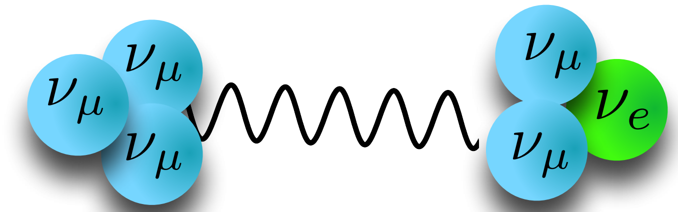
Neutrino cross-sections theory

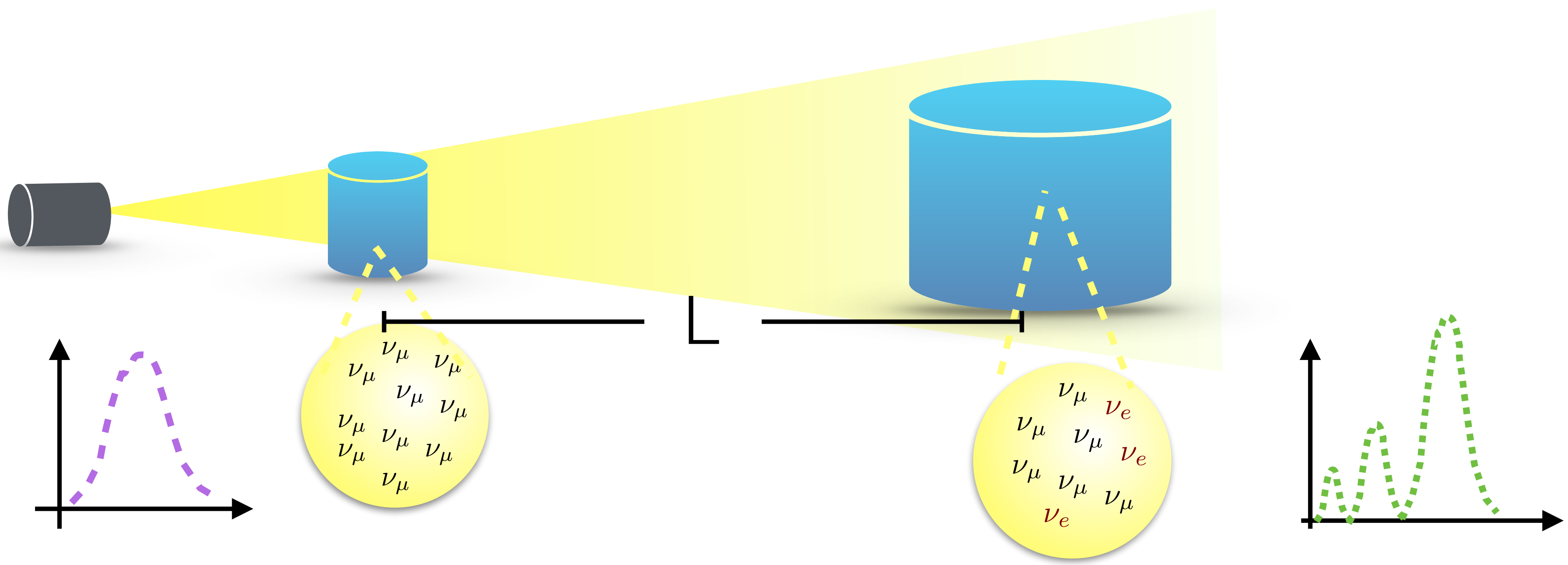
Noemi Rocco

August 5th, 2021

Addressing Neutrino-Oscillation Physics

$$P_{\nu_\mu \to \nu_e}(E,L) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \to \Phi_e(E,L)/\Phi_\mu(E,0)$$





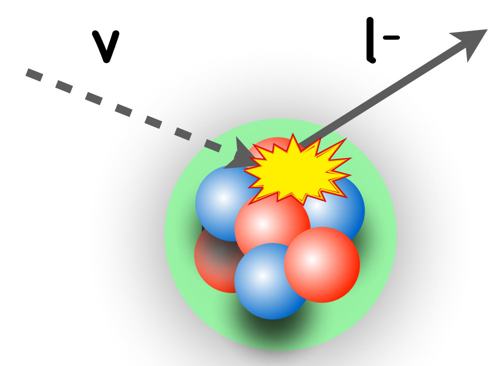
Detectors measure the **neutrino interaction rate:**

$$N_e(E_{\rm rec}, L) \propto \sum_i \Phi_e(E,L)\sigma_i(E) f_{\sigma_i}(E, E_{\rm rec}) dE$$

Reconstructed ν energy

Cross Section

Smearing matrix



A precise determination of σ(E) is crucial to extract ν oscillation parameters

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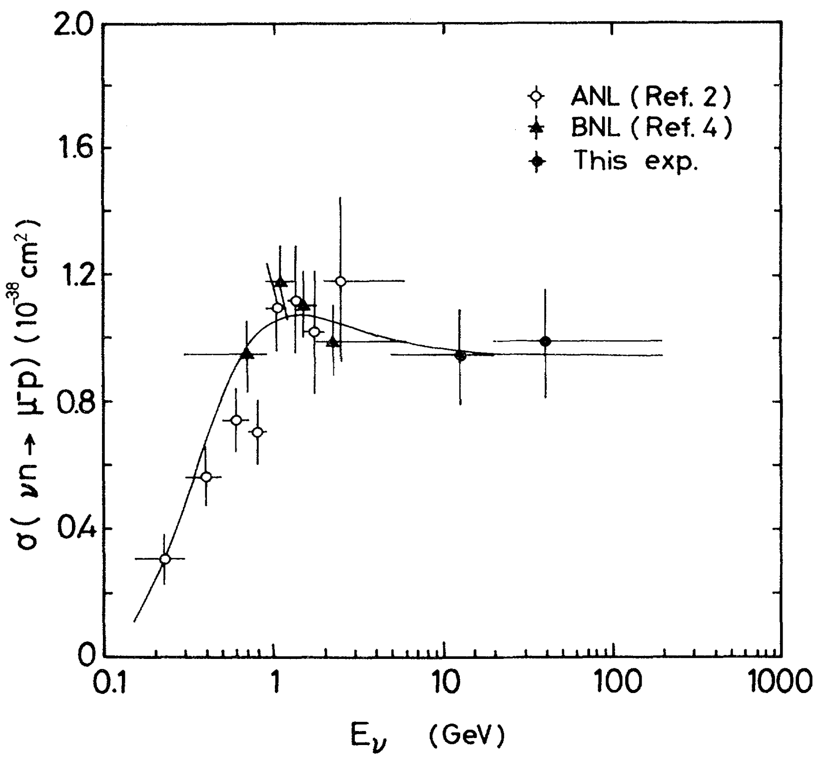
To study neutrinos we use nuclei



T. Kitagaki et al, Phys. Rev. D 28, 436 (1983)

Neutrino scattering extensively studied 1970-90's using deuterium-filled **bubble chambers**

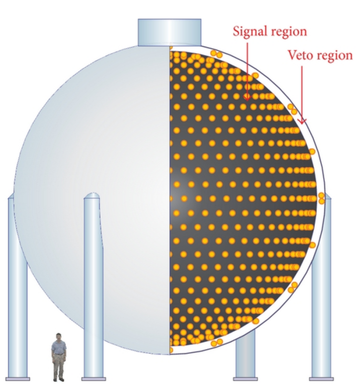
$$\mathcal{N}_{\rm hits} = \sigma \times \Phi \times N$$

Targets

Bubble Chamber experiment at Fermilab

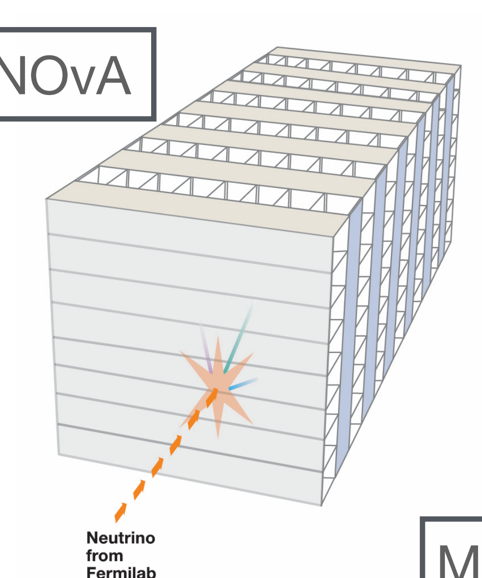
Utilize **heavy target** in neutrino detectors to maximize interactions→ understand **nuclear structure**

