#SOMOSUA

Non-Standard Physics at NOvA and T2K

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for the NOvA Collaboration

19th Rencontres du Vietnam
NEUTRINO WORKSHOP AT IFIRSE 2023
International Centre for Interdisciplinary Science Education (ICISE)
Quy Nhon (Central Vietnam), July 2023

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Outline

- **NOvA and T2K Experiments**

- **Non-Standard Neutrino Physics**
- ➢ Phenomenology and Results
  - *Sterile Neutrinos*
  - *Non-Standard Interactions*
  - Heavy neutrinos
  - … and more.

- **Conclusions**

THE EXPERIMENTS

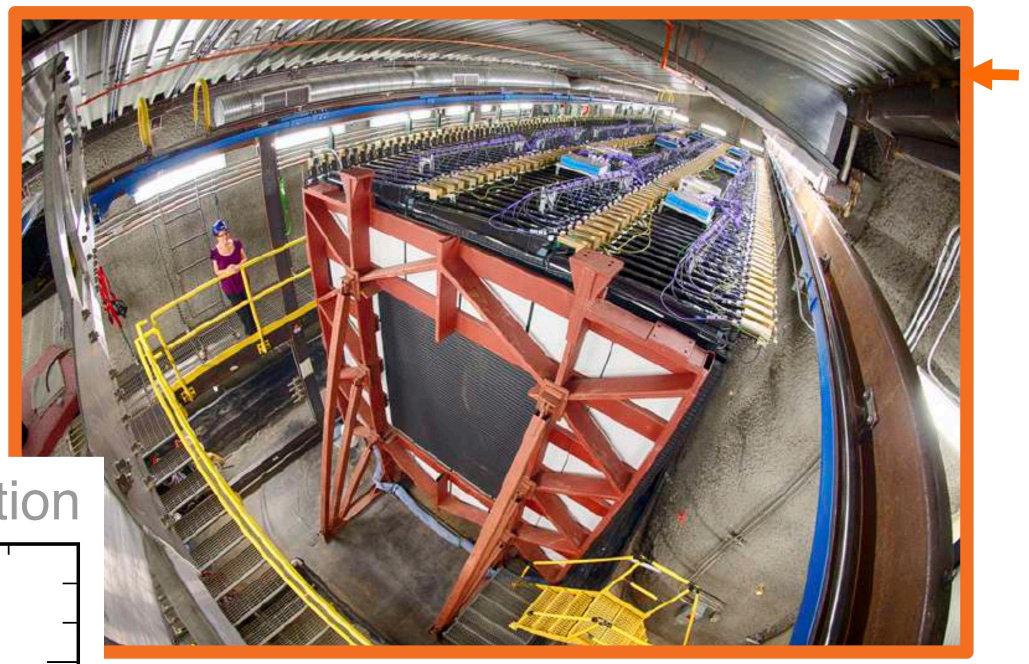
A 2-slides review

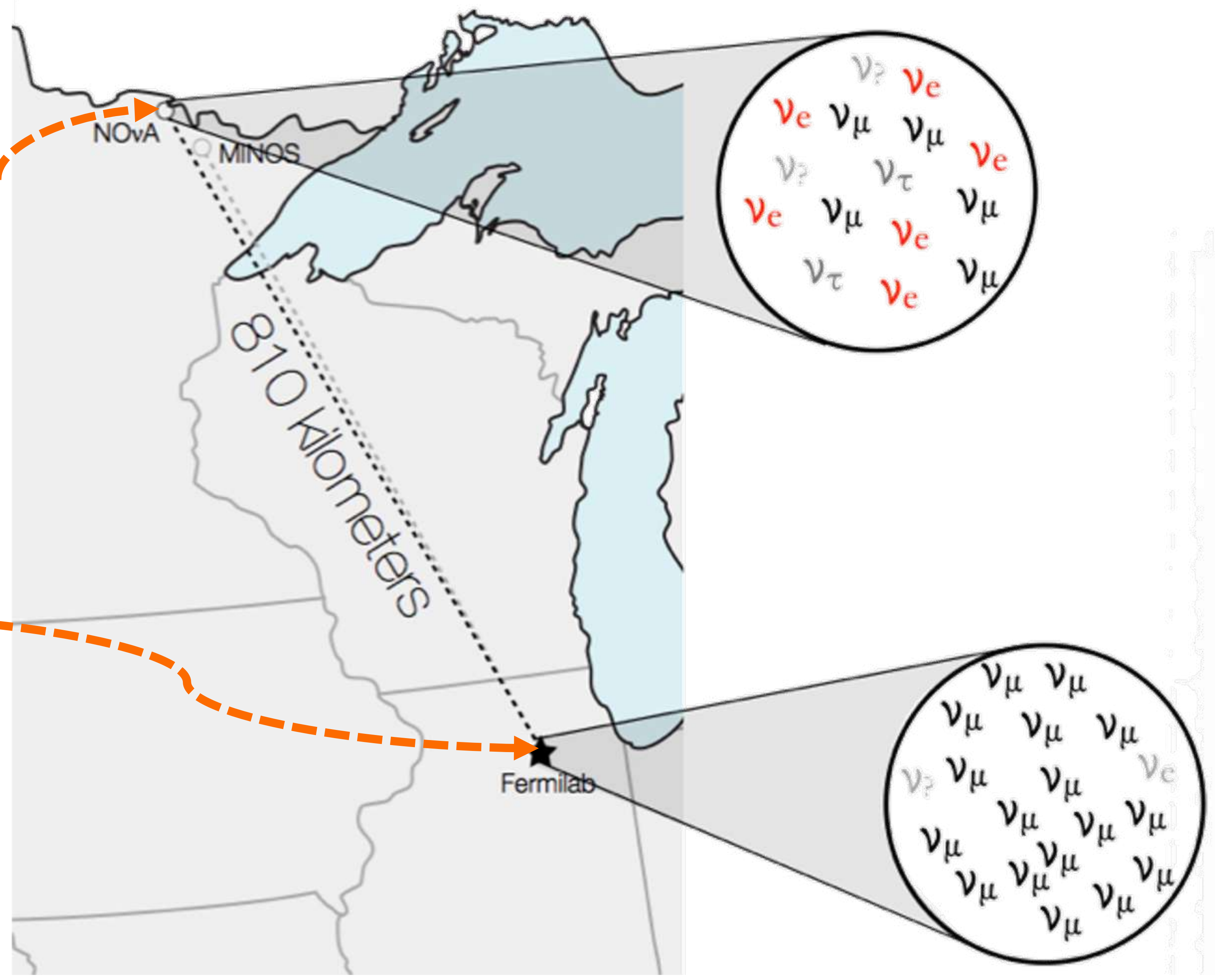
NOvA

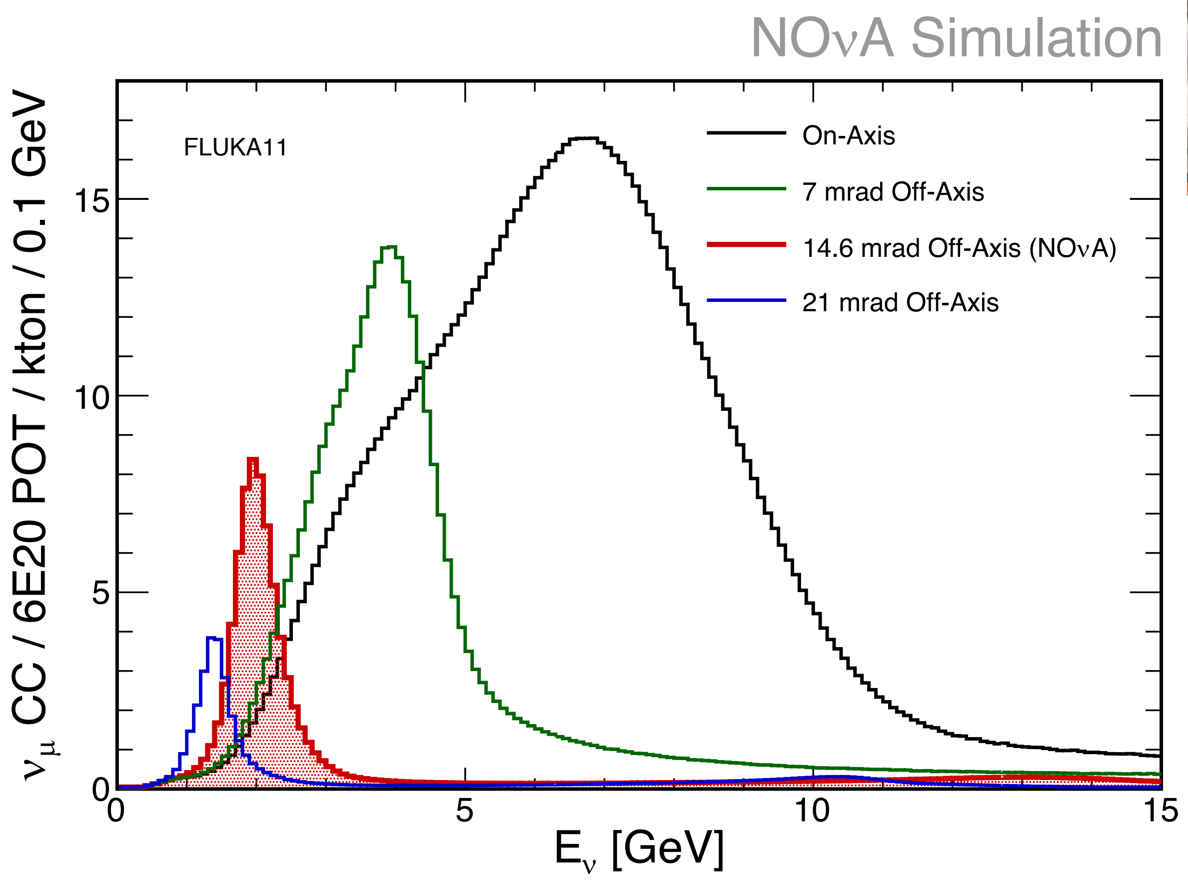
The Experiment in the US

- 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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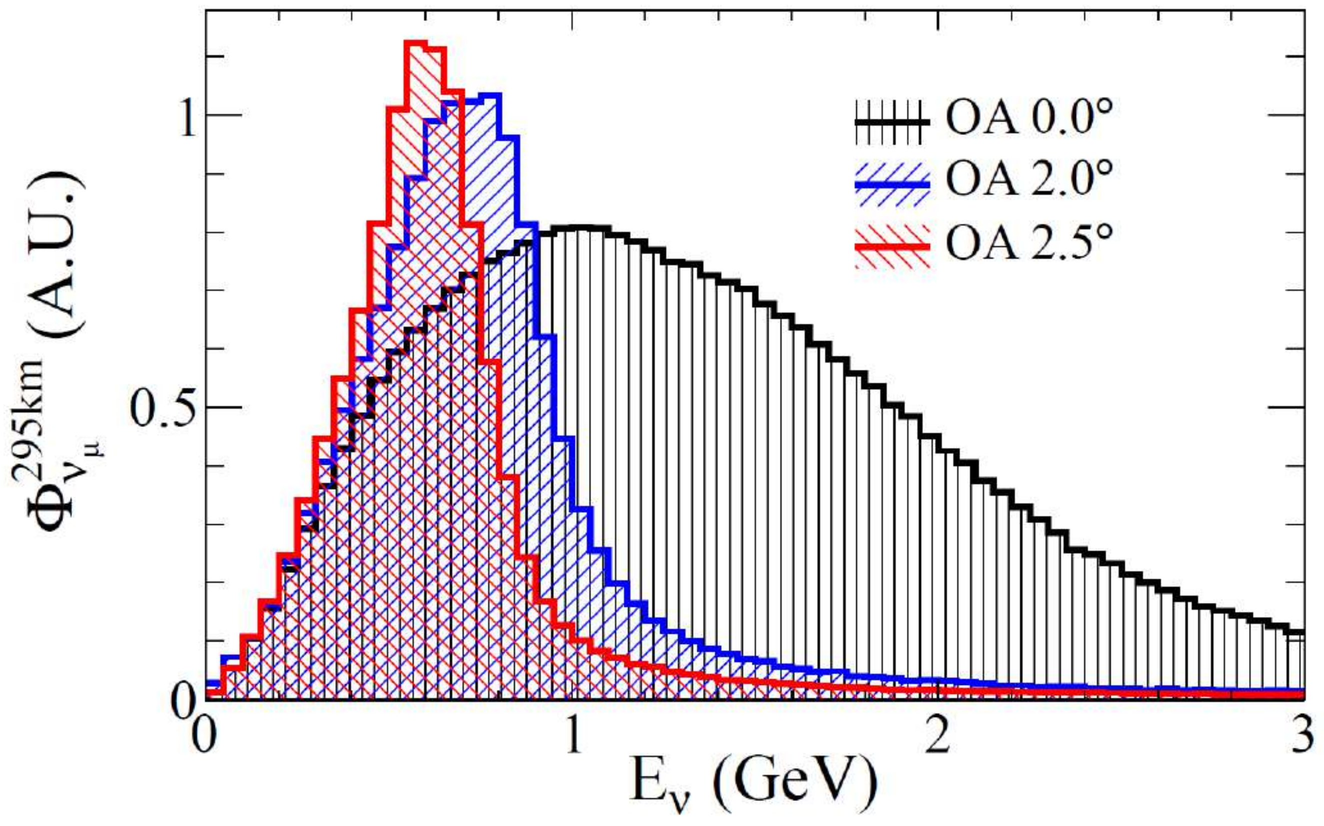
- Long-baseline (295 km) neutrino oscillation experiment
- Muon Neutrinos from the J-PARC acceleration complex
- Two detectors:
  - **Far Detector**: Super-Kamiokande
  - **Near Detector(s)**: ND280; INGRID (on-axis)
- Off-axis (2.5º) position (beam peaks at ~0.6 GeV)

2.5º ~ 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

A quick review

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

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

Neutrino Oscillations

The 3-neutrino mixing

The neutrino evolution (in vacuum):

$$\mathcal{H}_0 |\nu_k\rangle = E_k |\nu_k\rangle\,, \qquad |\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle\,, \qquad E_k = \sqrt{\mathbf{p}^2 + m_k^2}$$

But neutrinos interact with matter

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_I, \qquad \mathcal{H}_I |\nu_\alpha\rangle = V_\alpha |\nu_\alpha\rangle$$

Effective potential

$$V_\alpha = V_{CC}\delta_{\alpha e} + V_{NC} = \sqrt{2} G_F \left(N_e \delta_{\alpha e} - \frac{1}{2} N_n \right)$$

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

NON-STANDARD NEUTRINO OSCILLATIONS

Additional neutrinos – Additional interactions

Sterile Neutrinos

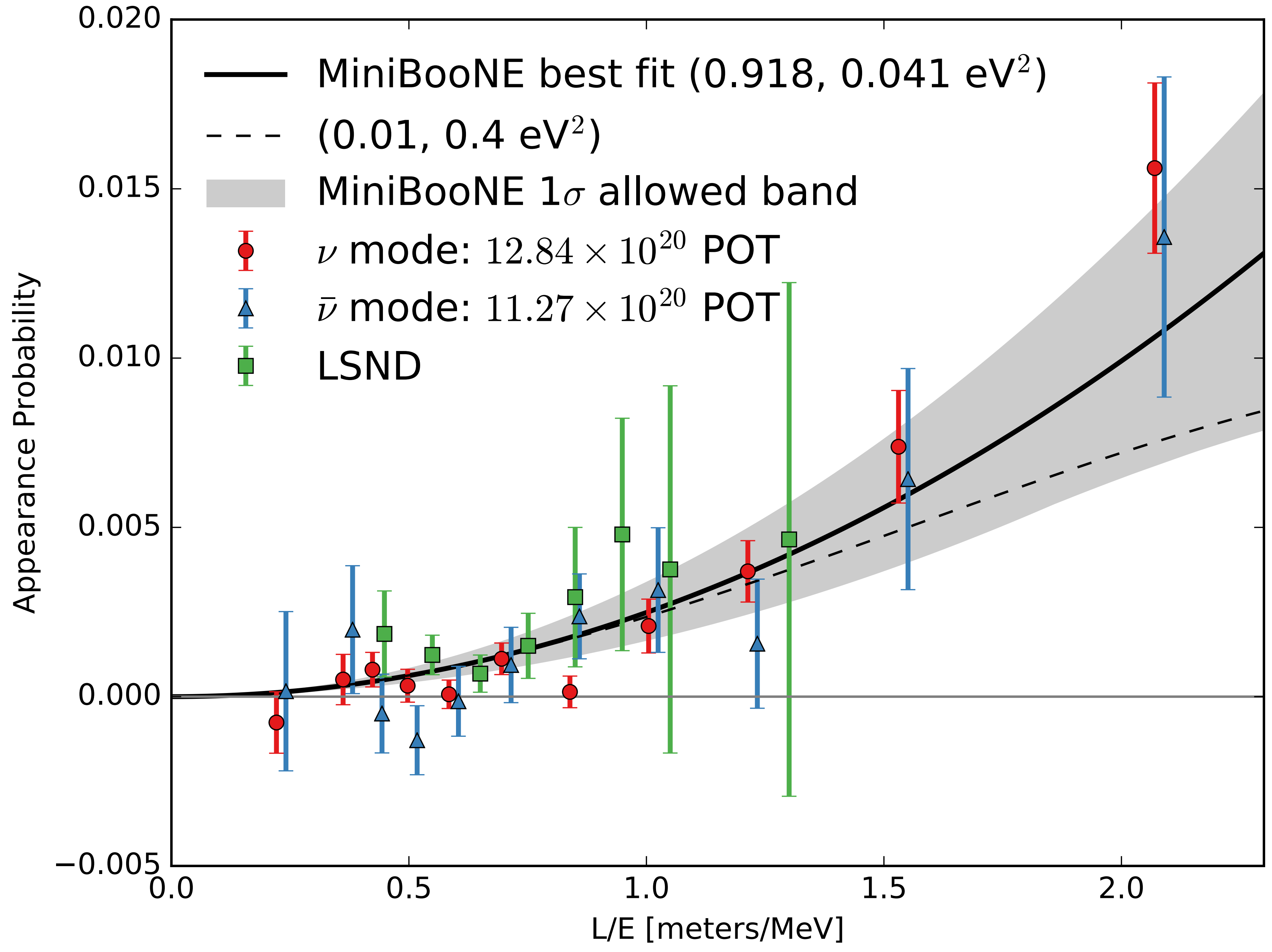
Phenomenology and Results

Sterile neutrinos

The motivations and implications

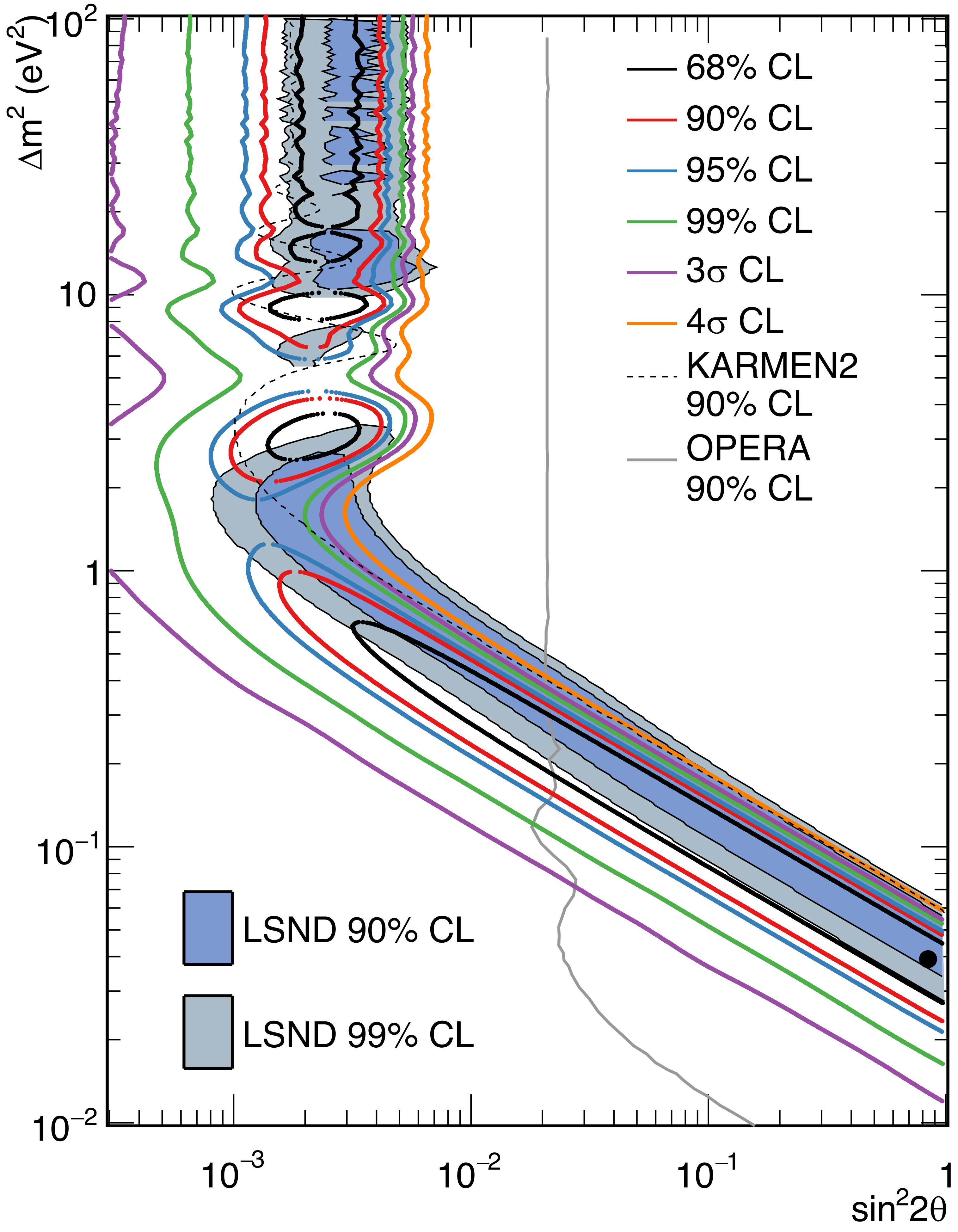
The possible existence of a 4th ***sterile neutrino*** as an explanation to the event excess observed by LSND and MiniBooNE…

[MiniBooNE Coll., PRL121 (2018)]



Possible implications

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



[MiniBooNE Coll., PRL121 (2018)]

Additional (sterile) neutrinos

The effects of on the neutrino evolution

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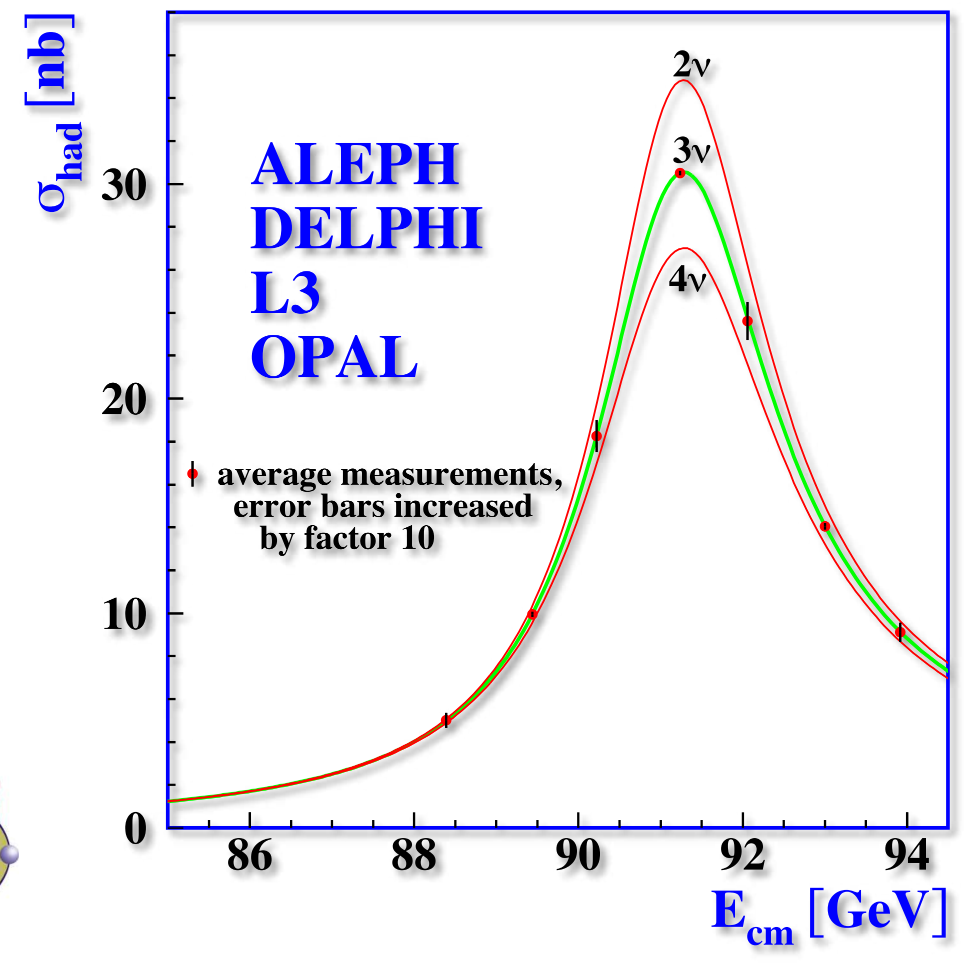
… Also leads to a modification of the Hamiltonian.

