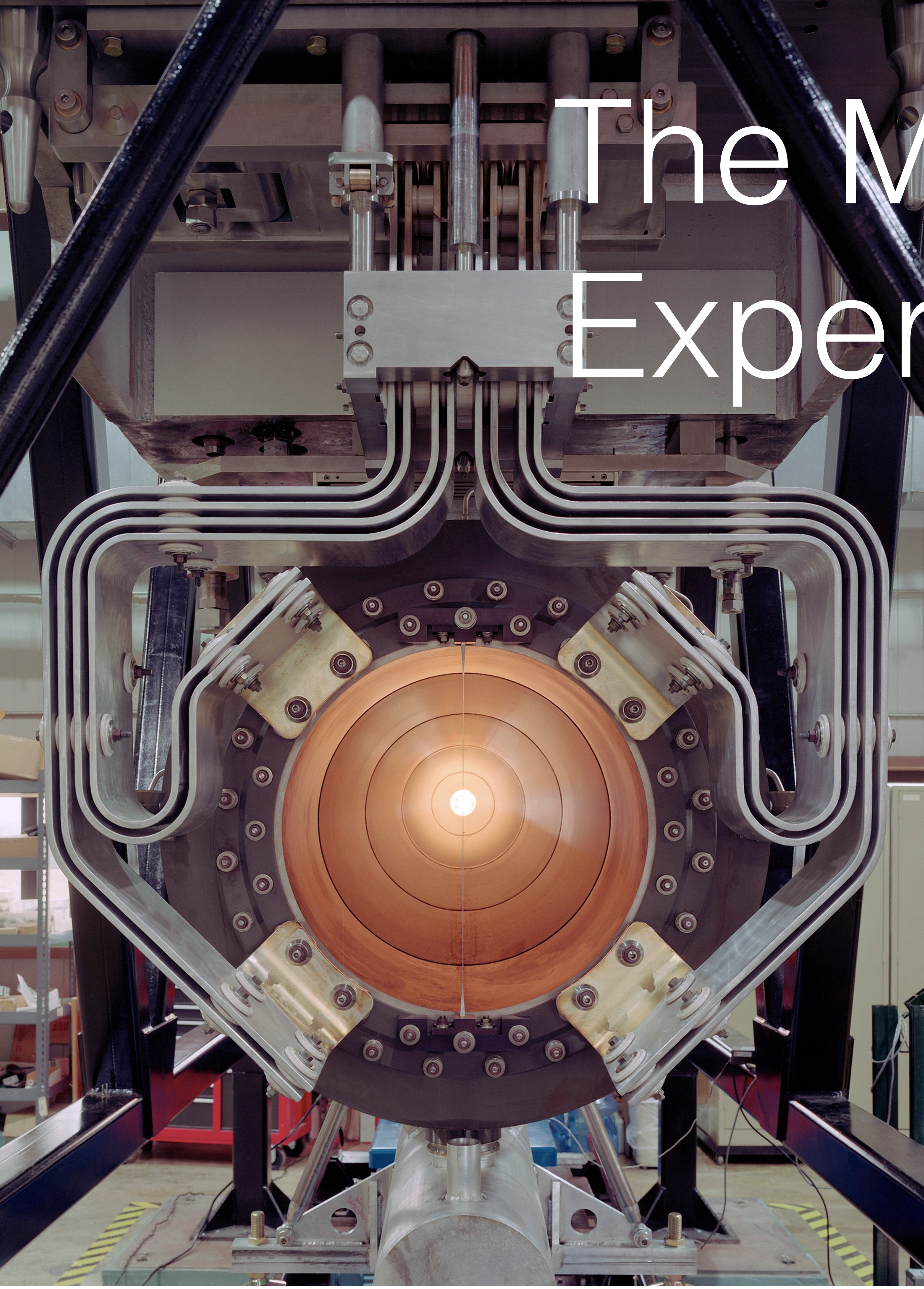
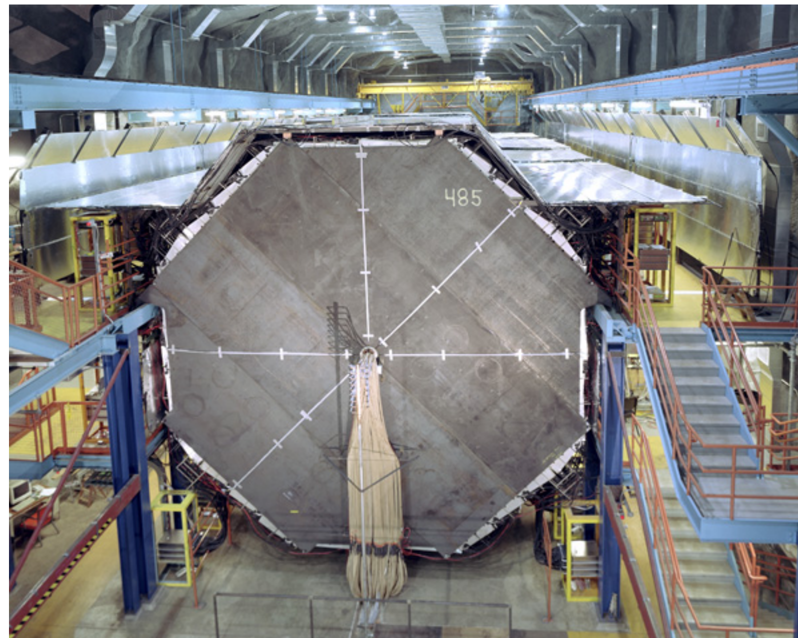
The MINOS Experiment



Alexander Radovic
College of William and Mary

The MINOS Experiment



MINOS or Main

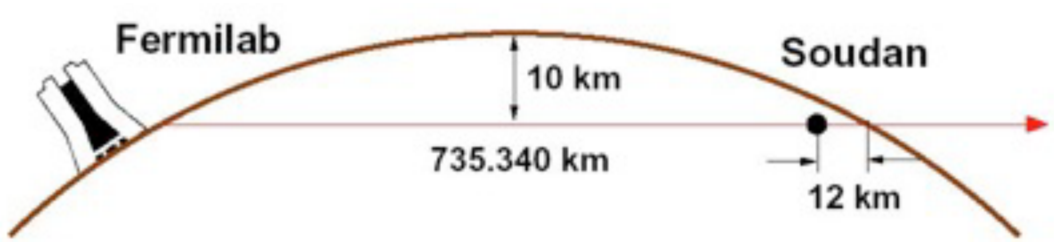
Injector Neutrino

Oscillation Search

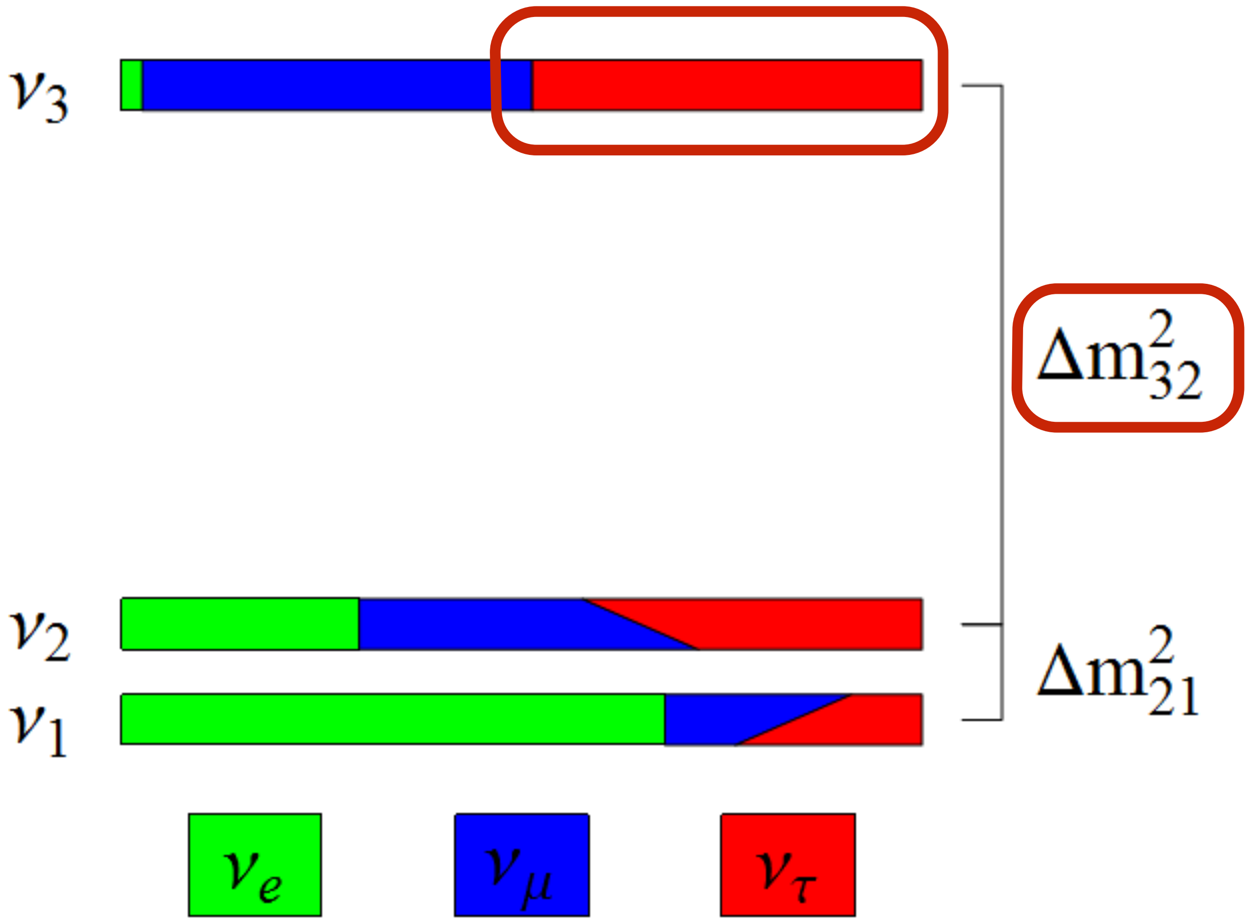
Uses Neutrinos from the NuMI beam line

Has a peak L/E of ~250km/GeV

Leading measure of $|\Delta m^2_{atm}|$



MINOS Physics Goals



Precise measurements:

Δm^2_{32} and $\sin^2(2\theta_{23})$ for neutrinos and antineutrinos

Constraints on:

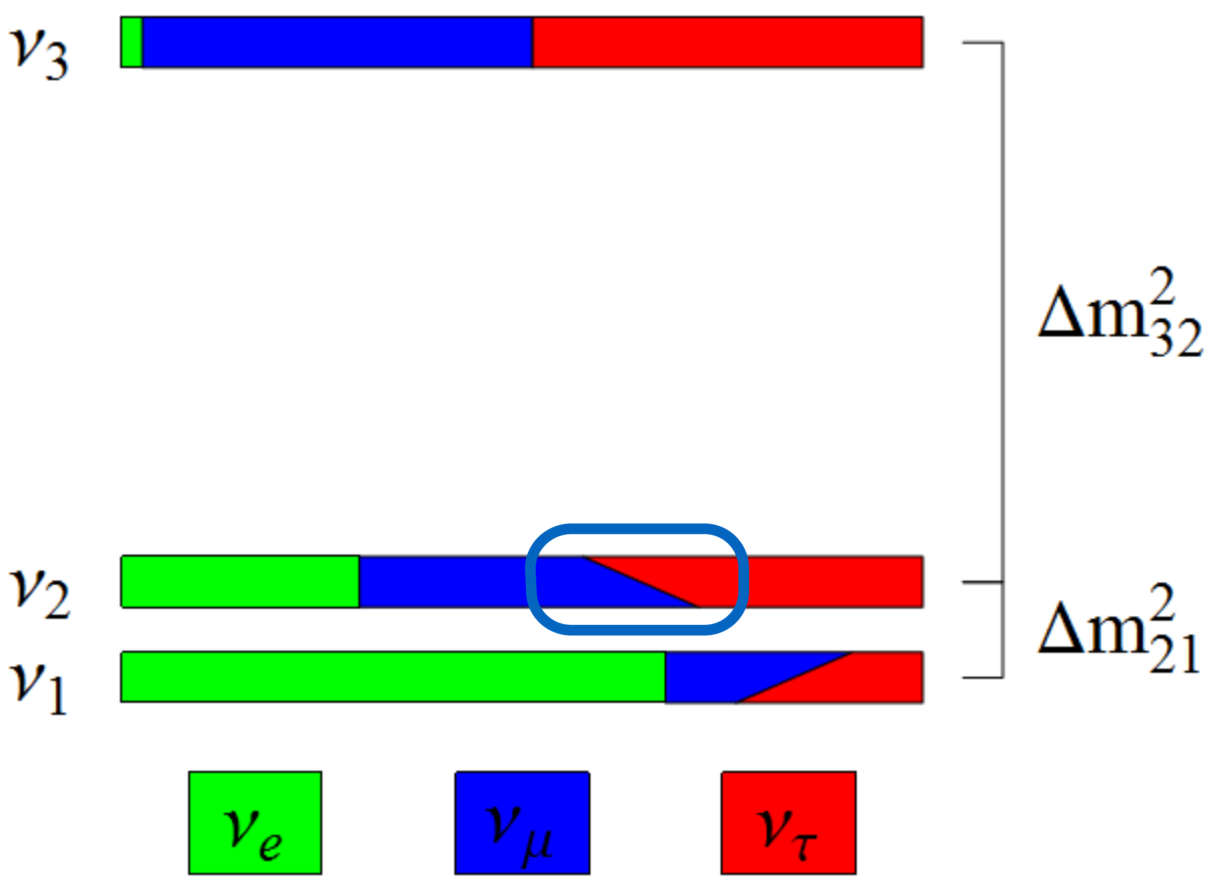
θ_{23} octant

δ_{cp}

mass hierarchy

sterile neutrino mixing

MINOS Physics Goals



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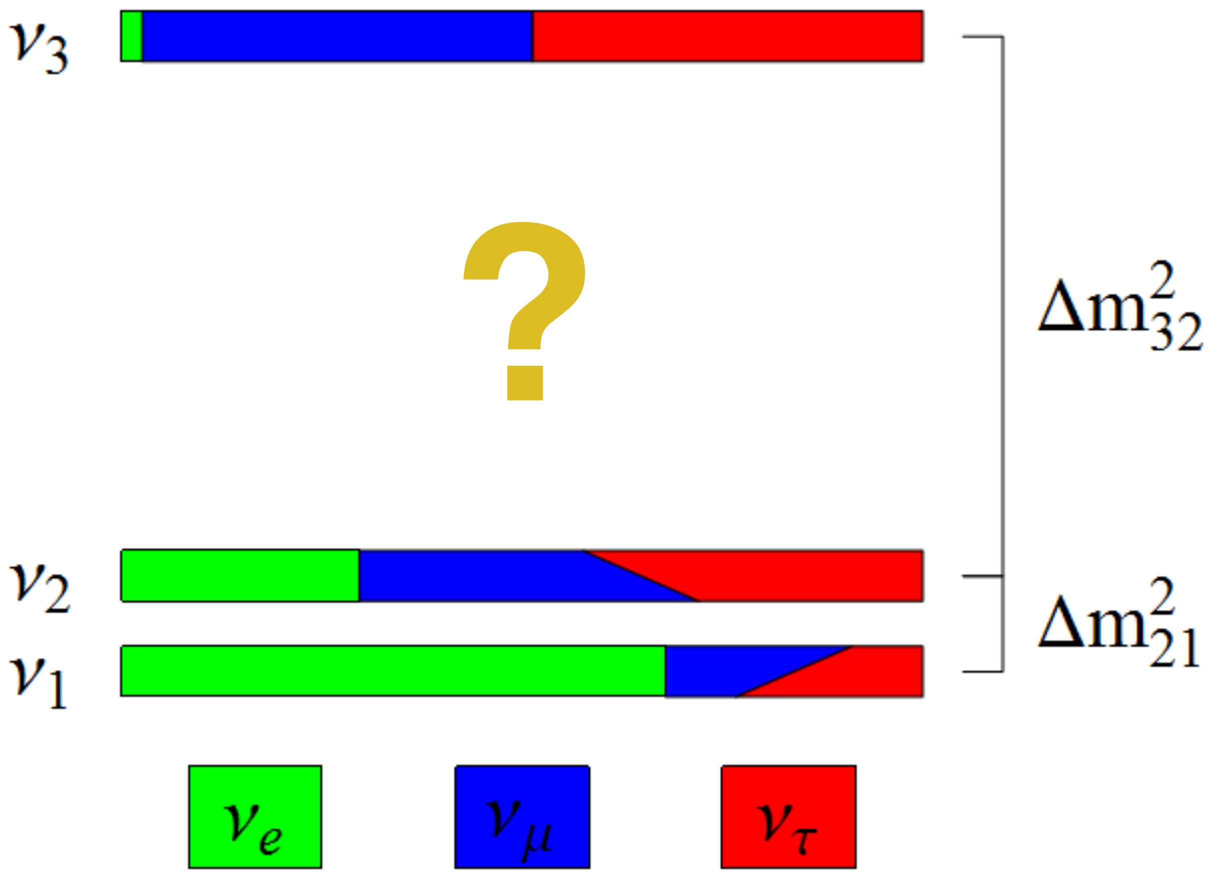

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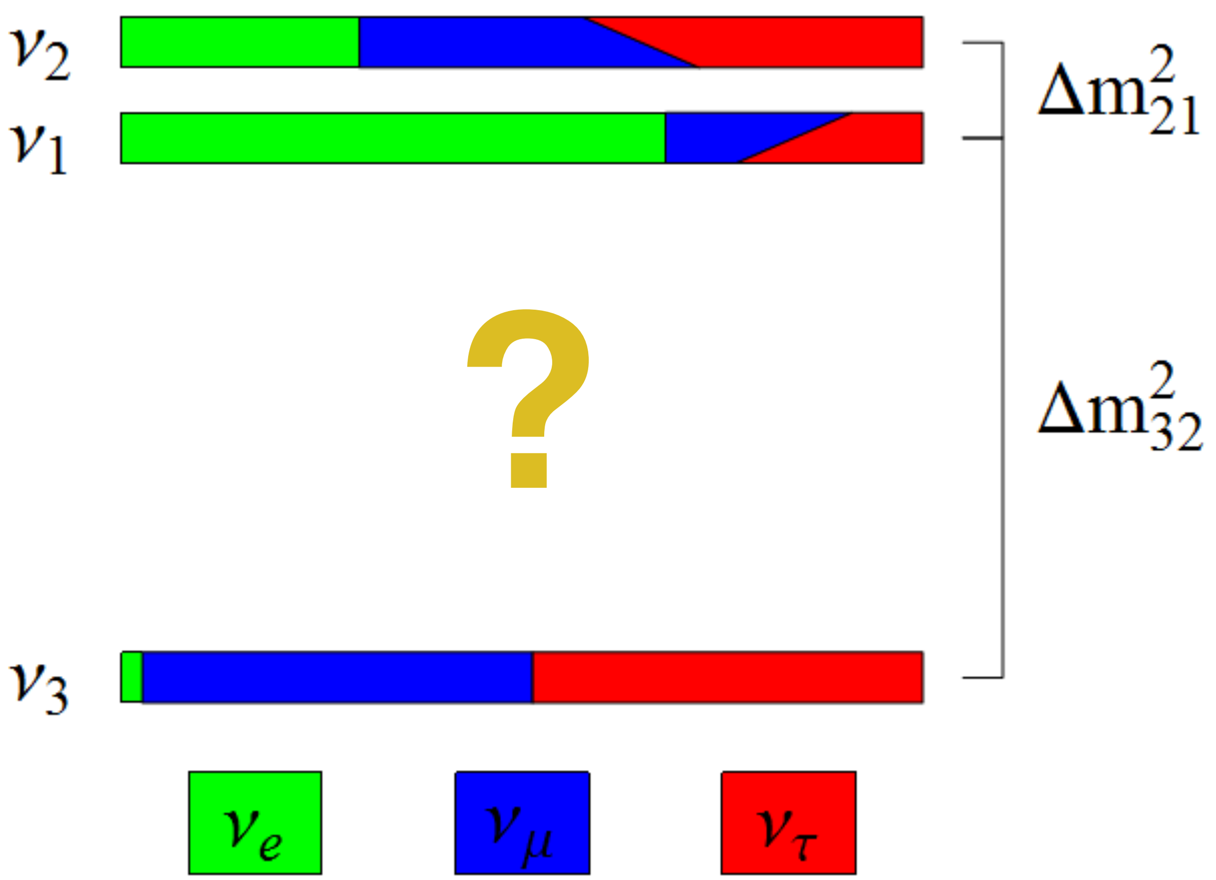

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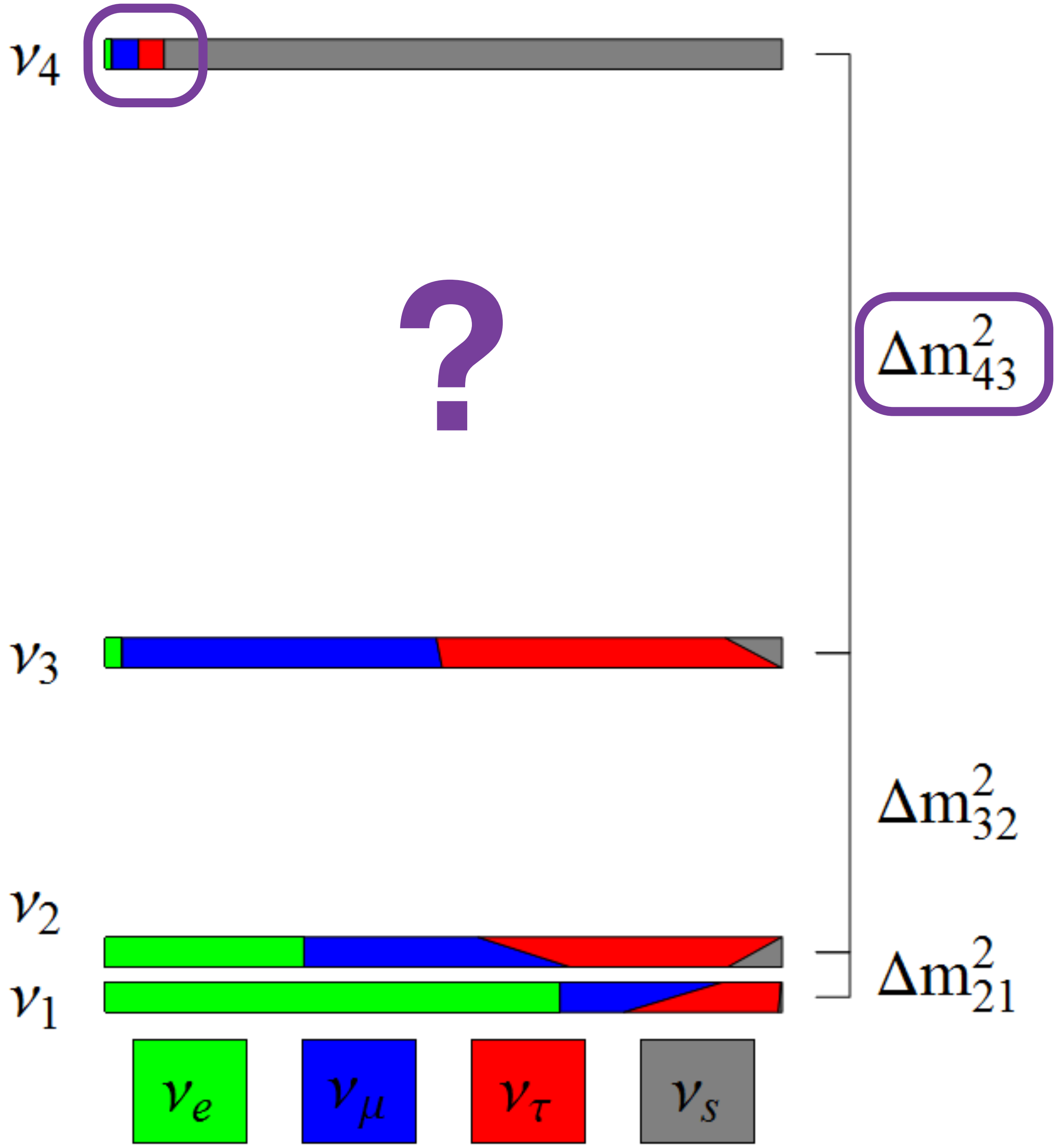

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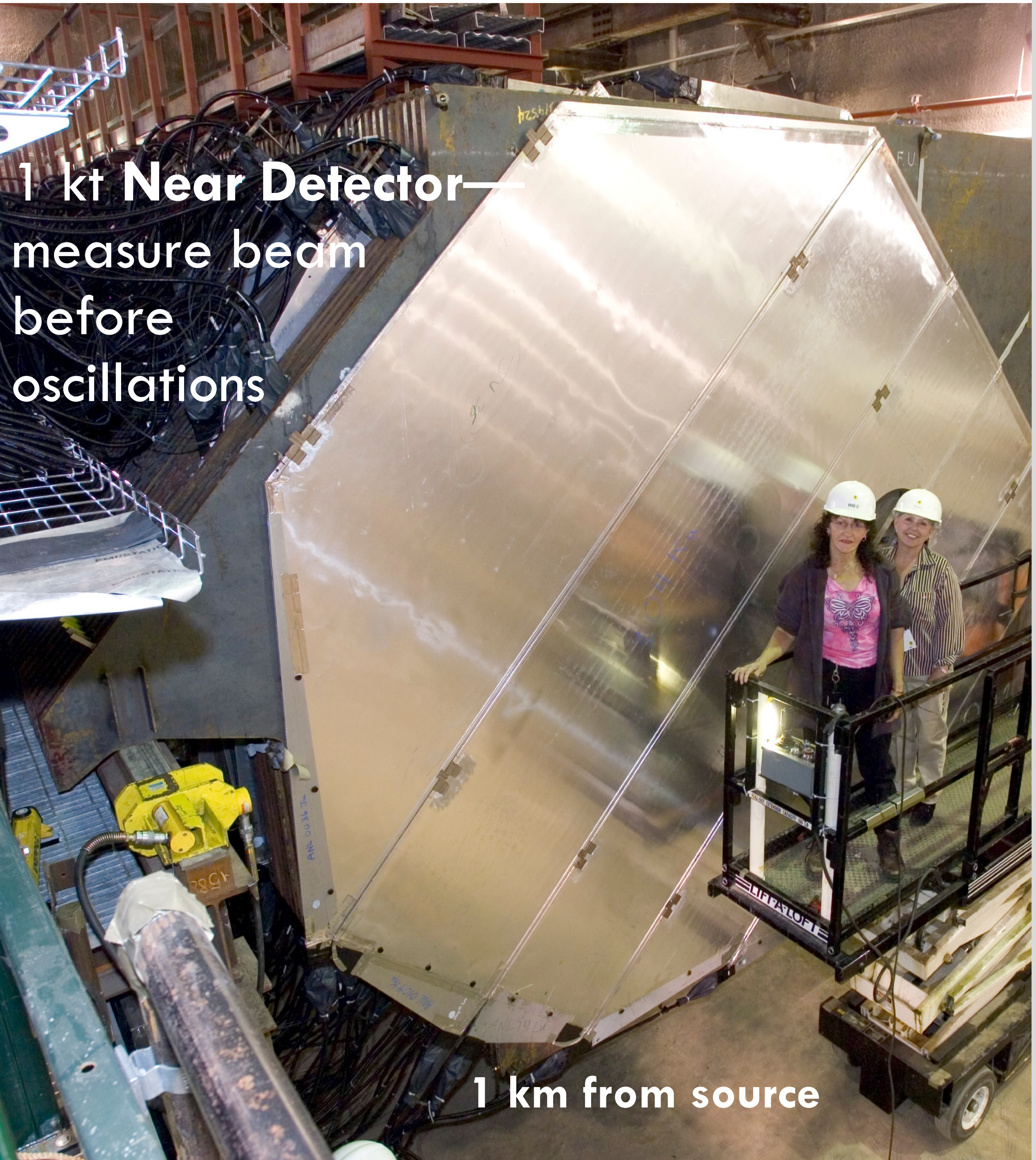
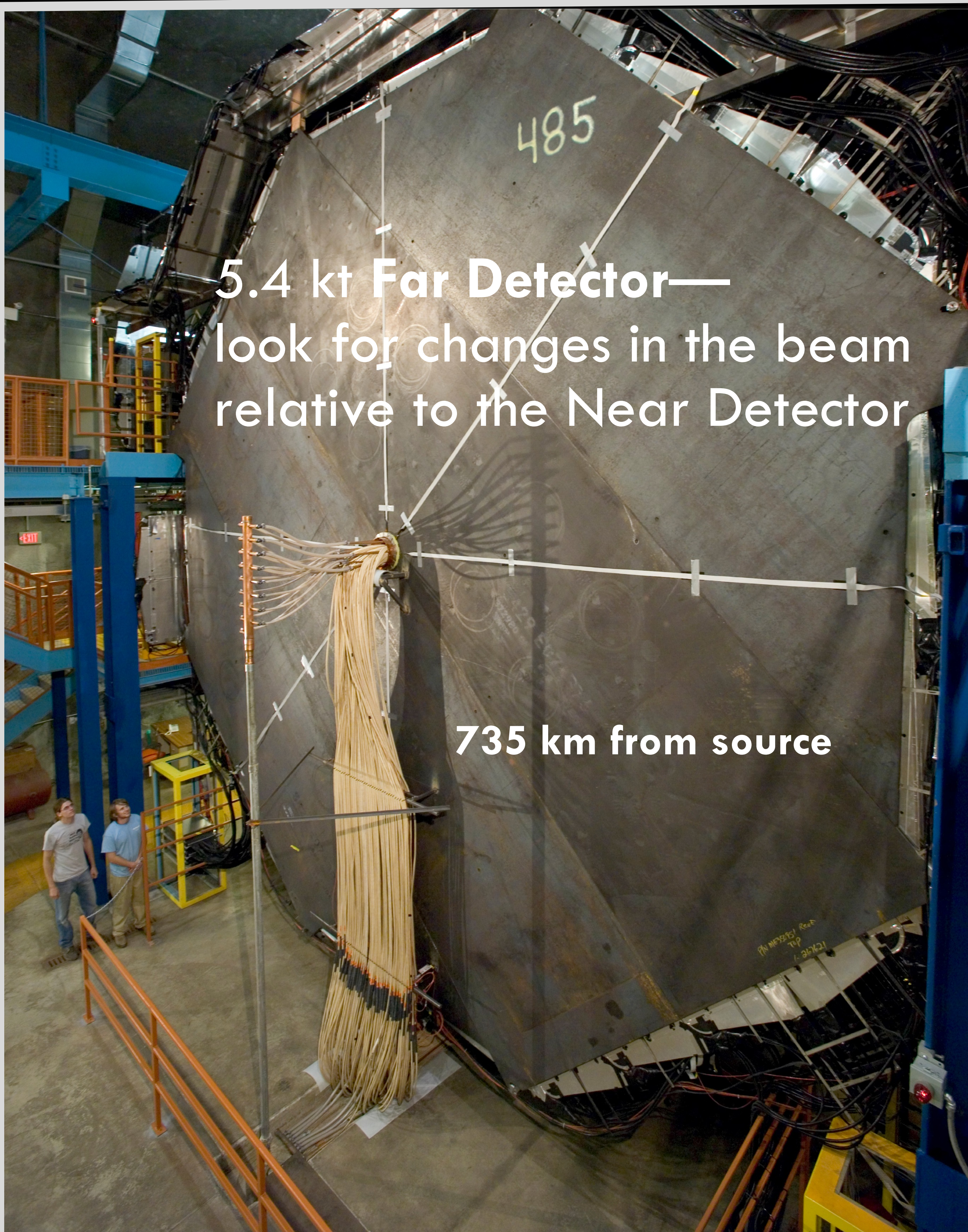
The Detectors

A pair of magnetized tracking calorimeters





Detector Technology

Tracking sampling calorimeters

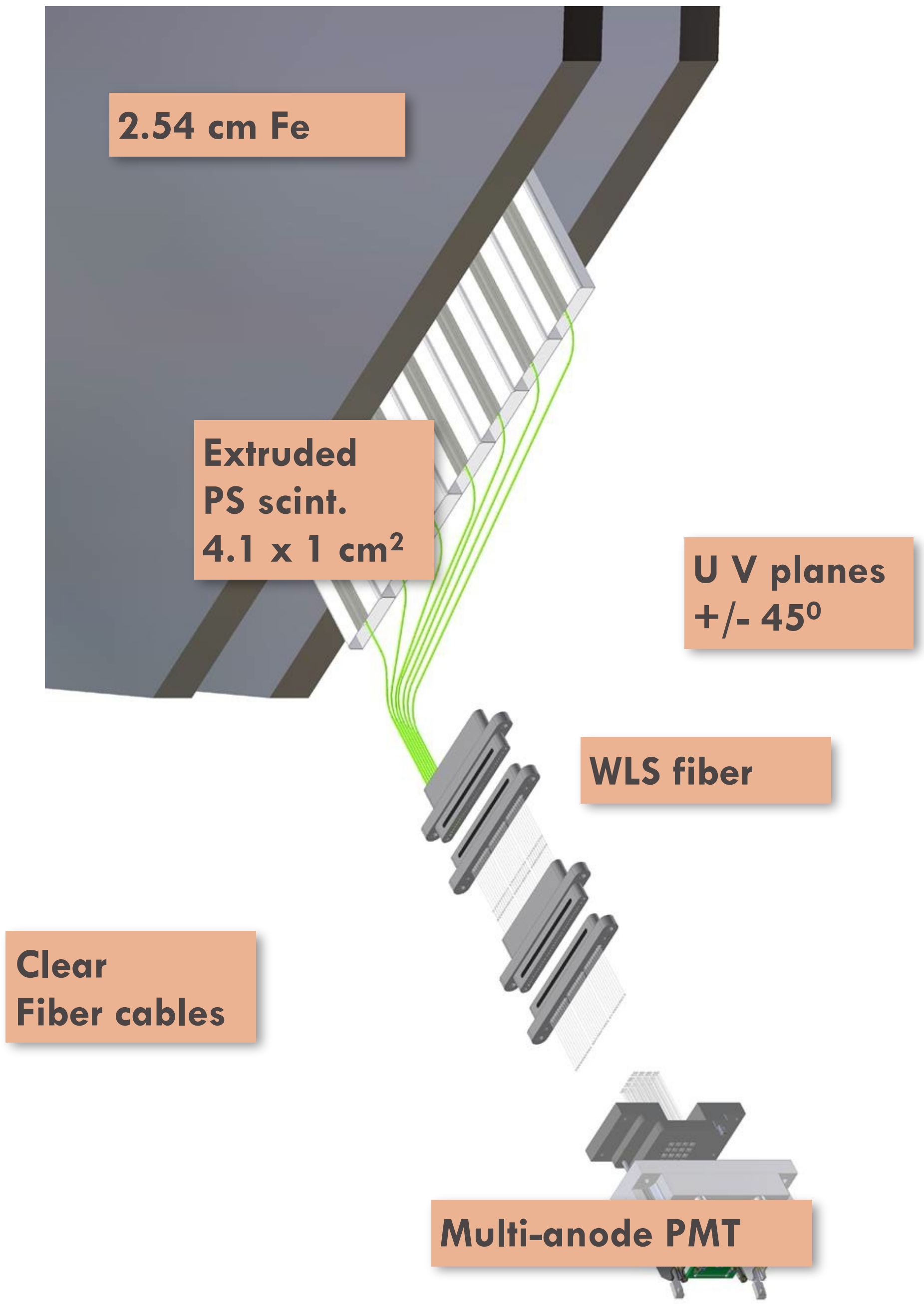
- steel absorber 2.54 cm thick (1.4 X_0)
- scintillator strips 4.1 cm wide (1.1 Moliere radii)
- 1 GeV muons penetrate 28 layers

Magnetized

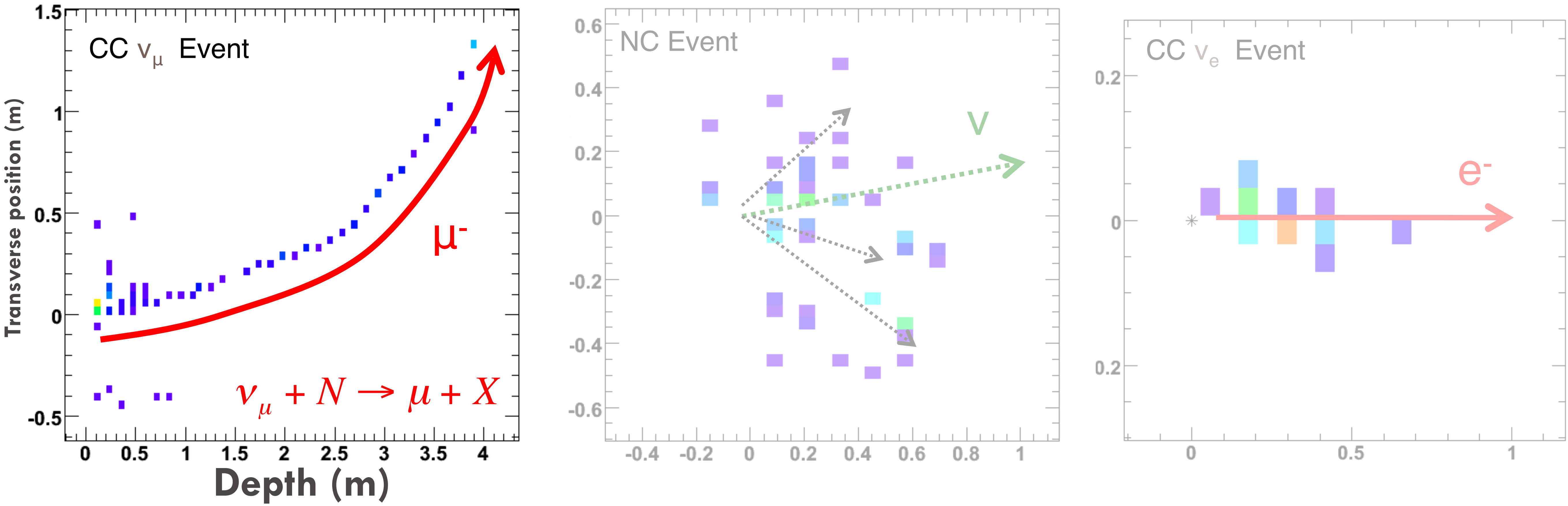
- muon energy from range/curvature
- distinguish μ+ from μ-

Functionally equivalent

- same segmentation
- same materials
- same mean B field (1.3 T)



