A.D. 1308
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DIPARTIMENTO
DI FISICA E GEOLOGIA

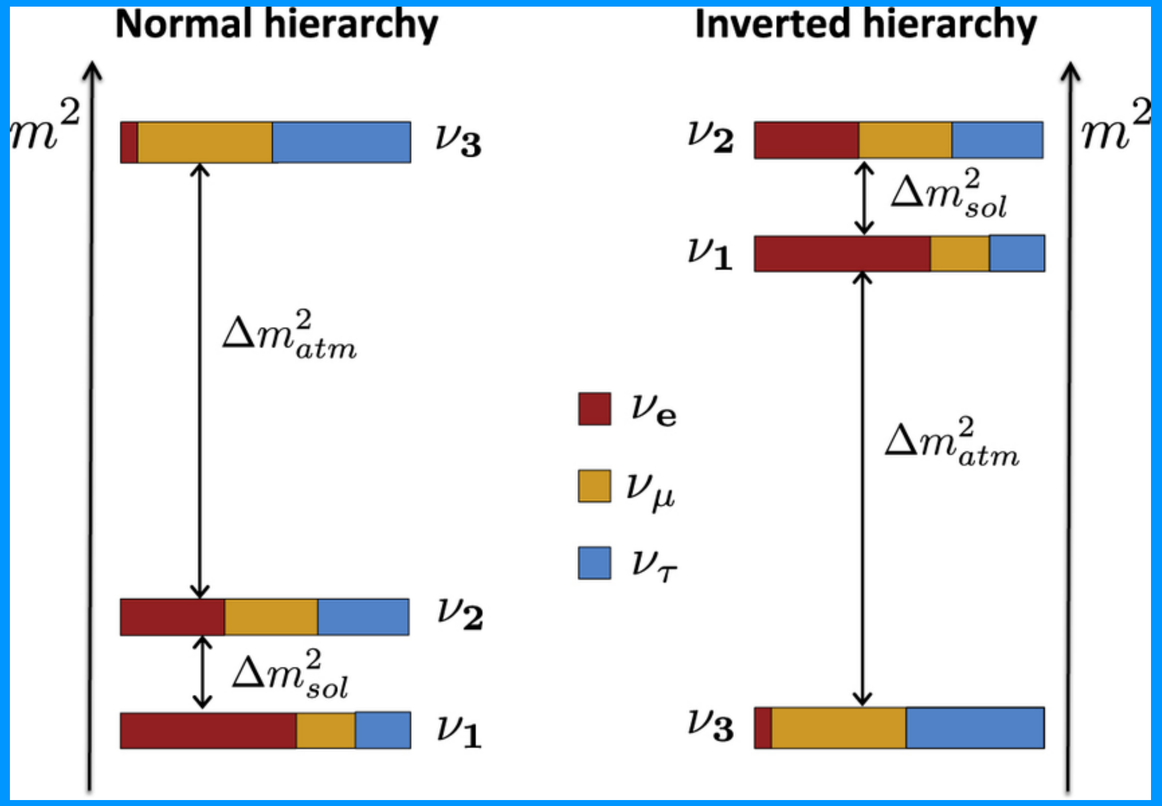
Neutrino Oscillation Results from the MINOS/MINOS+ Experiment

16th International Workshop on Tau Lepton Physics

30/9/2021

S. Germani - Università degli Studi di Perugia
On behalf of the MINOS+ Collaboration

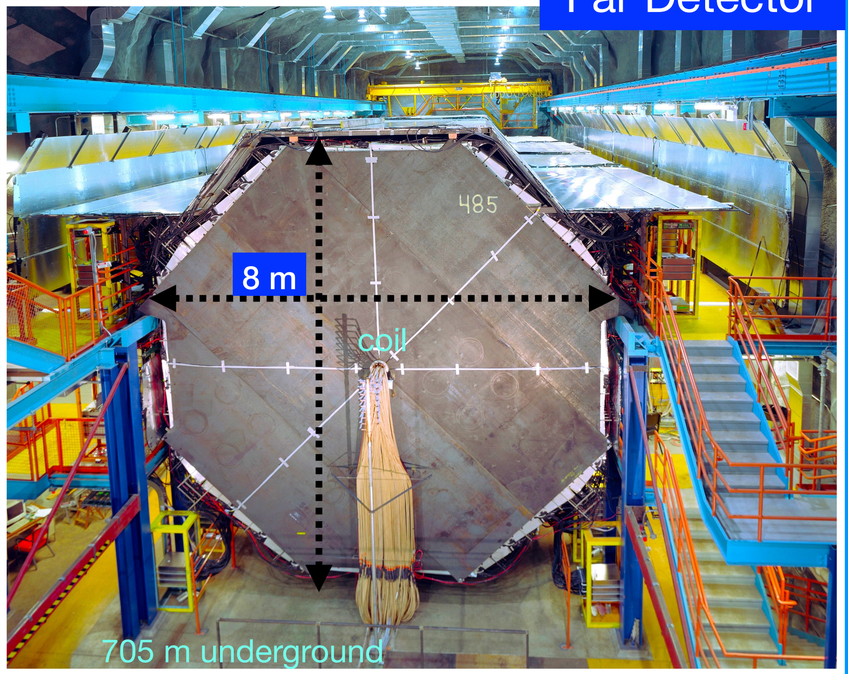
Neutrino Oscillation Questions for MINOS



- Mass Hierarchy?
- Maximal Mixing in θ_{23}?
- Sterile Neutrinos?

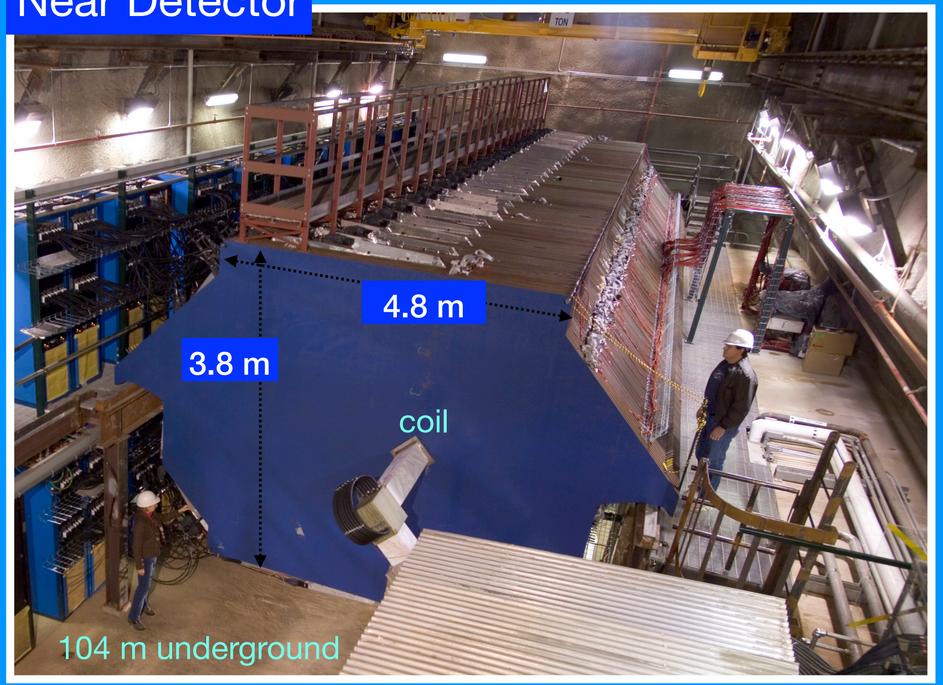
MINOS Detectors

Far Detector



- 735 km from target
- 5.4 ktons

Near Detector

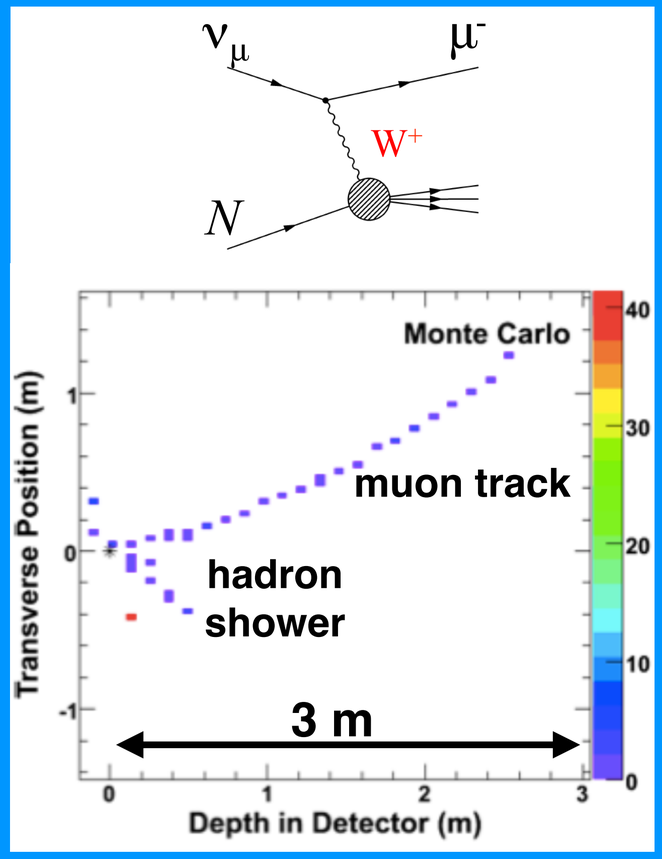


- 1 km from target
- 980 tons

- On-axis long-baseline neutrino oscillation experiments
- Identical detector technology
- Magnetized steel tracking sampling calorimeters

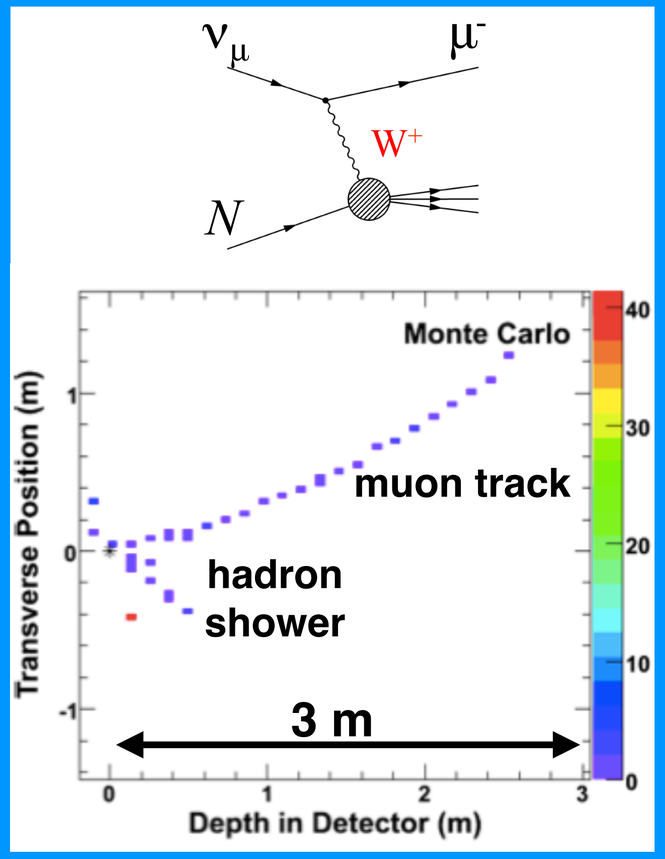
Neutrino Events

ν_μ Charged Current (CC)

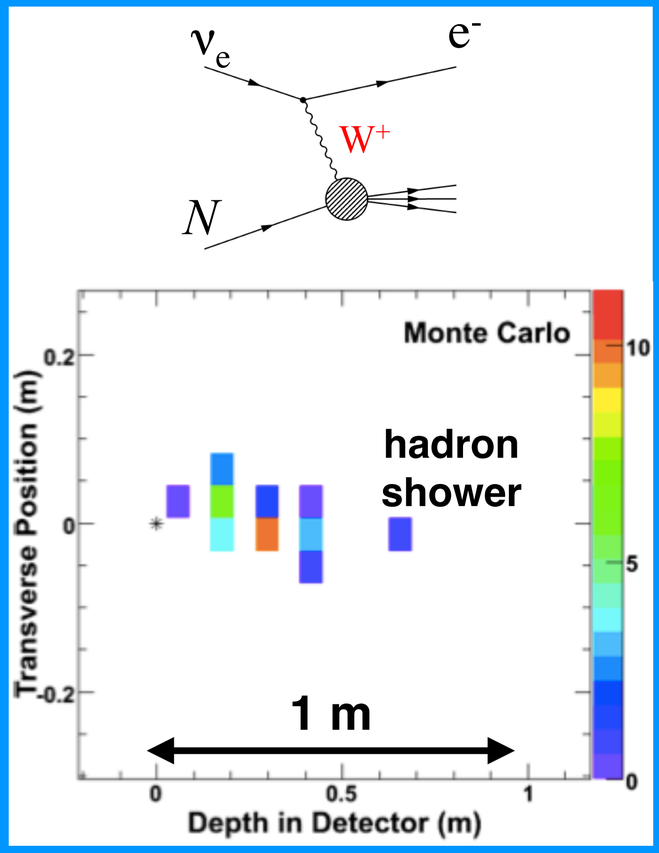


Neutrino Events

ν_μ Charged Current (CC)

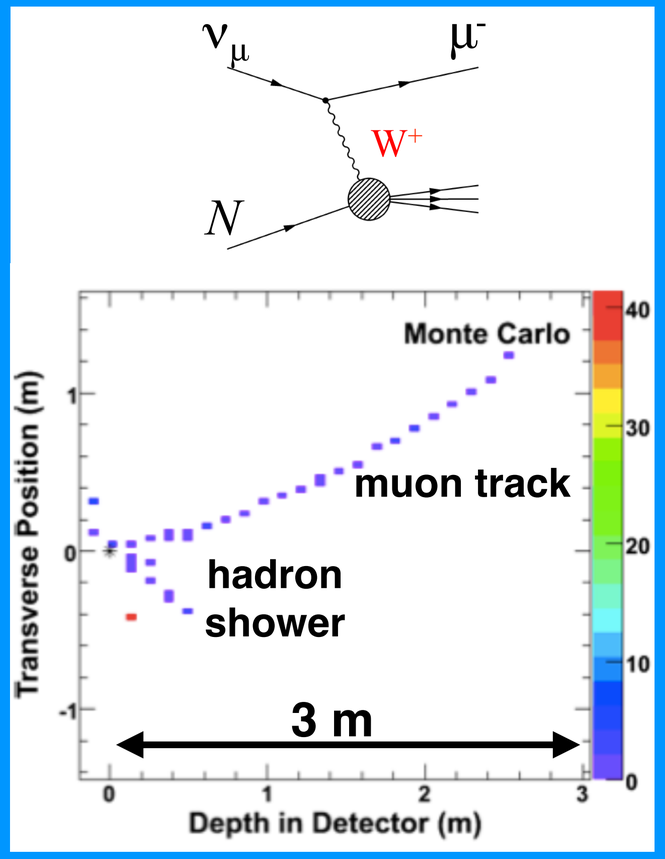


ν_e Charged Current (CC)

