Neutrino Interaction Cross Sections: From Low to High Energies

Yu-Feng Li (李玉峰)

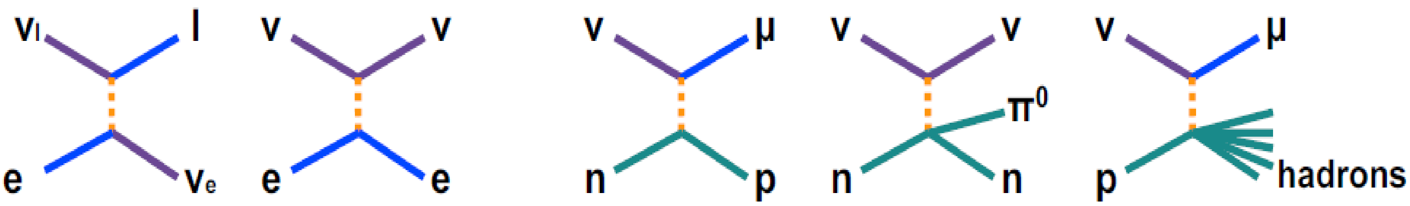
Institute of High Energy Physics &

University of Chinese Academy of Sciences, Beijing

νSTEP@HIAS, Hangzhou

18th May 2024

Neutrino interactions from low to high energies



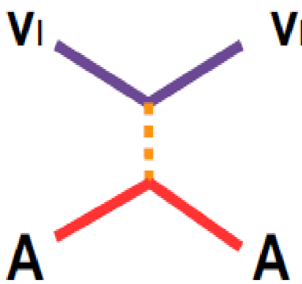
inverse muon (tau) decay

elastic electron scattering

(quasi) - elastic nucleon scattering

nuclear excitation and resonant production

Deep inelastic scattering and jet production



- **Neutrino-lepton interactions:**

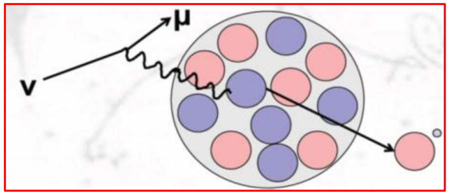
$$\overset{(-)}{\nu}_\alpha + e^- \rightarrow \overset{(-)}{\nu}_\alpha + e^- \,.$$

- **Neutrino-nucleon interactions**

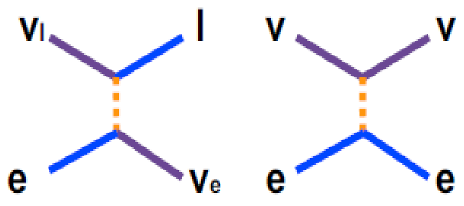
$$\nu_\ell + n \longrightarrow p + \ell^-$$

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

- **Neutrino-nucleus interactions**



Neutrino-lepton interactions



inverse muon (tau) decay

elastic electron scattering

- **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

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

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

Prompt signal

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

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

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

- **Famous inverse beta decay on free proton (in Hydrogen rich detectors)**
- **Hadron weak current: induced currents**

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

- **Isospin symmetry**
- **Correlated with free neutron decay**

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

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

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%

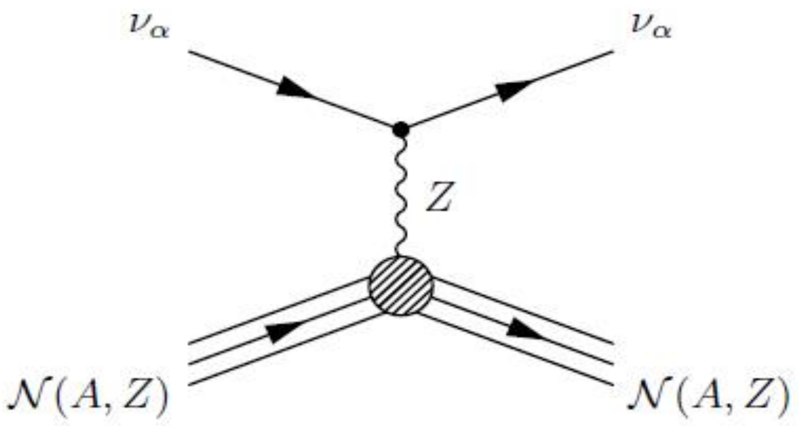
May affect the reactor antineutrino anomaly
Giunti, YFL, Ternes, Xin PLB (2022)

A: low energy NC: CEνNS

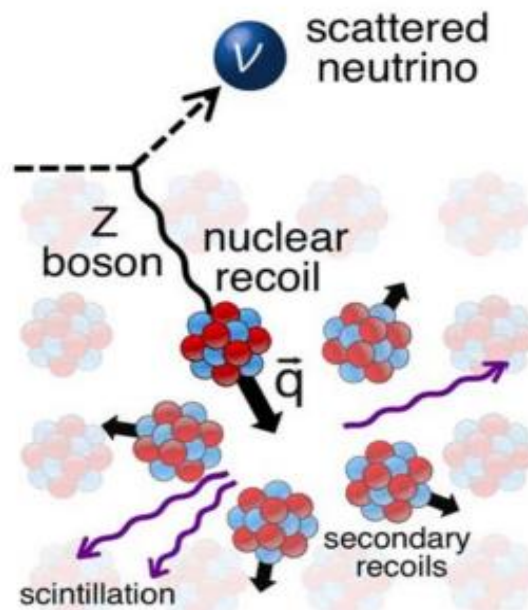
Coherent Elastic Neutrino-Nucleus Scattering

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

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

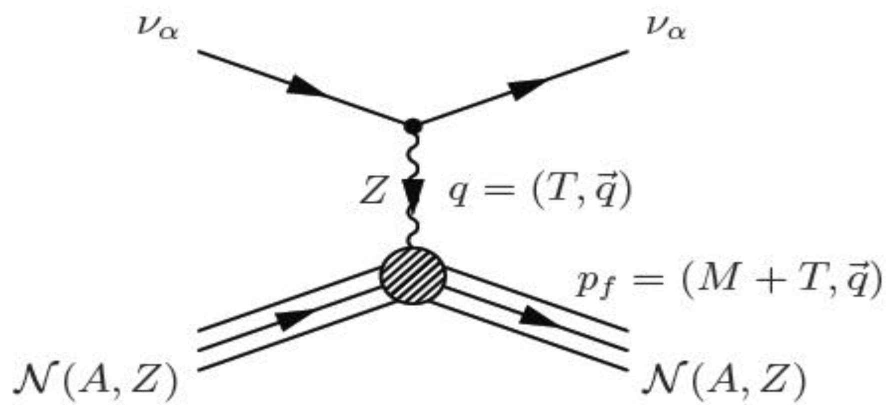


- The nucleus $\mathcal{N}(A,Z)$ recoils as a whole!
- So what?



The CEνNS kinematics

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



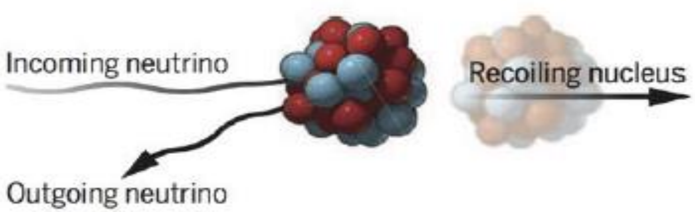
- Heavy target nucleus $\mathcal{N}(A, Z)$:

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

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

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

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



- Observable nuclear recoil kinetic energy:

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

The CEνNS Cross Section

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

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

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

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

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

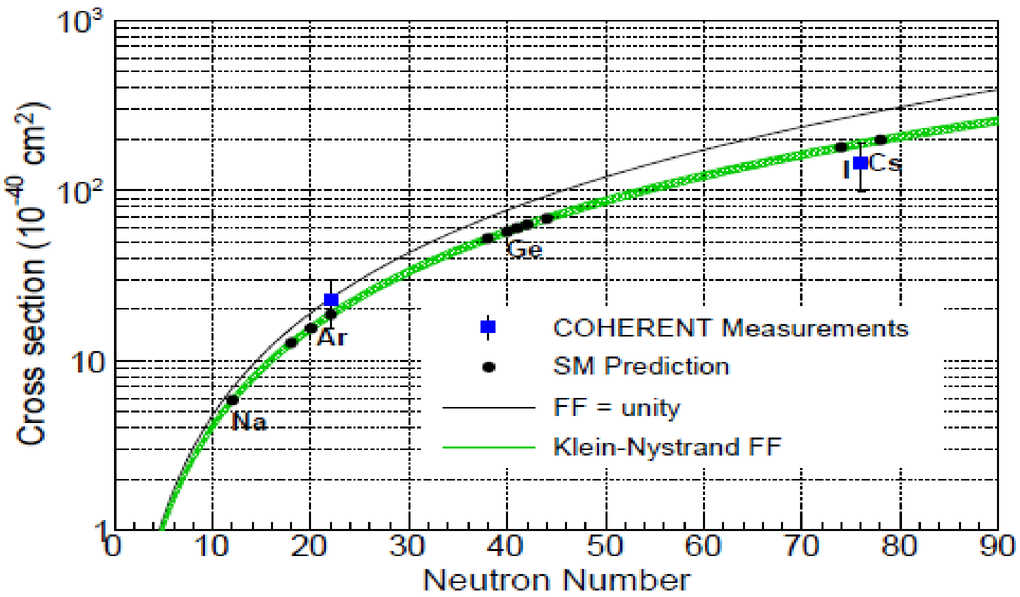
See the radiative correction in 2011.05960

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

[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: $\sigma_{\text{NC}}^{\text{incoherent}} \propto N \Longrightarrow \sigma_{\text{CE}\nu\text{NS}}/\sigma_{\text{NC}}^{\text{incoherent}} \propto N$
- 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