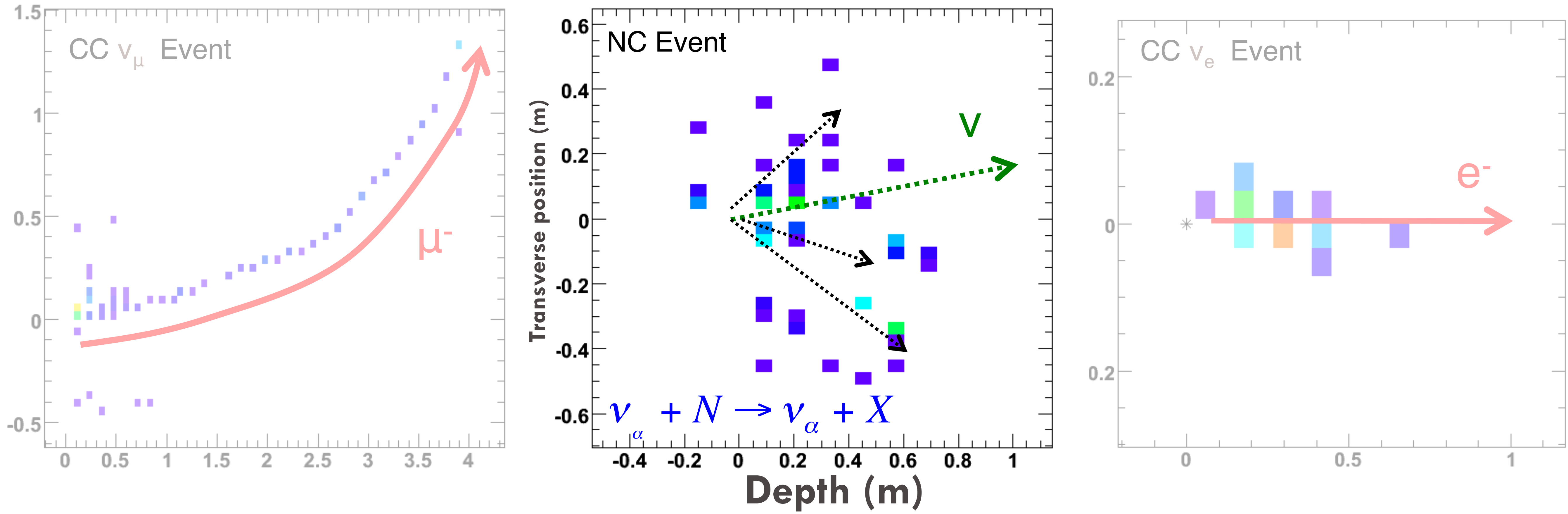
Example Events



ν_μ Charged Current events:

- long μ track, with hadronic activity at vertex
- neutrino energy from sum of muon energy (range or curvature) and shower energy

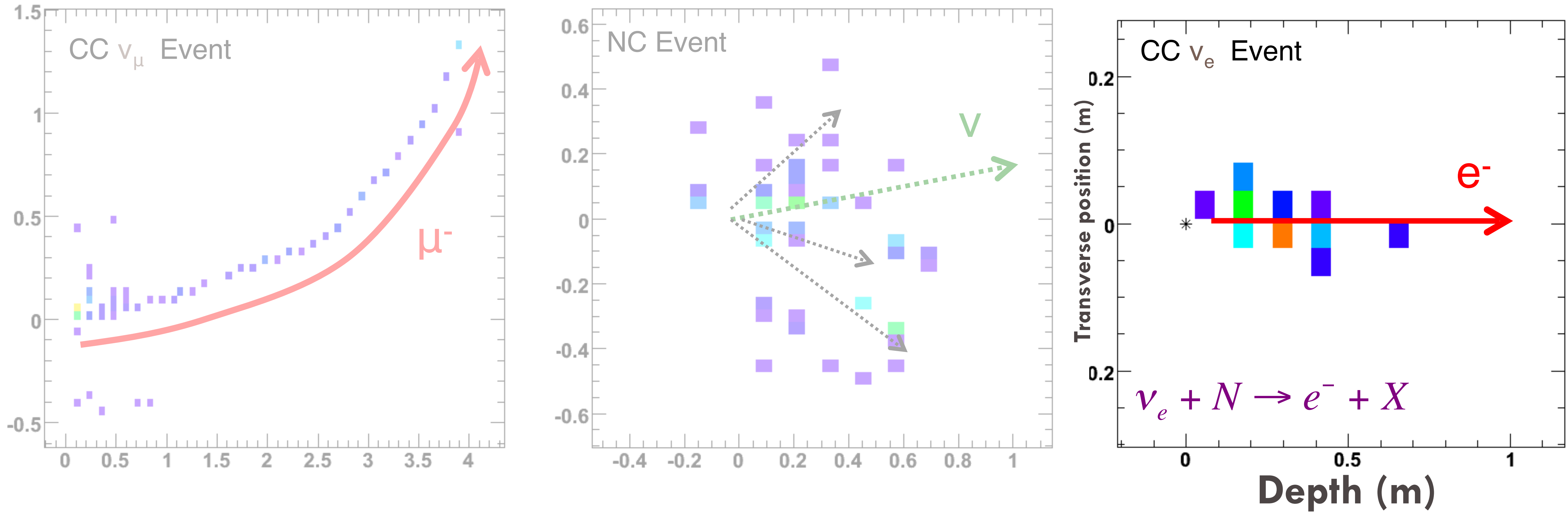
Example Events



ν_a Neutral Current events:

- short and diffuse hadronic shower
- visible energy from calorimetric response

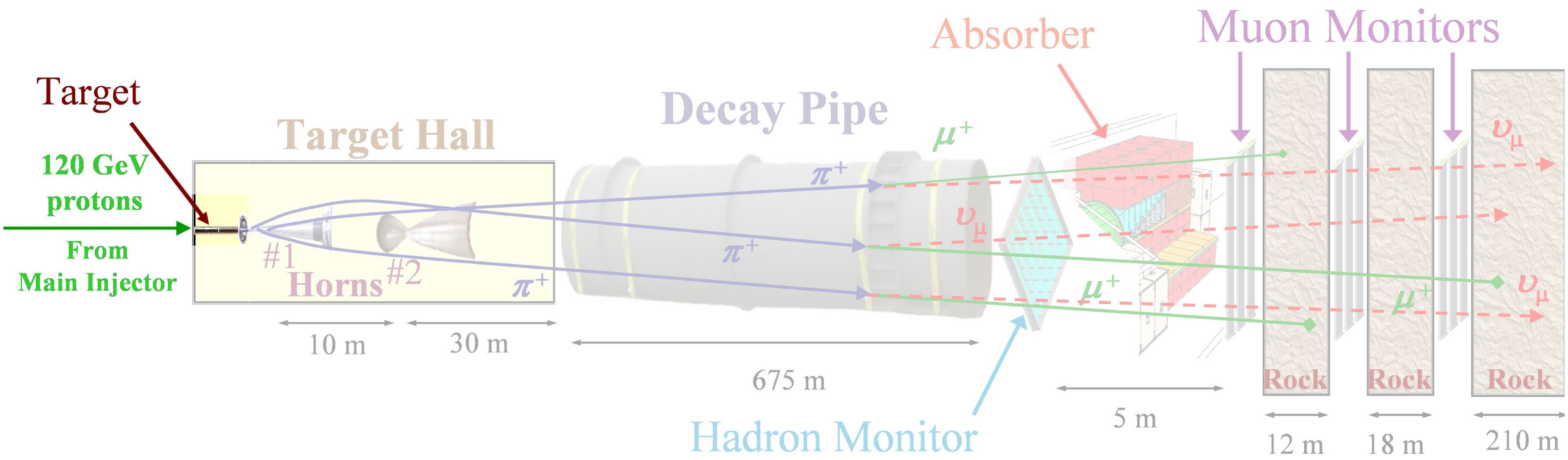
Example Events



ν$_e$ Charged Current events:

- compact shower with an em core
- neutrino energy from calorimetric response

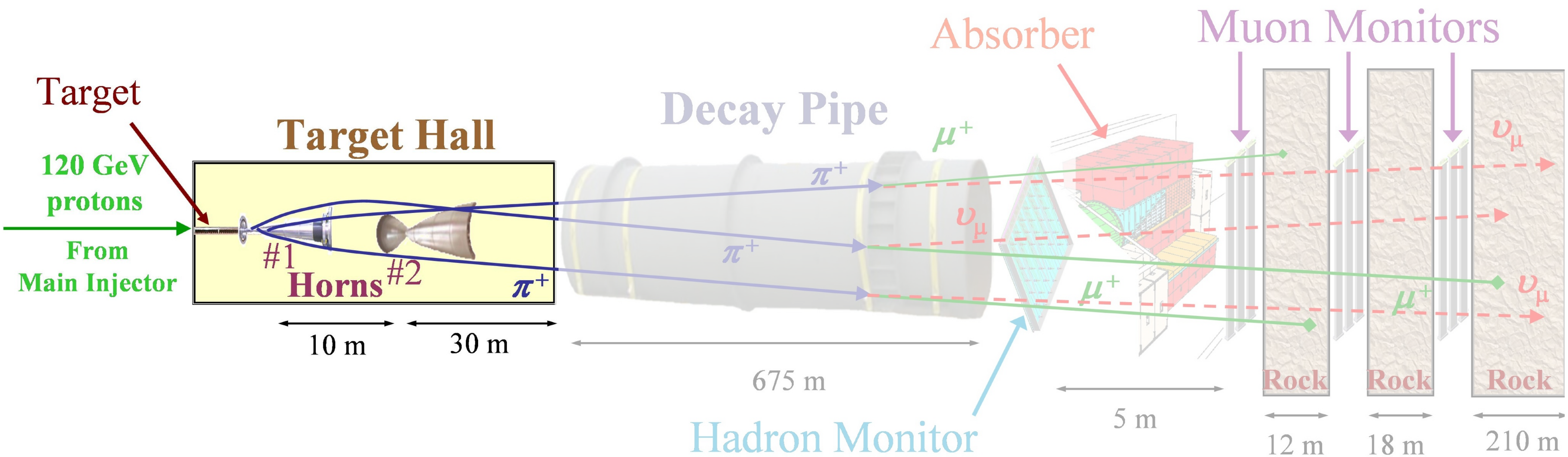
The NuMI Beam



The Target:

- 120 GeV protons from the fermilab main injector are impinged on a carbon target to produce a secondary beam of pions and kaons
- Originally run at 300kw the target has been redesigned for the NOvA era such that it can withstand powers of up to 700kw

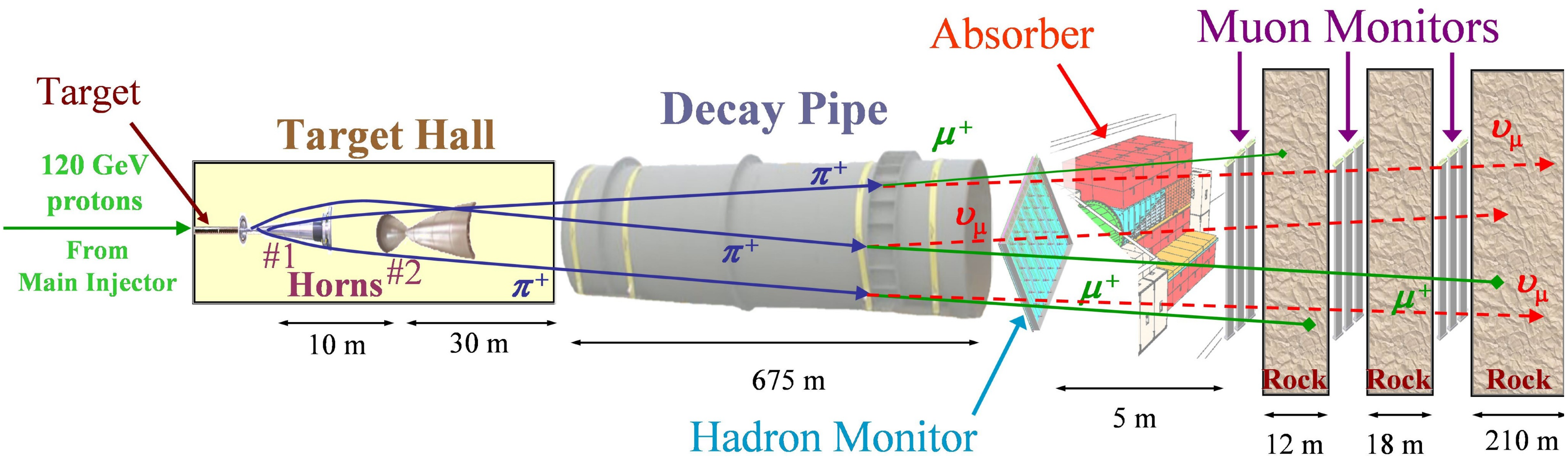
The NuMI Beam



The Focusing System:

- That secondary beam of pions and kaons is focused by a pair of electromagnetic horns
- Changing the target and horns relative positions allows us to tune the energy of the focus pions and kaons and hence the peak energy of our final neutrino beam
- Additionally allows us charge sign select our pions and kaons such that we can create either a predominately neutrino or anti-neutrino beam

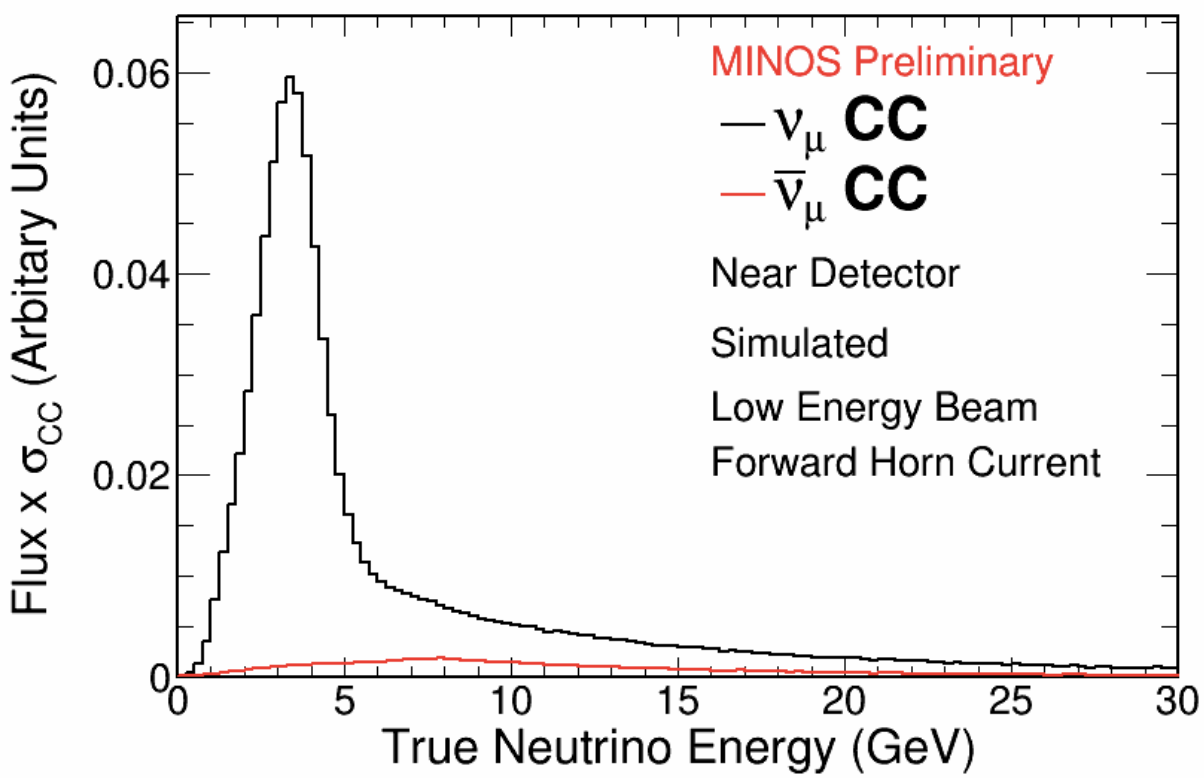
The NuMI Beam

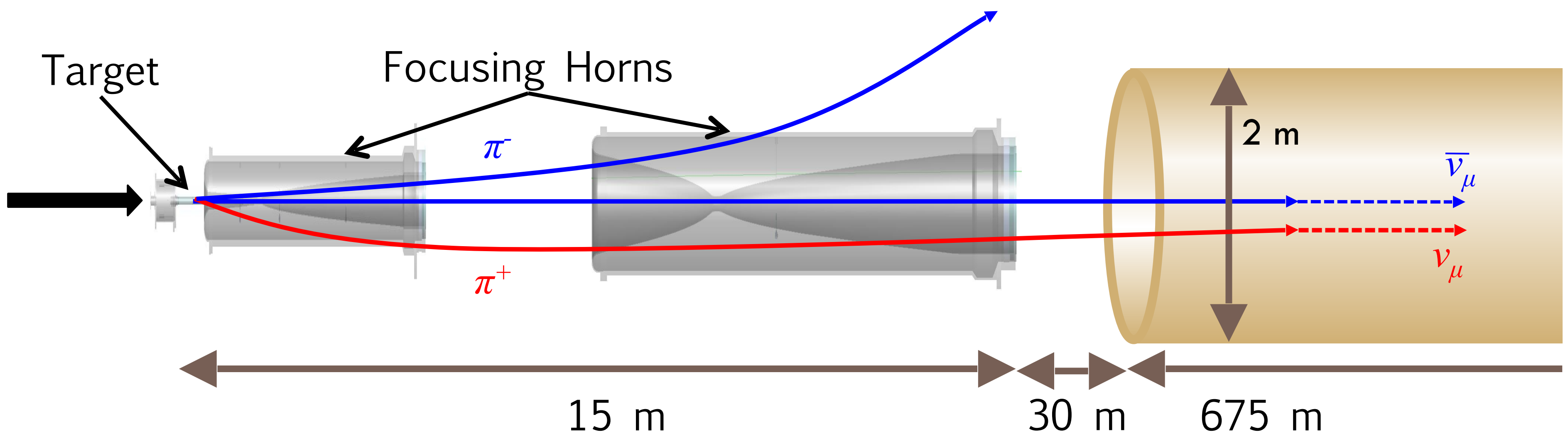


The Decay Pipe

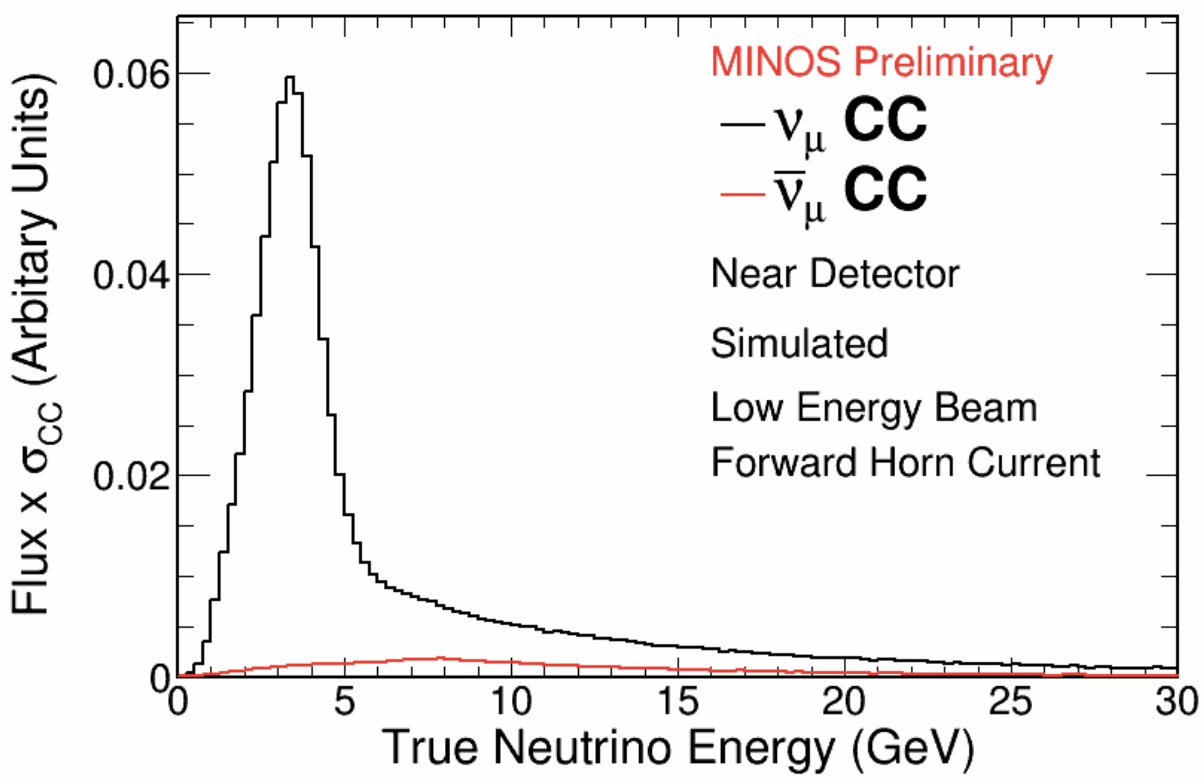
- 2m diameter pipe makes for a wideband beam as under or over focused pions and kaons can still contribute
- Secondary beam monitored both directly by a hadron monitor and indirectly via muon alcoves

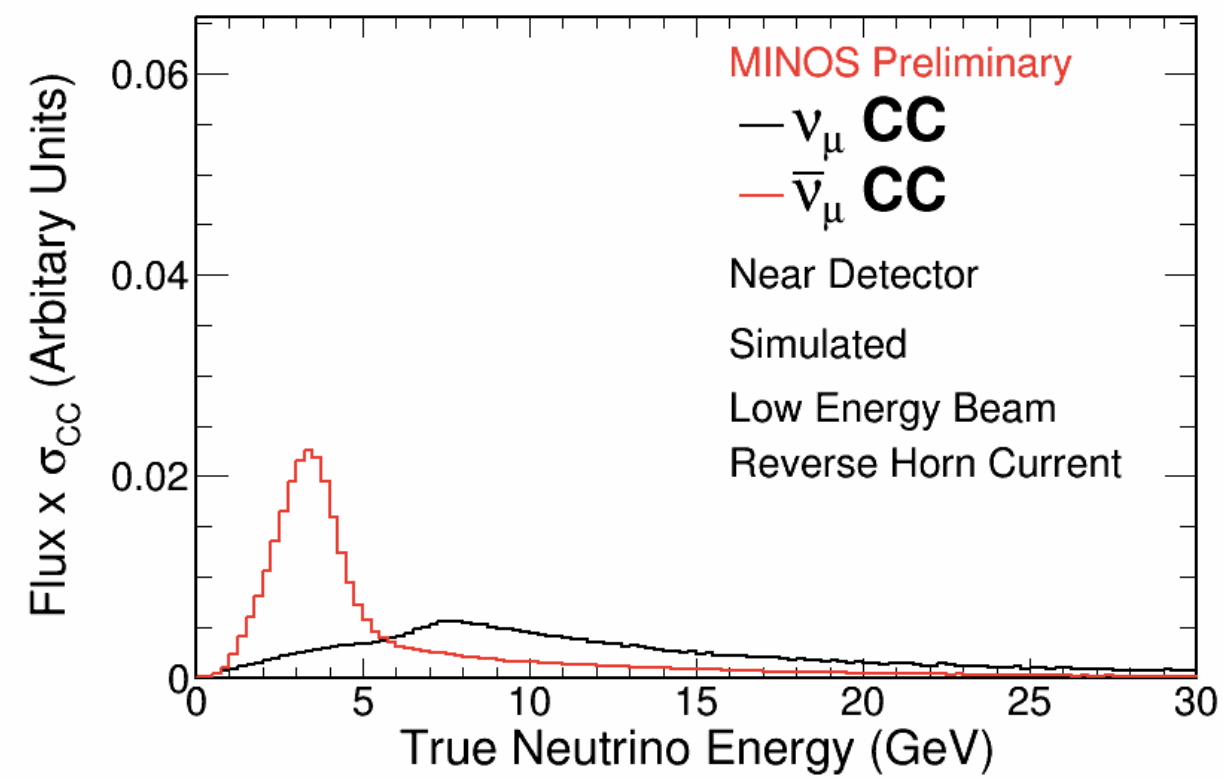
MINOS Era Beam: Neutrino Mode

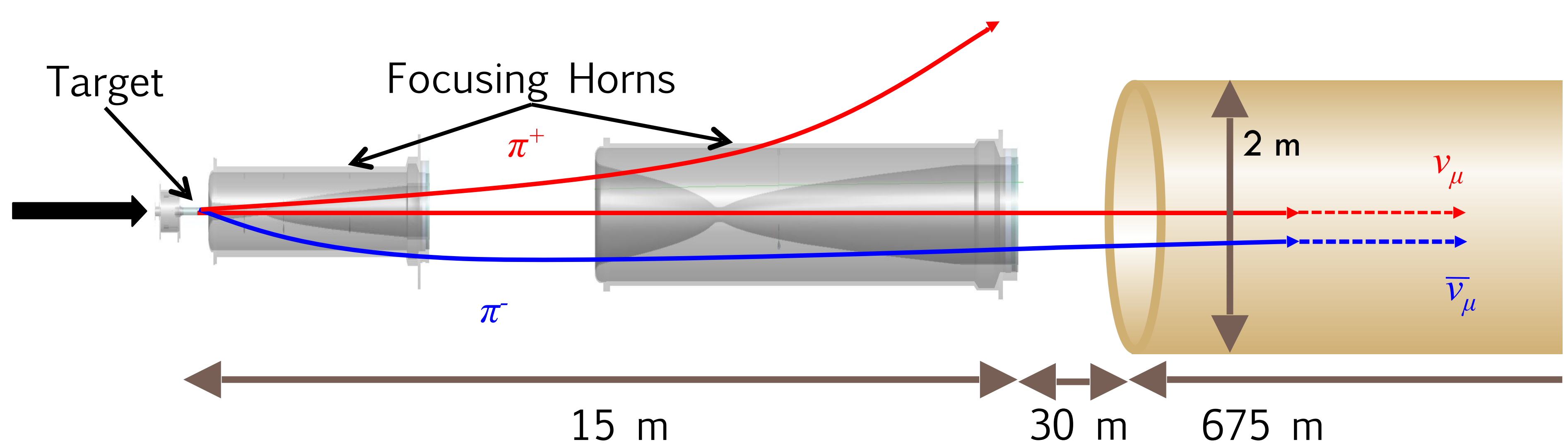




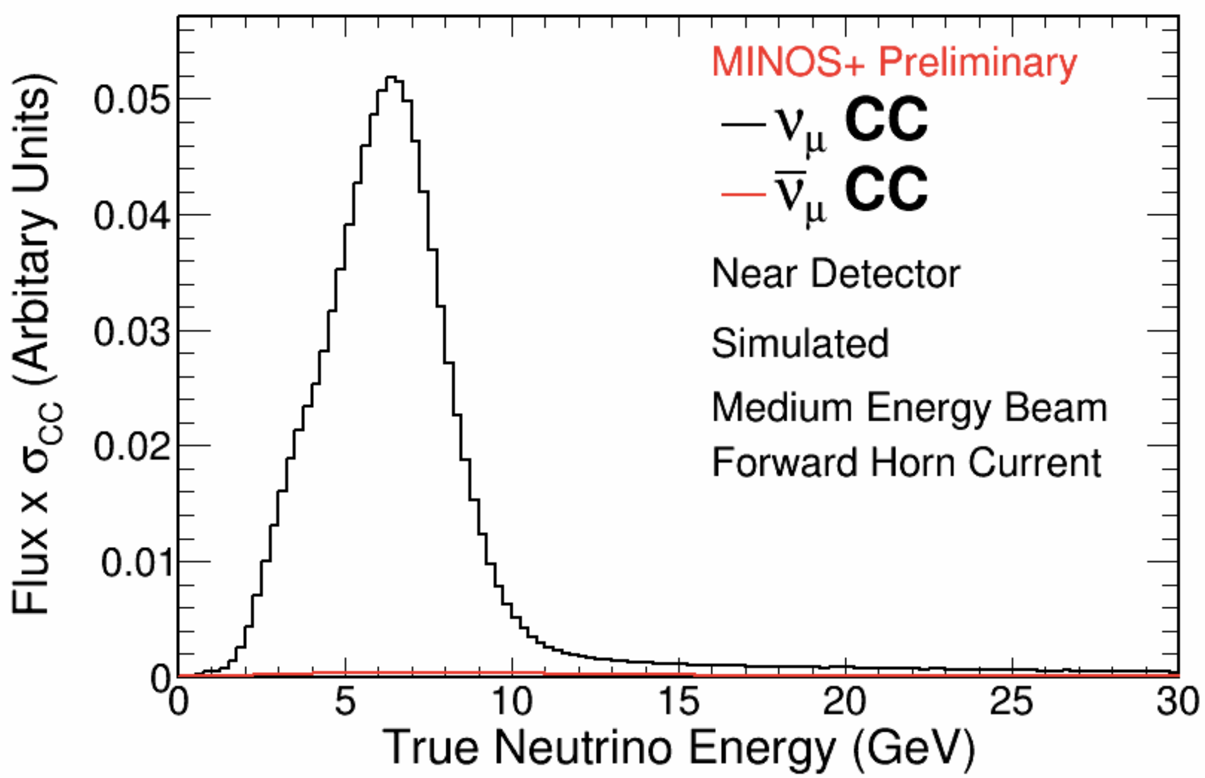
MINOS Era Beam: Anti-neutrino Mode

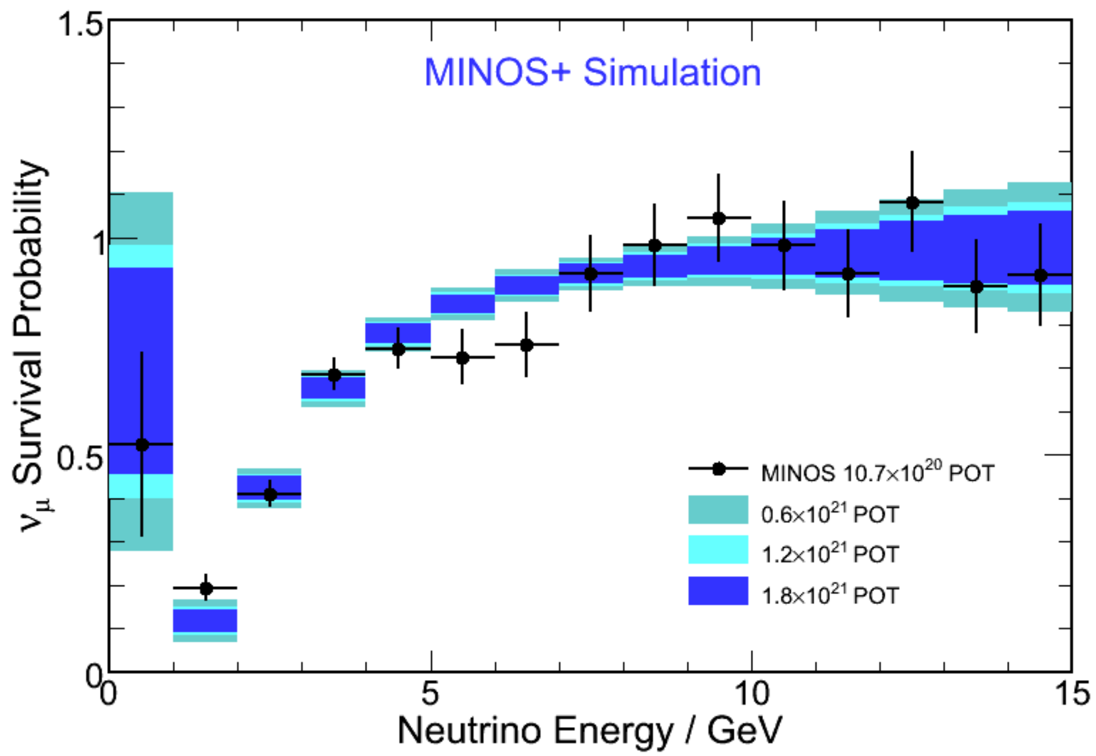


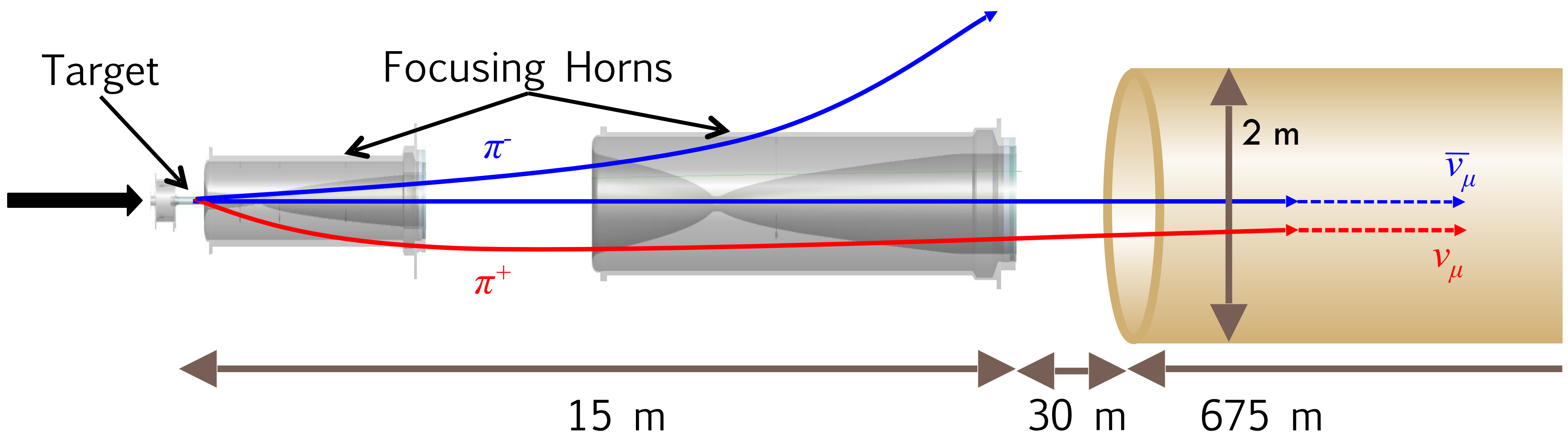




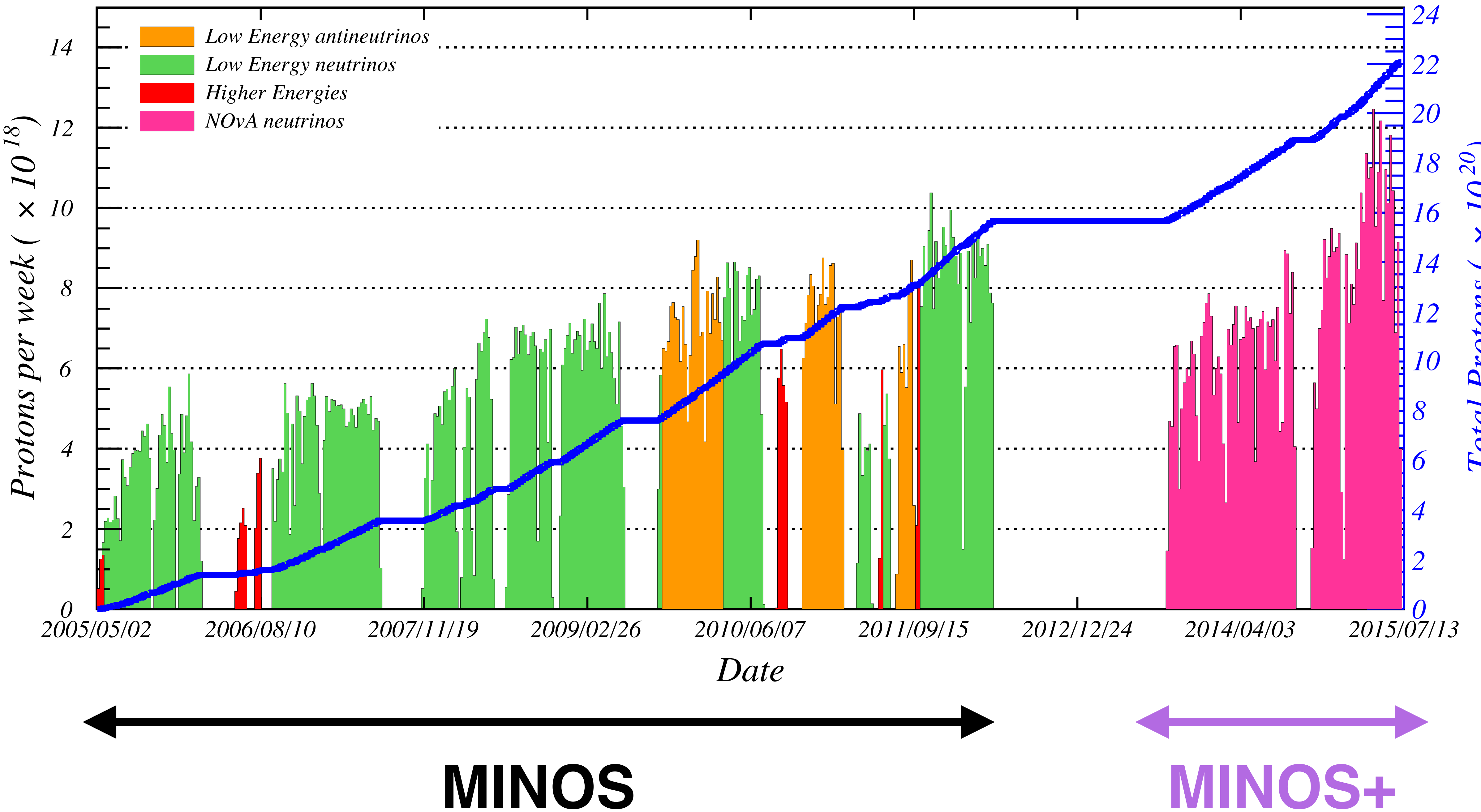
NOvA Era Beam: Neutrino Mode





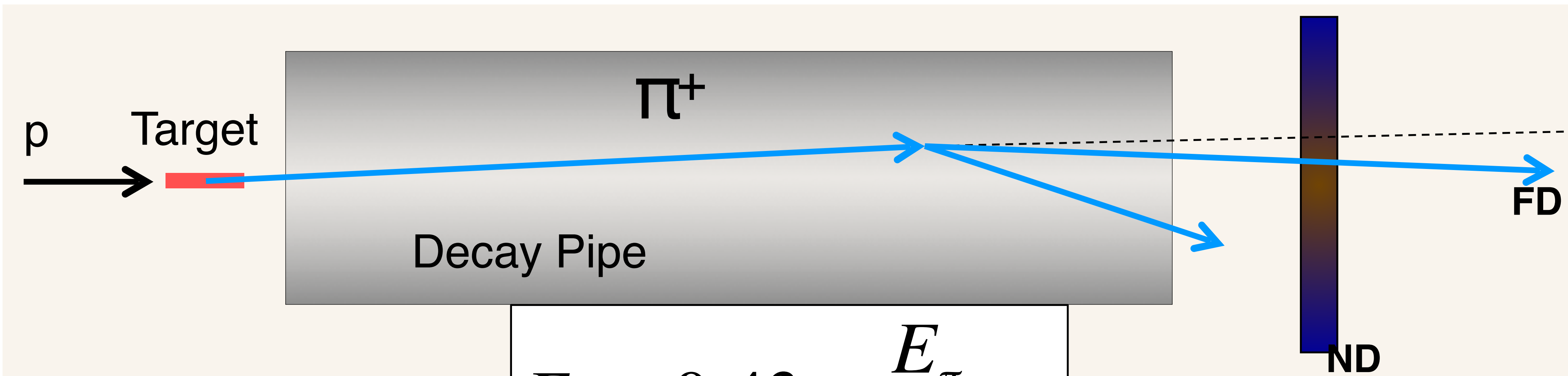


MINOS/MINOS+ Dataset



Near to Far

With a wide band beam your near and far detector spectra will be similar but not identical.



