Fermilab

Exploring the MeV Frontier in LArTPC Neutrino Experiments

Vishvas Pandey (विश्वास पाण्डेय)

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U.S. DEPARTMENT of ENERGY

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CETUP* 2026, Lead, South Dakota, July 2026

New stuff on low-energy since my last year's talk here:

Dark Matter–Induced Nuclear De-Excitation at SBND with Ab Initio Nuclear Theory

Bhaskar Dutta,[1,*] Debopam Goswami,[1,†] Baishan Hu,[2,‡] Wei-Chih Huang,[1,§] and Vishvas Pandey[3,¶]

arXiv:2602.02817 [hep-ph]

Continuum contribution to charged-current absorption of low-energy ν_e on ^{40}Ar

Steven Gardiner,[1,*] Pablo Barham Alzás,[2,†] Alexis Nikolakopoulos,[3,4]
Luca H. Abu El-Haj,[1,5] Natalie Jachowicz,[4] and Vishvas Pandey[1]

arXiv:2604.26801 [hep-ph]

A Unified Ab Initio and CRPA Description of Solar and Supernova Neutrino Scattering in DUNE

Marco Vanderpoorten,[1,*] Baishan Hu,[2,†] Wei-Chih Huang,[3,‡] Jayden L. Newstead,[4,§]
Bhaskar Dutta,[3,¶] Natalie Jachowicz,[1,**] and Vishvas Pandey[5,††]

arXiv:2608.xxxx [hep-ph]

Scope and Context for the Talk

- MeV-Scale physics opportunity in SBN Program and DUNE
- Supernova & Solar neutrino physics
  Dark Sector & New Physics
  - via Inelastic neutrino- and DM-argon scattering
- Towards precision with nuclear-model ladder:
  - Gamow-Teller (Allowed Approximation) for bound states
  - Ab-initio nuclear theory for bound states
  - Continuum RPA for the continuum states and giant resonances

MeV scale capability of LArTPCs are real

ArgoNeuT Demonstrated MeV-Scale Blip Reconstruction

Acciarri et al. (ArgoNeuT), Phys. Rev. D 99, 012002 (2019)

MicroBooNE Demonstrated MeV-Scale Energy Resolution

Abratenko et al. (MicroBooNE), arXiv:2605.30709v

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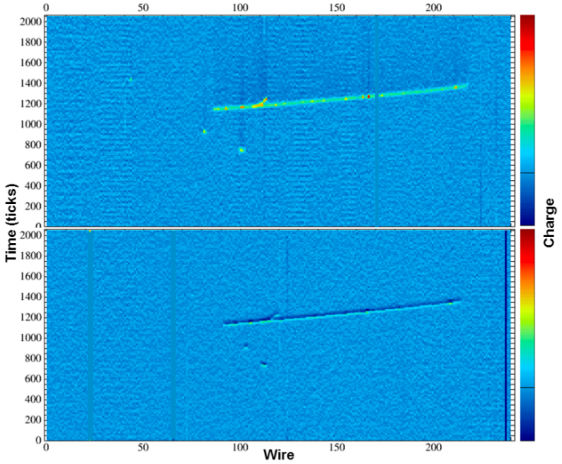
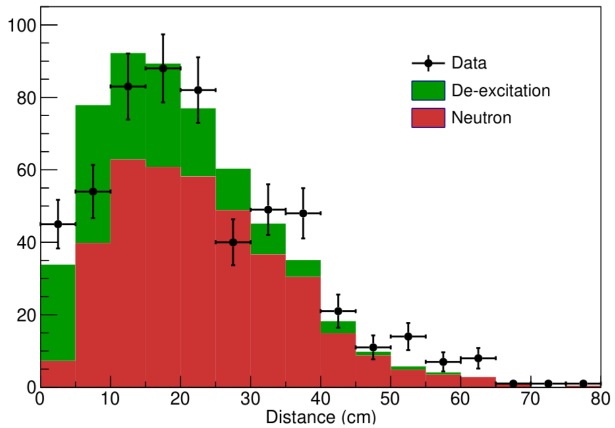
- using beam-neutrino

- Isolated "blip" hits identified from:
    - nuclear de-excitation γ-rays
    - final-state neutron-capture γ-rays
    - $\langle E \rangle \approx 1.11$ MeV/event





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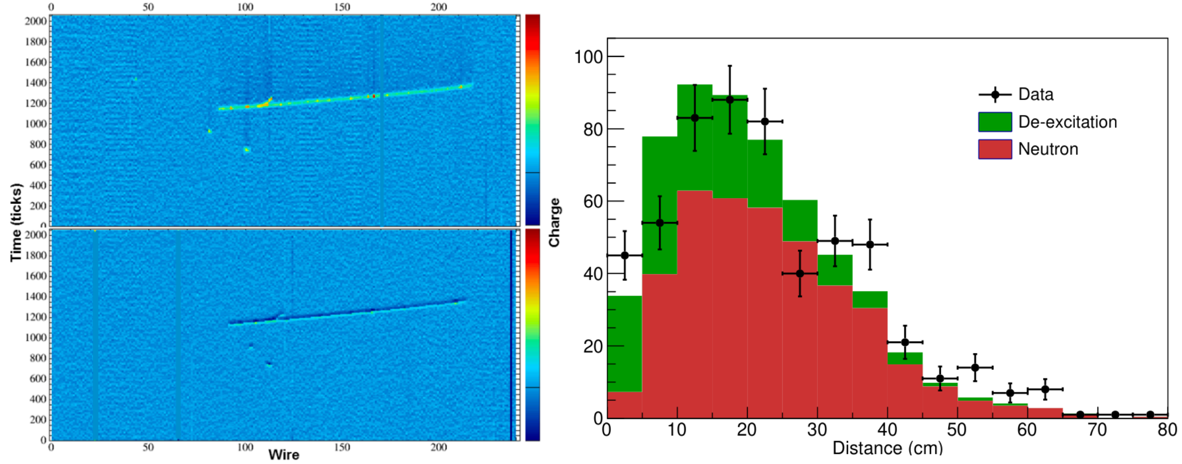


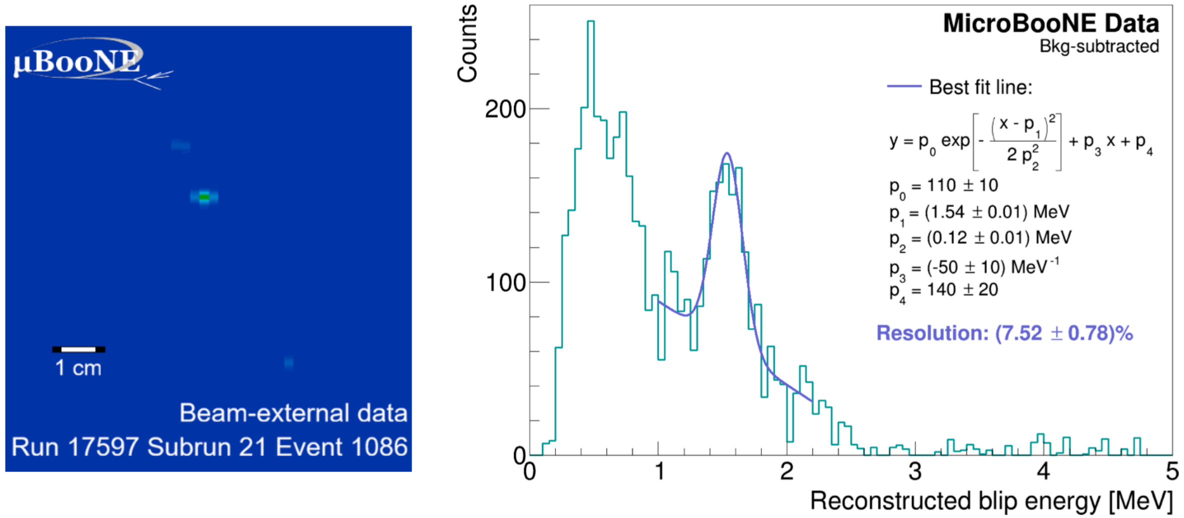
Acciarri et al. (ArgoNeuT), Phys. Rev. D 99, 012002 (2019)

MicroBooNE Demonstrated MeV-Scale Energy Resolution

- using ambient $^{232}Th \rightarrow {}^{208}Tl$ 2.614 MeV γ pair-production

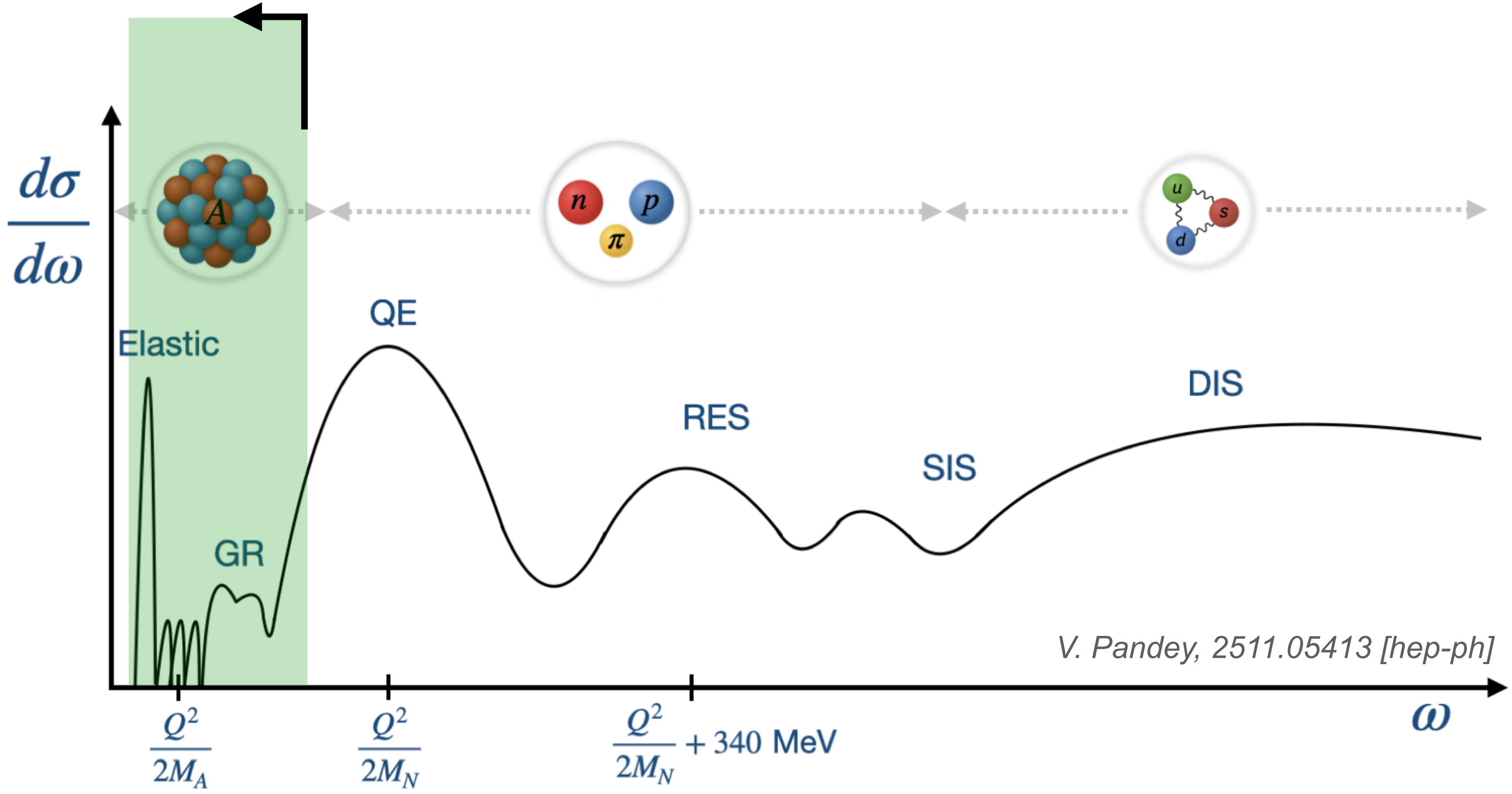
- e^+e^-, back-to-back, annihilation blips

- The resolution of reconstructed energy at ≈1.5 MeV



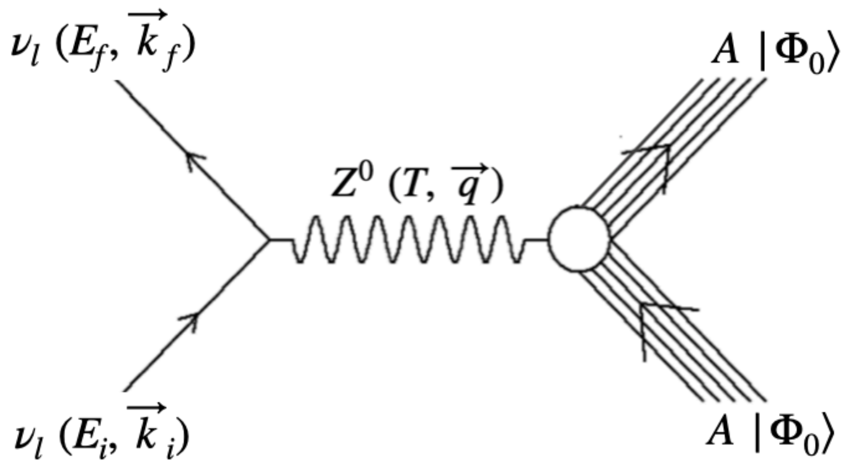
Abratenko et al. (MicroBooNE), arXiv:2605.30709v

