# Long-Baseline Sterile Neutrino Searches: The MINOS(+) and NOvA Experiences

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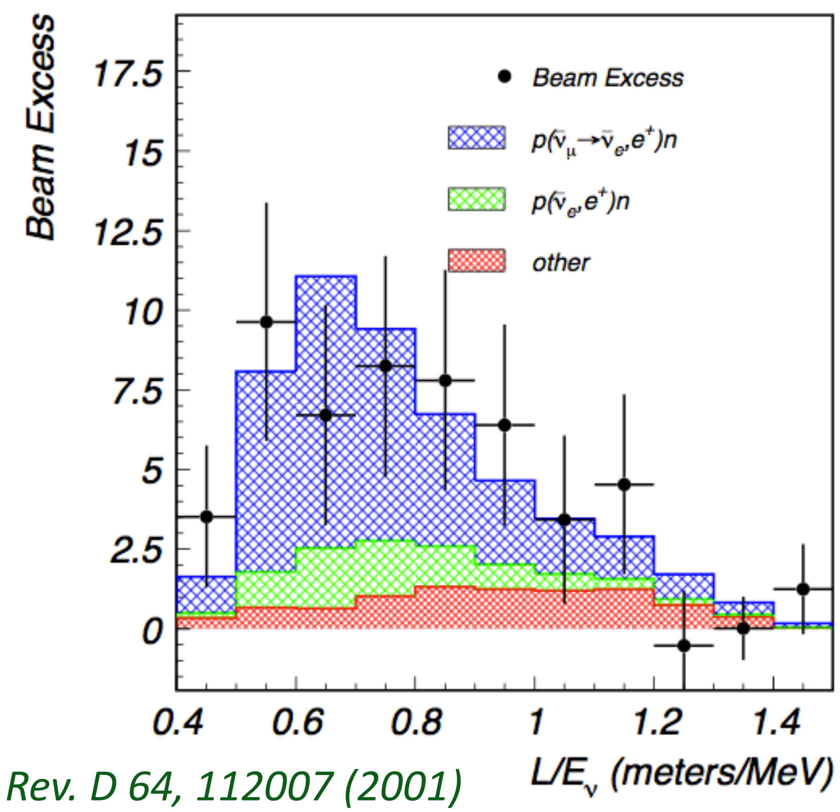
DUNE BSM Physics Phone Meeting
November 3, 2015

# Foreword

- Strongest indication (3.8σ) of large $\Delta m^2$ oscillations from LSND's observation of excess $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam over 30 m short baseline

- No evidence seen by similar muon decay-at-rest experiment KARMEN

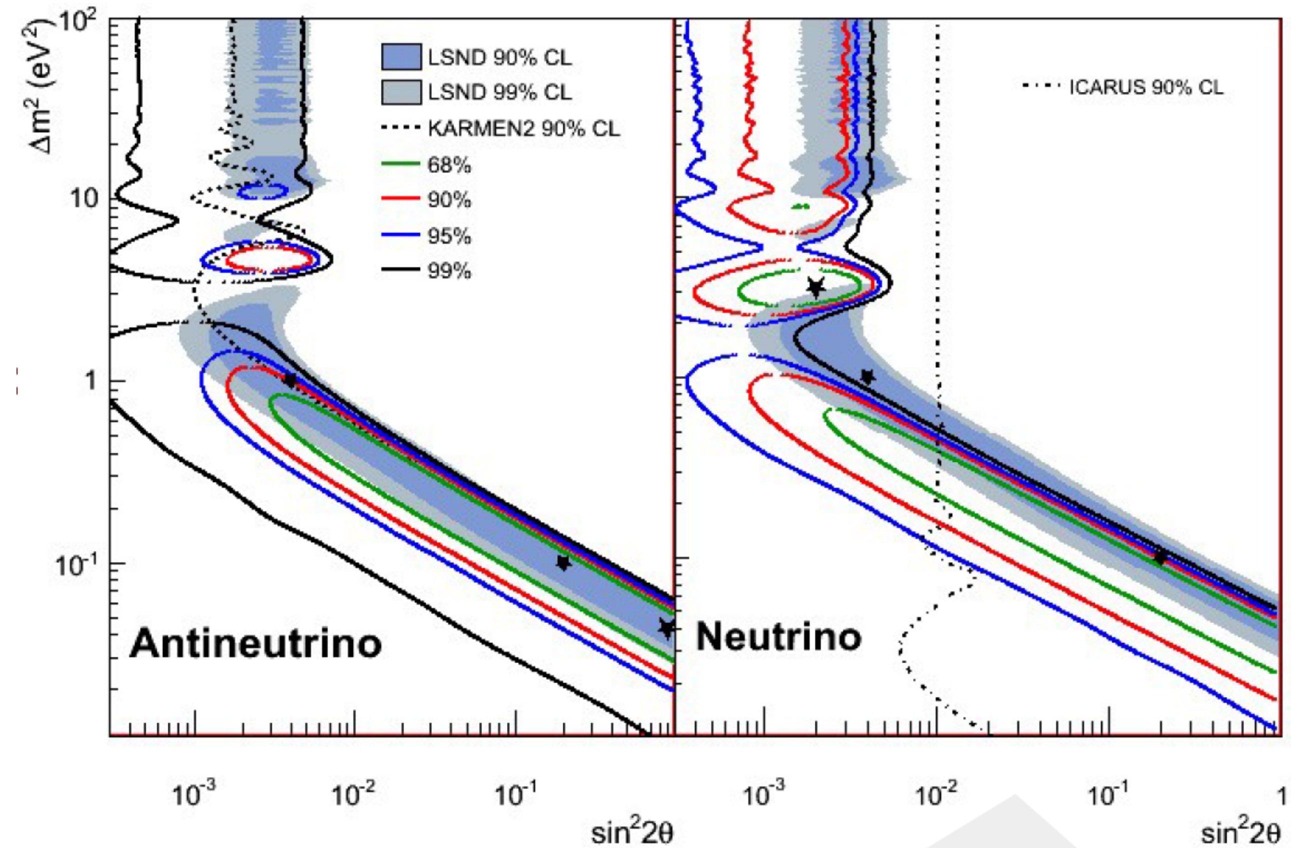
- MiniBooNE saw ~3σ indication for anomalous $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, but at somewhat different L/E from LSND




*Phys. Rev. D 64, 112007 (2001)*

- However, no evidence for sterile mixing-driven disappearance seen

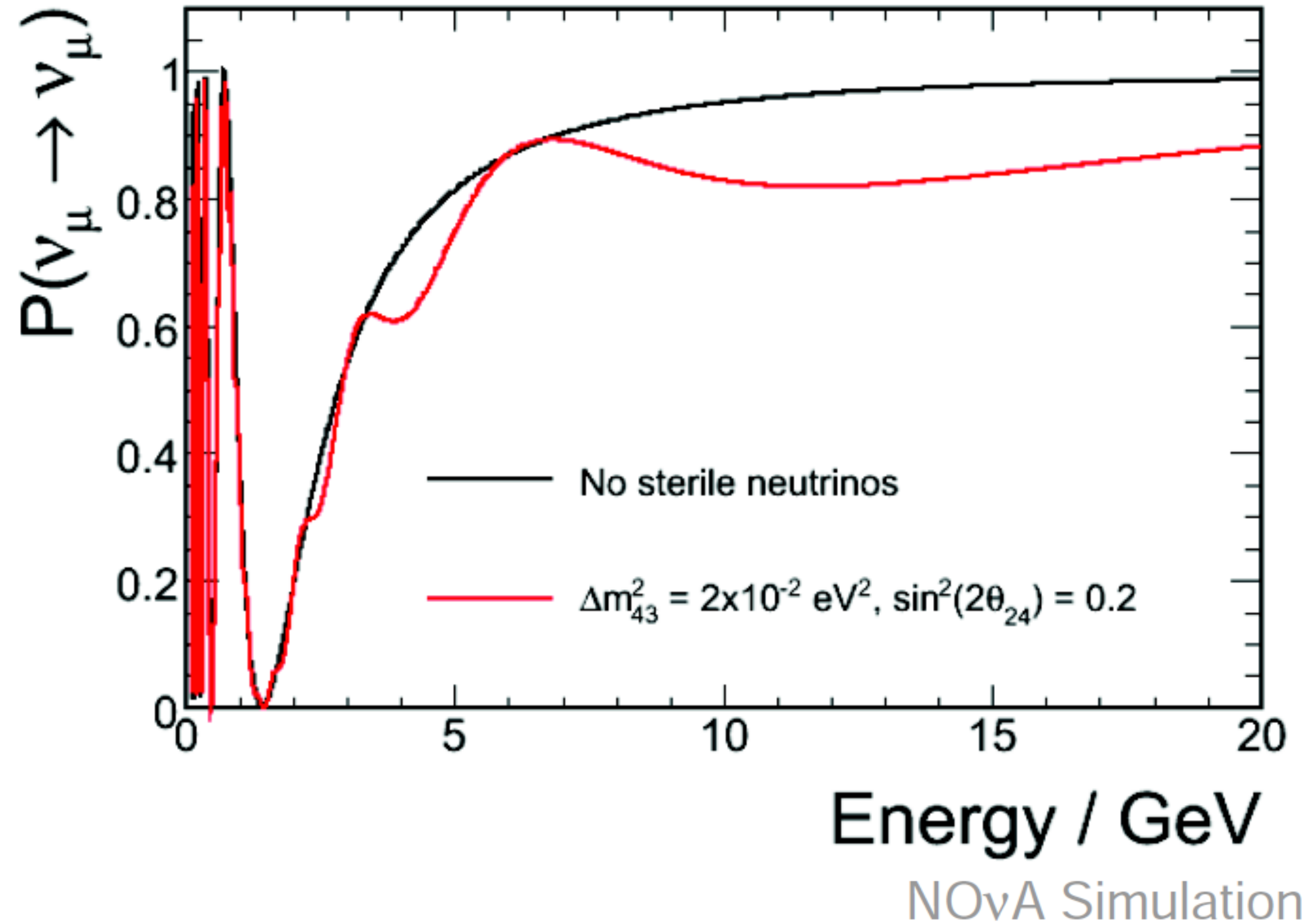
- Long-Baseline experiments like MINOS(+), NOvA, and DUNE can provide powerful probes of $\nu_\mu$, $\bar{\nu}_\mu$ disappearance driven by sterile mixing




*Phys. Rev. Lett.110, 161801*

# Long-Baseline $\nu_\mu \rightarrow \nu_s$ Mixing Probe

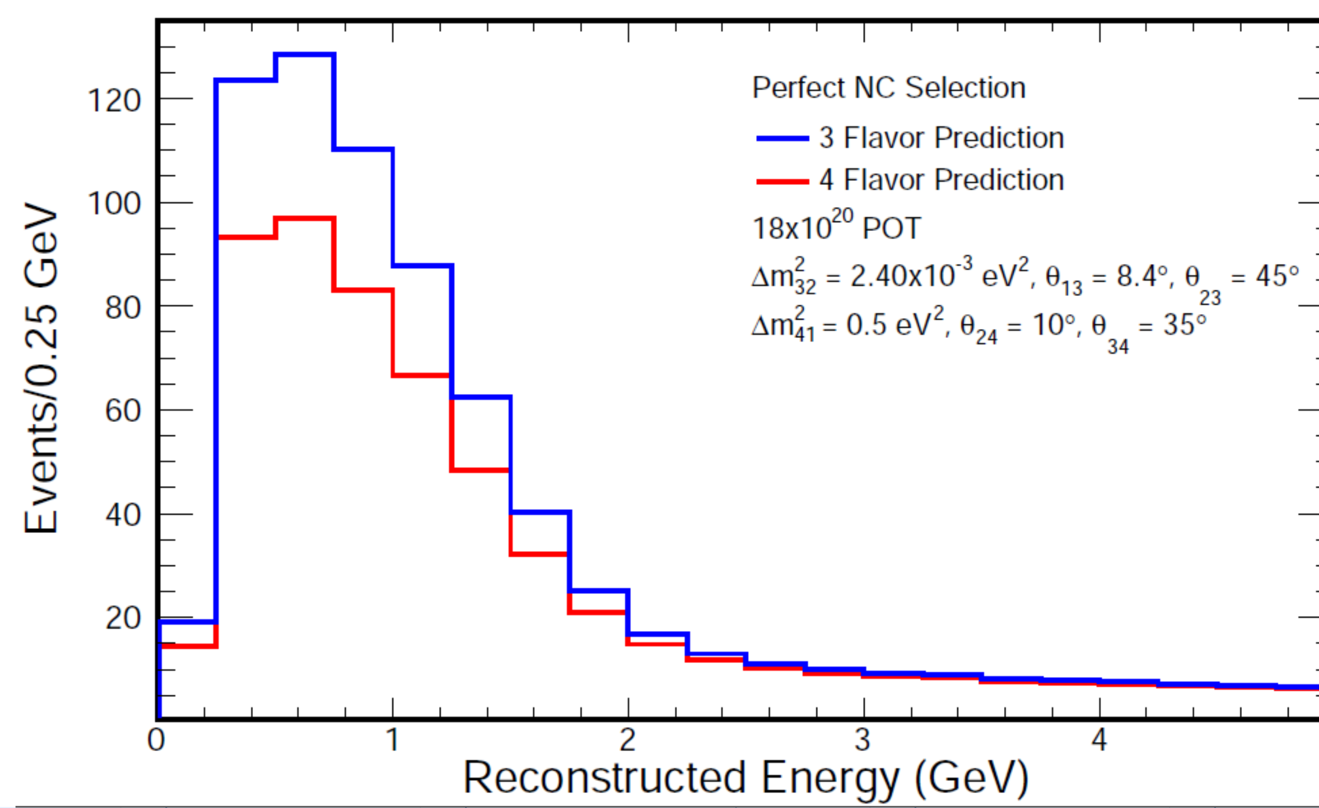
- Look for energy-dependent depletion of CC events at the FD modulated by three-flavor survival probability
  - plot to the right assumes 3+1 model




- NC interactions initiated by $\nu_e$, $\nu_\mu$, $\nu_\tau$ are topologically indistinguishable
  - NCs are insensitive to 3-flavor oscillations

- However, $\nu_\mu \rightarrow \nu_s$ mixing would reduce NC interaction rate as $\nu_s$ do not interact in the detectors

- Look for energy-dependent depletion of NC events at the FD



# What LBL Expts. and Others Measure

- Different experiments are sensitive to different angles (3+1 model)
  - Reactor experiments ($\bar{\nu}_e$ disappearance): $\theta_{14}$

$$P_{ee} \approx 1 - 2\sin^2 2\theta_{14} \times \sin^2 \frac{\Delta m^2_{41} L}{E} \qquad |U_{e4}|^2$$

  - MiniBooNE, LSND, and KARMEN, T2K ND ($\nu_e$, $\bar{\nu}_e$ appearance): $\theta_{14}$, $\theta_{24}$

$$P_{\mu e} \approx 2\sin^2 2\theta_{14} \sin^2 \theta_{24} \times \sin^2 \frac{\Delta m^2_{41} L}{E} \qquad 4|U_{e4}|^2 |U_{\mu 4}|^2$$

  - MiniBooNE, CDHS, CCFR ($\nu_\mu$, $\bar{\nu}_\mu$ disappearance): $\theta_{24}$

$$P_{\mu\mu} \approx 1 - 2\sin^2 2\theta_{24} \times \sin^2 \frac{\Delta m^2_{41} L}{E} \qquad |U_{\mu 4}|^2$$

  - MINOS/MINOS+, SuperK, NOvA ($\nu_\mu$, $\bar{\nu}_\mu$ disappearance and NC): $\theta_{24}$, $\theta_{34}$

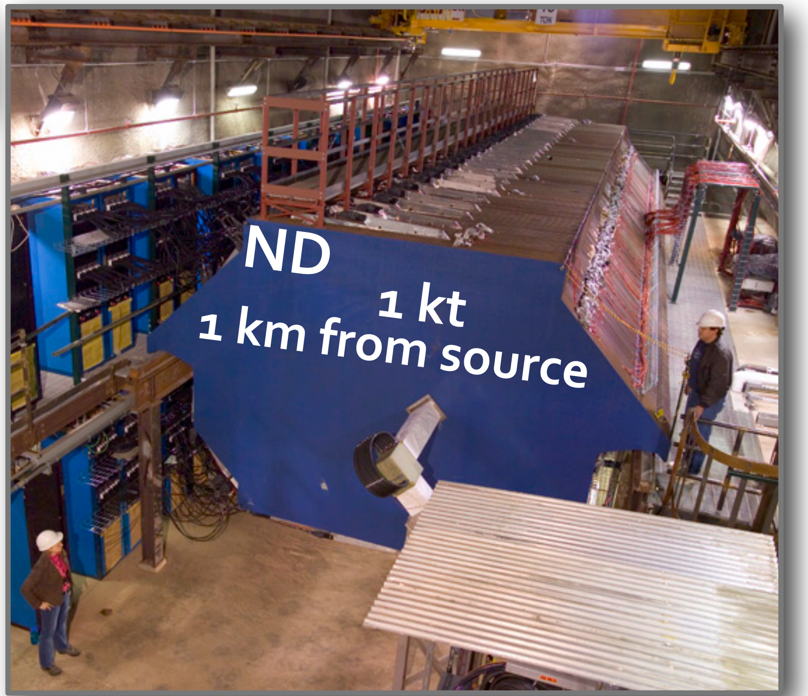
$$1 - P_{\mu s} \approx \cos^2 \theta_{24} \sin^2 \theta_{34} \times \sin^2 \frac{\Delta m^2_{41} L}{E} \sin^2 \frac{\Delta m^2_{31} L}{E} \qquad |U_{\mu 4}|^2,\ |U_{\tau 4}|^2$$

