Analyzing light sterile ν at DUNE: Roles of beam tune, neutral current, near detector

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ibs 기초과학연구원 Institute for Basic Science
APCTP Asia Pacific Center for Theoretical Physics
NRF National Research Foundation of Korea
DAEJEON Tourism Organization

Plan of the talk

- Motivation
- Effect of sterile neutrino on probability
- Beams and different analysis configurations
- Results: Statistical analysis
- Summary

Unresolved issues

Table: de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle: 2006.11237

Oscillation parameter	Best fit value	3σ range
$\theta_{12}/^\circ$	34.3	$[31.4, 37.4]$
$\theta_{23}/^\circ$	48.8	$[41.6, 51.3]$
$\theta_{13}/^\circ$	8.6	$[8.2, 8.9]$
δ_{13}/π	-0.8	$[-1, 0] \cup [0.8, 1]$
$\Delta m^2_{21}/10^{-5}$ eV^2	7.5	$[6.9, 8.1]$
$\Delta m^2_{31}/10^{-3}$ eV^2	2.6	$[2.5, 2.7]$

- Origin of ν mass?
- Ordering of ν masses?
- Matter-antimatter asymmetry? $(\delta \neq 0,\pi?)$
- $\theta_{23} < \pi/4$ or $> \pi/4$?
- Nonstandard ν interaction (NSI)?
- Sterile ν?
- Lorentz Invariance Violation?
- ν from astrophysical sources

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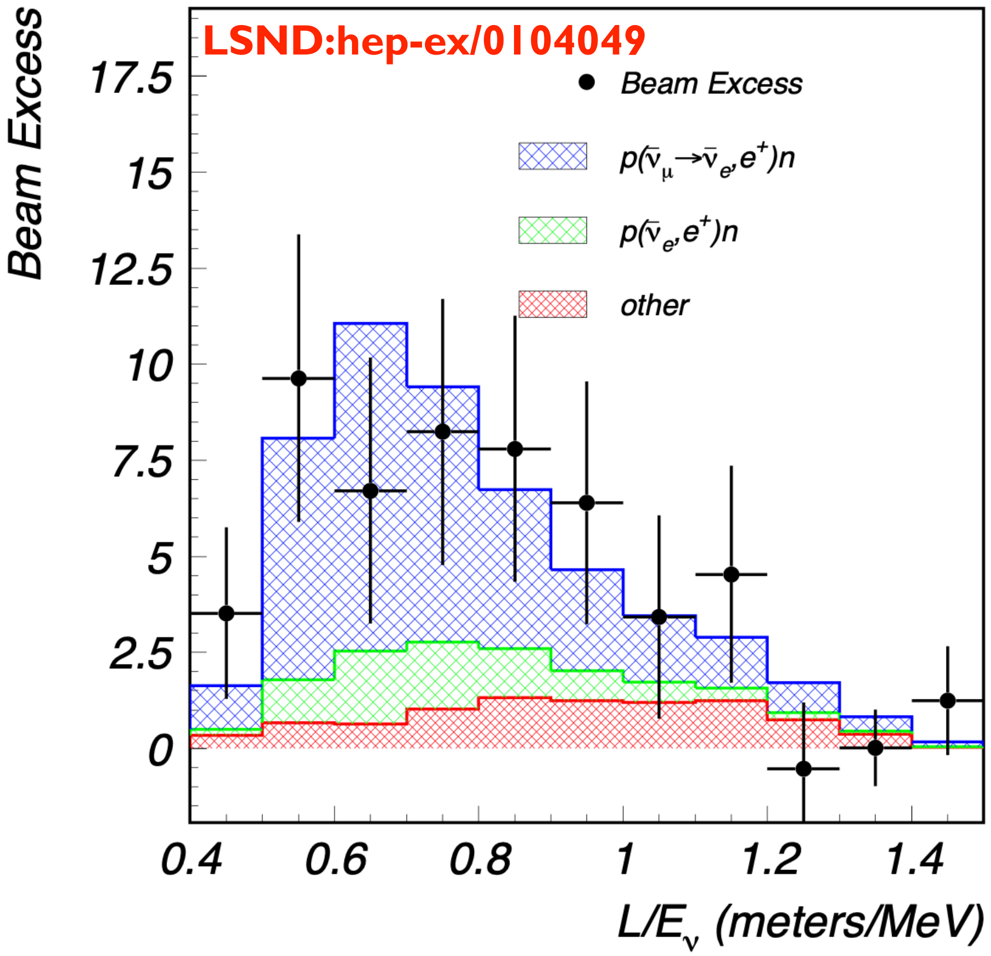
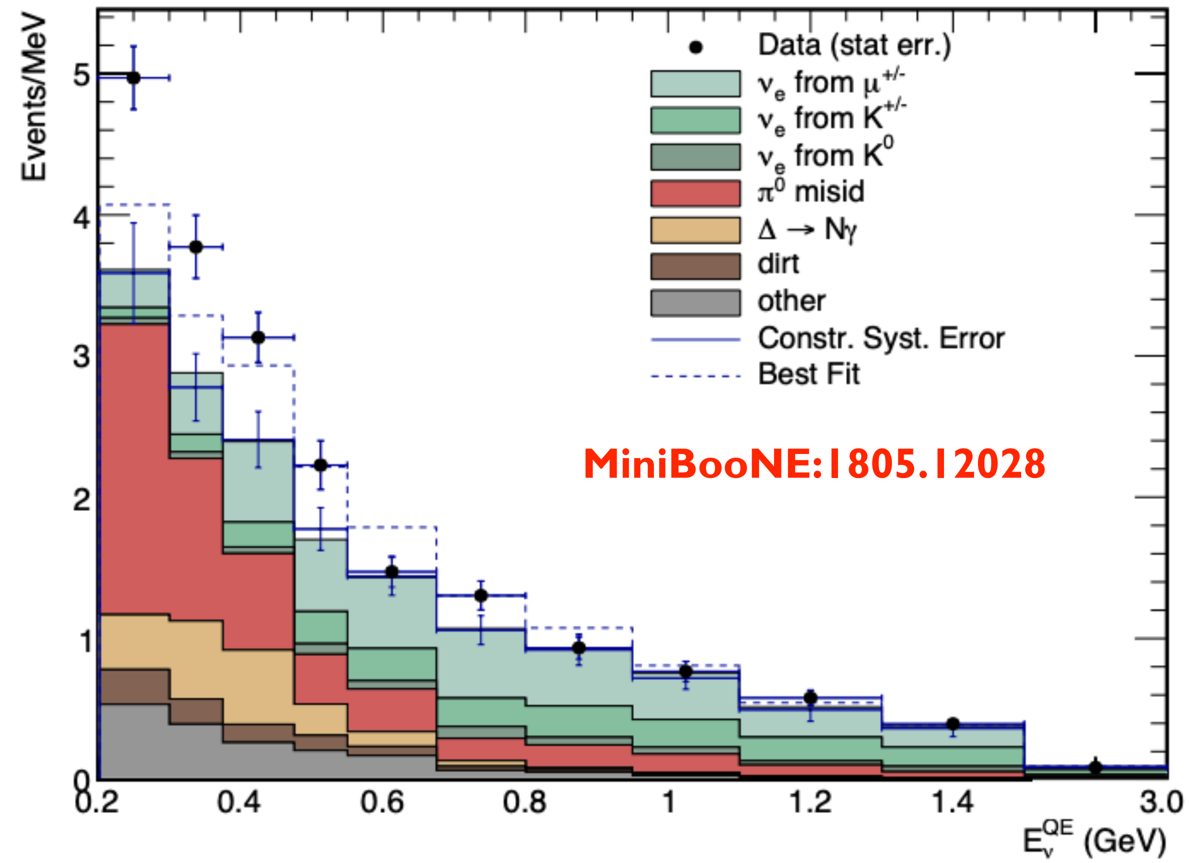
Hints for new physics?





VERY intense proton beam

$$p + X \to \pi^+ + X'$$

(800 MeV) $\quad \hookrightarrow \mu^+ \nu_\mu$ (DAR)

$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

Detection signature:
IBD ($\bar{\nu}_e\, p \to e^+ n$)

LSND detected more $\bar{\nu}_e$ than expected: 87.9 ± 23.2 events (3.8σ excess)

Measures $\nu_\mu \to \nu_e$ osc.

