

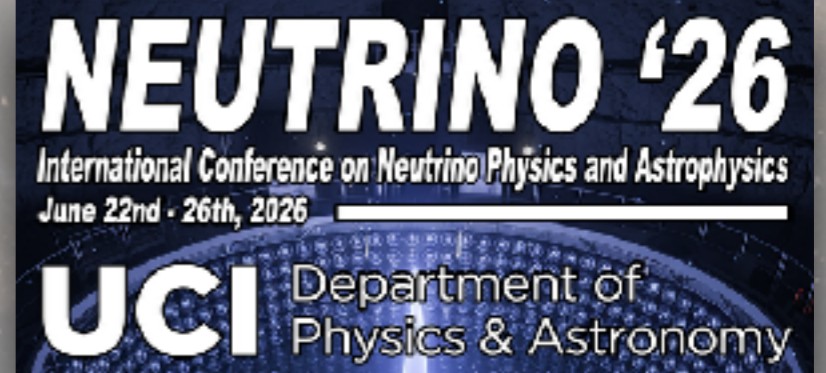
Theory of neutrino-nucleus cross sections

Joanna Sobczyk

24 June 2026

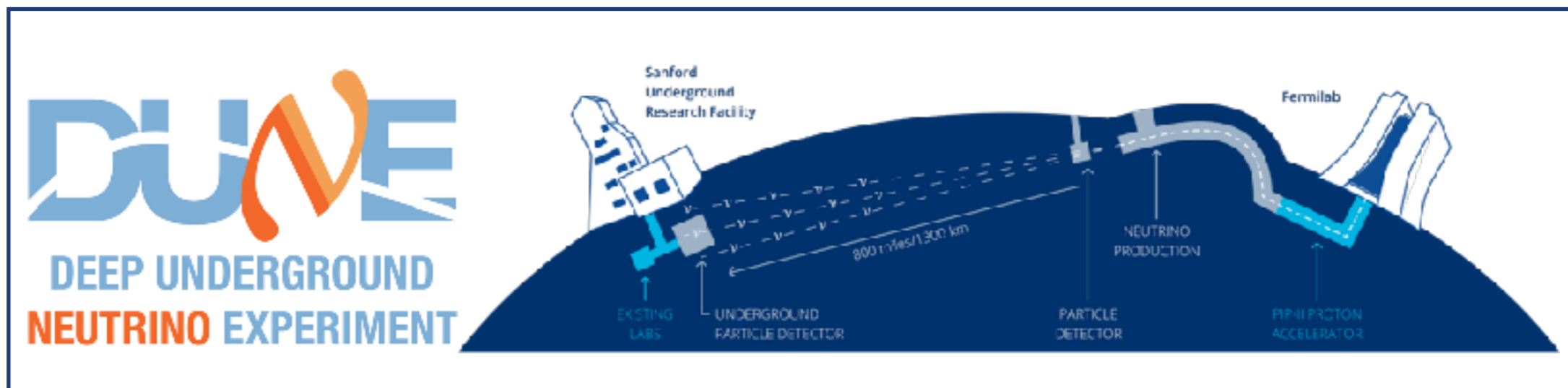
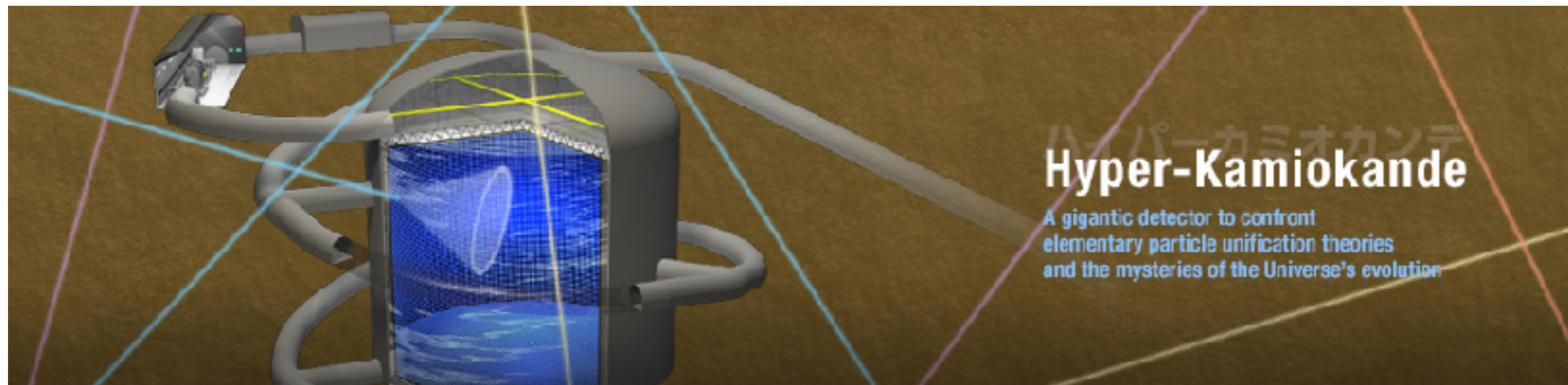


