

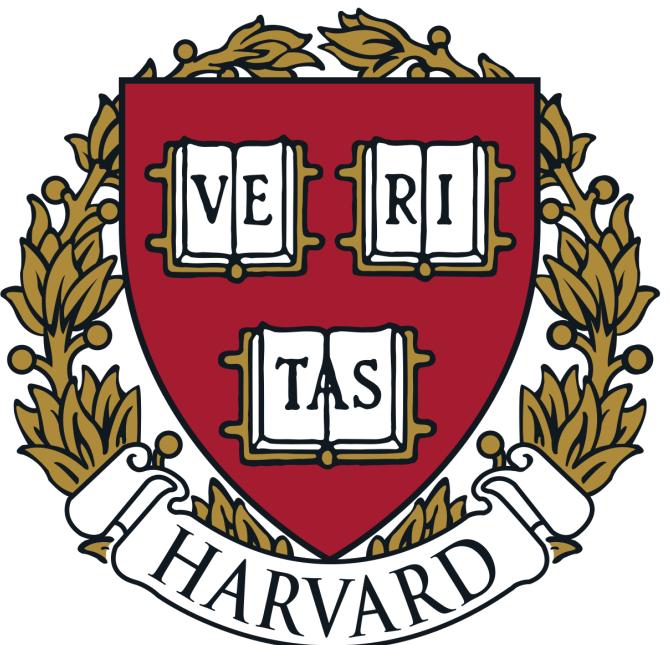


Interpretation of MicroBooNE results

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Neutrino Theory Network Workshop

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3+1 scenario

- Several anomalies point to the existence of an eV sterile neutrino.
- In the 3+1 scenario, neutrino evolution is described by

$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E} [U^\dagger Diag(0, \Delta m_{21}^2, \Delta m_{31}^2, \Delta m_{41}^2) U \pm V_{mat}] \vec{\nu} \quad \vec{\nu} = (\nu_e \nu_\mu \nu_\tau)^T$$

The evolution depends on:

Matter potential

- 6 mixing angles and 3 complex phases

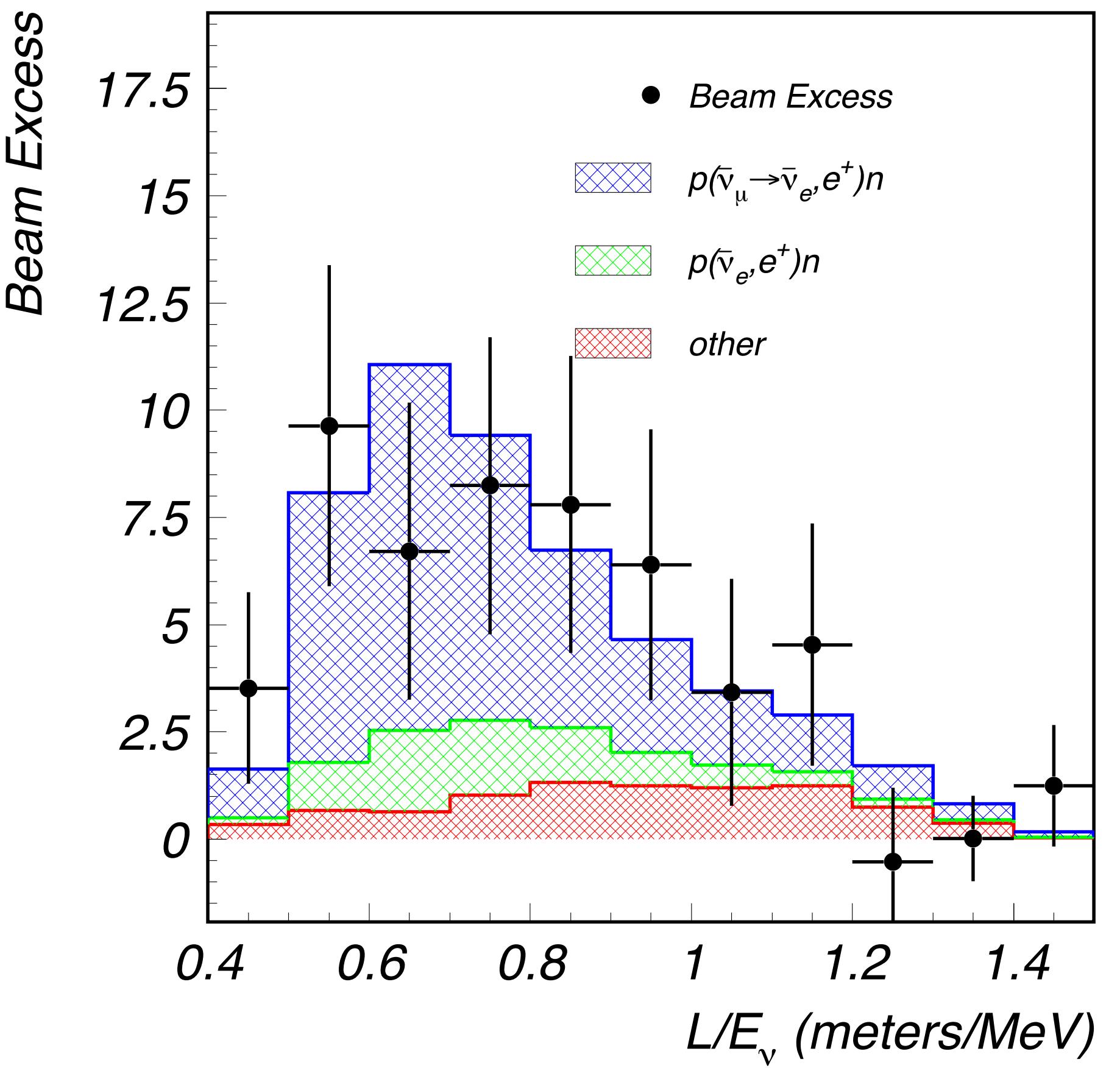
$$U \equiv R_{34}(\theta_{34}) R_{24}(\theta_{24}, \delta_{24}) R_{14}(\theta_{14}) R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta_{13}) R_{12}(\theta_{12}, \delta_{12})$$

- Three mass splittings $\Delta m_{21}^2 \sim 10^{-5}\text{eV}^2$ $\Delta m_{31}^2 \sim 10^{-3}\text{eV}^2$ and $\Delta m_{41}^2 \sim \text{eV}^2$

Excess of ν_e in a ν_μ beam

LSND

- The first channel that pointed to ν_s with masses in the eV scale
- Excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam ($E_\nu \sim 30\text{MeV}$ and $L \sim 35\text{m}$)
- $\pi^+ \rightarrow \mu^+ \nu_\mu$ and $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

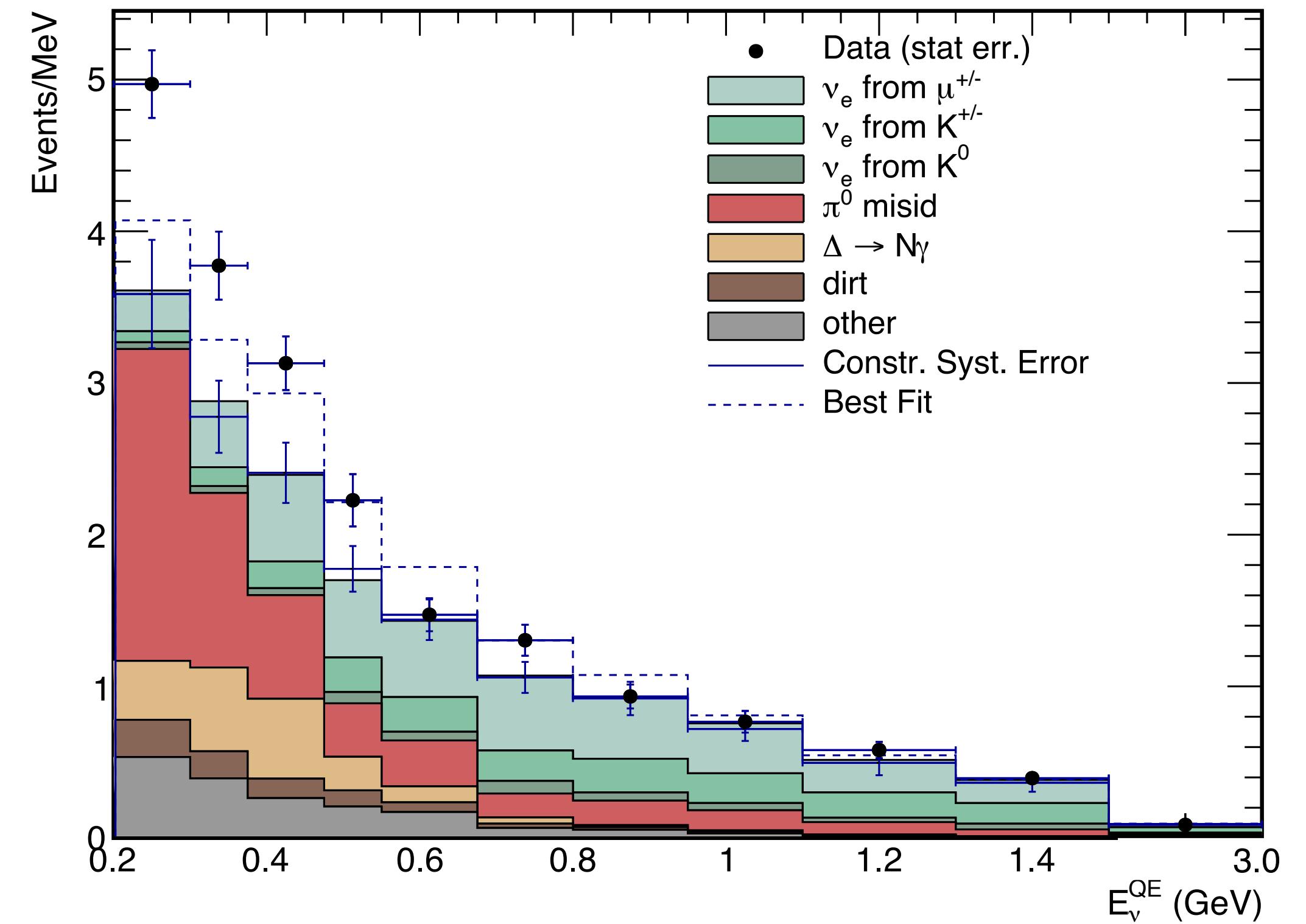


A. Aguilar-Arevalo et al. (Phys.Rev. D64 (2001) 112007)

Excess of ν_e in a ν_μ beam

MiniBooNE

- Designed to search for $\nu_\mu \rightarrow \nu_e$ at the same L/E as LSND
- Low energy excess of ν_e ($200\text{MeV} \leq E \leq 500\text{MeV}$)



MiniBooNE PRL 121 (2018)

ν_e appearance

The excess can be explained by the oscillation

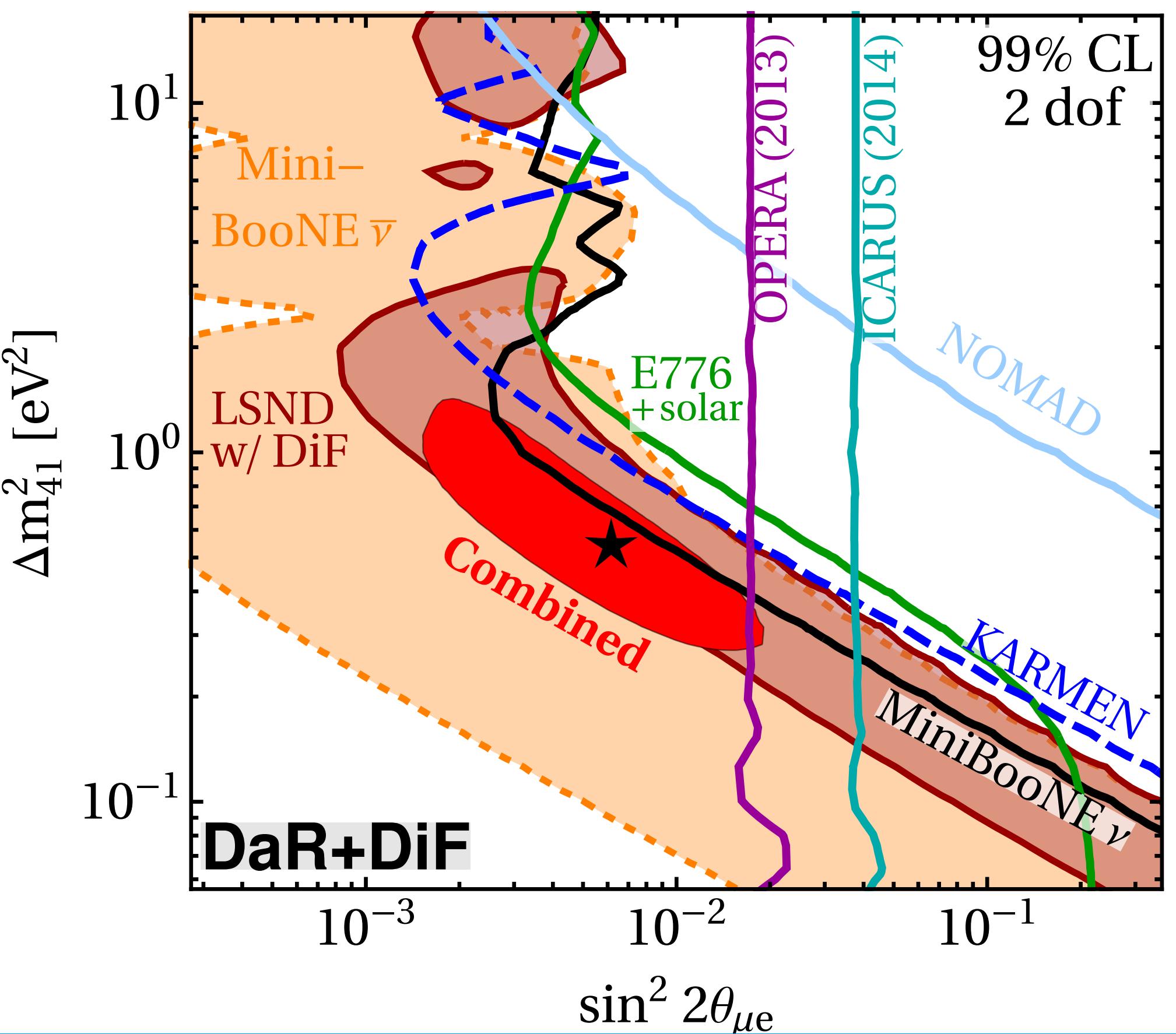
$$\nu_\mu \rightarrow \nu_e$$

$$P_{\mu e}^{SBL} = \sin^2 2\theta_{e\mu} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

