Sterile Neutrino Search at MINOS

New Perspective 2016

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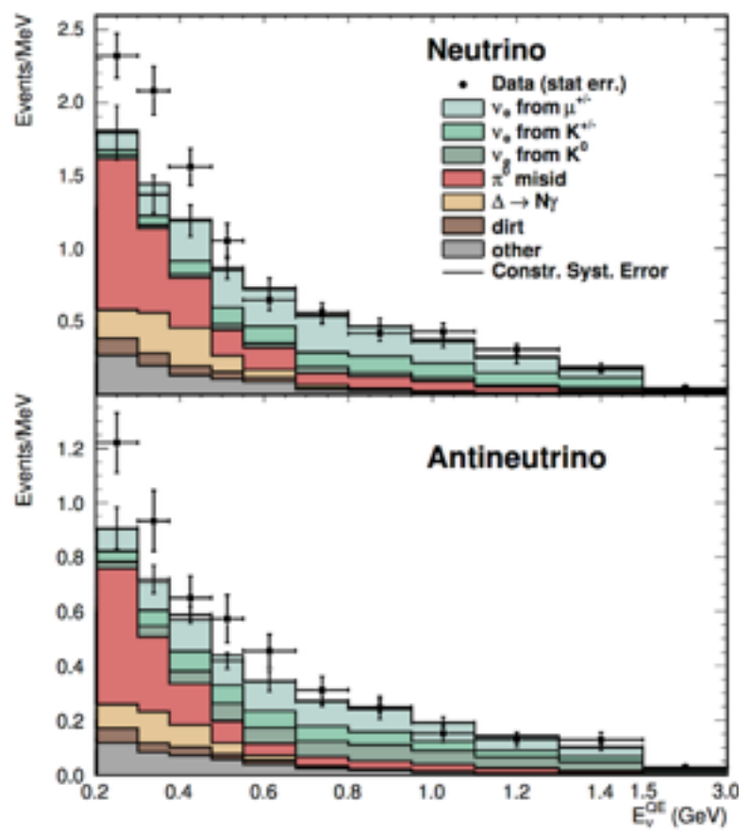
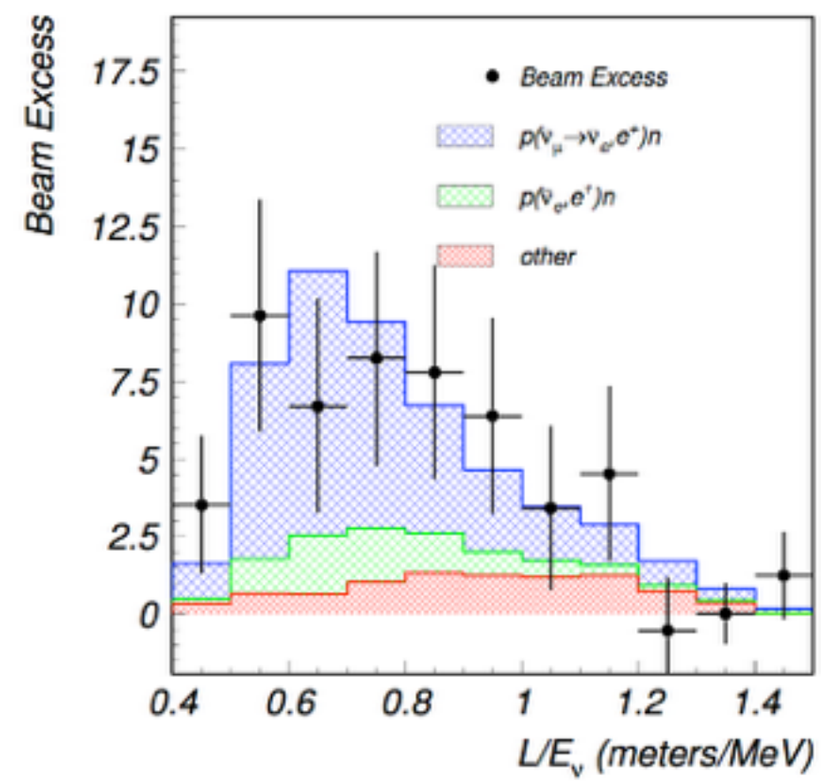
on behalf of the MINOS/MINOS+ collaboration

Why sterile?

- Both LSND and MiniBooNE have reported low energy excesses of electron (anti)neutrinos
- We know it's sterile because LEP's measurement for Z boson's decay width ⇒ Three active neutrinos





MiniBooNE reconstructed energy distribution (left) and LSND L/E distribution (right) [1][2][3]

[1] A. Aguilaret al.(LSND Collaboration), Phys.Rev.D64, 112007 (2001), arXiv:hep-ex/0104049 [hep-ex].
[2] A. Aguilar-Arevaloet al.(The MiniBooNE Collaboration), Phys.Rev.Lett.105, 181801 (2010),arXiv: 1007.1150 [hep-ex].
[3] A. Aguilar-Arevaloet al.(MiniBooNE Collaboration), Phys.Rev.Lett.102, 101802 (2009),arXiv: 0812.2243 [hep-ex].

But!

- They are looking for ν_e appearance in ν_μ beam.
- The L/E ~ 1 km/GeV → Δm^2_{41} ~ 1 eV^2

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

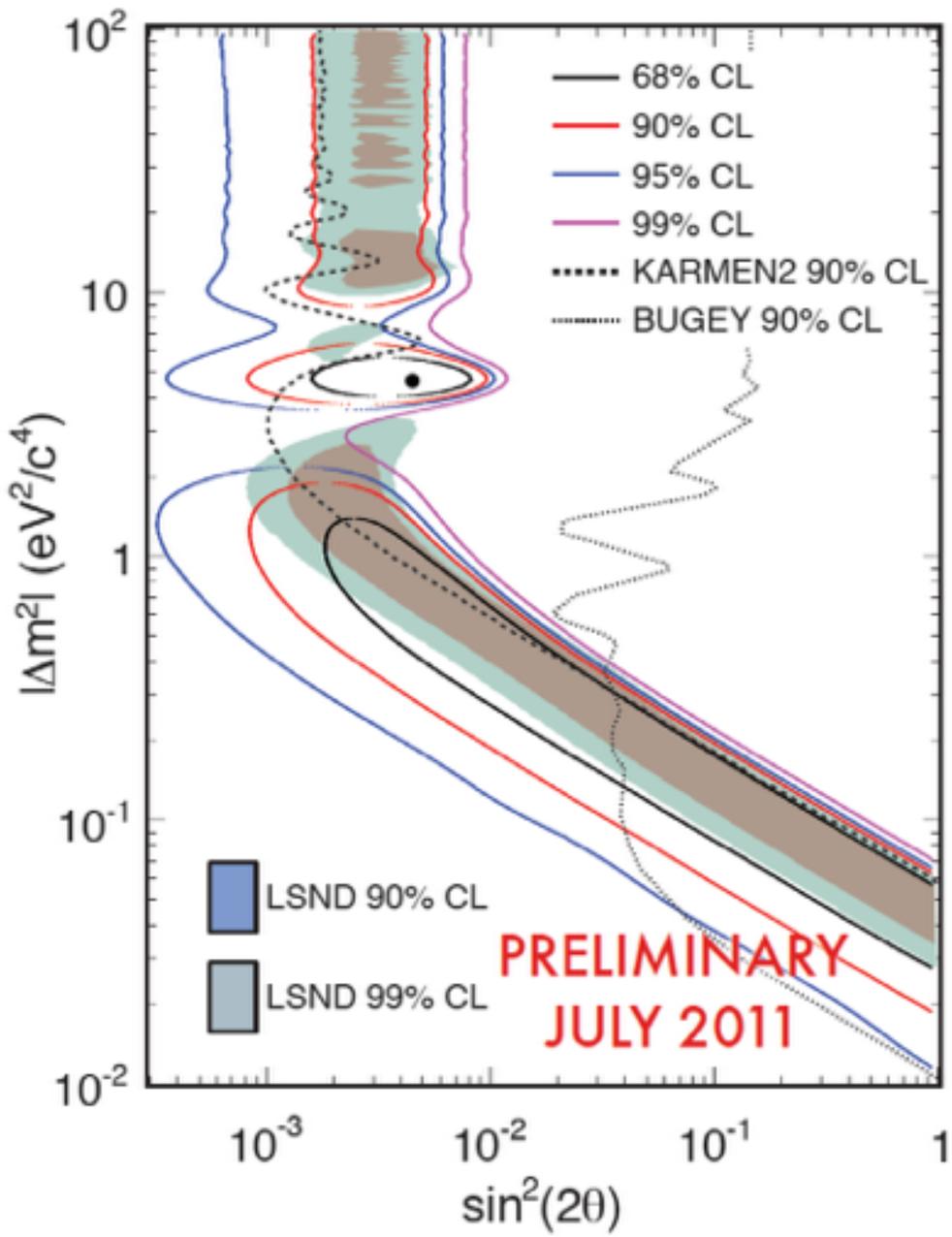
amplitude of oscillations

energy dependence of oscillations

$$\Delta_{41} = \frac{\Delta m^2_{41} L}{4 E_\nu}$$

$$P(\nu_\mu \to \nu_e) = 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2 \Delta_{41}$$

LSND and MiniBooNE limits



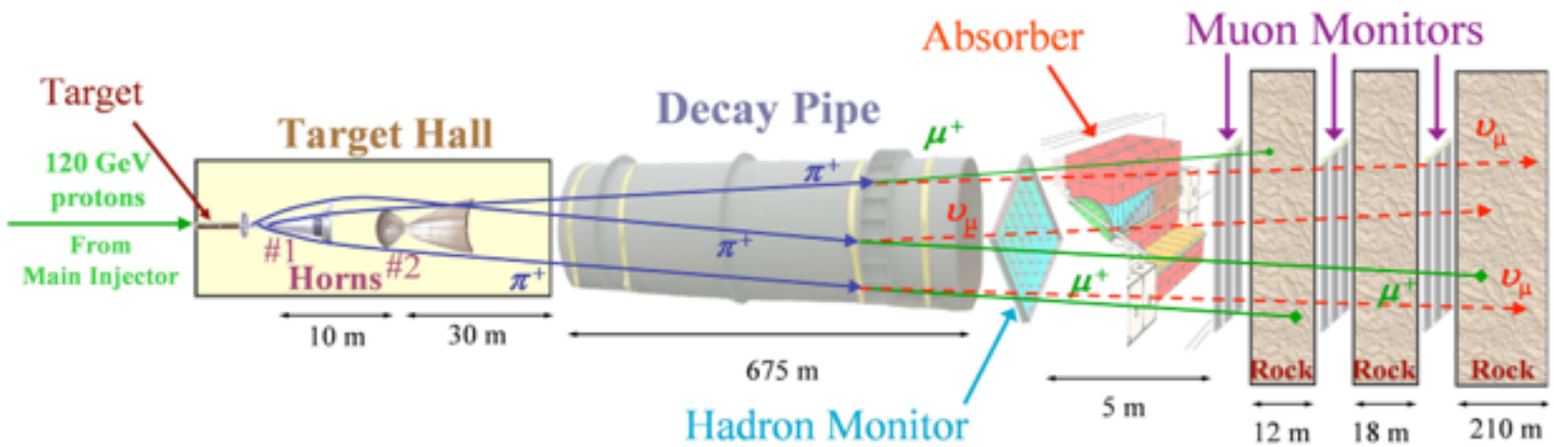
LSND, MiniBooNE, Karmen and Bugey results [4]

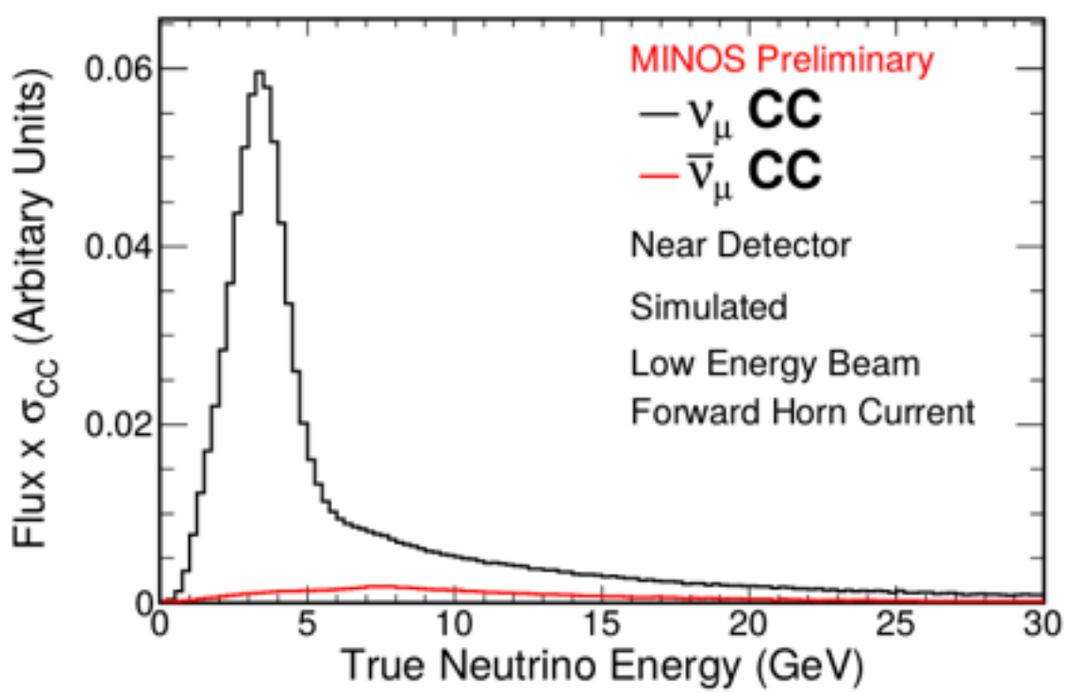
[4] K.N. ABAZAJIAN et al., Light Sterile Neutrinos: A White Paper (2012)