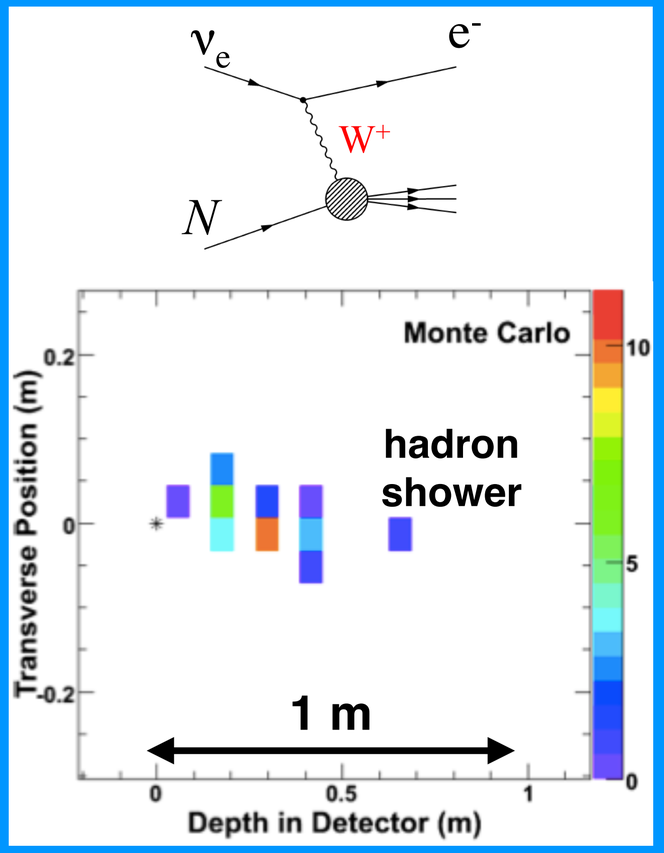


Neutrino Events

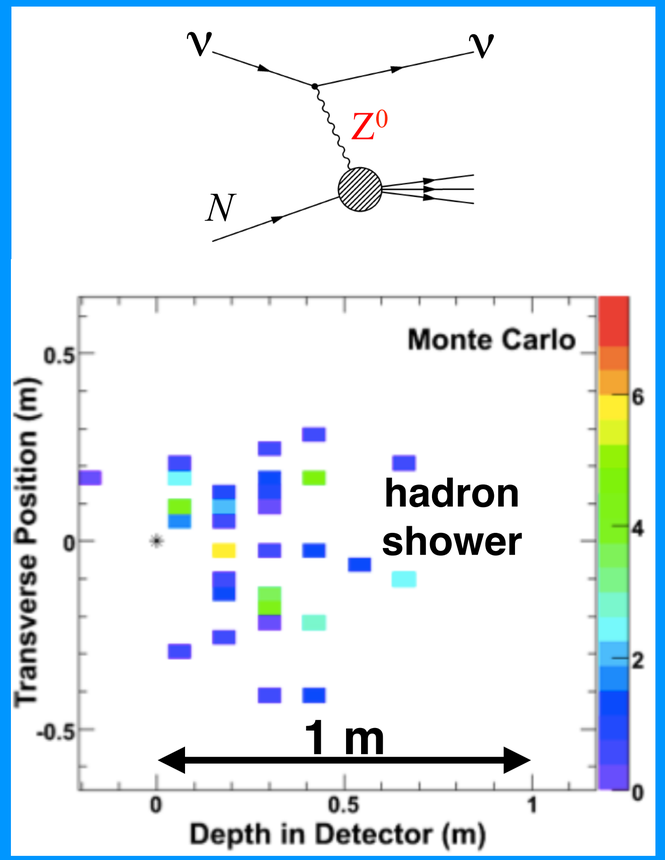
ν_μ Charged Current (CC)



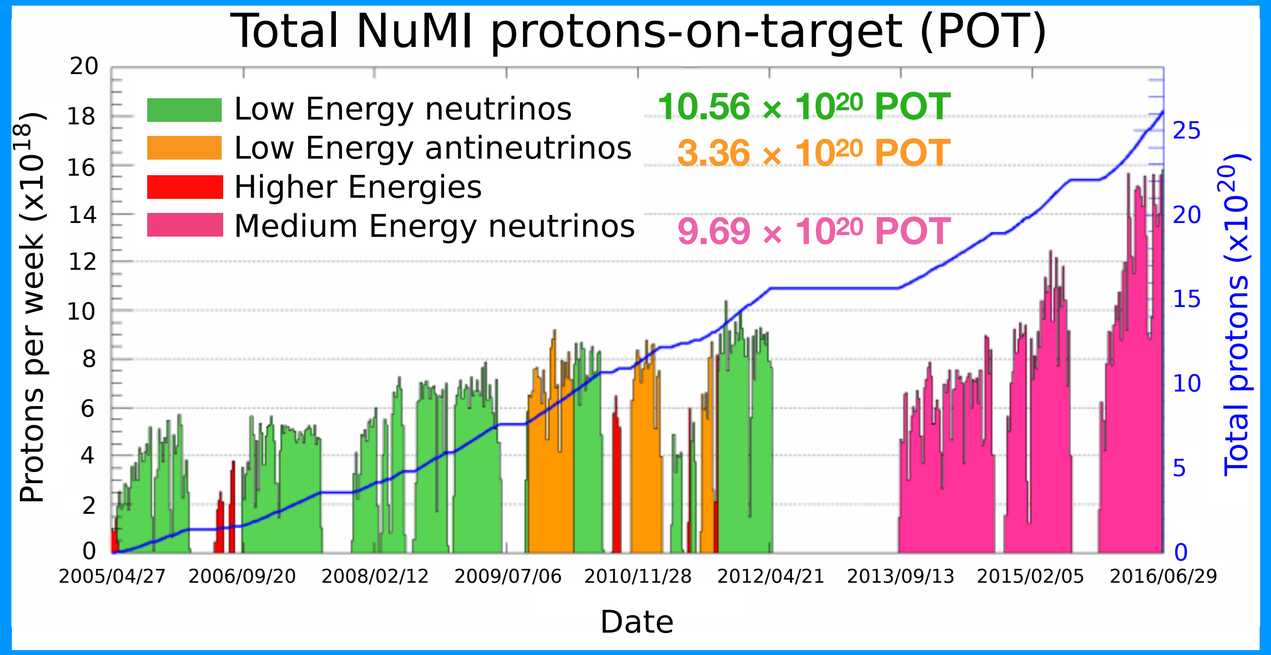
ν_e Charged Current (CC)

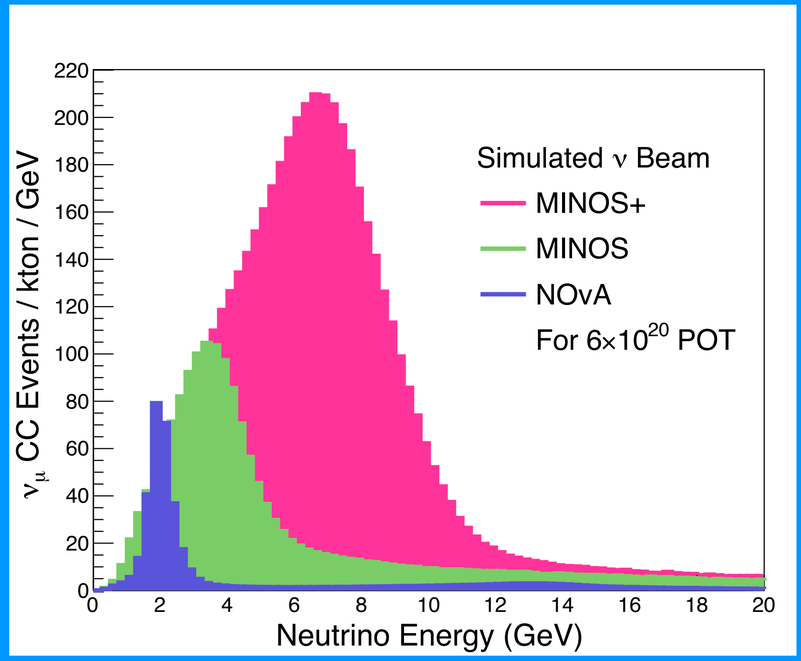


Neutral Current (NC)



Beam Neutrinos Exposure



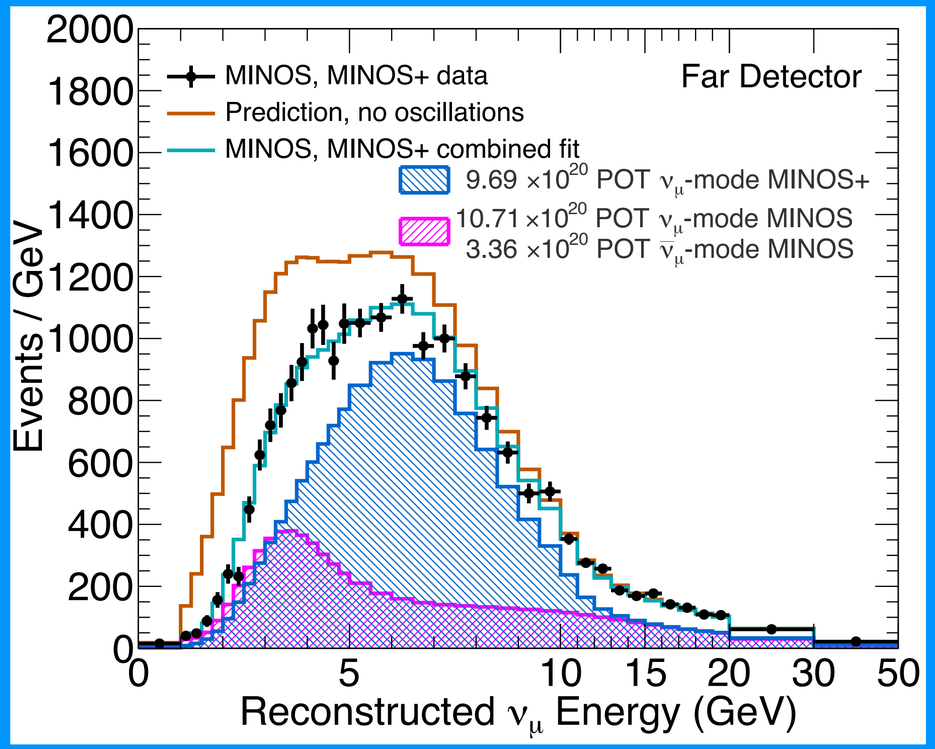


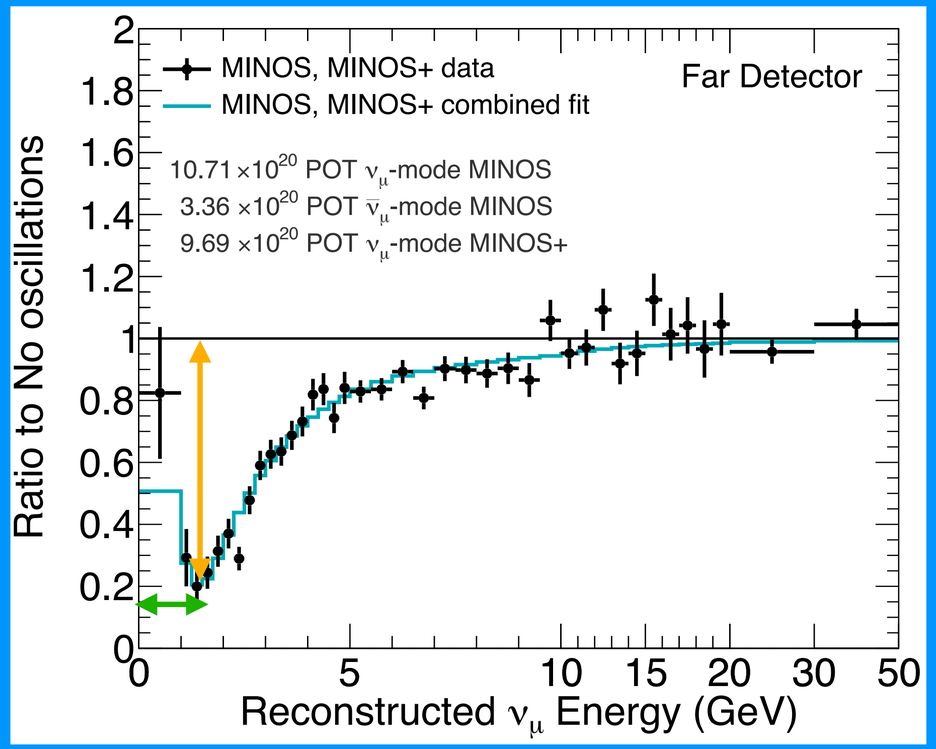
- 23.61 x 10^{20} protons on target (11 years of accelerator neutrino data)
- 60.75 kt-yr exposure (13 years of atmospheric neutrino data)

