Overview on Neutrino Theory/Phenomenology

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K-neutrino symposium 2024

Chonnam Nat'l Univ. @ Gwangju

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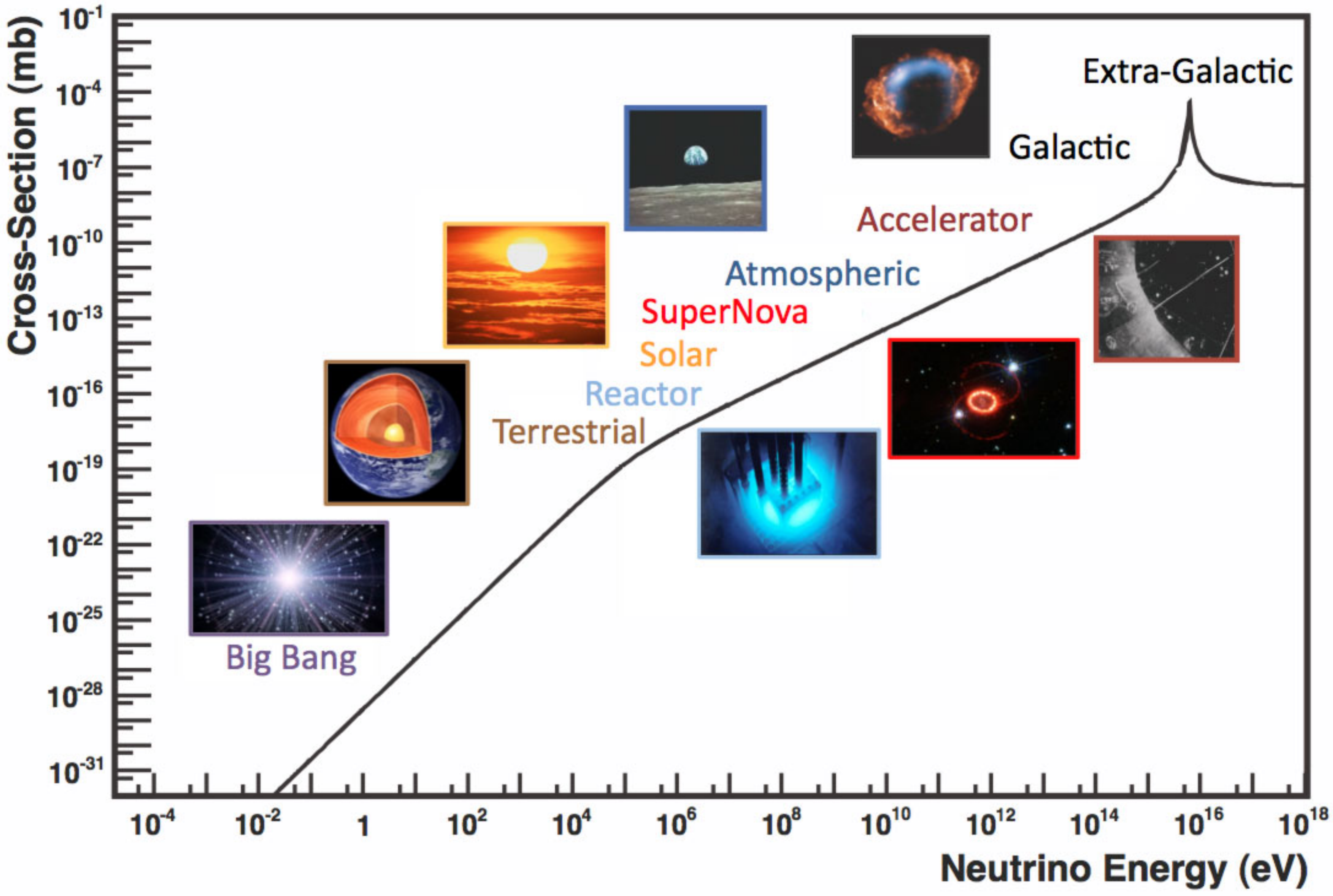
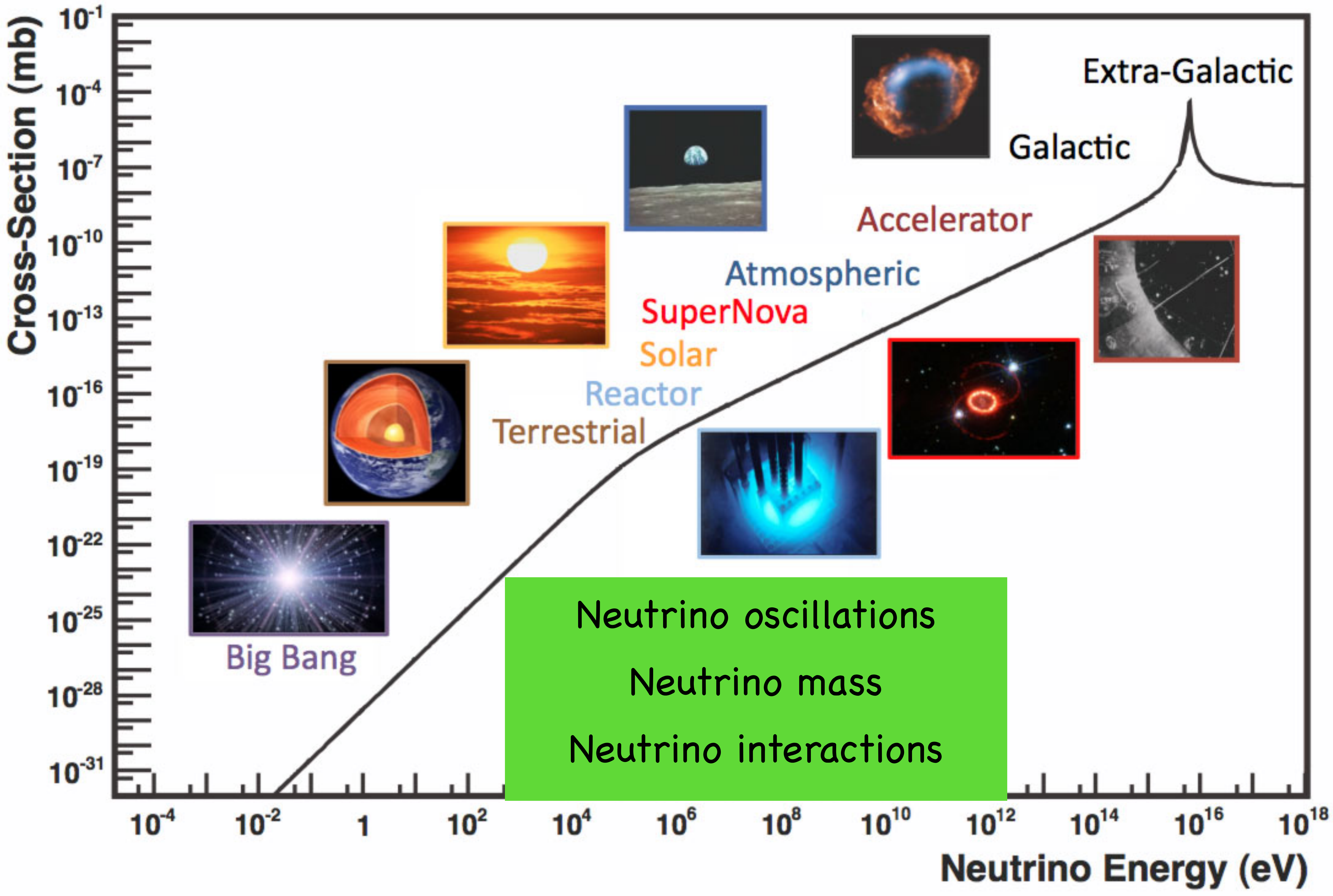
Neutrinos in broad energies



Neutrinos in broad energies



Neutrino oscillations between three flavor neutrinos

- Neutrino flavor eigenstates are superposition of mass eigenstates. In the standard three flavor active neutrino framework:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- When neutrinos propagate through space, the different mass eigenstates acquire different phase. Such phase difference cause non-zero probability for flavor change.

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \sum_{k,j} U_{\alpha k} U^*_{\beta k} U^*_{\alpha j} U_{\beta j} \, \exp\left(-i \frac{\Delta m^2_{kj} L}{2E} \right)$$

$$|\nu_\alpha(t, l)\rangle = \sum_k U_{\alpha k} e^{-i(E_k t - p_k l)} |\nu_k\rangle \qquad (\alpha = e,\ \mu,\ \tau, \quad k = 1,\ 2,\ 3)$$

Three neutrino mixing parameters

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Parameter		Data from
θ_{23}	$\sin^2(\theta_{23})$ ~ 0.55	Atmospheric, Accelerator
θ_{13}	$\sin^2(\theta_{13})$ ~ 0.022	**Reactors**, Accelerator
θ_{12}	$\sin^2(\theta_{12})$ ~ 0.307	**Solar**, KamLAND
Δm^2_{21}	~ 7.53×10^{-5} eV^2	Solar, **KamLAND**
Δm^2_{31}	~ $\pm$ 2.5×10^{-3} eV^2	Accelerators, Atmospheric, Reactors
δ	~ 1.19	**Accelerator**, Atmospheric

https://pdg.lbl.gov/2024/listings/rpp2024-list-neutrino-mixing.pdf

- Reactor: RENO, Daya Bay, Double Chooz
- Accelerator (LBL): T2K, NOVA, MINOS
- Atmospheric: SK, IceCube
- Solar:

✷ $\Delta m^2_{ij} = m^2_i - m^2_j$

Current status of oscillation parameters by global analysis

NuFIT 5.3 (2024)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
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$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.411 \to 0.606$	$0.568^{+0.016}_{-0.021}$	$0.412 \to 0.611$
$\theta_{23}/^\circ$	$42.3^{+1.1}_{-0.9}$	$39.9 \to 51.1$	$48.9^{+0.9}_{-1.2}$	$39.9 \to 51.4$
$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.02047 \to 0.02397$	$0.02222^{+0.00069}_{-0.00057}$	$0.02049 \to 0.02420$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.13}_{-0.11}$	$8.23 \to 8.95$
$\delta_{CP}/^\circ$	232^{+39}_{-25}	$139 \to 350$	273^{+24}_{-26}	$195 \to 342$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
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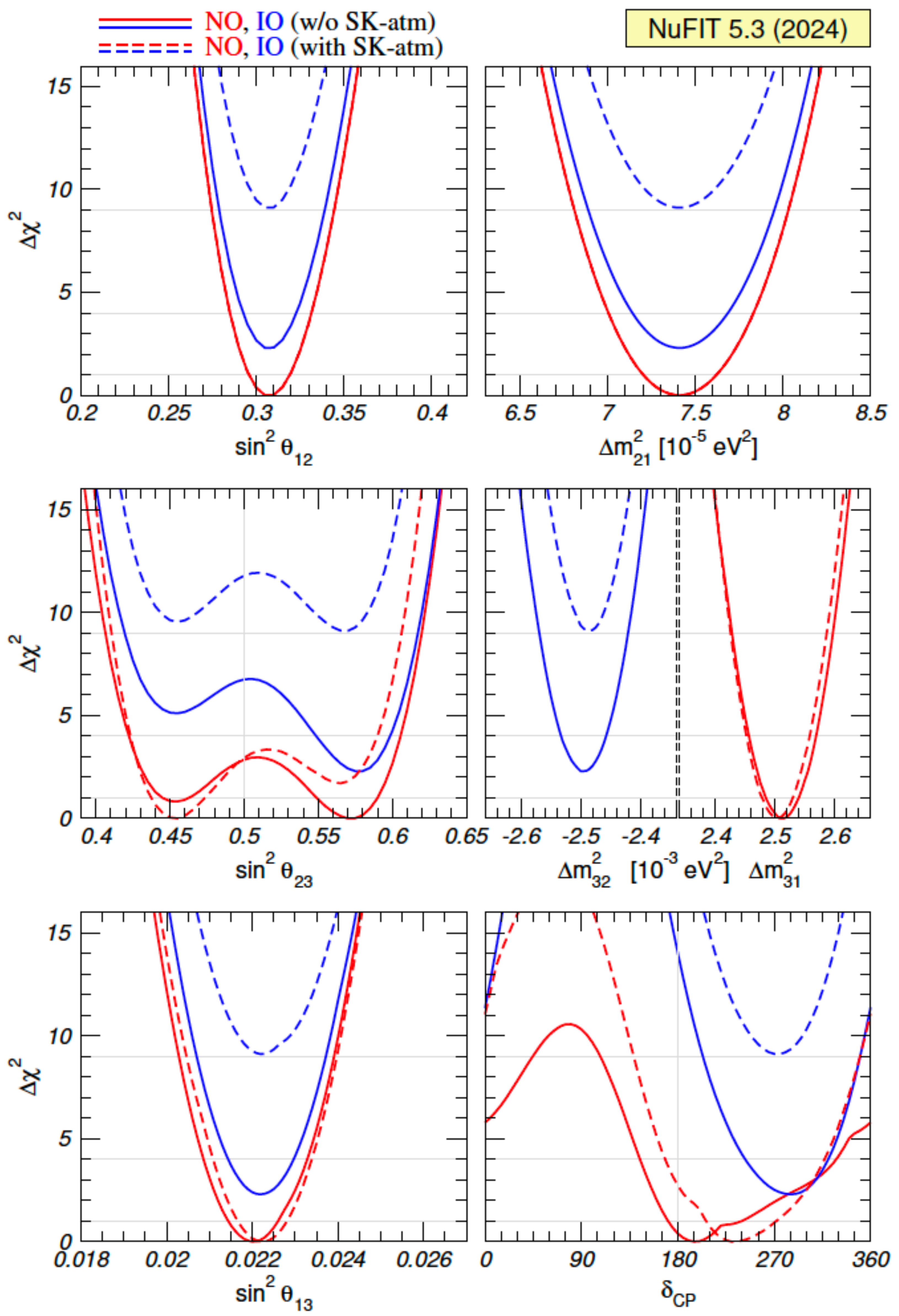

