Theory Overview of Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

Vishvas Pandey

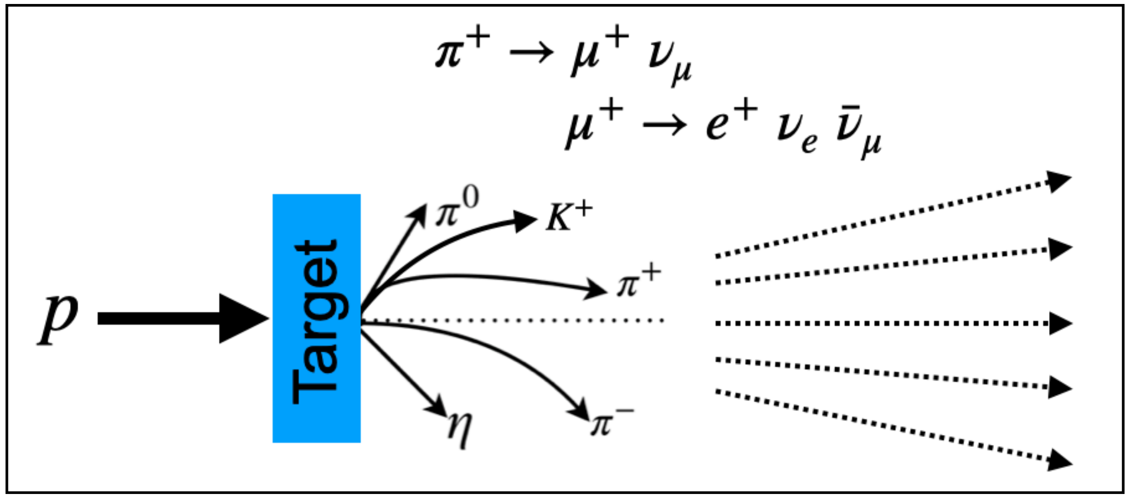
CIPANP 2022, 14th Conference on the Intersections of Particle and Nuclear Physics
Orlando, Florida, August 19 - September 4, 2022

Low-energy Neutrinos

✦ **Low-energy ≈ 10s of MeV (E_ν and/or ω)**

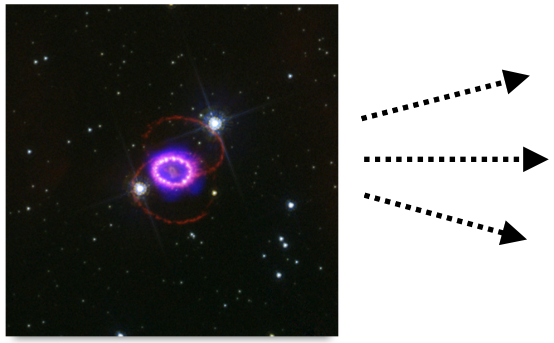
E_ν : Neutrino energy
ω : Energy transferred to the nucleus

- **Pion decay-at-rest (piDAR) Neutrinos**
  (SNS at ORNL, LANSCE at LANL, MLF at JPARC, FNAL, …)

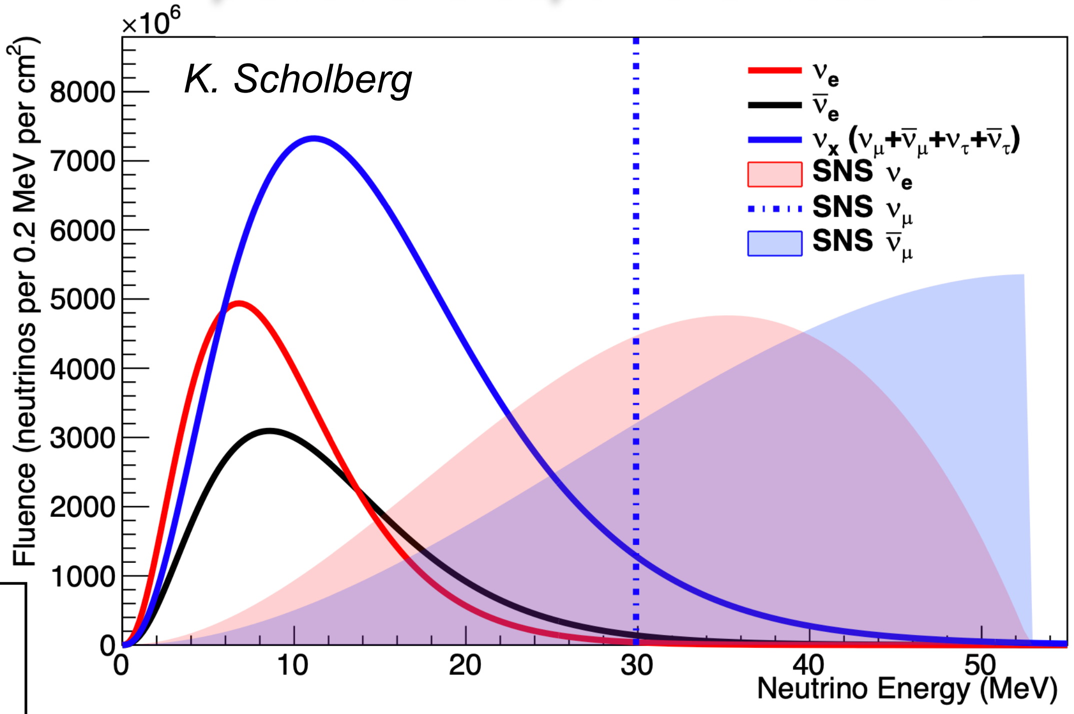


- **Core-collapse Supernova Neutrinos**

A short, sharp “neutronization” (or “breakout”) burst primarily composed of ν_e from $e^- + p \to \nu_e + n$.



piDAR and Supernova Neutrinos



Fermilab

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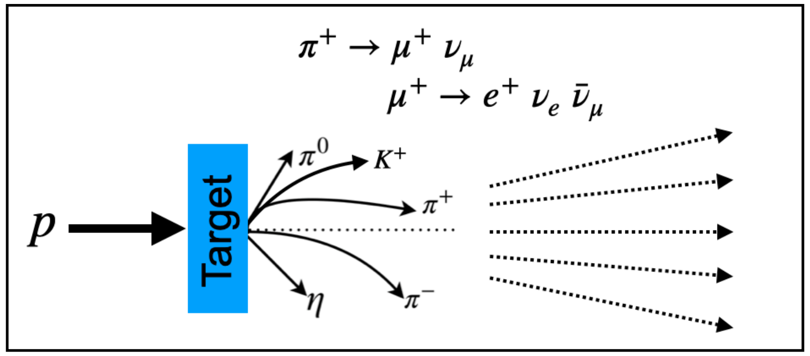

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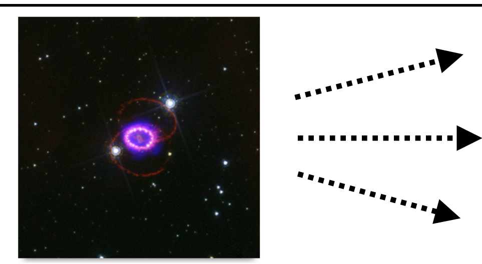

- **Kaon decay-at-rest (KDAR) Neutrinos**

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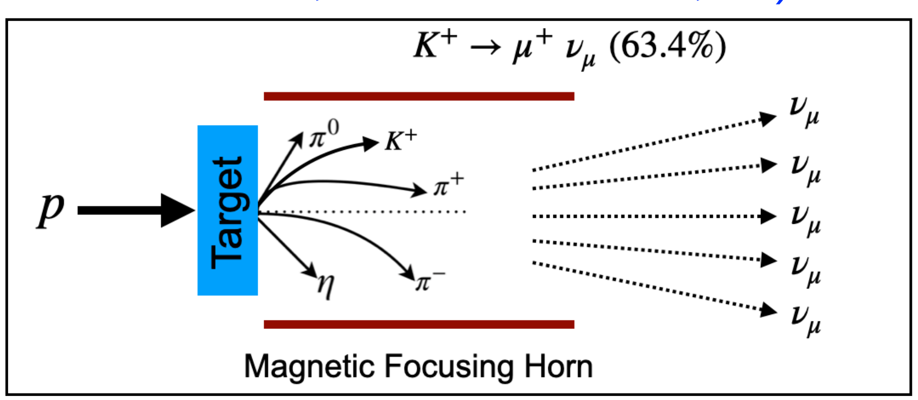
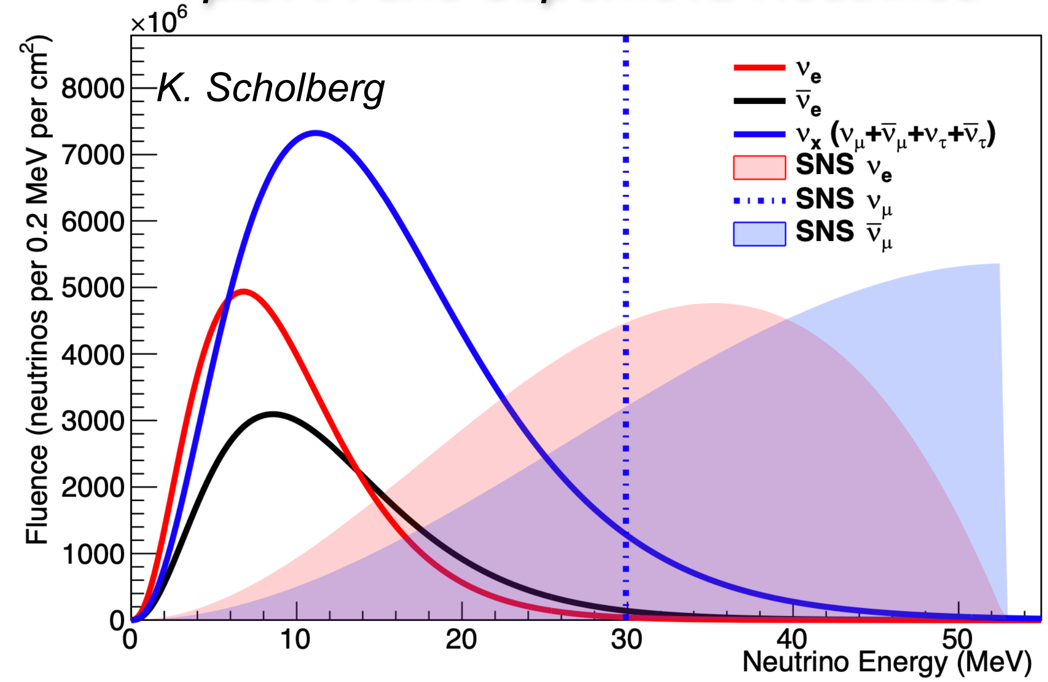


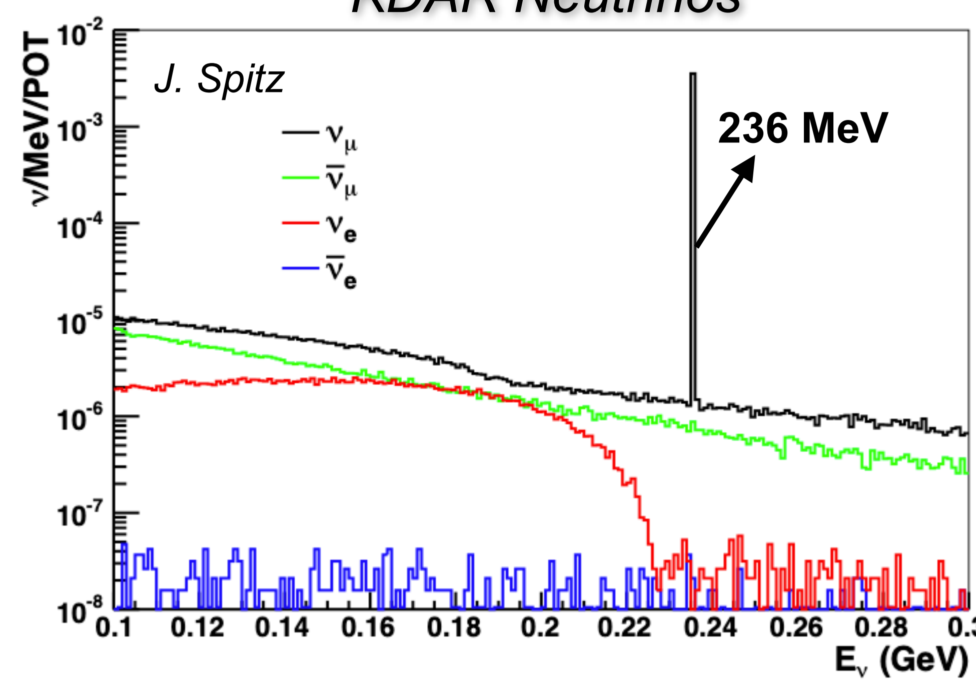
- **Forward Scattering of decay-in-flight (DIF) Neutrinos**

  (BNB/NuMI at FNAL, JPARC, …)

piDAR and Supernova Neutrinos

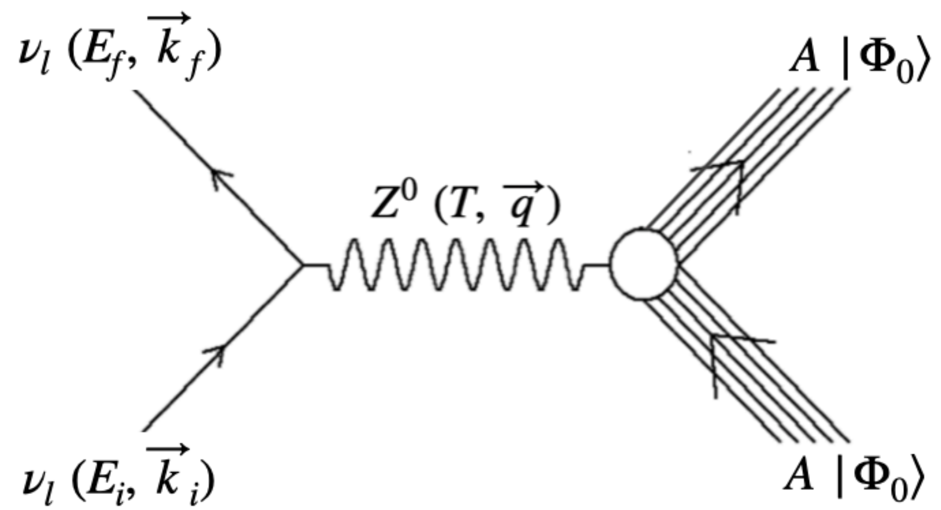


KDAR Neutrinos



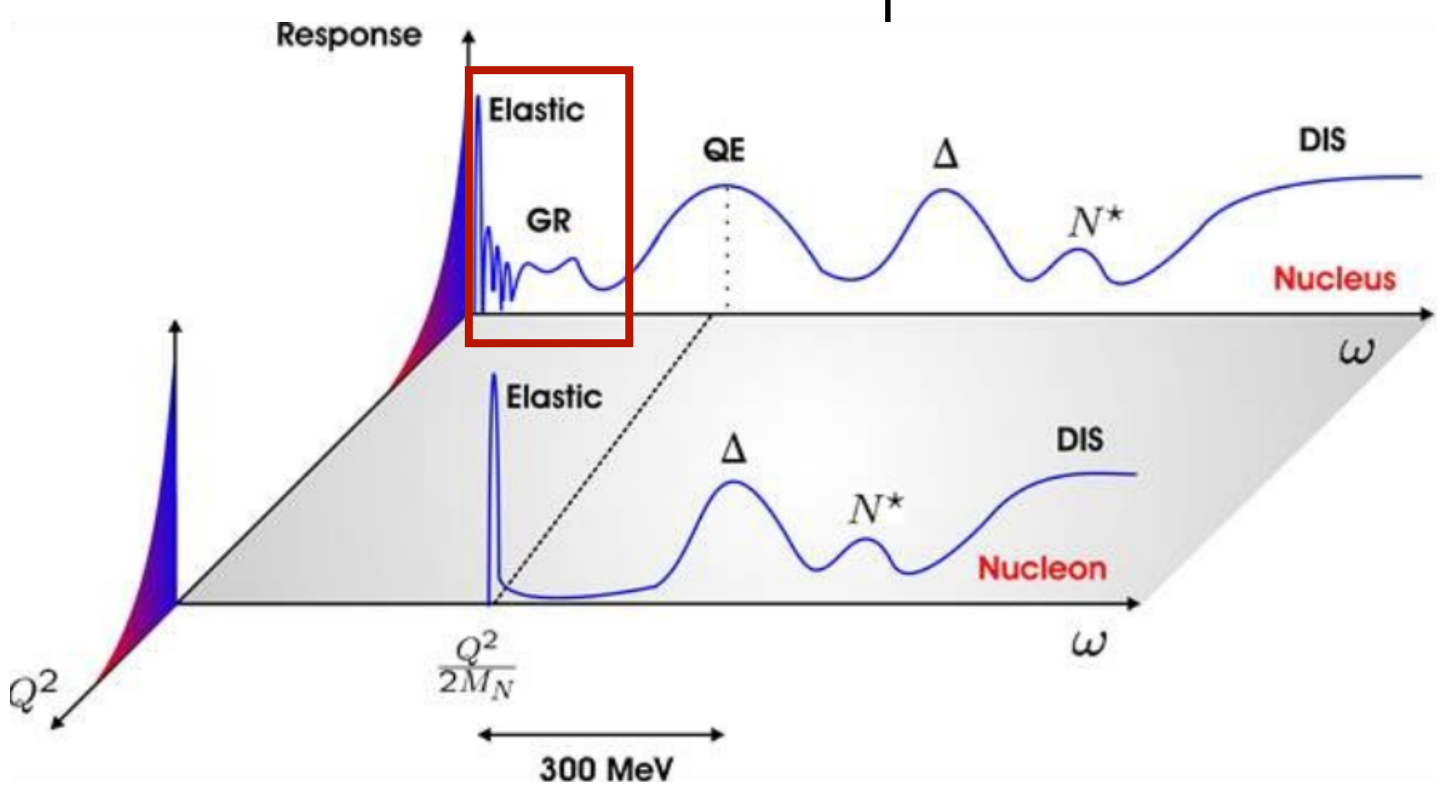
Low-energy Neutrinos-Nucleus Scattering

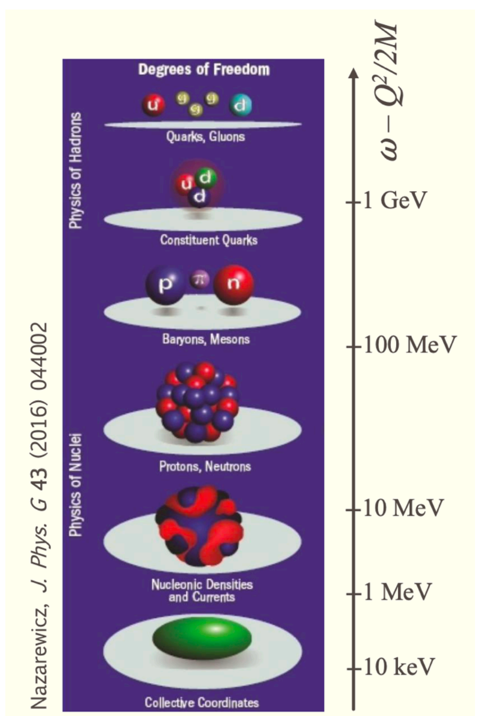
Coherent elastic [CEvNS]



