Nuclear physics uncertainties in neutrino experiments

Noemi Rocco

P5 Town Hall meeting

March 22, 2023

Addressing Neutrino-Oscillation Physics

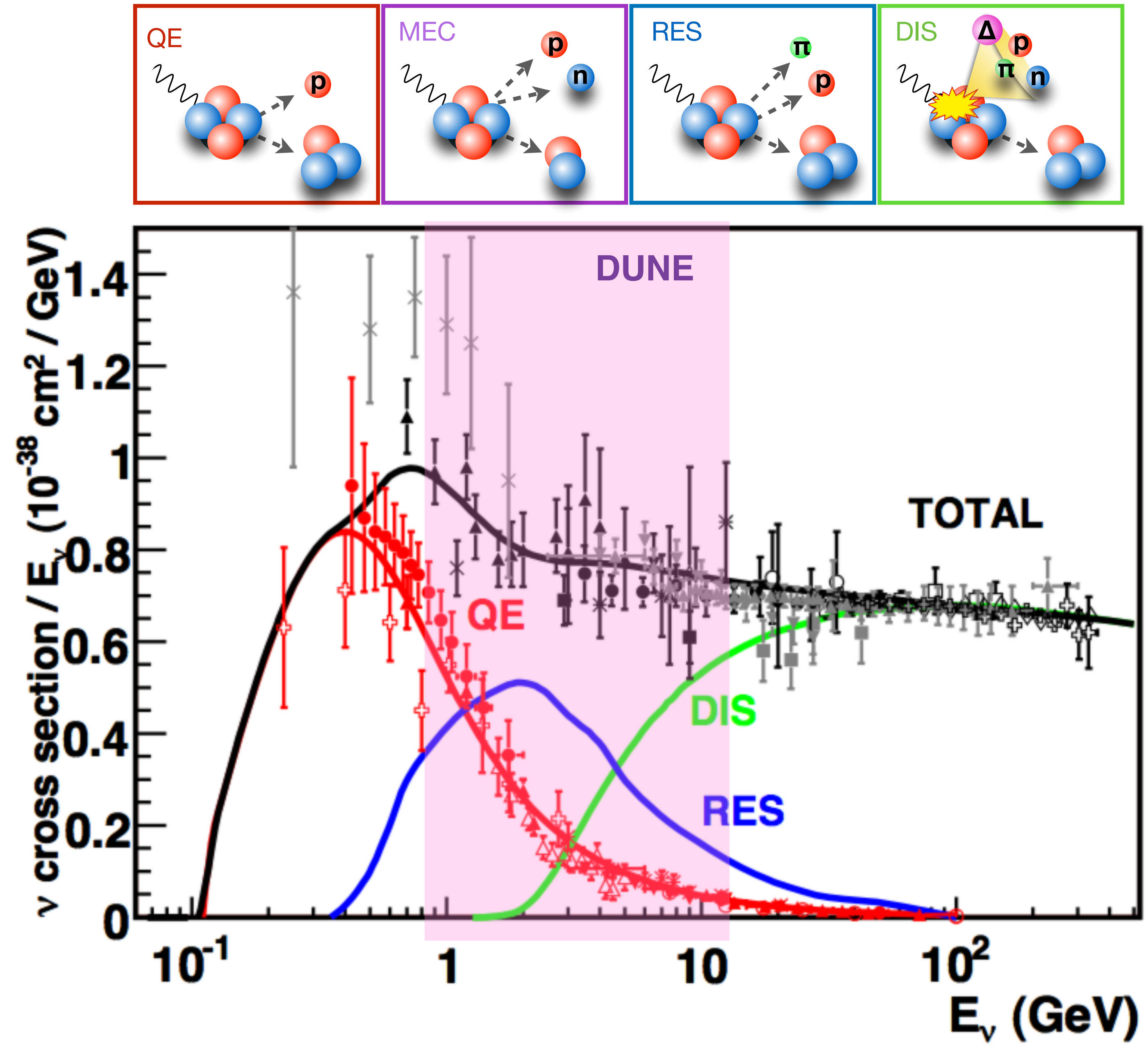
Unprecedented accuracy in the determination of **neutrino-argon cross section** is required to achieve design sensitivity to CP violation at DUNE

Nuclei are **complicated quantum many-body systems**;

More than 60% of the interactions at DUNE are non-quasielastic

Theoretical tools for neutrino scattering, Contribution to: 2022 Snowmass Summer Study

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



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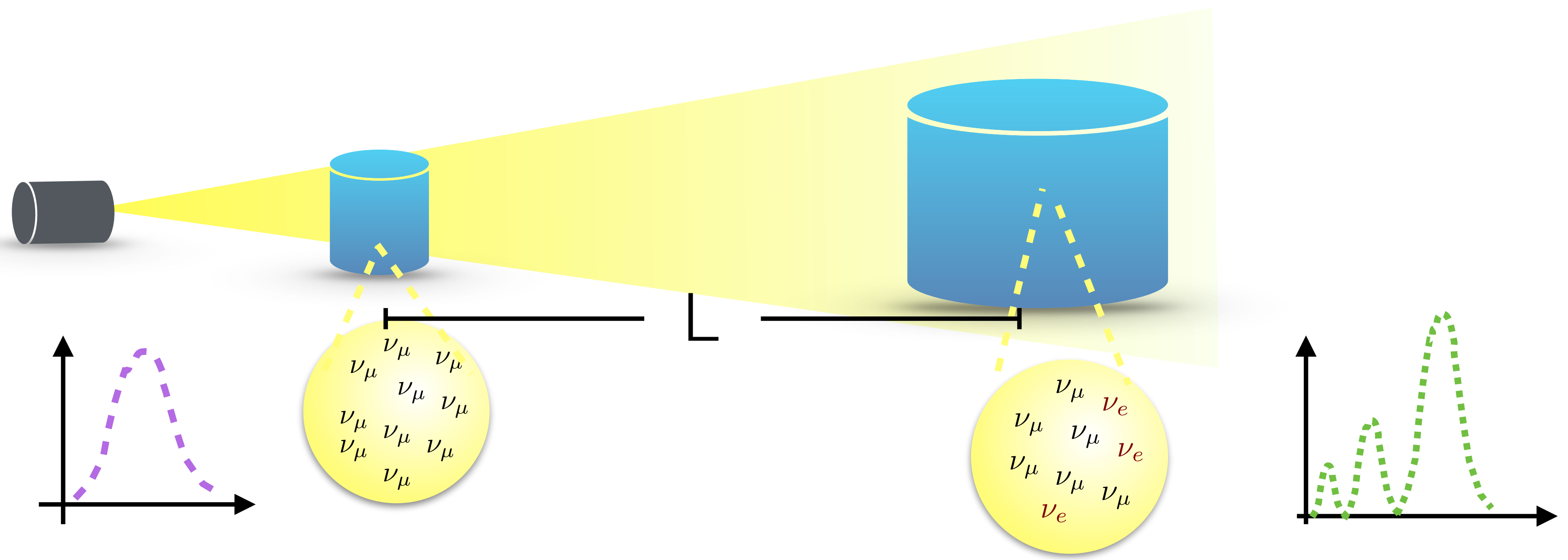
Why do we need more precision?