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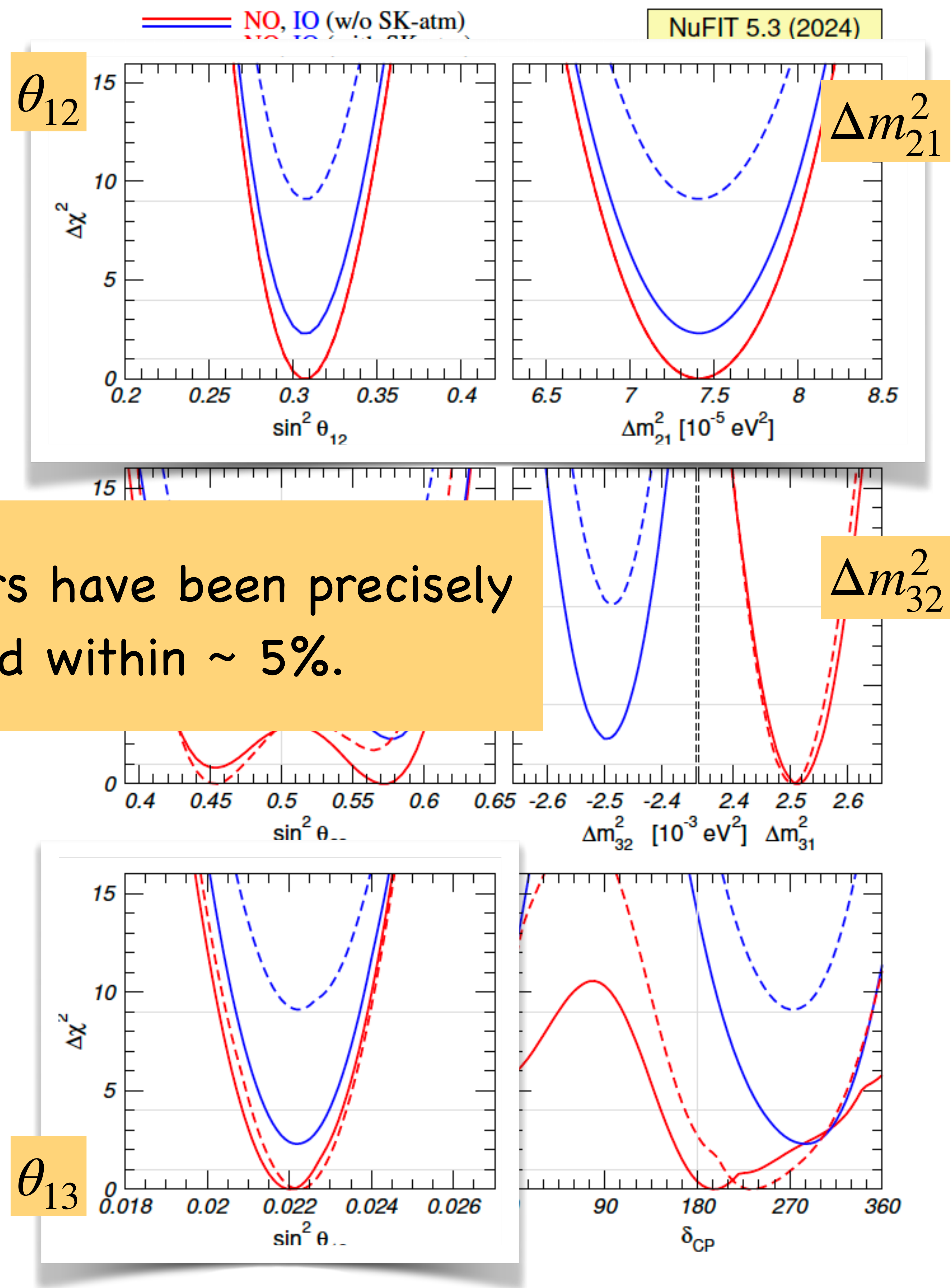
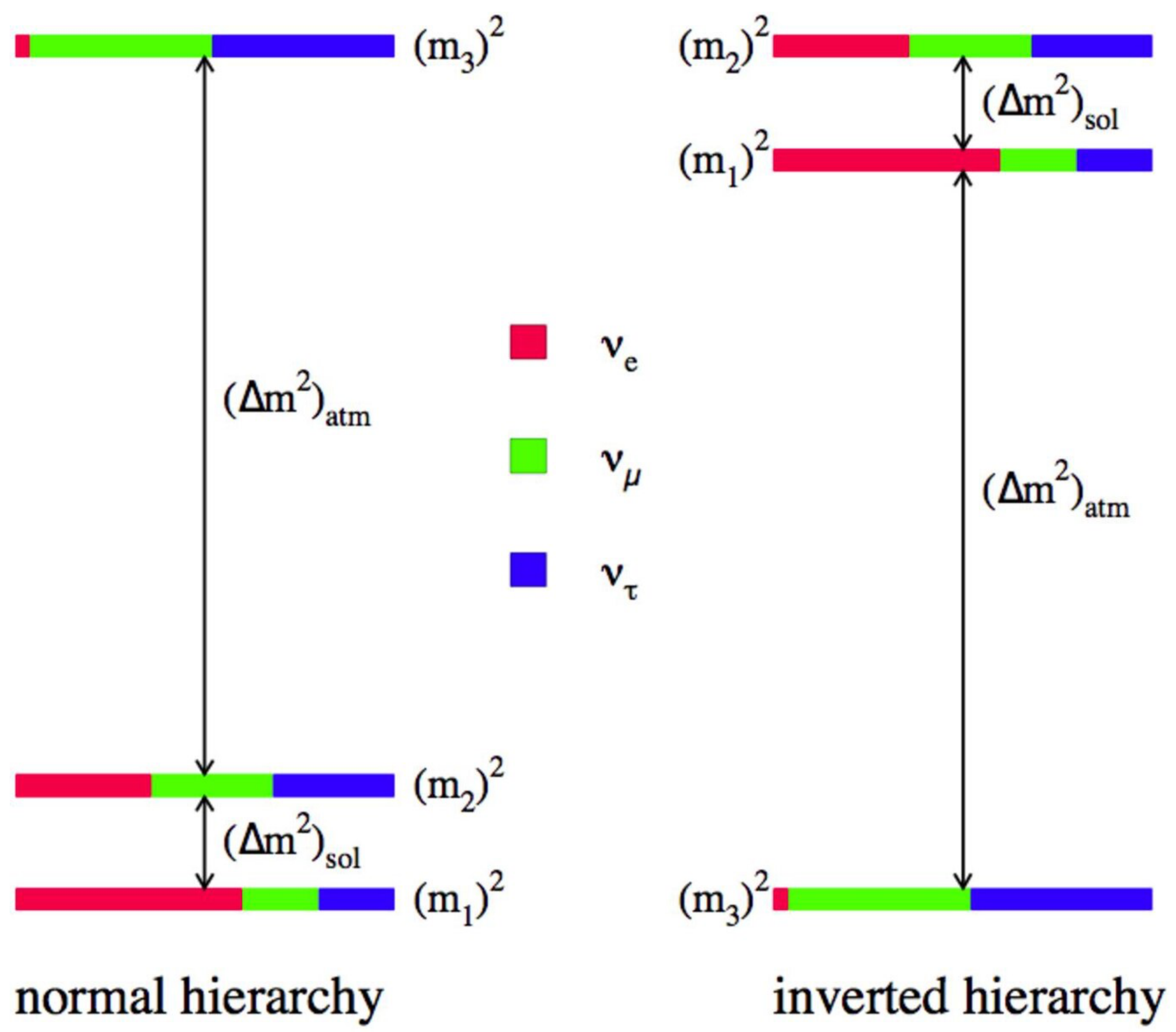
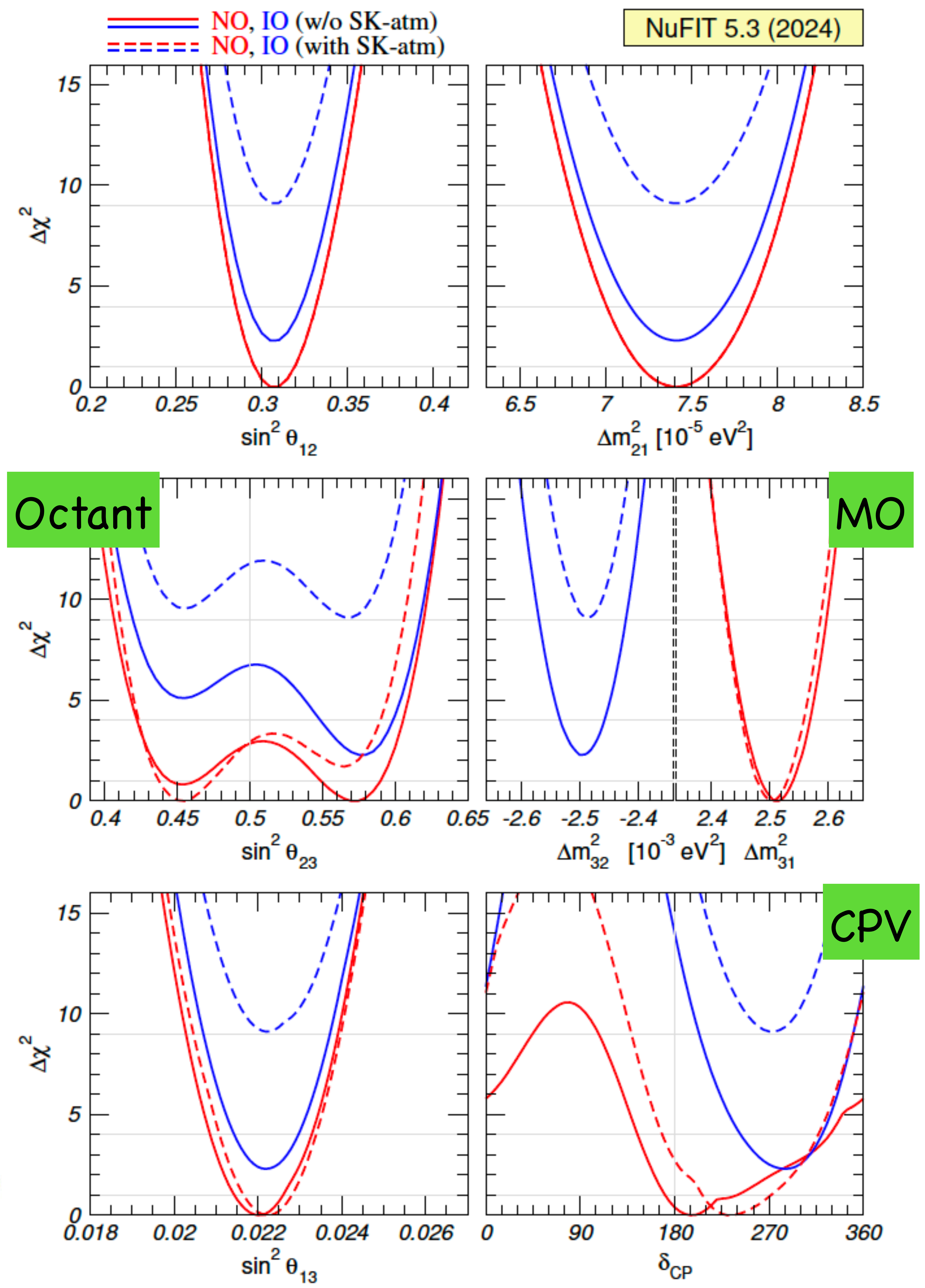


Most parameters have been precisely measured within ~ 5%.

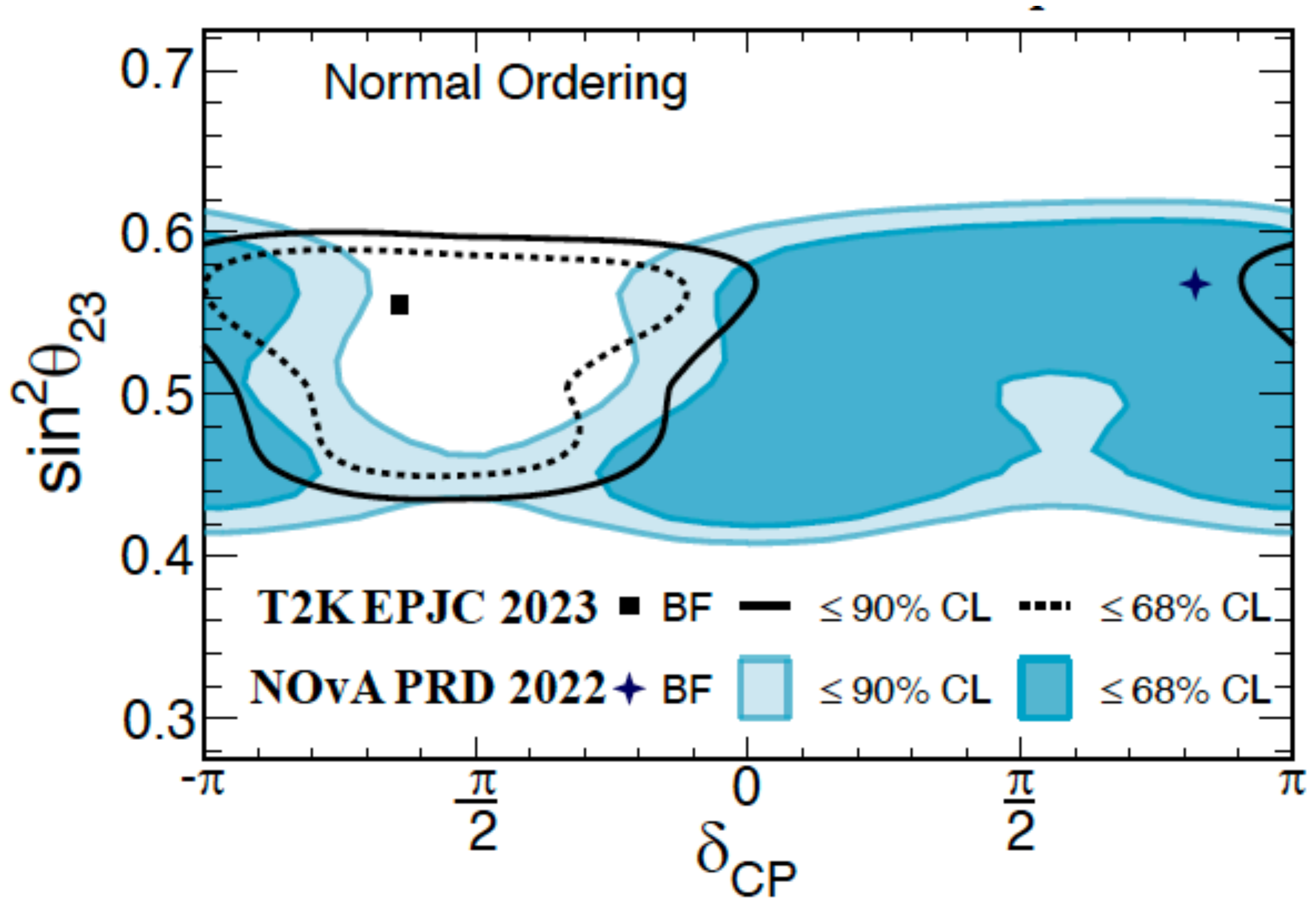
Current status of oscillation parameters by global analysis

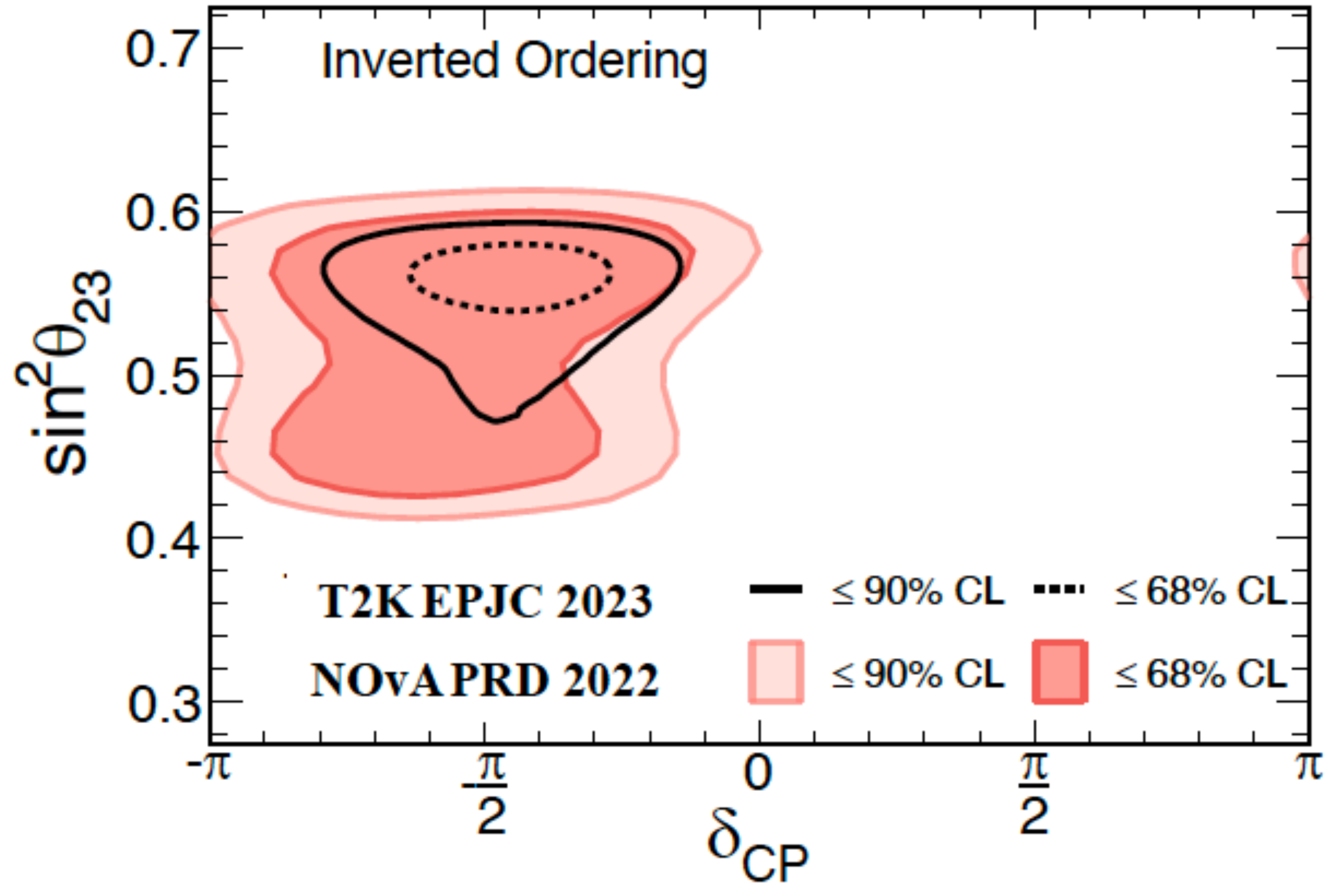
- Things still unknown:
  - What is the lightest neutrinos, i.e. $\Delta m^2_{3l} > 0$ or $\Delta m^2_{3l} < 0$?
  - Octant of θ_{23}: $0 < \theta_{23} < 45°$ or $45° < \theta_{23} < 90°$?
  - CP violation in the lepton sector?