M. Dentler, A. Hernandez-Cabezudo, J. Kopp, P.A.N. Machado, M. Maltoni, IMS, T. Schwetz, JHEP 1808 (2018) 010

See also A. Diaz, C.A. Arguelles, G.H. Collin, J.M. Conrad, M.H. Shaevitz Phys.Rept. 884 (2020)

The combined analysis has a preference for ν_s of 6σ



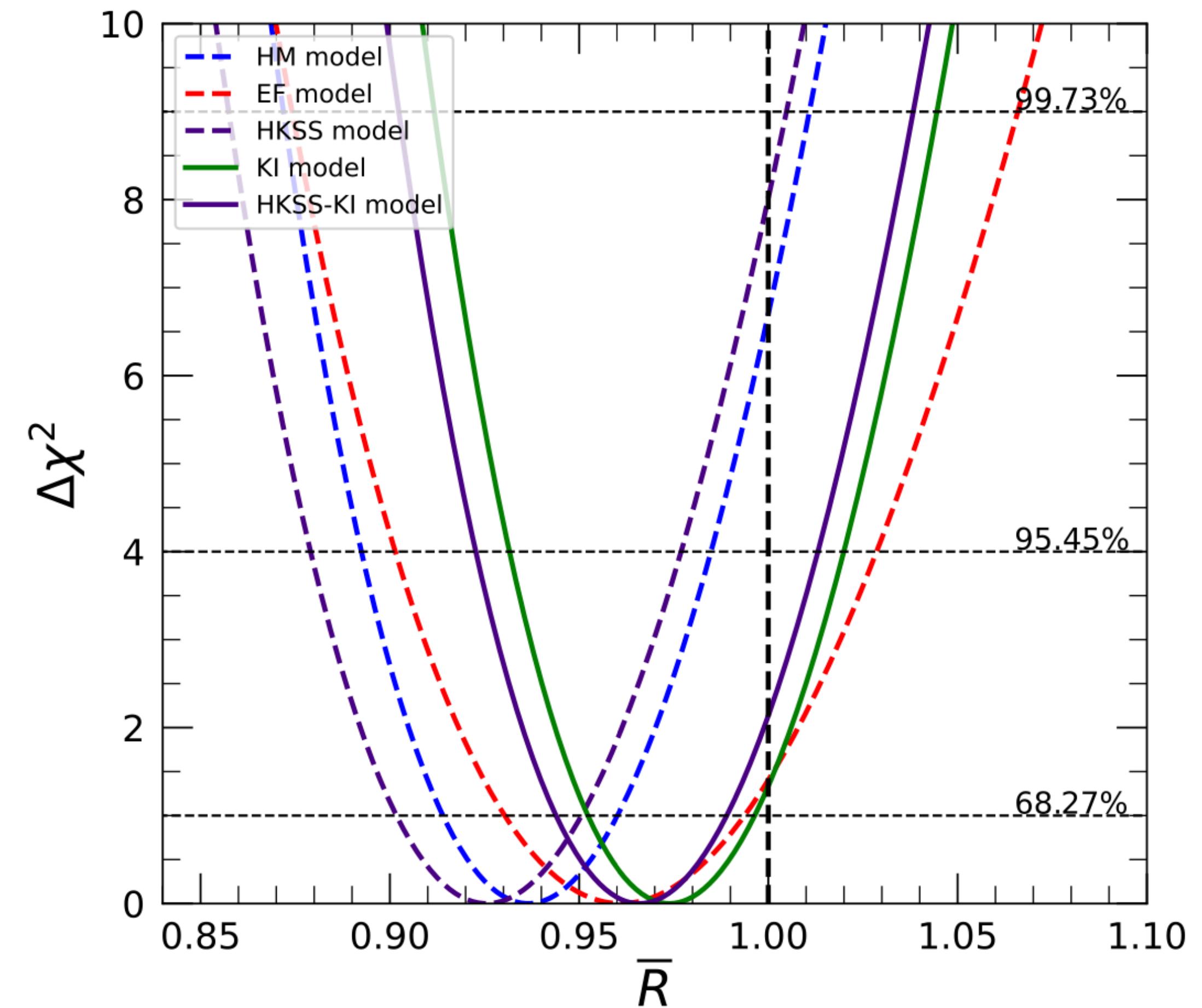
Reactor anomaly

Reevaluations of the $\bar{\nu}_e$ flux from reactors showed a deficit in the observed flux

- Data/Prediction = 0.941 ± 0.015 from HM prediction
Kyung Kwang Joo et al. (RENO NEUTRINO 2022)
- The deficit can be explained in terms of a sterile neutrino with a high mass

$$P_{ee}^{SBL} \simeq 1 - \sin^2 2\theta_{ee} \frac{1}{2}$$

- New evaluations of the flux alleviate that tension

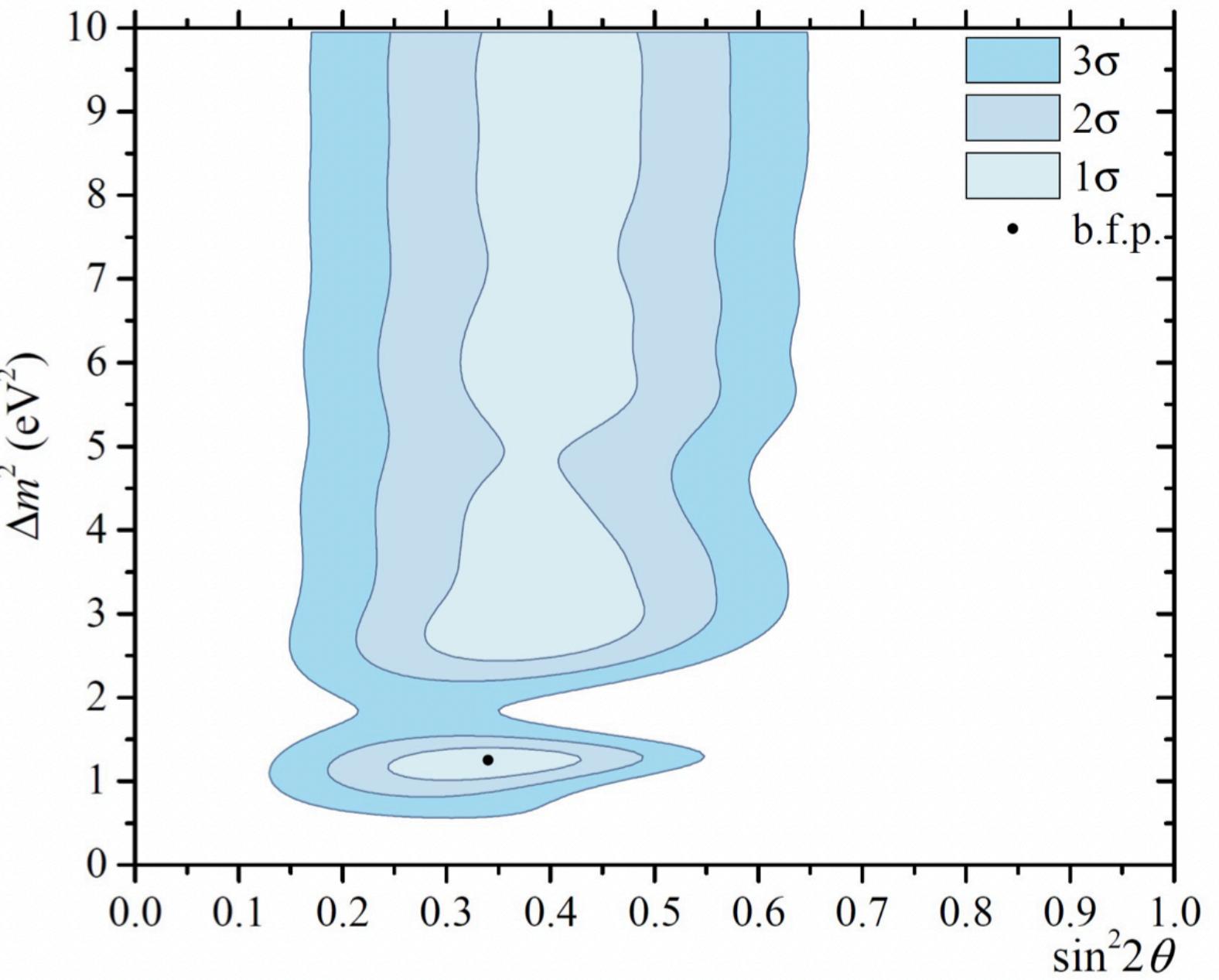
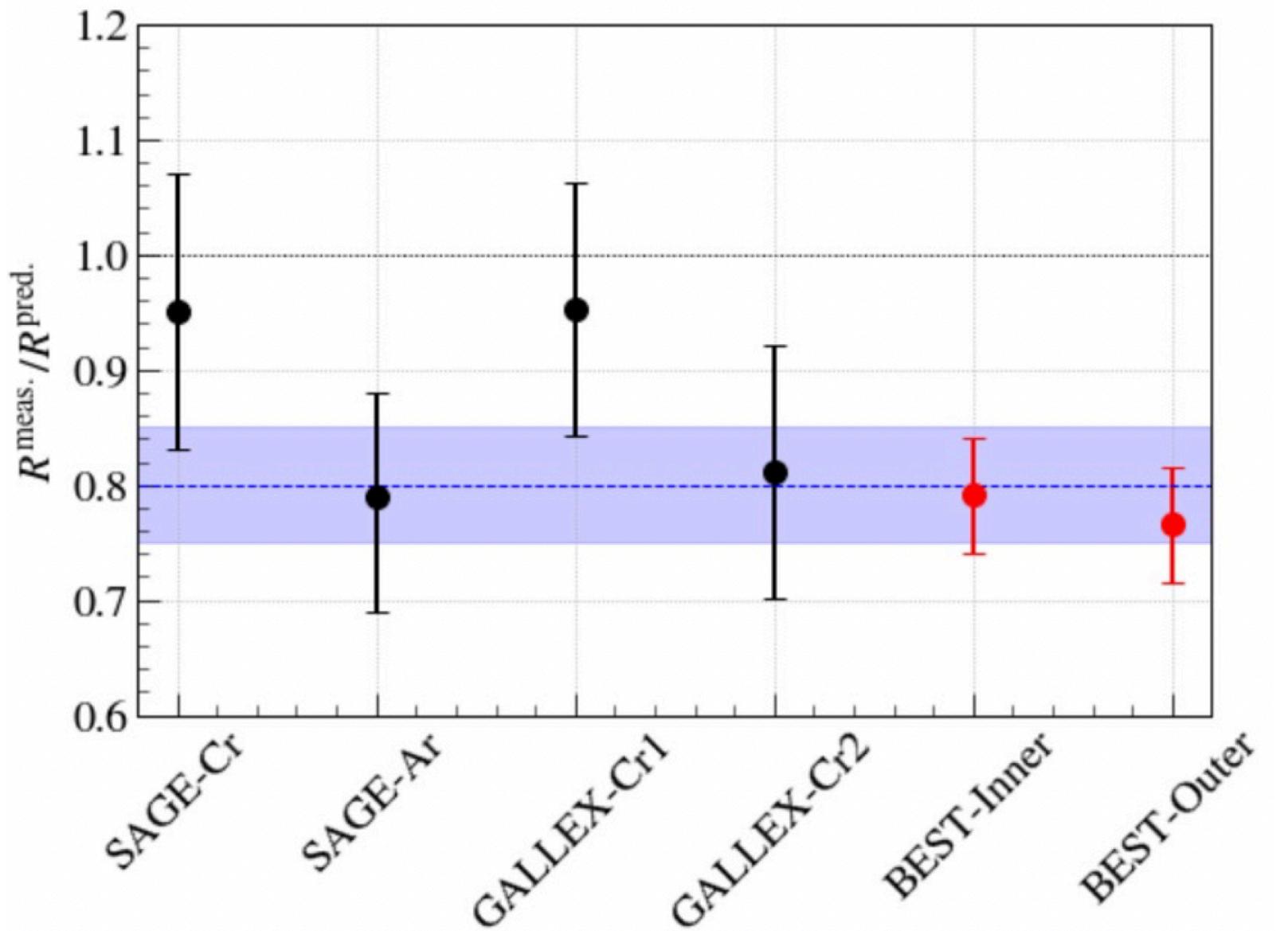