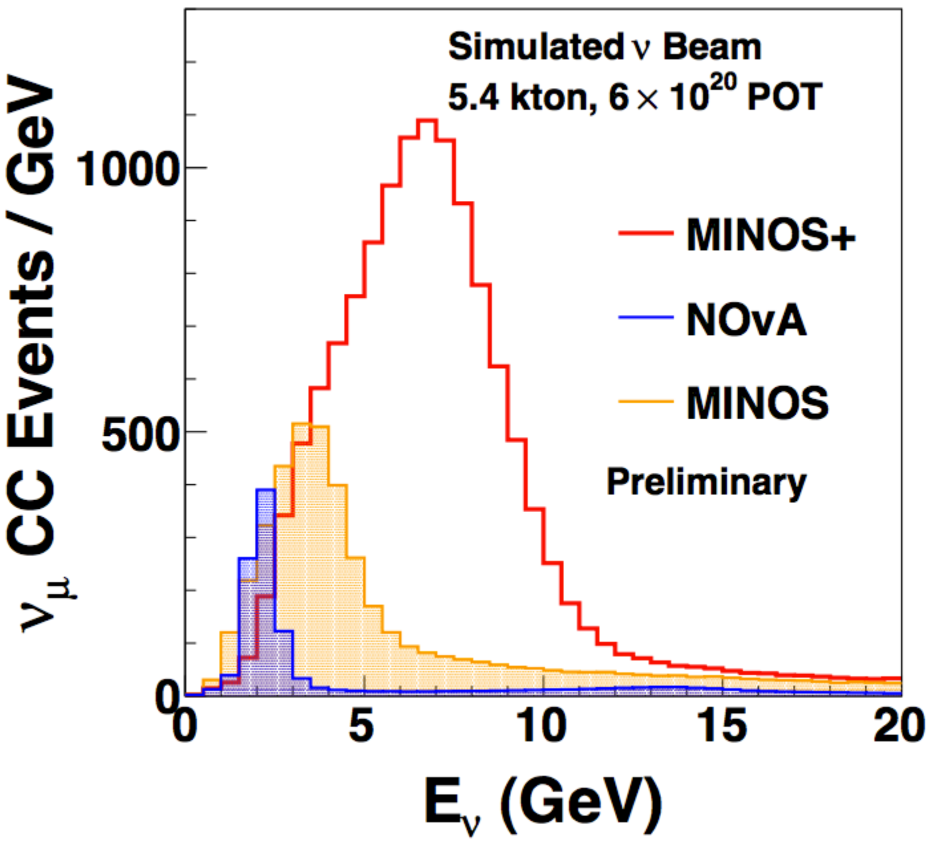
# MINOS/MINOS+ in a Nutshell

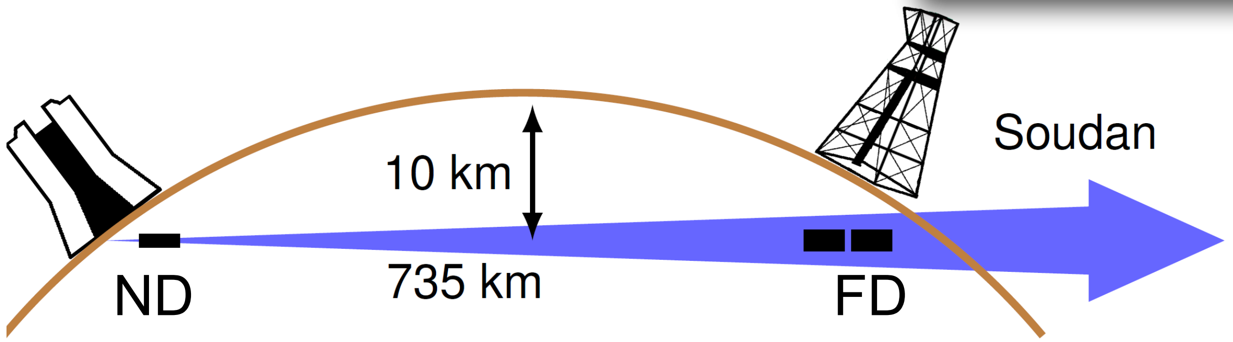
Main Injector Neutrino Oscillation Search



- Long-baseline neutrino oscillation experiment
- Measure NuMI Neutrino beam energy and flavor composition with two detectors over 735 km
  - L/E ~ 500 km/GeV

