Neutrino Physics Opportunities with Pion and Kaon Decay-at-Rest Neutrino Source

Vishvas Pandey (विश्वास पाण्डेय)

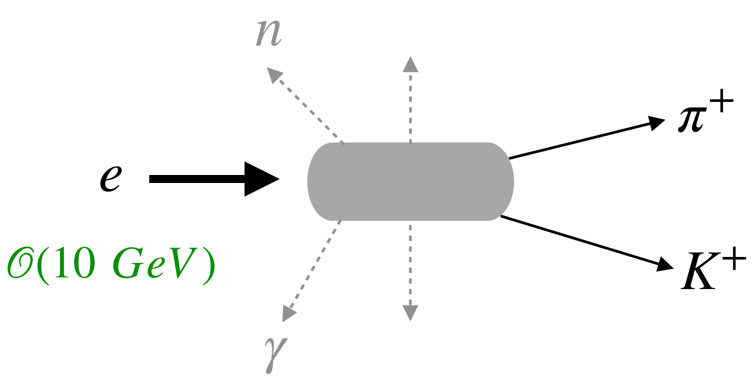
Fermi National Accelerator Laboratory

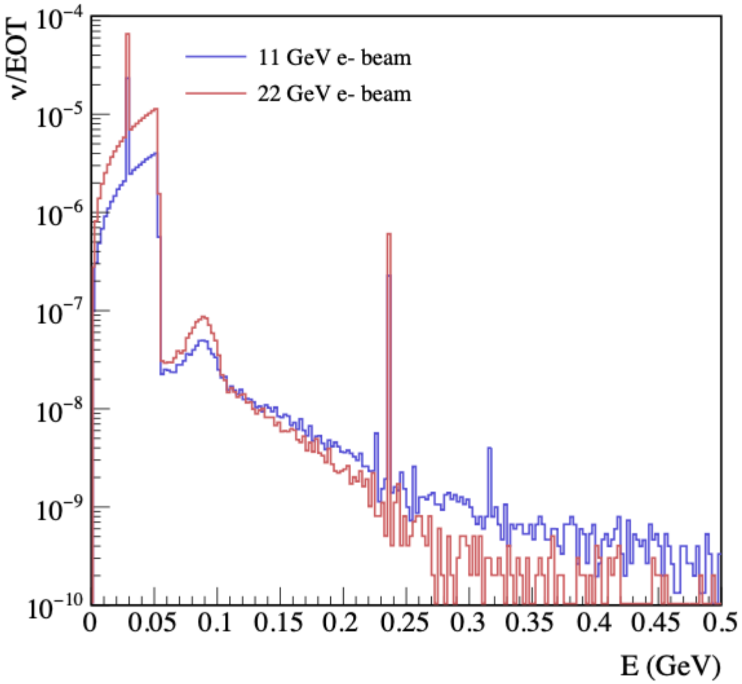
Secondary Beams at Jefferson Lab Workshop (BDX & Beyond), JLab, September 4 - 5, 2025

U.S. DEPARTMENT of ENERGY

Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

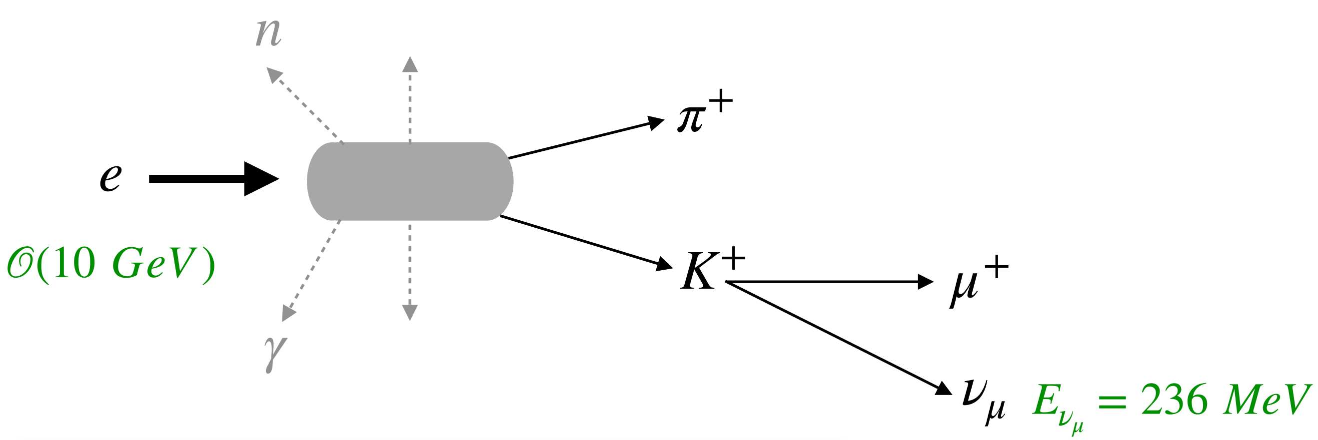
Neutrinos at BDX Facility at JLab

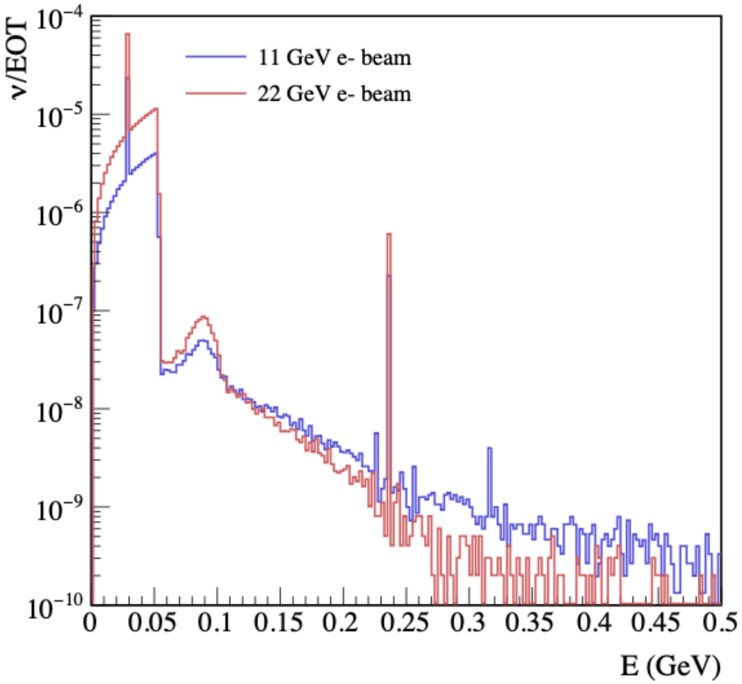




M. Battaglieri et al., Instruments 8, 1 (2024)

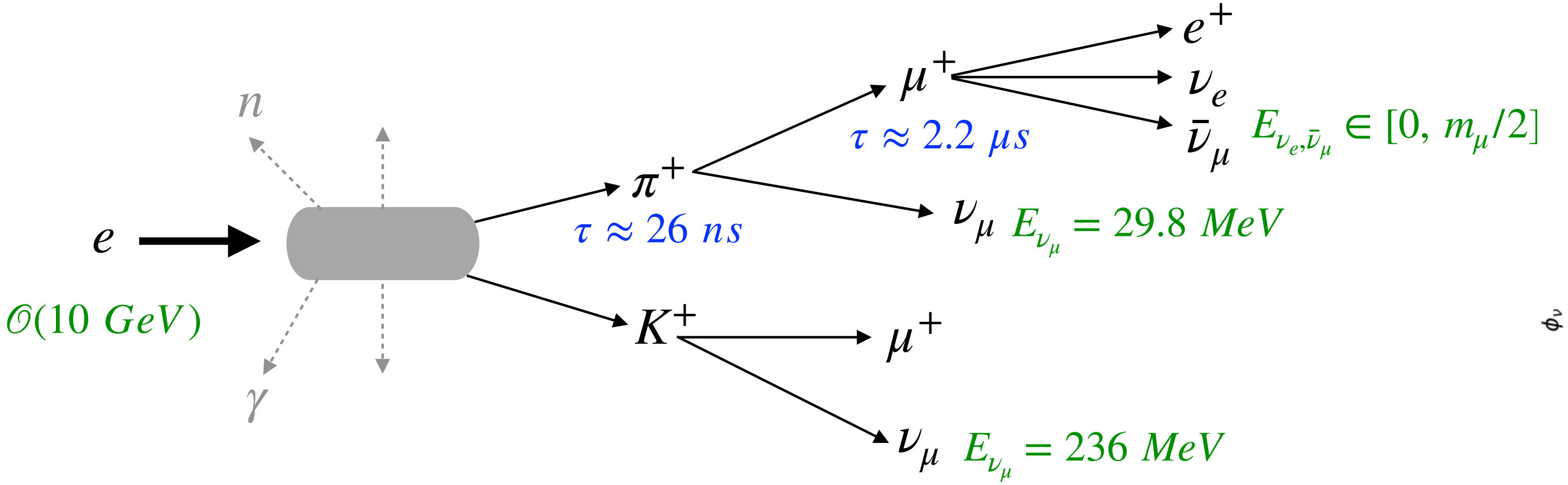
Neutrinos at BDX Facility at JLab

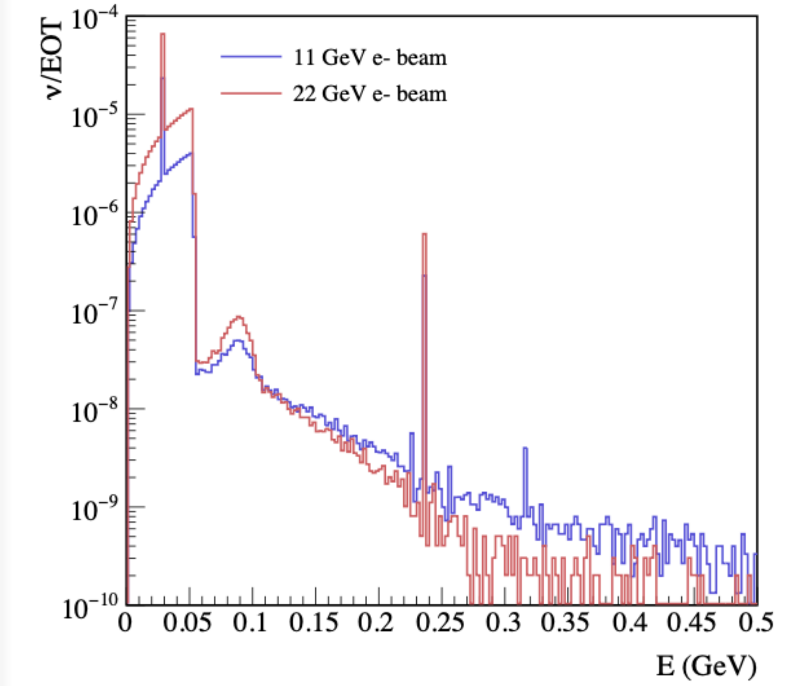




M. Battaglieri et al., Instruments 8, 1 (2024)

Neutrinos at BDX Facility at JLab

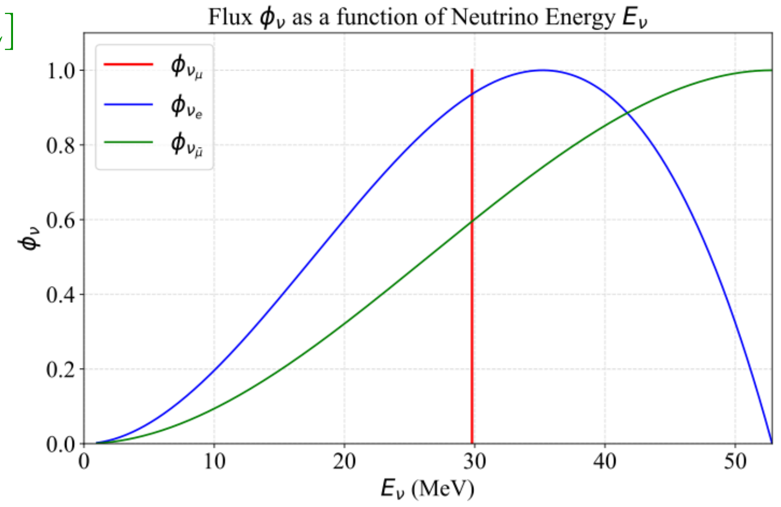




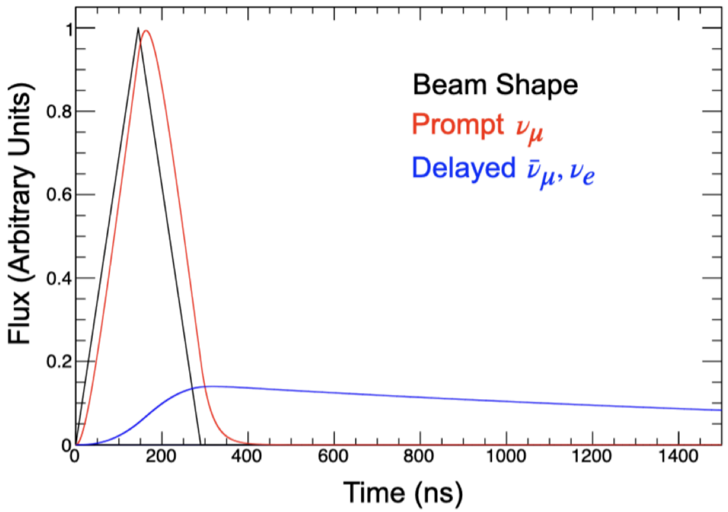
M. Battaglieri et al., Instruments 8, 1 (2024)

- Prompt ν_μ can be separated from delayed $\nu_e, \bar{\nu}_\mu$ using timing information.

