Prediction for Neutrino Interaction Cross Sections: From Low to High Energies

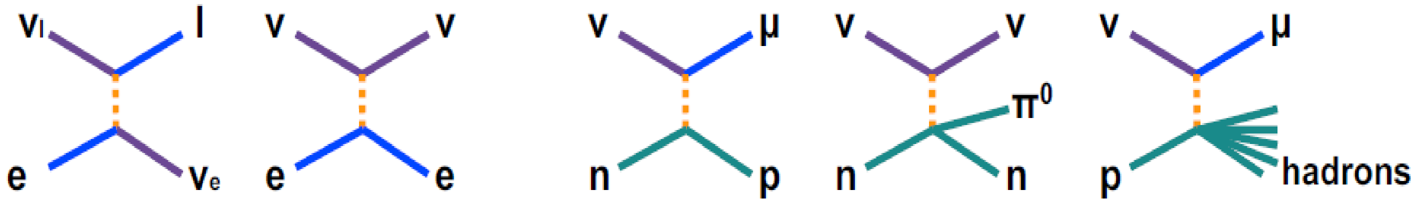
Yu-Feng Li (李玉峰)

Institute of High Energy Physics &

University of Chinese Academy of Sciences, Beijing

The 23rd International Conference on Few-Body Problems in Physics, Beijing, 27th Sep. 2024

Neutrino interactions from low to high energies



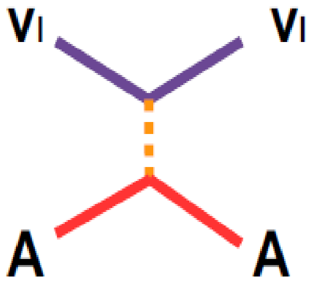
inverse muon (tau) decay

elastic electron scattering

(quasi) - elastic nucleon scattering

nuclear excitation and resonant production

Deep inelastic scattering and jet production



- **Neutrino-lepton interactions:**

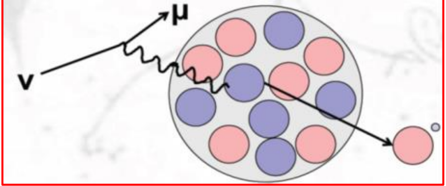
$$\overset{(-)}{\nu}_\alpha + e^- \to \overset{(-)}{\nu}_\alpha + e^- \,.$$

- **Neutrino-nucleon interactions**

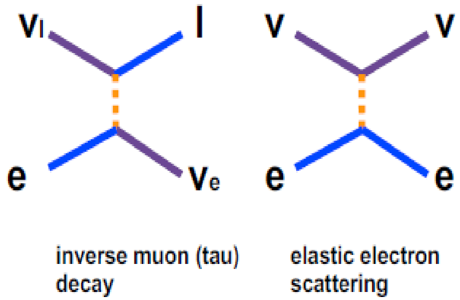
$$\nu_\ell + n \to p + \ell^-$$

$$\bar{\nu}_\ell + p \to n + \ell^+$$

- **Neutrino-nucleus interactions**



Neutrino-lepton interactions



- **Neutrino-lepton interactions:**

Pure leptonic process and easy to calculate (at tree level)
See radiative corrections in Bacall et al., PRD 51 (1995) 6146-6158

Accelerator νμ: Observation of NC (Gargamelle, 1973)
Measurement of weak mixing angle (CHARM-II, 1994)

Solar neutrinos: Super-Kamiokande, Borexino, JUNO etc.
Dark Matter Direct Detection experiments

New physics: neutrino magnetic moment
GEMMA: $2.9\times10^{-11}\ \mu_B$ [Rev.Mod.Phys. 87 (2015) 531]

XENON-nT: $6.4\times10^{-12}\ \mu_B$ (2207.11330)

Neutrino-nucleon interactions

$$\nu_\ell + n \longrightarrow p + \ell^-$$

$$\bar{\nu}_\ell + p \longrightarrow n + \ell^+$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

- **Famous inverse beta decay on free proton (in Hydrogen rich detectors)**

- **Hadron weak current: induced currents**

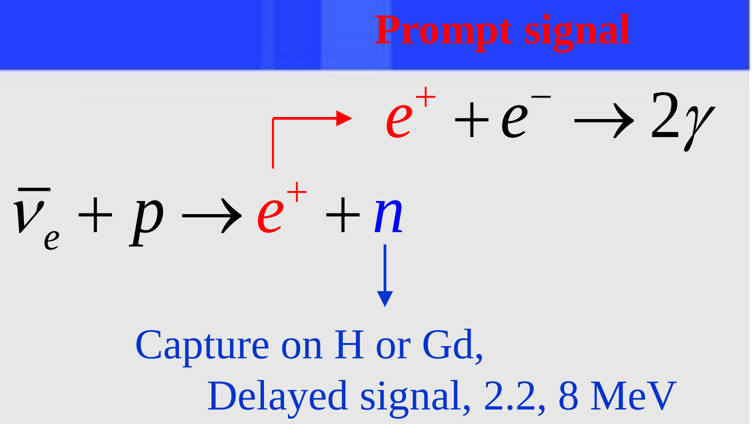
$$\overline{u_u}(p_u)\,\gamma^\rho\left(1-\gamma^5\right)u_d(p_d) \rightarrow \langle p(p_p)|h^\rho_W(0)|n(p_n)\rangle$$

- **Isospin symmetry**

- **Correlated with free neutron decay**

$$\langle p(p_p)|v^\rho_W(0)|n(p_n)\rangle = \overline{u_p}(p_p)\left[\gamma^\rho F_1(Q^2) + \frac{i\,\sigma^{\rho\eta}\,q_\eta}{2\,m_N}F_2(Q^2) + \frac{q^\rho}{m_N}F_3(Q^2)\right]u_n(p_n)$$

$$\langle p(p_p)|a^\rho_W(0)|n(p_n)\rangle = \overline{u_p}(p_p)\left[\gamma^\rho\gamma^5 G_A(Q^2) + \frac{q^\rho}{m_N}\gamma^5 G_P(Q^2) + \frac{p^\rho_p + p^\rho_n}{m_N}\gamma^5 G_3(Q^2)\right]u_n(p_n)\,.$$



Prompt signal

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$e^+ + e^- \rightarrow 2\gamma$$

Capture on H or Gd,
Delayed signal, 2.2, 8 MeV

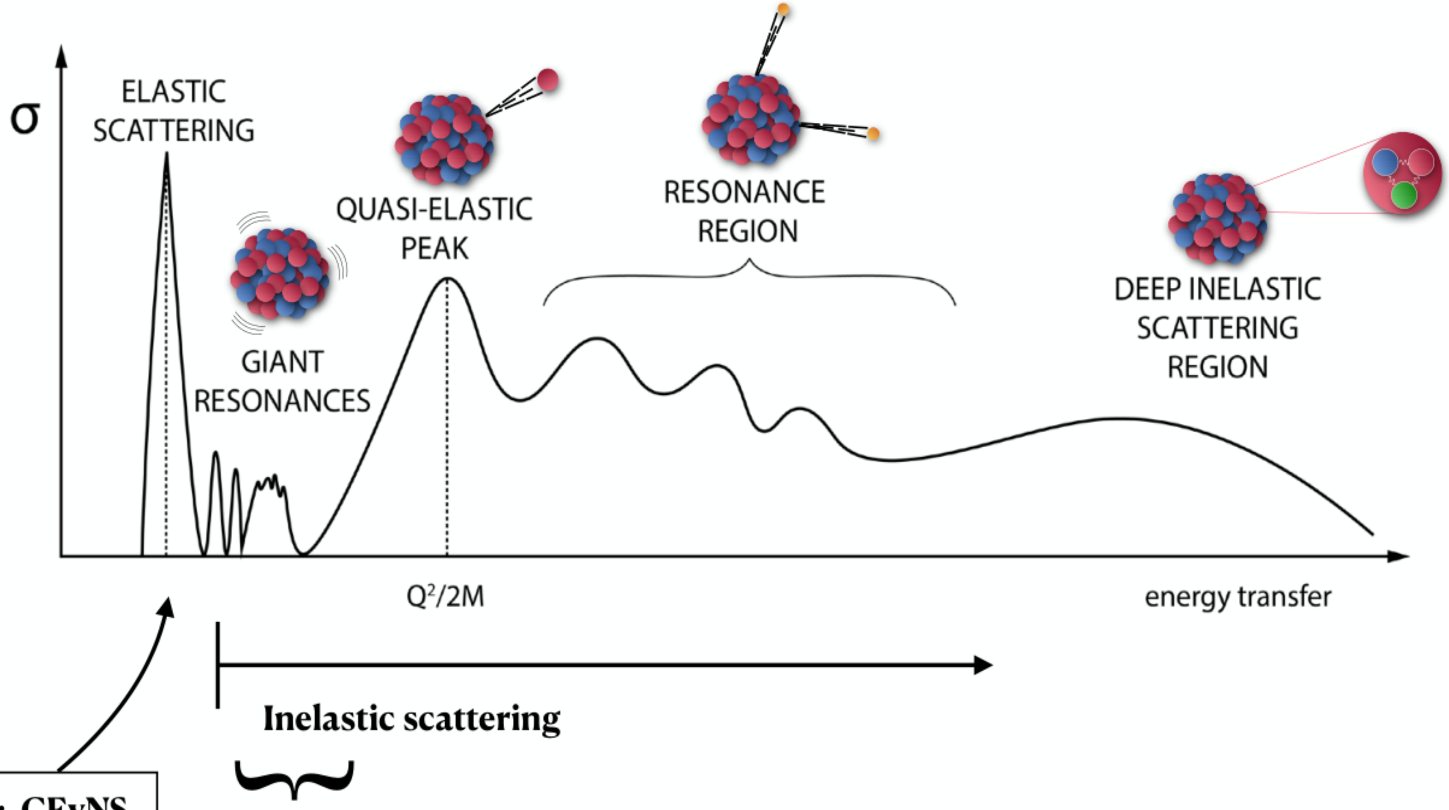
Dedicated calculations in :
Vogel & Beacom, 1999
Strumia & Vissani, 2003
Ricciardi, Vignaroli, Vissani, 2022

Radiative correction:
Kurylov, Ramsey-Musolf, Vogel, 2003

Uncertainty as small as ~0.2%

May affect the reactor antineutrino anomaly
Giunti, YFL, Ternes, Xin PLB (2022)

Neutrino-nucleus interactions



Elastic scattering: CEvNS (coherent elastic neutrino-nucleus scattering)

e.g. Supernovae neutrinos

Long-baseline experiments (DUNE, HyperK)

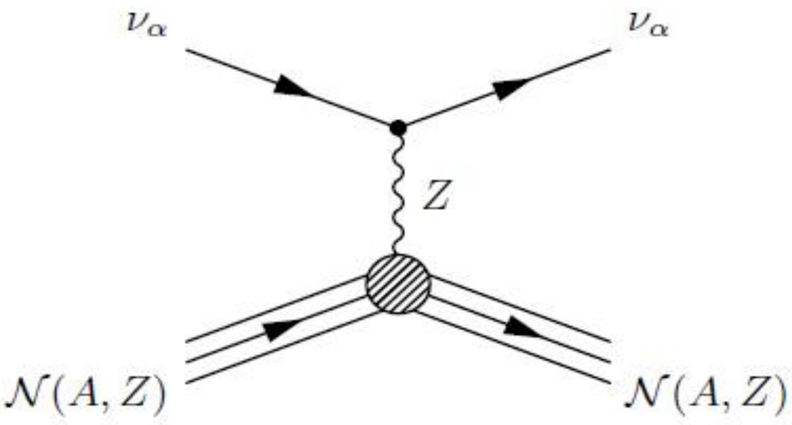
- **Nuclear response at different energy transfer regions is crucial to make the predictions.**

A: low energy NC: CEνNS

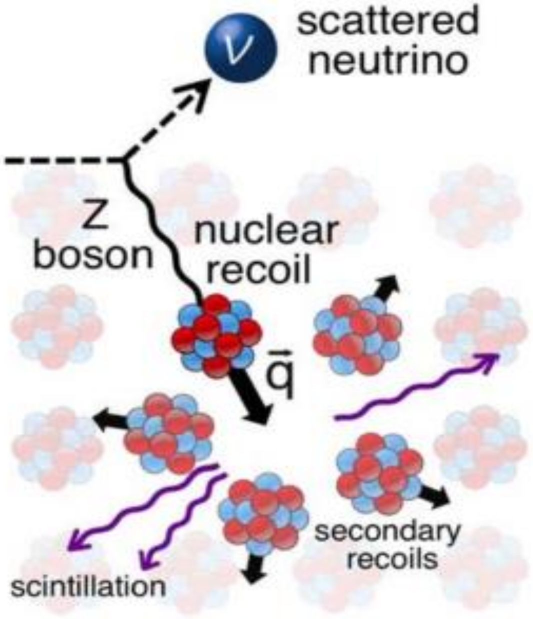
Coherent Elastic Neutrino-Nucleus Scattering

- CEνNS: pronounced "sevens"
- Weak Neutral-Current (NC) interaction:

$$\boxed{\nu_\alpha + \mathcal{N}(A,Z) \to \nu_\alpha + \mathcal{N}(A,Z)}$$

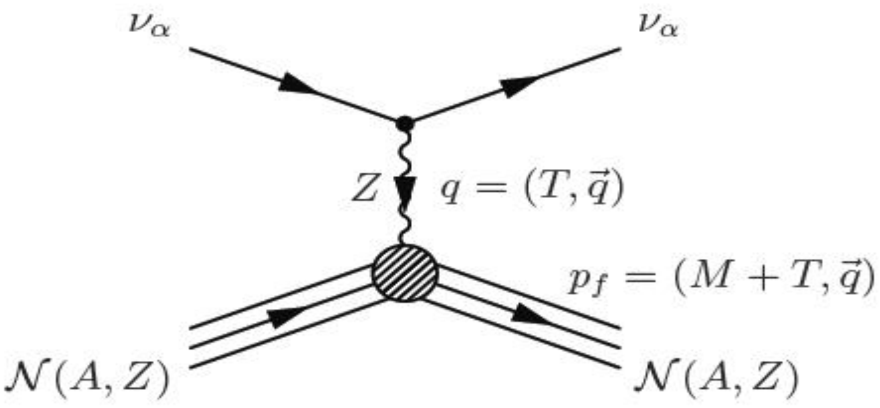


- The nucleus $\mathcal{N}(A,Z)$ recoils as a whole!
- So what?