C. Giunti, et al., Phys.Lett.B 829

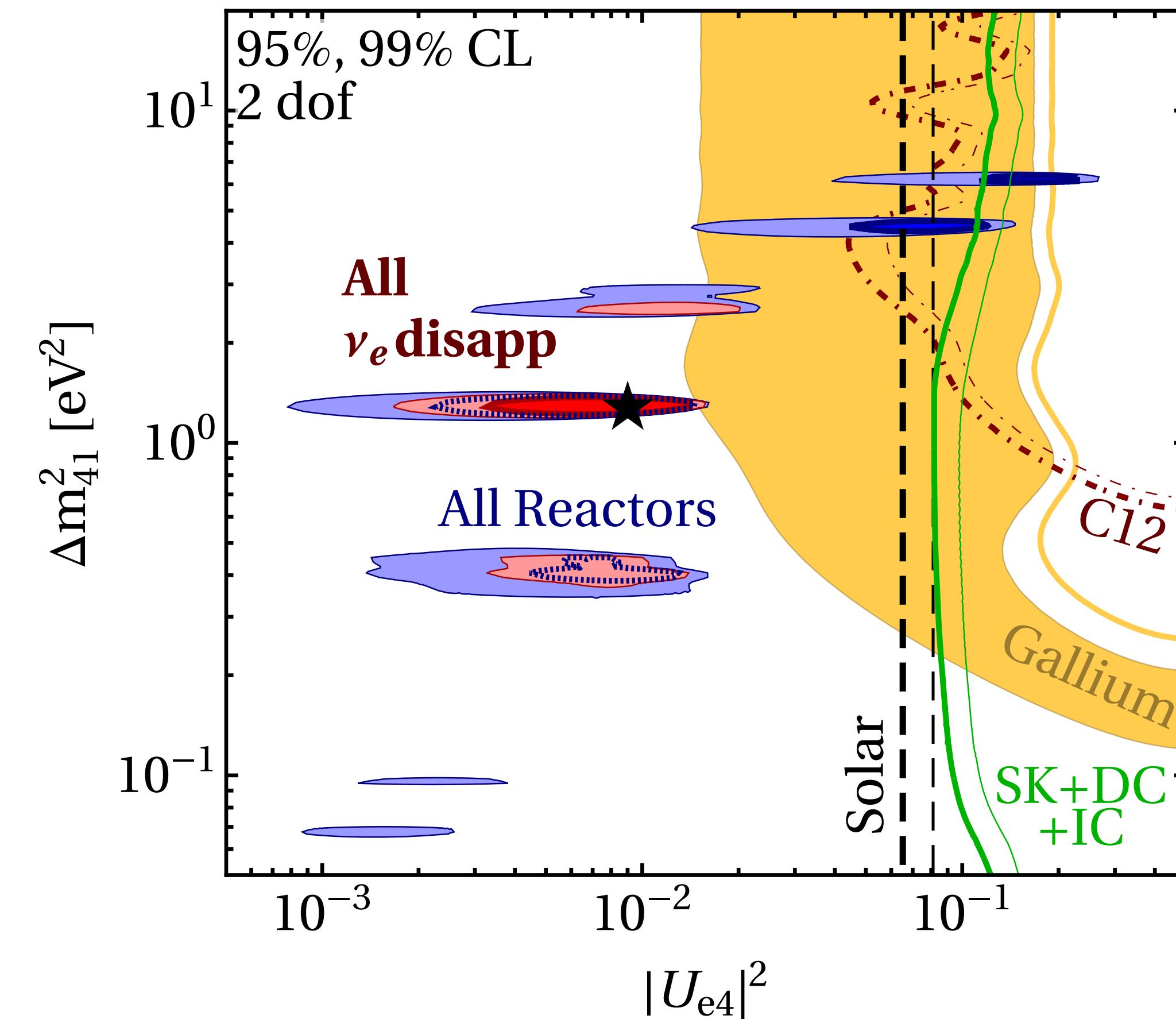
Gallium anomaly

- GALLEX and SAGE (Solar Gallium experiments) were tested using radioactive sources (^{51}Cr , ^{37}Ar)
- The observation has been confirmed by BEST
- The combined results shows: $R_0 = 0.8 \pm 0.05$
- The anomaly can be explained in terms of an oscillation with large $\Delta m_{41}^2 \geq 1$

$$P_{ee}^{SBL} \simeq 1 - \sin^2 2\theta_{ee} \frac{1}{2}$$



Combining all the ν_e disappearance



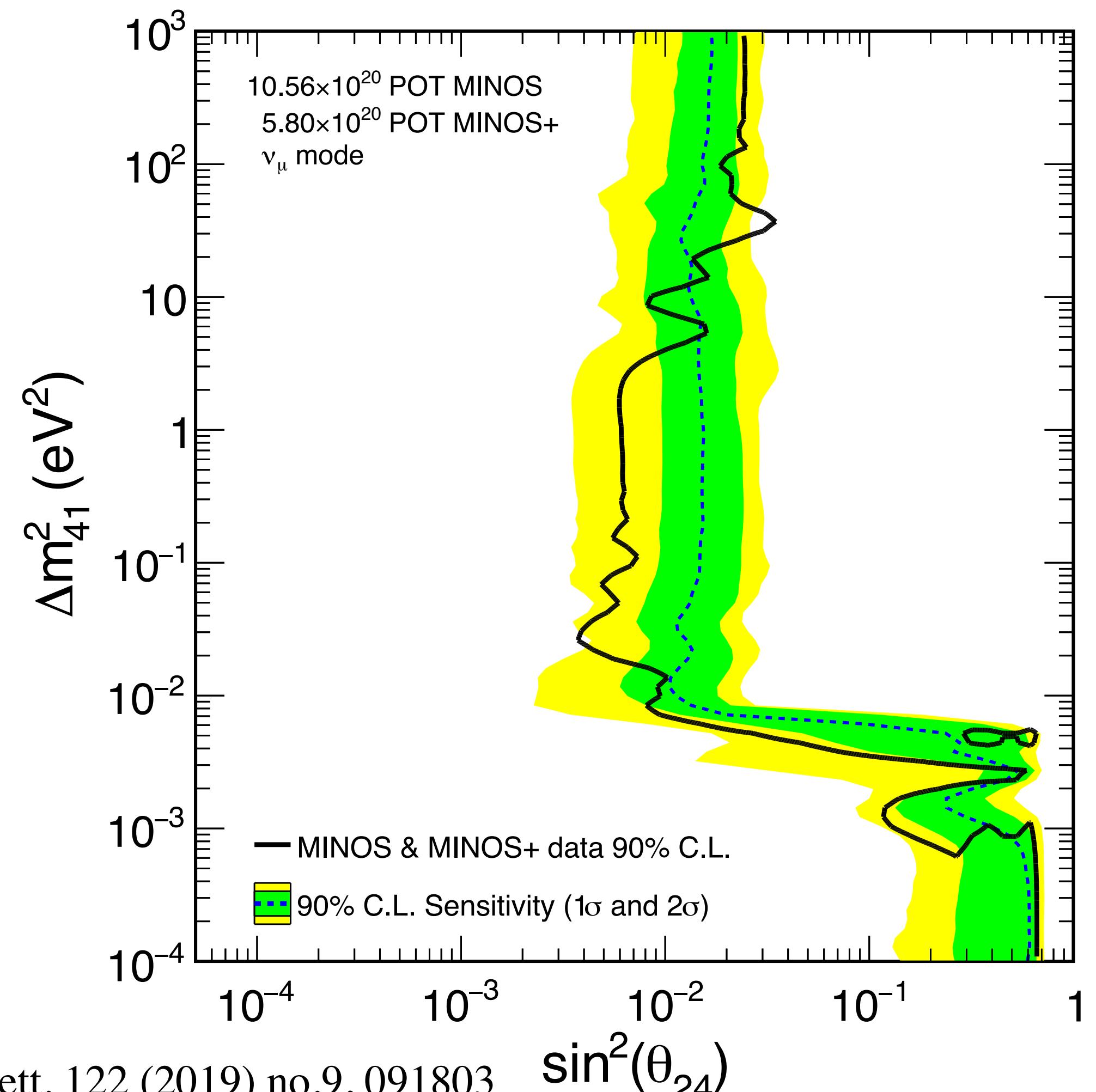
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ν_μ disappearance

LBL experiments:

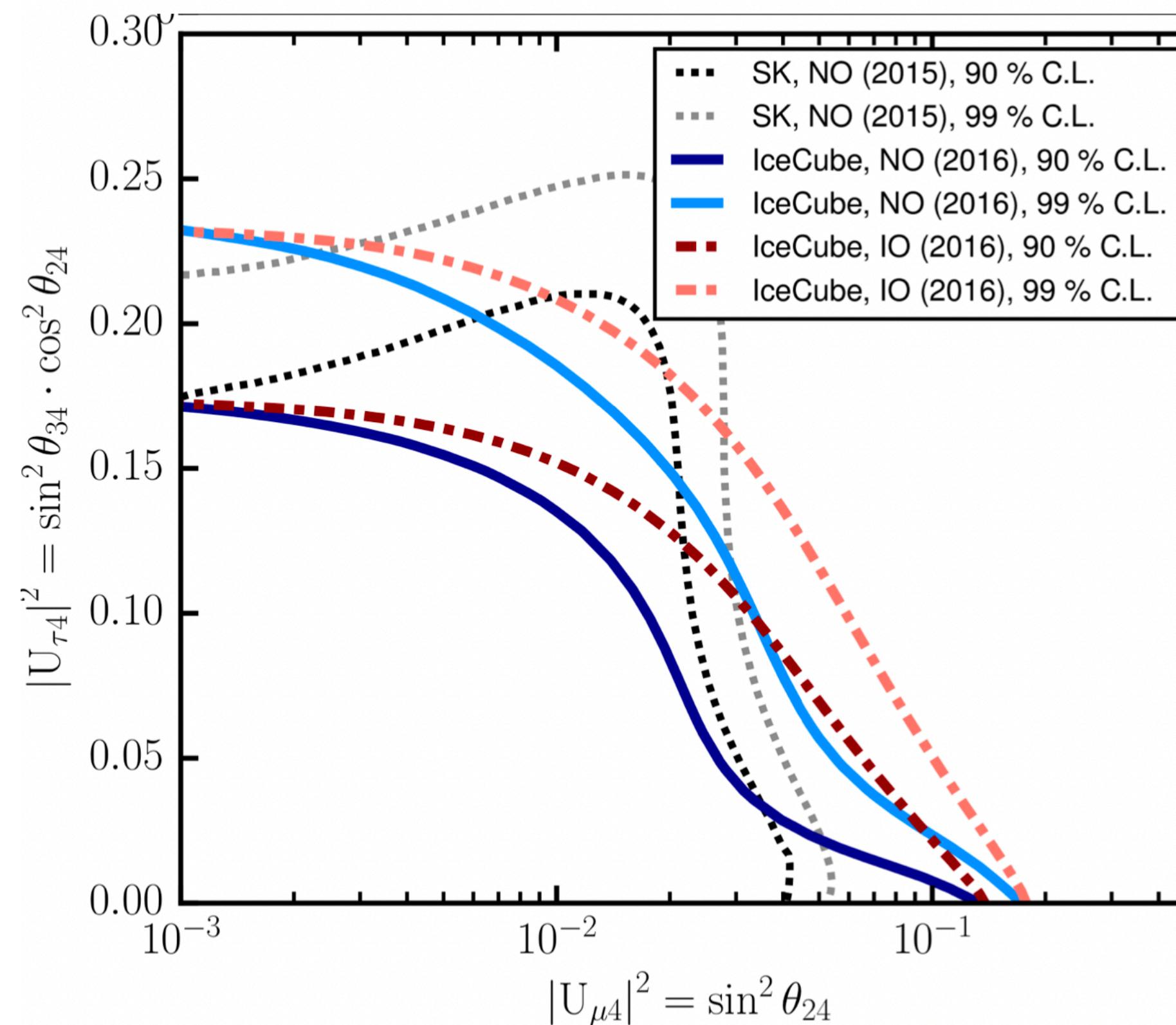
- MINOS/MINOS+ combined analysis dominates the sensitivity for high masses
 - For $10^{-3} \leq \Delta m_{41}^2 \leq 10^{-1}$ oscillation in the **far** detector
 - For $1 \leq \Delta m_{41}^2 \leq 100$ oscillation in the **near** detector
- NOVA has shown in Neutrino 2022 an analysis that includes CC and NC
 - Less sensitive than MINOS/MINOS+