More on Chris Marshall's talk

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

Detectors measure the **neutrino interaction rate:**



A precise determination of σ(E) is crucial to extract ν oscillation parameters. Nuclear effects at near and far detector **do not** cancel

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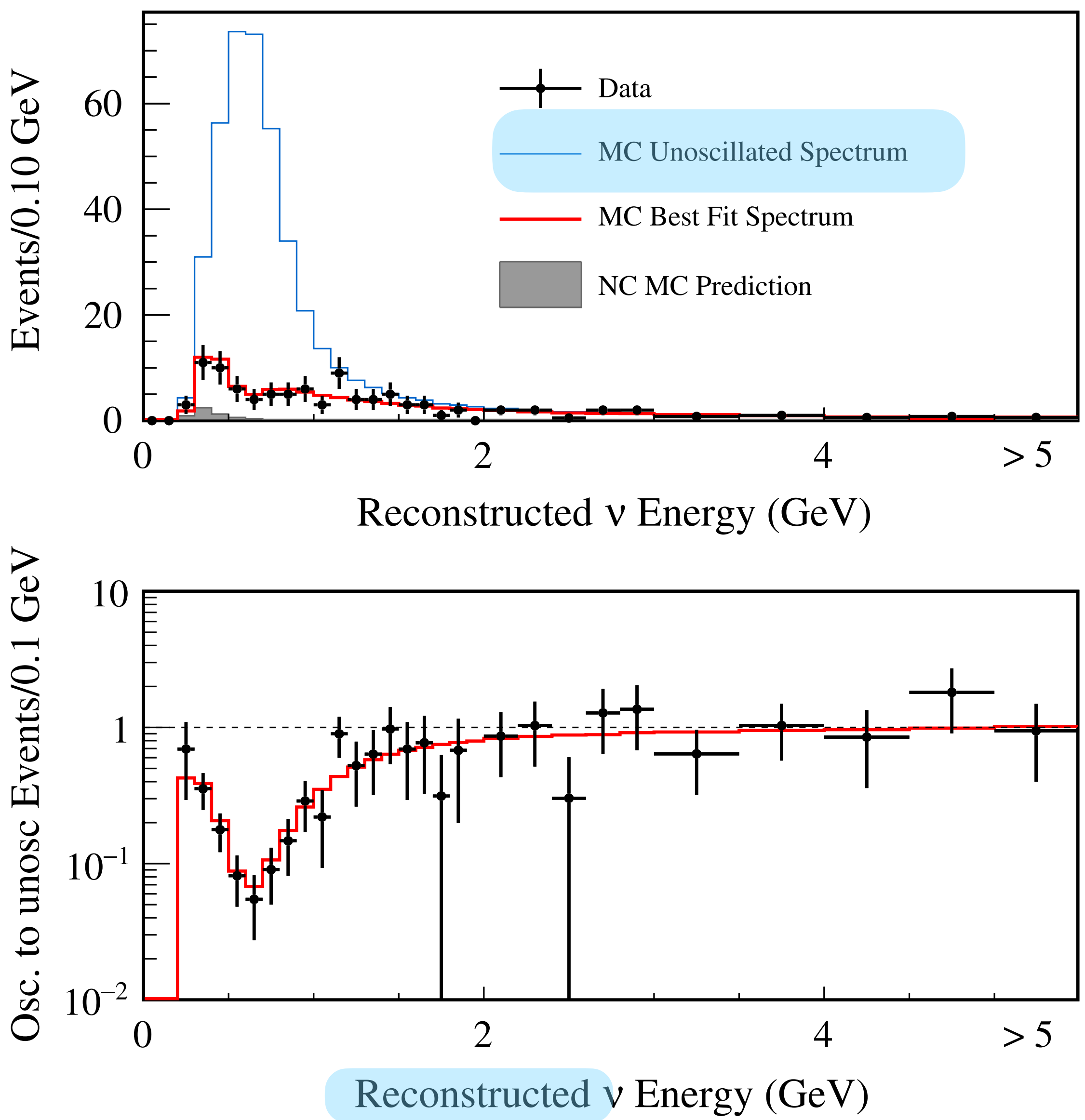
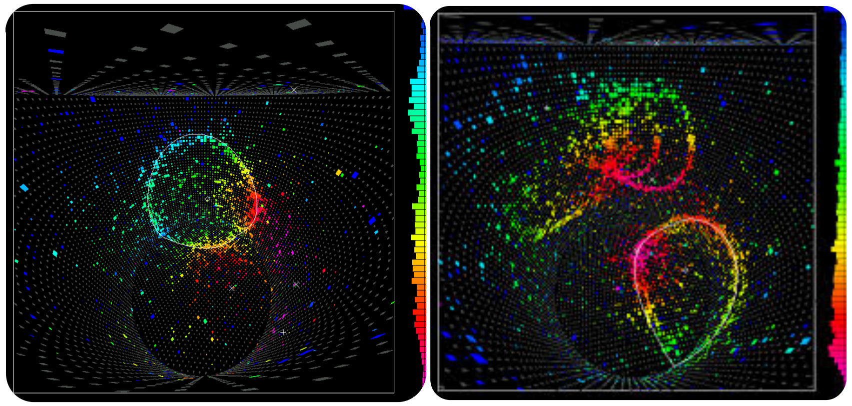
Oscillations Require E_ν reconstruction

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

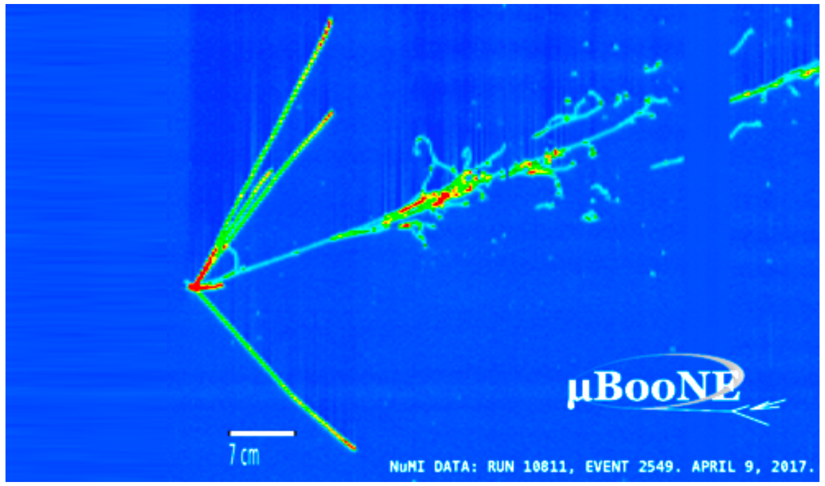


$$P(\nu_\mu \to \nu_x) \sim \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{true}}\right)$$

Cherenkov detector: kinematic reconstruction



Tracking detector: calorimetric reconstruction



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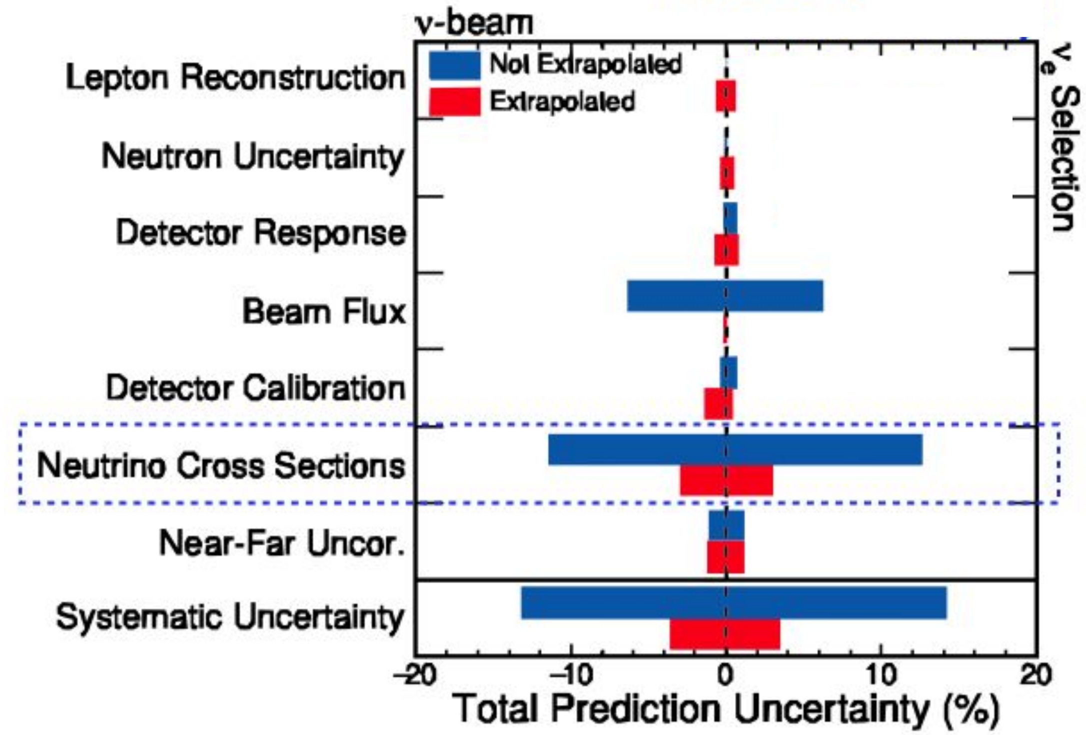
Neutrino-nucleus cross section systematics