$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

The final neutrino energy relies on a combination angle between the point of pion decay and neutrino interaction, and the pions own energy

The Near detector sees decays from a broader range of angles, and the Far detector a point source, hence slight changes in the observed neutrino spectra

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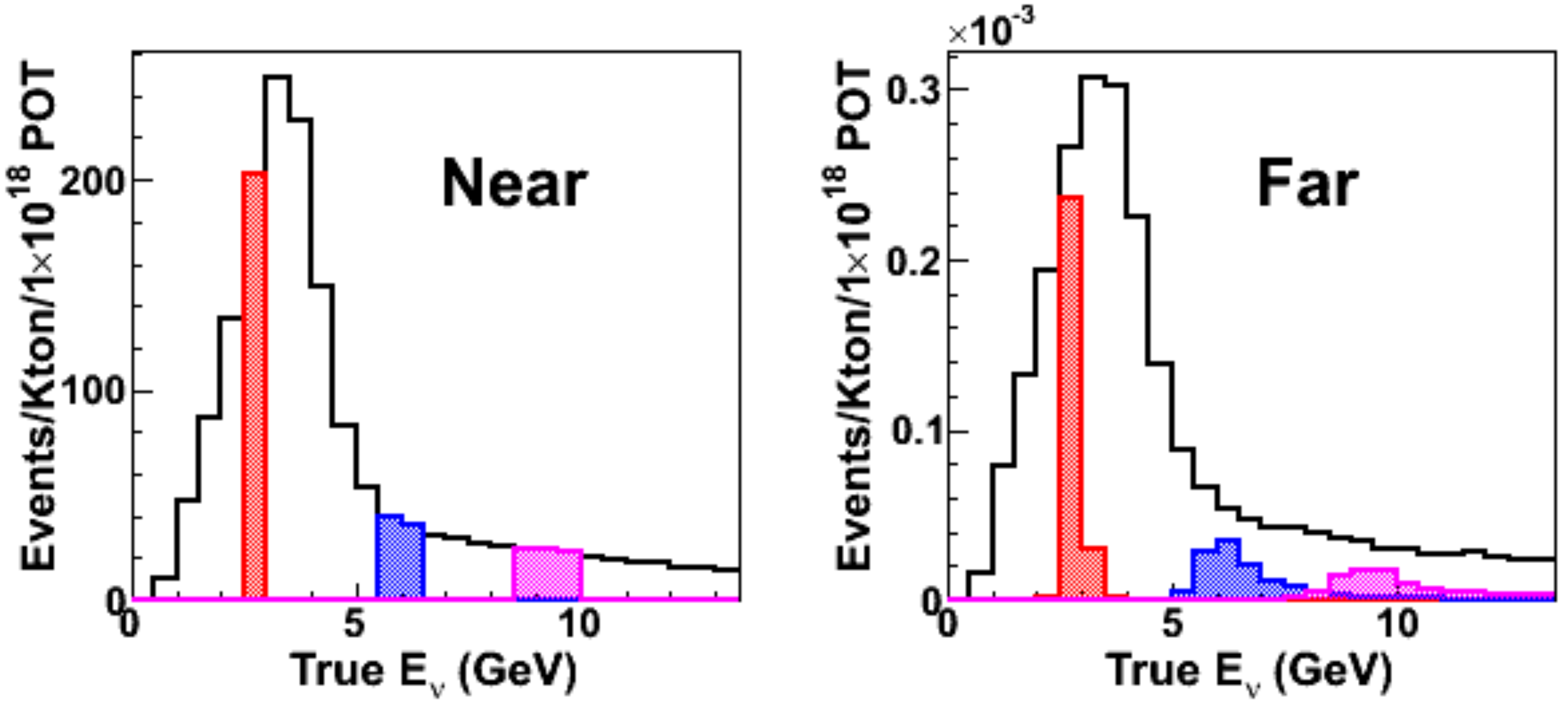

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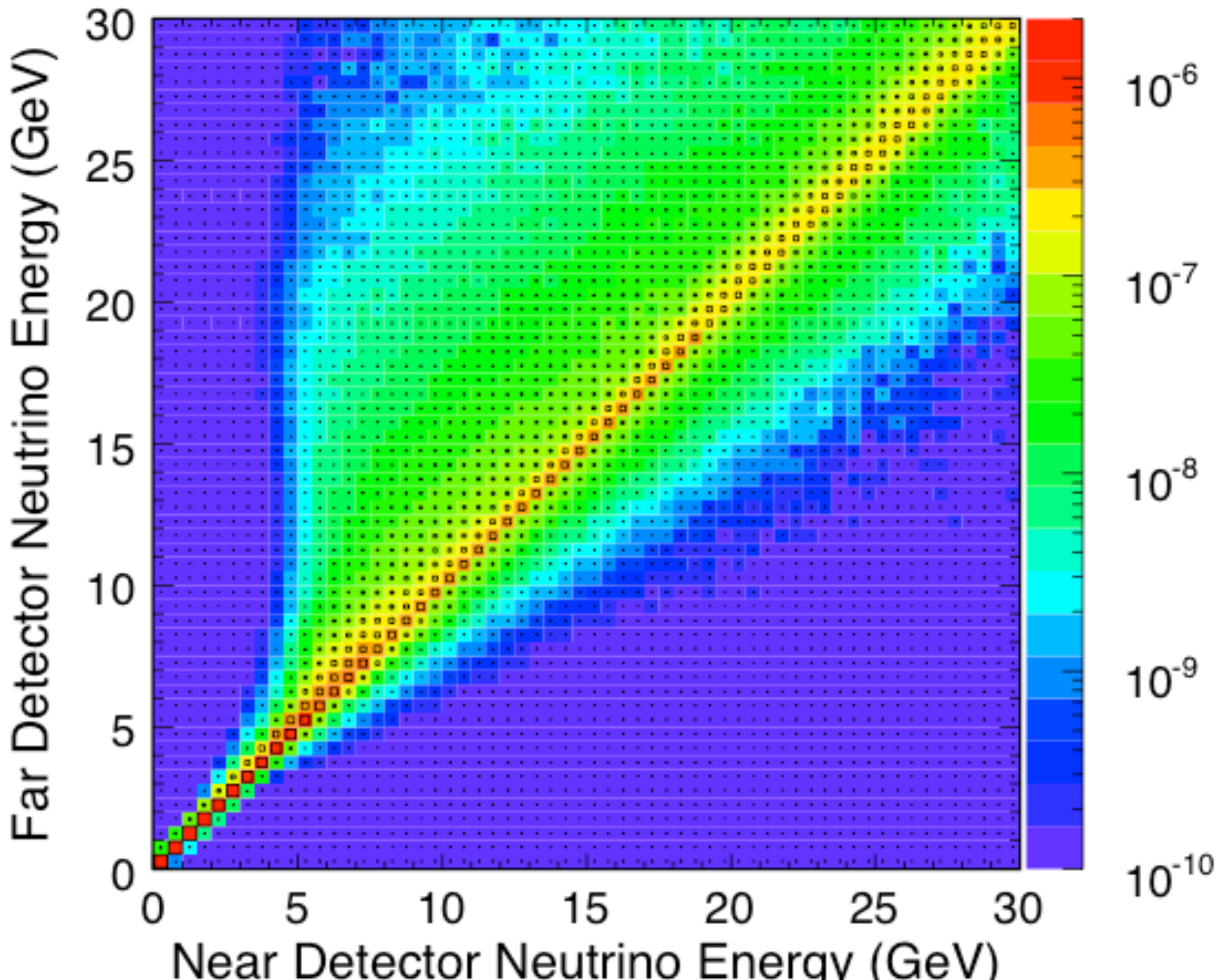
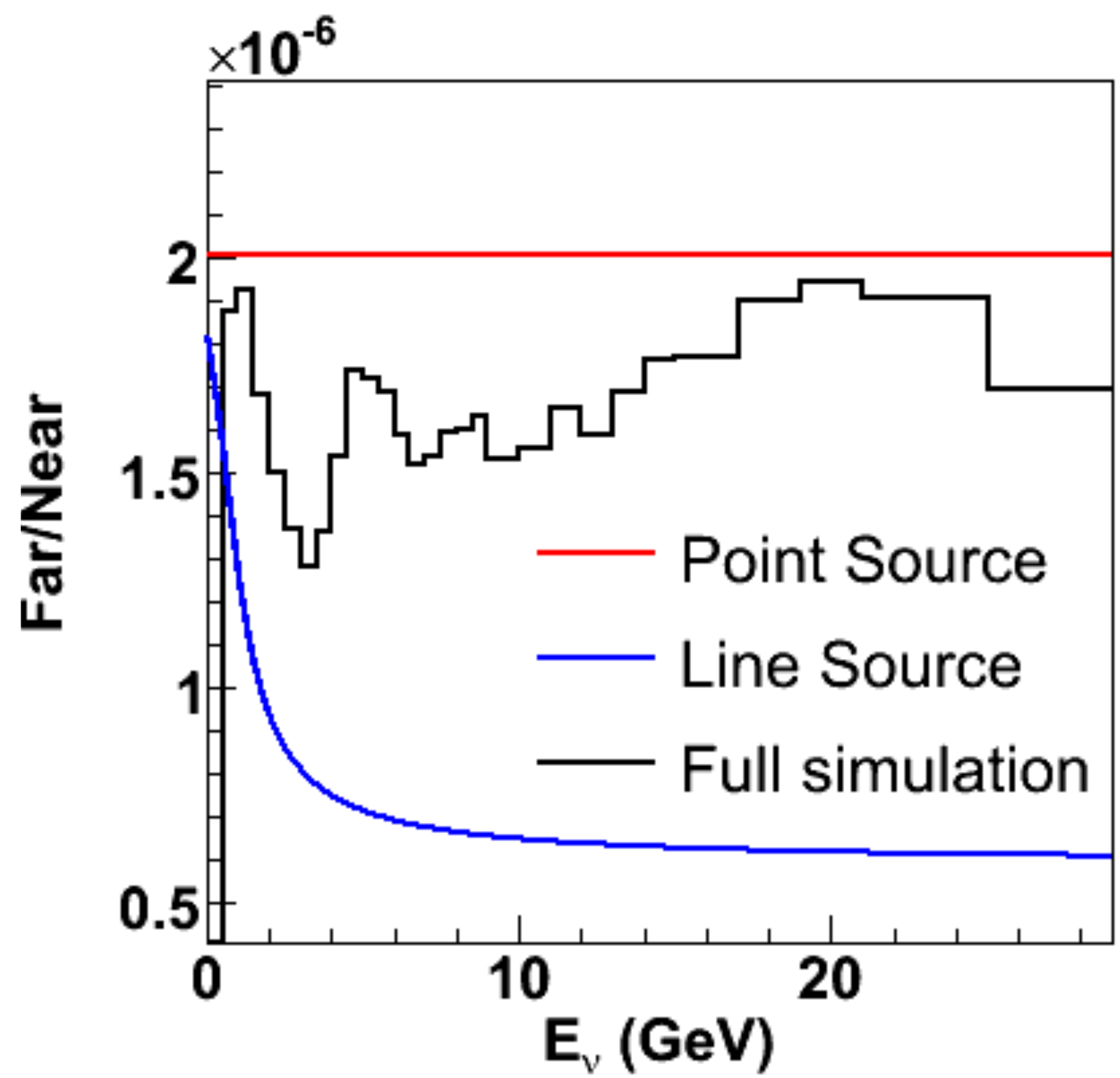
The Near detector sees decays from a broader range of angles, and the Far detector a point source, hence slight changes in the observed neutrino spectra

Direct Extrapolation

As the differences in Near and Far spectra are well understood, we can rely on a direct extrapolation based on the MC

Two direct extrapolation methods were used at MINOS, the beam matrix (NuMu) and Far/Near method (NuE)





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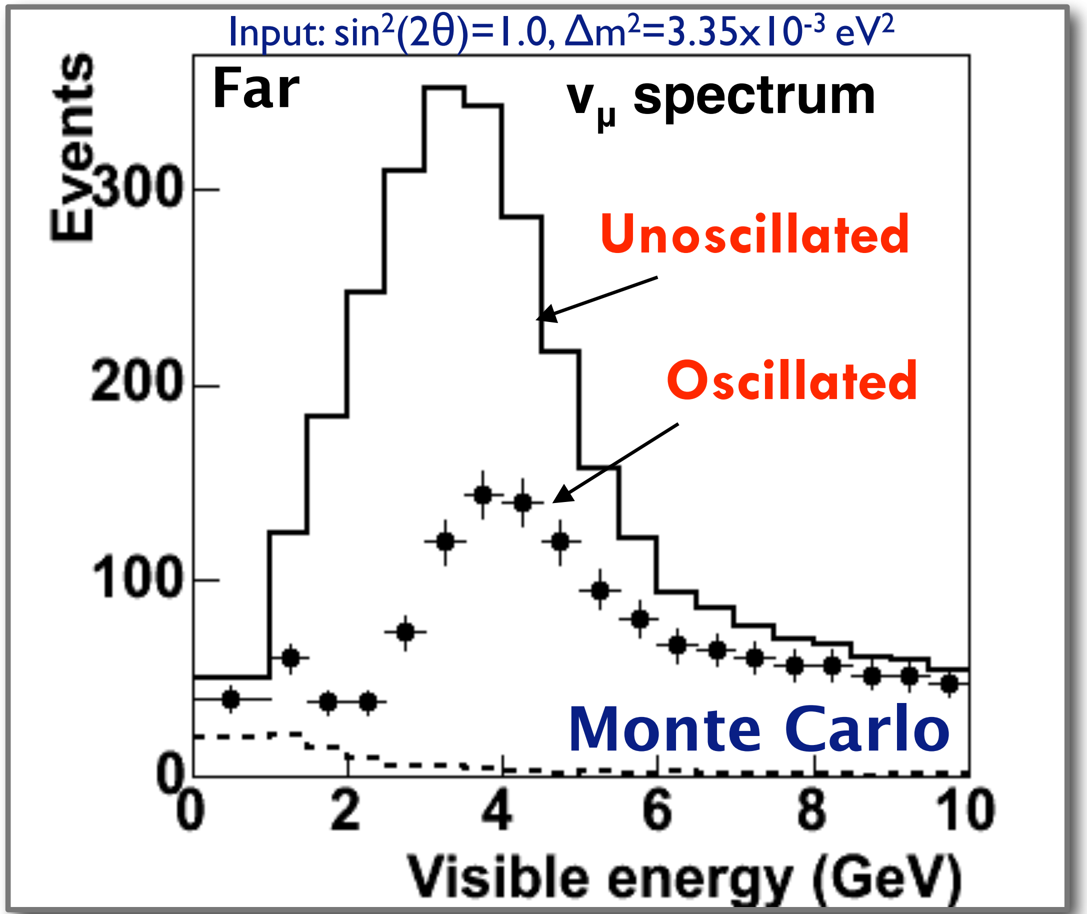
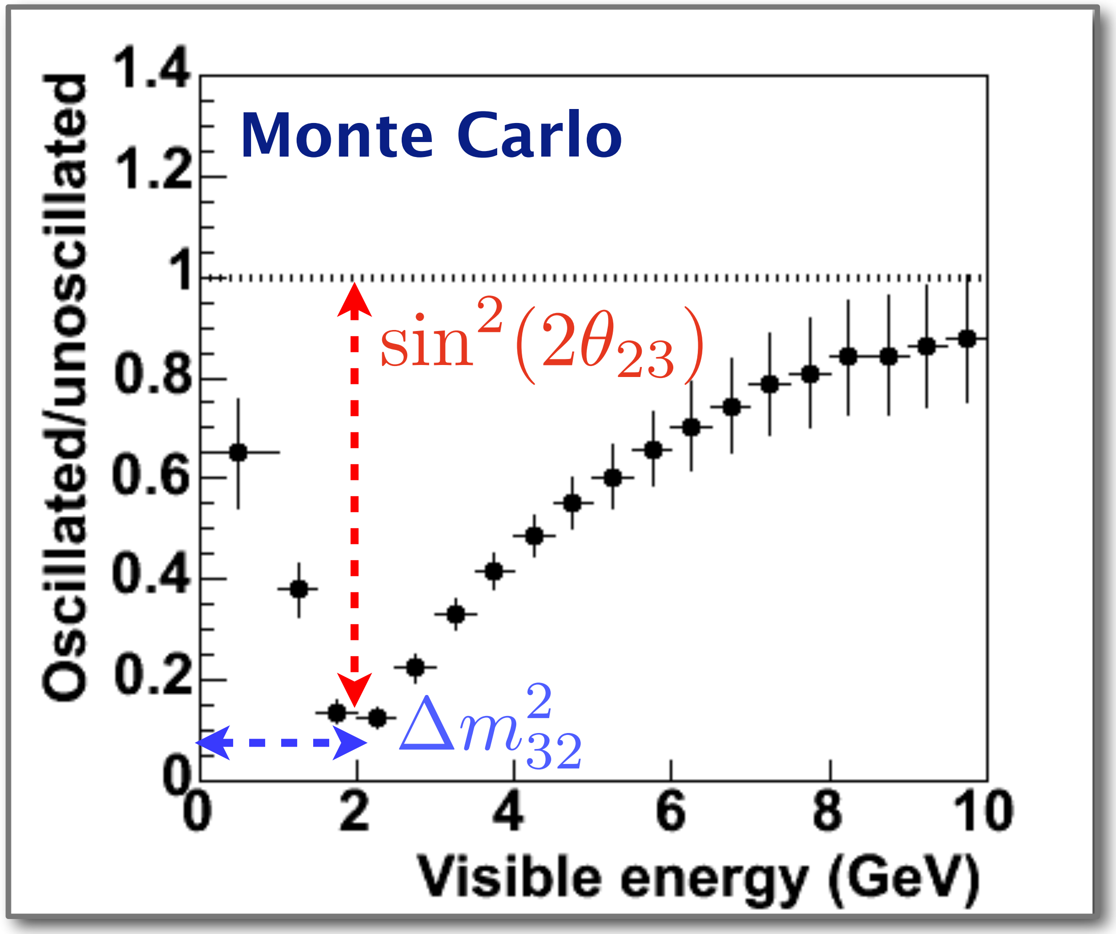
Muon Neutrino Disappearance

Beam NuMu Disappearance

- Far detector prediction from near detector is compared to far detector measurement
- Neutrino oscillations deplete rate and distort the energy spectrum

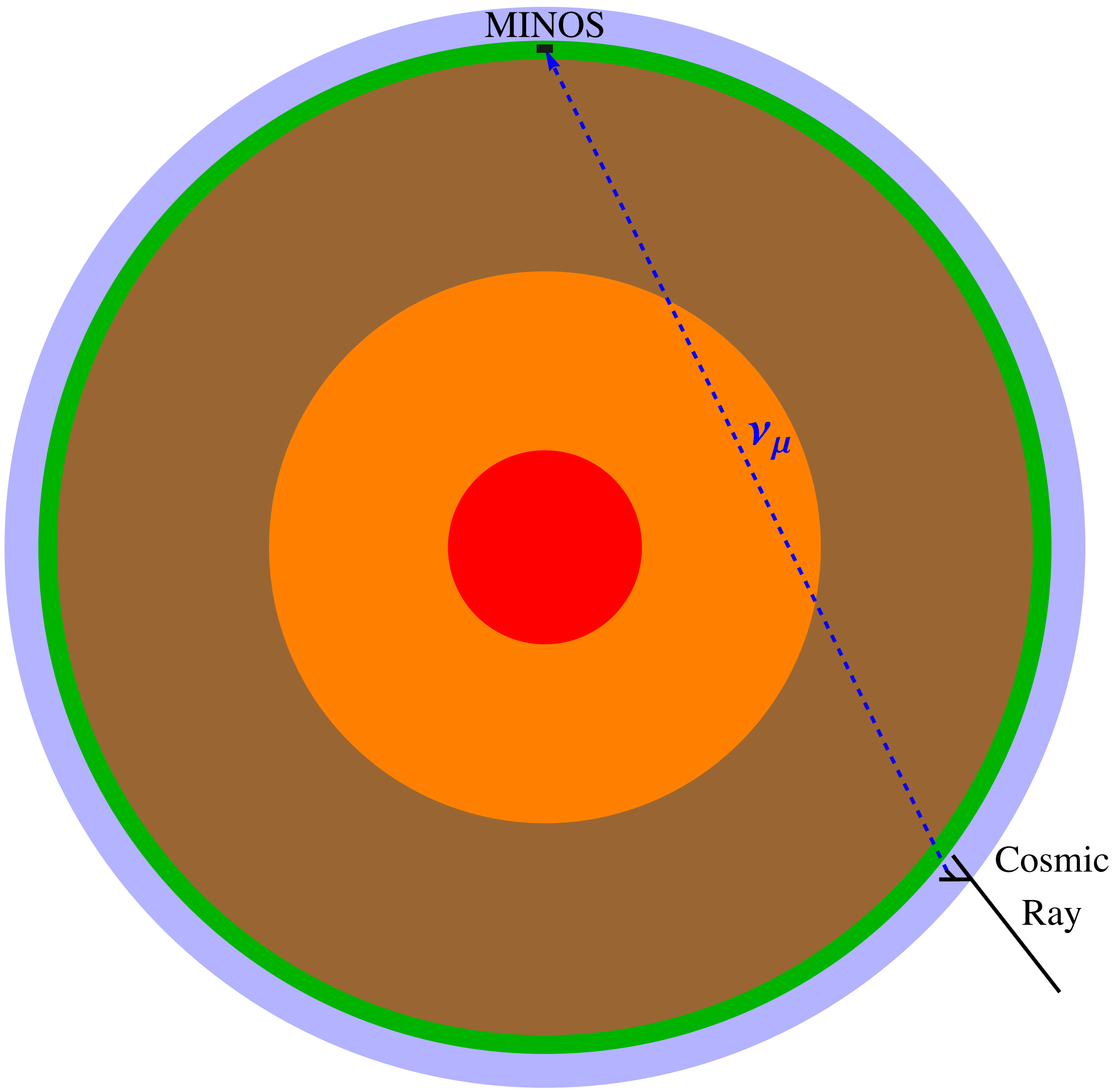
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E}\right)$$





Atmospheric NuMu Disappearance

- Not just limited to studying the disappearance of NuMI muon neutrinos- 48.7 kton-years of atmospheric neutrinos in Far Detector between 2003 and 2014
- Very long baselines through matter compared to NuMI disappearance analysis
- Some sensitivity to octant, mass hierarchy and δ_{cp}



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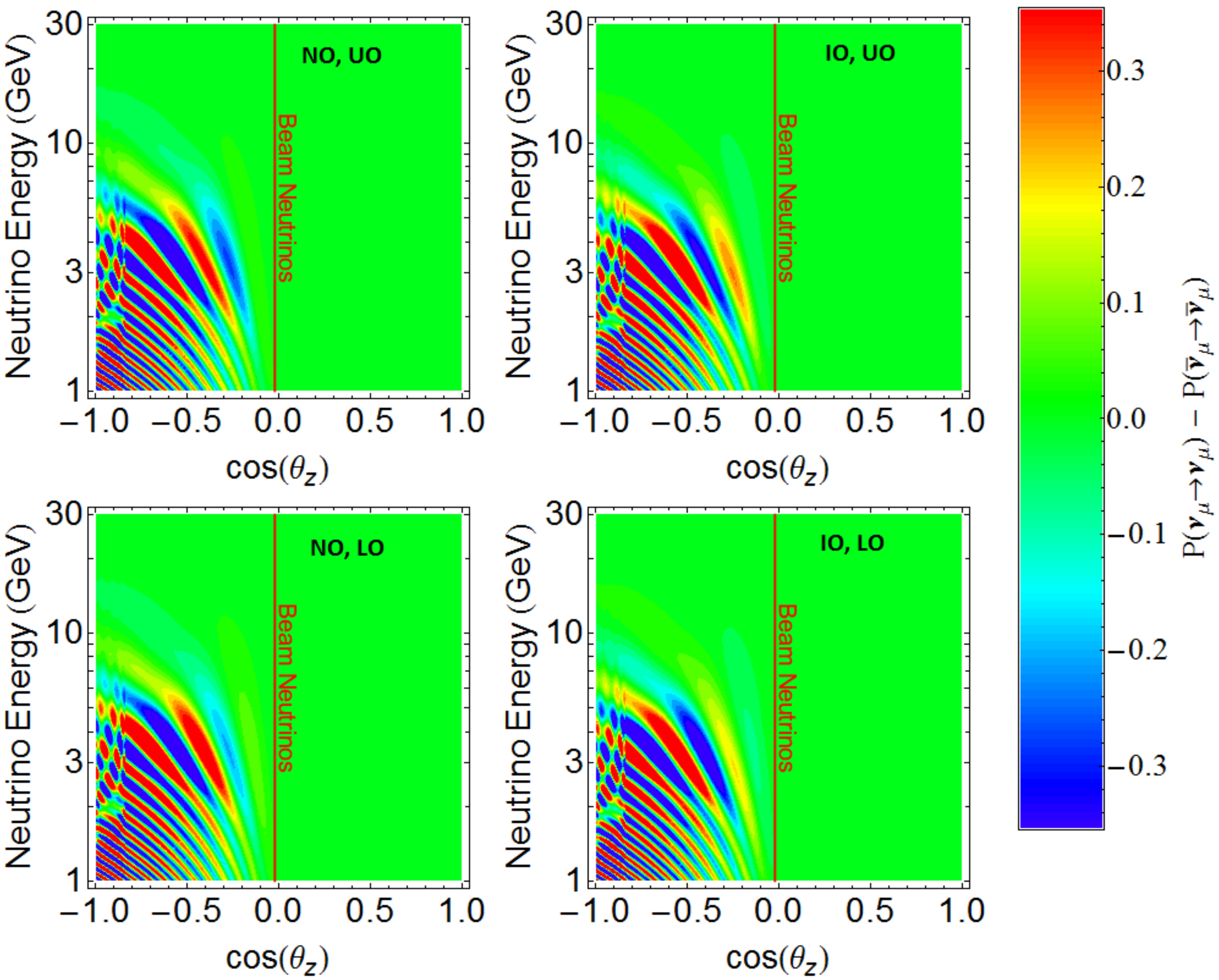
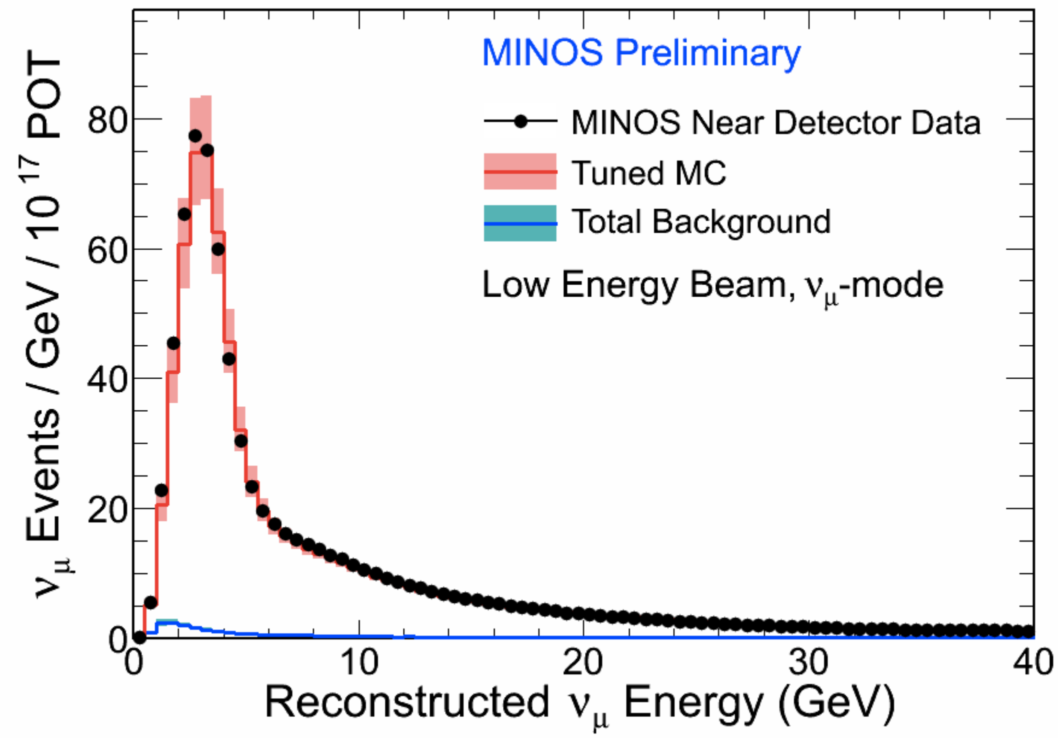
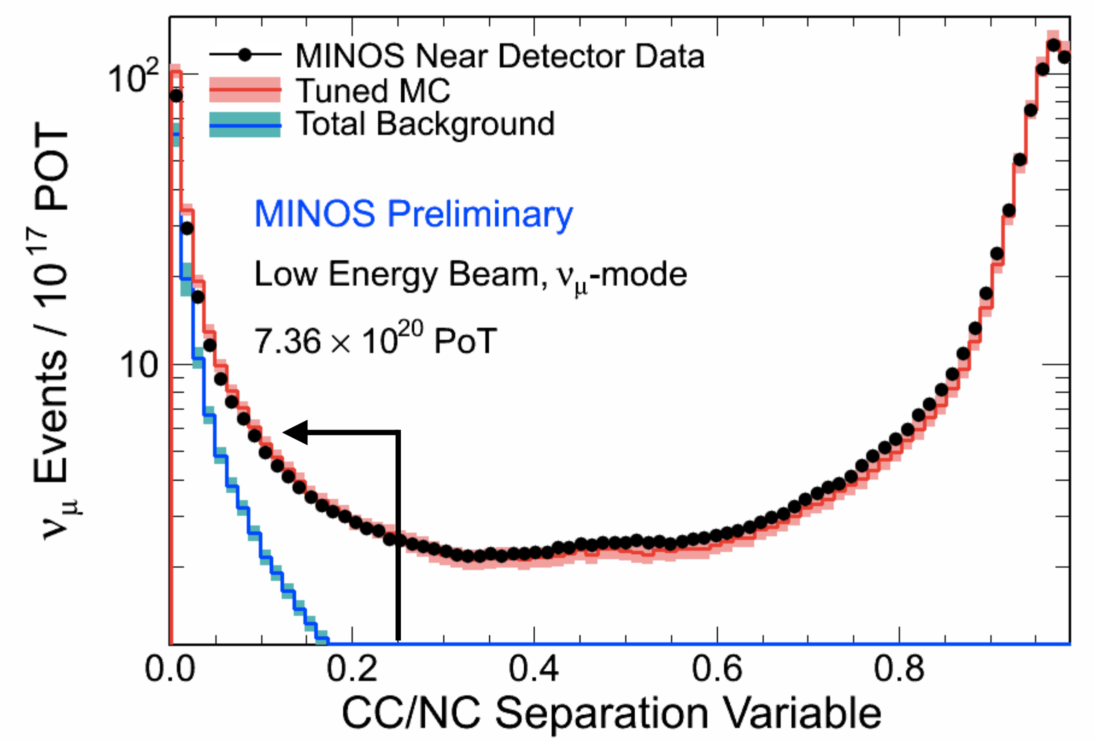


Beam Muon Neutrino Events in the Near Detector

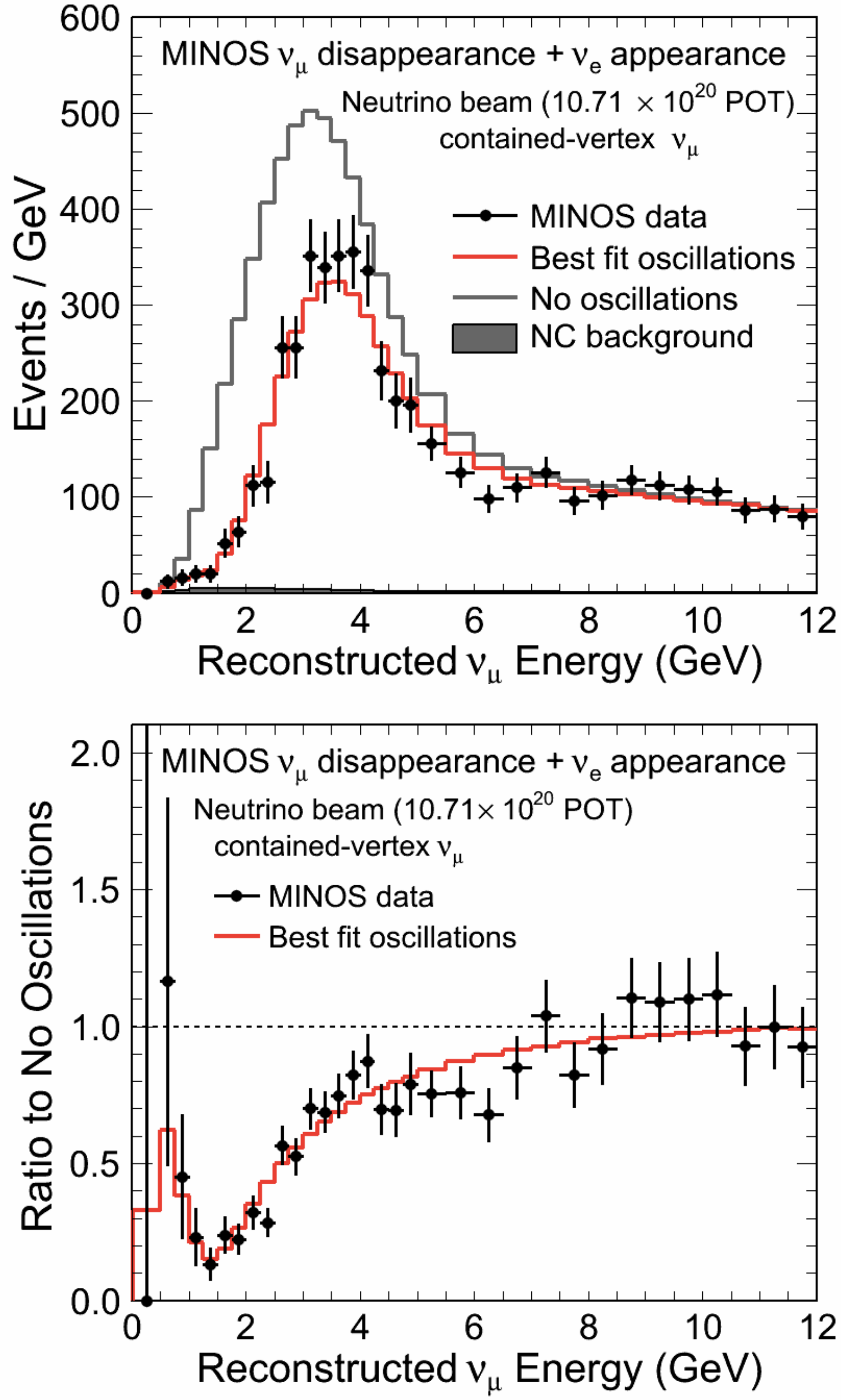
- Events with tracks originating in the fiducial volume are candidate events
- Selection is based on multivariate selection algorithm using the k-nearest-neighbour technique
- Below 6 GeV
  - Purity = 97%
  - Efficiency = 53.2%



