New Physics v.s. Nuclear Physics from Neutrino Physics (NP3)

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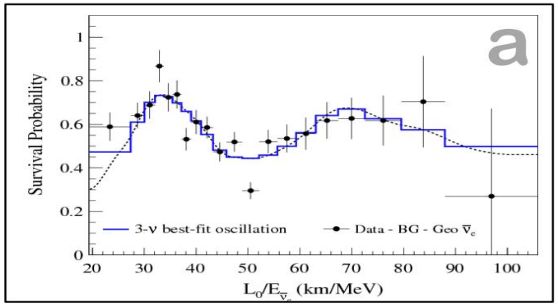
第四届高能物理理论与实验融合发展研讨会

辽宁大连

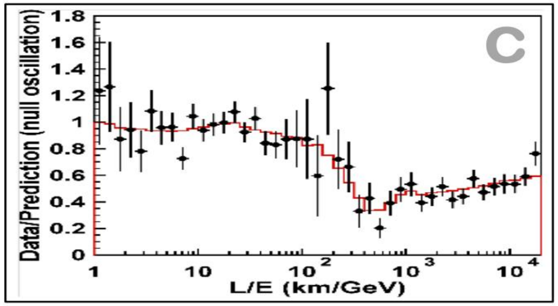
21st Sep. 2025

Neutrinos Do Oscillate!

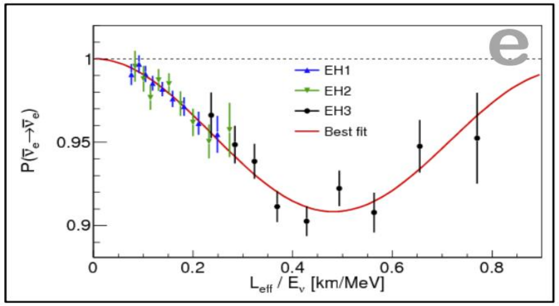
e→e



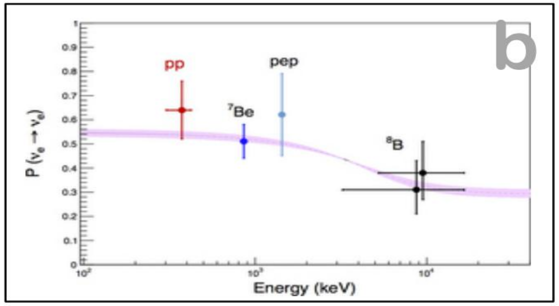
μ→μ



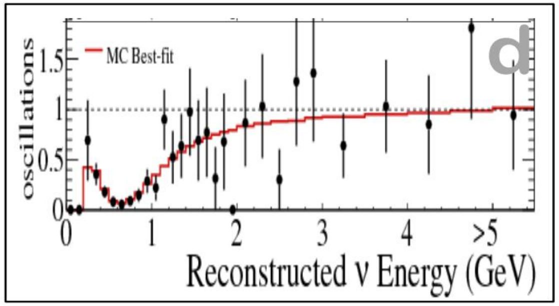
e→e



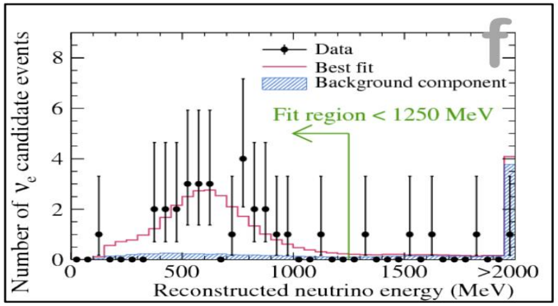
e→e



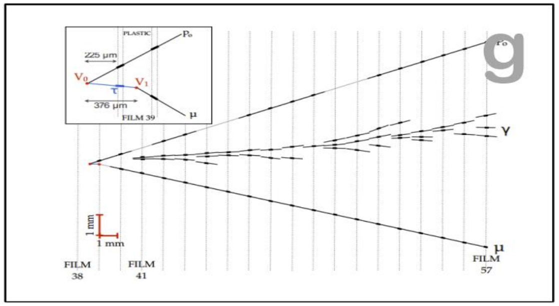
μ→μ



μ→e



μ→τ



Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

Three Neutrino Paradigm

Standard Parameterization of Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $\quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

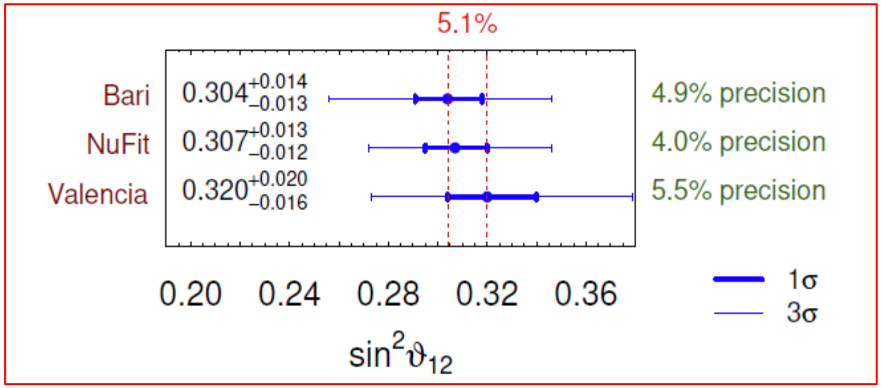
3 Mixing Angles: $\vartheta_{12}, \vartheta_{23}, \vartheta_{13}$

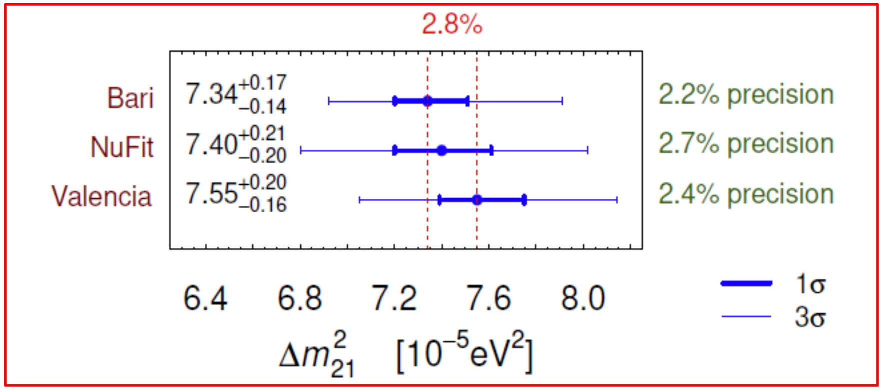
1 CPV Dirac Phase: δ_{13}

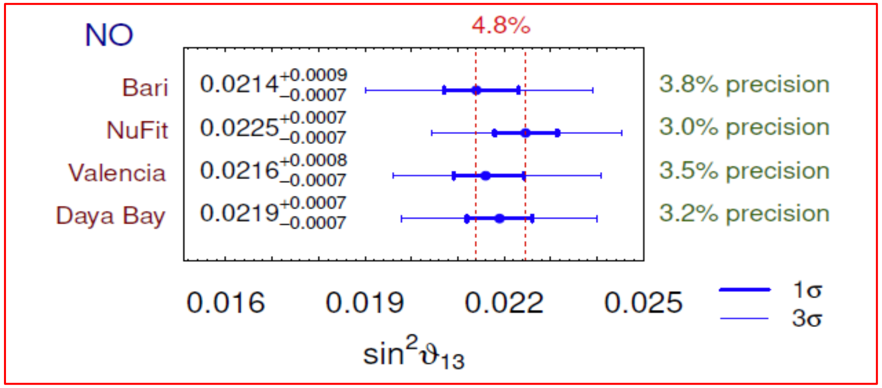
2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: $\Delta m^2_{21}, \Delta m^2_{31}$

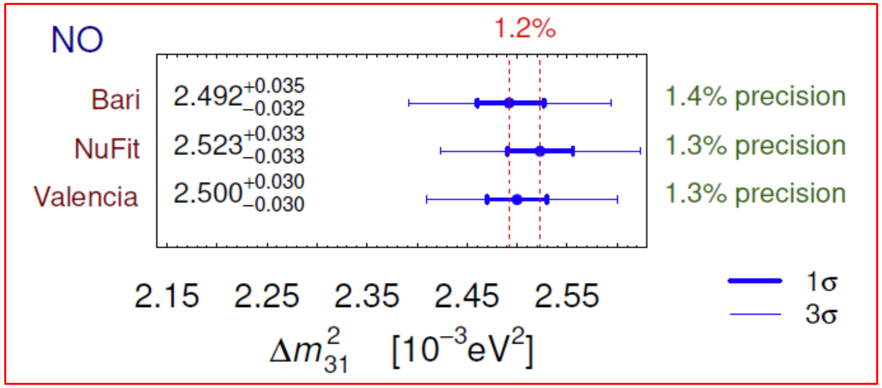
- **Absolute Mass Scale**
- **Two CPV Majorana Phases**

