#SOMOSUA

Long-baseline accelerator neutrino experiments

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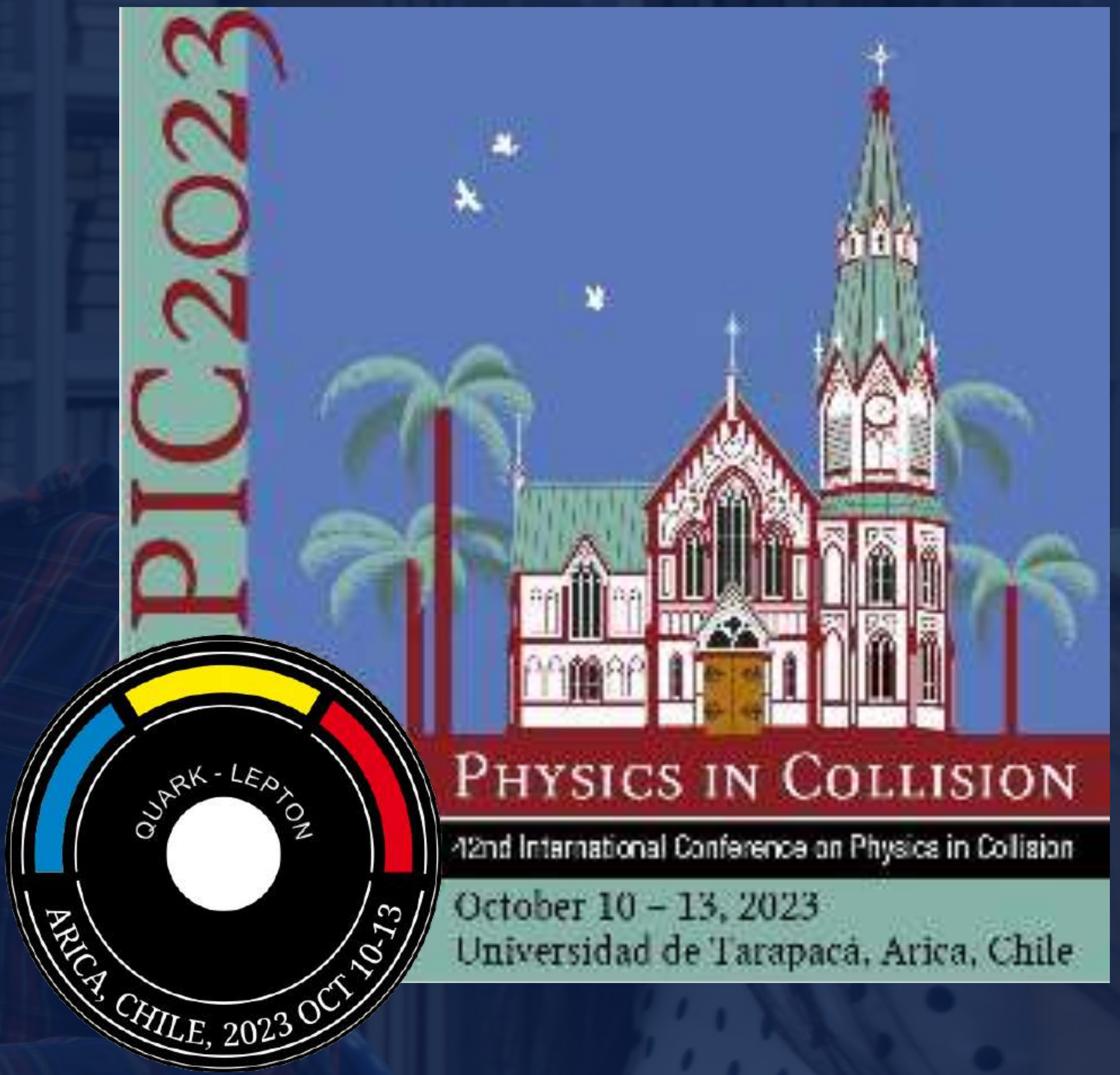
42nd International Symposium on
PHYSICS IN COLLISIONS
University of Tarapacá
Arica (Chile), October 2023



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Outline

- Neutrino oscillations:
  A 2-slides review

- The present: Recent experimental results
  NOvA and **T2K**

- The future: The main goals
  DUNE and **Hyper-Kamiokande**

- Summary

STANDARD NEUTRINO OSCILLATIONS

A quick review

Neutrino Oscillations

The 3-neutrino mixing

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The 3-neutrino model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})}_{\text{Mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$R(\theta_{23}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \qquad R(\theta_{12}) = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric/Accelerators

Solar

Reactor

$$R(\theta_{13}, \delta_{CP}) = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}$$

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Neutrino Oscillations

The 3-neutrino oscillations in matter

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Evolution in matter is governed by an *effective* Hamiltonian

$$\mathcal{H}_F = \frac{1}{2E}\left(U\mathbb{M}^2U^\dagger + \mathbb{A}\right)$$

$$\mathbb{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} \qquad \mathbb{A} = \begin{pmatrix} A_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Leading to the well-known ***Mikheev-Smirnov-Wolfenstein*** **(MSW)** effect

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THE PRESENT

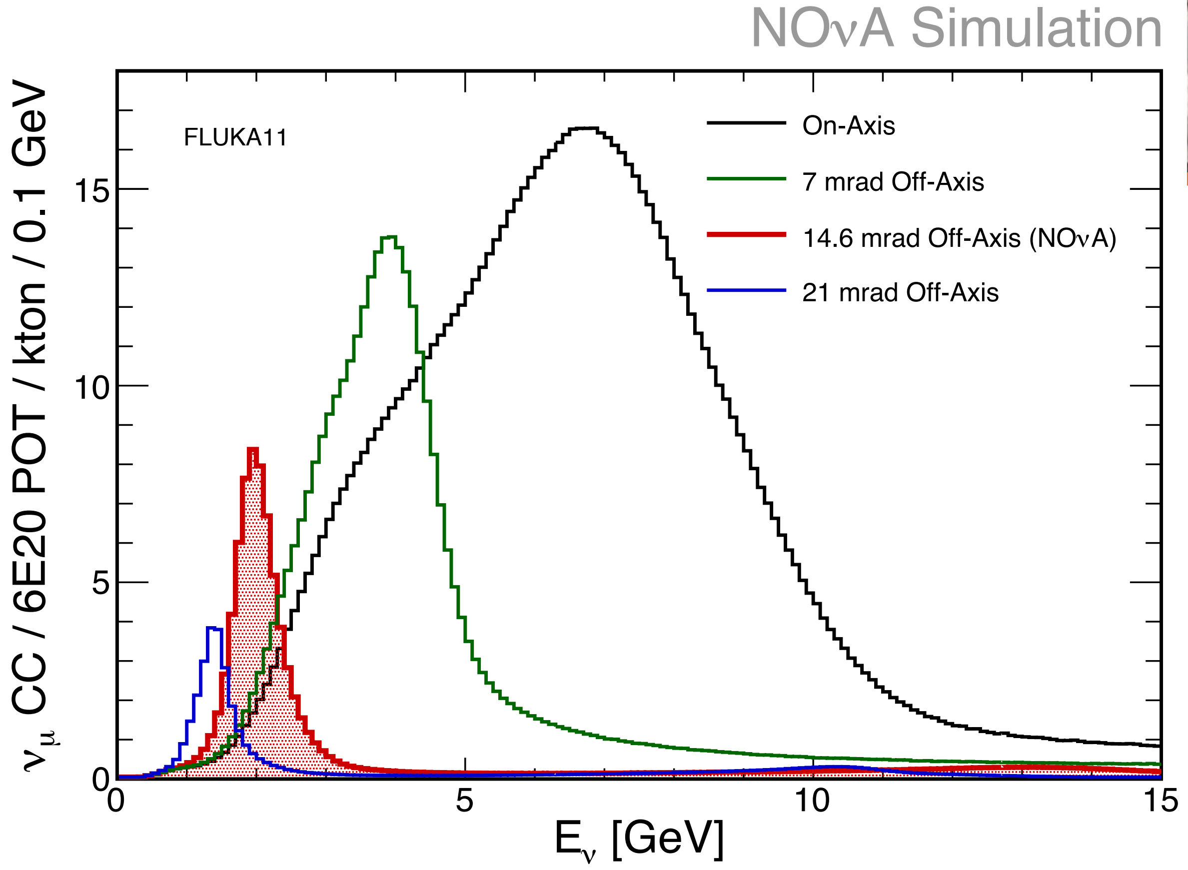
NOvA and T2K Experiments

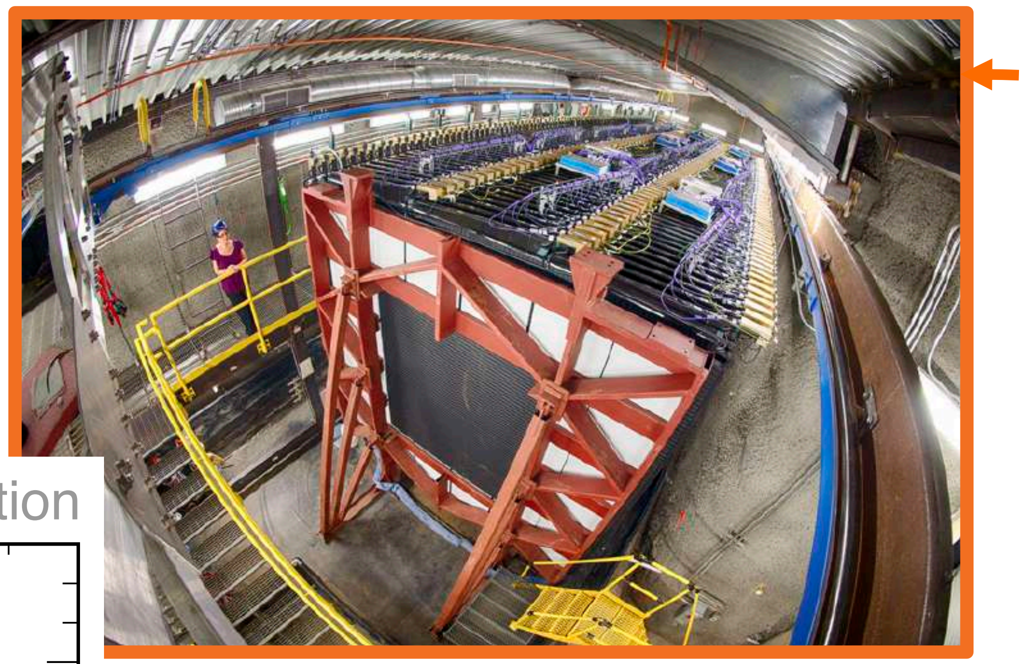
NOvA

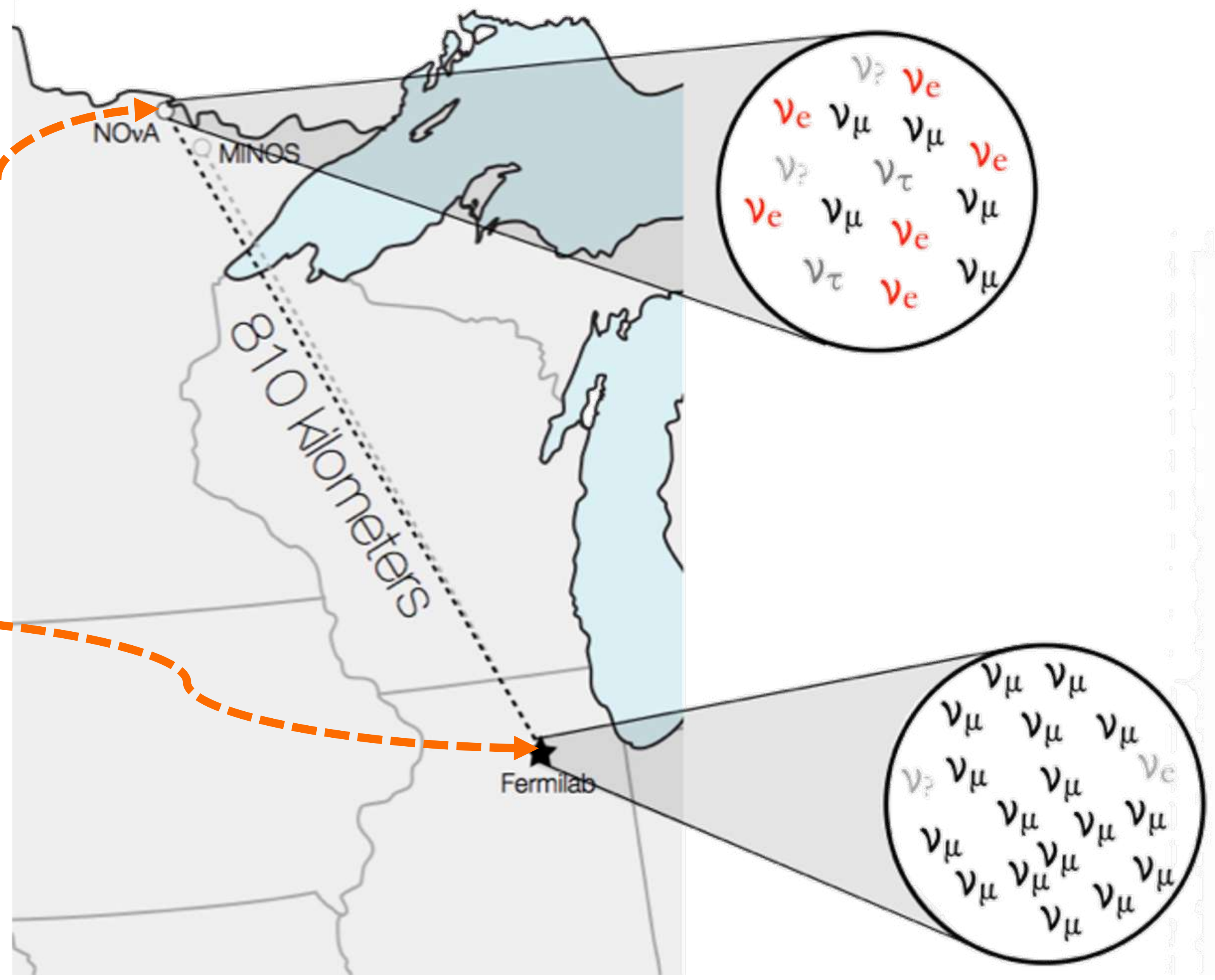
The Experiment in the US

- Long-baseline (810 km) neutrino oscillation experiment
- Muon Neutrinos from the NuMI Beam at Fermilab
- Two (functionally equivalent) detectors:
  - **Far Detector**: 14 kton; on the surface
  - **Near Detector**: 0.3 kton; underground
- Off-axis (14.6 mrad) position (beam peaks at ~2 GeV)

14.6 mrad ~ 0.84°







~270 members, 49 Institutes, 8 countries

T2K

The Experiment in Japan

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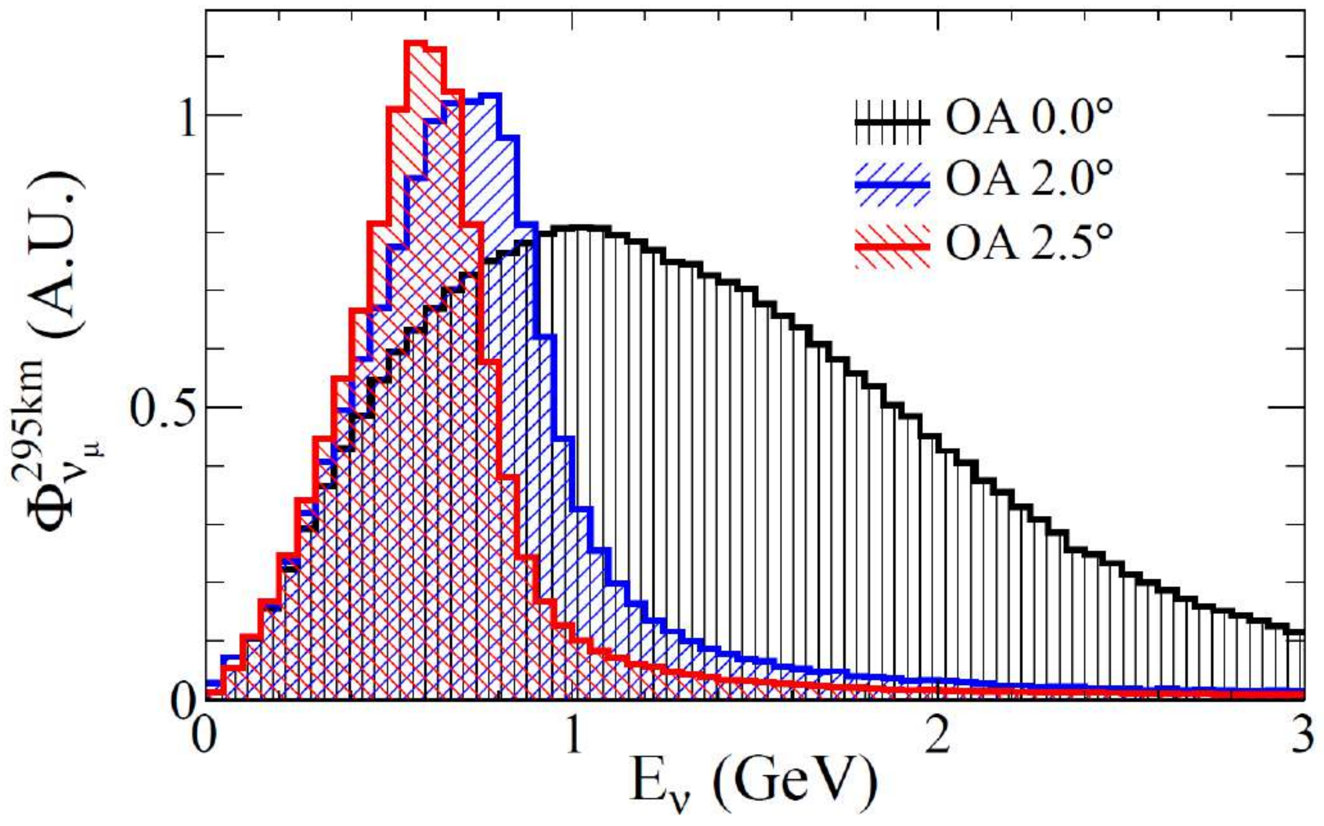
- Long-baseline (295 km) neutrino oscillation experiment

- Muon Neutrinos from the J-PARC acceleration complex

- Two detectors:
  - **Far Detector**: Super-Kamiokande
  - **Near Detector(s)**: ND280; INGRID (on-axis)

- Off-axis (2.5°) position (beam peaks at ~0.6 GeV)

2.5° ~ 43.6 mrad



~530 members, 76 Institutes, 14 countries

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NOvA and T2K

The Experiments

Physics Goals

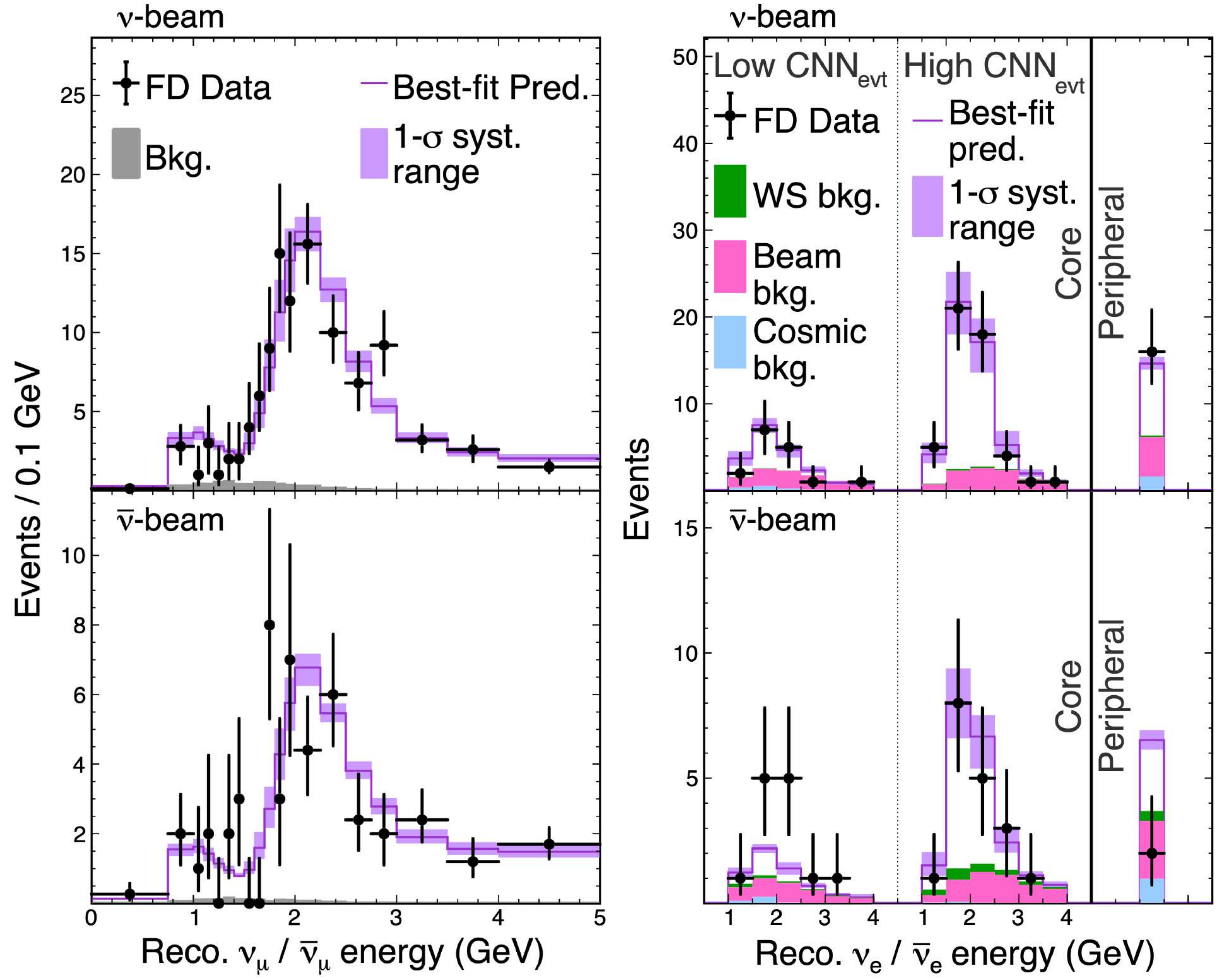
- *Muon* (anti)neutrino disappearance and *Electron* (anti)neutrino appearance
- Measurement of the oscillation parameters (Δm^2_{32}, θ_{23}, δ_{CP})
- Mass Ordering
- Neutrino interactions (cross sections)
- Sterile and supernova neutrinos
- ‘Exotic’ physics