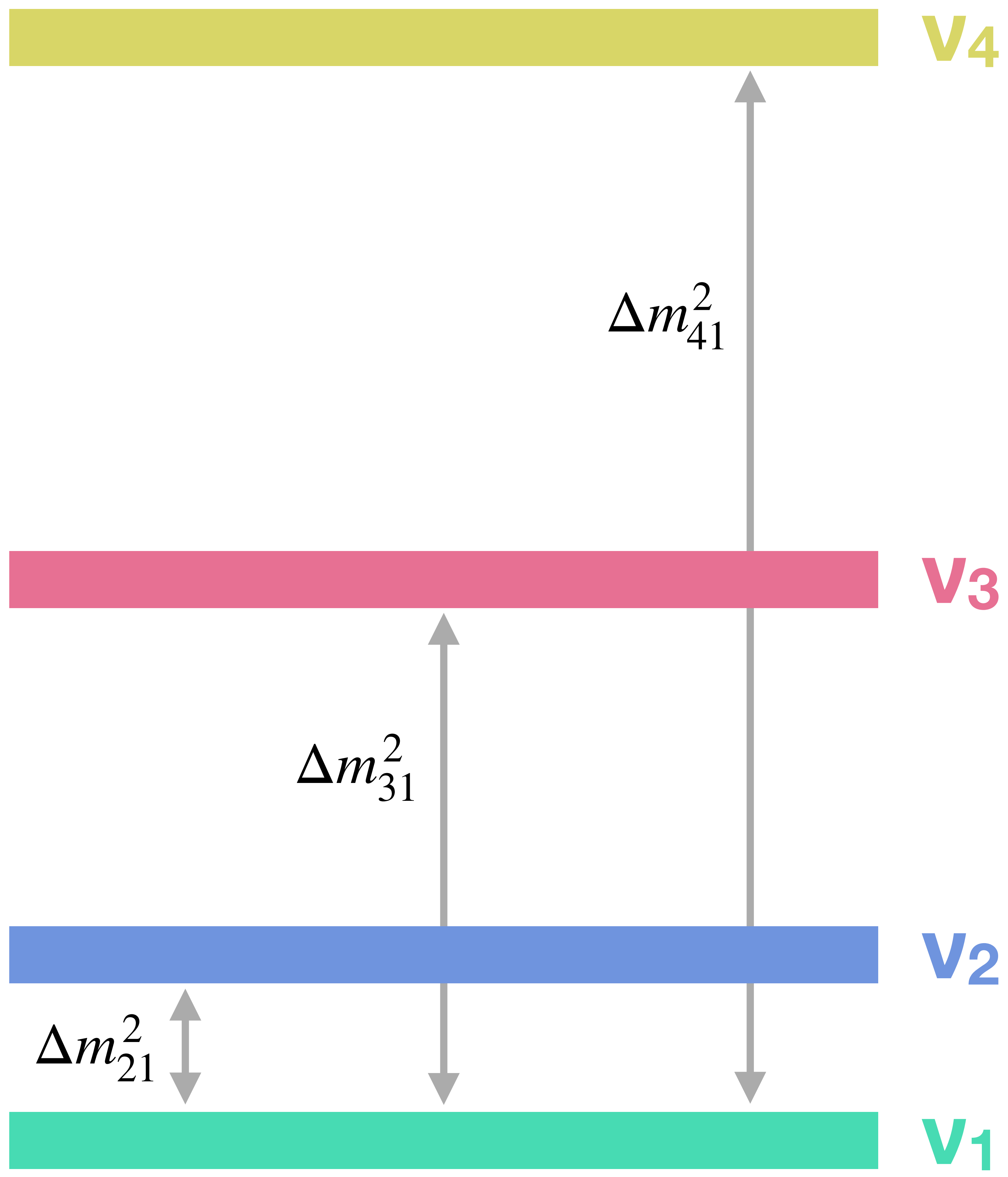
The PMNS mixing matrix becomes 4x4.

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

[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)]

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Additional (sterile) neutrinos

The effects of on the neutrino oscillation

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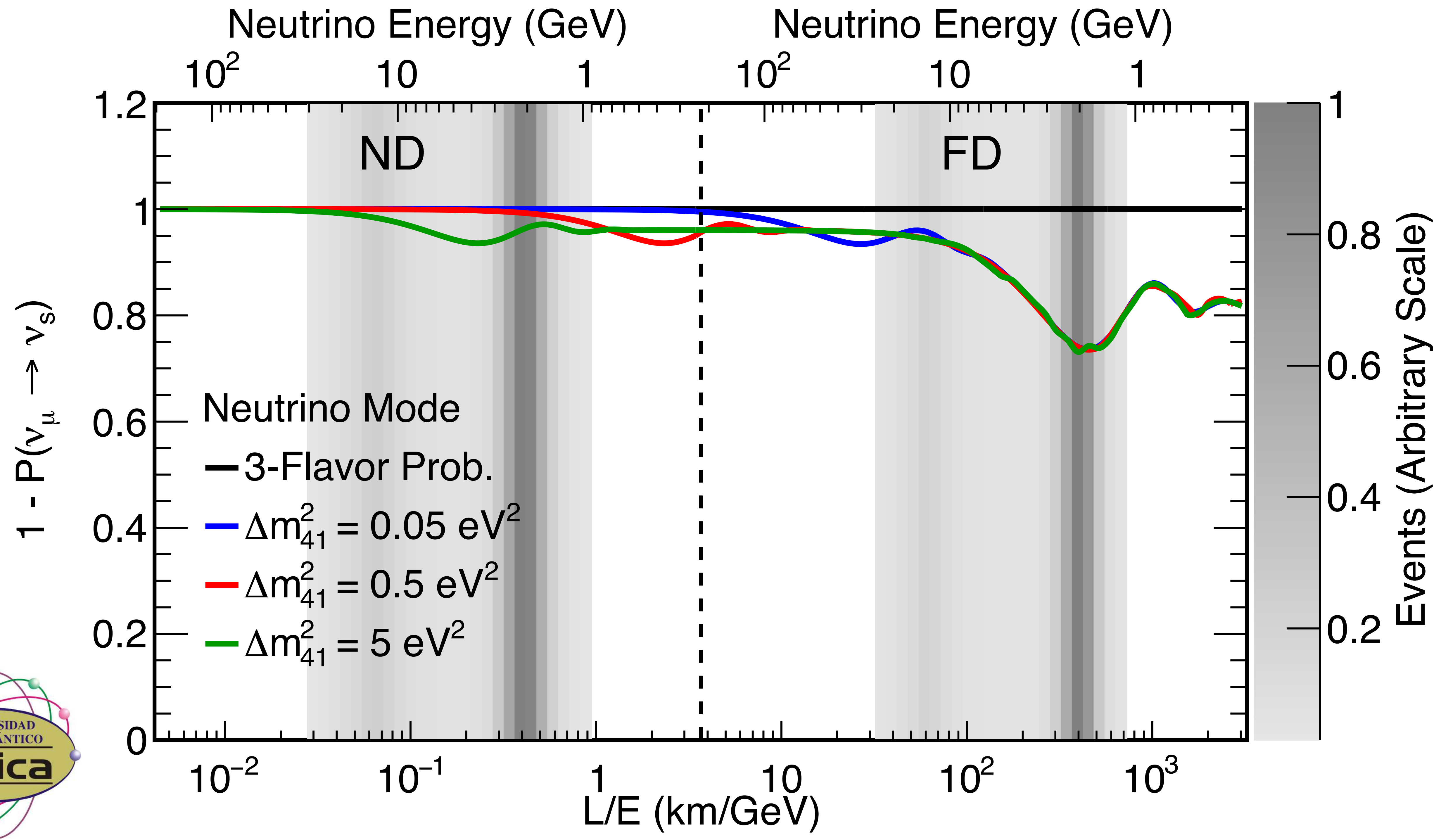
Fourth neutrino does not couple to SM forces, but modifies the oscillations

- 3+1 neutrino oscillations studied trough ***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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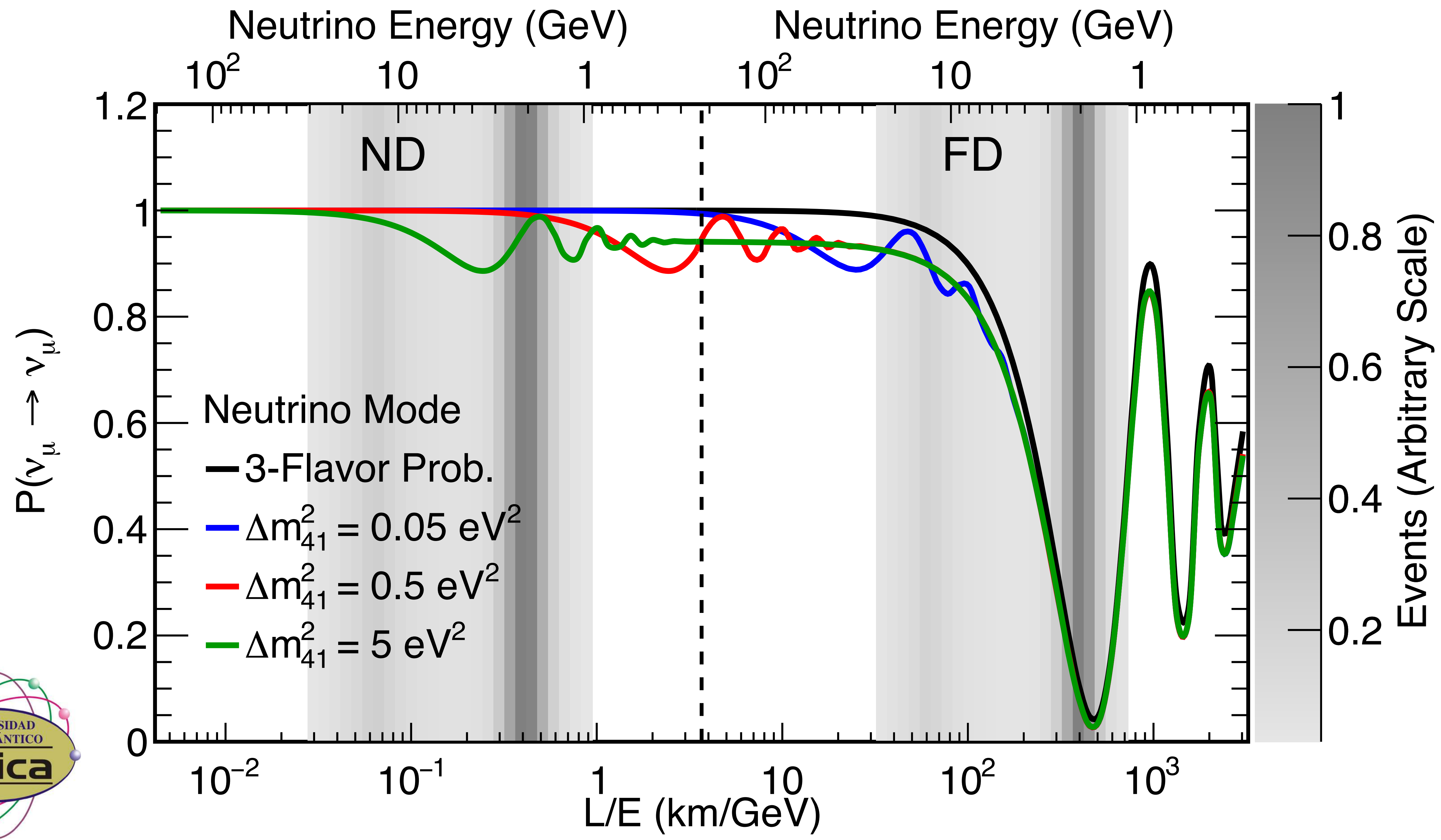
Additional (sterile) neutrinos

The effects of on the neutrino oscillation

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

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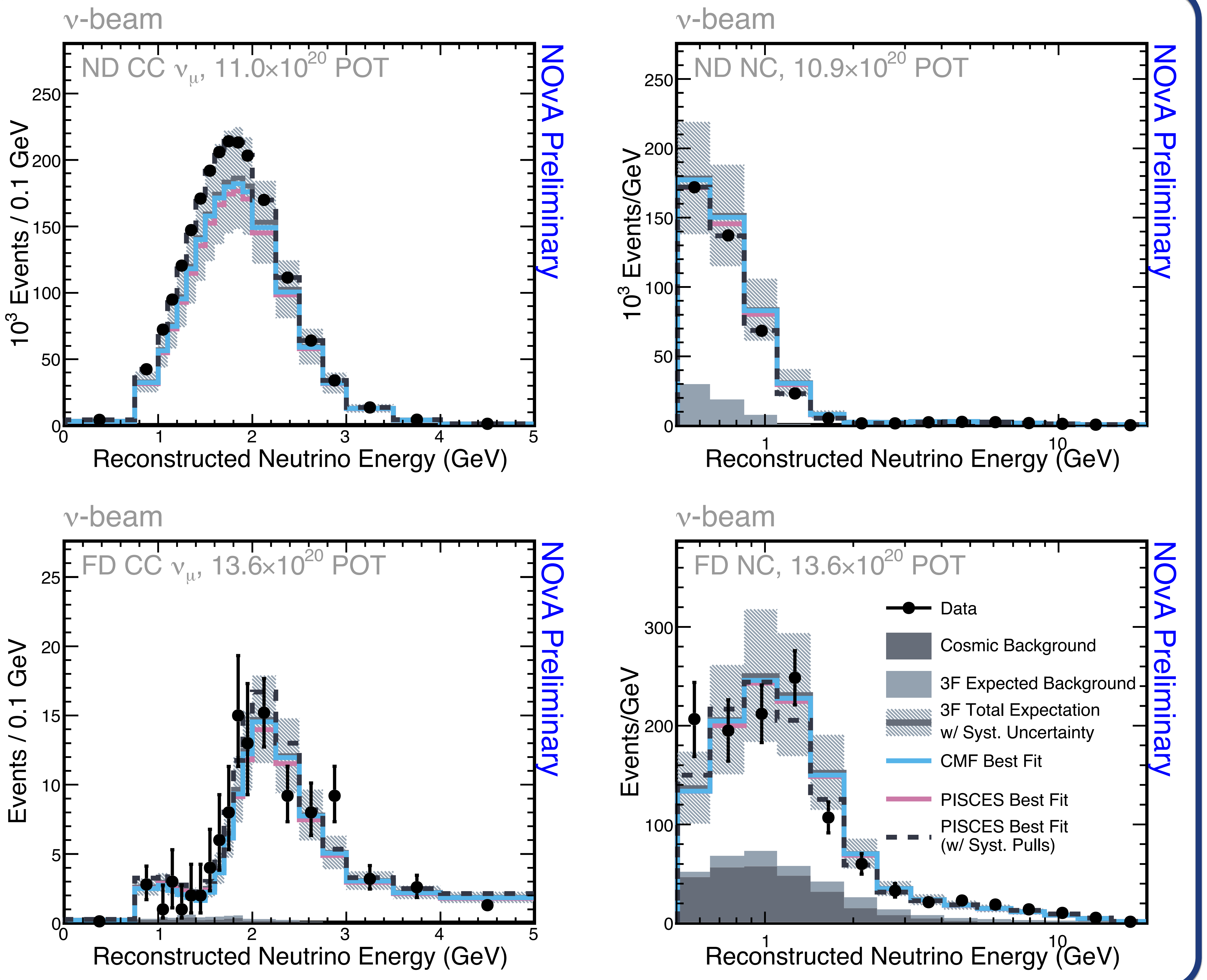
Sterile neutrino Spectra