Tension between NOvA - T2K





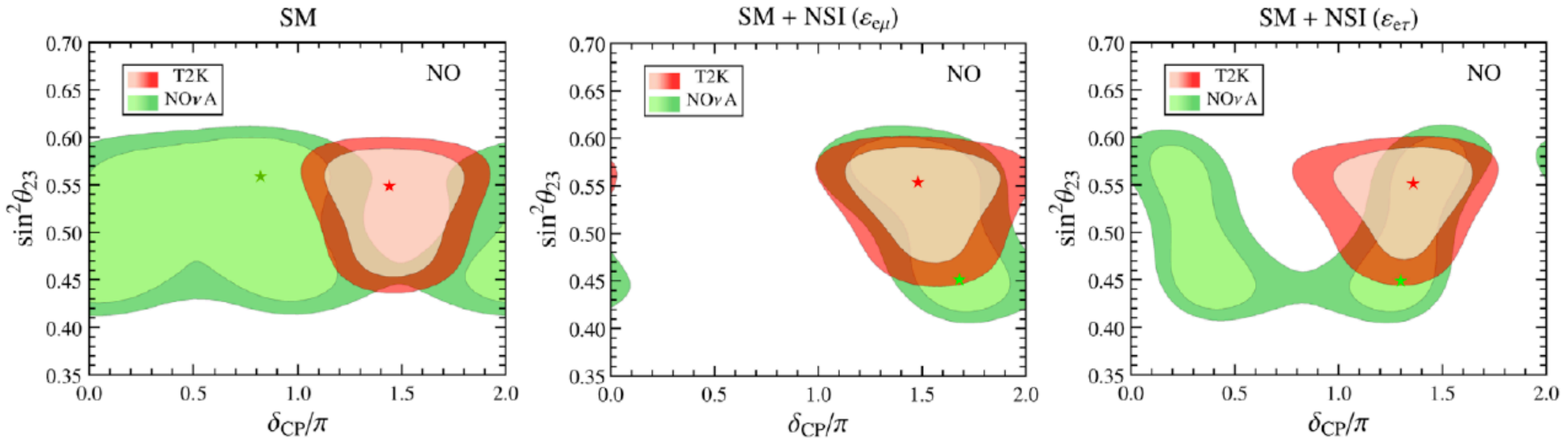
- Both NOvA and T2K prefer normal ordering individually, but they favor different value of CP phase.
- T2K and NOvA results coincide with the inverted ordering.

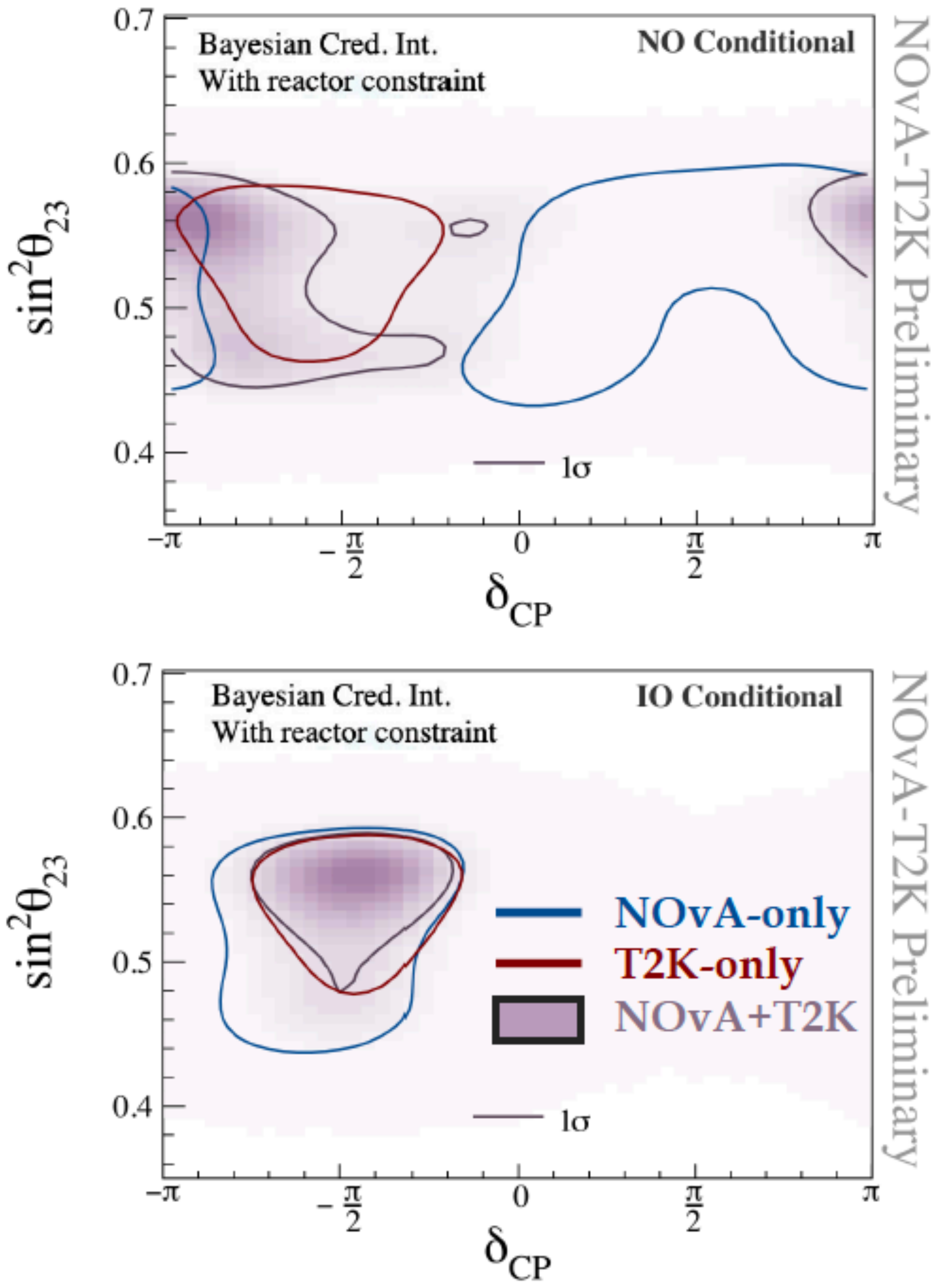
↓

- Joint analysis
- Interpretation with BSM physics

Tension between NOvA - T2K

- Joint analysis - in progress
  - Preliminary results show that the tension is still remained.
- Interpretation with BSM physics
  - e.g. Non-standard interaction can resolve the tension.
    (Chatterjee and Palazzo, Phys. Rev. Lett. 126, 051802 (2021) / Denton, Gehrlein, Pestes, Phys.Rev.Lett. 126 (2021) 5, 051801)

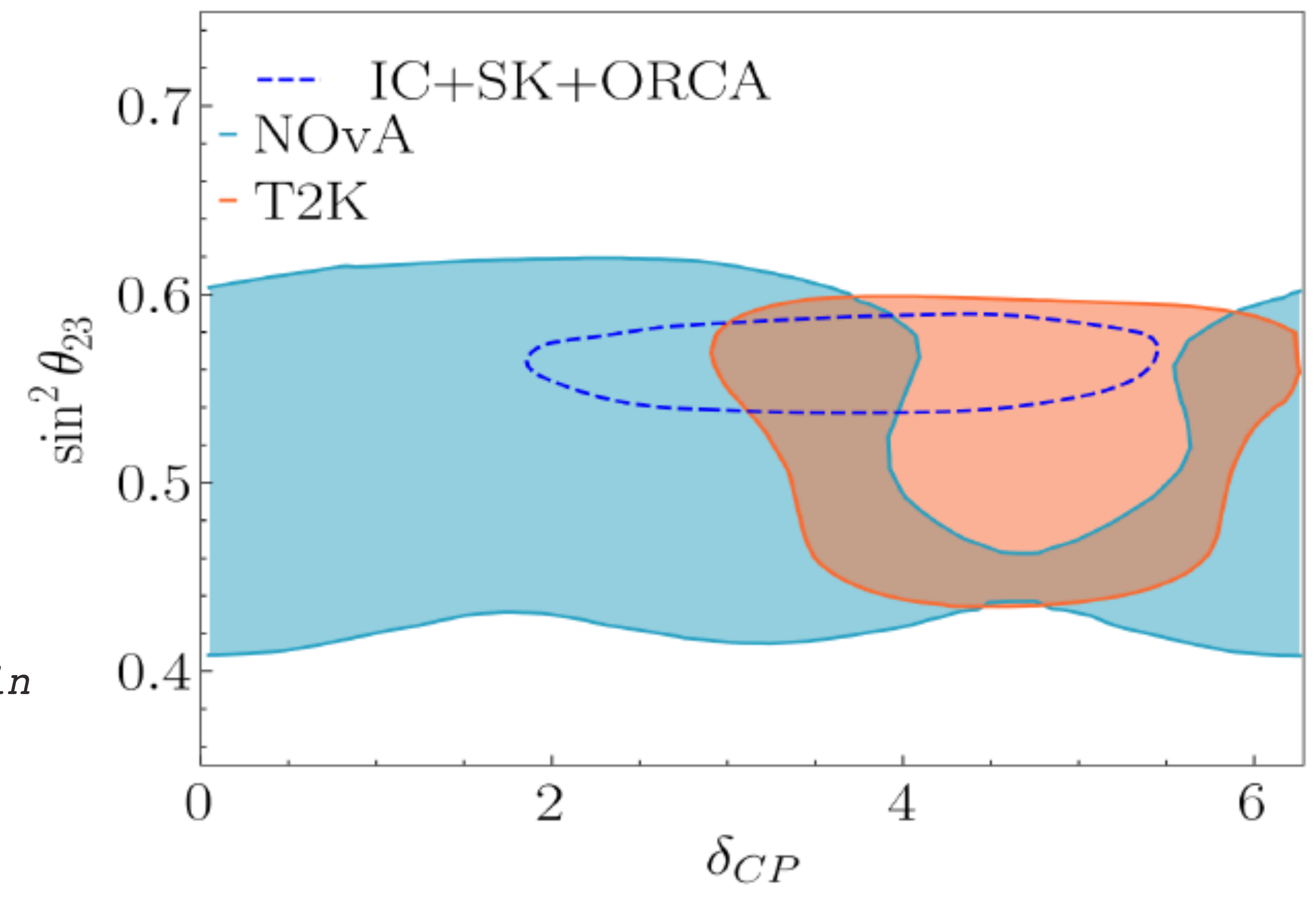




Future LBL experiments

- The LBL oscillation experiments are sensitive to the parameters Δm^2_{3l}, θ_{23}, and δ_{CP}.
    - (e.g.) JUNO, DUNE, Hyper-K, IceCube, KM3NeT-ORCA...

- More data from current and future LBL experiments and neutrino telescopes can help
    - To address the remained questions about mass ordering, octant of θ_{23}, and CP violation.
    - To resolve the current tension between NOvA and T2K.



Argüelles, Fernández, Martínez-Soler, Jin
Phys.Rev.X 13, 041055 (2023)

Questions related with neutrino mass

- Oscillation of neutrinos implies that neutrinos have masses.

- Questions about neutrino mass
  - How neutrino masses are ordered?
  - What is the mass (scale) of the lightest neutrino?
  - Neutrino is Dirac or Majorana particle?
  - How neutrinos acquire mass?

Absolute mass using tritium β decay

- Tritium β decay :

$$^3\mathrm{H} \rightarrow ^3\mathrm{He} + e^- + \bar{\nu}_e$$

- The energy spectrum of electron:

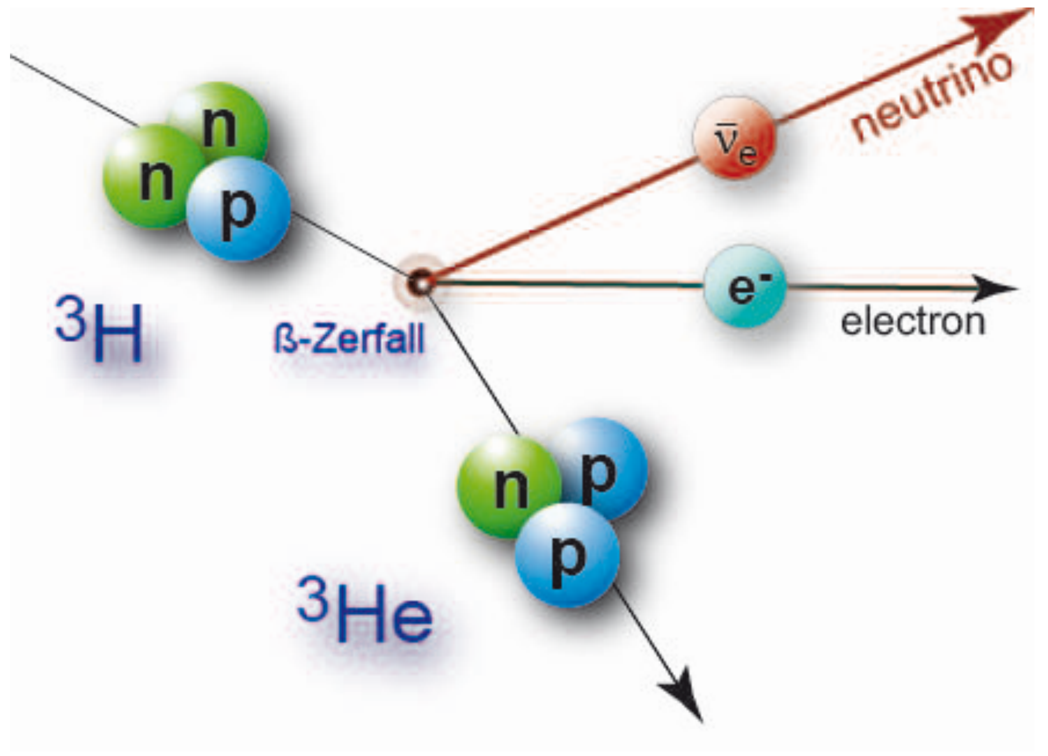
$$\frac{dN_e}{dE_e} \propto F(E) p_e E_e (Q - E_e) \sqrt{(Q - E_e)^2 - m_{\bar{\nu}_e}^2}\, \theta(Q - E_e - m_{\bar{\nu}_e}^2)$$

