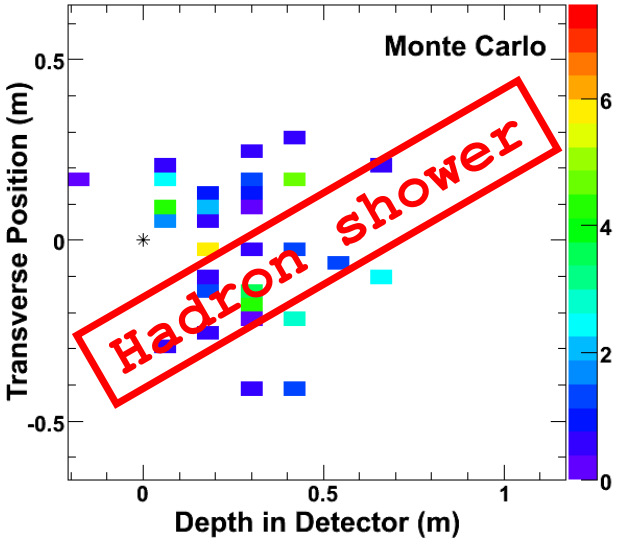


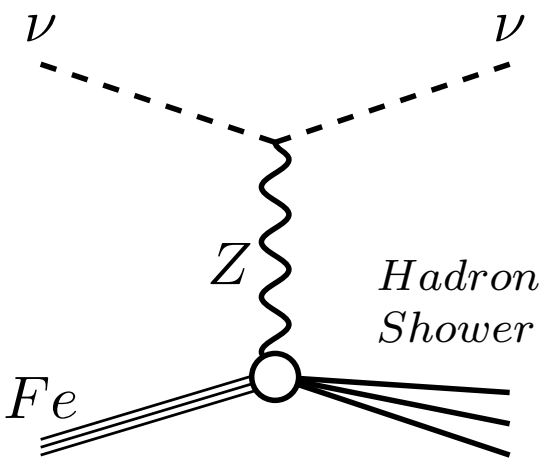
ν_e-CC event





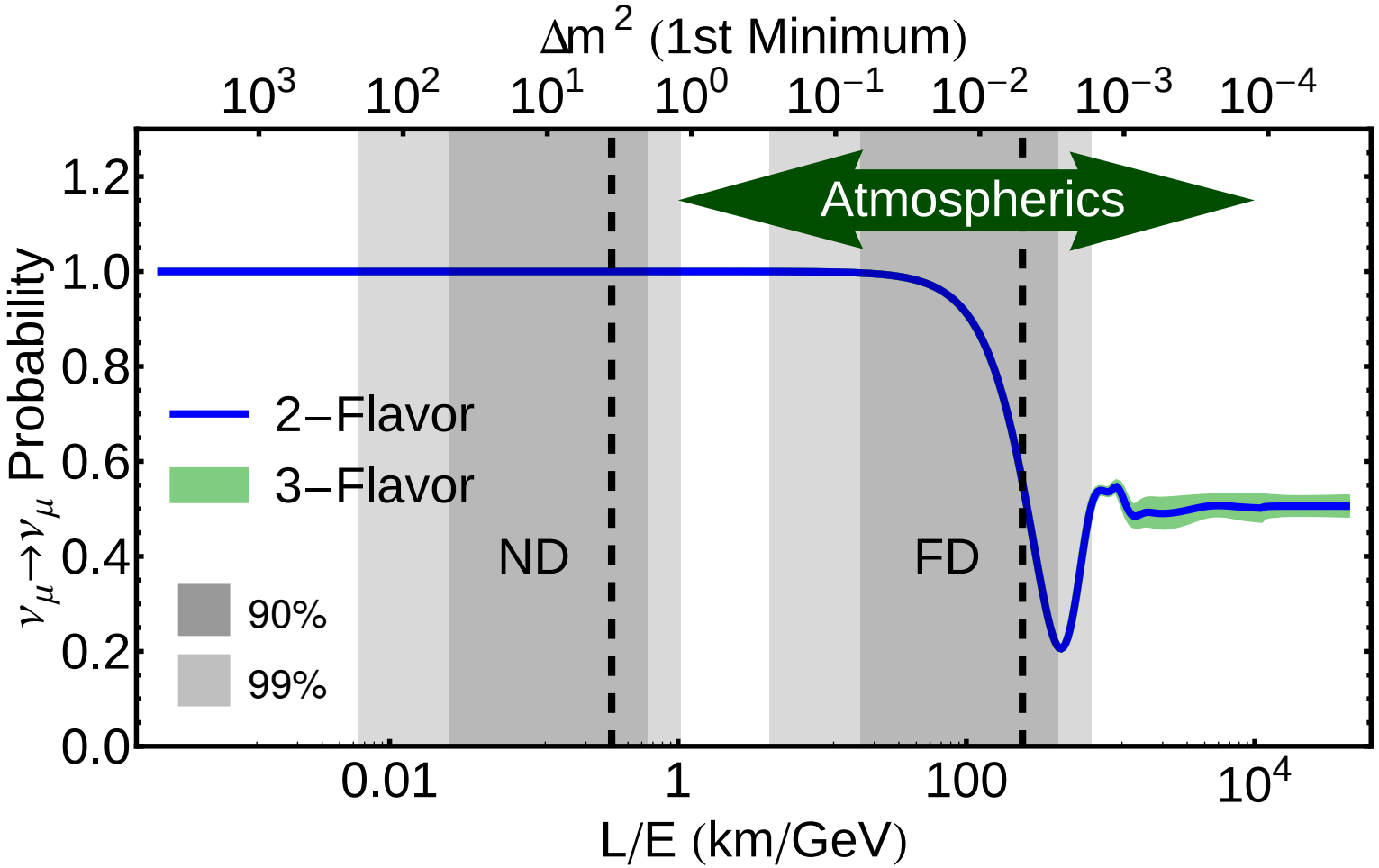
NC event





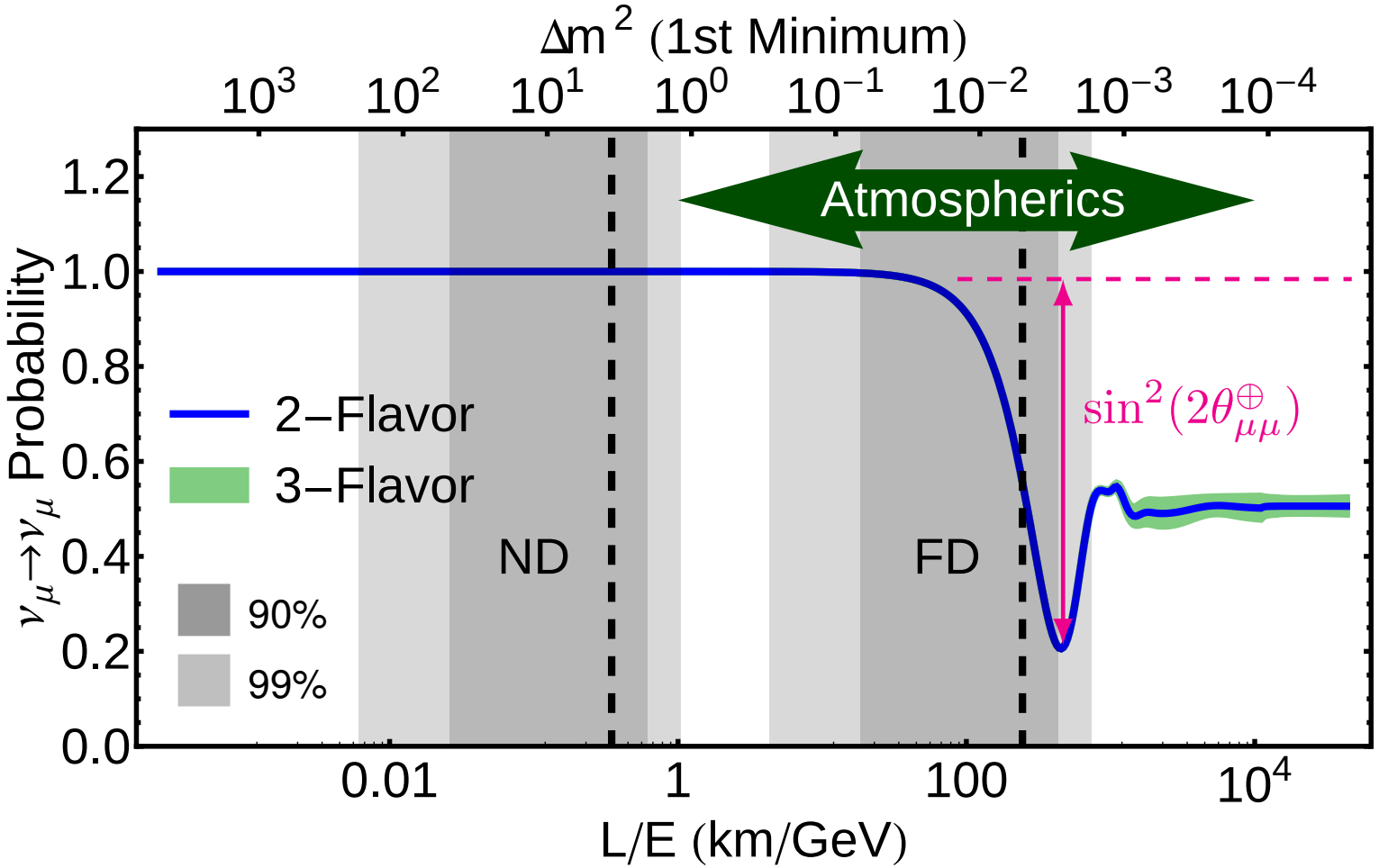
Three-flavor results

Survival probability



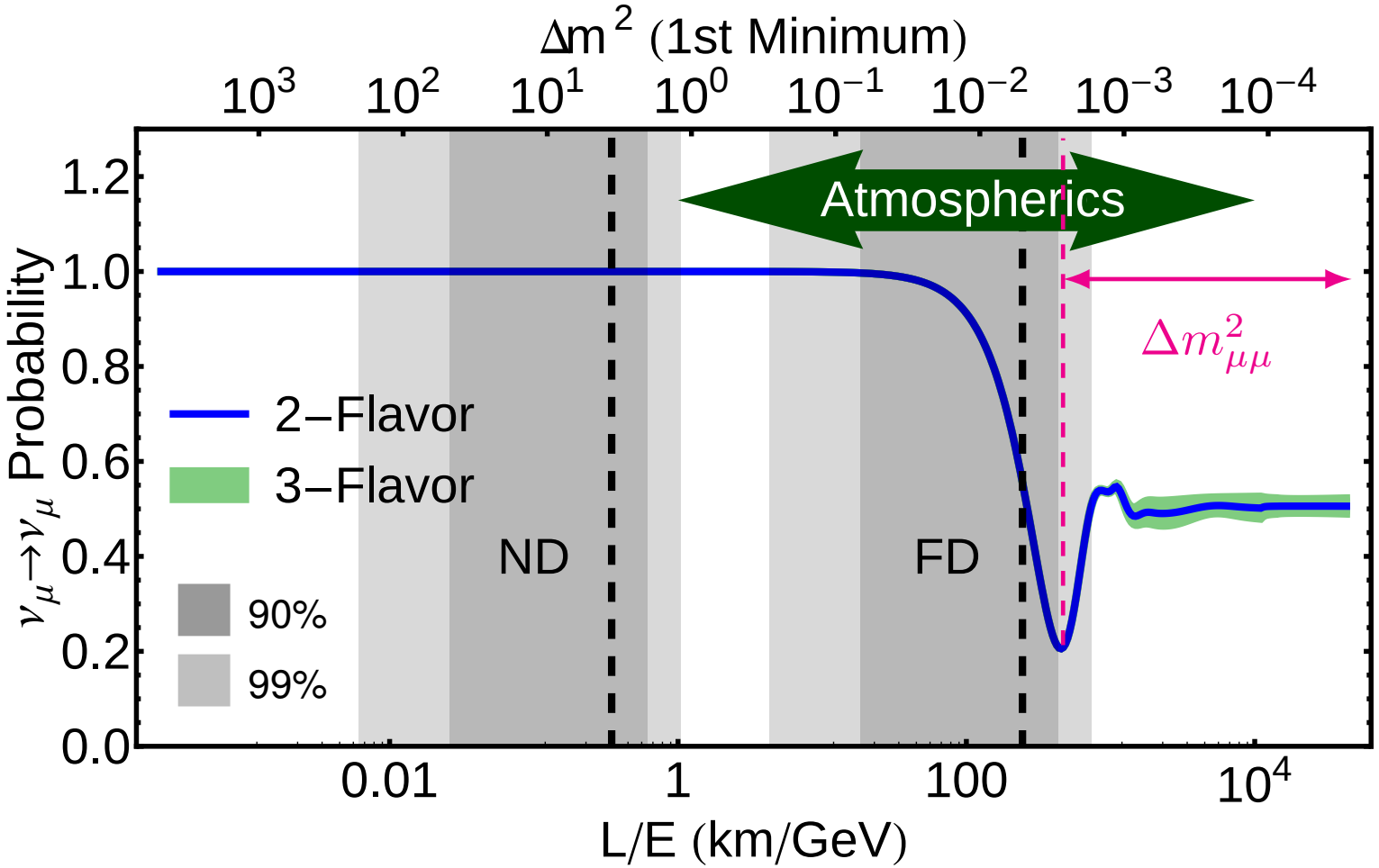
$$\mathcal{P}_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2(2\theta^{\oplus}_{\mu\mu}) \sin^2(1.27 \Delta m^2_{\mu\mu} \tfrac{L}{E}) + \mathcal{O}(\Delta m^2_{\odot} \tfrac{L}{E})^2$$

Survival probability



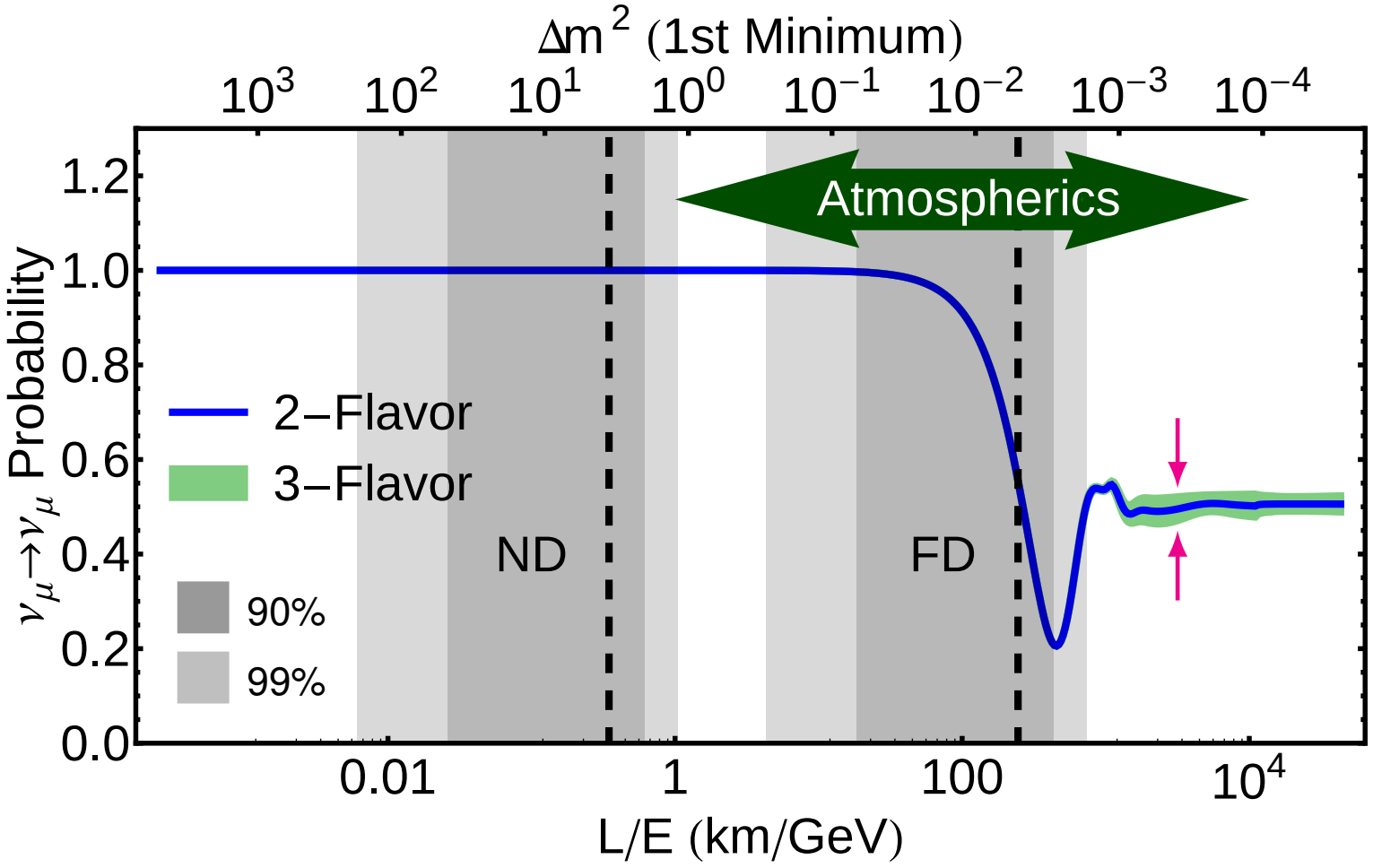
$$\mathcal{P}_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2(2\theta^{\oplus}_{\mu\mu}) \sin^2(1.27\Delta m^2_{\mu\mu} \tfrac{L}{E}) + \mathcal{O}(\Delta m^2_{\odot} \tfrac{L}{E})^2$$

Survival probability



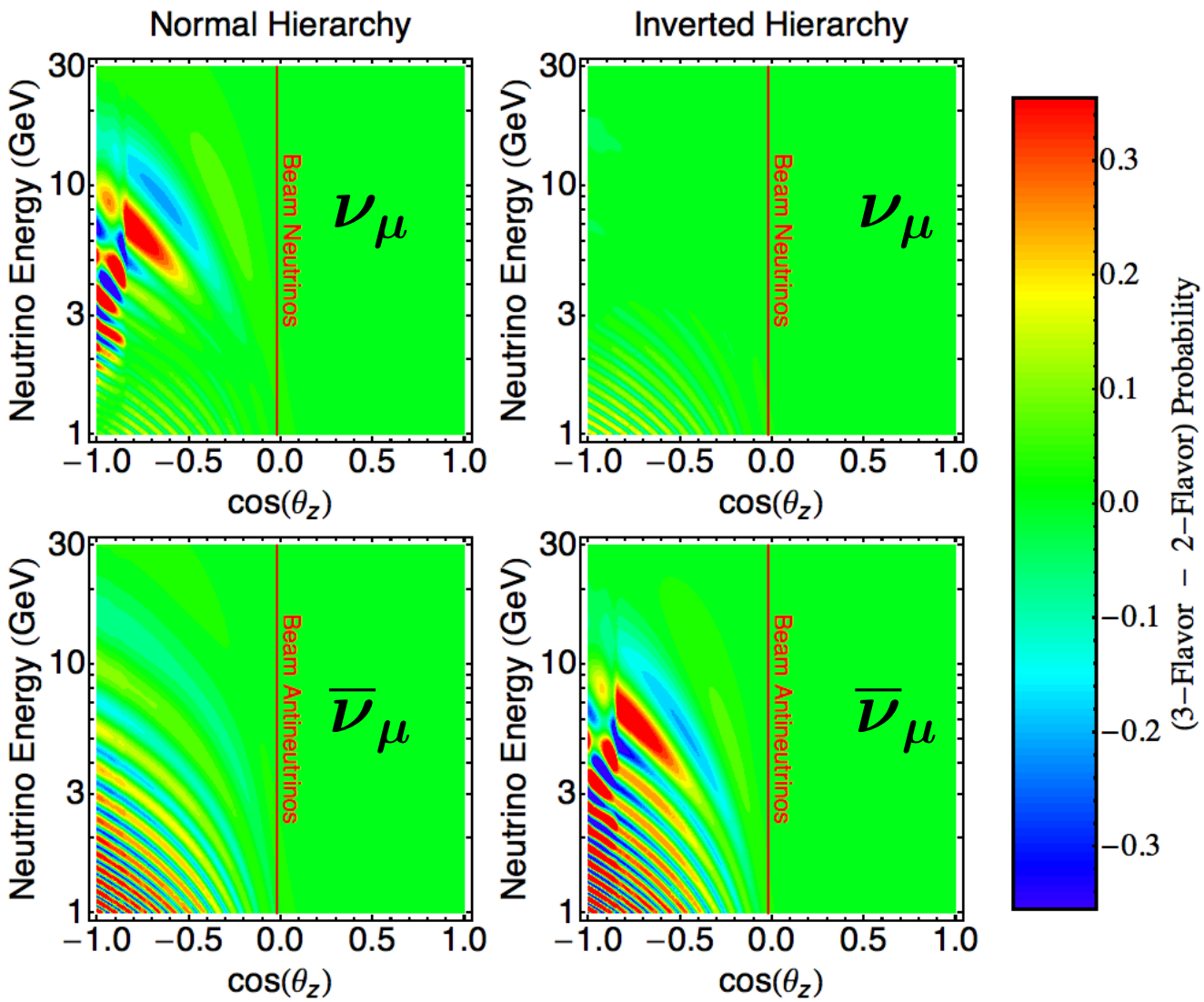
$$\mathcal{P}_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2(2\theta^{\oplus}_{\mu\mu}) \sin^2(1.27 \Delta m^2_{\mu\mu} \frac{L}{E}) + \mathcal{O}(\Delta m^2_{\odot} \frac{L}{E})^2$$

