Cross check of ν_μ to ν_e oscillation results

A. Paoloni

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Formulas

$$
\begin{aligned}
P(E) \;=\; & C^2 \sin^2 \Delta_{31} \;+\; \sin^2 2\theta_{\mu e} \;\sin^2 \Delta_{41} \\
& + \; 0.5\; C \;\sin 2\theta_{\mu e} \;\cos \phi_{\mu e} \;\sin 2\Delta_{31} \;\sin 2\Delta_{41} \\
& - \; C \;\sin 2\theta_{\mu e} \;\sin \phi_{\mu e} \;\sin^2 \Delta_{31} \;\sin 2\Delta_{41} \\
& + \; 2\; C \;\sin 2\theta_{\mu e} \;\cos \phi_{\mu e} \;\sin^2 \Delta_{31} \;\sin^2 \Delta_{41} \\
& + \; C \;\sin 2\theta_{\mu e} \;\sin \phi_{\mu e} \;\sin 2\Delta_{31} \;\sin^2 \Delta_{41}
\end{aligned}
$$

ν_μ to ν_e

$C = 2\,|U_{\mu 3}\, U^*_{e3}|$ $\quad$ $\text{Sin } 2\theta_{\mu e} = 2\,|U_{\mu 4}\, U^*_{e4}|$ $\quad$ $\phi_{\mu e} = \text{Arg}\,(U_{\mu 3}\, U^*_{e3}\, U^*_{\mu 4}\, U_{e4})$

$\Delta_{ij} = 1.27\, \Delta m^2_{ij}\, L/E$

$$P(E) \;=\; 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\;\sin^2 \Delta_{41}$$

ν_e disappearance

Formulas

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\begin{aligned}
P(E) \;=\; & C^2 \sin^2\Delta_{31} \;+\; \sin^2 2\theta_{\mu e}\; \sin^2\Delta_{41} \\
& +\; 0.5\, C\; \sin 2\theta_{\mu e}\; \cos\phi_{\mu e}\; \sin 2\Delta_{31}\; \sin 2\Delta_{41} \\
& -\; C\; \sin 2\theta_{\mu e}\; \sin\phi_{\mu e}\; \sin^2\Delta_{31}\; \sin 2\Delta_{41} \\
& +\; 2\, C\; \sin 2\theta_{\mu e}\; \cos\phi_{\mu e}\; \sin^2\Delta_{31}\; \sin^2\Delta_{41} \\
& +\; C\; \sin 2\theta_{\mu e}\; \sin\phi_{\mu e}\; \sin 2\Delta_{31}\; \sin^2\Delta_{41}
\end{aligned}
$$

ν_μ to ν_e

$C = 2\,|U_{\mu 3}\, U^*_{e3}|$ $\quad$ $\sin 2\theta_{\mu e} = 2\,|U_{\mu 4}\, U^*_{e4}|$ $\quad$ $\phi_{\mu e} = \mathrm{Arg}\,(U_{\mu 3}\, U^*_{e3}\, U^*_{\mu 4}\, U_{e4})$

$\Delta_{ij} = 1.27\, \Delta m^2_{ij}\, L/E$

$$P(E) \;=\; 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\; \sin^2\Delta_{41}$$

ν_e disappearance

This formula however is not correct at OPERA Baseline.

