Neutrino-nucleus interactions and the quest for new and precision physics searches in neutrino experiments

Vishvas Pandey

Fermi National Accelerator Laboratory

CETUP* 2024, Lead, South Dakota, June-July, 2024

Scope of this talk: 10s of MeV to a few GeV neutrino energy

✦ $E_\nu \approx$ **10s of MeV**

✦ $E_\nu \approx$ **100s of MeV to a few GeV**

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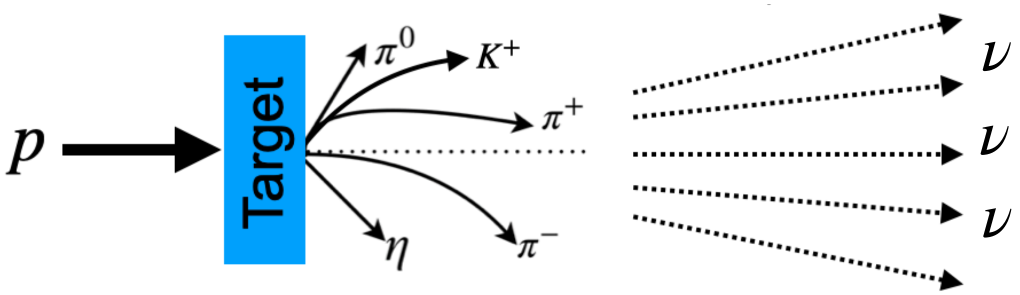
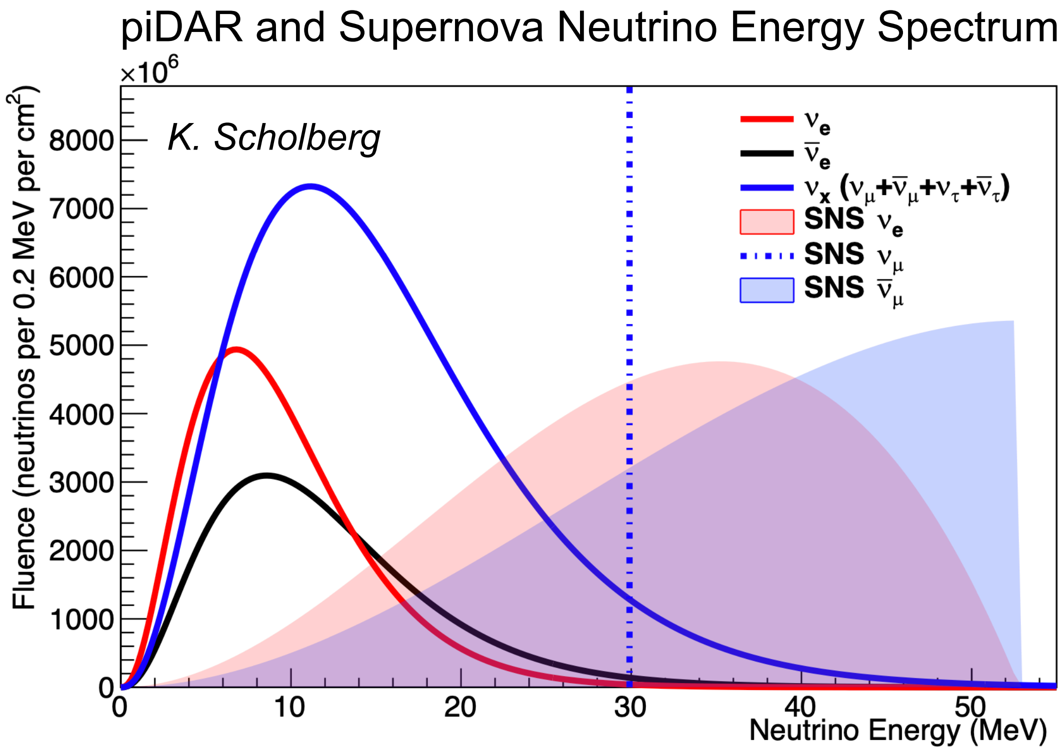
  (SNS at ORNL, LANSCE at LANL, MLF at JPARC, FNAL, …)



- **Core-collapse Supernova Neutrinos**



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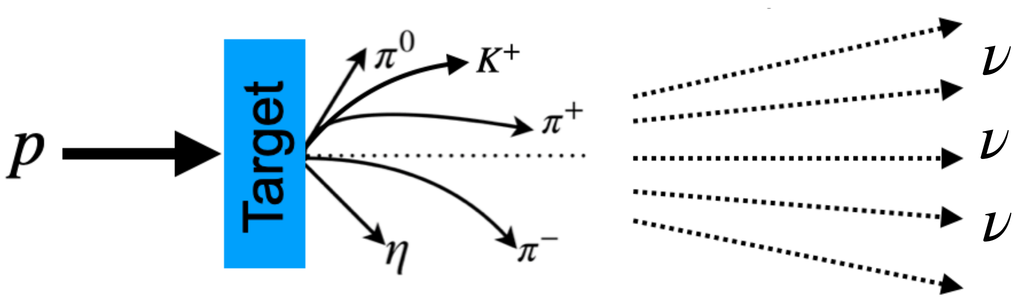

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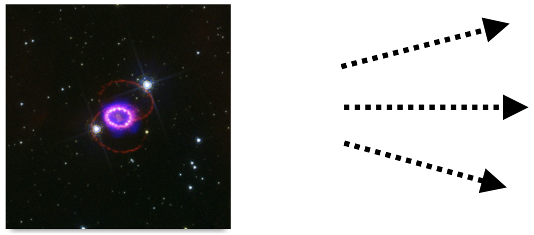

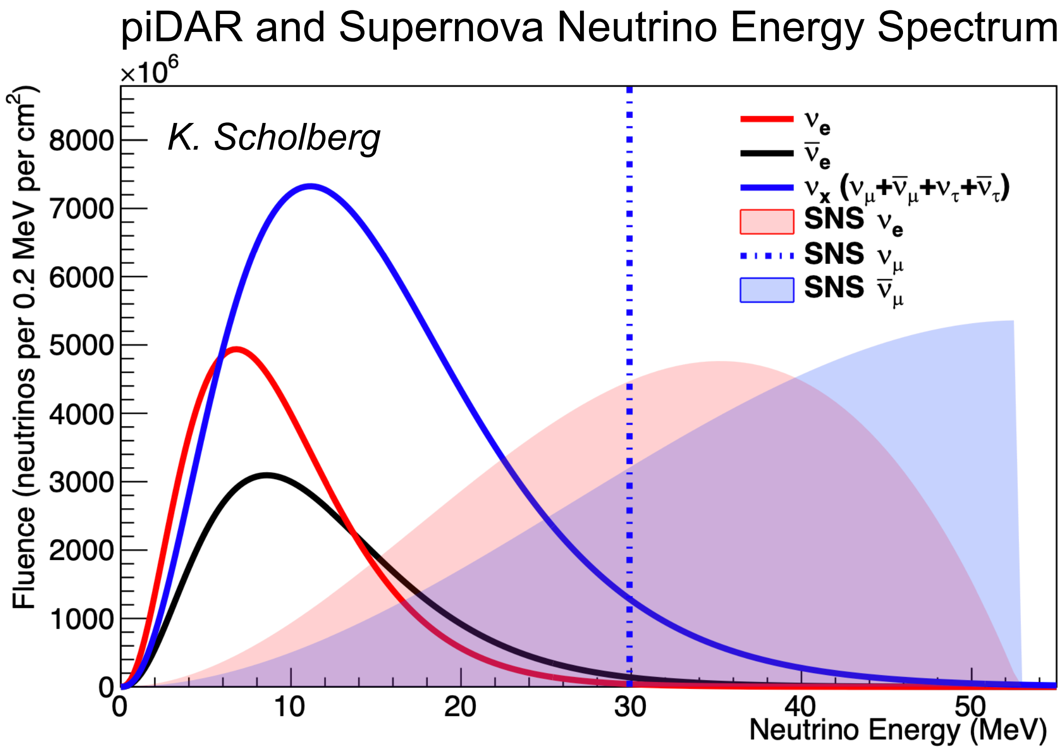

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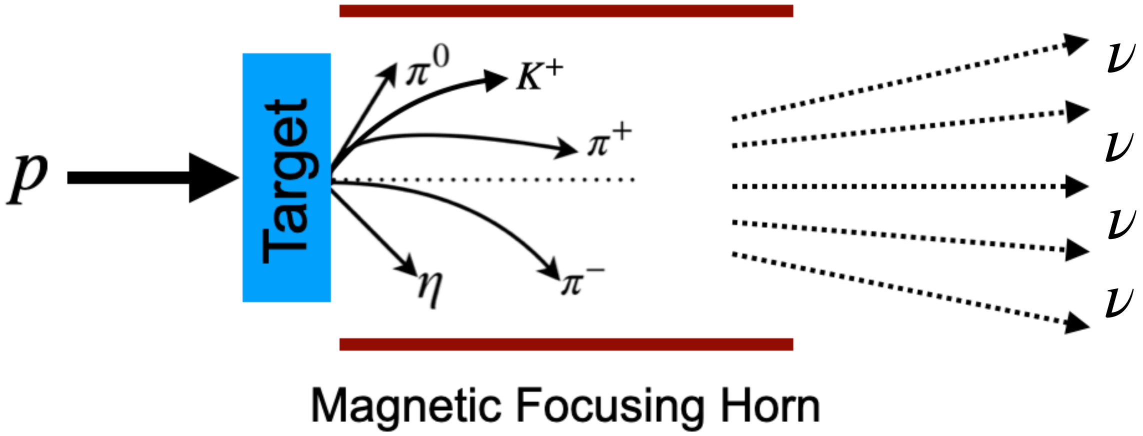
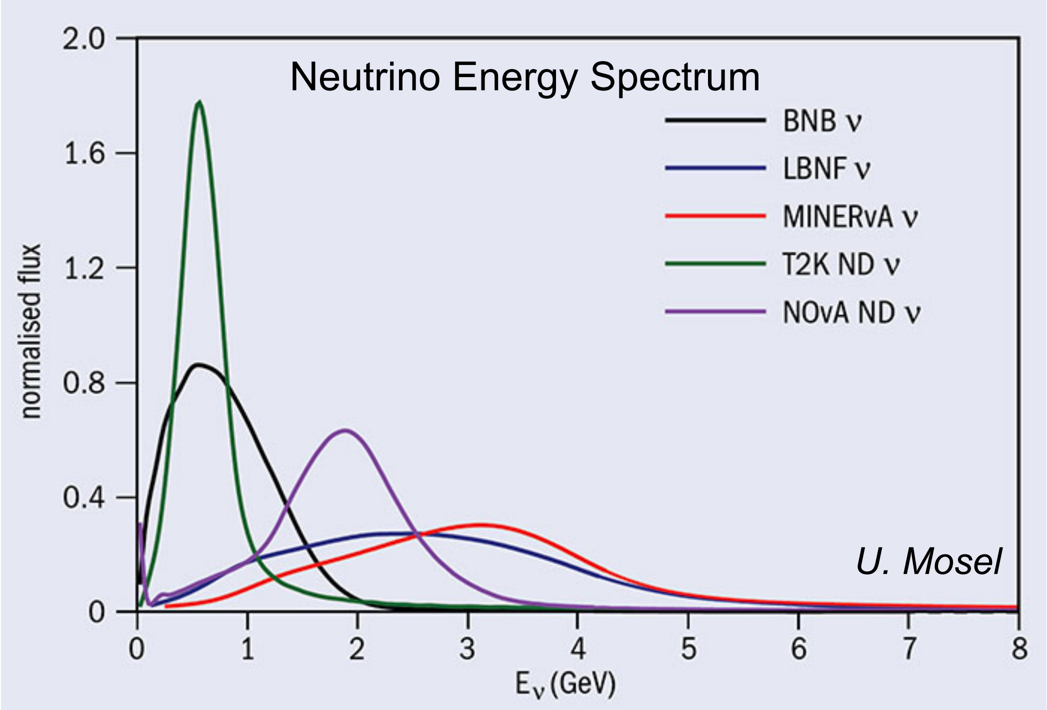
- **Pion decay-in-flight neutrinos**

  (BNB/NUMI/LBNF at FNAL, JPARC, …)

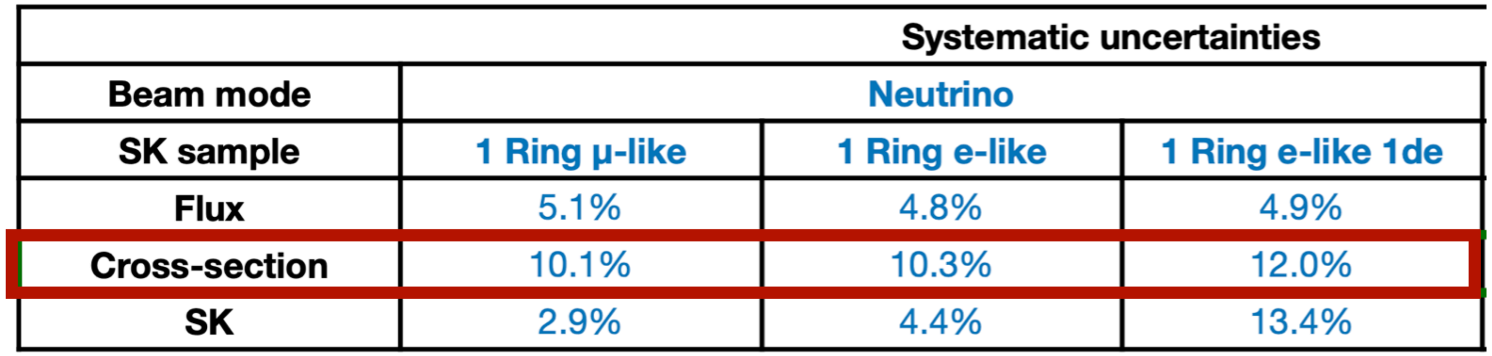




Neutrino-Nucleus Interactions Uncertainty

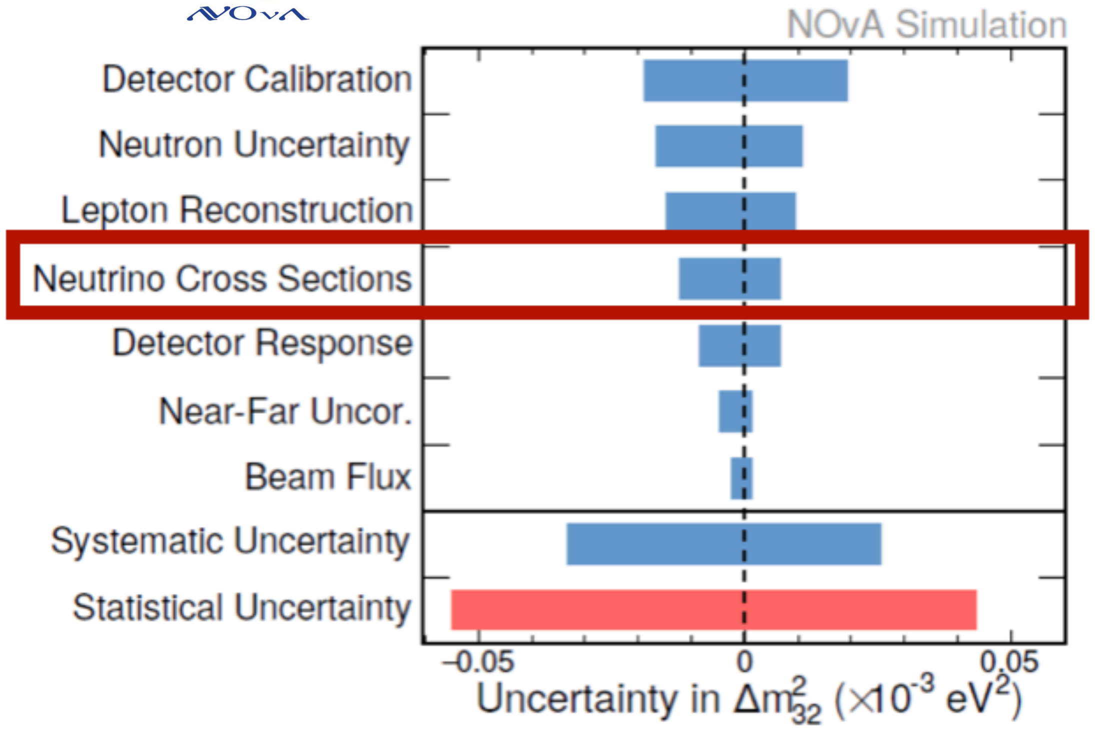
- In **accelerated-based neutrino oscillation** program, neutrino-nucleus interactions constitute one of the dominant systematic uncertainties.
  - One of the largest uncertainties in current long-baseline experiments, T2K and NOvA.

T2K



	Systematic uncertainties		
Beam mode	**Neutrino**		
SK sample	**1 Ring μ-like**	**1 Ring e-like**	**1 Ring e-like 1de**
Flux	5.1%	4.8%	4.9%
Cross-section	10.1%	10.3%	12.0%
SK	2.9%	4.4%	13.4%

NOvA



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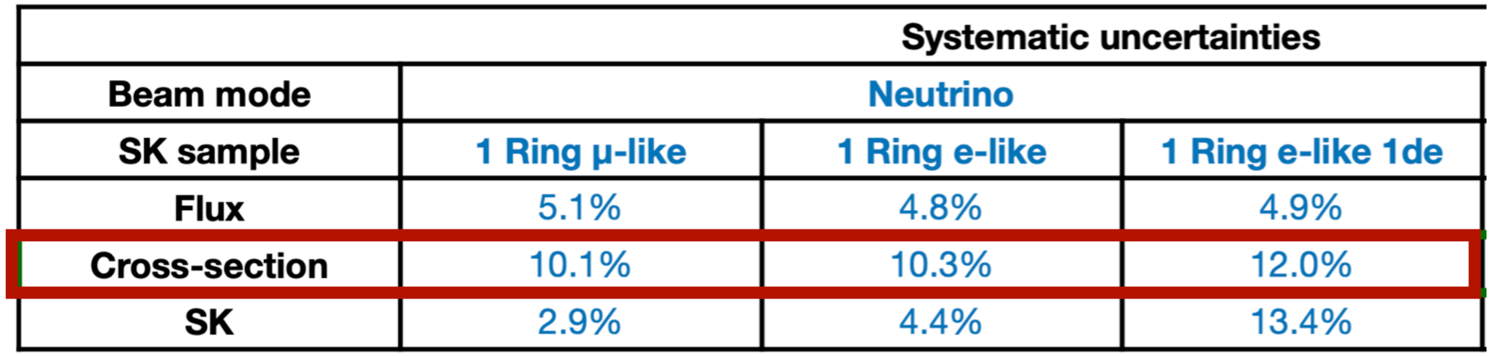

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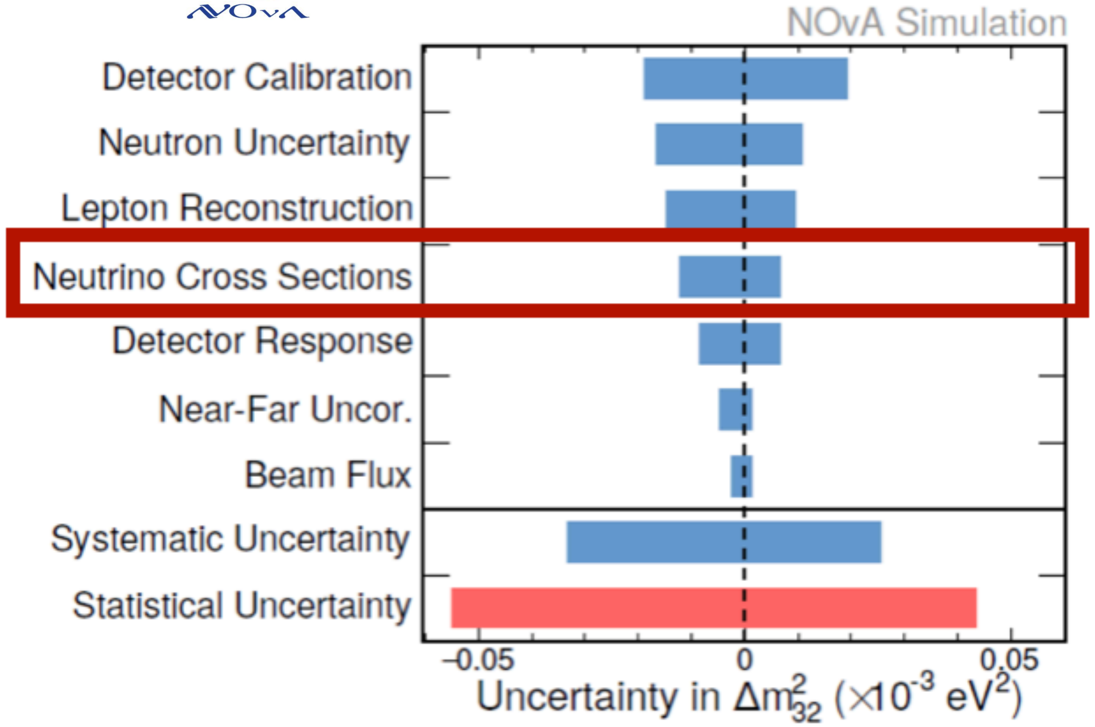


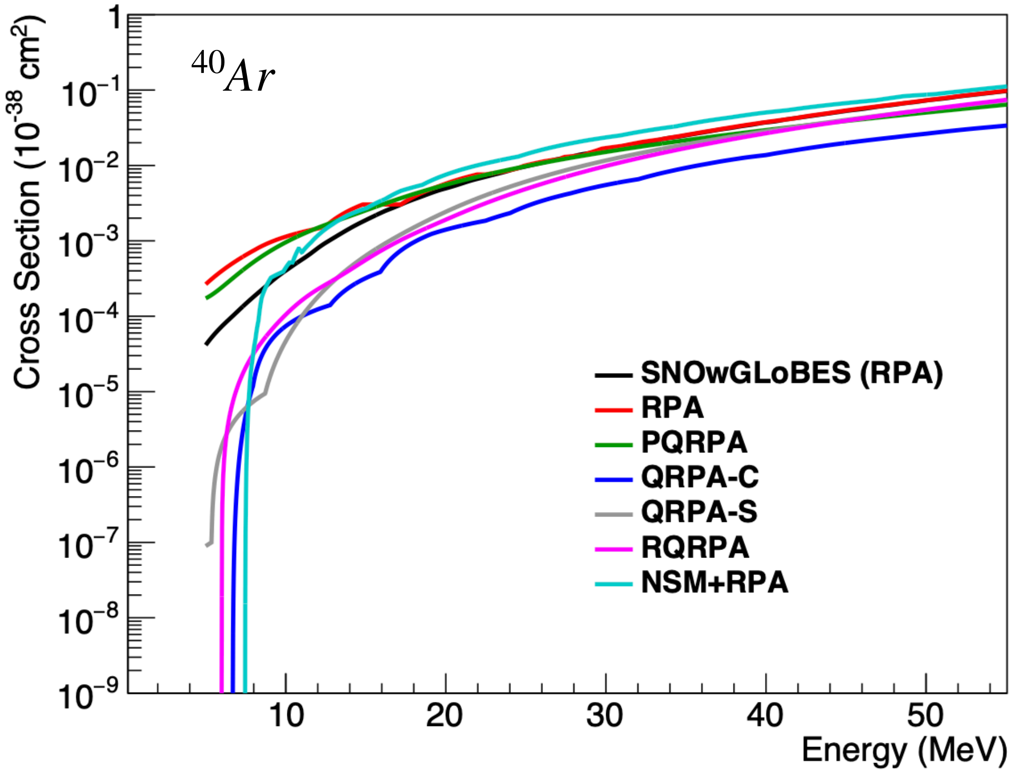
- In future experiments, DUNE and HyperK, the statistics will significantly increase and neutrino interaction systematics uncertainties will be dominant.

  - It can not only delay physics results by years but could well be difference in achieving or missing discovery (level precision).

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Neutrino-Nucleus Interactions Uncertainty

- Similarly for low-energy (10s of MeV) neutrinos:
  - The uncertainties on inelastic $\nu_e\ CC$ neutrino-nucleus interaction, the detection channel for **supernova neutrinos** in DUNE, is large (often not even quantified).



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!"

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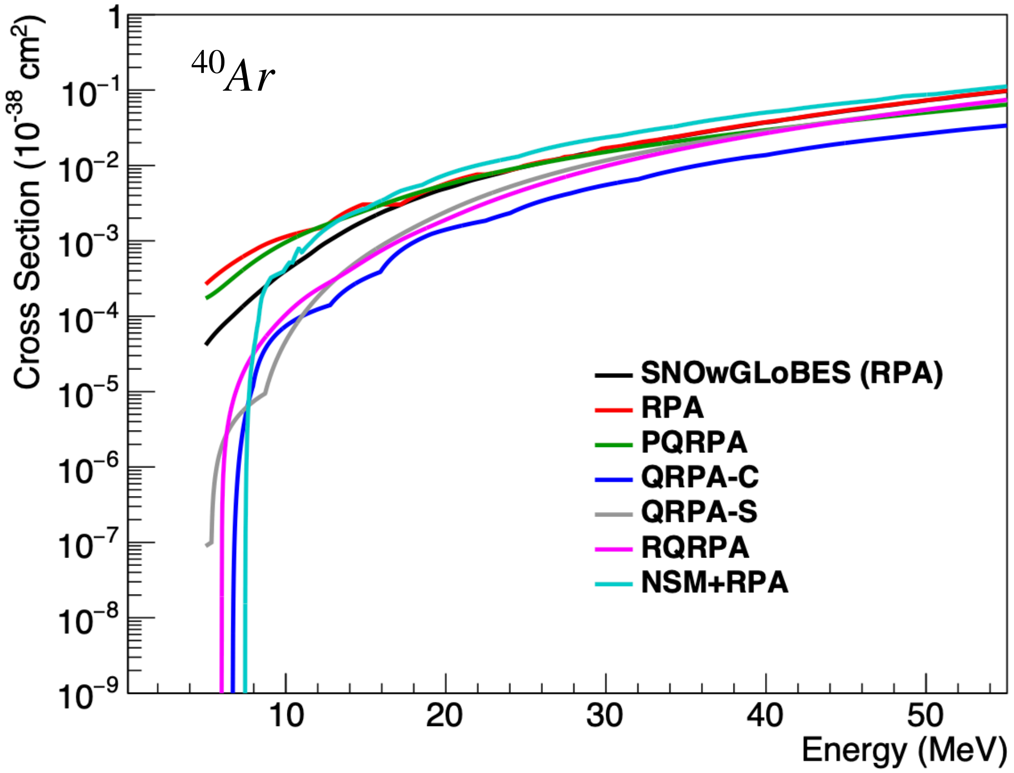

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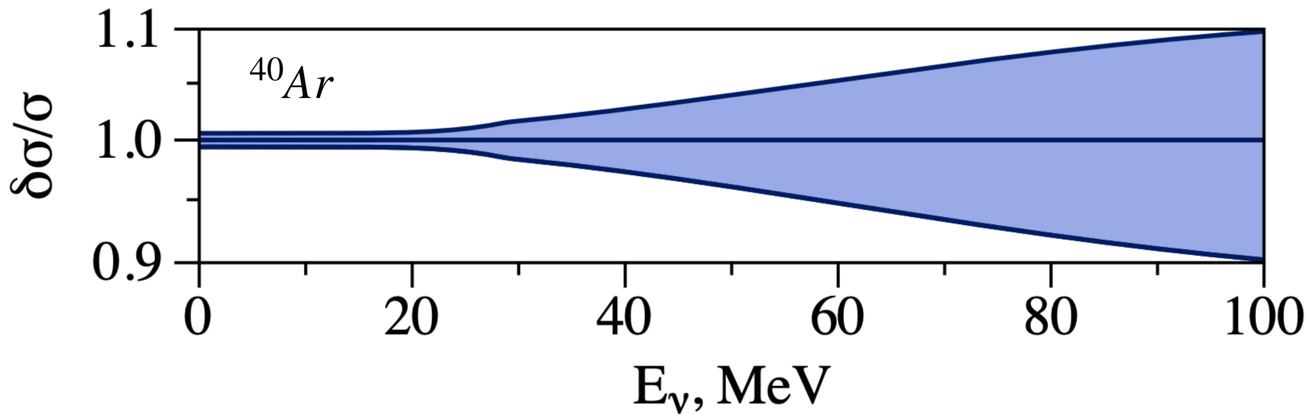
"Current understanding of $\sigma(E_\nu)$ is inadequate. Measuring ε energy release (other parameters) to 10% requires 5% (20%) knowledge of the cross section!"

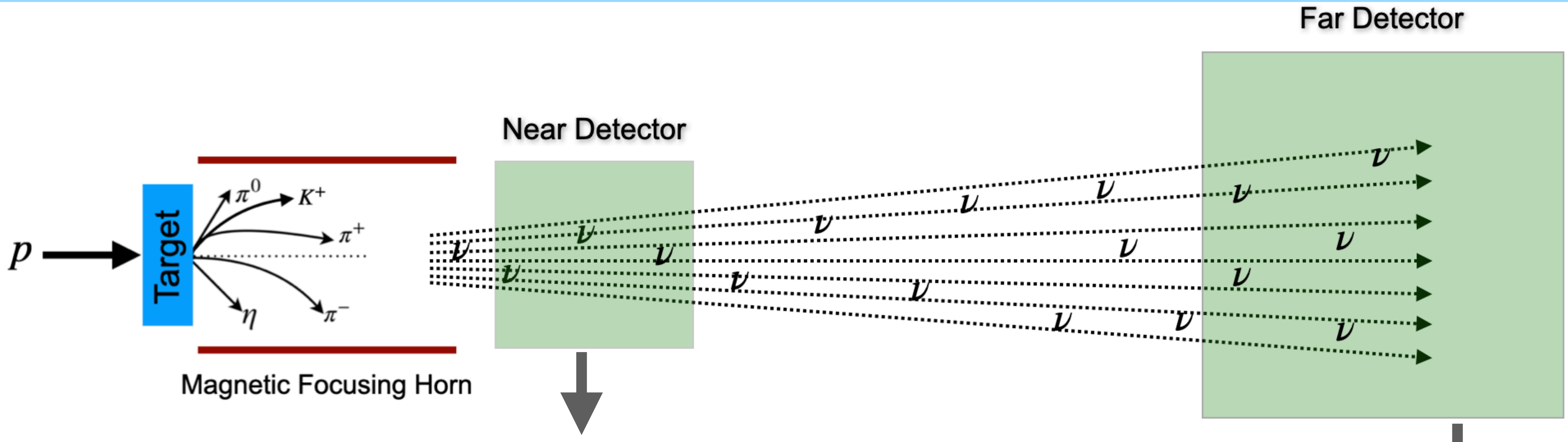
- Although theoretical uncertainties are relatively small in **CEvNS** case. Percent level precision might be needed to disentangle new physics signals.