Phys.Rev.Lett. 122 (2019) no.9, 091803

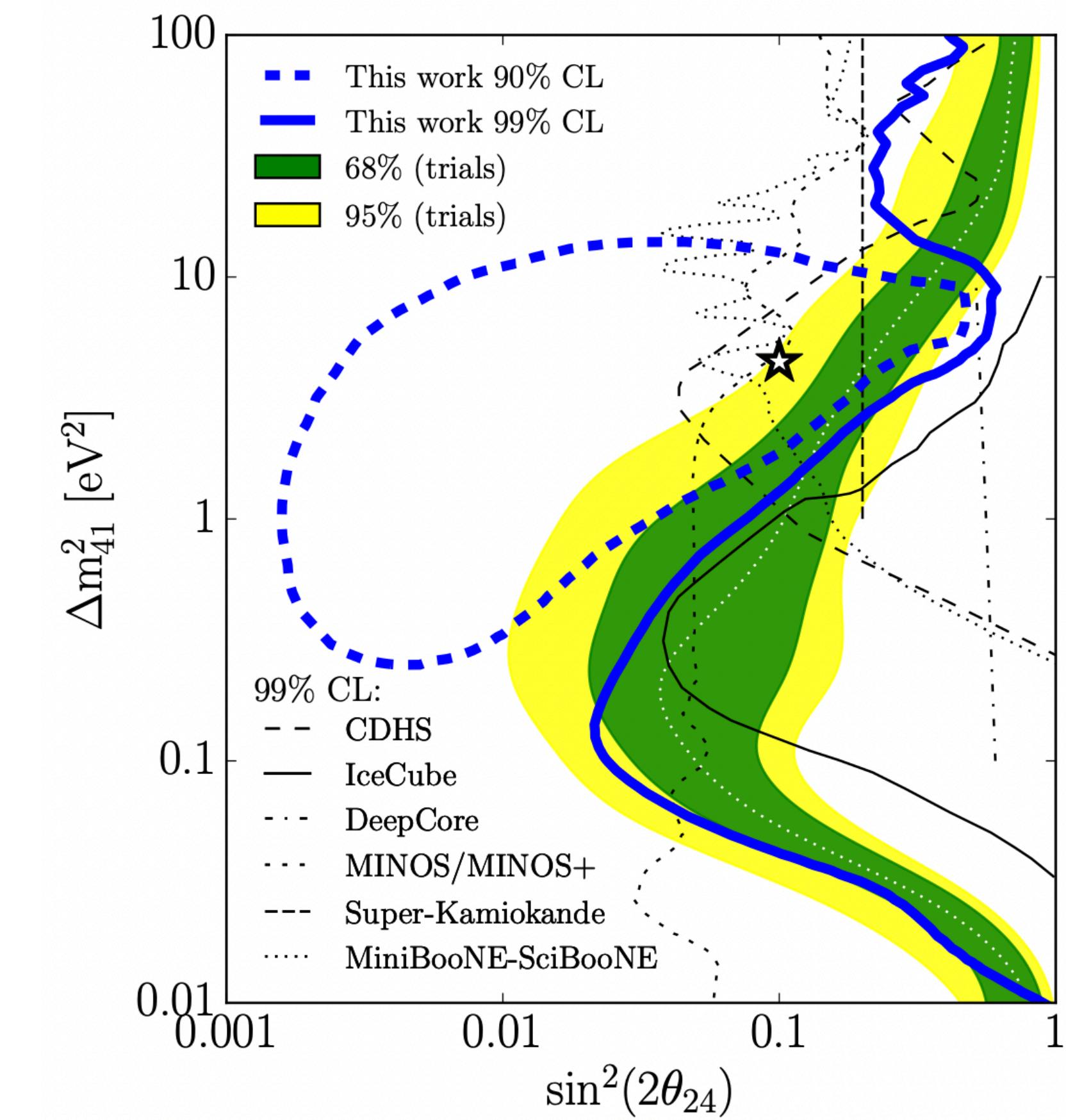
ν_μ disappearance

At the GeV scale, IceCube and SK are mainly sensitive to $U_{\mu 4}$ and $U_{\tau 4}$



M.G. Aartsen et al. (IceCube) Phys.Rev.D 95 (2017) 11

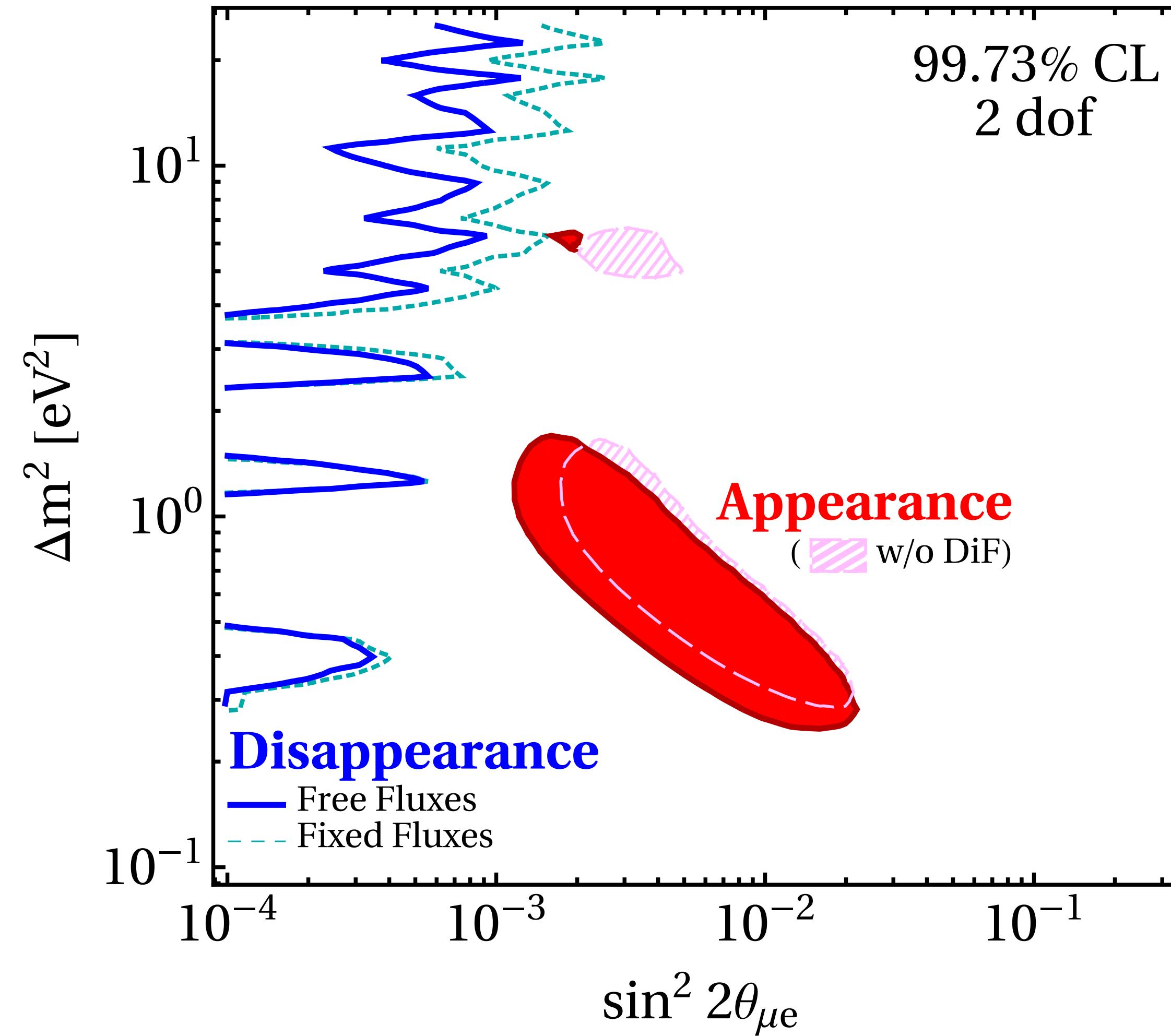
At the TeV scale, an eV ν_s will produce a flavor resonance for neutrinos crossing the Earth



M.G. Aartsen et al. (IceCube) Phys.Rev.Lett 125 (2020) 14

Appearance/disappearance tension

Strong tension between appearance and disappearance results. $\text{PG} = 3.7 \times 10^{-7}$

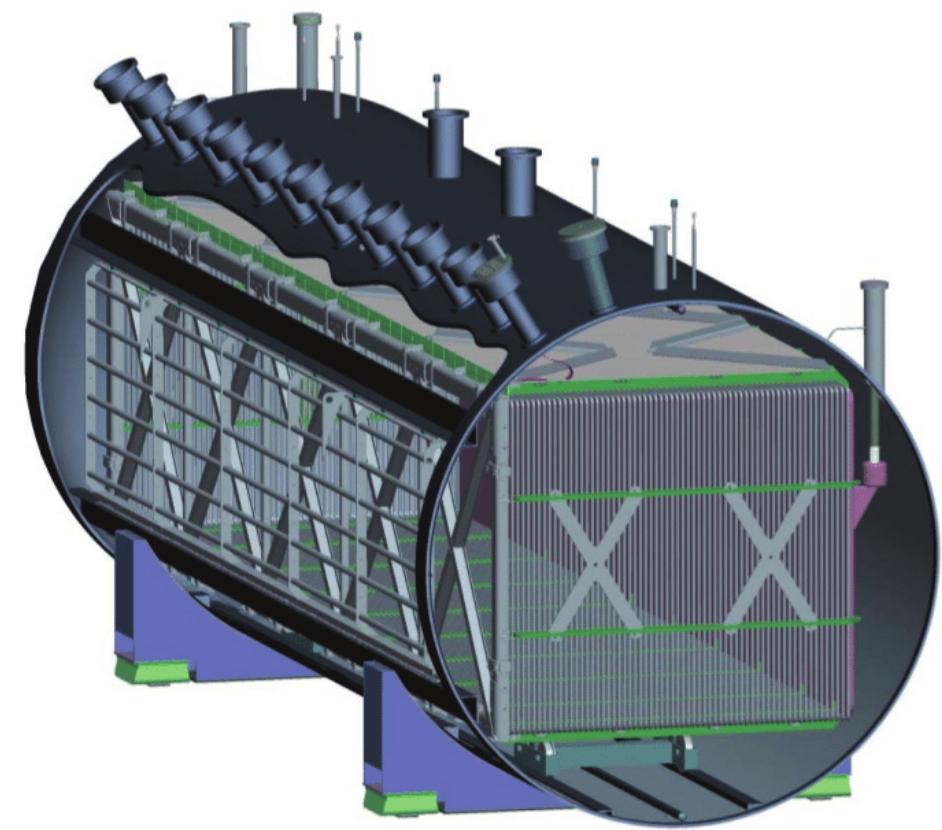


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**We need further efforts to search for light sterile
neutrinos...MicroBooNE**

MicroBooNE

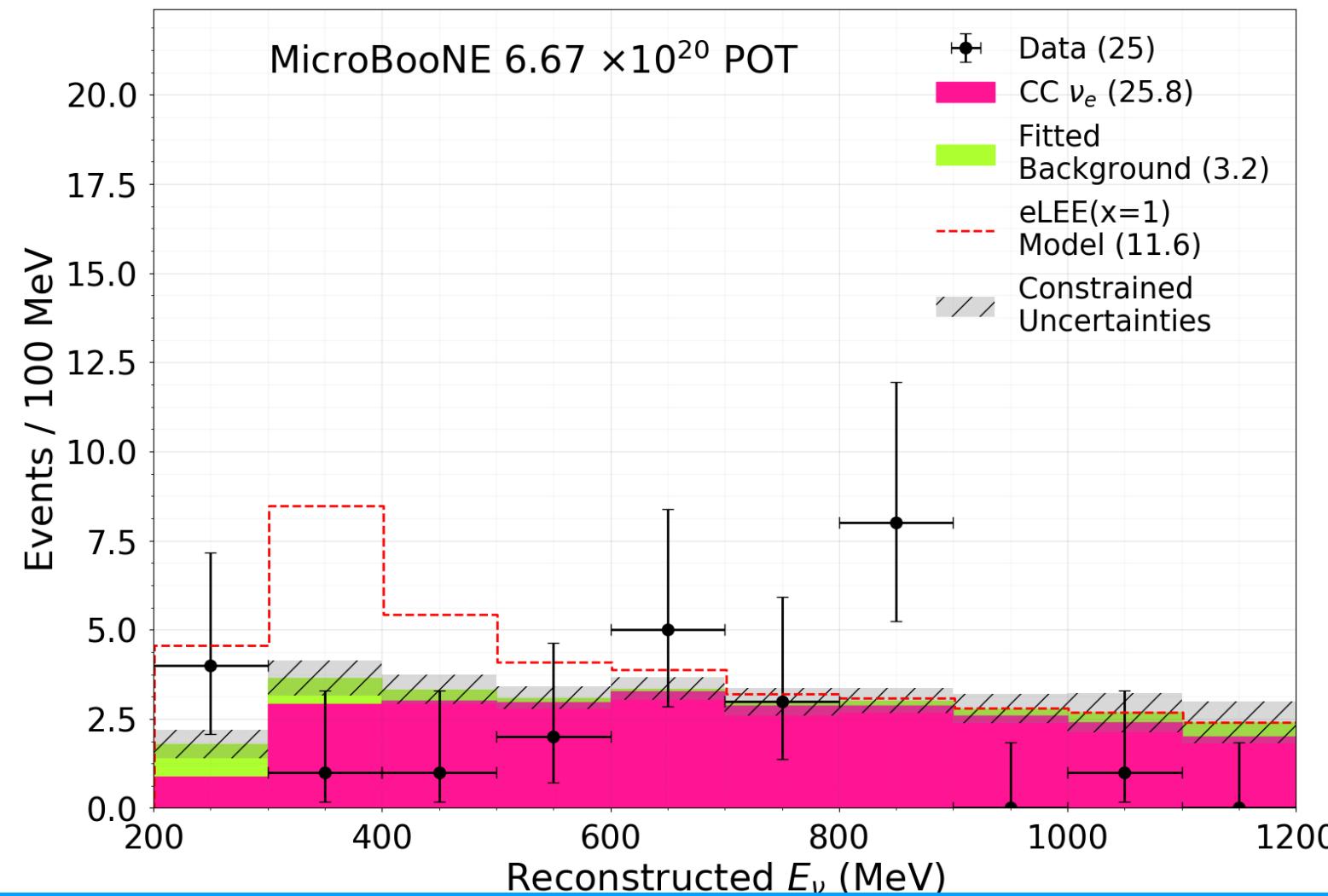
- LArTPC
 - mm-scale spatial resolution
 - Low energy detector threshold
- ~ 500 m baseline
- Booster Neutrino Beam