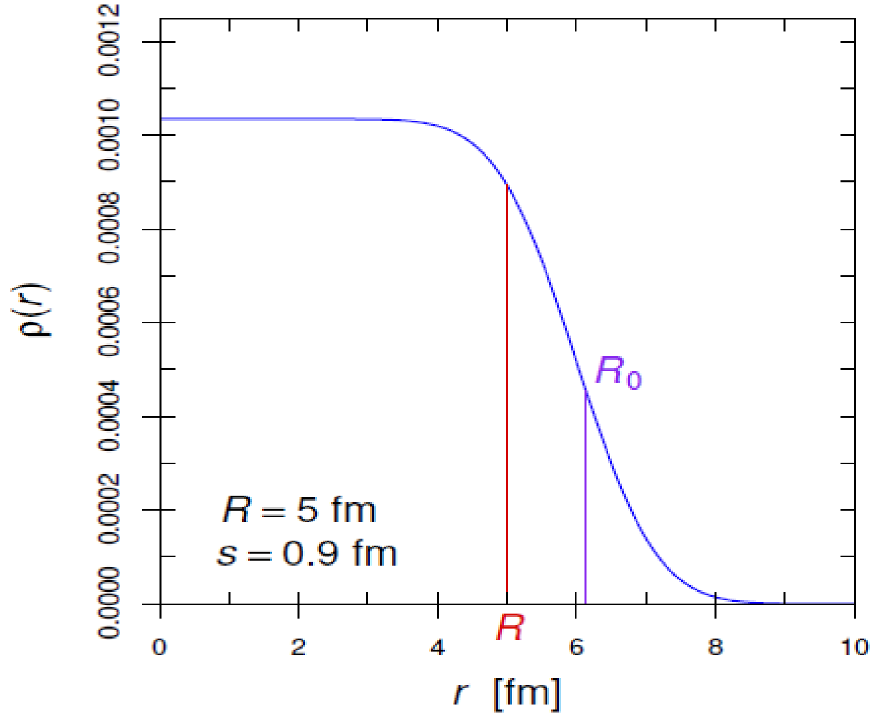
See also nuclear shell model calculation in 2007.08529

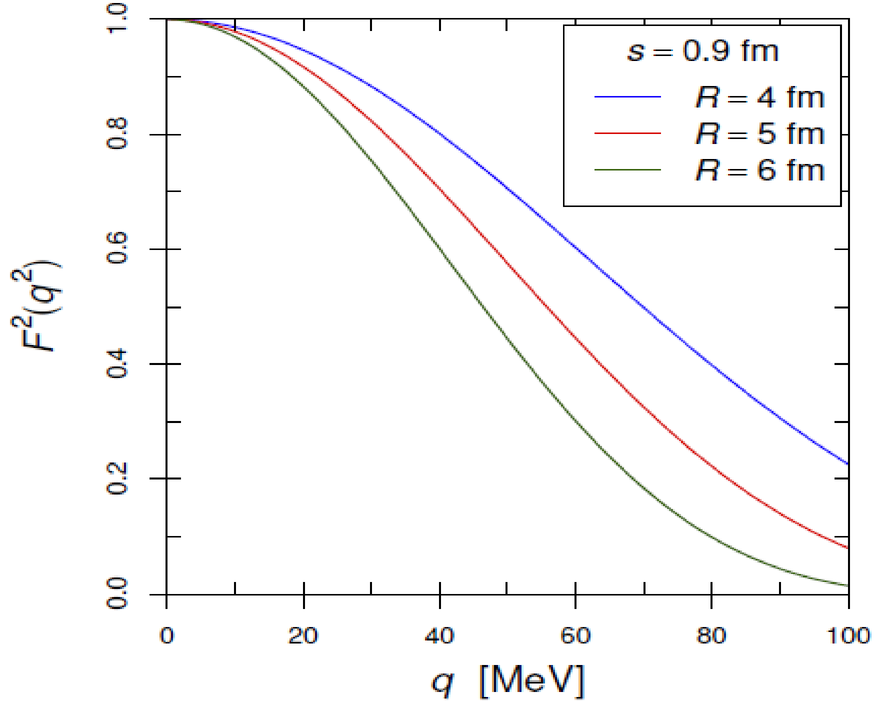
Helm form factor: $F_N^{\text{Helm}}(|\vec{q}|^2) = 3\,\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0}\,e^{-|\vec{q}|^2 s^2/2}$

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

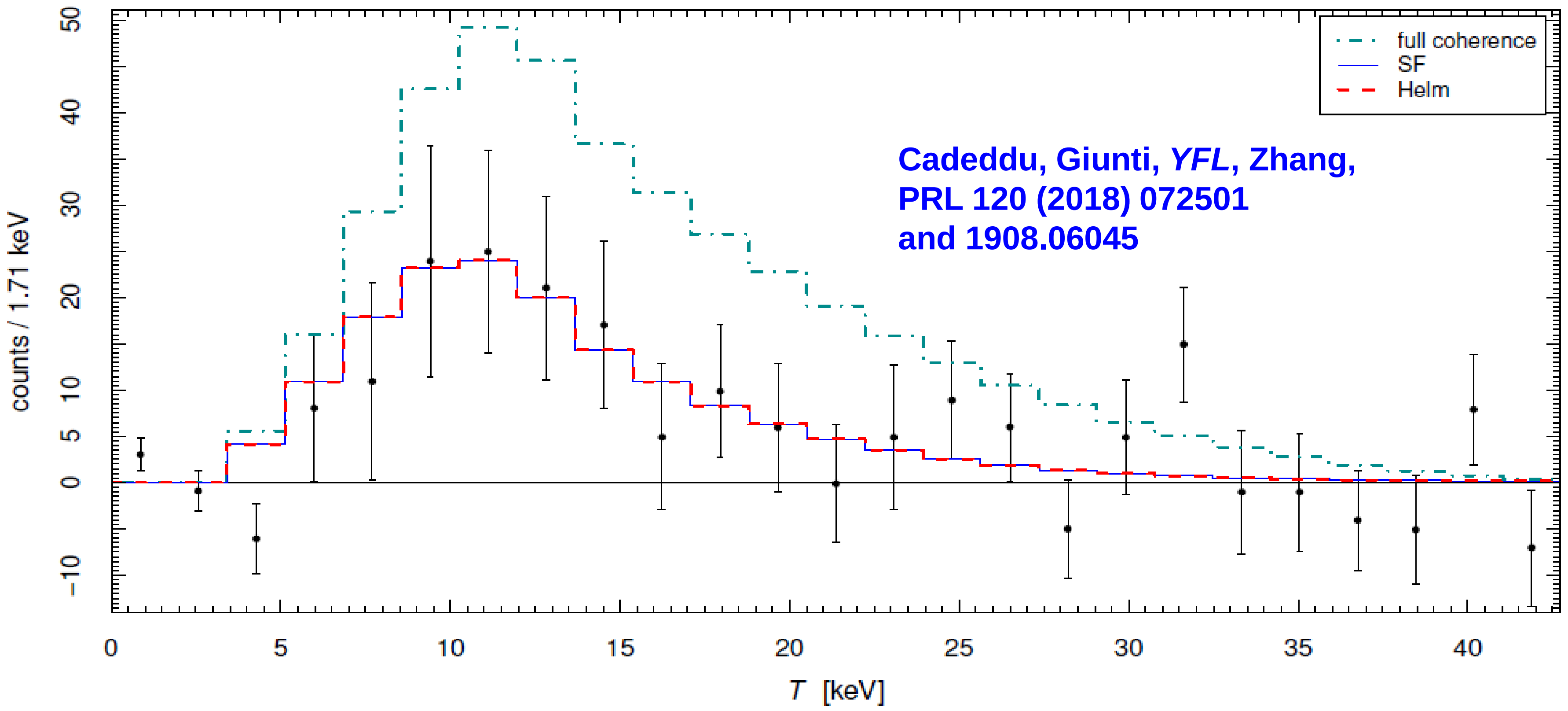
Obtained from the convolution of a sphere with constant density with radius R_0 and a gaussian density with standard deviation s

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





Test of Coherency

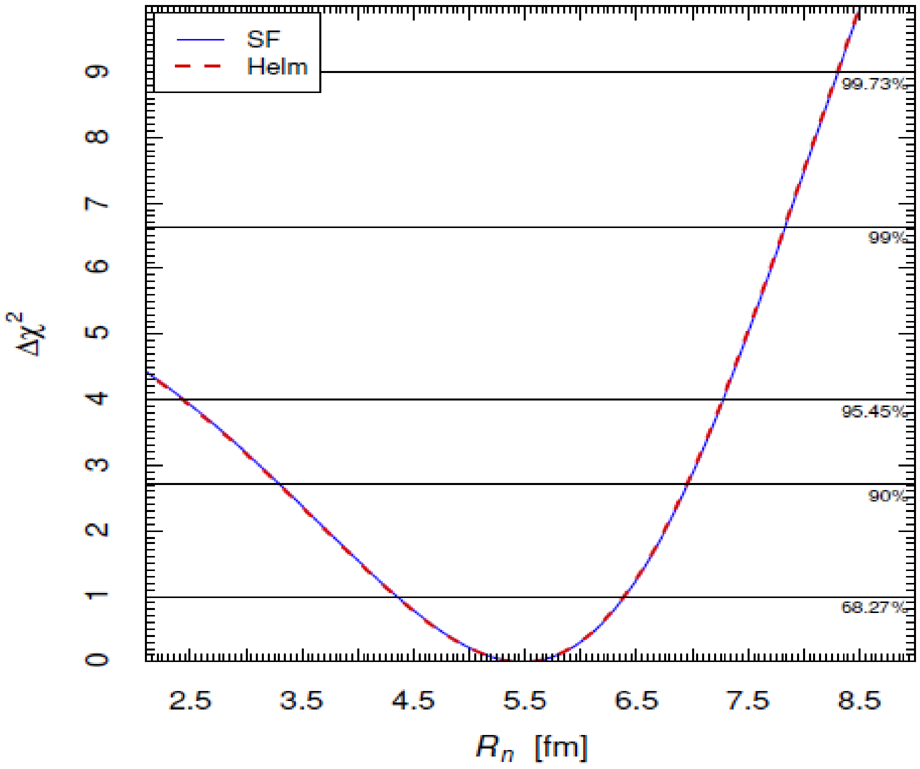


(1) **Full coherence → F(proton) = F(neutron) =1.**

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

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:

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

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

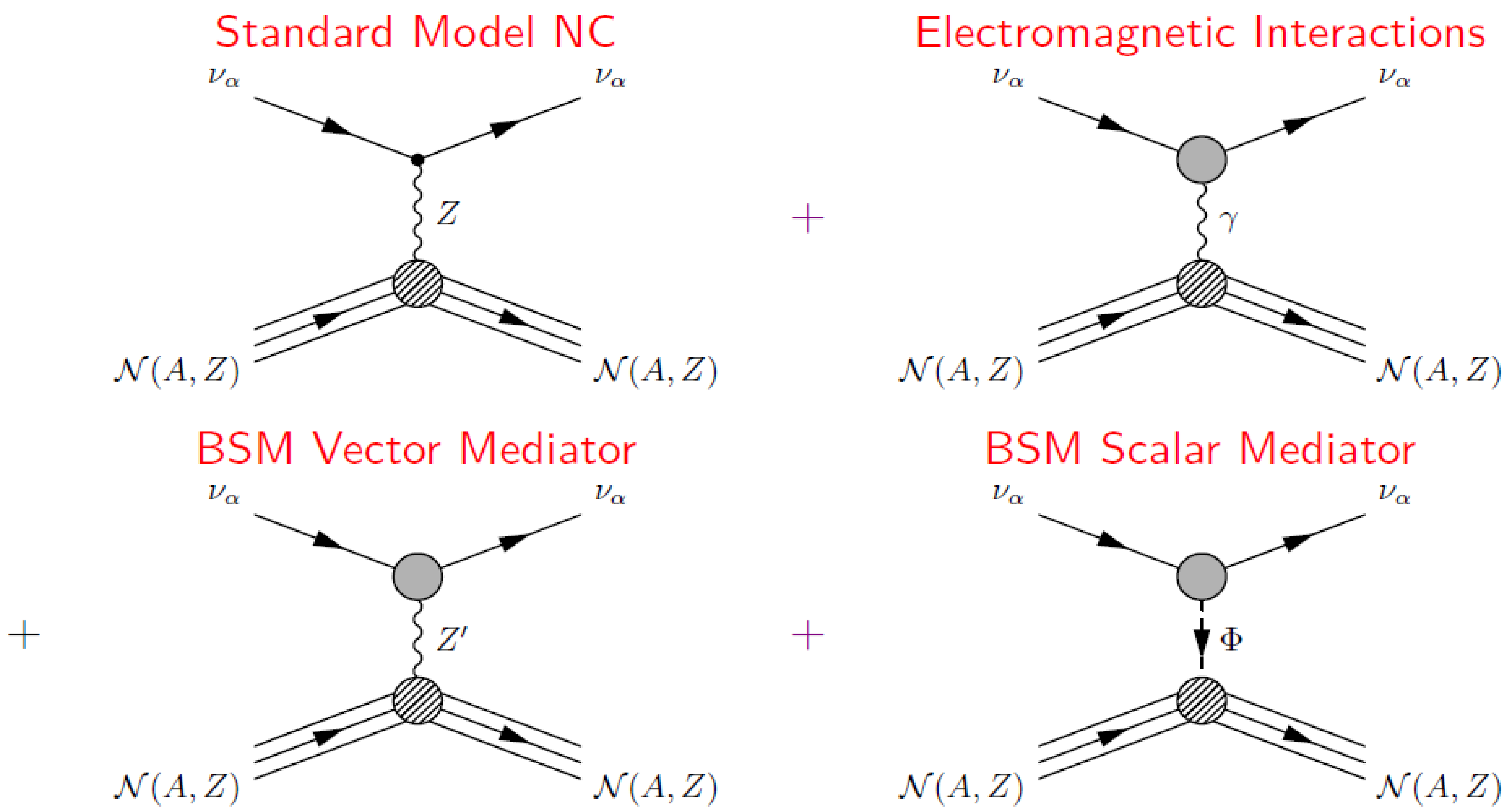
- With new 2020 COHERENT CsI data:

[Pershey @ Magnificent CEνNS 2020]

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

[Cadeddu et al, arXiv:2102.06153]

BSM Neutrino Interactions in CEvNS

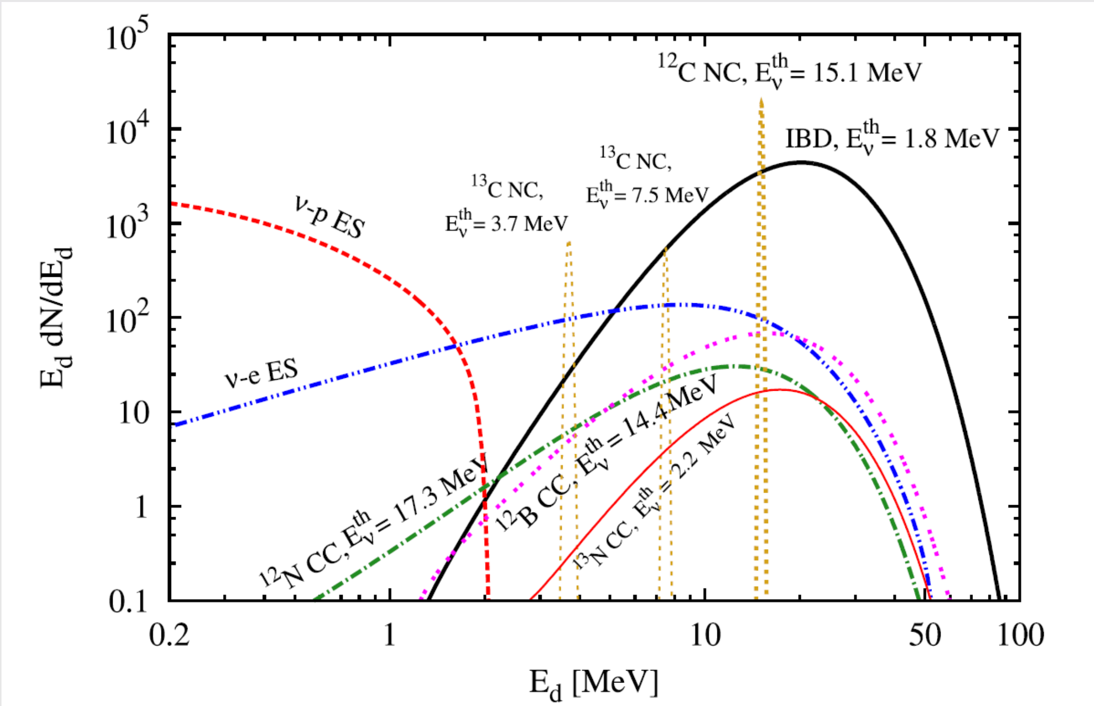


See the Talk by Jiajun Liao

B: low energy CC:

QE on the Target Nuclei

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



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

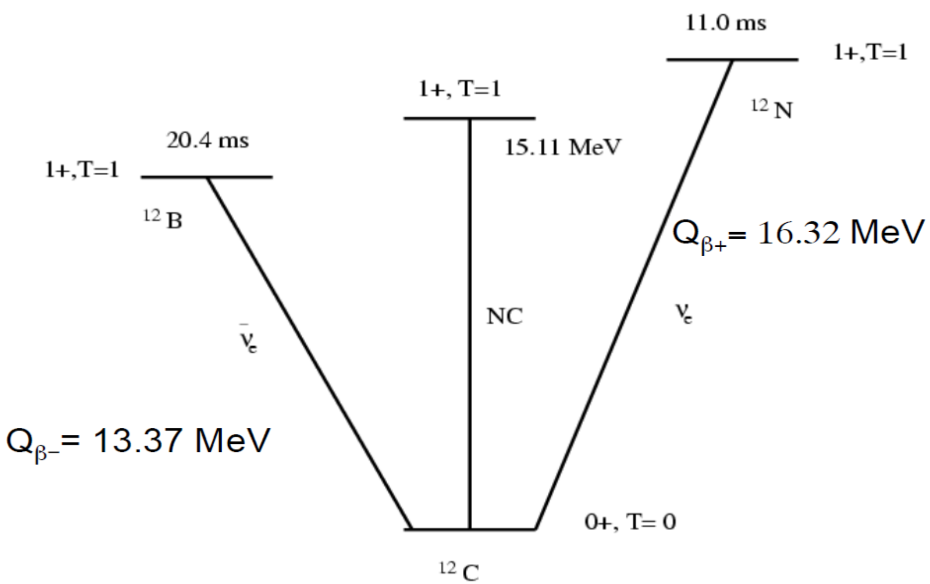
***JUNO, Prog.Part.Nucl.Phys.* 123 (2022) 103927**

	Channels	Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	Event numbers 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

A=12 triad



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]	$9.4\pm0.5\pm0.8$	–	$11\pm0.85\pm1.0$
Experiment [32]	$9.1\pm0.4\pm0.9$	$66\pm10\pm10$	–
Experiment [33]	$10.5\pm1.0\pm1.0$	–	–
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

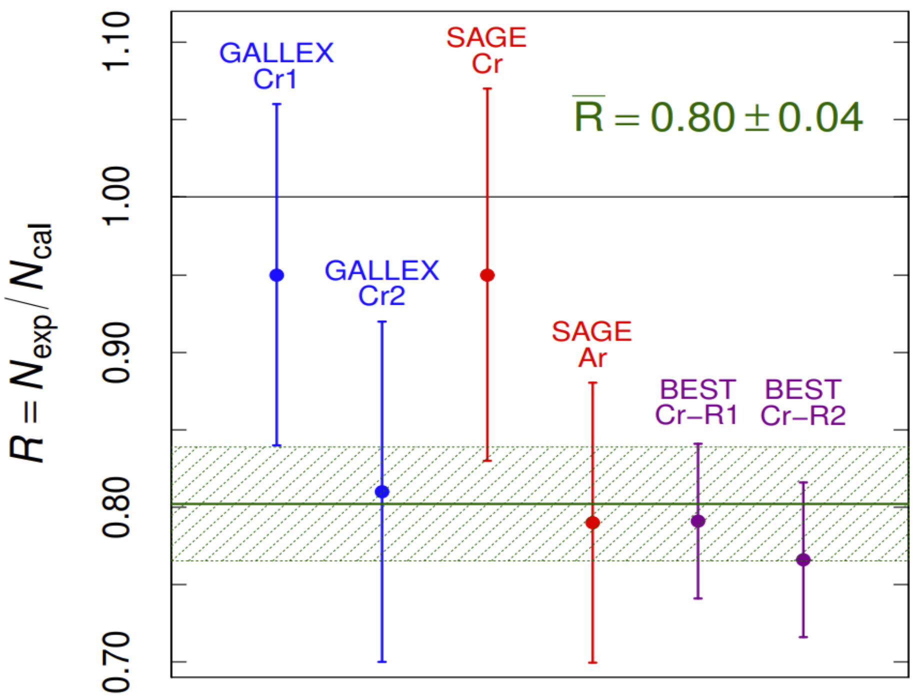
Gallium Anomaly

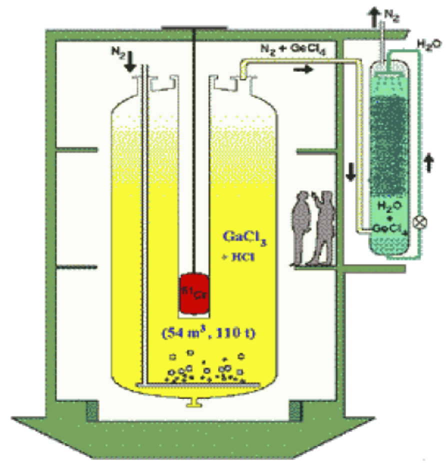
Gallium Radioactive Source Experiments: GALLEX, SAGE, BEST (2021)