STANDARD NEUTRINO OSCILLATIONS

The most recent results

Events Spectra

The results



[NOvA Collaboration, PRD106 (2022)]

Data and predicted spectra

Neutrino beam

- 211 ν_μ candidates (bkg: 8.2)
- 82 ν_e candidates (bkg: 26.8)

Antineutrino beam

- 105 $\bar{\nu}_\mu$ candidates (bkg: 2.1)
- 33 $\bar{\nu}_e$ candidates (bkg: 14.0)

$> 4\sigma$ $\bar{\nu}_e$ appearance

Parameter Measurements

The results

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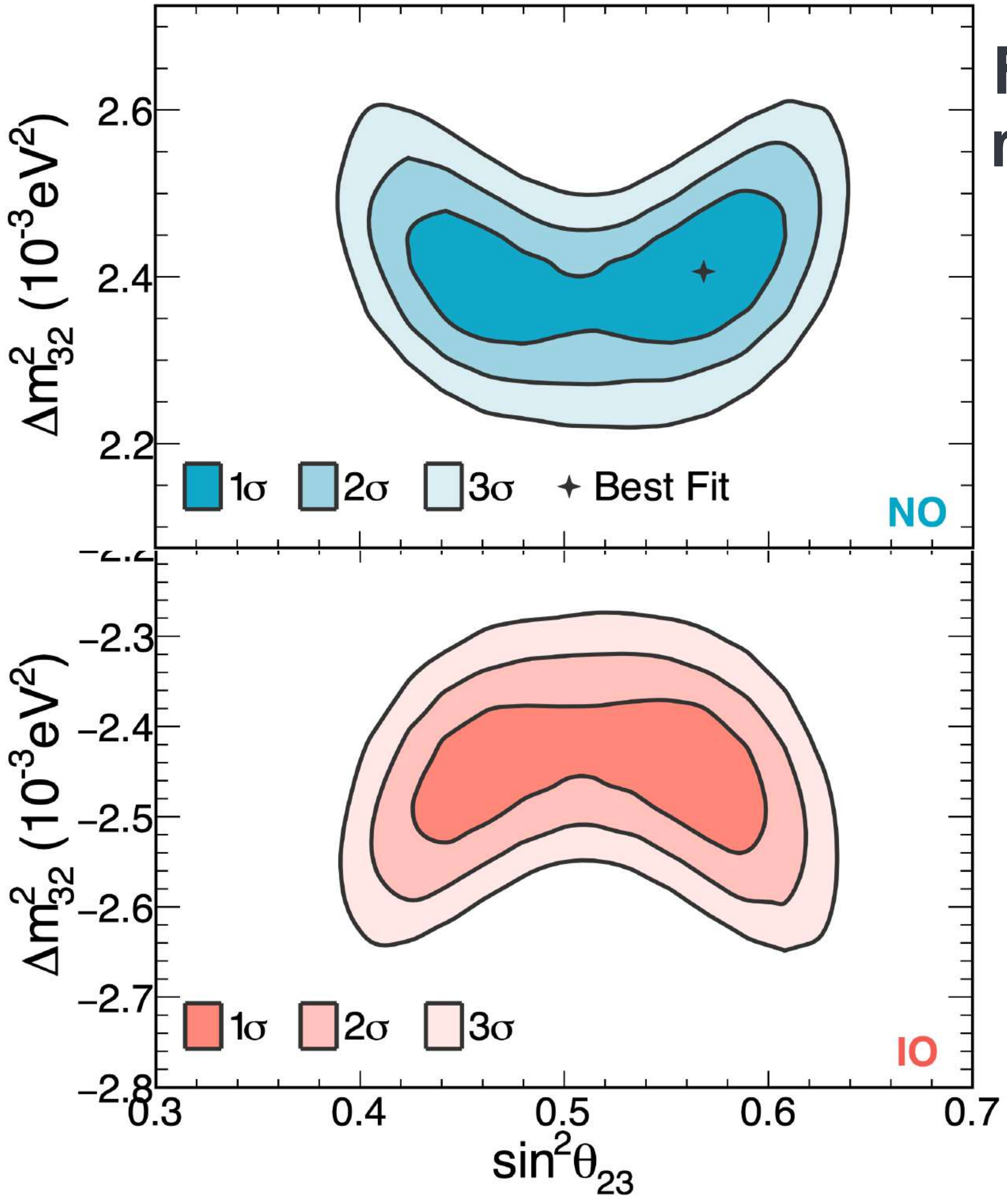
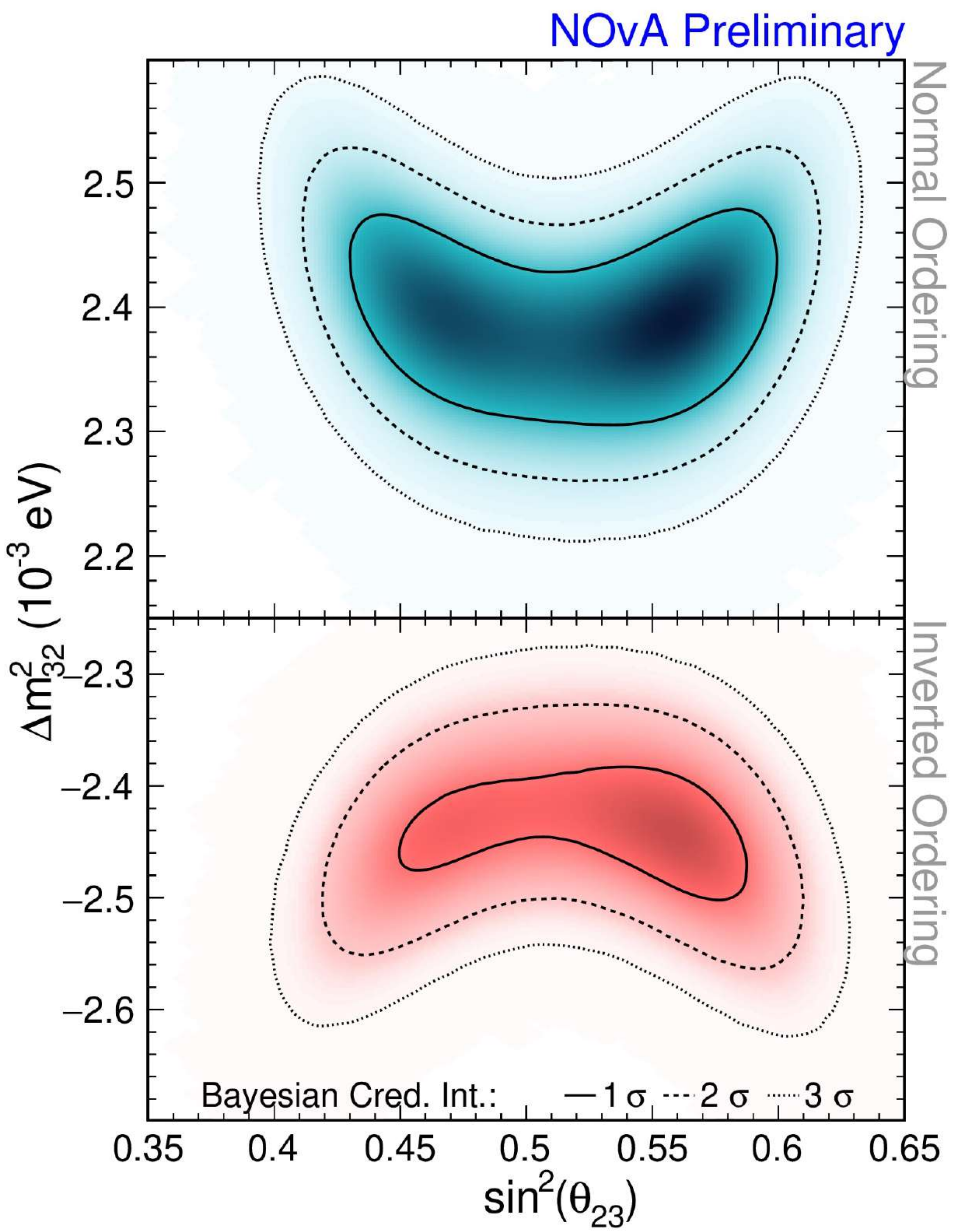
Frequentist results



Consistent and equivalent results

Bayesian results



[NOvA Collaboration, PRD106 (2022)]

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Parameter Measurements

The results

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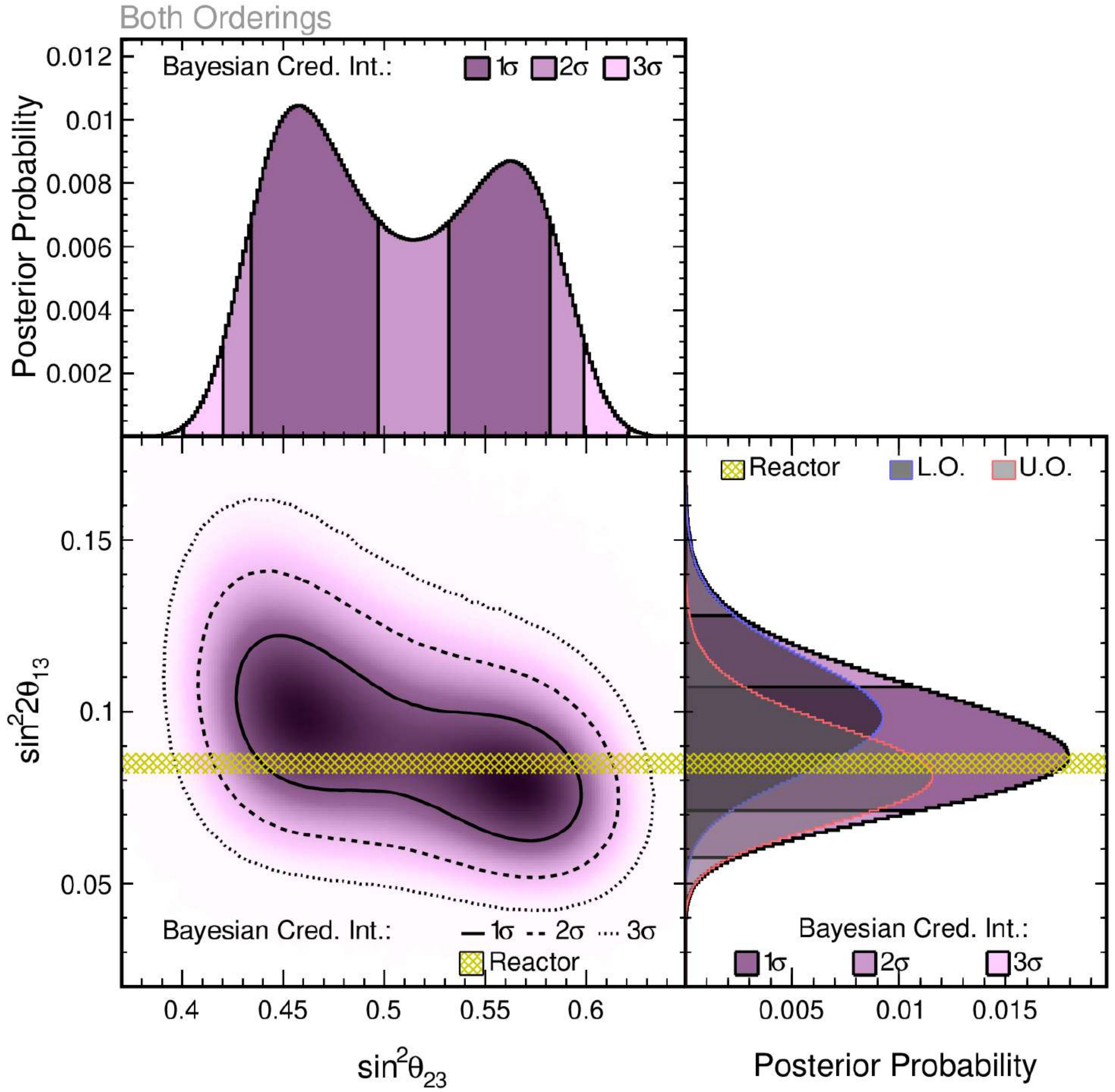
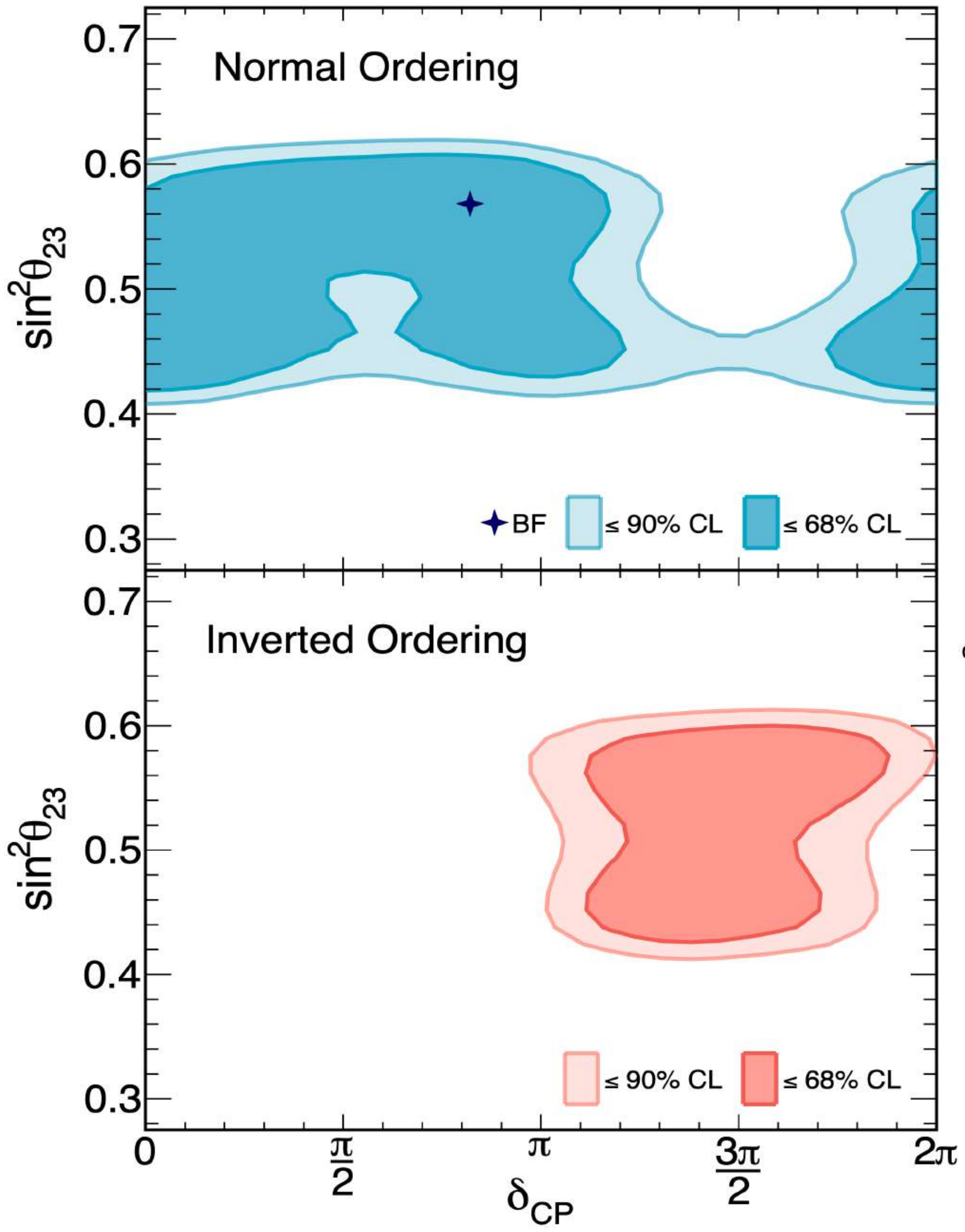


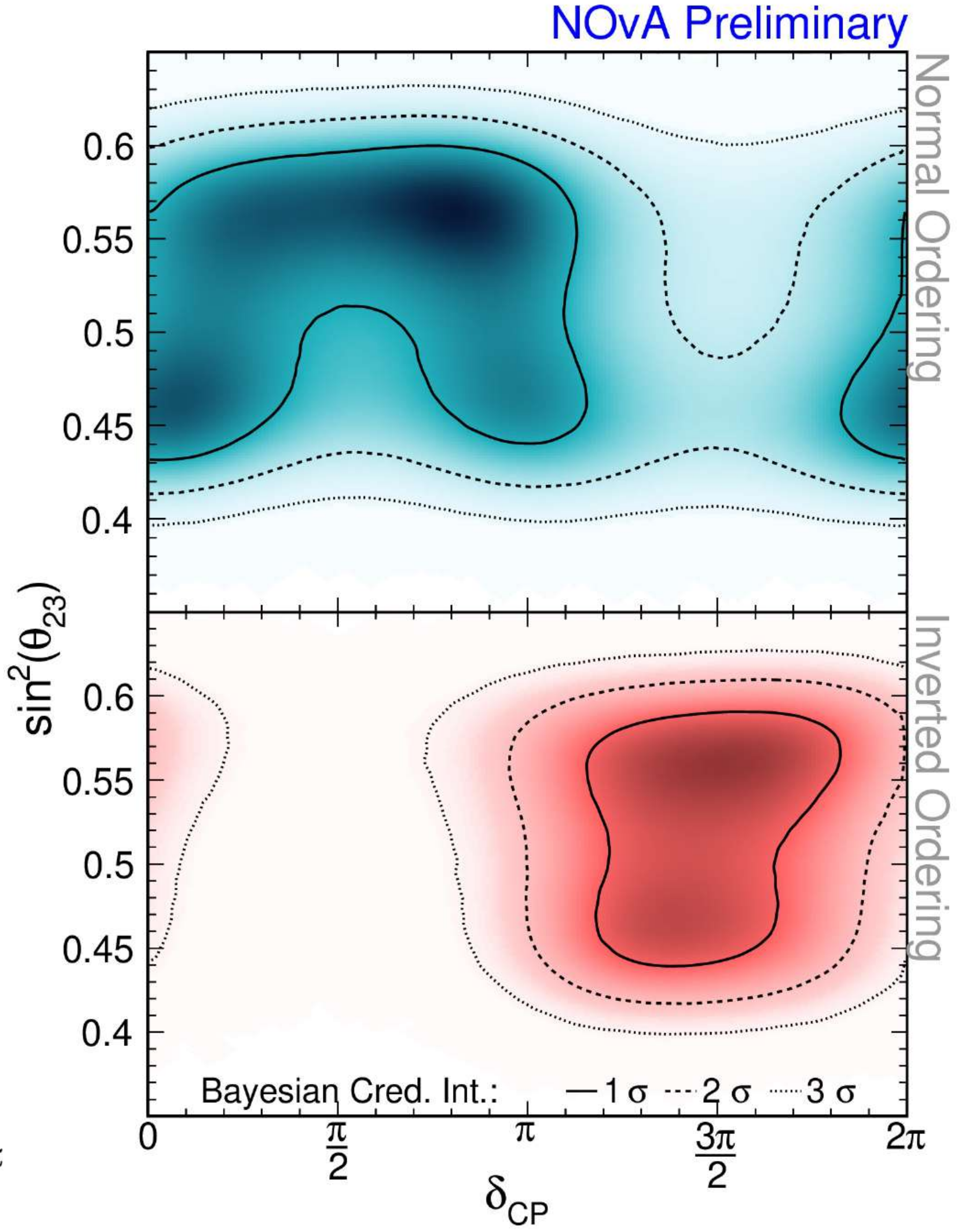
Bayesian – w/o reactor constraint

Frequentist vs Bayesian Analyses

[NOvA Collaboration, PRD106 (2022)]



Preference for ***Normal Ordering*** and the ***upper octant of θ_{23}***



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Events Spectra

The results

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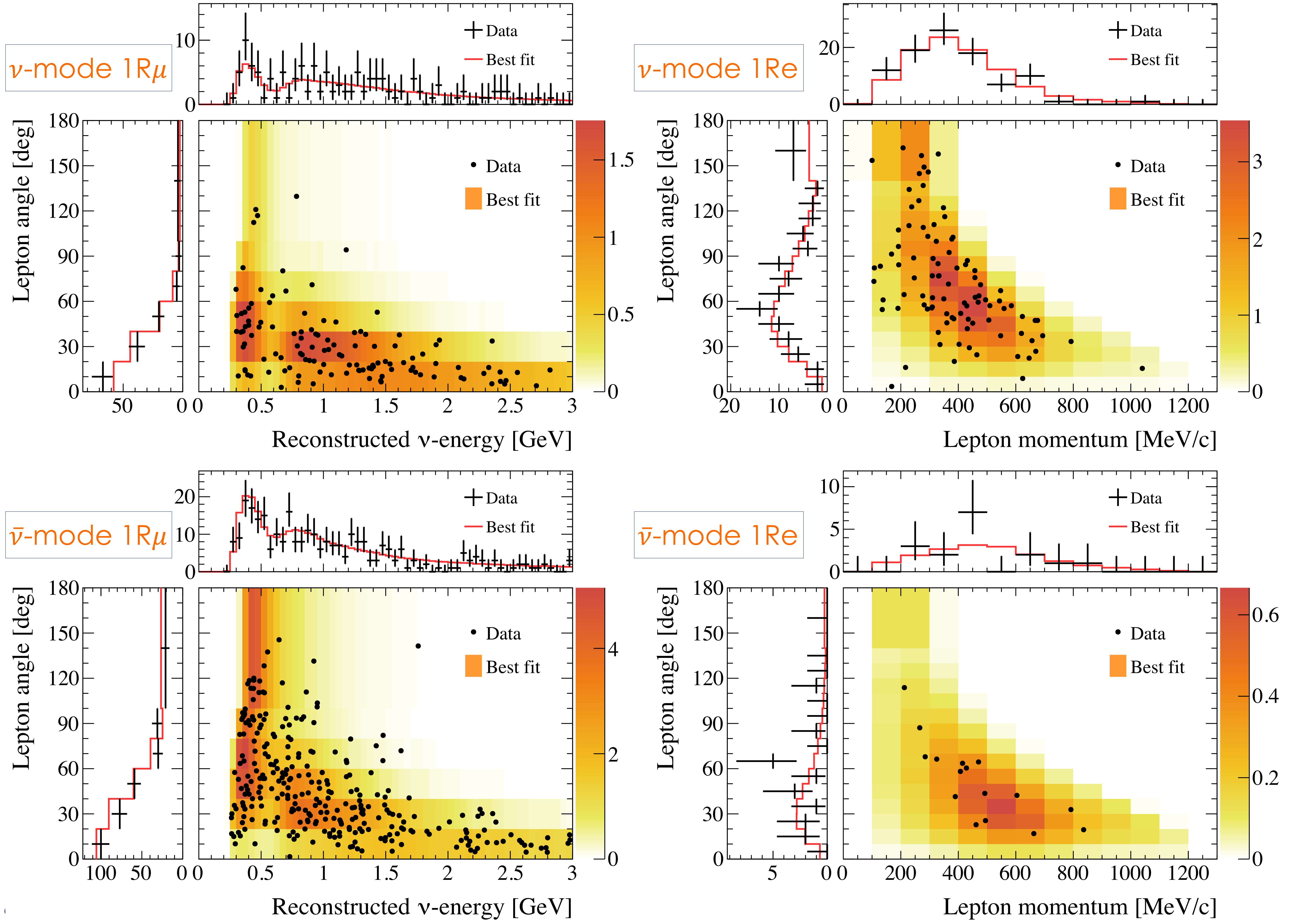

