Recent Progress in Low-Energy Neutrino-Nucleus Interactions Physics

Vishvas Pandey
Fermi National Accelerator Laboratory

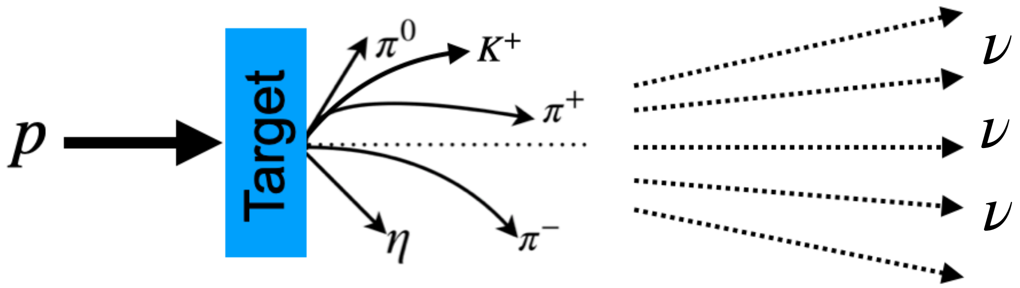
NuFact 2024, Argonne National Laboratory, September 16 - 21, 2024

Neutrino Sources and Physics Scope

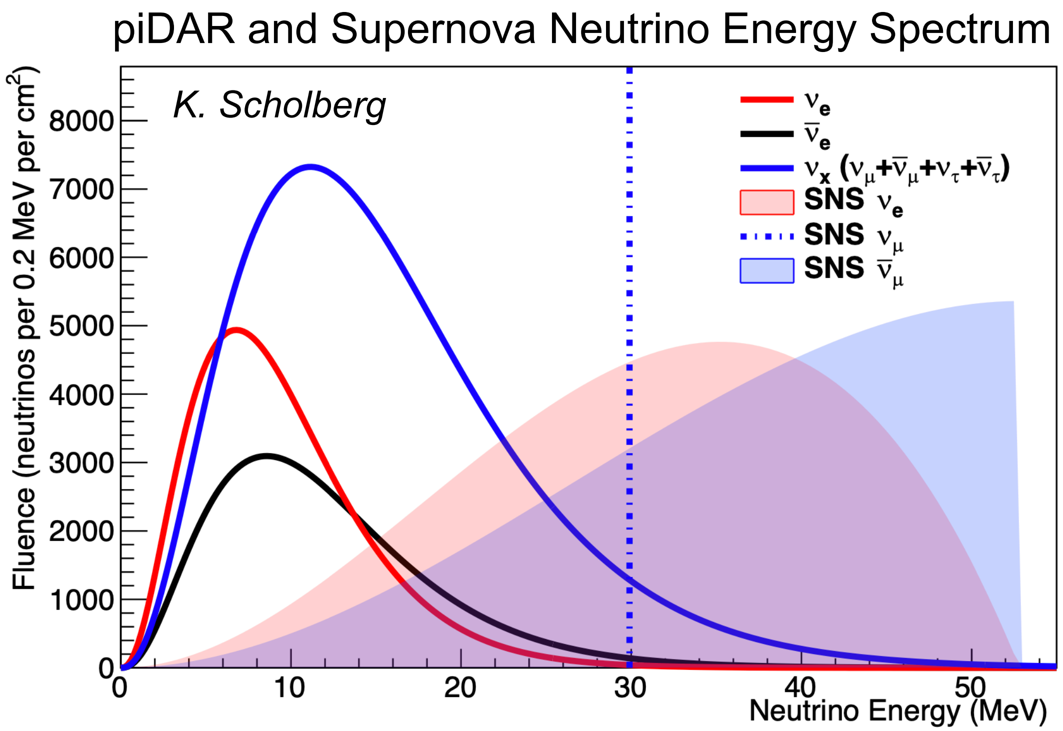
✦ $E_\nu \approx$ **10s of MeV**

- **Pion decay-at-rest neutrinos**

(SNS at ORNL, LANSCE at LANL, MLF at JPARC, F2D2 at FNAL, ESS, ..)



- **Core-collapse Supernova Neutrinos**



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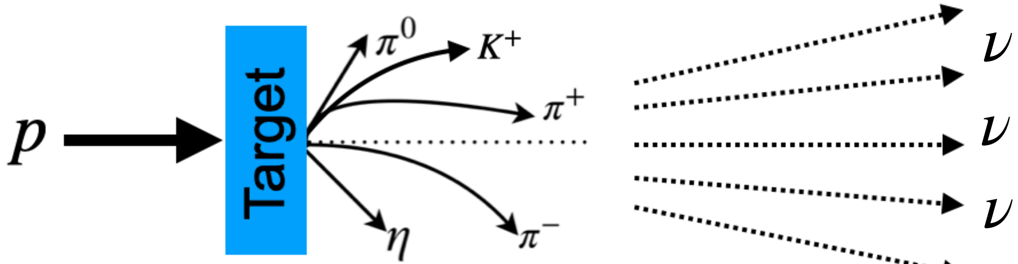

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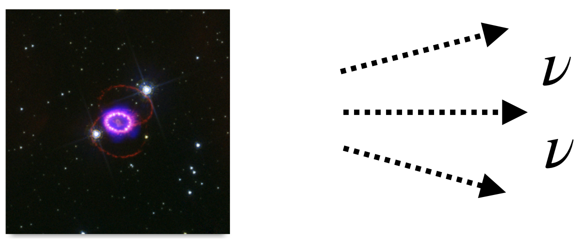
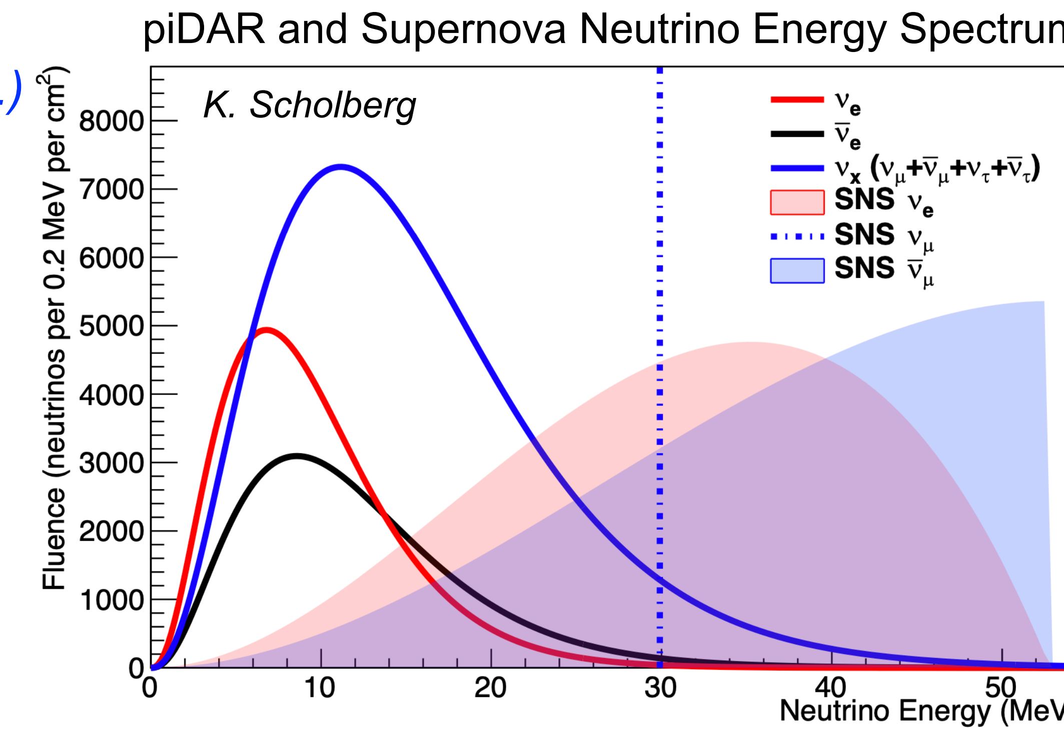
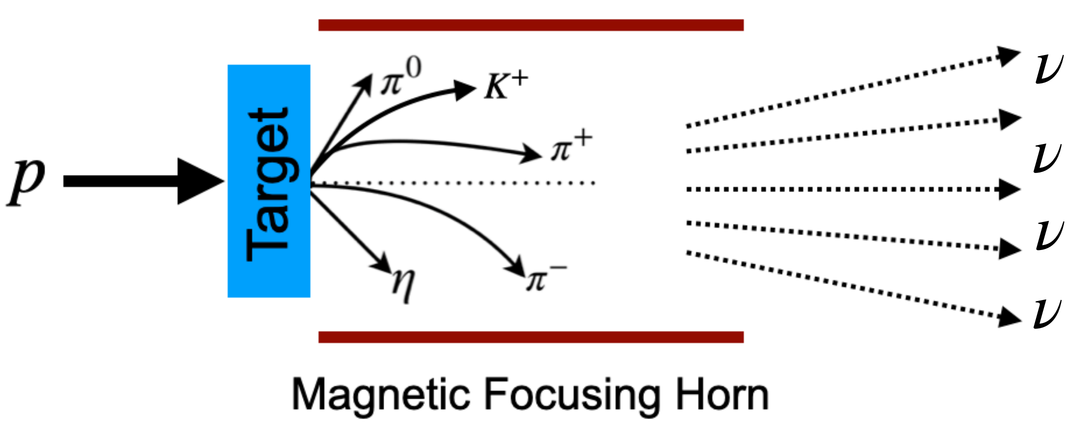
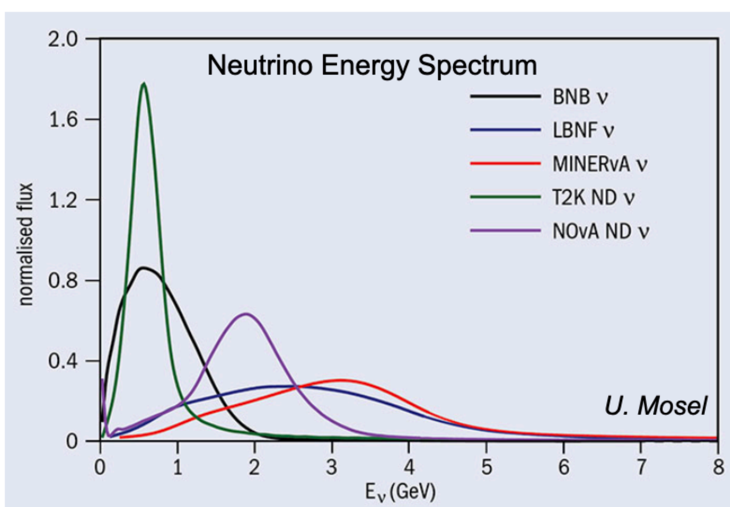


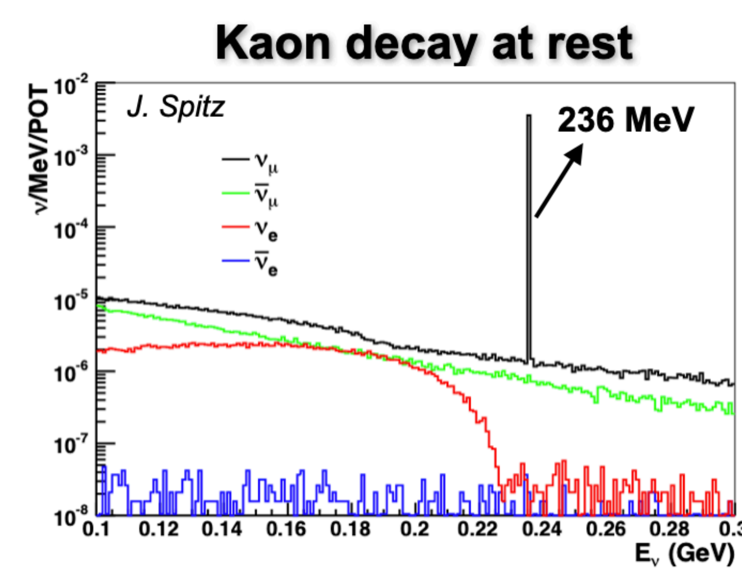


✦ 10s MeV scale physics in GeV scale ν beam

- **Pion decay-in-flight neutrinos**
  (BNB/NUMI/LBNF at FNAL, JPARC, …)







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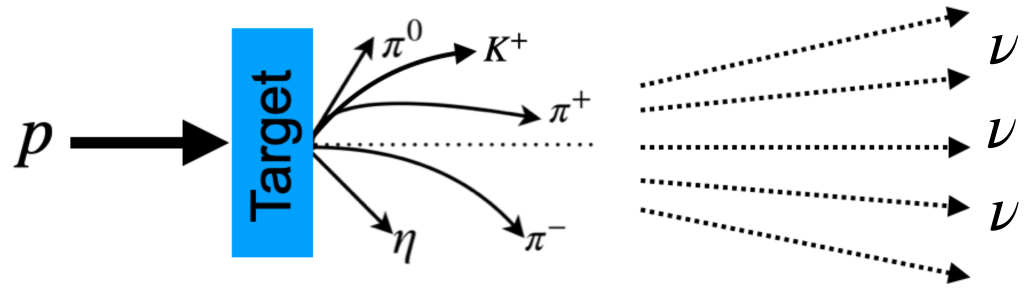
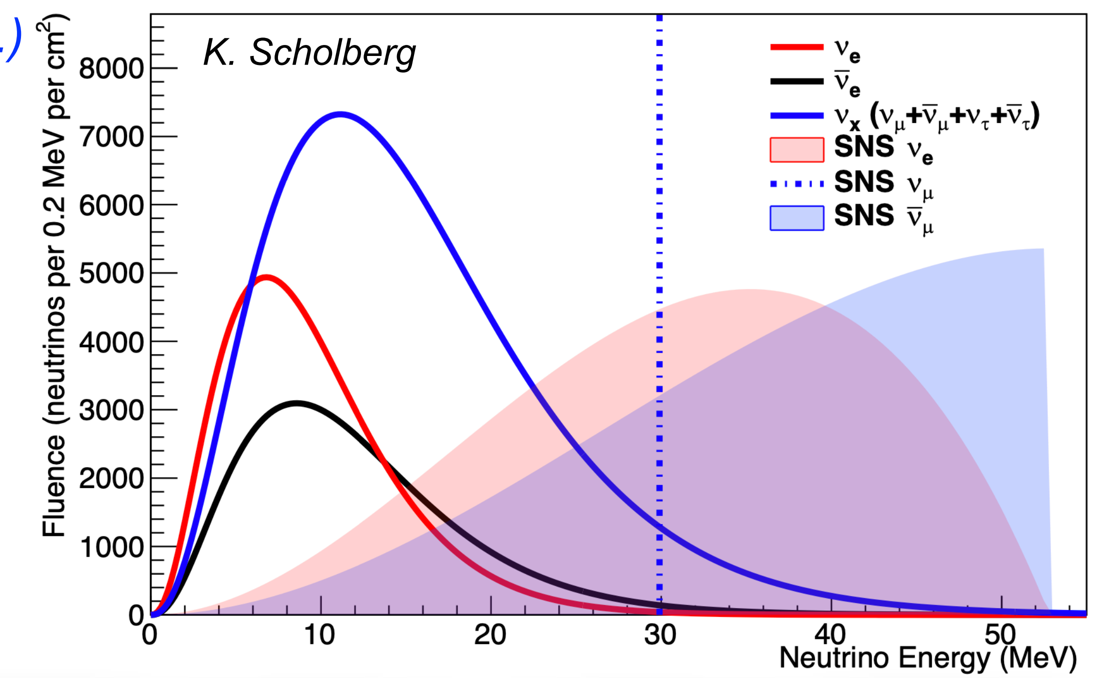


piDAR and Supernova Neutrino Energy Spectrum



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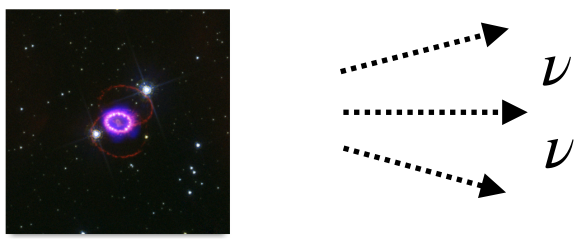

Neutrino physics, SM precision test, astrophysics, nuclear physics, BSM physics

✦ 10s MeV scale physics in GeV scale ν beam

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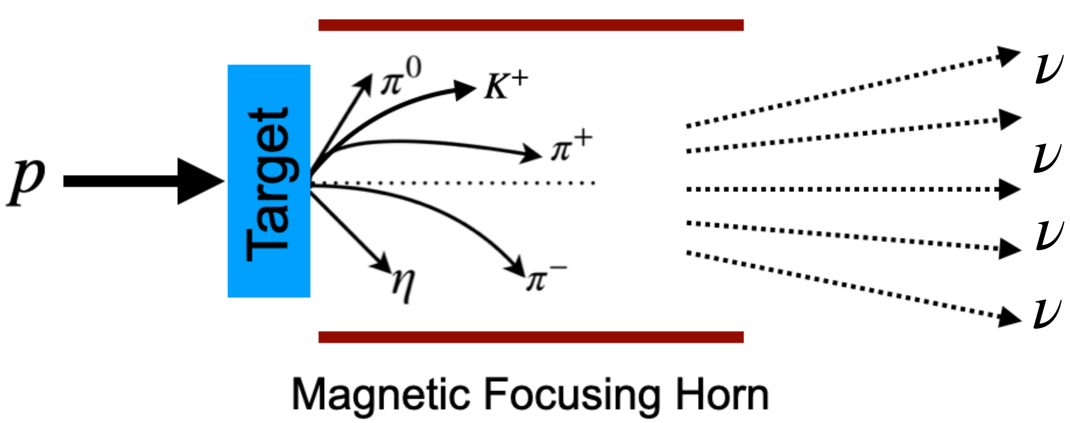
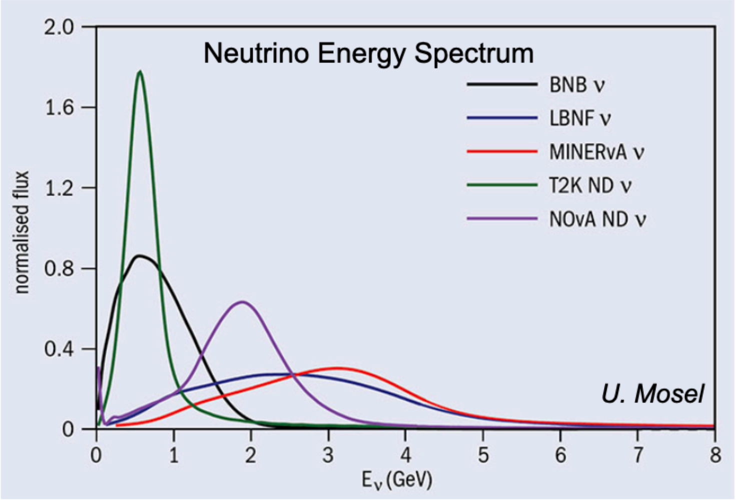
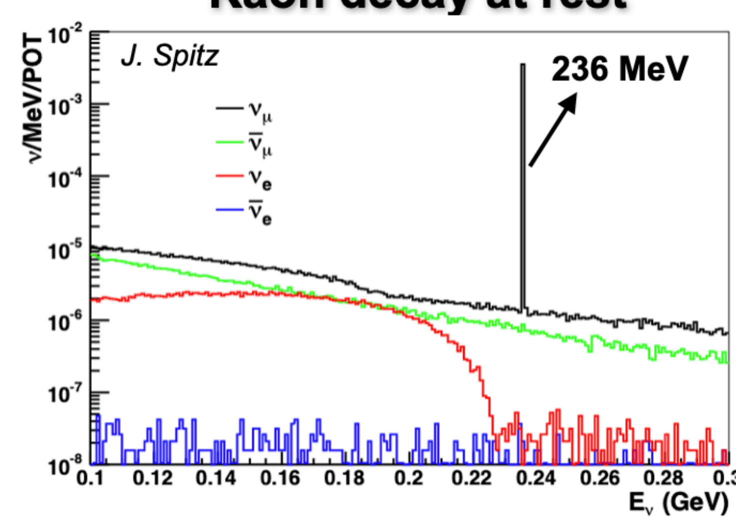


