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

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Brookhaven National Laboratory, February 4, 2021

Outline

- ✦ Neutrinos: the portal to new frontiers in physics
- ✦ Neutrino interactions: a multi-scale, multi-process problem
- ✦ Tackling neutrino interactions

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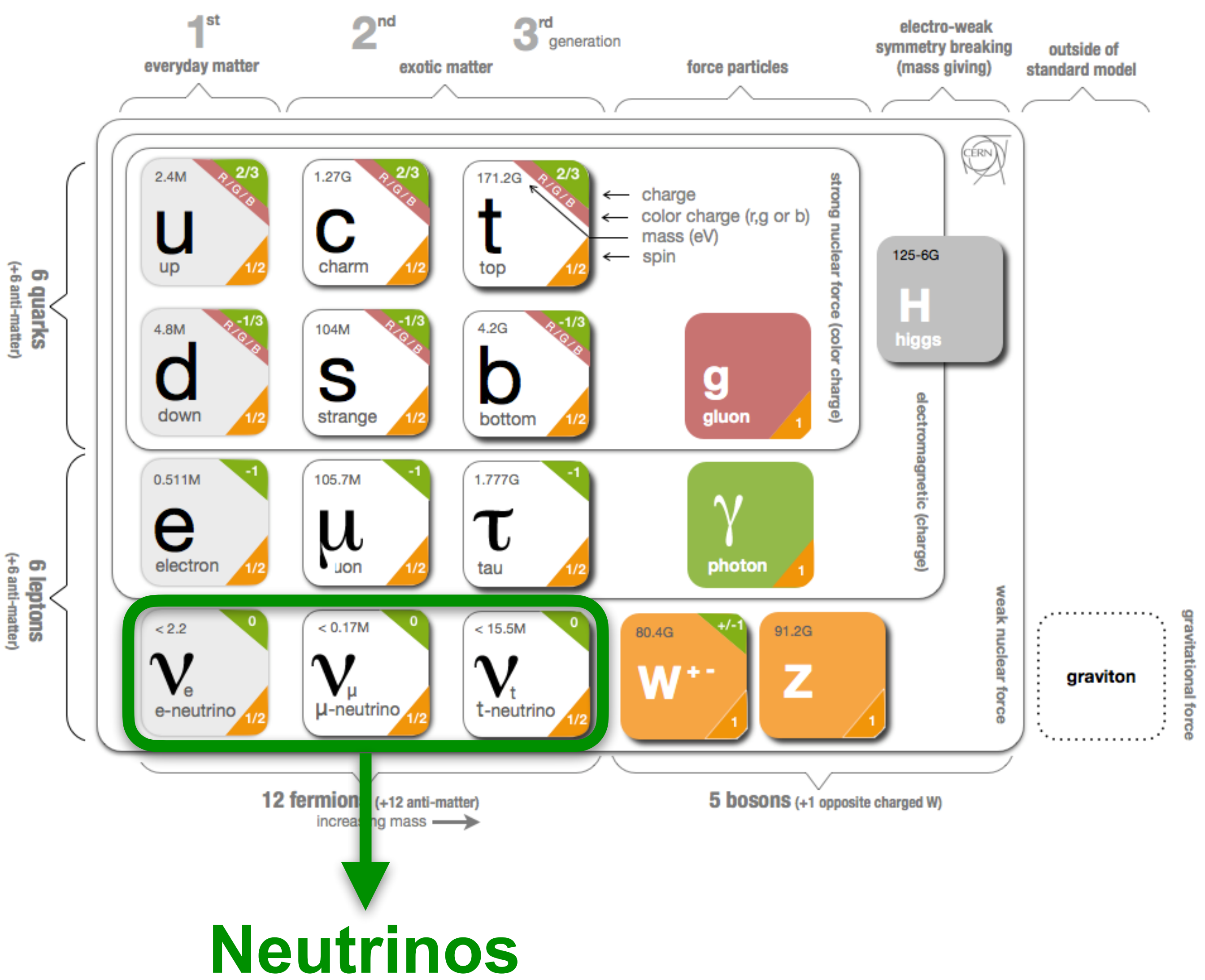
- ✦ **Neutrinos: the portal to new frontiers in physics**
- ✦ Neutrino interactions: a multi-scale, multi-process problem
- ✦ Tackling neutrino interactions

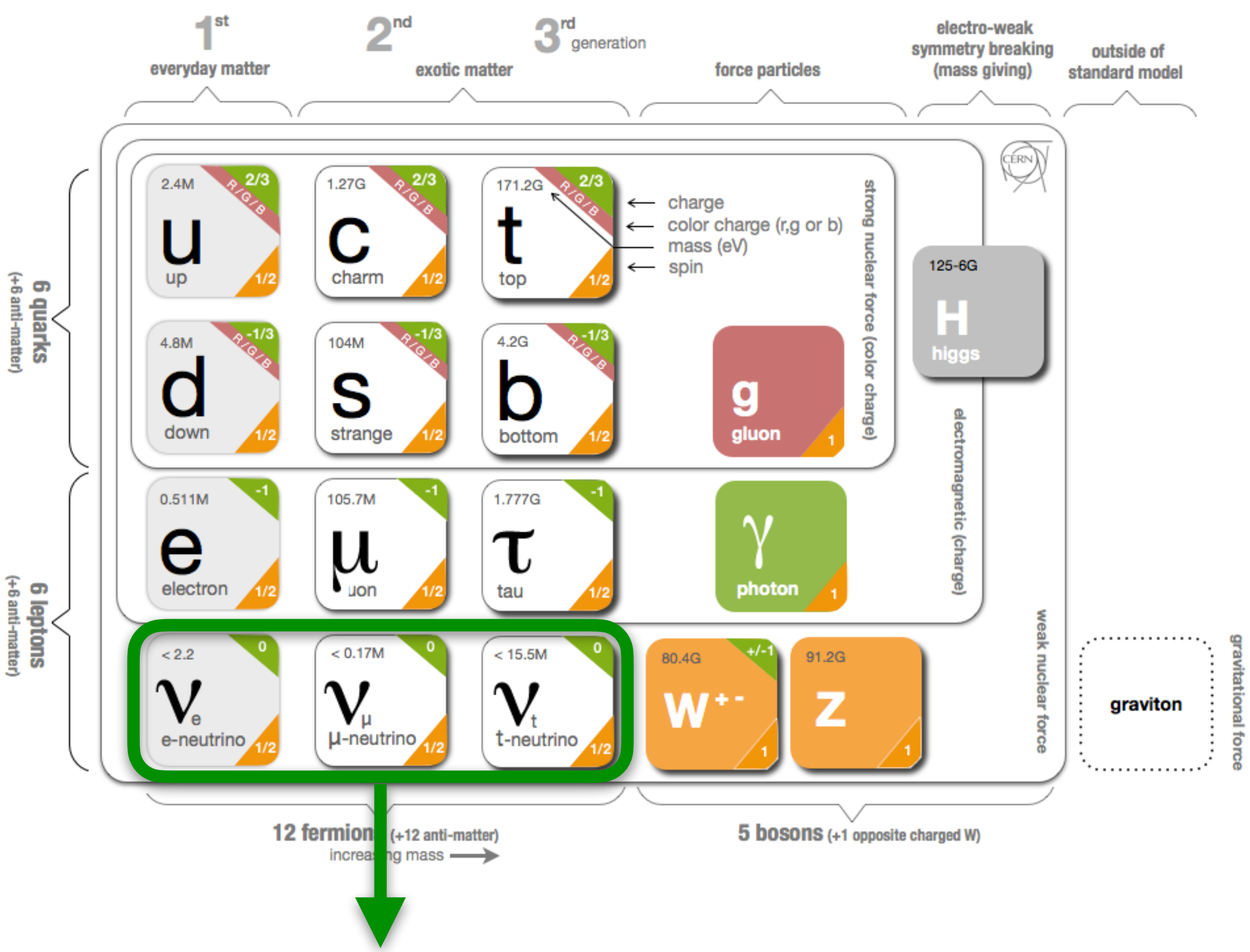
Standard Model and Neutrinos

Standard Model



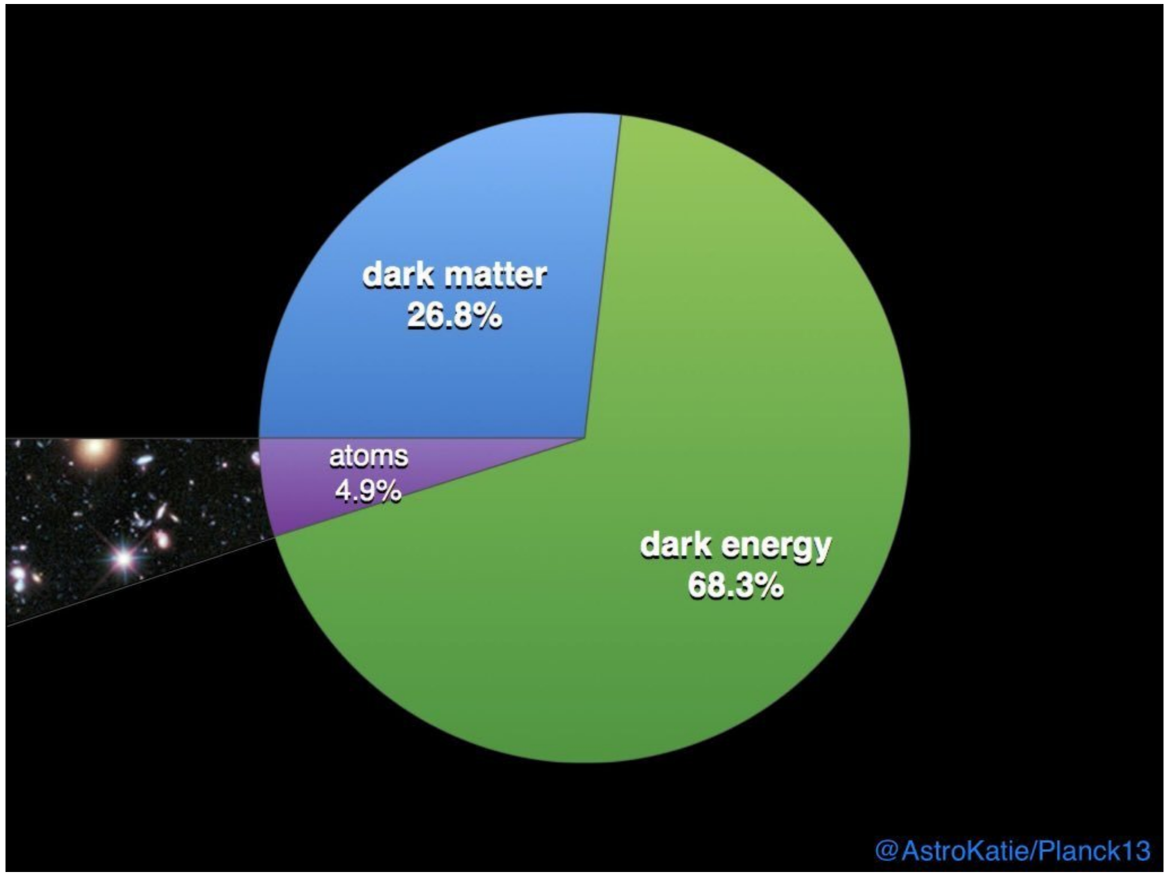
Standard Model and Neutrinos

Standard Model



Neutrinos

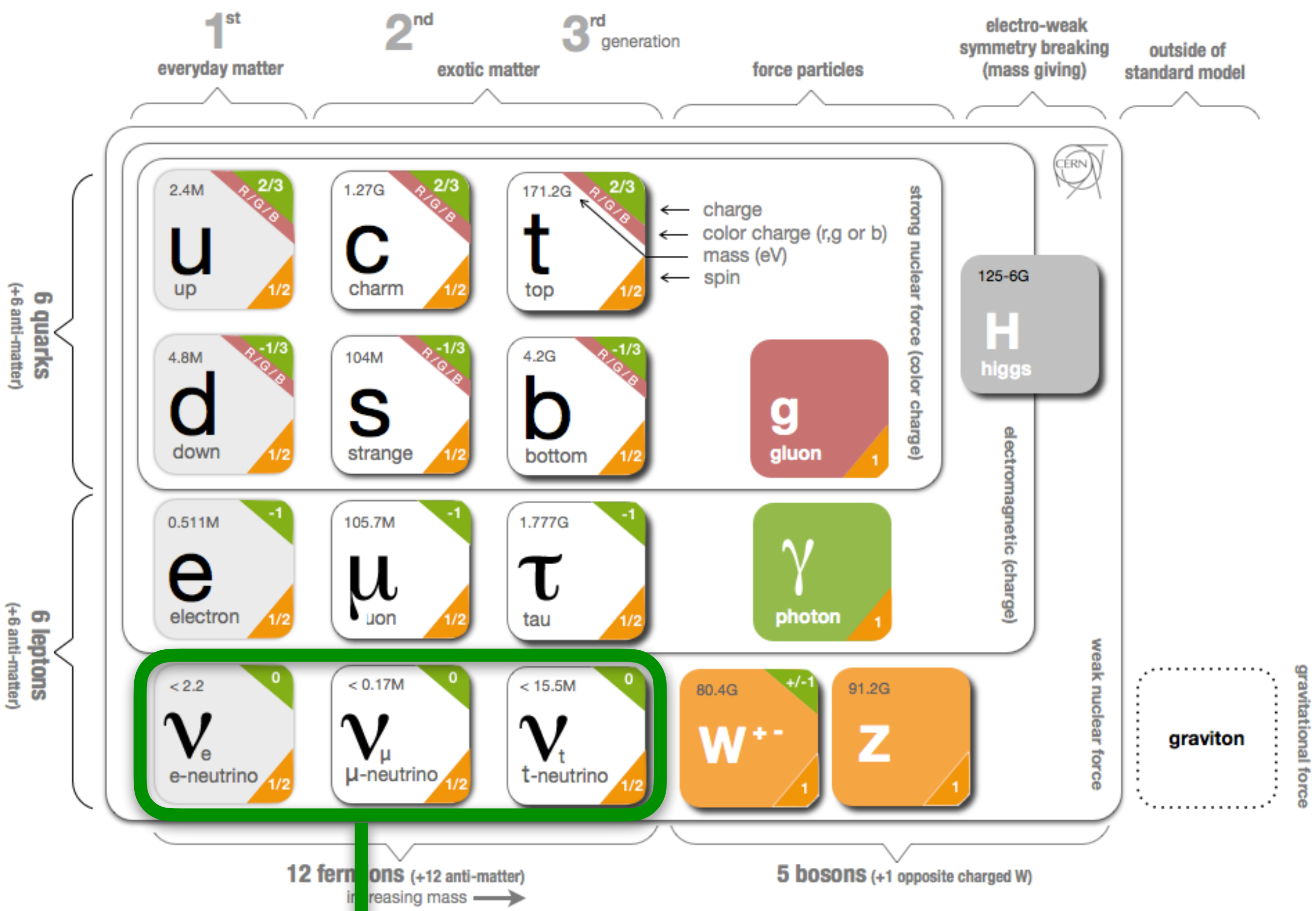
The Universe



- Need to explore physics Beyond the Standard Model (BSM)

Beyond the Standard Model and Neutrinos

Standard Model



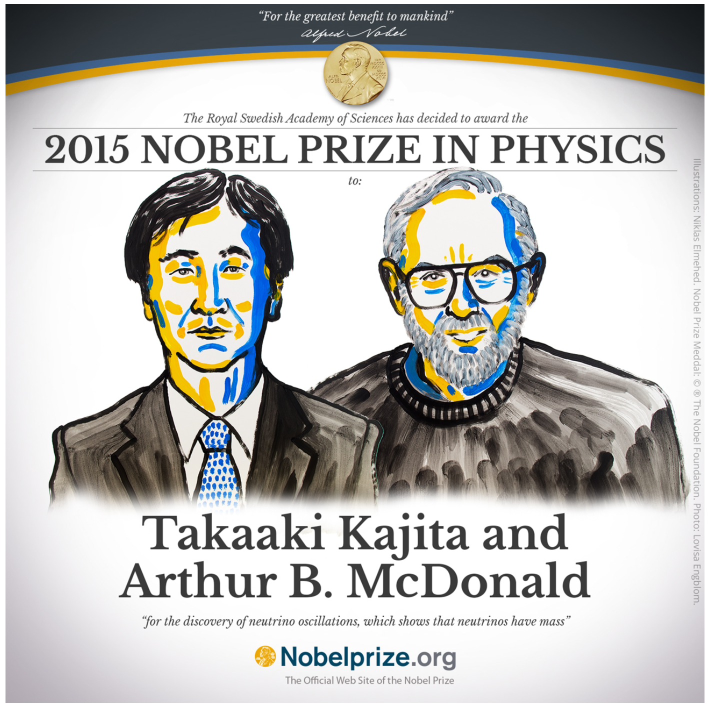
Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor States

Mass States

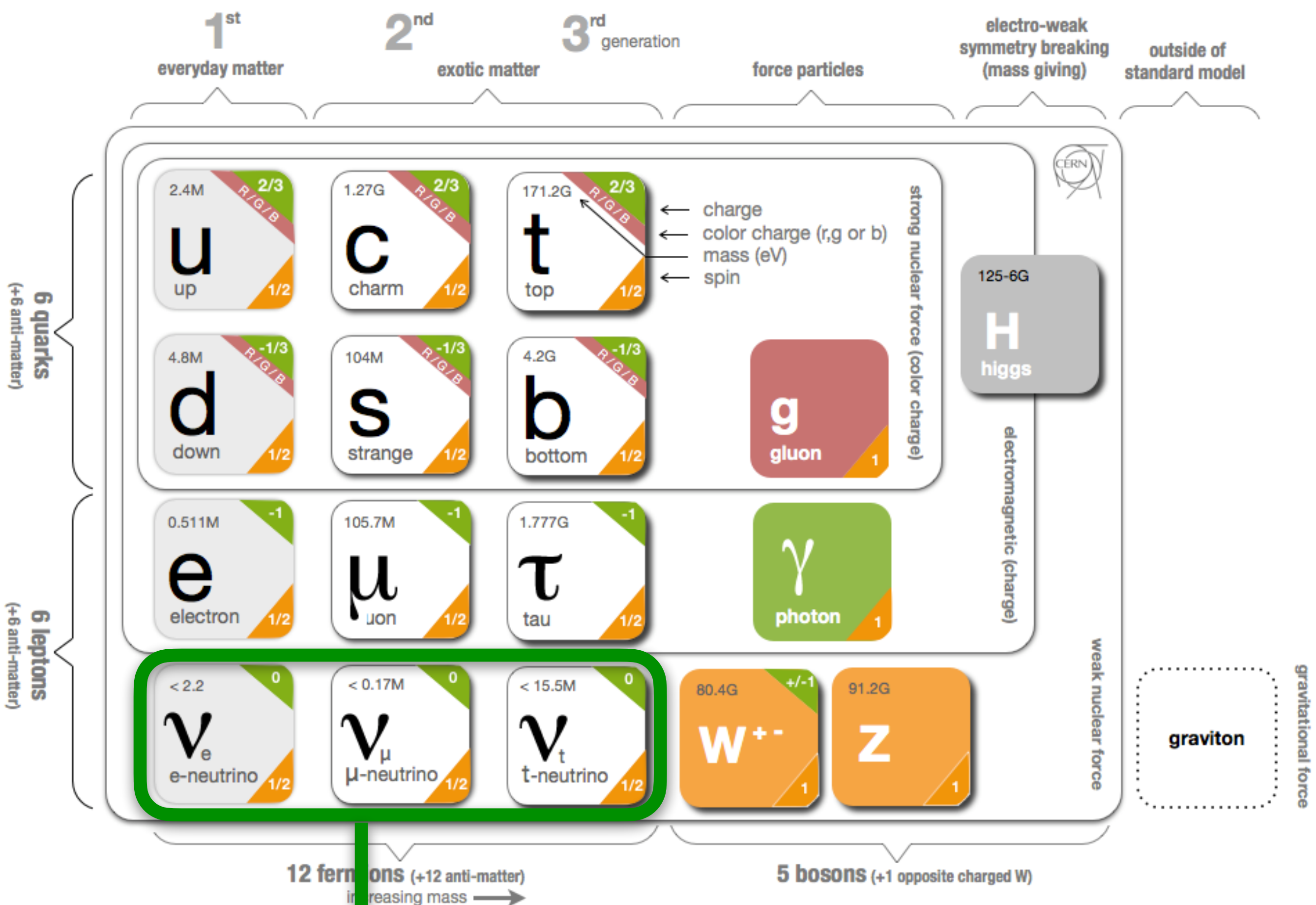
Neutrino Oscillation



For the discovery of neutrino oscillations which shows neutrino has mass.

Beyond the Standard Model and Neutrinos

Standard Model



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$$

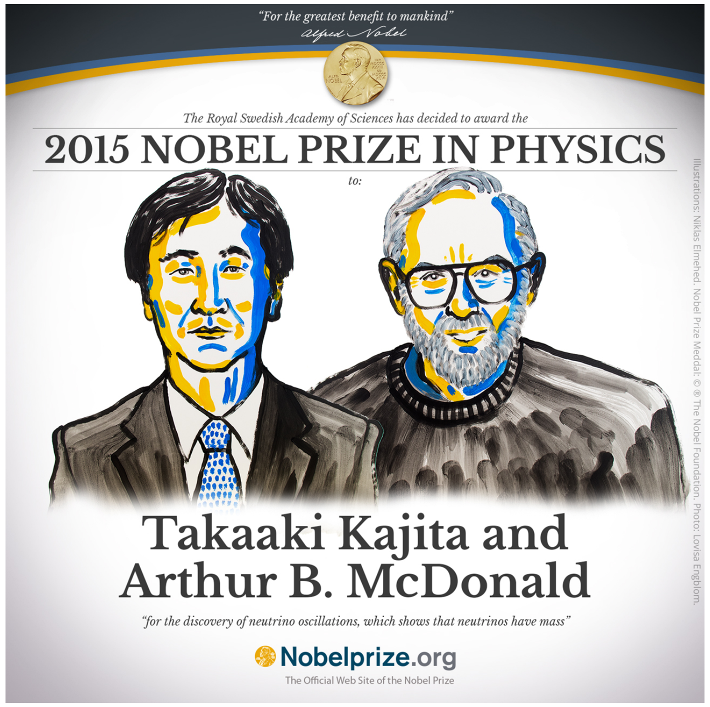
Flavor States — Mass States

Neutrino Oscillation

- Oscillation Probability:

$$
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \ \sin^2\left(\frac{\Delta m_{ij}^2}{4}\frac{L}{E}\right)
$$

- The mixing angle, θ, sets the amplitude of the oscillation
- Δm^2 determines the frequency of the oscillation
- L = distance traveled, E = neutrino energy



For the discovery of neutrino oscillations which shows neutrino has mass.

The Brave ν World

- These are exciting times. We are at the beginning of a new era in our understanding of the Universe and a new era of discoveries!

- **Building Neutrino Experiments**
  - Measure neutrino properties:
  - Use neutrinos as a probe for BSM physics:
  - Enabling multi-messenger astronomy:

The Brave ν World

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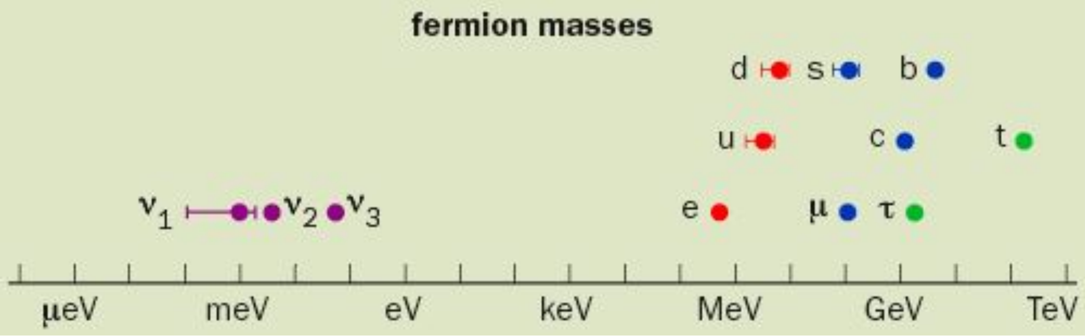
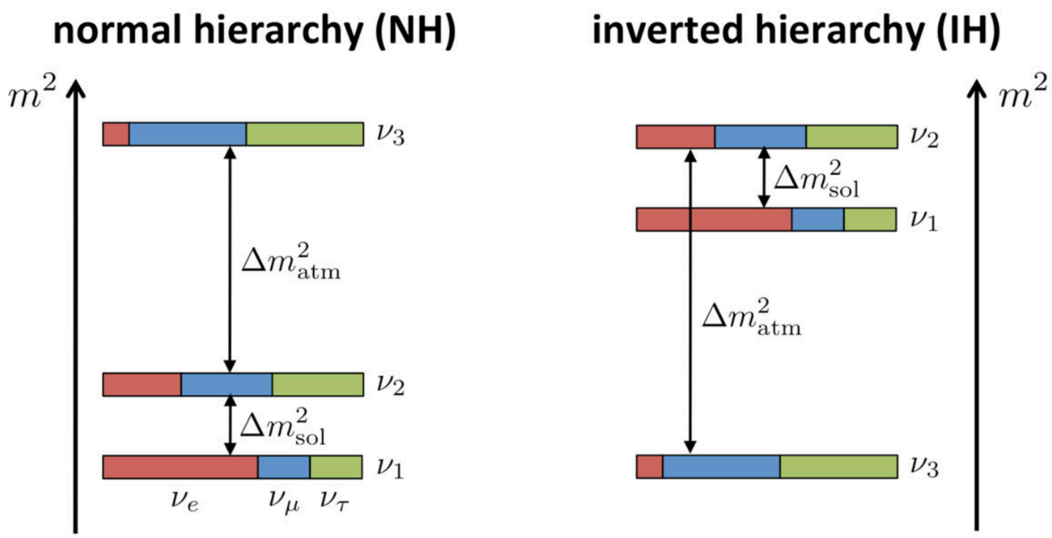
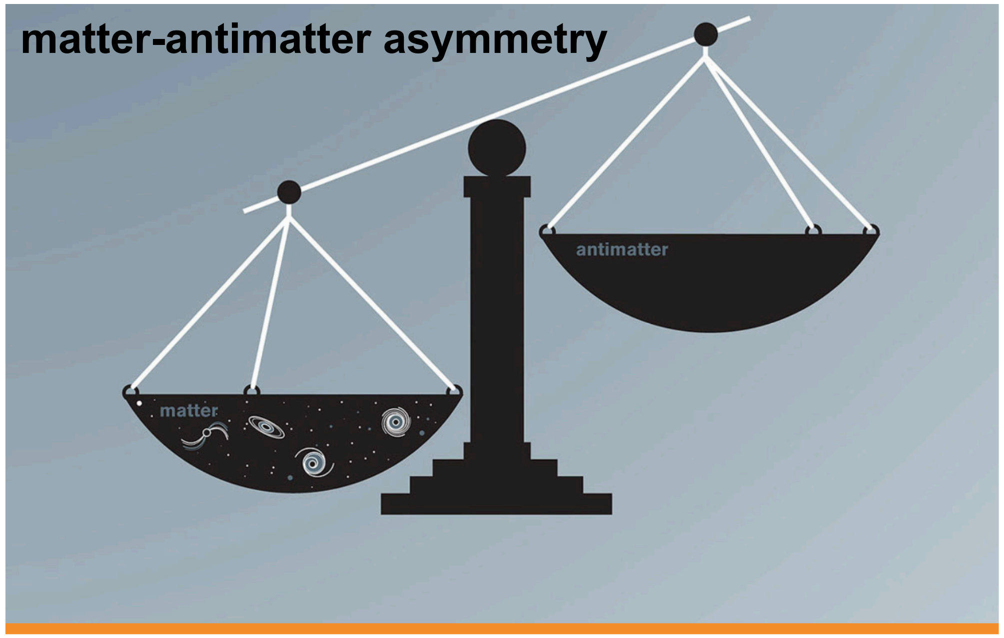






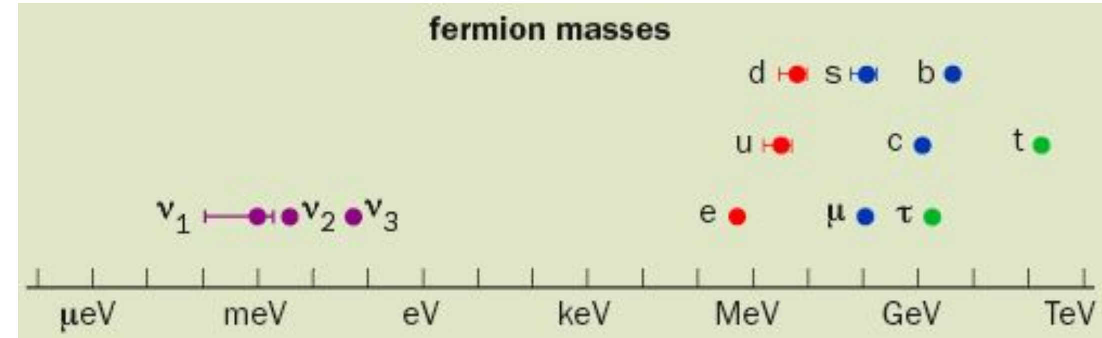
Credit: Symmetry Magazine / Sandbox Studio, Chicago

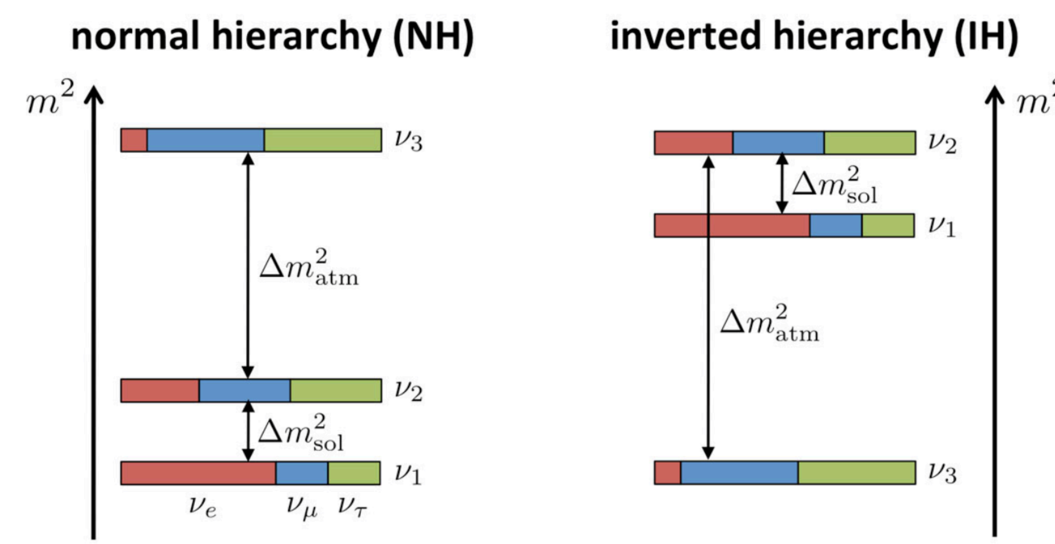
The Brave ν World

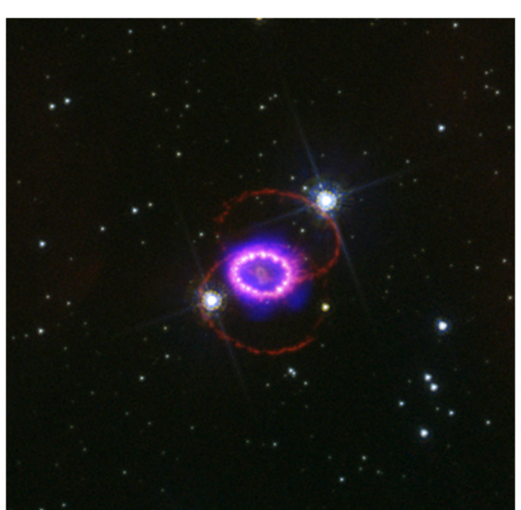
✦ These are exciting times. We are at the beginning of a new era in our understanding of the Universe and a new era of discoveries!

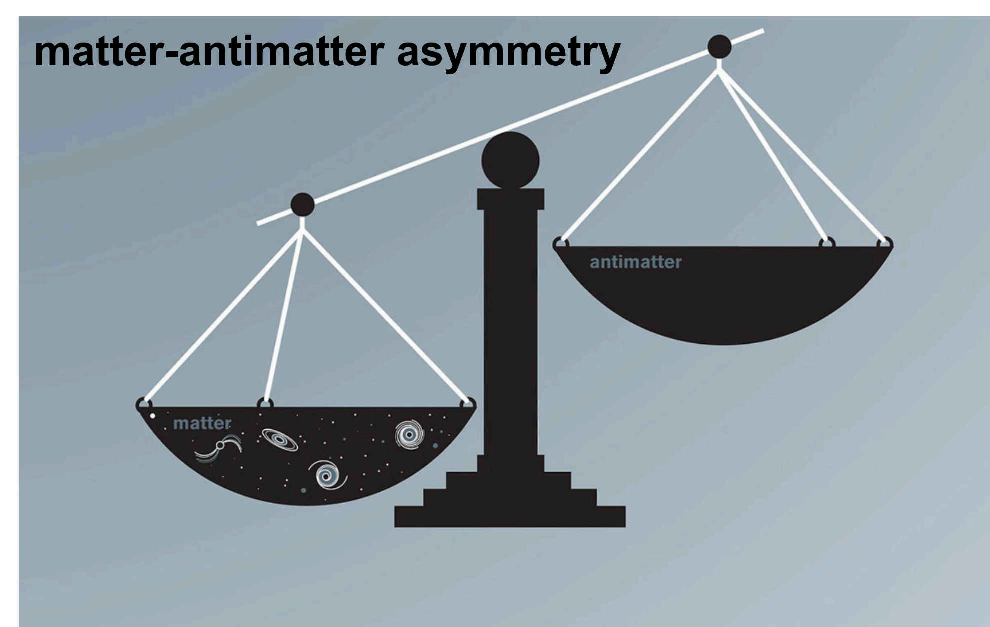
✦ Building Neutrino Experiments

- Measure neutrino properties:
  - Determine neutrino masses and hierarchy
  - Determine neutrino mixing parameters
  - Determine CP violation phase
- Use neutrinos as a probe for BSM physics:
  - Additional neutrino flavors (*sterile neutrinos)*
  - Dark matter
  - …..
- Enabling multi-messenger astronomy:
  - Detecting Supernova
  - ……



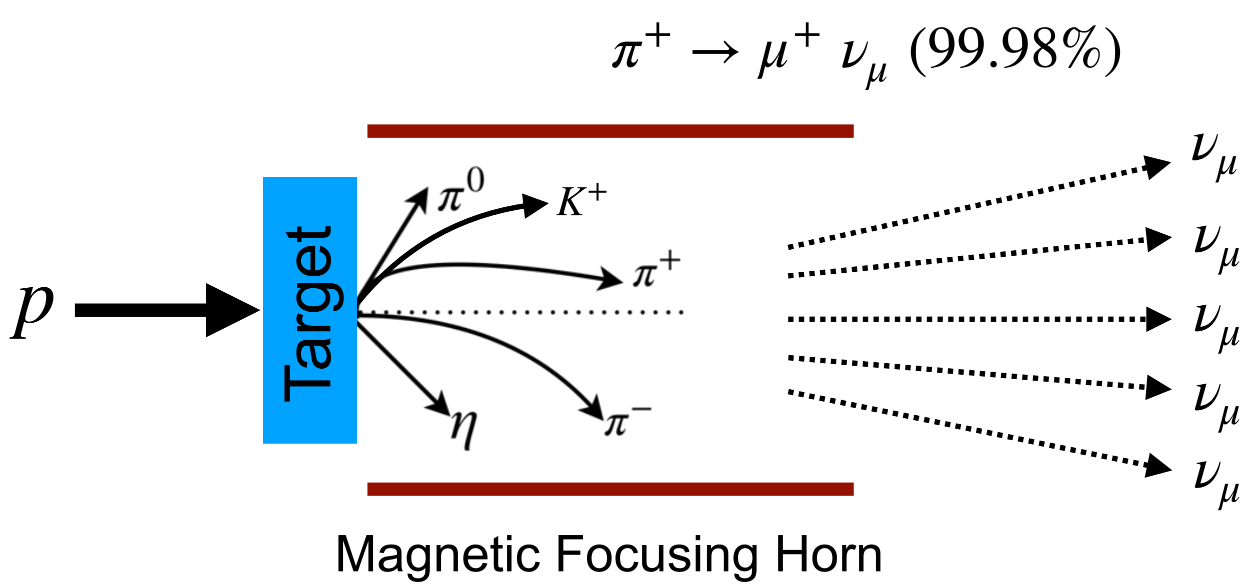


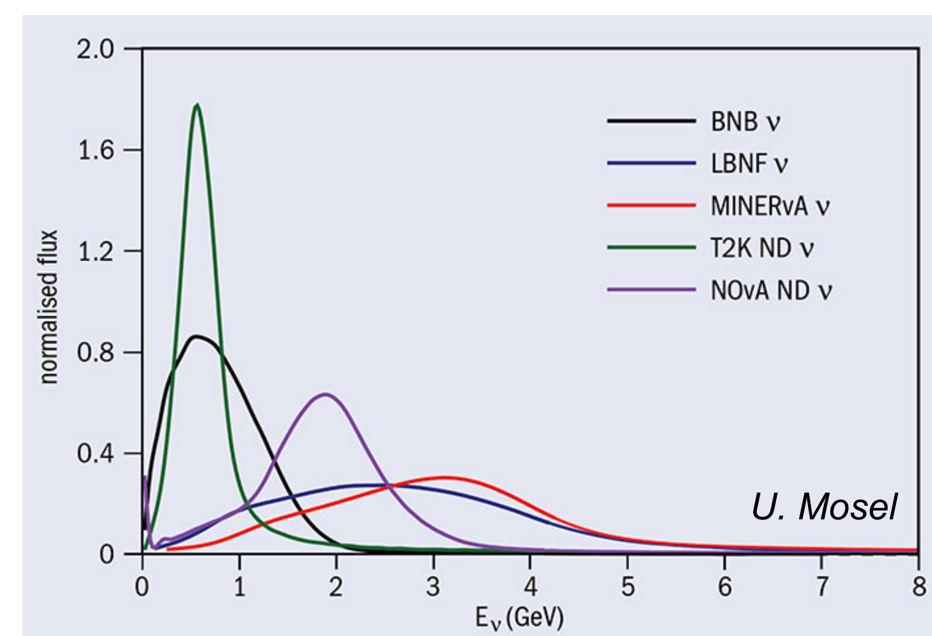




Credit: Symmetry Magazine / Sandbox Studio, Chicago

Neutrinos Sources and Experiments of My Interest





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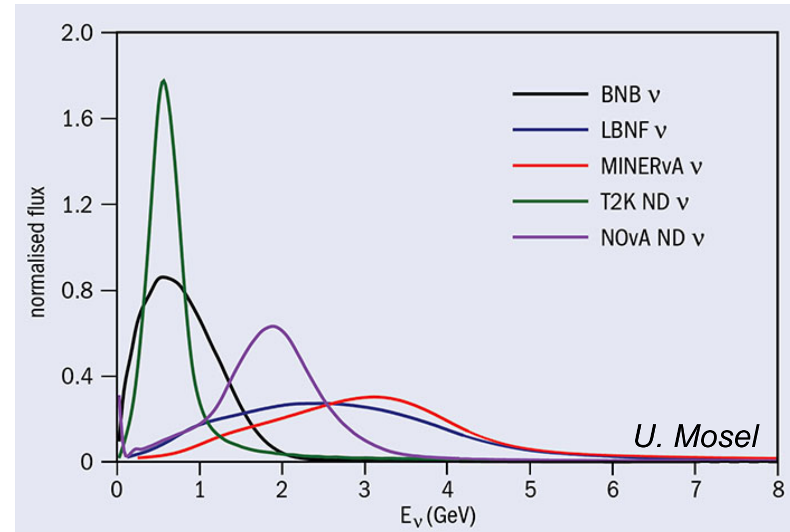
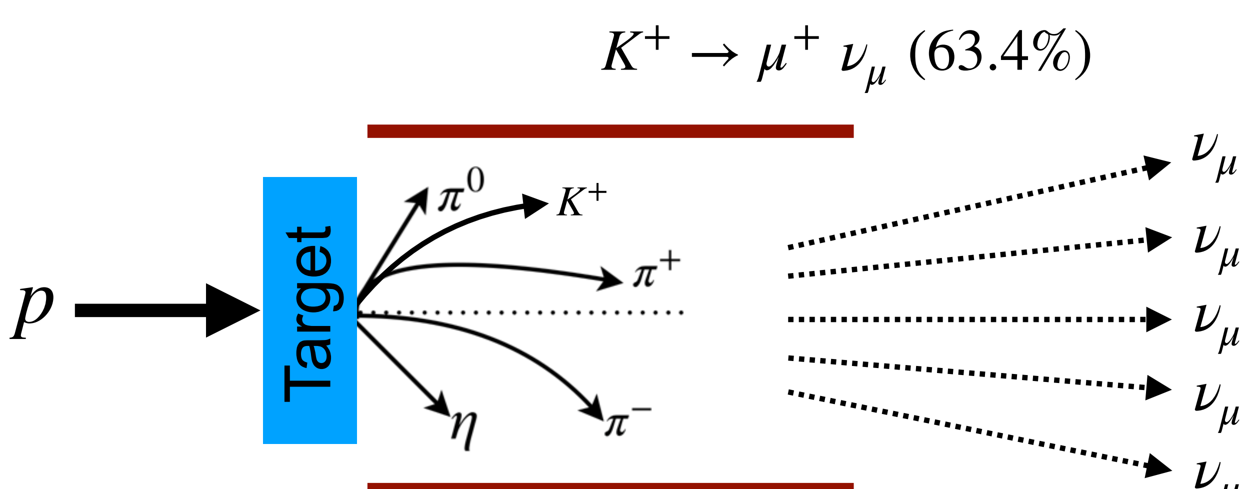
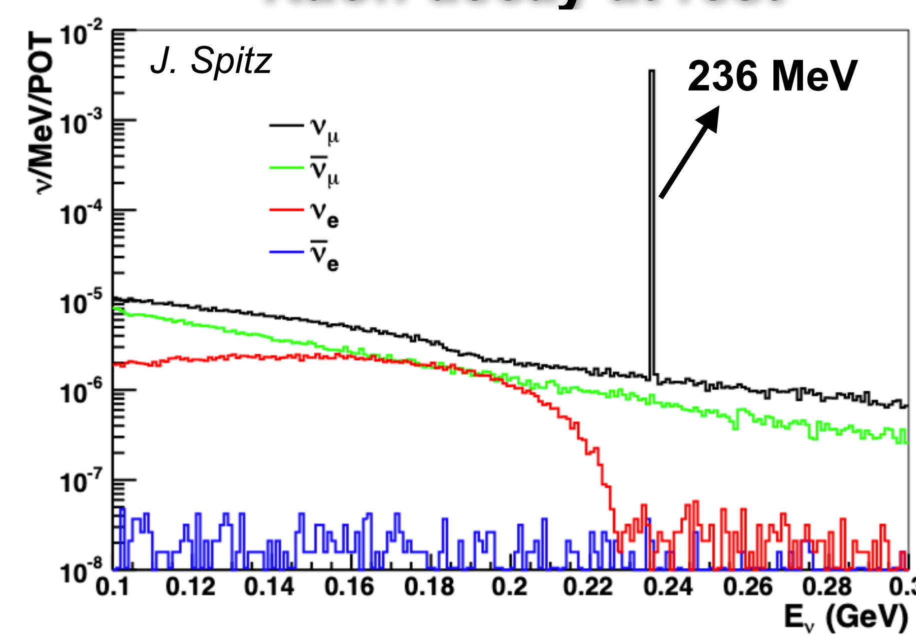