- Final state nucleus stays in its ground state
- Tiny recoil energy, large cross section
- Signal: keV energy nuclear recoil

Inelastic CC/NC





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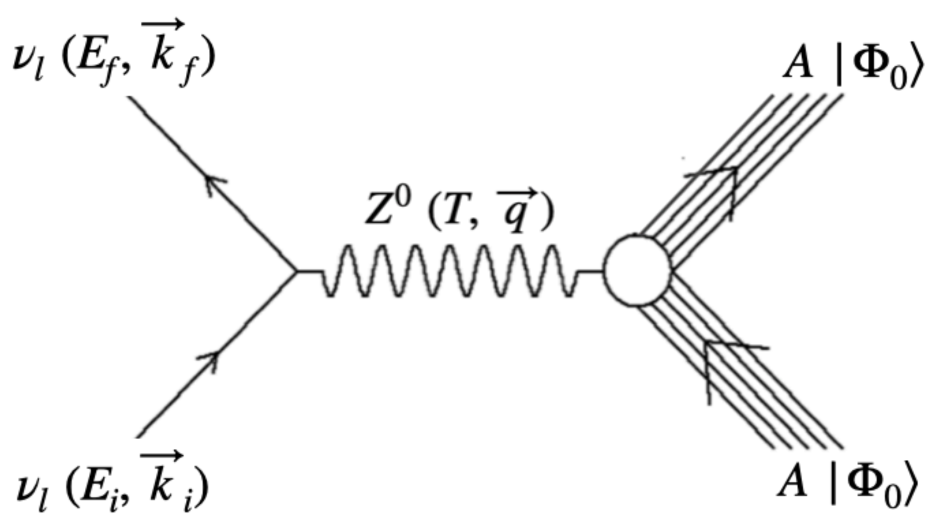

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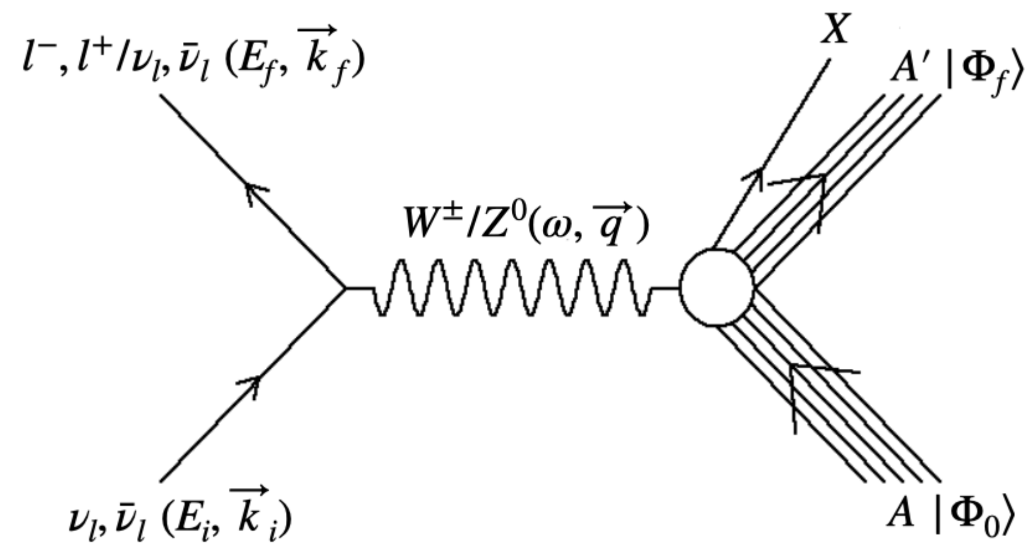
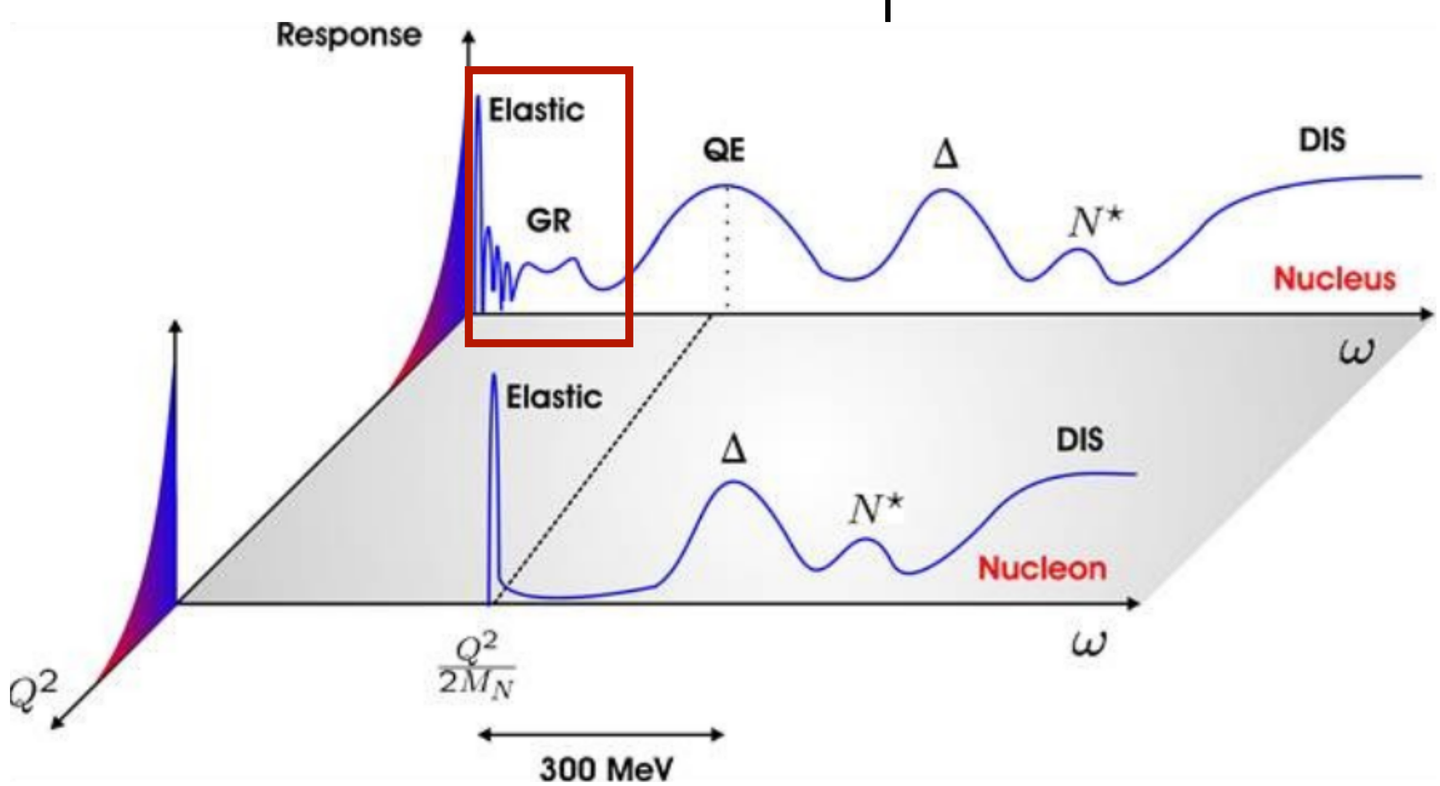
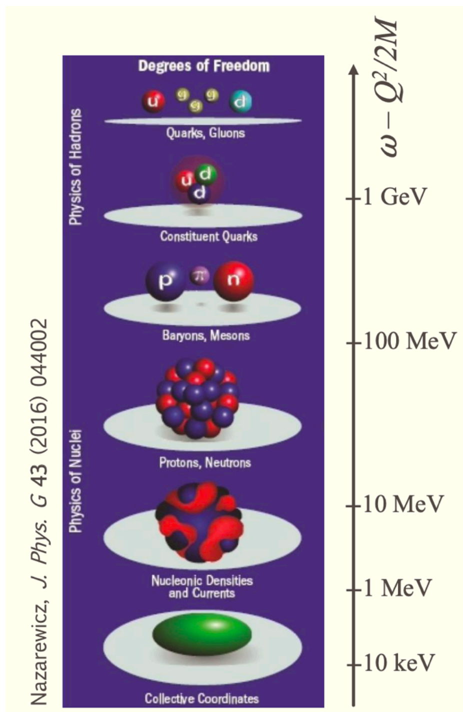


- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π)
- Followed by nuclear de-excitation into gammas, n, p, and nuclear fragmentations.





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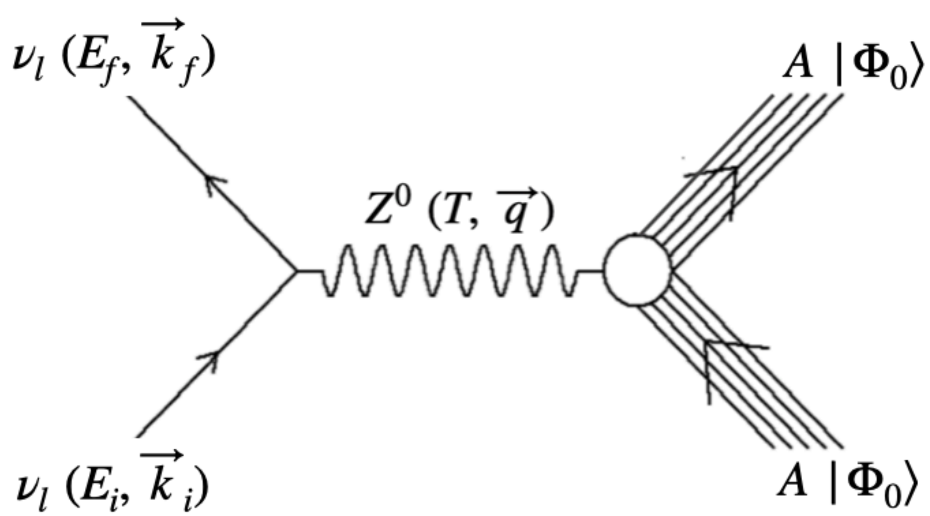

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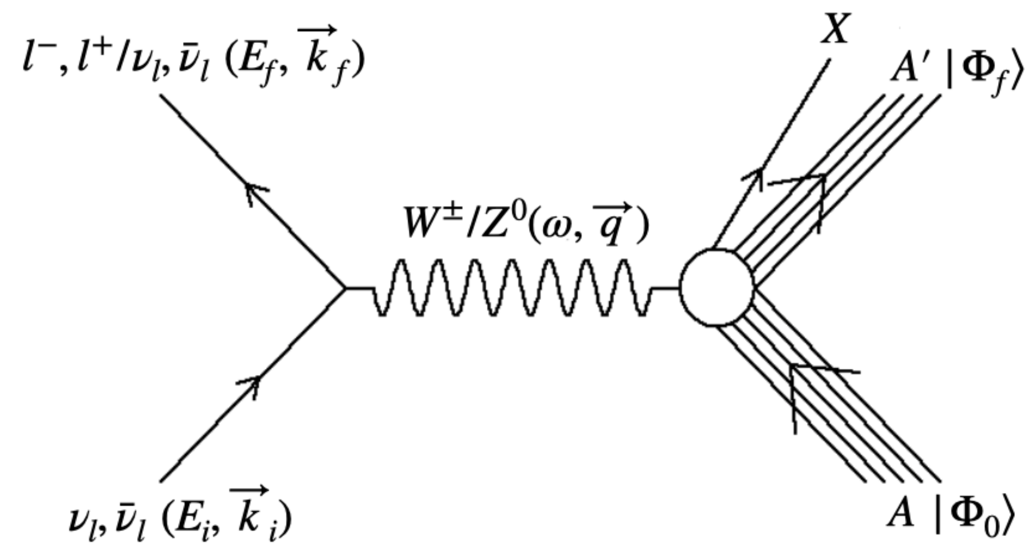

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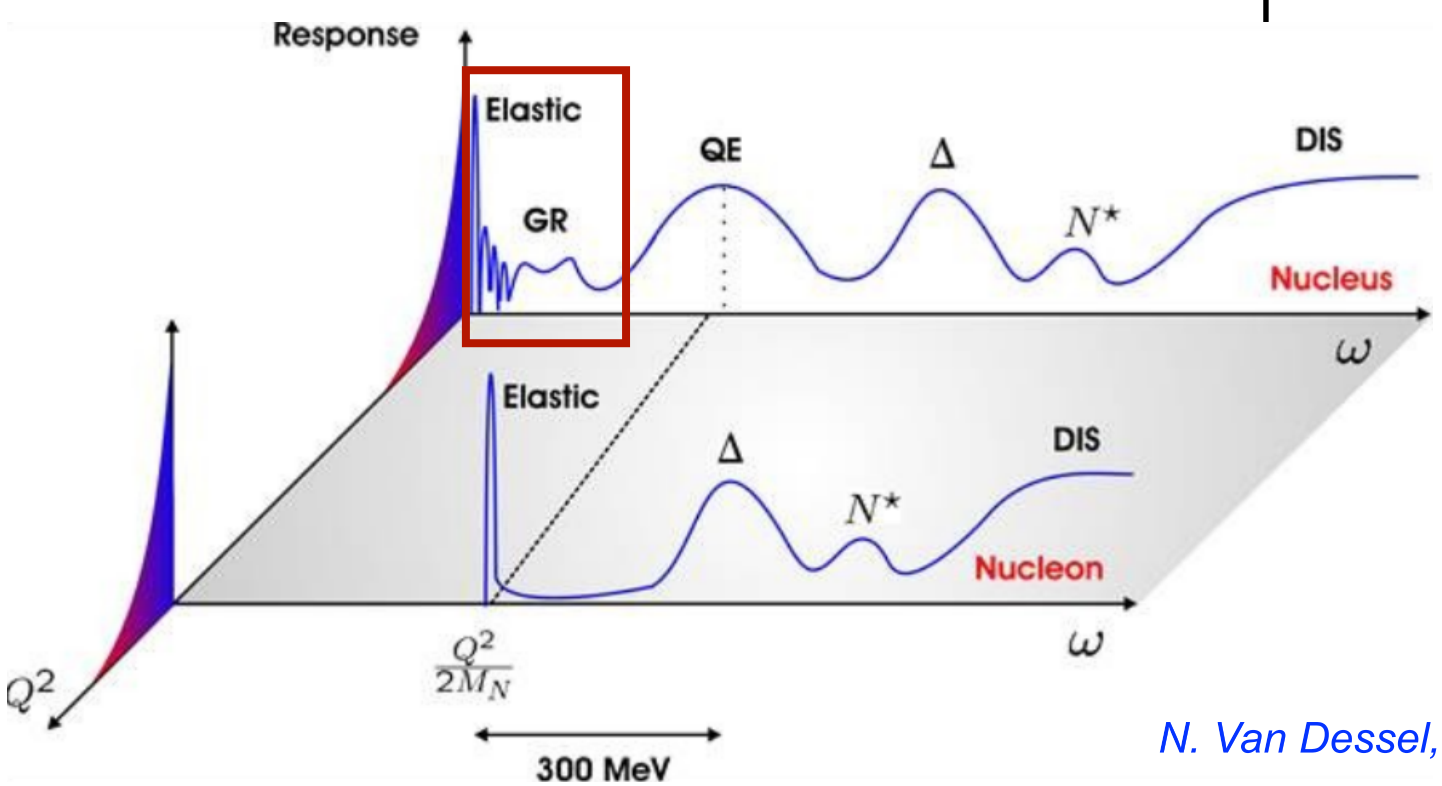

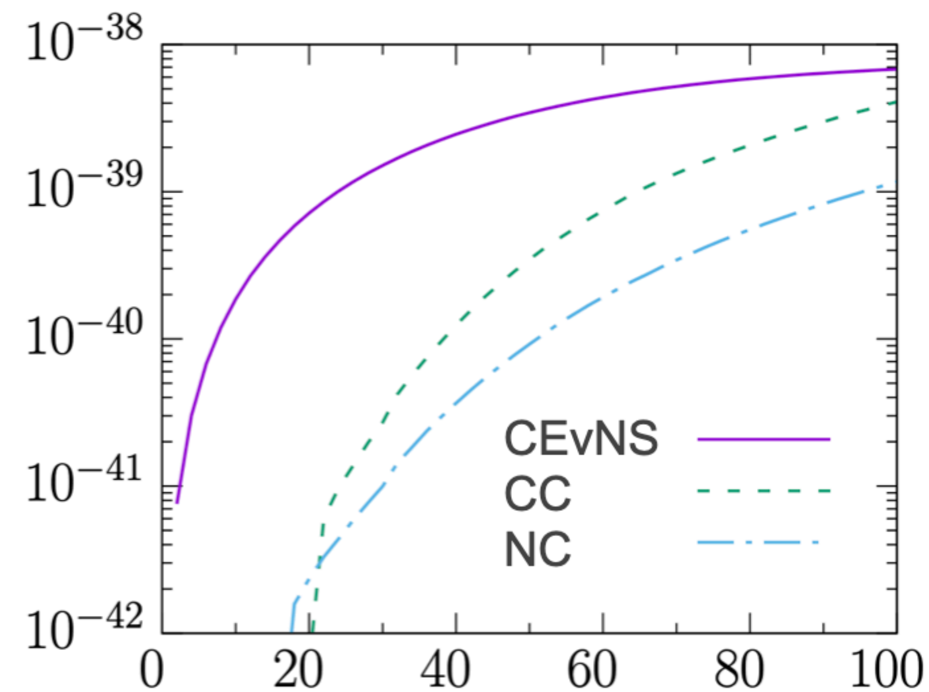

N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

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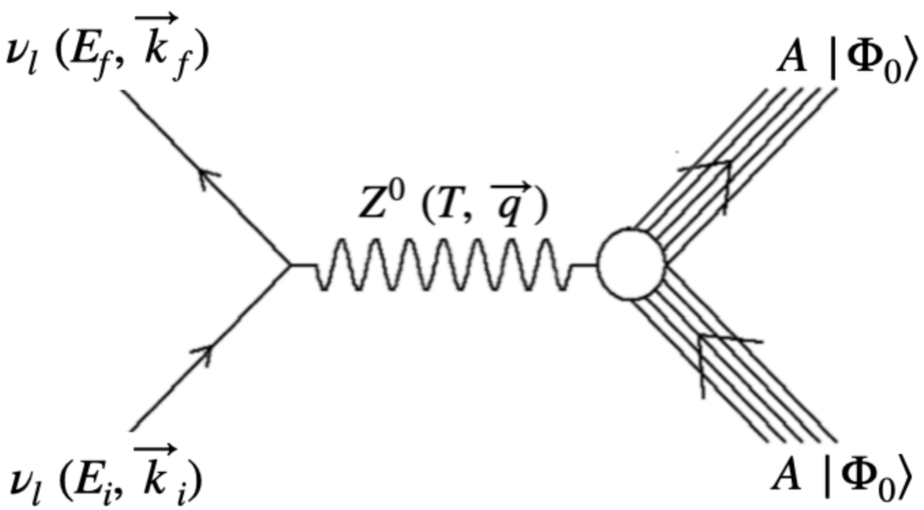

