Synergy neutrino interactions

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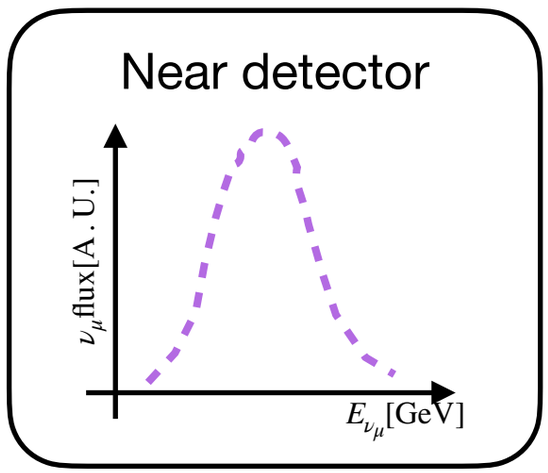
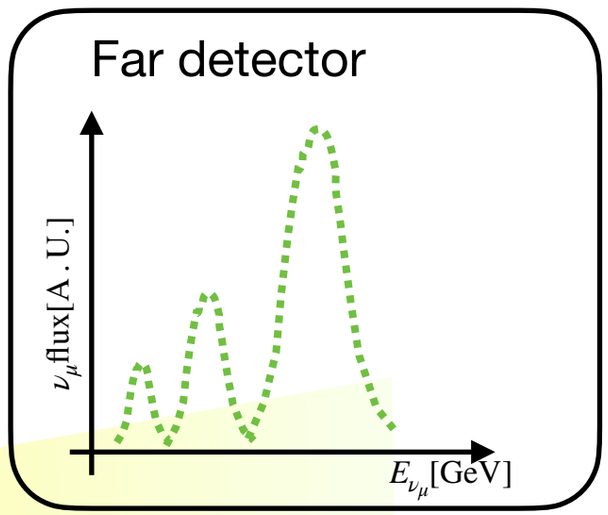
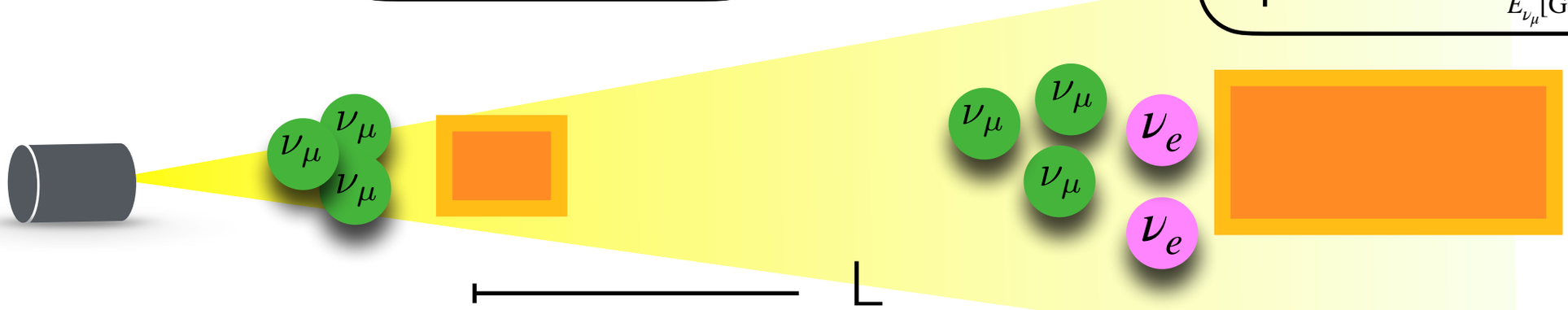
Why do we need more precision?

New generation of neutrino experiments will measure the unknown PMNS parameters with unprecedented accuracy