MeV scale blips from nuclear excitations



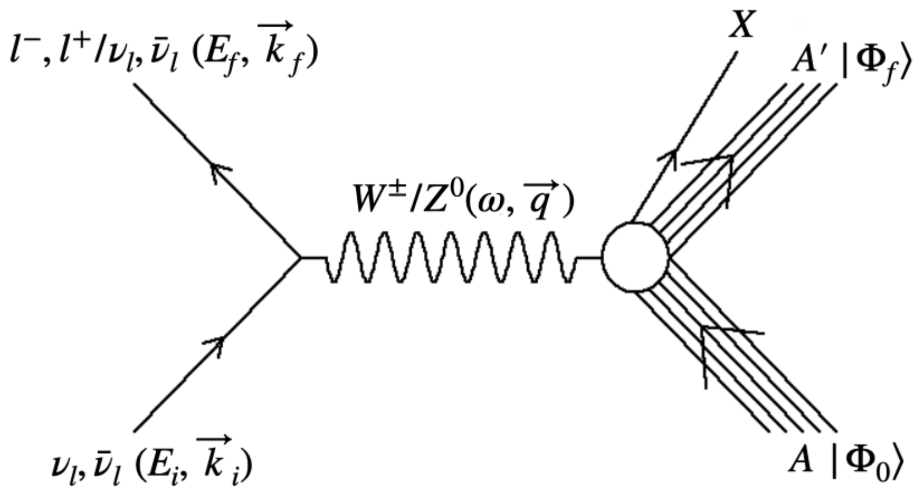
10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

Inelastic CC/NC



- Final state nucleus stays in its ground state
- Tiny recoil energy, larger cross section
- Signal: keV energy nuclear recoil (gammas)
- First observed by COHERENT collaboration in 2017
- Opens new window of opportunity to look for weakly interacting new physics at low energies

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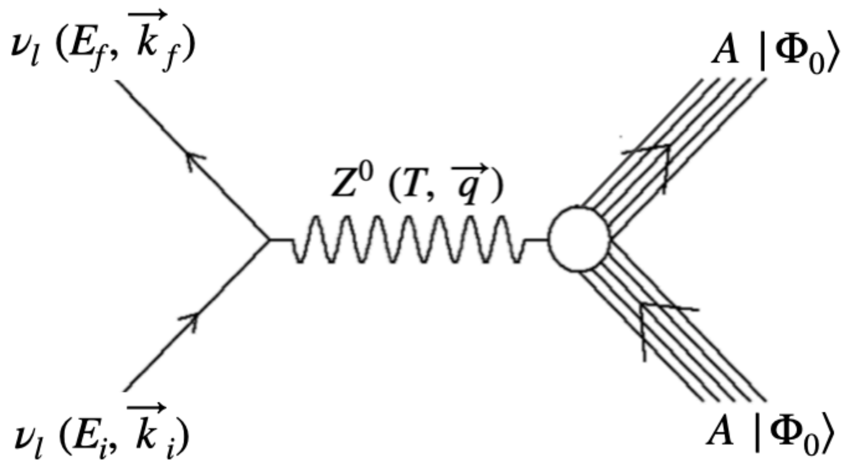

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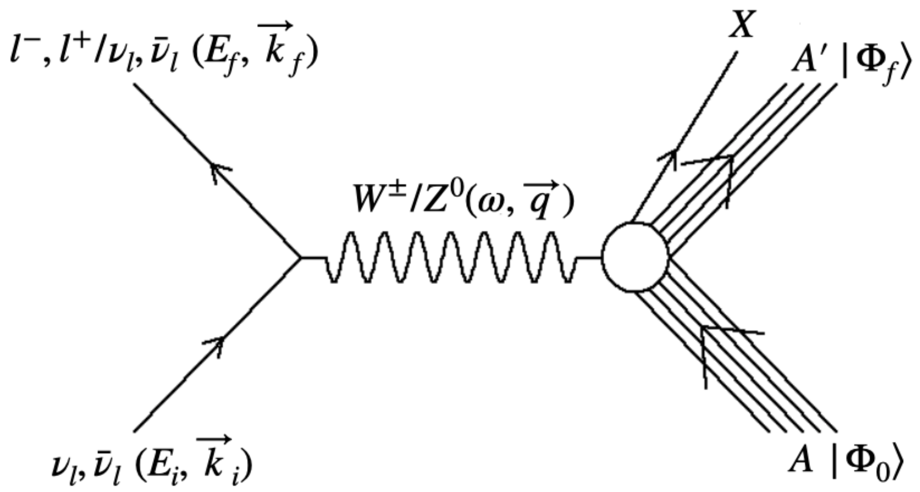

- Small energy transferred to the nucleus
- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π).
- Followed by nuclear de-excitation into gammas, p, n, nuclear fragmentations.
- Opportunity for supernova, solar neutrino studies, and new physics via inelastic scattering

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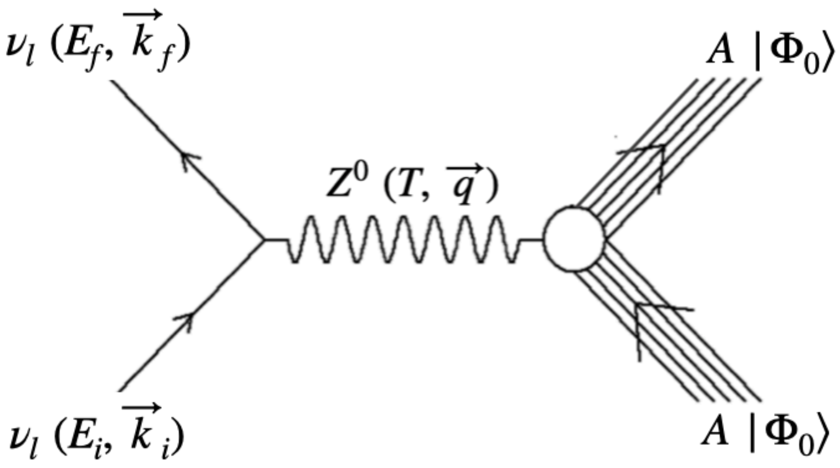

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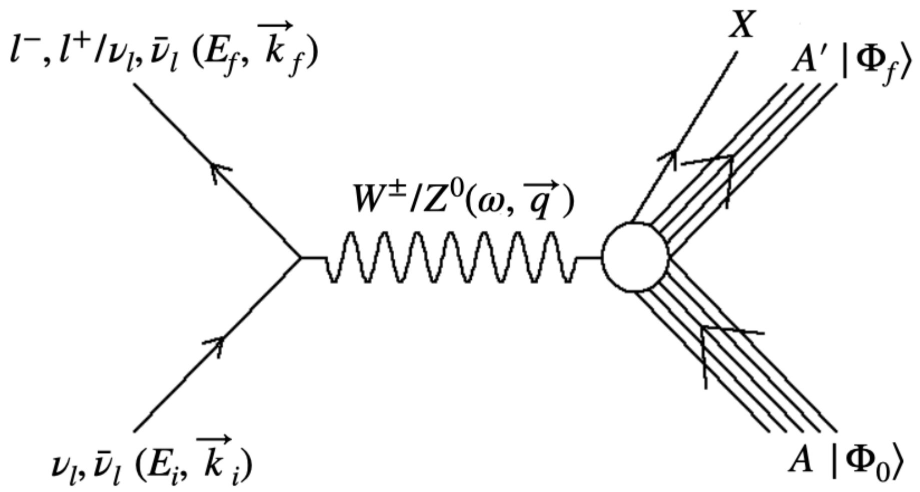

$$\sum_{fi} |\mathscr{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

Leptonic Tensor: $L_{\mu\nu} = \sum_{fi} (\mathscr{J}_{l,\mu})^\dagger \mathscr{J}_{l,\nu}$

Hadronic Tensor: $W^{\mu\nu} = \sum_{fi} (\mathscr{J}_n^\mu)^\dagger \mathscr{J}_n^\nu$

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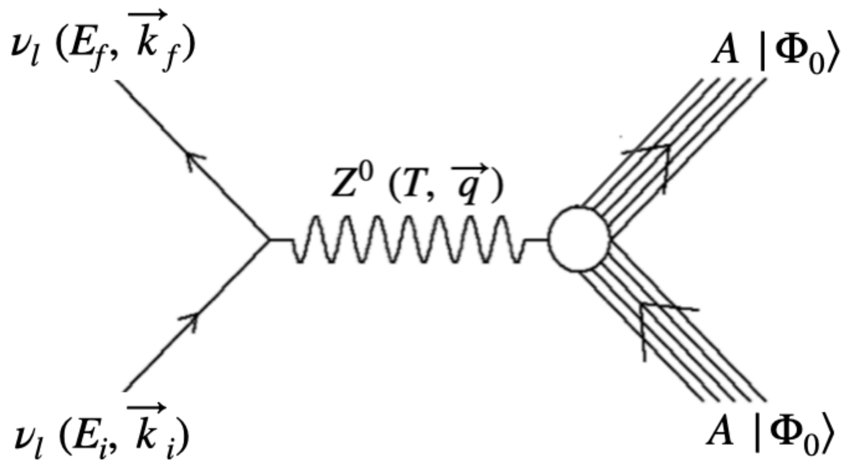

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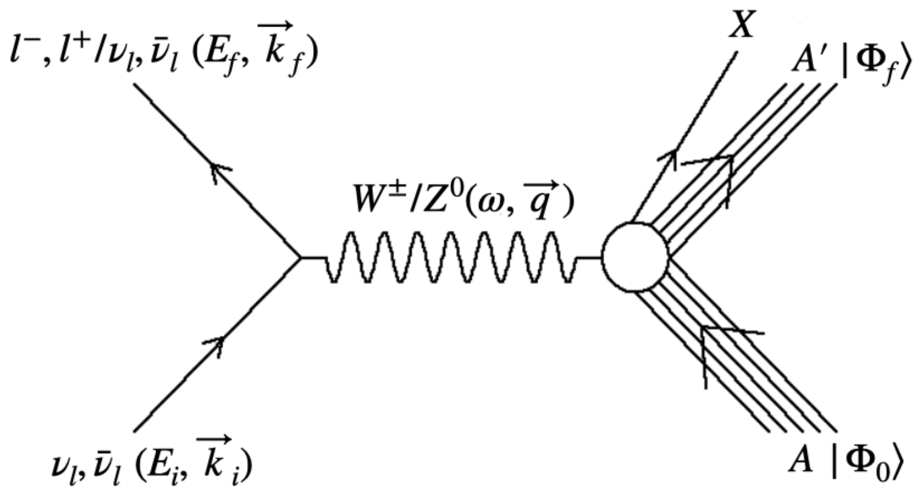

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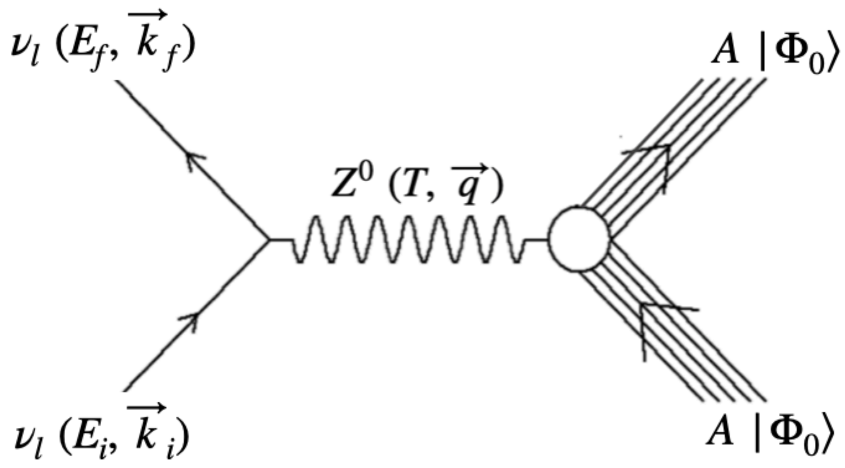
Transition Amplitude: $\mathscr{J}_n^\mu = \langle \Phi_0 | \hat{J}_n^\mu(q) | \Phi_0 \rangle$

Cross Section:

$$d\sigma \propto \frac{G_F^2}{4\pi}\ Q_W^2 F_W^2(q)$$

10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



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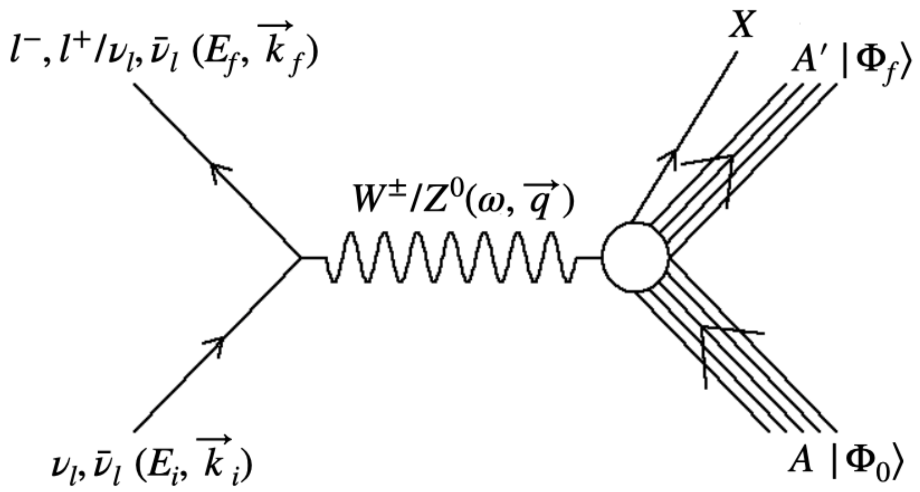

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Cross Section:

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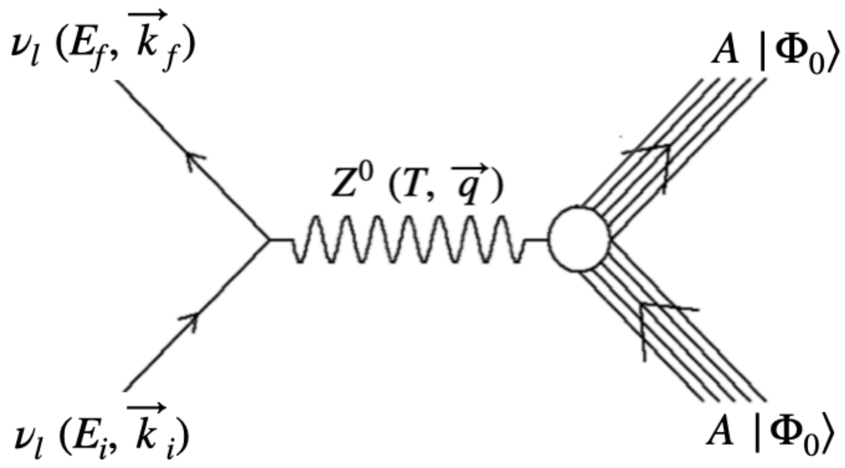
Cross Section:

$$d\sigma \propto \frac{G_F^2}{4\pi} \sum_{J^\pi} [v_{CC} W_{CC} + v_{CL} W_{CL} + v_{LL} W_{LL} + v_T W_T \pm v_{T'} W_{T'}]$$

10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



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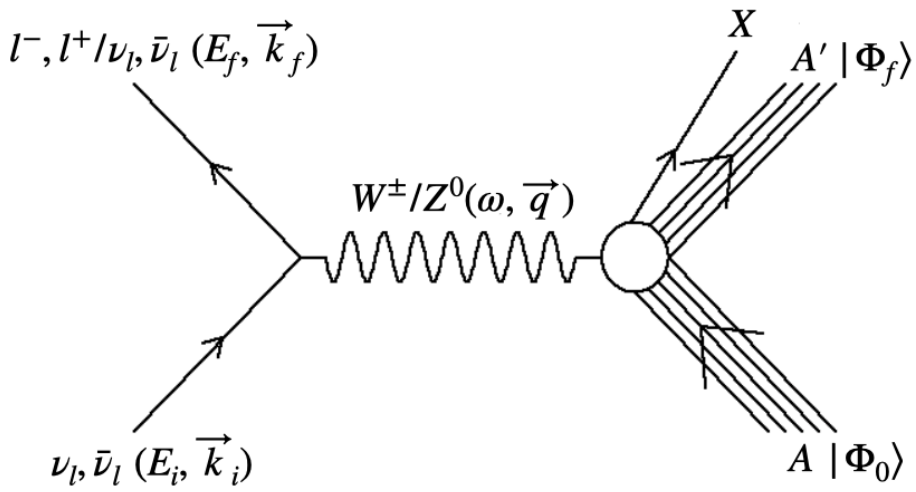
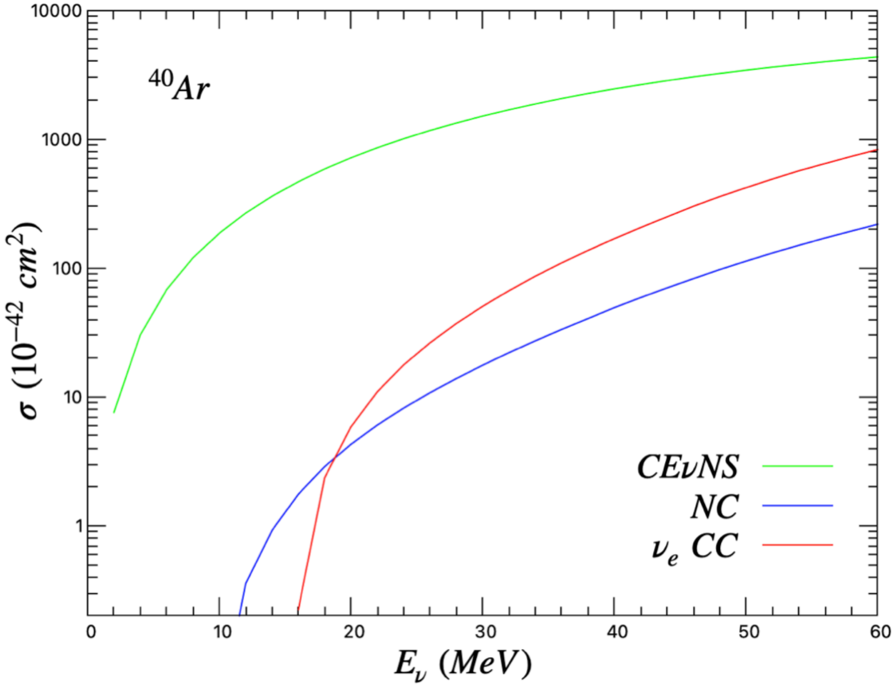


More recent work on CEvNS, please see:

S. Carey and V. Pandey, arXiv:2510.14015 [hep-ph] (accepted in JHEP)



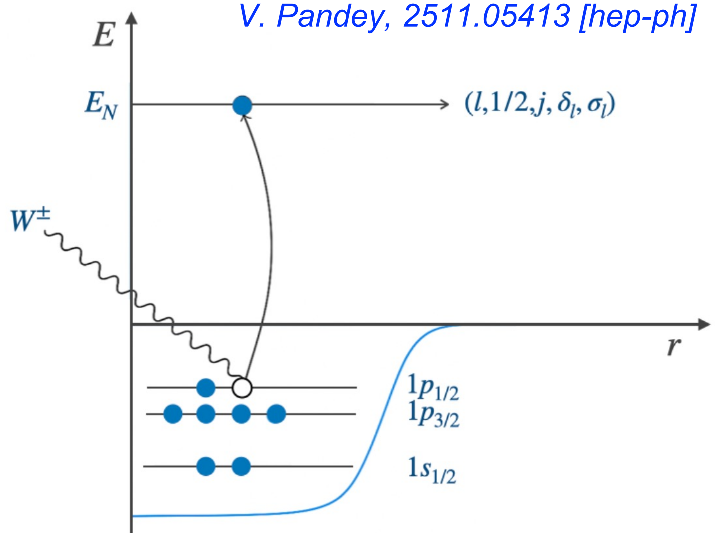
- At 10s of MeV, CEvNS cross section is significantly larger than inelastic ones.

V. Pandey, Prog. Part. Nucl. Phys., 104078 (2024)

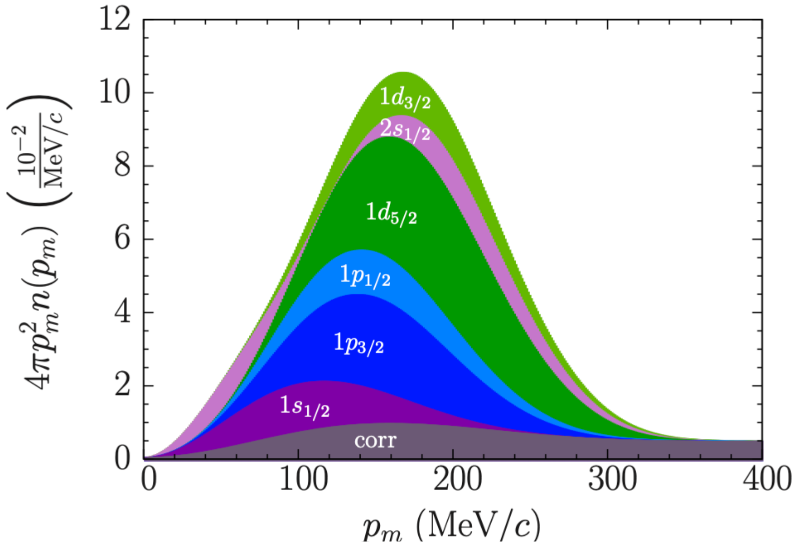
Nucleus: Many-Body System, Nuclear Effects

- Nucleus is a complex many-body quantum mechanical system
- Nucleons bound in the nucleus subject to various nuclear effects
- Fermi momentum, Pauli blocking, multi-body nucleon correlation, intra-nuclear hadronic interaction, …

V. Pandey, 2511.05413 [hep-ph]



JLab Hall A, Phys. Rev. D 105, 112002 (2022)



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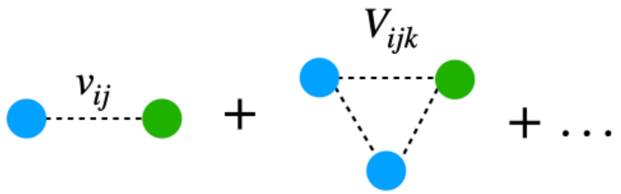
Neutrino-Nucleus Interactions: Many-Body QM Problem

- **The Nuclear Many-body Problem**
  - In the low-energy regime, quark and gluons are confined within hadrons and the effective degrees of freedoms are nucleons and pions
    - Nuclear Many-body Hamiltonian

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \dots$$



v_{ij} and V_{ijk} are two- and three-nucleon potential operators

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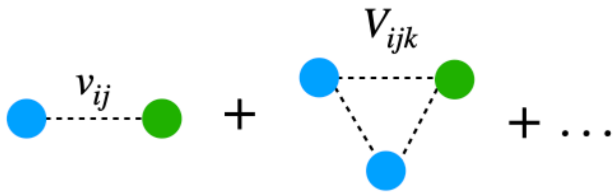


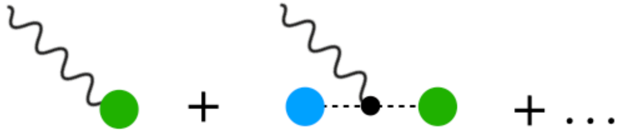
v_{ij} and V_{ijk} are two- and three-nucleon potential operators

  - The interactions of nuclei with external electroweak probes is mediated by charge and current operators that are consistent with the nuclear interactions.

Nuclear Current Operators:

$$J^\mu = \sum_i j_i^\mu + \sum_{i<j} j_{ij}^\mu + \ldots$$

one and two-body contributions



  - The response functions contain all nuclear-dynamics information

$$W(\omega, \mathbf{q}) = \sum_f \langle \Psi_0 | J^\dagger | \Psi_f \rangle \langle \Psi_f | J | \Psi_0 \rangle \delta(\omega - E_f + E_0)$$

Neutrino-Nucleus Scattering Cross Section

Expand the nuclear current in multipole operators:

$$\mathscr{J}_n^\mu = \langle \Phi_f | \hat{J}_n^\mu(q) | \Phi_0 \rangle = \frac{-G}{\sqrt{2}} \langle f | \left\{ -\sum_{J \geq 1} \sqrt{2\pi(2J+1)}(-i)^J \sum_{\lambda=\pm 1} l_\lambda \left[\lambda \hat{\mathcal{T}}^{\text{mag}}_{J-\lambda}(\kappa) + \hat{\mathcal{T}}^{\text{el}}_{J-\lambda}(\kappa) \right] \right.$$
$$\left. + \sum_{J \geq 0} \sqrt{4\pi(2J+1)}(-i)^J \left[l_3 \hat{\mathcal{L}}_{J0}(\kappa) - l_0 \hat{\mathcal{M}}_{J0}(\kappa) \right] \right\} |i\rangle$$

Definition of multipole operators with vector and axial currents.

$$\hat{\mathcal{M}}_{JM}(\kappa) \equiv \hat{M}_{JM} + \hat{M}^5_{JM} = \int d^3x [j_J(\kappa x) Y_{JM}(\Omega_x)] \hat{\mathcal{J}}_0(\mathbf{x})$$

$$\hat{\mathcal{L}}_{JM}(\kappa) \equiv \hat{L}_{JM} + \hat{L}^5_{JM} = \frac{i}{\kappa} \int d^3x \{\nabla [j_J(\kappa x) Y_{JM}(\Omega_x)]\} \cdot \hat{\boldsymbol{\mathcal{J}}}(\mathbf{x})$$

$$\hat{\mathcal{T}}^{\text{el}}_{JM}(\kappa) \equiv \hat{T}^{\text{el}}_{JM} + \hat{T}^{\text{el}5}_{JM} = \frac{1}{\kappa} \int d^3x [\nabla \times j_J(\kappa x) \boldsymbol{\mathcal{Y}}^M_{JJ1}(\Omega_x)] \cdot \hat{\boldsymbol{\mathcal{J}}}(\mathbf{x})$$

$$\hat{\mathcal{T}}^{\text{mag}}_{JM}(\kappa) \equiv \hat{T}^{\text{mag}}_{JM} + \hat{T}^{\text{mag}5}_{JM} = \int d^3x [j_J(\kappa x) \boldsymbol{\mathcal{Y}}^M_{JJ1}(\Omega_x)] \cdot \hat{\boldsymbol{\mathcal{J}}}(\mathbf{x})$$

J. D. Walecka, Theoretical Nuclear and Subnuclear Physics (2004)

Neutrino-Nucleus Scattering Cross Section

A. The Allowed Approximation

q→0, slow-nucleon limit:

- only Fermi (0^+) and Gamow-Teller (1^+) multipoles survive

Fermi: dominated by a single transition to the isobaric analog state

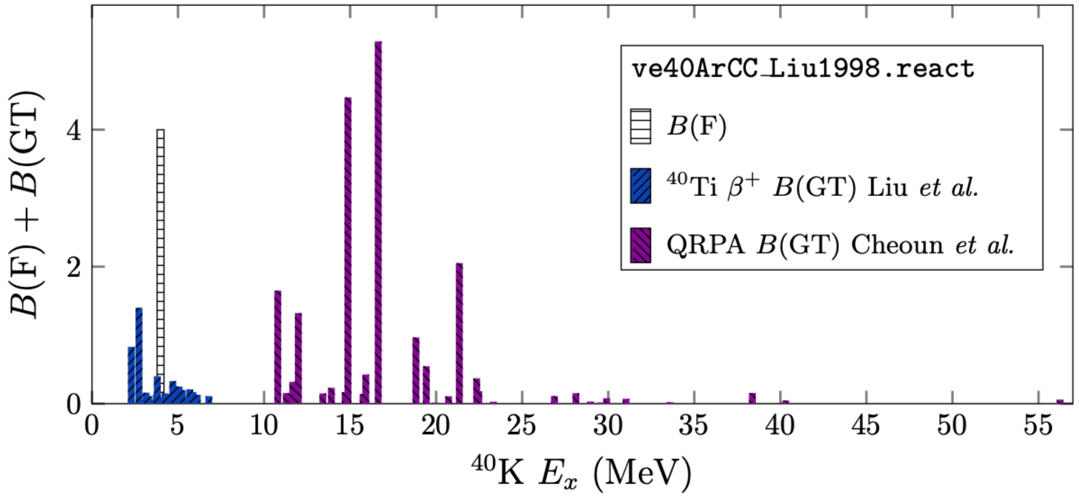
$$B(F) \equiv \frac{1}{2J_i+1}|\langle J_f||\mathcal{M}_0||J_i\rangle|^2$$

Gamow-Teller: many discrete transitions, governed by the Ikeda sum rule

$$S(G) \equiv \sum_{J_f} \frac{1}{2J_i+1}|\langle J_f||\mathcal{L}_1||J_i\rangle|^2$$

Both can be somewhat data-driven:

Measured via ^{40}Ti mirror β-decay and ^{40}Ar(p,n)^{40}K* charge-exchange reactions



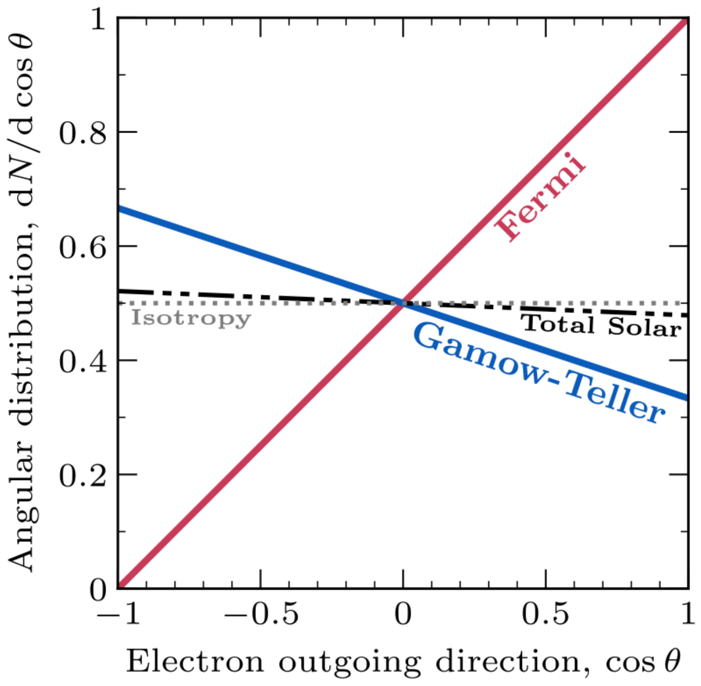
S. Gardiner, Phys.Rev.C 103, 044604 (2021)

Neutrino-Nucleus Scattering Cross Section

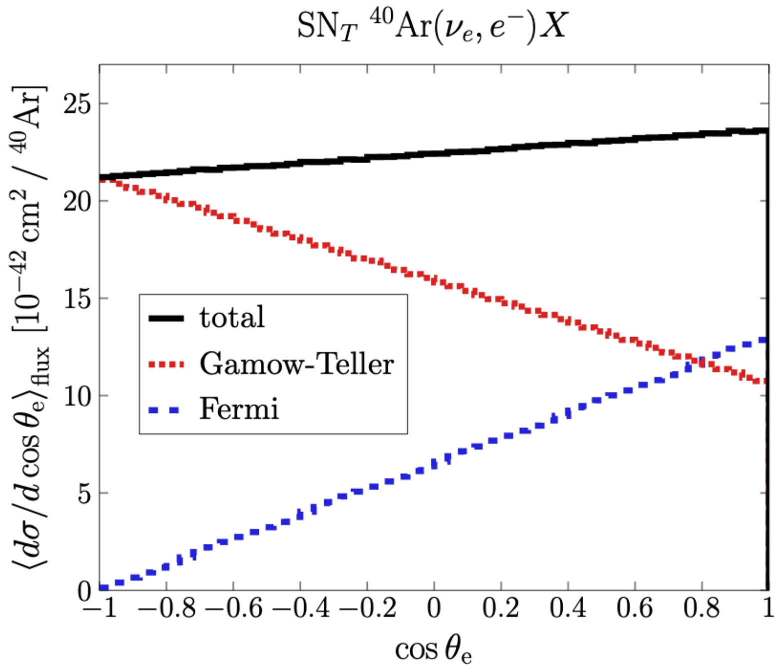
A. The Allowed Approximation

Cross Section in the AA

$$\frac{d\sigma}{d\cos\theta_\ell} = \frac{G_F^2\,|V_{\rm ud}|^2}{2\,\pi}\,F_C\left[\frac{E_i\,E_f}{s}\right]E_\ell\,|\mathbf{p}_\ell|\left[\left(1+\beta_\ell\cos\theta_\ell\right)B(\mathrm{F})+\left(1-\frac{1}{3}\beta_\ell\cos\theta_\ell\right)B(\mathrm{GT})\right]$$



R. Hajjar, O. Nairat, and J. F. Beacom, arxiv:2606.18347



S. Gardiner, Phys.Rev.C 103, 044604 (2021)

Neutrino-Nucleus Scattering Cross Section

A. The Allowed Approximation

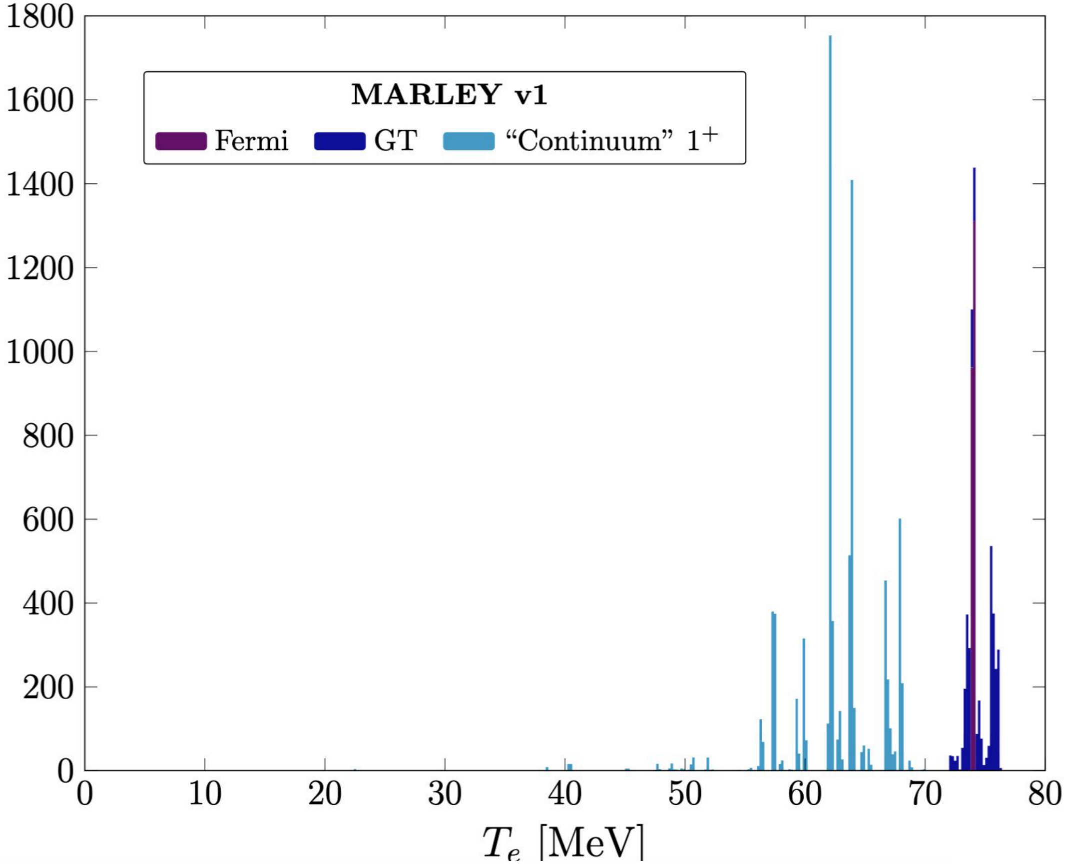
- Valid at low Ev, but by tens of MeV, forbidden (higher-J) transitions matter

- The true continuum gets mis-modeled as a set of discrete spikes:

  unphysical behavior for a monoenergetic neutrino beam

MARLEY (Model of Argon Reaction Low Energy Yields):
S. Gardiner PhD thesis
Low energy neutrino generator Used by DUNE

$80\,\mathrm{MeV}\ {}^{40}\mathrm{Ar}(\nu_e, e^-)X$



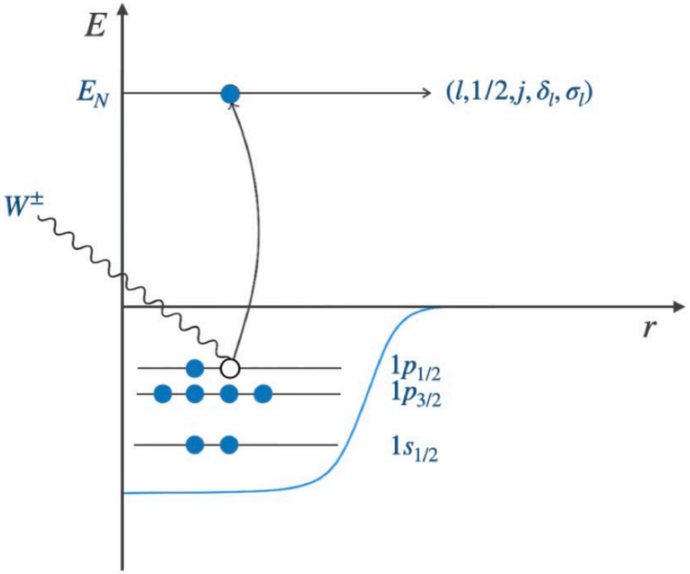
S. Gardiner, P. Barham Alzás, A. Nikolakopoulos, L. Abu El-Haj, N. Jachowicz, V. Pandey, arXiv:2604.26801

Neutrino-Nucleus Scattering Cross Section

B. Continuum Random Phase Approximation (CRPA)

Hartree-Fock (HF): Self-consistent mean field with effective Skyrme (SkE2) interaction.

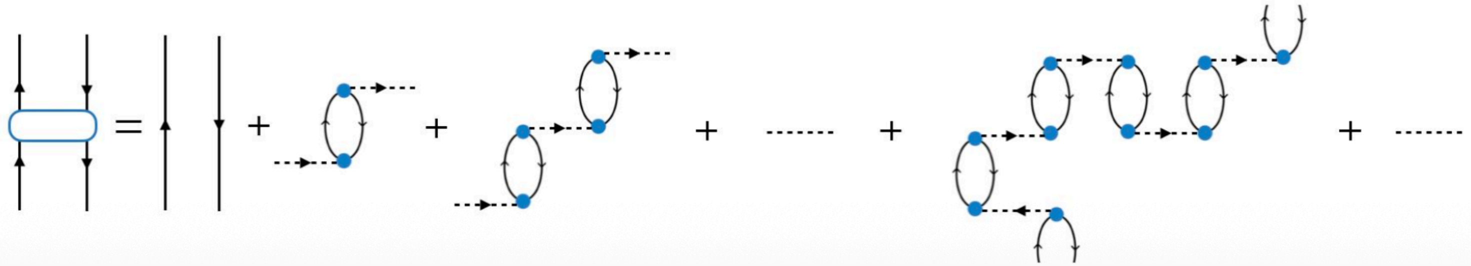
- Mean field potential, single-particle wavefunctions, binding energies, orthogonal states (-> Pauli-blocking)



Continuum Random Phase Approximation (CRPA): The influence of long-range correlations between the nucleons is introduced through CRPA on top of the HF-SkE2 approach.

