Low-Energy Neutrino-Nucleus Scattering

UNIVERSITY of FLORIDA

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

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with Steven Gardiner, Alexis Nikolakopoulos,
Nils Van Dessel, and Natalie Jachowicz

NDNN NuSTEC Workshop, March 15-18, 2021

Low-Energy Neutrino-Nucleus Scattering

Outline

- ✦ 10s of MeV Neutrino Sources
- ✦ Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
- ✦ Inelastic Neutrino-Nucleus Scattering
- ✦ 10s of MeV Physics in GeV-scale Neutrino Beams

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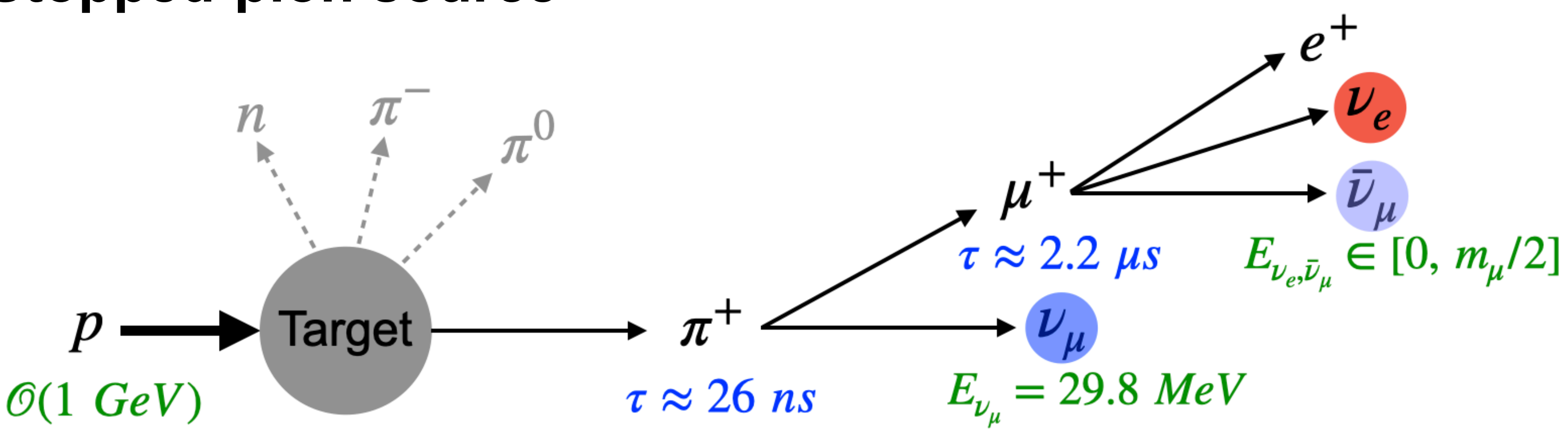
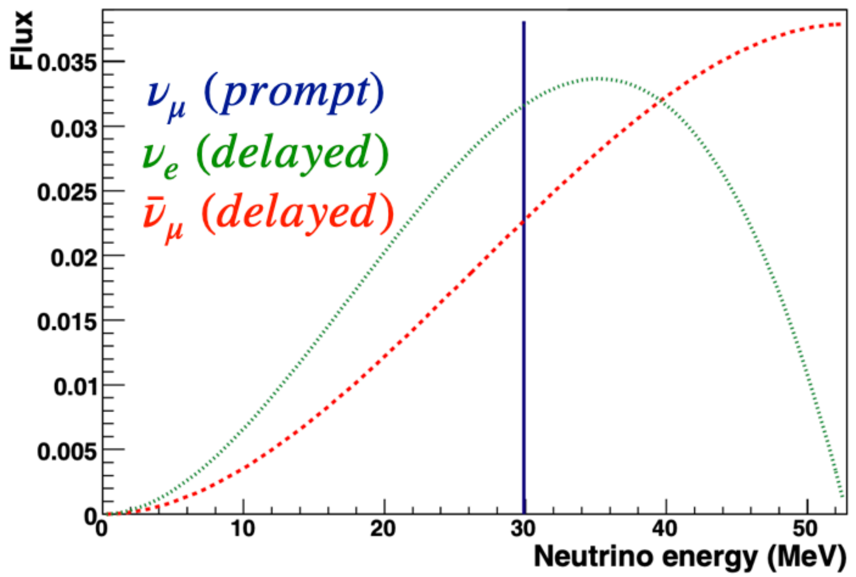
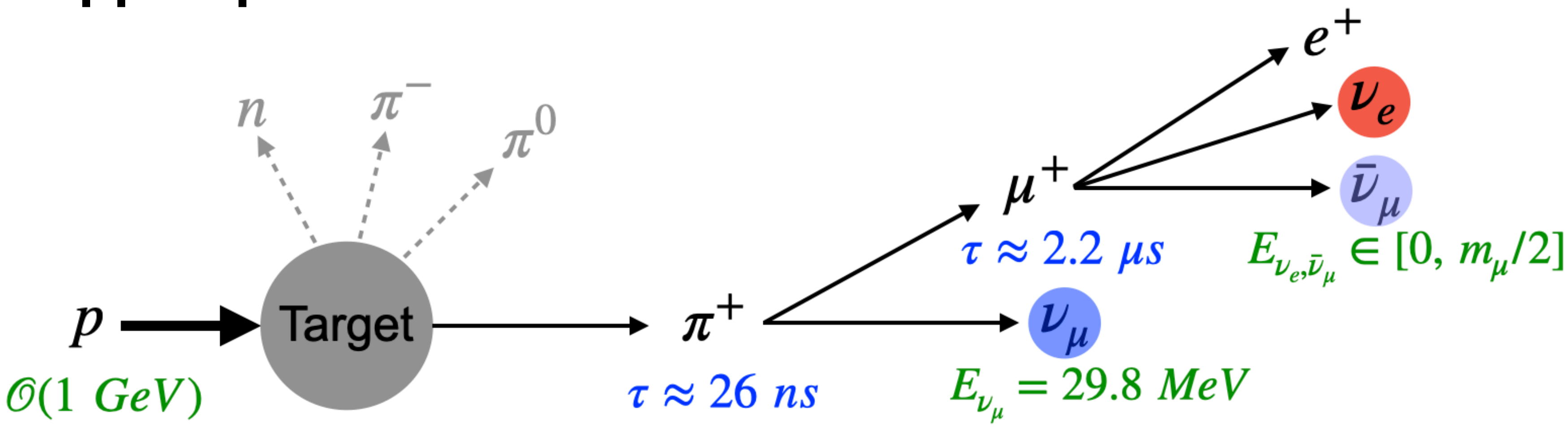
- **Stopped-pion source**

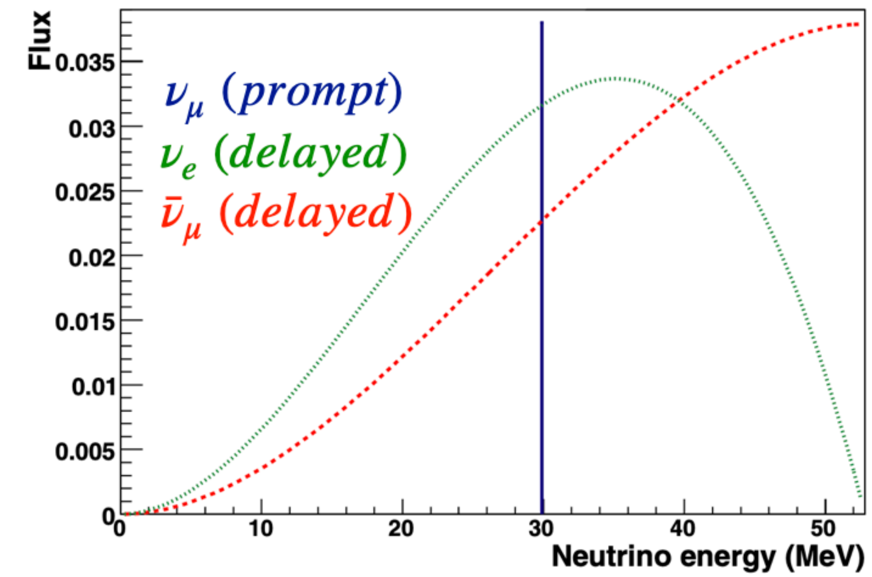


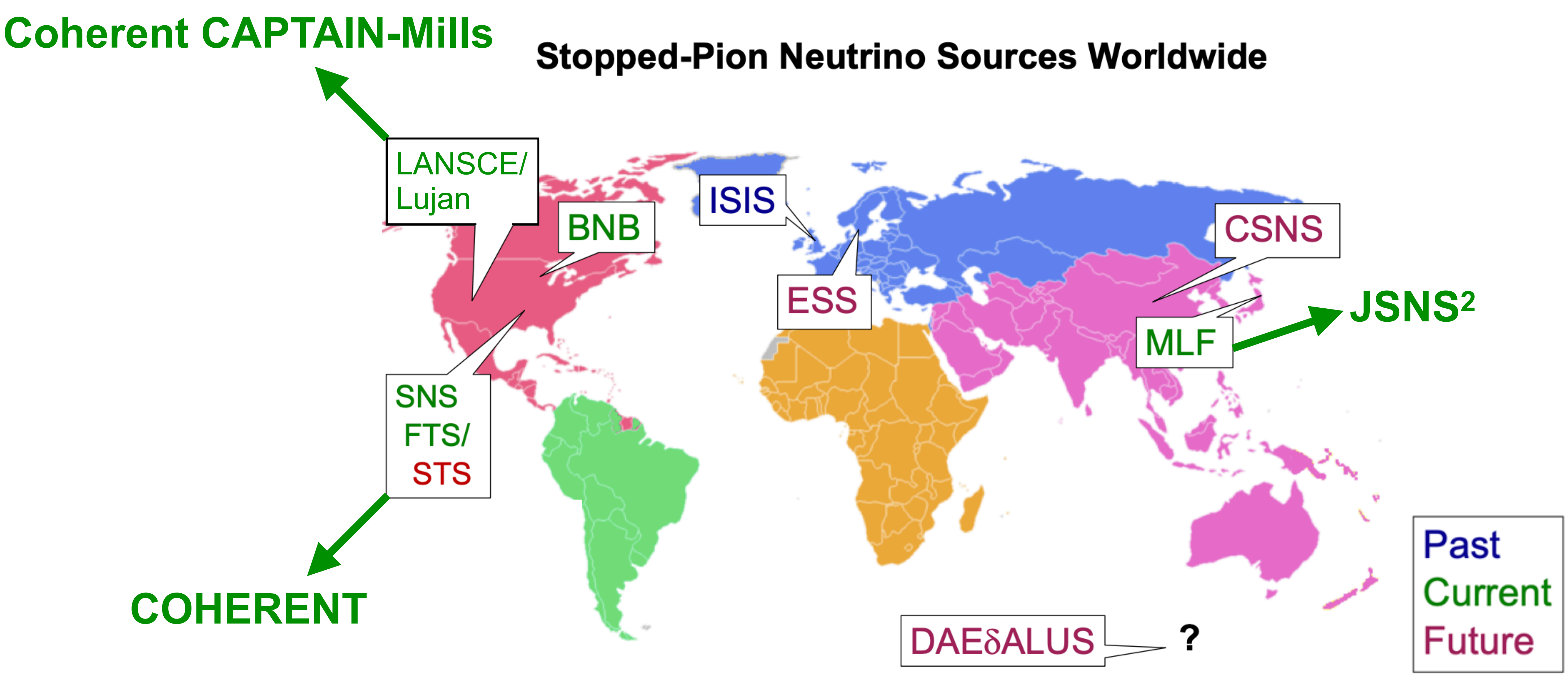


10s of MeV Neutrino Sources

- **Stopped-pion source**

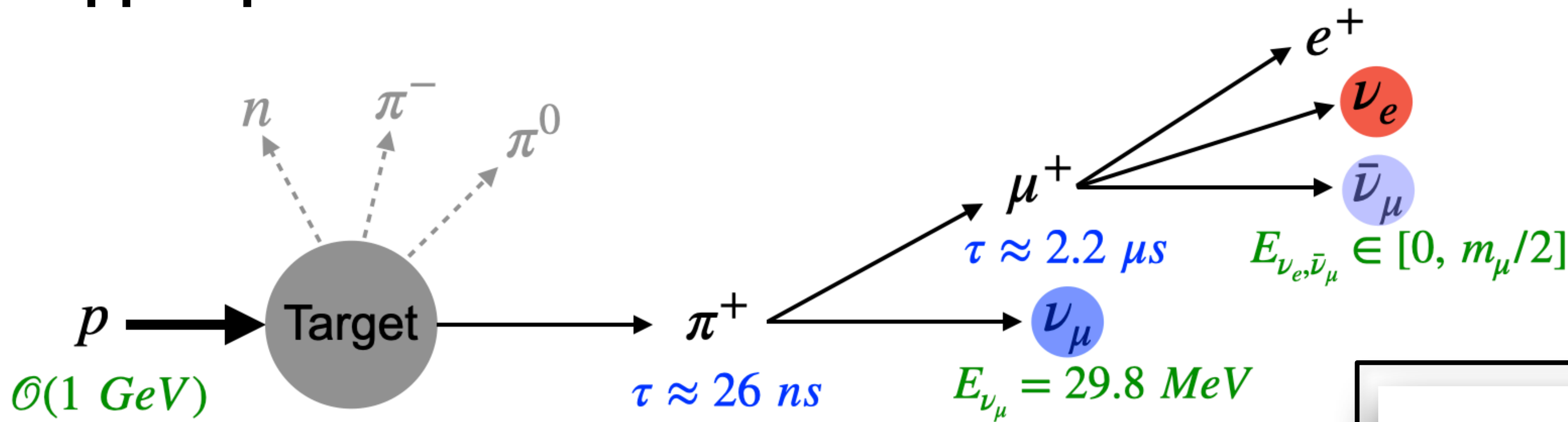


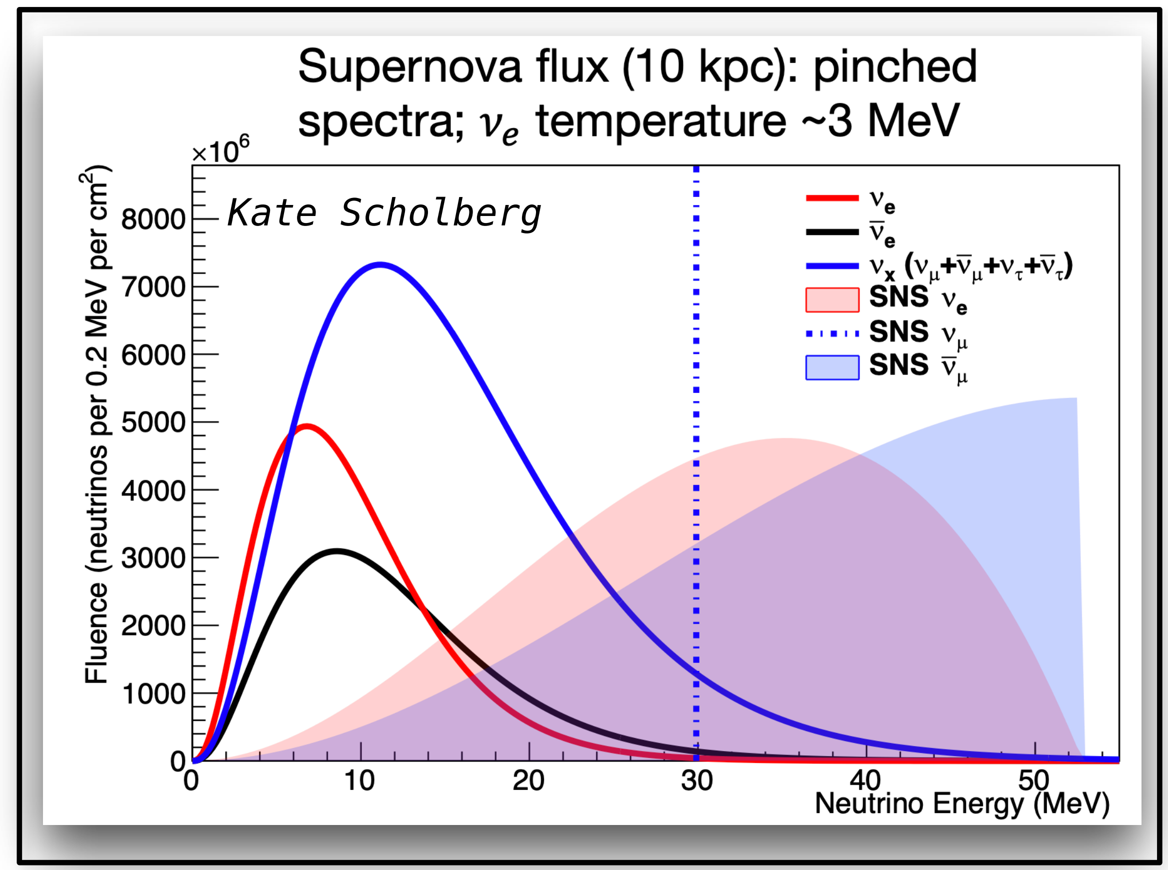




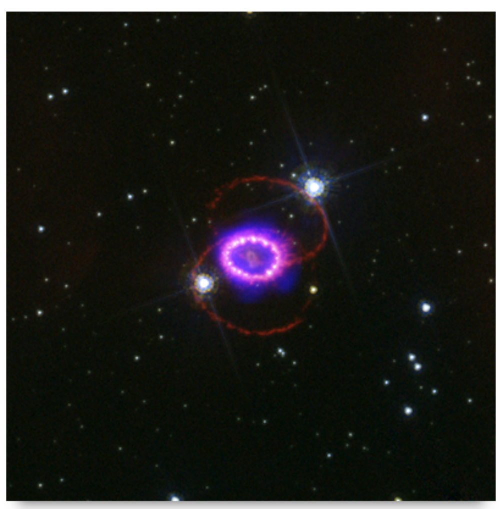
Adapted from Kate Scholberg's talk in the MITP workshop, July 2020

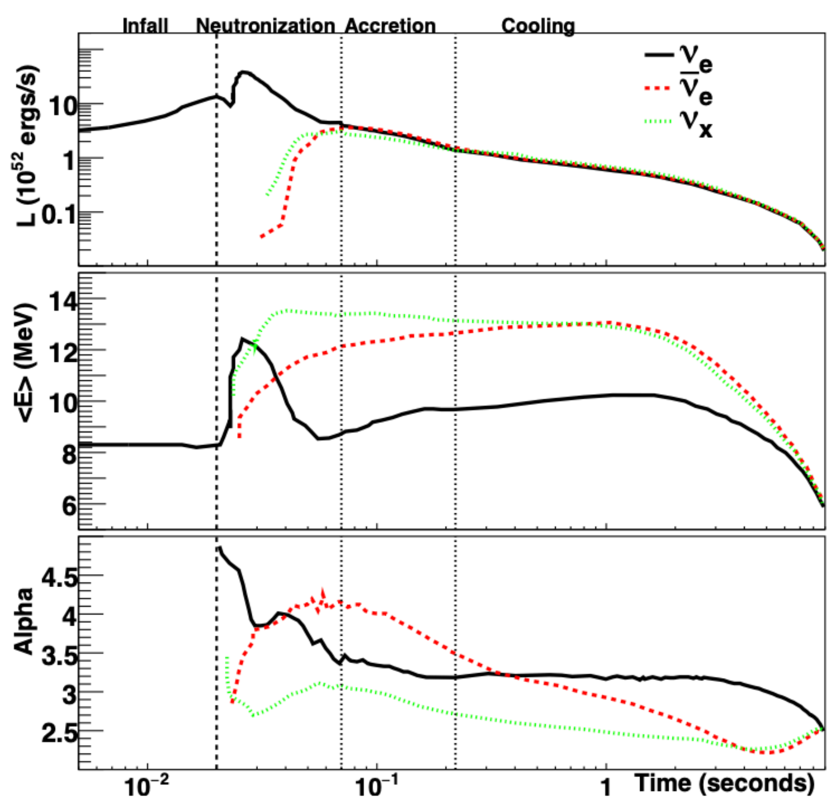
- **Stopped-pion source**





- **Core-collapse supernova**



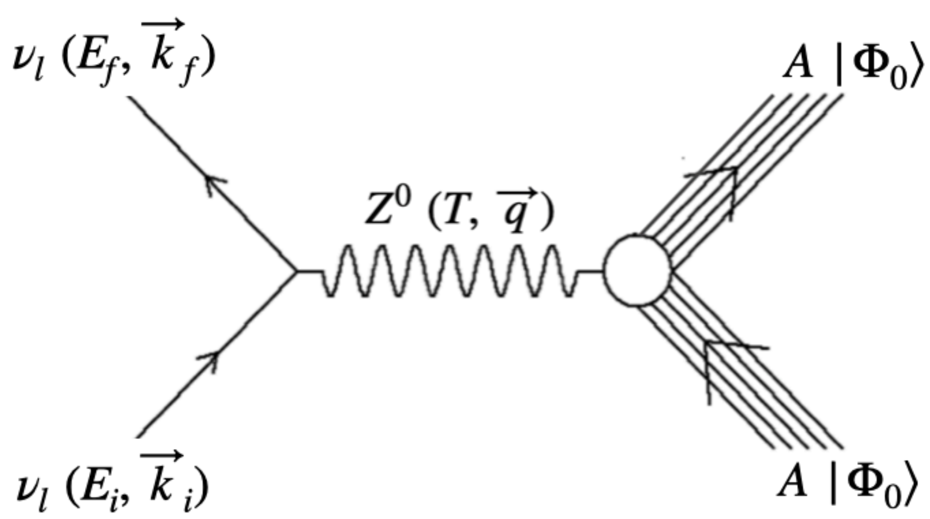


Neutrino signal from the core-collapse supernova starts with a short, sharp "neutronization" (or "breakout") burst primarily composed of ν_e from $e^- + p \to \nu_e + n$.