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

Error source	ν_e FHC	$\bar{\nu}_e$ RHC	$\nu_e / \bar{\nu}_e$ FHC/RHC
Flux and (ND unconstrained)	15.1	12.2	1.2
cross section (ND constrained)	3.2	3.1	2.7
SK detector	2.8	3.8	1.5
SK FSI + SI + PN	3.0	2.3	1.6
Nucleon removal energy	7.1	3.7	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	2.6	1.5	3.0
NC1γ	1.1	2.6	1.5
NC other	0.2	0.3	0.2
$\sin^2\theta_{23}$ and Δm^2_{21}	0.5	0.3	2.0
$\sin^2\theta_{13}$ PDG2018	2.6	2.4	1.1
All systematics	8.8	7.1	6.0



T2K, Phys. Rev. D 103, 112008 (2021)

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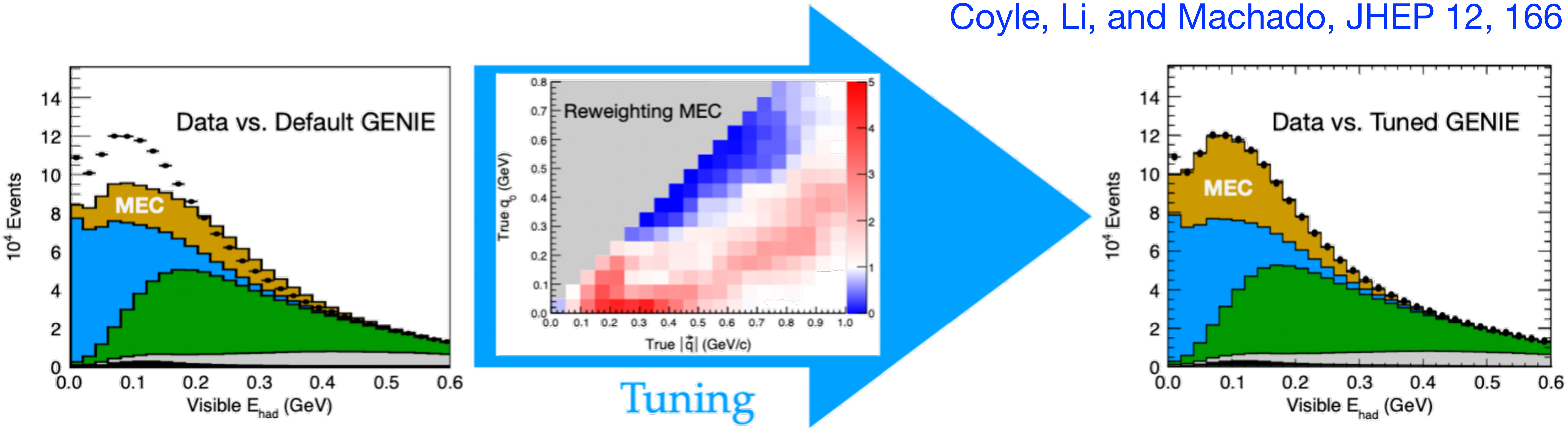
Tuning

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)



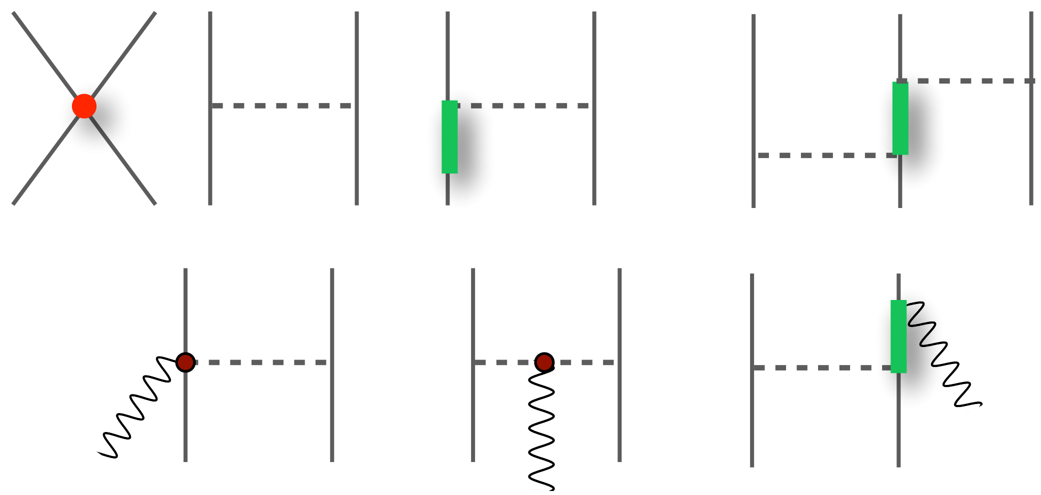
Mis-modeling can distort signals of new physics, **biasing** measurement of **new physics parameters**

Studies on the impact of different neutrino interactions and nuclear models on the determination 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

A more fundamental approach

Effective Hamiltonians and consistent currents

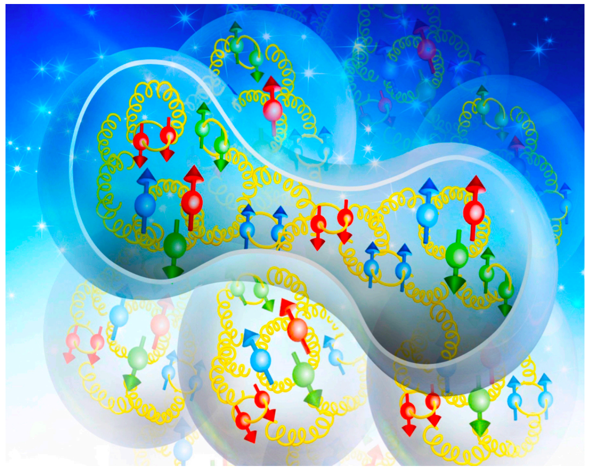


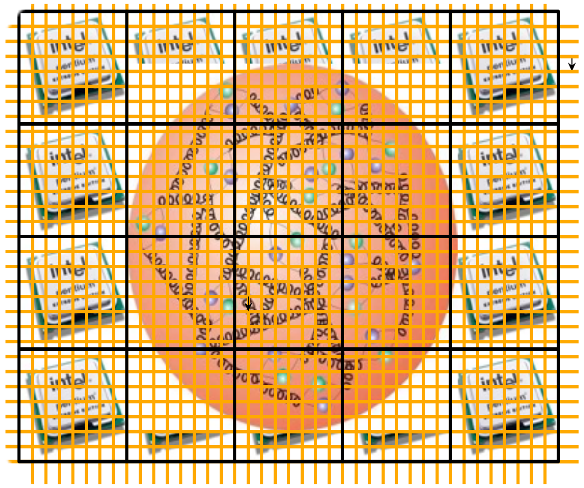
Accurate nuclear many-body methods

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

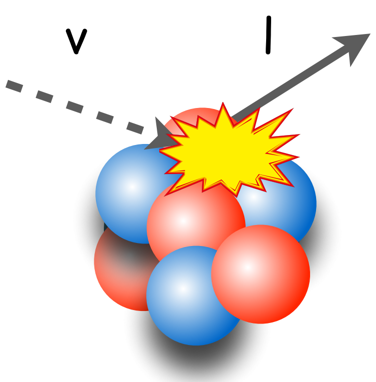
$$J_{mn} = \langle\Psi_m|J|\Psi_n\rangle$$