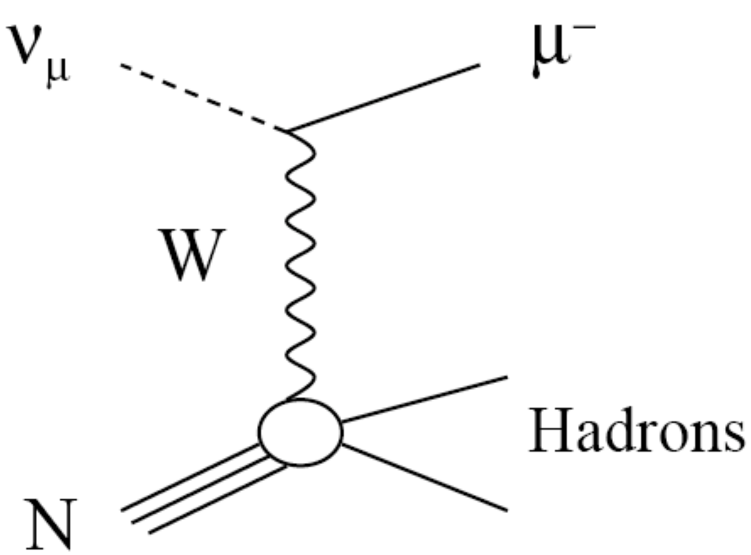


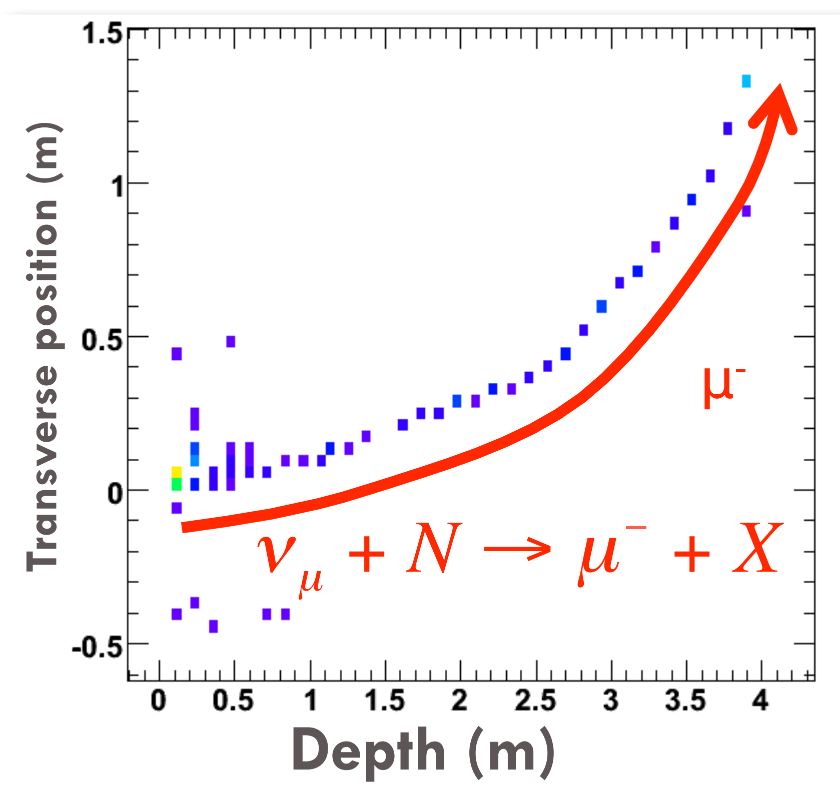



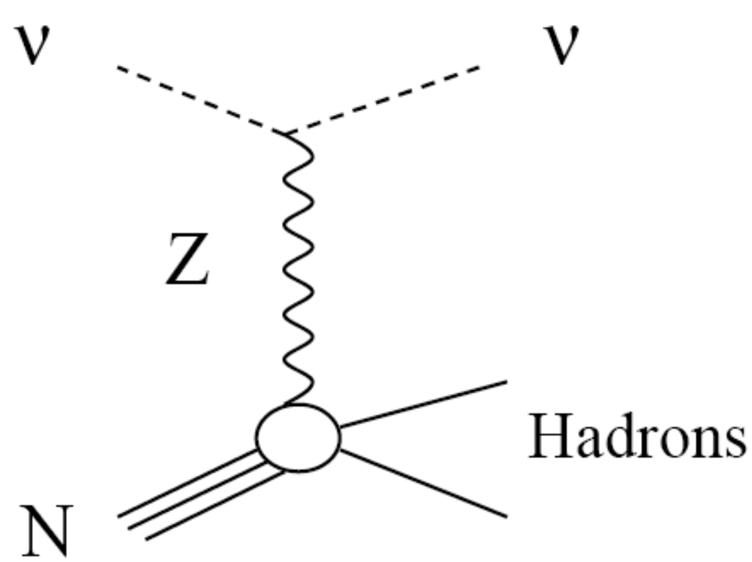
# Event Topologies

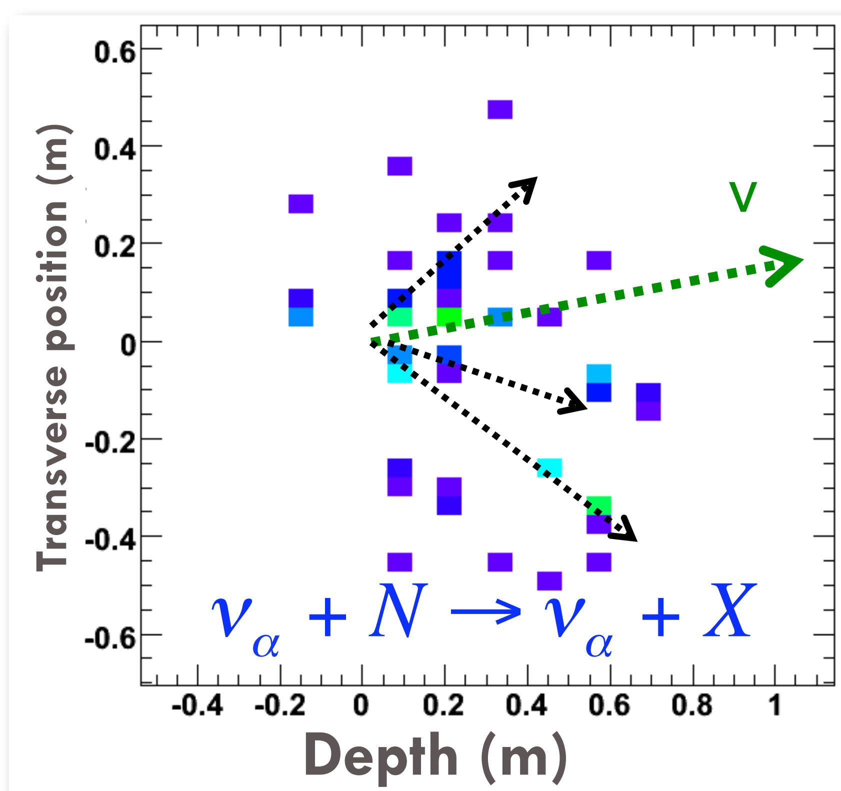
## $\nu_\mu$ CC Event



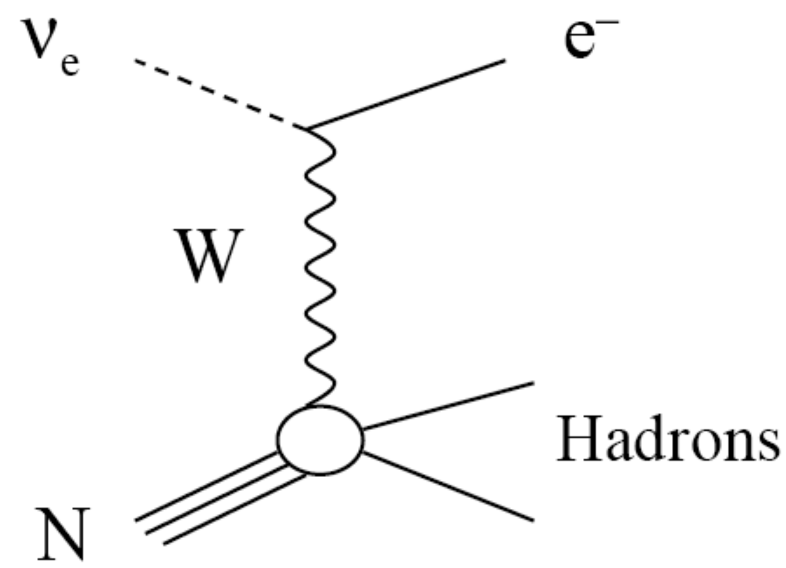



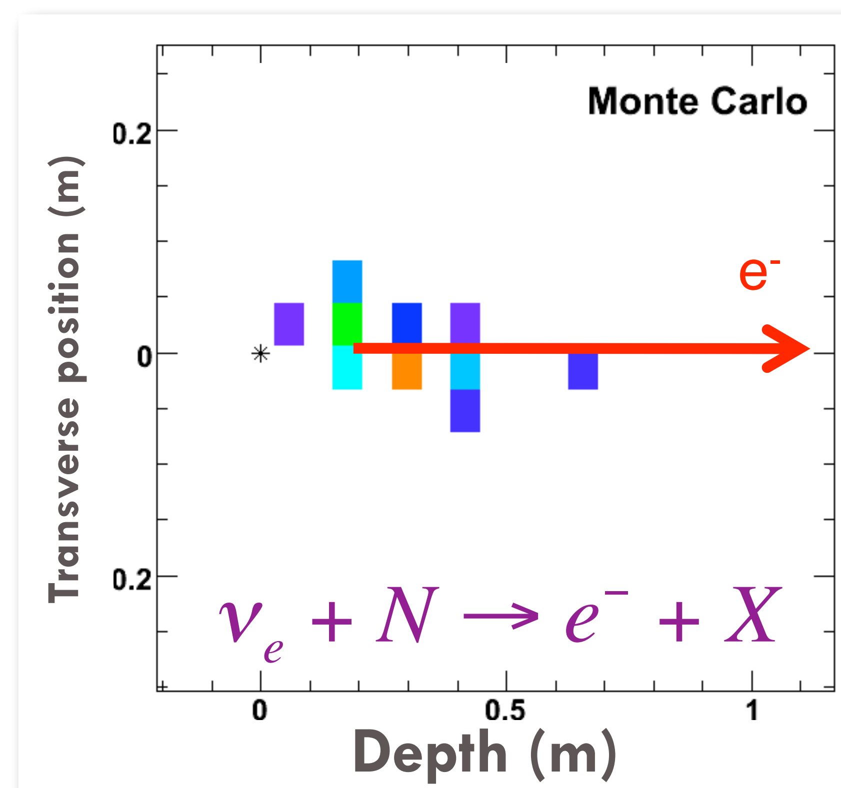

## NC Event



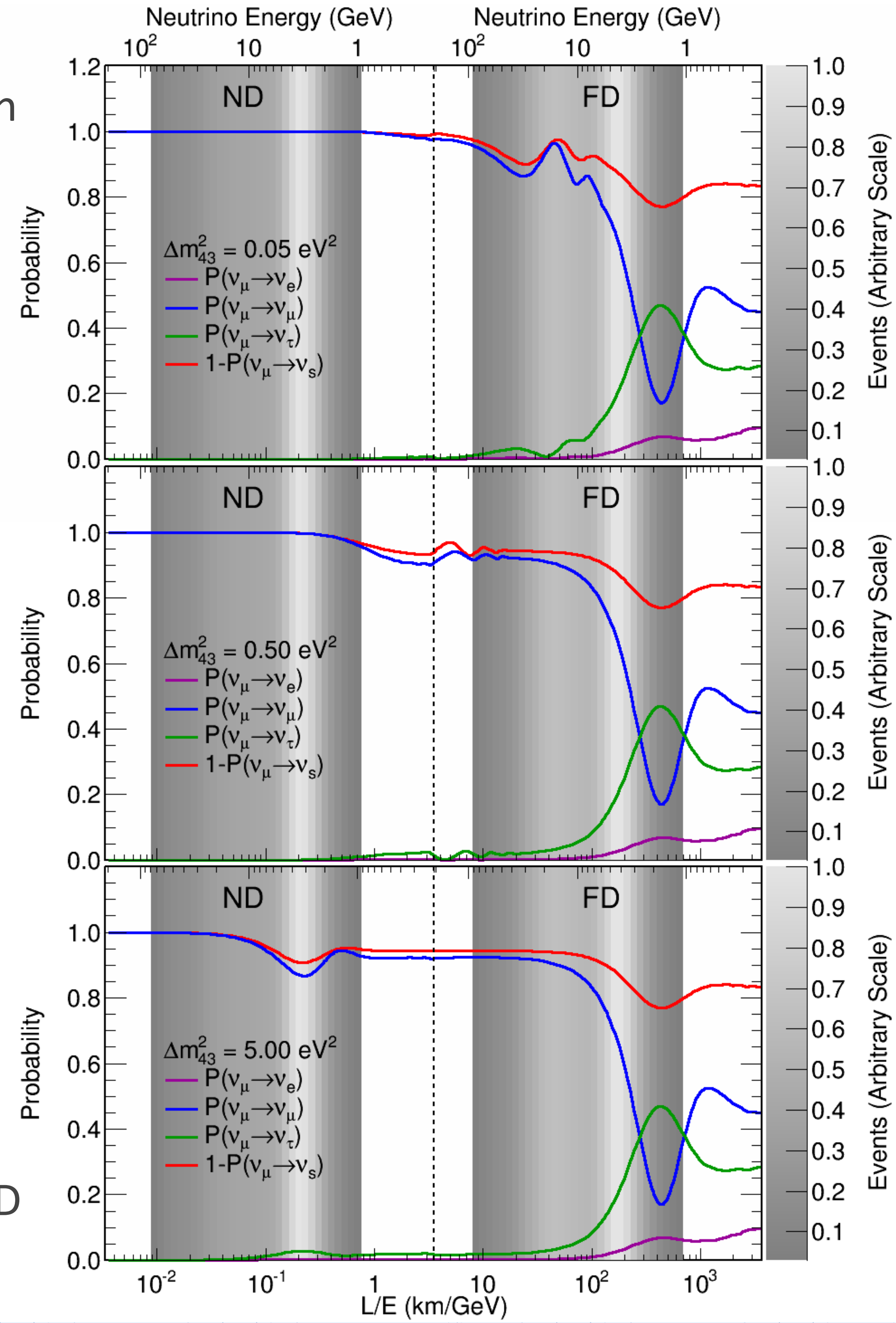

## $\nu_e$ CC Event



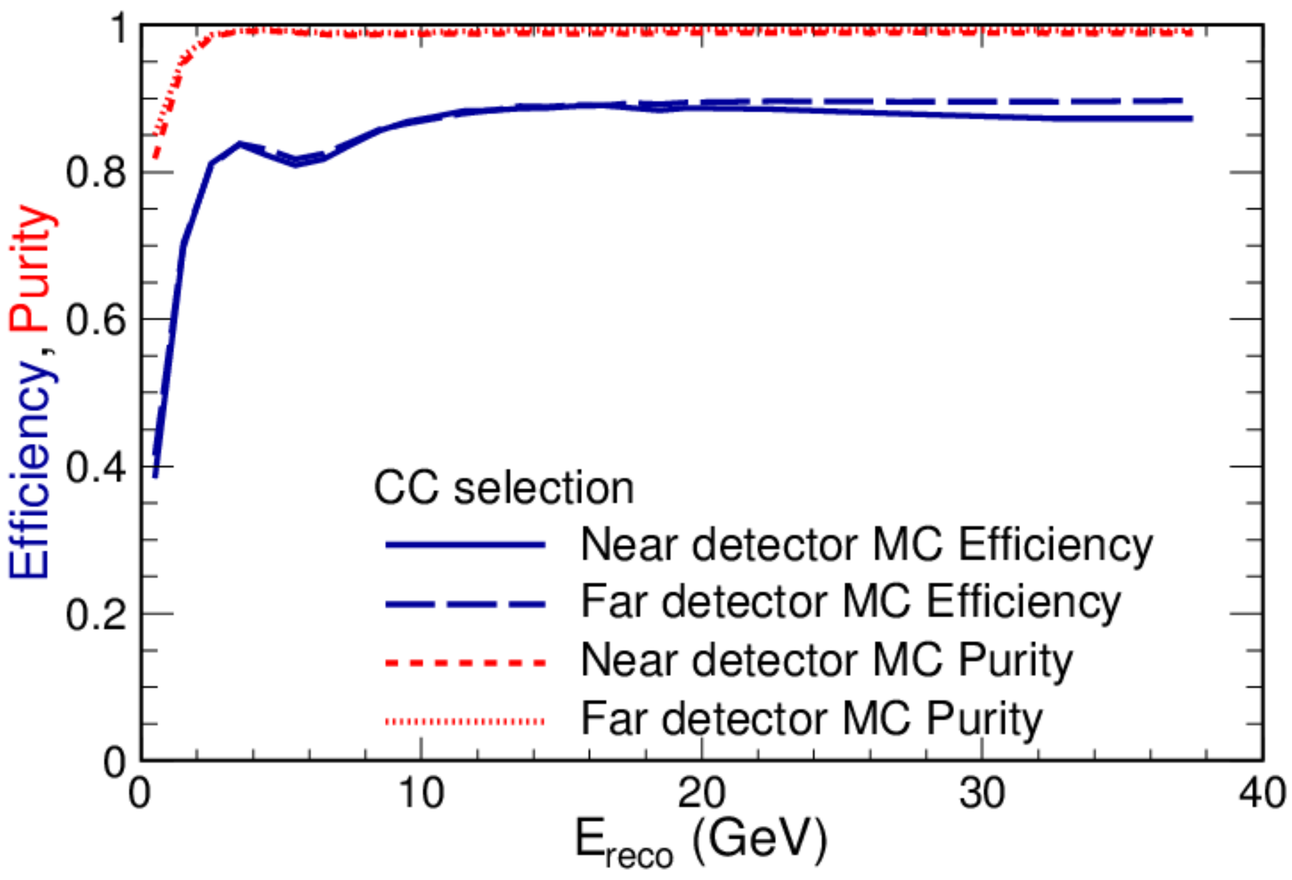



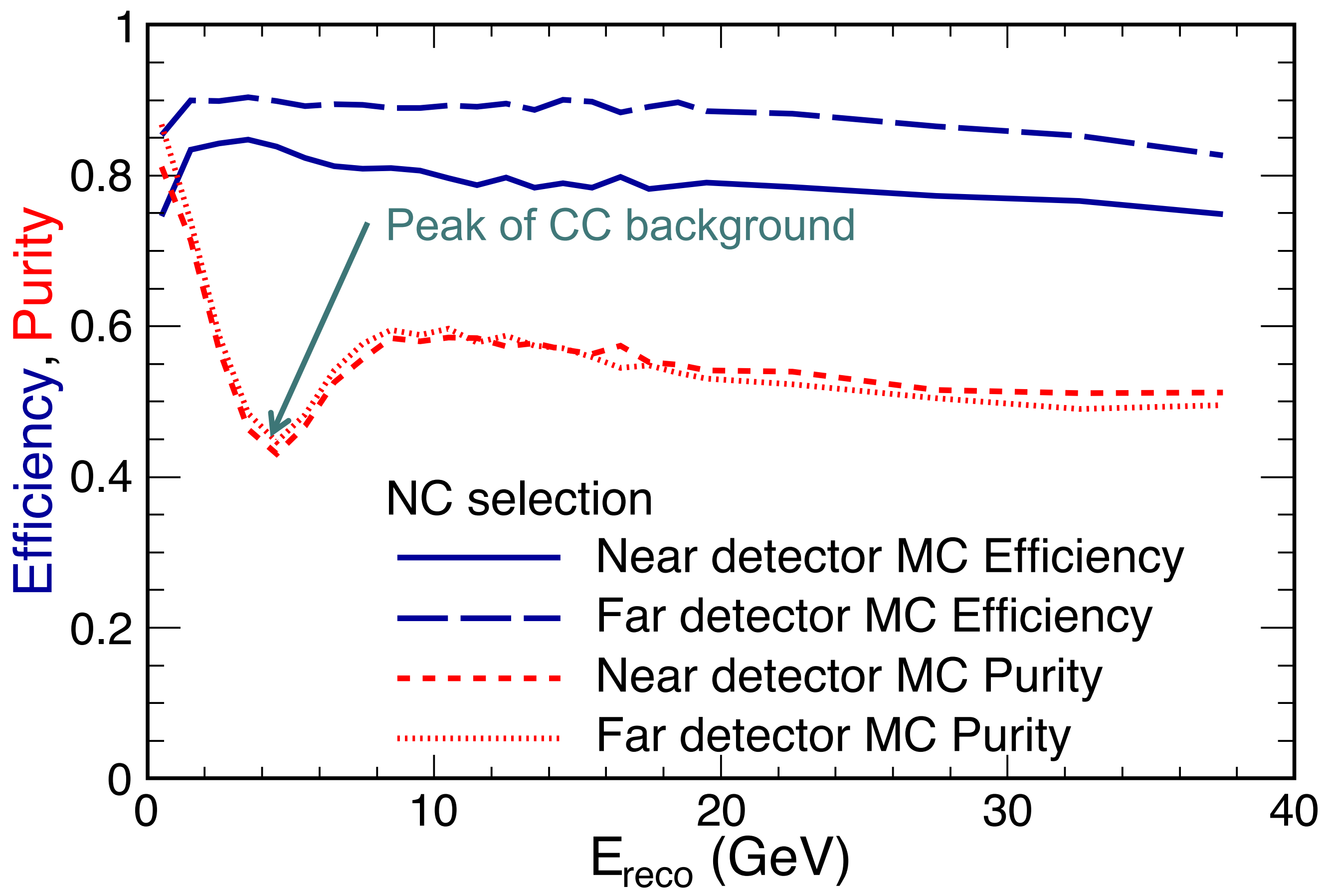
# MINOS and 4-Flavor Oscillations

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



# MINOS FD CC and NC Selections




- MINOS was designed to separate $\nu_\mu$ CC interactions from NCs, but isolating a pure NC sample is more difficult
  - Main background originates from inelastic (high-y) $\nu_\mu$ CC events
  - NC events selected with 89% efficiency and 61% purity in FD
  - 97% of $\nu_e$ CC selected as NC
  - In ND, need to worry about reconstruction failures due to pile-up => one of the largest systematic uncertainties in NC analysis

# MINOS FD CC and NC Energy Spectra

- Comparison with 3-flavor prediction for full MINOS low-energy beam neutrino mode sample: $10.56\times10^{20}$ POT
- Selected $\nu_\mu$-CC and CC candidates in both detectors
  - 2563 $\nu_\mu$-CC-like events in FD
  - 1211 NC-like events in FD
- Looked at model-independent rate measurement for NC Selection

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

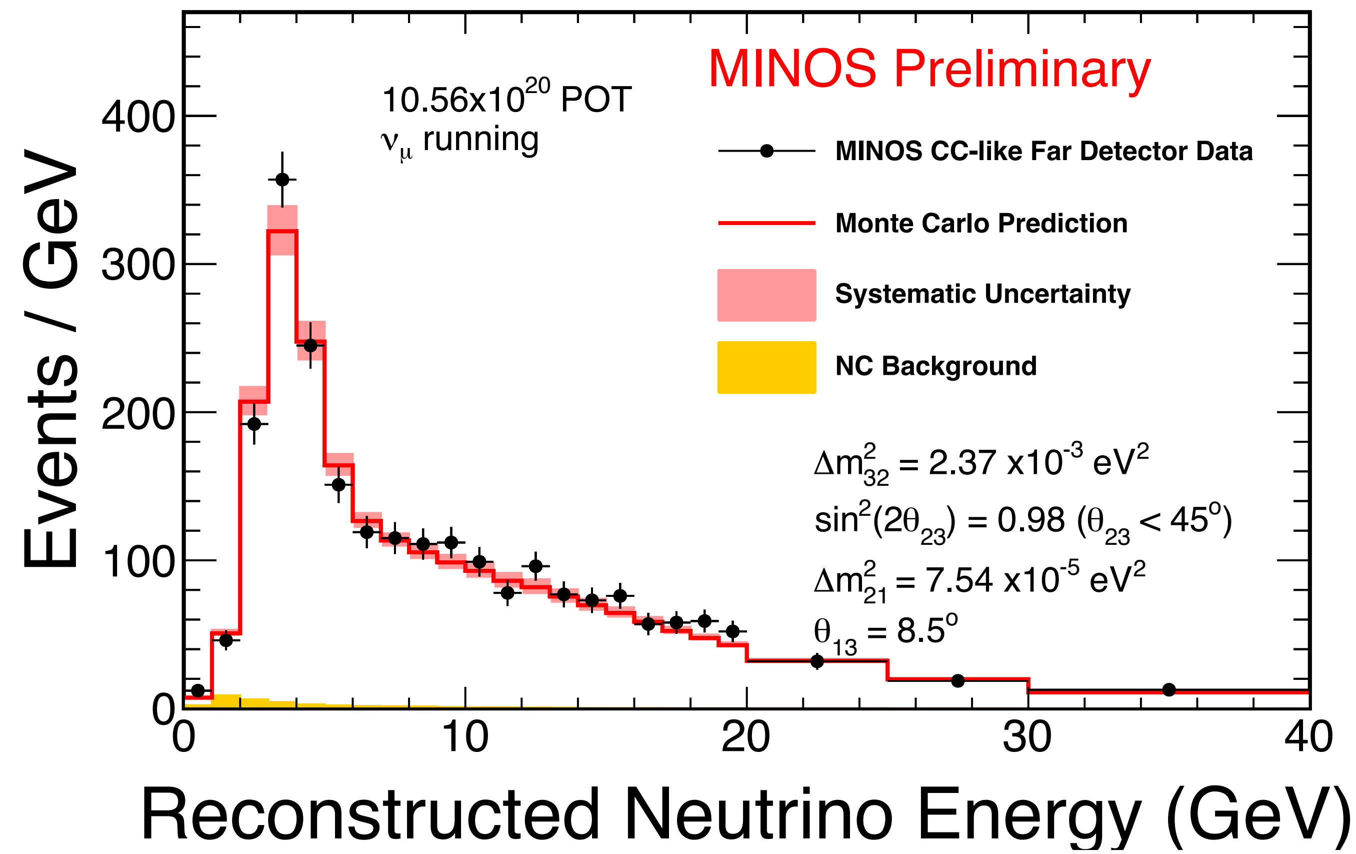
Predicted CC background from all flavors ($\sum B_{CC}$)

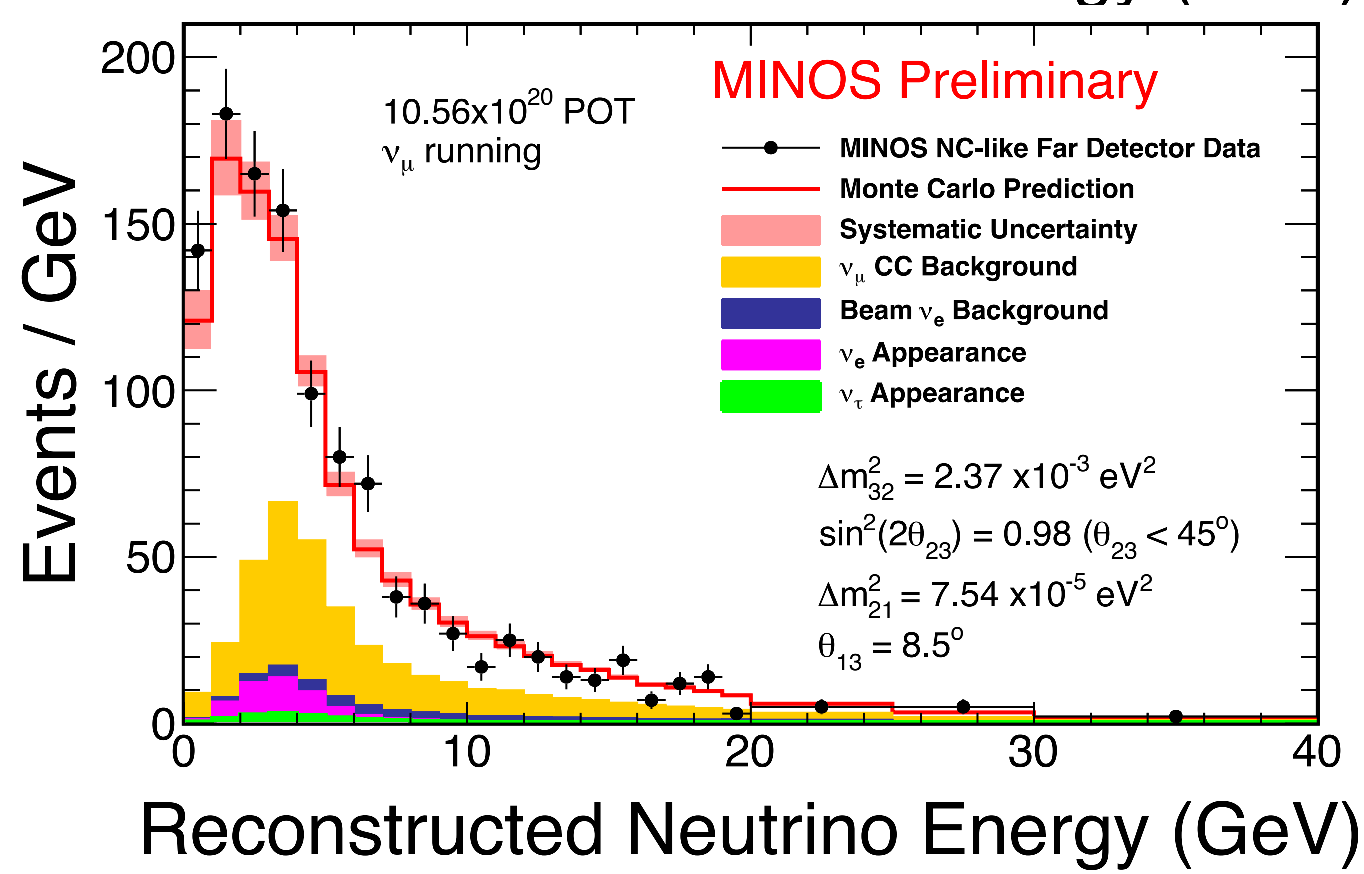
Predicted NC interaction signal ($S_{NC}$)

$R$ =1.08 ± 0.11 (0 - 40 GeV)

$R$ =1.11 ± 0.10 (0 - 3 GeV)

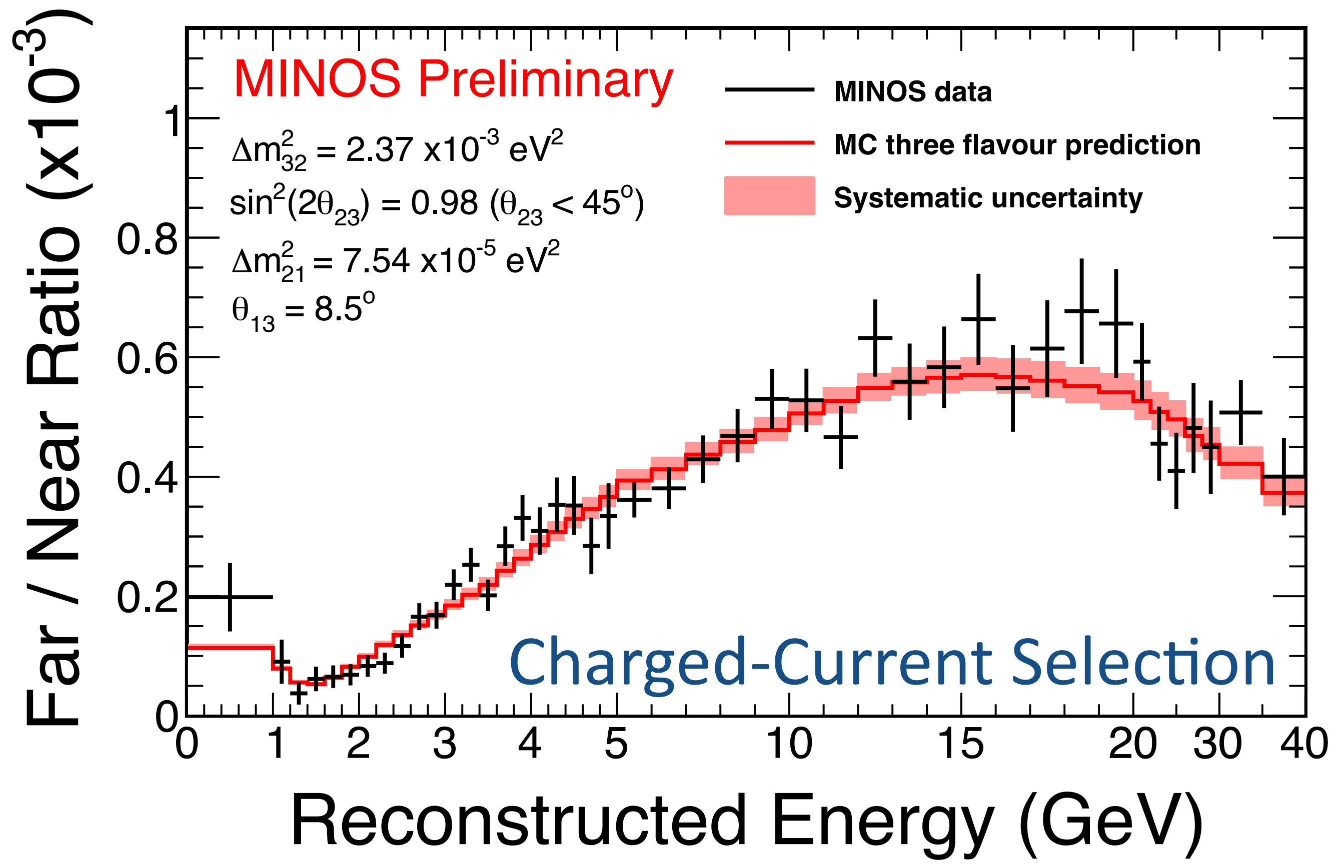
- No evidence for oscillations into sterile neutrinos at $\Delta m^2_{43}\simeq0.5$ eV$^2$