7

Three Falvours Oscillation Results

Far Detector Beam Data



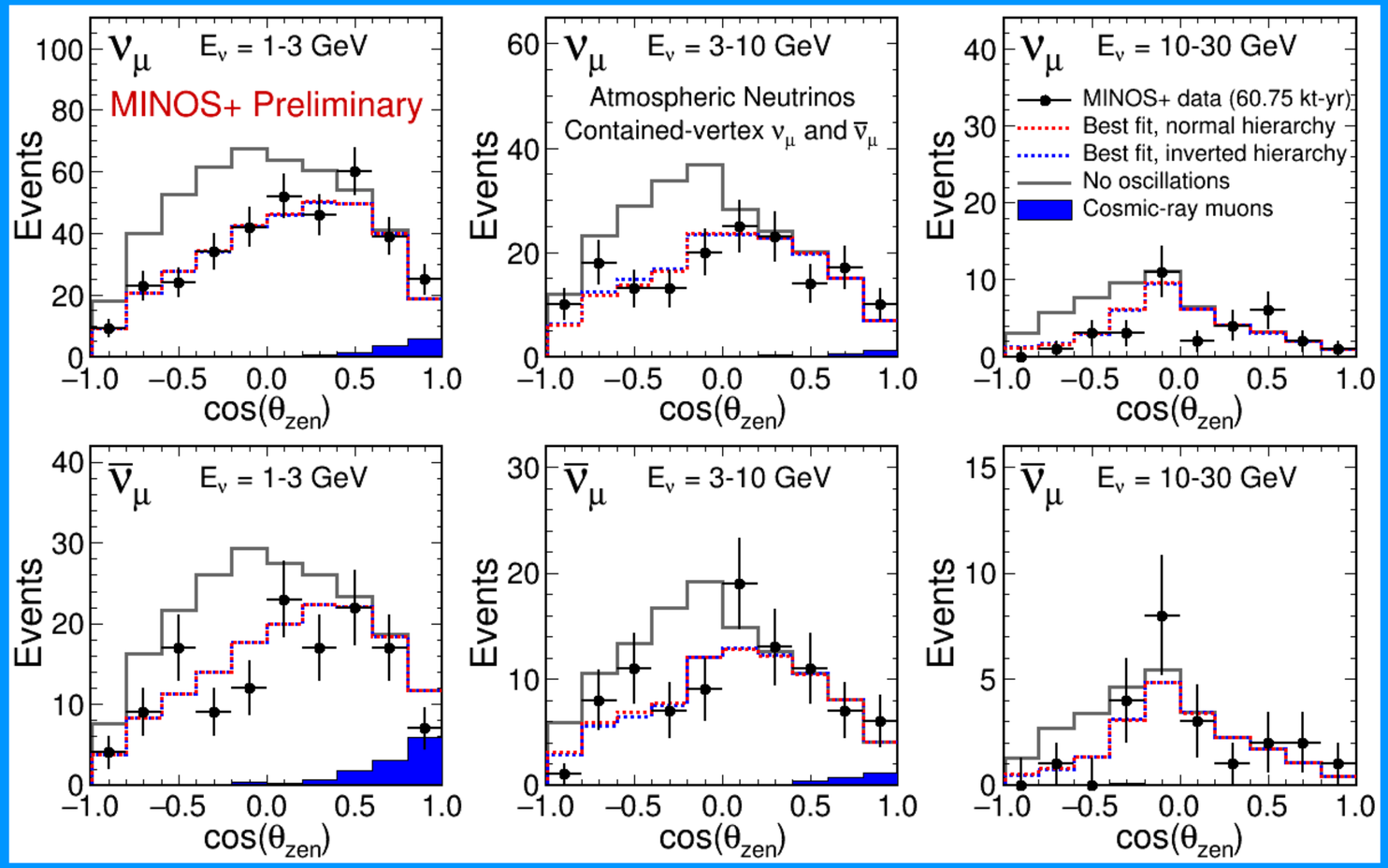


$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \cos^2\theta_{13}\sin^2(2\theta_{23})\sin^2\frac{\Delta m^2_{32} L}{4E_\nu}$$

Atmospheric Data

ν_μ

$\bar{\nu}_\mu$

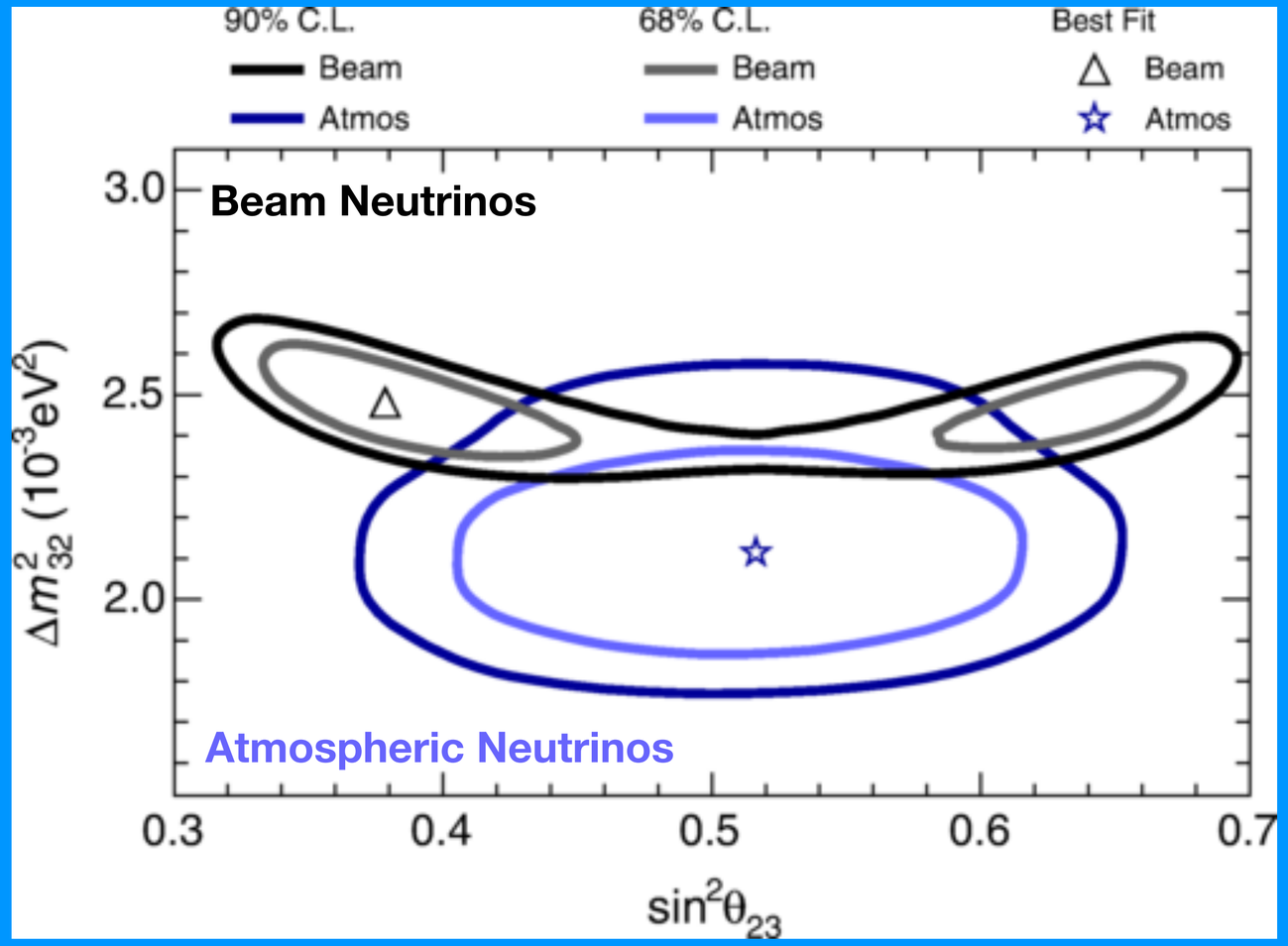


Independent from Beam Data

- Different baselines

Fit in neutrino energy and $\cos(\theta_{zen})$

Beam and Atmospheric Constraints



Beam Best Fit
Normal Hierarchy

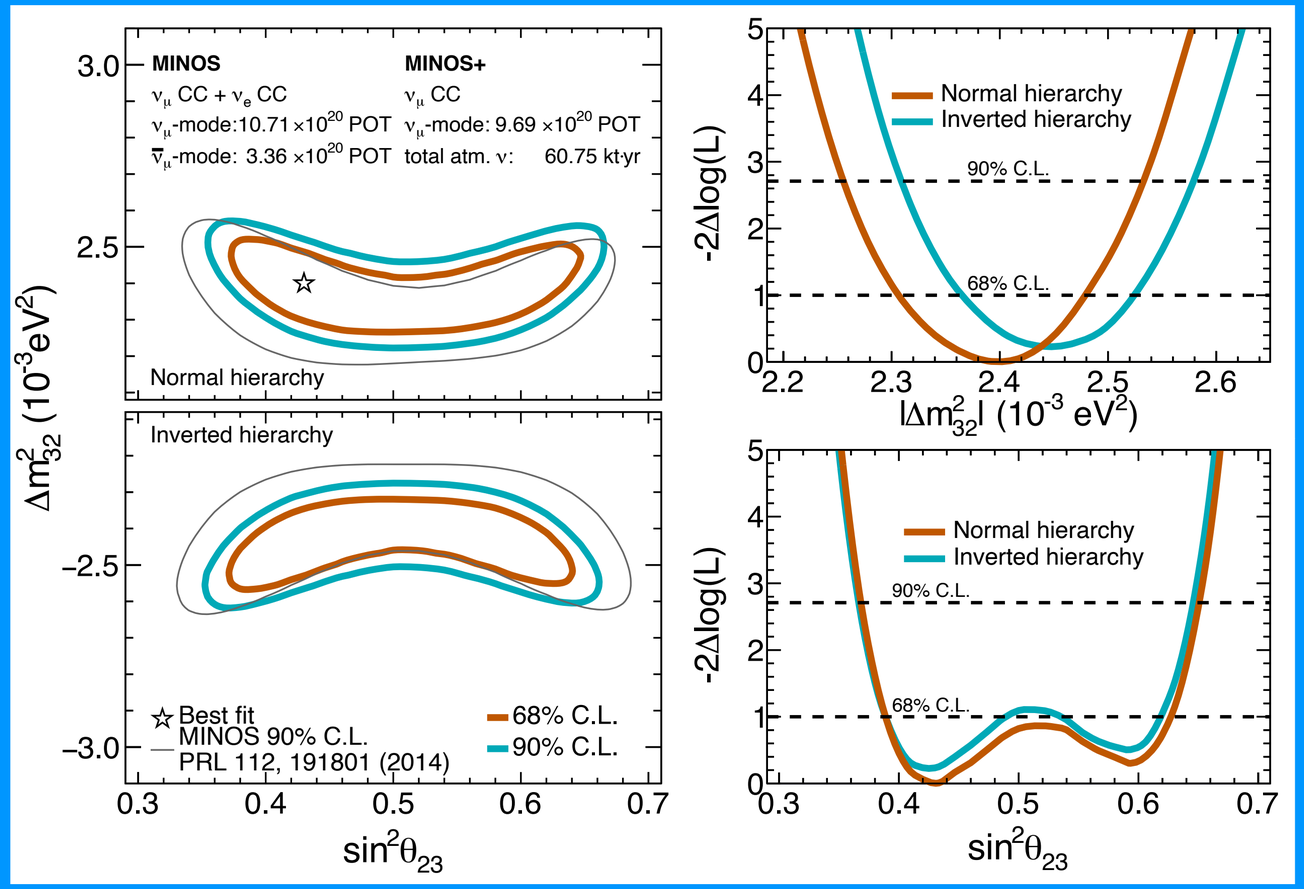
$$\Delta m^2_{32} = 2.48 \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.38$$

Atmospheric Best Fit
Normal Hierarchy

$$\Delta m^2_{32} = 2.11 \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.52$$

Results consistent with the combined fit with a p-value of 22%

Combined Fit



Best fit in Normal Hierarchy

$\Delta m^2_{32} = 2.40^{+0.08}_{-0.09} \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2\theta_{23} = 0.43\ (0.39 \leftrightarrow 0.63)$

Inverted Hierarchy

$\Delta m^2_{32} = 2.45^{+0.07}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2\theta_{23} = 0.42\ (0.39 \leftrightarrow 0.49)$

Disfavor maximal mixing:	0.91σ
Preference for lower octant:	0.55σ
Preference for normal hierarchy:	0.45σ

Combined Fit

Comparing with Other Experiments

Best fit in Normal Hierarchy

$$\Delta m^2_{32} = 2.40^{+0.08}_{-0.09} \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.43\ (0.39 \leftrightarrow 0.63)$$

Inverted Hierarchy

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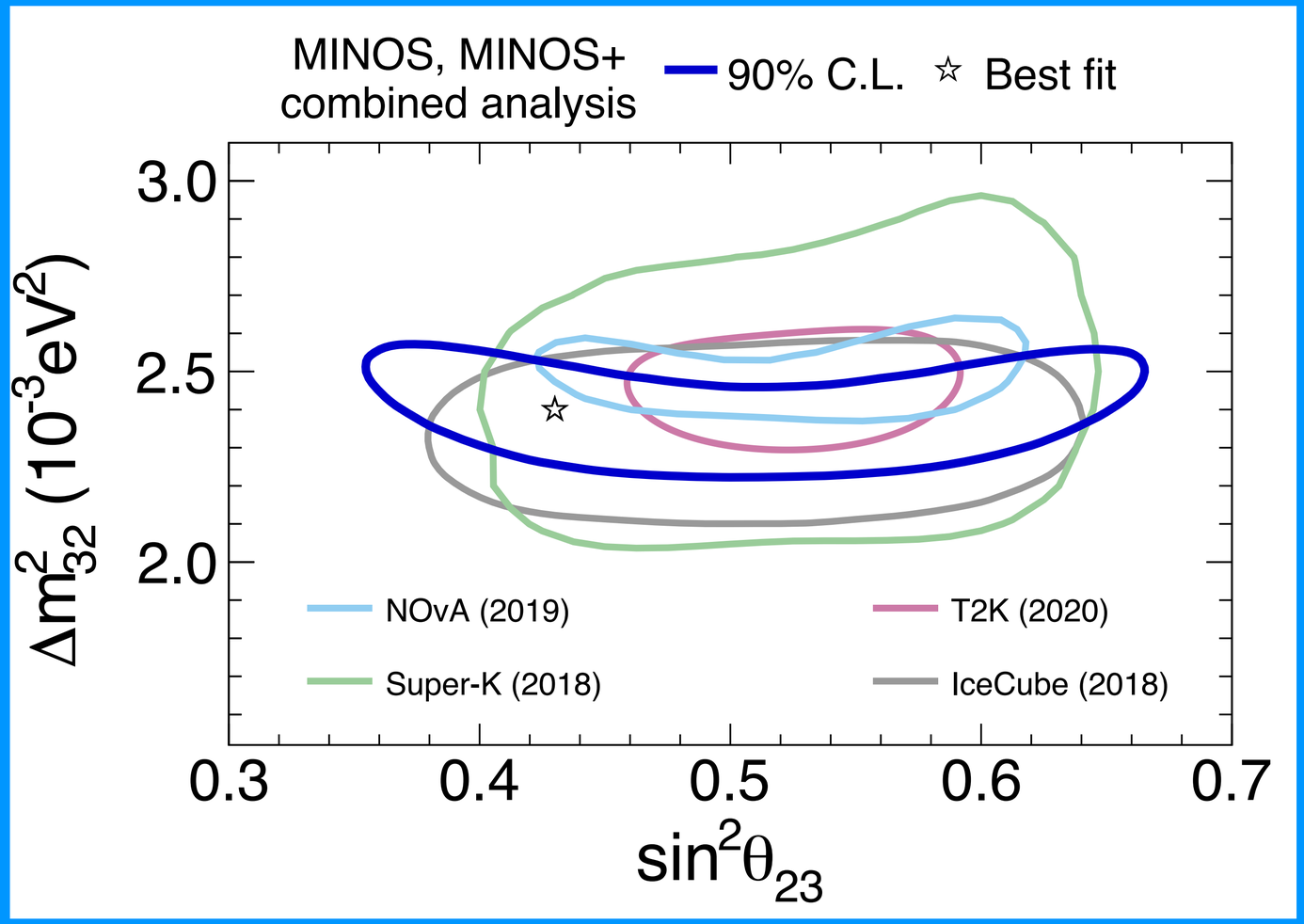
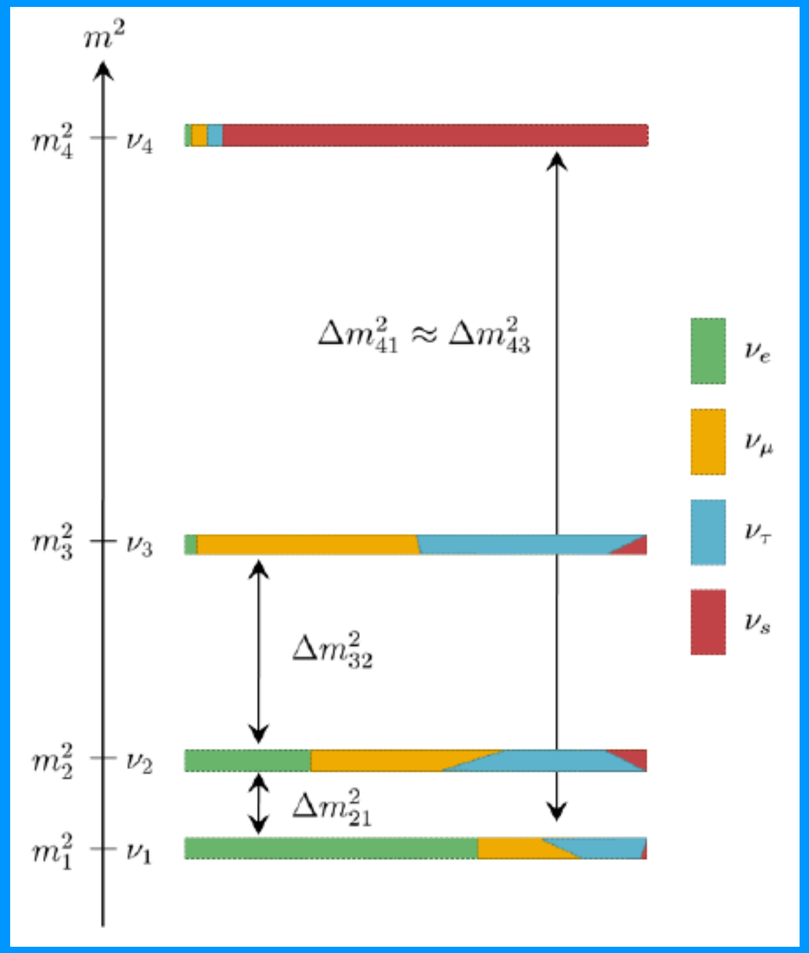
Phys. Rev. Lett. **125**, 131802 (2020)



