Theory of neutrino cross-sections

Joanna Sobczyk

WG2: Neutrino Scattering Physics

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Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

JG|U

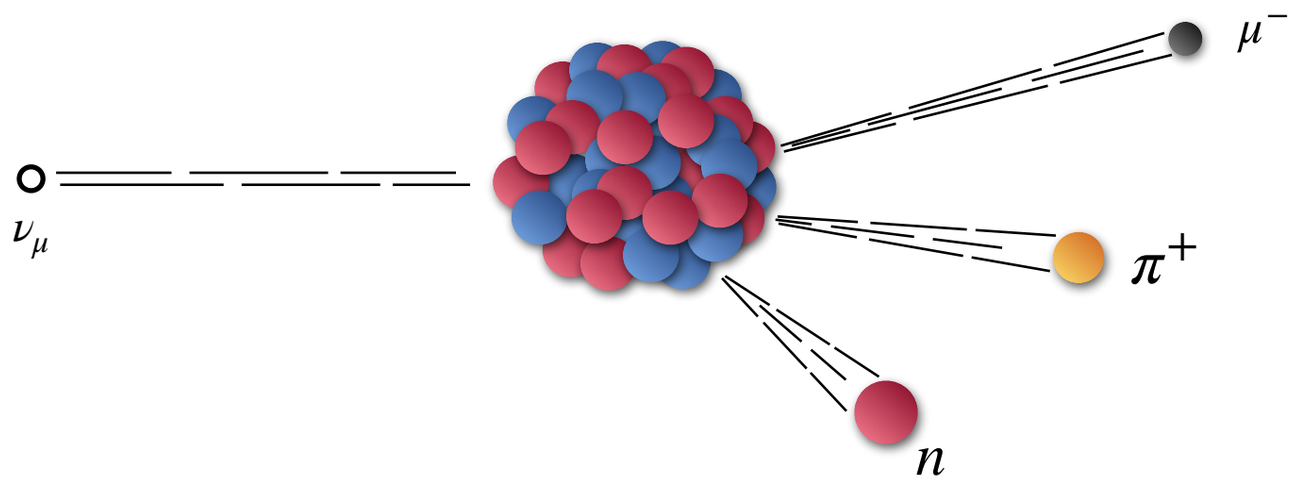
Alexander von Humboldt Stiftung/Foundation

MARIE CURIE ACTIONS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101026014

ν scattering

- ➡ Neutrino basic properties
- ➡ Nature of neutrino sources
- ➡ Nuclear structure



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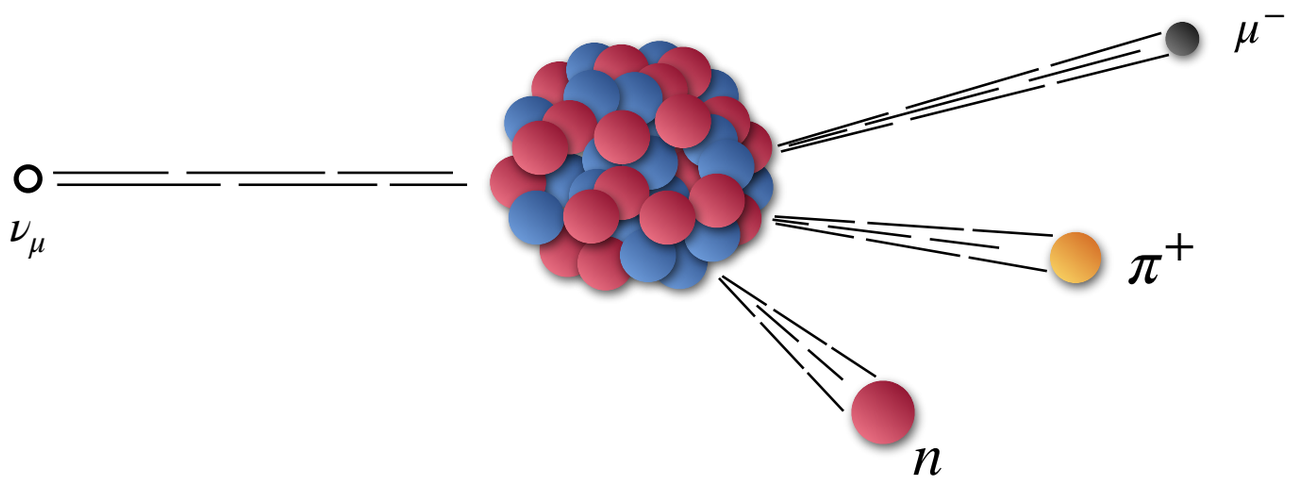
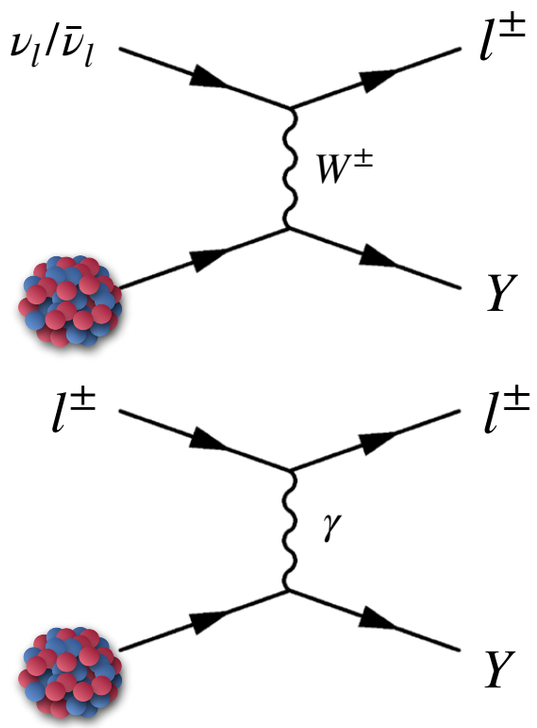


ANALOGY between **electron** and **neutrino** scattering



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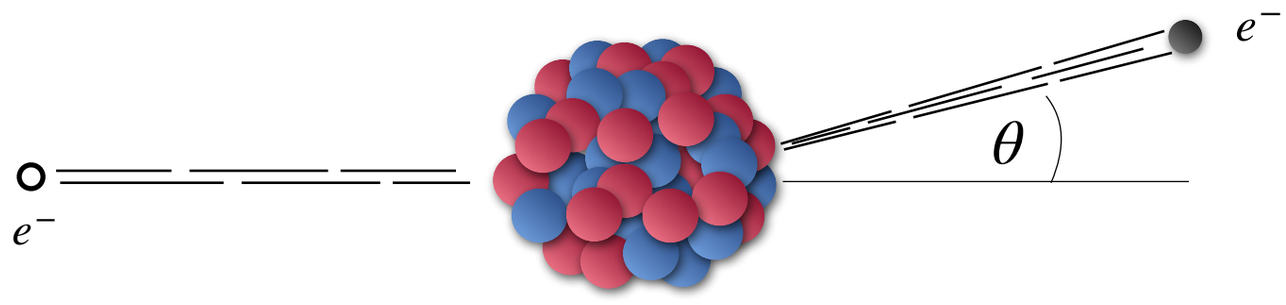

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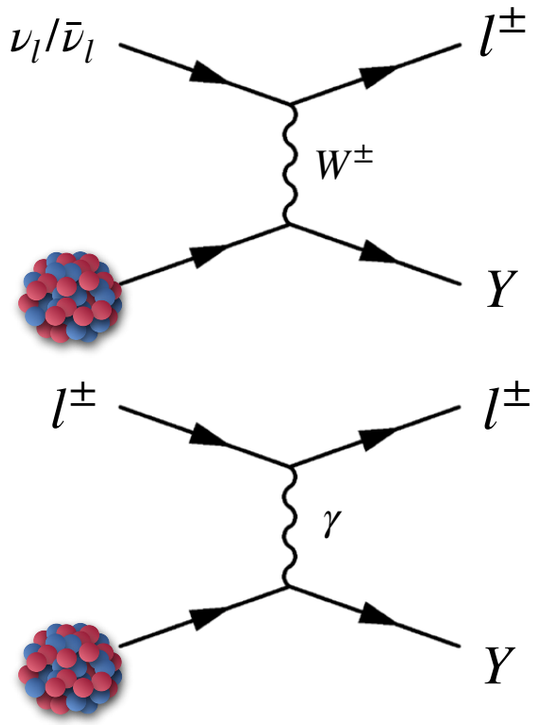

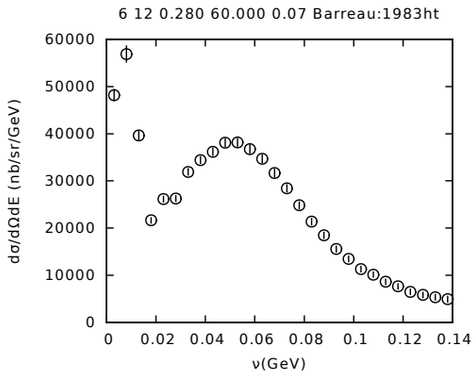

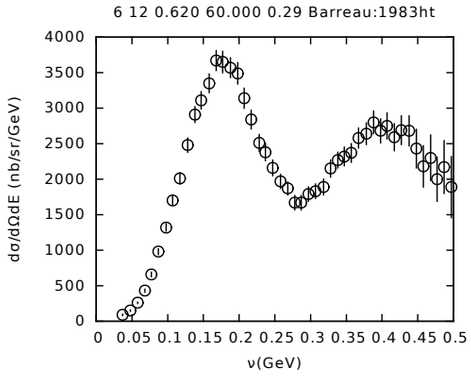

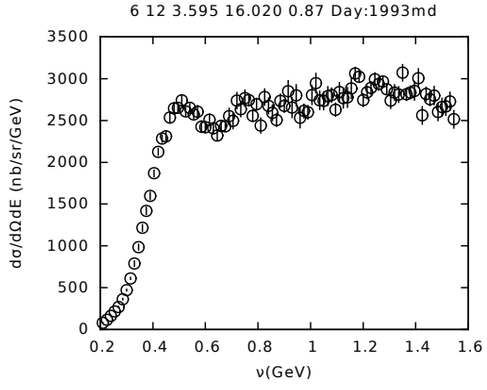

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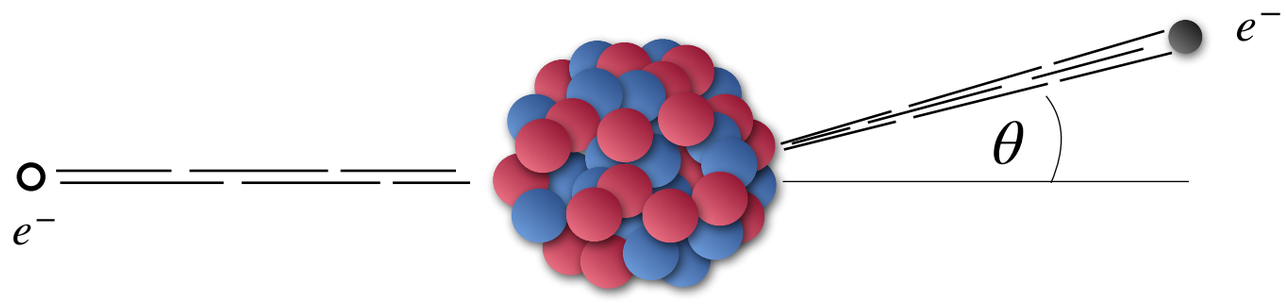

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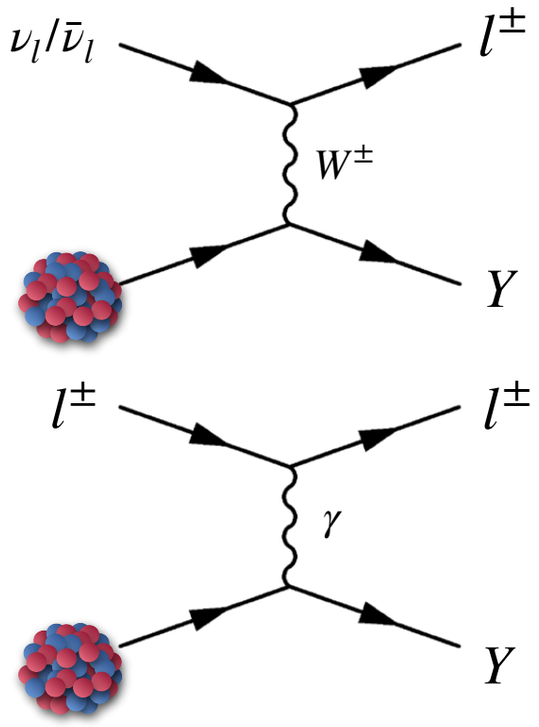

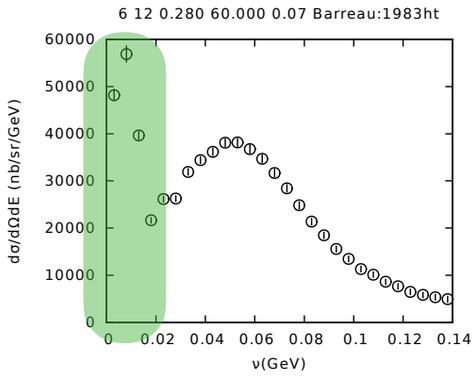

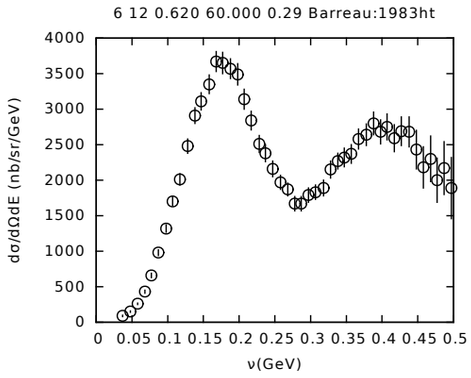

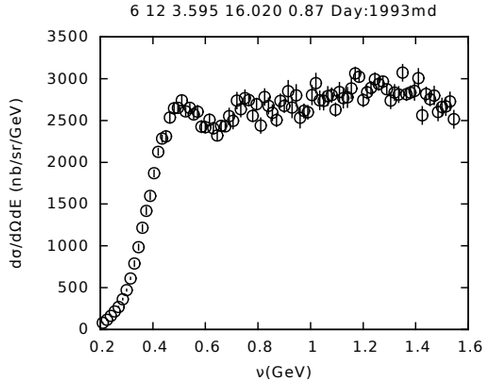

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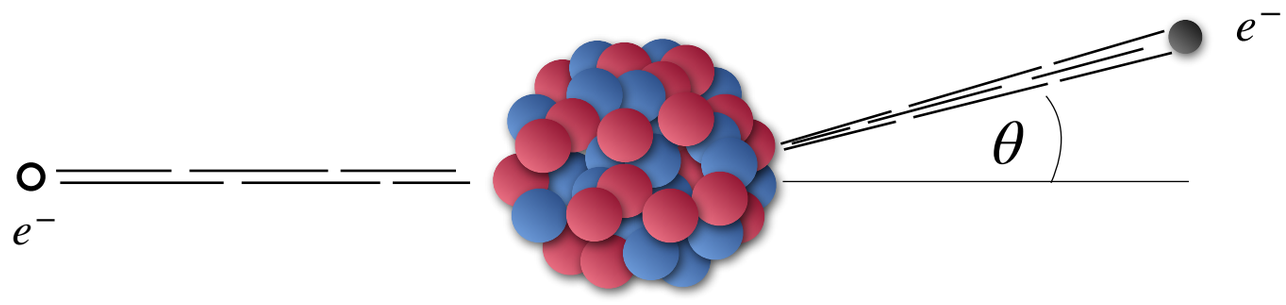

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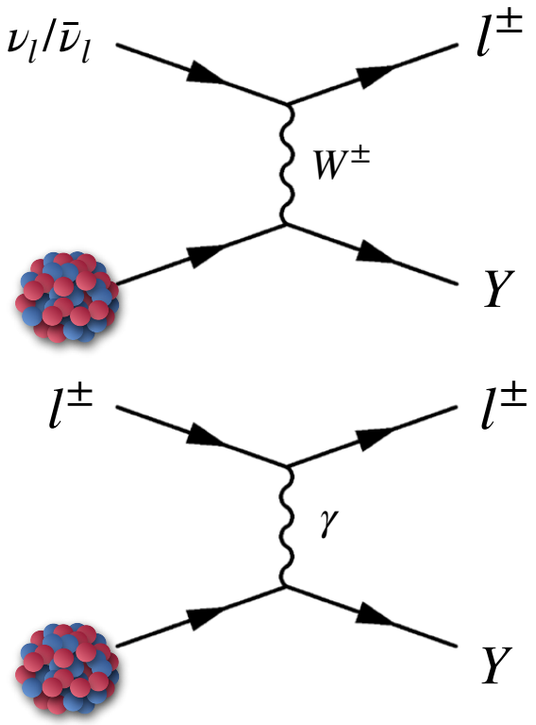

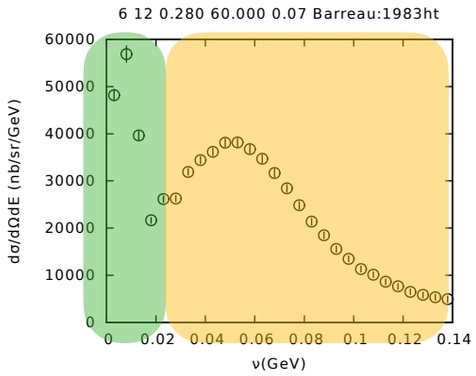

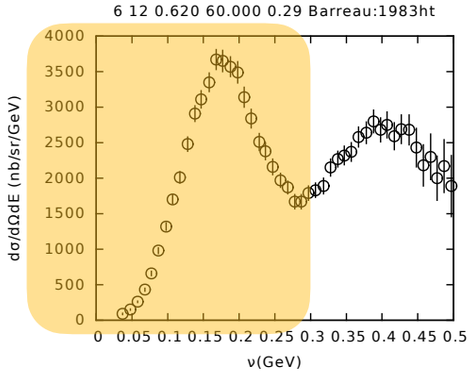

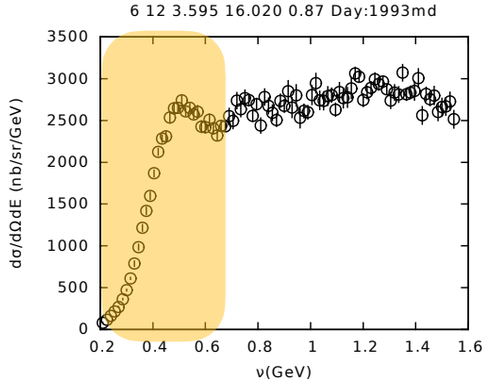

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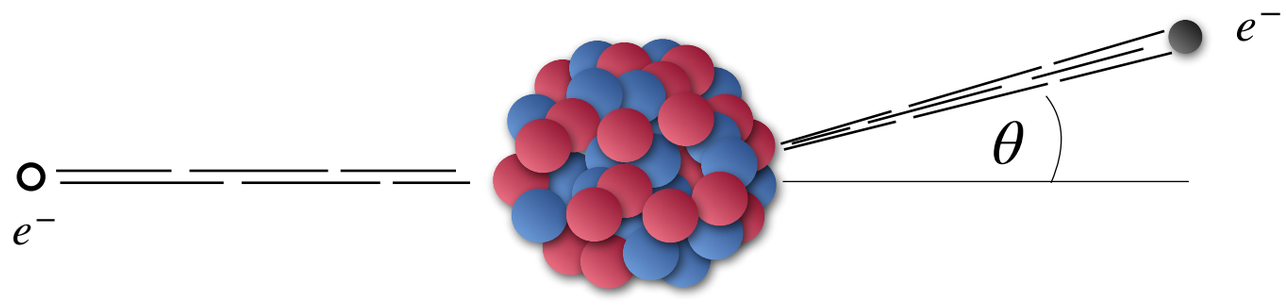