CHALMERS
UNIVERSITY OF TECHNOLOGY



Next generation experiments

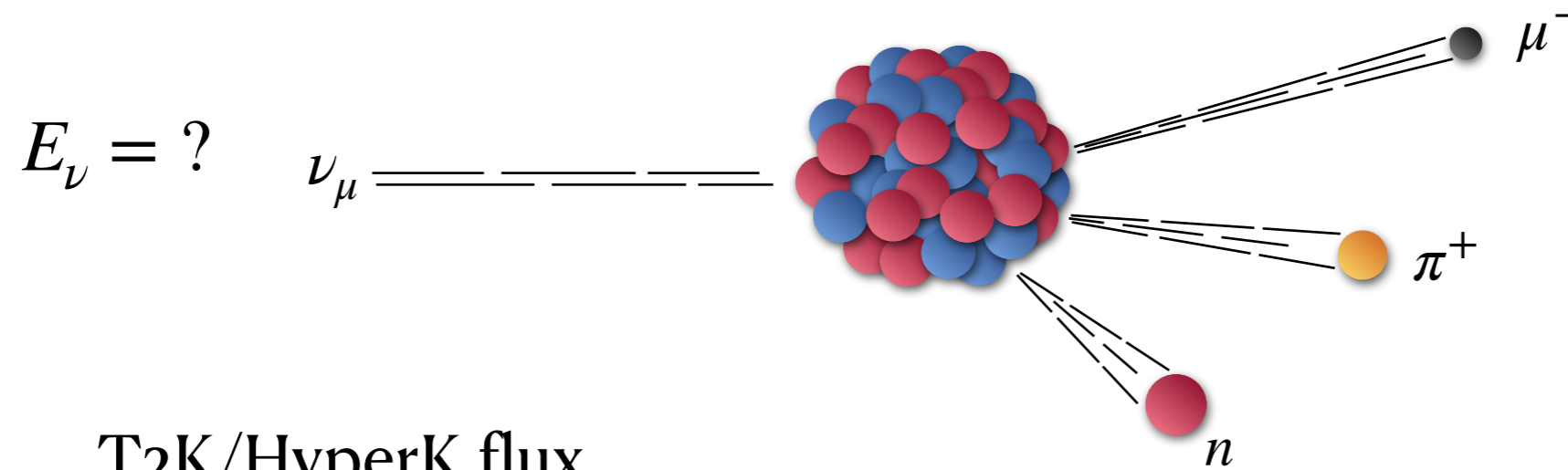
Long-baseline oscillation experiments