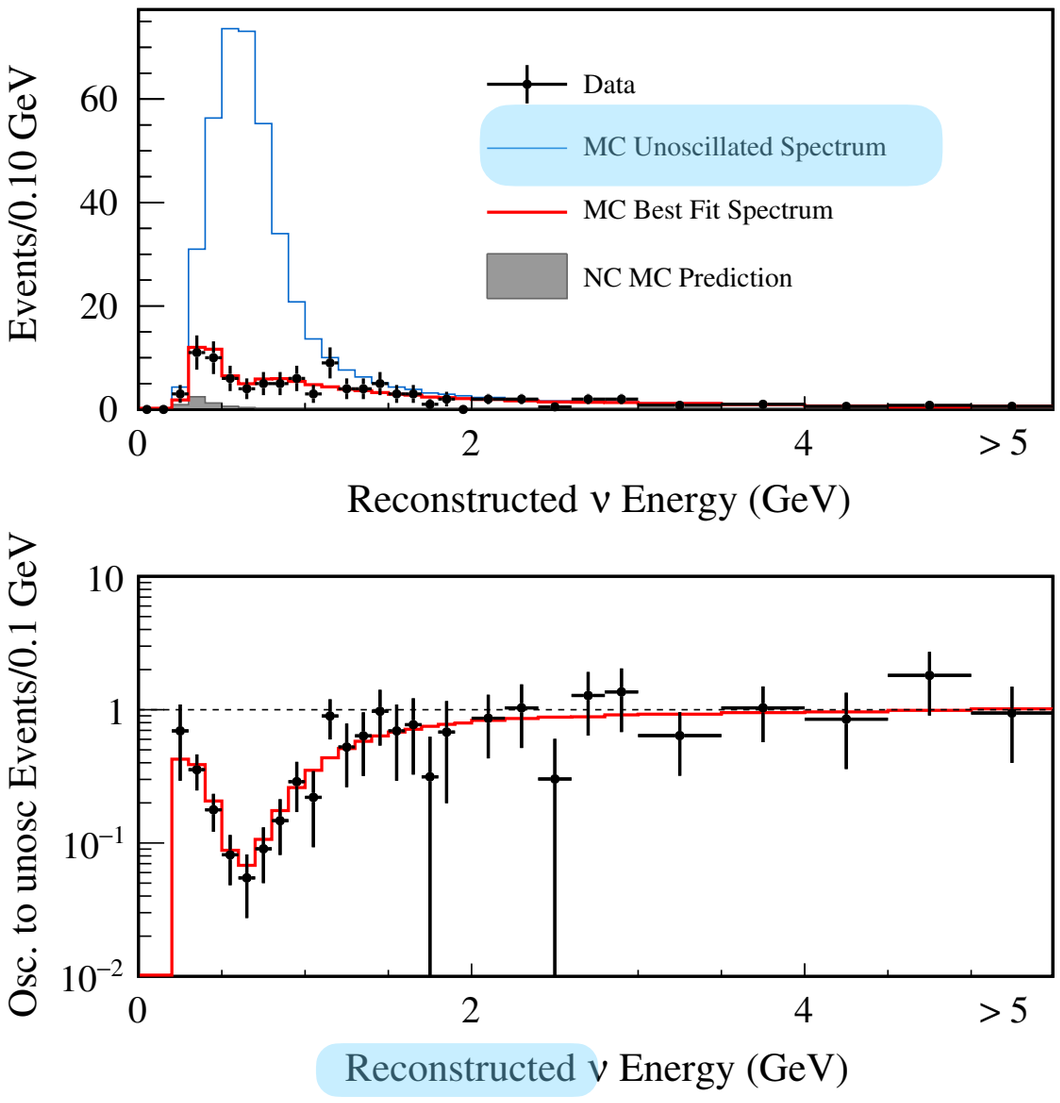


$$P(\nu_\mu \to \nu_e, E_\nu, L) = \frac{\Phi(E_\nu, L)}{\Phi_\mu(E_\nu, 0)} = \frac{N_e(E_\nu, L)/\sigma_e(E_\nu)}{N_\mu(E_\nu, L)/\sigma_\mu(E_\nu)}$$

Theory

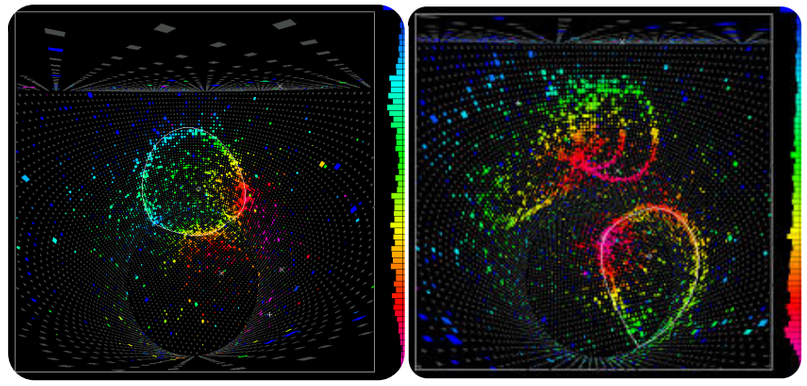
Experiment

Oscillations Require E_ν reconstruction

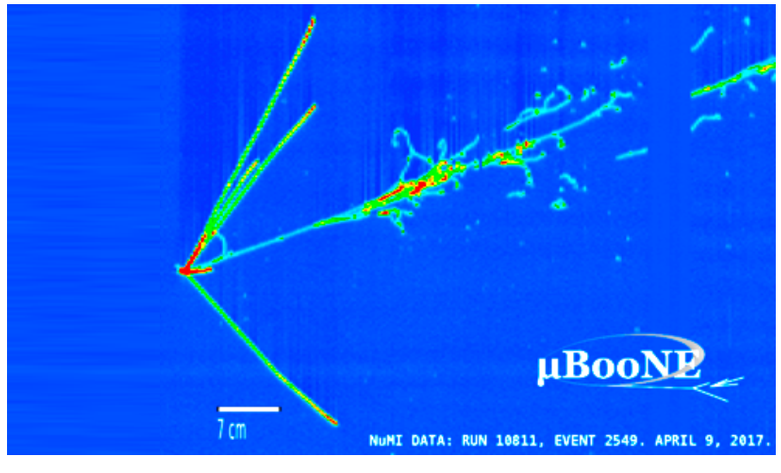


$$P(\nu_\mu \to \nu_x) \sim \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{true}}\right)$$

Cherenkov detector: kinematic reconstruction



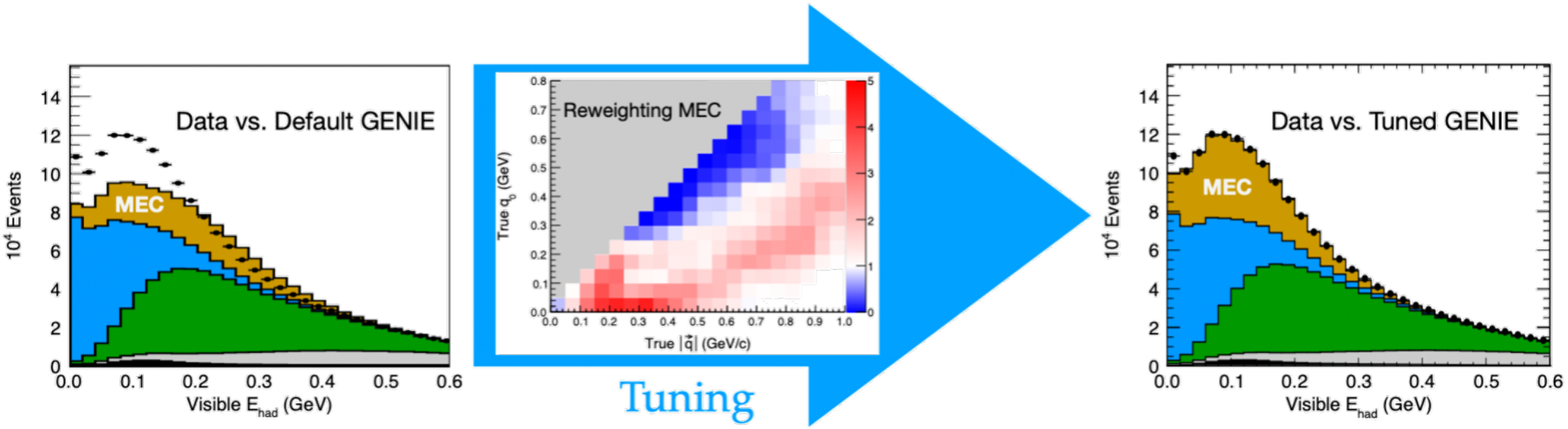
Tracking detector: calorimetric reconstruction



T2K, Phys. Rev. D 91, 072010 (2015)

Tuning & BSM

Discrepancies between generators and data often corrected by tuning an empirical model of the least well known mechanism: MEC (“meson exchange”/two-body currents)



Coyle, Li, and Machado, JHEP 12, 166 (2022)

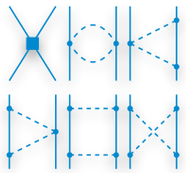
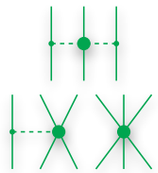
Mis-modeling can distort signals of new physics, **biasing** measurement of **new physics parameters**

Studies on the impact of different neutrino interactions and nuclear models on determining neutrino oscillation parameters are critical. These enable us to assess the level of precision we aim at.