Magnetic Focusing Horn

Kaon decay at rest



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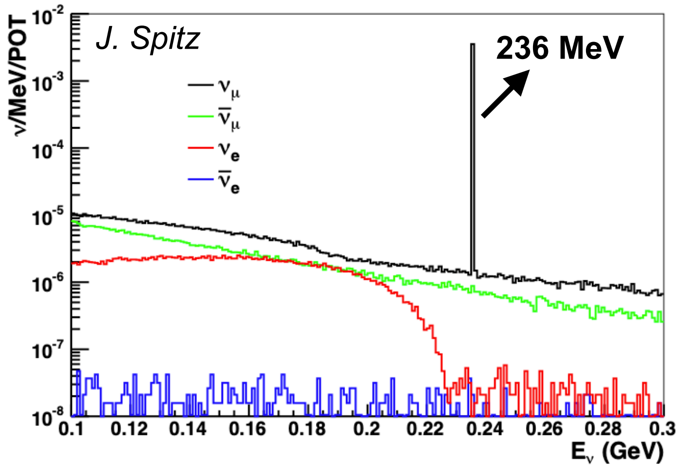
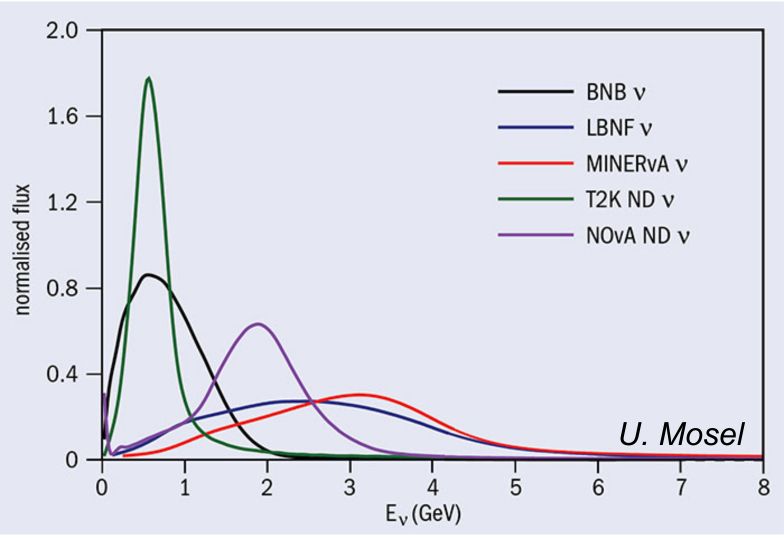
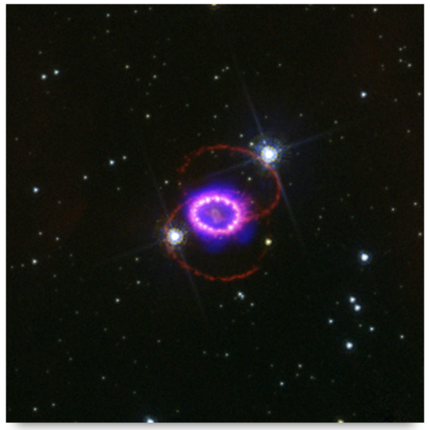
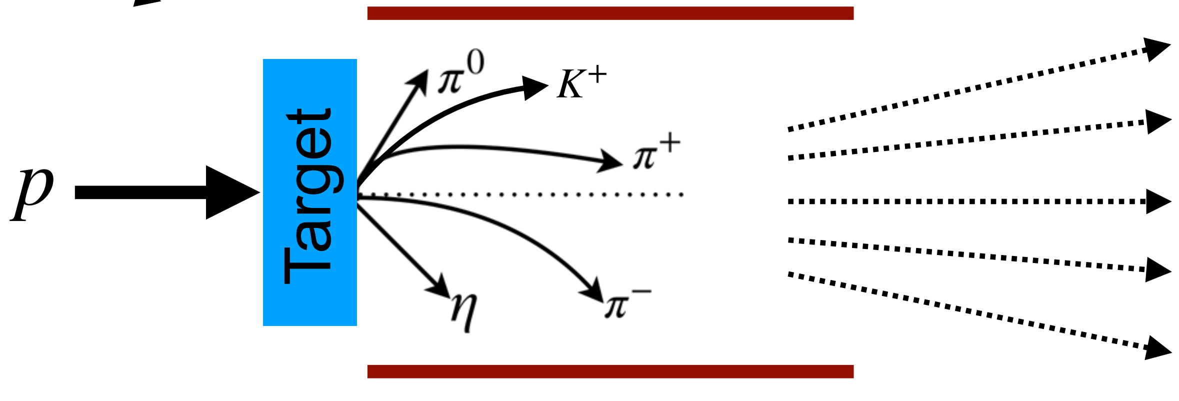




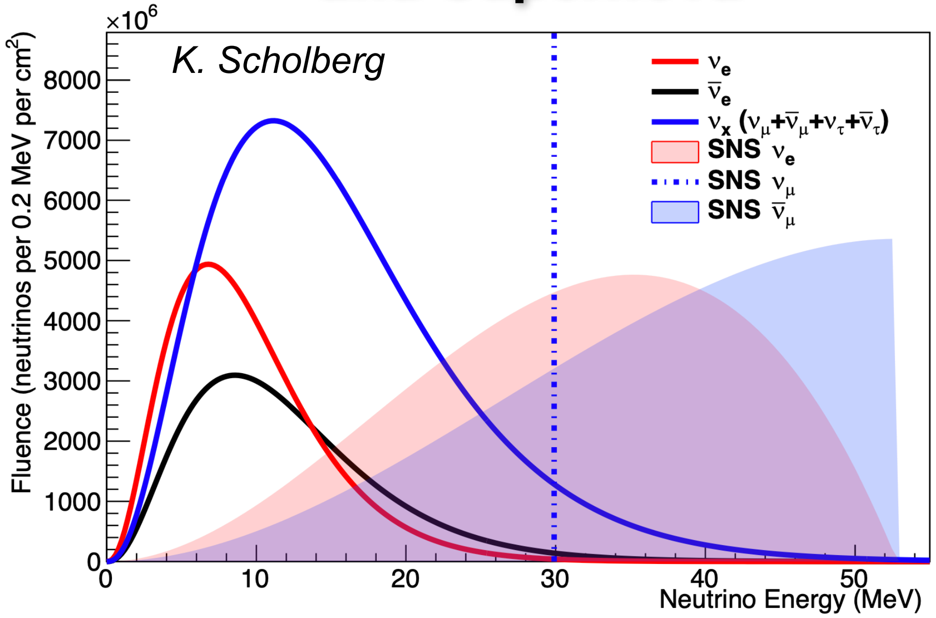
10 MeV | 100 MeV | 1 GeV | 10 GeV



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



Pion decay at rest and Supernova



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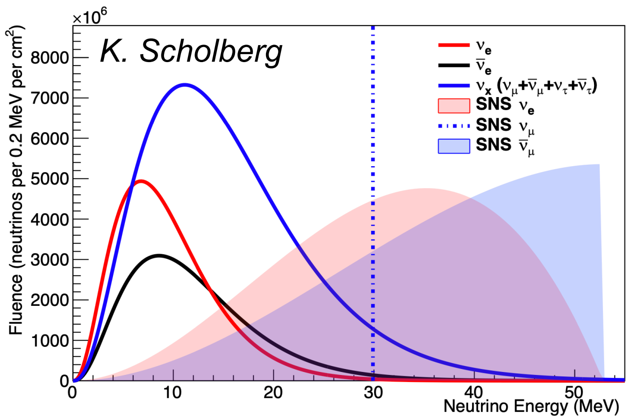
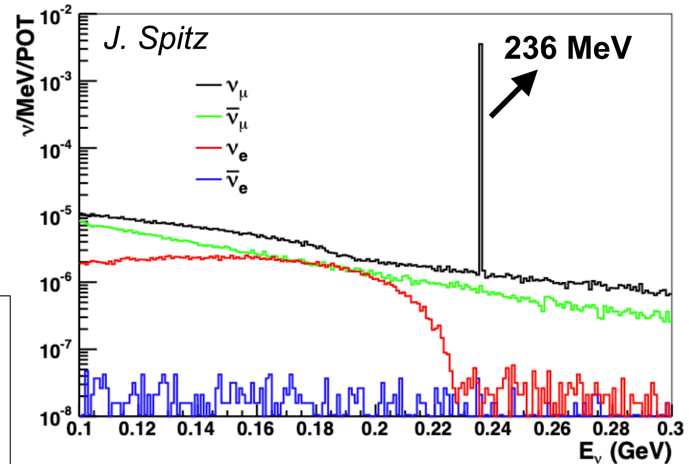
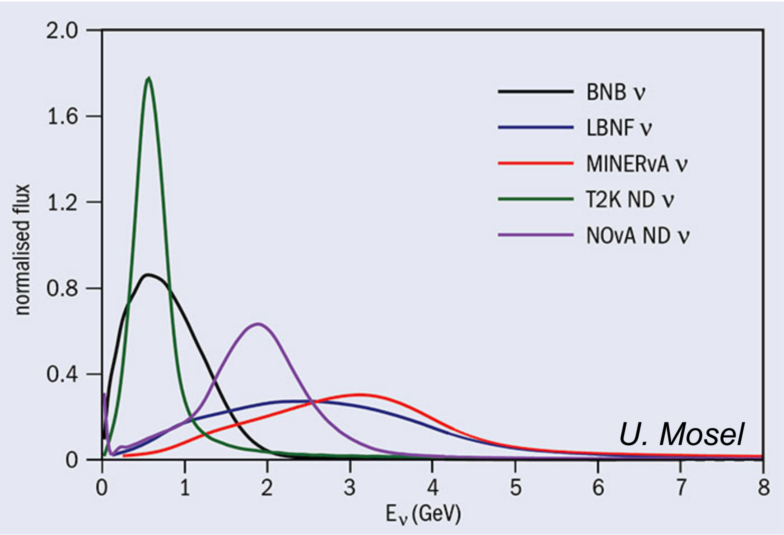


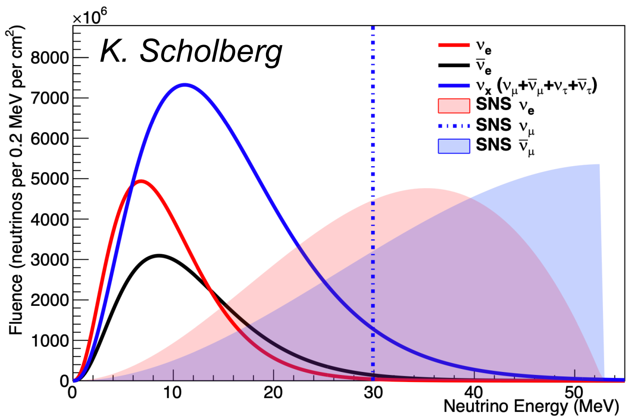


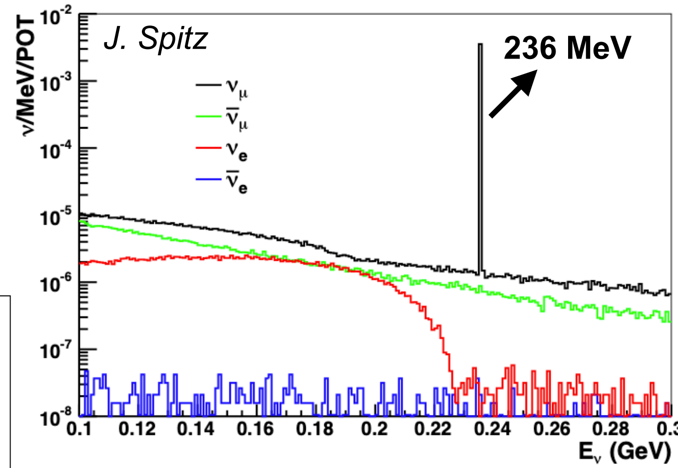


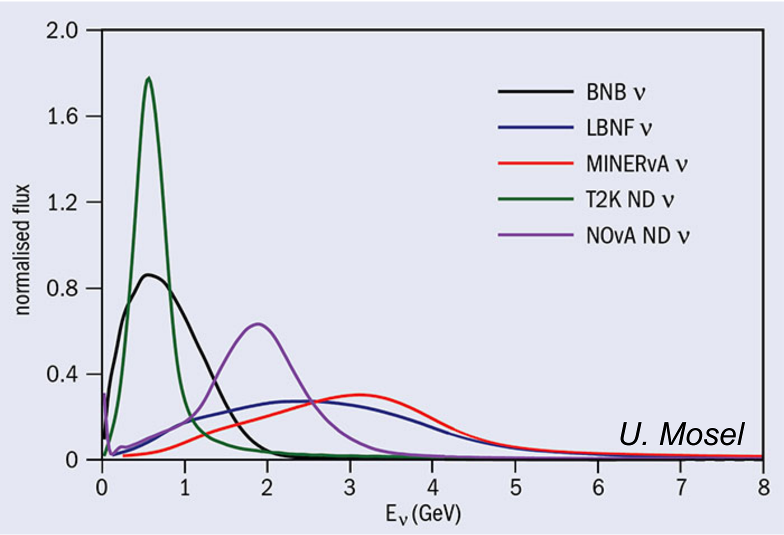
10 MeV **100 MeV** **1 GeV** **10 GeV**

Liquid Argon Detectors

Neutrinos Sources and Experiments of My Interest







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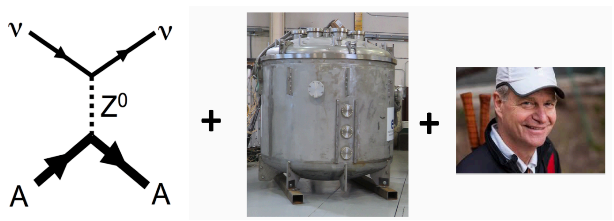
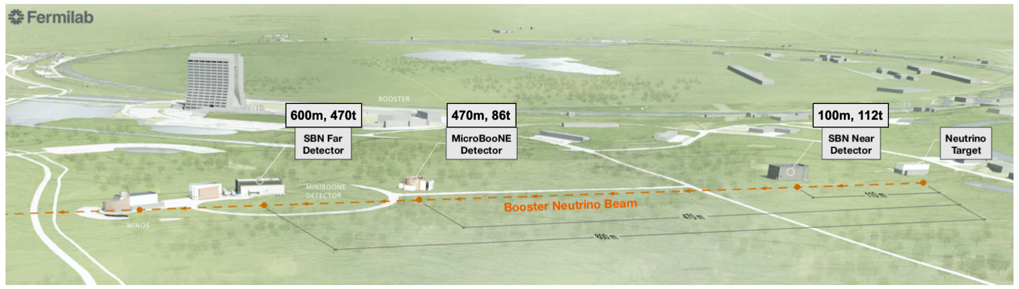
Liquid Argon Detectors

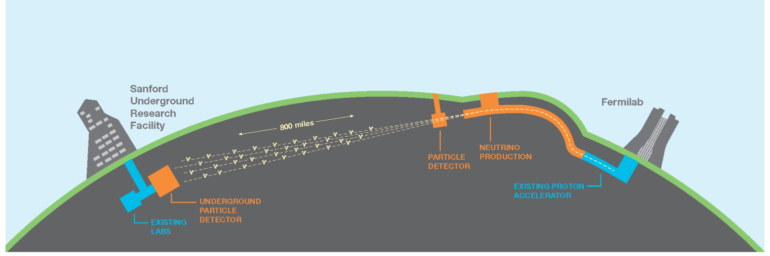
Coherent CAPTAIN-Mills (CCM) Experiment at LANL



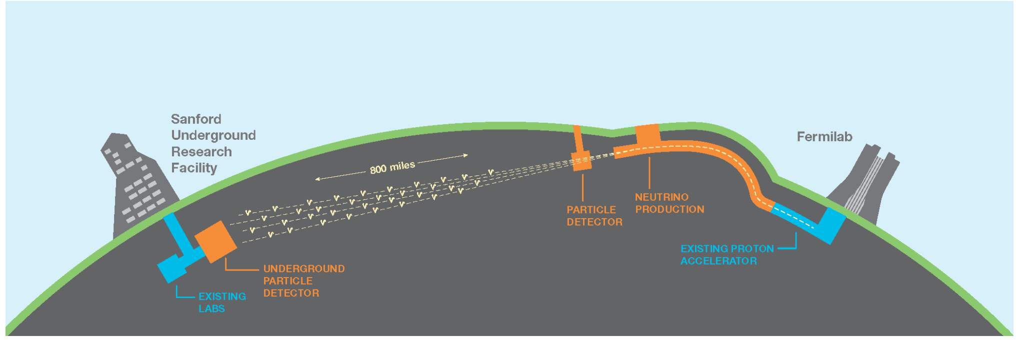
Short-Baseline Neutrino (SBN) Program at FNAL



Low-Energy Physics in DUNE



Deep Underground Neutrino Experiment (DUNE) at FNAL



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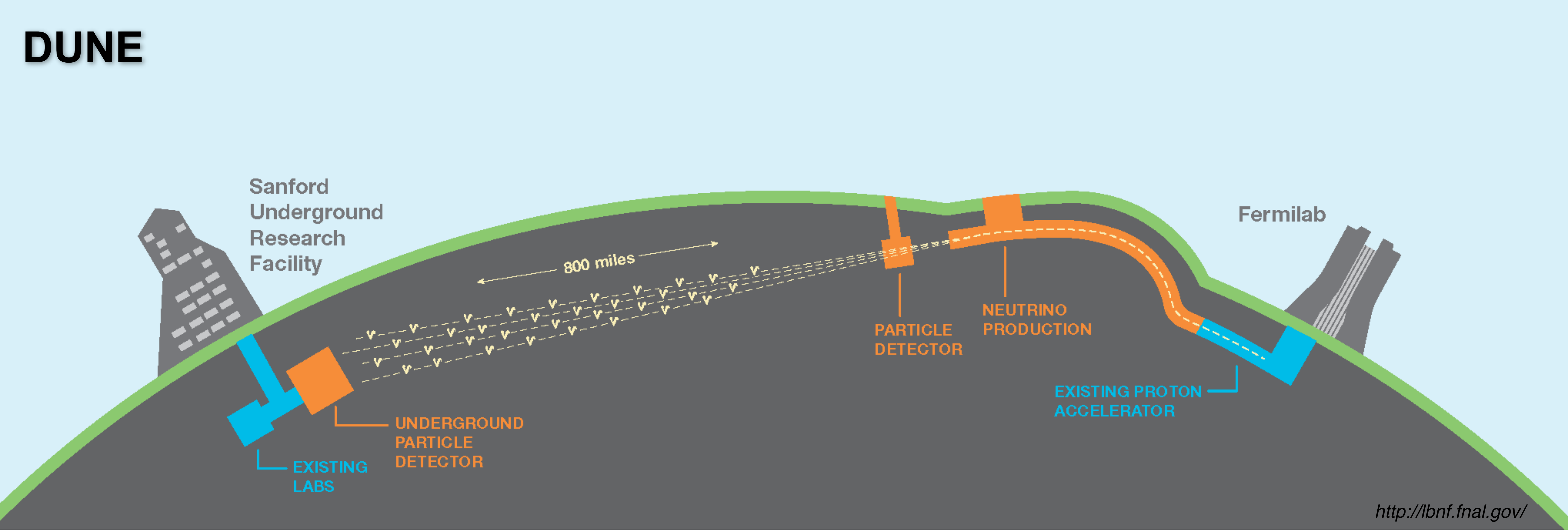
- ✦ Neutrinos: the portal to new frontiers in physics
- ✦ **Neutrino interactions: a multi-scale, multi-process problem**
- ✦ Tackling neutrino interactions

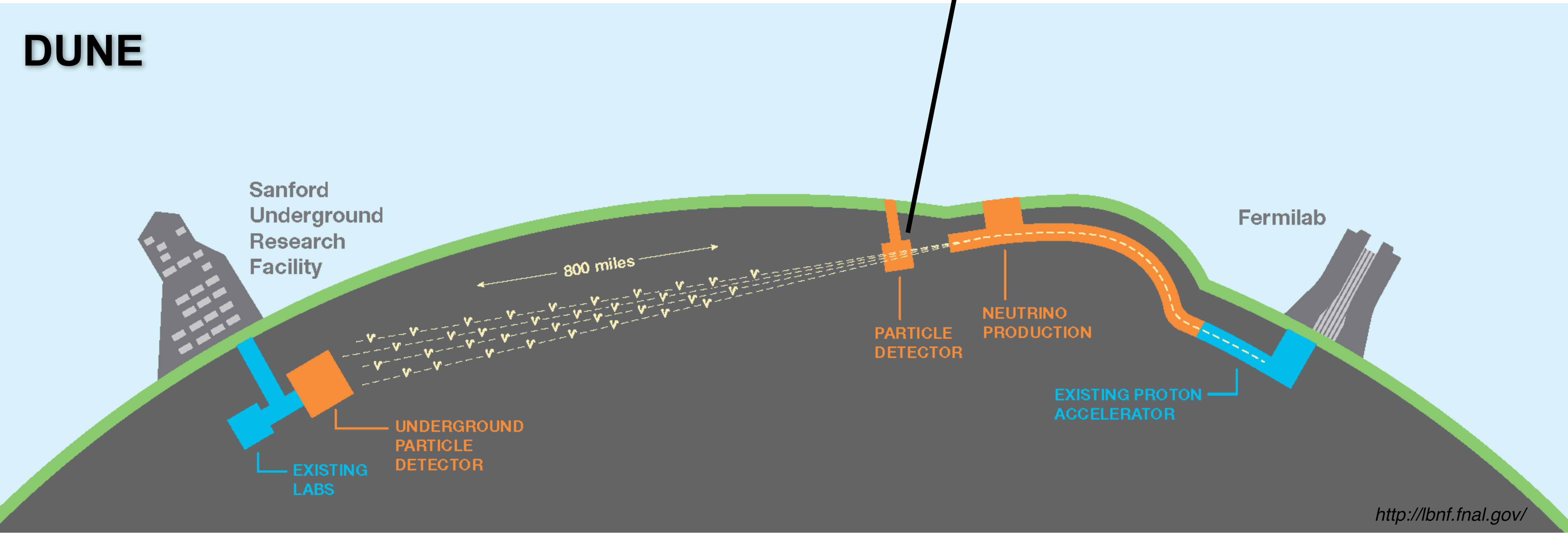
Neutrino Oscillation Experiment



Neutrino Oscillation Experiment

- <u>Event Rate at Near Detector:</u>

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



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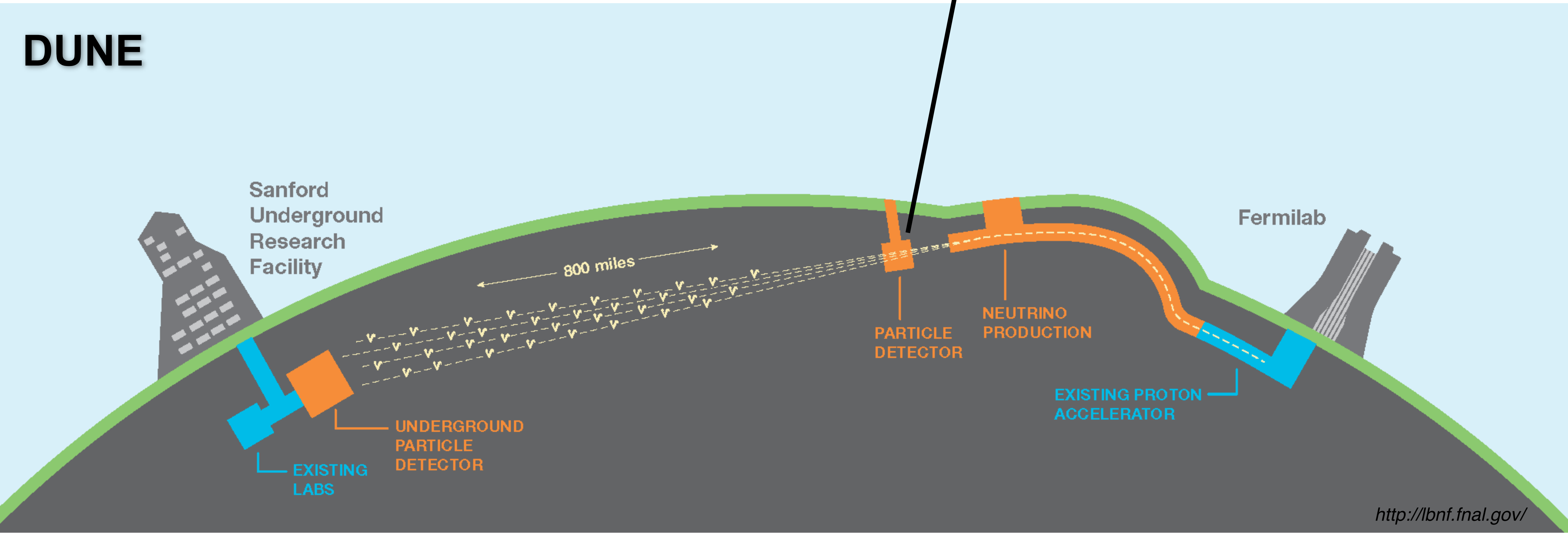
- <u>Oscillation Probability</u>:

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



Neutrino Oscillation Experiment

- Event Rate at Far Detector:

$$N_{FD}^{\alpha\to\beta}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_\beta^i(E_\nu) \times P(\nu_\alpha \to \nu_\beta) \times \epsilon_\beta(E_\nu, E_{\nu,rec})$$

- Event Rate at Near Detector:

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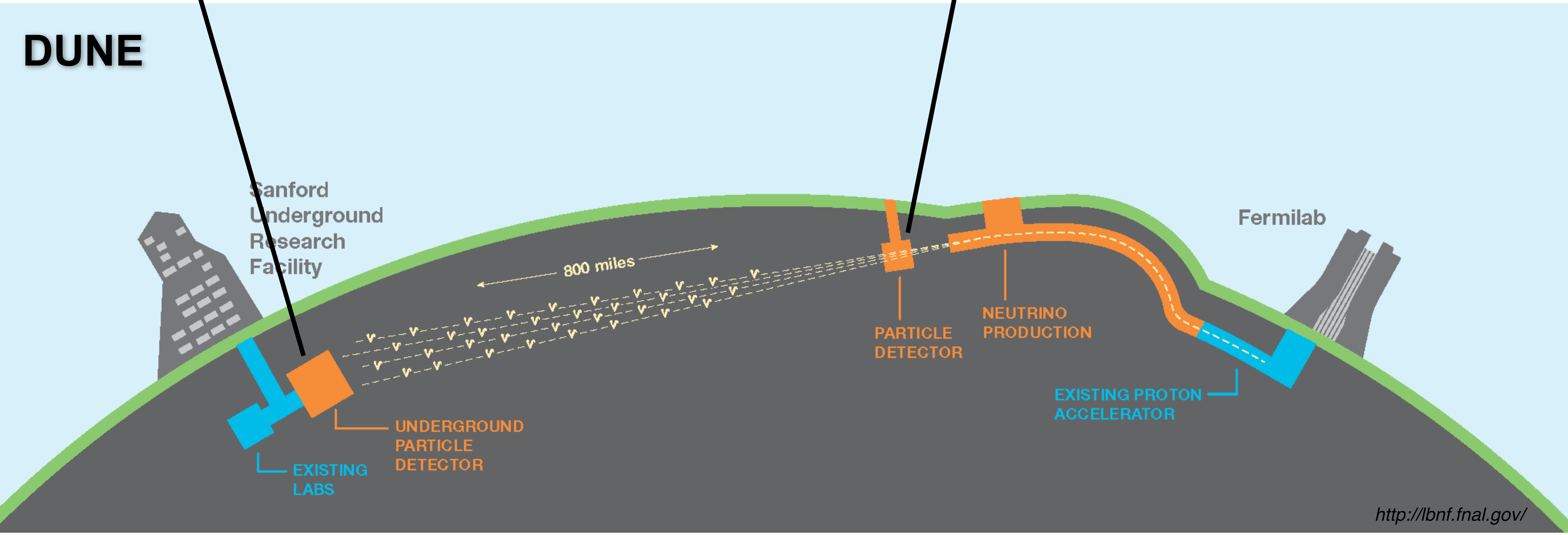

Neutrino Energy and Neutrino-nucleus Interactions

$$\frac{N_{FD}^{\alpha\rightarrow\beta}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_\beta^i(E_\nu) \times P(\nu_\alpha \rightarrow \nu_\beta) \times \epsilon_\beta(E_\nu, E_{\nu,rec})}{N_{ND}^{\alpha}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_\alpha^i(E_\nu) \times \epsilon_\alpha(E_\nu, E_{\nu,rec})}$$

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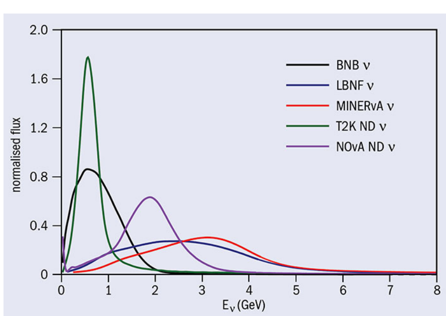
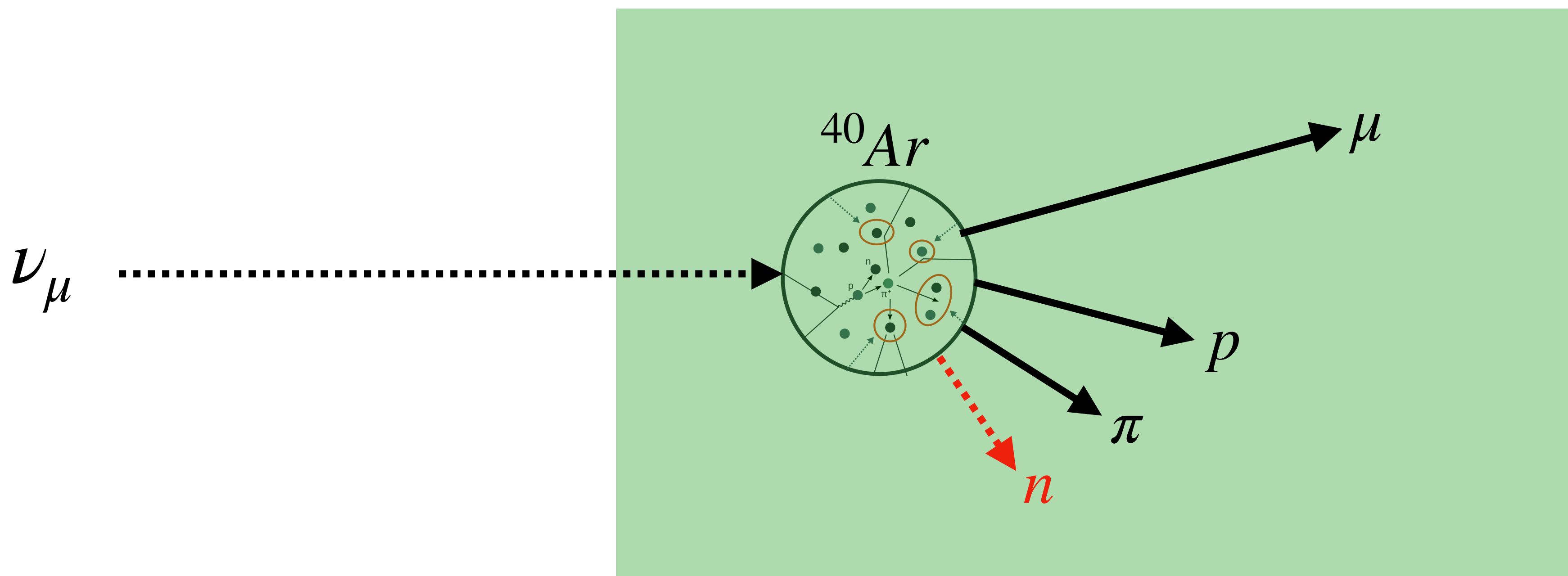
$$P(\nu_\alpha\to\nu_\beta) = \sin^2 2\theta_{ij}\ \sin^2\left(\frac{\Delta m_{ij}^2}{4}\frac{L}{E_\nu}\right)$$

- **<u>Neutrino Energy</u>:**

Energy Reconstruction:

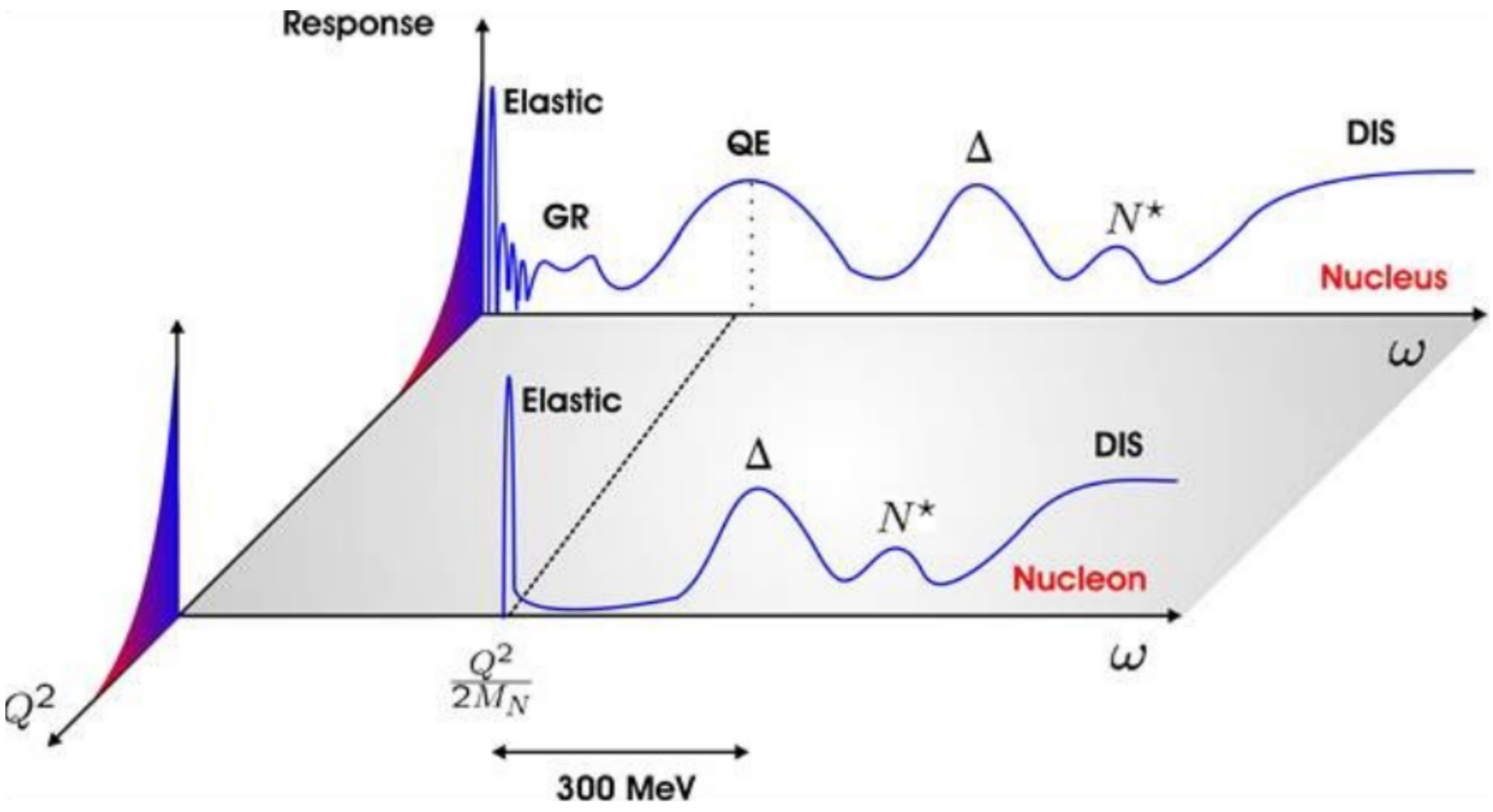
$$E_\nu = \sum E_{observed\ particles} + E_{neutrons} + E_{missing}$$

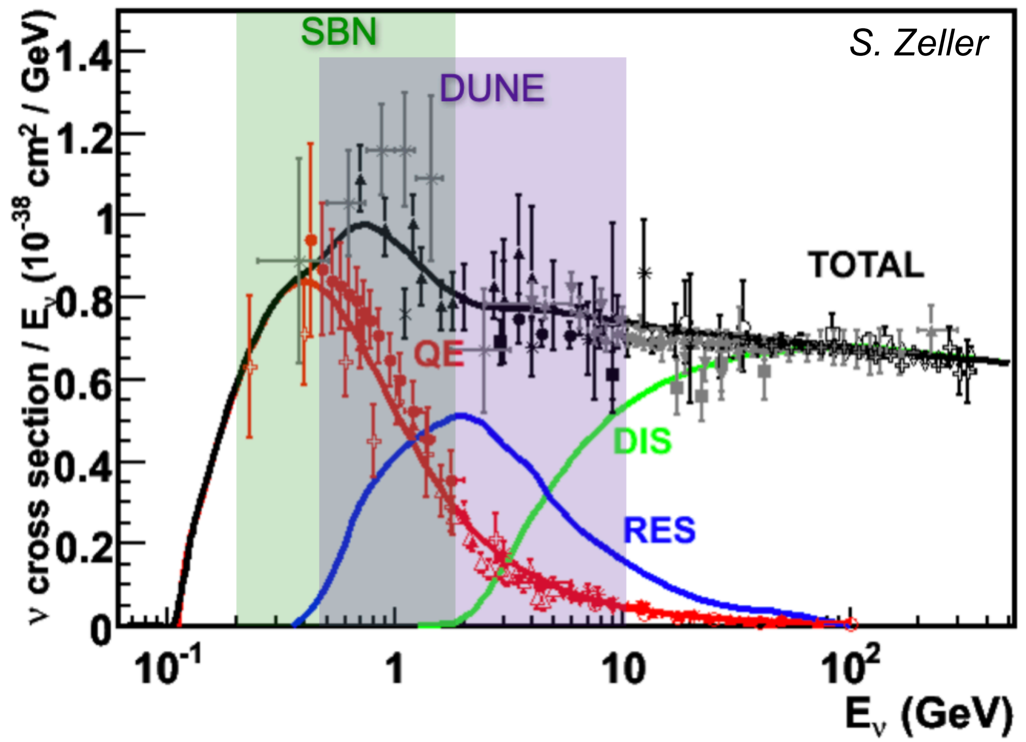


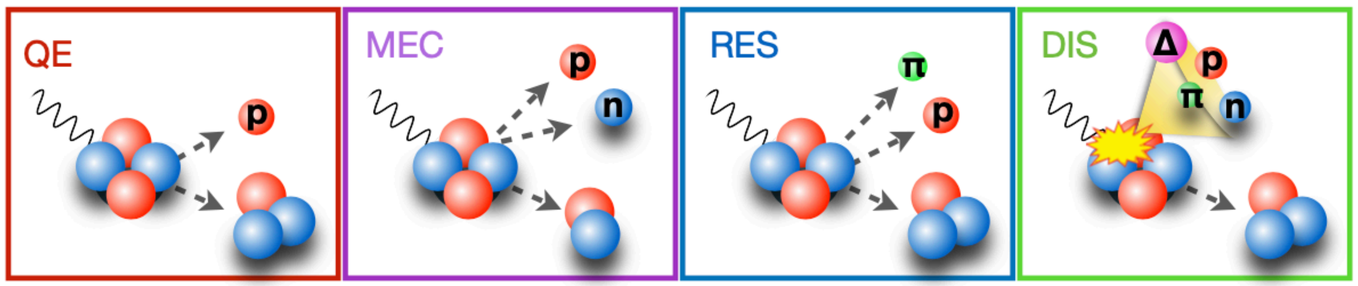


✦ Neutrino energy reconstruction requires predictions from the interaction model.