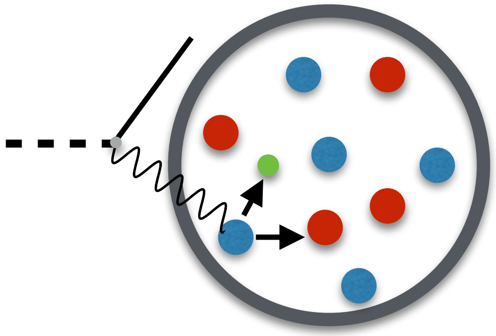
Quantum Chromodynamcs





Neutrino-nucleus interactions





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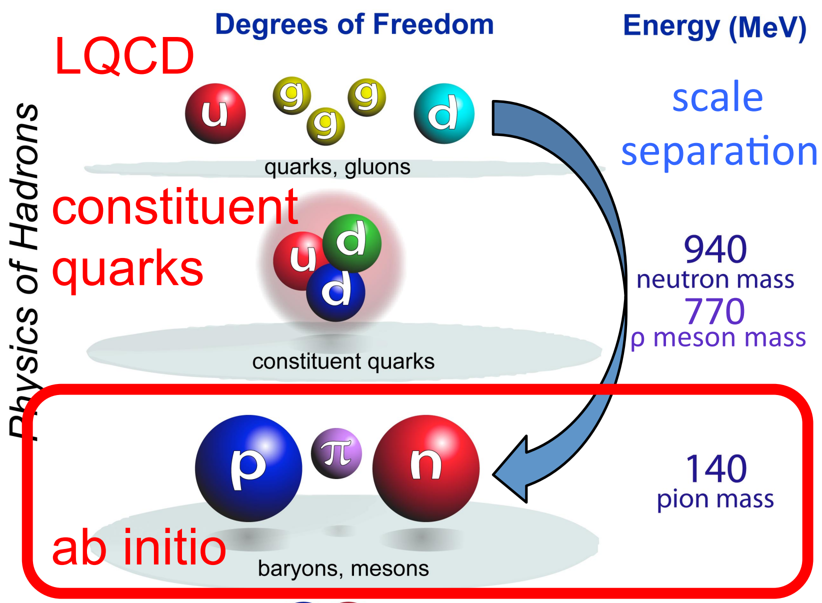
Chiral effective field theory



Wesolowski , et al, PRC 104, 064001 (2021)

T. Djärv, et al, PRC 105, 014005 (2022)

Formulate statistical models for UQ in EFT including Bayesian estimates of EFT truncation errors

Input that can be used in models for neutrino-nucleus interactions

Systematic construction of nuclear forces used to make predictions

Exploits the (approximate) broken chiral symmetry of QCD to construct interactions

Identify the soft and hard scale of the problem:

$$\mathcal{L}^{(n)} \sim \left(\frac{q}{\Lambda_b}\right)^n$$

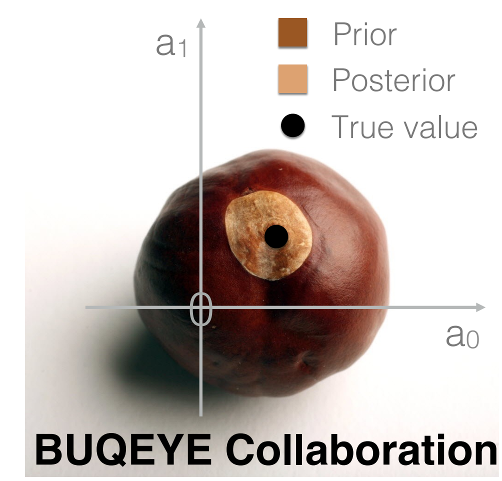
~ 100 MeV soft scale

~ 1 GeV hard scale

Design an organizational scheme to distinguish between more and less important terms

BAND Bayesian Analysis of Nuclear Dynamics

https://bandframework.github.io/



https://buqeye.github.io/

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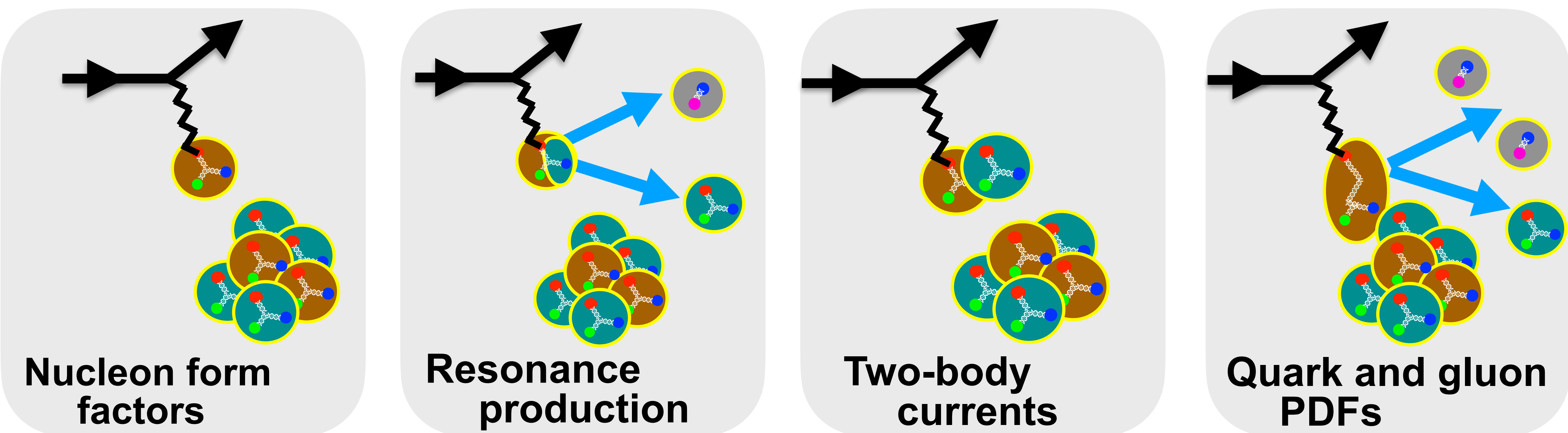
Input parameters and their precision

There is no EFT that coverages over all of DUNE kinematics

The first steps towards getting few-% cross-section uncertainties are understanding what input parameters we will need and what precision we will need them at.