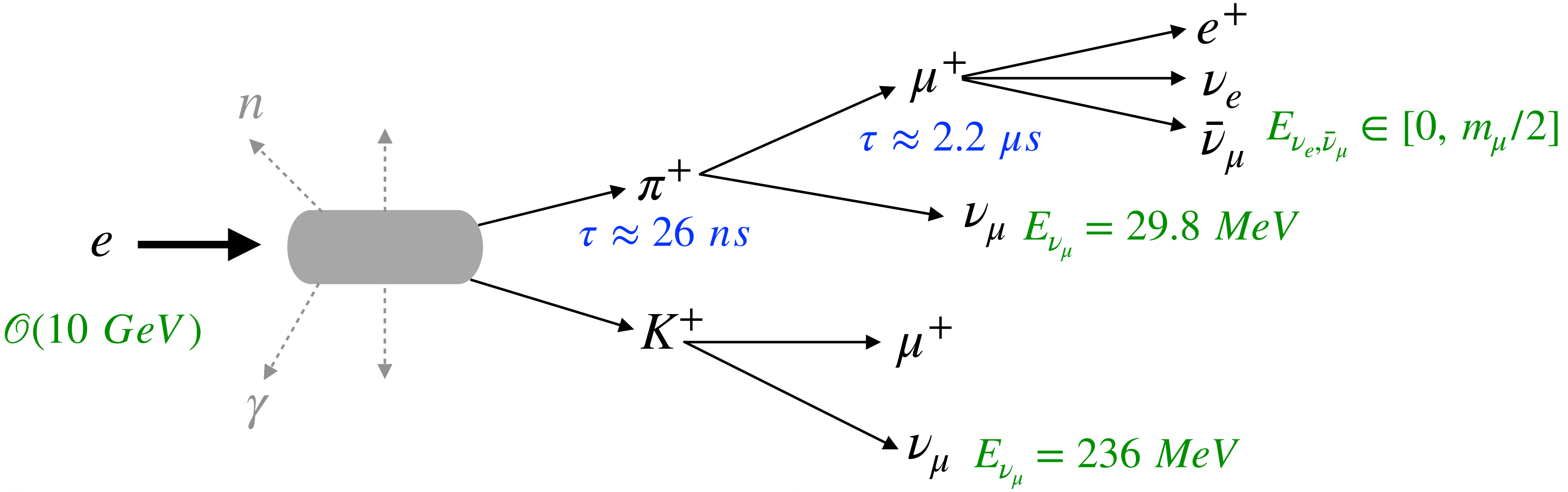
piDAR Neutrinos: Energy Profile

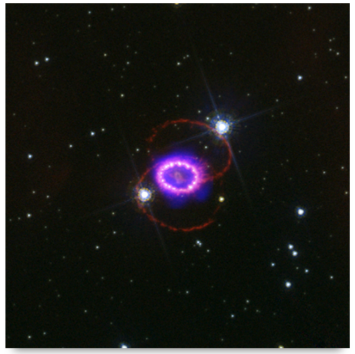


piDAR Neutrinos: Timing Profile

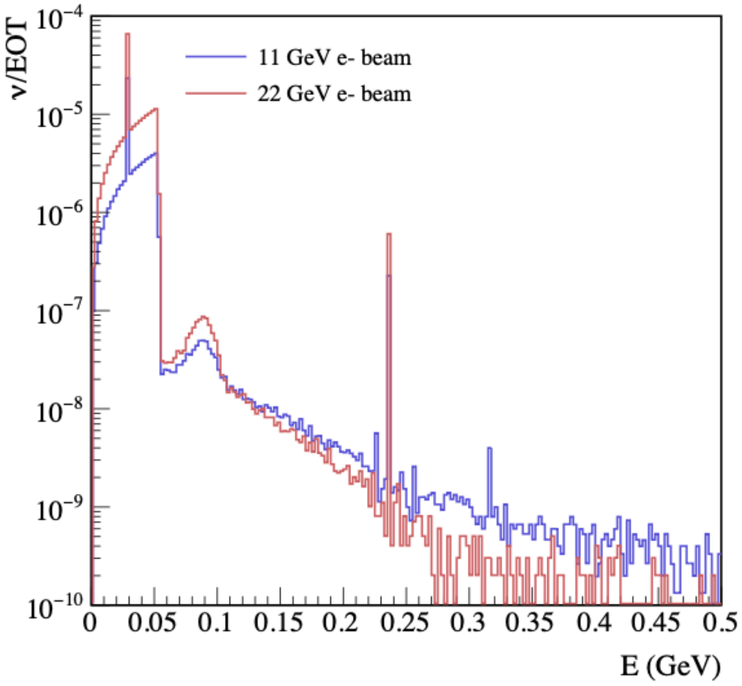


Neutrinos at BDX Facility at JLab

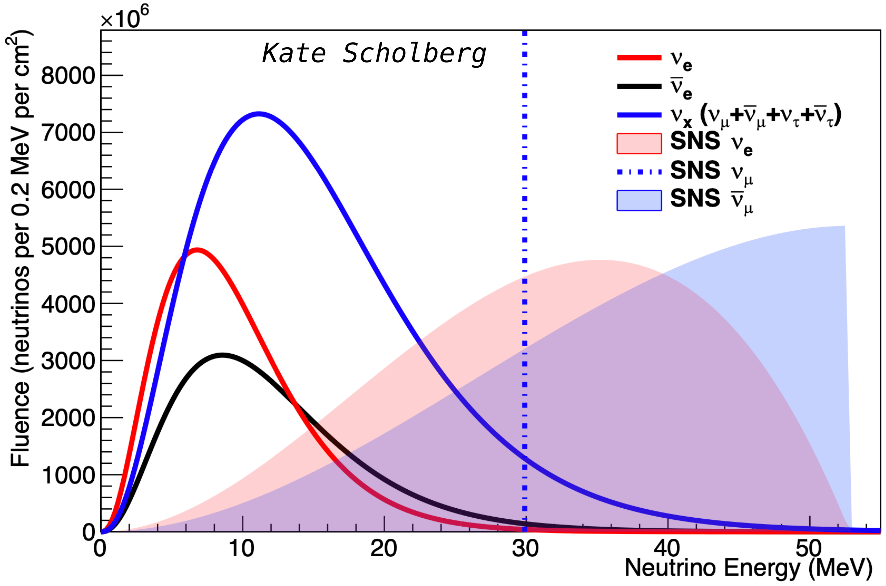




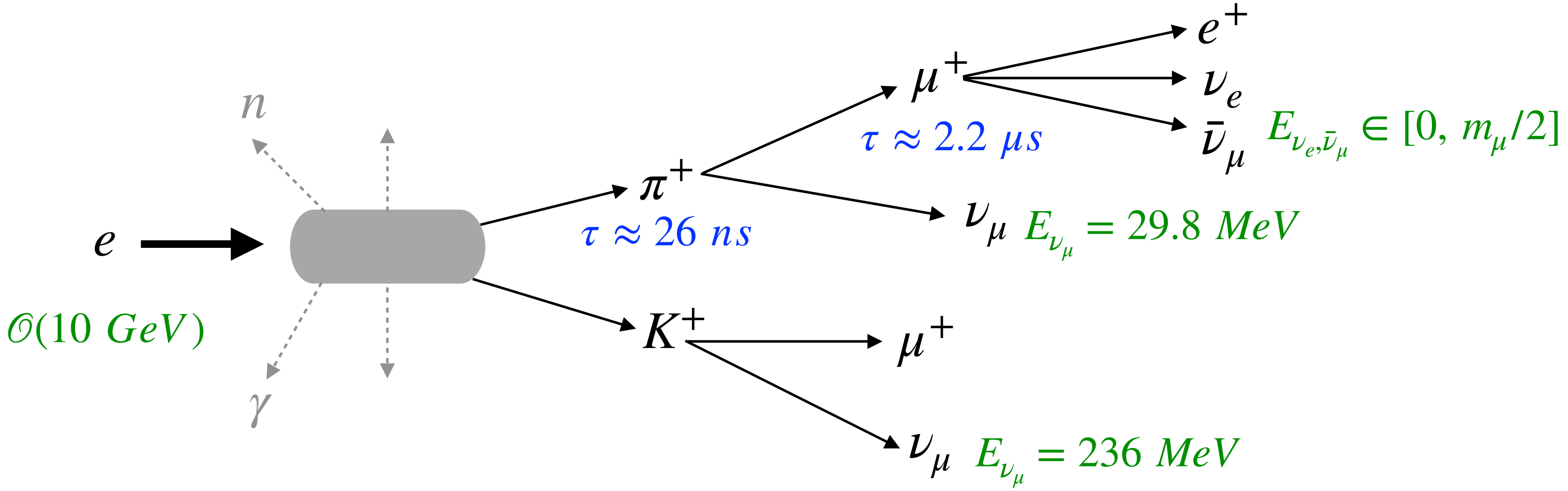
piDAR and Supernova Neutrinos

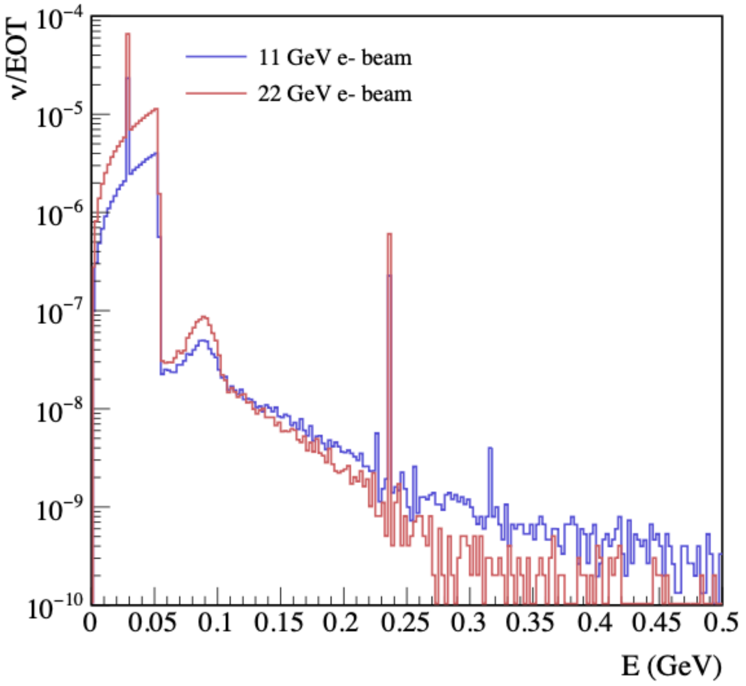


M. Battaglieri et al., Instruments 8, 1 (2024)



Neutrinos at BDX Facility at JLab





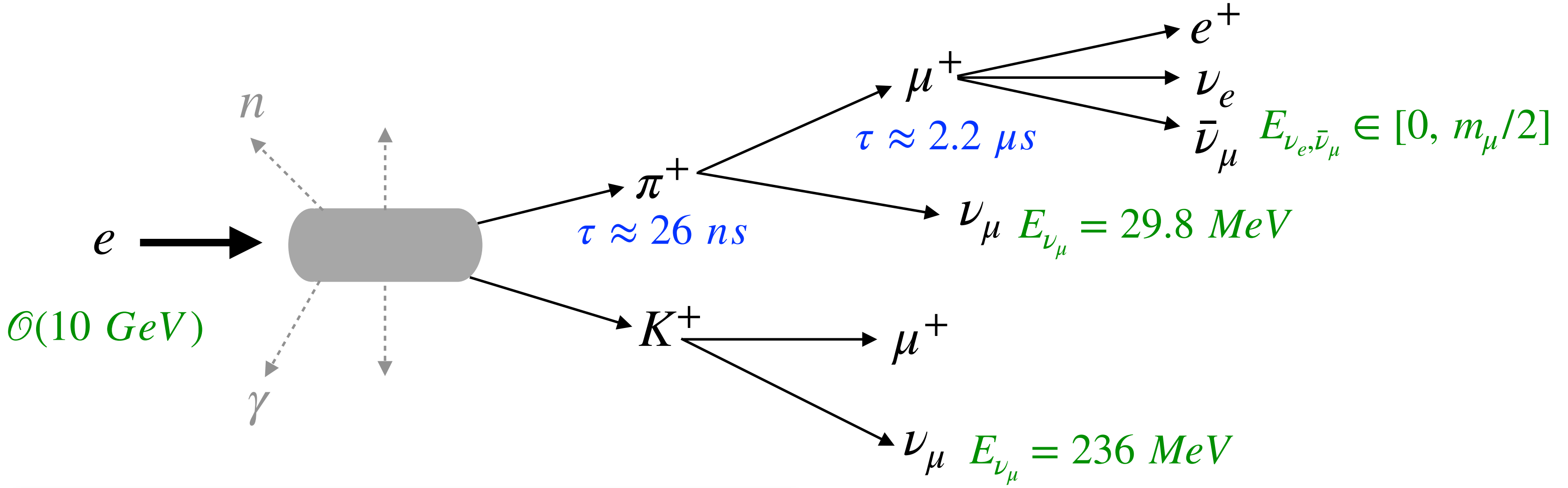
M. Battaglieri et al., Instruments 8, 1 (2024)

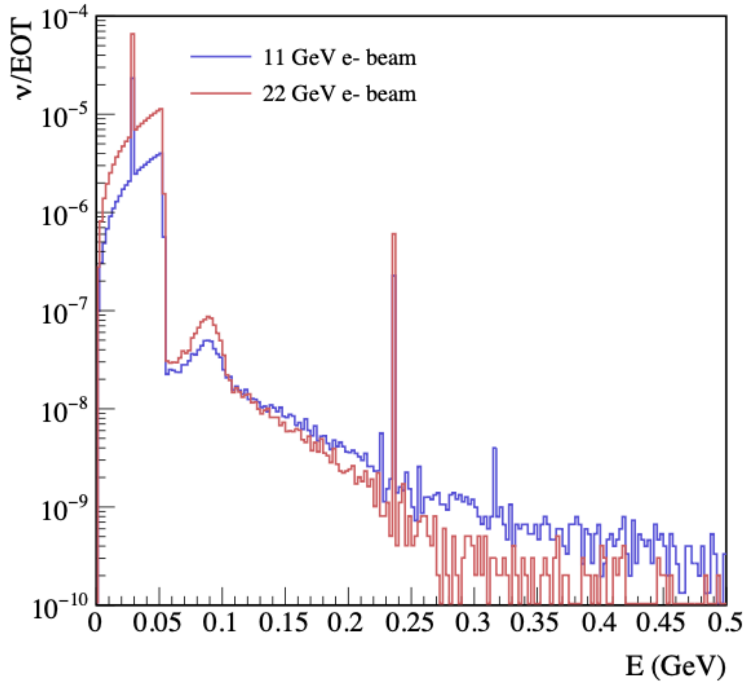
Physics Opportunities with PiDAR and KDAR Neutrinos:

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

FERMI NATIONAL ACCELERATOR LABORATORY

Neutrinos at BDX Facility at JLab





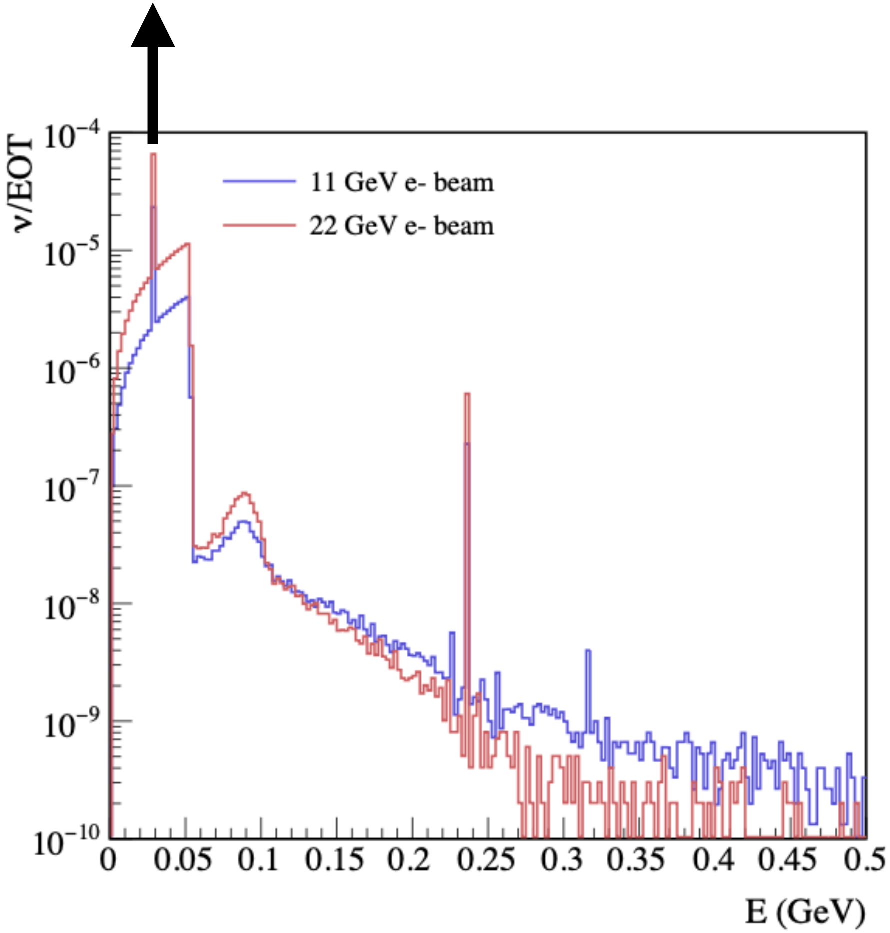
M. Battaglieri et al., Instruments 8, 1 (2024)