Event excess: 381.2 ± 85.2 (4.5σ)

Current bound on sterile neutrinos

$$U^{(3+1)} = O(\theta_{34}, \delta_{34}) O(\theta_{24}, \delta_{24}) O(\theta_{14}) \underbrace{O(\theta_{23}) O(\theta_{13}, \delta_{13}) O(\theta_{12})}_{U_{\mathrm{PMNS}}}$$

$$P_{\alpha\beta} \approx P_{\alpha\beta}^{3+0} + |U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \Delta_{41} \quad (\alpha \neq \beta)$$

$$P_{\alpha\alpha} \approx P_{\alpha\alpha}^{3+0} - |U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) \sin^2 \Delta_{41}$$

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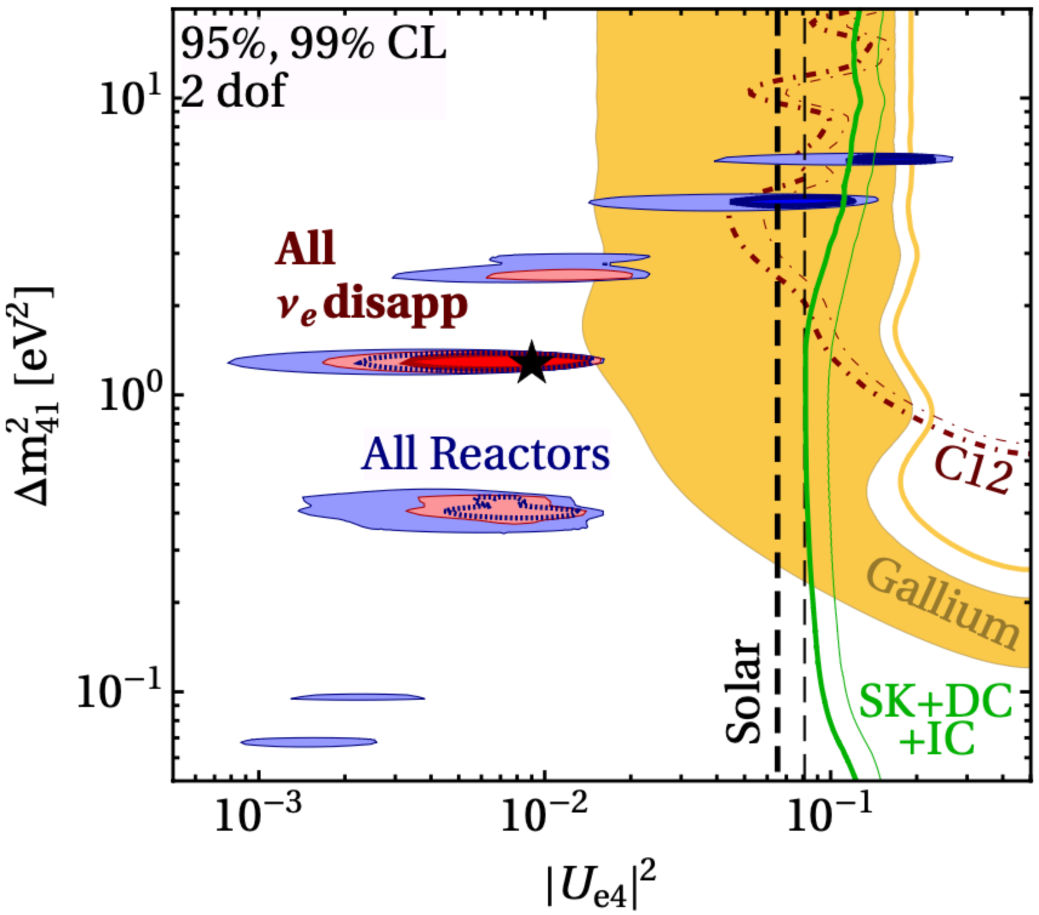
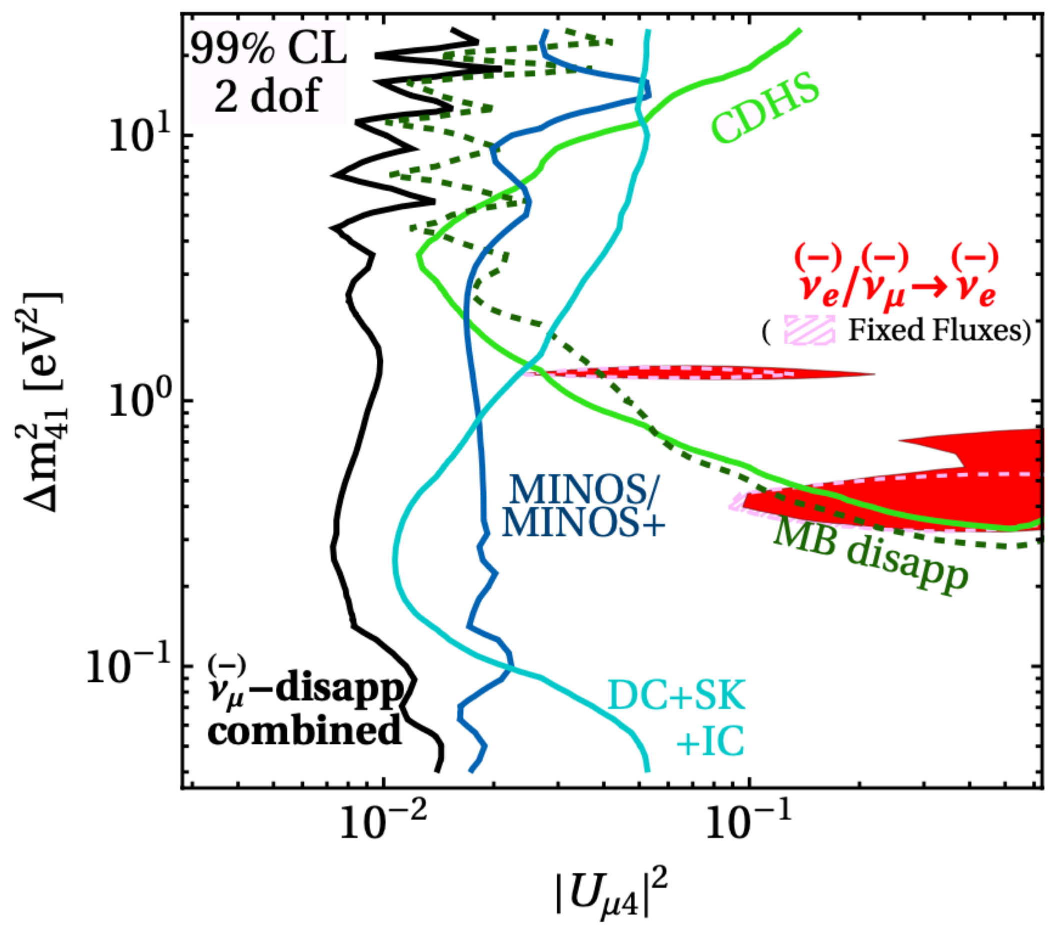
Dentler, Cabezudo, Kopp, Machado, Maltoni, Soler, Schwetz (2018)





$$\sin^2\theta_{14} \lesssim 0.01, \sin^2\theta_{24} \lesssim 0.008, \sin^2\theta_{34} \lesssim 0.12$$