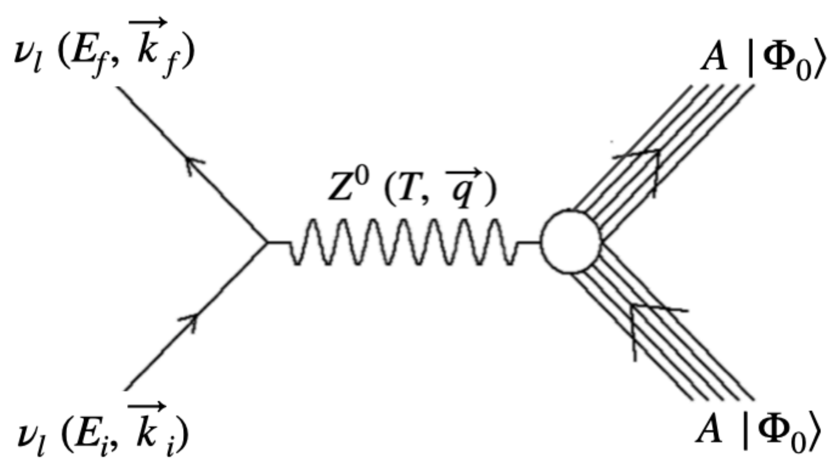


Kaon decay at rest

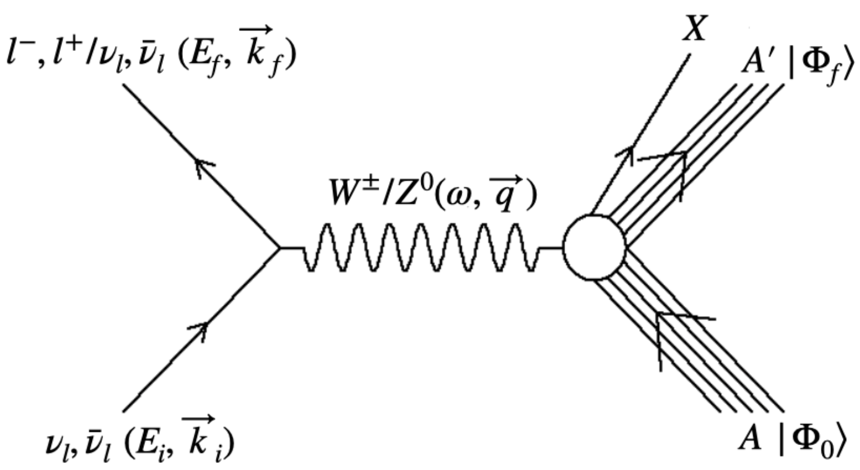


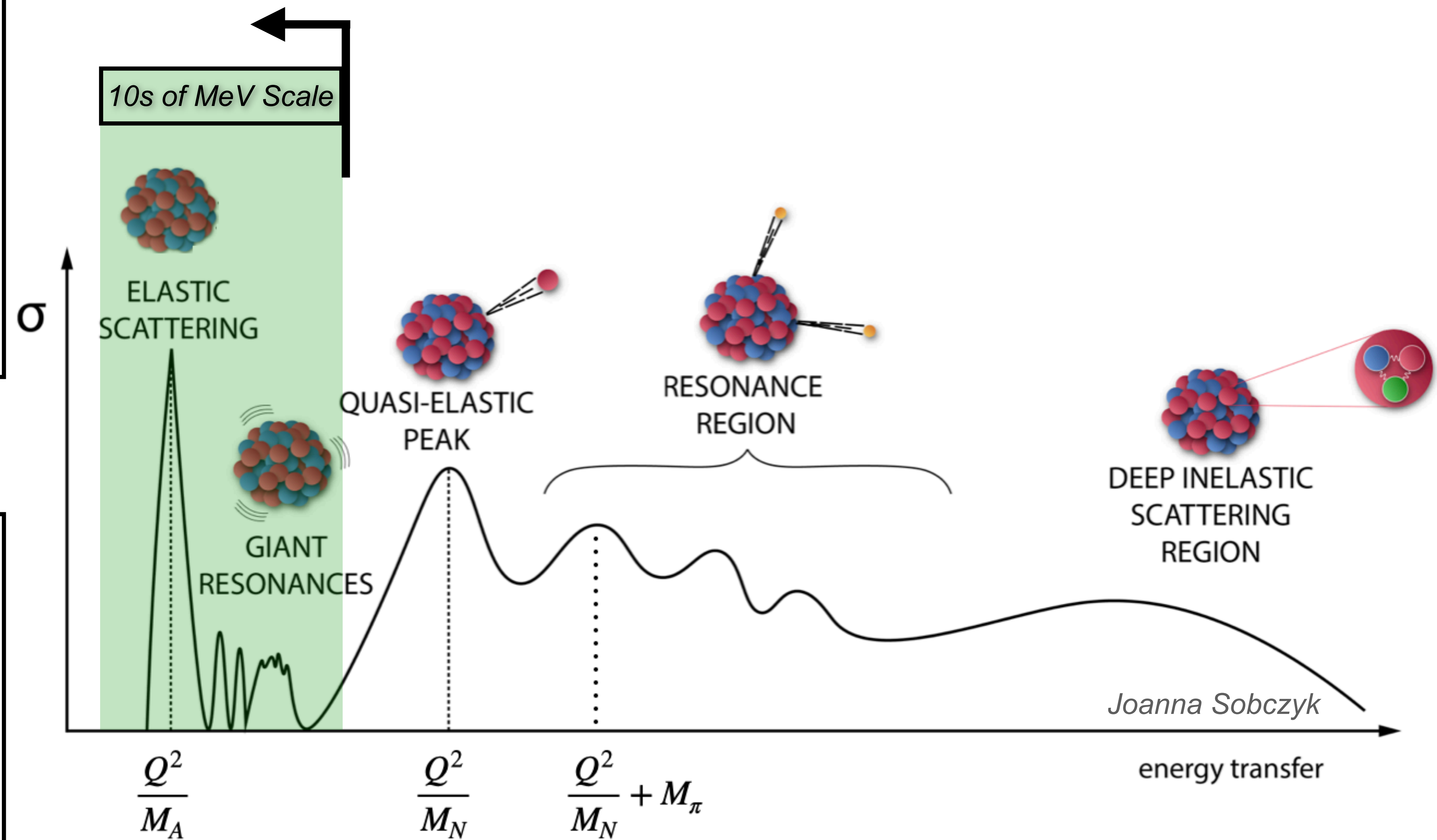
Low-energy Neutrino-nucleus Scattering

Coherent elastic [CEvNS]



Inelastic CC/NC





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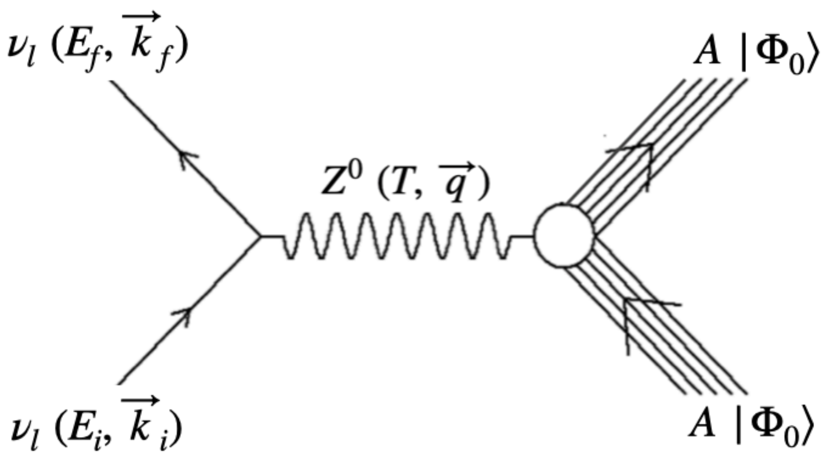

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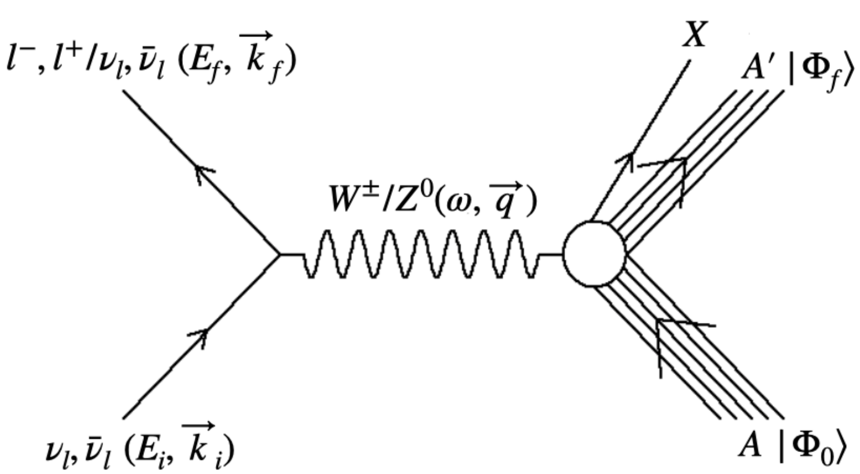

- **CEvNS Experiments: Yuri Efremenko this Morning**

- **Inelastic Scattering in MARLEY: Steven Gardiner on Tuesday**

Physics modeling improvements in the MARLEY neutrino event generator

Steven Gardiner, Pablo Barham Alzás, Luca Abu El-Haj

Progress in Particle and Nuclear Physics 134 (2023) 104078

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

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Review

Recent progress in low energy neutrino scattering physics and its implications for the standard and beyond the standard model physics

Vishvas Pandey

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Check for updates

10s of MeV Neutrinos-Nucleus Scattering

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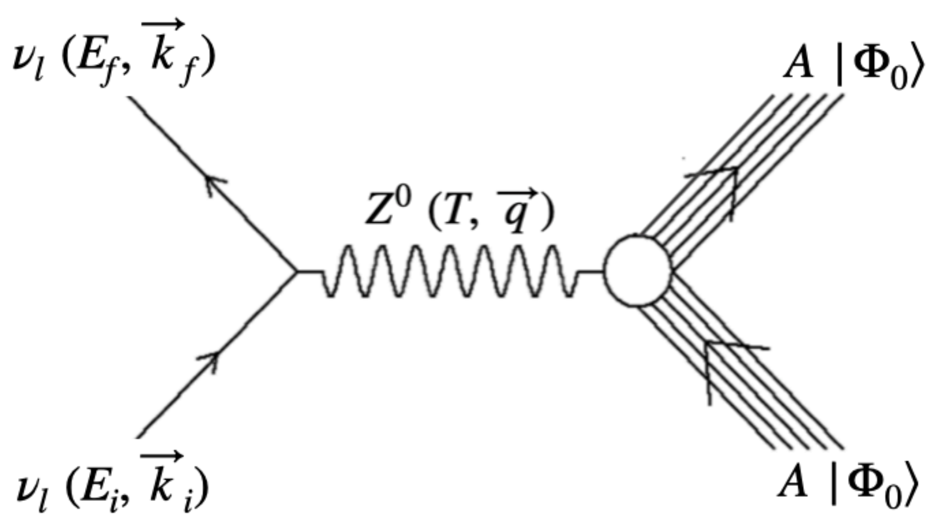

- Final state nucleus stays in its ground state
- Signal: keV energy nuclear recoil
- Tiny recoil energy, large cross section

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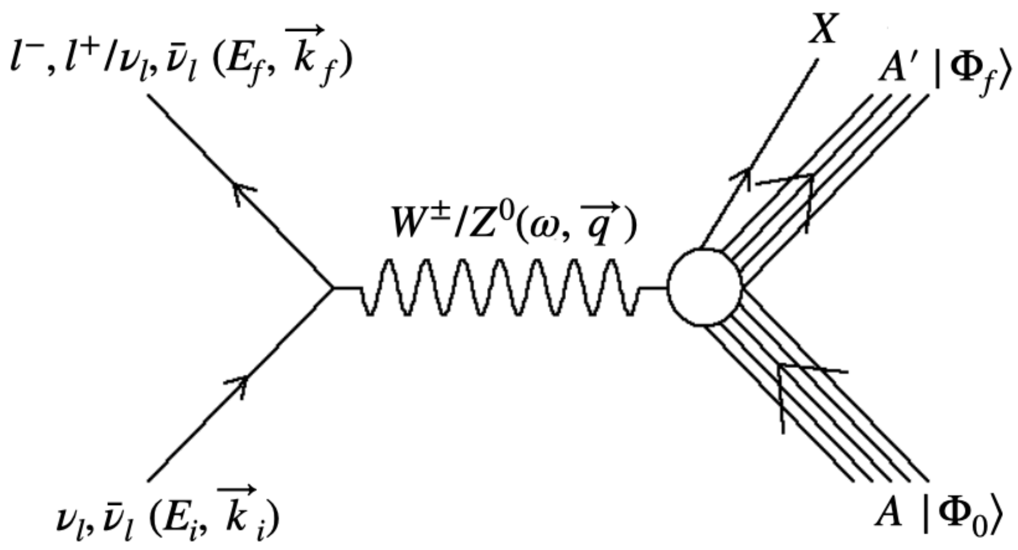

- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π)
- Followed by nuclear de-excitation into MeV energy gammas, including n, p or nuclear fragmentation emission.

10s of MeV Neutrinos-Nucleus Scattering

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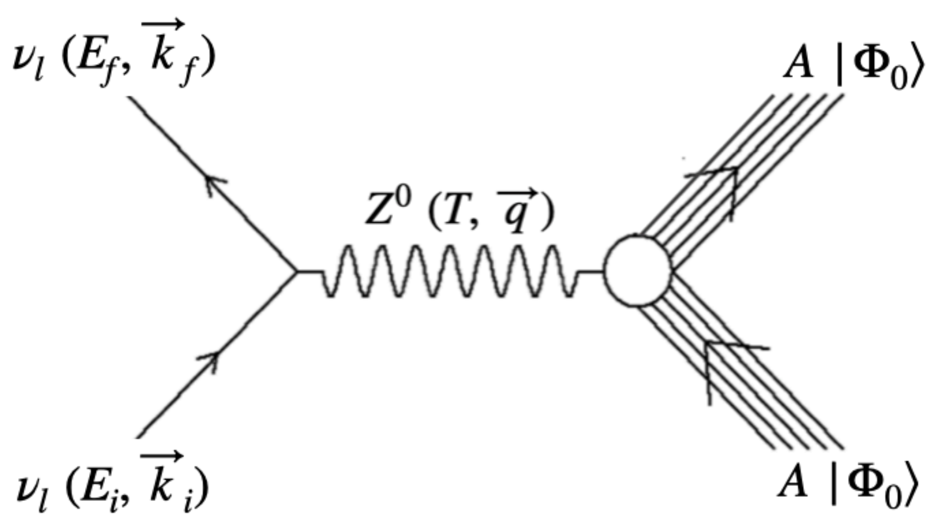

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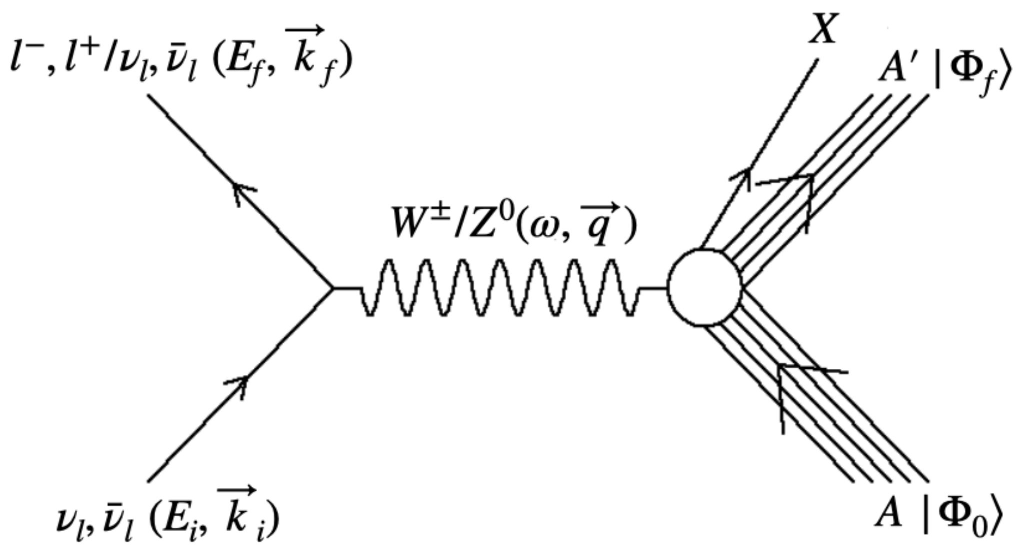

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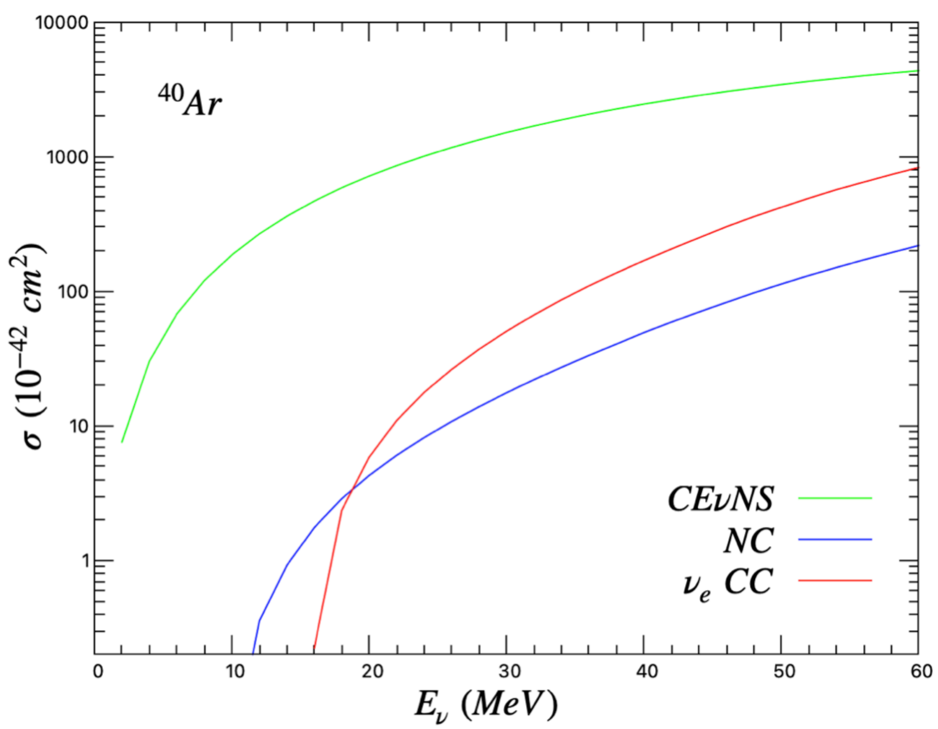

V. Pandey, Prog. Part. Nucl. Phys., 104078 (2024)

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

10s of MeV Neutrinos-Nucleus Scattering

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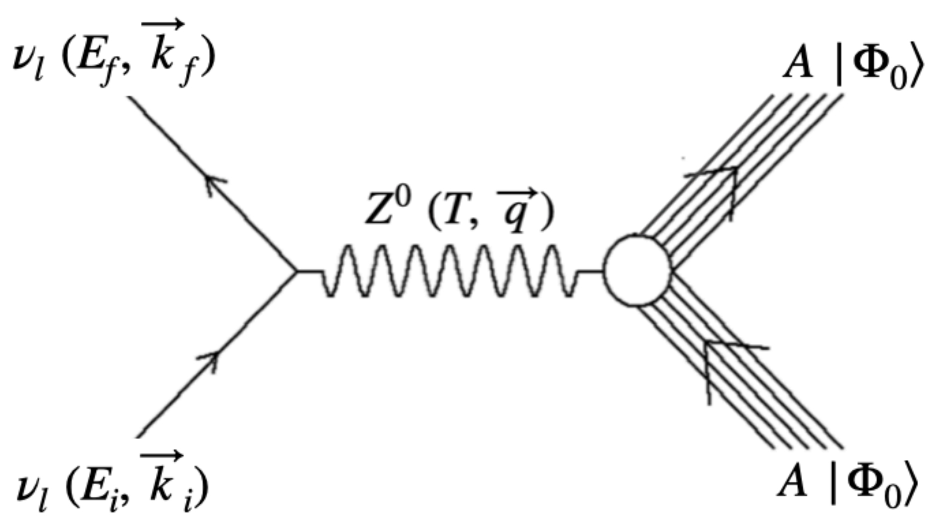