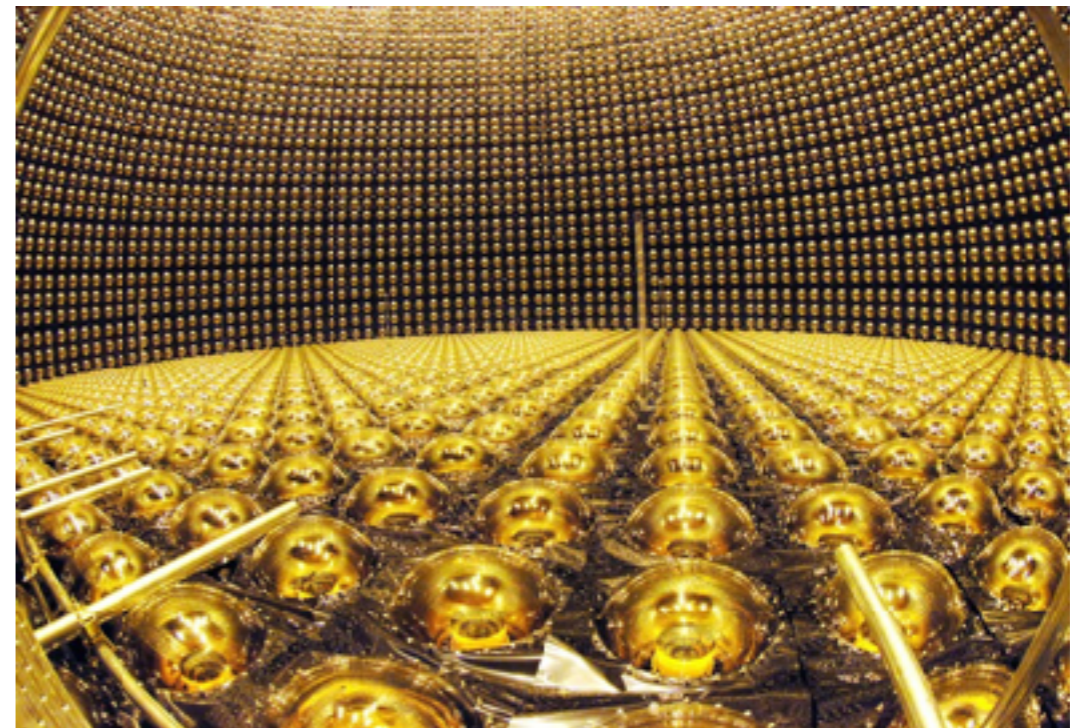
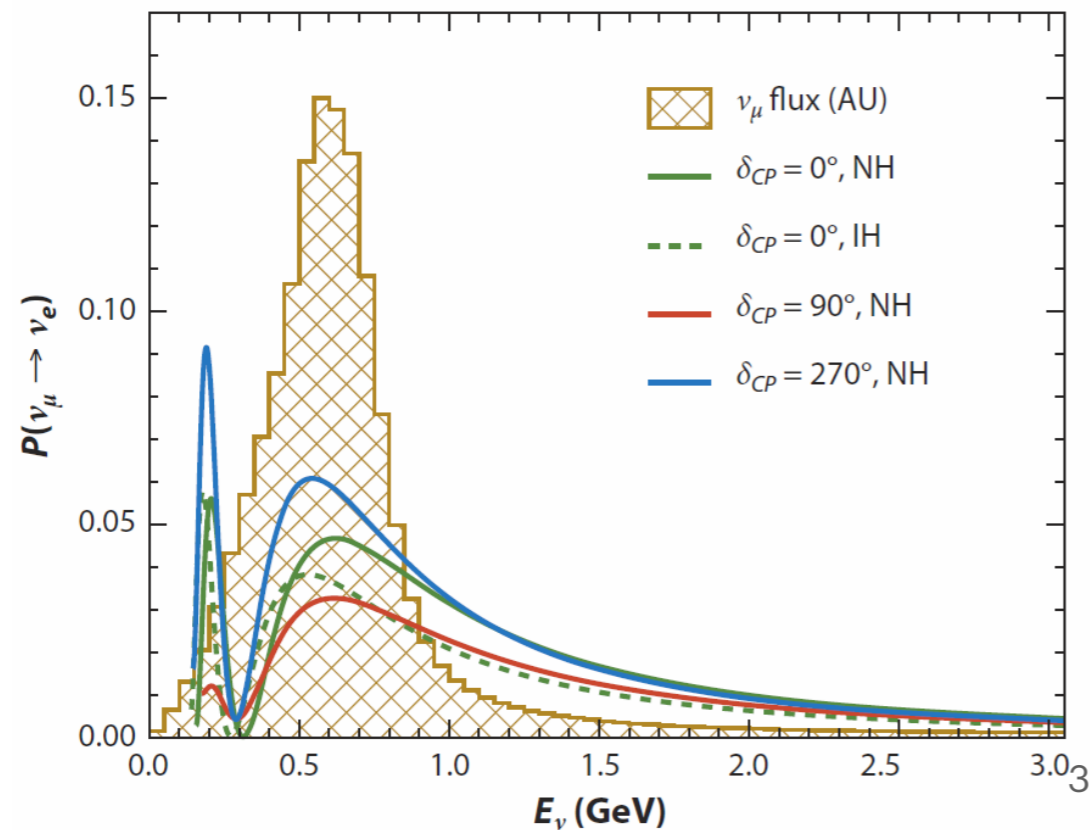
- ✓ CP-violation measurement
- ✓ Determining ν mass ordering
- ✓ *BSM searches*