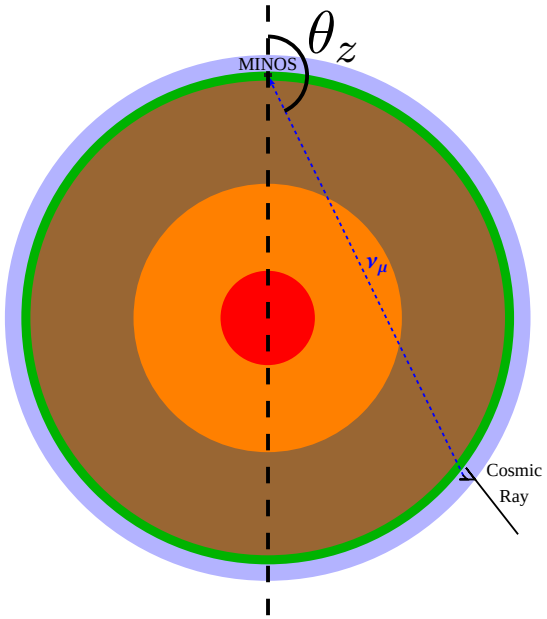
Survival probability



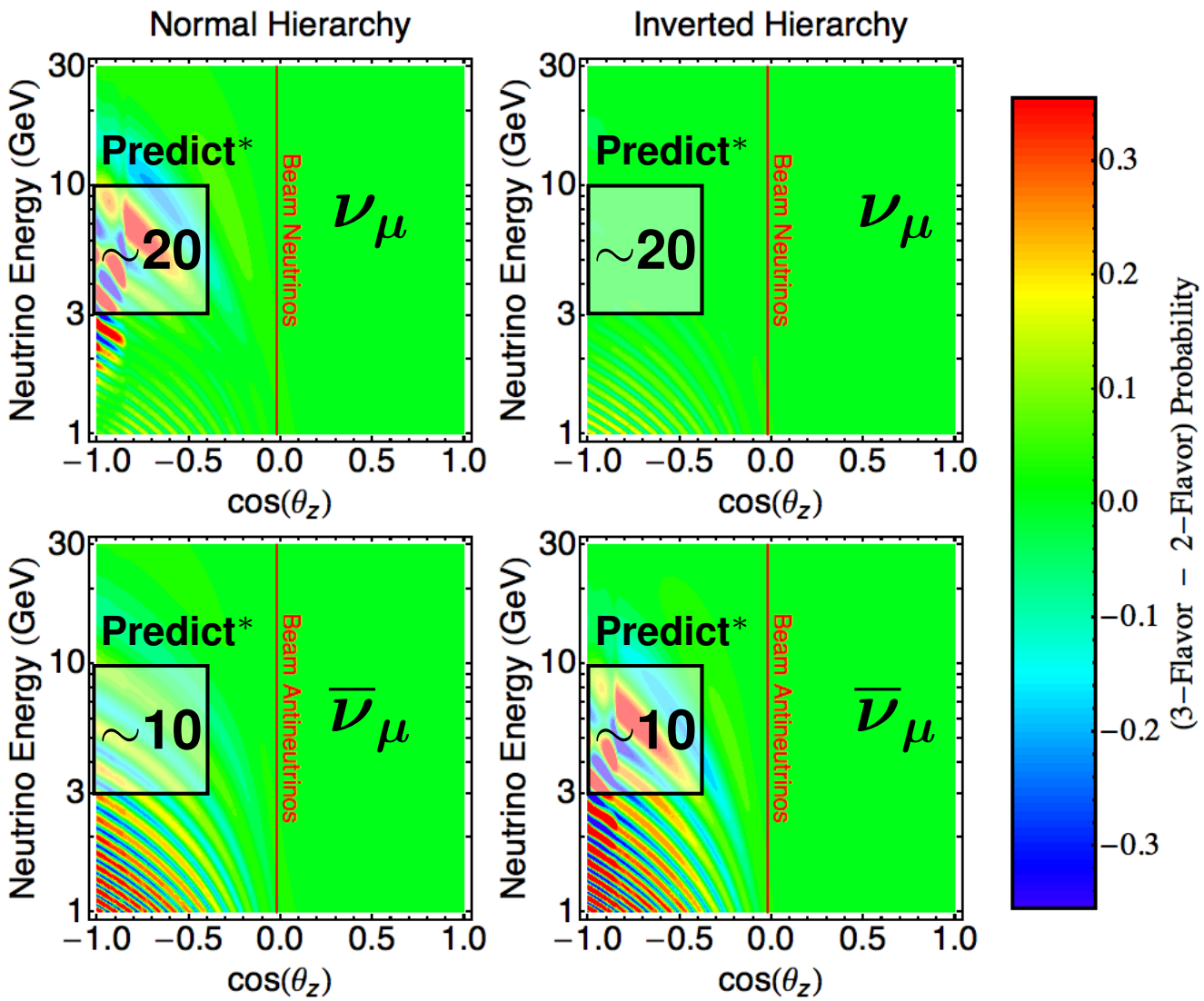
$$\mathcal{P}_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2(2\theta^{\oplus}_{\mu\mu}) \sin^2(1.27 \Delta m^2_{\mu\mu} \tfrac{L}{E}) + \mathcal{O}(\Delta m^2_{\odot} \tfrac{L}{E})^2$$

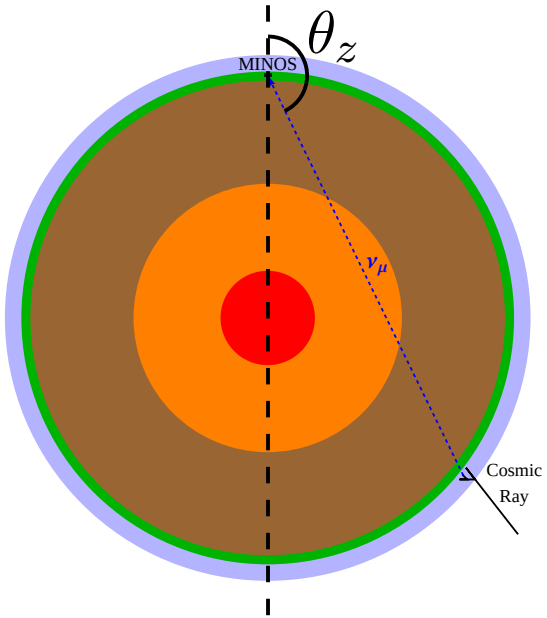
Mantle Resonance





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
  - $\sin^2\theta_{12} = 0.307$

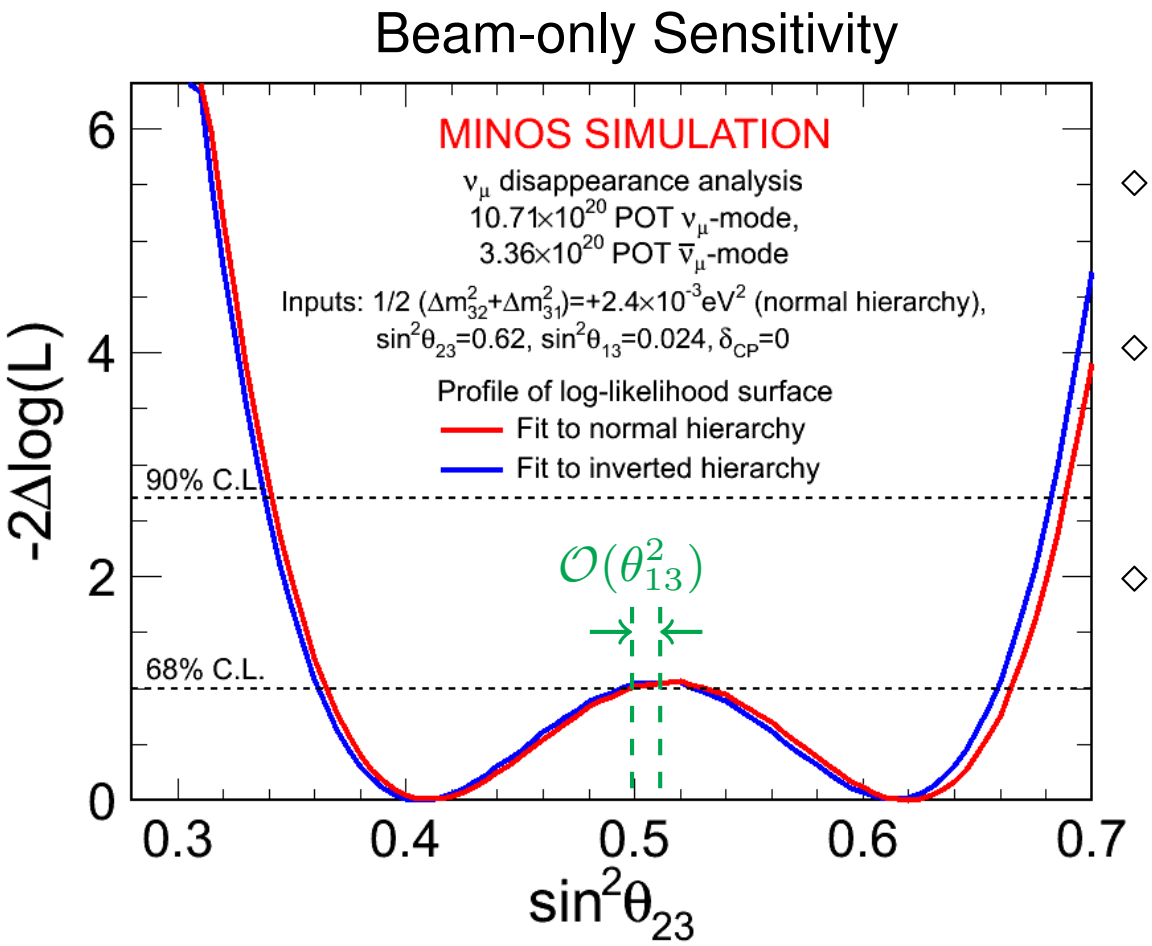
†Phys. Rev. Lett. 110, 251801 (2013)

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

Data Samples

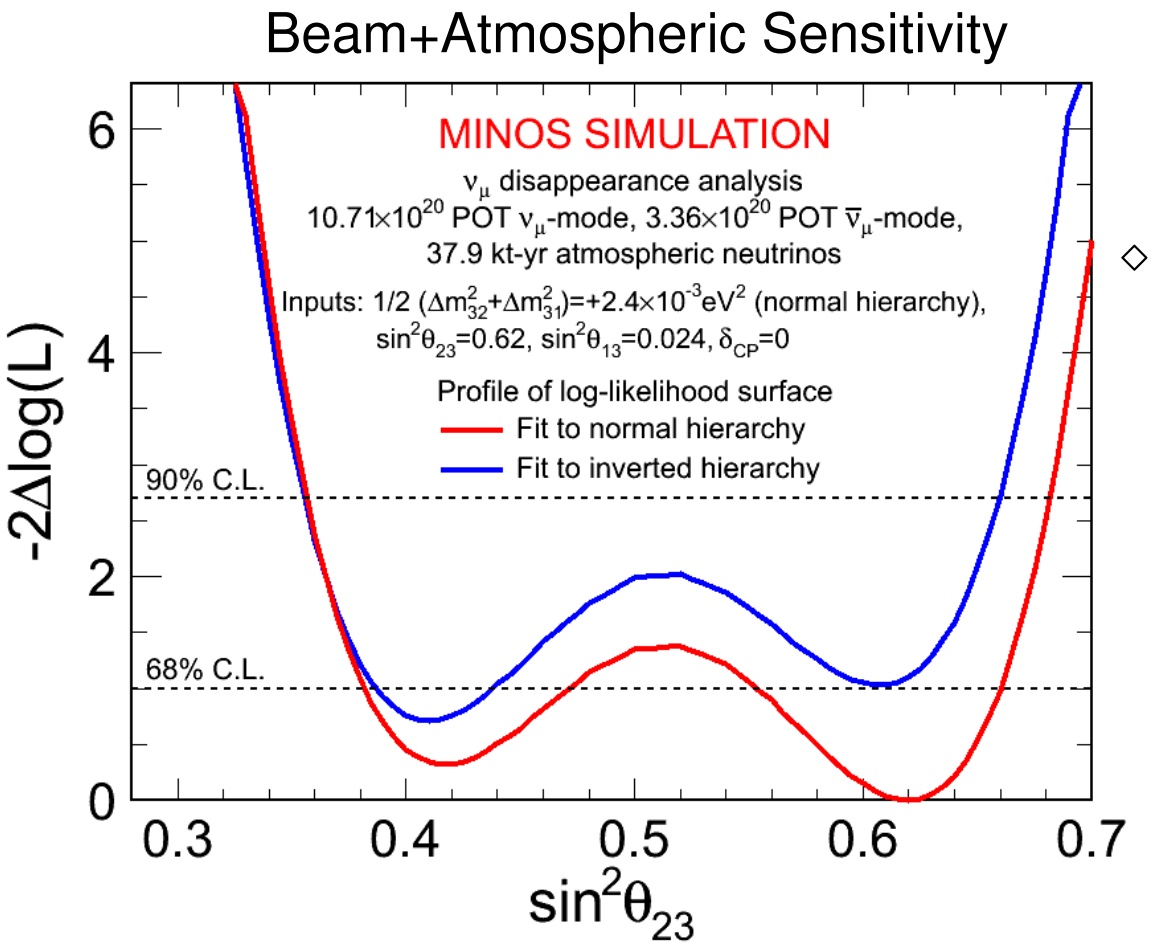
- Uses the same data samples as the 2ν result
- Full beam exposure:
  - 10.71×10^{20} POT taken in neutrino mode
    - Select ν_μ-CC interactions
    - Select $\overline{\nu}_\mu$-CC interactions
  - 3.36×10^{20} POT taken in anti-neutrino mode
    - Select $\overline{\nu}_\mu$-CC interactions
- 37.88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

Sensitivities



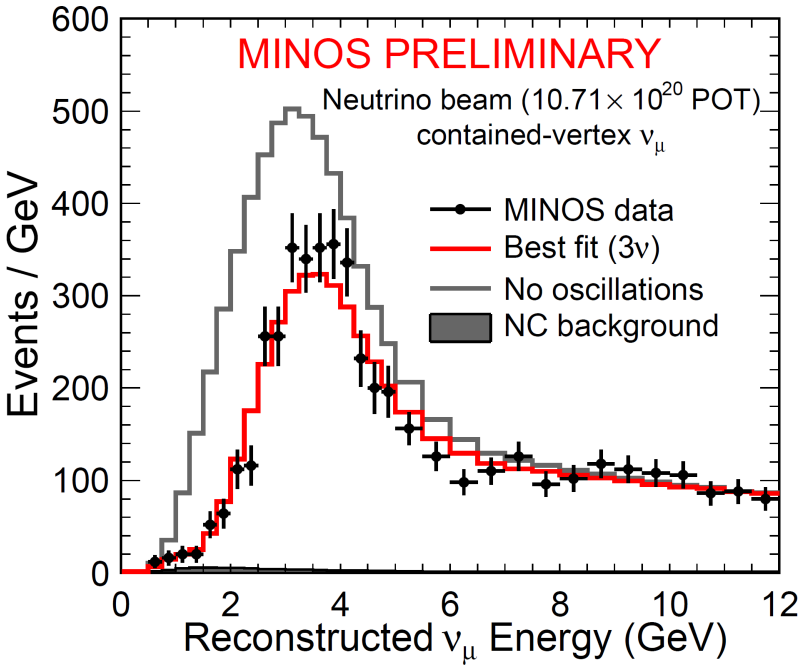
- $\sin^2\theta_{\mu\mu} = \sin^2\theta_{23}\cos^2\theta_{13}$
- Oscillation maximum: $\theta_{\mu\mu} = \pi/4 \neq \theta_{23}$
- No octant discrimination from beam neutrinos

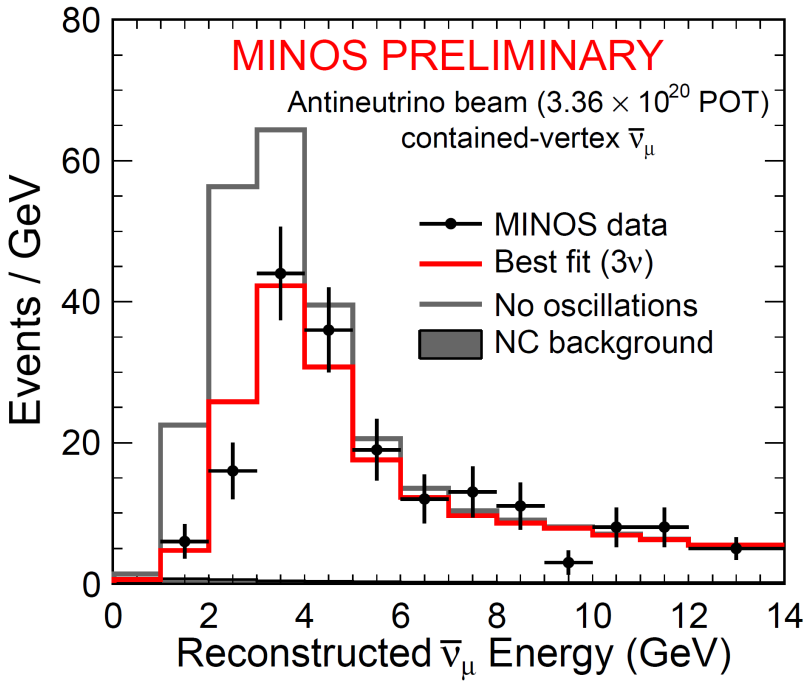
Sensitivities



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

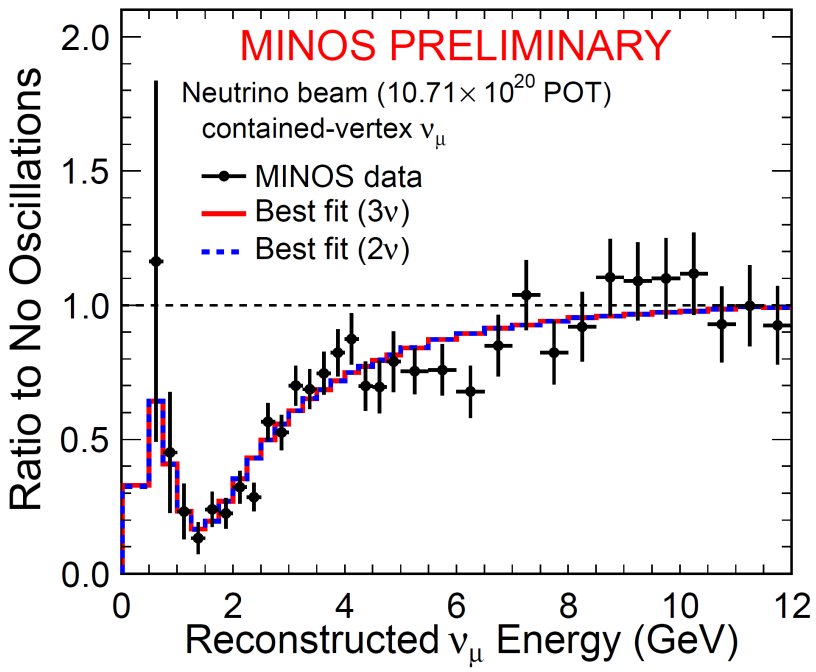
Beam Data

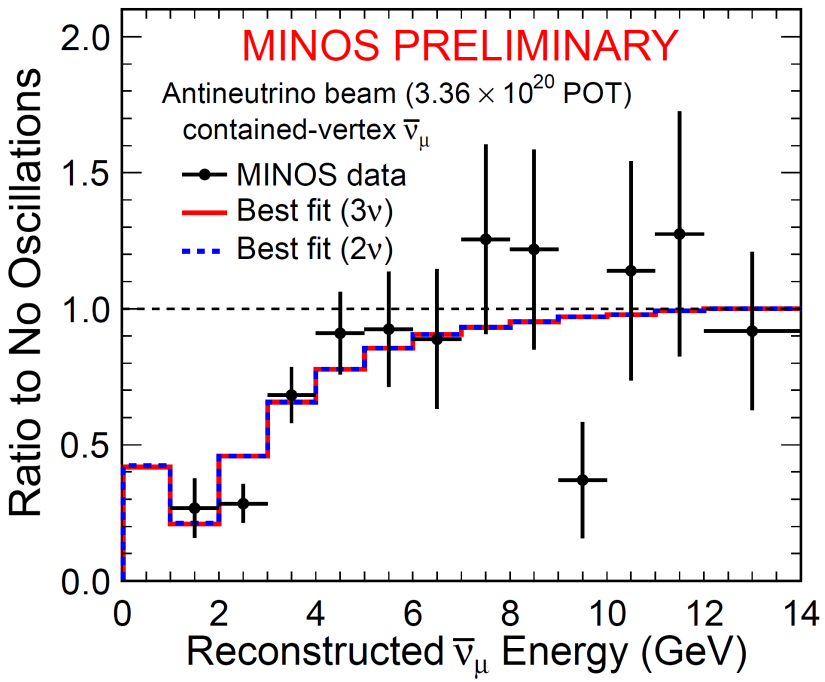




- Predicted 3201 ν_μ-CC candidates and 363 $\overline{\nu}_\mu$-CC candidates
- Observed 2579 ν_μ-CC candidates and 312 $\overline{\nu}_\mu$-CC candidates