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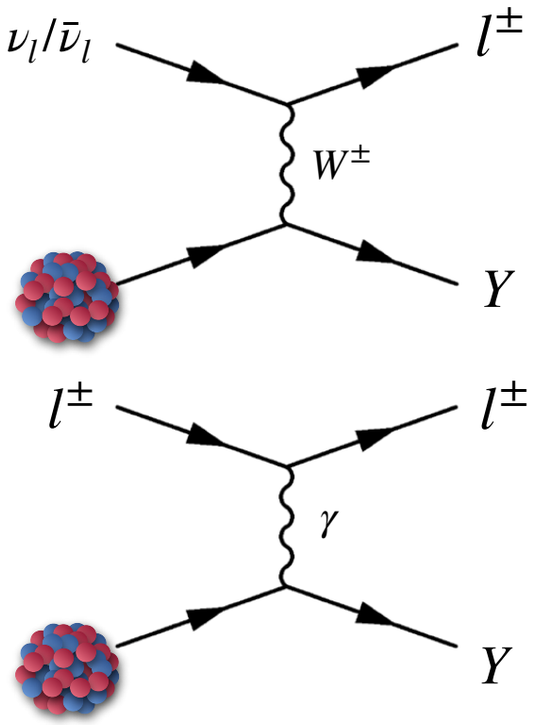
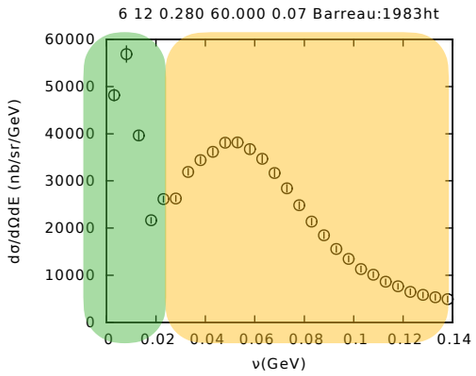
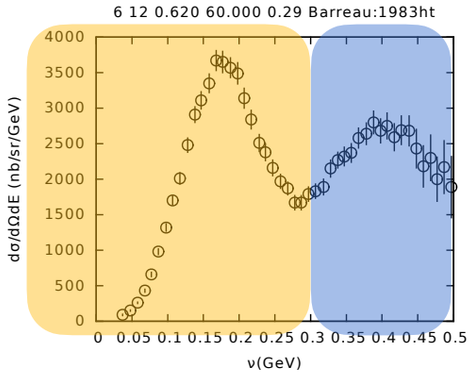
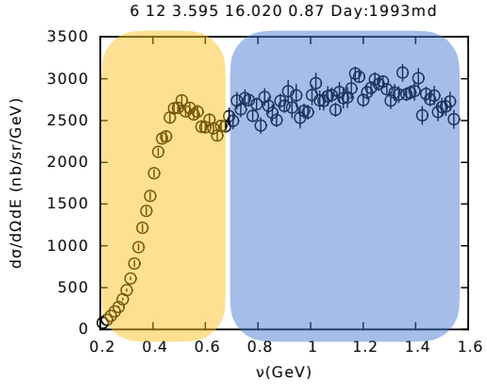


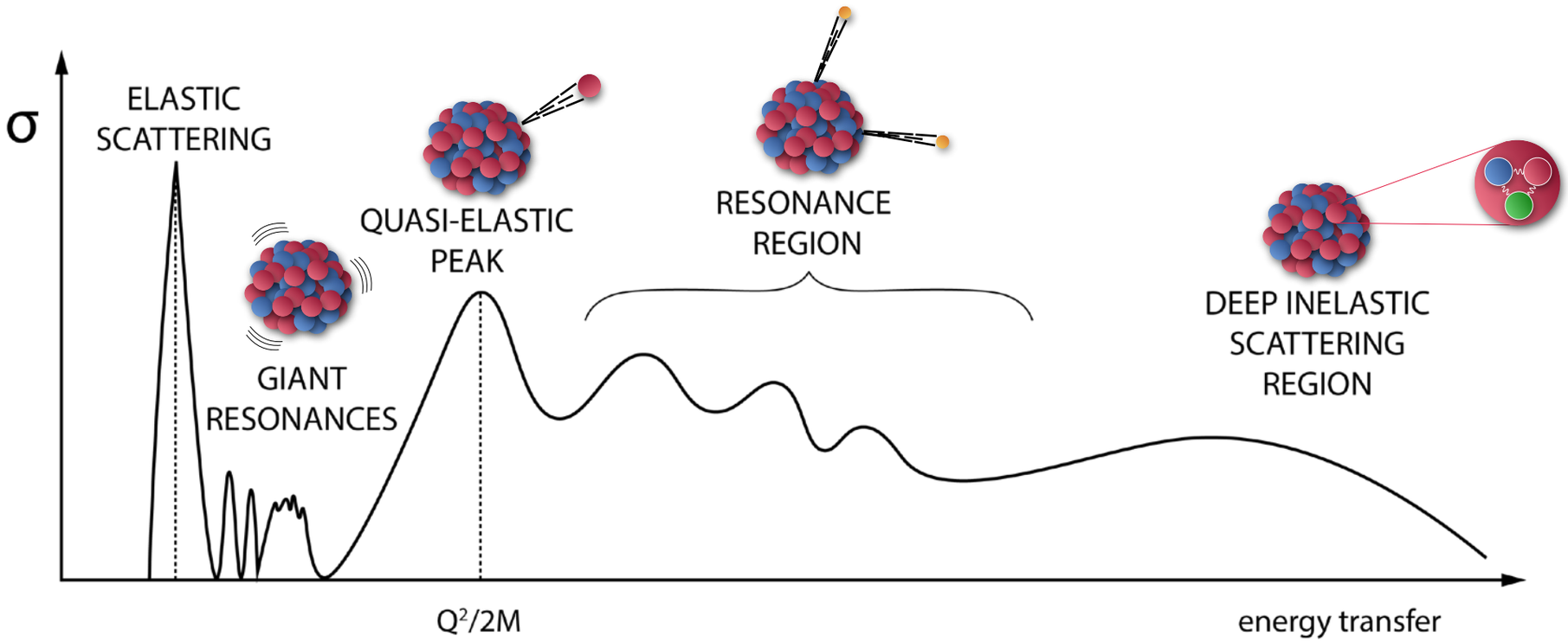






Motivation

Electroweak nuclear responses



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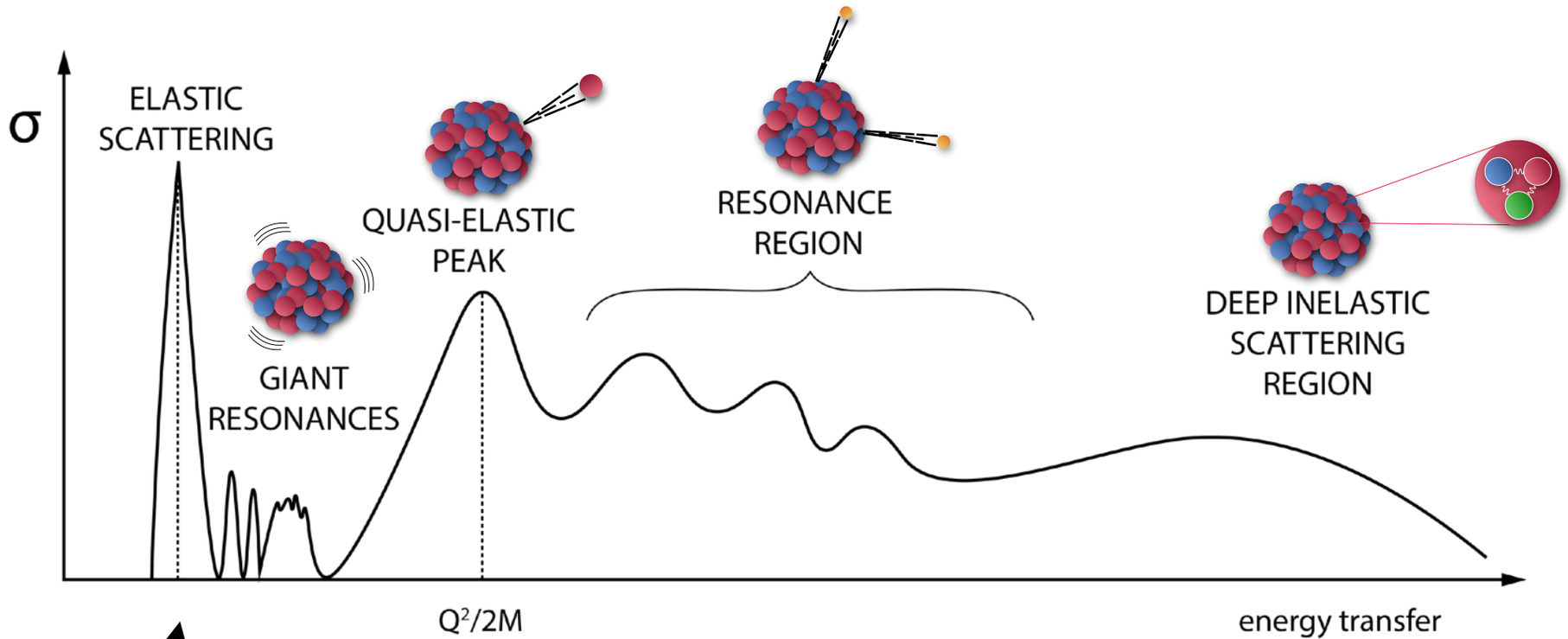

Inelastic scattering

Elastic scattering: CEvNS (coherent elastic neutrino-nucleus scattering)

e.g. Supernovae neutrinos

Long-baseline experiments (DUNE, HyperK)

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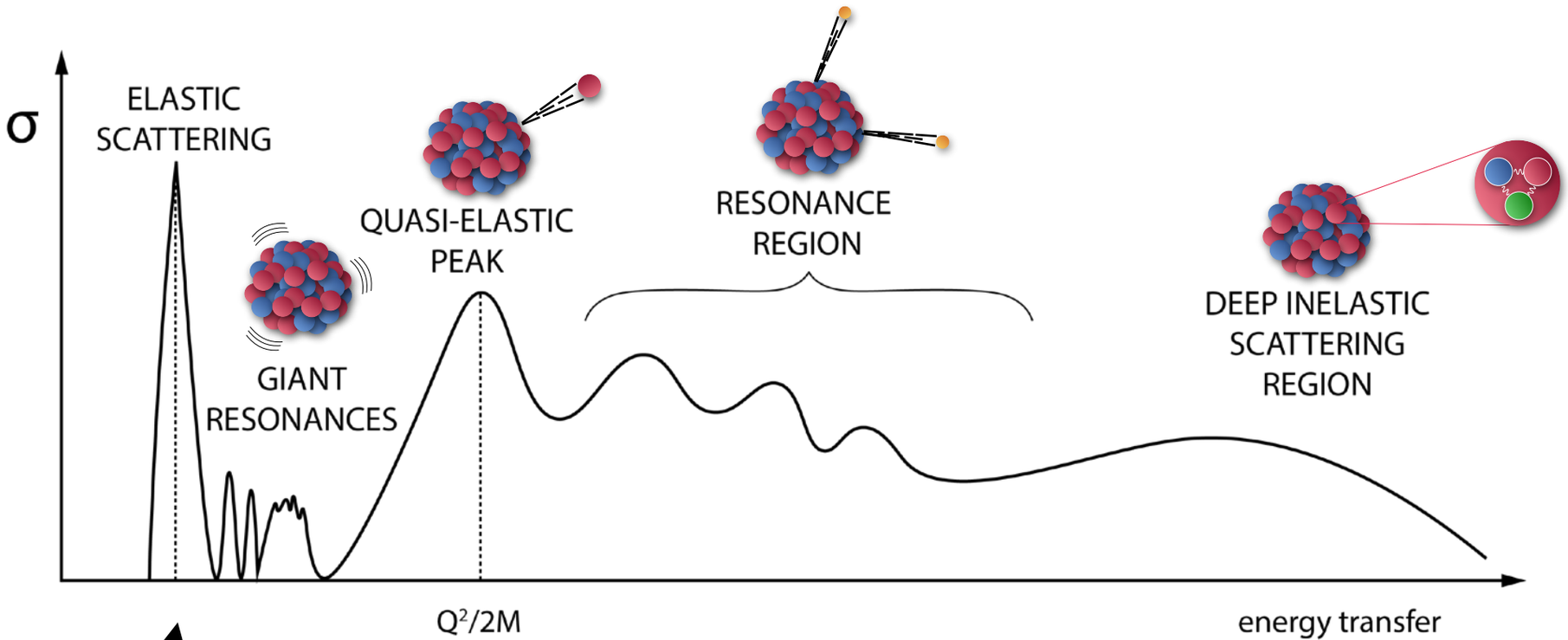
Electroweak nuclear responses



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SEE TALK: Vishvas Pandey (Thursday)

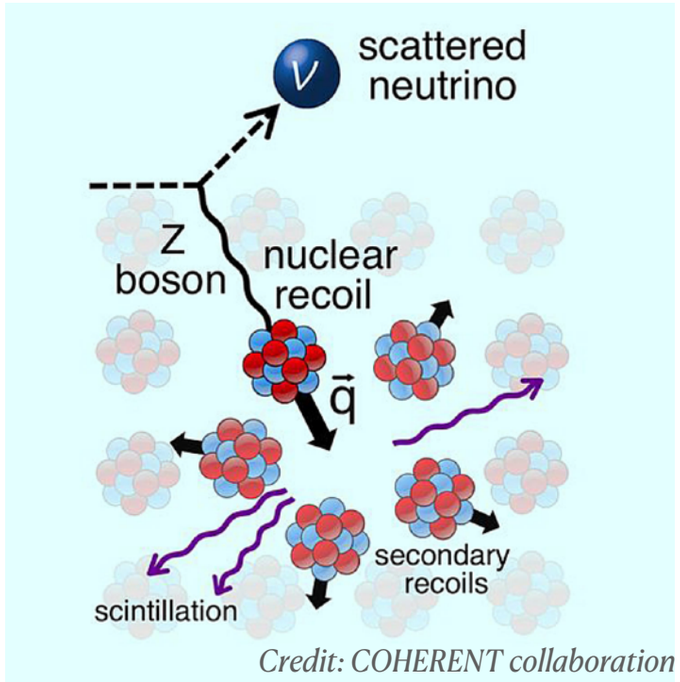
Coherent elastic ν-nucleus scattering

CEvNS

- Neutral current reaction
- Valid for $q \lesssim 1/R, E_\nu \approx 50$ MeV

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} N^2 \left| F_W(q) \right|^2 M\left(1 - \frac{T}{E} - \frac{MT}{2E^2}\right)$$

Weak nuclear form-factor



Credit: COHERENT collaboration

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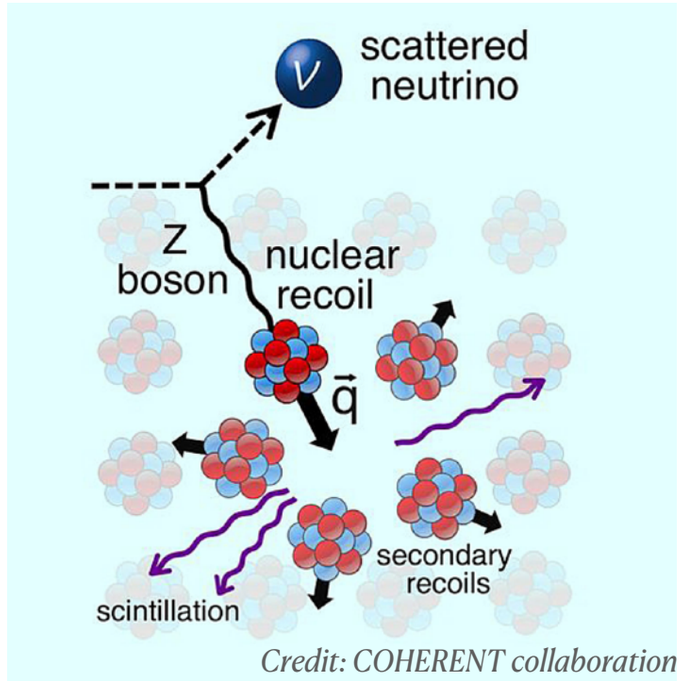

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Weak nuclear form-factor

$$F_W(q) = \frac{1}{N} \int e^{iqr} \left((1 - 4\sin^2\theta_W)\rho_p(r) + \rho_n(r) \right) d^3r$$

≈ 0

Neutron distribution

- Probes **neutron distribution**
  (complementary to electron scattering)

Coherent elastic ν-nucleus scattering

CEvNS

- Neutral current reaction
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Weak nuclear form-factor

$$F_W(q) = \frac{1}{N} \int e^{iqr} \left(\cancel{(1 - 4\sin^2\theta_W)\rho_p(r)} \approx 0 + \rho_n(r) \right) d^3r$$

Neutron distribution

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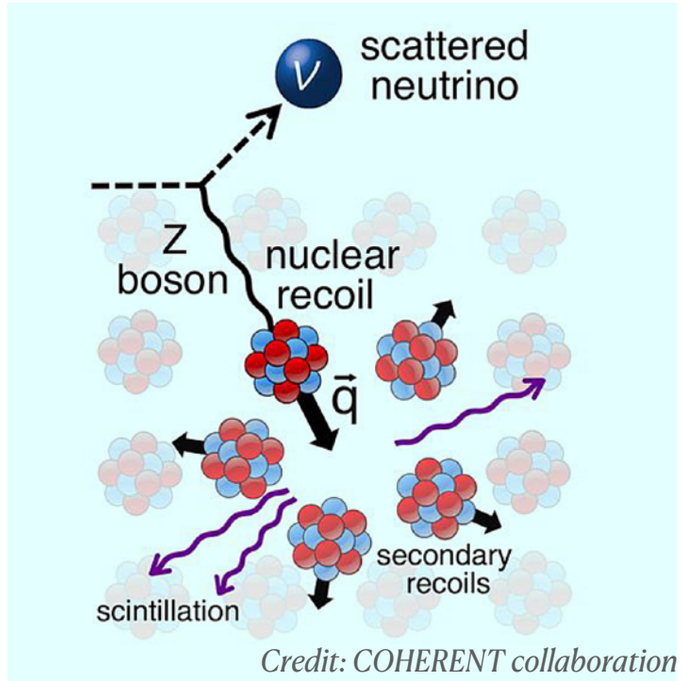

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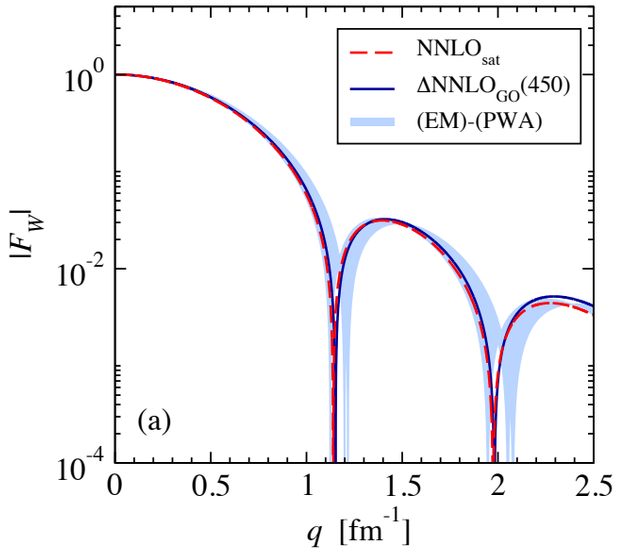
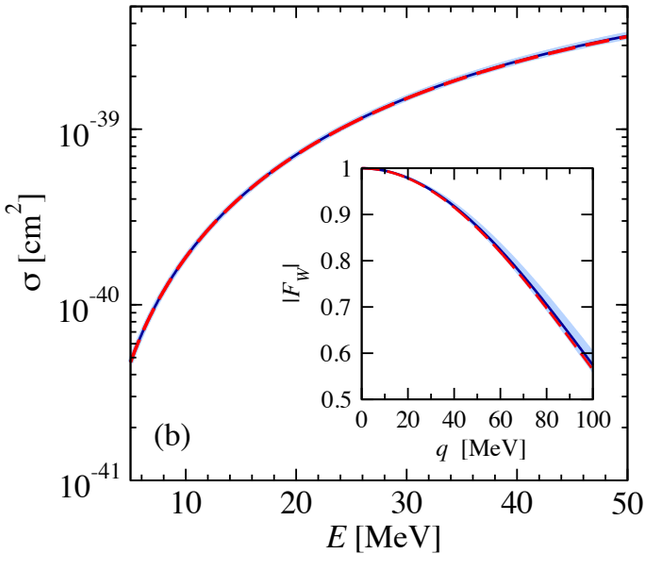
SEE TALK: Yuri Efremenko (Thursday)