Relative CEvNS cross section theoretical uncertainty

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

Neutrino Oscillations Physics at Accelerator Neutrino Facilities



Measure Event Rate at the Near Detector:

$$\boxed{N^{\alpha}_{ND}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma^i_\alpha(E_\nu) \times \epsilon_\alpha(E_\nu, E_{\nu,rec})}$$

Measure Event Rate at the Far Detector:

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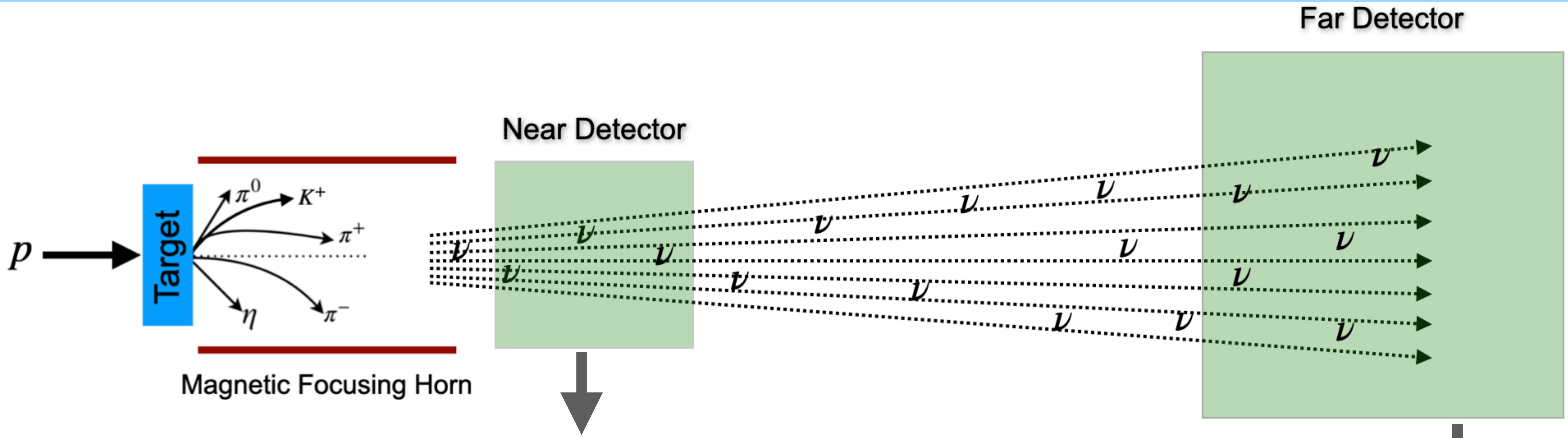

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Take Ratio of Near to Far Event Rate:

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Extract Oscillation Parameters:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} \ \sin^2\left(\frac{\Delta m^2_{ij}}{4}\frac{L}{E_\nu}\right)$$

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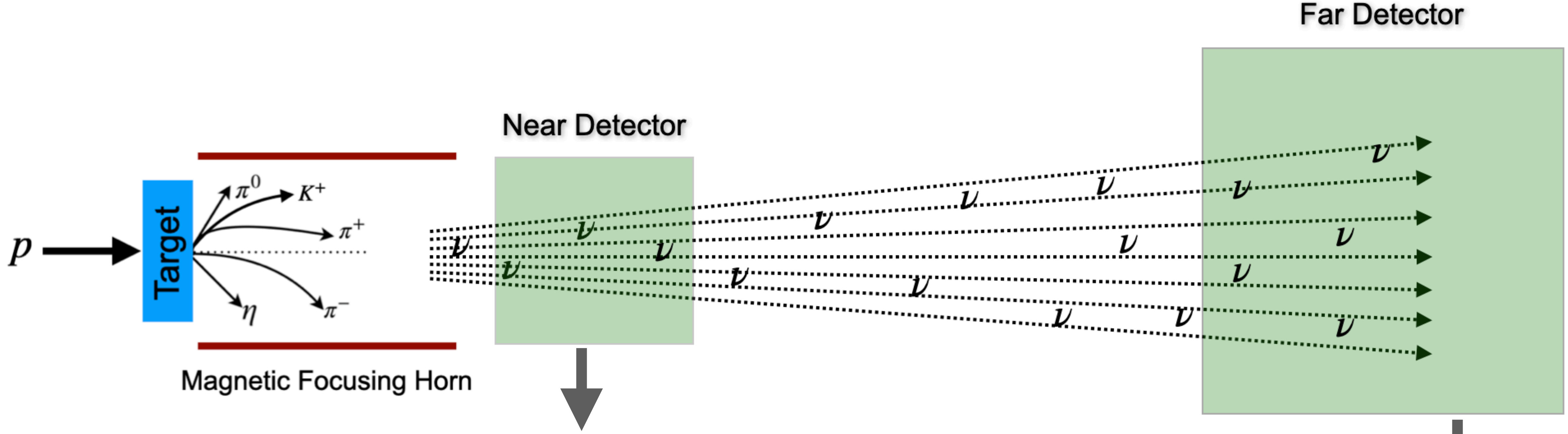

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Near to far ratio does not cancel out cross sections dependence

- Flux and cross sections are convoluted
- Different neutrino energy spectrum at near and far detector
- Different neutrino flavor at ND and at FD (appearance)
- Different Near and Far Detector geometry, acceptance, etc.

Neutrino Energy and Neutrino-nucleus Interactions

- **Reconstructing Neutrino Energy**:

- Neutrino energy is not known, need to reconstruct based on the interaction products measured in the detector

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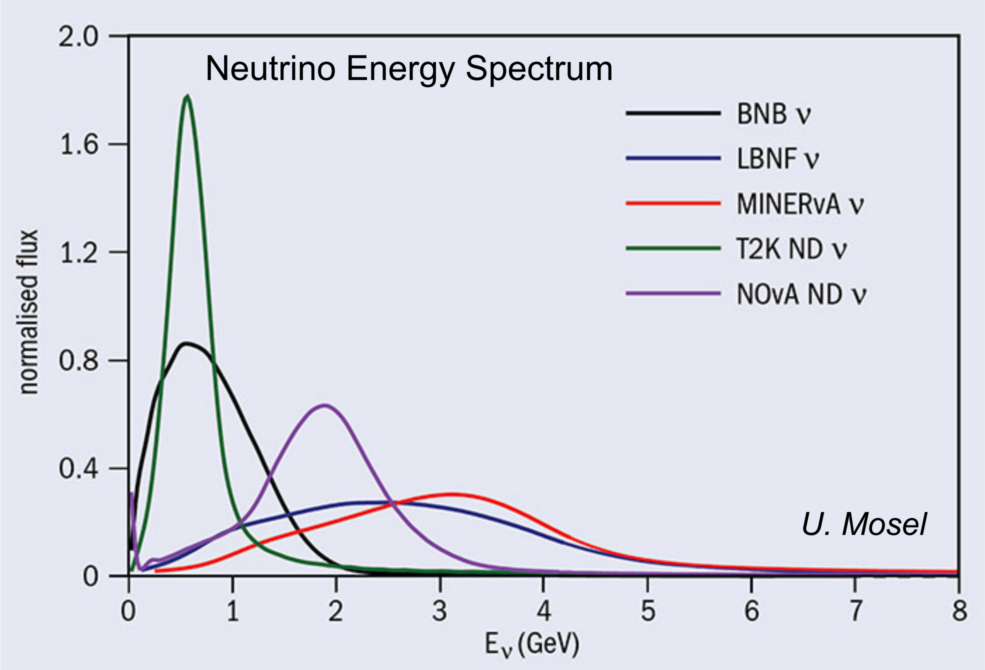

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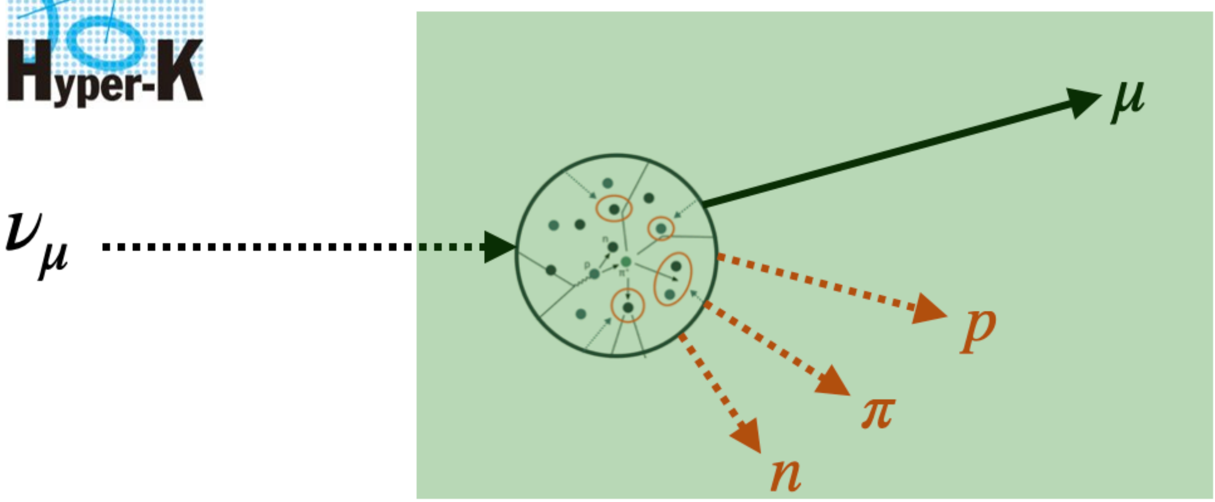

- Depends on lepton reconstruction
- “CCQE” topology, selecting $1\mu 0\pi$, may have contribution from 2p2h, pion absorption, etc.

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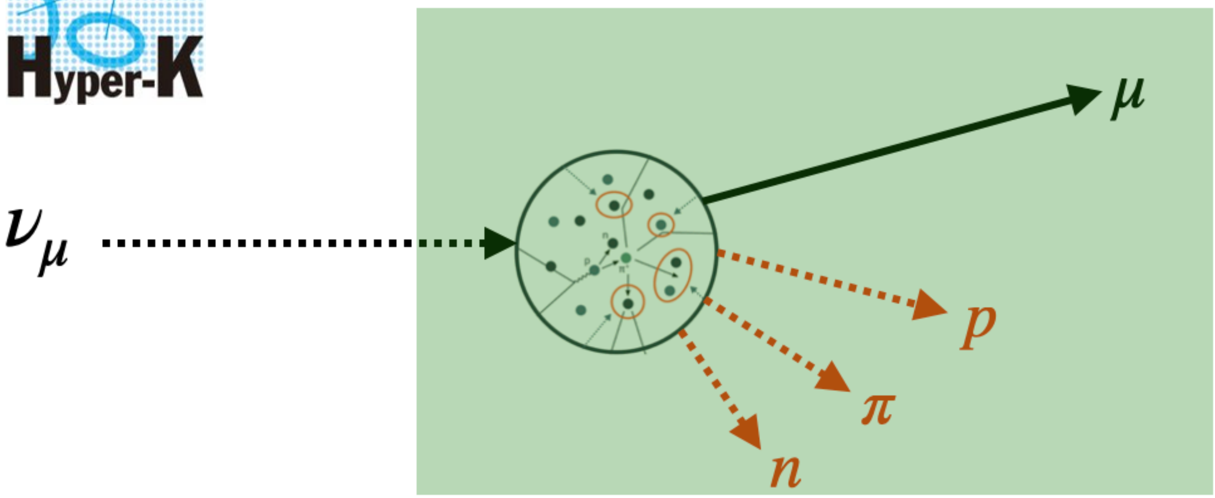

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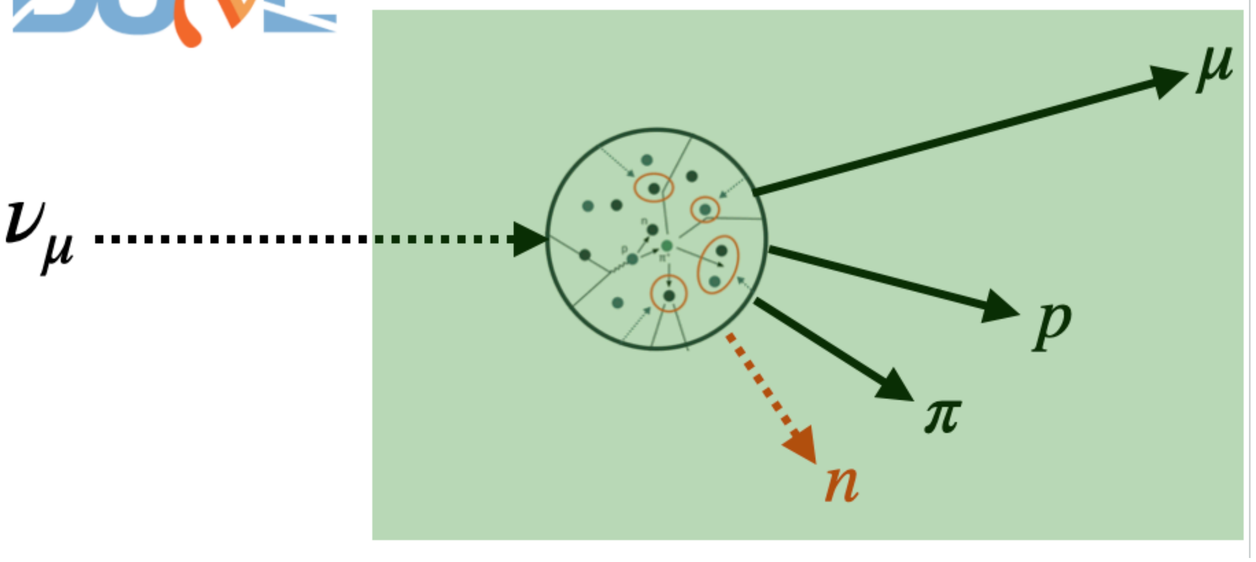

- Energy conservation, relies on visible energy
- Missing energy from neutrons, detector threshold, pion absorption, etc.

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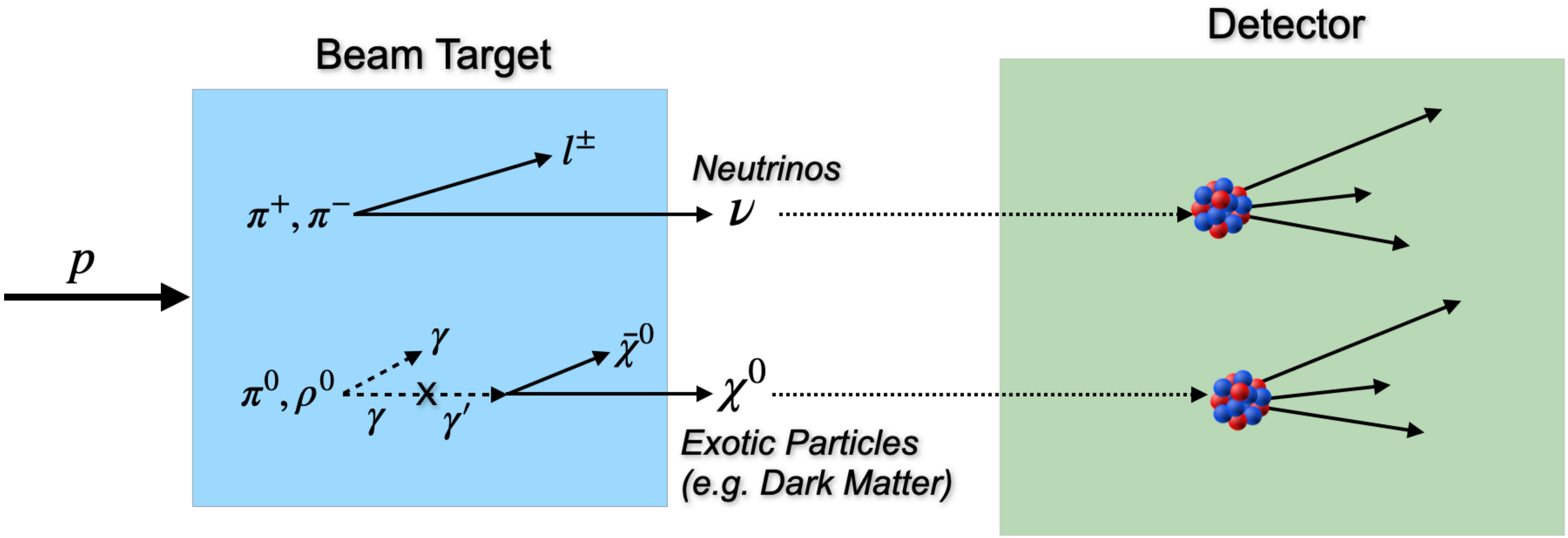
BSM Physics at Accelerator Neutrino Facilities

Interplay of Standard and non-Standard Physics Signals

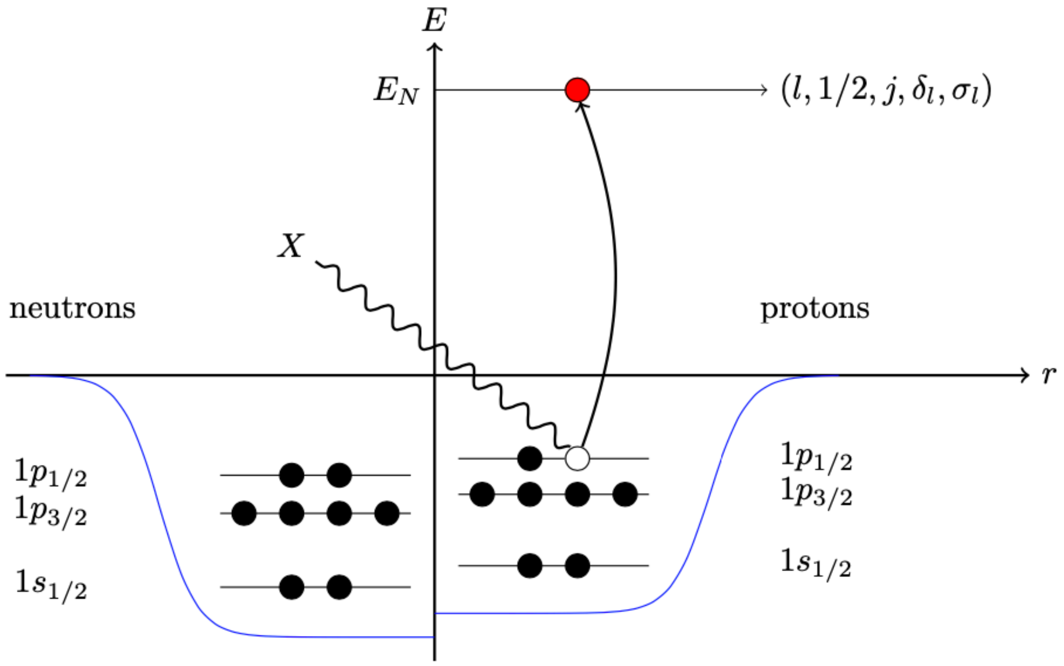


- Typical BSM signatures include charged leptons ($e^\pm$, $\mu^\pm$), photons and hadrons in the final states.
- Neutrino-nucleus interaction products are the primary background.

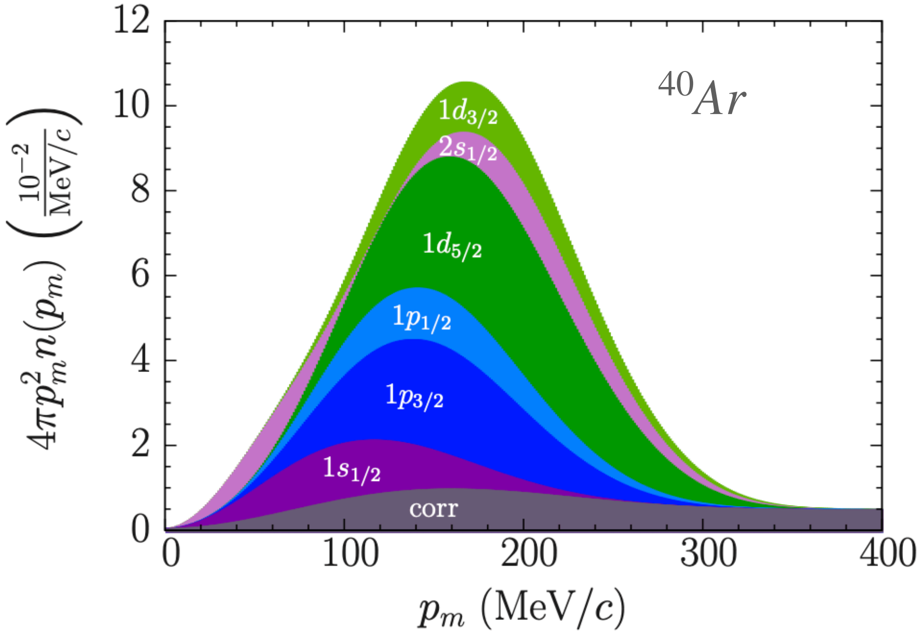
✦ Need to constrain neutrino-nucleus interaction cross sections in order to disentangle new physics signals.

Neutrino-Nucleus Interactions

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



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



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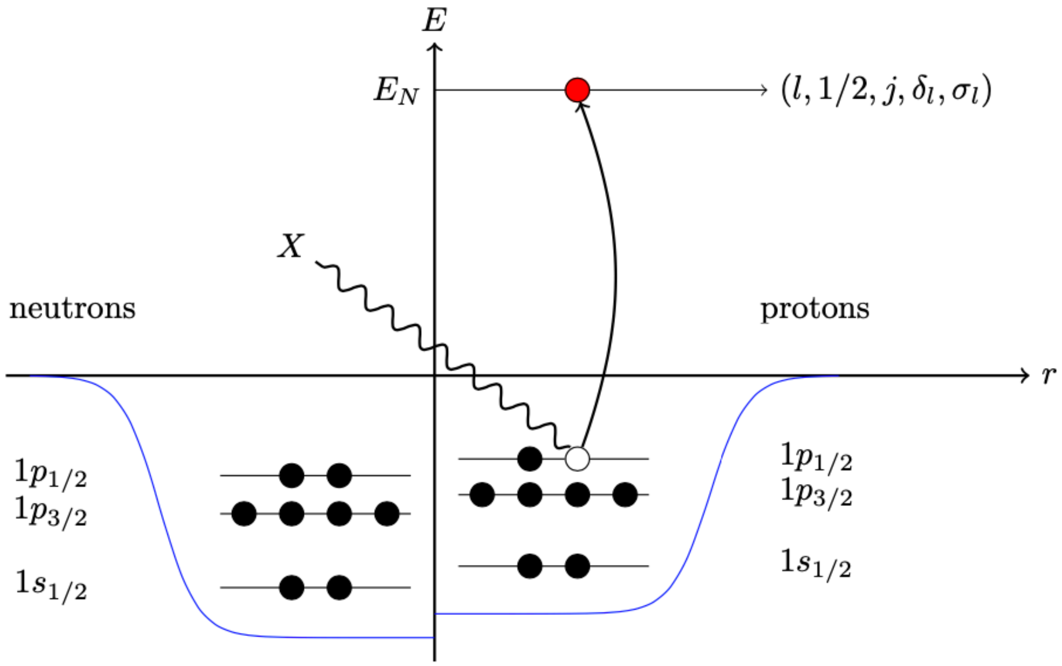

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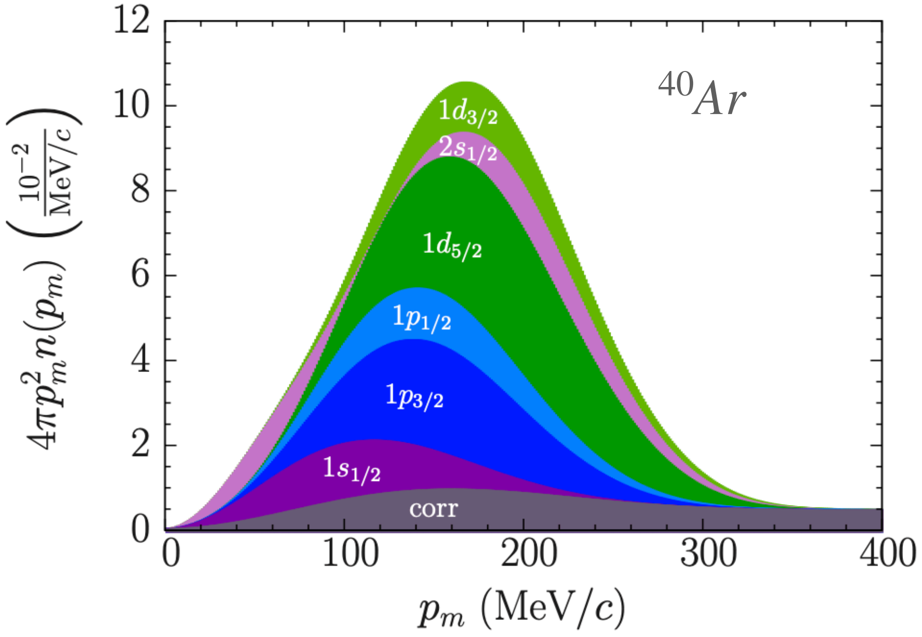
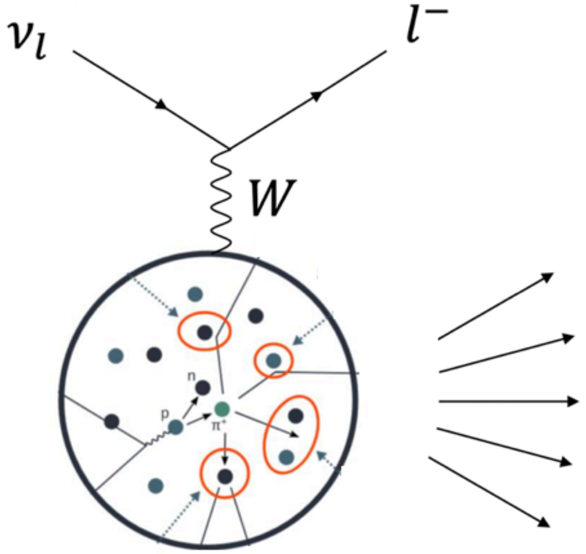


- Hadrons re-interact inside the nuclear medium before exiting: Final State Interaction (FSI)

  - FSI can cause different interaction modes to have the same final state



(adapted from T. Golan)

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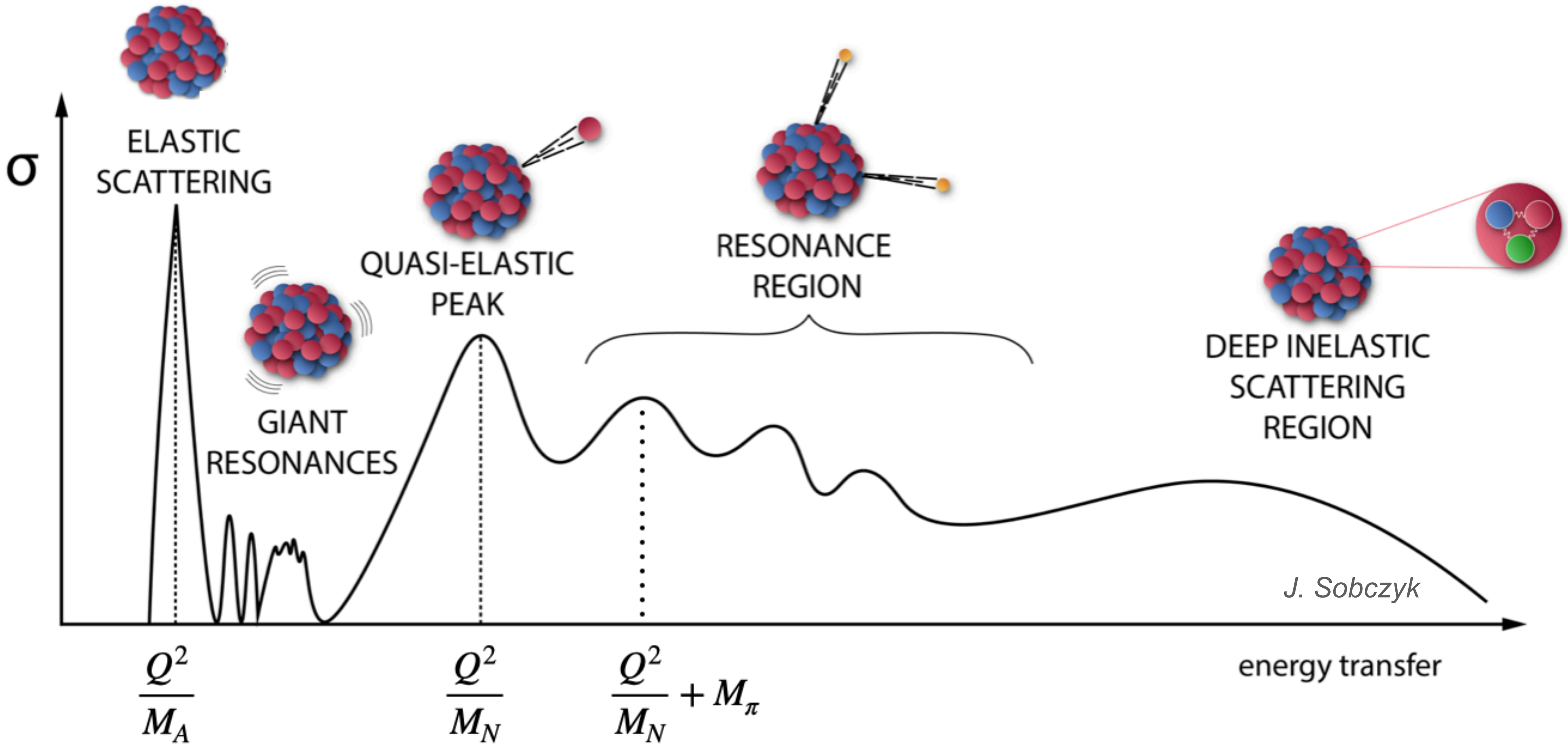
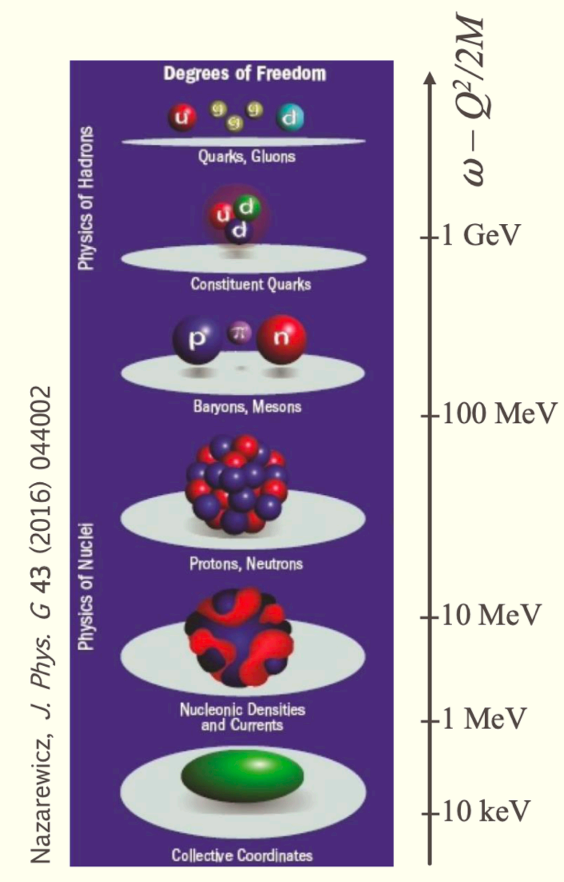
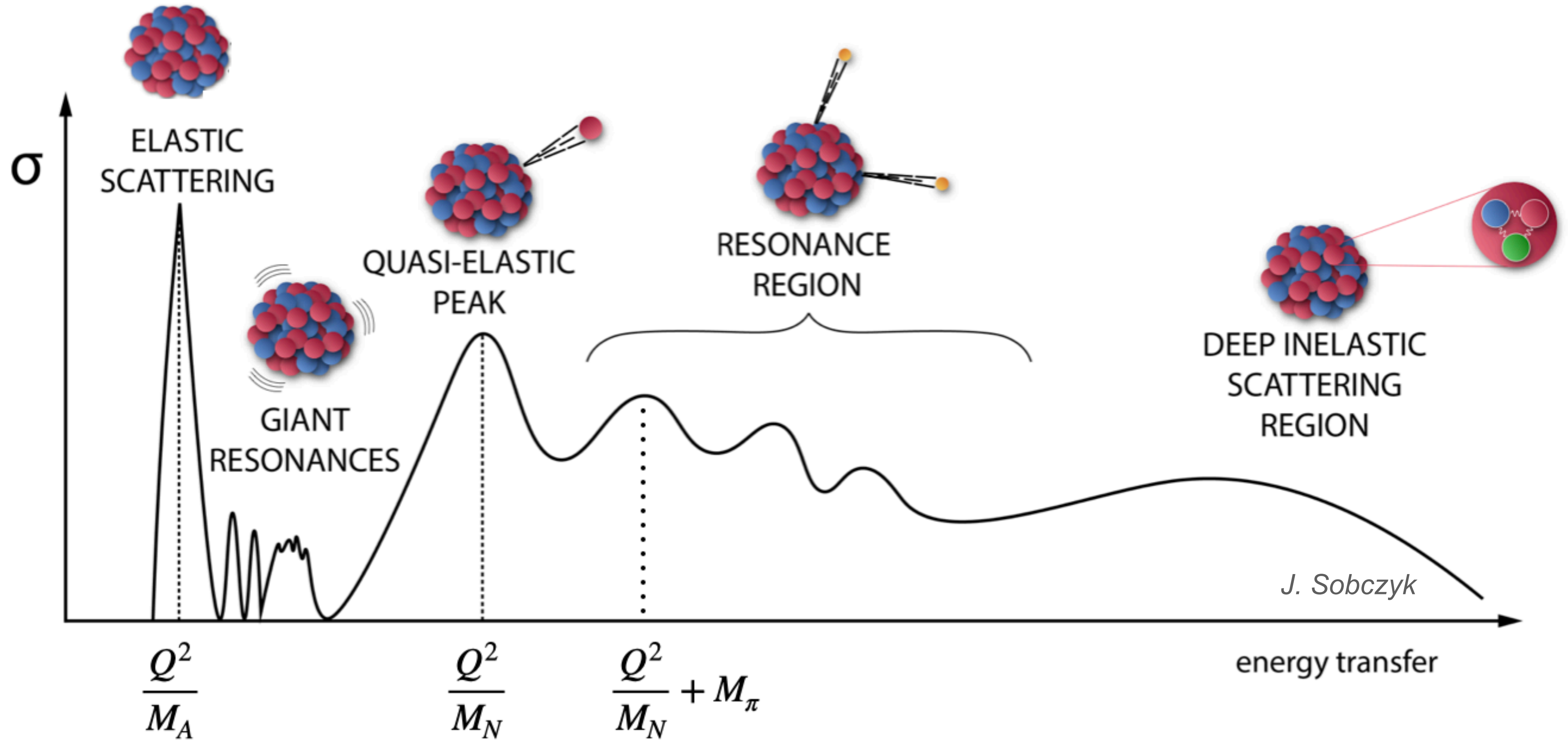
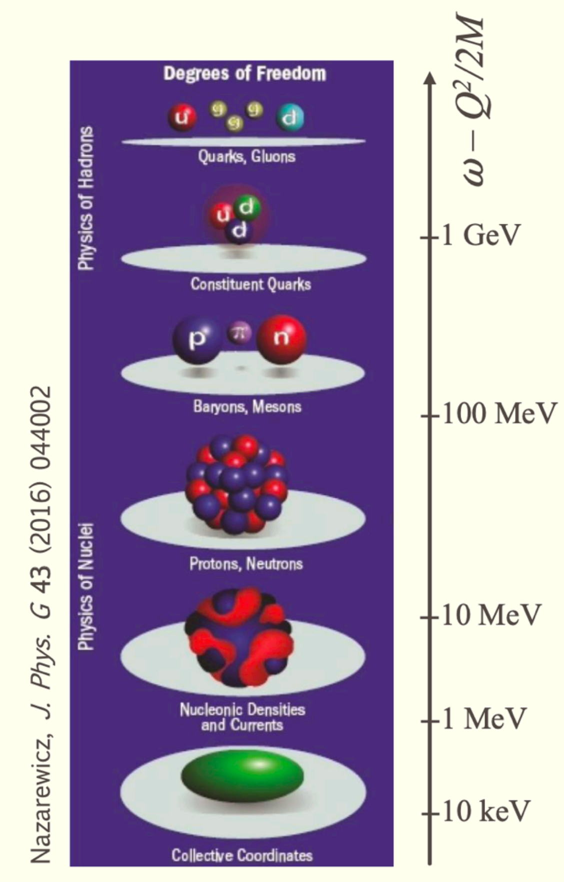