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

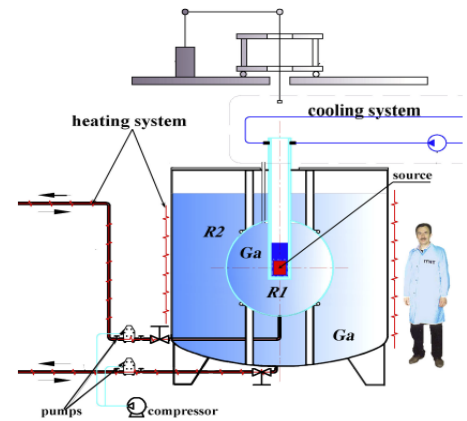
$E \simeq 0.75\,\mathrm{MeV}$ $\quad E \simeq 0.81\,\mathrm{MeV}$

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





GALLEX



BEST

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

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

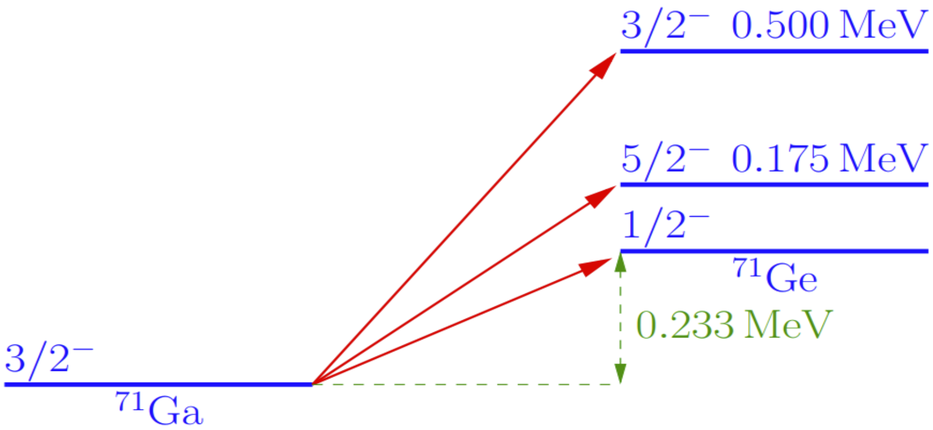
$\langle L \rangle^{\mathrm{R1}}_{\mathrm{BEST}} \simeq 0.7\,\mathrm{m}$ $\quad \langle L \rangle^{\mathrm{R2}}_{\mathrm{BEST}} \simeq 1.1\,\mathrm{m}$

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

[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 $\sim 5\%$! [Bahcall, hep-ph/9710491]

Cross section calculation: excited states

$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$ cross sections in units of 10^{-45} 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]	$T_{1/2}(^{71}\text{Ge})$	5.539 ± 0.019	—	6.625 ± 0.023	—	0.844 ± 0.031	5.0σ
Bahcall [hep-ph/9710491]	$^{71}\text{Ga}(p,n)^{71}\text{Ge}$	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]	$^{71}\text{Ga}(^3\text{He},{}^3\text{H})^{71}\text{Ge}$	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

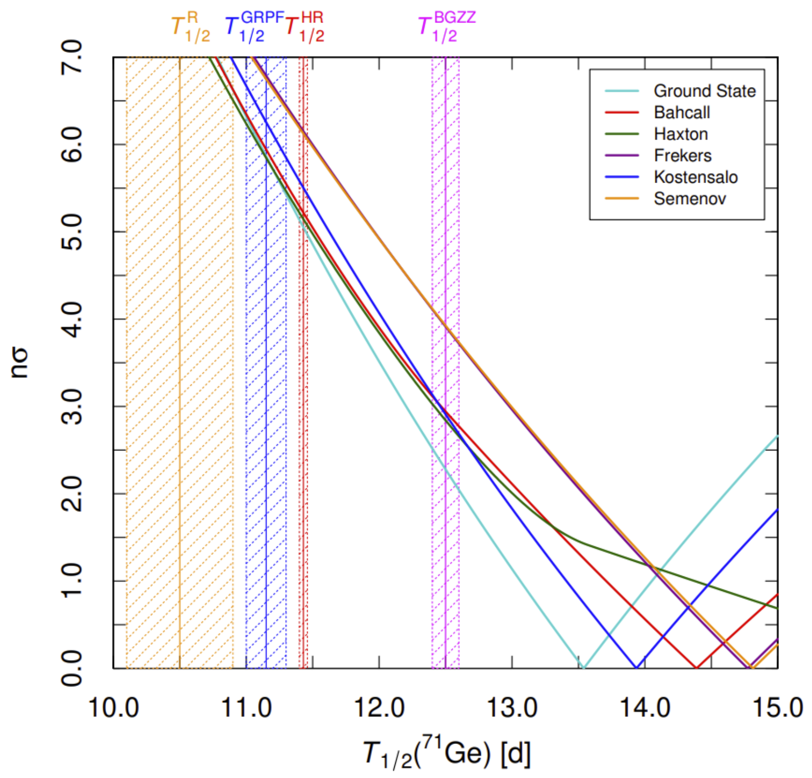
$$T_{1/2}^{BGZZ}(^{71}Ge) = 12.5 \pm 0.1\,d \quad \text{(Bisi, Germagnoli, Zappa, and Zimmer, 1955) [39]},$$

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

Giunti, YFL,Ternes, Xin, arXiv: 2212.09722

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

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



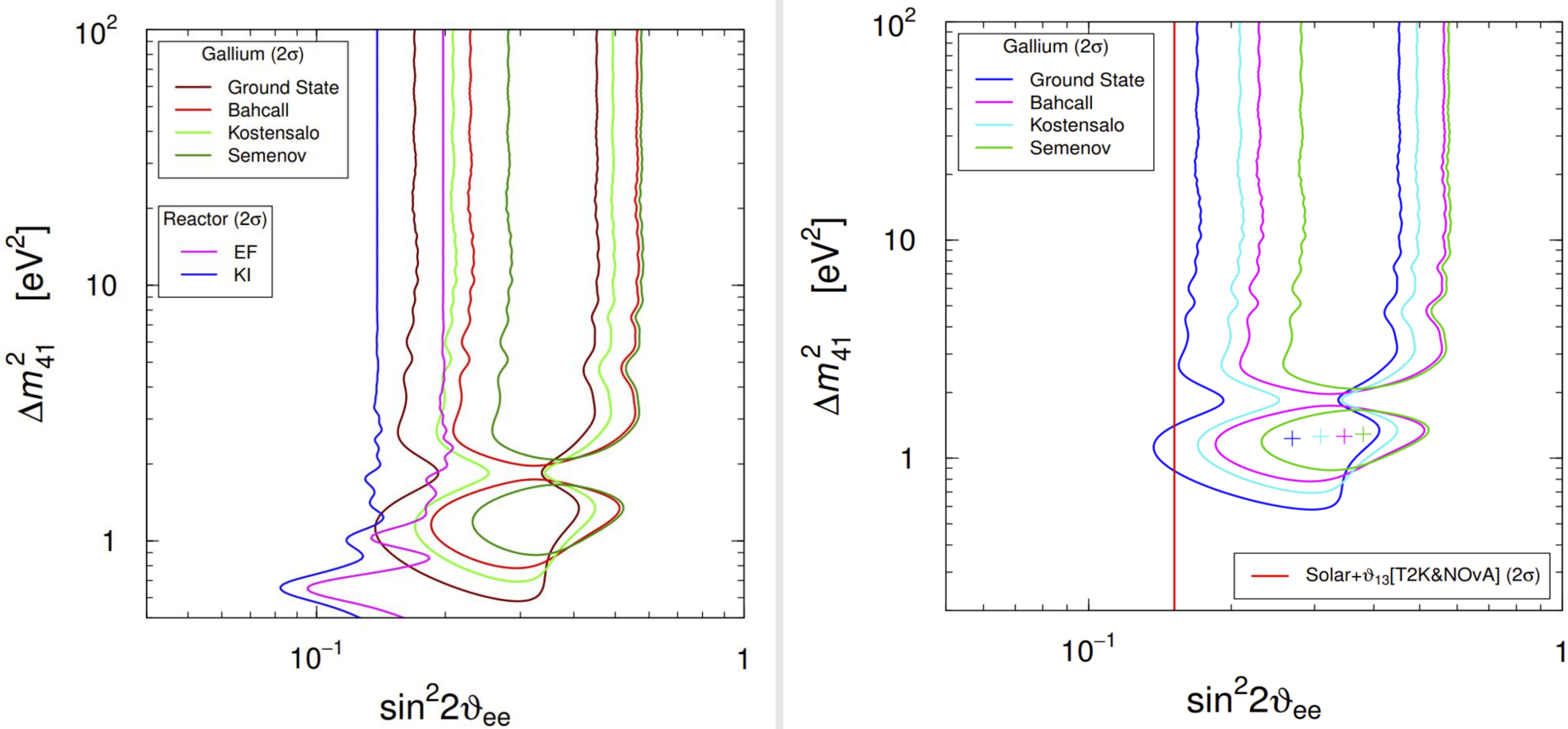
- **An enlarged life-time will reduce or eliminate the anomaly.**
- **Triggered an active campaign of re-measurement !**

11.43±0.03 days (2307.05353)

11.468 ± 0.008 days (2401.15286)

Measurement at IMP (From B.S. Gao)

3+1 mixing ?