Data and predicted spectra

Neutrino mode

- 318 $1R\mu$ events
- 94 $1Re$ events

Antineutrino mode

- 137 $1R\mu$ events
- 16 $1Re$ events

1R stands for "single ring"

[T2K Collaboration, EPJC83 (2023)]

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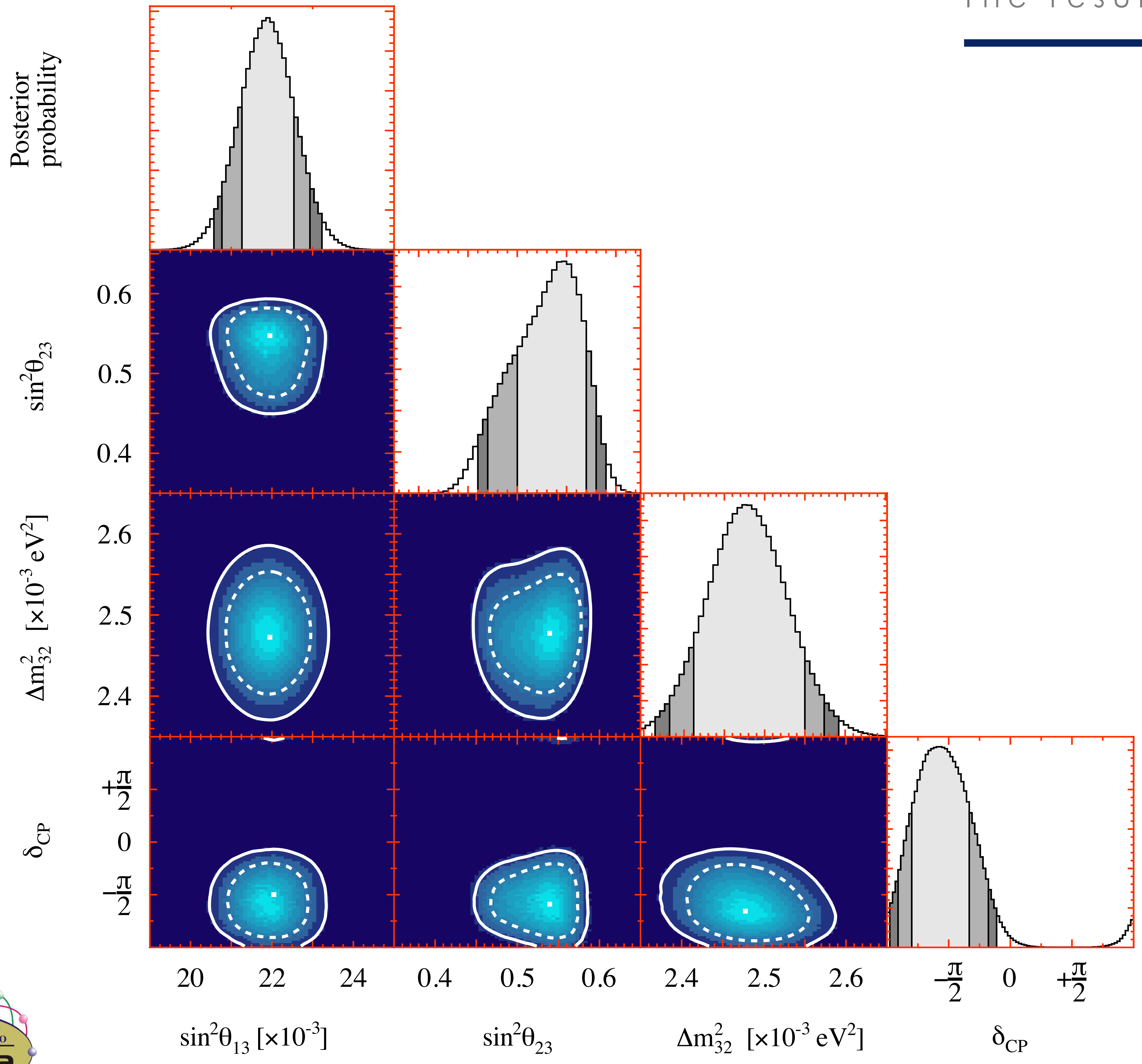
Parameter Measurements

The results



Bayesian Analysis

2D 68% and 90% credible intervals

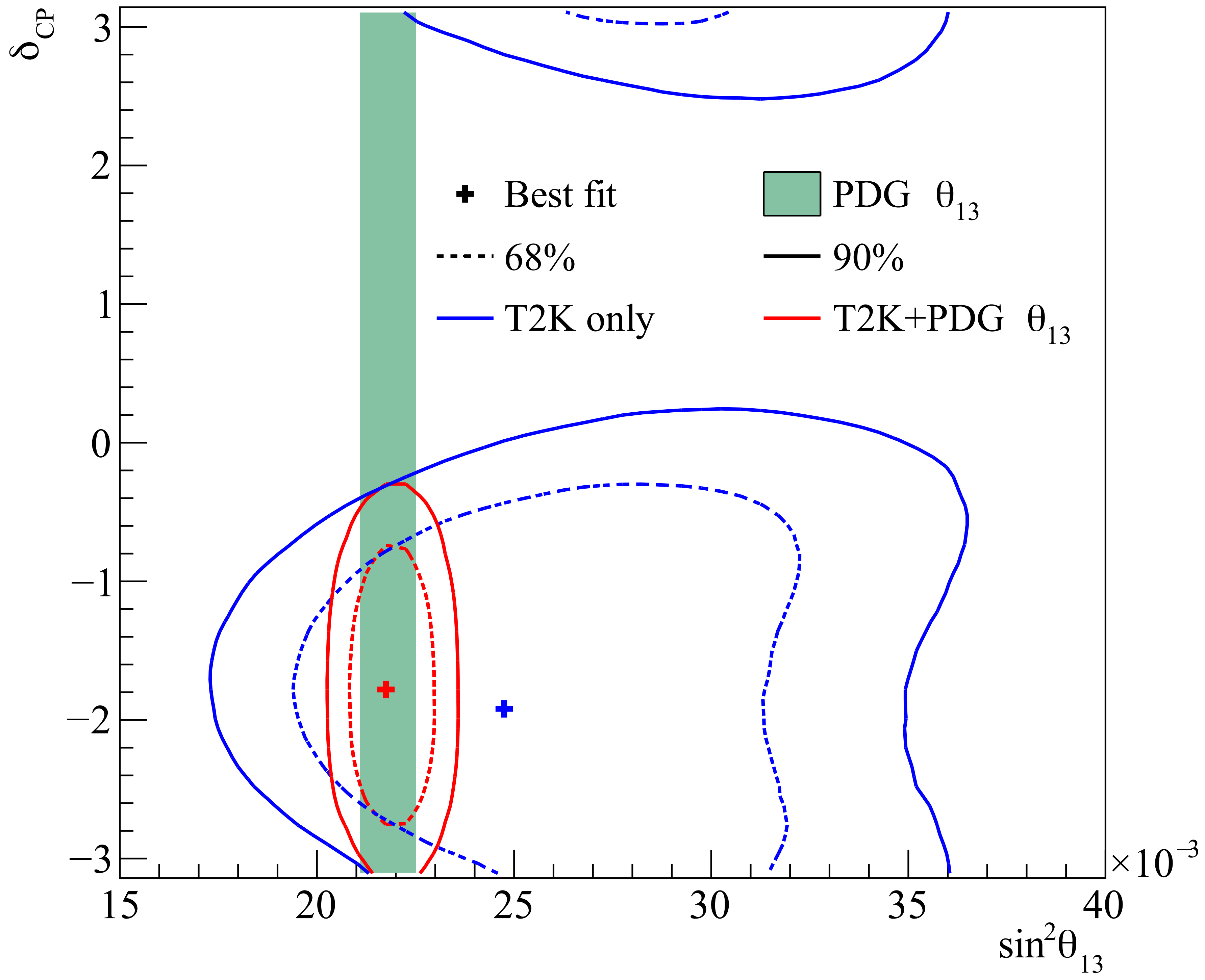
1D 68%, 90% and 95% credible intervals

[T2K Collaboration, EPJC83 (2023)]

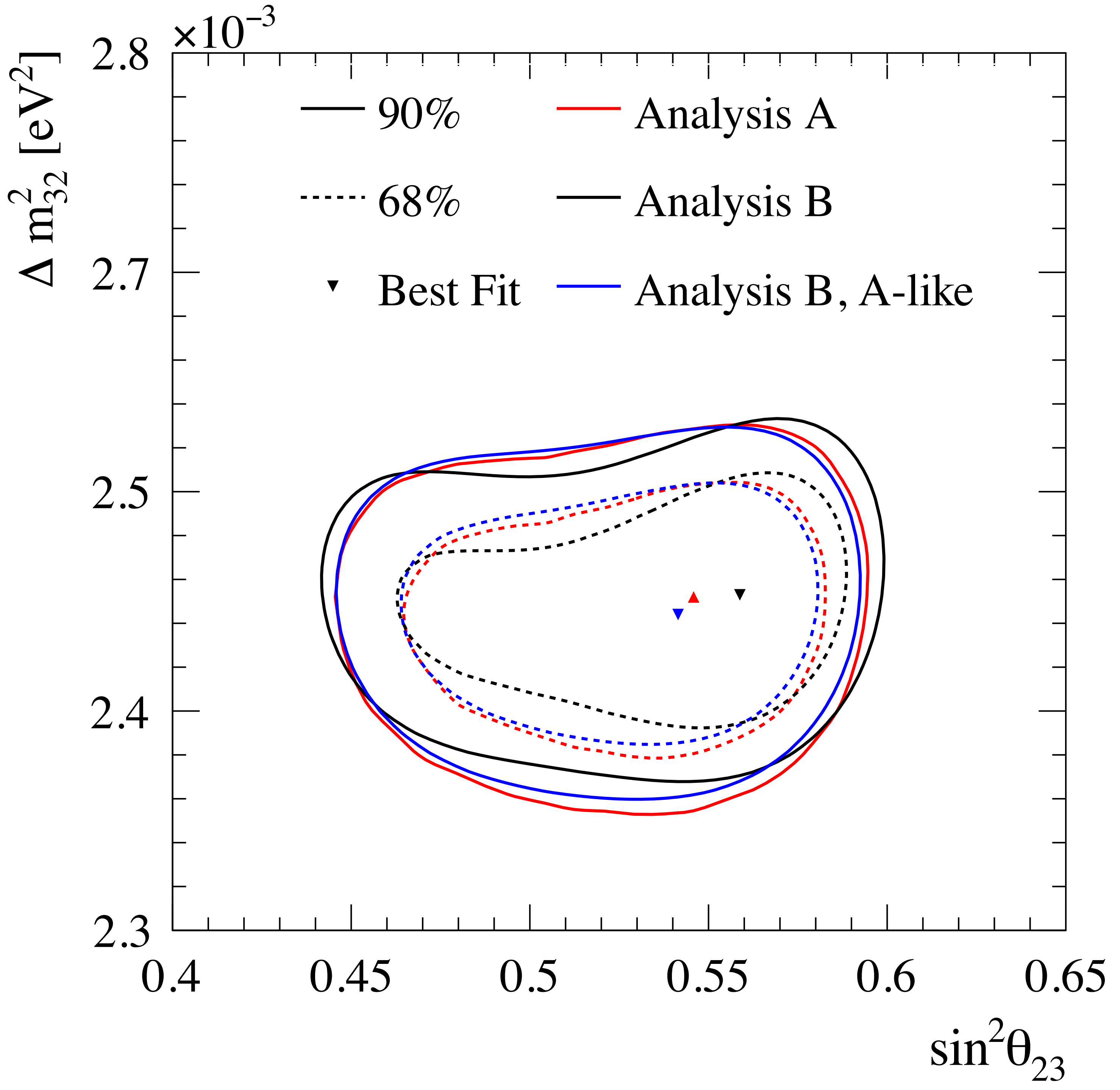
Parameter Measurements

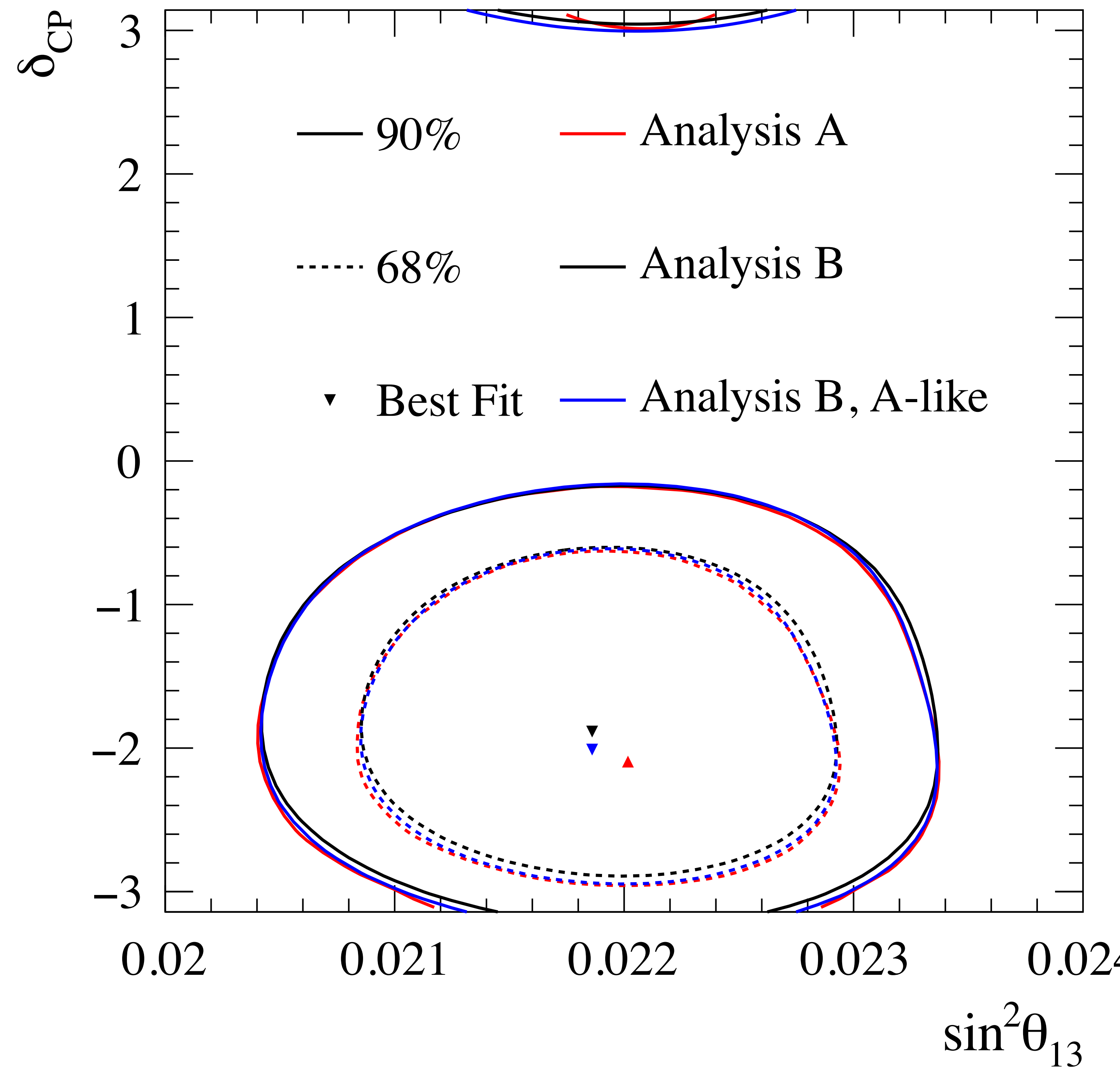
The results

Bayesian – w/ and w/o reactor constraint



Bayesian vs. Frequentist Analyses



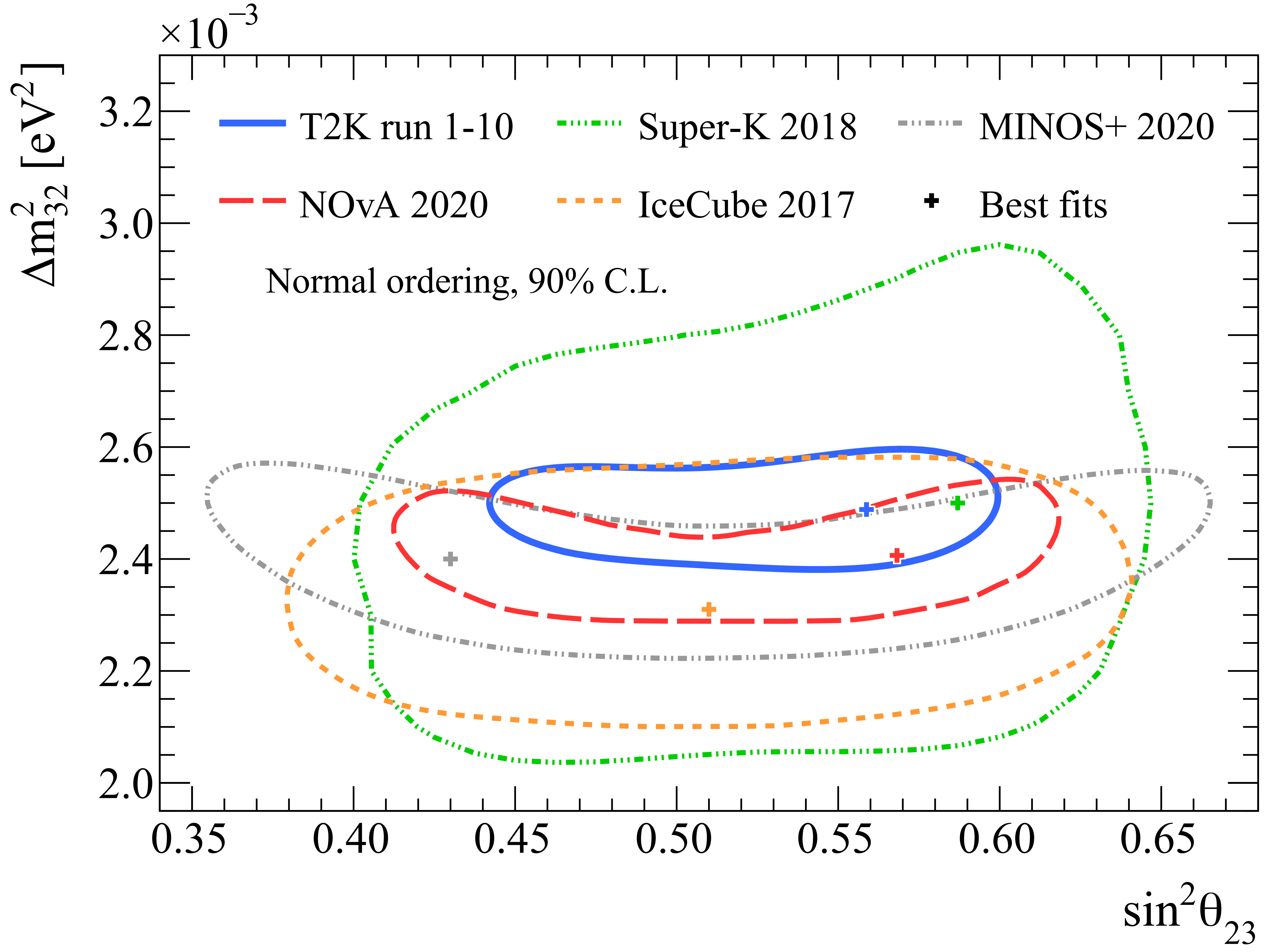


NO and w/ reactor constraint

[T2K Collaboration, EPJC83 (2023)]

Parameter Contours

The results



Comparison among experiments

[T2K Collaboration, EPJC83 (2023)]

[NOvA Collaboration, PRD106 (2022)]

[SK Collaboration, PRD97 (2018)]

[IceCube Collaboration, PRL120 (2018)]

[MINOS+ Collaboration, PRL125 (2020)]

More Physics Results

Not only neutrino oscillations

Much more Physics!