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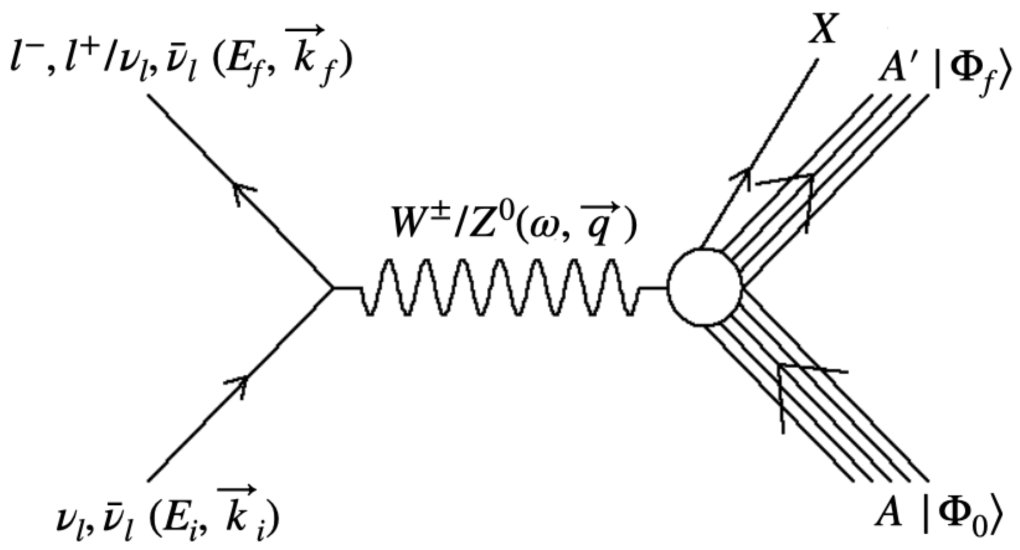

$$\sum_{fi} |\mathscr{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

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

10s of MeV Neutrinos-Nucleus Scattering

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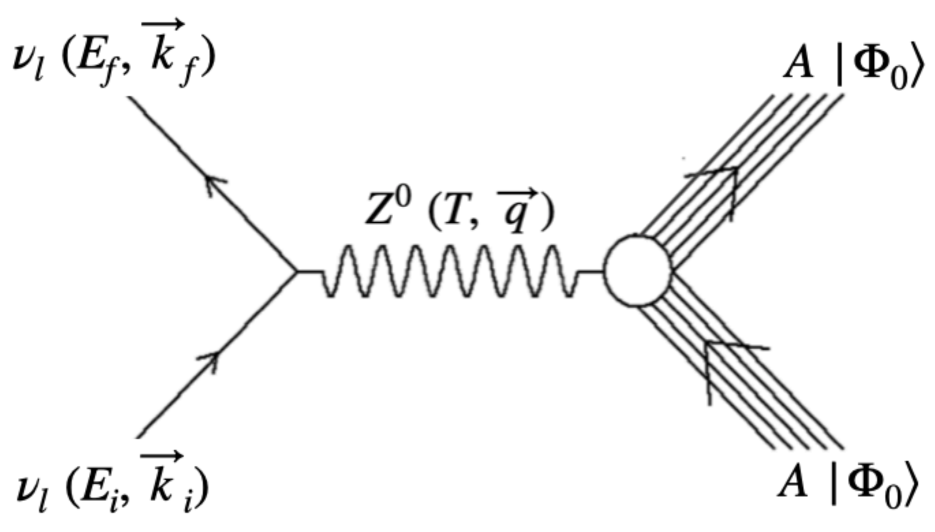

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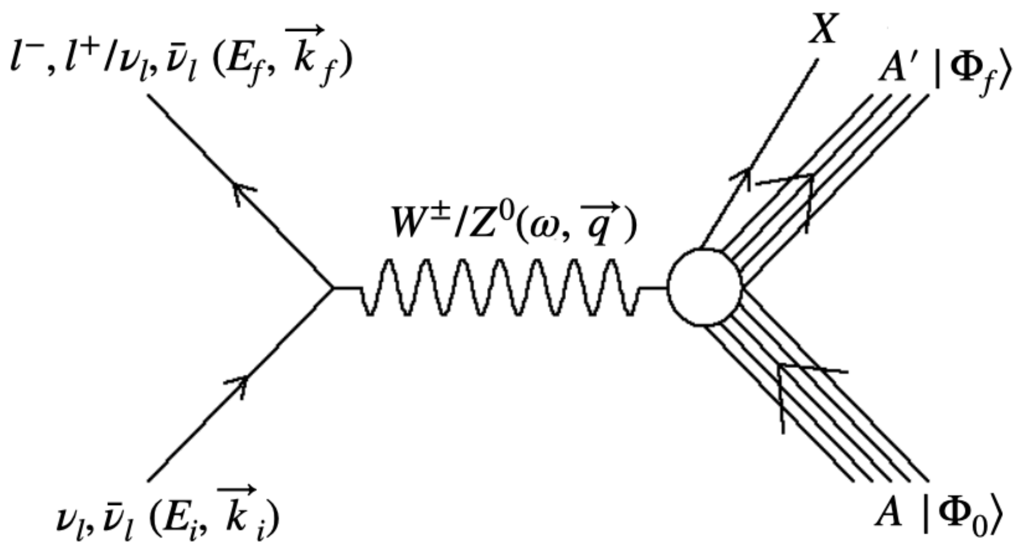

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Transition Amplitude: $\mathscr{J}_n^\mu = \langle \Phi_0 | \hat{J}_n^\mu(q) | \Phi_0 \rangle$

Cross Section:

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

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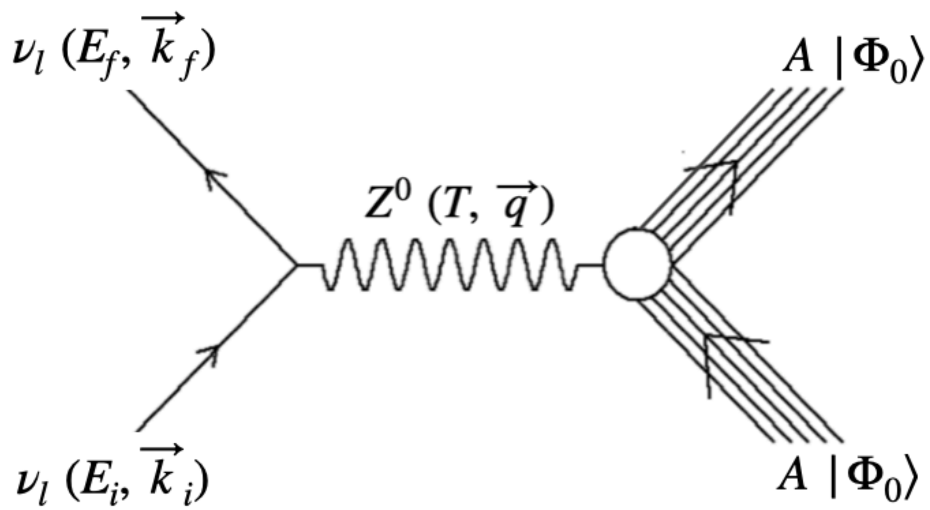

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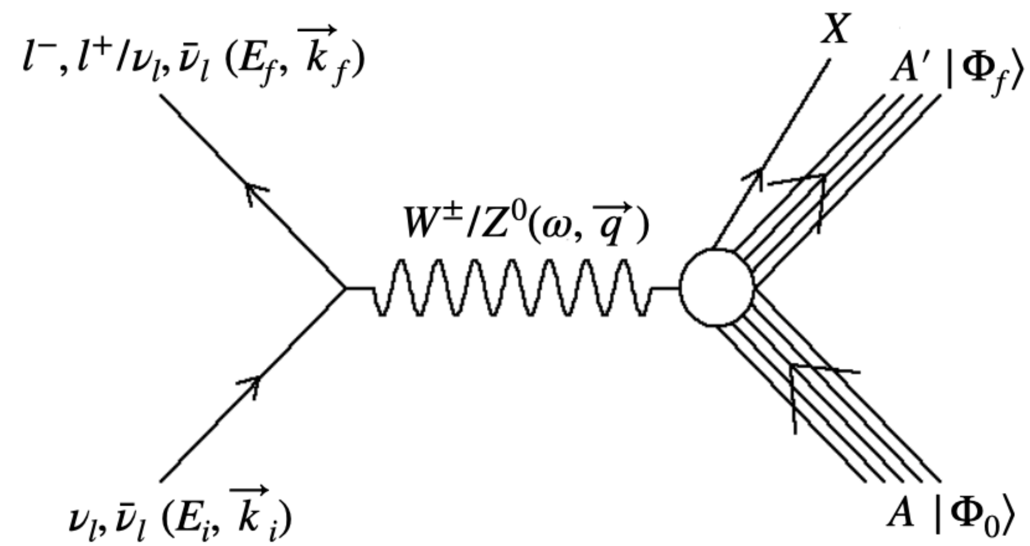

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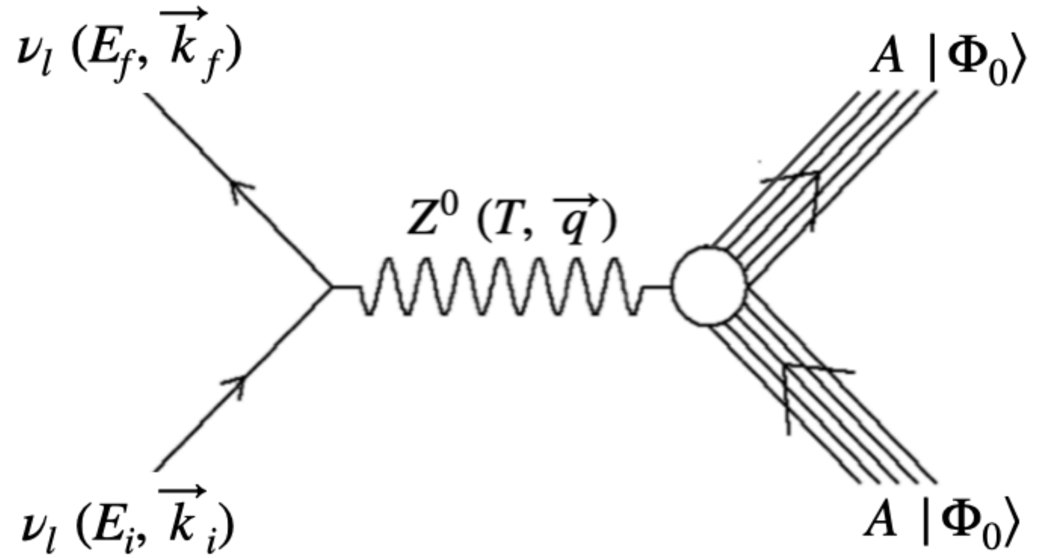
$$d\sigma \propto \frac{G_F^2}{4\pi} \sum_{J^\pi} [v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T \pm v_{T'} W_{T'}]$$

CEvNS Cross Section and Form Factors

- **Cross section (tree level and spin zero nuclei)*:**

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



- **Weak Form Factor:**

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

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

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

*barring radiative corrections, please see:
O. Tomalak, P. Machado, V. Pandey, R. Plestid, JHEP 02, 097 (2021)

*barring axial-vector operator, please see:
M. Hoferichter, J. Menendez and A. Schwenk, Phys. Rev. D 102, 074018 (2020)

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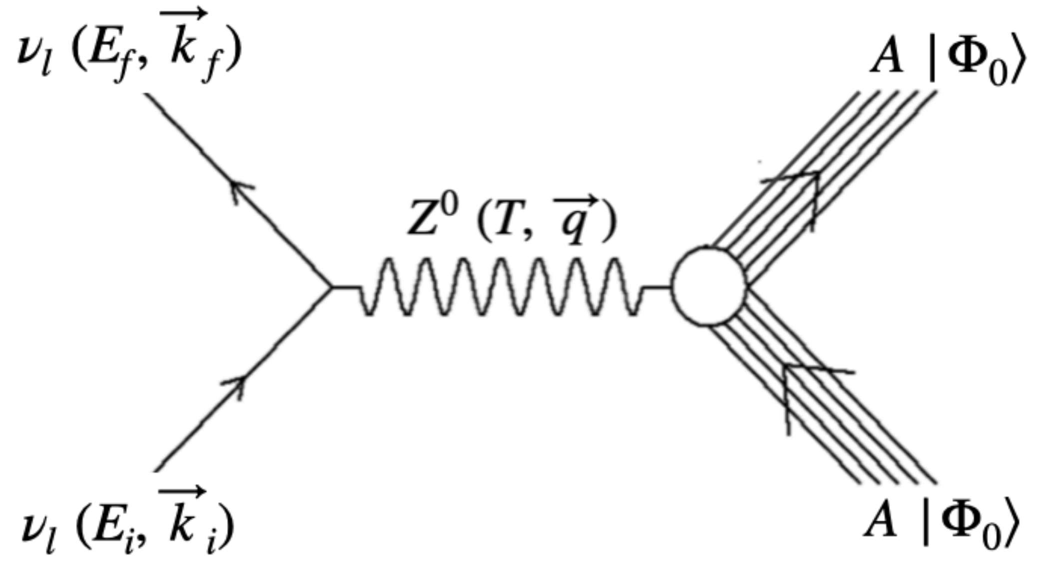

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Charge density and charge form factor: proton densities and charge form factors are well know through decades of elastic electron scattering experiments.

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

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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.

T. W. Donnelly, J. Dubach and I. Sick,, Nucl. Phys. A 503, 589-631 (1989).

- **CEvNS Cross Section**

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

- **PVES Asymmetry**

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

- Both processes are described in first order perturbation theory via the exchange of an electroweak gauge boson between a lepton and a nucleus.
- CEvNS: the lepton is a neutrino and a Z^0 boson is exchanged.
- PVES: the lepton is an electron, but measuring the asymmetry allows one to select the interference between the γ and Z^0 exchange.
- As a result, both the CEvNS cross section and the PVES asymmetry depend on the weak form factor $F_W(Q^2)$, which is mostly determined by the neutron distribution within the nucleus.

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- **CEvNS Cross Section**

D. Z. Freedman, Phys. Rev. D 9, 1389-1392 (1974)

"Freedman declared that the experimental detection of CEvNS would be an "act of hubris" due to the associated "grave experimental difficulties".

- The maximum recoil energy

$$T_{\max} = \frac{E_\nu}{1 + M_A/(2E_\nu)}$$

- **PVES Asymmetry**

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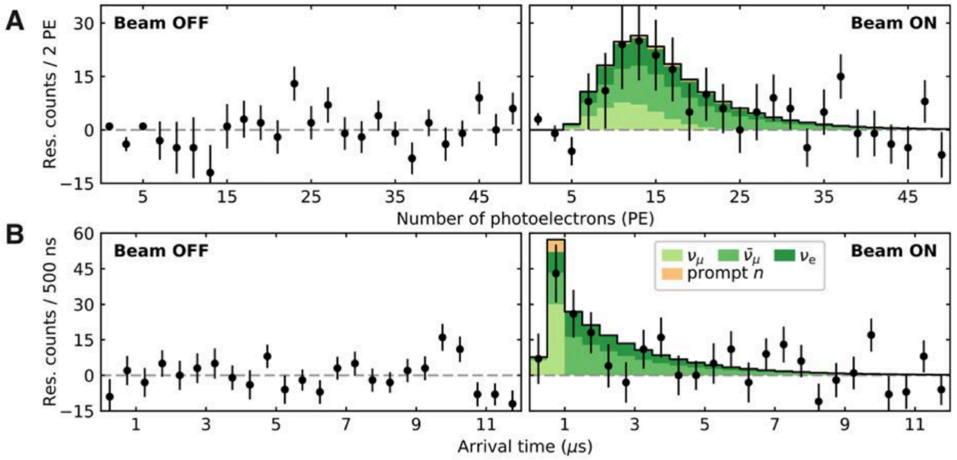
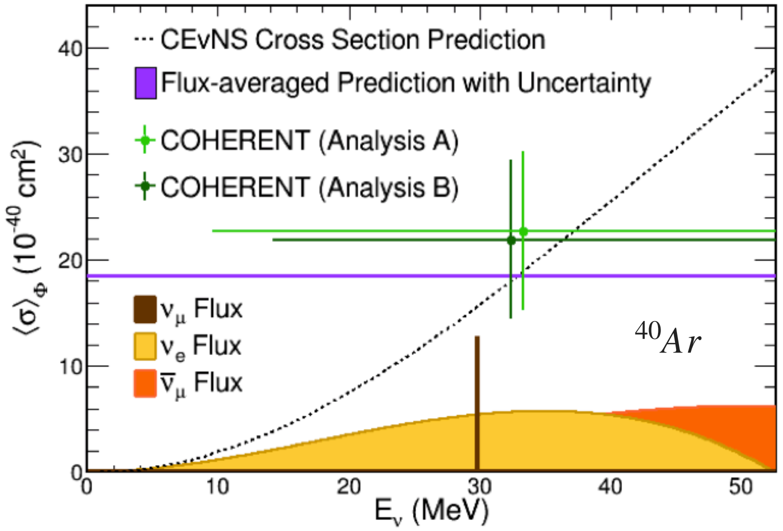
COHERENT Collaboration at SNS at ORNL





- Multiple measurements by COHERENT since 2017, and many CEvNS experimental programs worldwide

- See Yuri Efremenko's talk from this morning.

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

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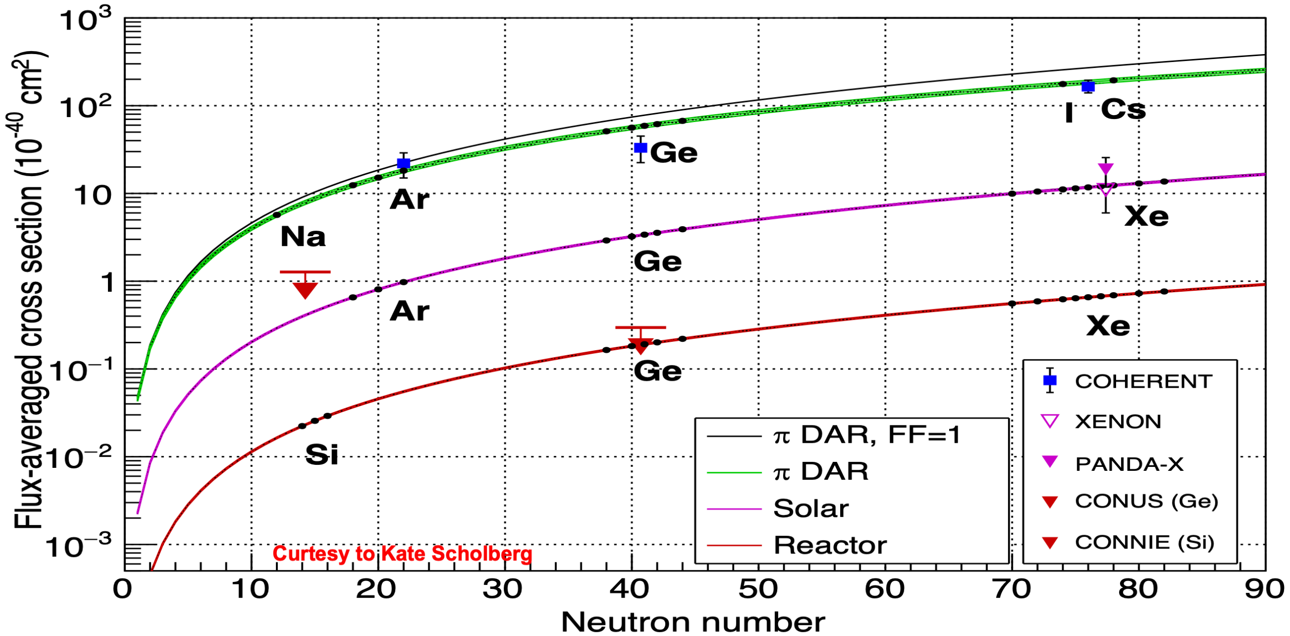

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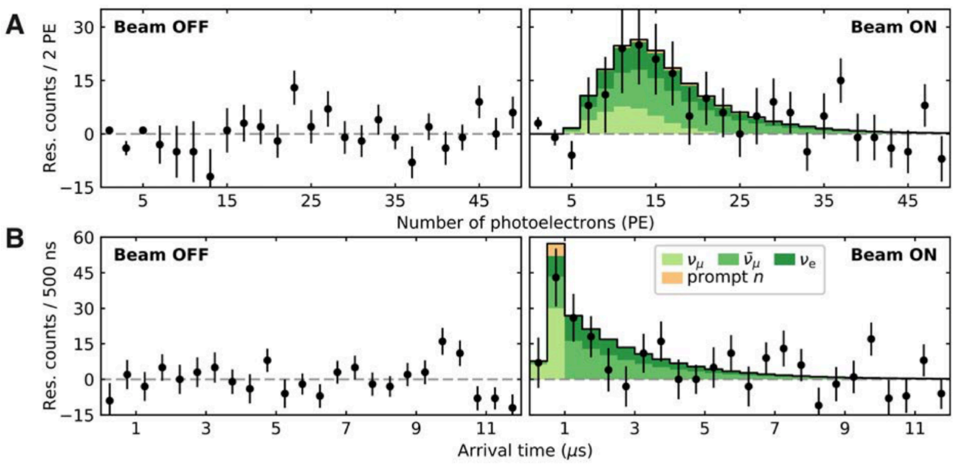
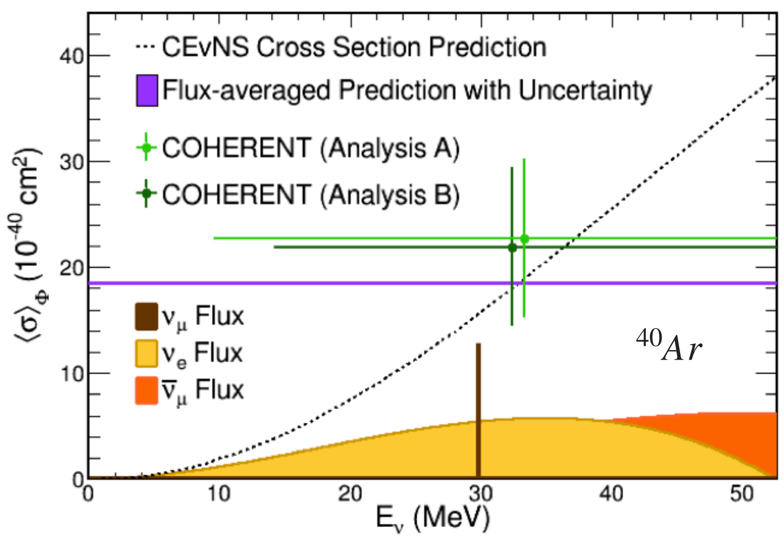
COHERENT Collaboration at SNS at ORNL





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• PVES Asymmetry

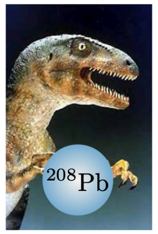
- The parity violating asymmetry for elastic electron scattering is the fractional difference in cross section for positive helicity and negative helicity electrons.