- **Neutrino-nucleus Interactions**:



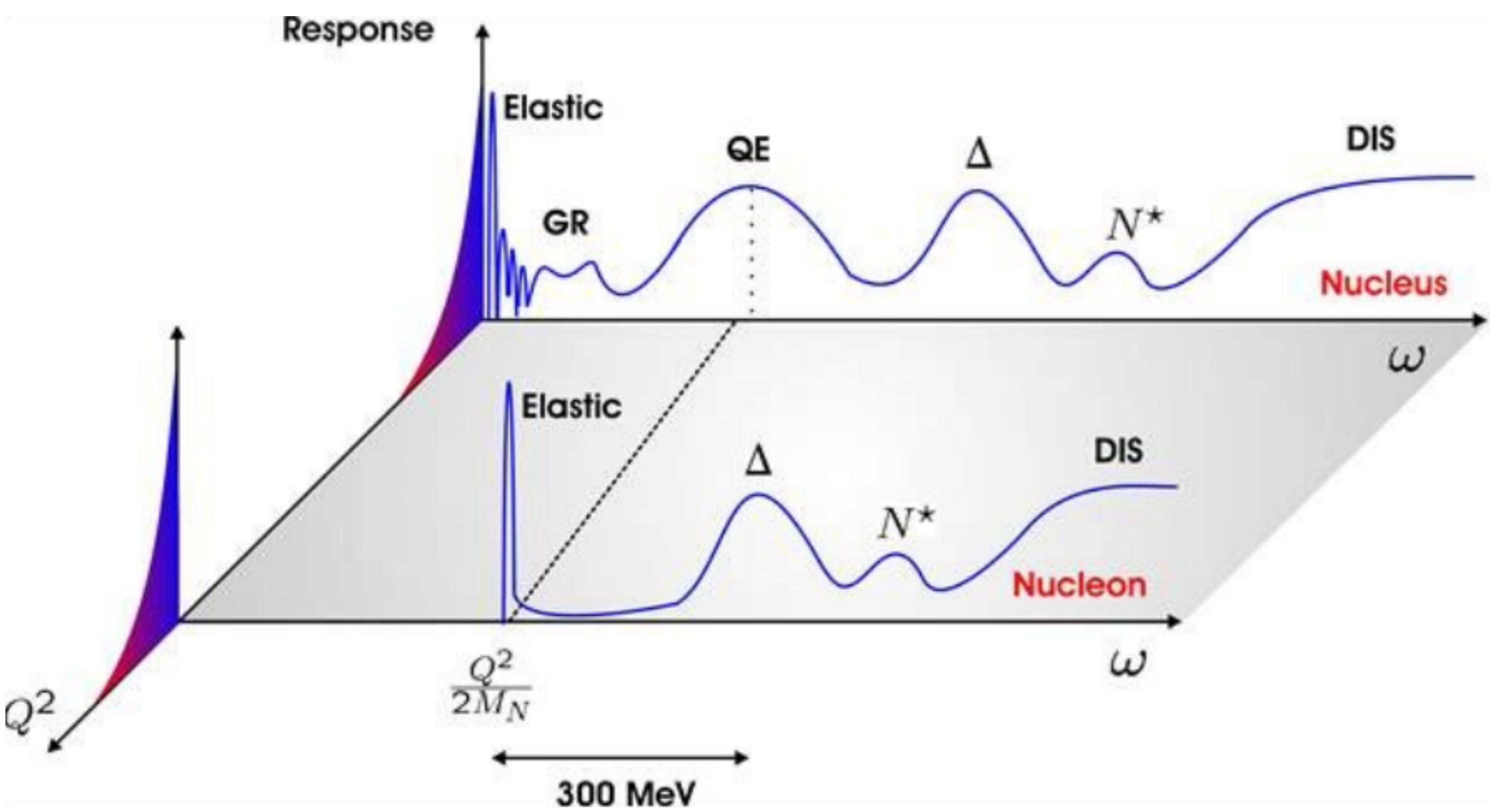


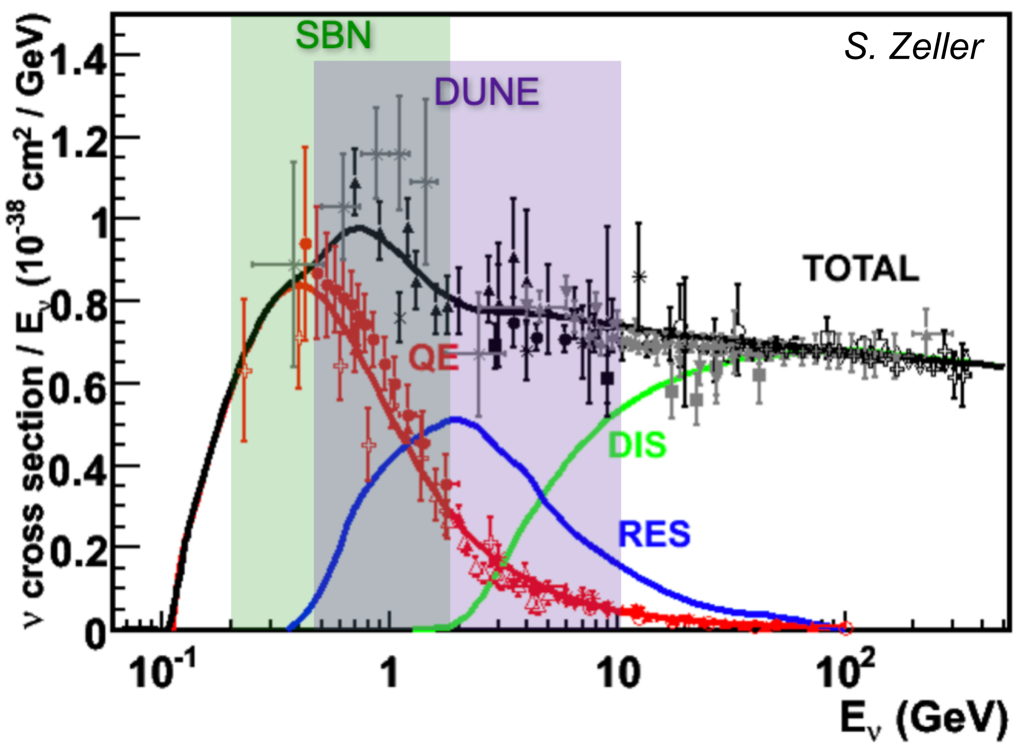


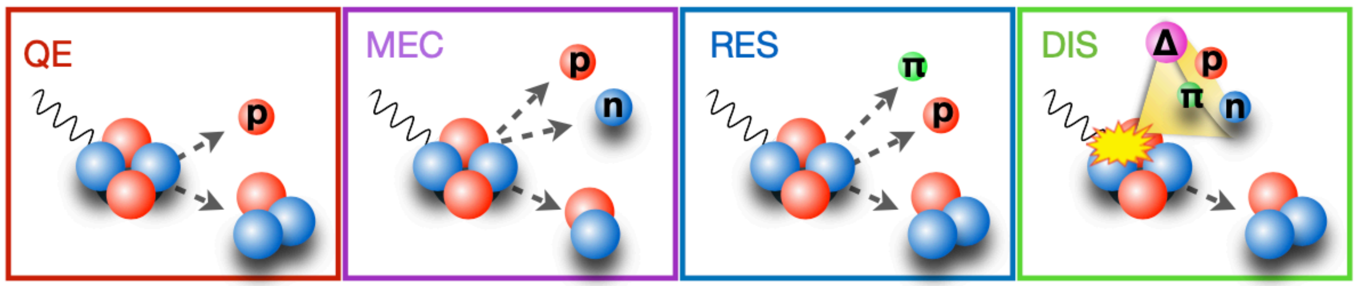
✦ Neutrino fluxes span over a wide range of energies where a number of complex nuclear reaction mechanisms overlap.

Neutrino Energy and Neutrino-nucleus Interactions

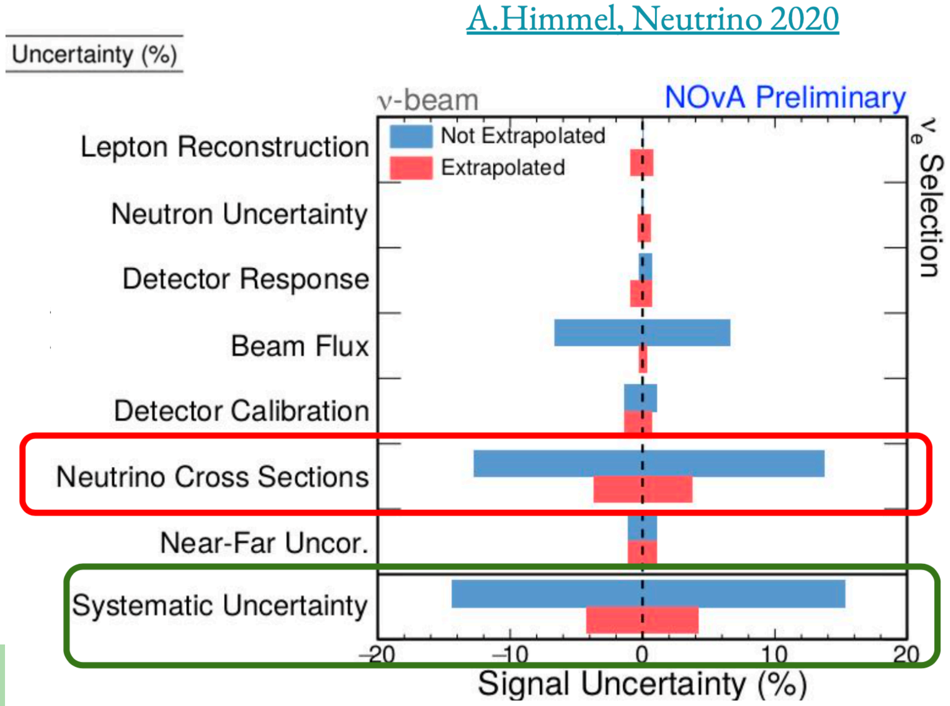
- **Neutrino-nucleus Interactions**:







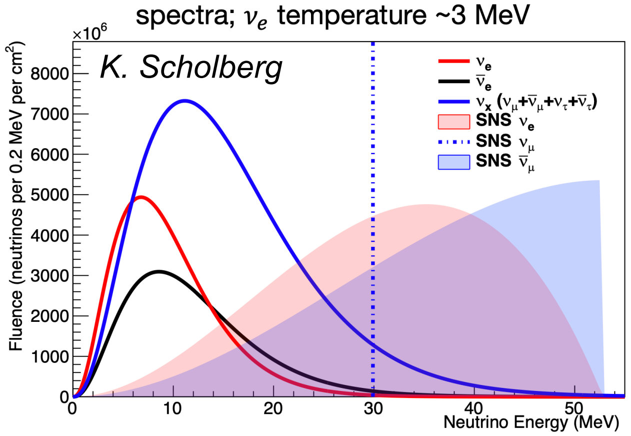
A.Himmel, Neutrino 2020

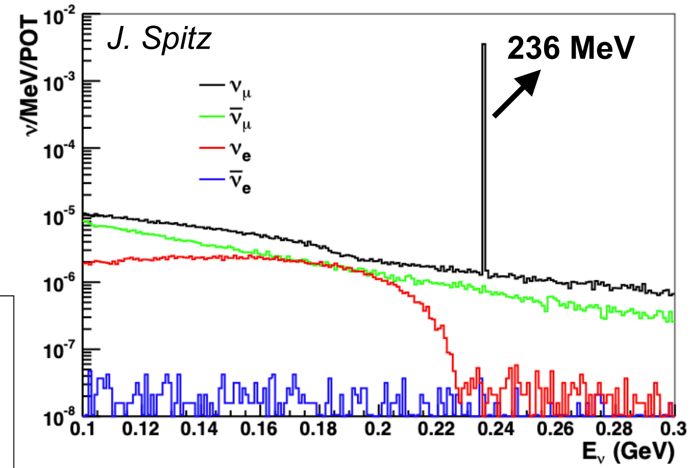


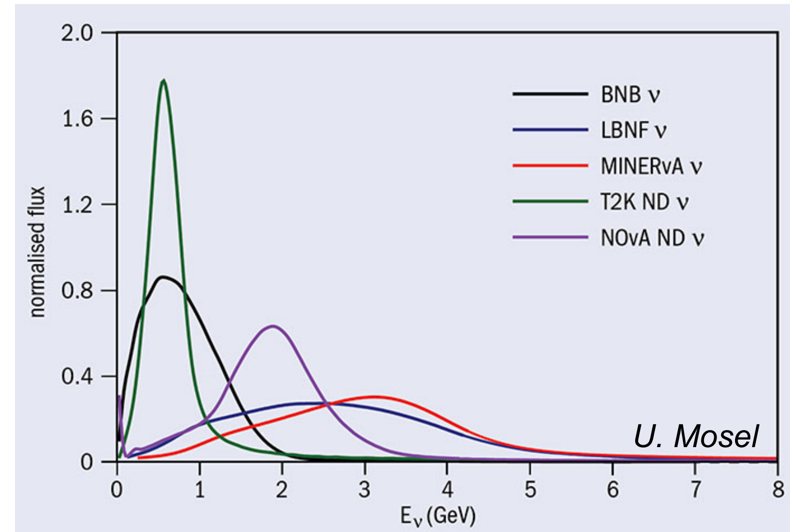
✦ Neutrino fluxes span over a wide range of energies where a number of complex nuclear reaction mechanisms overlap.

Neutrino Energy and Neutrino-nucleus Interactions

Supernova flux (10 kpc): pinched spectra; ν_e temperature ~3 MeV







10 MeV **100 MeV** **1 GeV** **10 GeV**

← **Atomic Systems**

QCD →

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

✦ Nucleus as a many-body system with pions and nucleons as (effective) d.o.f.

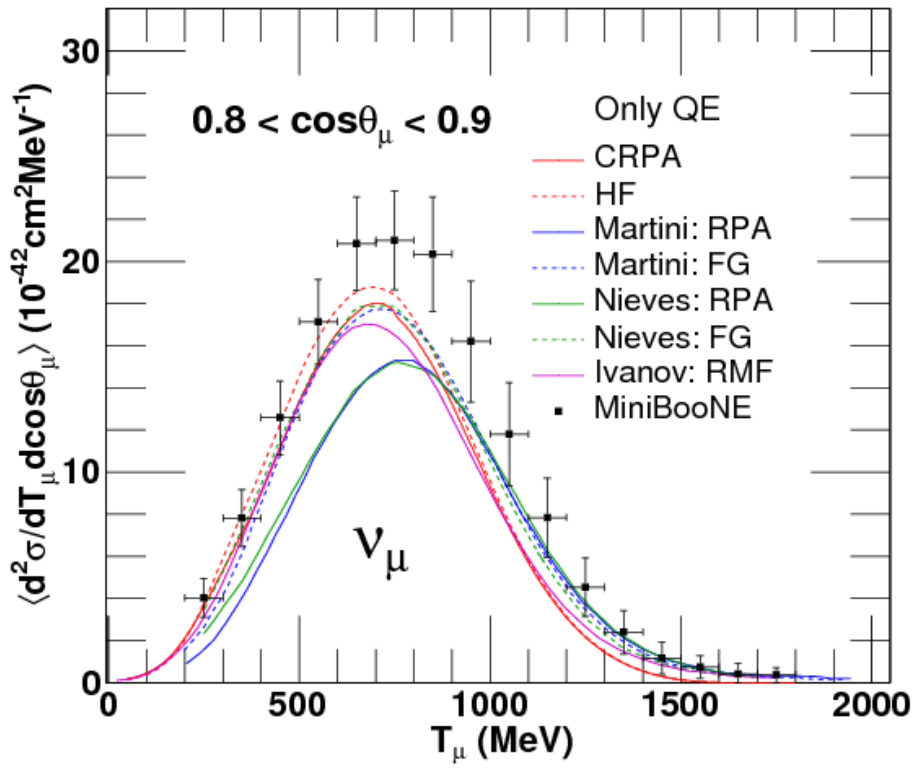
✦ Multi-scale, multi-process, many-body, non-perturbative problem subject to complex nuclear structure and dynamics.

✦ Transition from the hadronic d.o.f. to quark d.o.f

Neutrino Energy and Neutrino-nucleus Interactions

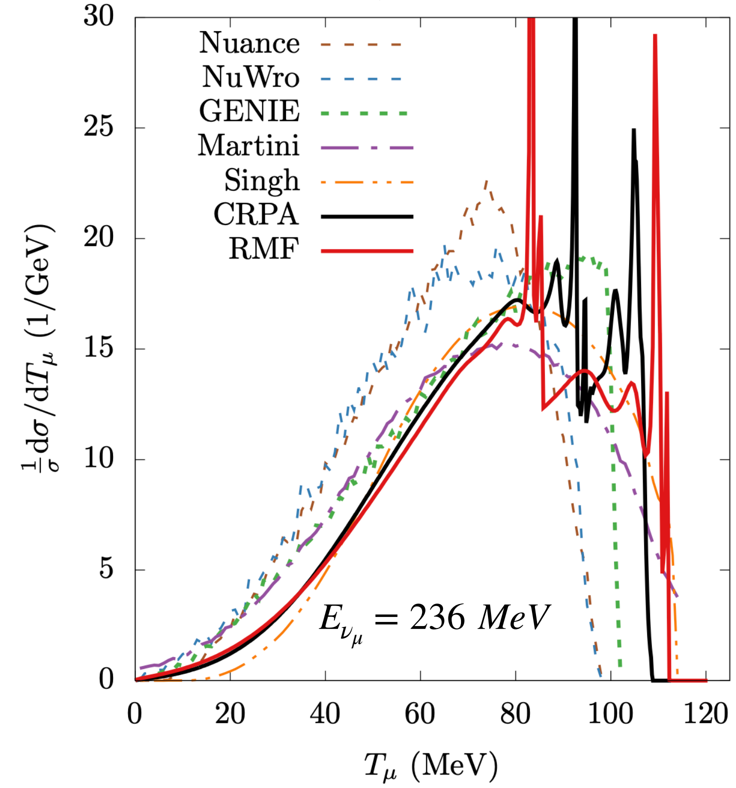
✦ No unified theory, different models predict different cross sections.

MiniBooNE flux folded



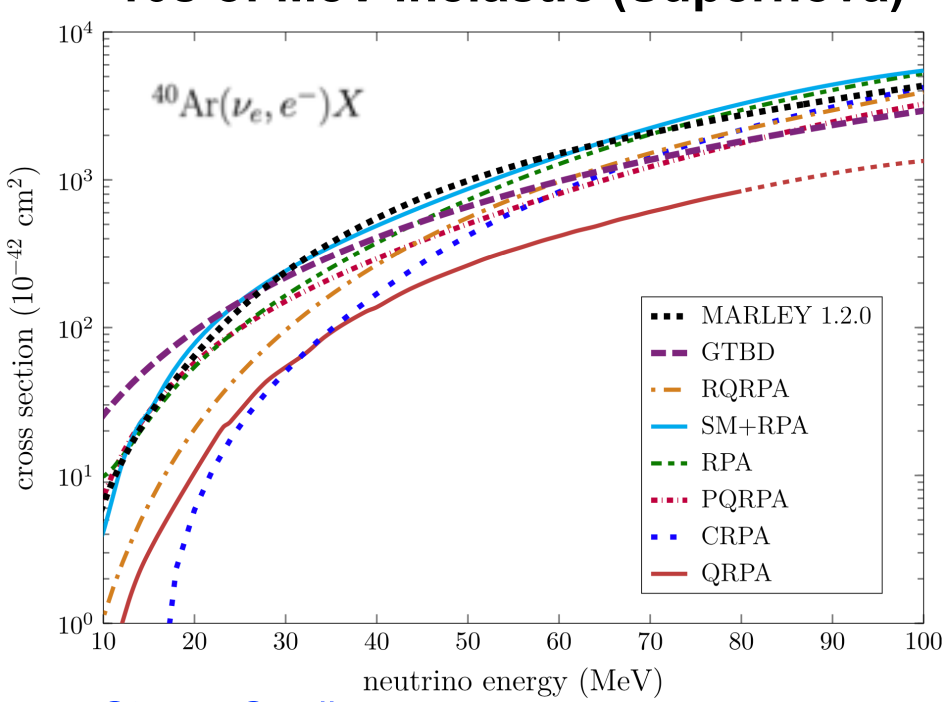
VP, N. Jachowicz et al., Phys. Rev. C94, 054609 (2016)

KDAR, 236 MeV



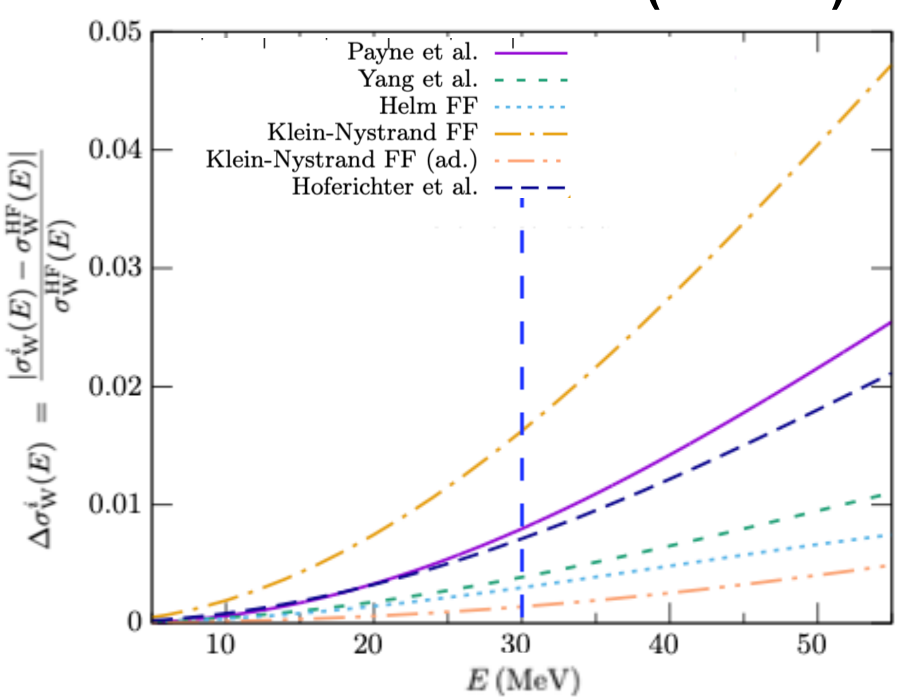
A. Nikolakopoulos, VP et al., arXiv:2010.05794 [nucl-th].

10s of MeV inelastic (Supernova)



Steven Gardiner

10s of MeV elastic (CEvNS)

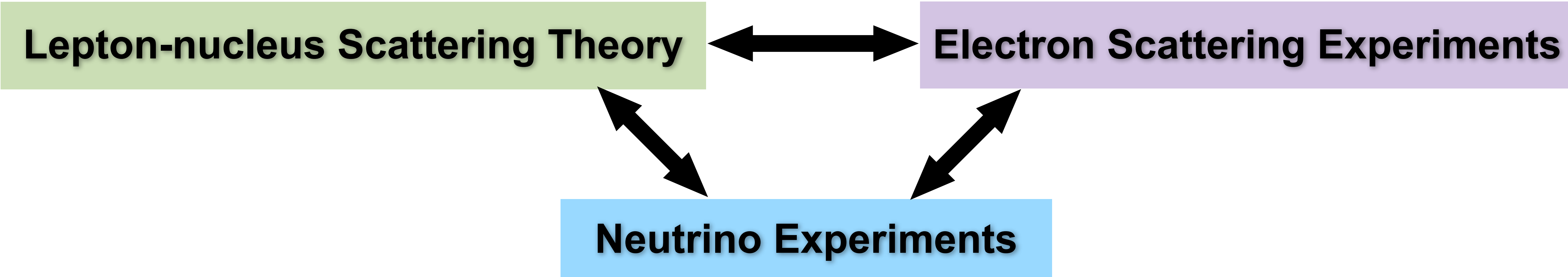


N. Van Dessel, VP et al., arXiv:2007.03658 [nucl-th]

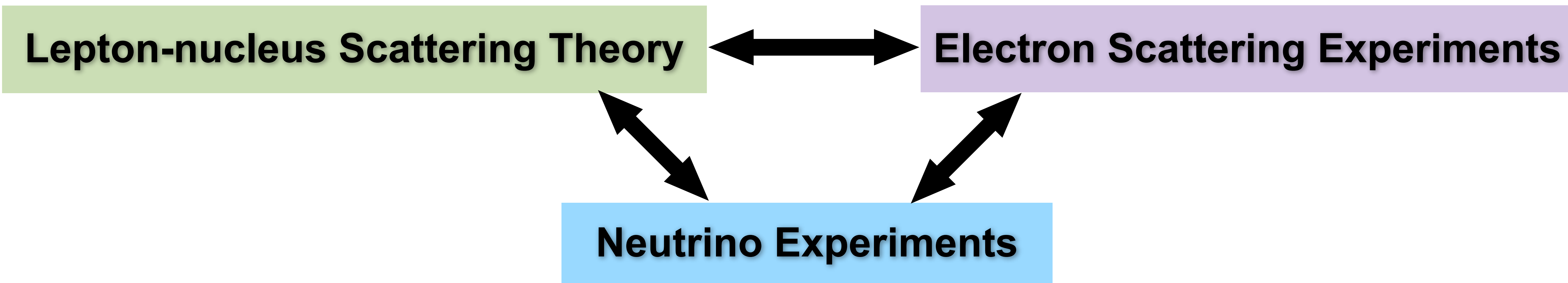
Outline

- ✦ Neutrinos: the portal to new frontiers in physics
- ✦ Neutrino interactions: a multi-scale, multi-process problem
- ✦ **Tackling neutrino interactions**

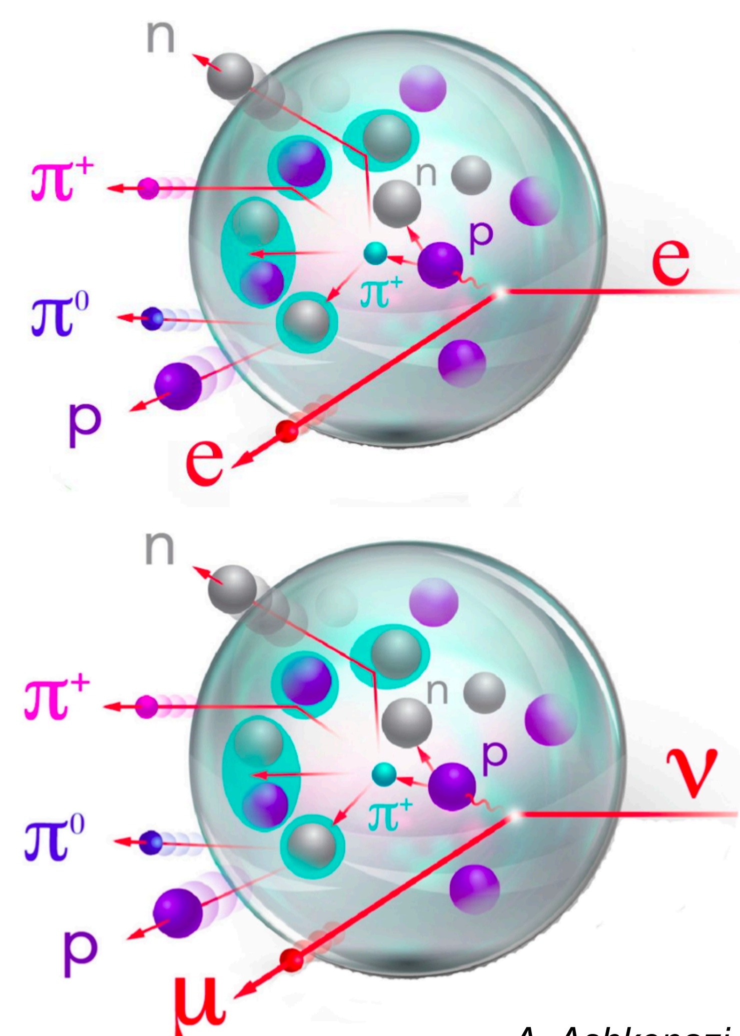
Tackling Neutrino Interactions



Tackling Neutrino Interactions



- **Electron Scattering Experiments**
  - Electron beams have well known energy. Kinematics of interests can be separated.
  - The vector current is conserved between electromagnetic and weak interactions.
  - The ground state nuclear properties and nuclear effects (final state interactions, etc.) are same.



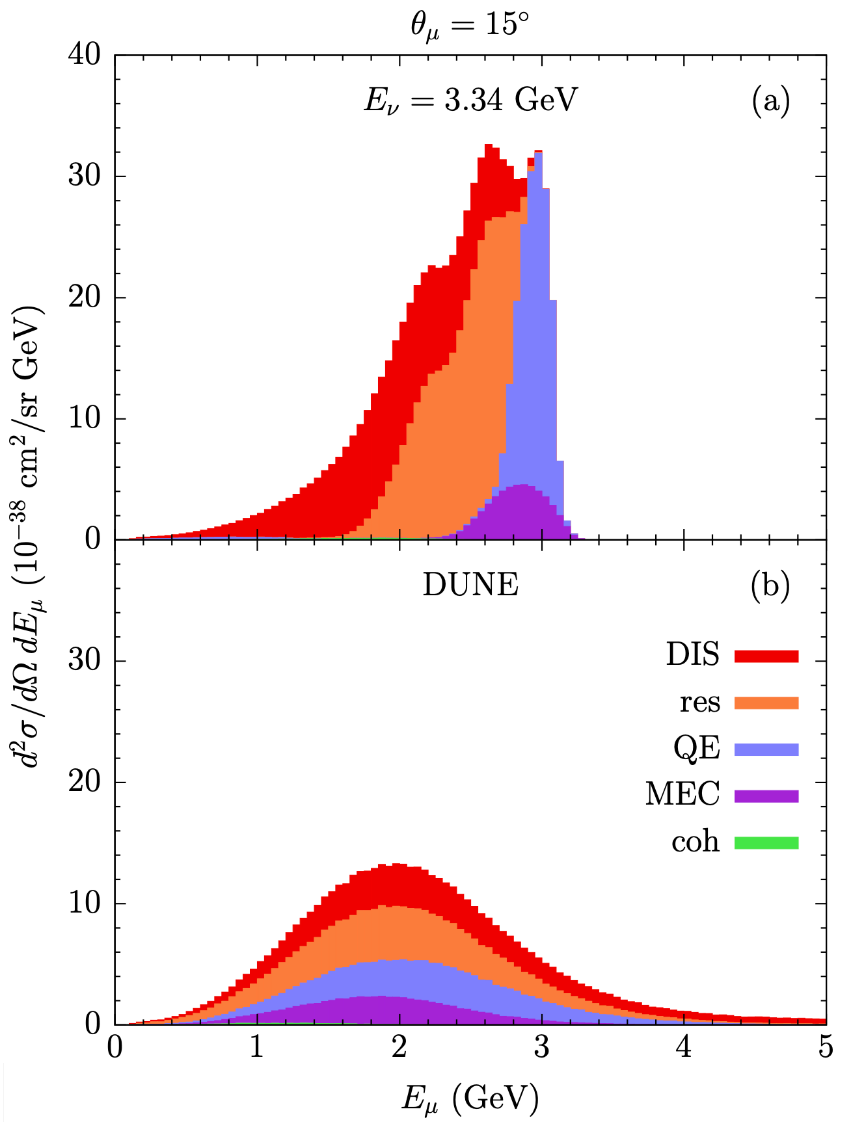
A. Ashkenazi

Tackling Neutrino Interactions

Lepton-nucleus Scattering Theory ↔ **Electron Scattering Experiments**

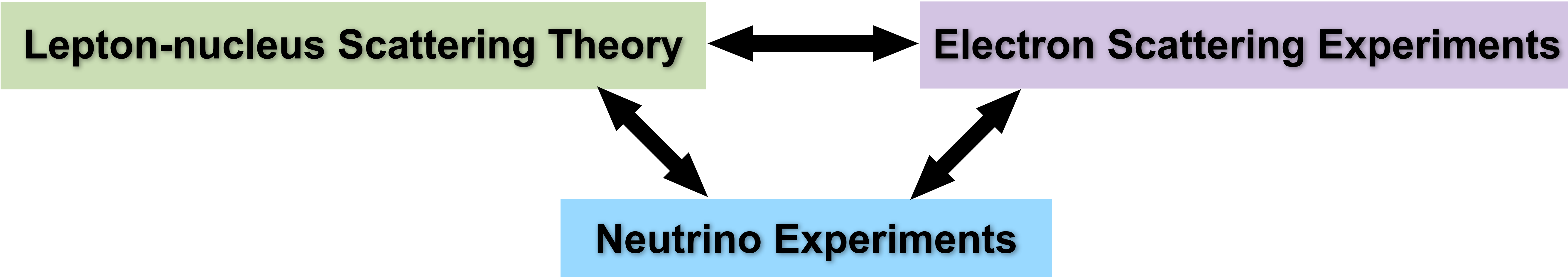
Neutrino Experiments

- **Neutrino Experiments**
  - Not possible to separate different processes
  - Axial contributions
  - ν_μ to ν_e differences: lepton mass effects, electron or muon in the final state experience different coulomb effects
  - ν to $\bar{\nu}$ differences: for isospin asymmetric nuclei, ^{40}Ar, neutrinos and antineutrinos may behold different nuclear effects



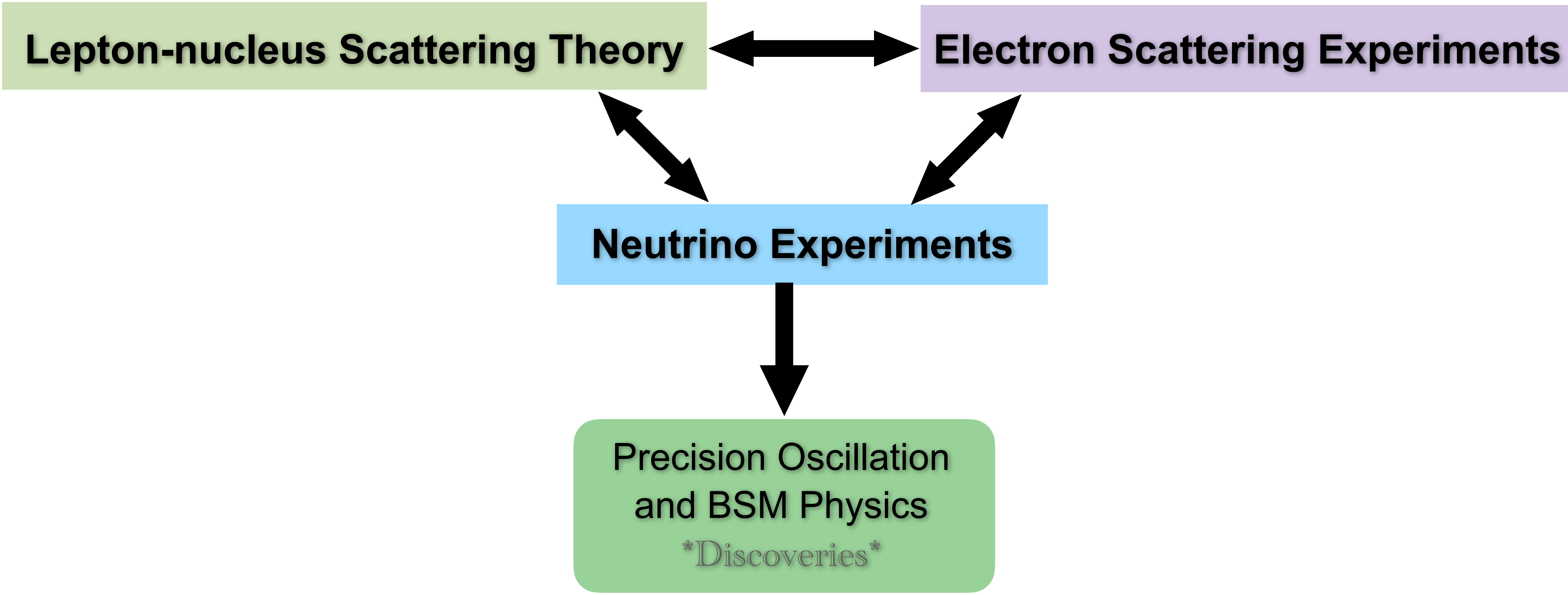
A. M. Ankowski et al., Phys. Rev. D 102, 053001 (2020)

Tackling Neutrino Interactions



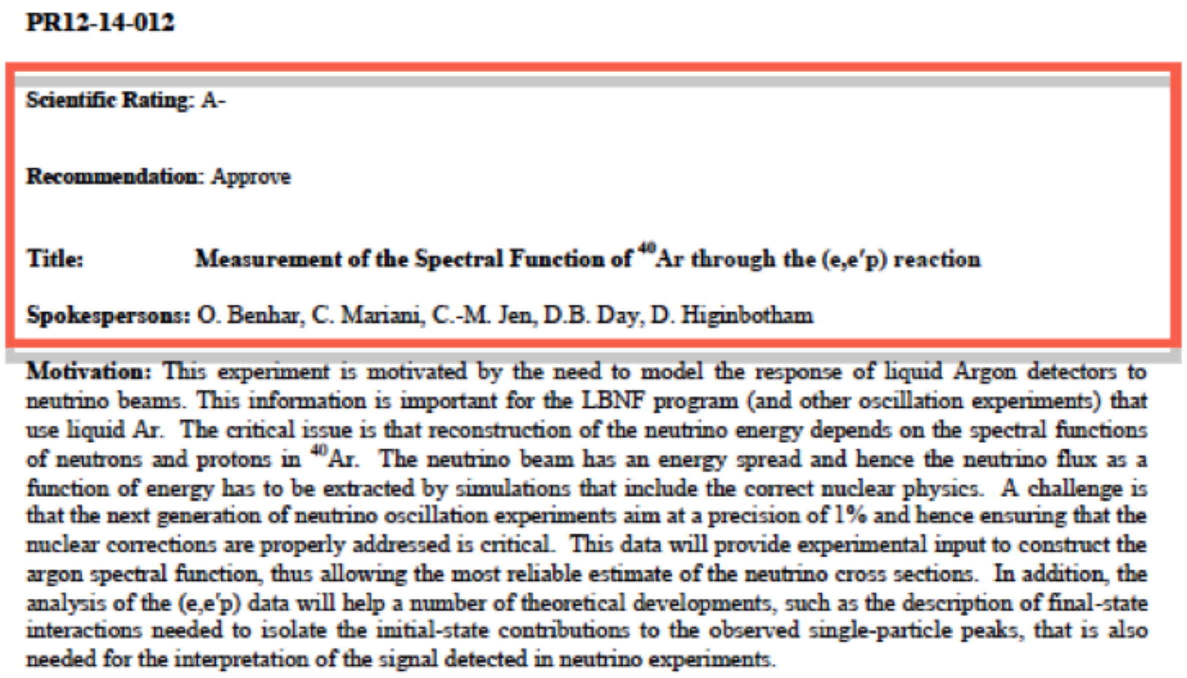
- **Lepton-nucleus Scattering Theory**
  - Microscopic consistent model
  - Tested and developed against electron and neutrino data
  - Implemented in neutrino generators

Tackling Neutrino Interactions



Electron-argon Experiment at JLab Hall A [E12-14-012]

- Measuring (e, e') and $(e, e'p)$ cross sections on Ar, Ti (and C, Al) nuclei.
- Measuring spectral functions of Ar nucleus.