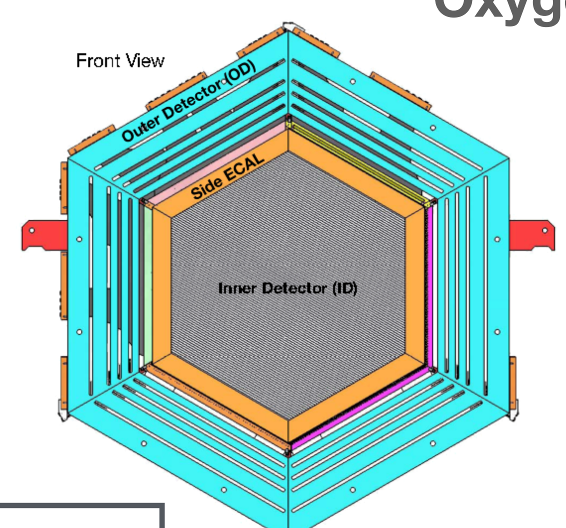
Carbon



MiniBooNE

NOvA



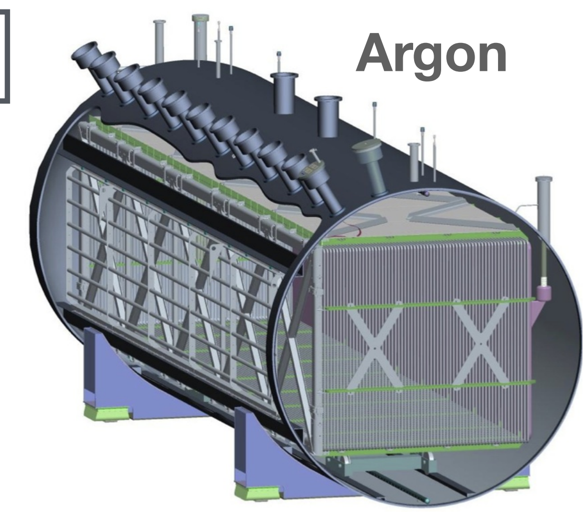


MINERvA

Oxygen

S-K

Argon



MicroBooNE

Fermilab

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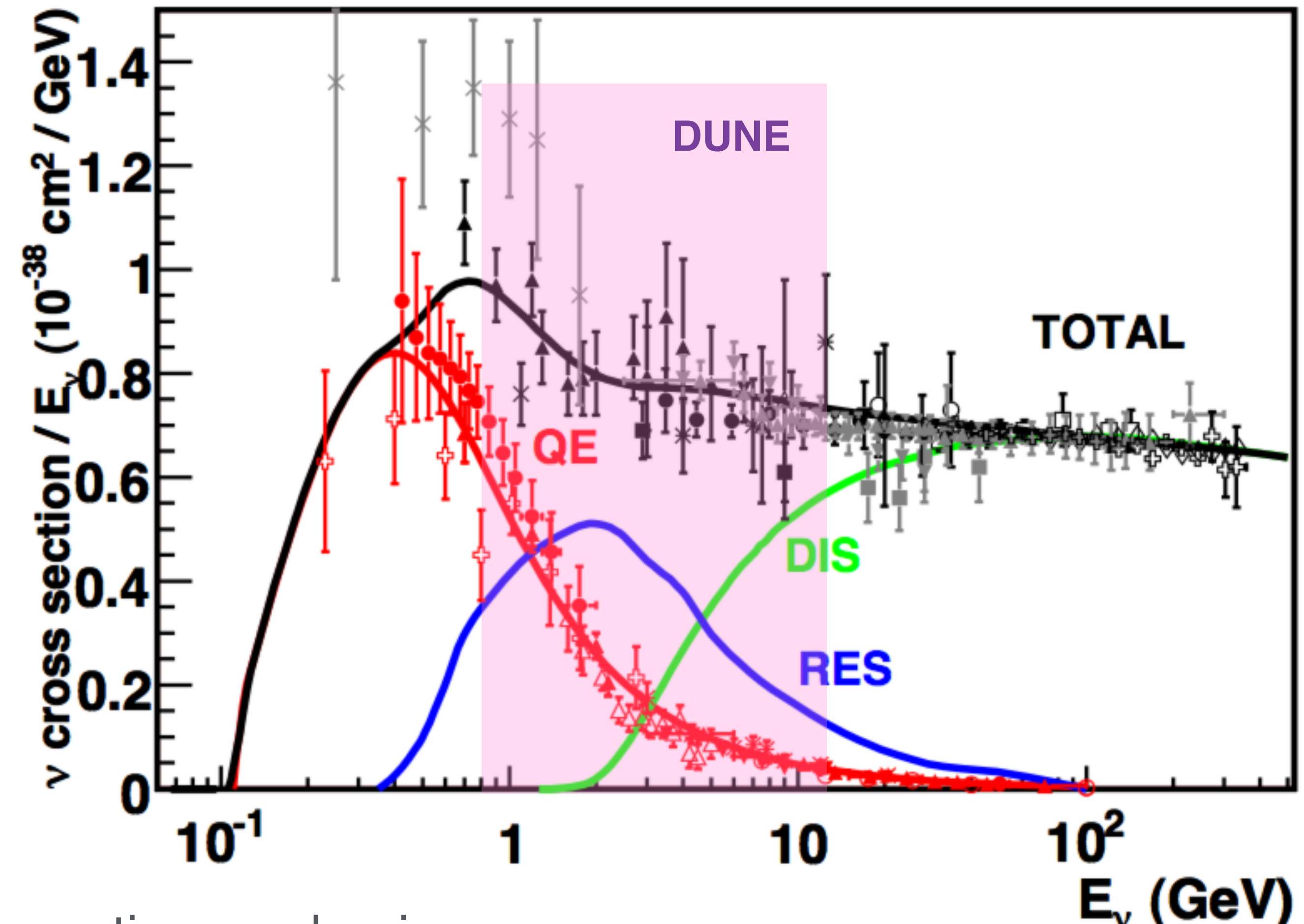
Addressing Neutrino-Oscillation Physics

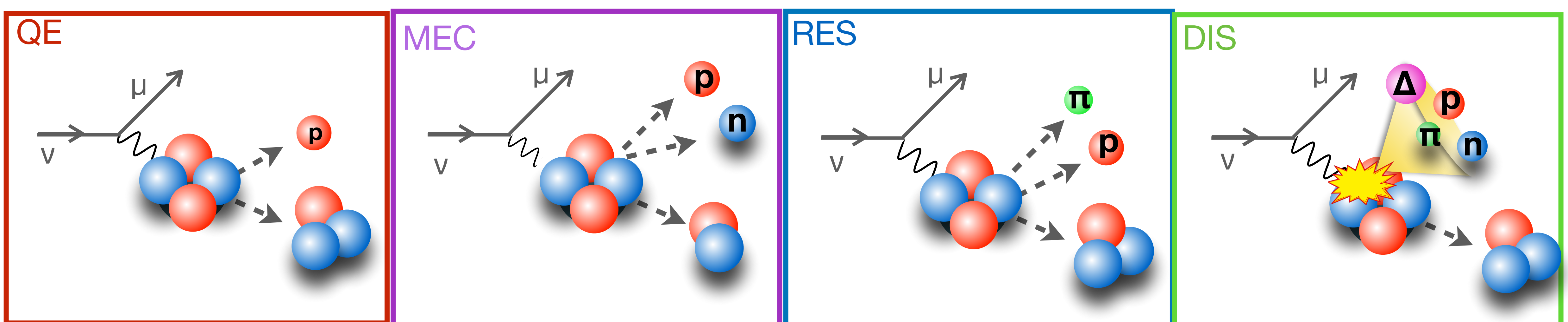
Unprecedented accuracy in the determination of **neutrino-argon cross section** is required to achieve design sensitivity to CP violation at DUNE

Current oscillation experiments report **large systematic uncertainties** associated with the neutrino- nucleus interaction models.

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



Nuclei are complicated objects. Many different reaction mechanisms



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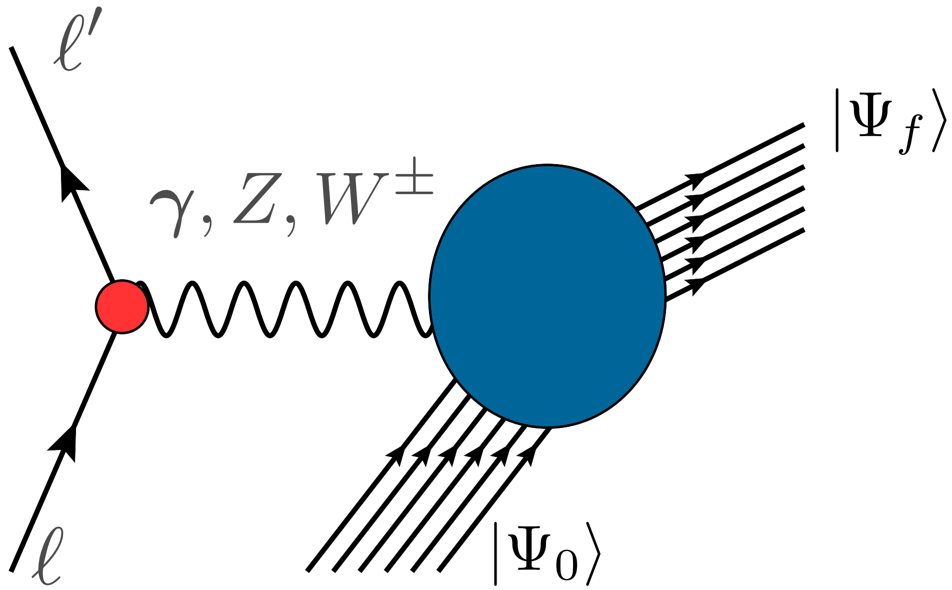
Theory of lepton-nucleus scattering

- The cross section of the process in which a lepton scatters off a nucleus is given by

$$d\sigma \propto L^{\alpha\beta} R_{\alpha\beta}$$

Leptonic Tensor: can include new physics models

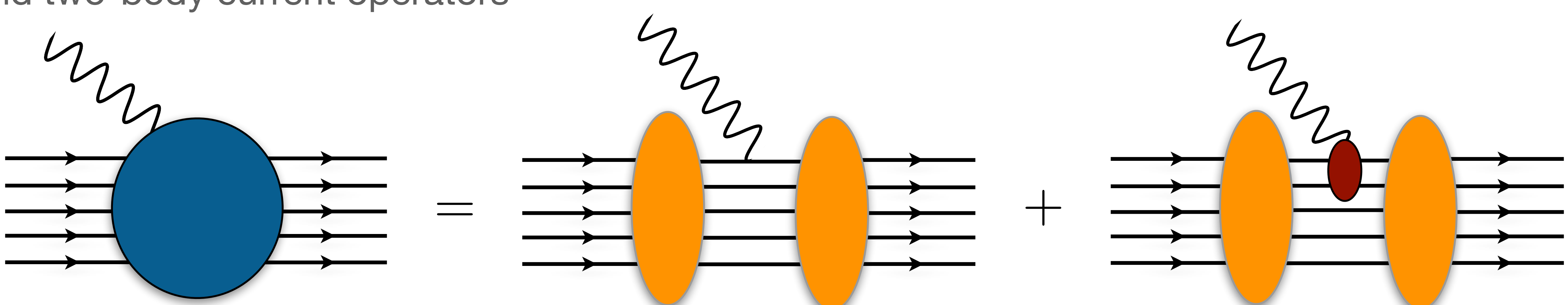
Hadronic Tensor: nuclear response function



The initial and final wave functions describe many-body states:

$$|0\rangle = |\Psi_0^A\rangle \ , |f\rangle = |\Psi_f^A\rangle, |\psi_p^N, \Psi_f^{A-1}\rangle, |\psi_k^\pi, \psi_p^N, \Psi_f^{A-1}\rangle \ldots$$