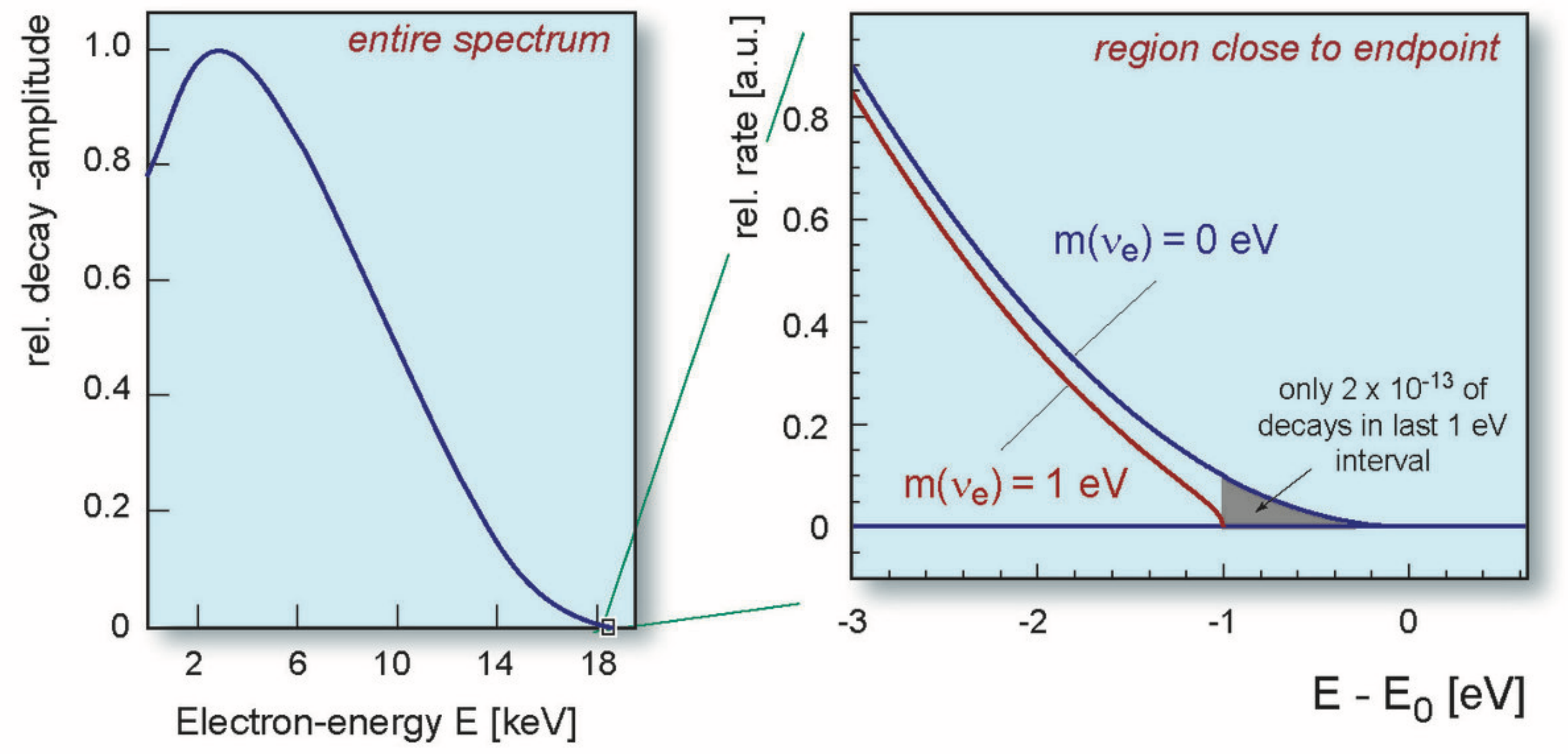
$$m_{\bar{\nu}_e} \equiv \sqrt{\sum_j |U_{ej}|^2 m_j^2}$$

- The upper limit:

$$m_\nu < 0.45 \text{ eV } (90\,\% \text{ CL})$$

KATRIN Collaboration
arXiv: 2406.13516

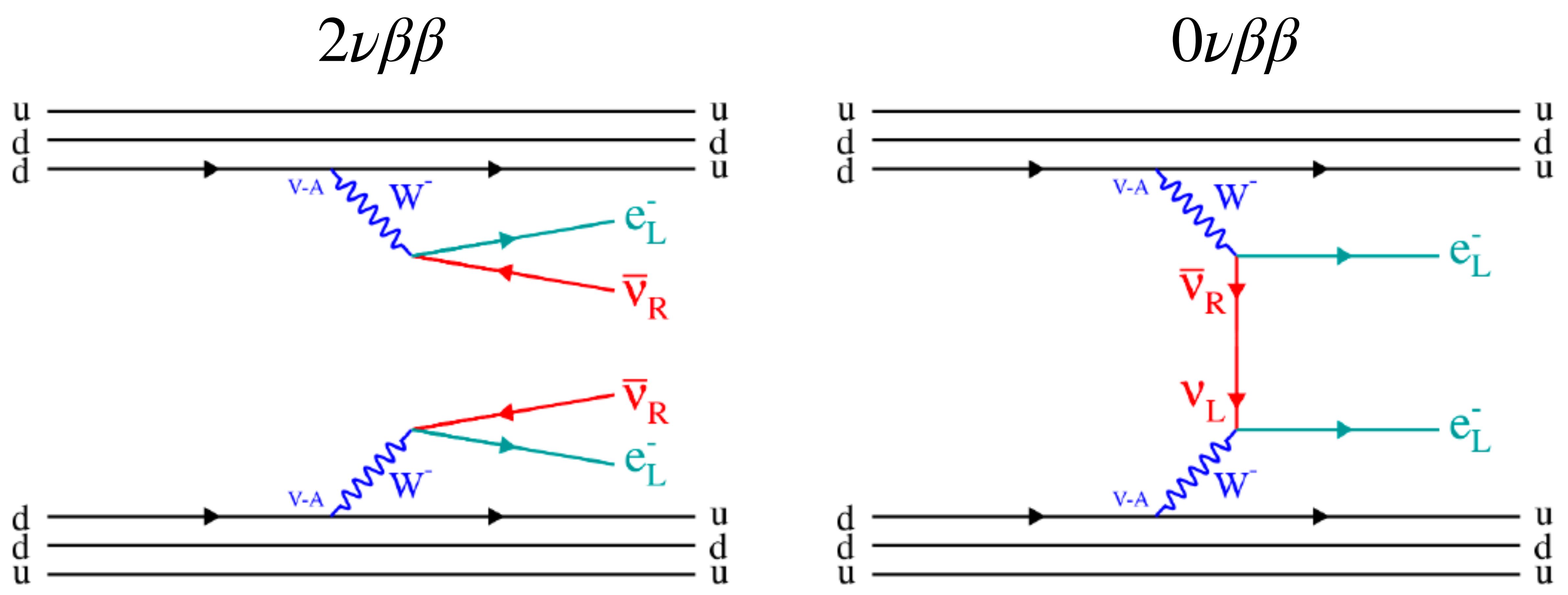


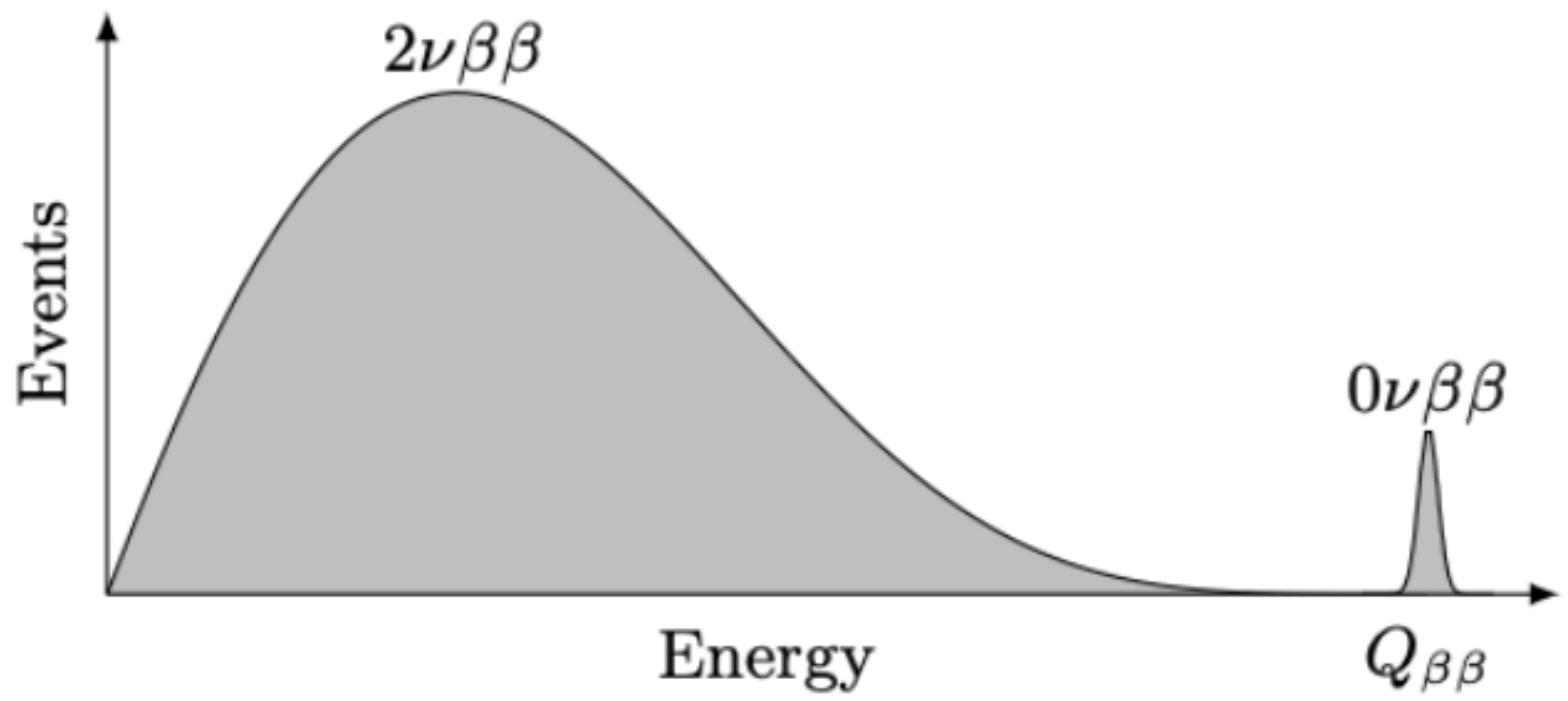


Figures from https://www.katrin.kit.edu/79.php

Search for 0νββ

- Double beta decay
  - General process: $(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$
  - Neutrinoless process: $(Z, A) \rightarrow (Z+2, A) + 2e^-$
    - Lepton number is not conserved ($\Delta L = 2$).
    - Can happen if neutrino is Majorana particle.





Limit on neutrino mass from 0νββ search

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\, m^2_{\beta\beta}$$

$$m_{\beta\beta} \equiv |\sum_{i=1}^{3} m_i U^2_{ei}|$$

- Some current experiments
  - (KamLAND-Zen), CUORE, LEGEND-200 (running)
  - SNO+, NEXT-100, SuperNEMO, CDEX-300ν (soon)
- KamLAND-Zen limit reported @ Neutrino 2024:
  - $< m_{\beta\beta} > = 28 - 122$ meV

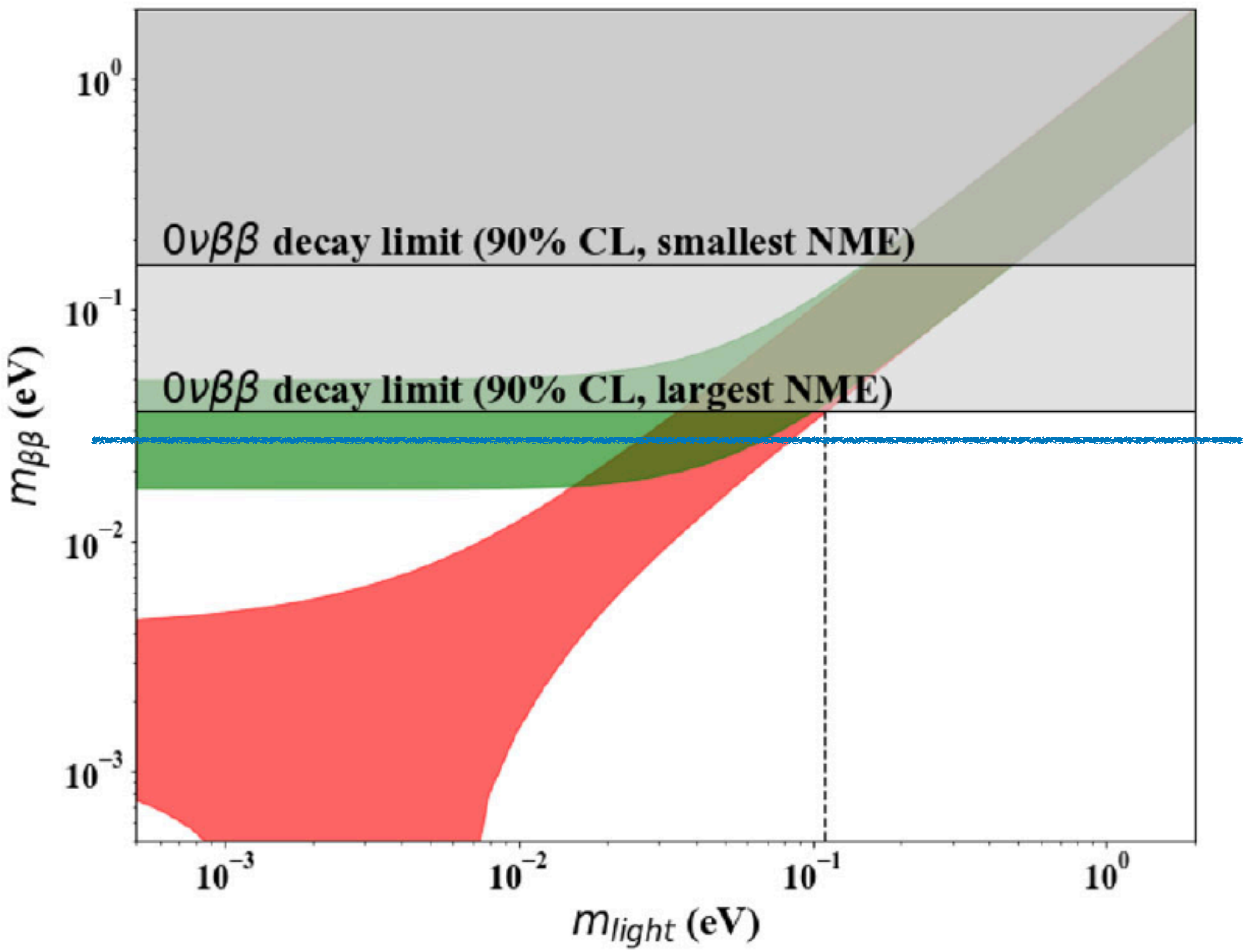
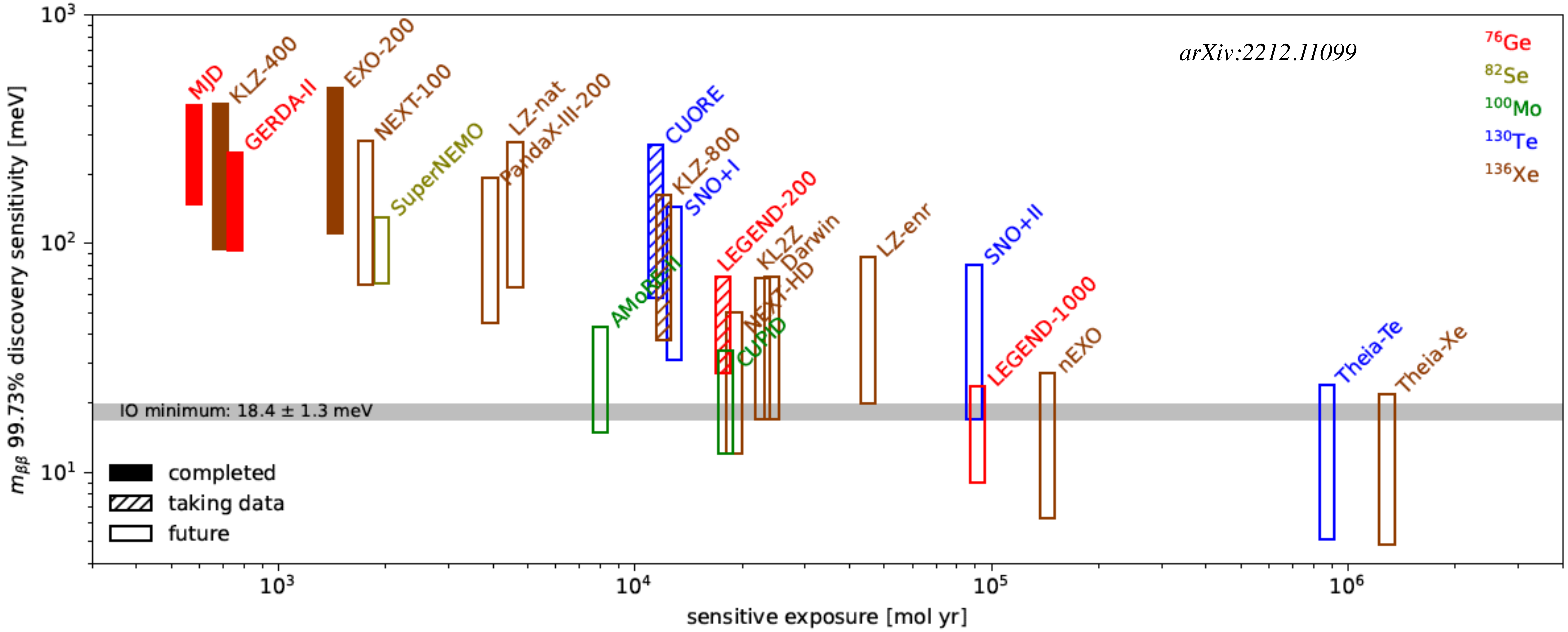