- ✓ Proton decay searches
- ✓ Cosmic neutrino observation

Motivation: long-baseline oscillation experiment

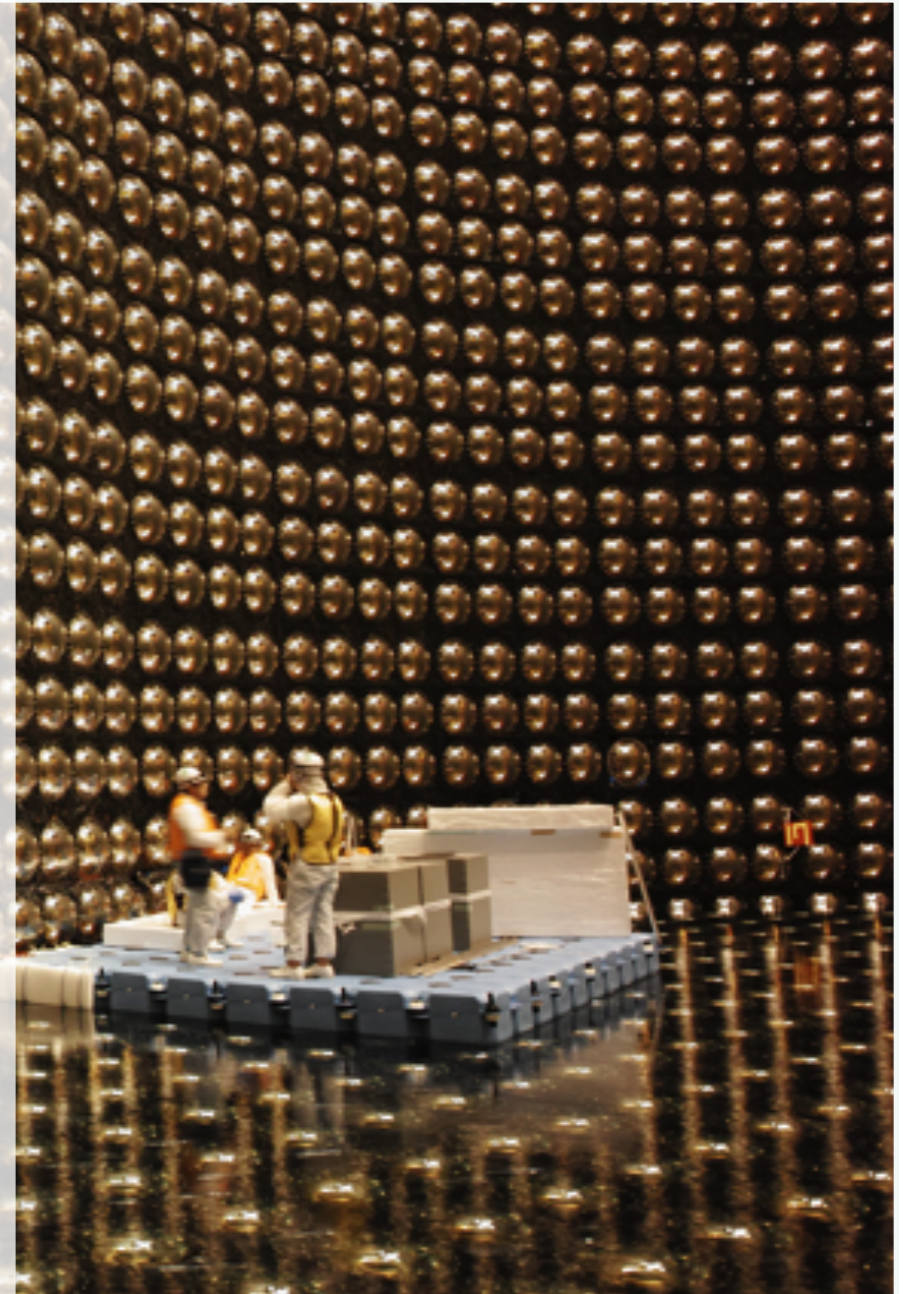


T2K/HyperK flux

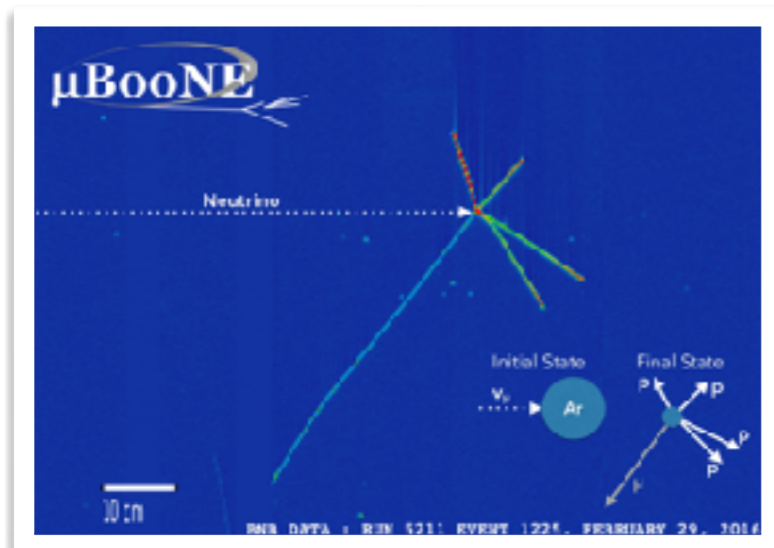


Why theory neutrino-nucleus scattering?

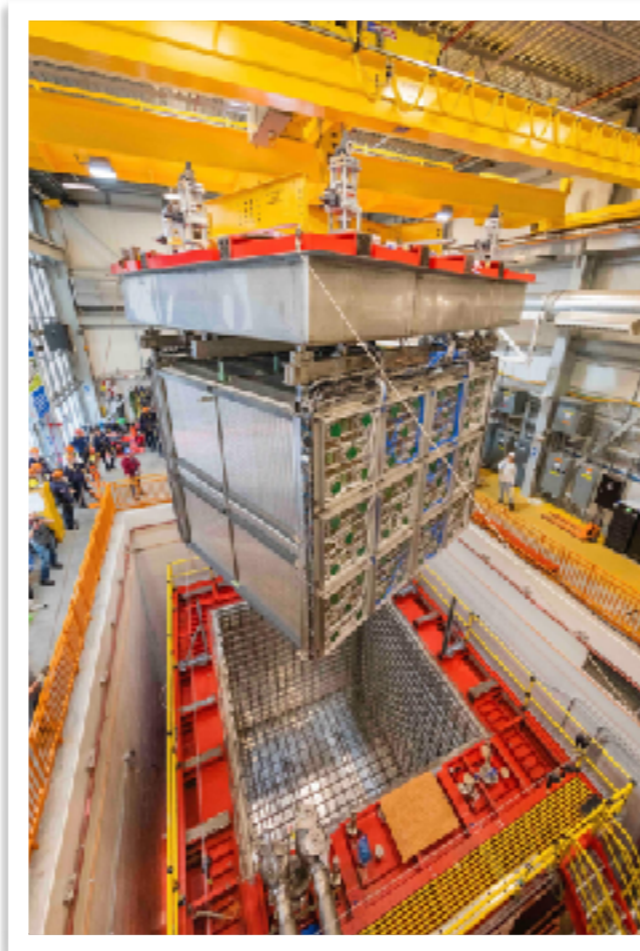
- ✓ One of the dominant **systematic uncertainty** at LBL programs
- ✓ Mismodeling nuclear effects can **bias** oscillation analysis
- ✓ Understand Standard Model effects (nuclear effects) to assess sensitivity to **BSM** signals
- ✓ Unique probe to learn about **nuclear structure**