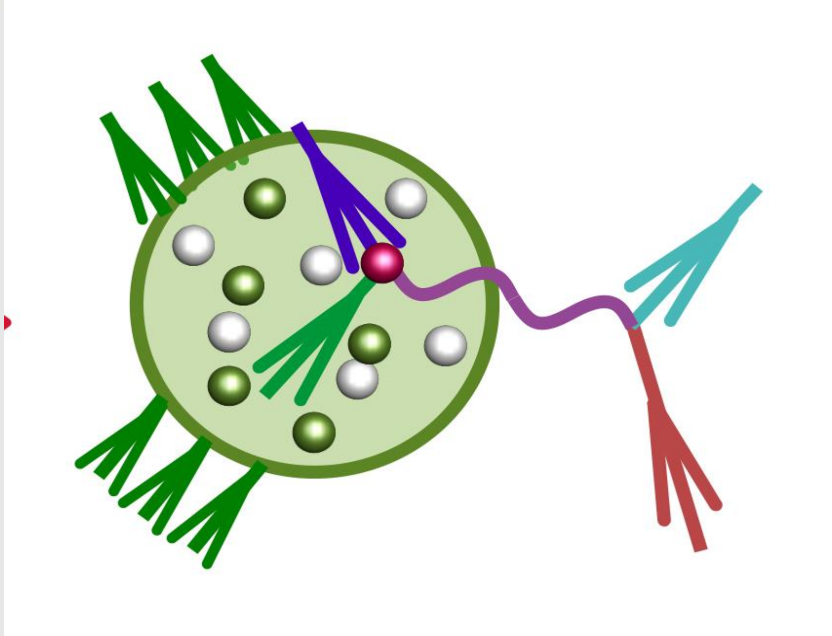
- **No 3+1 neutrino mixing and oscillation solution**
- **No CPT violation solution**

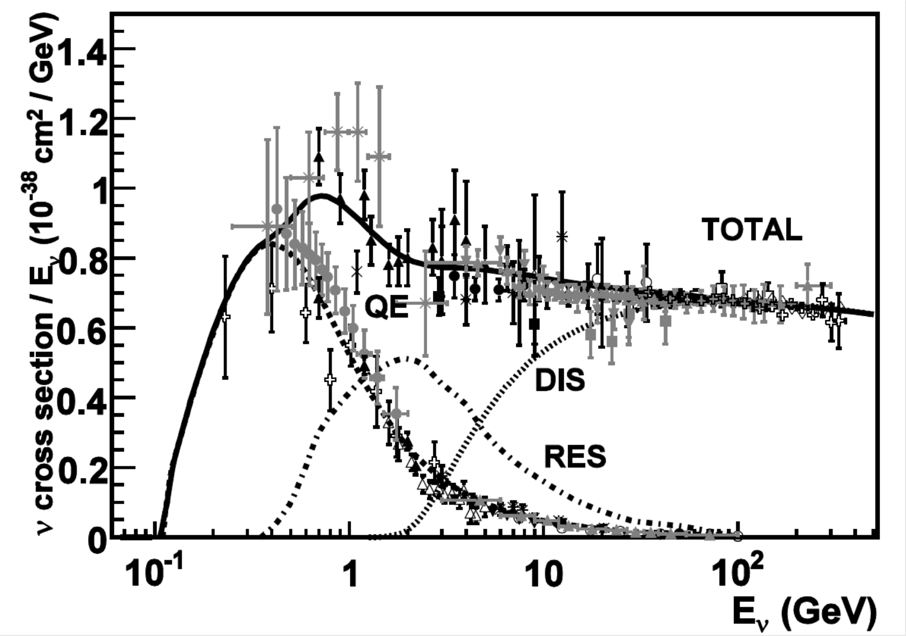
Giunti, YFL,Ternes, Xin, arXiv: 2209.00916

→ Source problem?

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

GeV neutrino interactions





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

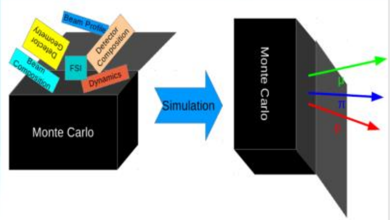
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

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)



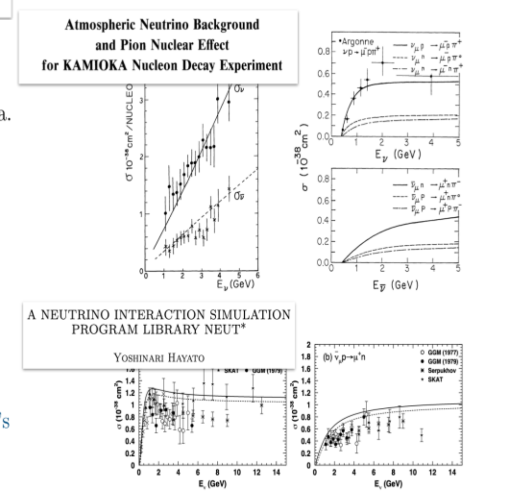
- Monte Carlo generator of neutrino interactions
- Beginning ~ 2005 at the University of Wrocław
- Optimized for ~1 GeV
- Can handle all kind of targets, neutrino fluxes, equipped with detector interface
- Written in C++
- Output files in the ROOT format
- PYTHIA6 used for hadronization in DIS
- Open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

3

Patrick Stowell @ NUINT24

The NEUT neutrino interaction simulation program library

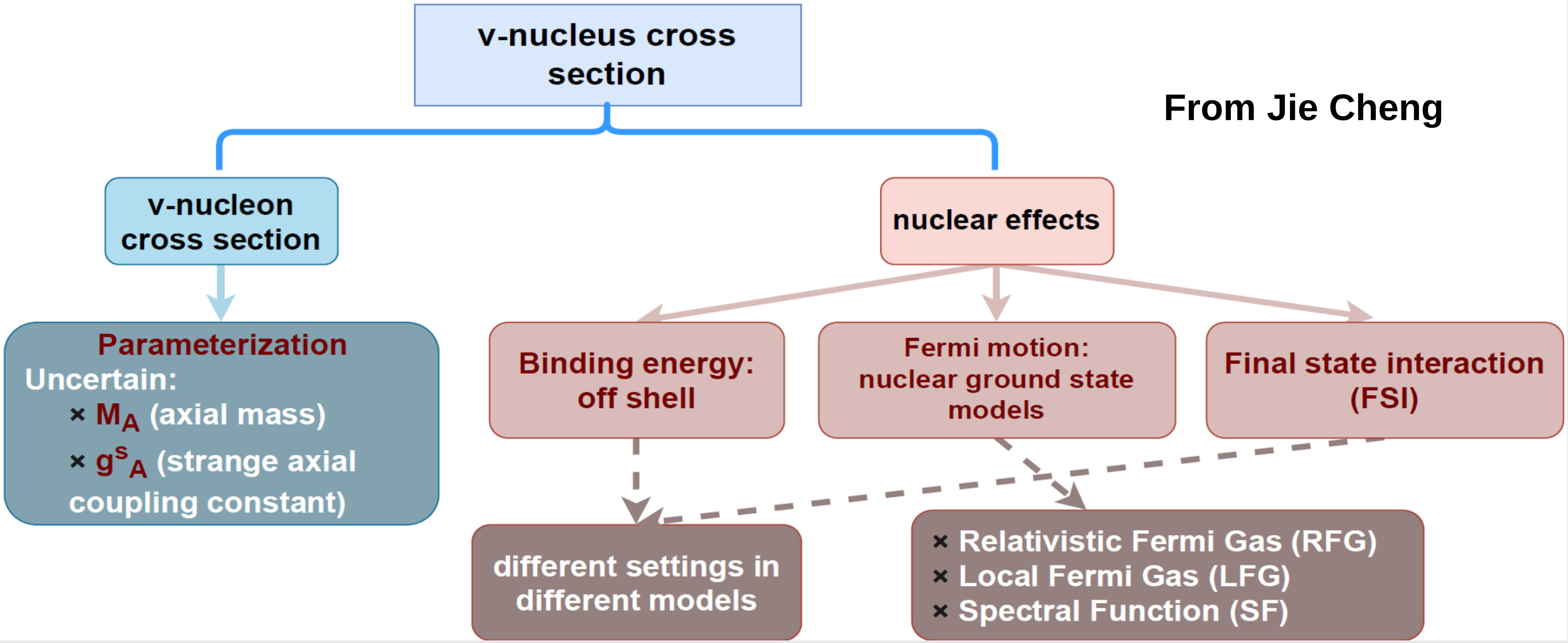
- MeV to TeV scale neutrino interaction generator originally created in the 70s to support neutrino backgrounds at Kamioka.
- Long history of development driven by evolving requirements of KamiokaNDE, Super-KamiokaNDE, and T2K.
- Currently the primary interaction generator for SK and T2K, used in all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