Nuclear physics and CEvNS

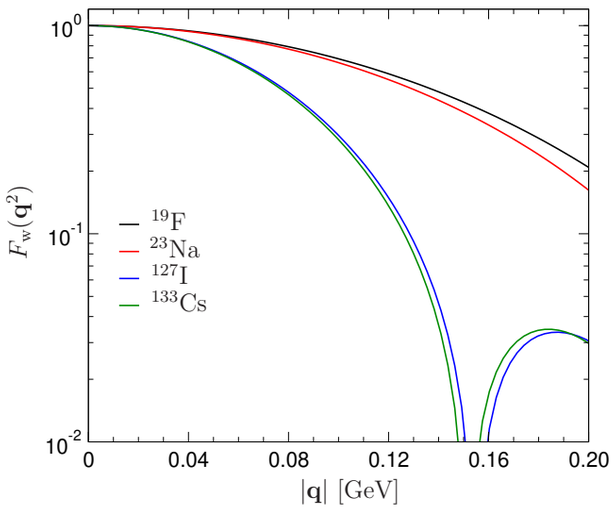
Weak form-factor of ^{40}Ar
- Ab initio method (coupled-cluster theory)
- various nuclear potentials

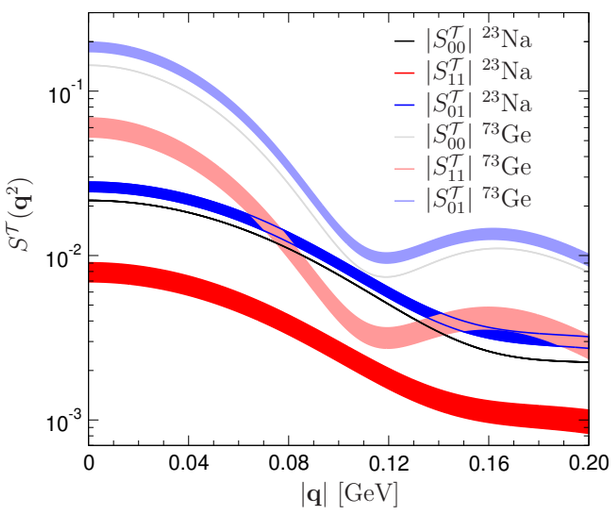




C. Payne at al.
Phys.Rev.C 100 (2019) 6, 061304

Shell model calculations
- Generalisation for beyond SM — new nuclear responses

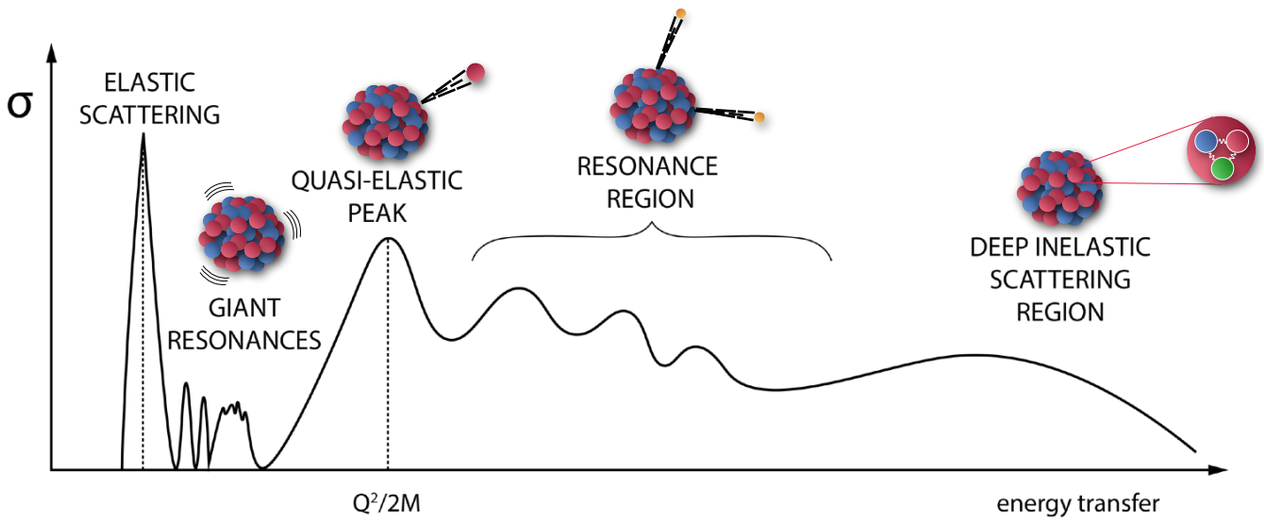




M. Hoefichter, J. Menendez, A.Schwenk
Phys.Rev.D 102 (2020) 7, 074018

Nuclear responses — inclusive cross-section

Cross-section $\sigma \propto L^{\mu\nu} R_{\mu\nu}$

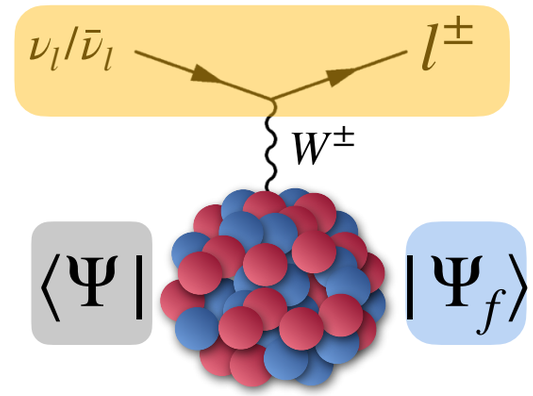


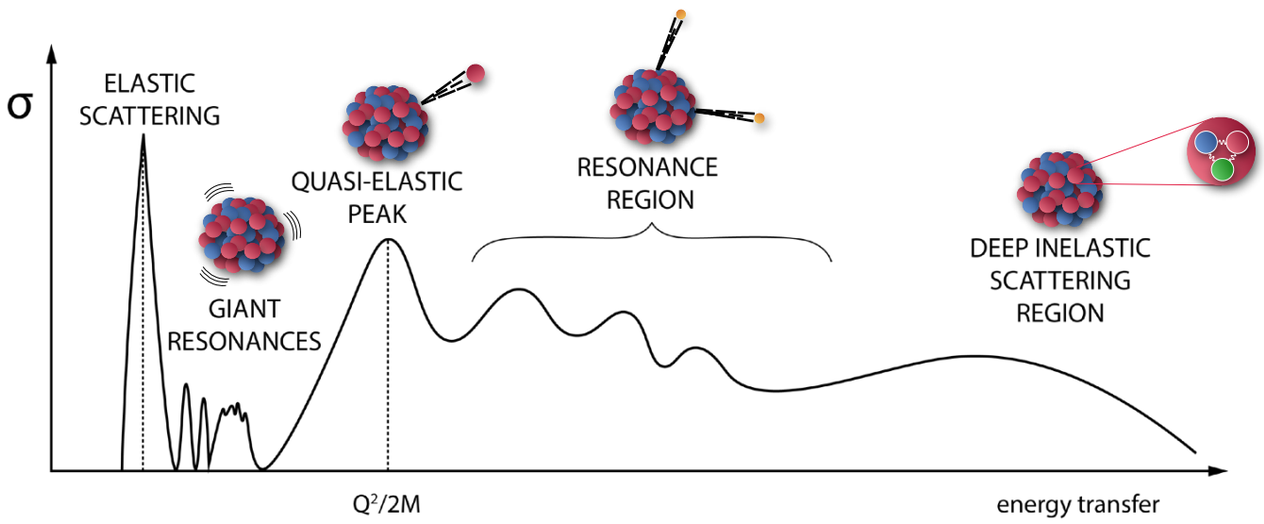
Nuclear responses — inclusive cross-section

Cross-section $\sigma \propto L^{\mu\nu} \; R_{\mu\nu}$

lepton tensor

nuclear responses





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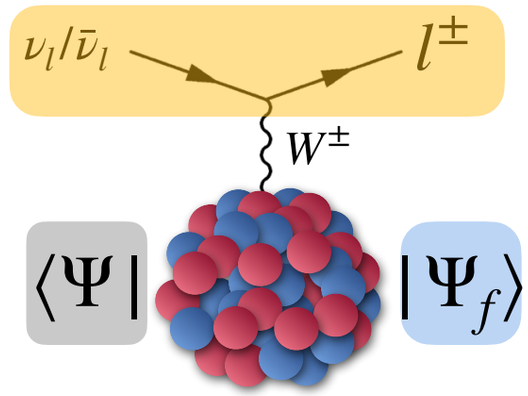
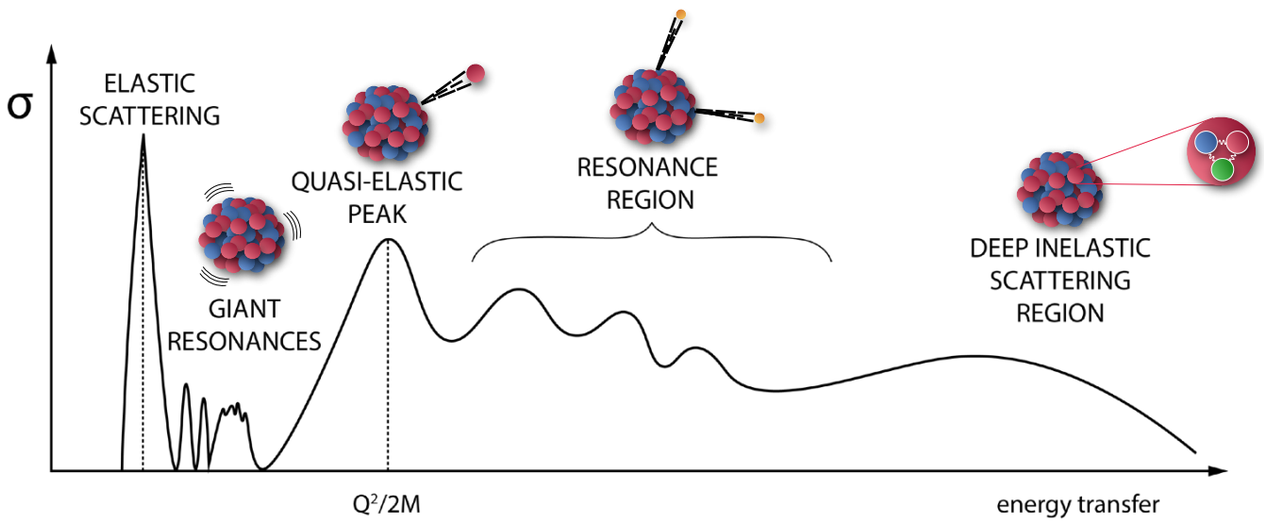


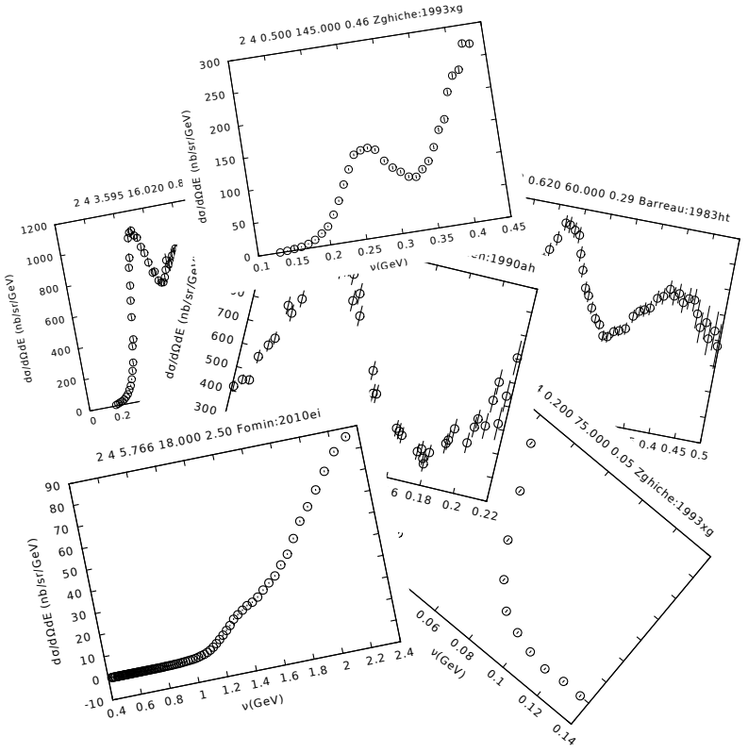


$$R_{\mu\nu}(\omega, q) = \sum_f \langle\Psi| J_\mu^\dagger(q) |\Psi_f\rangle\langle\Psi_f| J_\nu(q) |\Psi\rangle \delta(E_0 + \omega - E_f)$$

Challenging sum over continuum spectrum

Electron scattering: Rosenbluth separation

Inclusive cross-section



$$\left.\frac{d\sigma}{dE'd\Omega}\right|_e$$

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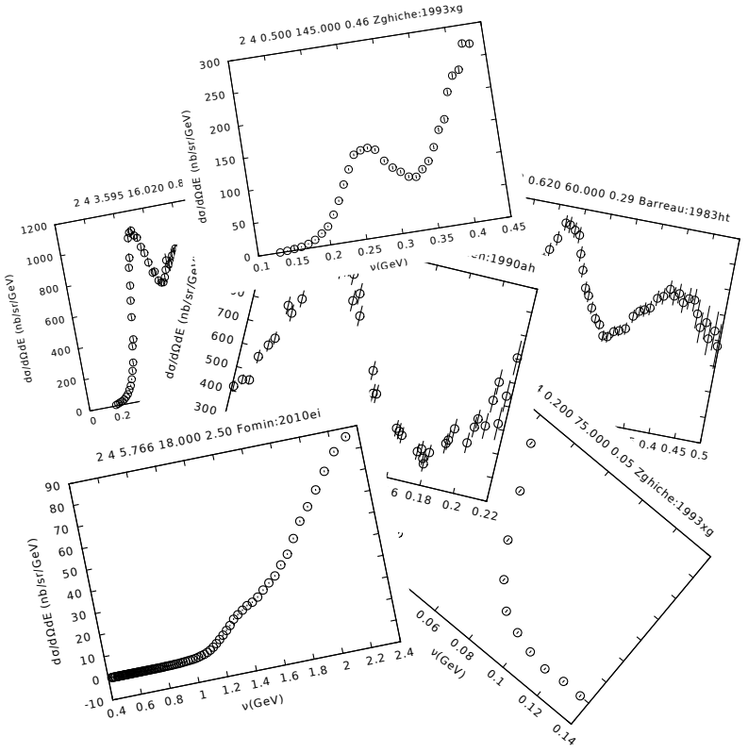

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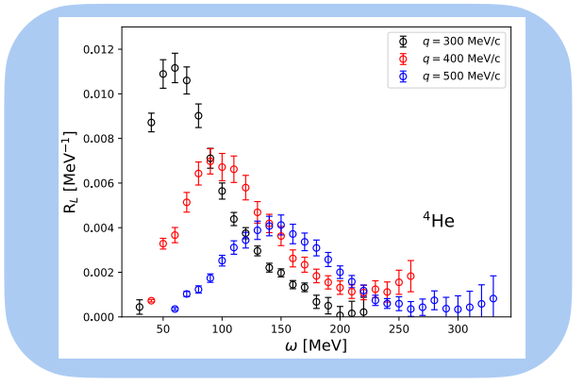
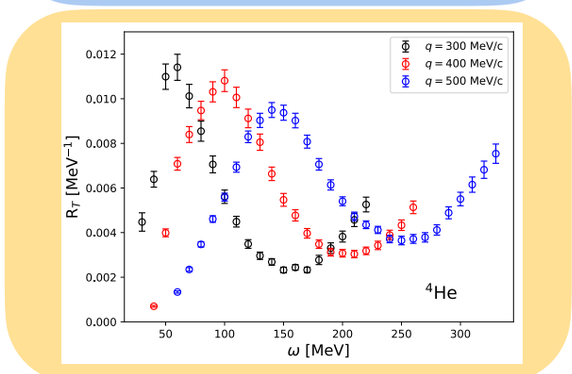
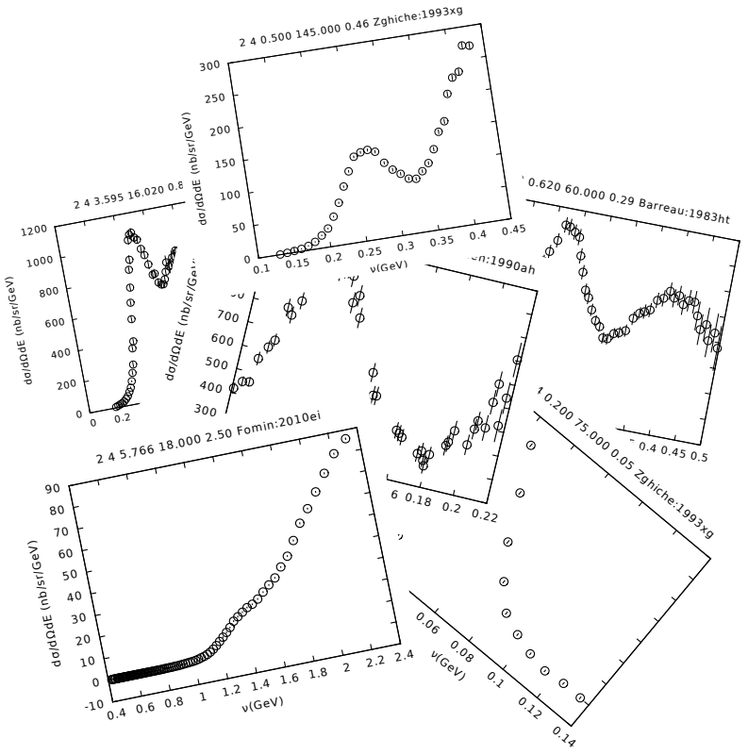




$$\left.\frac{d\sigma}{dE'd\Omega}\right|_e = \sigma_M\left(v_L R_L(\omega,\bar{q}) + v_T R_T(\omega,\bar{q})\right)$$

Electron scattering: Rosenbluth separation

Inclusive cross-section



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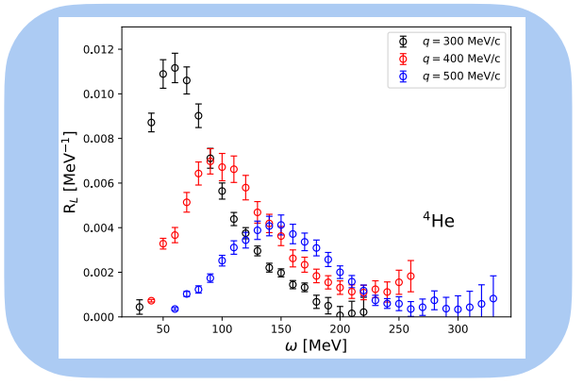
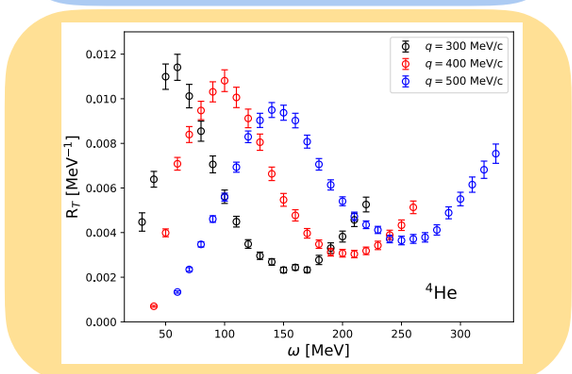
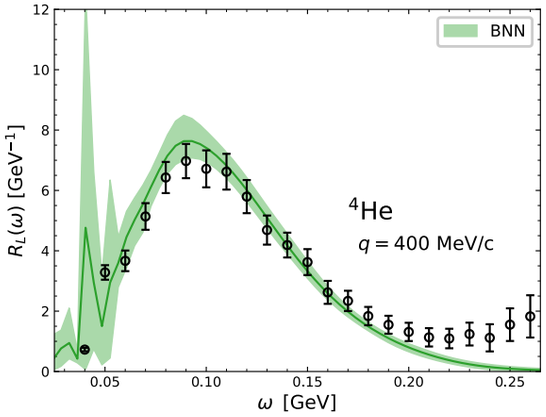