- **Proton beam-dump based sources worldwide:**

  piDAR: SNS at ORNL, LANSCE at LANL, MLF at JPARC, F2D2 at FNAL, ESS, …

  KDAR: NuMI/LBNF at FNAL, MLF at JPARC, …

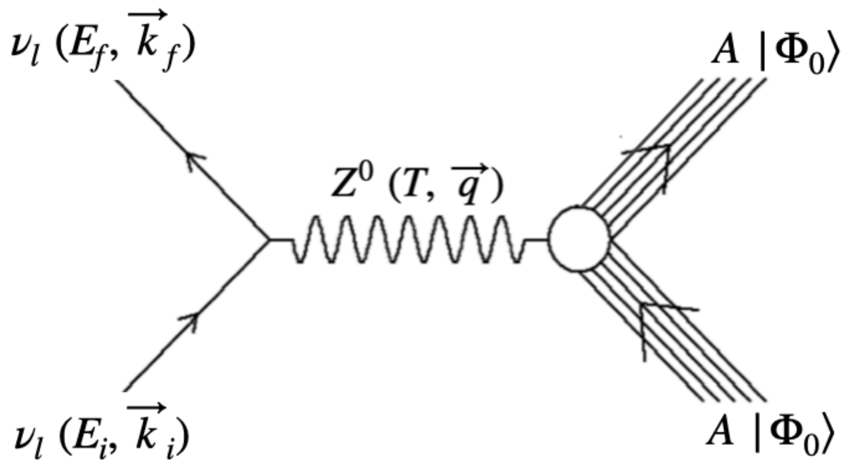
Physics with piDAR Neutrinos



M. Battaglieri et al., Instruments 8, 1 (2024)

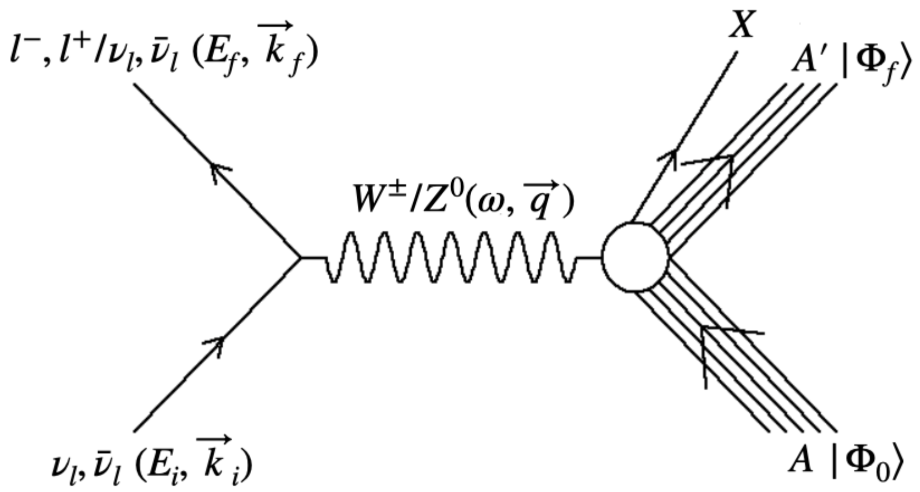
10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



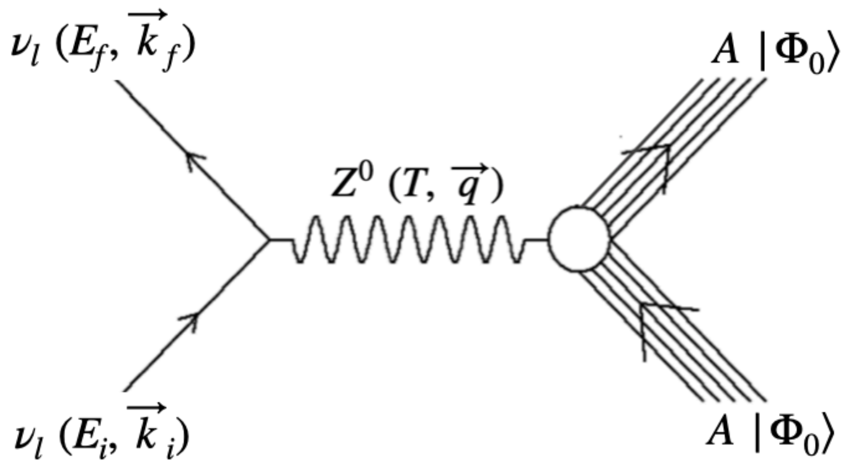
Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

Inelastic CC/NC



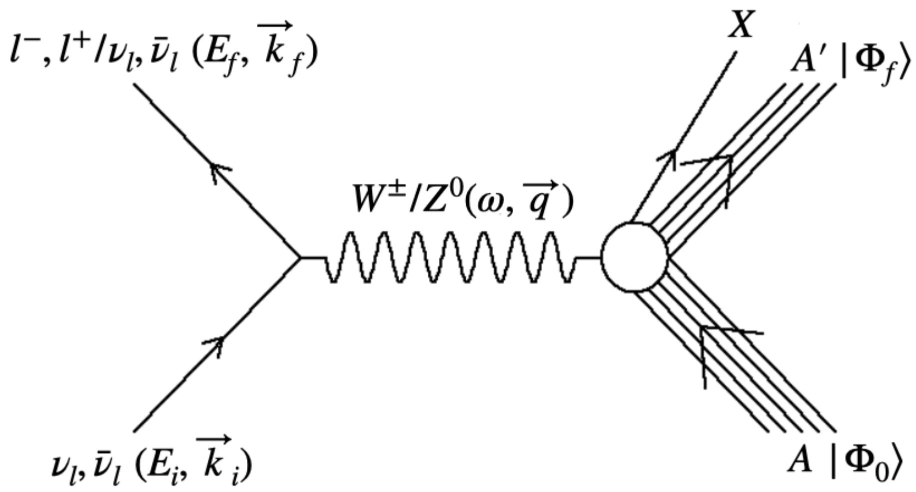
10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

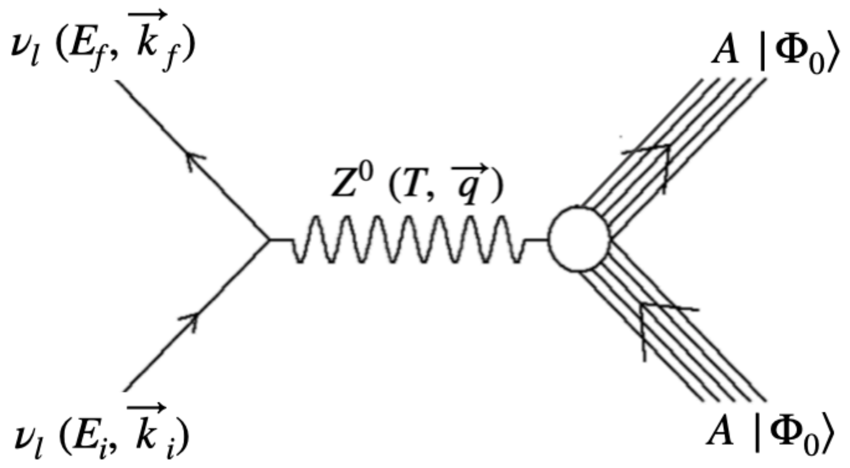
Inelastic CC/NC



- 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

10s of MeV Neutrinos-Nucleus Scattering

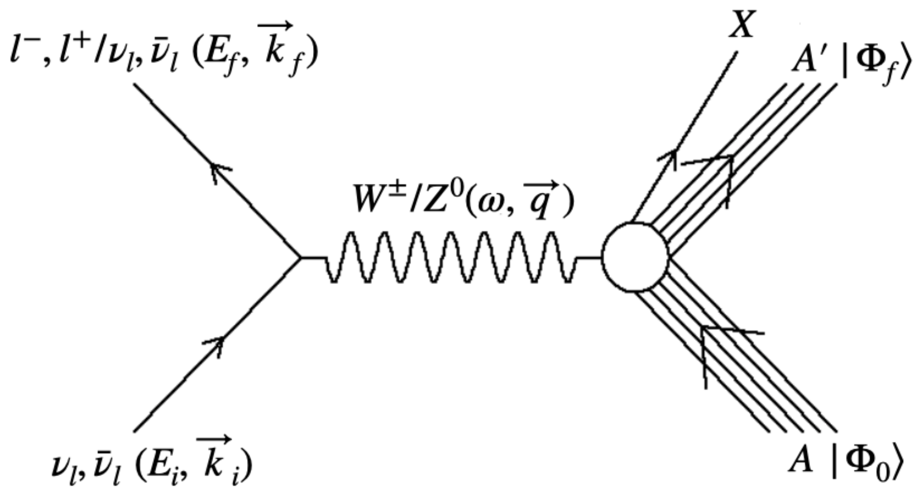
Coherent elastic [CEvNS]



Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

- 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

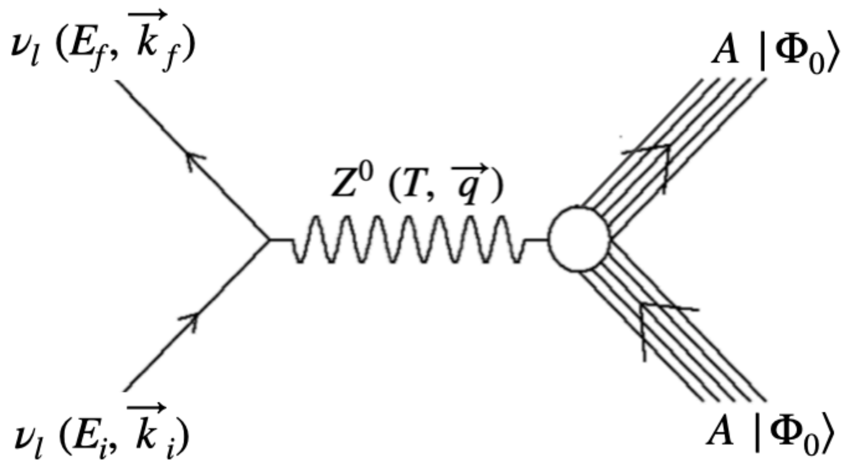
Inelastic CC/NC



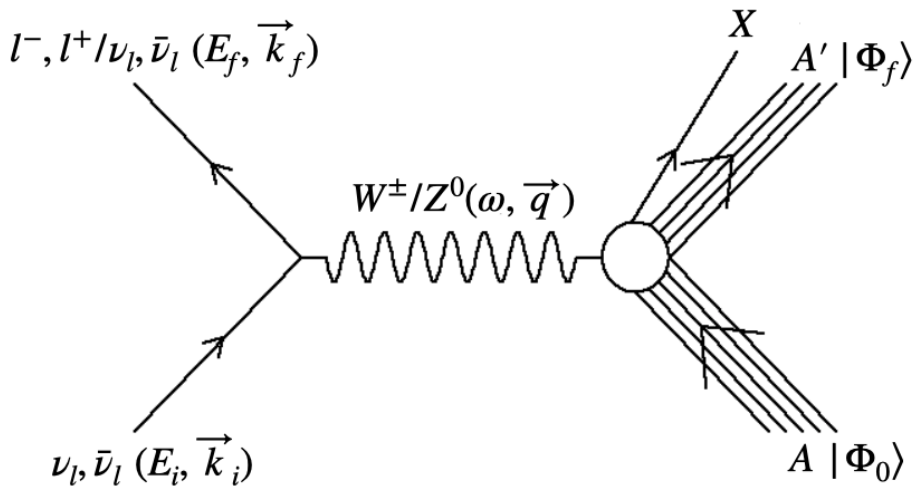
- Small energy transferred to the nucleus
- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π).
- Followed by nuclear de-excitation into gammas, p, n, nuclear fragmentations.
- Complementary with supernova neutrinos

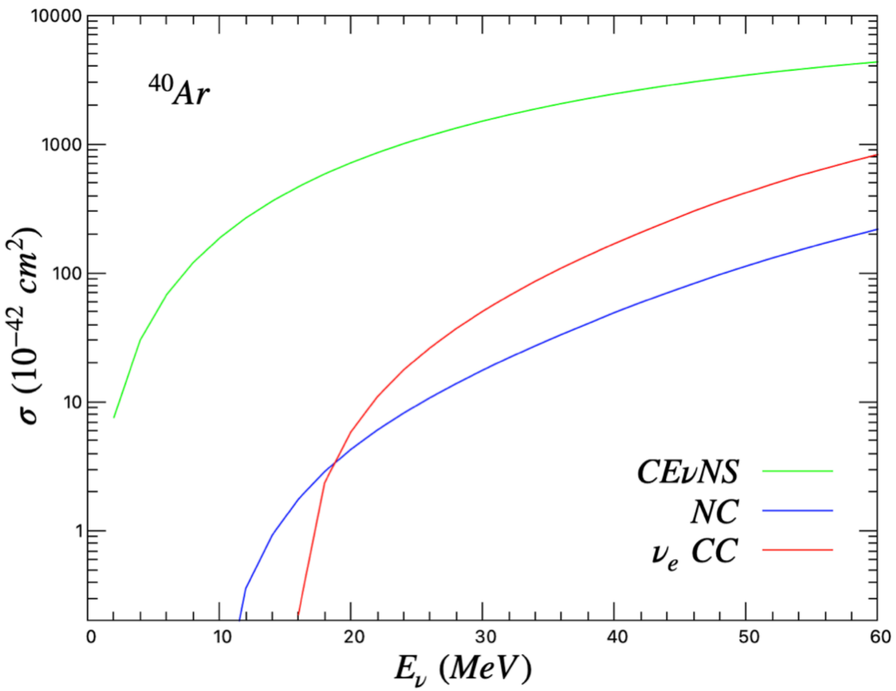
10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



Inelastic CC/NC



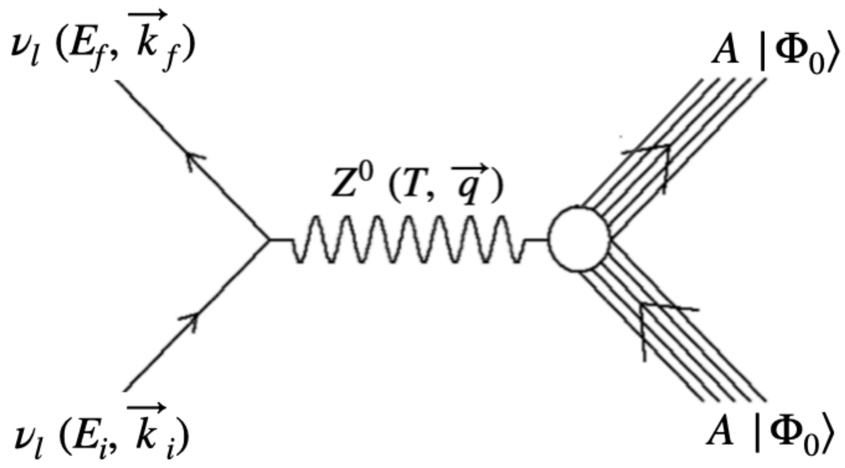


- At 10s of MeV, CEvNS cross section is significantly larger than inelastic ones.