Nazarewicz, *J. Phys. G* 43 (2016) 044002

Neutrino-Nucleus Interactions





Nazarewicz, *J. Phys. G* 43 (2016) 044002

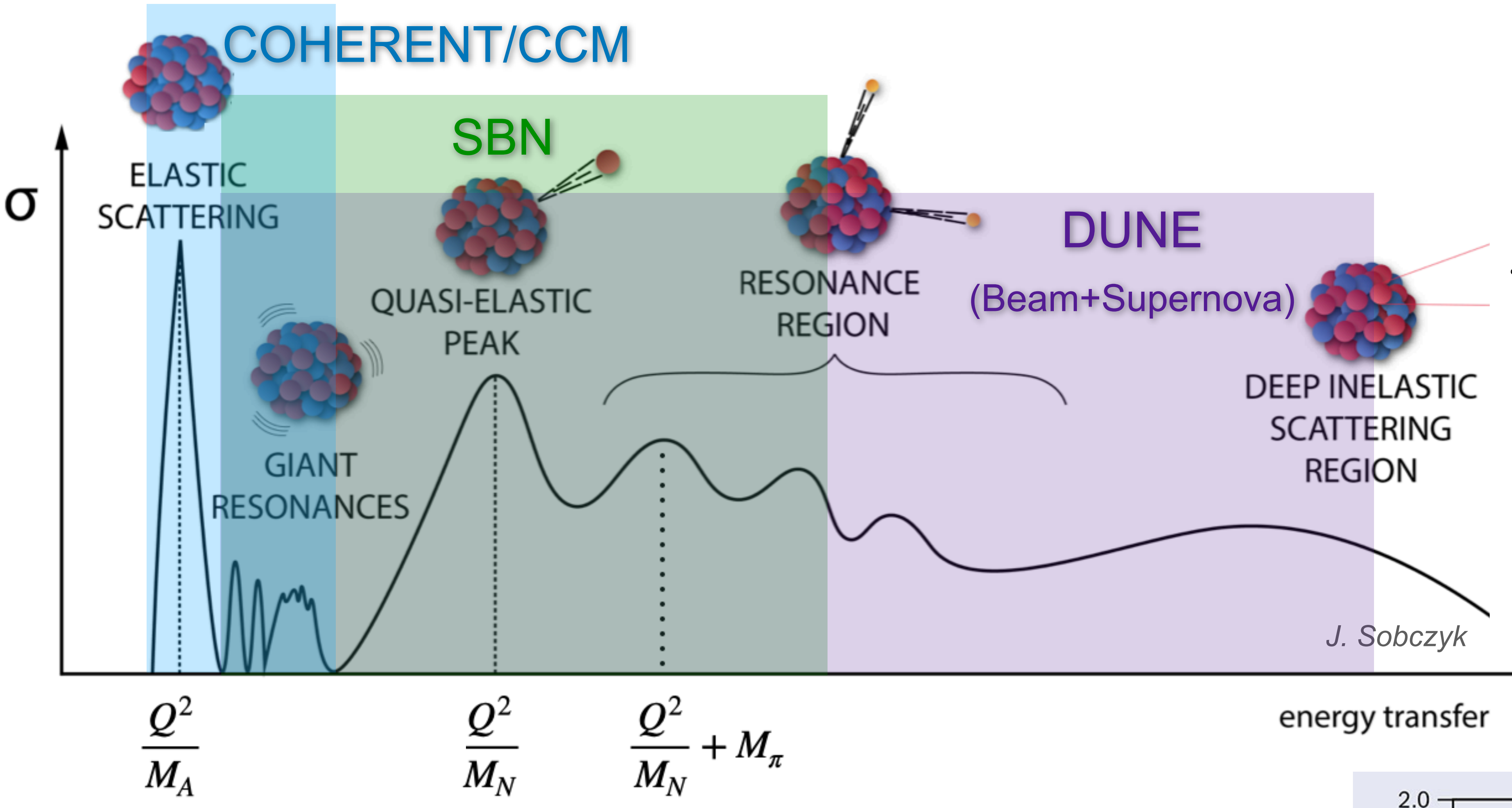
Atomic Systems

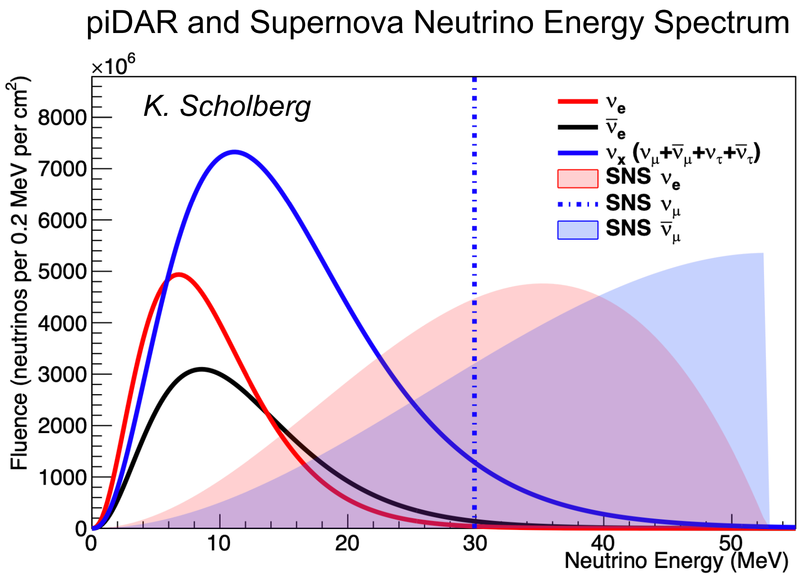
- No unified underlying theory to describe neutrino-nucleus interactions.
- Multi-scale, multi-process, many-body, non-perturbative problem subject to complex nuclear structure and dynamics.
- Transition between different degrees of freedom.

QCD

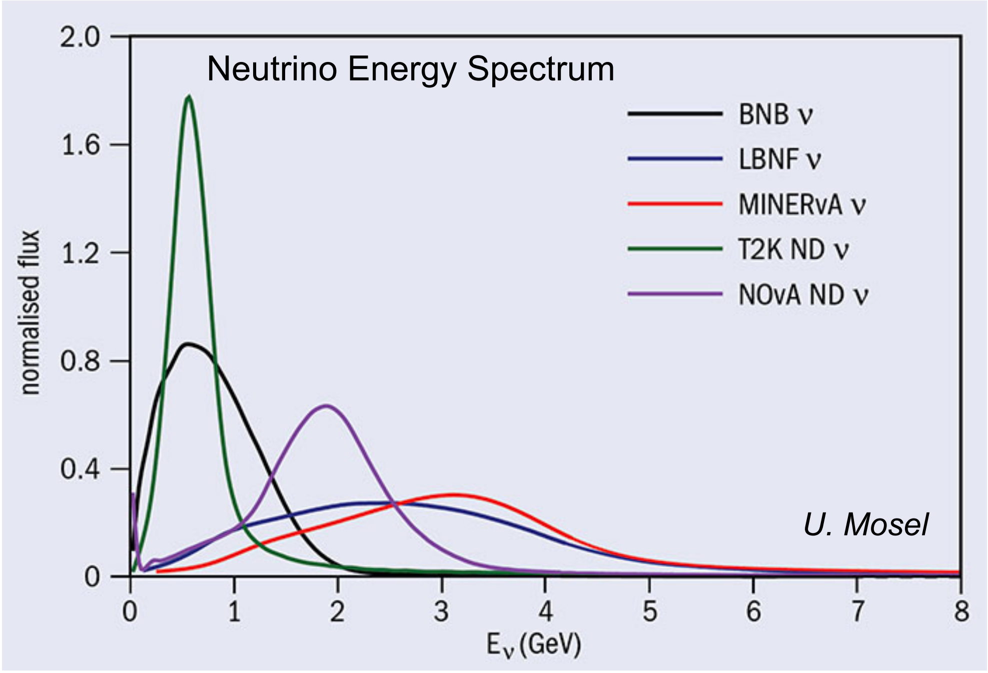
- d.o.f. :
  quarks and gluons
- Asymptotic freedom
- Confinement

Neutrino-Nucleus Interactions





- Neutrino fluxes span over a wide range of energies where a number of nuclear reaction mechanisms overlap.



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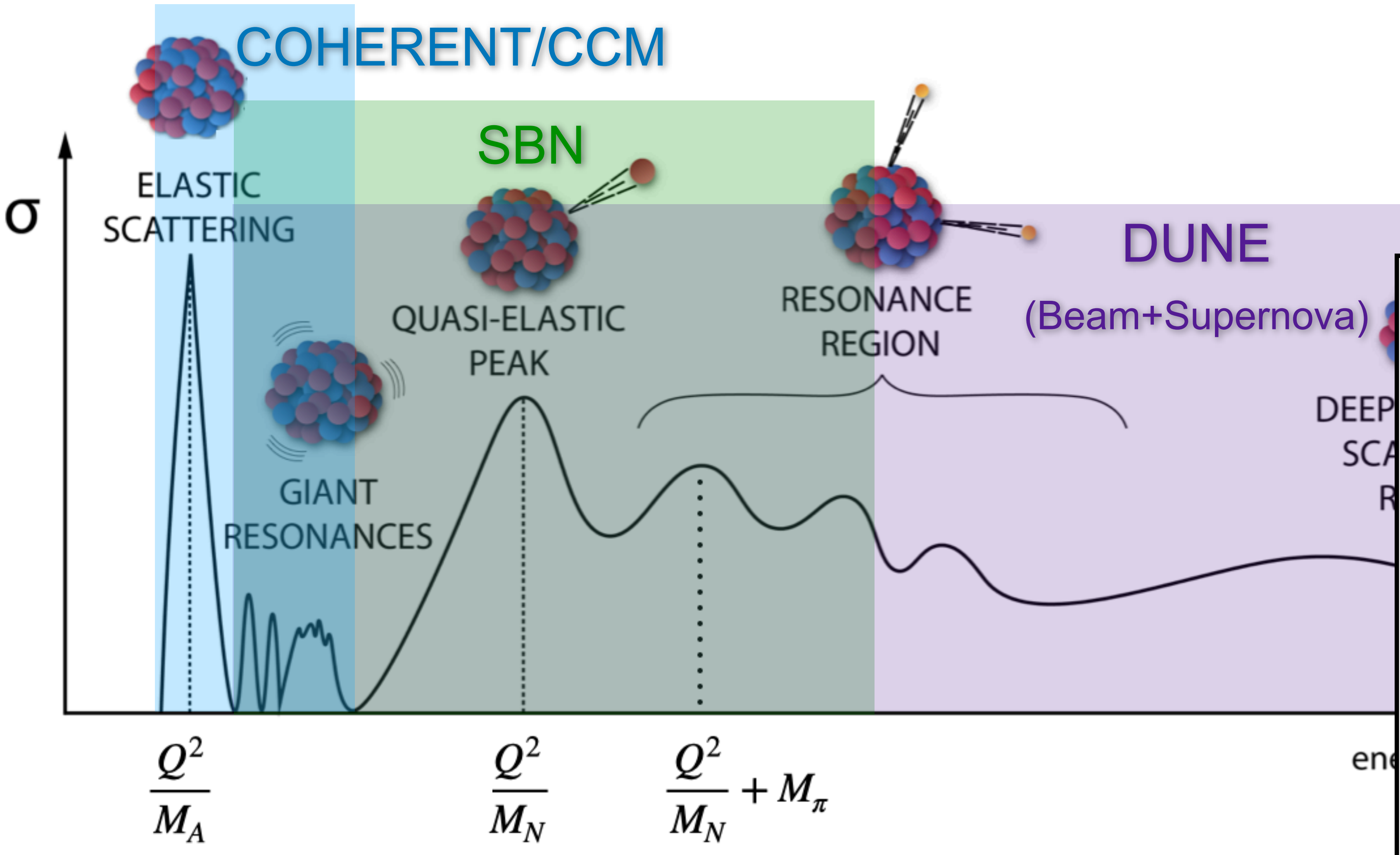

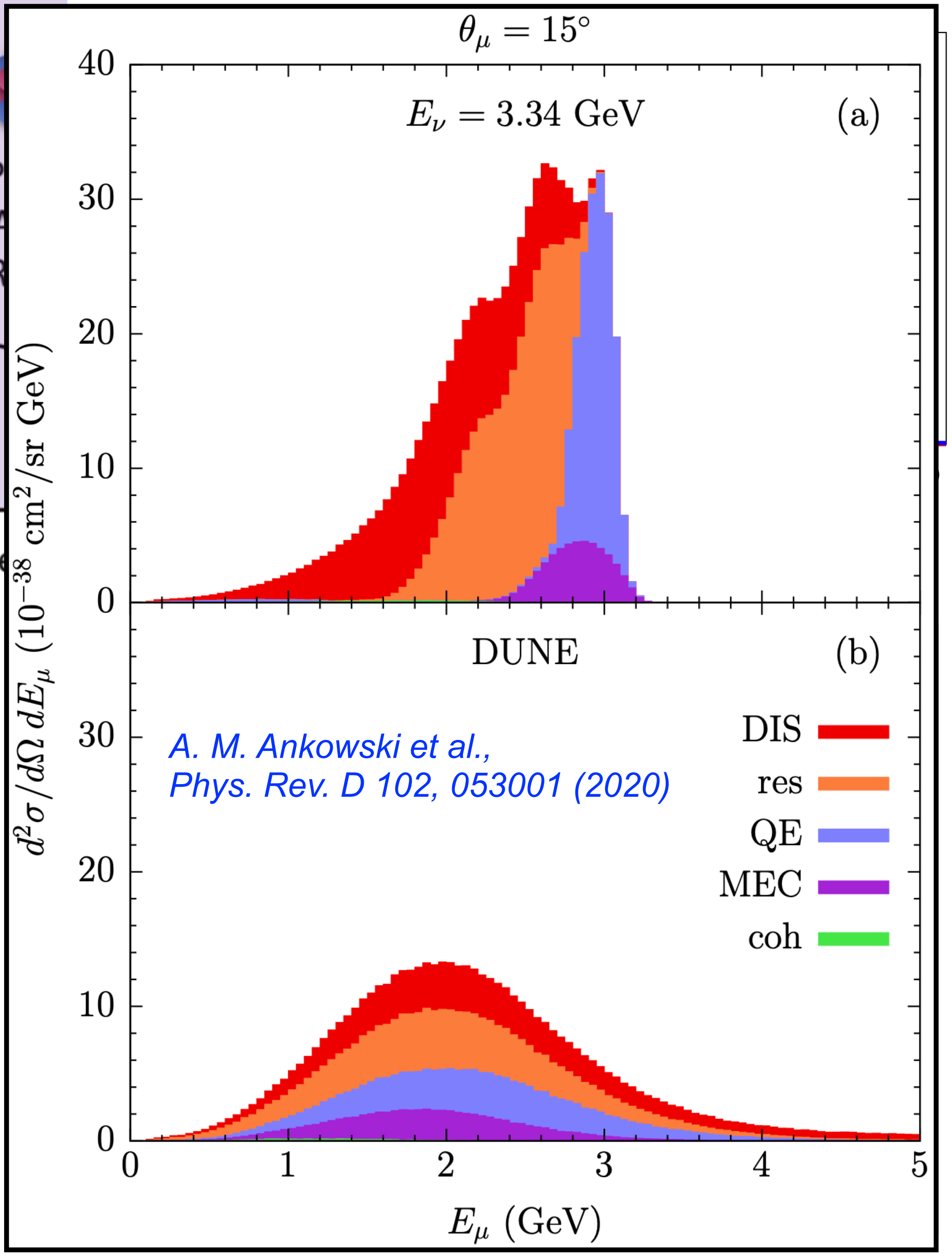

A. M. Ankowski et al.,
Phys. Rev. D 102, 053001 (2020)

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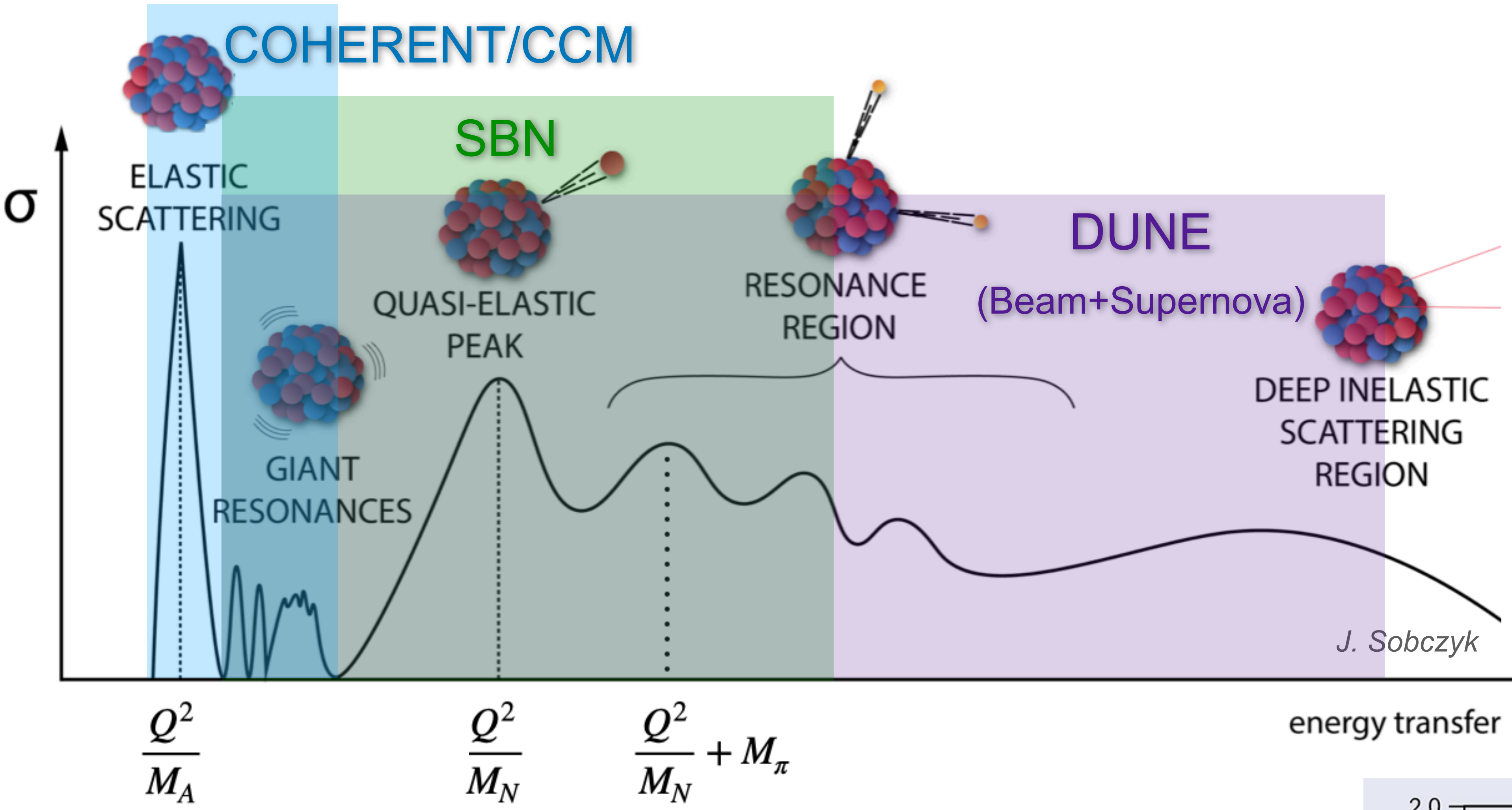
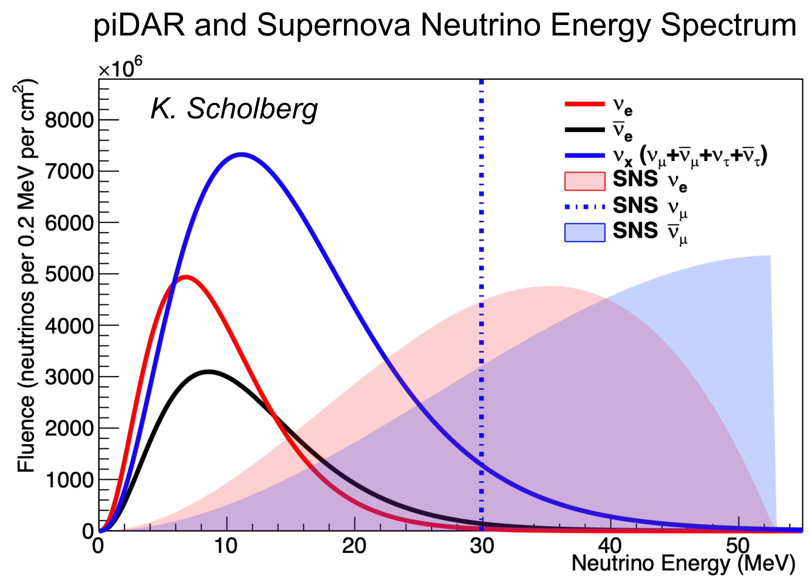
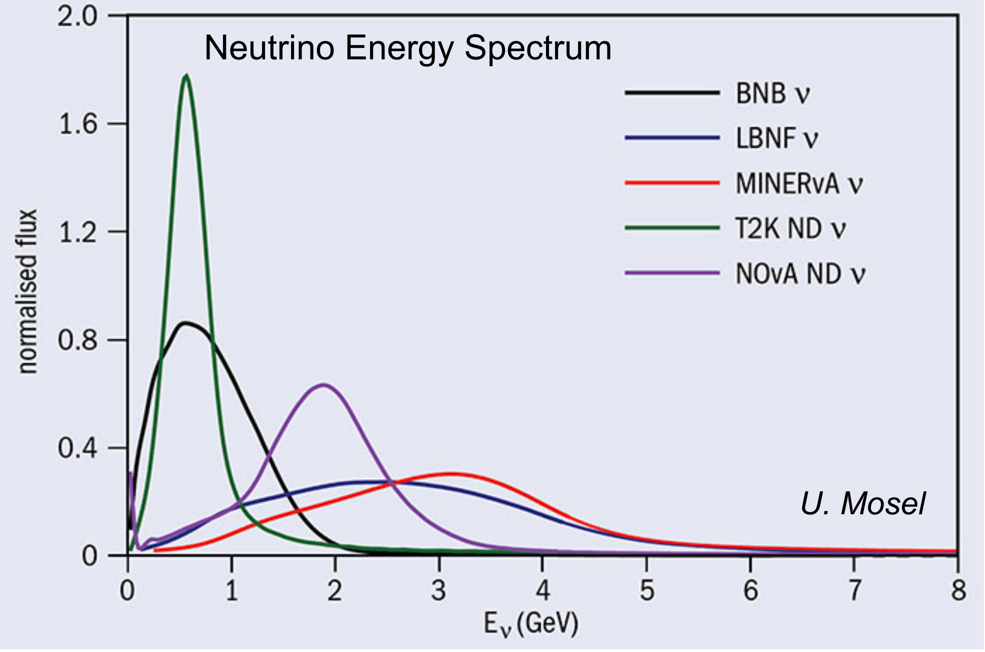


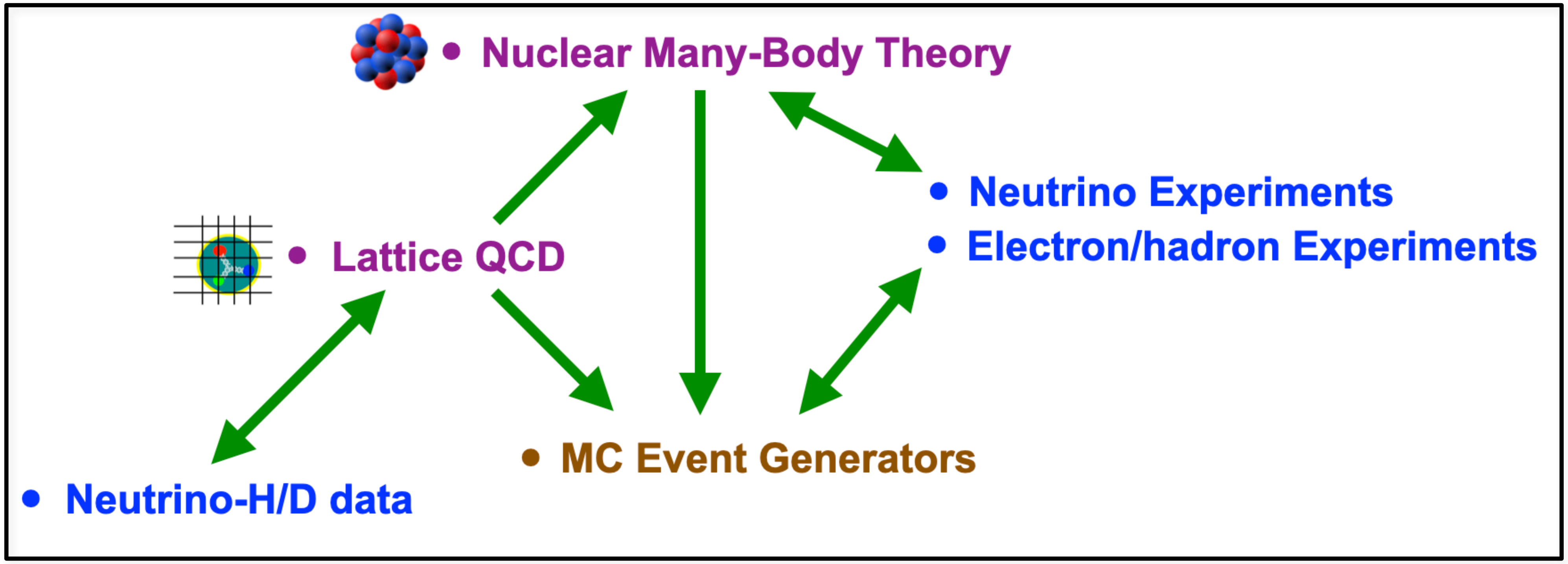




- Neutrino fluxes span over a wide range of energies where a number of nuclear reaction mechanisms overlap.
- Each of these regimes requires knowledge of the nuclear ground state, its electroweak response and the propagation of the struck nucleons or hadrons.
- Transitions between processes are challenging (need to carefully account for transitions, avoiding double counting, keeping consistency), which can span different degrees of freedom.

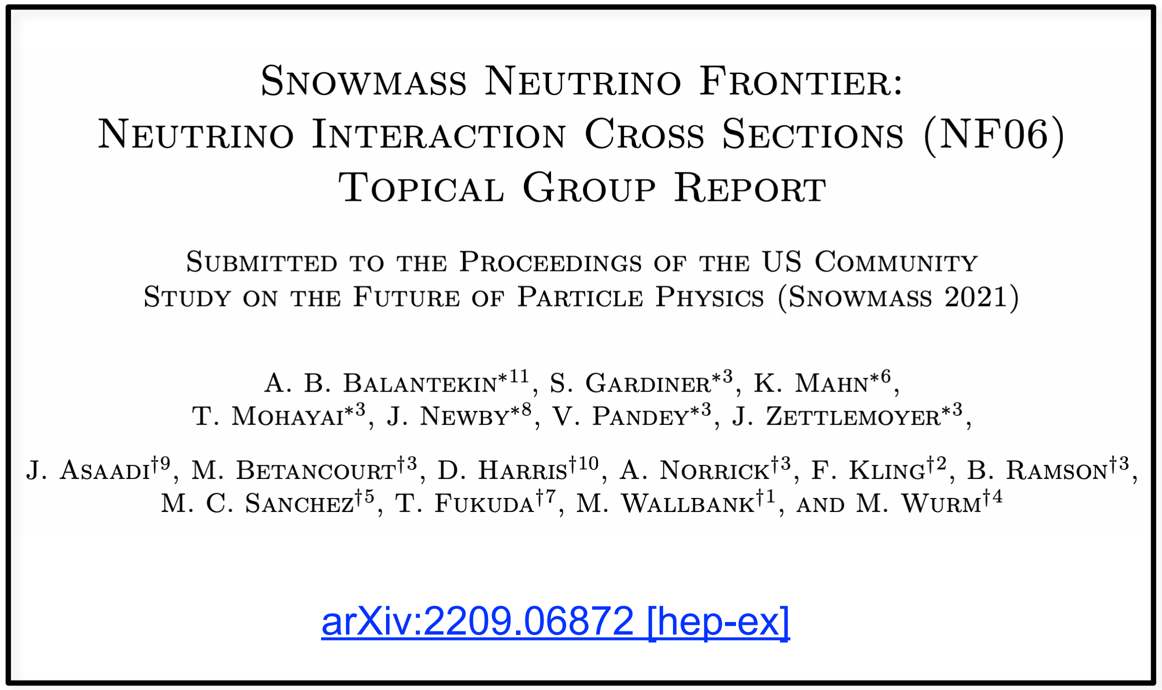
Constraining Neutrino-Nucleus Interactions

- Precision needs of neutrino physics and other new physics searches at neutrino facilities require:



- **Nuclear Many-Body Theory**
- **Lattice QCD**
- **Neutrino Experiments**
- **Electron/hadron Experiments**
- **MC Event Generators**
- **Neutrino-H/D data**

- These efforts require, and benefit from, significant expertise from both High Energy Physics (HEP) and Nuclear Physics (NP) communities.
- Require close collaboration between theorists, experimentalists and generator developers.