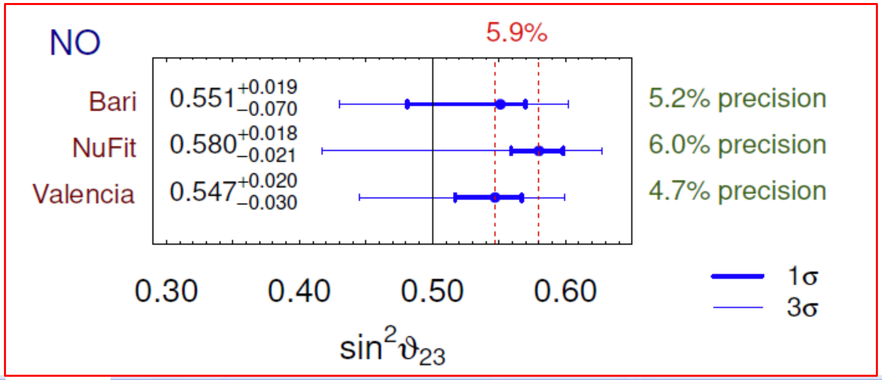
Global picture





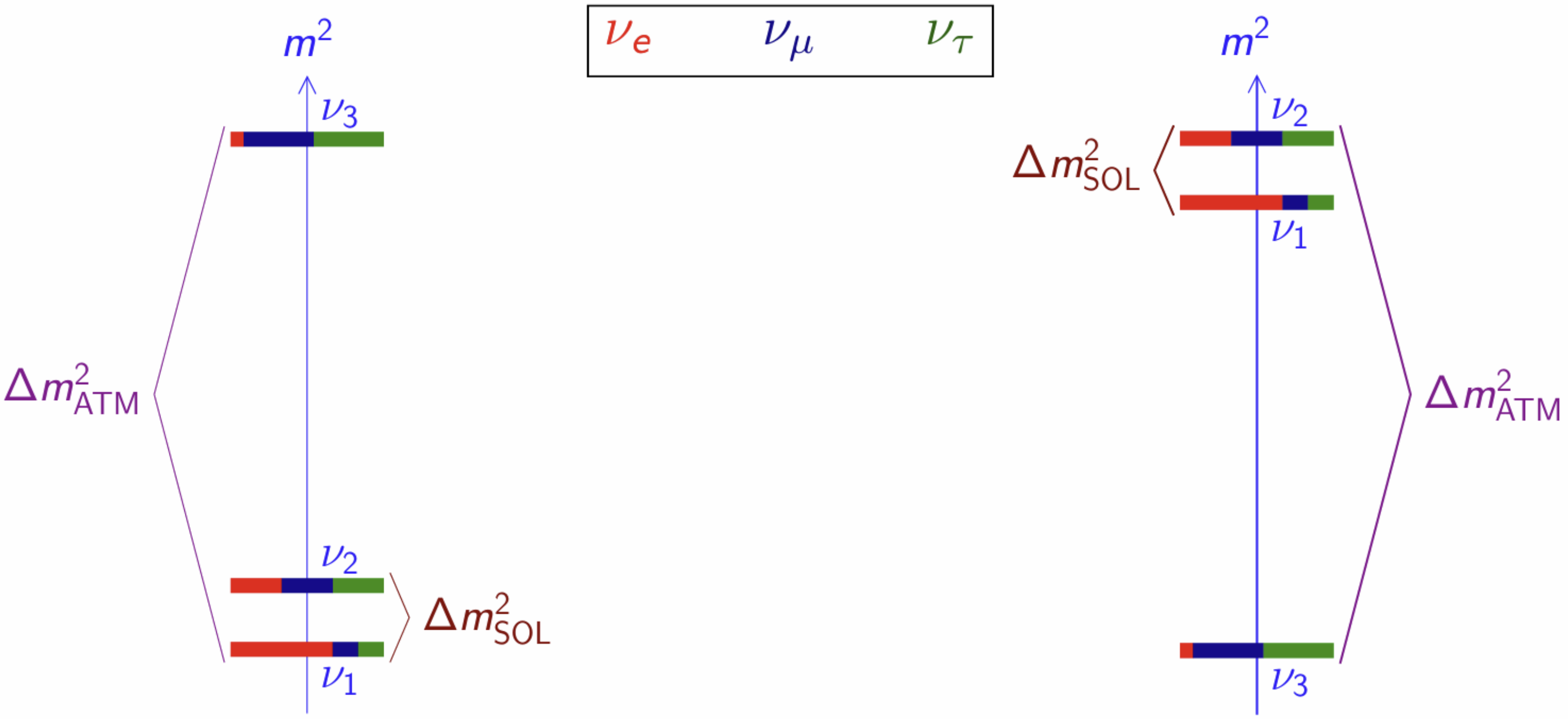






- **5 parameters: measured with rather high accuracy**
- **Mass ordering, CP violation to be determined**

Unknowns: mass ordering and CP violation



Normal Ordering

$$\Delta m^2_{31} > \Delta m^2_{32} > 0$$

Inverted Ordering

$$\Delta m^2_{32} < \Delta m^2_{31} < 0$$

absolute scale is not determined by neutrino oscillation data

Unknowns: mass ordering and CP violation

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \underbrace{\sum_{k>j} \mathrm{Re}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)}_{\text{CP conserving}}$$

$$+ 2 \underbrace{\sum_{k>j} \mathrm{Im}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*\right] \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)}_{\text{CP violating}}$$

- The oscillation probabilities depend on the quartic rephasing invariants

$$U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*$$

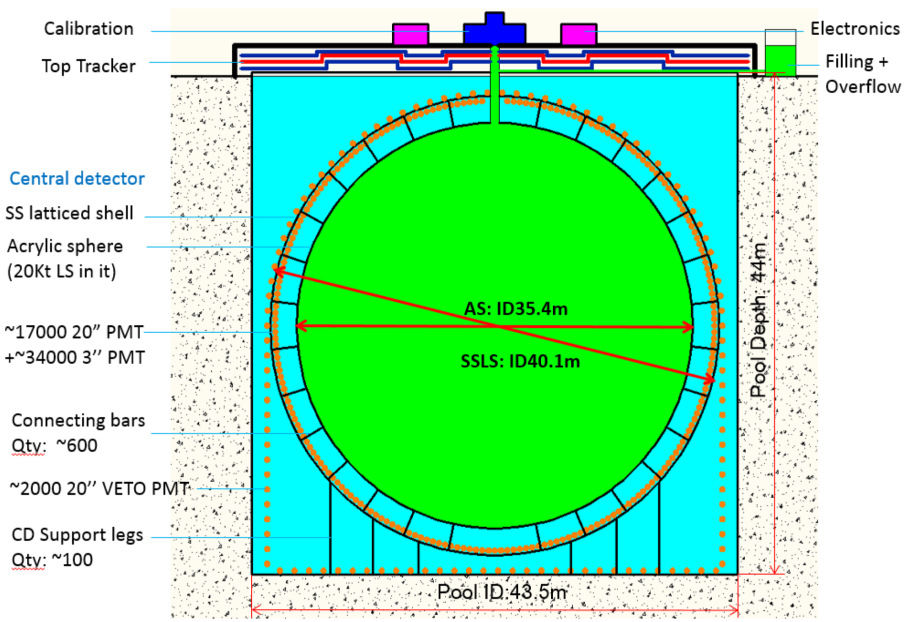
- CP violation depends on the Jarlskog invariant

$$J_{\mathrm{CP}} = \pm \, \mathrm{Im}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*\right] = c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} \sin\delta_{13}$$

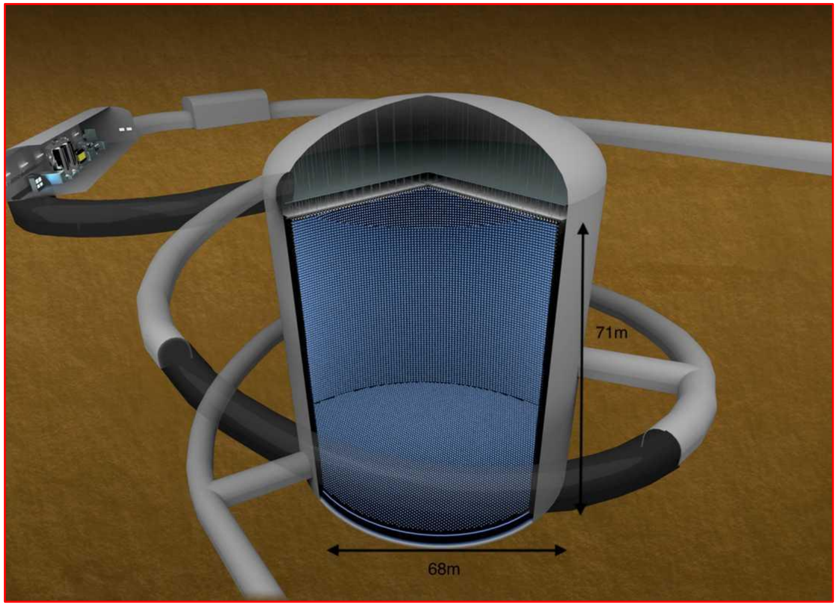
Open questions

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), ...
- CP violation ? $\delta_{13} \approx 3\pi/2$?
  - T2K (Japan), NOνA (USA), DUNE (USA), HyperK (Japan), ...
- Mass Ordering ?
  - JUNO (China), PINGU (Antarctica), ORCA (EU), INO (India), ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

Three future experiments



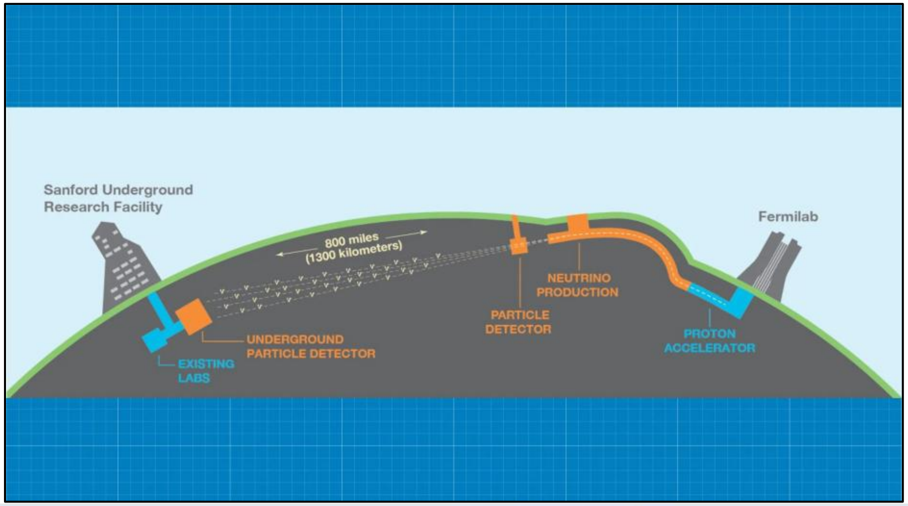
AS: Acrylic sphere; SSLS: stainless steel latticed shell