Beyond Three Flavour Standard Oscillation

Sterile Neutrinos 3+1 Model

New Mass Eigenstate



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

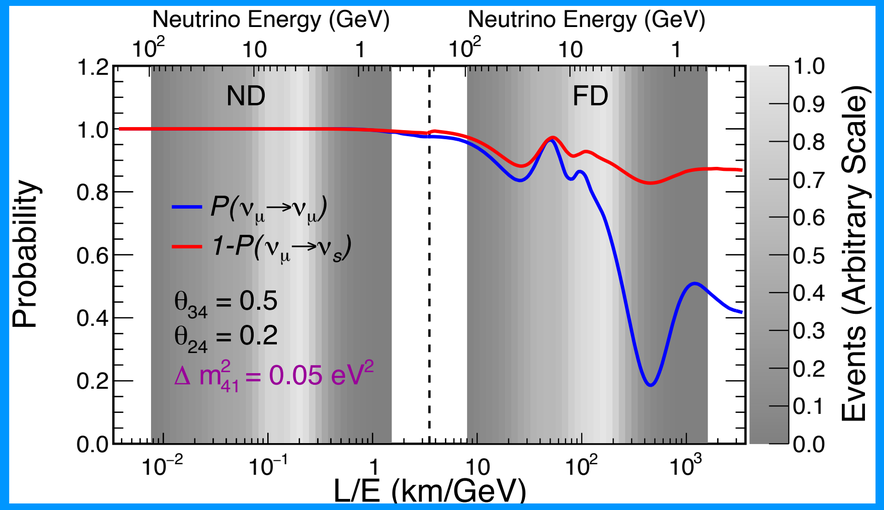
- 3 mass scales: Δm^2_{21}, Δm^2_{32}, Δm^2_{41}
- 6 mixing angles: θ_{12}, θ_{23}, θ_{13}, θ_{14}, θ_{24}, θ_{34}
- 3 CP-violating phases: δ_{13}, δ_{14}, δ_{24}

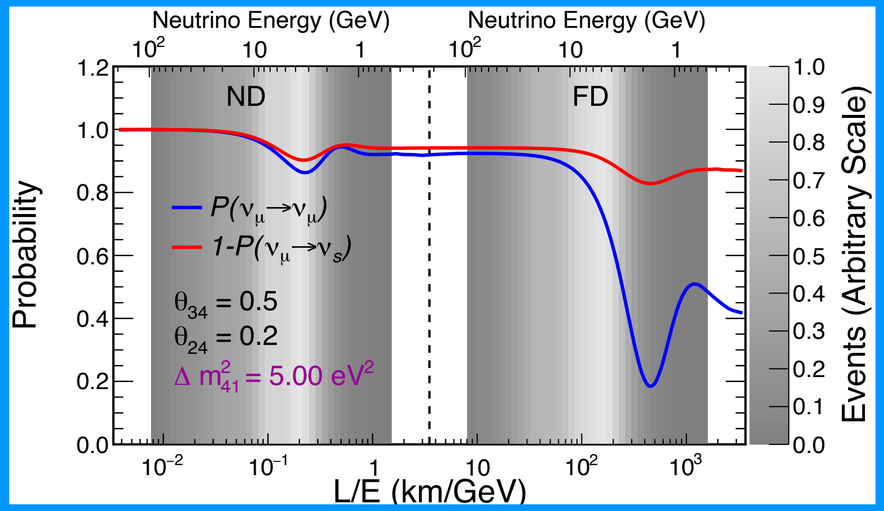
4 Flavour Oscillations at MINOS

Small

Δm^2_{41}

Large





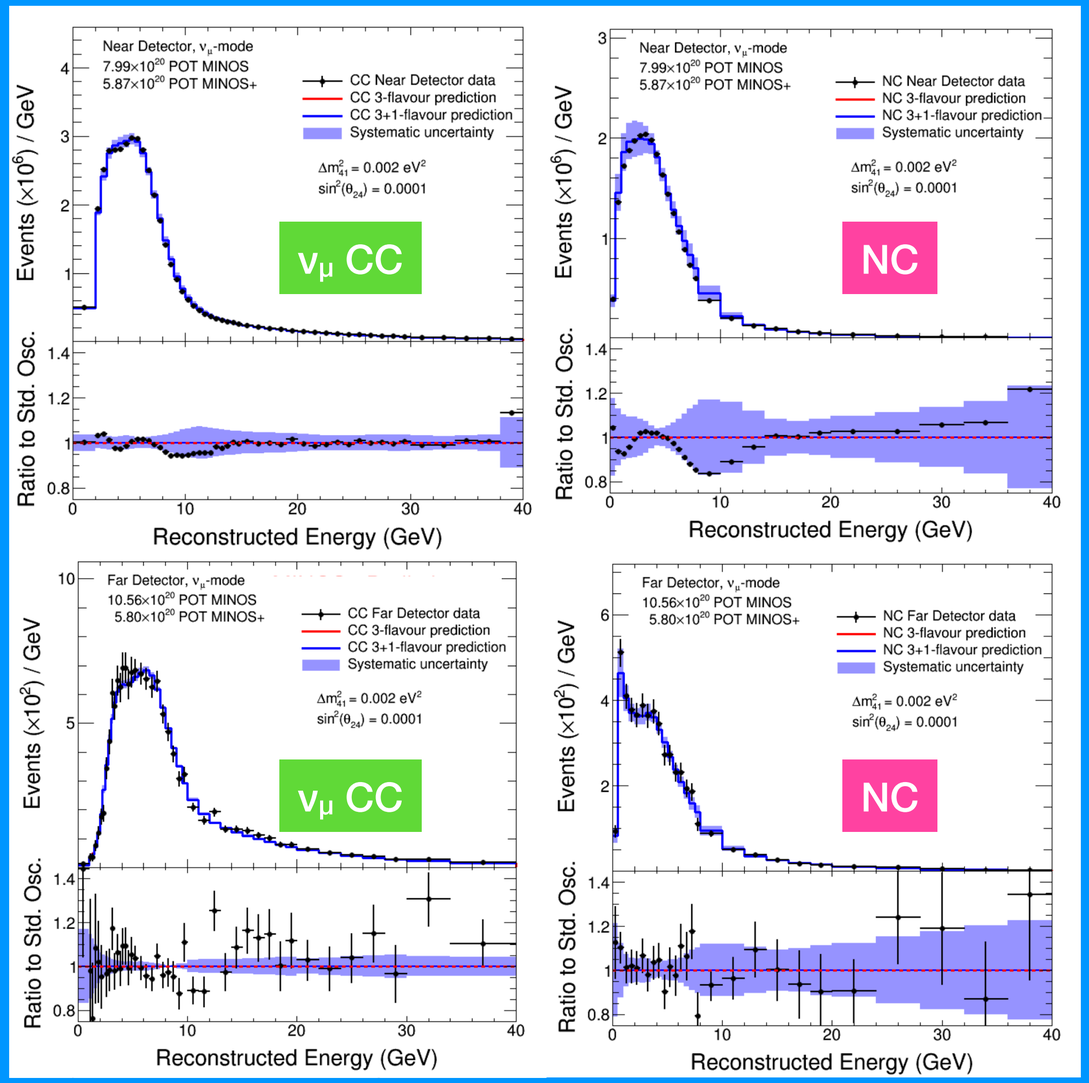
Small Δm^2_{41} :
Oscillations at the FD

Large Δm^2_{41}:
Large oscillations at the ND

Sterile Neutrino Fit - Data Sampels

Near Detector

Far Detector



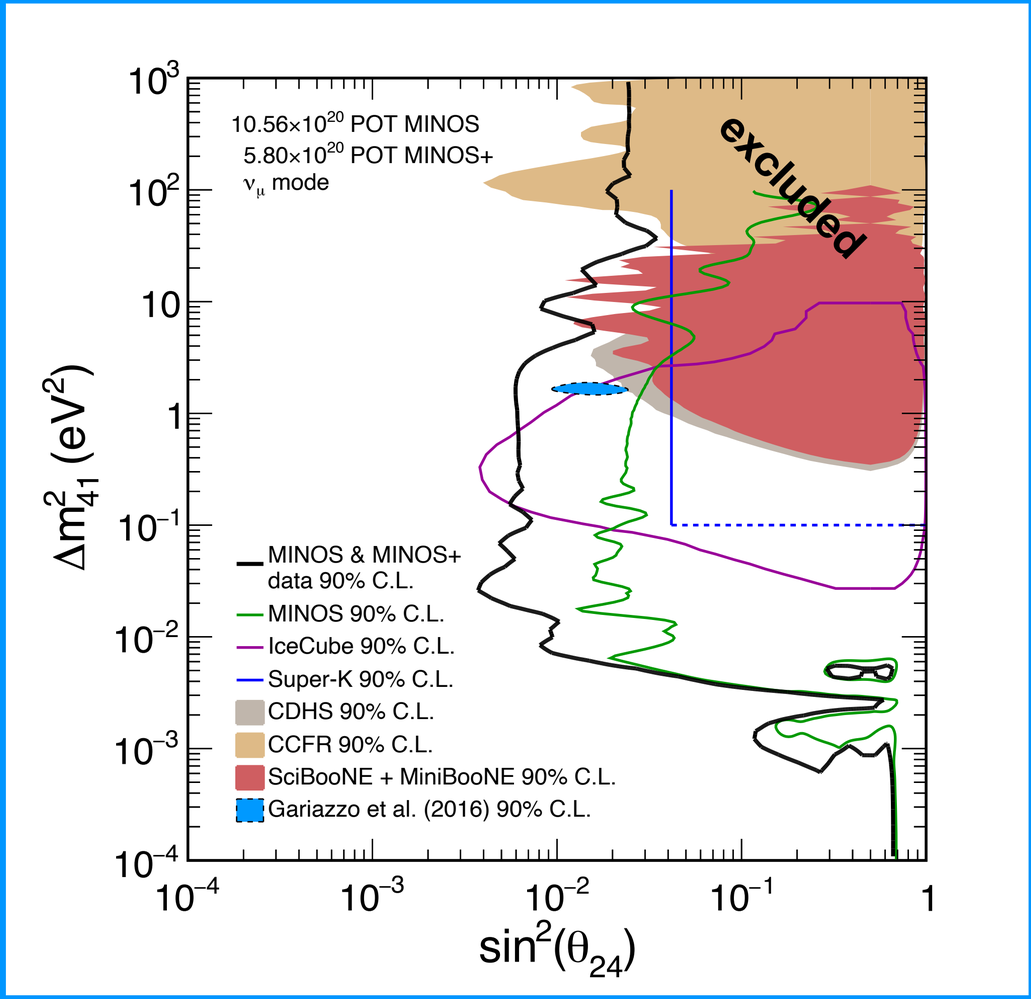
Two Detector Fit

CC EVENTS
Sensitive to Δm^2_{41} and θ_{24}

NC EVENTS
Sensitive to Δm^2_{41} and θ_{24}
Sensitive to θ_{34}

MINOS+ Exclusion

Phys. Rev. Lett. **122**, 091803 (2019)