SNOWMASS NEUTRINO FRONTIER:
NEUTRINO INTERACTION CROSS SECTIONS (NF06)
TOPICAL GROUP REPORT

SUBMITTED TO THE PROCEEDINGS OF THE US COMMUNITY
STUDY ON THE FUTURE OF PARTICLE PHYSICS (SNOWMASS 2021)

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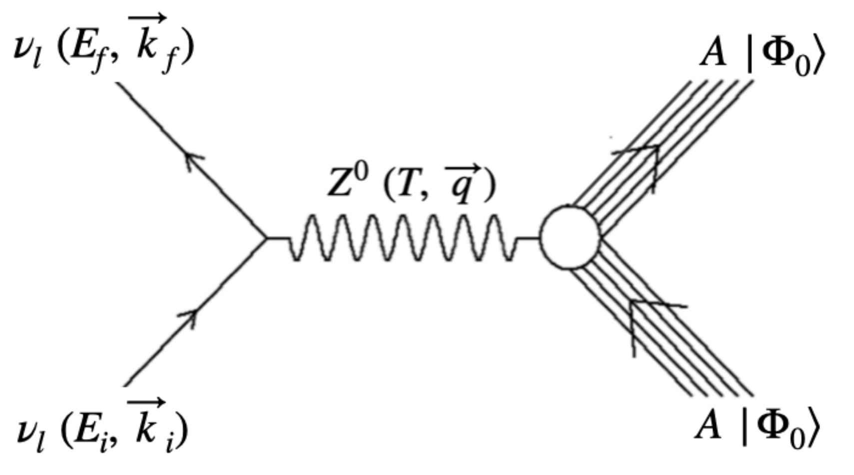
M. C. SANCHEZ[†5], T. FUKUDA[†7], M. WALLBANK[†1], AND M. WURM[†4]

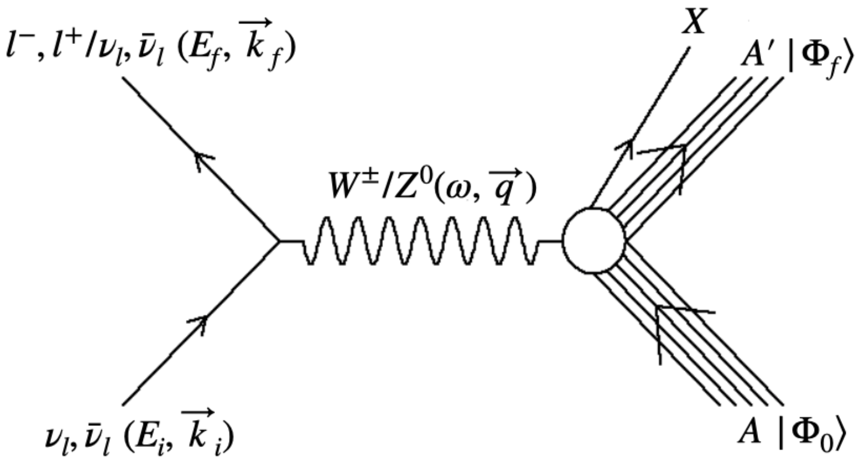
arXiv:2209.06872 [hep-ex]

10s of MeV Neutrinos-Nucleus Scattering

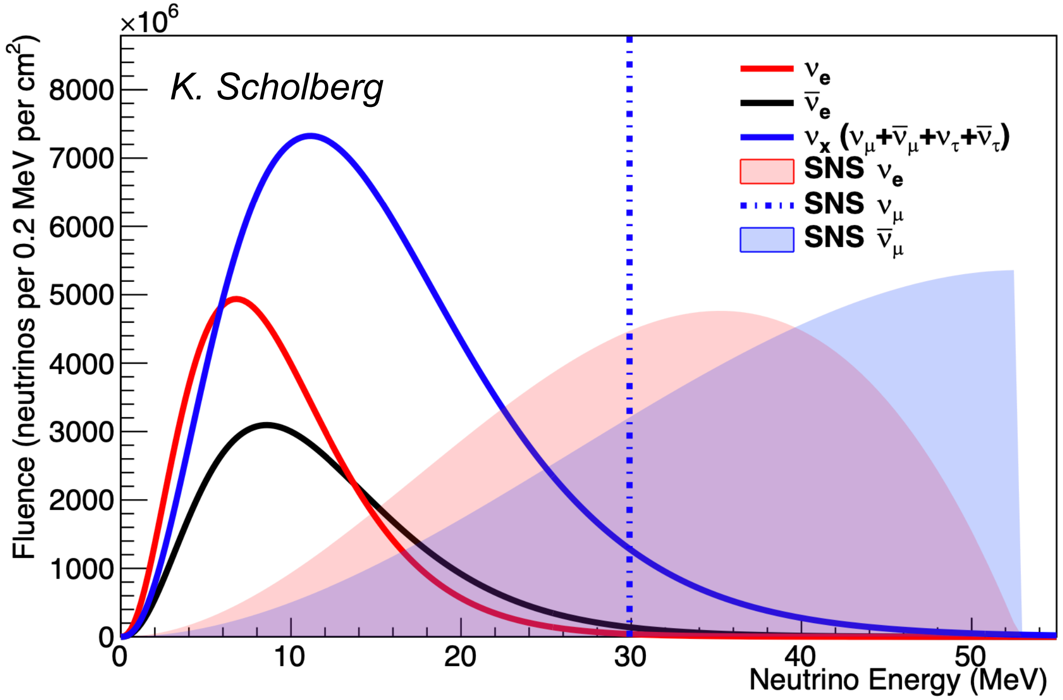
Coherent elastic [CEvNS]



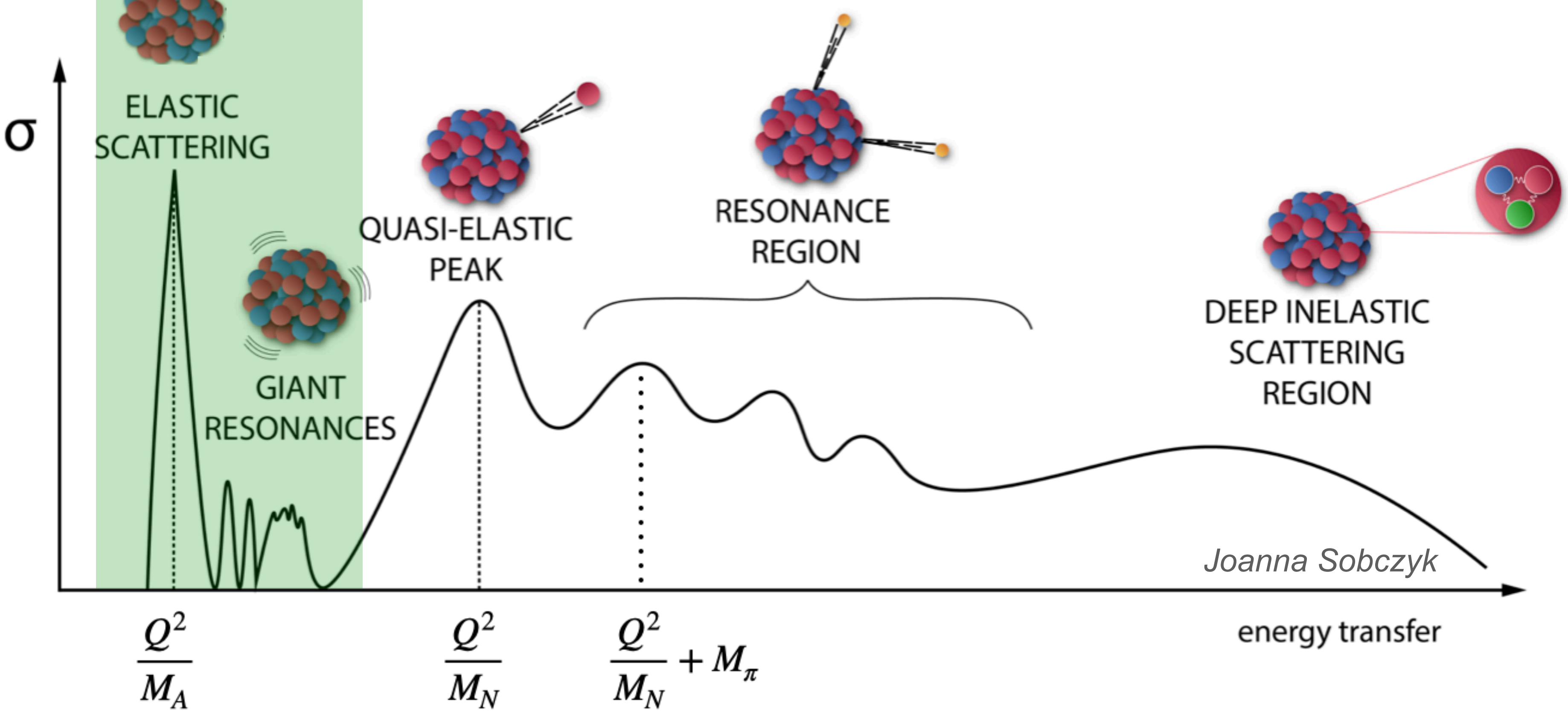
Inelastic CC/NC



piDAR and Supernova Neutrino Energy Spectrum



10s of MeV Scale



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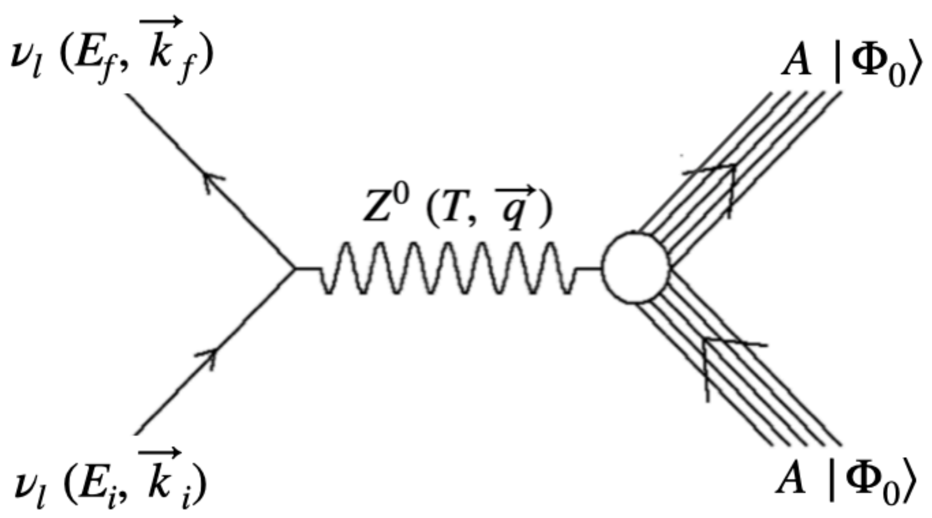

- Final state nucleus stays in its ground state
- Tiny recoil energy, large cross section
- Signal: keV energy nuclear recoil

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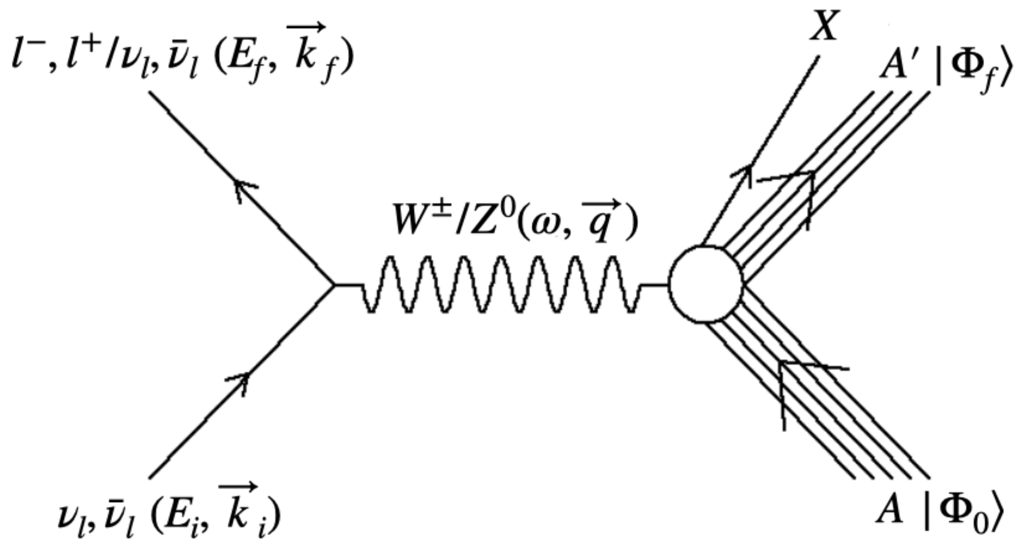

- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π)
- Followed by nuclear de-excitation into MeV energy gammas, including n, p or nuclear fragmentation emission.

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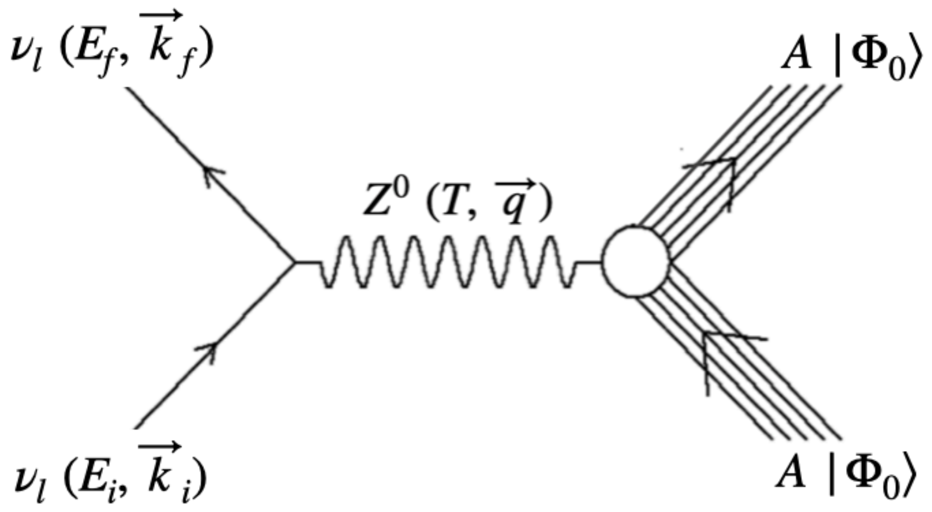

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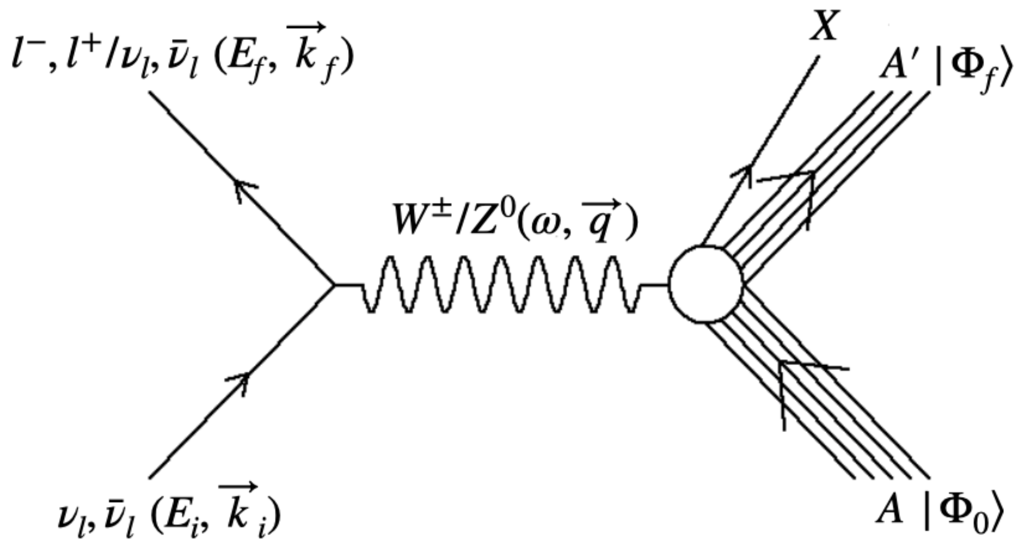

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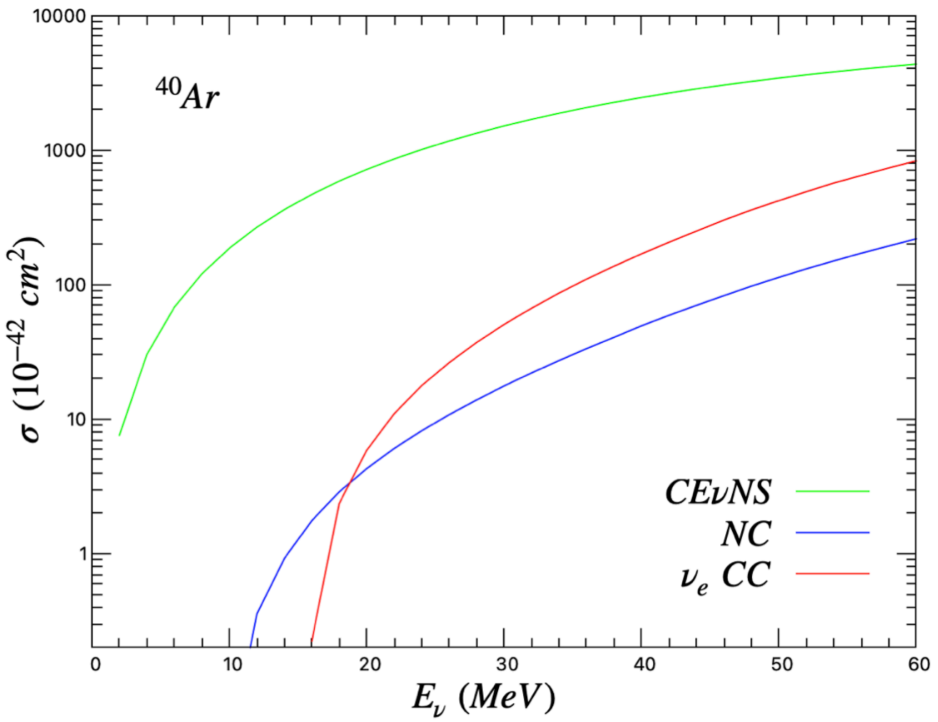
V. Pandey, Prog. Part. Nucl. Phys., 104078 (2024)



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

10s of MeV Neutrinos-Nucleus Scattering

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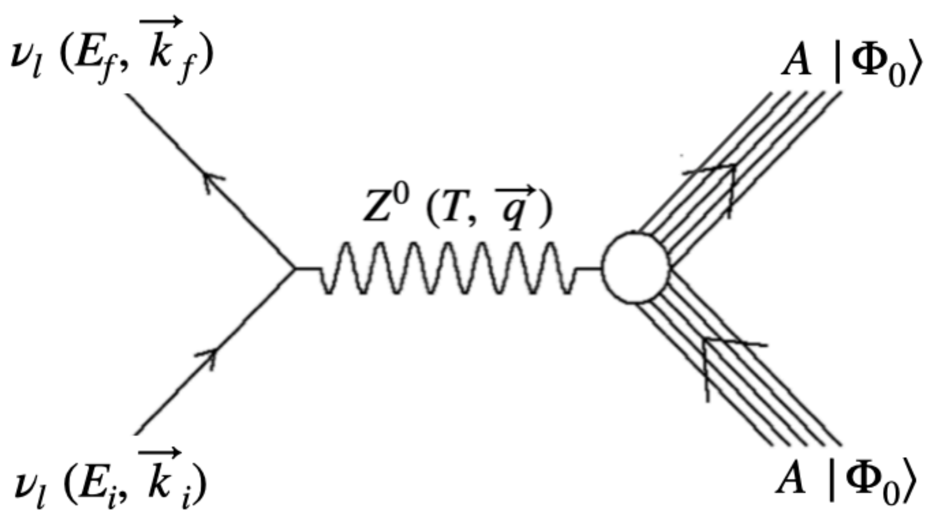

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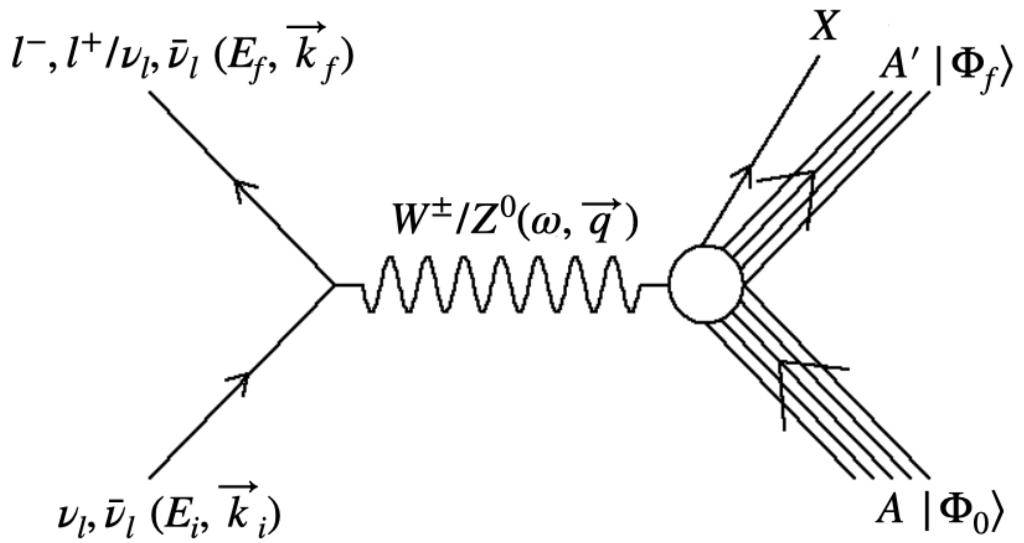

$$\sum_{fi} |\mathscr{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

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

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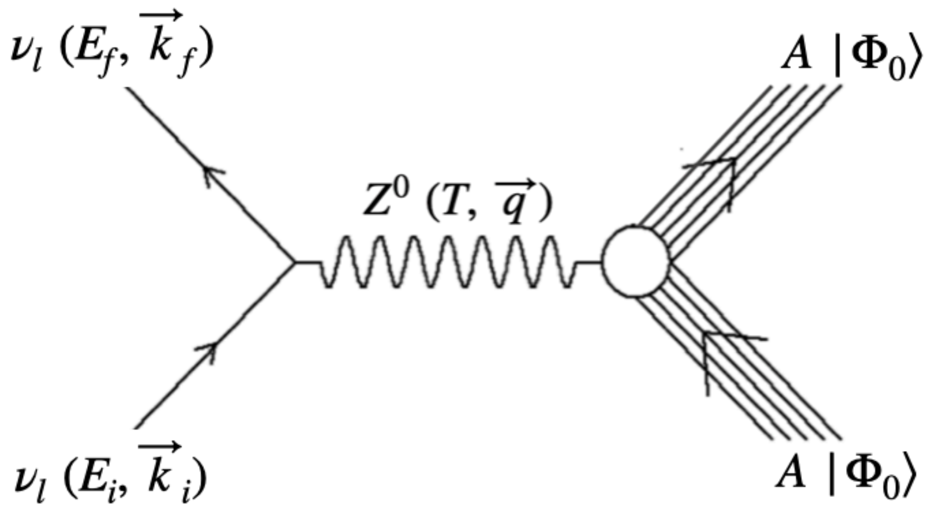

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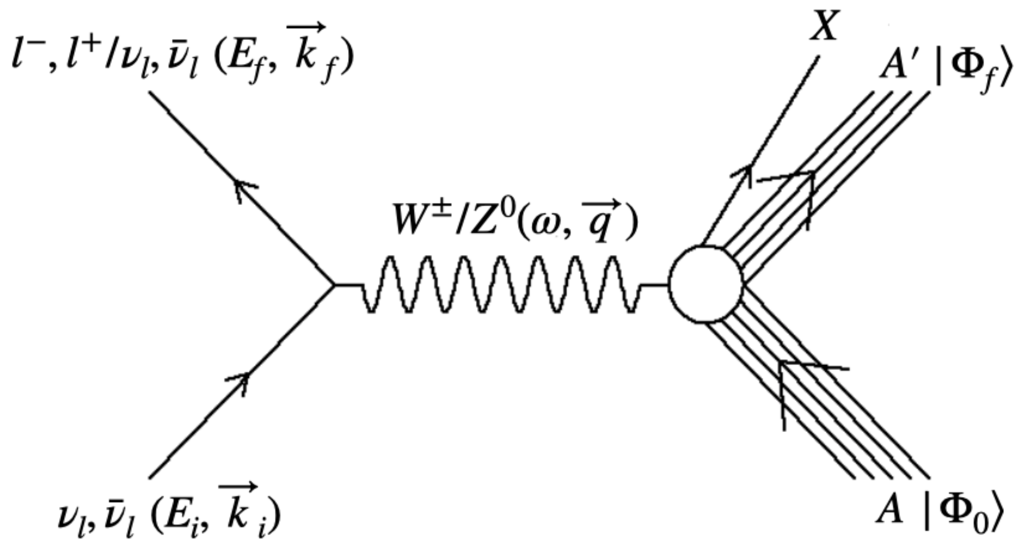

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Cross Section:

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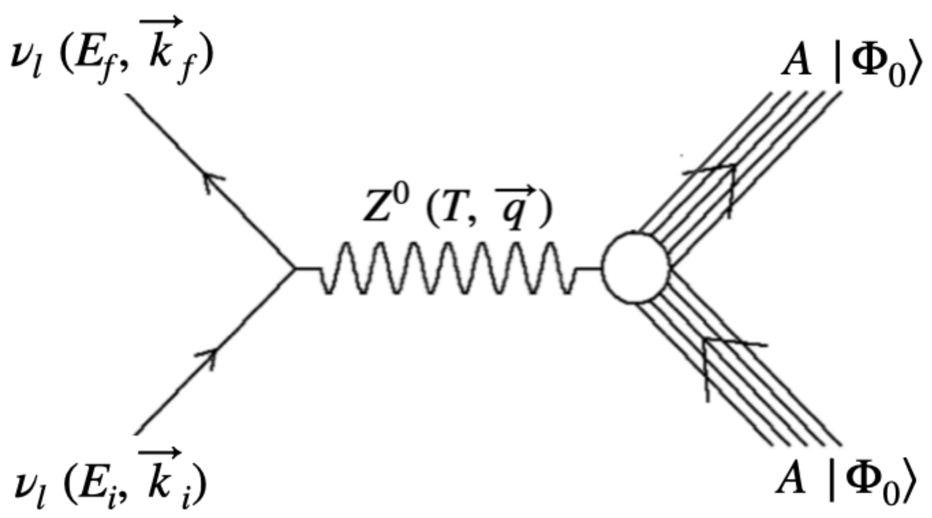

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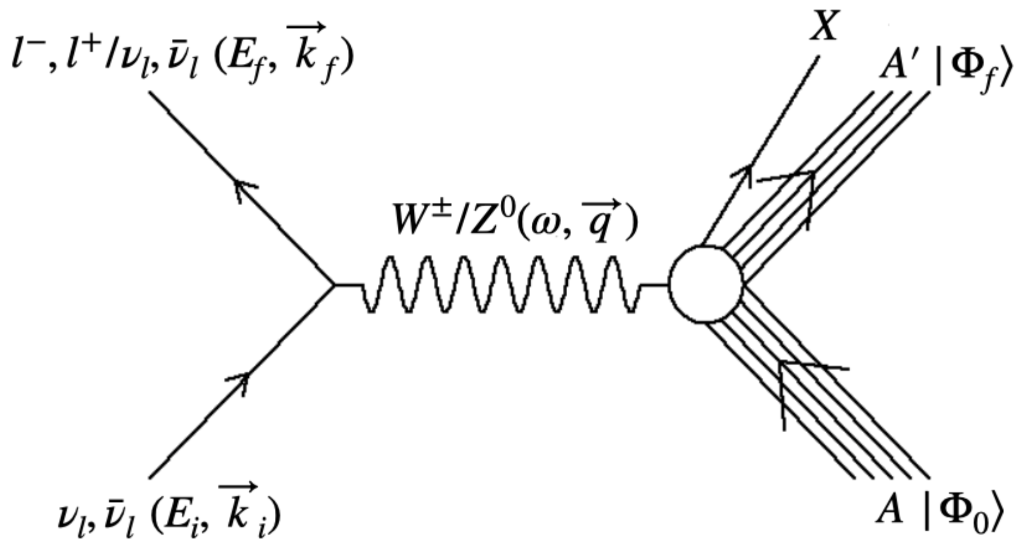

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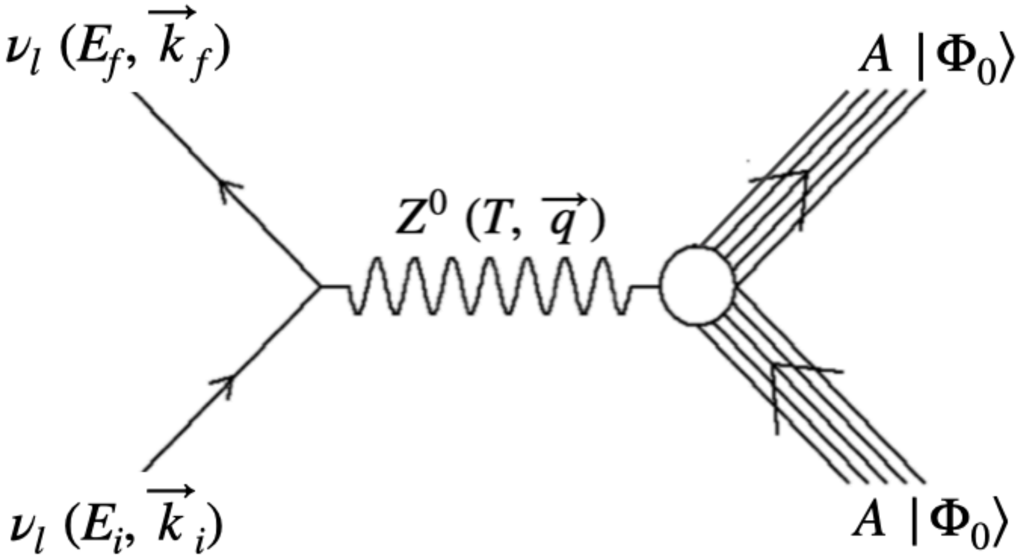
$$\boxed{\begin{aligned} d\sigma \propto \frac{G_F^2}{4\pi} \sum_{J^\pi} [& v_{CC} W_{CC} + v_{CL} W_{CL} + v_{LL} W_{LL} \\ & + v_T W_T \pm v_{T'} W_{T'}] \end{aligned}}$$

CEvNS Cross Section and Form Factors

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

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



- **Weak Form Factor:**

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

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

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

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*barring radiative corrections, for radiate corrections, see:

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

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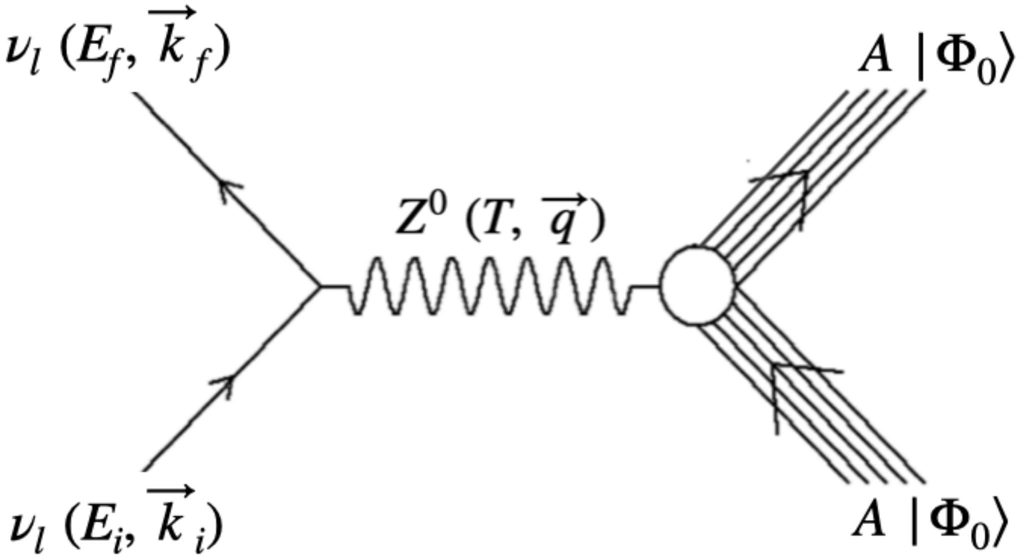

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Charge density and charge form factor: proton densities and charge form factors are well know through decades of elastic electron scattering experiments.