The CEνNS kinematics

$$\boxed{|\vec{q}|\,R \lesssim 1}$$



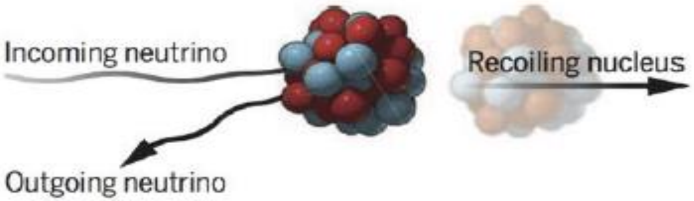
- Heavy target nucleus $\mathcal{N}(A, Z)$:

$$A \sim 100 \qquad M \sim 100\,\text{GeV}$$

$$R \approx 1.2\,A^{1/3}\,\text{fm} \approx 5\,\text{fm}$$

- CEνNS for $|\vec{q}| \lesssim 40\,\text{MeV}$
- Non-Relativistic nuclear recoil:

$$|\vec{q}| \simeq \sqrt{2\,M\,T} \qquad\qquad q^0 = T \quad \leftarrow \quad \text{Kinetic Energy}$$



- Observable nuclear recoil kinetic energy:

$$T \simeq \frac{|\vec{q}|^2}{2\,M} \lesssim 10\,\text{keV} \quad \leftarrow \quad \text{Very Small!}$$

The CEνNS Cross Section

Standard Model: $$\frac{d\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[Q_W(Q^2)\right]^2$$

- Weak charge of the nucleus $\mathcal{N}$:

$$\boxed{|\vec{q}| = \sqrt{2\,M\,T}}$$

$$Q_W(Q^2) = g_V^n\, N\, F_N(|\vec{q}|) + g_V^p\, Z\, F_Z(|\vec{q}|)$$

$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W(Q^2 \simeq 0) = 0.0227 \pm 0.0002$$

See the radiative correction in 2011.05960

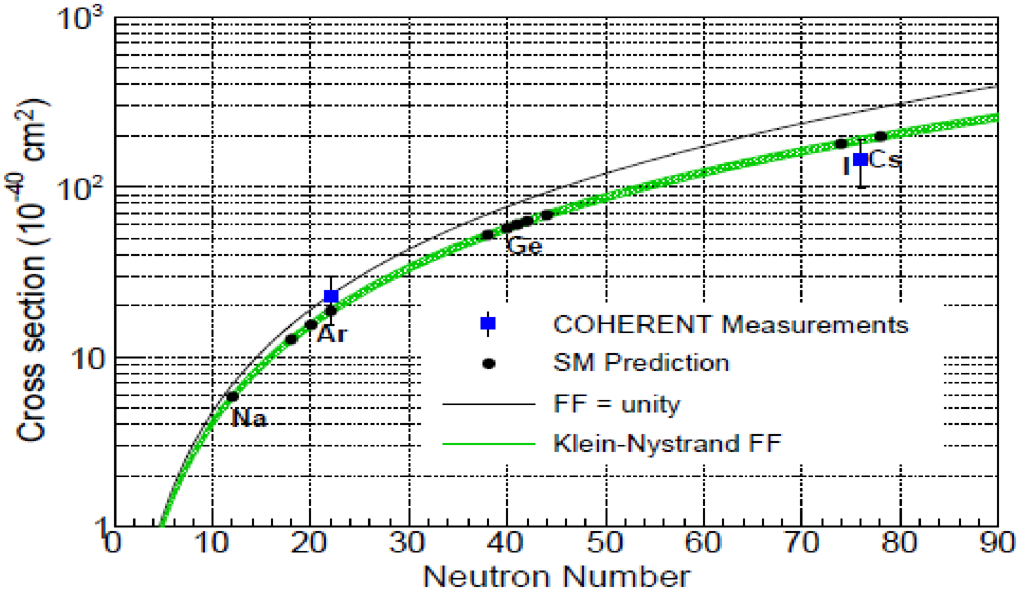
The neutron contribution is dominant! $\Longrightarrow$ $\frac{d\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{dT} \underset{\sim}{\propto} N^2$

[Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299]

- The coherent nuclear recoil gives a big cross section enhancement for heavy nuclei: $\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \underset{\sim}{\propto} N \Longrightarrow \sigma_{\mathrm{CE}\nu\mathrm{NS}}/\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \underset{\sim}{\propto} N$

- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel et al, arXiv:2007.03658]

Neutron Form Factor



[COHERENT, arXiv:2003.10630]

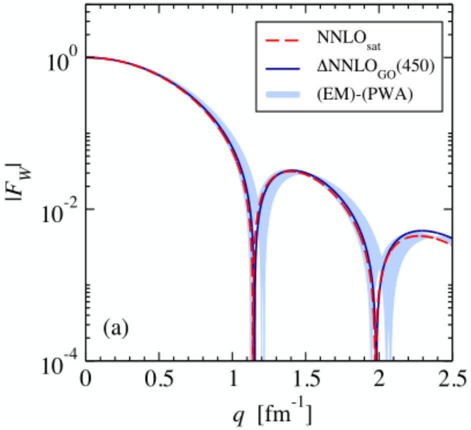
- Partial coherency is described by the nuclear neutron form factor $F_N(|\vec{q}|)$
- Fourier transform of the neutron distribution in the nucleus $\rho_N(r)$:

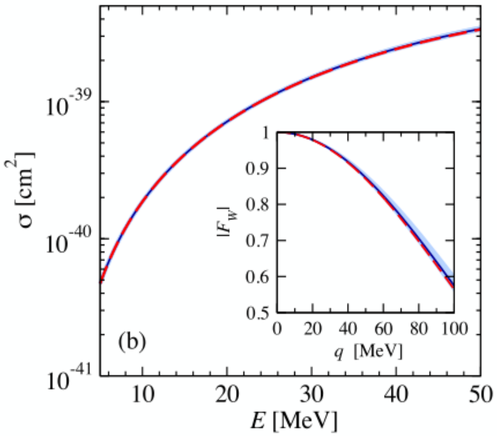
$$F_N(|\vec{q}|) = \int e^{-i\vec{q}\cdot\vec{r}} \rho_N(r)\, d^3r$$

- Measurable parameter: the radius R_n of the nuclear neutron distribution

Neutron Form Factor: nuclear inputs

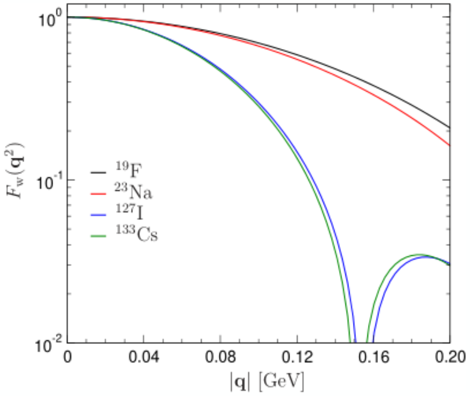
Weak form-factor of ⁴⁰Ar
- Ab initio method (coupled-cluster theory)
- various nuclear potentials



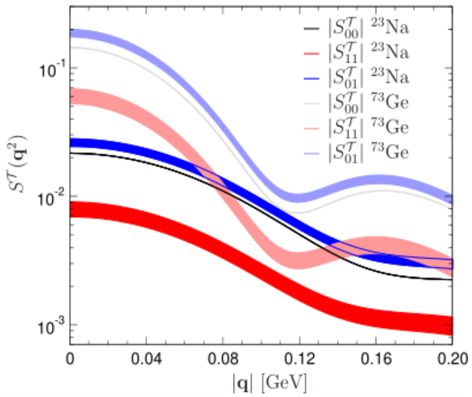


C. Payne at al.
Phys.Rev.C 100 (2019) 6, 061304

Shell model calculations
- Generalisation for beyond SM — new nuclear responses



5



M. Hoefichter, J. Menendez, A.Schwenk
Phys.Rev.D 102 (2020) 7, 074018

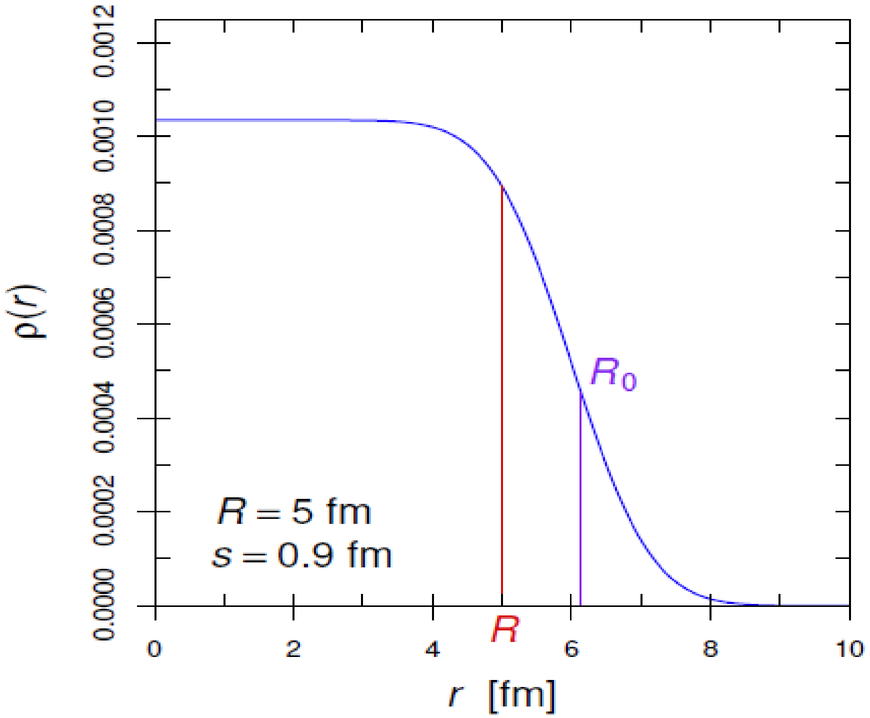
Neutron Form Factor: neutron radius

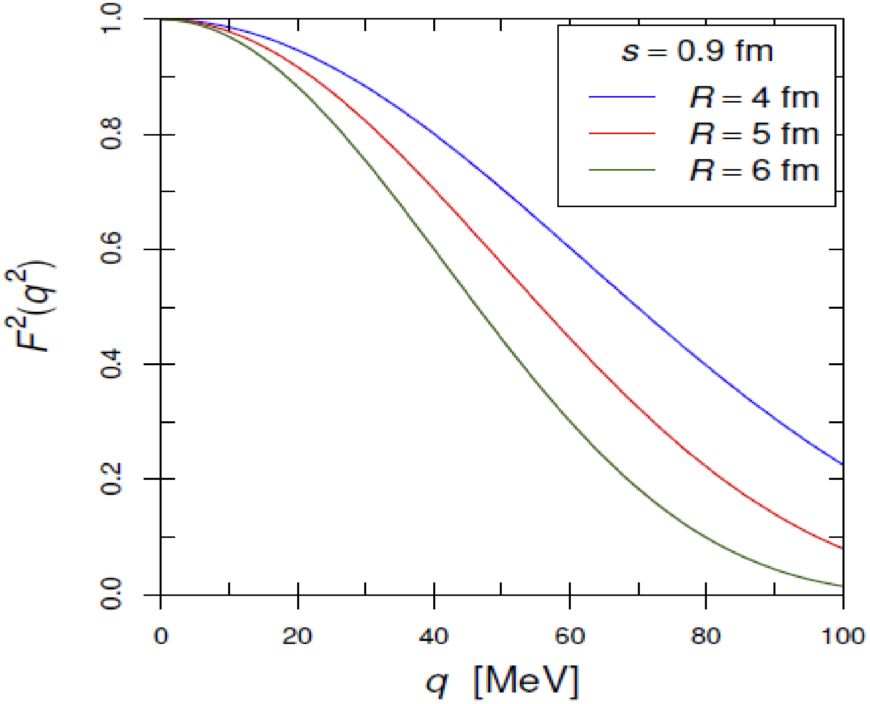
Helm form factor: $F_N^{\text{Helm}}(|\vec{q}|^2) = 3\,\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0}\,e^{-|\vec{q}|^2 s^2/2}$

Spherical Bessel function of order one: $j_1(x) = \sin(x)/x^2 - \cos(x)/x$

Obtained from the convolution of a sphere with constant density with radius R_0 and a gaussian density with standard deviation s

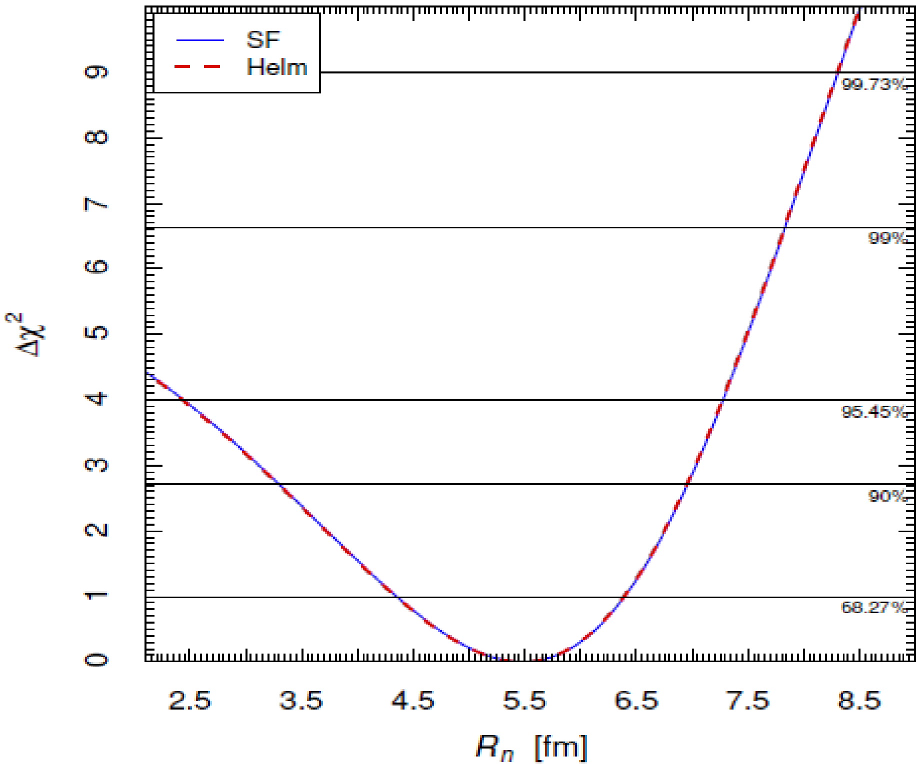
Rms radius: $R^2 = \langle r^2 \rangle = \frac{3}{5}\,R_0^2 + 3s^2$ Surface thickness: $s \simeq 0.9\,\text{fm}$





Neutron Distributions of Cs & I

- Fit of the 2017 COHERENT CsI data to get $R_n(^{133}\mathrm{Cs}) \simeq R_n(^{127}\mathrm{I})$:



First determination of R_n with neutrino-nucleus scattering:

$$\boxed{R_n(\mathrm{CsI}) = 5.5^{+0.9}_{-1.1}\ \mathrm{fm}}$$

[Cadeddu, Giunti, Li, Zhang, arXiv:1710.02730]

- With new 2020 COHERENT CsI data:

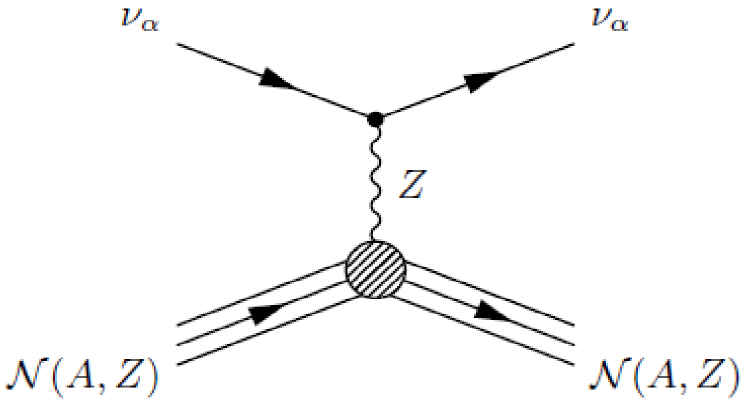
[Pershey @ Magnificent CEνNS 2020]

$$\boxed{R_n(\mathrm{CsI}) = 5.55 \pm 0.44\ \mathrm{fm}}$$

[Cadeddu et al, arXiv:2102.06153]

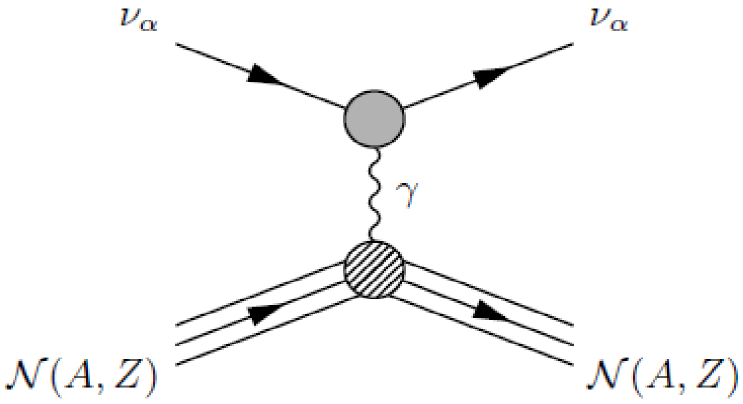
BSM Neutrino Interactions in CEvNS

Standard Model NC



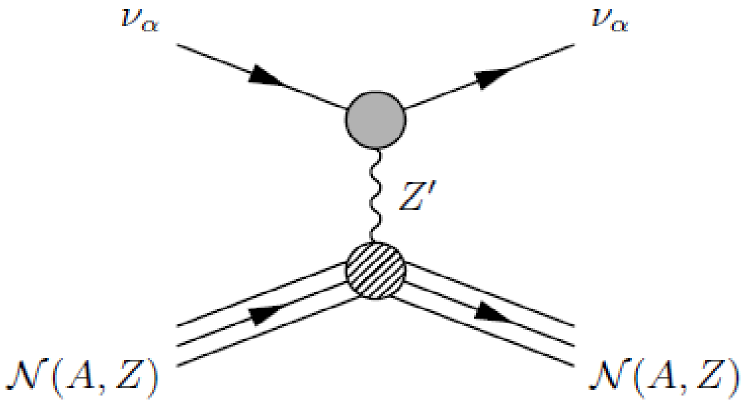
$+$

Electromagnetic Interactions



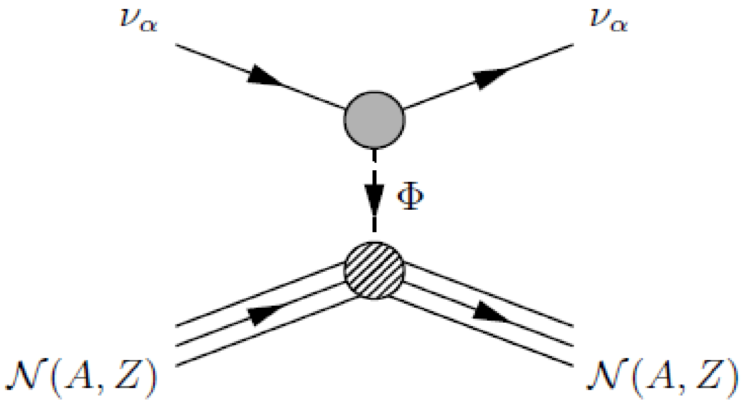
$+$

BSM Vector Mediator



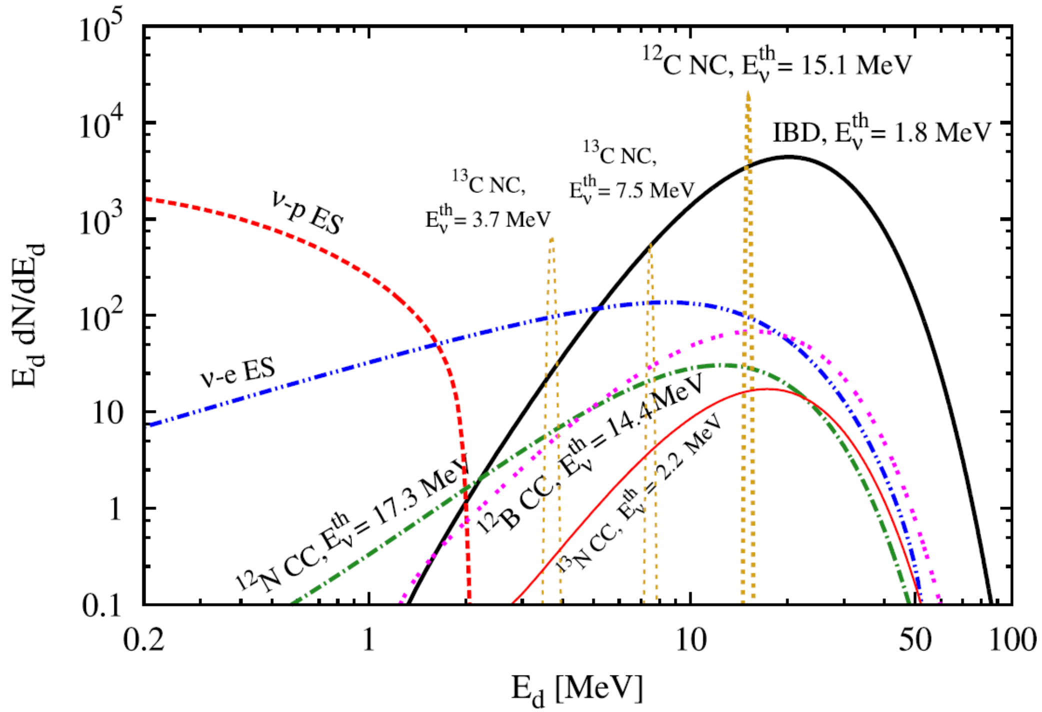
$+$

BSM Scalar Mediator

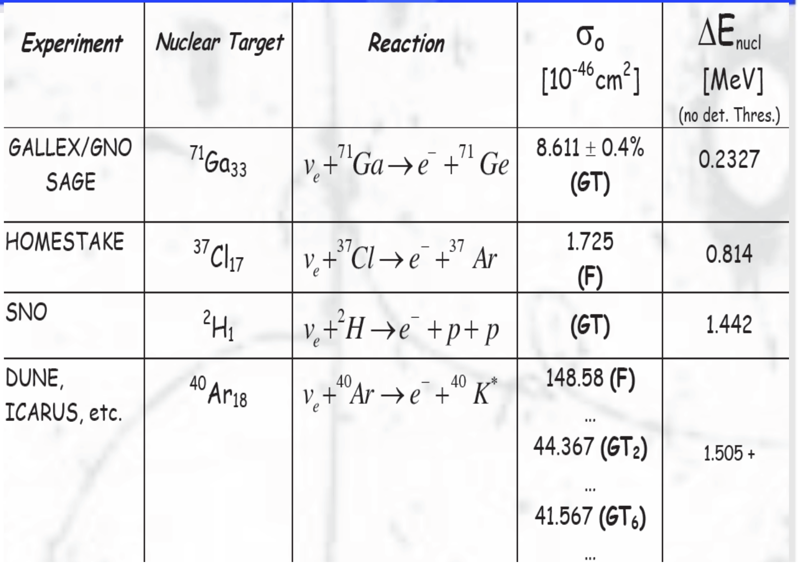


B: low energy CC:
QE on the Target Nuclei

(Quasi-)elastic ν-nucleus CC/NC interactions



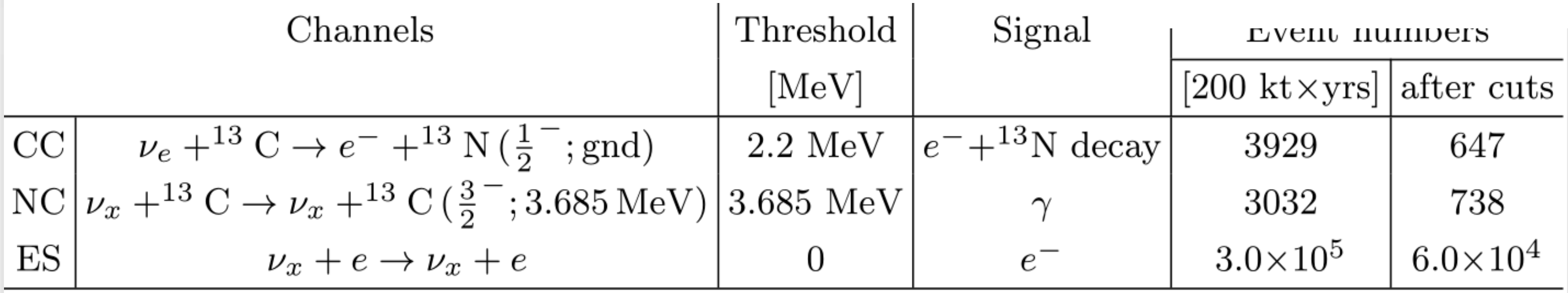
JUNO, Prog.Part.Nucl.Phys. **123 (2022) 103927**



Experiment	*Nuclear Target*	*Reaction*	σ_0 [10^{-46}cm^2]	ΔE_{nucl} [MeV] (no det. Thres.)
GALLEX/GNO SAGE	$^{71}Ga_{33}$	$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$	8.611 ± 0.4% (GT)	0.2327
HOMESTAKE	$^{37}Cl_{17}$	$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$	1.725 (F)	0.814
SNO	$^{2}H_{1}$	$\nu_e + {}^{2}H \rightarrow e^- + p + p$	(GT)	1.442
DUNE, ICARUS, etc.	$^{40}Ar_{18}$	$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$	148.58 (F) ... 44.367 (GT_2) ... 41.567 (GT_6) ...	1.505 +

From Kevin McFarland

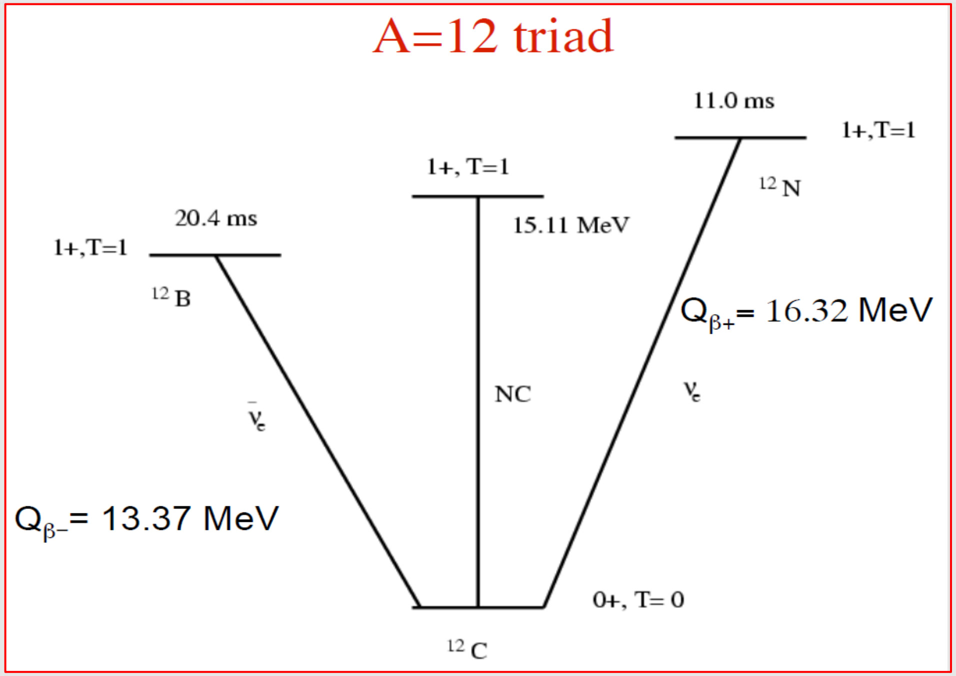
- ***Important for solar & supernova neutrino detection***



	Channels	Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	after cuts
CC	$\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N}\,(\frac{1}{2}^-; \mathrm{gnd})$	2.2 MeV	$e^- + {}^{13}$N decay	3929	647
NC	$\nu_x + {}^{13}\mathrm{C} \rightarrow \nu_x + {}^{13}\mathrm{C}\,(\frac{3}{2}^-; 3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \rightarrow \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

JUNO, Astrophys.J. 965 (2024) 2, 122

(Quasi-)elastic ν-nucleus CC/NC interactions



Nuclear structure effects:

- **beta (M1) decay calibration**
- **ν-energy ~ nuclear excitation energy: shell model**
- **giant resonance: CRPA or shell model**
- **>100 MeV, fermi Gas models or spectral function method**
- **DIS region: Parton**

From Vogel, NPA 777 (2006) 340-355

	$^{12}C(\nu_e, e^-)^{12}N_{gs}$ decay at rest	$^{12}C(\nu_\mu, \mu^-)^{12}N_{gs}$ decay in flight	$^{12}C(\nu_e, e^-)^{12}C(15.11)$ decay at rest
Experiment [31]	9.4±0.5±0.8	–	11 ± 0.85 ± 1.0
Experiment [32]	9.1±0.4±0.9	66 ± 10 ± 10	–
Experiment [33]	10.5±1.0±1.0	–	–
Shell model [36]	9.1	63.5	9.8
CRPA [34,35]	8.9	63.0	10.5
EPT [37]	9.2	59	9.9