Coloma, et al, Phys.Rev.D 89 (2014) 7, 073015

Ab initio theory achievements

Effective Hamiltonians and consistent currents

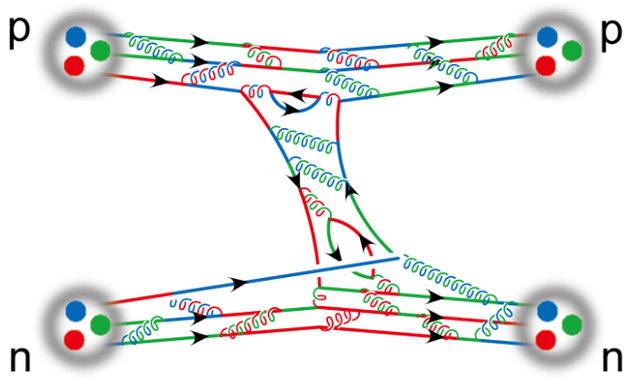
	NN	3N
LO $(Q/\Lambda_\chi)^0$		
NLO $(Q/\Lambda_\chi)^2$		
NNLO $(Q/\Lambda_\chi)^3$		

Accurate nuclear many-body methods

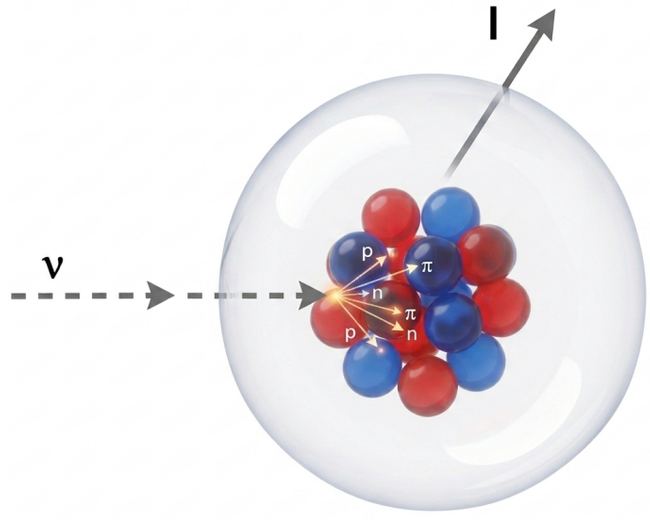
$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