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

- 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)
PREX	^{208}Pb	0.00616	0.550 ± 0.018
CREX	^{48}Ca	0.0297	
Qweak	^{27}Al	0.0236	2.16 ± 0.19
MREX	^{208}Pb	0.0073	

arXiv:2203.06853 [hep-ex]



Pb Radius Experiment (PREX)

Calcium Radius Experiment (CREX)

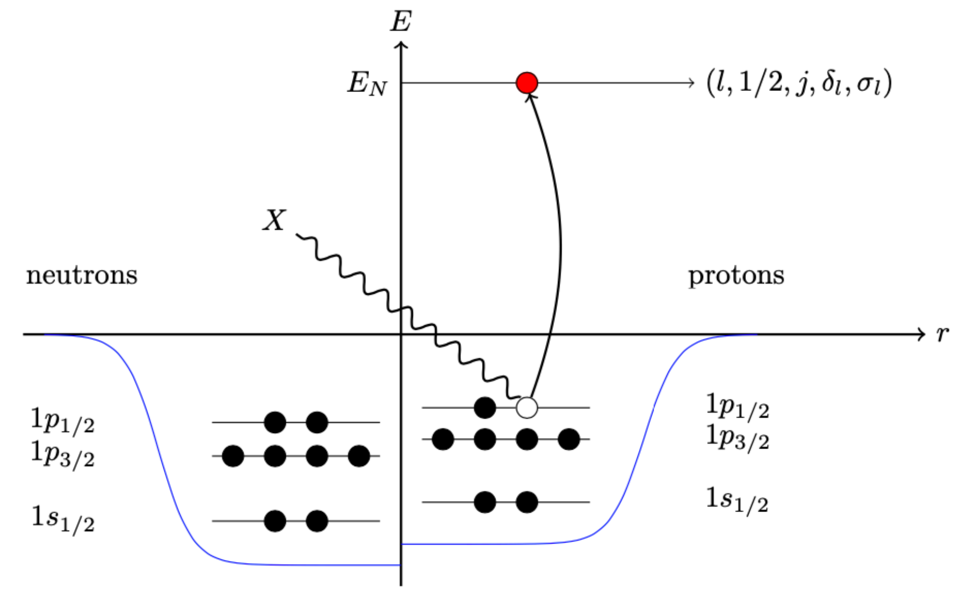
MREX

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

Fermilab

CEvNS Cross Section Calculations: HF-SkE2

- 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

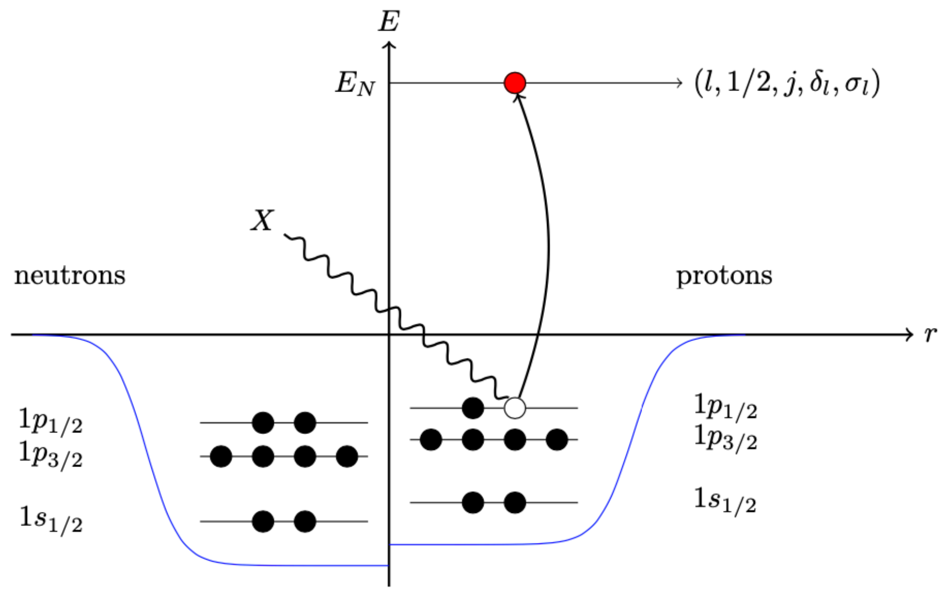


$$\rho_\tau(r) = \frac{1}{4\pi r^2} \sum_\alpha v^2_{\alpha,\tau} \, (2j_\alpha + 1) \, |\phi_{\alpha,\tau}(r)|^2 \qquad F_\tau(q) = \frac{1}{N} \int d^3r \; j_o(qr) \; \rho_\tau(r)$$

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

$$(\tau = p, n)$$

- 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

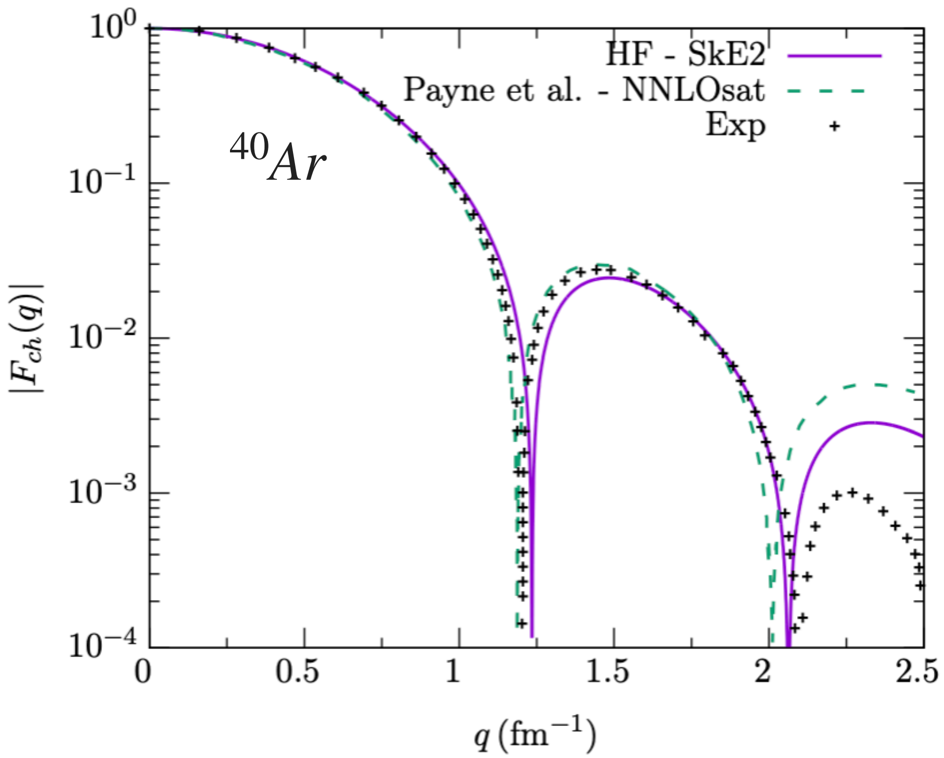


$$\rho_\tau(r) = \frac{1}{4\pi r^2} \sum_\alpha v^2_{\alpha,\tau}\ (2j_\alpha + 1)\,|\,\phi_{\alpha,\tau}(r)\,|^2 \qquad F_\tau(q) = \frac{1}{N}\int d^3r\ j_o(qr)\ \rho_\tau(r)$$

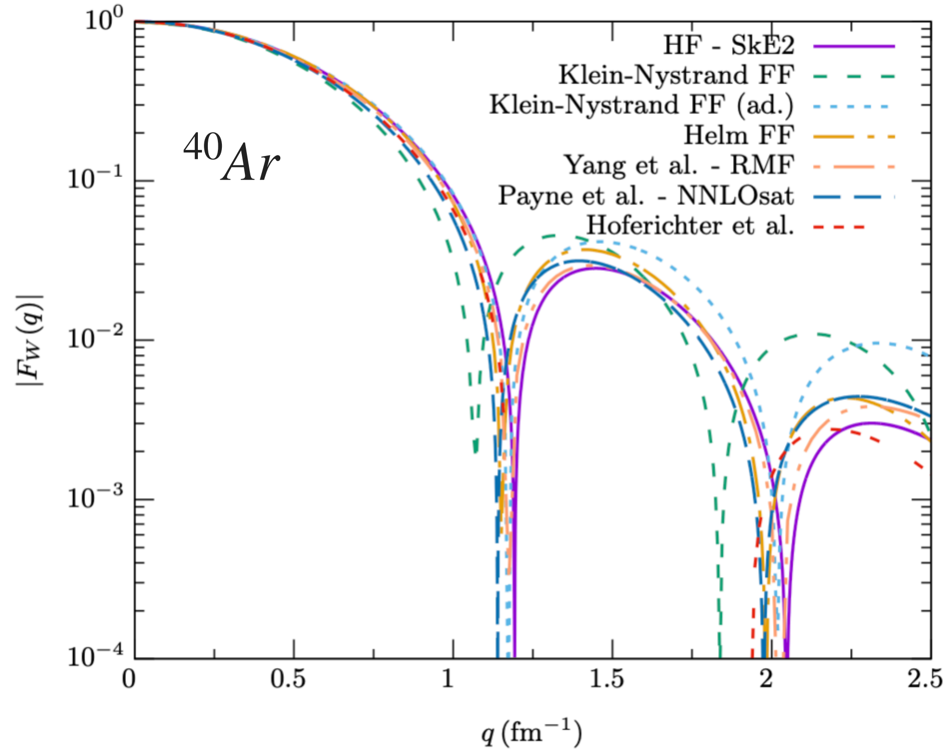
$$(\alpha \in n_\alpha, l_\alpha, j_\alpha)$$

$$(\tau = p, n)$$

Charge Form Factor



Weak Form Factor

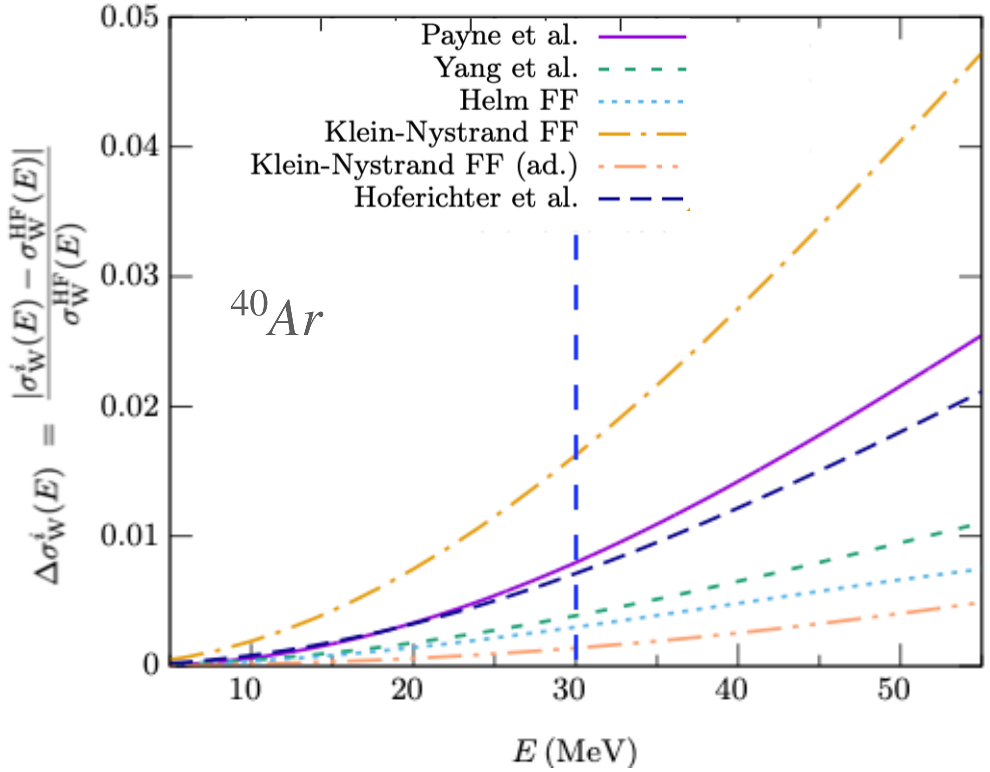


N. Van Dessel, V. Pandey, H. Ray and N. Jachowicz, Universe 9, 207 (2023)

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)

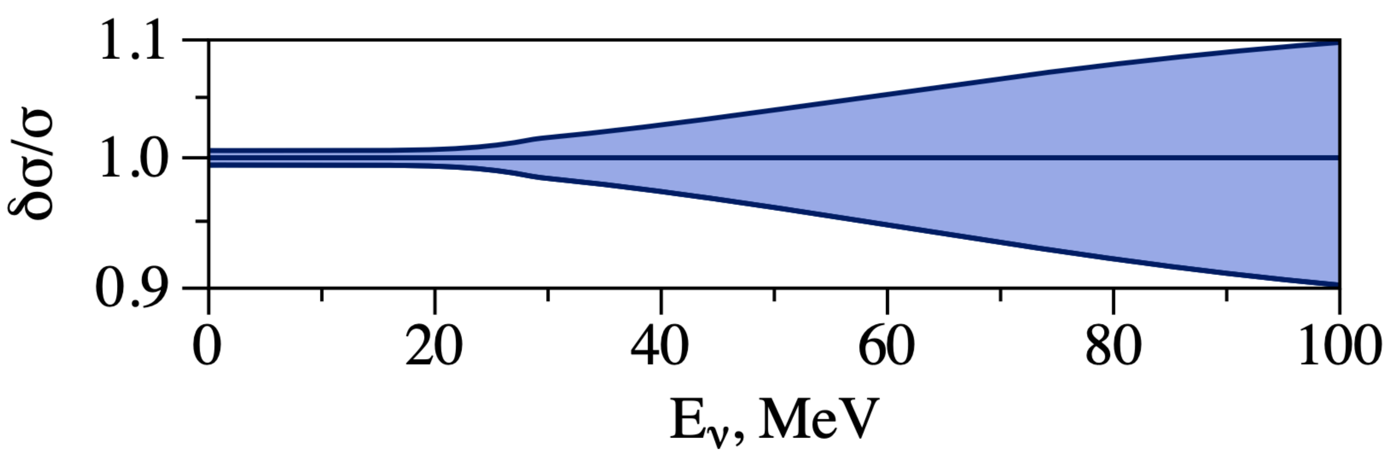
✱ Only a few percent theoretical uncertainty on the CEvNS cross section!

- Relative CEvNS cross section differences between the results of different calculations.



N. Van Dessel, V. Pandey, H. Ray and N. Jachowicz, Universe 9, 207 (2023)

- 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)

Yang et al. Phys. Rev. C 100, 054301 (2019)]

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

Hoferichter et al. [arXiv:2007.08529 [hep-ph]]

CEvNS Cross Section and Form Factors

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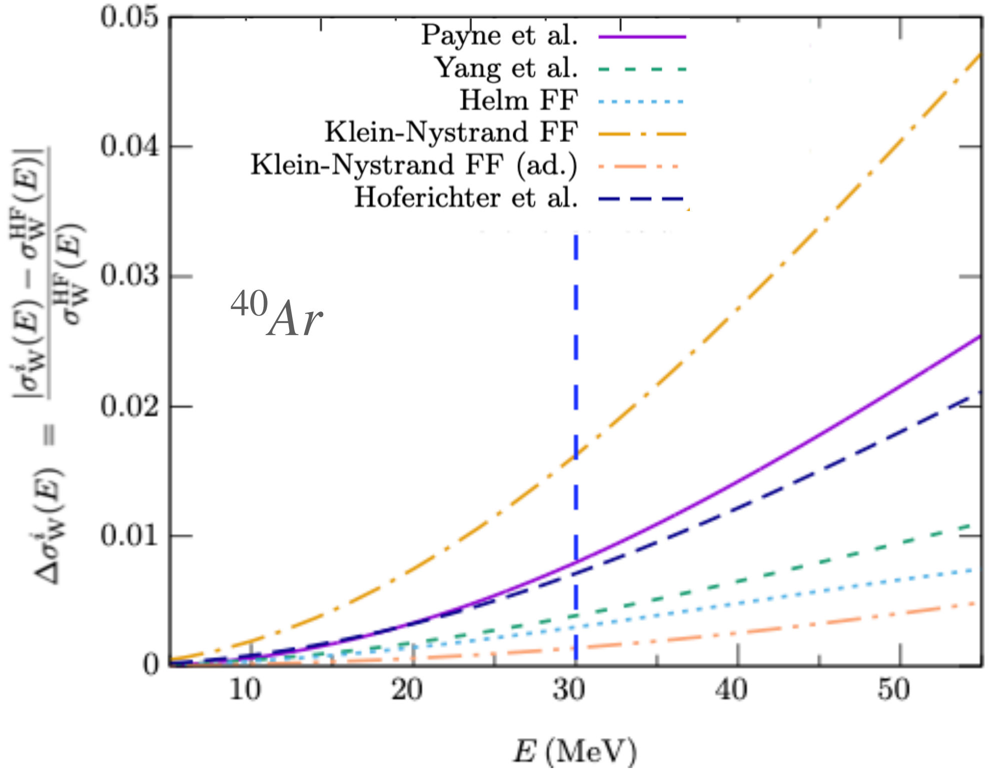

N. Van Dessel, V. Pandey, H. Ray and N. Jachowicz, Universe 9, 207 (2023)

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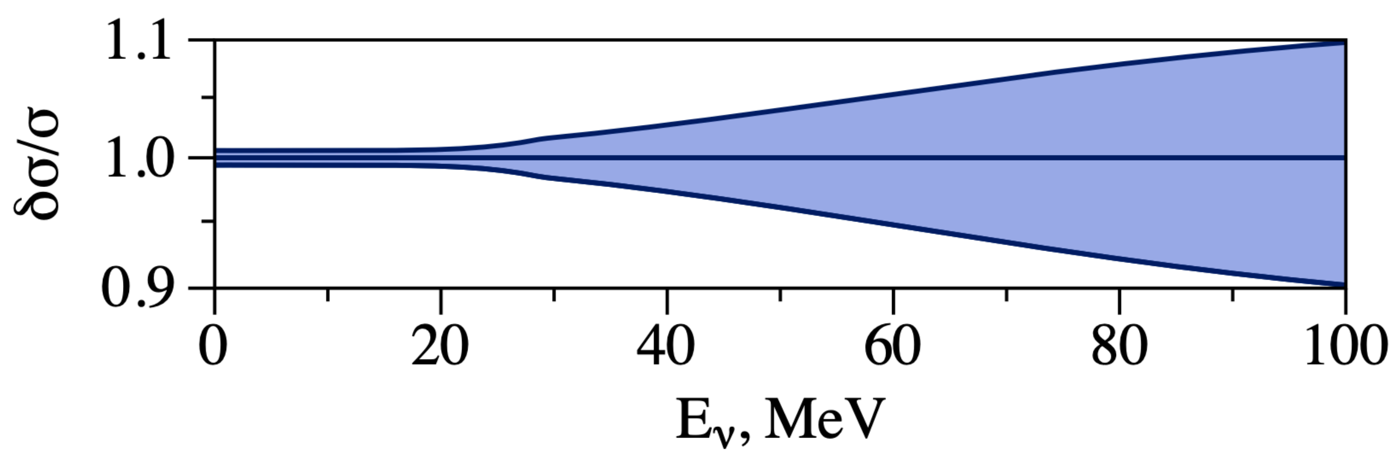
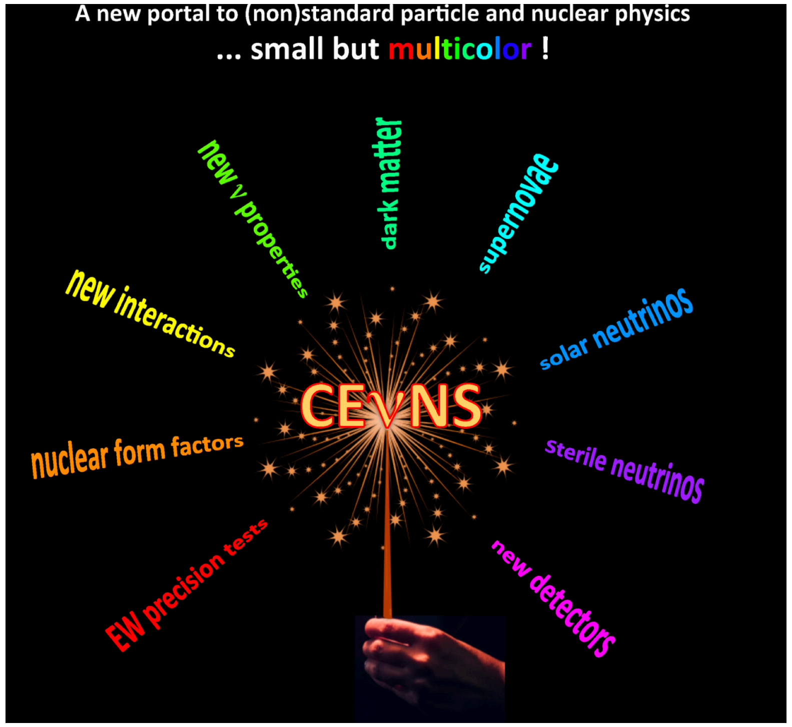


O. Tomalak, P. Machado, V. Pandey, R. Plestid, JHEP 02, 097 (2021)

- Any deviation from the SM predicted event rate either with a change in the total event rate or with a change in the shape of the recoil spectrum → new physics.