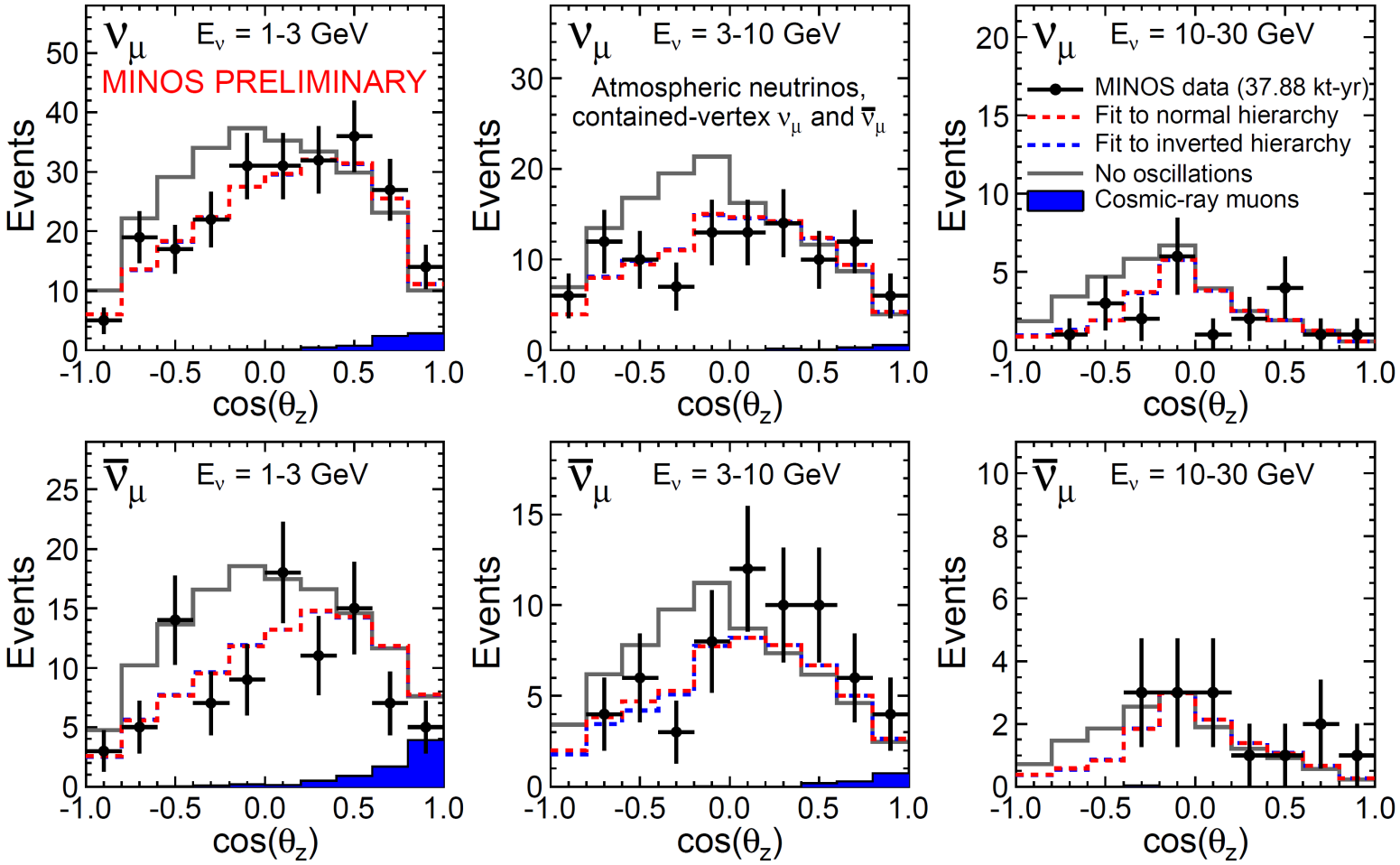
Beam Data





- Predicted 3201 ν_μ-CC candidates and 363 $\overline{\nu}_\mu$-CC candidates
- Observed 2579 ν_μ-CC candidates and 312 $\overline{\nu}_\mu$-CC candidates
- 2ν and 3ν best fits are almost indistinguishable for beam ν's

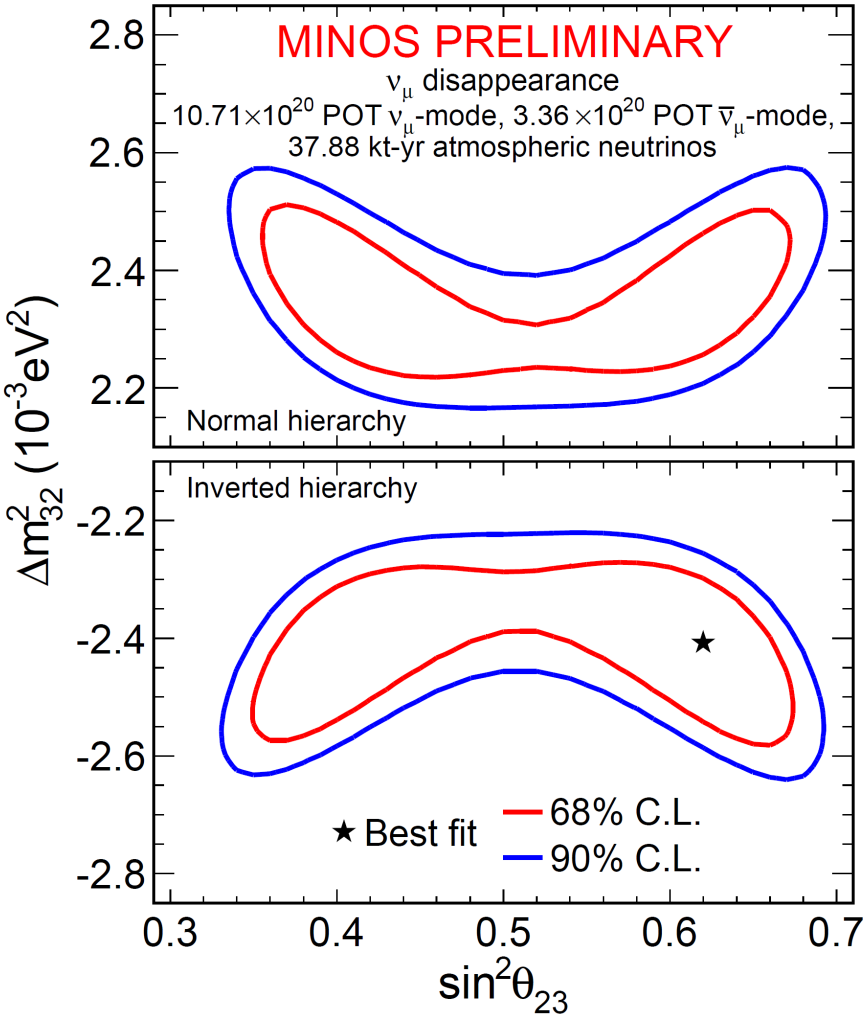
Atmospheric Data



- Predicted 1100 events, observed 905 events
- Small effects from hierarchy in the resonance region

Results

- Marginal preference for inverted hierarchy and upper octant
- Normal Hierarchy
  - $|\Delta m^2_{32}| = 2.35^{+0.10}_{-0.08} \times 10^{-3}$eV^2
  - $0.34 < \sin^2\theta_{23} < 0.68$ at 90% C.L.
- Inverted Hierarchy
  - $|\Delta m^2_{32}| = 2.41^{+0.12}_{-0.10} \times 10^{-3}$eV^2
  - $0.35 < \sin^2\theta_{23} < 0.68$ at 90% C.L.



Results

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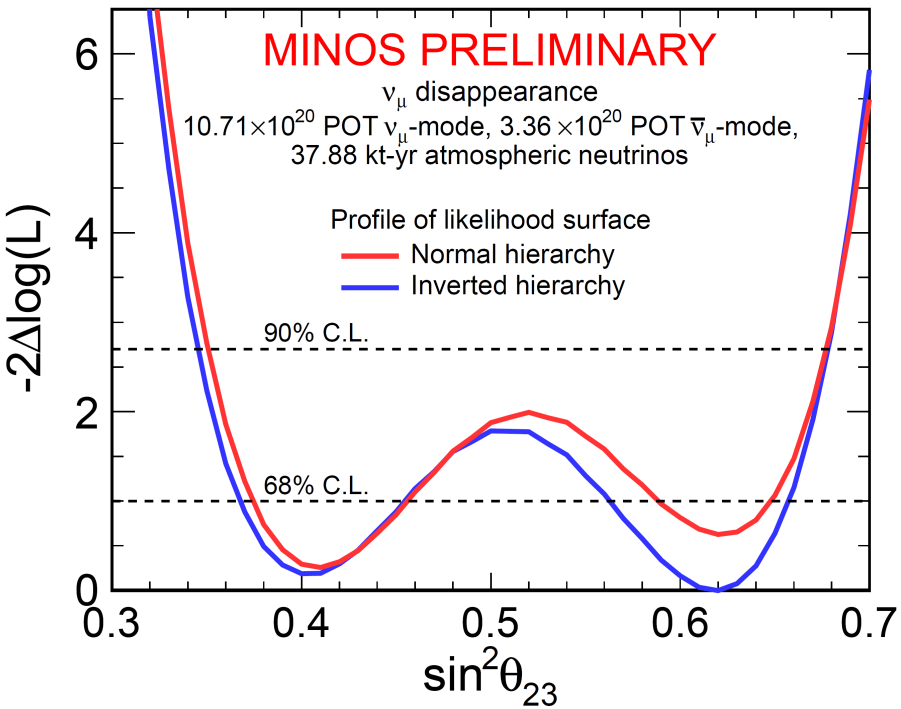
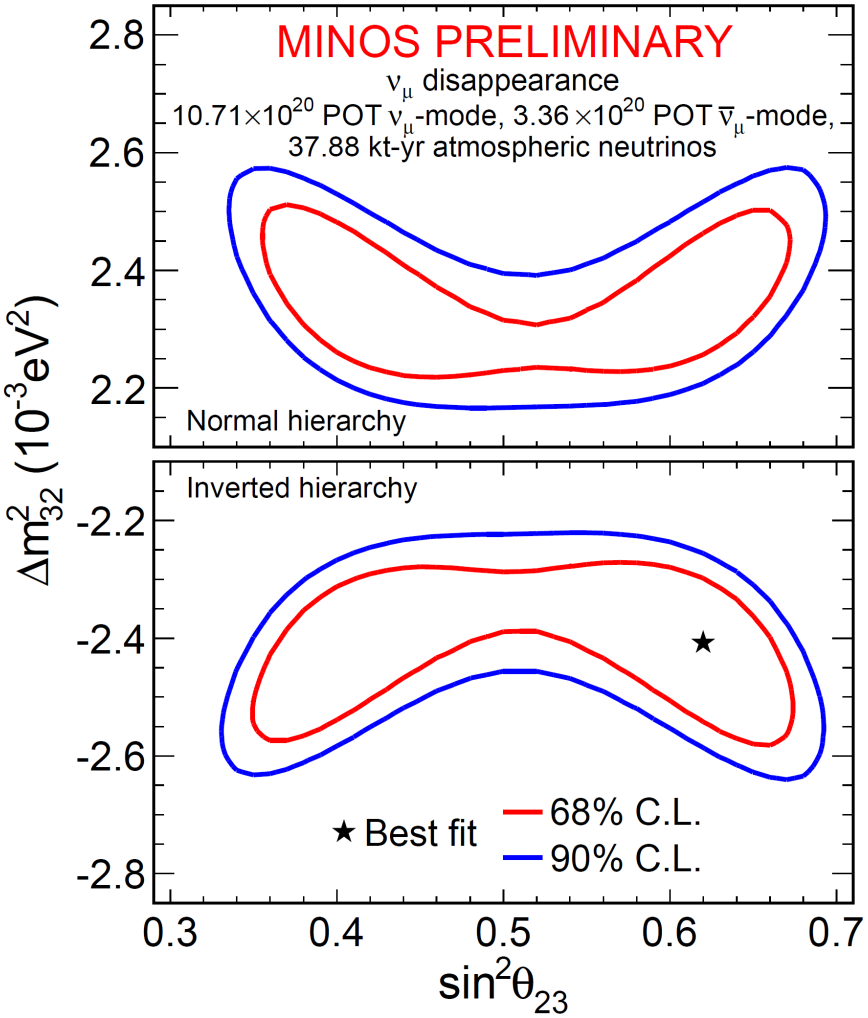
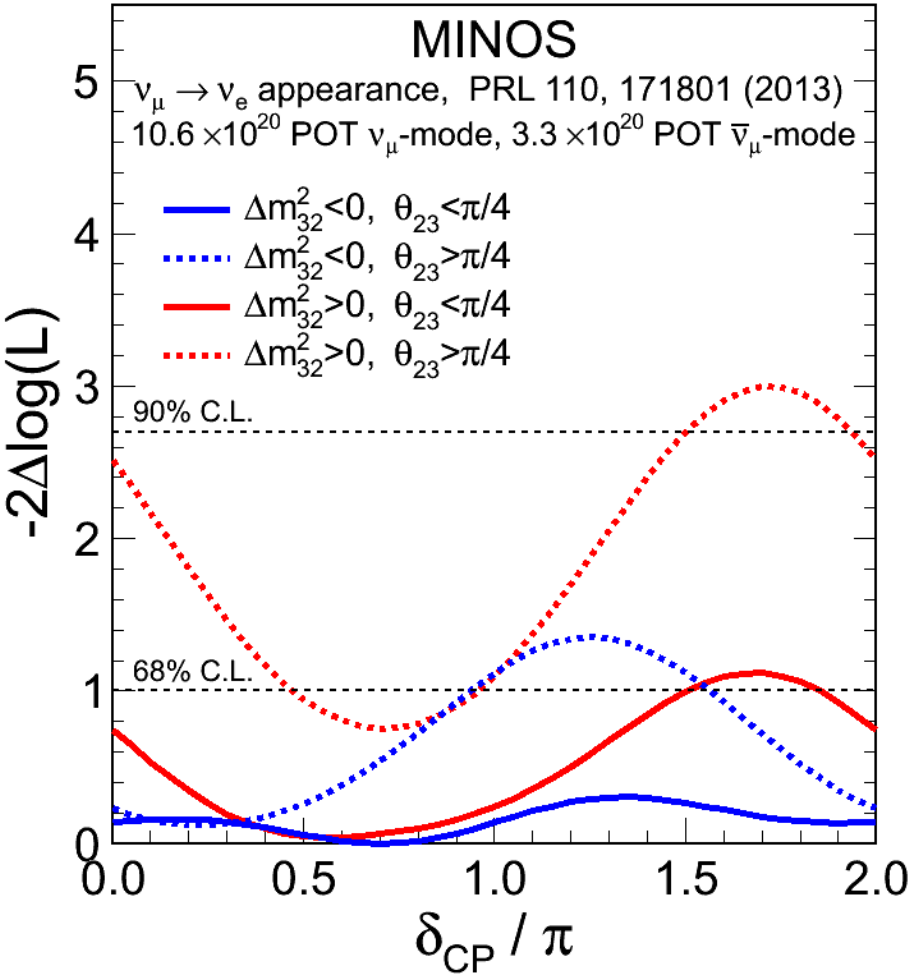


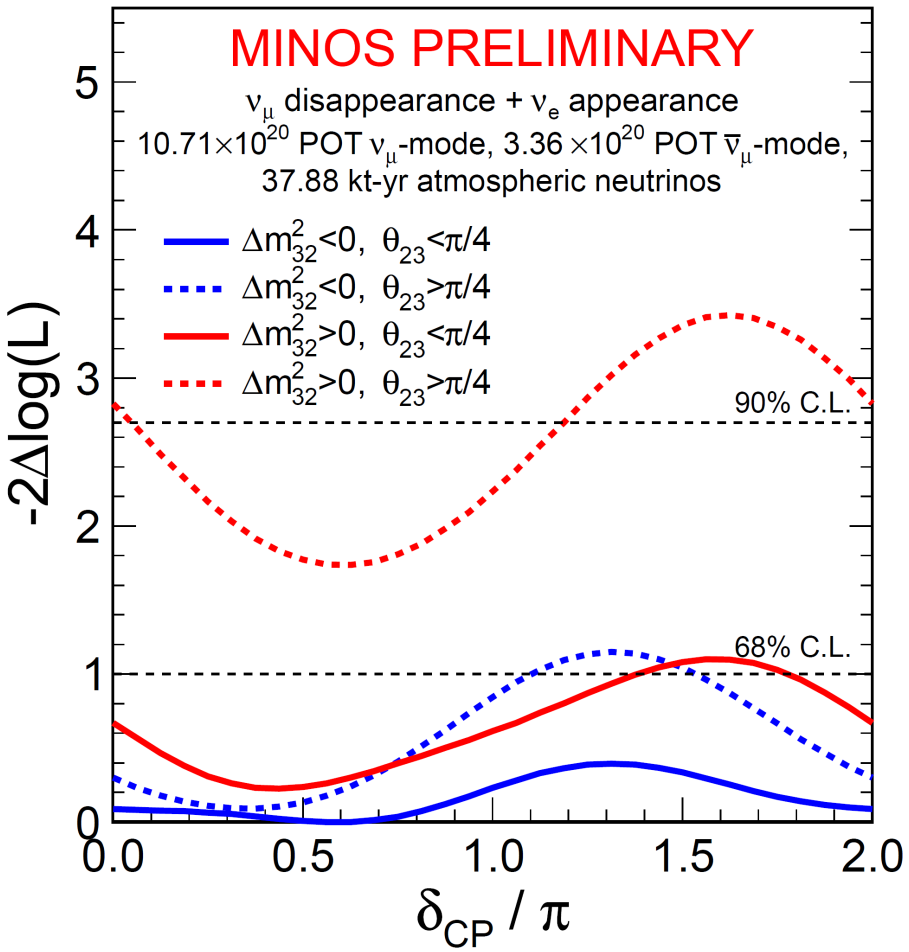


Combining with ν_e Appearance



- Appearance result also probes 3-flavor oscillations

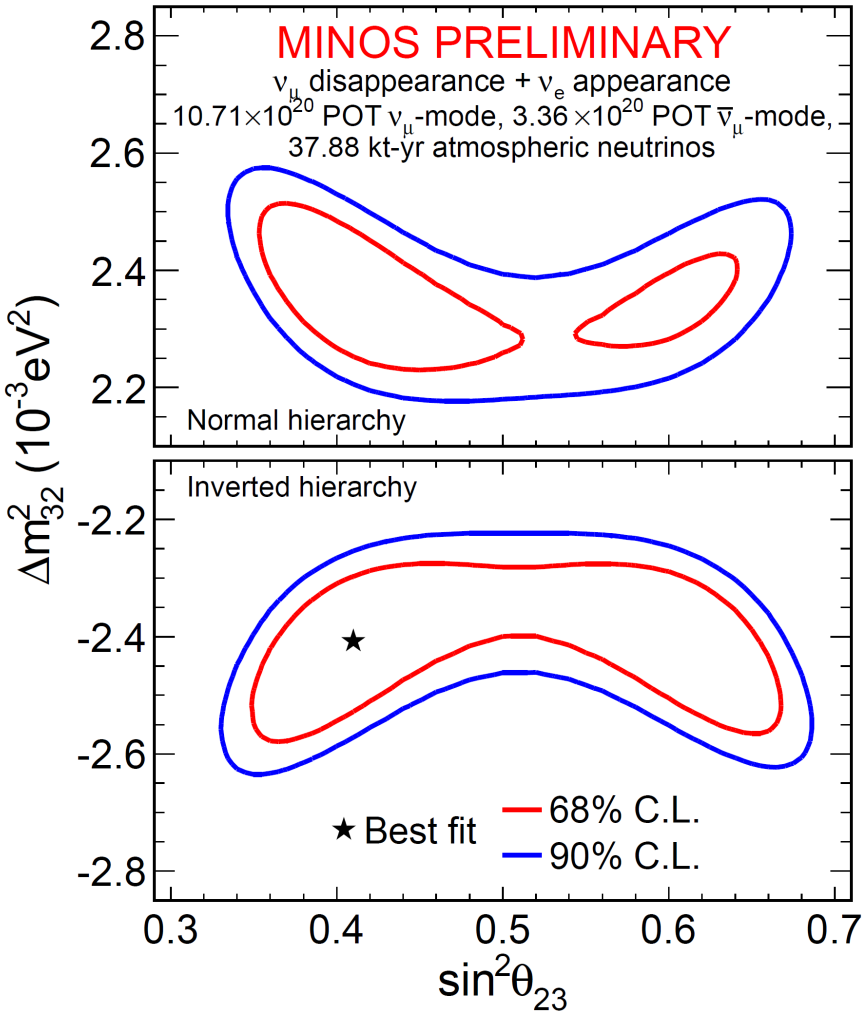
Combining with ν_e Appearance



- 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.