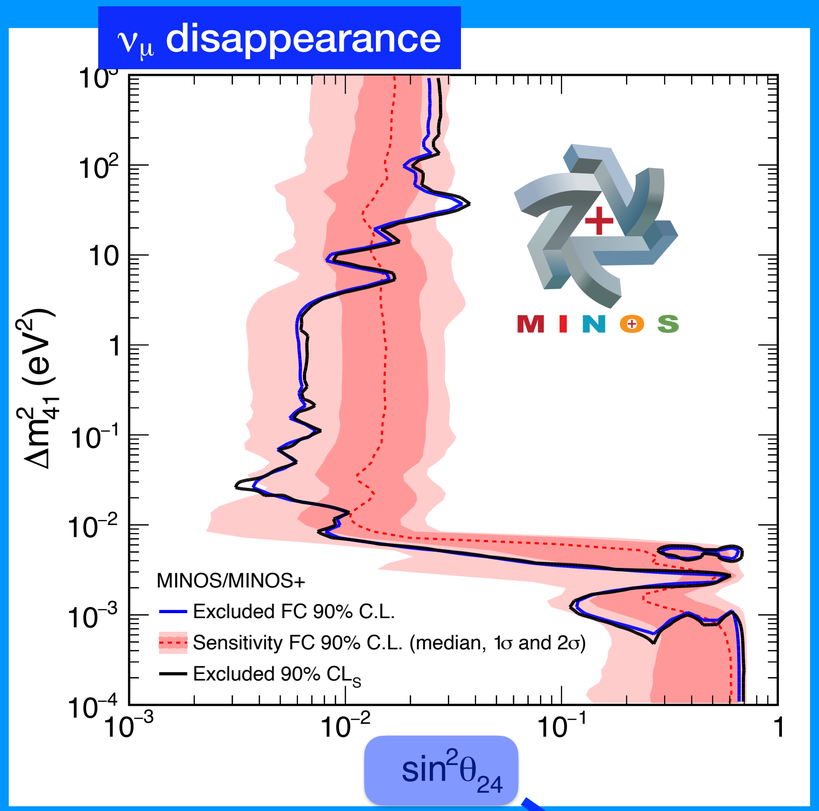
Fit θ_{23}, θ_{24}, Δm^2_{32}, and Δm^2_{41}

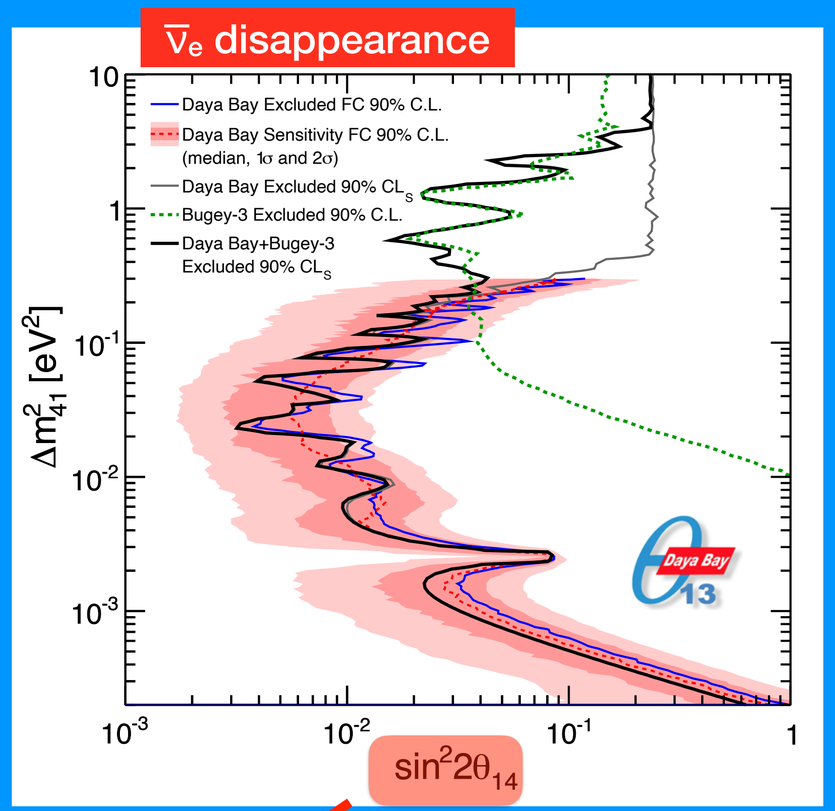
Fix δ_{13}, δ_{14}, δ_{24}, and θ_{14} to zero (no sensitivity)

- Simultaneous 2 detector fit over long baseline
- Improvement over previous FD/ND ratio method
- Improvement with MINOS+ extra statistics

MINOS+/Daya Bay/Bugey-3 Exclusion

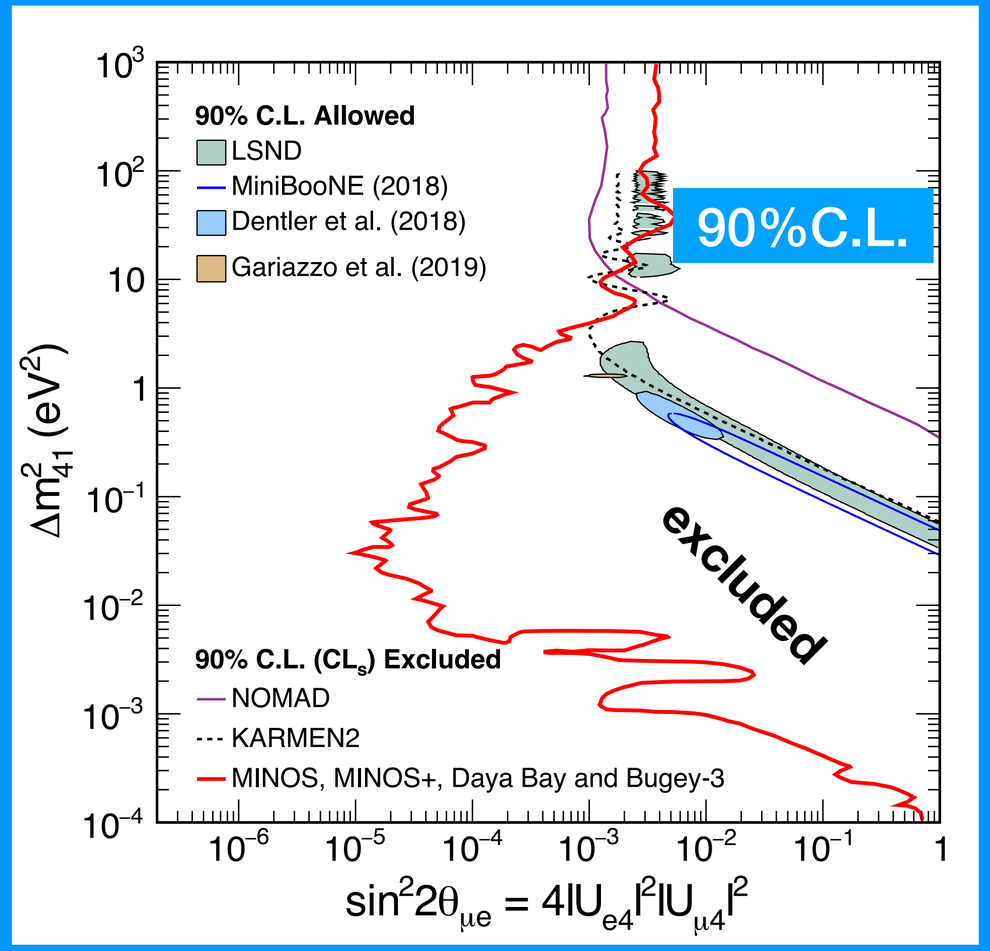
Phys. Rev. Lett. **125**, 071801

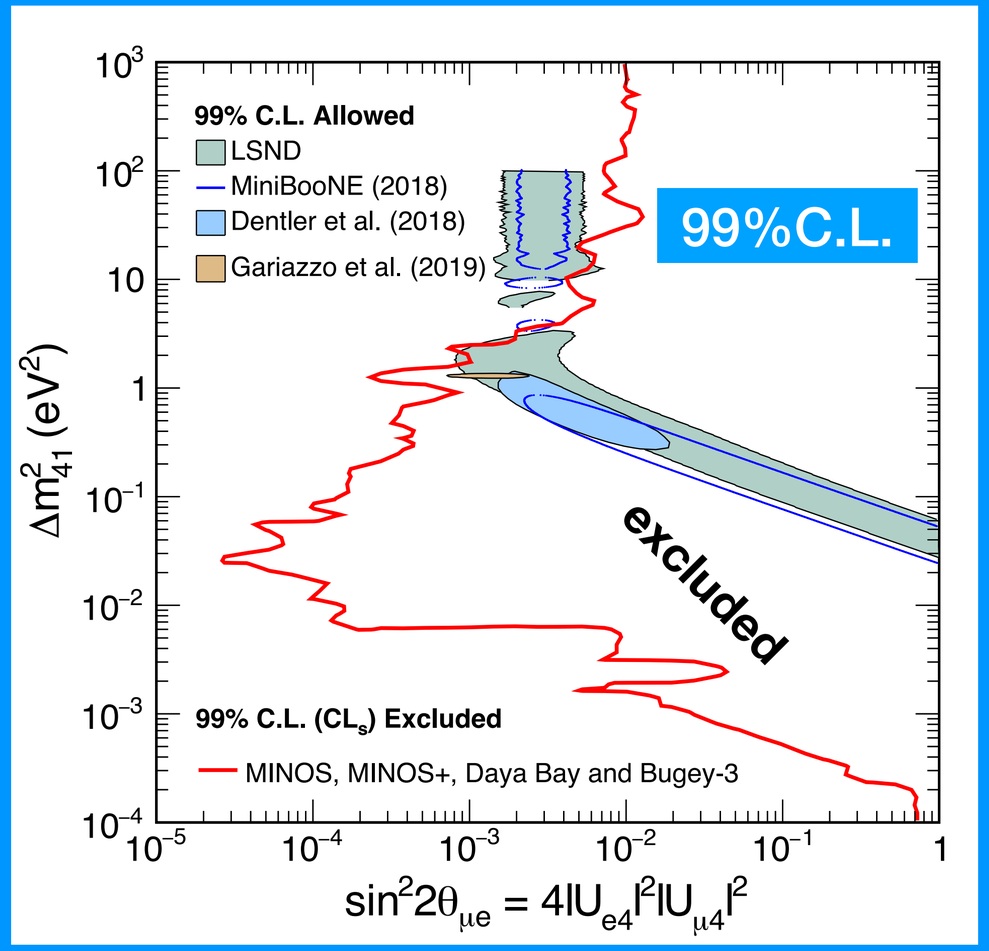




$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

MINOS+/Daya Bay/Bugey-3 Exclusion





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

Sterilre driven ν_e appearance

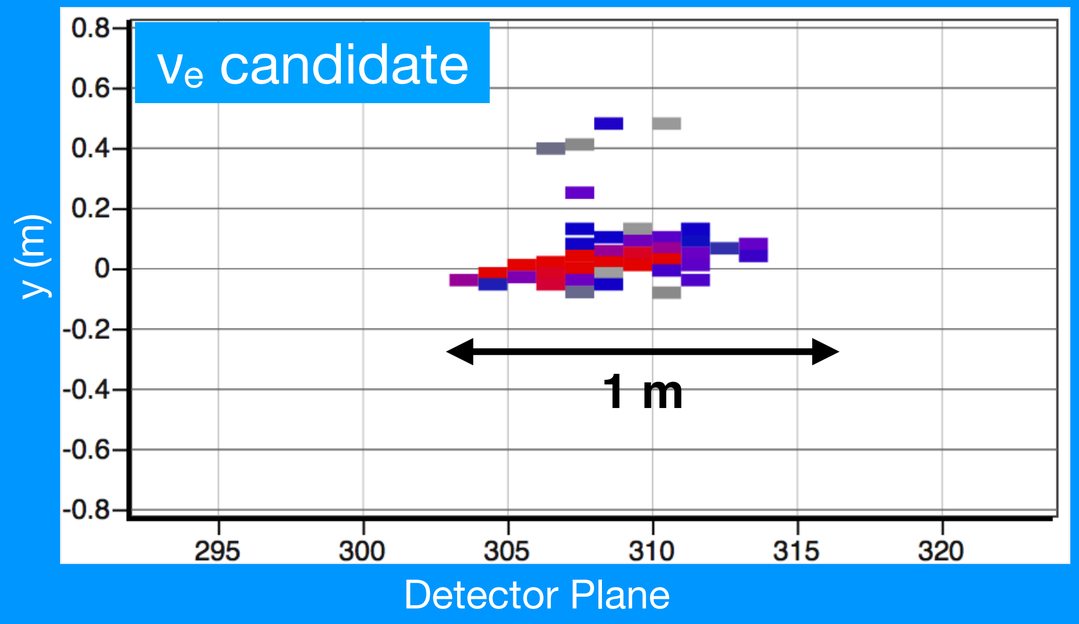
Sterile-driven ν_e Appearance

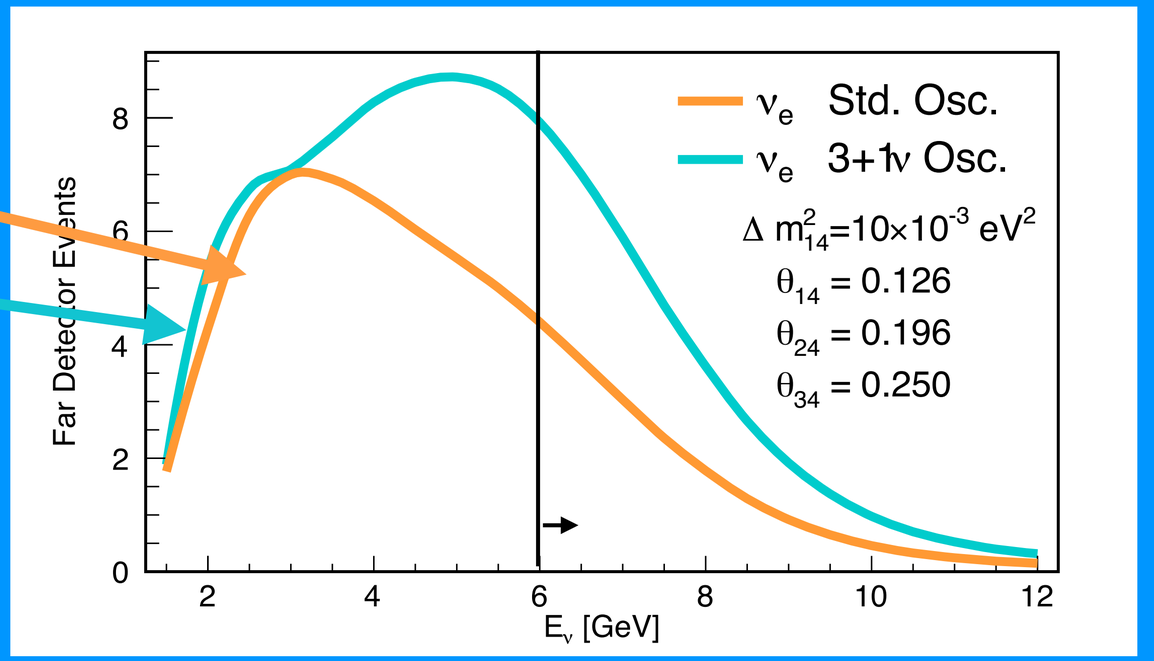
3-flavor terms

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(1.27\Delta m^2 L/E)$$

$$+ \sin(\theta_{23})\sin(2\theta_{13})\sin(2\theta_{24})\sin(\theta_{14})\sin^2\Delta_{32} + \sin^2(2\theta_{14})\sin^2(\theta_{24})\sin^2\Delta_{43} + \ldots$$