One and two-body current operators



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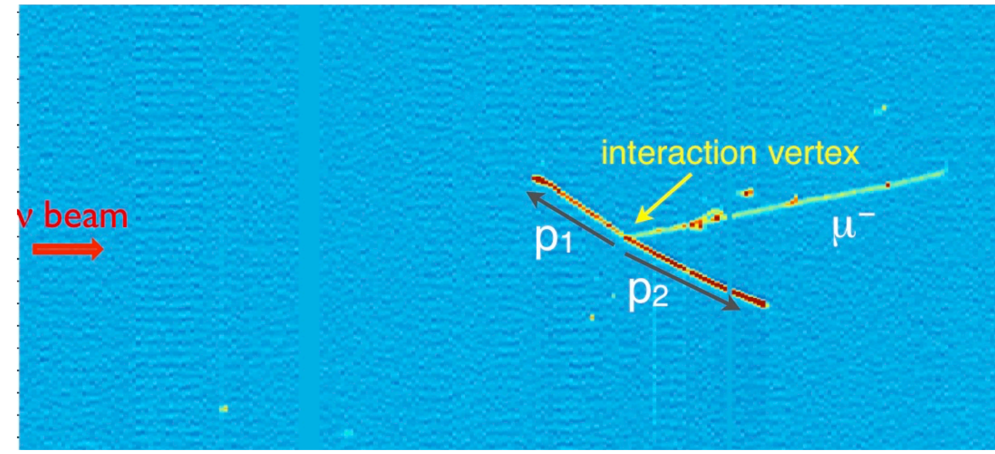
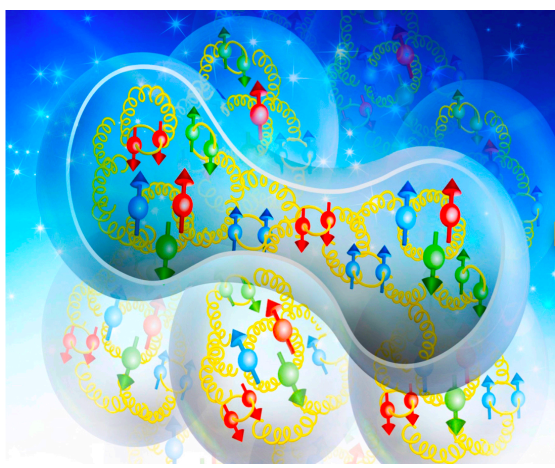
Nuclear many-body theory

Neutrino experiments are becoming more and more sensitive to the complexity of nuclear dynamics.

Same starting point for different many-body methods: Effective Field Theory interactions and currents

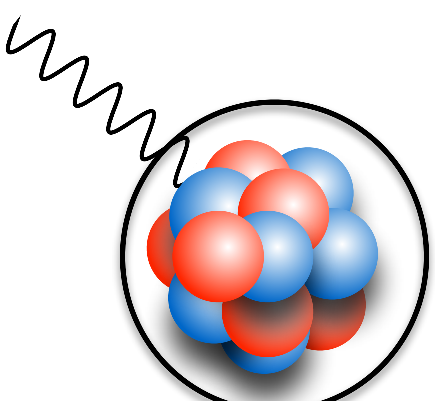


Argoneut

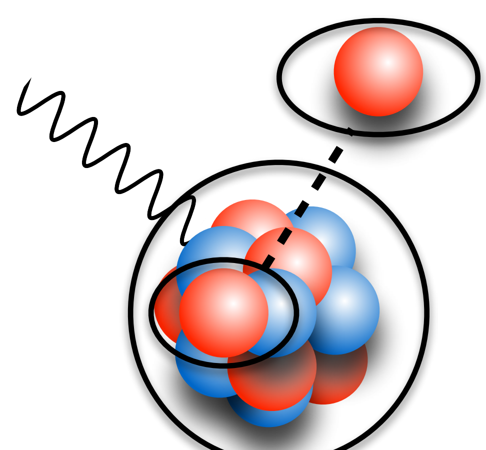


$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

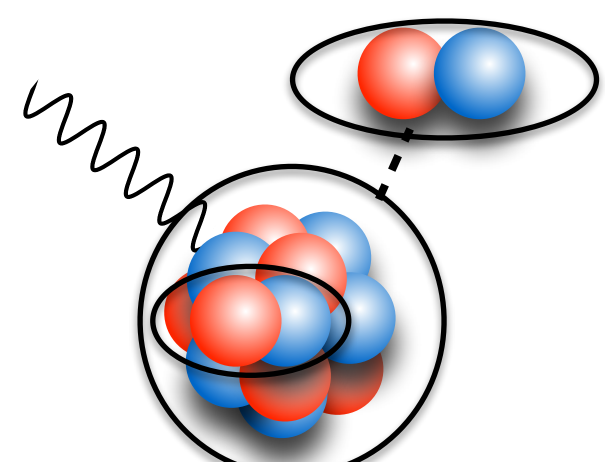
Green's Function Monte Carlo



Spectral Function (SF)



Short-time Approximation (STA)



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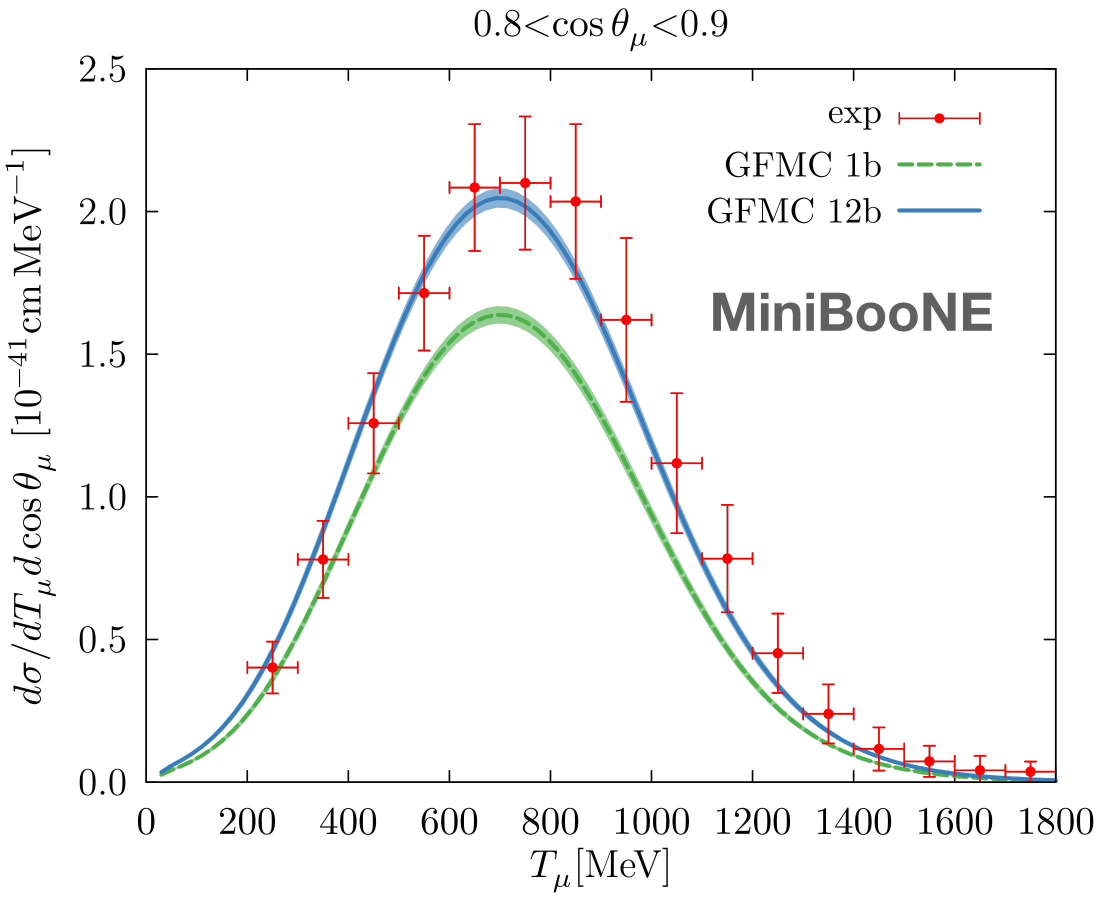
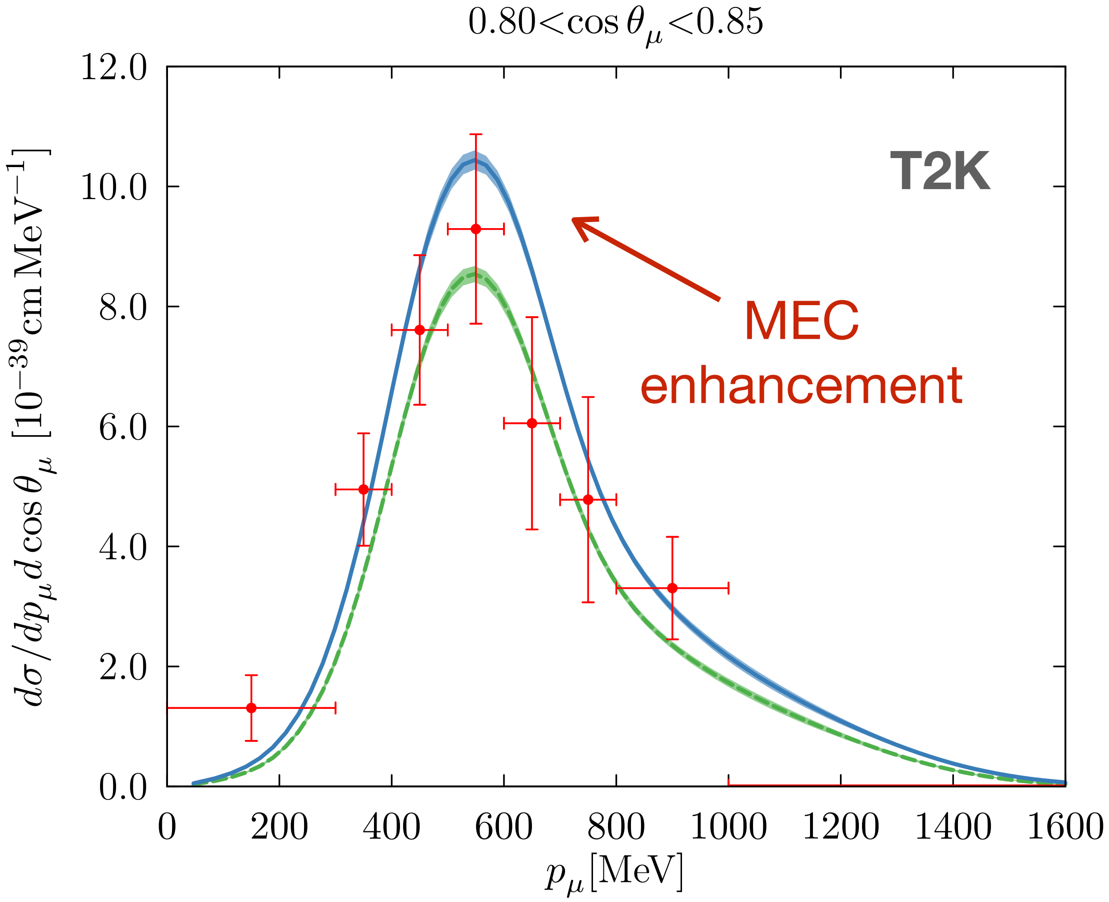
Cross sections: Green's Function Monte Carlo

GFMC accurately obtain the properties of nuclei to ^{12}C using high performance computing

Exact results for ν-cross sections in the **quasi-elastic region** up to moderate values of **q**.