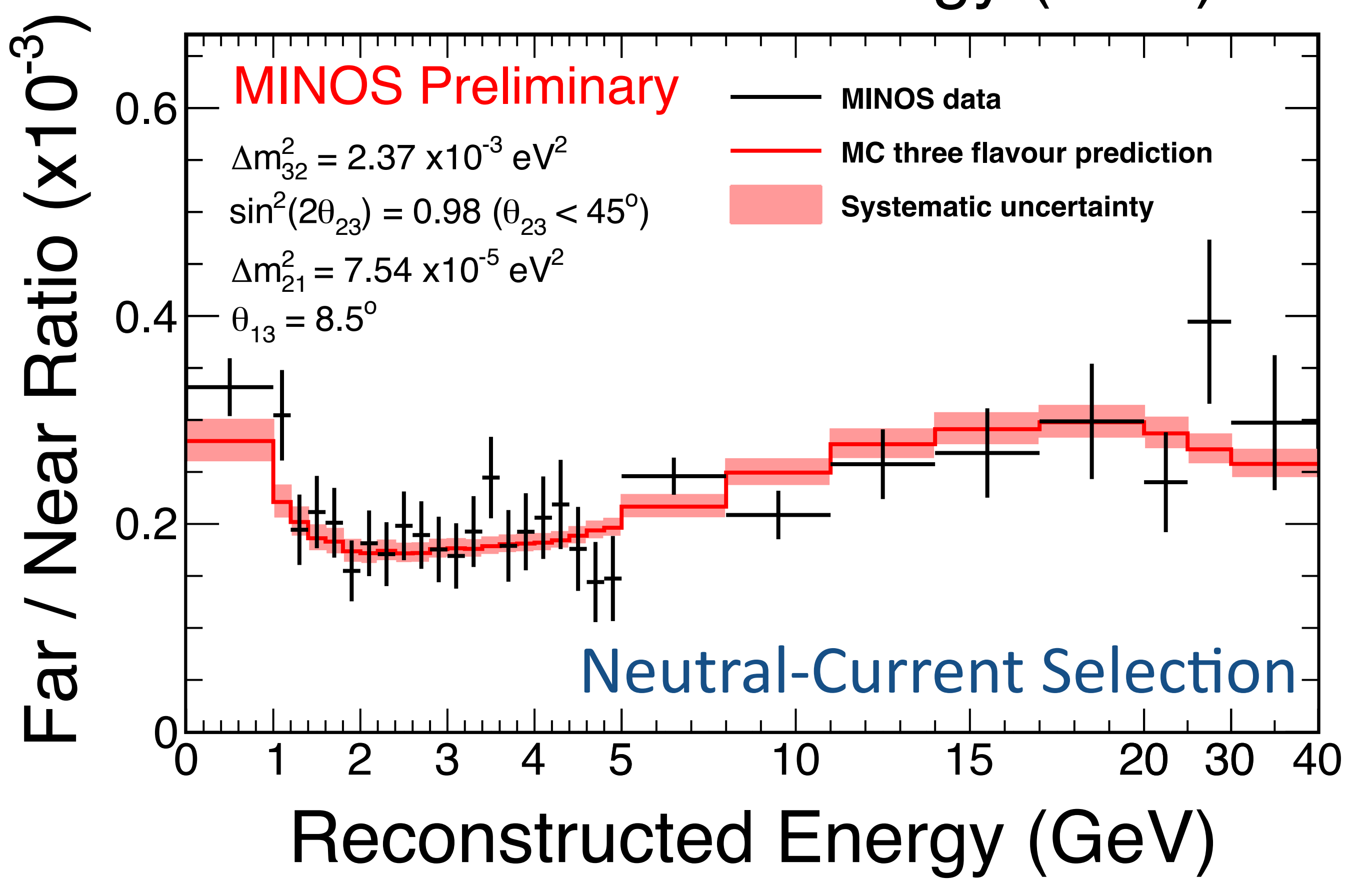


# MINOS 4-Flavor Analysis Strategy

- Assume 3+1 sterile neutrino mixing scenario
  - Apply oscillations to both ND and FD
  - Use distance to meson decay point
  - Fit for $|\Delta m^2_{32}|$, $\theta_{23}$, $|\Delta m^2_{43}|$, $\theta_{24}$, $\theta_{34}$
- To account for ND distortions, fit oscillated F/N ratio directly to F/N data ratio
  - Include constraint on ND rate
- Carefully assessed systematic uncertainties affecting high-energy tail of spectrum with respect to previous CC and NC analyses
  - Re-evaluated beam flux uncertainties
- Log-likelihood surfaces are Feldman-Cousins corrected



# Systematics

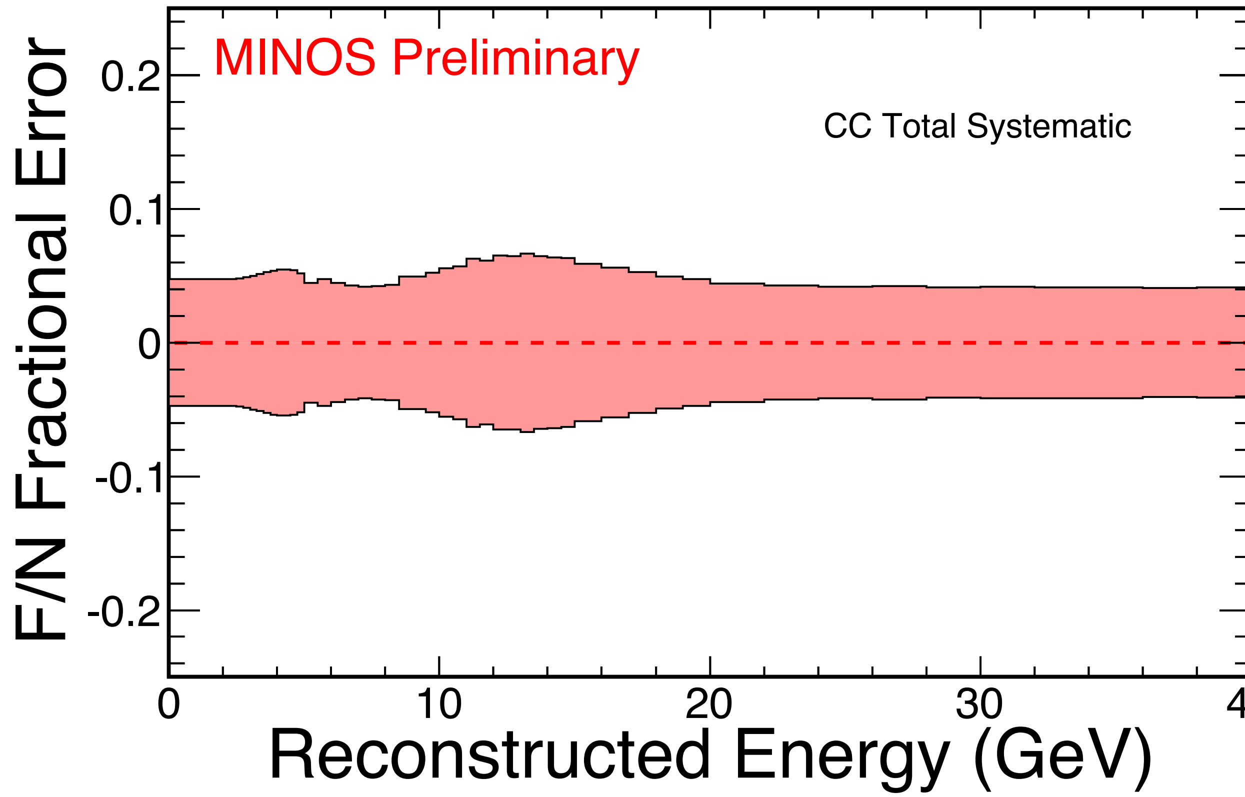
- Including 26 systematic uncertainties in fit via covariance matrices, accounting for:
  - Normalization
  - Detector acceptance
  - NC selection
  - Hadron production, beam optics, cross sections, energy scale, and backgrounds

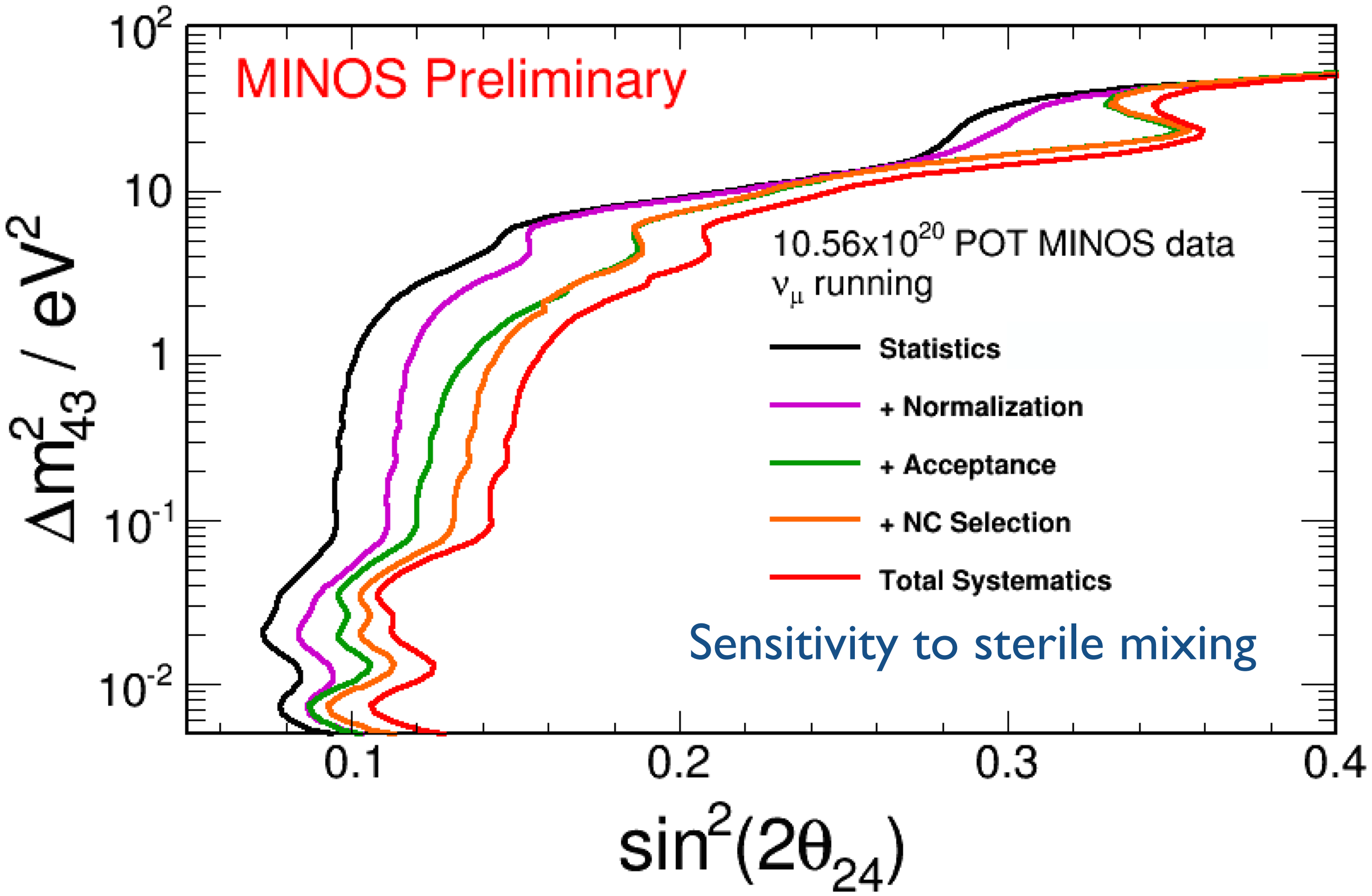
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T[V^{-1}]_{ij}(o_j - e_j)$$

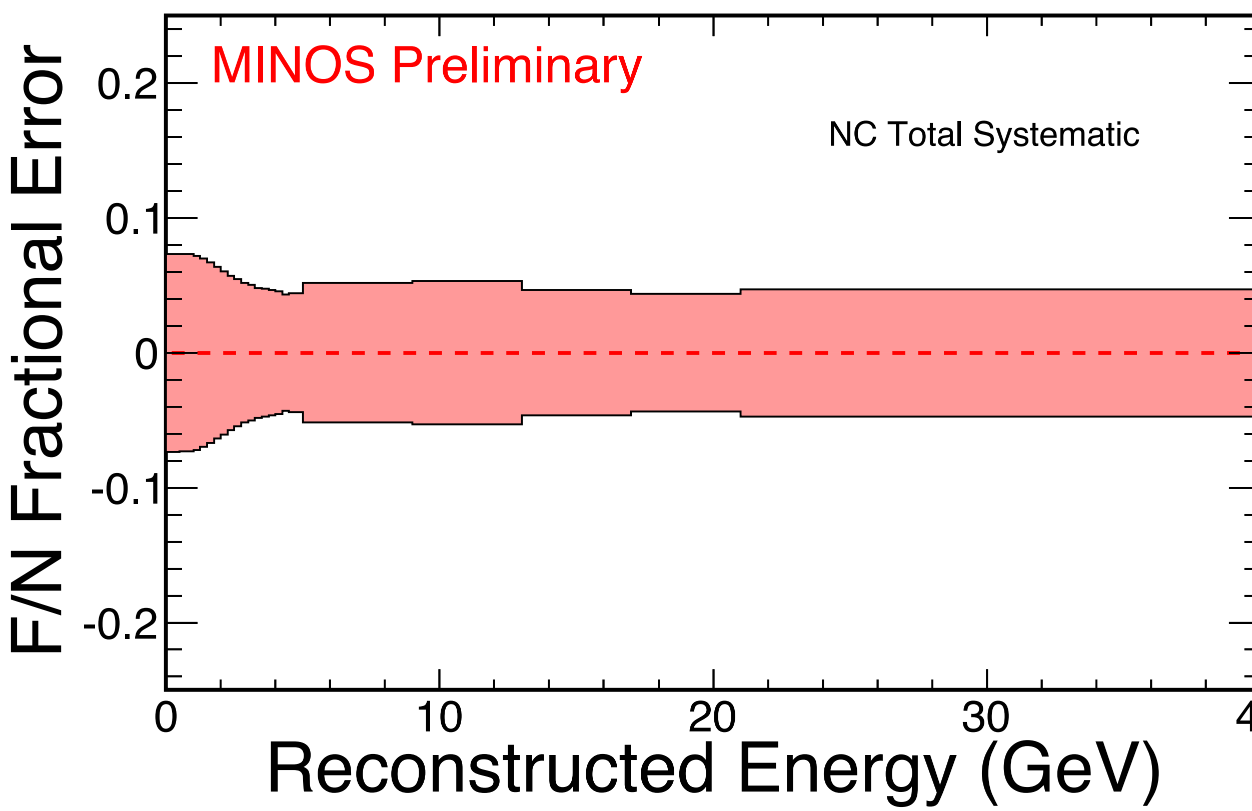
$o_i$ : Observed events in bin $i$

$e_i$ : Predicted events in bin $i$

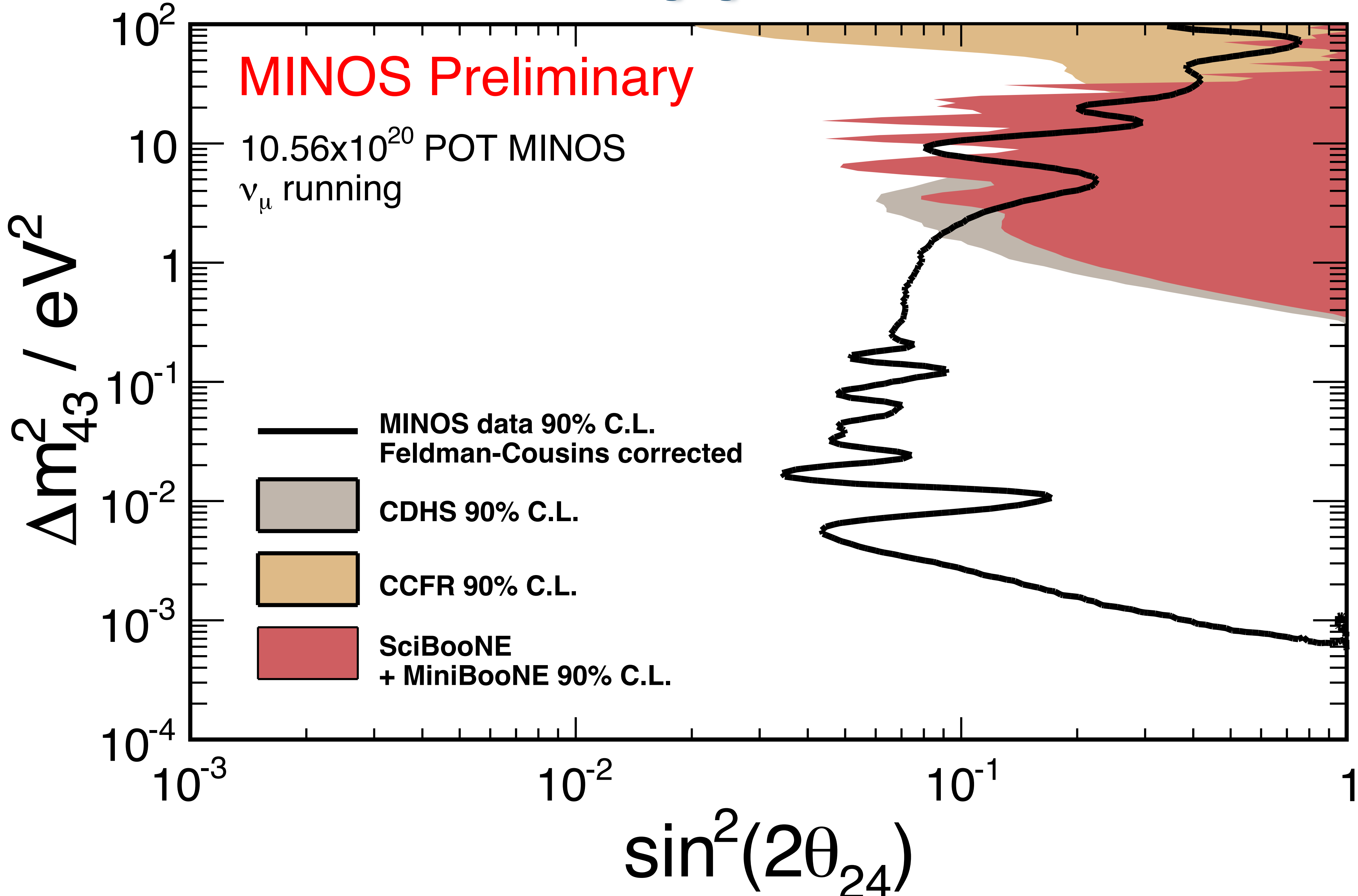
$V$ : Covariance matrix



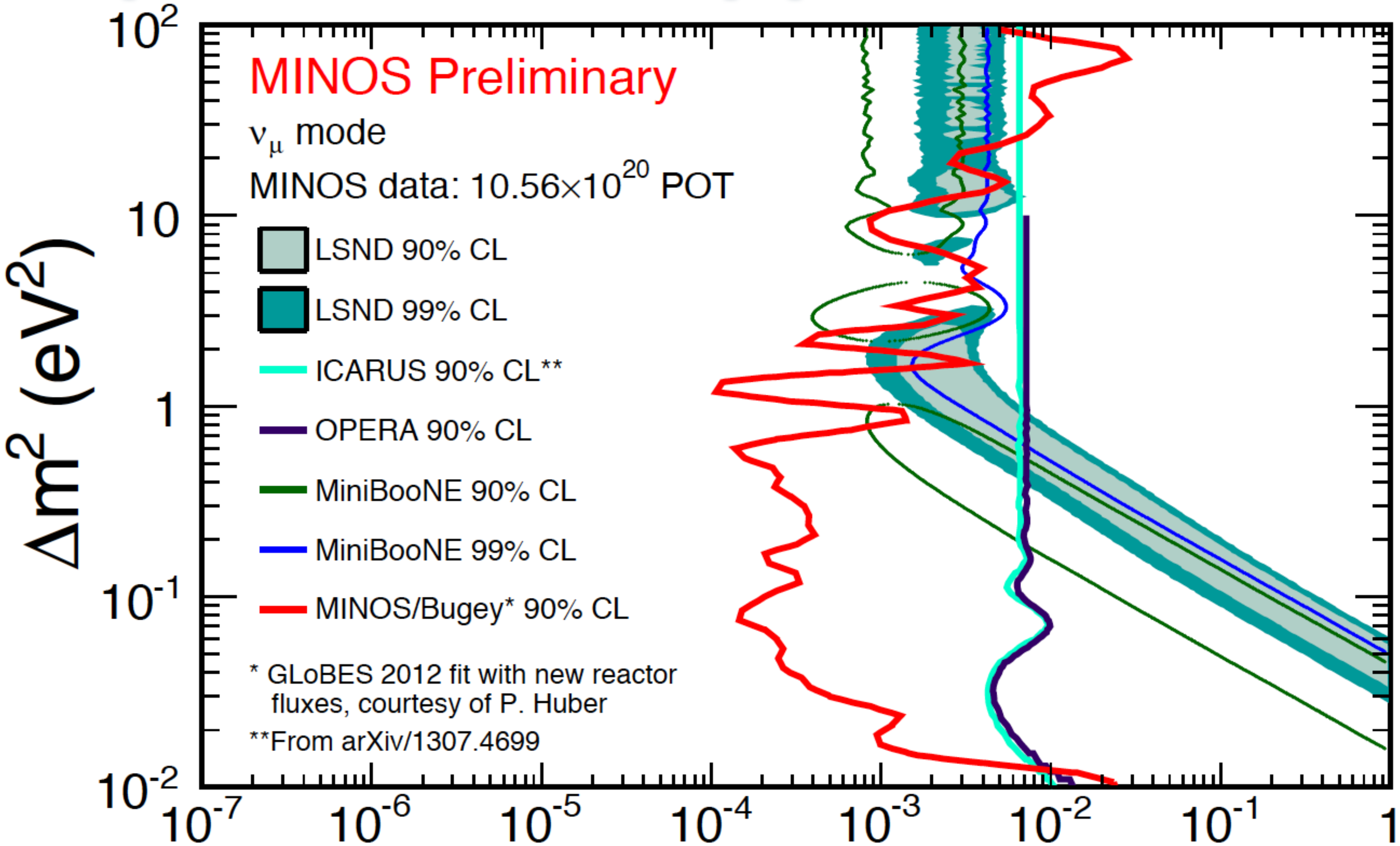
# MINOS Disappearance Limit




- Limit is Feldman-Cousins corrected

MINOS 90% C.L. exclusion limit ranges over 4 orders of magnitude in $\Delta m^2_{43}$!
Strongest constraint on $\nu_\mu$ disappearance into $\nu_s$ for $\Delta m^2_{43} < 1$ eV$^2$