- The local RPA-polarization propagator is obtained by an iteration to all orders of the first order contribution to the particle-hole Green's function.
- Same Skyrme (SkE2) residual interaction as initial state, self-consistent calculations

$$\Pi^{\mathrm{CRPA}}(x_1, x_2, E_x) = \Pi^{(0)}(x_1, x_2, E_x) + \frac{1}{\hbar} \int \mathrm{d}x \int \mathrm{d}x' \left[\Pi^{(0)}(x_1, x, E_x) \times \tilde{V}(x, x') \, \Pi^{\mathrm{CRPA}}(x', x_2, E_x) \right]$$



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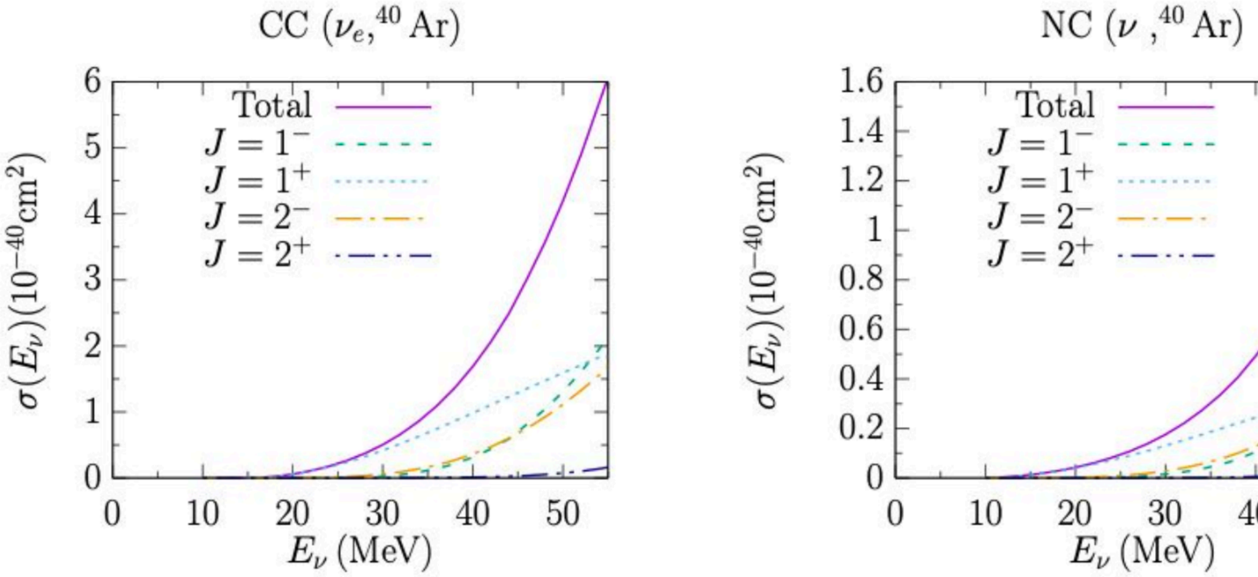
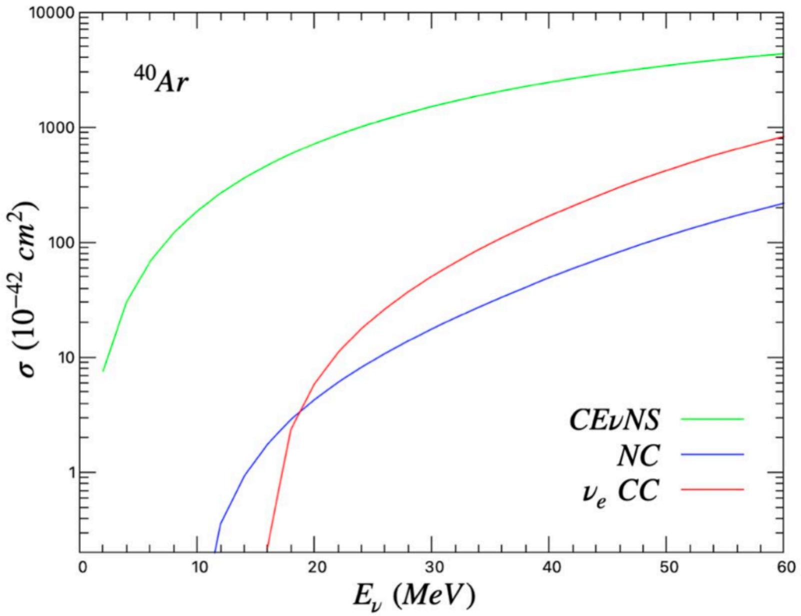
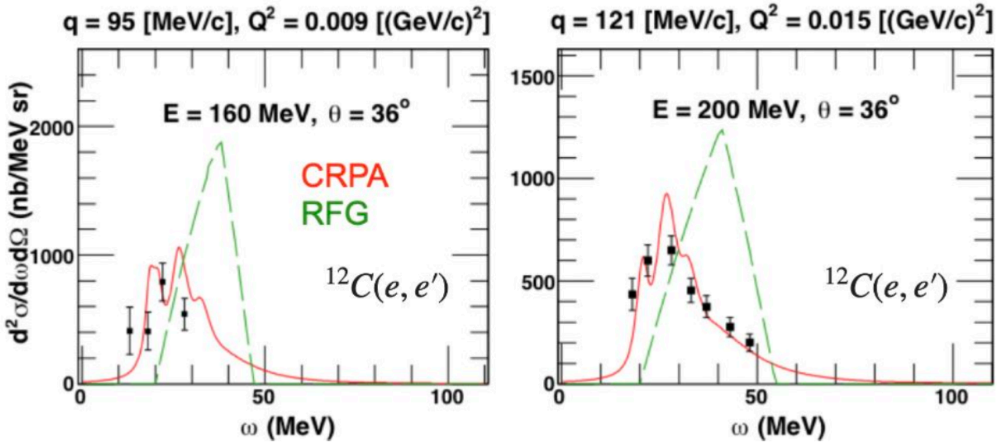




- N. Jachowicz, K. Heyde, J. Ryckebusch, and S. Rombouts, Phys. Rev. C 65, 025501 (2002)
- V. Pandey, N. Jachowicz, T. Van Cuyck, J. Ryckebusch and M. Martini, Phys. Rev. C 92, 024606 (2015)
- N. Van Dessel, N. Jachowicz, A. Nikolakopoulos, Phys. Rev. C 100, 055503 (2019)
- N. Van Dessel, V. Pandey, H. Ray and N. Jachowicz, Universe 9, 207 (2023)
- …….



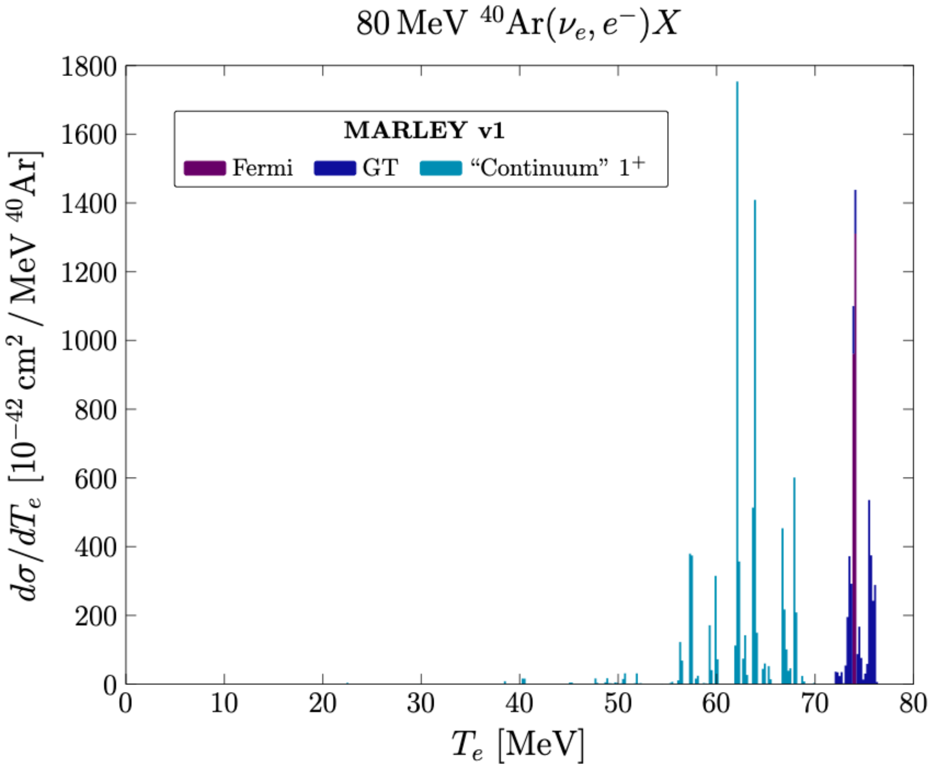
V. Pandey, PhD thesis (2016)

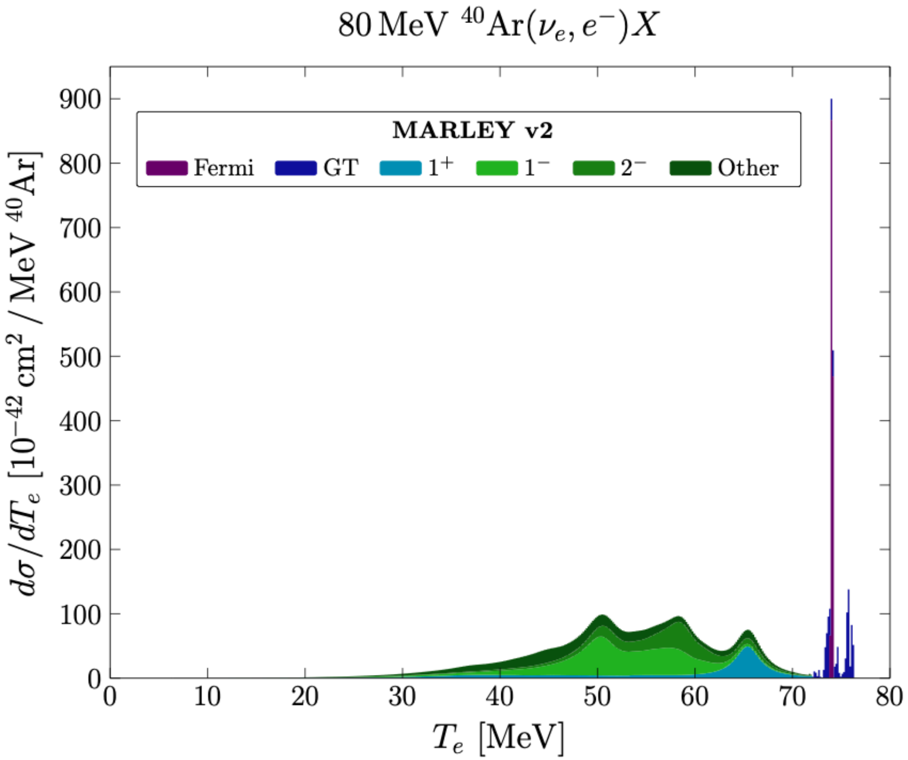
Neutrino-Nucleus Scattering Cross Section

Recent Updates to MARLEY: MARLEY v2

- Discrete transitions retained: B(F)/B(GT) transitions with some modifications

- Rest replaced by HF-CRPA





S. Gardiner, P. Barham Alzás, A. Nikolakopoulos, L. Abu El-Haj, N. Jachowicz, V. Pandey, arXiv:2604.26801

Neutrino-Nucleus Scattering Cross Section

Recent Updates to MARLEY: MARLEY v2

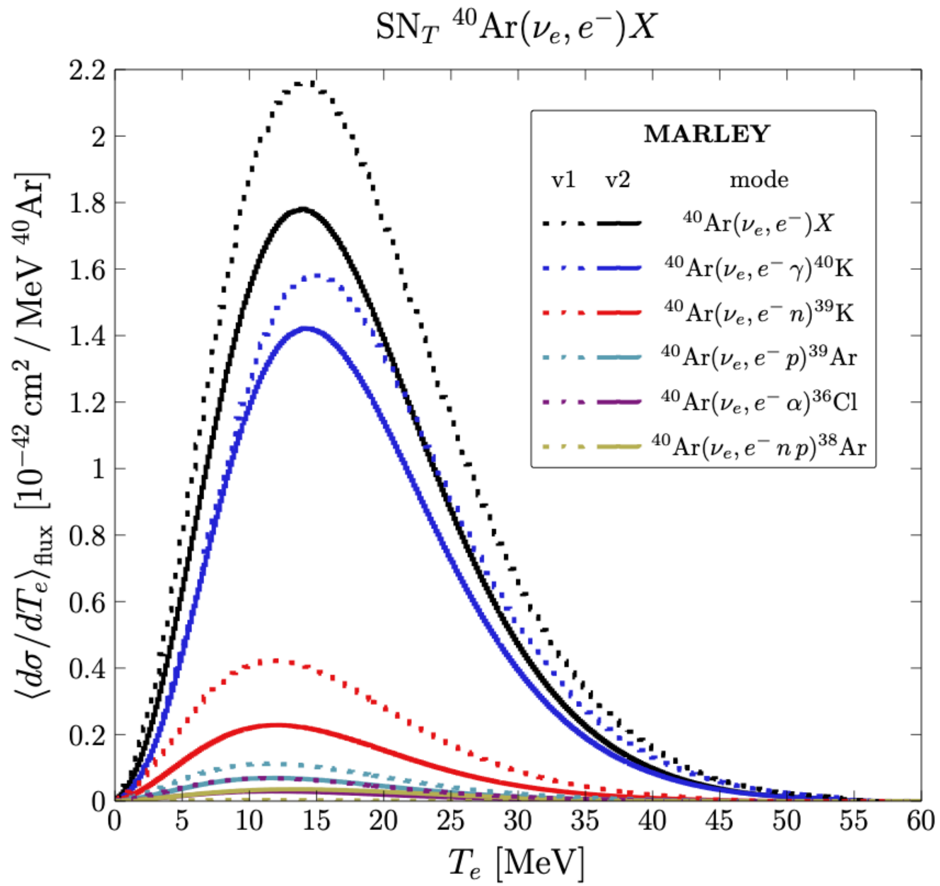
- For a reference time-integrated supernova ν_e spectrum:

    v2 predicts ~20% fewer events than v1 in a **DUNE-**like detector

- Mean visible electron energy shifts down by ~0.4 MeV

- Channel breakdown:

    Nγ still dominant (~73%→80% of total)