- SM expectation of CEvNS cross section have to be know at a precision that allows resolving degeneracies in the standard and non-standard physics observables.



Eligio Lisi, NuINT 2018

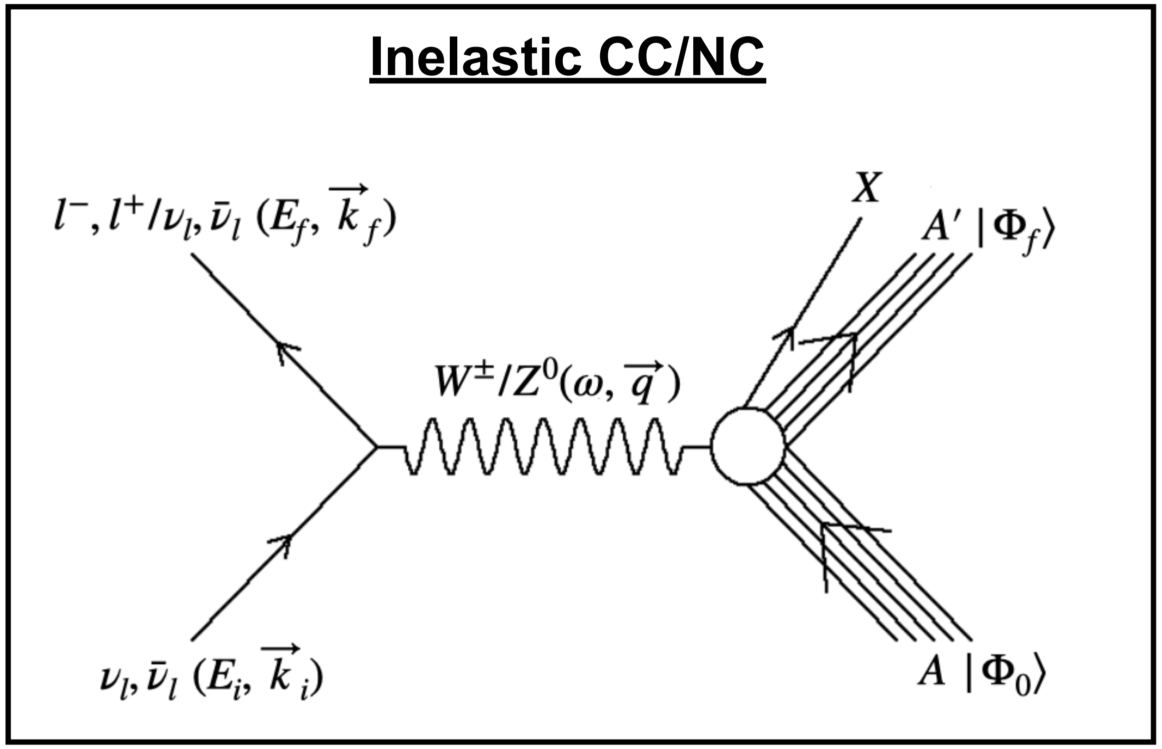
10s of MeV Inelastic Neutrino-Nucleus Scattering

10s of MeV Inelastic Neutrino-Nucleus Scattering

- **Core-collapse supernova** can be detected in DUNE using e.g. ν_e 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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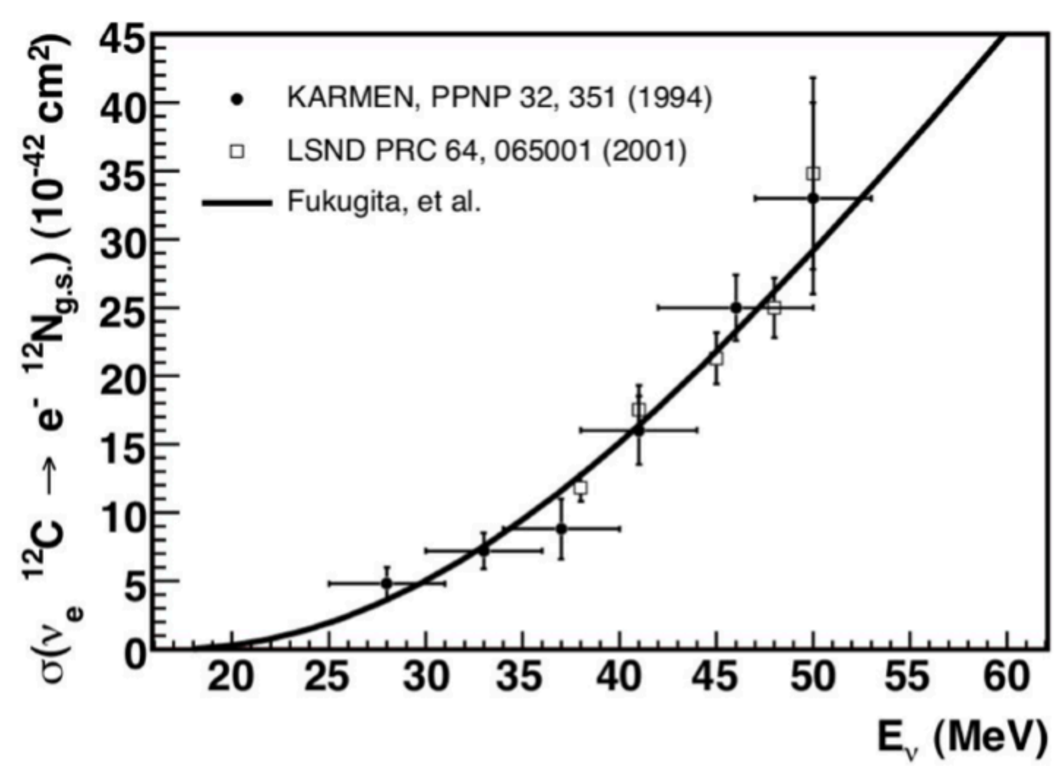
Reaction Channel	Experiment	Measurement (10^{-42} cm^2)
$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)
	E225	10.5 ± 1.0(stat) ± 1.0(sys)
	LSND	8.9 ± 0.3(stat) ± 0.9(sys)
$^{12}C(\nu_e, e^-)^{12}N^*$	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)
	E225	3.6 ± 2.0(tot)
	LSND	4.3 ± 0.4(stat) ± 0.6(sys)
$^{12}C(\nu_\mu, \nu_\mu)^{12}C^*$	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)
$^{12}C(\nu, \nu)^{12}C^*$	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)
$^{56}Fe(\nu_e, e^-)\ ^{56}Co$	KARMEN	256 ± 108(stat) ± 43(sys)
$^{127}I(\nu_e, e^-)^{127}Xe$	LSND	284 ± 91(stat) ± 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 (2023)

Past measurements on Carbon



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

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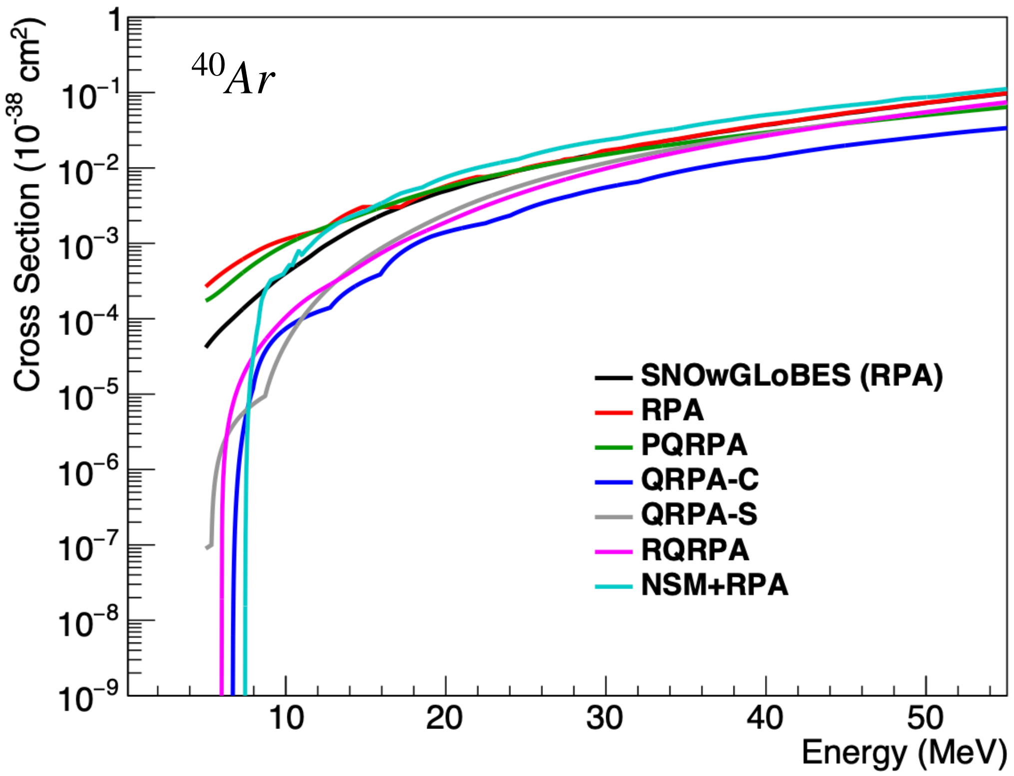
No measurements on Argon yet

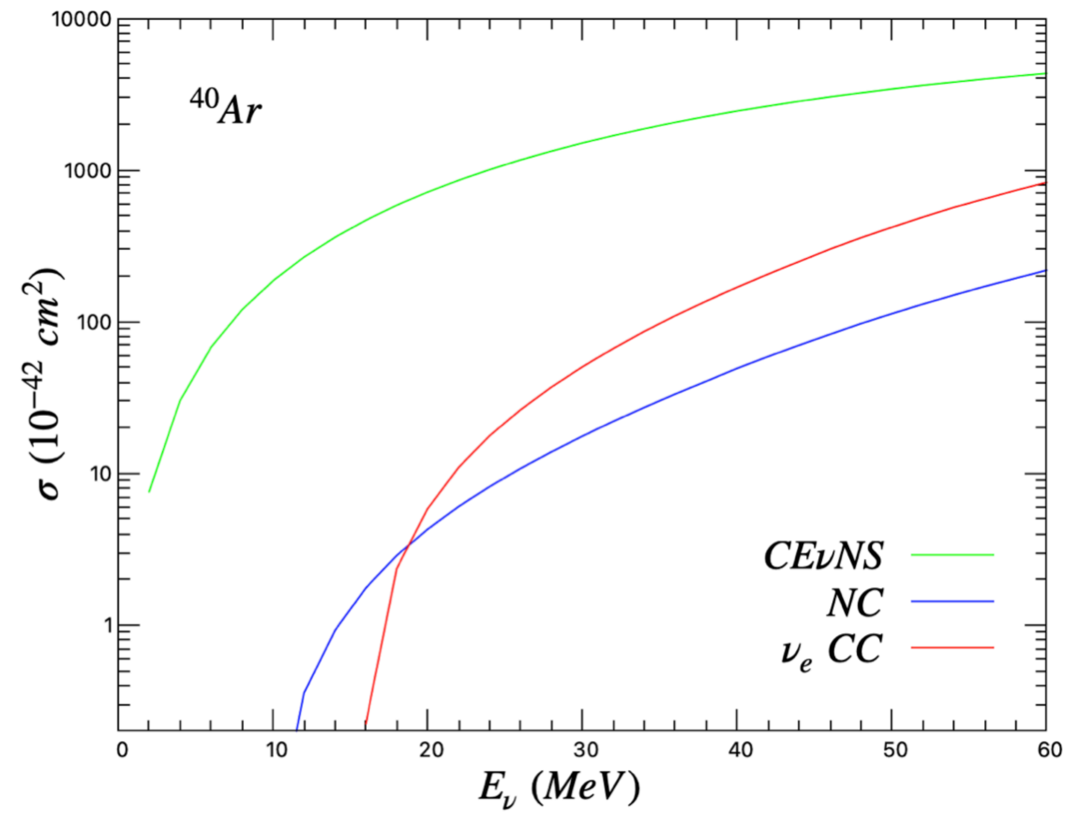


DUNE Collaboration, arXiv:2303.17007 [hep-ex]

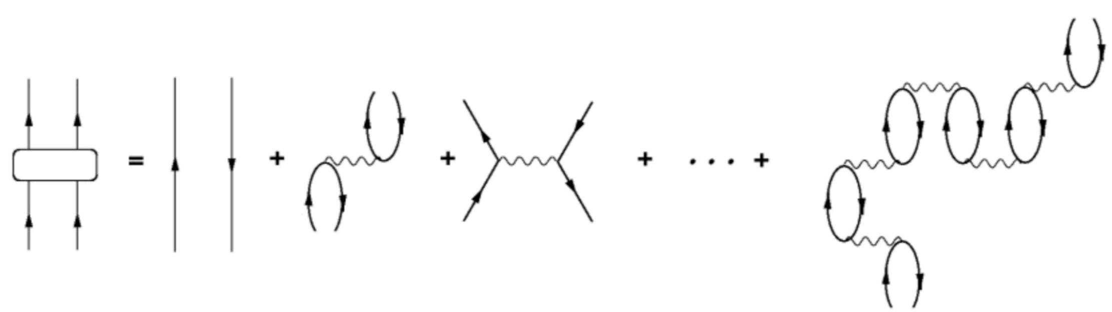
"Current understanding of $\sigma(E_\nu)$ is inadequate. Measuring ε energy release (other parameters) to 10% requires 5% (20%) knowledge of the cross section!"

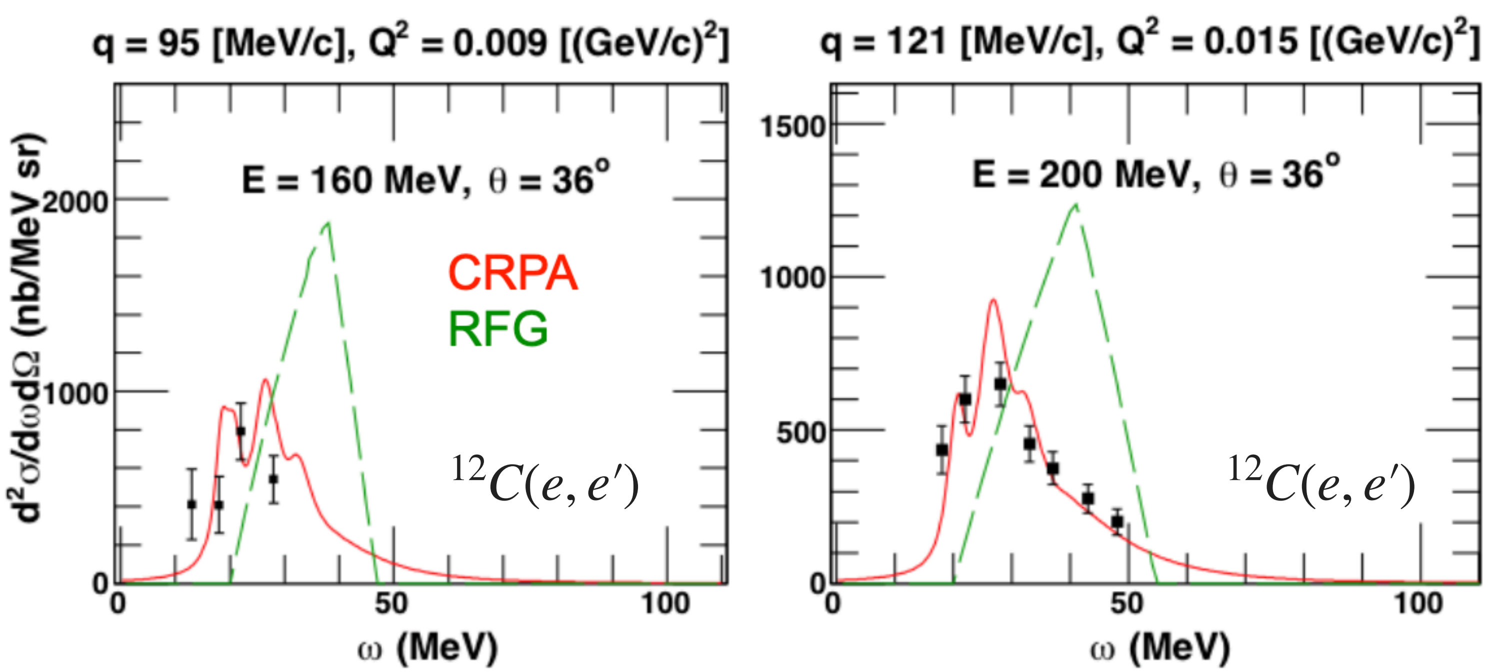
10s of MeV Inelastic Neutrino-Nucleus Scattering: HF-CRPA Model

- 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.