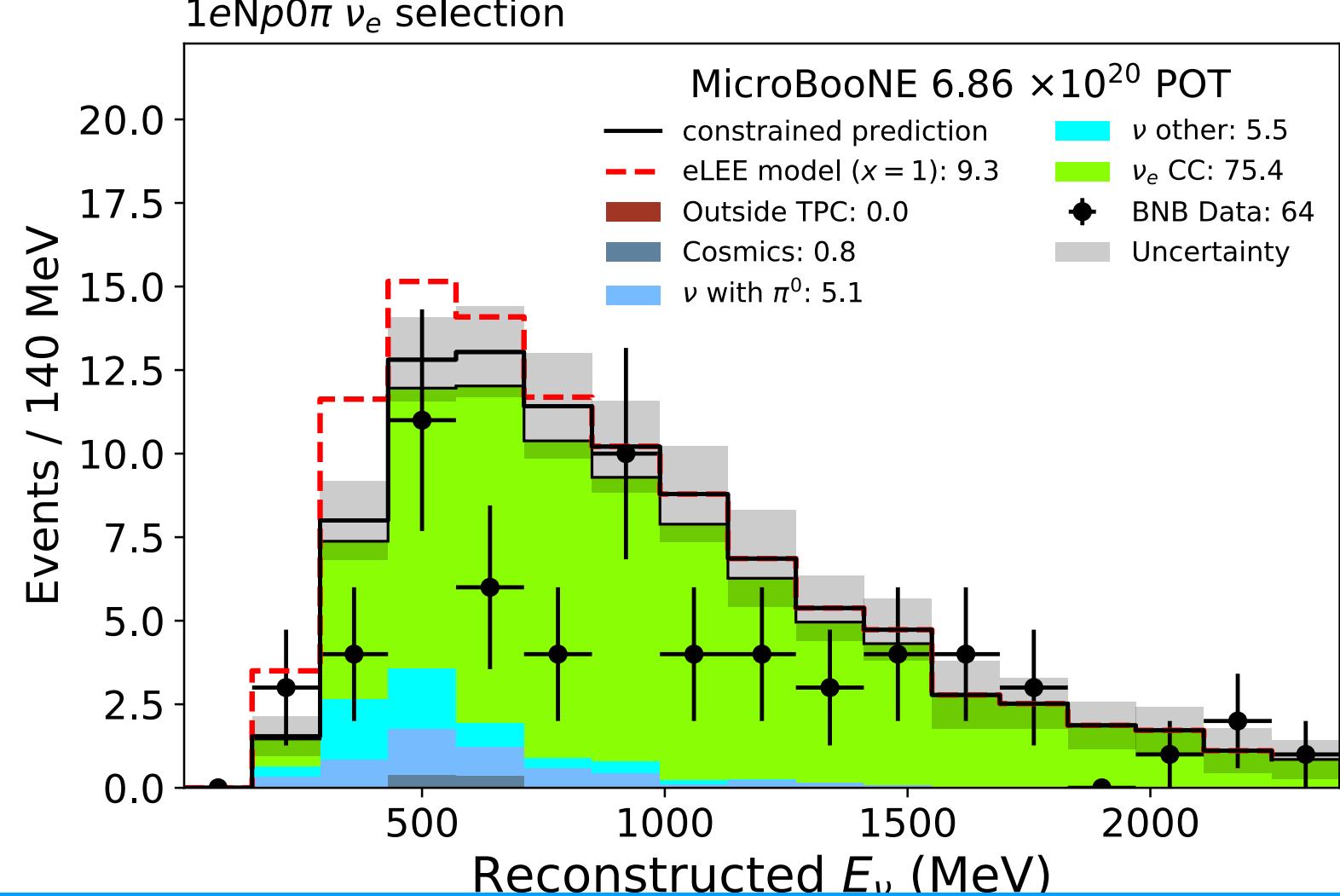
Three different event topologies to search for ν_e

MicroBooNE (2110.14054)

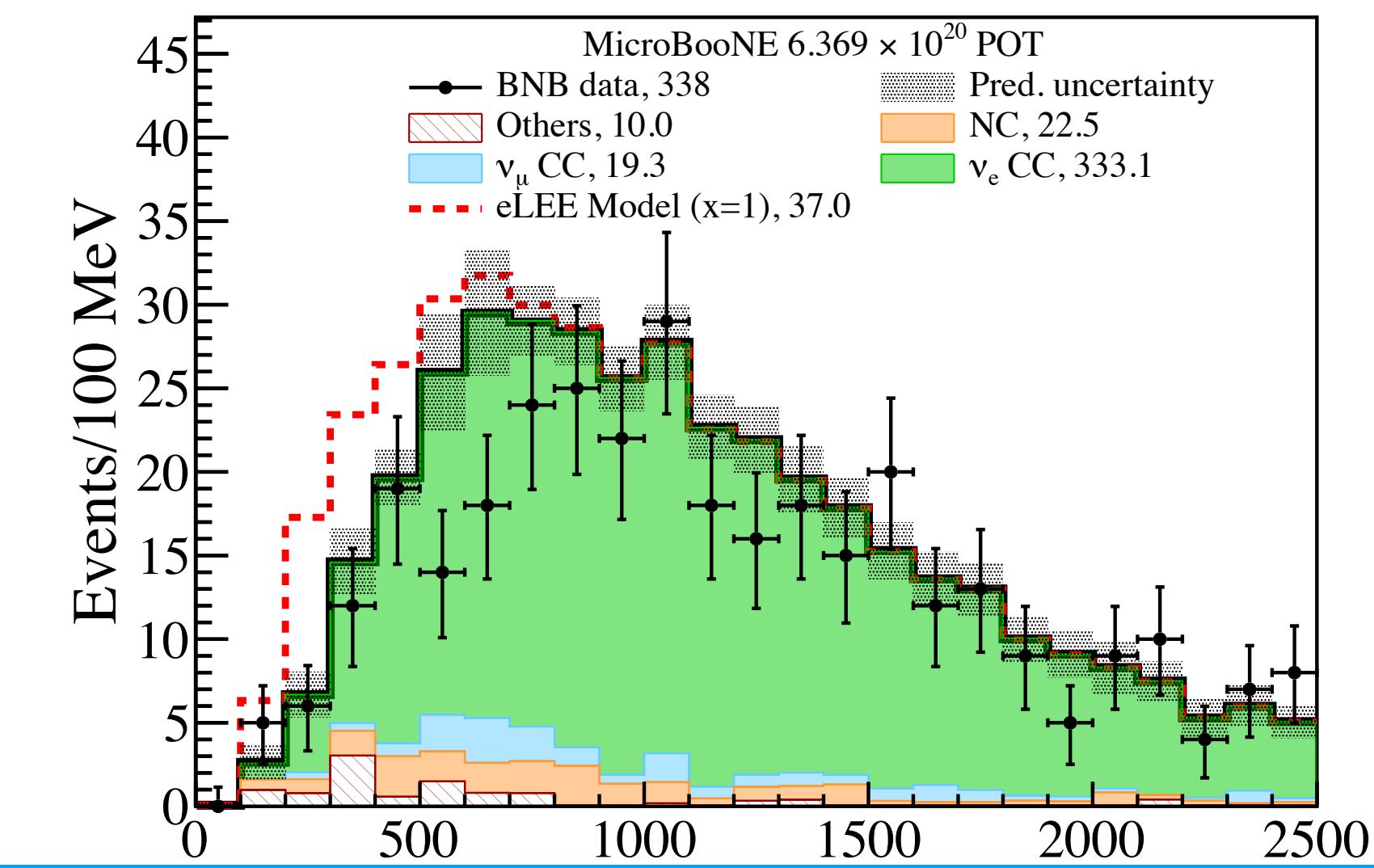
CCQE (1e1p)



Pinless ν_e (1eNp0 π , 1e0p0 π)



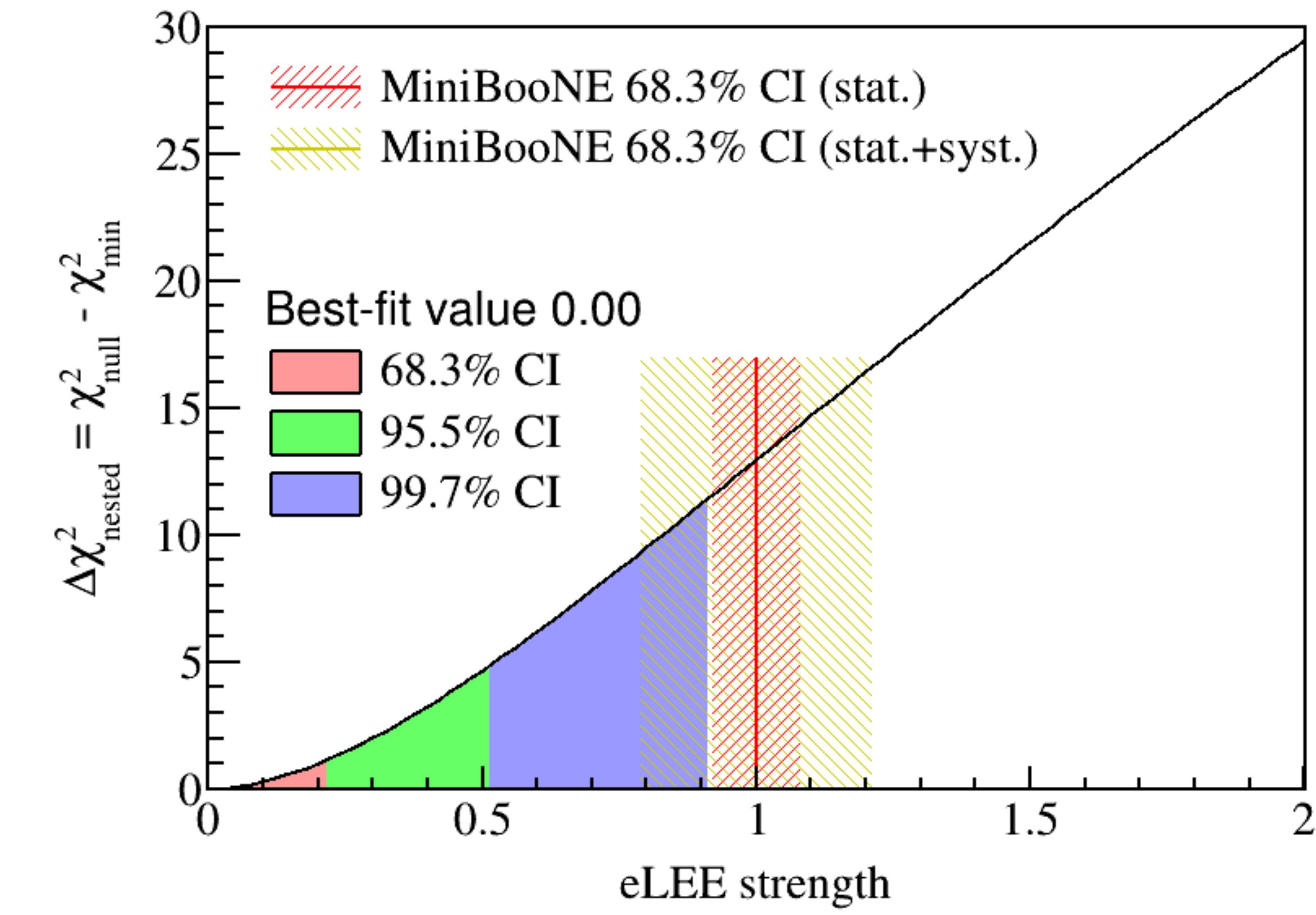
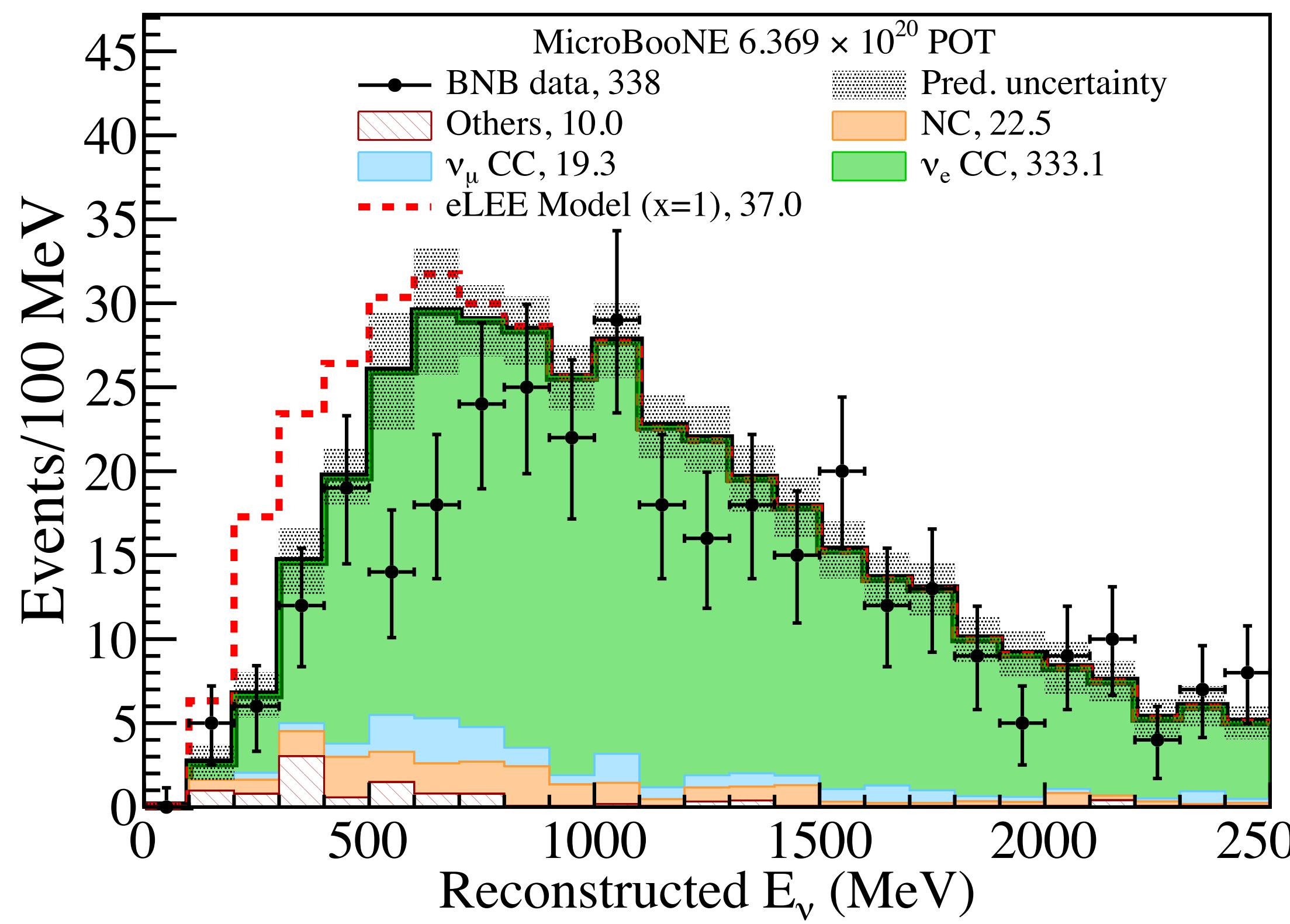
Inclusive (1eX)