Current bound on sterile neutrinos

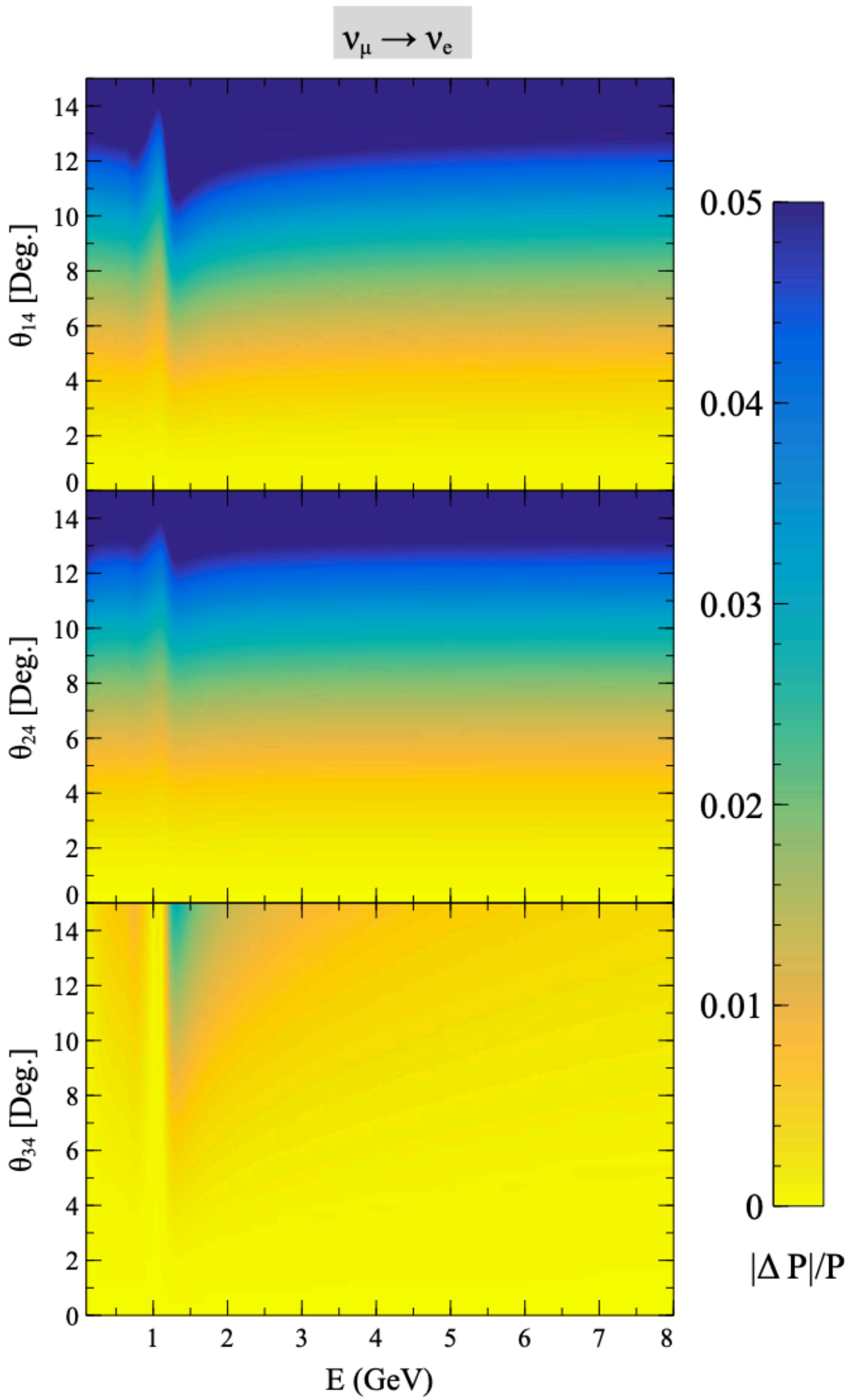
$$\sin^2\theta_{14} \lesssim 0.01, \sin^2\theta_{24} \lesssim 0.008, \sin^2\theta_{34} \lesssim 0.12$$

We want to see whether DUNE is capable of improving these limits

First, we need to have some idea about how active-sterile mixing angles impact the probabilities for different channels

A relevant quantity is $\Delta P_{\alpha\beta} = P_{\alpha\beta}^{3+1} - P_{\alpha\beta}^{3+0}$

Variation of $P_{\mu e}$



- Heatplots for $\dfrac{|\Delta P|}{P} = \dfrac{|P^{3+1} - P^{3+0}|}{P^{3+0}}$

- Monotonically increasing with θ_{14} and θ_{24}

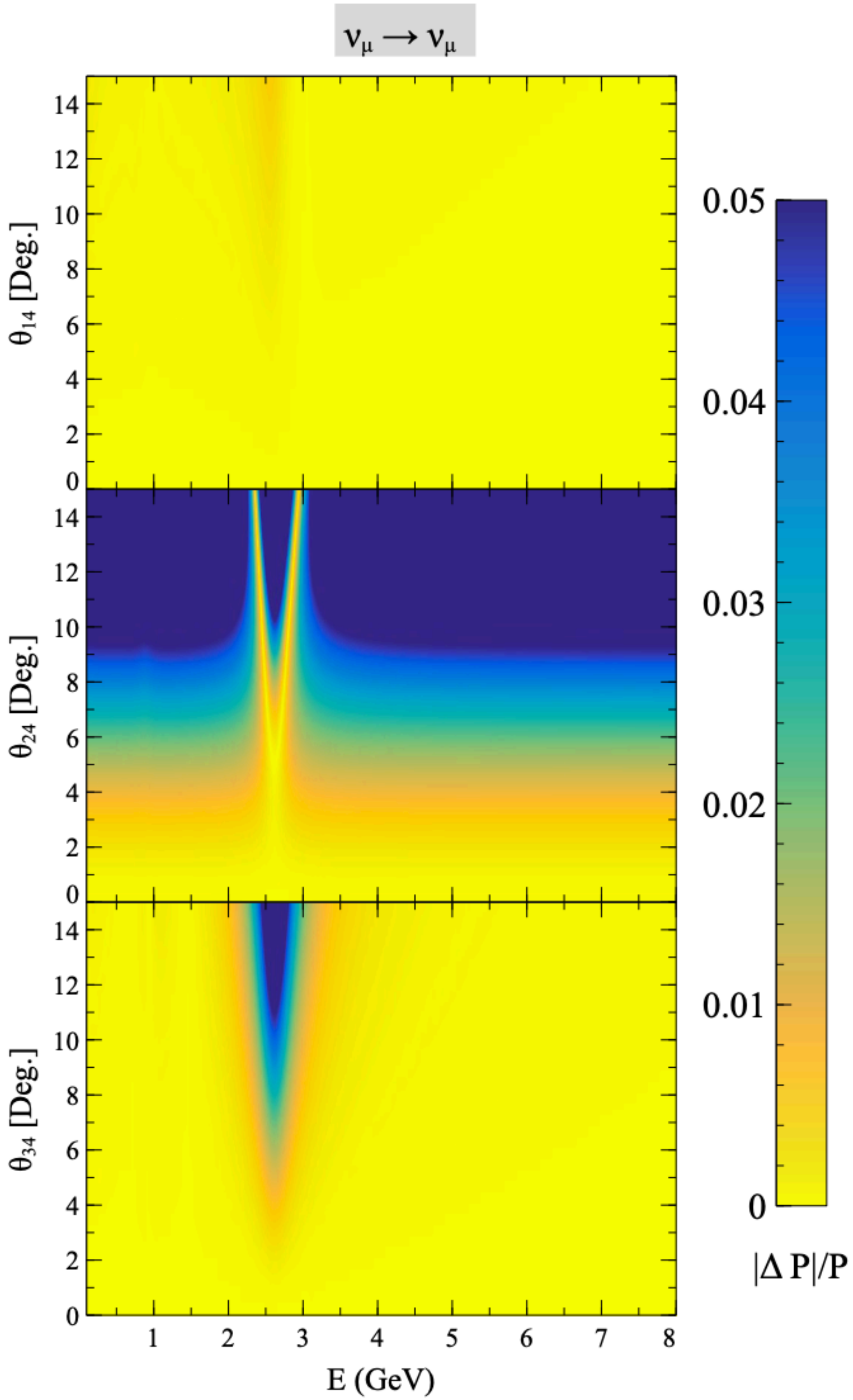
- $\dfrac{\Delta P}{P}(\theta_{14}) \simeq \sin^2\theta_{14}$