3+1 terms

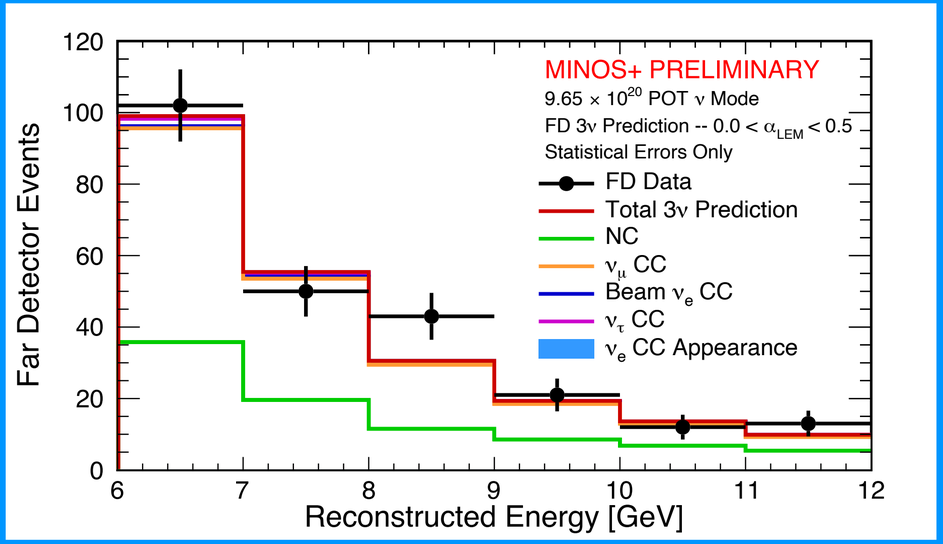




- MINOS+ data set is at high energy
- Standard ν_e sample drops off above 6 GeV
- Signal events are more compact showers
- Background to ν_e events in MINOS+ manageable at high energy