Combined Results

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



Combined Results

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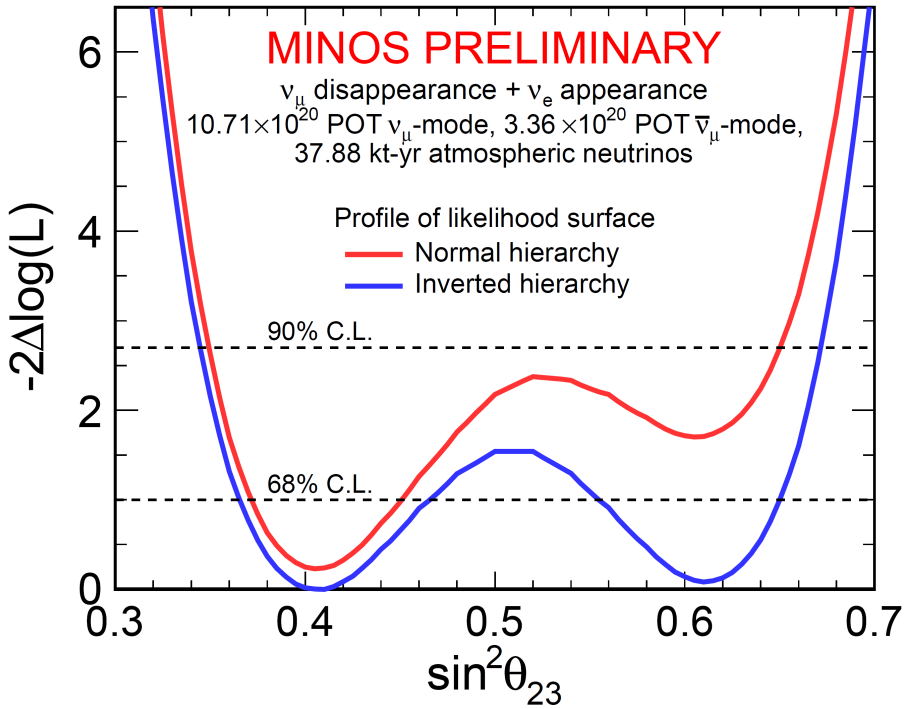
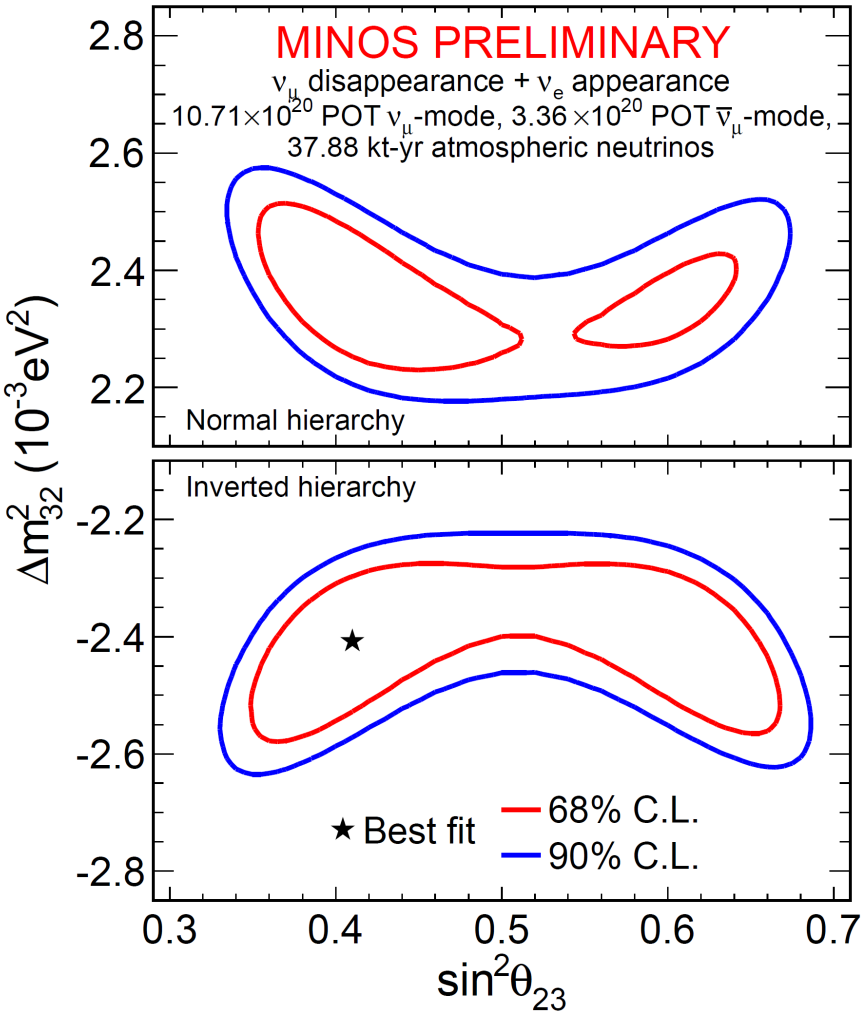
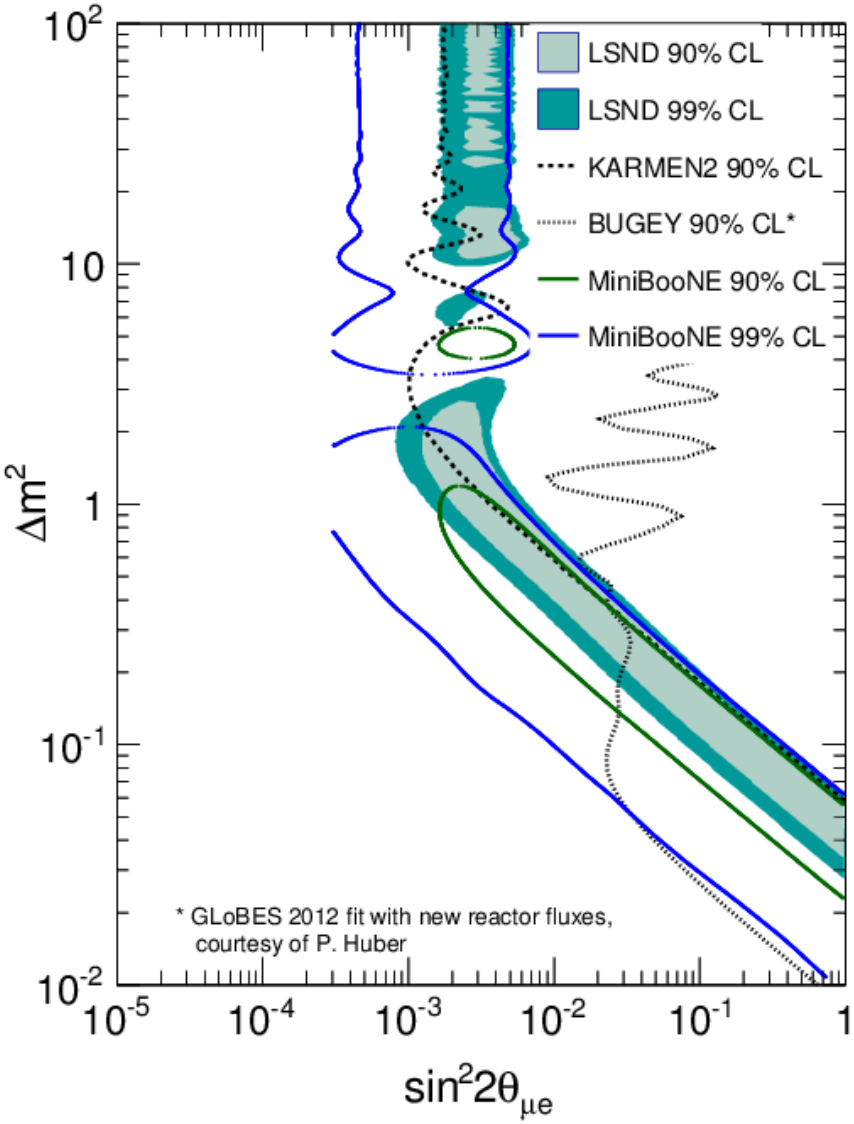




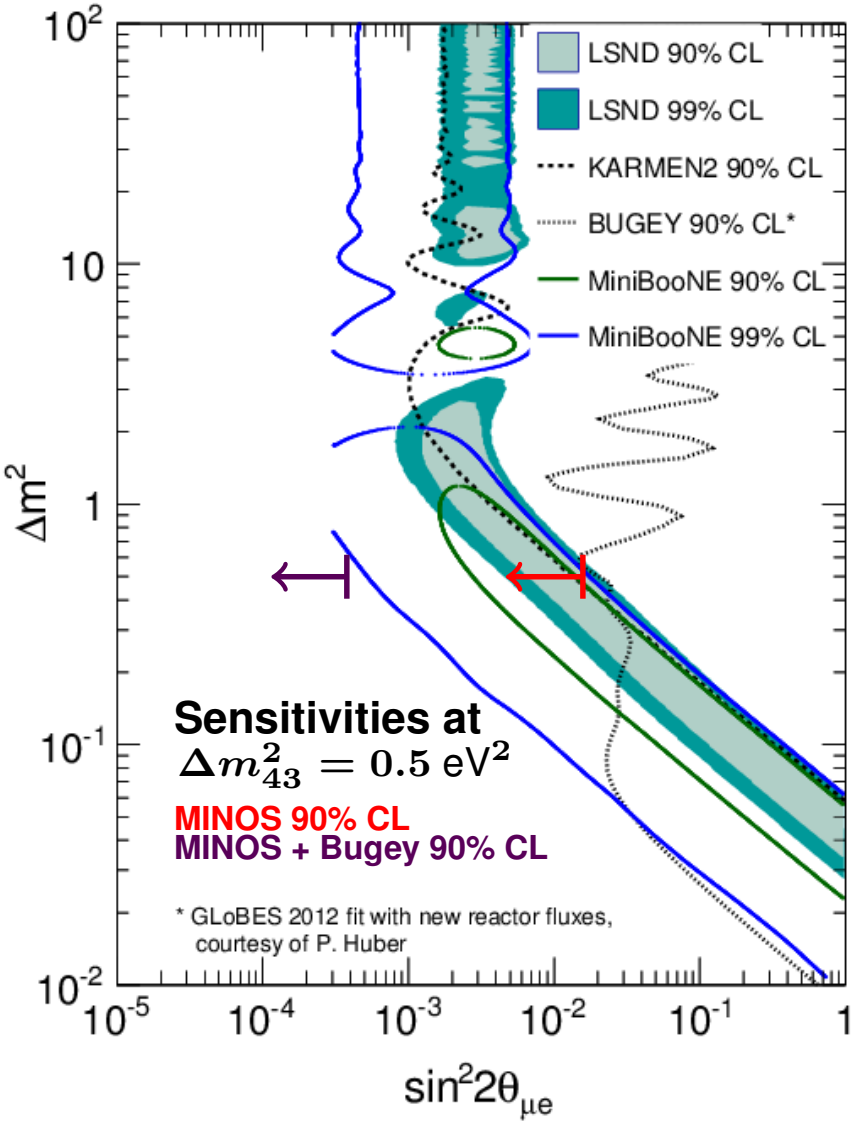
Four-flavor results

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:
  - $\sin^2(2\theta^{\oslash}_{\mu e}) \sim \sin^2(2\theta_{14}) \sin^2\theta_{24}$
  - $\sin^2(2\theta^{\oslash}_{ee}) \sim \sin^2(2\theta_{14}) \lesssim 2\%$
  - $\sin^2(2\theta^{\oslash}_{\mu\mu}) \sim \sin^2(2\theta_{24})$
  - $\sin^2(2\theta^{\oslash}_{\mu s}) \sim \sin^2(2\theta_{24}) \cos^2\theta_{34}$

Sterile Neutrino Controversy



- LSND and MiniBooNE have seen $\nu_\mu \to \nu_e$ signals with $> 3\sigma$ at $L/E \sim 1$ km/GeV
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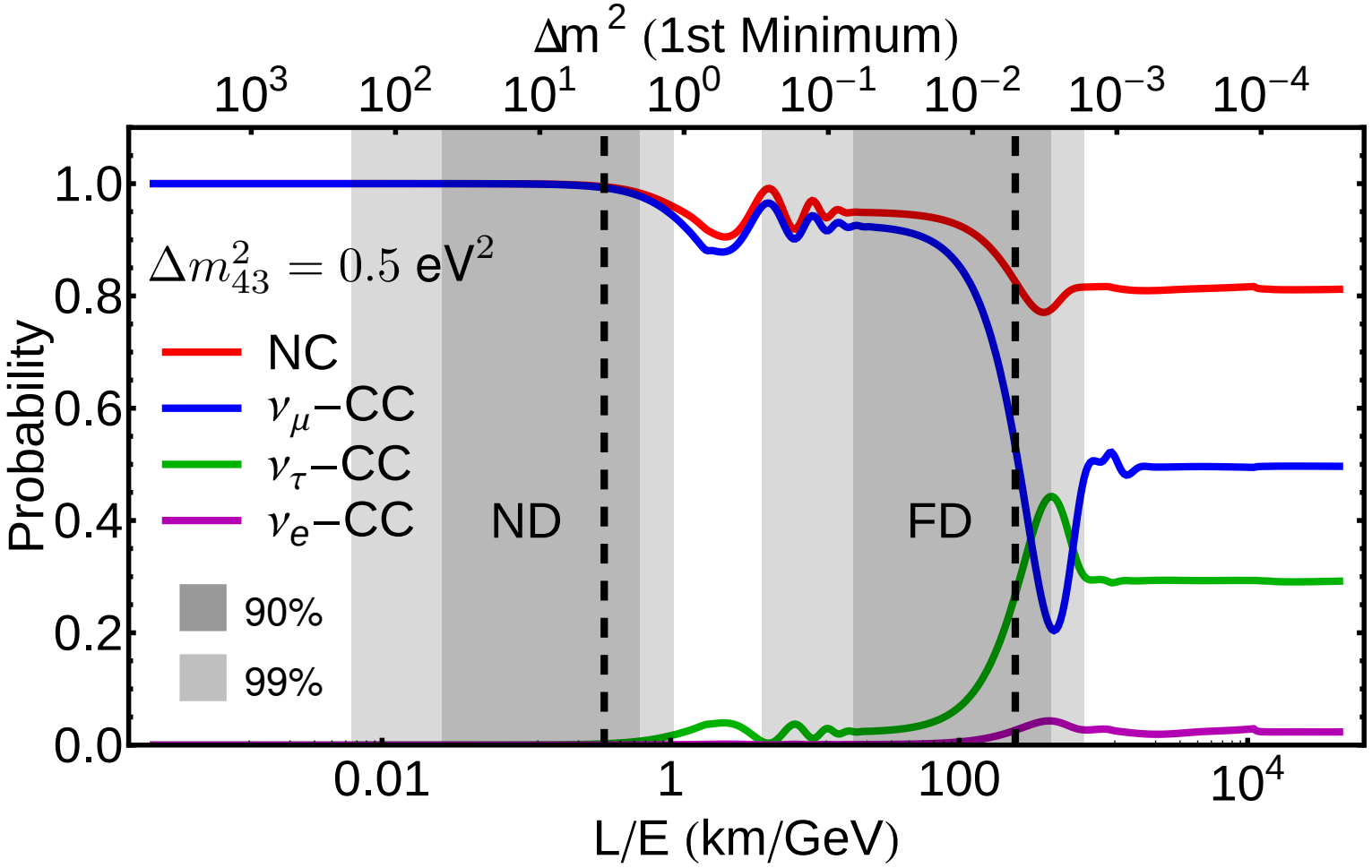
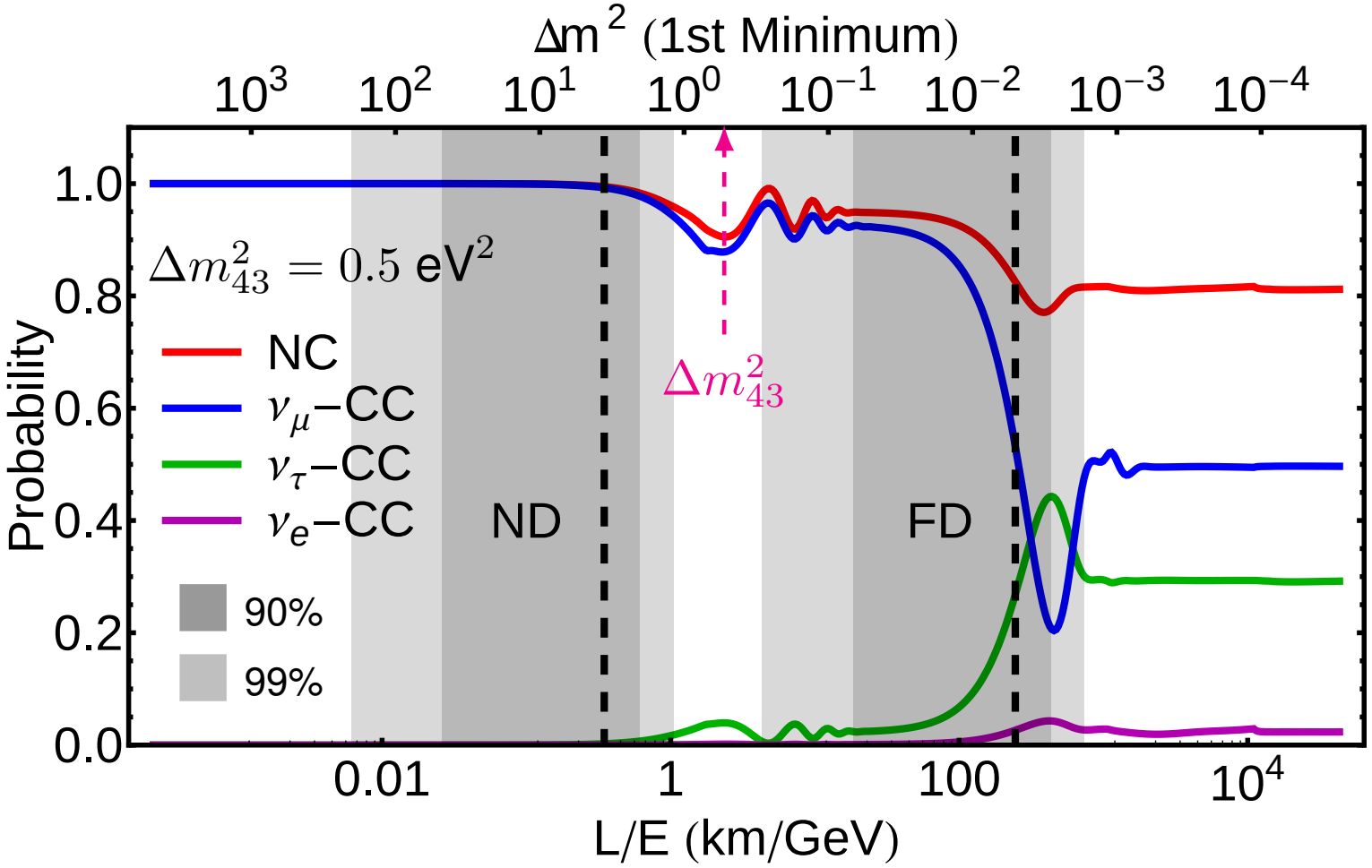
  - $\sin^2(2\theta^{\not{\odot}}_{\mu\mu}) \sim \sin^2(2\theta_{24})$
  - $\sin^2(2\theta^{\not{\odot}}_{\mu s}) \sim \sin^2(2\theta_{24}) \cos^2\theta_{34}$