  $\dfrac{\Delta P}{P}(\theta_{24}) \simeq \sin^2\theta_{24}$

  Very small dependence on θ_{34} at leading order

- Mild kink at 1 Gev due to matter effect

Variation of $P_{\mu\mu}$



- Practically no dependence on θ_{14} for $P_{\mu\mu}$

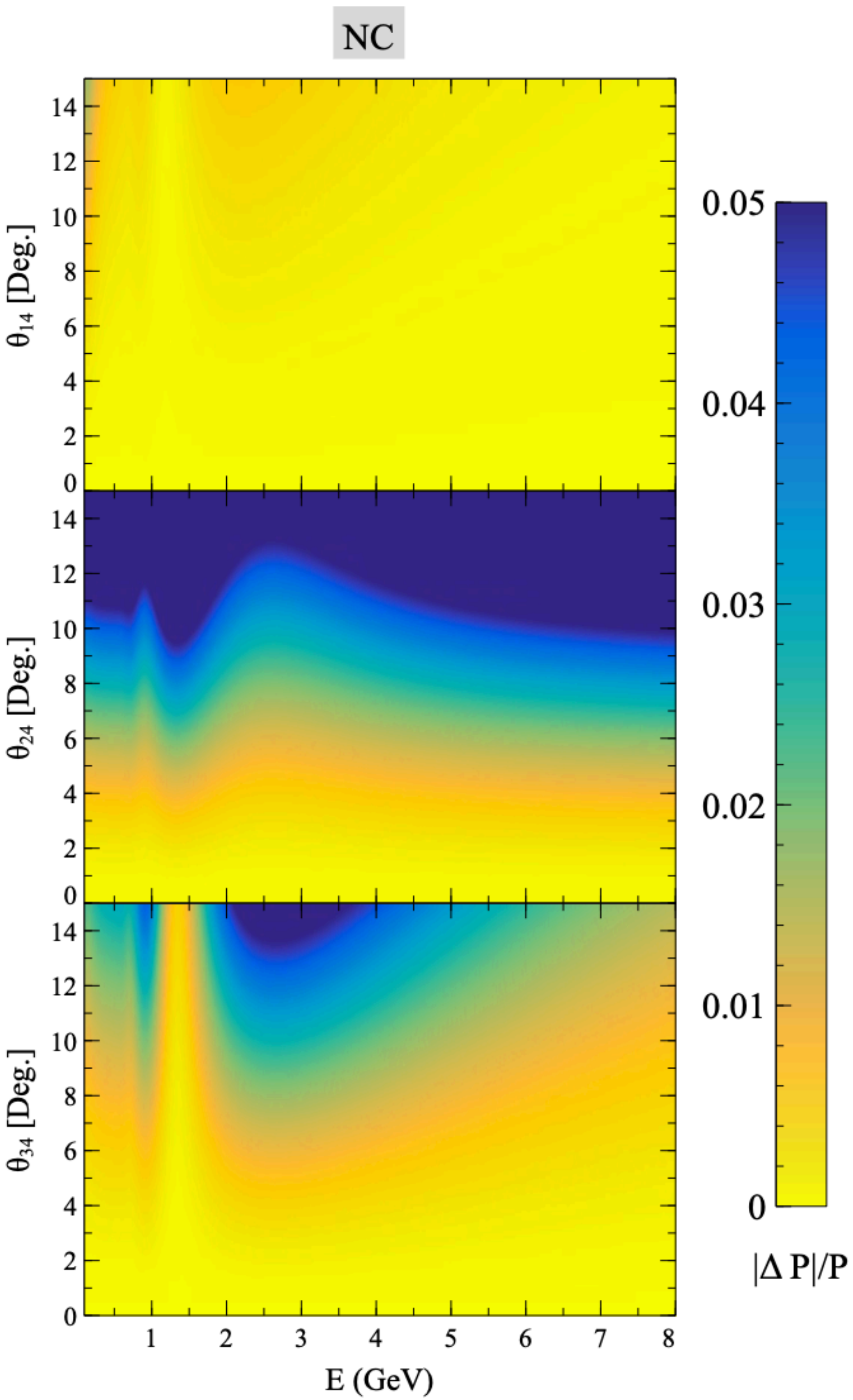
- $\dfrac{\Delta P}{P}(\theta_{24})$

$$\simeq \frac{2\sin^2\theta_{24} - \cos^2\theta_{13}\sin^2\theta_{24}\left[1-\sin^2\theta_{13}-\sin^2\theta_{24}\right]\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)}{1-\left(\cos^2\theta_{13}+\frac{1}{4}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)}$$

+ (matter effects)

- θ_{34} increases $|\Delta P_{\mu\mu}|$ only around the oscillation maxima

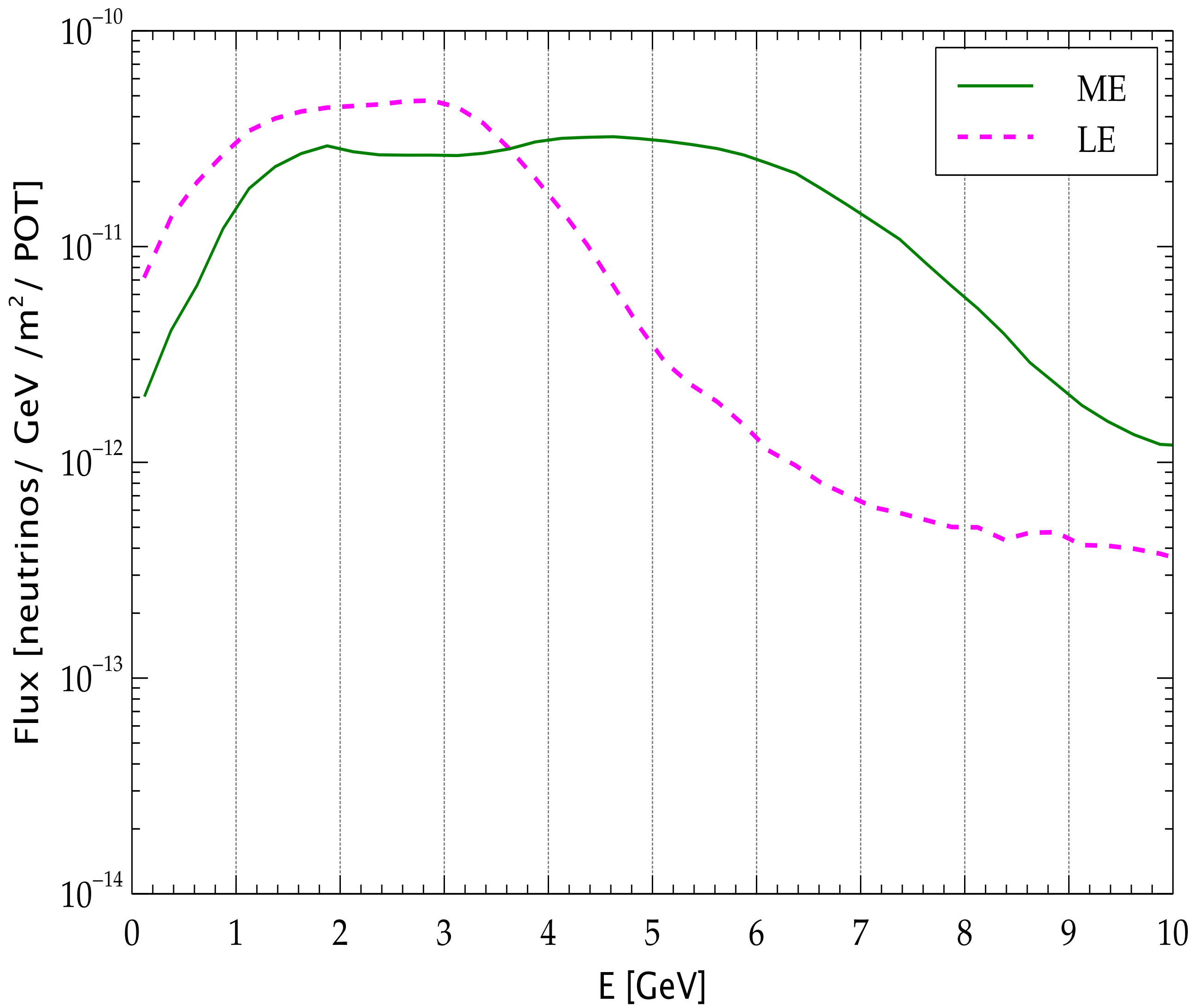
Variation of P_{NC}



- $P_{\text{NC}} = P_{\mu e} + P_{\mu\mu} + P_{\mu\tau} = 1 - P_{\mu s}$
- Practically no dependence on θ_{14} for P_{NC}
- $\frac{\Delta P}{P}(\theta_{24}) \simeq \frac{1}{2}\sin^2 2\theta_{24} - \frac{1}{4}\cos^2\theta_{13}\sin^2 2\theta_{24}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$

  + (matter effects)
- $\frac{\Delta P}{P}(\theta_{34}) \simeq \cos^4\theta_{13}\sin^2\theta_{34}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$