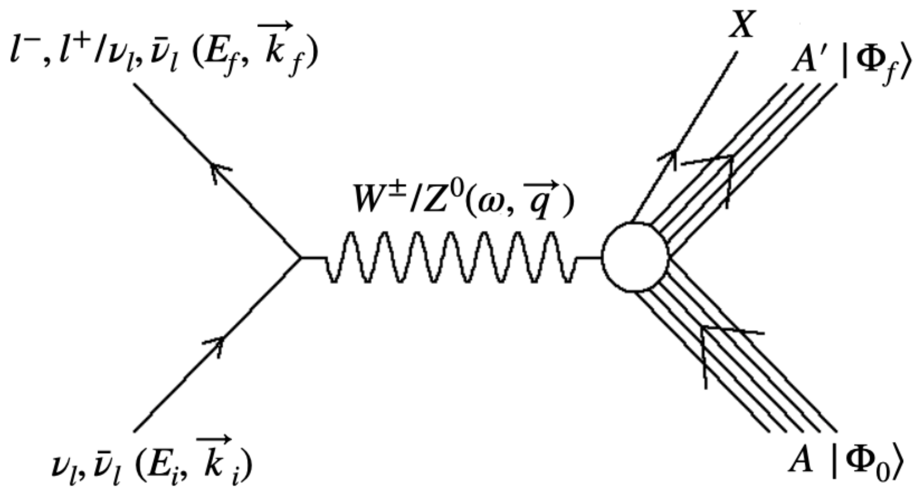
V. Pandey, Prog. Part. Nucl. Phys., 104078 (2024)

10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



Inelastic CC/NC



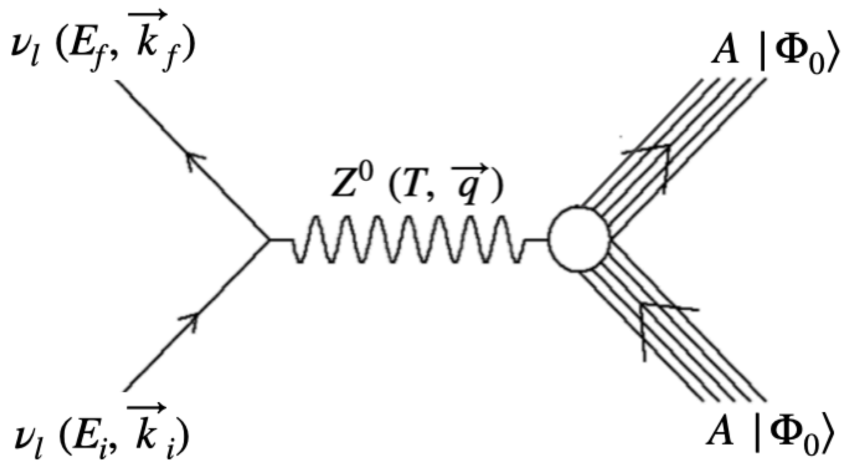
$$\sum_{fi} |\mathscr{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

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

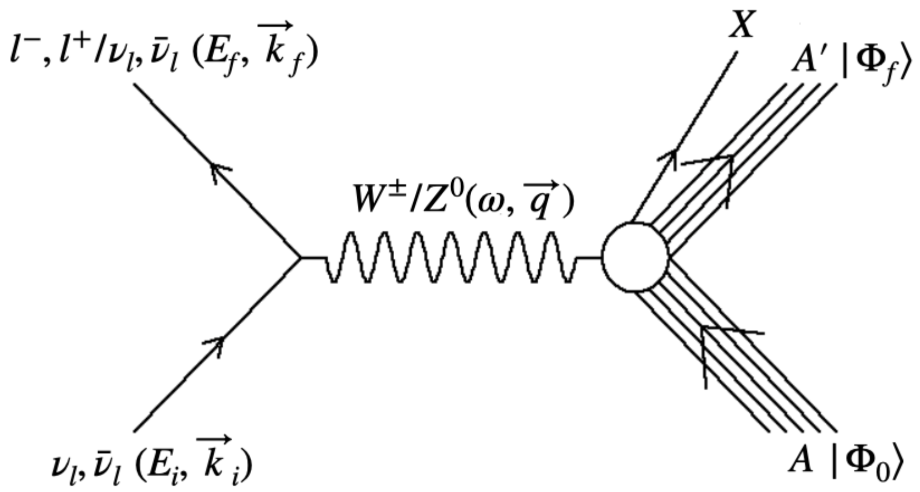
Hadronic Tensor: $W^{\mu\nu} = \sum_{fi} (\mathscr{J}_n^\mu)^\dagger \mathscr{J}_n^\nu$

10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



Inelastic CC/NC



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

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

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

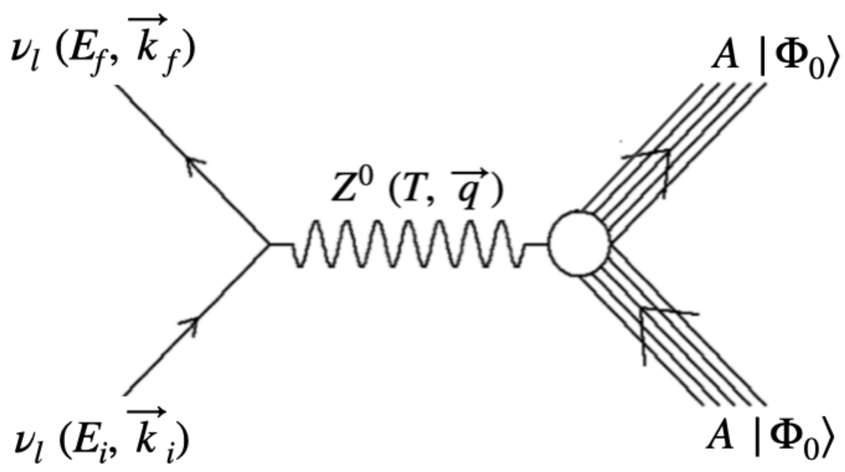
Transition Amplitude: $\mathscr{J}_n^\mu = \langle \Phi_0 | \hat{J}_n^\mu(q) | \Phi_0 \rangle$

Cross Section:

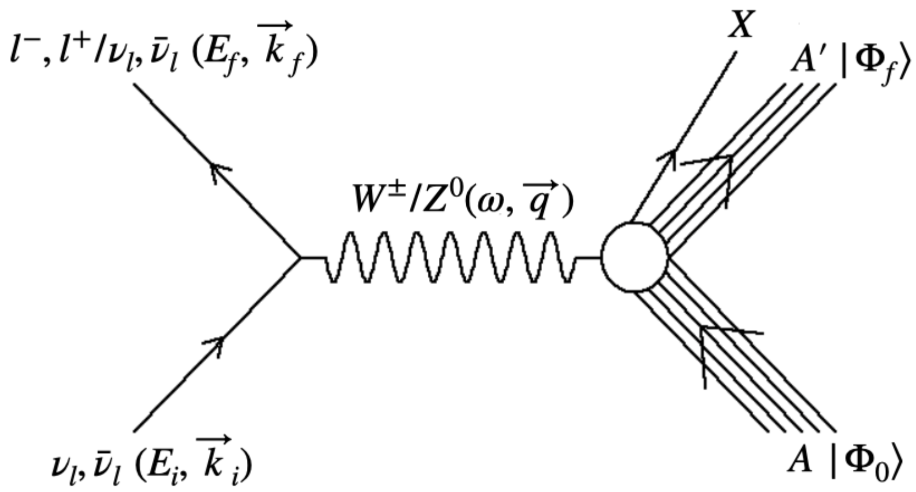
$$d\sigma \propto \frac{G_F^2}{4\pi}\ Q_W^2 F_W^2(q)$$

10s of MeV Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]



Inelastic CC/NC



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

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:

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

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

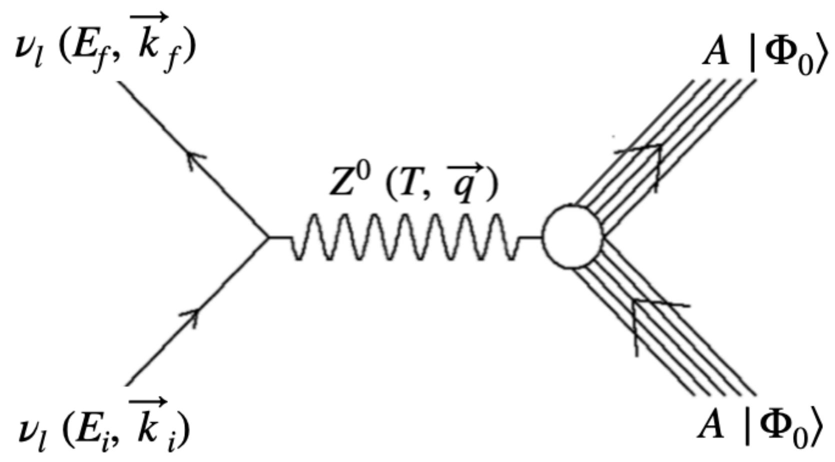
Cross Section:

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

CEvNS Cross Section and Form Factors

- **Cross section (tree level)***:

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



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

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

- **Weak Form Factor**:

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

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.

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.

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.

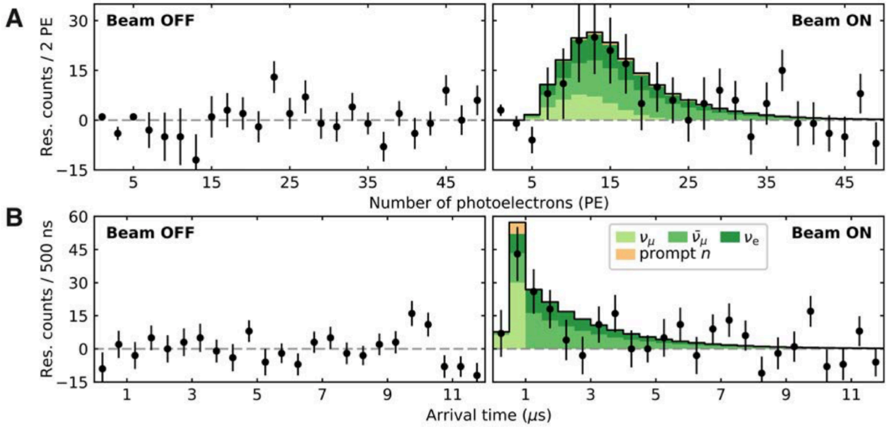
T. W. Donnelly, J. Dubach and I. Sick,, Nucl. Phys. A 503, 589-631 (1989).

- **CEvNS Cross Section**

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

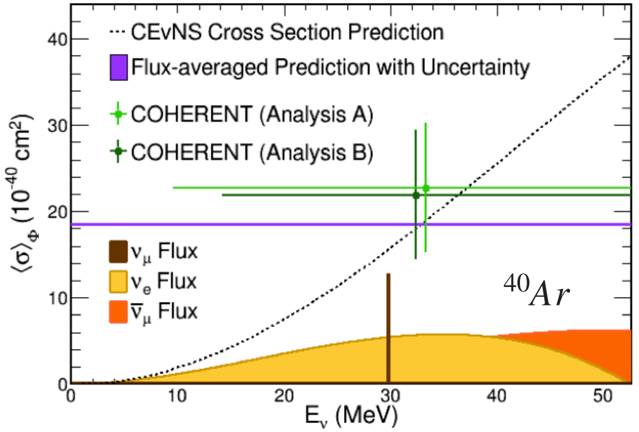
"Freedman declared that the experimental detection of CEvNS would be an "act of hubris" due to the associated "grave experimental difficulties".

COHERENT Collaboration at SNS at ORNL



- The maximum recoil energy

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



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

FERMI NATIONAL ACCELERATOR LABORATORY

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).

• PVES Asymmetry

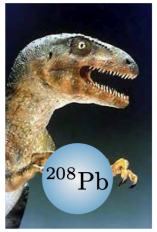
- The parity violating asymmetry for elastic electron scattering is the fractional difference in cross section for positive helicity and negative helicity electrons.

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

- 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]



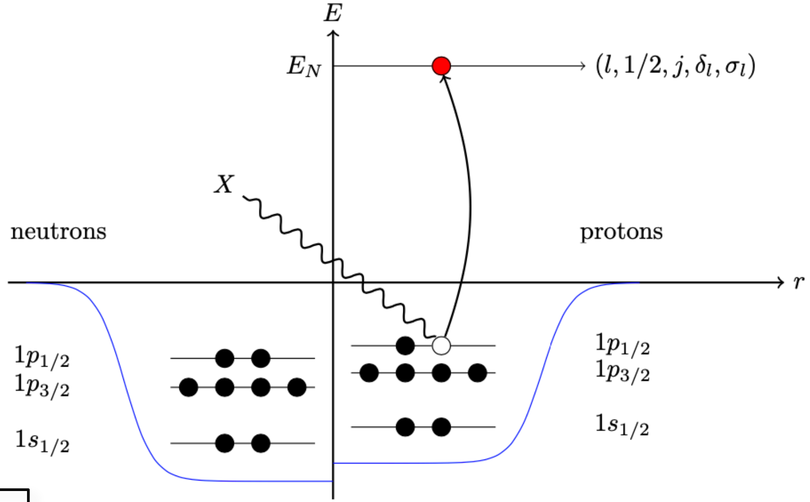
Pb Radius Experiment (PREX)

Calcium Radius Experiment (CREX)

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

CEvNS Cross Section and Form Factors

- 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



$$\rho_\tau(r) = \frac{1}{4\pi r^2} \sum_\alpha v^2_{\alpha,\tau}\ (2j_\alpha + 1)\,|\phi_{\alpha,\tau}(r)|^2$$

$$F_\tau(q) = \frac{1}{N} \int d^3r\ j_o(qr)\ \rho_\tau(r)$$

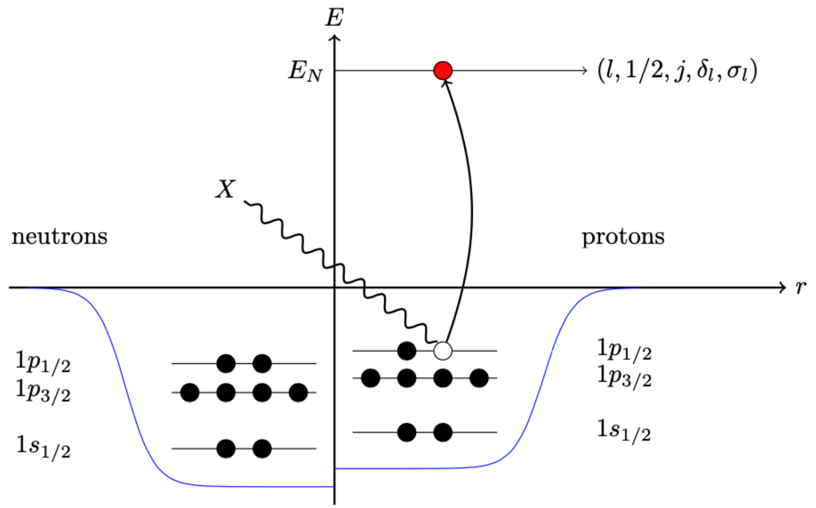
$(\alpha \in n_\alpha, l_\alpha, j_\alpha)$