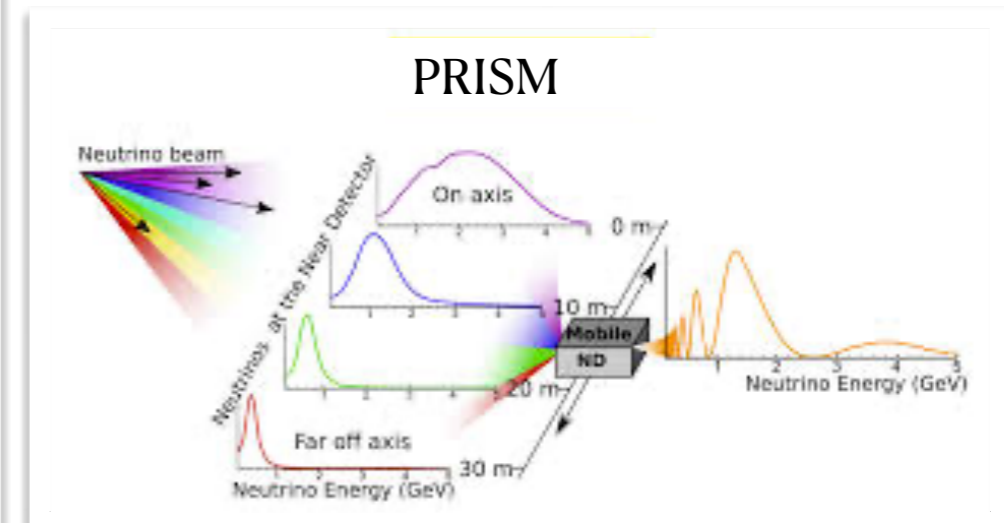
New possibilities to test theory



New detector technologies: excellent particle detection

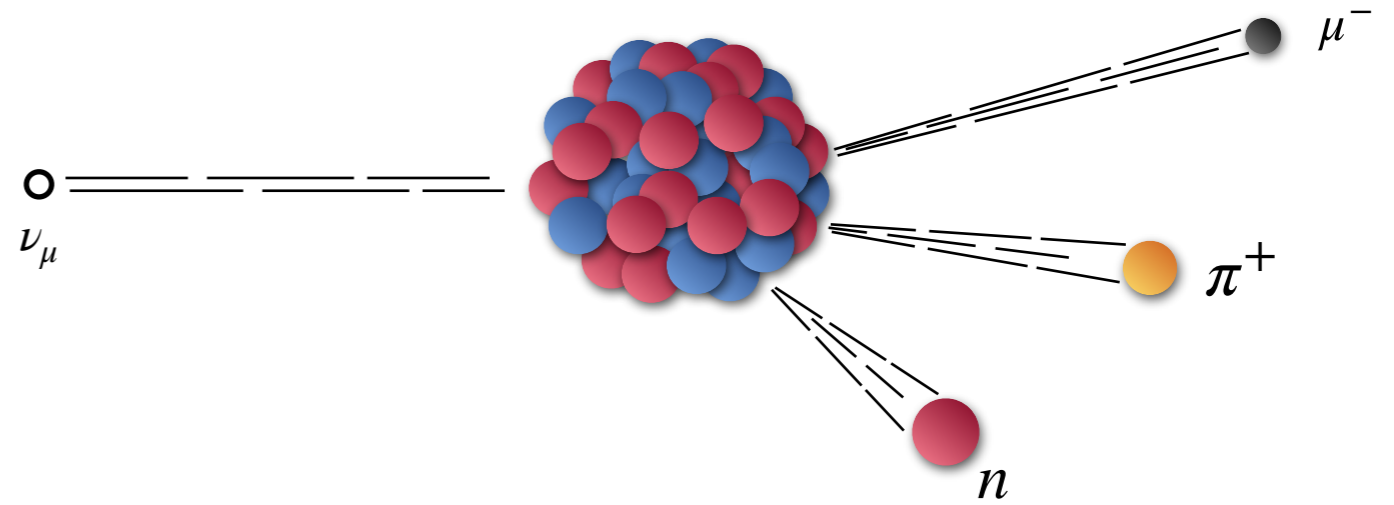
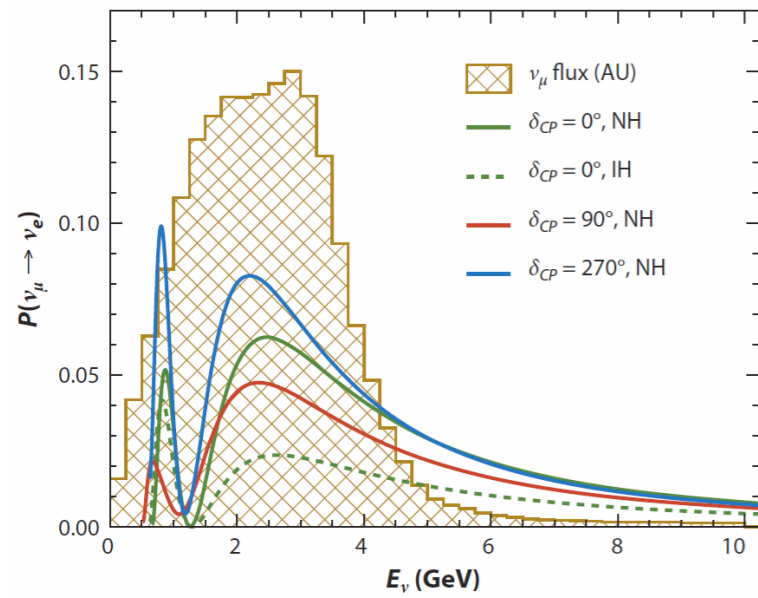