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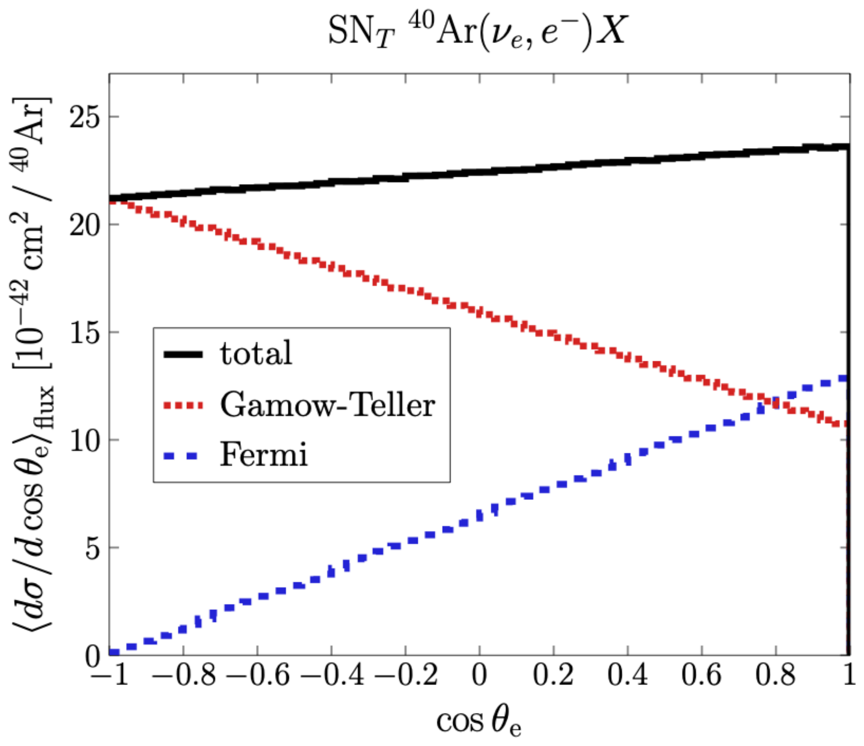
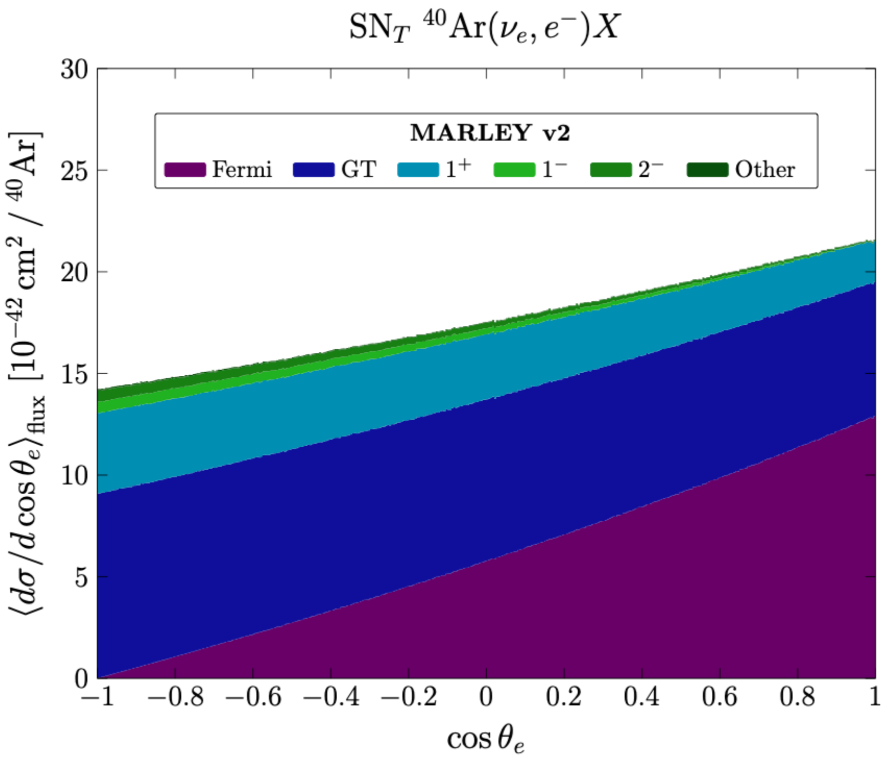
Neutrino-Nucleus Scattering Cross Section

Recent Updates to MARLEY: MARLEY v2

about ~40-50% higher xsec at θe = 0° than at θe = 180°





S. Gardiner, P. Barham Alzás, A. Nikolakopoulos, L. Abu El-Haj, N. Jachowicz, V. Pandey, arXiv:2604.26801

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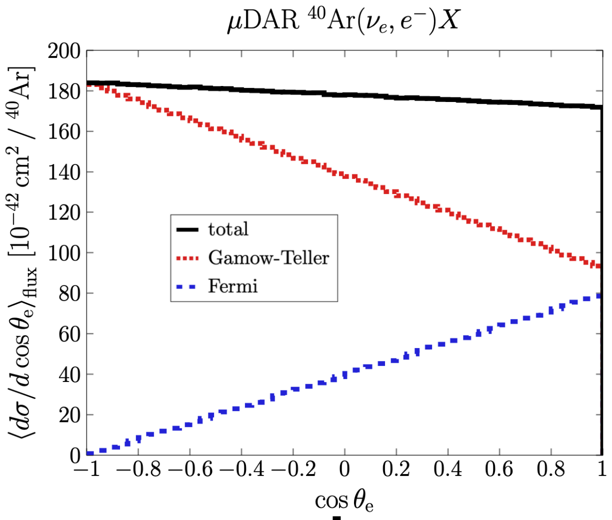
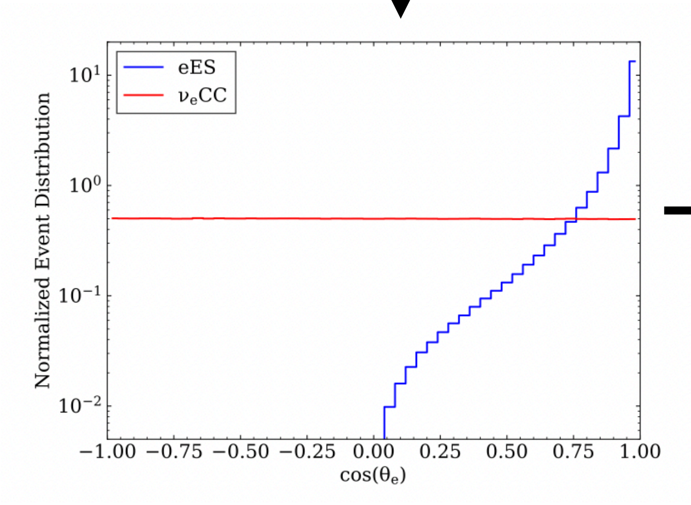
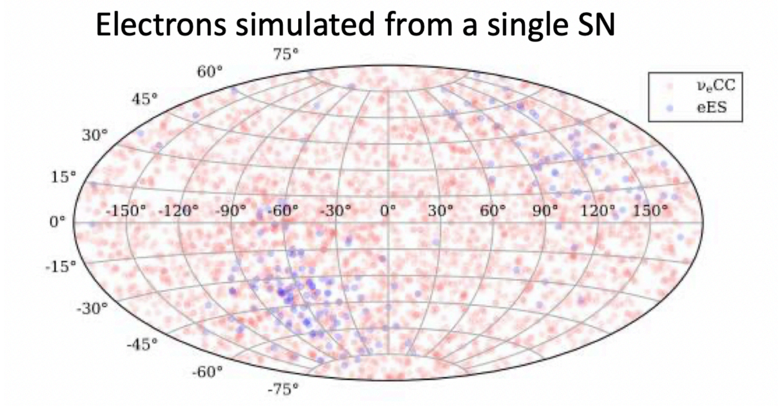
Neutrino-Nucleus Scattering Cross Section

- **Electron angular distribution is important for Supernova pointing capability**



- The angular distribution of the outgoing electron carries information about the direction of the incoming neutrino.
- That, in turn, enables DUNE's ability to point back to a supernova and enable multi-messenger exploration.



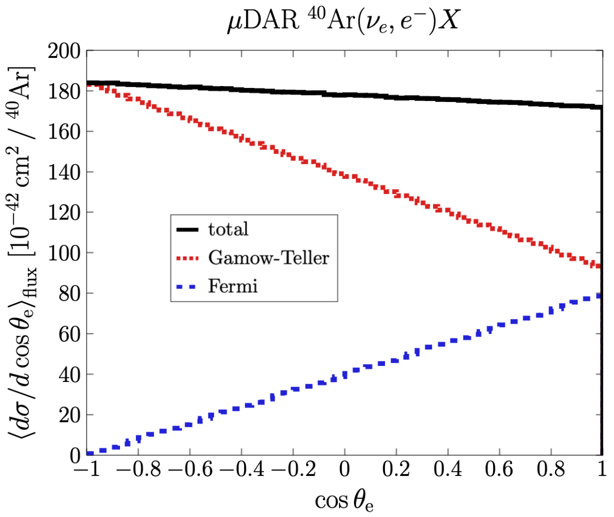


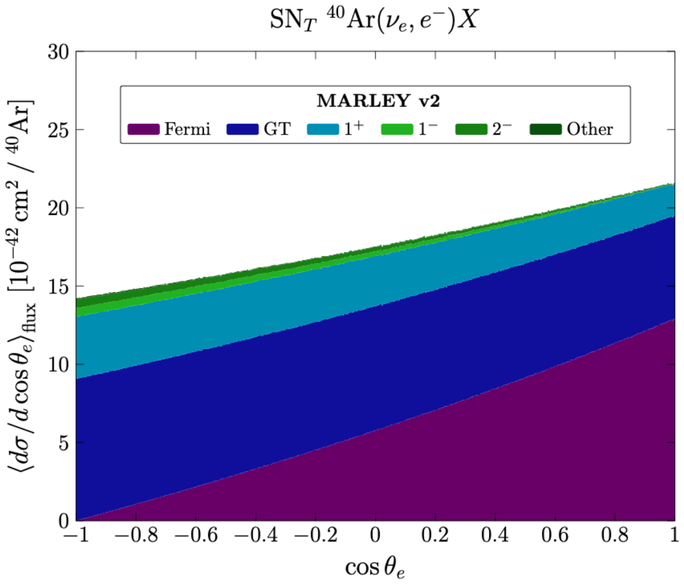
Channel	Events "GKVM" model
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	3350
$\overline{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	260
Total	3770

DUNE Collaboration, arXiv:2407.10339 [hep-ex]

Neutrino-Nucleus Scattering Cross Section

- **Electron angular distribution is important for Supernova pointing capability**





Supernova pointing is a high-value DUNE capability:

- independent early-warning triangulation alongside other observatories

- DUNE currently avoids CC ν_e-Ar pointing and relies on ν-e elastic scattering (eES) instead 10× fewer events

- In MARLEY v2' the electron angular distribution becomes more forward-peaked than v1

- Ongoing work in re-examining DUNE's pointing sensitivity using non-isotropic CC angular distribution
Sam Carey, Garv Chauhan, Vishvas Pandey et al, in progress

Channel	Events "GKVM" model
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	3350
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Total	3770

Neutrino-Nucleus Scattering Cross Section

C. Ab Initio Nuclear Structure Calculations for bound states

Chiral effective-field-theory 2N+3N forces:

1.8/2.0(EM), ΔNNLO_GO(394), N3LO_Texas interactions

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

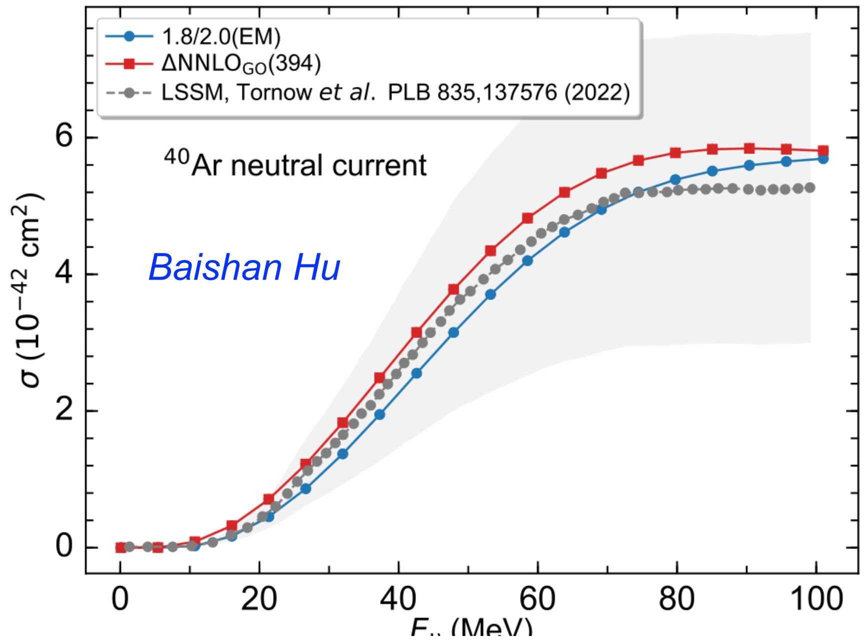
No fitted or quenched operators

VS-IMSRG (valence-space in-medium similarity renormalization group) decouples a valence Hamiltonian, then KSHELL exactly diagonalizes it

1^+-state ν-^{40}Ar cross section:

two independent ab initio interactions — 1.8/2.0(EM) and ΔNNLO_GO(394)

Agree with the tuned/quenched LSSM (Tornow et al., PLB 835, 137576 (2022)) within its uncertainty band