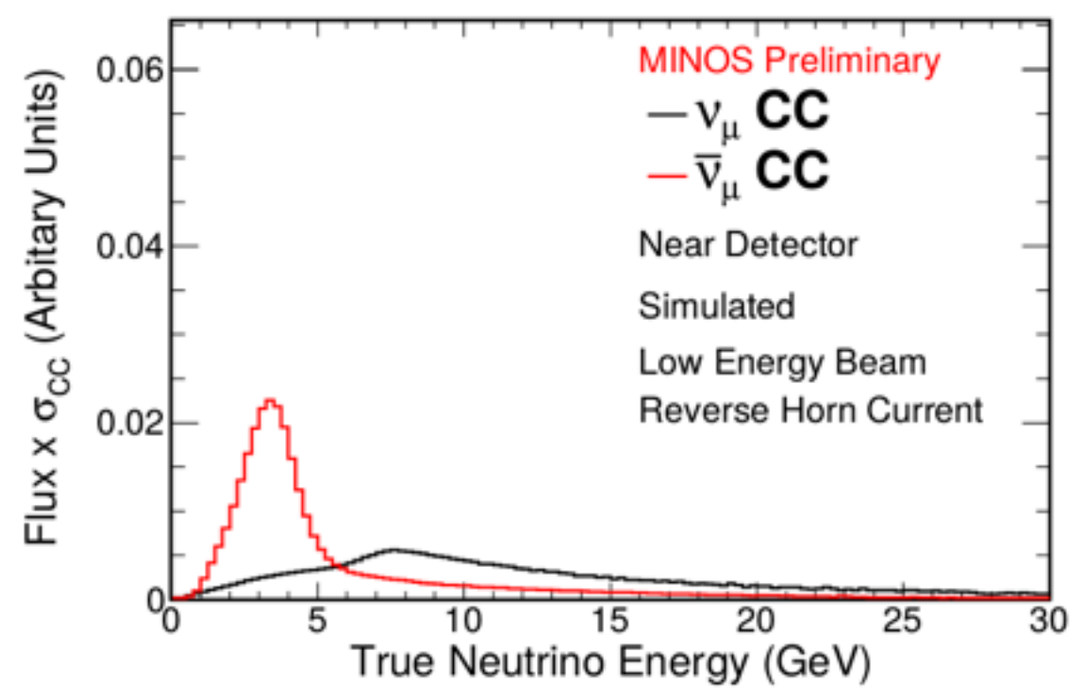
MINOS

- Keys: 734 km, on-axis.

NuMI Beam

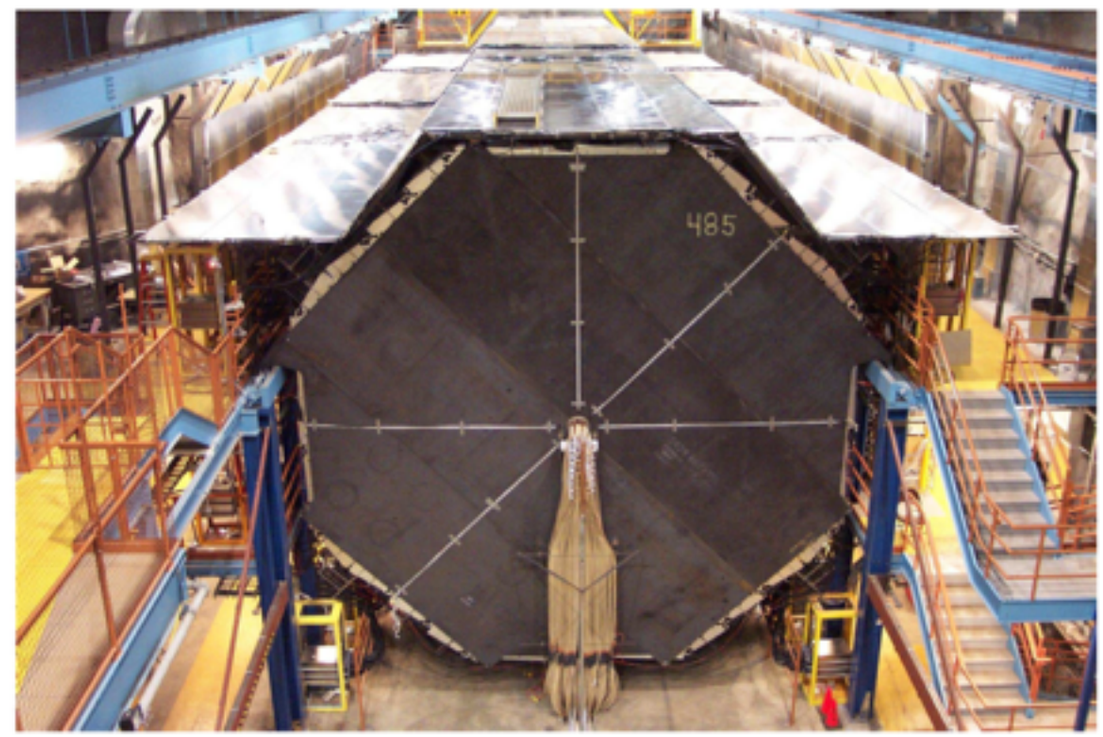






Forward Horn Current (FHC) Reversed Horn Current (RHC)

Two detectors



- Near Detector (ND)
- 23.7 T Fiducial mass
- 1.04 km downstream

- Far Detector (FD)
- 4.2 kT
- Veto shield for cosmic suppression
- 705 m underground

Why two-detector?

- The two detectors were designed to be functionally equivalent.
- It then allows the cancellation of systematic uncertainties to first order which affect both detectors in the same way. (i.e. cross sections neutrino flux from the beam etc..)

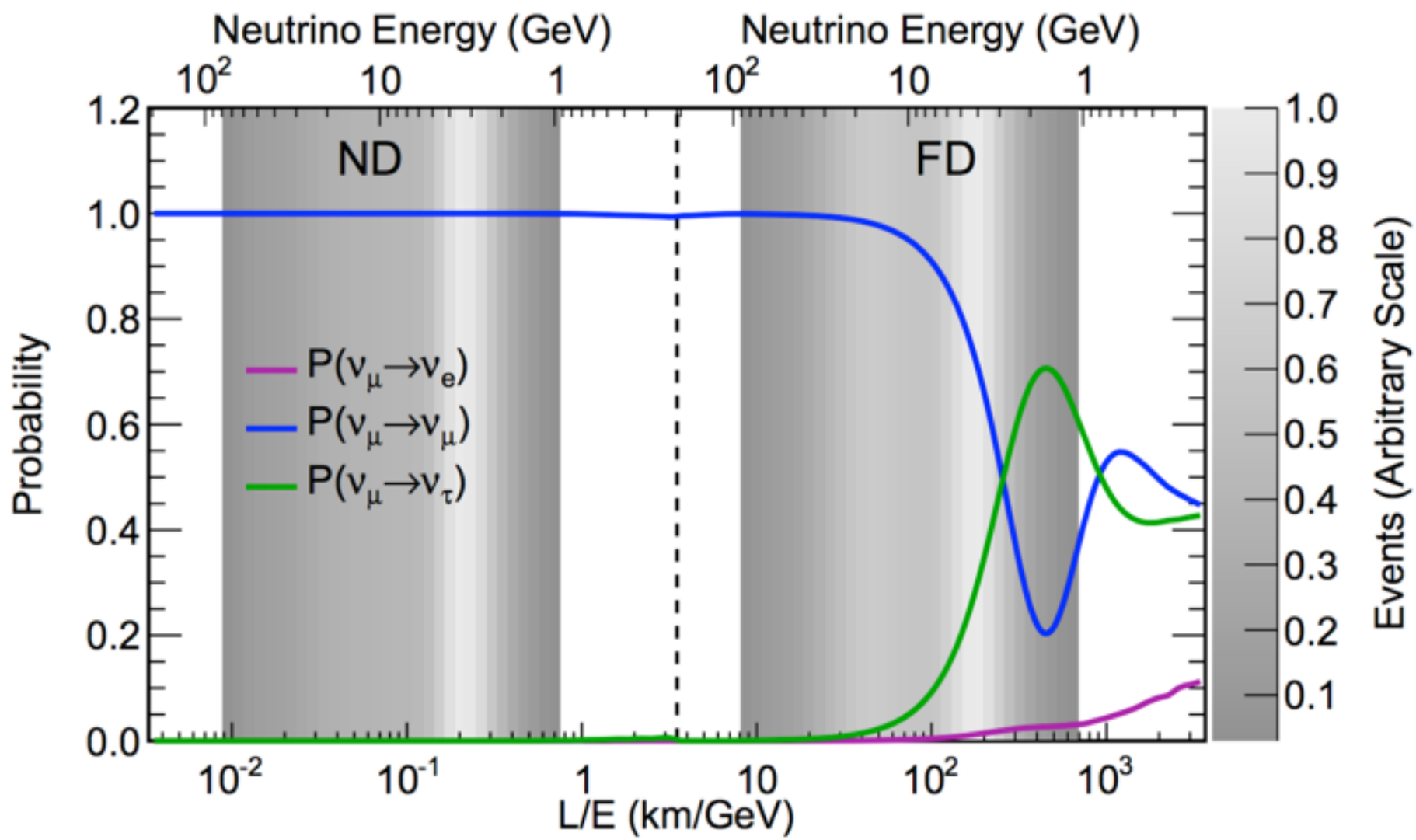
ν_μ disappearance

- The MINOS experiment was originally designed to search Δm^2_{32} for ν_μ disappearance

- When considering the 3 active + 1 sterile model, MINOS is sensitive to θ_{24}, Δm^2_{41}.

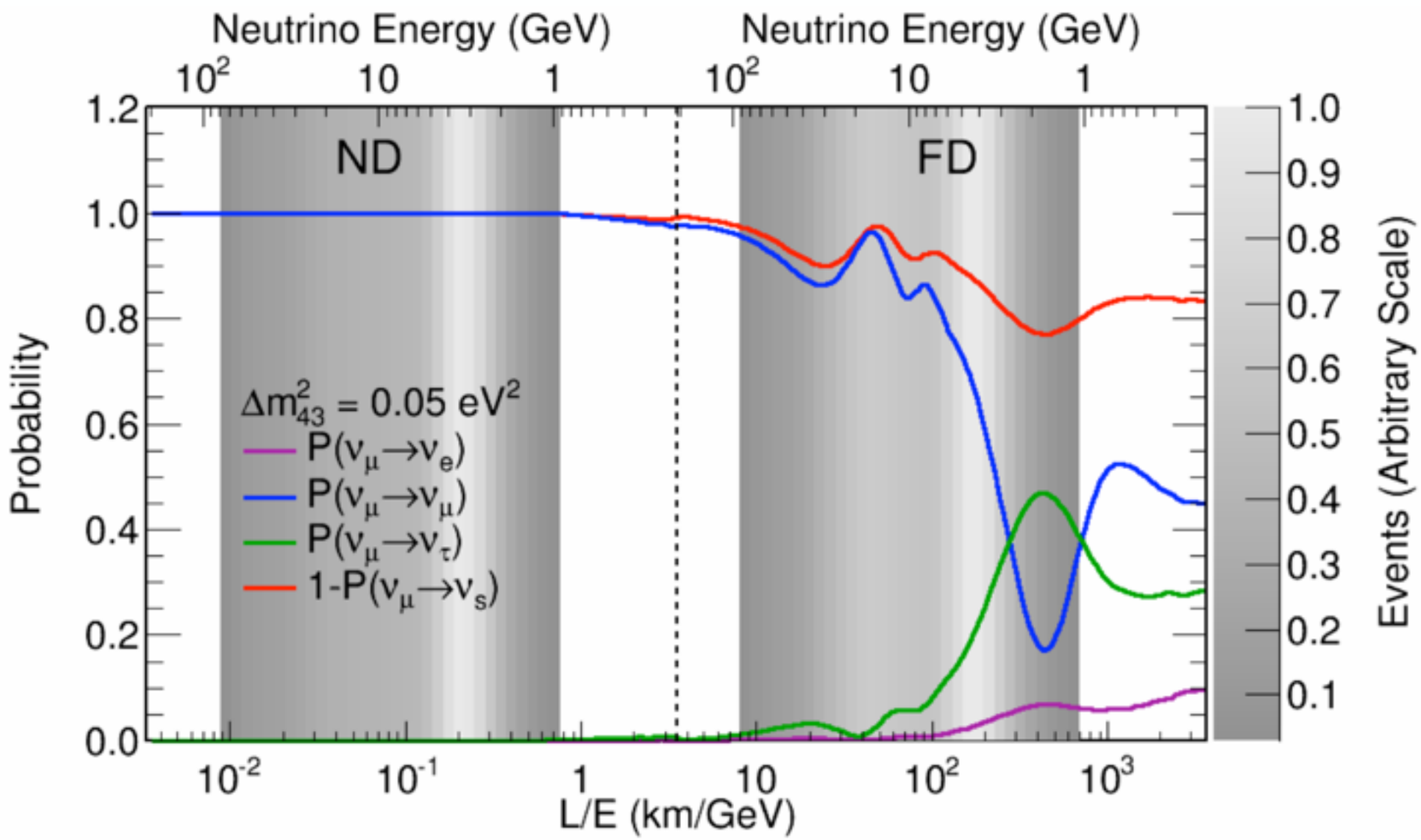
$$P_{Dis}(\nu_\mu) \approx \sin^2(2\theta_{23})\cos(2\theta_{24})\sin^2(\Delta_{31}) + \sin^2(2\theta_{24})\sin^2(\Delta_{41})$$