General components in generators

Brief summary of GeV neutrino interaction models

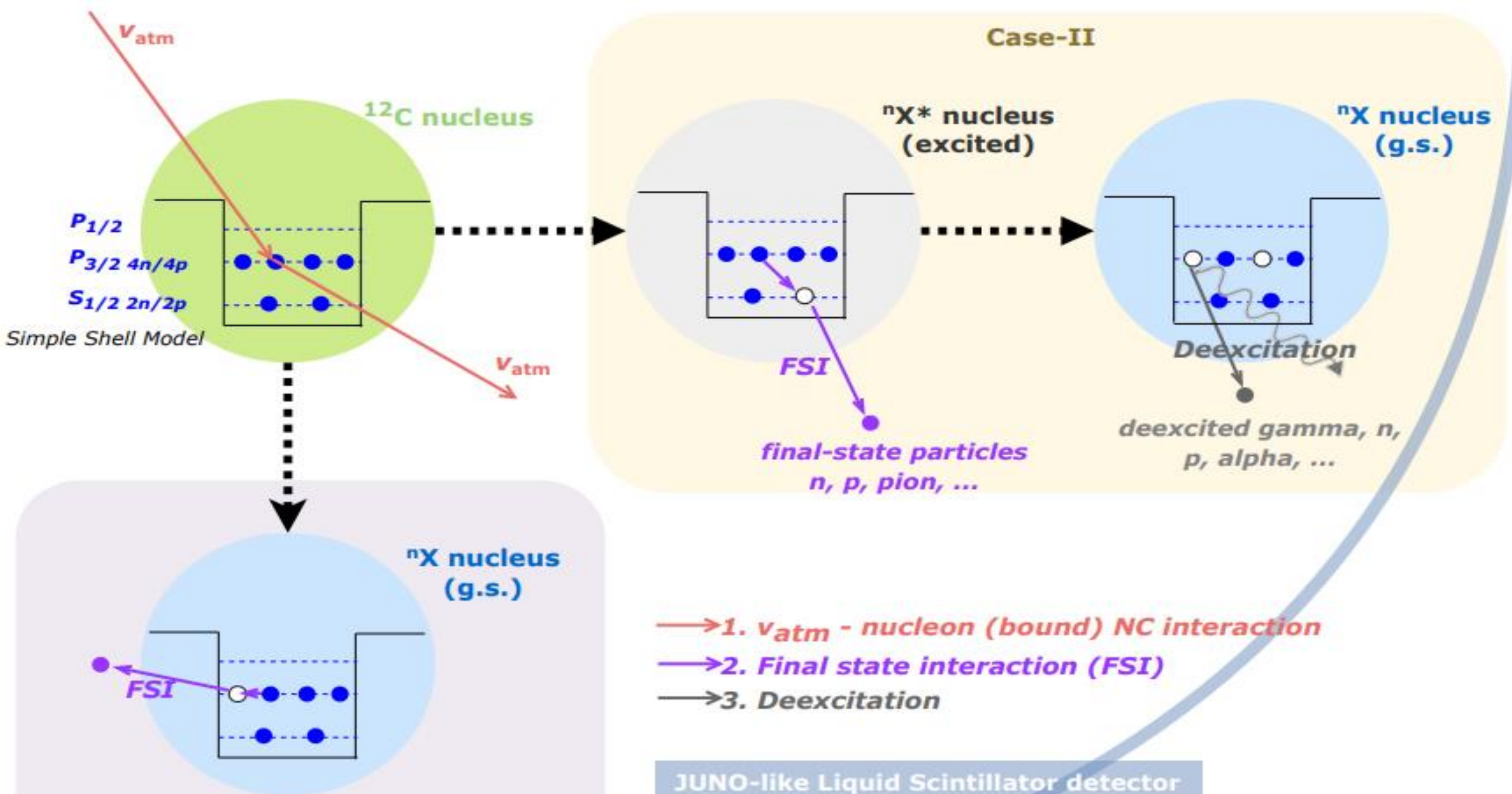
From Jie Cheng



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

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

New Methodology: adding deexcitation



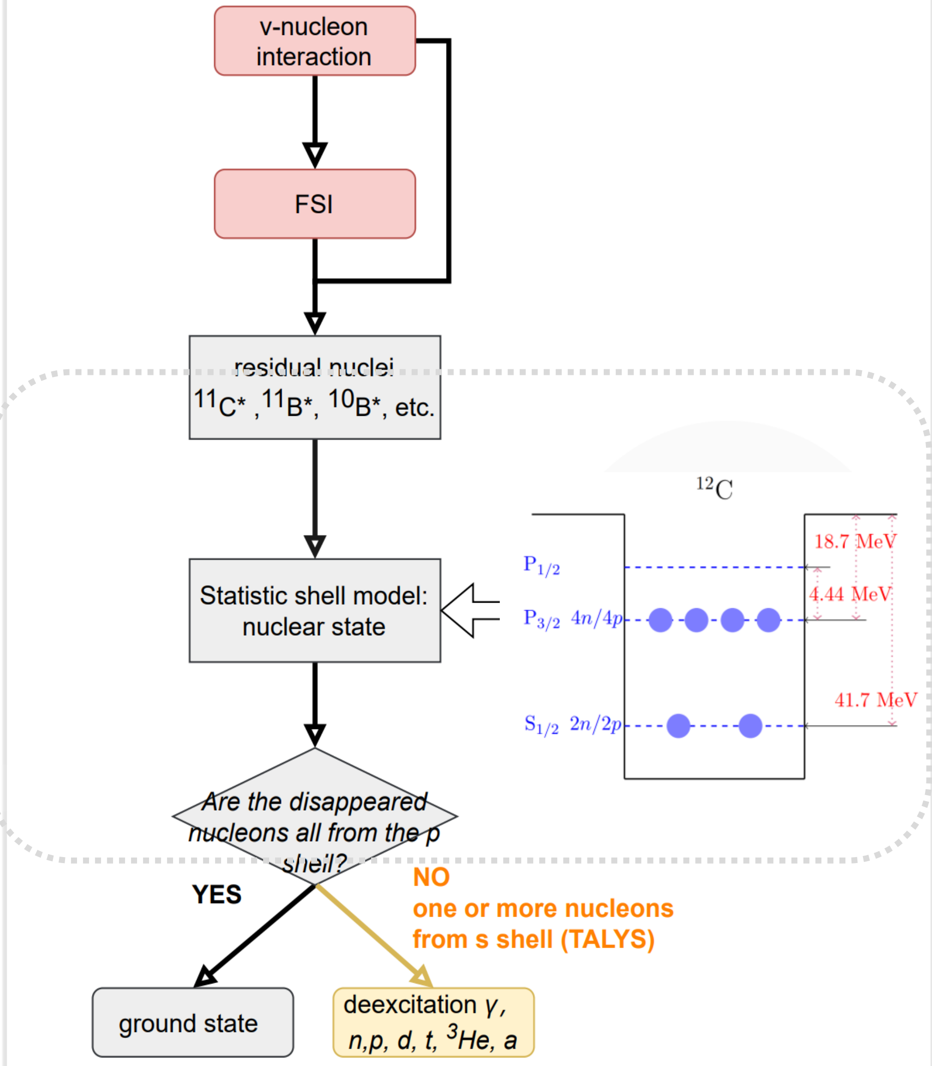
Take NC interactions as example

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

Cheng et al, arXiv 2404.07429

More detailed in Jie Cheng's talk

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

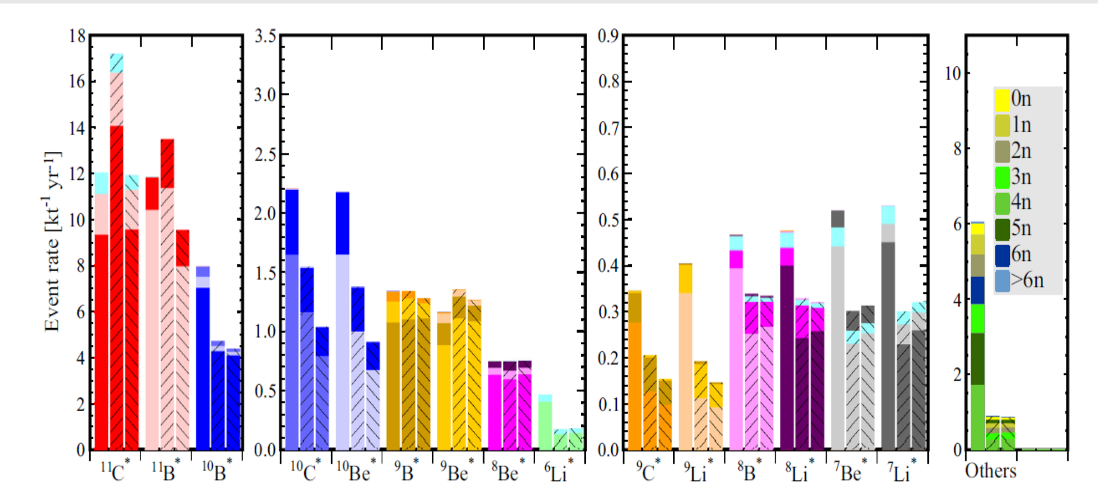
Daughter Nuclei	Shell Hole	Configuration Probability	Excitation Energy
$^{11}C^*$ or $^{11}B^*$	$s_{1/2}$	1/3	$E^* = 23$ MeV
	$p_{3/2}$	2/3	$E^* = 0$ MeV
$^{10}C^*$ or $^{10}Be^*$	$s_{1/2}$	1/15	$E^* = 46$ MeV
	$p_{3/2}$	6/15	$E^* = 0$ MeV
	$s_{1/2}$ & $p_{3/2}$	8/15	$E^* = 23$ MeV
$^{10}B^*$	$s_{1/2}$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

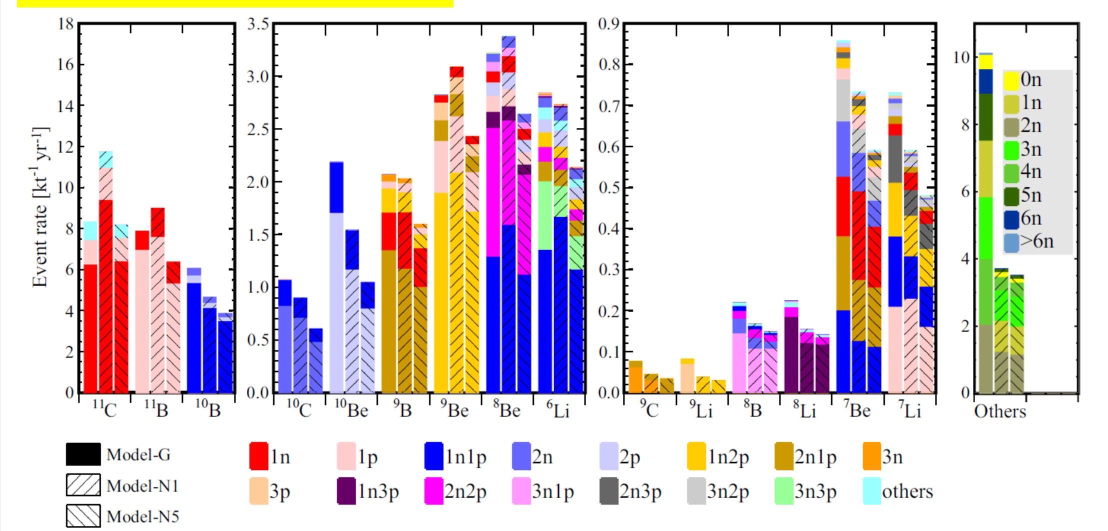
More complicated shell information can be included.