PR12-14-012

Scientific Rating: A-

Recommendation: Approve

Title: **Measurement of the Spectral Function of ^{40}Ar through the (e,e′p) reaction**

Spokespersons: O. Benhar, C. Mariani, C.-M. Jen, D.B. Day, D. Higinbotham

Motivation: This experiment is motivated by the need to model the response of liquid Argon detectors to neutrino beams. This information is important for the LBNF program (and other oscillation experiments) that use liquid Ar. The critical issue is that reconstruction of the neutrino energy depends on the spectral functions of neutrons and protons in ^{40}Ar. The neutrino beam has an energy spread and hence the neutrino flux as a function of energy has to be extracted by simulations that include the correct nuclear physics. A challenge is that the next generation of neutrino oscillation experiments aim at a precision of 1% and hence ensuring that the nuclear corrections are properly addressed is critical. This data will provide experimental input to construct the argon spectral function, thus allowing the most reliable estimate of the neutrino cross sections. In addition, the analysis of the (e,e′p) data will help a number of theoretical developments, such as the description of final-state interactions needed to isolate the initial-state contributions to the observed single-particle peaks, that is also needed for the interpretation of the signal detected in neutrino experiments.

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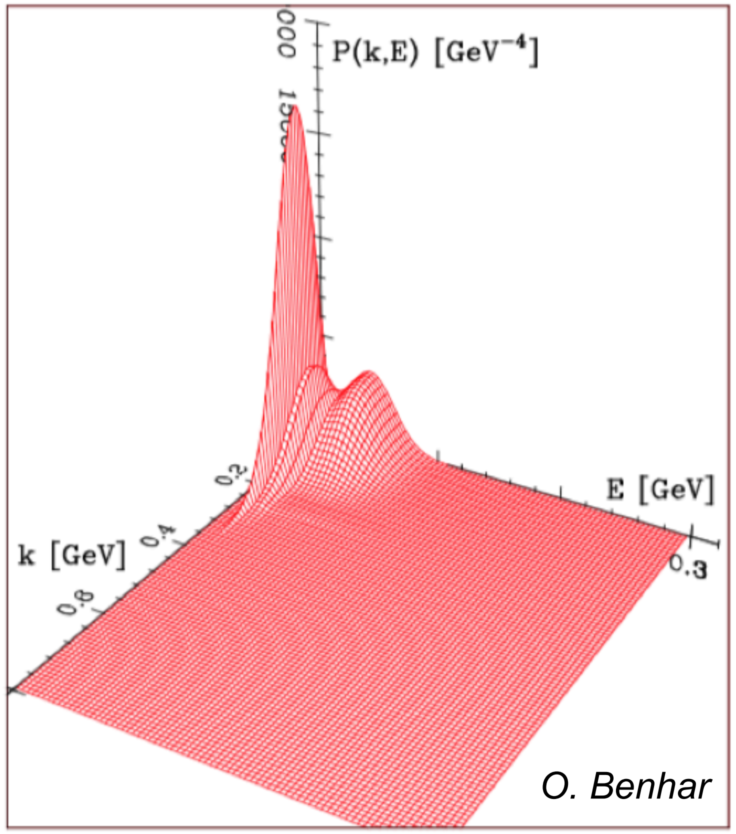
Spectral Function

- The spectral function, P(k,E), yields the probability of removing a nucleon of momentum k from the nuclear ground state leaving the residual system with excitation energy E.



Electron-argon Experiment at JLab Hall A [E12-14-012]

- We study the coincidence $(e, e'p)$ processes in the kinematical region in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

Coincidence *(e,e'p)* process:

- Both the outgoing electron and the proton are detected in coincidence, and the recoiling nucleus can be left in any bound state.

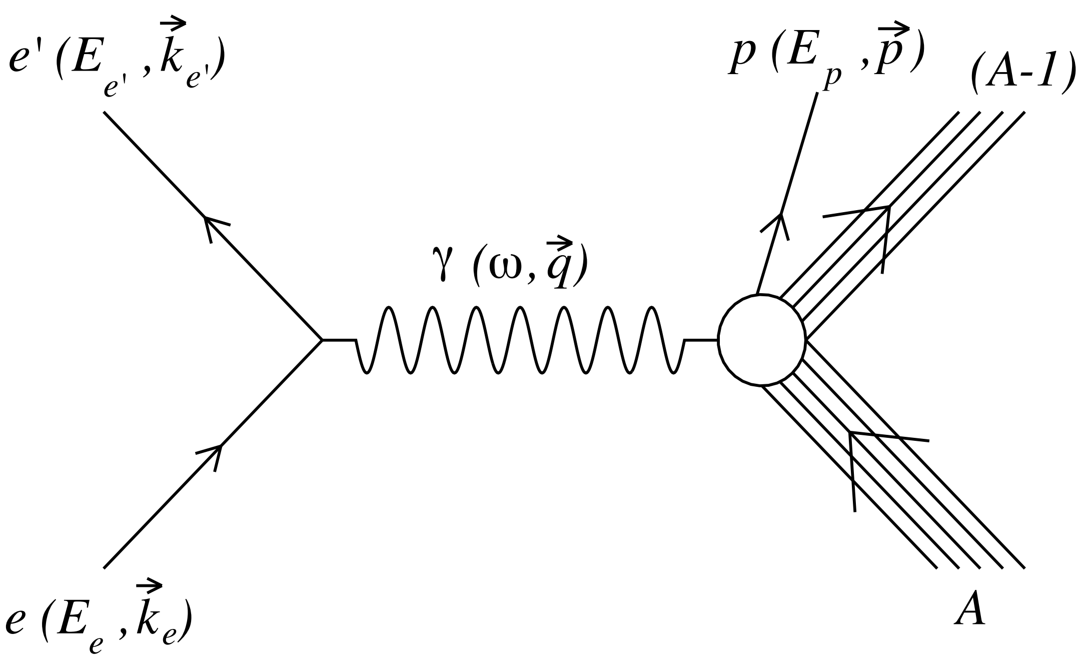
- Within the Plane Wave Impulse Approximation (PWIA) scheme:

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

- The initial energy and momentum of the knocked out nucleon can be identified with the measured missing momentum and energy, respectively as

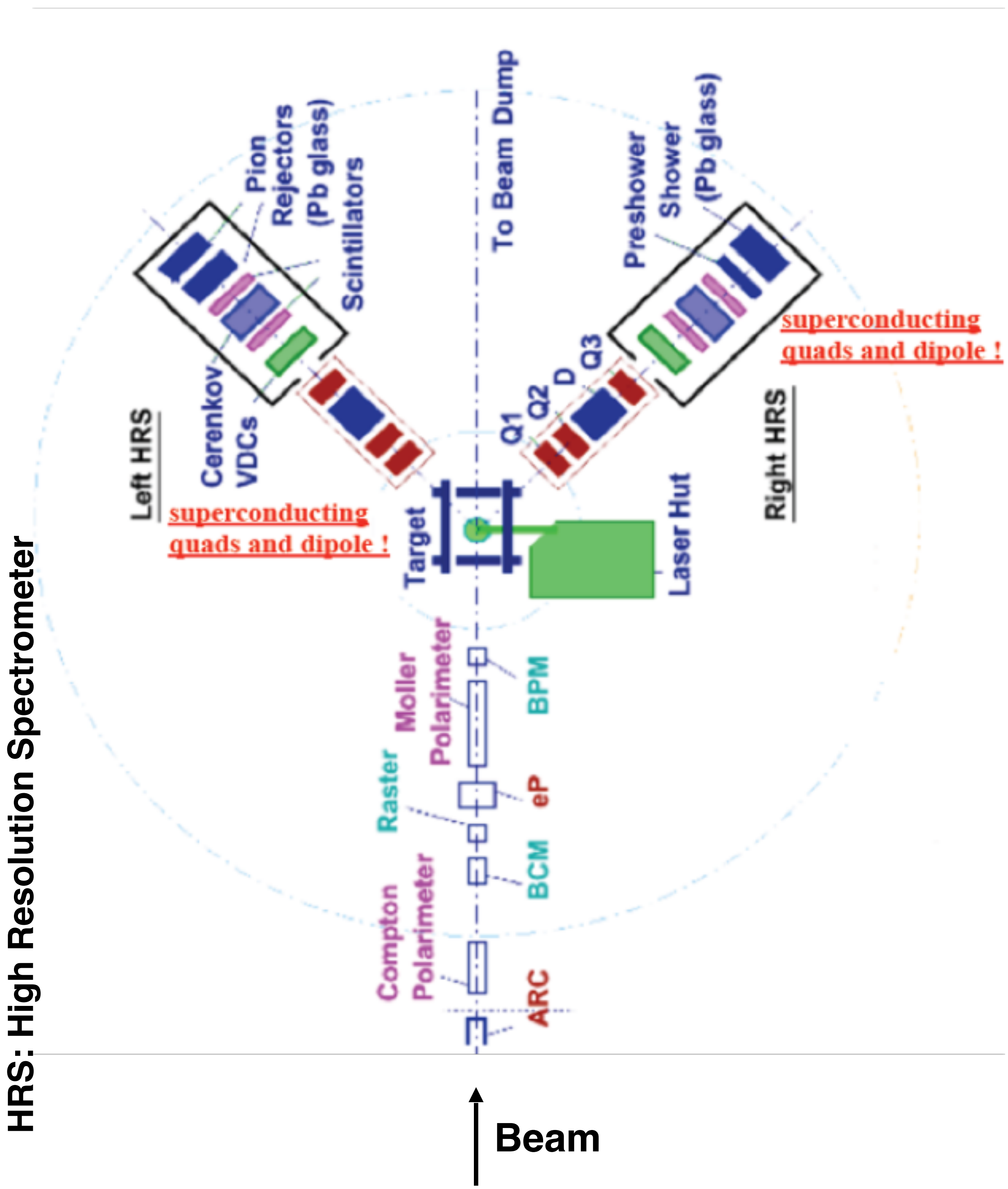
$$\mathbf{p}_m = \mathbf{p} - \mathbf{q}$$
$$E_m = \omega - T_p - T_{A-1} \sim \omega - T_p$$

Where $T_p = E_p - m$, is the kinetic energy of the outgoing proton.



Electron-argon Experiment at JLab Hall A [E12-14-012]

HALL A Schematics



High Resolution Spectrometer

Superconducting magnets:

- large acceptance in both angle and momentum
- good resolution in position and angle

Detector Package:

Vertical Drift Chambers:

- collecting tracking information (position and direction)

Scintillators:

- trigger to activate the data-acquisition electronics
- precise timing information for time-of-flight measurements and coincidence determination

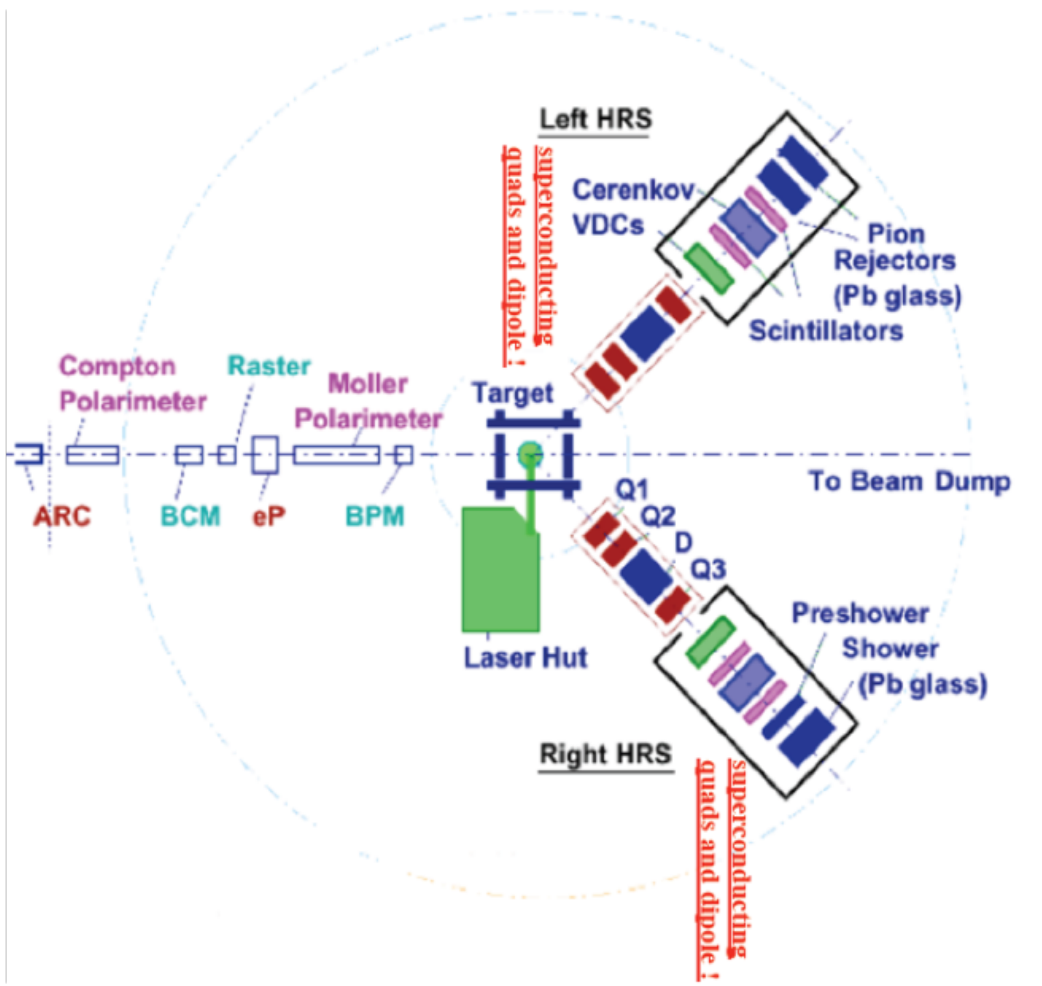
Cherenkov:

- The particle identification, obtained from a variety of Cherenkov type detectors (aerogel and gas) and lead-glass shower counters

Electron-argon Experiment at JLab Hall A [E12-14-012]

Kinematic Setups

	E_e MeV	$E_{e'}$ MeV	θ_e deg	P_p MeV/c	θ_p deg	$\lvert\mathbf{q}\rvert$ MeV/c	p_m MeV/c
kin1	2222	1799	21.5	915	−50.0	857.5	57.7
kin3	2222	1799	17.5	915	−47.0	740.9	174.1
kin4	2222	1799	15.5	915	−44.5	658.5	229.7
kin5	2222	1716	15.5	1030	−39.0	730.3	299.7
kin2	2222	1716	20.0	1030	−44.0	846.1	183.9
Inc-kin5	2222	-	15.5			730.3	299.7



Run Period: Feb-Mar 2017

kin1

Collected Data	Hours	Events (k)
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

kin3

Collected Data	Hours	Events (k)
Ar	13.5	73176
Ti	8.6	28423
Dummy	0.6	2948

kin2

Collected Data	Hours	Events(k)
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

kin4

Collected Data	Hours	Events(k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

kin5

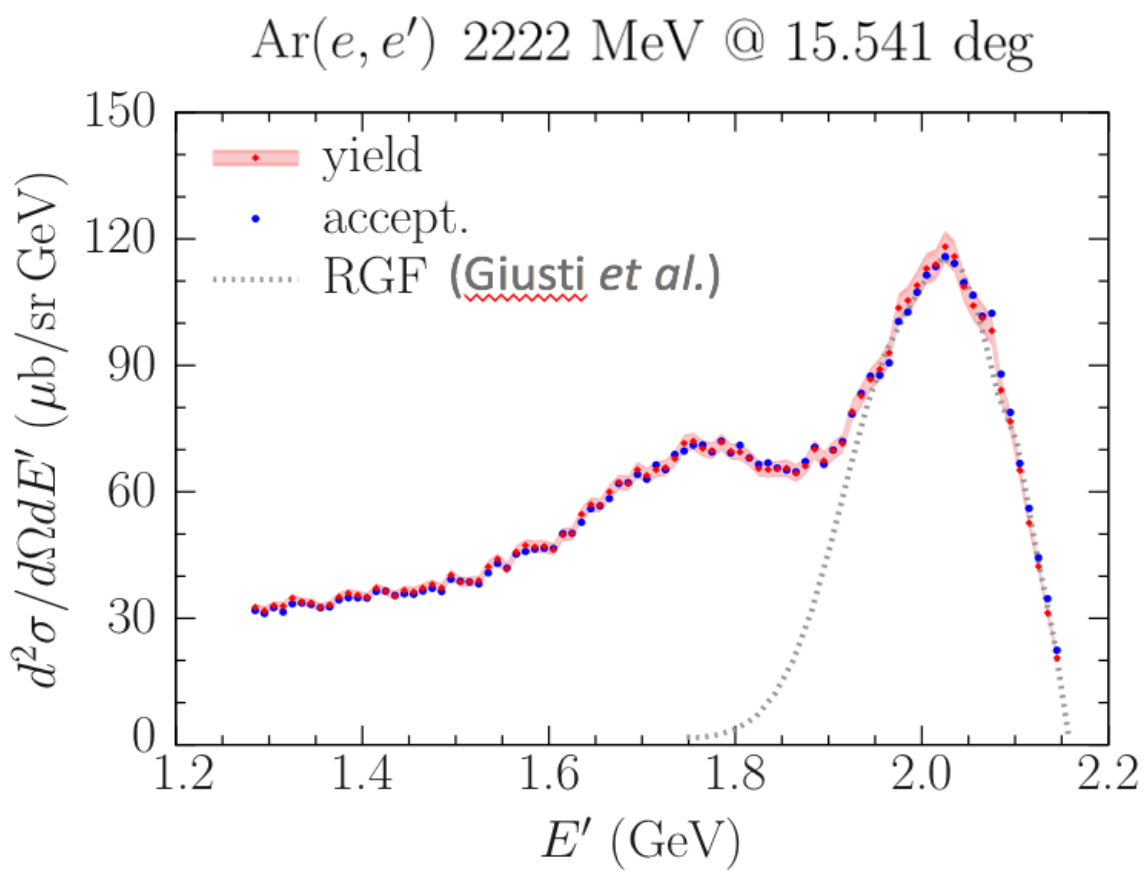
Collected Data	Hours	Events (k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

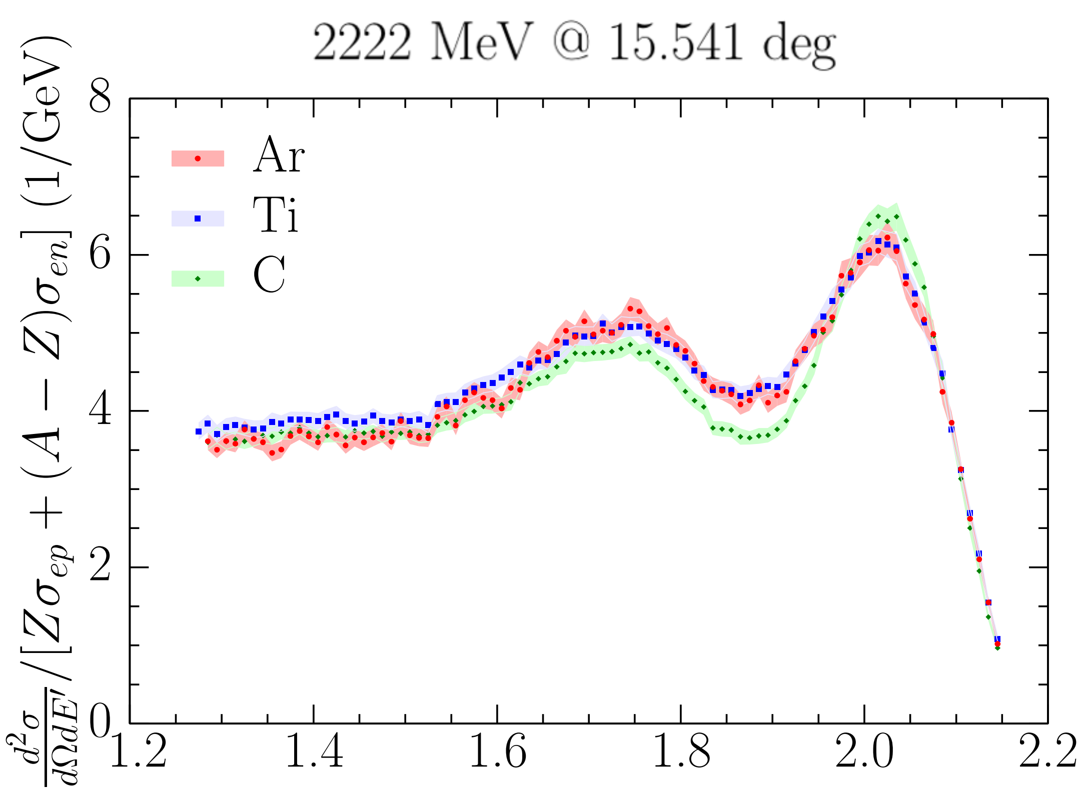
kin5 - Inclusive

Collected Data	Minutes	Events (k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

Electron-argon Experiment at JLab Hall A [E12-14-012]

Inclusive Cross Section Results





*H. Dai, M. Murphy, **VP** et al. [JLab Hall A Collaboration], Phys. Rev. C99, 054608 (2019)*
*H. Dai, M. Murphy, **VP** et al. [JLab Hall A Collaboration], Phys. Rev. C98, 014617 (2018)*

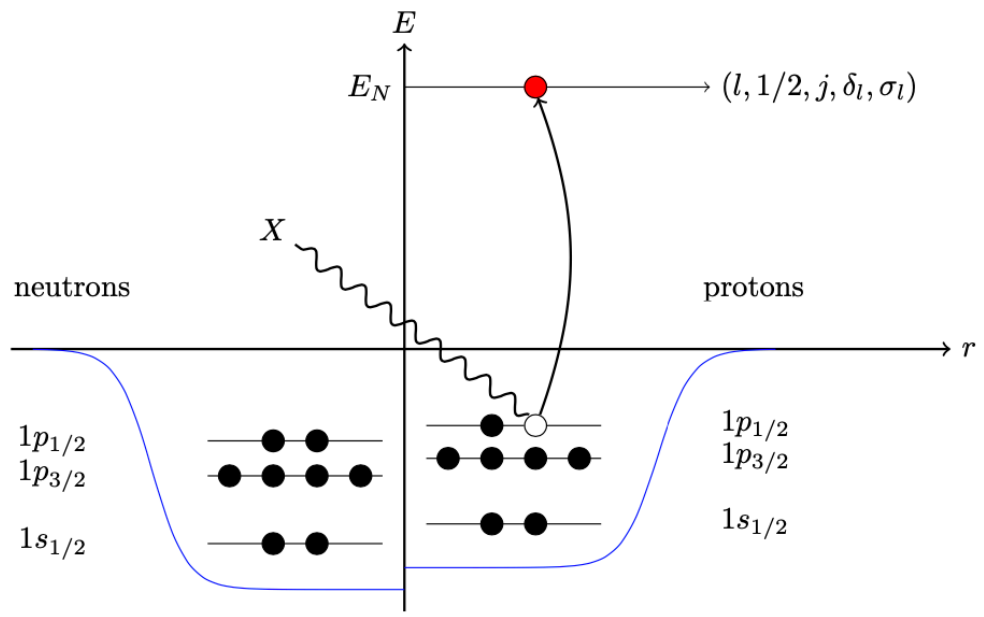
✦ First high-precision electron-argon cross section measurement, vital input to liquid argon based neutrino program.

Lepton-nucleus Scattering: HF-CRPA 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.

- Introduce long-range correlations between the nucleons through the continuum Random Phase Approximation (**CRPA**).



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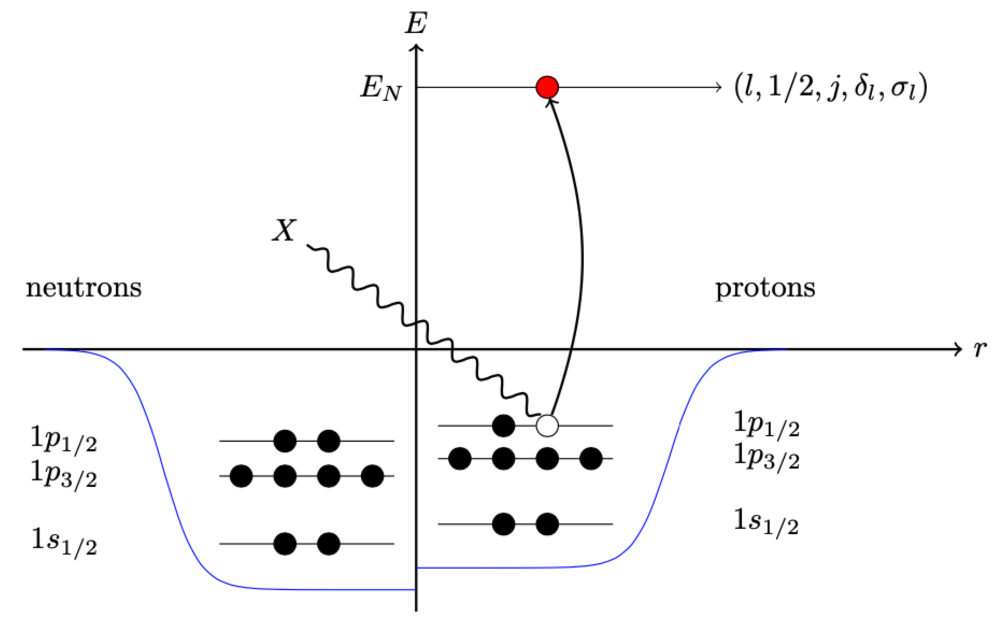

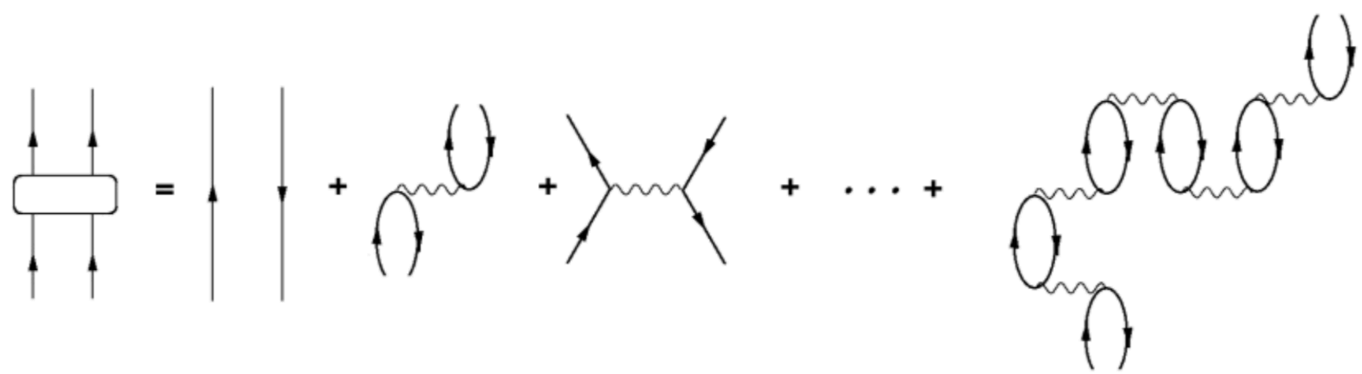

$$\Pi^{(RPA)}(x_1, x_2; \omega) = \Pi^{(0)}(x_1, x_2; \omega) + \frac{1}{\hbar} \int dx \int dx' \; \Pi^{(0)}(x_1, x; \omega)\, \widetilde{V}(x, x')\, \Pi^{(RPA)}(x', x_2; \omega)$$

- Naturally includes: Binding, Fermi motion, elastic final state interaction (distortion of the outgoing nucleon in real MF potential), Pauli blocking, and orthogonality (both bound and scattered nucleon wave-functions are computed in the same nuclear potential).

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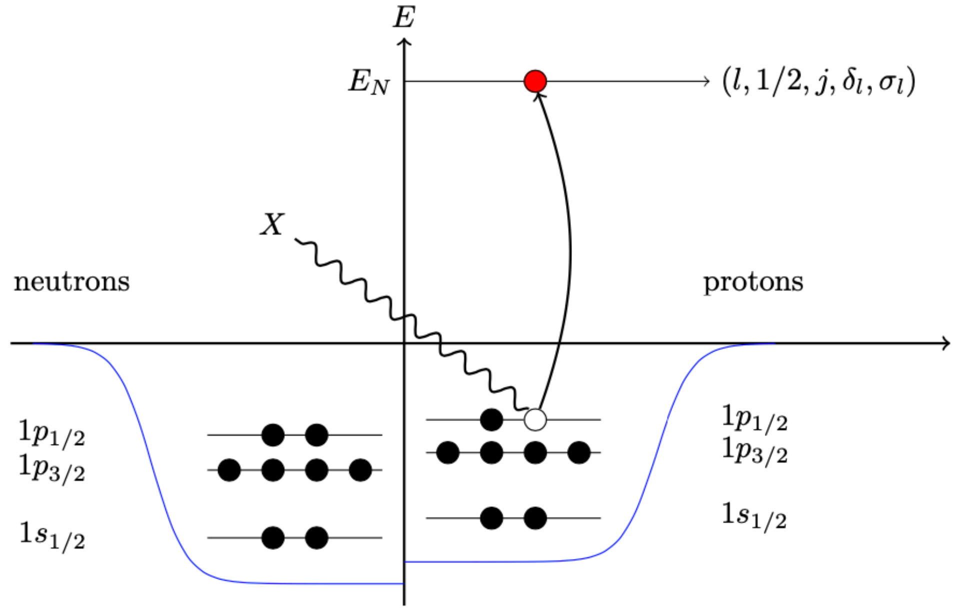
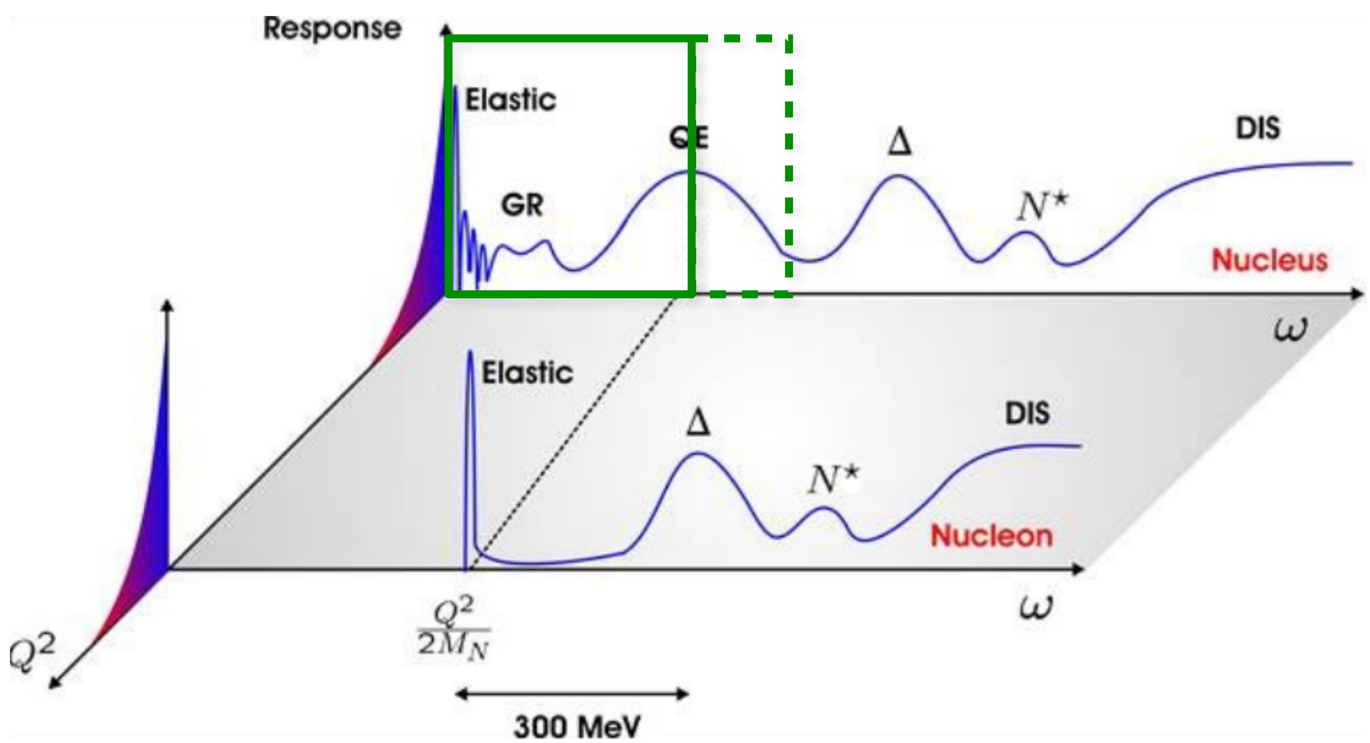


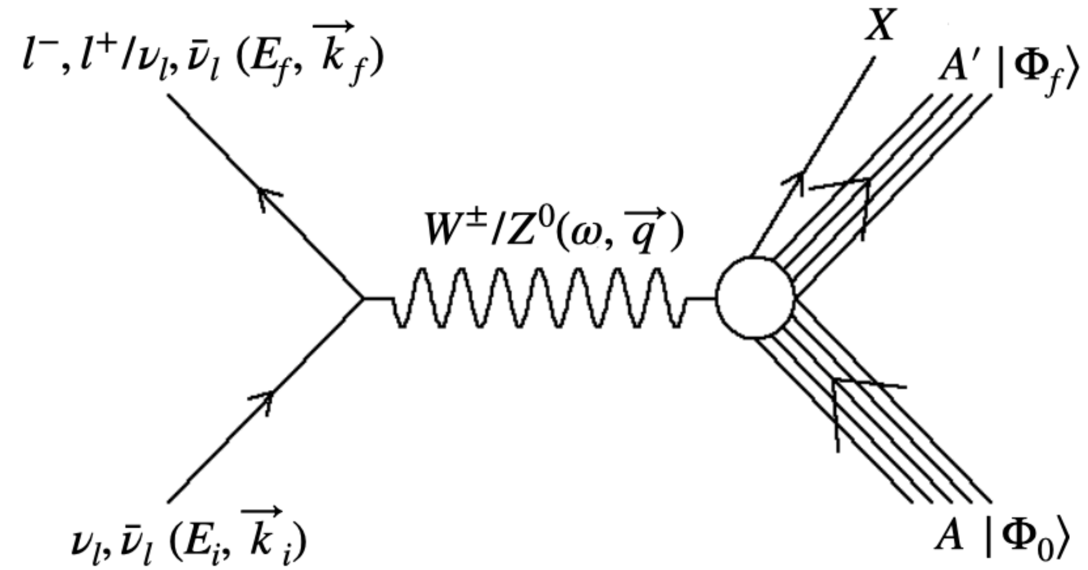


✦ A consistent many-body theory framework that describes lepton-nucleus processes from threshold to QE region: CEvNS, low-energy inelastic (supernova neutrinos) and QE processes.