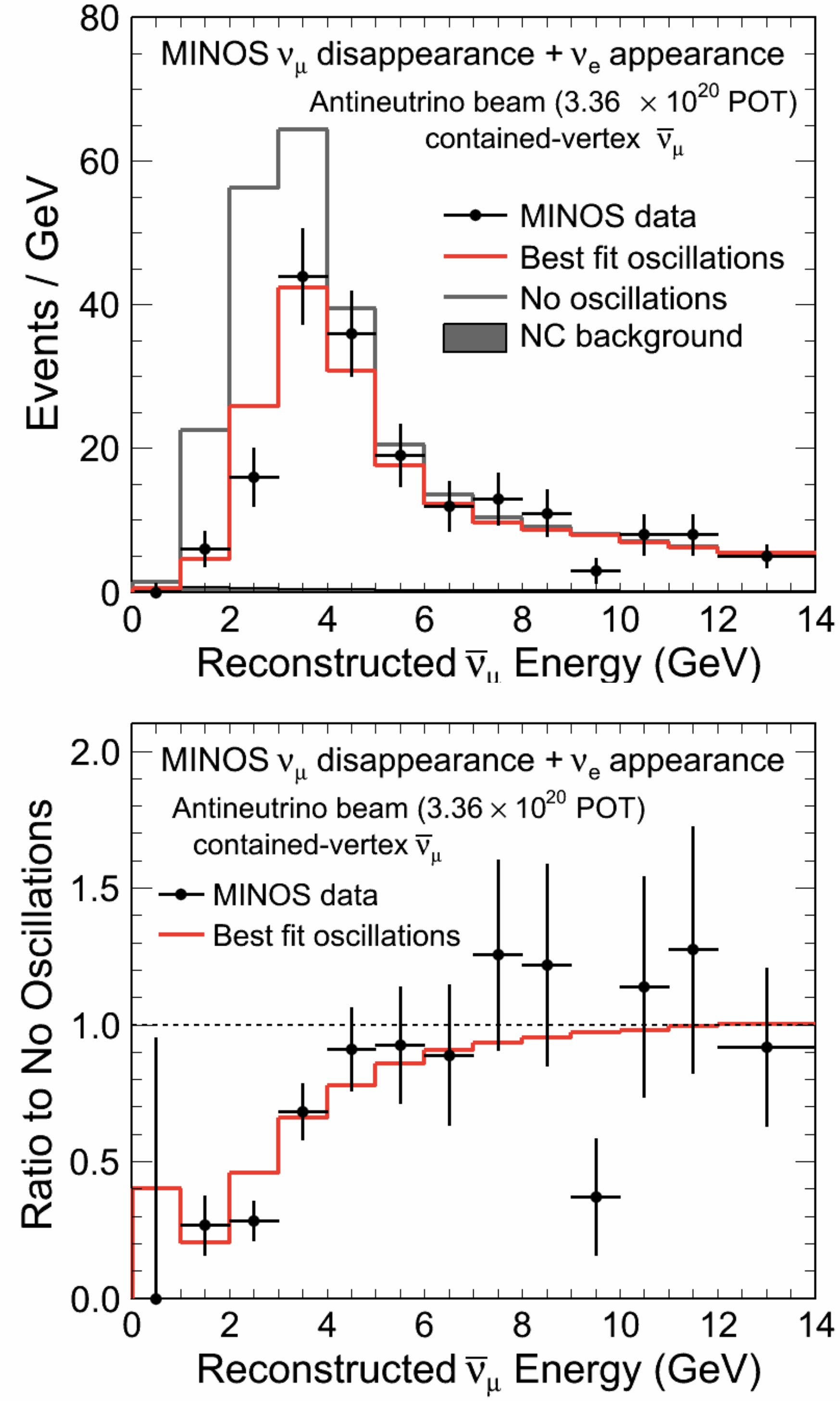


Beam Muon Neutrino Events in the Far Detector

Neutrinos

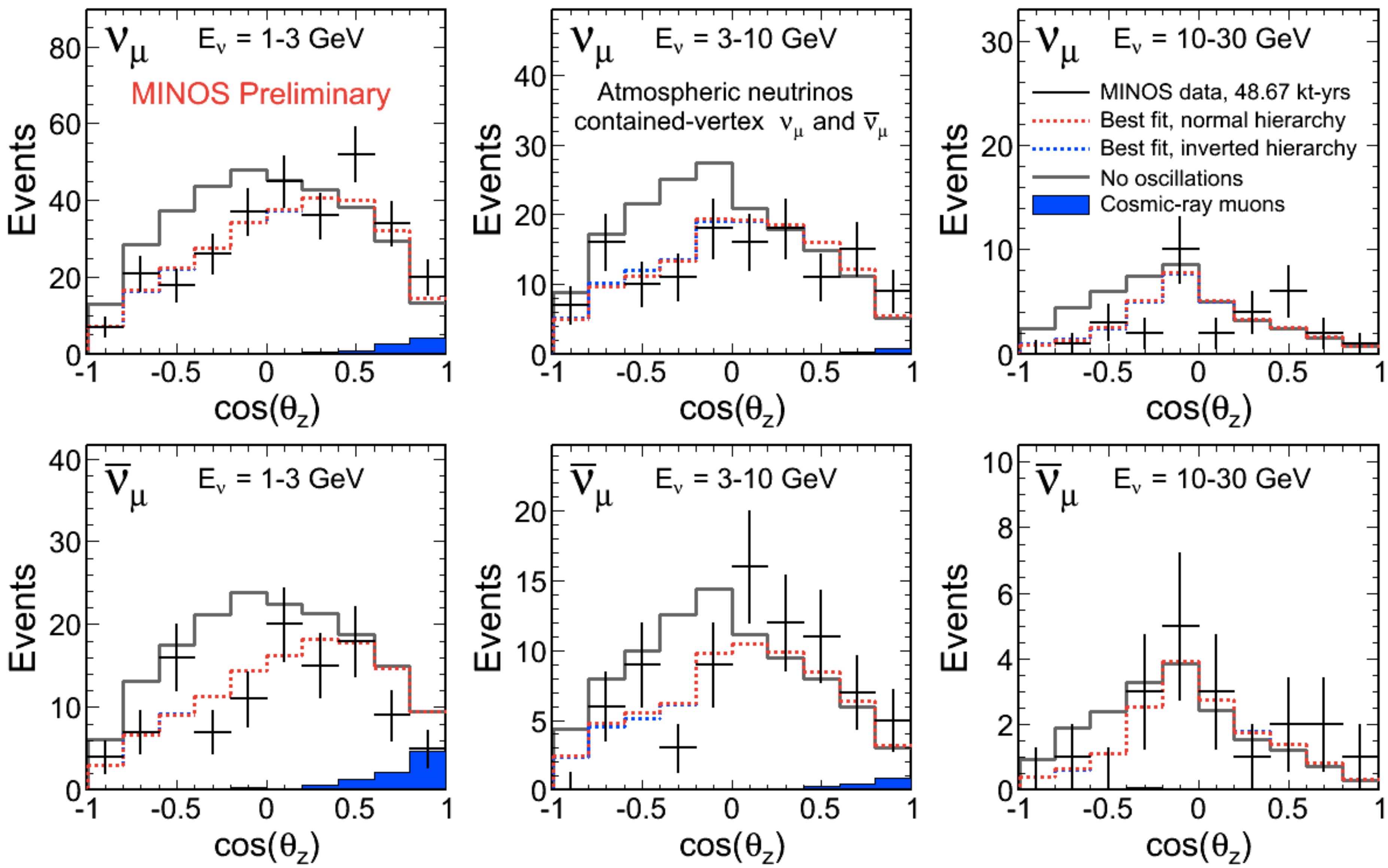


Antineutrinos



Atmospheric Muon Neutrino Events in the Far Detector

Contained vertex selected atmospheric neutrino events

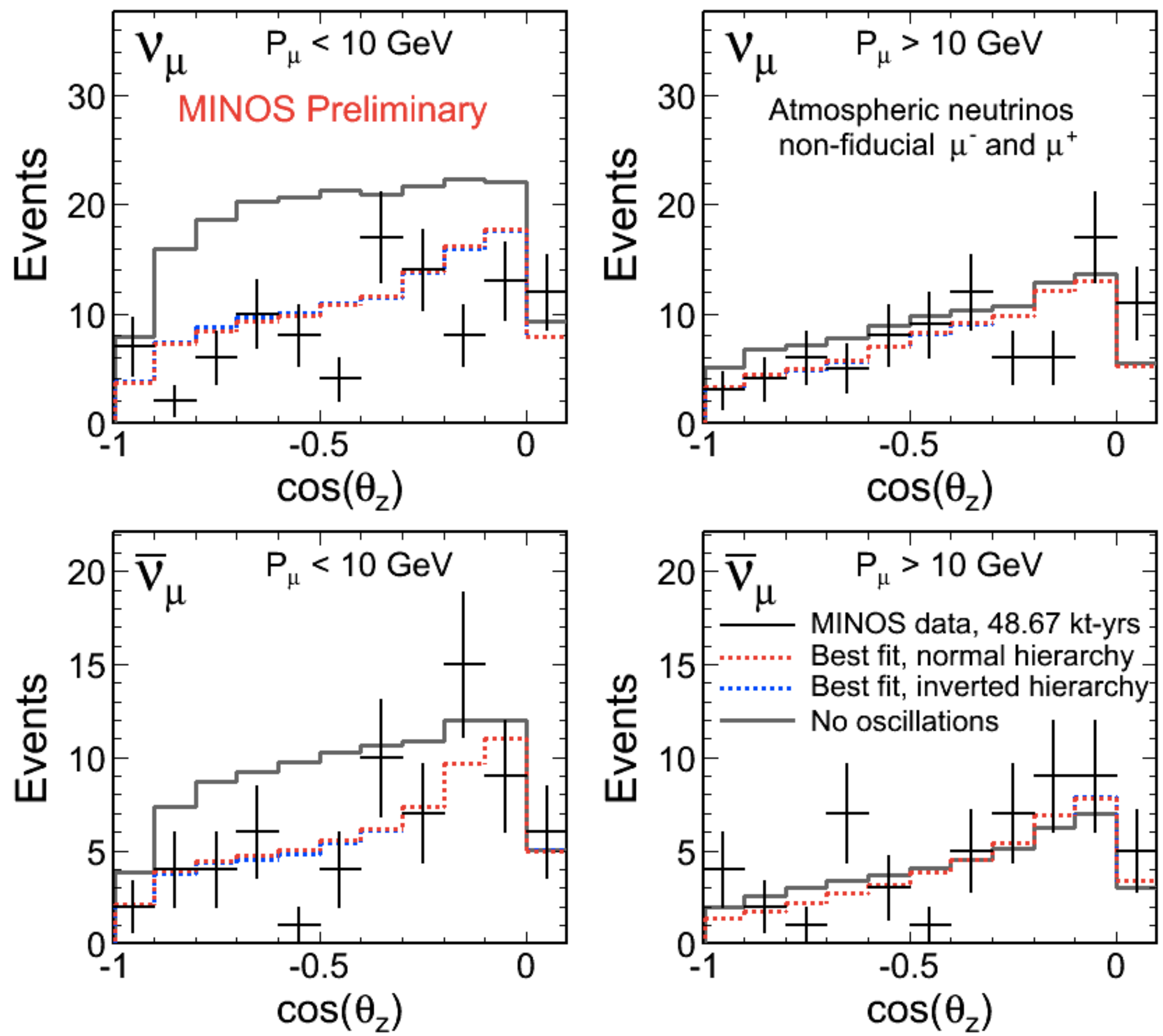


Neutrinos

Antineutrinos

Atmospheric Muon Neutrino Events in the Far Detector

Non fiducial selected atmospheric neutrino events



Neutrinos

Antineutrinos

Atmospheric and Beam Muon Neutrino Event Rates in the Far Detector

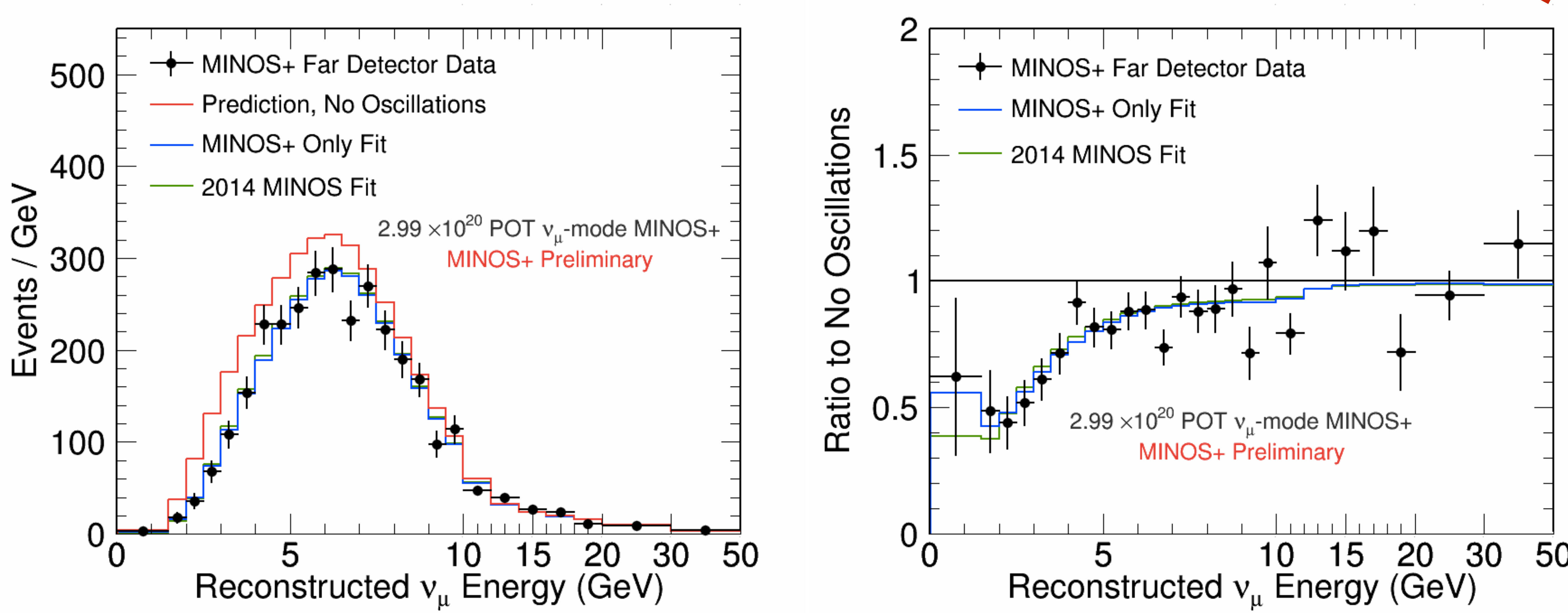
	Simulation		Events
Data Set	No osc.	With osc.	Observed
ν_μ from ν_μ beam	3201	2496	2579
$\bar{\nu}_\mu$ from ν_μ beam	363	319	312
Non-fiducial ν from ν_μ beam	3197	2807	2911
Atm. contained-vertex $\nu_\mu + \bar{\nu}_\mu$	1414	1024	1134
Atm. non-fiducial $\mu^+ + \mu^-$	732	575	590
Atm. showers	932	877	899

	Data	Expectation ($\Delta m^2_{32} = 2.10 \times 10^{-3}, \sin^2\theta_{23} = 0.5$)					
		cosmic	atmos $\nu_e/\bar{\nu}_e$ & $\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_\tau/\bar{\nu}_\tau$ CC	NC	ν-induced μ	Total
CV$_\mu$	1134	44 ± 4	1023 ± 150	3 ± 1	32 ± 8	7 ± 2	1109 ± 158
NIM	590	0 ± 0	20 ± 3	0 ± 0	0 ± 0	571 ± 143	591 ± 143
CV$_e$	899	110 ± 11	636 ± 79	5 ± 1	159 ± 40	1 ± 0	911 ± 120
Total	2623	2611 ± 244					

	Data	Expectation (no oscillations)					
		cosmic	atmos $\nu_e/\bar{\nu}_e$ & $\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_\tau/\bar{\nu}_\tau$ CC	NC	ν-induced μ	Total
CV$_\mu$	1134	44 ± 4	1327 ± 196	0 ± 0	32 ± 8	11 ± 3	1414 ± 204
NIM	590	0 ± 0	33 ± 5	0 ± 0	0 ± 0	699 ± 175	732 ± 175
CV$_e$	899	110 ± 11	661 ± 83	0 ± 0	159 ± 40	1 ± 0	932 ± 124
Total	2623	3078 ± 296					

MINOS+ Beam Data

NOT YET USED IN THE FIT



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Electron Neutrino Appearance

NuE Appearance

By measuring beam muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

θ_{23} octant

δ_{cp}

mass hierarchy

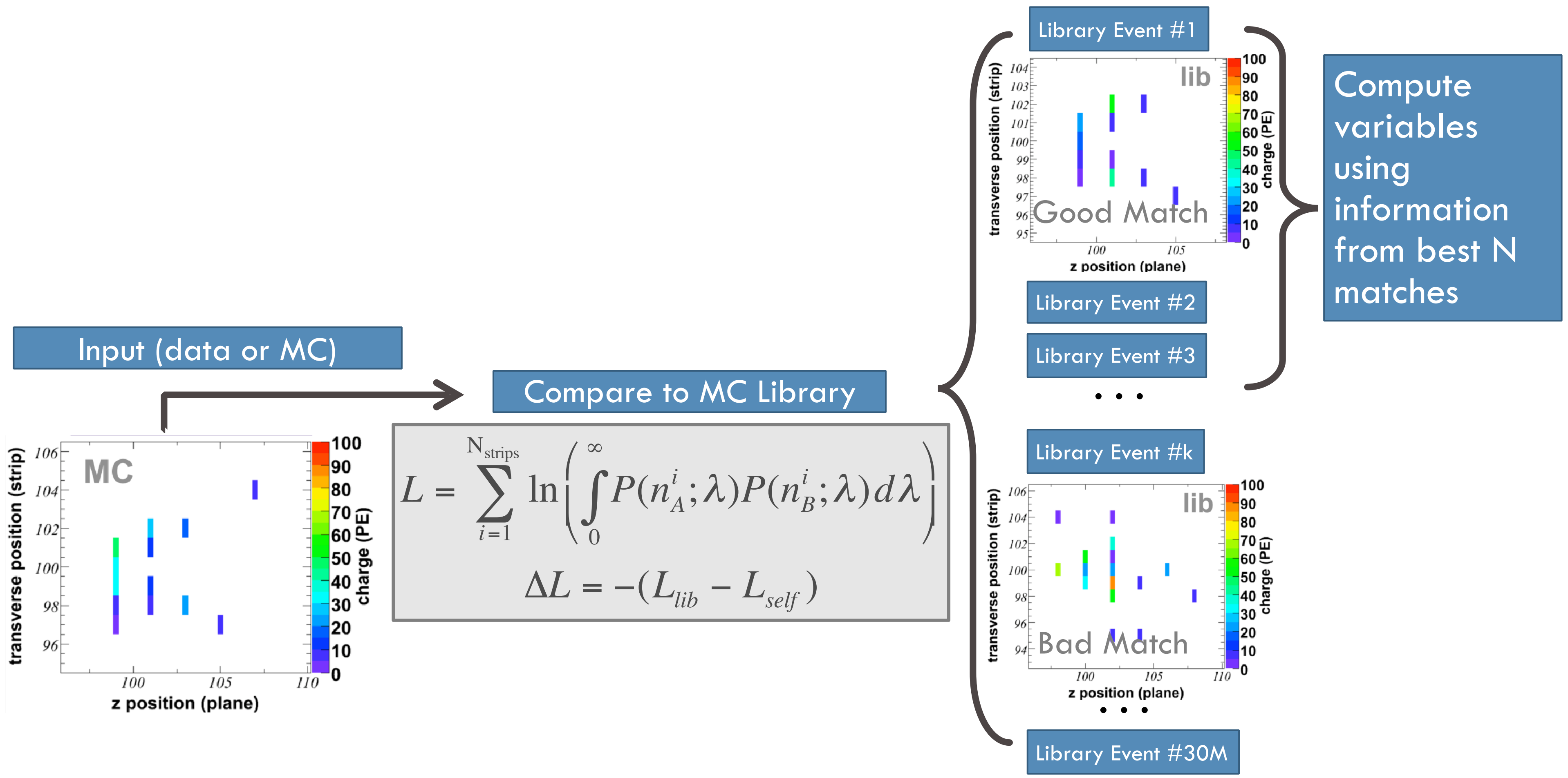
$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

Solar term contributes <1% at MINOS L/E

Selecting NuE Candidates

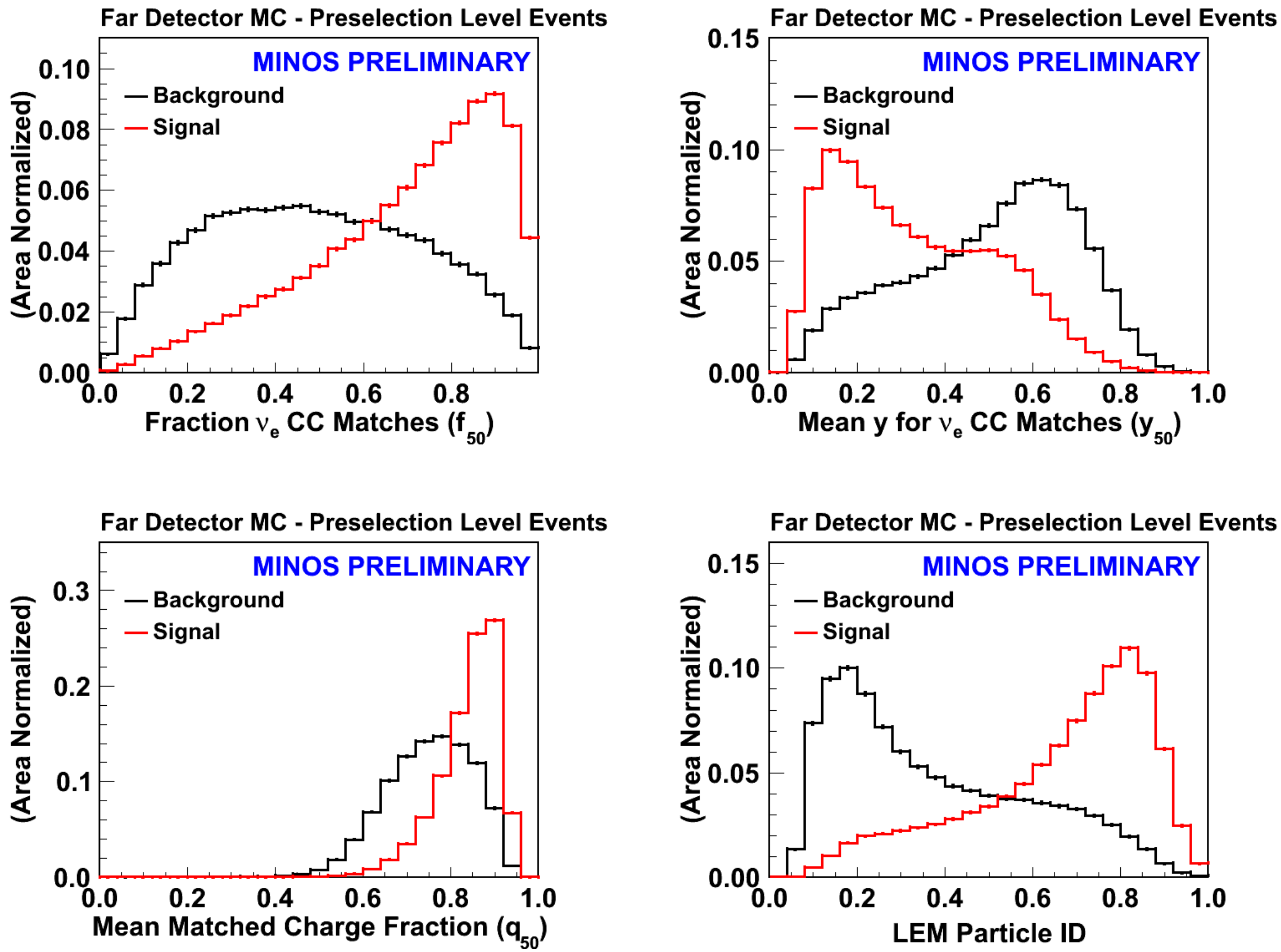
- MINOS detector granularity makes ν_e CC identification challenging
- Compare candidate events to a library of simulated signal and background events
- Comparison made on a strip by strip basis
- Discriminating variables formed using information from 50 best matches



Selecting NuE Candidates

- Three discriminating variables are then combined via a neural net to form our final PID

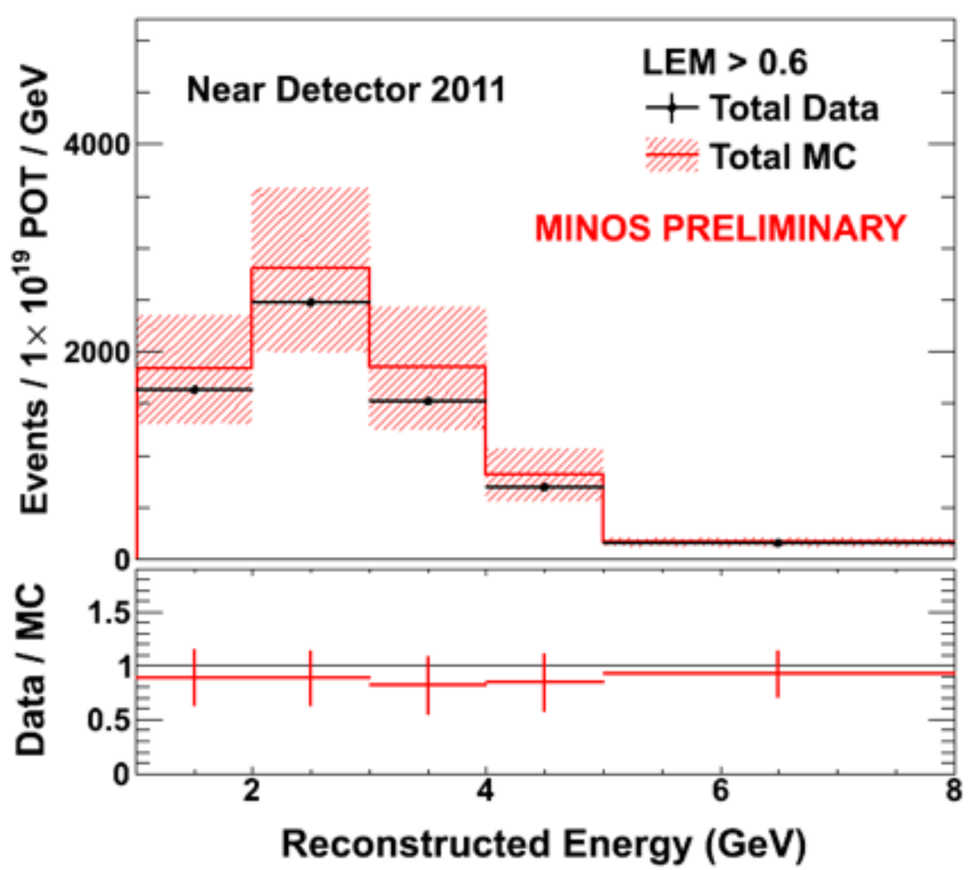
- Achieve ~40% signal efficiency, ~98% BG rejection

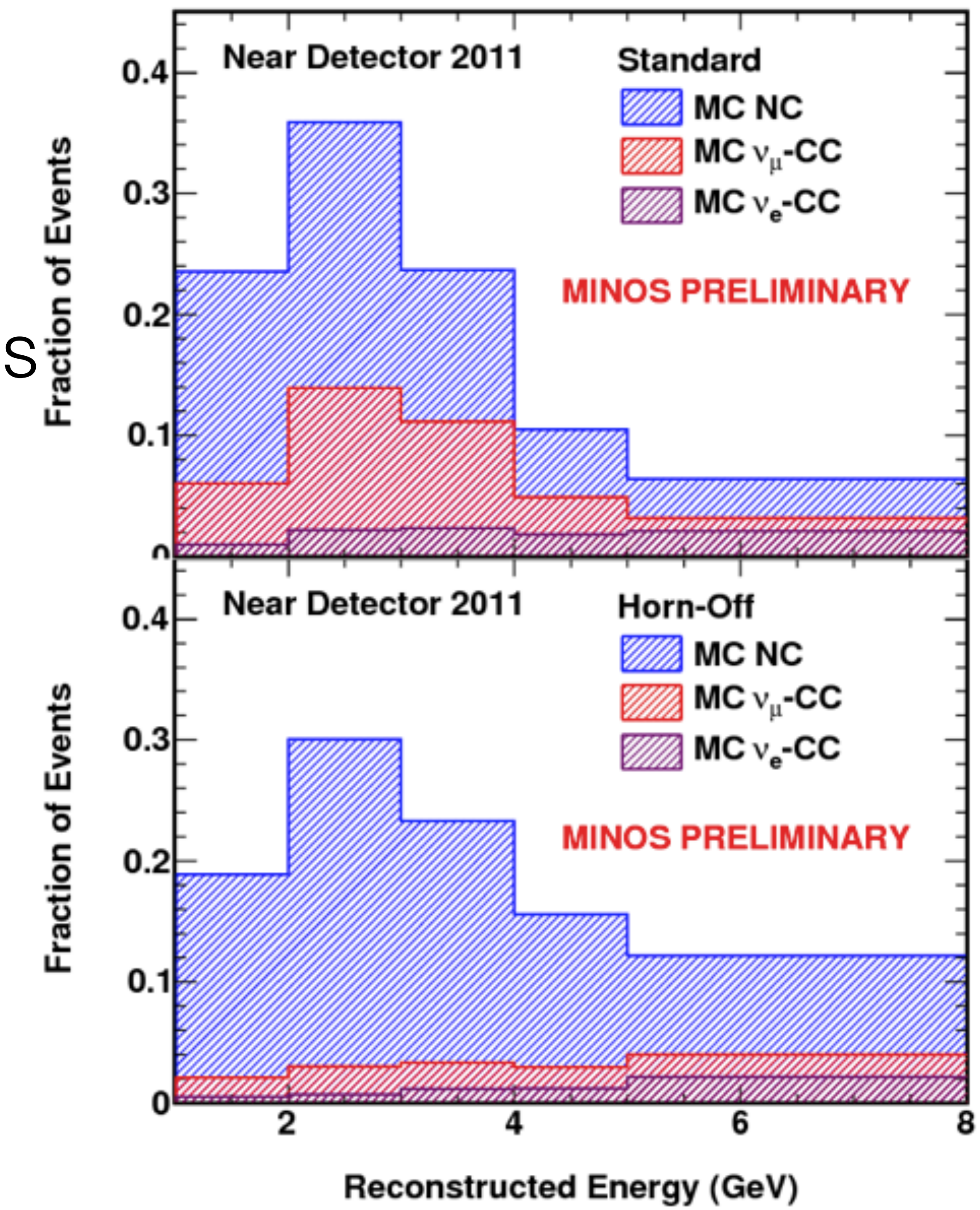


Selecting NuE Candidates

- Selected Near Detector Sample allows us to extrapolate our backgrounds to the Far Detector

- Data taken in multiple beam modes allowed us to decompose





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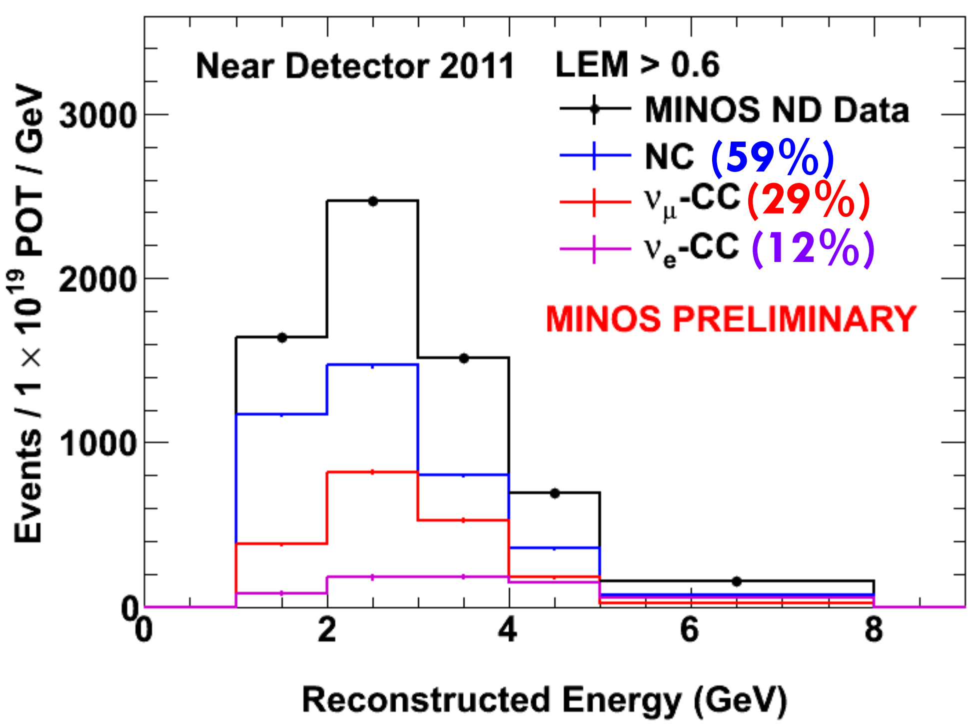
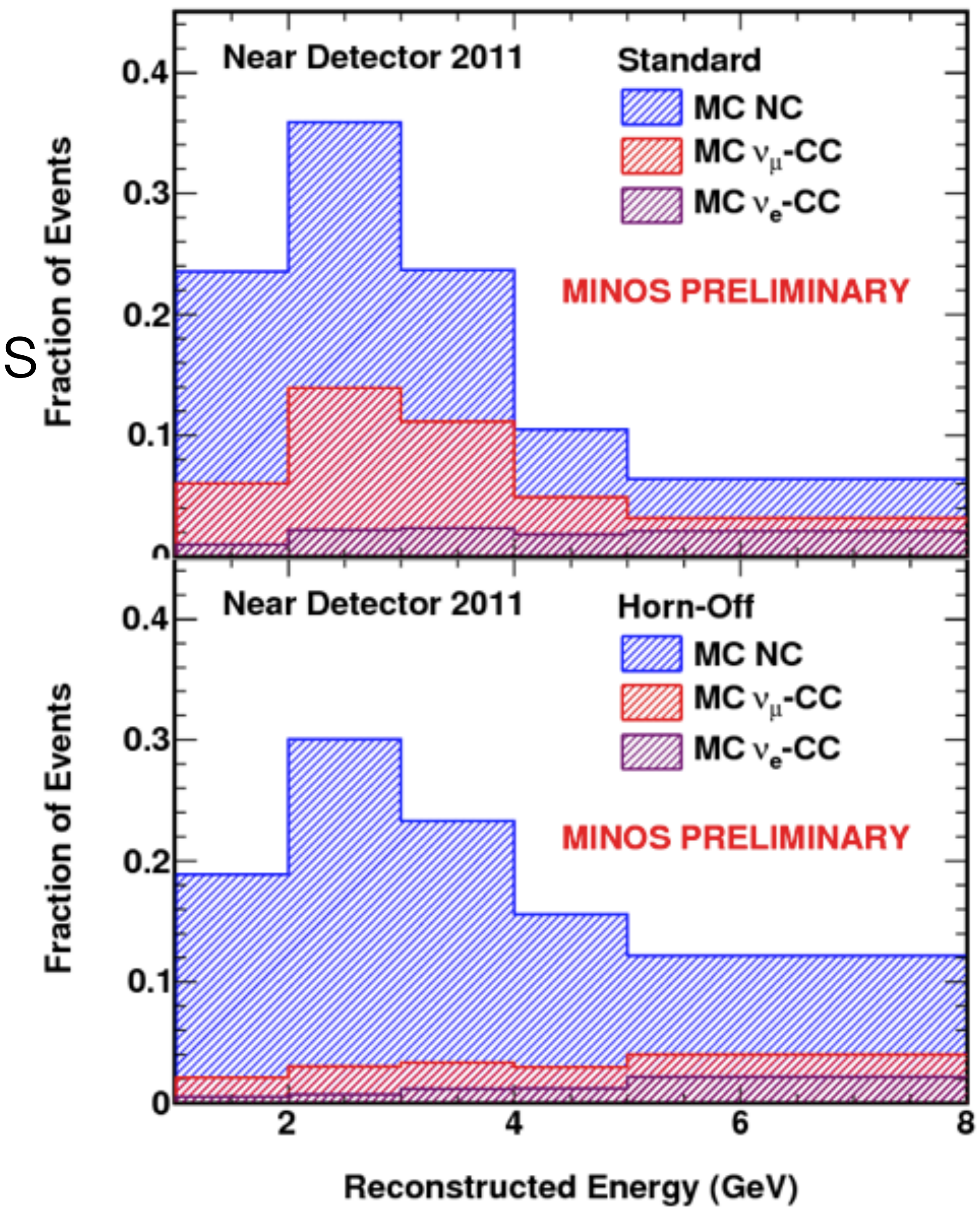
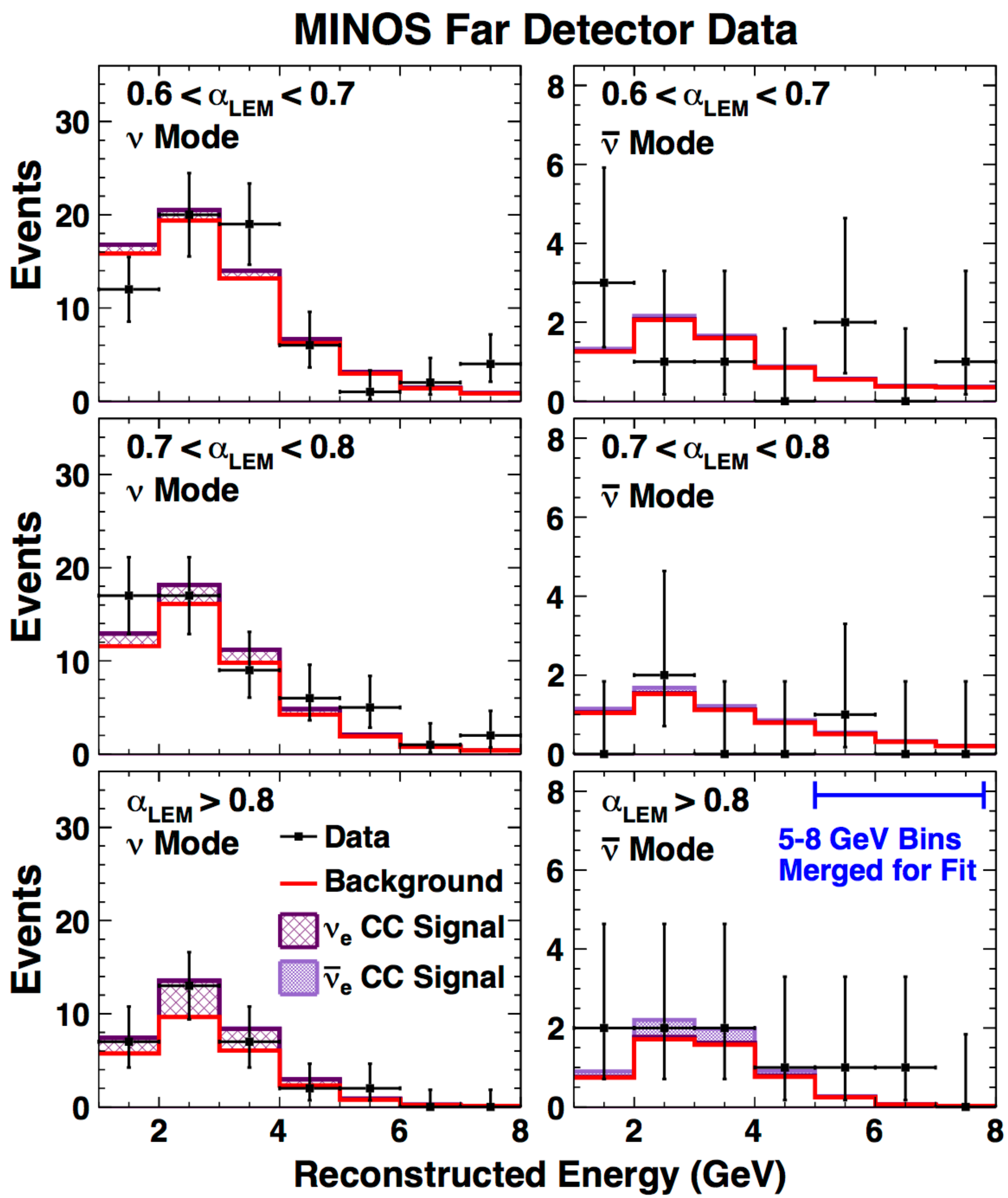




NuE FD Sample

FD event yields for normal mass hierarchy, $\delta_{CP}=0$, $\theta_{23}=\pi/4$

	ν-beam	$\bar{\nu}$-beam
$\theta_{13}=0$	69.1	10.5
$\theta_{13}=0.1$	+26.0	+3.1
Obs.	88	12