✐A.Lovato, NR et al, Phys.Rev.X 10 (2020) 3, 031068





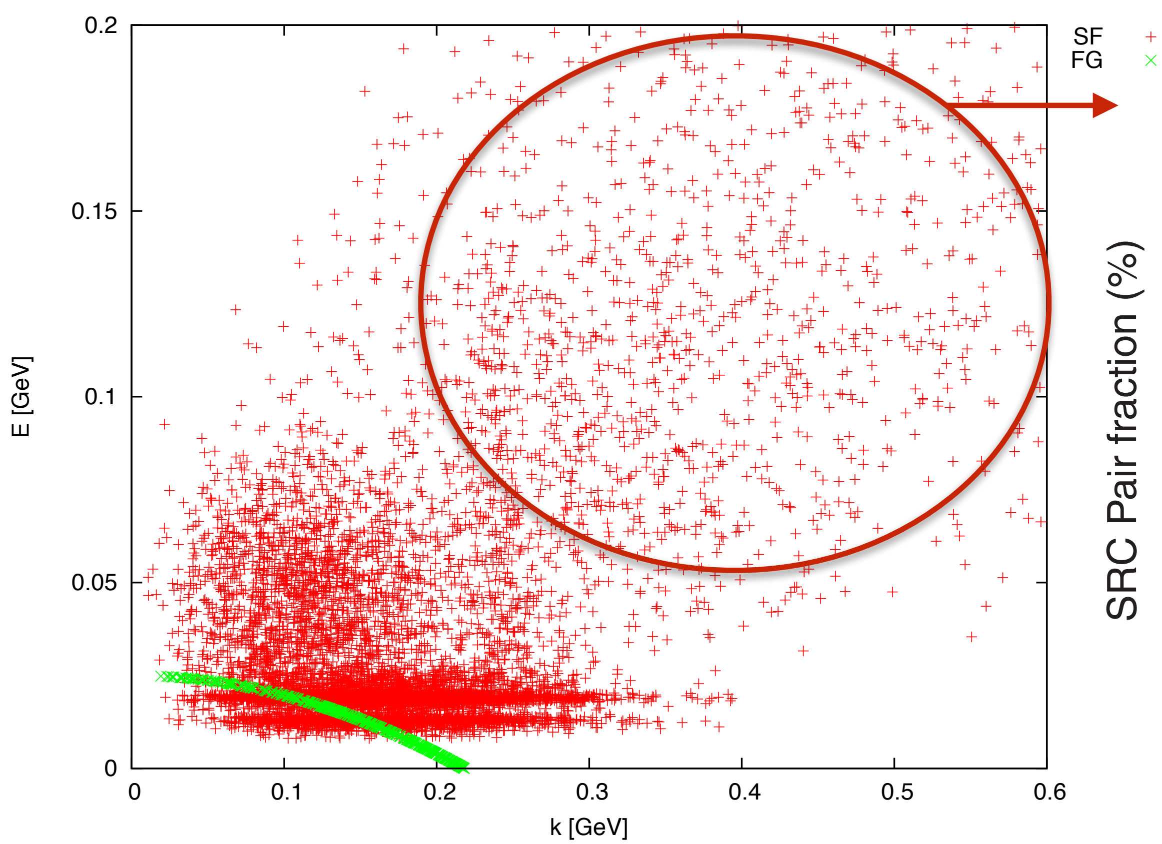
Limitations: high energy regions, pions can not be explicitly included

Cross sections: Spectral function approach

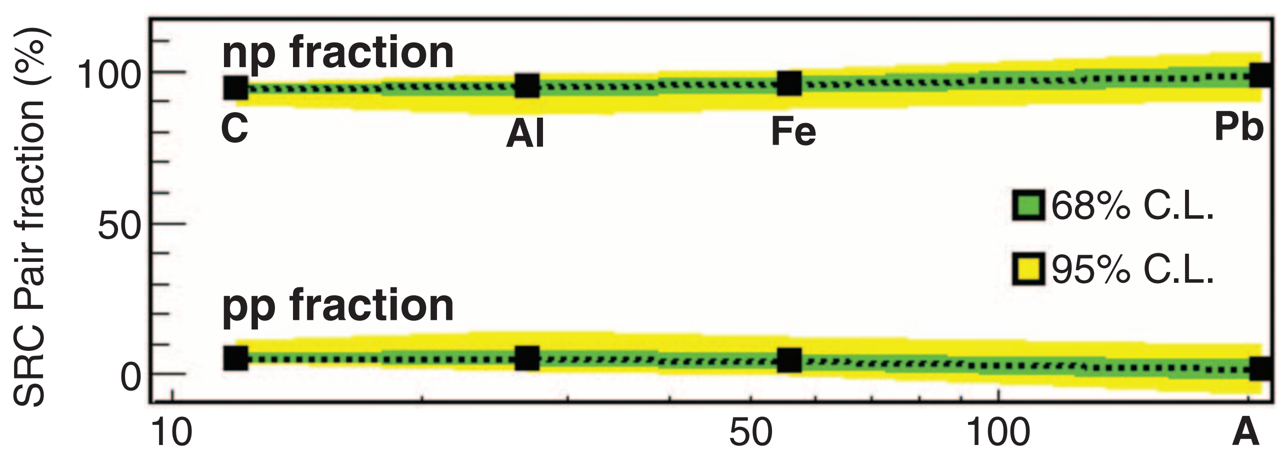
The intrinsic properties of the nucleus are described by the **Spectral Function**→ effective field theory and nuclear many-body methods

$$|f\rangle \rightarrow |p\rangle \otimes |f_{A-1}\rangle$$

$$d\sigma_A = \int dE d^3k \; d\sigma_N P(\mathbf{k}, E)$$



High energy and momentum correlated pairs



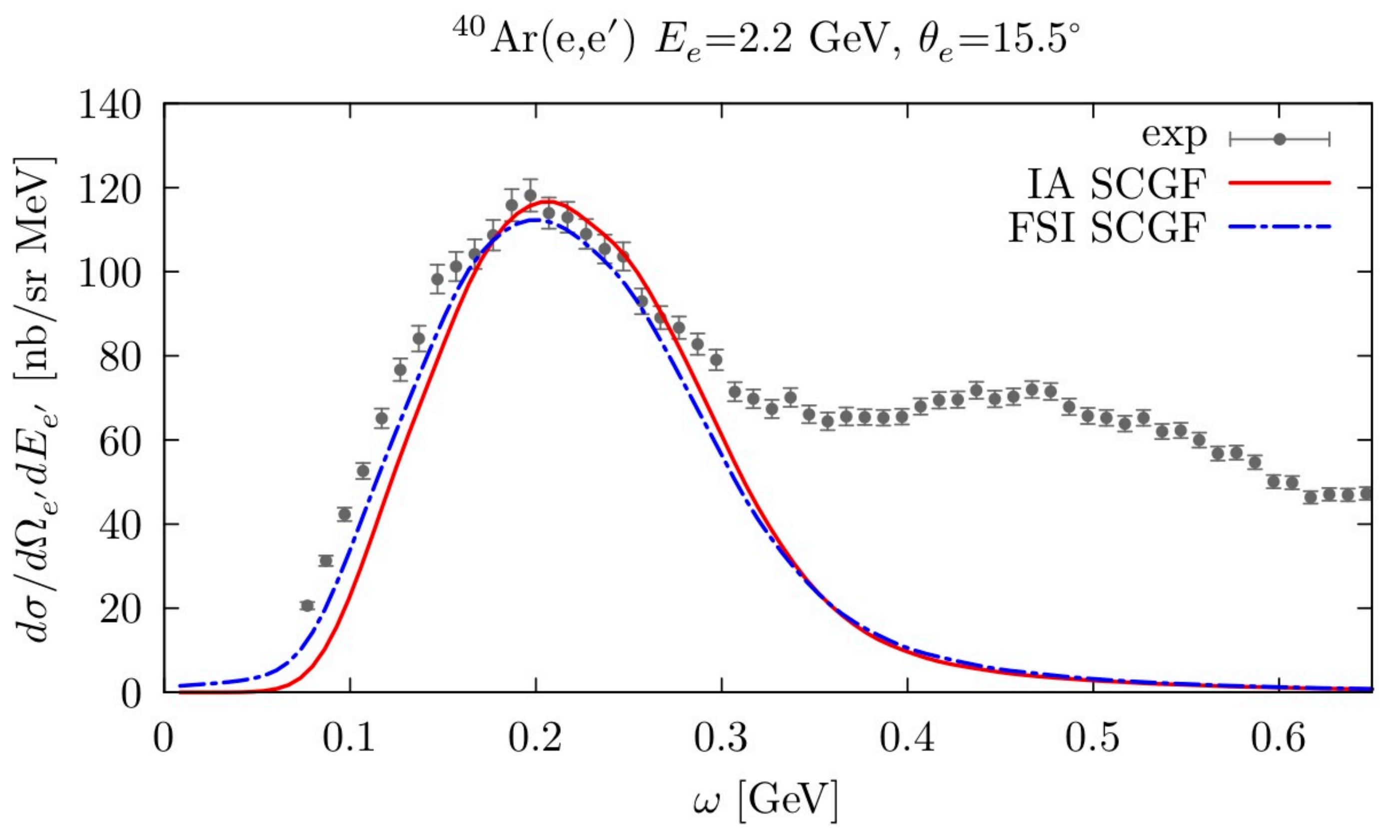
Observed **dominance of np-over-pp** pairs for a variety of nuclei