The mixing matrix U

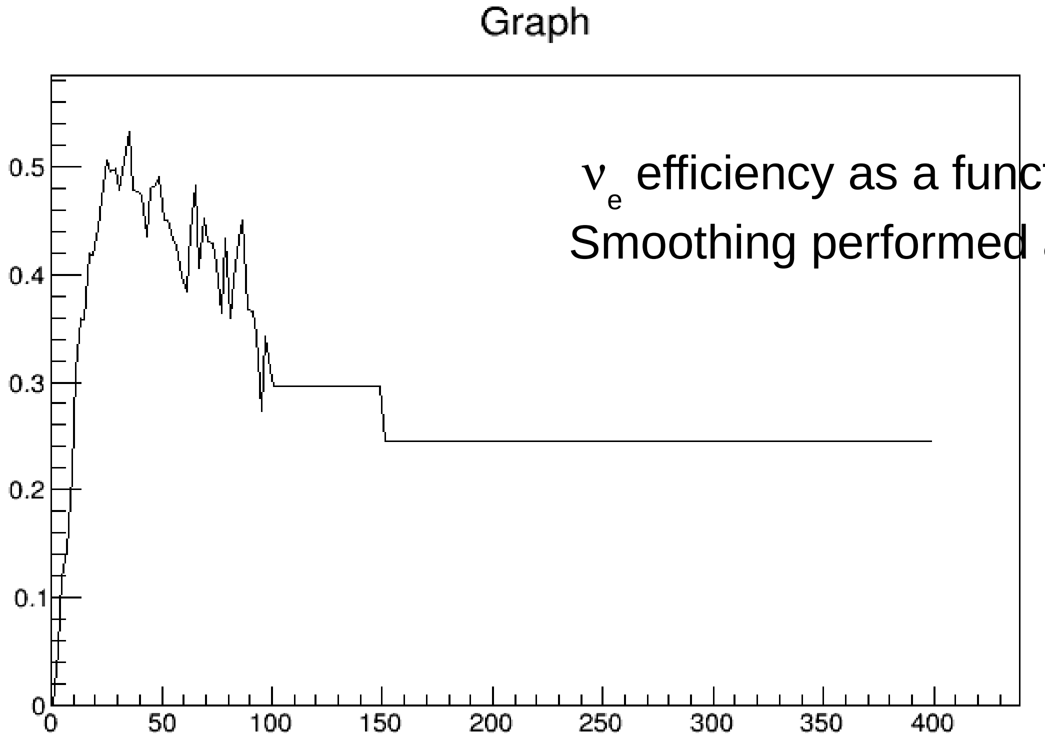
$$U = \begin{pmatrix} U_{e1} & U_{e2} & c_{14}s_{13}e^{-i\delta_1} & s_{14} \\ U_{\mu1} & U_{\mu2} & -s_{14}s_{13}e^{-i\delta_1}s_{24}e^{-i\delta_2} + c_{13}s_{23}c_{24} & c_{14}s_{24}e^{-i\delta_2} \\ U_{\tau1} & U_{\tau2} & -s_{14}c_{24}s_{34}s_{13}e^{-i\delta_1} - c_{13}s_{23}s_{34}s_{24}e^{i\delta_2} + c_{13}c_{23}c_{34} & c_{14}c_{24}s_{34} \\ U_{s1} & U_{s2} & -s_{14}c_{24}c_{34}s_{13}e^{-i\delta_1} - c_{13}s_{23}c_{34}s_{24}e^{i\delta_2} - c_{13}c_{23}s_{34} & c_{14}c_{24}c_{34} \end{pmatrix}$$

Matrix elements of interest for OPERA baseline

Normalization

Folding between flux, oscillation probability, cross section, efficiency.
Normalization to Matteo presentation in July PC.

Observed events: 34
Expected ν_μ to ν_e oscillations (without 3+1): 3.0
Beam ν_e contamination (without 3+1): 36.5
Other bkg (τ to e, π^0 mis-identification): 1.2



ν_e efficiency as a function of neutrino energy.
Smoothing performed above 100 GeV.

Analysis description

For high Δm^2_{41} values (>1 eV^2) or at fixed Δm^2_{41} values:
10^6 extractions of U parameters. $\Delta m^2_{31}=2.43 \cdot 10^{-3}$ eV^2 , $\Delta m^2_{21}=0$

Pure counting analysis. No cut on neutrino energy.

$$L(\Delta m^2_{41}, \phi_{\mu e}, \sin^2 2\theta_{\mu e}, C^2) = e^{-\mu}\ \mu^n/n!$$