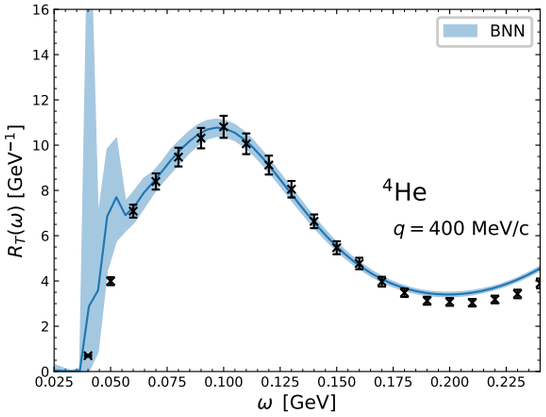


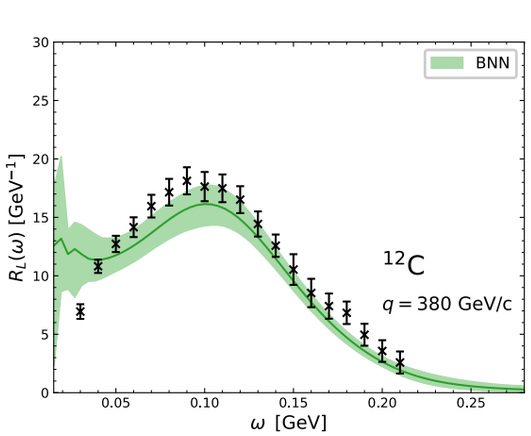
$$\left.\frac{d\sigma}{dE'd\Omega}\right|_{e} = \sigma_M\left(v_L R_L(\omega,\bar{q}) + v_T R_T(\omega,\bar{q})\right)$$

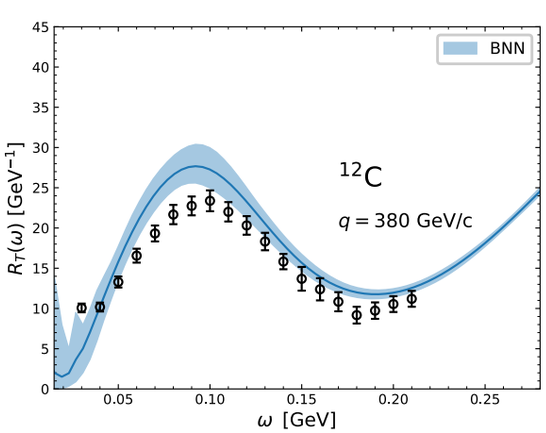
$$\left.\frac{d\sigma}{dE'd\Omega}\right|_{\nu/\bar{\nu}} = \sigma_0\left(v_{CC}R_{CC} + v_{CL}R_{CL} + v_{LL}R_{LL} + v_T R_T \pm v_{T'}R_{T'}\right)$$

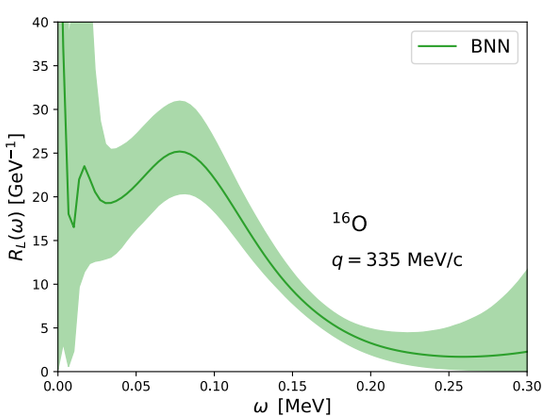
Rosenbluth separation with Bayesian neural network

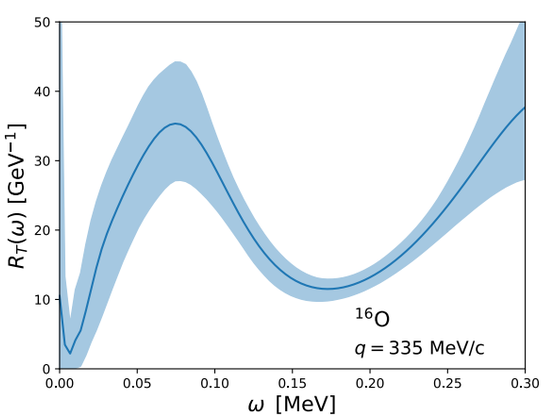












- Trained on ^{4}He, ^{6}Li, ^{12}C, ^{16}O, ^{40}Ca
- Rosenbluth separation possible for kinematics and nuclei where there is less data

ML approaches to reconstruct electron scattering cross-sections:

O. Al Hammal et al. *Phys.Rev.C* 107 (2023) 6, 065501

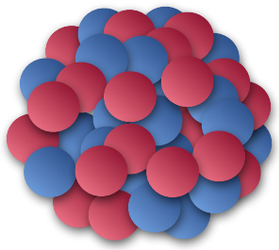
B. Kowal et al. *Phys.Rev.C* 110 (2024) 2, 025501

K. Graczyk et al. arxiv:2408.09936

JES, N.Rocco, A.Lovato, 2406.06292

“Ab initio” nuclear theory

nucleons — degrees of freedom



$$\mathscr{H}\,|\,\Psi\rangle = E\,|\,\Psi\rangle$$

$$\mathscr{H} = \sum_{i=1}^{A} t_{kin} + \sum_{i>j=1}^{A} v_{ij} + \sum_{i>j>k=1}^{A} v_{ijk} + \ldots$$

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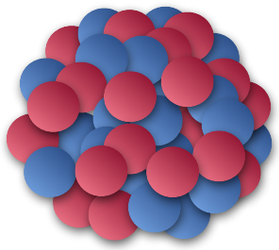

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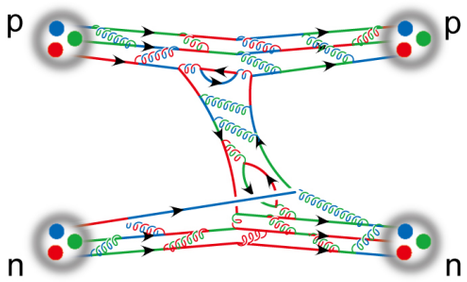
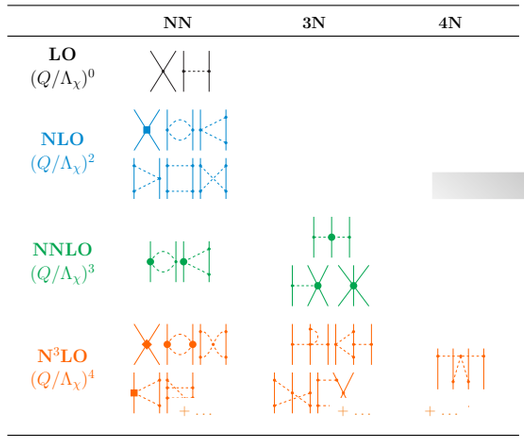
How the **nuclear force** is rooted in the fundamental theory of QCD?

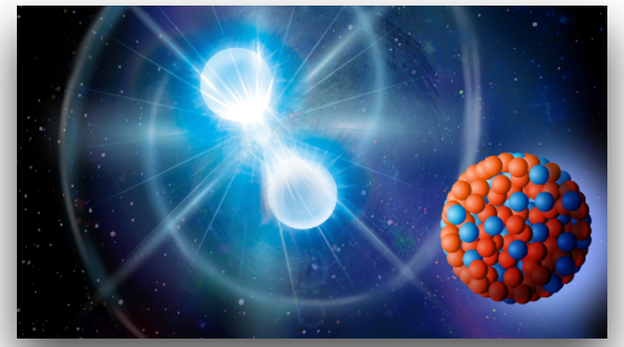
Quantum Chromodynamics



Chiral Effective Field Theory



Nuclei & nuclear matter



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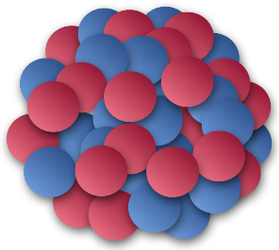

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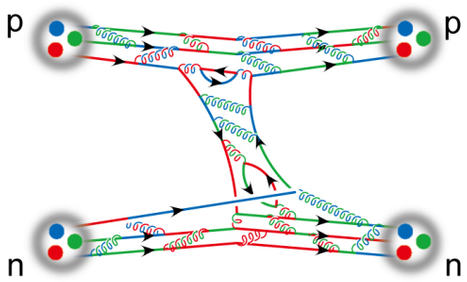

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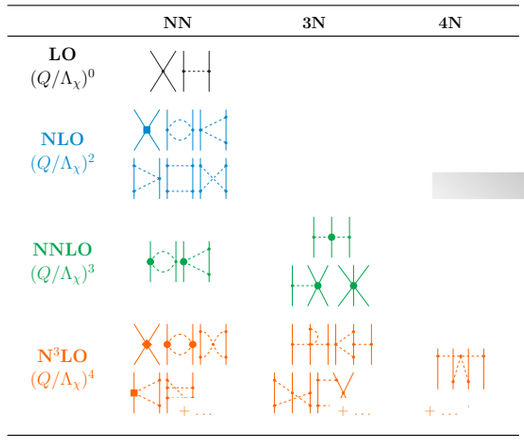

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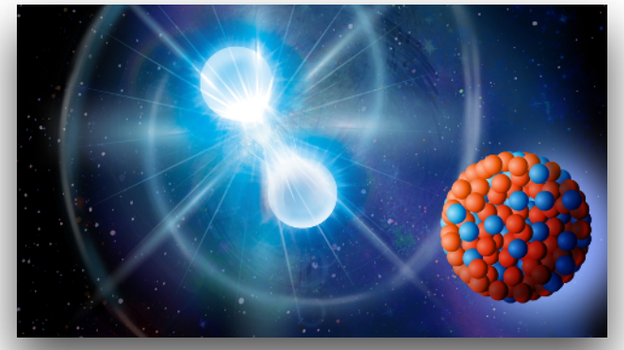
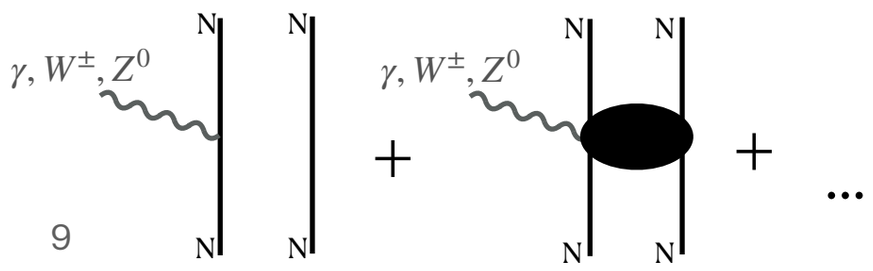


Allows to construct **electroweak currents** consistently with the chiral potential

$$j = \sum_{i=1}^{A} j_i + \sum_{j<i=1}^{A} j_{ij} + \sum_{k<j<i=1}^{A} j_{ijk} + \dots$$



How to solve Schrödinger equation?

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Green's Function Monte Carlo

Coupled cluster theory

How to solve Schrödinger equation?

Green's Function Monte Carlo

To obtain the **ground state**, expand the trial wave function in the Hamiltonian eigenstates

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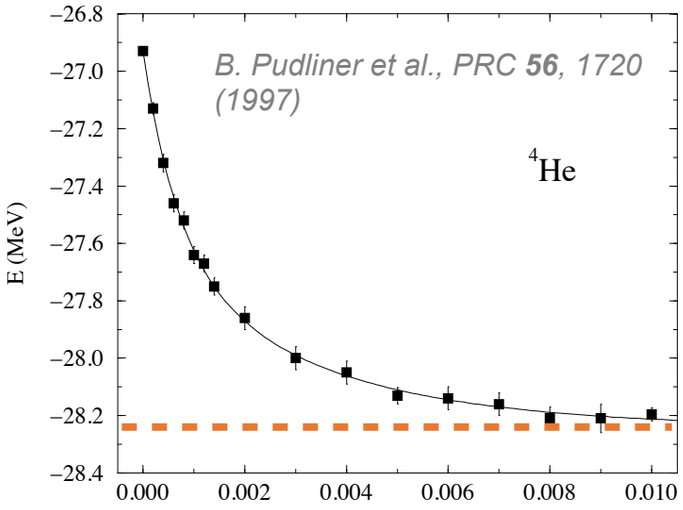

*J. Carlson Phys. Rev. C **36**, 2026 (1987)*

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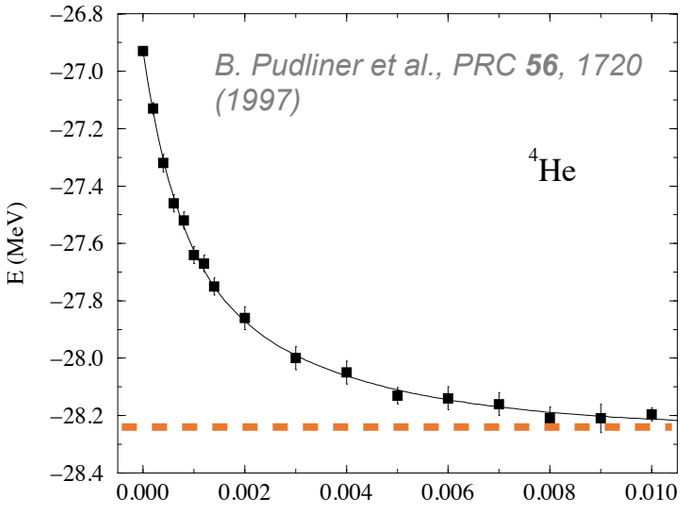

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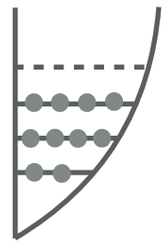

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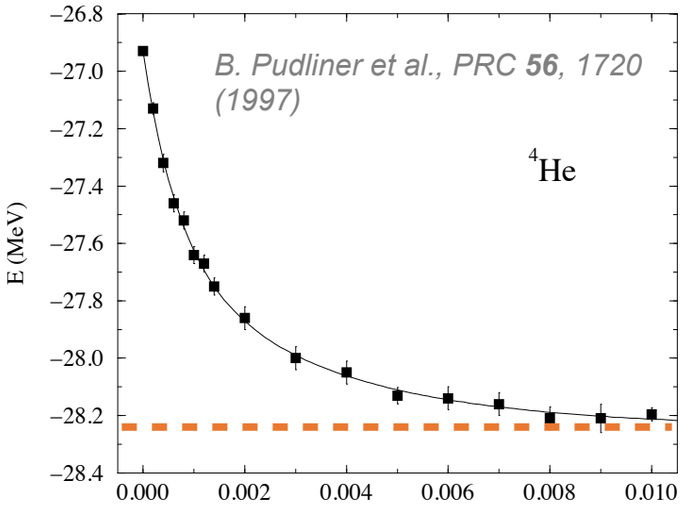

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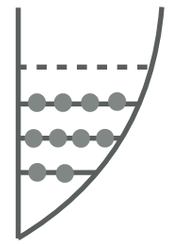


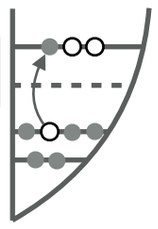
Include **correlations** beyond mean-field through e^T operator

$$\mathscr{H}_N e^T|\Psi\rangle = E e^T|\Psi\rangle$$

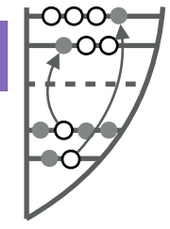
Expansion: $T = \sum t_a^i a_a^\dagger a_i + \frac{1}{4}\sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \ldots$

1p1h 2p2h

singles



doubles



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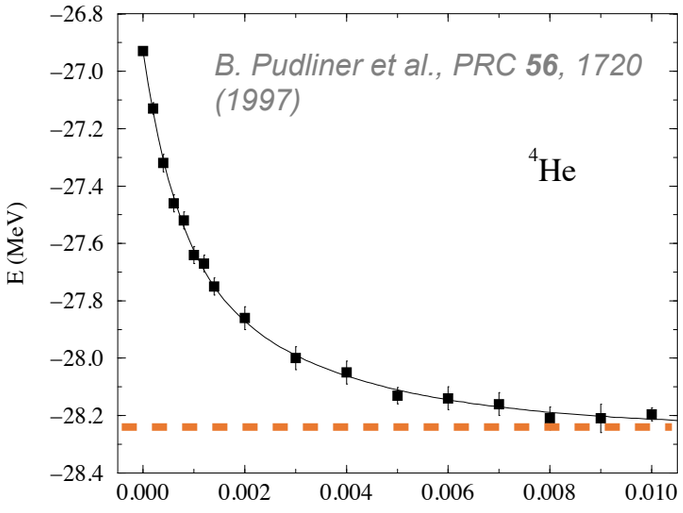

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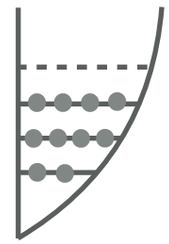

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1p1h 2p2h

singles doubles

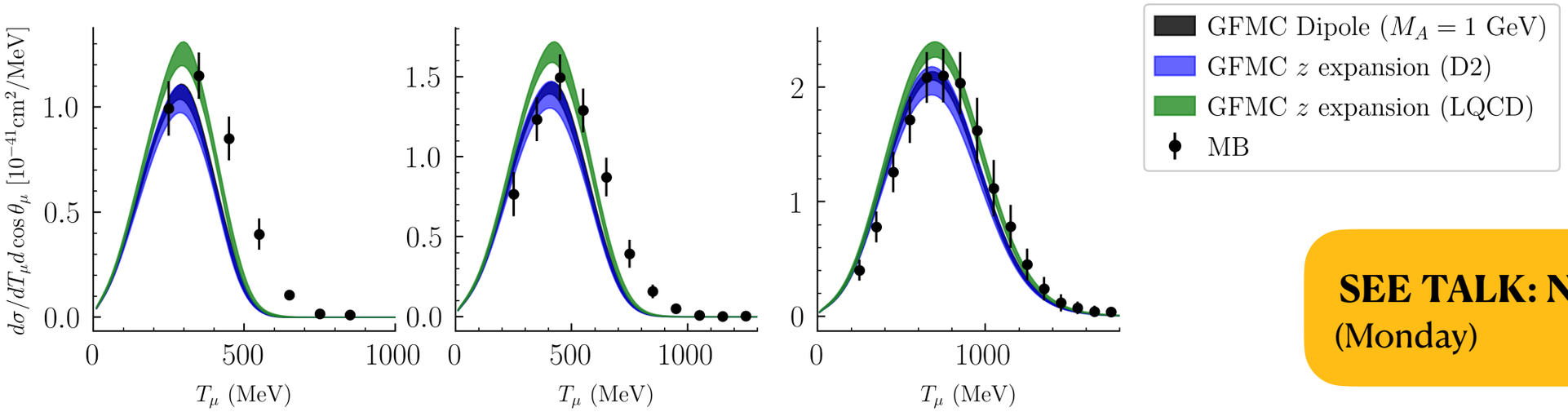
- ✓ Controlled approximation through truncation in T
- ✓ Polynomial scaling with A (predictions for ^{132}Sn and ^{208}Pb)