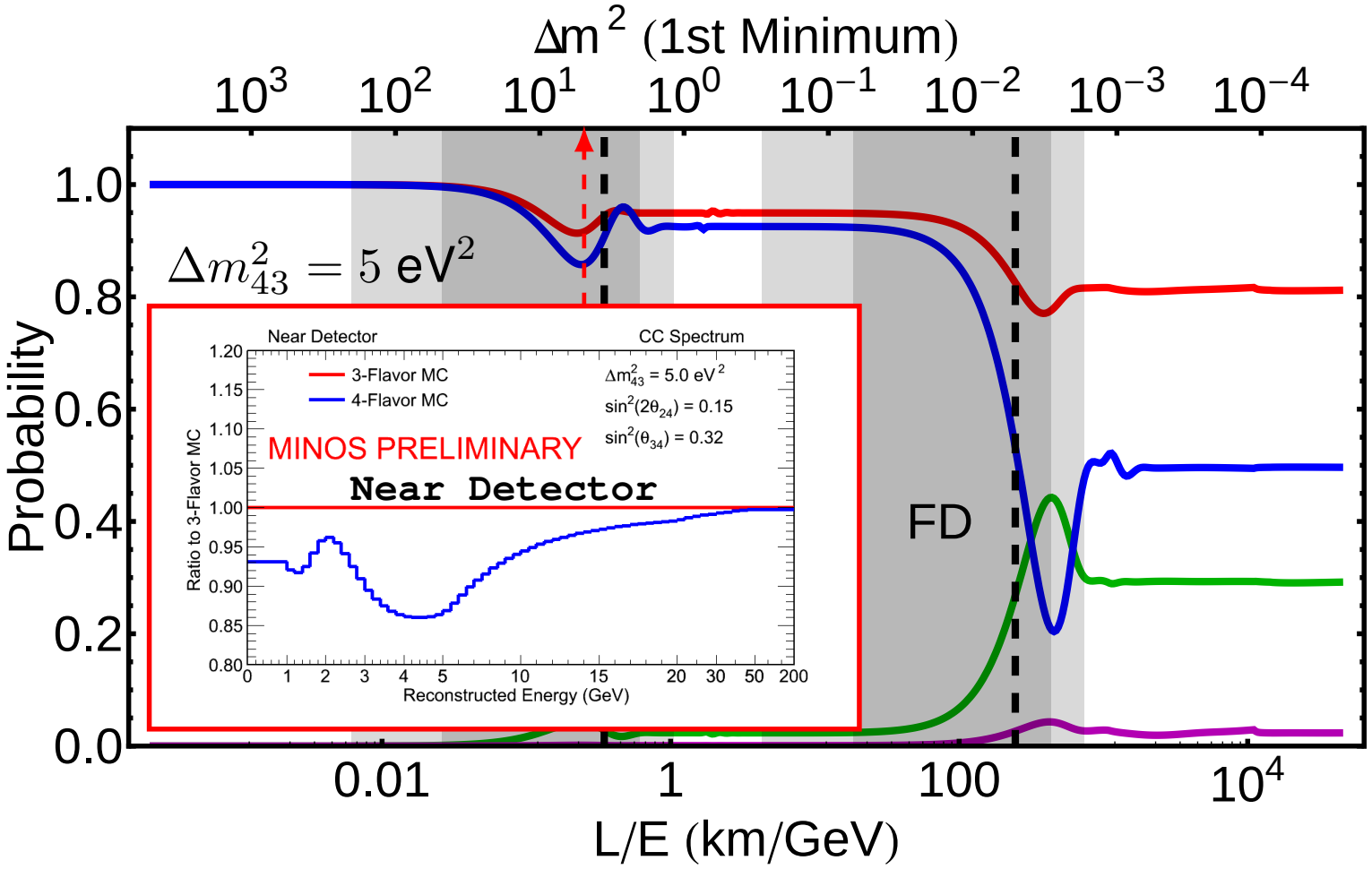
Survival probability



Survival probability

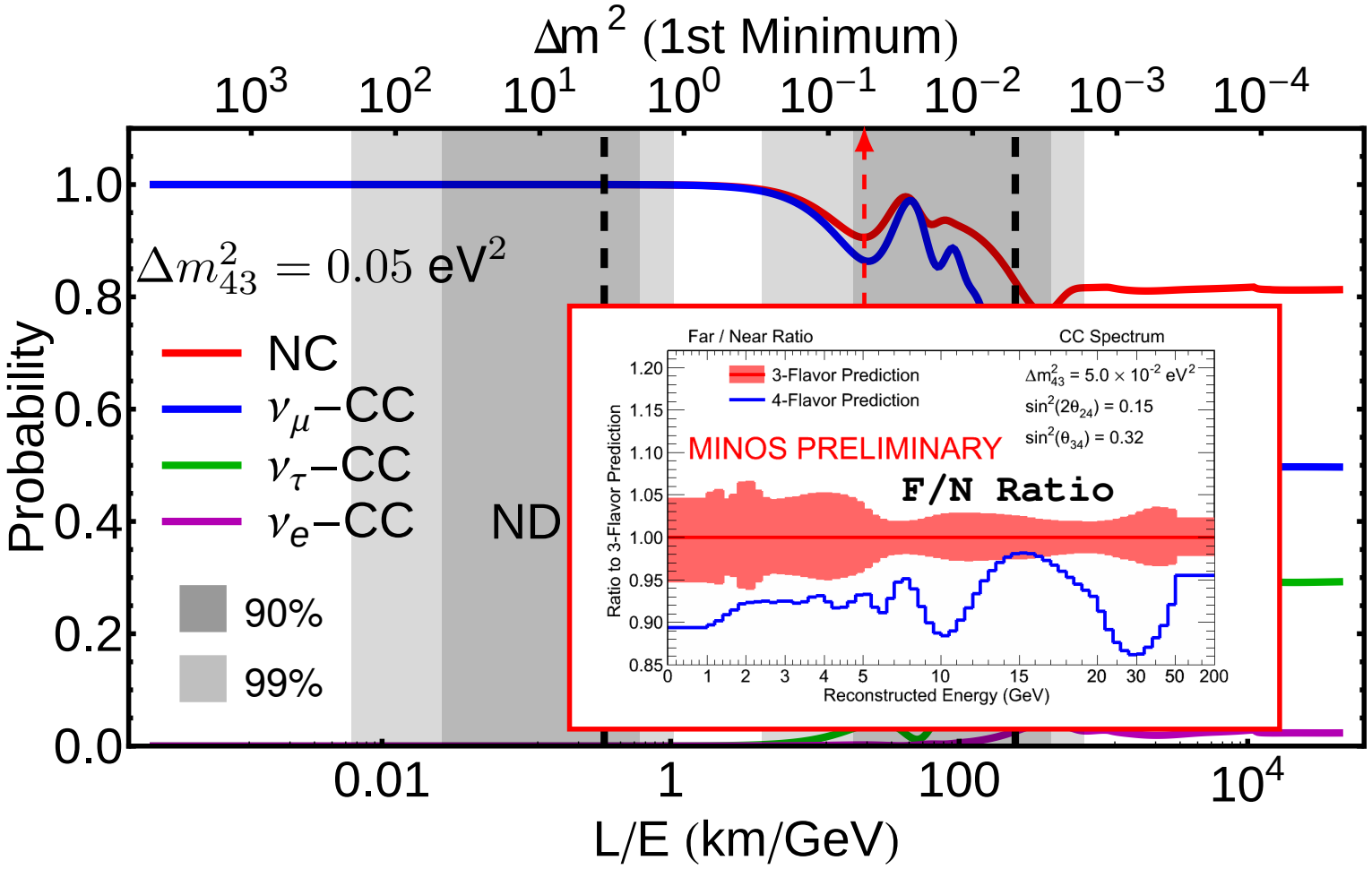


Survival probability



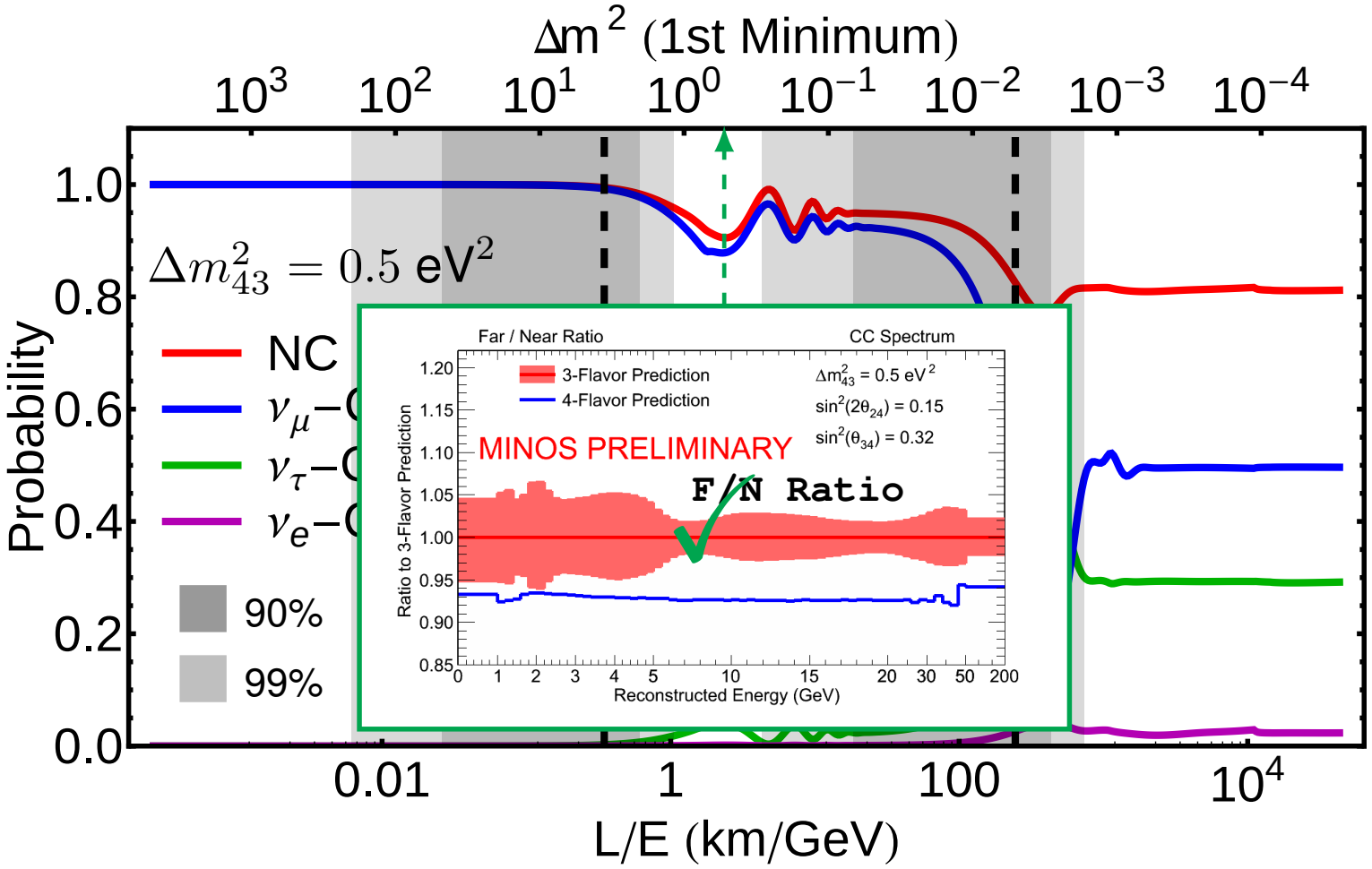
Sensitive to π decay position and additional systematics

Survival probability



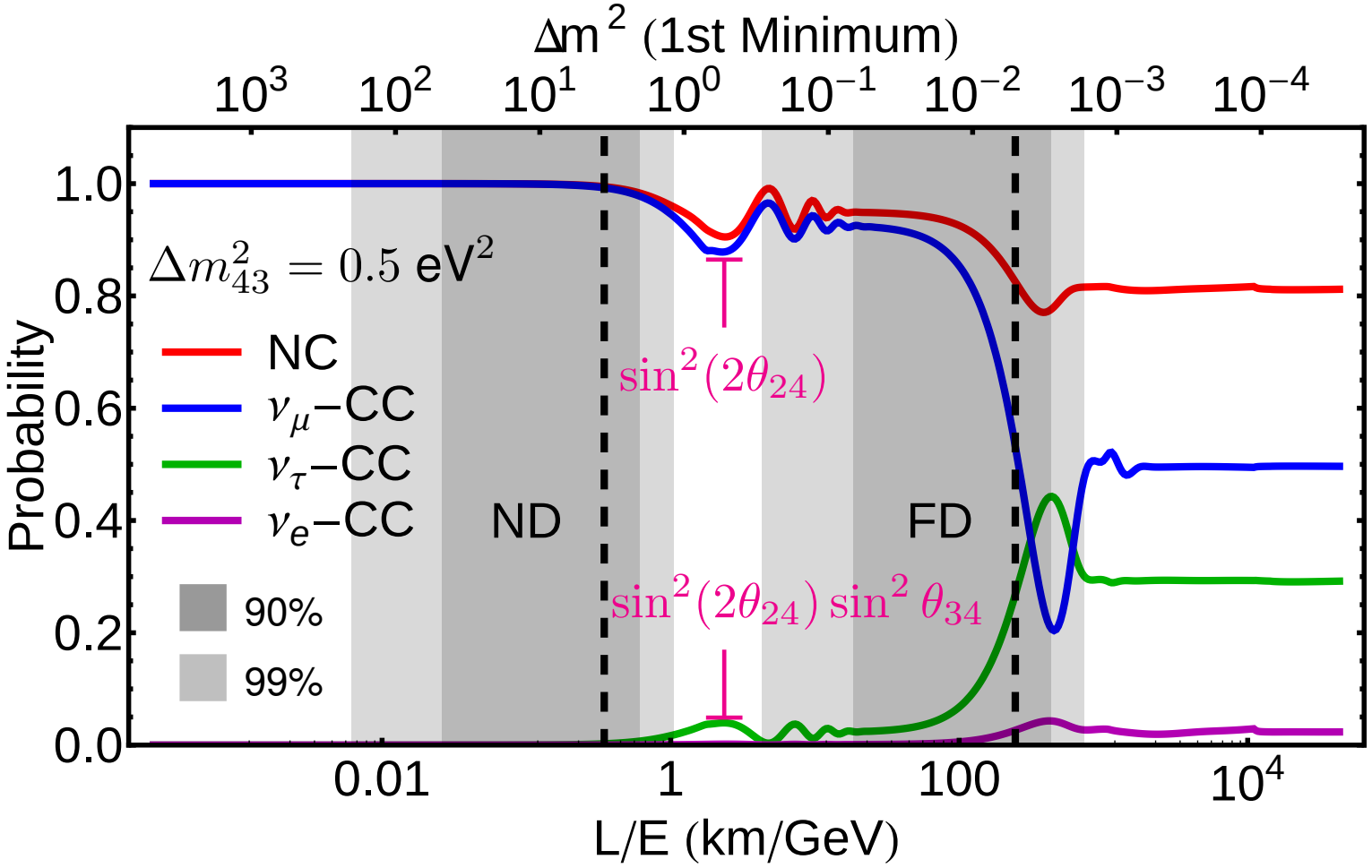
Uncertainty in Far/Near ratio is less well known at high energies