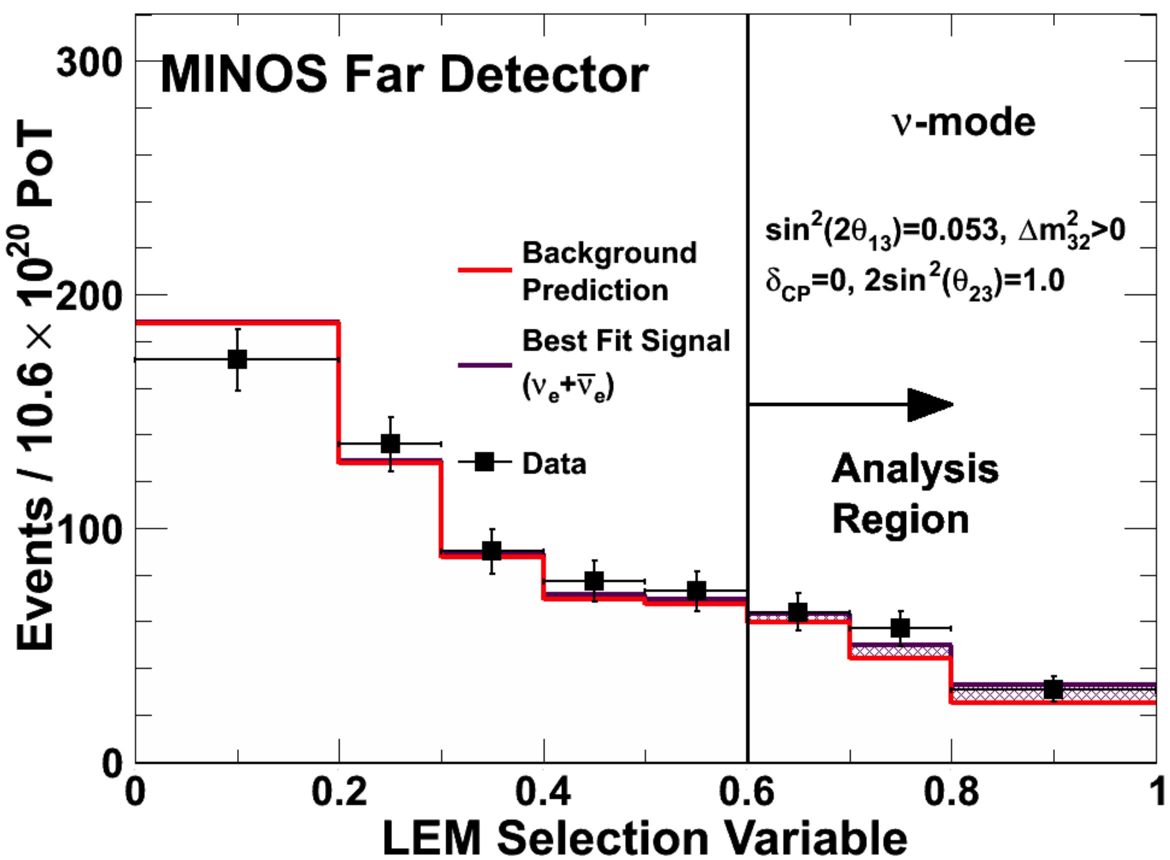
NuE FD Sample

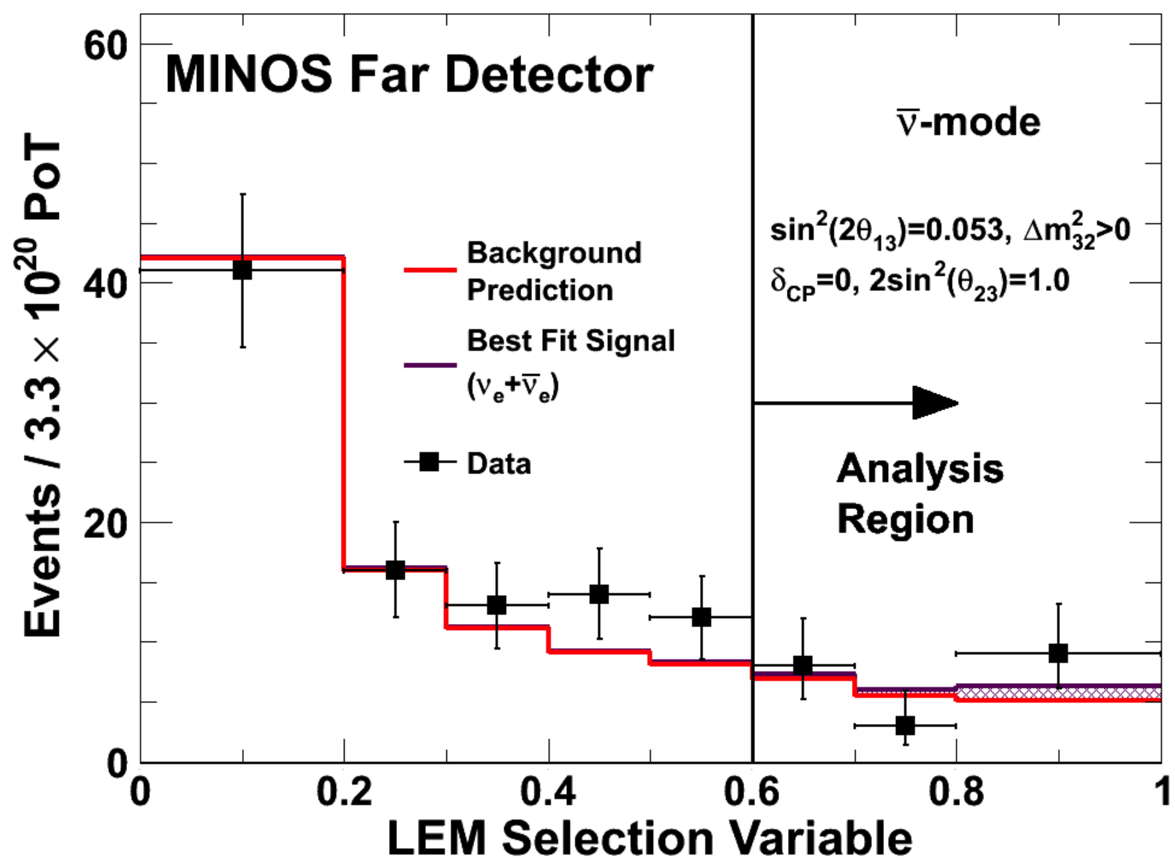
With the neutrino-enhanced beam in Signal Enhanced Region:

If $\theta_{13} = 0$: 128.6 BG Events
If $\sin^2(2\theta_{13}) = 0.1$: +32.5 Events
Total Prediction: 161 Events
Observed: 152 Events

With the antineutrino-enhanced beam in Signal Enhanced Region:

If $\theta_{13} = 0$: 17.5 BG Events
If $\sin^2(2\theta_{13}) = 0.1$: +3.7 Events
Total Prediction: 21.2 Events
Observed: 20 Events





Combined Standard Oscillations Fit Result

Combined Best Fit

Atmospheric Data Only

Hierarchy	Best fit oscillation parameters				-2Δlog(L)
	Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	
Normal	2.03	0.50	0.0242	0	-
Inverted	2.13	0.50	0.0242	1.57	0.559

Atmos+Disappearance Data

Hierarchy	Best fit oscillation parameters				-2Δlog(L)
	Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	
Normal	2.31	0.59	0.0243	0	0.020
Inverted	2.37	0.43	0.0243	1.57	-

Atmos+Disappearance+Appearance Data

Hierarchy	Best fit oscillation parameters				-2Δlog(L)
	Δm^2_{32} ($\times 10^{-3}$ eV^2)	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	
Normal	2.34	0.43	0.0242	1.77	0.16
Inverted	2.37	0.43	0.0243	1.77	-

Hierarchy	Parameter	Best fit	Confidence limits
Normal	$\|\Delta m^2_{32}\|$ ($\times 10^{-3}$ eV^2)	2.34	2.25 - 2.43 (68% C.L.)
	$\sin^2\theta_{23}$	0.43	0.39 - 0.59 (68% C.L.) 0.37 - 0.64 (90% C.L.)
Inverted	$\|\Delta m^2_{32}\|$ ($\times 10^{-3}$ eV^2)	2.37	2.30 - 2.48 (68% C.L.)
	$\sin^2\theta_{23}$	0.43	0.38 - 0.62 (68% C.L.) 0.36 - 0.65 (90% C.L.)

Preference for inverted hierarchy:
$-2\Delta\log\mathscr{L}=0.16$

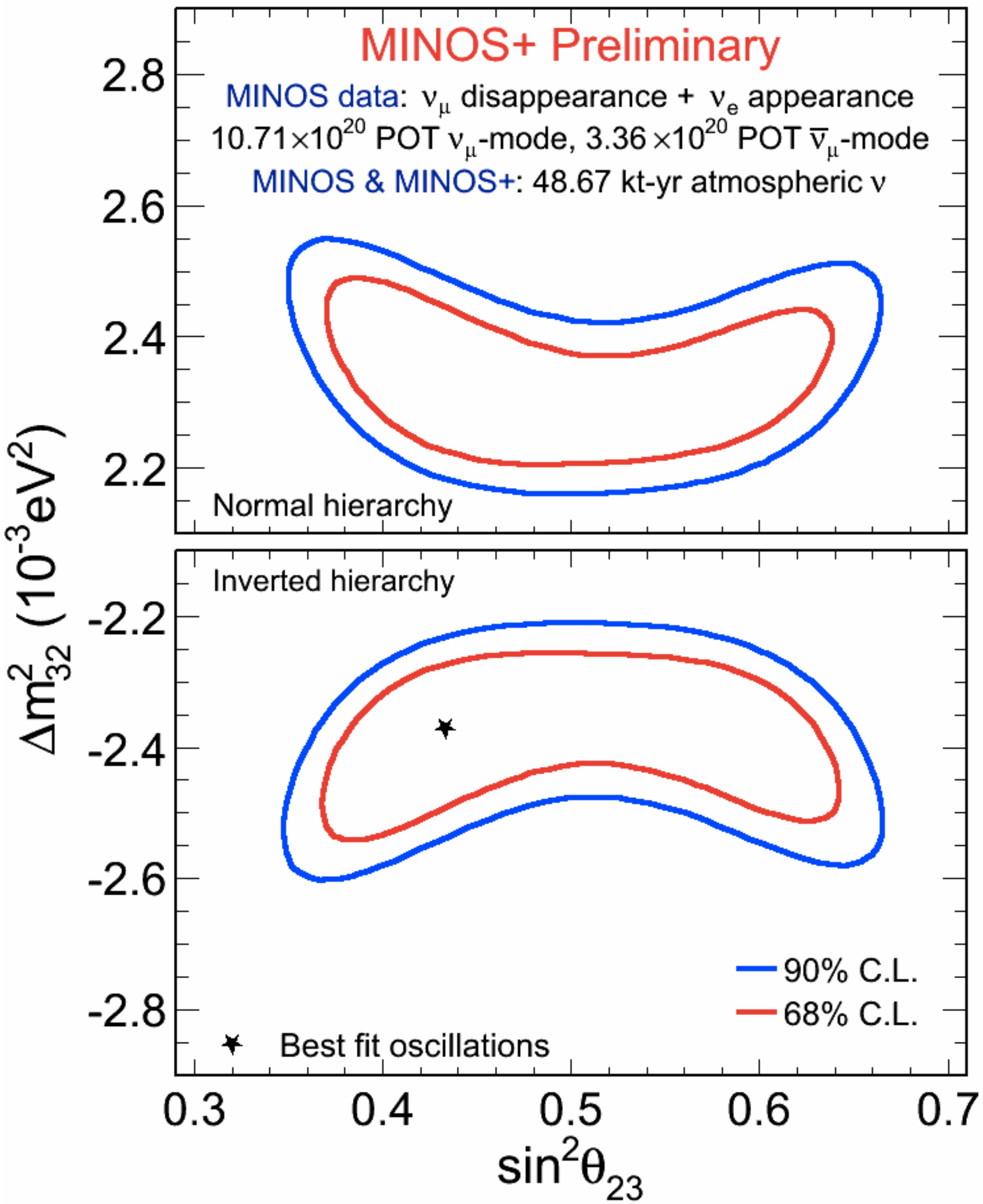
Preference for lower octant of θ_{23}:
$-2\Delta\log\mathscr{L}=0.38$

Preference for non-maximal mixing:
$-2\Delta\log\mathscr{L}=0.66$

Preference for inverted hierarchy:

$-2\Delta\log\mathscr{L}=0.16$

Combined Best Fit



Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

Normal Hierarchy

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$

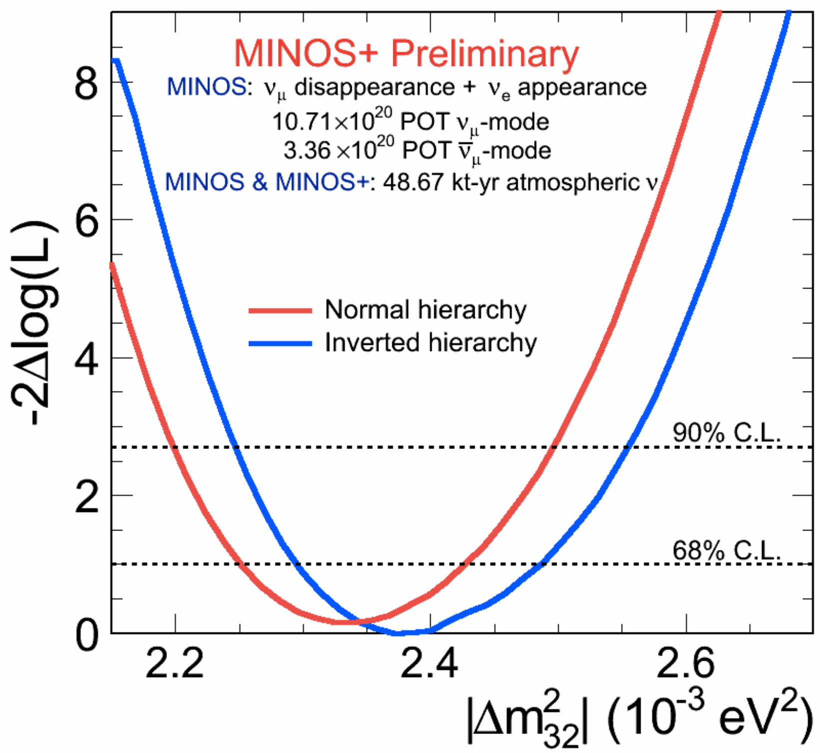
$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

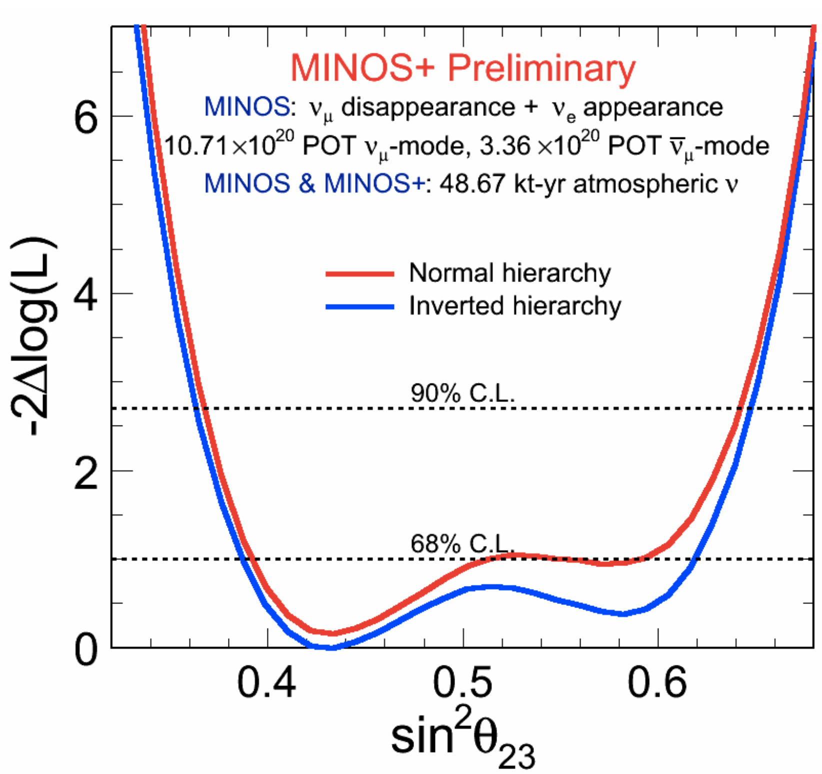
$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

Most precise measurement of $|\Delta m^2_{32}|$

Consistent with maximal mixing

Combined Best Fit





Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

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Normal Hierarchy

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$

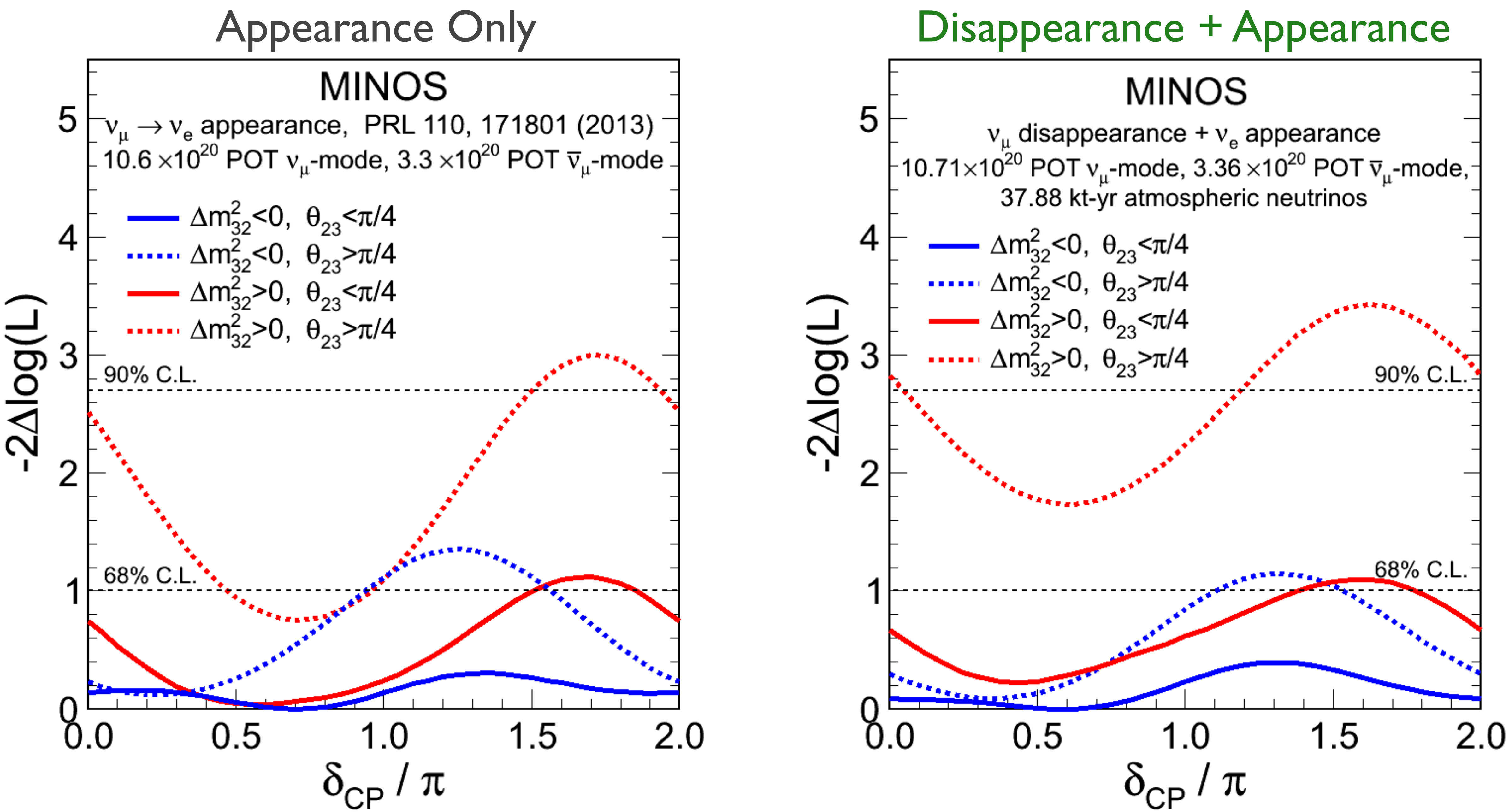
$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

Most precise measurement of $|\Delta m^2_{32}|$

Consistent with maximal mixing

Combined Best Fit



Phys. Rev. Lett. **112**, 191801 (2014)

Adding disappearance data (beam+atmospherics) further disfavors normal hierarchy and upper octant

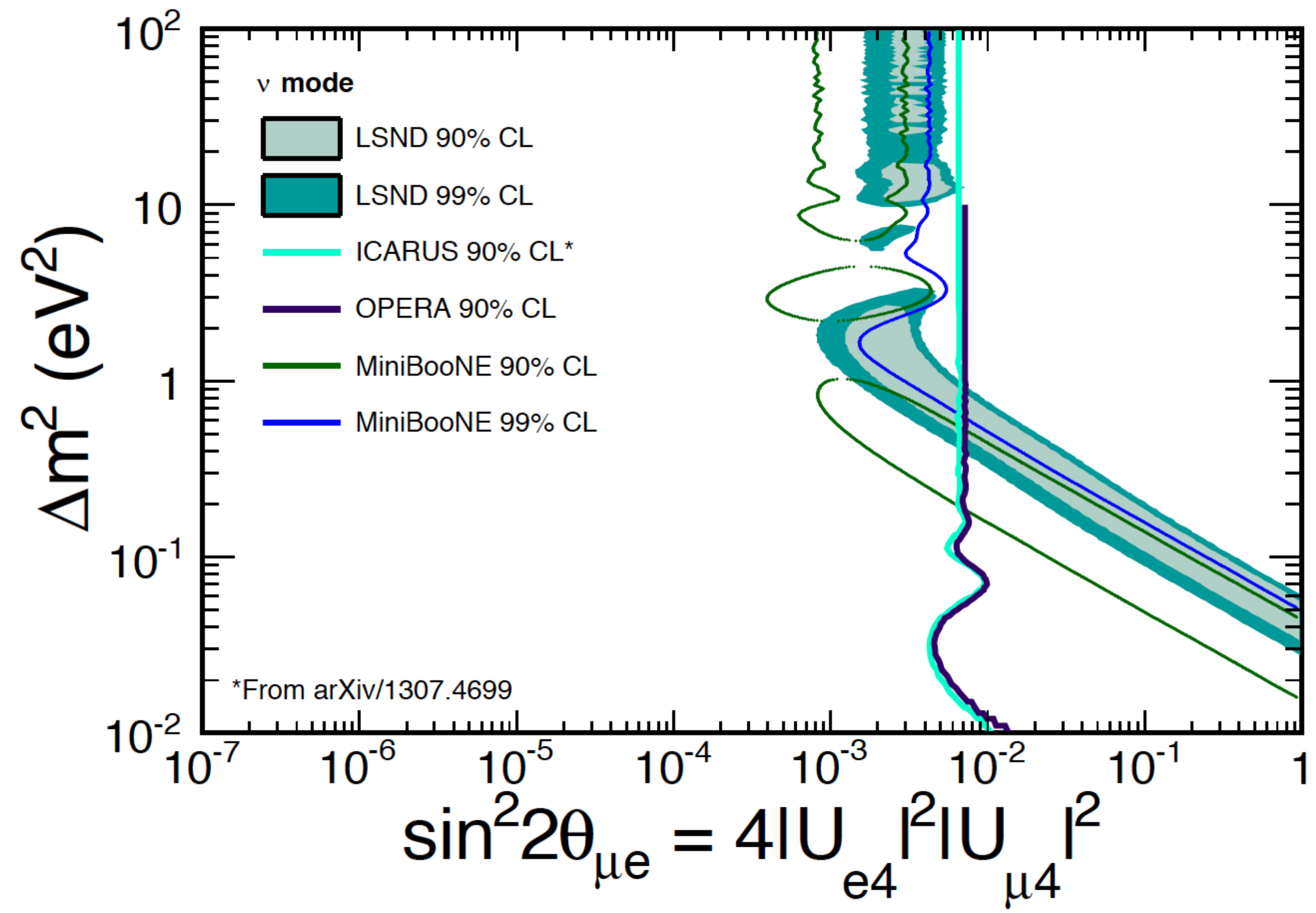
Sterile Neutrino Constraints in from Disappearance Channel at MINOS

Sterile Neutrinos at MINOS

- Oscillations into light sterile neutrinos may explain anomalies seen in SBL, reactor, and radiochemical experiments

- Evidence for sterile neutrino mixing remains inconclusive due to severe tension between appearance and disappearance measurements

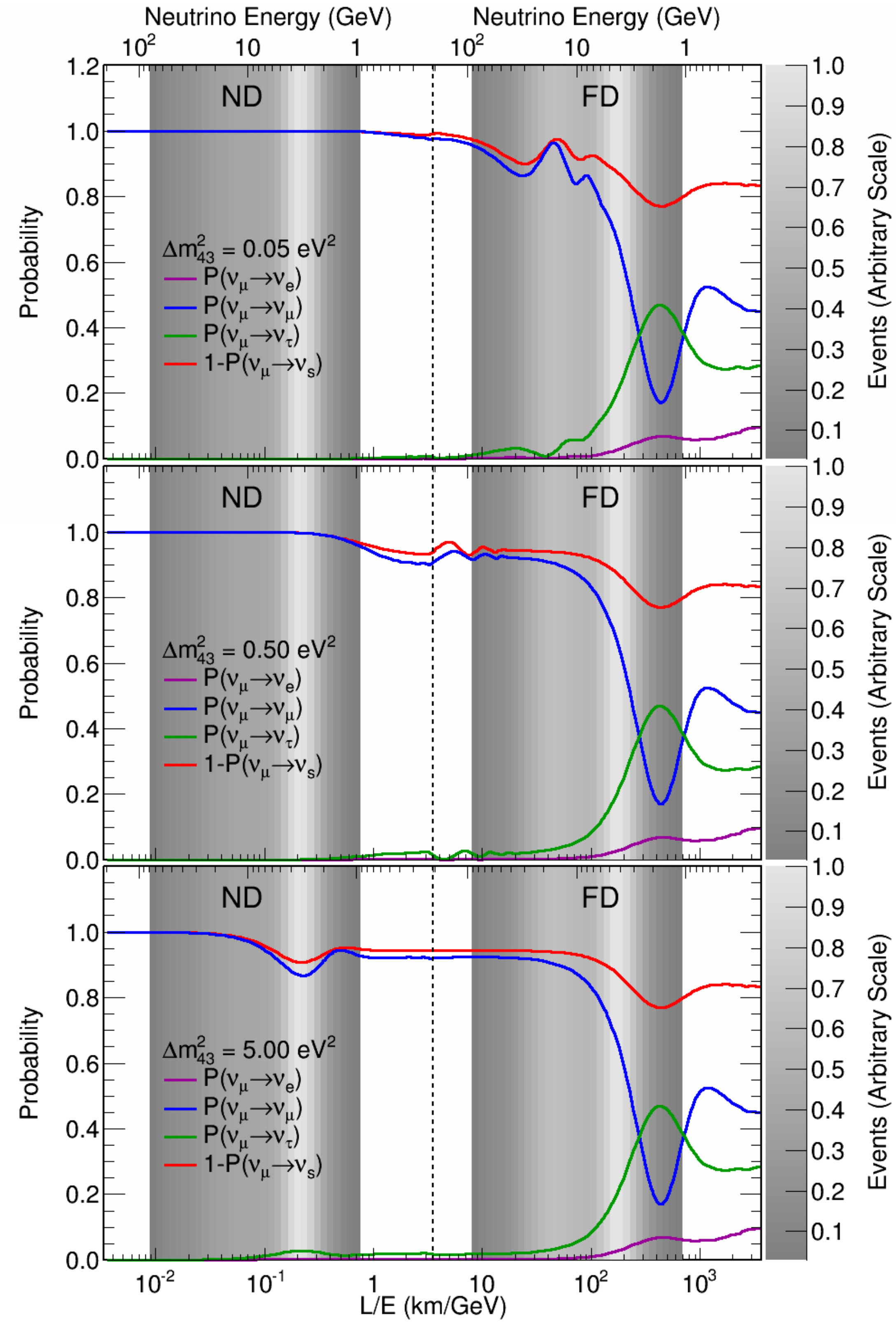
- What can MINOS say?



MiniBooNE, PRL 110, 161801(2013)

Sterile Neutrinos at MINOS

- $\nu_\mu \rightarrow \nu_s$ mixing causes energy-dependent depletion of NC and ν_μ-CC energy spectra w.r.t 3-flavor mixing
- Small Δm^2_{43} (> Δm^2_{32}):
  - FD spectral distortions at energies above 3-flavor oscillation maximum
  - No ND effects
- Medium Δm^2_{43}:
  - Rapid oscillations at FD average out
  - No ND effects
  - Counting experiment
- Large Δm^2_{43}:
  - Rapid oscillations at FD average out
  - ND spectral distortions affect extrapolation to FD



FD CC and NC Samples

- Comparison with 3-flavor prediction for full MINOS low-energy beam neutrino mode sample: 10.56×10^{20} POT
- Selected ν_μ-CC and CC candidates in both detectors:
  - 2712 ν_μ-CC-like events in FD
  - 1221 NC-like events in FD
- NC Selection:

$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

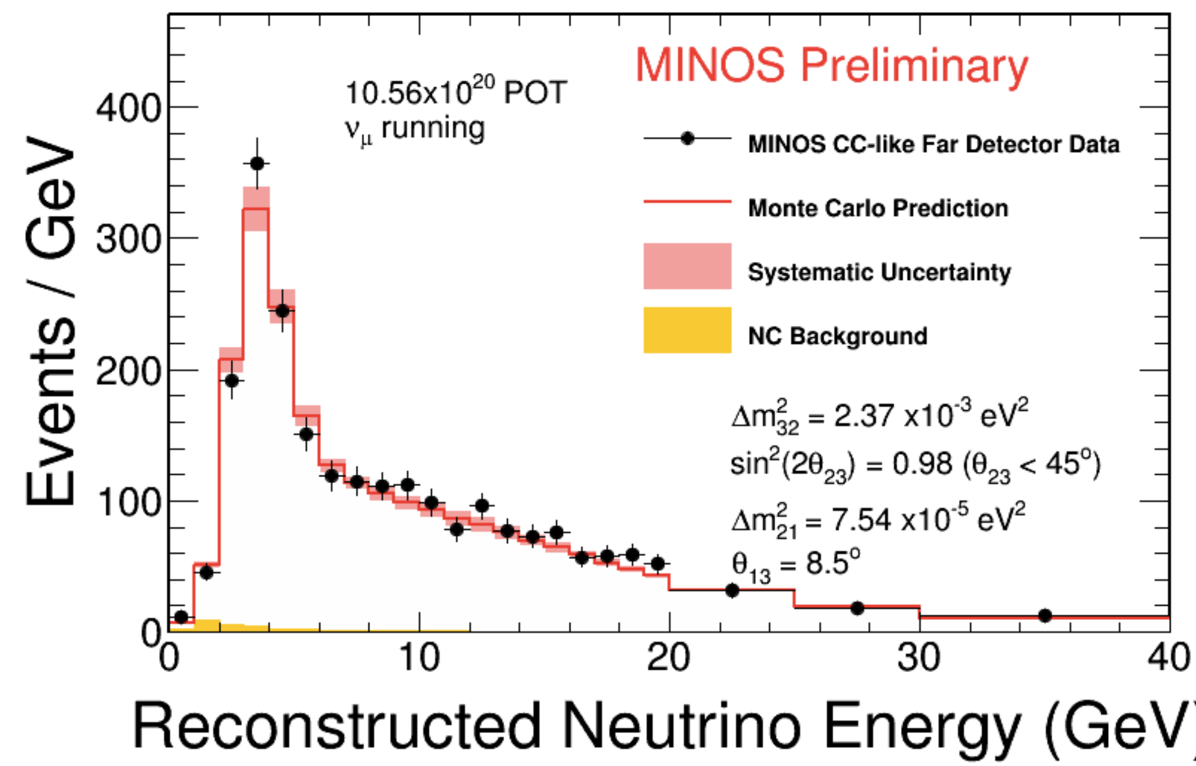
Predicted CC background from all flavors

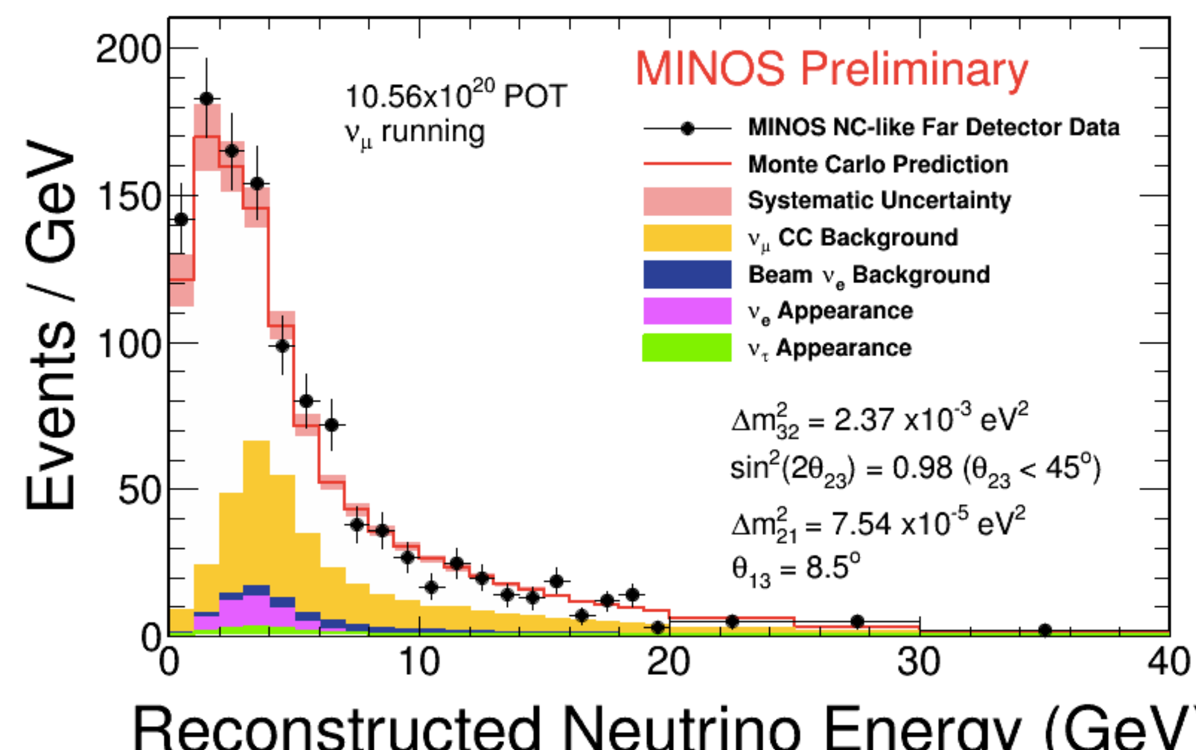
Predicted NC interaction signal

0-40 GeV: $R = 1.075 \pm 0.107$

0-3 GeV: $R = 1.109 \pm 0.096$

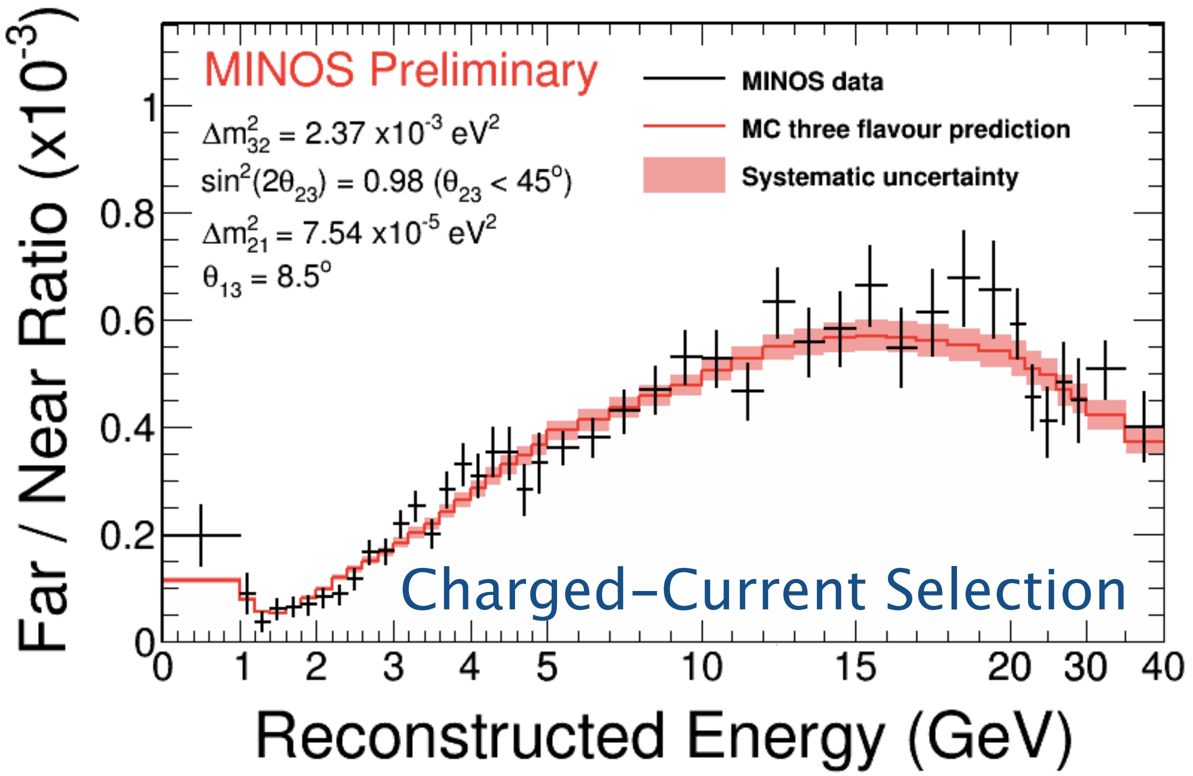
No evidence for oscillations into sterile neutrinos at $\Delta m^2_{43} \simeq 0.5$ eV^2

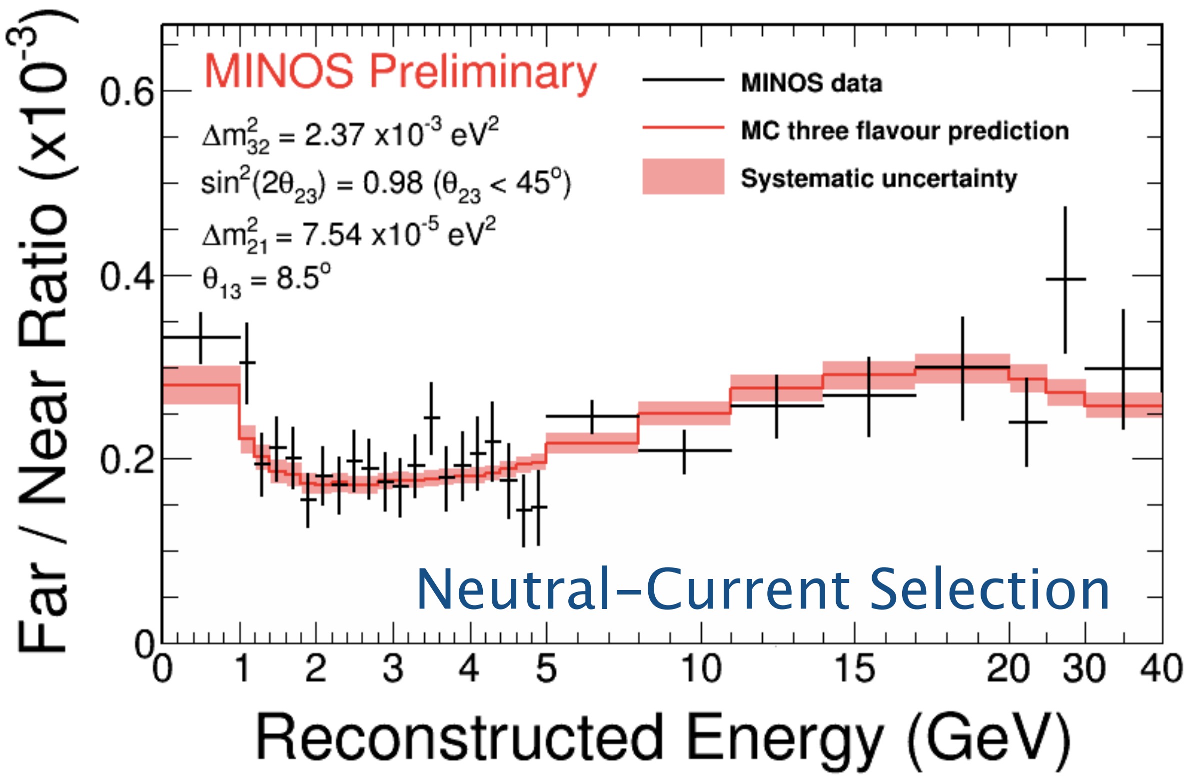




Sterile Fit Strategy

- Assume 3+1 sterile neutrino mixing scenario
  - Apply oscillations to both ND and FD
  - Use distance to meson decay point
  - Fit for $|\Delta m^2_{32}|$, θ_{23}, $|\Delta m^2_{43}|$, θ_{24}, θ_{34}
- To account for ND distortions, fit oscillated F/N ratio directly to F/N data ratio
  - Include constraint on ND rate
- Log-likelihood surfaces are Feldman-Cousins corrected