Oscillation in MINOS detectors



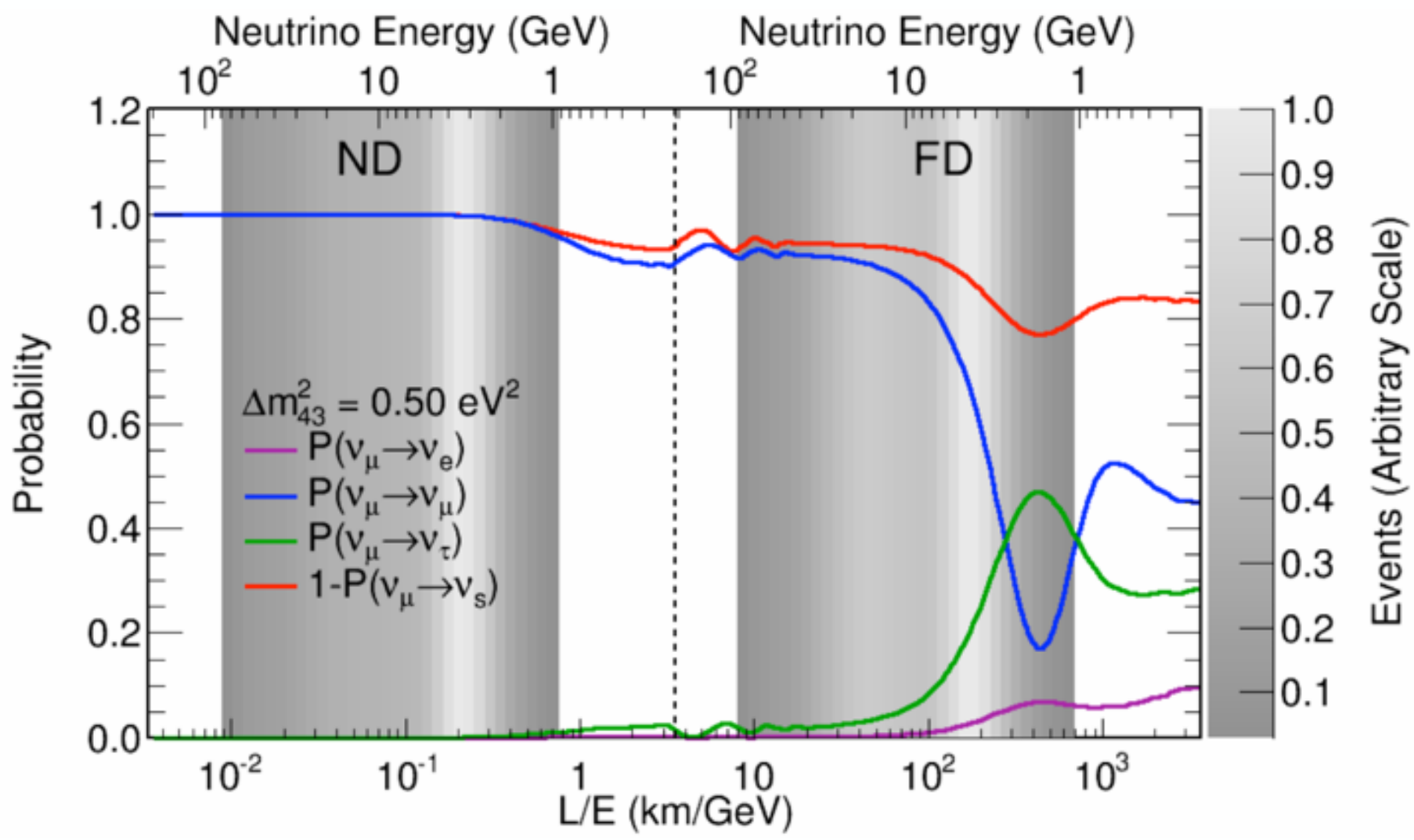
Standard oscillation in our detectors

Oscillation in MINOS detectors



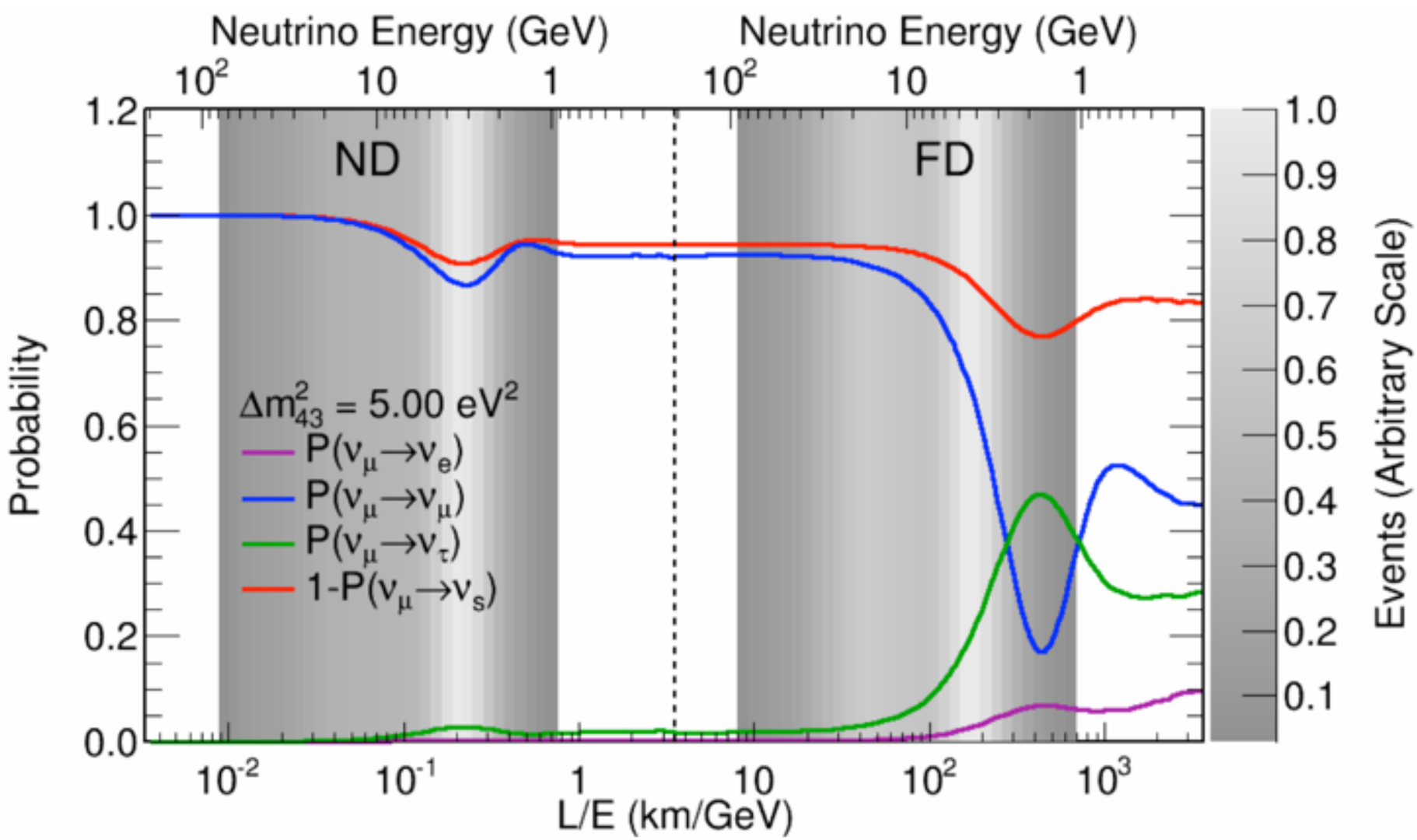
(3+1) model with low mass splitting

Oscillation in MINOS detectors



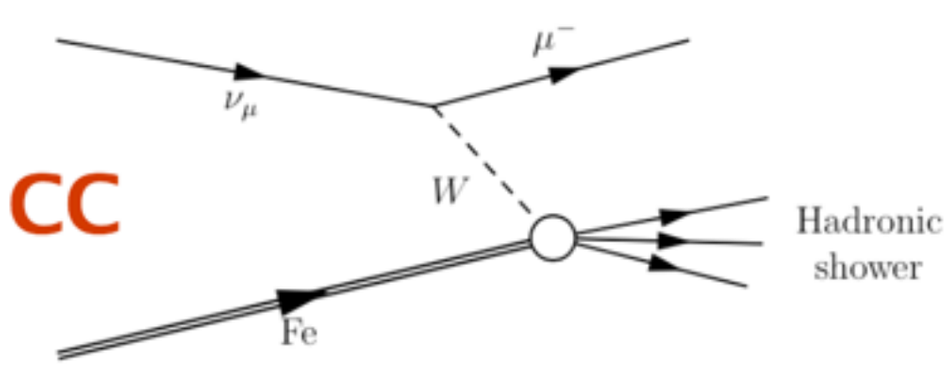
(3+1) model with medium mass splitting

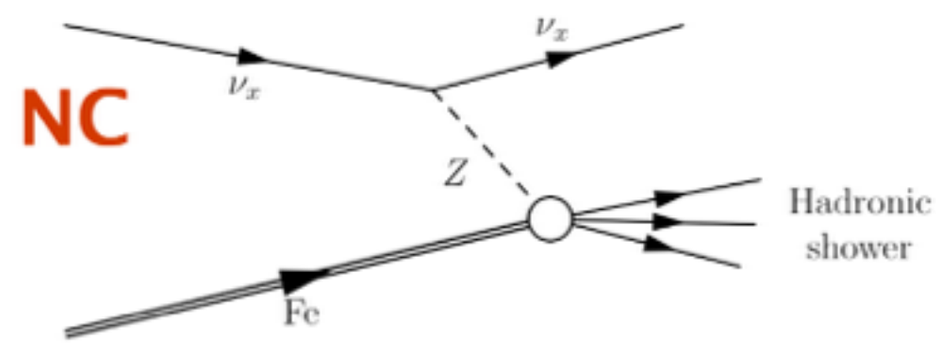
Oscillation in MINOS detectors

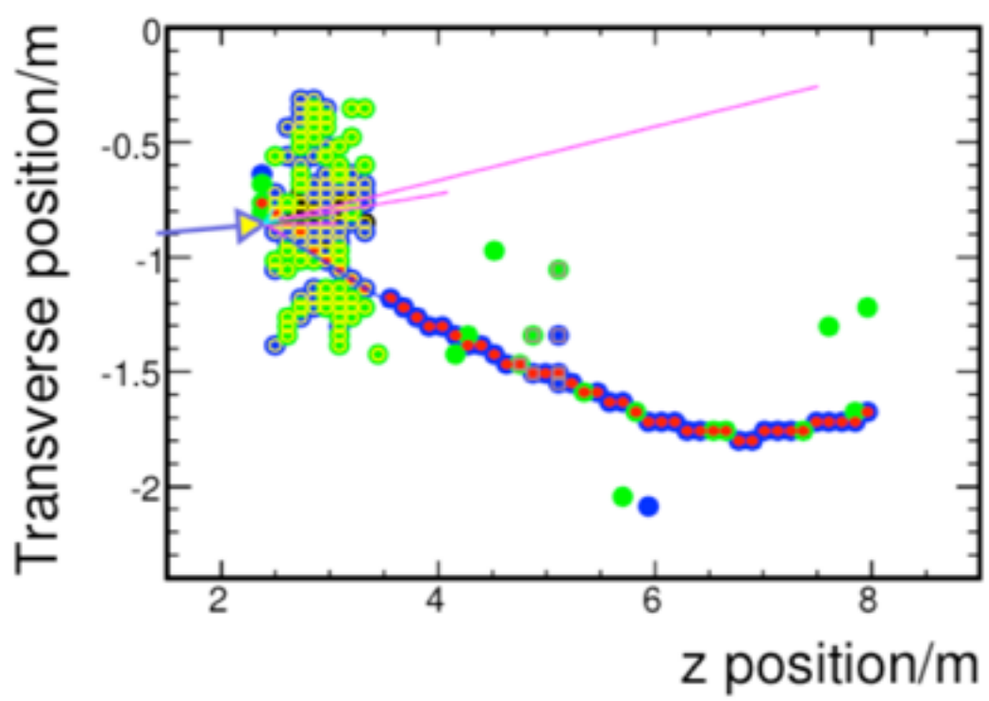


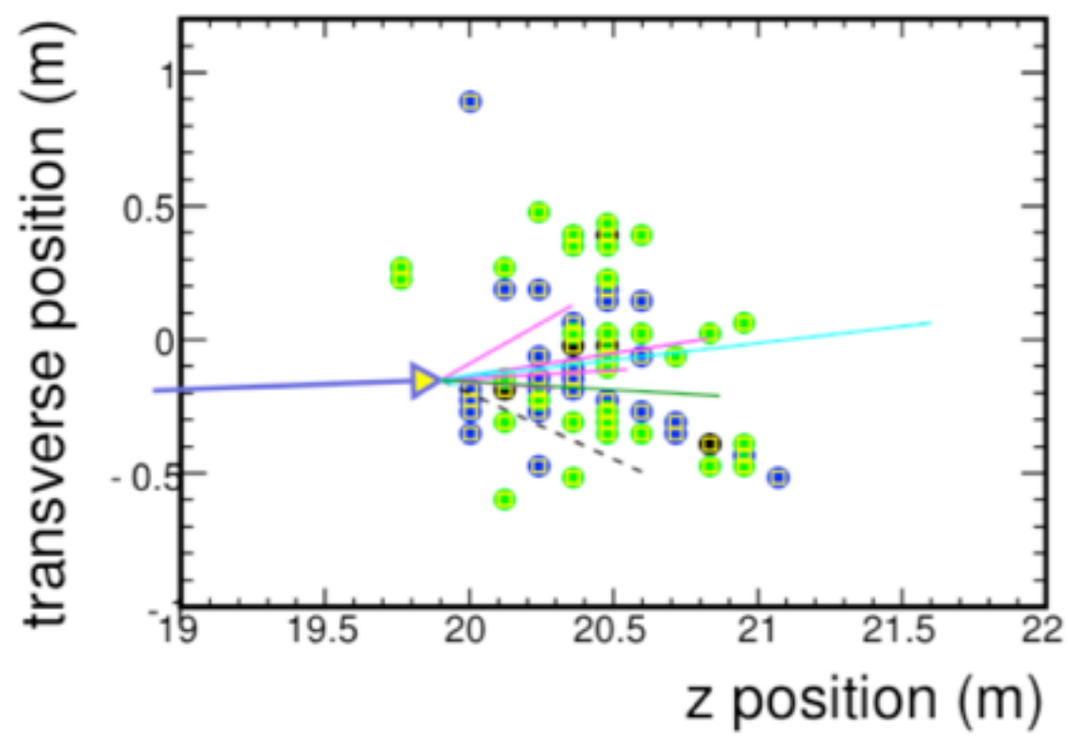
(3+1) model with high mass splitting

Events

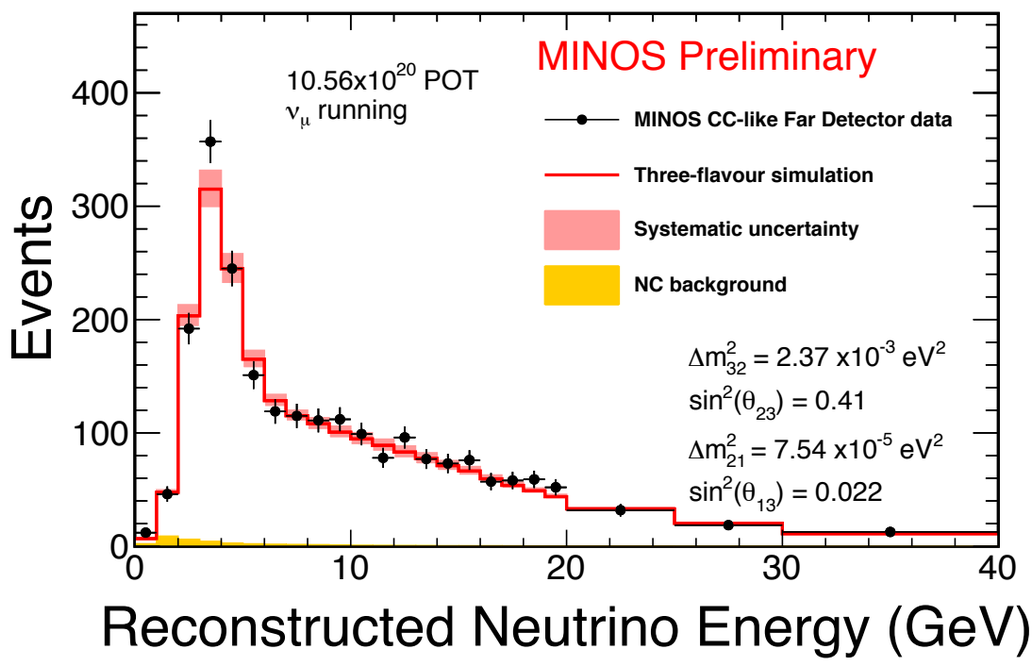

CC
ν_μ
μ^-
W
Fe
Hadronic shower

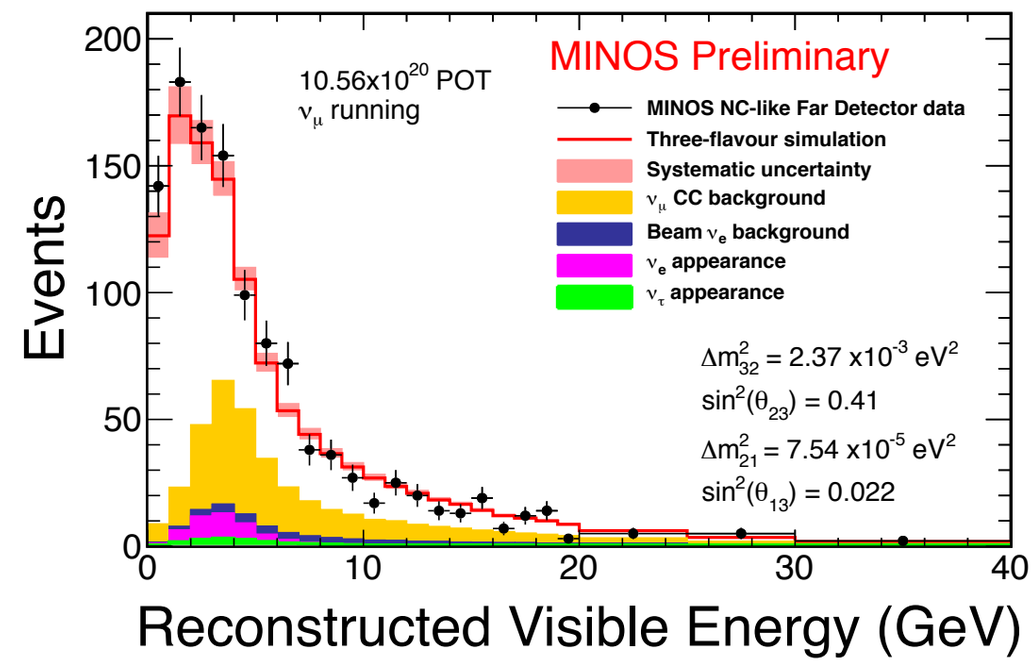