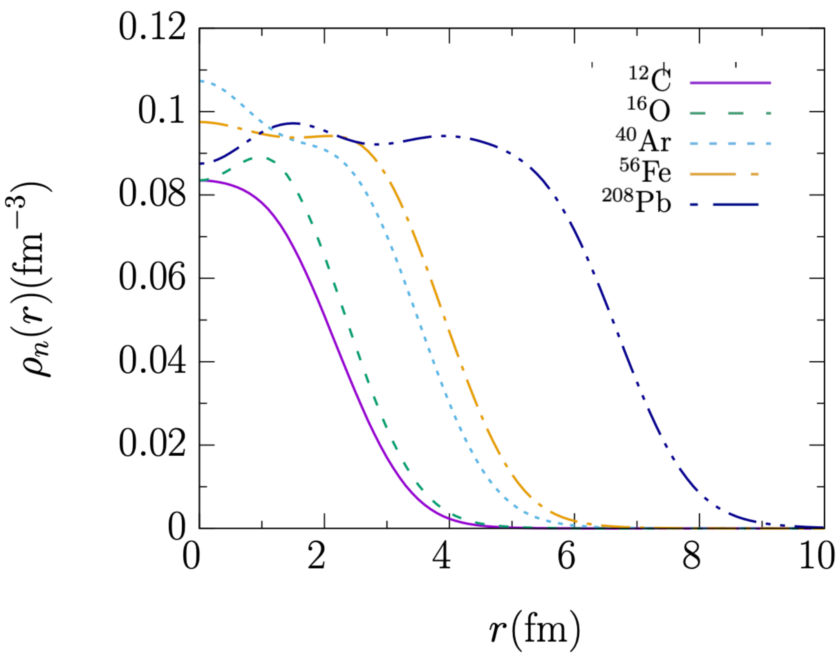
$(\tau = p, n)$

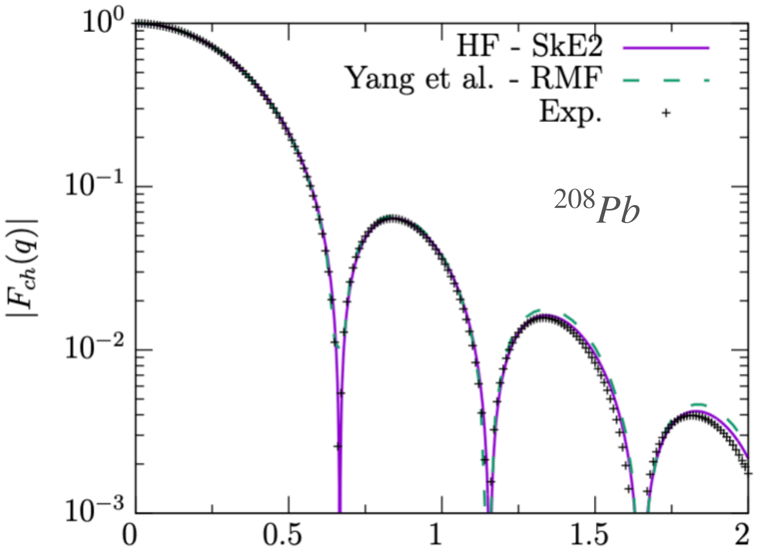
N. Van Dessel, V. Pandey, H. Ray and N. Jachowicz, Universe 9, 207 (2023)

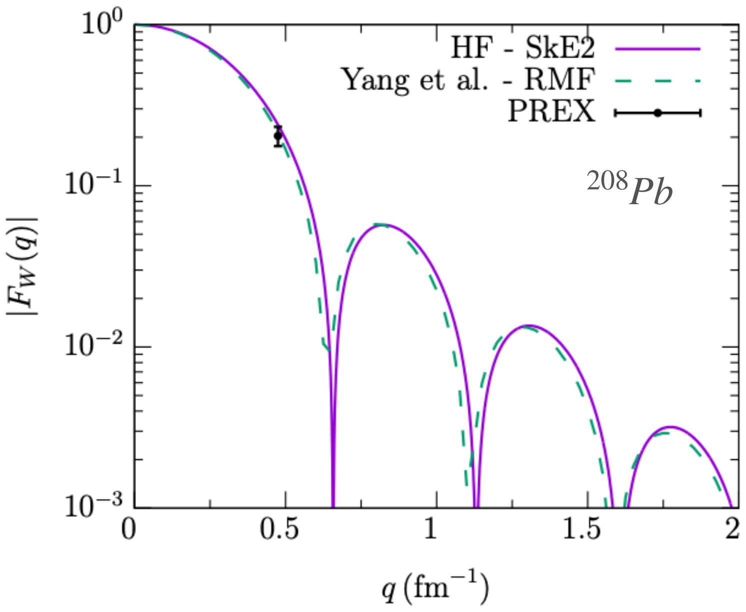
CEvNS Cross Section and Form Factors

- 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







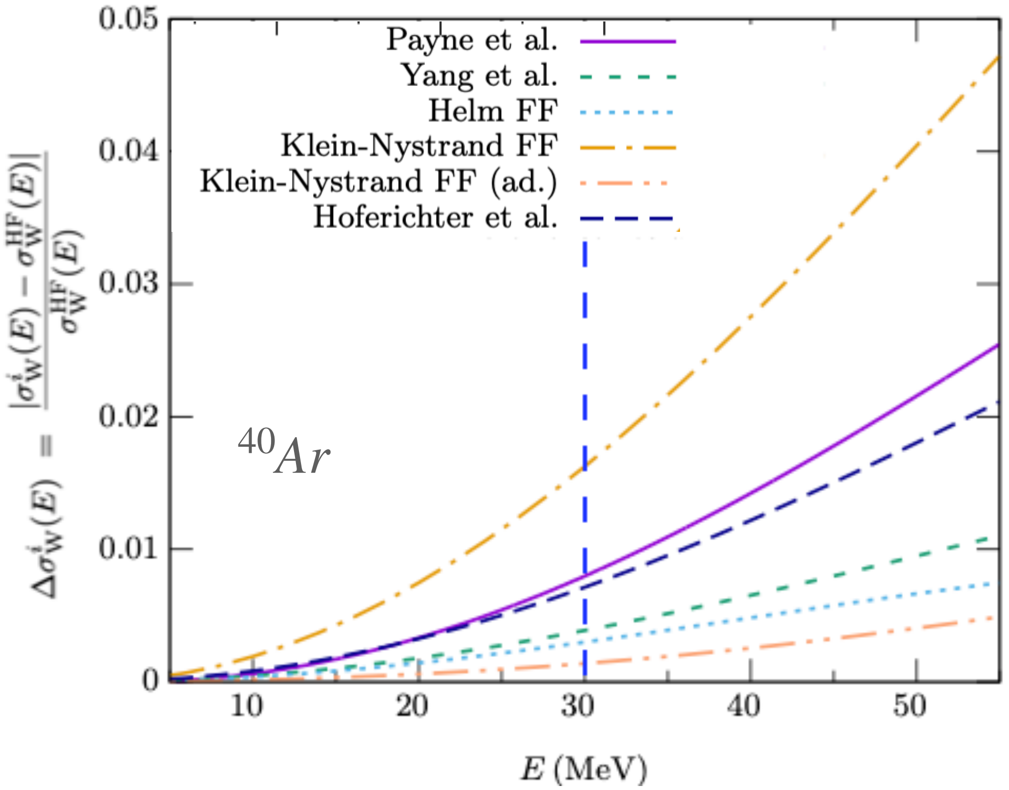


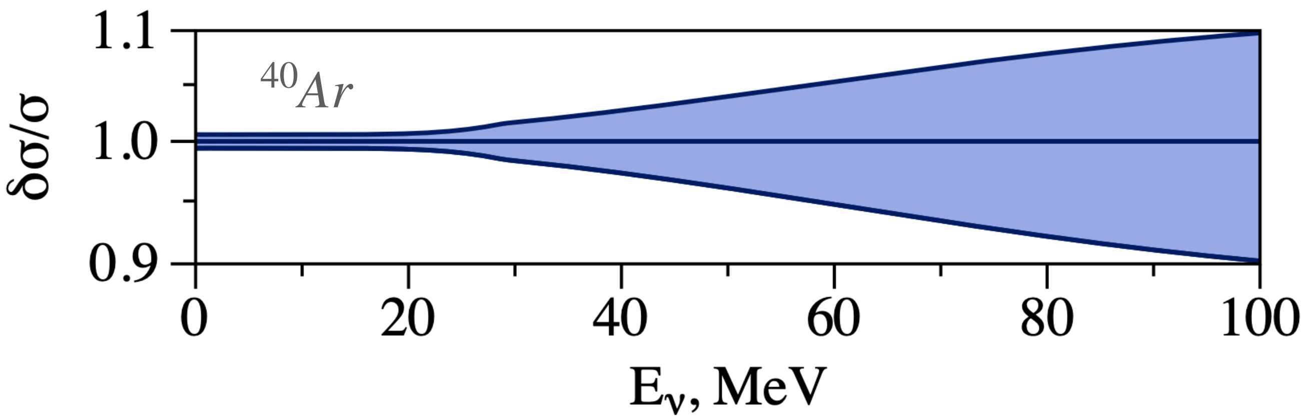
Data: H. De Vries, et al., Atom. Data Nucl. Data Tabl. 36, 495 (1987), S. Abrahamyan et al., Phys. Rev. Lett. 108, 112502 (2012)

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

CEvNS Cross Section and Form Factors

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





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

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

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

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

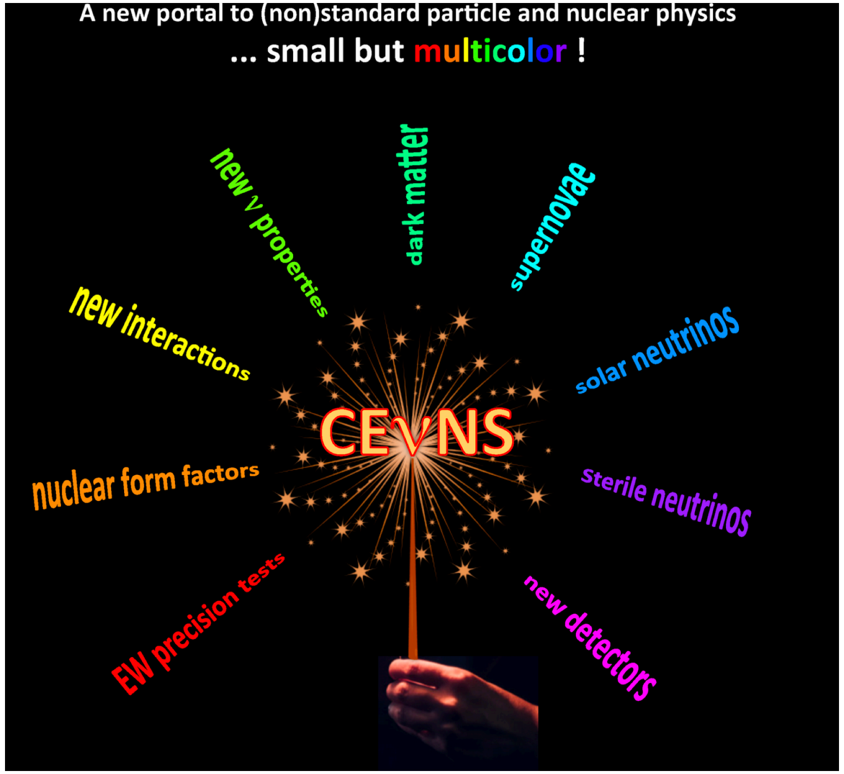
Hoferichter et al. [arXiv:2007.08529 [hep-ph]]

CEvNS and New Physics

- 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, could indicate new contributions to the interaction cross-section.

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

$$Q_W^2 = [g_p^V Z + g_n^V N]^2 = [(1 - 4\sin^2\theta_W)Z - N]^2$$



Eligio Lisi, NuINT 2018

CEvNS and New Physics

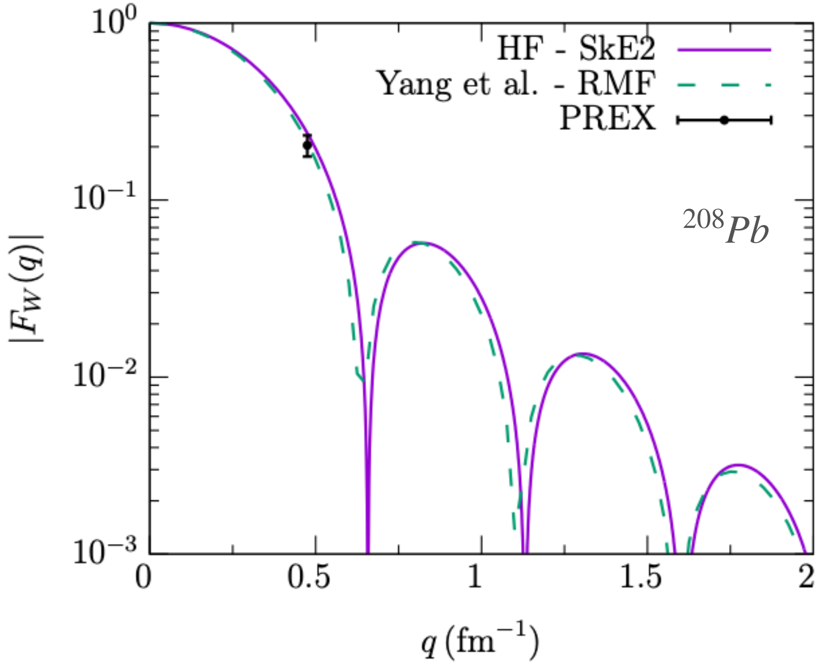
- Any deviation from the SM predicted event rate, either with a change in the total event rate or with a change in the shape of the recoil spectrum, could indicate new contributions to the interaction cross-section.

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

$$Q_W^2 = [g_p^V Z + g_n^V N]^2 = [(1 - 4\sin^2\theta_W)Z - N]^2$$

■ Standard Model Physics:

- **Weak Nuclear Form Factor** $F_W(q)$ at low Q
  neutron density distribution, neutron skin of a nucleus
  complements PVES experiments



CEvNS and New Physics

- 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, could indicate new contributions to the interaction cross-section.

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

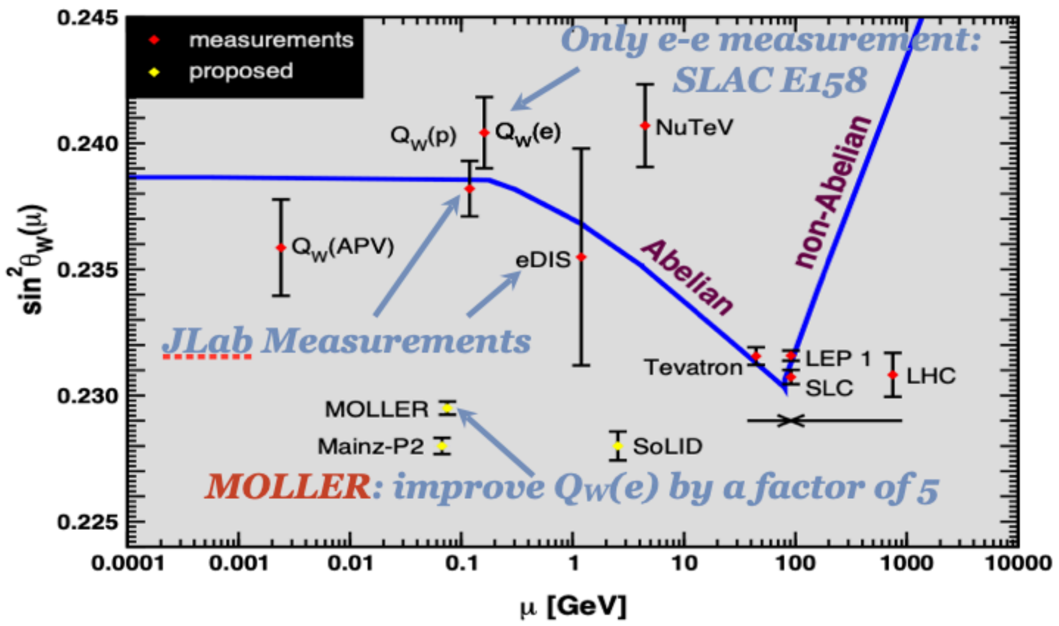
$$Q_W^2 = [g_p^V Z + g_n^V N]^2 = [(1 - 4\sin^2\theta_W)Z - N]^2$$

■ Standard Model Physics:

- **Weak Nuclear Form Factor** $F_W(q)$ at low Q
  neutron density distribution, neutron skin of a nucleus
  complements PVES experiments

- **Weak Mixing Angle** θ_W at low Q
  complements MOLLER experiment

Cynthia Keppel, this morning



CEvNS and New Physics

- 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, could indicate new contributions to the interaction cross-section.