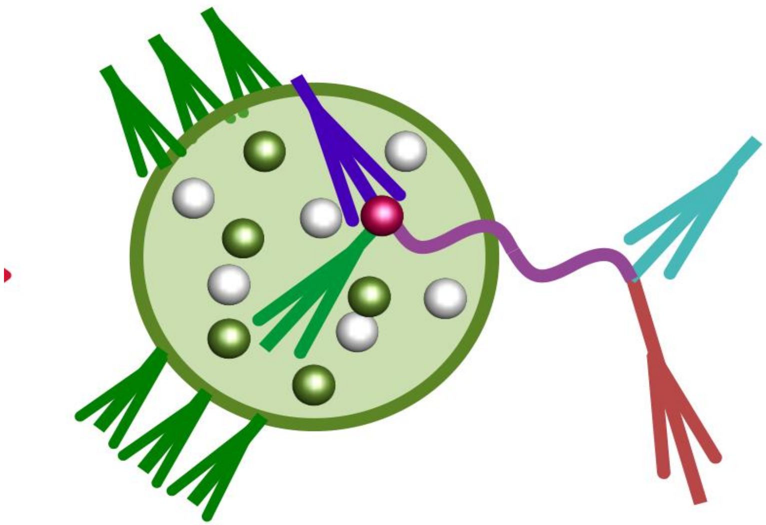
JUNO: 2025 (running)
Reactor neutrinos for MO

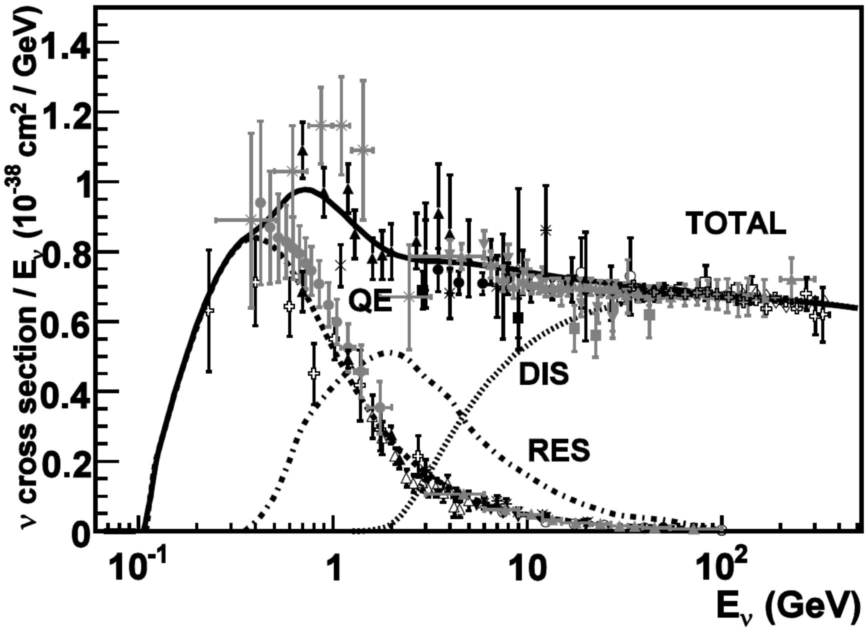
Hyper-Kamiokande: 2028
Acc. & Atm. neutrinos, MO & CP

DUNE: 2031
Acc. & Atm. neutrinos, MO & CP



A: GeV neutrino-nucleus interactions





quasielastic scattering	resonance production	deep-inelastic scattering
$\nu_l + n \rightarrow l^- + p$ $\overline{\nu_l} + p \rightarrow l^+ + n$	$\nu_l + n \rightarrow l^- + \Delta^+$ $\nu_l + p \rightarrow l^- + \Delta^{++}$ $\overline{\nu_l} + n \rightarrow l^+ + \Delta^-$ $\overline{\nu_l} + p \rightarrow l^+ + \Delta^0$	$\nu_l + N \rightarrow l^- + N' + n\pi$ $\overline{\nu_l} + N \rightarrow l^- + N' + n\pi$
Fermi motion, binding energy, M_A, 2p2h, … …	**Hardon production, FSI**	**Parton Model, FSI**

GeV neutrino interaction generators

Marco Roda @ NUINT24

Status overview

GENIE — UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

- Well established generator
  - Used by many experiments around the world
    - Main new addition is JUNO
  - Main generator for all the LAr experiments
- Two main efforts
  - Model development
  - Tuning
- Contacts, details and code are all available from our website: www.genie-mc.org/
- Latest release: version 3.04.02, released in April 2024
  - Previous release was 3.04.00, released in March 2023
  - http://releases.genie-mc.org/
- Recent publications
  - Neutrino-nucleon cross-section model tuning in GENIE v3 - Phys.Rev.D 104 (2021) 7, 072009
  - Hadronization model tuning in genie v3 - Phys.Rev.D 105 (2022) 1, 012009

GiBUU

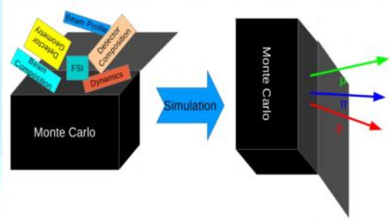
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Ulrich Mosel and Kai Gallmeister @ NUINT24

- GiBUU is presently used to describe
  1. Dilepton and pion production in heavy-ion collisions (HADES experiment at GSI)
  2. Inelastic electron scattering at JLAB (and SLAC, MAMI)
  3. Neutrino-nucleus reactions at Fermilab, T2K and FASER
- All with the same theory input and code!
- We provide the code for download from gibuu.hepforge.org,

NuWro - general information (1)

Jan T. Sobczyk @ NUINT24



- Monte Carlo generator of neutrino interactions
- Beginning ~ 2005 at the University of Wrocław
- Optimized for ~1 GeV
- Can handle all kind of targets, neutrino fluxes, equipped with detector interface
- Written in C++
- Output files in the ROOT format
- PYTHIA6 used for hadronization in DIS
- Open source code, repository: https://github.com/NuWro/nuwro

NuWro — Wroclaw Neutrino Event Generator

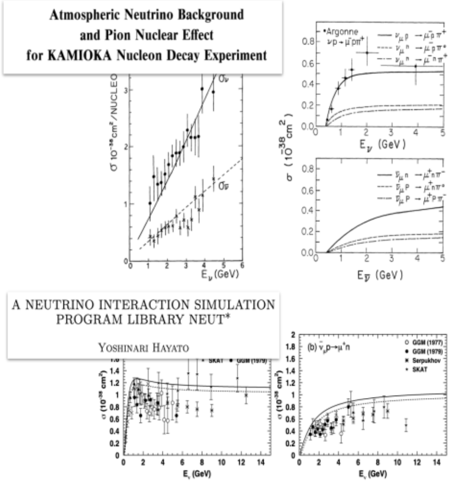
3

Patrick Stowell @ NUINT24

The NEUT neutrino interaction simulation program library

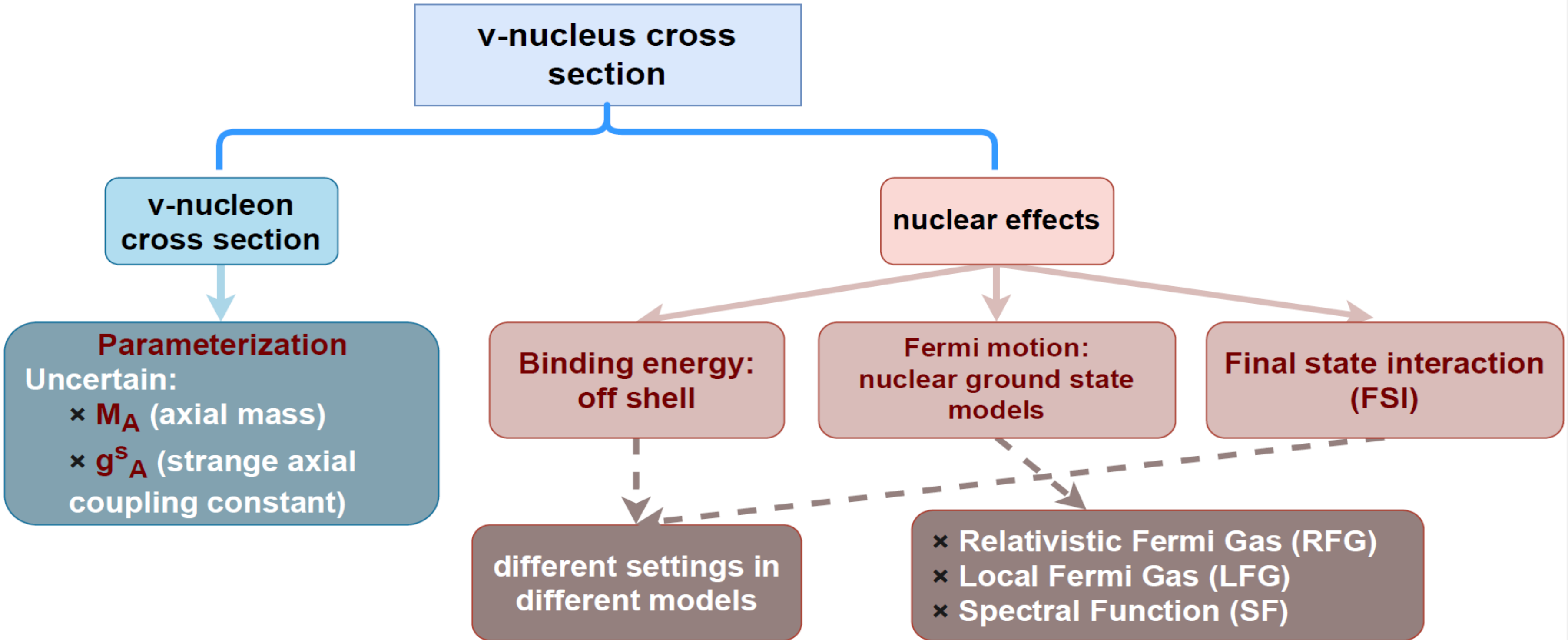
Yoshinari Hayato and Luke Pickering — The European Physical Journal Special Topics volume 230, pages 4469–4481 (2021)

- MeV to TeV scale neutrino interaction generator originally created in the 70s to support neutrino backgrounds at Kamioka.
- Long history of development driven by evolving requirements of KamiokaNDE, Super-KamiokaNDE, and T2K.
- Currently the primary interaction generator for SK and T2K, used in all oscillation/cross-section analyses.
  - See Laura, Stephen, Ulyesse, and Cesar's talks this NuINT!