NC
ν_x
ν_x
Z
Fe
Hadronic shower


Transverse position/m
z position/m
0
-0.5
-1
-1.5
-2
2
4
6
8


transverse position (m)
z position (m)
1
0.5
0
- 0.5
19
19.5
20
20.5
21
21.5
22

FHC Far Detector Event Spectra





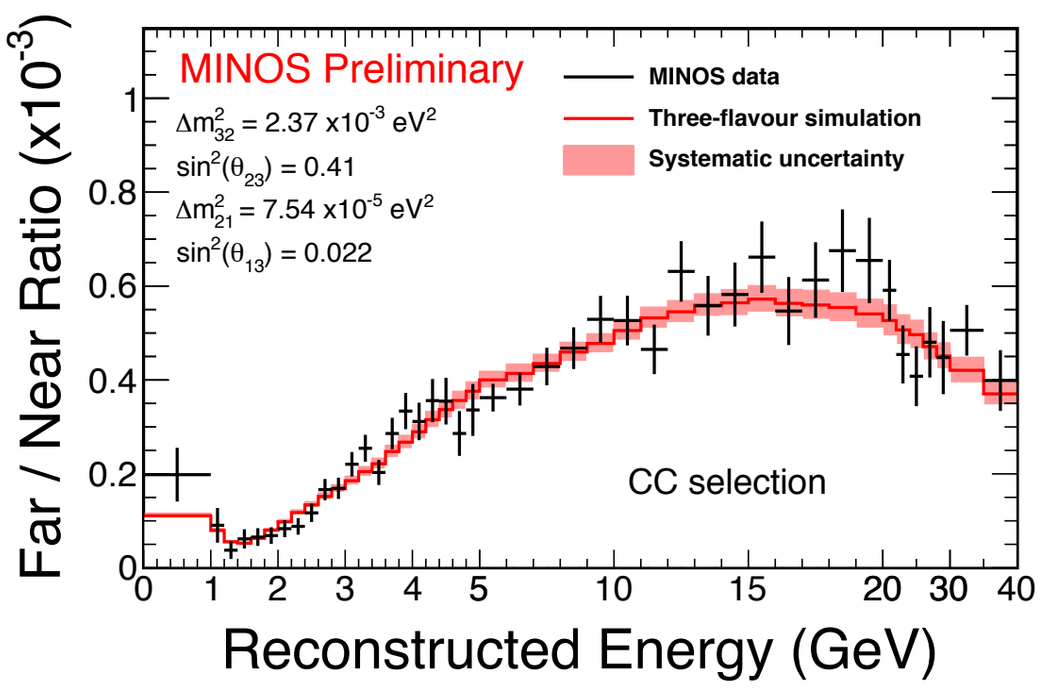
- We observed 2563 CC like events
- We observed 1211 NC like events

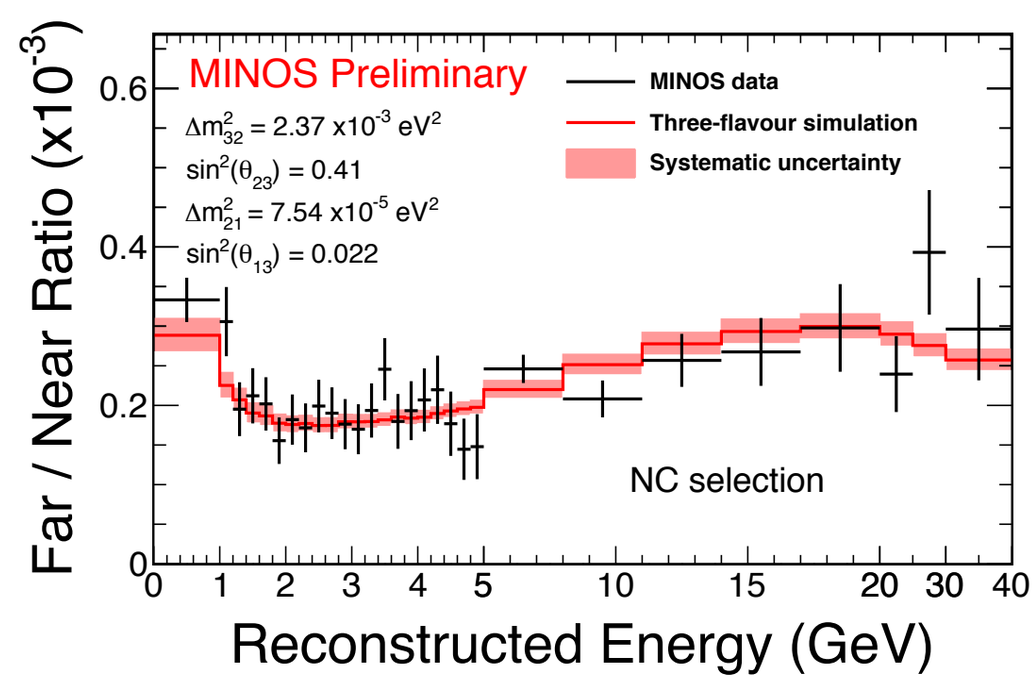
Analysis method

- We use our predicted Far/Near MC energy spectrum to fit our Far/Near data by using (3+1) model

- We fixed: δ_{13}, δ_{14}, δ_{24} and θ_{14} to zero (no $\nu_e \rightarrow \nu_s$)

- We free: Δm^2_{32}, θ_{23}, θ_{24}, θ_{34} and Δm^2_{41}.