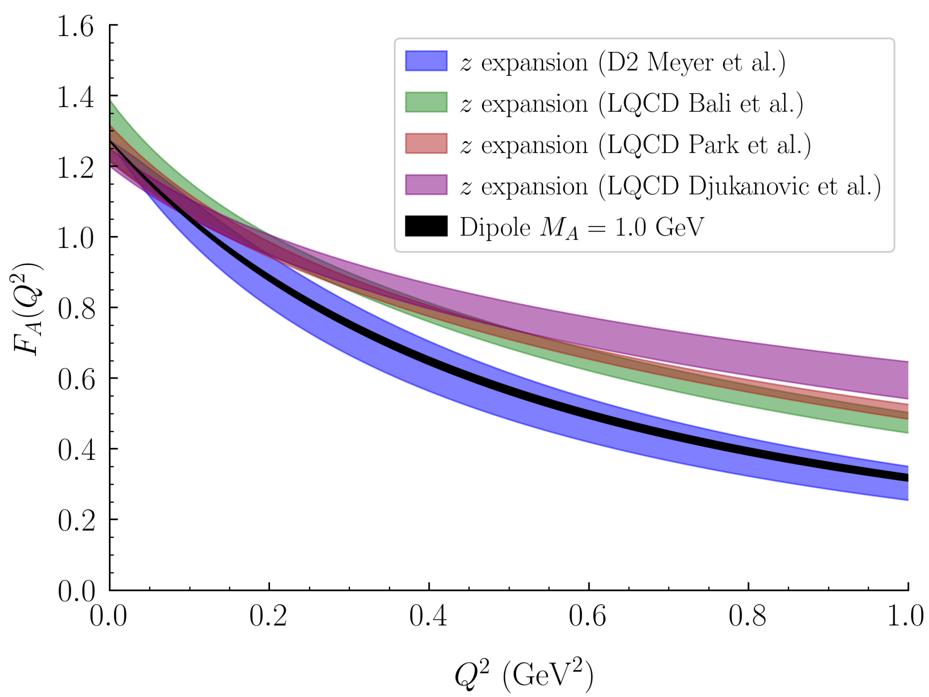
Lattice QCD can provide inputs to be included in EFTs and nuclear many-body methods



Courtesy of M. Wagman

Quantifying form factor uncertainties

D.Simons, N. Steinberg et al, arXiv:2210.02455



Different determinations of nucleon axial form factor using the z-expansion

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

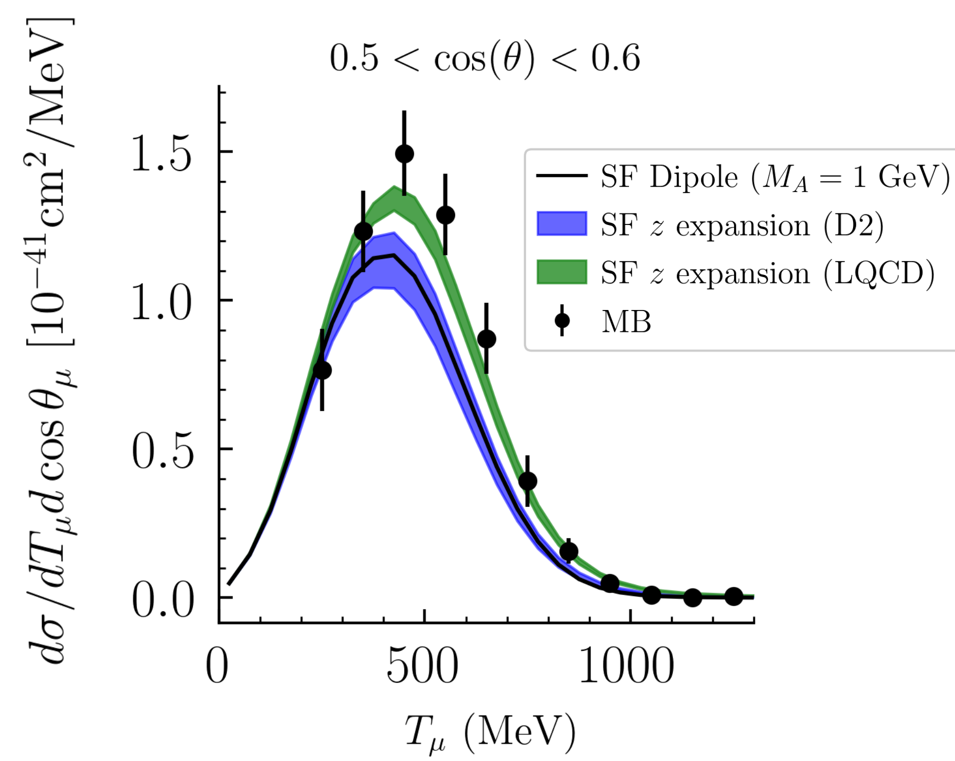
UQ independent on assumptions about the shape of the axial form factor.

LQCD results are 2-3σ larger than D2 Meyer ones for $Q^2 > 0.3$ GeV^2

Use different axial form factors leads to ~ 20% difference in the cross section at the peak

Studies able to determine the target precision for the input parameters are critical

MiniBooNE



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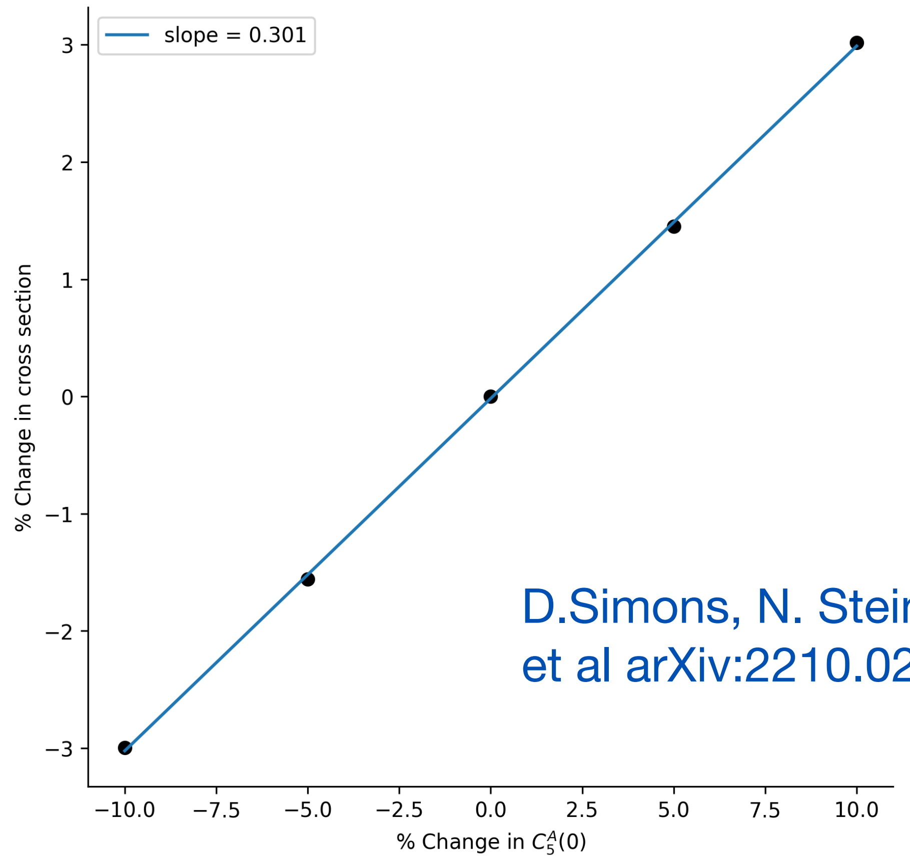
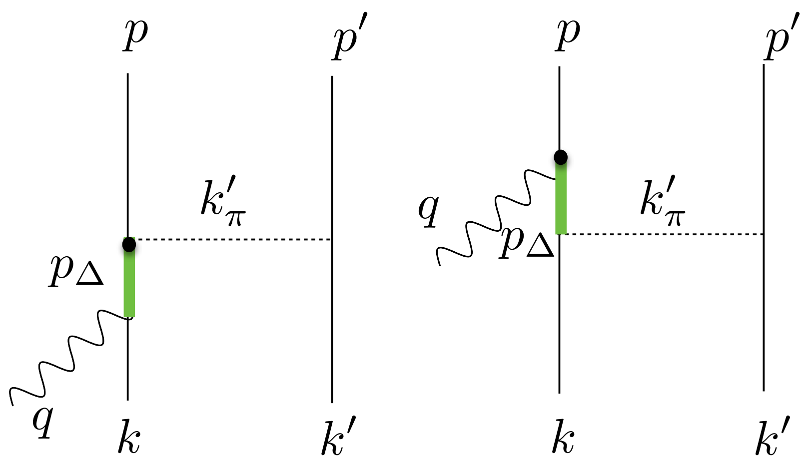
Resonance Uncertainty needs