# Comparison to Appearance Results

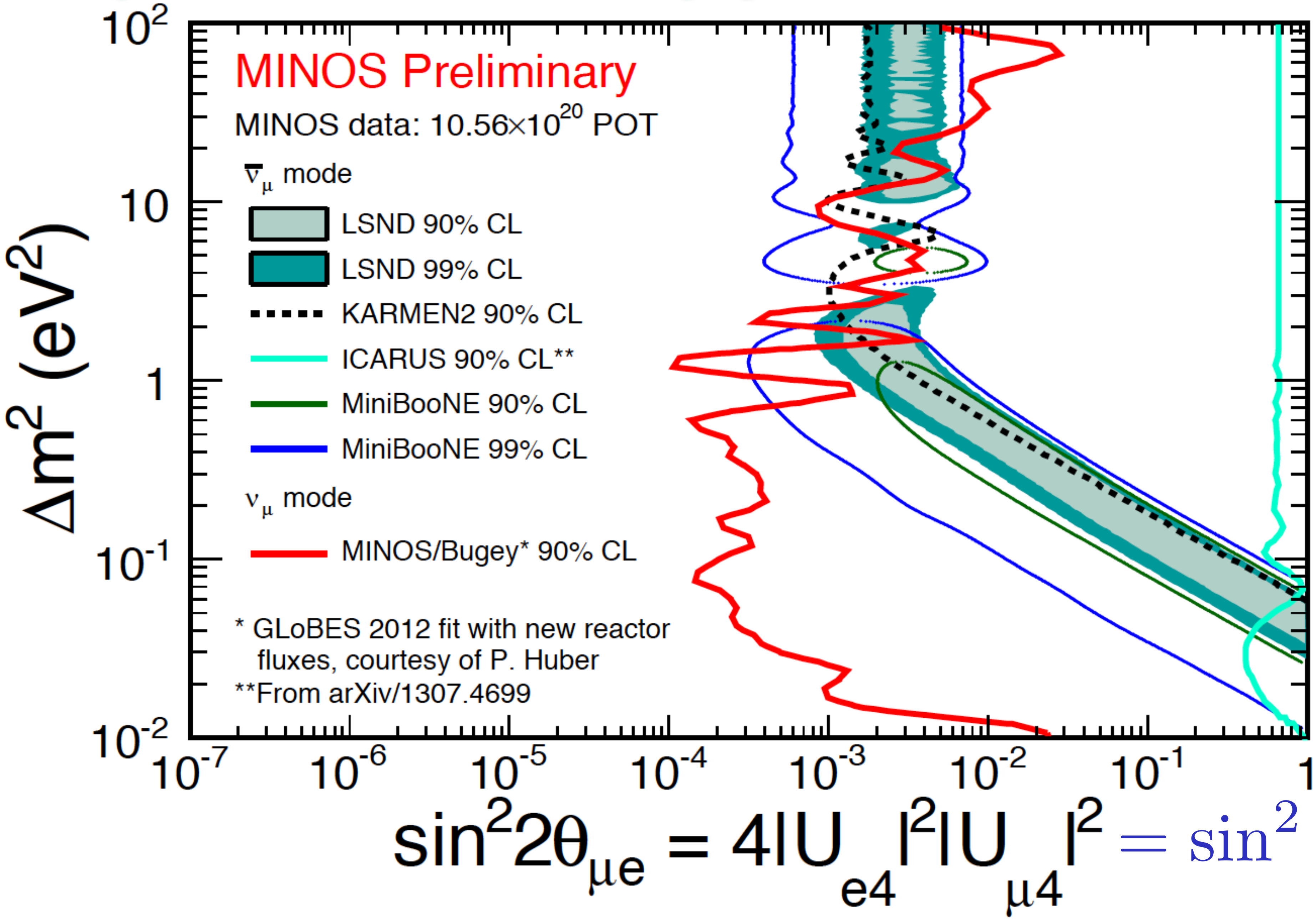



$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$

- **With MiniBooNE Neutrino Mode**
- Assuming 3+1 model, combine MINOS disappearance 90% C.L. limit in $\theta_{24}$ to Bugey reactor experiment 90% C.L. disappearance limit in $\theta_{14}$
- Working with Daya Bay to produce MINOS & Daya Bay combined limit
- 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 $\Delta m^2_{43} < 1\ \text{eV}^2$

# Comparison to Appearance Results



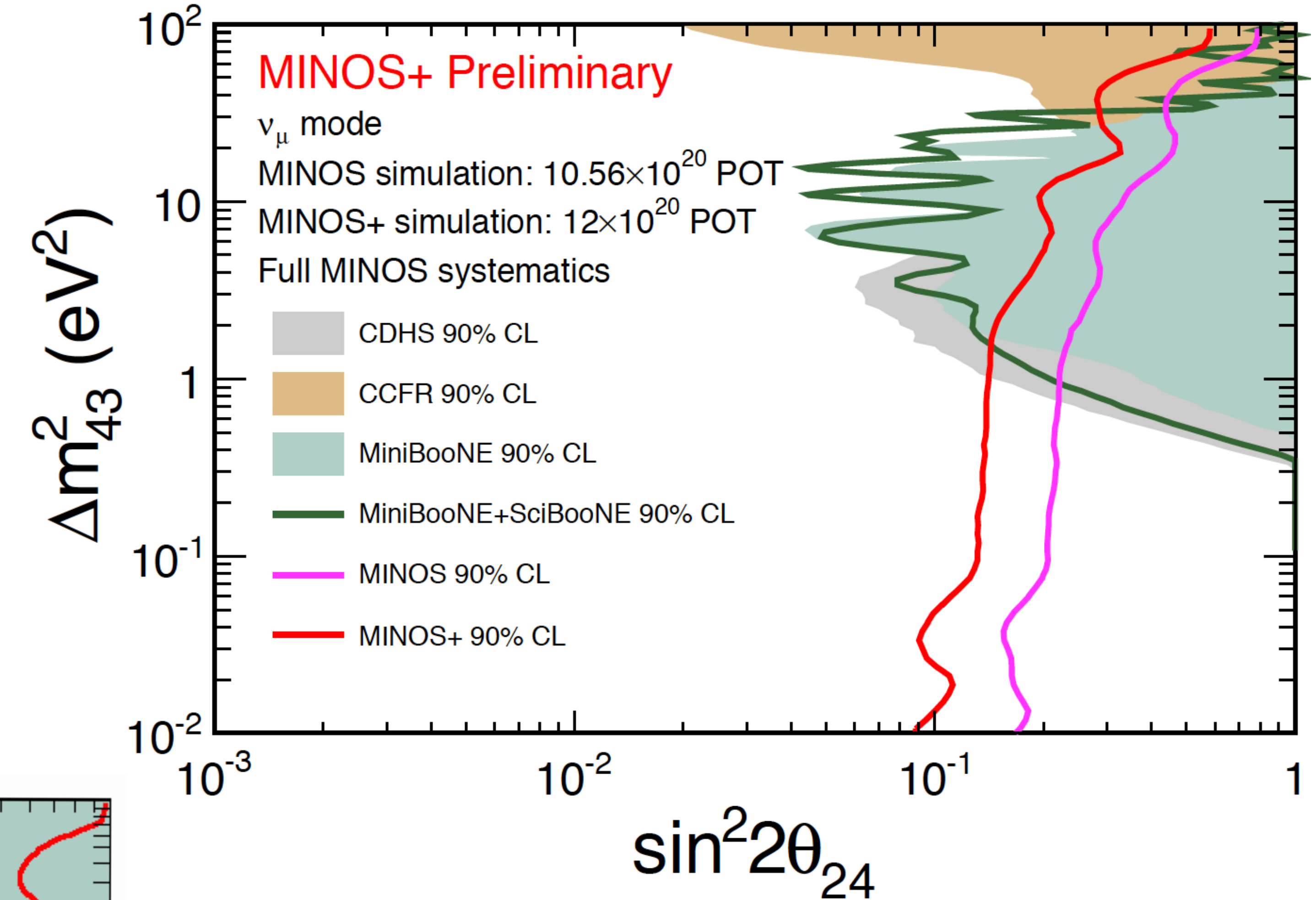

$= \sin^2 2\theta_{14} \sin^2 \theta_{24}$

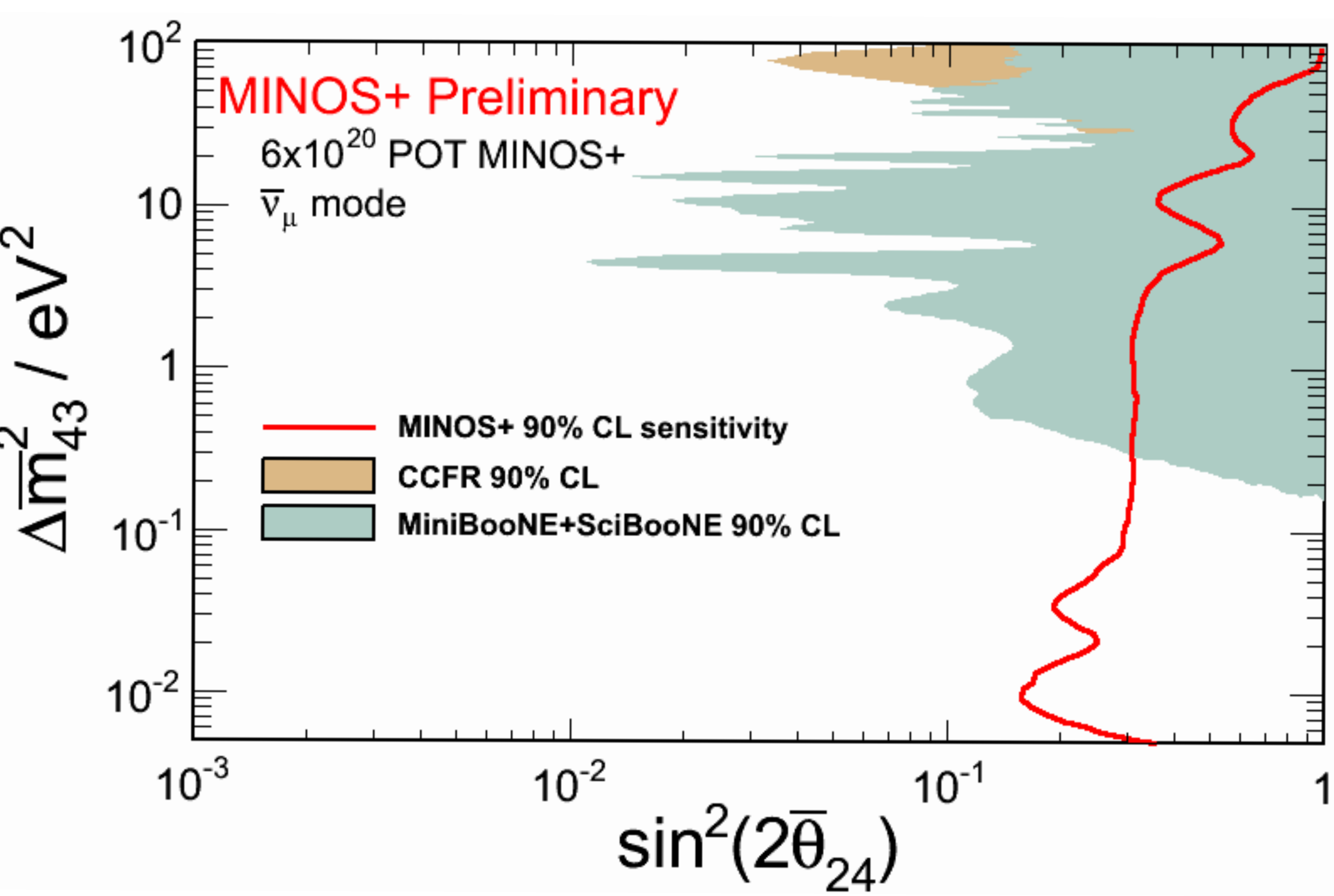
- **With MiniBooNE Antineutrino Mode**
- Assuming a 3+1 model and CPT conservation so SBL neutrino and antineutrino oscillations are identical
- Working on sterile neutrino search in $3.4\times10^{20}$ POT of MINOS antineutrino running

MINOS data increases tension between null and signal results for $\Delta m^2_{43} < 1$ eV$^2$

# Improvements with MINOS+

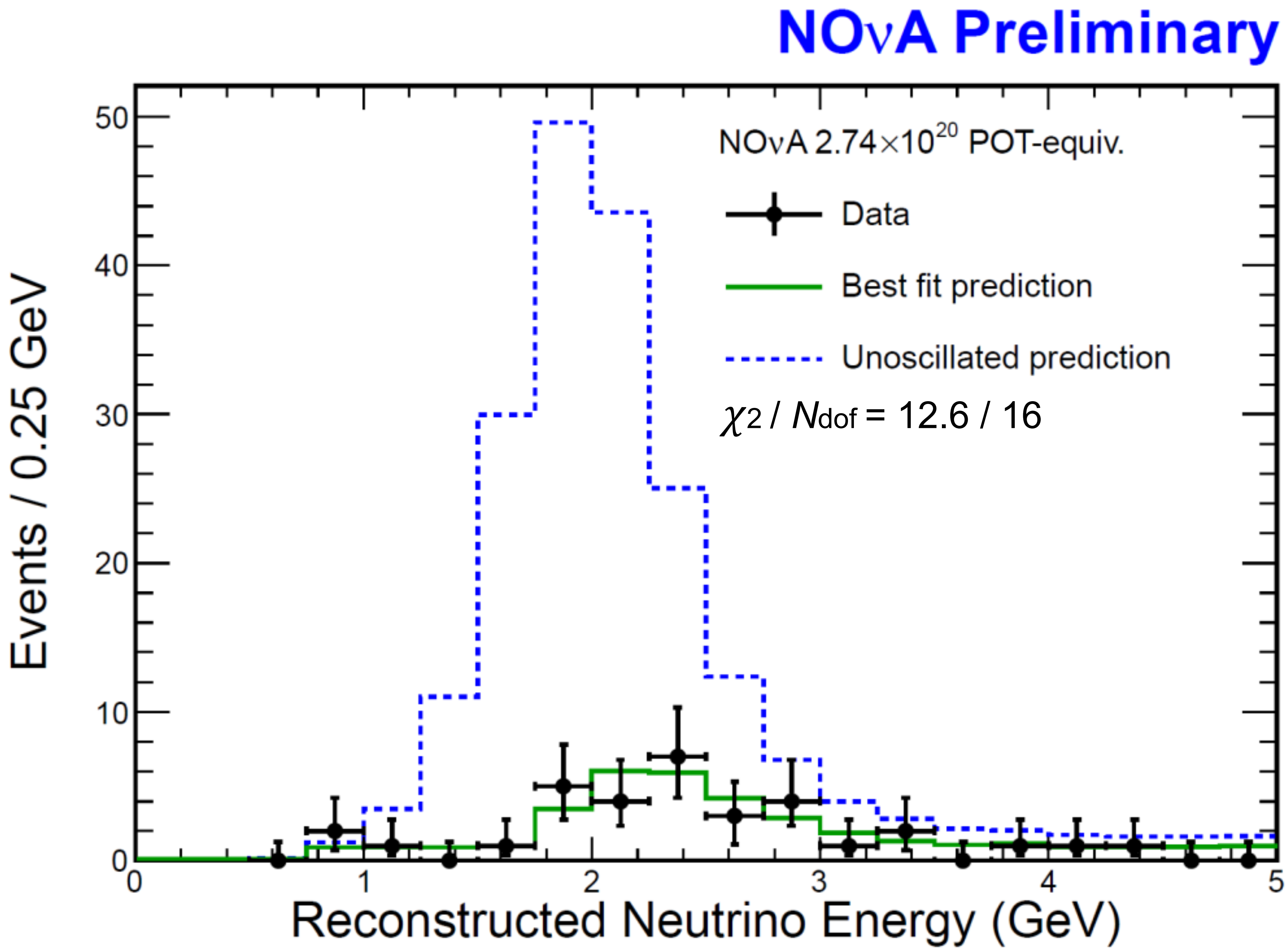
- MINOS+ vs MINOS disappearance limits by 2016, compared to SBL disappearance experiments




- Projected MINOS+ sensitivity to sterile neutrino mixing for 1 year of antineutrino running