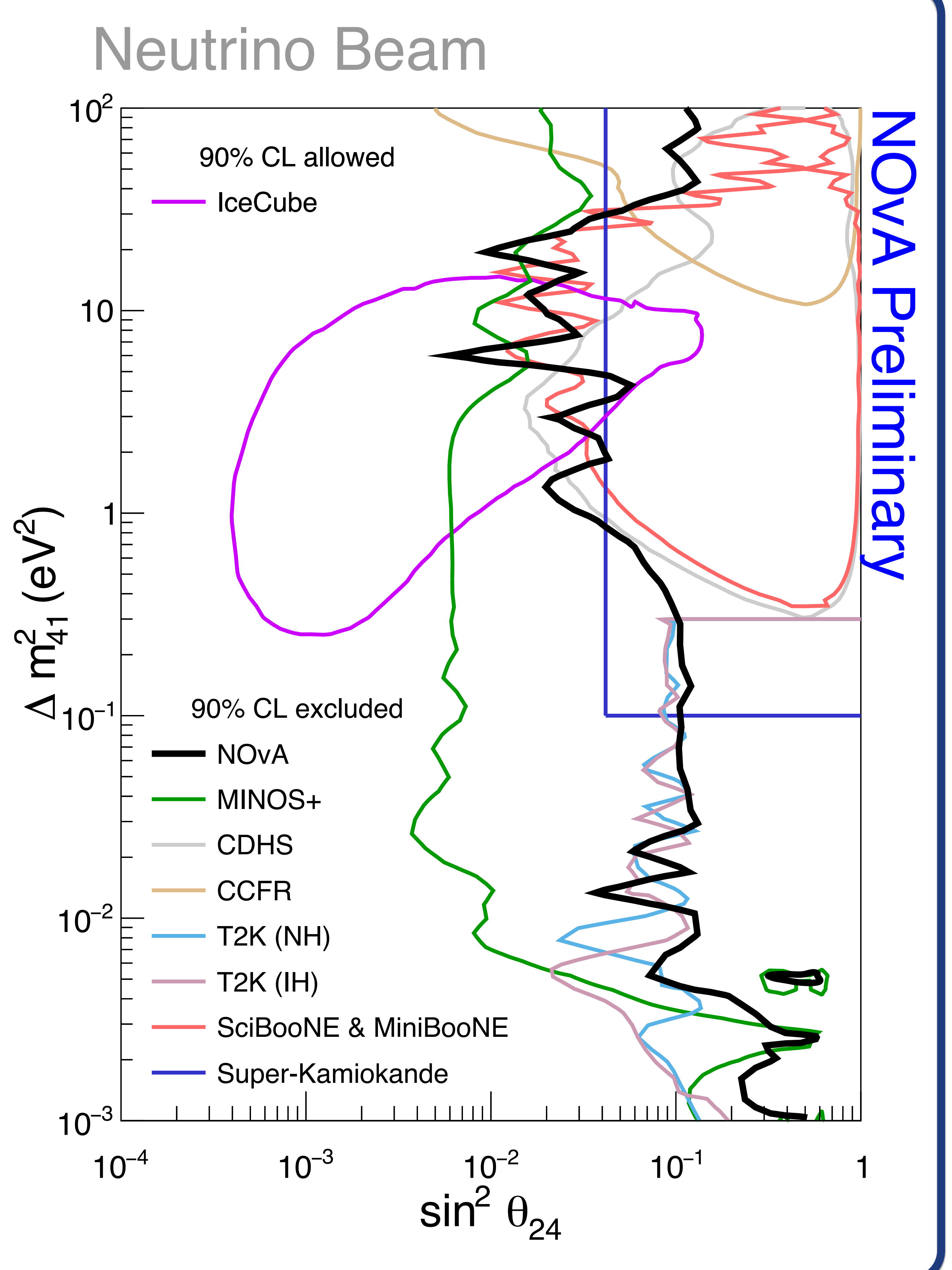
The results



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

Sterile neutrino parameters

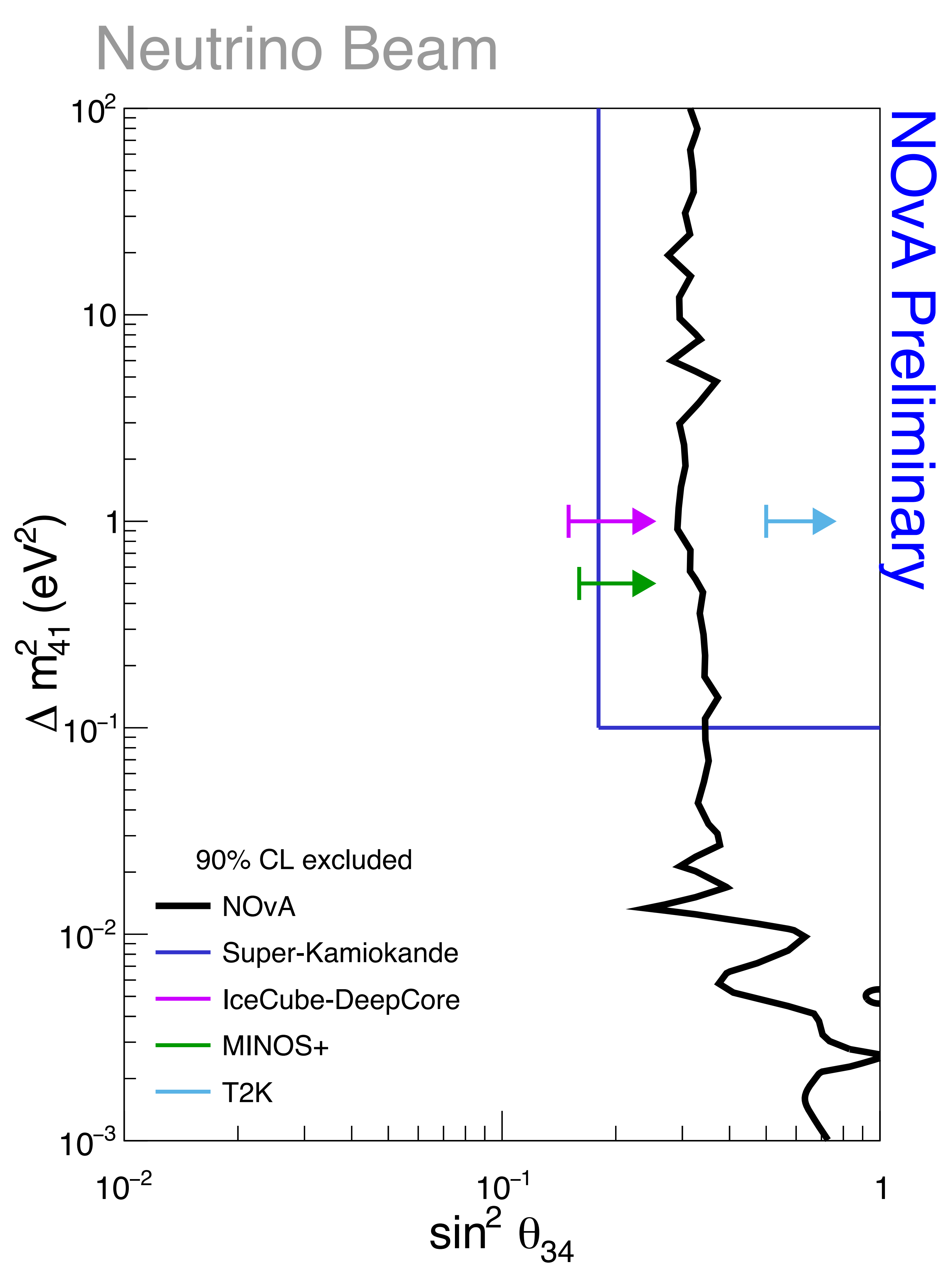
The results



90% CL critical values corrected using Profiled Feldman Cousins approach

Competitive limits on θ_{24} in the high Δm_{41}^2 regime

World-leading limits for θ_{34} as a function of Δm_{41}^2



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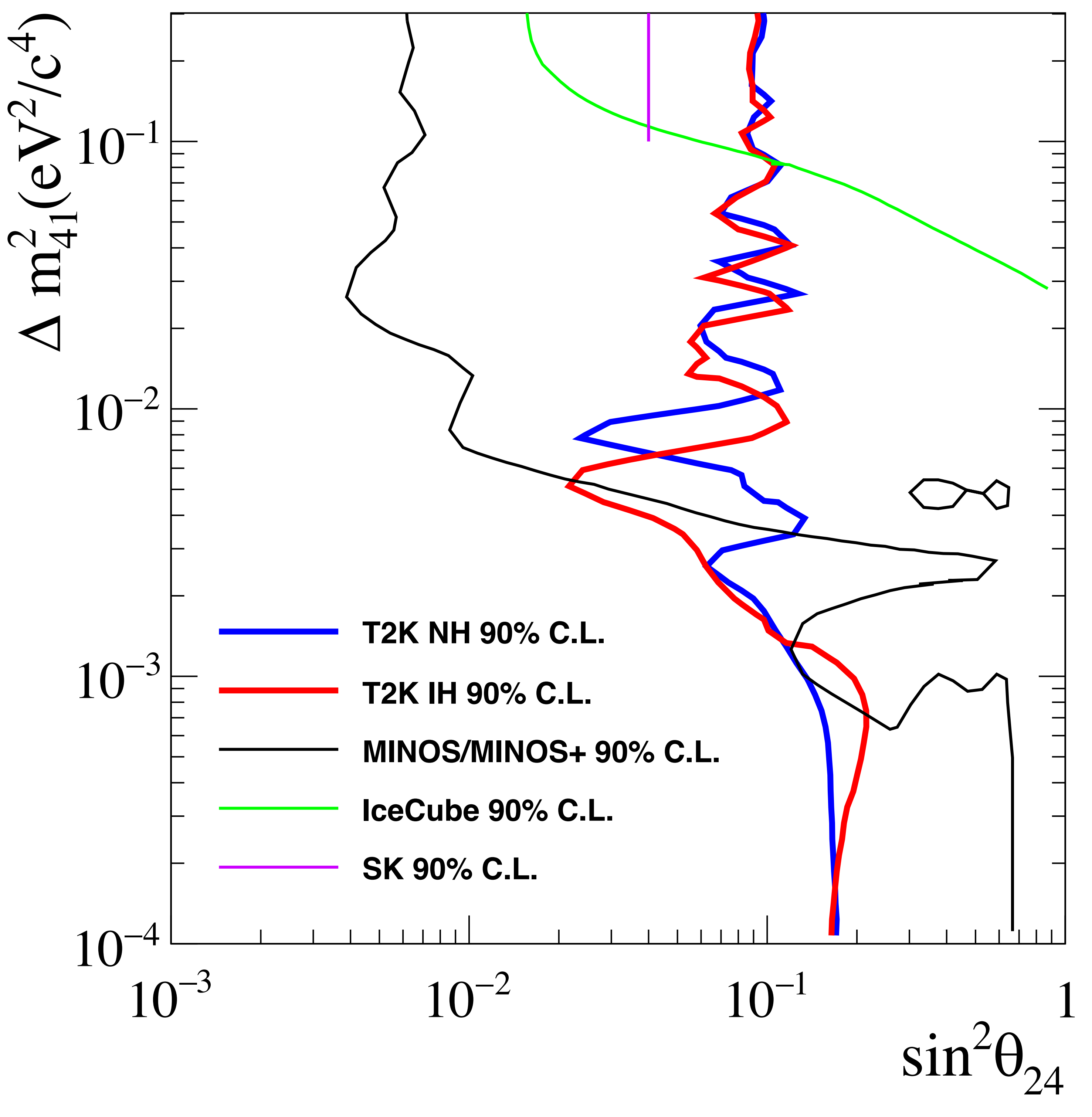
Sterile neutrino parameters

The results

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

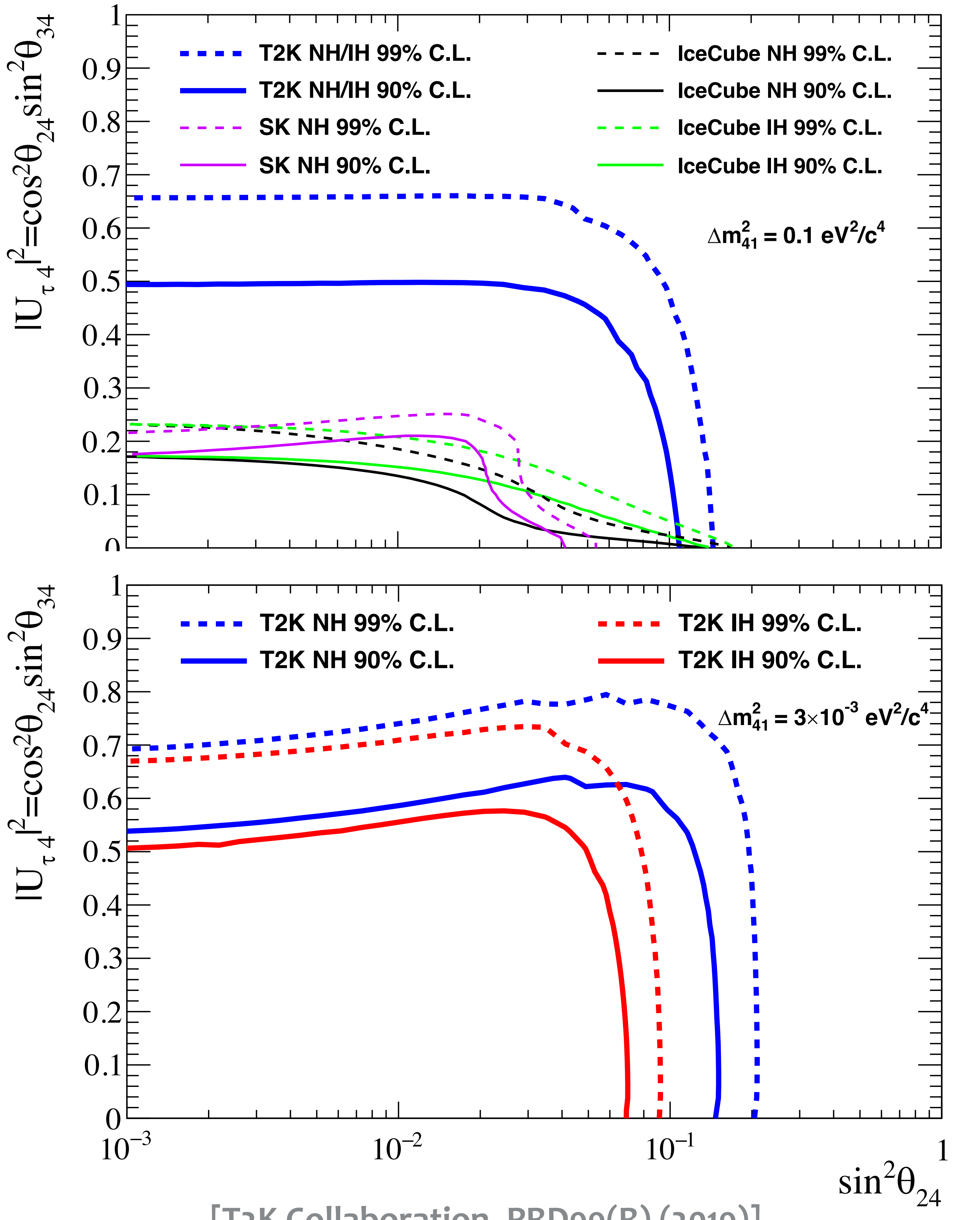


No evidence of ν_s mixing in a 3+1 model

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

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

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



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

NON-STANDARD NEUTRINO OSCILLATIONS

Additional neutrinos – Additional interactions

Heavy Neutrinos

Phenomenology and Results

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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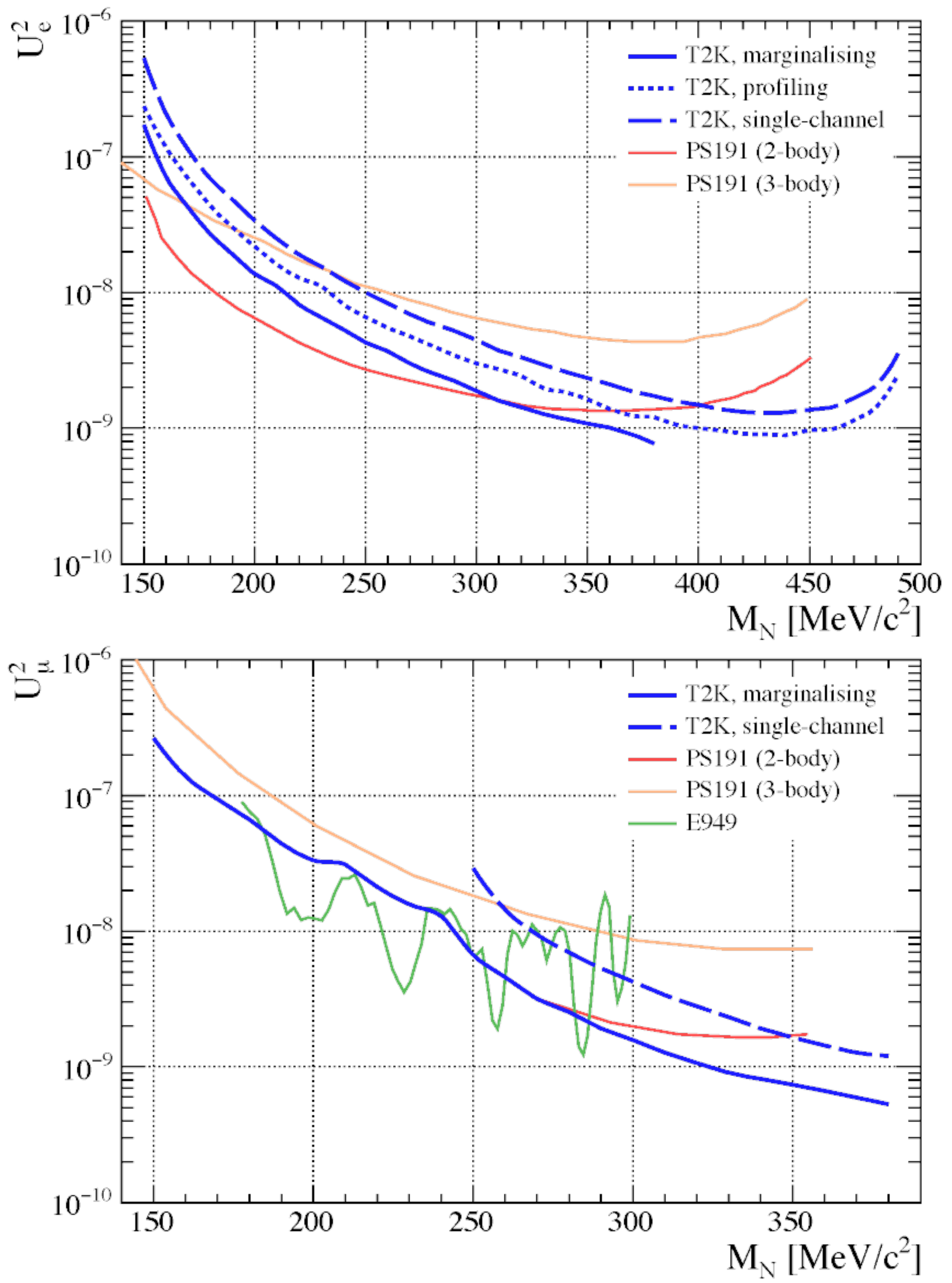
Heavy neutrinos

The results

[T2K Collaboration, PRD100 (2019)]



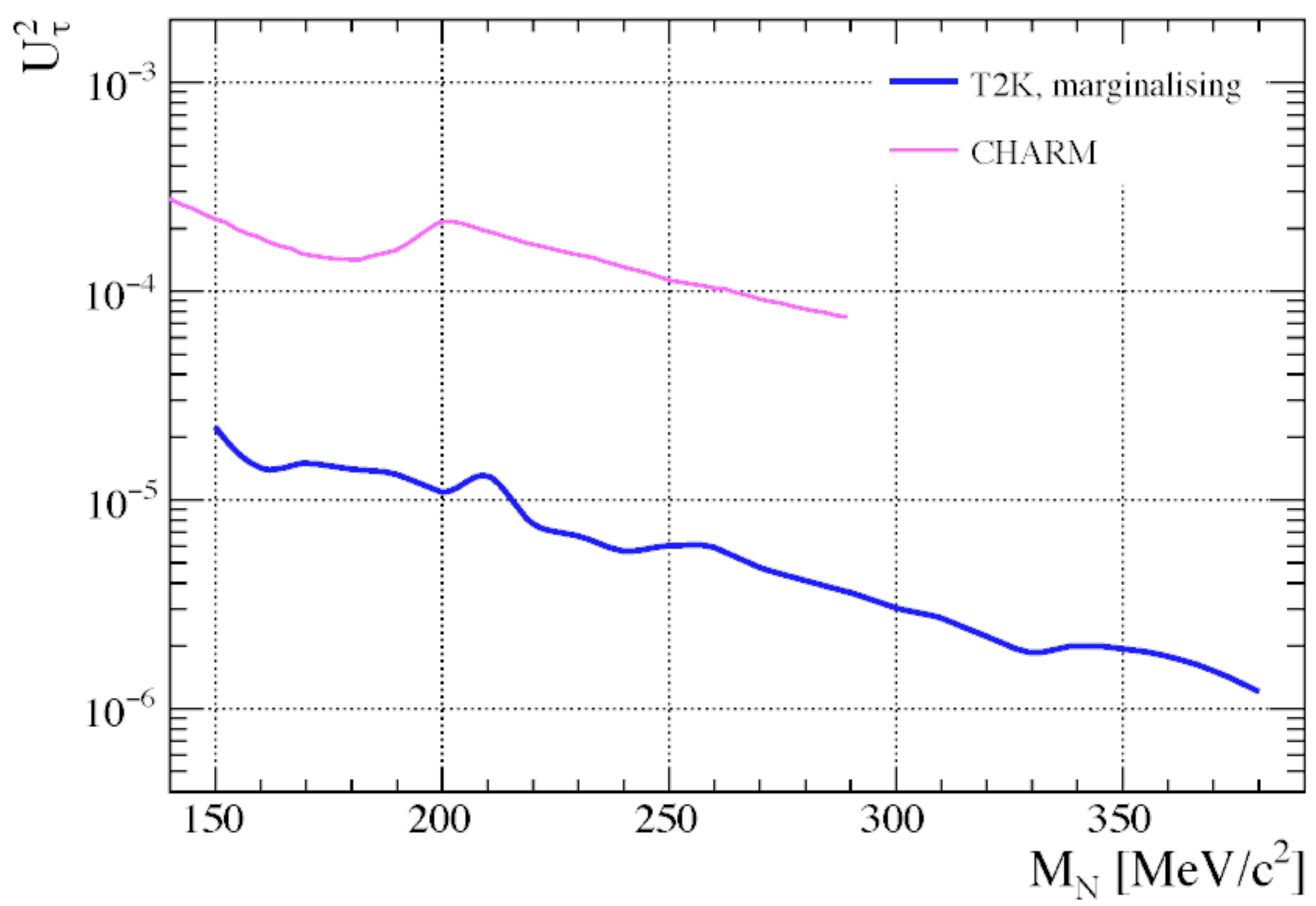
Search for heavy neutrinos
(decaying in the ND280)

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

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

No excess of events was observed

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



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

[T2K Collaboration, PRD100 (2019)]

NON-STANDARD NEUTRINO OSCILLATIONS

Additional neutrinos – Additional interactions

Non-Standard Interactions

Phenomenology and Results

Non-Standard Interactions

The motivations and implications

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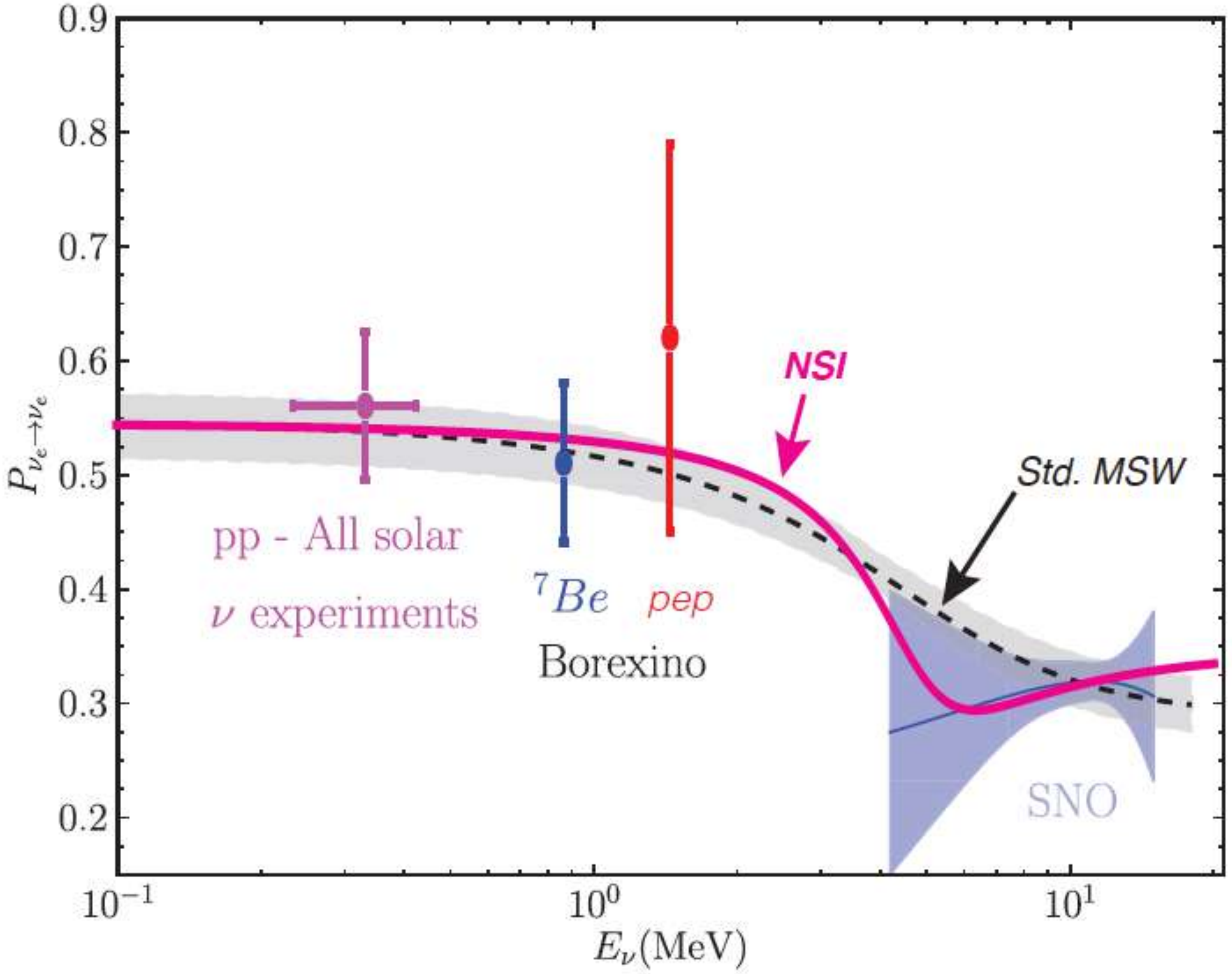
The possible existence of NSI implies a modification of neutrino propagation…

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

… 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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Non-Standard Interactions