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





V. Pandey, PhD Thesis (2016)

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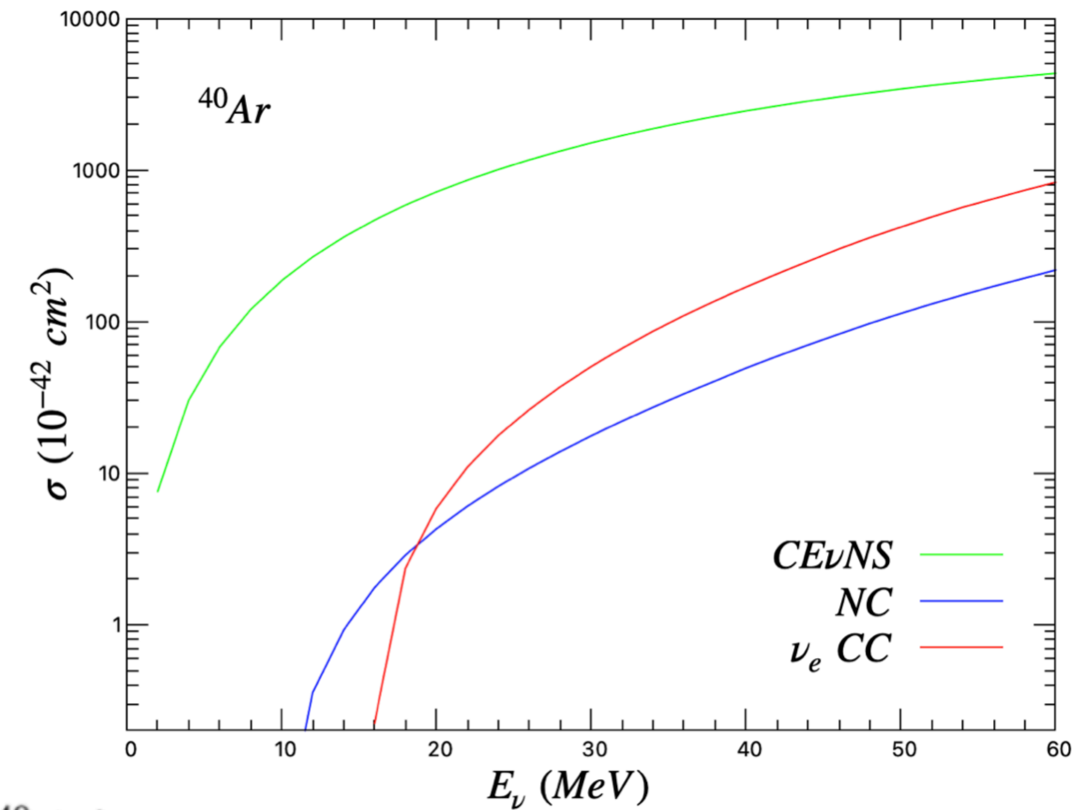
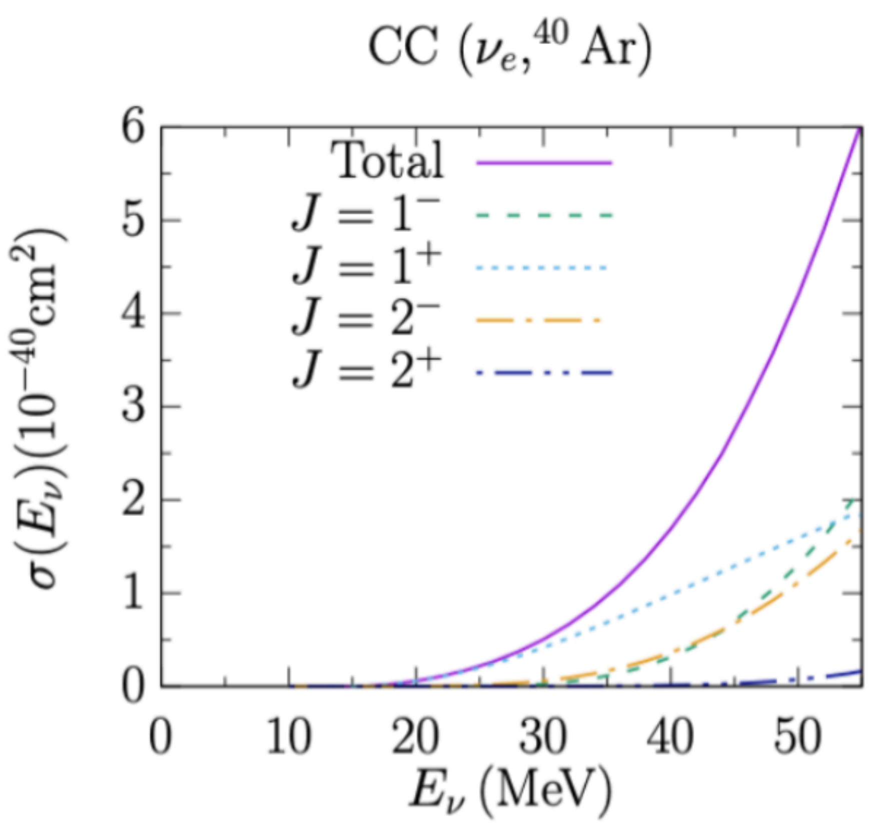
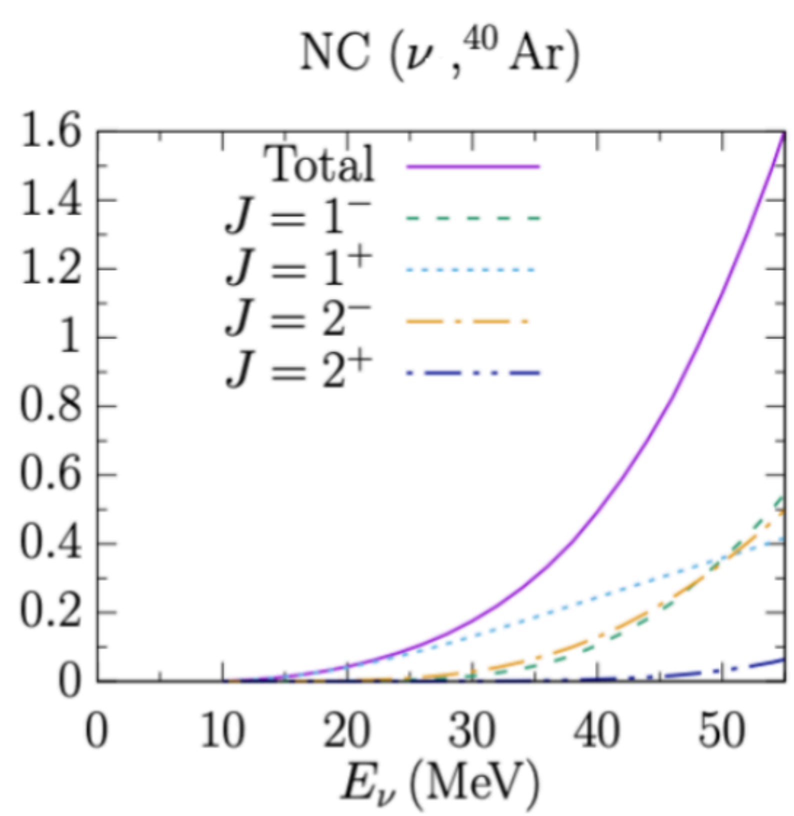


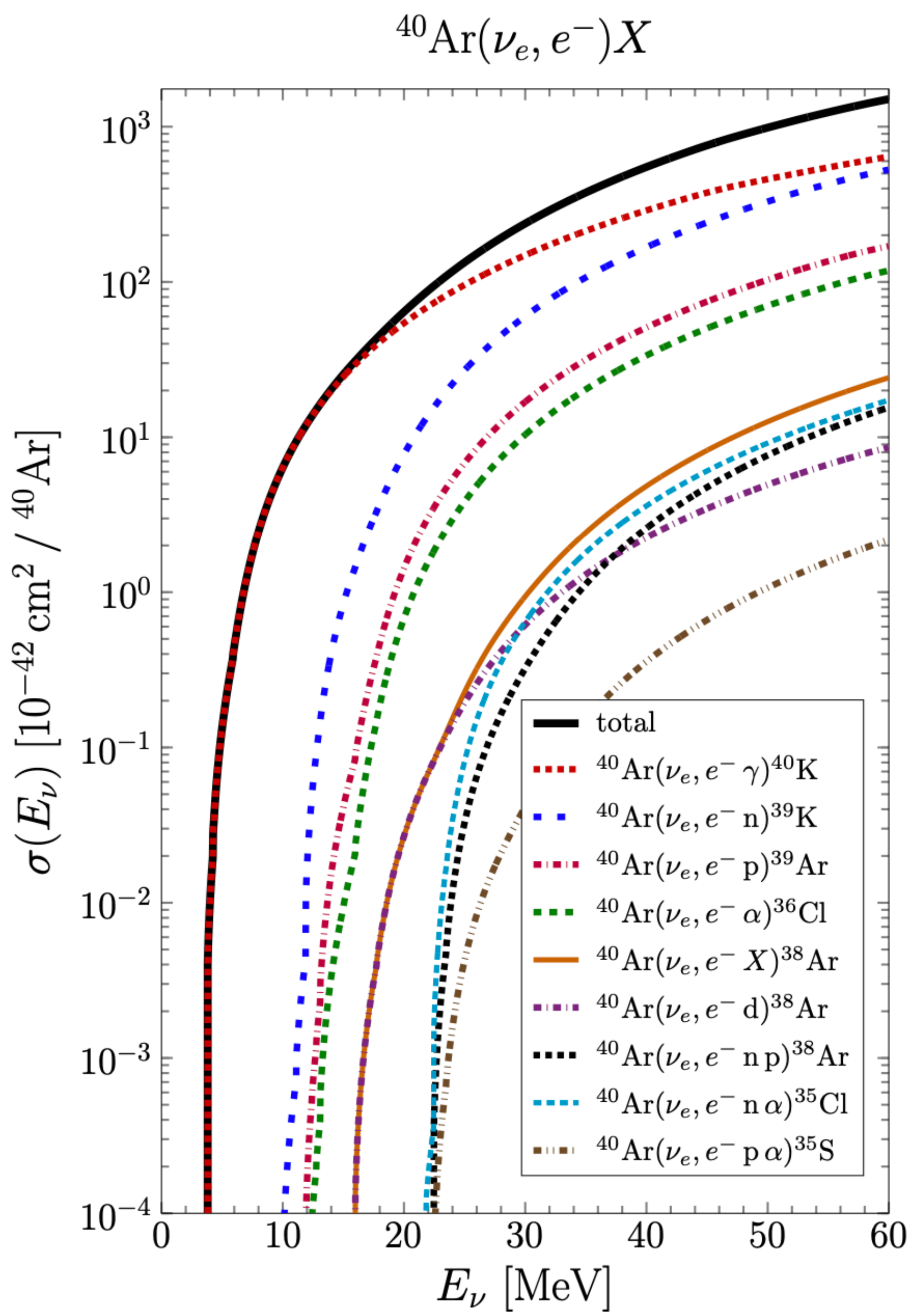




N. Van Dessel, V. Pandey, H. Ray and N. Jachowicz, Universe 9, 207 (2023)

10s of MeV Inelastic Neutrino-Nucleus Scattering: MARLEY

- MARLEY (Model of Argon Reaction Low Energy Yields) is a dedicated low-energy neutrino event generator developed by Steven Gardiner to simulate tens-of-MeV neutrino-nucleus interactions on argon.



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

I. Inclusive scattering on the nucleus:

Allowed approximation (long–wavelength ($q \to 0$) and slow nucleons ($p_N/m_N \to 0$) limit), Fermi and Gamow-Teller matrix elements:

II. Nuclear de-excitation:

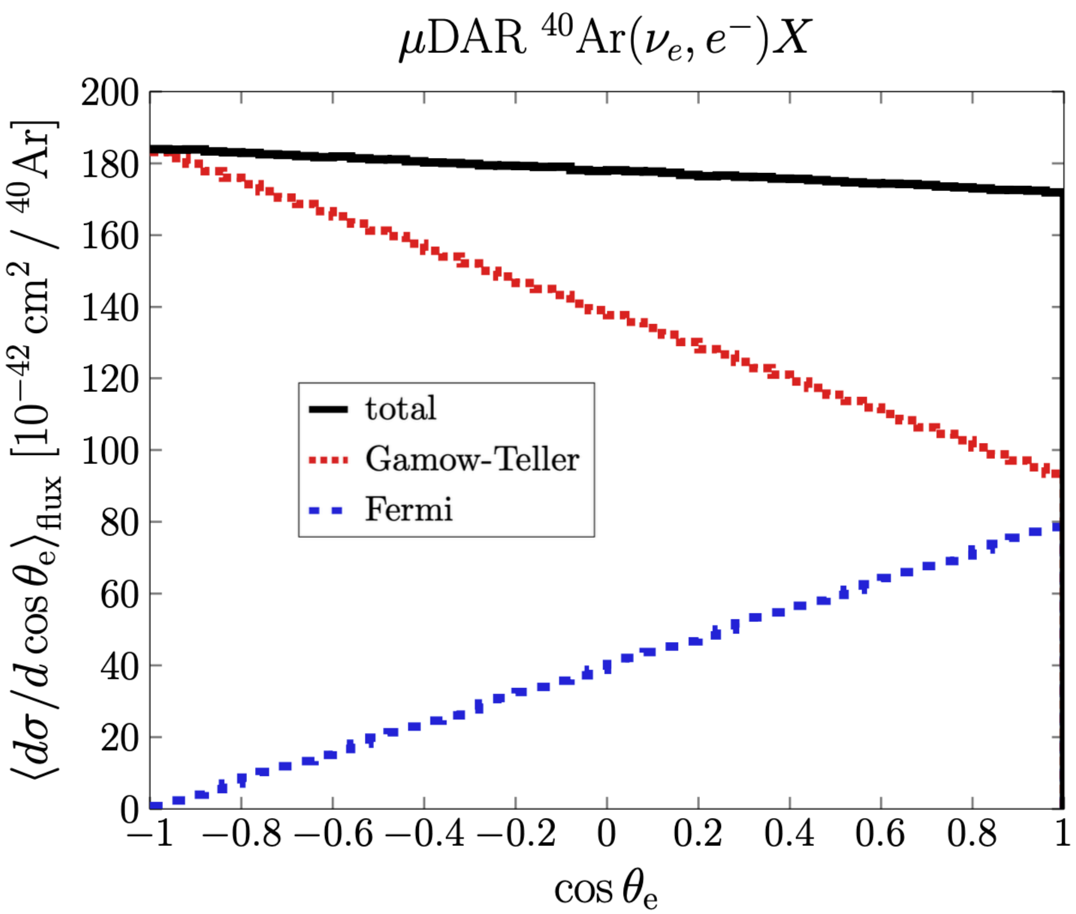
For bound nuclear states, the de-excitation gamma rays are sampled using tables of experimental branching ratios.

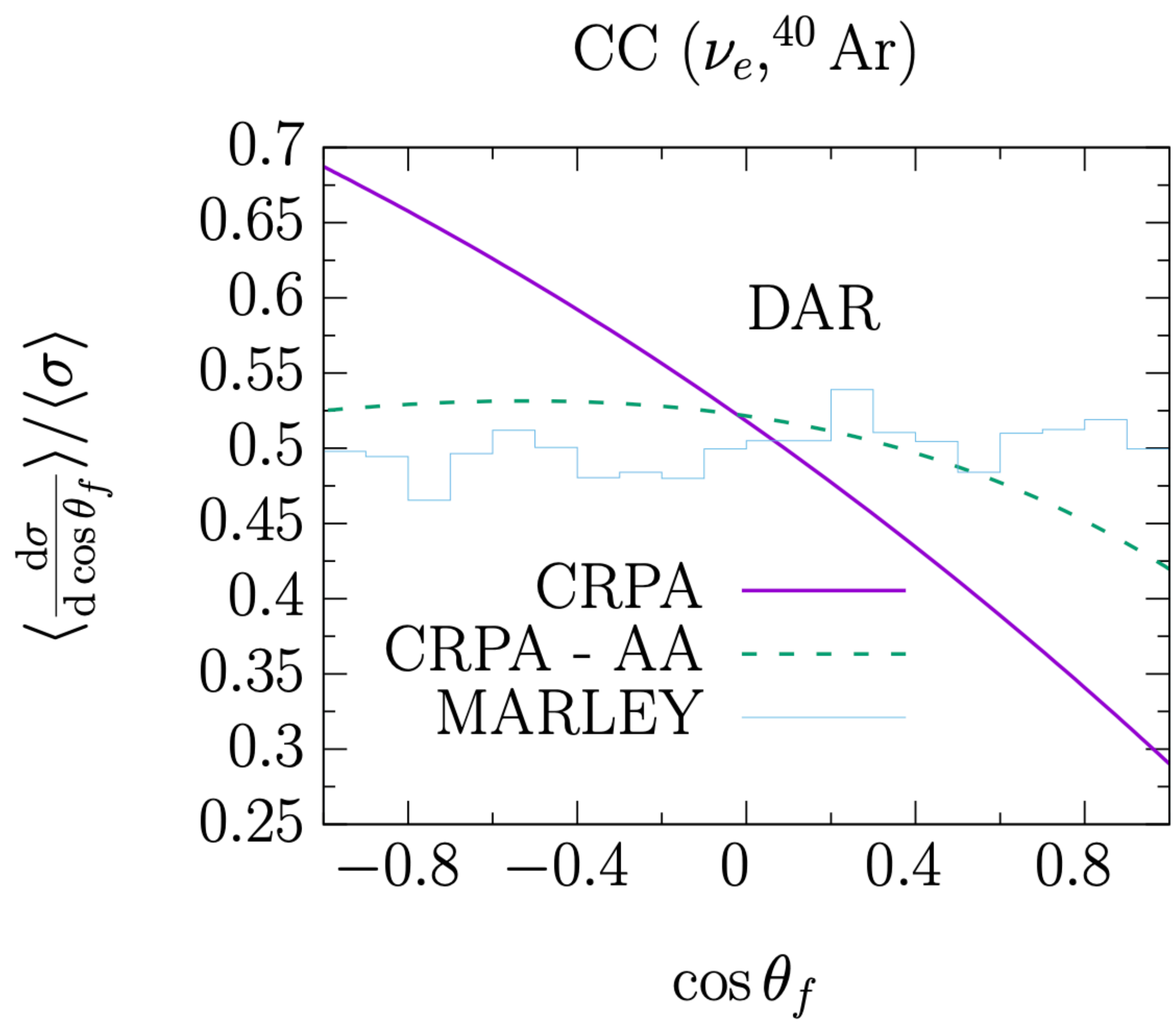
For unbound nuclear states, MARLEY simulates the competition between gamma-ray and nuclear fragment emission using the Hauser-Feshbach statistical model.

See Steven Gardiner's talk from Tuesday

- **CRPA and MARLEY**

- **Allowed and forbidden transitions**





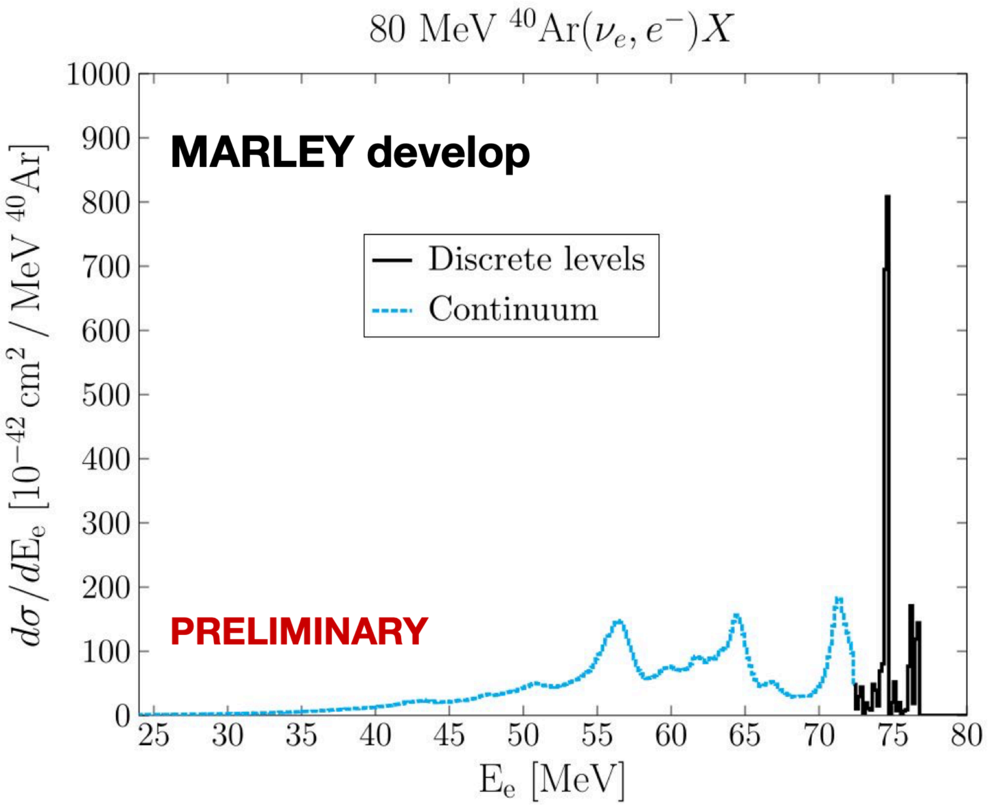
- MARLEY: Allowed approximation (long–wavelength ($q \to 0$) and slow nucleons ($p_N/m_N \to 0$) limit), Fermi and Gamow-Teller matrix elements predicts a nearly flat angular distribution.