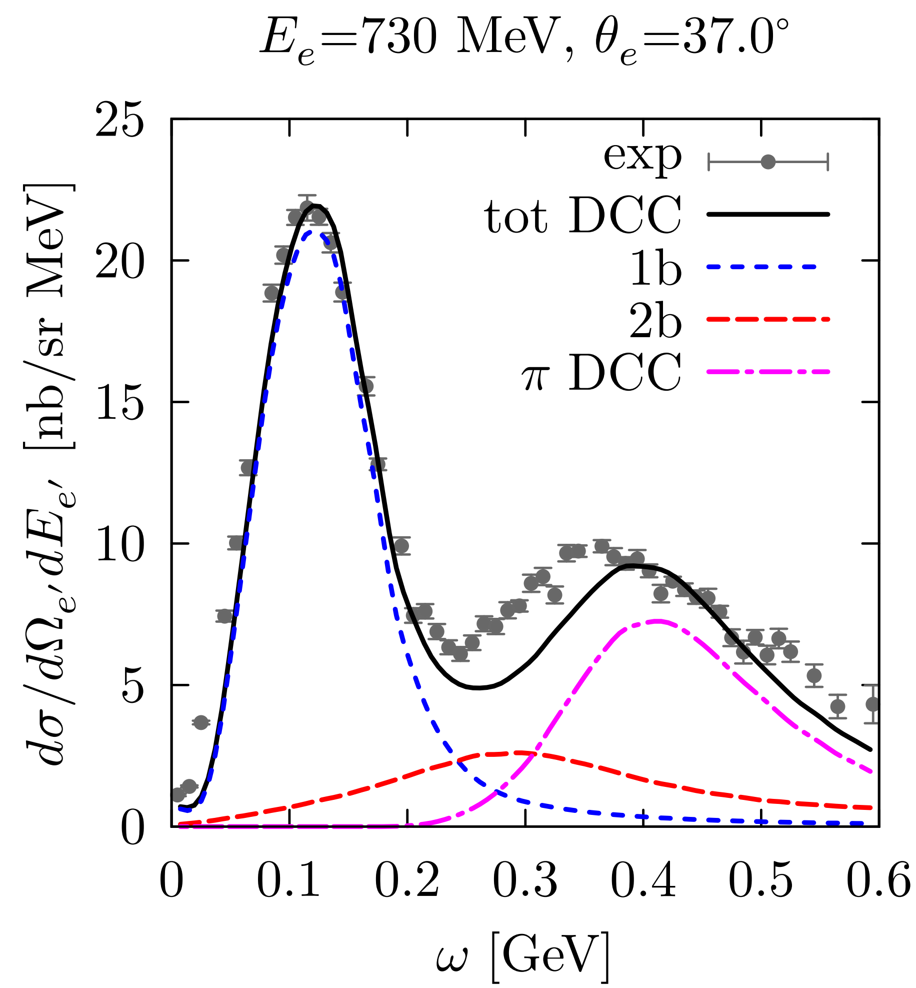
Cross sections: Spectral function approach

Spectral function formalism: unified framework able to describe the different reaction mechanisms retaining an accurate treatment of nuclear dynamics

- NR, S. Gardiner, M. Betancourt working on efficiently **implementing the spectral function model in GENIE**

NR, Frontiers in Phys. 8 (2020) 116





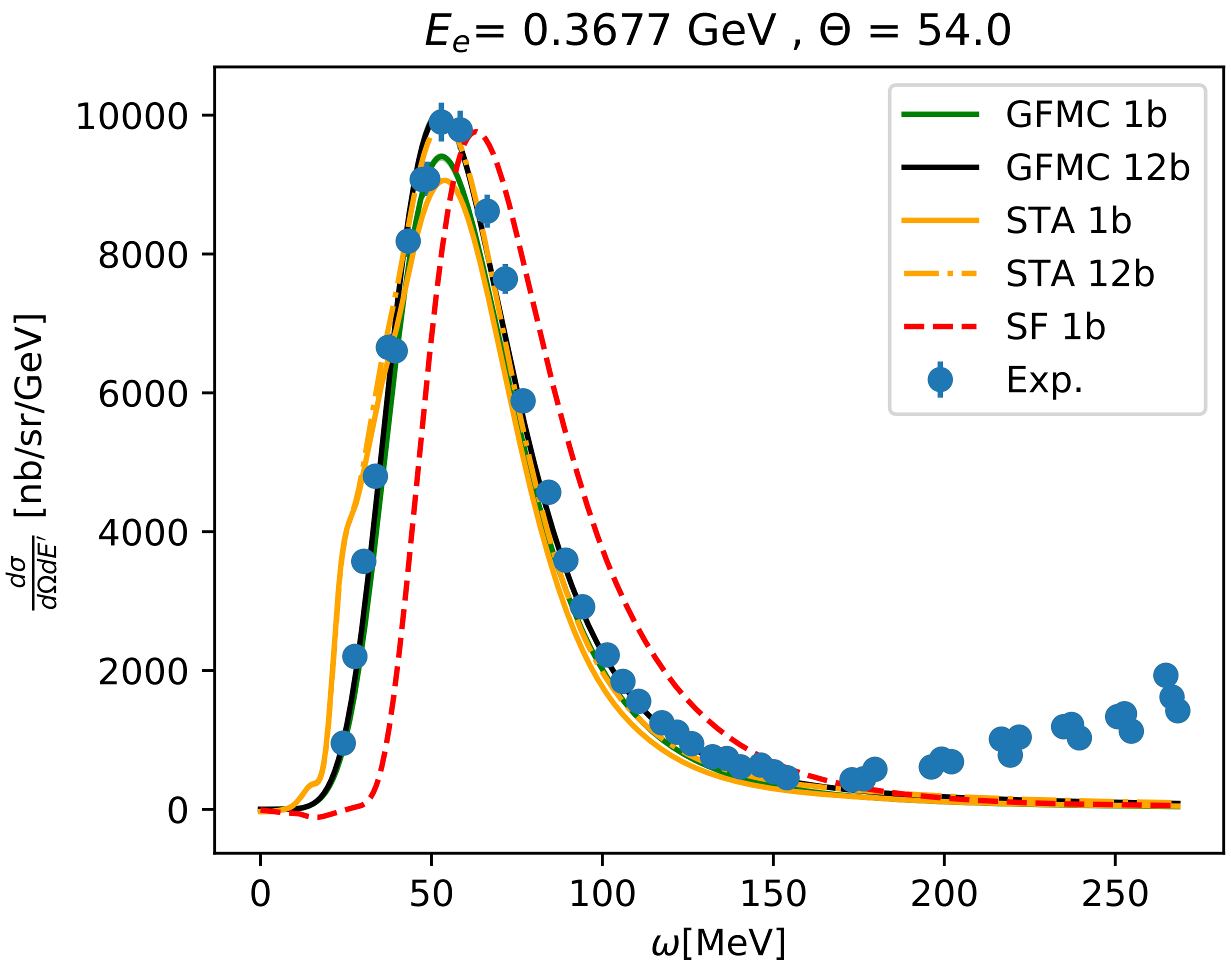
Using electron scattering data to validate our predictions for ^{40}Ar

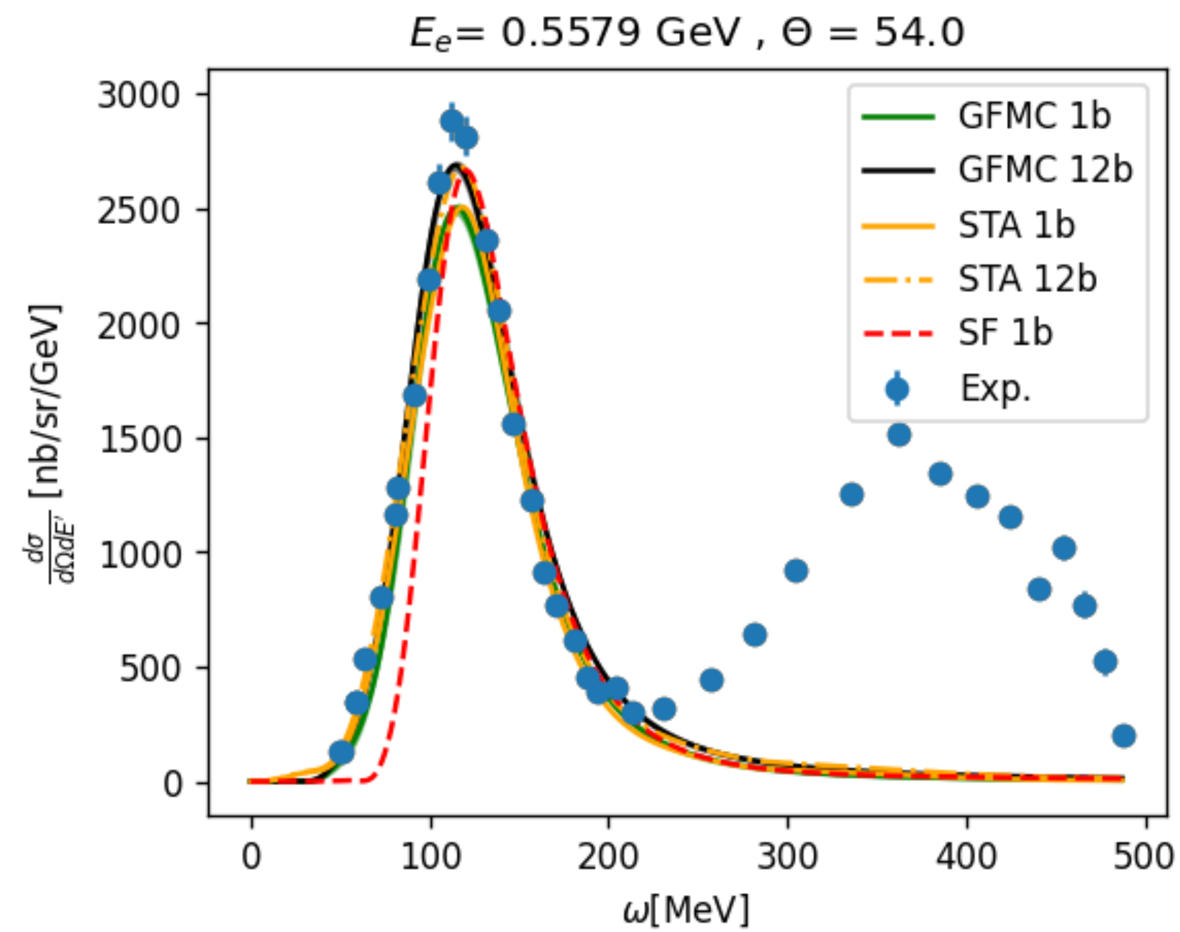
NR, J. Isaacson, S. English (SULI program) predictions for the DIS region convoluting spectral function+nucleon pdf

Comparing different many-body methods

- e -^{3}H: inclusive cross section

NR, A. Lovato, S. Pastore, et al, in preparation





- Comparisons among QMC, SF, and STA approaches: first step to precisely **quantify the uncertainties i**nherent to the factorization of the final state.

- Gauge the role of **relativistic effects** in the energy region relevant for neutrino experiments.