General components in generator

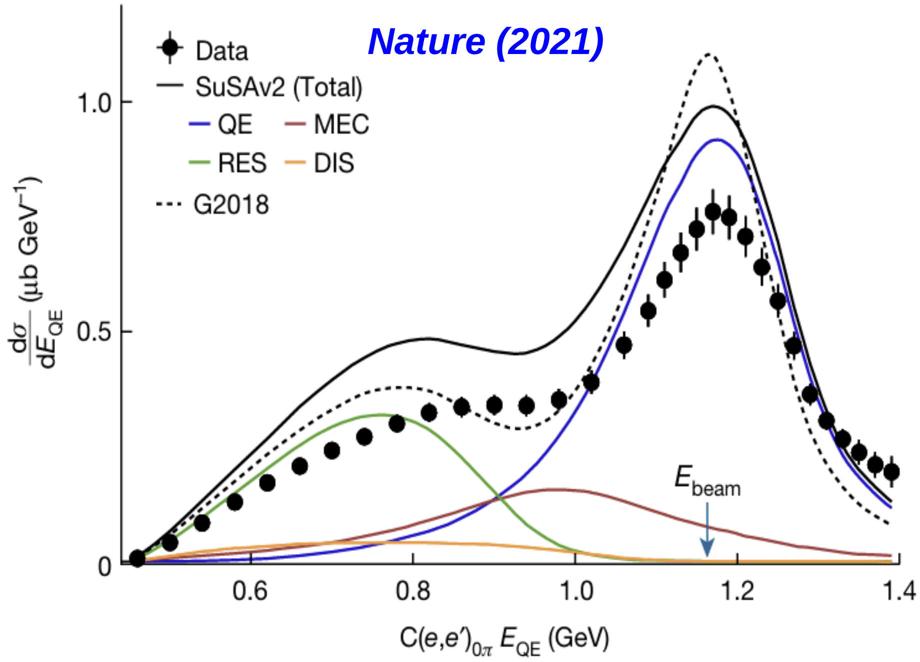
Brief summary of GeV neutrino interaction models

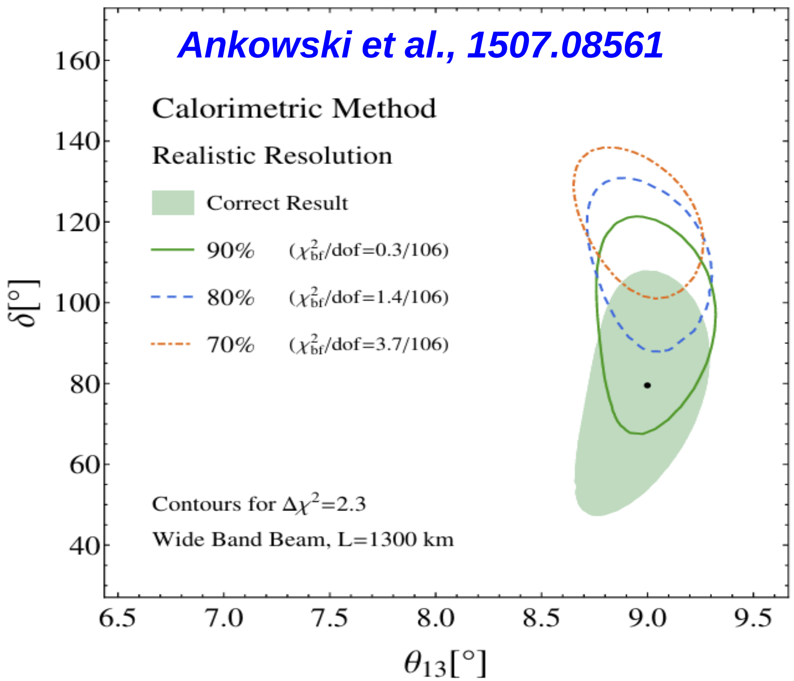


$$\frac{d\sigma^{\mathrm{IA}}_{\ell A}}{d\omega d\Omega} = \sum_N \int \boxed{d^3p\, dE\, P^N_{\mathrm{hole}}(\mathbf{p}, E)} \boxed{\frac{M}{E_{\mathbf{p}}} \frac{d\sigma^{\mathrm{elem}}_{\ell N}}{d\omega d\Omega}} \boxed{P^N_{\mathrm{part}}(\mathbf{p}', \mathcal{T}')}$$

average over the initial nucleon state | nucleon cross section | final-state interactions

Nuclear effects on oscillation search

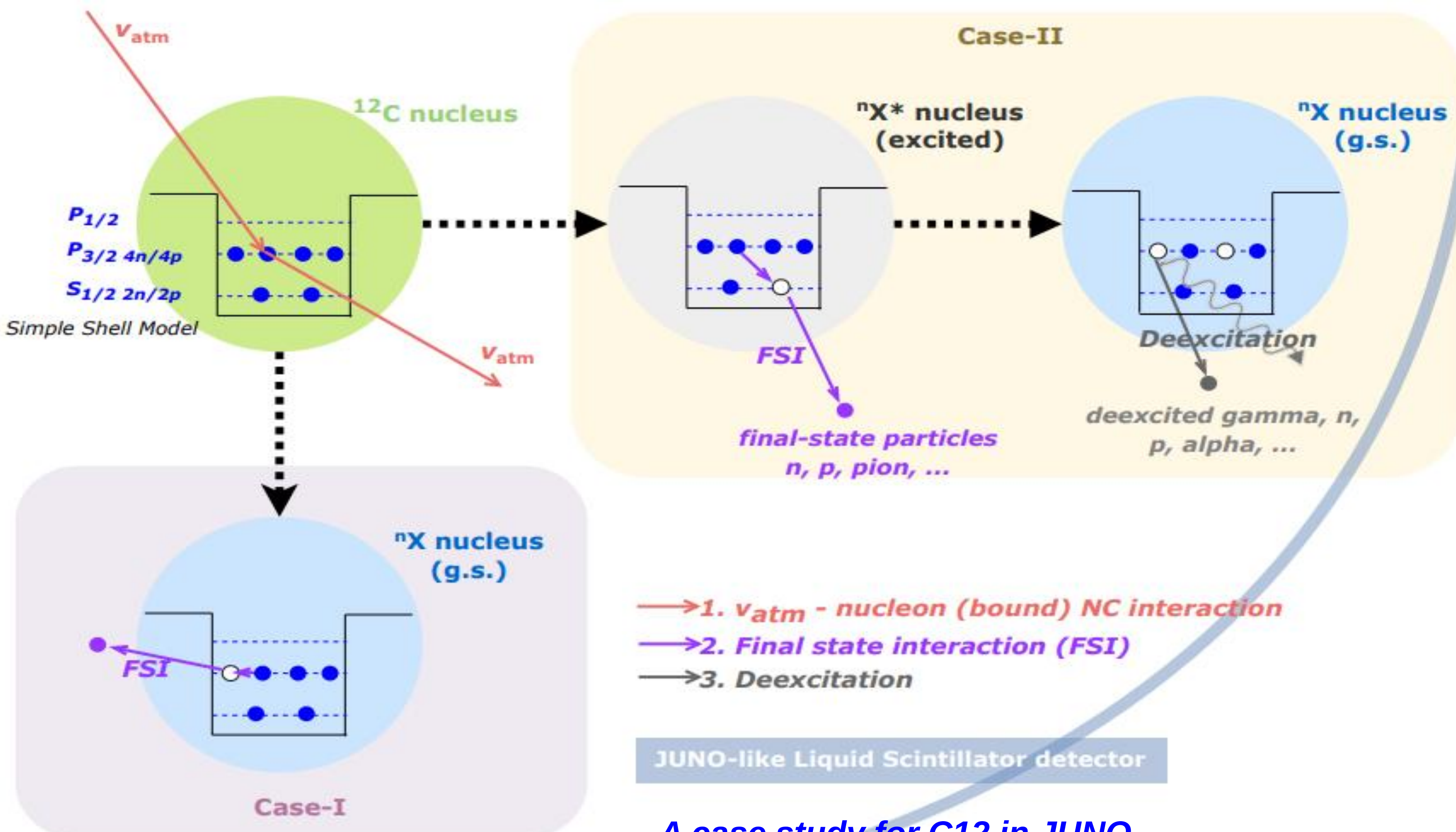




$$E_\nu^{\rm cal} = E_\ell + \sum_i T_i^N + \epsilon_n + \sum_j E_j,$$

- **The energy is reconstructed within the calorimetric method.**
- **Missing neutrons (pions) may bias the energy and then result in wrong oscillation parameters.**