G. Hagen, T. Papenbrock, M. Hjorth-Jensen, D. J. Dean, Rep. Prog. Phys. 77, 096302 (2014).

Green's Function Monte Carlo for ^{12}C

Laplace Integral Transform + GFMC

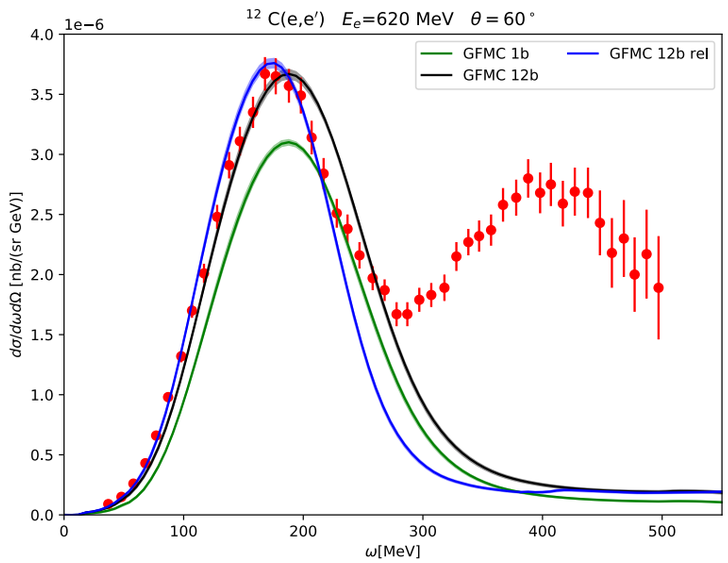
MiniBooNE results; study of the dependence on the axial form factor:



SEE TALK: Noemi Rocco
(Monday)

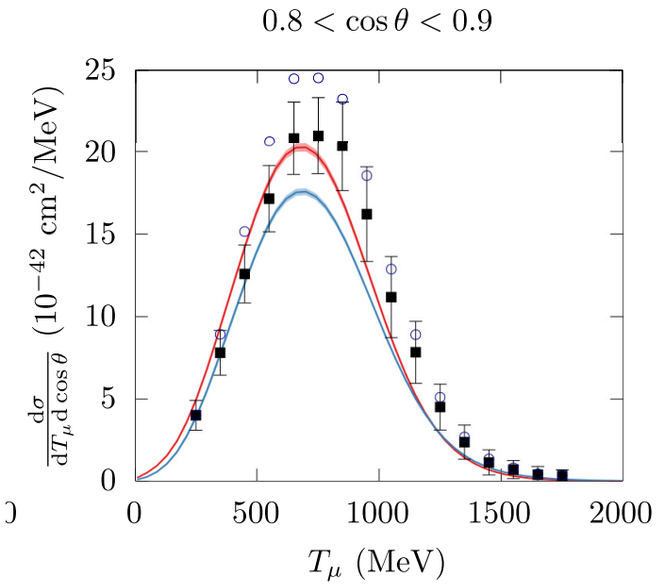
Including relativistic corrections in both electron and neutrino- scattering

- electron-12C scattering



A.Lovato, N.Rocco, et al, Universe 9 (2023) 8, 367

- muon-neutrino CC MiniBooNE results

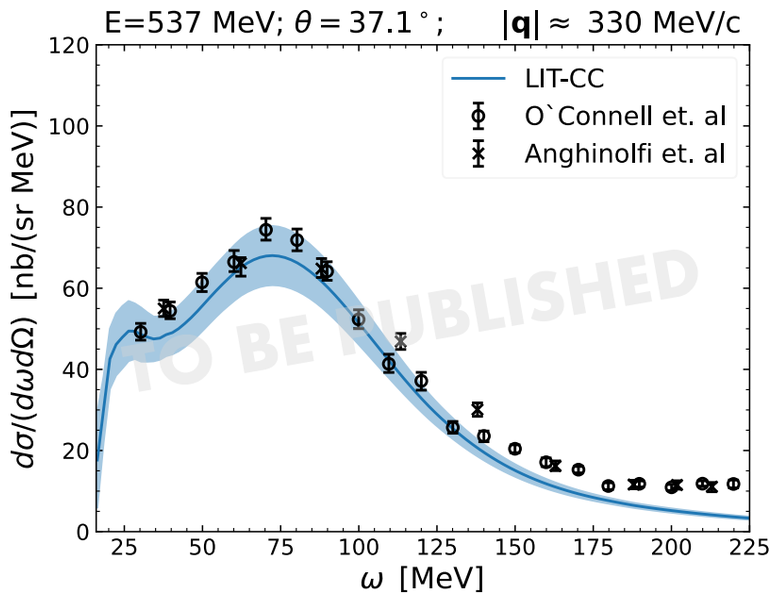


A. Nikolakopoulos, N.Rocco, et al, PRC 109, 014623 (2024)

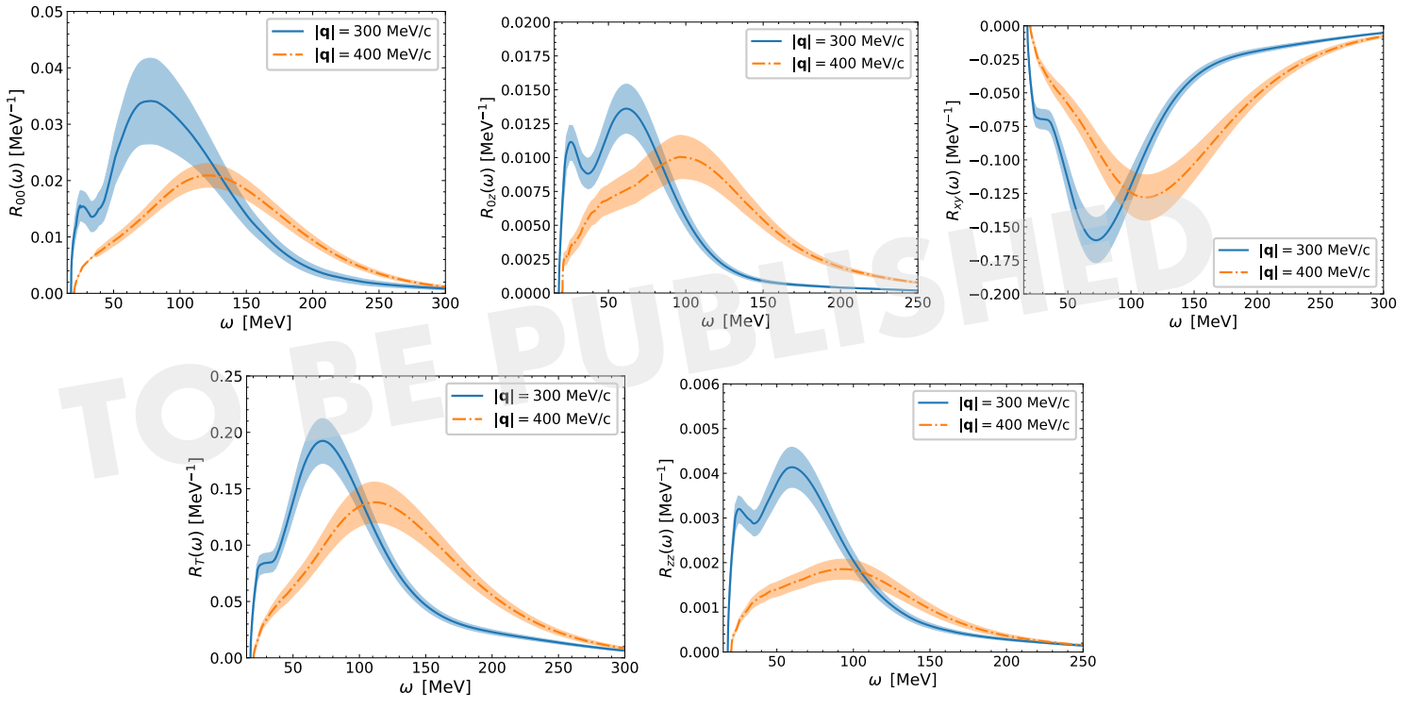
Coupled cluster for ^{16}O, ^{40}Ca

Lorentz Integral Transform + Coupled Cluster **(LIT-CC)**

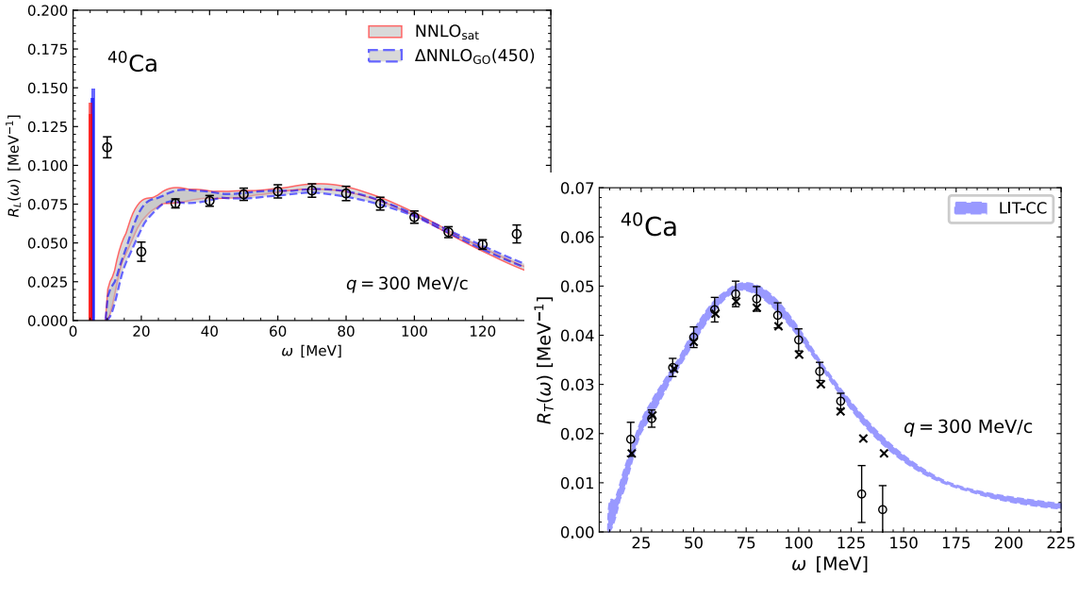
Electron scattering ^{16}O



Neutrino charge-current responses ^{16}O



Electron scattering ^{40}Ca



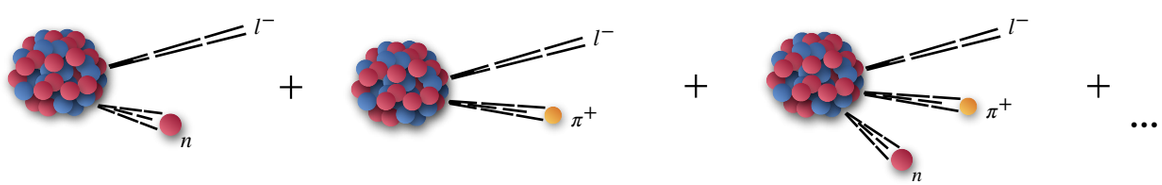
$$\left.\frac{d\sigma}{dE'd\Omega}\right|_{\nu/\bar{\nu}} = \sigma_0\left(v_{00}R_{00} + v_{0z}R_{0z} + v_{zz}R_{zz} + v_T R_T \pm v_{xy}R_{xy}\right)$$

First ab-initio results for many-body system of 16 and 40 nucleons

Challenges

- Inclusive cross-section:

$$\frac{d^2\sigma}{d\Omega d\omega} \propto L^{\mu\nu}\left[\sum_{t\in\text{topology}}\int\prod_{i=1}^{n} d^3p_i \langle\Psi|J_\mu^\dagger(q)|\Psi_f\rangle\langle\Psi_f|J_\nu(q)|\Psi\rangle\delta(E_0+\omega-E_f)\right]$$

topologies: 

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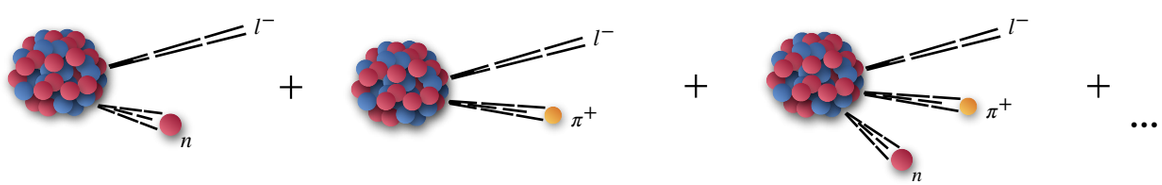
topologies: 

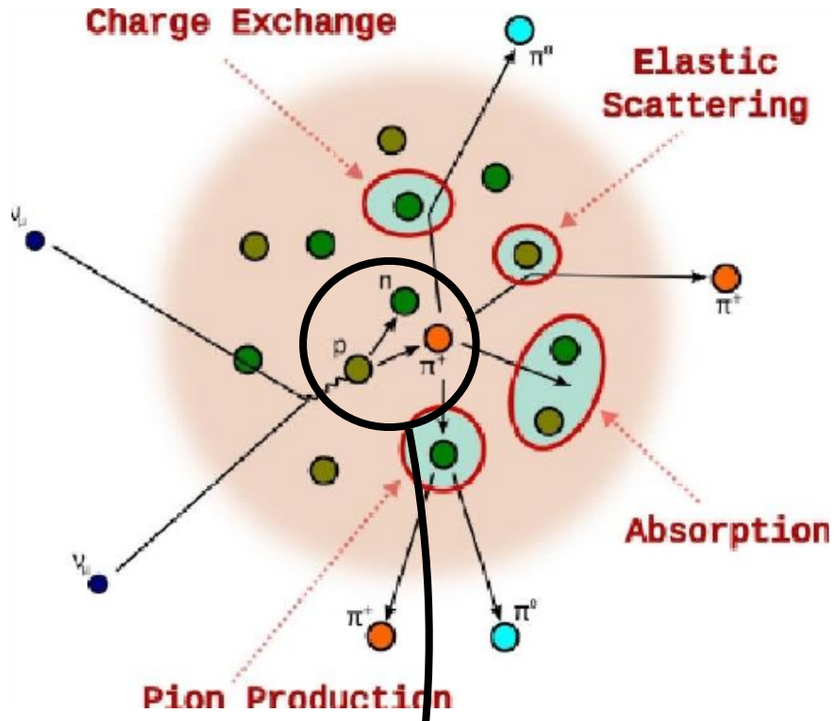
- Semi-exclusive observables

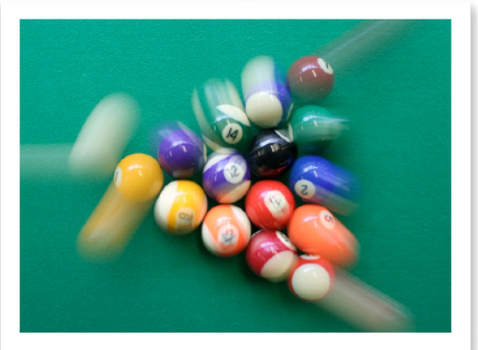
$$\left.\frac{d\sigma}{d\Omega d\omega\, d^3p_1\cdots d^3p_n}\right|_{\text{t-topology}} \propto L^{\mu\nu}\left[\langle\Psi|J_\mu^\dagger(q)|\Psi_f\rangle\langle\Psi_f|J_\nu(q)|\Psi\rangle\delta(E_0+\omega-E_f)\right]$$

- Each topology treated separately
- Relativistic processes
- Pion production

Monte Carlo event generators

- Experiments measure distributions of final hadrons — exclusive cross-sections.
- Each scattering event is obtained in a two-step process:
  - **Primary interaction vertex** (hadrons produced at some point in nucleus)
  - **Intra-nuclear cascade**
- This factorisation assumes **impulse approximation** — interaction takes place on a single nucleon





Primary interaction vertex

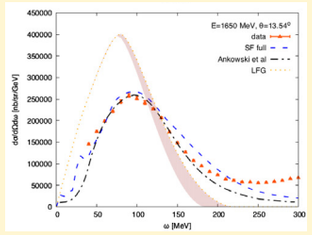
SEE TALKS: Tuesday (WG2)

NEUT
GENIE
NuWro
MARLEY
ACHILLES
GIBUU

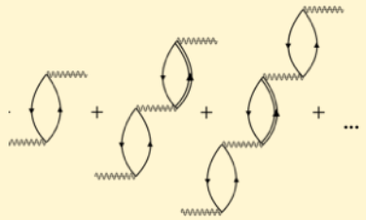
Quasi-elastic peak

Local density approximation (LDA)

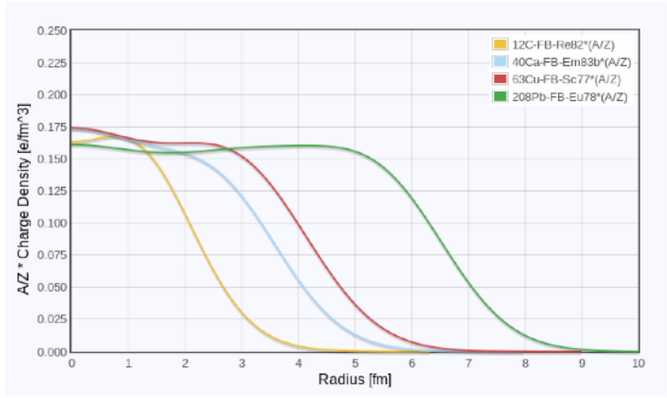
Fermi Gas model:
Constant binding energy



Valencia model:
RPA & spectral functions



GiBUU:
Relativistic
mean-field potential



- ✓ Locally, nucleus treated as nuclear matter
- ✓ No shell structure

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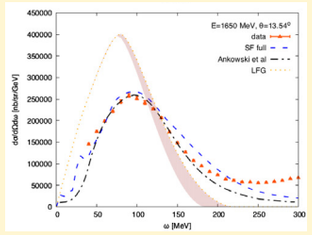

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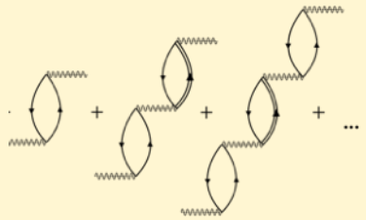

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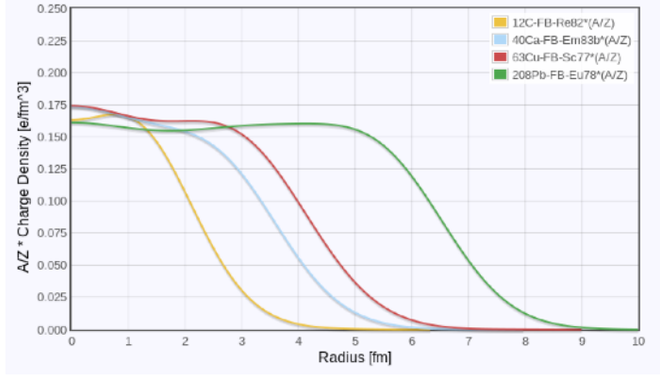

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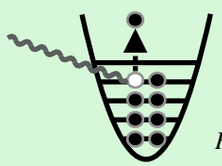
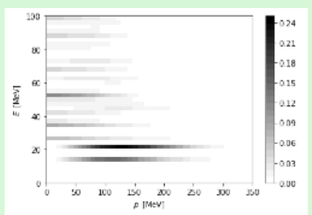
Mean-field approaches

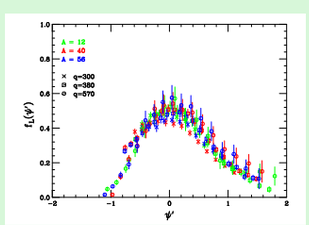


$$H_{\mathrm{MF}}|\phi_i\rangle = \epsilon_i|\phi_i\rangle$$

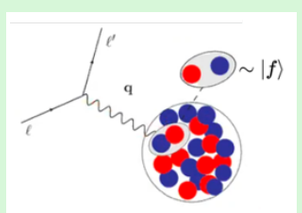
Spectral function



SuSA
(universal scaling function)



Short-time approximation
(based on QMC)



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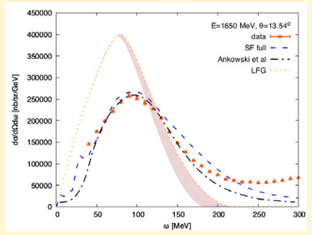
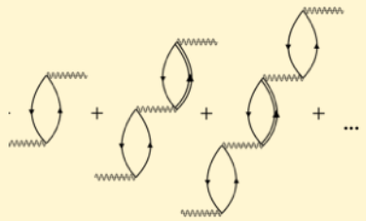
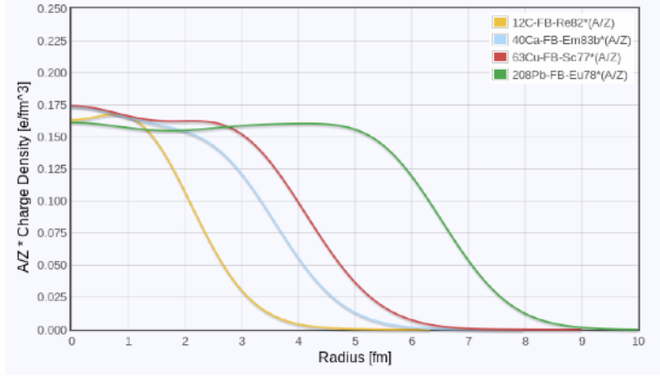