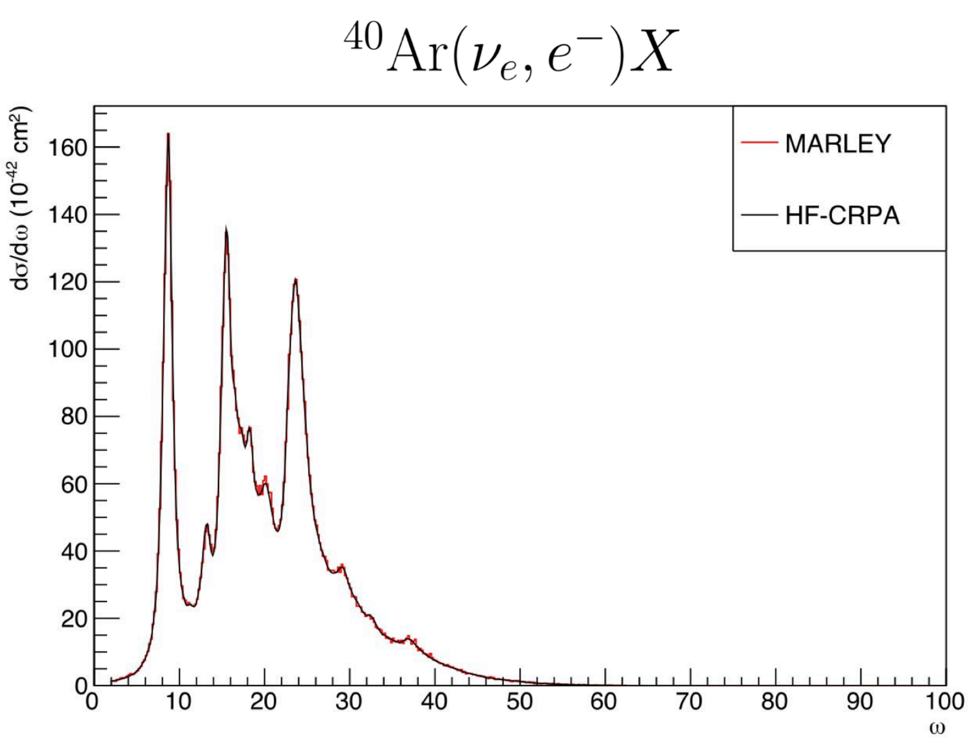
- CRPA: includes full multipole expansion of nuclear matrix element (allowed as well as forbidden transitions), predict more backwards strength.

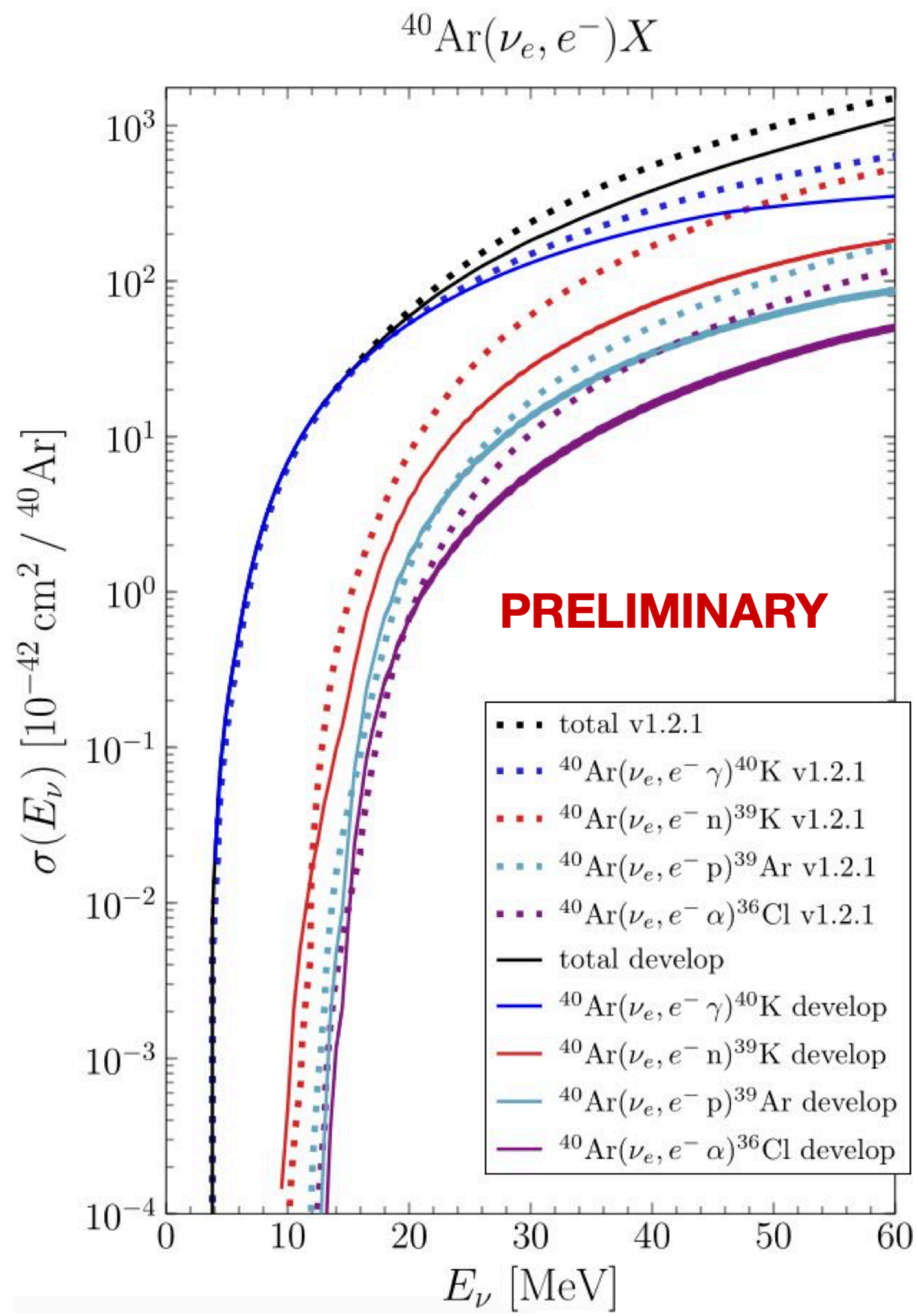
- **CRPA implementation in MARLEY is on-going.**

L. A. El-Haj, P. B. Alzas, S. Gardiner, N. Jachowicz, A. Nikolakopoulos, V. Pandey, in preparation.

More details in Steven Gardiner's talk on Tuesday



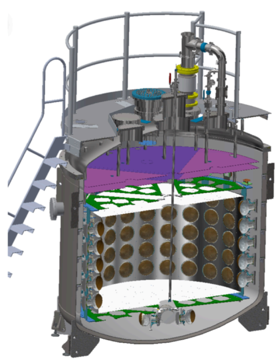




10s of MeV Inelastic Neutrino-Nucleus Scattering: Measurements

✦ **CEvNS experiments at pion-decay at rest facilities are well suited to perform these measurements.**

- **Coherent CAPTAIN Mills at LANL:** 10 ton LAr detector at Lujan center at LANL. Collected data in 2019, 2021, 2022, and currently is in operation.

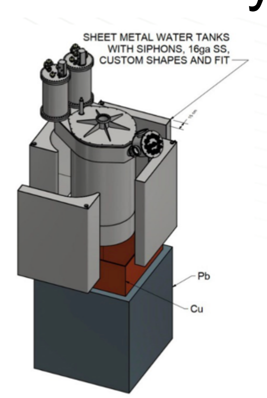


	Total events/year*
CEvNS	300.82
CC (ν_e)	57.25
NC	5.28

*6 months of running, at 23 m, for 5 tons. E_ν =30 MeV.

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

See Yuri Efremenko's talk this morning



- **F2D2 at Fermilab**: Opportunity to measure these cross sections with ~100 ton scale LAr detectors at PIP-II Beam Stop Facility.

See Jonathan Williams's talk on Tuesday

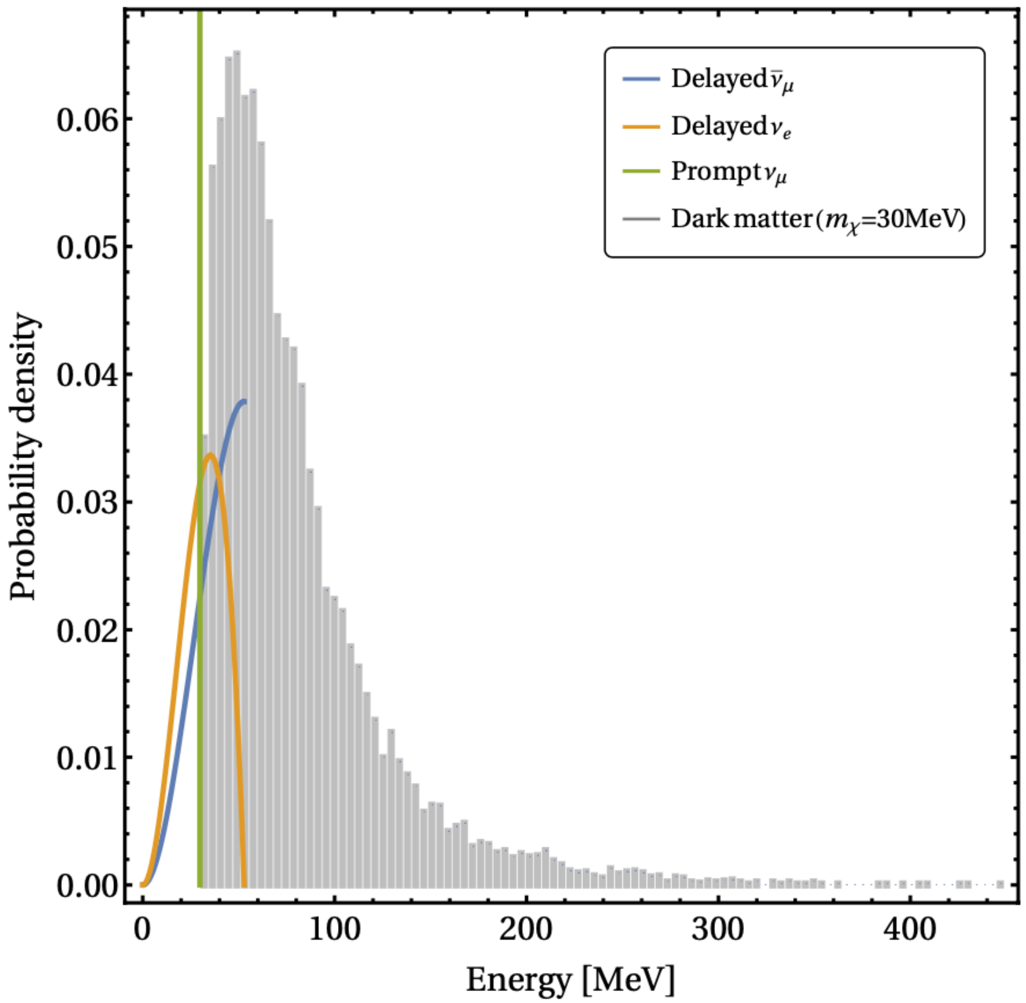
"Physics Opportunities at a Beam Dump Facility at PIP-II at Fermilab and Beyond", 2311.09915 [hep-ex]

Neutrino-nucleus Scattering => DM-nucleus Scattering

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

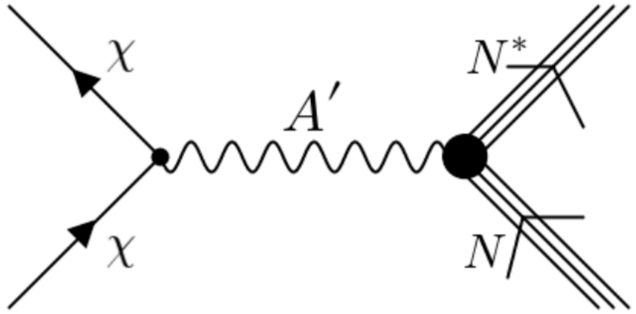
  B. Dutta, et al., arXiv:2006.09386 [hep-ph]

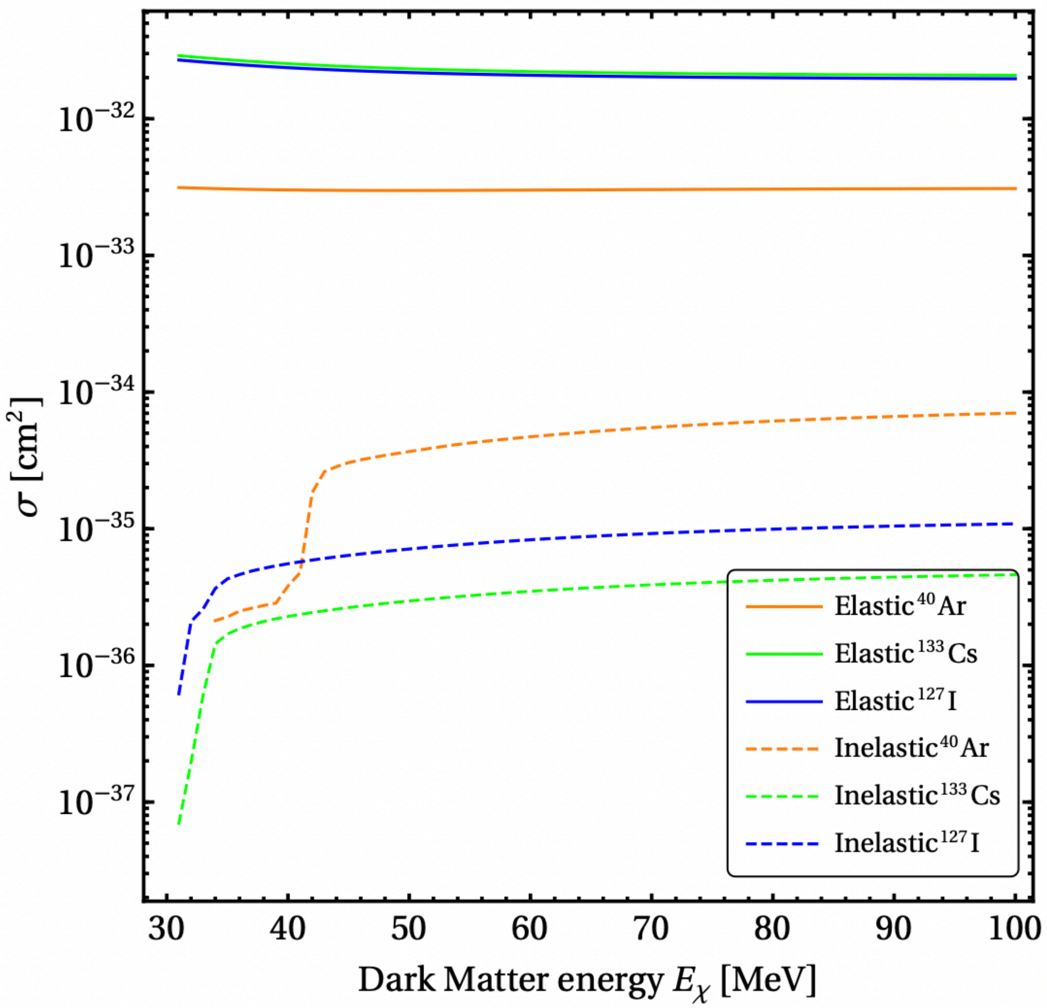
- Dark photon produced in pion decay (e.g. at SNS or at LANL)



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.



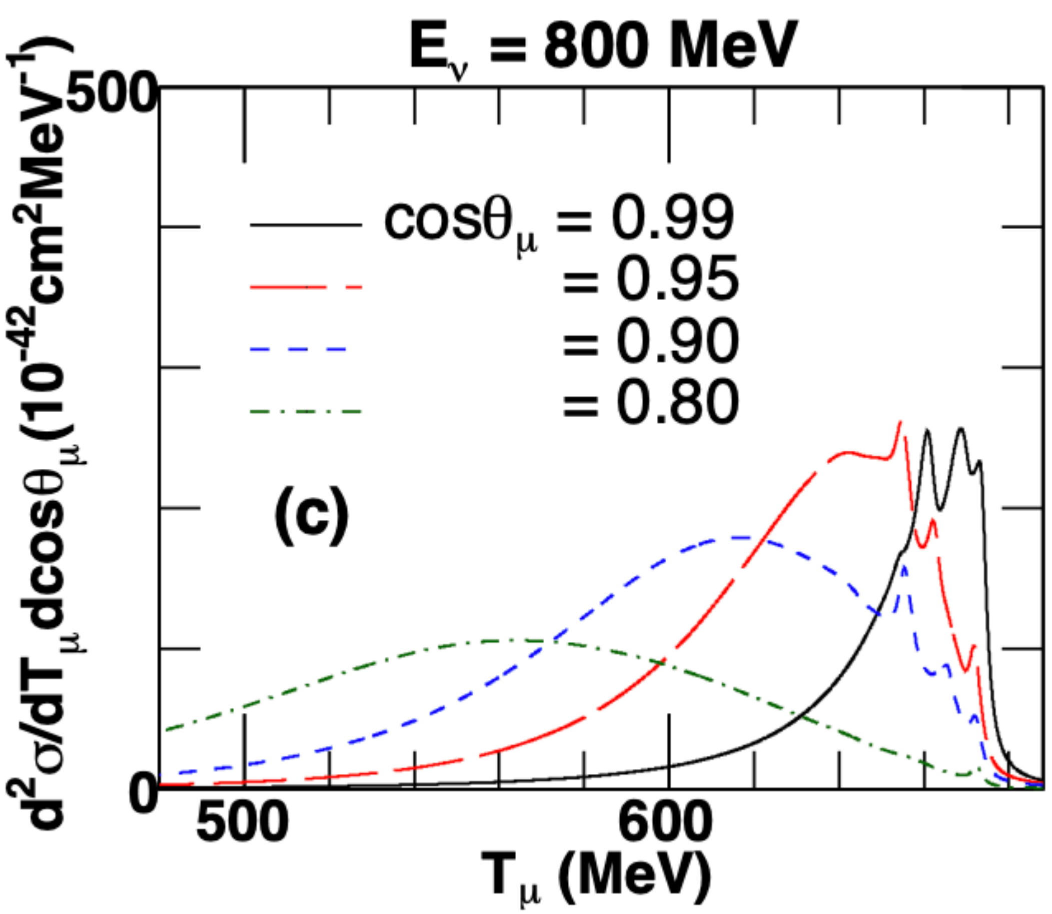


B. Dutta, W. C. Huang, J. L. Newstead, V. Pandey, Phys. Rev. D 106, 113006 (2022)

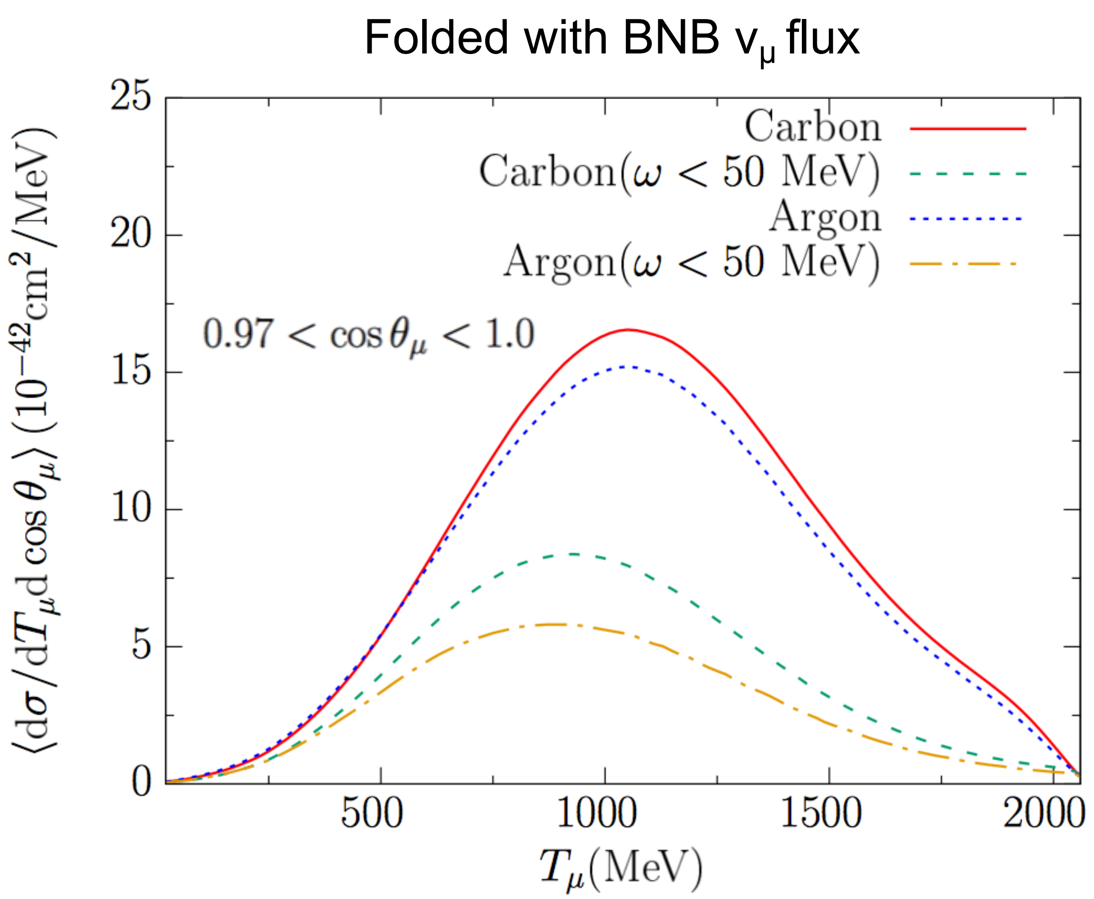
10s of MeV Physics in GeV-scale Neutrino Beams

10s of MeV Physics in GeV-scale Neutrino Beams

- 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.