New Methodology: adding deexcitation

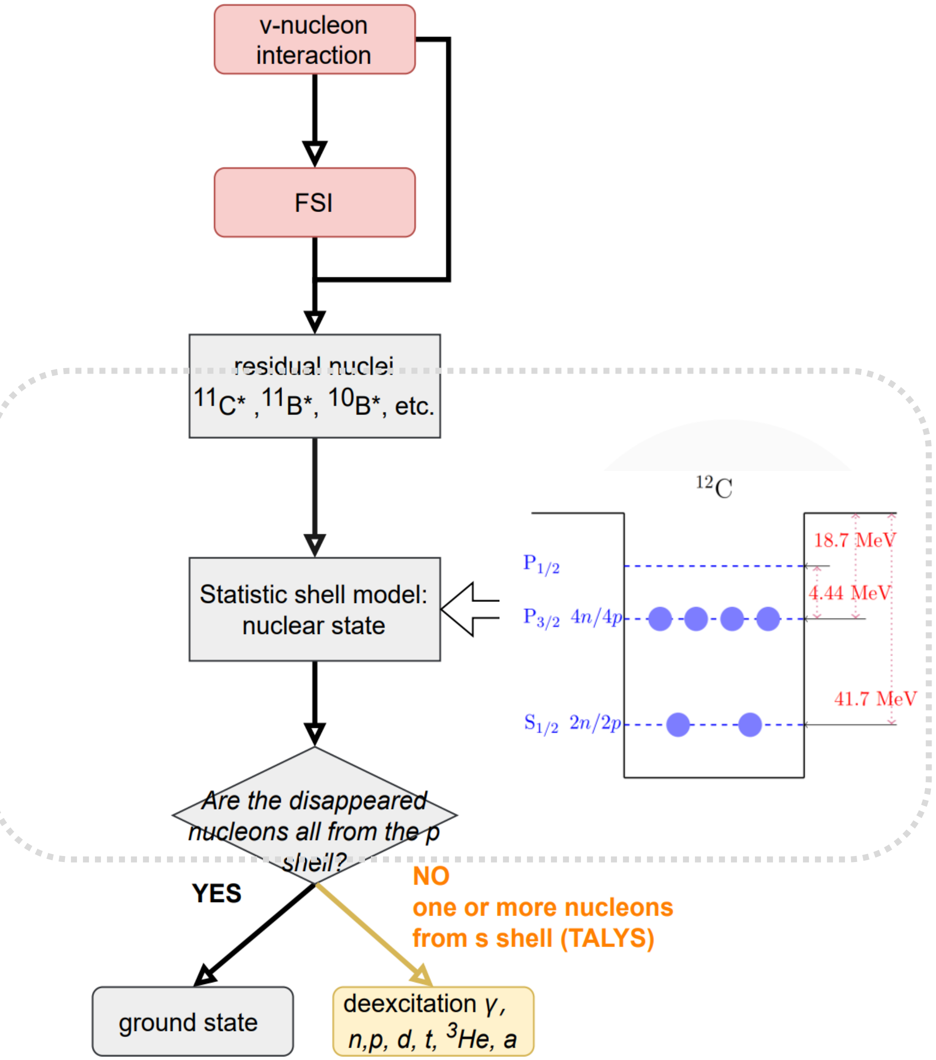


A case study for C12 in JUNO

Cheng, YFL, et al., Phys. Rev. D 103, 05001 (2021)

Cheng, Li,YFL, et al, Eur.Phys.J.C 85, 295 (2025)

TALYS-based Deexcitation



Simple shell model → Status of the residual nuclei

- All residual nuclei with A>5 have been considered
- Taking 11C*, 11B*, 10C*, 10Be* and 10B* for example

Daughter Nuclei	Shell Hole	Configuration Probability	Excitation Energy
$^{11}C^*$ or $^{11}B^*$	$s_{1/2}$	1/3	$E^* = 23$ MeV
	$p_{3/2}$	2/3	$E^* = 0$ MeV
$^{10}C^*$ or $^{10}Be^*$	$s_{1/2}$	1/15	$E^* = 46$ MeV
	$p_{3/2}$	6/15	$E^* = 0$ MeV
	$s_{1/2}$ & $p_{3/2}$	8/15	$E^* = 23$ MeV
$^{10}B^*$	$s_{1/2}$	1/9	$E^* = 46$ MeV
	$p_{3/2}$	4/9	$E^* = 0$ MeV
	$s_{1/2}$ & $p_{3/2}$	4/9	$E^* = 23$ MeV

Triggered a variety of research interest in the neutrino interaction community:

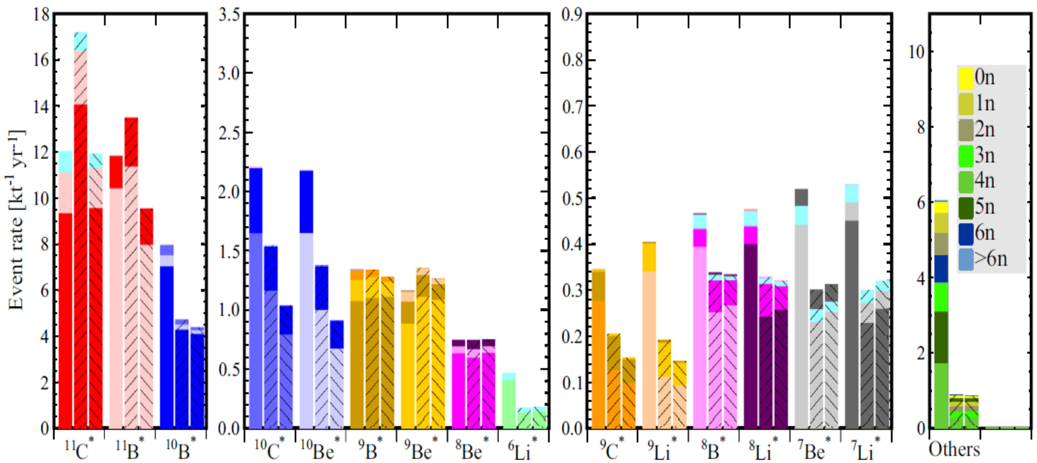
Abe, PRD (2024), 2508.04040, etc.

Guo et al, PLB (2022), PLB (2025) etc.