Lepton-nucleus Scattering Cross Section

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

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



$$\omega = E_i - E_f, \quad q = |\vec{k}_i - \vec{k}_f|, \quad Q^2 = q^2 - \omega^2$$

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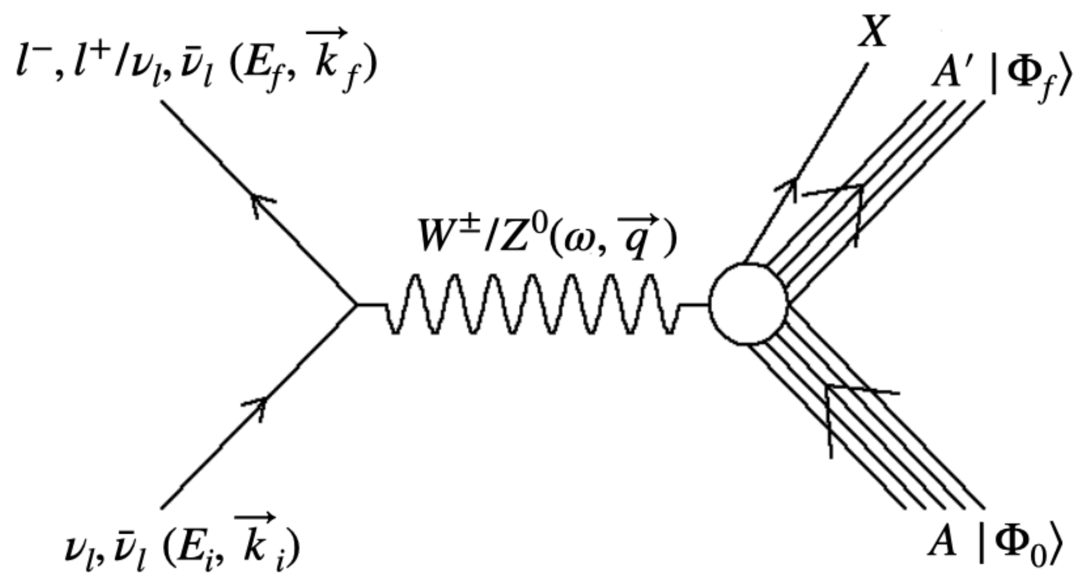

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$$\omega = E_i - E_f, \quad q = |\vec{k}_i - \vec{k}_f|, \quad Q^2 = q^2 - \omega^2$$

- Electron-nucleus cross sections:

$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i} \times \zeta^2(Z', E_f, q_e)\left[\sum_{J=0}^{\infty}\sigma_{L,e}^J + \sum_{J=1}^{\infty}\sigma_{T,e}^J\right]$$

- Neutrino-nucleus cross sections:

$$\left(\frac{d^2\sigma}{d\omega_\nu d\Omega}\right)_\nu = \frac{G_F^2 \cos^2\theta_c}{(4\pi)^2}\left(\frac{2}{2J_i+1}\right)\varepsilon_f \kappa_f \times \zeta^2(Z', \varepsilon_f, q_\nu)\left[\sum_{J=0}^{\infty}\sigma_{CL,\nu}^J + \sum_{J=1}^{\infty}\sigma_{T,\nu}^J\right]$$

$$\sigma_{L,e} = v_e^L R_e^L$$

$$\sigma_{T,e} = v_e^T R_e^T$$

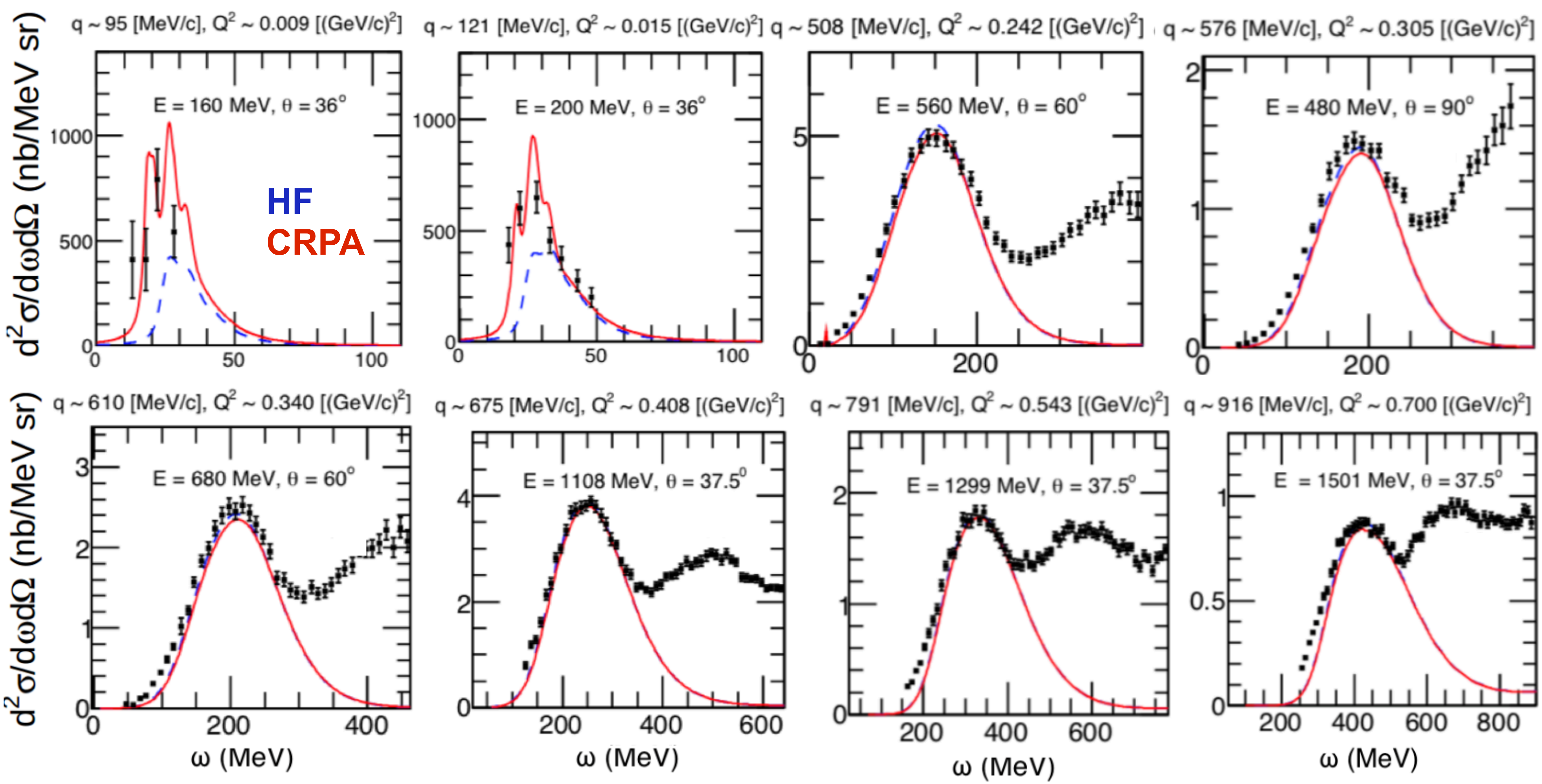
$$\sigma_{CL,\nu}^J = \left[v_\nu^{\mathcal{M}} R_\nu^{\mathcal{M}} + v_\nu^{\mathcal{L}} R_\nu^{\mathcal{L}} + 2\, v_\nu^{\mathcal{ML}} R_\nu^{\mathcal{ML}}\right]$$

$$\sigma_{T,\nu}^J = \left[v_\nu^T R_\nu^T \pm 2\, v_\nu^{TT} R_\nu^{TT}\right]$$

- $\zeta^2(Z', E_f, q_e)$ takes care of the influence of the Coulomb field of nucleus on the outgoing charged lepton.
- σ_L and σ_T are summed over multipoles corresponds to discrete and continuum states of a nucleus having angular momentum and parity (J^π) as good quantum numbers.

Comparison with (e, e') data on ^{12}C, ^{16}O, and ^{40}Ca

- **^{12}C(e,e') cross sections**
  - Range of three momentum transfer at the QE peak: $100\ MeV \lesssim |q| \lesssim 1000\ MeV$



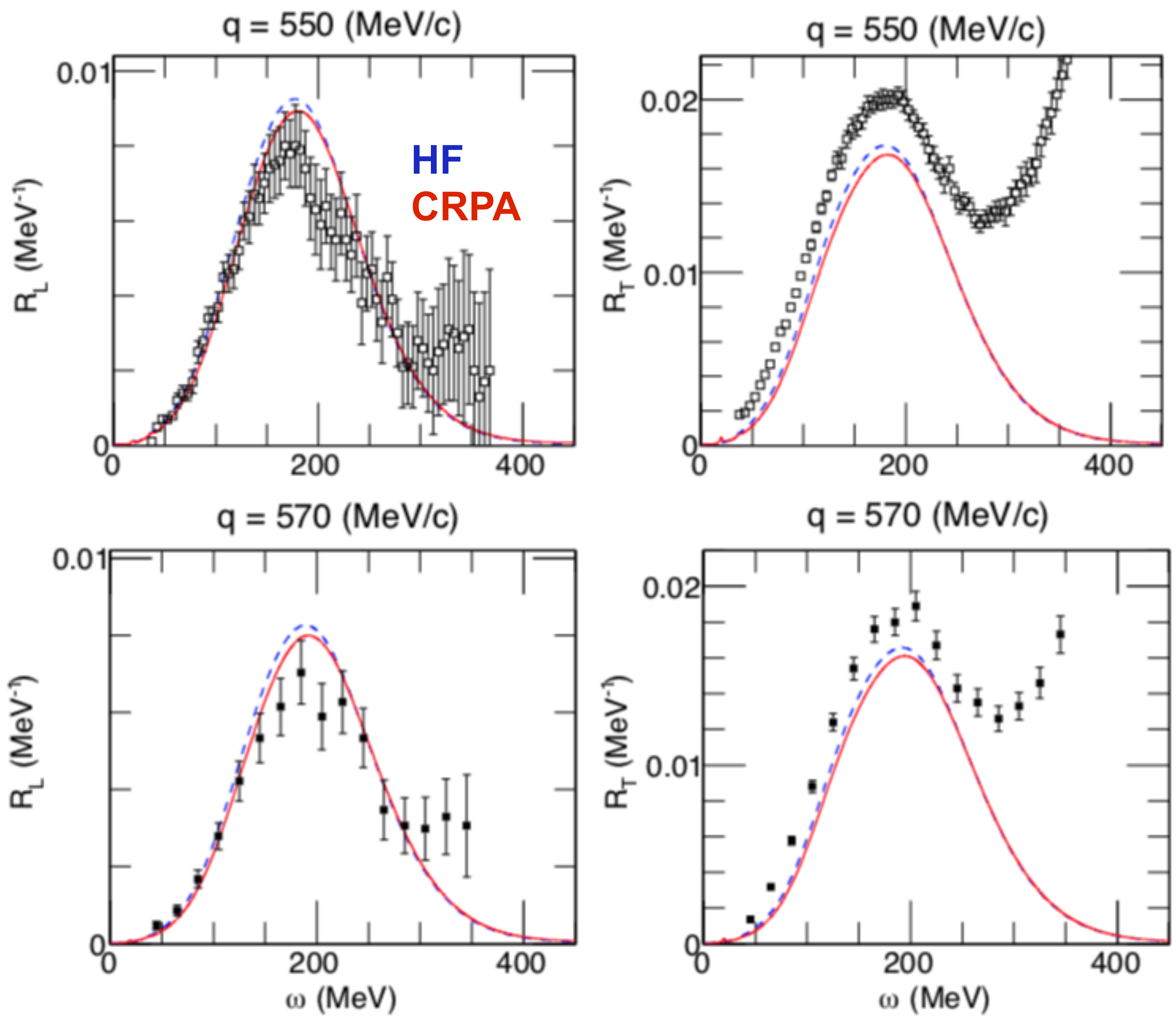
***VP**, N. Jachowicz, T. Van Cuyck, J. Ryckebusch, M. Martini, Phys. Rev. C92, 024606 (2015)*

Data from:

D. Zeller, DESY-F23-73-2 (1973); P. Barreau et al., Nucl. Phys. A402, 515 (1983); J. S. O'Connell et al., Phys. Rev. C35, 1063 (1987); D. S. Bagdasaryan et al., YERPHI-1077-40-88 (1988); R. M. Sealock et al., Phys. Rev. Lett.62, 1350 (1989); D. B. Day et al., Phys. Rev. C 48, 1849 (1993); M. Anghinolfi et al., Nucl. Phys. A602, 405 (1996); J. Jourdan, Nucl. Phys. A603, 117 (1996); C. F. Williamsonet al., Phys. Rev. C56, 3152 (1997)

Comparison with (e, e') data on ^{12}C, ^{16}O, and ^{40}Ca

- ^{12}C(e,e') R_L and R_T



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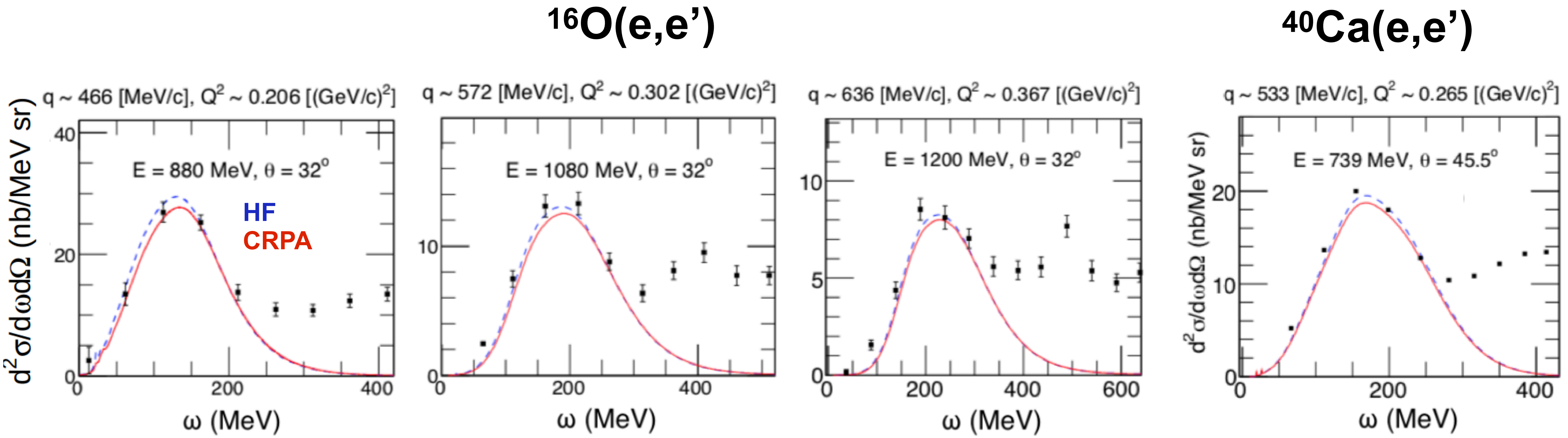
- **$^{16}O(e,e')$ and $^{40}Ca(e,e')$ cross sections**



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

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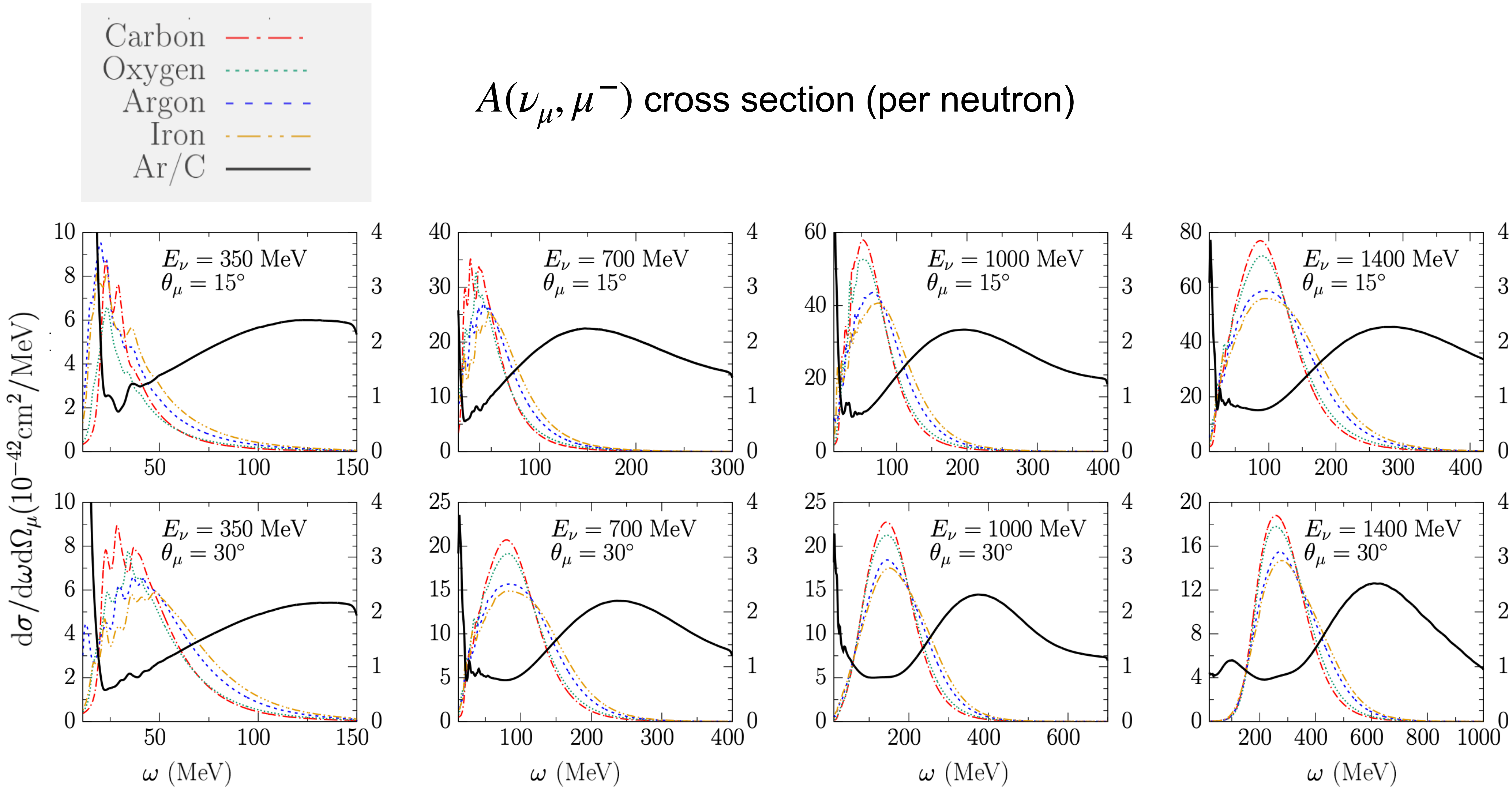
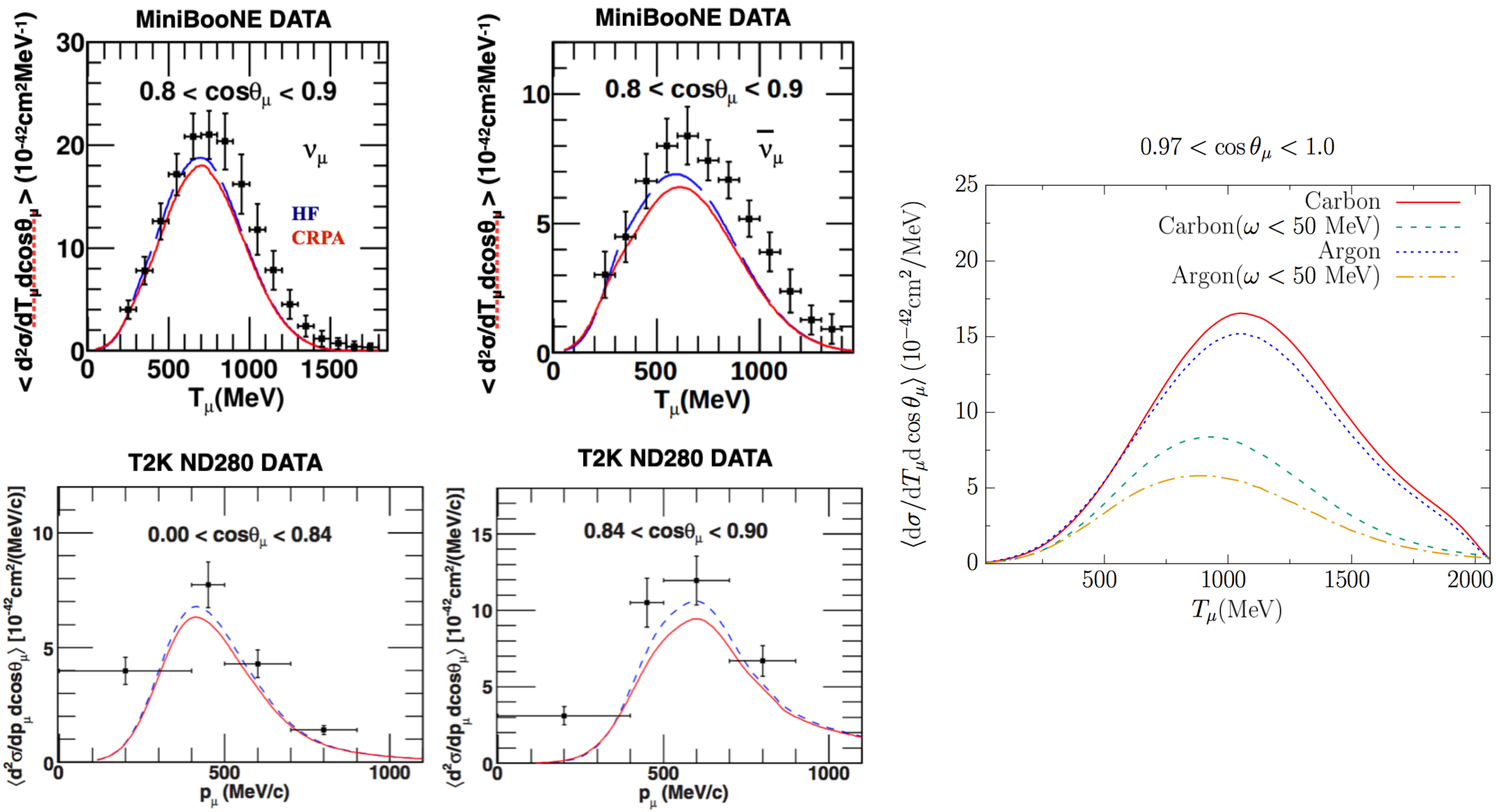
Neutrino Cross Sections on ^{12}C, ^{16}O, ^{40}Ar and ^{56}Fe

$A(\nu_\mu, \mu^-)$ cross section (per neutron)



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

Comparison with Neutrino Data

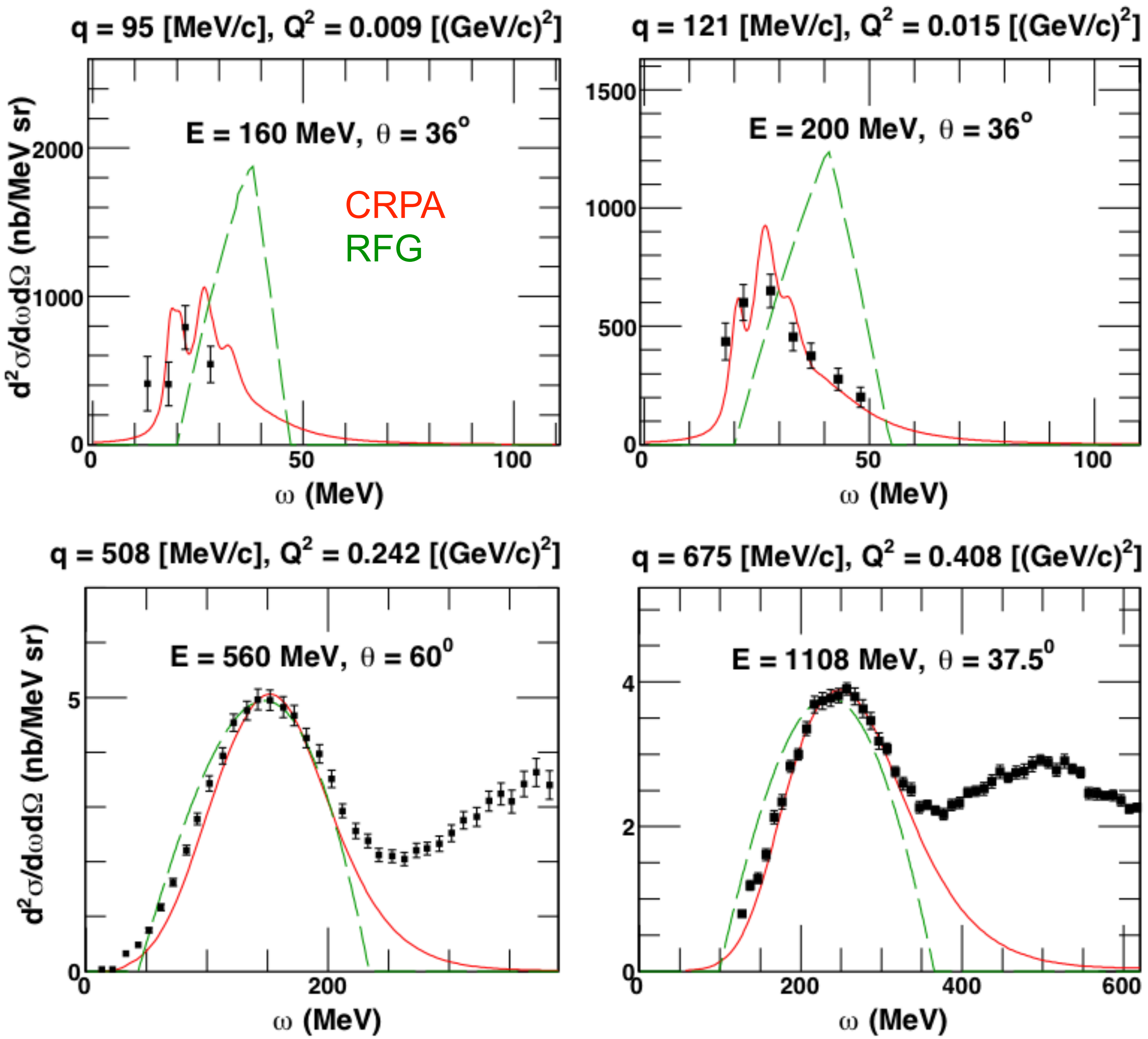


***VP**, N. Jachowicz, M. Martini, R. González Jiménez, J. Ryckebusch et al., Phys. Rev. C94, 054609 (2016)*
*N. Van Dessel, N. Jachowicz, R. González-Jiménez, **VP**, T. Van Cuyck, Phys. Rev. C97, 044616 (2018)*

MiniBooNE data: Phys. Rev. D 81, 092005 (2010), Phys. Rev. D 88, 032001 (2013).
T2K data: Phys. Rev. D87, 092003 (2013).

Comparison with Relativistic Fermi Gas (RFG) model and GENIE

- **Electron-nucleus Scattering**



Comparison with Relativistic Fermi Gas (RFG) model and GENIE

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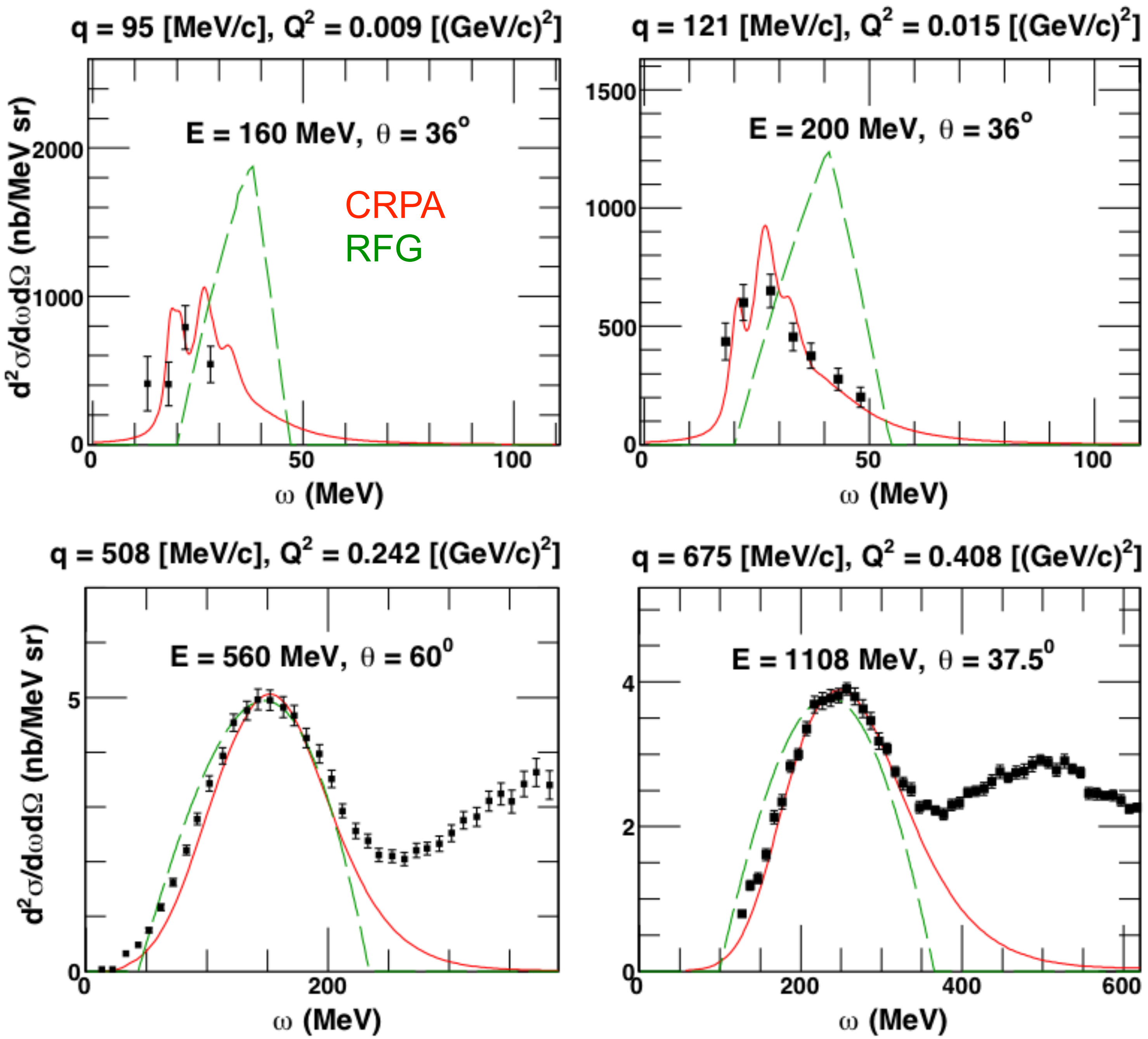
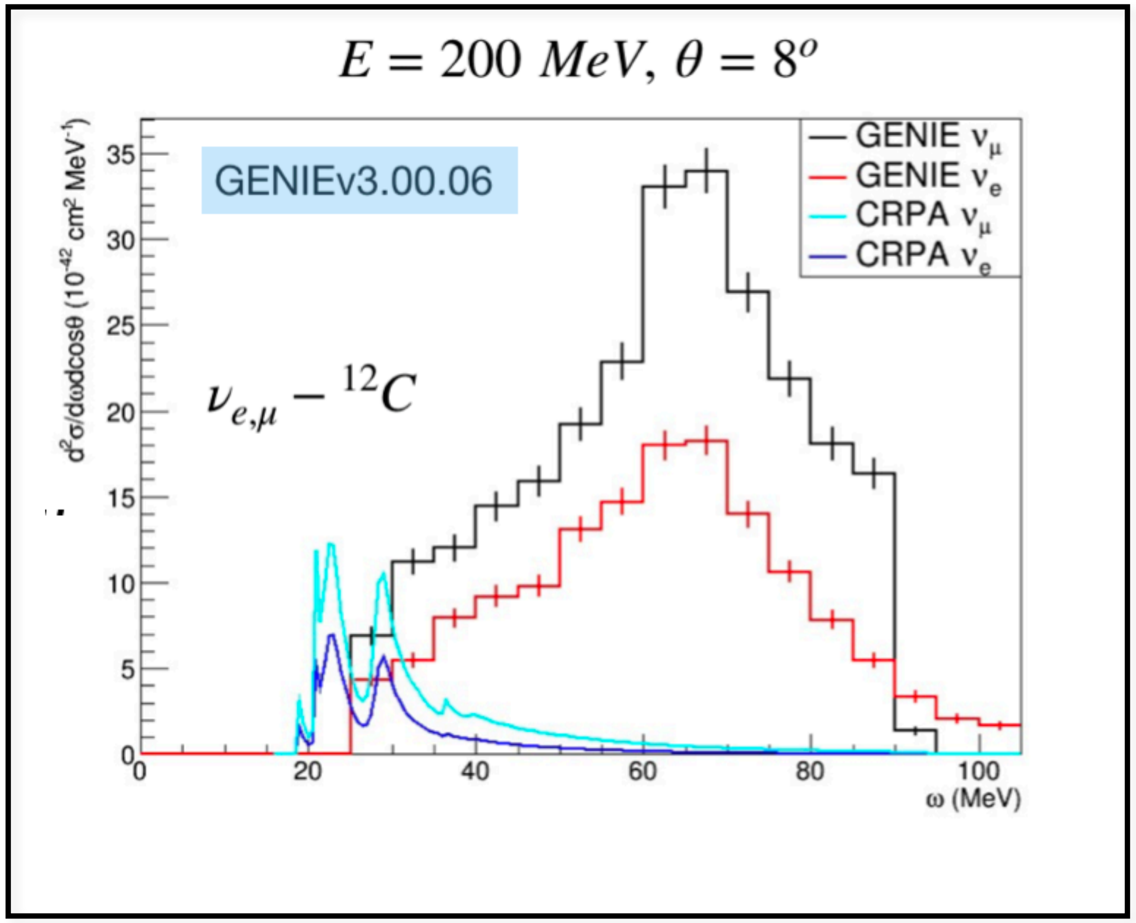


- **Neutrino-nucleus Scattering**

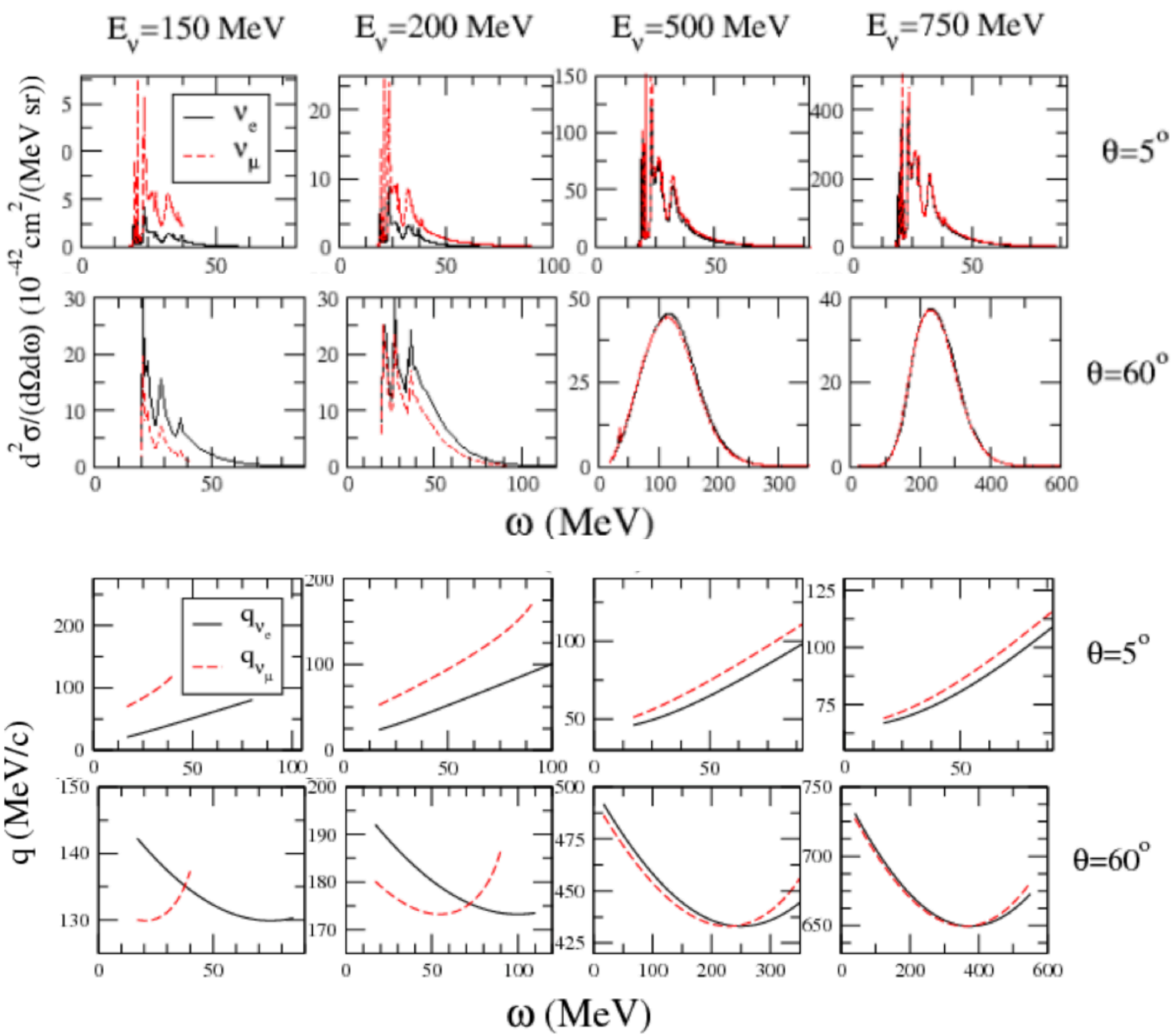


ν_e to ν_μ Cross Section Differences

ν_e to ν_μ Cross Section Differences

- At lower energies:
  - For small scattering angles, ν_μ cross sections are higher than the ν_e ones.
  - For larger scattering angles, this behavior is opposite.

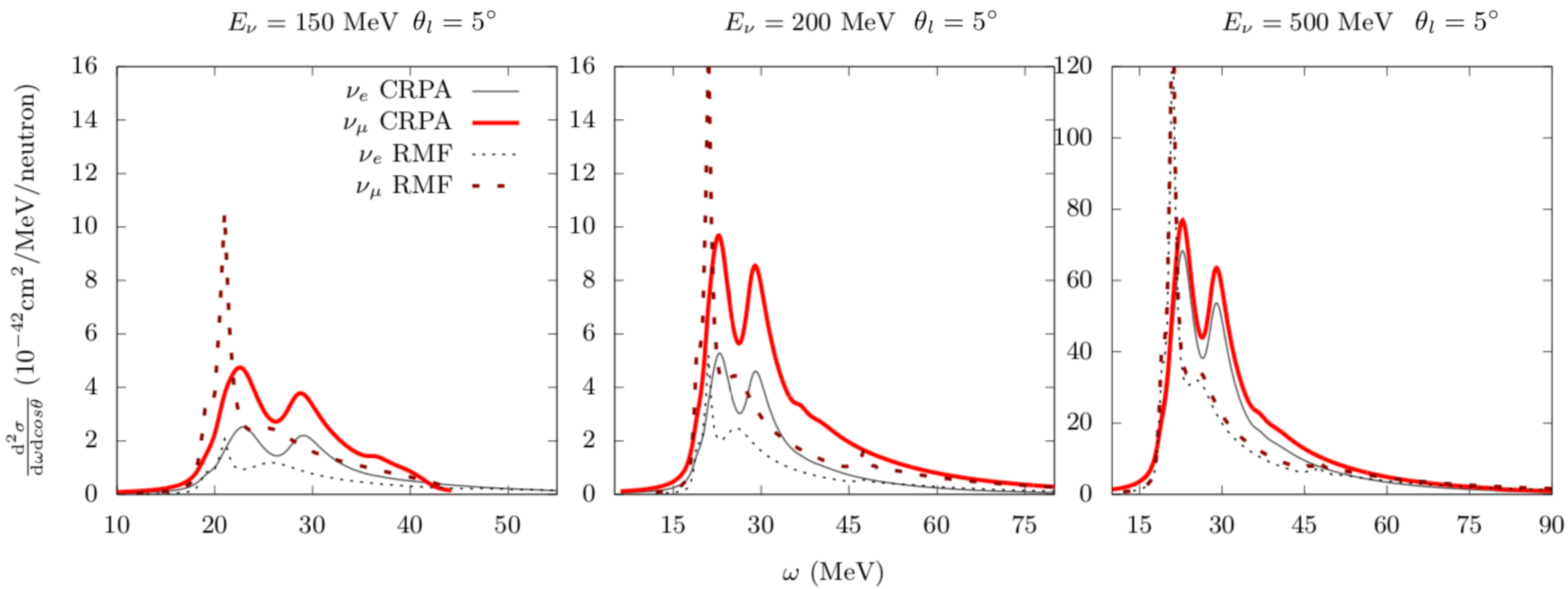
- At higher energies:
  - ν_e and ν_μ cross sections roughly coincide.