Analysis configurations

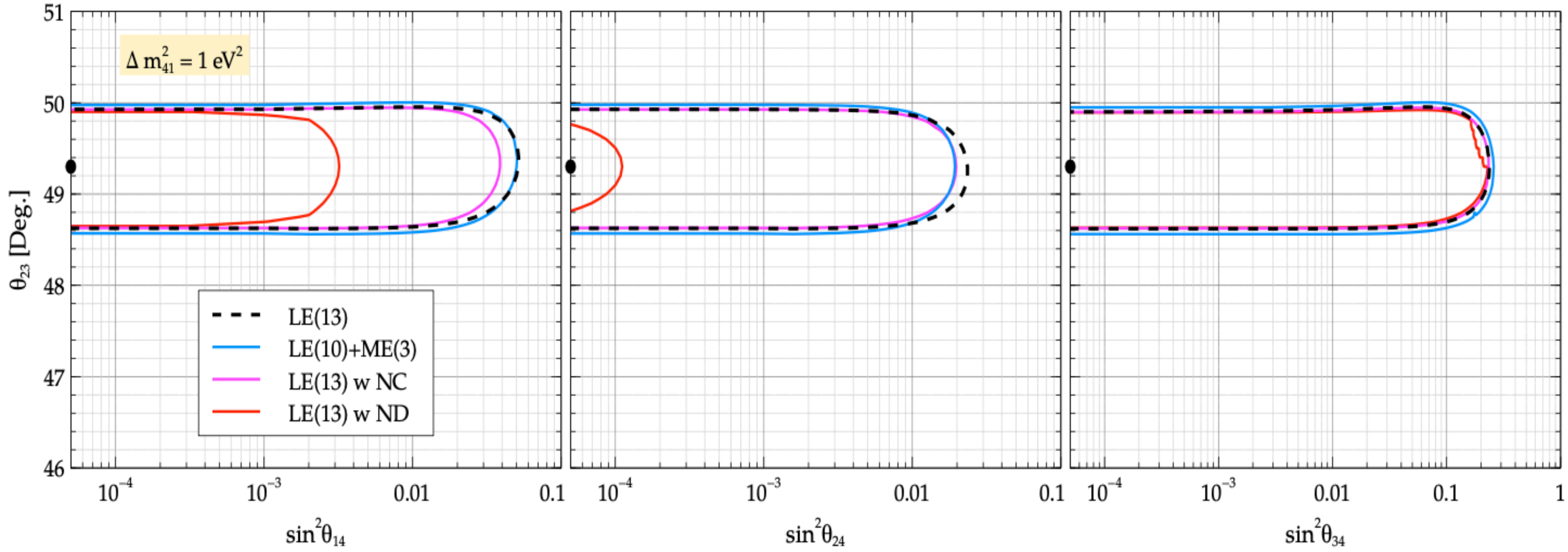


- 13 yrs. runtime, low energy (LE) beam, FD, CC
- 10 yrs. LE + 3 yrs. ME beam, FD, CC
- 13 yrs. LE, FD, CC + NC
- 13 yrs. LE, FD + ND

Simulation and analysis using GLoBES: $\Delta\chi^2 \sim \sum \frac{\left(N_{\text{fit}}^{3+1} - N_{\text{data}}^{3+0}\right)^2}{N_{\text{data}}^{3+0}}$ + prior + systematics

$\sum \rightarrow$ energy and channels

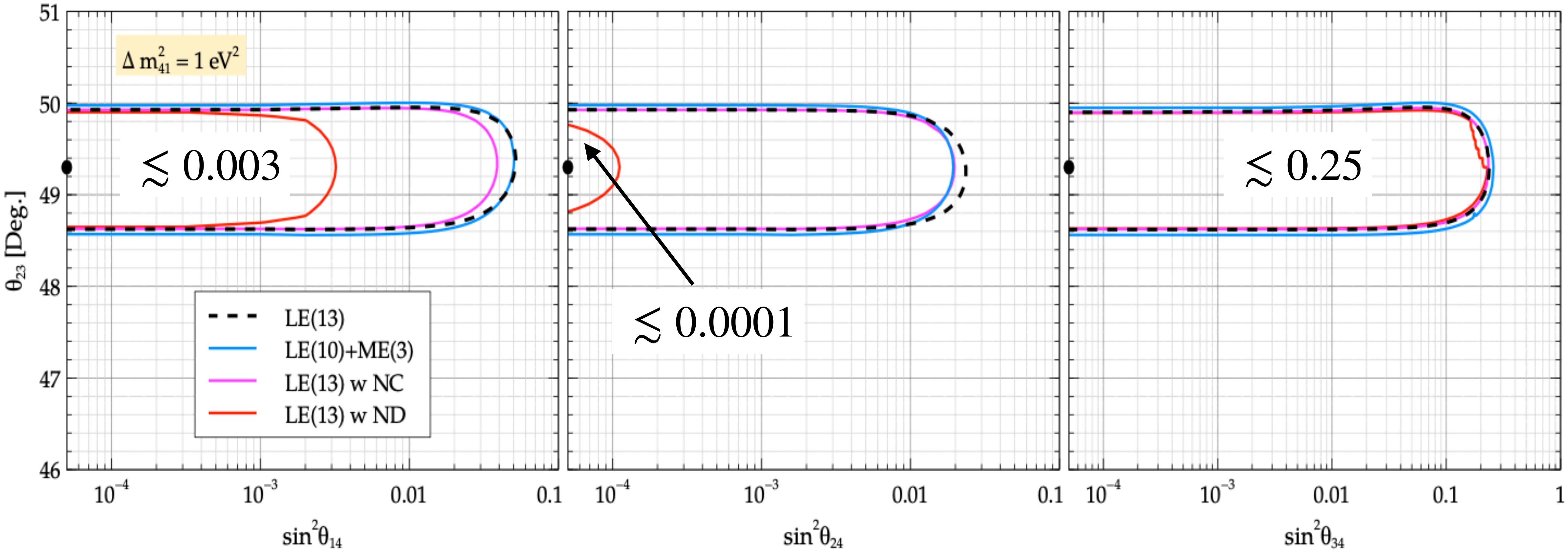
Excluded regions in $(\theta_{23} - \sin^2\theta_{i4})$ space



- Regions outside the contours are excluded at $90\,\%$ C.L.

- Constraints on $\sin^2\theta_{14}$ & $\sin^2\theta_{24}$ are much stronger than $\sin^2\theta_{34}$ while $\sin^2\theta_{24}$ is constrained better than $\sin^2\theta_{14}$

Excluded regions in $(\theta_{23} - \sin^2\theta_{i4})$ space



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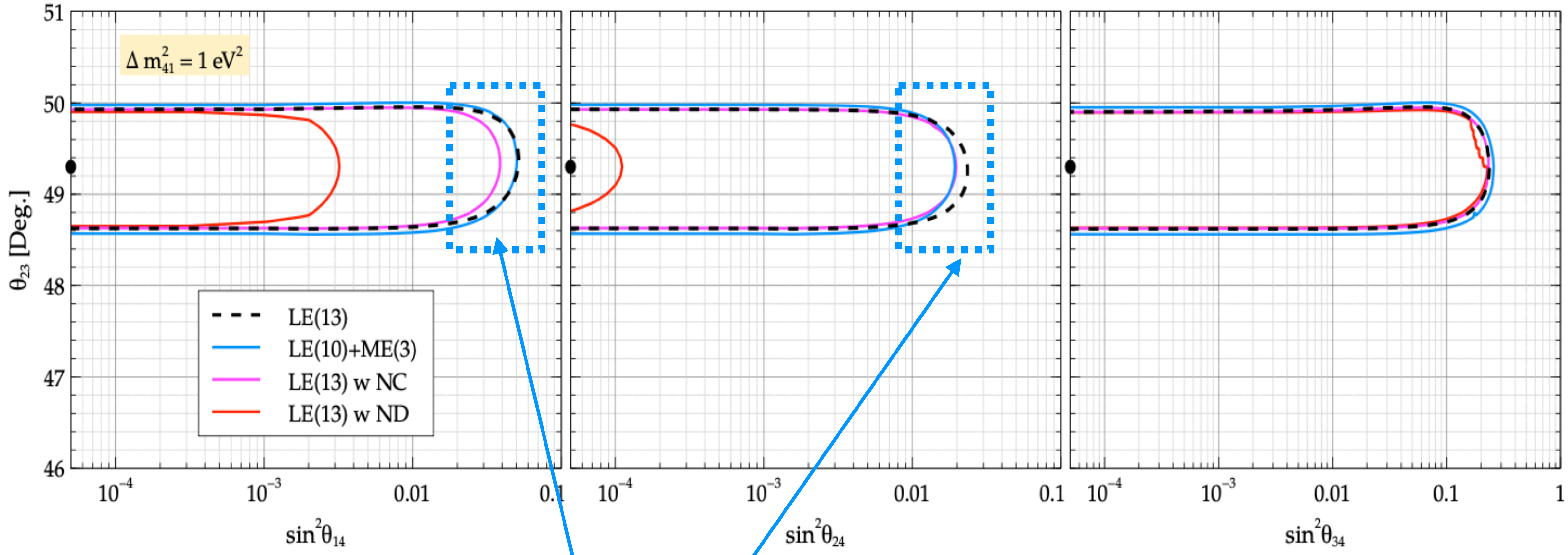
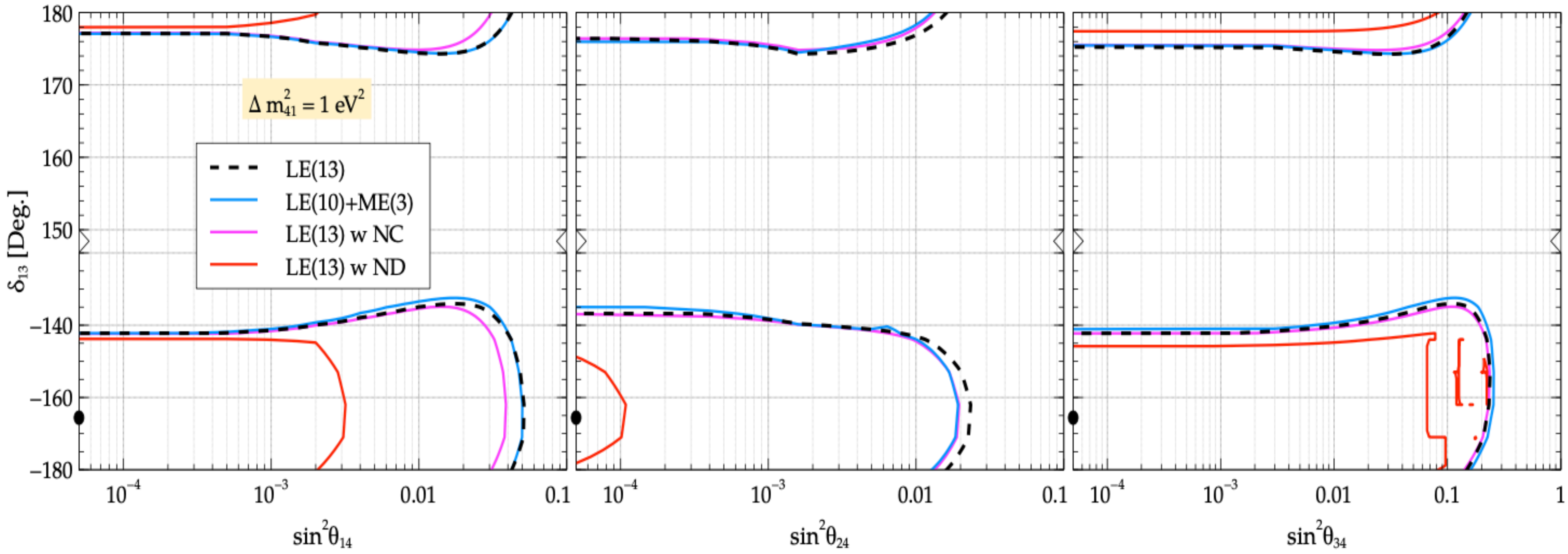
Excluded regions in $(\theta_{23} - \sin^2\theta_{i4})$ space