Valencia model:
RPA & spectral functions



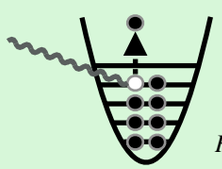
GiBUU:
Relativistic
mean-field potential



✓ Locally, nucleus treated as nuclear matter

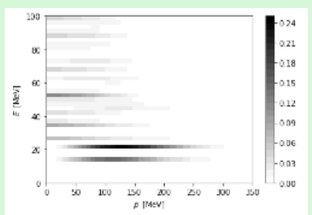
✓ No shell structure

Mean-field approaches

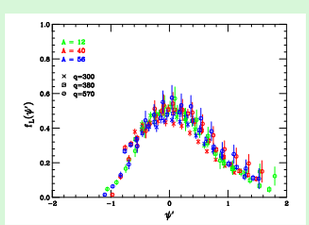


$$H_{\mathrm{MF}}|\phi_i\rangle = \epsilon_i|\phi_i\rangle$$

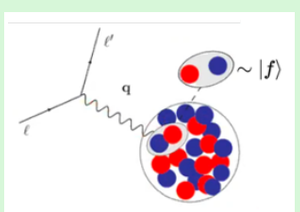
Spectral function



SuSA
(universal scaling function)



Short-time approximation
(based on QMC)



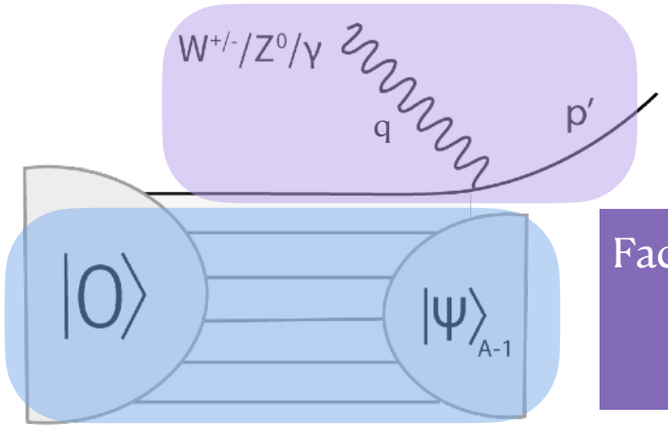
Current directions and efforts:

➡ Interplay of 1-body and 2-body currents (2p2h)

➡ Axial part of interaction

➡ Uncertainty quantification

Spectral function approach



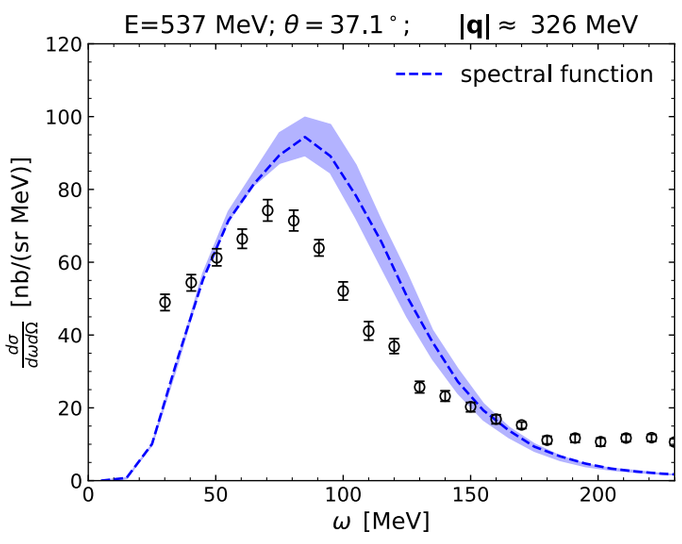
$$\sigma \propto |\mathcal{M}|^2 S(E,p)$$

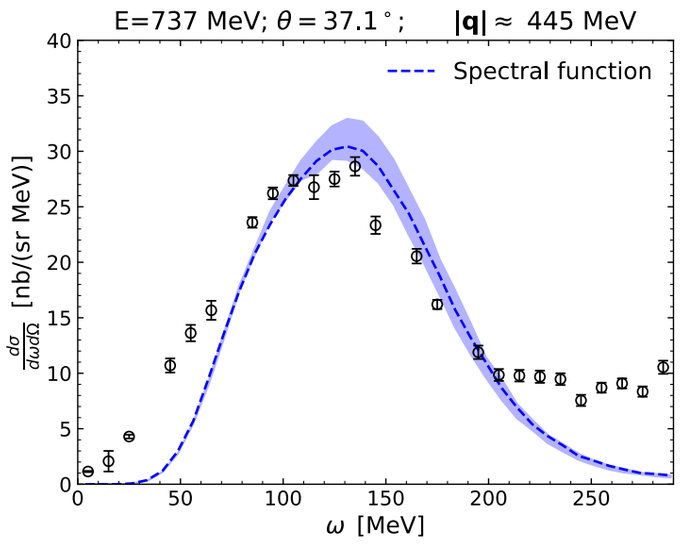
Factorized interaction vertex (relativistic, pion production...)

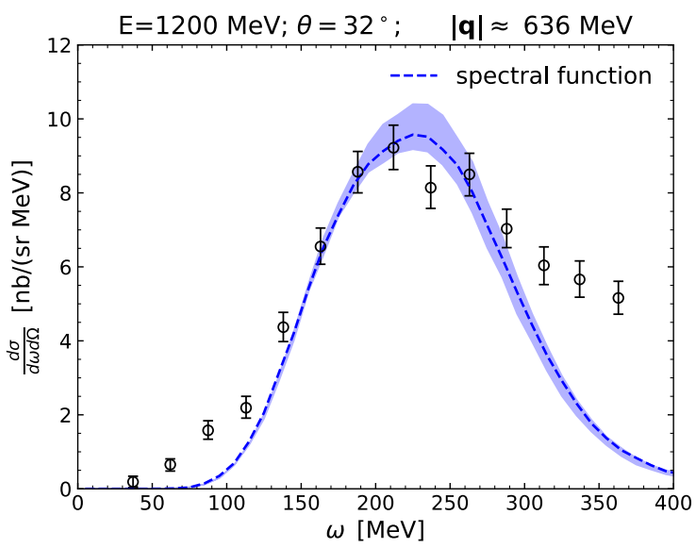
Spectral function - nuclear information

Different ways to calculate SF:
- *Ab initio calculations*
- *Phenomenological approaches*
- *extracted from (ee'p) data*
- ...

growing **q** momentum transfer → final state interactions play minor role



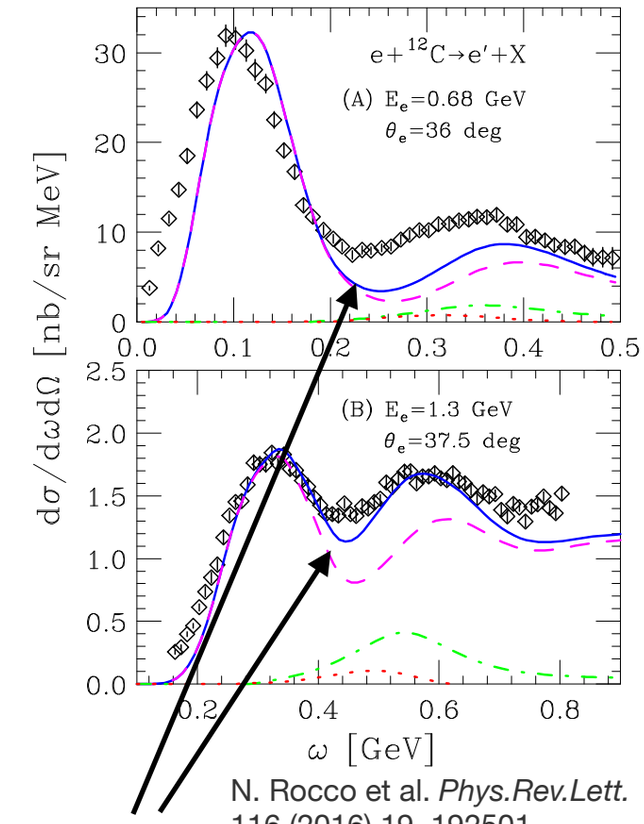




JES , S. Bacca, ***PRC* 109 044314**

2p2h (2-body mechanism)

- Scattering on a pair of correlated nucleons, modelled as **meson exchange currents**
- Can lead to the final state knocking out 1 nucleon, 2 nucleons, …
- Populates mostly the ‘dip’ region **above quasi-elastic peak** (overlaps with pion production)



N. Rocco et al. *Phys.Rev.Lett.* 116 (2016) 19, 192501

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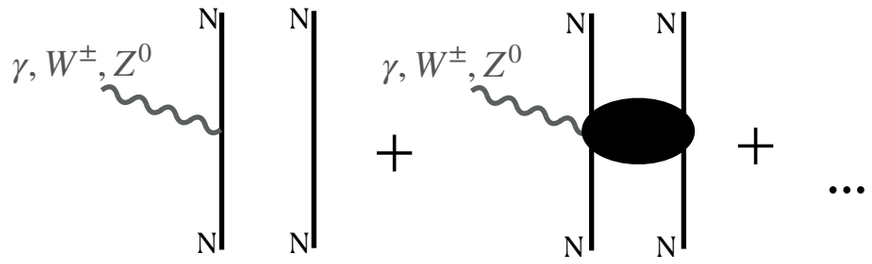

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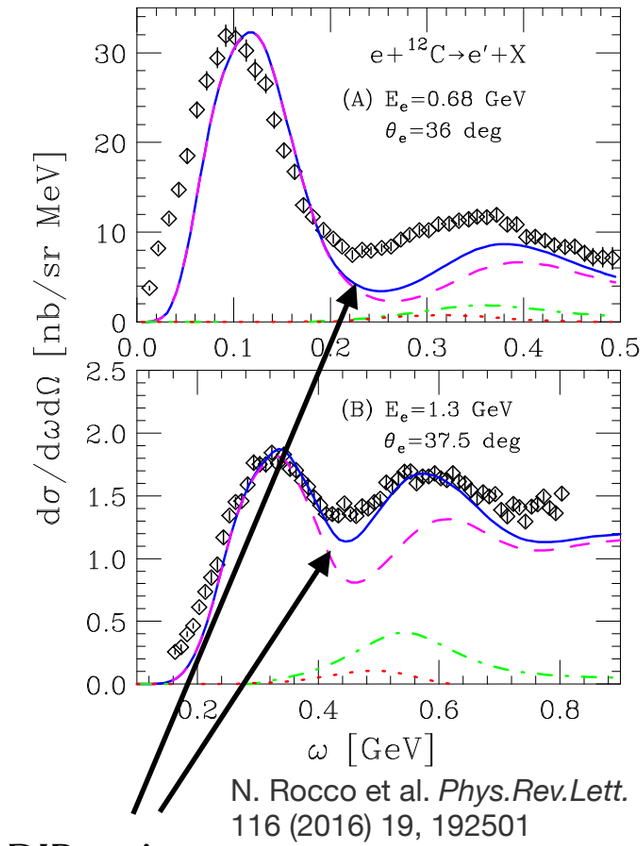

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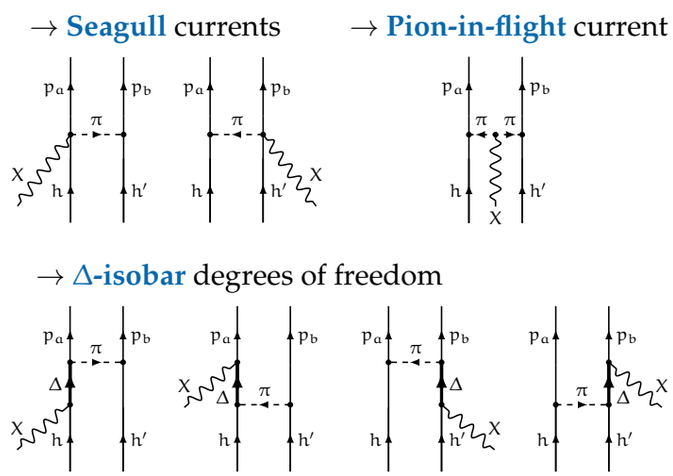
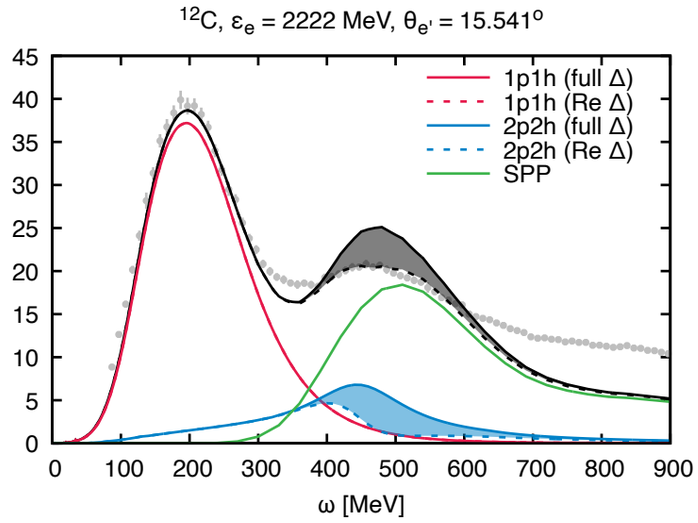
2p2h

Recent developments: mean-field approaches

Ghent group

- Meson exchange currents
- Short-range correlations

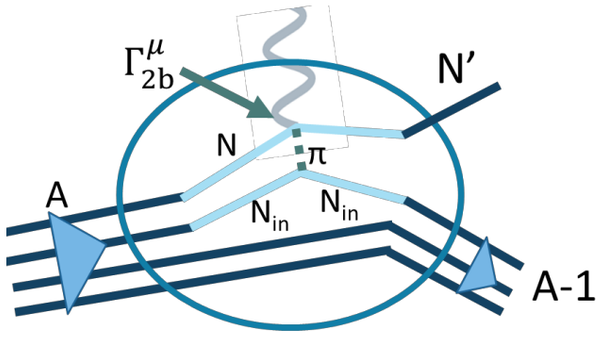


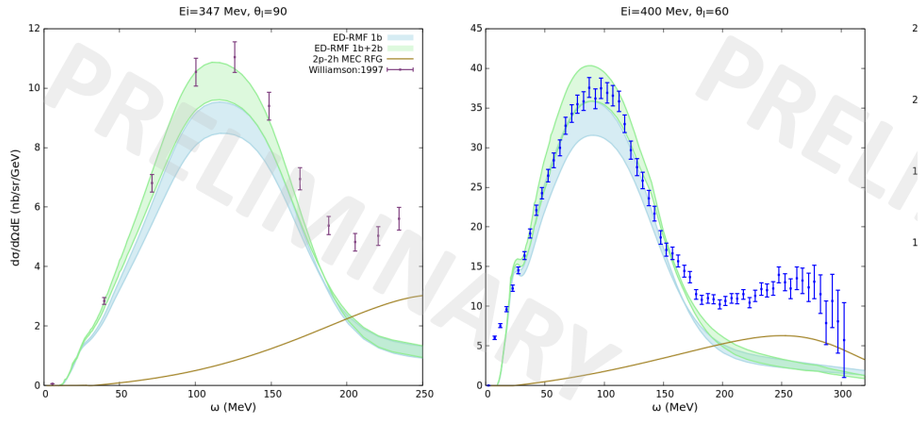


(K. Niewczas, NuInt2024)

Relativistic mean-field

- Meson exchange currents in particle-hole excitations





(T. Franco Muñoz, NuInt2024)

2p2h

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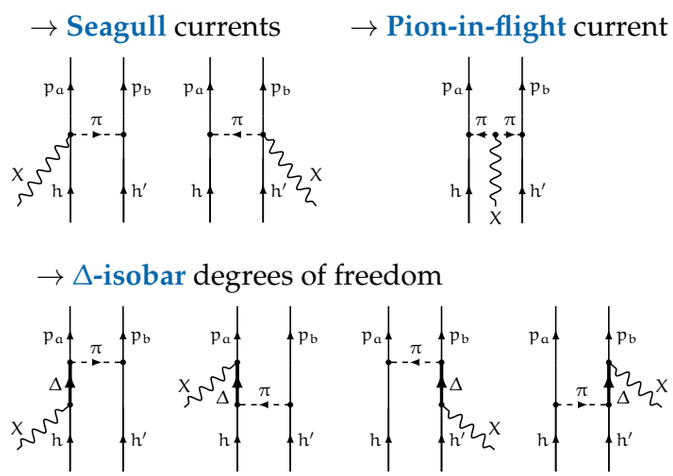

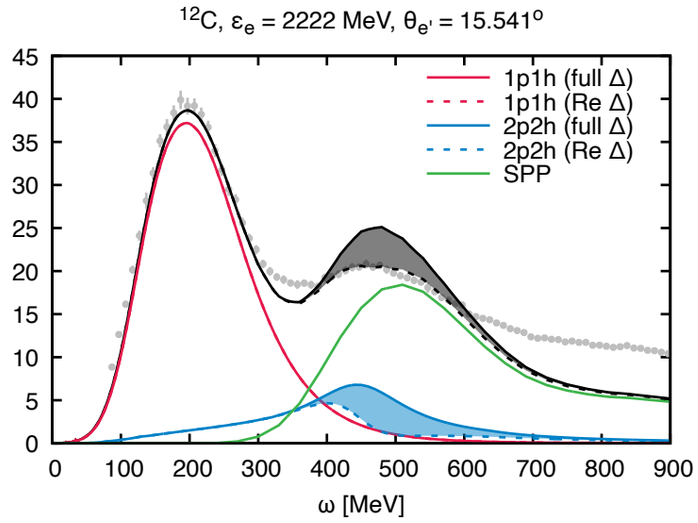

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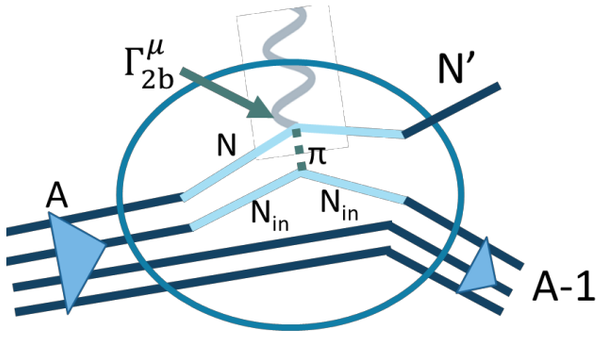
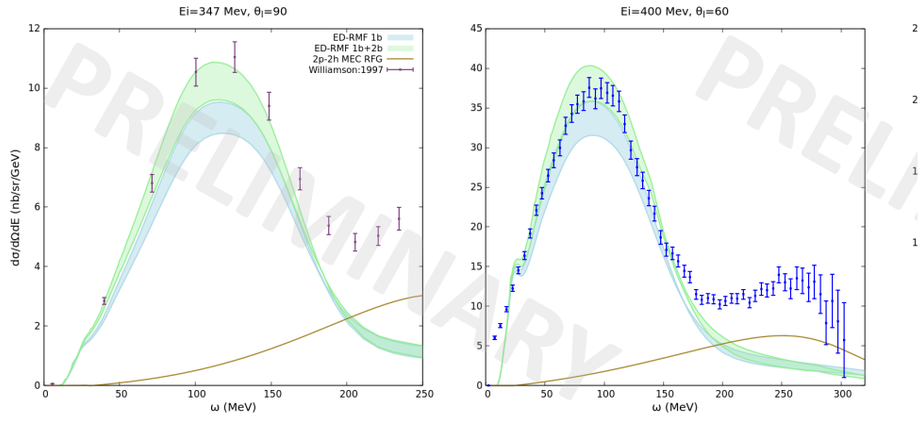




SEE TALK: Tania Franco Muñoz (Monday)