*M. Martini, N. Jachowicz, M. Ericson, **VP**, T. Van Cuyck, N. Van Dessel, Phys. Rev. C94, 015501 (2016)*

ν_e to ν_μ Cross Section Differences

- Using two independent Mean-Field approaches: RMF and HF-CRPA
  - MF approaches (in a nutshell): All bound and scattering states are obtained by solving the Schrödinger (or Dirac) equation in a central mean field potential. This means all states are consistent and orthogonal. Naturally includes: Binding, Fermi motion, Elastic final state interactions, Pauli blocking, orthogonality (the nucleon wave function does not overlap with a bound state).

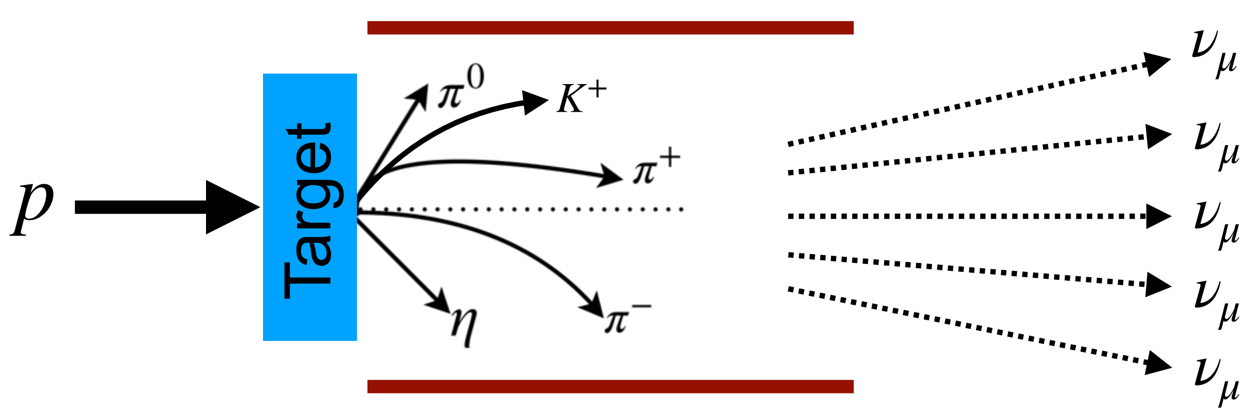


*A. Nikolakopoulos, N. Jachowicz, N. Van Dessel, K. Niewczas, R. González-Jiménez, J. M. Udías, **VP**, Phys. Rev. Lett. 123, 052501 (2019).*

- Larger ν_μ than ν_e cross sections for low ω and q (if the initial and final state wave functions are treated consistently).
  - The muon mass in the final state leads to a larger momentum transfer which shifts the response to larger values.

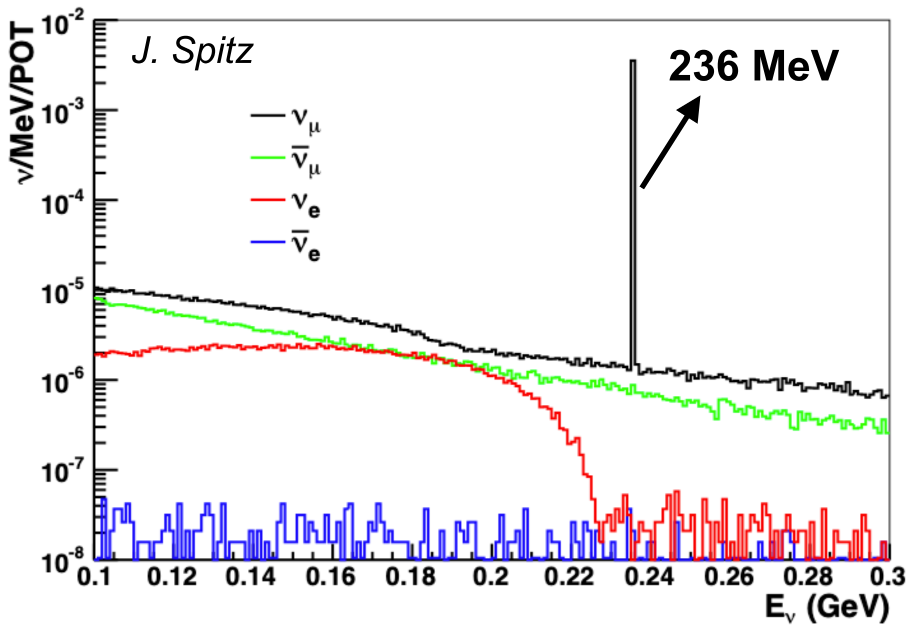
10 MeV 100 MeV 1 GeV 10 GeV

$K^+ \rightarrow \mu^+ \nu_\mu$ (63.4%)



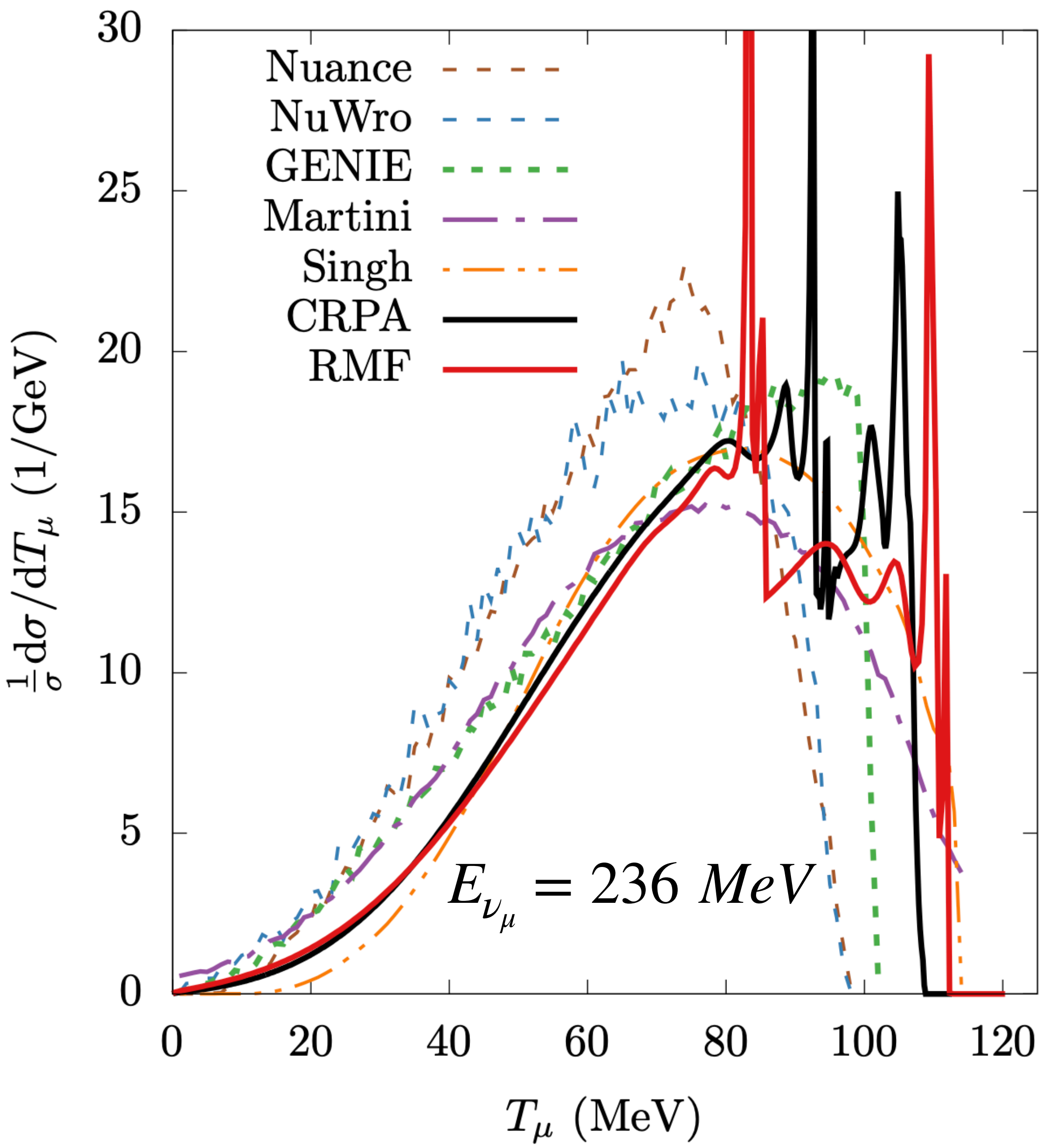
Magnetic Focusing Horn

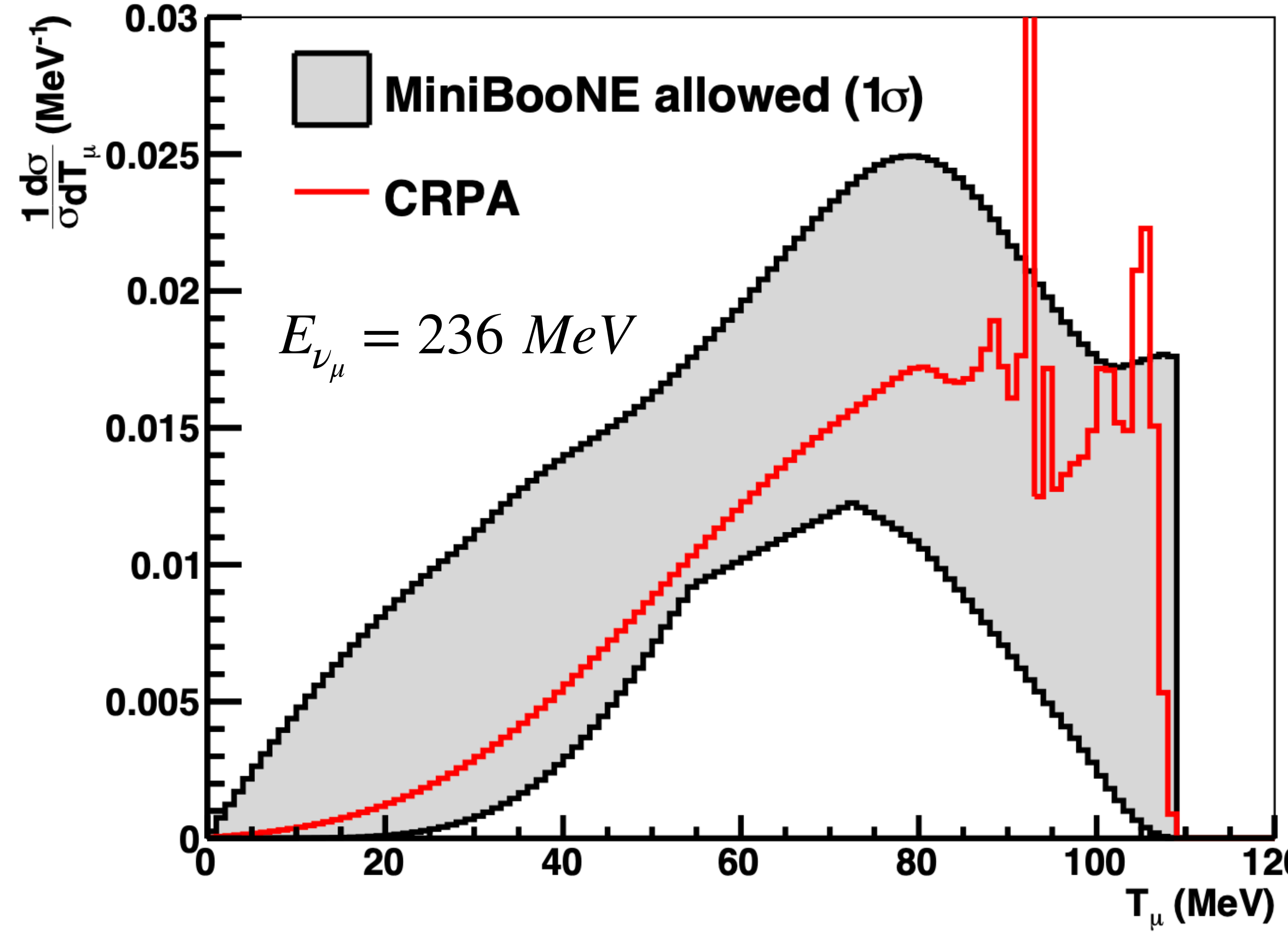
Kaon decay at rest



Mono-energetic kaon decay at rest neutrinos

- Mono-energetic neutrino source: kaon decay at rest $K^+ \rightarrow \mu^+\nu_\mu, E_{\nu_\mu} = 236\ MeV$



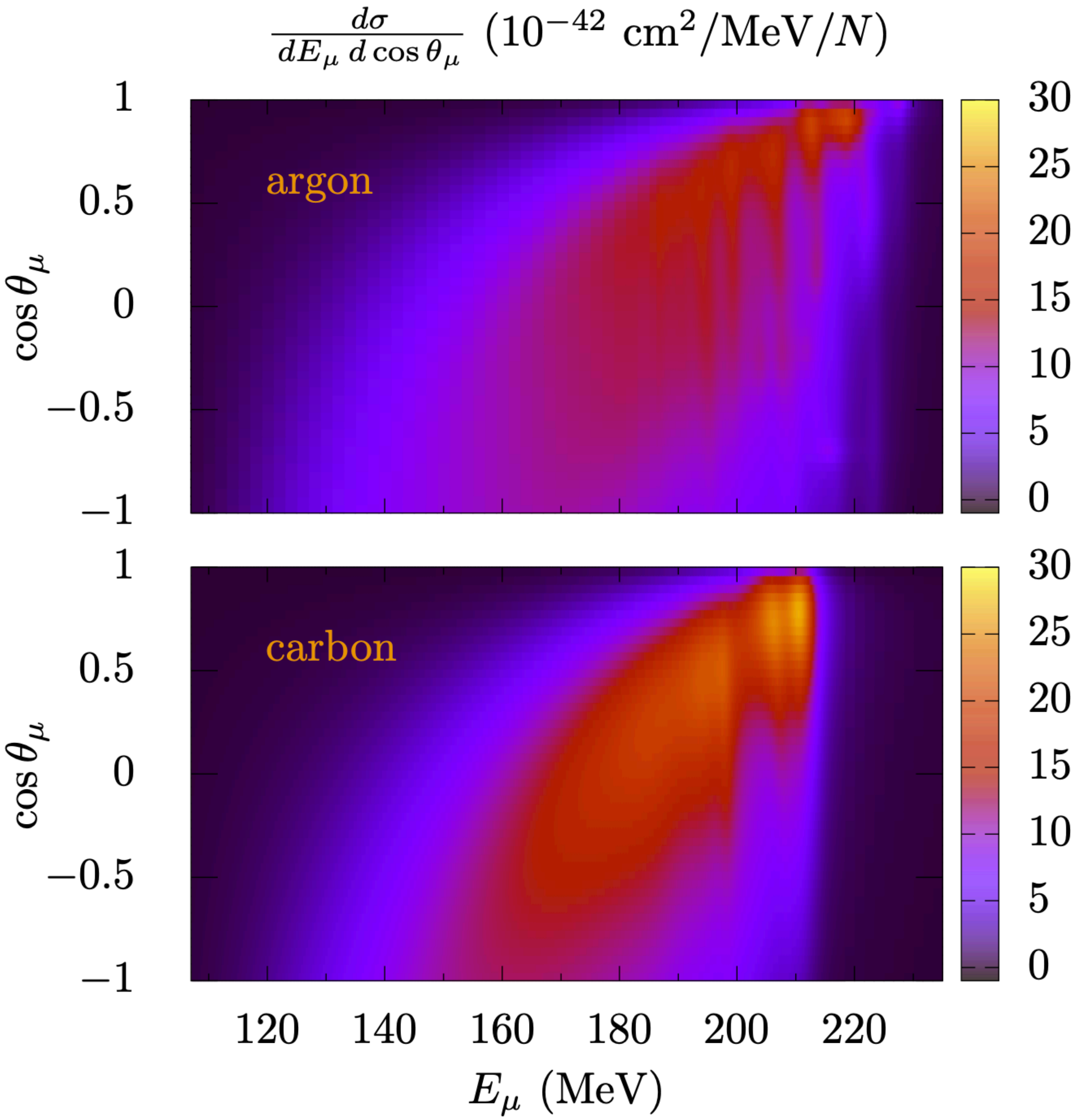


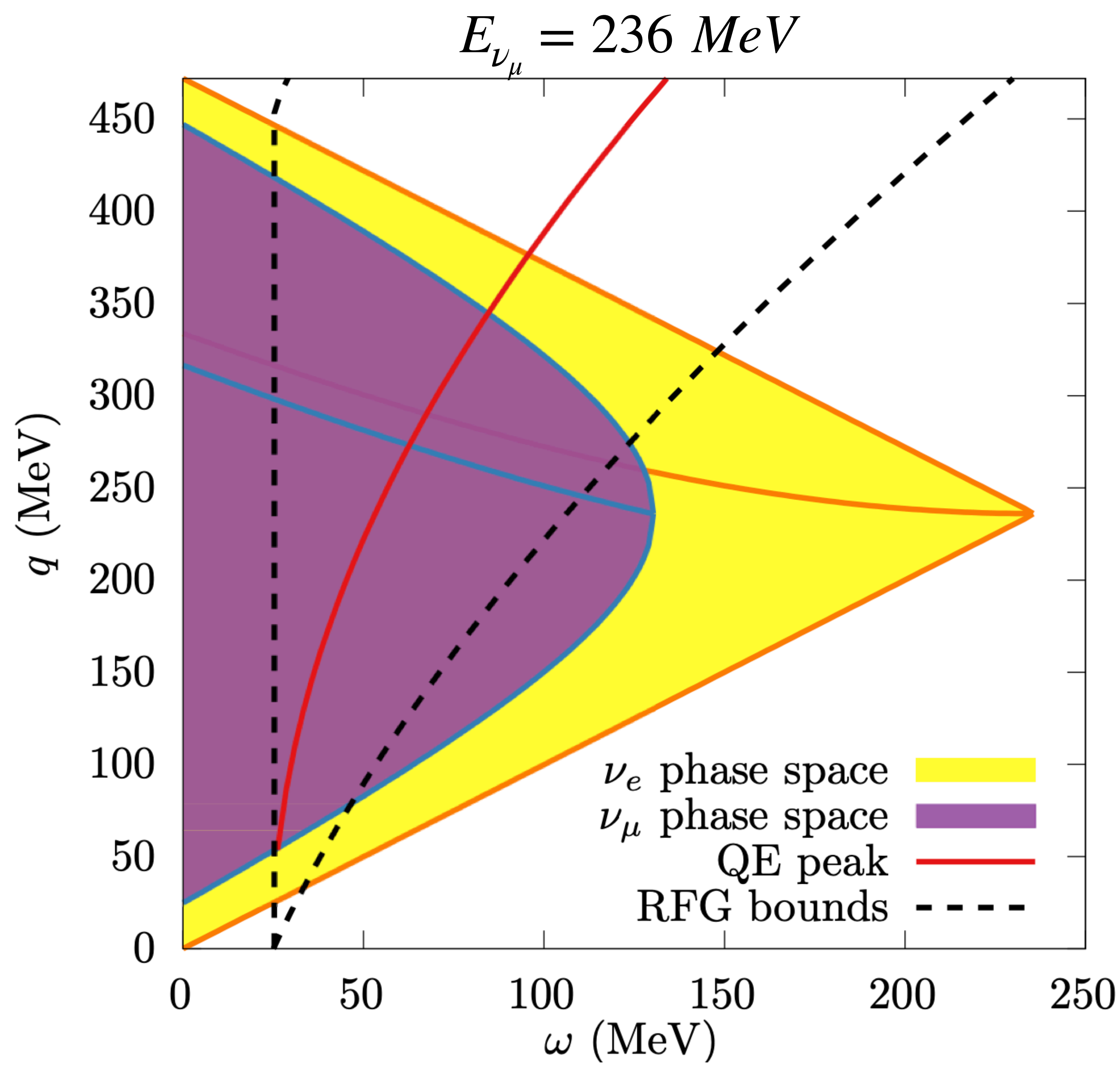
MiniBooNE data: Phys. Rev. Lett. 120, 141802 (2018)

*A. Nikolakopoulos, **VP**, J. Spitz and N. Jachowicz, arXiv:2010.05794 [nucl-th].*

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

Mono-energetic kaon decay at rest neutrinos



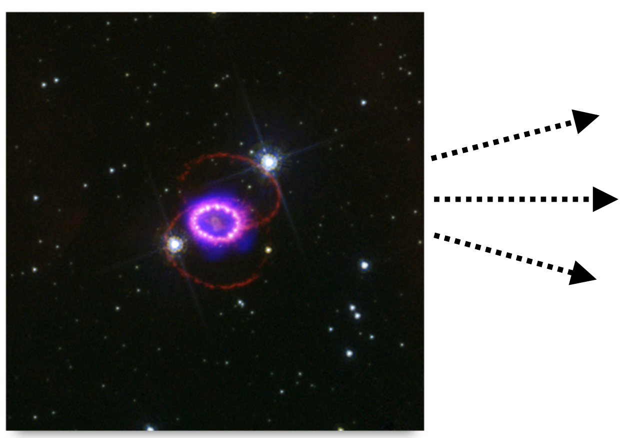


*A. Nikolakopoulos, **VP**, J. Spitz and N. Jachowicz, arXiv:2010.05794 [nucl-th].*

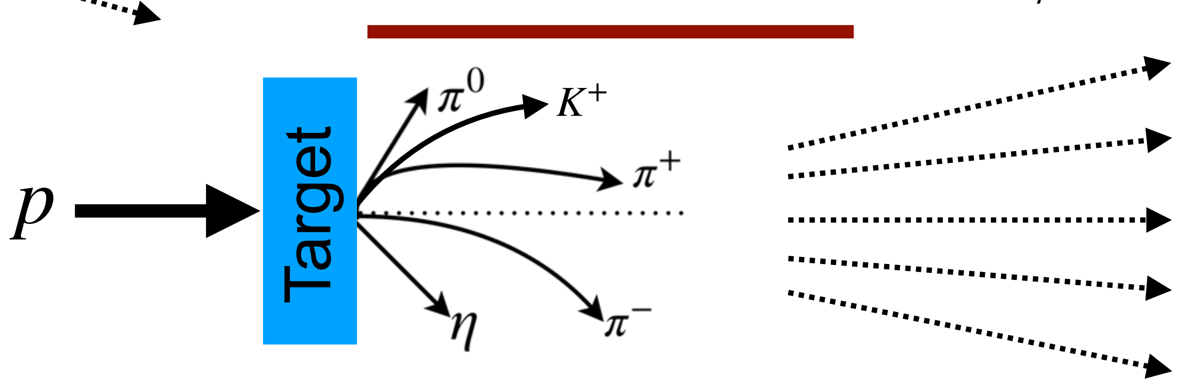
- Exciting near future measurements: MicroBooNE and ICARUS (argon), JSNS^2 at J-PARC (carbon)
- Combined analysis of (e, e') and ν_μ cross sections can give a strong handle on the axial responses

Neutrinos Sources and Experiments

10 MeV — **100 MeV** — **1 GeV** — **10 GeV**

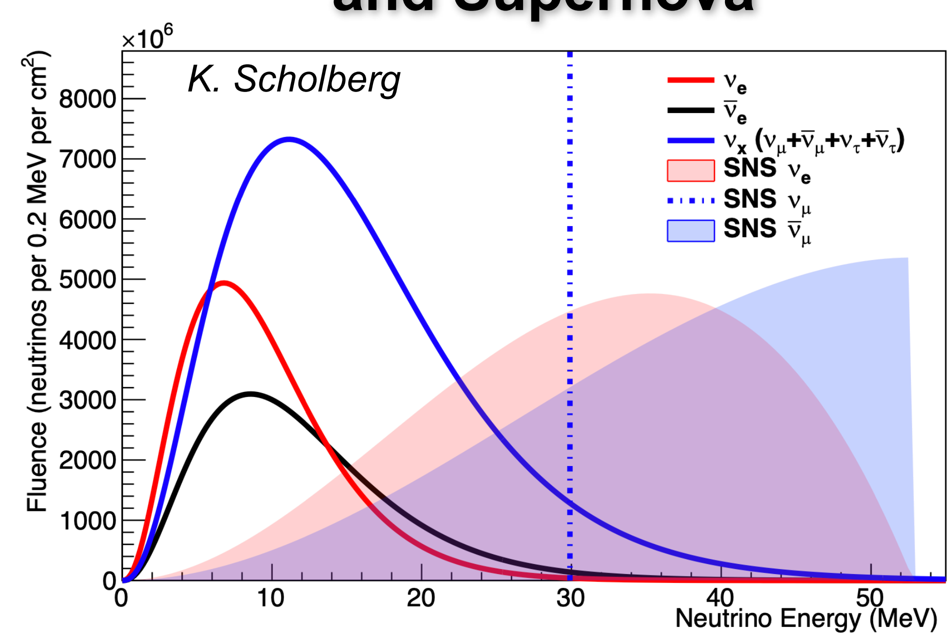


$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$



Magnetic Focusing Horn

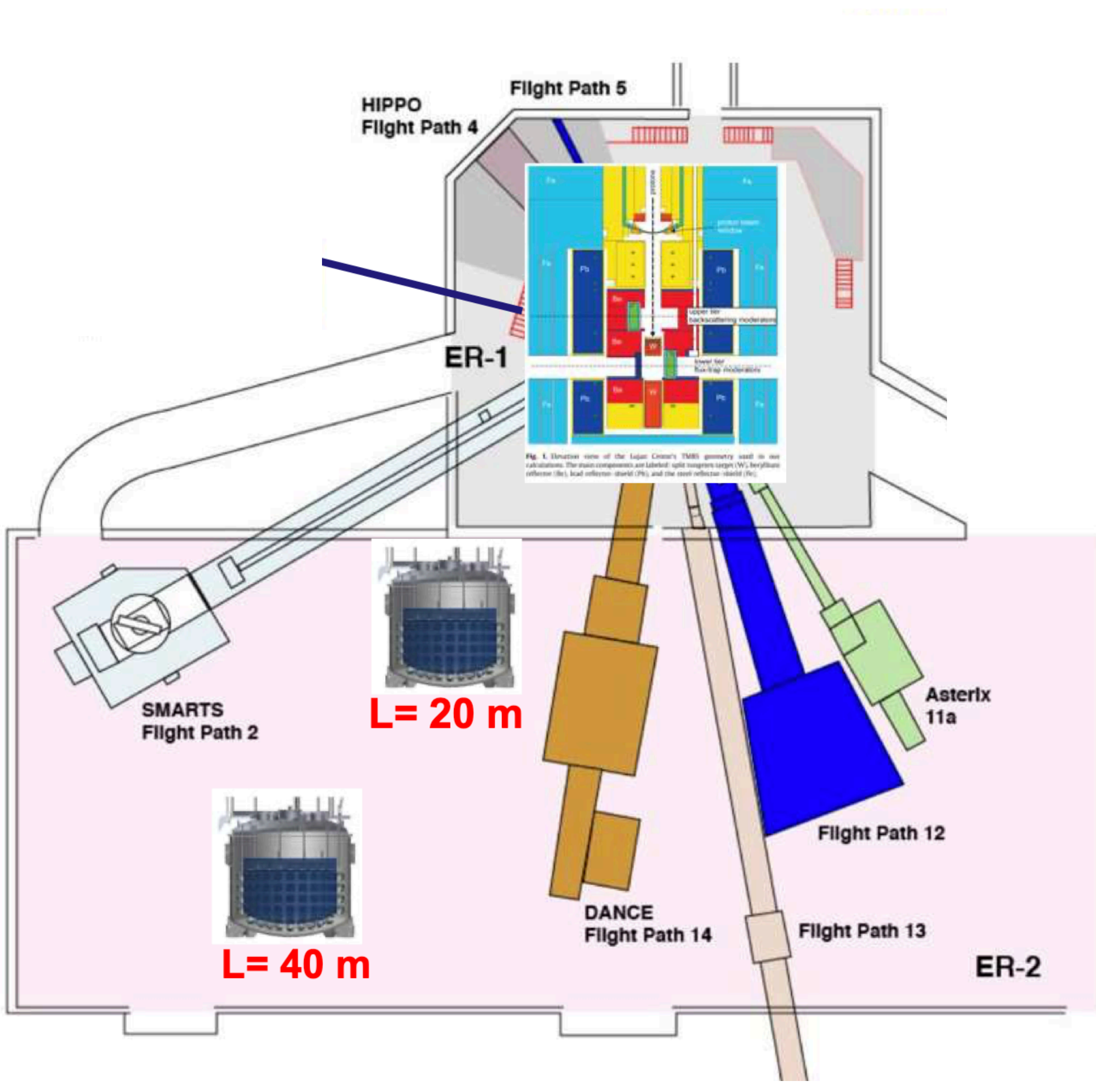
Pion decay at rest and Supernova

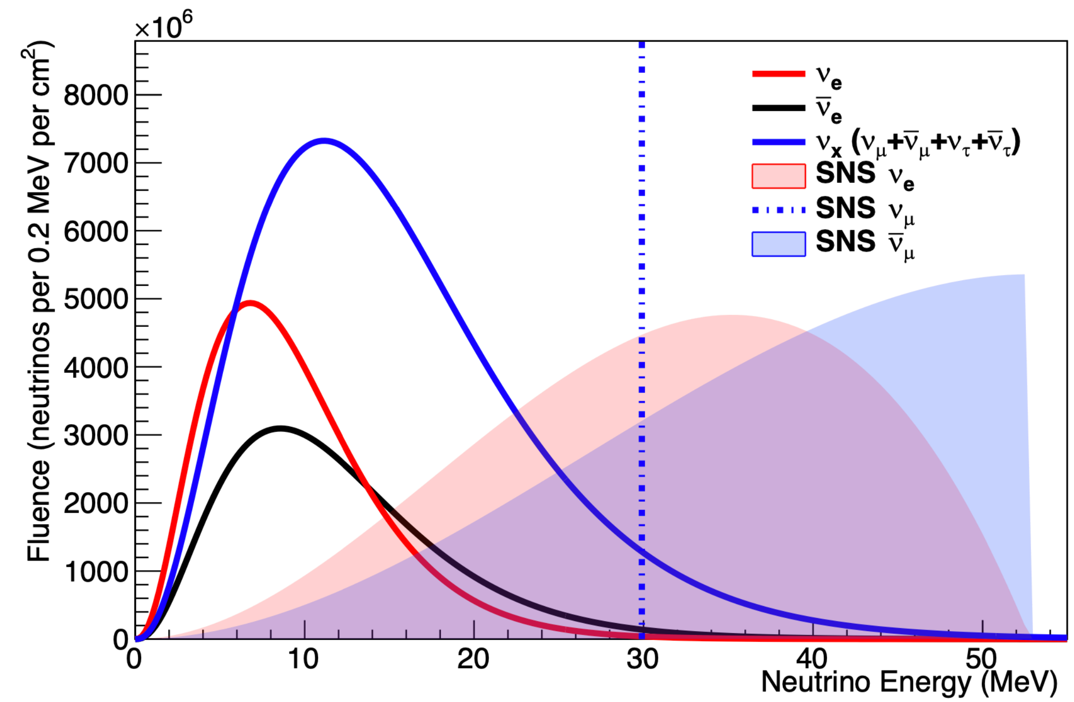


10s of MeV Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

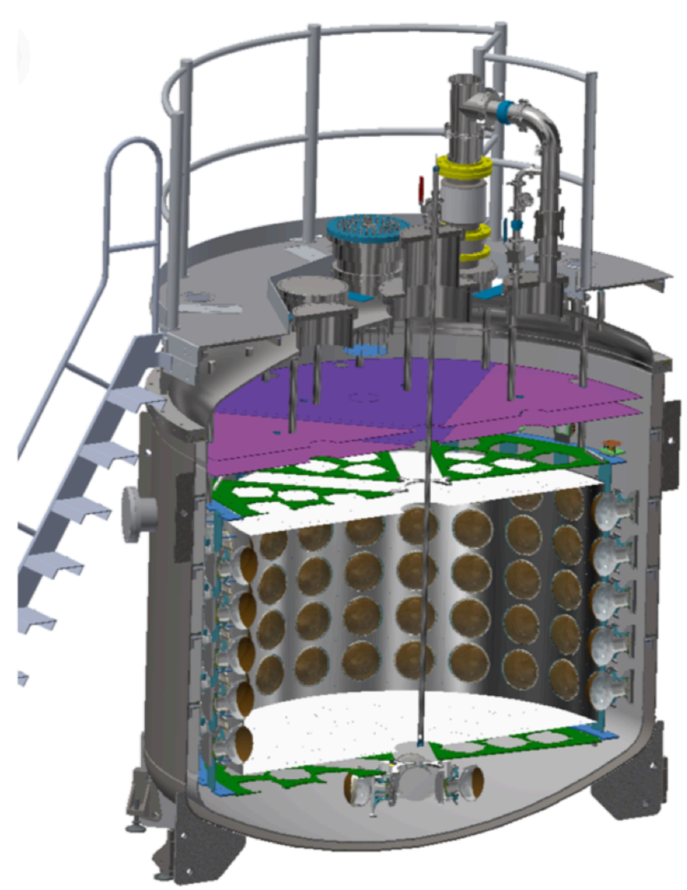
Coherent CAPTAIN-Mills (CCM)

- 10 ton LAr detector at Lujan center at LANL
  - Measure CEvNS cross section on ^{40}Ar
  - Measure 10s of MeV inelastic CC/NC cross section on ^{40}Ar



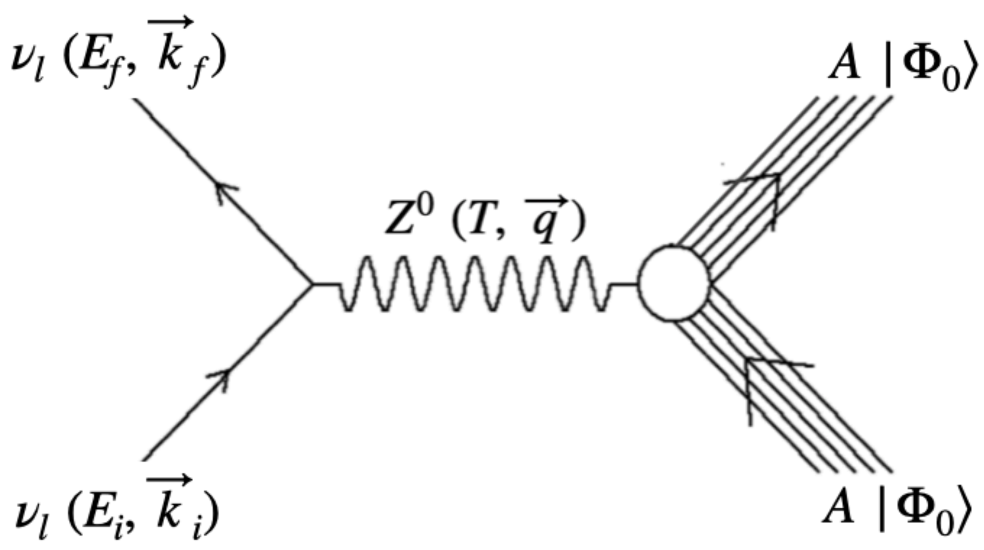


- Collected data in 2019, analysis ongoing
- Detector is being upgraded, will collect more data in summer 2021



10s of MeV Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

Coherent elastic



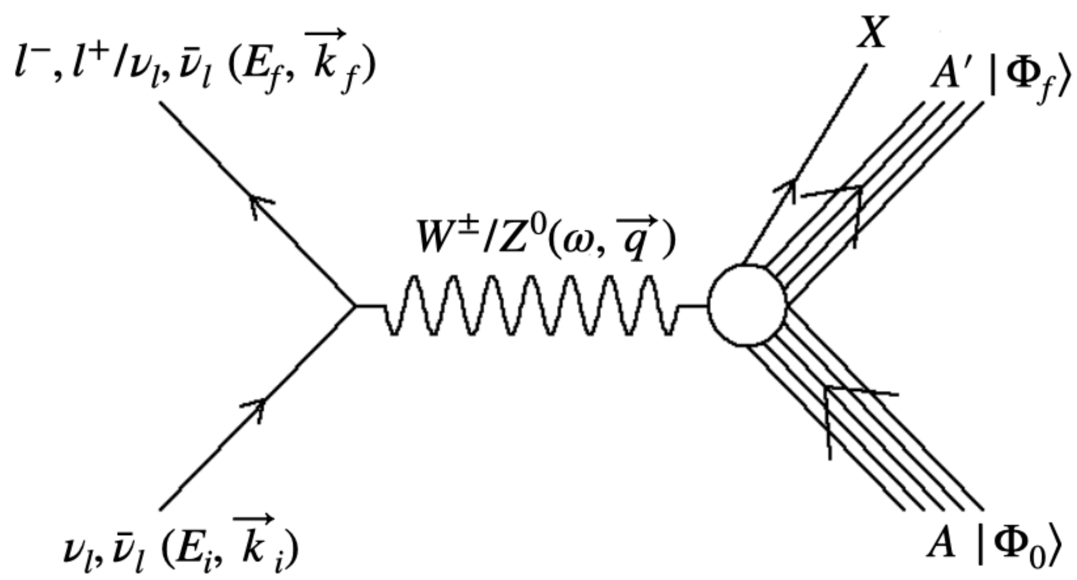
Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

- Tiny recoil energy
- Final state nucleus stays in its ground state
- Signal: keV energy nuclear recoil
- First observed by COHERENT collaboration in 2017
- Opens new window of opportunity to look for weakly interacting new physics at low energies

CEvNS Cross Section:

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

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.