Systematics

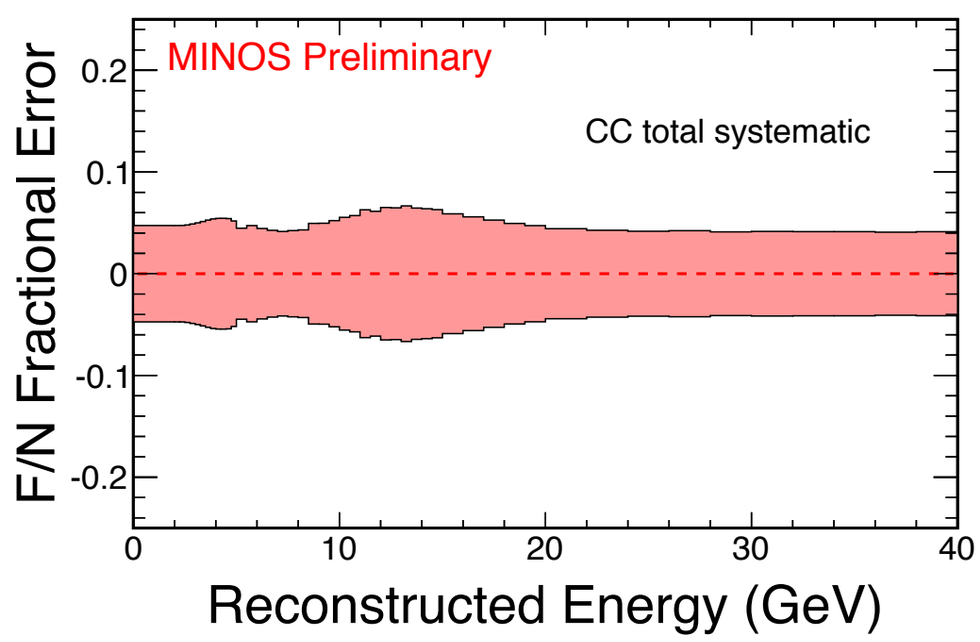
- We used in total 26 systematic uncertainties in covariance matrix form.
- These systematics includes: normalisation, detector acceptance, NC selection, hadronic production, beam focusing, cross section energy scale and background

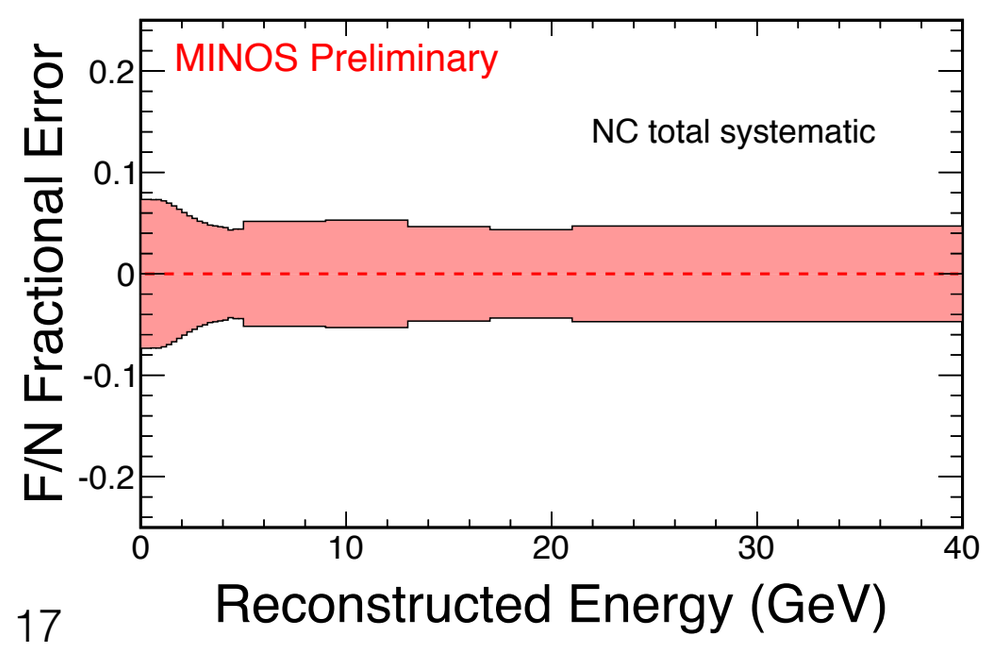
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T[V^{-1}]_{ij}(o_j - e_j)$$