Systematics

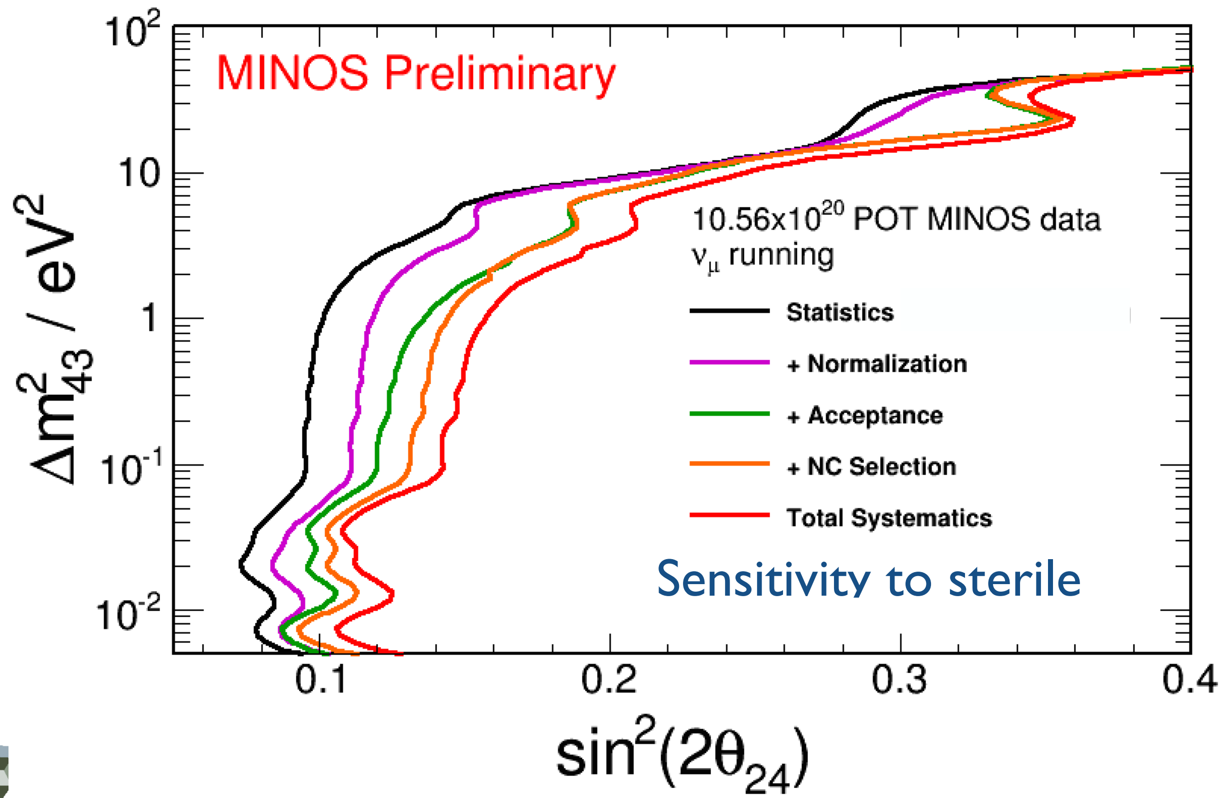
- Including 26 systematic uncertainties in fit via covariance matrices, accounting for:
  - Normalization
  - Detector acceptance
  - NC selection
  - Hadron production, beam optics, cross sections, energy scale, and backgrounds

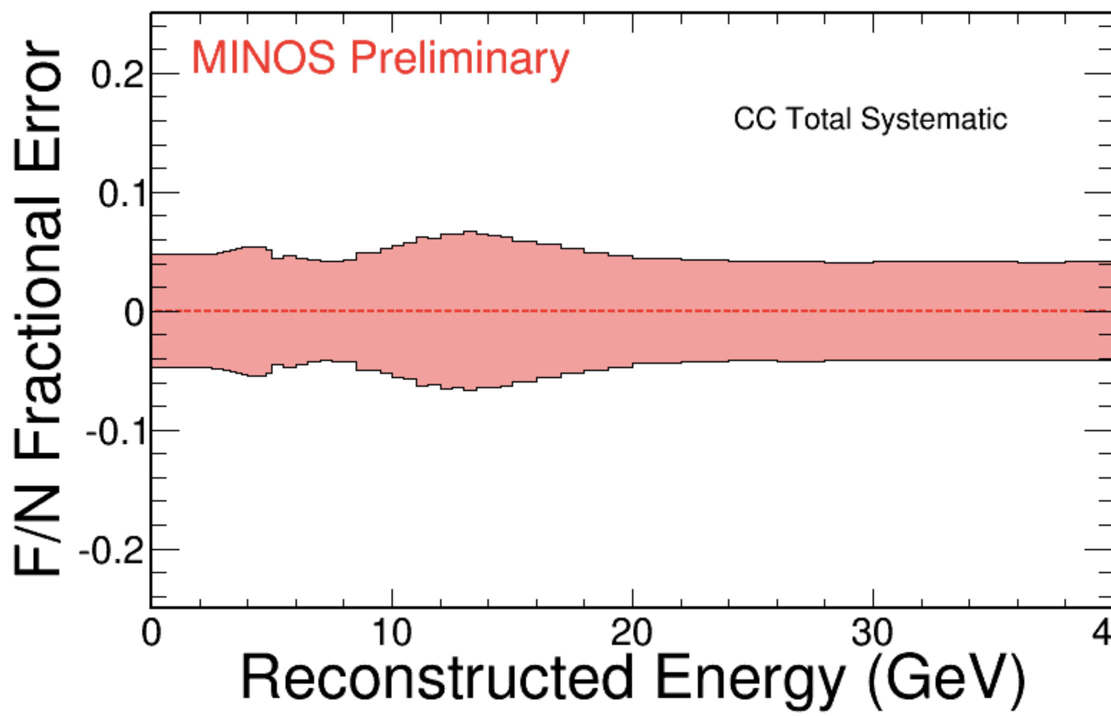
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T[V^{-1}]_{ij}(o_j - e_j)$$

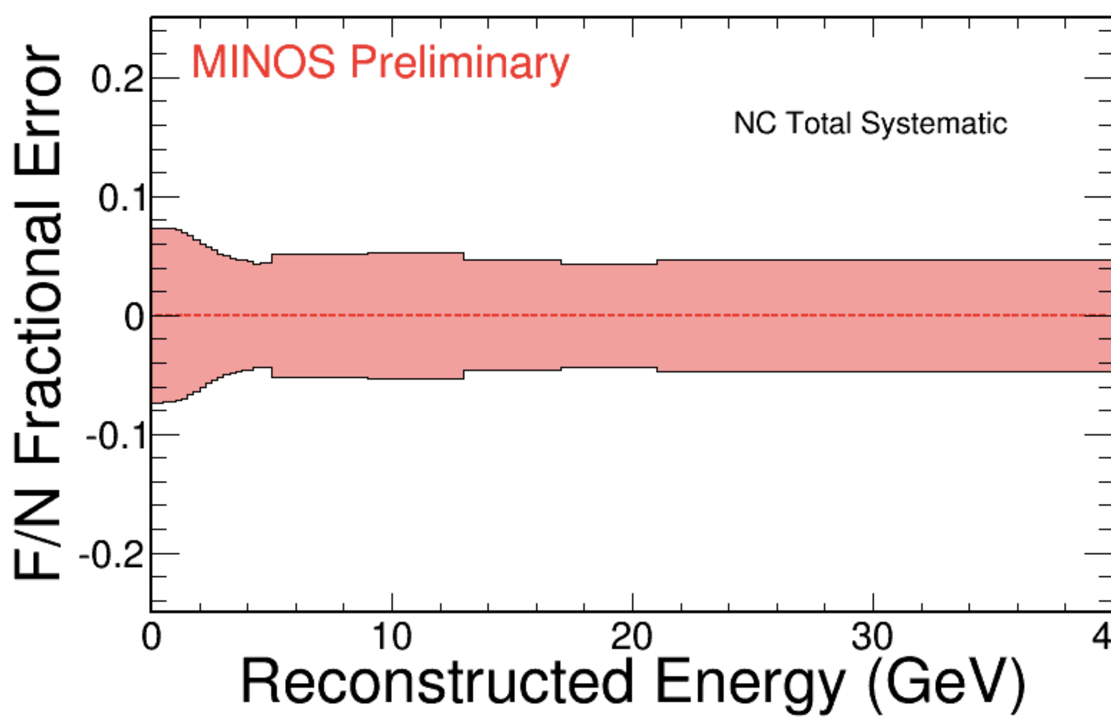
o_i : Observed events in bin i

e_i : Predicted events in bin i

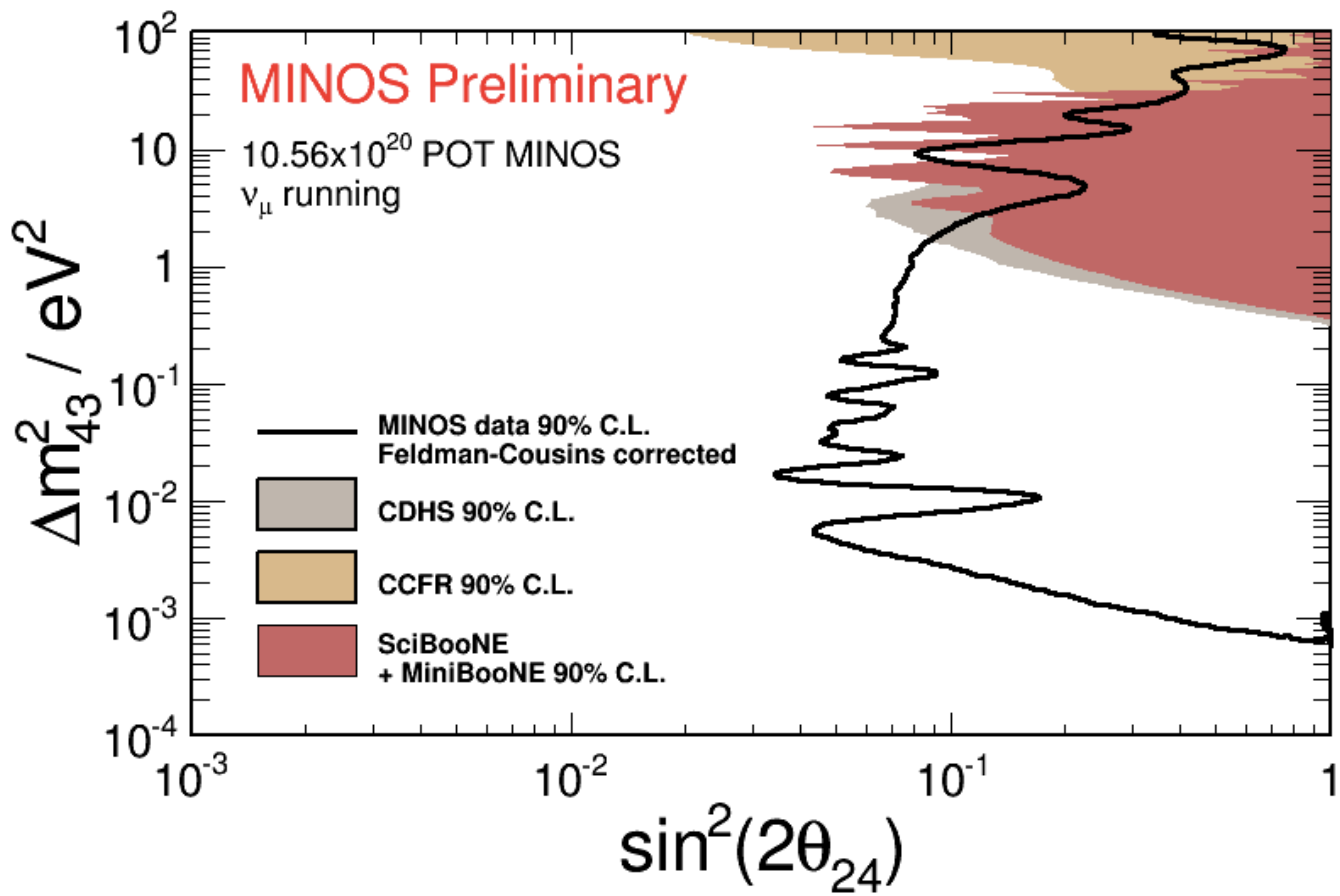
V : Covariance matrix





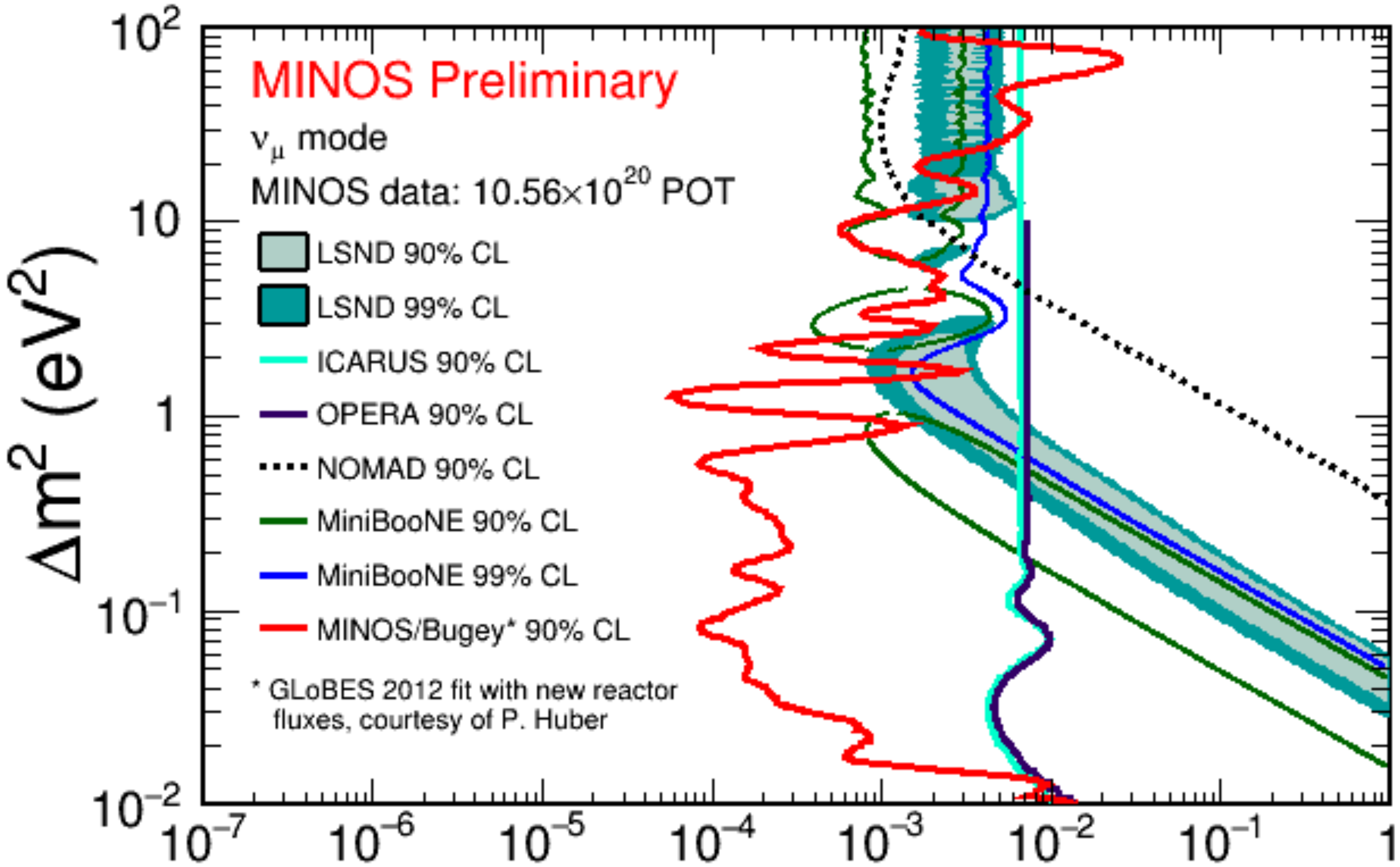


MINOS Disappearance Limit



Feldman Cousin corrected MINOS 90% C.L. exclusion limit ranges over 4 orders of magnitude in Δm^2_{43}!

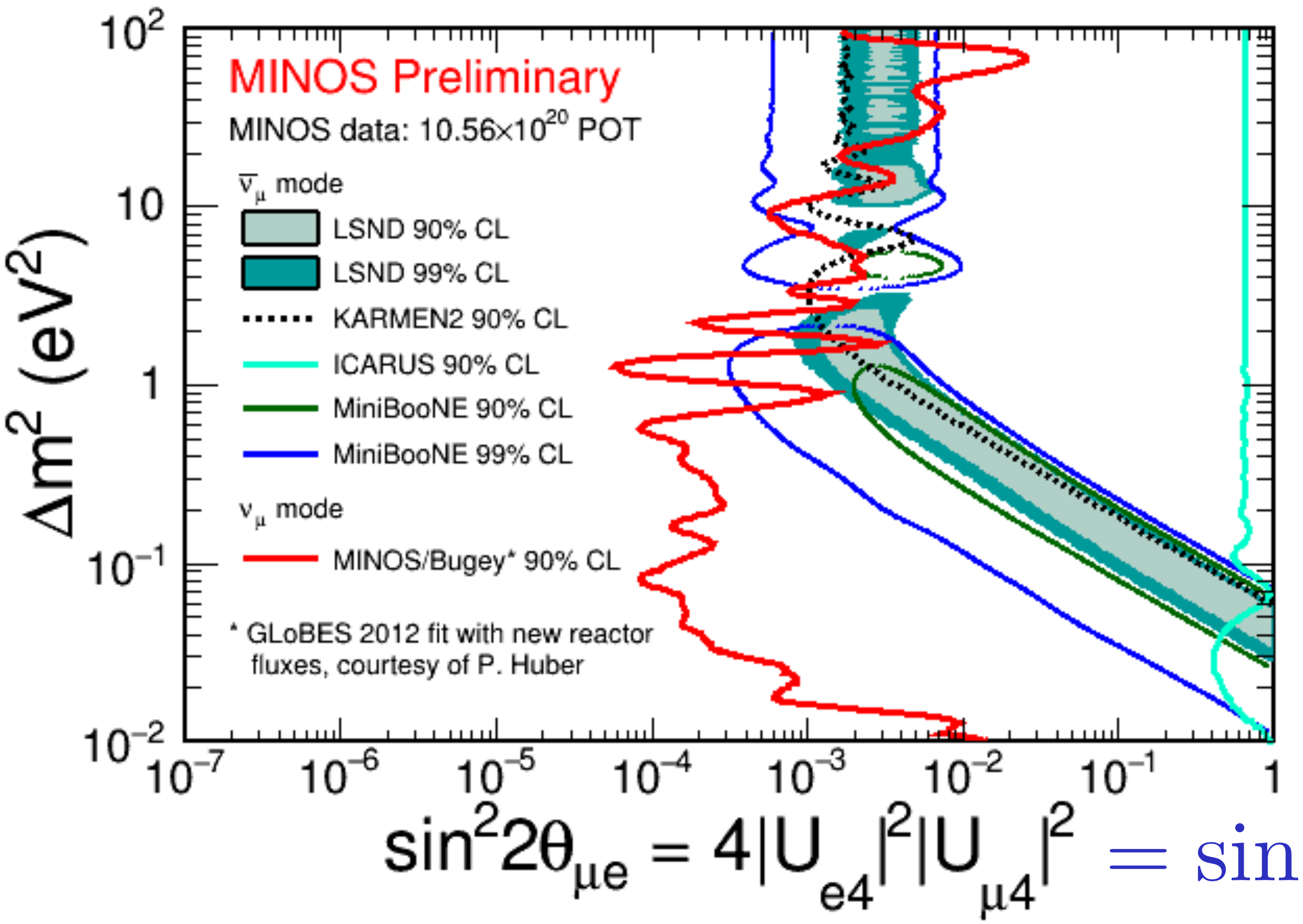
MINOS Combination with Bugey Limit



$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14} \sin^2 \theta_{24}$

- **MiniBooNe Neutrino mode**
- Assuming 3+1 model, combine MINOS disappearance 90% C.L. limit in θ_{24} to Bugey reactor experiment 90% C.L. disappearance limit in θ_{14}
- Bugey limit computed from GLoBES 2012 fit using new reactor fluxes, provided by Patrick Huber
- MINOS data increases tension between null and signal results for $\Delta m^2_{43} < 1$ eV^2

MINOS Combination with Bugey Limit



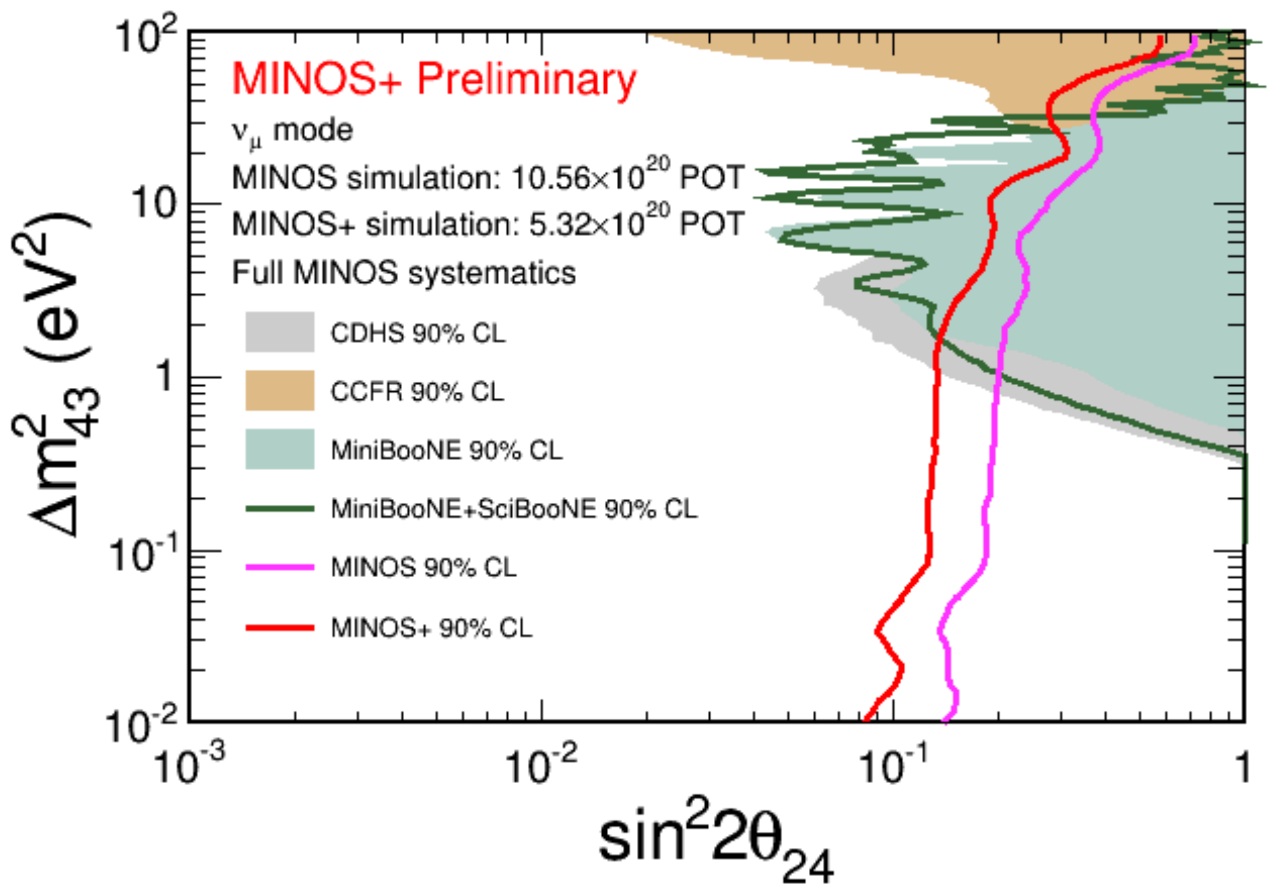
$= \sin^2 2\theta_{14} \sin^2 \theta_{24}$

- **MiniBooNe Anti-Neutrino mode**
- Assuming 3+1 model, combine MINOS disappearance 90% C.L. limit in θ_{24} to Bugey reactor experiment 90% C.L. disappearance limit in θ_{14}

- Working on sterile neutrino search in 3.4×10^{20} POT of MINOS antineutrino running
- MINOS data increases tension between null and signal results for $\Delta m^2_{43} < 1$ eV^2

MINOS+ Sensitivity

With an enhanced high energy tail MINOS+ data rapidly improves our disappearance limits, the plot below shows a stats only limit with 12×10^{20} PoT of MINOS+ exposure



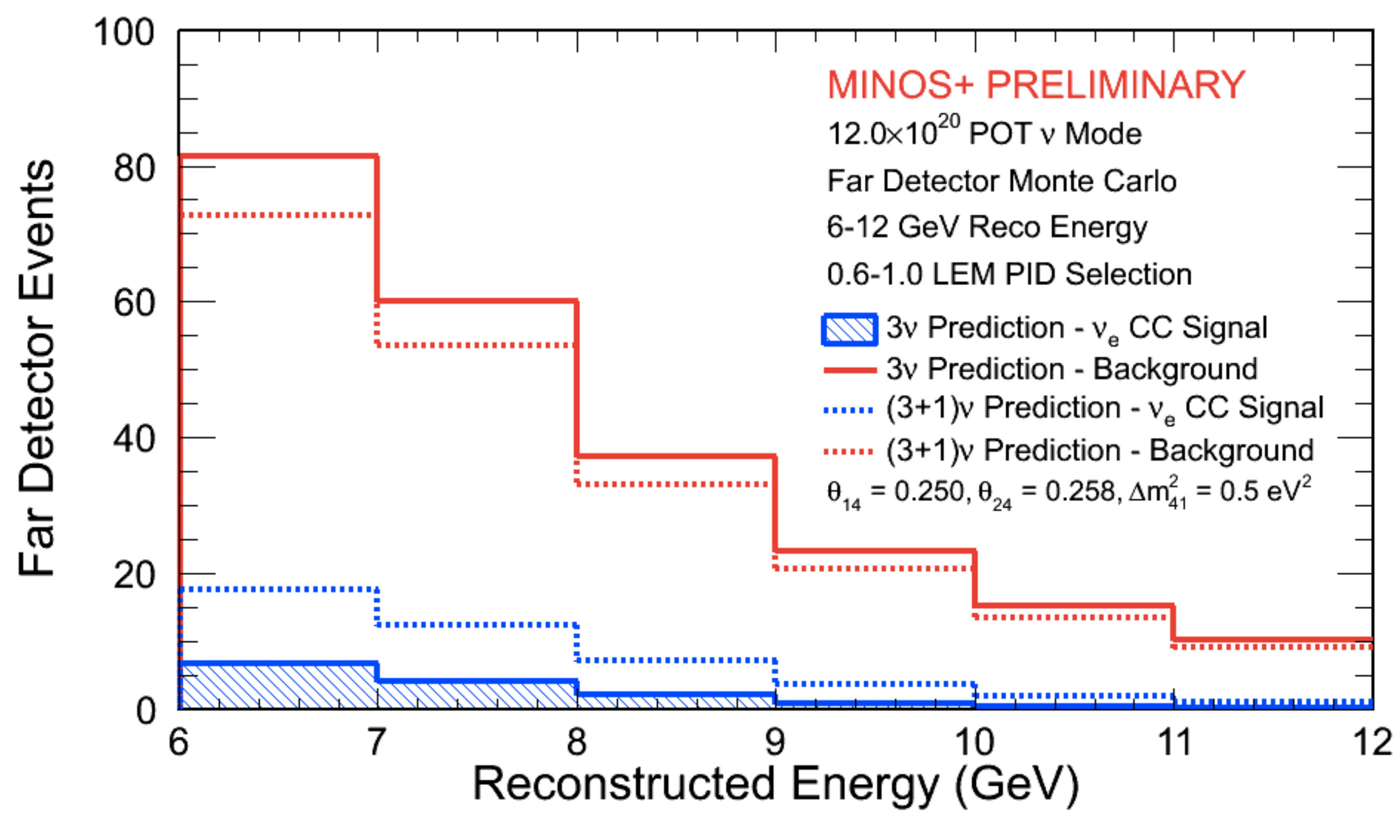
The College Of WILLIAM & MARY

Sterile Neutrino Constraints from the Appearance Channel at MINOS+

Sterile Neutrinos at MINOS

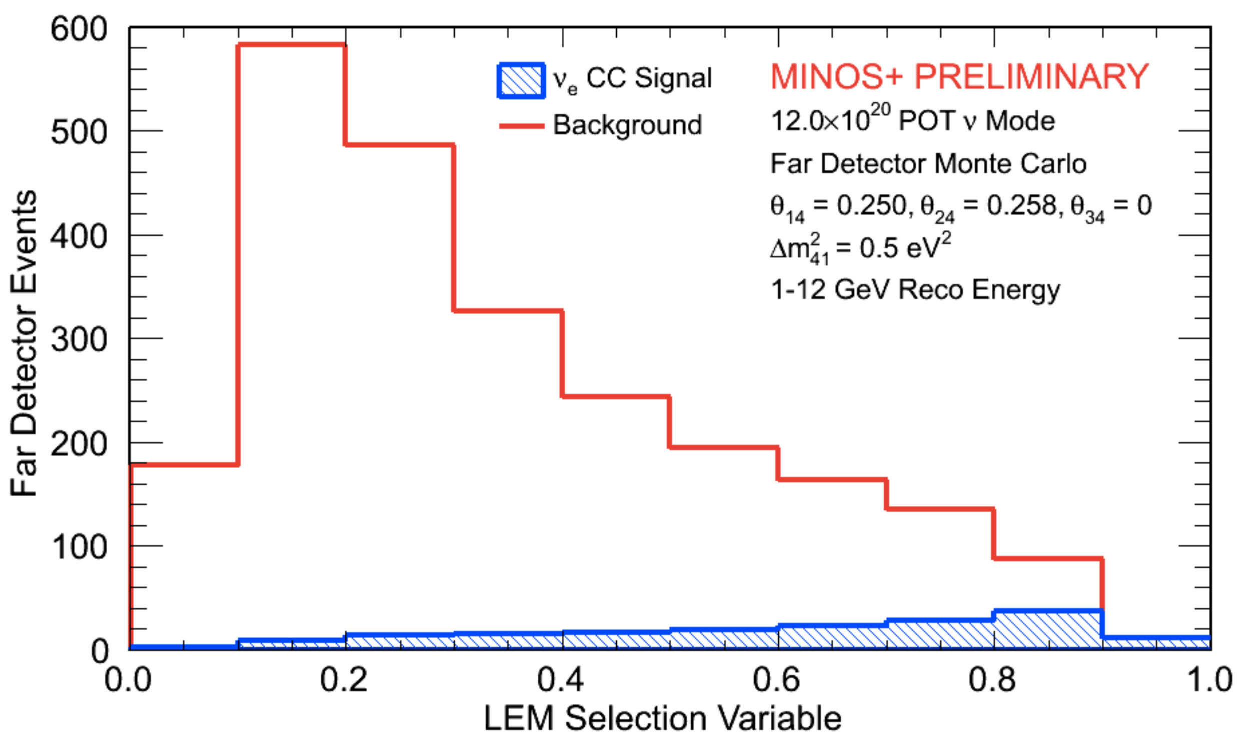
- So far we've been looking for sterile mixing in disappearance channels, deficits in the ν_μ or ν_a spectra at our near and far detectors

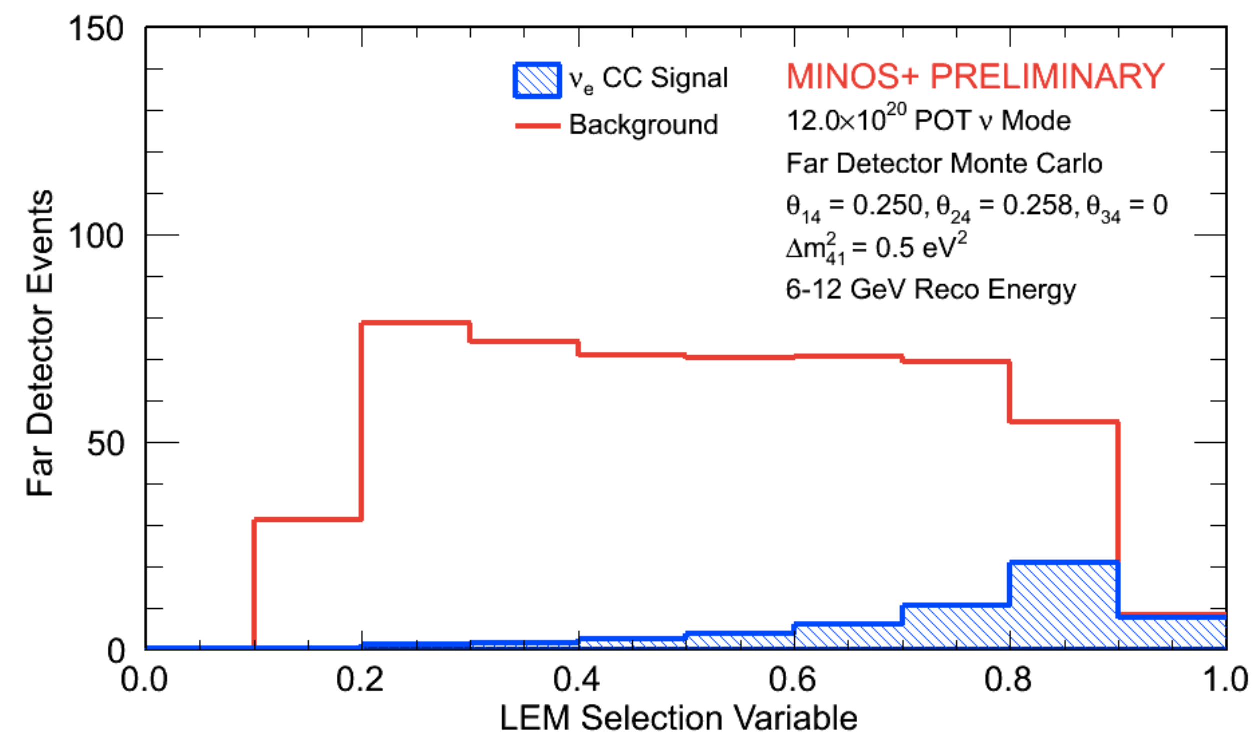
- Instead now we can search for evidence of sterile mixing in our ν_e channel where it could cause an excess of events at higher energies



MINOS+ LEM PID Performance

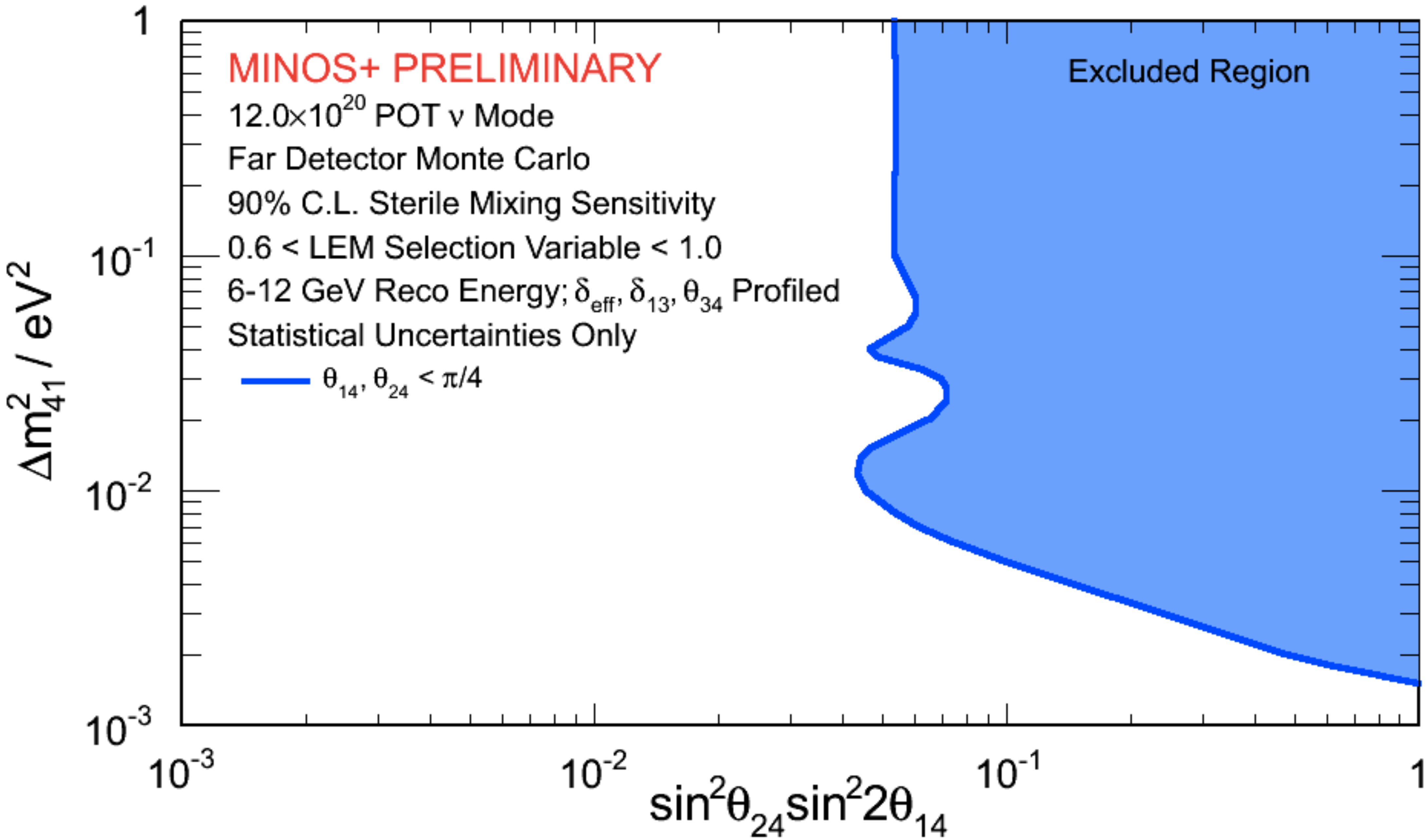
- LEM, retrained for the MINOS+ beam, shows good separation at higher energies- the most important region for this search





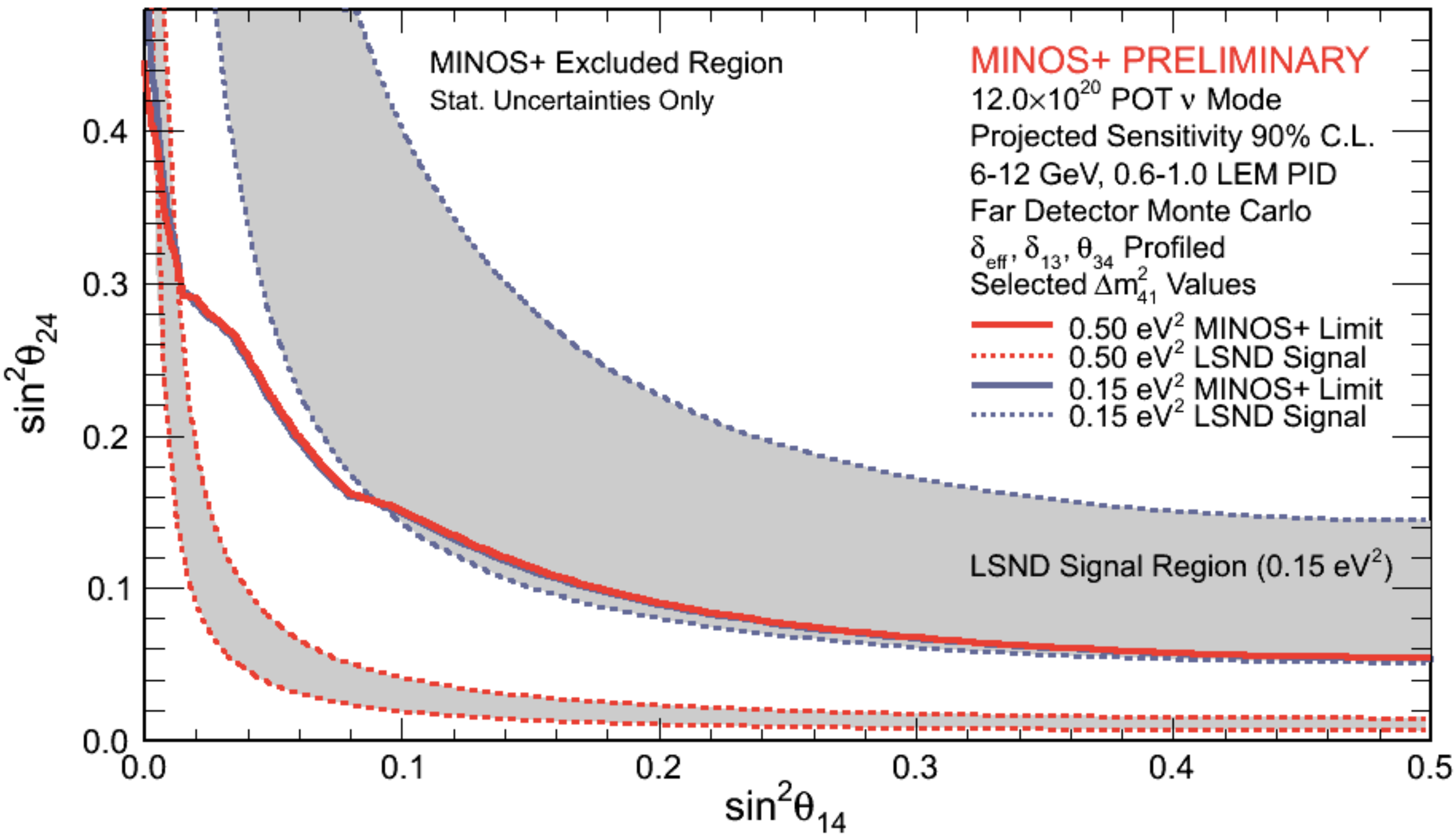
MINOS+ Appearance Channel Sensitivity

90% C.L. sensitivity to four-flavor oscillation parameters using MINOS+ Far Detector Monte Carlo. The contour is generated assuming θ_{14}, $\theta_{24} < \pi/4$.