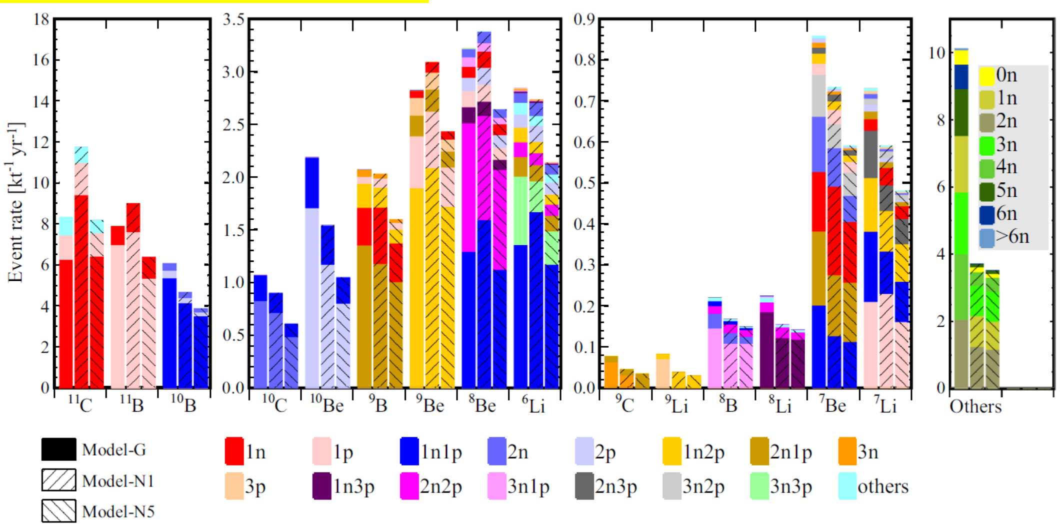
Gardiner, MARLEY

Impact on exclusive cross sections

Before deexcitation



After deexcitation

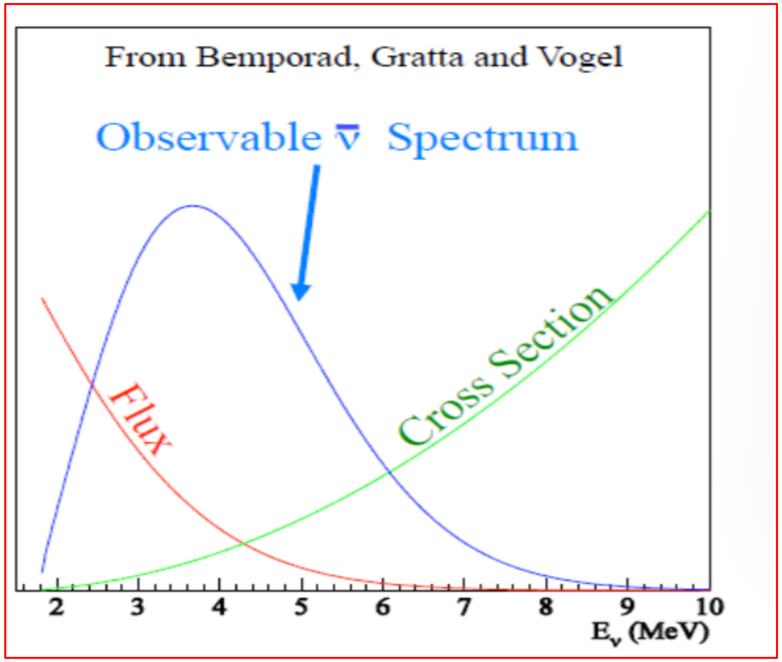


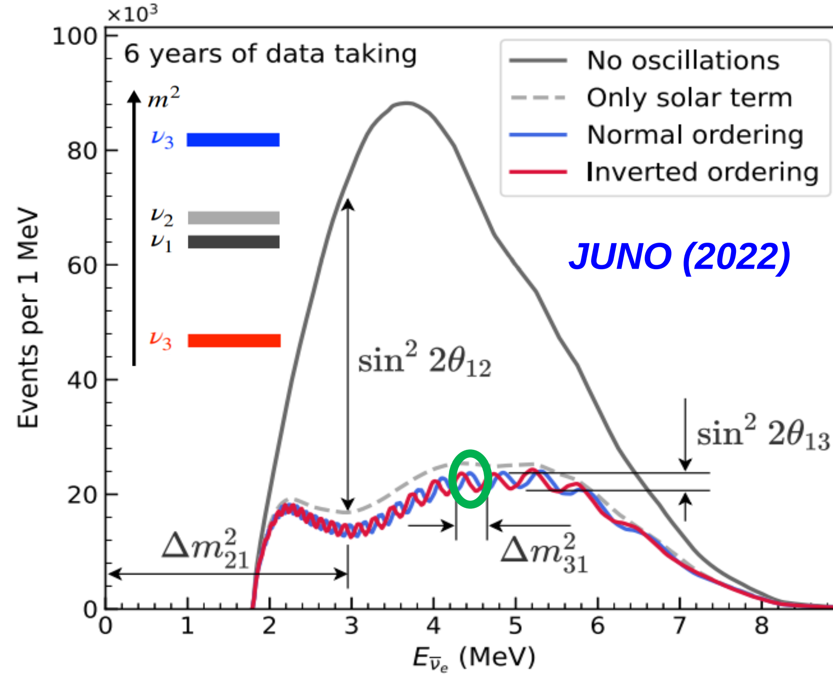
- ^{11}C, ^{11}B, ^{10}B reduced, and lighter nuclei increased; neutron multiplicity redistributed.
- Exclusive final-state information, such as **the neutron multiplicity, the charge pion multiplicity, the unstable nuclei,** is important for

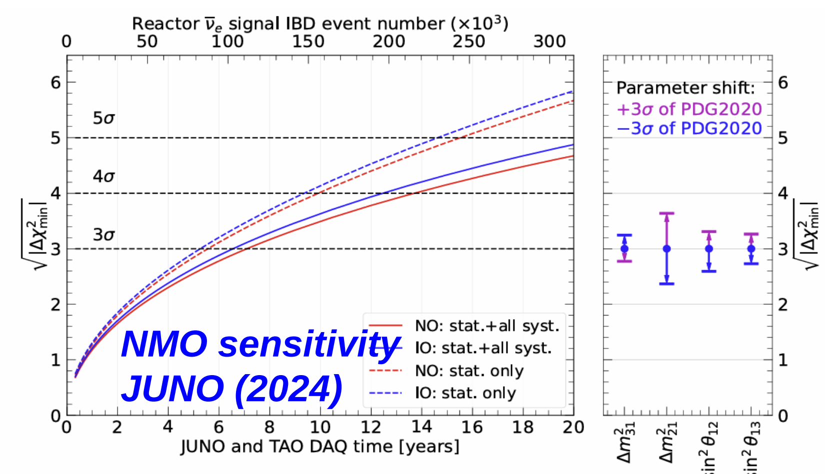
(a) Energy reconstruction

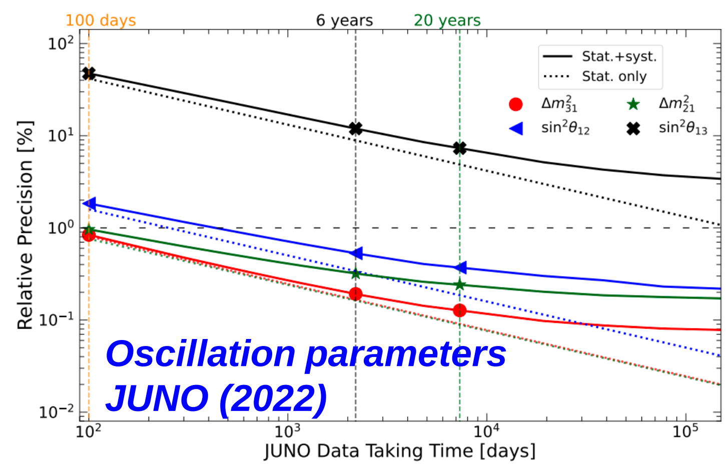
(b) Evaluate systematics

B: MeV neutrino production from Reactors



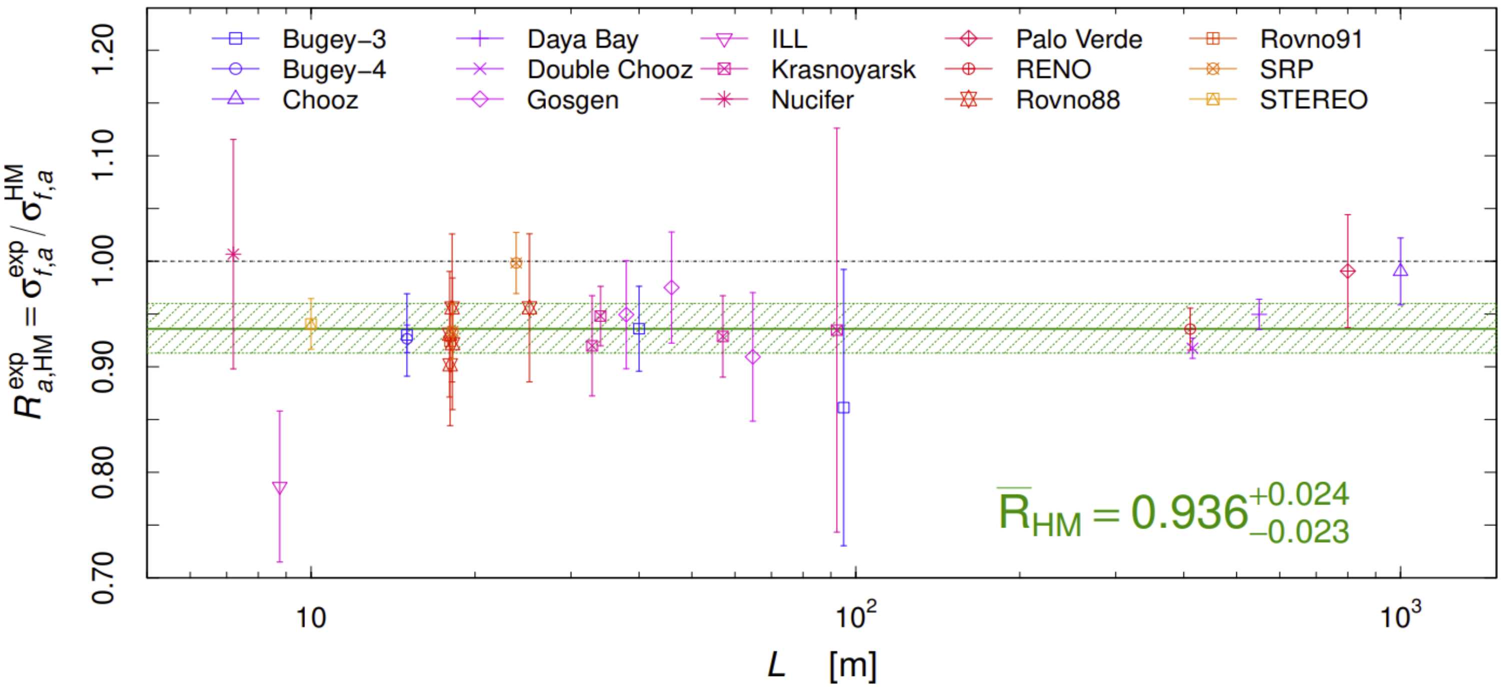






2011: HM fluxes (conversion method)

[Mueller et al, arXiv:1101.2663], Huber, arXiv:1106.0687]

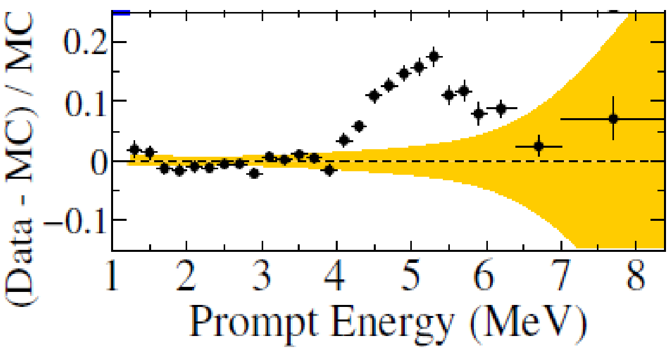


$2.5\,\sigma$ deficit $\Longrightarrow$ Anomaly!

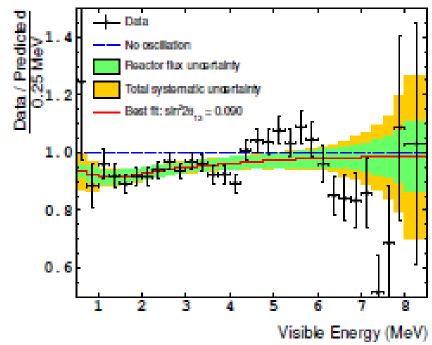
Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

- Original 2011 Reactor Antineutrino Anomaly: 2.5σ [Mention et al, arXiv:1101.2755]

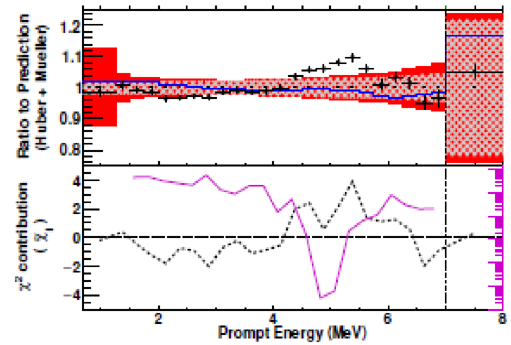
Even worse for spectral measurement



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

(1) "5 MeV bump" (cannot be explained by oscillation) questioned the theoretical reactor model (HM model).