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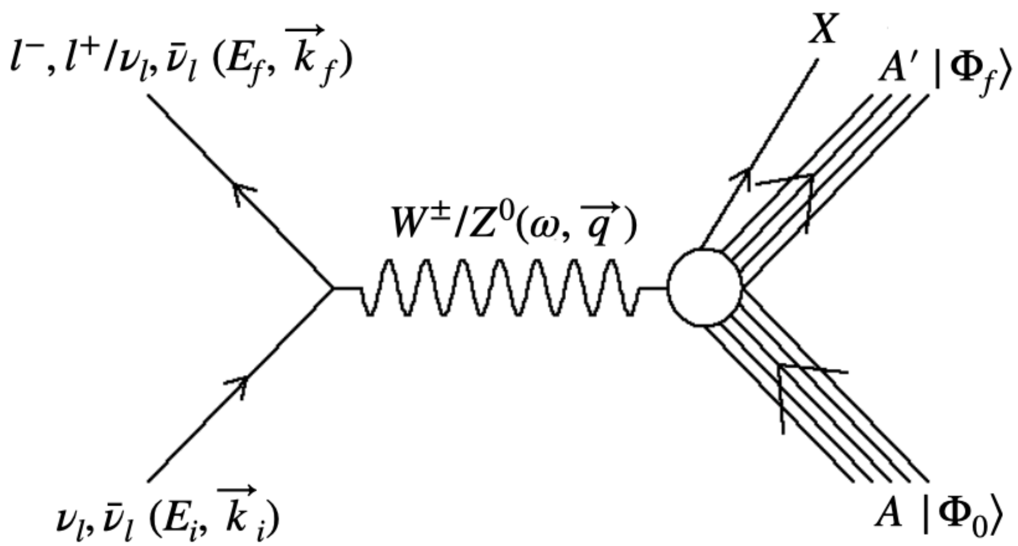

$$\sum_{fi} |\mathscr{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

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

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

Cross Section:

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

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

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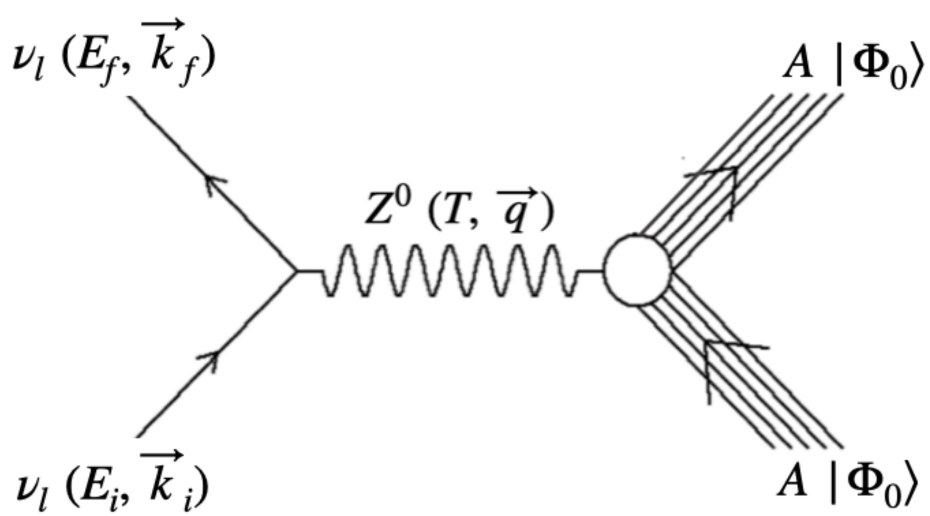

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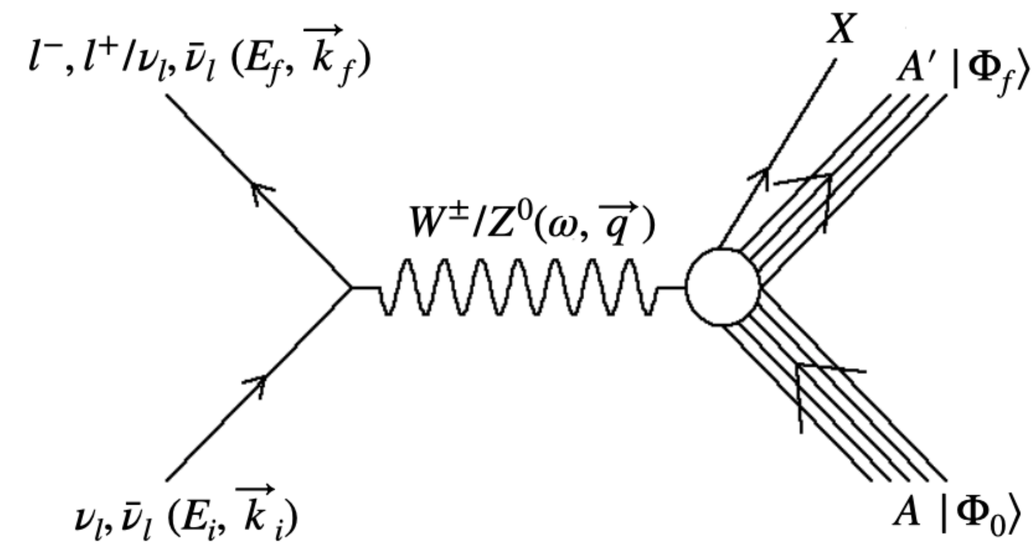

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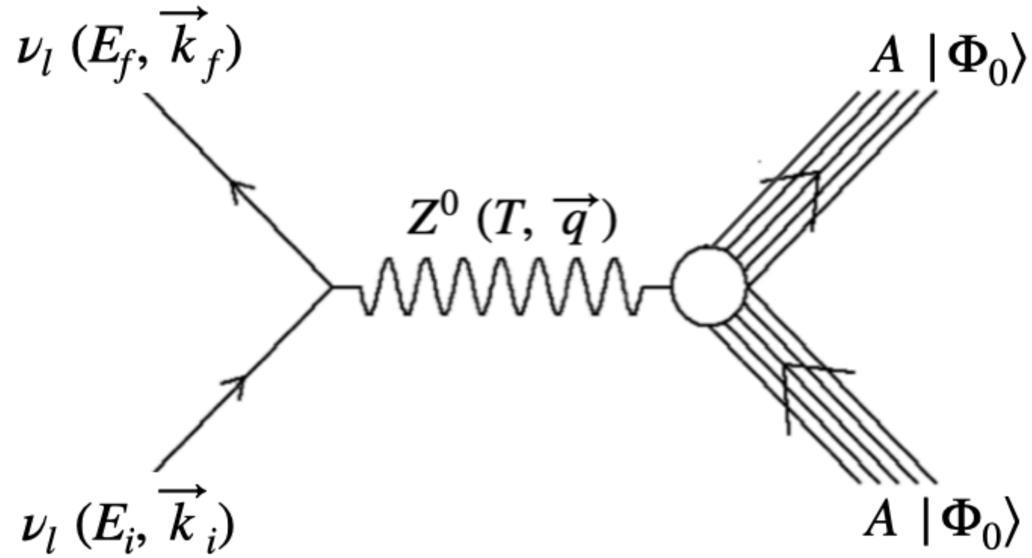
- **CEvNS cross section**, sensitive to nuclear weak form factor, need to be known at percent level precision to allows **resolving degeneracies in the standard and non-standard physics observables** in CEvNS experiments (e.g. COHERENT, CCM, ..).
- **Inelastic CC and NC cross sections**, subject to detailed underlying nuclear structure and dynamics, are poorly known but are vital in future neutrino experiments' (e.g. DUNE, HyperK, ..) capability of detecting **core-collapse supernovae**.

CEvNS Cross Section and Form Factors

- **Cross section***:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{\pi} M_A \left[1 - \frac{T}{E_i} - \frac{M_A T}{2E_i^2}\right] \frac{Q_W^2}{4} F_W^2(q)$$



- **Weak Form Factor**:

$$\begin{aligned} Q_W \, F_W(q) &\approx \langle \Phi_0 | \hat{J}_0(q) | \Phi_0 \rangle \\ &\approx \left(1 - 4\sin^2\theta_W\right) Z \, F_p(q) - N \, F_n(q) \\ &\approx 2\pi \int d^3r \, \left[(1 - 4\sin^2\theta_W) \, \rho_p(r) - \rho_n(r)\right] j_0(qr) \end{aligned}$$

$$T \in \left[0, \frac{2E_i^2}{(M_A + 2E_i)}\right]$$

$$Q_W^2 = [g_n^V N + g_p^V Z]^2$$

N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

Charge density and charge form factor: proton densities and charge form factors are well know through decades of elastic electron scattering experiments.

Neutron densities and neutron form factor: neutron densities and form factors are poorly known. Note that CEvNS is primarily sensitive to neutron density distributions $(1 - 4\sin^2\theta_W \approx 0)$.

*barring radiative corrections, for radiate corrections, see:

O. Tomalak, P. Machado, V. Pandey, R. Plestid, JHEP 02, 097 (2021)

CEvNS and PVES Experimental Measurements

- **Electroweak probes** such as parity–violating electron scattering (**PVES**) and **CEvNS** provide relatively model-independent ways of determining weak form factor and neutron distributions.
  - **CEvNS Cross Section**
  - **PVES Asymmetry**

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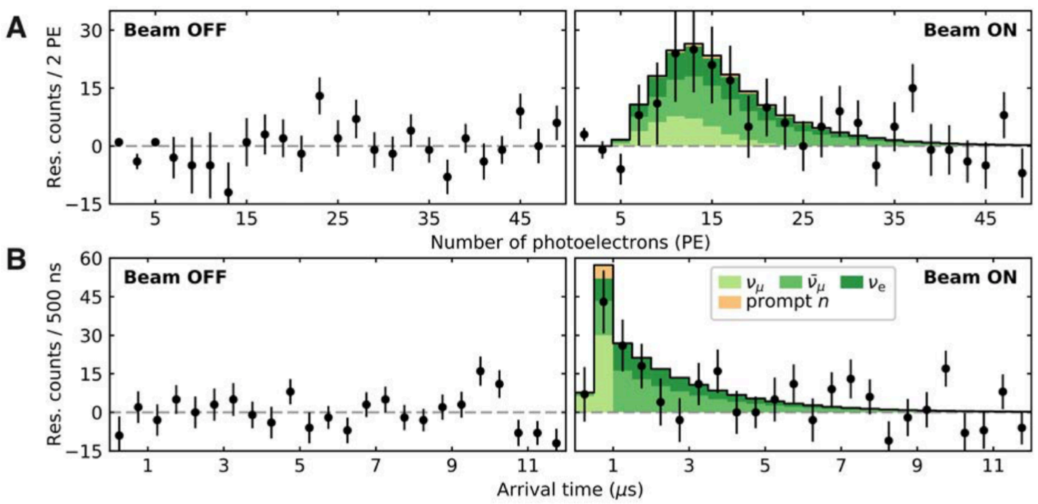
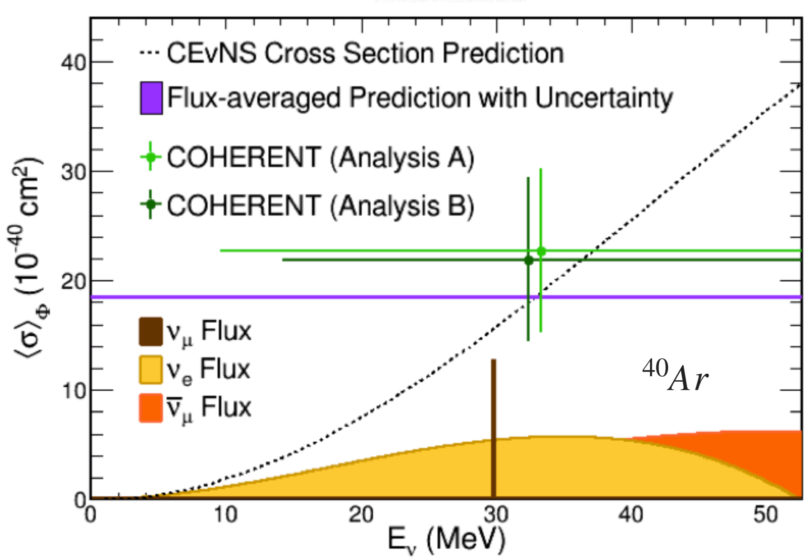
COHERENT Collaboration at SNS at ORNL





Science 357, 6356, 1123-1126 (2017)
Phys. Rev. Lett. 126, 012002 (2021)

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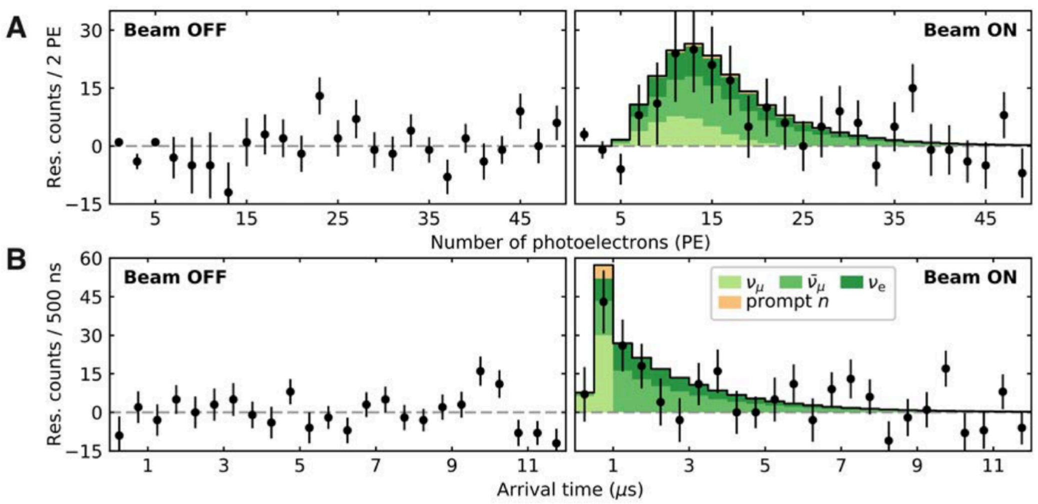

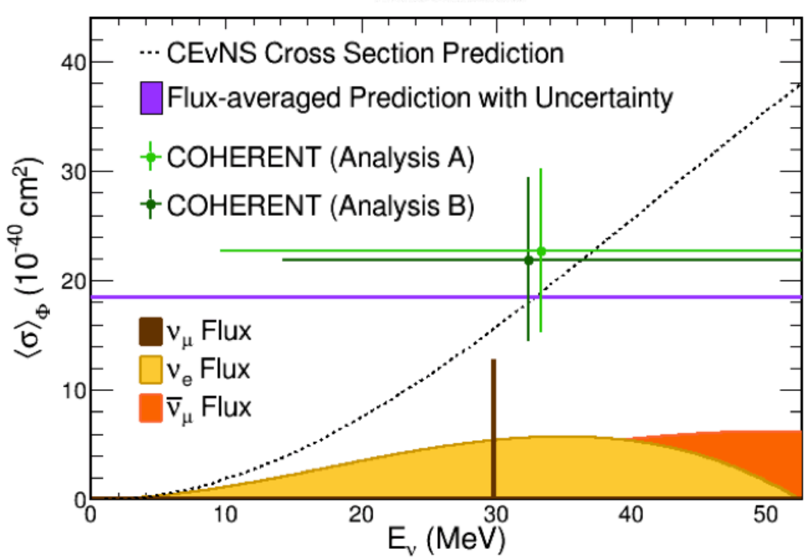

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• PVES Asymmetry

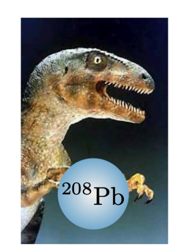
- The parity violating asymmetry for elastic electron scattering is the fractional difference in cross section for positive helicity and negative helicity electrons.

$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-} = \frac{G_F q^2 |Q_W|}{4\pi\alpha\sqrt{2}Z} \frac{F_W(q)}{F_{ch}(q^2)}$$

- Here F_{ch} is the charge form factor that is typically known from unpolarized electron scattering. Therefore, one can extract F_W from the measurement of A_{PV}.