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**

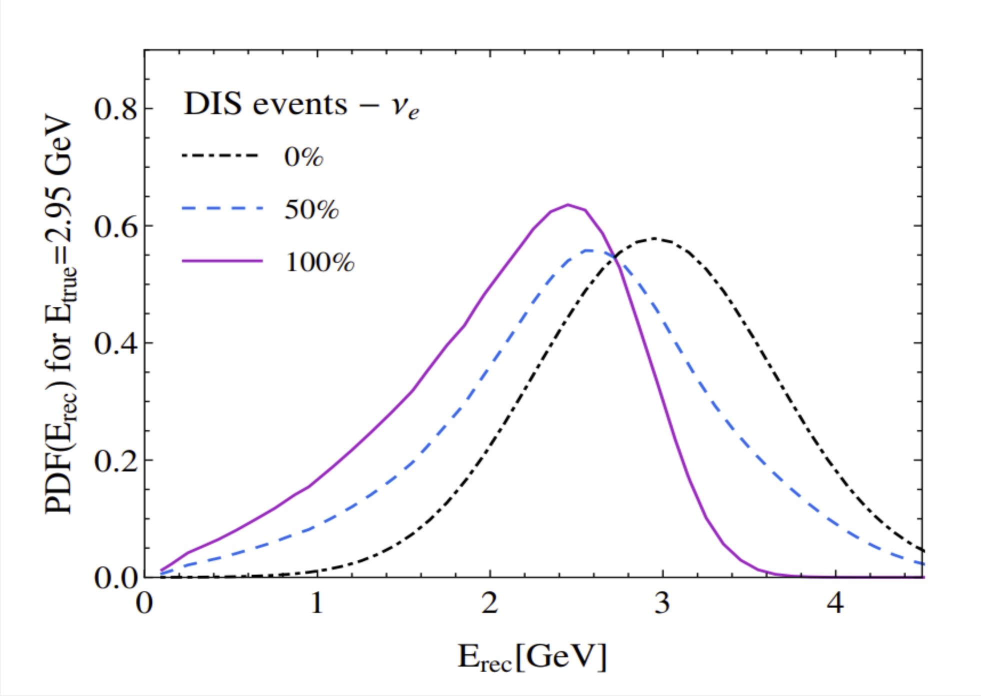
(a) energy reconstruction

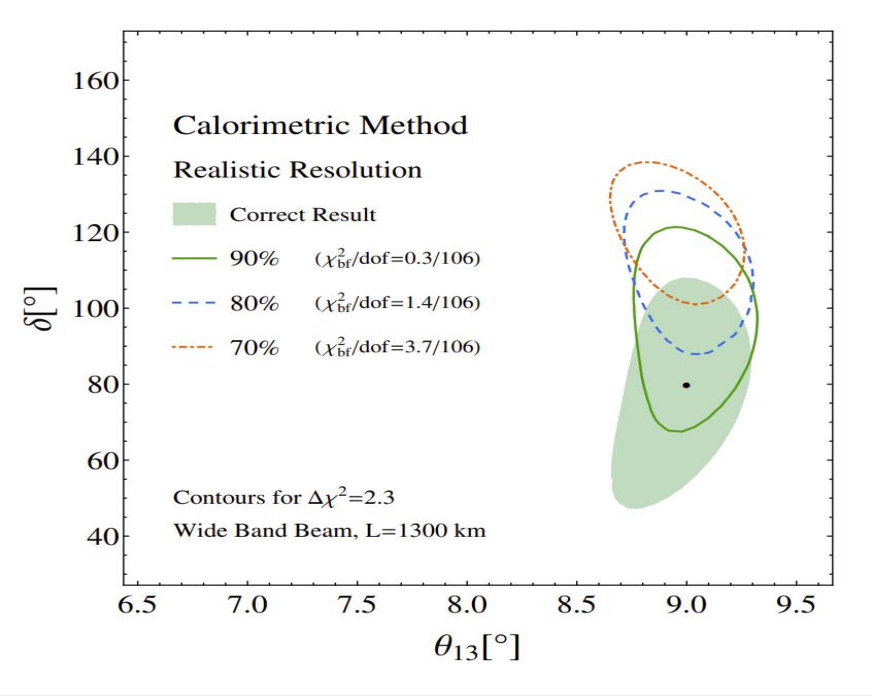
(b) tagging and reducing the backgrounds

Energy reconstruction in DUNE

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

Ankowski, Coloma, Huber, Mariani, Vagnoni, 1507.08561



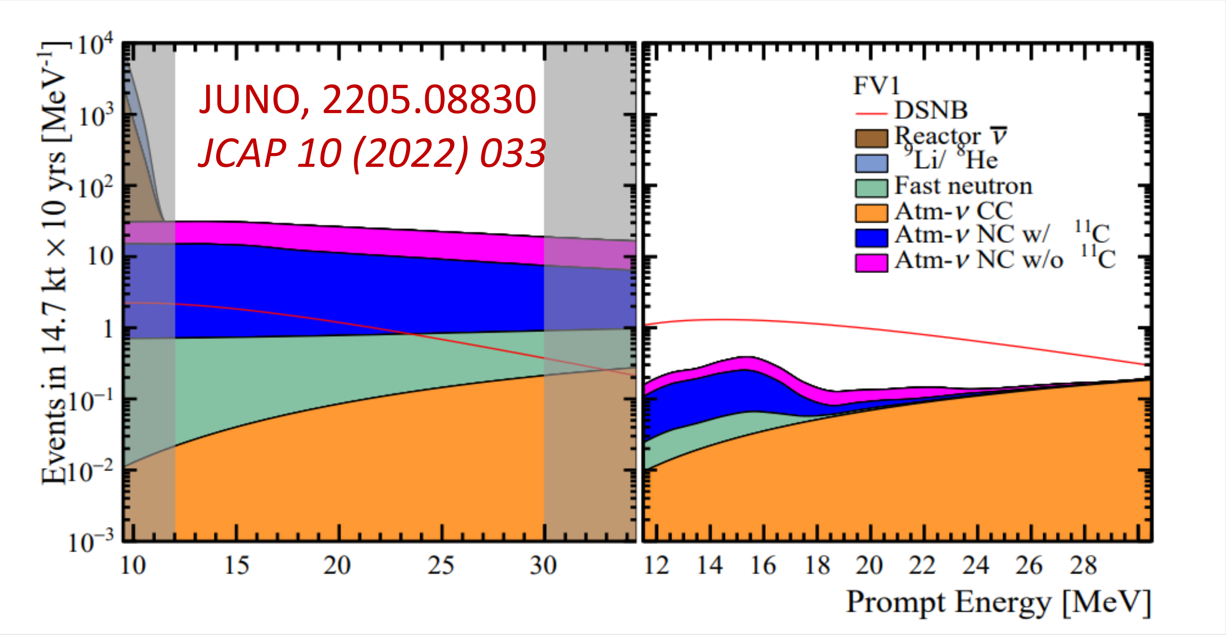


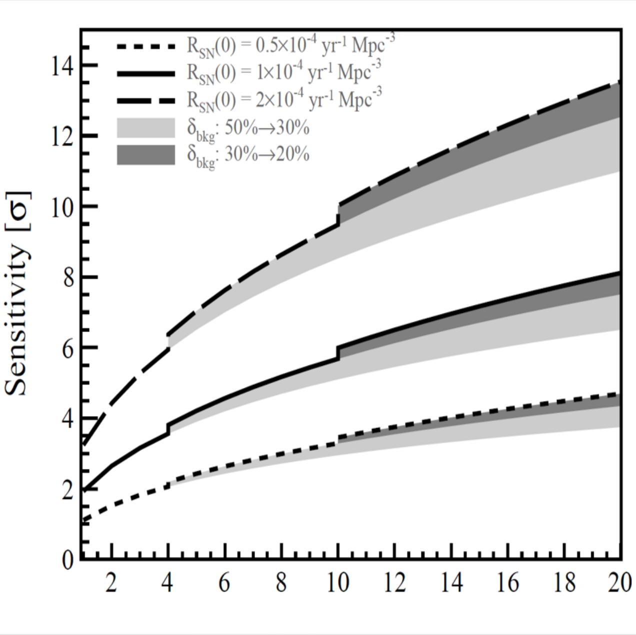
- **The energy is reconstructed with calorimetric method.**
- **Missing neutrons (pions) may bias the energy and then result in wrong oscillation parameters.**

Rare searches in JUNO

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

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





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 hardron and nuclear physics. (Shell structure, Binding energy, Fermi Motion, Final state interactions, Deexcitation, Parton properties, etc.)

Many thanks to my collaborators

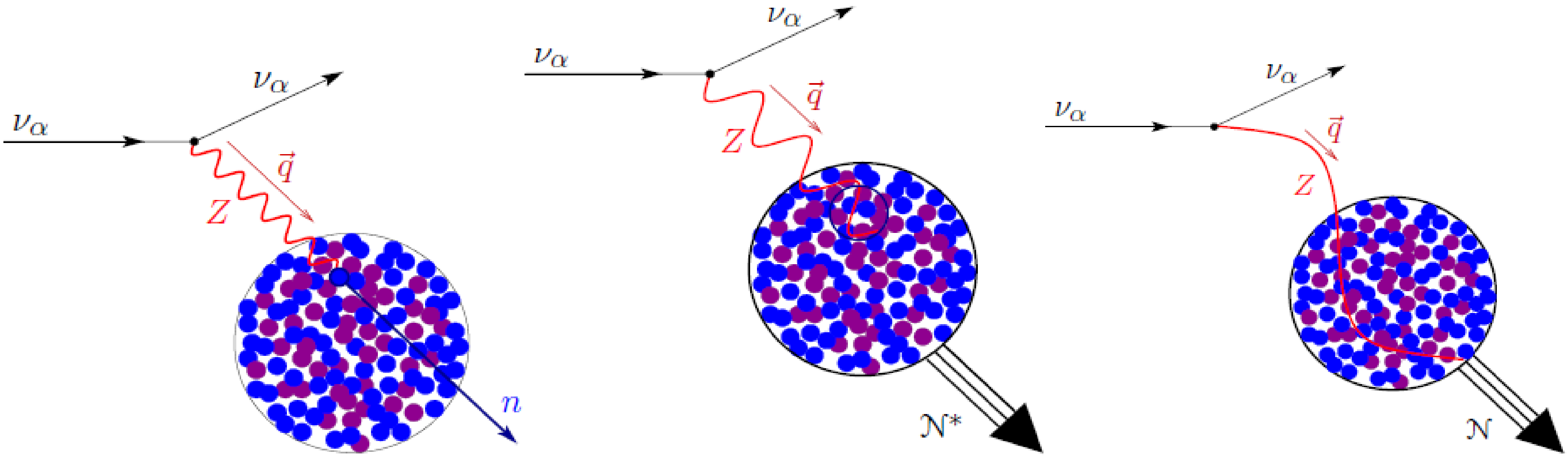
Cadeddu, Giunti, Zhao Xin,Yiyu Zhang, … …

Jie Cheng, Dong-liang Fang, Shun Zhou, … …

Thank you !