$$J_{mn} = \langle\Psi_m|J|\Psi_n\rangle$$

Quantum Chromodynamcs

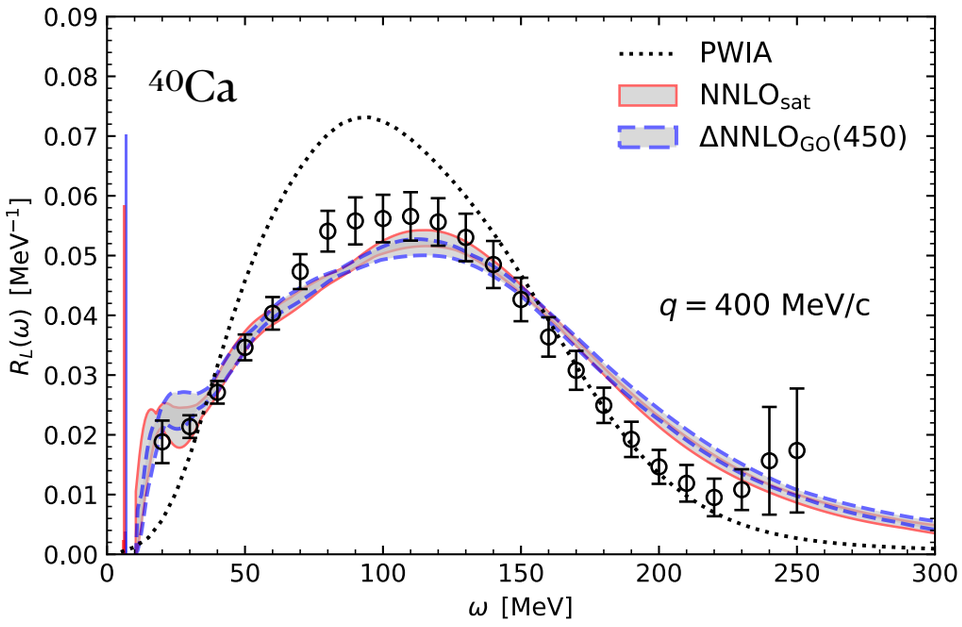


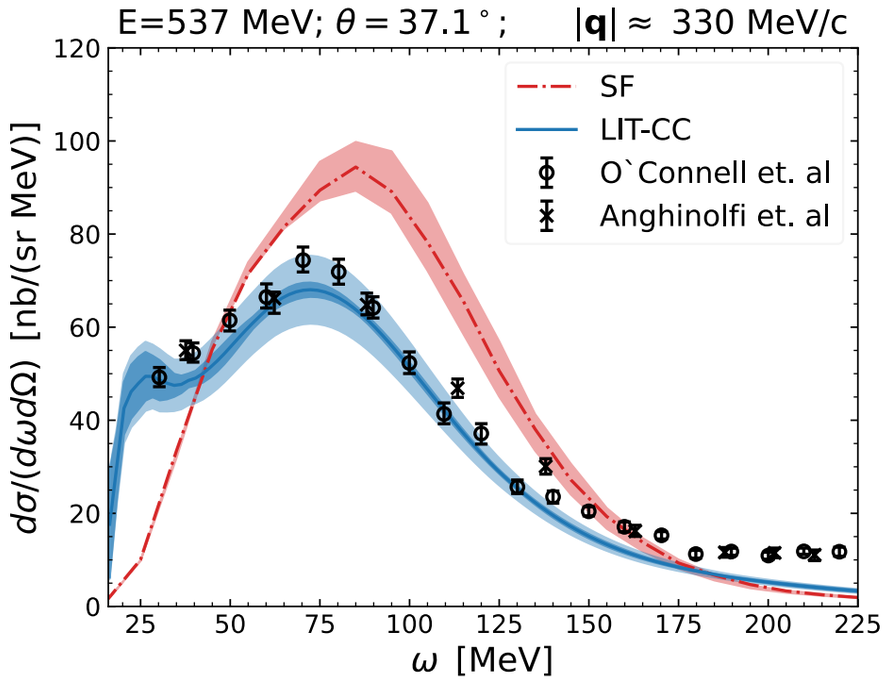
Neutrino-nucleus interactions



Ab initio theory achievements

Coupled-Cluster e-scattering

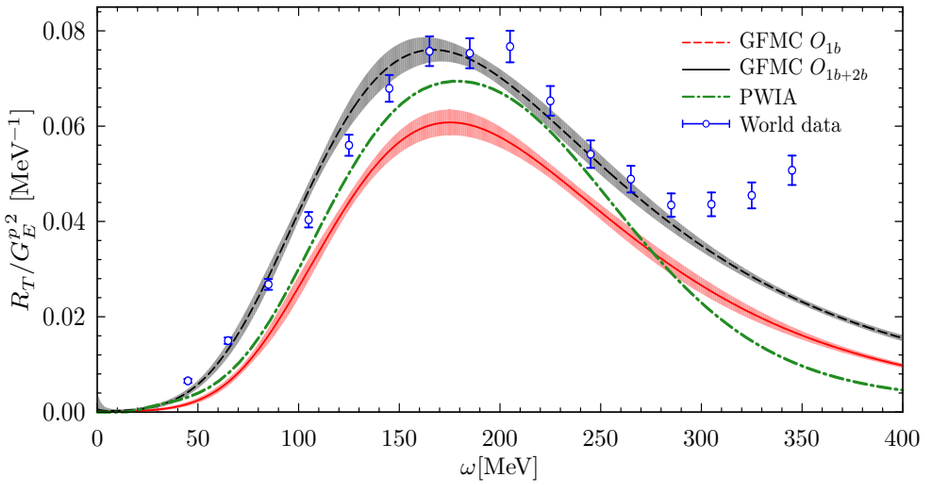


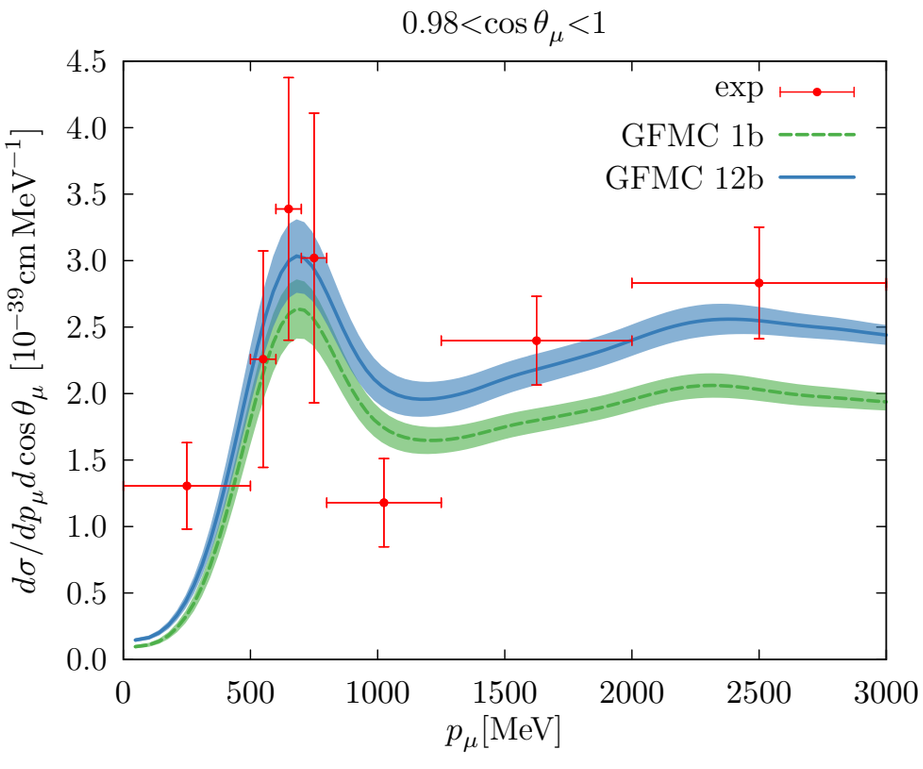


J. Sobczyk et al, PRC 109 (2024) 2, 025502

J. Sobczyk et al, PRL 134 (2025) 20, 202501

Green's Function Monte Carlo





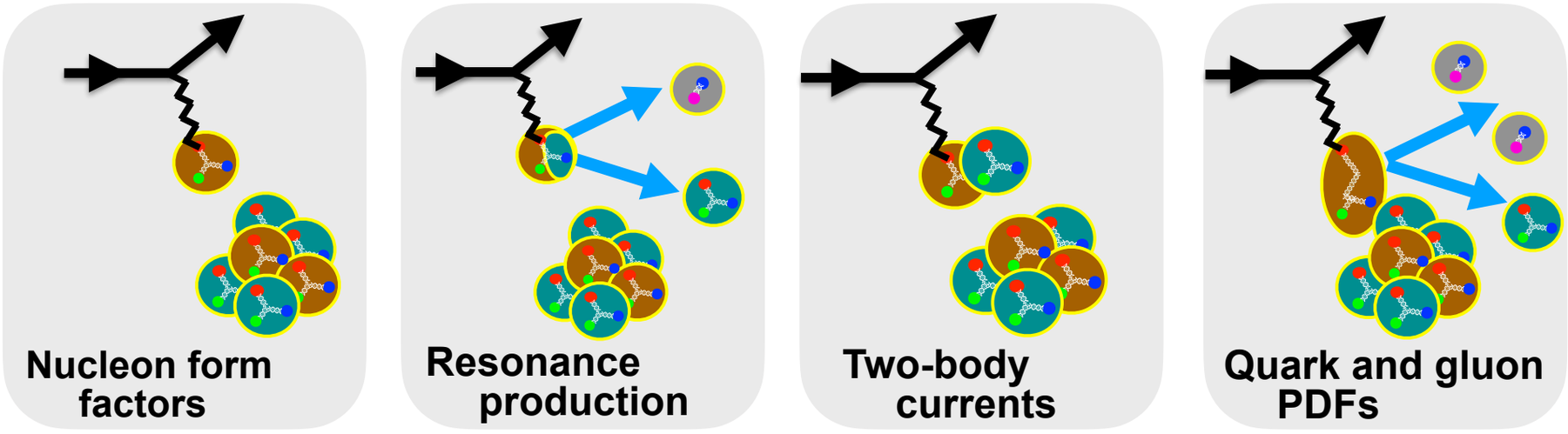
A.Lovato et al, PRL 117 (2016) 8, 082501

A.Lovato et al, PRX 10 (2020) 3, 031068

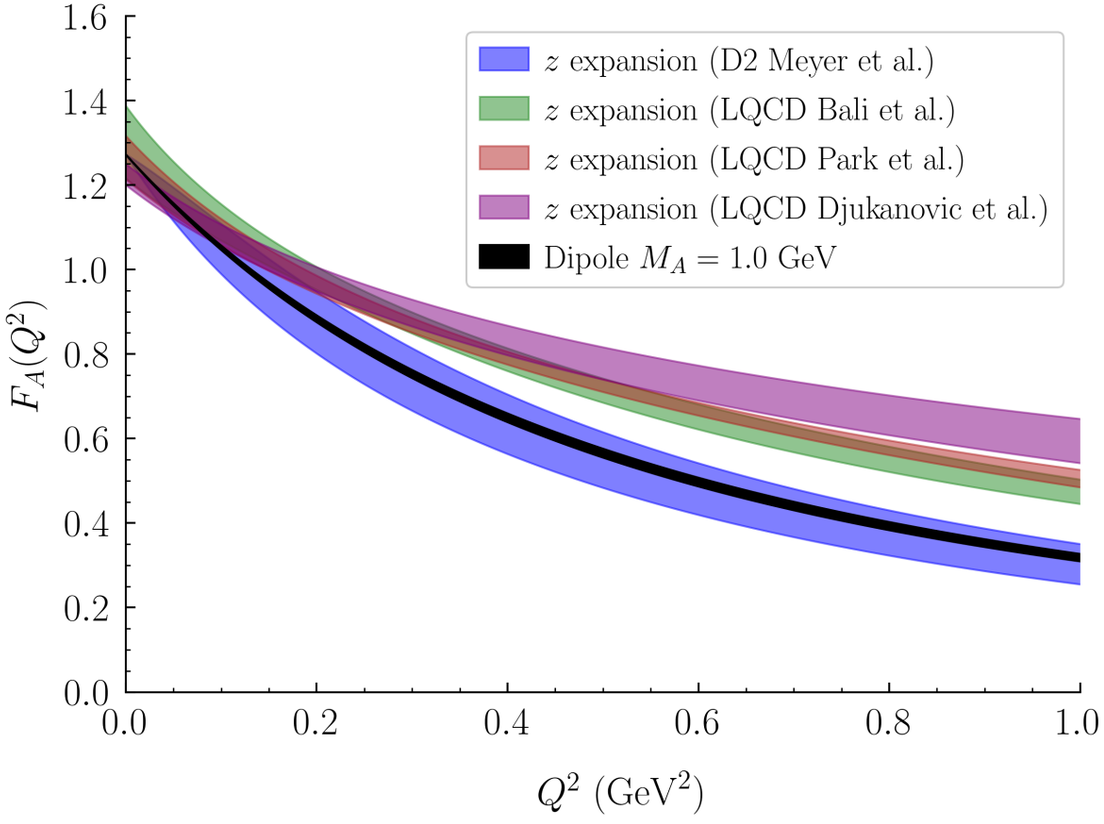
Input parameters and their precision: LQCD

LQCD can provide inputs to be included in EFTs and nuclear many-body methods

Courtesy of M. Wagman



- Axial form factors determination from LQCD



D. Djukanovic et al., "The isovector axial form factor of the nucleon from lattice QCD," Phys. Rev. D 106, 074503 (2022)

O. Tomalak, et al, "Confronting the axial-vector form factor from lattice QCD with MINERvA antineutrino-proton data," Phys. Rev. D 108, 074514 (2023).

- Exploratory studies on amplitudes containing pions

Y. S. Gao et al., "Lattice QCD Study of Pion Electroproduction and Weak Pion Production," PRL 134, 171904 (2025)

C.Alexandrau, et al, "Elastic Nucleon-Pion scattering amplitudes in the Δ channel at physical pion mass from Lattice QCD", Phys.Rev.D 109 (2024) 3, 3