Experiment	Target	q^2 (GeV^2)	A_{pv} (ppm)	$\pm\delta R_n$ (%)
PREX	^{208}Pb	0.00616	0.550 ± 0.018	1.3
CREX	^{48}Ca	0.0297		0.7
Qweak	^{27}Al	0.0236	2.16 ± 0.19	4
MREX	^{208}Pb	0.0073		0.52

arXiv:2203.06853 [hep-ex]



Pb Radius Experiment (PREX)

Calcium Radius Experiment (CREX)

MREX

Mainz Radius Experiment (MREX)
At P2 experimental hall with ^{208}Pb

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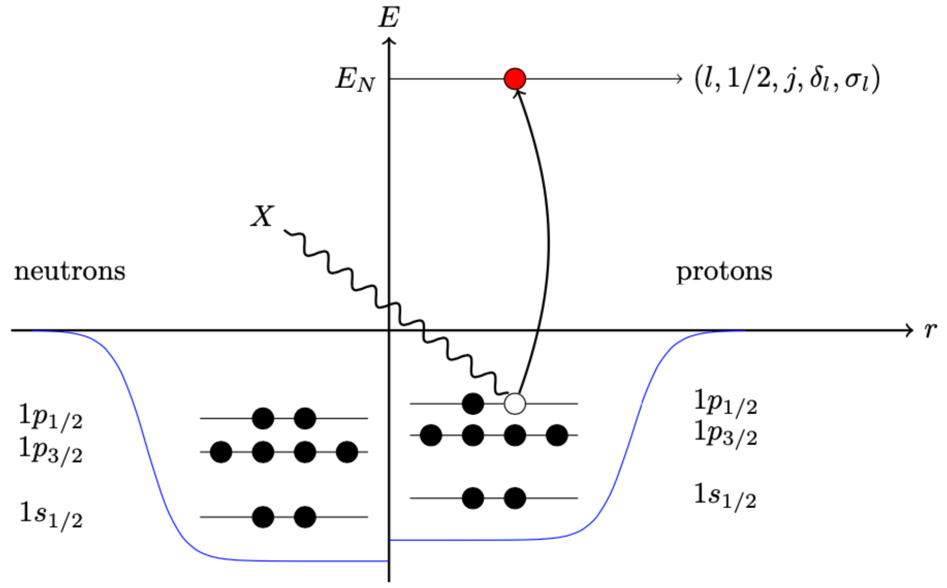
CEvNS Cross Section Calculations

- Nuclear ground state described as a many-body quantum mechanical system where nucleons are bound in an effective nuclear potential.
- Solve Hartree-Fock (**HF**) equation with a Skyrme (**SkE2**) nuclear potential to obtain single–nucleon wave functions for the bound nucleons in the nuclear ground state.
- Evaluate proton and neutron density distributions and form factors



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$$(\alpha \in n_\alpha, l_\alpha, j_\alpha)$$

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N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

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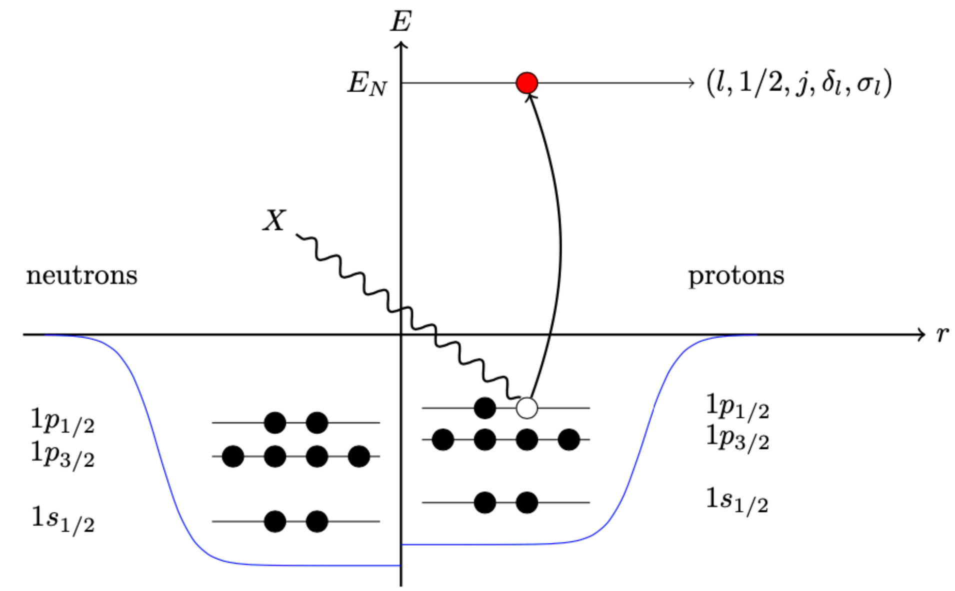

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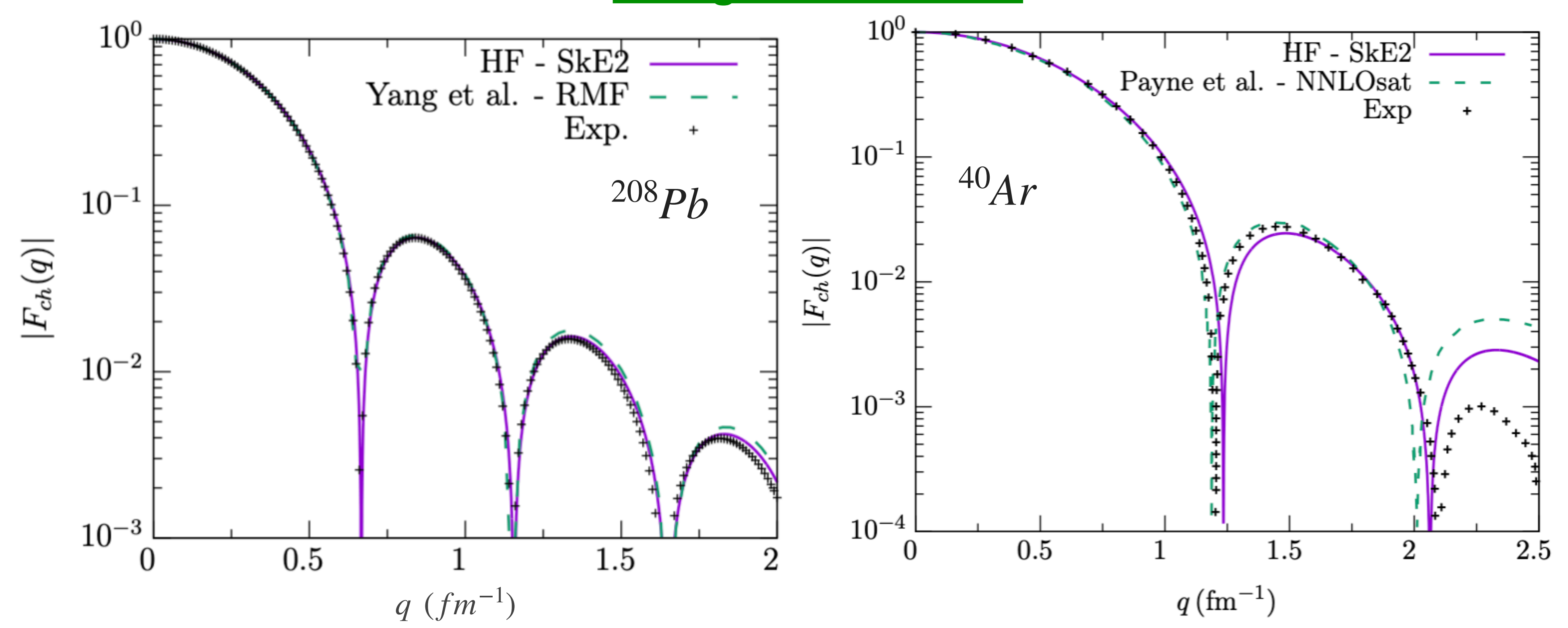
Charge Form Factor



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Data: H. De Vries, et al., Atom. Data Nucl. Data Tabl. 36, 495 (1987), C. R. Ottermann et al., Nucl. Phys. A 379, 396 (1982)

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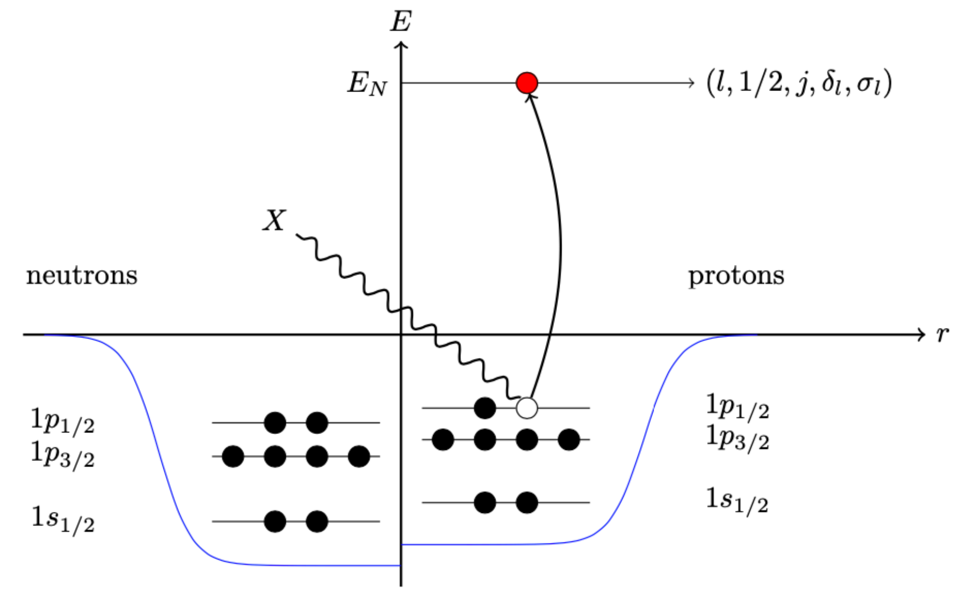

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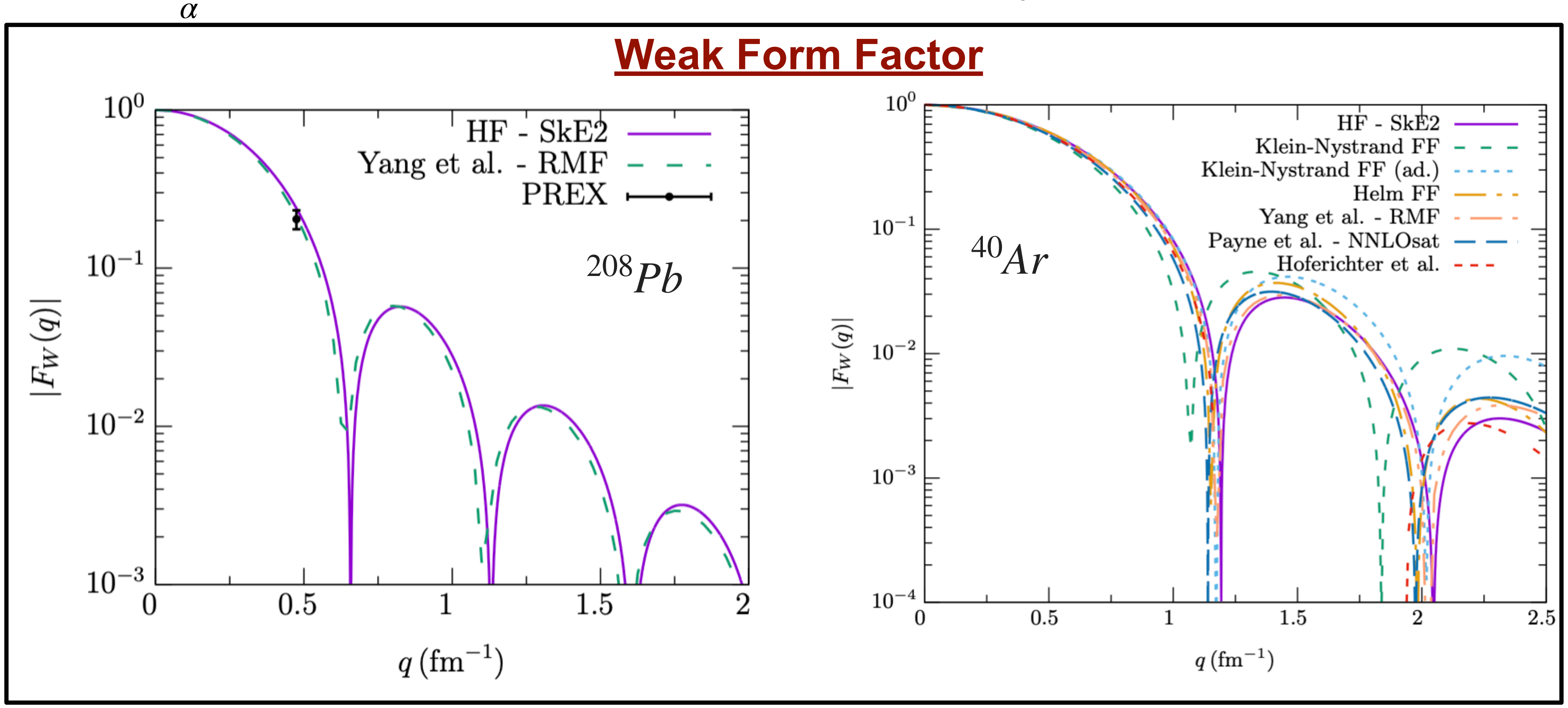

N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

Data: S. Abrahamyan et al., Phys. Rev. Lett. 108, 112502 (2012)

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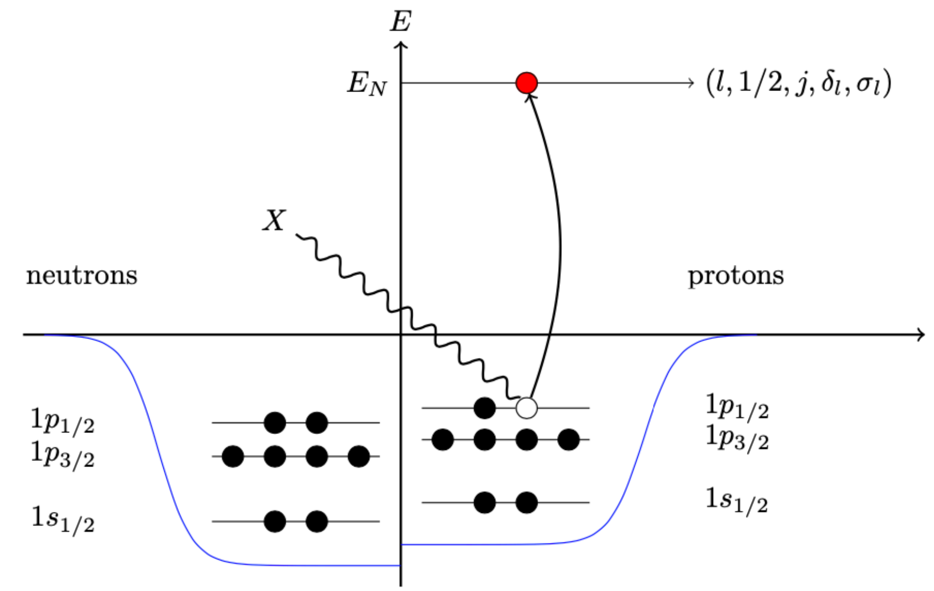

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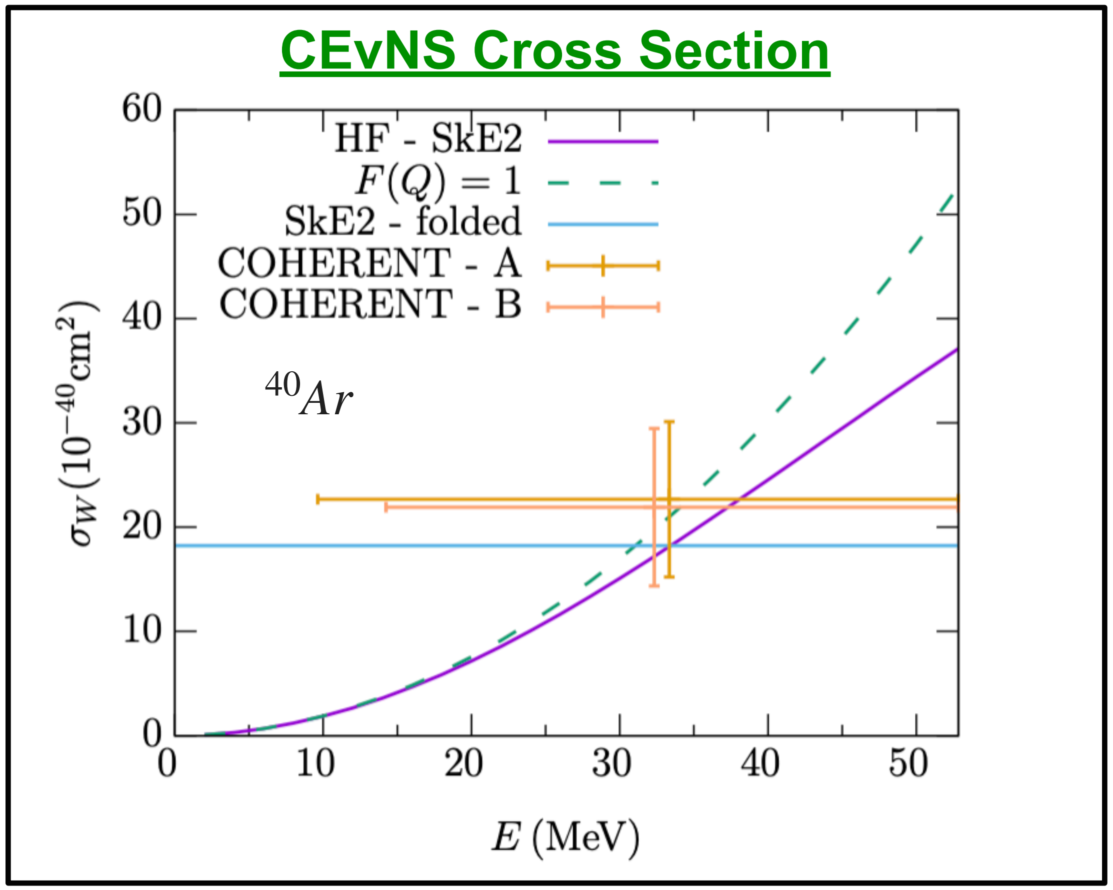

N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

COHERENT data: arXiv:2003.10630 [nucl-ex].