(2) New development in theoretical models

- **New summation model**
- **KI (Kurchatov Institute) beta spectrum measurements**

(3) New development in experimental measurements

- **Fission evolution data from Daya Bay & RENO**

New reactor flux models

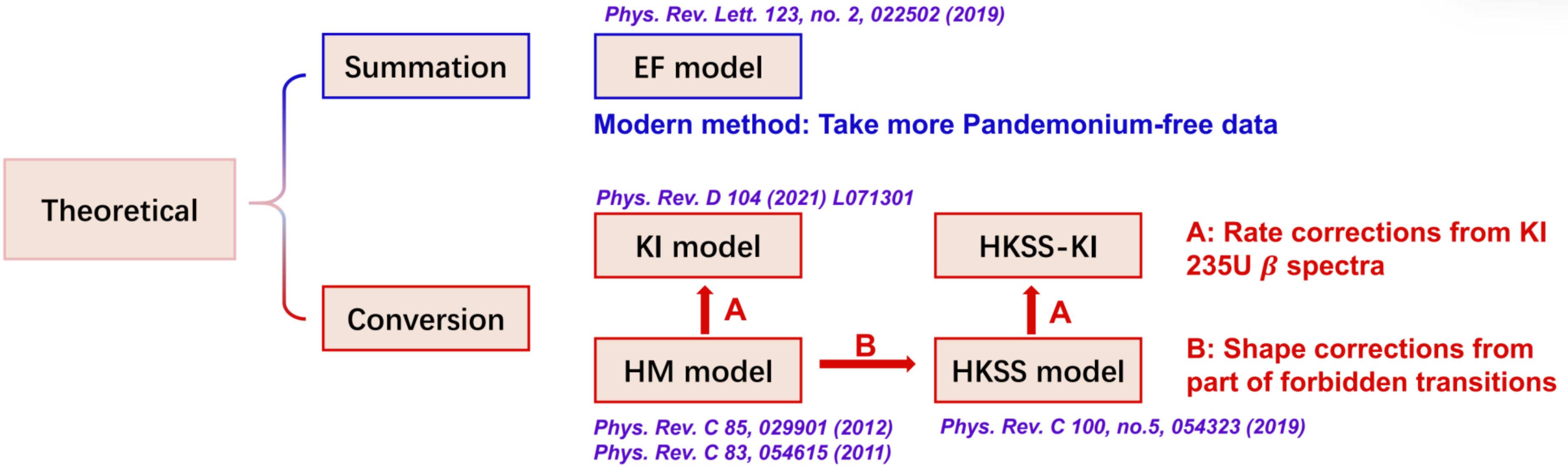
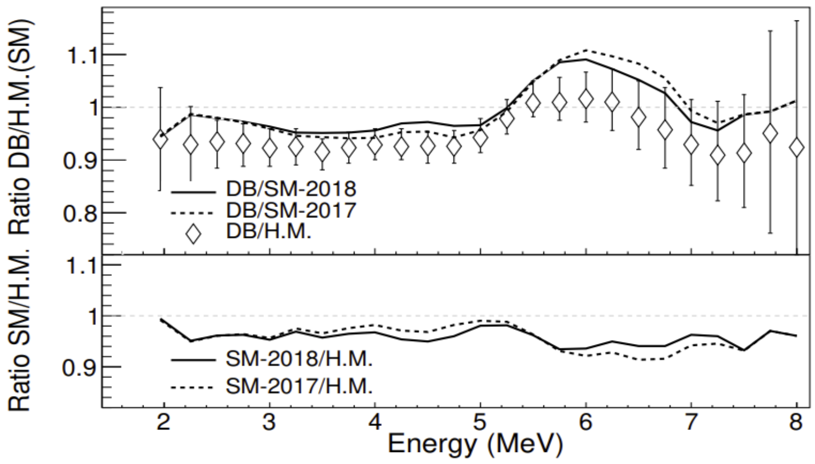


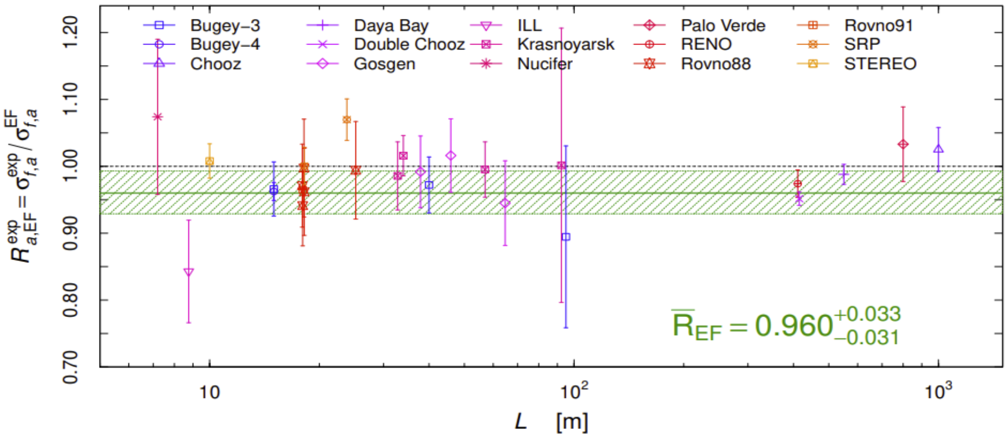
Diagram Courtesy: XIN Zhao

Many efforts from nuclear physics community!

2019: EF fluxes (summation method)

[Estienne, Fallot, et al, arXiv:1904.09358]





Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

$1.2\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

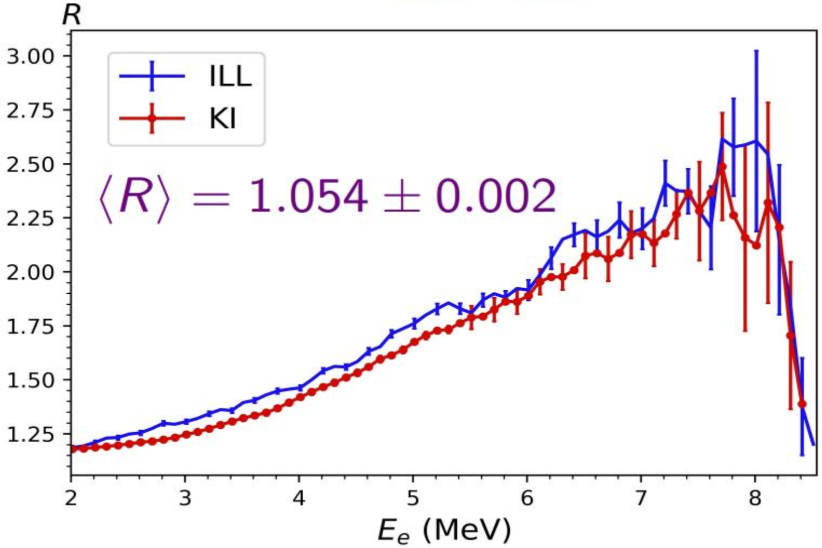
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

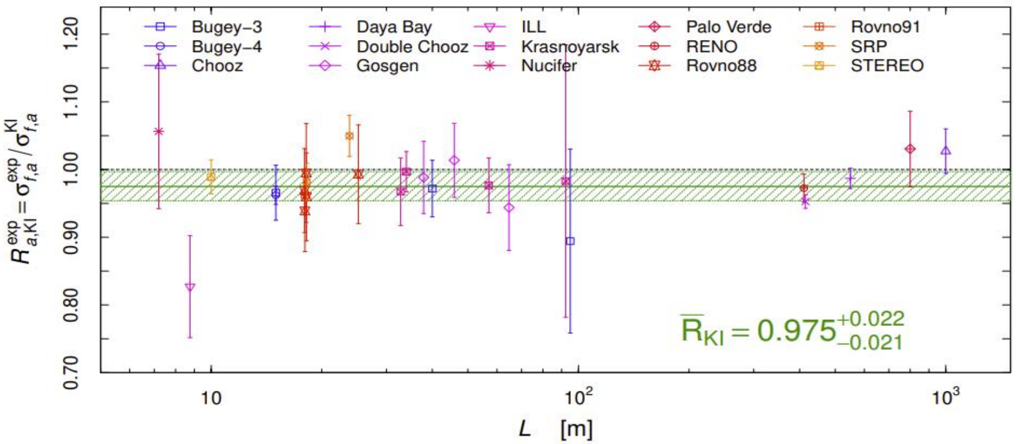
- UNKNOWN UNCERTAINTIES!
- Rough estimation used in our calculations: 5% for ^{235}U, ^{239}Pu, ^{241}Pu and 10% for ^{238}U. [Hayes, Jungman, McCutchan, Sonzogni, Garvey, Wang, arXiv:1707.07728]

2021: KI fluxes (conversion method)

[Kurchatov Institute: Kopeikin, Skorokhvatov, Titov, arXiv:2103.01684]

$$R = S^{(e)}_{235} / S^{(e)}_{239}$$





Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

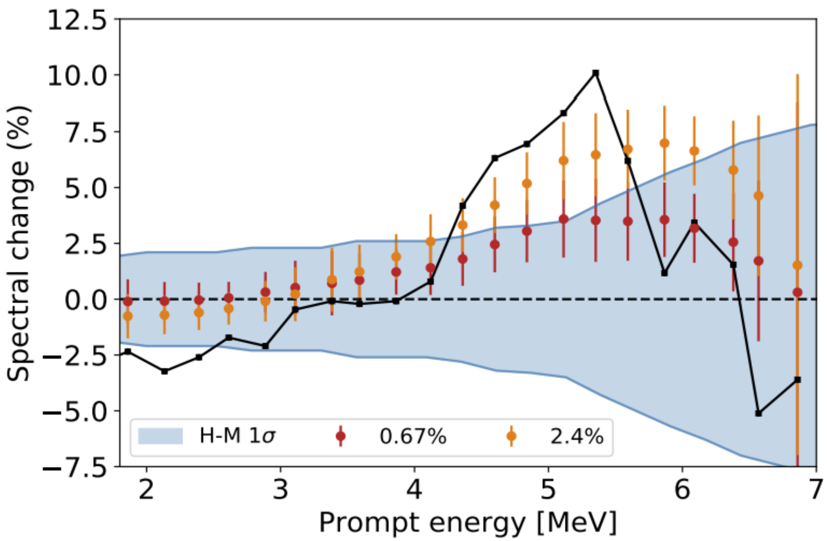
$1.1\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