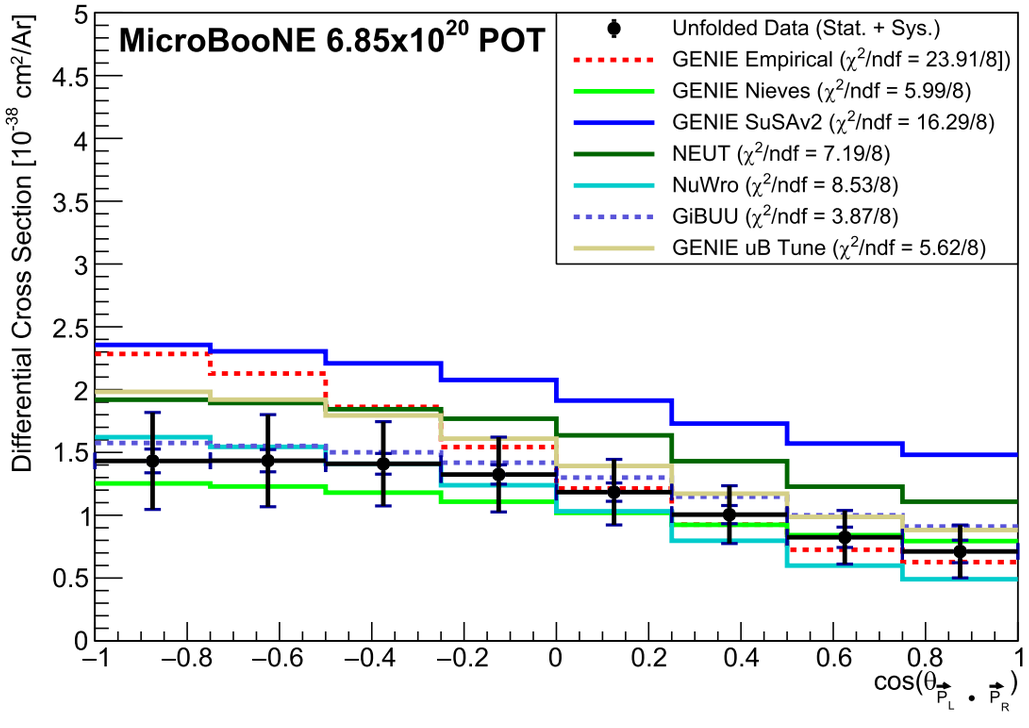
A. Grebe, et al, "Nucleon-Pion Spectroscopy from Sparsened Correlators", *PoS* LATTICE2023 (2024) 049

Noemi Rocco, nrocco@fnal.gov

Two nucleon emission

MicroBooNE provided first **two-proton knockout** single-differential **cross section on argon**

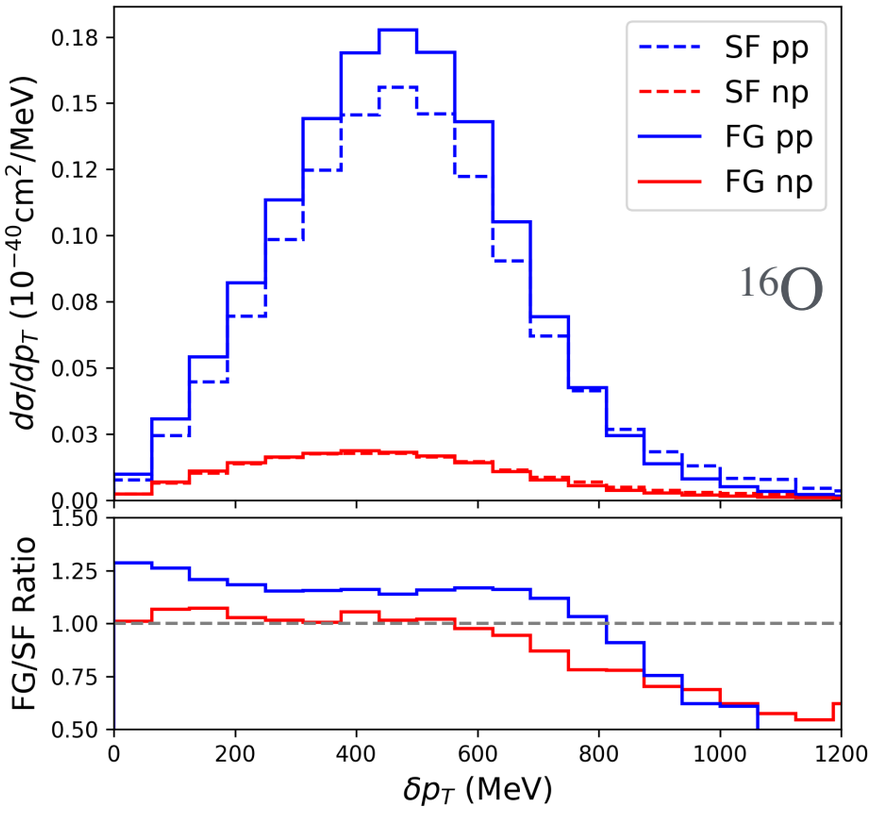
Phys. Lett. B 872 (2026) 140052



Critical to support these measurements developing nuclear models able to describe these 'exclusive' scattering with high accuracy