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

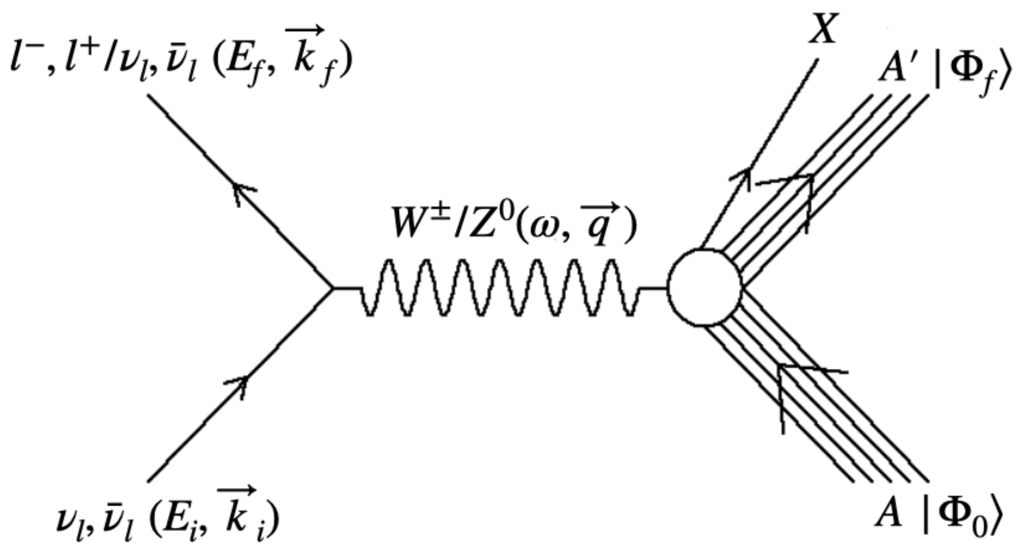
Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

Coherent elastic [CEvNS]

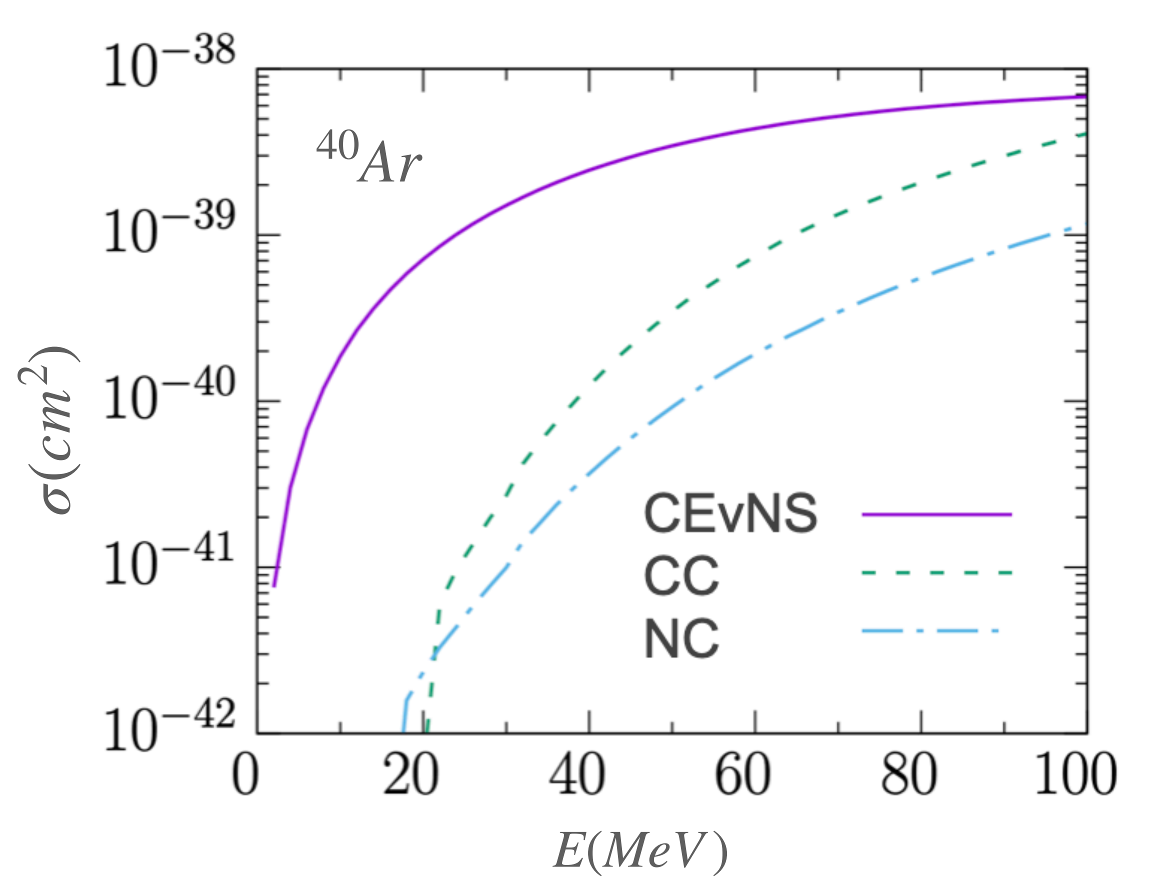


- Tiny recoil energy, large cross section
- Final state nucleus stays in its ground state
- Signal: keV energy nuclear recoil (gammas)

Inelastic CC/NC



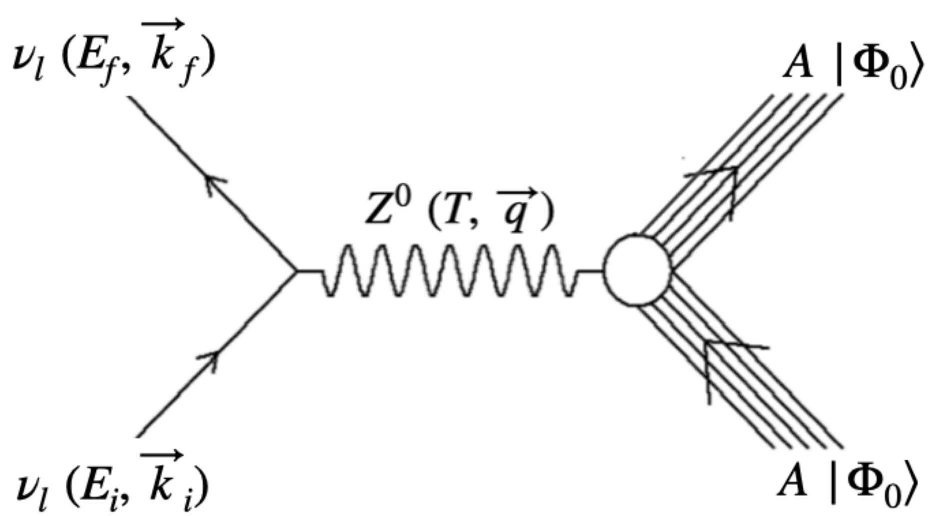
- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π)
- Followed by nuclear de-excitation into gammas, n, p, and nuclear fragmentations.



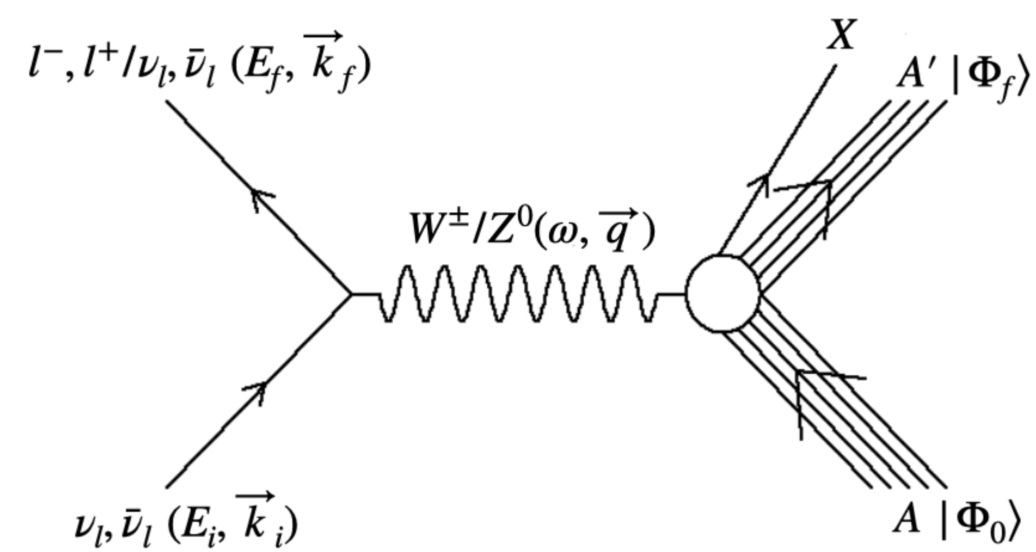
arXiv:2007.03658 [nucl-th]

Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

Coherent elastic [CEvNS]



Inelastic CC/NC



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

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

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

Cross Section:

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

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

Cross Section:

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

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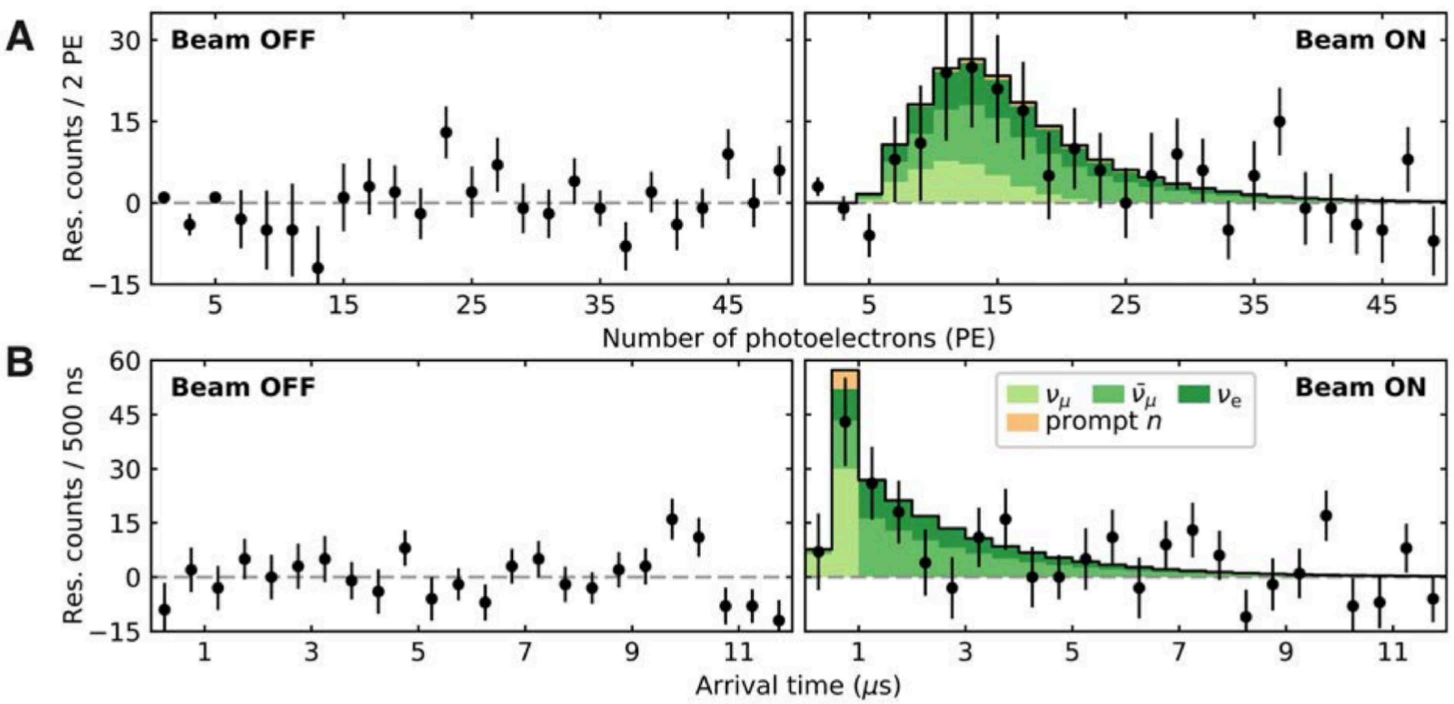
Coherent Elastic Neutrino-Nucleus Scattering

COHERENT Collaboration at SNS at ORNL

Matthew Heath's talk today

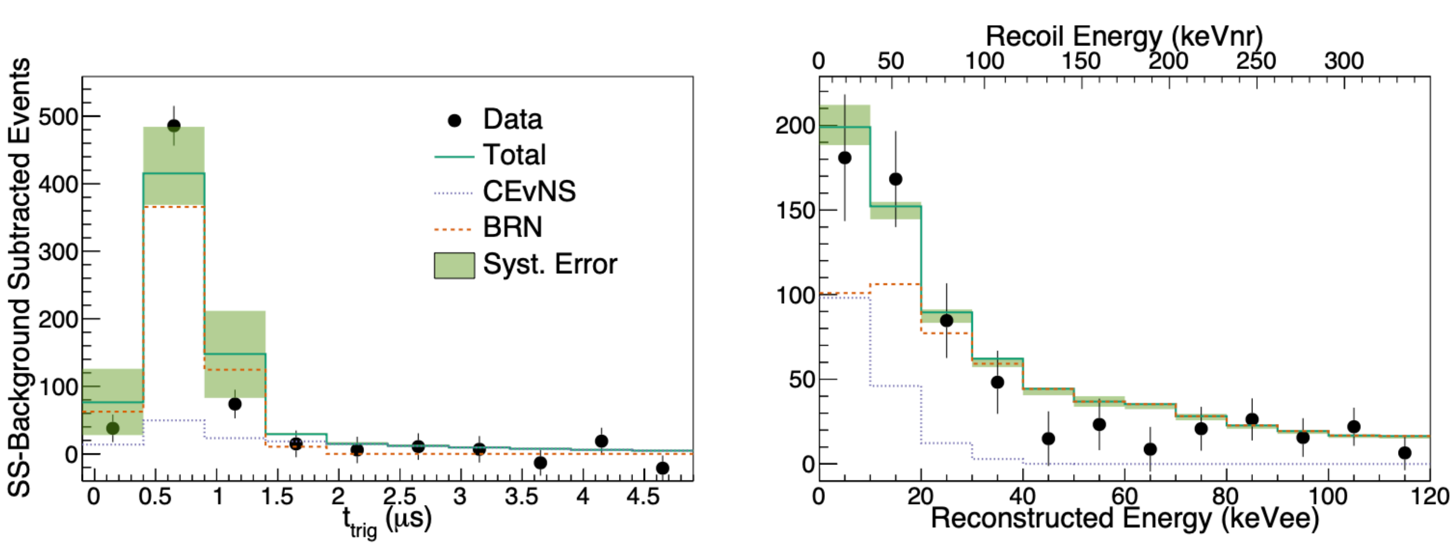
14 kg CSI detector

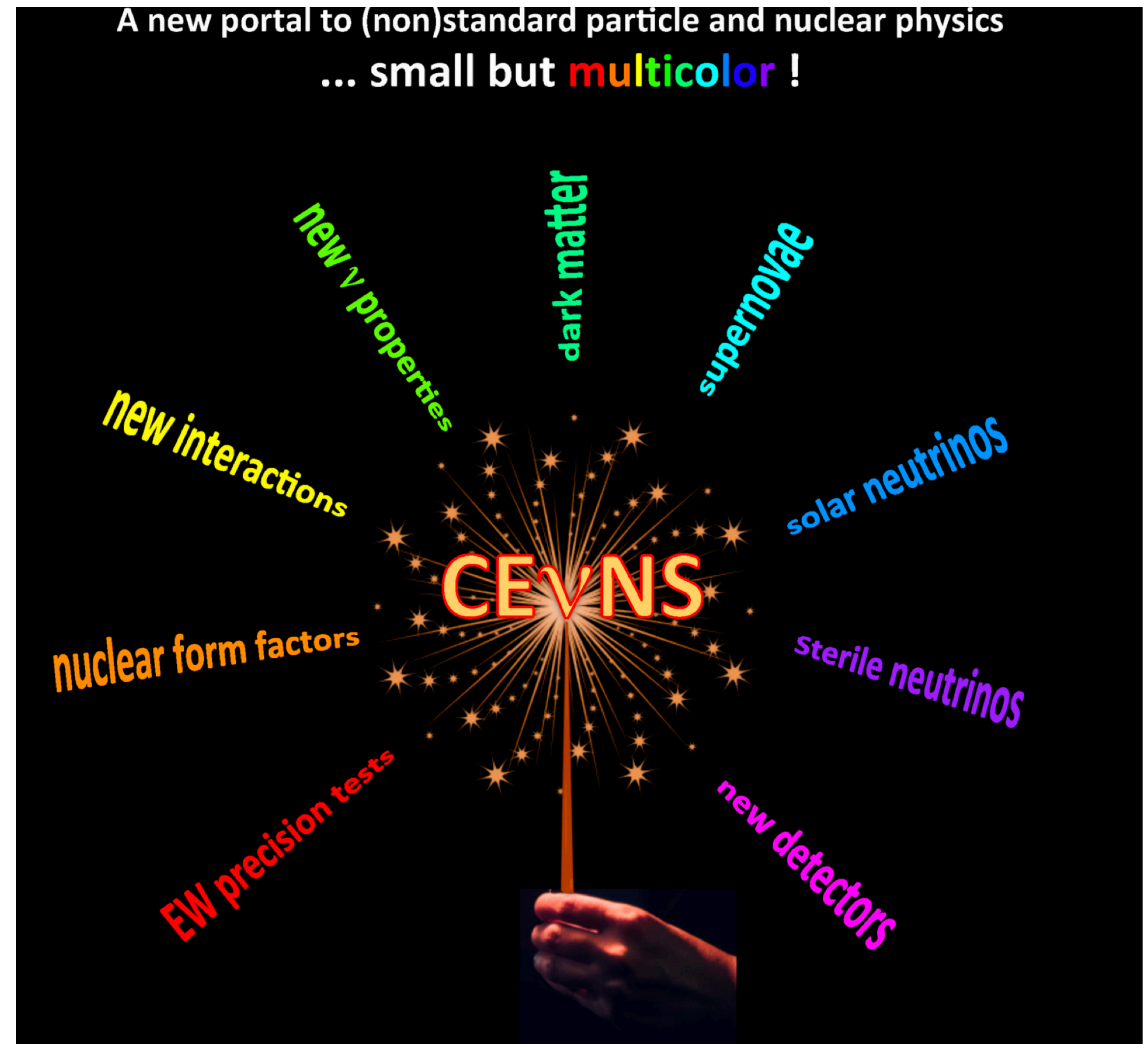
COHERENT Collaboration, Science 357, 6356, 1123–1126 (2017)



24 kg LAr (CENNS-10) detector

COHERENT Collaboration, Phys. Rev. Lett. 126, 012002 (2021)