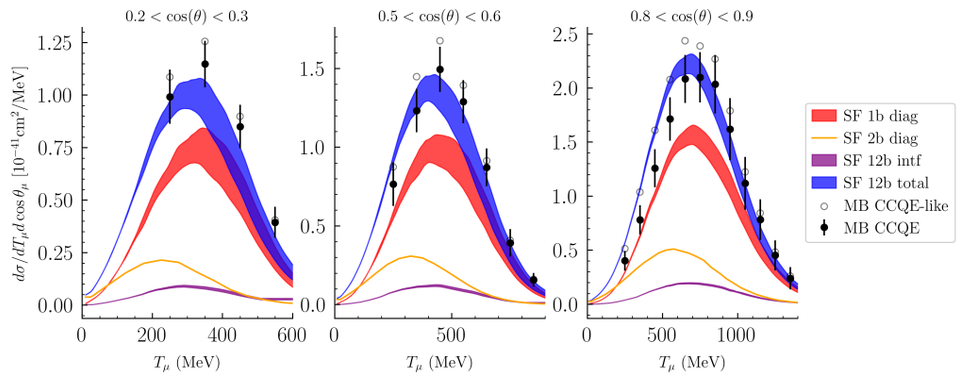
2p2h

Recent developments: results for neutrino scattering

Spectral function approach

- Meson-exchange currents
- Interference between 1-body and 2-body

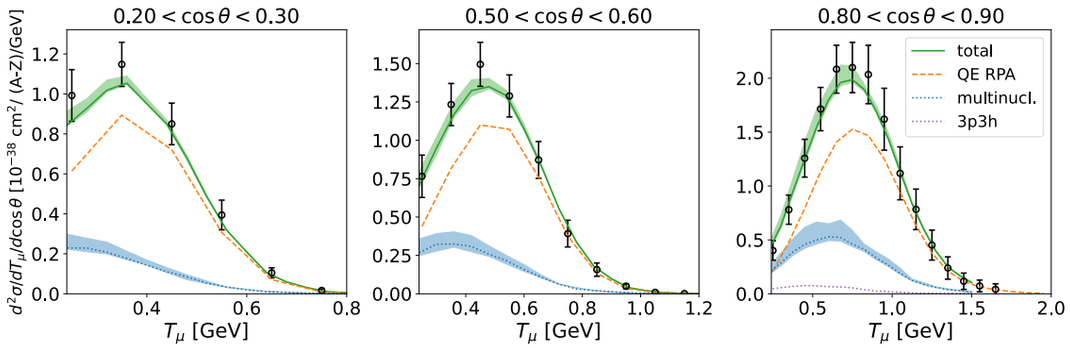
Comparison with MiniBooNE CCQE on 12C



A.Lovato, N.Rocco, et al arxiv:2312.12545

Valencia model

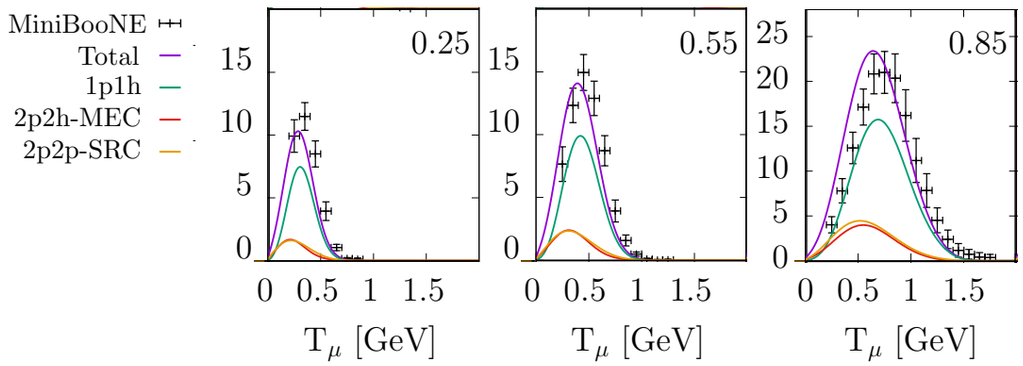
- Meson exchange current with effective interaction
- Uncertainty estimation: treatment of Δ self-energy



JES., J. Nieves arxiv:2407.21587

SuSA

- Distinguish meson-exchange currents and short-range correlations
- Inherently inclusive approach



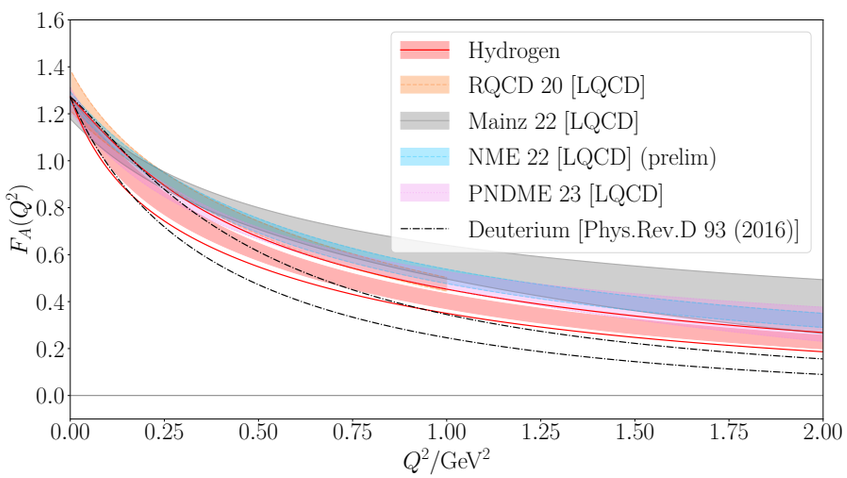
Phys.Rev.D 108 (2023) 1, 013007

Axial form factor

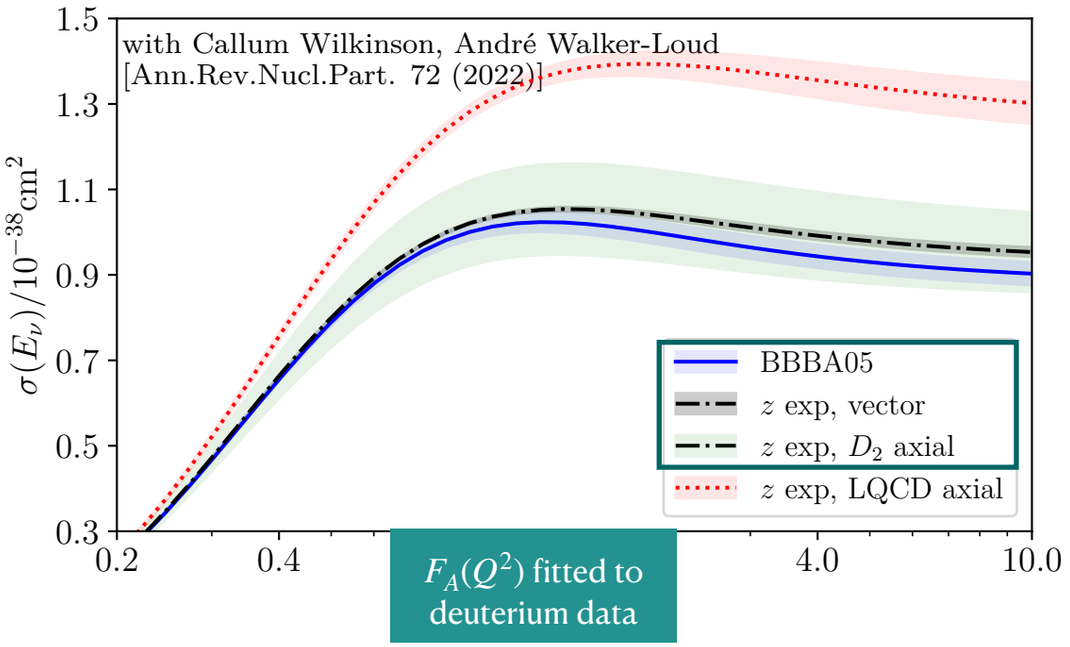
- Dipole ansatz

$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{m_A^2}\right)^{-2}$$

- Deuterium data: $m_A = 1014(14)$ MeV
- Recent results:
  - LQCD calculations
  - MINERνA measurement on hydrogen (T. Cai et al. Nature 614, 48–53 (2023))

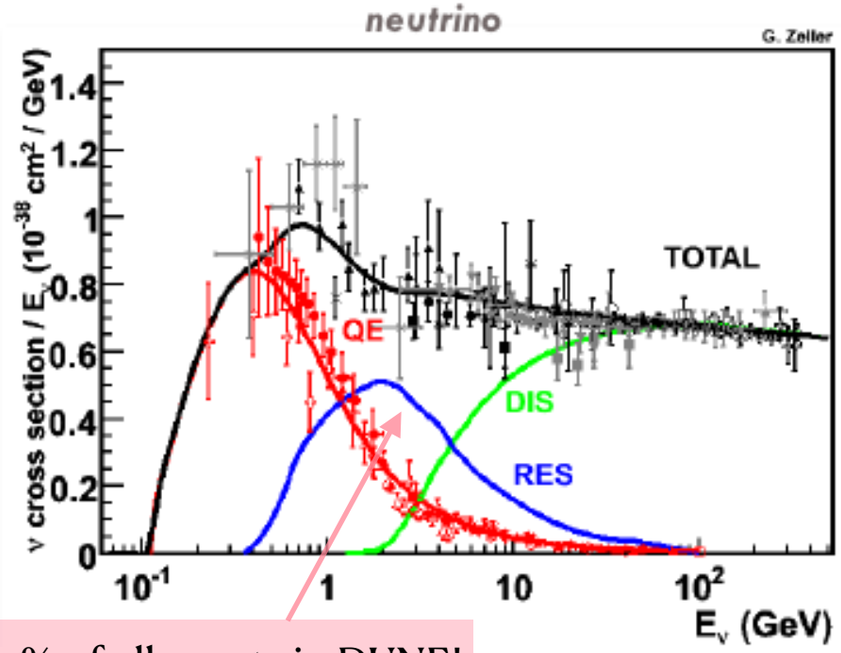


~ 30 % difference coming from the LQCD form-factor

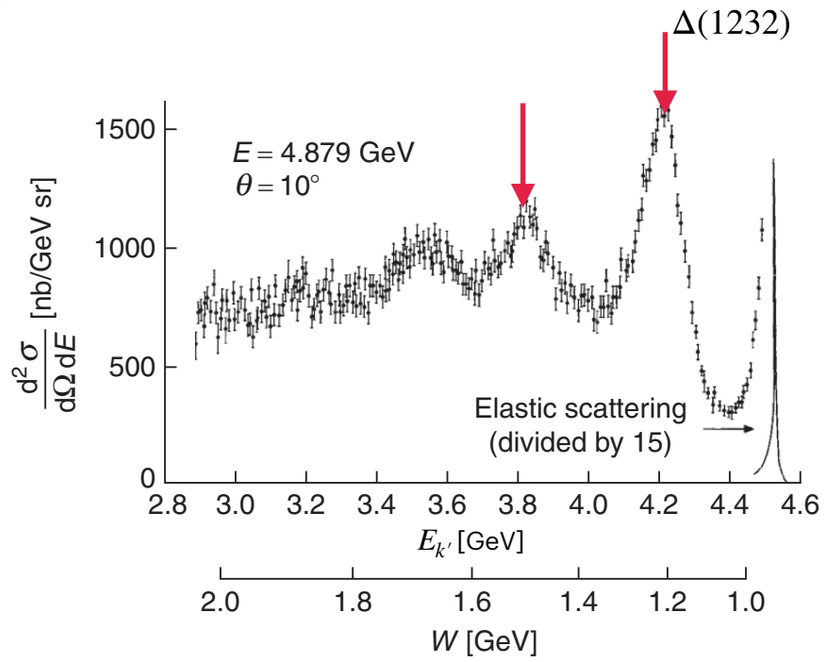


Ann.Rev.Nucl.Part.Sci. 72 (2022) 205-232

Pion production

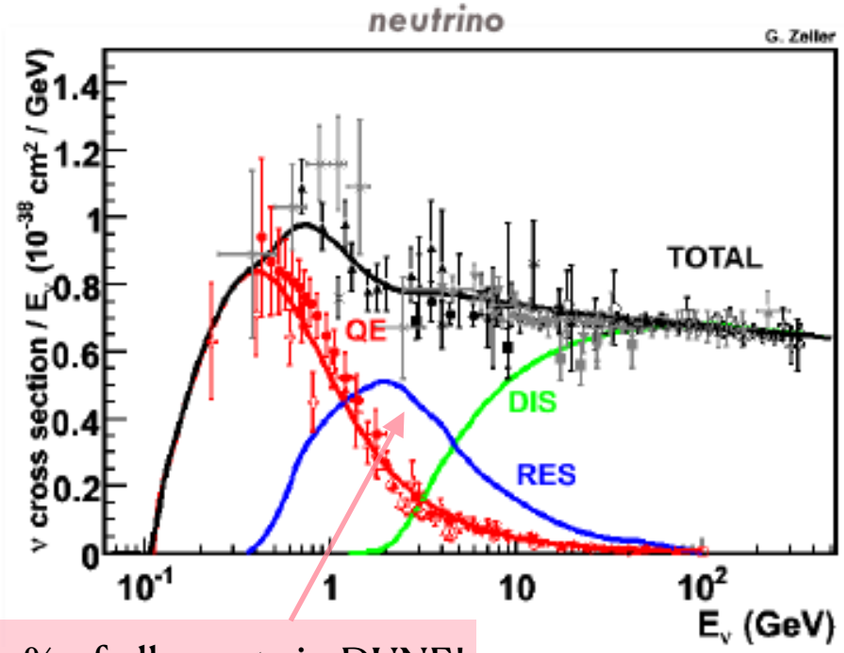


Over 30% of all events in DUNE!



Invariant mass of hadronic system $W^2 = (p+q)^2$

Pion production



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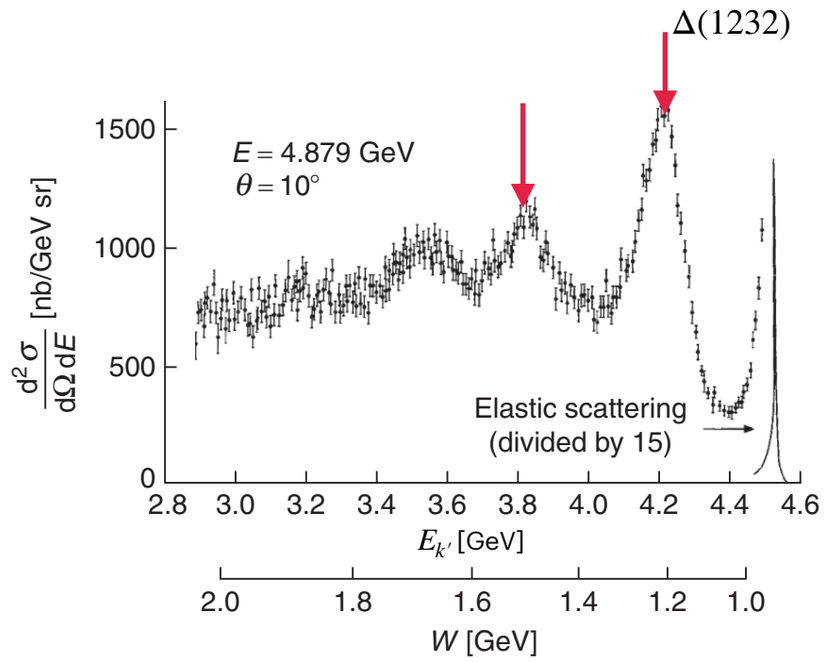
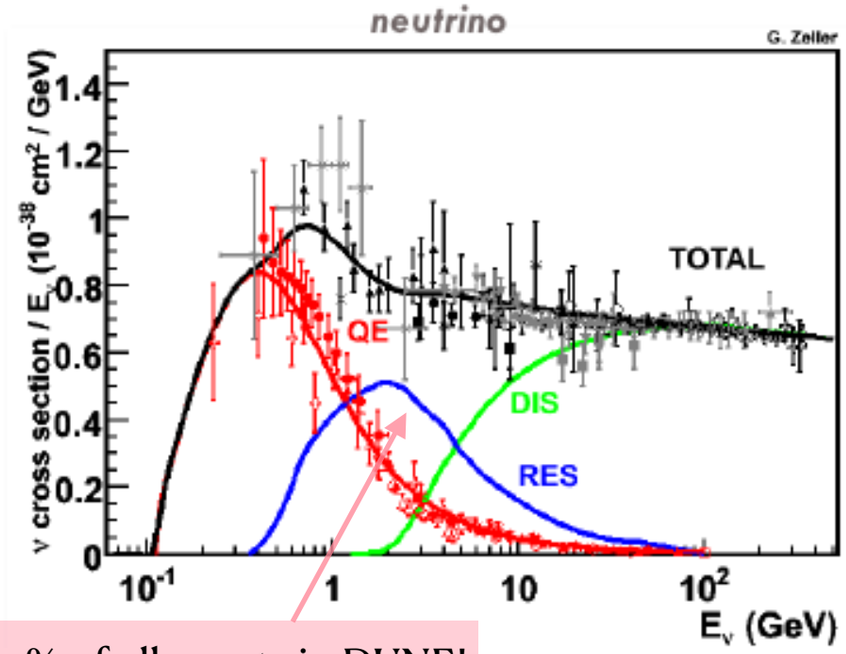


Invariant mass of hadronic system $W^2 = (p+q)^2$

- **@nucleon** level: various (sophisticated) models of meson production
  - *Julich-Bonn, ANL-Osaka DCC (dynamical channels)*
  - *MAID07, SAID ("unitary isobar model")*
  - *Valencia model*
- **@nucleus**: less theoretical expertise
- **Δ region**: approach of Δ in nuclear matter model by E. Oset

E. Oset L. L. Salcedo, Nucl. Phys. A 468, 631 (1987)

Pion production



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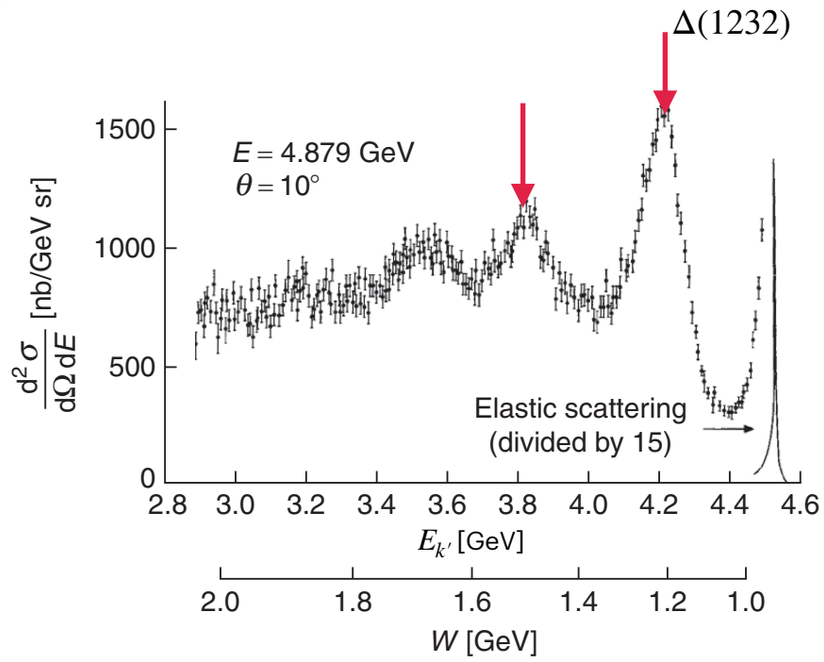