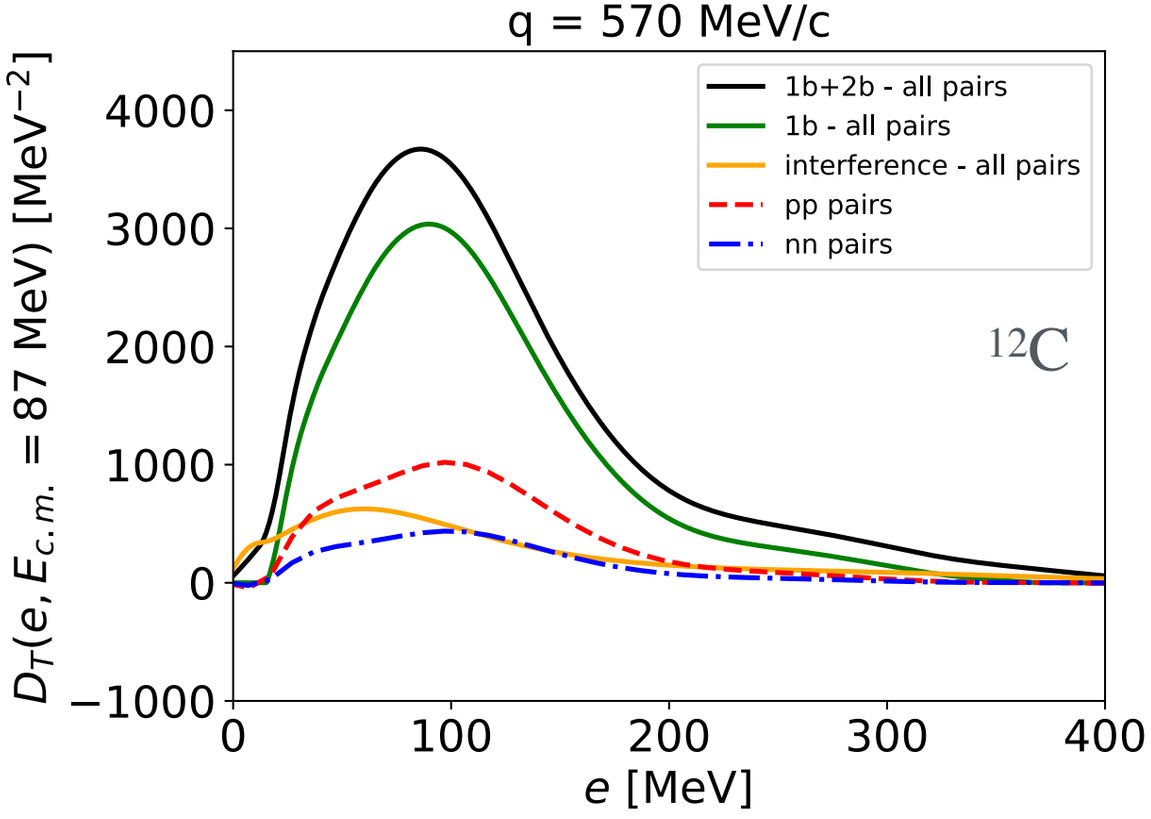
NR, N. Steinberg, 2602.02231

- Spectral function using QMC distributions

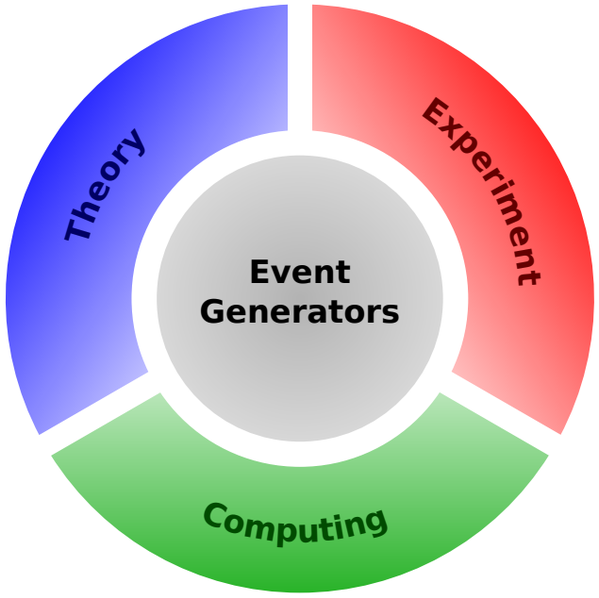


L. Andreoli et al, Phys.Rev.C 110 (2024) 6, 064004

- Short-time approximation

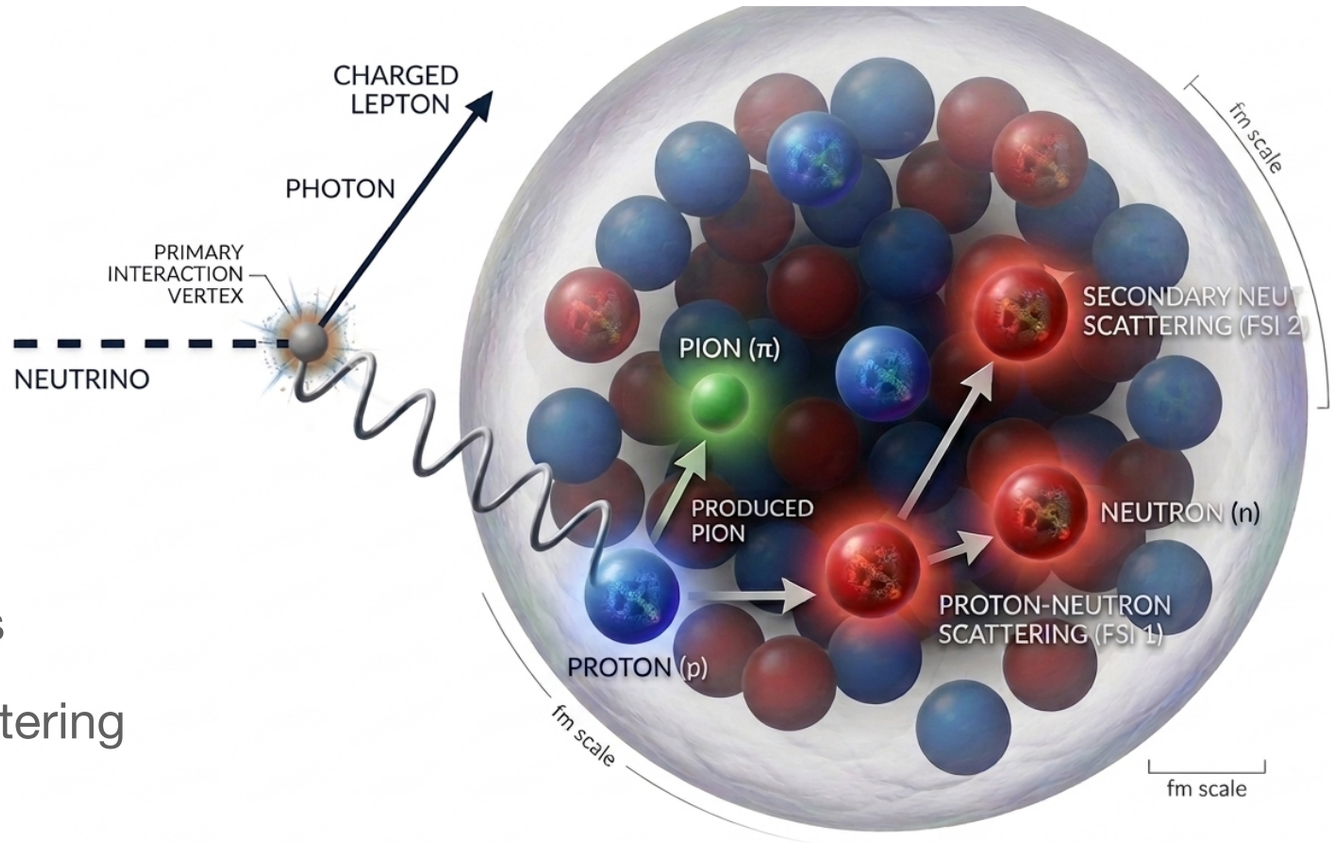


Event Generators



The propagation of **hadrons** through the **nuclear medium** is crucial in the analysis of neutrino oscillation experiments.