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

$$Q_W^2 = [g_p^V Z + g_n^V N]^2 = [(1 - 4\sin^2\theta_W)Z - N]^2$$

■ Beyond the Standard Model Physics:

- **Neutrino Electromagnetic Properties:**

- Neutrino Magnetic Moment

- Neutrino Charge Radius

CEvNS and New Physics

- 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, could indicate new contributions to the interaction cross-section.

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

$$Q_W^2 = [g_p^V Z + g_n^V N]^2 = [(1 - 4\sin^2\theta_\mathrm{W})Z - N]^2$$

■ Beyond the Standard Model Physics:

- **Neutrino Electromagnetic Properties:**

- Neutrino Magnetic Moment

$$\left(\frac{d\sigma}{dT}\right)_{\mathrm{tot}} = \left(\frac{d\sigma}{dT}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT}\right)_{\mathrm{EM}}$$

$$\left(\frac{d\sigma}{dT}\right)_{\mathrm{EM}} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1 - T/E_\nu}{T} + \frac{T}{4E_\nu^2}\right) F_{\mathrm{ch}}^2(q^2)$$

- Neutrino Charge Radius

$$\sin^2\theta_W \to \sin^2\theta_W + \frac{\sqrt{2}\pi\alpha}{3G_F}\langle r_{\nu_\alpha}^2\rangle .$$

Flavor-dependent effect; muon- and electron-neutrino's event rates can be separated using the timing structure of piDAR

CEvNS and New Physics

- 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, could indicate new contributions to the interaction cross-section.

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

$$Q_W^2 = [g_p^V Z + g_n^V N]^2 = [(1 - 4\sin^2\theta_{\mathrm{W}})Z - N]^2$$

■ Beyond the Standard Model Physics:

- **Sterile Neutrino Oscillations**

  Flavor-independent CEvNS can be used to probe the disappearance of active neutrinos by setting up multiple identical detectors at different baselines from the neutrino production point.

- **Non-Standard Interactions (NSI) of Neutrinos**

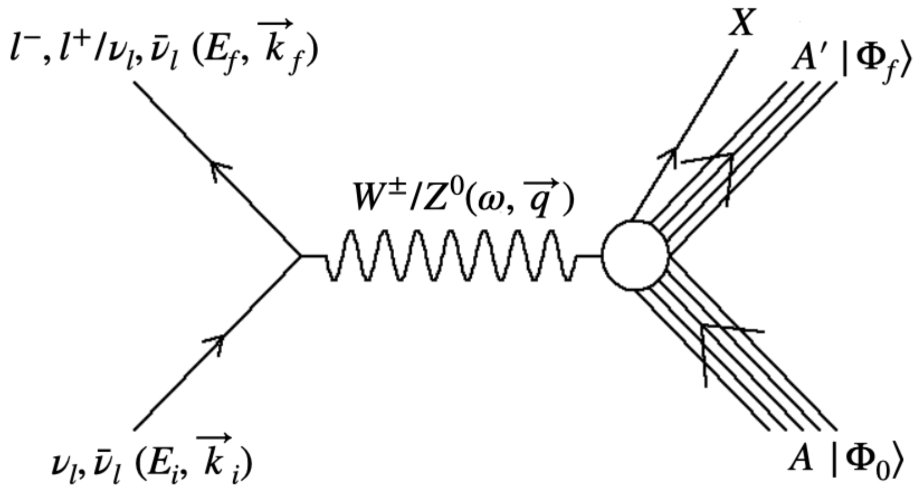
  All coupling except $\epsilon_{\tau\tau}$ are accessible

  Timing can allow separating electron and muon couplings

FERMI NATIONAL ACCELERATOR LABORATORY

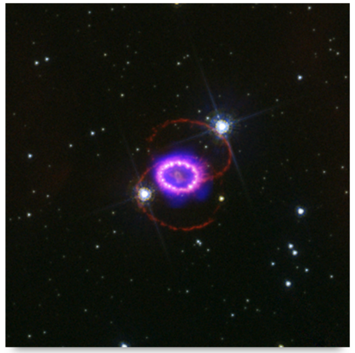
10s of MeV Inelastic Neutrino-Nucleus Scattering

Inelastic CC/NC

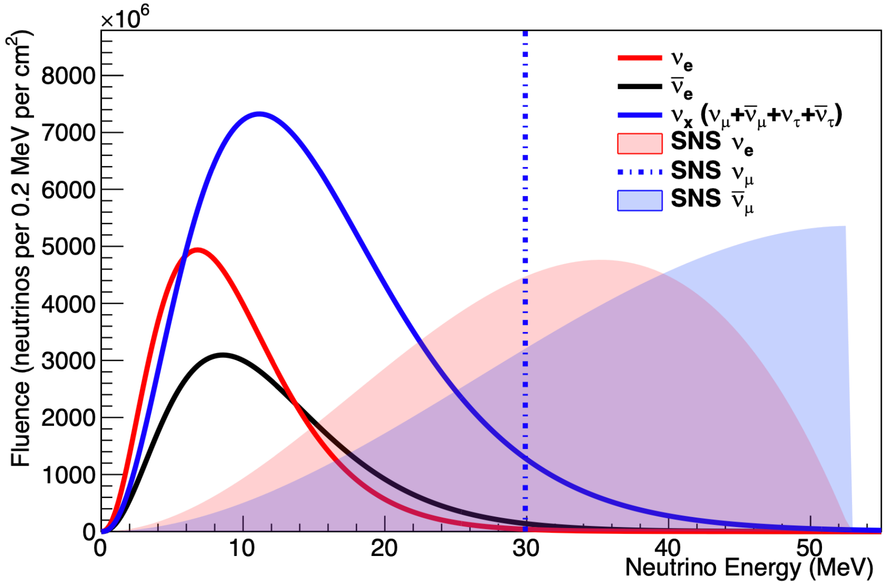


- Small energy transferred to the nucleus
- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π).
- Followed by nuclear de-excitation into gammas, p, n, nuclear fragmentations.
- Complementary with supernova neutrinos

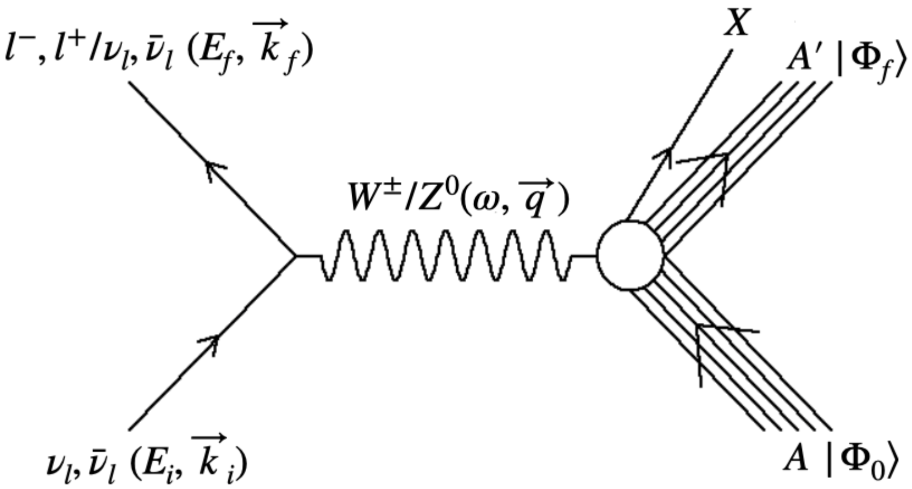
10s of MeV Inelastic Neutrino-Nucleus Scattering: Supernova Neutrinos



piDAR and Supernova Neutrinos



Inelastic CC/NC



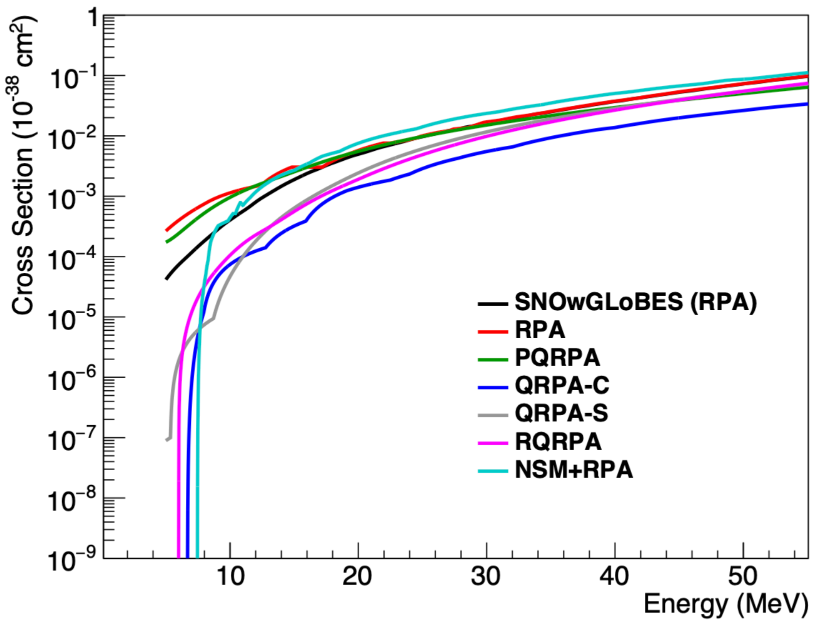
- Small energy transferred to the nucleus
- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π).
- Followed by nuclear de-excitation into gammas, p, n, nuclear fragmentations.
- Complementary with supernova neutrinos

10s of MeV Inelastic Neutrino-Nucleus Scattering: Supernova Neutrinos

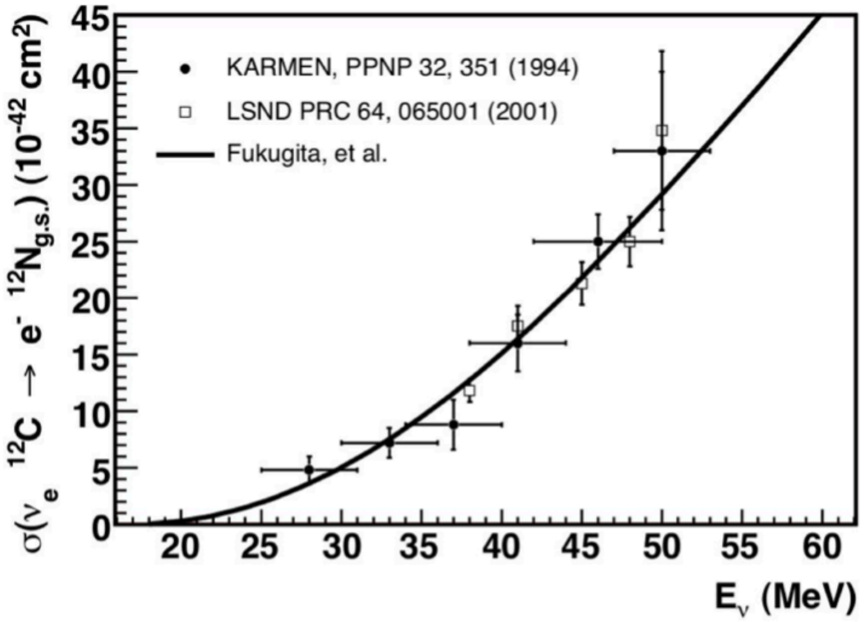
- DUNE relies on ν_eCC inelastic neutrino-nucleus scattering process to detect neutrinos from **core-collapse supernova.**

- 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.

No measurements on Argon yet



Past measurements on Carbon



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

10s of MeV Inelastic Neutrino-Nucleus Scattering: Supernova Neutrinos

- DUNE relies on ν_eCC inelastic neutrino-nucleus scattering process to detect neutrinos from **core-collapse supernova.**
- 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.

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

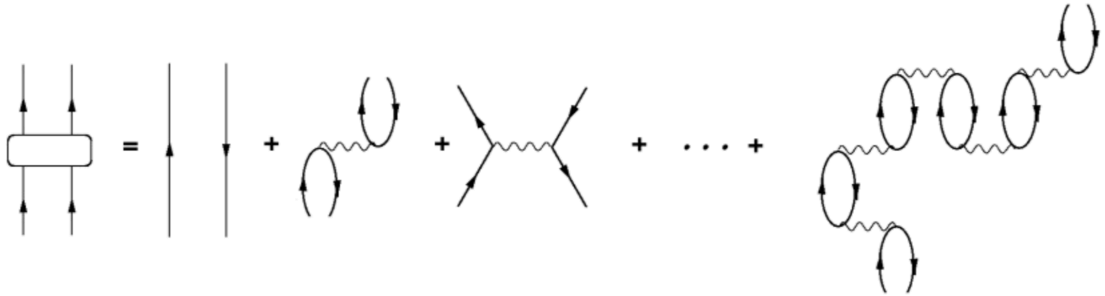
10s of MeV Inelastic Neutrino-Nucleus Scattering

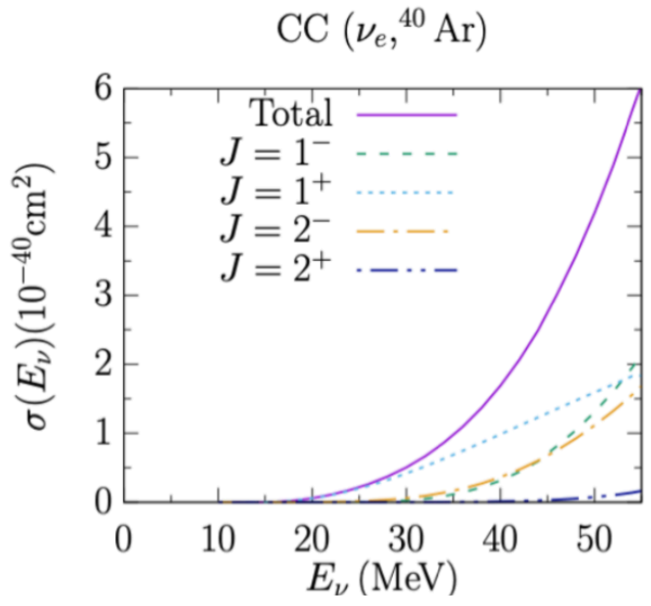
- In the inelastic cross section calculations, the influence of long-range correlations between the nucleons is introduced through the continuum Random Phase Approximation (CRPA) on top of the HF-SkE2 approach.