MINOS+ Appearance Channel Sensitivity

90% C.L. sensitivity in a two dimensional parameter space where θ_{14}, $\theta_{24} < \pi/4$ to four-flavor oscillation parameters using MINOS+ Far Detector Monte Carlo. The effective CP phase and θ_{34} mixing angle are profiled.



Summary

- Over its long livetime MINOS has found ways to contribute to our knowledge of large parts of the PMNS matrix through neutrino appearance and disappearance in the NuMI beam as well as muon neutrino disappearance in atmospheric neutrinos.

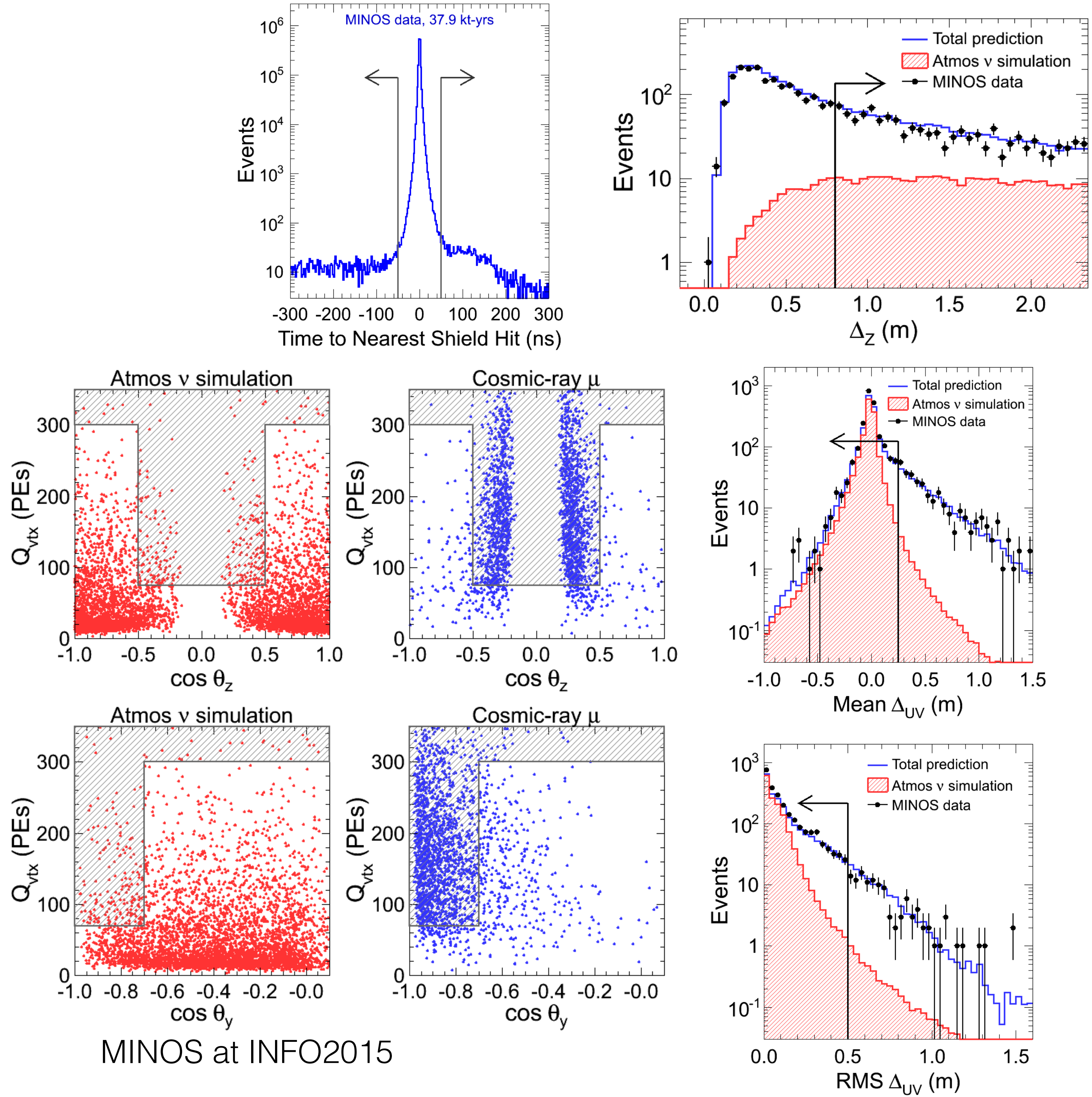
- We have also been able to make strong statements about evidence for sterile neutrinos in the disappearance channel which are set to only get stronger once we add the MINOS+ data.

- Promising work towards constraints on sterile mixing in the appearance channel with a full 4v framework from MINOS+

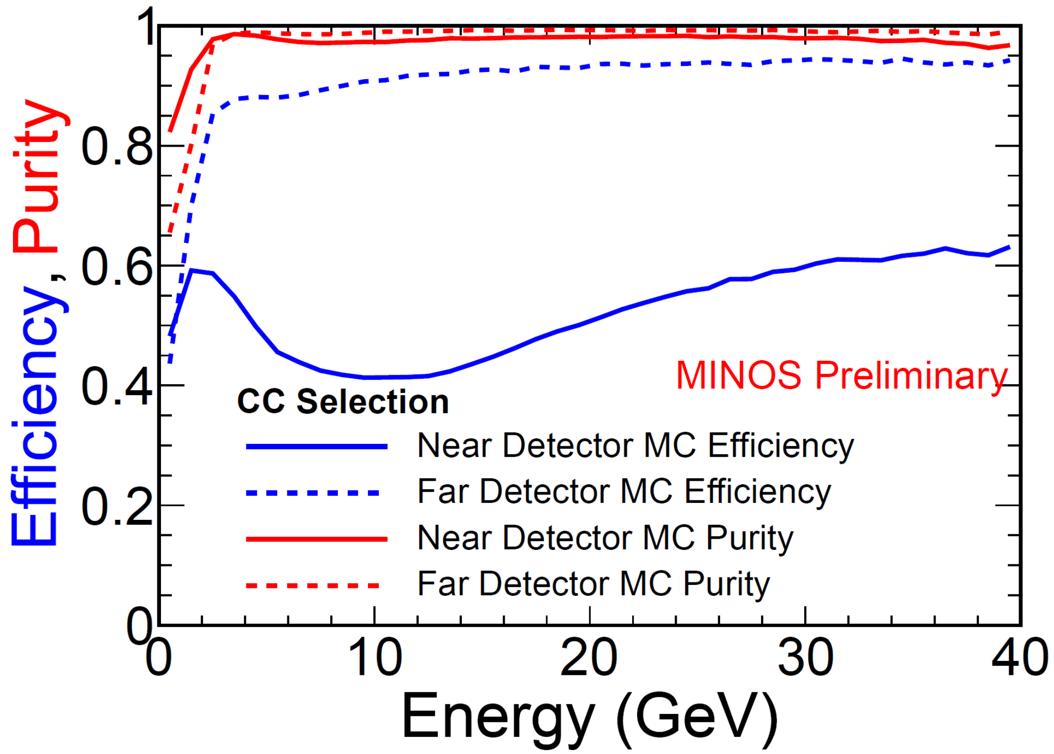
Q&A

Atmospheric Neutrino Selection

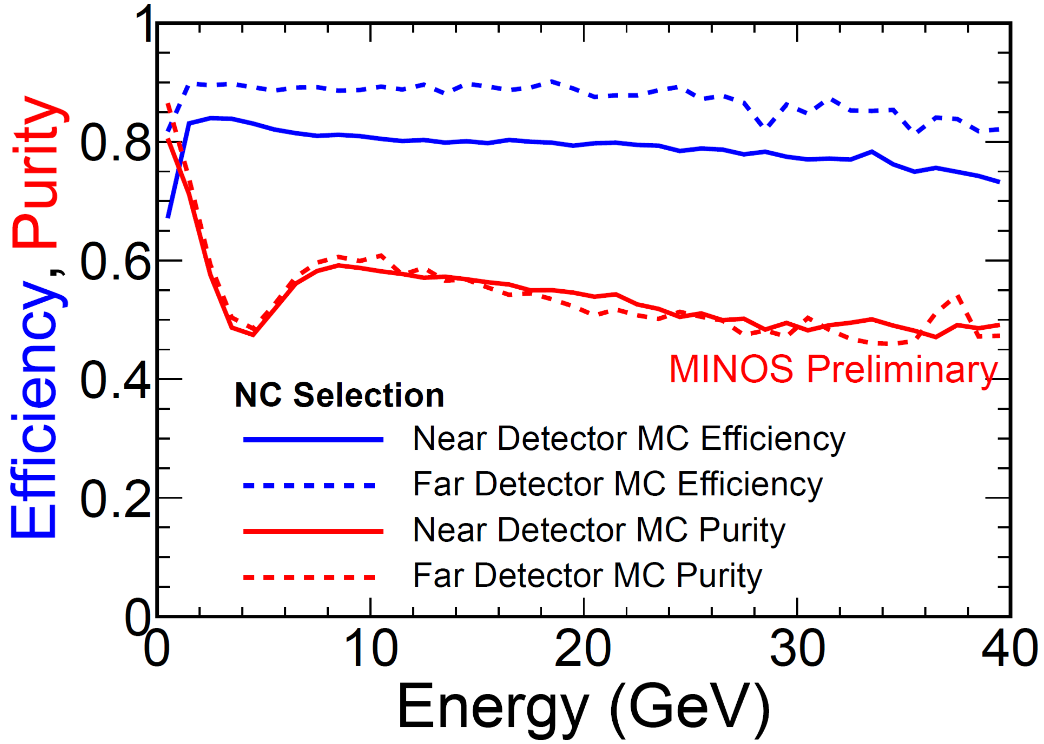
- Contained-vertex selection:
  - Select events with long tracks (>8 planes)
  - Use timing, direction and topology to remove cosmic rays
  - Background reduced by a factor of 107
- Also included samples of shower-like events and rock induced events from up going and horizontal muons

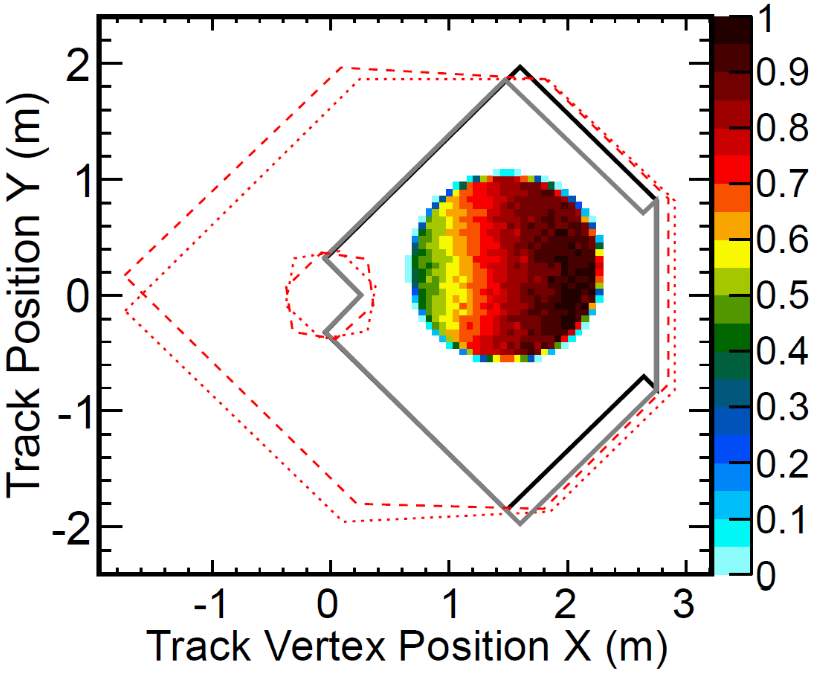


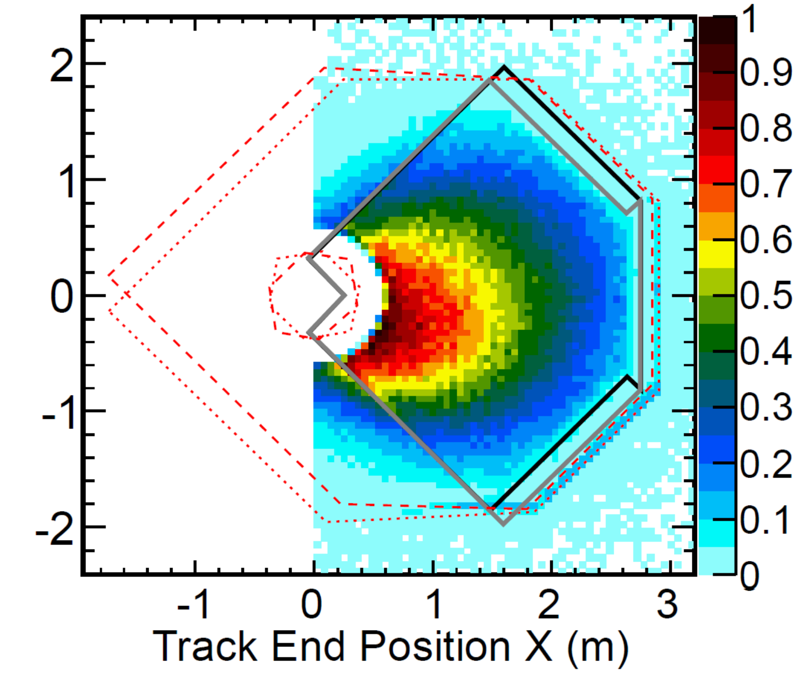
CC and NC Efficiency and Purity



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

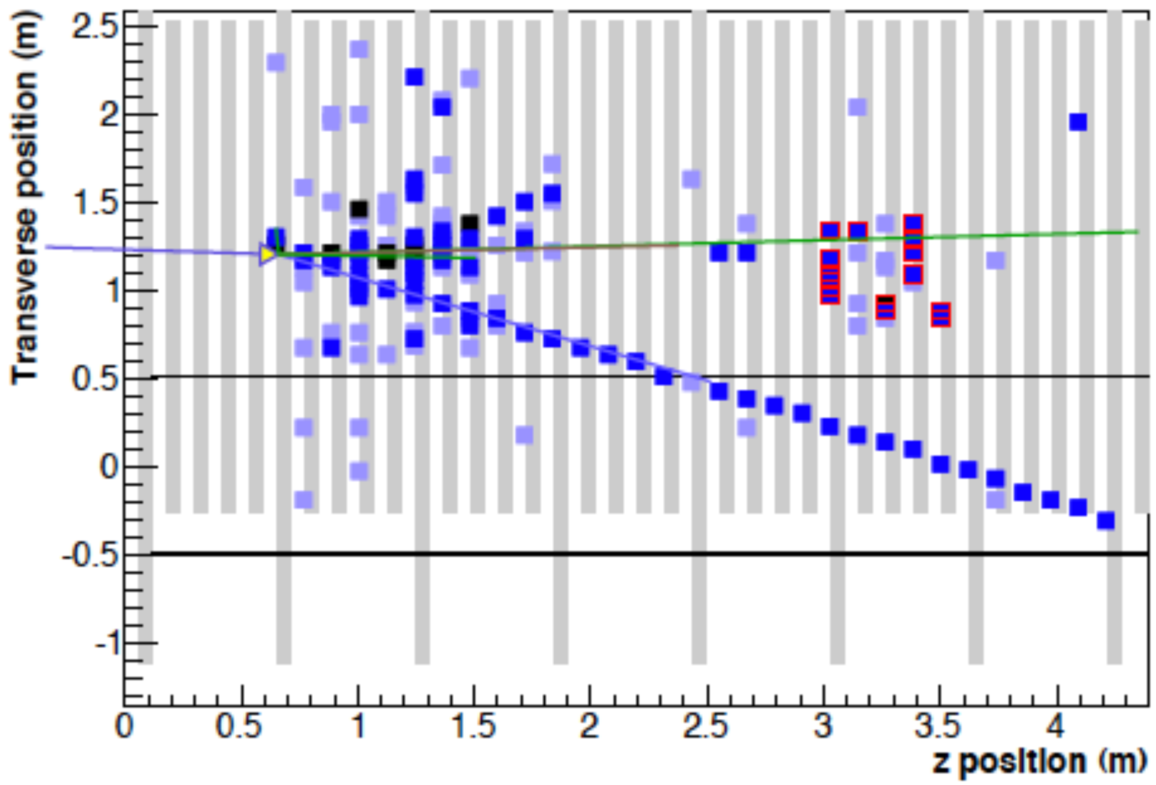


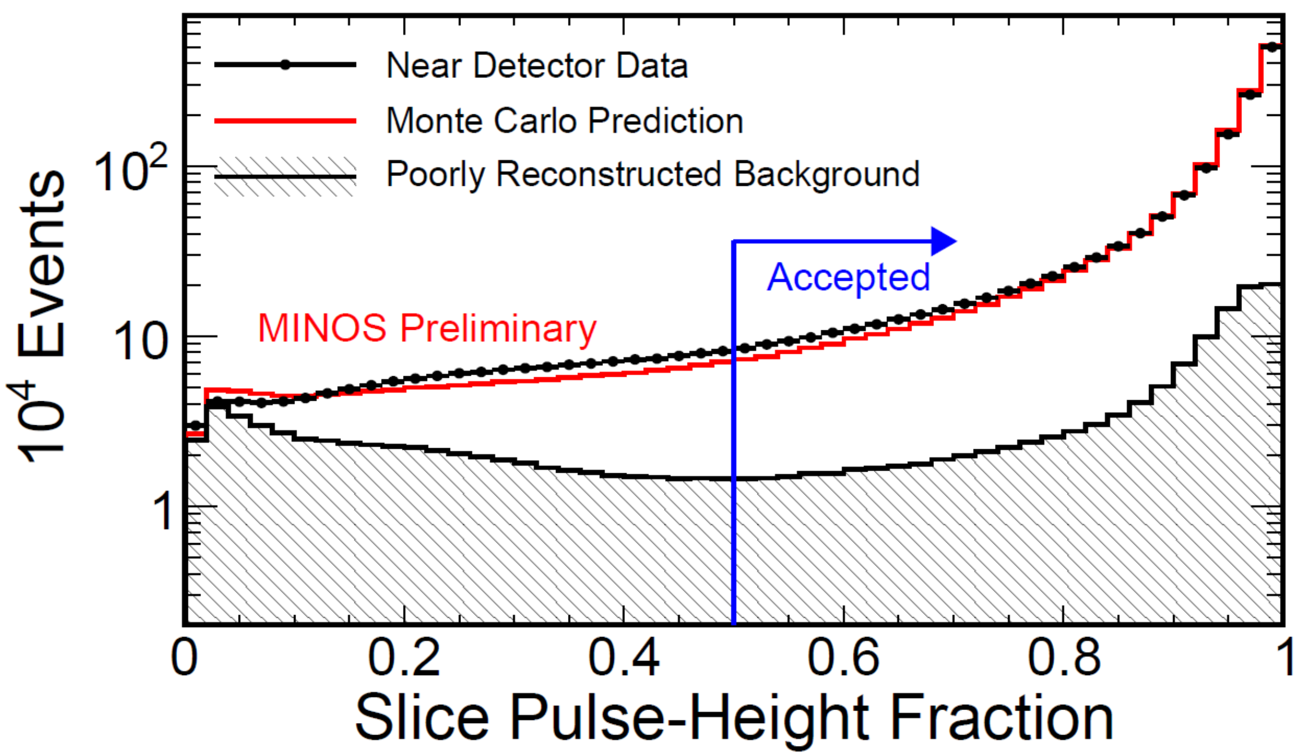




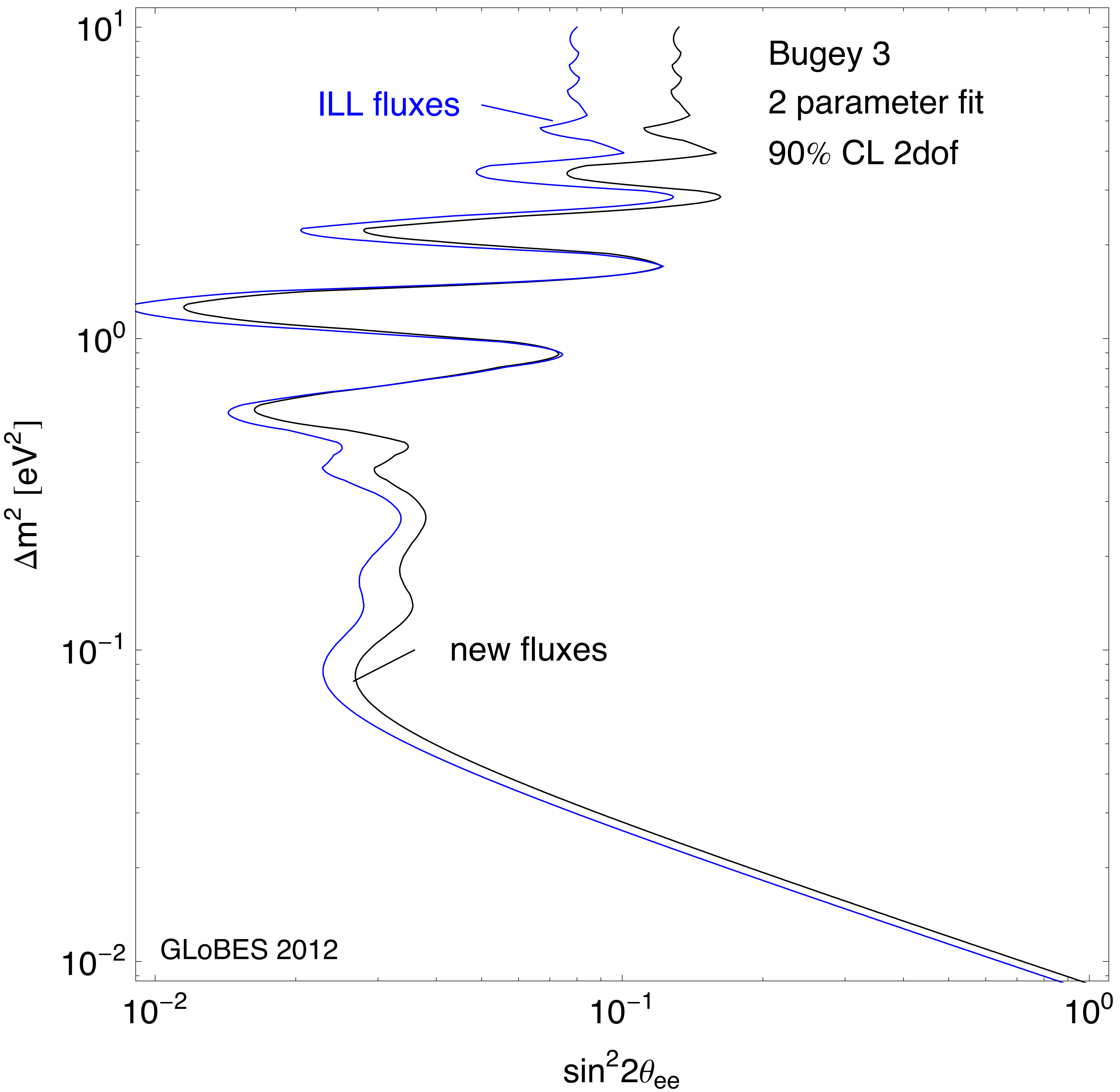
ND Cleaning Cuts

- 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



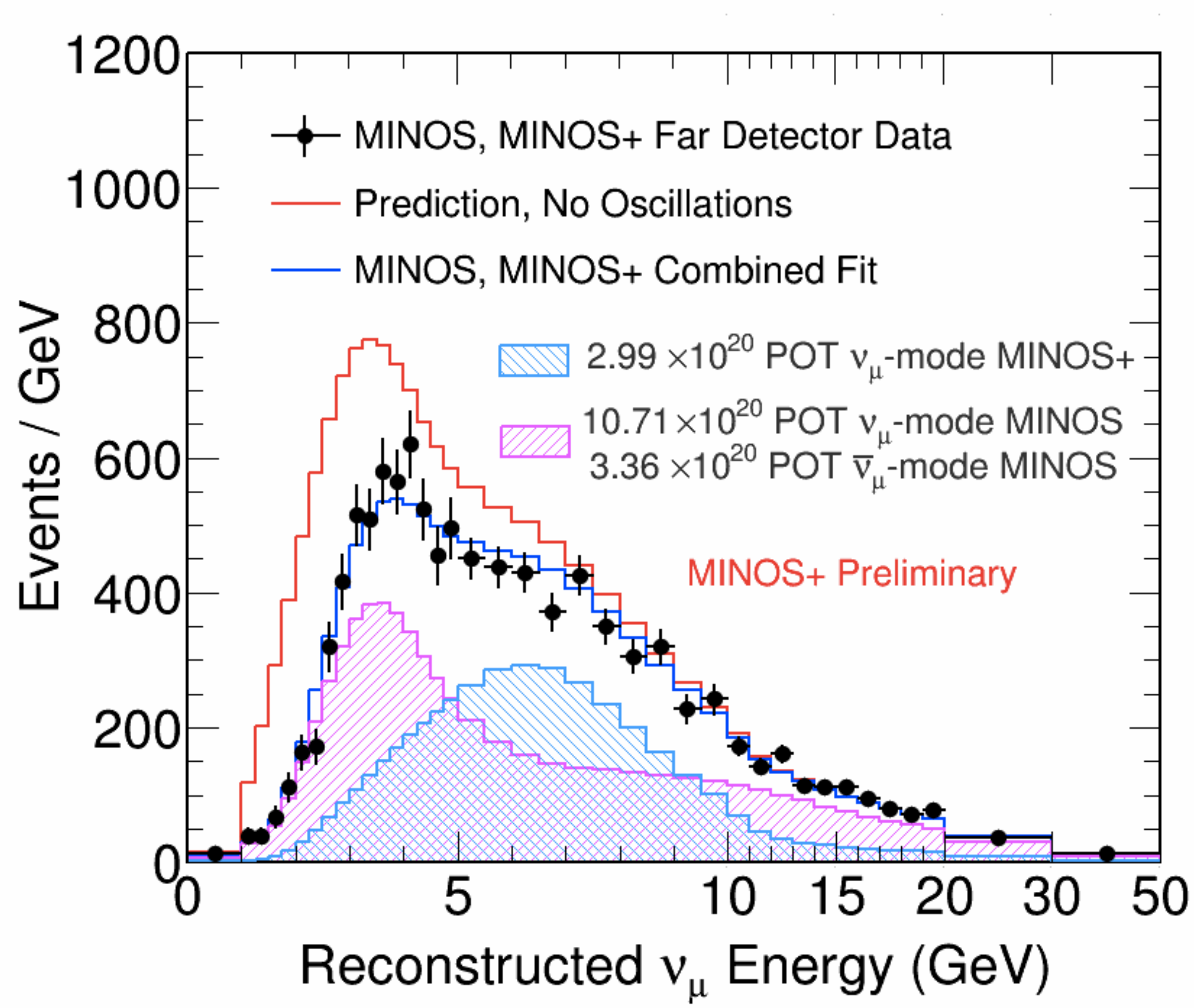


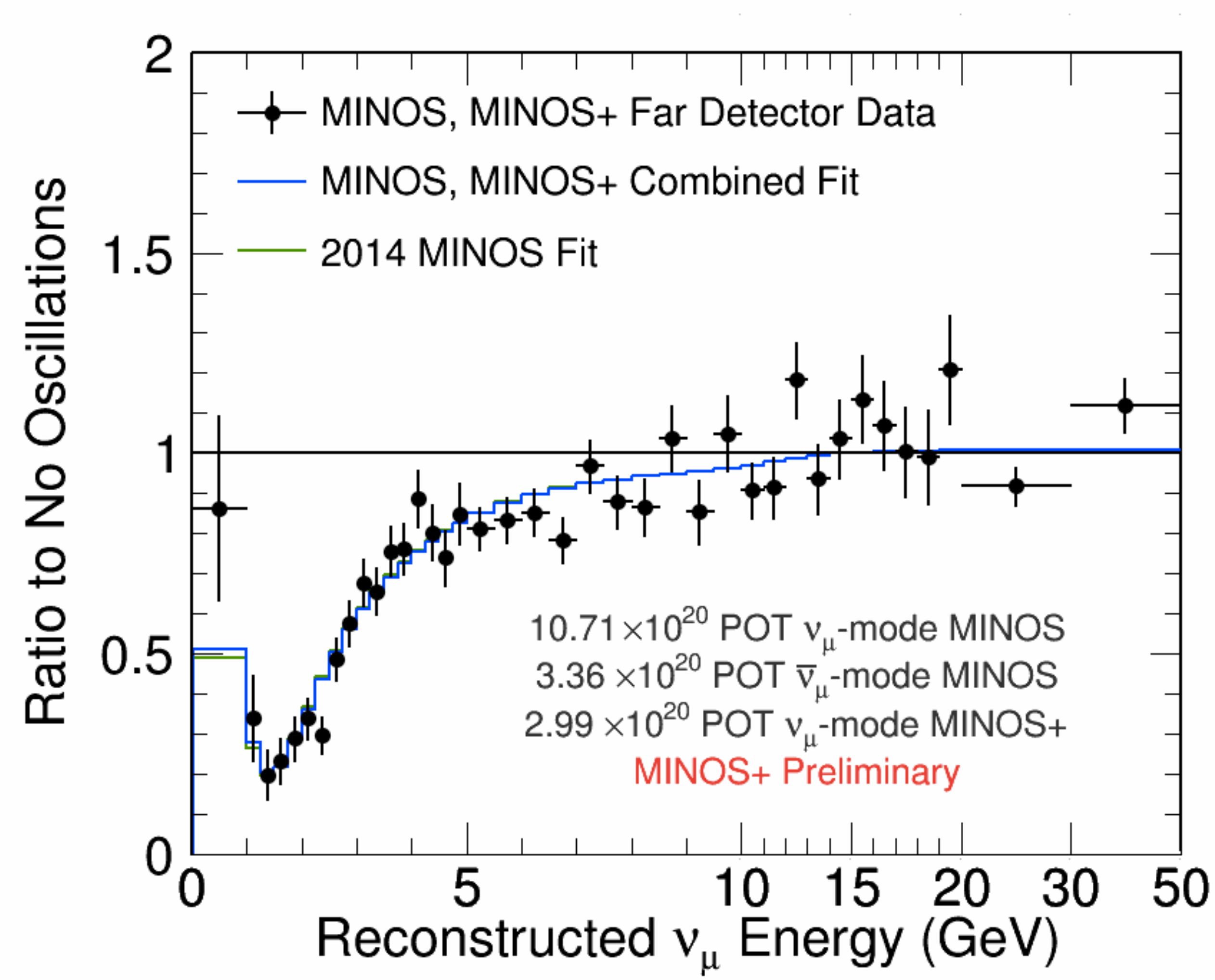
Bugey Limit



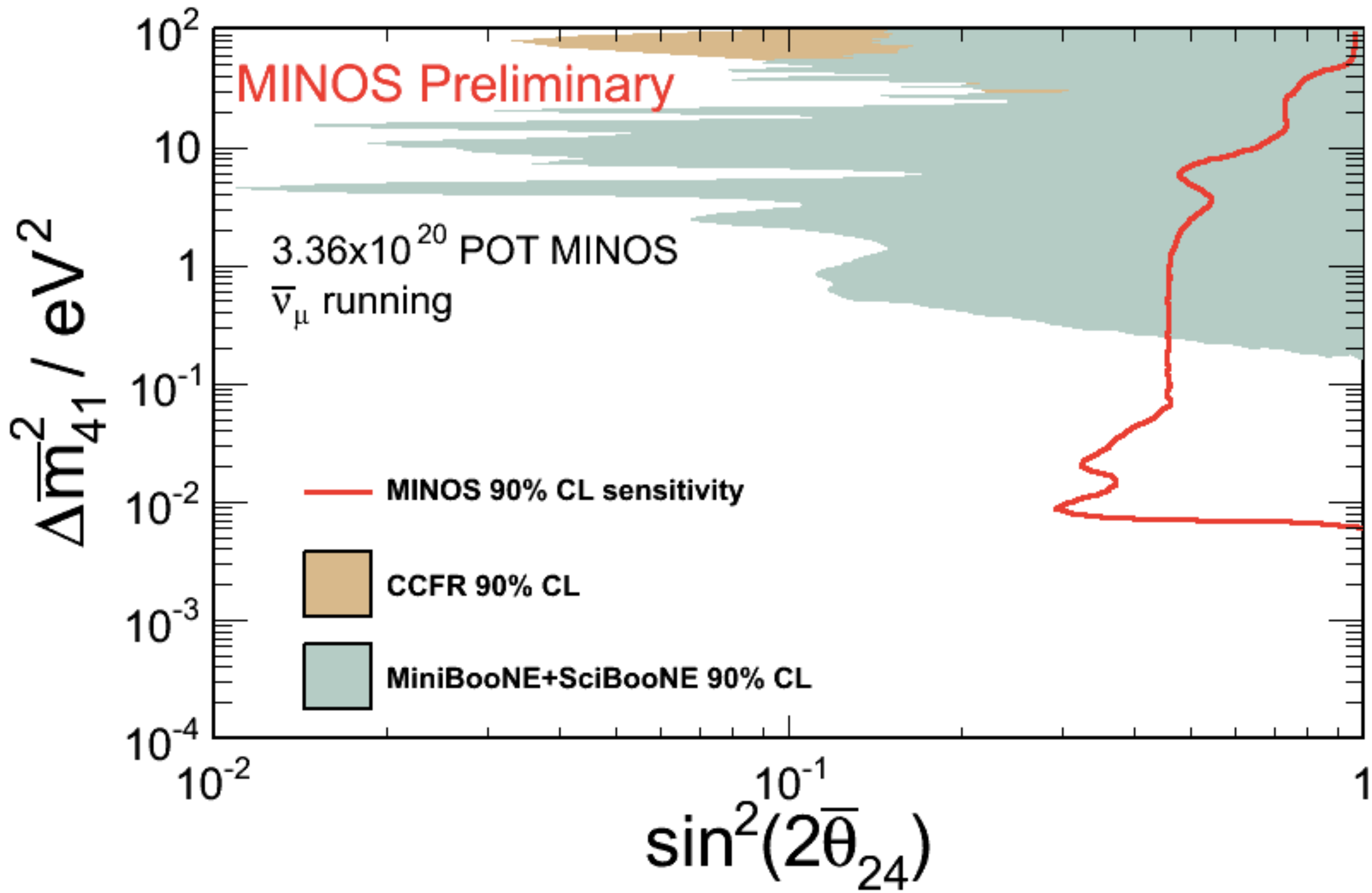
Bugey limit computed from GLoBES 2012 fit using new reactor fluxes, provided by Patrick Huber