Survival probability

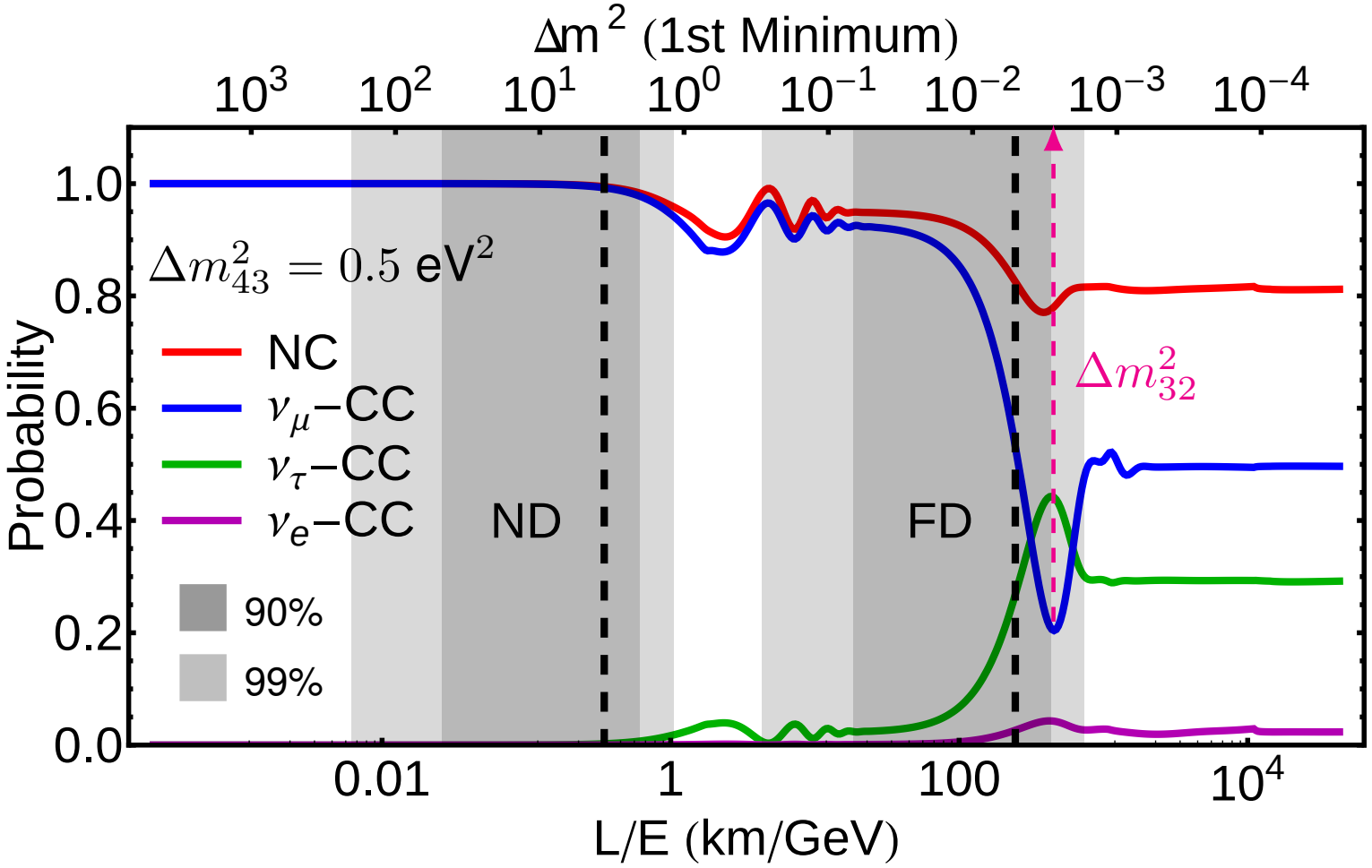


Very little spectral distortion in both detectors

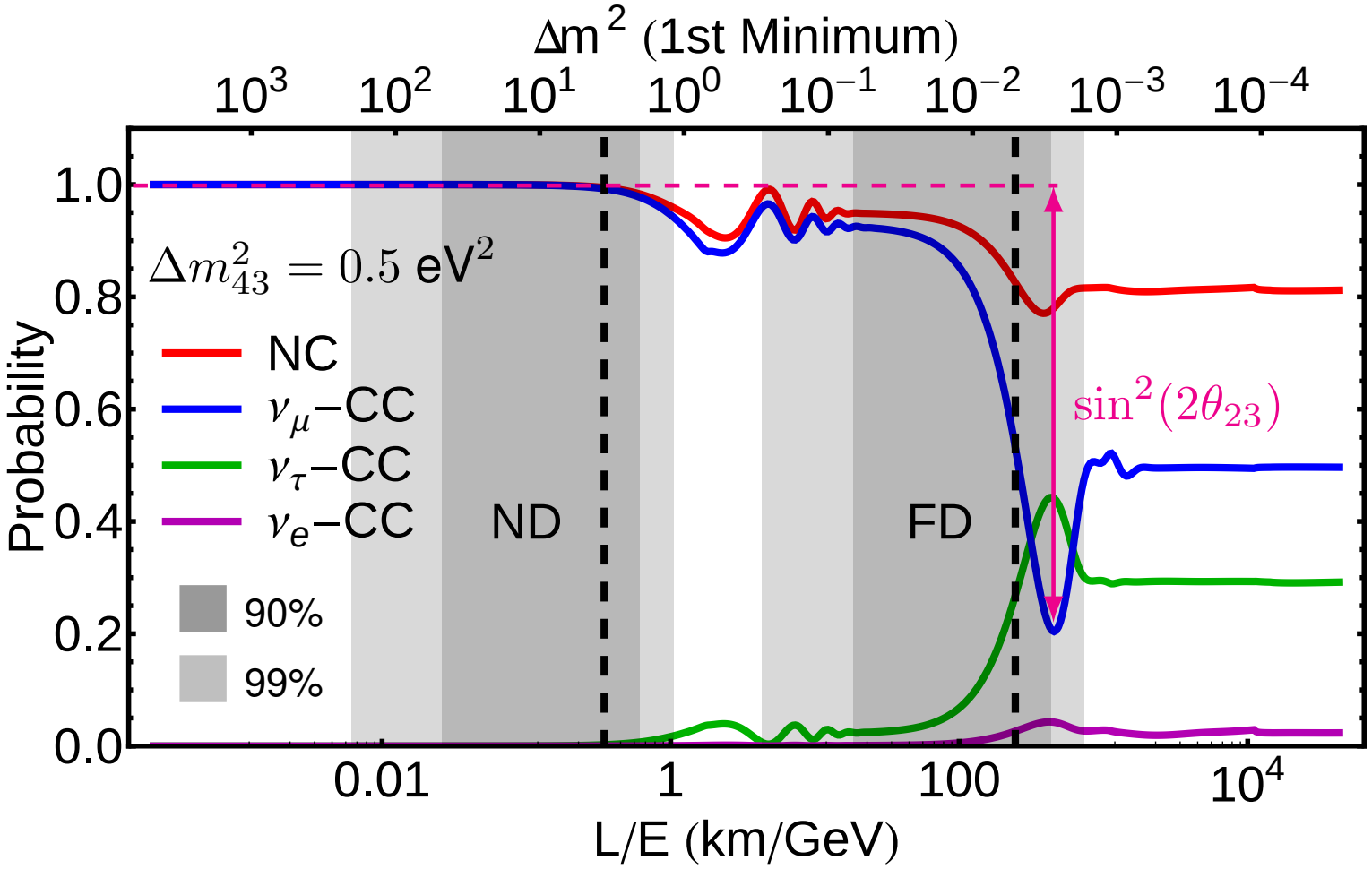
Survival probability



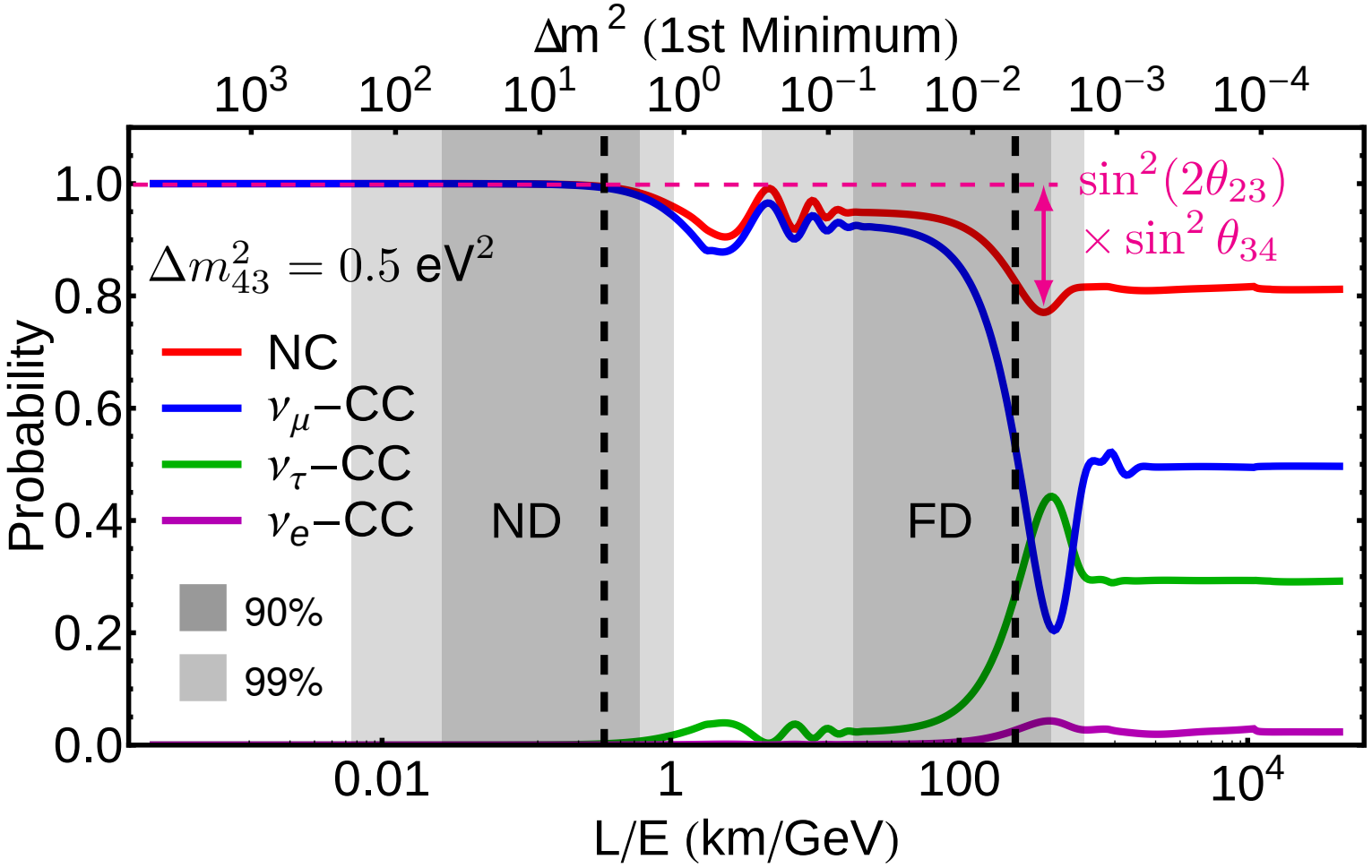
Survival probability



Survival probability



Survival probability

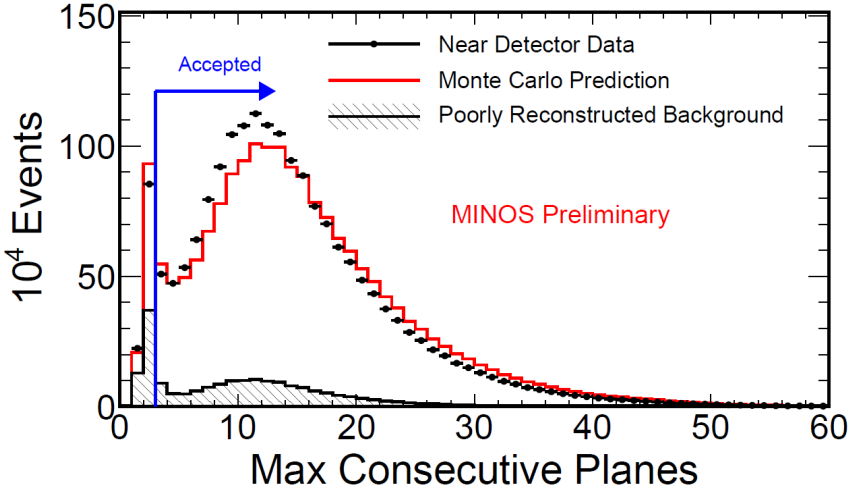


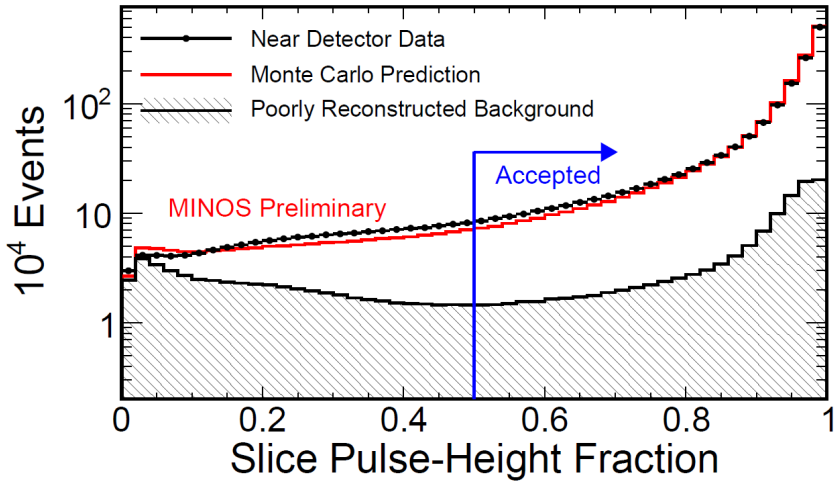
Analysis overview

- Beam exposure: 10.56×10^{20} POT taken in low energy neutrino mode
  - Select for NC interactions
  - Select for $\nu_\mu + \overline{\nu}_\mu$ CC interactions
- Oscillate MC predictions in both detectors
- Use ratio of ND data and MC to correct FD prediction
- Not sensitive to effects correlated between detectors
- Fit in 4D parameter space: $(\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2\theta_{24}, \sin^2\theta_{34})$
- Include 11 systematics as nuisance parameters in the fit

Event Selection

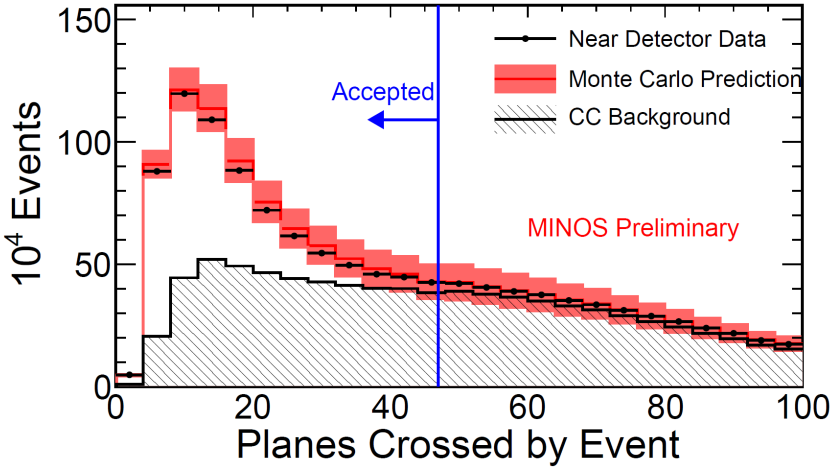
- Event Cleaning
  - Remove poorly reconstructed events in the ND
  - Remove noise and cosmic background in the FD

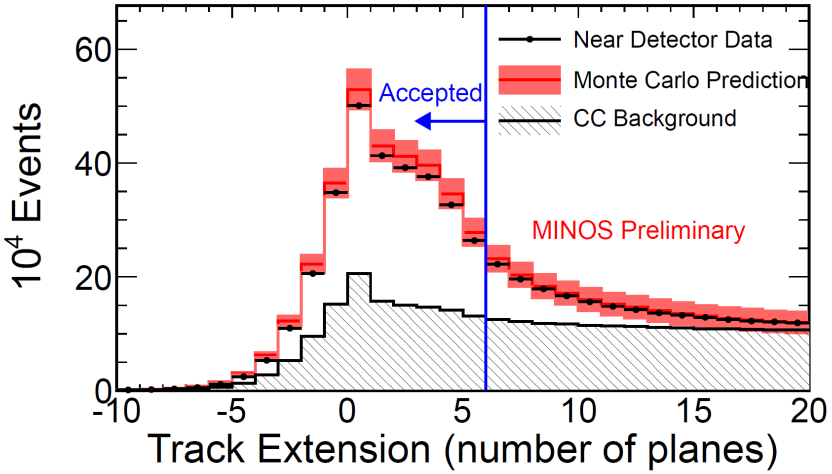




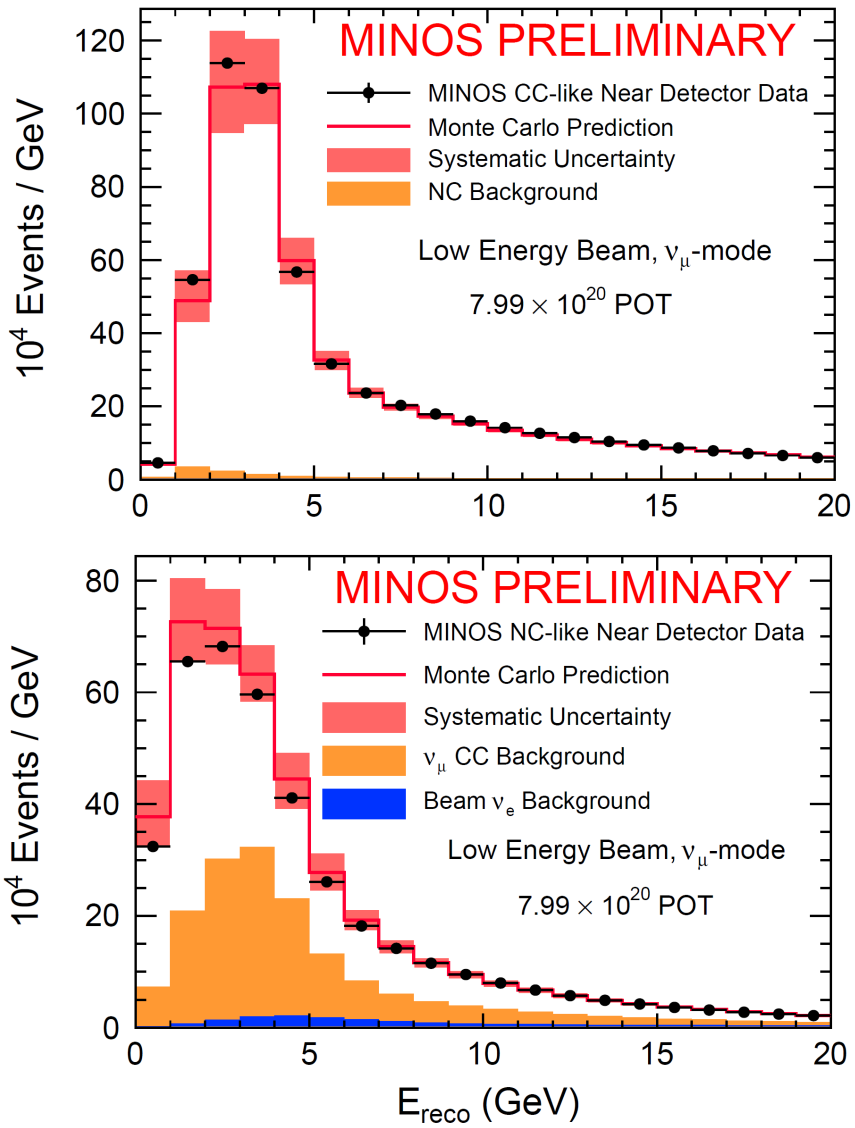
Event Selection

- Event Cleaning
  - Remove poorly reconstructed events in the ND
  - Remove noise and cosmic background in the FD
- NC Selection
  - Event crosses $<$47 planes
  - Existing tracks extend $<$6 planes over the event shower
- ν_μ-CC Selection
  - Standard ν_μ-CC selection applied to events that fail NC cuts

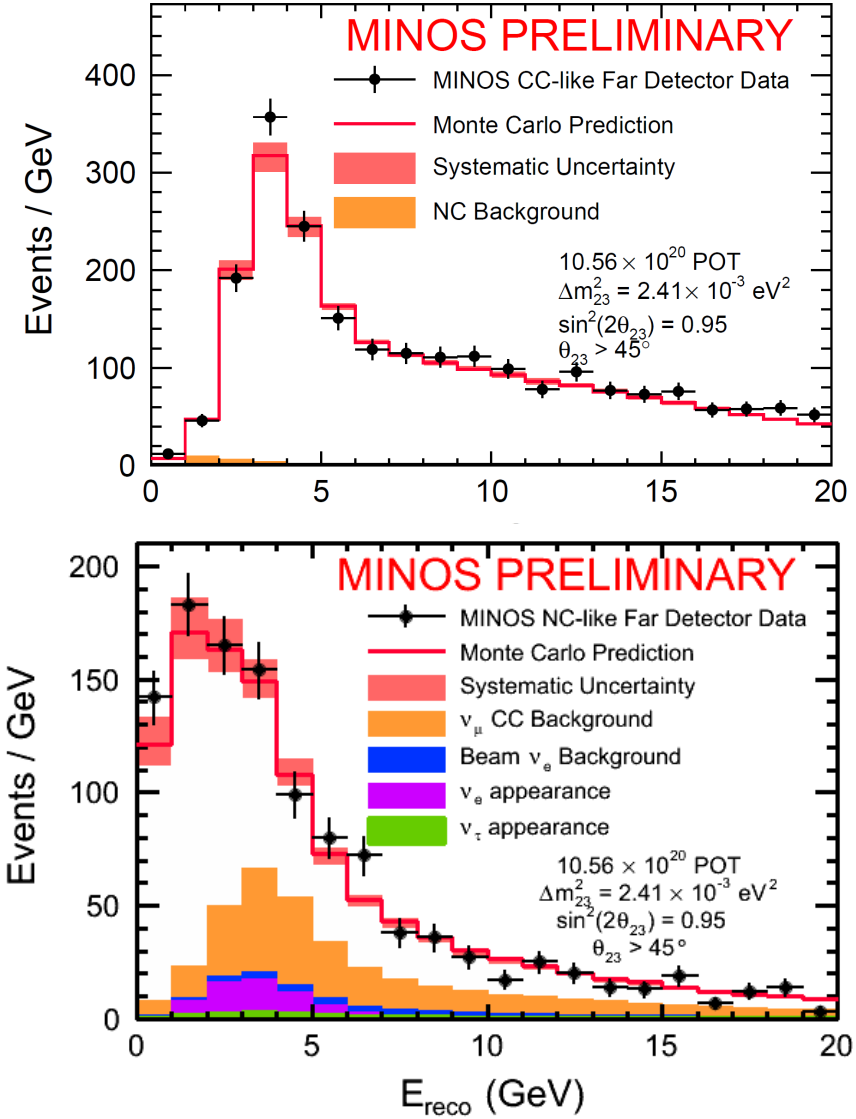




Results

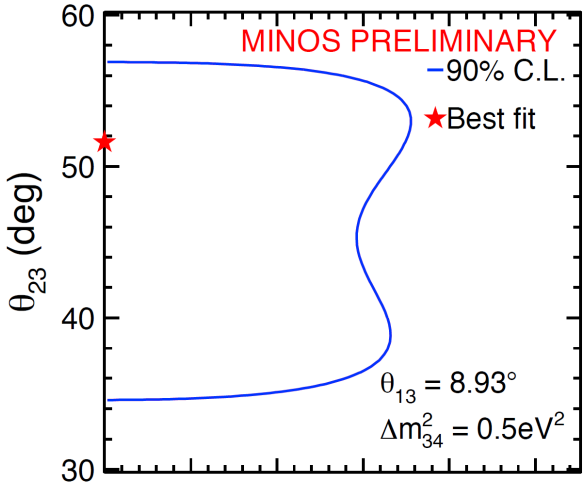

MINOS PRELIMINARY
MINOS CC-like Near Detector Data
Monte Carlo Prediction
Systematic Uncertainty
NC Background
Low Energy Beam, ν_μ-mode
7.99×10^{20} POT
10^4 Events / GeV
MINOS PRELIMINARY
MINOS NC-like Near Detector Data
Monte Carlo Prediction
Systematic Uncertainty
ν_μ CC Background
Beam ν_e Background
Low Energy Beam, ν_μ-mode
7.99×10^{20} POT
10^4 Events / GeV
E_{reco} (GeV)