o_i : Observed events in bin i

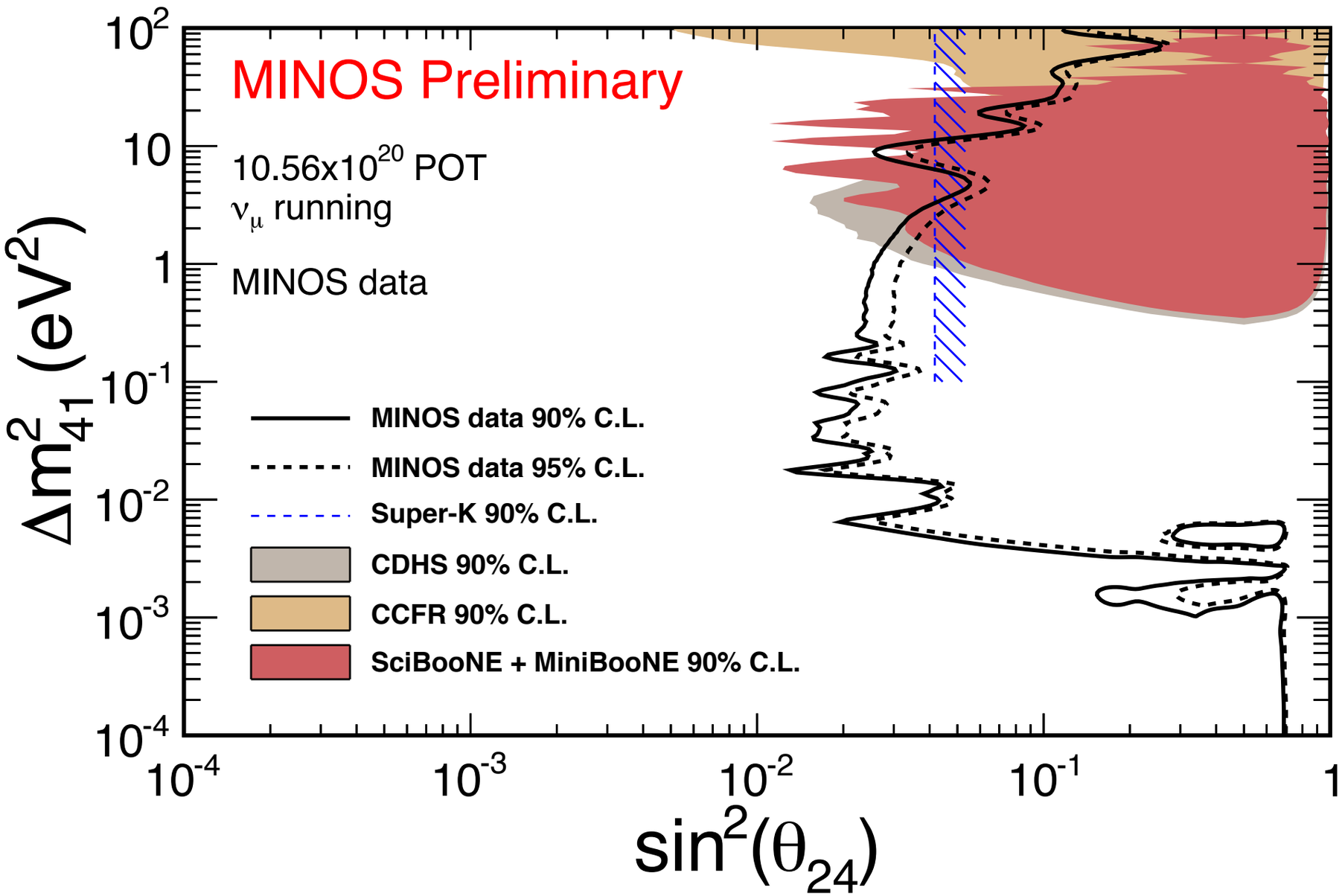
e_i : Predicted events in bin i

V : Covariance matrix



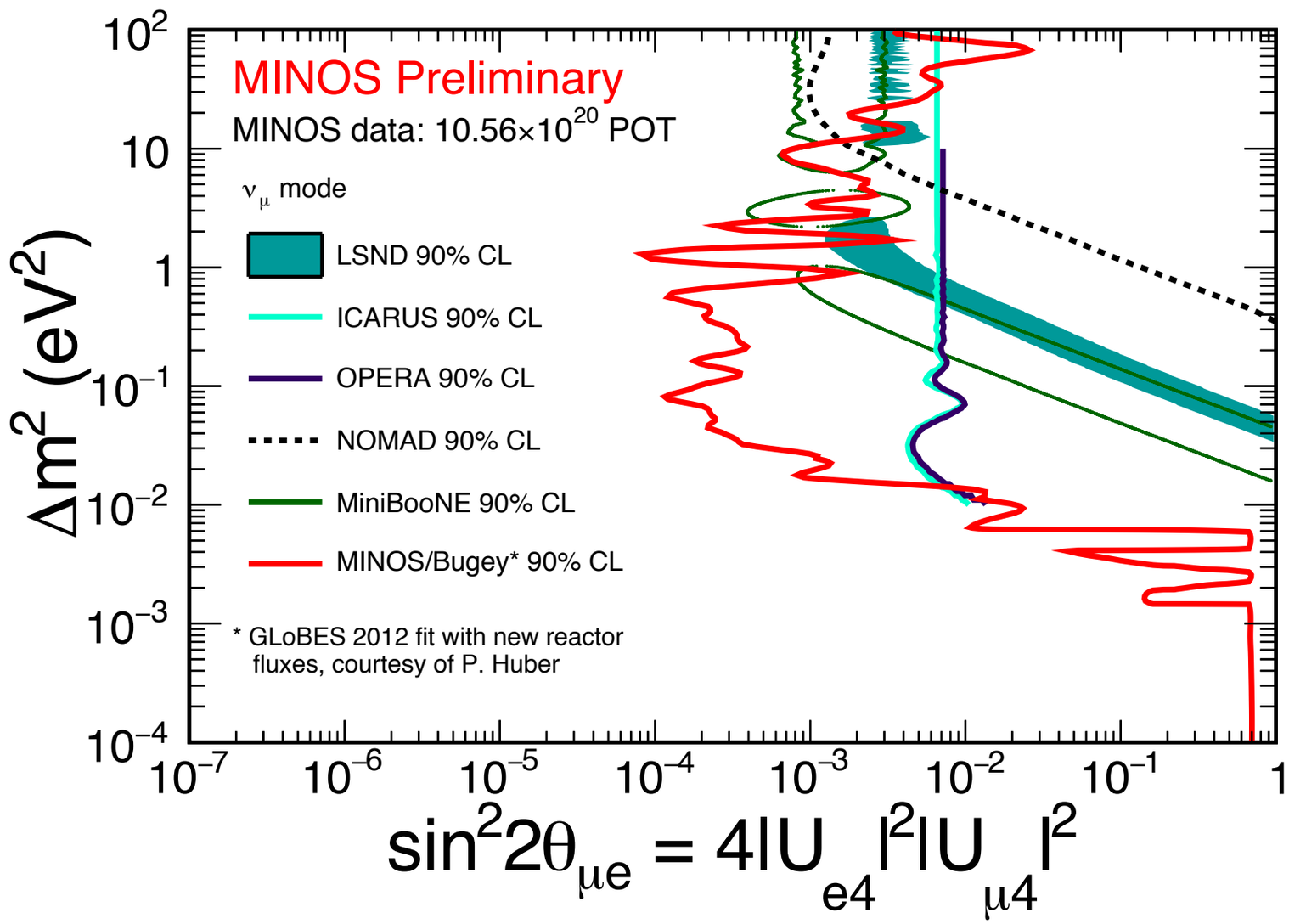


Disappearance limits

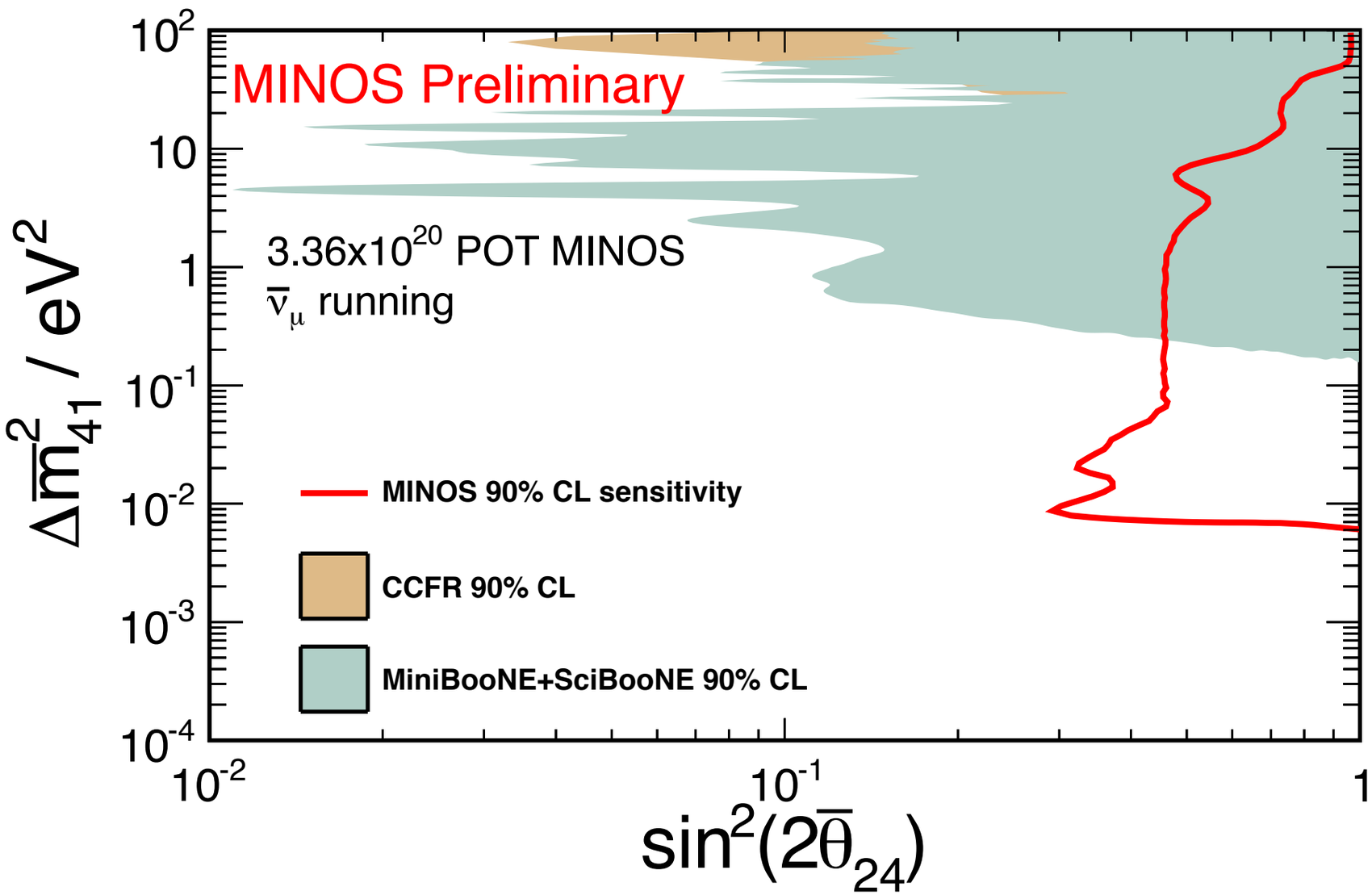


Combined limits with Bugey

- Bugey experiment is looking for electron anti-neutrino disappearance → θ_{14}
- It's possible to combine it since it have largely uncorrelated systematics uncertainties



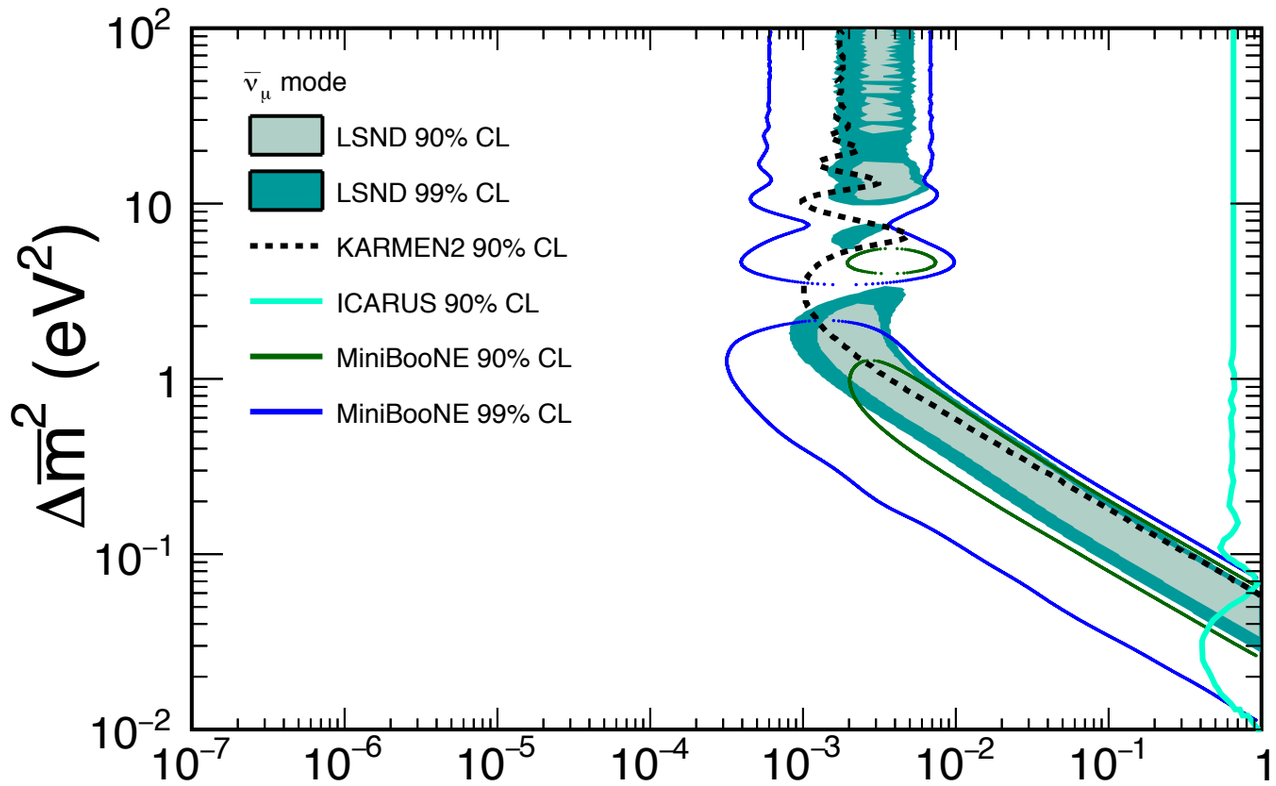
RHC Anti-neutrino limits



Summary

- MINOS limits on sterile neutrino assuming (3+1) model.
- MINOS and Bugey combined limits.
- Future results from RHC, combined FHC RHC, combined MINOS and MINOS+ results.