MINOS & MINOS+ Combined Spectra

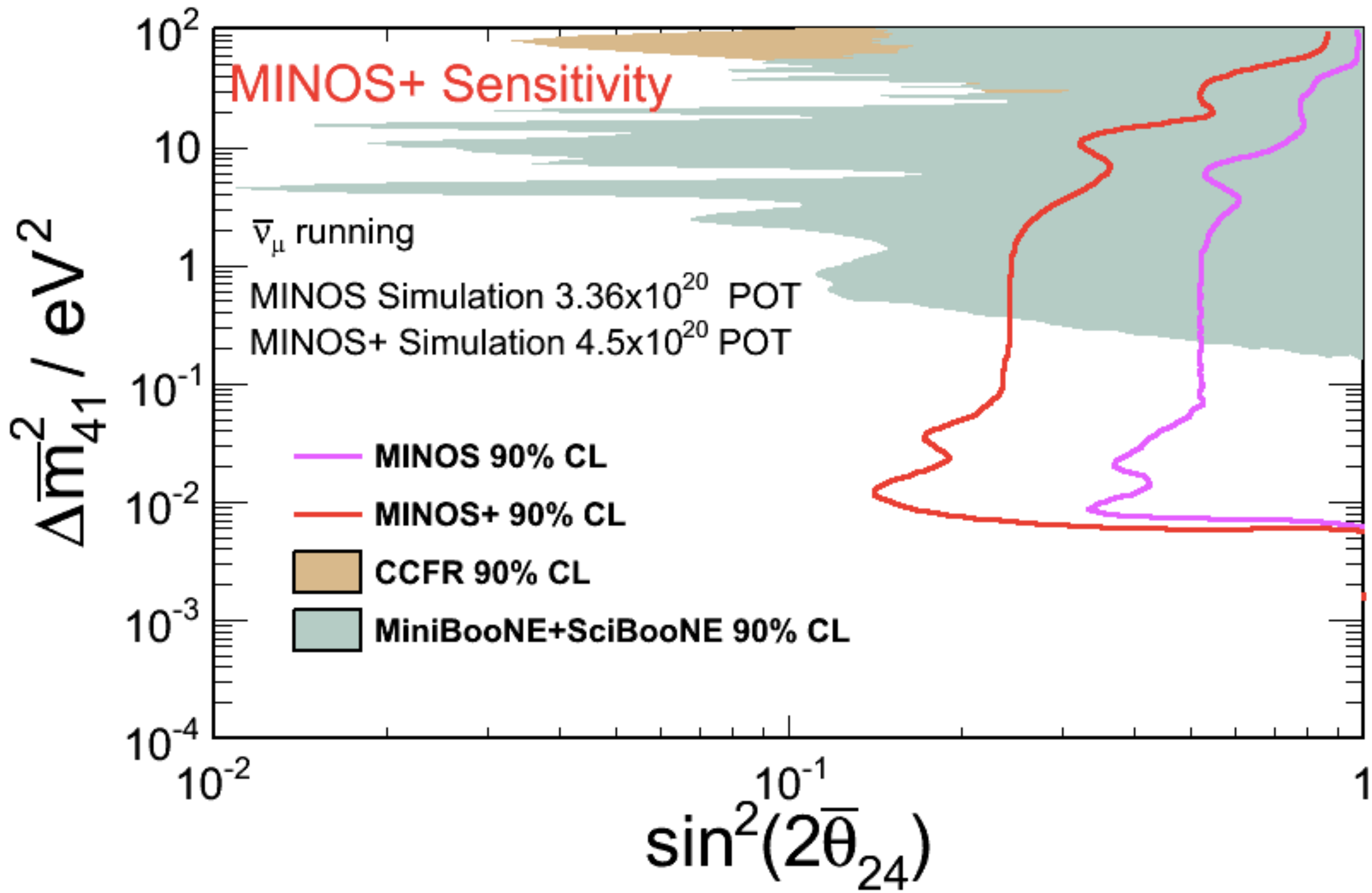




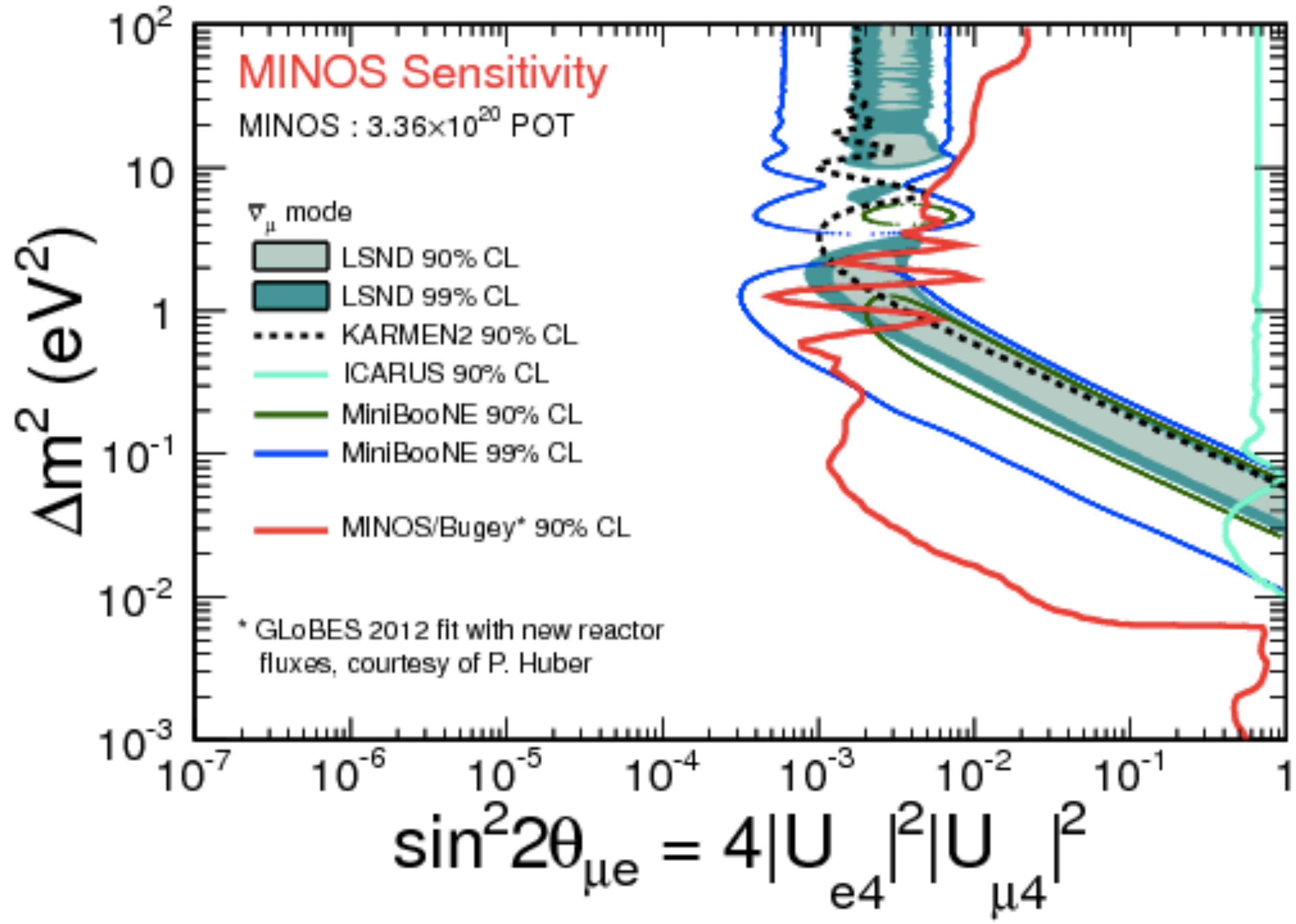
MINOS RHC Sterile Sensitivity



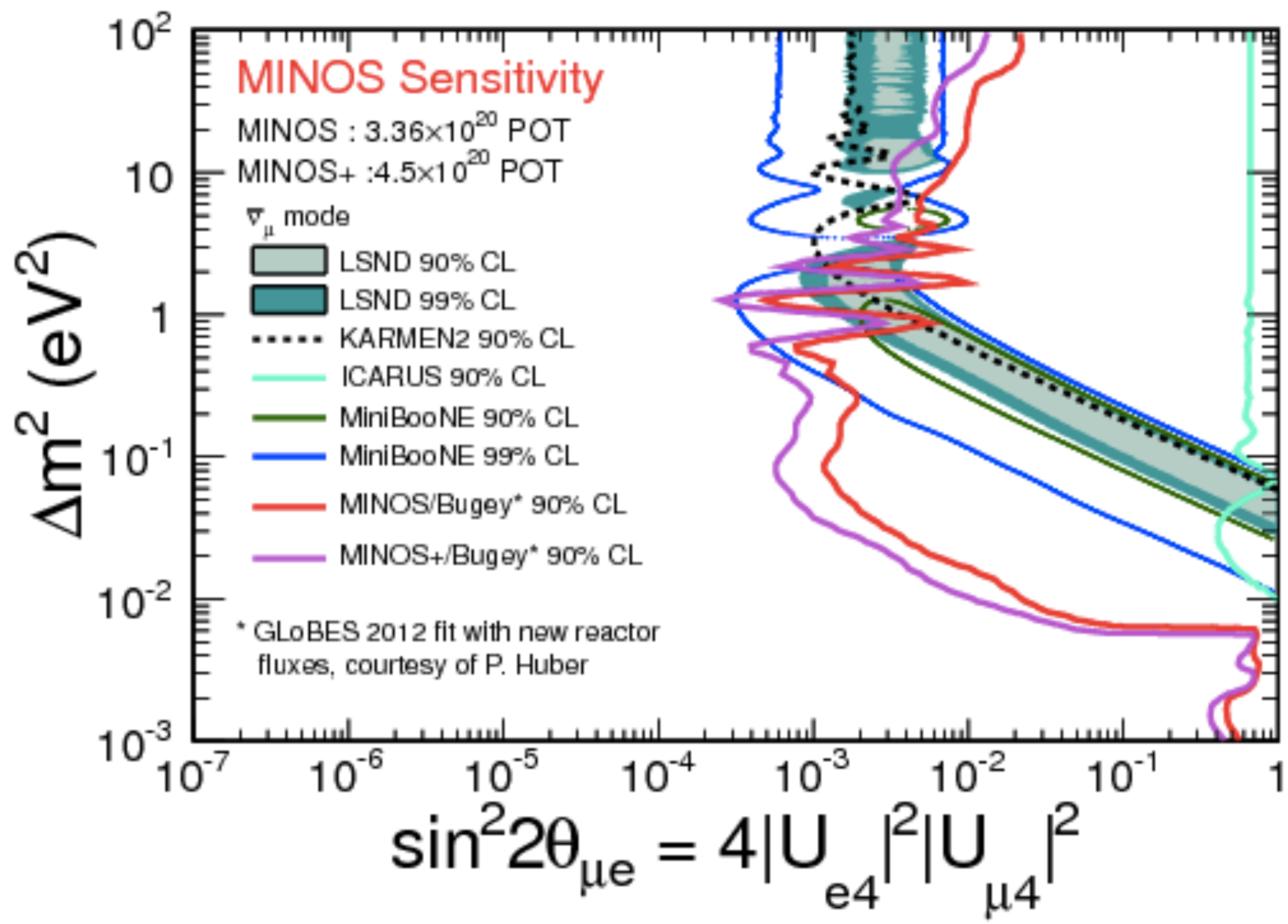
MINOS and MINOS+ RHC Sterile Sensitivity



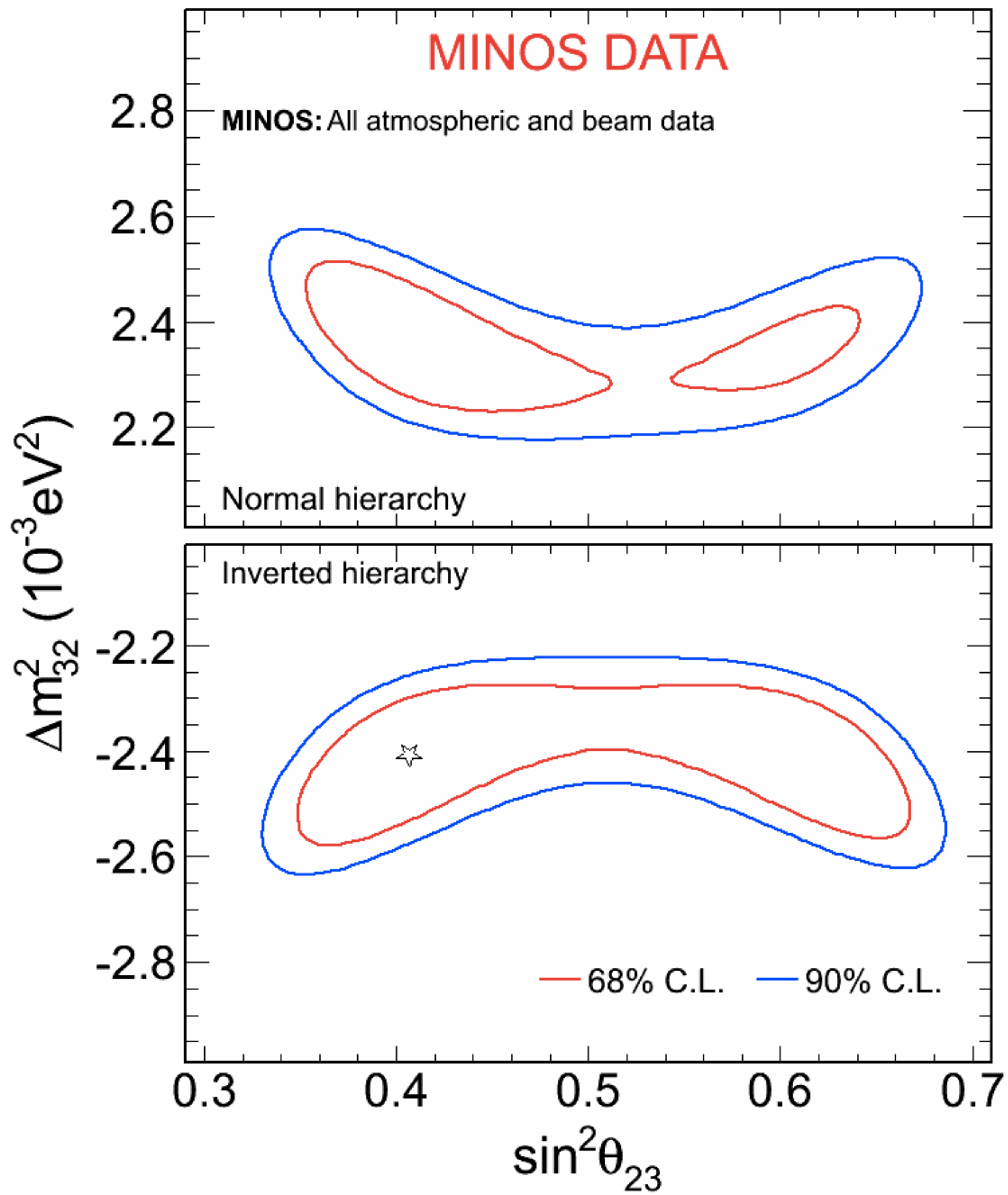
MINOS RHC Sterile Sensitivity With Bugey



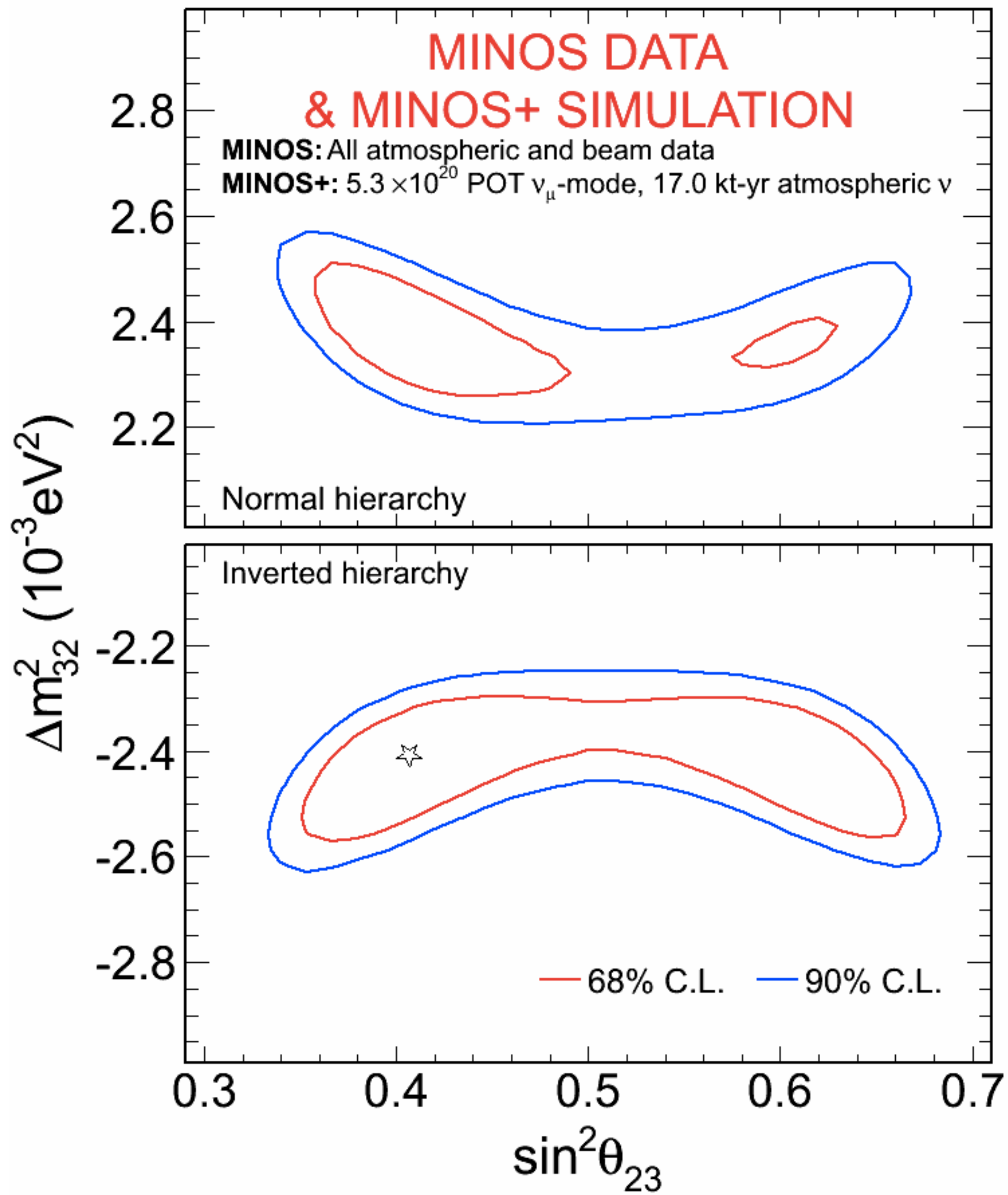
MINOS and MINOS+ RHC Sterile Sensitivity with Bugey



MINOS Only Sensitivity

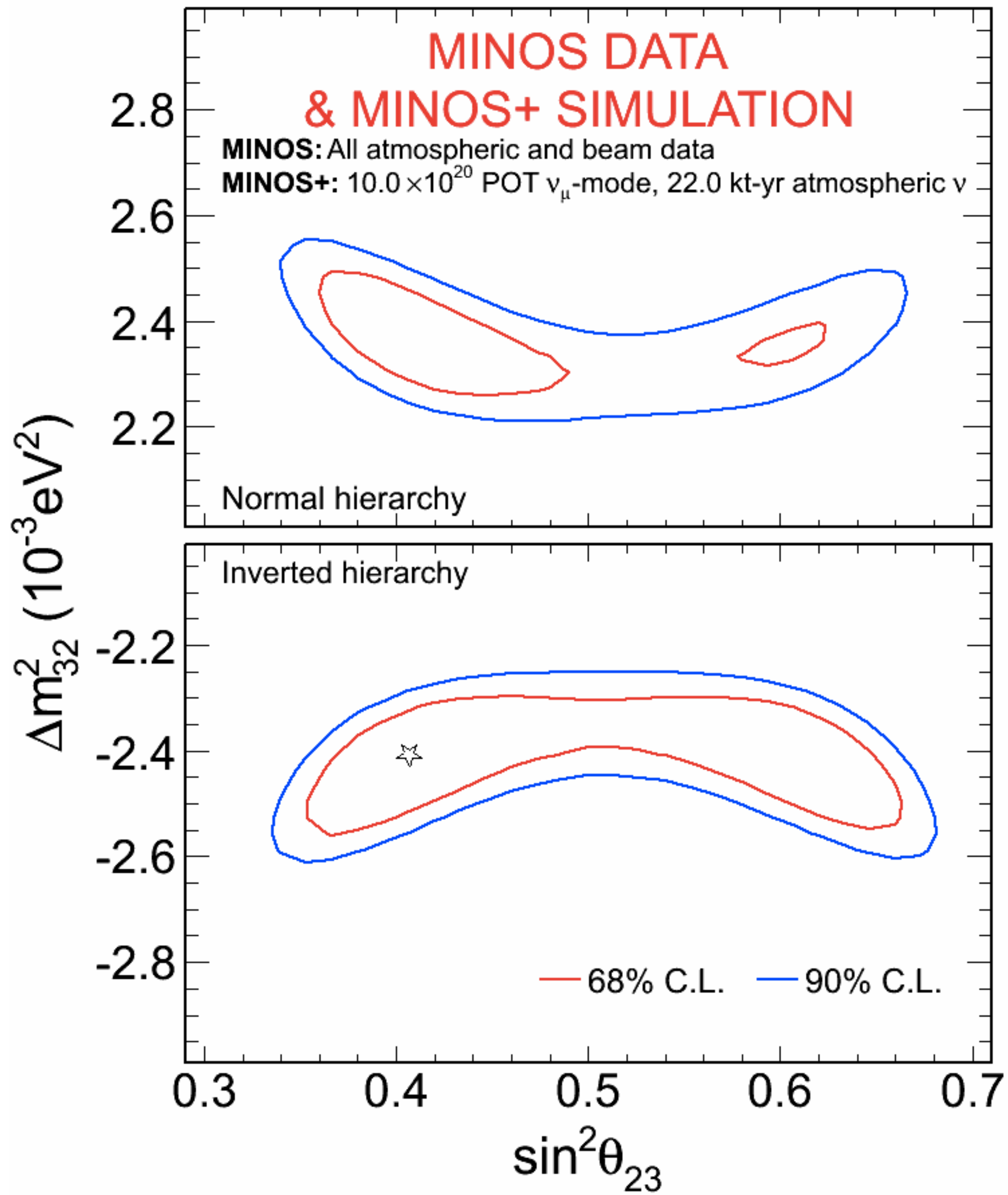


MINOS & MINOS+



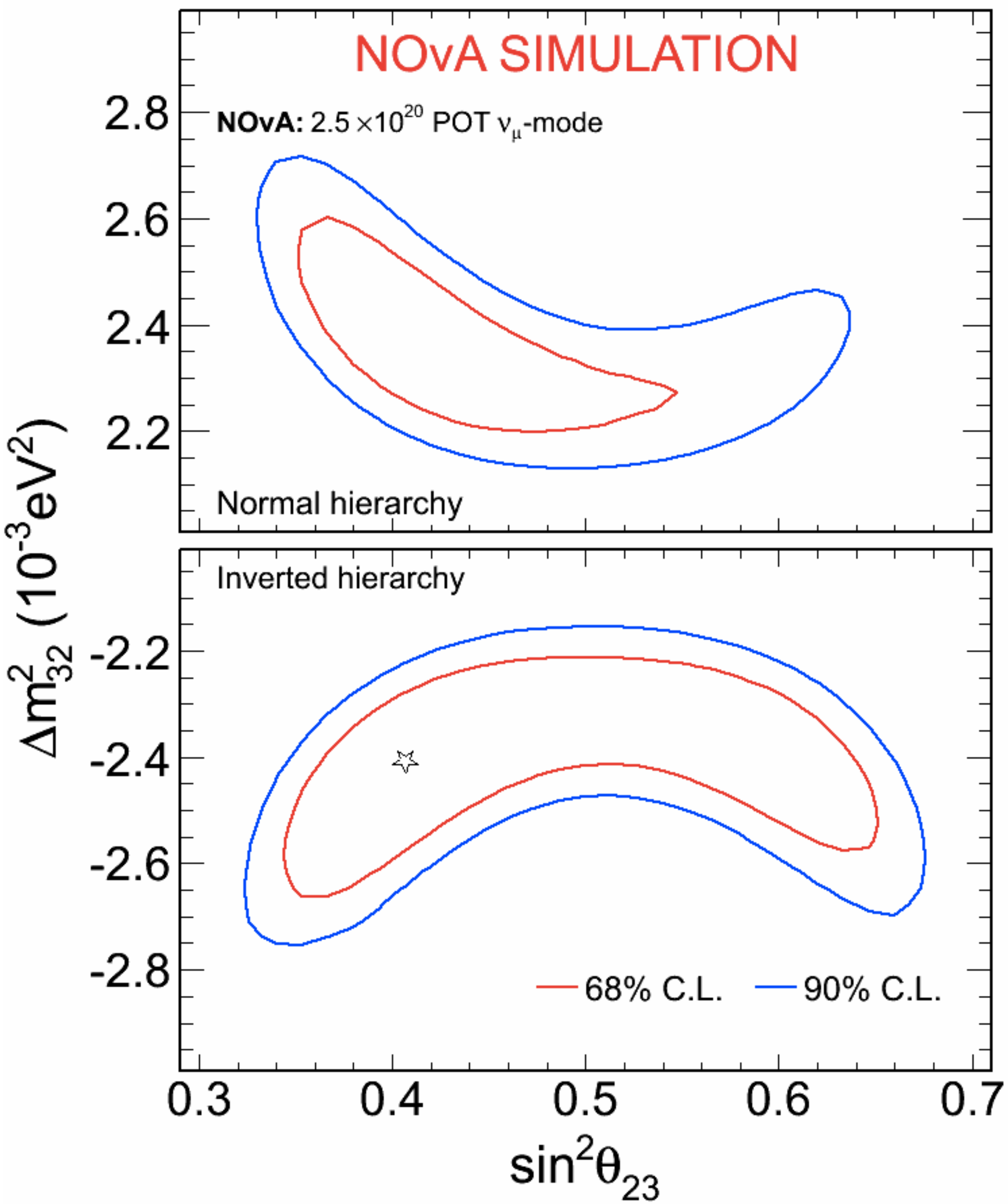
MINOS DATA
& MINOS+ SIMULATION
MINOS: All atmospheric and beam data
MINOS+: 5.3 ×10^20 POT ν_μ-mode, 17.0 kt-yr atmospheric ν
Normal hierarchy
Inverted hierarchy
68% C.L.
90% C.L.
2.8
2.6
2.4
2.2
-2.2
-2.4
-2.6
-2.8
0.3
0.4
0.5
0.6
0.7
Δm^2_{32} (10^{-3}eV^2)
$\sin^2\theta_{23}$

MINOS & MINOS+



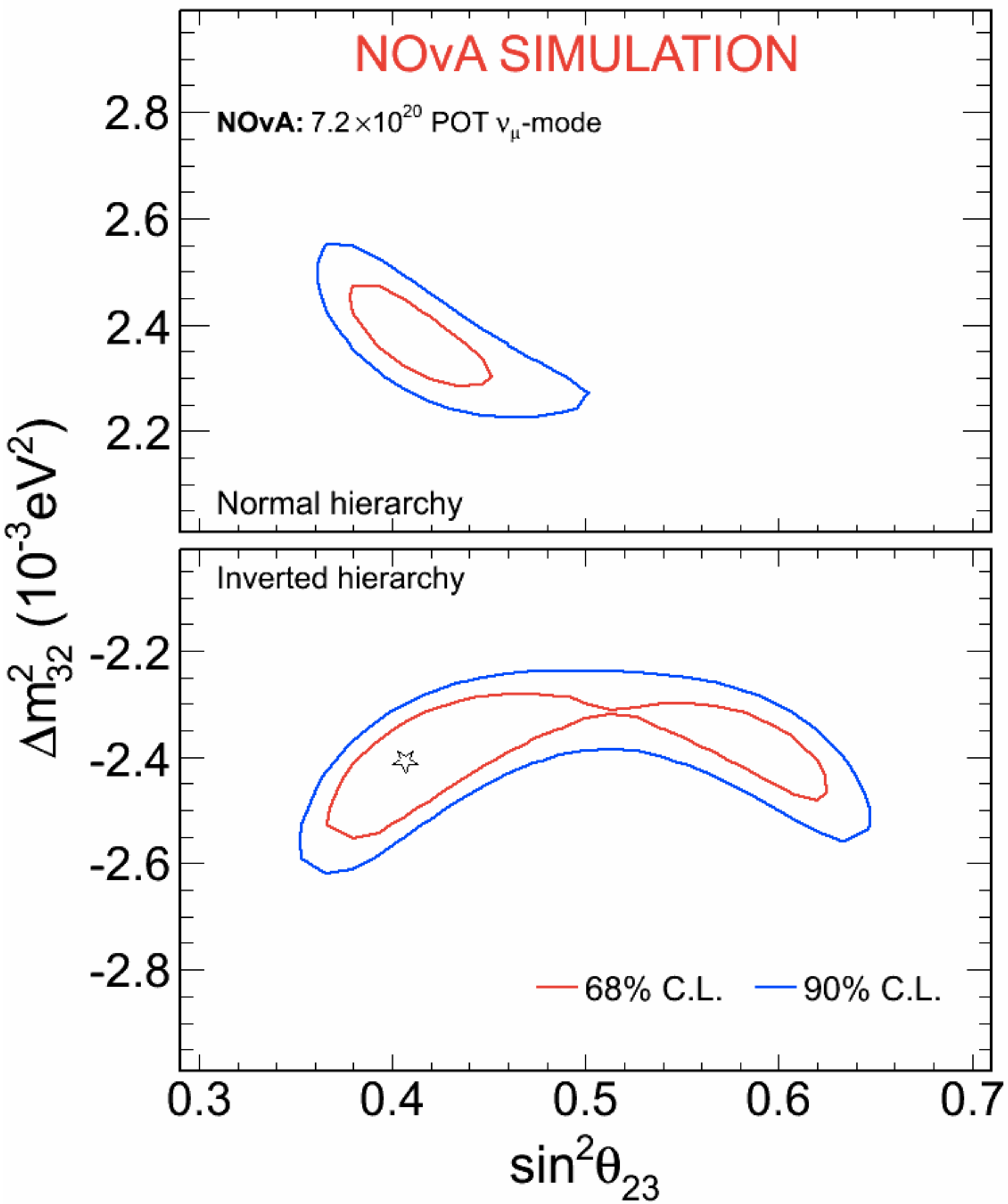
MINOS DATA
& MINOS+ SIMULATION
MINOS: All atmospheric and beam data
MINOS+: 10.0 ×10^20 POT ν_μ-mode, 22.0 kt-yr atmospheric ν
Normal hierarchy
Inverted hierarchy
68% C.L.
90% C.L.
2.8
2.6
2.4
2.2
-2.2
-2.4
-2.6
-2.8
0.3
0.4
0.5
0.6
0.7
Δm^2_{32} ($10^{-3}eV^2$)
$\sin^2\theta_{23}$

NOvA



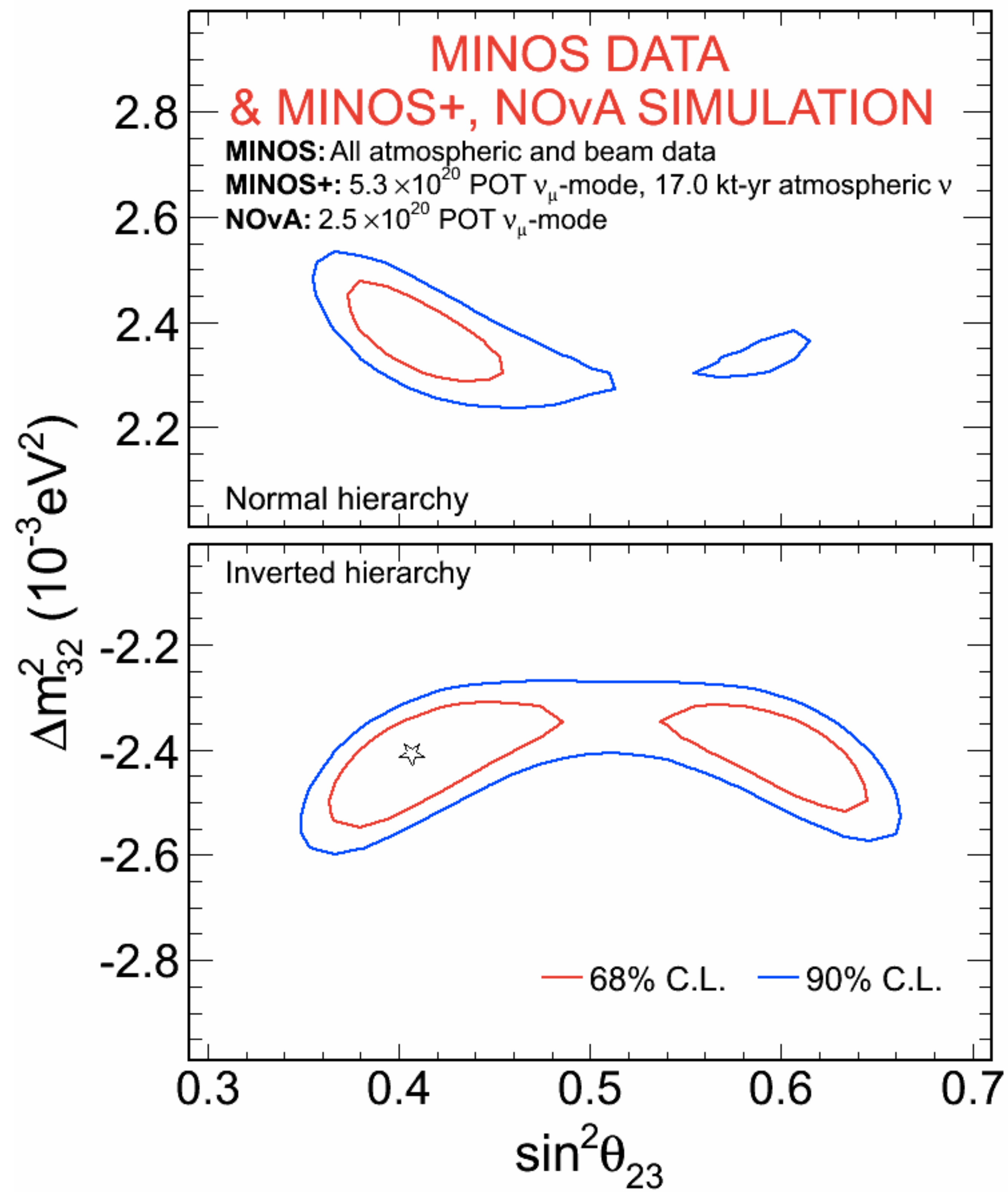
NOvA SIMULATION
NOvA: 2.5 ×10^20 POT ν_μ-mode
Normal hierarchy
Inverted hierarchy
68% C.L.
90% C.L.
2.8
2.6
2.4
2.2
-2.2
-2.4
-2.6
-2.8
0.3
0.4
0.5
0.6
0.7
Δm²_32 (10⁻³eV²)
sin²θ_23

NOvA



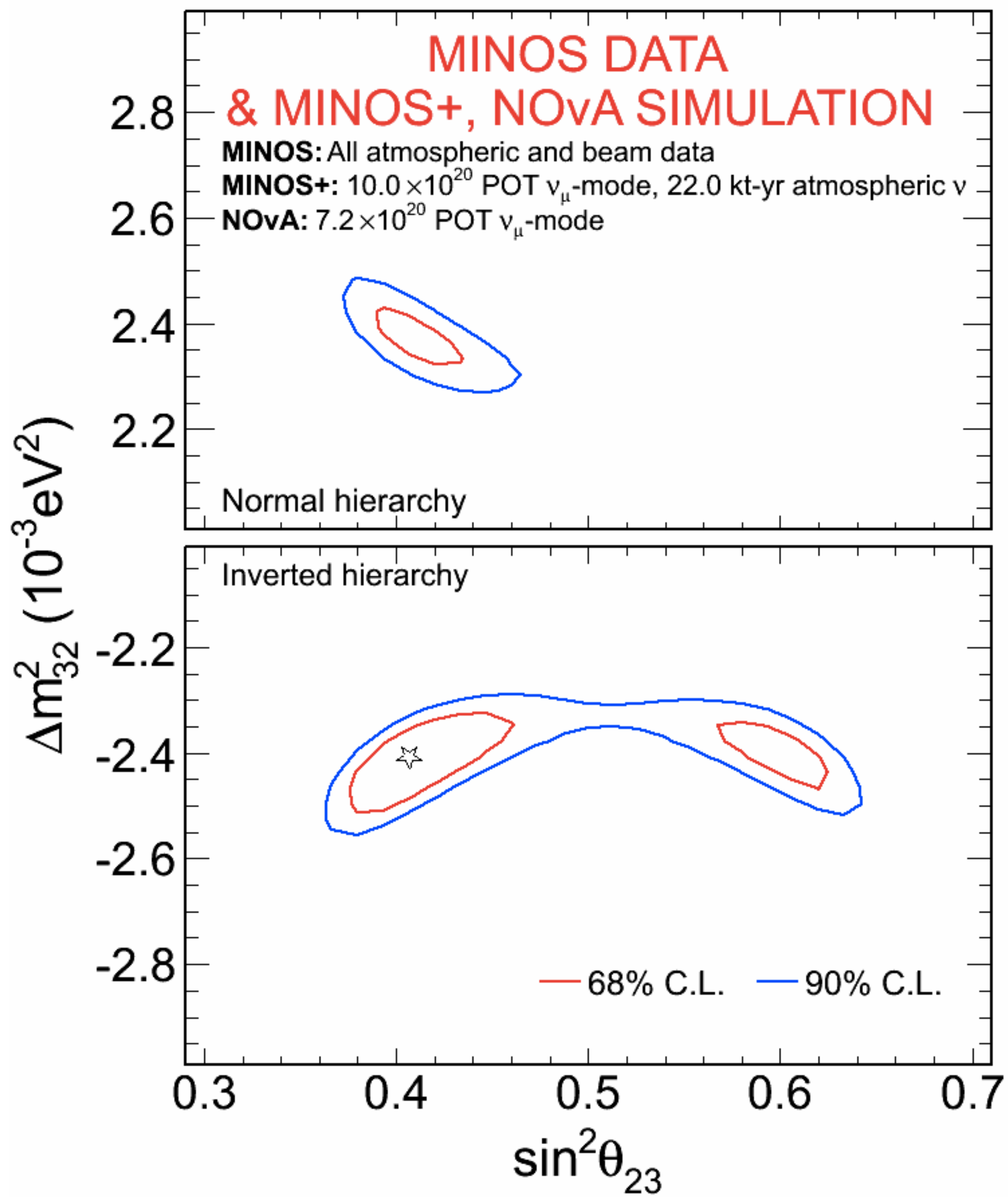
NOvA SIMULATION
NOvA: 7.2×10^20 POT ν_μ-mode
Normal hierarchy
Inverted hierarchy
68% C.L.
90% C.L.
2.8
2.6
2.4
2.2
-2.2
-2.4
-2.6
-2.8
Δm²_32 (10⁻³eV²)
0.3
0.4
0.5
0.6
0.7
sin²θ_23

MINOS & NOvA



MINOS DATA
& MINOS+, NOvA SIMULATION
MINOS: All atmospheric and beam data
MINOS+: 5.3 ×10^20 POT ν_μ-mode, 17.0 kt-yr atmospheric ν
NOvA: 2.5 ×10^20 POT ν_μ-mode
Normal hierarchy
Inverted hierarchy
68% C.L.
90% C.L.
2.8
2.6
2.4
2.2
-2.2
-2.4
-2.6
-2.8
0.3
0.4
0.5
0.6
0.7
Δm²₃₂ (10⁻³eV²)
sin²θ₂₃

MINOS & NOvA


MINOS DATA
& MINOS+, NOvA SIMULATION
MINOS: All atmospheric and beam data
MINOS+: 10.0×10^20 POT ν_μ-mode, 22.0 kt-yr atmospheric ν
NOvA: 7.2×10^20 POT ν_μ-mode
Normal hierarchy
Inverted hierarchy
68% C.L.
90% C.L.
Δm²_32 (10^-3 eV²)
sin²θ_23
2.8
2.6
2.4
2.2
-2.2
-2.4
-2.6
-2.8
0.3
0.4
0.5
0.6
0.7

Atmospheric NuMu Disappearance

- Not just limited to studying the disappearance of NuMI muon neutrinos- 48.7 kton-years of atmospheric neutrinos in Far Detector between 2003 and 2014
- Very long baselines through matter compared to NuMI disappearance analysis
- Some sensitivity to octant, mass hierarchy and δ_{cp}