Eligio Lisi, NuINT 2018

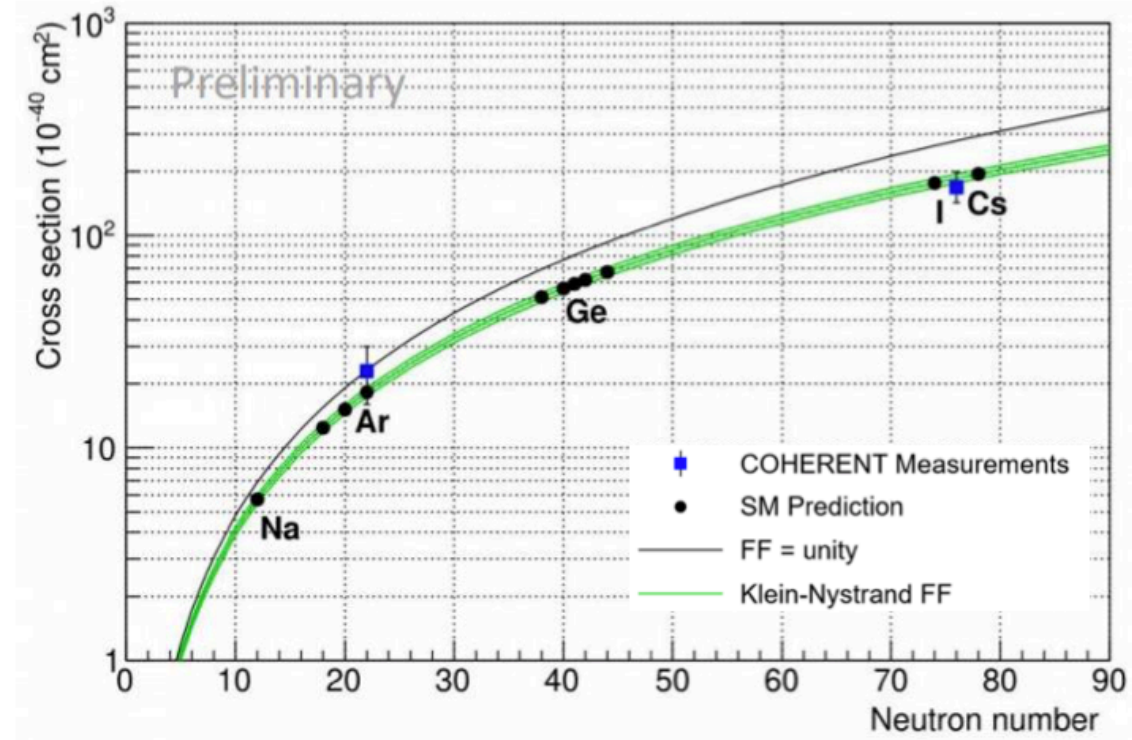
COHERENT Collaboration at SNS at ORNL

Matthew Heath's talk today

- **CsI:14.6 kg**
  - Flux averaged cross section extracted

CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

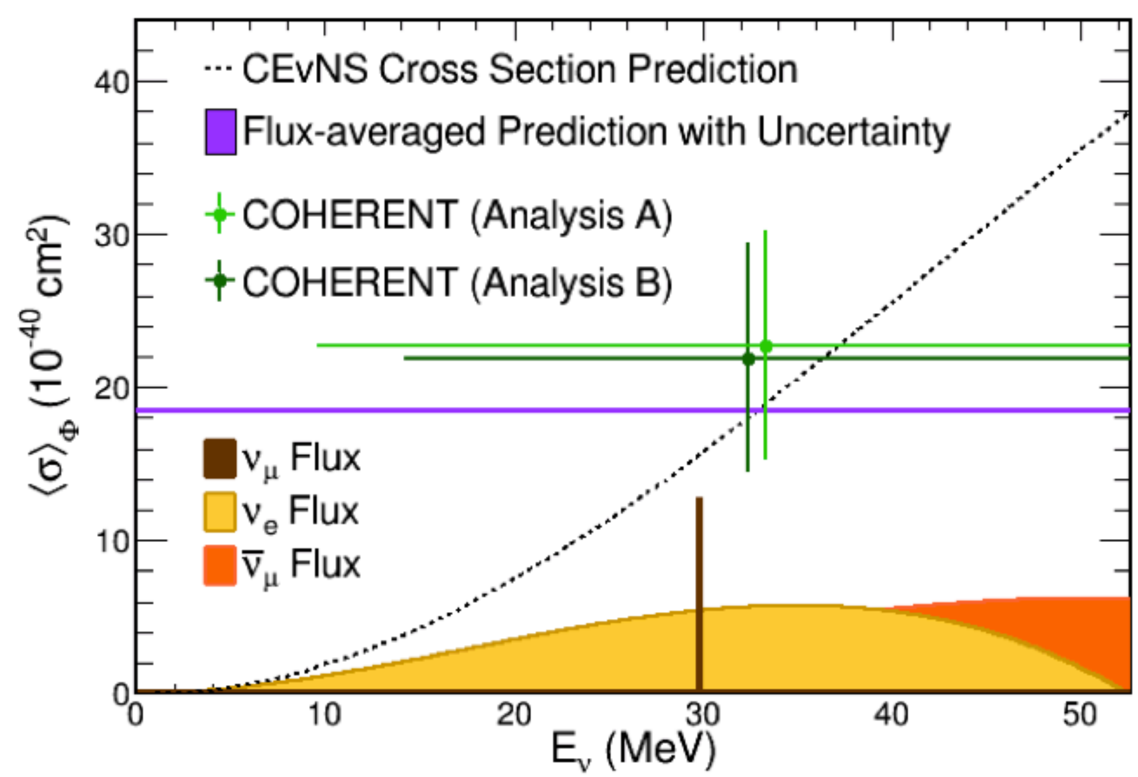
  - Systematic uncertainty reduced from 28% (2017 results) to 13% (2020 results in M7 workshop)
  - Detector decommissioned



- **^{40}Ar: CENNS-10, 24 kg**
  - Flux averaged cross section extracted

$$(2.3 \pm 0.7) \times 10^{-39}\ cm^2$$

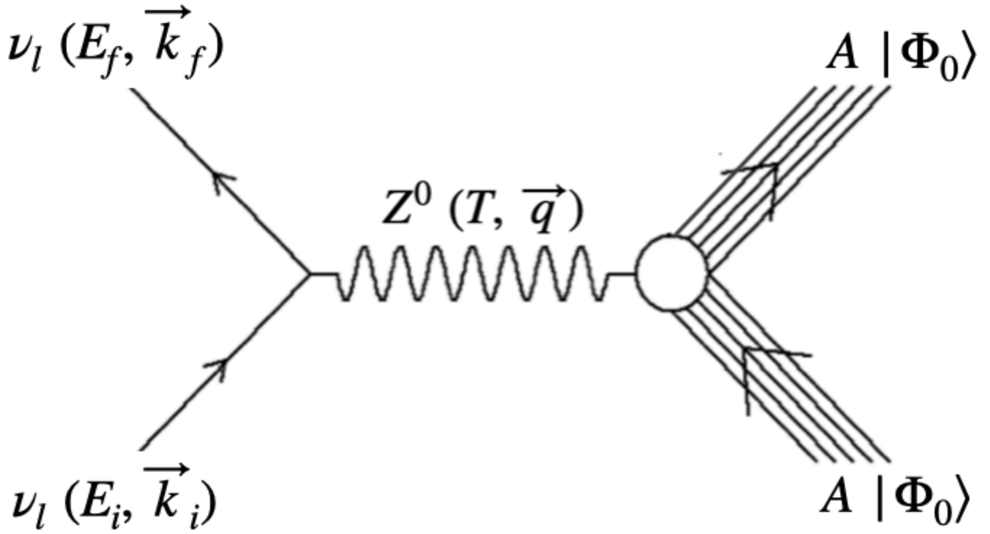
  - Collecting more data



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

- **Cross section**:

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



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

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

- Weak Form Factor:

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

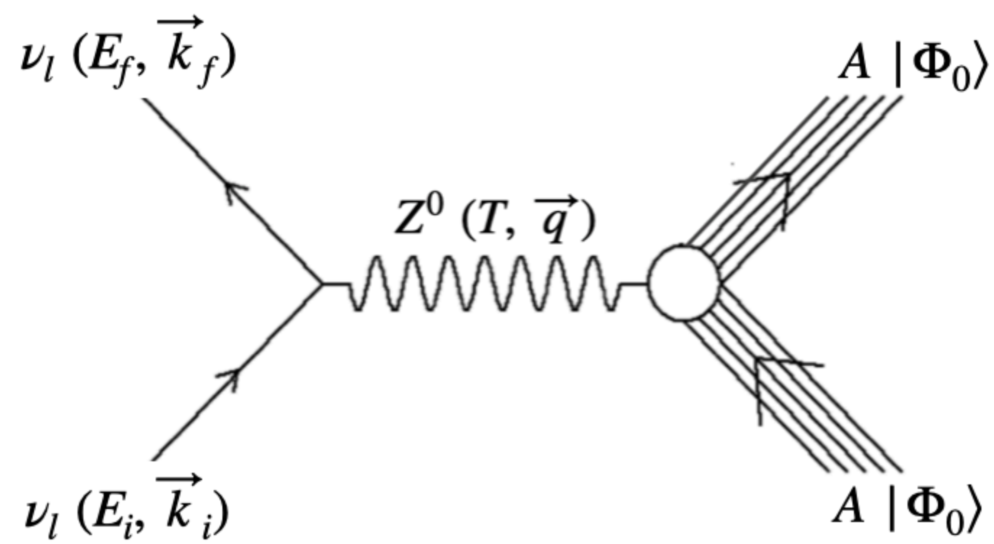
Charge density and charge form factor: proton densities and charge form factors are well know through decades of elastic electron scattering experiments.

Neutron densities and neutron form factor: neutron densities and form factors are poorly known. Note that CEvNS is primarily sensitive to neutron density distributions.

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:

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

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

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

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

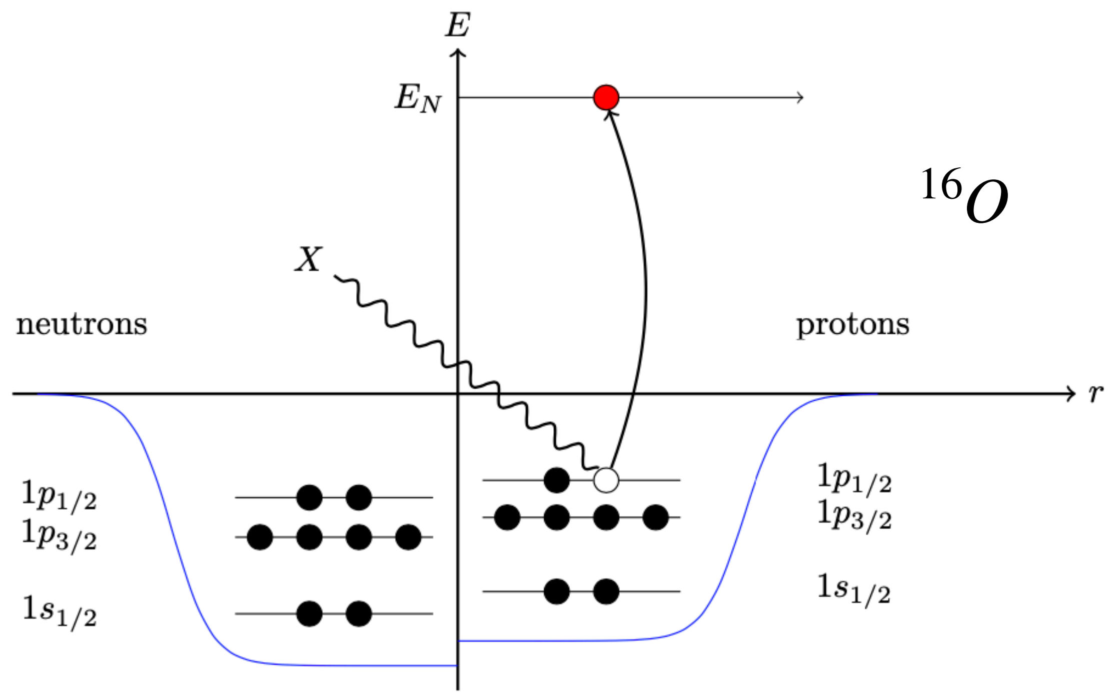
Neutron densities and neutron form factor: neutron densities and form factors are poorly known. Note that CEvNS is primarily sensitive to neutron density distributions.

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

$$A_{PV}(q^2) = \frac{G_F q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(q^2)}{Z F_{ch}(q^2)}$$

- PVES experiments at **JLab**: PREX has measured the weak charge of ^{208}Pb at a single value of momentum transfer. PREX–II (^{208}Pb) is underway and CREX (^{48}Ca) is planned.
- Future PVES experiments are planned at **MESA (Mainz)**.

CEvNS Cross Section: HF-SkE2 Model



- A microscopic many–body nuclear theory model.
- Nuclear ground state is 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. Fill up nuclear shells following Pauli principle.
- Evaluate proton and neutron density distributions from those wave functions:

$$\rho_\tau(r) = \frac{1}{4\pi r^2} \sum_\alpha v_{\alpha,\tau}^2 \, (2j_\alpha + 1) \, |\phi_{\alpha,\tau}(r)|^2 \quad (\tau = p, n)$$

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

- Proton and neutron densities are utilized to calculate proton and neutron form factors:

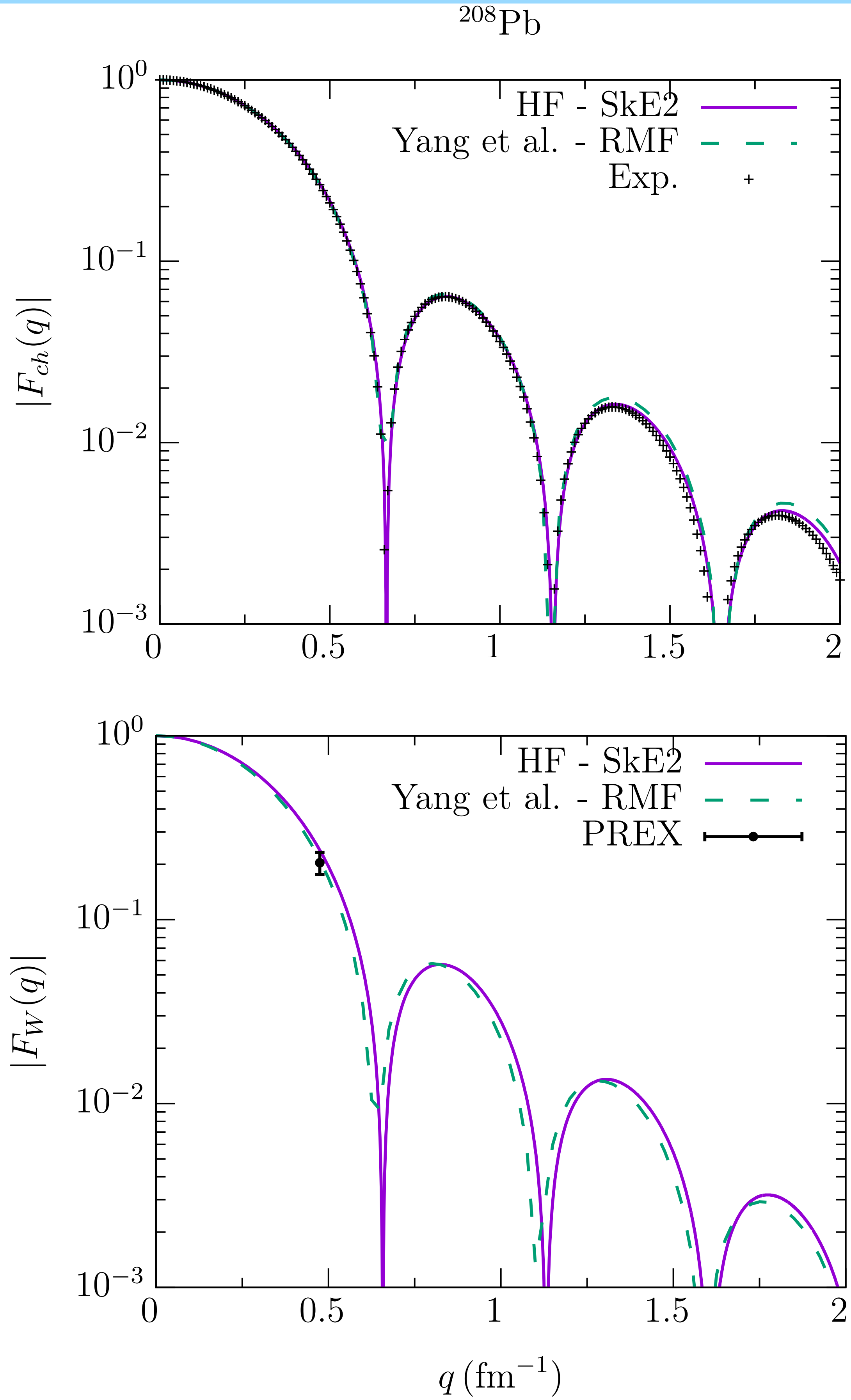
$$F_p(q) = \frac{1}{Z} \int d^3r \, j_o(qr) \, \rho_p(r), \qquad F_n(q) = \frac{1}{N} \int d^3r \, j_o(qr) \, \rho_n(r)$$

HF-SkE2 Model: ^{208}Pb Results

Charge Form Factor

- Our charge form factor predictions of ^{208}Pb describe the elastic electron scattering experimental data remarkably well.

Experimental data from:
H. De Vries, et al., Atom. Data Nucl. Data Tabl. 36, 495 (1987)



Weak Form Factor

- Weak form factor predictions shown along with the single data point measured by the PREX collaboration at a momentum transfer of q = 0.475 fm^{-1}.

- The follow–up PREX–II measurement at Jefferson lab aims to reduce the error bars by at least a factor of three.

PREX data from:
- S. Abrahamyan et al., Phys. Rev. Lett. 108, 112502 (2012).
- C. J. Horowitz et al., Phys. Rev. C 85, 032501 (2012).

- Both calculations compared with RMF predictions of *Yang et al. Phys. Rev. C 100, 054301 (2019)*.

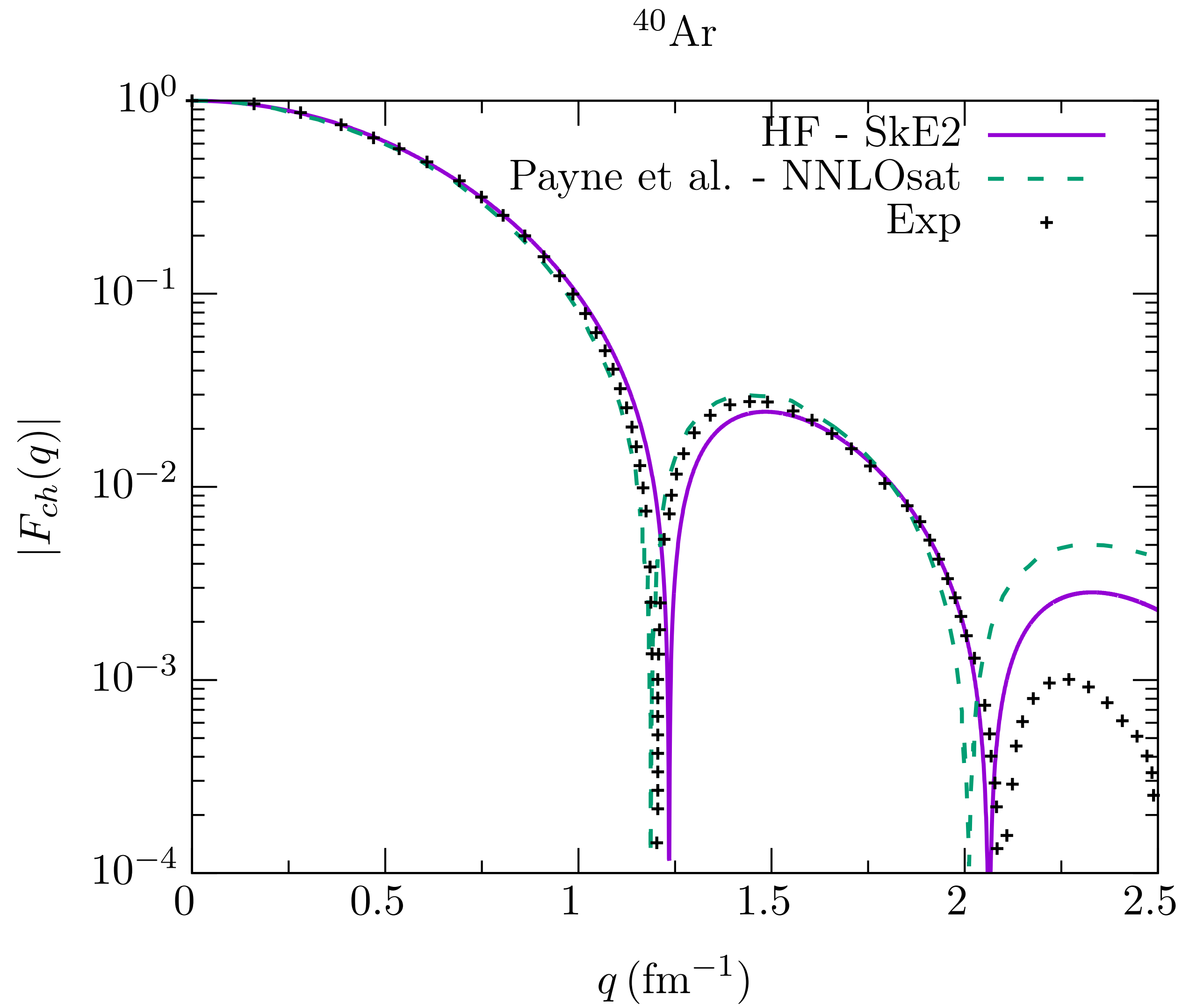
arXiv:2007.03658 [nucl-th]

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

■ **Charge Form Factor**

- The ^{40}**Ar** charge form factor predictions describe experimental elastic electron scattering data well for q < 2 fm^{-1}.
- For energies relevant for pion decay–at–rest neutrinos, the region above q > 0.5 fm^{-1} does not contribute to CEvNS cross section.