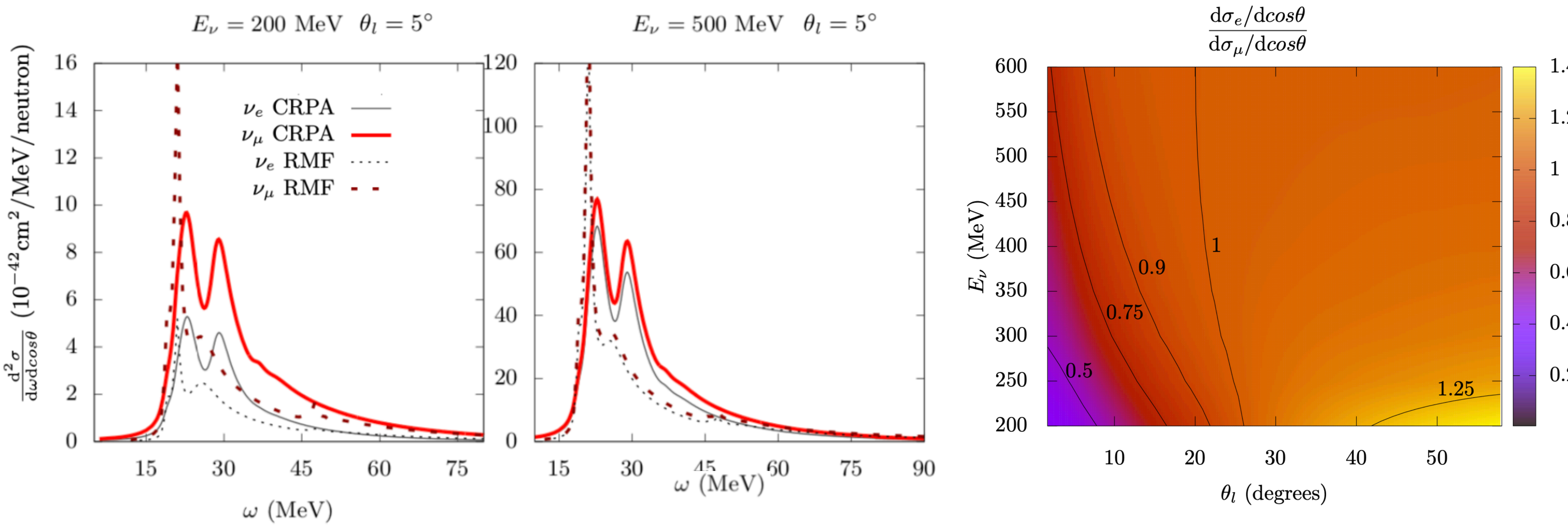
V. Pandey, N. Jachowicz, T. Van Cuyck, J. Ryckebusch, M. Martini, Phys. Rev. C92, 024606 (2015)



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

10s of MeV Physics: Effect on ν_e to ν_μ cross-sections

- 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.
  - At low energy, the ν_e to ν_μ cross-section ratio depends on the details of the nuclear physics.
  - At low energy, (ω, q) transferred are different due to the lepton mass difference. The cross section is function of (ω, q) therefore the cross sections are different.
  - The muon mass in the final state leads to a larger momentum transfer which shifts the response to larger values.

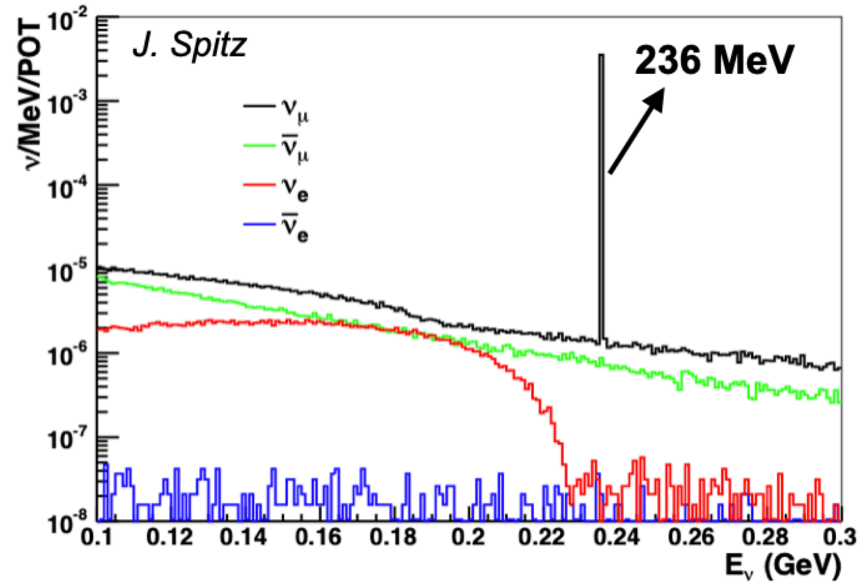


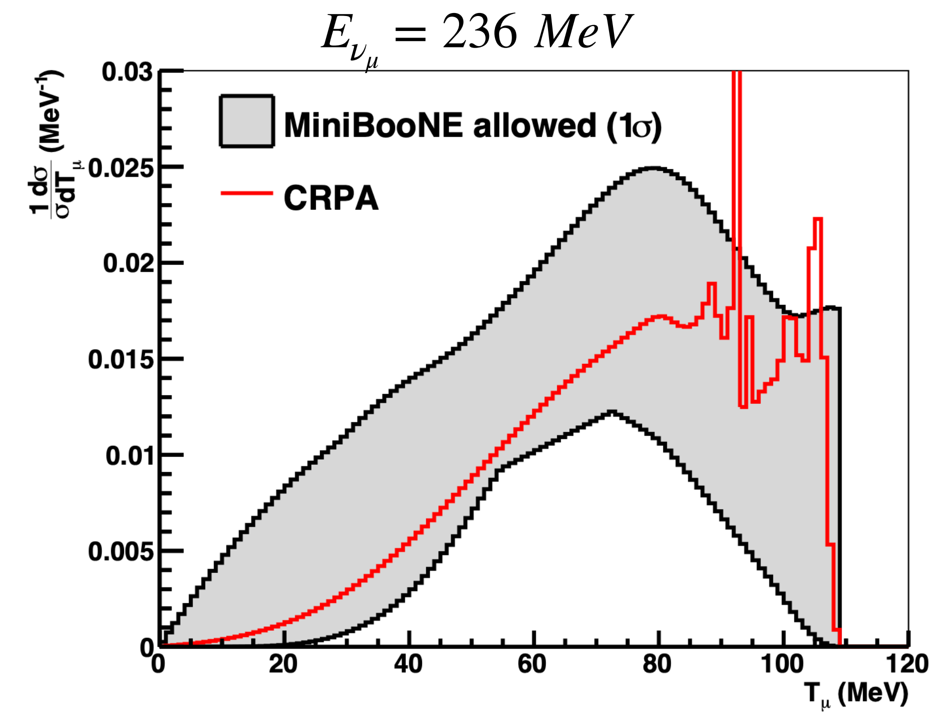
A. Nikolakopoulos, N. Jachowicz, N. Van Dessel, K. Niewczas, R. González-Jiménez, J. M. Udías, V. Pandey, Phys. Rev. Lett. 123, 052501 (2019).

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

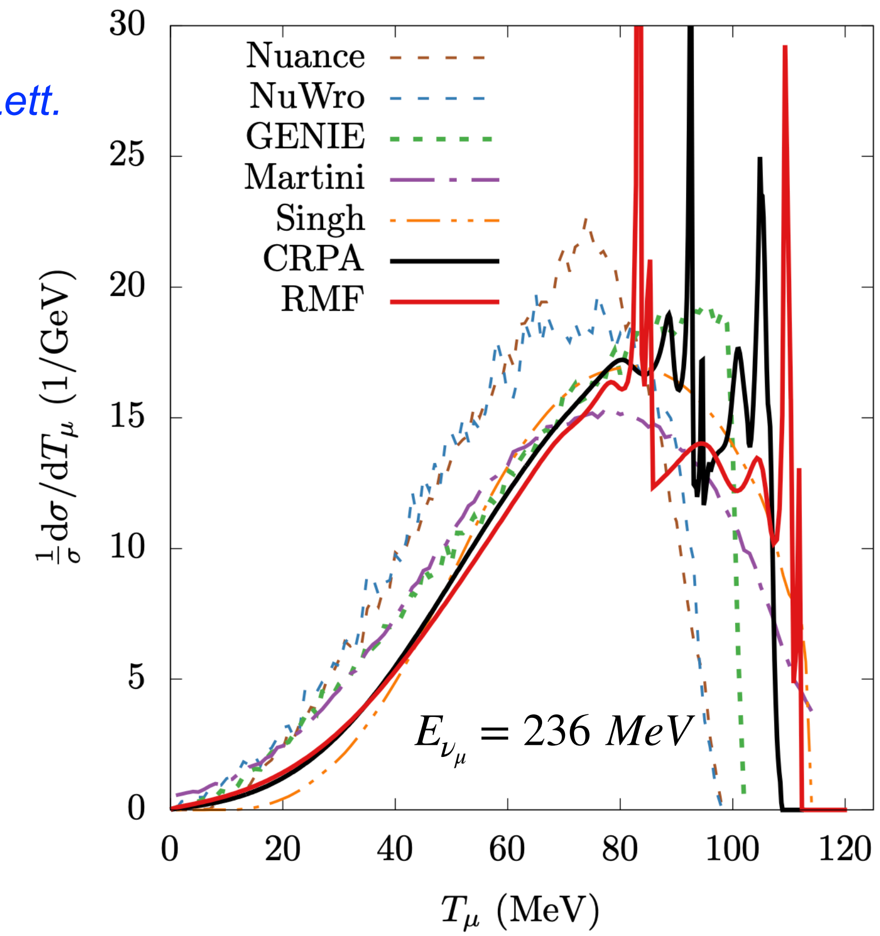
$$K^+ \rightarrow \mu^+\nu_\mu, E_{\nu_\mu} = 236\ MeV$$

Kaon decay at rest





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



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

10s of MeV Physics in GeV-scale Neutrino Beams: KDAR Neutrinos

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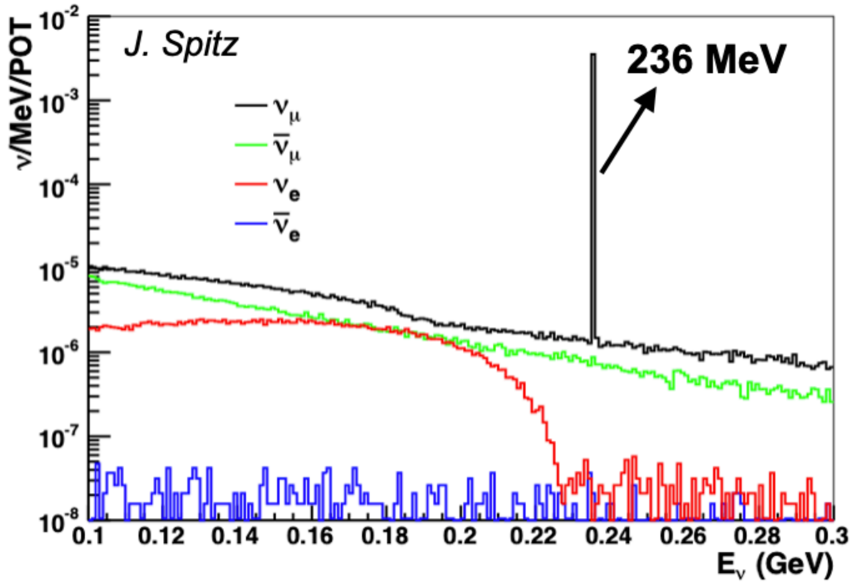
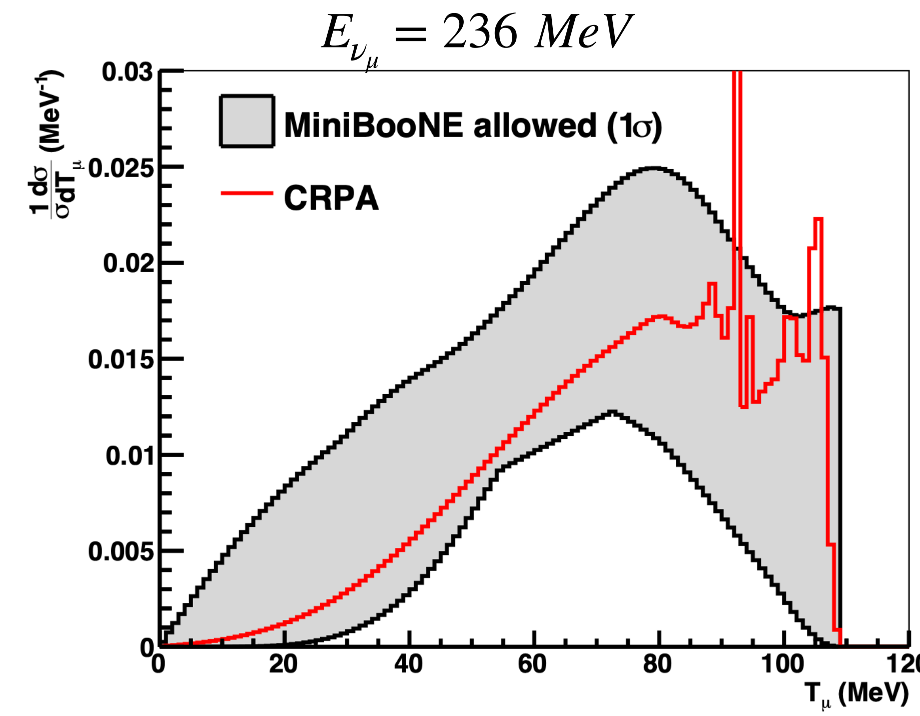




- New Measurement from JSNS^2 at JPARC.

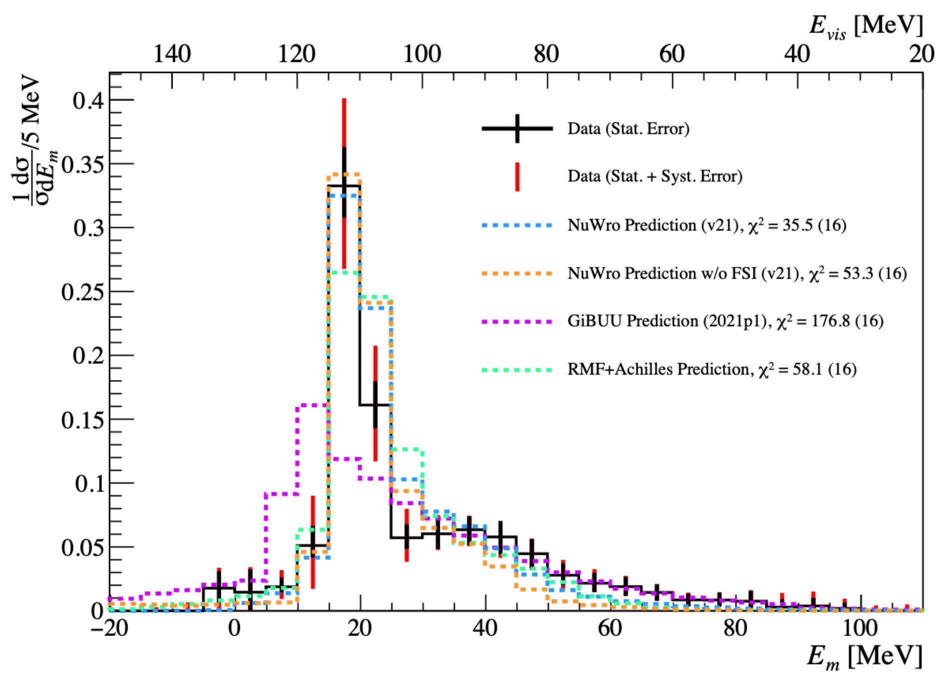
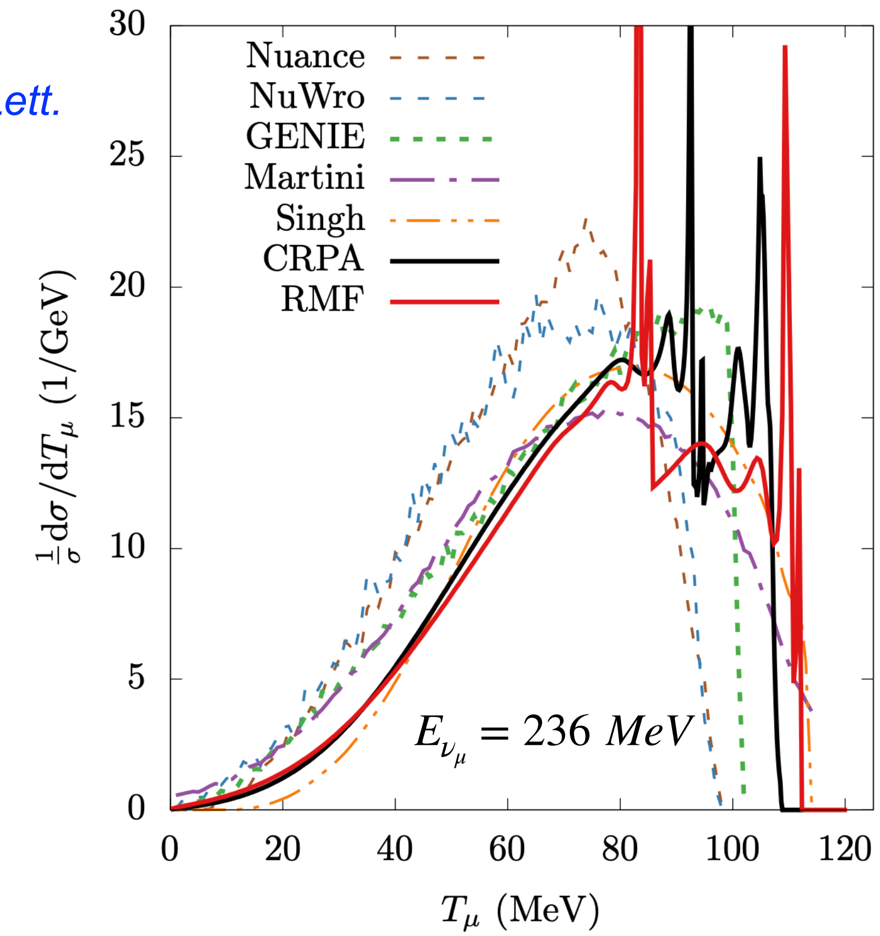


FIG. 4. The KDAR ν_μ CC missing energy, E_m, shape-only differential cross section measurement compared to several neutrino event generator/model predictions. The top x-axis provides the corresponding E_{vis} for each E_m value.

JSNS^2 Collaboration: arXiv:2409.01383 [hep-ex]

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



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

Summary

- Interactions of low energy (10s of MeV) neutrinos with the nucleus - elastic (CEvNS) and inelastic - are interesting for studies of various nuclear, neutrino, BSM and astrophysical processes.

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

- Microscopic calculations, future precise measurements of CEvNS cross section and PVES asymmetry measurements will enable precise determination of weak form factor and neutron distributions.

- CEvNS experiments at stopped-pion sources are powerful avenues to measure 10s of MeV inelastic CC and NC neutrino-nucleus cross sections. These measurements will play a vital role in enhancing DUNE’s capability of detecting core-collapse supernovae neutrinos.

- There has been a significant development in the last few years at all front, lot more work is needed to achieve the required precision.