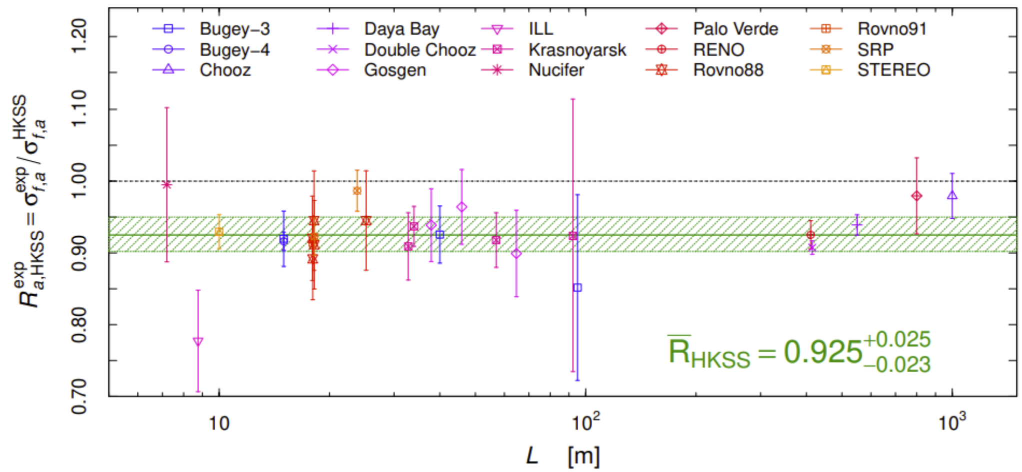
Approximate agreement with ab initio EF fluxes!

- HM + KI uncertainties.

2019: HKSS fluxes (conversion method)

[Hayen, Kostensalo, Severijns, Suhonen, arXiv:1908.08302]





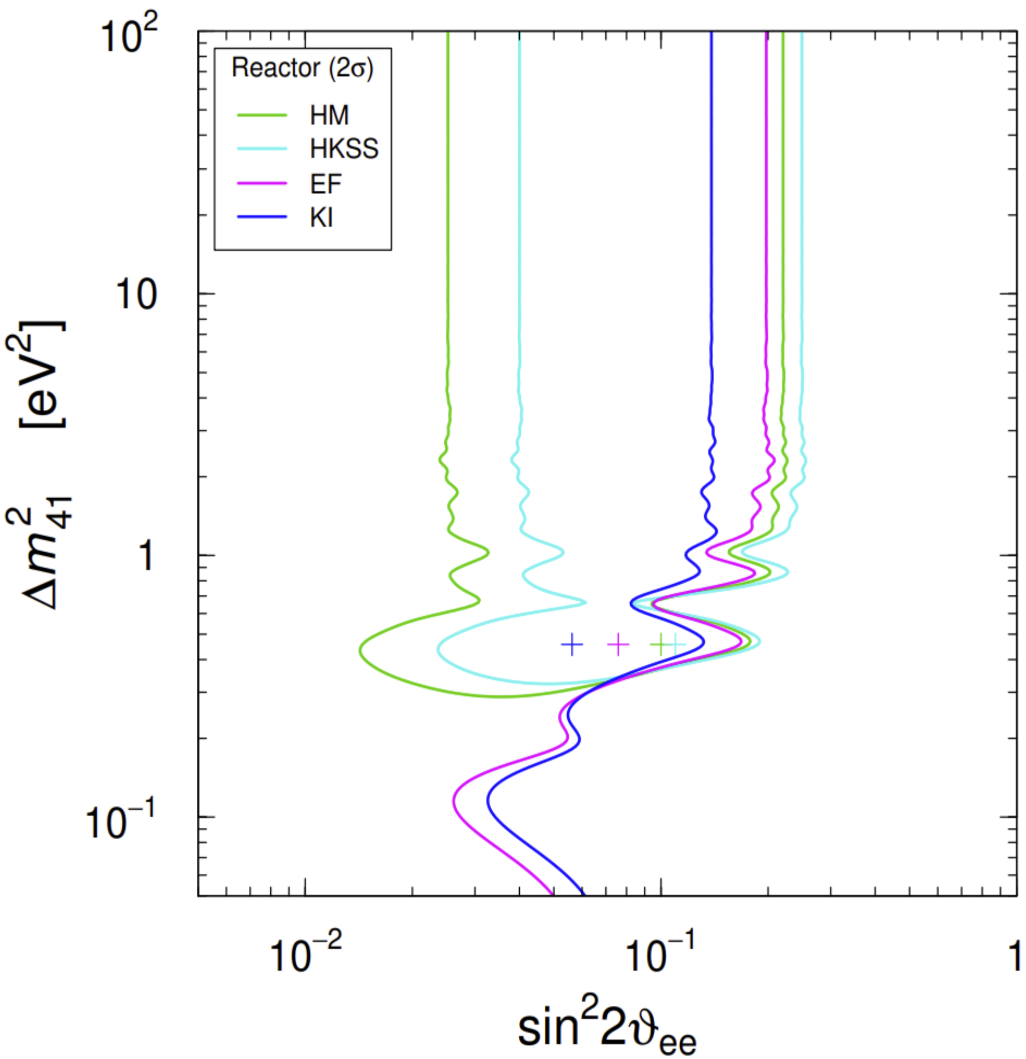
Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

$2.9\,\sigma$ deficit $\Longrightarrow$ Anomaly larger than the $2.5\,\sigma$ HM anomaly!

[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

- HM + HKSS uncertainties.

Limits on Sterile Neutrinos

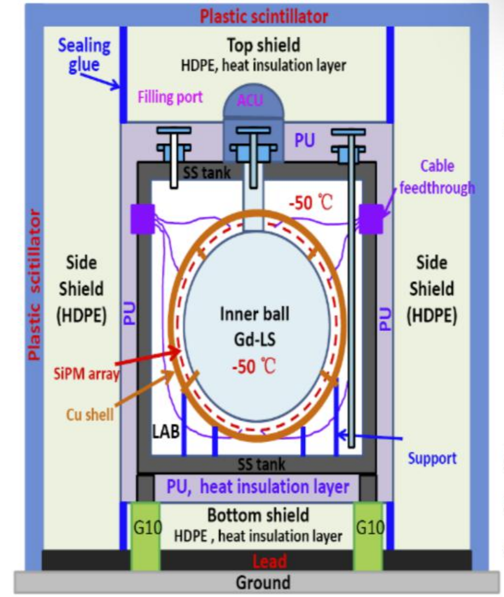


- The favored KI and EF models are compatible with the absence of SBL oscillations and give only 2σ upper bounds on the effective mixing parameter $\sin^2 2\vartheta_{ee} = \sin^2 2\vartheta_{14}$.
- Independently from the reactor neutrino flux model, we have

$$\sin^2 2\vartheta_{ee} \lesssim 0.25 \text{ at } 2\sigma.$$

JUNO-TAO

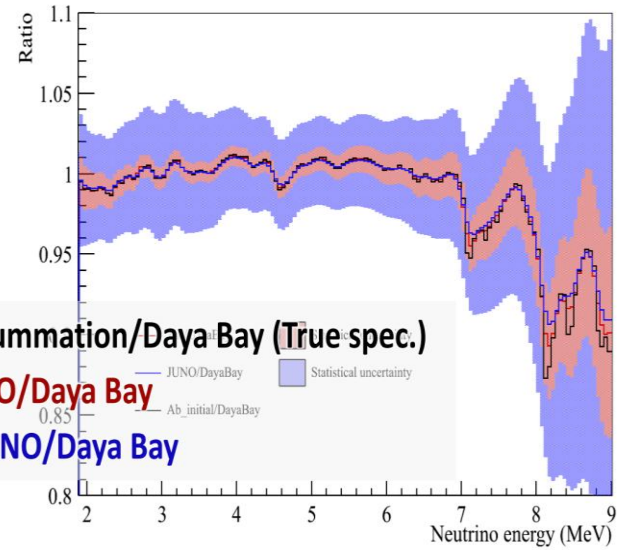
- **Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the 4.6 GW$_{th}$ core, a satellite exp. of JUNO.**
- **Measure reactor neutrino spectrum w/ high E resolution.**
  - Model-independent reference spectrum for JUNO
  - A benchmark for testing the nuclear database



CDR: 2005.08745

Calibration strategy: 2204.03256

- **Detector Features**
  - 2.8 ton Gd-LS, 10 m^2 SiPM (84.6% photocathode coverage) w/ PDE > 50%
  - Operate at -50 ℃ (SiPM dark noise)
  - 4500 p.e./MeV, <2% resolution @ 1MeV
- **2025 (Commissioning now)**



Solid: Summation/Daya Bay (True spec.)
RED: TAO/Daya Bay
Blue: JUNO/Daya Bay

Constrain the fine structure in [2.5, 6] MeV to < 1%

2111.10112

Conclusion and Outlook

Nuclear physics effects play crucial roles in new physics search of neutrino physics:

- **GeV neutrino-nucleus interactions**
  - → **Strong effects in energy reconstruction and systematics**
  - → **CP violation from long-baseline neutrino experiments**
- **MeV neutrino production from reactors**
  - → **important inputs for mass ordering measurement at JUNO**
  - → **Also affects other new physics search (sterile neutrinos)**

- **Nuclear Matrix Element of Neutrinoless Double Beta Decay**
- **Coherent Elastic Neutrino-Nucleus Scattering**

→ ***Opportunities for interdisciplinary research between particle, nuclear, (astro- physics) community!***