Results

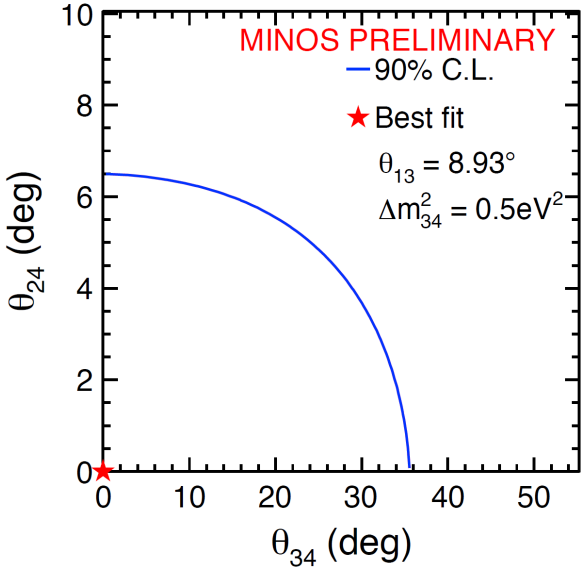


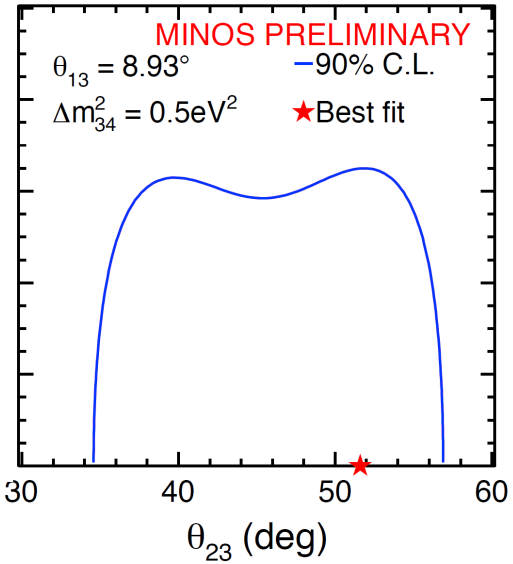
- We have found no evidence of sterile neutrino mixing at $\Delta m^2_{43} = 0.5$ eV^2
- Selected 2712 ν_μ-CC candidates
- Selected 1221 NC candidates
- NC Statistics:
  - $R = \frac{Data - CC_{Bkgd}}{NC_{Pred}}$
  - 0-200 GeV: $R = 1.049 \pm 0.076$
  - 0-3 GeV: $R = 1.093 \pm 0.097$
  - 3-200 GeV: $R = 1.009 \pm 0.095$
- Predict 55 ν_e-CC background events in the NC sample due to $\nu_\mu \rightarrow \nu_e$ oscillations

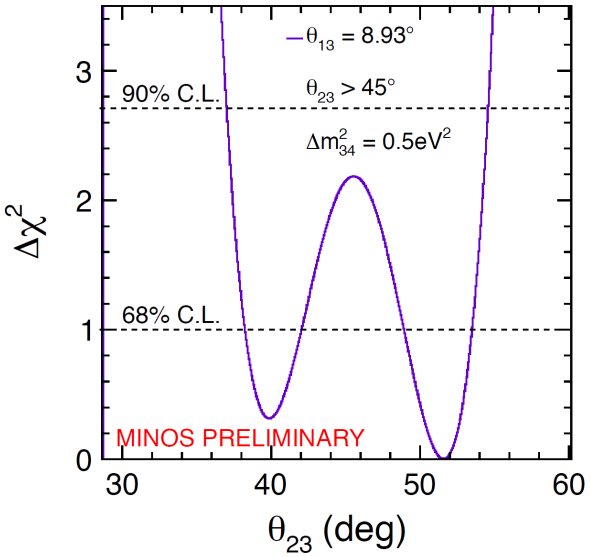
Results



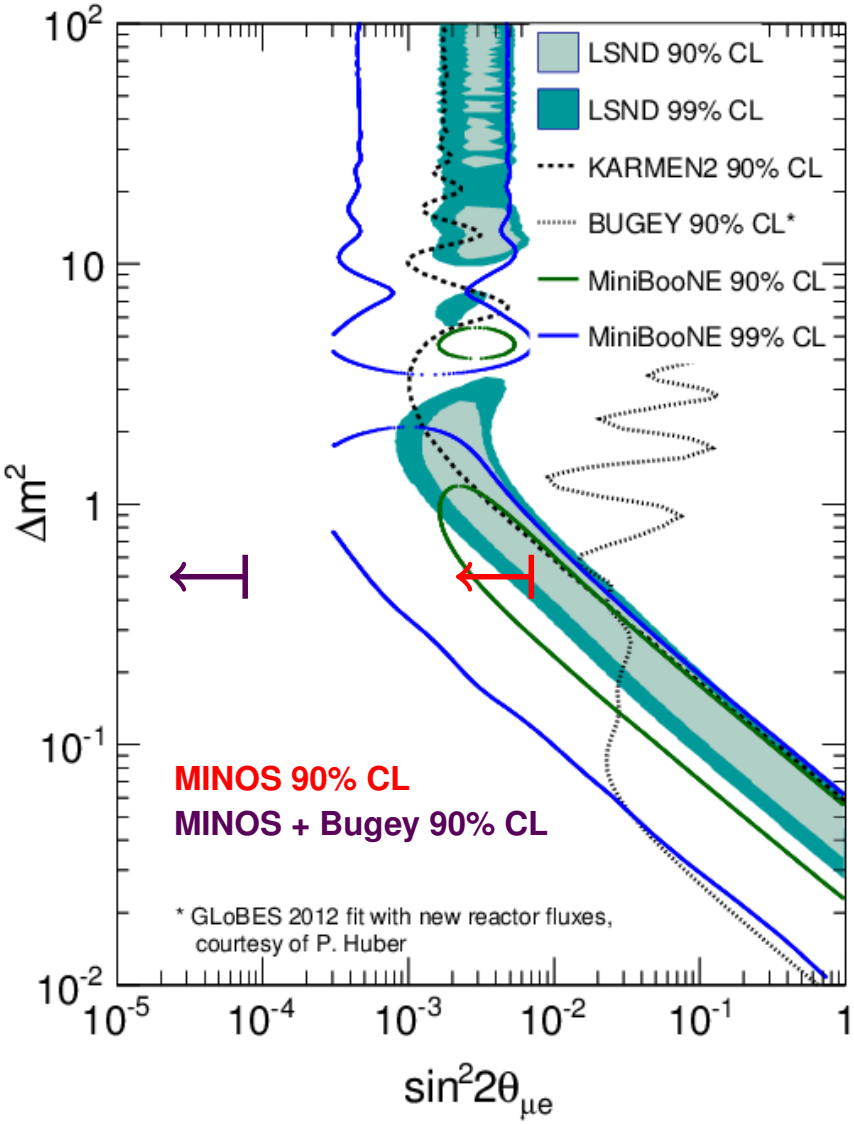
- Sensitivity to ν_e appearance gives slight preference for $\theta_{23} > 45^\circ$
- $\sin^2\theta_{24} < 0.0071$ ($\theta_{24} < 4.8^\circ$) at 90% C.L.
- $\sin^2\theta_{34} < 0.17$ ($\theta_{34} < 24^\circ$) at 90% C.L.







Sterile Limits



- Due to a small overall excess observed in data, we obtain stronger limits than our sensitivity
- At $\Delta m^2_{43} = 0.5$ eV^2:
- MINOS only: $\sin^2(2\theta^{\oslash}_{\mu e}) < 7.1 \times 10^{-3}$ at 90% C.L.
- MINOS + Bugey: $\sin^2(2\theta^{\oslash}_{\mu e}) < 7.7 \times 10^{-5}$ at 90% C.L.

Summary

- Updated results with full 3-flavor framework

	Parameter	Best fit	Confidence limits
Normal hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}$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	$\lvert\Delta m^2_{32}\rvert/10^{-3}$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: $-2\Delta\log L = 0.09$

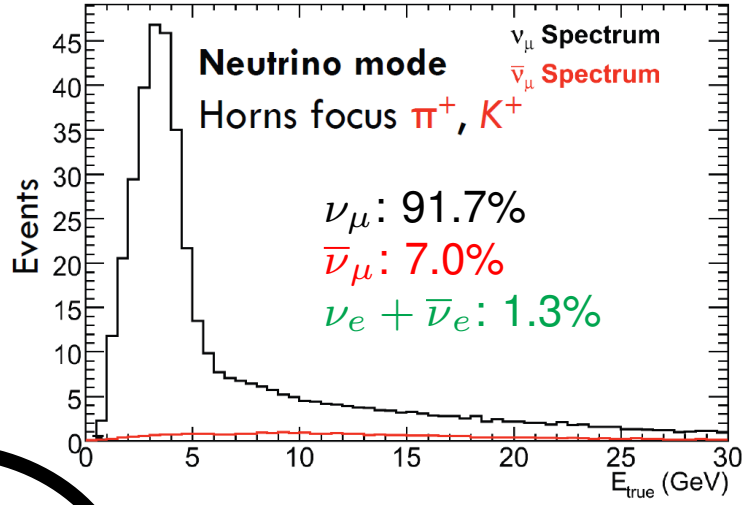
Exclusion of maximal mixing: $-2\Delta\log L = 1.54$ ($\Rightarrow$ 79% C.L.)

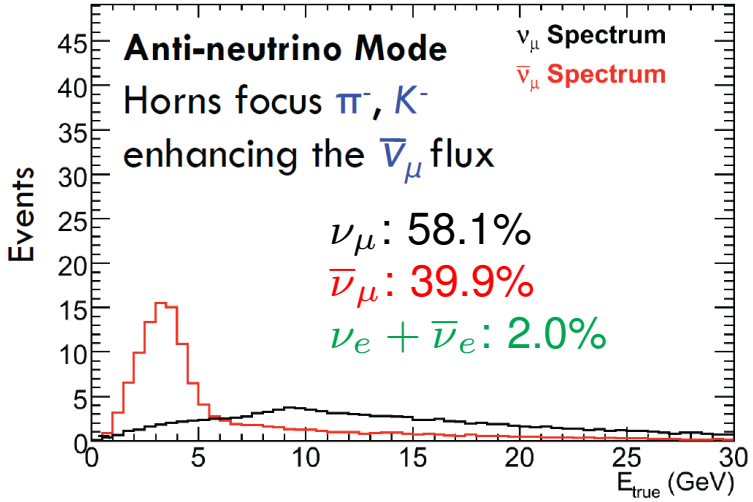
- No evidence of sterile mixing at $\Delta m^2_{43} = 0.5$ eV^2
- $\sin^2\theta_{24} < 0.0071$ ($\theta_{24} < 4.8^\circ$) at 90% C.L.
- $\sin^2\theta_{34} < 0.17$ ($\theta_{34} < 24^\circ$) at 90% C.L.
- Stay tuned for full Δm^2_{43} result

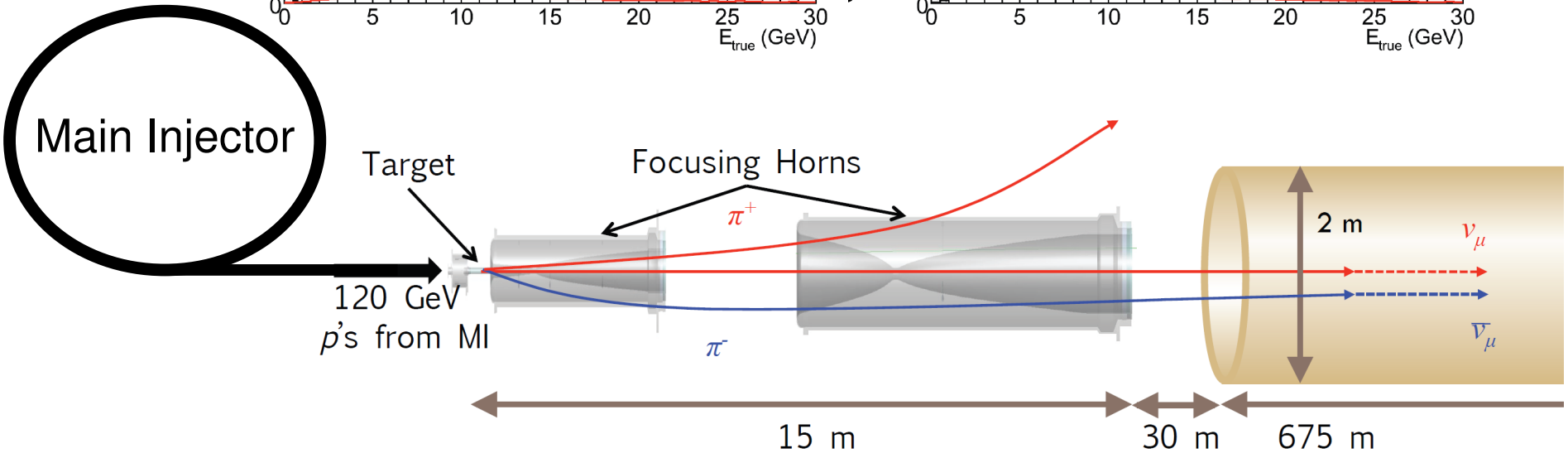
Thank you!

Backup Slides

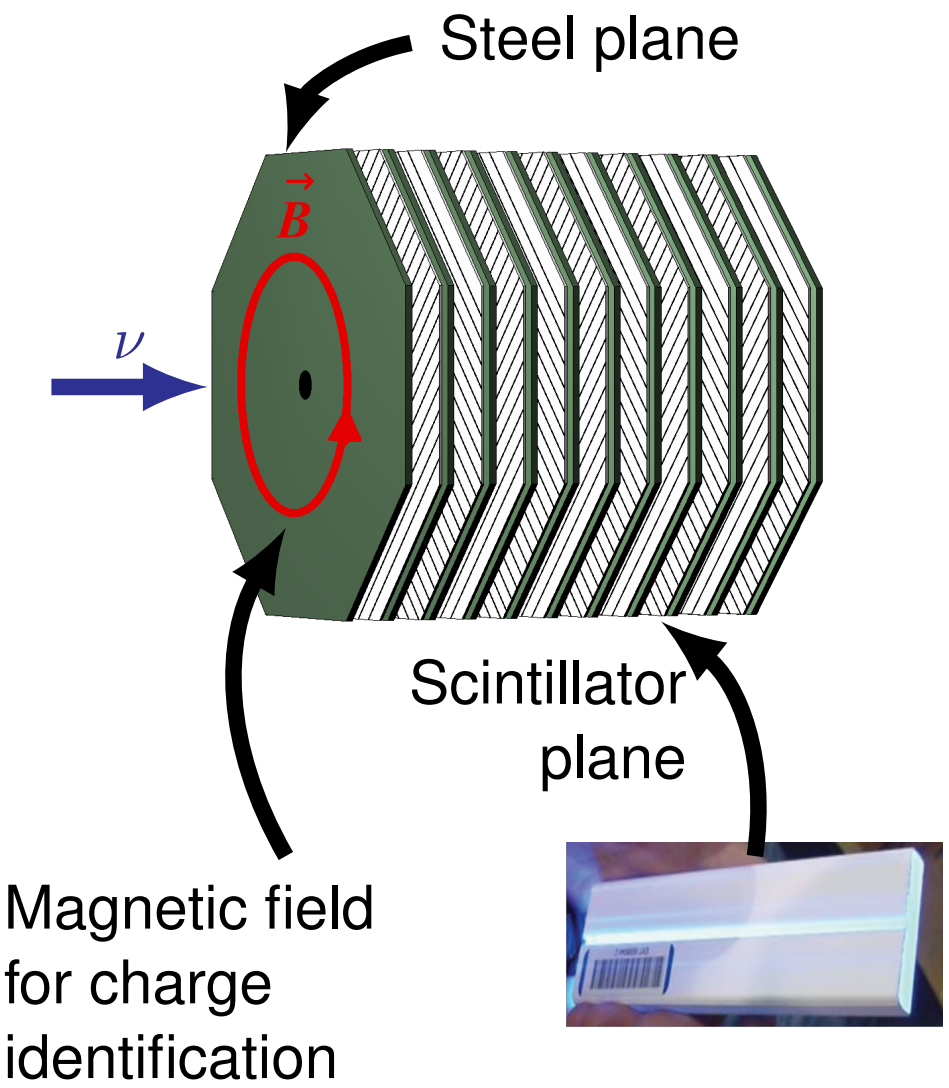
The NuMI beam

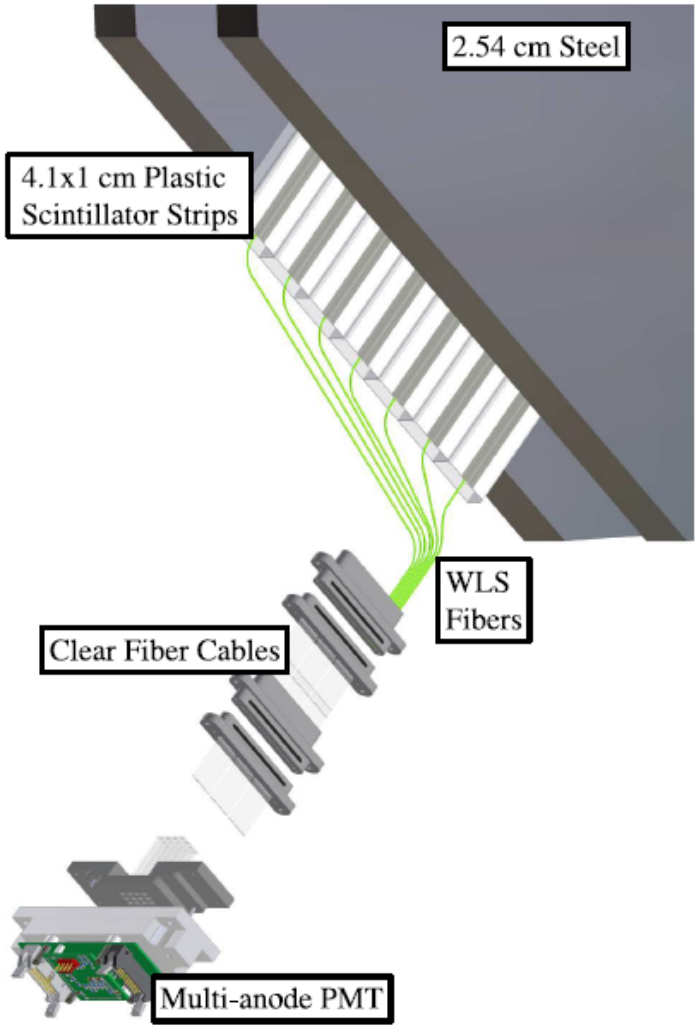






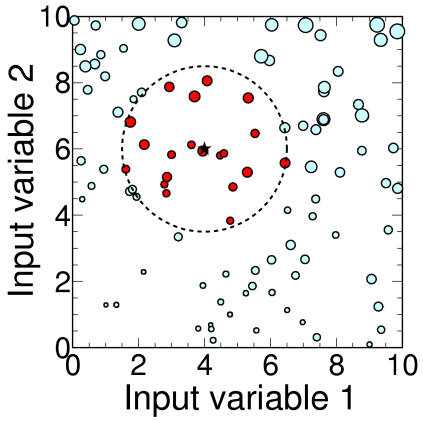
The MINOS detectors

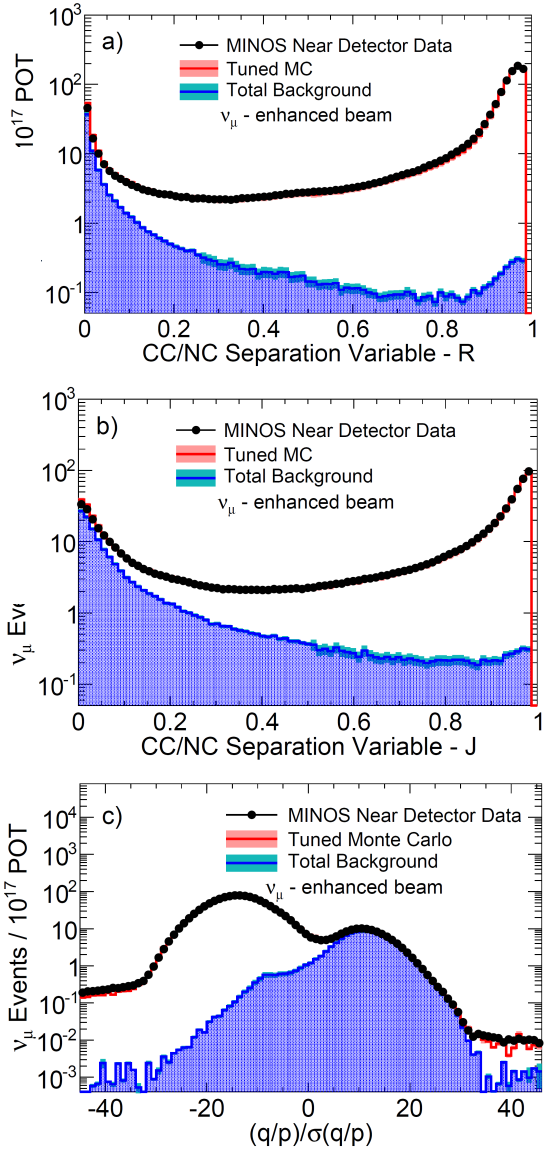




Beam ν_μ-CC selection

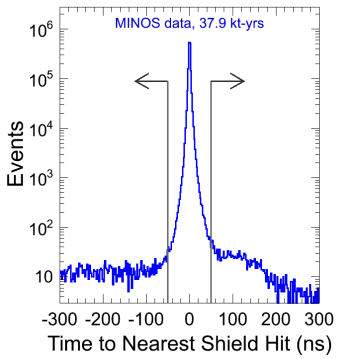
- R input variables
  - # of active planes
  - Mean PH per plane
  - PH fluctuation
  - Transverse profile
- J input variables
  - # of active planes
  - Track end PH
  - Scattering
- Select if $J > 0.5 \,||\, R > 0.25$
- Charge determined by curvature