The results

Search for **Lorentz** and **CPT** violations
[PRD95 111101(R) (2017)]

Upper bound on the **neutrino mass**
[PRD93 012006 (2016)]

Sterile neutrinos
[PRD99 071103(R) (2019)]

Heavy neutral leptons
[PRD100 052006 (2019)]

And several **cross-section** measurements

T2K

Coincidences with **LIGO/Vigo** detections
[PRD104 063024 (2021), PRD101 112006 (2020)]

Search for slow magnetic **monopoles**
[PRD103 012007 (2021)]

Supernova neutrinos
[JCAP10 014 (2020)]

Seasonal variation of **multi-muon** events
[PRD104 012014 (2021), PRD99 122004 (2019)]

Sterile neutrinos, **NSI** and **cross-section** measurements

NOvA

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THE FUTURE

DUNE and Hyper-Kamiokande Experiments

DUNE

A worldwide effort

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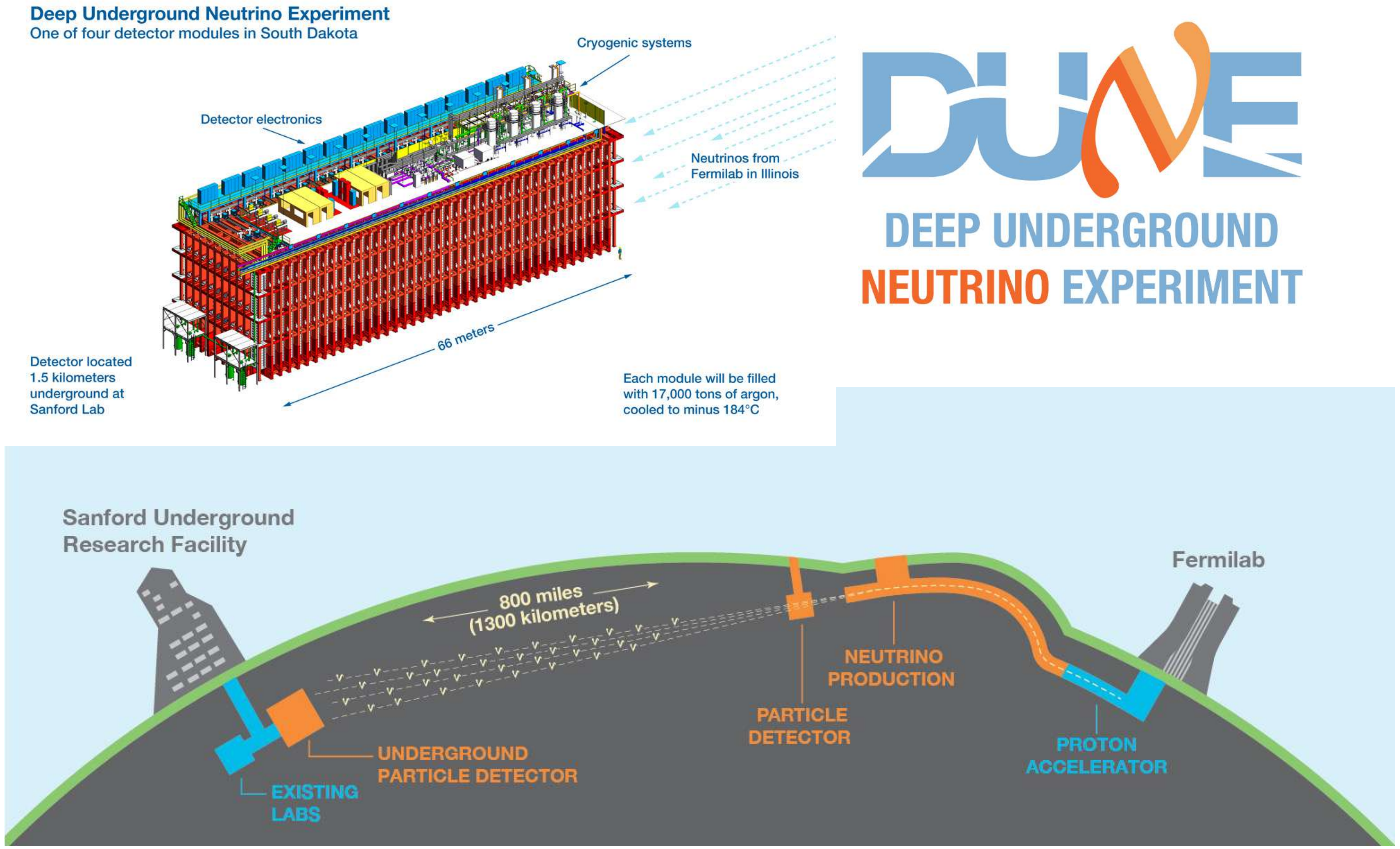
- Long-baseline (1285 km) neutrino oscillation experiment
- Muon Neutrinos from a high intensity beam at Fermilab
- Two detectors:
  - **Far Detector**: 40 kton, LArTPC; at SURF
  - **Near Detector**: at Fermilab
- Broad-band energy beam (peaks at ~2.5 GeV)



~1400 members, 200 Institutes, 30 countries

DUNE

A worldwide effort

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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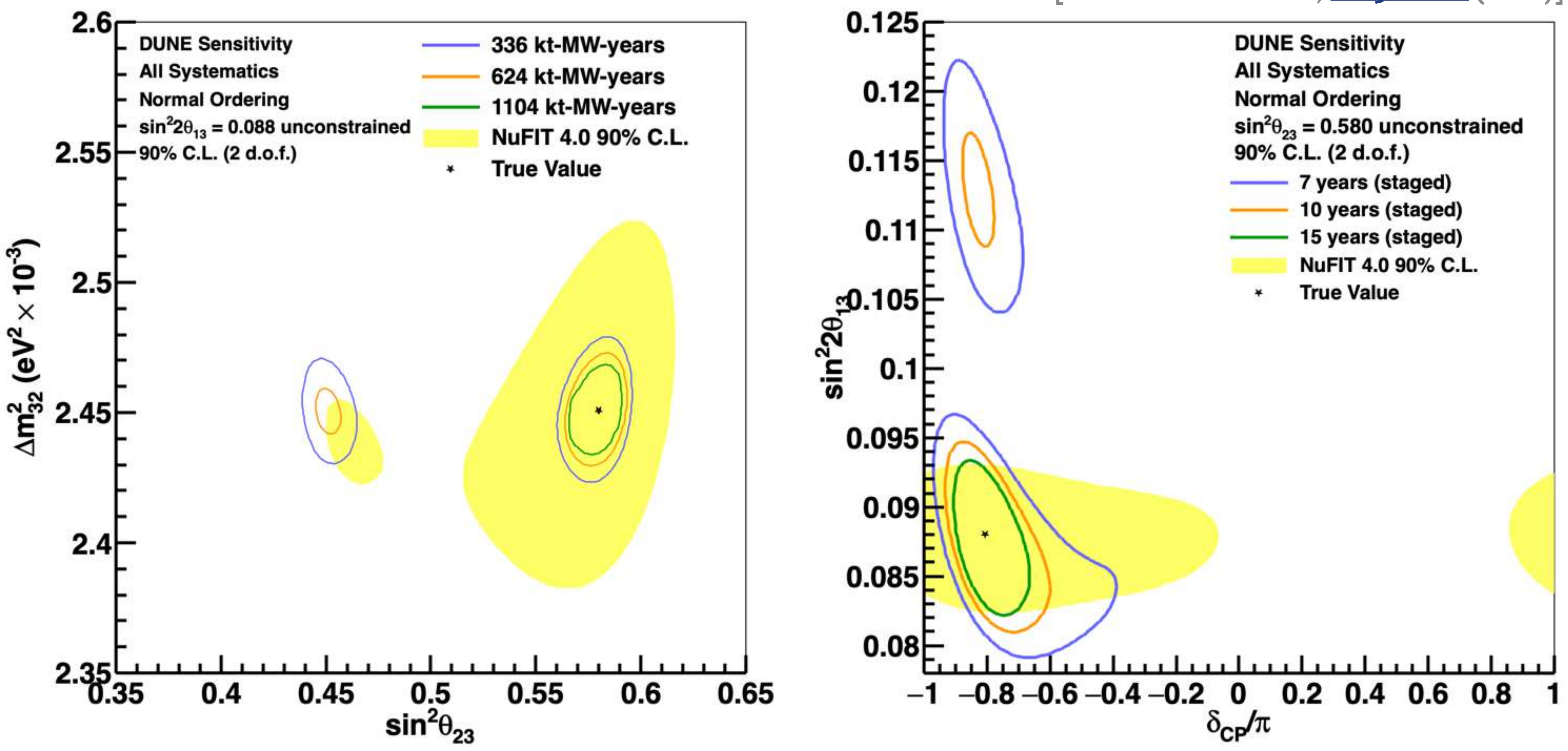
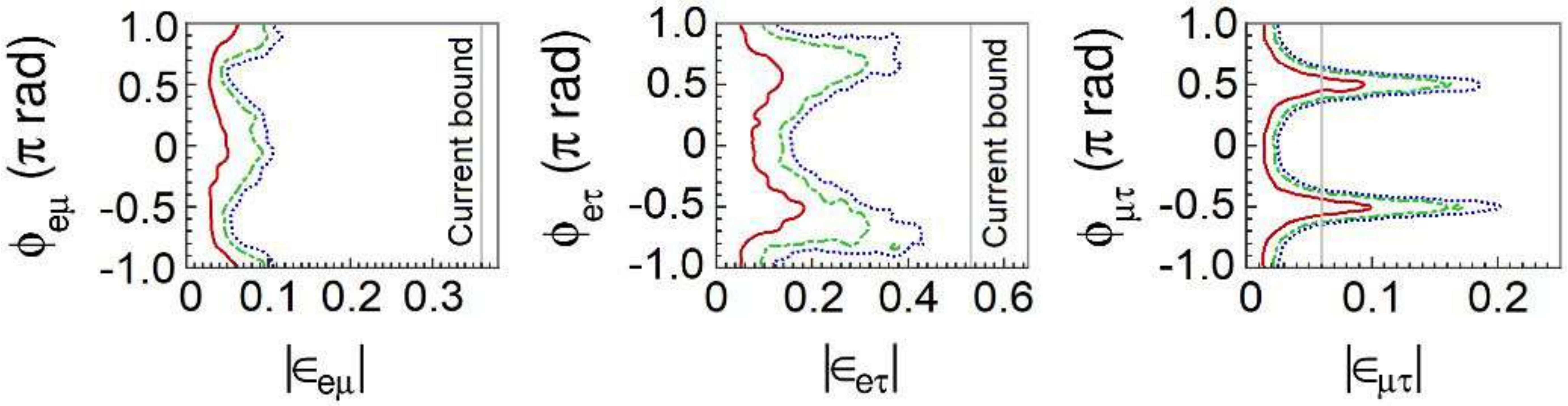
Physics Goals

- Accelerator neutrinos
  - Standard 3F oscillations, ass ordering, CP violation
- Low energy neutrinos
  - Sun, core-collapse supernova
- Baryon number violation
  - Proton decay, neutron-antineutron
- BSM physics
  - Deviations from 3F (steriles, NSI), new particles (DM)

[DUNE Collaboration, 2203.06100 (2022)]





[DUNE Collaboration, EPJC81 (2021)]

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Hyper-Kamiokande

A Japan-Based effort

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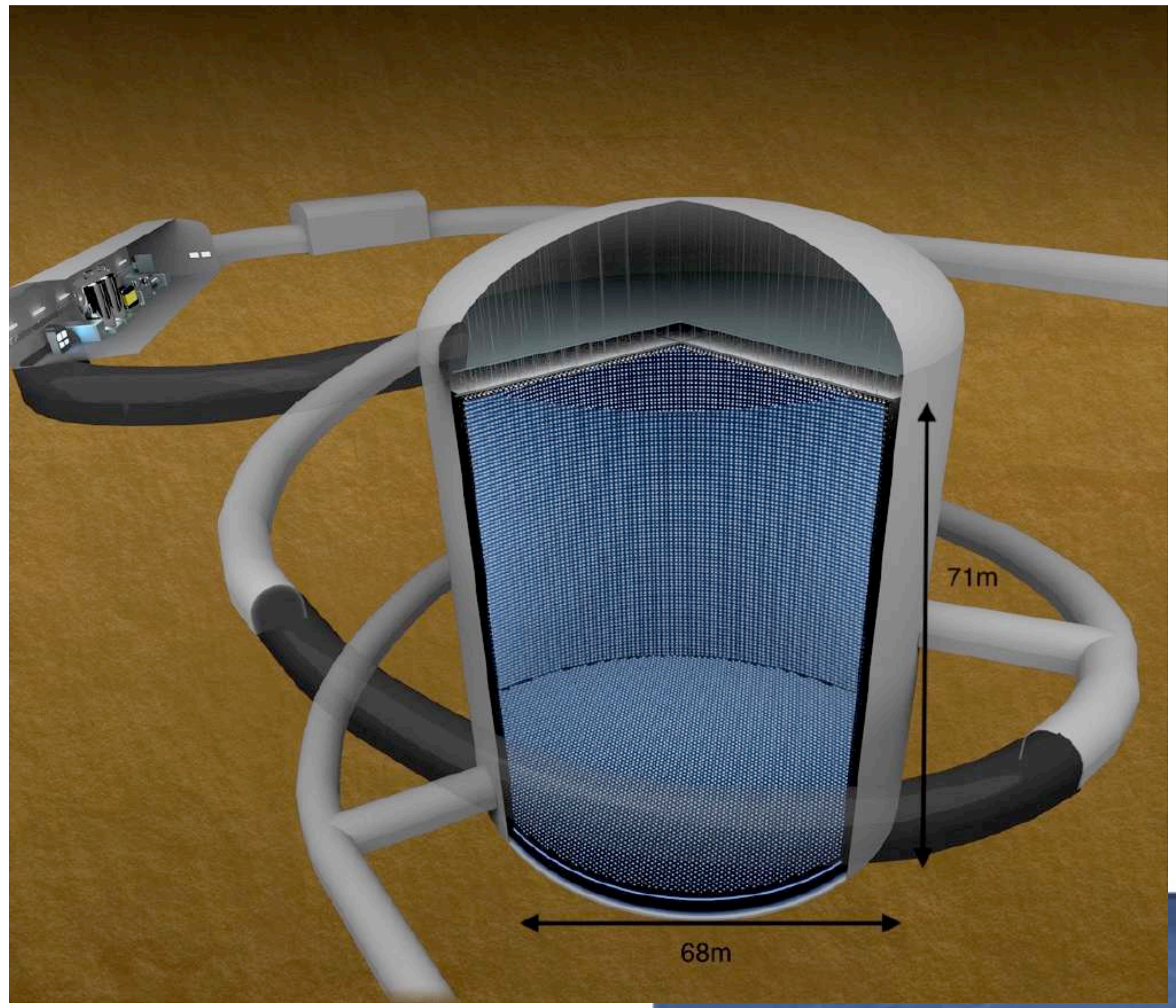
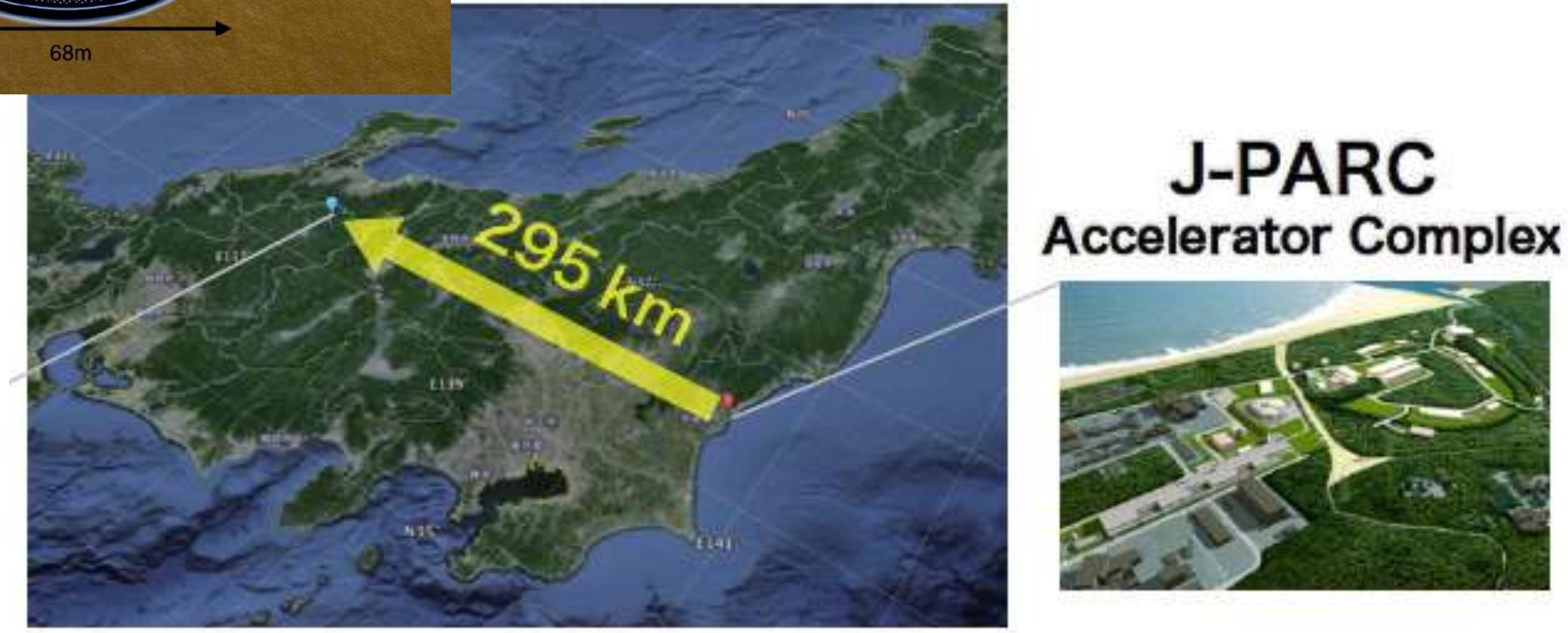
- Long-baseline (295 km) water Cherenkov neutrino oscillation experiment

- Muon Neutrinos from the J-PARC acceleration complex

- Two detectors:
  - **Far Detector**: 68 m in diameter, 71 m in height (8.4x SK fiducial volume)
  - **Near Detector(s)**: upgraded ND280; Intermediate Water Cherenkov

- FD is off-axis (2.5°) position (beam peaks at ~0.6 GeV)





~560 members, 101 Institutes, 21 countries

Hyper-Kamiokande

A Japan-Based effort

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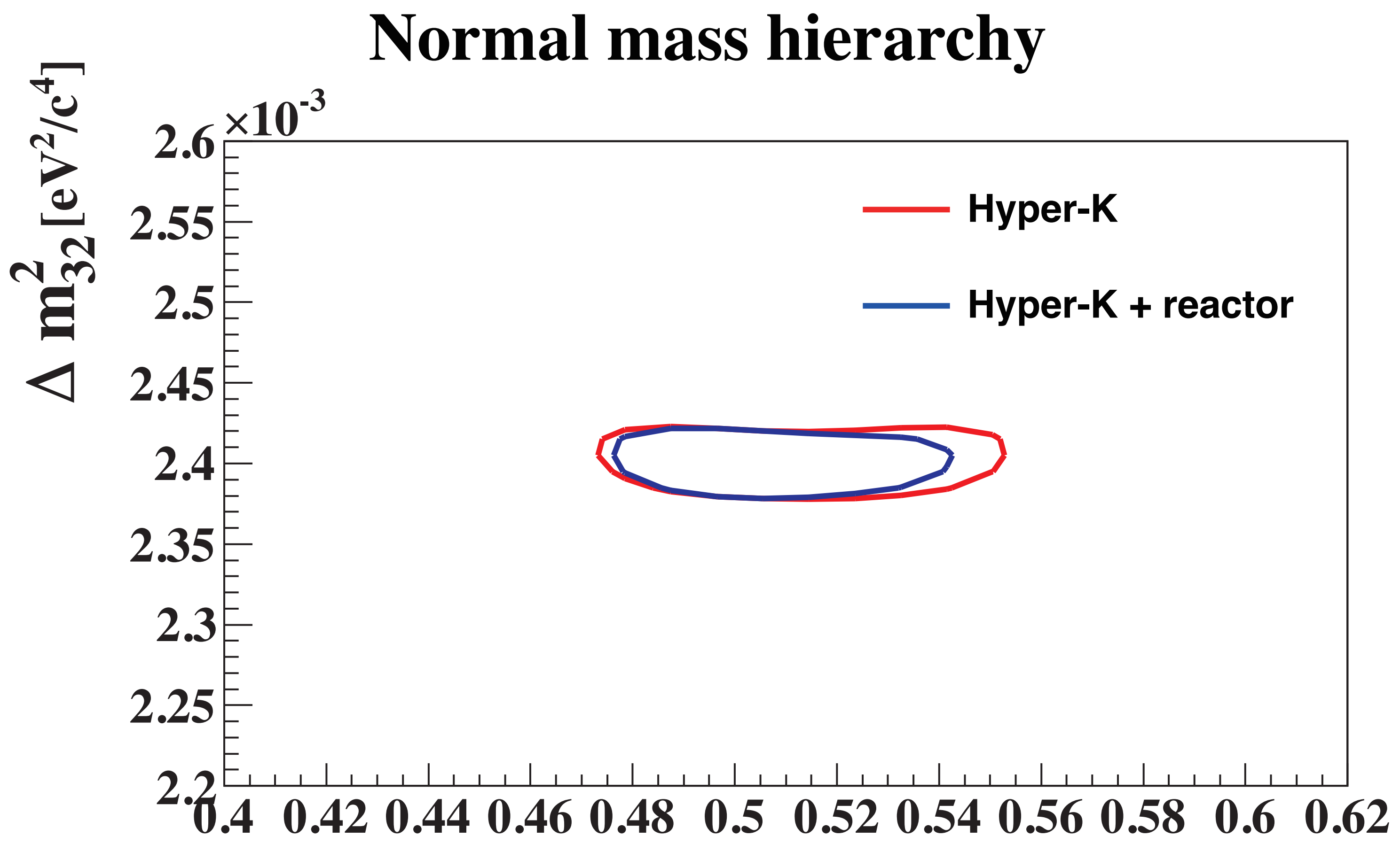
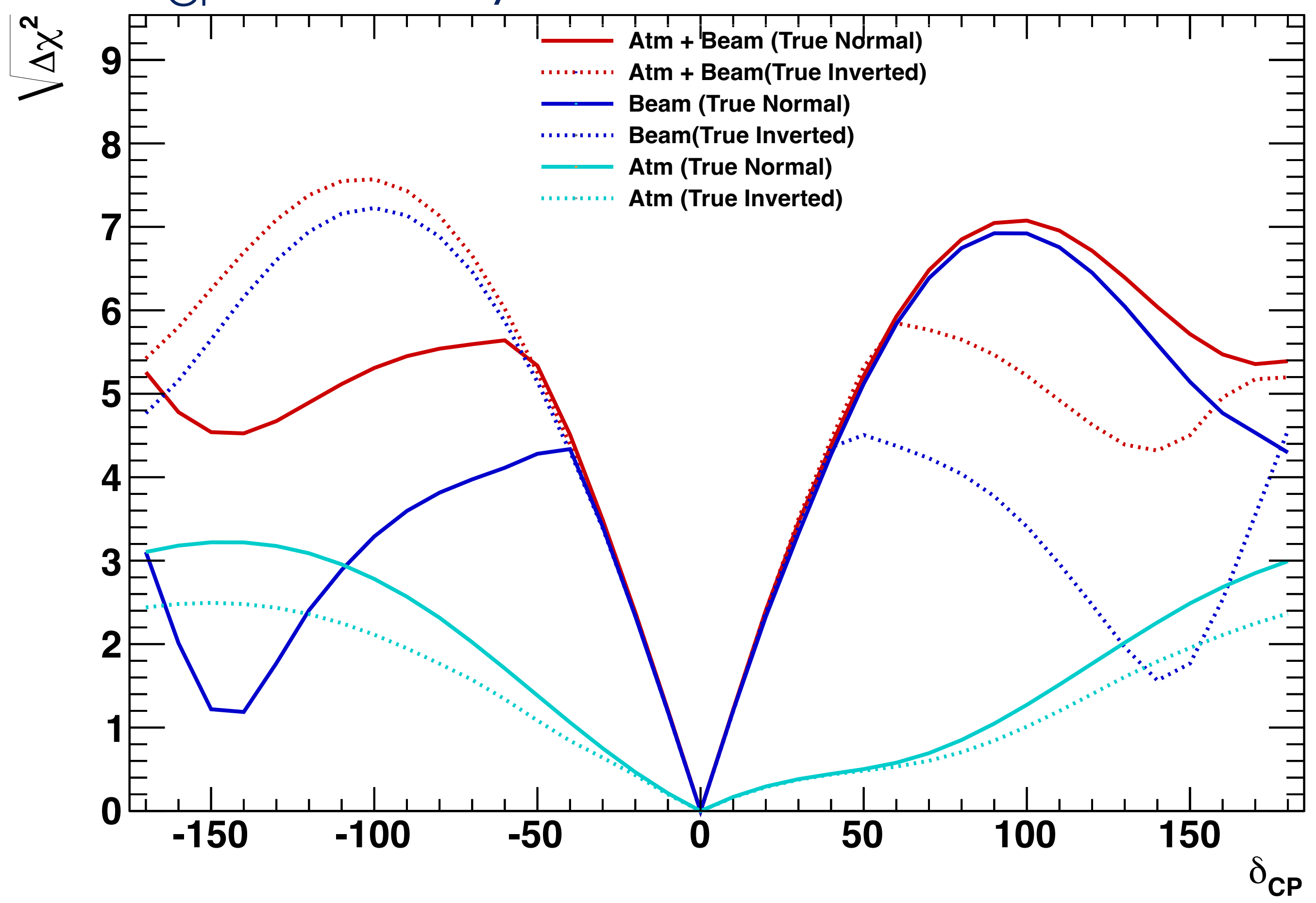
Physics Goals