# What about NOvA?

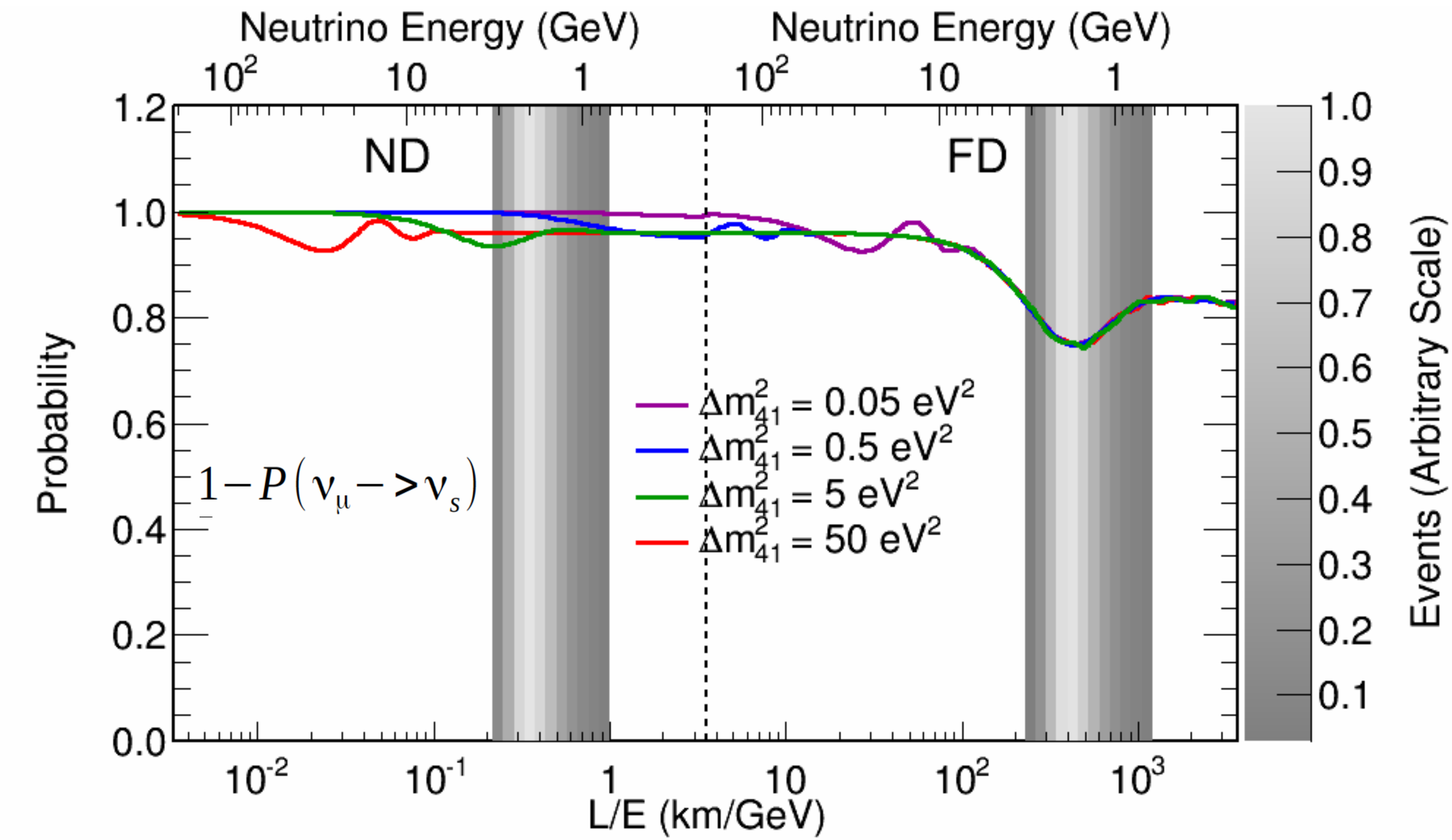



- **201 events predicted** without neutrino oscillations (including 2.0 beam bkgnd and 1.4 cosmic bkgnd)

**33 events observed**

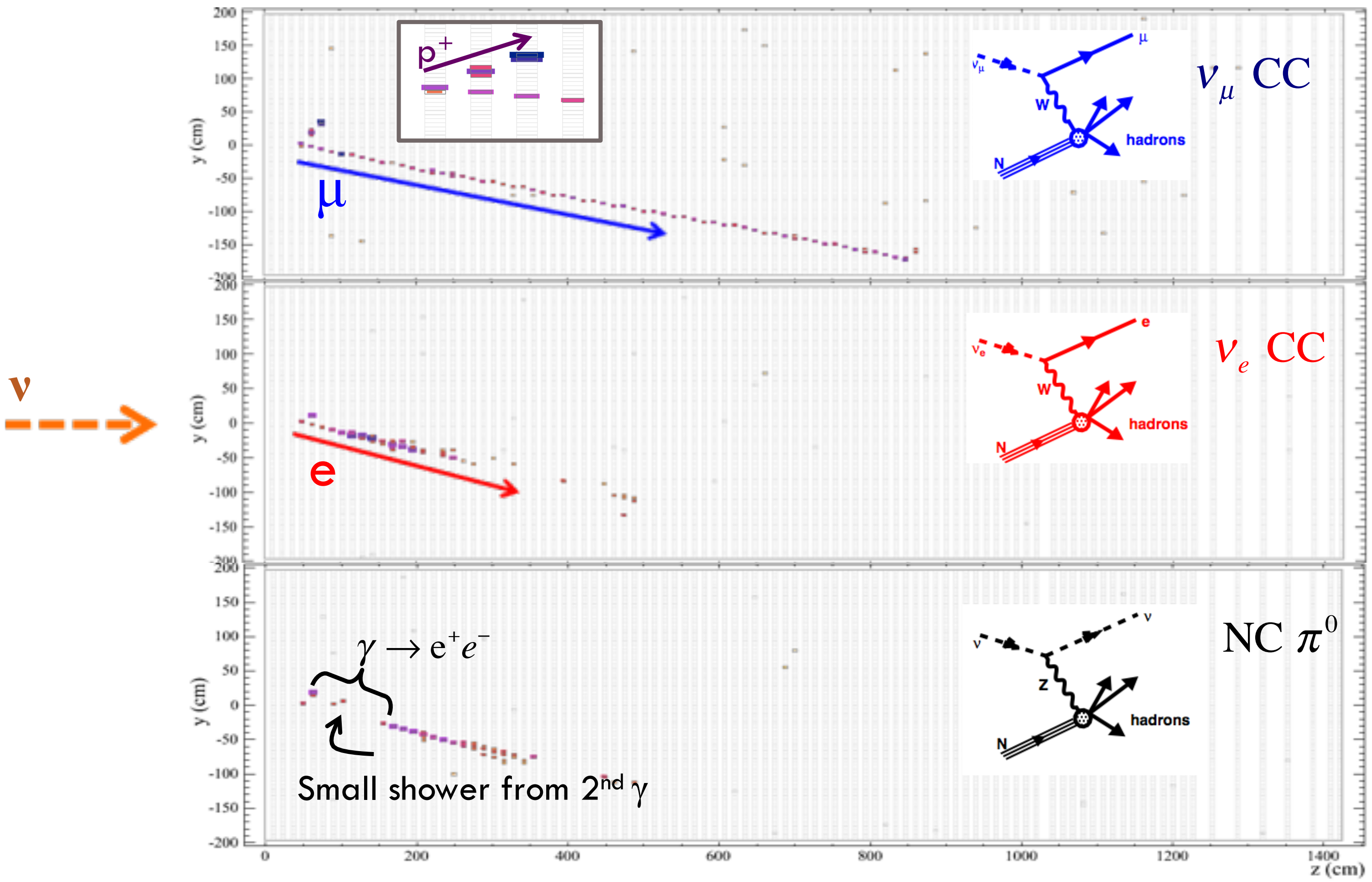
- CC events at the FD highly suppressed by 3-flavor oscillations, and absence of high energy tail limits range of $\Delta m^2_{43}$ that can be probed.
- However, NC events will be the largest sample measured by NOvA

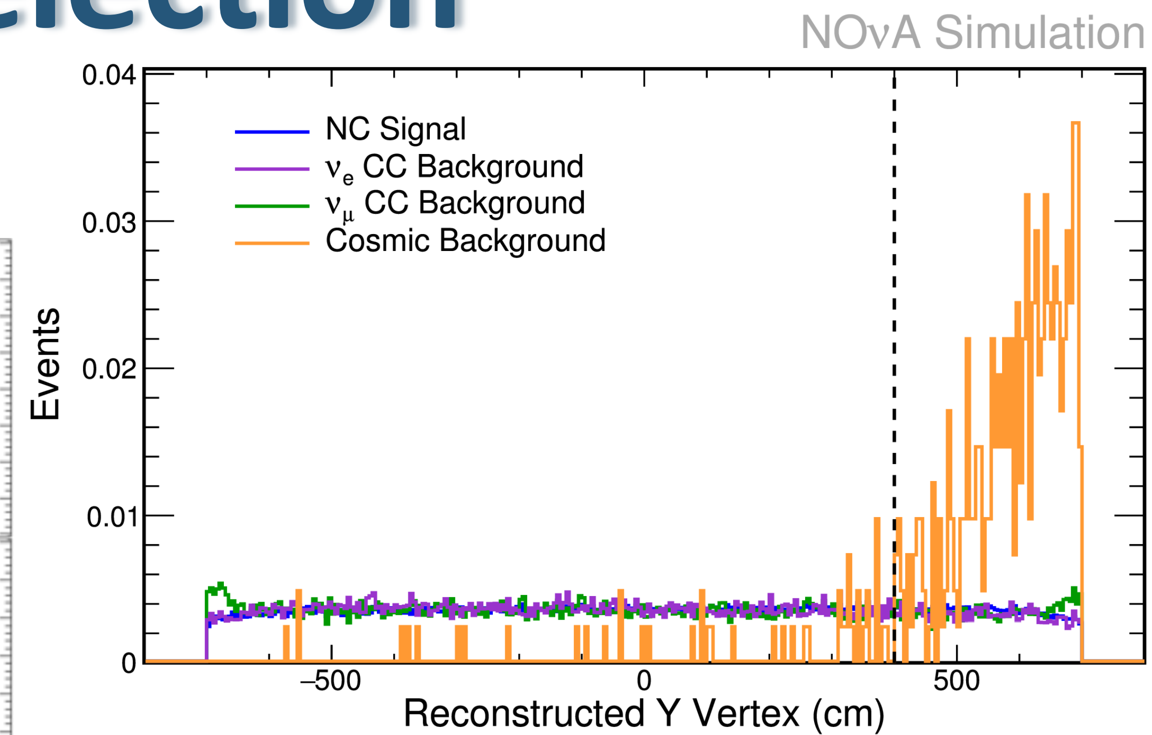
# NOvA NC Disappearance due to $\nu_\mu \rightarrow \nu_s$ Mixing

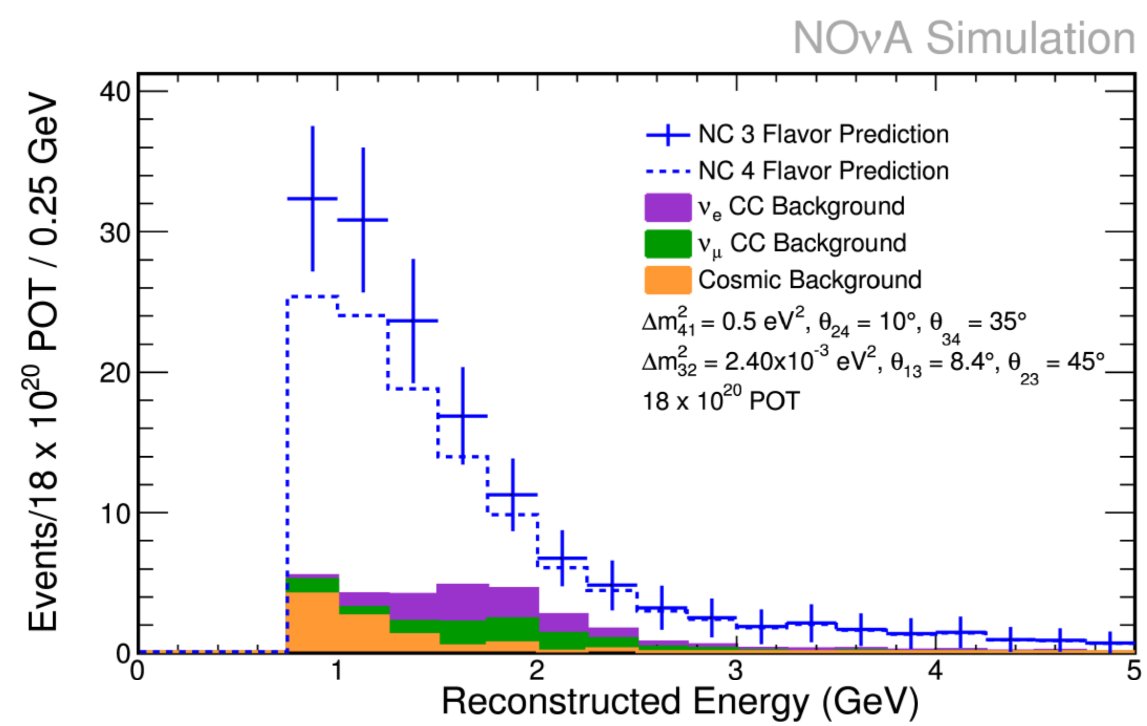



- For first analysis, will assume $\Delta m^2_{41} < 0.5$ eV$^2$, so that we have no oscillations at the ND, but rapid oscillations average out at the FD

# NOvA NC Selection



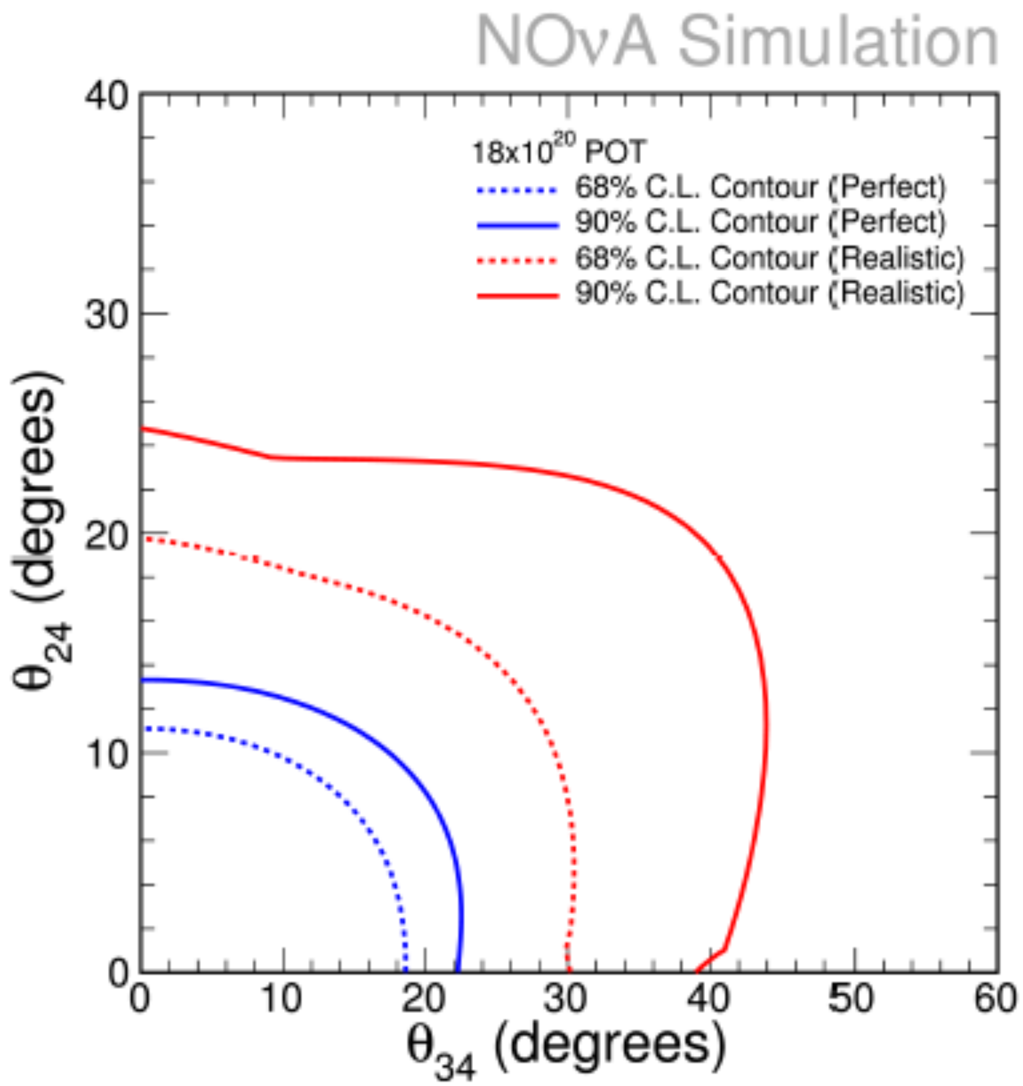

- Main challenge for NC analysis is cosmic neutron interactions in the upper part of the FD. Have developed preliminary cut-based NC selection:

- ND Purity = 63.4%; Efficiency [All cuts/(DQ+Fid.)] = 32.2%
- FD Purity = 69.3% or 83.6% without cosmics; Efficiency [All cuts/(DQ+Fid.)] = 13.5%