Constraining ^{40}Ar form factor and CEvNS cross section

- Comparison of ^{40}Ar form factor predictions from four nuclear theory and three phenomenological calculations.
  - *The HF–SkE2 model [arXiv:2007.03658 [nucl-th].*
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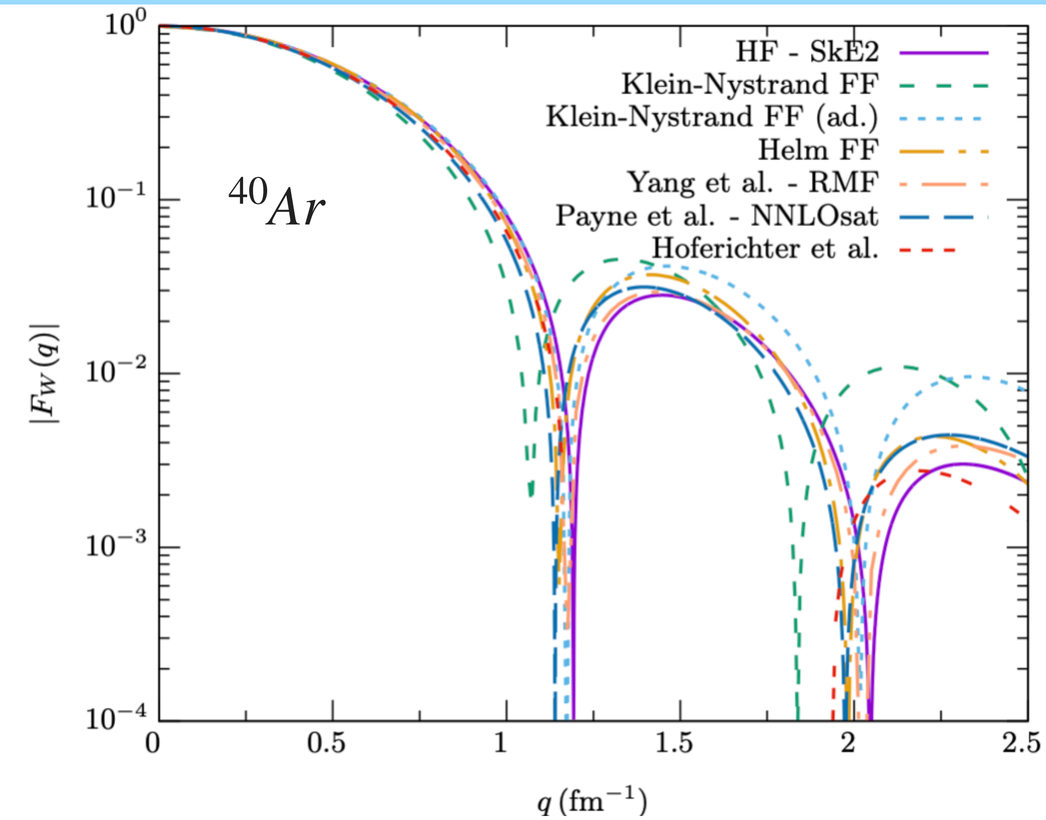

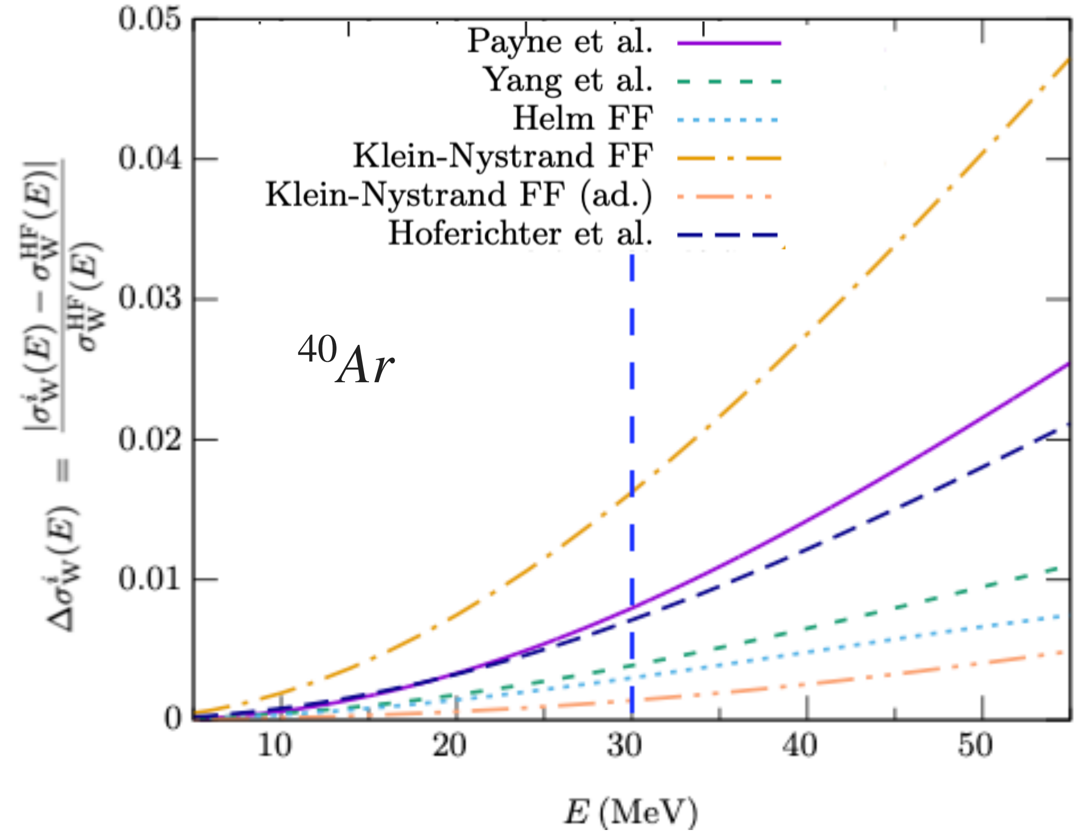

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  - *Model of Hoferichter et al. [Phys. Rev. D 102, 074018 (2020)] where form factors are calculated within a large-scale nuclear shell model.*
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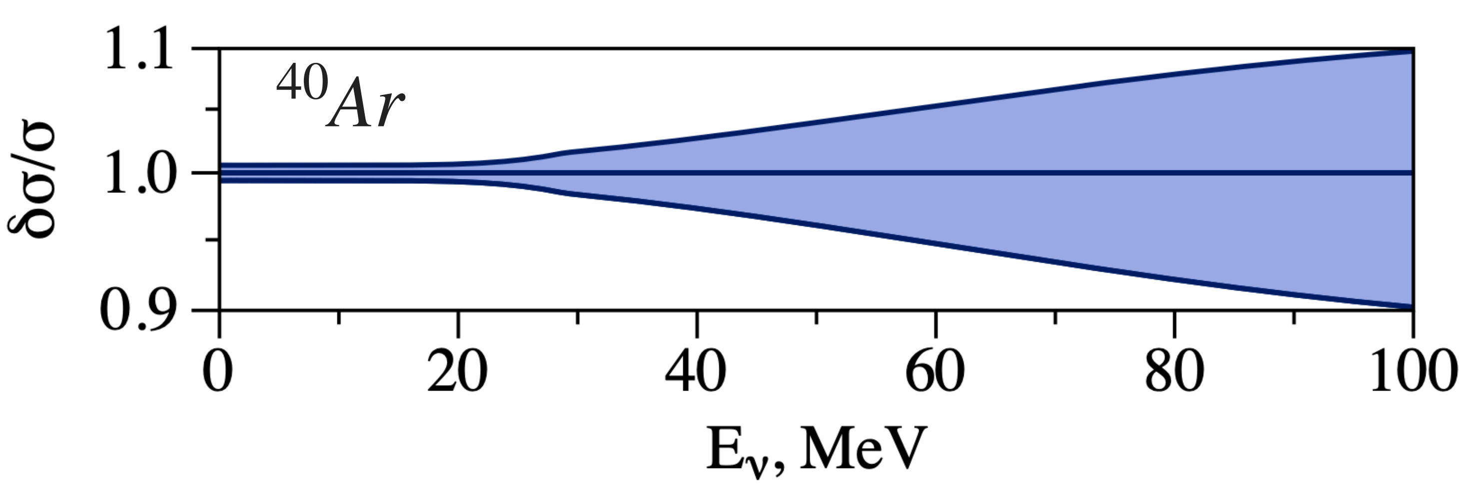
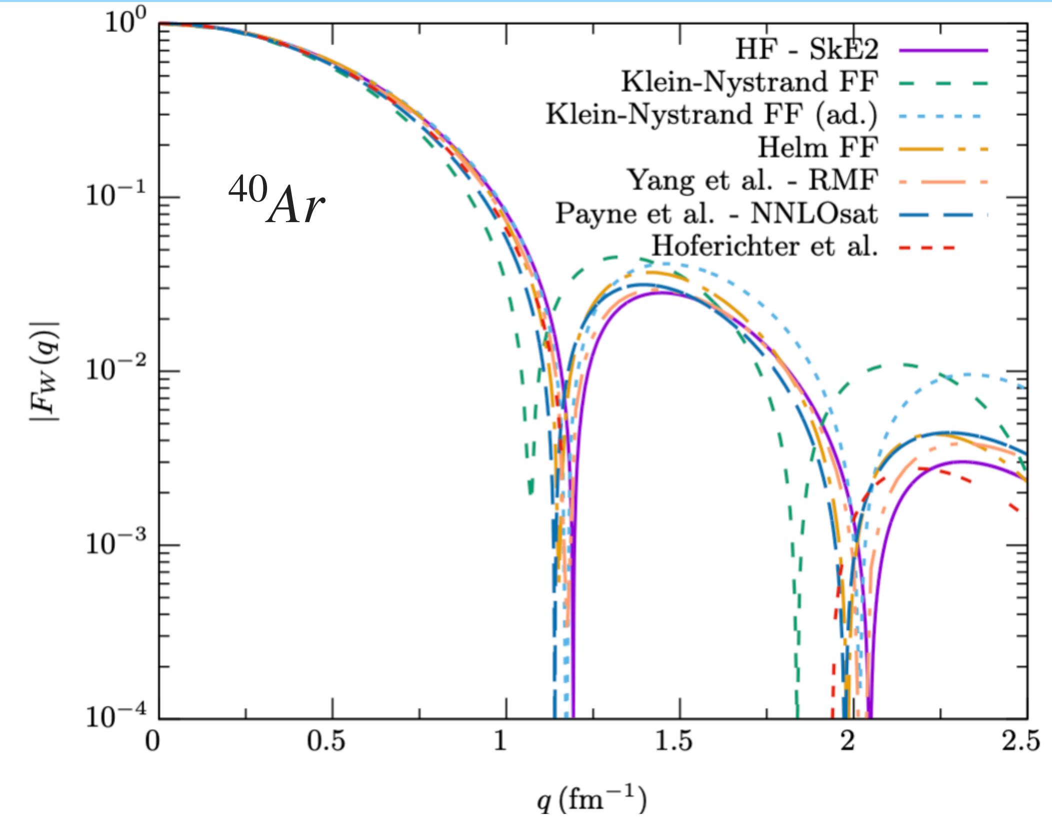
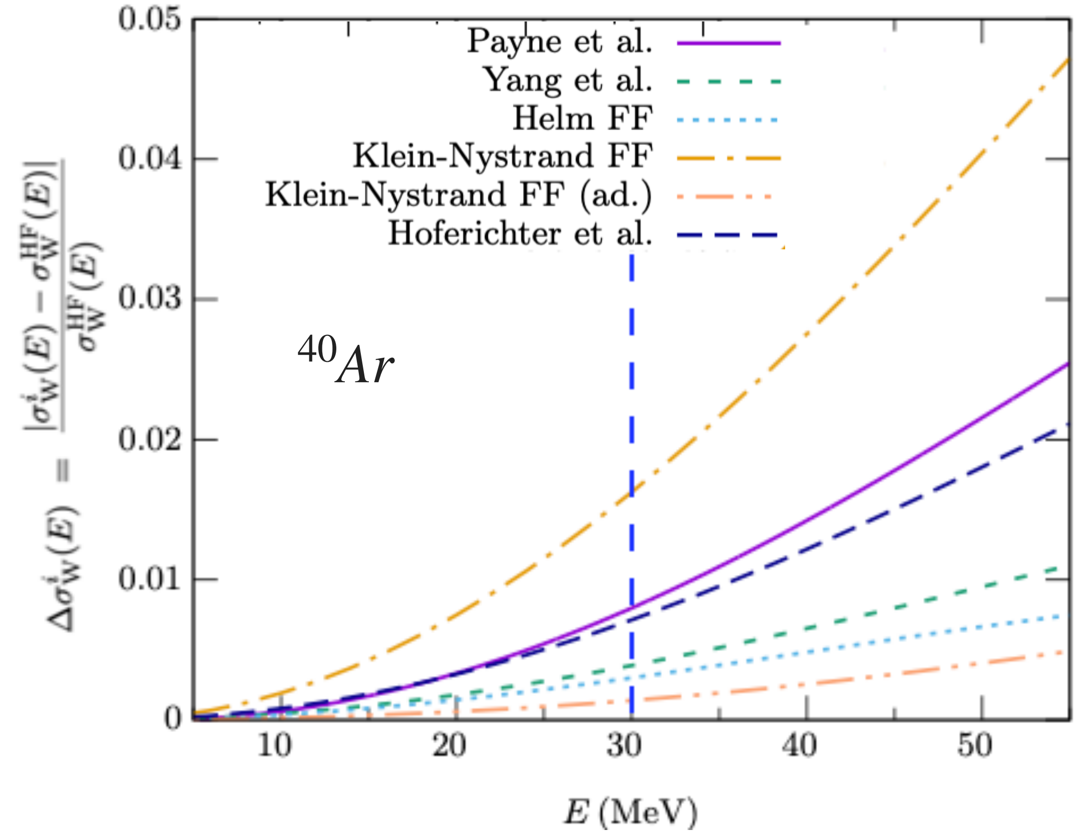
- Relative CEvNS cross section theoretical uncertainty on ^{40}Ar (includes nuclear, nucleonic, hadronic, quark levels as well as perturbative errors):



O. Tomalak, P. Machado, V. Pandey, R. Plestid, JHEP 02, 097 (2021)

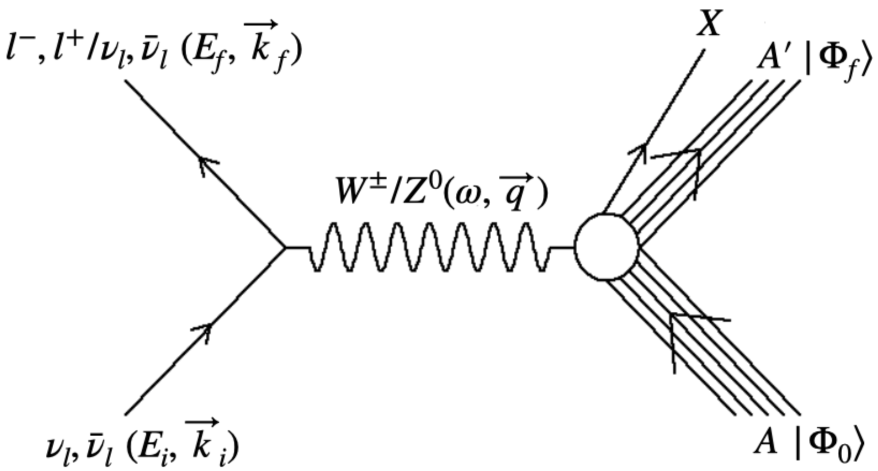




N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

10s of MeV Inelastic Neutrino-Nucleus Scattering

- **Core-collapse supernova** can be detected (in DUNE, HyperK) using e.g. charge current inelastic neutrino-nucleus scattering process.
- These 10s of MeV neutrinos inelastically scatter off the nucleus, exciting nucleus to its low-lying excitation states, subject to nuclear structure physics.
- The inelastic neutrino-nucleus cross sections are quite poorly understood. There are very few existing measurements, none at better than the 10% uncertainty level. As a result, the uncertainties on the theoretical calculations of, e.g., neutrino-argon cross sections are not well quantified at all at these energies.



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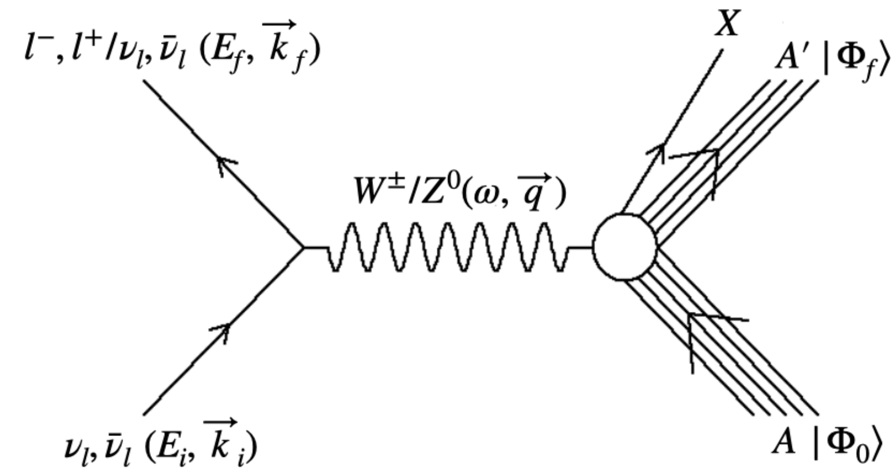
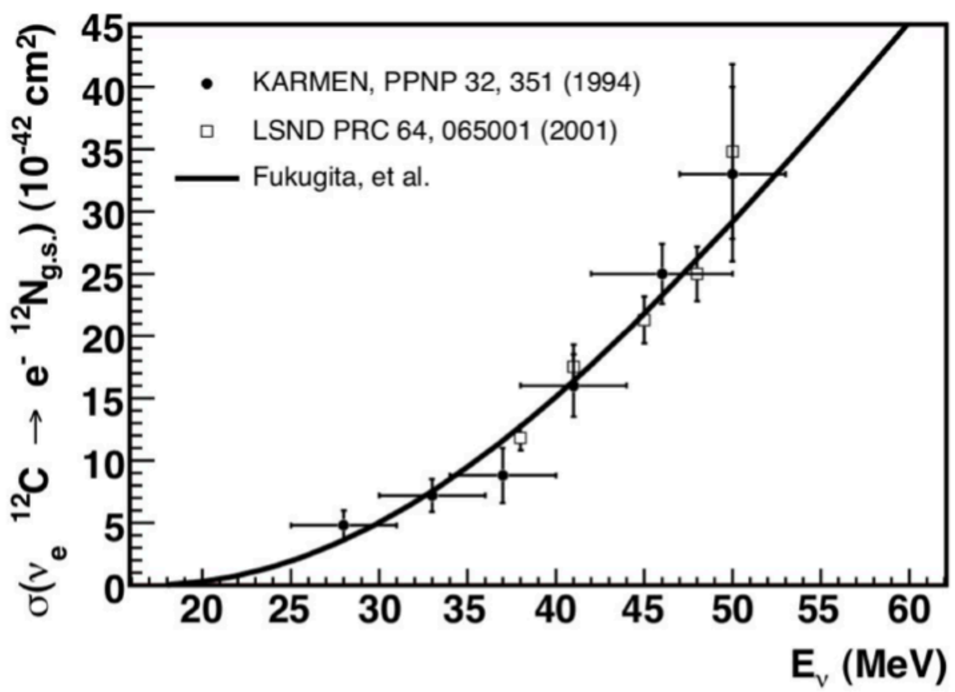
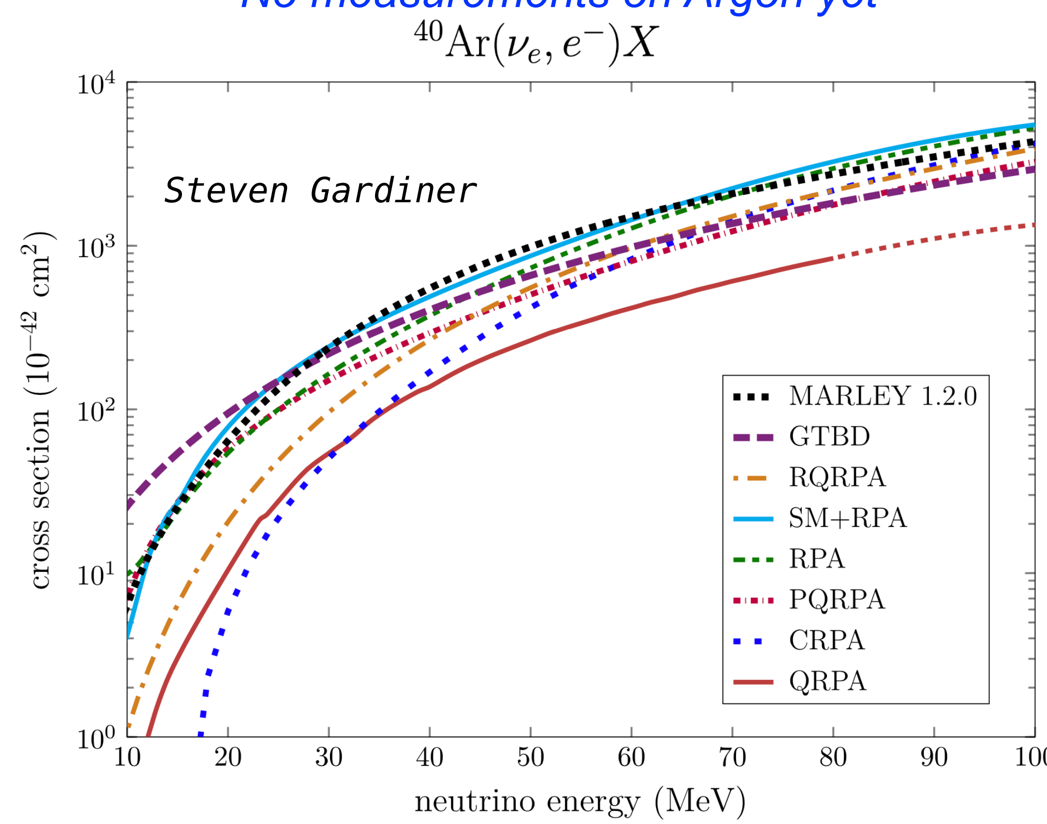