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.
  - **CEvNS Cross Section**
  - **PVES Asymmetry**

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

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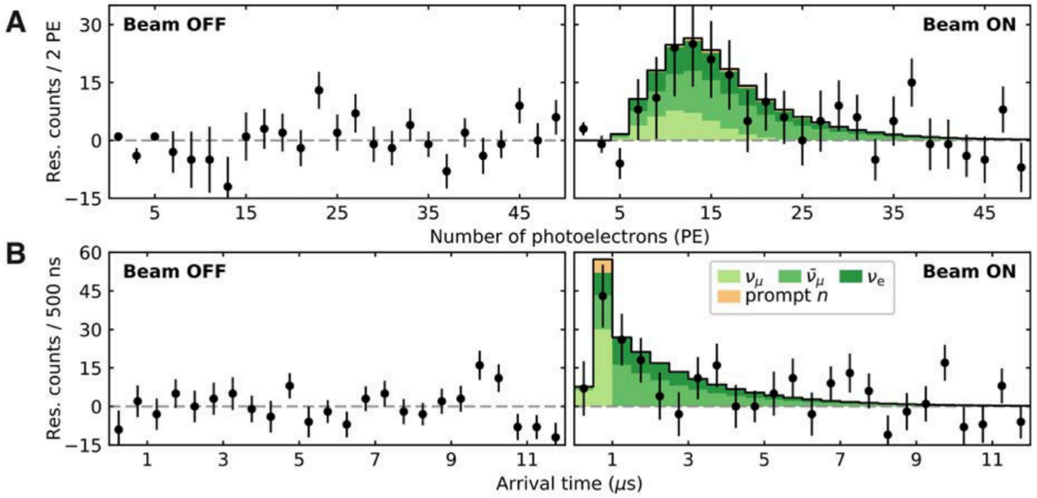
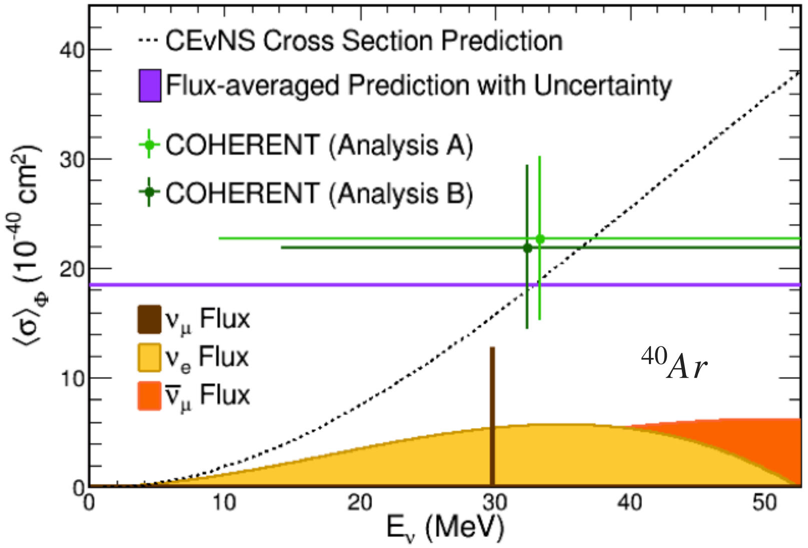
COHERENT Collaboration at SNS at ORNL





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

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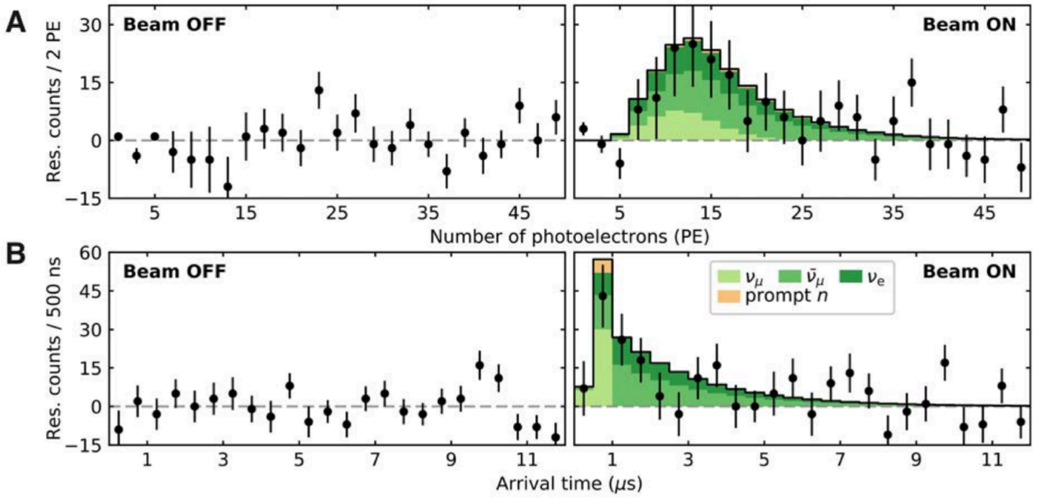

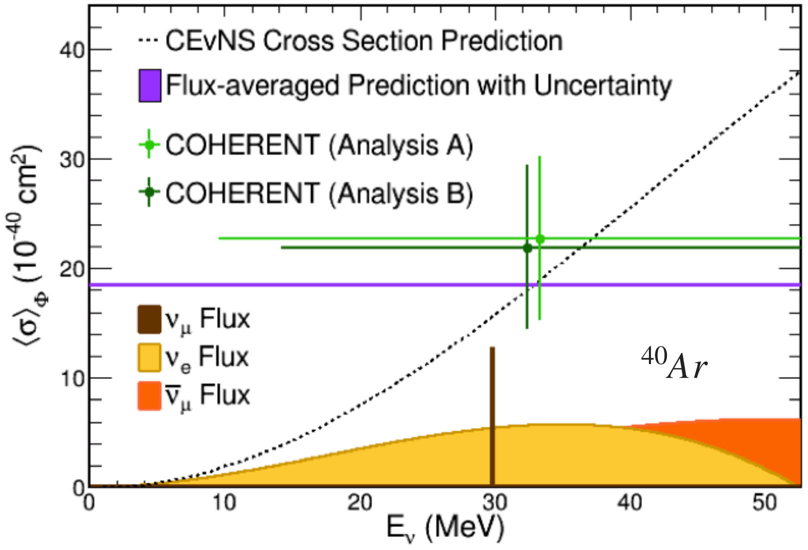

Science 357, 6356, 1123-1126 (2017)
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• PVES Asymmetry

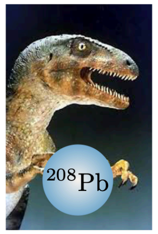
▸ The parity violating asymmetry for elastic electron scattering is the fractional difference in cross section for positive helicity and negative helicity electrons.

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

- 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)

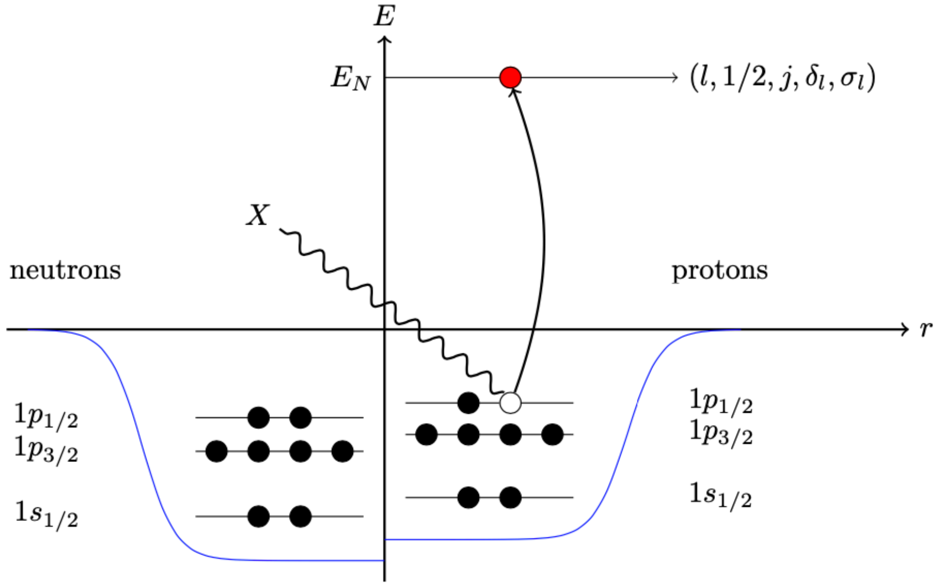
Mainz Radius Experiment (MREX)
At P2 experimental hall with ^{208}Pb

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



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

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

$(\tau = p, n)$

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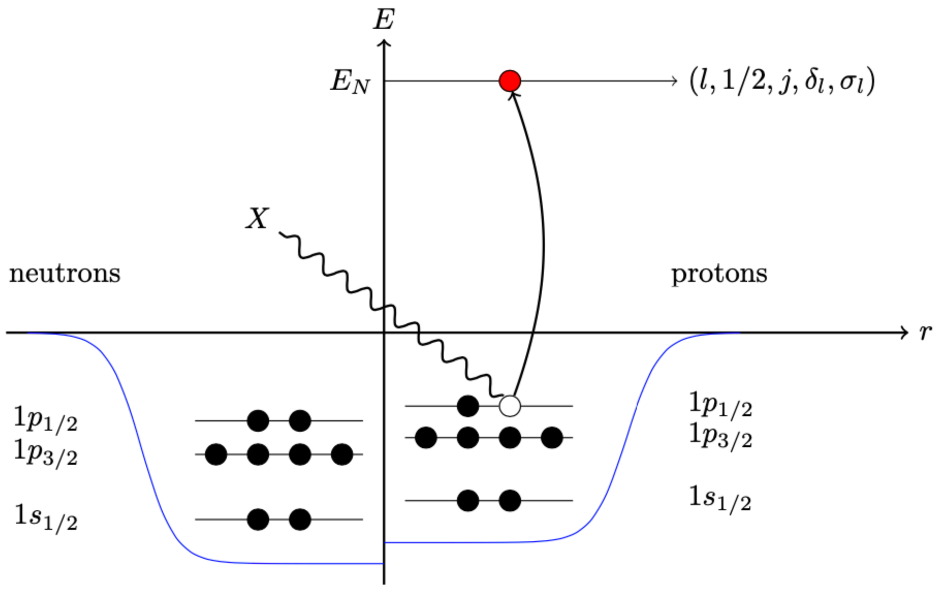

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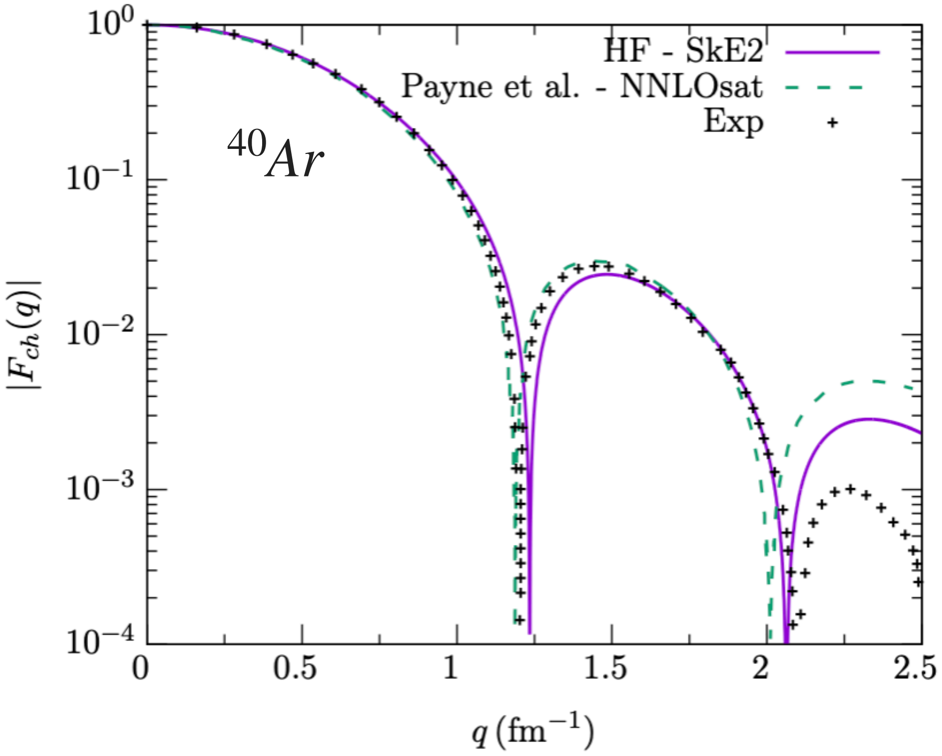
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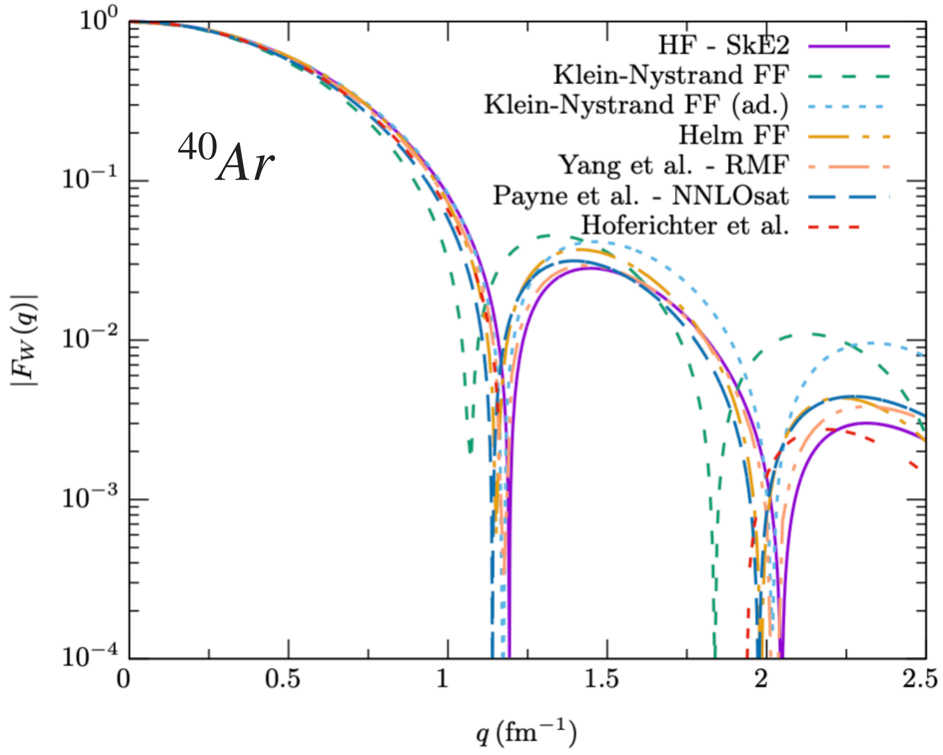

Weak Form Factor

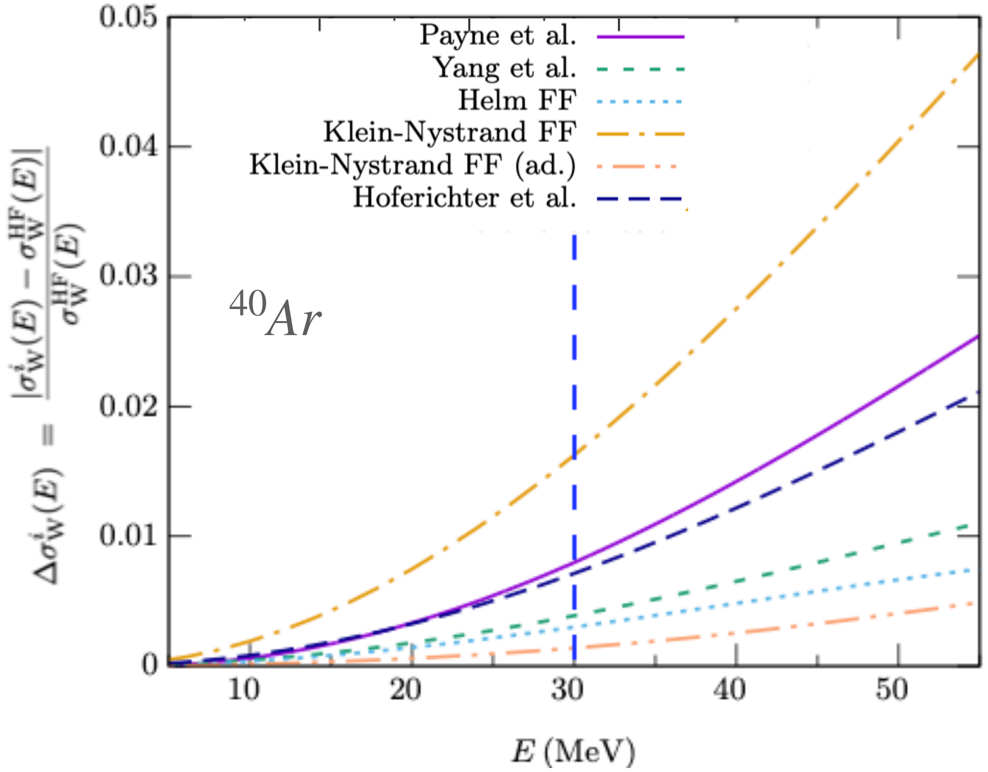
N. Van Dessel, VP, H. Ray and N. Jachowicz, Universe 9, 207 (2023)

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)

CEvNS Cross Section and Form Factors

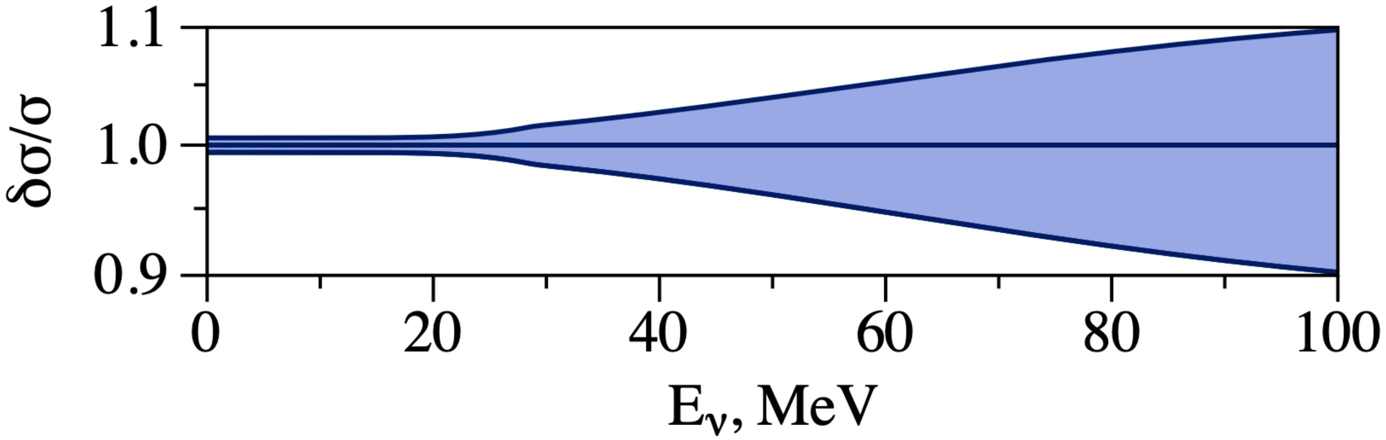
✱ Only a few percent theoretical uncertainty on the CEvNS cross section!

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



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

- Relative CEvNS cross section theoretical uncertainty on ^{40}Ar (includes nuclear, nucleonic, hadronic, quark levels as well as perturbative errors):



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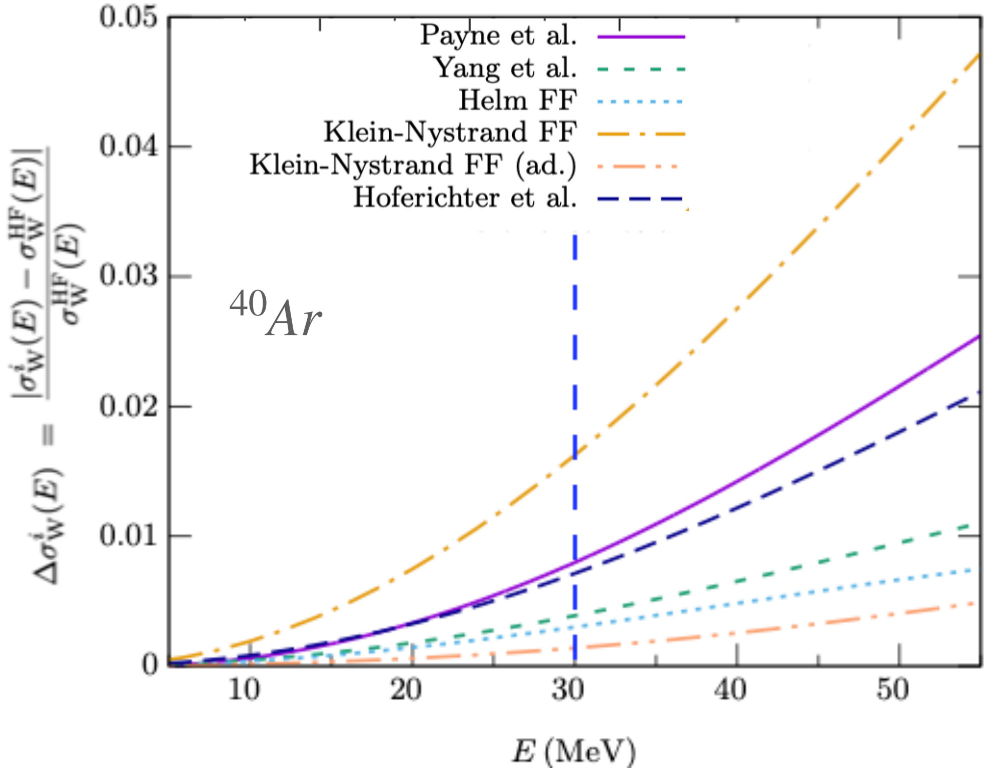

N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

- A low statistics measurement performed by COHERENT collaboration with a 24 kg LAr (CENNS-10) detector

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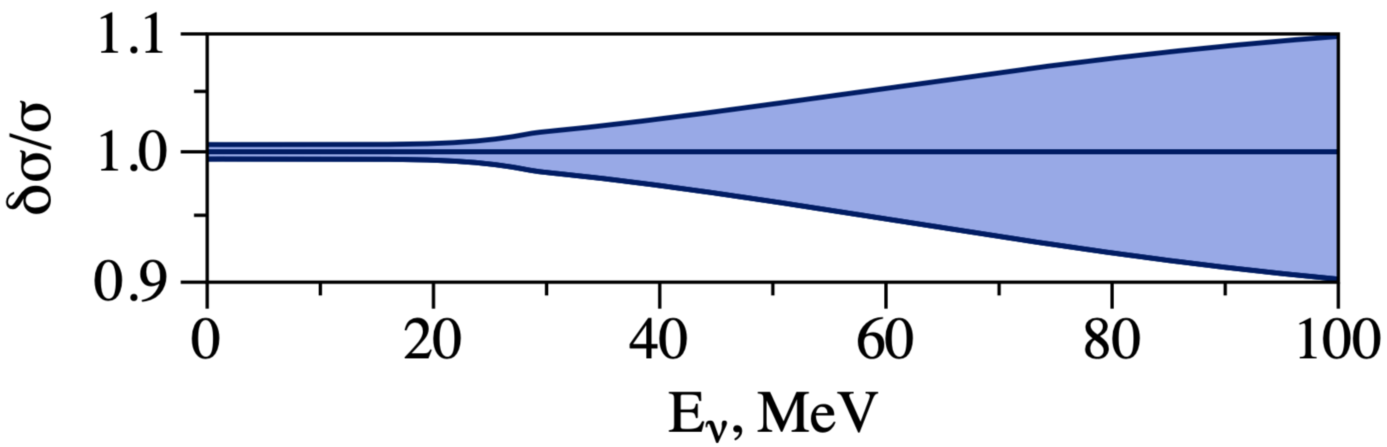

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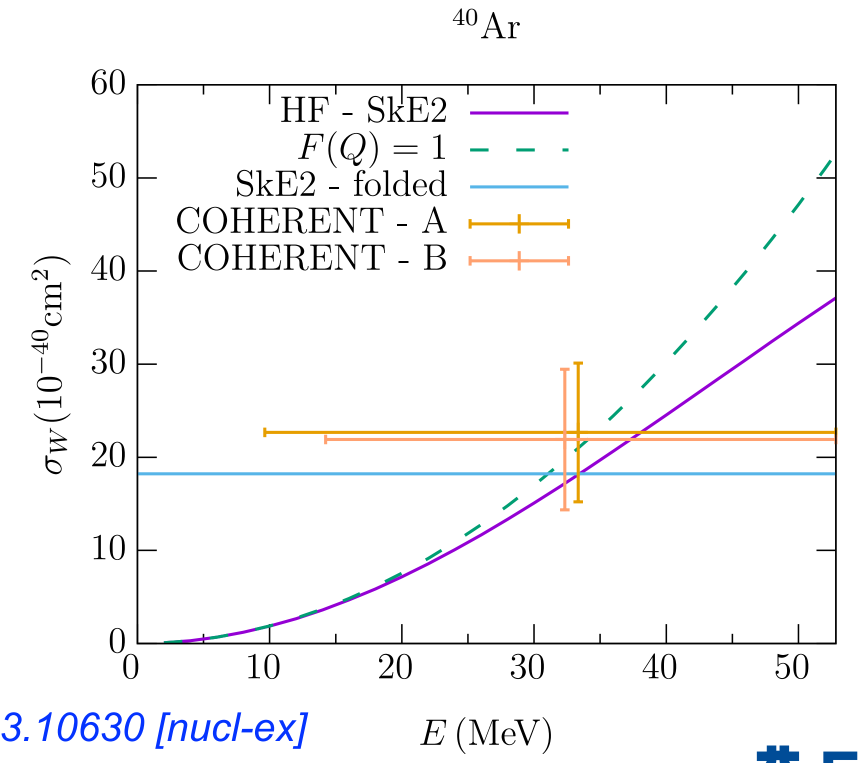


COHERENT data: arXiv:2003.10630 [nucl-ex]

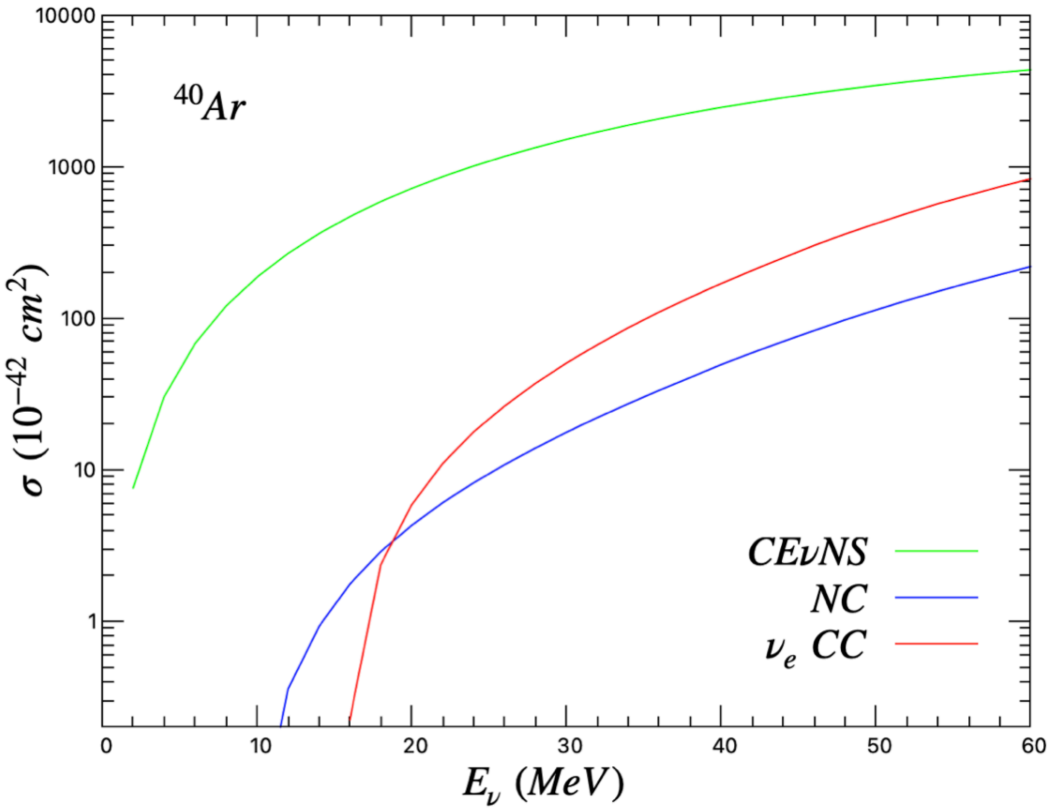
10s of MeV Inelastic Neutrino-Nucleus Scattering: HF-CRPA Model

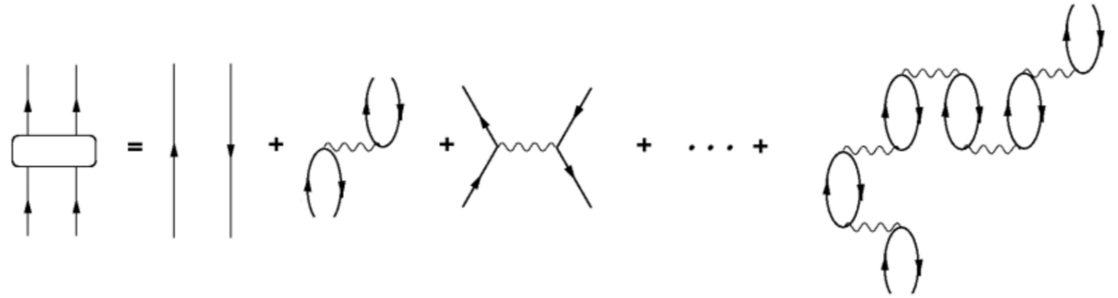
- In the inelastic cross section calculations, the influence of long-range correlations between the nucleons is introduced through the continuum Random Phase Approximation (CRPA) on top of the HF-SkE2 approach.