SBND experiment: Millions neutrino- ^{40}Ar interactions per year

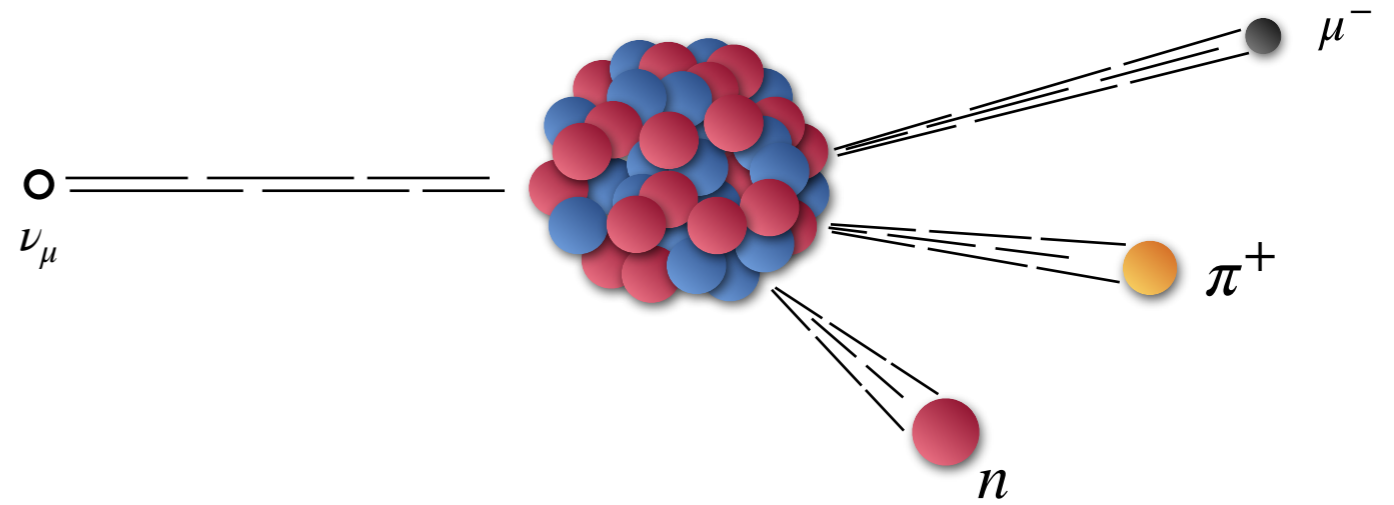
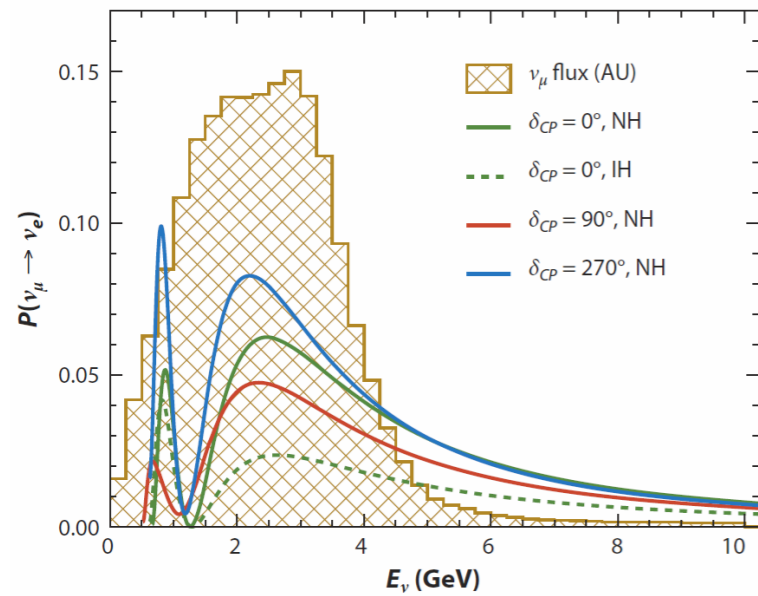