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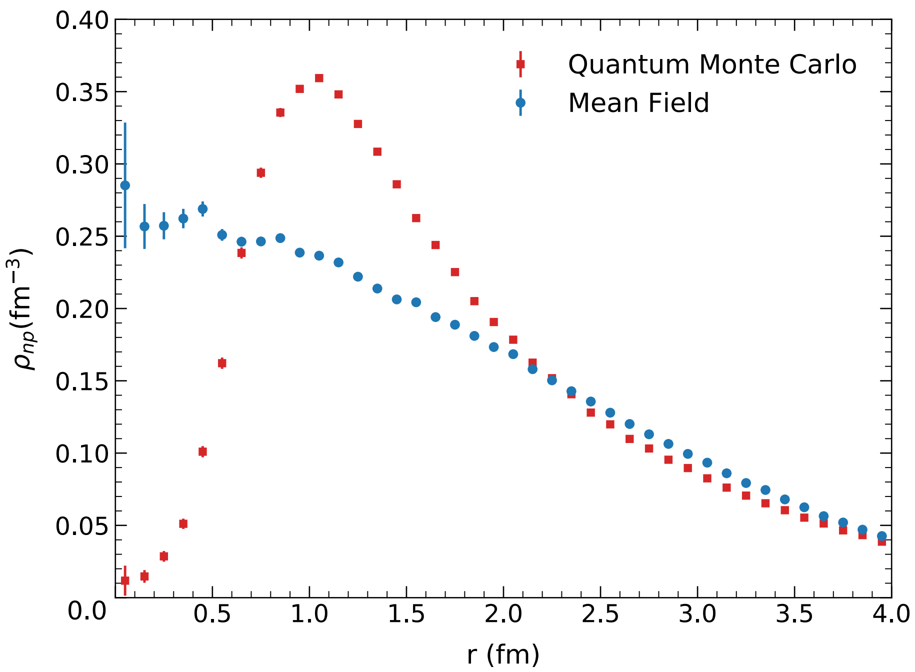
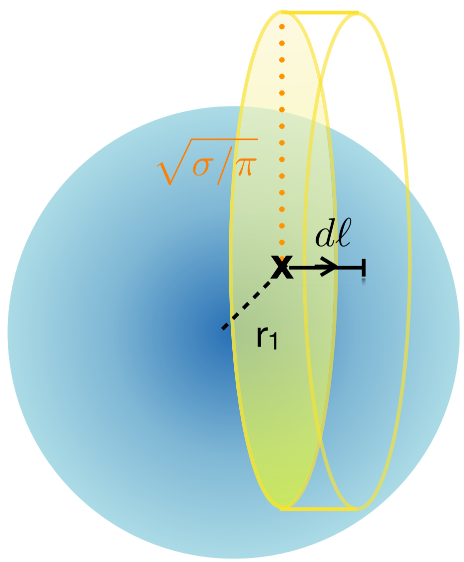
A Quantum Monte Carlo based cascade



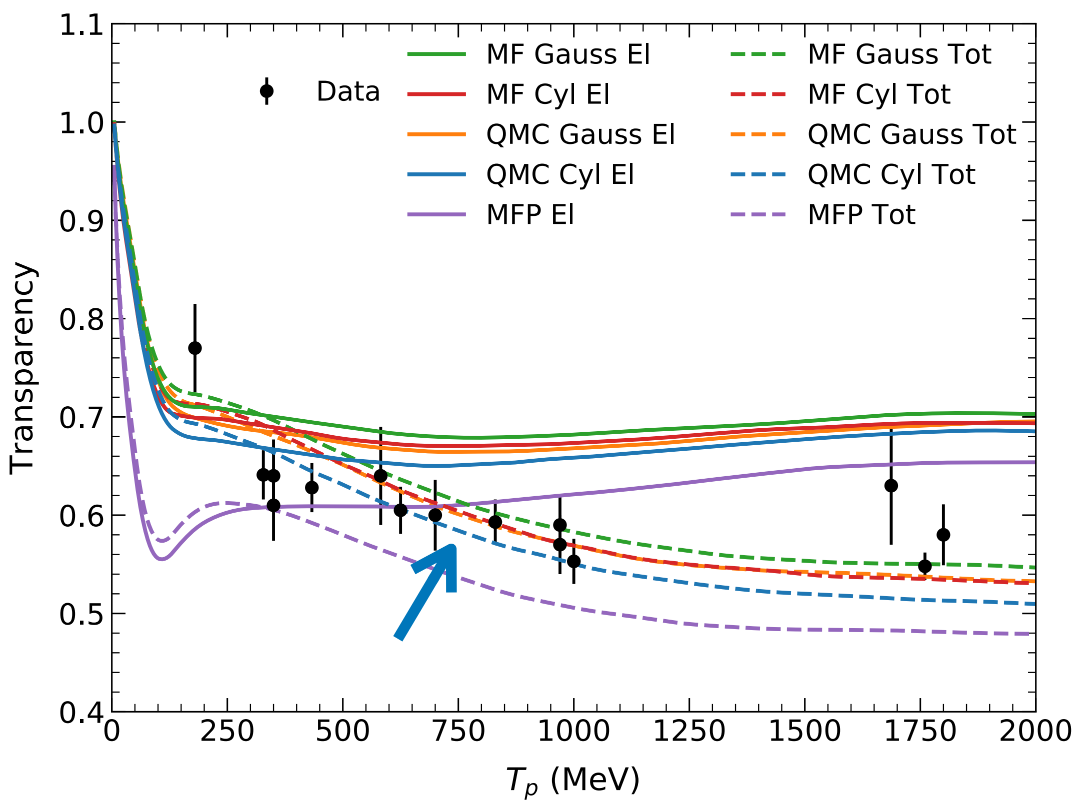
We investigated the role of nuclear effects in intra-nuclear cascade

*J.Isaacson, W Jay, A. Lovato, P Machado, NR, Phys. Rev. C **103**, 015502 (2021)*

The nucleons' positions are sampled from **36000 GFMC configurations**.



Check interaction: **accept-reject** test with a cylinder probability distribution.



- We computed different observables: p-^{12}C cross section, ^{12}C transparency and obtained a fair agreement with data
- Extend the model to include pion degrees of freedom and compare with exclusive observables.

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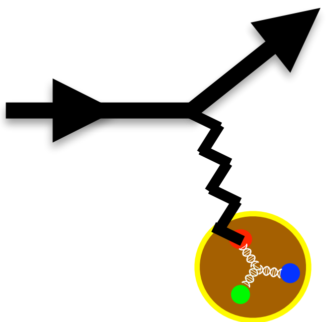
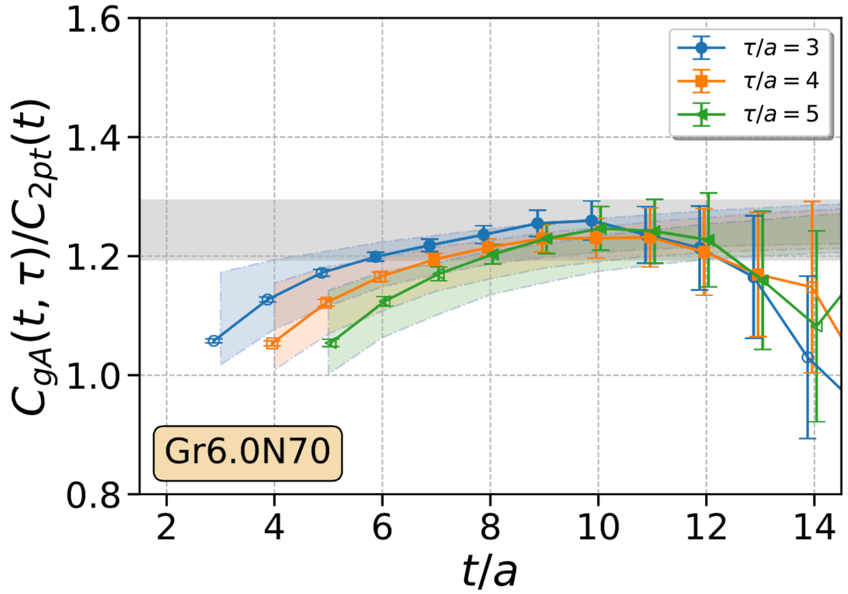
Lattice QCD and neutrino-nucleus

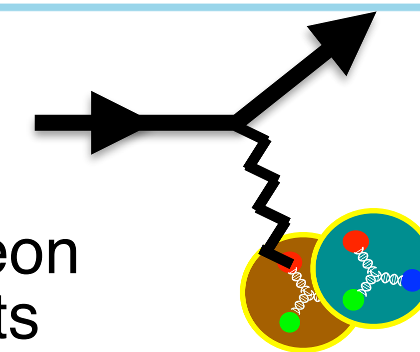


Nucleon form factors

Lin, Meyer, Gottlieb, Hughes, Kronfeld, PRD 103 (2021)

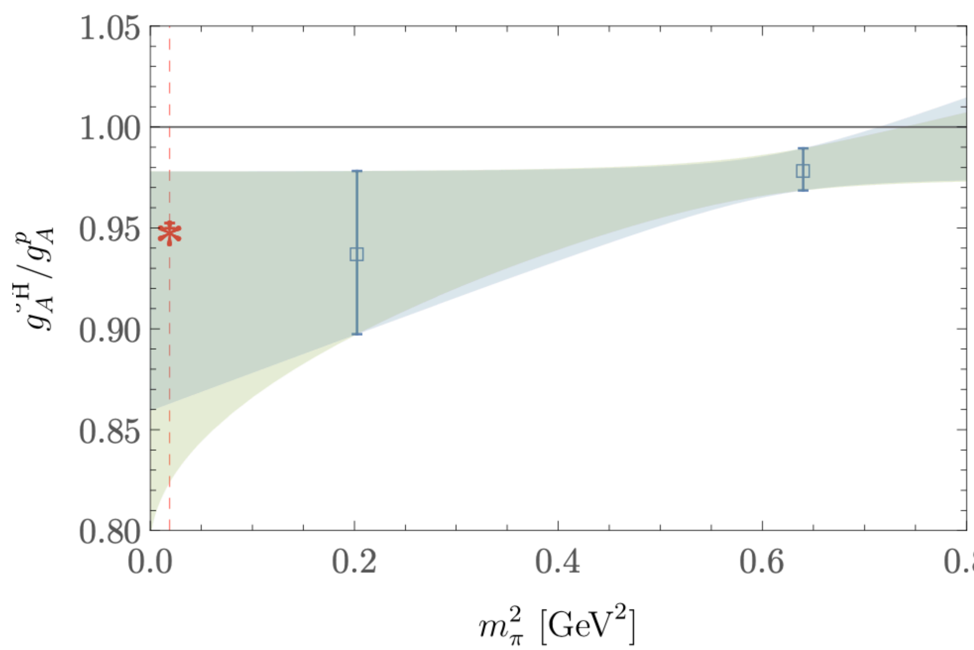


- First LQCD calculation using staggered fermions of nucleon axial charge g_A



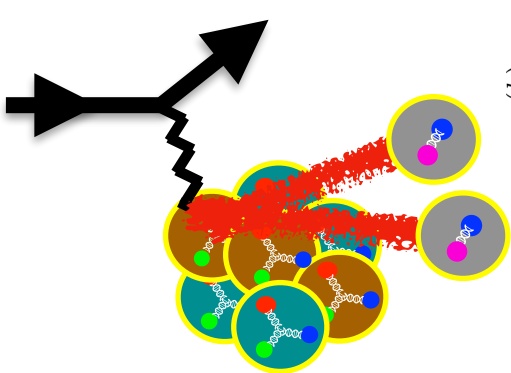
Two nucleon currents

Parreño et al [NPLQCD] PRD 103 (2021)