Figure from
La Rivista del Nuovo Cimento (2023) 46:619–692

Sensitivity of 0νββ experiments

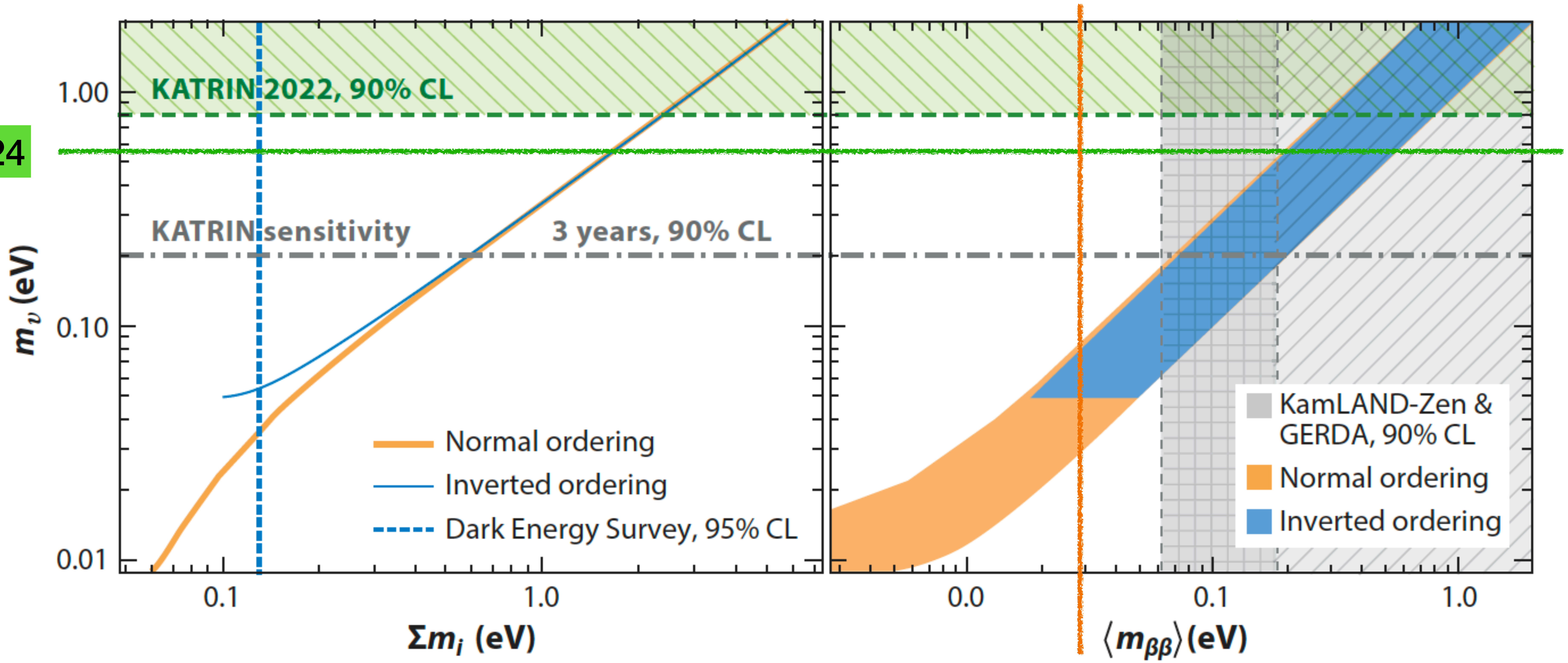


- Some proposed experiments are expected to cover the mass region for inverted ordering
  - AMORE-II, LEGEND-1000, CUPID, nEXO, NEXT-HD…

Absolute mass observables

KATRIN-2024

From KATRIN
Direct measurement,
Model independent



From cosmological observation
Most stringent, but model dependent

KamLAND-zen

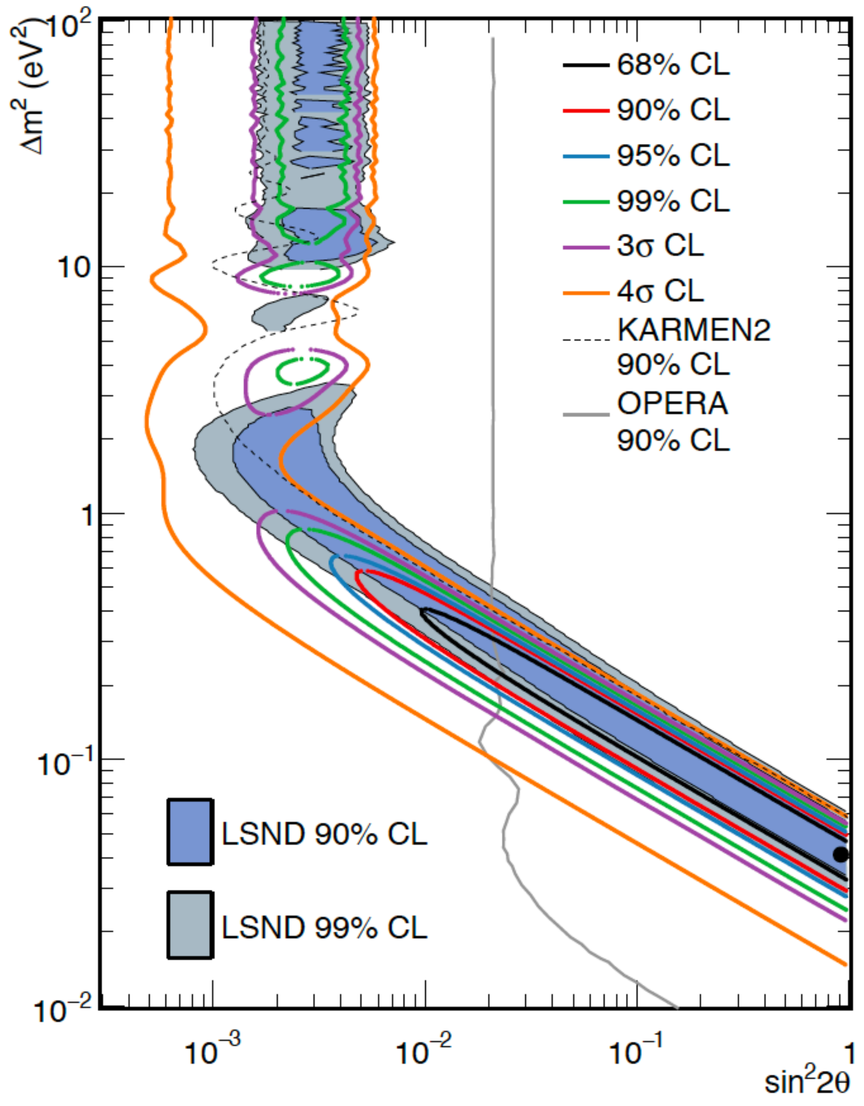
Figure from Lokhov, Mertens, Parno, Schlösser, Valerius, Ann.Rev.Nucl.Part.Sci. 72 (2022) 259-282

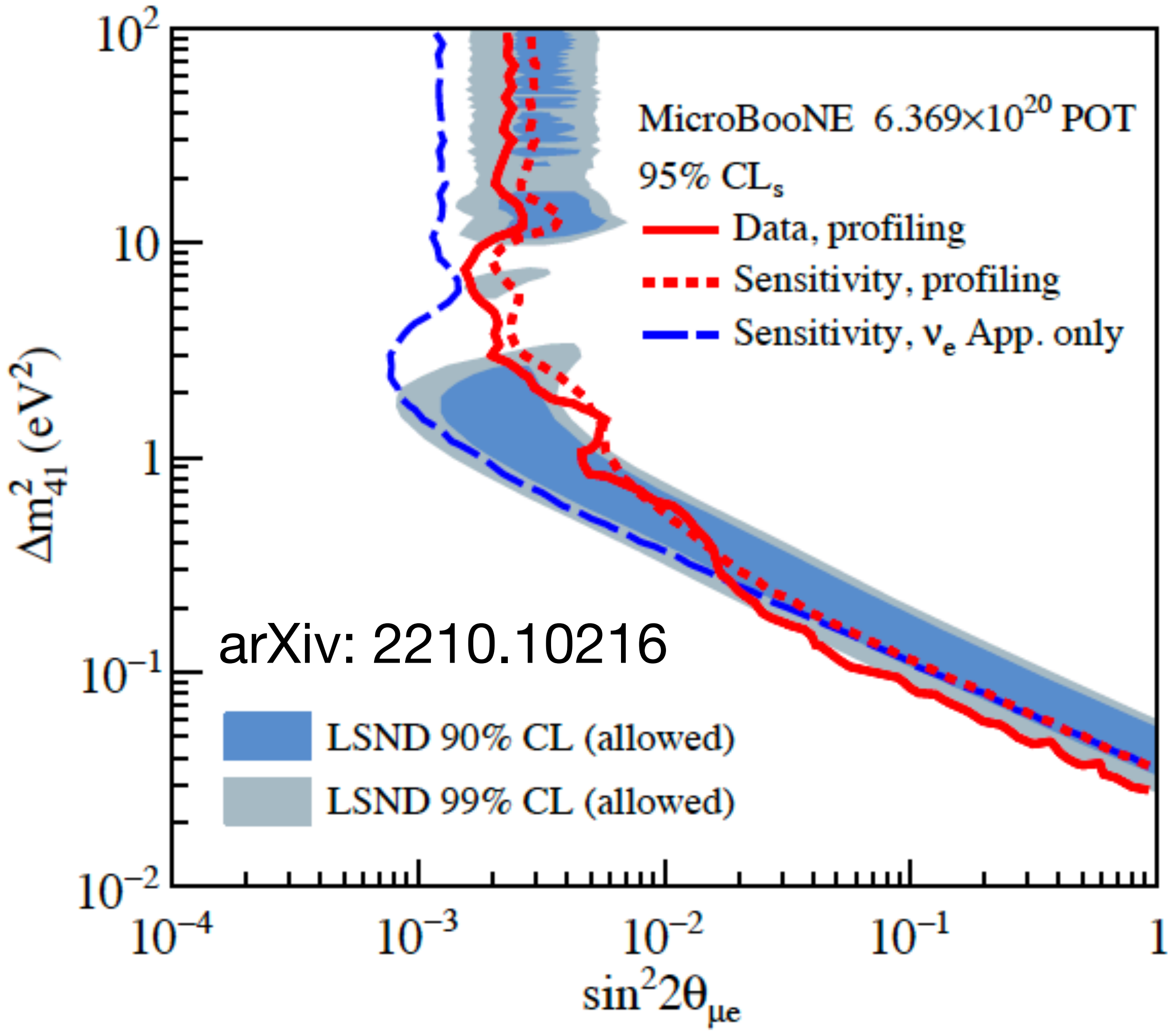
Motivation of sterile neutrinos

- Sterile neutrinos have been suggested and probed in a wide mass range according to various motivations.
  - Light sterile neutrinos in eV scale were motivated by anomalies observed at neutrino oscillation experiments.
  - keV sterile neutrinos can be dark matter candidates.
  - GeV sterile neutrinos were introduced to generate neutrino mass and explain baryon asymmetry of Universe (BAU).

Status of light sterile neutrinos - SBL accelerator

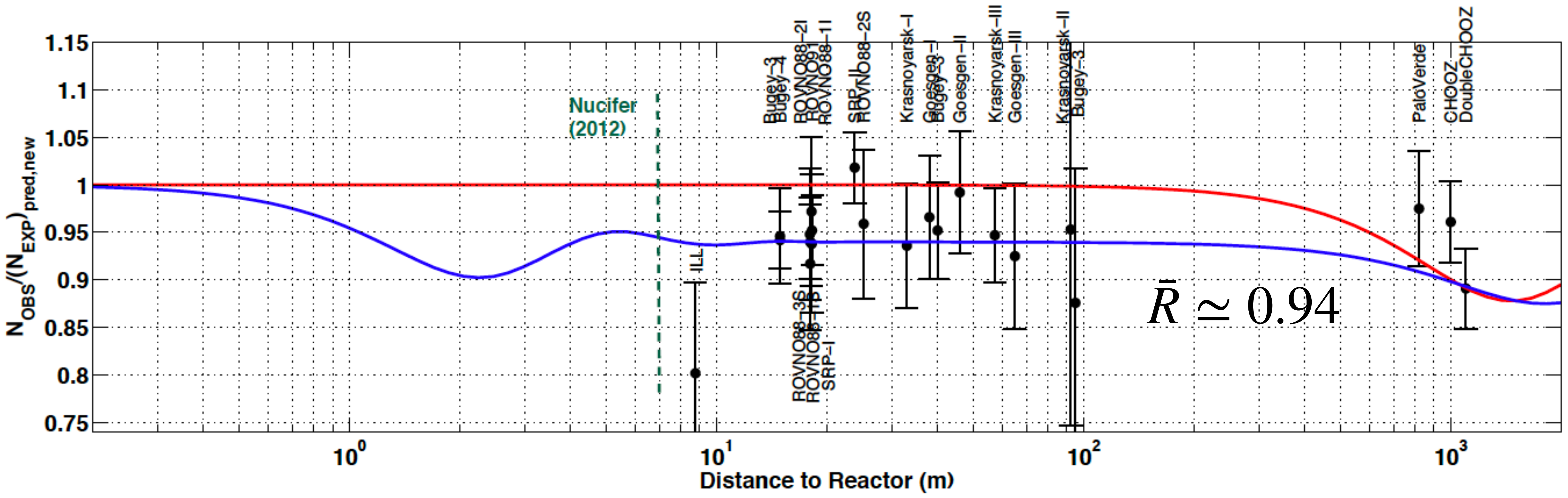
- LSND and MiniBooNE observed excess of $\overline{\nu}_e$ (ν_e) from $\overline{\nu}_\mu \to \overline{\nu}_e$ $(\nu_\mu \to \nu_e)$.
- Recent MicroBooNE results:
  - no evidence of sterile neutrino oscillations and consistent with 3 neutrino oscillations hypothesis.
- Can be cross-checked by other experiments, JSNS² and SBNP@Fermilab.