Past measurements on Carbon



Rev. Mod. Phys. 84,1307 (2012)

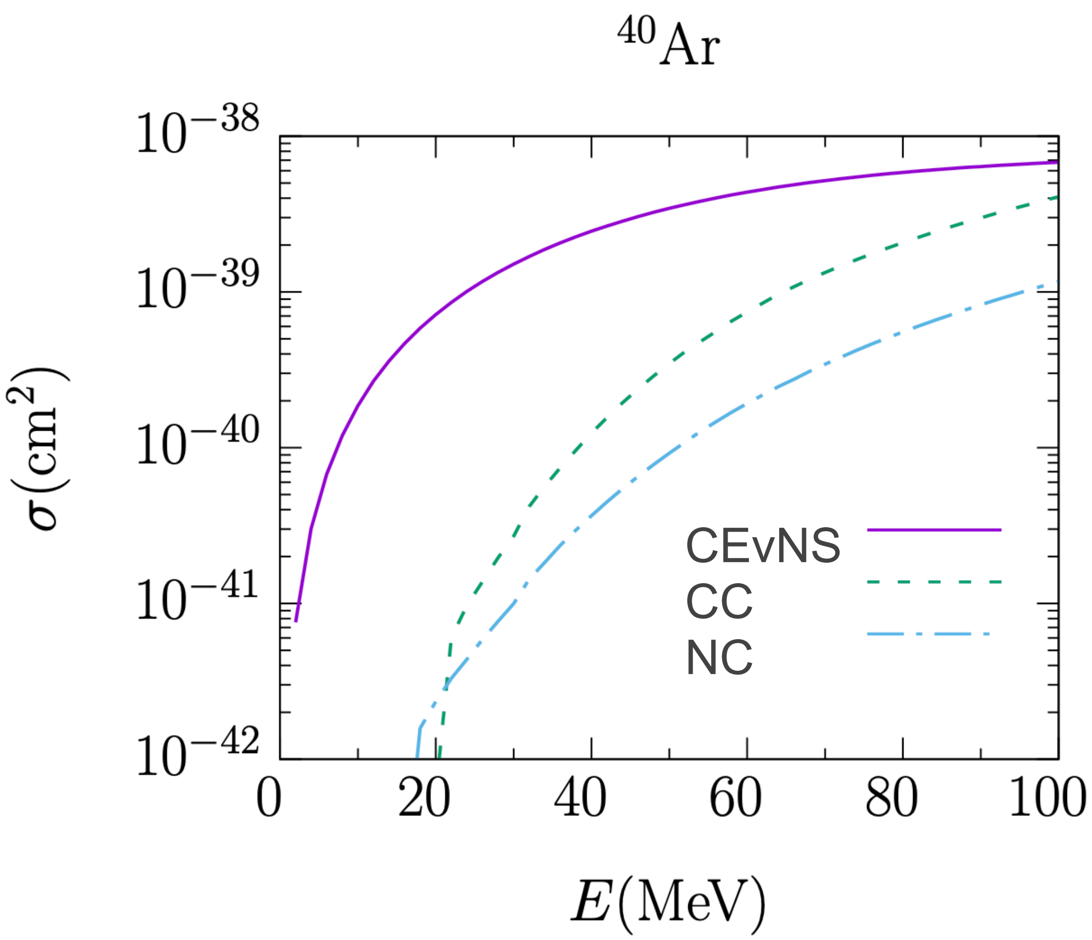
No measurements on Argon yet



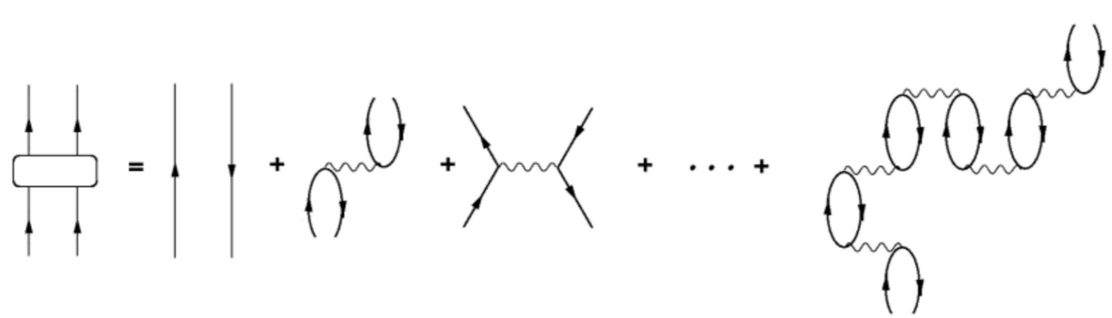
- CEvNS experiments at pion-decay at rest facilities - COHERENT at ORNL and CCM at LANL, well suited to perform these measurements.

10s of MeV Inelastic Neutrino-Nucleus Scattering Calculations

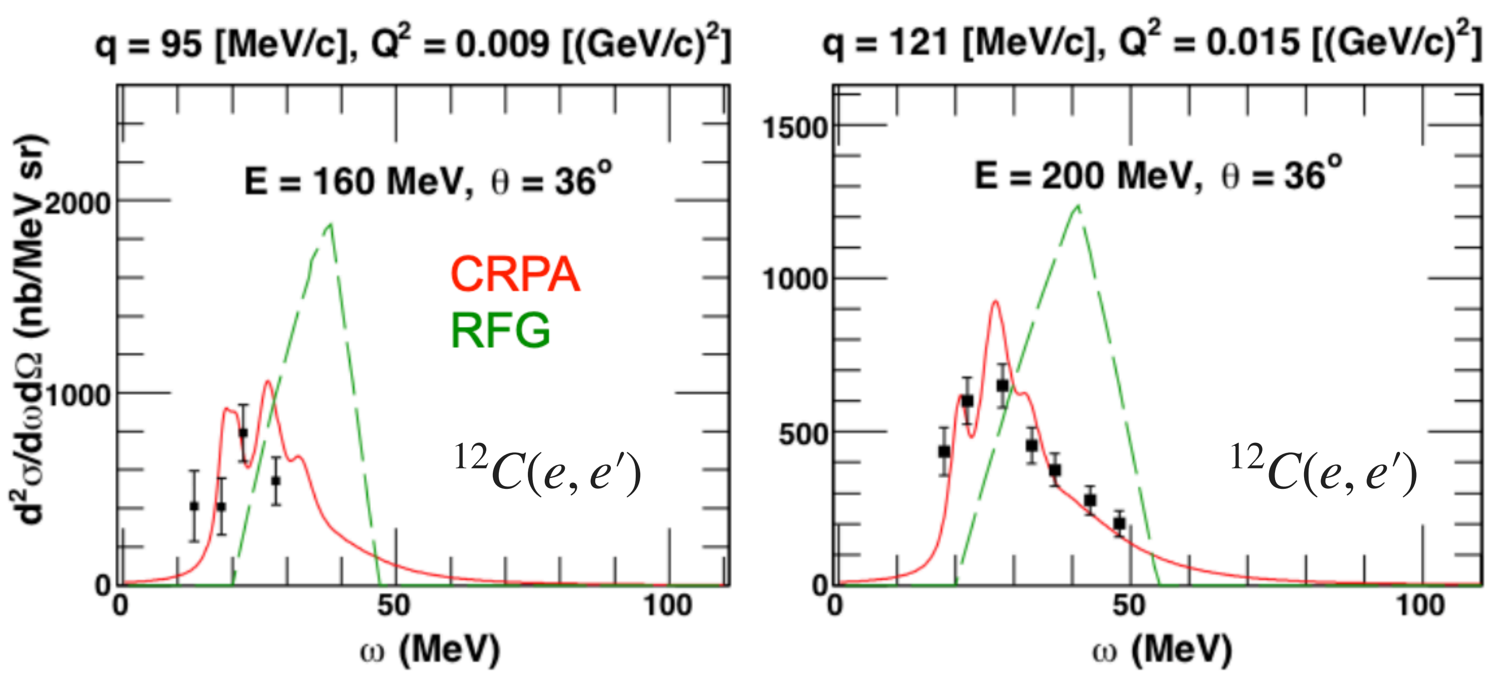
- In the inelastic cross section calculations, the influence of long-range correlations between the nucleons is introduced through the continuum Random Phase Approximation (CRPA) on top of the HF-SkE2 approach.
- CRPA effects are vital to describe the process where the nucleus can be excited to low-lying collective nuclear states.
- 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.



$$\Pi^{(RPA)}(x_1, x_2; E_x) = \Pi^{(0)}(x_1, x_2; E_x) + \frac{1}{\hbar}\int dx dx' \; \Pi^0(x_1, x; E_x) \times \tilde{V}(x, x') \; \Pi^{(RPA)}(x', x_2; E_x)$$



Comparison with electron scattering data



Fermilab

10s of MeV Inelastic Neutrino-Nucleus Scattering Calculations

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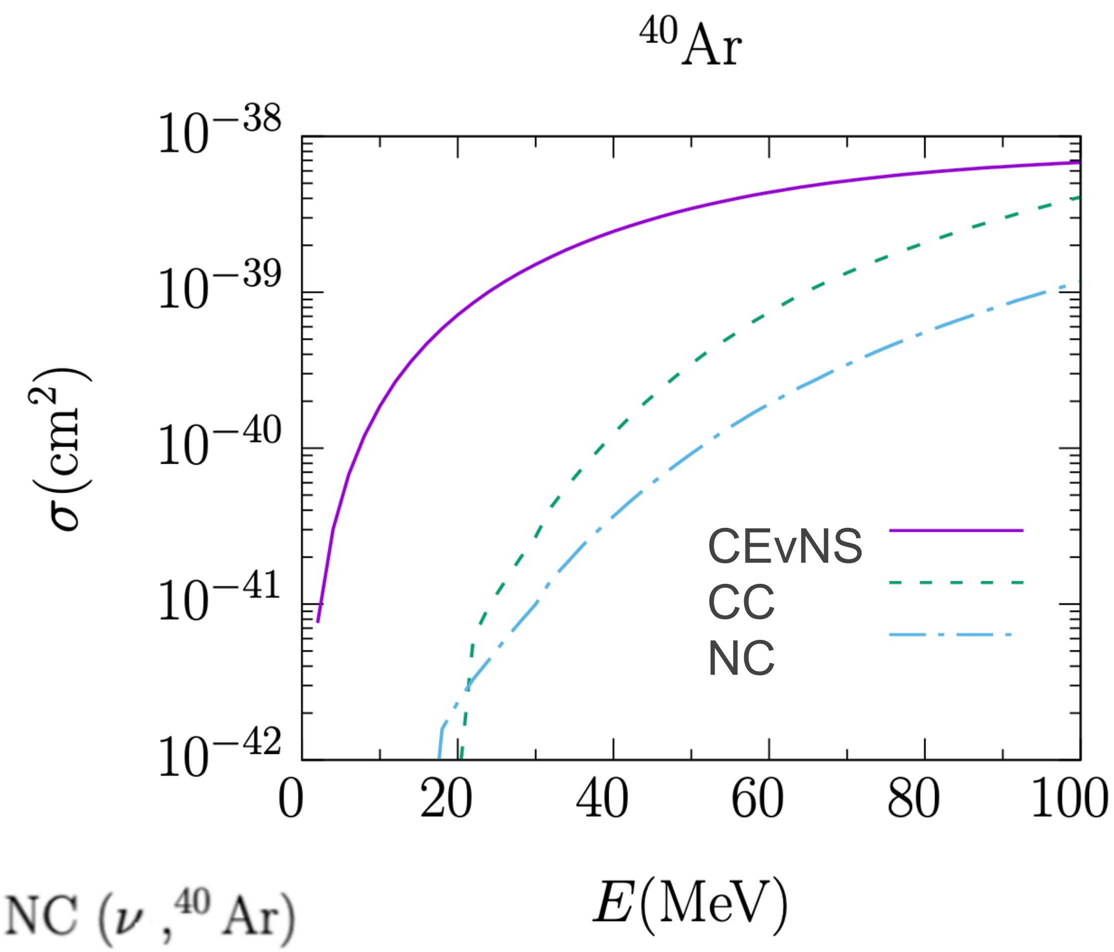
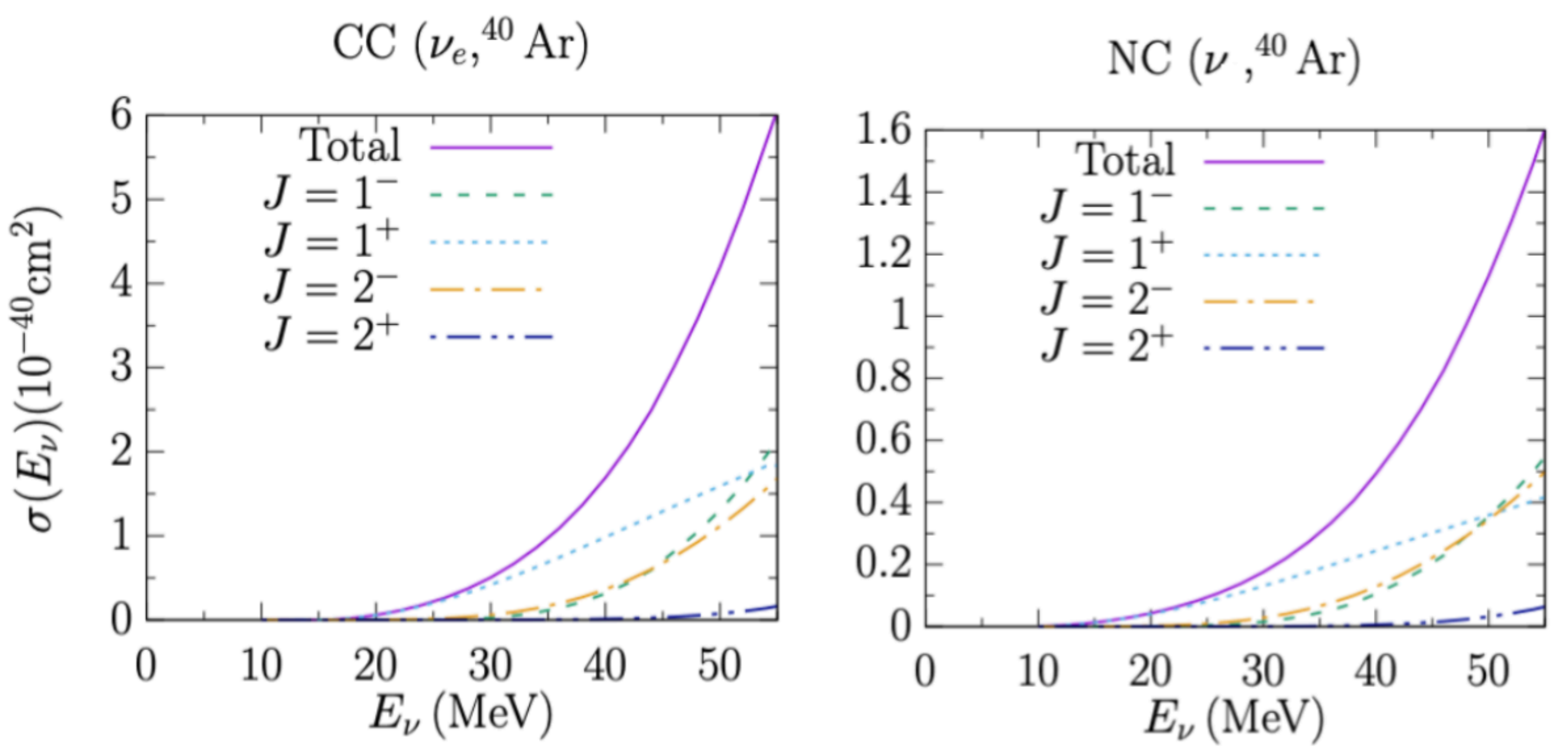