- Regions outside the contours are excluded at $90\,\%$ C.L.

- Use of higher energy beams improves the constraints on $\sin^2\theta_{24}$ very slightly, but has no impact on $\sin^2\theta_{14}$
  — Since $\Delta P_{\mu\mu}$ increases with θ_{24} but not impacted by θ_{14}

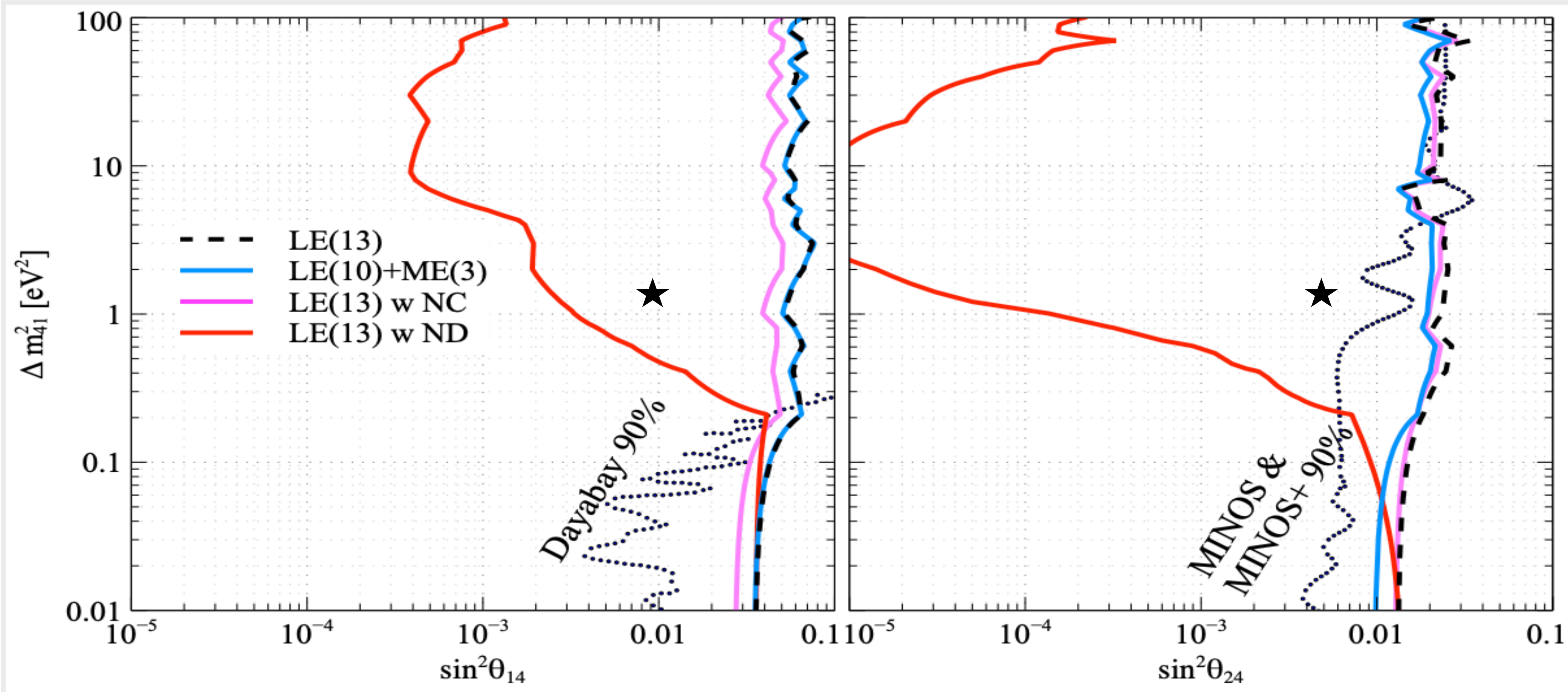
Excluded regions in $(\delta_{13} - \sin^2\theta_{i4})$ space



- Regions outside the contours are excluded at $90\,\%$ C.L.

- Constraints on $\sin^2\theta_{14}$ & $\sin^2\theta_{24}$ are much stringent than $\sin^2\theta_{34}$ while $\sin^2\theta_{24}$ is constrained better than $\sin^2\theta_{14}$