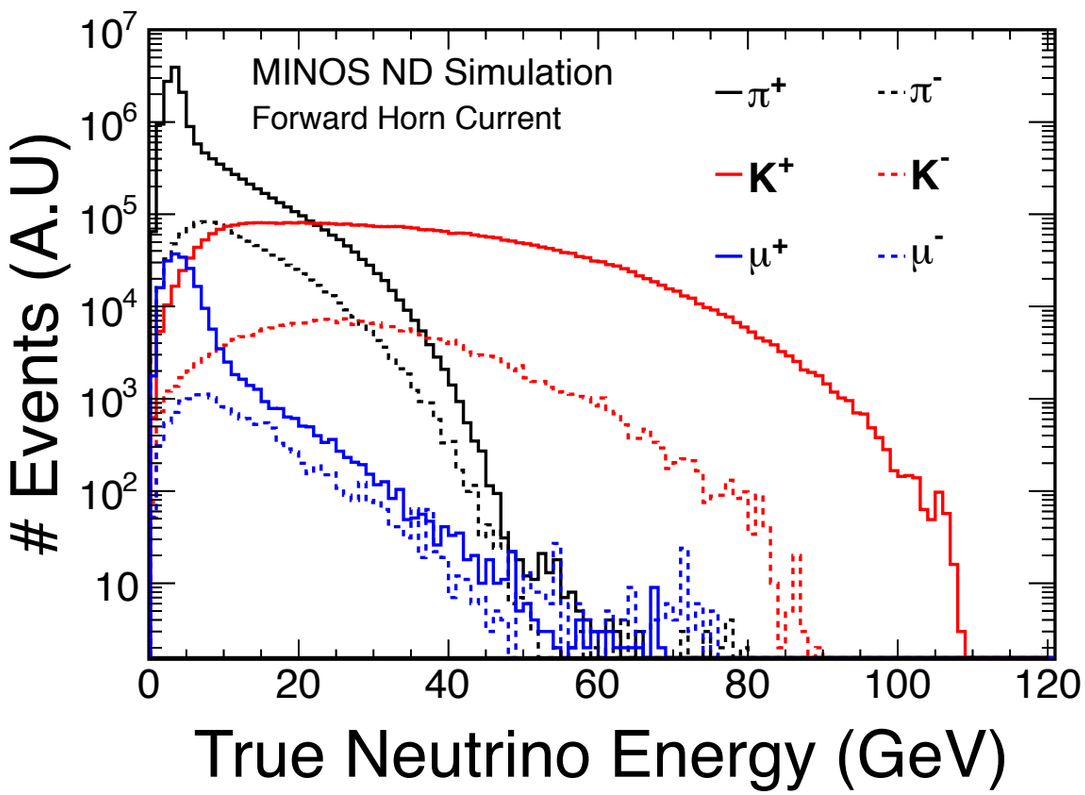
Backup

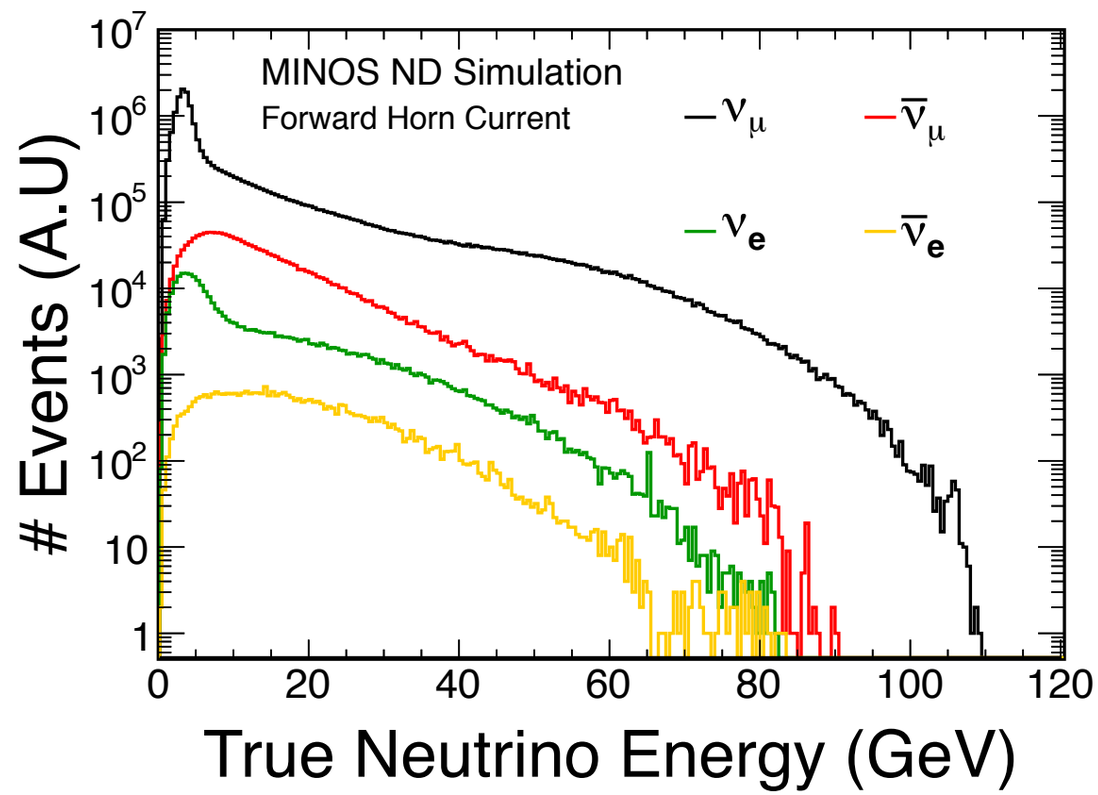


$$\sin^2 2\bar{\theta}_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

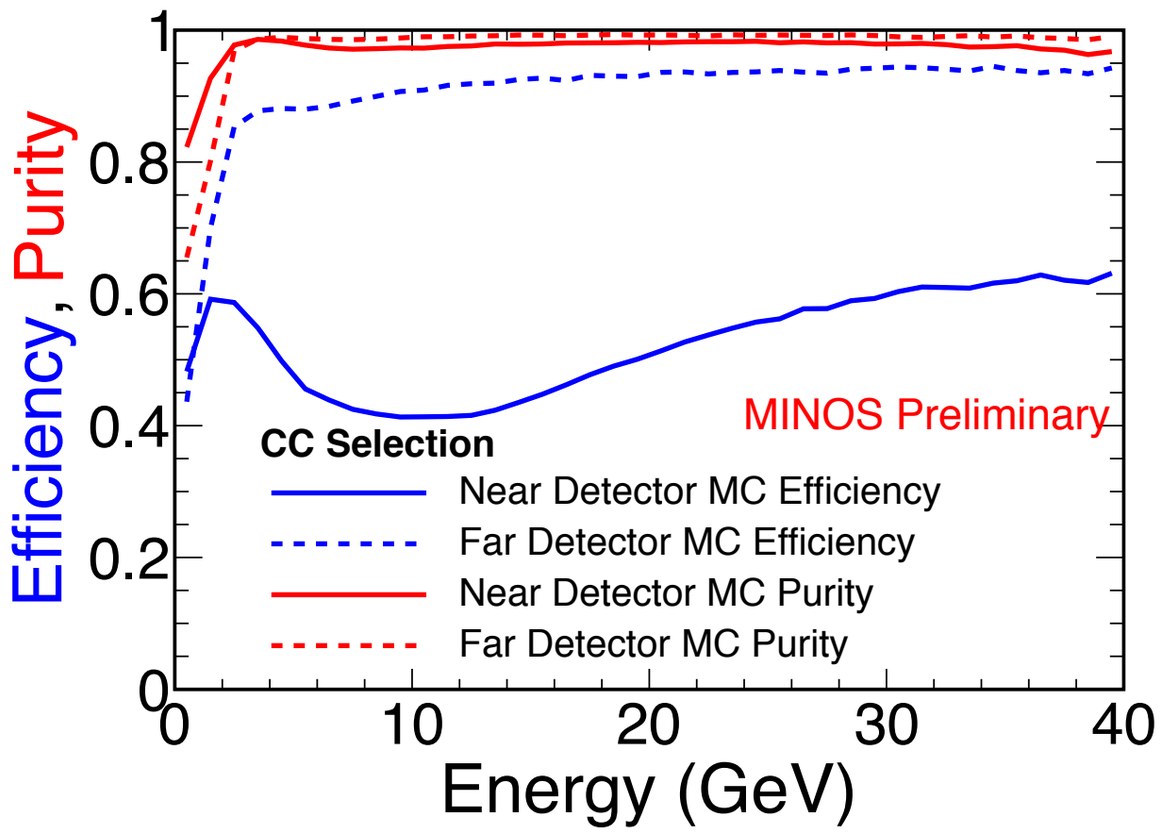
$$|U_{e4}|^2 = \sin^2\theta_{14},$$
$$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14},$$
$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}.$$

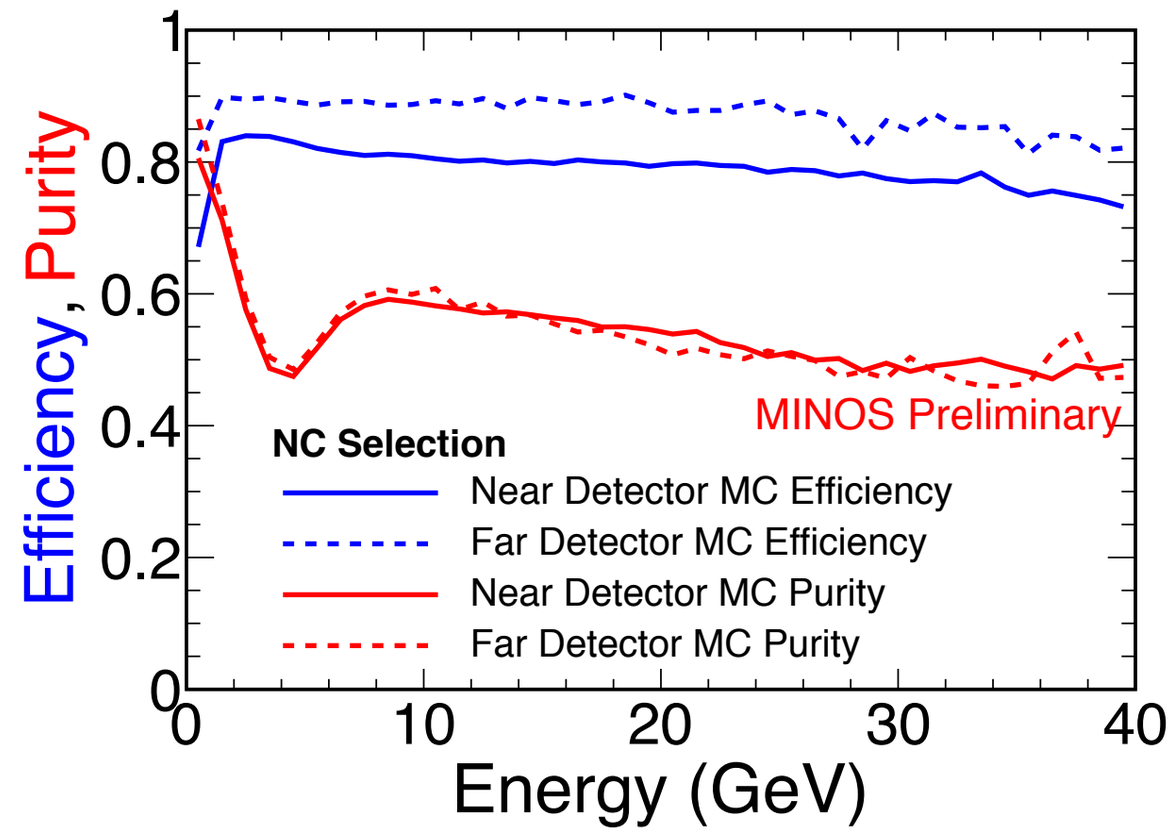
Beam compositions





Event selection efficiency and purity

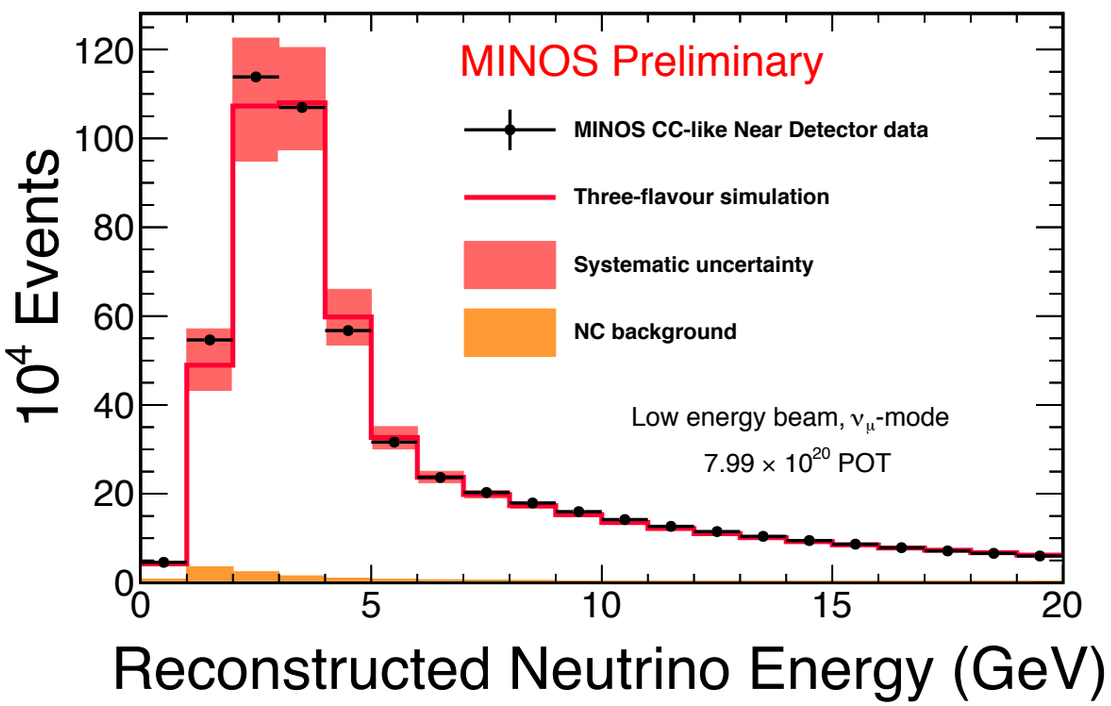


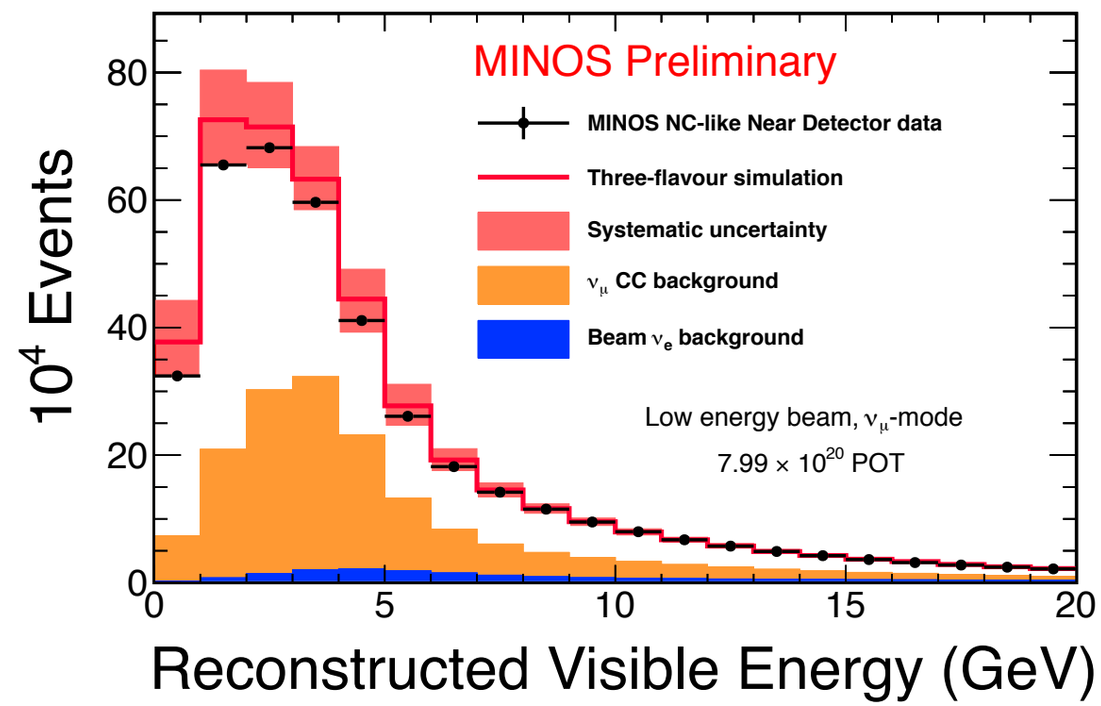


CC ND efficiency is low due to events with tracks ending near the coil hole

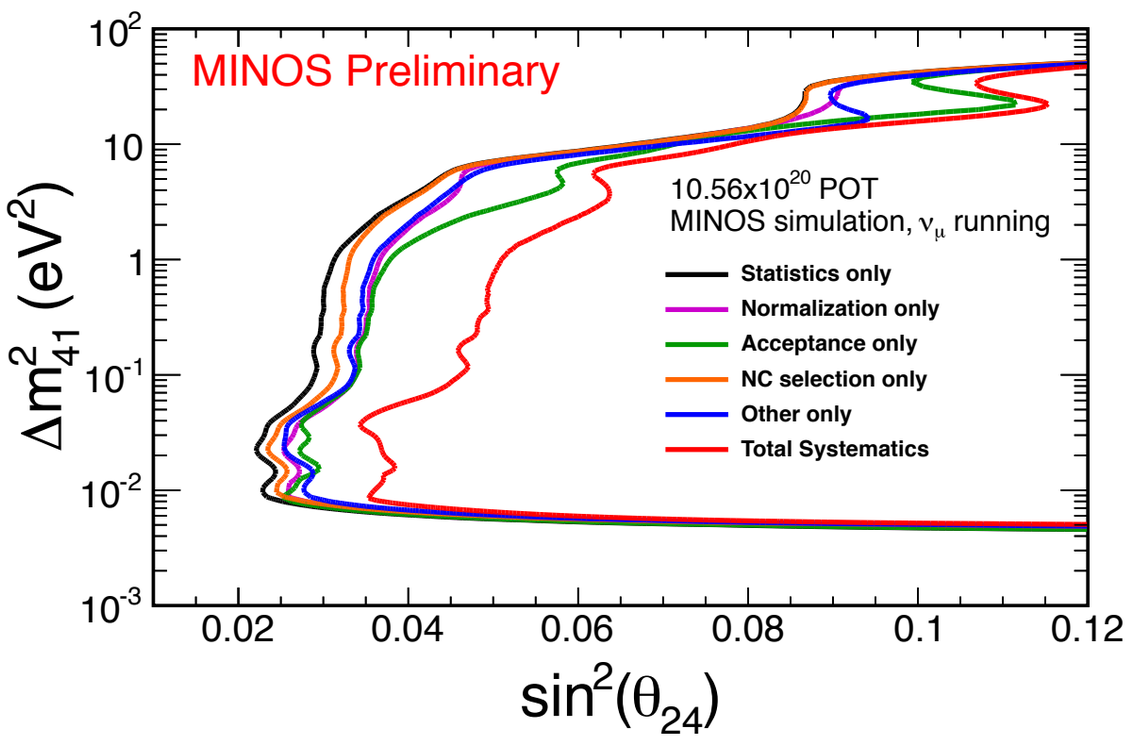
NC events it is more difficult: 86% efficiency, 61% Purity at the FD main background from inelastic ν_μCC events