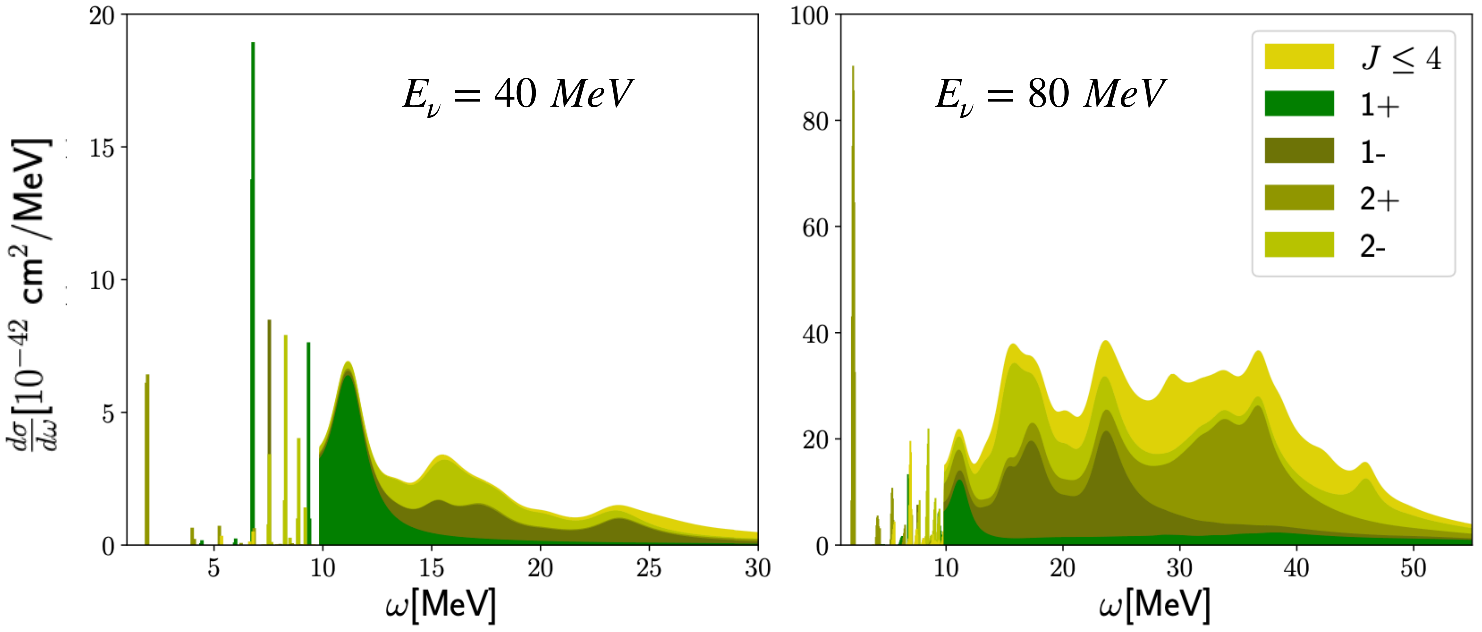


Neutrino-Nucleus Scattering Cross Section

Unifying CRPA with Ab Initio

- Same discrete/continuum split as MARLEY v2 but the discrete piece is now ab initio

- Applied first to the neutral-current channel



M. Vanderpoorten, B. Hu, W. C. Huang, J. Newstead, B. Dutta, N. Jachowicz, V. Pandey, in progress

Neutrino-Nucleus Scattering Cross Section

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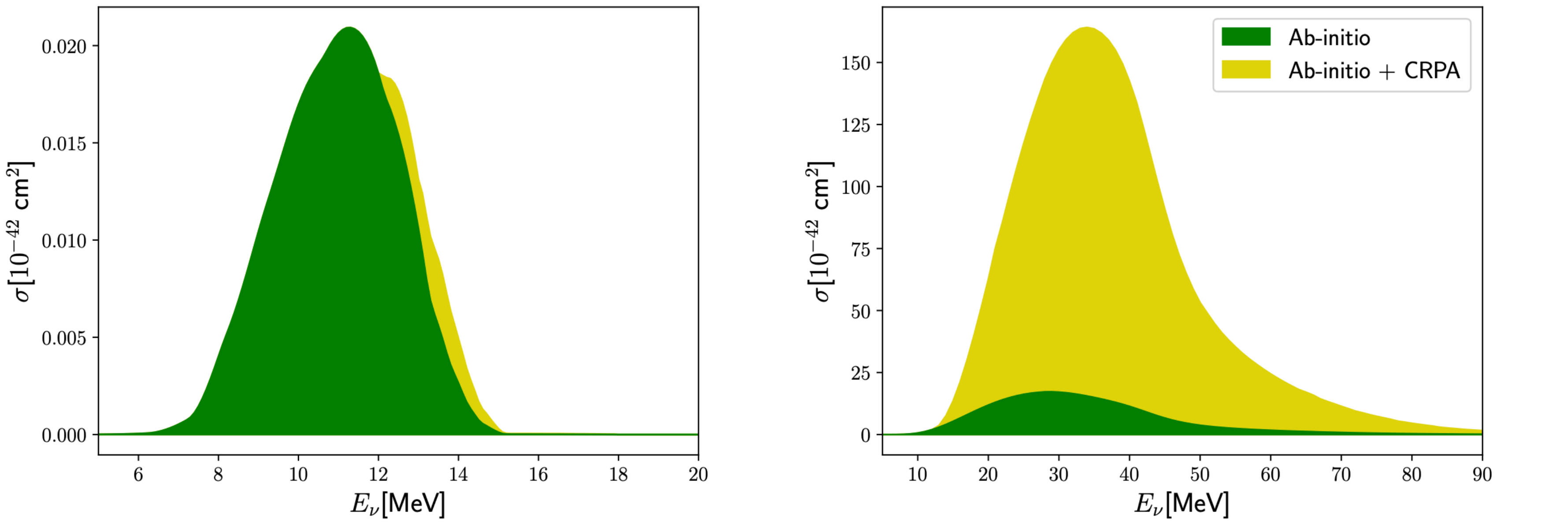


FIG. 2: Neutral current neutrino-argon scattering cross section weighted with the solar (left) and supernova flux (right) as a function of the neutrino energy.

M. Vanderpoorten, B. Hu, W. C. Huang, J. Newstead, B. Dutta, N. Jachowicz, V. Pandey, in progress

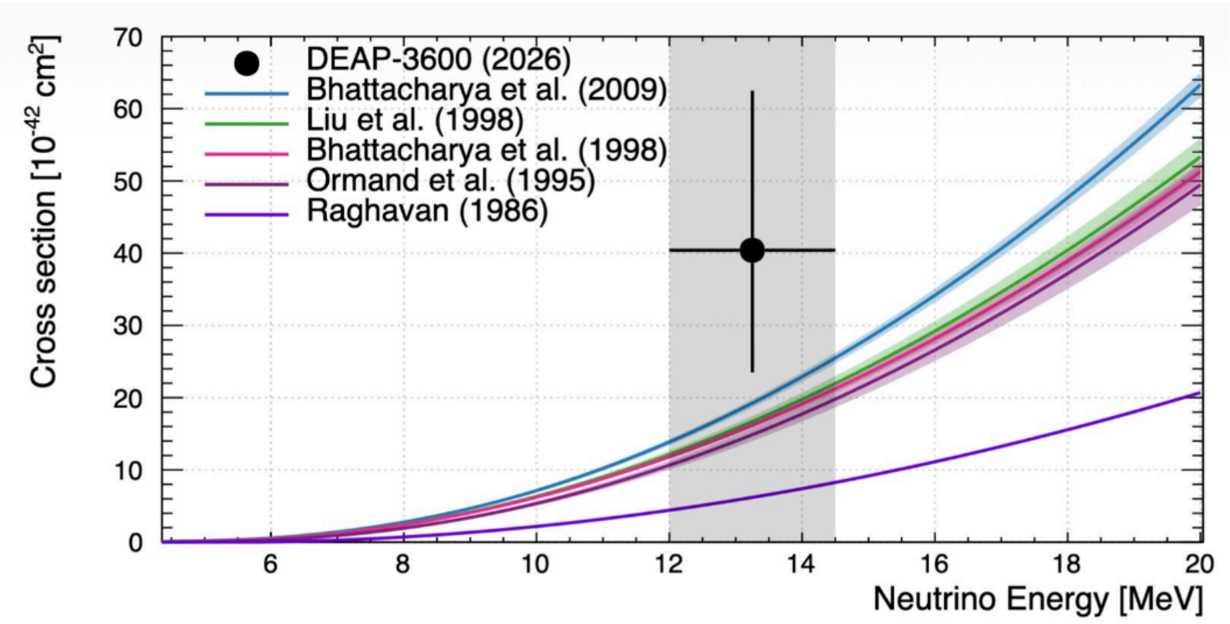
Limited Measurements

- There are very few existing measurements, none at better than the 10% uncertainty level.

Reaction Channel	Experiment	Measurement (10^{-42} cm^2)
$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	KARMEN	$9.1 \pm 0.5(stat) \pm 0.8(sys)$
	E225	$10.5 \pm 1.0(stat) \pm 1.0(sys)$
	LSND	$8.9 \pm 0.3(stat) \pm 0.9(sys)$
$^{12}C(\nu_e, e^-)^{12}N^*$	KARMEN	$5.1 \pm 0.6(stat) \pm 0.5(sys)$
	E225	$3.6 \pm 2.0(tot)$
	LSND	$4.3 \pm 0.4(stat) \pm 0.6(sys)$
$^{12}C(\nu_\mu, \nu_\mu)^{12}C^*$	KARMEN	$3.2 \pm 0.5(stat) \pm 0.4(sys)$
$^{12}C(\nu, \nu)^{12}C^*$	KARMEN	$10.5 \pm 1.0(stat) \pm 0.9(sys)$
$^{56}Fe(\nu_e, e^-)\ ^{56}Co$	KARMEN	$256 \pm 108(stat) \pm 43(sys)$
$^{127}I(\nu_e, e^-)^{127}Xe$	LSND	$284 \pm 91(stat) \pm 25(sys)$
$^{127}I(\nu_e, e^-)X$	COHERENT	$920^{+2.1}_{-1.8}$
$^{nat}Pb(\nu_e, Xn)$	COHERENT	– –

TABLE III. Flux-averaged cross-sections measured at stopped pion facilties on various nuclei. Experimental data gathered from the LAMPF [89], KARMEN [90–93], E225 [94], LSND [95–97], and COHERENT [98, 99] experiments. Table adapted from the Ref. [9].

V. Pandey, Prog. Part. Nucl. Phys., 104078 (2024)



DEAP-3600, arXiv:2605.12769

Inelastic Dark Matter Scattering off Nuclei

Production:

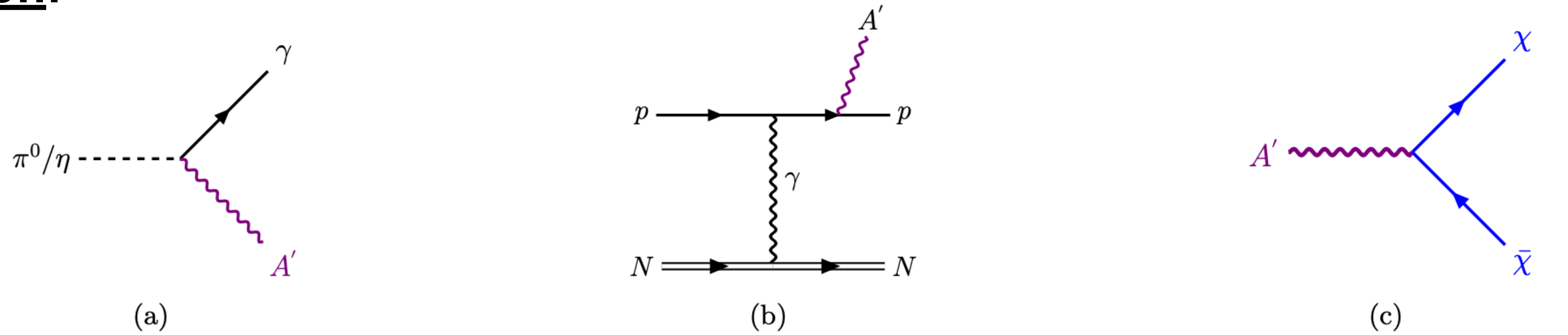


FIG. 1: Feynman diagrams depicting (a) the production of $A^{'}$ via neutral meson two-body decay, (b) the production of $A^{'}$ through proton bremsstrahlung, and (c) the two-body decay of $A^{'}$ into a $\bar{\chi}$ and χ pair.