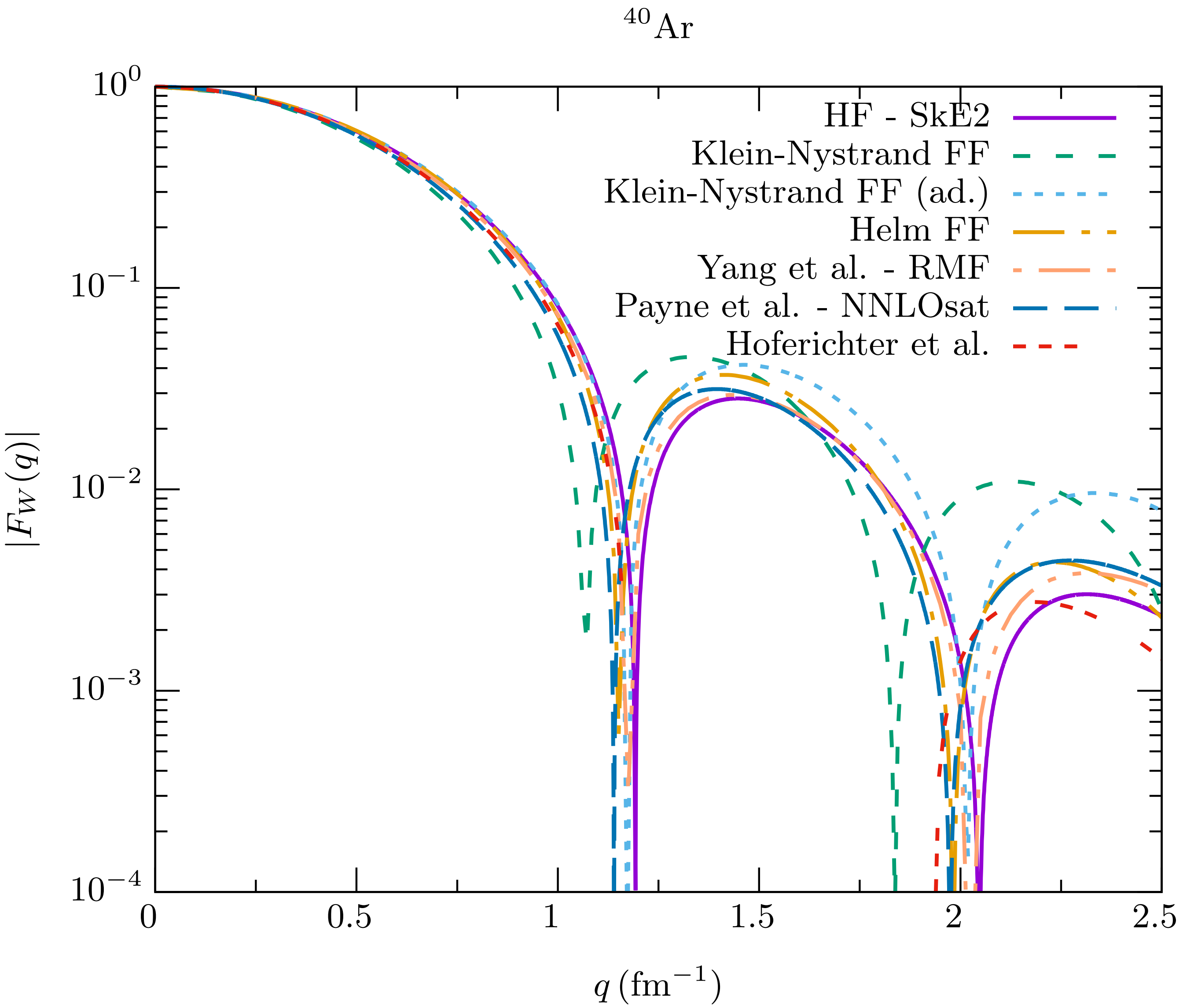
Experimental data from:
C. R. Ottermann et al., Nucl. Phys. A 379, 396 (1982).



- Our calculations compared with Payne *et al.* Phys. Rev. C 100, 061304 (2019) where form factors are calculated within a coupled-cluster theory from first principles using a chiral NNLO$_{sat}$ interaction (See Joanna Sobczyk's talk today).

arXiv:2007.03658 [nucl-th]

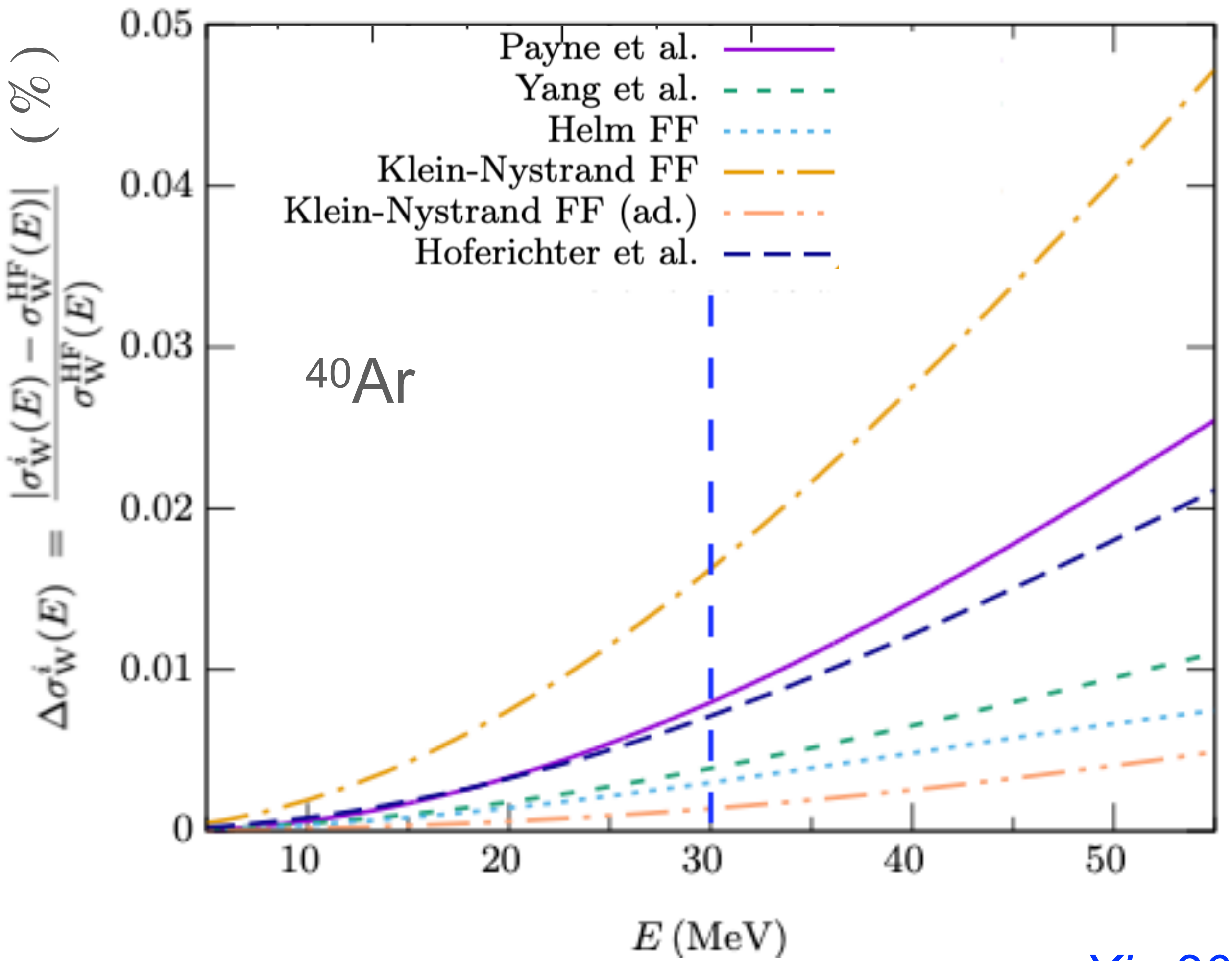
- **Weak Form Factor**
  - Comparison of ^{40}Ar form factor predictions from four nuclear theory and three phenomenological calculations.
  - Different approaches are based on different representations of the nuclear densities.



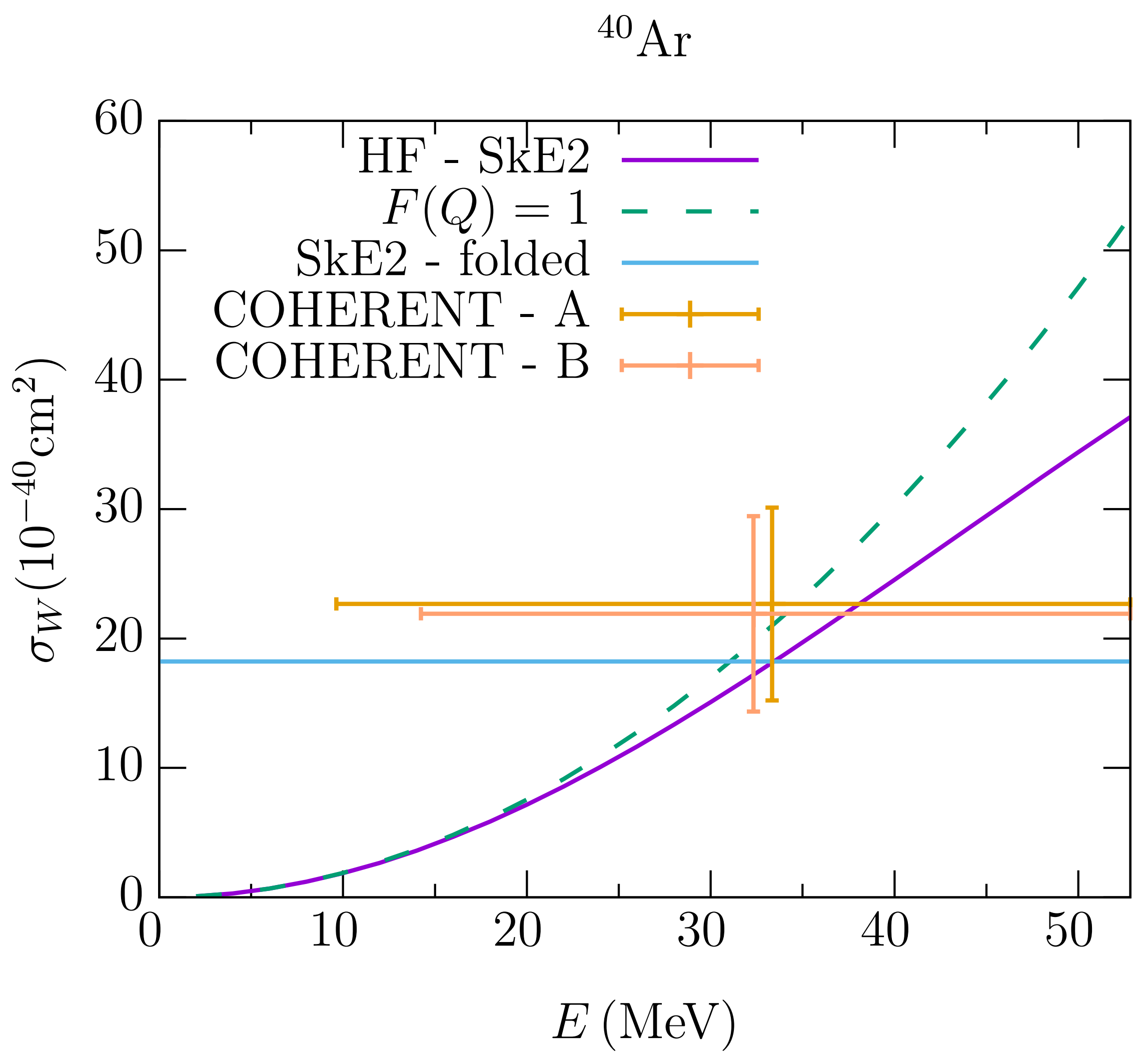
- *The HF–SkE2 model [arXiv:2007.03658 [nucl-th]]*
- *Model of Payne et al. [Phys. Rev. C 100, 061304 (2019)] where form factors are calculated within a coupled-cluster theory from first principles using a chiral NNLO$_{sat}$ interaction.*
- *Model of Yang et al. [Phys. Rev. C 100, 054301 (2019)] where form factors are predicted within a relativistic mean–field model informed by the properties of finite nuclei and neutron stars.*
- *Model of Hoferichter et al. [Phys. Rev. D 102, 074018 (2020)] where form factors are calculated within a large-scale nuclear shell model.*
- *Helm and Klein-Nystrand [adapted by COHERENT] predictions*

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

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



- Comparison with COHERENT CENNS-10 data.



arXiv:2007.03658 [nucl-th]

- For a full theoretical error estimate see Oleksandr Tomalak's talk from Tuesday.

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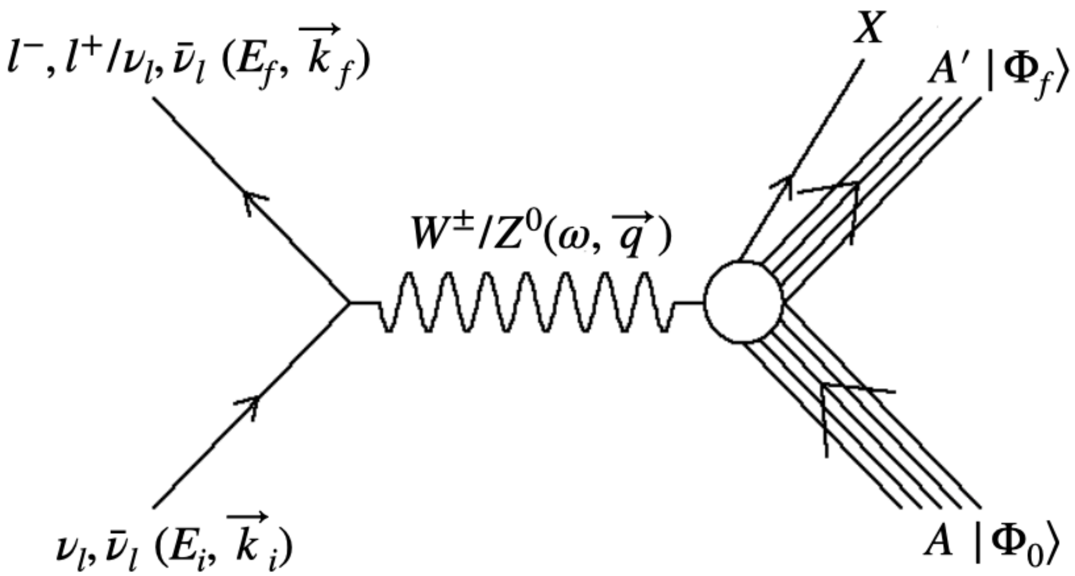
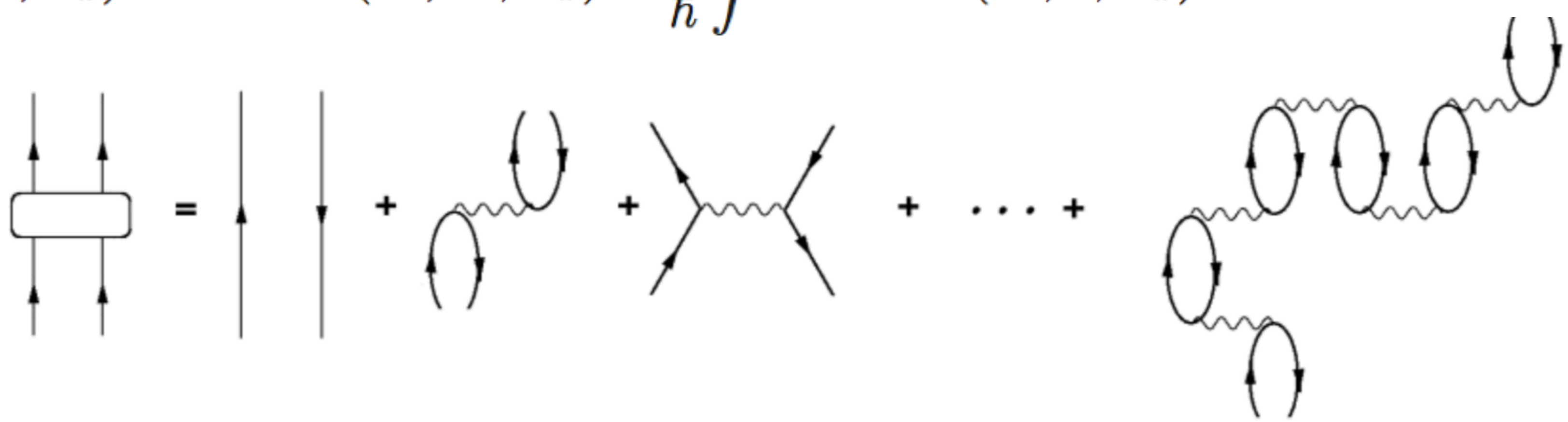
Inelastic CC/NC Neutrino-Nucleus Scattering: HF-CRPA Model

- 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 quasielastic scattering 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.



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

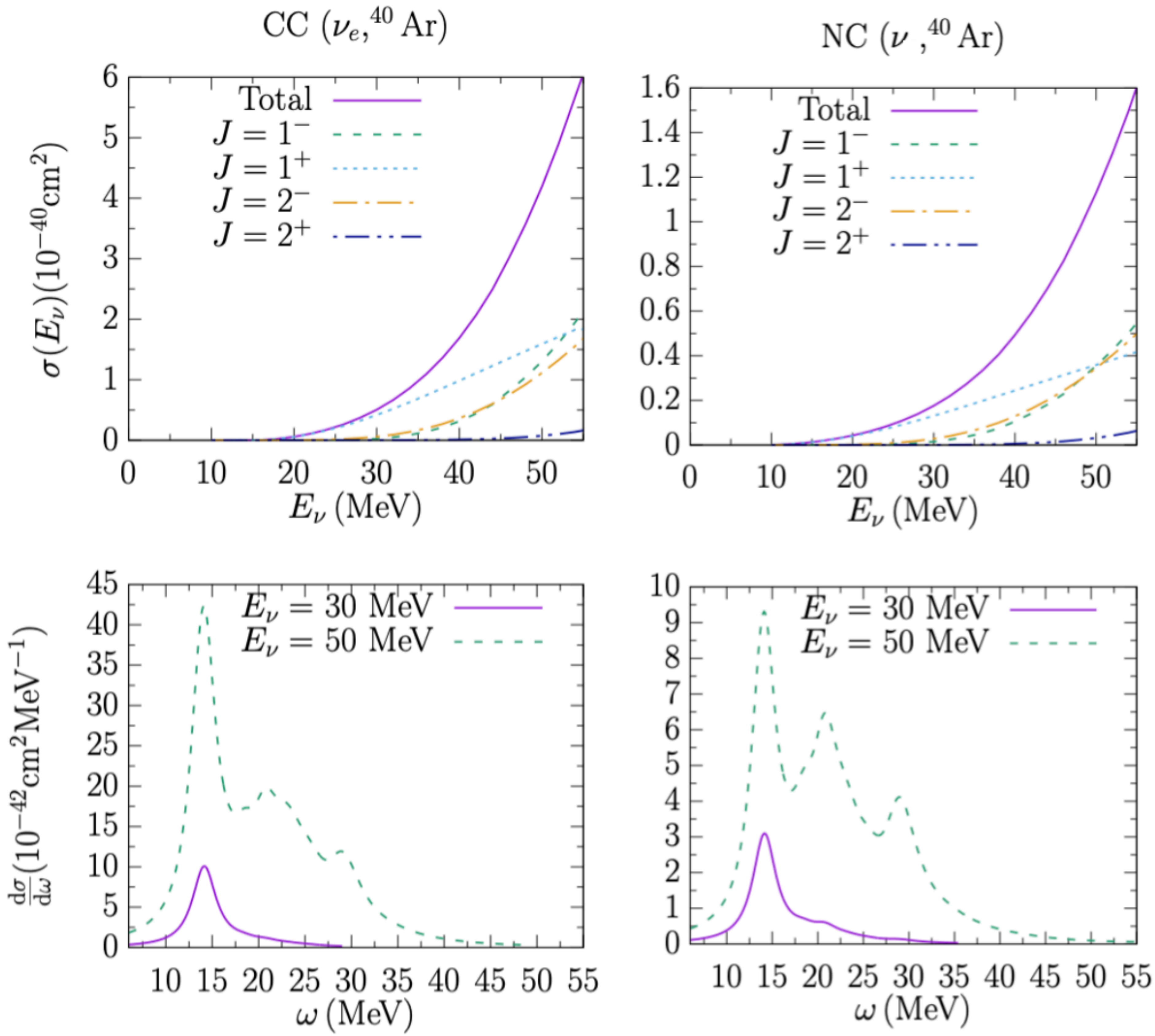


$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega \mathrm{d}\Omega} = \sigma_W E_f k_f \zeta^2(Z', E_f)\left(v_{CC}R_{CC} + v_{CL}R_{CL} + v_{LL}R_{LL} + v_T R_T + h v_{T'} R_{T'}\right)$$

Coulomb correction factor: $\zeta^2(Z', E_f)$

$$\sigma_W^{CC} = \left(\frac{G_F \cos\theta_c}{2\pi}\right)^2, \quad \sigma_W^{NC} = \left(\frac{G_F}{2\pi}\right)^2$$

Inelastic CC/NC Neutrino-Nucleus Scattering: HF-CRPA Model



Inelastic CC/NC Neutrino-Nucleus Scattering: MARLEY Generator

- 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.