The effects of on oscillation probability

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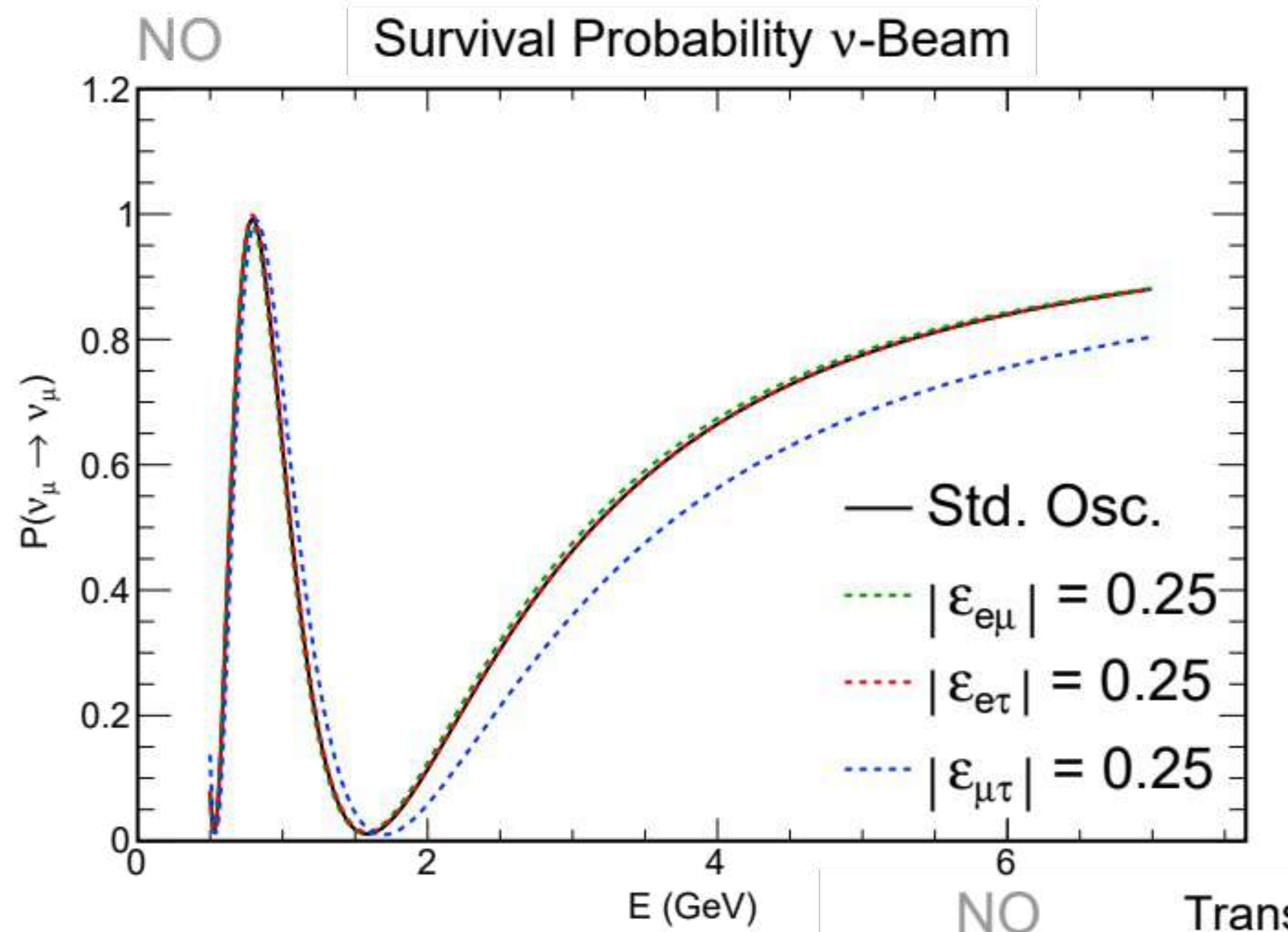
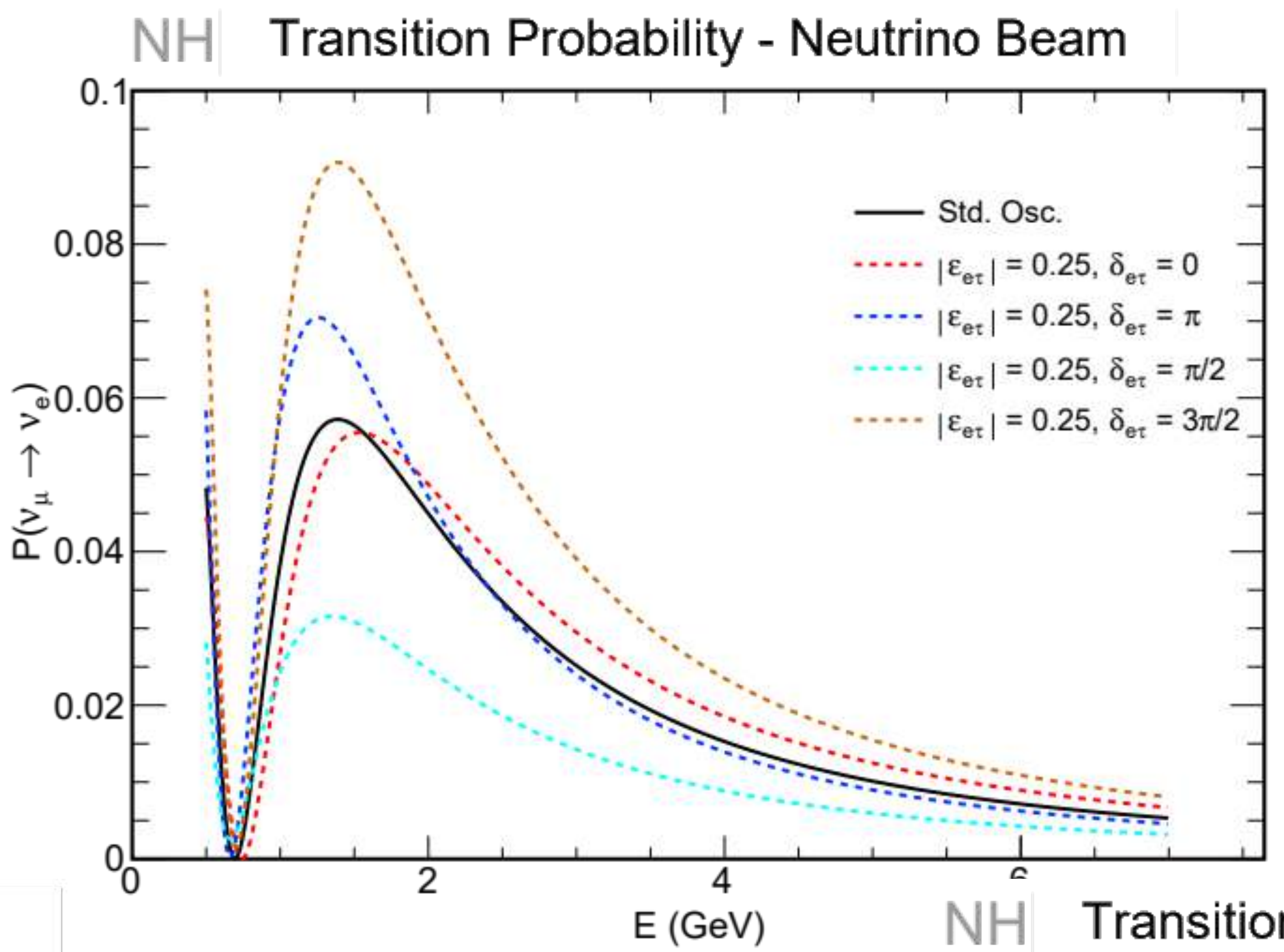
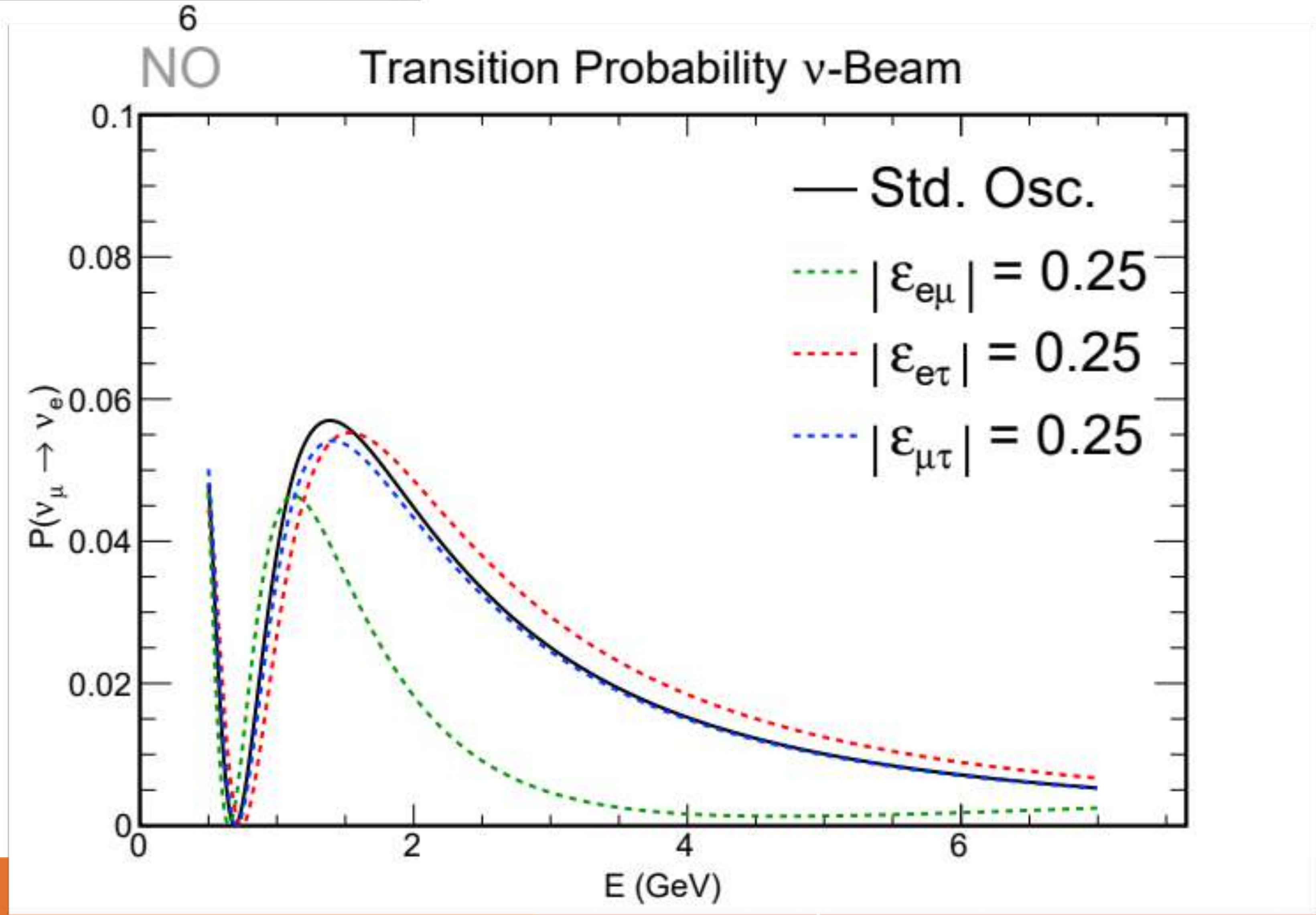
… With visible effects on the oscillation probability.

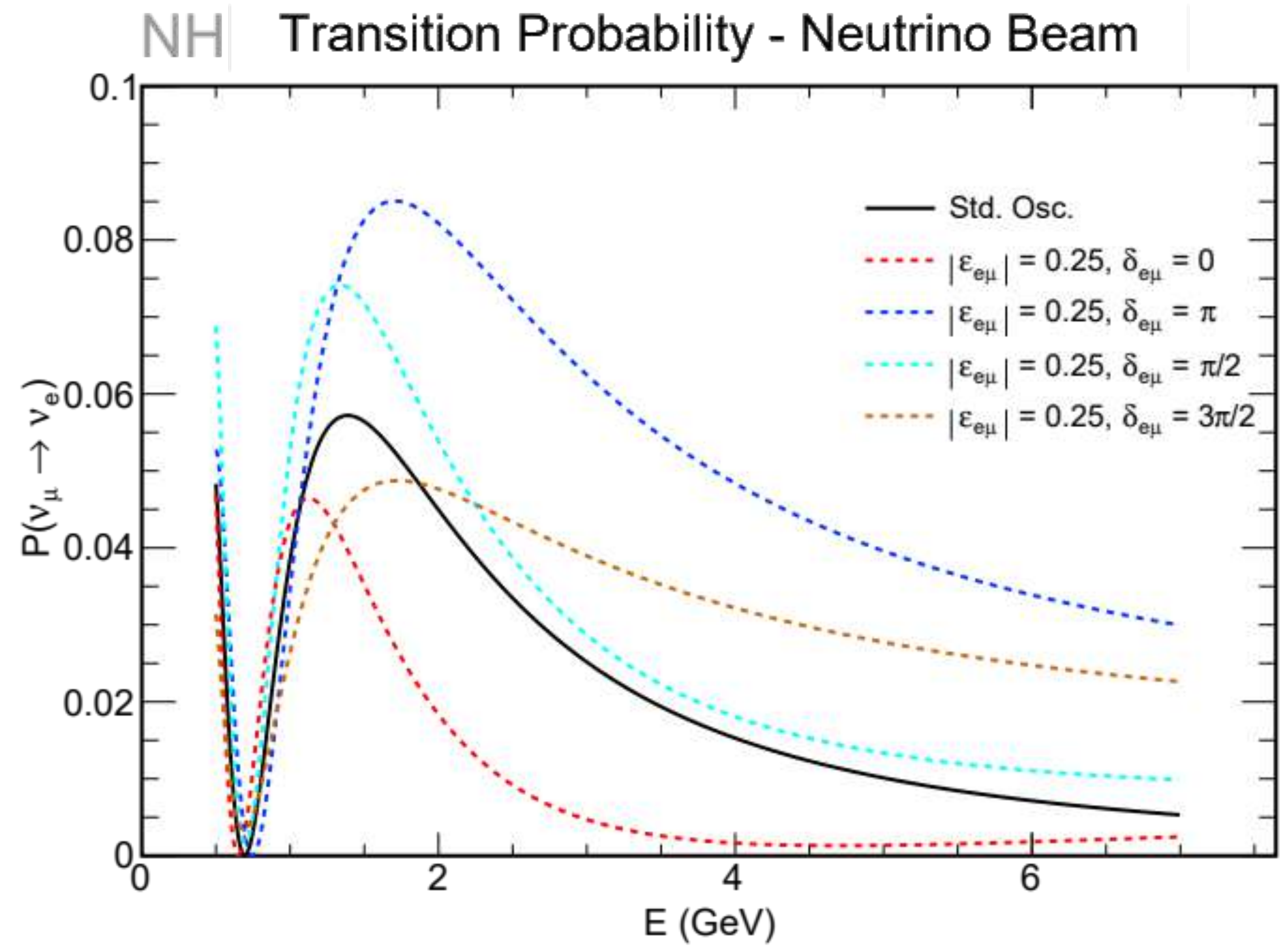




And here the changes generated by the NSI **phase**

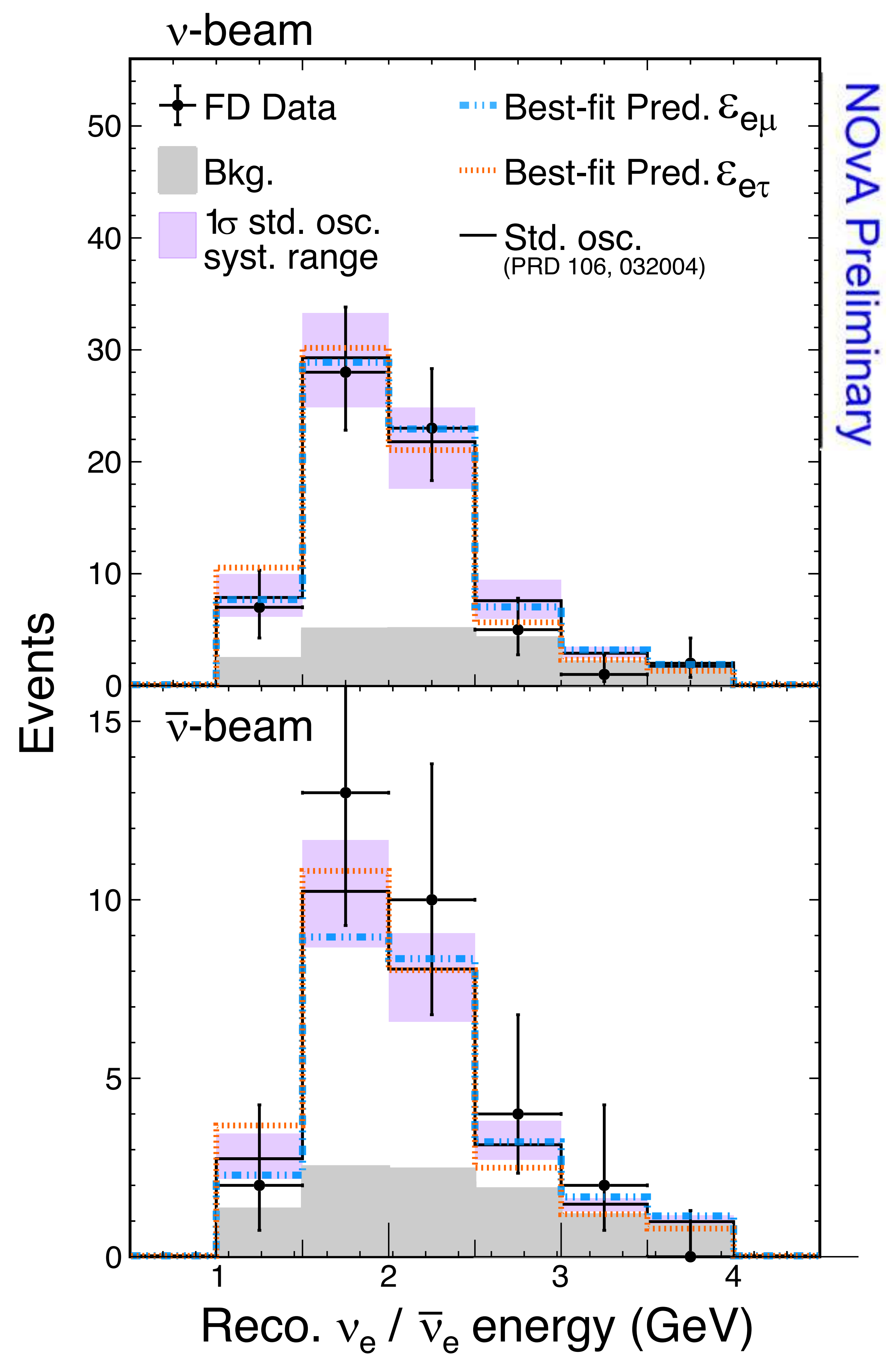
Here, changes from the **norm** of the NSI parameter





NSI – eμ and eτ Spectra

The results

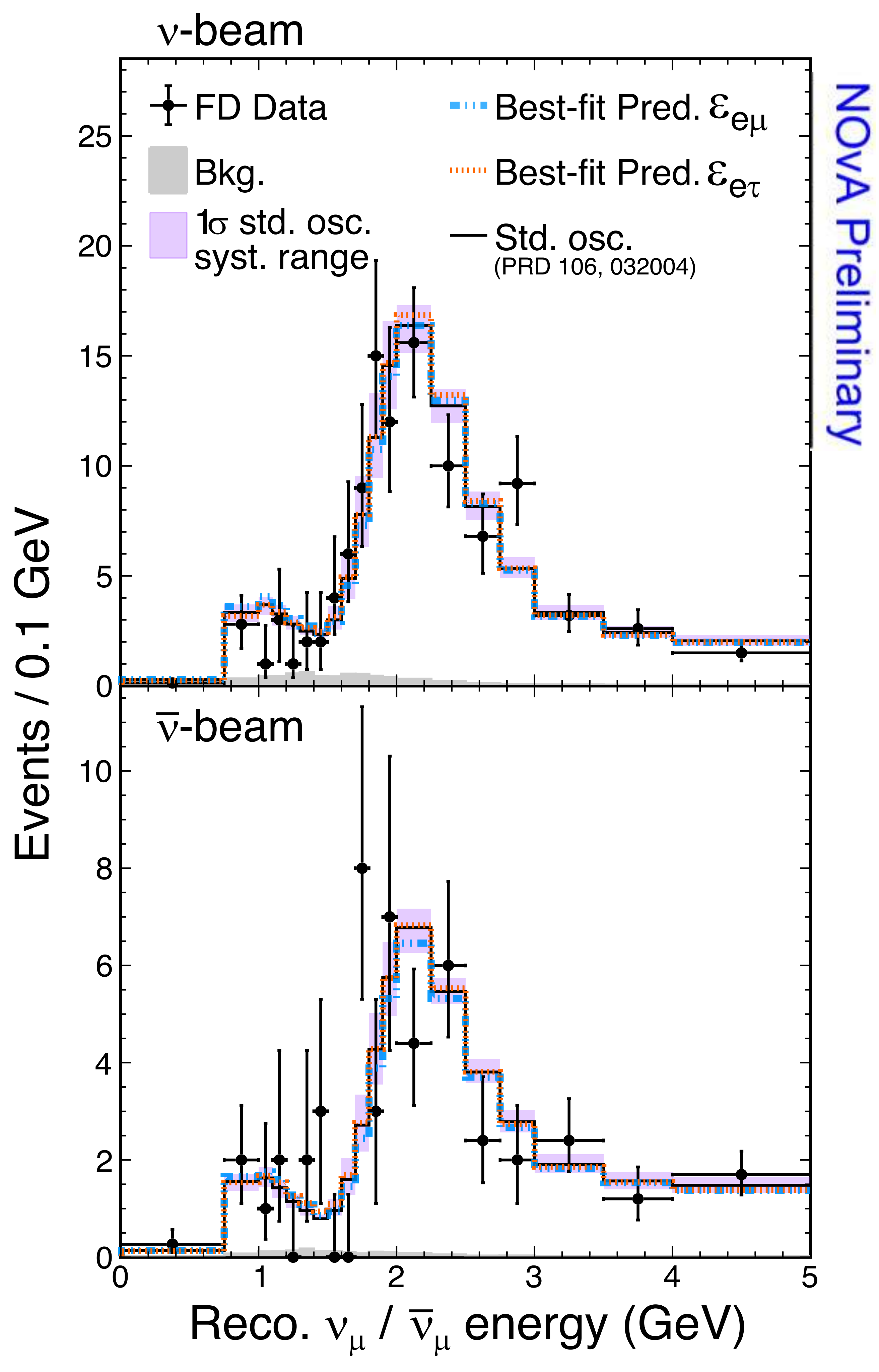


NSI not needed to explain NOvA spectra.