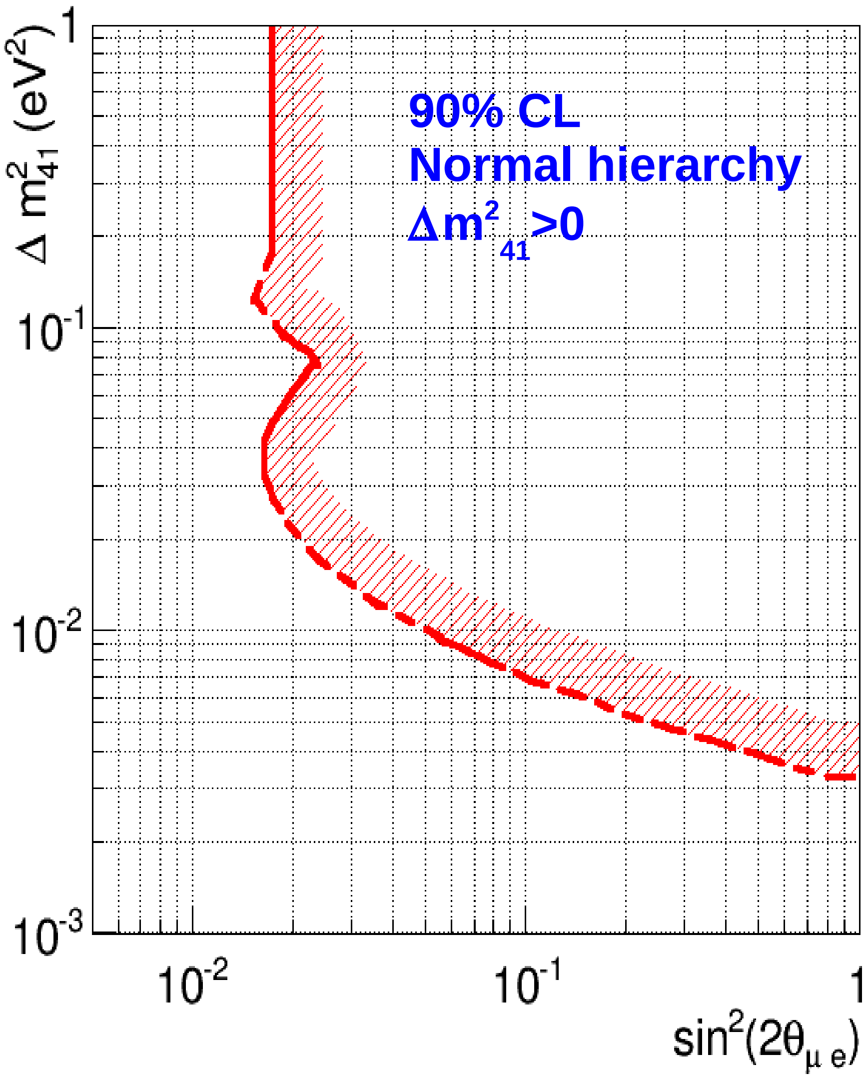
Likelihood definition

$$\Delta\chi^2 = -2\ \ln\ \frac{\widetilde{L}(\Delta m^2_{41}, \sin^2 2\theta_{\mu e})}{\widetilde{L}_{max}}$$

Profile likelihood (maximization over U Parameter extractions)

Exclusion limits using χ2 statistics with 1 degree of freedom.