  Steven Gardiner, arXiv:2010.02393 [nucl-th] (accepted in PRC), arXiv:2101.11867 [nucl-th]

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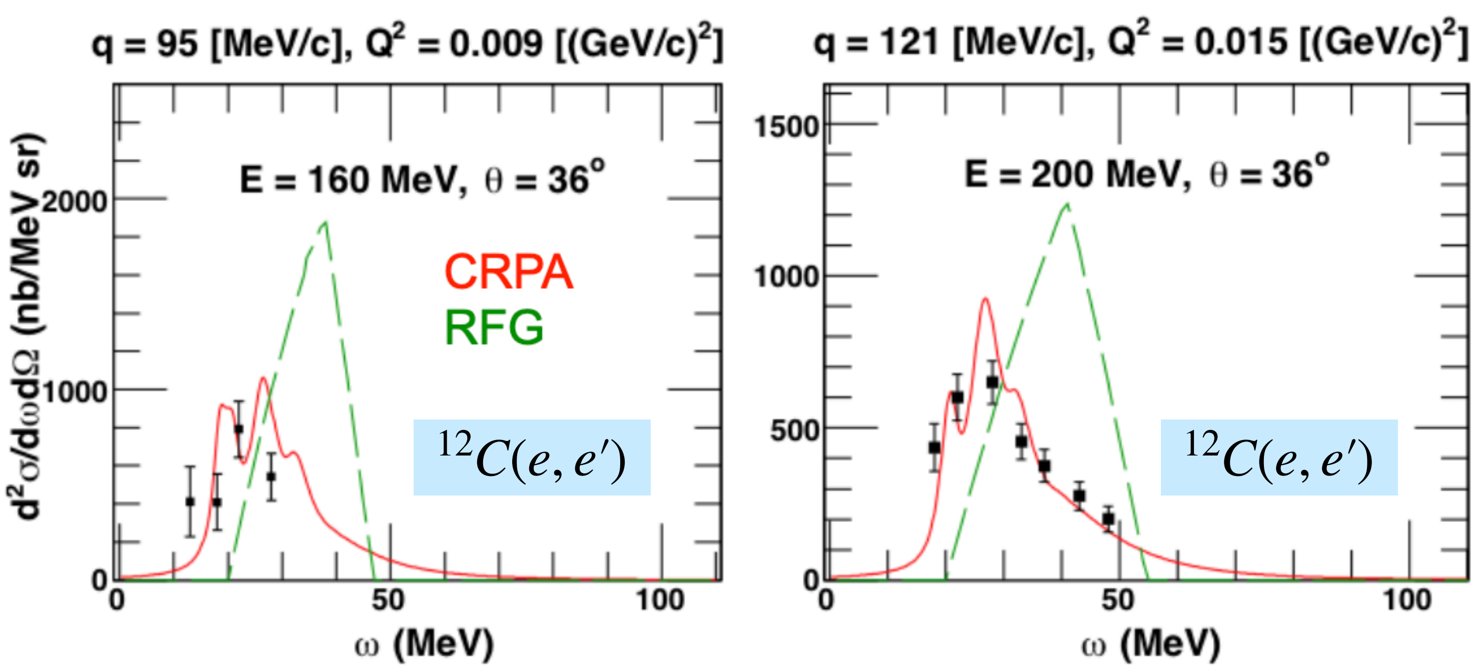
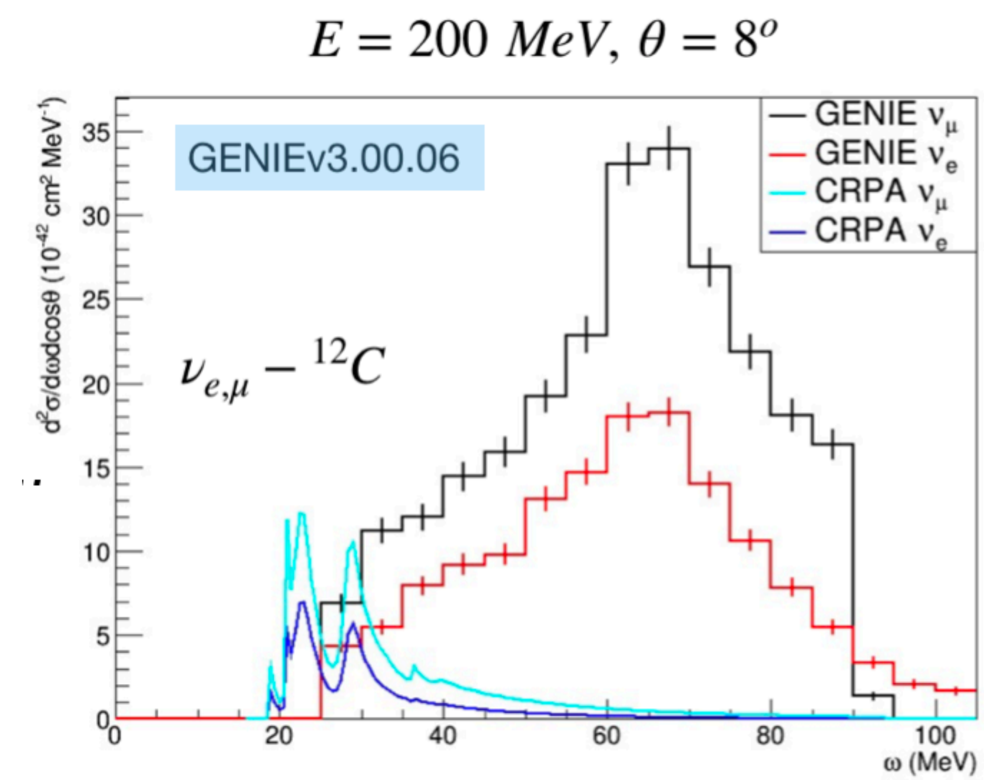
- Fermi gas-based approximation, hence "traditional" neutrino generators, are inadequate at these energies where low-energy excitations, giant resonances and a handle on the de-excitation γ-rays play the central role.





- Dedicated low-energy generators are needed.

- Other emerging generator efforts: sntools (^{12}C, ^{16}O) J. Migenda, arXiv:2002.01649
  newton (^{16}O) B. Bodur, https://github.com/itscubist/newton

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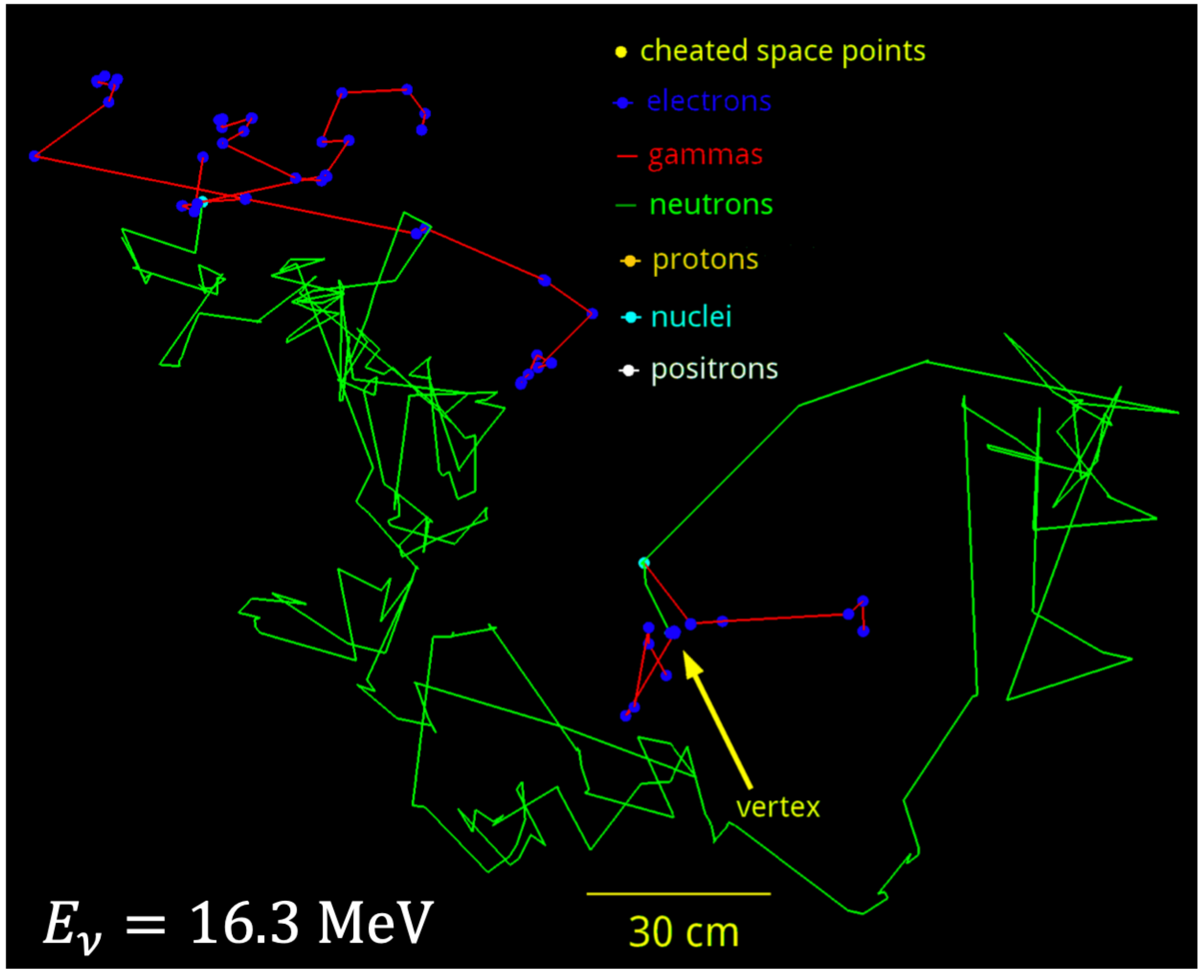
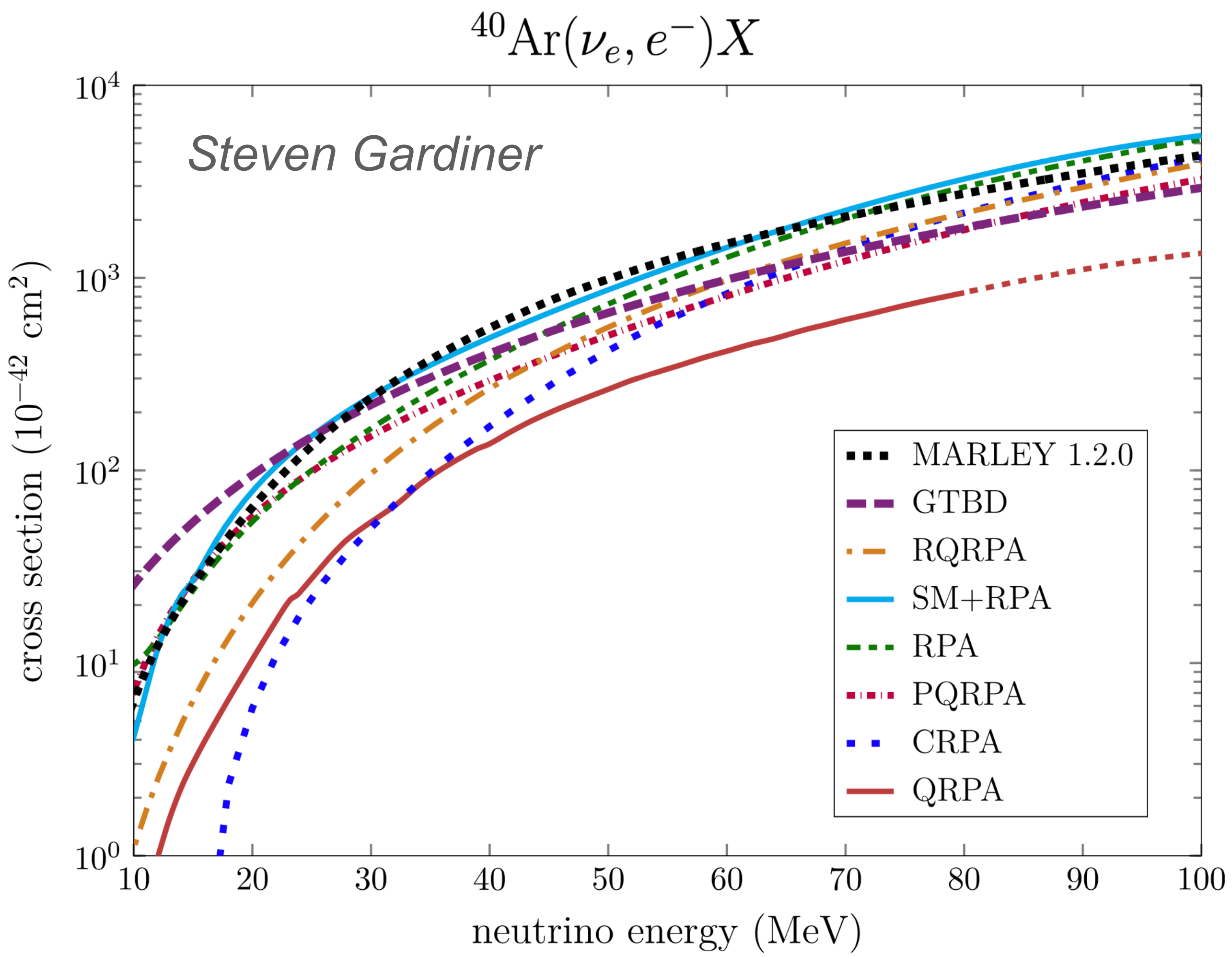
- An example of MARLEY ν_e CC event simulated in LArSoft, showing the trajectories and energy deposition points of the interaction products.



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



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  - **MARLEY Cross Section Model:** two-step process

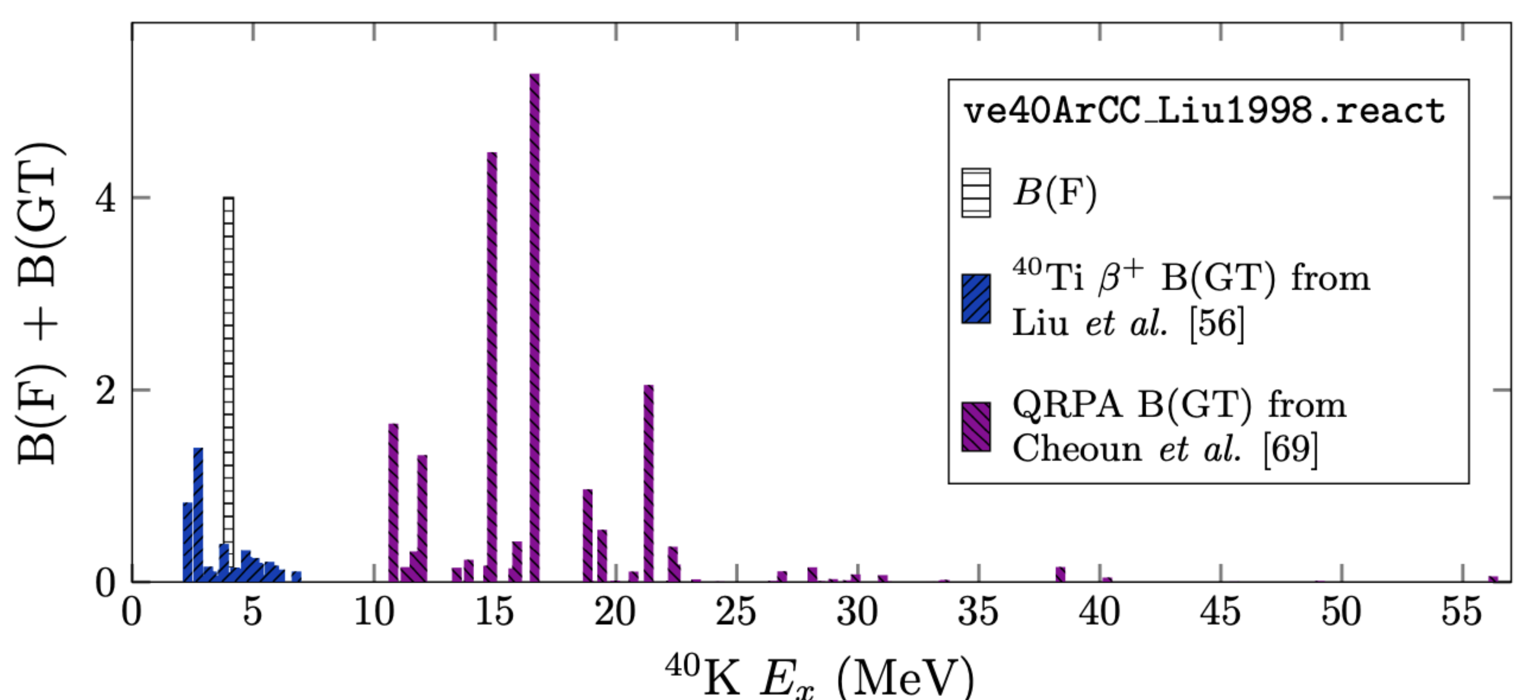
    I. Inclusive scattering on the nucleus:

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

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

$$B(\mathrm{F}) \equiv \frac{g_V^2}{2J_i+1}\left|\langle J_f \,\|\, \mathcal{O}_{\mathrm{F}} \,\|\, J_i\rangle\right|^2 \qquad B(\mathrm{GT}) \equiv \frac{g_A^2}{2J_i+1}\left|\langle J_f \,\|\, \mathcal{O}_{\mathrm{GT}} \,\|\, J_i\rangle\right|^2$$

based on a combination of indirect measurements (e.g., β decay) and a QRPA calculation



Inelastic CC/NC Neutrino-Nucleus Scattering: MARLEY Generator

- 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.

  Steven Gardiner, arXiv:2010.02393 [nucl-th] (accepted in PRC), arXiv:2101.11867 [nucl-th]

- **MARLEY Cross Section Model:** two-step process

  II. Nuclear de-excitation:

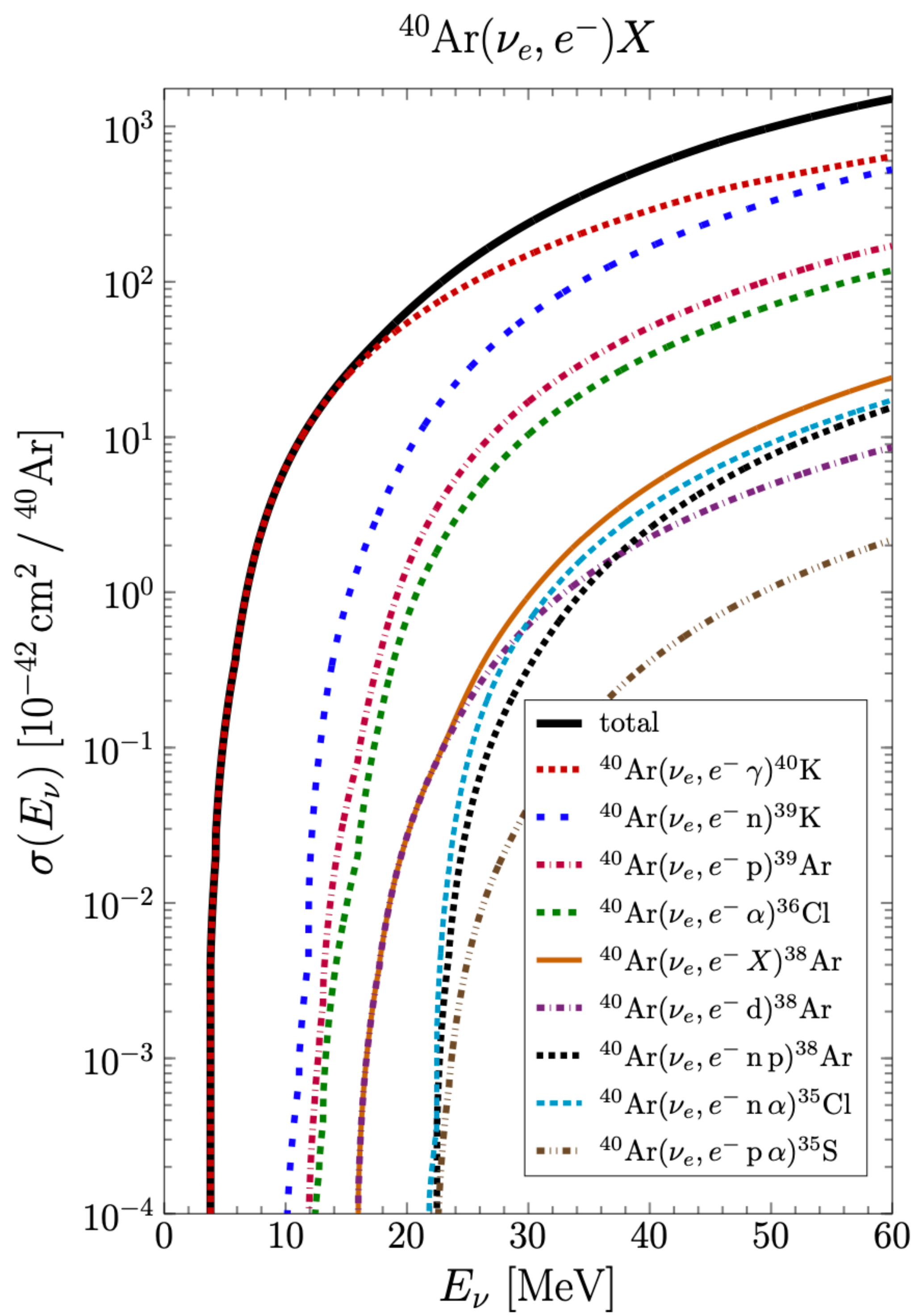
  For bound nuclear states, the de-excitation gamma rays are sampled using tables of experimental branching ratios.