Muon (anti)neutrinos

Electron (anti)neutrinos

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



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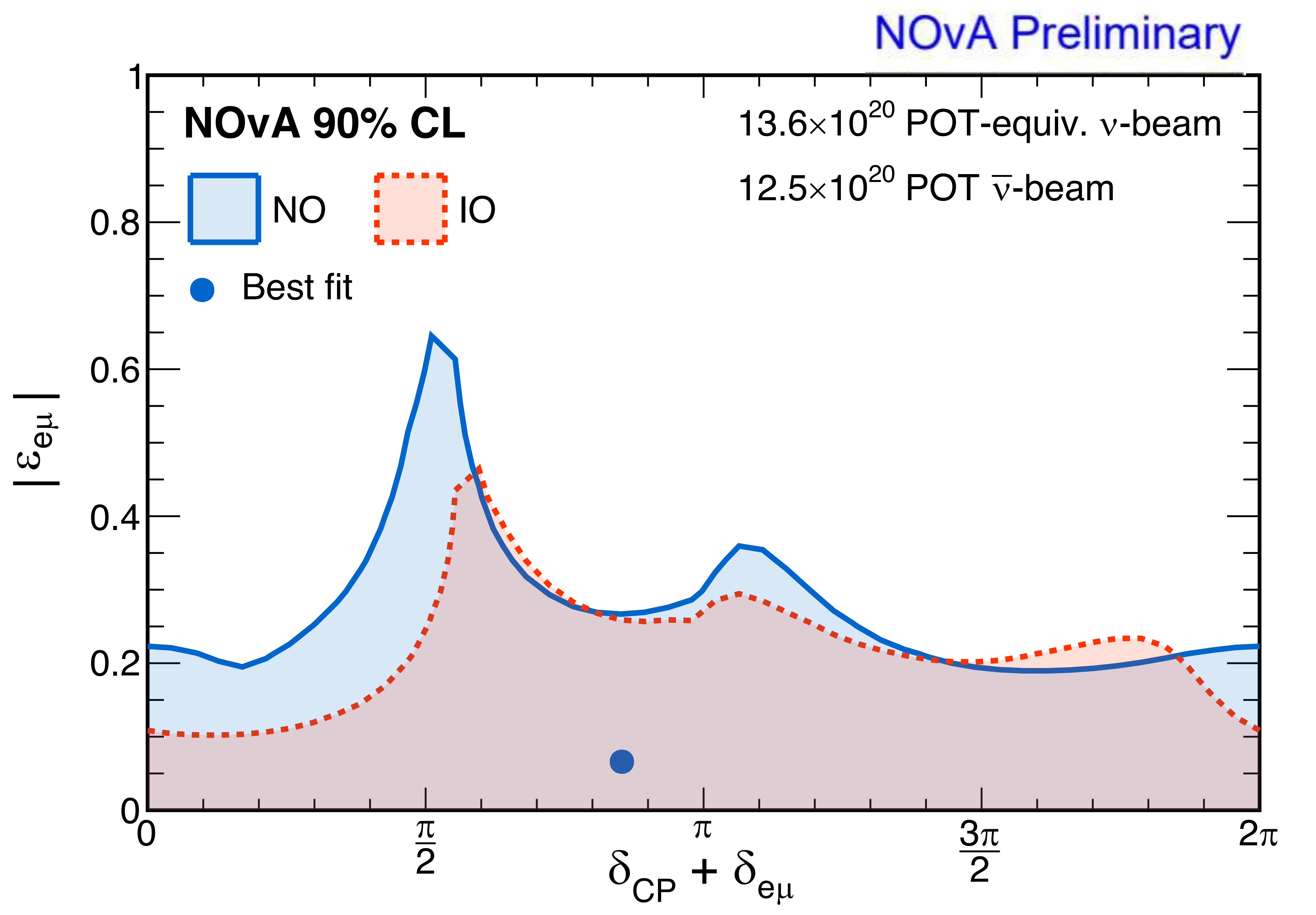
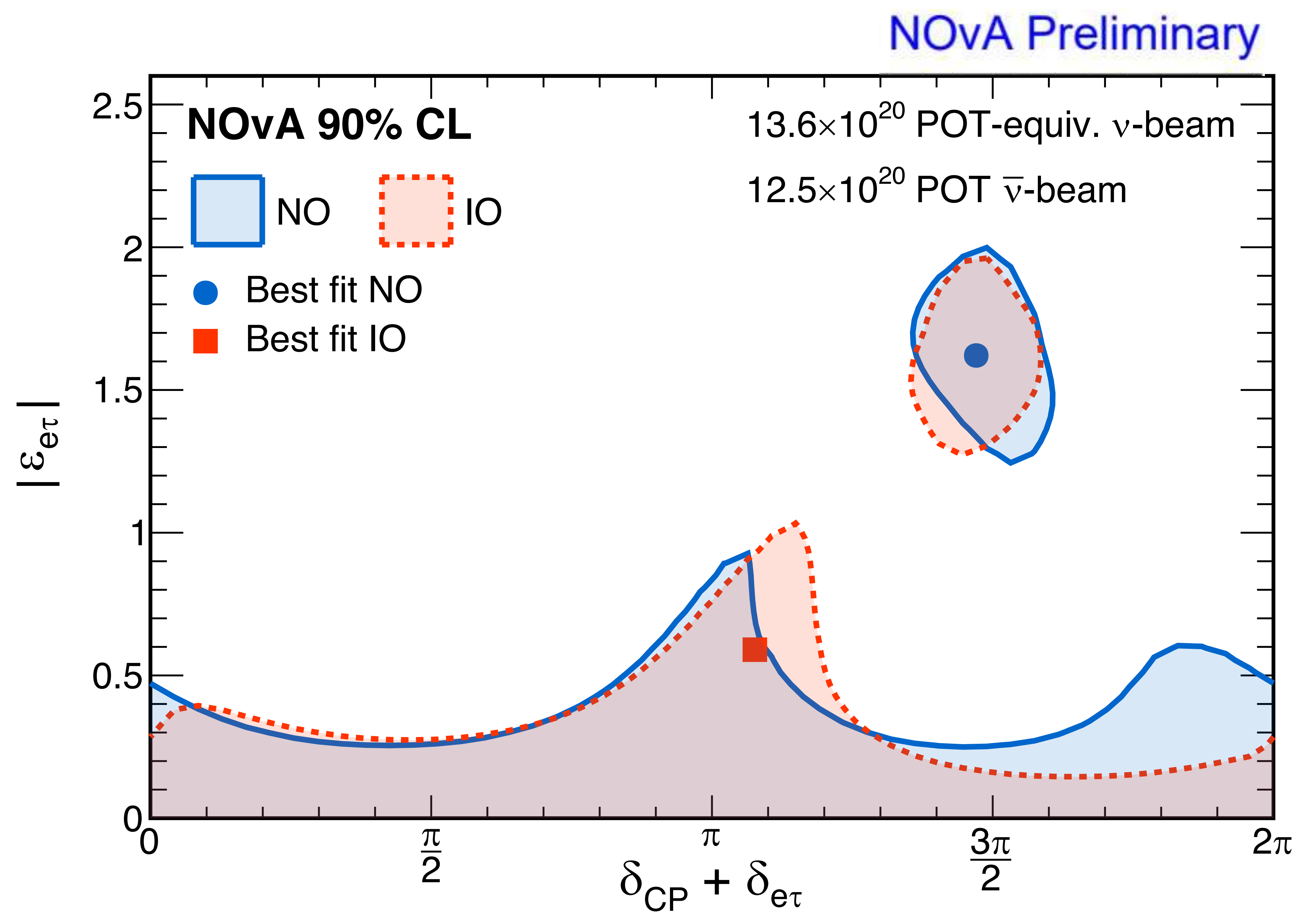
NSI – eμ and eτ Constraints

The results



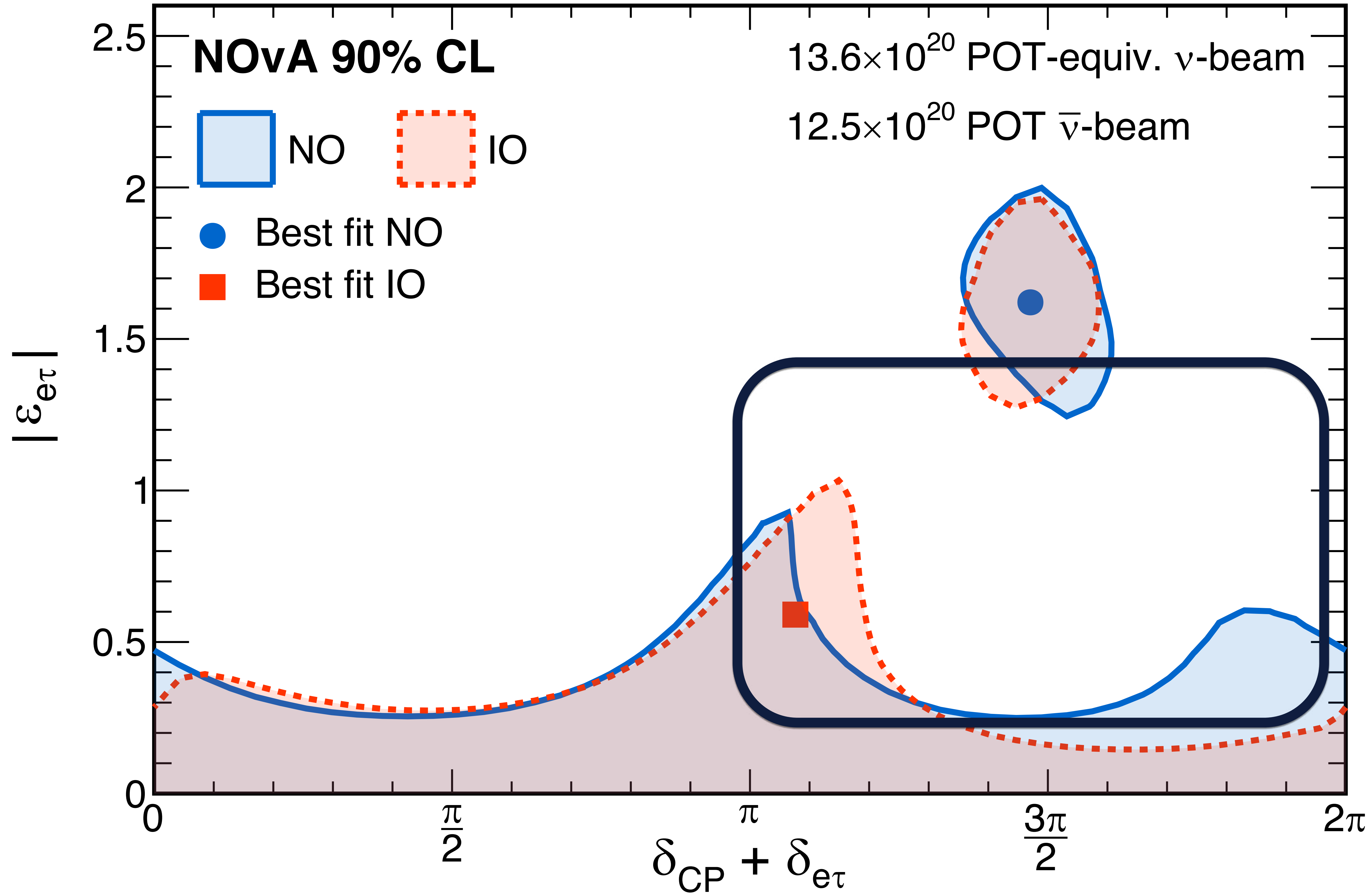
$$|\varepsilon_{e\mu}| \lesssim 0.3$$

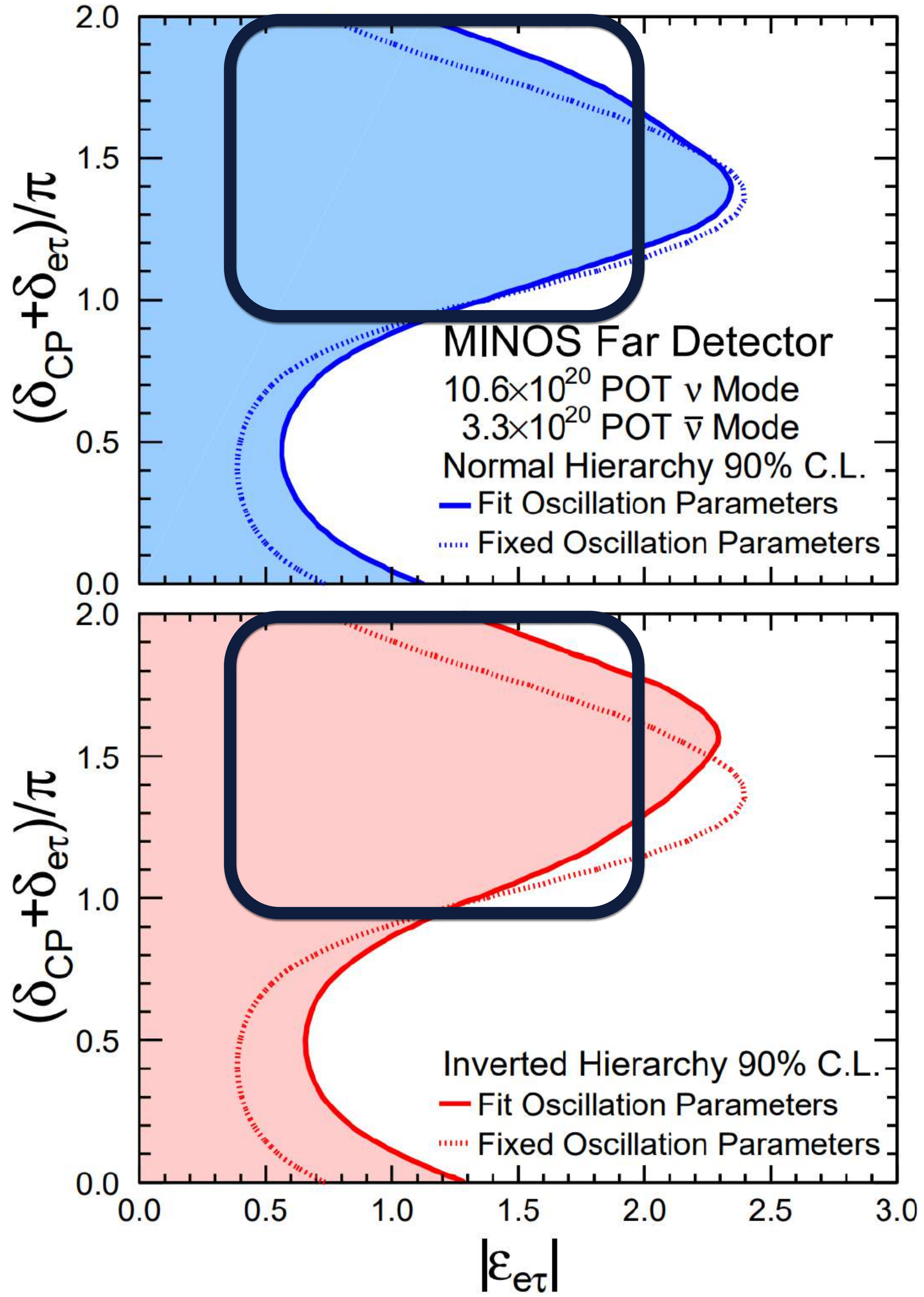


$$|\varepsilon_{e\tau}| \lesssim 0.4$$

eτ Result: Vs. MINOS

The results





[MINOS, PRD95 (2017)]

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More Physics Results

Other than neutrino oscillations

Even more!

The results

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

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

And several cross-section measurements

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)]

Conclusions

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- Rich physics research at and great results from both, **NOvA** and **T2K**, beyond standard neutrino oscillations.
- No signal of sterile neutrinos observed by T2K or NOvA.
- NOvA spectra do not need NSI.
- No signals from heavy neutrinos observed by T2K.
- Amazing potential for exploring BSM physics, too.

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THANKS!

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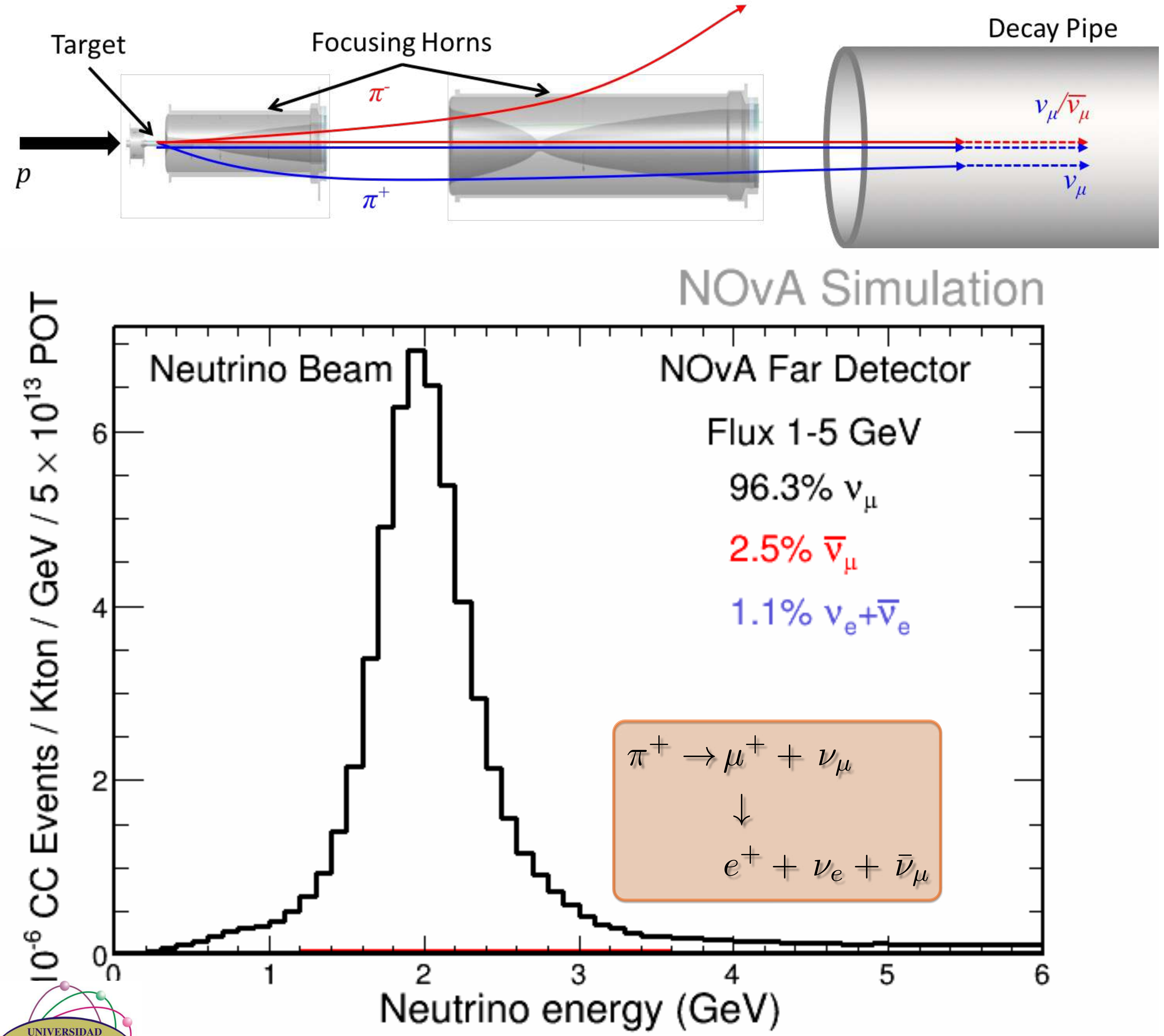
2019 -2023

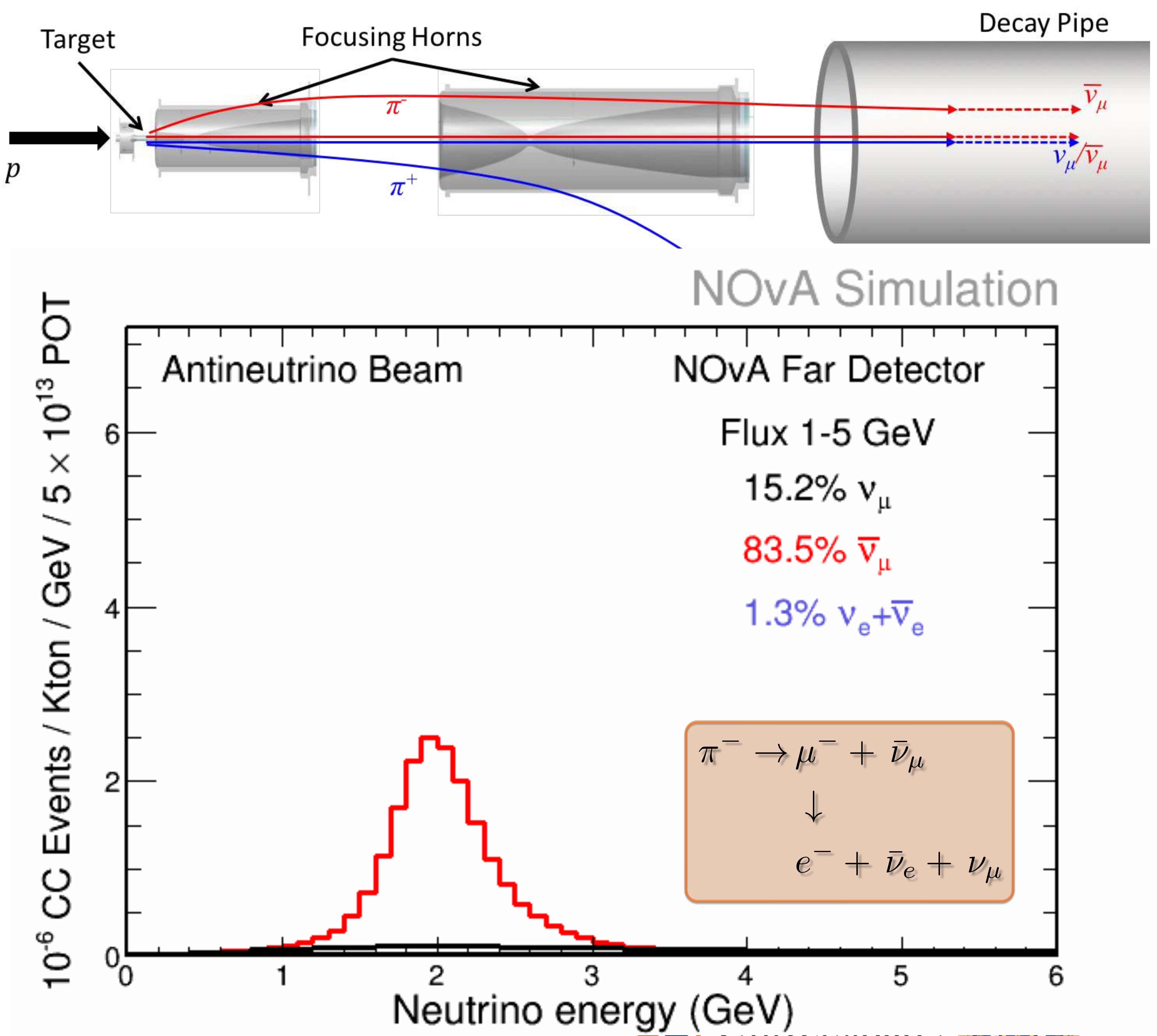
Backup Slides

Additional information

NOvA

Neutrinos from NuMI beam





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NOvA

The Detectors

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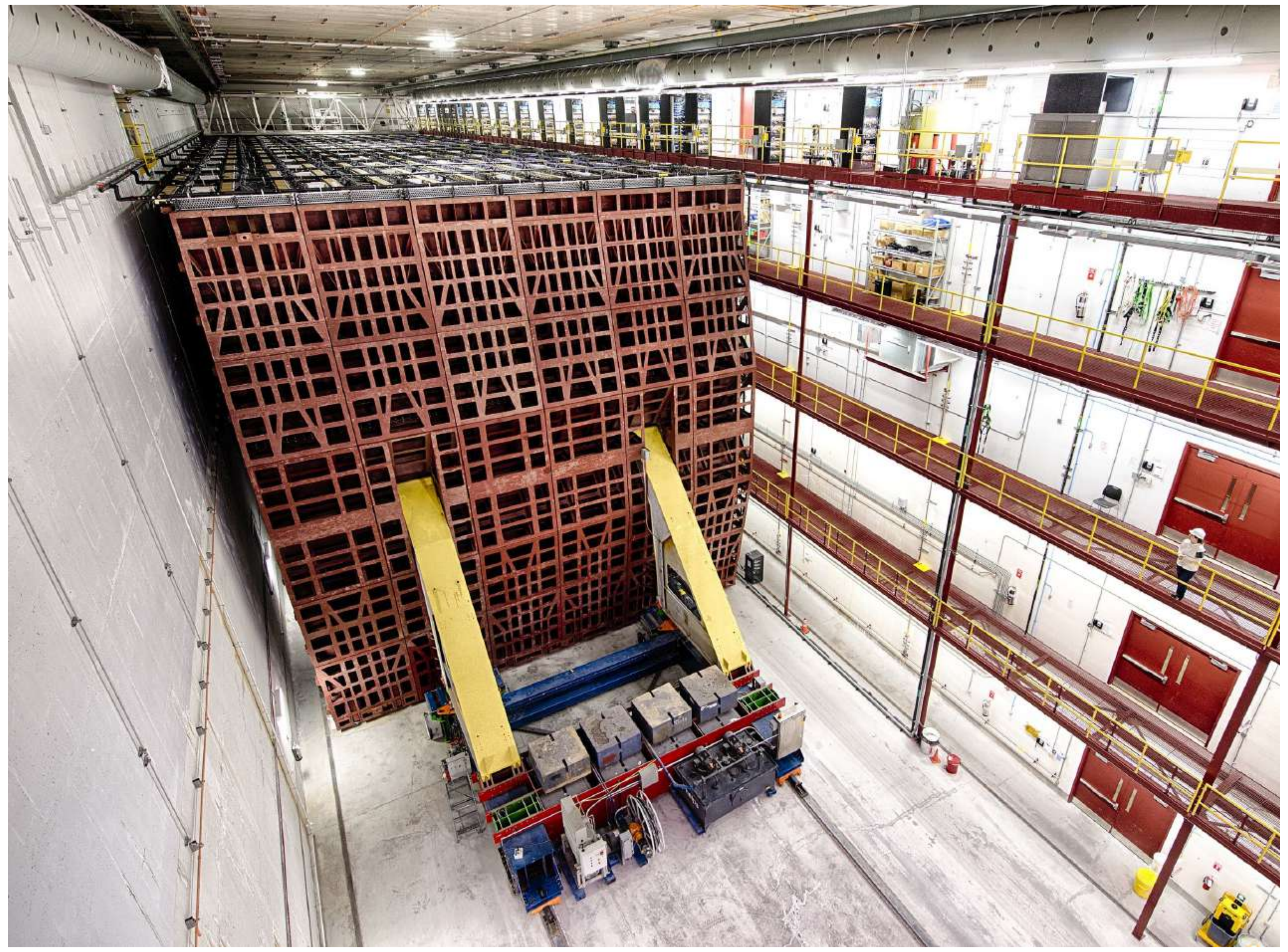