Event Generators for High-Energy Physics Experiments, 2022 Snowmass Summer Study



In event generators nuclear inputs are crucial in the modeling of:

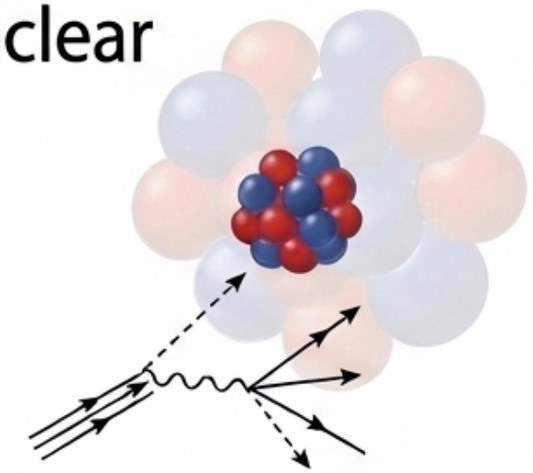
- Nucleons spatial and momentum distributions
- Hadron propagation; elastic and inelastic scattering
- Nuclear clustering

Event generators involve unknown model parameters that must be tuned to experiments, while maintaining the integrity of the underlying nuclear physics models.

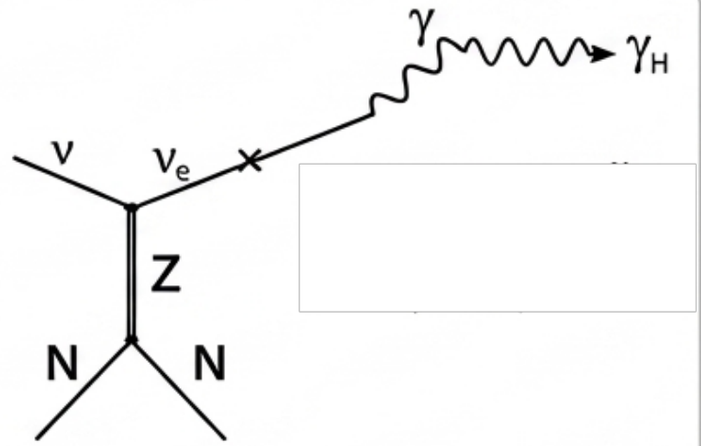
NEUT ACHILLES NuWro Genie

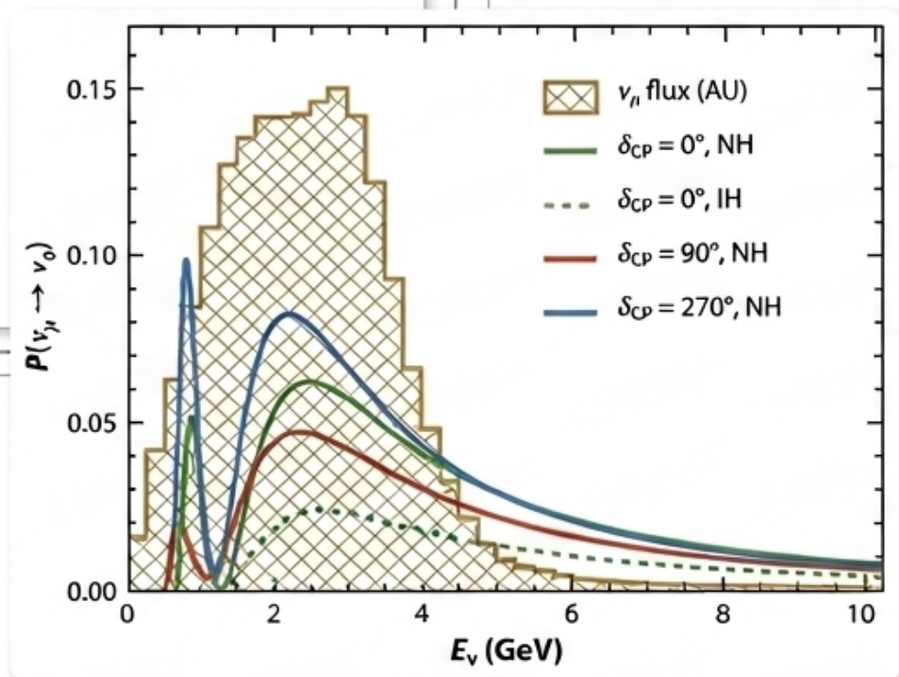
Summary

Nuclear

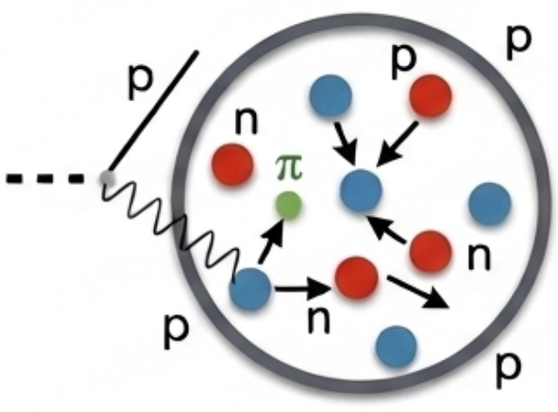


BSM

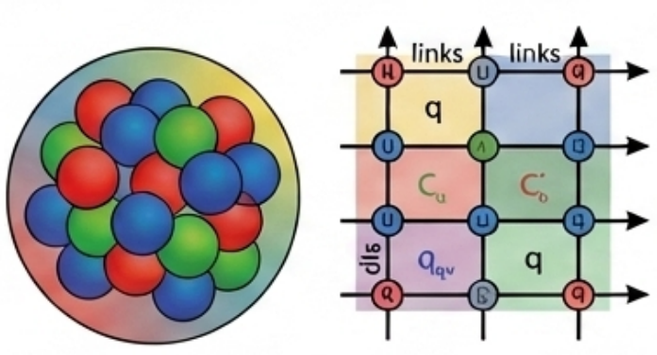




Event Generator



Lattice QCD



Neutrino Theory Network

SciDAC
Scientific Discovery through Advanced Computing