Backup

Why Coherent ?



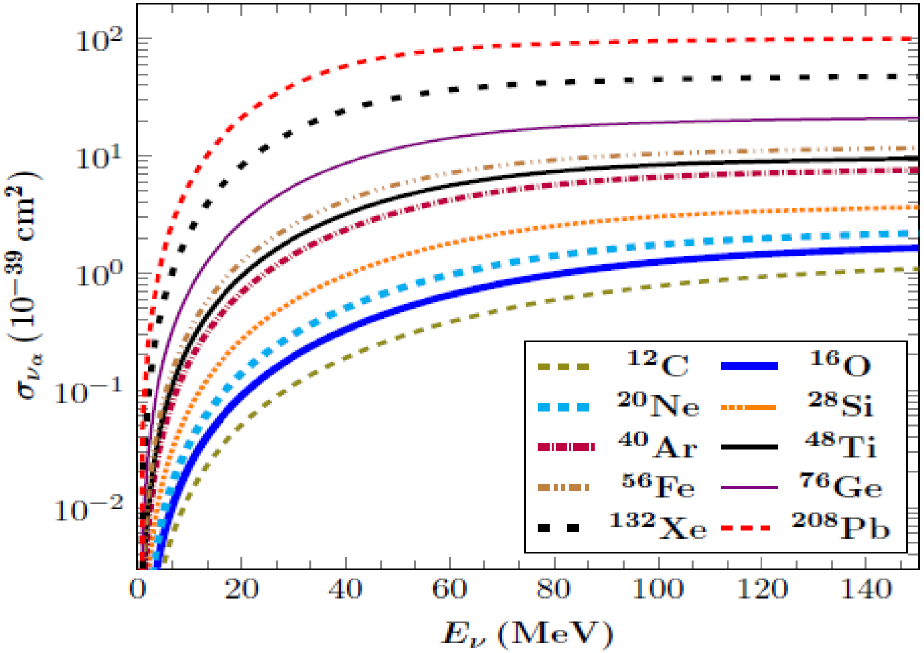
Inelastic Incoherent	Elastic Incoherent	Elastic Coherent
$\lambda_Z \ll R$	$\lambda_Z \lesssim R$	$\lambda_Z \gtrsim 2R$

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

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

The CEνNS Cross Section

- Big cross section enhancement for heavy nuclei $\mathcal{N}(A, Z)$ with many nucleons N_i:
  - Incoherent scattering: $\sigma(\nu\mathcal{N}) \sim \sum_i |\mathcal{A}(\nu N_i)|^2 \propto A$
  - Coherent scattering: $\sigma(\nu\mathcal{N}) \sim \left|\sum_i \mathcal{A}(\nu N_i)\right|^2 \propto A^2$



[Papoulias, Kosmas, Kuno, arXiv:1911.00916]

The COHERENT experiment

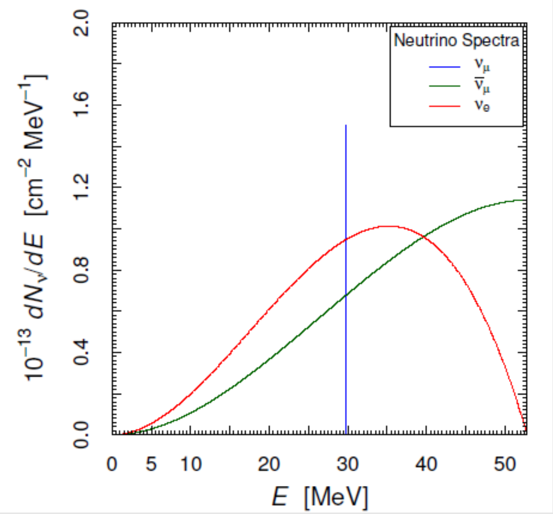
- **14.6 kg CsI scintillating crystal and 24 kg LAr detector.**
- **Prompt monochromatic ν_μ from stopped pion decays:**

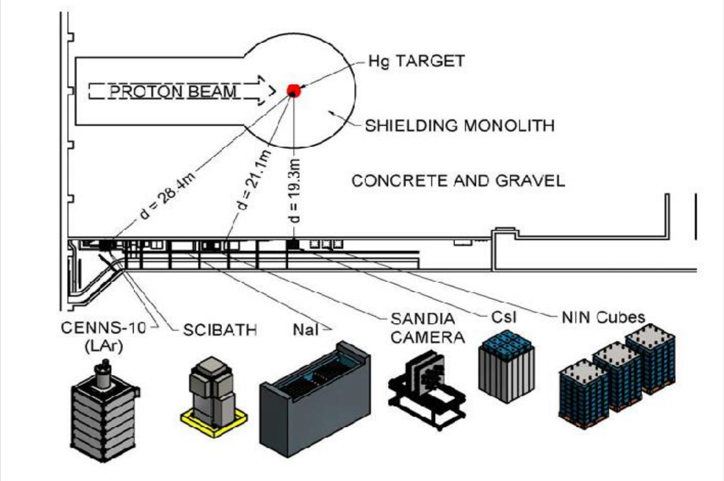
$$\pi^+ \to \mu^+ + \nu_\mu$$

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

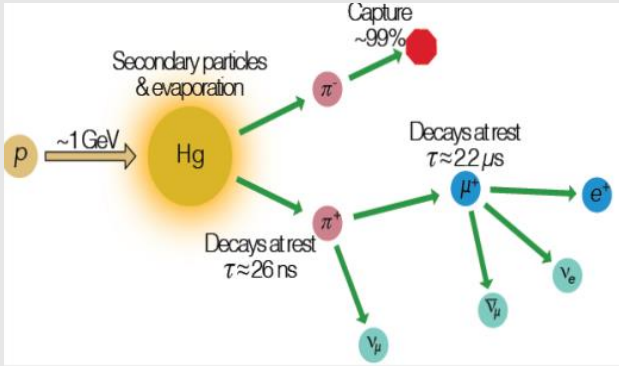
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

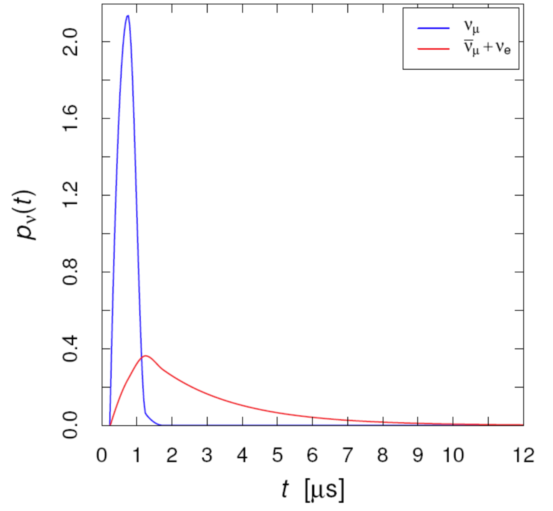
- **The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ and $\bar{\nu}_\mu$**



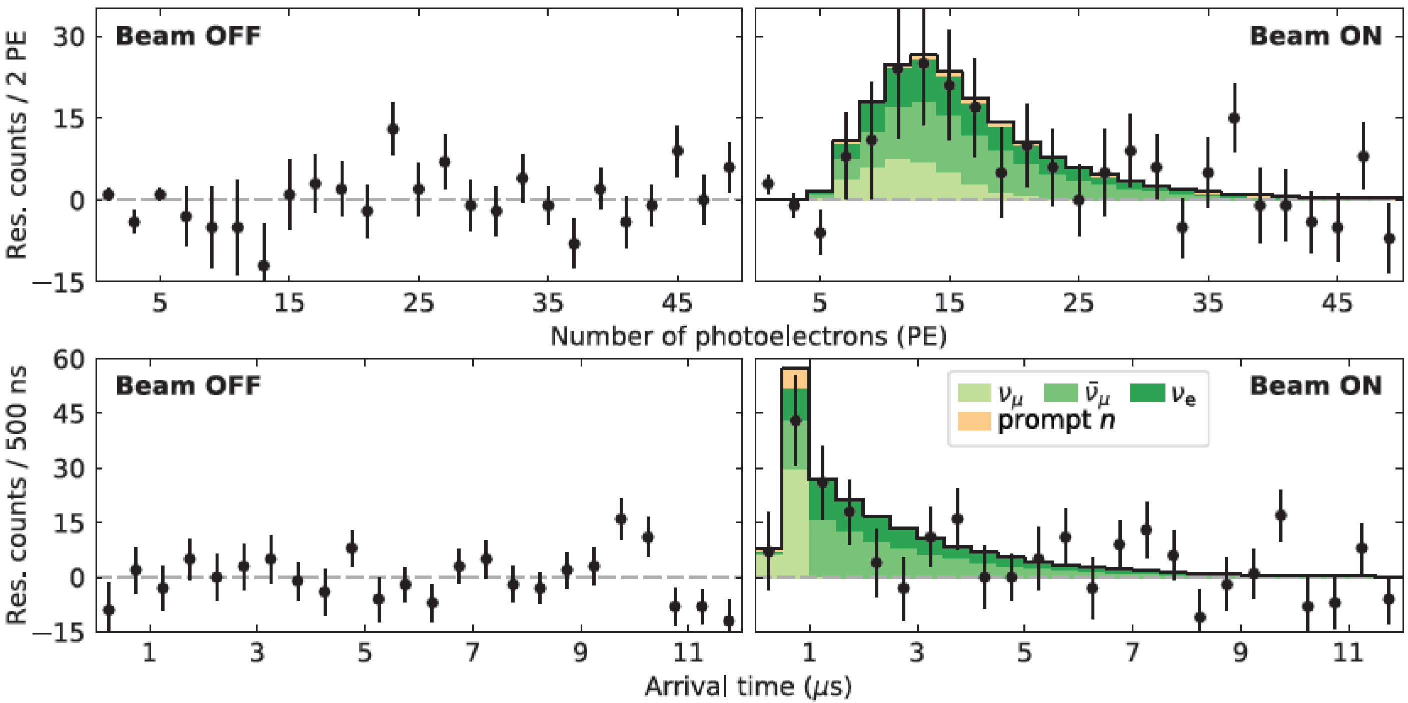


[COHERENT, arXiv:1803.09183]





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