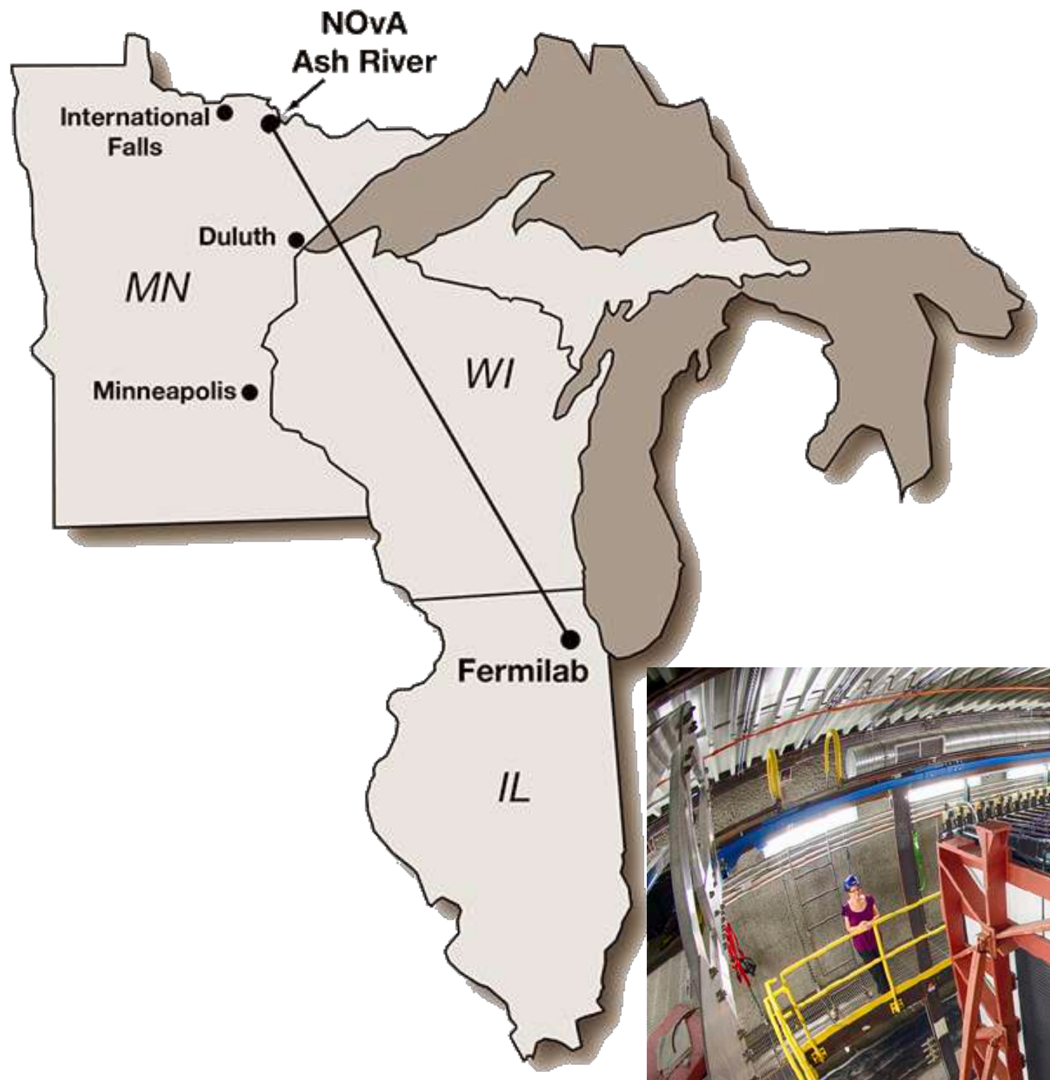

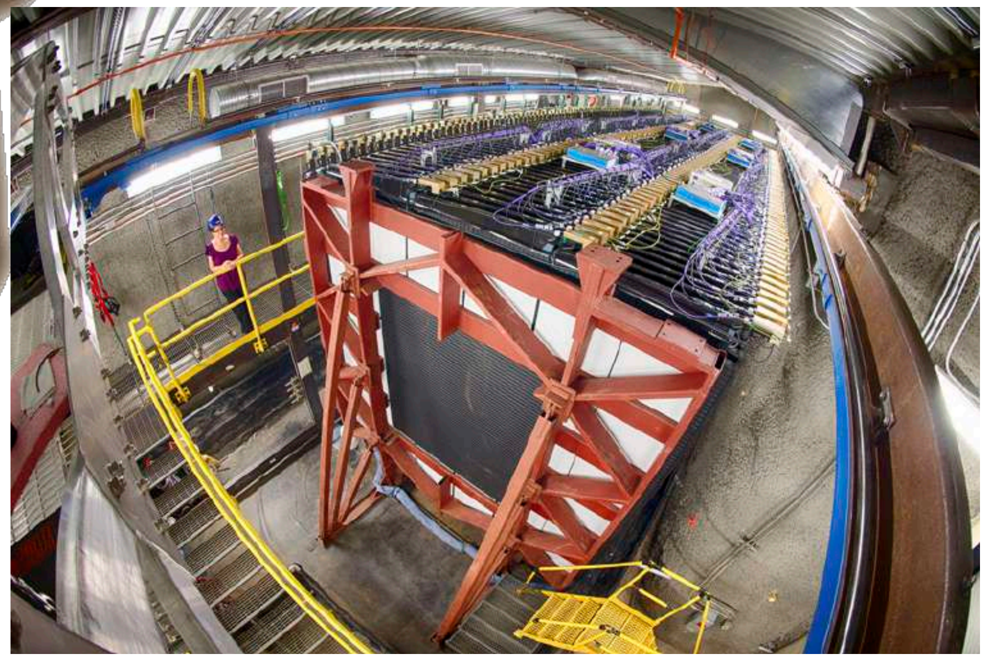

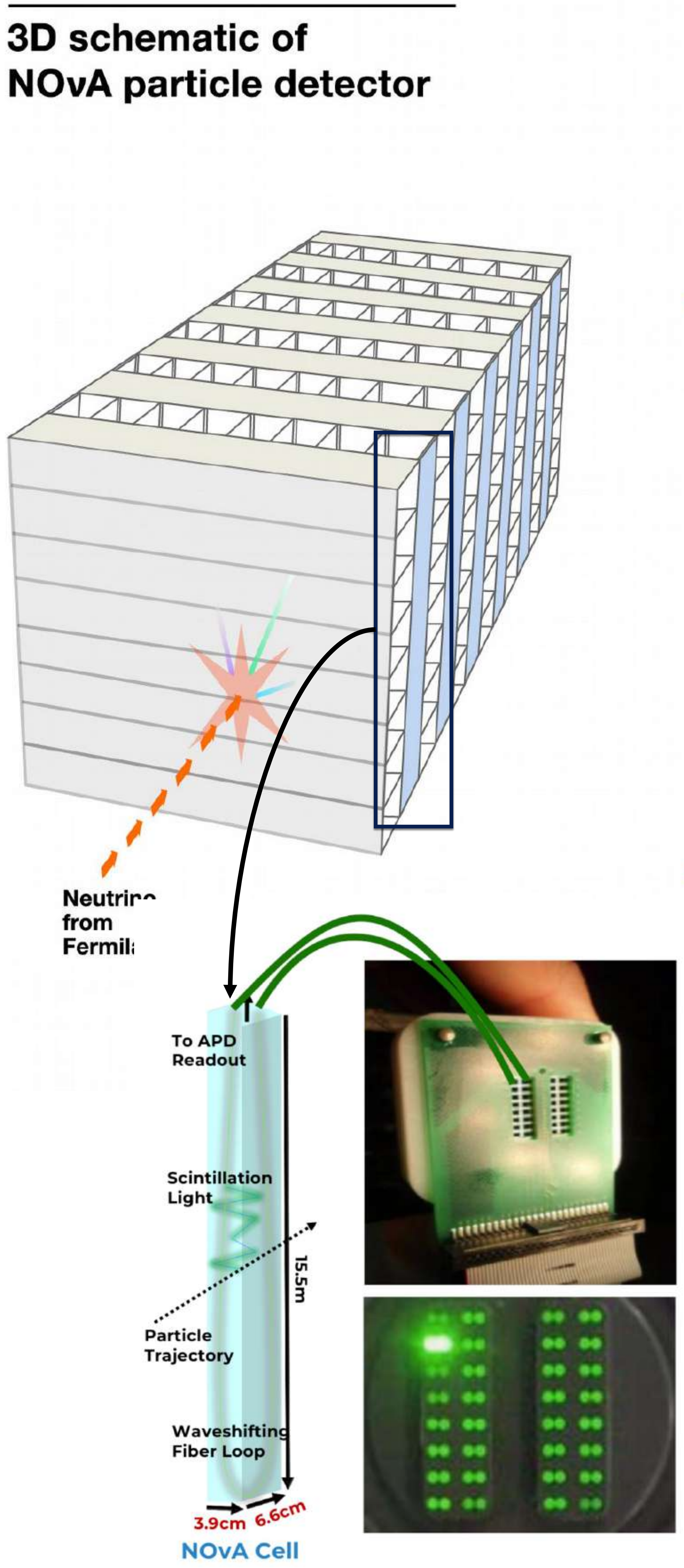

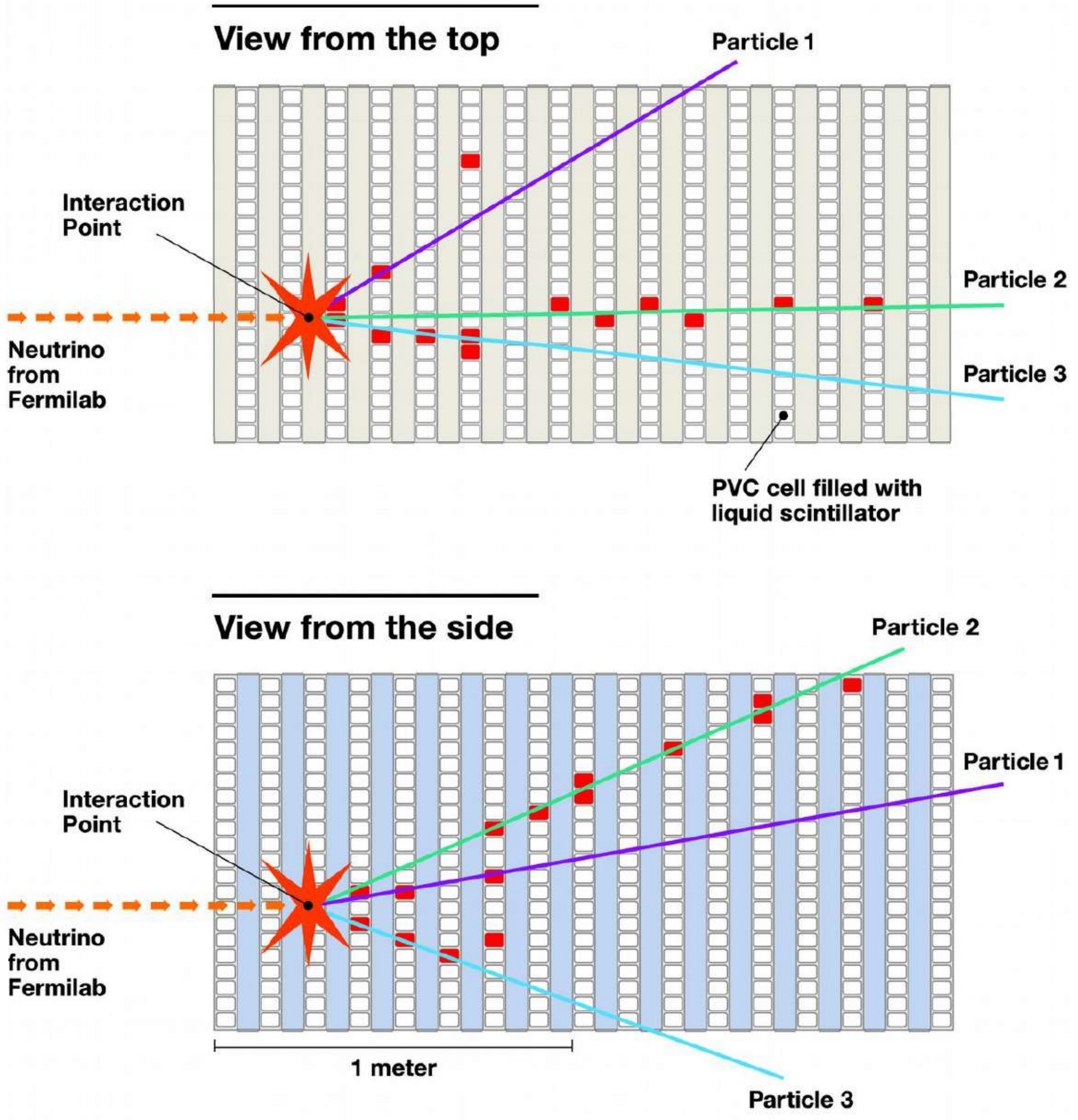

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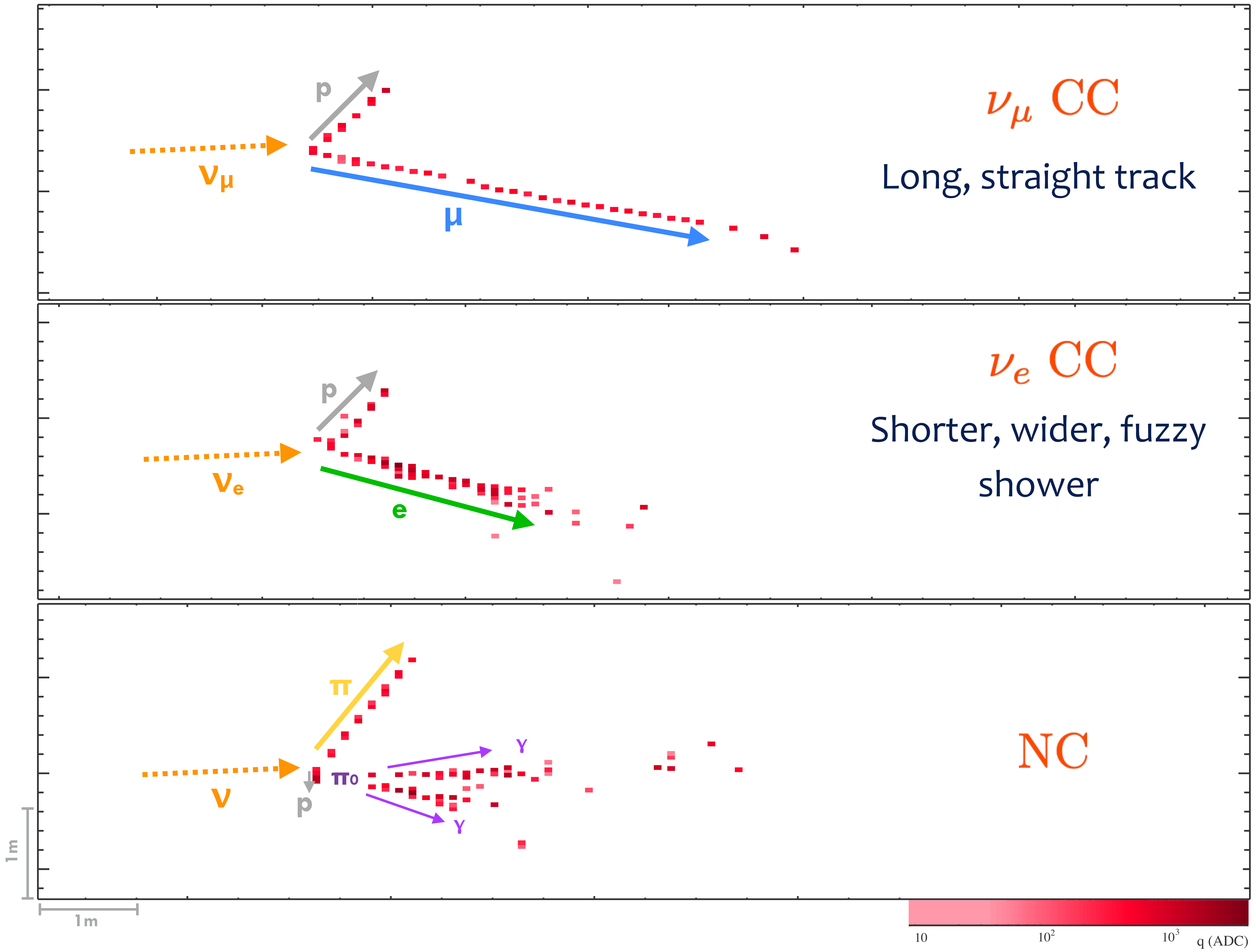
Events selection

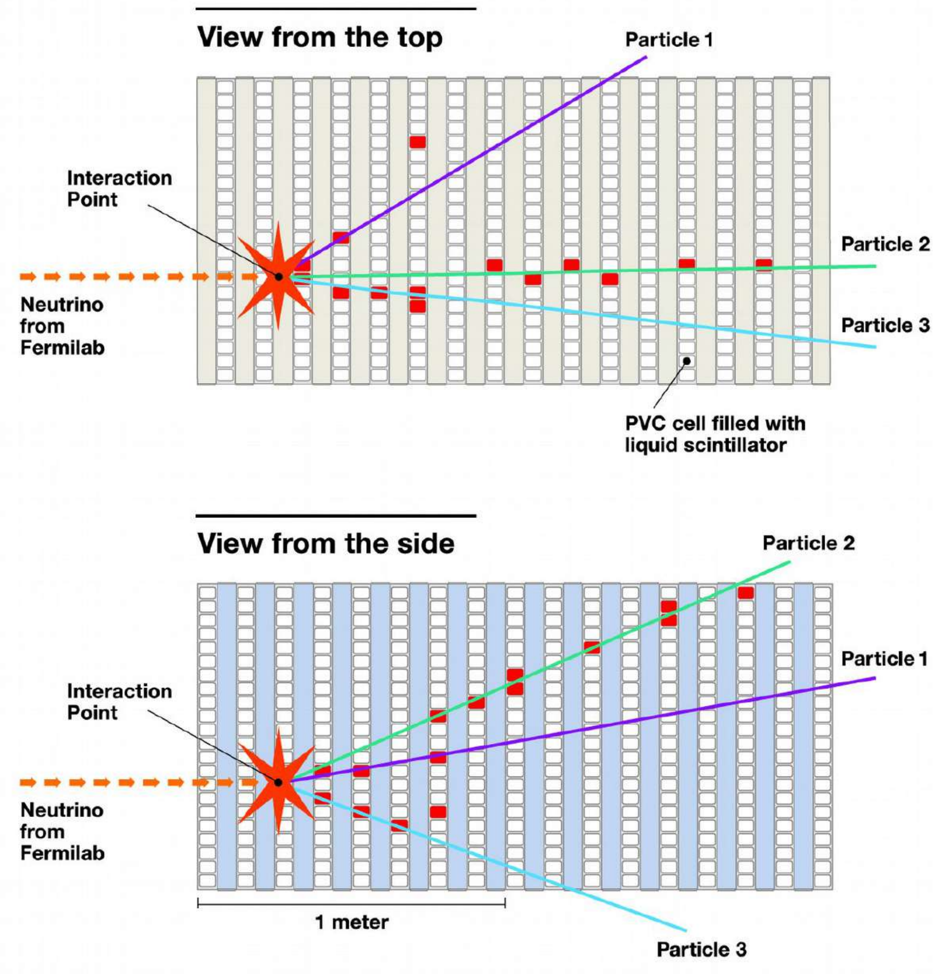
Some details

Classification

- We use Deep learning techniques for event selection: Convolutional Neural Network (CNN)
- Apply some cuts (conditions)

  - Contained
  - Track reconstruction
  - Cosmic rejection





For the NSI Analysis

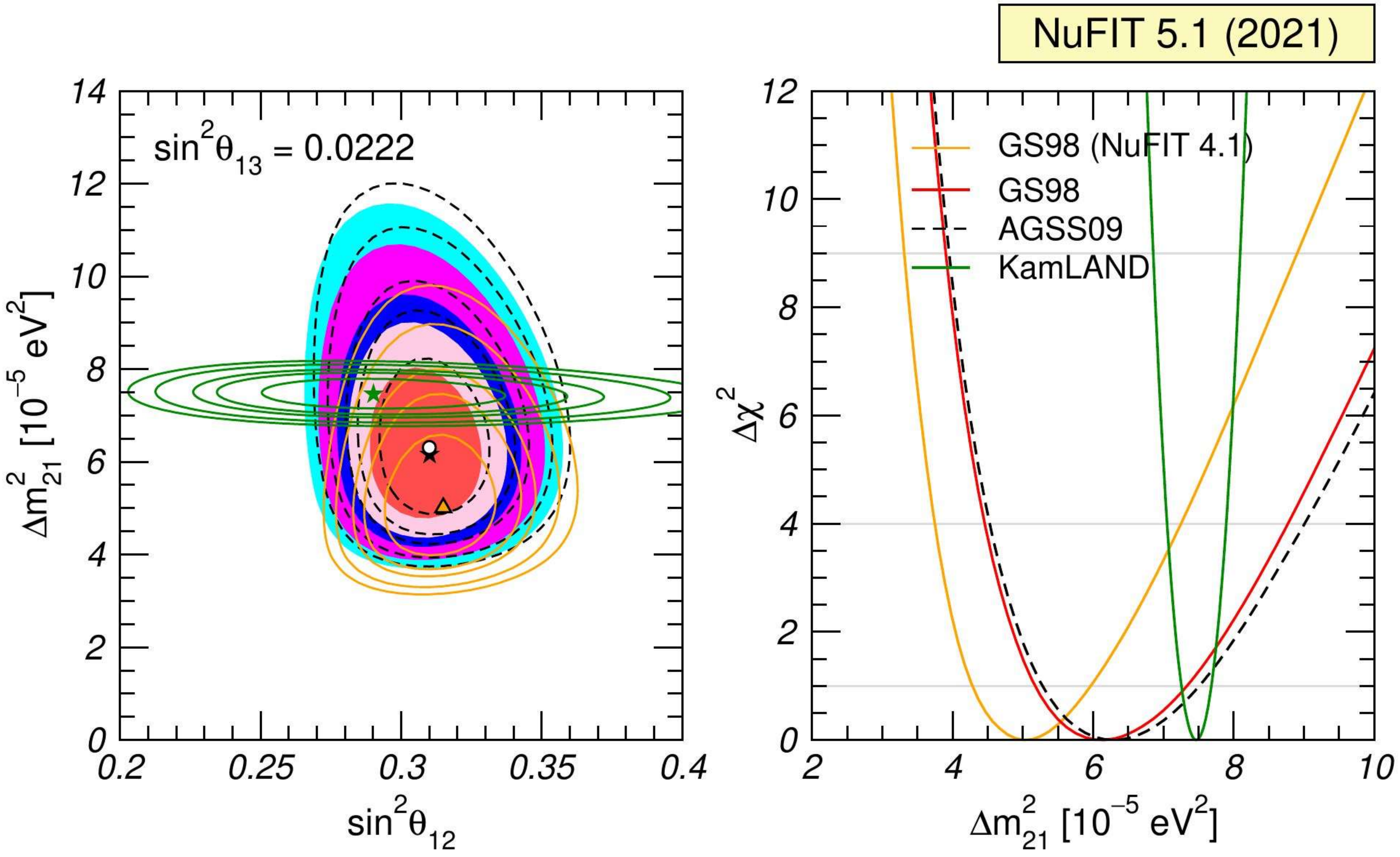
Some important constraints

Backup

Other results matter

- We are insensitive to some oscillation paramenters
  -Use information from other sources: PDG, NuFIT