Excluded regions in $(\Delta m^2_{41} - \sin^2\theta_{i4})$ space

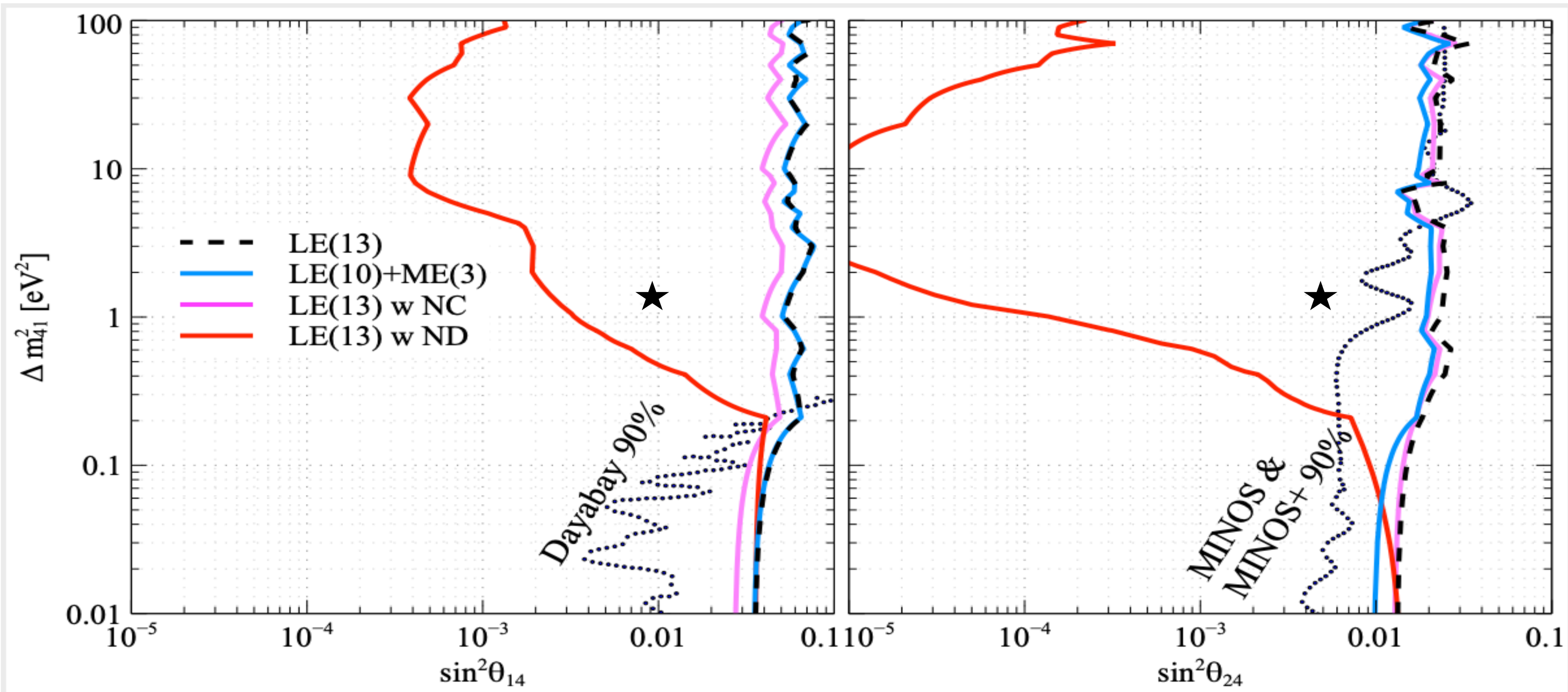


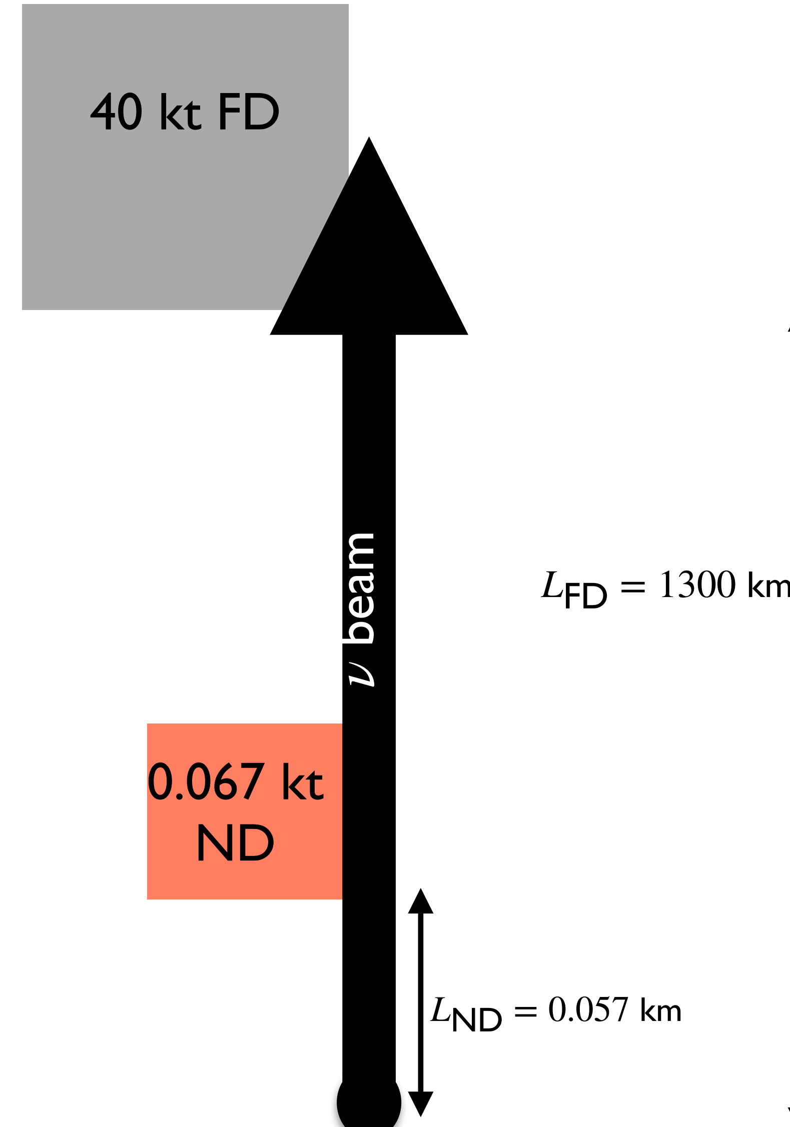
- Regions to the right of the contours are excluded at $90\,\%$ C.L.

- ND has no impact for $\Delta m^2_{41} \lesssim 0.03$ eV^2
  ND offers the most improvement for $\Delta m^2_{41} \gtrsim 1$ eV^2

- *A Caveat:This is an optimistic analysis ignoring the shape-related systematic uncertainties at ND.*
  ND sensitivity is expected to slightly with a more sophisticated covariance-matrix-$\Delta\chi^2$ like analysis. Needs modification of GLoBES

Excluded regions in $(\Delta m_{41}^2 - \sin^2\theta_{i4})$ space





- Rough comparative estimation of FD and ND:

$$\text{FD} \sim \sin^2\left(1.27 * \frac{\Delta m_{31}^2[\text{eV}^2] L_{\text{FD}}[\text{km}]}{E[\text{GeV}]}\right) \sim 1 \text{ for } E \sim 2 - 3 \text{ GeV}$$

$$\text{ND} \sim \frac{M_{\text{ND}}}{M_{\text{FD}}}\left(\frac{L_{\text{FD}}}{L_{\text{ND}}}\right)^2 \sin^2\left(1.27\frac{\Delta m_{41}^2[\text{eV}^2] L_{\text{ND}}[\text{km}]}{E[\text{GeV}]}\right) \sim 8.7\times 10^3 \sin^2\left(0.6\frac{\Delta m_{41}^2}{E}\right)$$

- $\text{ND} \lesssim \text{FD}/10 \implies \Delta m_{41}^2 \lesssim 0.01E \lesssim (0.02 - 0.03)$ eV^2 for $E = 2 - 3$ GeV

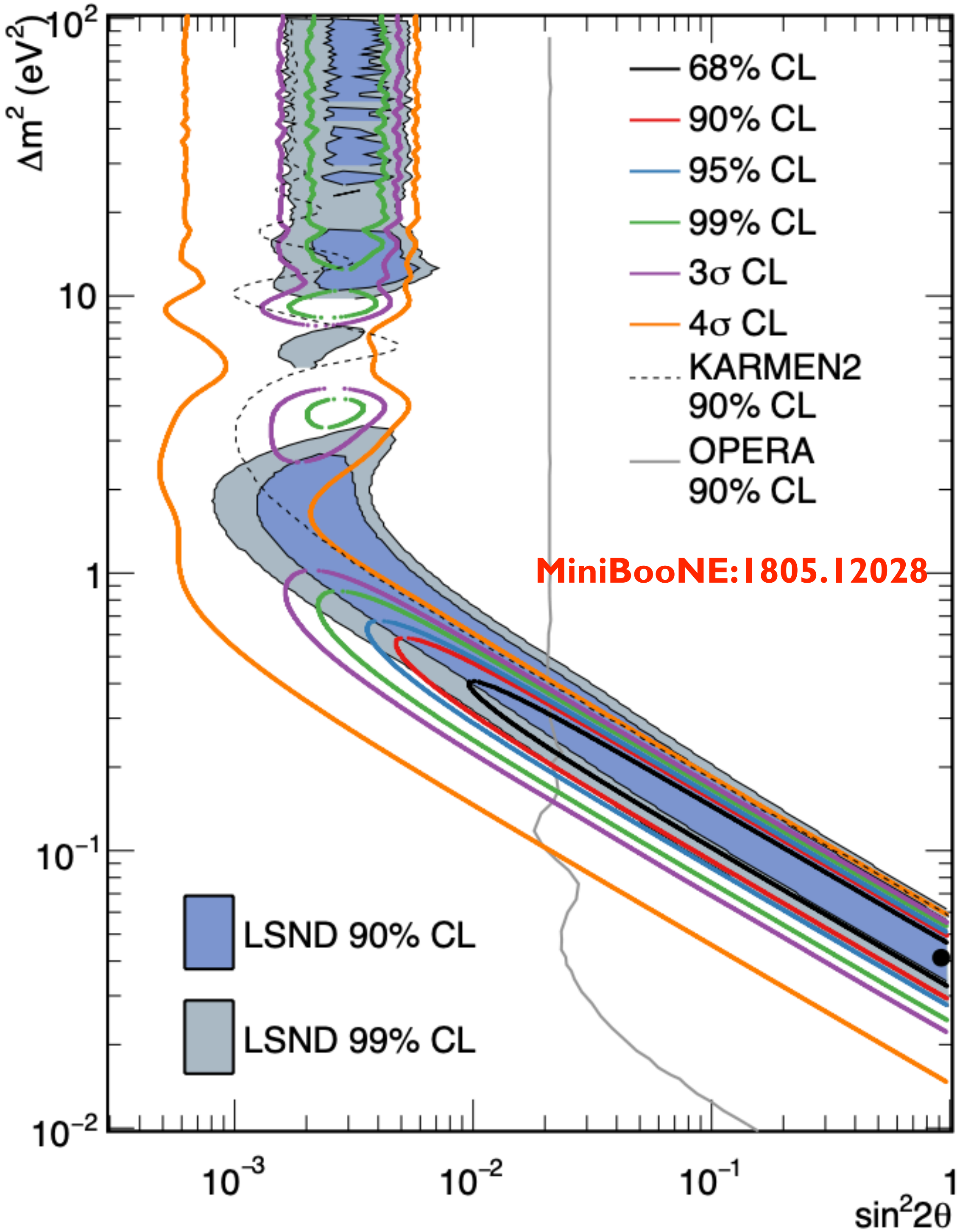
- ND is max when $\Delta m_{41}^2 \sim 2.7E \sim 6 - 8$ GeV