Results

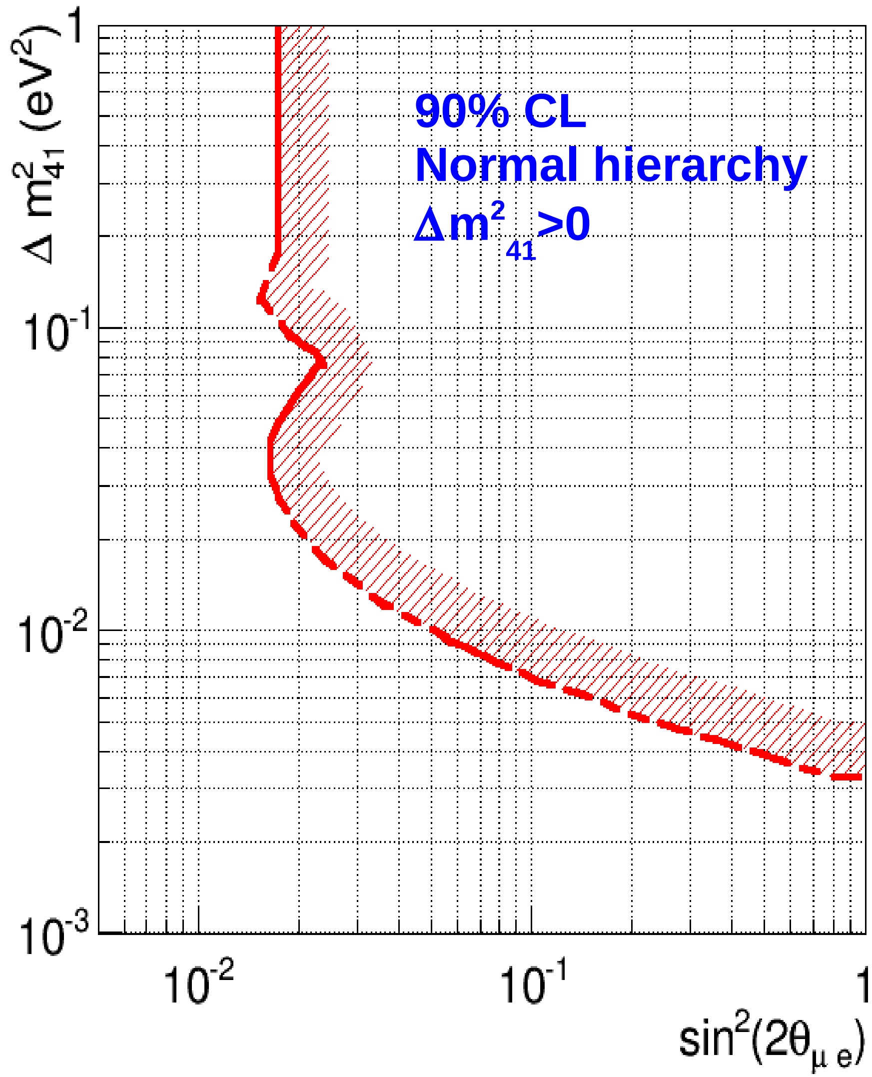


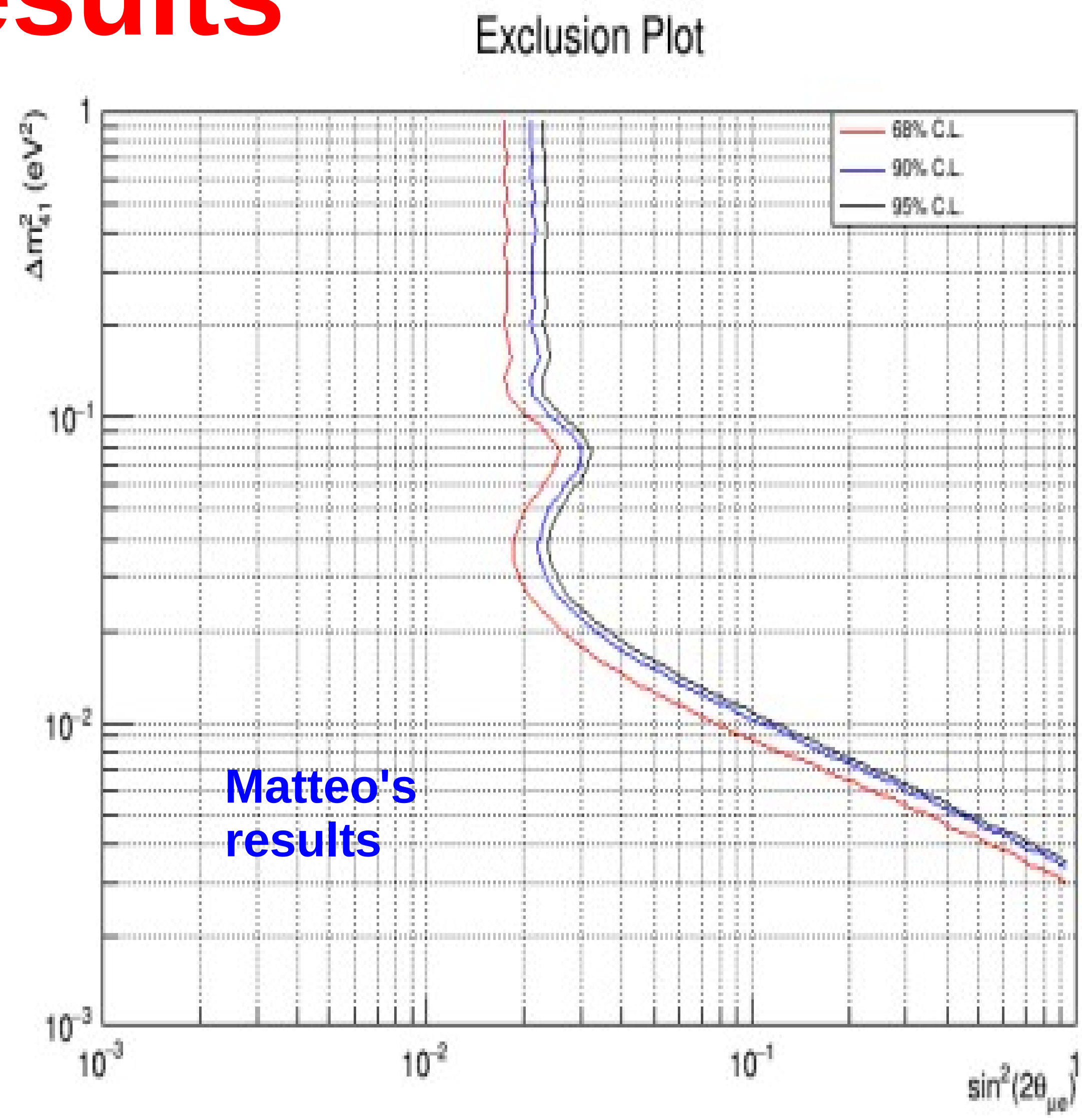
Exclusion Limits:

$\sin^2 2\theta_{\mu e} > 0.017$ for high Δm^2_{41}

$\Delta m^2_{41} > 3*10^{-3}$ for $\sin^2 2\theta_{\mu e} = 1.0$

Results





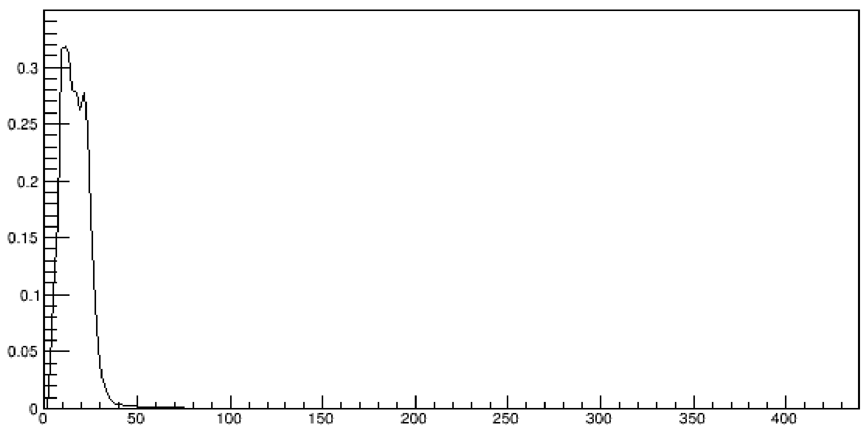
Exclusion Limits of present analysis:
$\sin^2 2\theta_{\mu e} > 0.017$ for high Δm^2_{41}
$\Delta m^2_{41} > 3 \cdot 10^{-3}$ for $\sin^2 2\theta_{\mu e} = 1.0$

Results are similar but not perfectly equal.
In this analysis, however, ν_e disapperance is not well described.