- Accelerator neutrinos
  - Standard oscillations
- Atmospheric neutrinos
  - Mass ordering, CP violation, NSI, sterile, PMNS unitarity, ν_τ
- Solar neutrinos
  - Oscillations and NSI
- Supernova neutrinos
  - Multi-messenger
- Nucleon decay
  - SM tests
- Dark Matter
  - BSM physics



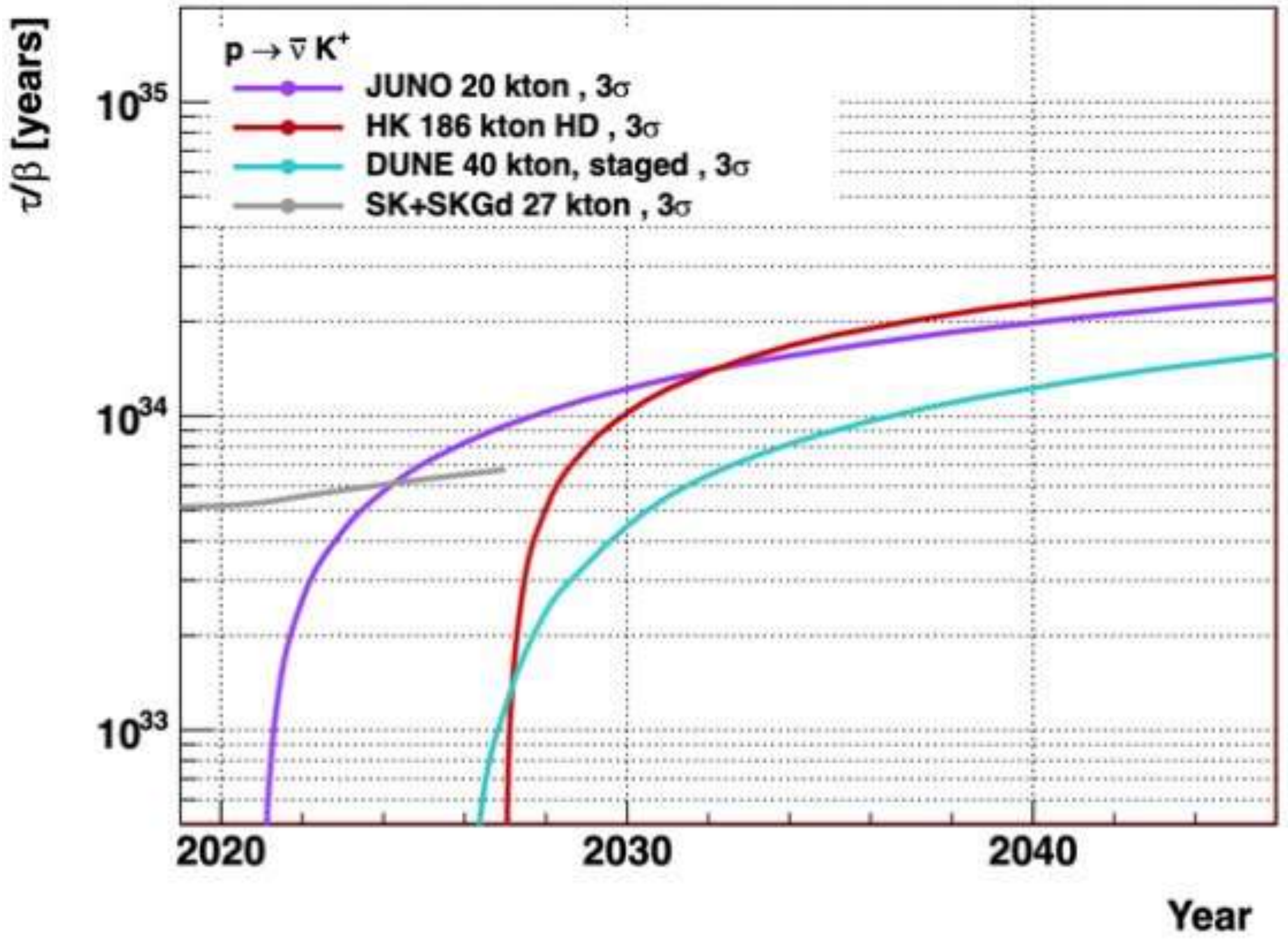
[HK Collaboration, 1805.04163 (2018)]

δ_{CP} after 10 years



[HK Collaboration, 1805.04163 (2018)]

[Y. Itow, HK Coll., PoS1192 (2021)]



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DUNE - HyperK

In the calendar…

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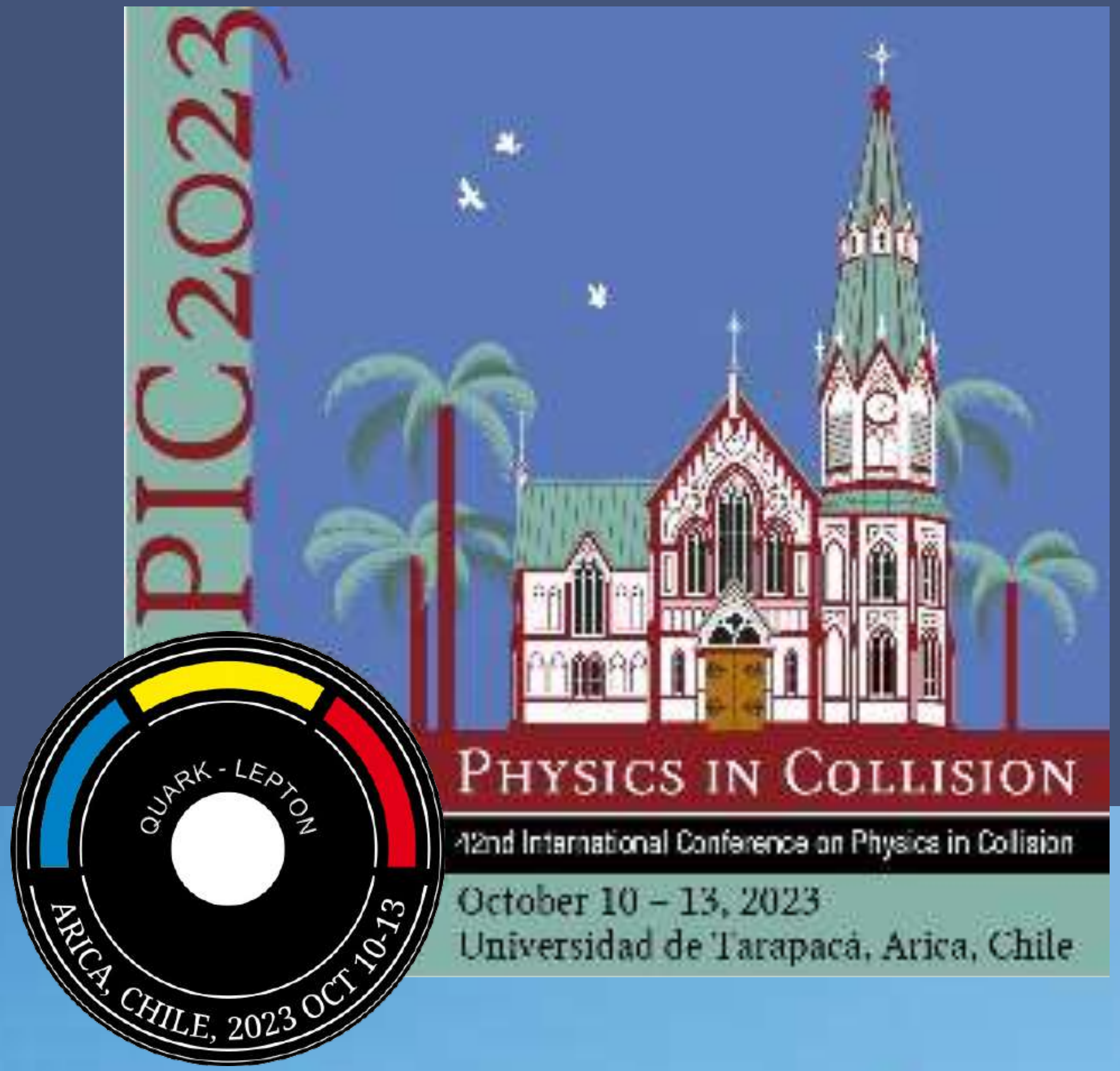
DUNE

- Preliminary studies
  ProtoDUNE – 2018-2020.
- ProtoDUNE 2nd run
  Planed for 2024
- Data taking at FD
  2028/2029
  (atmospheric neutrinos + astrophysics)
- Phase I (1.2 MW)
  2031
  (+ oscillation physics)
- Phase II (2.4 MW)
  2037/2038
  (full physics)

Hyper-Kamiokande

- Cavern excavation
  Until ~mid 2025
- Beamline upgrade (1.3 MW)
  Until ~2026
- Tank and PMTs installation
  ~2025 – 2027
- Electronics: Testing and installation
  ~2025 – 2027
- Data taking
  2027



Summary

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- **NOvA** and **T2K**, have been developing a rich physics research program and obtained great results on standard neutrino oscillations and beyond, making it a **fascinating** present.

- **DUNE** and **HyperK** are building a **stimulating** future, looking for providing the conditions to provide precise measurements and answer to open questions.

- Long-baseline experiments are an **open window** to explore a wide spectrum of physics, beyond neutrinos!

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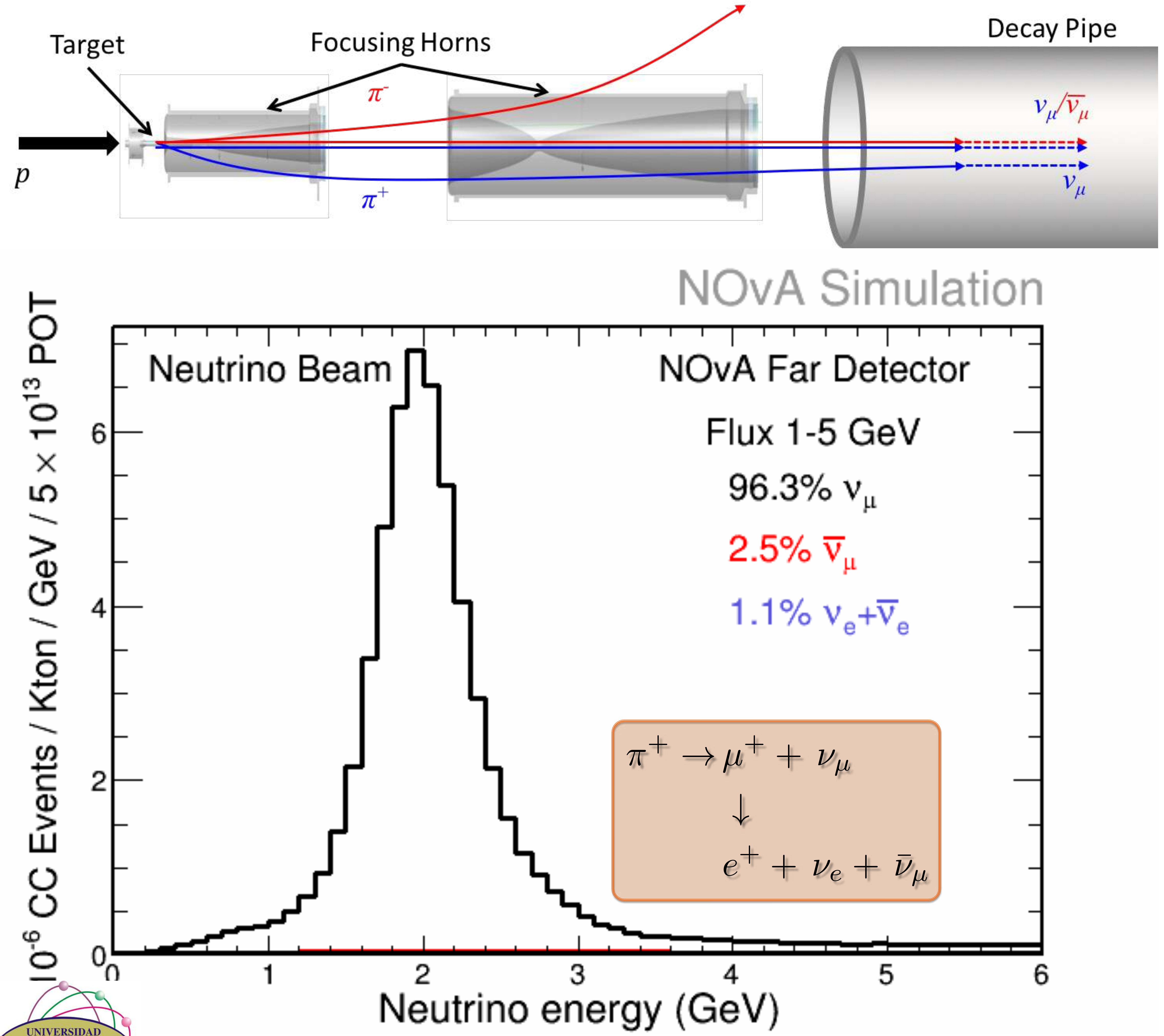
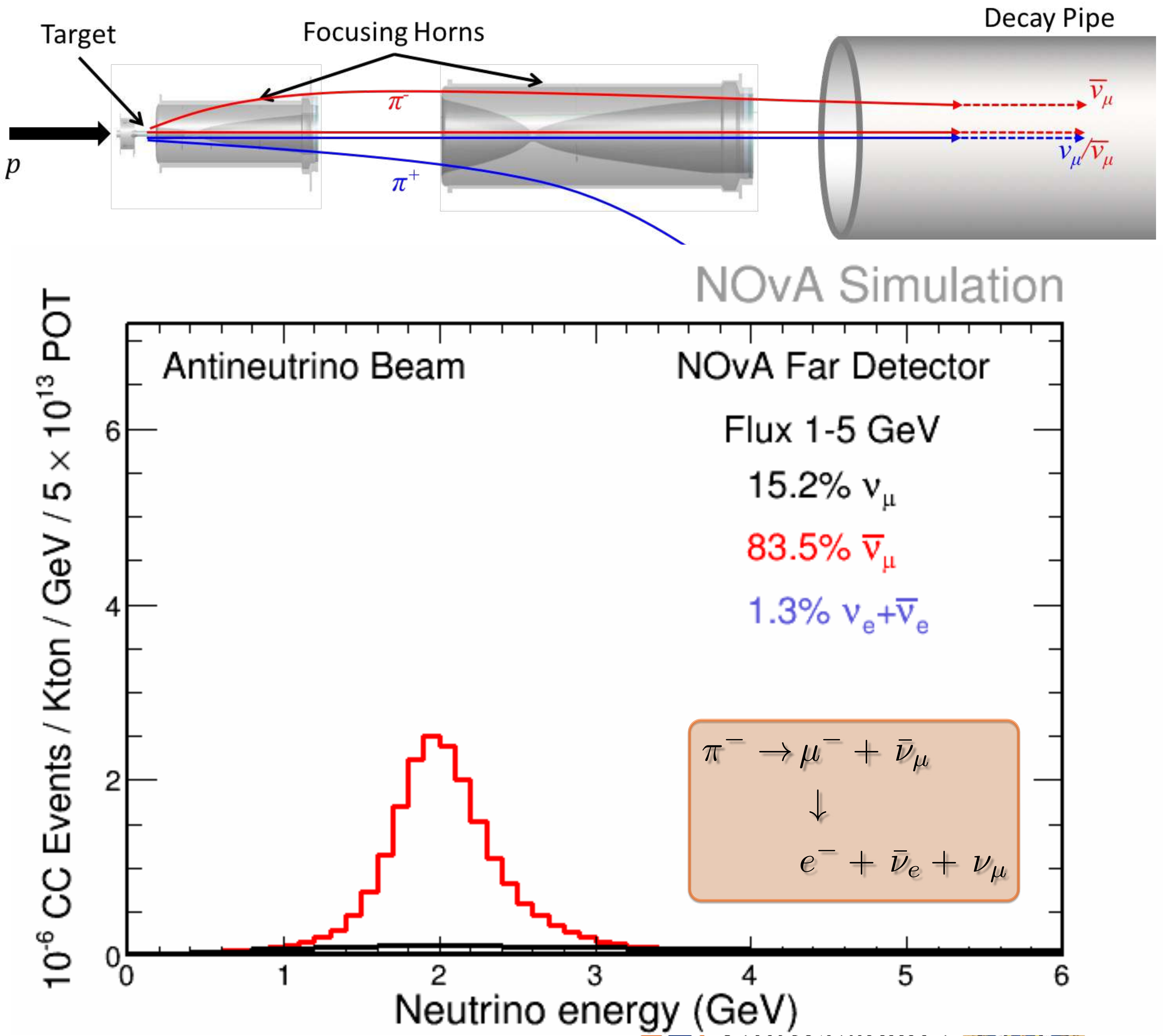
THANKS!

Backup Slides

NOvA

Neutrinos from NuMI beam





Sterile neutrinos

The motivations and implications

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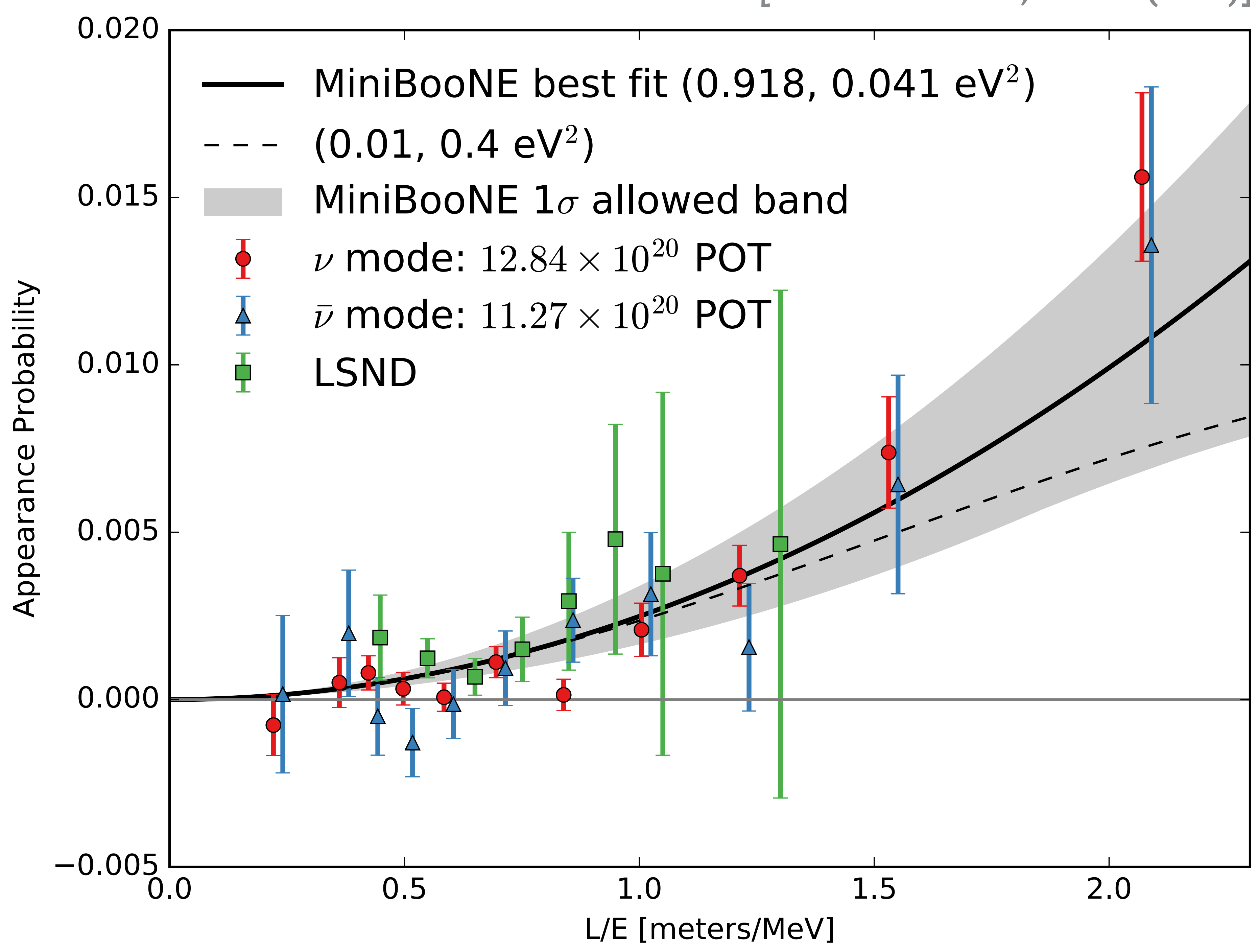
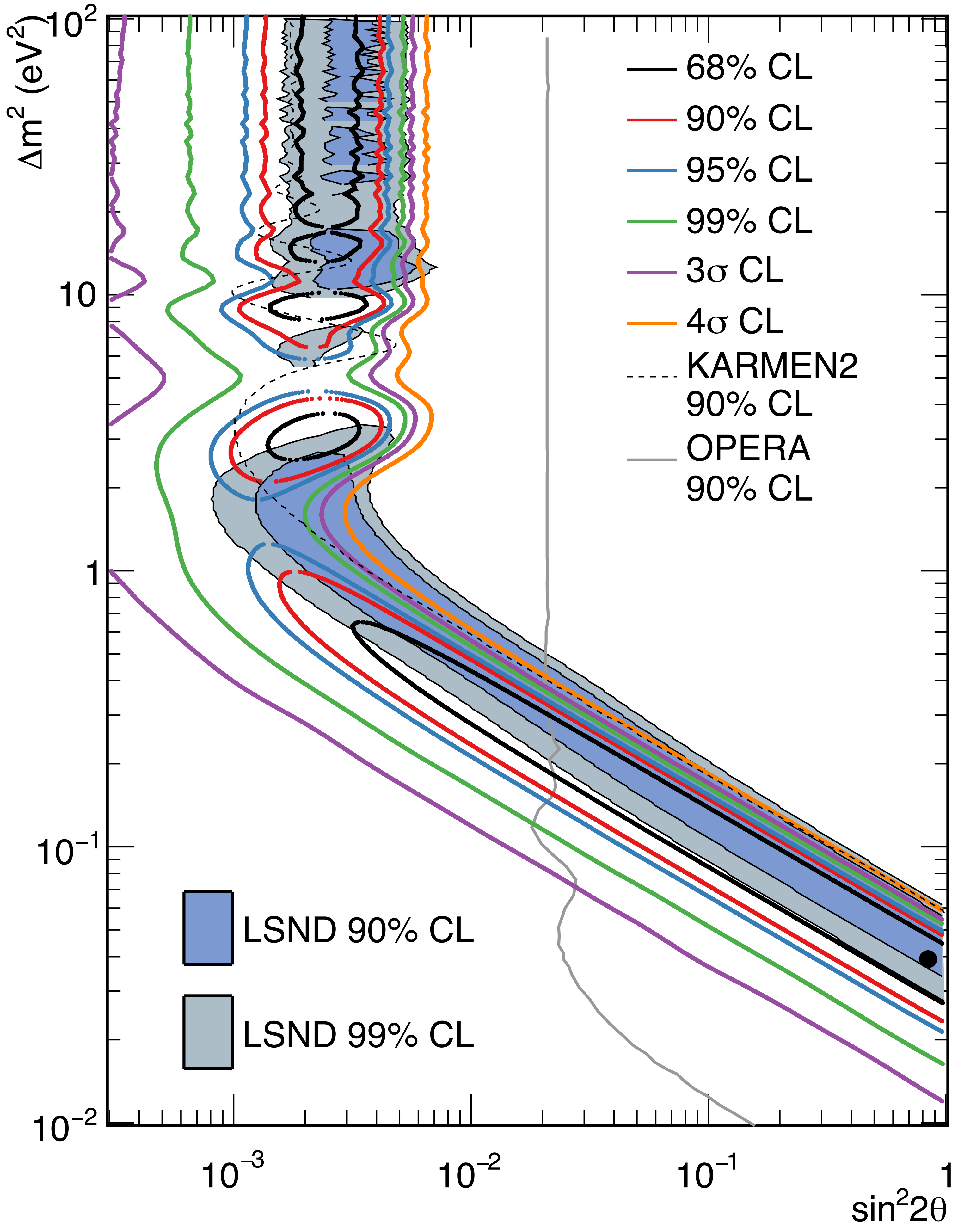
The possible existence of a 4th ***sterile neutrino*** as an explanation to the event excess observed by LSND and MiniBooNE…