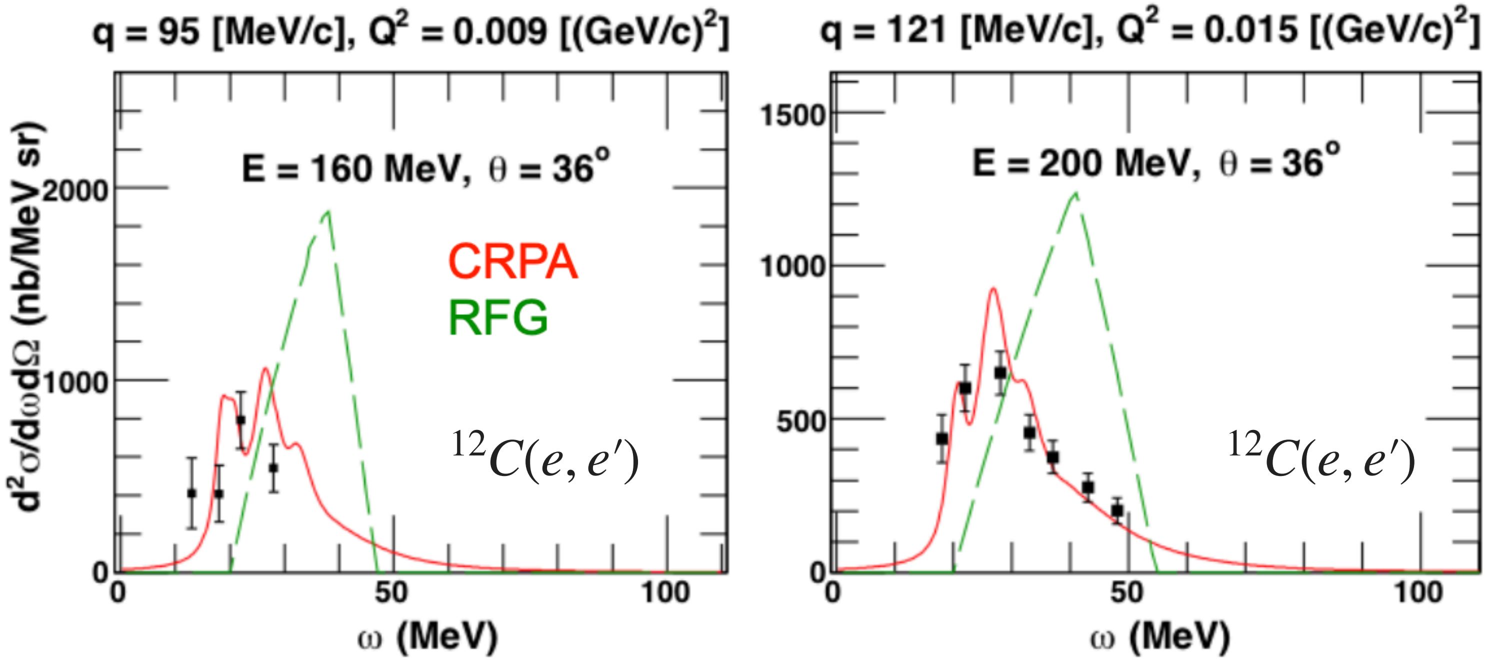
- CRPA effects are vital to describe the process where the nucleus can be excited to low-lying collective nuclear states.

- 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.

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







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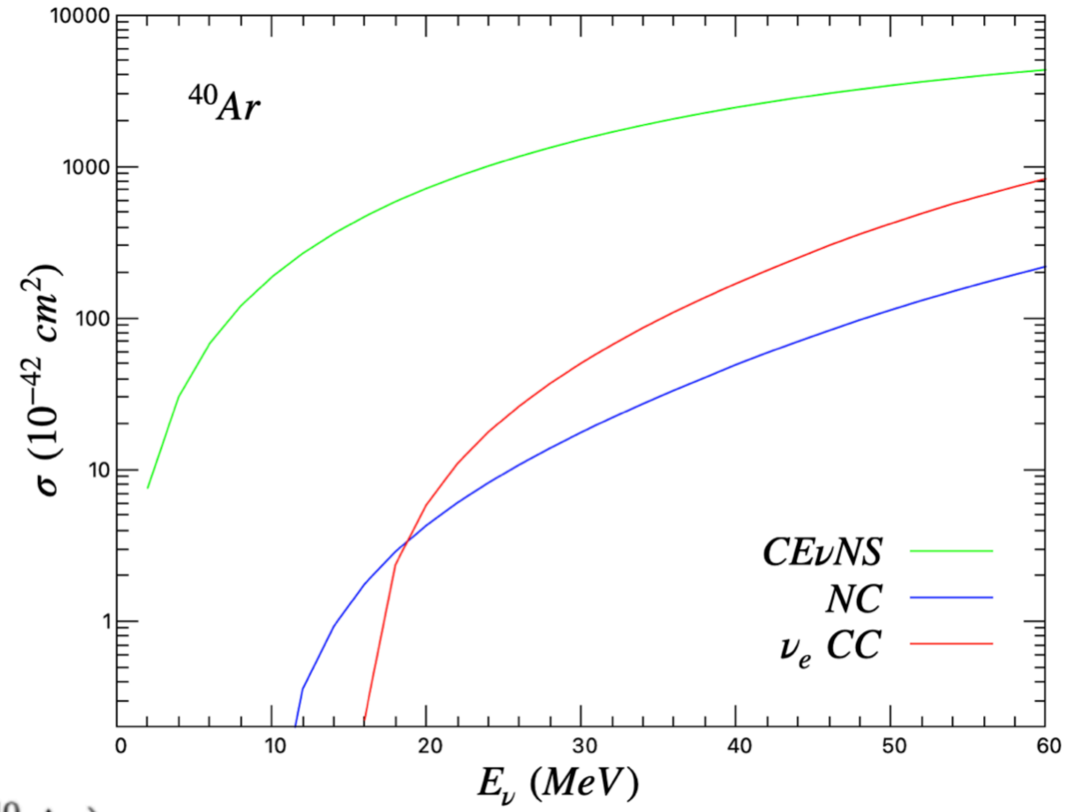
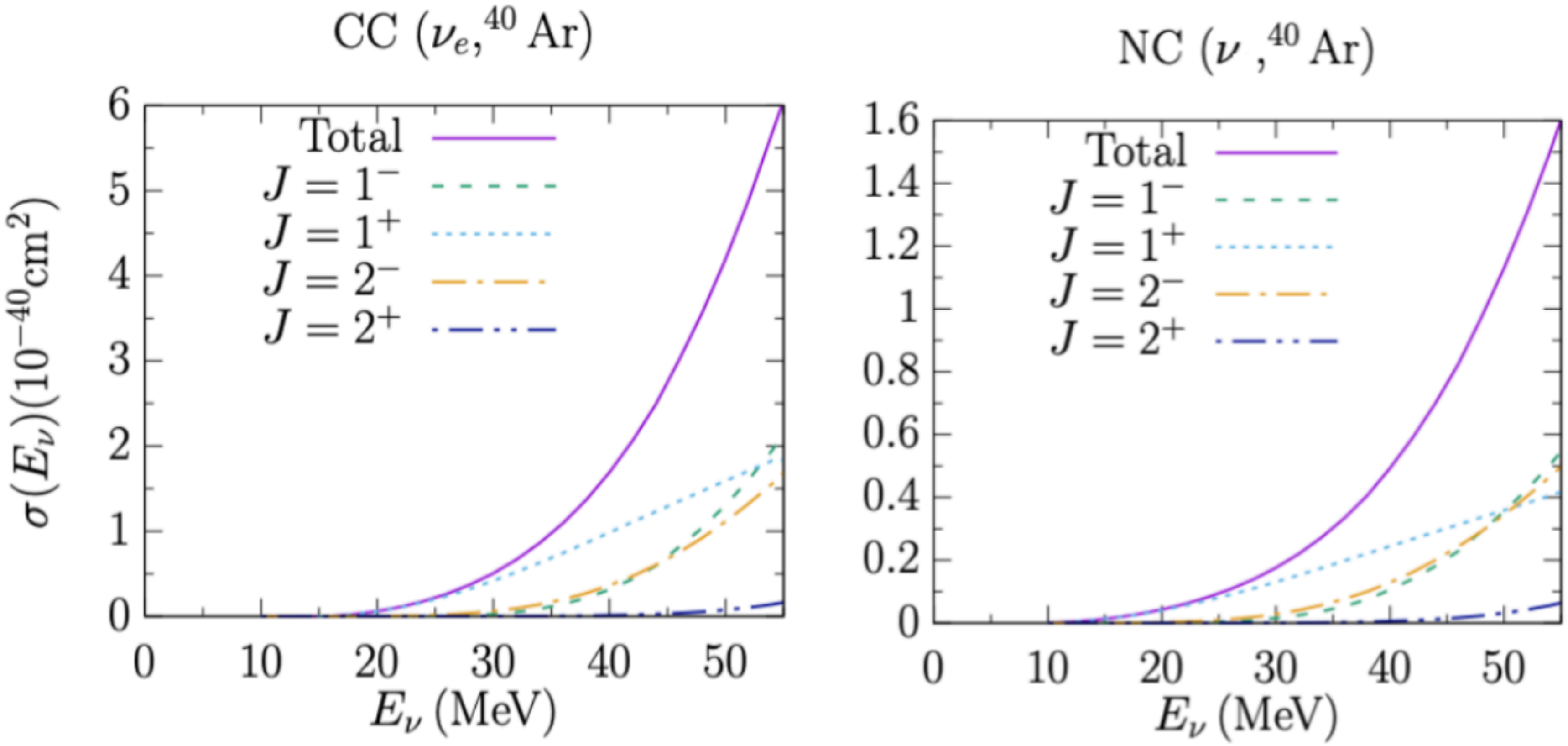




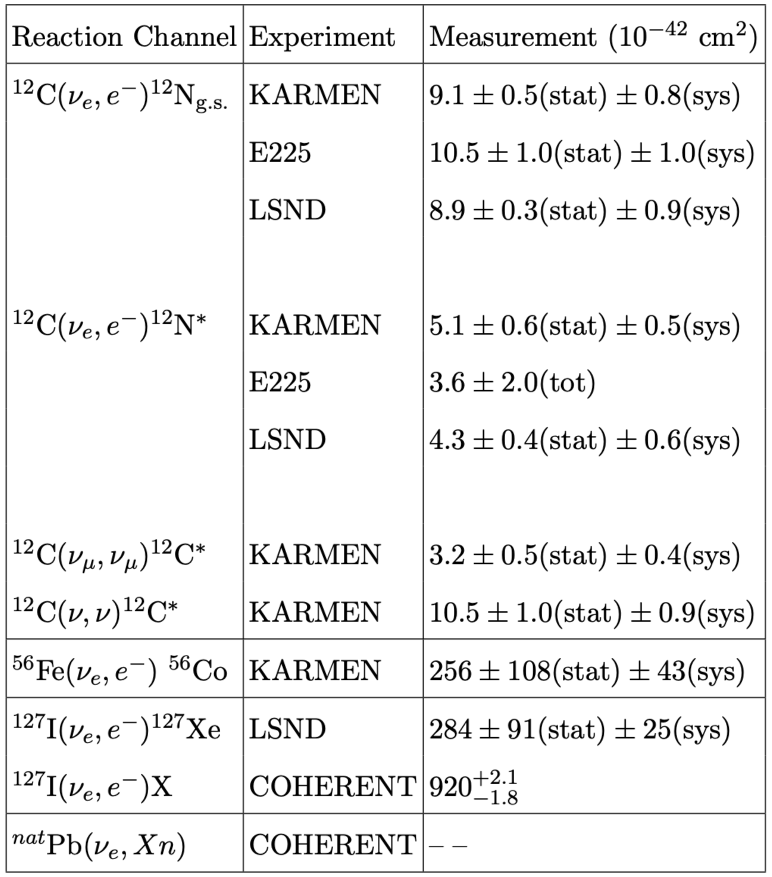
N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

10s of MeV Inelastic Neutrino-Nucleus Scattering: Uncertainty

- **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.

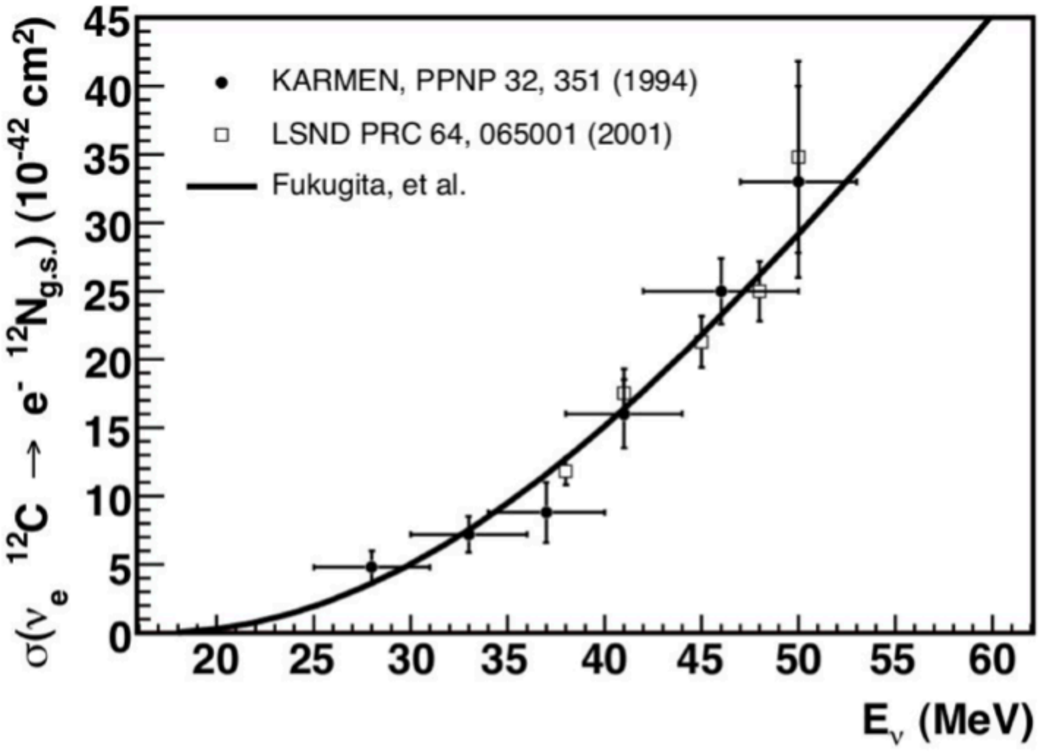


Reaction Channel	Experiment	Measurement (10^{-42} cm^2)
$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)
	E225	10.5 ± 1.0(stat) ± 1.0(sys)
	LSND	8.9 ± 0.3(stat) ± 0.9(sys)
$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)
	E225	3.6 ± 2.0(tot)
	LSND	4.3 ± 0.4(stat) ± 0.6(sys)
$^{12}\mathrm{C}(\nu_\mu, \nu_\mu)^{12}\mathrm{C}^*$	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)
$^{12}\mathrm{C}(\nu, \nu)^{12}\mathrm{C}^*$	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)
$^{56}\mathrm{Fe}(\nu_e, e^-)\ ^{56}\mathrm{Co}$	KARMEN	256 ± 108(stat) ± 43(sys)
$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	LSND	284 ± 91(stat) ± 25(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 (2023)

Past measurements on Carbon

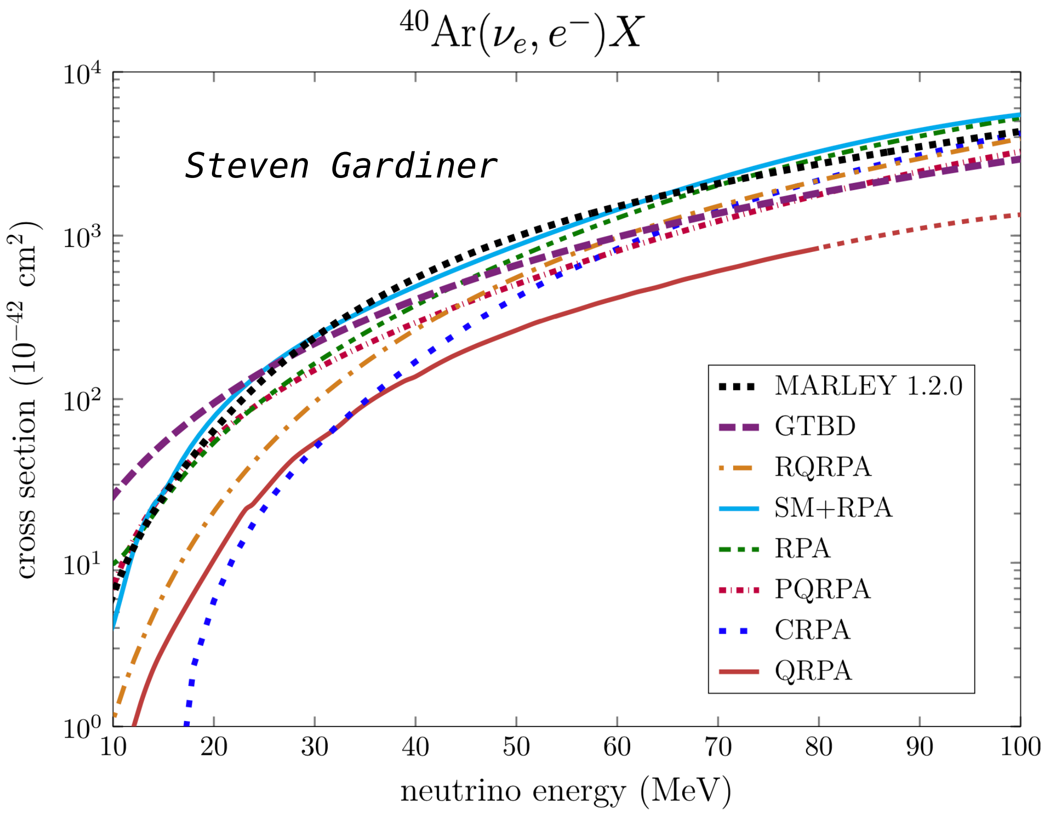


Rev. Mod. Phys. 84,1307 (2012)

10s of MeV Inelastic Neutrino-Nucleus Scattering: Uncertainty

- **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.

No measurements on Argon yet



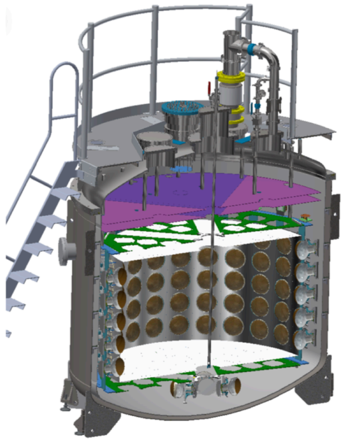
DUNE Collaboration, arXiv:2303.17007 [hep-ex]

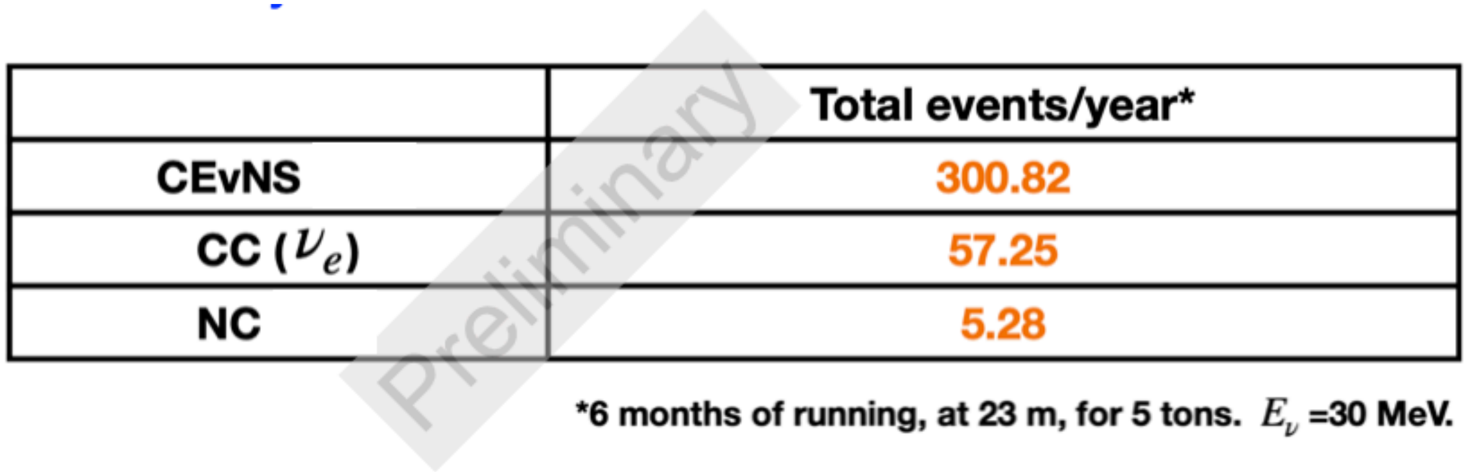
“Current understanding of $\sigma(E_\nu)$ is inadequate. Measuring ε energy release (other parameters) to 10% requires 5% (20%) knowledge of the cross section!

10s of MeV Inelastic Neutrino-Nucleus Scattering: Uncertainty

✦ **CEvNS experiments at pion-decay at rest facilities - COHERENT at ORNL and CCM at LANL, 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.

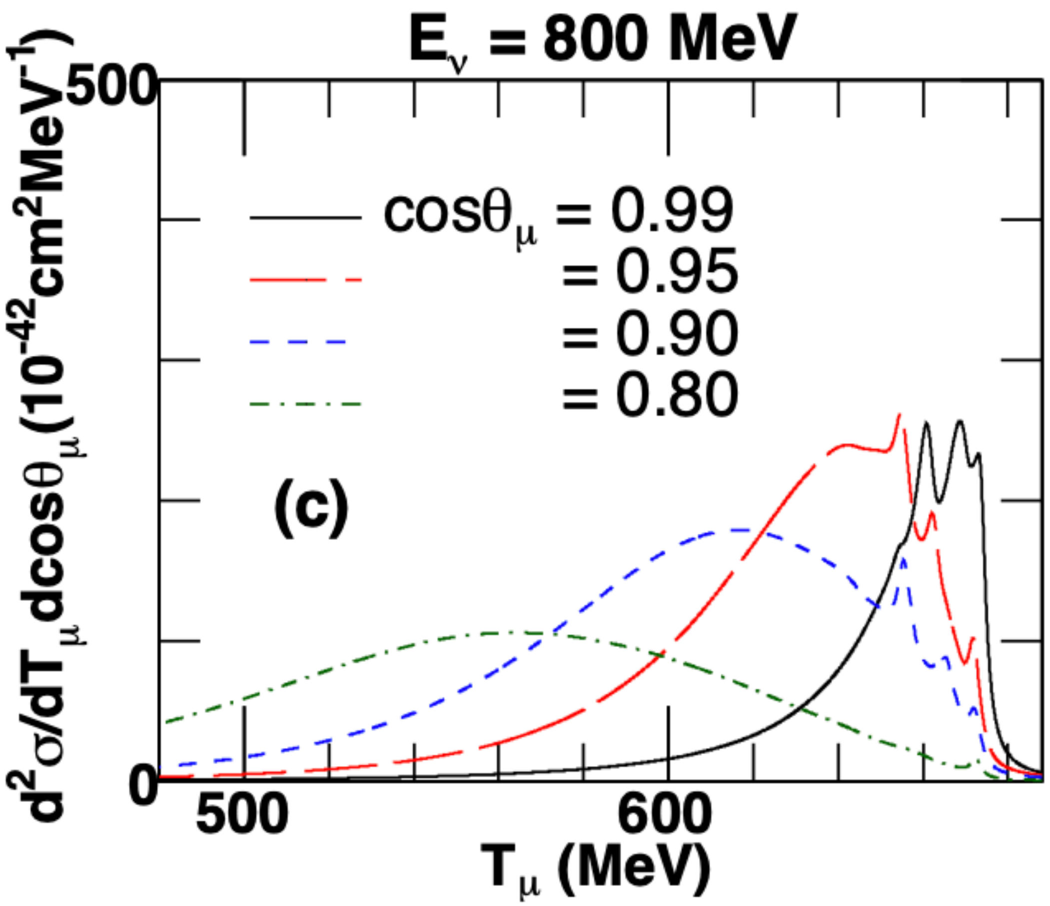
- **Electron Scattering experiment**

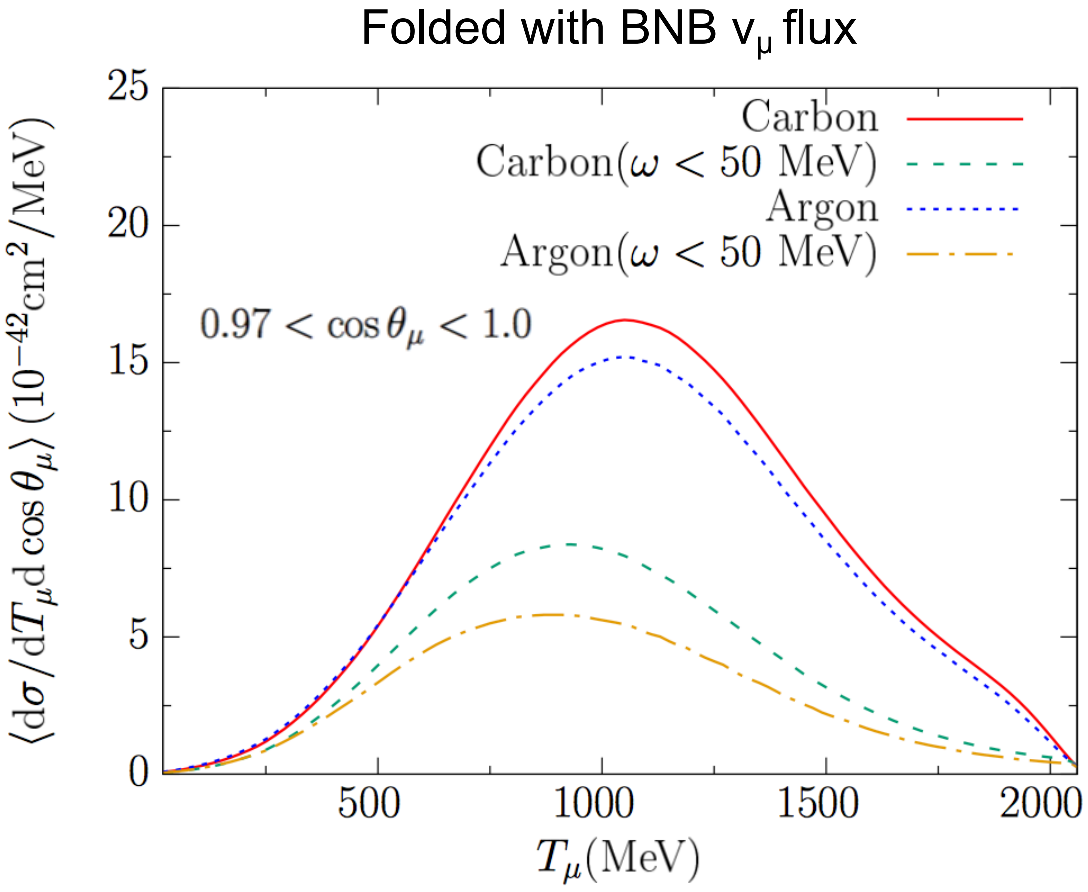
  - MAGIX Collaboration at MESA (Mainz):
  MESA, a new cw multi-turn energy recovery linac for precision particle and nuclear physics experiments with a beam energy range of 100-200 MeV is currently being built.

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.





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

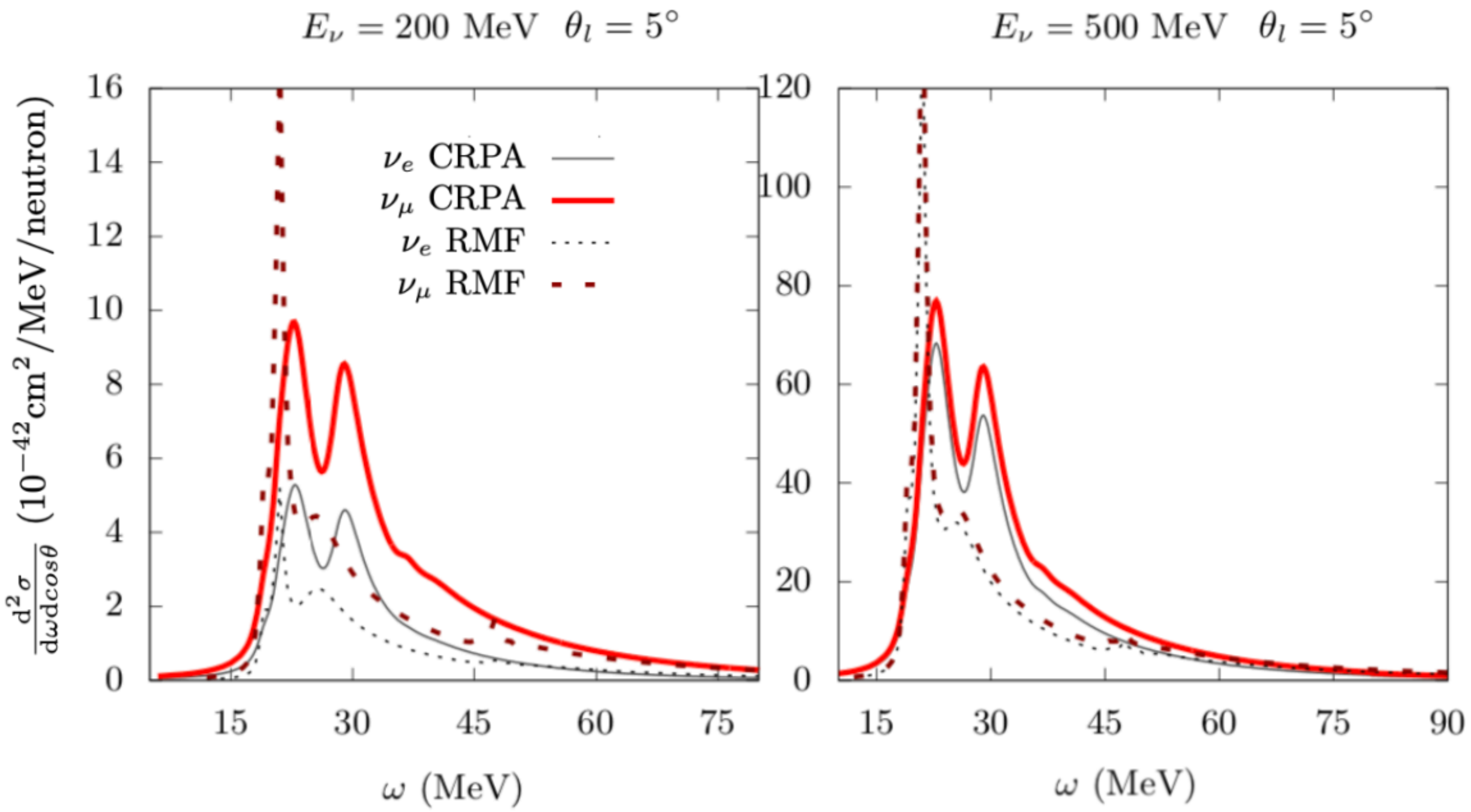
N. Van Dessel, N. Jachowicz, R. González-Jiménez, VP, T. Van Cuyck, Phys. Rev. C97, 044616 (2018).

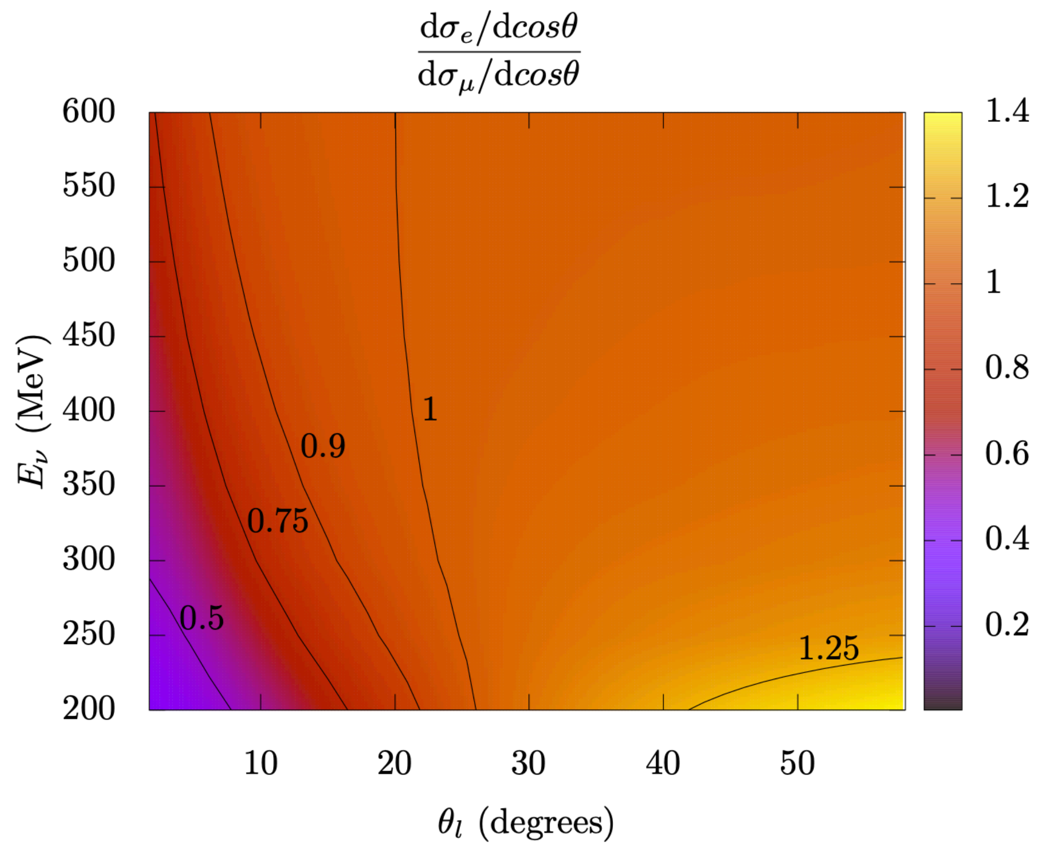
10s of MeV Physics: Effect on ν_e to ν_μ cross-sections

- 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.