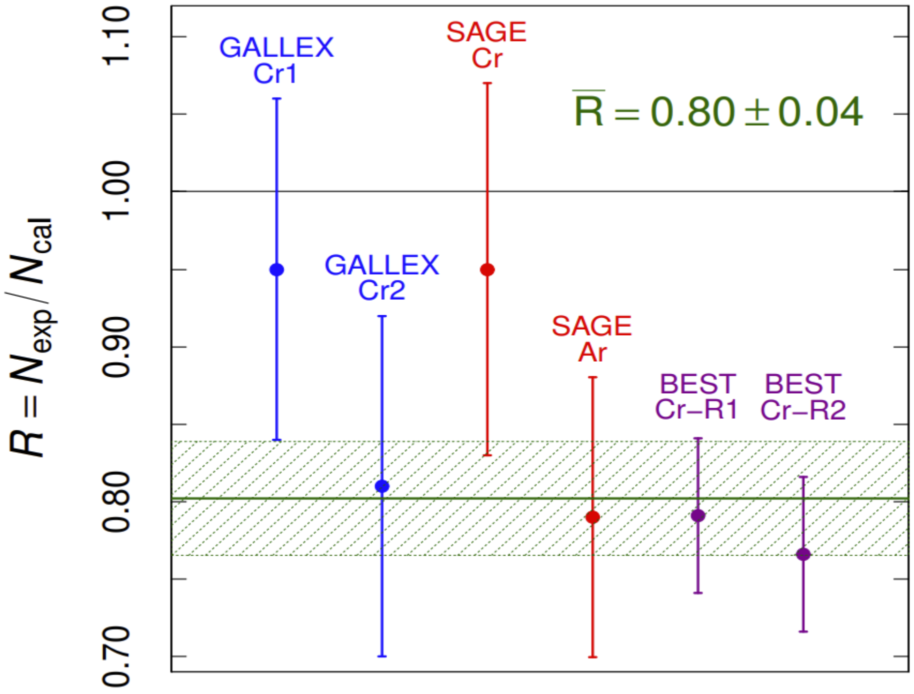
Gallium Anomaly

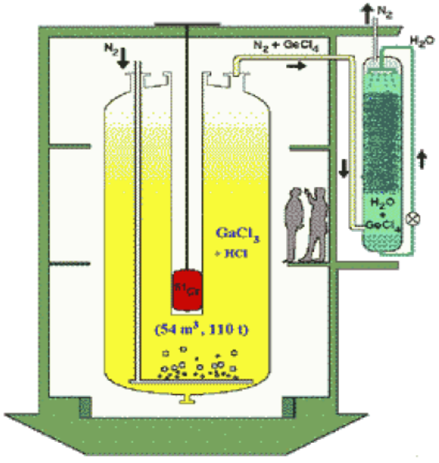
Gallium Radioactive Source Experiments: GALLEX, SAGE, BEST (2021)

ν_e Sources: $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$ $\quad e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$

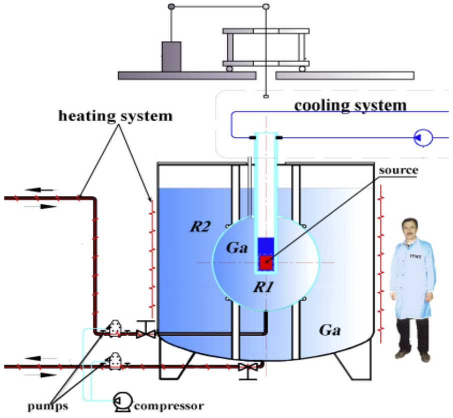
$E \simeq 0.75\,\mathrm{MeV}$ $\quad E \simeq 0.81\,\mathrm{MeV}$

$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$





GALLEX



BEST

$\approx$ 5-6σ deficit $\Longrightarrow$ Anomaly!

$\langle L \rangle_{\mathrm{GALLEX}} \simeq 1.9\,\mathrm{m}$ $\quad \langle L \rangle_{\mathrm{SAGE}} \simeq 0.6\,\mathrm{m}$

$\langle L \rangle_{\mathrm{BEST}}^{\mathrm{R1}} \simeq 0.7\,\mathrm{m}$ $\quad \langle L \rangle_{\mathrm{BEST}}^{\mathrm{R2}} \simeq 1.1\,\mathrm{m}$

$\Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}}$

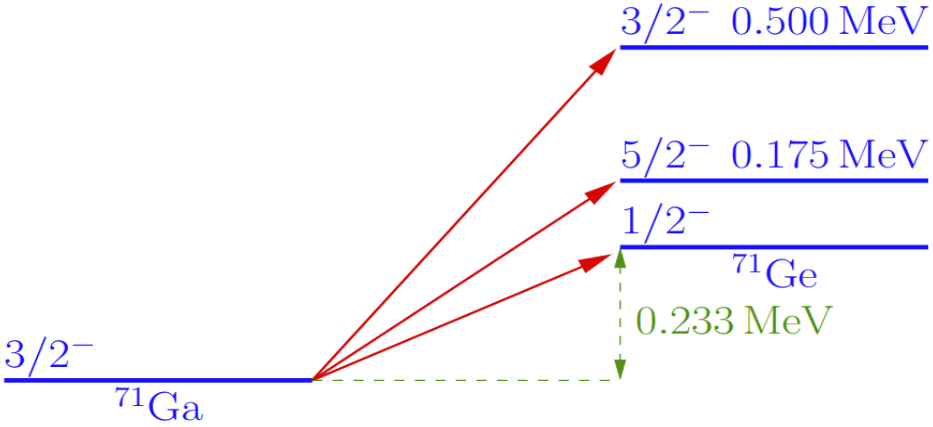
[SAGE, arXiv:nucl-ex/0512041, arXiv:0901.2200; Laveder et al, NPPS 168 (2007) 344, arXiv:hep-ph/0610352, arXiv:0711.4222, arXiv:1006.3244; Kostensalo et al, arXiv:1906.10980; BEST, arXiv:2109.11482, arXiv:2109.14654; Berryman et al, arXiv:2111.12530]

Cross section calculation

- A deficit could be due to an overestimate of

$$\sigma(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-)$$

- First calculation: Bahcall, PRC 56 (1997) 3391, hep-ph/9710491



- $\sigma_{\text{G.S.}}$ from $T_{1/2}({}^{71}\text{Ge}) = 11.43 \pm 0.03\,\text{days}$ [Hampel, Remsberg, PRC 31 (1985) 666]

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = (5.54 \pm 0.02) \times 10^{-45}\,\text{cm}^2$$

- $\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669\,\frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}} + 0.220\,\frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}}\right)$

- The contribution of excited states is only ~ 5%! [Bahcall, hep-ph/9710491]

Cross section calculation: excited states

$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$ cross sections in units of $10^{-45}\,\mathrm{cm}^2$:

		^{51}Cr		^{37}Ar			
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}	$\overline{R}$	GA
Ground State [Phys.Atom.Nucl. 83 (2020) 1549]	$T_{1/2}({}^{71}\mathrm{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–	0.844 ± 0.031	5.0σ
Bahcall [hep-ph/9710491]	${}^{71}\mathrm{Ga}(p,n){}^{71}\mathrm{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%	0.802 ± 0.037	5.4σ
Kostensalo et al. [arXiv:1906.10980]	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%	0.824 ± 0.031	5.6σ
Semenov [Phys.Atom.Nucl. 83 (2020) 1549]	${}^{71}\mathrm{Ga}({}^3\mathrm{He},{}^3\mathrm{H}){}^{71}\mathrm{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%	0.786 ± 0.033	6.6σ

Giunti, YFL,Ternes, Xin, arXiv: 2212.09722

Cross section calculation: ground state

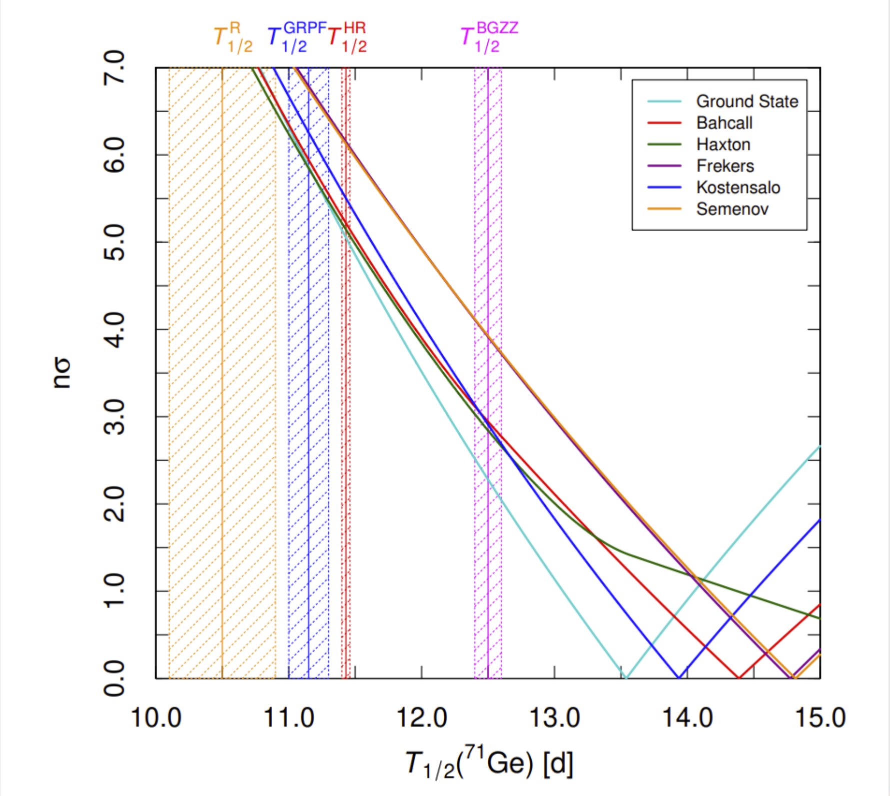
$$T_{1/2}^{\mathrm{BGZZ}}({}^{71}\mathrm{Ge}) = 12.5 \pm 0.1\,\mathrm{d} \quad \text{(Bisi, Germagnoli, Zappa, and Zimmer, 1955) [39],}$$

$$T_{1/2}^{\mathrm{R}}({}^{71}\mathrm{Ge}) = 10.5 \pm 0.4\,\mathrm{d} \quad \text{(Rudstam, 1956) [40],}$$

Giunti, YFL,Ternes, Xin, arXiv: 2212.09722

$$T_{1/2}^{\mathrm{GRPF}}({}^{71}\mathrm{Ge}) = 11.15 \pm 0.15\,\mathrm{d} \quad \text{(Genz, Renier, Pengra, and Fink, 1971) [41],}$$

$$T_{1/2}^{\mathrm{HR}}({}^{71}\mathrm{Ge}) = 11.43 \pm 0.03\,\mathrm{d} \quad \text{(Hampel and Remsberg, 1985) [42].}$$



- **An enlarged life-time will reduce or eliminate the anomaly.**
- **Triggered an active campaign of re-measurement !**

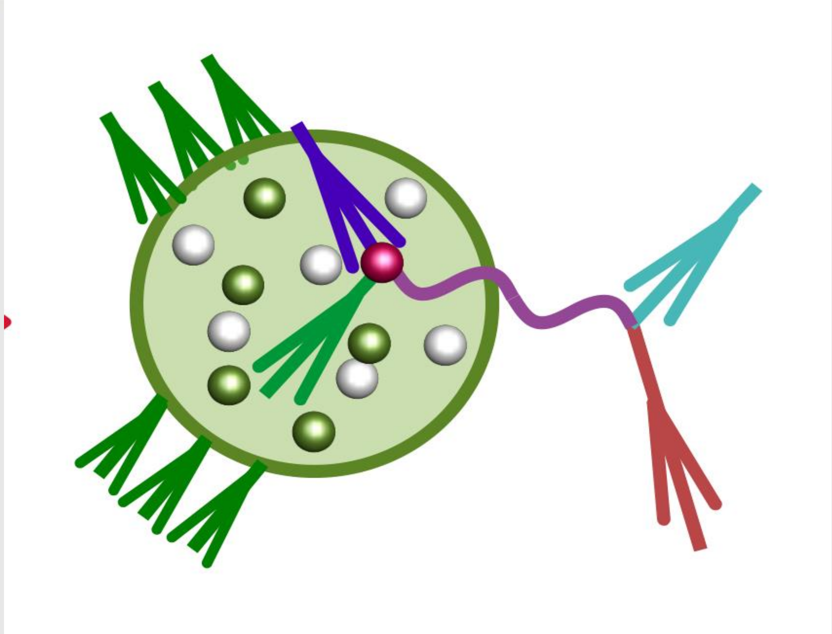
11.43±0.03 days (2307.05353)

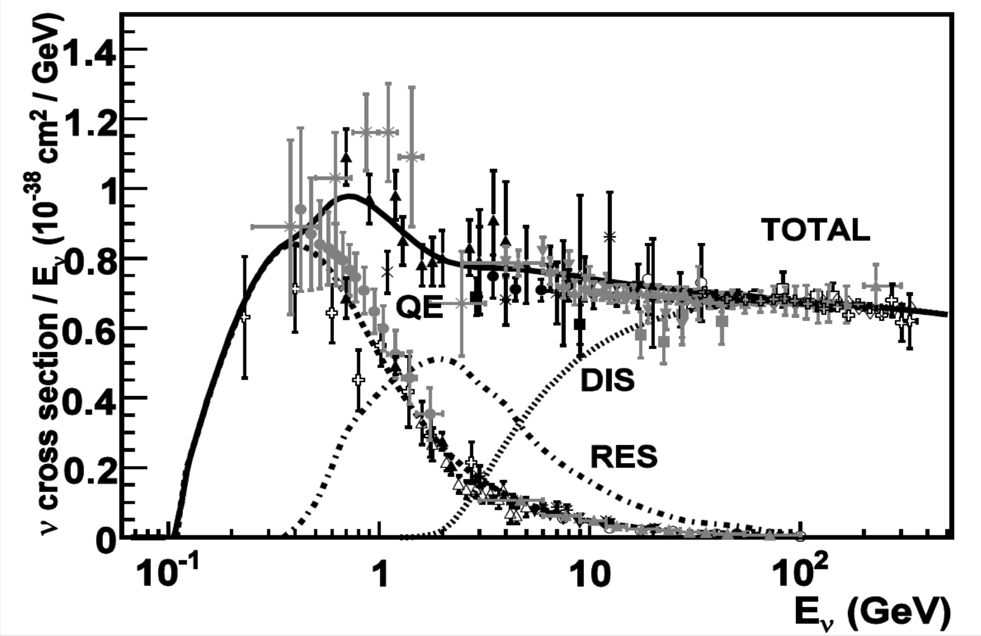
11.468 ± 0.008 days (2401.15286)