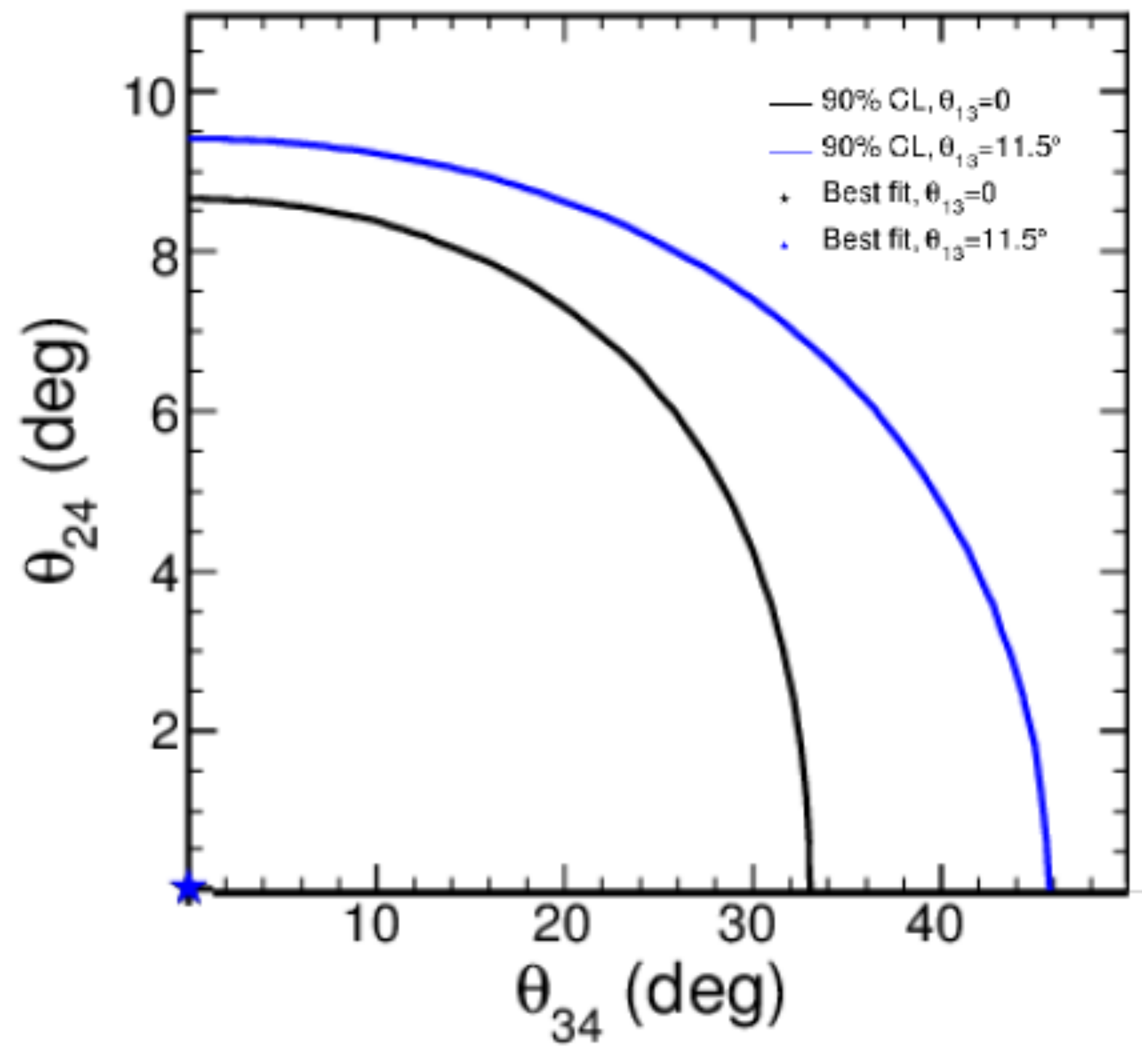
# NOvA Sensitivities vs MINOS

- For 3 years of NOvA neutrino running

MINOS: Phys. Rev. Lett. 107, 011802

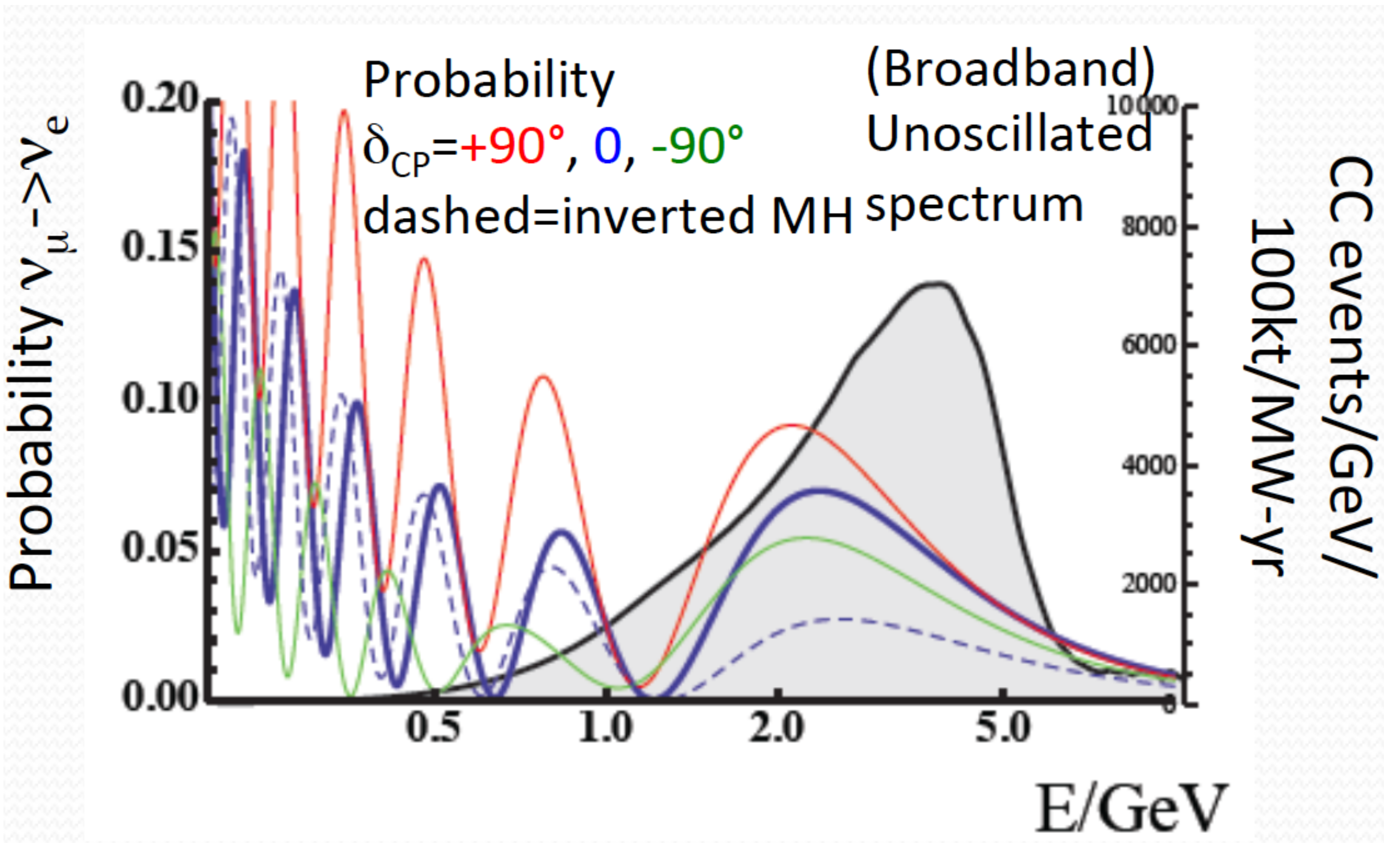


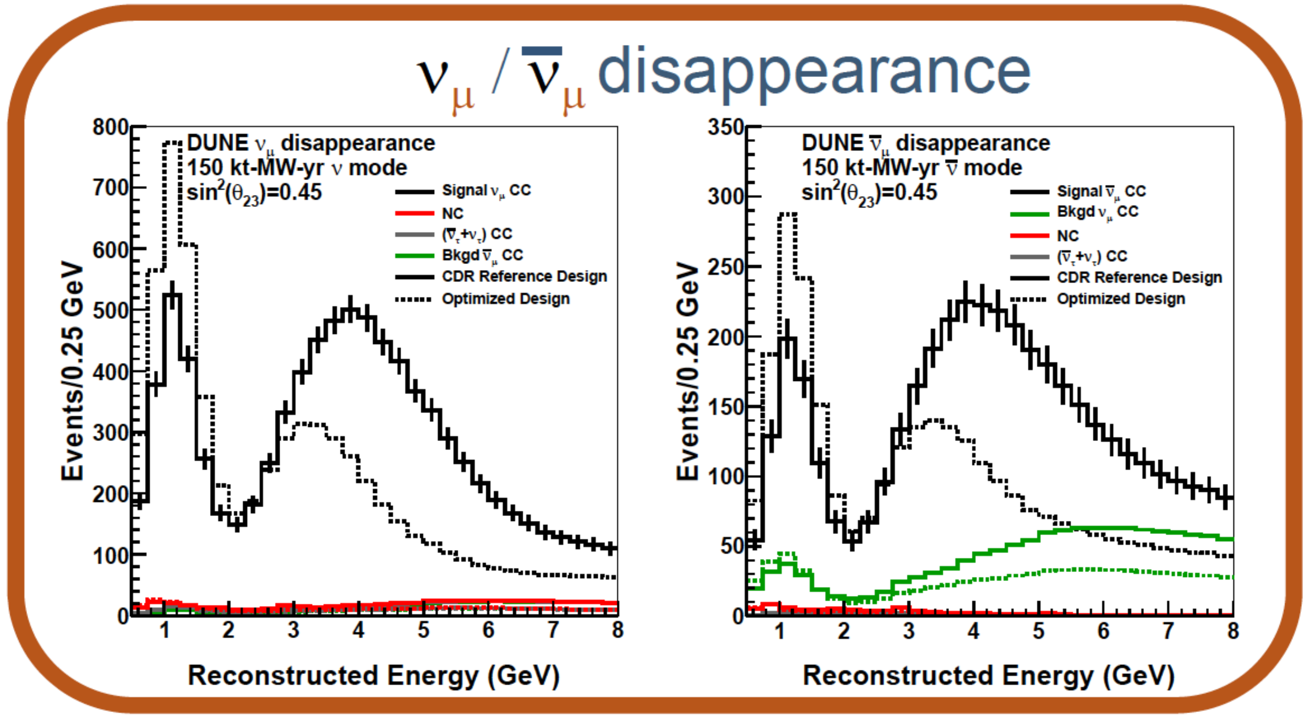

Presented at DPF2015




- NOvA plot shows constraints on $\theta_{24}$ and $\theta_{34}$ for the cut-based NC selection compared with prediction using a perfect NC selection

# Brief Thoughts on DUNE Sterile Searches

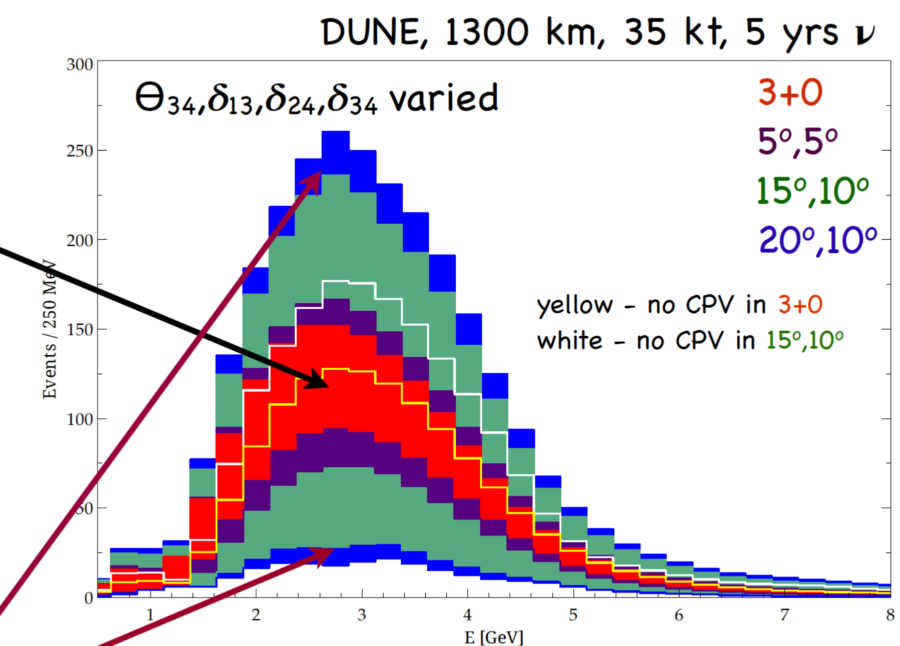



- On-axis broadband beam will confer DUNE sensitivity over a wide range of sterile neutrino masses
- NC channel provides a 3-flavor-independent handle on sterile-induced $\nu_\mu$ disappearance
- Underground detector, exquisite NC/CC separation, and 1.2 MW beam provide much more powerful sensitivity than MINOS
- Can also do SBL searches for $\nu_e$ appearance using the ND, FD atmospherics, Xtra Dimens.

The 3+1 band can potentially encompass the 3+0 band, leading to substantial degeneracy.

For large active-sterile mixings, an excess or shortage of events, esp. at osc. max. will be pointers to the existence of new physics.




$\Theta_{12}$ = 33.48°, $\Theta_{13}$ = 8.5°, $\Theta_{23}$ = 45°

$\Delta m^2_{31}$ = +2.457e-3 eV$^2$, $\Delta m^2_{21}$ = 7.5e-5 eV$^2$

R. Gandhi, B. Kayser, M. Masud, S. Pakrash, arXiv:1508.06275

# Summary

- Long-baseline sterile neutrino searches complement current and future SBL searches, and provide unique sensitivity to large portions of parameter space and sterile mixing matrix elements such as $|U_{\tau 4}|^2$
- DUNE should have powerful sensitivity to sterile mixing over long-baselines. Sensitivity to $\nu_e$ appearance at the ND should be investigated. FD atmospheric searches à la SuperK also possible.
- NC disappearance channel should offer a handle in disentangling CP violation from light sterile neutrino admixture, assuming Fermilab's SBL program would have not fully excluded that possibility by then.

# Backup

# 3+1 Oscillations

$$P(\nu_a \to \nu_b) = \delta_{ab} - 4\sum_{j>i} \mathcal{R}(U^*_{aj}U_{bj}U_{ai}U^*_{bi}) \sin^2\Delta_{ji} + 2\sum_{j>i} \mathcal{I}(U^*_{aj}U_{bj}U_{ai}U^*_{bi}) \sin 2\Delta_{ji}$$

$$\begin{aligned}
P_{\nu_\mu\to\nu_\mu} &= 1 - 4\Big\{|U_{\mu3}|^2(1-|U_{\mu3}|^2-|U_{\mu4}|^2)\sin^2\Delta_{31} + |U_{\mu4}|^2|U_{\mu3}|^2\sin^2\Delta_{43} \\
&\quad + |U_{\mu4}|^2(1-|U_{\mu3}|^2-|U_{\mu4}|^2)\sin^2\Delta_{41}\Big\}, \\
P_{\nu_\mu\to\nu_\alpha} &= 4\mathcal{R}\Big\{|U_{\mu3}|^2|U_{\alpha3}|^2\sin^2\Delta_{31} + |U_{\mu4}|^2|U_{\alpha4}|^2\sin^2\Delta_{41} \\
&\quad + U^*_{\mu4}U_{\alpha4}U_{\mu3}U^*_{\alpha3}(\sin^2\Delta_{31} - \sin^2\Delta_{43} + \sin^2\Delta_{41})\Big\} \\
&\quad + 2\mathcal{I}\Big\{U^*_{\mu4}U_{\alpha4}U_{\mu3}U^*_{\alpha3}(\sin 2\Delta_{31} - \sin 2\Delta_{41} + \sin 2\Delta_{43})\Big\},
\end{aligned}$$

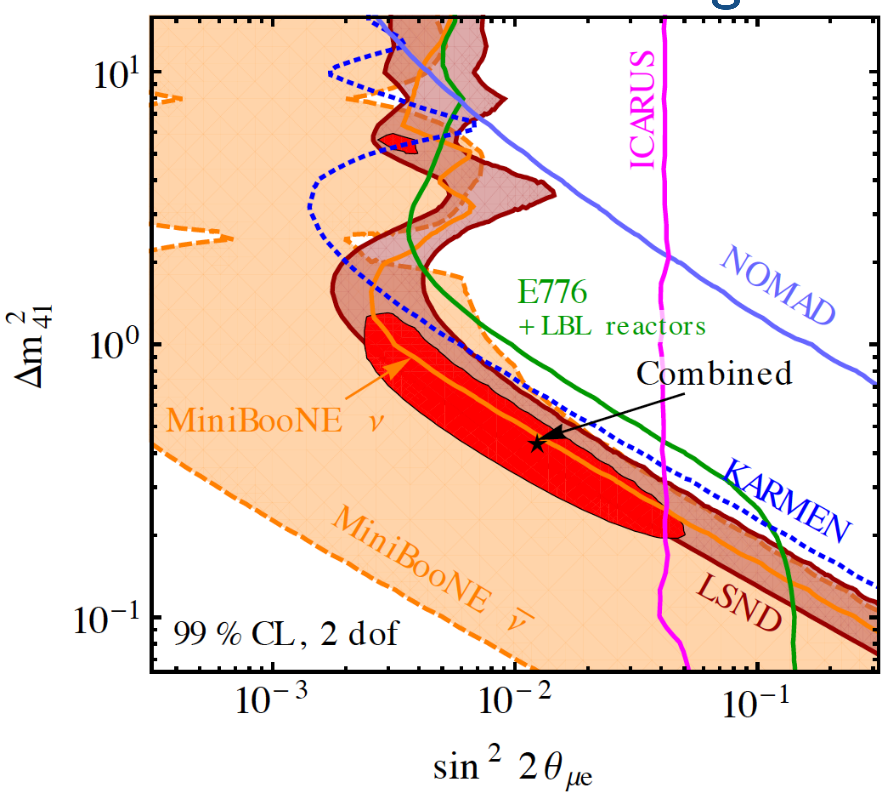
# 3+1 Oscillations

$$
\begin{aligned}
|U_{e3}|^2 &= c_{14}^2 s_{13}^2, \\
|U_{e4}|^2 &= s_{14}^2, \\
|U_{\mu3}|^2 &= s_{13}^2 s_{14}^2 s_{24}^2 + c_{13}^2 s_{23}^2 c_{24}^2 - \frac{1}{2} s_{23} s_{14} \sin(2\theta_{13}) \sin(2\theta_{24}) \cos(\delta_1 + \delta_2), \\
|U_{\mu4}|^2 &= c_{14}^2 s_{24}^2, \qquad (8) \\
|U_{\tau3}|^2 &= s_{13}^2 s_{14}^2 c_{24}^2 s_{34}^2 + c_{13}^2 s_{23}^2 s_{24}^2 s_{34}^2 + c_{13}^2 c_{23}^2 c_{34}^2 + \frac{1}{2} s_{23} s_{14} s_{34}^2 \sin(2\theta_{13}) \sin(2\theta_{24}) \cos(\delta_1 + \delta_2) \\
&\quad - \frac{1}{2} c_{23} s_{14} c_{24} \sin(2\theta_{13}) \sin(2\theta_{34}) \cos\delta_1 - \frac{1}{2} c_{13}^2 s_{24} \sin(2\theta_{23}) \sin(2\theta_{34}) \cos\delta_2, \\
|U_{\tau4}|^2 &= c_{14}^2 c_{24}^2 s_{34}^2, \\
|U_{s3}|^2 &= s_{13}^2 s_{14}^2 c_{24}^2 c_{34}^2 + c_{13}^2 s_{23}^2 s_{24}^2 c_{34}^2 + c_{13}^2 c_{23}^2 s_{34}^2 + \frac{1}{2} s_{23} s_{14} c_{34}^2 \sin(2\theta_{13}) \sin(2\theta_{24}) \cos(\delta_1 + \delta_2) \\
&\quad + \frac{1}{2} c_{23} s_{14} c_{24} \sin(2\theta_{13}) \sin(2\theta_{34}) \cos\delta_1 + \frac{1}{2} c_{13}^2 s_{24} \sin(2\theta_{23}) \sin(2\theta_{34}) \cos\delta_2, \text{ and} \\
|U_{s4}|^2 &= c_{14}^2 c_{24}^2 c_{34}^2.
\end{aligned}
$$