The largest contributions to two-body currents arise from resonant $N \rightarrow \Delta$ transitions yielding pion production





D.Simons, N. Steinberg et al arXiv:2210.02455

The normalization of the dominant $N \rightarrow \Delta$ transition form factor needs be known to 3% precision to achieve 1% cross-section precision for MiniBooNE kinematics

State-of-the-art determinations of this form factor from experimental data on pion electroproduction achieve 10-15% precision (under some assumptions)

Hernandez et al, PRD 81 (2010)

Further constraints on $N \rightarrow \Delta$ transition relevant for two-body currents and π production will be necessary to achieve few-percent cross-section precision

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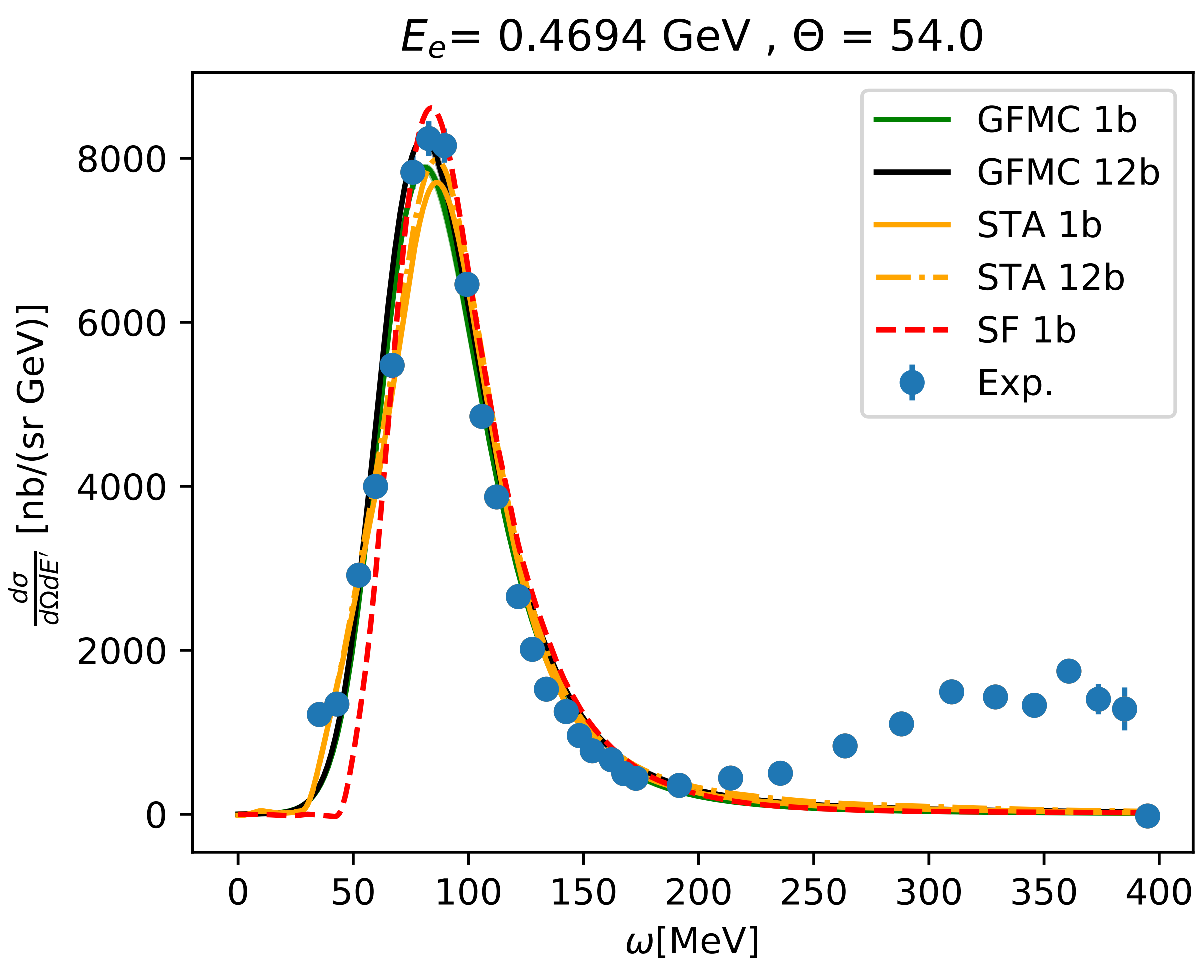
Model selection