Looking for MiniBooNE LEE

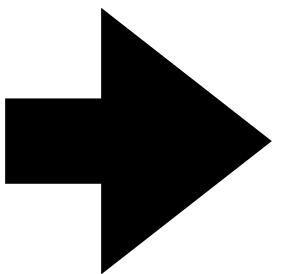
MicroBooNE searched for the LEE observed in MiniBooNE:

- The normalization is fitted (signal strength)
- The shape is fixed
- LEE excluded at 2.6σ (3σ)

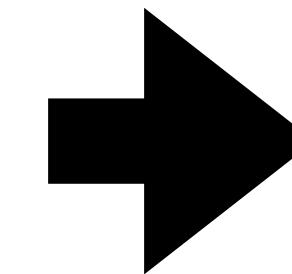


Looking for MiniBooNE LEE

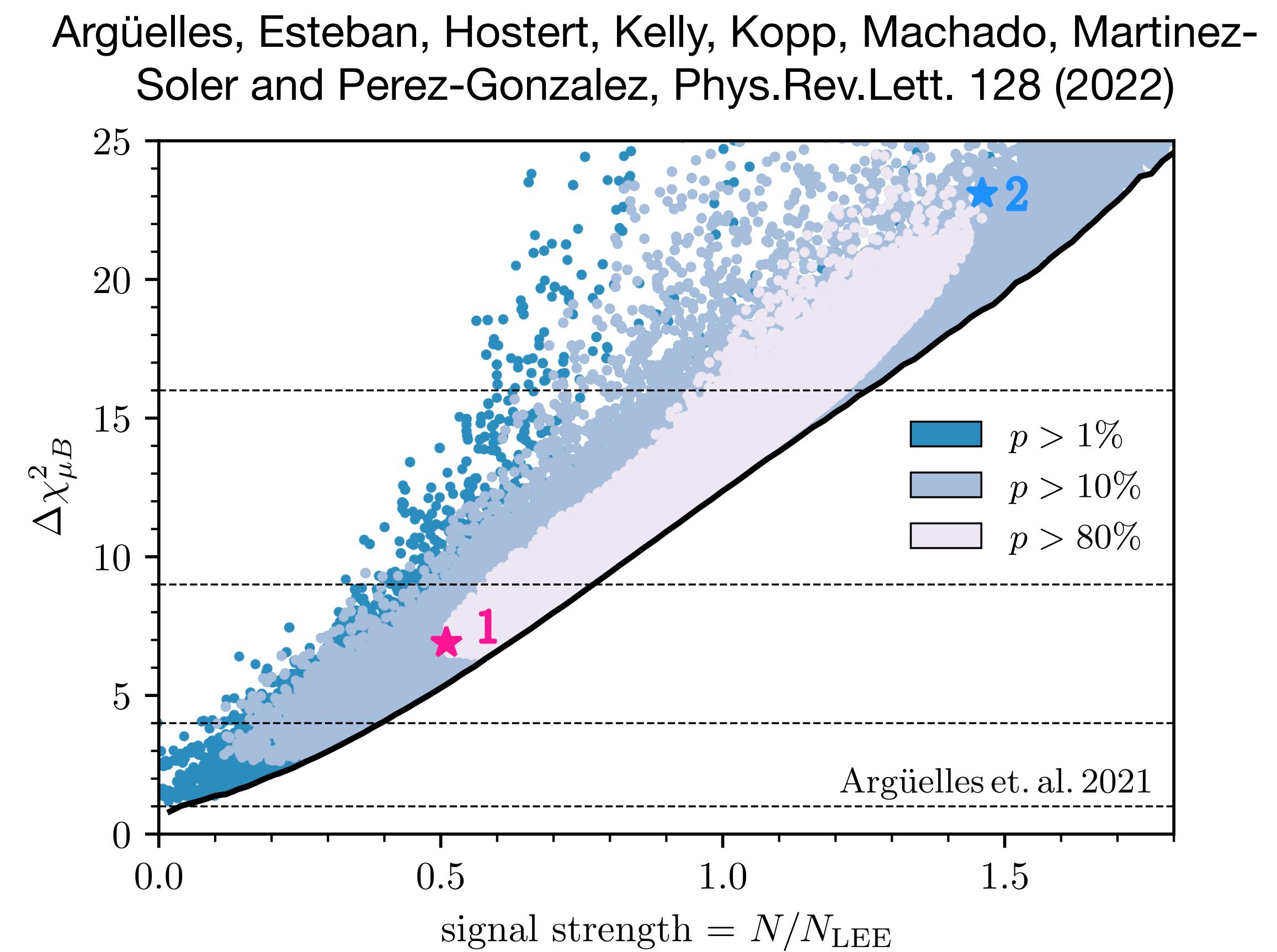
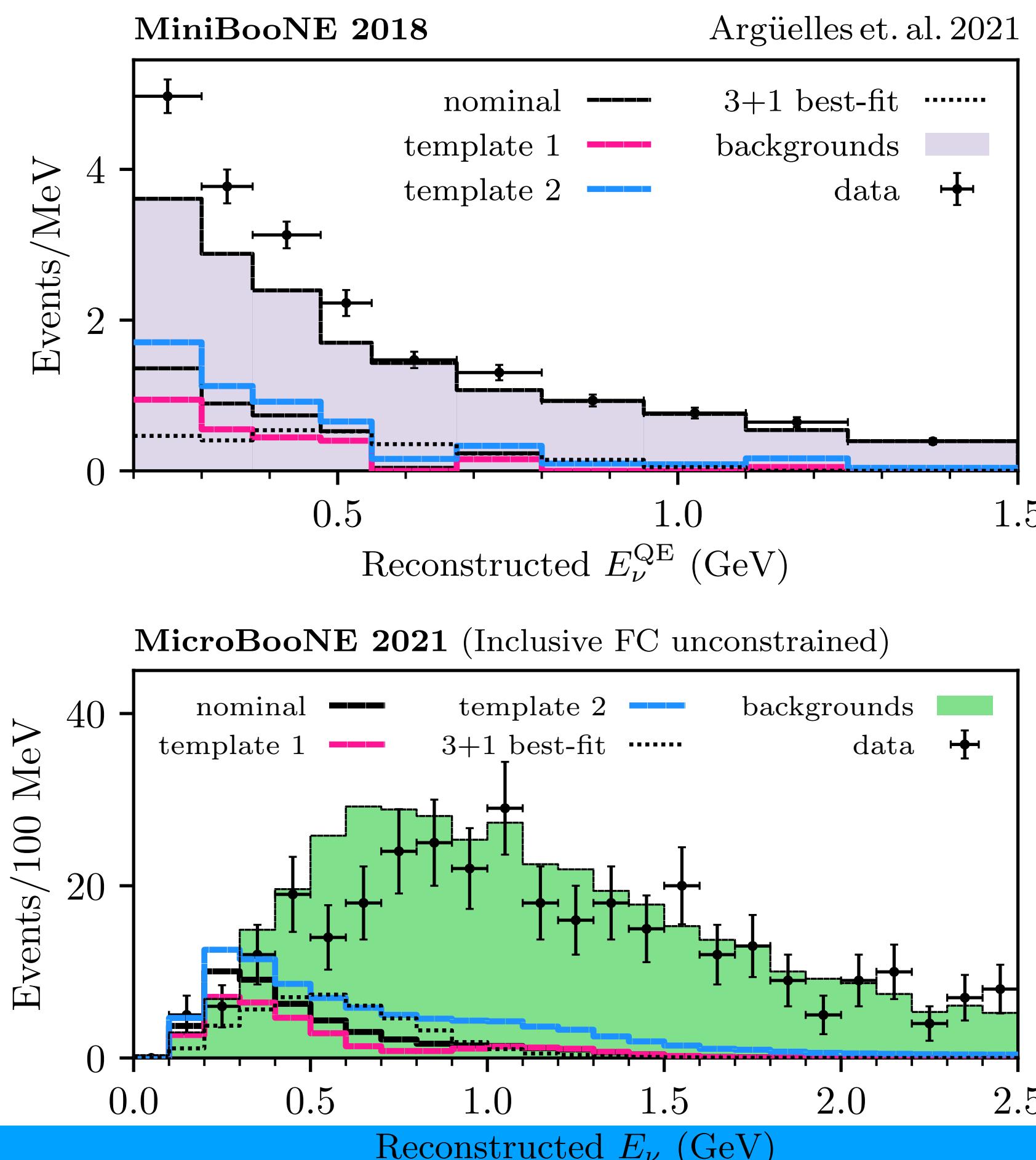
Background
uncertainties in MB