PRISM: off-axis near detectors

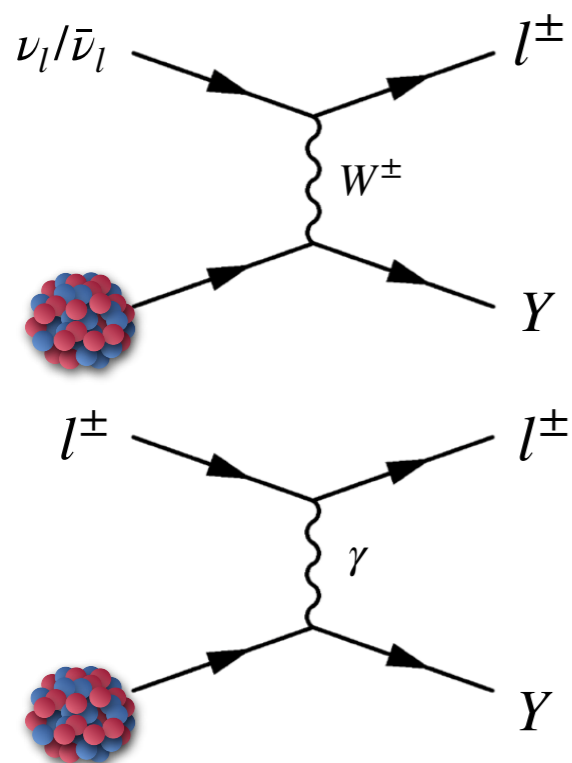
ν scattering



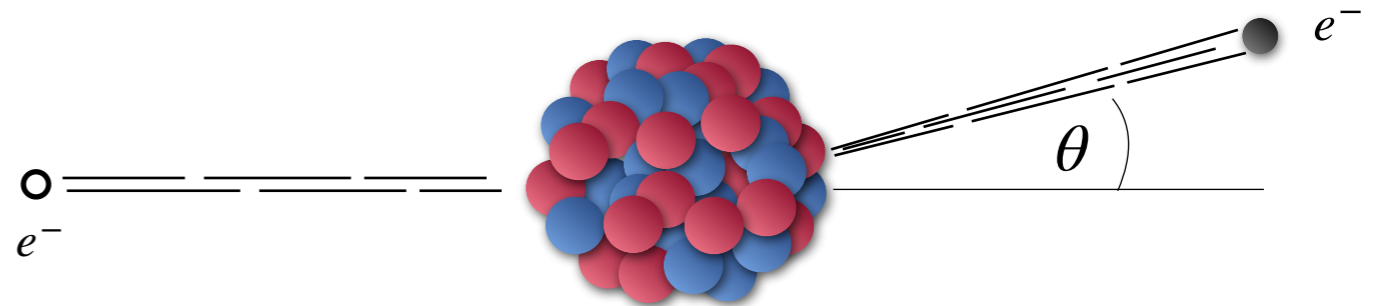
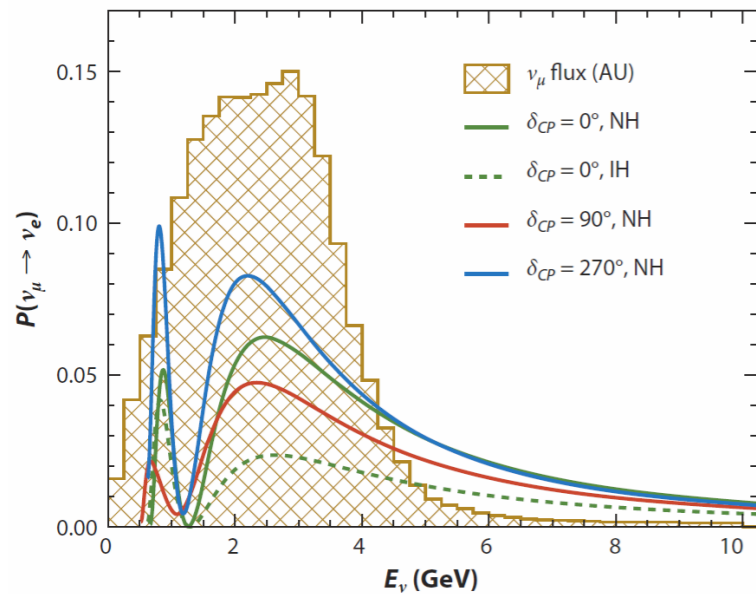
ν scattering



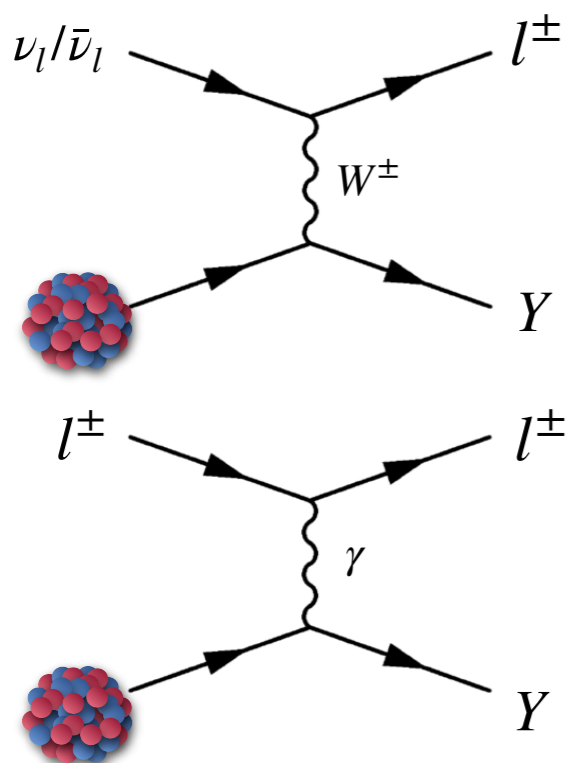
ANALOGY between **electron** and **neutrino** scattering