- Combination of different experiments. But…



[NuFIT5.1, www.nu-fit.org (2012)]

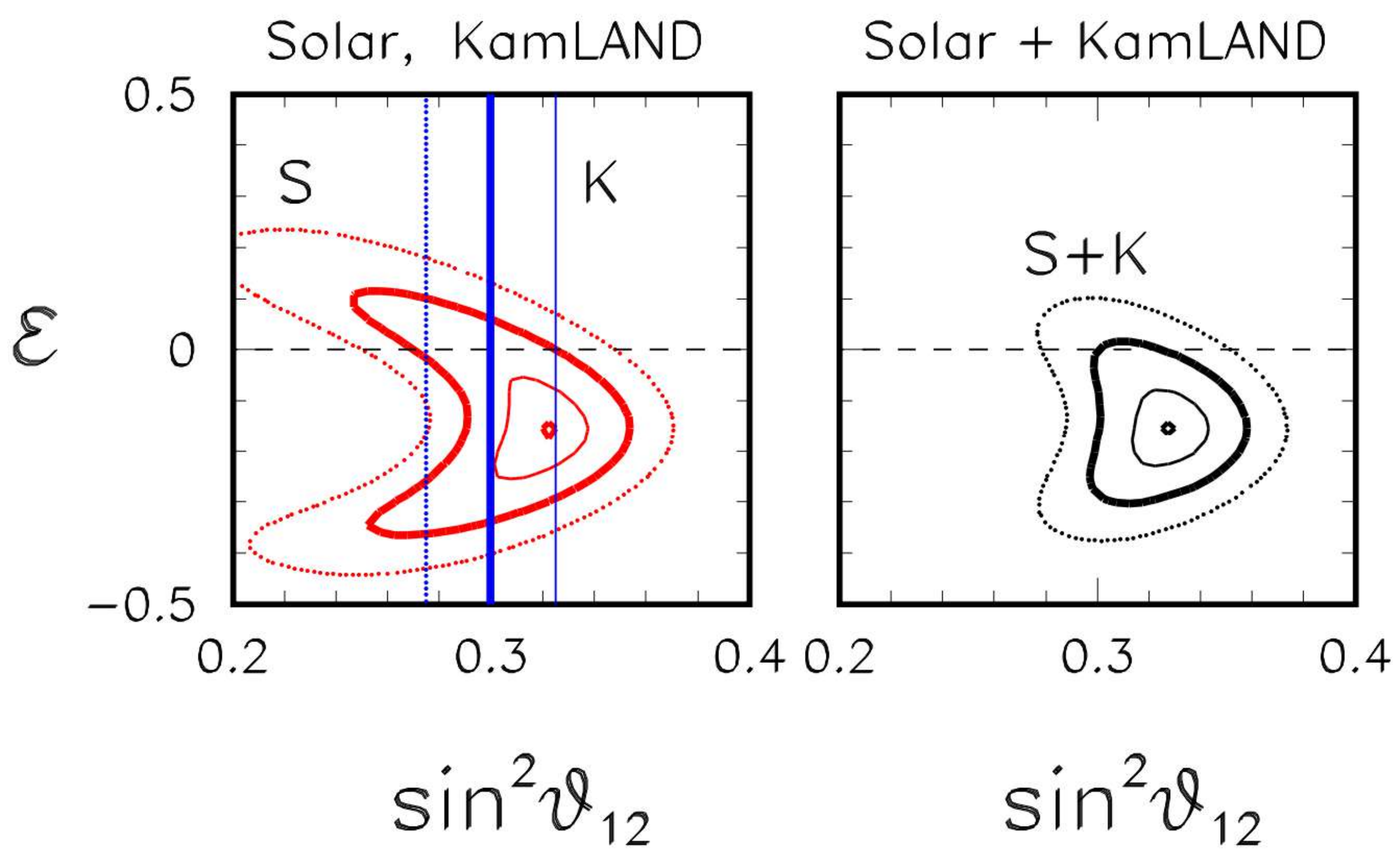
For the NSI Analysis

Some important constraints

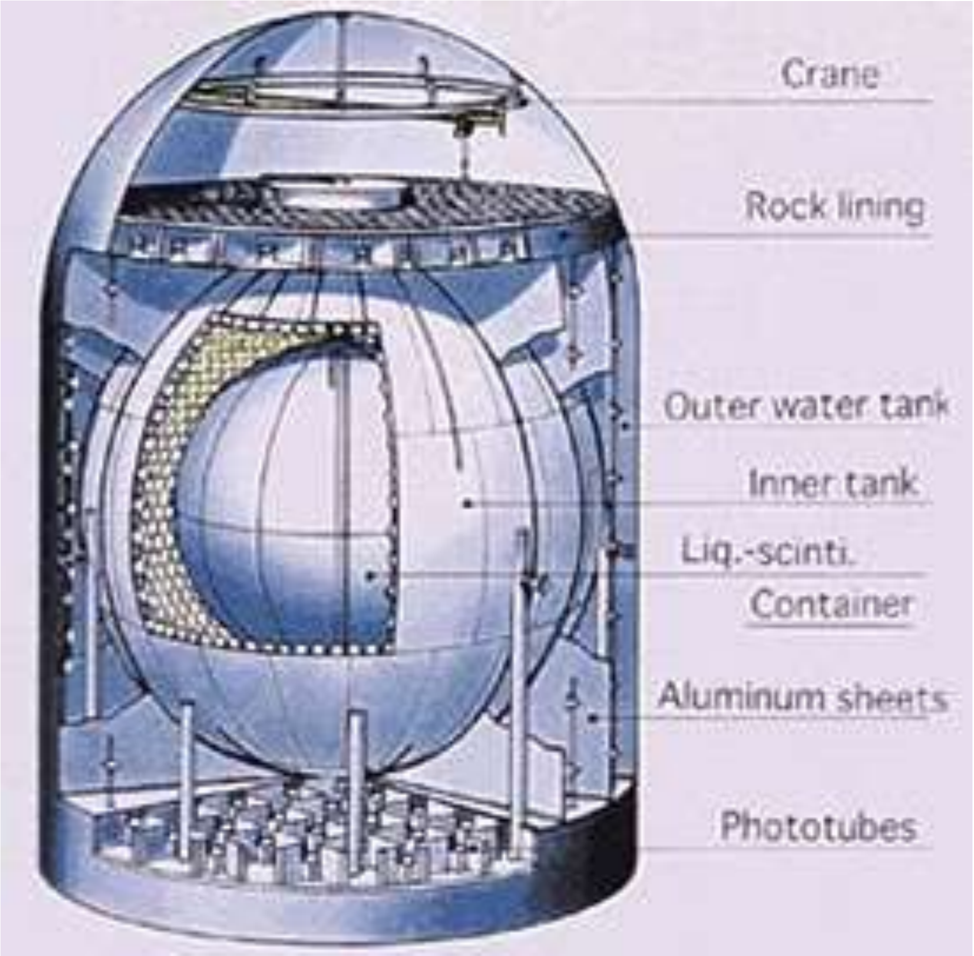
Backup

Other results matter

- We are insensitive to some oscillation paramenters
  -Use information from other sources: PDG, NuFIT
- Combination of different experiments. But…
- NSI could affect some of the measurements
  Solar + KamLAND prefer NSI at 1.9σ



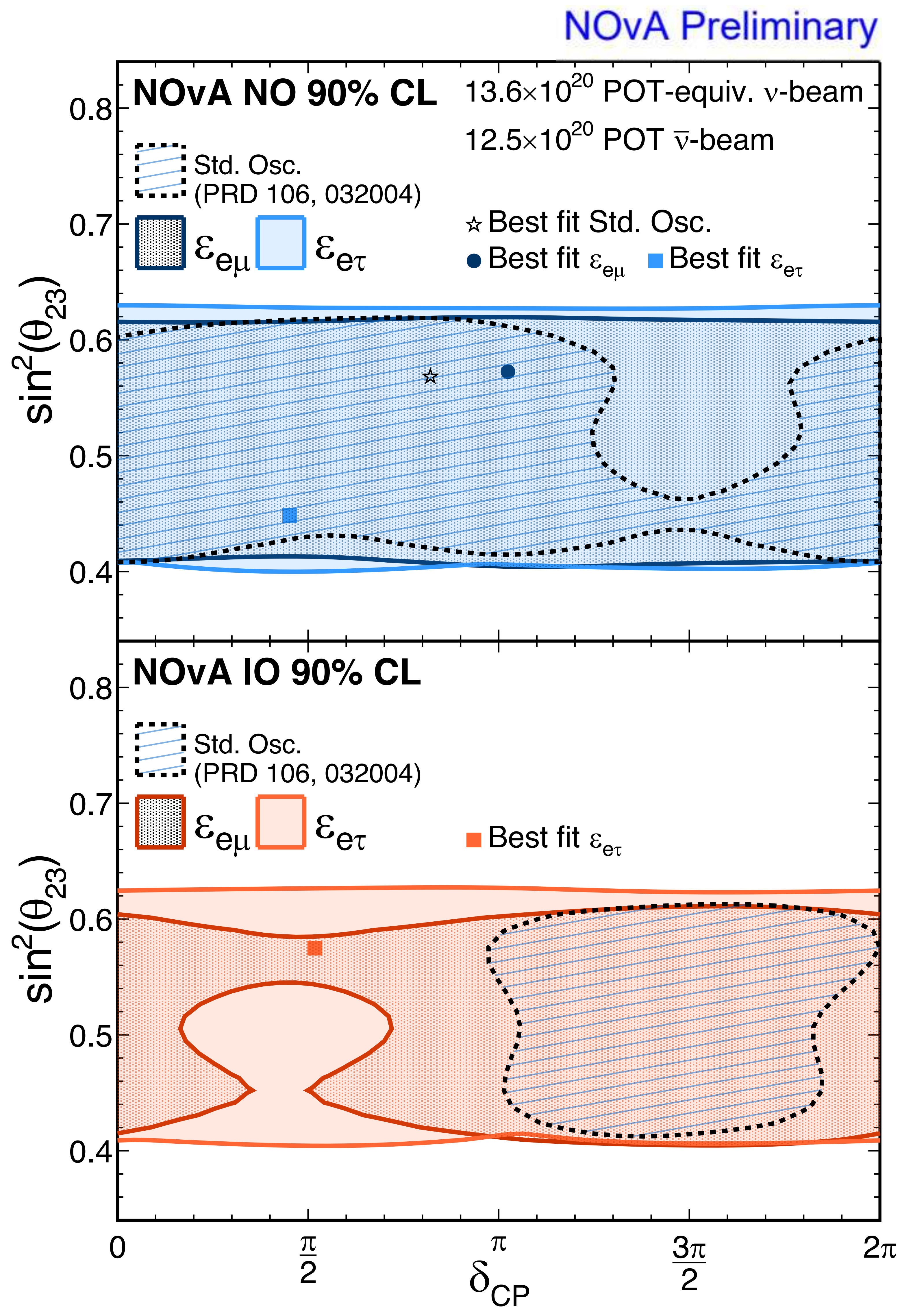
[A. Palazzo, PRD83 (2011)]



SO with the eμ and eτ models

The results

ν_e disappearance affected by NSI

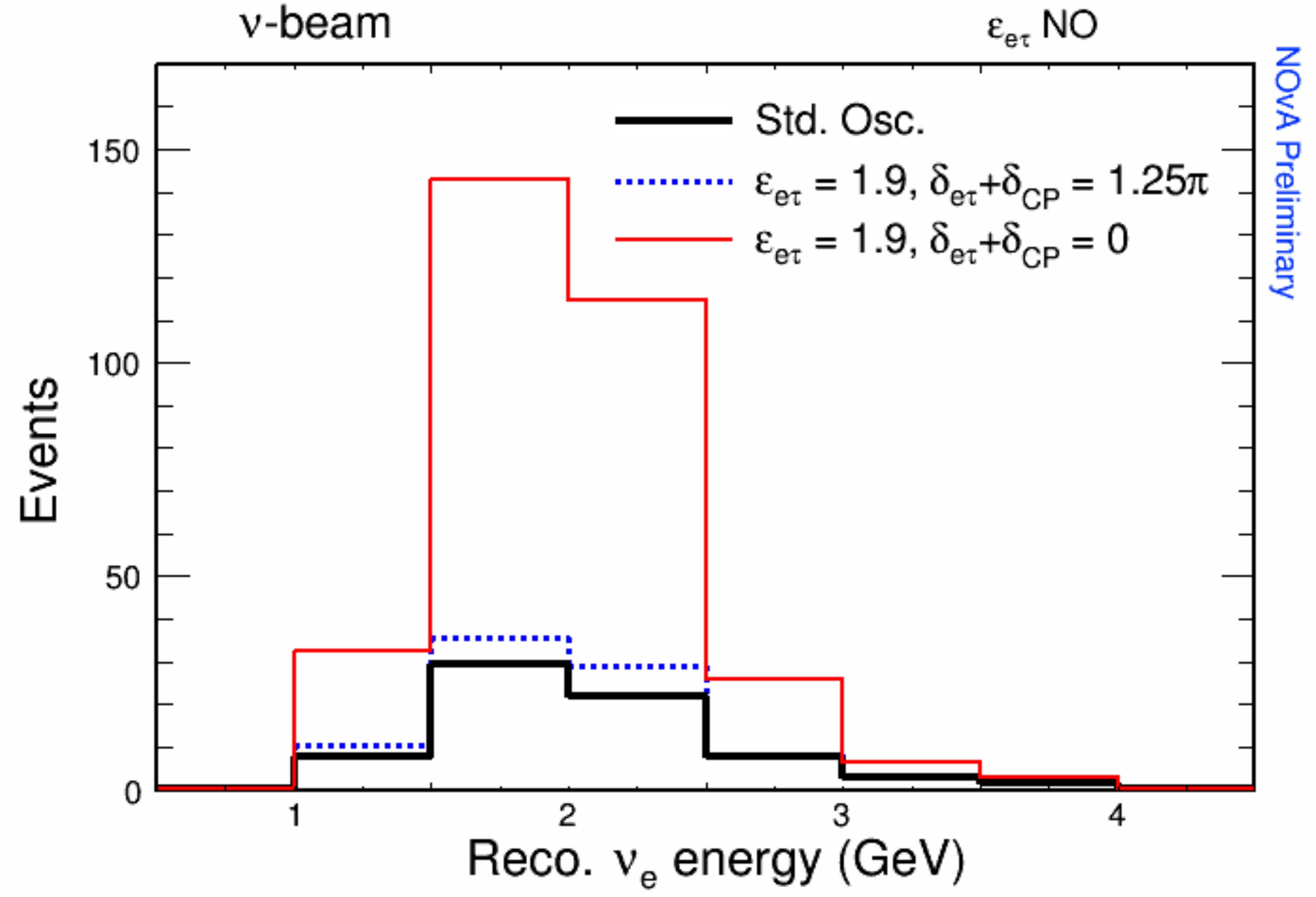


Degeneracy

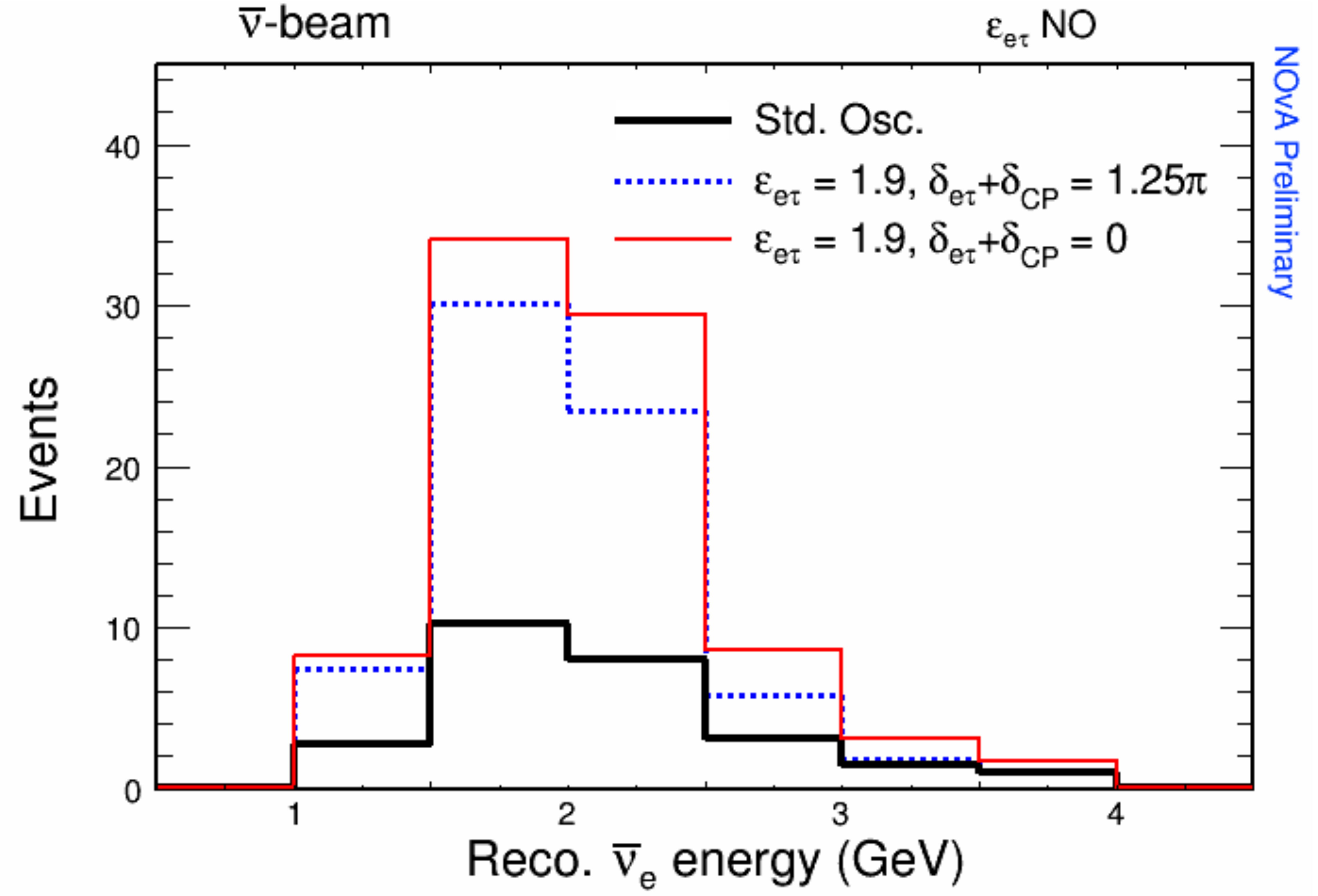
The results

Backup

Neutrinos



Antineutrinos



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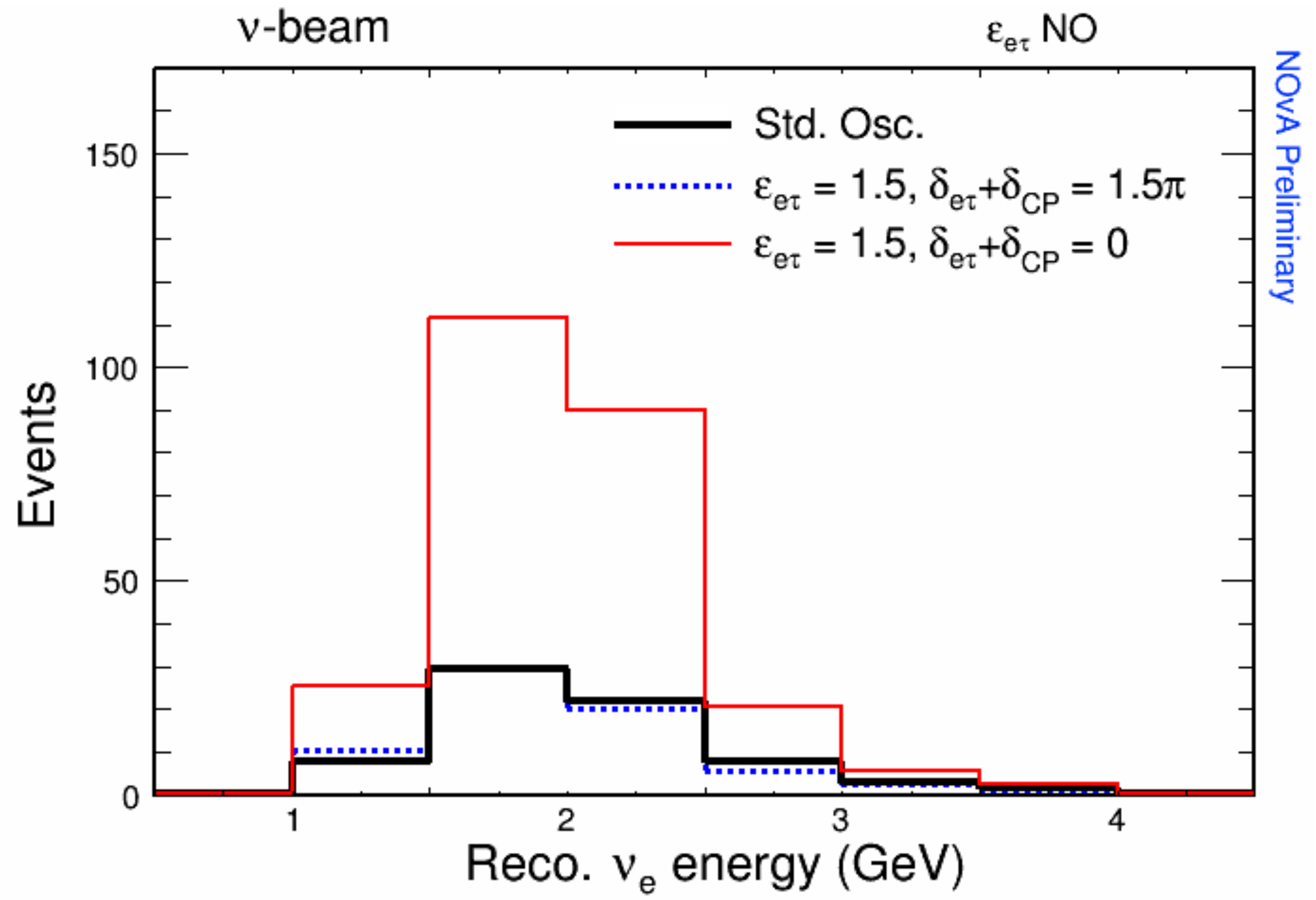
Dual Degeneracy