Inelastic Cross Section:

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

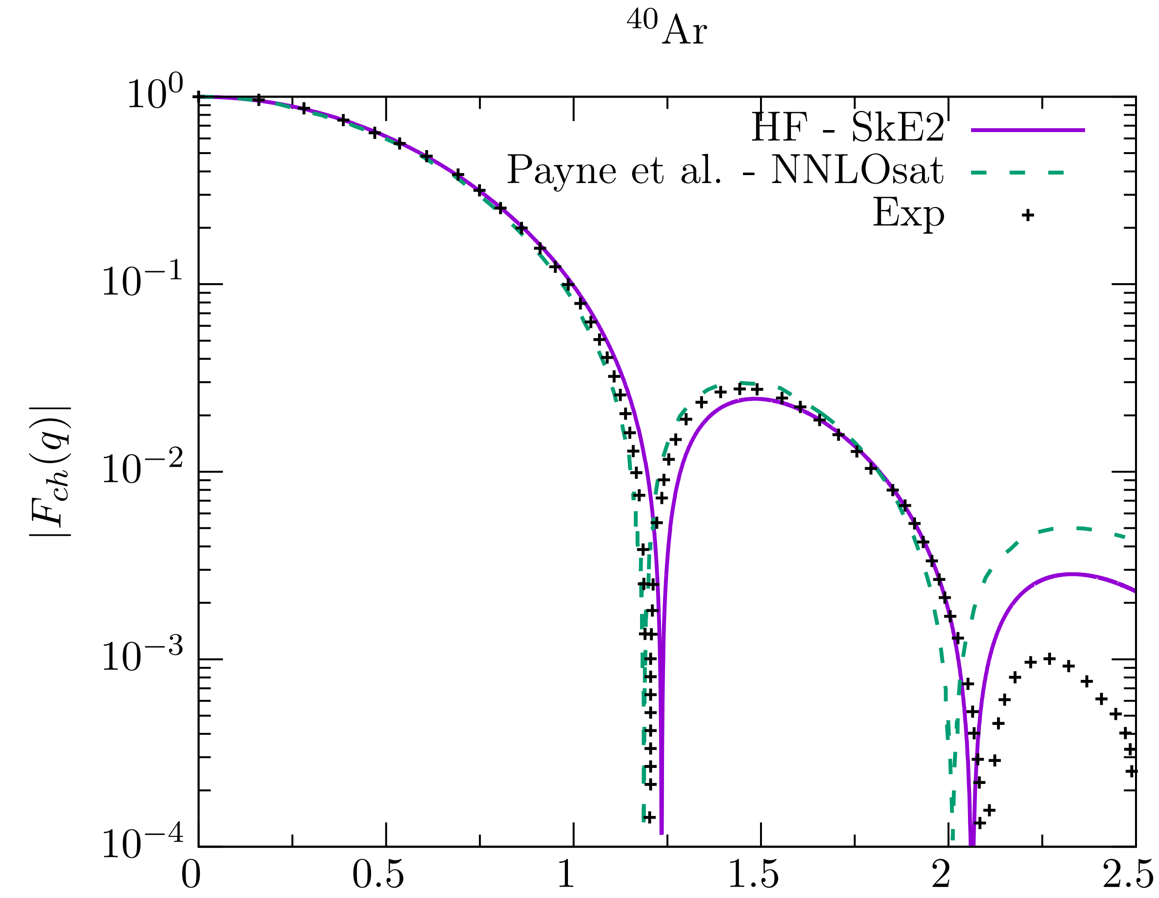
Constraining ^{40}Ar form factor and CEvNS cross section

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.

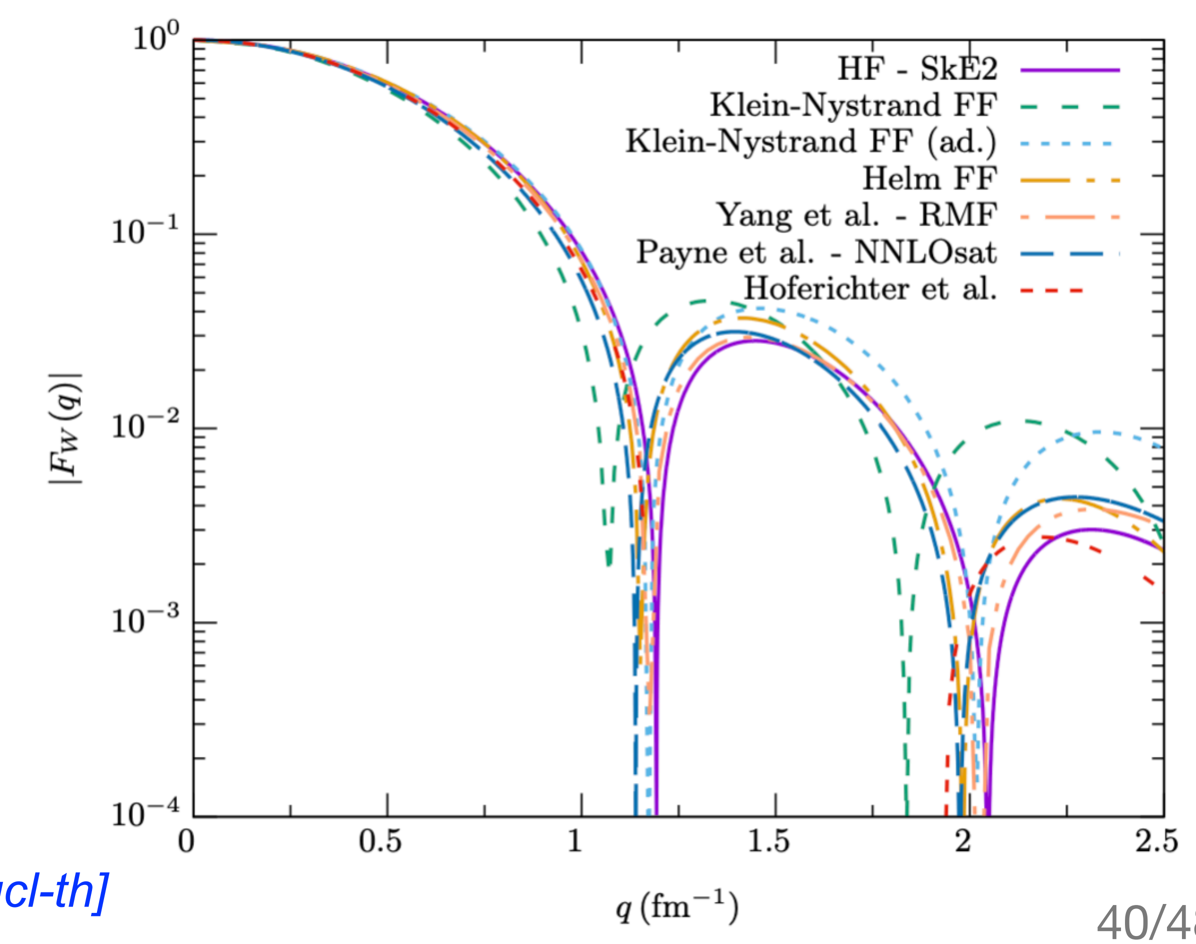
Experimental data from:
C. R. Ottermann et al., Nucl. Phys. A 379, 396 (1982).



Weak Form Factor

- Comparison of ^{40}Ar form factor predictions with other calculations.

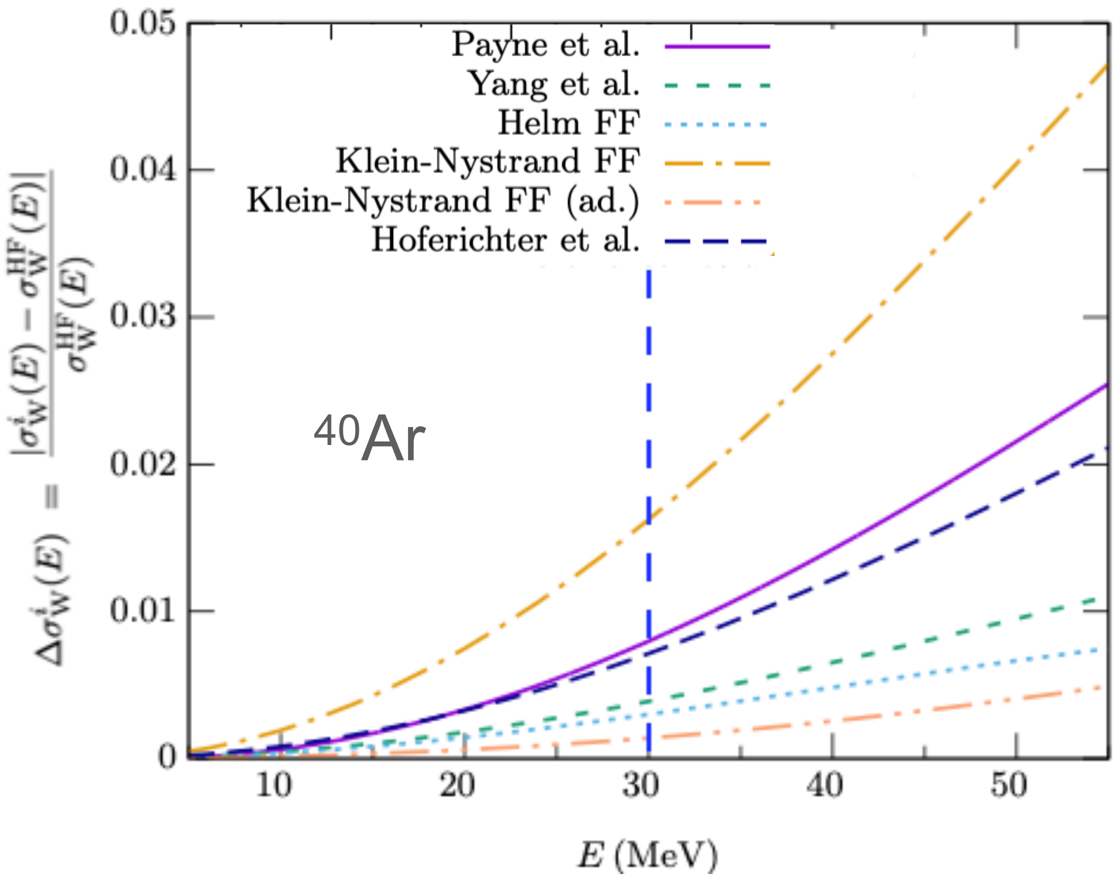
- Different approaches are based on different representations of the nuclear densities.



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

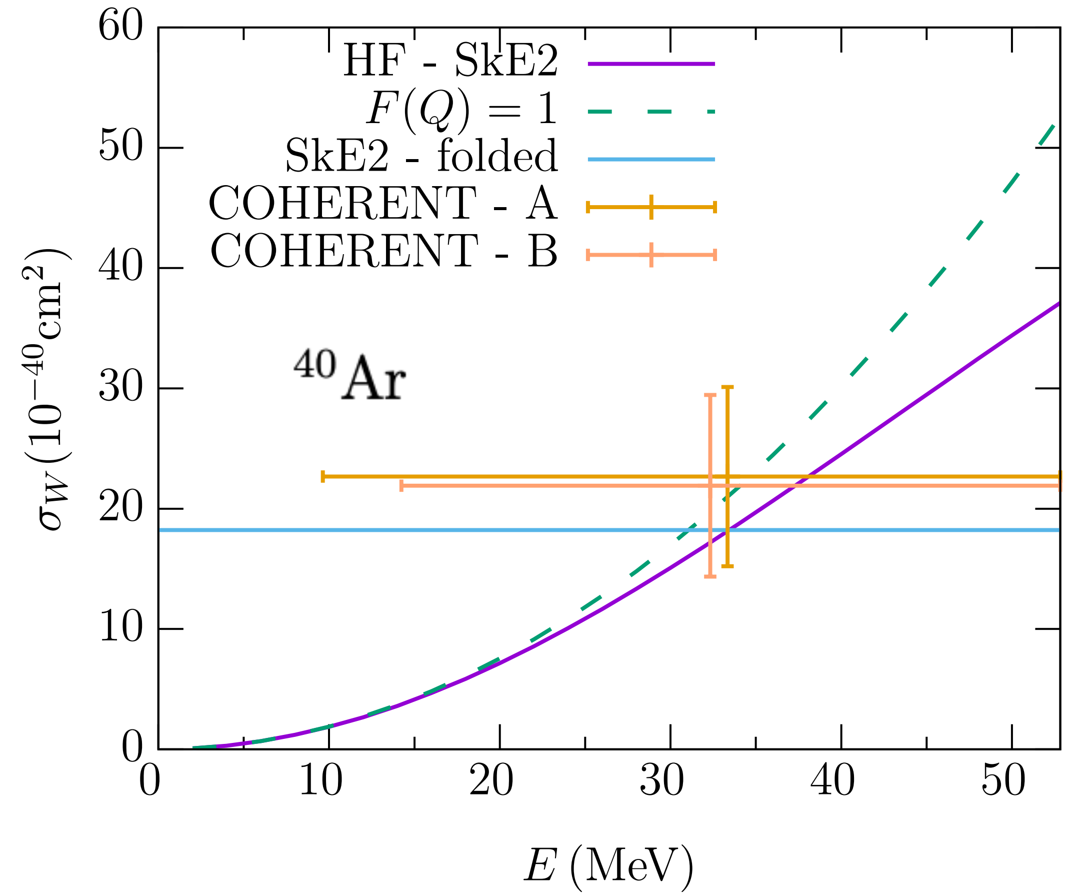
Constraining ^{40}Ar form factor and CEvNS cross section

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



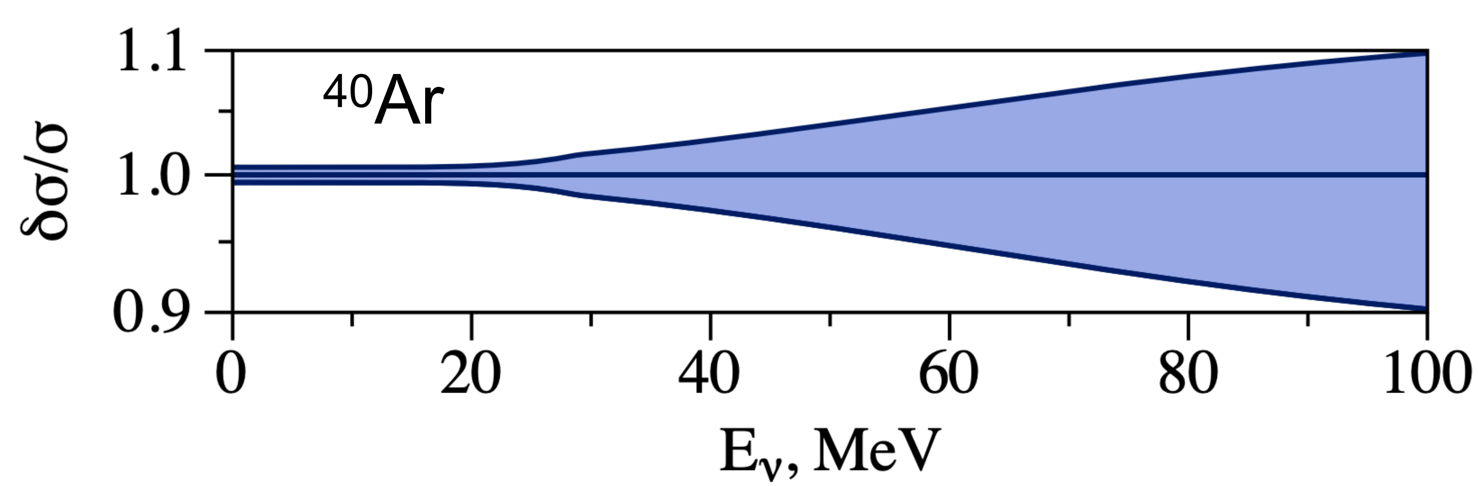
N. Van Dessel, ***VP***, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

- Comparison with COHERENT data



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

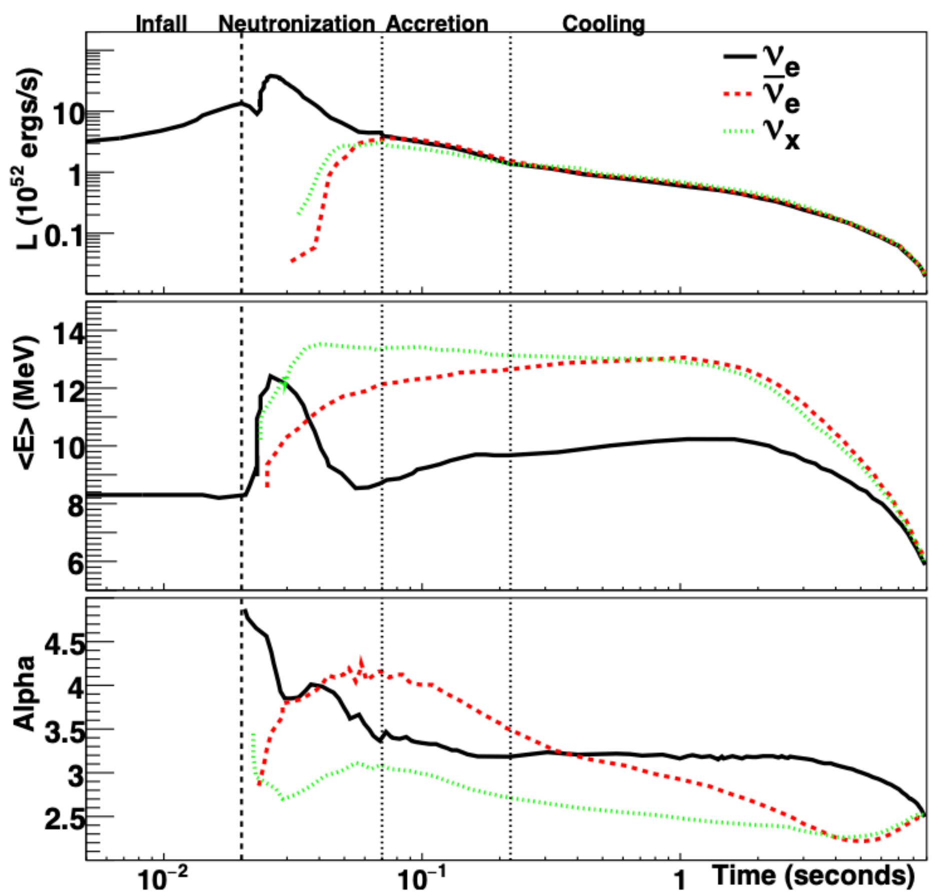
- Relative CEvNS cross section theoretical uncertainty on ^{40}Ar (includes nuclear, nucleonic, hadronic, quark levels as well as perturbative errors):

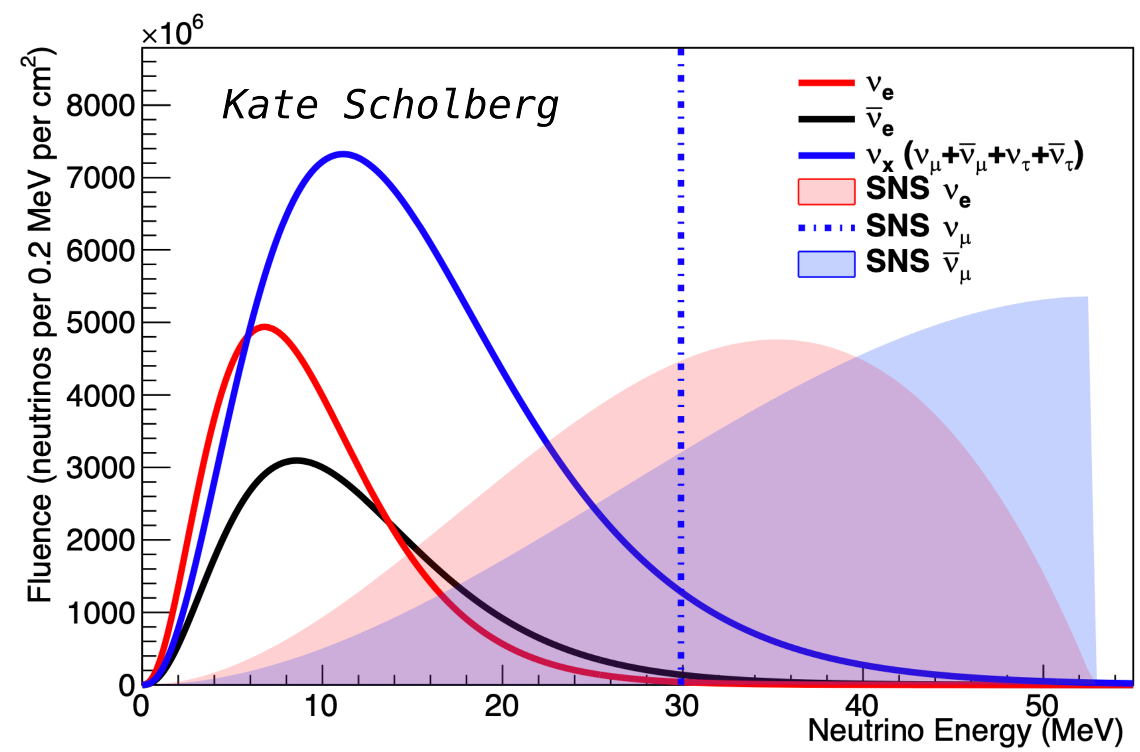


O. Tomalak, P. Machado, ***VP***, R. Plestid, arXiv:2011.05960 [hep-ph]

10s of MeV Inelastic Neutrino-Nucleus Scattering

- CEvNS experiments at **stopped-pion sources** are also powerful avenues to measure **10s of MeV inelastic CC and NC** cross sections subject to detailed underlying nuclear structure and dynamics.
  - These are vital in understanding of core-collapse supernovae, but are almost completely unexplored experimentally so far
  - These measurement will greatly enhance the prospects of detecting neutrinos from a core-collapse supernova in future neutrino experiments such as DUNE.





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

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

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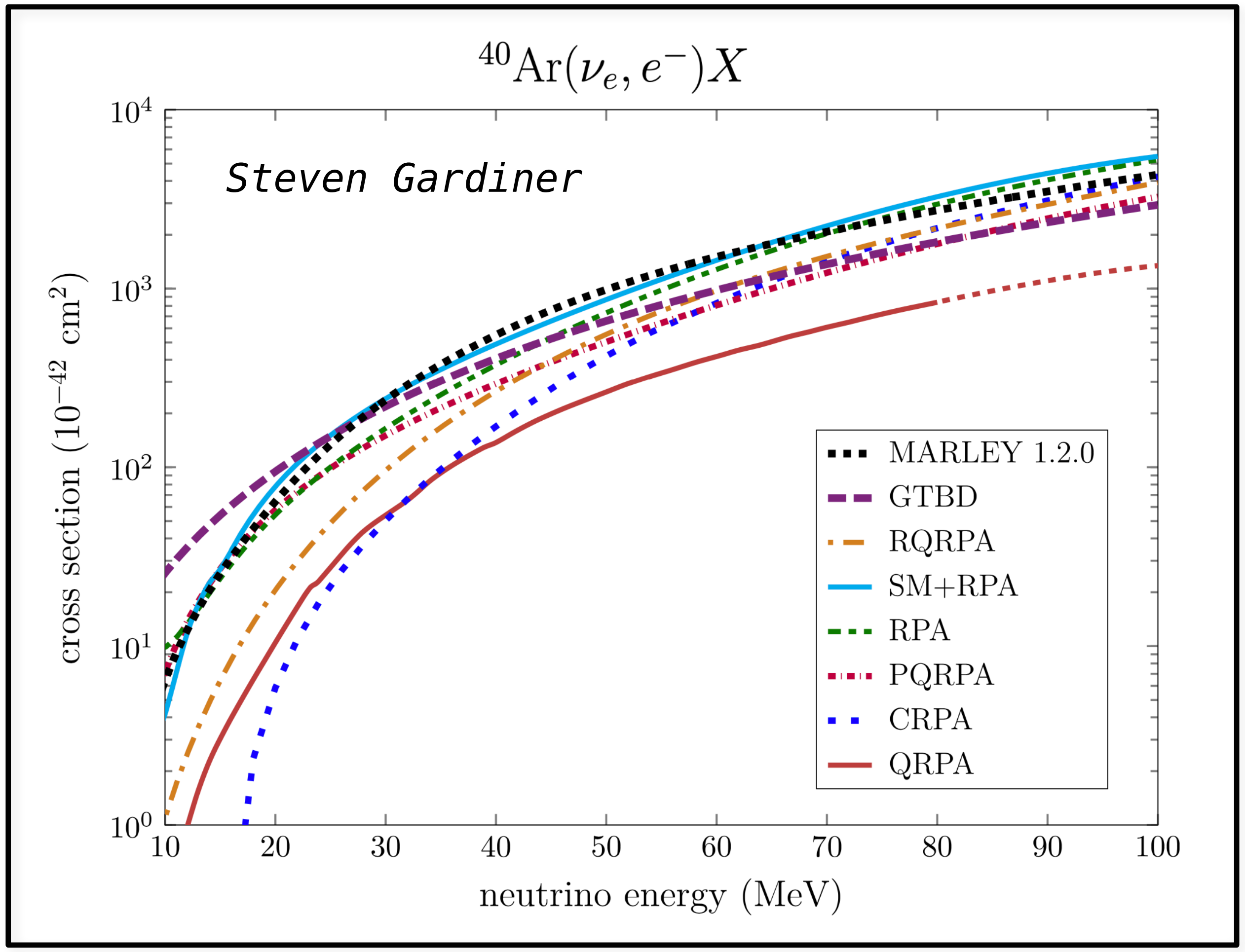
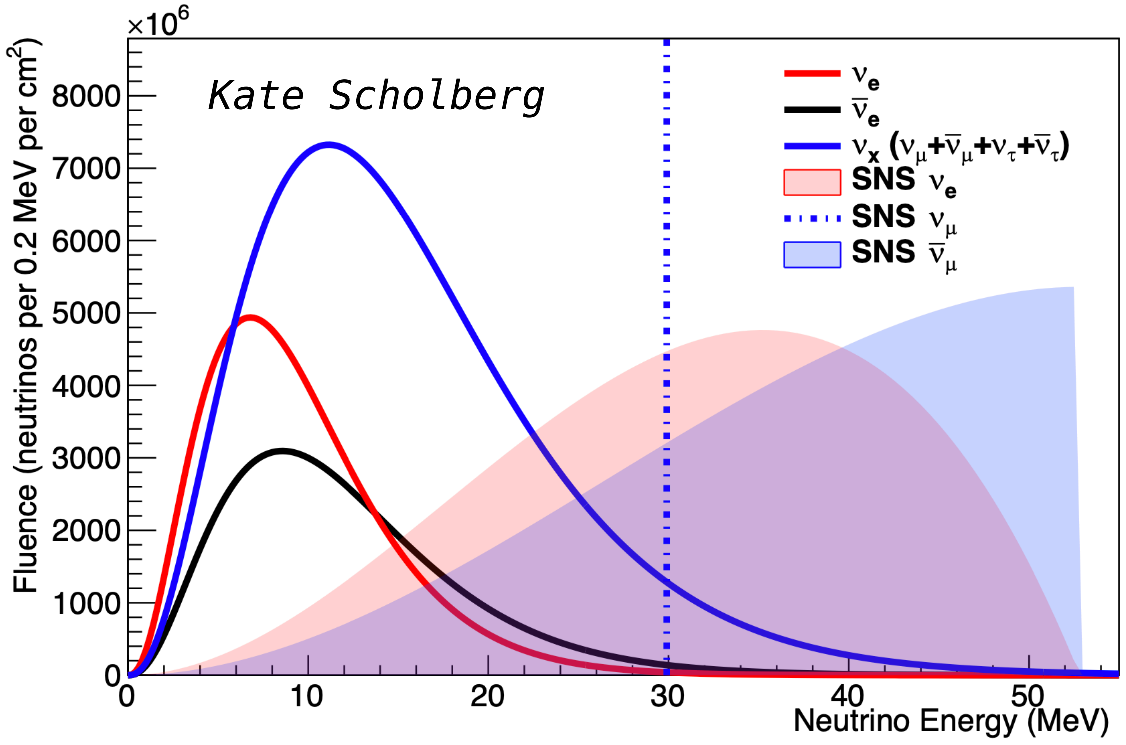
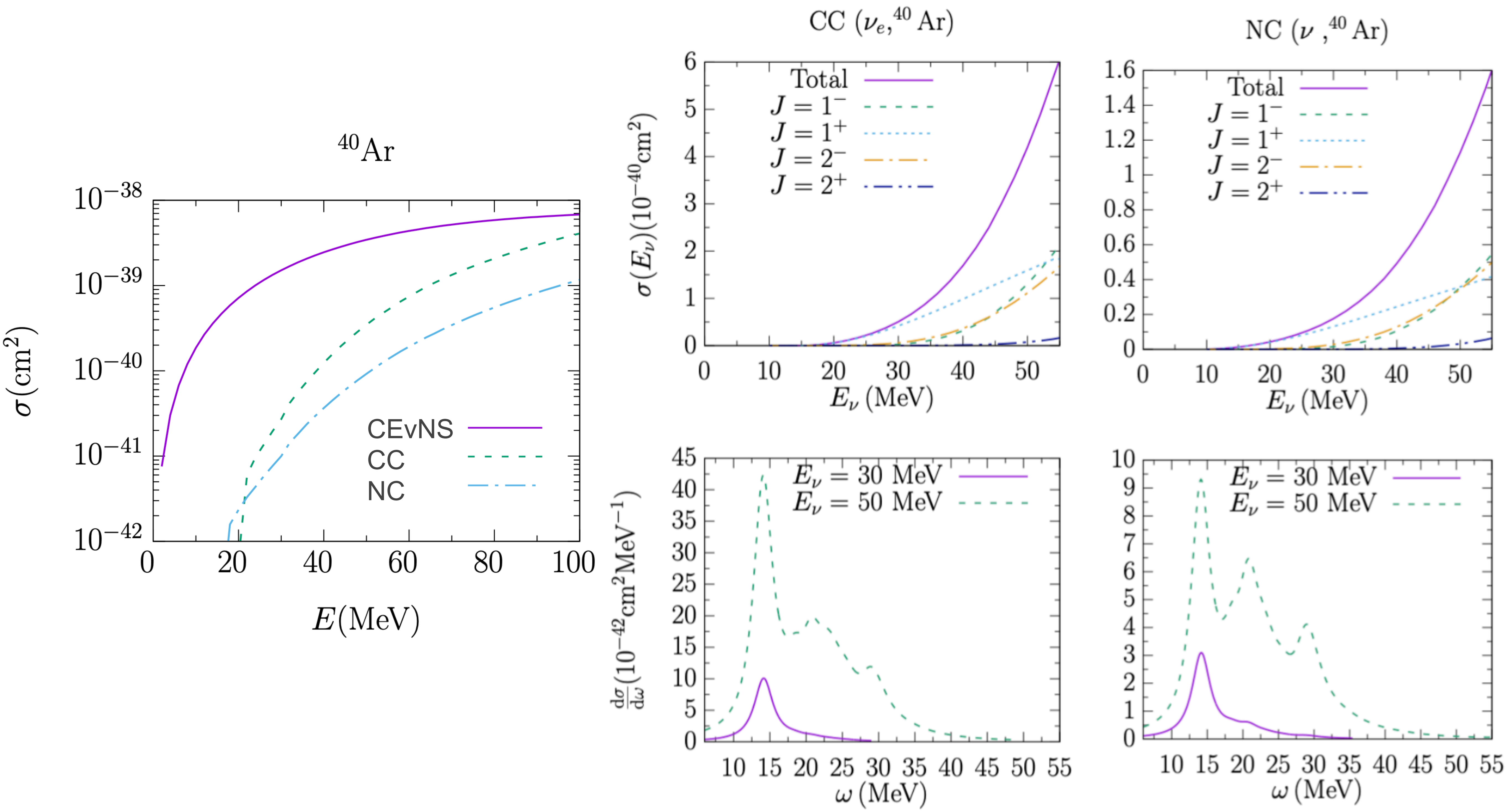




Need Measurements!

HF-CRPA Model: CC and NC ^{40}Ar Cross Sections

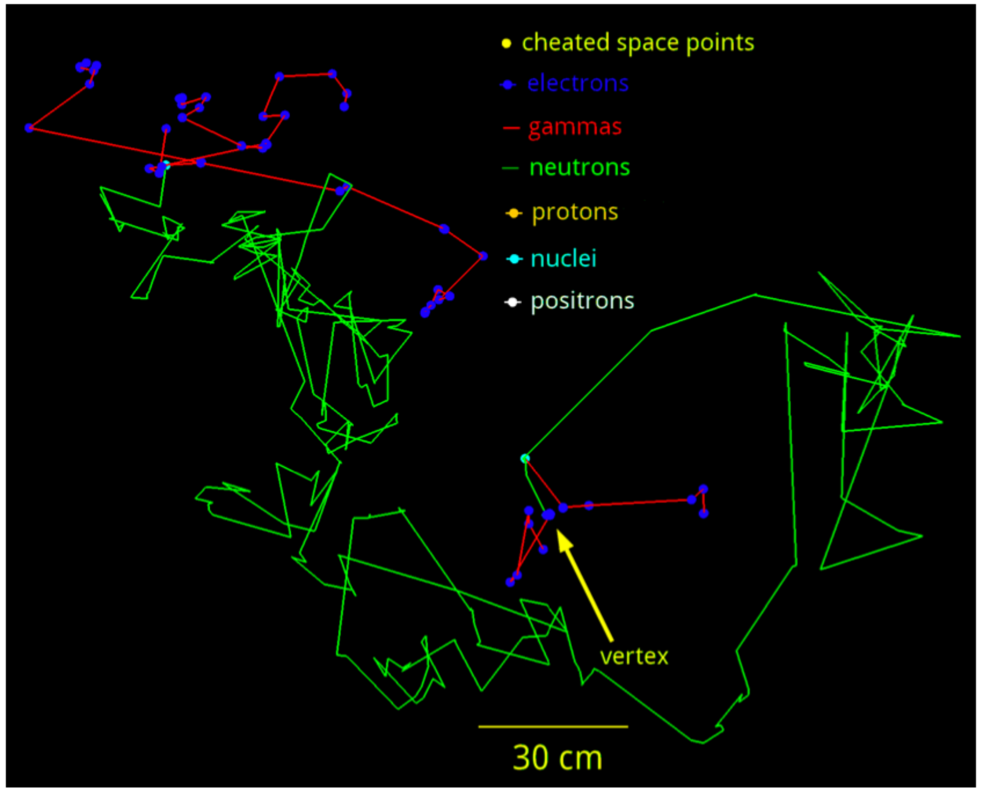


Inelastic CC/NC Neutrino-Nucleus Scattering: MARLEY Generator

- MARLEY (Model of Argon Reaction Low Energy Yields) is a neutrino event generator specifically developed to simulate tens-of-MeV neutrino-nucleus interactions in liquid argon.

  Steven Gardiner [arXiv:2010.02393 [nucl-th].

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



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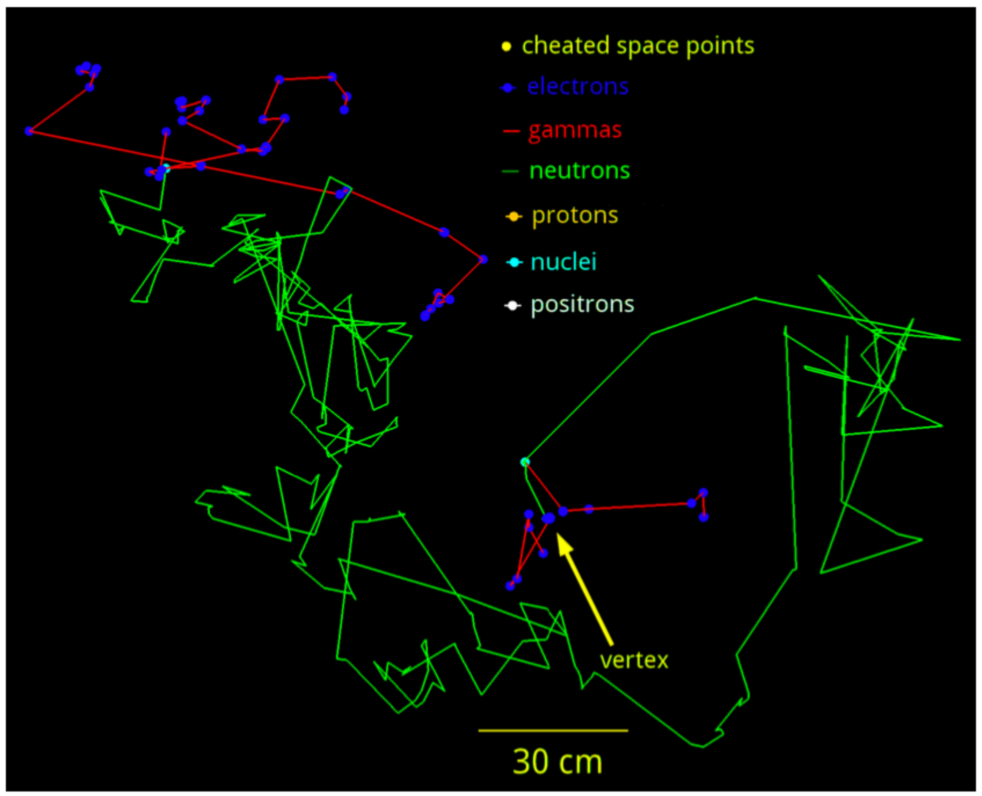
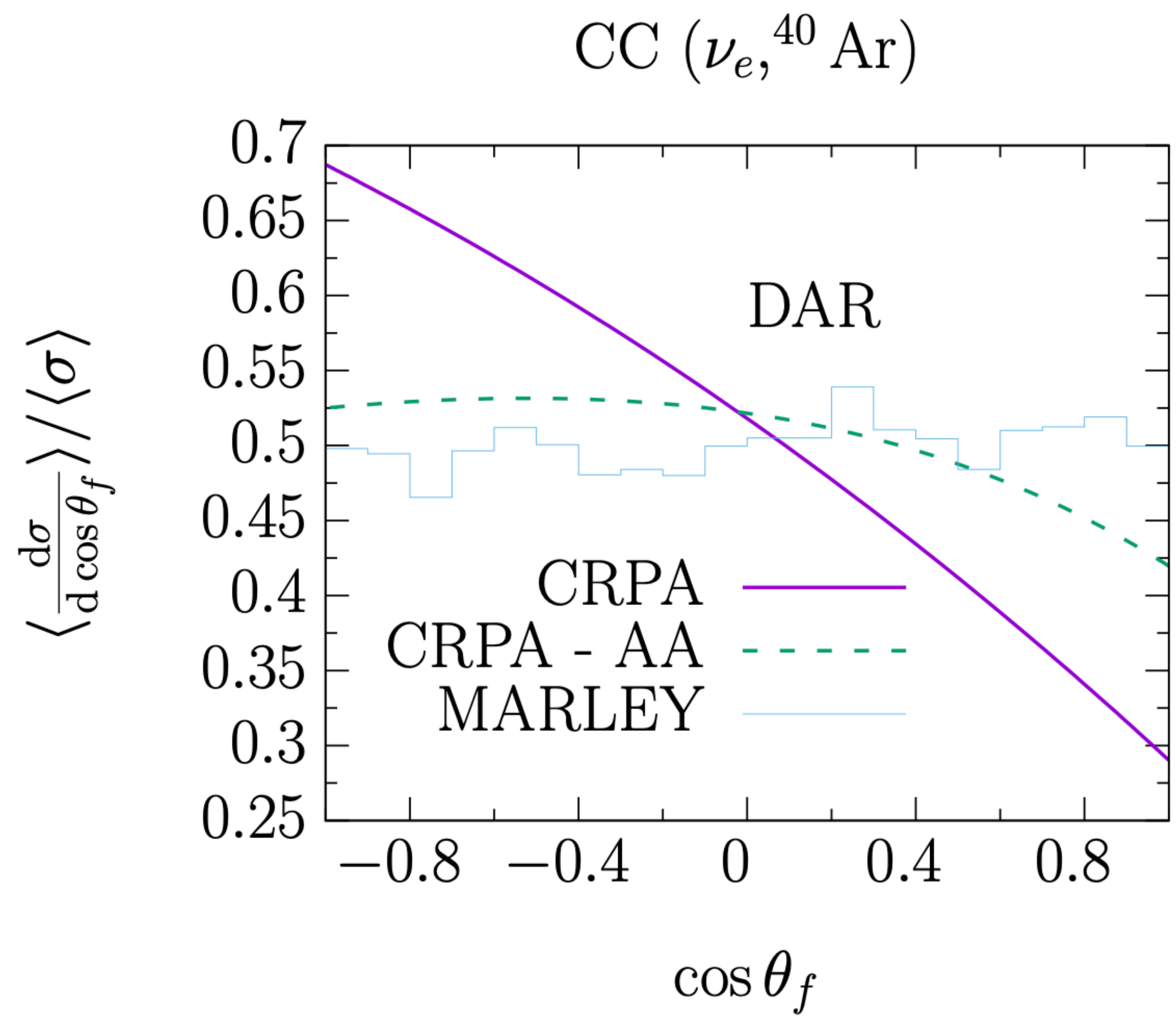


arXiv:2008.06647 [hep-ex] [DUNE Collaboration]



- MARLEY predicts a nearly flat angular distribution (only allowed transitions).
- CRPA includes full expansion of nuclear matrix element as (allowed as well as forbidden transition), predict more backwards strength.