[MiniBooNE Coll., PRL121 (2018)]



Possible implications

- Modification of the neutrino mass states mixing
- Anomalous ν_e appearance



[MiniBooNE Coll., PRL121 (2018)]

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Additional (sterile) neutrinos

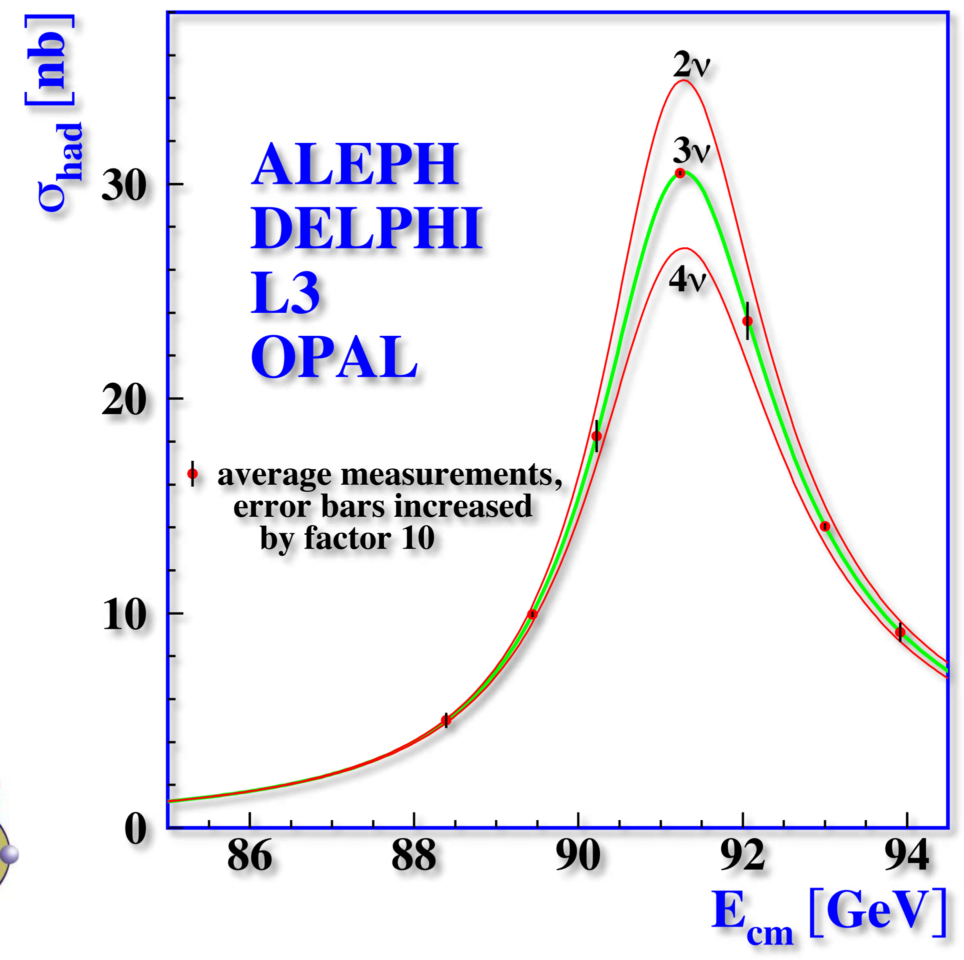
The effects of on the neutrino evolution

… Also leads to a modification of the Hamiltonian.

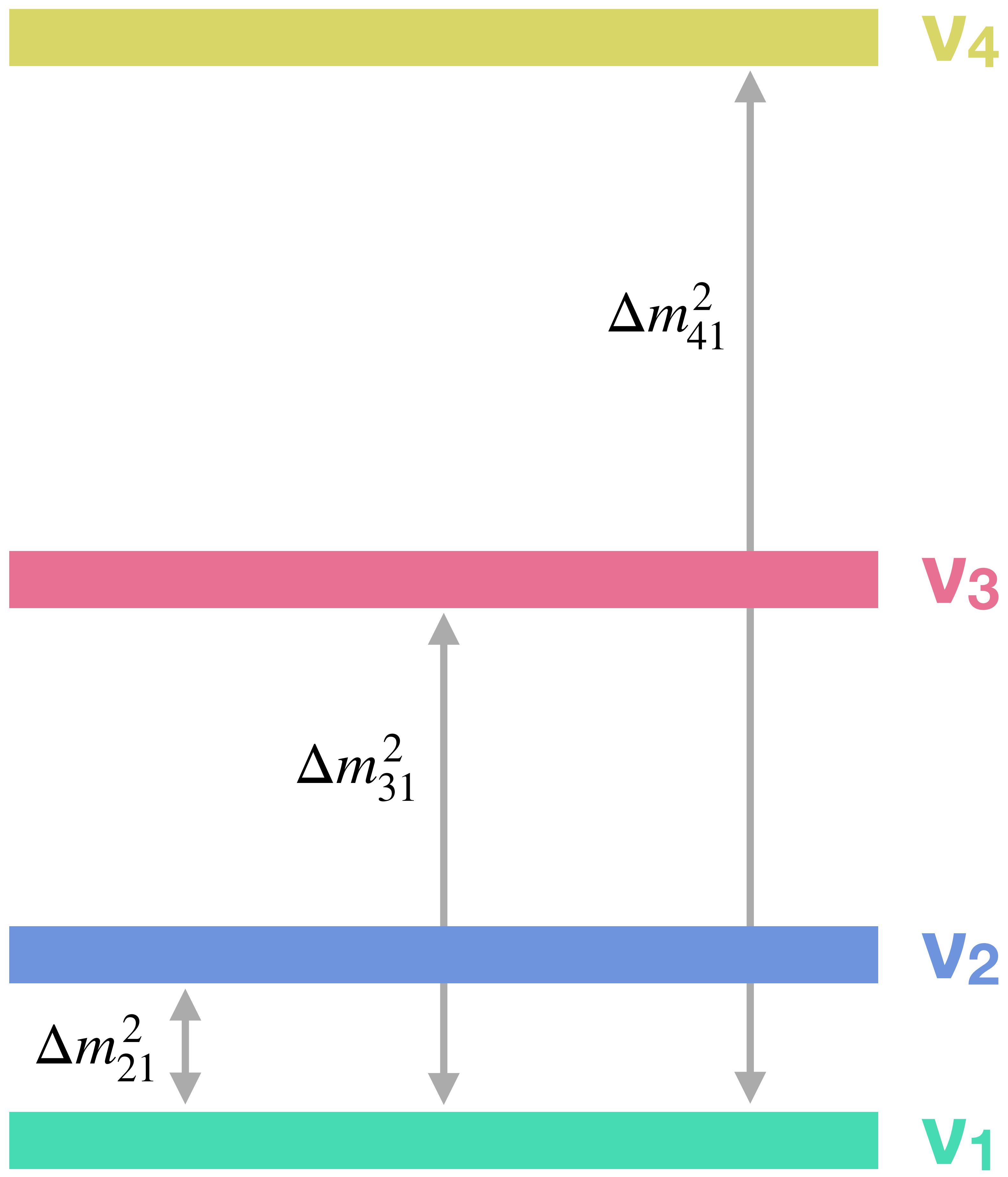
The PMNS mixing matrix becomes 4x4.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4}\\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} & U_{\tau 4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

[S. Shael et al., Phys. Rept 427 (2006)]



Fourth neutrino does not couple to SM forces, but modifies the oscillations



[V Hewes, Fermilab JETP Seminar (2022)]

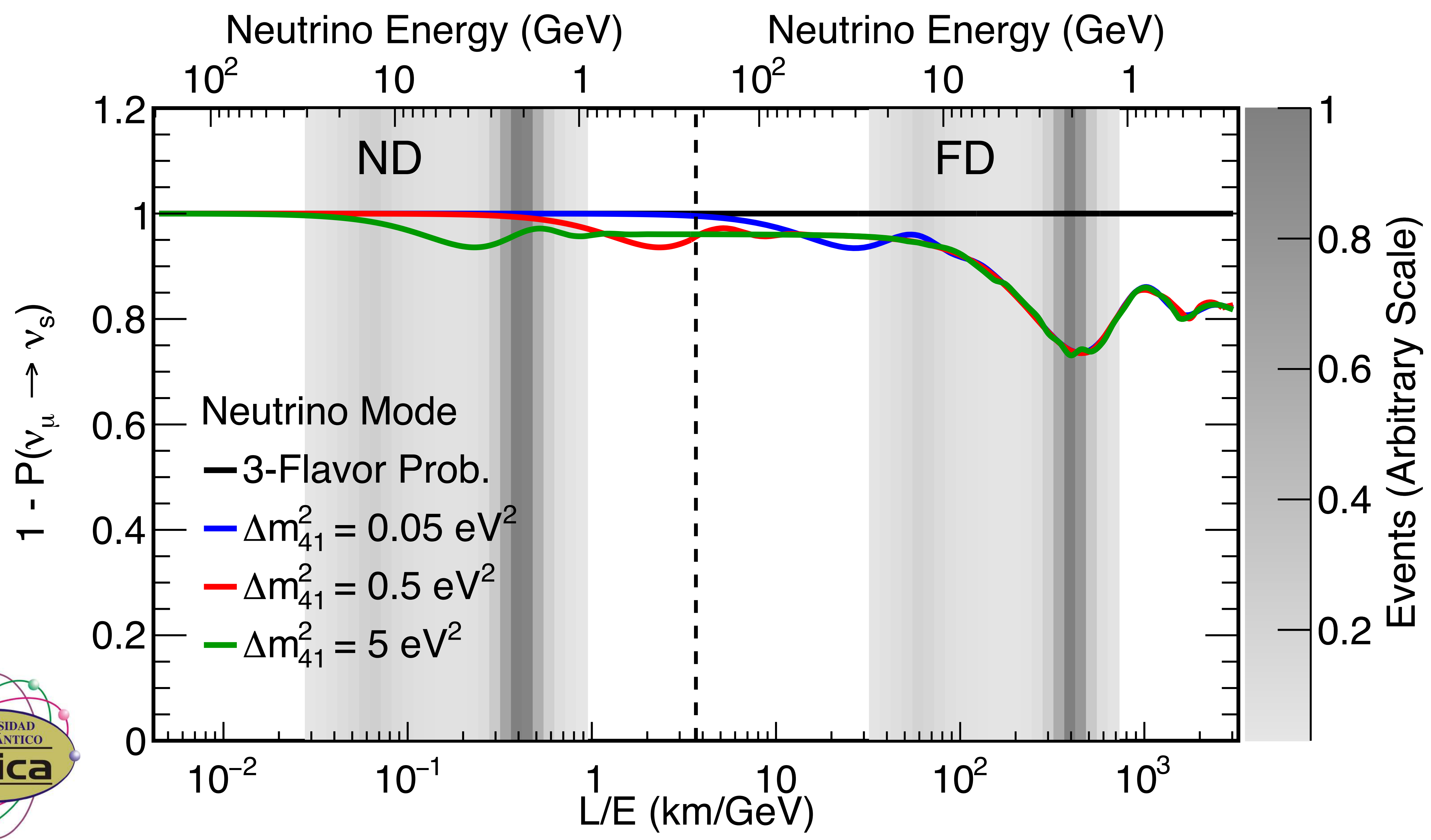
Additional (sterile) neutrinos

The effects of on the neutrino oscillation

#SOMOSUA

Fourth neutrino does not couple to SM forces, but modifies the oscillations

- 3+1 neutrino oscillations studied trough ***neutral current*** disappearance
- NC are flavor independent – clean measurement of **active** → **sterile** disappearance



$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}$$
$$- \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$
$$+ \frac{1}{2}\sin\delta_{24}\sin^2\theta_{24}\sin 2\theta_{23}\sin\Delta_{31}$$

$$\Delta_{ji} \equiv \frac{\Delta m^2_{ji} L}{4E}$$

Sensitivity to θ_{34} independent of θ_{24}

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Additional (sterile) neutrinos

The effects of on the neutrino oscillation

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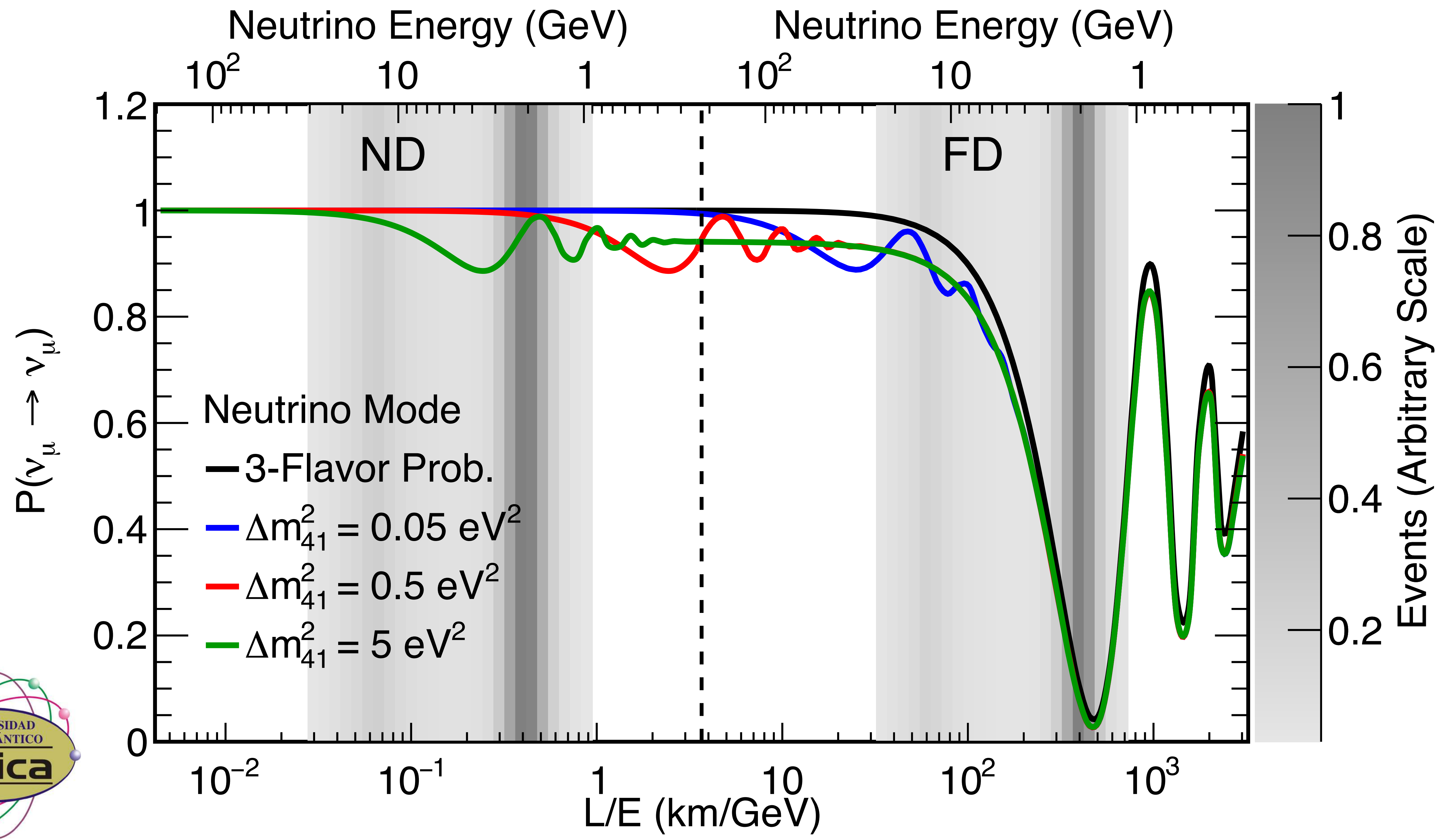
Fourth neutrino does not couple to SM forces, but modifies the oscillations

- 3+1 neutrino oscillations studied trough ***charged current*** ν_μ disappearance
- Extra ν_μ **disappearance** → **sterile** (compared to 3F)



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{24} \sin^2 \Delta_{41} + 2\sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$

$$\Delta_{ji} \equiv \frac{\Delta m^2_{ji} L}{4E}$$

Sensitivity to θ_{24} from both detectors

Sterile neutrino Spectra

The results

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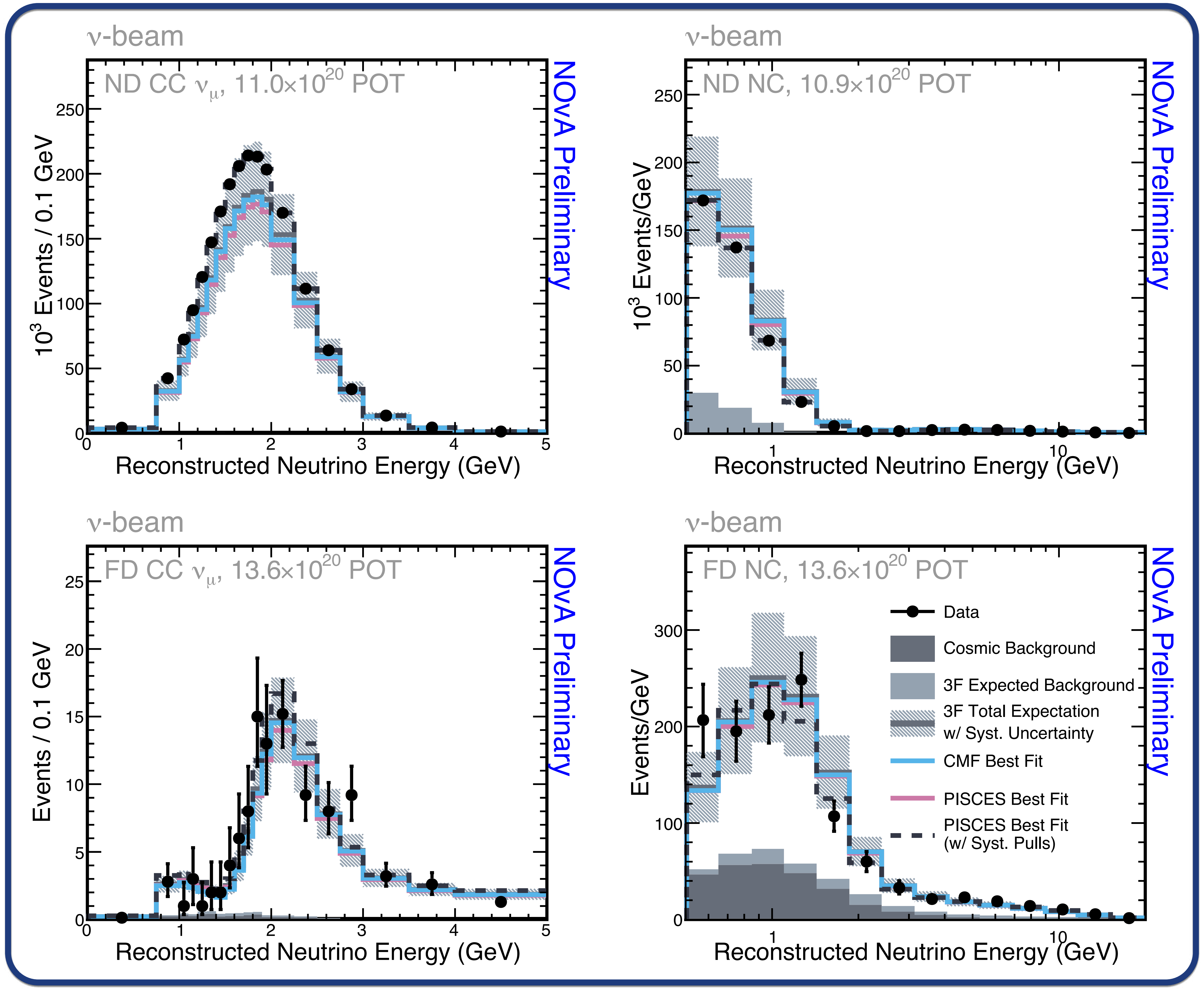