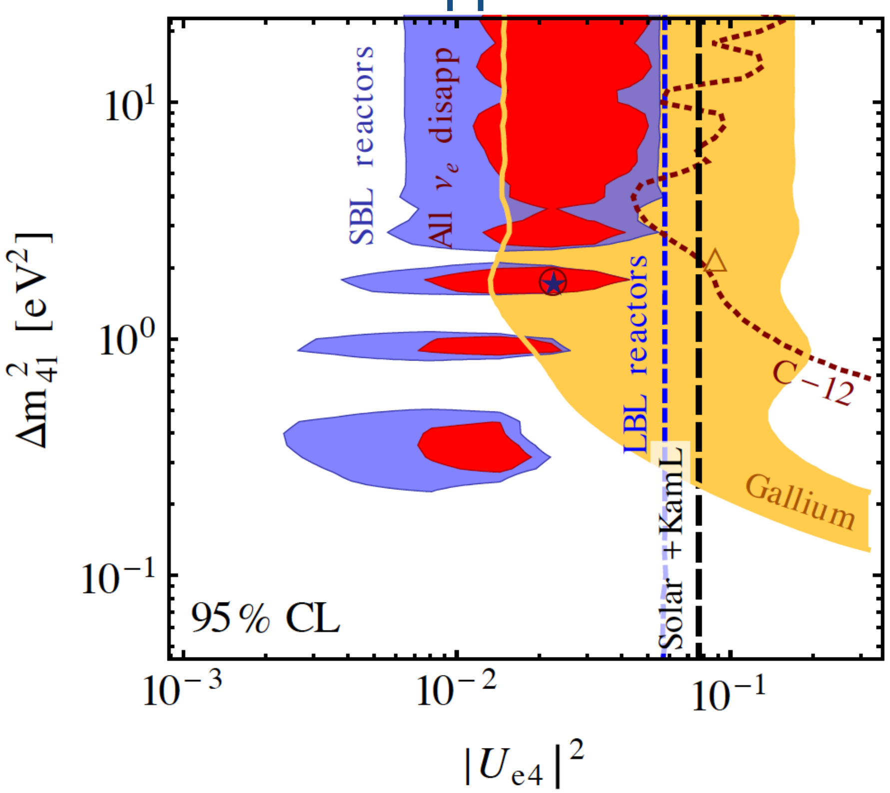
# Sterile Neutrinos

- Oscillations into light sterile neutrinos are a proposed explanation for anomalies seen in short-baseline accelerator experiments, reactor experiments (following re-evaluation of $\bar{\nu}_e$ reactor flux to be 3.5% higher), and from gallium anomaly
- Severe tension between appearance, and disappearance measurements or appearance measurements that see no signal

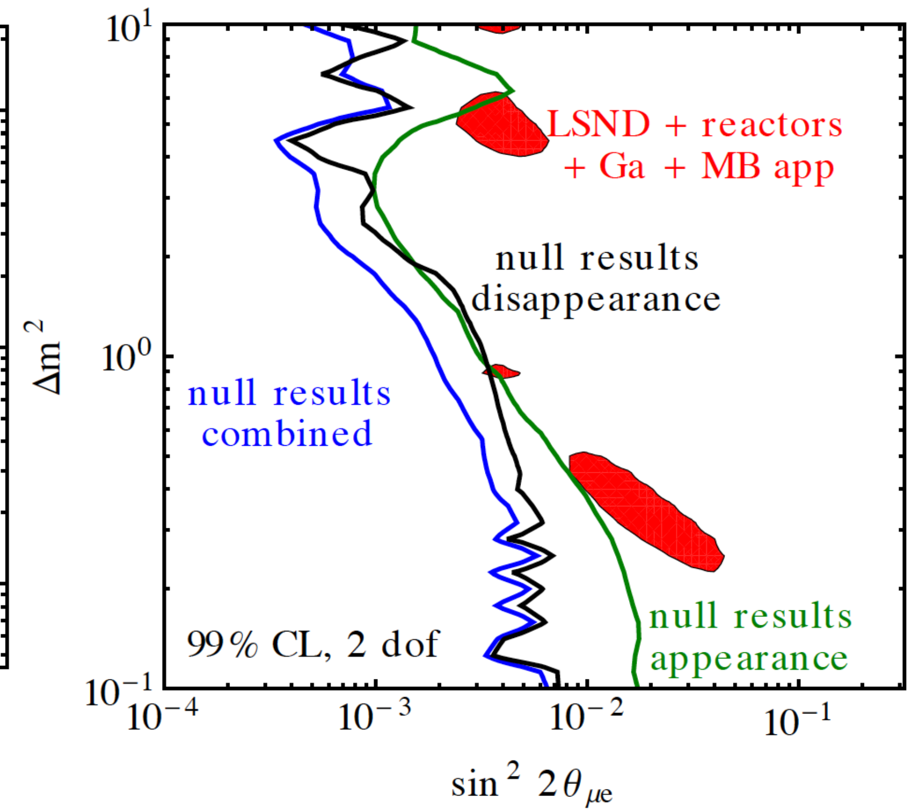
3+1 $\bar{\nu}_e$, $\nu_e$ SBL Appearance LSND/MiniBooNE Signal




3+1 $\bar{\nu}_e$, $\nu_e$ Reactor, Gallium Disappearance




3+1 Evidence vs No-Evidence

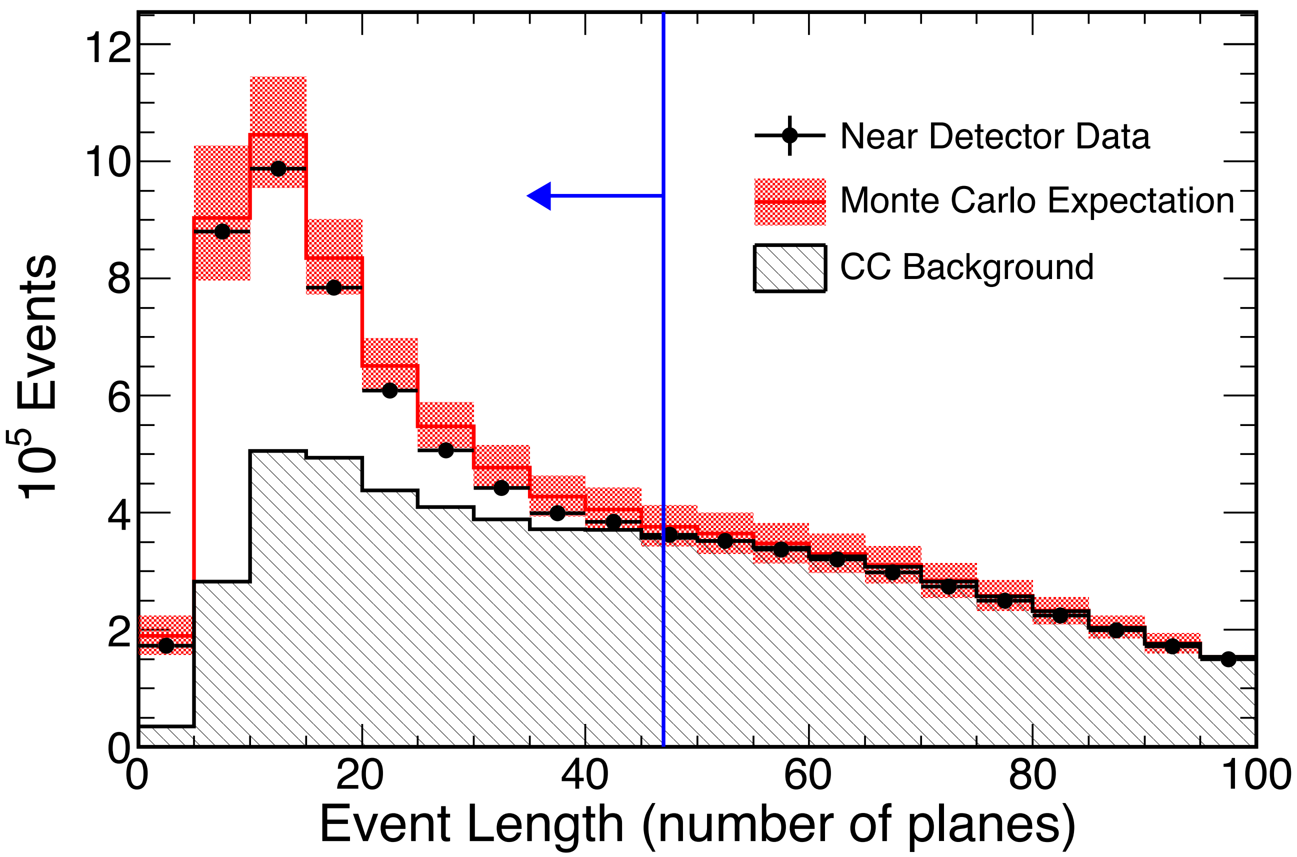


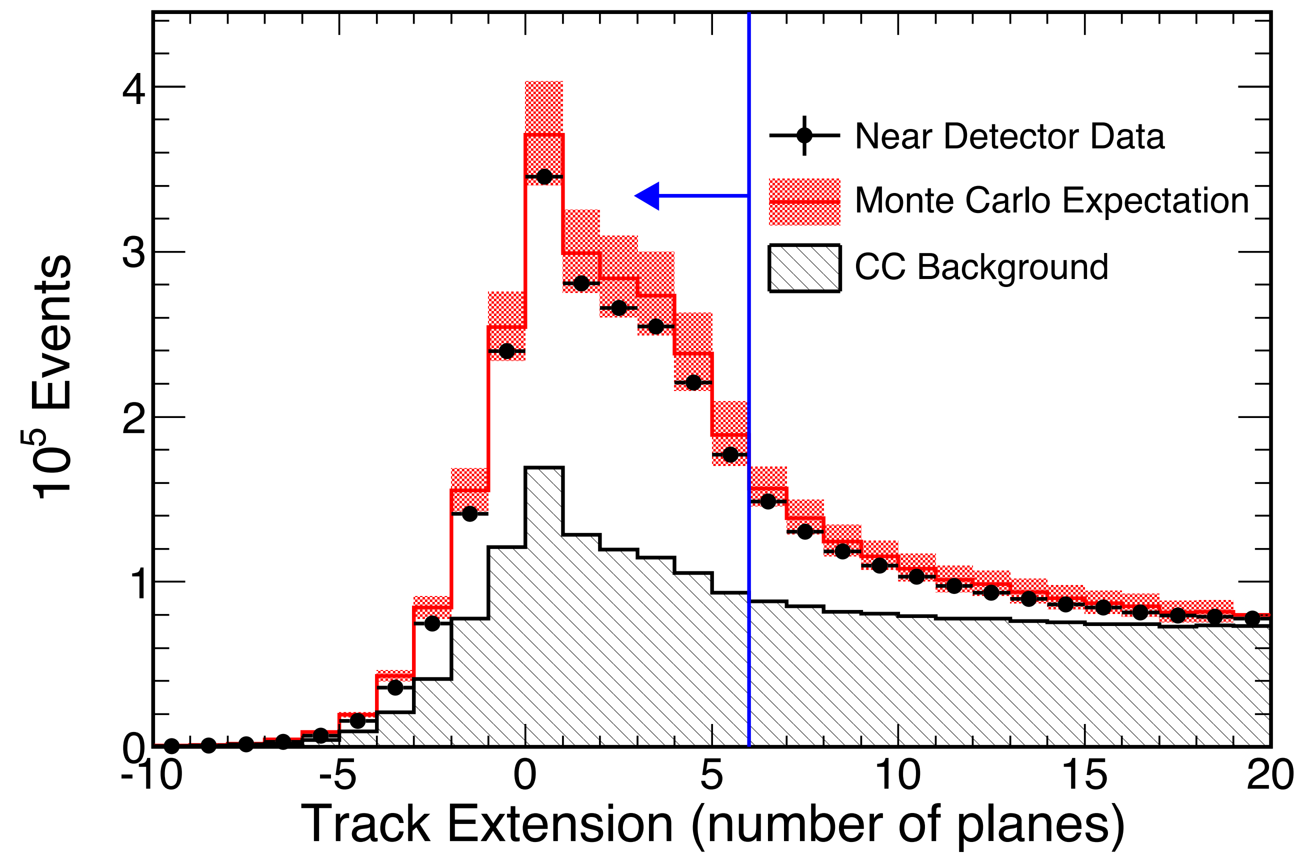

*Kopp, Machado, Maltoni, Schwetz, arXiv:1303.3011*

- Short and long-baseline accelerator, reactor, radioactive, and atmospherics experiments planned to resolve these anomalies over next 10-15 years

# MINOS NC Event Selection

- NC/CC event separation achieved via cuts on topological variables




- Discard events with length > 47 planes
- Discard events with a track > 6 planes longer than the shower

- Same selection applied to data and MC in Far Detector

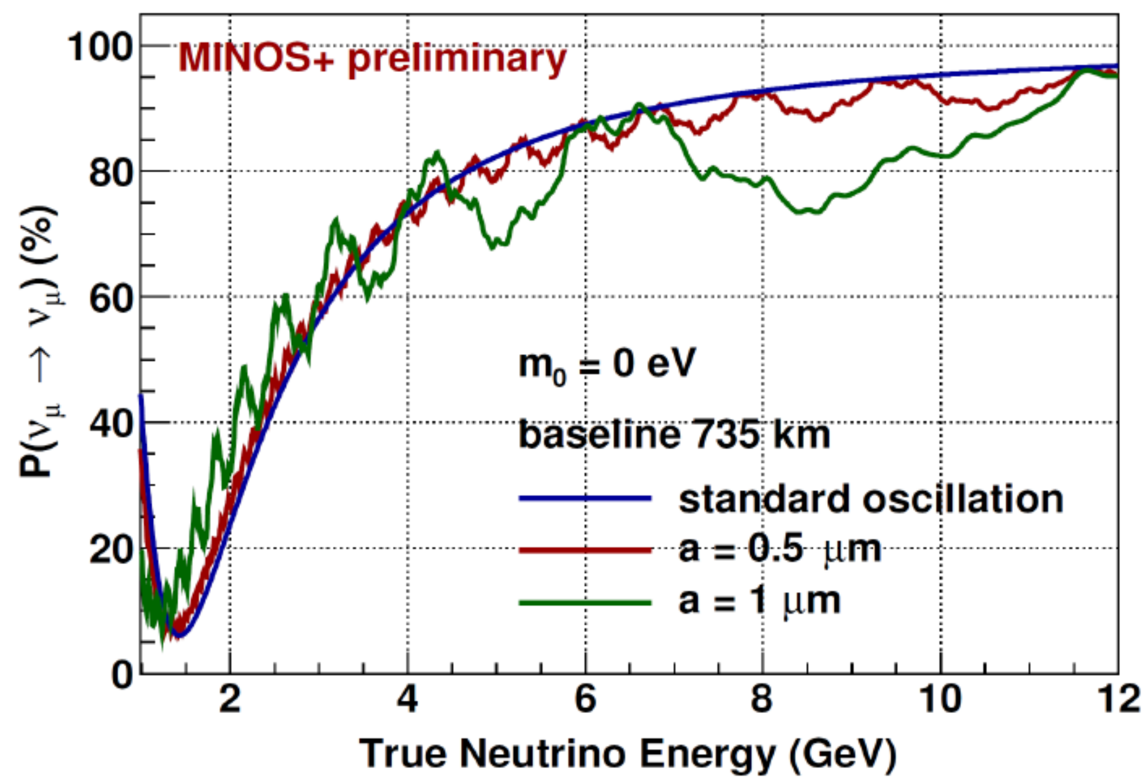
# MINOS NC Systematics

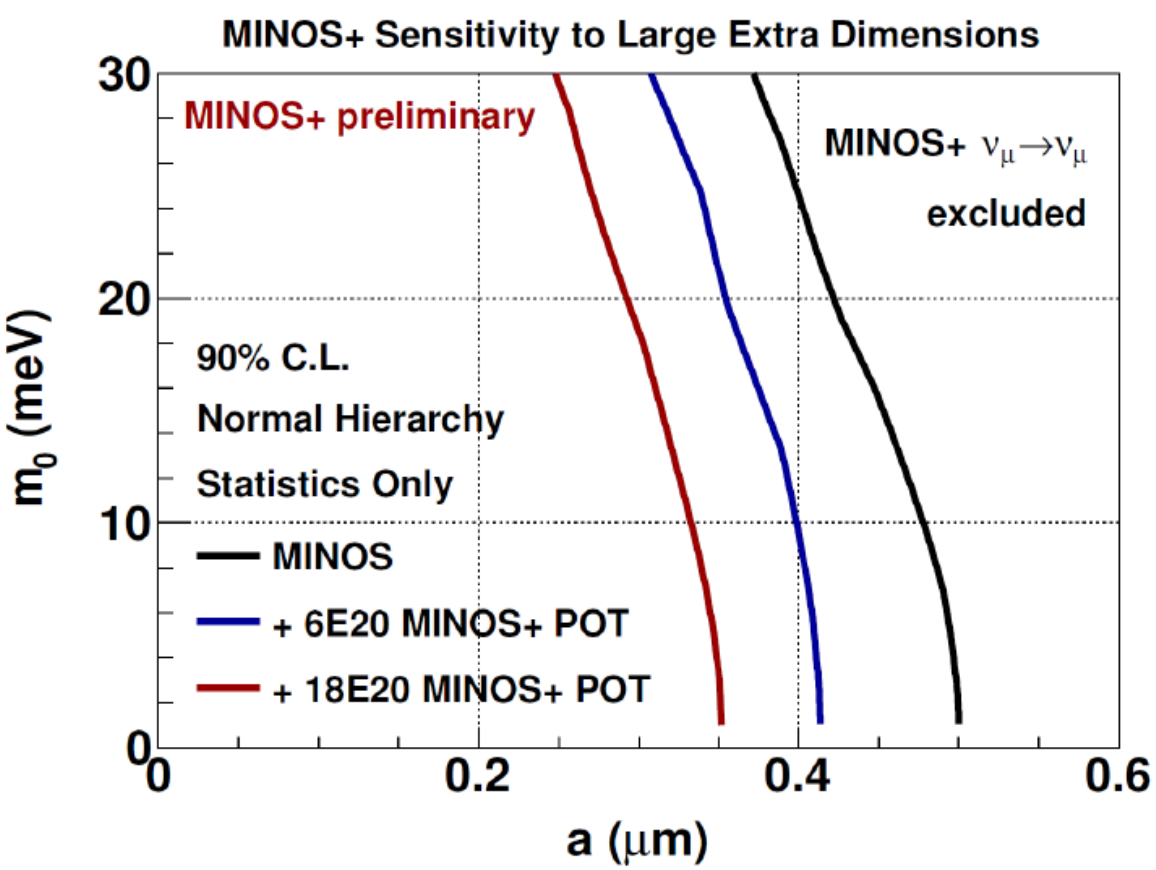
- Normalization: 2.2%
  - Livetime, Near/Far reconstruction efficiency, fiducial mass
- Relative Hadronic Calibration: 2.1%
  - Inter-Detector calibration uncertainty
- Absolute Hadronic Calibration: [±10%, ±6.5%]
  - Hadronic Shower Energy Scale(±5.6%), Intranuclear rescattering([±8%, ±4%] )
- Muon energy scale: 2%
  - Uncertainty in dE/dX in MC
- CC Contamination of NC-like sample: ±15%
- NC contamination of CC-like sample: ±25%
- Cross-section uncertainties:
  - $m_A$ (QE) and $m_A$ (Res): ±15%
  - KNO scaling: ±33%
- Near Detector NC Selection: ±10% in 0-1 GeV bin
- Far Detector NC Selection: ±5% if E < 1 GeV, <2.5% if E > 1 GeV
- Beam uncertainty: 1σ error band around beam fit results

Effect of largest uncertainties on *R*

| Uncertainty | $\Delta R$ (0-120 GeV) |
|---|---|
| Absolute $E_{\text{Hadronic}}$ | 0.4% |
| Relative $E_{\text{Hadronic}}$ | 0.0% |
| Normalization | 3.2% |
| CC Background | 2.1% |
| ND Selection | 2.7% |
| FD Selection | 2.5% |
| Total | 5.3% |

# MINOS+ Sensitivity to Extra-Dimensions



# MINOS+ Decay, Decoherence