- **The Gallium anomaly remains and deserves further theoretical and experimental investigations.**

C: GeV range CC/NC:
accelerator and atmospheric neutrinos

GeV neutrino interactions





quasielastic
scattering

$$\nu_l + n \rightarrow l^- + p$$
$$\overline{\nu_l} + p \rightarrow l^+ + n$$

Fermi motion, binding energy, M_A, 2p2h, … …

resonance
production

$$\nu_l + n \rightarrow l^- + \Delta^+$$
$$\nu_l + p \rightarrow l^- + \Delta^{++}$$
$$\overline{\nu_l} + n \rightarrow l^+ + \Delta^-$$
$$\overline{\nu_l} + p \rightarrow l^+ + \Delta^0$$

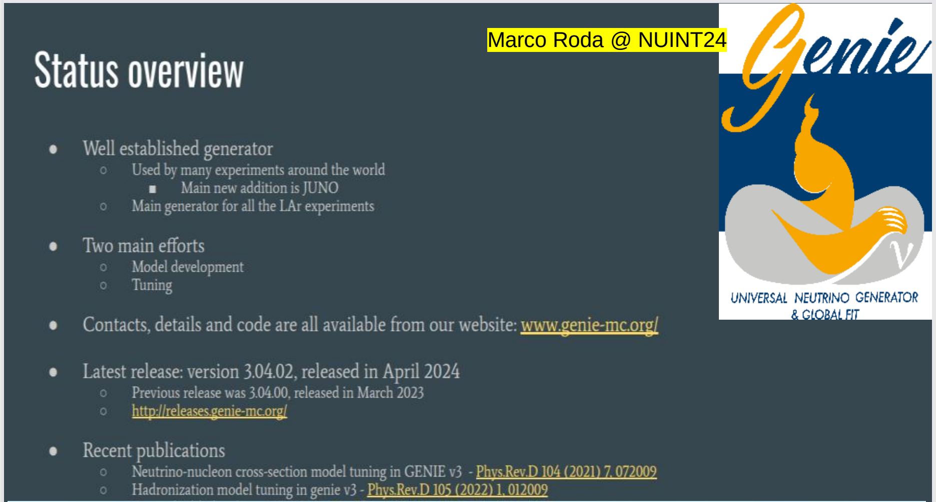
Hardon production, FSI

deep-inelastic
scattering

$$\nu_l + N \rightarrow l^- + N' + n\pi$$
$$\overline{\nu_l} + N \rightarrow l^- + N' + n\pi$$

Parton Model, FSI

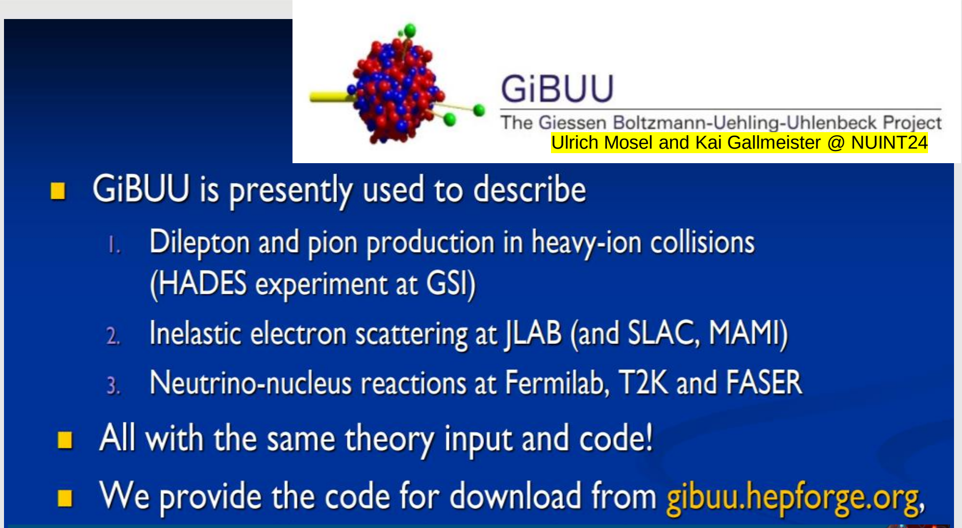
GeV neutrino interaction generators



Marco Roda @ NUINT24

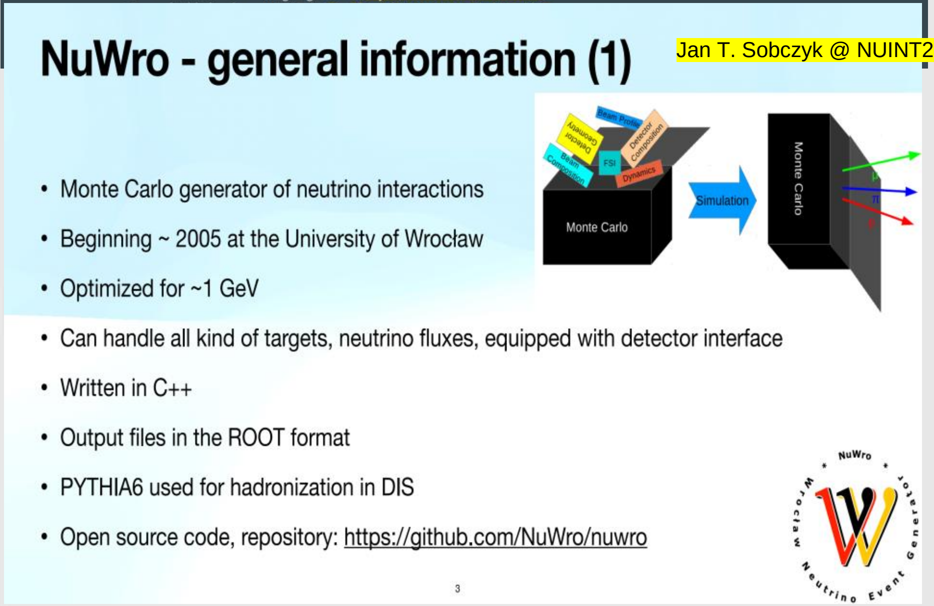
Status overview

- 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,

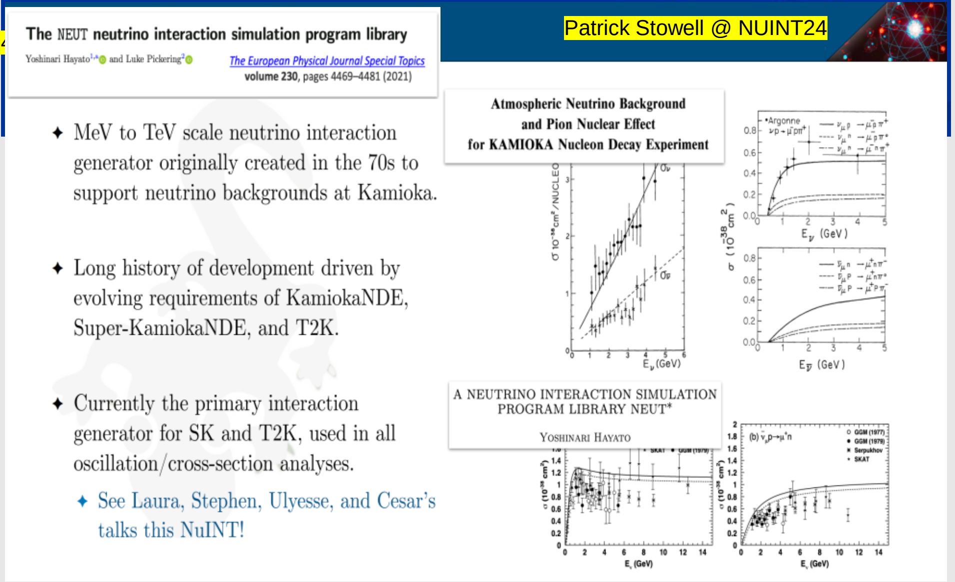


Jan T. Sobczyk @ NUINT24

NuWro - general information (1)

- 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

3



Patrick Stowell @ NUINT24

The NEUT neutrino interaction simulation program library
Yoshinari Hayato[1,a] and Luke Pickering[2]
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!

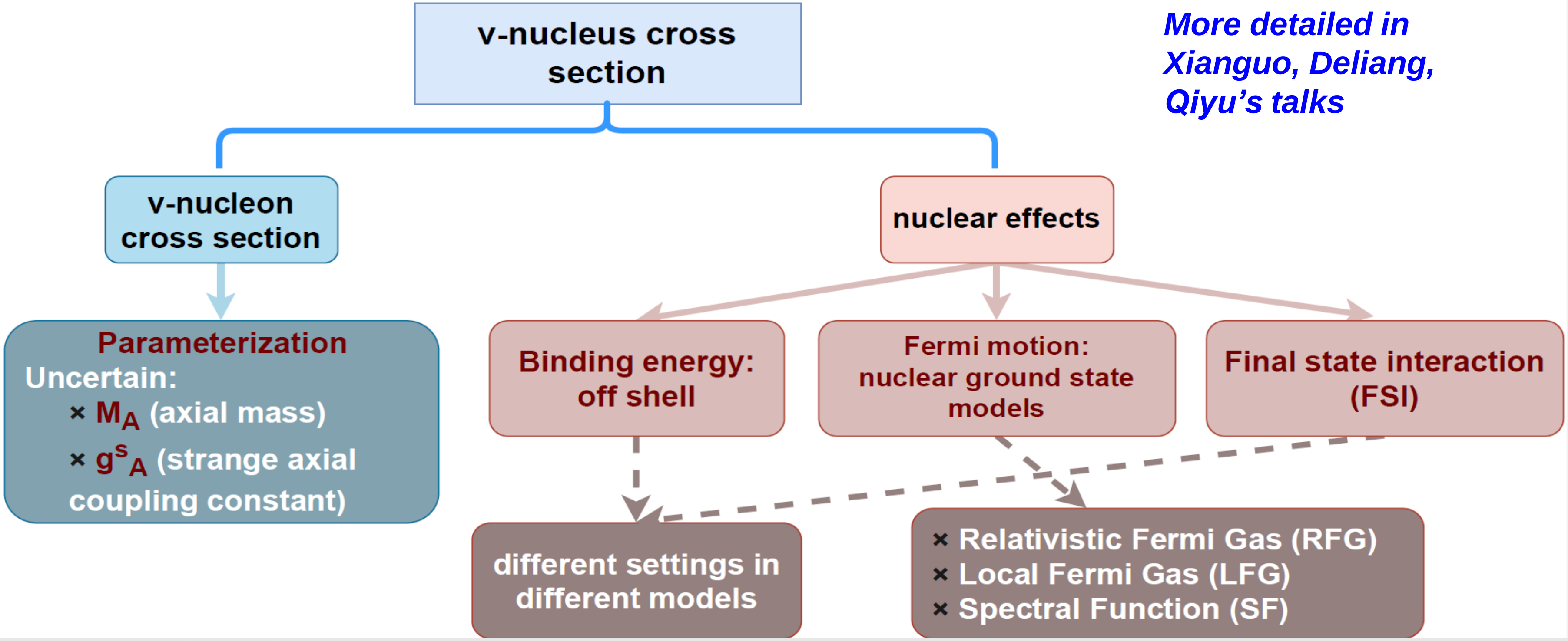
Atmospheric Neutrino Background and Pion Nuclear Effect for KAMIOKA Nucleon Decay Experiment

A NEUTRINO INTERACTION SIMULATION PROGRAM LIBRARY NEUT*
YOSHINARI HAYATO

General components in generators

Brief summary of GeV neutrino interaction models

More detailed in Xianguo, Deliang, Qiyu's talks



ν-nucleus cross section

ν-nucleon cross section

Parameterization

Uncertain:

- M_A (axial mass)
- g^s_A (strange axial coupling constant)

nuclear effects

Binding energy: off shell

Fermi motion: nuclear ground state models

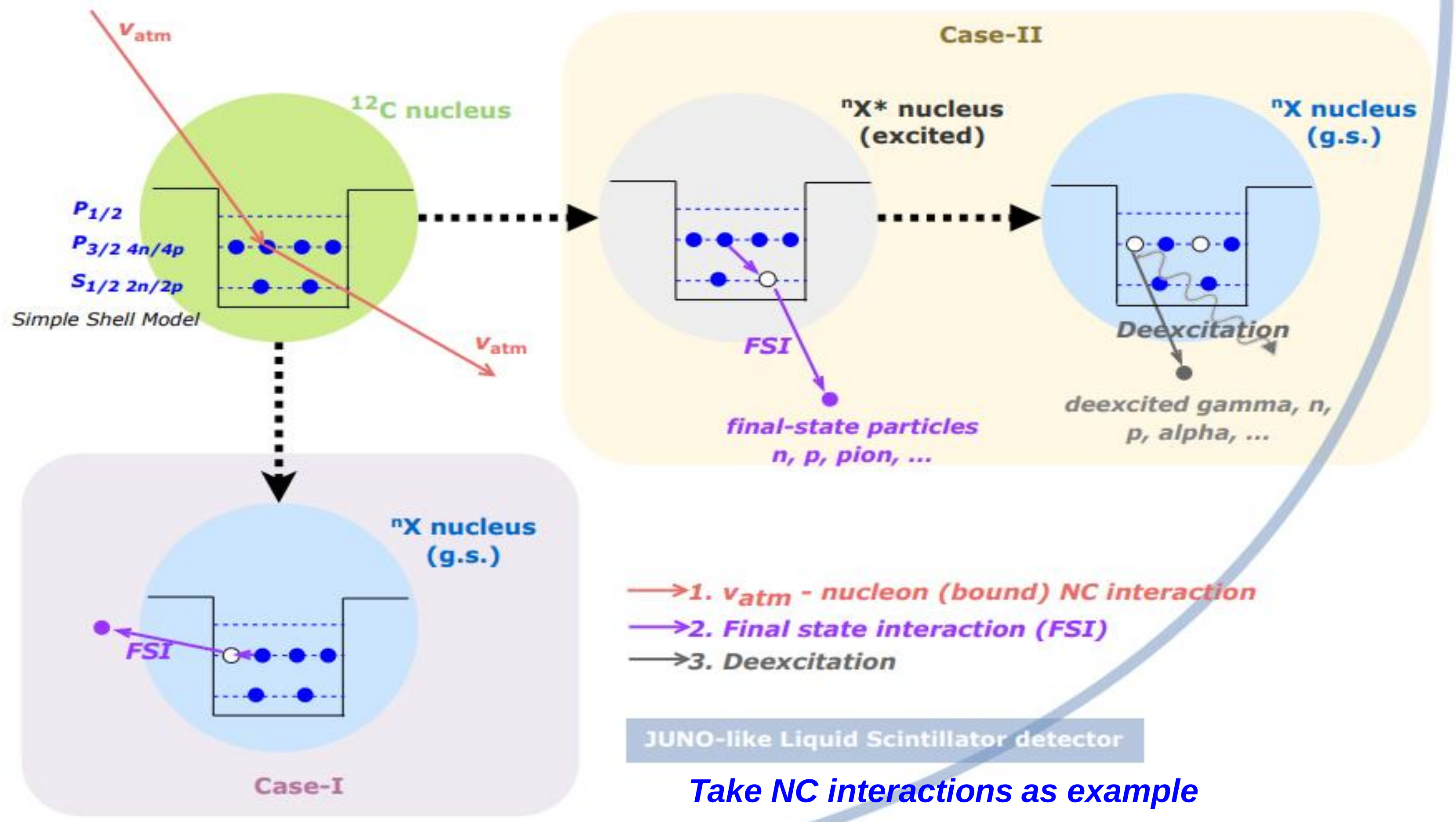
Final state interaction (FSI)

different settings in different models

- Relativistic Fermi Gas (RFG)
- Local Fermi Gas (LFG)
- Spectral Function (SF)

$$\frac{d\sigma^{\mathrm{IA}}_{\ell A}}{d\omega\, d\Omega} = \sum_N \int \underbrace{\boxed{d^3p\, dE\, P^N_{\mathrm{hole}}(\mathbf{p}, E)}}_{\boxed{\text{average over the initial nucleon state}}} \underbrace{\boxed{\frac{M}{E_{\mathbf{p}}} \frac{d\sigma^{\mathrm{elem}}_{\ell N}}{d\omega\, d\Omega}}}_{\boxed{\text{nucleon cross section}}} \underbrace{\boxed{P^N_{\mathrm{part}}(\mathbf{p}', \mathcal{T}')}}_{\boxed{\text{final-state interactions}}}$$