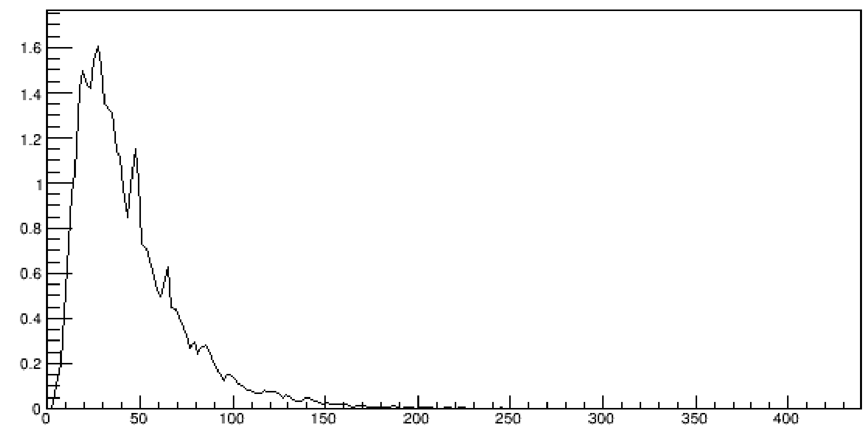
Number of expected ν_e

$\Delta m^2_{41} > 1\ eV^2$

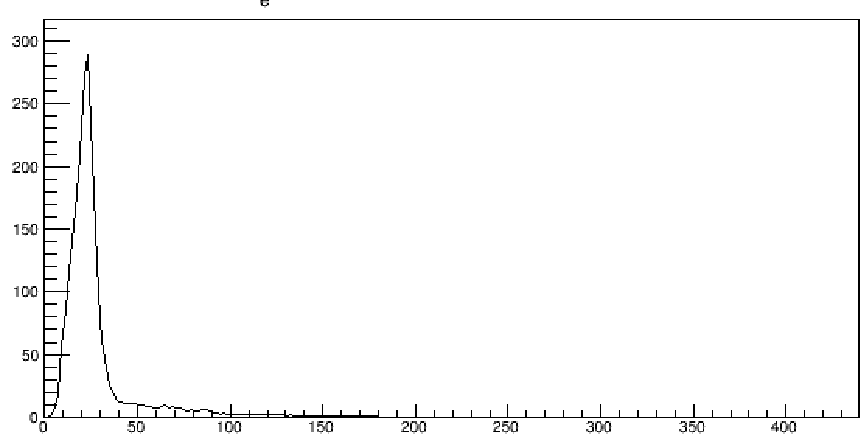
ν_e from osc. - no sterile



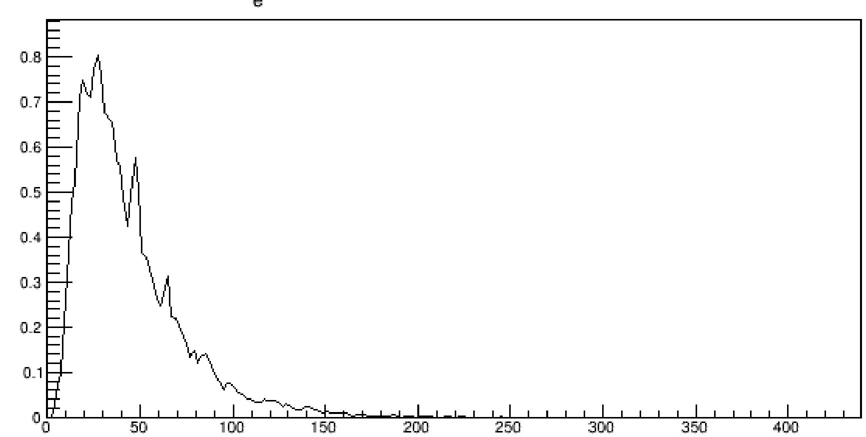
ν_e from beam - no sterile



ν_e from osc. - sterile max. effect



ν_e from beam - sterile max. effect



Summary of systematic studies

Table 1: Limits of the 90% CL exclusion region 1 in the $|\Delta m^2_{41}|$ vs $sin^2(2\theta_{\mu e})$ plane