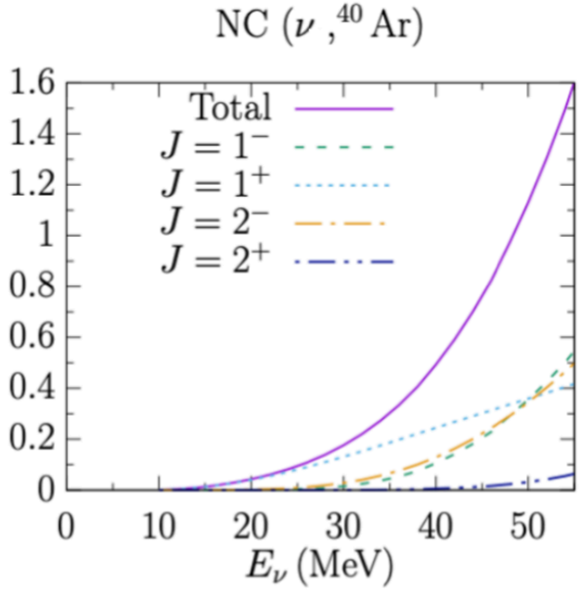
- CRPA effects are vital to describe the process where the nucleus can be excited to low-lying collective nuclear states.

- 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.

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



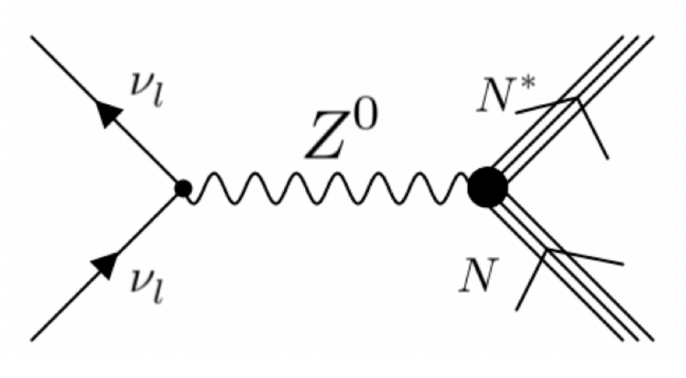


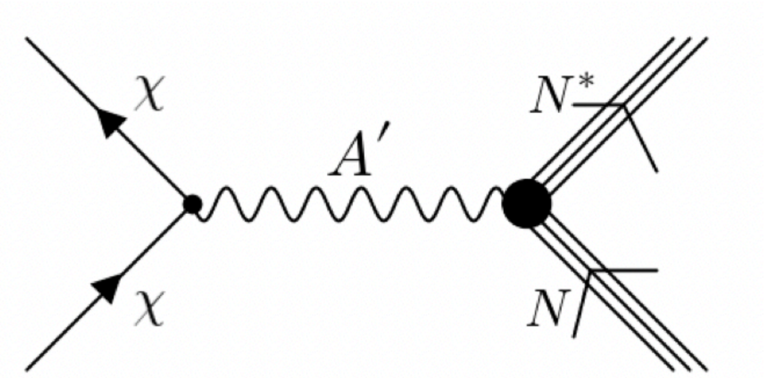


N. Van Dessel, V. Pandey, H. Ray and N. Jachowicz, Universe 9, 207 (2023)

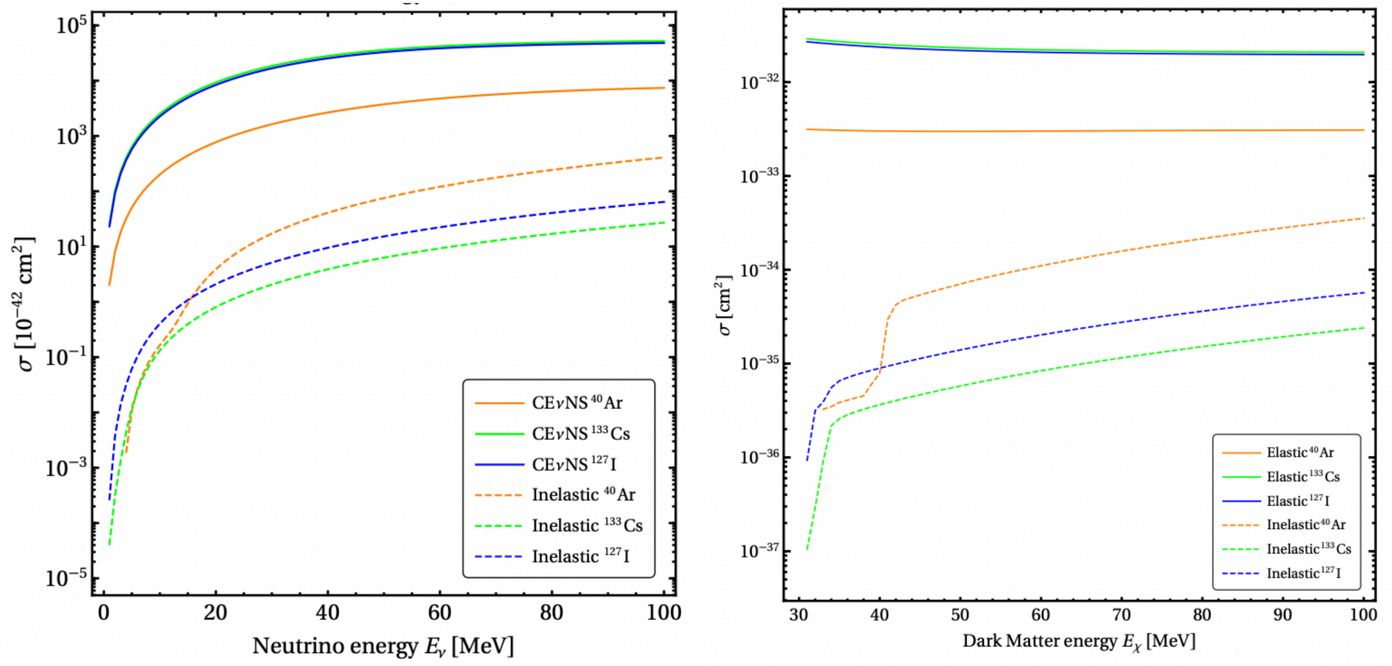
10s of MeV Inelastic Neutrino/DarkMatter-Nucleus Scattering

- **NC ν-nucleus → χ-nucleus scattering**

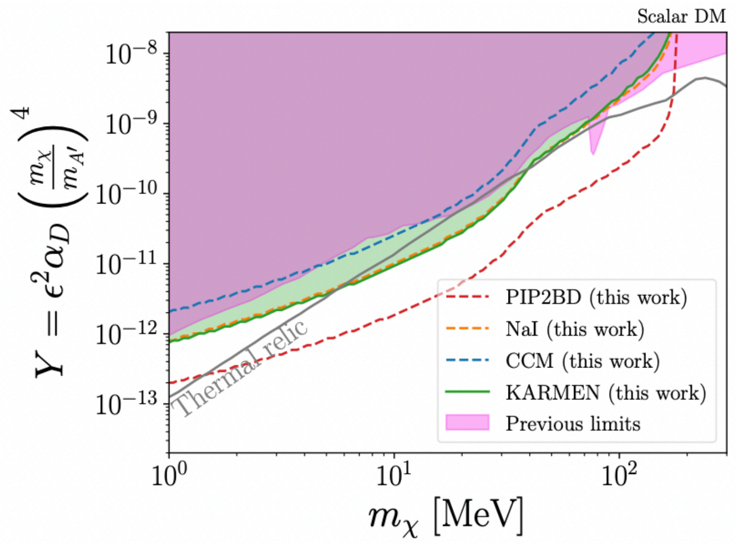




$$\pi^- + p \to n + A'$$
$$\pi^0 \to \gamma + A'$$
$$\eta^0 \to \gamma + A'$$
$$e^{\pm *} \to e^\pm + A'$$
$$A' \to \chi\bar{\chi}$$

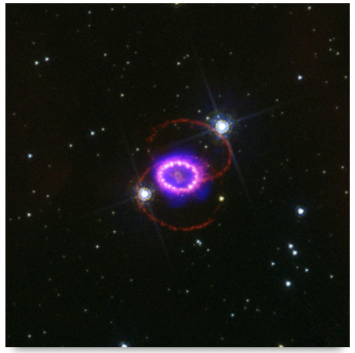


B. Dutta, W. C. Huang, J. L. Newstead, V. Pandey, Phys. Rev. D 106, 113006 (2022)

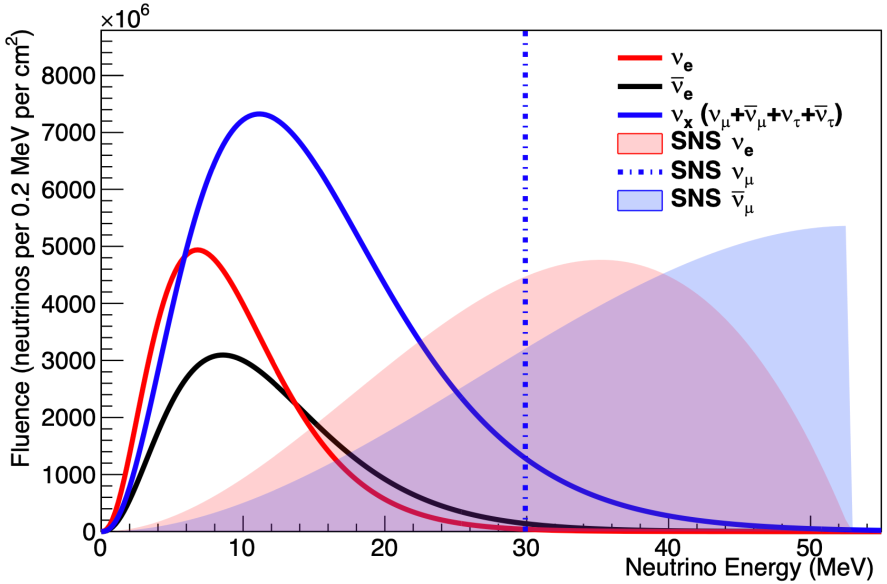


B. Dutta, W. C. Huang, J. L. Newstead, Phys. Rev. Lett. 131, 111801 (2023)

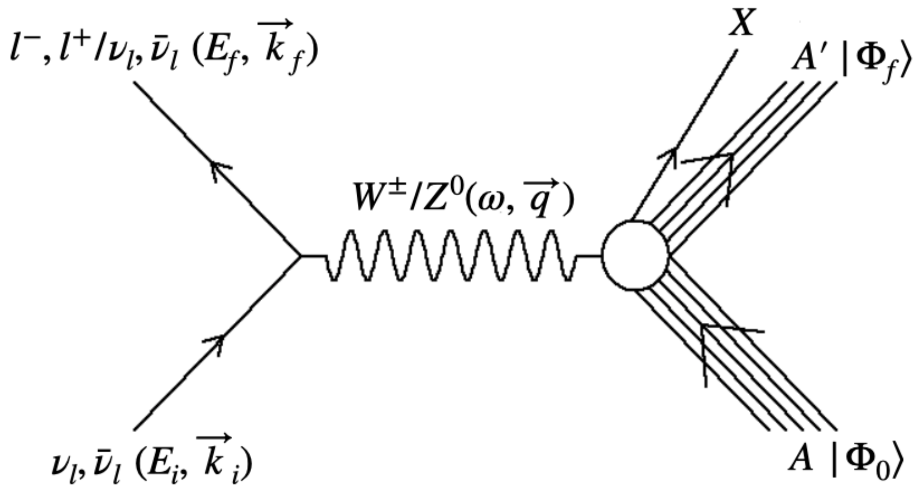
10s of MeV Inelastic Neutrino-Nucleus Scattering



piDAR and Supernova Neutrinos



Inelastic CC/NC

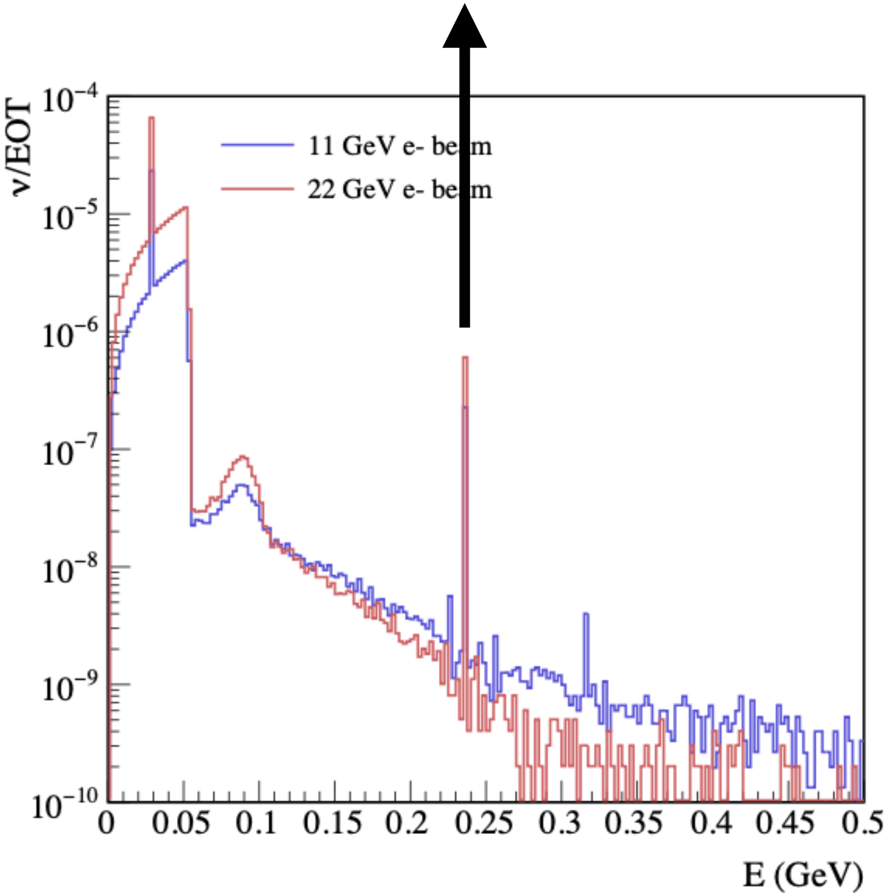


- **Nuclear Structure Physics**
- **Supernova Neutrinos**
- **Complimentary New Physics signals**
- **…..**