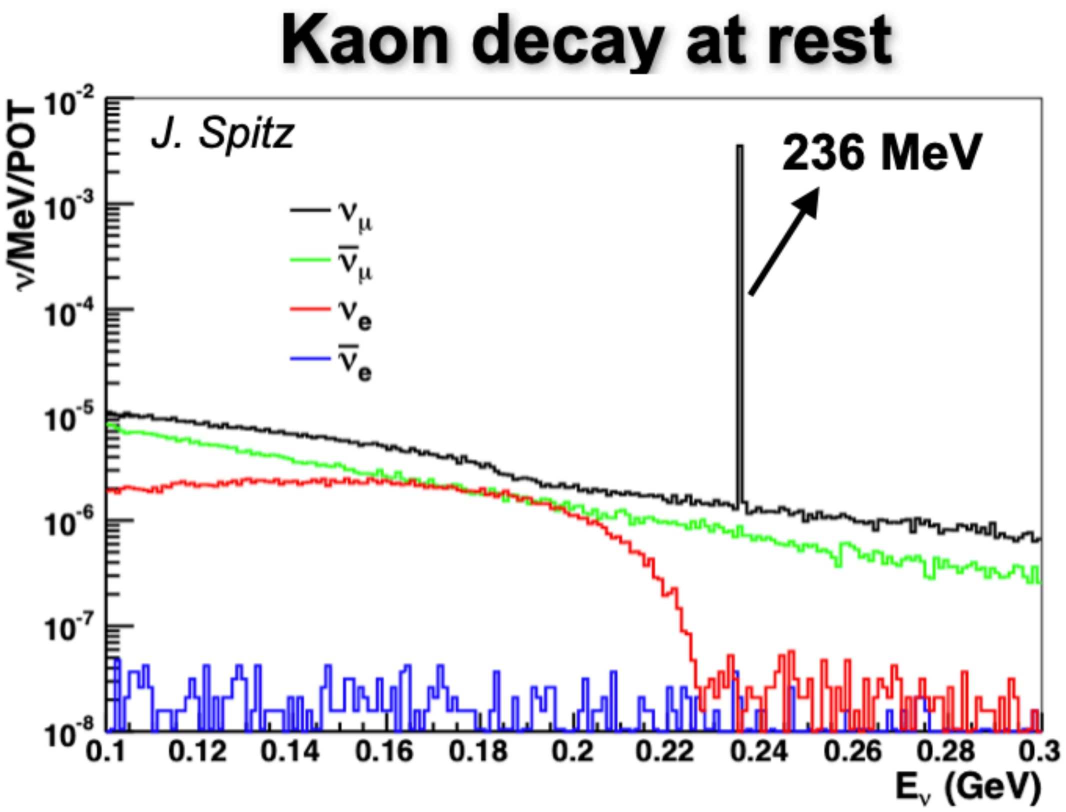


A. Nikolakopoulos, N. Jachowicz, N. Van Dessel, K. Niewczas, R. González-Jiménez, J. M. Udías, V. Pandey, Phys. Rev. Lett. 123, 052501 (2019).

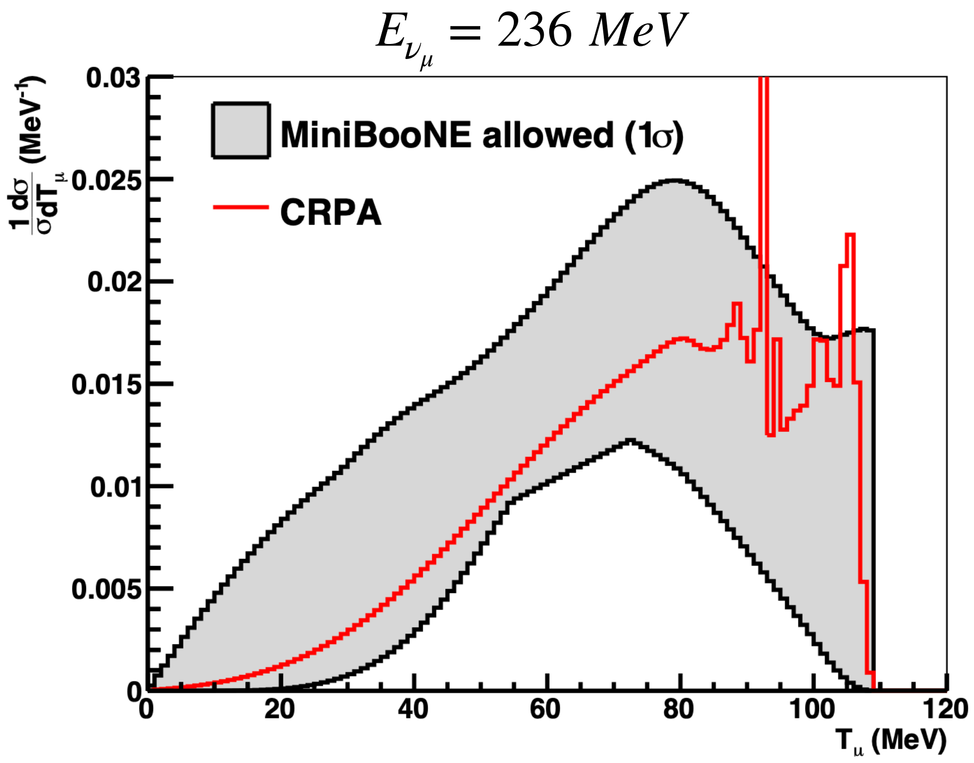
10s of MeV Physics in GeV-scale Neutrino Beams

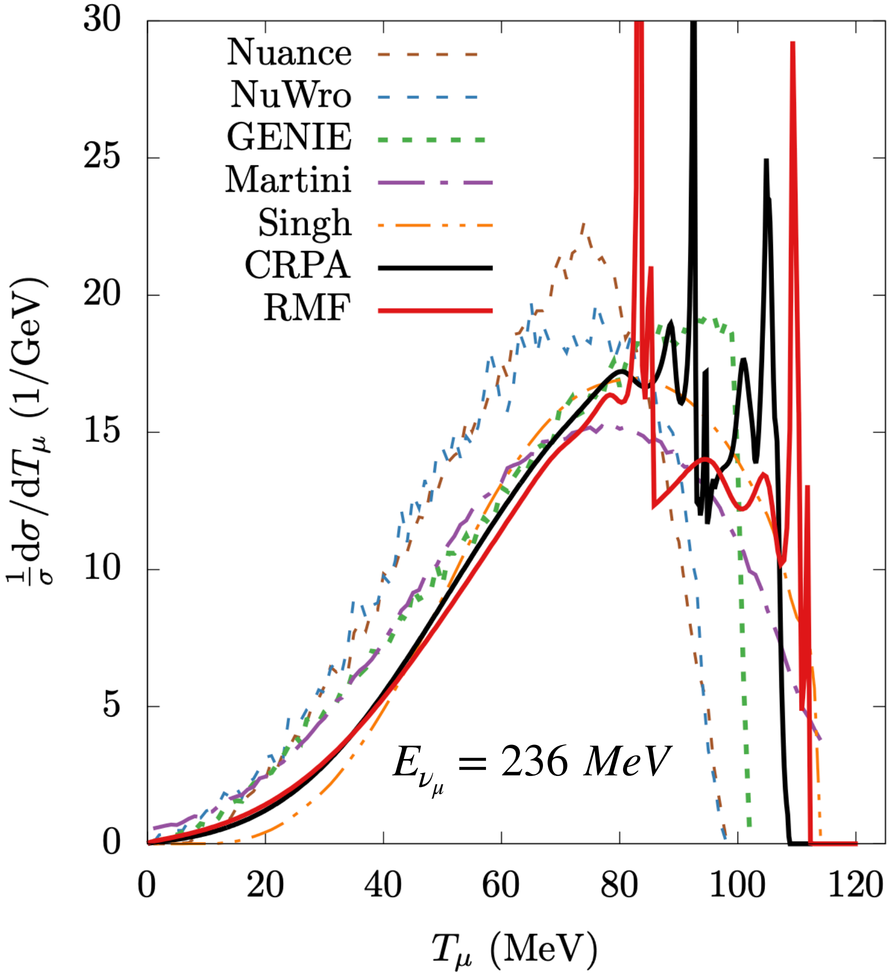
- Mono-energetic KDAR neutrinos at NuMI beam dump (FNAL) and at MLF (JPARC).

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



Kaon decay at rest





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

- Potential near future measurements: MicroBooNE and ICARUS (argon), JSNS^2 at J-PARC (carbon).

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

Neutrino-Nucleon Interactions

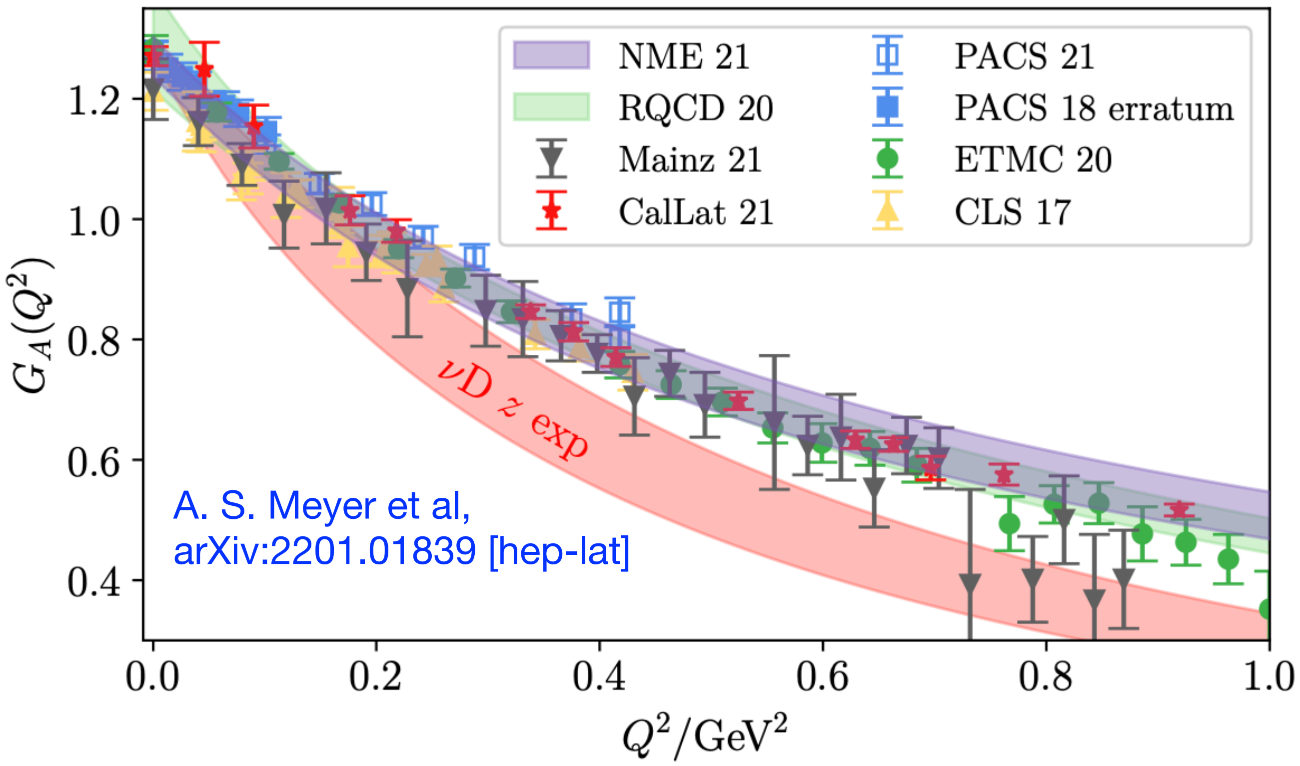
- **Axial Form Factor**
  - Historically parameterized as dipole form:

$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$

  - Modern description based on z-expansion

$$F_A(Q^2) \approx \sum_{k=0}^{k_{\max}} a_k \, z(Q^2)^k \qquad \sum_{k=0}^{k_{\max}} a_k z(0)^k = g_A$$

  - LQCD result higher at Q^2 > 0.3 GeV^2



A. S. Meyer et al,
arXiv:2201.01839 [hep-lat]

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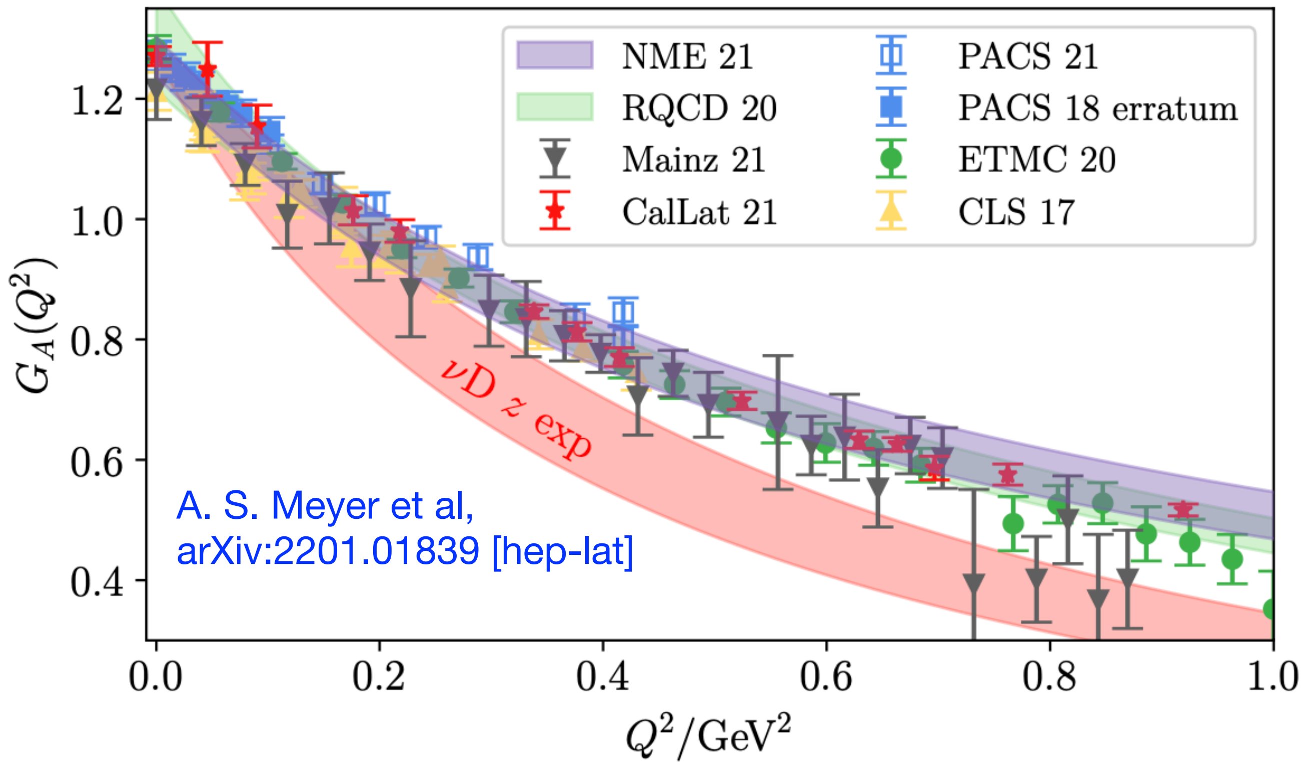


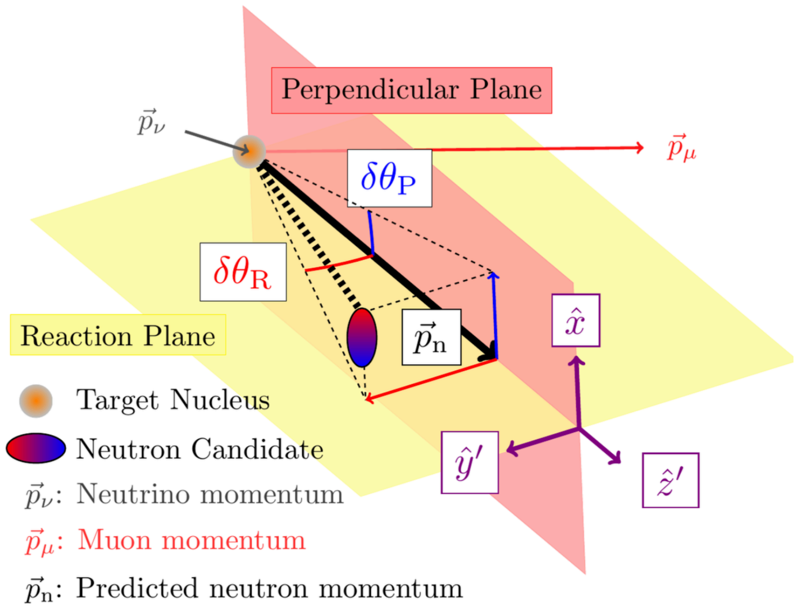
A. S. Meyer et al,
arXiv:2201.01839 [hep-lat]

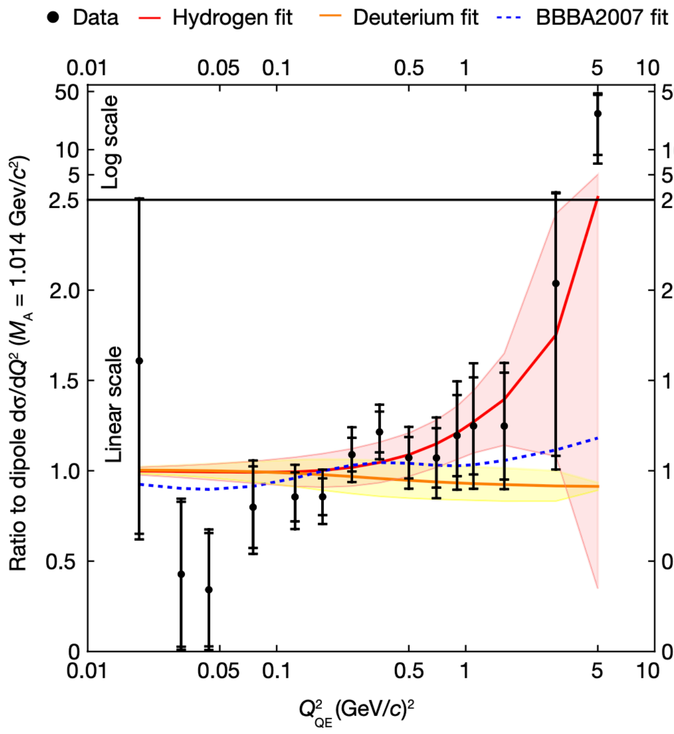
- **Recent MINERvA measurement**

$$\bar{\nu}_\mu p \rightarrow \mu^+ n$$

cross-section scattering off the hydrogen atom, using the plastic hydrocarbon target

Nature 614 (2023) 7946, 48-53





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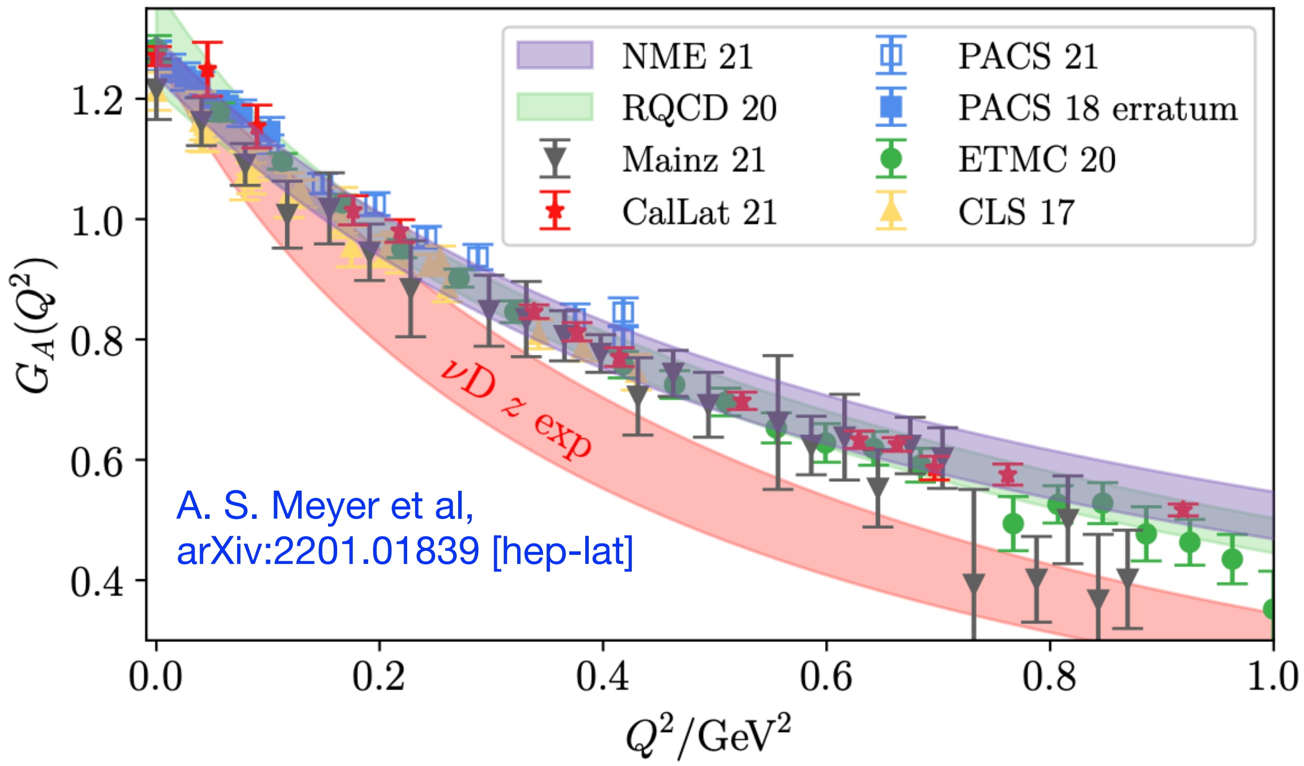

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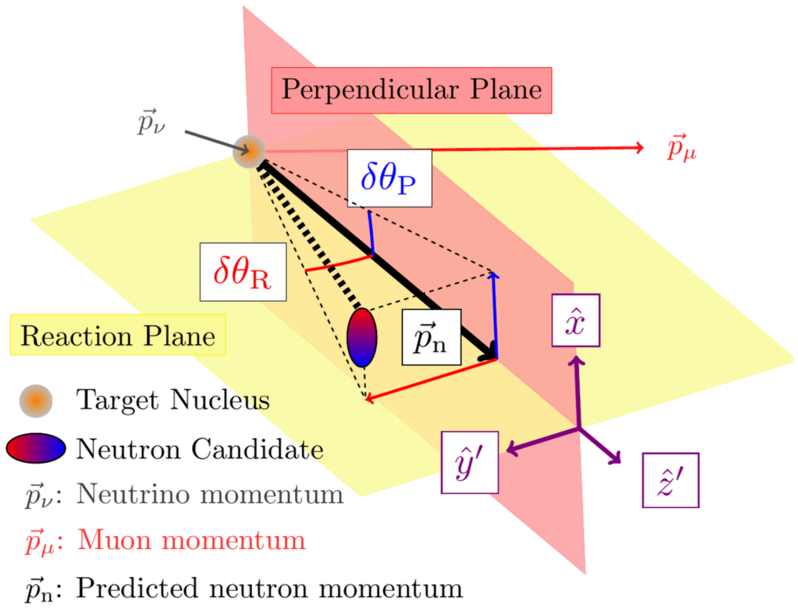
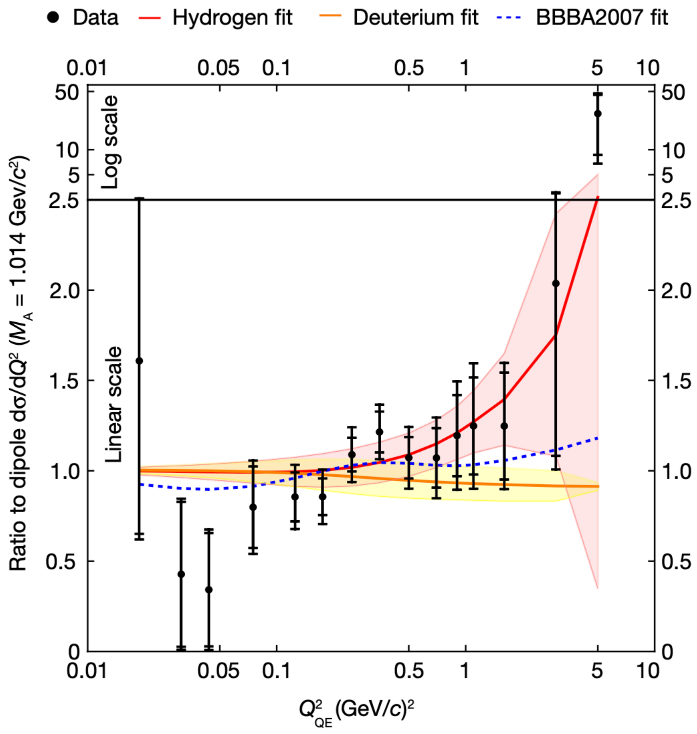
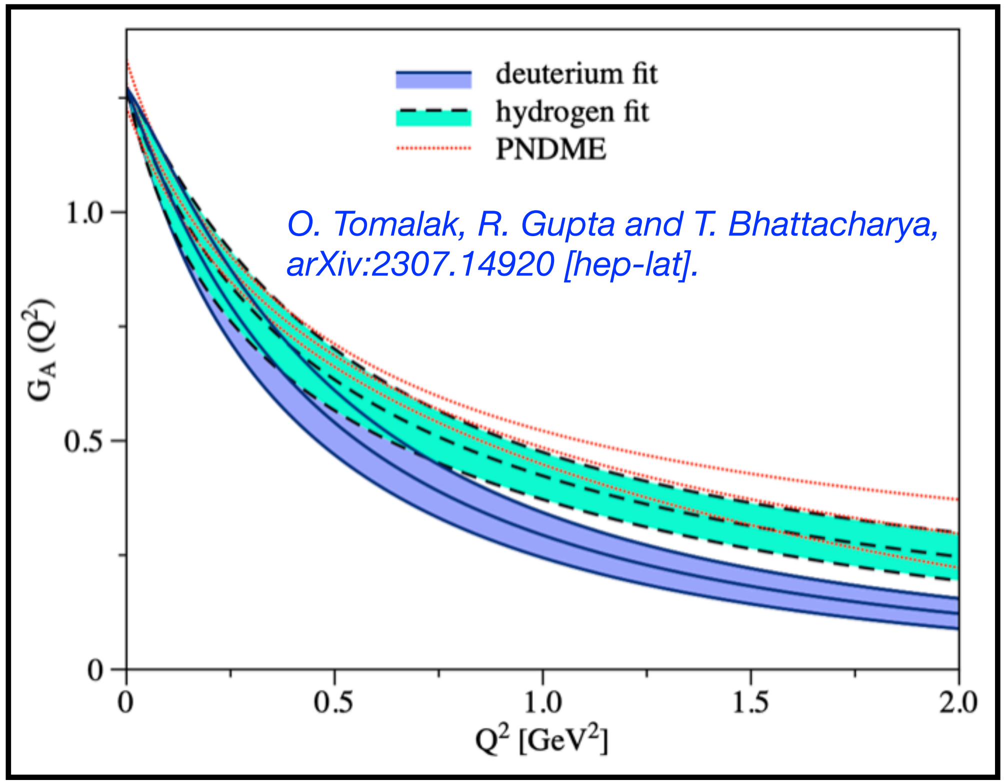


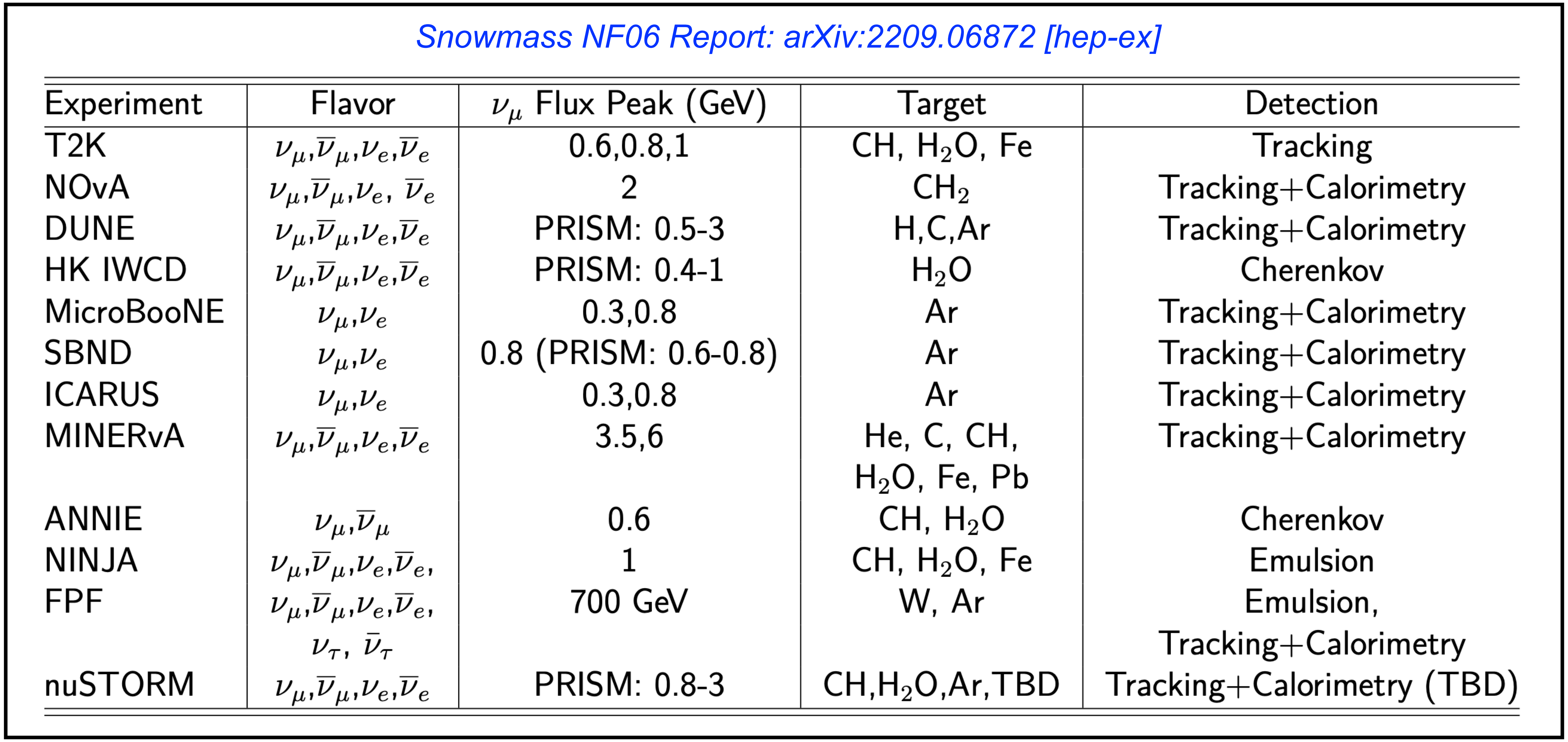




O. Tomalak, R. Gupta and T. Bhattacharya, arXiv:2307.14920 [hep-lat].

Constraining Neutrino-Nucleus Interactions: Neutrino Scattering Measurements

- In recent years, there have been a wide range of innovative cross-section measurements:
  - long-baseline experiments (T2K, NOvA), short-baseline experiments (MicroBooNE) and dedicated neutrino scattering measurements (MINERvA)
  - these measurements provide new information to develop interaction model theory and improve its implementation in event generators