Different shapes of the LEE
not excluded by MB



MicroBooNE sensitivity
can be affected

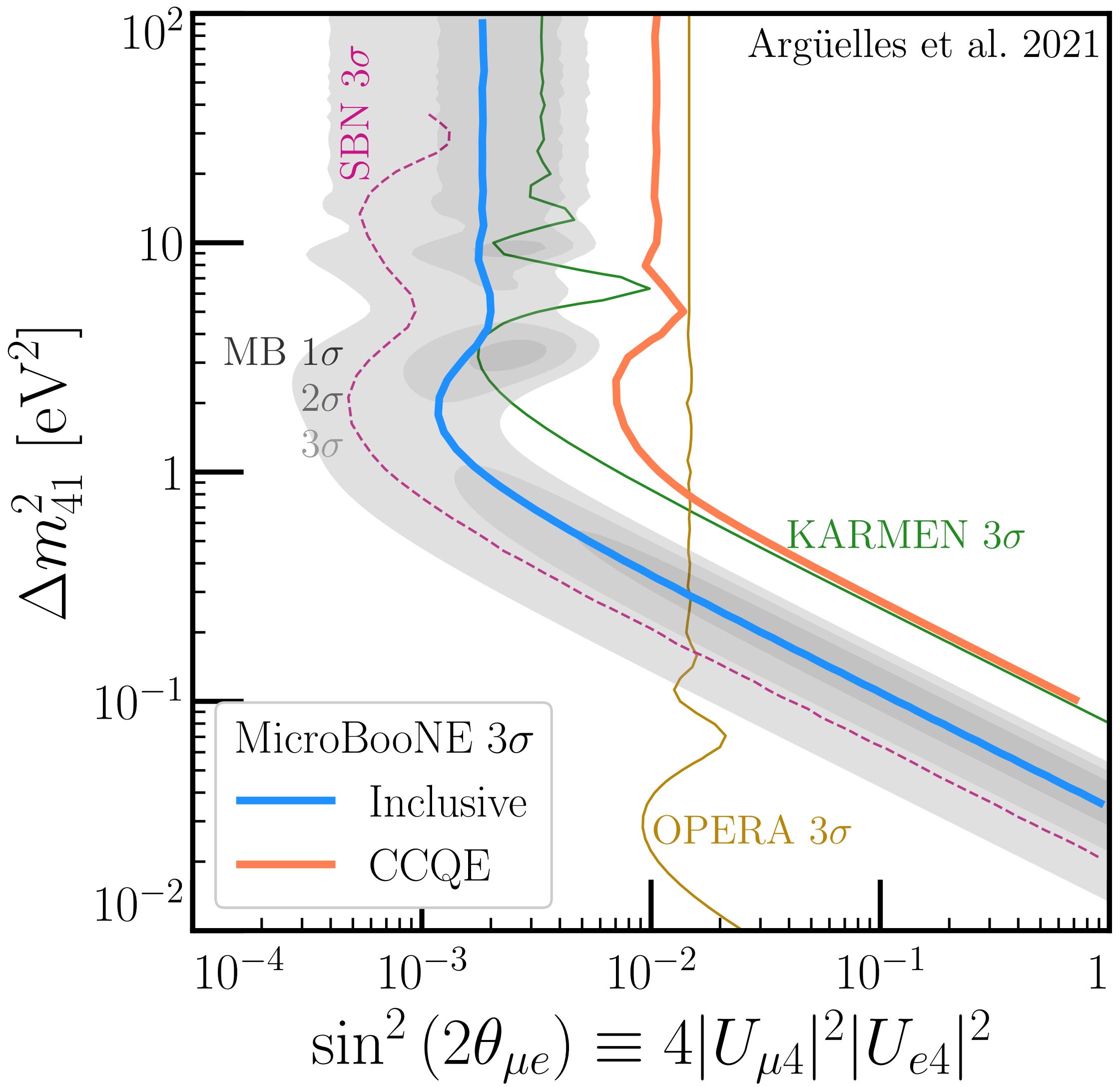


Searching for $\nu_\mu \rightarrow \nu_e$ in MicroBooNE

The background is independent of ν_s

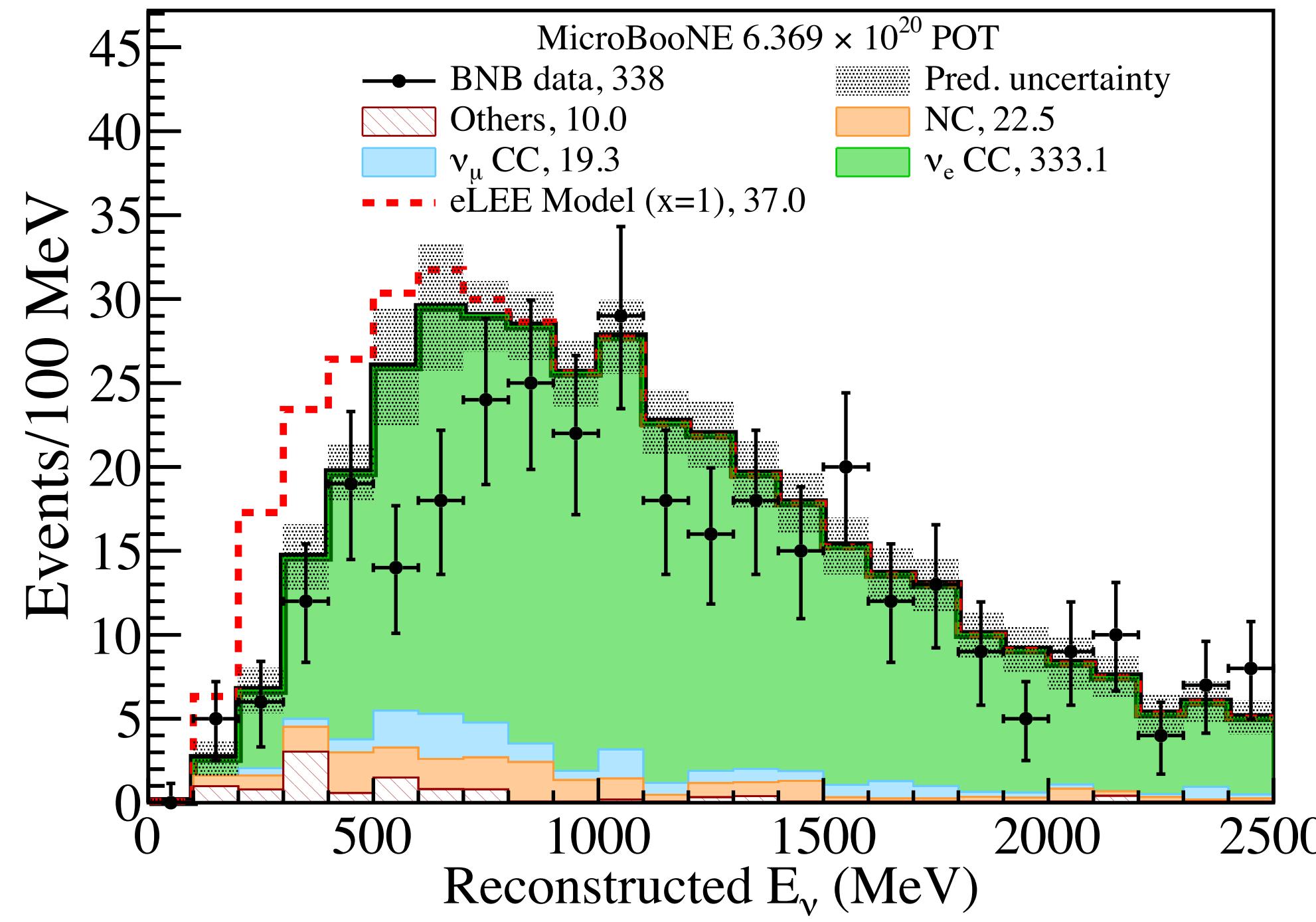
$$P_{\mu e}^{SBL} = \sin^2 2\theta_{e\mu} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

Argüelles, Esteban, Hostert, Kelly, Kopp, Machado, Martinez-Soler and Perez-Gonzalez, Phys.Rev.Lett. 128 (2022)

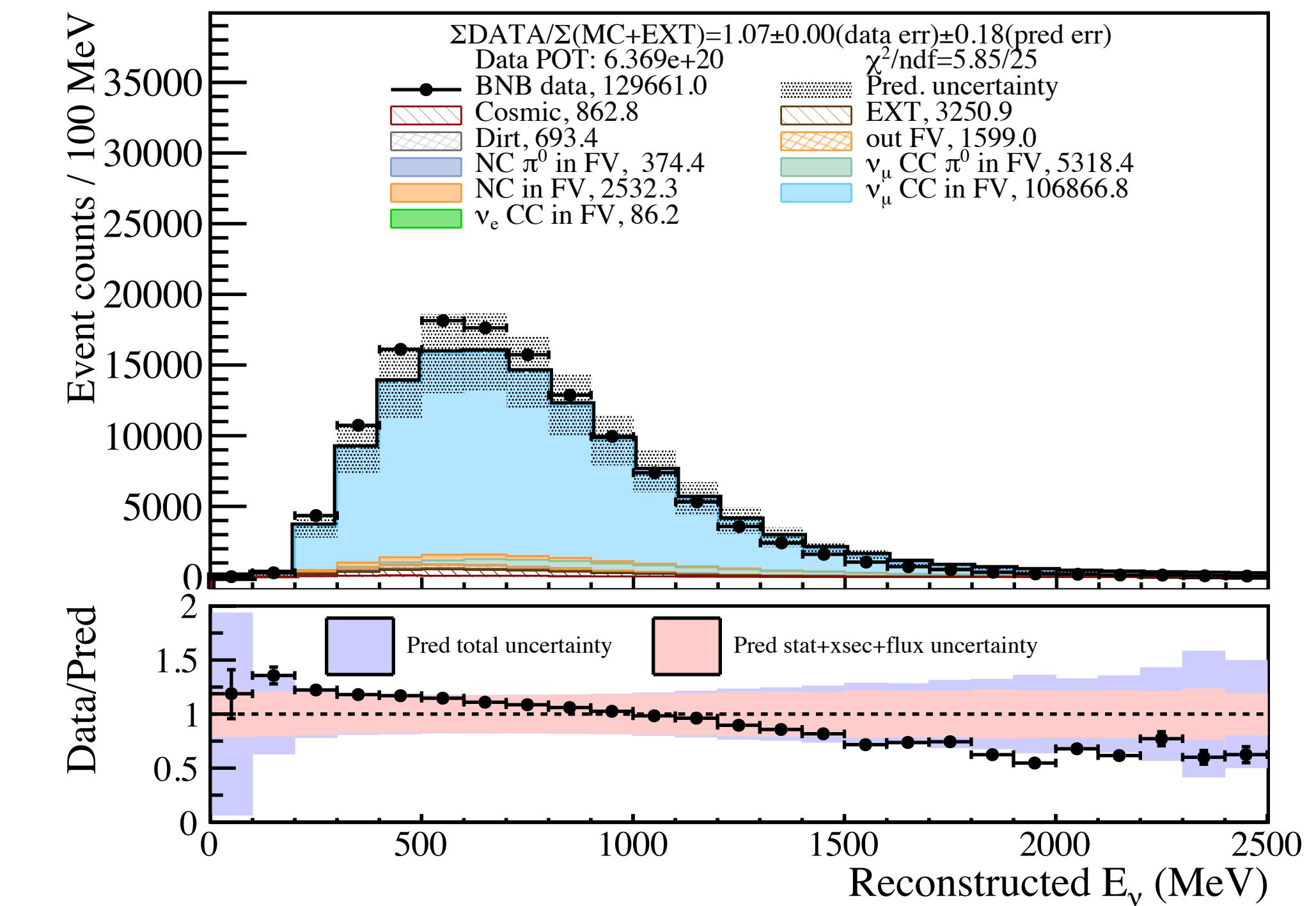


4ν oscillation analysis

Large background of ν_e -beam



Large ν_μ sample

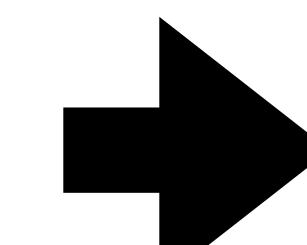


$$P_{ee}^{SBL} = 1 - \sin^2 2\theta_{ee} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

$$P_{\mu\mu}^{SBL} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

Are those channels correlated?

$$P_{e\mu}^{SBL} > 0$$



$$P_{\mu\mu}^{SBL} < 1$$

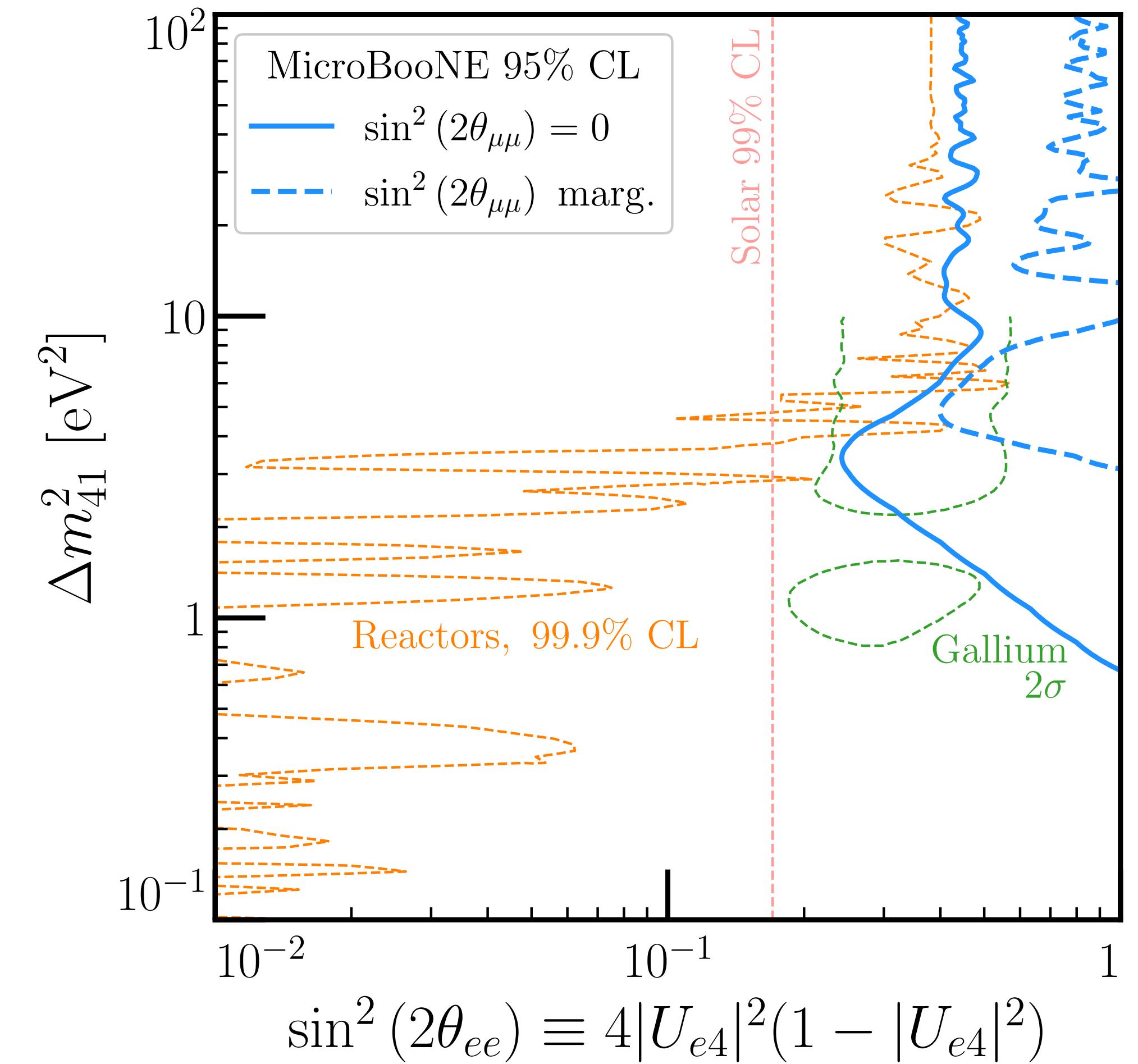
$$P_{ee}^{SBL} < 1$$

Disappearance results

MicroBooNE can set a bound over the ν_e disappearance

$$P_{ee}^{SBL} = 1 - \sin^2 2\theta_{ee} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