Physics with KDAR Neutrinos

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

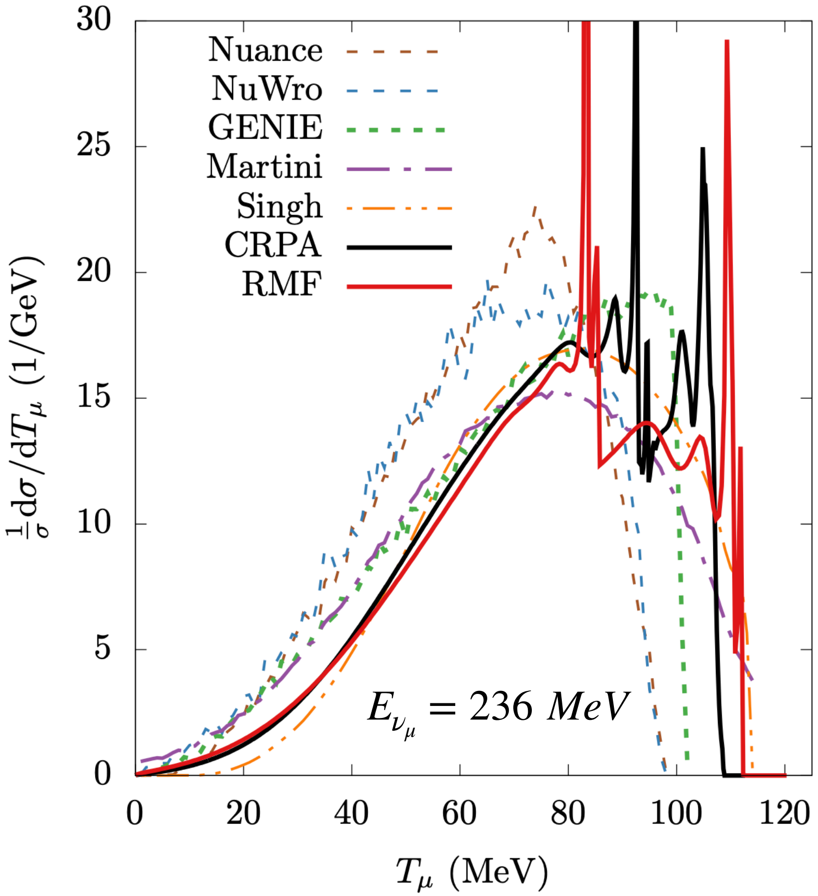
Physics with KDAR Neutrinos

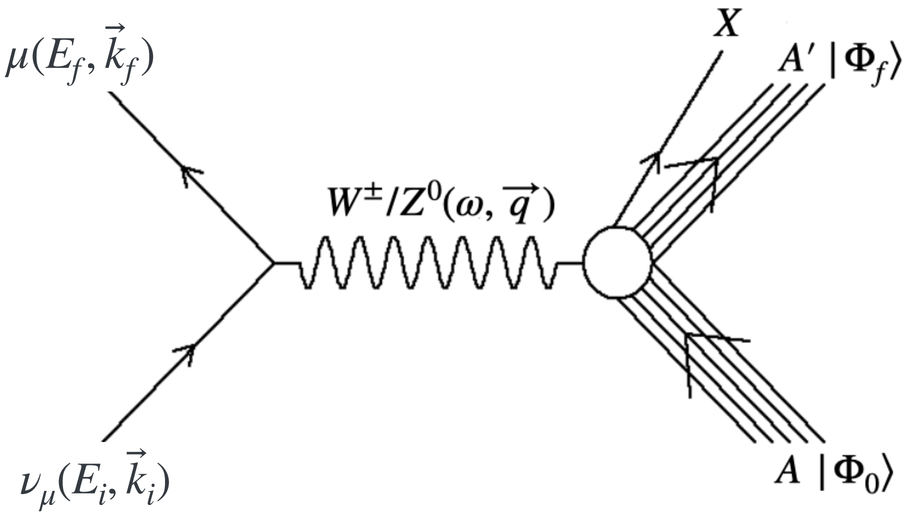


M. Battaglieri et al., Instruments 8, 1 (2024)

KDAR Neutrino-Nucleus Scattering

- Interaction lies in the difficult-to-model transition region:
  between neutrino-on-nucleus and neutrino-on-(bound)nucleons scattering, in which the interaction evolves from inducing collective nuclear excitations among multiple nucleons to quasielastic scattering off of individual bound nucleon.

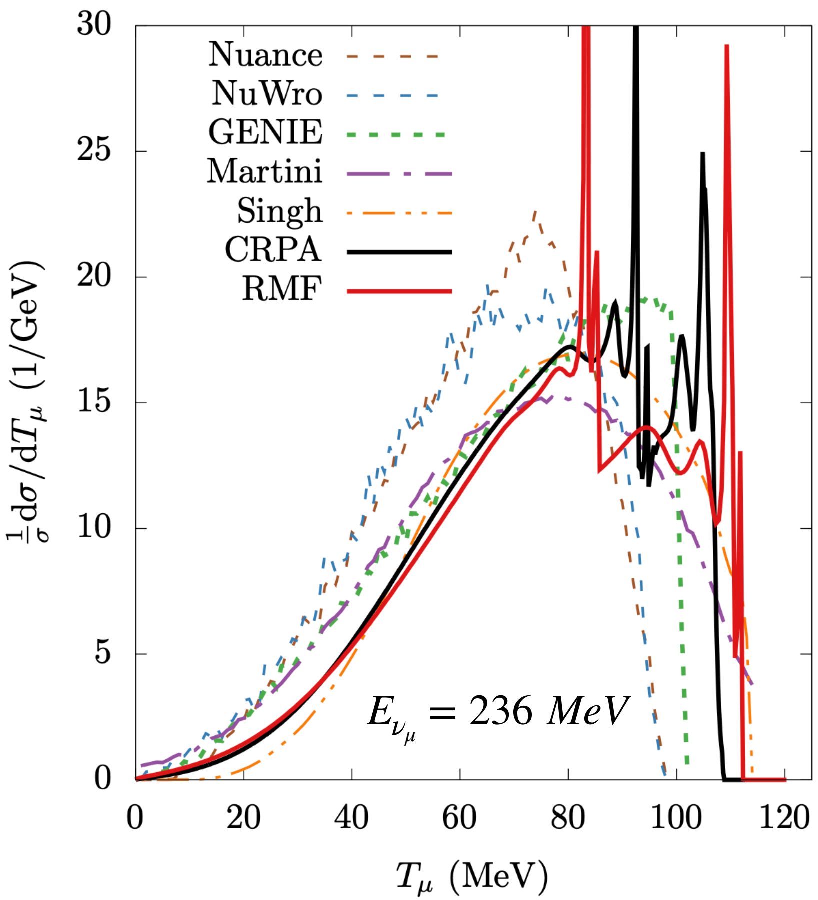


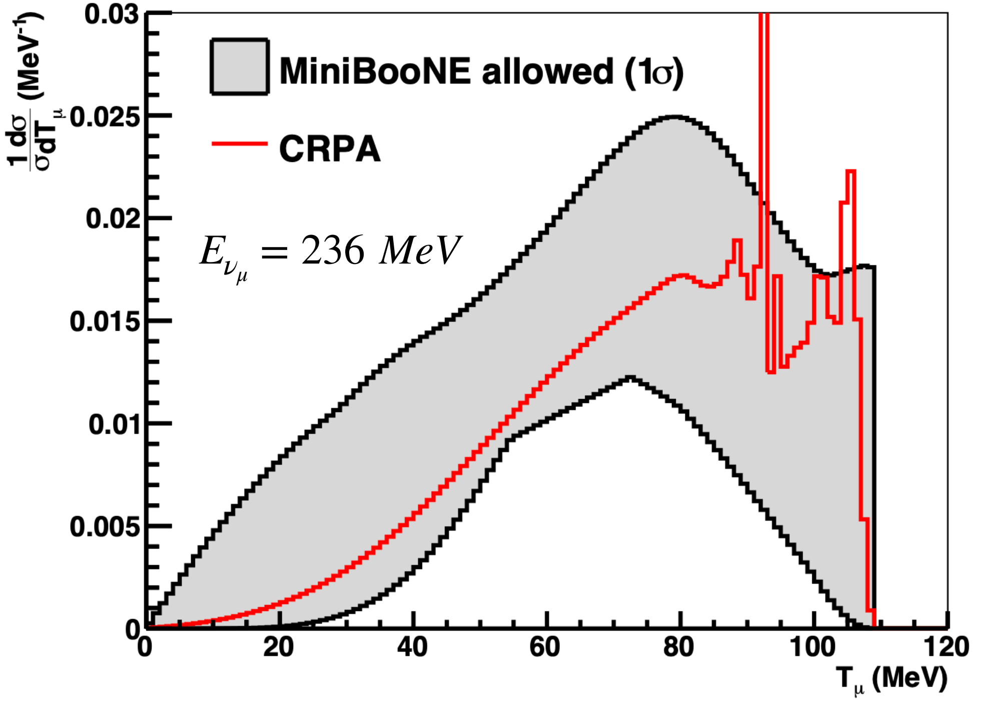


A. Nikolakopoulos, V. Pandey, J. Spitz and N. Jachowicz, Phys. Rev. C 103, 064603 (2021)

KDAR Neutrino-Nucleus Scattering

- Interaction lies in the difficult-to-model transition region:
  between neutrino-on-nucleus and neutrino-on-(bound)nucleons scattering, in which the interaction evolves from inducing collective nuclear excitations among multiple nucleons to quasielastic scattering off of individual bound nucleon.





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

- Shape-only comparison of several models, too low statistics to discriminate between models

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

KDAR Neutrino-Nucleus Scattering

- Interaction lies in the difficult-to-model transition region: between neutrino-on-nucleus and neutrino-on-(bound)nucleons scattering, in which the interaction evolves from inducing collective nuclear excitations among multiple nucleons to quasielastic scattering off of individual bound nucleon.

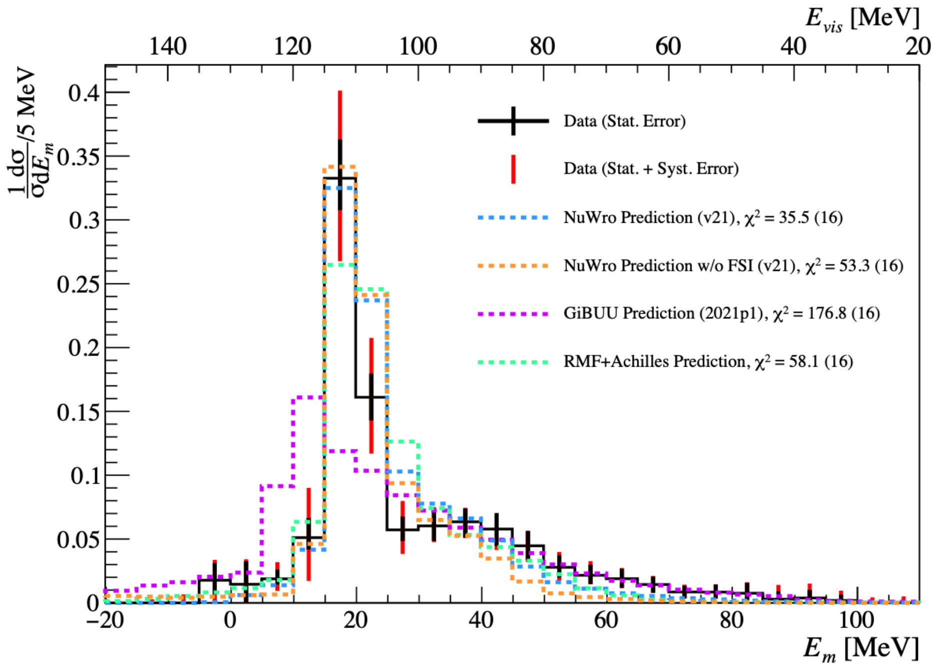


FIG. 4. The KDAR ν_μ CC missing energy, E_m, shape-only differential cross section measurement compared to several neutrino event generator/model predictions. The top x-axis provides the corresponding E_{vis} for each E_m value.

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

- New Measurement from JSNS^2 at JPARC.

KDAR Physics Opportunities

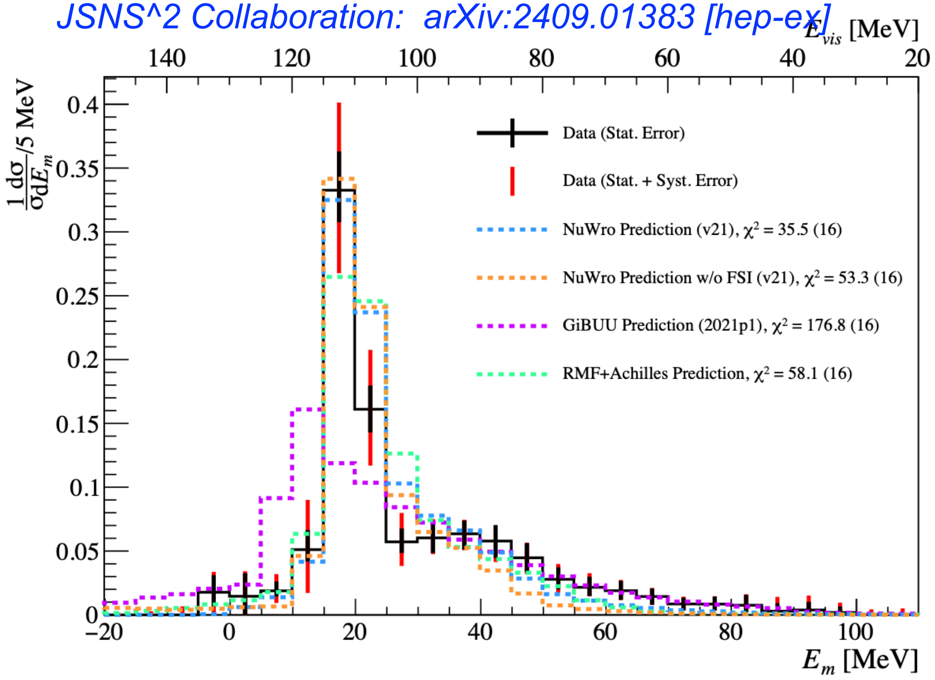
- **Nuclear Physics**
  Study of nuclear effects and axial current with fixed neutrino energy

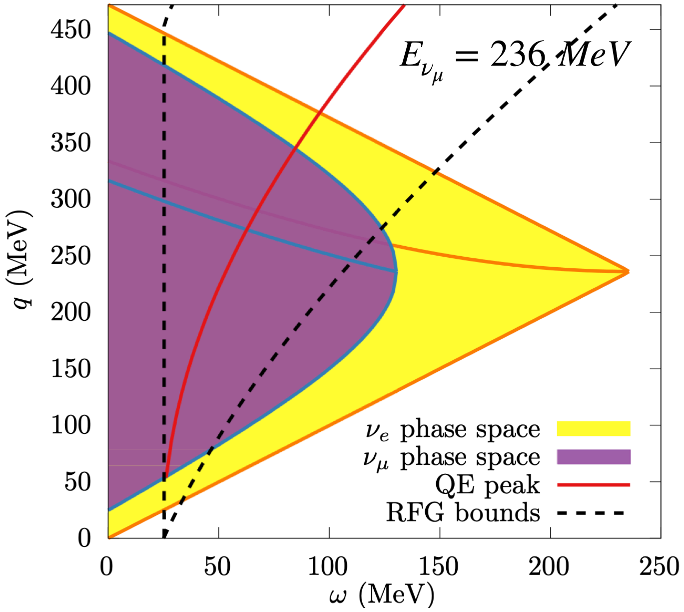
- ν_μ/ν_e **Ratio**
  at lower energies, where the mass of the lepton in the final state affects the accessible phase space considerably

- **KDAR** $\nu_\mu \rightarrow \nu_e$ **oscillations at short baselines**

- .....

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





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

FERMI NATIONAL ACCELERATOR LABORATORY

Summary

- Neutrinos from pion- and kaon-decay rest sources provide interesting avenues 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 and dynamics (inelastic).

Summary

- Neutrinos from pion- and kaon-decay rest sources provide interesting avenues 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 and dynamics (inelastic).

- In general, an electron beam dump produces far fewer neutrinos than a proton beam dump. It is worth exploring the competitiveness and complementarity of the (piDAR and KDAR) neutrino flux at BDX at JLab compared to other sources worldwide

Table 2. Summary of JLab secondary neutrino beam features. Yields are obtained integrating the neutrino flux in the energy range 0–500 MeV.

Beam Energy	Off-Axis Flux [ν/EOT/m^2]	On-Axis Flux [ν/EOT/m^2]
11 GeV	6.7×10^{-5}	2.9×10^{-5}
22 GeV	1.9×10^{-4}	6.3×10^{-5}

"…. when integrated over a 1 m^2 detector located 10 m above (downstream) of the beam dump. Considering a delivered charge of 10^{22} EOT per year, the annual neutrino flux would be in the range of 10^{18} ν."

M. Battaglieri et al., Instruments 8, 1 (2024)