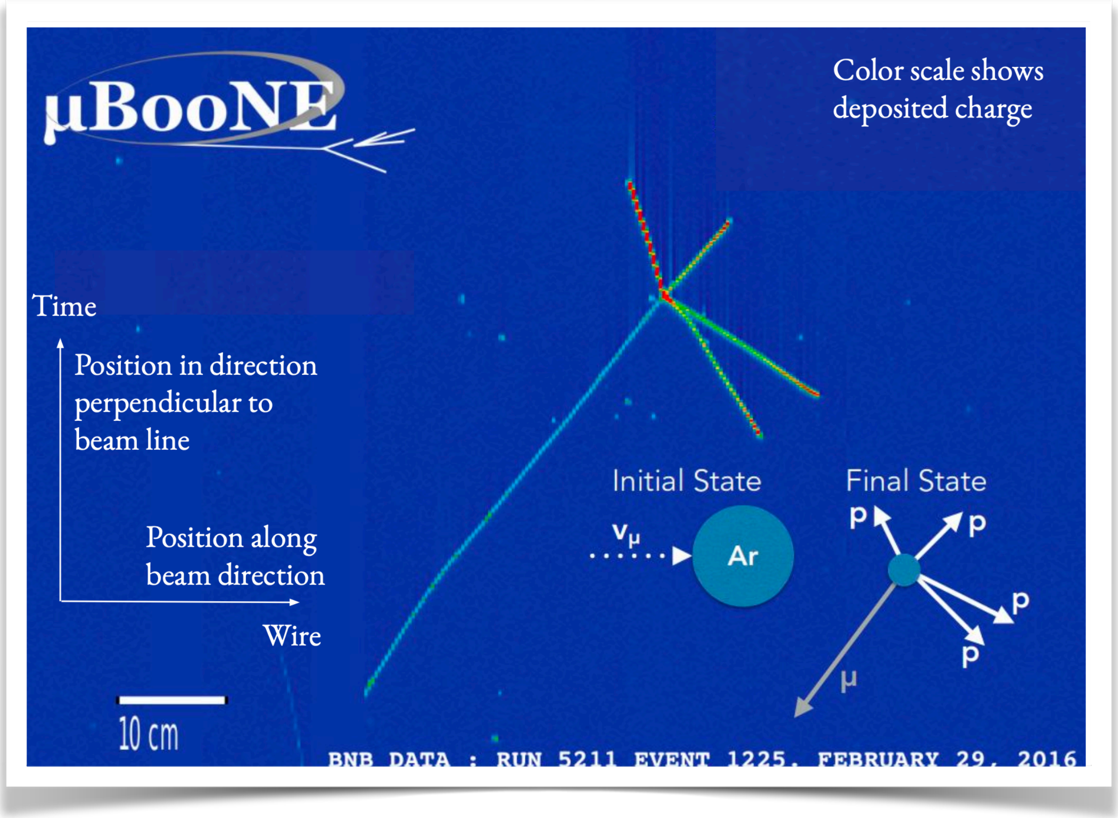


Snowmass NF06 Report: arXiv:2209.06872 [hep-ex]

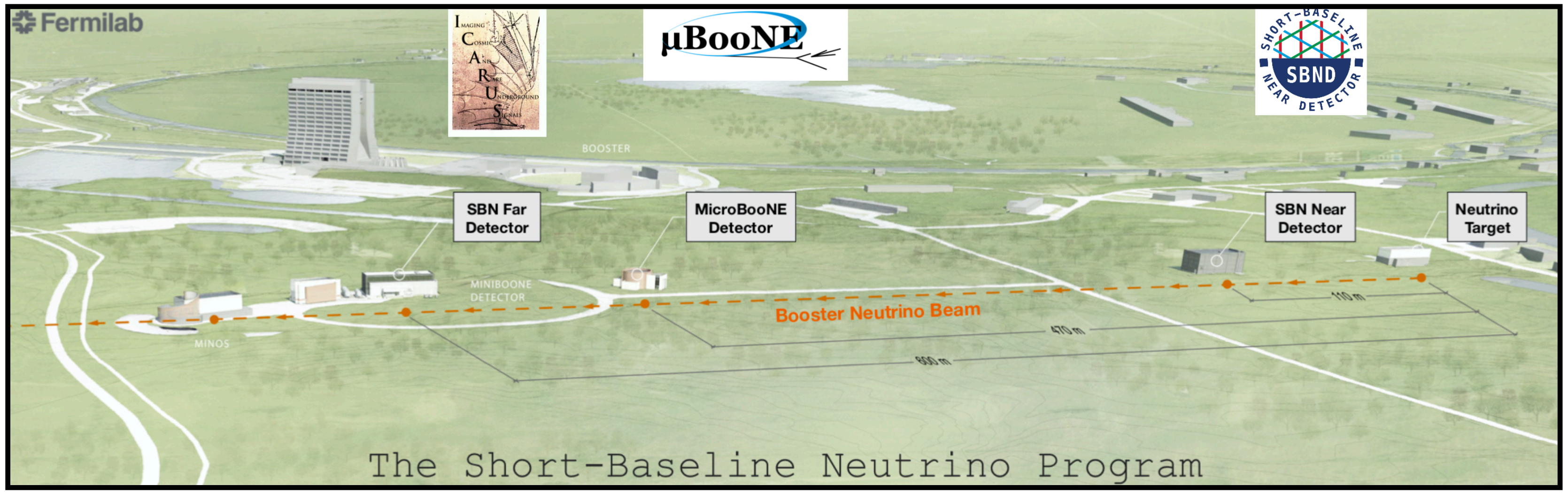
Experiment	Flavor	ν_μ Flux Peak (GeV)	Target	Detection
T2K	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$	0.6,0.8,1	CH, H_2O, Fe	Tracking
NOvA	ν_μ,$\overline{\nu}_\mu$,ν_e, $\overline{\nu}_e$	2	CH_2	Tracking+Calorimetry
DUNE	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$	PRISM: 0.5-3	H,C,Ar	Tracking+Calorimetry
HK IWCD	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$	PRISM: 0.4-1	H_2O	Cherenkov
MicroBooNE	ν_μ,ν_e	0.3,0.8	Ar	Tracking+Calorimetry
SBND	ν_μ,ν_e	0.8 (PRISM: 0.6-0.8)	Ar	Tracking+Calorimetry
ICARUS	ν_μ,ν_e	0.3,0.8	Ar	Tracking+Calorimetry
MINERvA	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$	3.5,6	He, C, CH, H_2O, Fe, Pb	Tracking+Calorimetry
ANNIE	ν_μ,$\overline{\nu}_\mu$	0.6	CH, H_2O	Cherenkov
NINJA	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$,	1	CH, H_2O, Fe	Emulsion
FPF	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$, ν_τ, $\bar{\nu}_\tau$	700 GeV	W, Ar	Emulsion, Tracking+Calorimetry
nuSTORM	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$	PRISM: 0.8-3	CH,H_2O,Ar,TBD	Tracking+Calorimetry (TBD)

Constraining Neutrino-Nucleus Interactions: Neutrino Scattering Measurements

- Liquid Argon Time Projection Chamber (LArTPC) detectors, utilized in current (SBN program) and future (DUNE) neutrino experiments, are expected to play a crucial role in constraining neutrino-argon interactions.



- Excellent spatial resolution
- Low detection thresholds
- Precise calorimetric information
- Powerful particle identification



- MicroBooNE is performing a detailed set of measurements with the BNB and NuMI beam.
- ICARUS has been taking data, and gearing up to cross section measurements primarily with NuMI beam.

Neutrino-argon Interactions in SBND

✦ **High-statistics and high-precision era with SBND!**

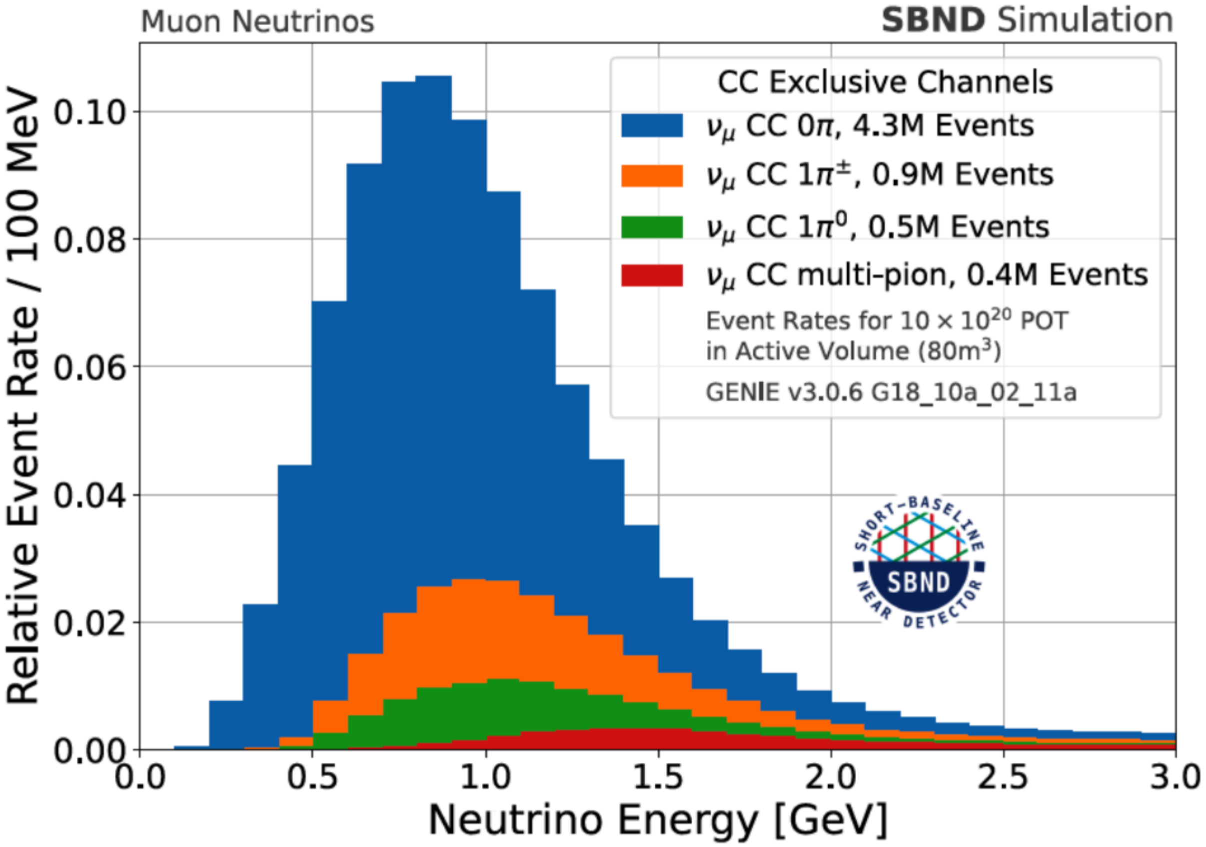
SBND started collecting BNB neutrino data this week!

- Due to its proximity to neutrino source, SBND expects approximately **2 million ν_μ CC and 15 thousand ν_e CC** interactions per year, with around
  7,000 total neutrino interactions observed per day

  - Every ~3 months, SBND will collect a dataset equivalent to the full MicroBooNE BNB five-year run
- SBND will record ~20–30x more neutrino–argon interactions than is currently available

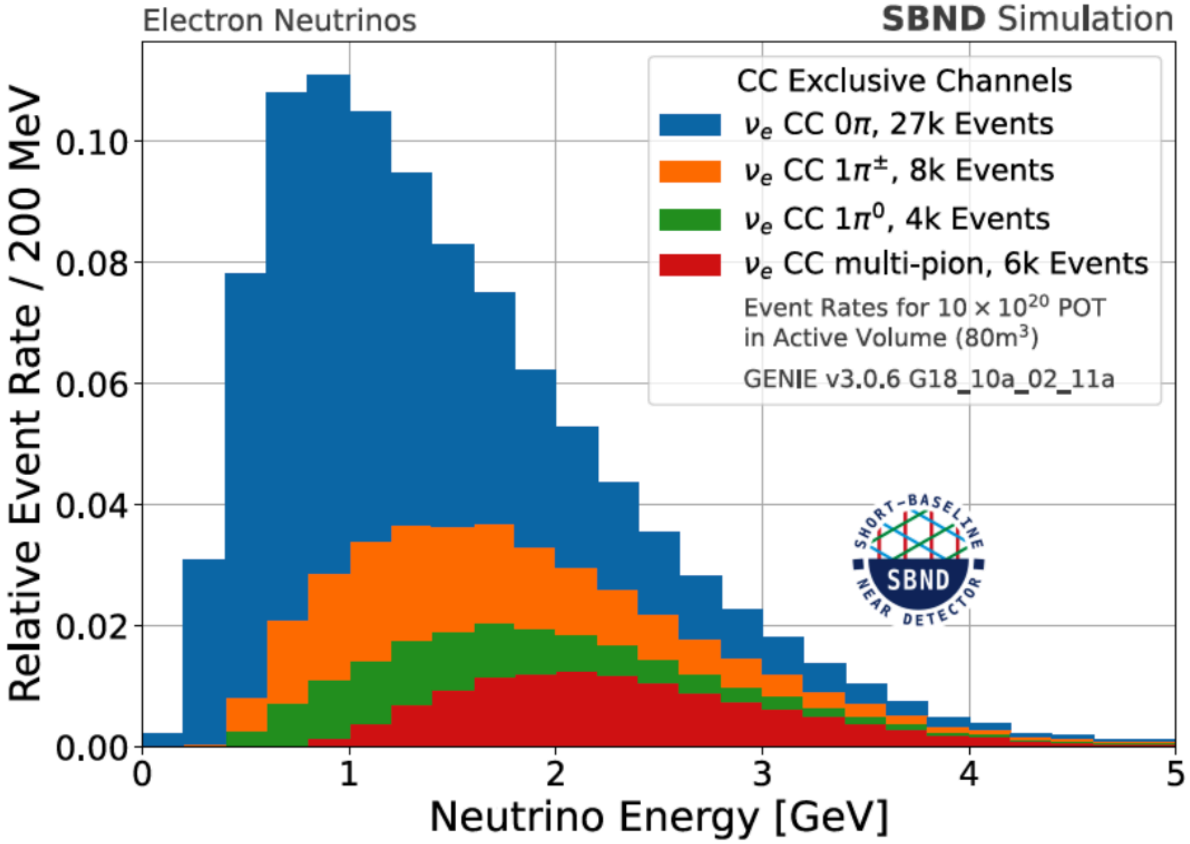
$\nu_\mu - {}^{40}Ar$

2M ν_μ CC events in 1 year



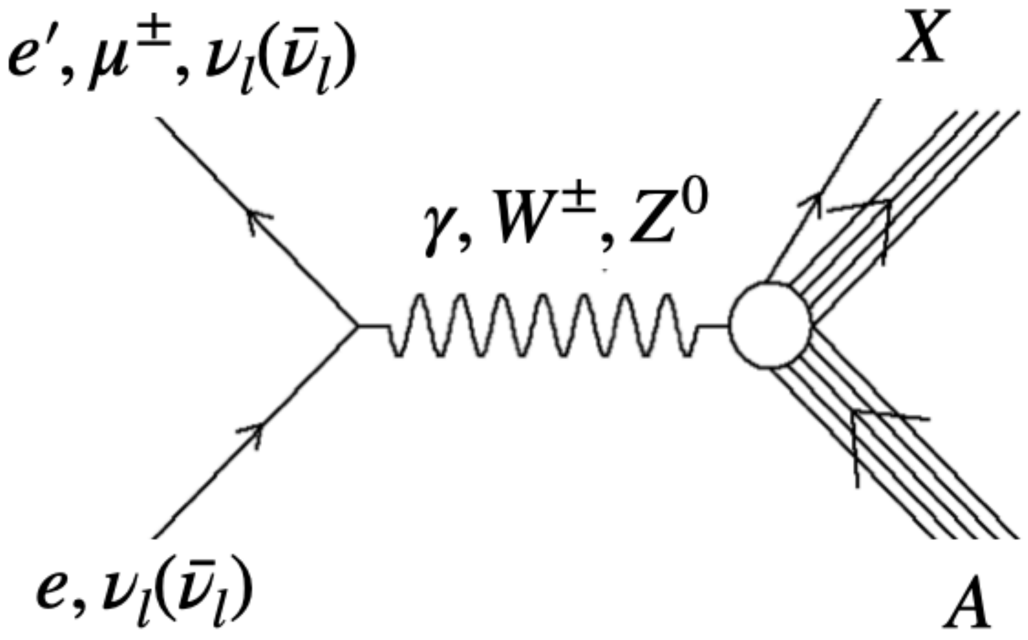
$\nu_e - {}^{40}Ar$

15k ν_e CC events in 1 year



Electron Scattering Measurements

Connections Between Electron and Neutrino Scattering



- **Cross Section:**

$$\sigma \propto L^{\mu\nu} \, R_{\mu\nu}$$

- Nuclear Response:

$$R_{\mu\nu} = \sum_f < \psi | J^\dagger_\mu(q) | \psi_f > < \psi_f | J_\nu(q) | \psi > \delta(E_0 + \omega - E_f)$$

- $e - A$ **Cross Section:**

$$\sigma_e \propto v_e^L R^L + v_e^T R^T$$

- $\nu - A$ **Cross Section:**

$$\sigma_\nu \propto v_\nu^M R^M + v_\nu^L R^L + 2 v_\nu^{ML} R^{ML} + v_\nu^T R^T \pm 2 v_\nu^{TT} R^{TT}$$

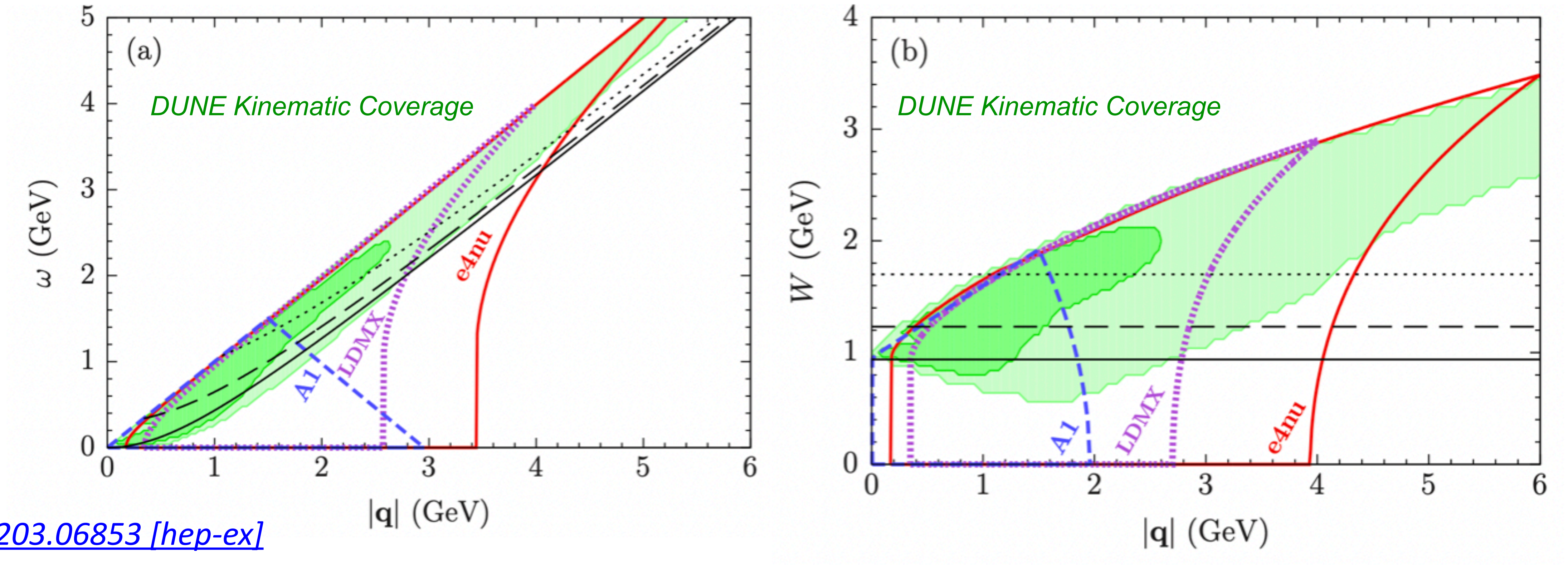
- Initial nucleus description is same
- Coupling at the vertex is Vector for electron and Vector+Axial for neutrinos
  - The vector current is conserved (CVC) between electromagnetic and weak interactions
- Final state interactions effects are same

Advantage of electron beams:

- Mono-energetic beams
- Large statistics
- High precision

Electron Scattering: Current and Planned Experiments

Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	$E_e = 2.222$ GeV $15.5° \leq \theta_e \leq 21.5°$ $-50.0° \leq \theta_p \leq -39.0°$	Ar, Ti Al, C	(e, e') e, p in the final state
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	$E_e = 1, 2, 4, 6$ GeV $\theta_e > 5°$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state
LDMX (SLAC) (Planned)	$E_e = 4.0, 8.0$ GeV $\theta_e < 40°$	W, Ti, Al	(e, e') e, p, n, π, γ in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	50 MeV $\leq E_e \leq 1.5$ GeV $7° \leq \theta_e \leq 160°$	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
A1 (eALBA) (Planned)	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e, e')



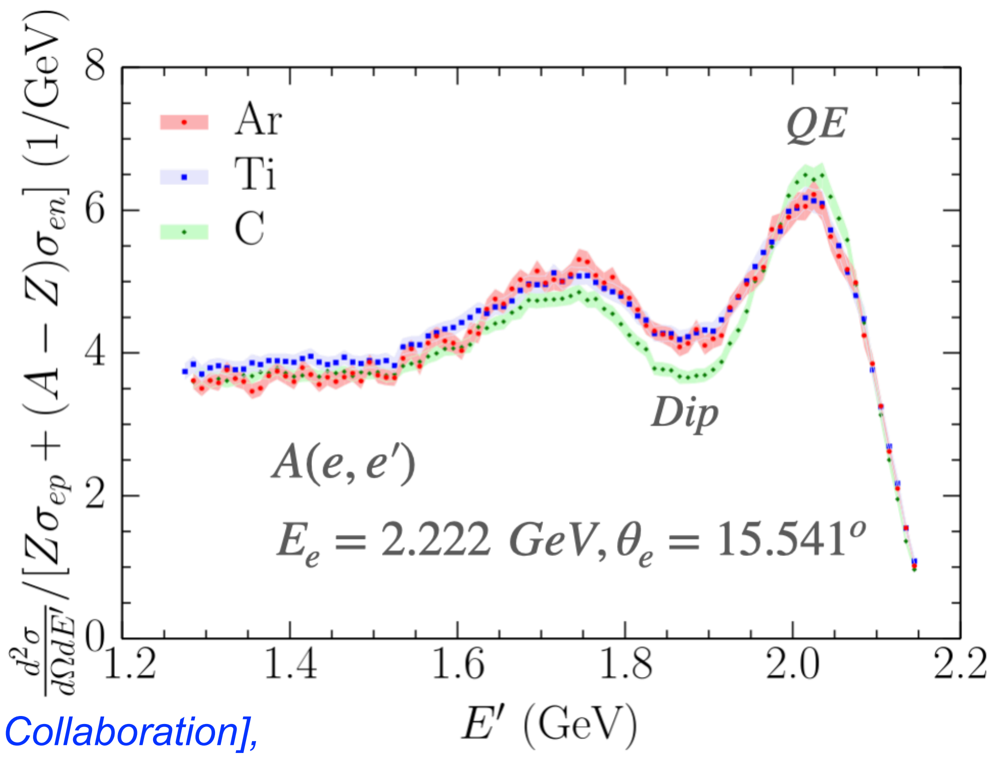
arXiv:2203.06853 [hep-ex]

*overlaid on the CC $\nu_\mu - Ar$ event distribution expected in the DUNE near detector according to GENIE 3.0.6

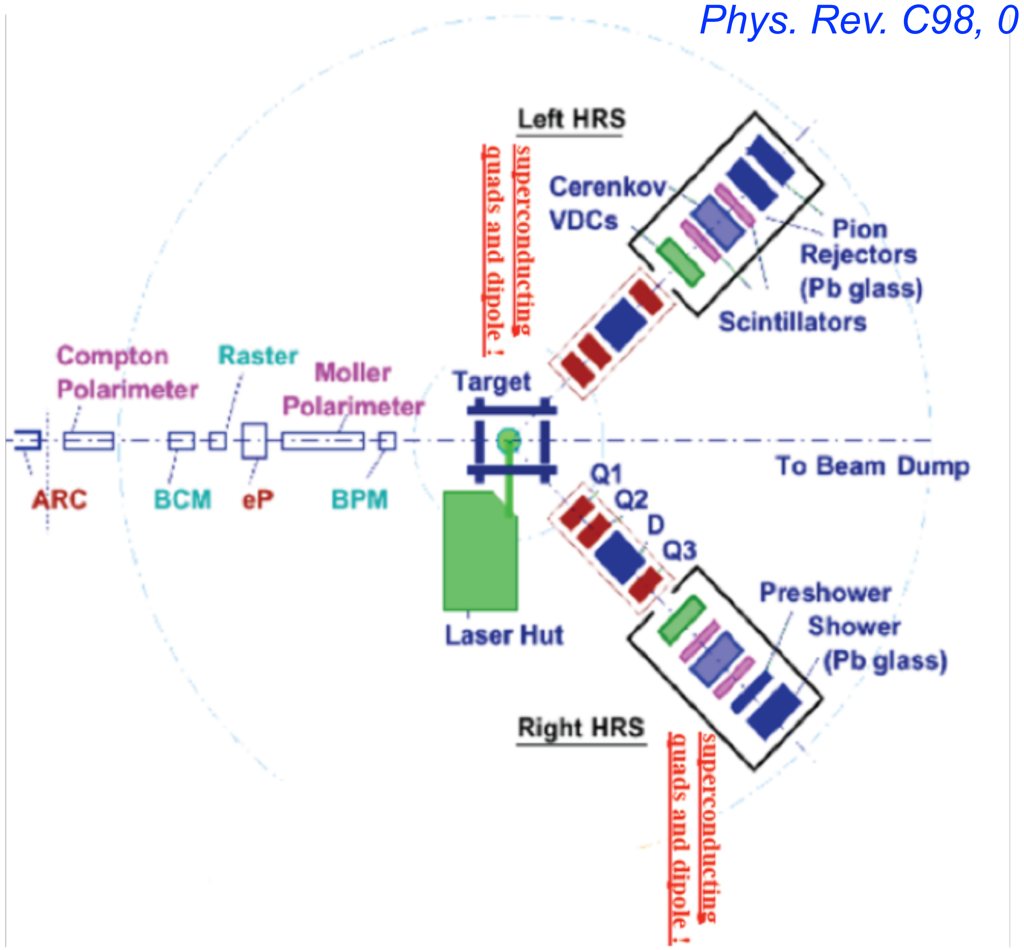
Electron Scattering Measurements

- **E12-14-012, JLab Hall A**

	E'_e (GeV)	θ_e (deg)	$\lvert\mathbf{p}'\rvert$ (MeV)	$\theta_{p'}$ (deg)	$\lvert\mathbf{q}\rvert$ (MeV)	p_m (MeV)	E_m (MeV)
kin1	1.777	21.5	915	−50.0	865	50	73
kin2	1.716	20.0	1030	−44.0	846	184	50
kin3	1.799	17.5	915	−47.0	741	174	50
kin4	1.799	15.5	915	−44.5	685	230	50
kin5	1.716	15.5	1030	−39.0	730	300	50

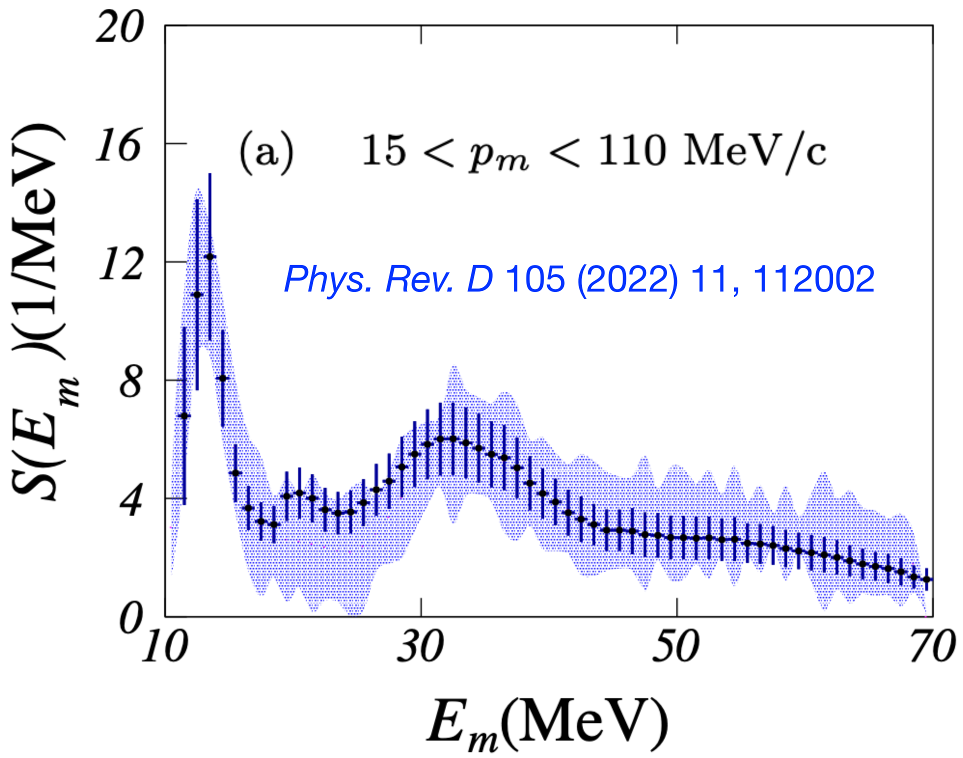


H. Dai, M. Murphy, V. Pandey et al. [JLab Hall A Collaboration], Phys. Rev. C98, 014617 (2018)



$(e, e'p)$ cross section within PWIA approach

$$\frac{d\sigma_A}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$



Phys. Rev. D 105 (2022) 11, 112002

Summary

- Neutrino interaction uncertainties constitute one of the largest source of uncertainty in the accelerator-based neutrino program, for both low-energy (tens of MeV) and medium-energy (few GeV) neutrino sources.

- Dedicated cross-community efforts and sustained dedicated efforts are needed in order to achieve global constraints on neutrino-nucleus interaction physics.

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

NEUTRINOS ARE...

FUNDAMENTAL

Neutrinos are fundamental particles, which means that—like quarks and photons and electrons—they cannot be broken down into any smaller bits.

ABUNDANT

Of all particles with mass, neutrinos are the most abundant in nature. They're also some of the least interactive. Roughly a thousand trillion of them pass harmlessly through your body every second.

ELUSIVE

Neutrinos are difficult but not impossible to catch. Scientists have developed many different types of particle detectors to study them.

OSCILLATING

Neutrinos come in three types, called flavors. There are electron neutrinos, muon neutrinos and tau neutrinos. One of the strangest aspects of neutrinos is that they don't pick just one flavor and stick to it. They oscillate between all three.

LIGHTWEIGHT

Neutrinos weigh almost nothing, and they travel close to the speed of light. Neutrino masses are so small that so far no experiment has succeeded in measuring them. The masses of other fundamental particles come from the Higgs field, but neutrinos might get their masses another way.

DIVERSE

Neutrinos are created in many processes in nature. They are produced in the nuclear reactions in the sun, particle decays in the Earth, and the explosions of stars. They are also produced by particle accelerators and in nuclear power plants.

MYSTERIOUS

Neutrinos are mysterious. Experiments seem to hint at the possible existence of a fourth type of neutrino: a sterile neutrino, which would interact even more rarely than the others.

VERY MYSTERIOUS

Scientists also wonder if neutrinos are their own antiparticles. If they are, they could have played a role in the early universe, right after the big bang, when matter came to outnumber antimatter just enough to allow us to exist.

Interested in how the universe works? Read *symmetry*, an online magazine about particle physics and its connections to life and other areas of science. Published by Fermi National Accelerator Laboratory and SLAC National Accelerator Laboratory. symmetrymagazine.org