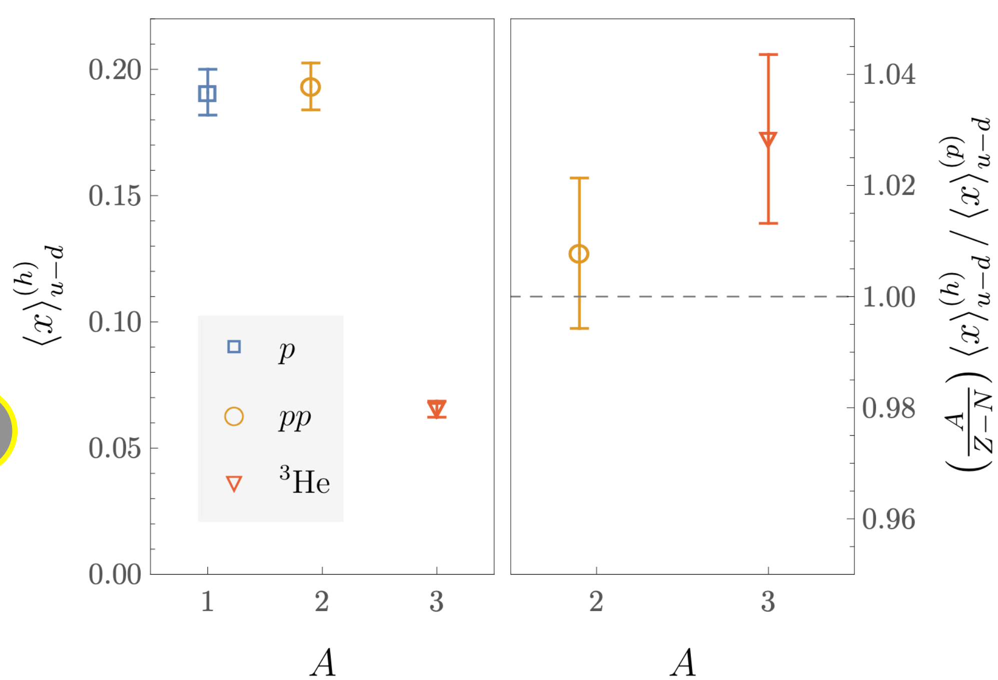


- Exploratory LQCD calculations of axial matrix elements governing triton β-decay performed at second, lighter quark mass

Deep Inelastic Scattering



Detmold et al [NPLQCD] PRL 126 (2021)



- First LQCD calculation of quark momentum fractions of nuclei

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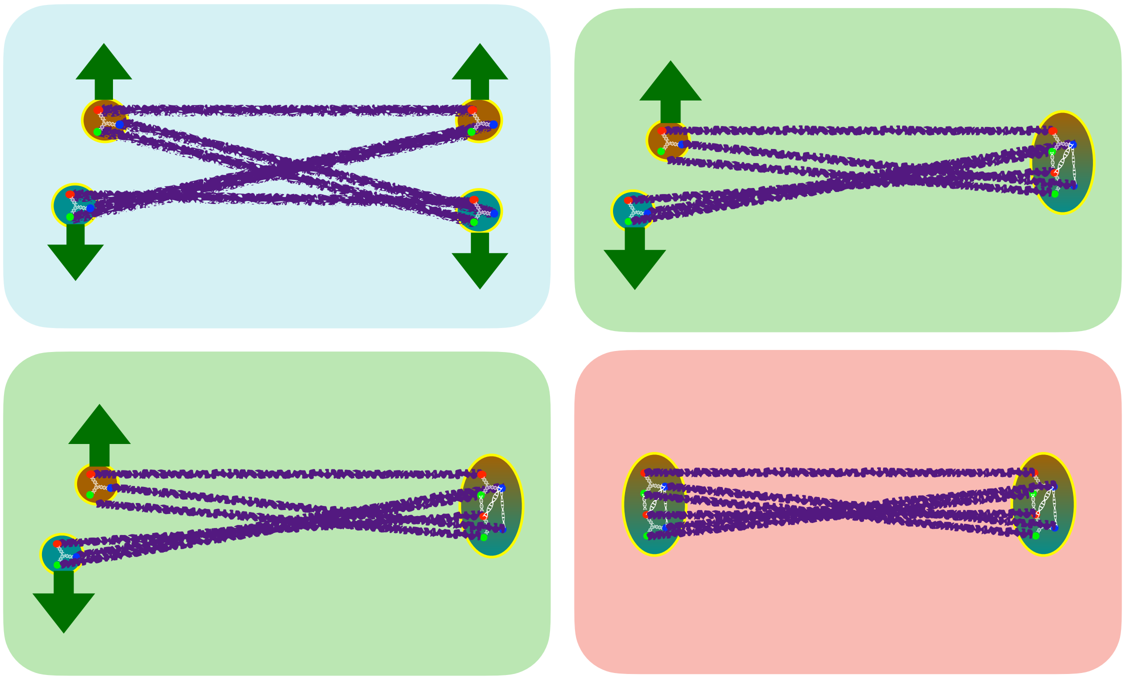
Lattice QCD and neutrino-nucleus

Several **systematic uncertainties** of nuclear matrix element calculations still need to be quantified

- Heavier than physical quark masses only
- One lattice spacing
- Finite size effects

Excited-state effects can be large in LQCD calculations of nuclei, because **energy gaps** between **bound states** and finite-volume **"scattering" states are small** vs Λ_{QCD}



Reliable but computationally challenging **variational method** — diagonalize correlation-function matrix involving many different creation/annihilation operator structures

Work in progress to understand excited-state effects for *NN* using variational method

Wagman and collaborators (NPLQCD++), arXiv:2108.xx

Similar tools can be applied to *Nπ* resonance production and elastic nucleon axial form factors

Jay, Wagman, and collaborators, *in progress*

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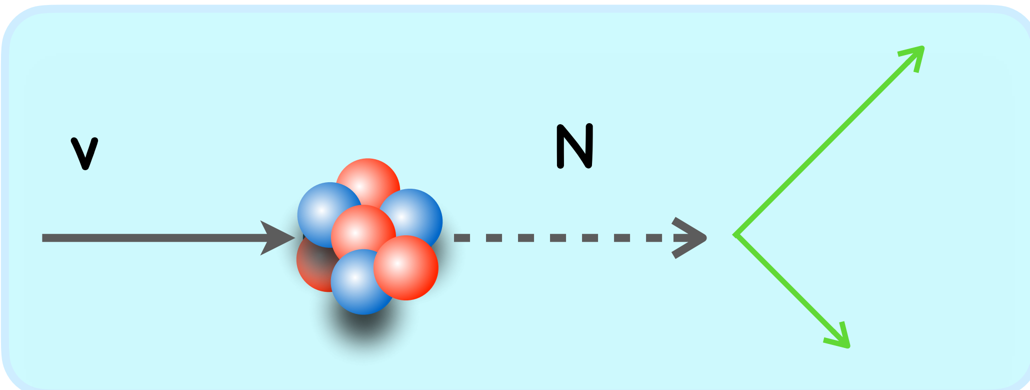
Double Bang events from New Physics at DUNE

- New physics models allows for neutrinos to up-scatter into **heavier neutrino states N**



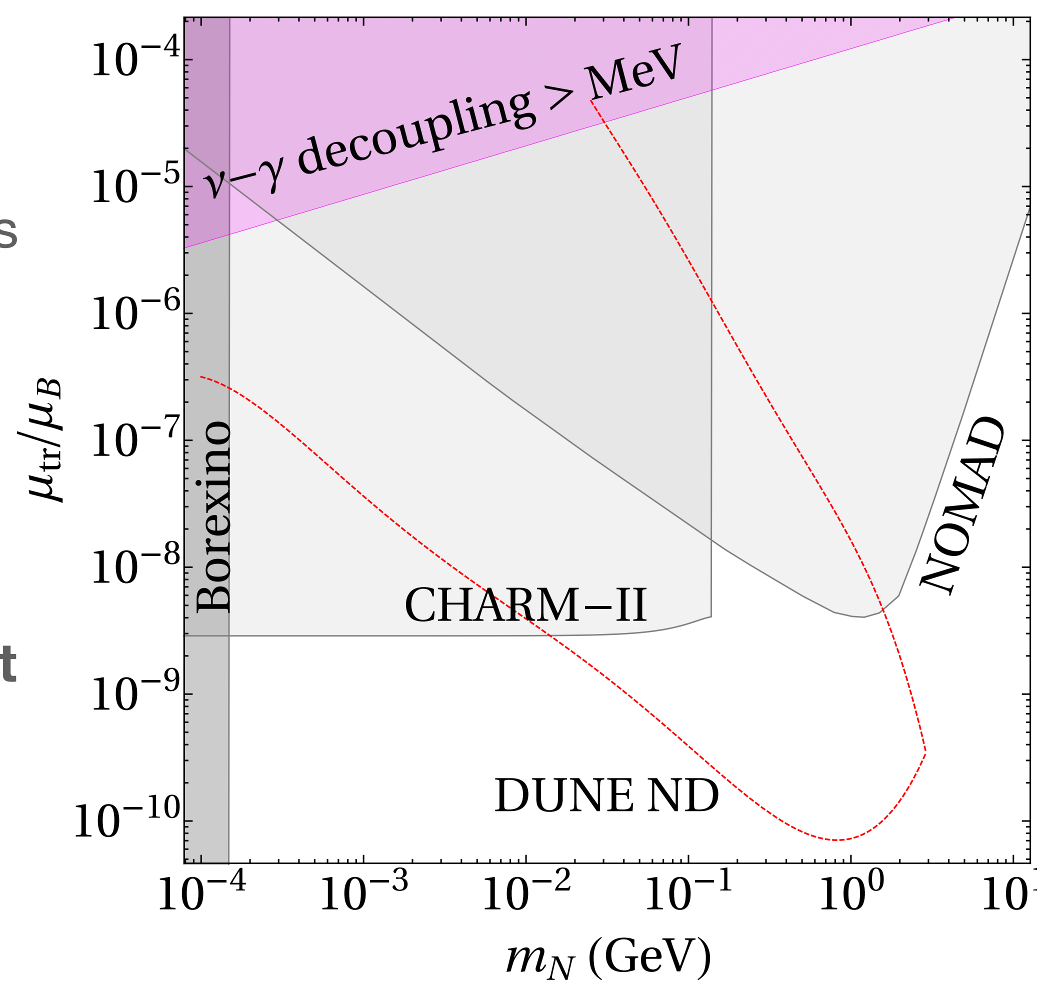
First bang: neutrino-nucleus interaction, production of heavy neutrino