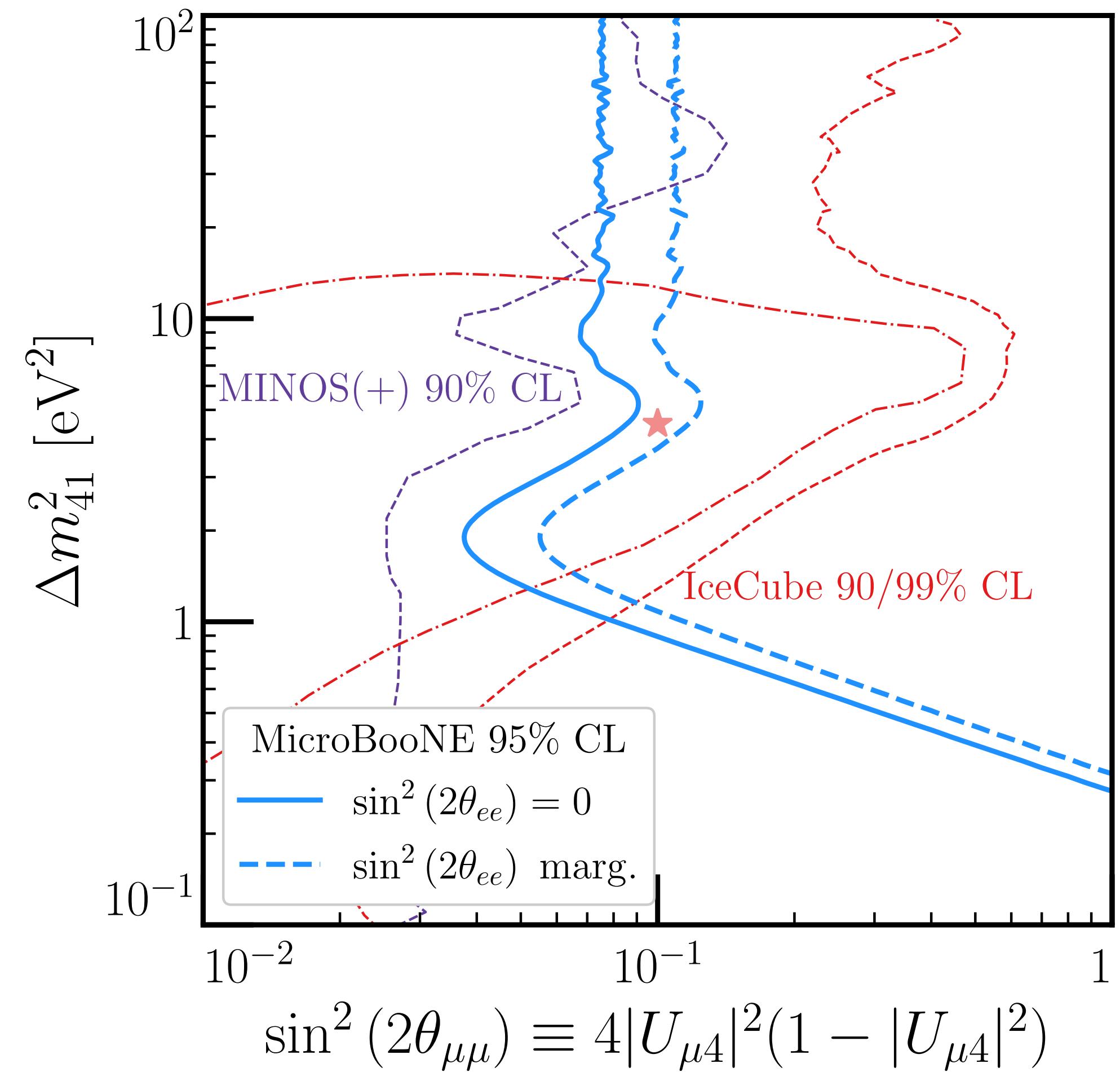
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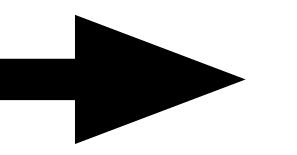


Argüelles, Esteban, Hostert, Kelly, Kopp, Machado, Martinez-Soler and Perez-Gonzalez, Phys.Rev.Lett. 128 (2022)

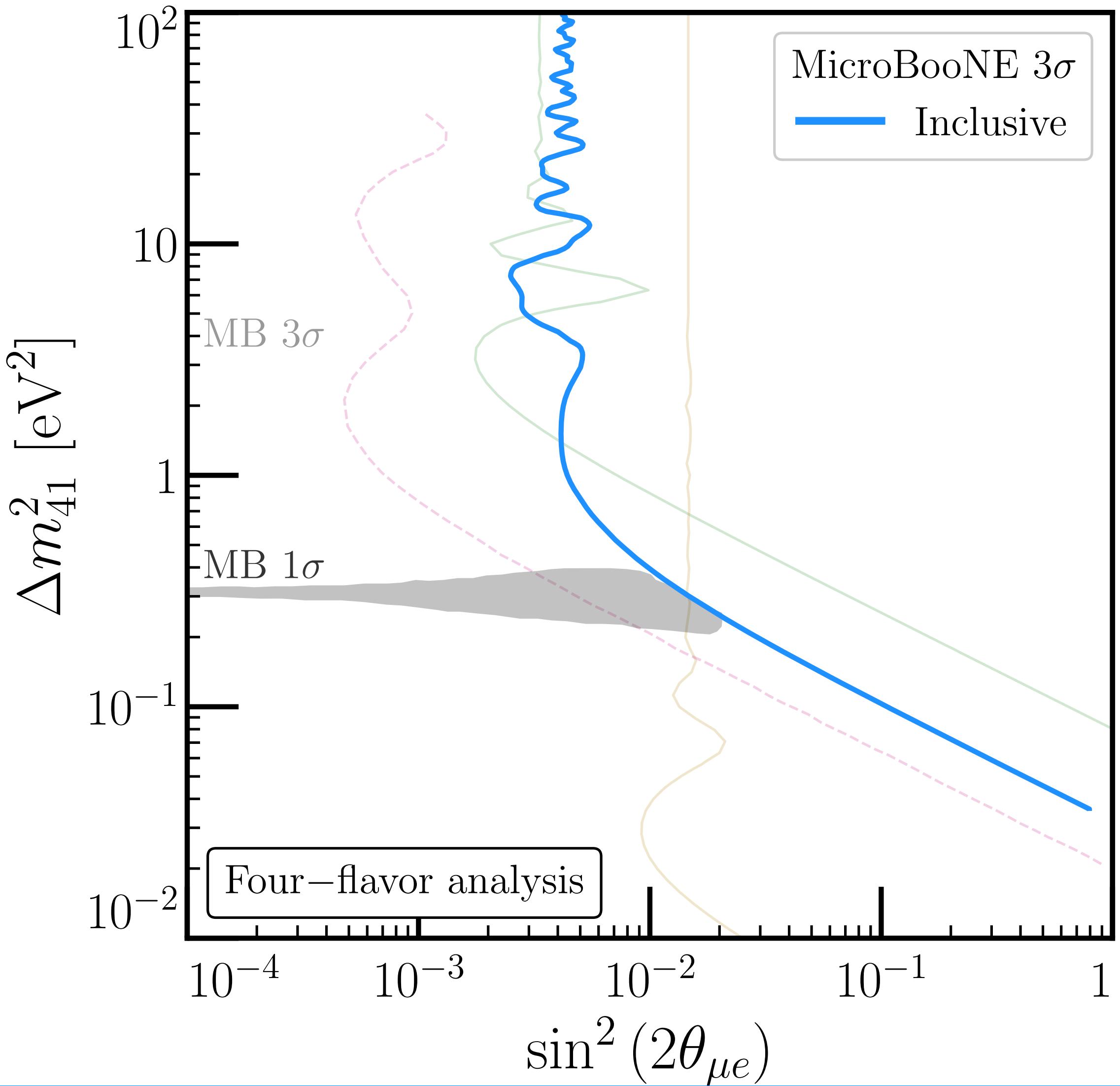
4ν analysis

A large region favored by
MiniBooNE is still allowed

Marginalization over $\sin^2 2\theta_{ee}$



Argüelles, Esteban, Hostert, Kelly, Kopp, Machado, Martinez-Soler and Perez-Gonzalez, Phys.Rev.Lett. 128 (2022)

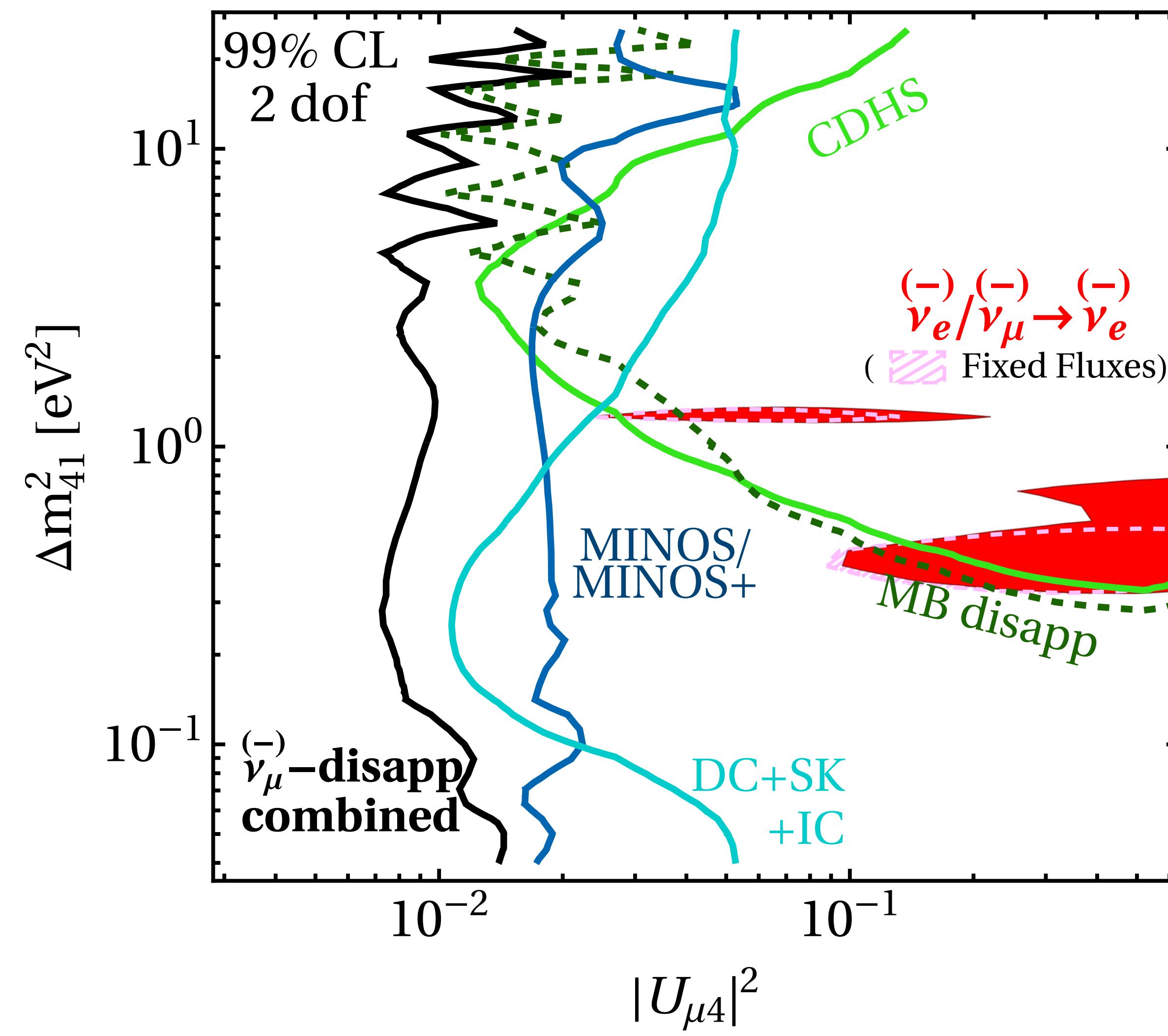


Conclusions

- Most of the **anomalies** in the ν_e disappearance and disappearance channels can be explained in the **$3 + 1 \nu$ scenario**.
- There is a **strong tension** between the **appearance** and **disappearance** channels. We need more data to resolve the tension.
- **MiniBooNE's uncertainties** over the LEE has a **sizable impact** over MicroBooNE's sensitivity.
- A **model-independent** analysis of the background uncertainties tells us that **templates** with a p-value $> 10\%$ are **allowed at 2σ** .
- We have carried out a **fully-consistent sterile** neutrino fit.
- In the sterile analysis, we find that **MicroBooNE's 3σ does not cover the 1σ** preferred by MiniBooNE.

Thank you!

Backup: ν_μ disappearance



Backup: Earth resonance

At the TeV scale, the muon disappearance channel will shows a flavor resonance if there are sterile neutrinos with masses around eV

$$E_{res} = 5.73 \text{TeV} \left(\frac{5 \text{g/cm}^3}{\rho_{\oplus}} \right) \left(\frac{\Delta m_{41}^2}{1 \text{eV}^2} \right)$$

- The resonance takes place for $\bar{\nu}$