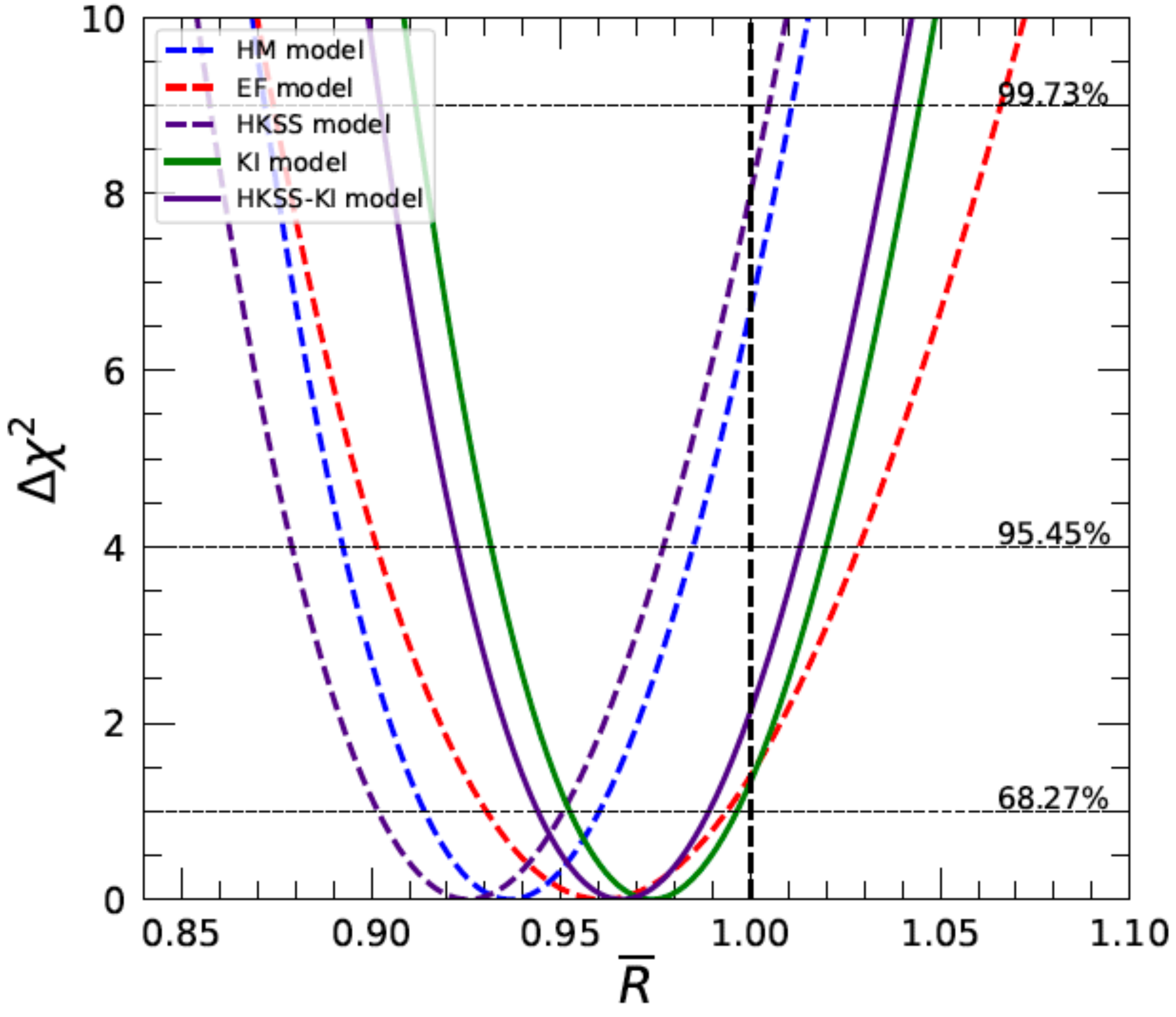


Status of light sterile neutrinos @ SBL Reactor

- Deficit was observed in $\bar{\nu}_e$ disappearance channel => Reactor Antineutrino Anomaly (RAA)
- Reactor neutrino fluxes have been re-evaluated.
- Improved flux models mostly reduce the RAA and disfavor the interpretation of sterile neutrino.
  -> but not conclusively excluded.

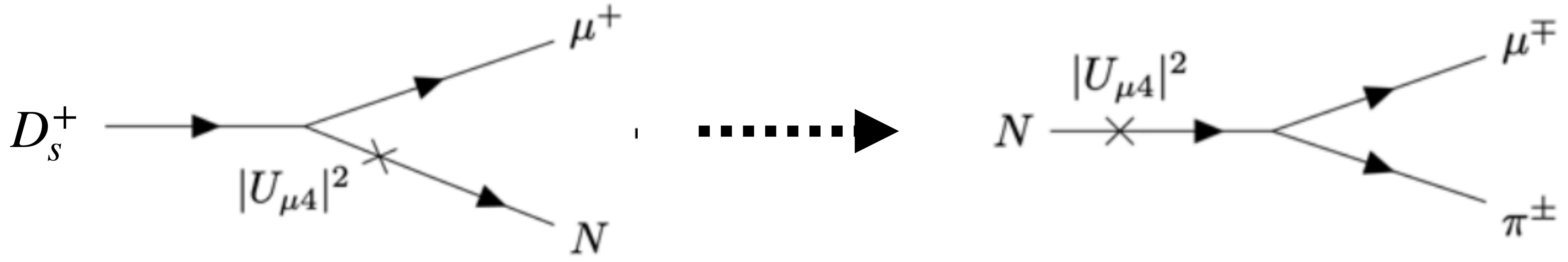


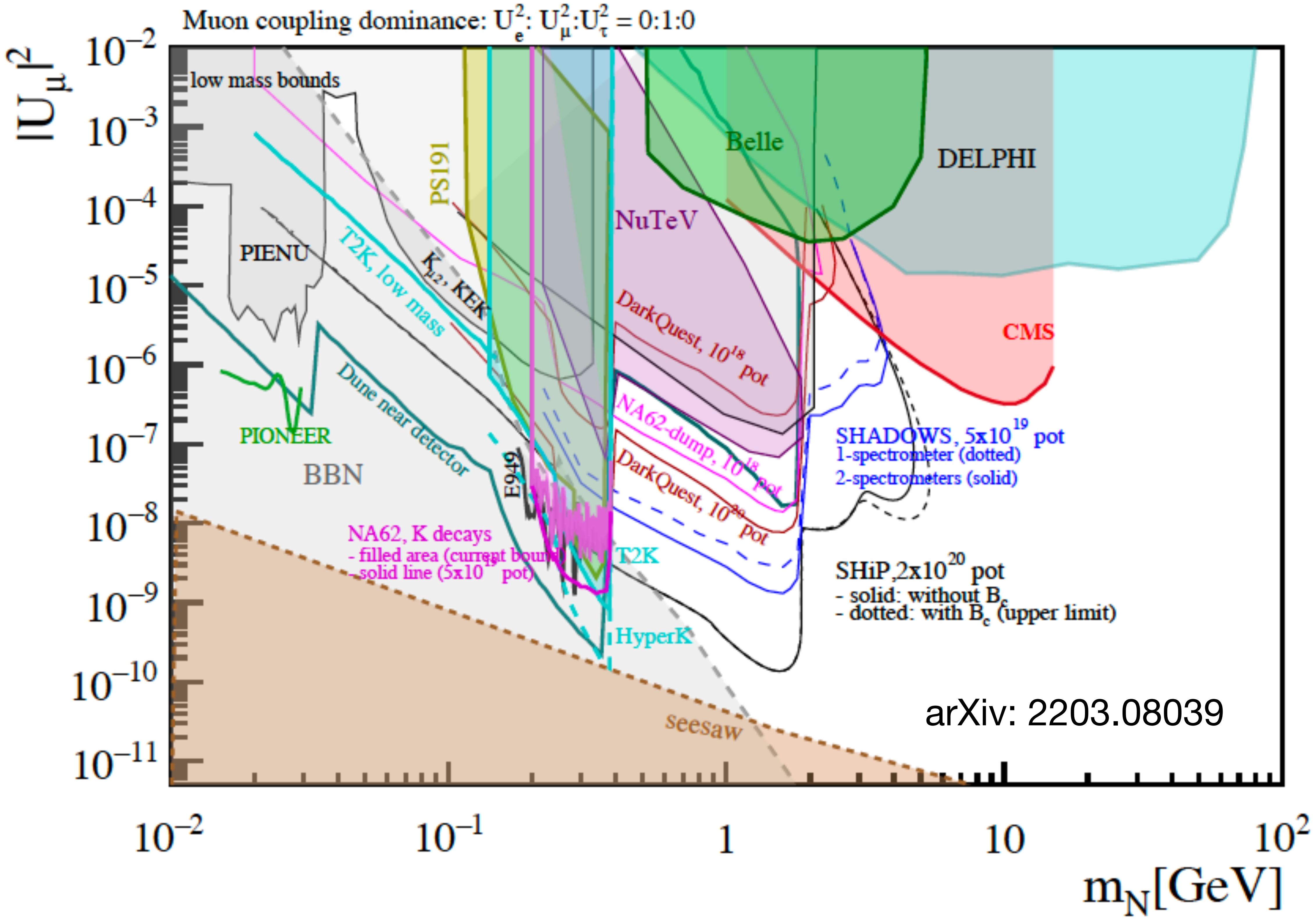
Giunti et al. arXiv:2110.06820



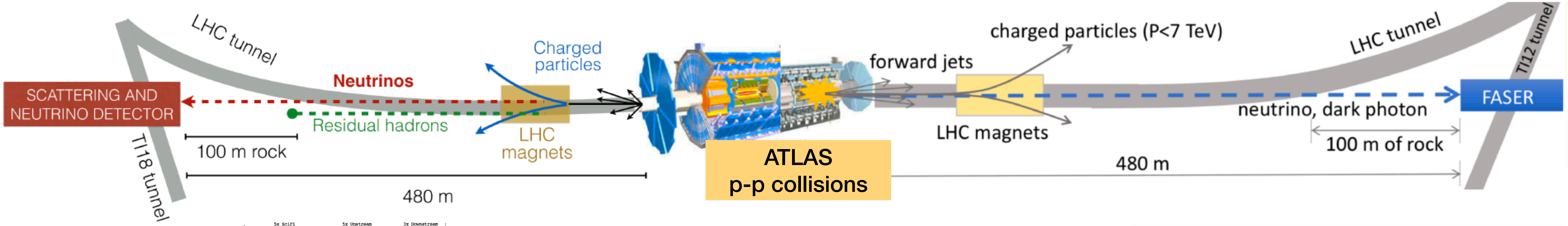
Heavy neutral lepton (HNL)

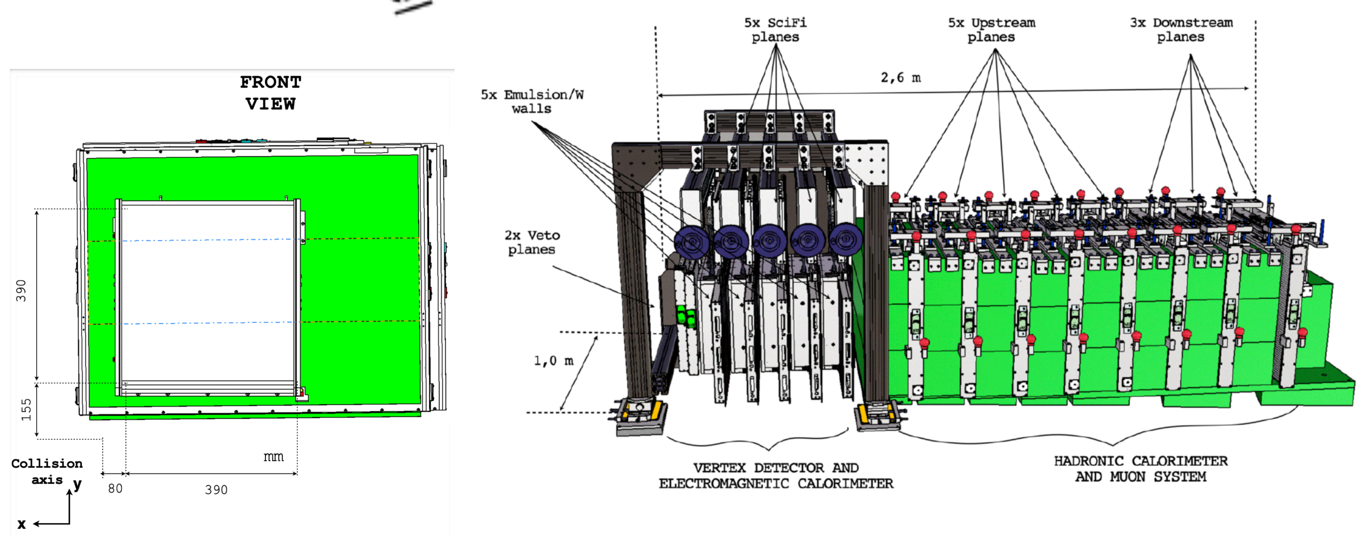
- GeV sterile neutrino is referred to as heavy neutral lepton (HNL).
- Can be probed by fixed target and collider experiments:
  - Fixed target: SHiP, (proto)DUNE, NA62, T2K, MicroBooNE …
  - Collider: FASER, CMS, ATLAS …
  - e.g. at SHiP