Second bang: decay of heavy neutrino after propagating for some distance

- The number of DB events depend on the ν-nucleus cross section and the probability for the heavy neutrino to decay after traveling for a distance L

I. Martinez-Soler, NR, et al, arXiv:2105.09357

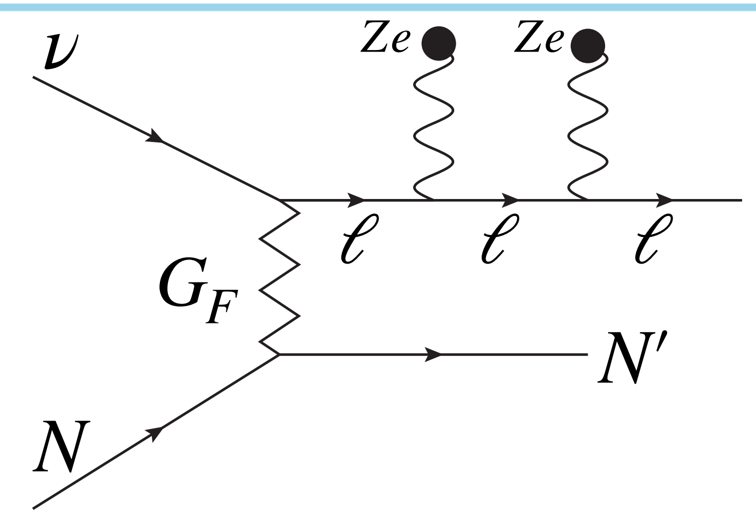
- Expected sensitivity to the **transition magnetic moment νμ – N from DBs** signals in the DUNE LAr near detector



More work on this topic: Harnik, Machado, Plestid, Brdar

Low energy effects in CC cross sections

- **Coulomb corrections :** R. Plestid, O. Tomalak, R. H.J. Hill, in progress

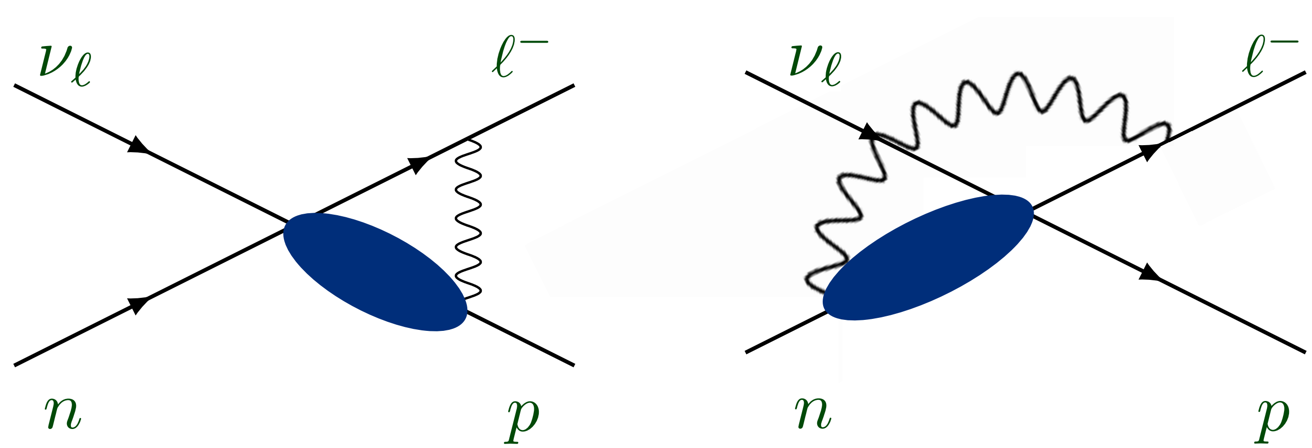


A charged lepton produced in a CC interaction experiences a Coulomb potential from the remnant nucleus, this effect is $\propto Z\alpha$

Currently handled by GENIE a Distorted Wave treatment based on J.Engel, PRC 57, 1998

Impact of this effect: extra asymmetry cross sections, altered lepton kinematics, shift effective momentum of the nuclear response functions

- **QED radiative corrections :** O. Tomalak, R. H.J. Hill, et al, arXiv:2105.07939



Radiative corrections crucial for %-level oscillation program

Effect is relevant also in the nuclear case

Radiative corrections to neutrino-nucleon interactions at LO are included in the factorization framework. Detailed calculations of cross sections for various experimental conditions.

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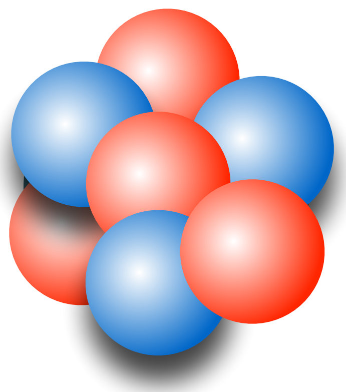
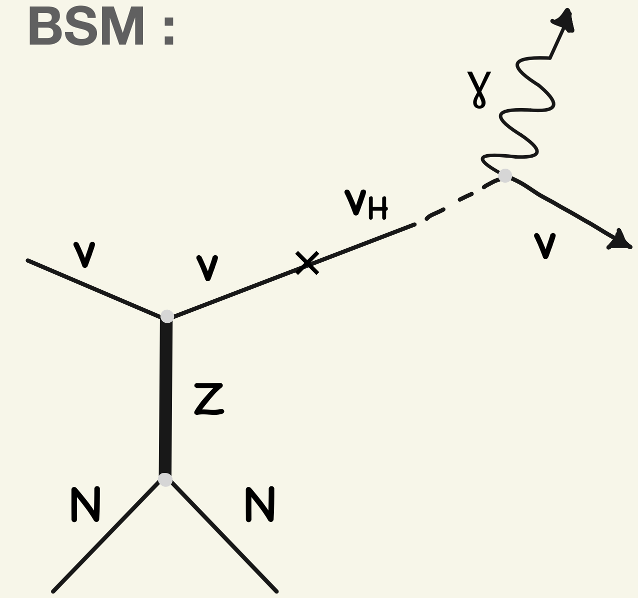
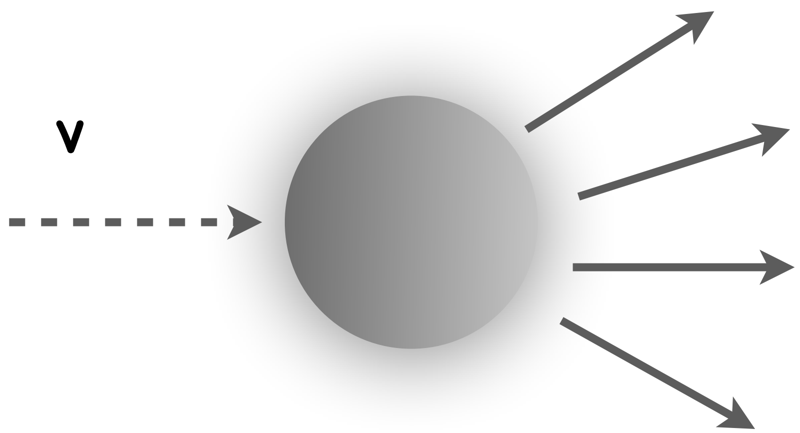
Summary

Nuclear Physics:



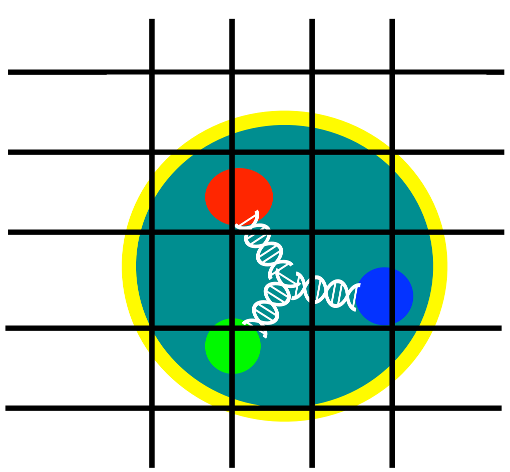
BSM :



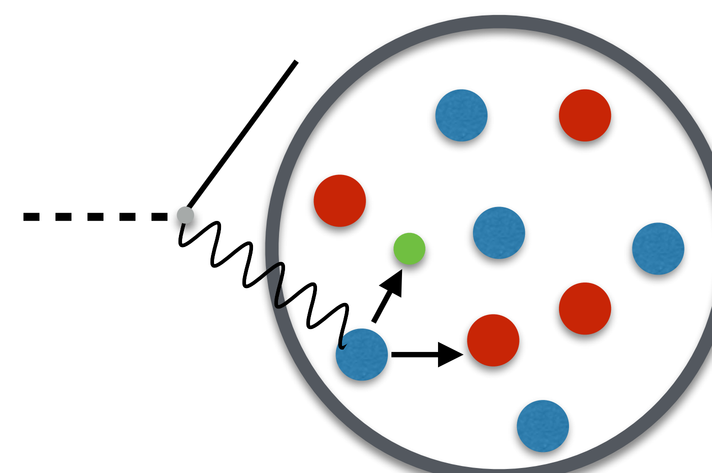


Simulate neutrino-nucleus interactions to untangle neutrino oscillations from the measured interactions

Lattice QCD :



Event Generator :



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