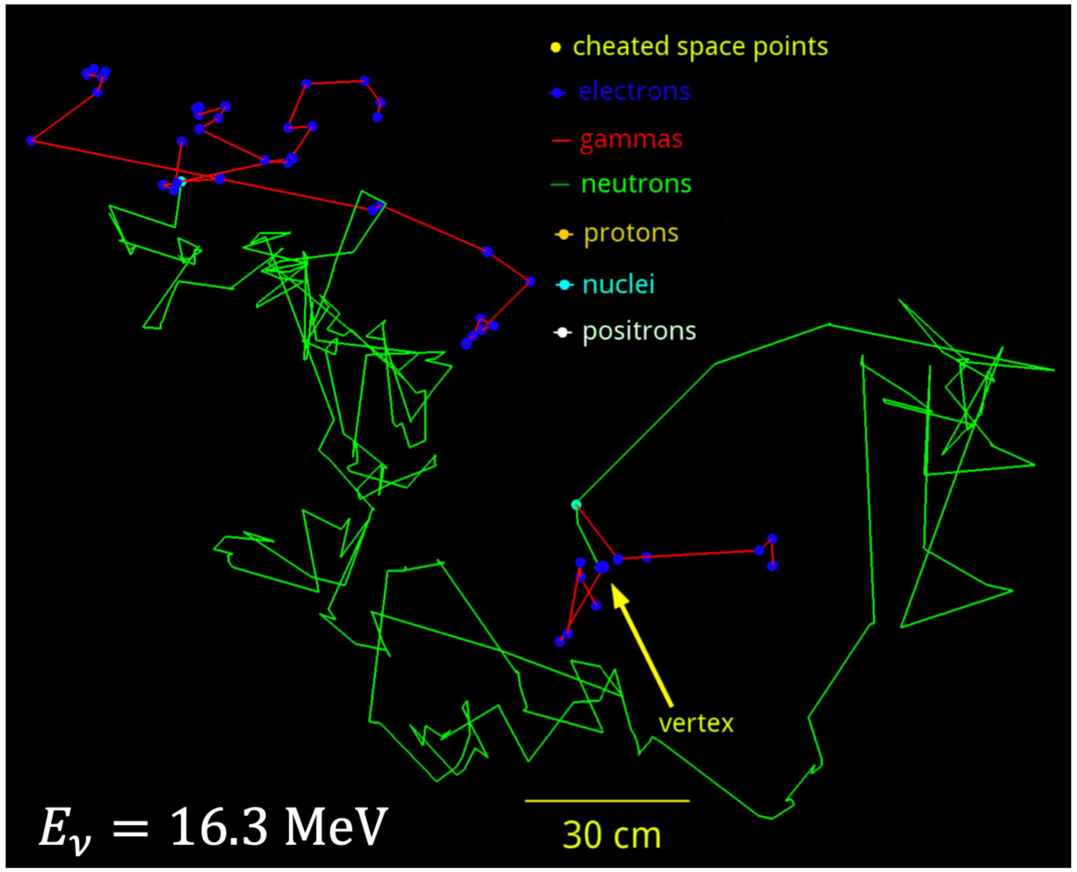


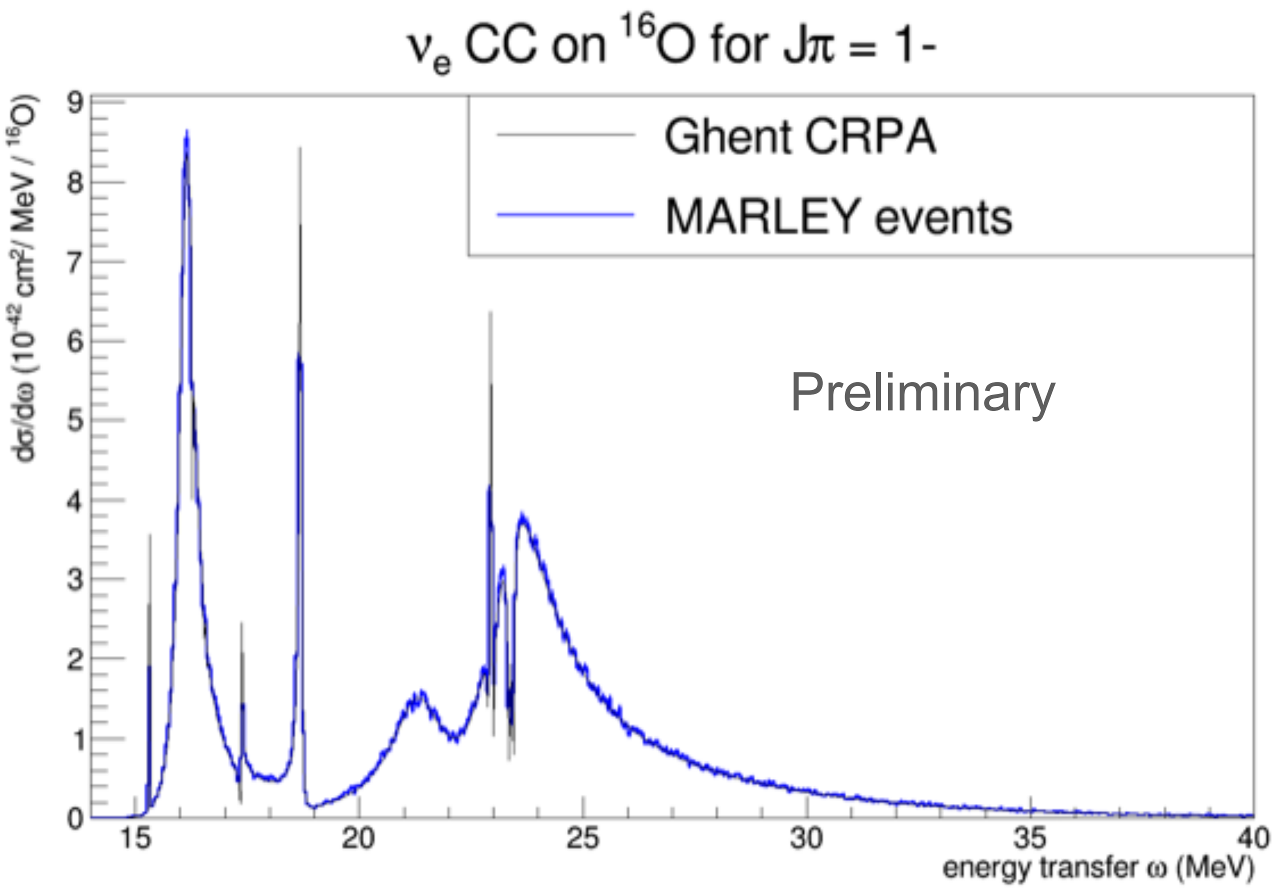
10s of MeV Inelastic Neutrino-Nucleus Scattering: Model in Generators

- Model recently implemented in GENIE.

  S. Dolan, A. Nikolakopoulos, O. Page, S. Gardiner, N. Jachowicz and V. Pandey, arXiv:2110.14601 [hep-ex].

- Model implementation in MARLEY (low-energy generator used by DUNE) is currently on-going, in collaboration with Steven Gardiner (FNAL) (sole author of MARLEY).





arXiv:2008.06647 [hep-ex] [DUNE Collaboration]

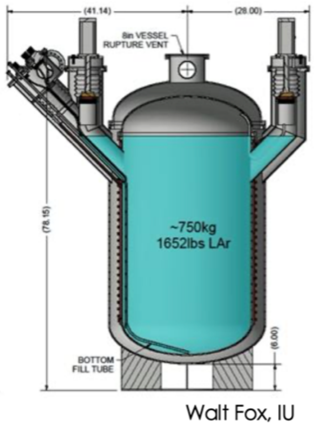
- MARLEY includes allowed approximation (long–wavelength ($q \to 0$) and slow nucleons ($p_N/m_N \to 0$) limit), Fermi and Gamow-Teller matrix elements. CRPA includes full expansion of nuclear matrix element (allowed as well as forbidden transition).

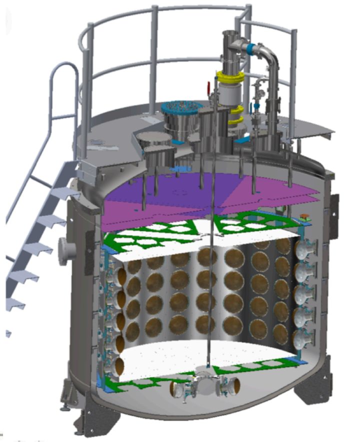
- **COHERENT at SNS:** COH-Ar-10 (24kg) LAr detector. COH-Ar-750 (750 kg) LAr detector is underway.

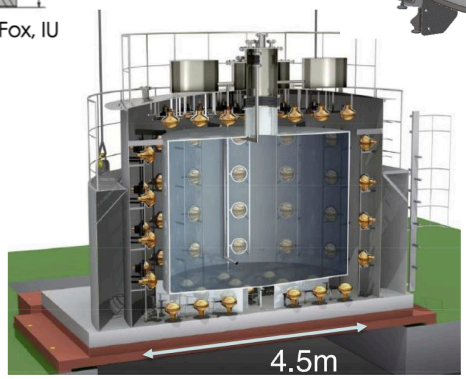
  Iodine (NaIvE) and Pb, Fe, Cu (NIN cubes) detectors.

- **Coherent CAPTAIN Mills at LANL:** 10 ton LAr detector at Lujan center at LANL. Collected data in 2019 and 2021, currently in operation.

- **JSNS² at JPARC-MLF:** 50 ton gd-loaded LS detector.

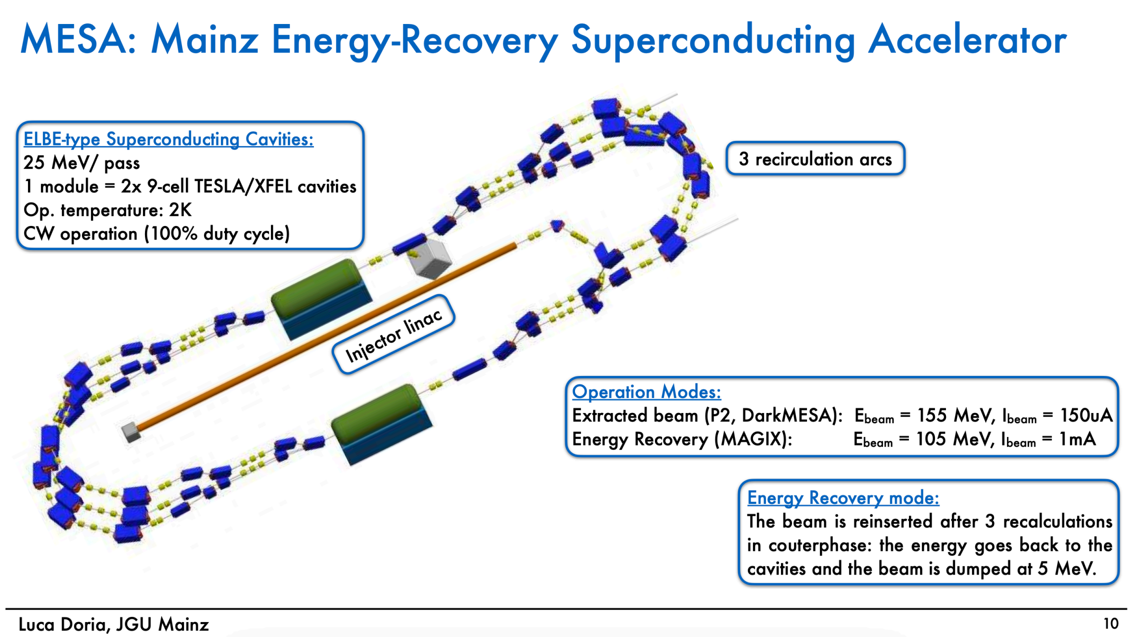






- **Electron Scattering experiment**

  - MAGIX Collaboration at MESA (Mainz): MESA, a new cw multi-turn energy recovery linac for precision particle and nuclear physics experiments with a beam energy range of 100-200 MeV is currently being built.

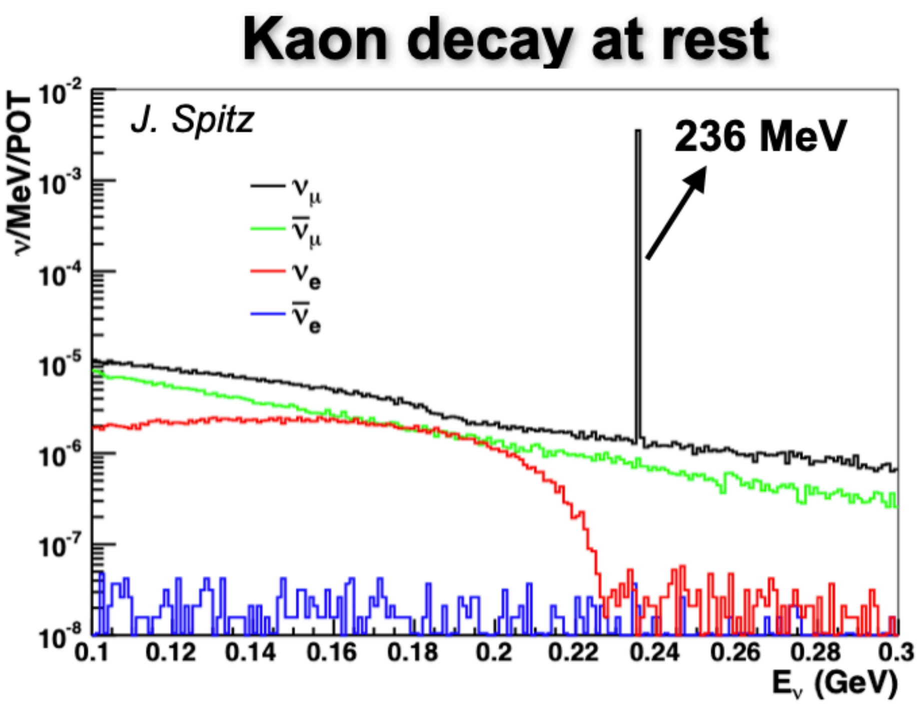


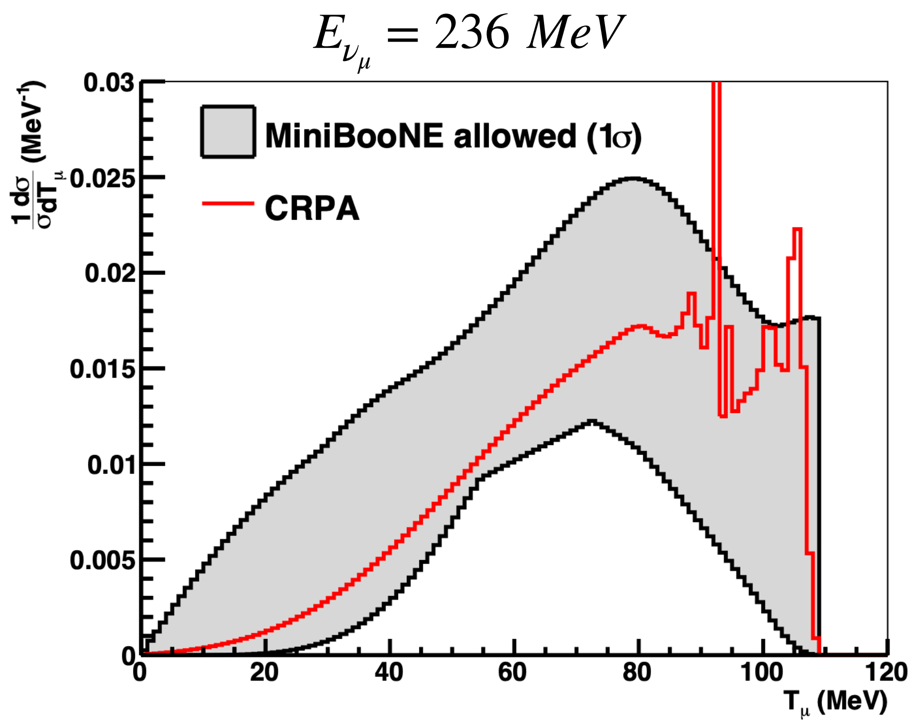
Luca Doria at a Snowmass workshop

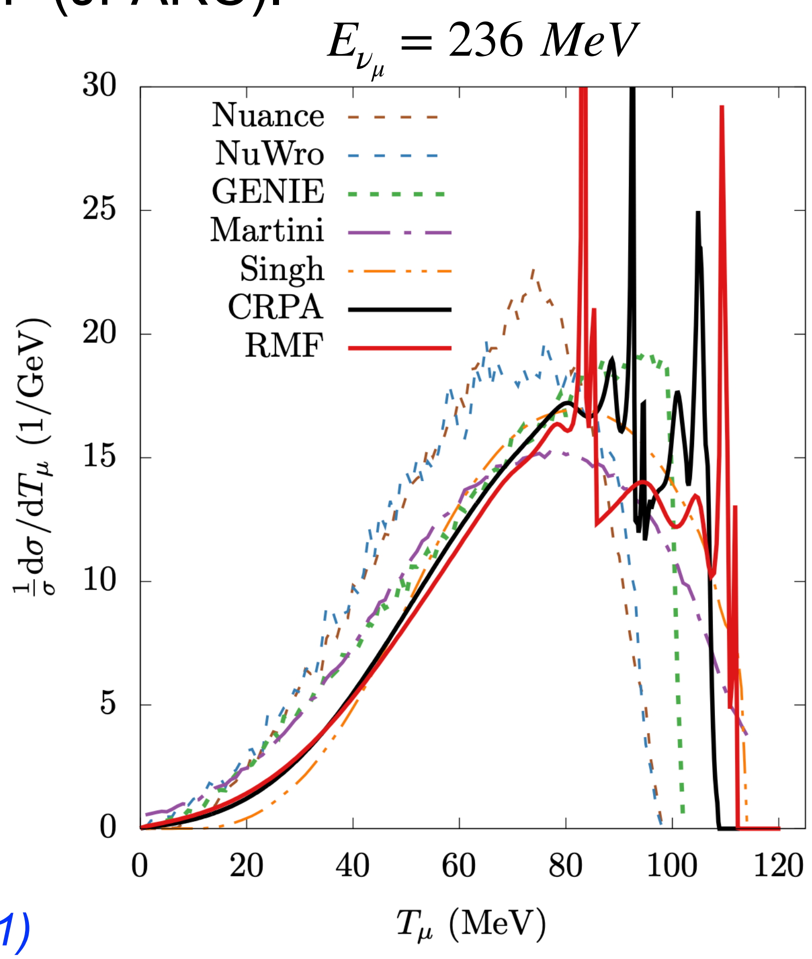
Mono-energetic KDAR Neutrinos

- Mono-energetic KDAR neutrinos at NuMI beam dump (FNAL) and at MLF (JPARC).