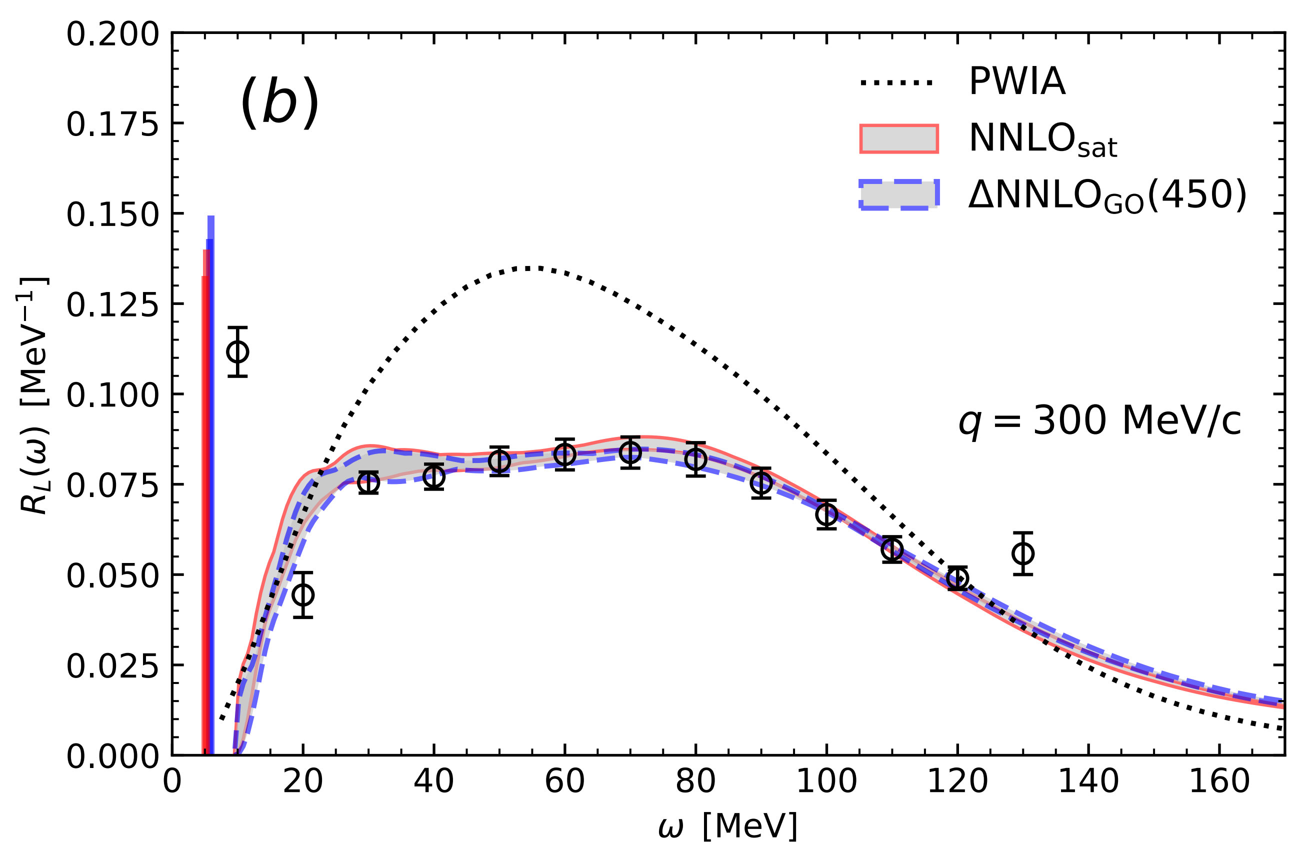


Andreoli et al, Phys.Rev.C 105 (2022) 1, 014002

Comparing different nuclear many-body methods is necessary to assess the uncertainty associated with factorization schemes, non-relativistic kinematics

Different Chiral EFT interactions can be used as input of the nuclear calculation

Sobczyk et al, Phys.Rev.Lett. 127 (2021) 7, 072501



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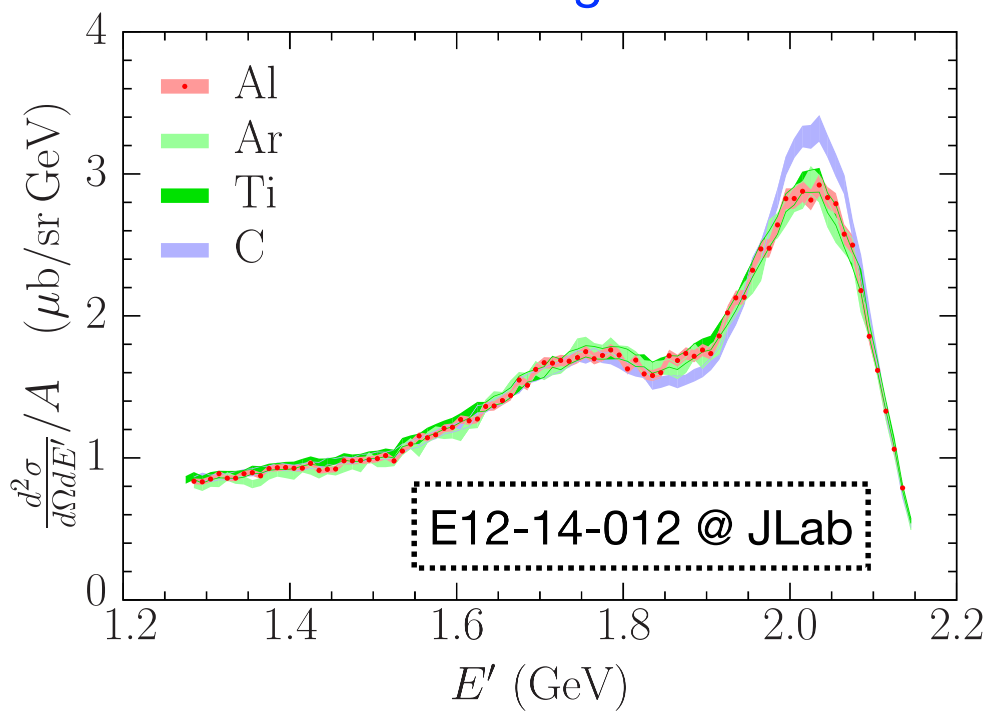
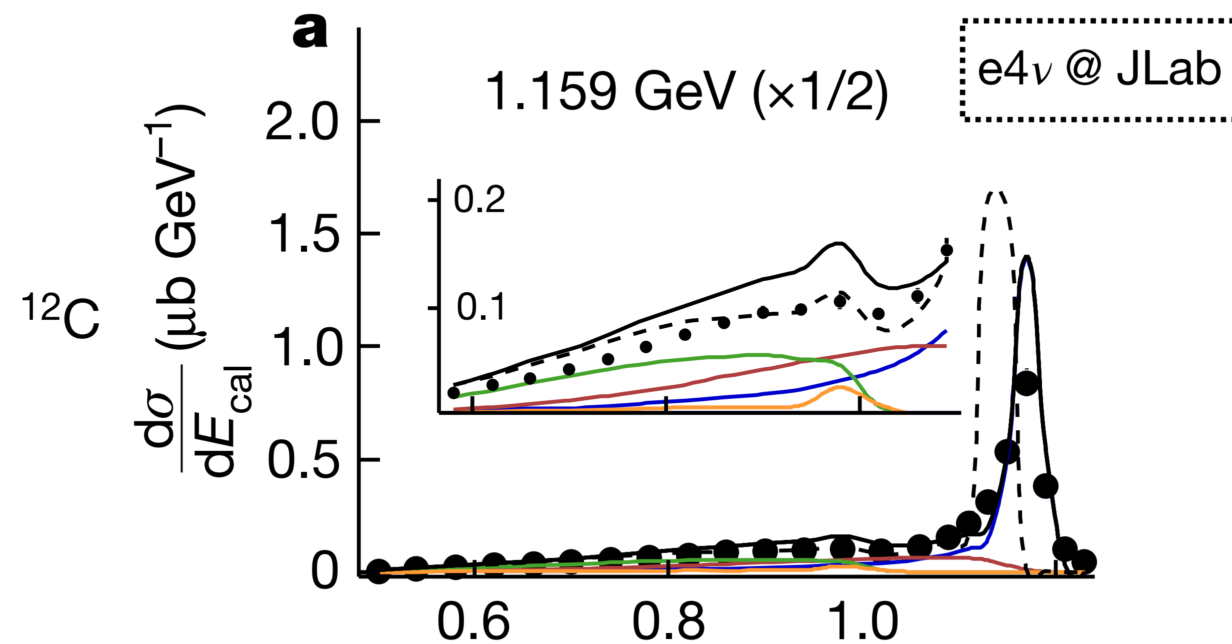
Testing our models

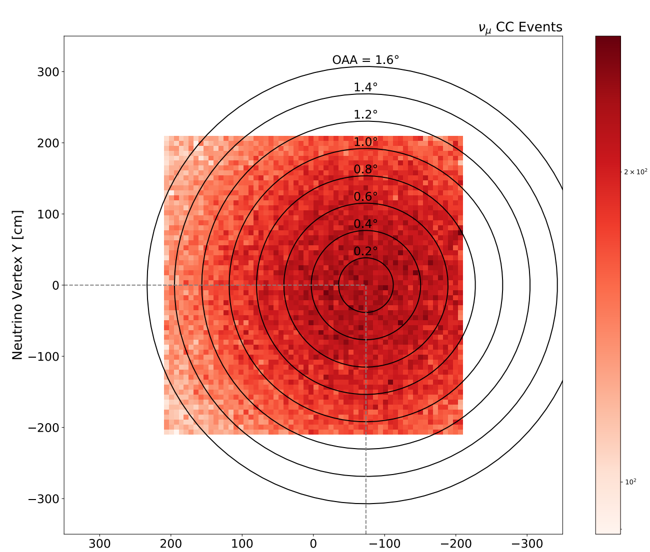
Semi-exclusive electron scattering data provide input and allow to test the accuracy of interaction models and event generators used in oscillation analyses

Electron Scattering and Neutrino Physics, 2022 Snowmass Summer Study





SBND-PRISM



The SBN program will provide an order of magnitude more data of neutrino-Argon interactions than is currently available (test exclusive predictions)