3 flavour ν_e

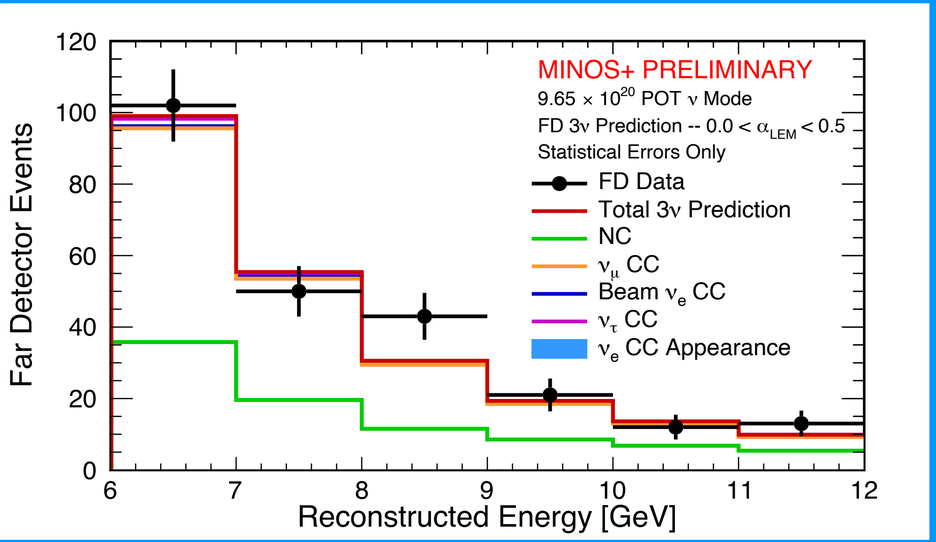
Background -like Events

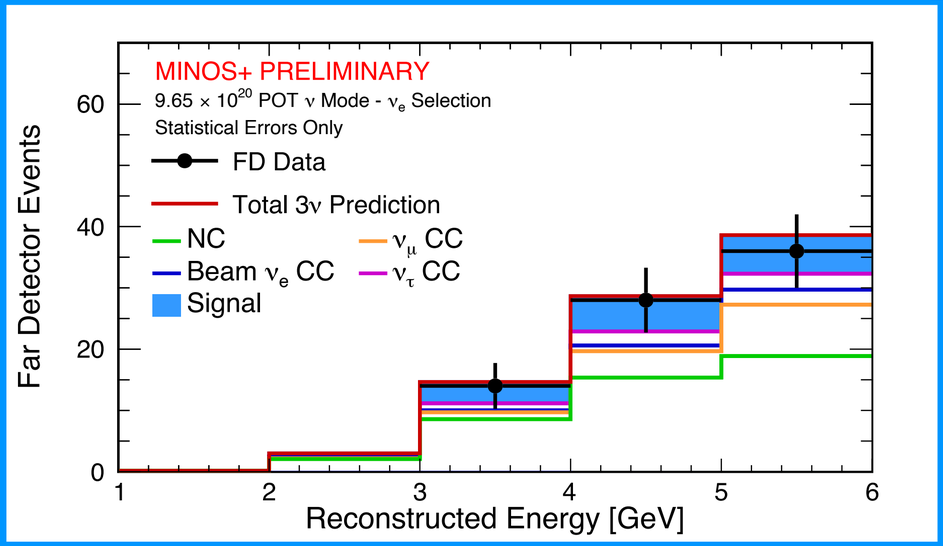


3 flavour ν_e

Low Energy ν_e like Events

Background -like Events

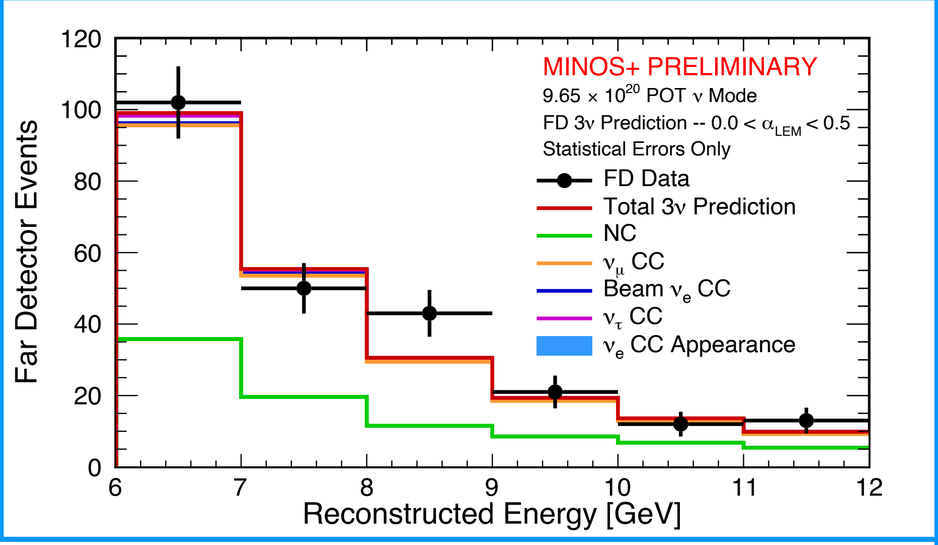


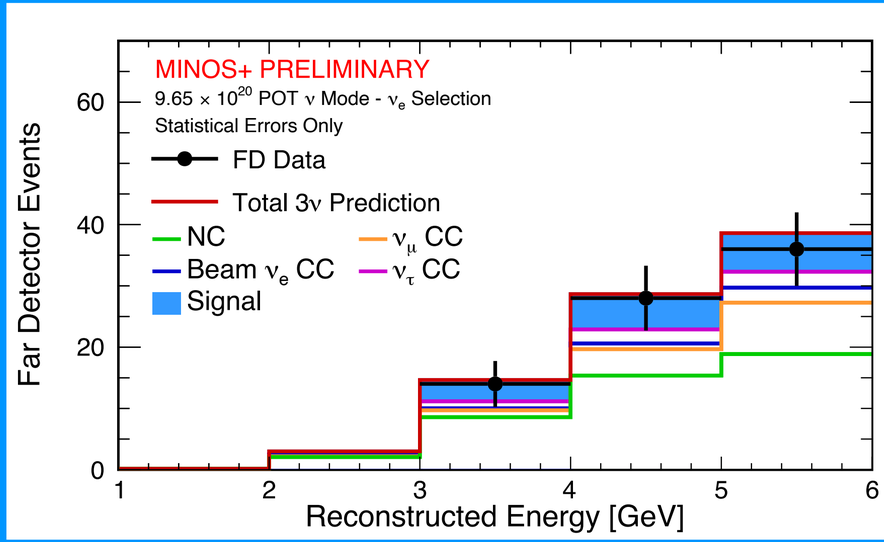


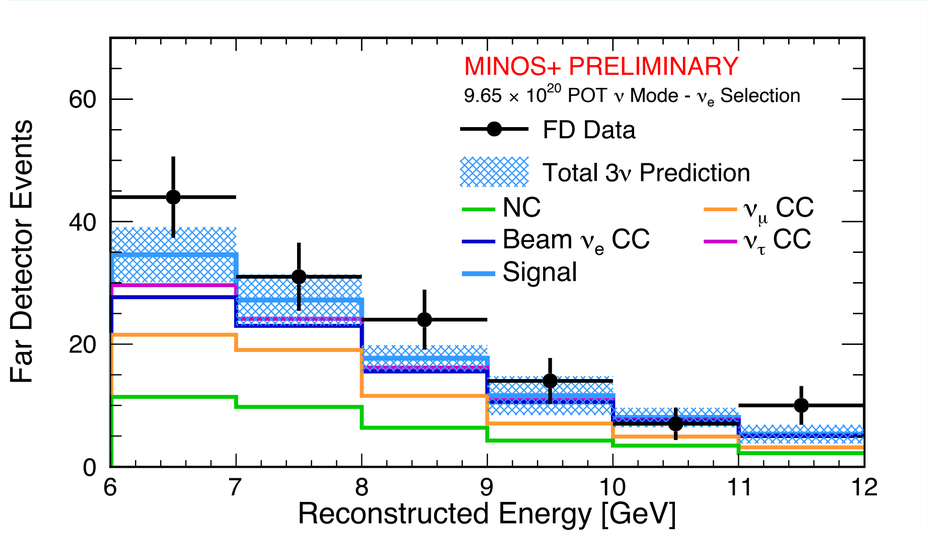
3 flavour ν_e

Low Energy ν_e like Events

Background -like Events



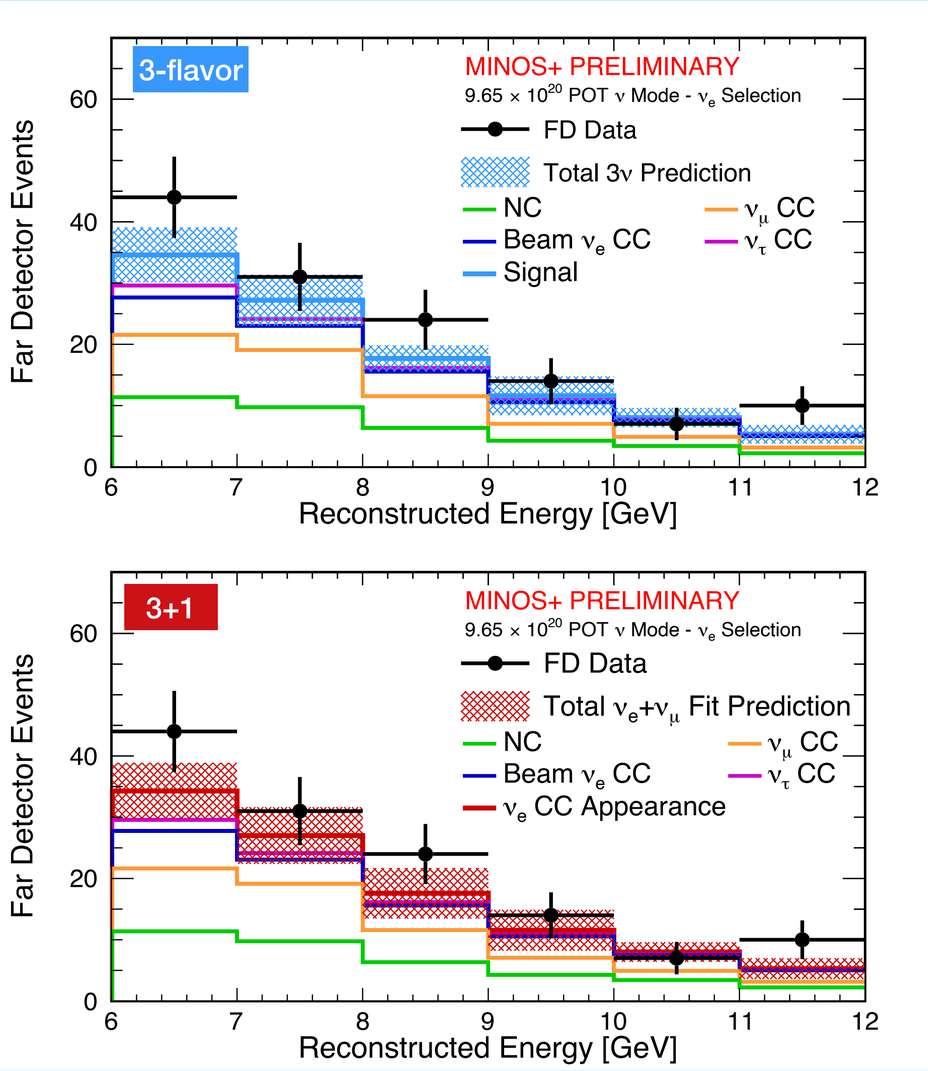




Signal Region ν_e like Events

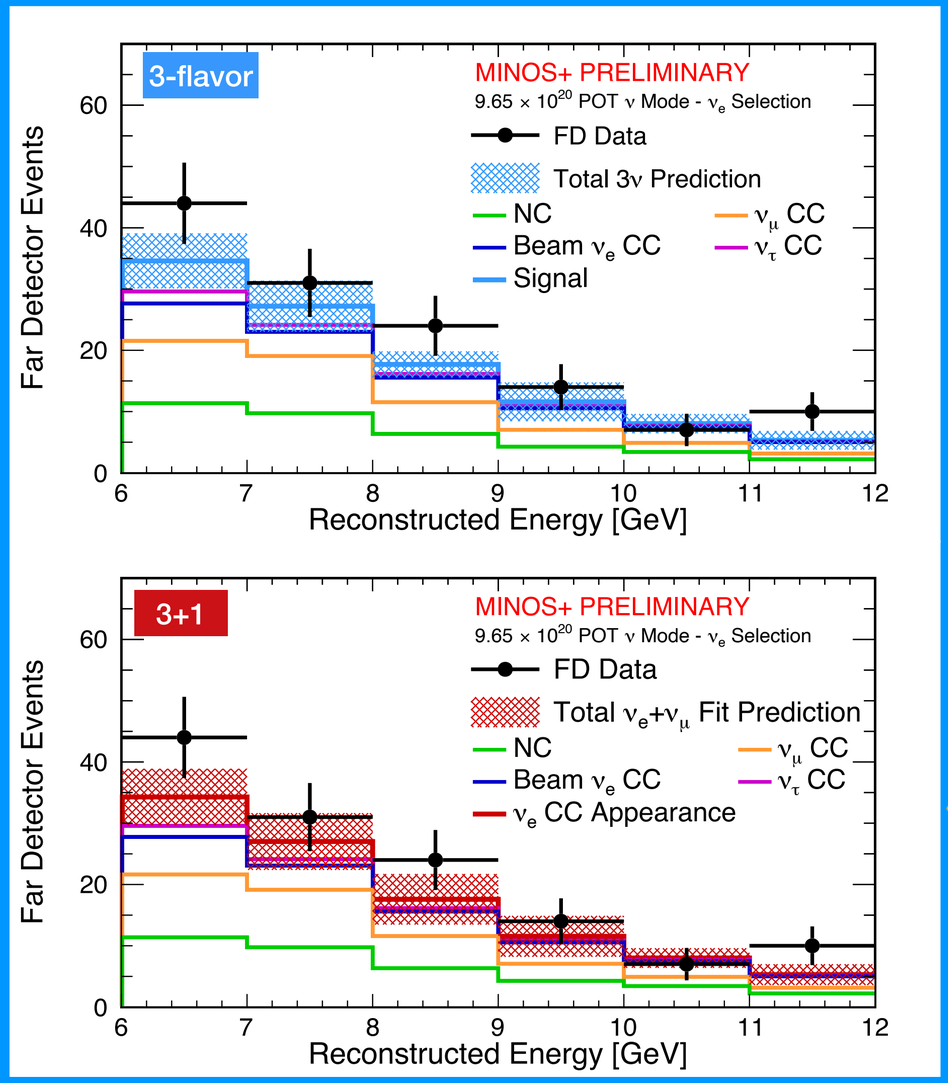
Consistent with 3-flavor oscillations

Joint $\nu_e - \nu_\mu$ Fit

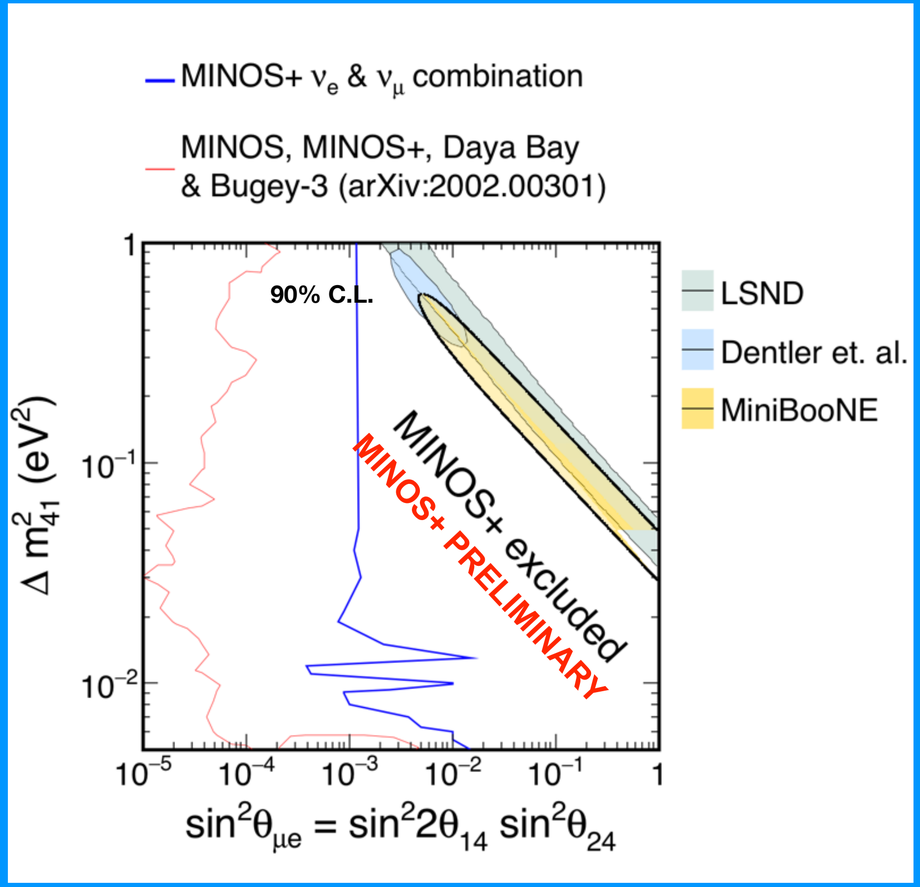


Using MINOS/MINOS+ appearance and disappearance

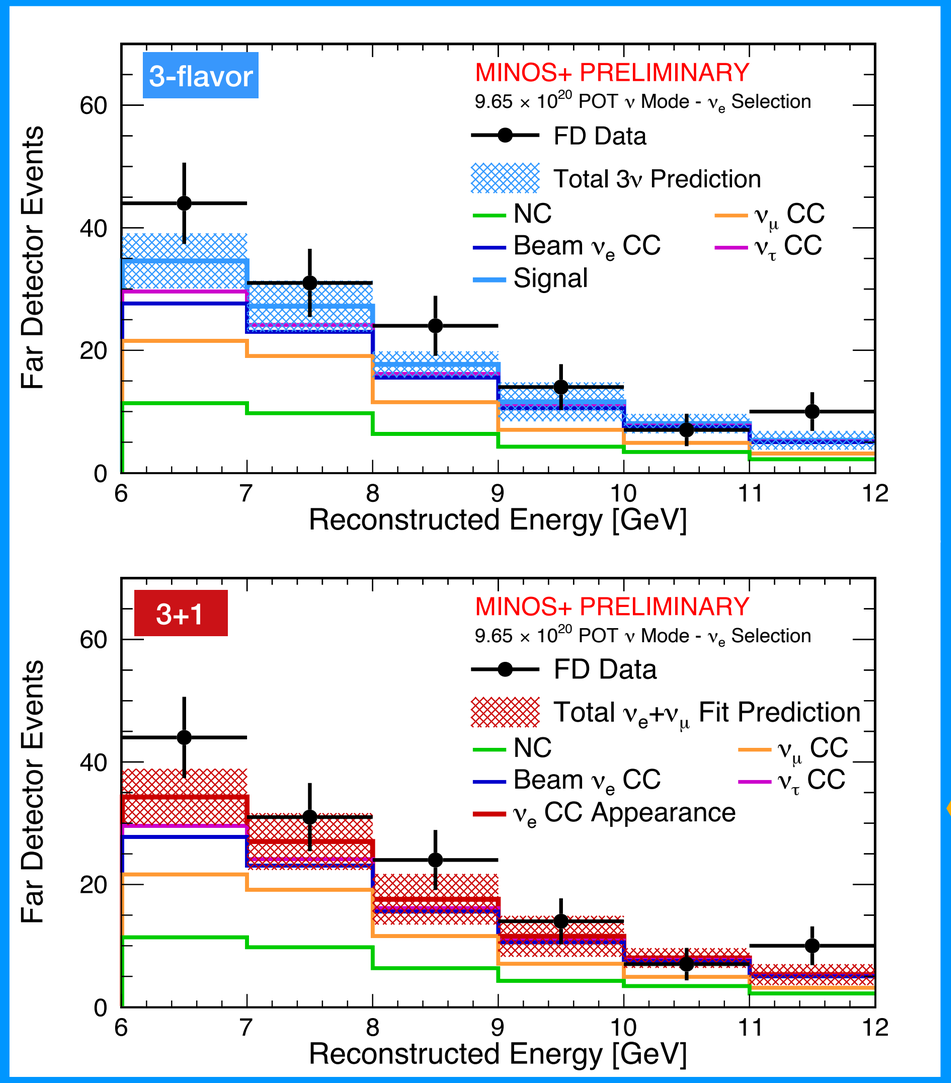
Joint $\nu_e - \nu_\mu$ Fit



Using MINOS/MINOS+ appearance and disappearance

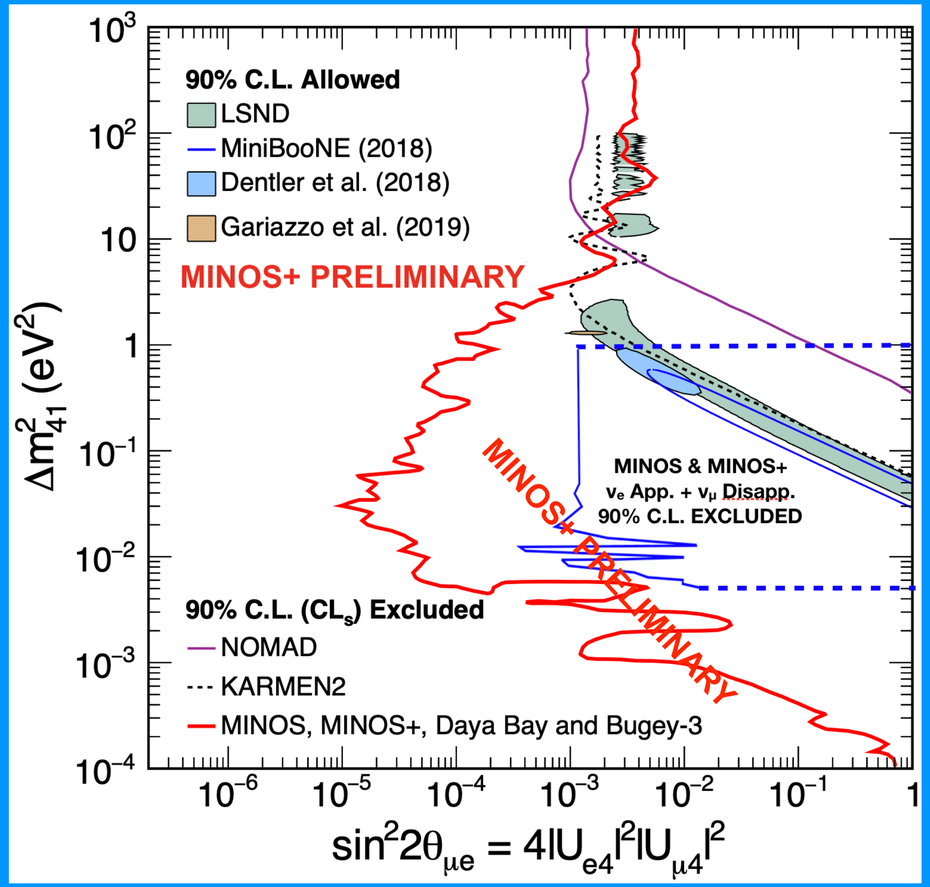


Joint $\nu_e - \nu_\mu$ Fit



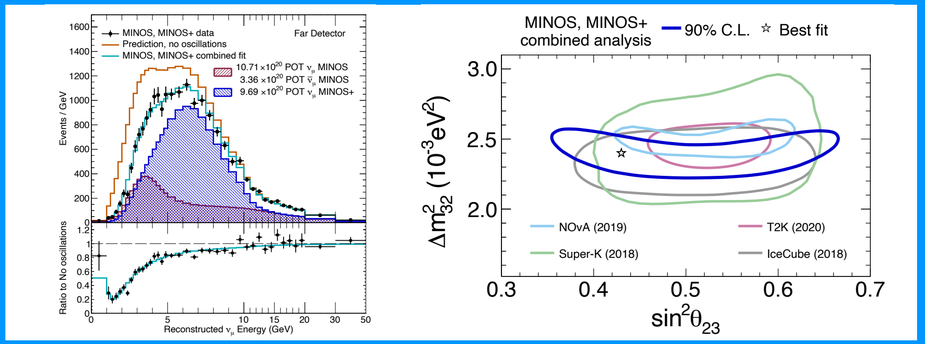
Using MINOS/MINOS+ appearance and disappearance

Complementary to MINOS+/Daya Bay/Bugey-3 Combination

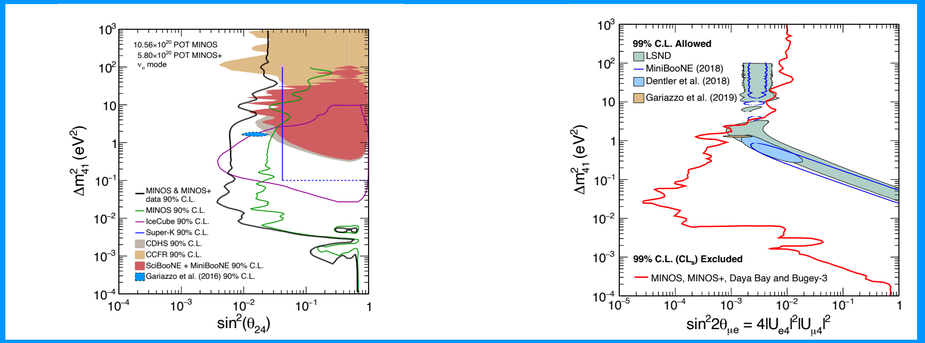


Conlclusions

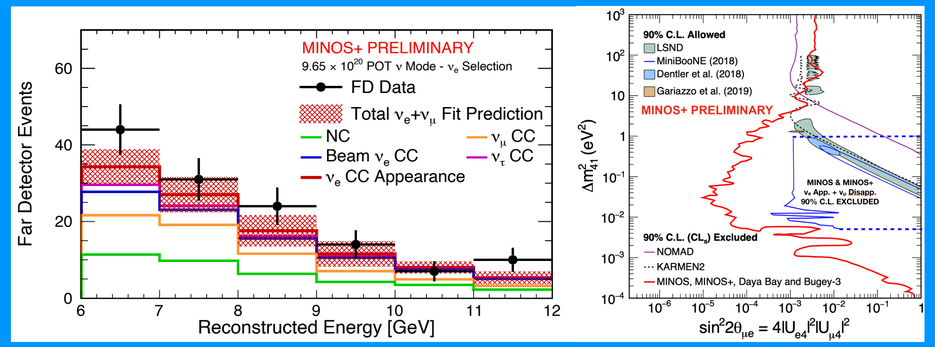
High stats long-baseline ν_μ disappearance:
tight constraints on 3 ν paradigm