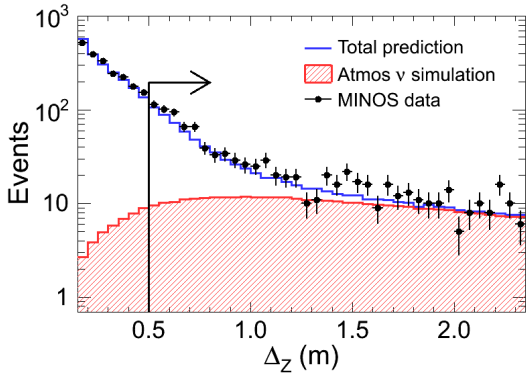


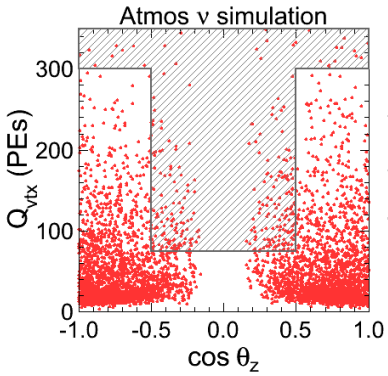


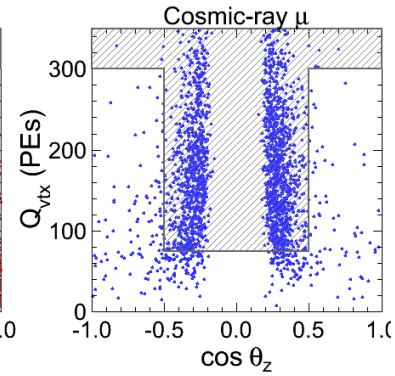
Atmospheric selection

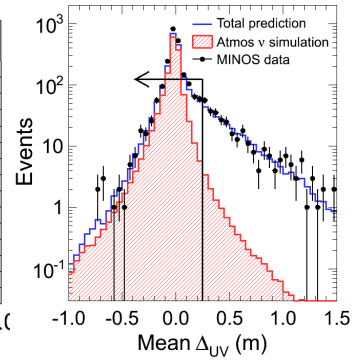
- Contained-vertex selection:
- Select events with long tracks (>8 planes)
- Use timing, direction and topology to remove cosmic rays
- Background reduced by a factor of 10^7
- Also included samples of shower-like events and rock-induced events from up-going and horizontal muons

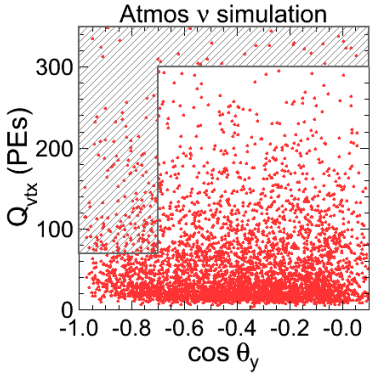


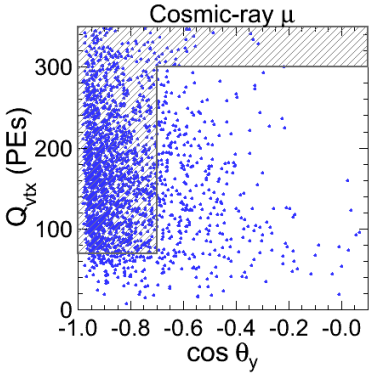


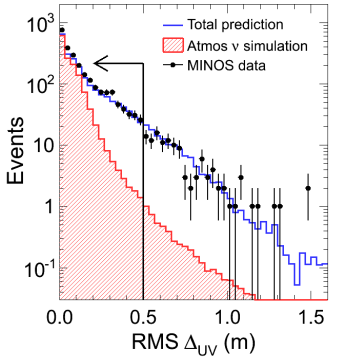








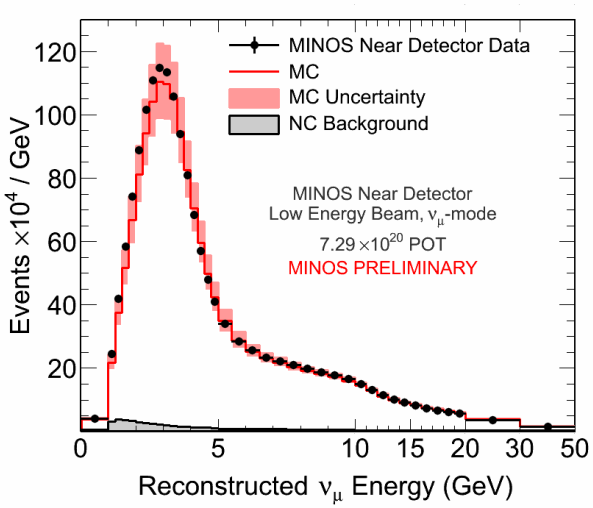


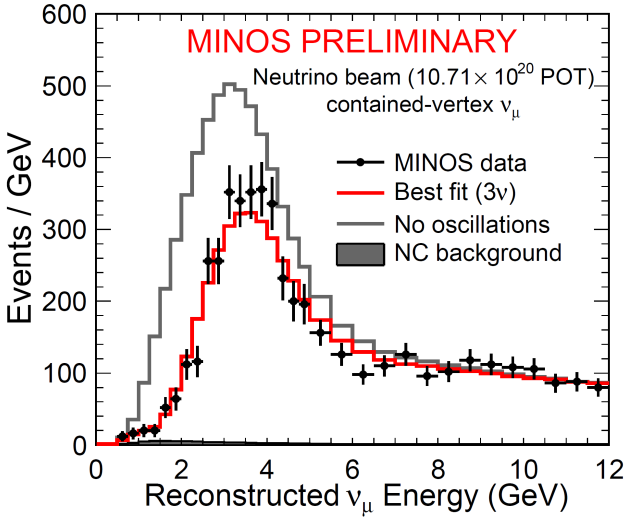


Disappearance Event Samples

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

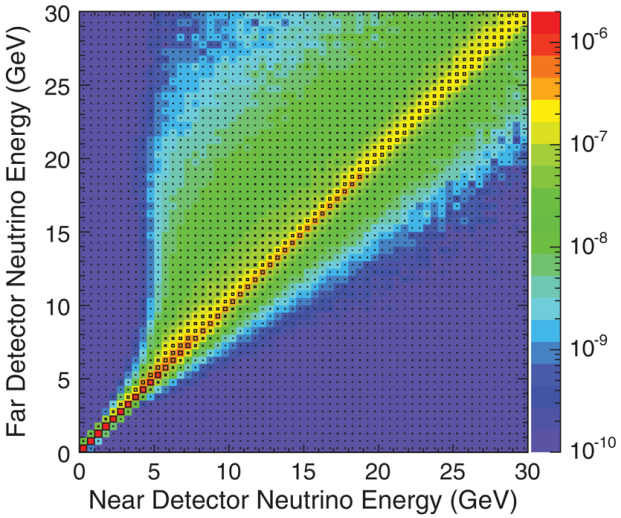
Extrapolation





Unfold

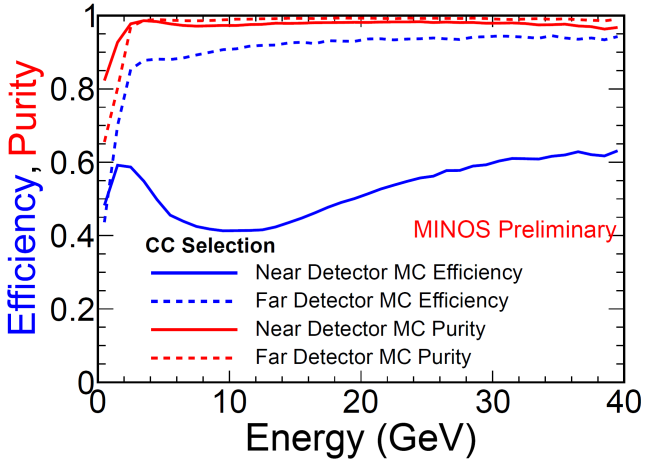
ND flux



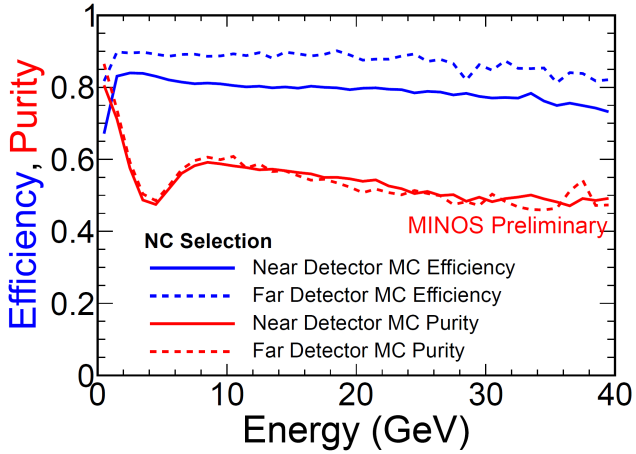
FD flux prediction

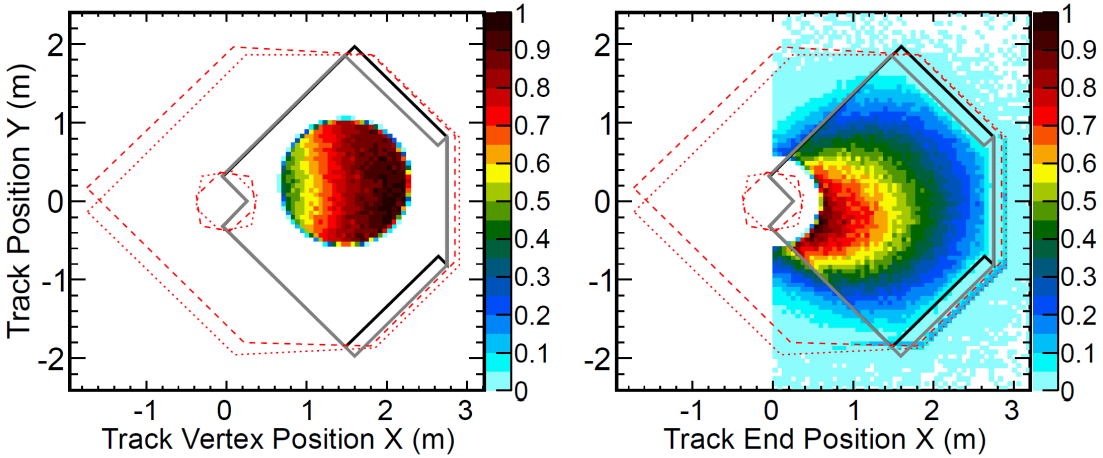
Fold

Purity and Efficiency

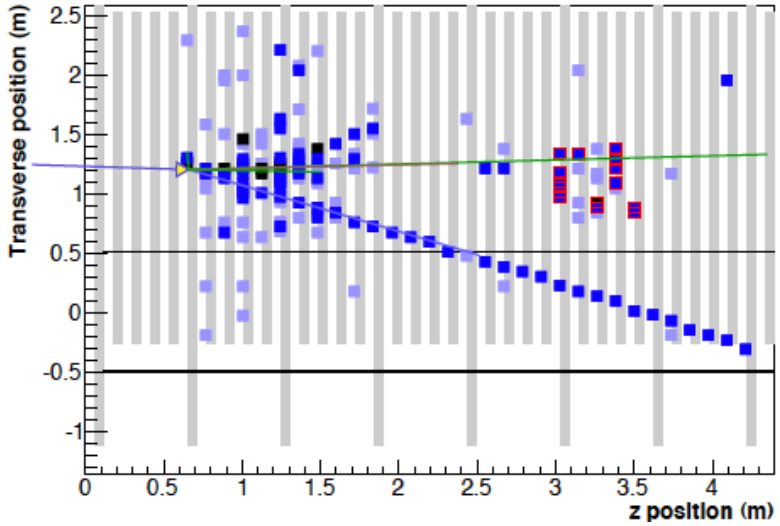


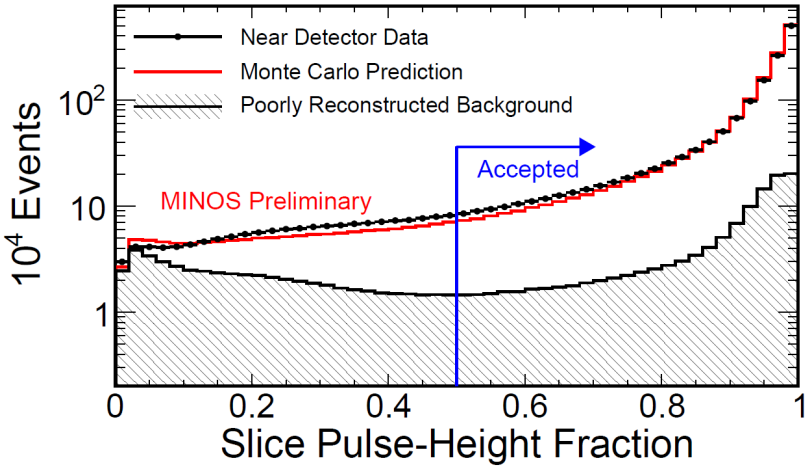
- Remove tracks near coil hole in ND
- Improves systematic uncertainty
- Efficiency less important in the ND





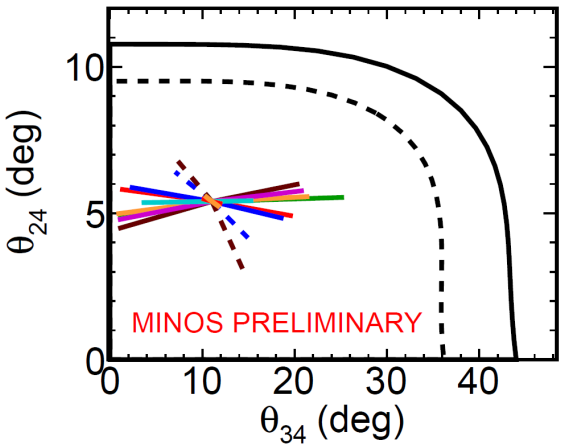
ND Cleaning

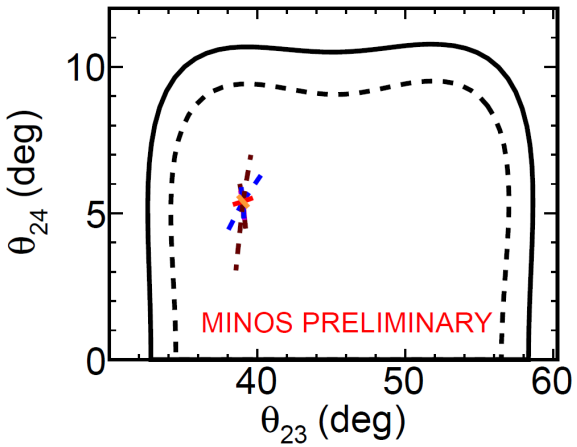


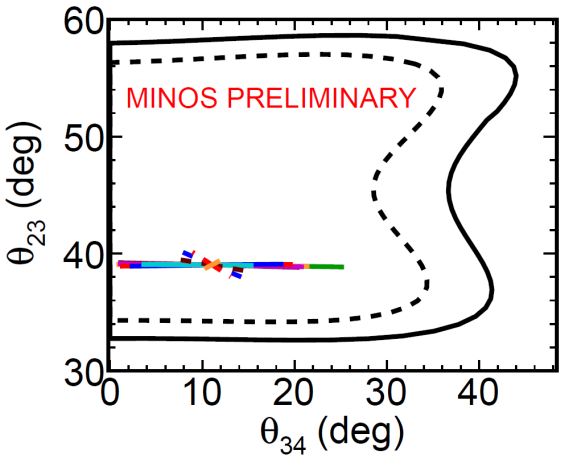


- Reconstruction may split one slice (time and space clustering) into more than one event
- Parts of the same interaction may get broken into separate events
- Well reconstructed event have a larger fraction of PH in the slice
- Data/MC discrepancies give rise to one of the systematics in the fit

Sterile Systematics







- ND Cleaning: $\Delta\chi^2 = 0.53$
- CC Background: $\Delta\chi^2 = 0.24$
- NC Rel. Normalization: $\Delta\chi^2 = 0.22$
- FD Cosmics: $\Delta\chi^2 = 0.22$
- Rel. NC Had. Energy: $\Delta\chi^2 = 0.15$
- Abs. NC Had. Energy: $\Delta\chi^2 = 0.11$
- FD Cleaning: $\Delta\chi^2 = 0.02$
- Abs. CC Had. Energy: $\Delta\chi^2 = 0.45$
- CC Rel. Normalization: $\Delta\chi^2 = 0.37$
- Track Energy: $\Delta\chi^2 = 0.17$
- NC Background: $\Delta\chi^2 = 0.01$

Uncertainty	$\Delta m^2_{43} = 1$ eV^2		
	$\Delta(\theta_{23})$	$\Delta(\theta_{24})$	$\Delta(\theta_{34})$
Absolute $E_{Hadronic}$	0.1	0.6	8.3
Relative $E_{Hadronic}$	0.1	0.5	9.2
Normalization	0.2	0.8	9.7
CC Background	0.1	0.3	10.3
ND Selection	0.1	0.3	12.1
FD Selection	0.0	0.0	5.8
FD Cosmics	0.1	0.5	10.0
CC Abs. $E_{Hadronic}$	1.4	1.2	4.5
Track Energy	1.0	0.2	2.0
CC Normalization	0.5	2.0	3.7
NC Background	0.3	0.2	0.8
Total	1.8	2.7	25.9