Consistent with no sterile neutrino oscillations
(within the 3F uncertainty)

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Sterile neutrino parameters

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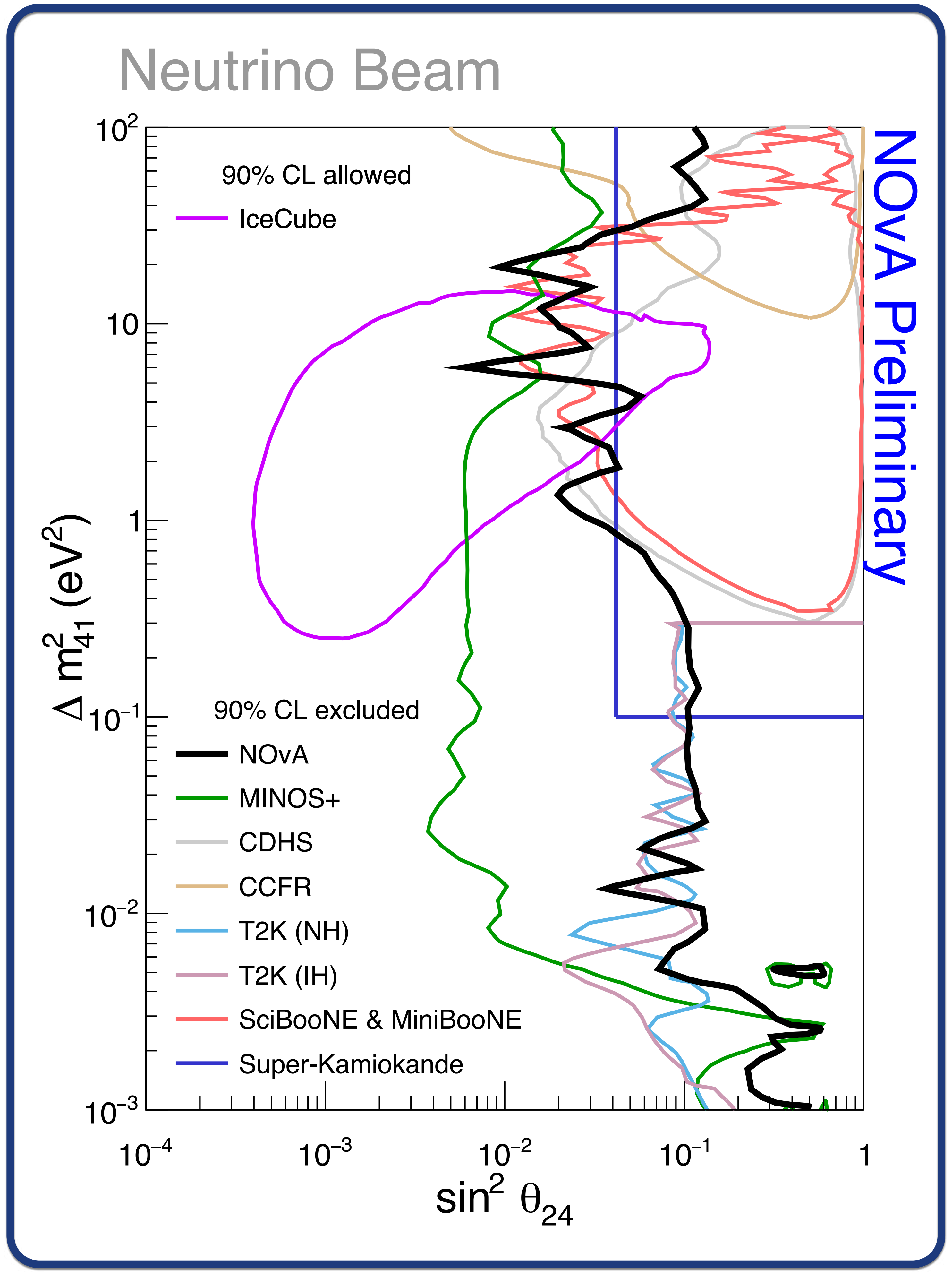
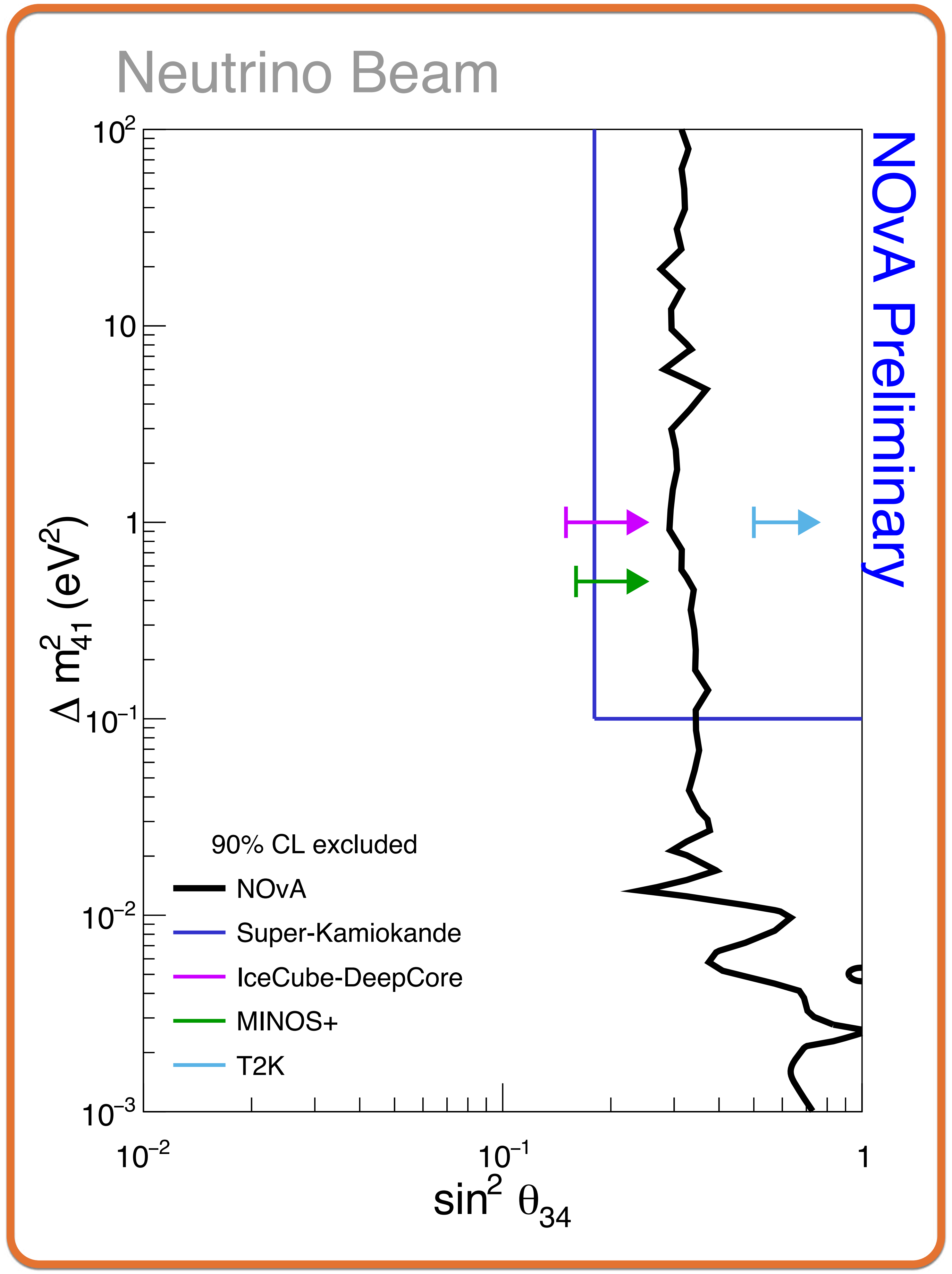
The results



90% CL critical values corrected using Profiled Feldman Cousins approach

Competitive limits on θ_{24} in the high $\Delta m_{41}{}^2$ regime

World-leading limits for θ_{34} as a function of $\Delta m_{41}{}^2$



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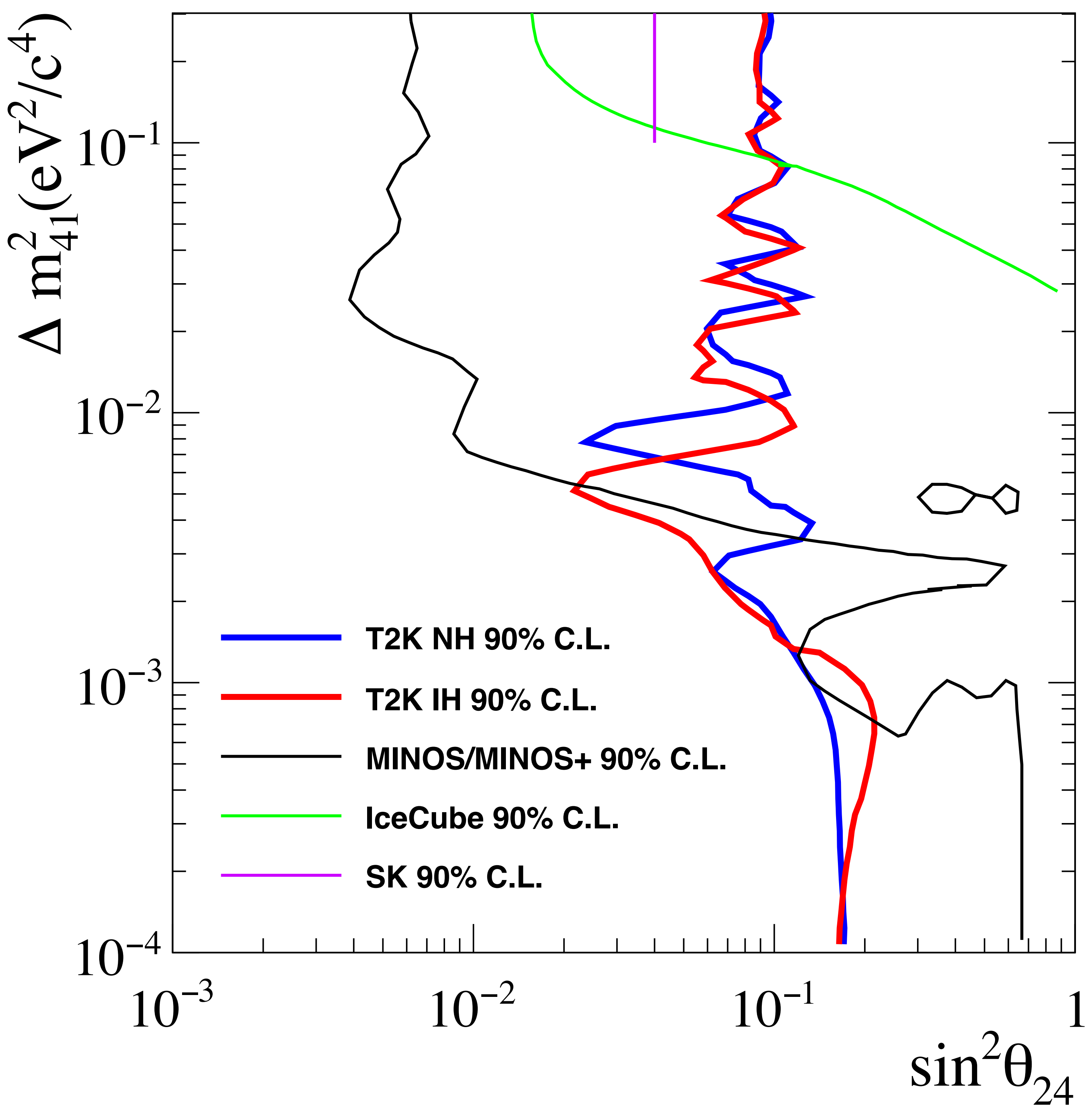
Sterile neutrino parameters

The results

[T2K Collaboration, PRD99(R) (2019)]

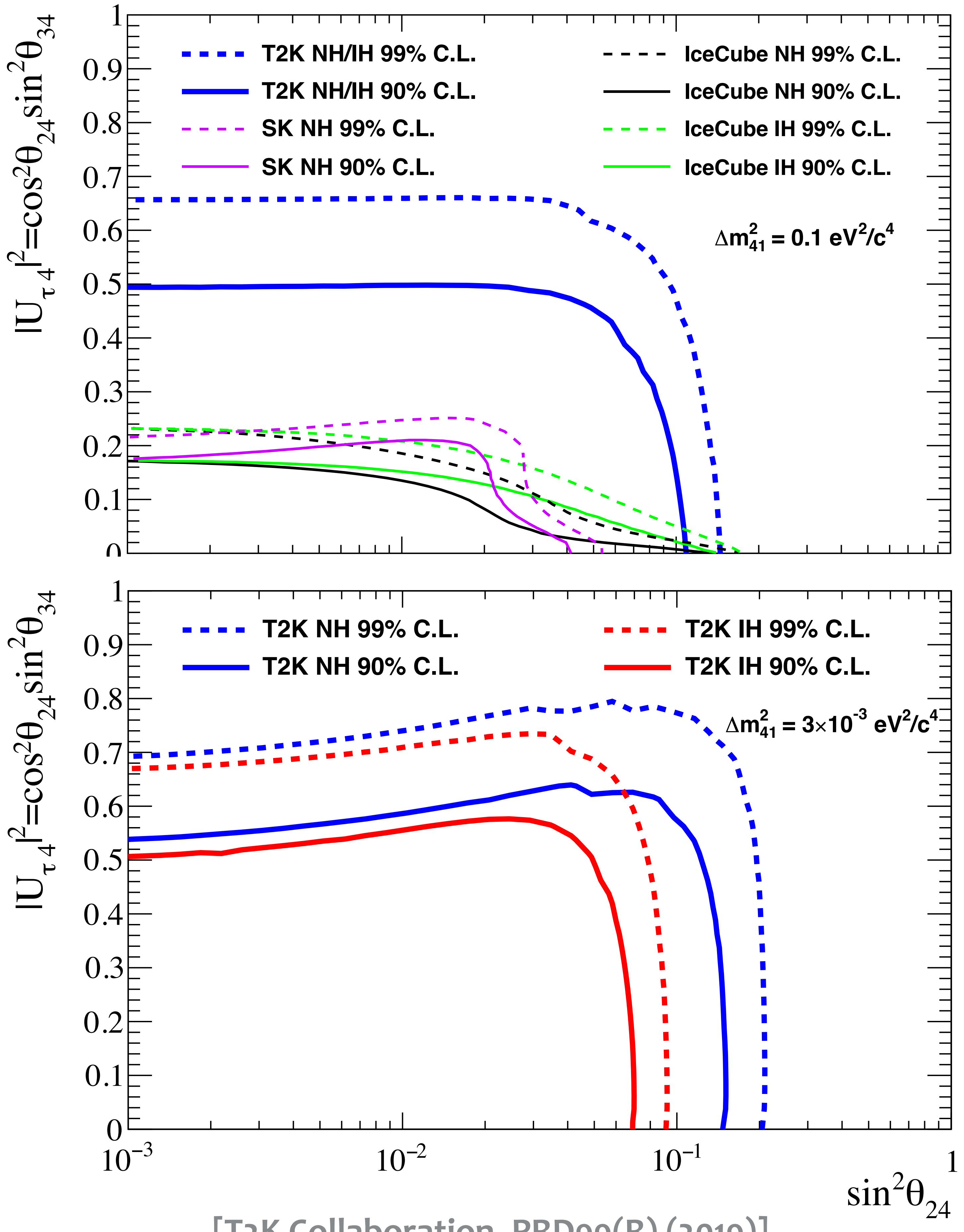


No evidence of ν_s mixing in a 3+1 model

CC $\nu_{\mu,e}$ and NC samples were used

Limits on θ_{24} for $\Delta m_{41}{}^2 < 10^{-3}$ eV²

Limits on θ_{24} and $|U_{\tau 4}|^2$ for $\Delta m_{41}{}^2$=1 eV² and $\Delta m_{41}{}^2$= 10^{-3} eV²



[T2K Collaboration, PRD99(R) (2019)]

Heavy neutrinos

The motivations and implications

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As an extension of the SM to include neutrino masses: inclusion of ***n* ≥ 2** right-handed neutrino fields

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\left(\bar{\nu}_L \; \bar{\nu}_R^c\right)\begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}\begin{pmatrix} \bar{\nu}_L^c \\ \bar{\nu}_R \end{pmatrix} + \text{h.c.}$$

nxn Majorana matrix

Possible implications

- *n* heavy Majorana mass eigenstates, *N*
- Modification of the mixing pattern

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + \sum_{I=1}^{n} \Theta_{\alpha I} N_i \qquad (\alpha = e, \mu, \tau)$$

Active-heavy mixing matrix

Constraints on $U_\alpha^2 \equiv \sum |\Theta_{\alpha I}|^2$ by searching for heavy neutrino decays

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Heavy neutrinos

The results

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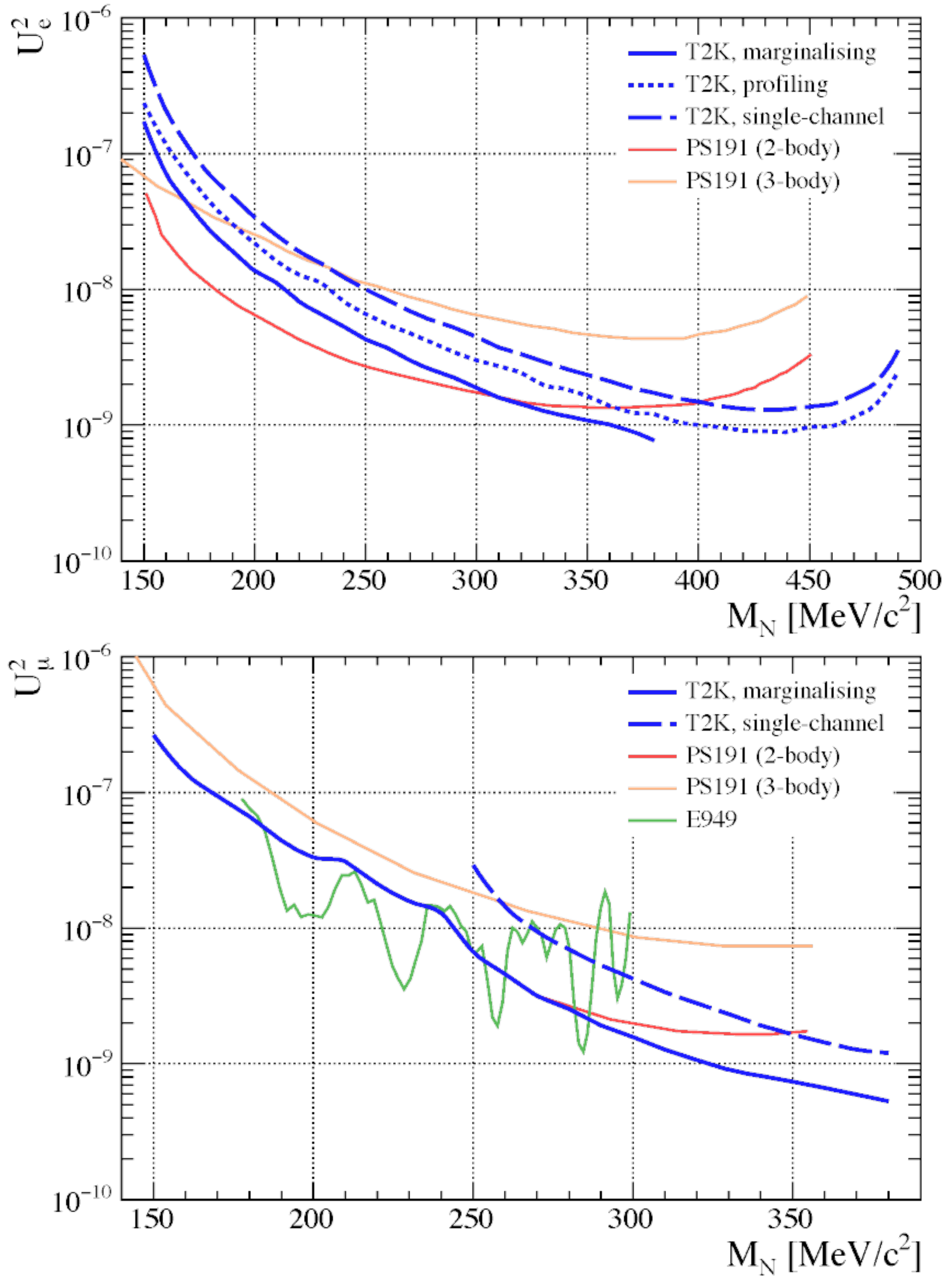
[T2K Collaboration, PRD100 (2019)]