Detection:

Elastic DM-nucleus scattering

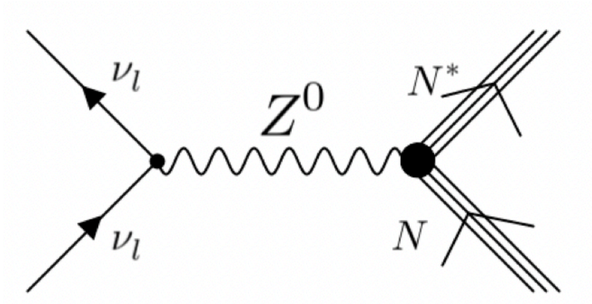
- keV-scale nuclear recoil
- Coherently enhanced, larger for heavier nuclei
- The traditional direct-detection channel

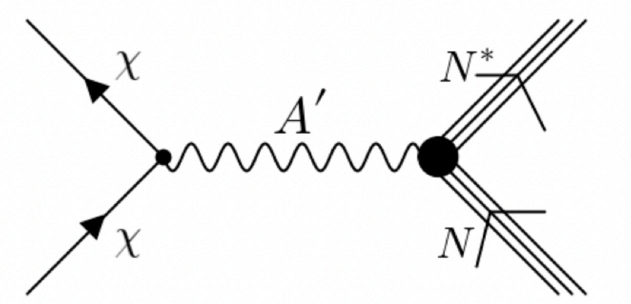
Inelastic DM-nucleus scattering

- MeV-scale nuclear excitation + discrete de-excitation γ's
- Much smaller cross section…
- …but a distinctive, low-background spectral signature exploitable in a LArTPC's excellent MeV-scale calorimetry

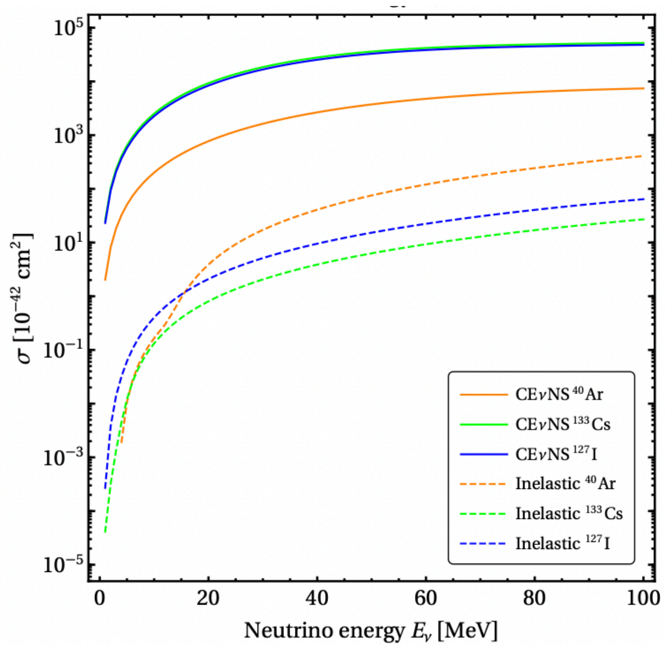
Inelastic Dark Matter Scattering off Nuclei

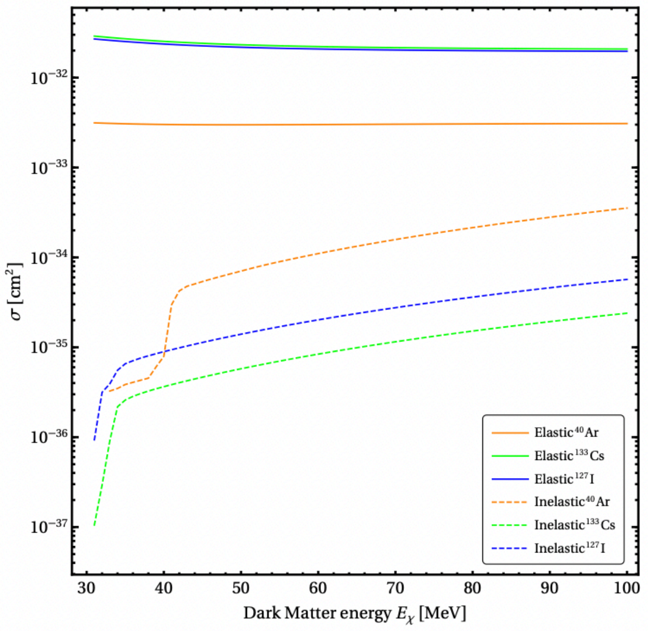
- **NC ν-nucleus $\rightarrow$ χ-nucleus scattering**





Computed using Gamow-Teller (allowed-approximation)





B. Dutta, W. C. Huang, J. L. Newstead, V. Pandey, Phys. Rev. D 106, 113006 (2022)

Inelastic Dark Matter Scattering off Nuclei

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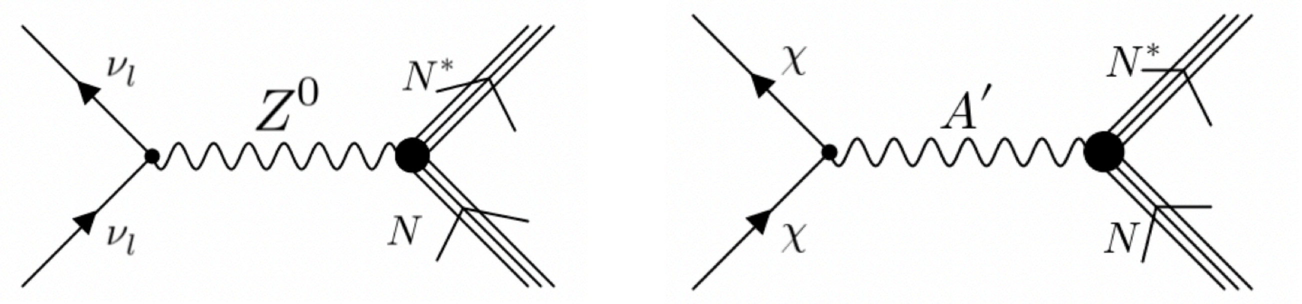

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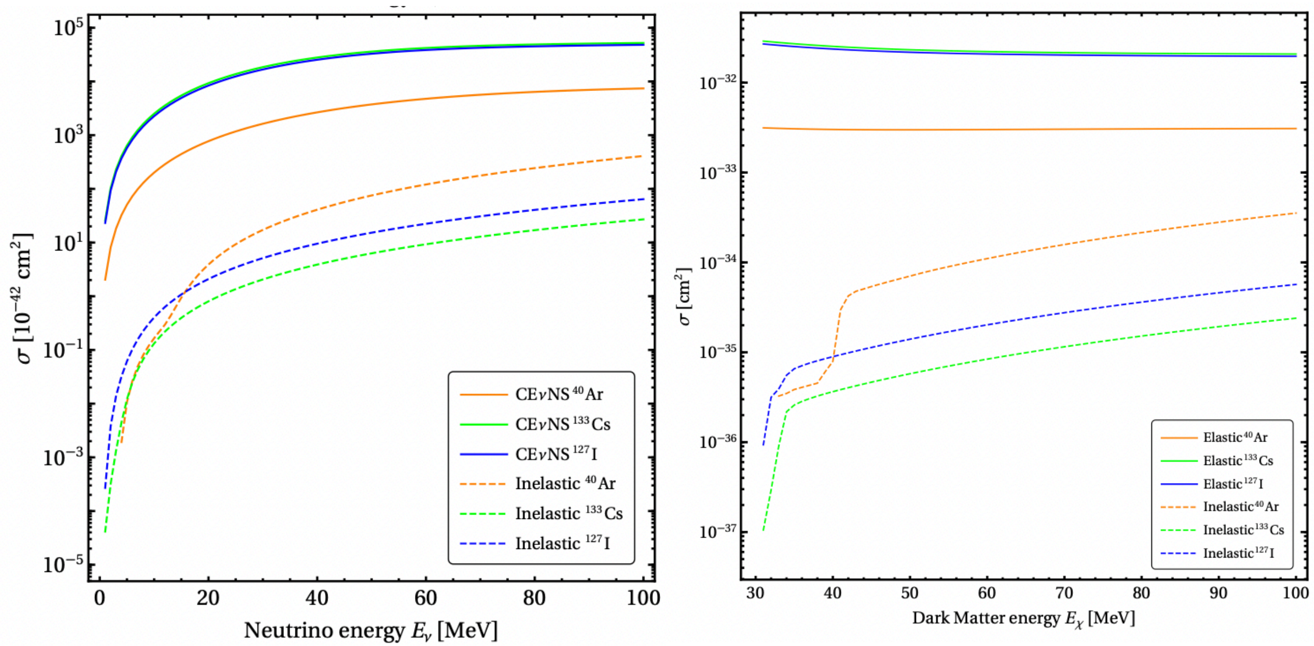
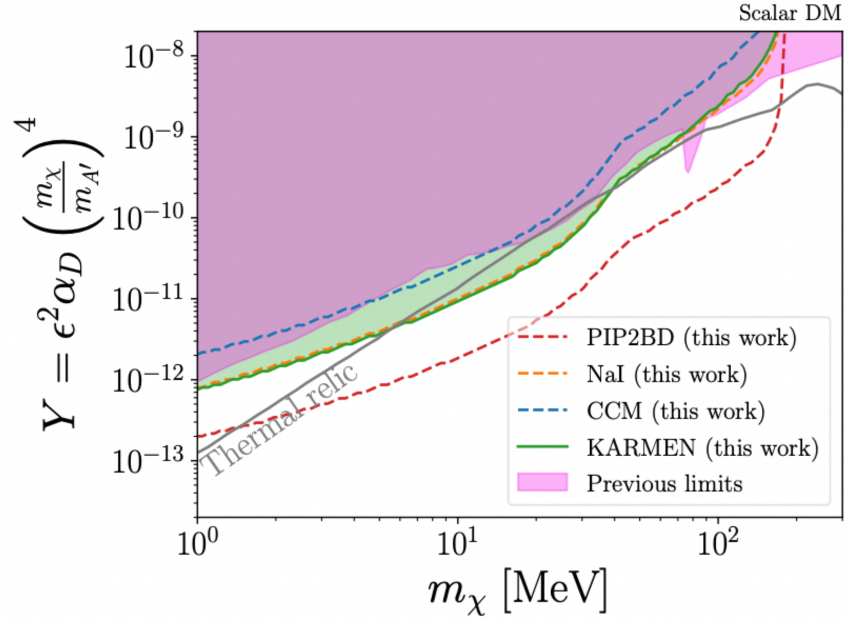


B. Dutta, W. C. Huang, J. L. Newstead, V. Pandey, Phys. Rev. D 106, 113006 (2022)



B. Dutta, W. C. Huang, J. L. Newstead, Phys. Rev. Lett. 131, 111801 (2023)

Inelastic Dark Matter Scattering off Nuclei

Gamow-Teller -> Ab-intio

B. Dutta, D. Goswami, B. Hu, W. C. Huang and V. Pandey, arXiv:2602.02817 [hep-ph]

Extends VS-IMSRG for the first time to inelastic DM-nucleus scattering:

all relevant ^{40}Ar excited states up to 18 MeV

1^+ states (4.5–10 MeV) and the first 2^+ (1.5 MeV) dominate

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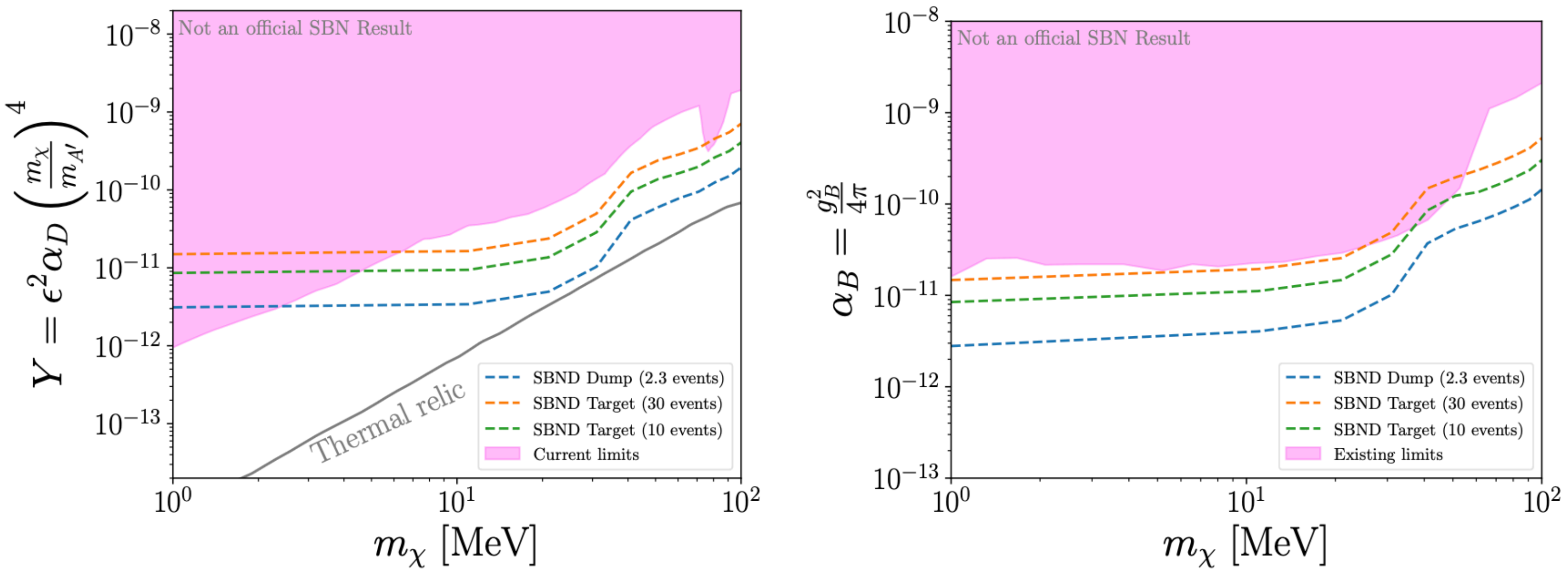

FIG. 3: Dark matter exclusion bounds at SBND obtained using ab initio nuclear calculations for the vector-portal dark photon model (left) and the leptophobic dark matter model (right), where $\alpha_B = \frac{g_q^2}{4\pi}$. The assumed numbers of signal events are indicated in the legend.

$$\mathcal{L}_{\rm int} \supset g_D \bar{\chi}\gamma^\mu \chi A'_\mu + \sum_f g_f \bar{f}\gamma^\mu f A'_\mu$$

$$g_f = \begin{cases} \varepsilon\, e\, Q_f, & \text{Dark photon model,} \\ g_q\, \delta_{f,q}, & \text{Leptophobic model.} \end{cases}$$

Next step: extending this with ab initio + CRPA together

Summary

- MeV-scale capabilities of LArTPCs are now experimentally established, with direct demonstrations by ArgoNeuT and MicroBooNE.
  - Opens potential for broad range of physics with solar, supernova neutrinos and inelastic scattering of dark sector particles.

- Improved nuclear-response modeling leads to significant changes:
  - MARLEY v2 with CRPA affects DUNE supernova event yields by ~20%, and restores the potential for using charged-current event for supernova pointing.
  - Ab initio nuclear calculations significantly expand SBND sensitivity to previously unexplored inelastic dark matter parameter space.

- First-principles (ab-initio) and many-body (CRPA) nuclear calculations for argon are now becoming computationally feasible for MeV-scale physics:
  - enhancing sensitivity to supernova and solar neutrinos
  - strengthening searches for dark-sector physics

  in LArTPC experiments such as SBN and DUNE.