Description	$\sin^2 2\theta_{\mu e}$	$\Delta m^2_{41}(eV^2)$
NH, $\Delta m^2_{31} = 2.43 \times 10^{-3} eV^2$	0.017	3×10^{-3}
IH, $\Delta m^2_{31} = -2.43 \times 10^{-3} eV^2$	0.017	0.8×10^{-3}
NH, $\Delta m^2_{31} = 2.3 \times 10^{-3} eV^2$	0.017	3×10^{-3}
NH, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$	0.017	3×10^{-3}
NH, $\Delta m^2_{31} = 2.43 \times 10^{-3} eV^2$, θ_{23} θ_{13} fixed	0.014	0.85×10^{-3}
IH, $\Delta m^2_{31} = -2.43 \times 10^{-3} eV^2$, θ_{23} θ_{13} fixed	0.014	0.75×10^{-3}
NH, $\Delta m^2_{31} = 2.43 \times 10^{-3} eV^2$, $\epsilon(E > 150 GeV) = 0$	0.017	3×10^{-3}
NH, $\Delta m^2_{31} = 2.43 \times 10^{-3} eV^2$, $\epsilon(E > 150 GeV) \times 2$	0.017	3×10^{-3}
NH, $\epsilon(E < 10 GeV) * 1.2$ $\epsilon(E > 10 GeV) * 1.1$	0.016	3×10^{-3}
NH, $\epsilon(E < 10 GeV) * 0.8$ $\epsilon(E > 10 GeV) * 0.9$	0.020	3.5×10^{-3}

Similarly to t analysis, Δm^2_{41}<0 is equivalent to exchange results for NH and IH.

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Inverse hierarchy:
Exclusion limits extend down to lower Δm^2_{41} values.

Similarly to t analysis, $\Delta m^2_{41}<0$ is equivalent to exchange results for NH and IH.

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NH, $\epsilon(E < 10 GeV) * 1.2$ $\epsilon(E > 10 GeV) * 1.1$	0.016	3×10^{-3}
NH, $\epsilon(E < 10 GeV) * 0.8$ $\epsilon(E > 10 GeV) * 0.9$	0.020	3.5×10^{-3}

Δm^2_{31}:

Exclusion limits not strongly dependent on Δm^2_{31} values.

Similarly to t analysis, $\Delta m^2_{41}<0$ is equivalent to exchange results for NH and IH.

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[illegible]	[illegible]	3×10^{-3}
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NH, $\epsilon(E < 10GeV) * 1.2$ $\epsilon(E > 10GeV) * 1.1$	0.010	3×10^{-3}
NH, $\epsilon(E < 10GeV) * 0.8$ $\epsilon(E > 10GeV) * 0.9$	0.020	3.5×10^{-3}

θ_{23} θ_{13} fixed at measured values: Greater excluded area.

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NH, $\epsilon(E < 10 GeV) * 0.8$ $\epsilon(E > 10 GeV) * 0.9$	0.020	3.5×10^{-3}

Efficiency studies (E>150 GeV):
Exclusion limits independent for a 100% variation.

Similarly to t analysis, Δm^2_{41}<0 is equivalent to exchange results for NH and IH.

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		3×10^{-3}
		3×10^{-3}
NH, $\epsilon(E < 10GeV) * 1.2$ $\epsilon(E > 10GeV) * 1.1$	0.016	3×10^{-3}
NH, $\epsilon(E < 10GeV) * 0.8$ $\epsilon(E > 10GeV) * 0.9$	0.020	3.5×10^{-3}

Efficiency studies:
Exclusion limit area increases with efficiency.

Similarly to t analysis, Δm^2_{41}<0 is equivalent to exchange results for NH and IH.