Summary

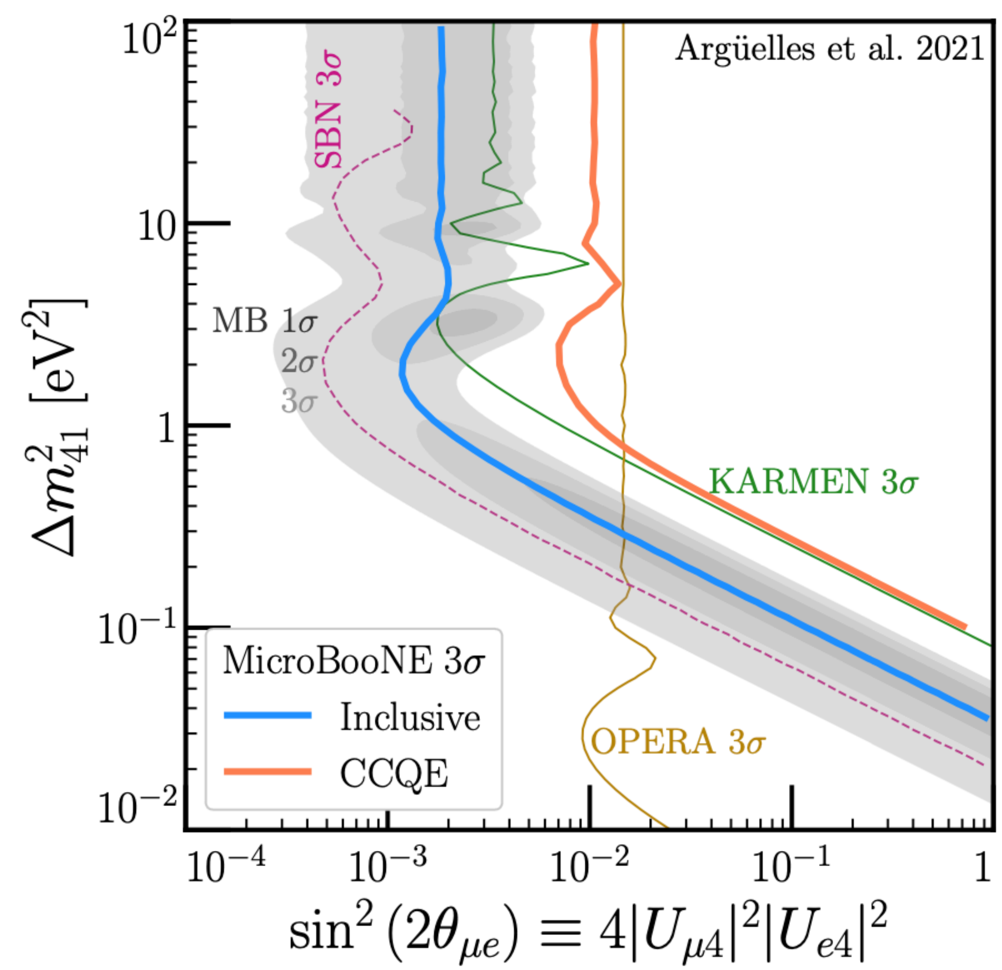
- $\sin^2\theta_{14}$ and $\sin^2\theta_{24}$ can be constrained much better than $\sin^2\theta_{34}$ (by more than one order of magnitude) at DUNE
- Constraints on $\sin^2\theta_{24}$ are stronger than $\sin^2\theta_{14}$
- Higher energy beam tunes improve the sensitivity slightly for $\sin^2\theta_{24}$
- NC offers slight improvement for both θ_{14}, θ_{24}
- Addition of ND offers the most stringent constraints on active-sterile mixing angles

Thank You!

Backup

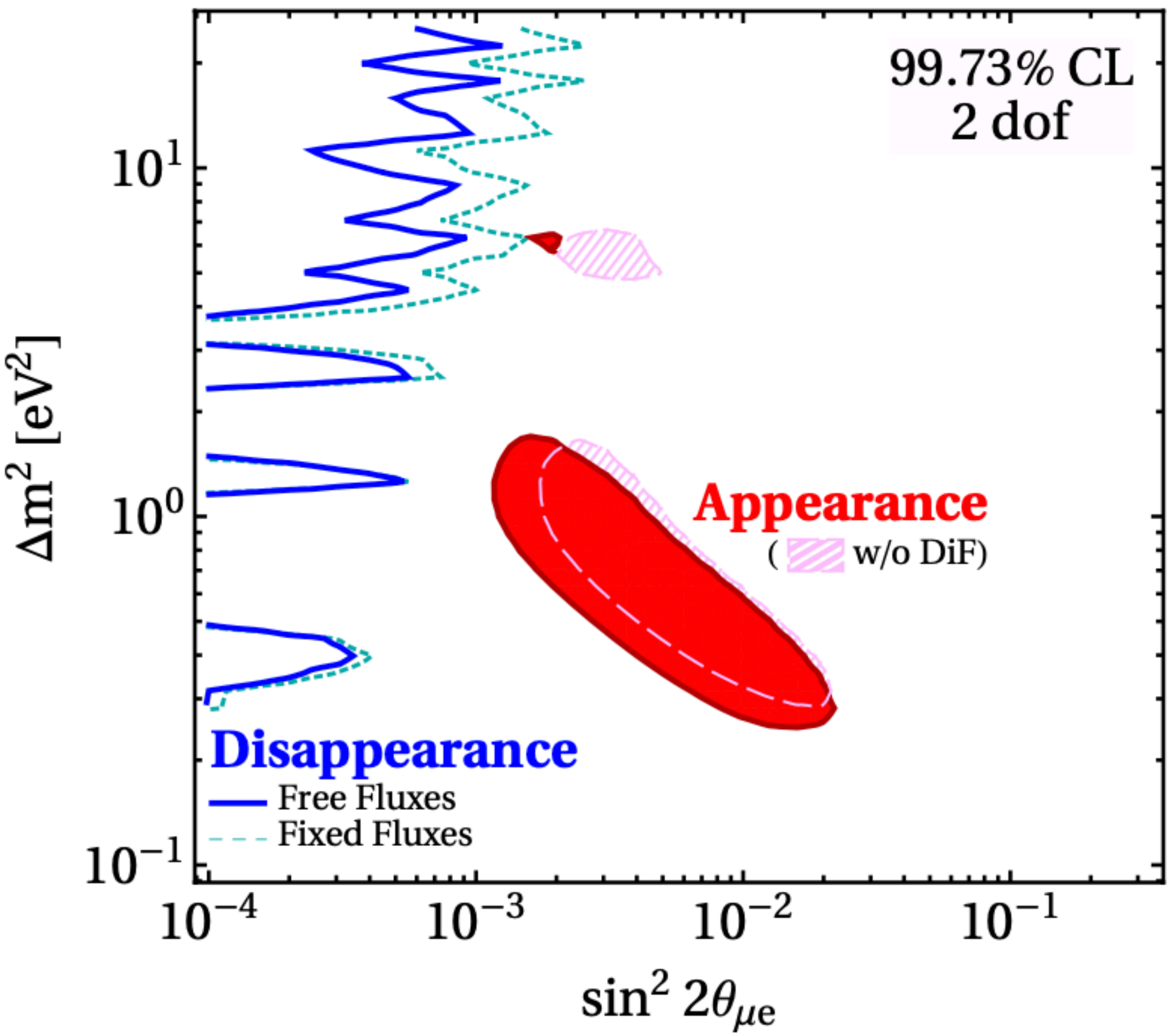


68% CL
90% CL
95% CL
99% CL
3σ CL
4σ CL
KARMEN2 90% CL
OPERA 90% CL
MiniBooNE:1805.12028
LSND 90% CL
LSND 99% CL
Δm² (eV²)
sin²2θ



Argüelles et al. 2021
SBN 3σ
MB 1σ
2σ
3σ
KARMEN 3σ
OPERA 3σ
MicroBooNE 3σ
Inclusive
CCQE
Δm^2_{41} [eV²]
$\sin^2(2\theta_{\mu e}) \equiv 4|U_{\mu 4}|^2|U_{e4}|^2$

Backup



Dentler et al (2018)