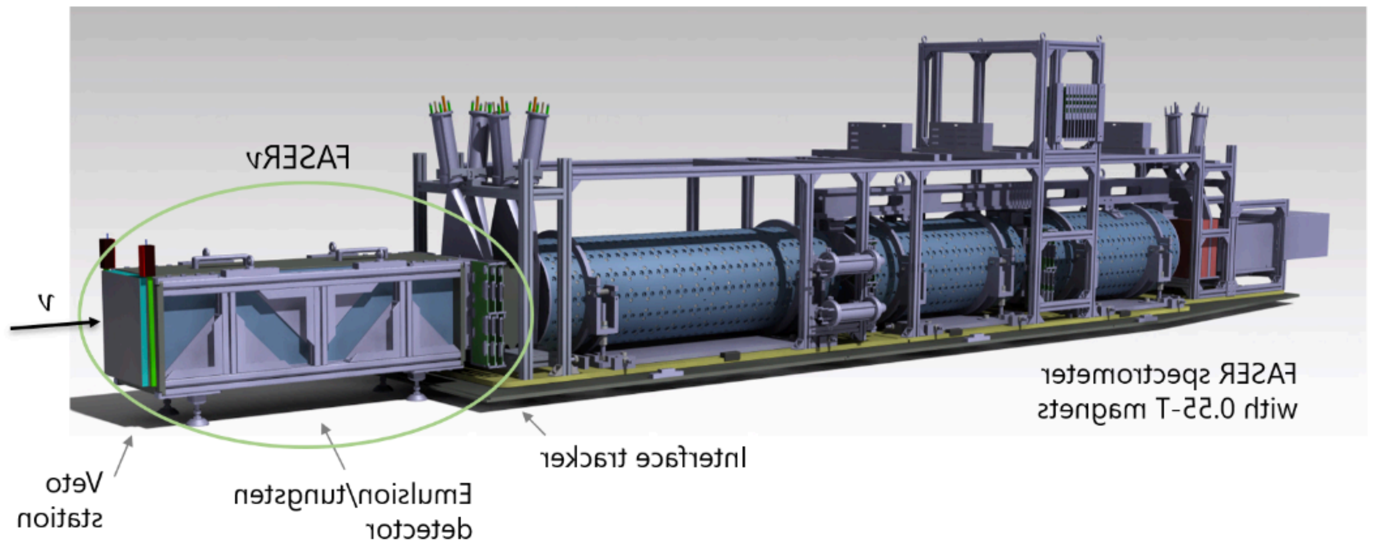




Forward neutrino search at the LHC





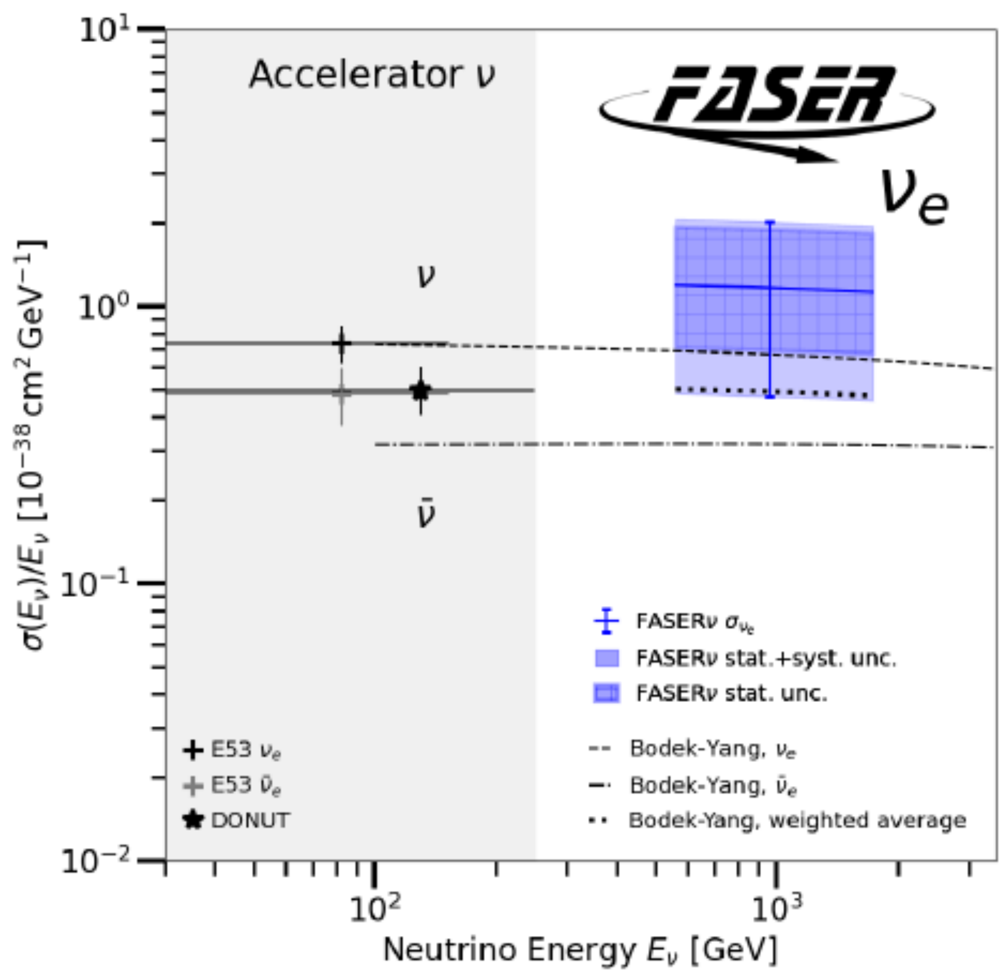


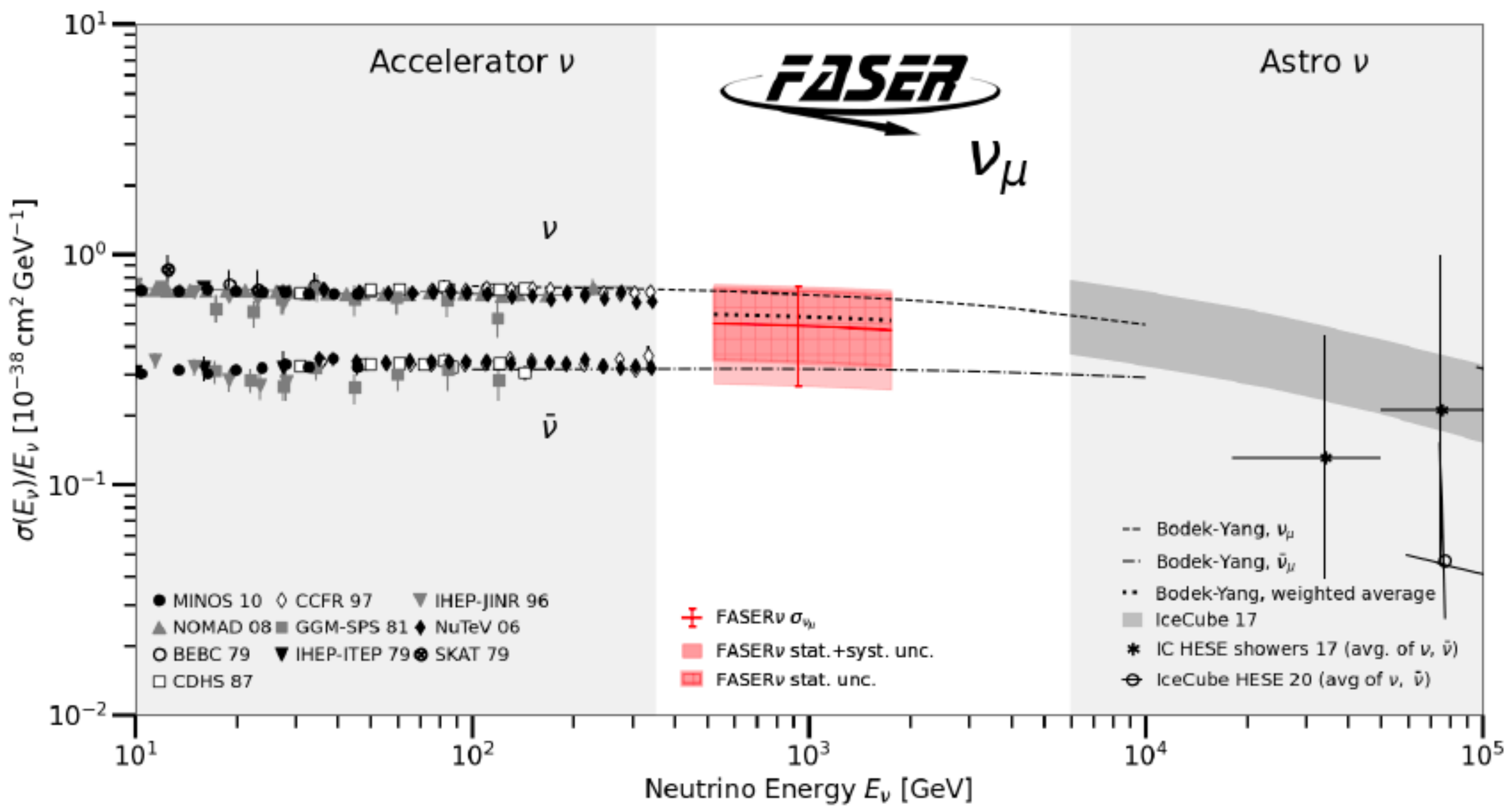
	SND@LHC	FASERν
Rapidity	$7.2 < \eta < 8.4$ (off-axis)	$\eta \gtrsim 8.5$ (on-axis)
Target material	Tungsten (w/ emulsion film)	Tungsten (w/ emulsion film)
Target mass	830 kg	1.1 tons
Surface	39 x 39 cm^2	25 x 30 cm^2 (1.1 m long)

Results from the 1st stage forward experiments

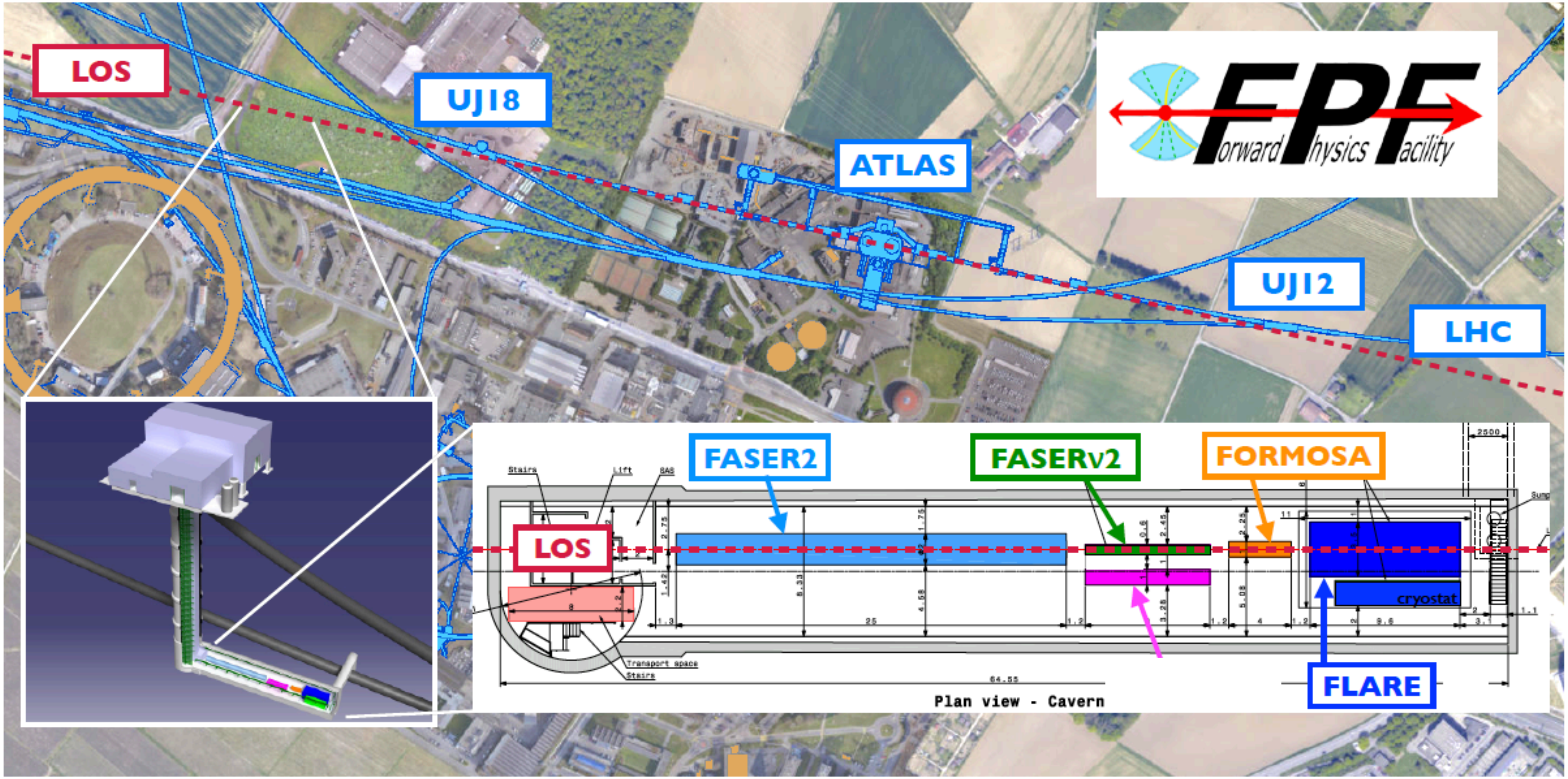
- First Observation of Collider Neutrinos
  - PRL 131, 031801 (2303.14185; FASER) - 153^{+12}_{-13} muon neutrinos
  - PRL 131, 031802 (2305.09383, SND@LHC) - 8 muon neutrinos

- First measurement of the neutrino interaction cross section (2403.12520, FASER)





Forward Physics Facility (FPF) during HL-LHC



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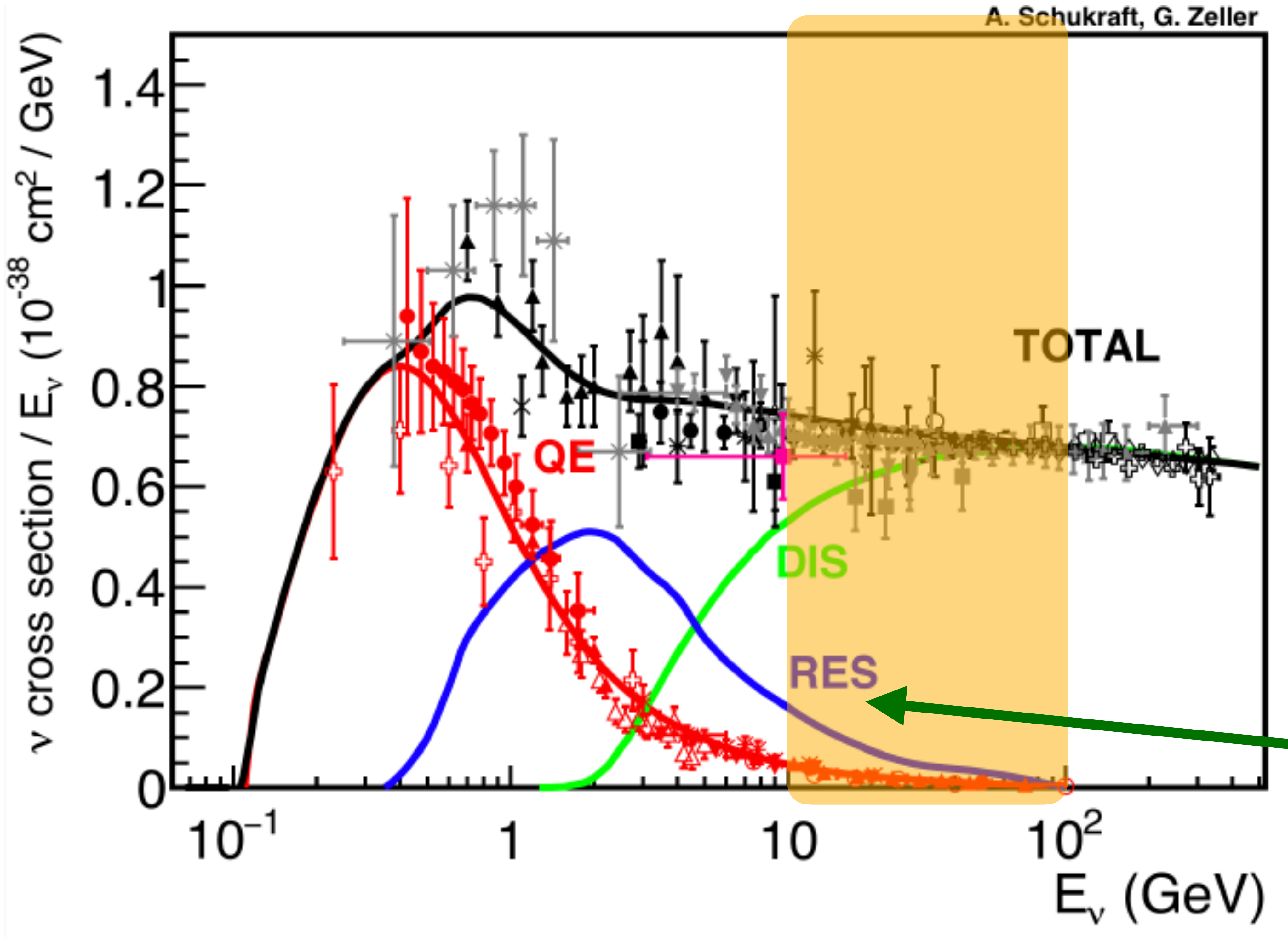
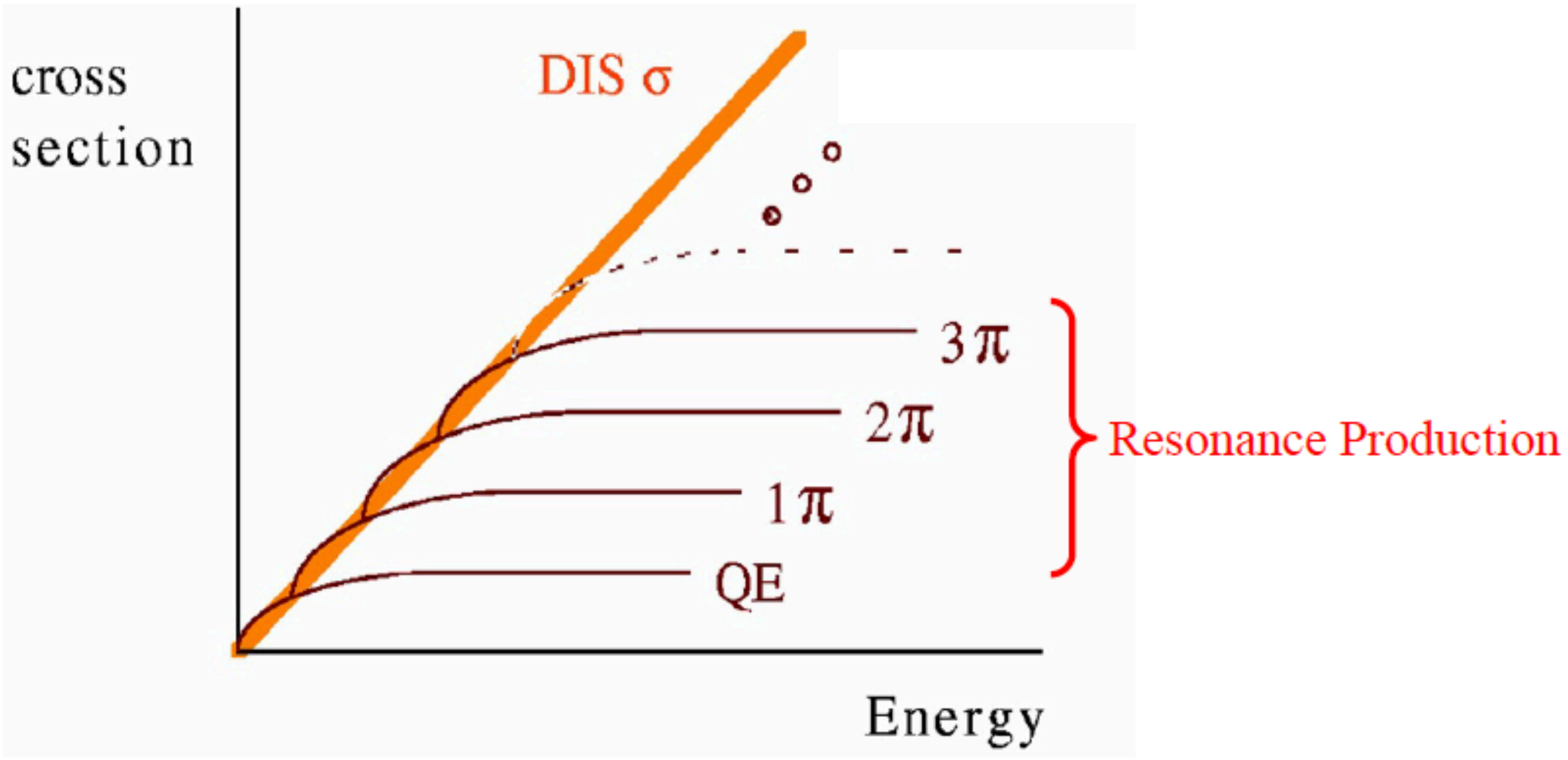
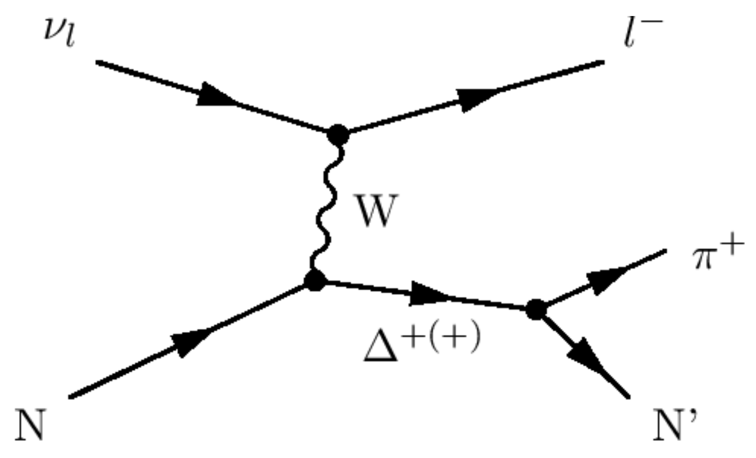
Interactions at transition region from RES to DIS