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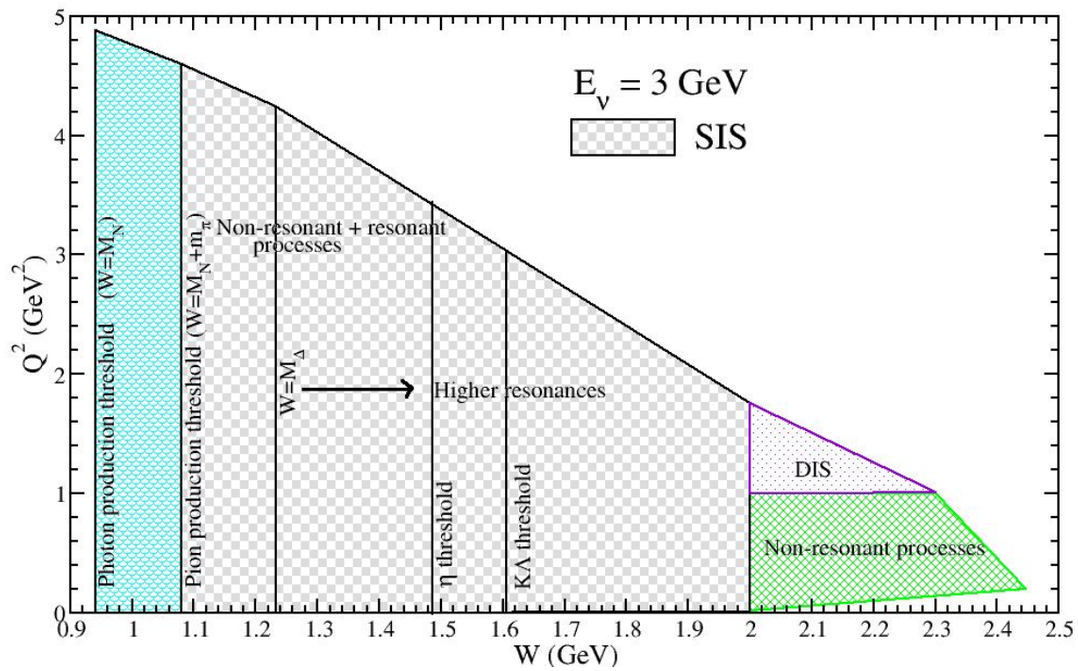
Current directions and efforts:

- ➡ Connecting Δ region and higher resonances + non-resonant background
- ➡ Axial form-factors of resonances
- ➡ Production of other multiple mesons

Pion production



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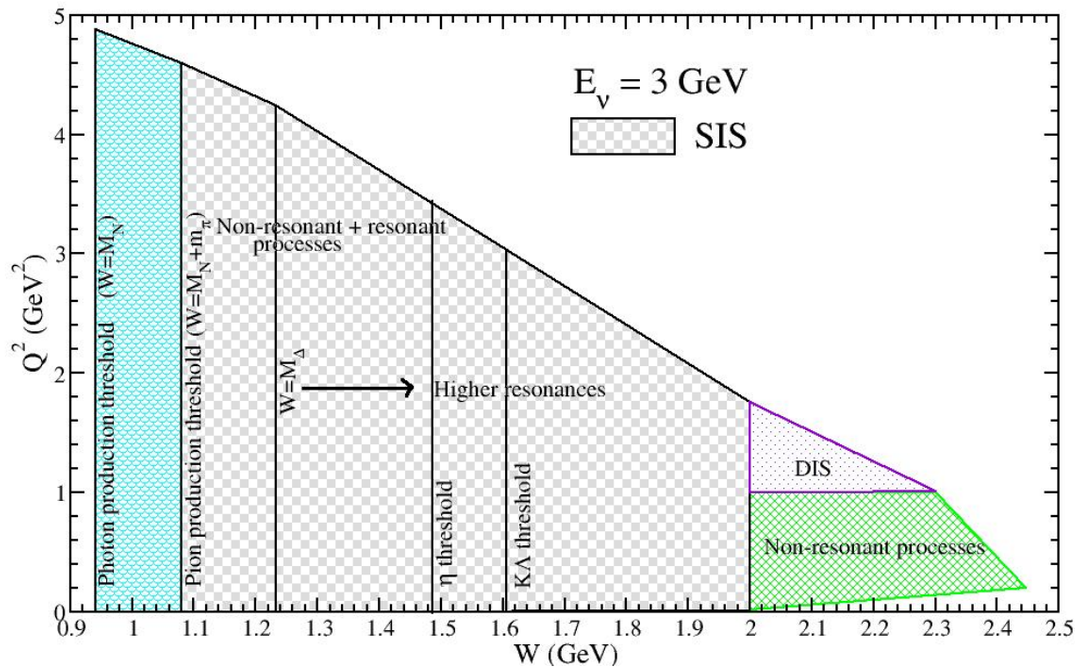
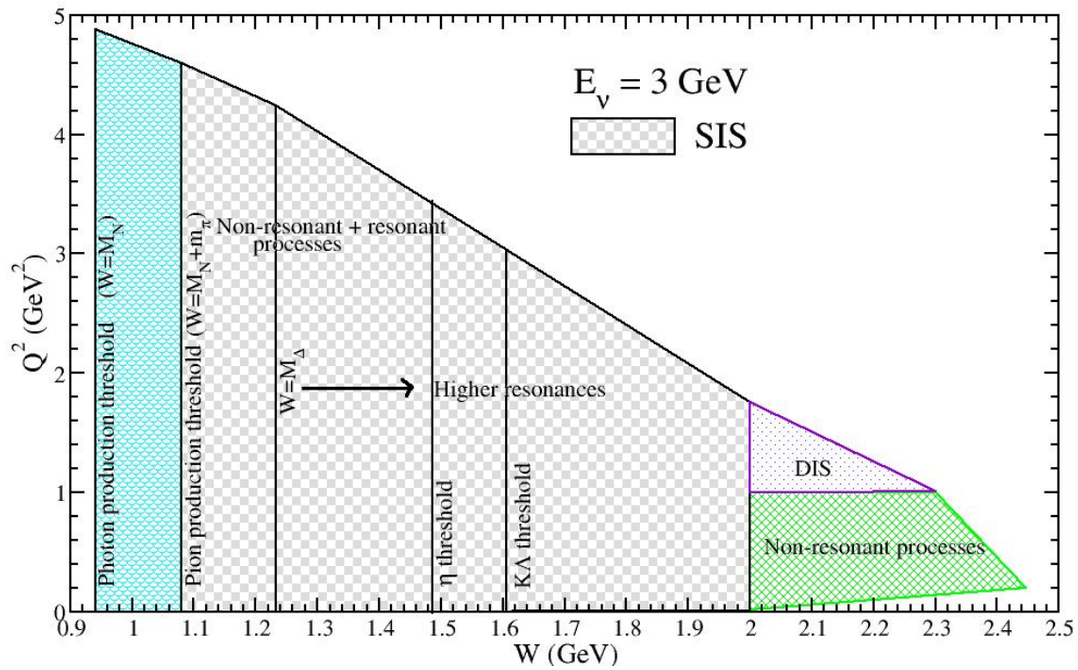


Merging pion models with nuclear models

- Valencia model: the same formalism for pion production, 2p2h, quasi-elastic
- Spectral function + DCC
- SuSAv2 + DCC

SEE TALK: Jesús González Rosa (Monday)

Pion production



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SEE TALK: Jesús González Rosa (Monday)

The Ghent Hybrid Model

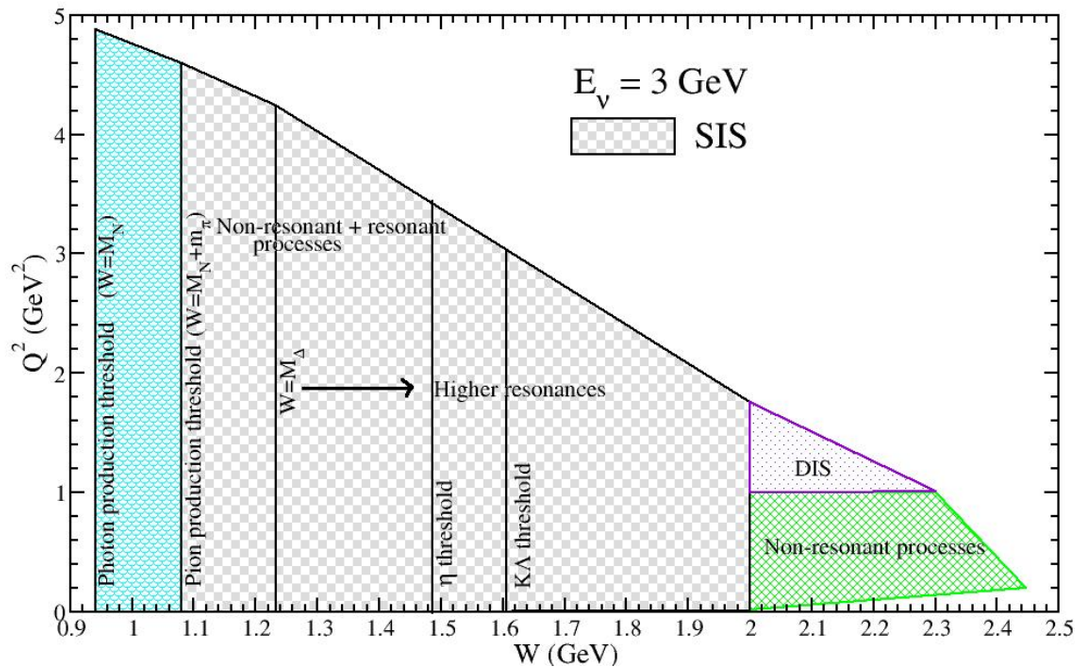
- Low energy: following Valencia model
- High energy: Regge theory to extrapolate background to higher invariant mass

Both regions mixed @amplitdude level

Recently implemented in NuWro

arxiv:2405.05212

Pion production



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(Monday)

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- High energy: Regge theory to extrapolate background to higher invariant mass

Both regions mixed @amplitdude level

Recently implemented in NuWro

arxiv:2405.05212

More exotic processes:
Eta, kaons, hyperons, … production

SEE TALK: Atika Fatima
(Thursday)

Summary

- Many new developments from various groups!
  - Exclusive distributions
    - 2p2h (meson exchange currents)
    - LQCD: form-factors
    - Incorporating pion physics
- Efforts to estimate **theoretical uncertainties**

Summary

- Many new developments from various groups!
  - Exclusive distributions
    - 2p2h (meson exchange currents)
    - LQCD: form-factors
    - Incorporating pion physics
- Efforts to estimate **theoretical uncertainties**

- Constant work to include theoretical calculations to MC generators
- “Stitching” theoretical models with intranuclear cascade
- Transition regions (hadrons/DIS)
- Benchmarks for electron scattering

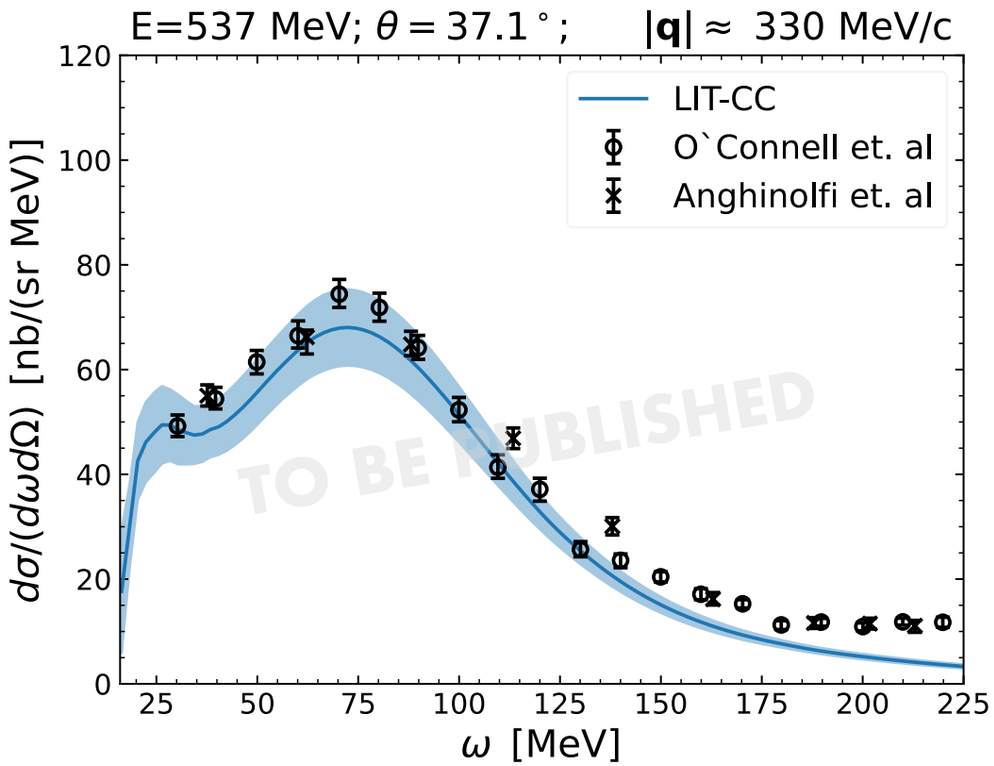
Thank you for attention!

Backup

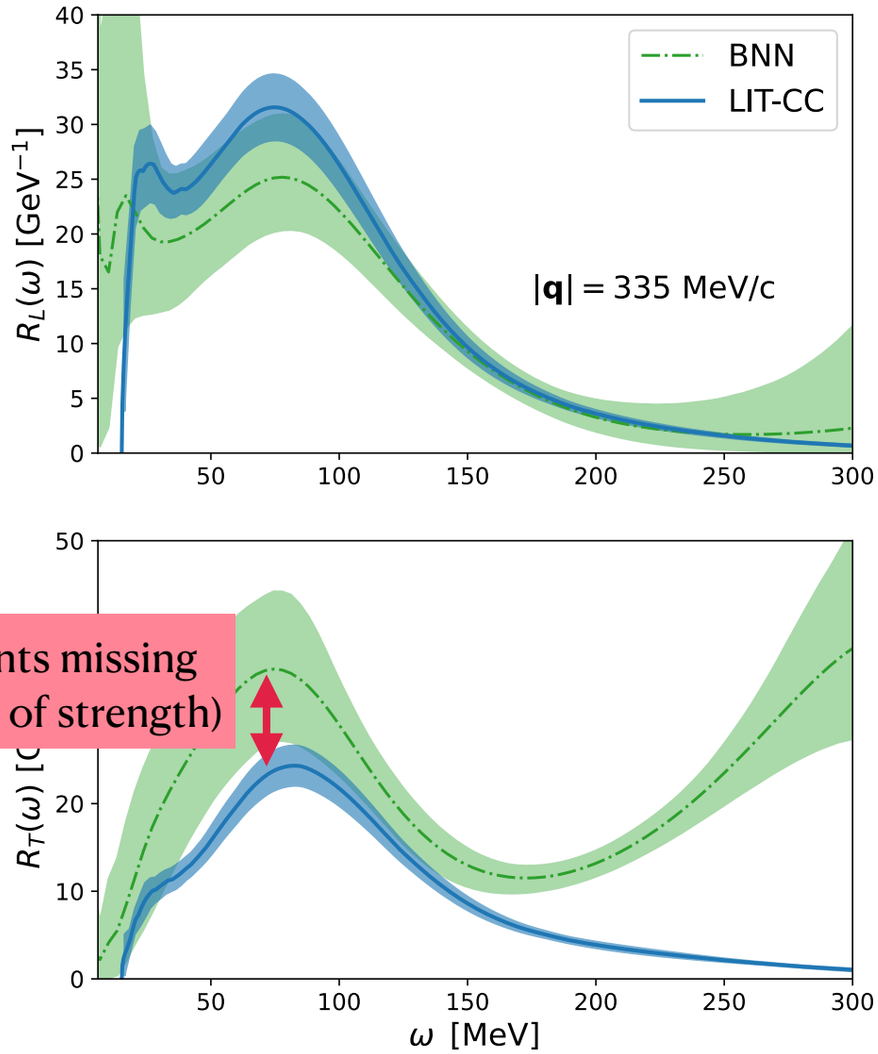
Coupled cluster for ^{16}O

Lorentz Integral Transform + Coupled Cluster **(LIT-CC)**

Electron scattering



First ab-initio results for many-body system of 16 nucleons

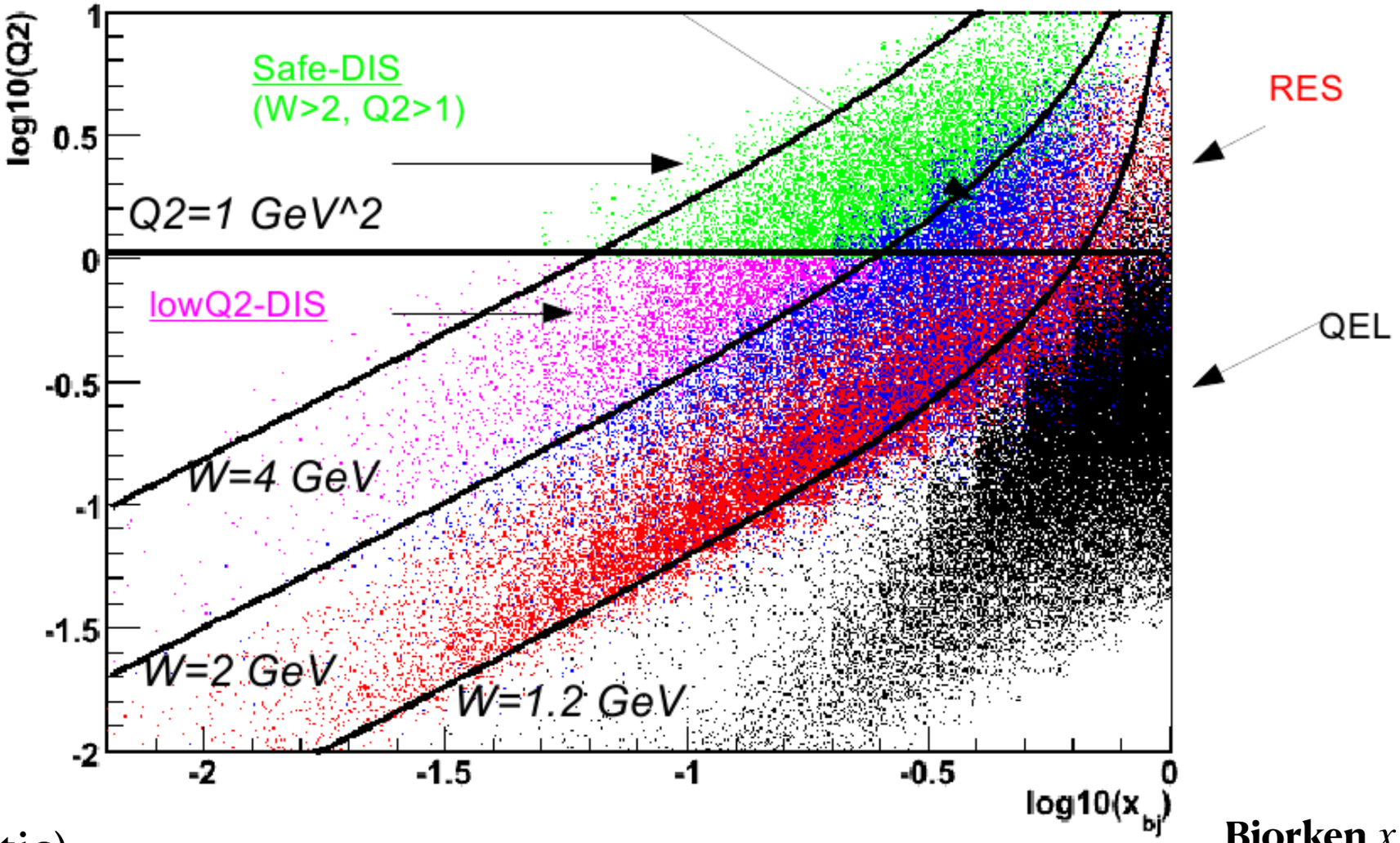


2-body currents missing (expected lack of strength)

$$R_{\mu\nu}(\omega, q) = \sum_f \oint \langle \Psi | J_\mu^\dagger | \Psi_f \rangle \langle \Psi_f | J_\nu | \Psi \rangle \delta(E_0 + \omega - E_f)$$

Consistent treatment of final state interactions.

Physical mechanisms



- **QE** (quasi-elastic)
- **RES** (resonance production)
- **DIS** (deep inelastic scattering

} Exact separation between these regions is generator-dependent

Bjorken $x = \dfrac{Q^2}{2p\,q}$

x measures the inelasticity

$0 \leq x \leq 1$ (elastic scattering)