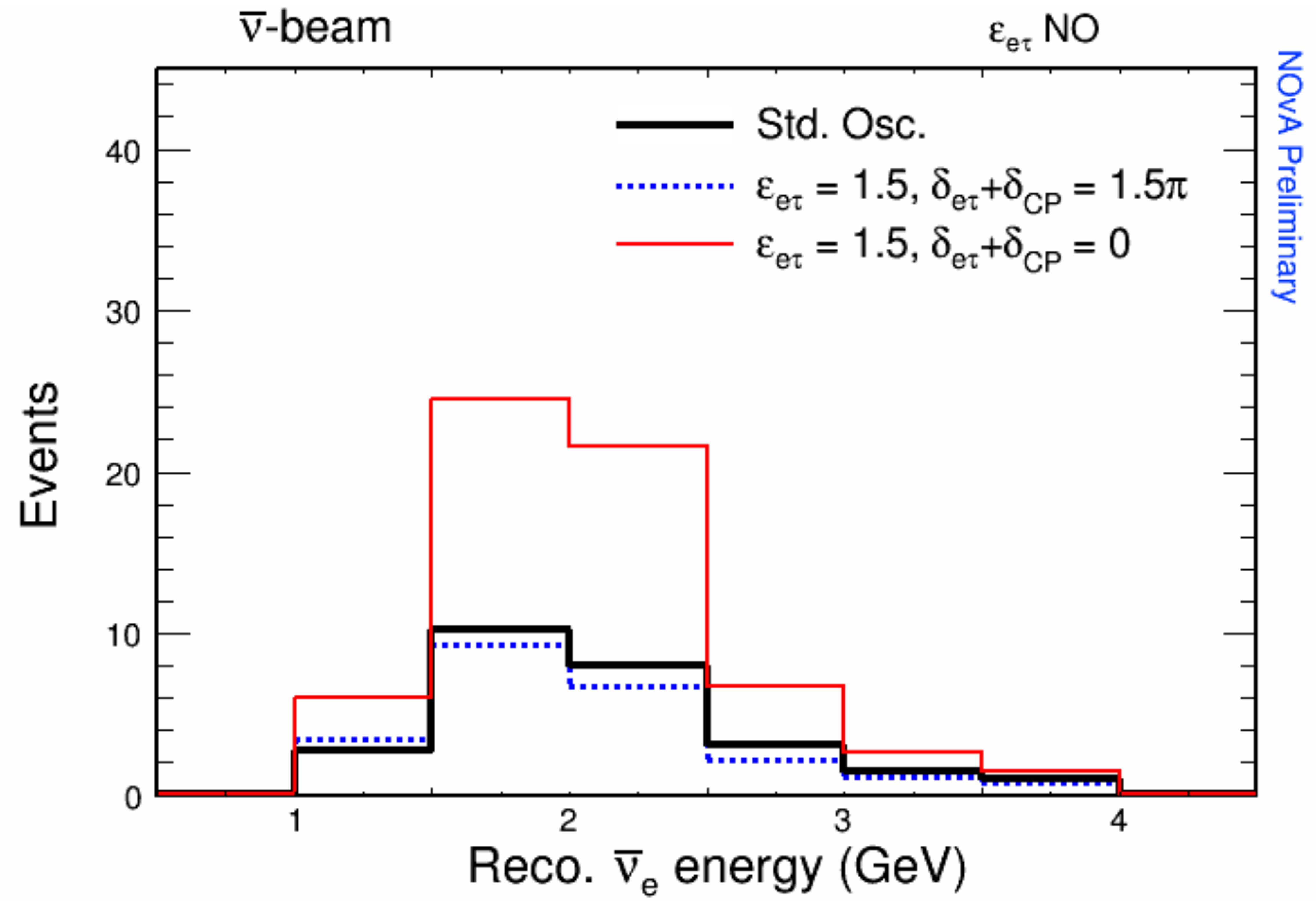
The results

Backup

Neutrinos



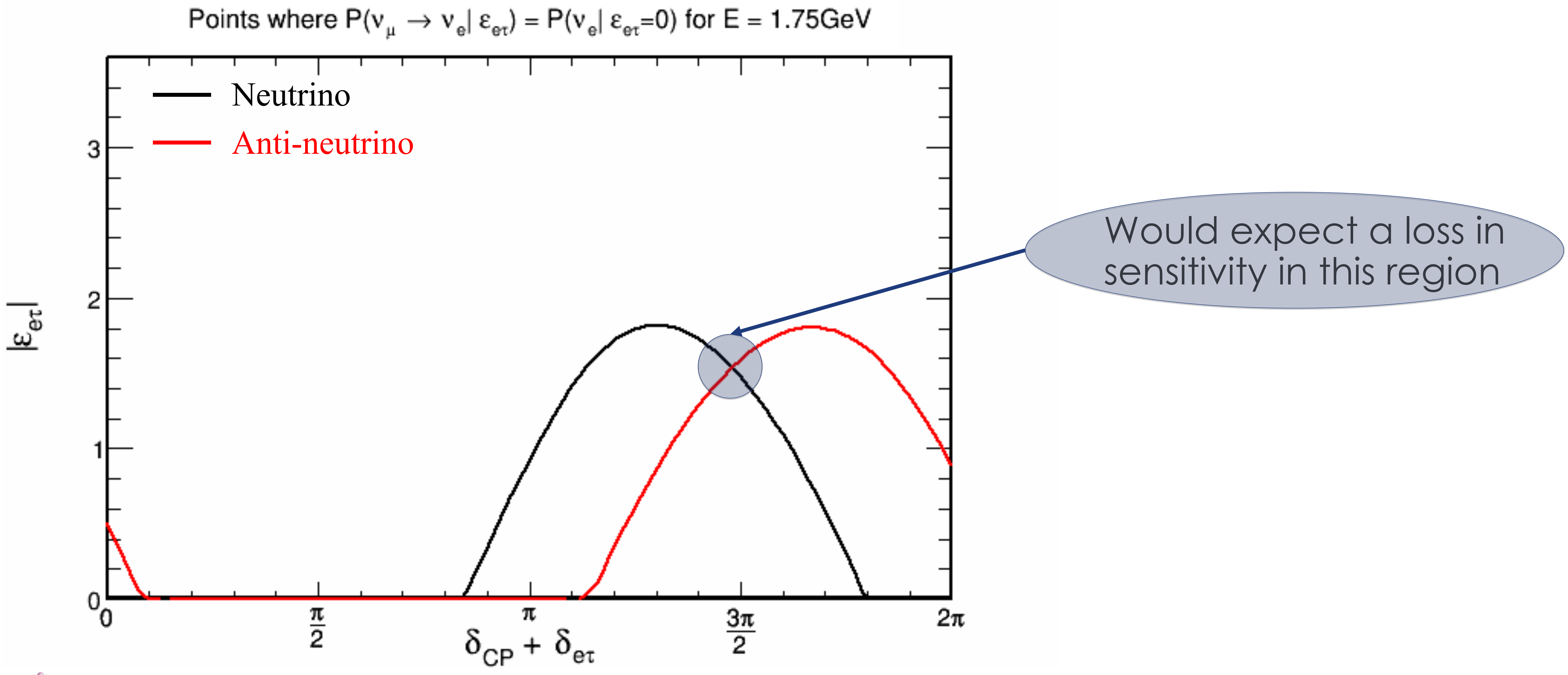
Antineutrinos



Degeneracy vs. Phase

The results

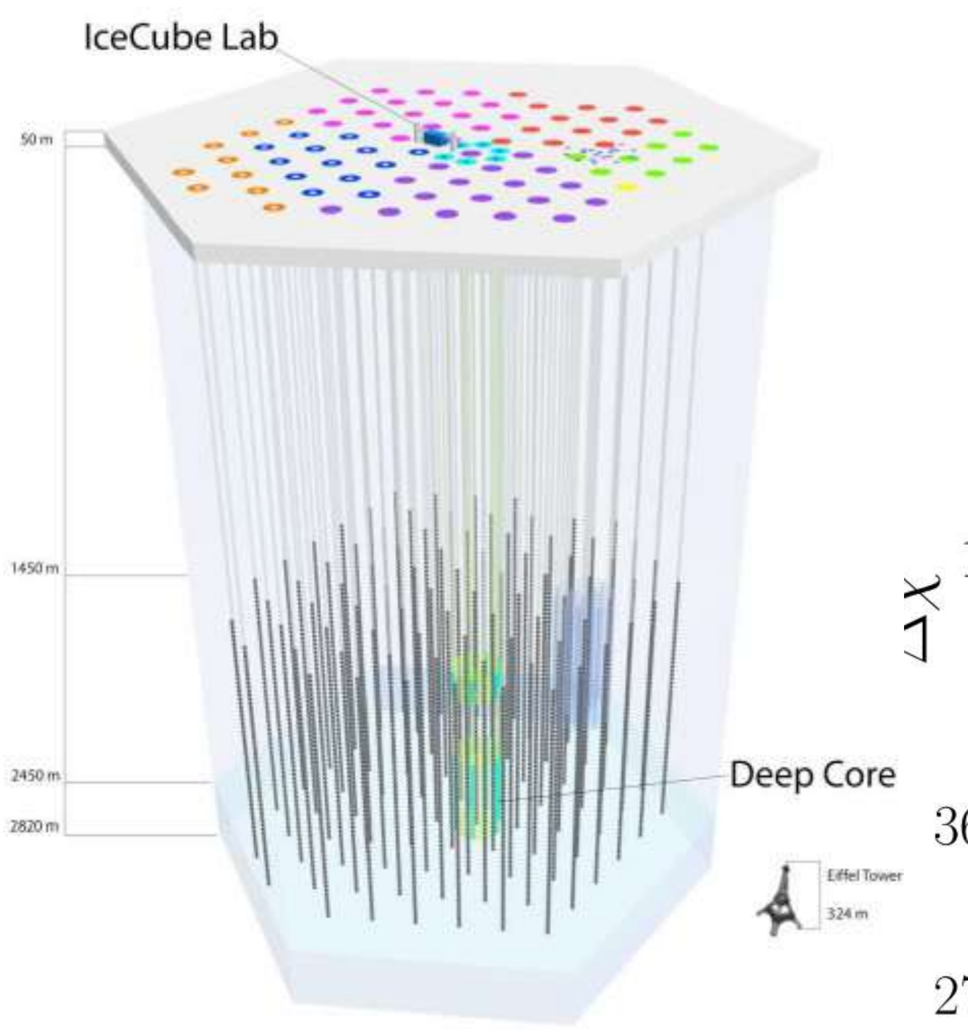
Backup



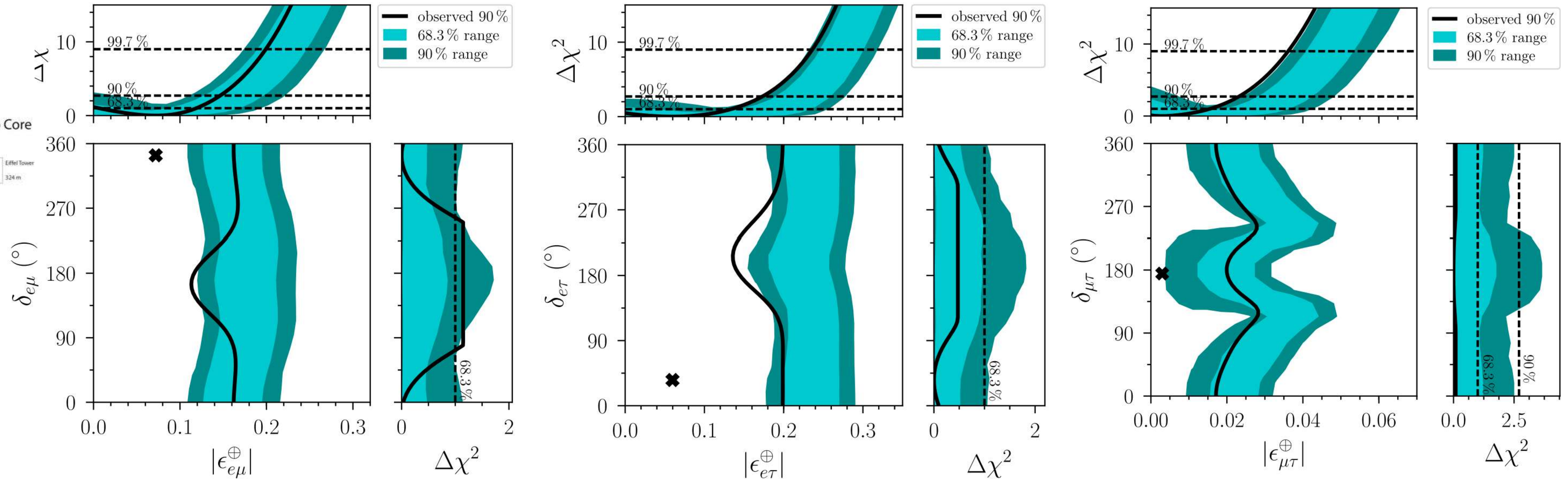
Resutls from IceCube

Thight Constaints

Backup



- Thigh constraints on NSI using atmospheric neutrinos
- One NSI parameter at a time and δ_{CP} **= 0**.

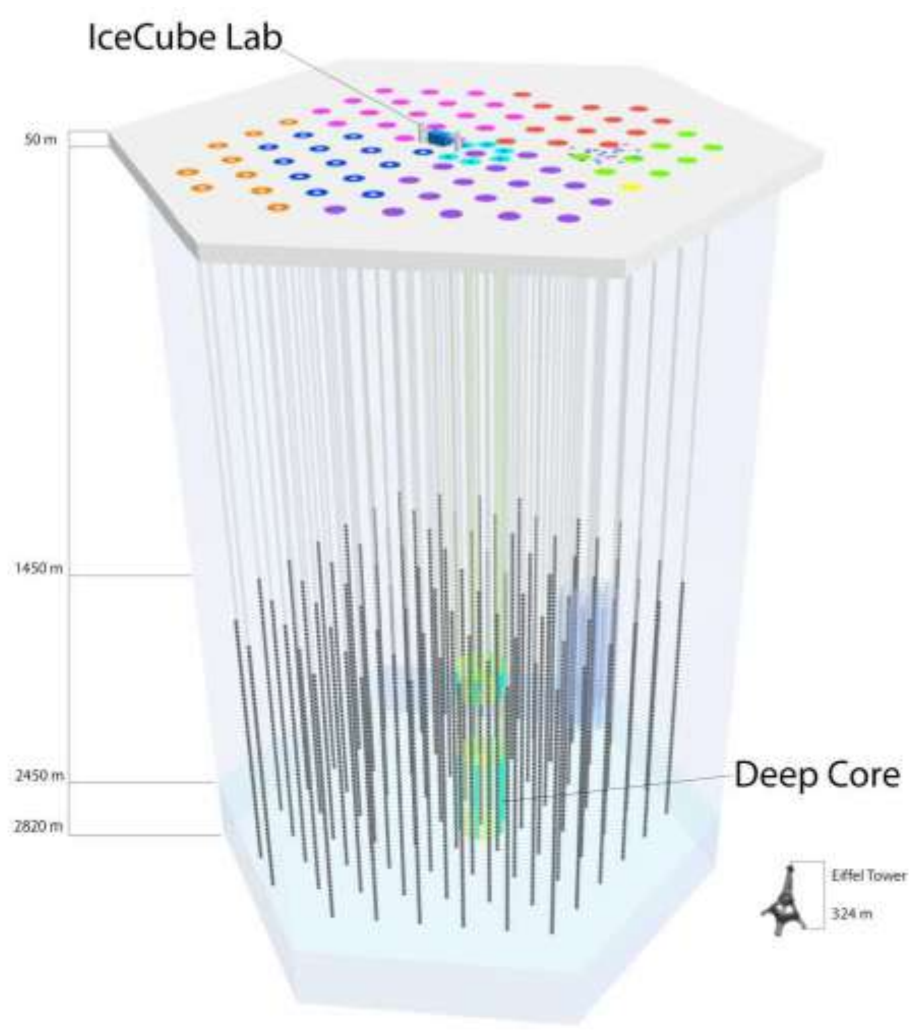


[IceCube, PRD104 (2021)]

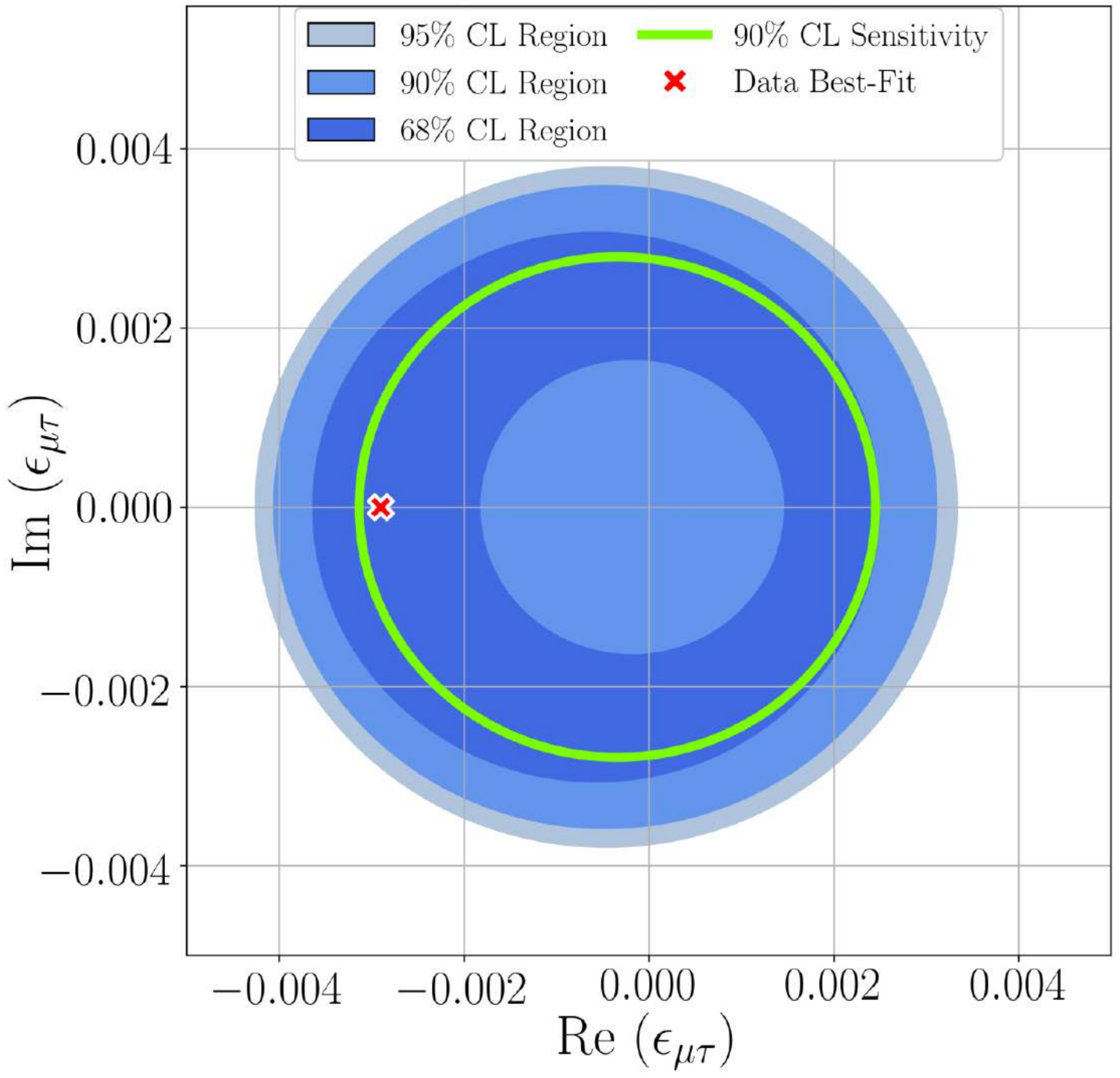
Resutls from IceCube

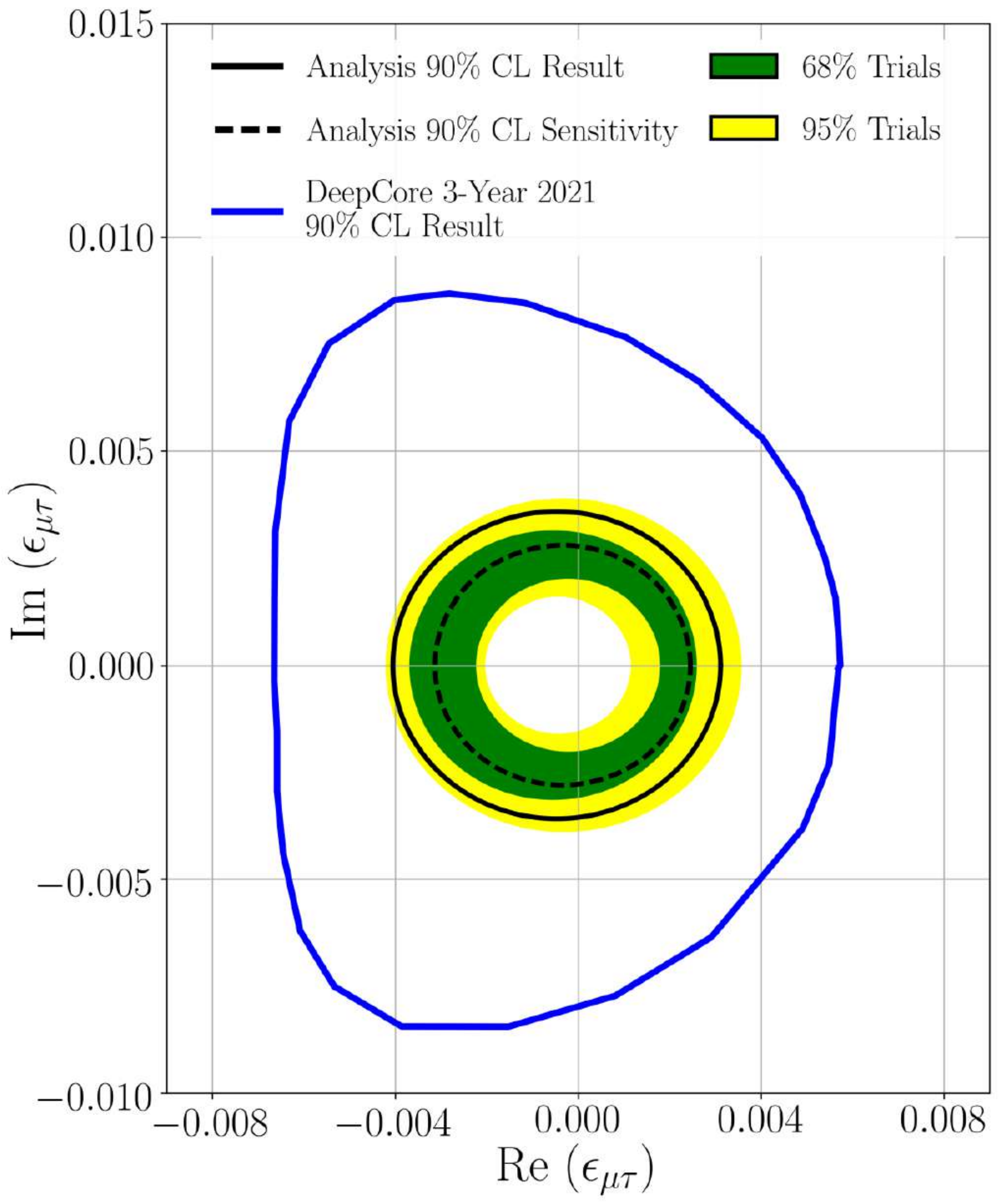
Thighter Constaints on $\mu\tau$

Backup



- Modelling NSI as $\varepsilon_{\mu\tau} = Re(\varepsilon_{\mu\tau}) + i\, Im(\varepsilon_{\mu\tau})$
- Using 8 years of TeV-scale atmospheric muon-neutrino data





[IceCube, PRL129 (2022)]

T2K – NOvA + NSI

Comunity interest

Backup

- Combination of NOvA and T2K
- Theorist's analyses

[Chatterjee & Palazzo, PRL126 (2021)]