Inelastic CC/NC Neutrino-Nucleus Scattering: MARLEY Generator

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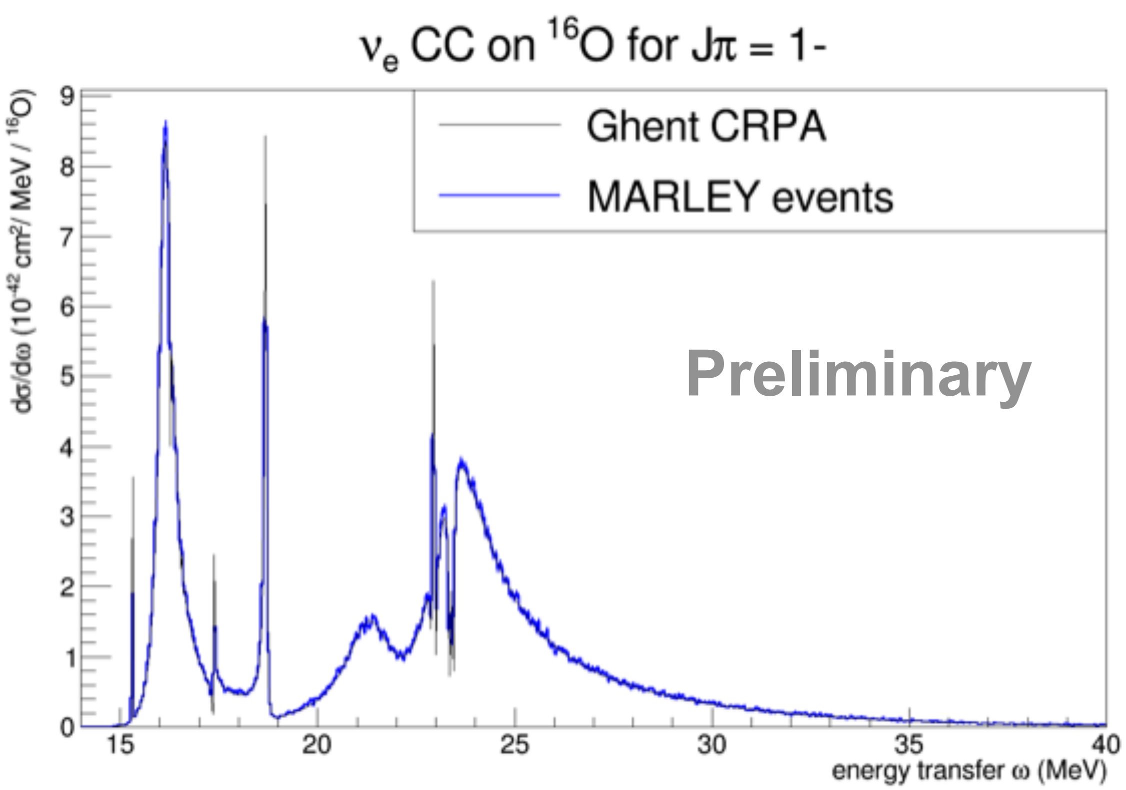
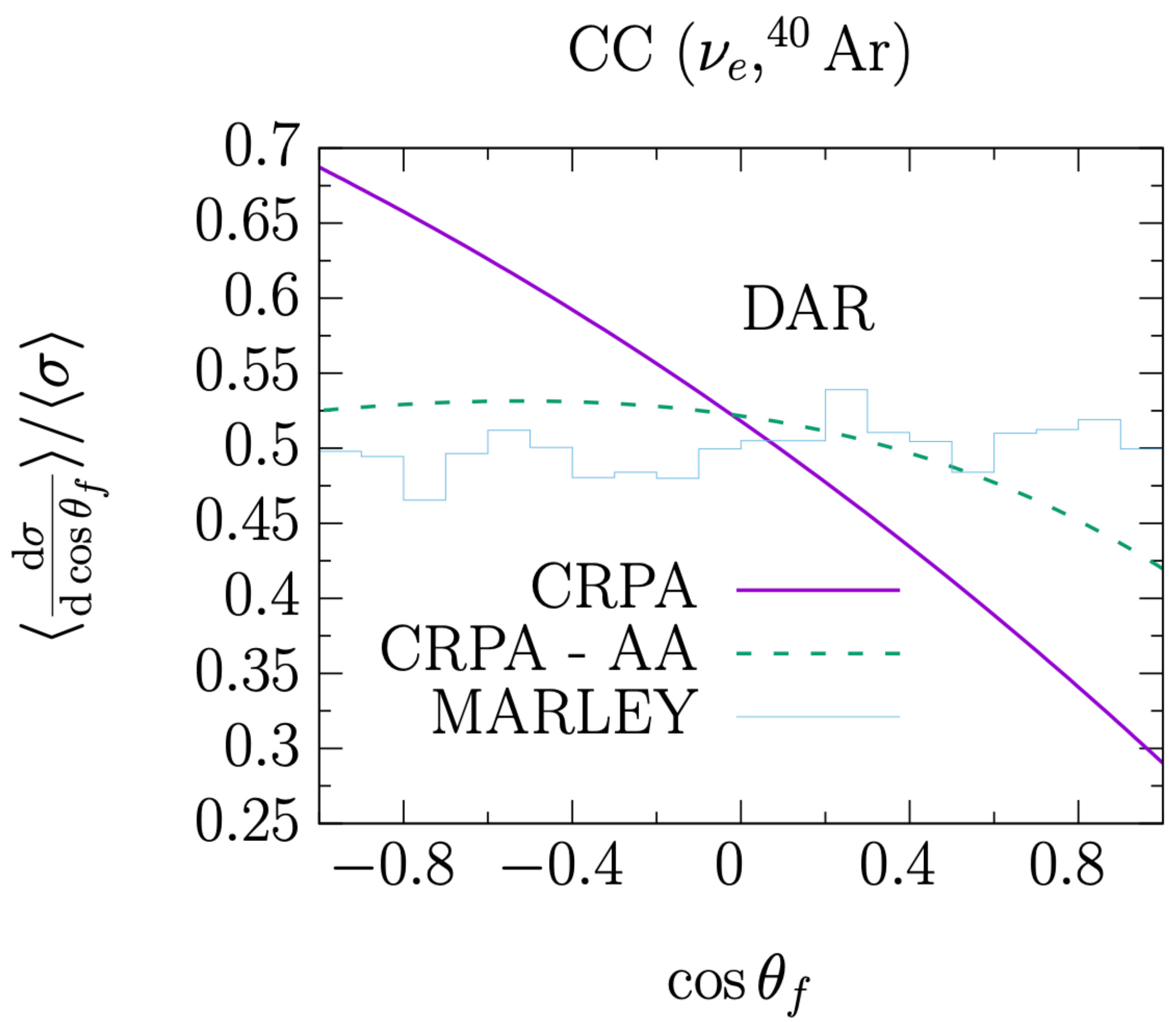




- CRPA implementation in MARLEY is currently on-going, in collaboration with Steven Gardiner.

✦ Utilizing these simulations in CCM to measure first 10s of MeV CC/NC cross section on ^{40}Ar. These simulations and measurements will pave the way for supernova physics in DUNE.

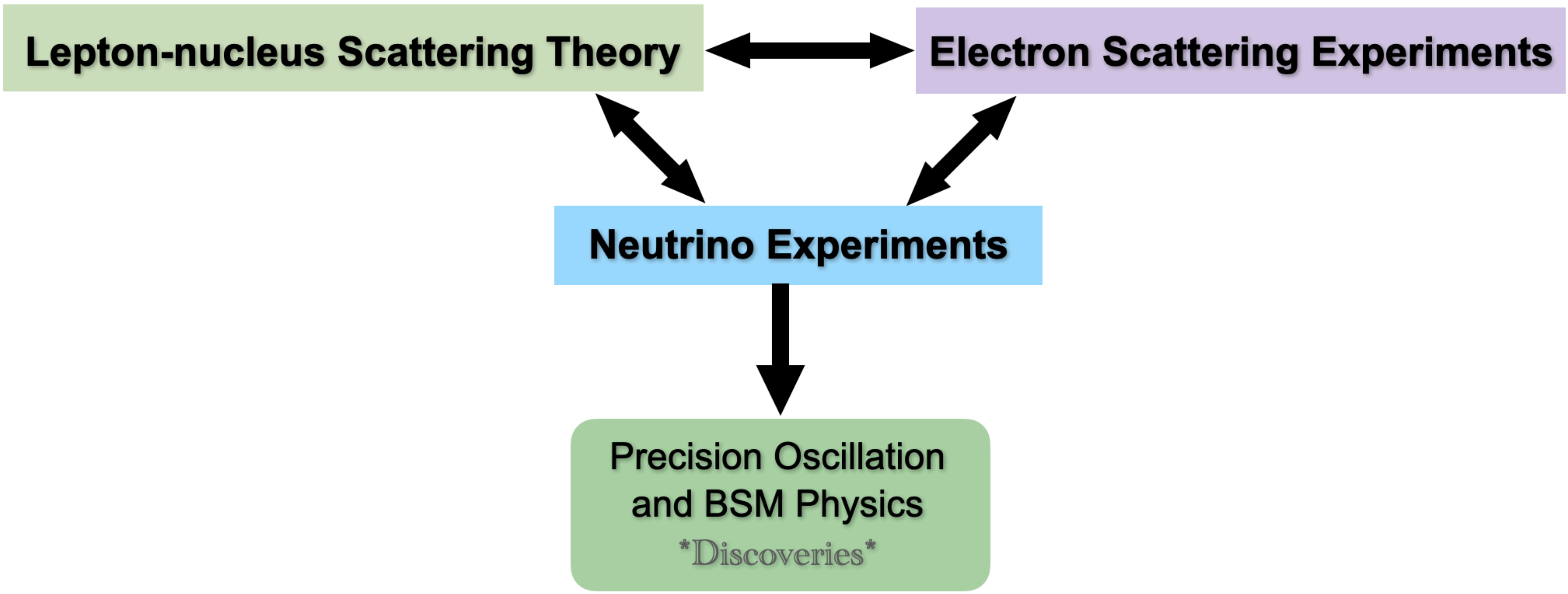
Summary

- These are exciting times. Neutrinos are opening the portal to new frontiers in physics. We are at the beginning of a new era in our understanding of the Universe and a new era of discoveries!

- The potential of achieving discovery level precision and fully exploring the physics capabilities of these experiments rely greatly on the precision with which the fundamental underlying process – how does neutrino interact with the target material in the detector – is known. A non-trivial multi-scale, multi-process problem.

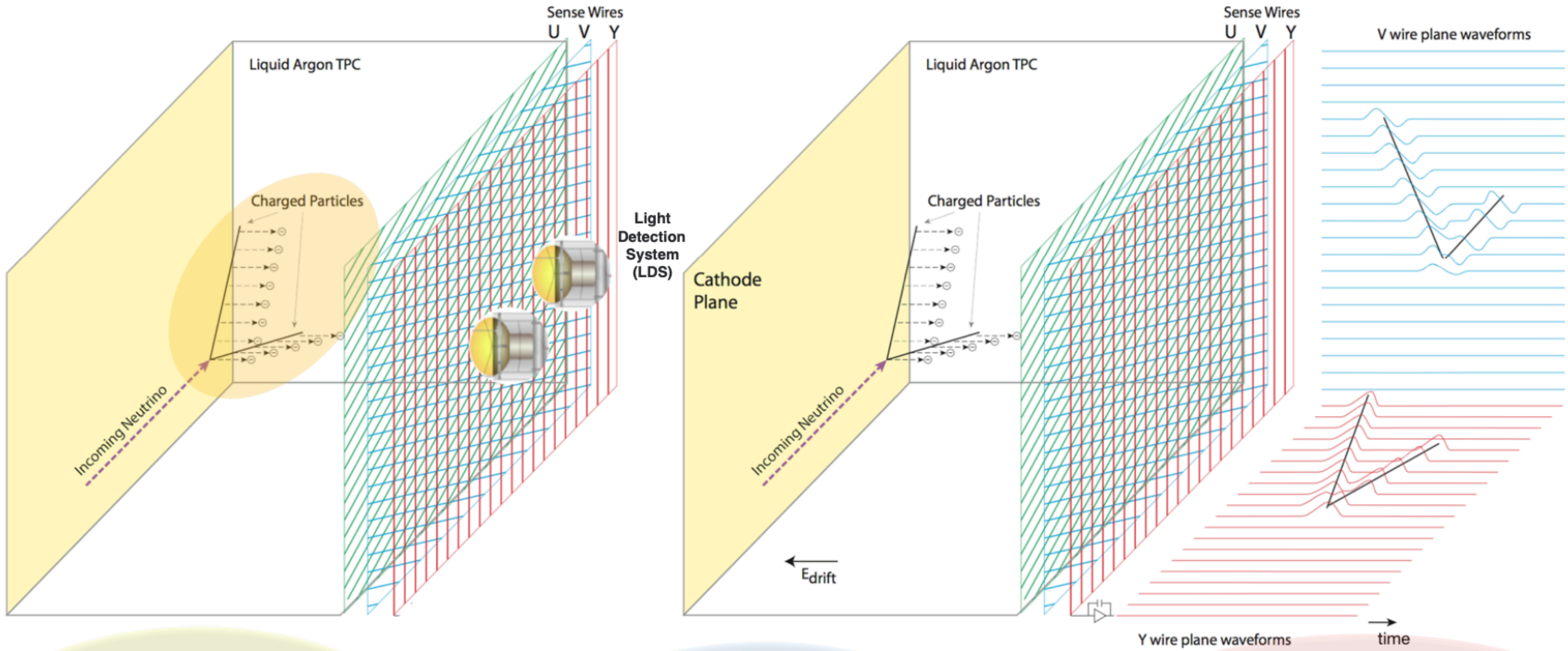
- I presented some theoretical as well as experimental efforts that tackle this problem from different directions.

- Dedicated cross-community efforts and expertise are required to tackle such a problem and establish global constraints on neutrino-nucleus interaction physics that can enable desired precision in neutrino experiments.



Thank you!

Liquid Argon Time Projection Chamber (LArTPC)



Charged particles in LAr produce free <u>ionization electrons</u> and <u>scintillation light</u>

Ionization charge <u>drifts</u> <u>in a uniform electric</u> field towards the readout wire-planes

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge]

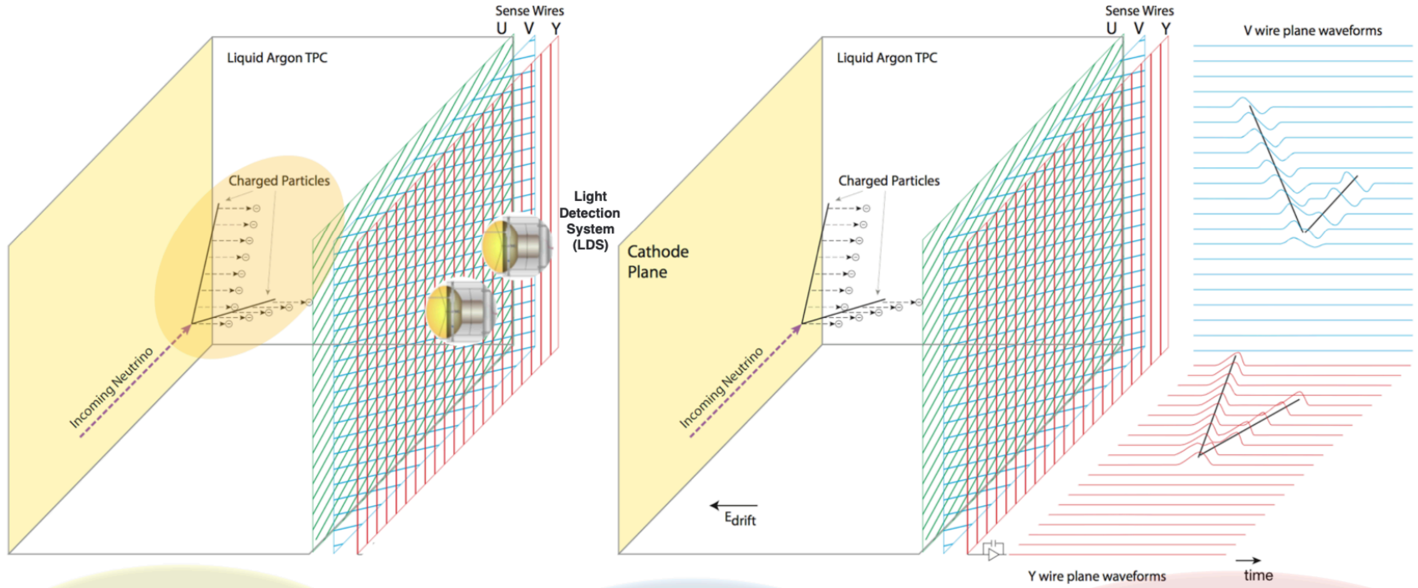
m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Electron drift time ~ ms

<u>VUV photons</u> propagate and are <u>shifted into VIS</u> photons

Scintillation light **fast** signals from LDSs give event timing

Liquid Argon Time Projection Chamber (LArTPC)



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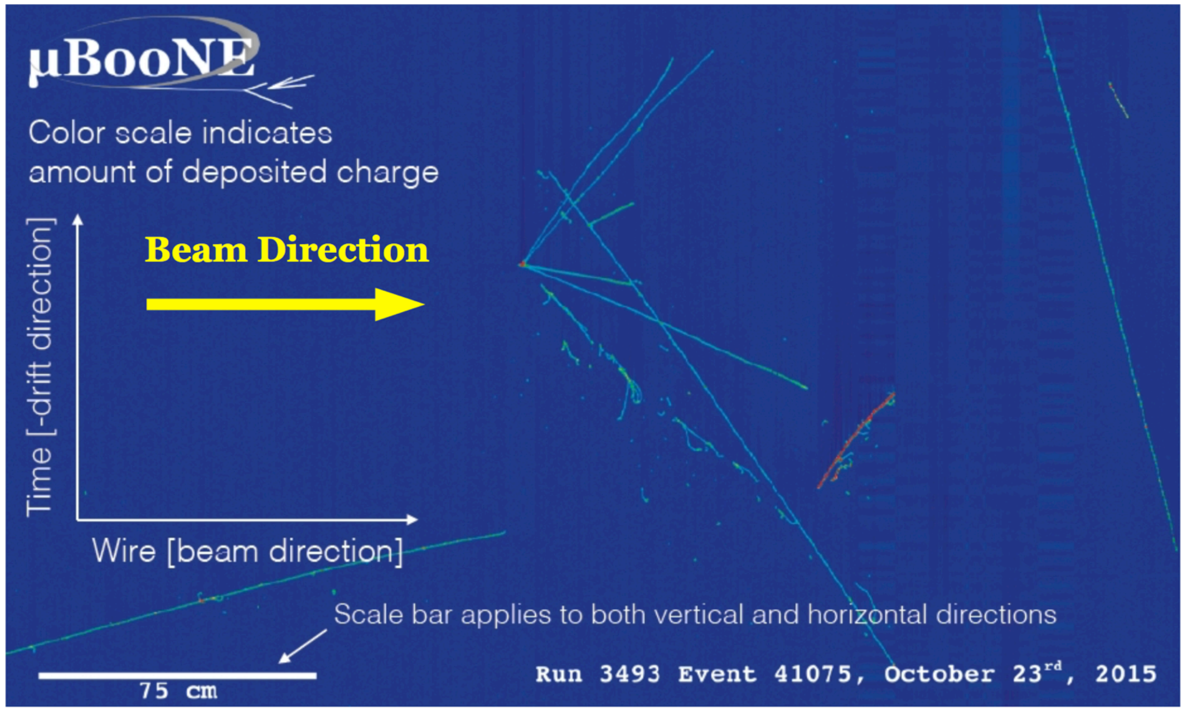
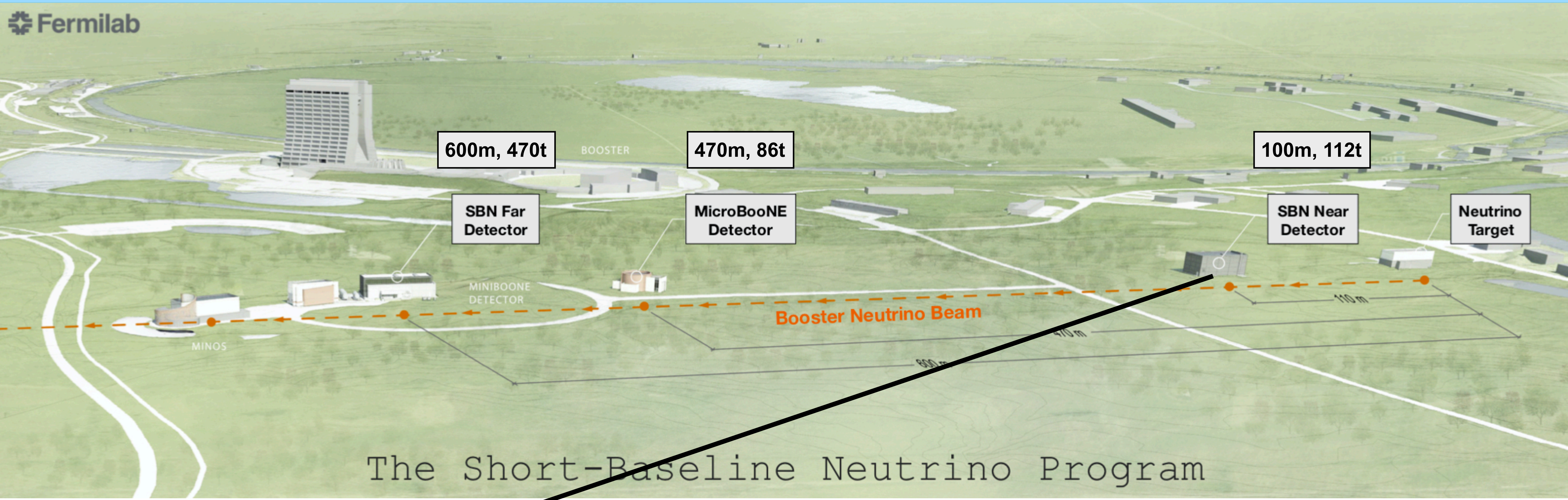
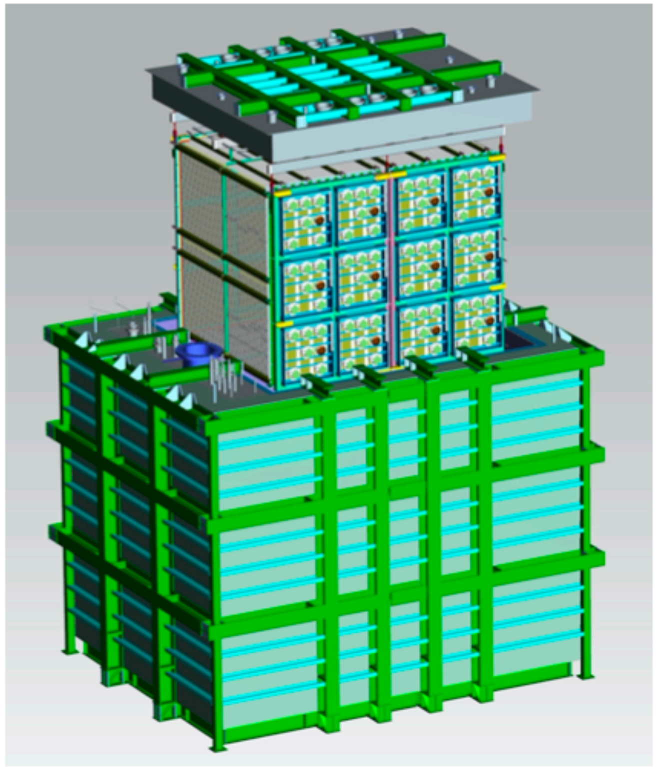


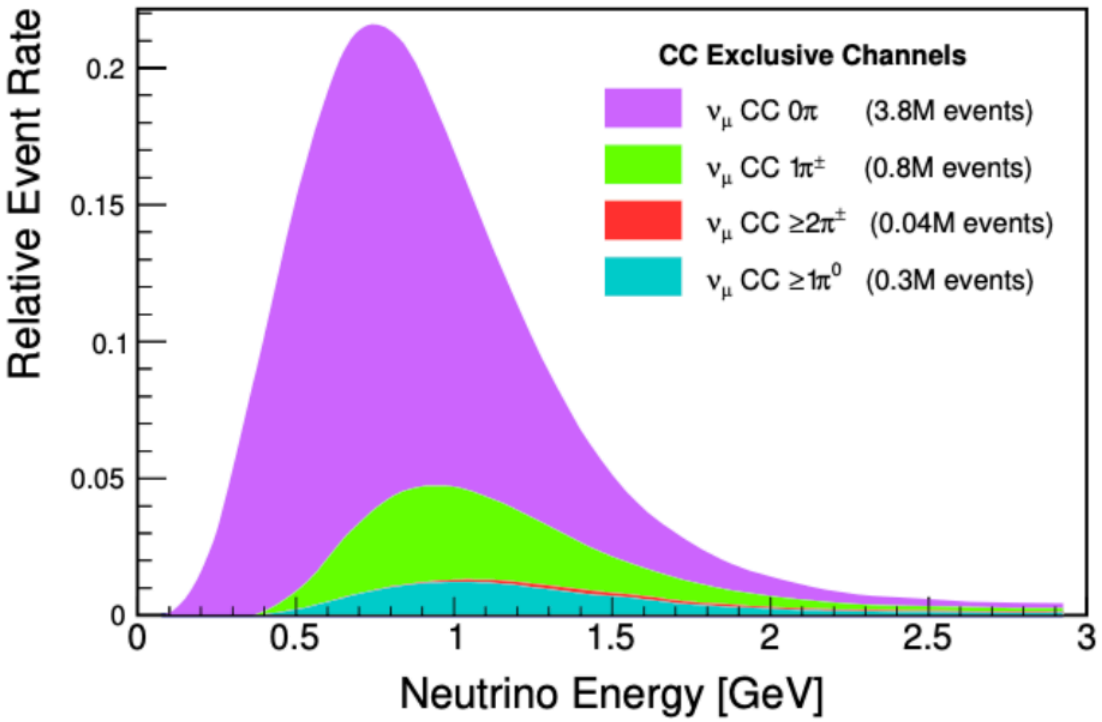
- Bubble chamber like imaging
- Fine sampling calorimetry
- Electronic readout
- Scalable to large volumes

SBN Program at Fermilab



SBND Experiment



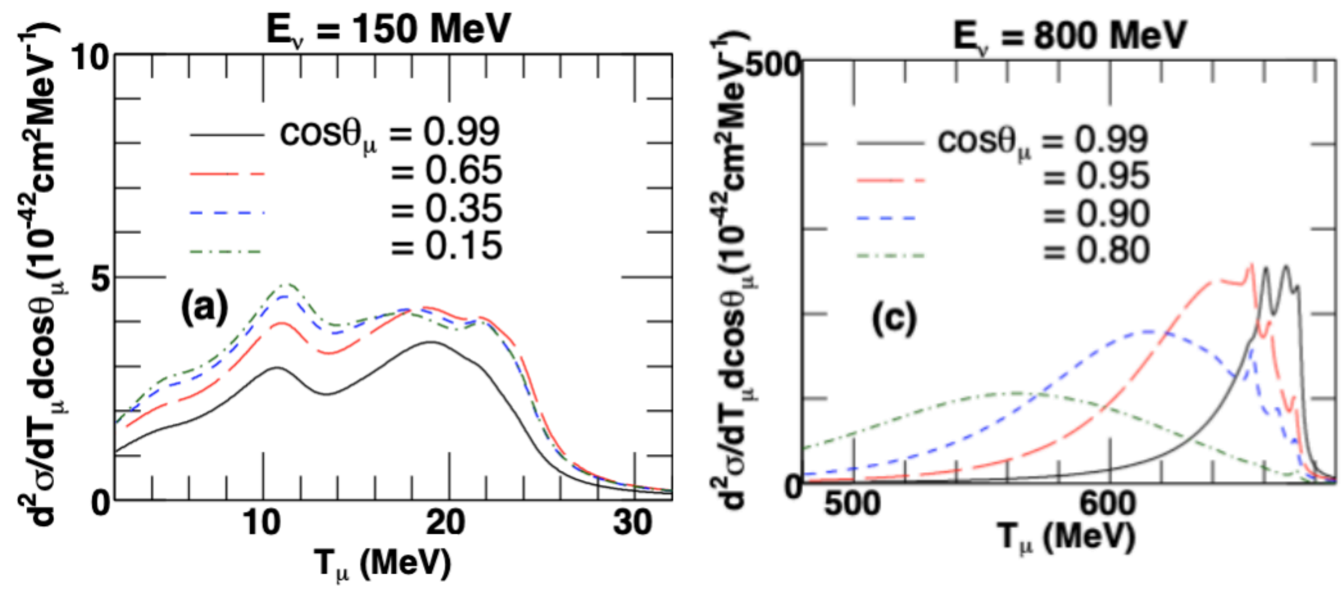


- SBND will compile data with an unprecedented high event rate due to its proximity to the neutrino source.
- It will record millions of events of neutrino interactions on argon, providing world's highest statistics of neutrino-argon cross section measurements.

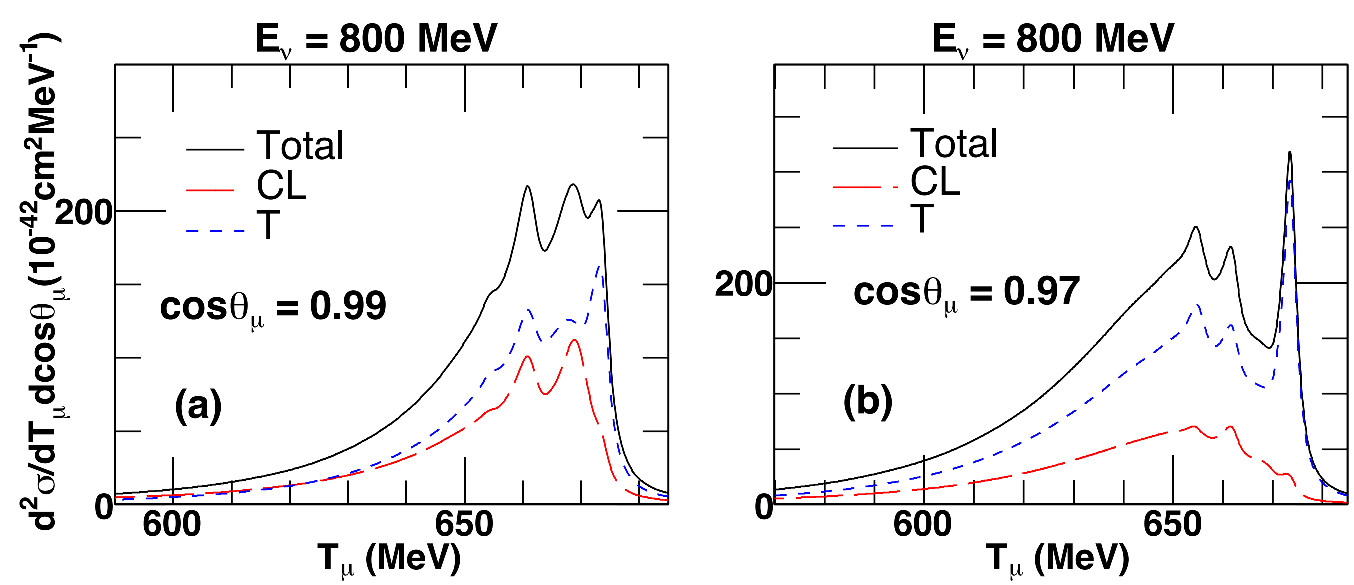
Low-energy neutrino-nucleus scattering

- In neutrino experiments, we don't know ω, so let's look at things through outgoing lepton kinematics. For a given neutrino energy E_ν, cross sections as a function of muon energy T_μ, and scattering angle θ_μ.

- Low E_ν: cross section is dominated by low-energy excitations.
- E_ν = 800 MeV: forward scattering receive contribution from low-energy excitations.



- In general neutrino cross sections are dominated by transverse contribution.
- The forward we go in scattering angle, for instance at energies ~ 800 MeV, the longitudinal contribution starts competing with the transverse one.

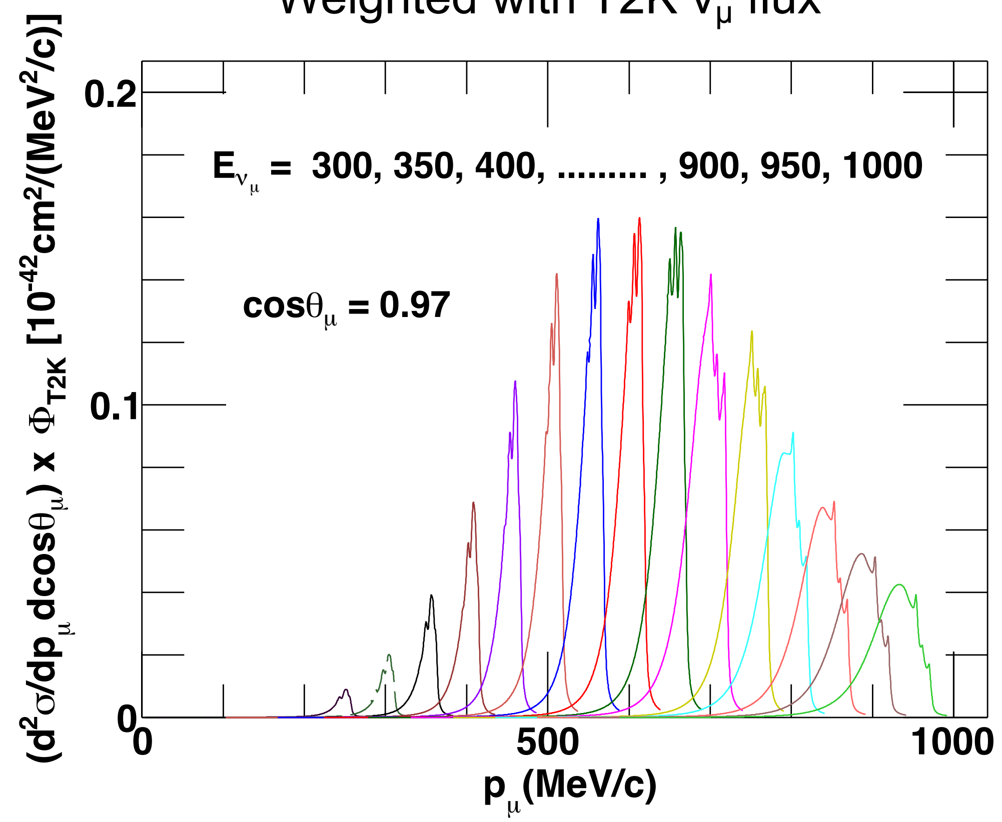


__VP__, N. Jachowicz, T. Van Cuyck, J. Ryckebusch, M. Martini, Phys. Rev. C92, 024606 (2015)

Low-energy neutrino-nucleus scattering

- **<u>What about flux-folded cross section?</u>**
  - Cross sections (on ^{12}C) for a fixed $\cos\theta_\mu = 0.97$ and for fixed neutrino energies from 300 MeV to 1000 MeV, weighted with the T2K ν_μ flux and plotted as a function of p_μ.
  - Integrating over energies (BNB flux-folded), the peaks disappear but the significant contributions of low-energy excitations (ω < 50 MeV) stays at forward scattering.

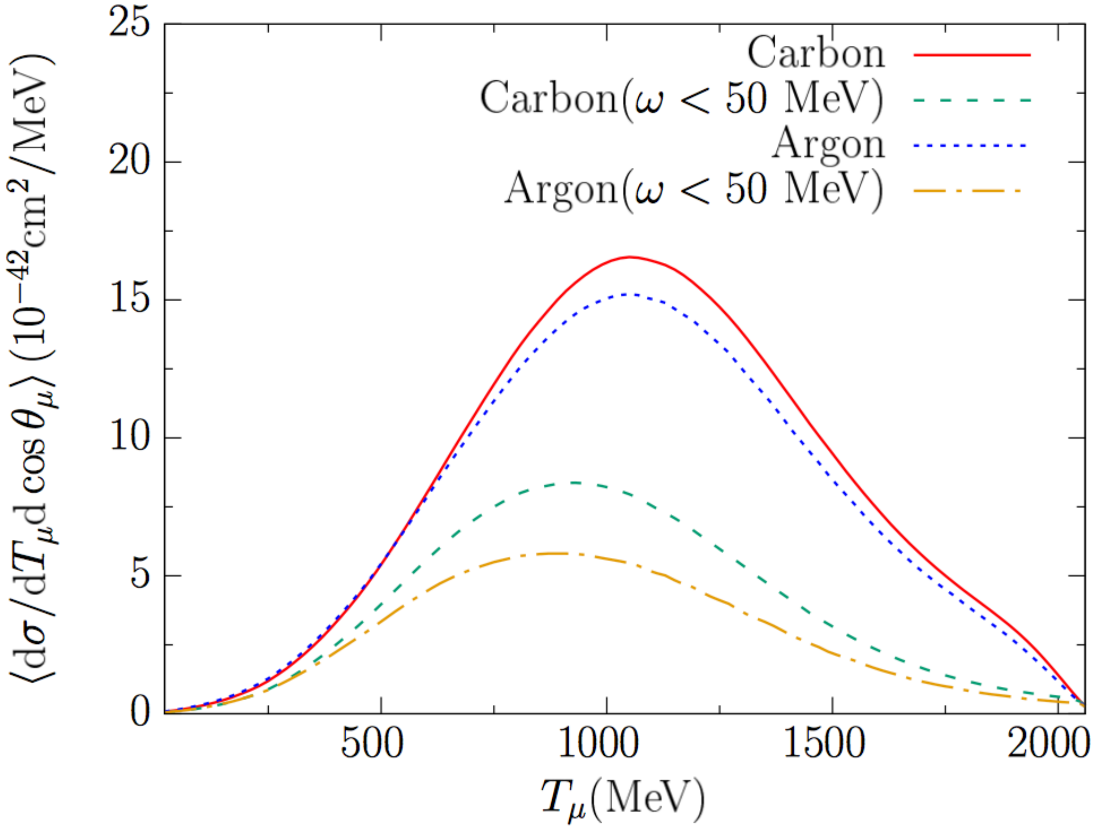
Weighted with T2K ν_μ flux



__VP__, N. Jachowicz, M. Martini, R. González-Jiménez, J. Ryckebusch, et al., Phys. Rev. C94, 054609 (2016).

Folded with BNB ν_μ flux

$0.97 < \cos\theta_\mu < 1.0$



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