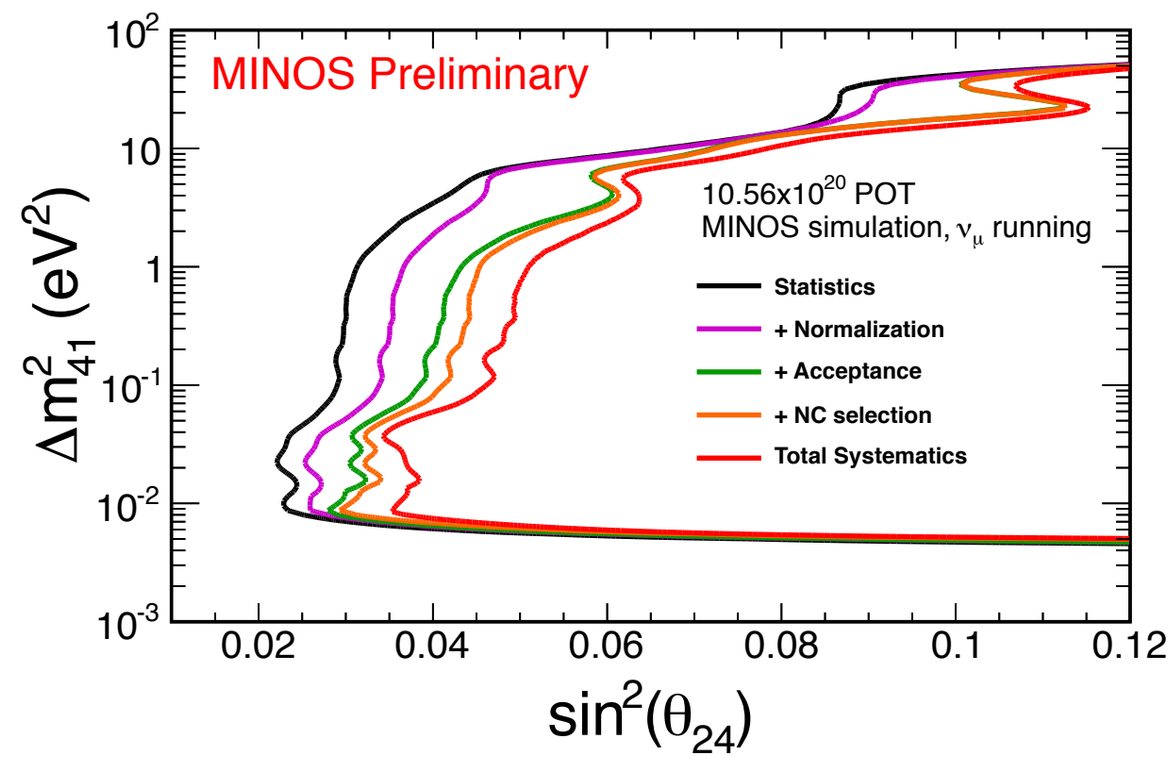
ND events


MINOS Preliminary
MINOS CC-like Near Detector data
Three-flavour simulation
Systematic uncertainty
NC background
Low energy beam, ν_μ-mode
7.99×10^{20} POT
10^4 Events
Reconstructed Neutrino Energy (GeV)

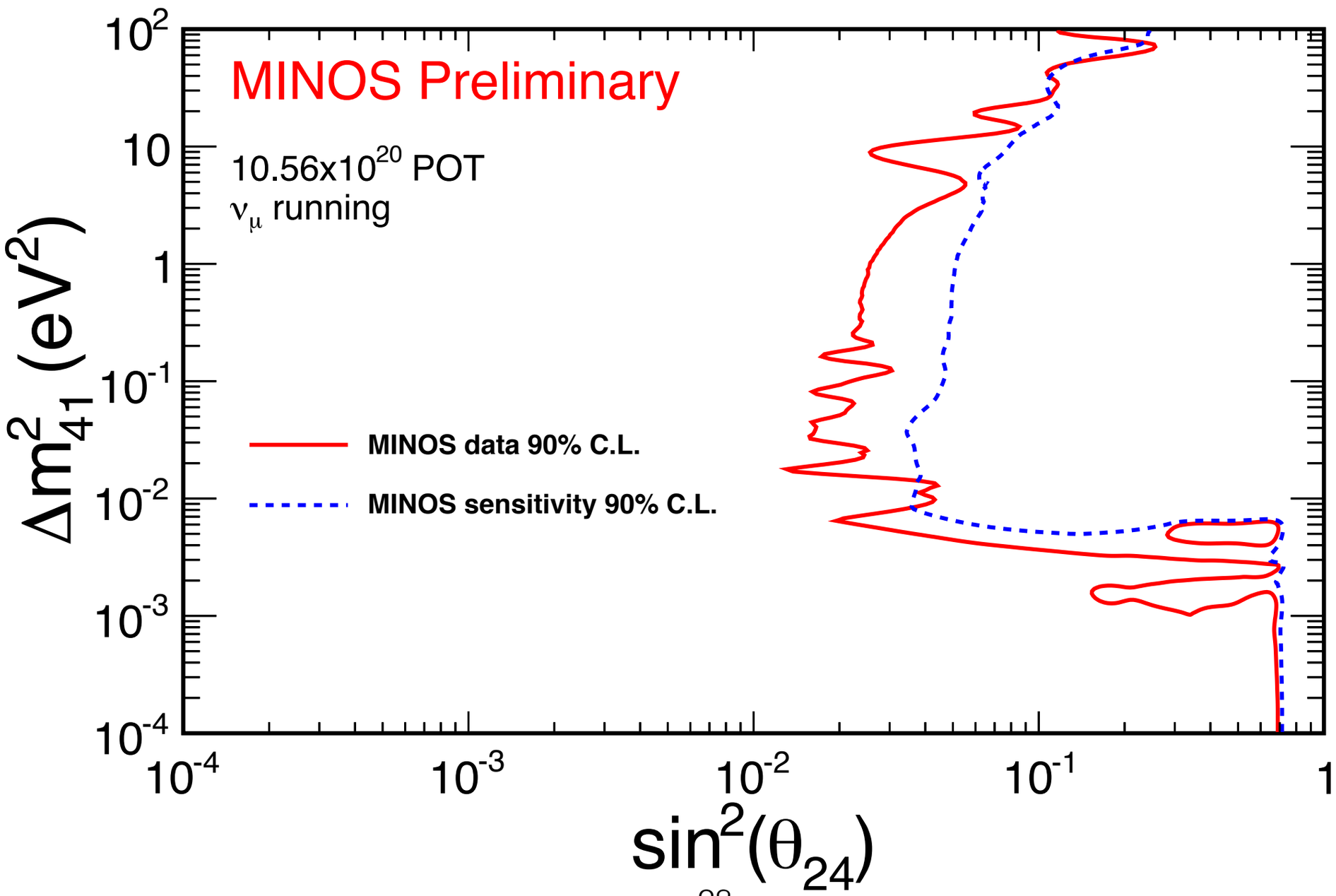

MINOS Preliminary
MINOS NC-like Near Detector data
Three-flavour simulation
Systematic uncertainty
ν_μ CC background
Beam ν_e background
Low energy beam, ν_μ-mode
7.99×10^{20} POT
10^4 Events
Reconstructed Visible Energy (GeV)

Systematic effects

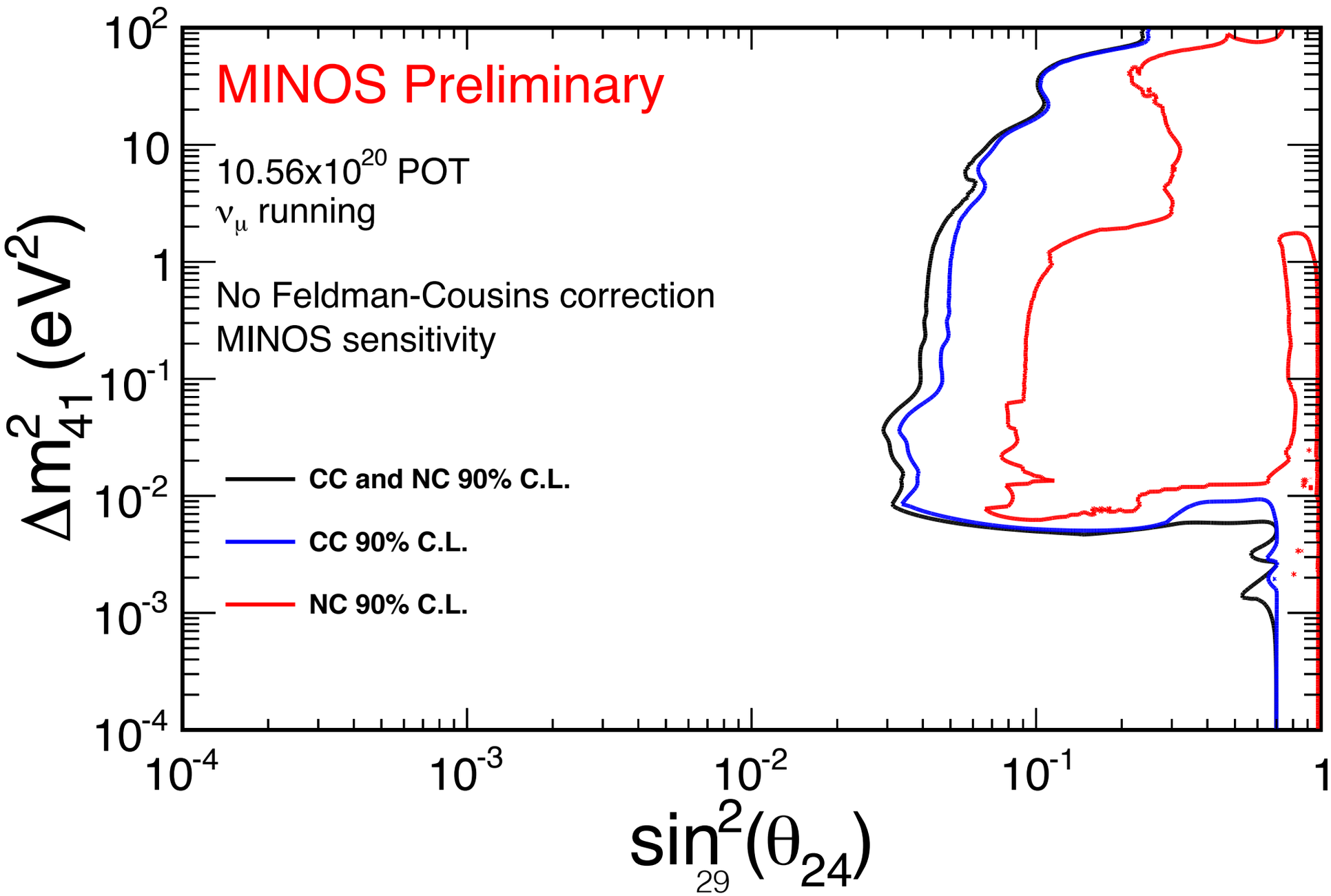




MINOS sterile sensitivity



Break down


MINOS Preliminary
10.56x10^20 POT
ν_μ running
No Feldman-Cousins correction
MINOS sensitivity
CC and NC 90% C.L.
CC 90% C.L.
NC 90% C.L.
Δm²_41 (eV²)
sin²(θ_24)
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-4
10^-3
10^-2
10^-1
1