Leverage the PRISM features of SBND to isolate the contribution of different reaction mechanisms and constrain systematic uncertainties

More on Ornella Palamara’s talk

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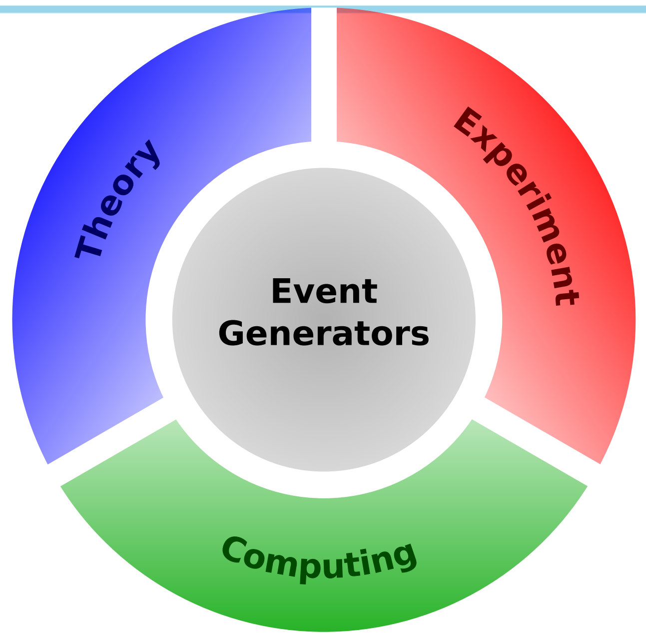
Event Generation and Simulation

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

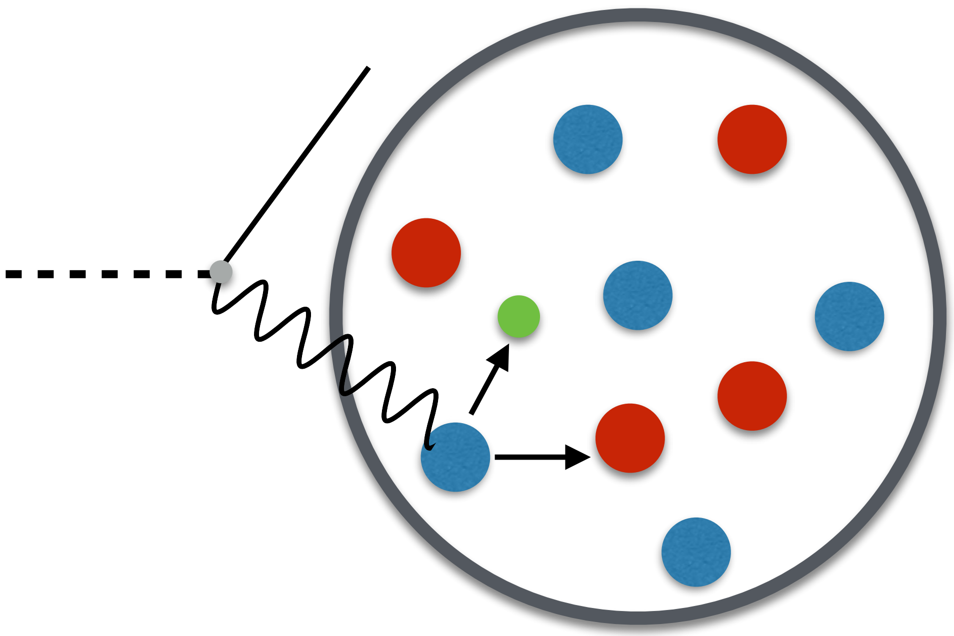


Event generators typically involve a number of unknown model parameters that must be tuned to experimental data, while maintaining the integrity of the underlying physics models.

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

Next-generation **uncertainty quantification** will permit a **better understanding** of how to **tune** models to experiment.

- Developing and maintaining event generators requires **tight collaboration between theory, experiment, and computing science**



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Event Generation and Simulation

Different Monte Carlo event generators

ACHILLES is a **novel effort** carried out at Fermilab

Event generators are used to predict **signal**, **backgrounds** and **efficiency**

The theoretical error from the interaction vertex needs to be consistently propagated / combined through the intra-nuclear cascade

Reweighting procedures only allow one to propagate a subset of model uncertainties.

Simulate the entire process using different inputs requires **highly optimized codes** and **high performance computing**

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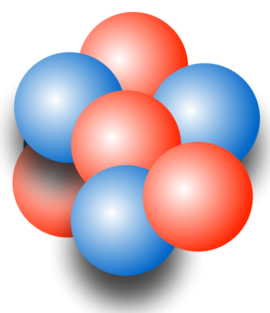
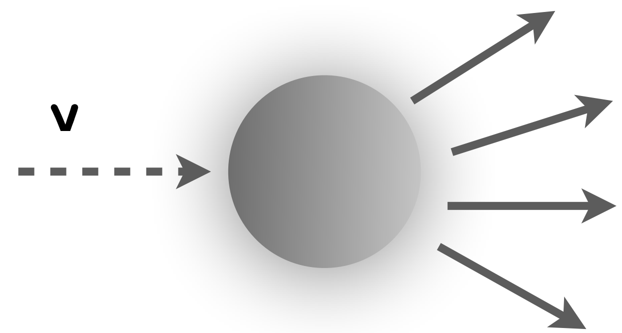
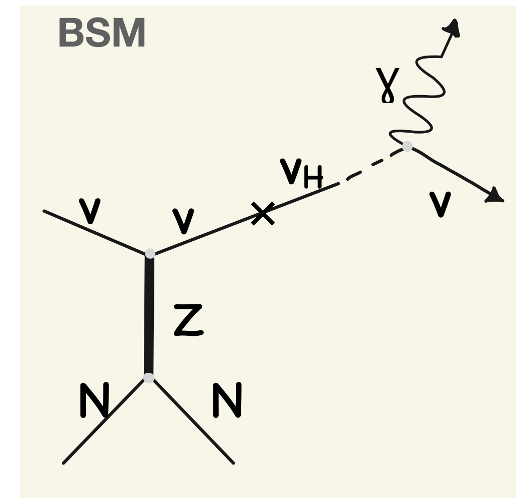
Summary

Support for efforts aimed at strengthening the US neutrino community and its impact on the US neutrino experimental program

Nuclear Physics:

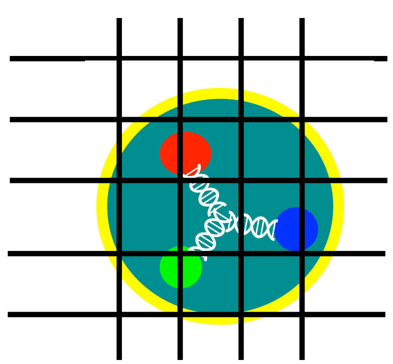




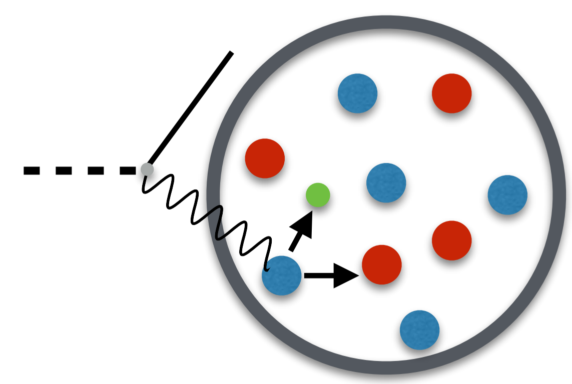


Simulate neutrino-nucleus cross sections to untangle neutrino oscillations from the measured interactions

Lattice QCD :



Event Generator :



Neutrino Theory Network

initiative of the DOE supporting the neutrino theory community