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

  Differential decay width for emission of nuclear fragment a (A $\leq$ 4 considered) or a γ-ray:

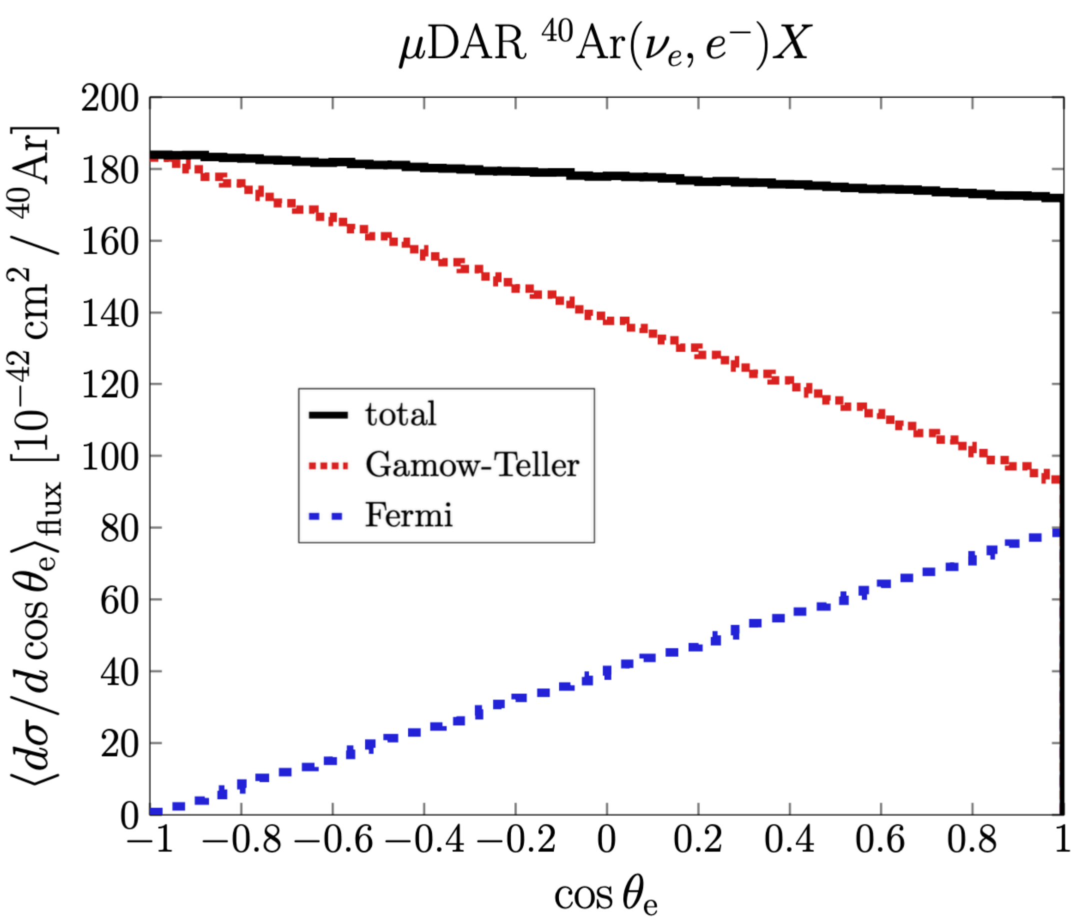
$$\frac{d\Gamma_a}{dE'_x} = \frac{1}{2\,\pi\,\rho_i(E_x, J, \Pi)} \sum_{\ell=0}^{\infty} \sum_{j=|\ell-s|}^{\ell+s} \sum_{J'=|J-j|}^{J+j} T_{\ell j}(\varepsilon)\,\rho_f(E'_x, J', \Pi')$$

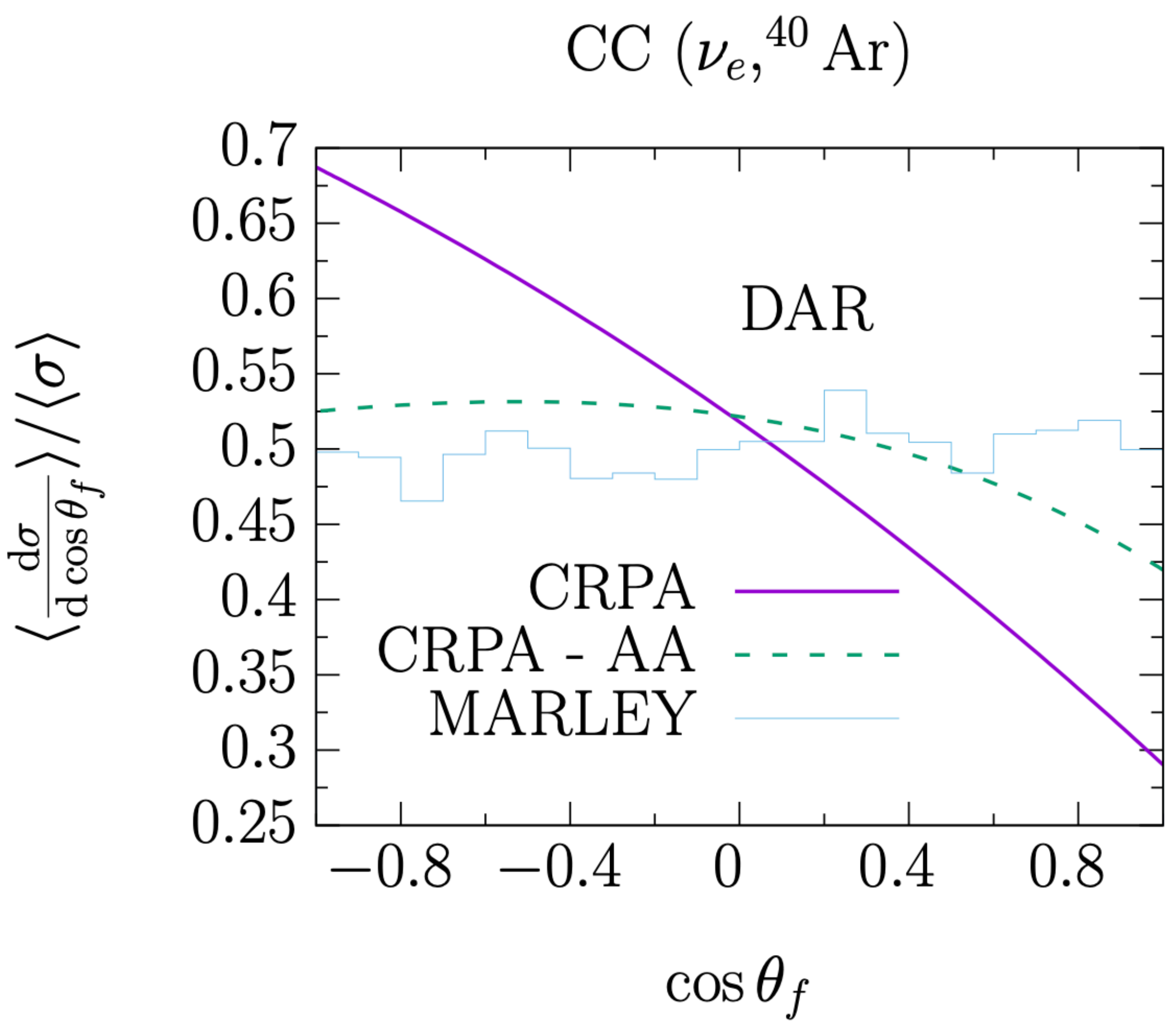
$$\frac{d\Gamma_\gamma}{dE'_x} = \frac{1}{2\,\pi\,\rho_i(E_x, J, \Pi)} \sum_{\lambda=1}^{\infty} \sum_{J'=|J-\lambda|}^{J+\lambda} \sum_{\Pi'\in\{-1,1\}} T_{X\lambda}(E_\gamma)\,\rho_f(E'_x, J', \Pi')$$



■ CRPA and MARLEY

- **Allowed and forbidden transitions**



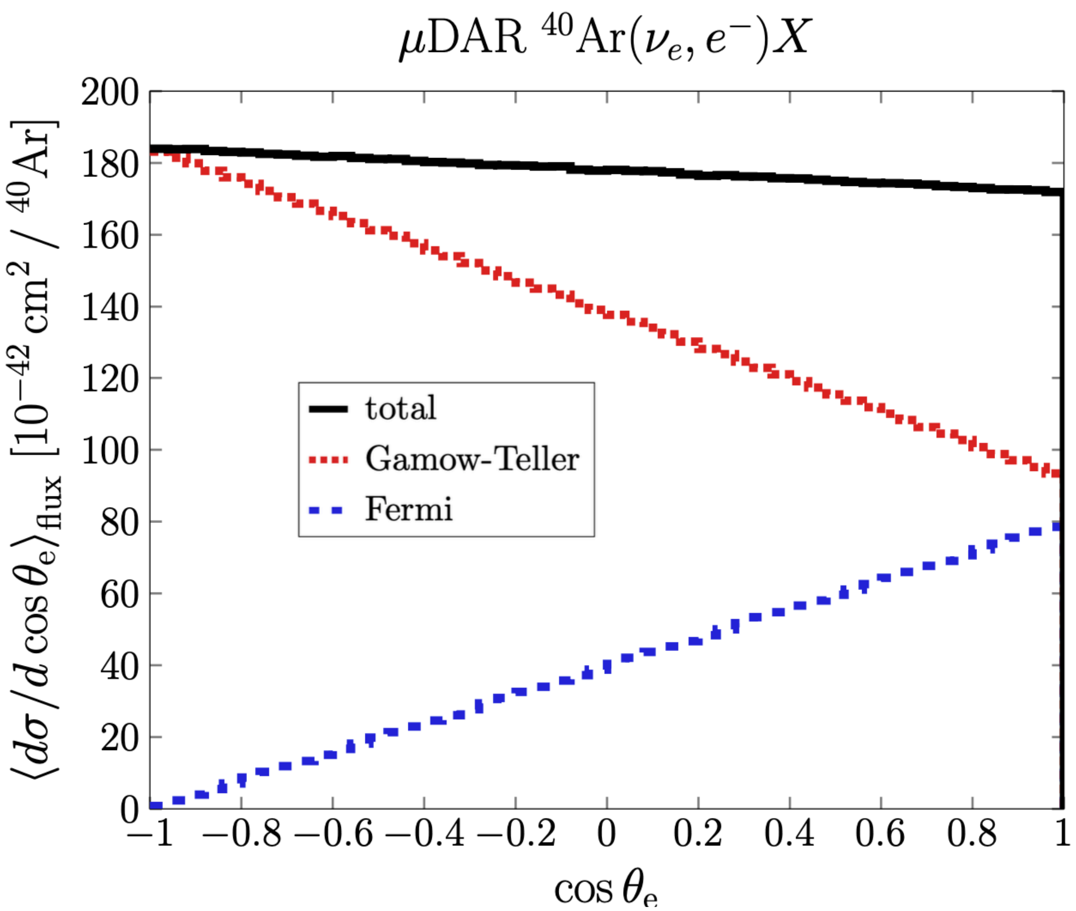


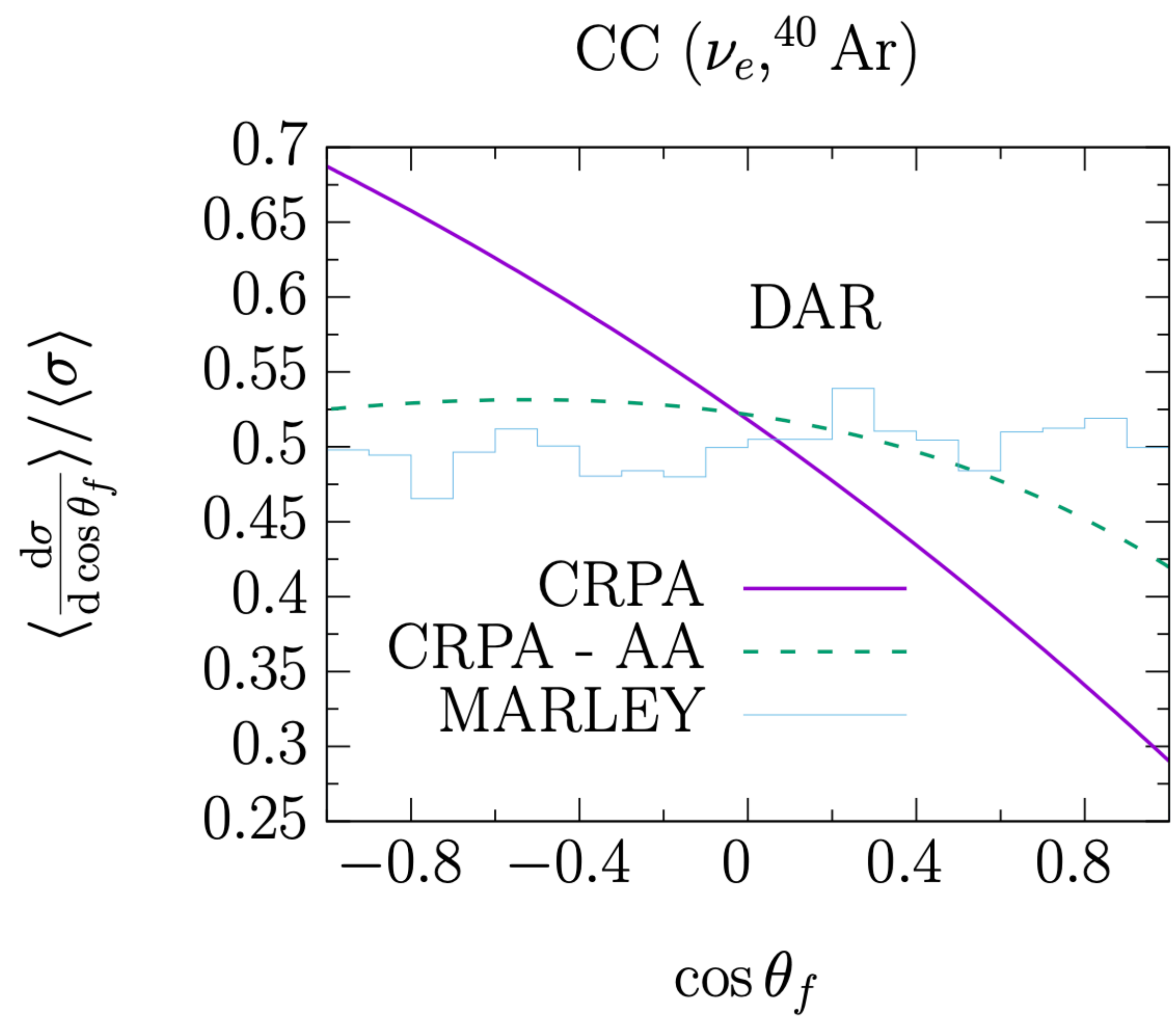
- MARLEY (only allowed transitions, Fermi and Gamow-Teller matrix elements) predicts a nearly flat angular distribution.

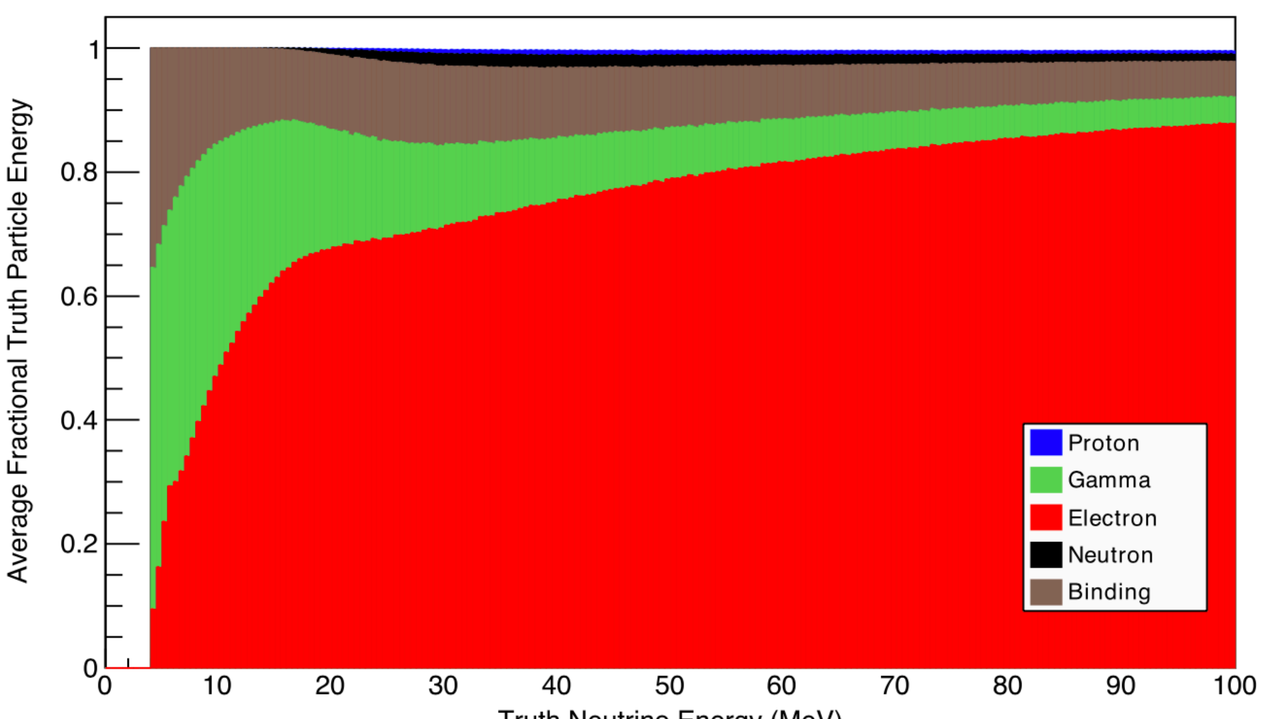
- CRPA includes full multipole expansion of nuclear matrix element (allowed as well as forbidden transitions), predict more backwards strength.