New Methodology: adding deexcitation



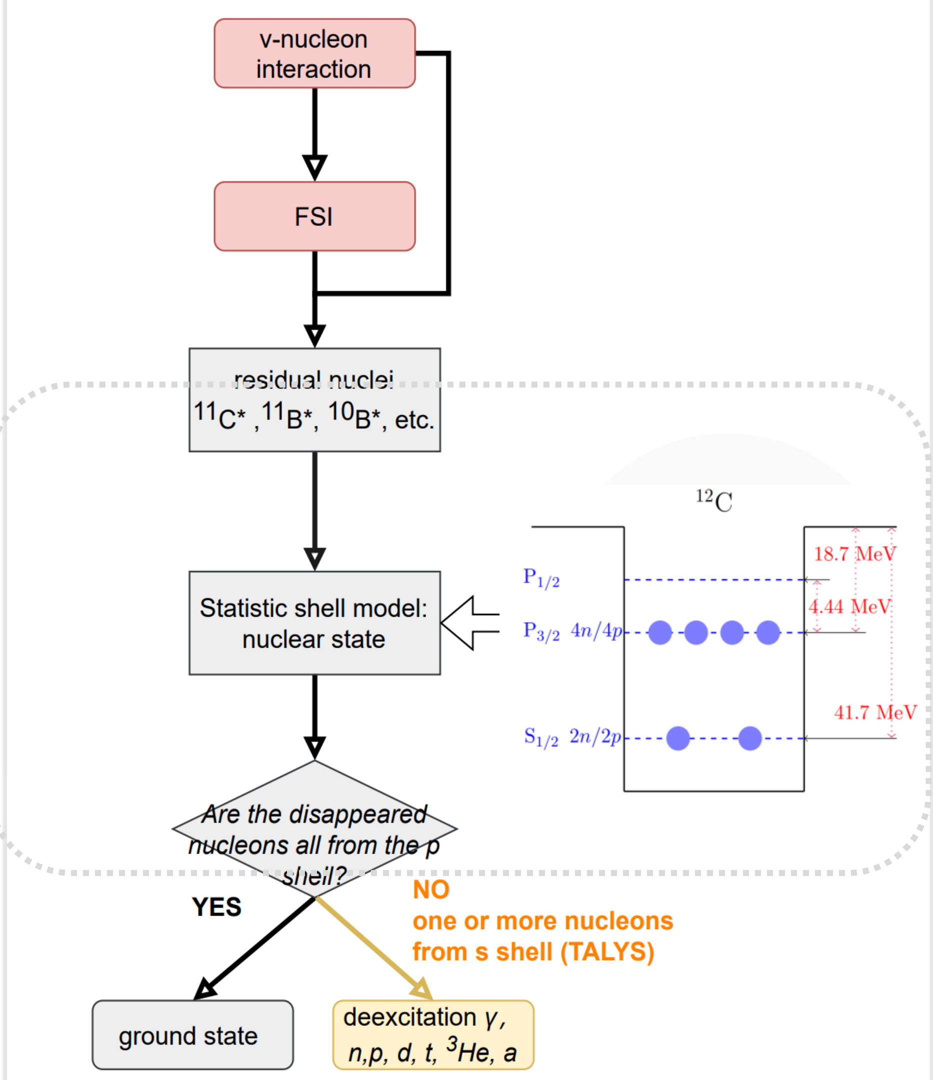
Take NC interactions as example

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

Cheng et al, arXiv 2404.07429

More detailed in Wanlei, Abe, Jie's talks

TALYS-based Deexcitation of Residual Nucleus



1. **Simple shell model → Status of the residual nuclei**

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

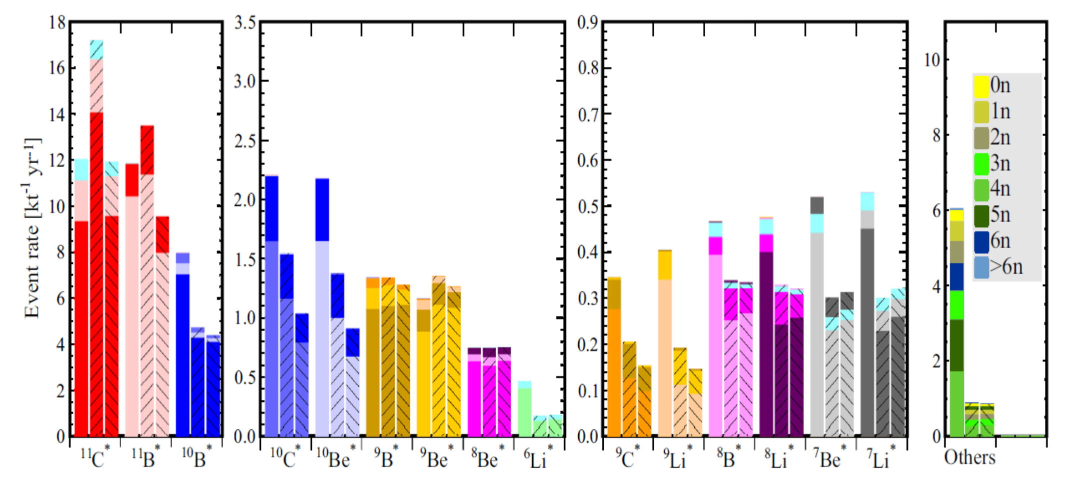
Daughter Nuclei	Shell Hole	Configuration Probability	Excitation Energy
$^{11}C^*$ or $^{11}B^*$	$s_{1/2}$	1/3	$E^* = 23$ MeV
	$p_{3/2}$	2/3	$E^* = 0$ MeV
$^{10}C^*$ or $^{10}Be^*$	$s_{1/2}$	1/15	$E^* = 46$ MeV
	$p_{3/2}$	6/15	$E^* = 0$ MeV
	$s_{1/2}$ & $p_{3/2}$	8/15	$E^* = 23$ MeV
$^{10}B^*$	$s_{1/2}$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

Assume each neutron or proton has same possibility(1/6) to leave the shell.

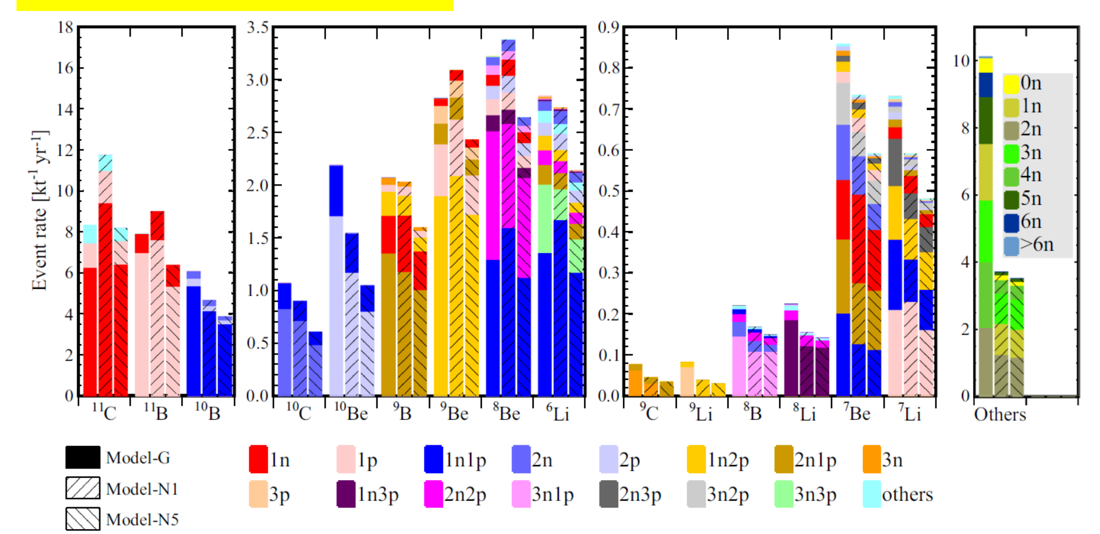
More complicated shell information can be included.

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**

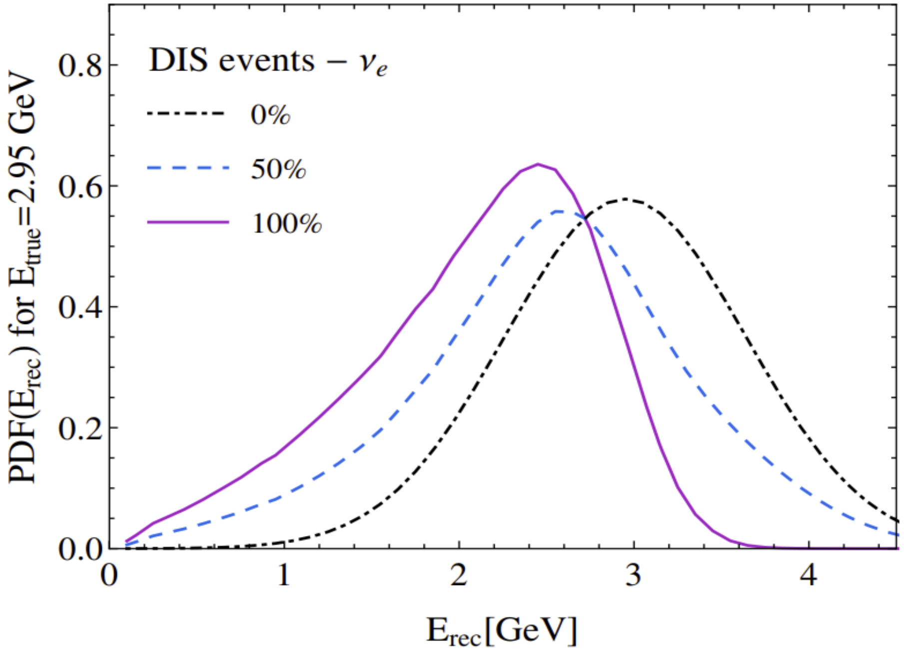
(a) energy reconstruction

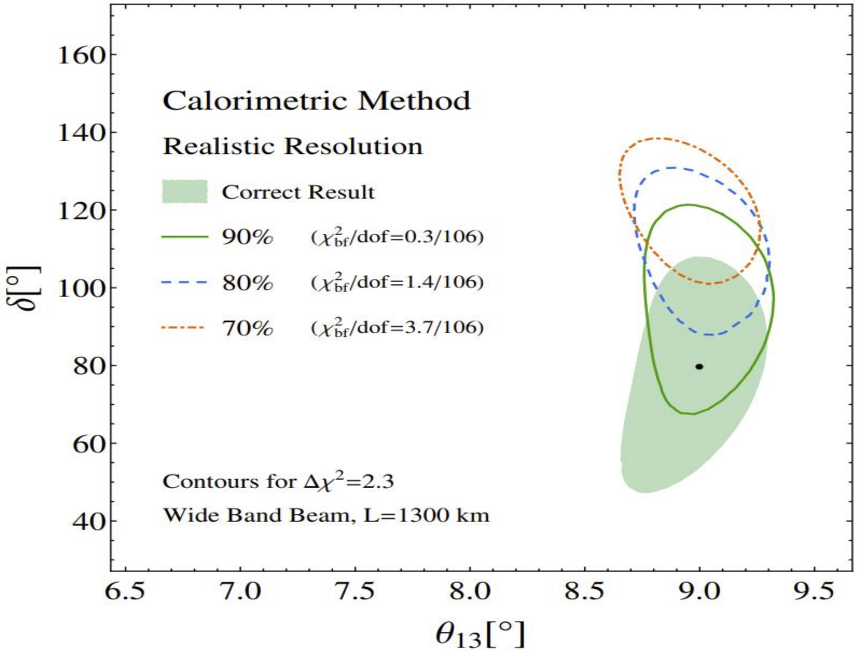
(b) tagging and reducing the backgrounds