- LHC neutrinos have energies from ~10 GeV to O(1) TeV.





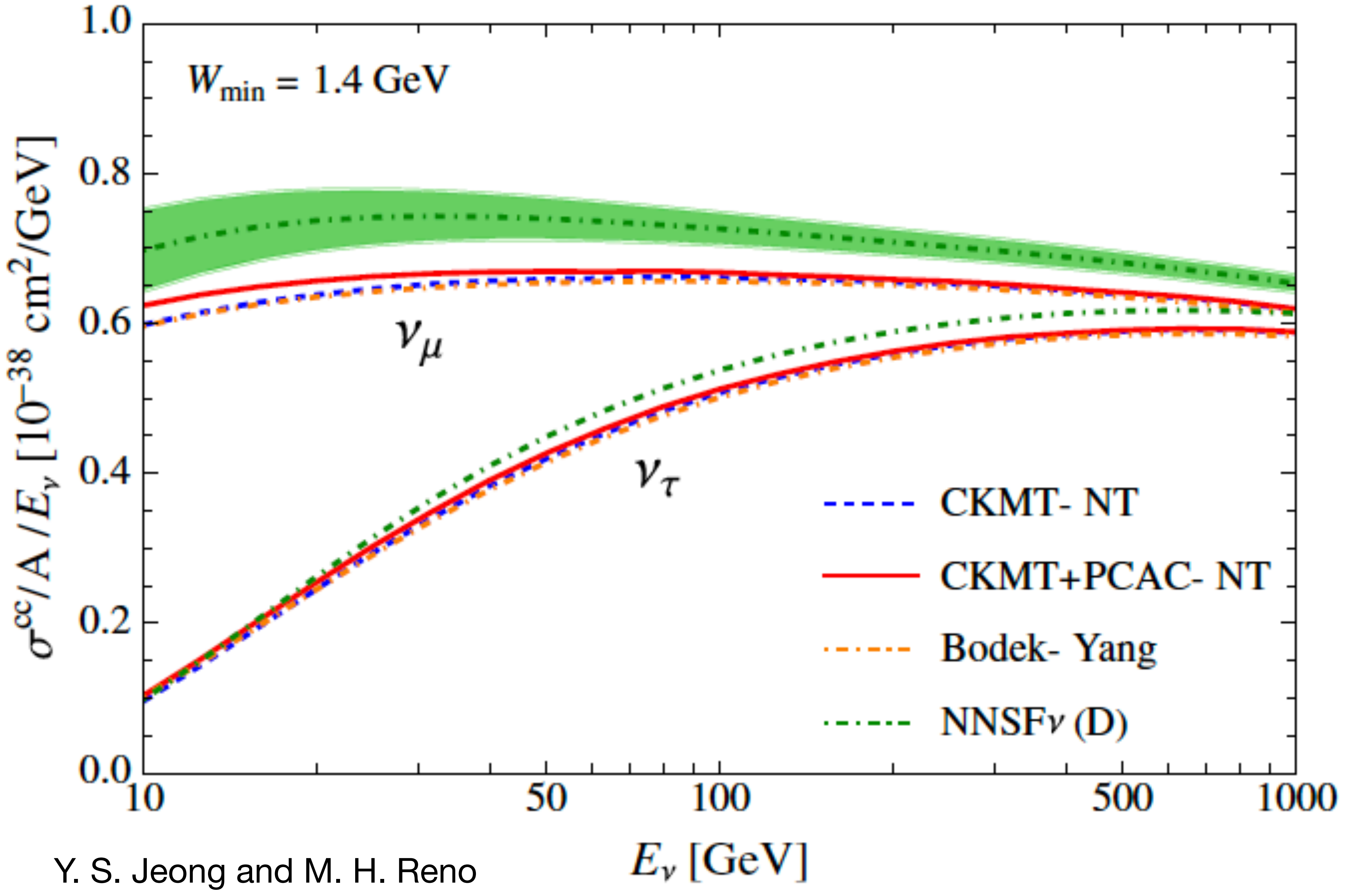
Single pion production



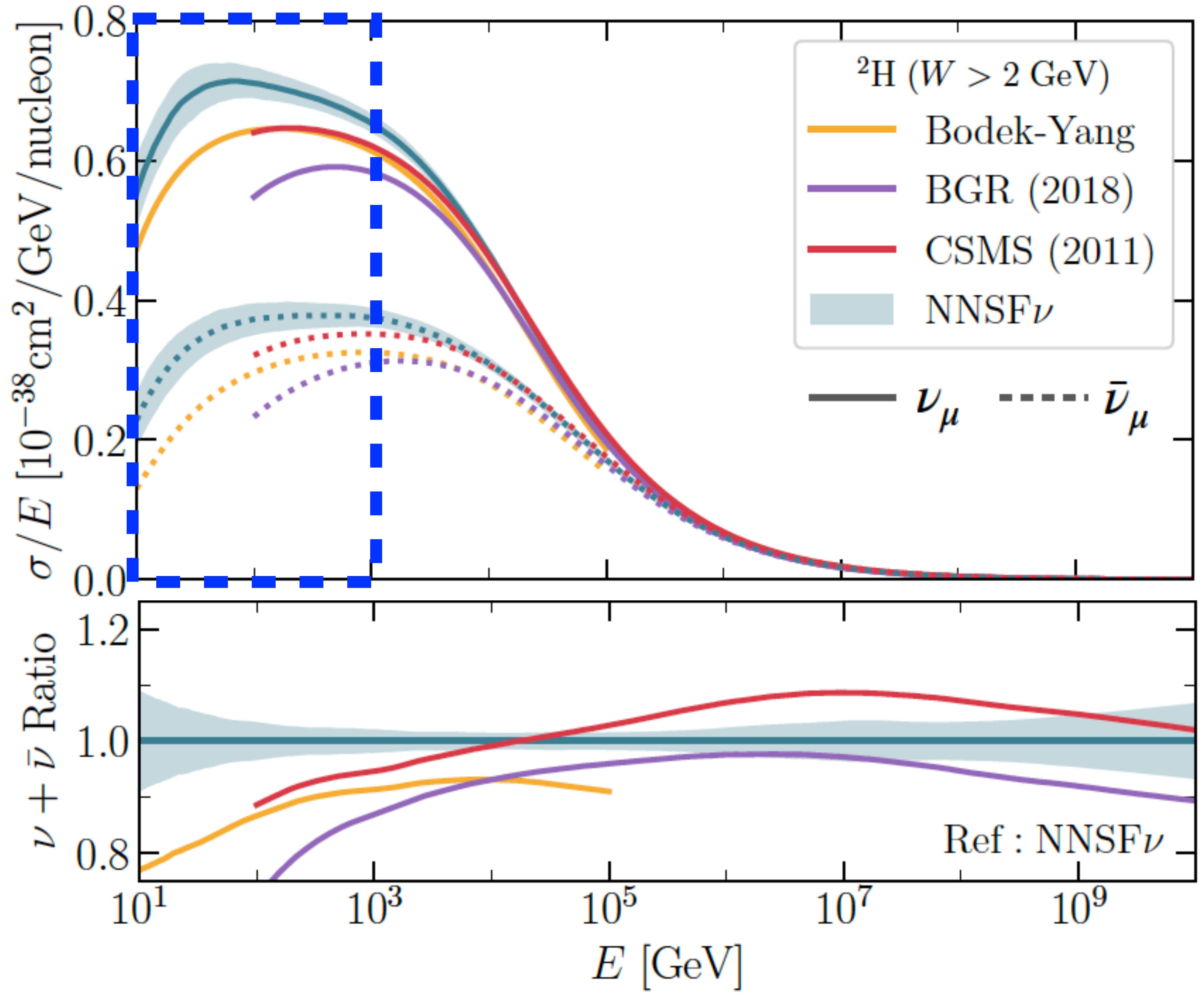
DIS cross sections from different low-Q structure functions

- Neutrino-nucleon charged-current (CC) cross section for deep inelastic scattering :

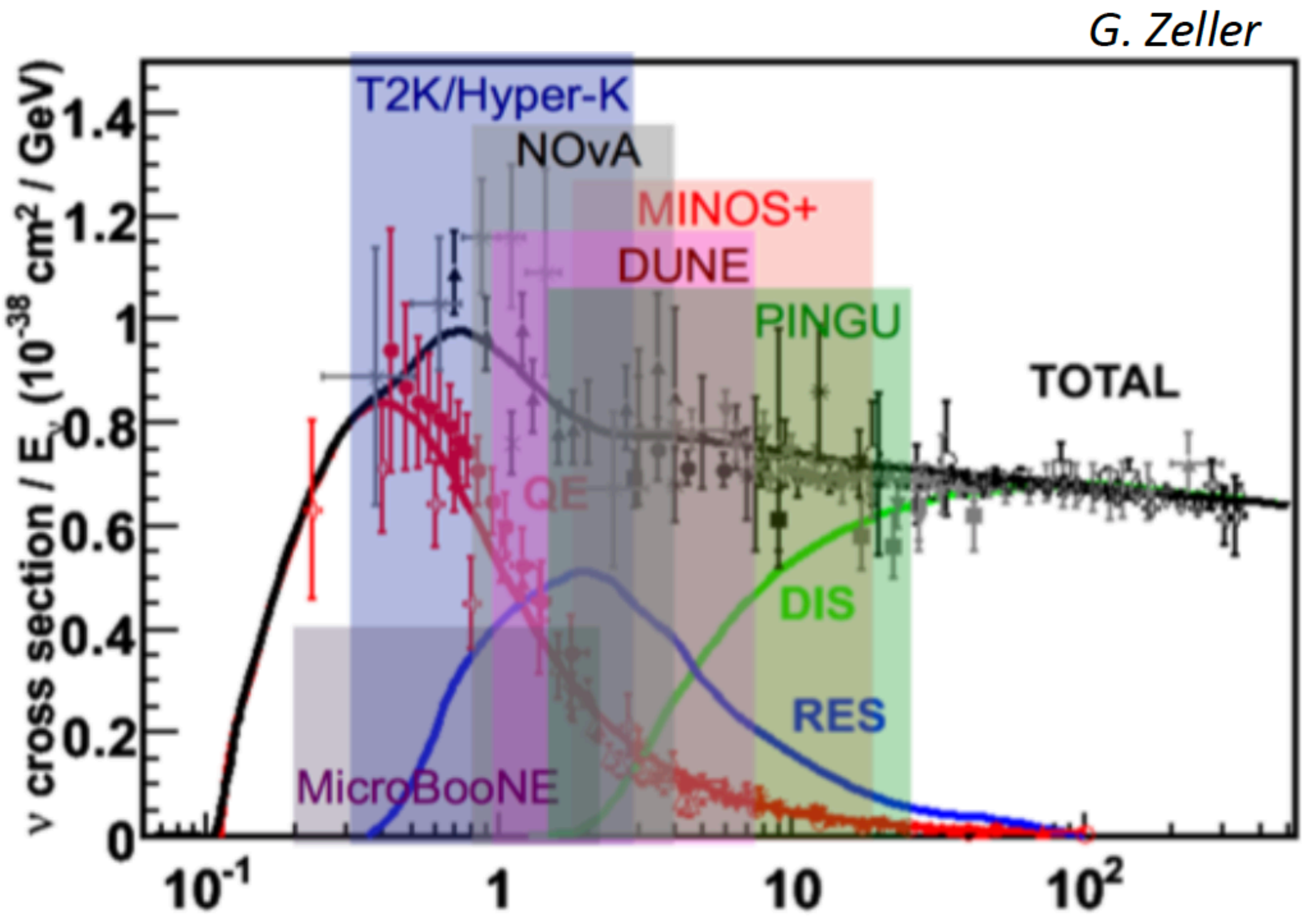
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} \simeq \frac{G_F^2 m_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\left[y^2 x\,F_{1,\mathrm{CC}}(x,Q^2) + \left((1-y) - \frac{m_N x}{2E_\nu}y\right)F_{2,\mathrm{CC}}(x,Q^2) \pm xy\left(1-\frac{y}{2}\right)F_{3,\mathrm{CC}}(x,Q^2)\right]$$



Y. S. Jeong and M. H. Reno
Phys. Rev. D 108, 113010 (2023)



Energy region for oscillation experiments



Summary

- The oscillations parameters in three neutrino framework are mostly well constrained.
  - There are still things to be understood; mass ordering, CP violation and T2K-NOvA tension.
  - More data from future LBL accelerator and atmospheric neutrinos will improve precision and could provide some clues for existing tension.
- Absolute mass measurements have been improved covering lower mass region.
- Evidence of light sterile neutrinos is getting weaker, although they are not conclusively excluded.
- There are new experiments and proposals to probe neutrino properties and BSM scenarios.