■ CRPA and MARLEY

- **Allowed and forbidden transitions**





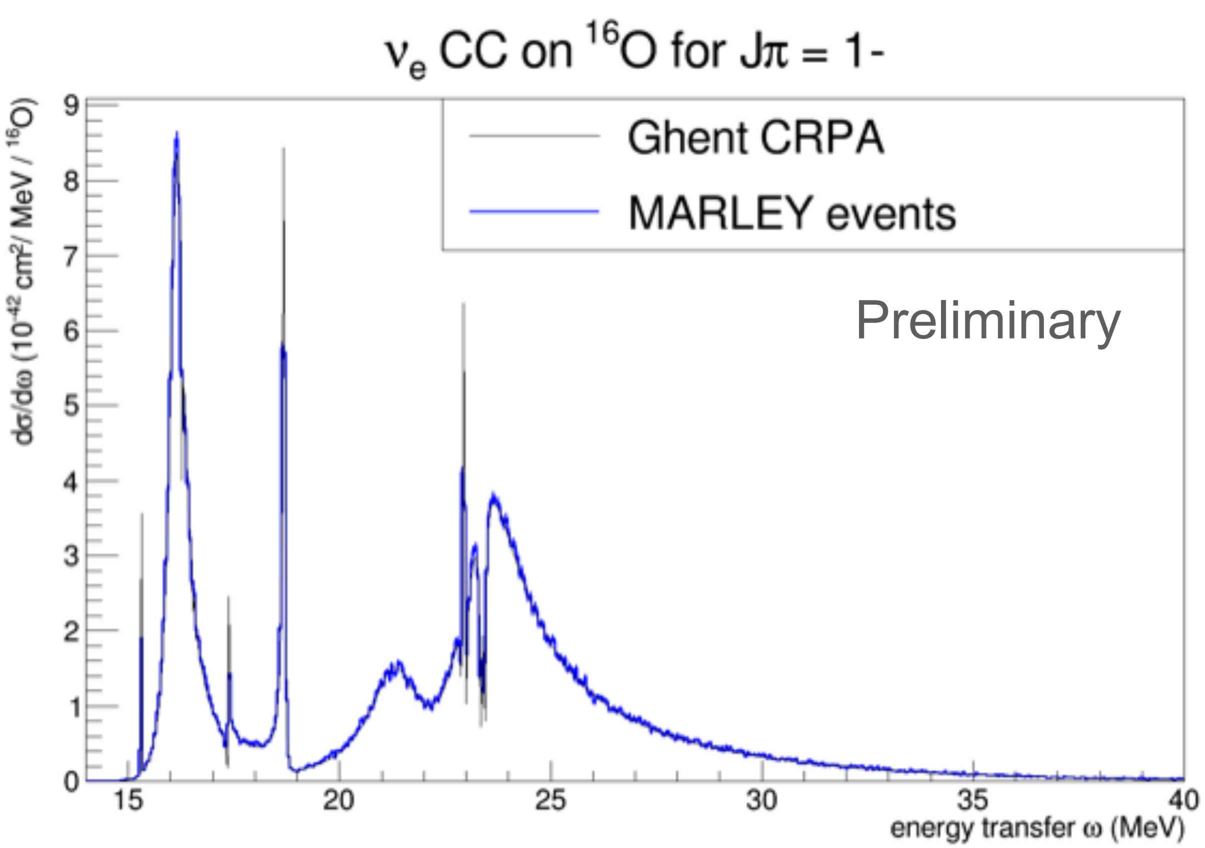


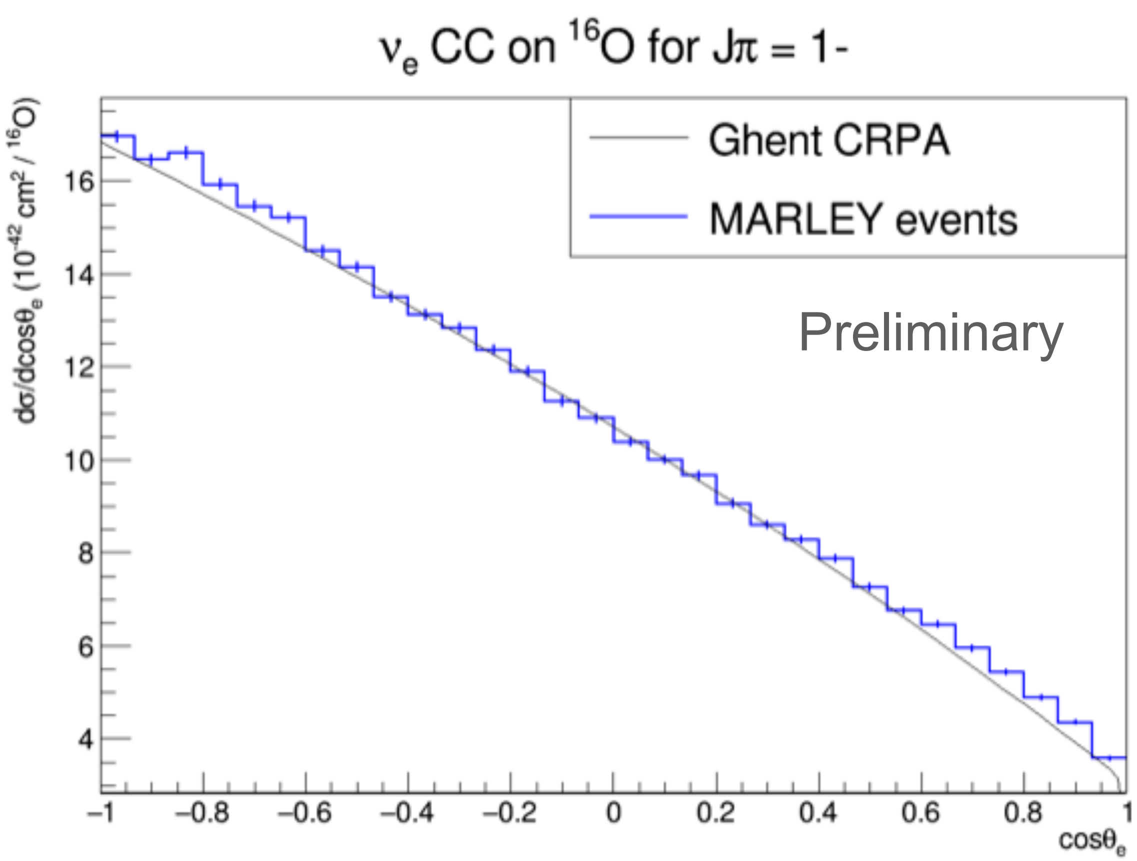
- MARLEY predicts that neutrons have a relatively small contribution to the overall “energy budget” at high energies. An artifact of the allowed approximation which underestimates the strength at high excitation energies.

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

CRPA and MARLEY

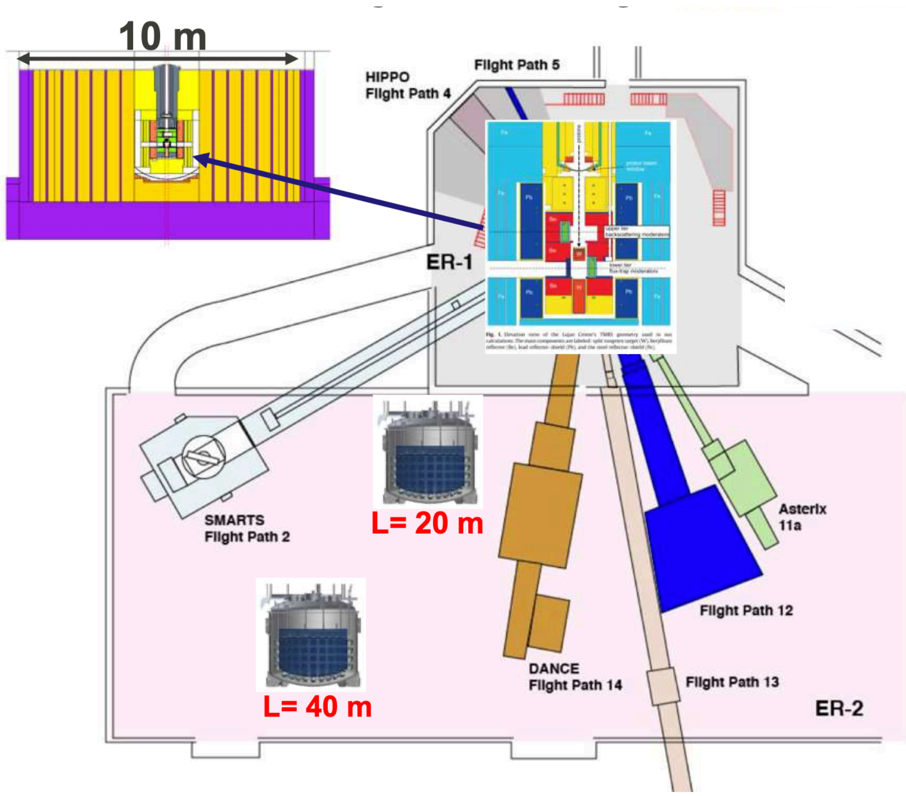
- CRPA implementation in MARLEY is on-going.
- Implementing inclusive nuclear response from CRPA predictions, and utilizing MARLEY's de-excitation model to predict energies of the final state particles.
- ^{16}O example:

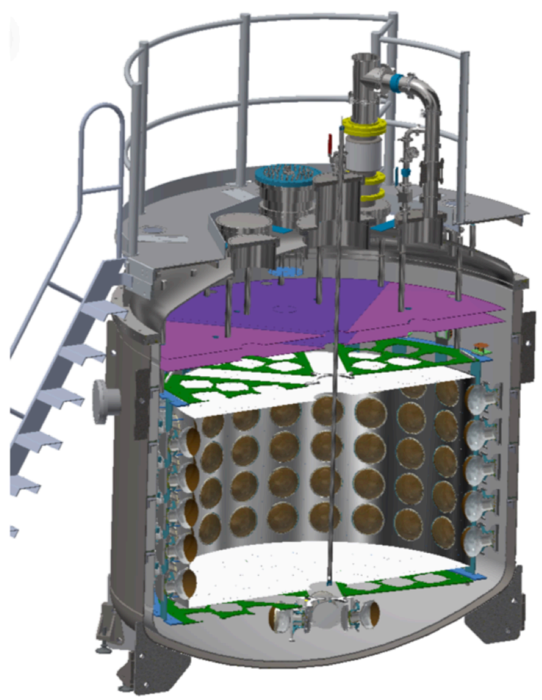




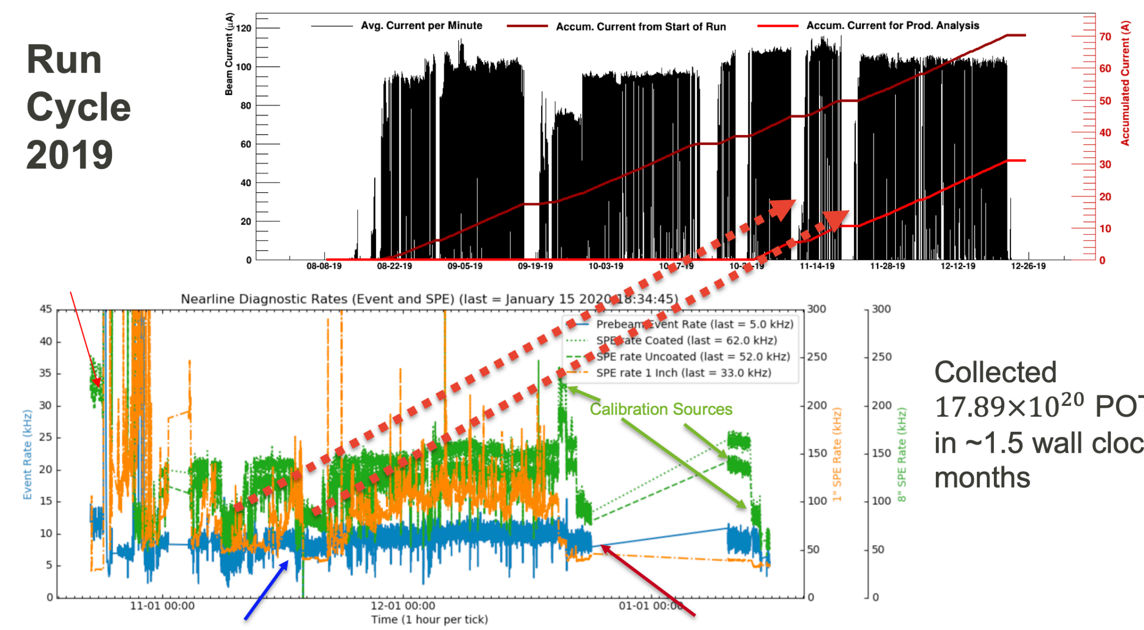
- ^{40}Ar Implementation is in progress.

- **Coherent CAPTAIN Mills at LANL:** 10 ton LAr detector at Lujan center at LANL. Collected data in 2019, analysis ongoing. Detector is being upgraded, gearing up to collect more data in the summer 2021. Stay tuned! See Tyler Thornton's talk at Magnificent CEvNS 2020.





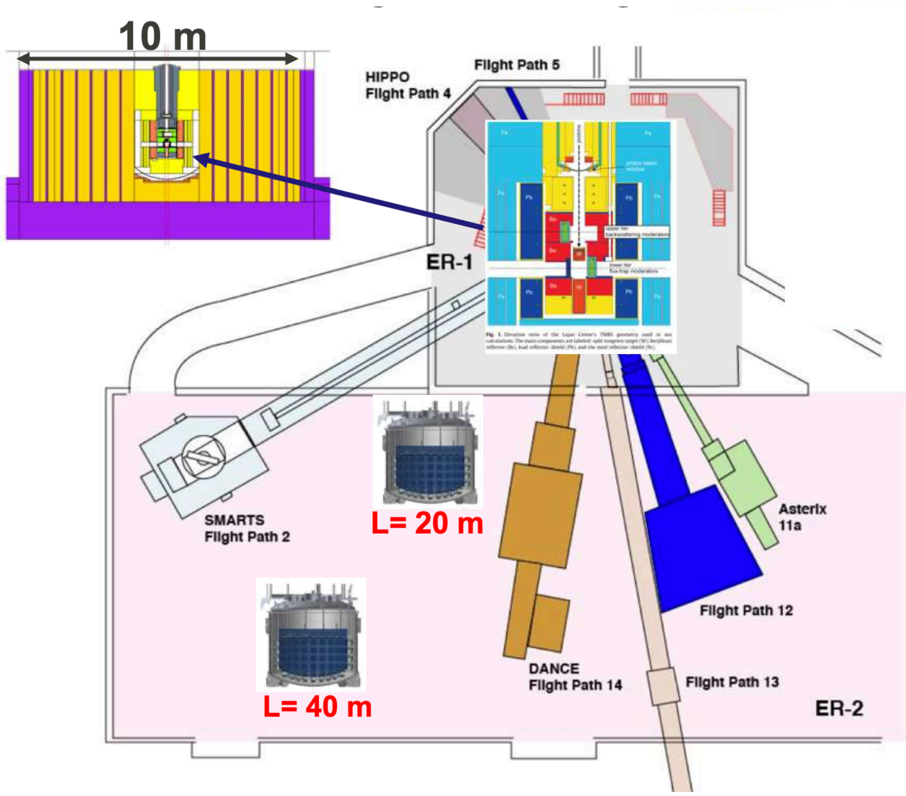
Run
Cycle
2019

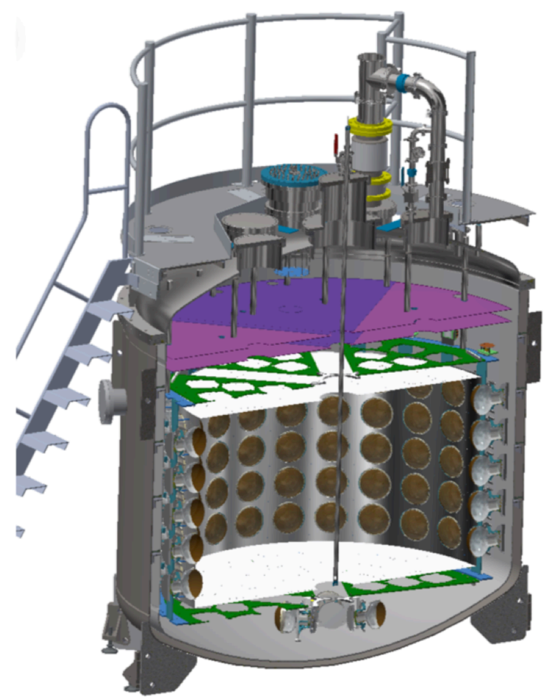


Collected 17.89×10^{20} POT in ~1.5 wall clock months

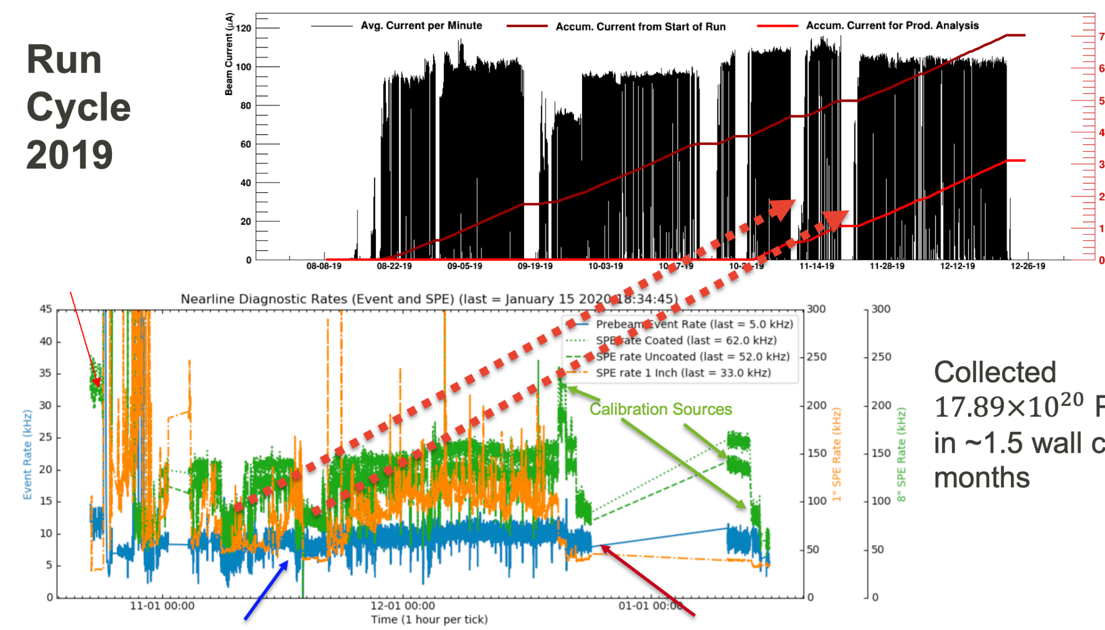
Inelastic CC/NC Neutrino-Nucleus Scattering: Near-Future Measurements

- **Coherent CAPTAIN Mills at LANL:** 10 ton LAr detector at Lujan center at LANL. Collected data in 2019, analysis ongoing. Detector is being upgraded, gearing up to collect more data in the summer 2021. Stay tuned! See [Tyler Thornton's talk at Magnificent CEvNS 2020]**.**





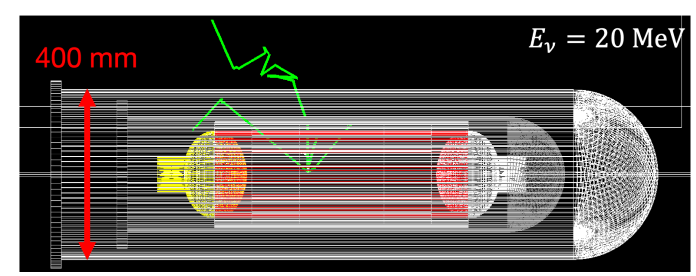
Run Cycle 2019

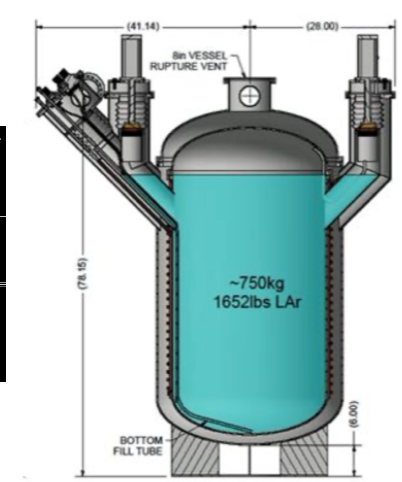


Collected 17.89×10^{20} POT in ~1.5 wall cloc months

- **COHERENT at SNS:** COH-Ar-10 (24kg) LAr detector, see Erin Conley's talk from Tuesday. COH-Ar-750 (750 kg) LAr detector is underway.

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





Walt Fox, IU

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

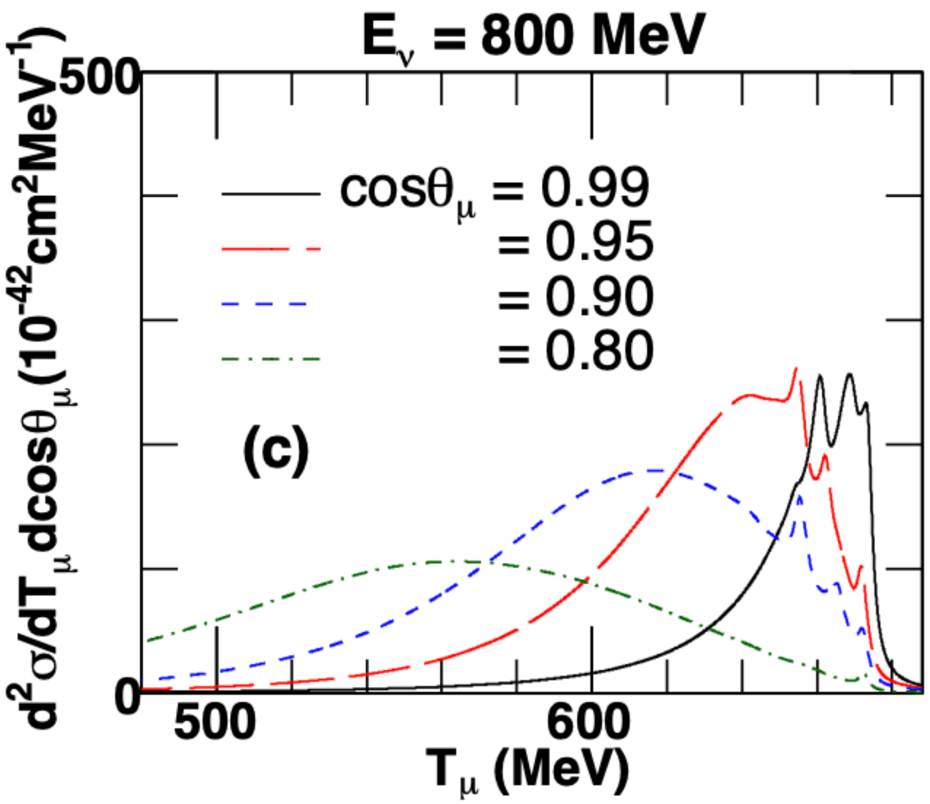
- **10s of MeV electron scattering experiment is planned at MESA, Mainz:** see Luca Doria's talk from Wednesday.