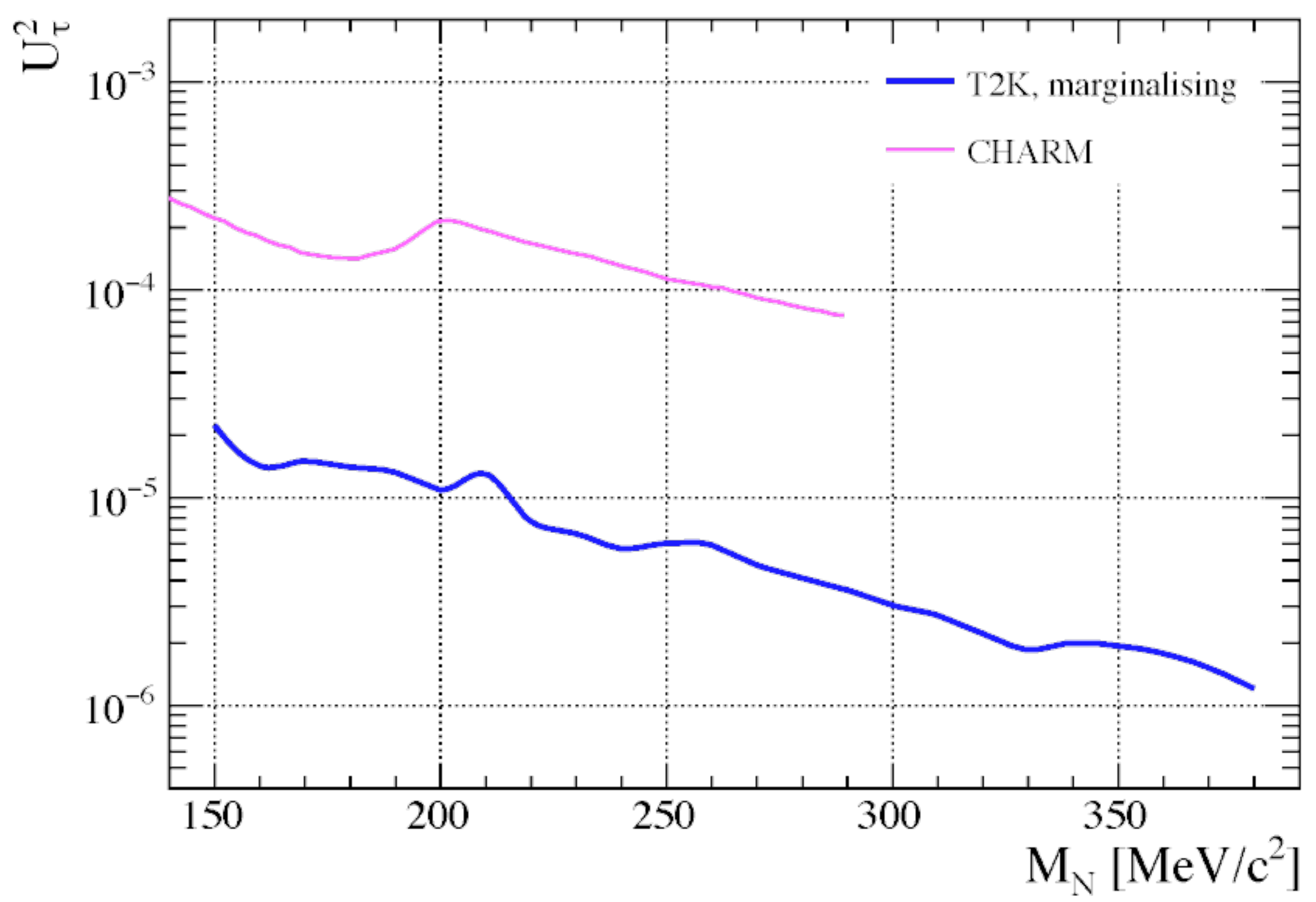
Search for heavy neutrinos
(decaying in the ND280)

$$N \to l_\alpha^\pm \pi^\mp$$

$$N \to l_\alpha^+ l_\beta^- \nu(\bar{\nu})$$

No excess of events was observed

Upper limits on the mixing elements U_e^2, U_μ^2, U_τ^2



$$140 < M_N < 493 \quad \mathrm{MeV/c^2}$$

[T2K Collaboration, PRD100 (2019)]

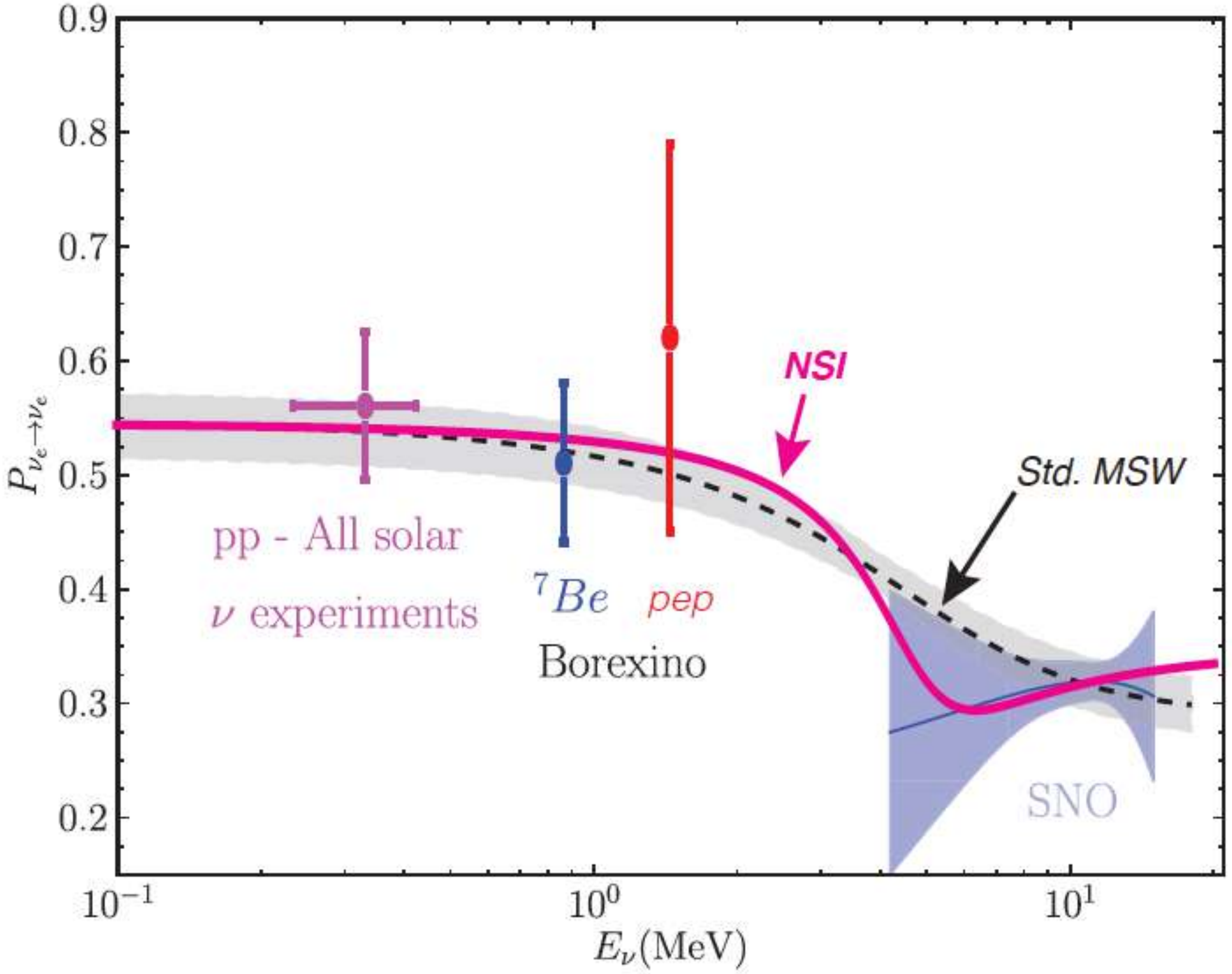
Non-Standard Interactions

The motivations and implications

The possible existence of NSI implies a modification of neutrino propagation…

Possible implications [S.S Chatterjee, A. Palazzo, PRL 126 (2021)]

- Low-energy manifestation of high-energy physics (new heavy states)
- Light mediators
- Modify the dynamics of neutrinos in matter
- Sizable impact on current data
- *Interfere with the determination of the standard parameters*



[A. Friedland, I.M. Shoemaker arXiv:1207.6642 (2012)]

Non-Standard Interactions

The effects of on the neutrino evolution

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… Then leading to a modification of the Hamiltonian

$$\mathcal{H} = \frac{1}{2E}\left(UM^2U^\dagger + \mathbb{A}\right) + V_{CC}\begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

with $\varepsilon_{\alpha\beta} = \left|\varepsilon_{\alpha\beta}\right| e^{i\delta_{\alpha\beta}}$.

Diagonal terms $\varepsilon_{\alpha\alpha}$, could be interpreted as the NSI effective mass squared differences
(possible new resonances even if neutrinos were massless)

Off-diagonal terms $\varepsilon_{\alpha\beta}$, could play a role like the mixing angles.

Complex phases $\delta_{\alpha\beta}$, could be a source of CP violation.

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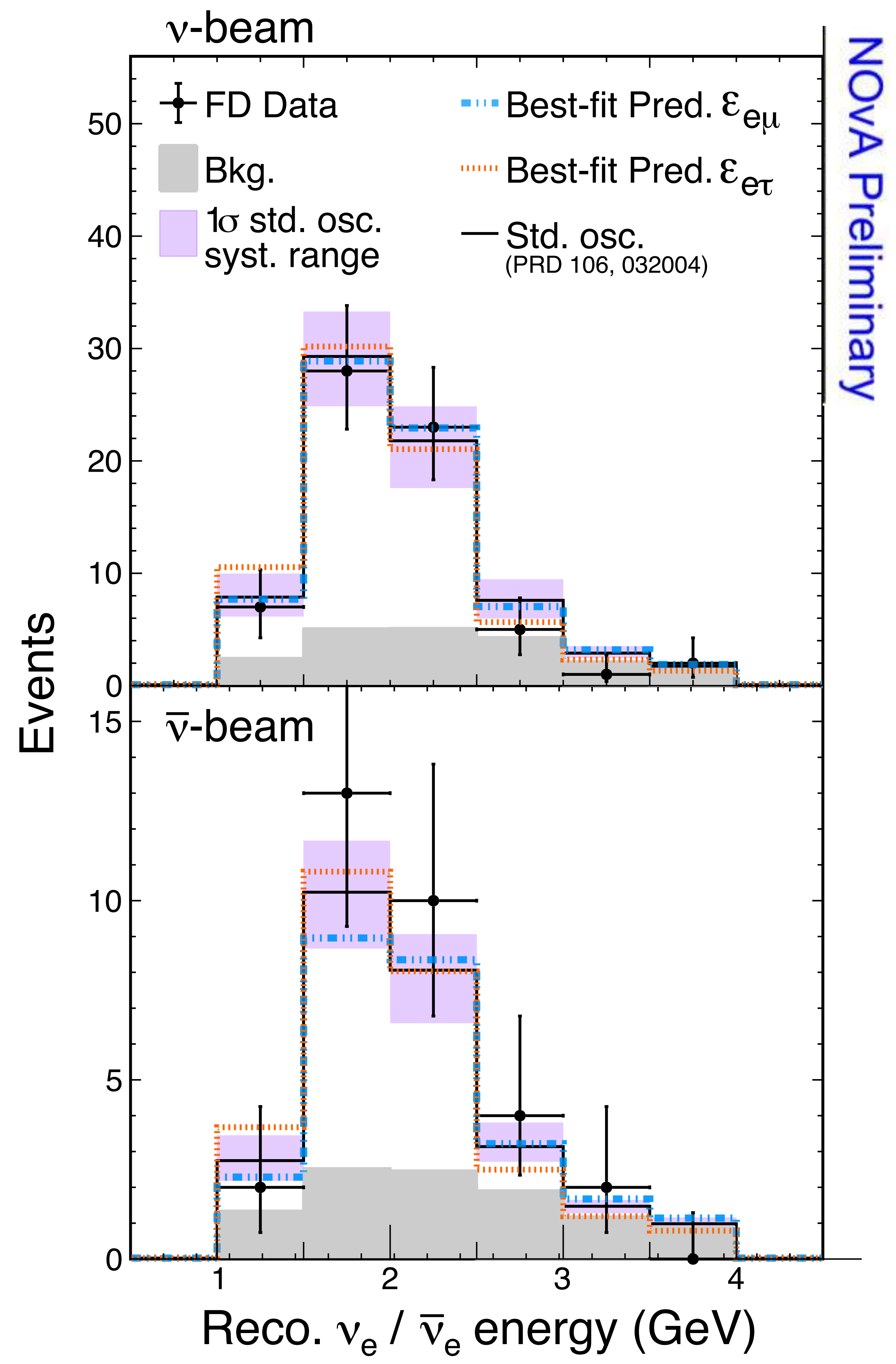
NSI – eμ and eτ Spectra

The results

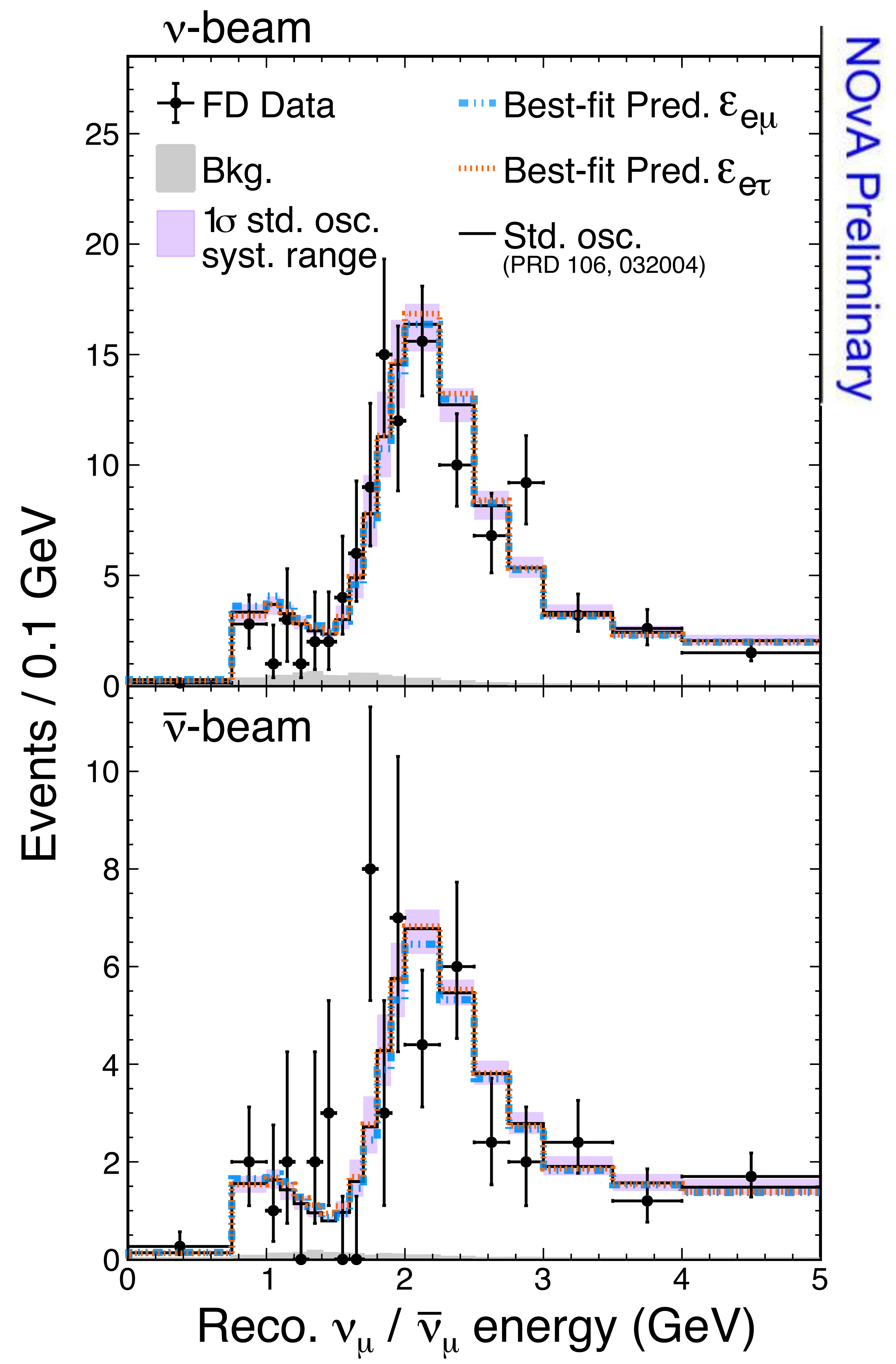


NSI not needed to explain NOvA spectra.

Muon (anti)neutrinos

Electron (anti)neutrinos

No evidence of NSI (results are consistent with 3F within uncertainties)



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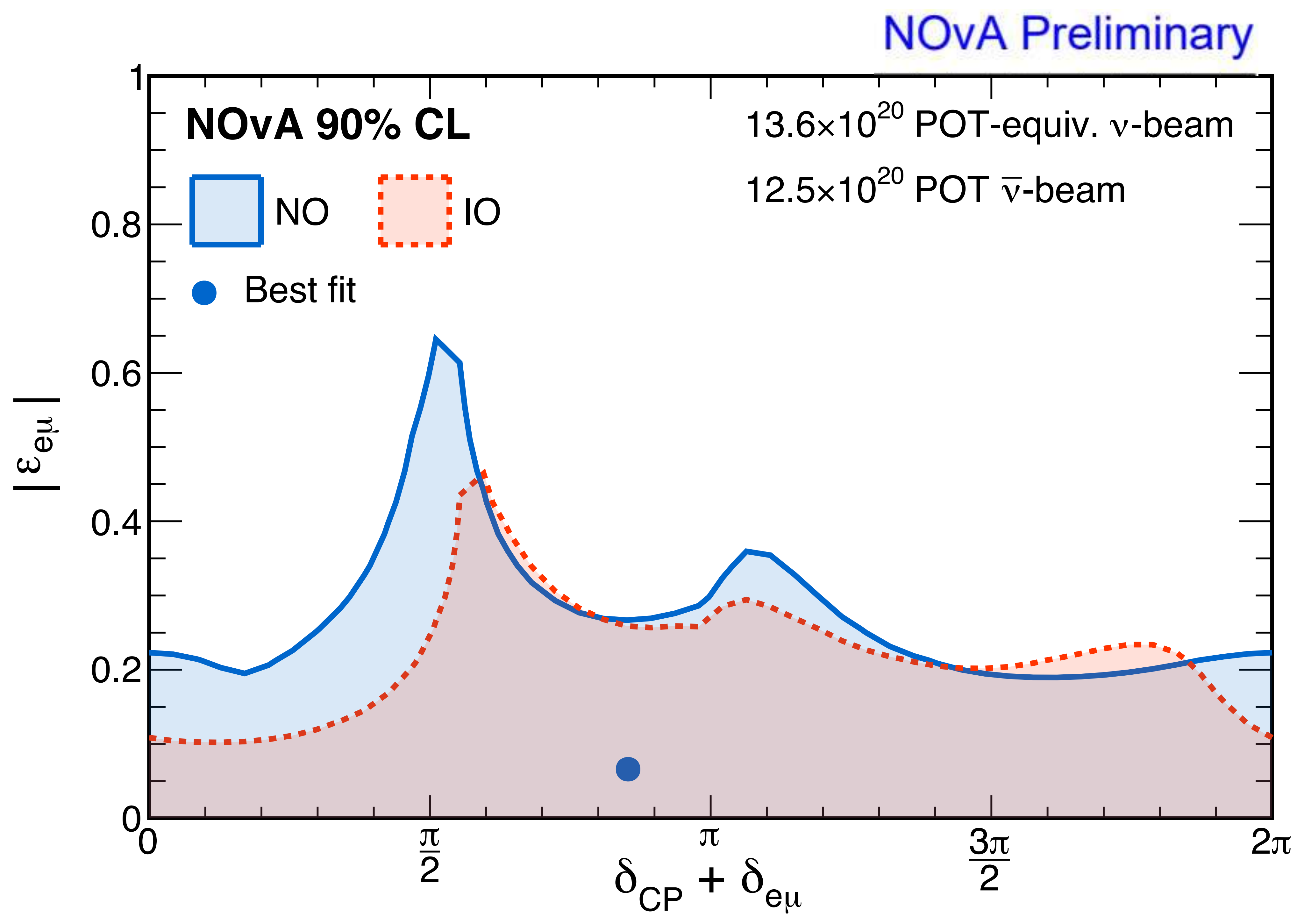
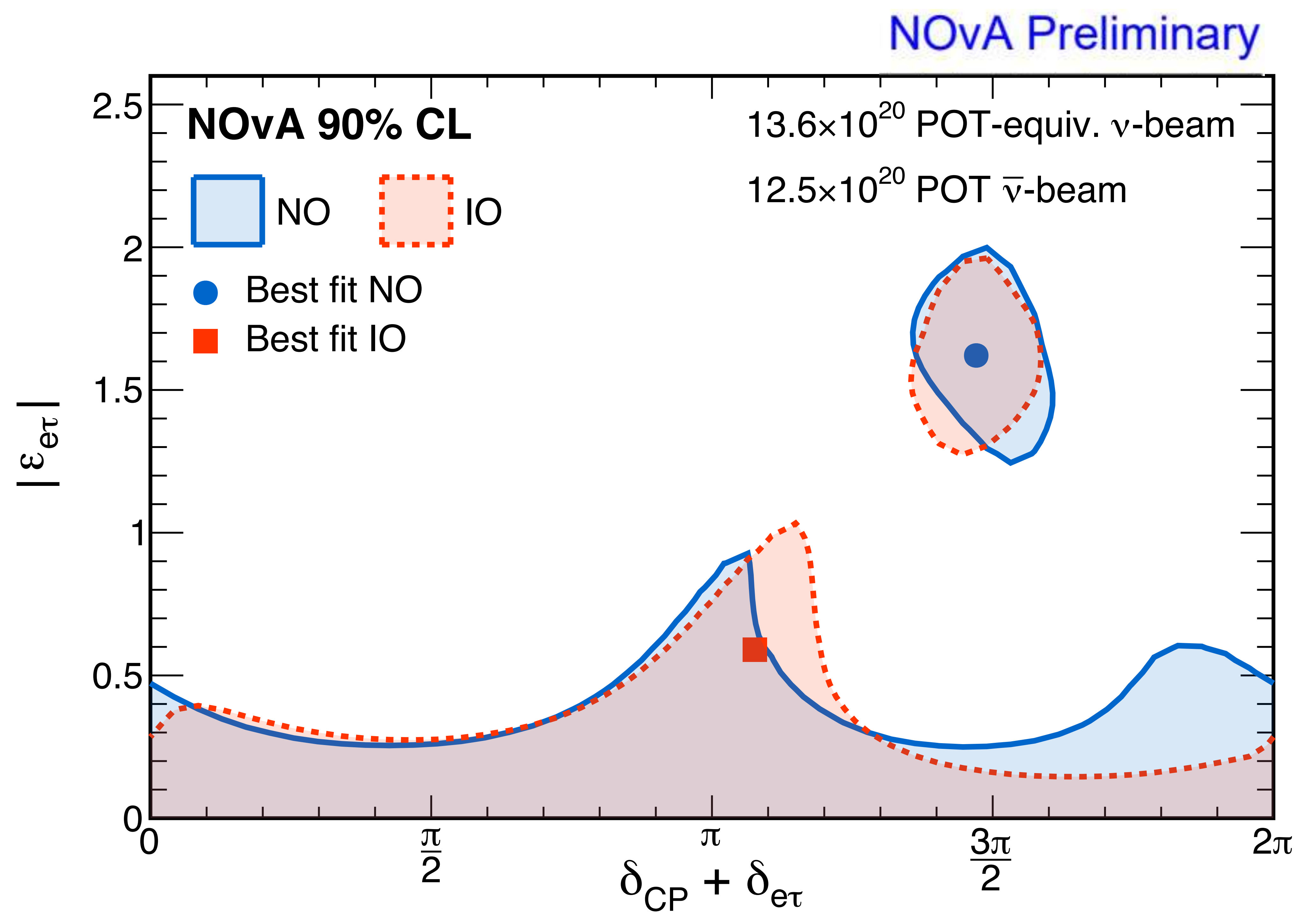
NSI – eμ and eτ Constraints

The results



$$|\varepsilon_{e\mu}| \lesssim 0.3$$



$$|\varepsilon_{e\tau}| \lesssim 0.4$$