$$K^+ \rightarrow \mu^+ \nu_\mu,\ E_{\nu_\mu} = 236\ MeV$$



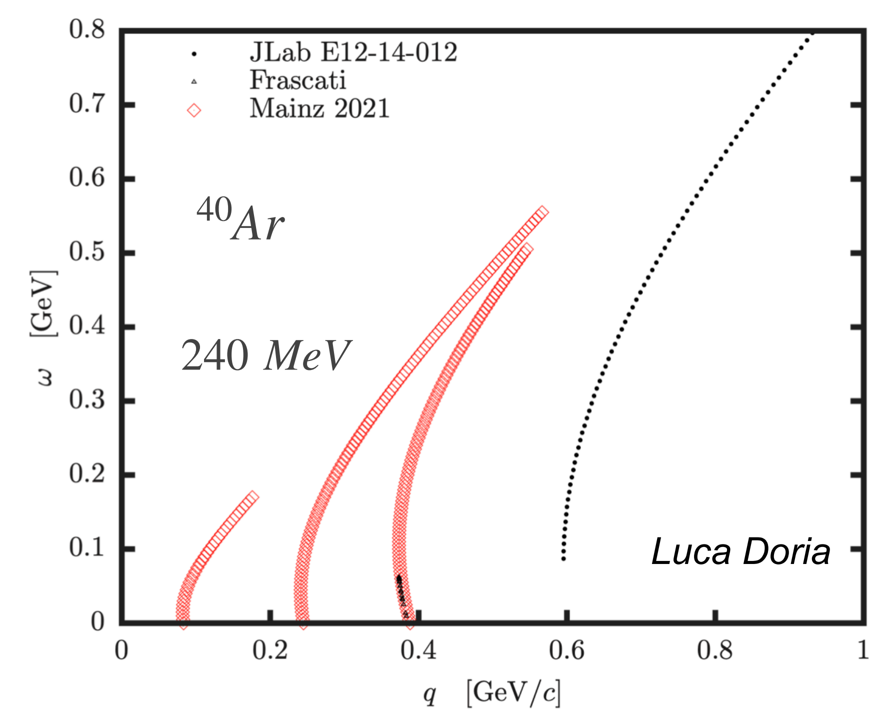




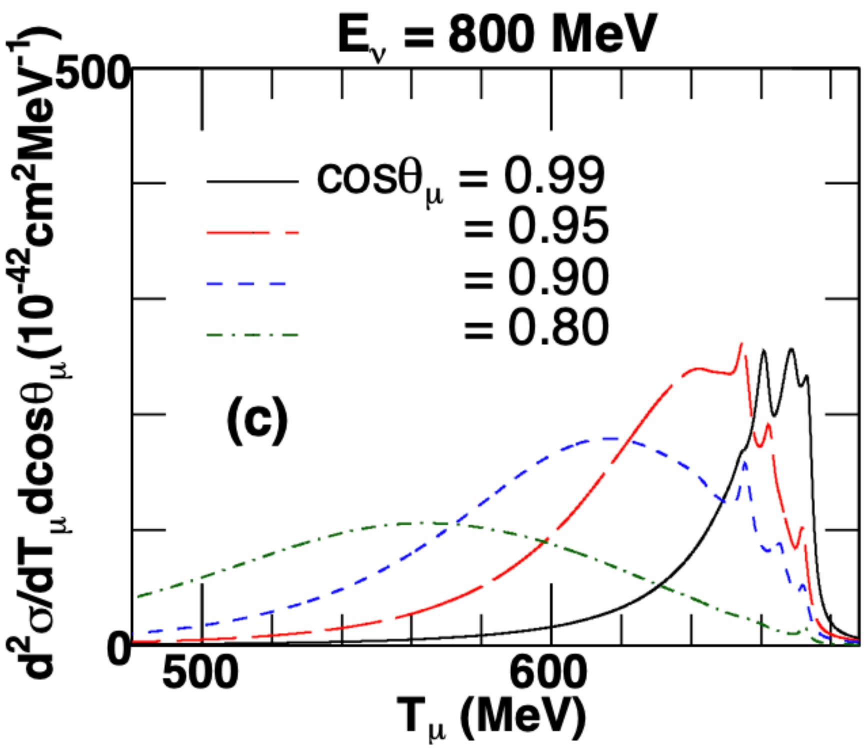
A. Nikolakopoulos, V. Pandey, J. Spitz and N. Jachowicz, Phys. Rev. C 103, 064603 (2021)

MiniBooNE data: Phys. Rev. Lett. 120, 141802 (2018)

- Exciting near future measurements: MicroBooNE and ICARUS (argon), JSNS² at J-PARC (carbon).
- 240 MeV electron scattering measurement planned at Mainz.
- Combined analysis of mono energetic electron and ν_μ cross sections will give great opportunity to constrains axial response at fixed energy.

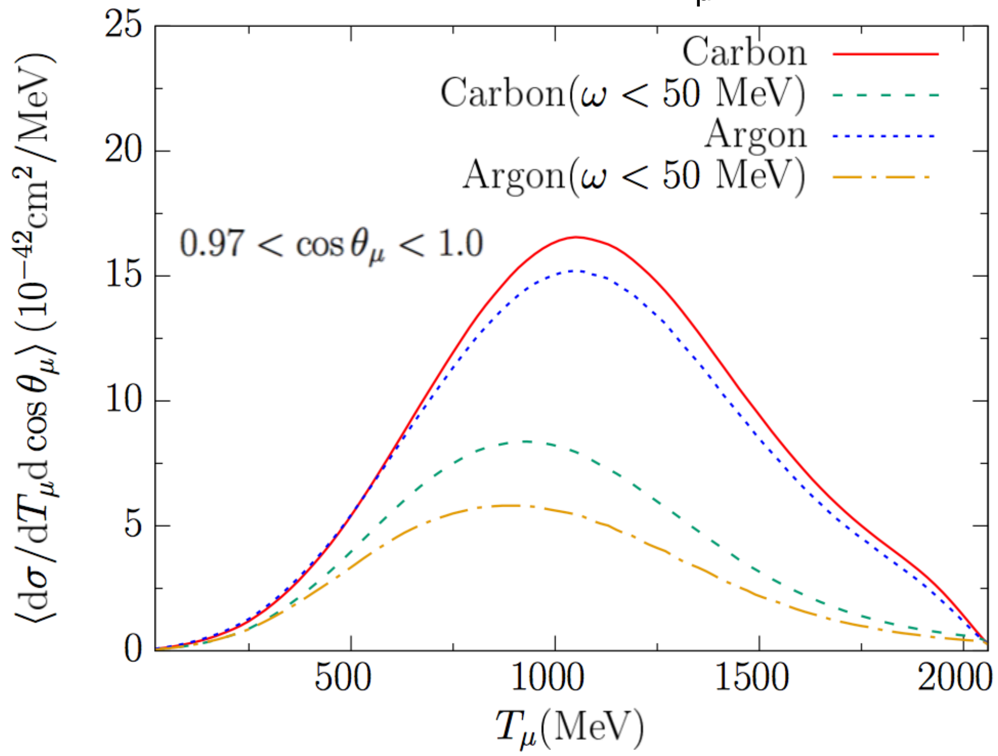


10s of MeV Physics in GeV-scale Beams

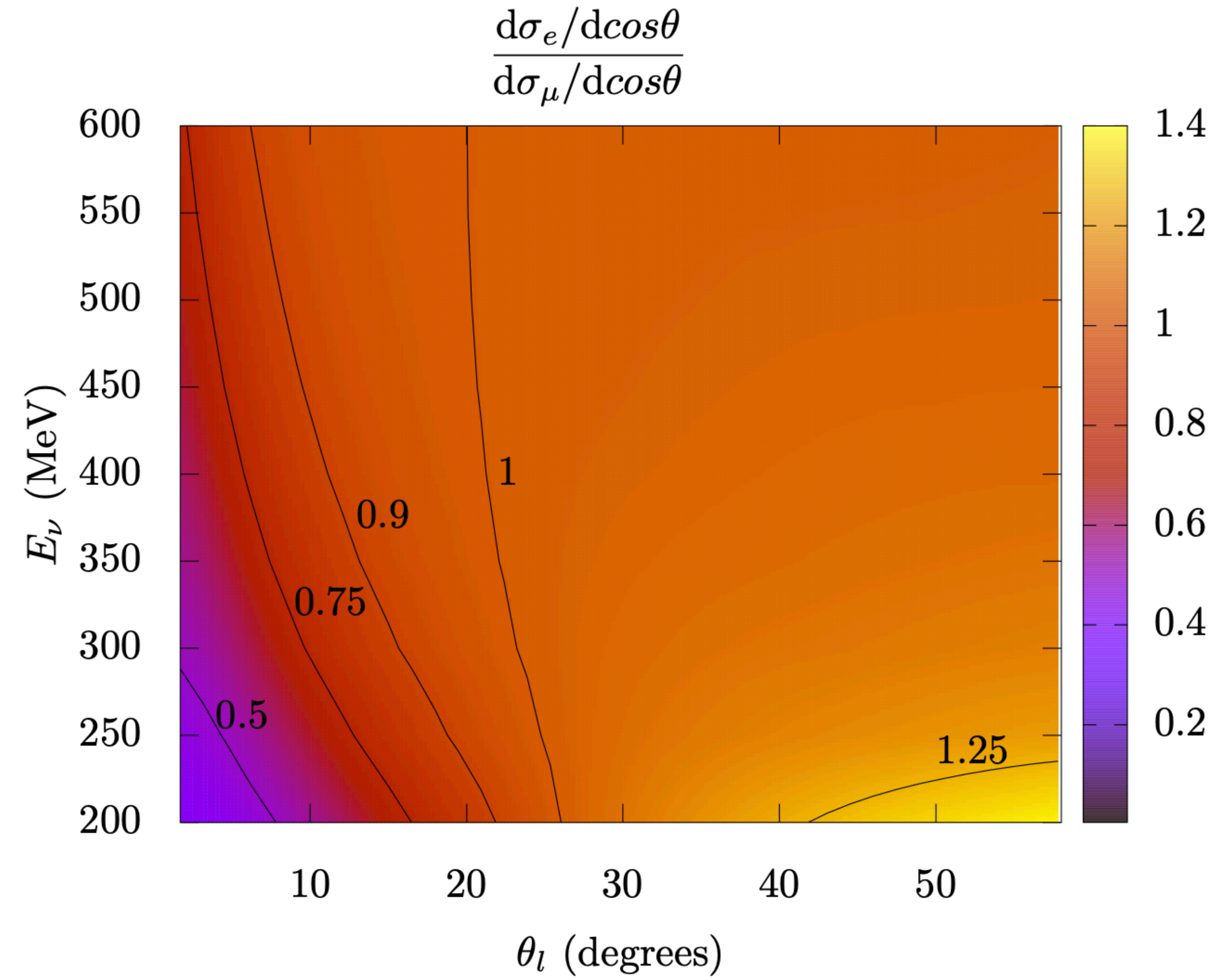


V. Pandey, N. Jachowicz, T. Van Cuyck, J. Ryckebusch, M. Martini, Phys. Rev. C92, 024606 (2015)

Folded with BNB ν_μ flux



N. Van Dessel, N. Jachowicz, R. González-Jiménez, V. Pandey, T. Van Cuyck, Phys. Rev. C97, 044616 (2018).



A. Nikolakopoulos, N. Jachowicz, N. Van Dessel, K. Niewczas, R. González-Jiménez, J. M. Udías, V. Pandey, Phys. Rev. Lett. 123, 052501 (2019).

- At forward scattering angles (low momentum transfer), the neutrino-nucleus cross section at GeV-scale energies is impacted by the same nuclear physics effects that are important for the low-energy case more generally.

- At these kinematics, differences between final-state lepton masses become vital and affect the ratio of the charged-current ν_e to ν_μ cross sections.

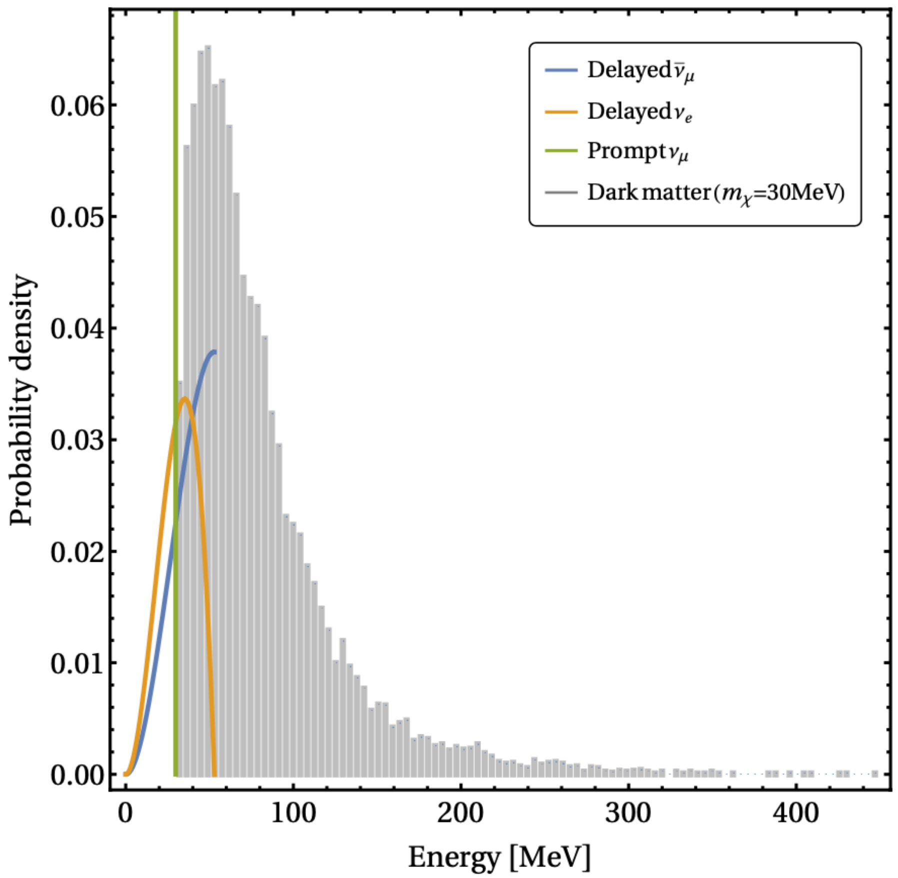
Neutrino-nucleus Scattering => DM-nucleus Scattering

- Boosted Dark Matter $\mathcal{L} \supset g_D A'_\mu \bar{\chi}\gamma^\mu \chi + e\epsilon Q_q A'_\mu \bar{q}\gamma^\mu q$

  B. Dutta, et al., arXiv:2006.09386 [hep-ph]

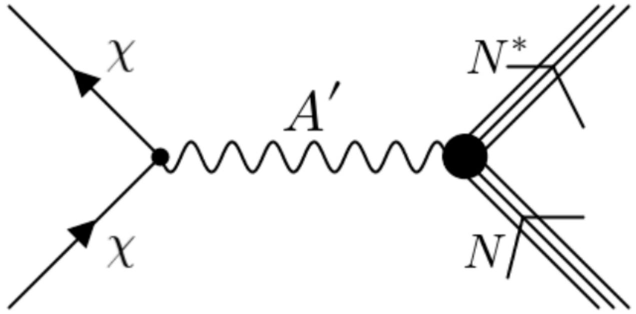
- Dark photon produced in pion decay (e.g. at SNS or at LANL)

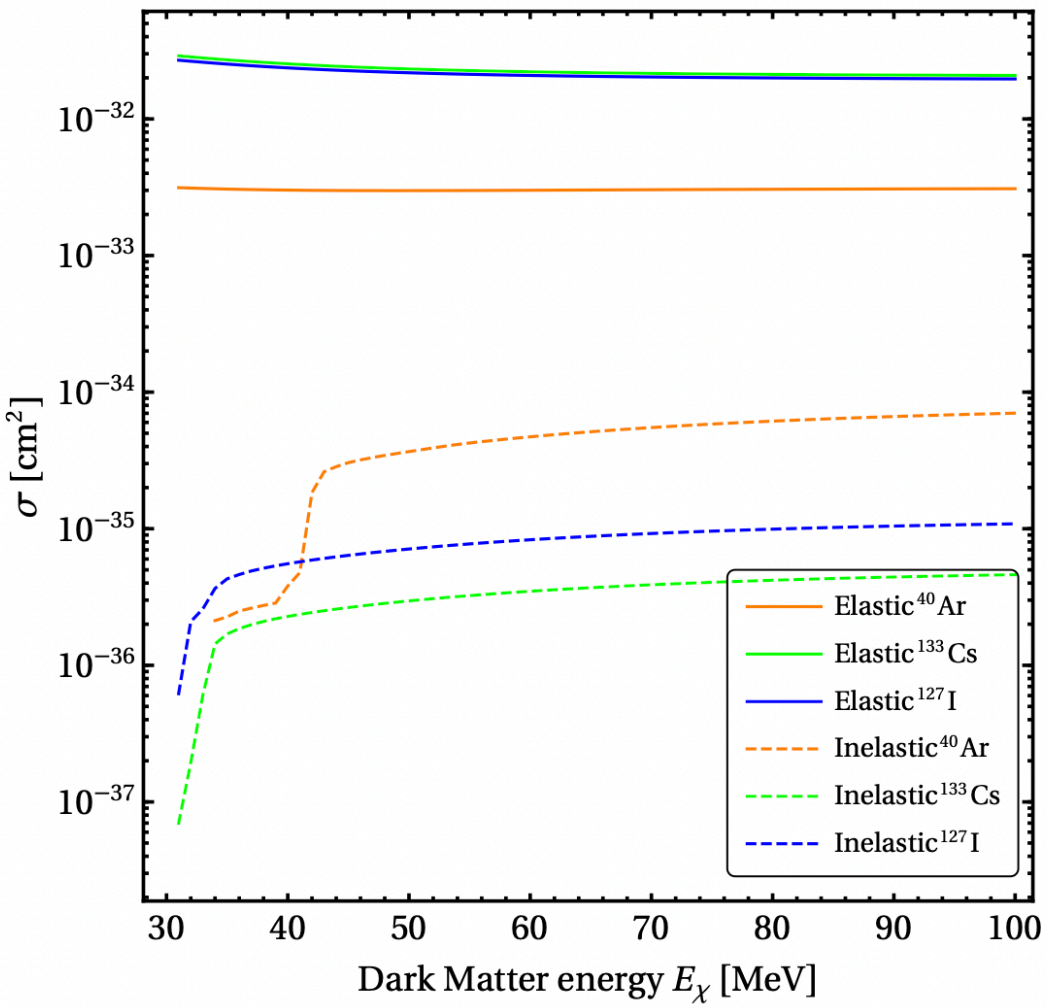
$$\pi^- + p \to n + A'$$
$$\pi^+ + n \to p + A'$$
$$\pi^0 \to \gamma + A'$$



Energy spectra of π-DAR neutrinos and a sample DM spectrum assuming $m_{A'} = 3m_\chi$

- Performing a similar DM-nucleus scattering calculations (dark matter interacting through an A') as for neutrino-nucleus case.





B. Dutta, W. C. Huang, J. L. Newstead, V. Pandey, arXiv:2206.08590 [hep-ph]

Summary

- Interactions of low energy (10s of MeV) neutrinos - elastic (CEvNS) and inelastic - are interesting for studies of various SM and BSM processes.

- Neutrino-nucleus interactions at these energies are sensitive to neutron radius and weak elastic form factor (CEvNS), and underlying nuclear structure (inelastic).

- Various neutrino facilities and experiments are sensitive to these processes.