Low-Energy Neutrino-Nucleus Scattering

Outline

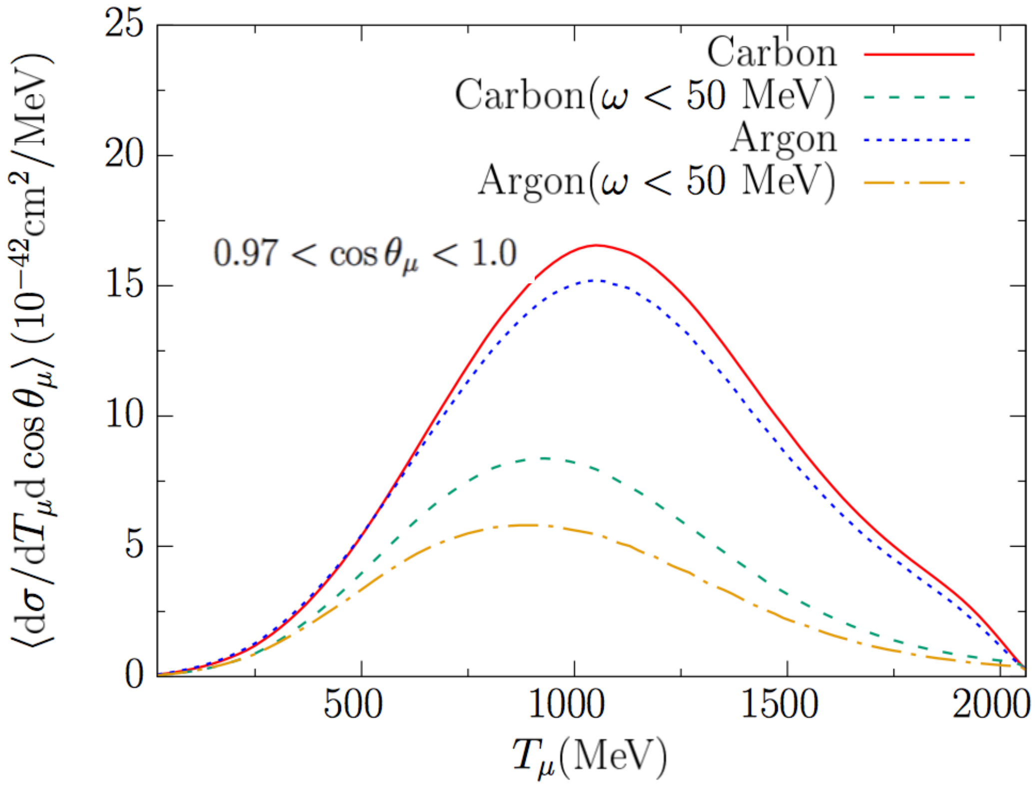
- 10s of MeV Neutrino Sources
- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
- Inelastic Neutrino-Nucleus Scattering
- **10s of MeV Physics in GeV-scale Neutrino Beams**

10s of MeV Physics in GeV-scale Beams

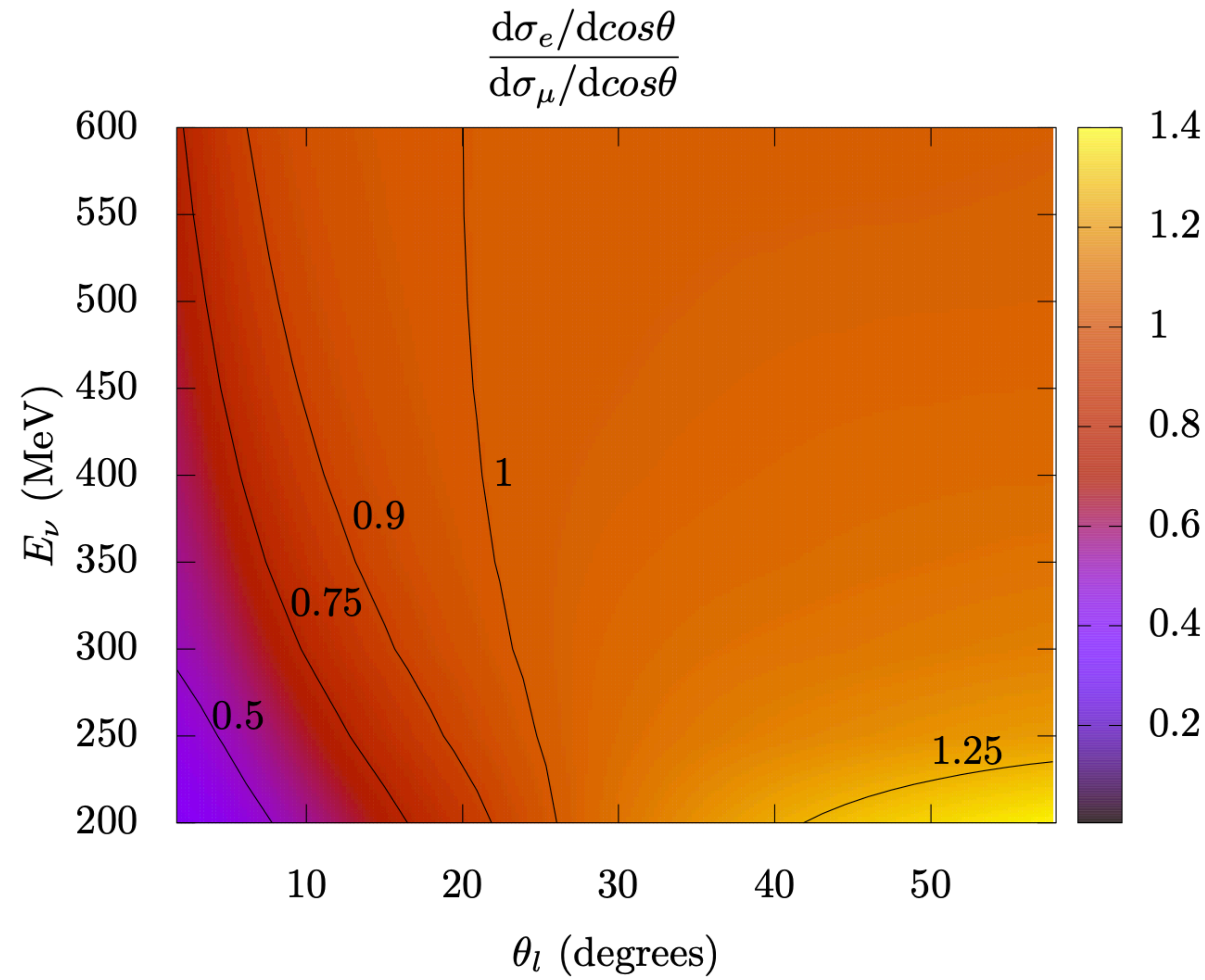


Phys. Rev. C92, 024606 (2015)

Folded with BNB ν_μ flux



Phys. Rev. C97, 044616 (2018)



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.

Summary

- Experimental observation of CEvNS opened a new portal of searching weakly interacting new physics at low energies. Entire nuclear dynamics in CEvNS process is embedded in the weak form factor which is not well constrained.
  - 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 future long baseline neutrino experiments' capability of detecting core-collapse supernovae neutrinos.
  - 10s of MeV electron-nucleus scattering cross sections at MESA will pave the way in constraining nuclear model at these energies.

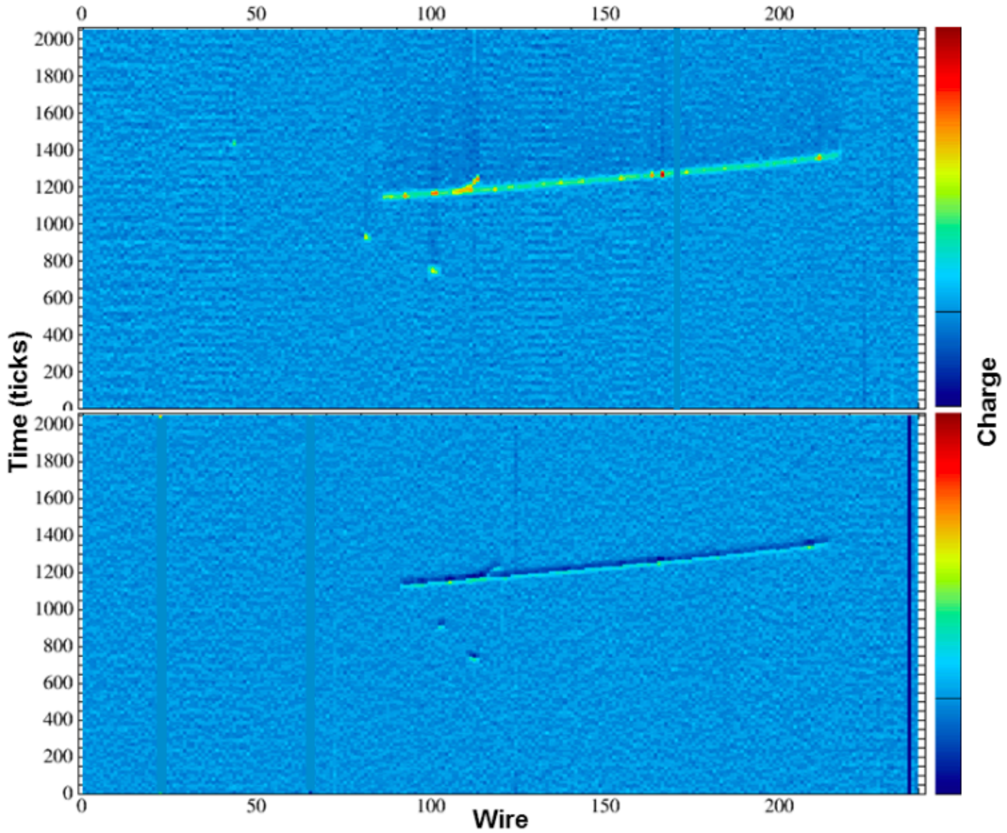
- We presented a consistent description of both coherent elastic and inelastic neutrino-nucleus scattering within a unified nuclear theory approach.
  - The model is currently being implemented in the dedicated low-energy neutrino event generator, MARLEY, for wider use.

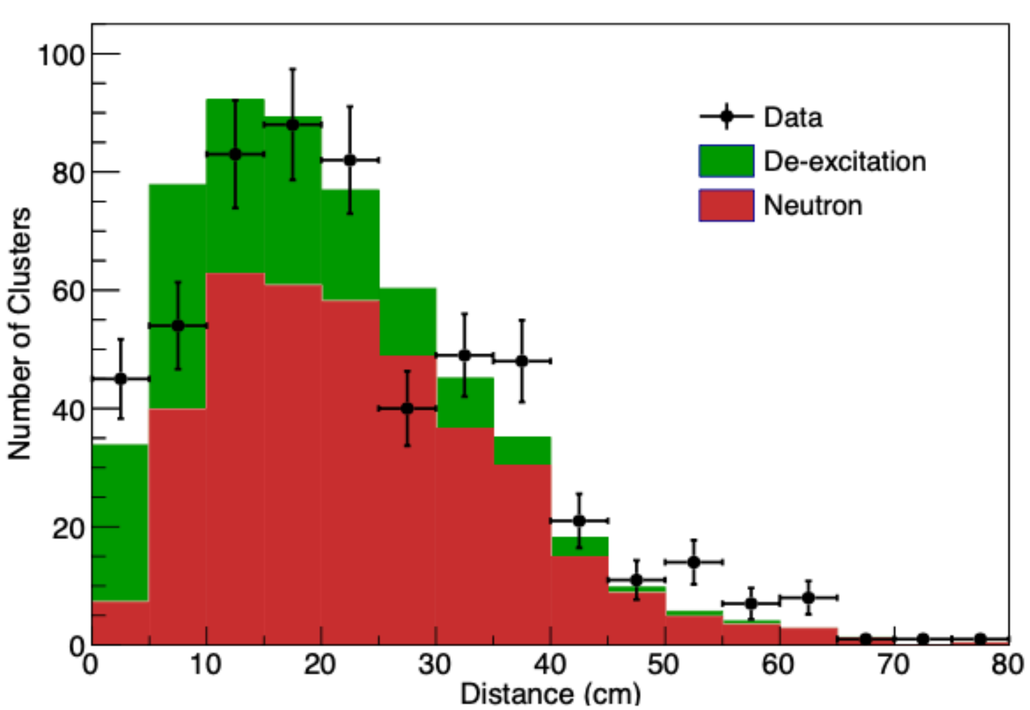
Back-up

MeV-scale Physics in GeV-scale Beams

"Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT"

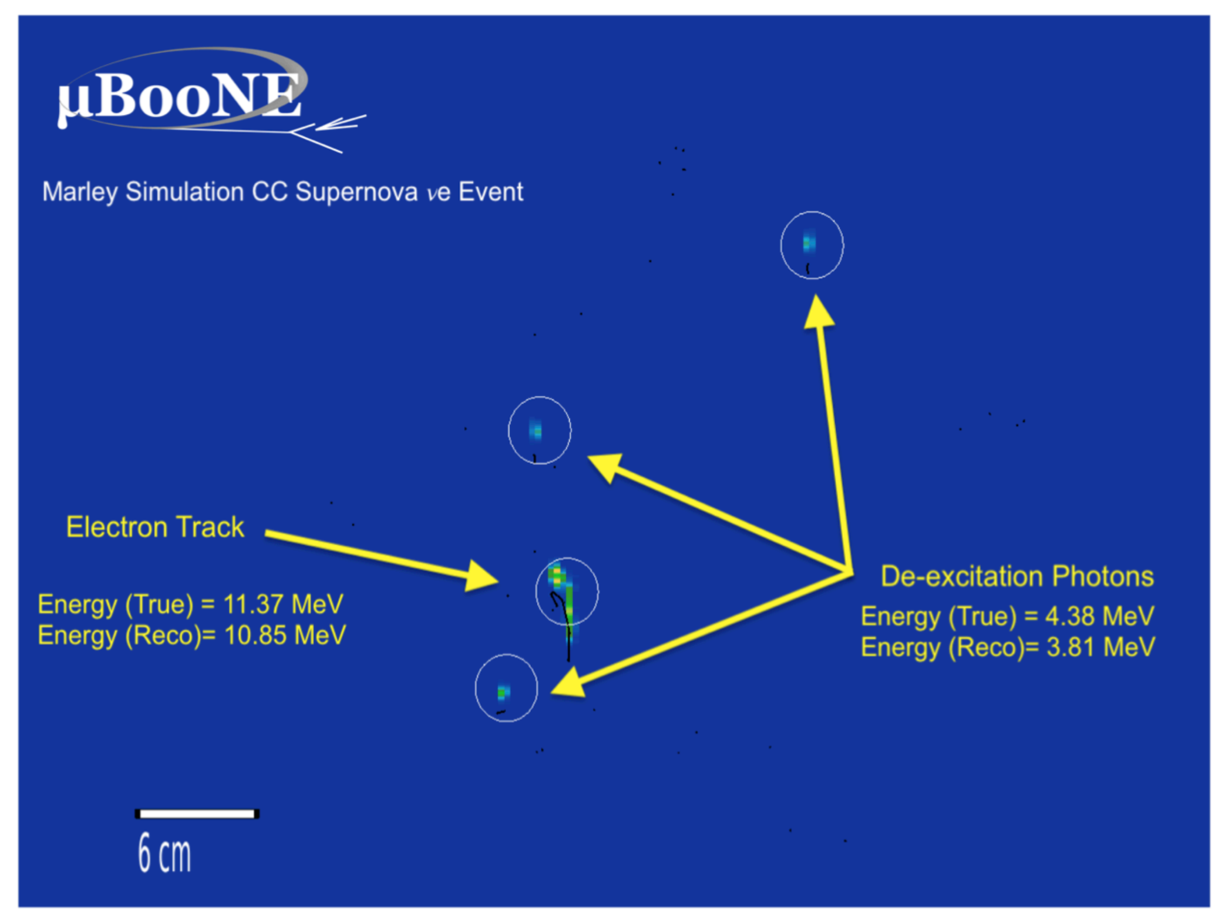
[ArgoNeut Collaboration] Phys. Rev. D 99, 012002 (2019)

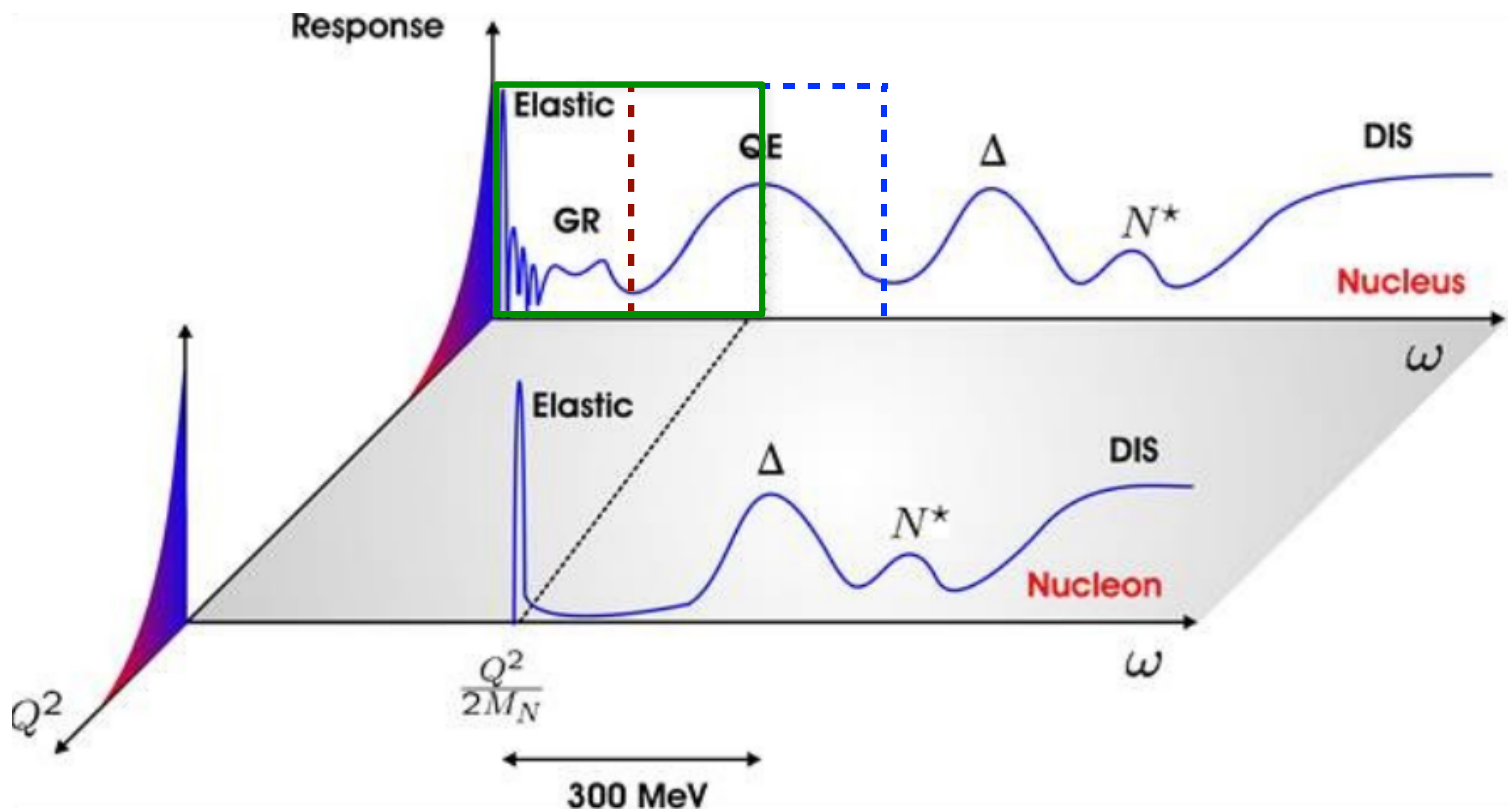




MeV-scale Physics in MicroBooNE

MICROBOONE-NOTE-1076-PUB




Response
Elastic
GR
QE
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N*
DIS
Nucleus
ω
Elastic
Δ
N*
DIS
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ω
Q^2
$\frac{Q^2}{2M_N}$
300 MeV