Energy reconstruction in DUNE

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

Ankowski, Coloma, Huber, Mariani, Vagnoni, 1507.08561



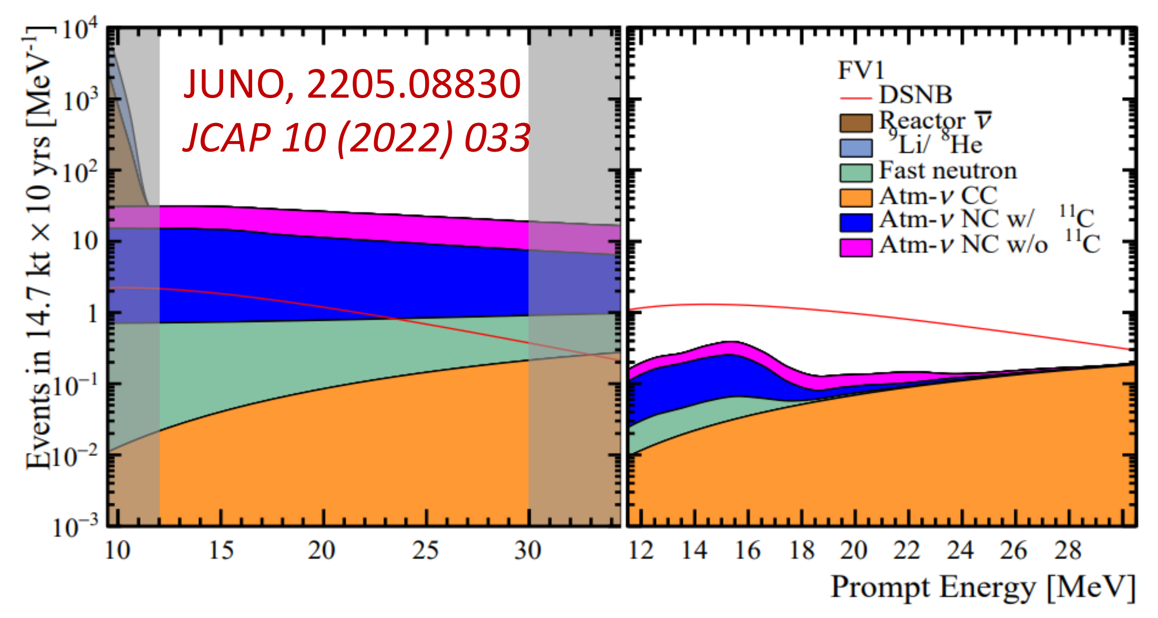


- **The energy is reconstructed with calorimetric method.**
- **Missing neutrons (pions) may bias the energy and then result in wrong oscillation parameters.**

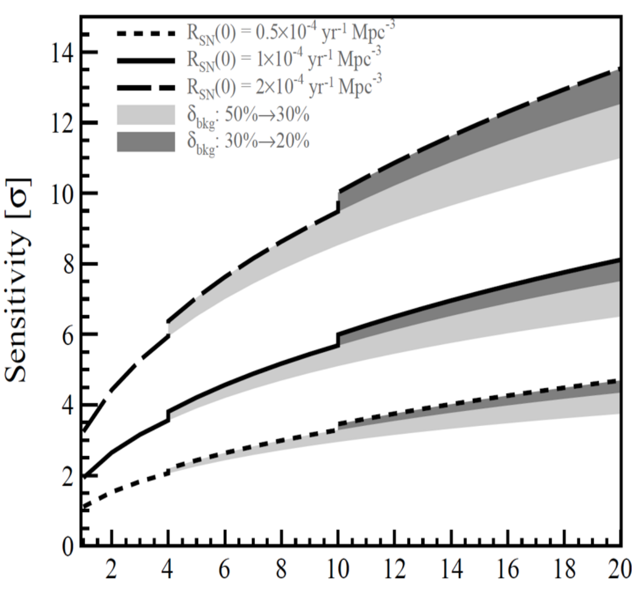
Rare searches in JUNO

- **Diffuse Supernova Neutrino Background via IBD process: 2-4 events in JUNO per year**
- **Dominant backgrounds are from atmospheric neutrino NC interactions (20 times larger than the signal.**

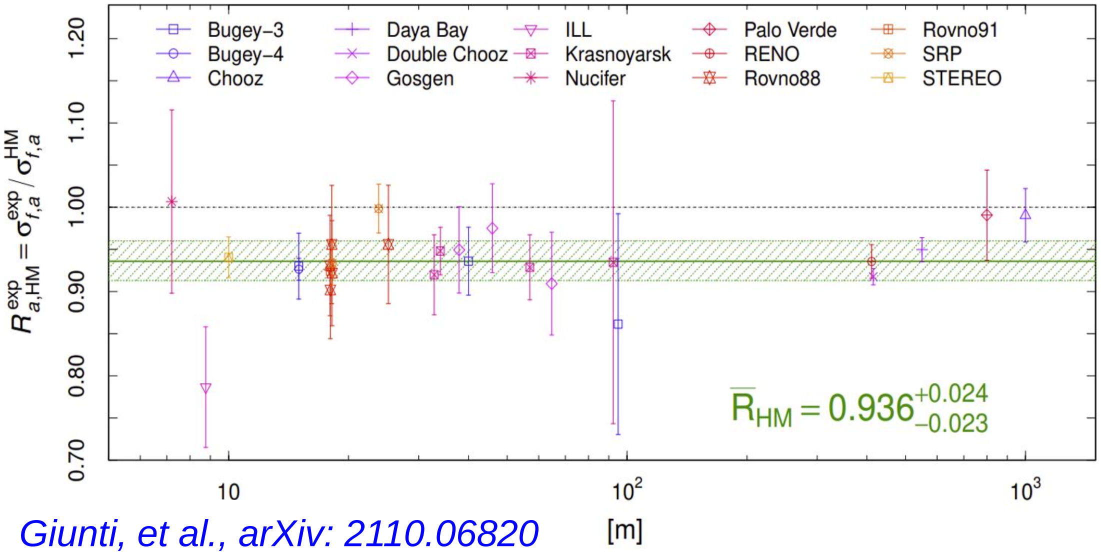
- **A precise exclusive NC cross section is crucial (with neutron, ^{11}C) !**
- **Also pion and kaon production is important for proton decay search.**



JUNO, 2205.08830
JCAP 10 (2022) 033

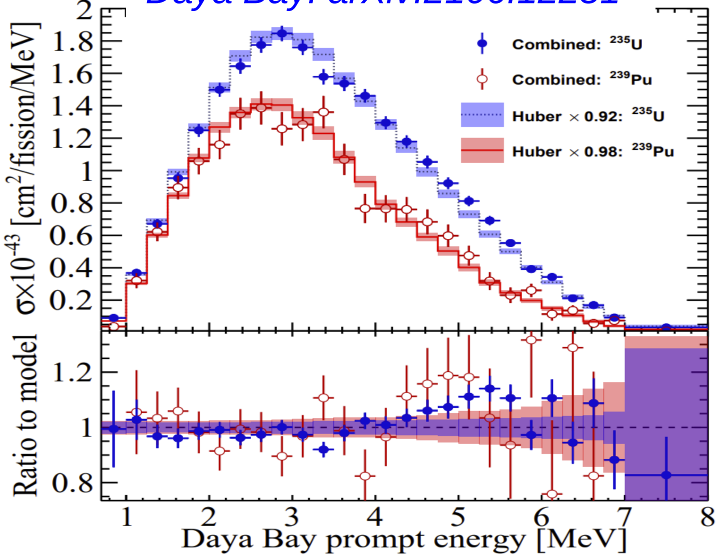


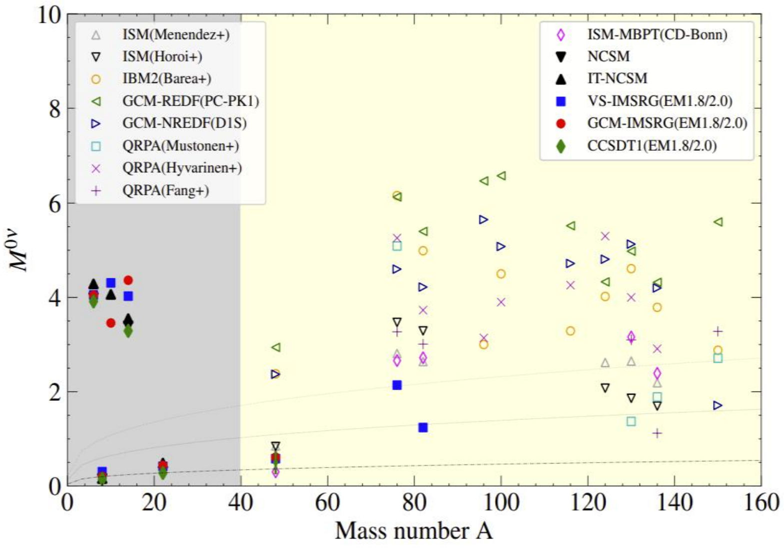
Neutrino-nuclear connection beyond cross sections



Giunti, et al., arXiv: 2110.06820

Daya Bay: arXiv:2106.12251





- ➢ **Solution to Reactor antineutrino anomaly requires precise energy spectrum of (forbidden) β decays!**
- ➢ **Search for neutrinoless double beta decay needs to better control of the nuclear matrix element**

Yao et al., arXiv: 2111.15543

Conclusion

Neutrino interaction cross sections are important prerequisite to study neutrino properties and new physics.

Neutrino-lepton and neutrino (free-)nucleon interactions are relatively simple and widely used in low energy neutrino detection.

Electron scattering, & IBD of free protons

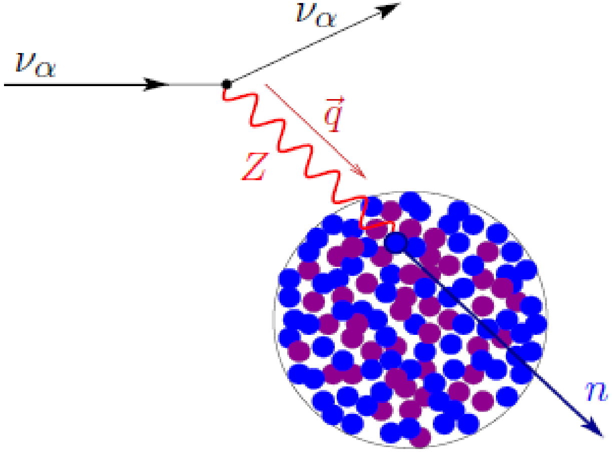
Neutrino-nucleus interactions:

From low to high energies, depend on different aspects of hardon and nuclear physics. (Shell structure, Binding energy, Fermi Motion, Final state interactions, Deexcitation, Parton properties, etc.)

Thank you !

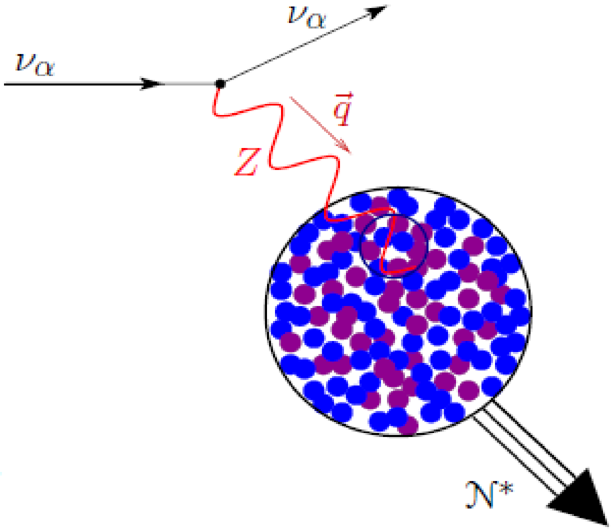
Backup

Why Coherent ?



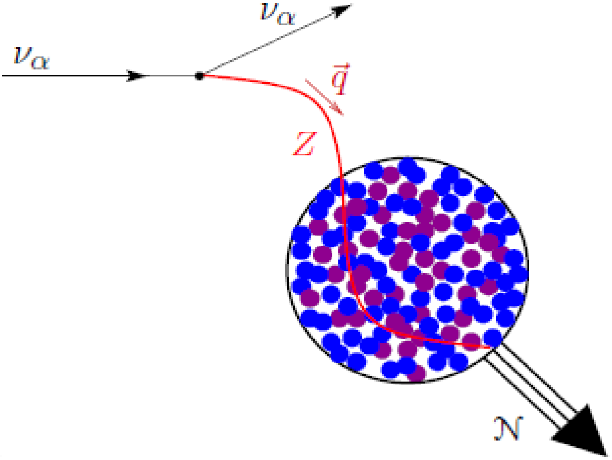
Inelastic Incoherent

$\lambda_Z \ll R$



Elastic Incoherent

$\lambda_Z \lesssim R$



Elastic Coherent

$\lambda_Z \gtrsim 2R$

$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}|} \quad \Longrightarrow \quad \text{CE}\nu\text{NS for } |\vec{q}|\, R \lesssim \hbar$$

$$\boxed{|\vec{q}|\, R \lesssim 1} \quad \leftarrow \quad \text{Natural Units}$$

The COHERENT experiment

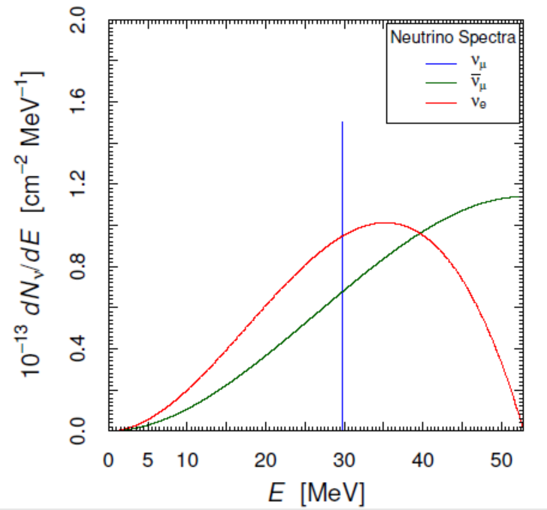
- 14.6 kg CsI scintillating crystal and 24 kg LAr detector.
- Prompt monochromatic ν_μ from stopped pion decays:

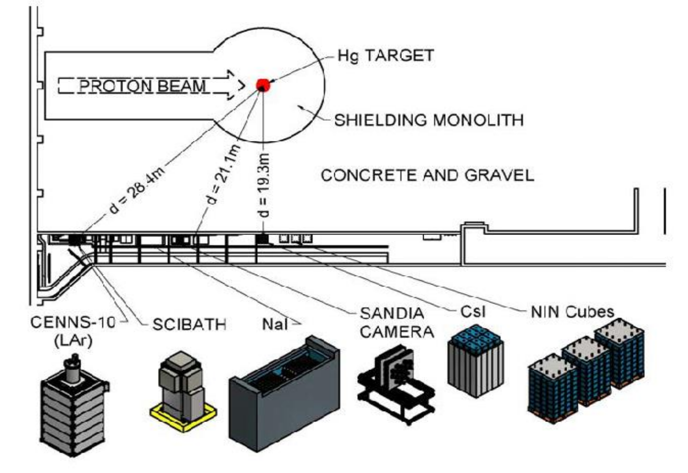
$$\pi^+ \to \mu^+ + \nu_\mu$$

- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:

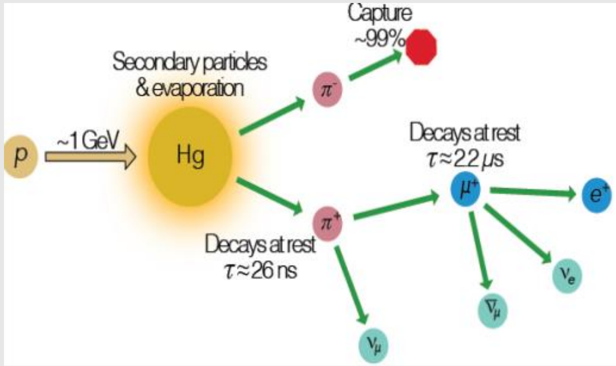
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

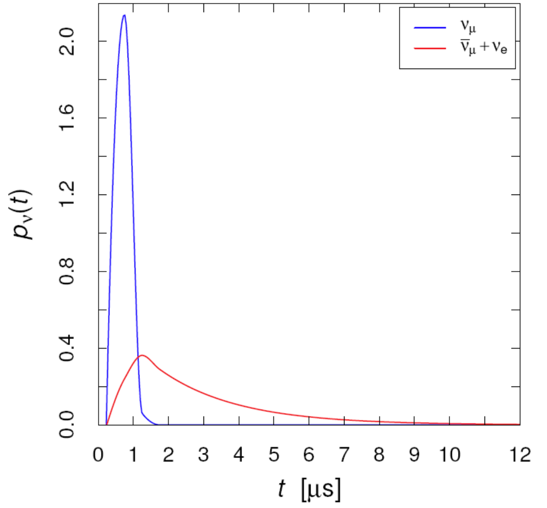
- The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ and $\bar{\nu}_\mu$



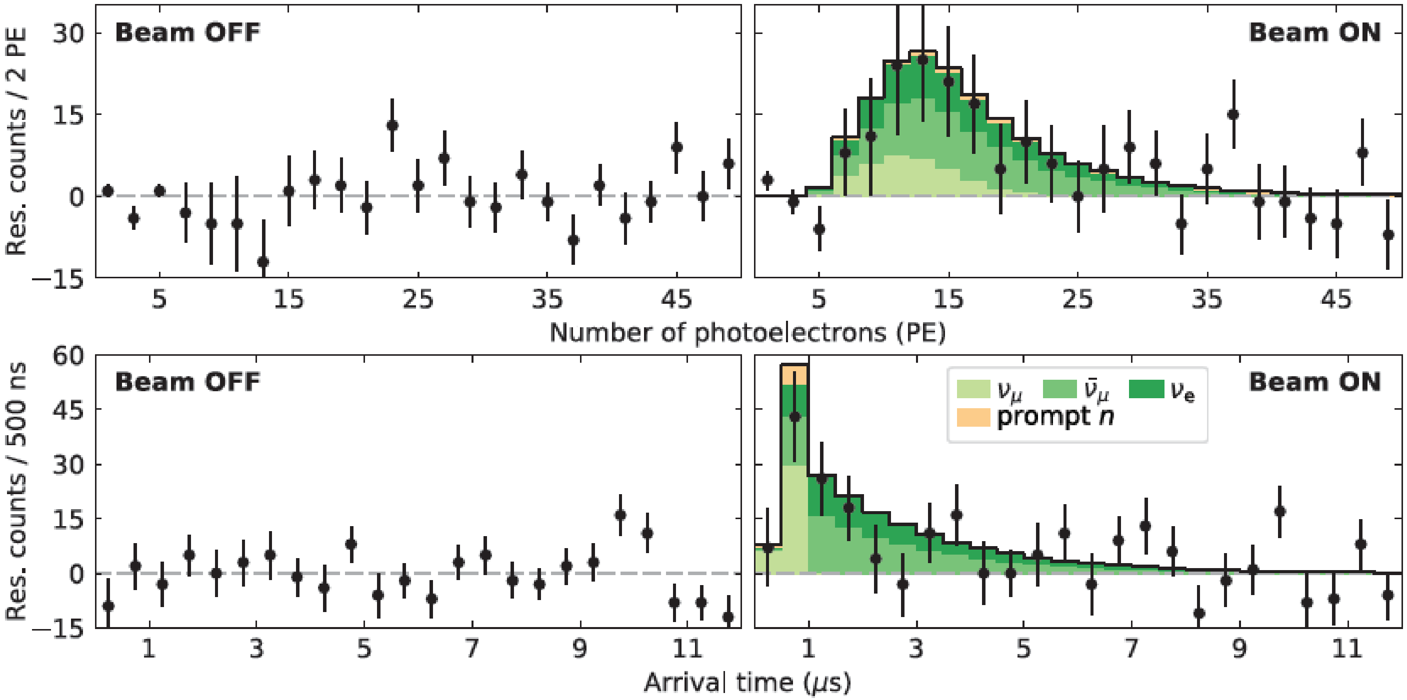


[COHERENT, arXiv:1803.09183]





First observation of CEvNS at CsI (2017)

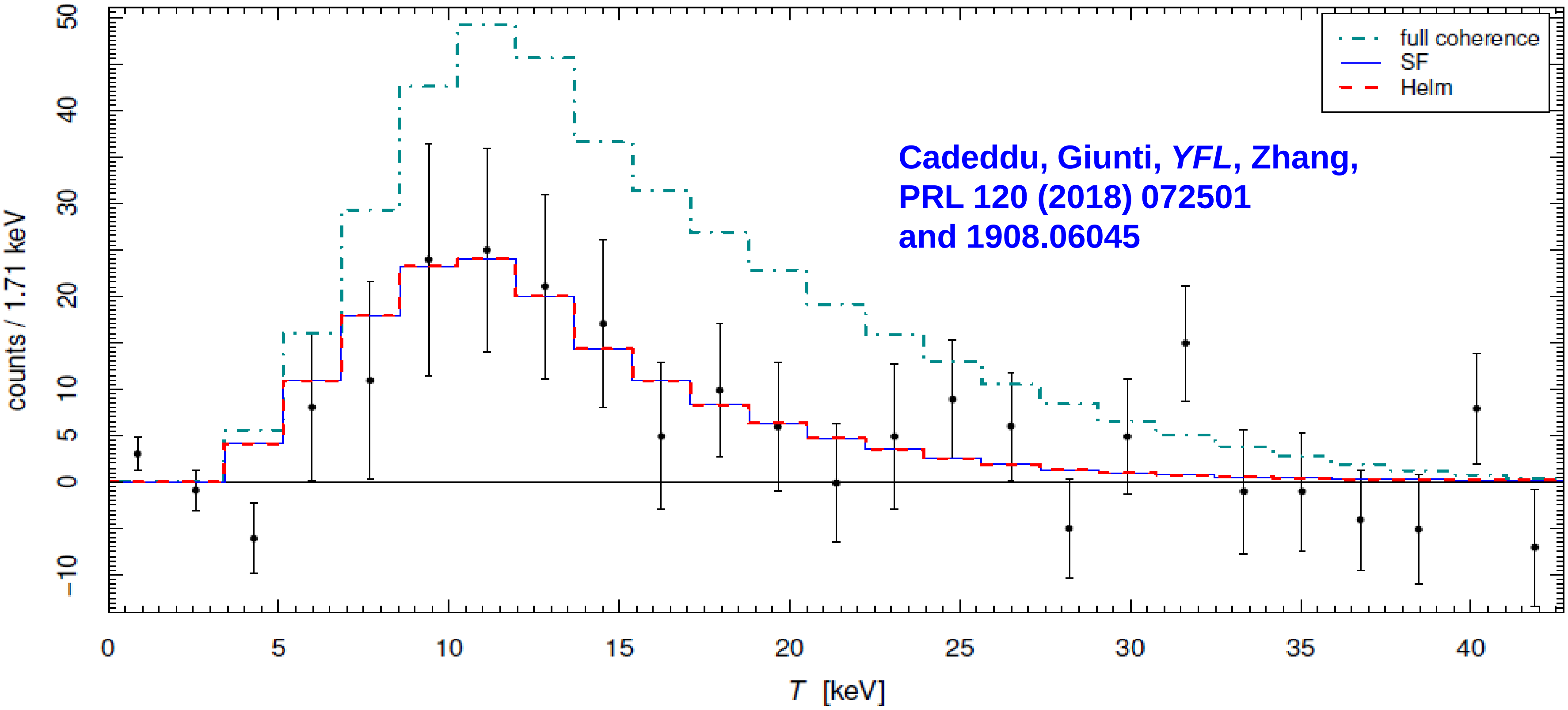


Akimov et al. *Science*
Vol 357, Issue 6356
15 September 2017

- Data are beam coincident and anti-coincident residuals during SNS operation, “On”, and during SNS shutdown periods, “Off”.
- Excess in light yield and timing distributions only for Beam on.

$^{133}_{55}\mathrm{Cs}_{78}$ and $^{127}_{53}\mathrm{I}_{74}$ ← Heavy nuclei well suited for CEνNS

Test of Coherency

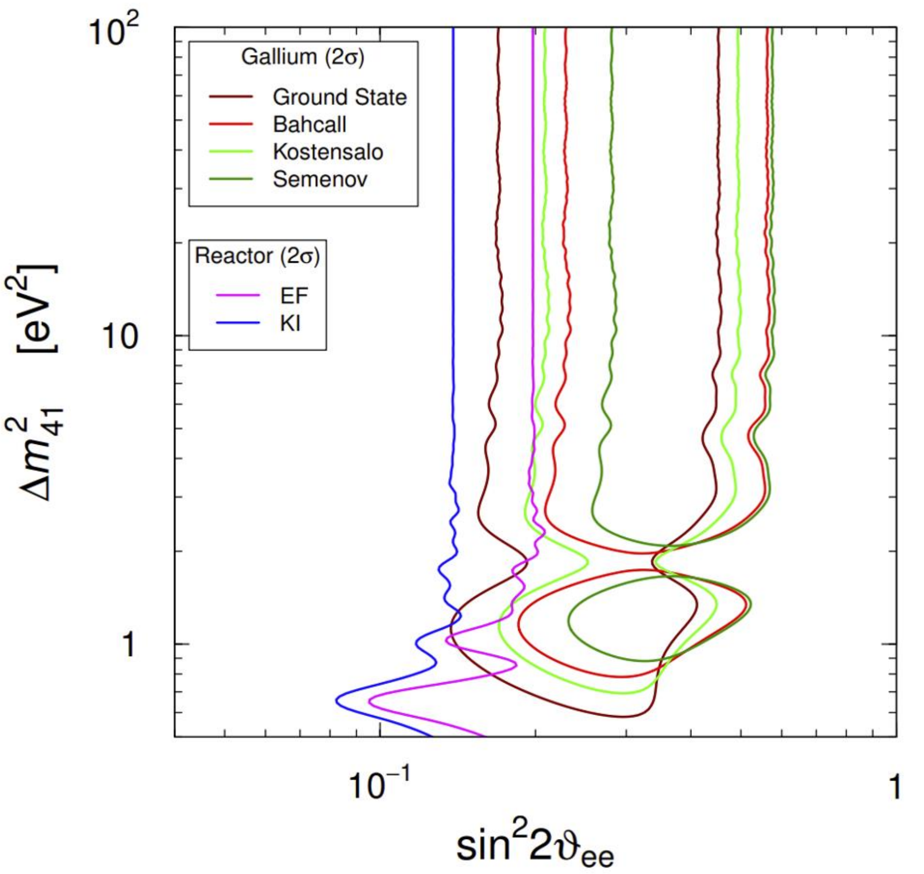


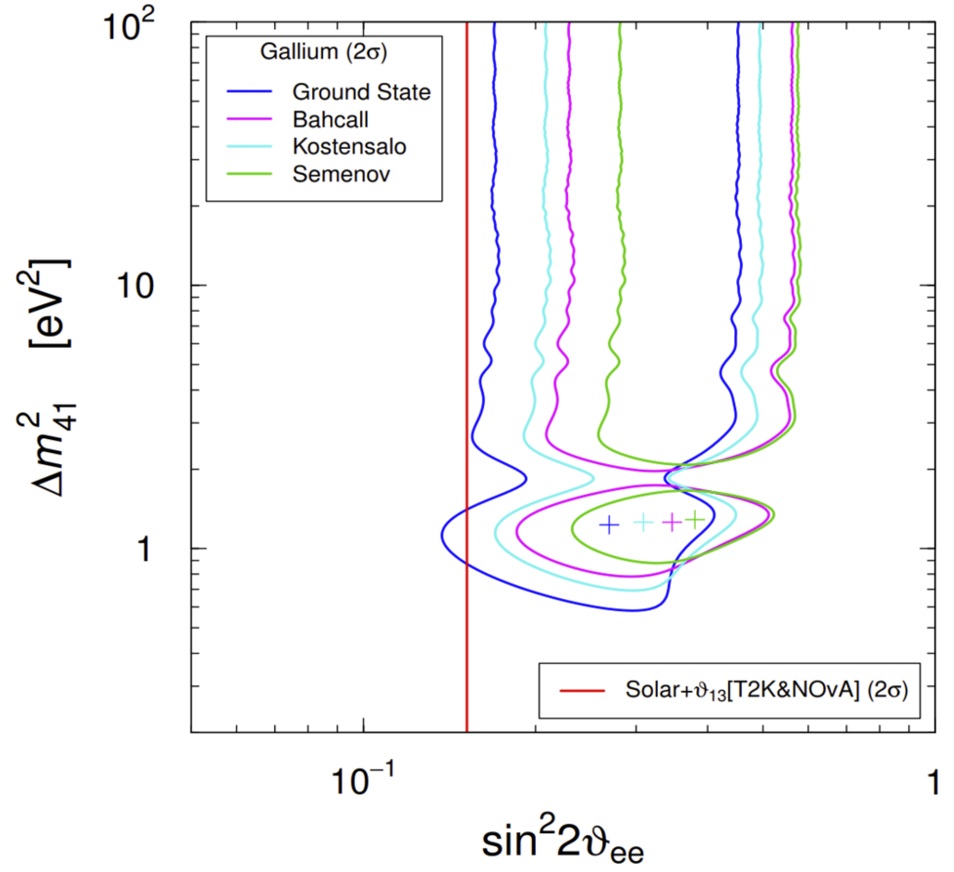
Cadeddu, Giunti, *YFL*, Zhang,
PRL 120 (2018) 072501
and 1908.06045

(1) **Full coherence → F(proton) = F(neutron) =1.**

(2) **COHERENT data show 3.7 sigma evidence of the nuclear structure suppression of the full coherence**

3+1 mixing ?





- **No 3+1 neutrino mixing and oscillation solution**
- **No CPT violation solution**

Giunti, YFL,Ternes, Xin, arXiv: 2209.00916

→ Source problem?