High stats long-baseline ν_μ disappearance:
tight constraints on "3+1" ν paradigm
and in combination with Daya Bay and Bugey-3

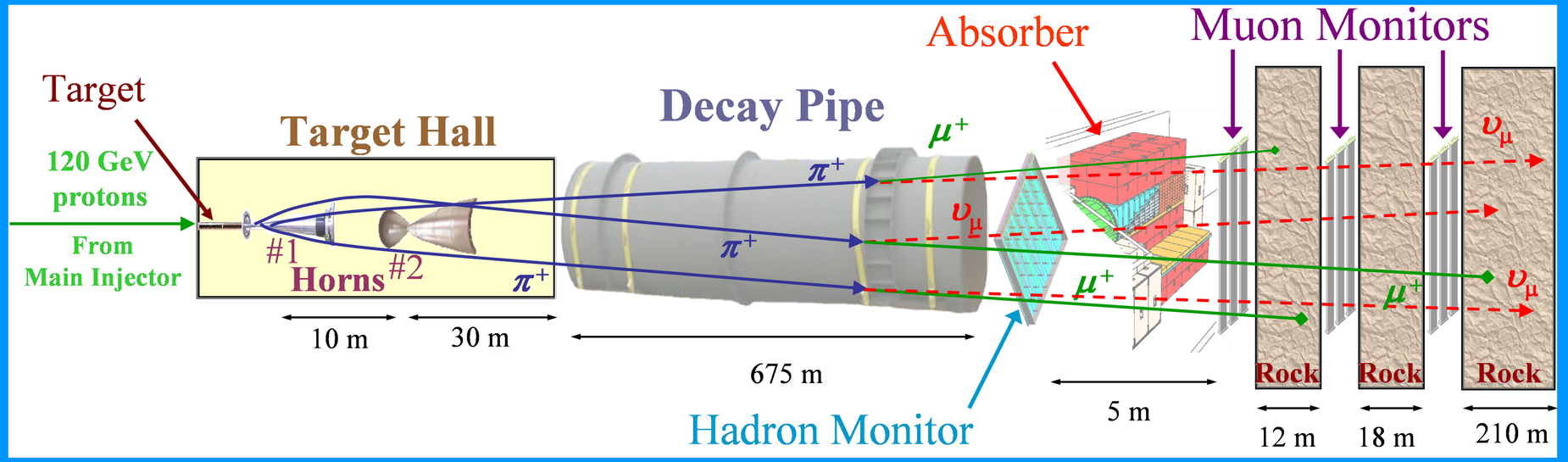


Exclude large parameter space of "3+1" ν models
from MINOS/MINOS+
ν_e appearance + ν_μ disappearance search



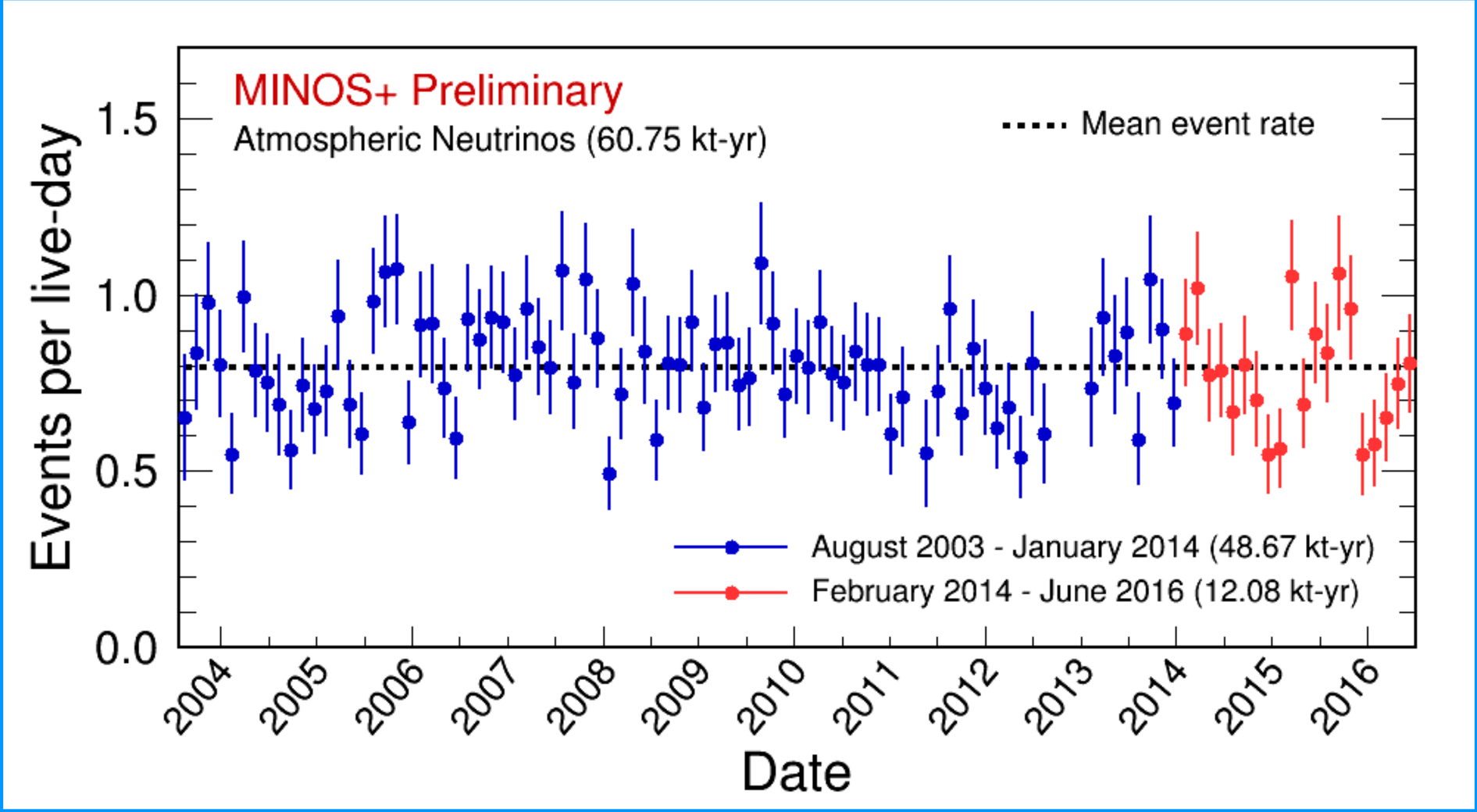
BACKUP

NuMI Beamline



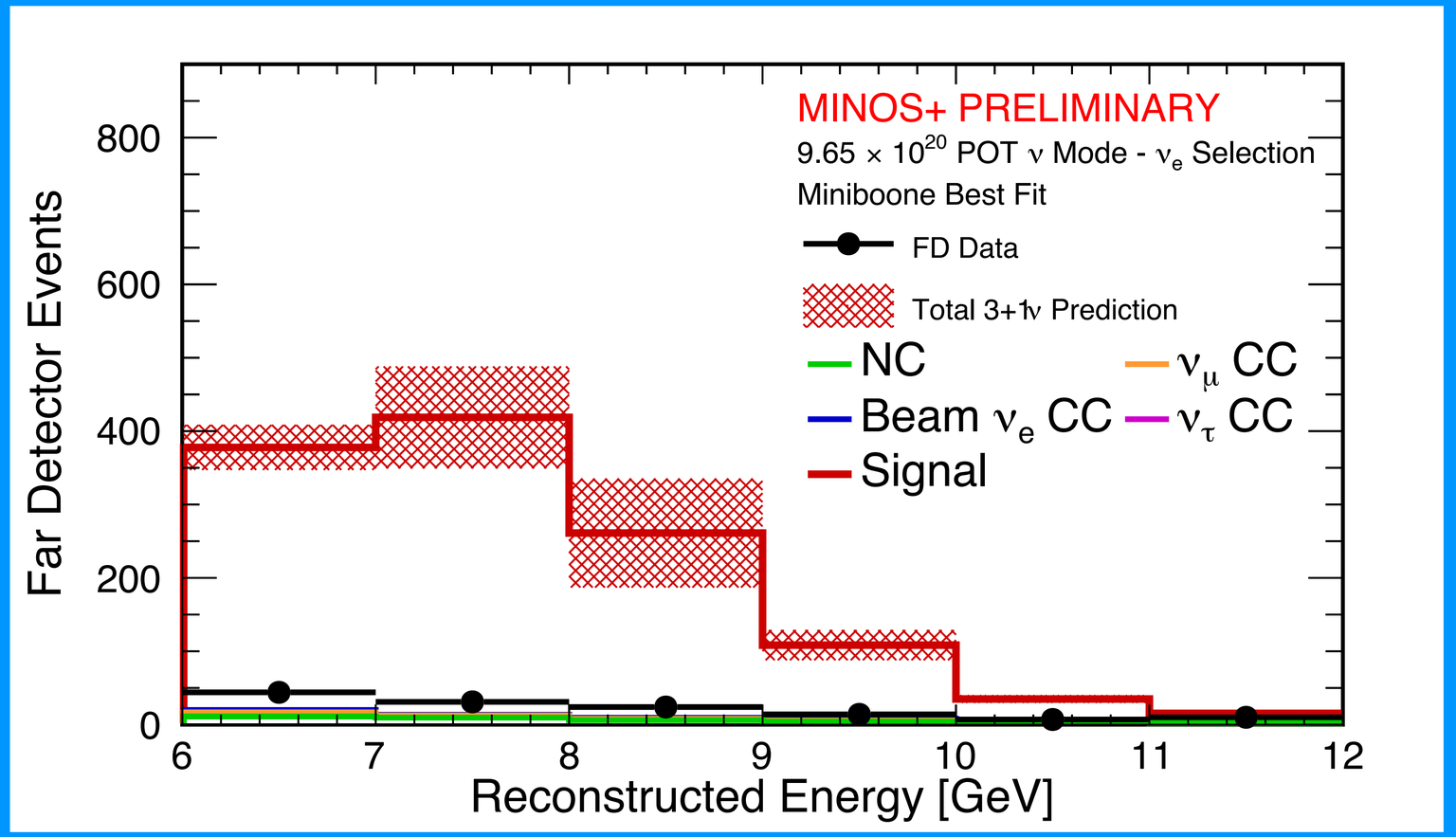
- 120 GeV protons hit a graphite target
- Two magnetic horns focus produced pions and kaons
  - ν_μ beam, focus π^+ and K^+
  - $\bar{\nu}_\mu$ beam, focus π^- and K^-

Atmospheric Neutrino Exposure

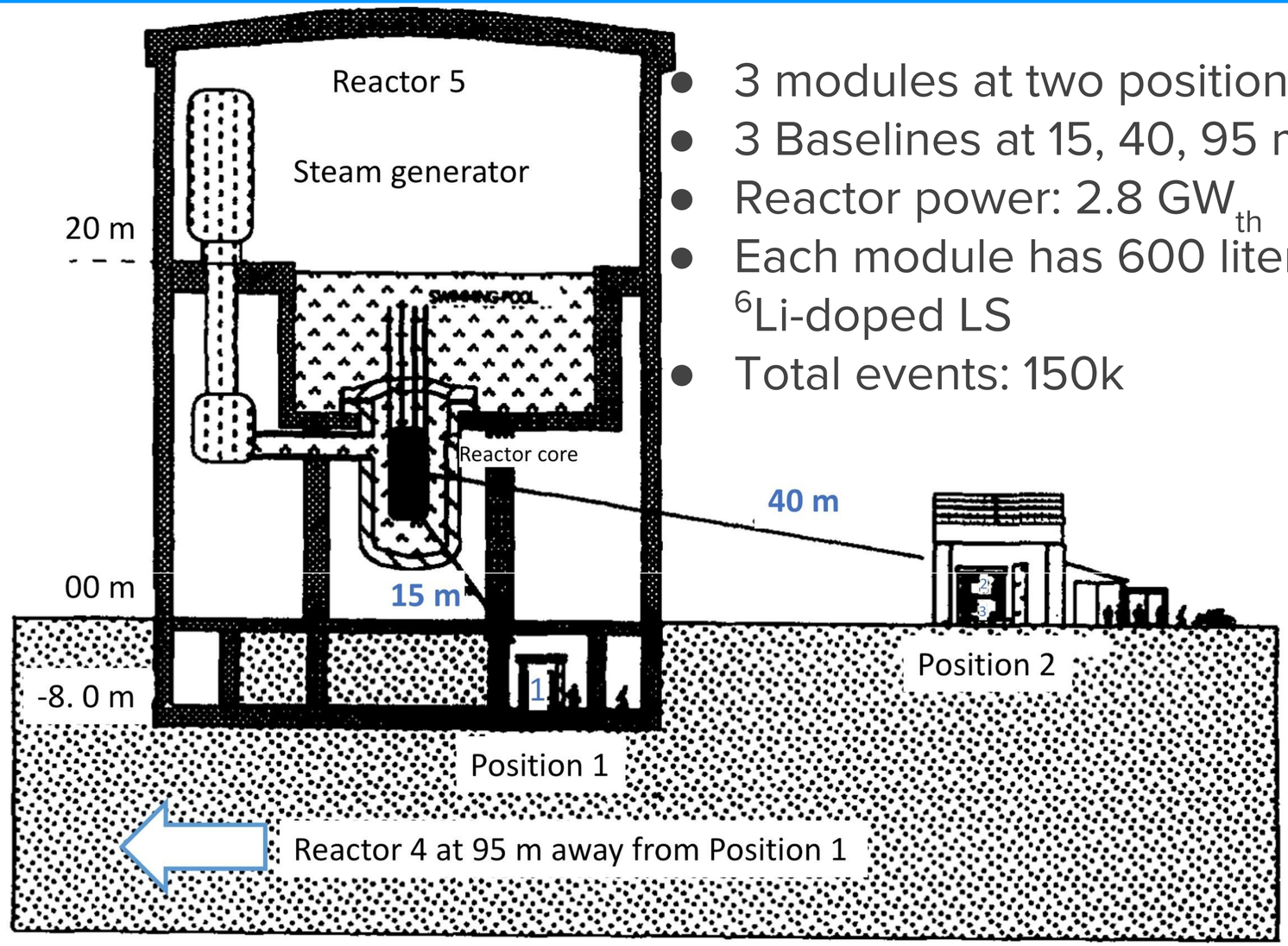


Sterile Driven ν_e

Predicted MINOS+ spectrum at the MiniBooNE best fit



Bugey-3



- 3 modules at two positions
- 3 Baselines at 15, 40, 95 m
- Reactor power: 2.8 GW_{th}
- Each module has 600 liters of ^{6}Li-doped LS
- Total events: 150k

Nucl.Phys. B434 (1995) 503-534, Nucl. Instrum. Meth. A374 (1996) 164-187