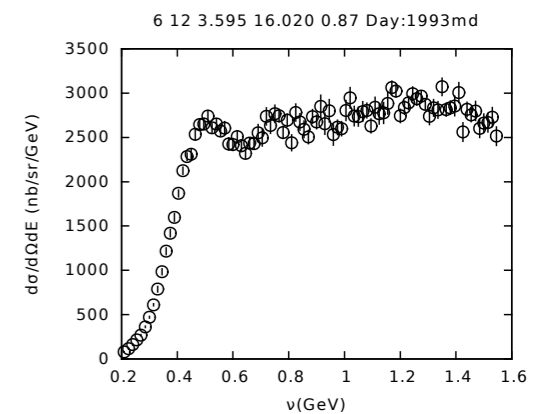
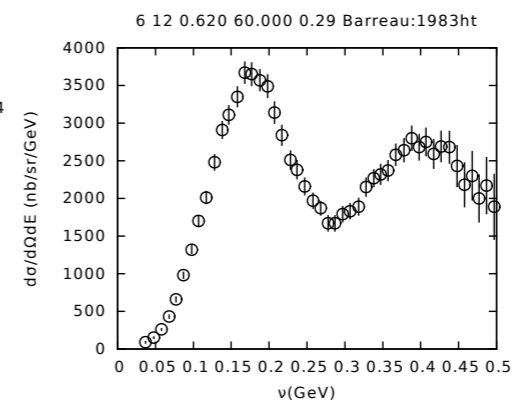
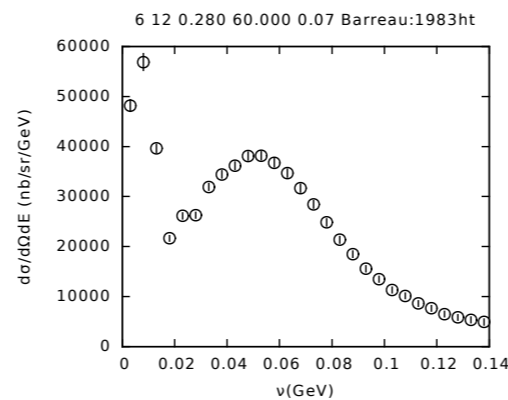
ν scattering



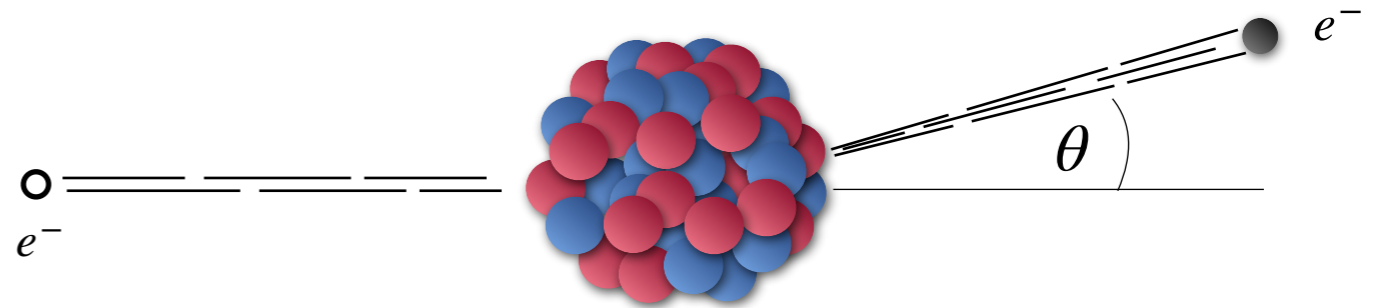
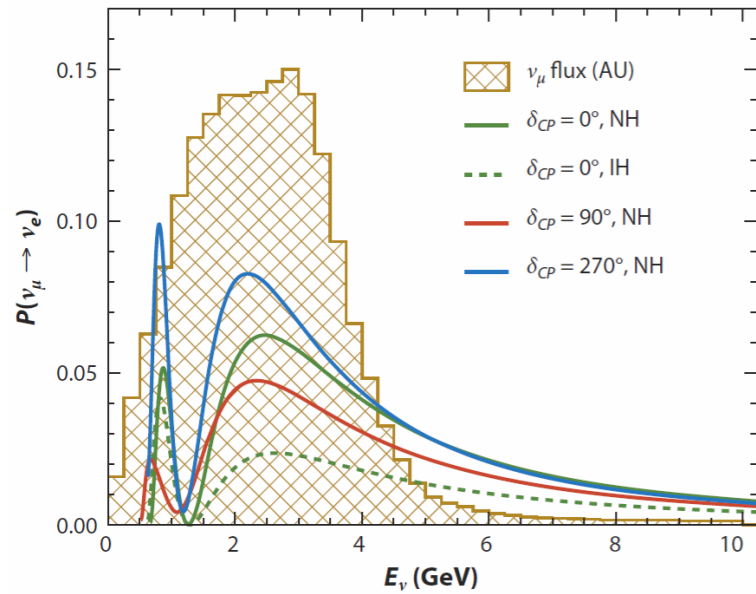
ANALOGY between **electron** and **neutrino** scattering



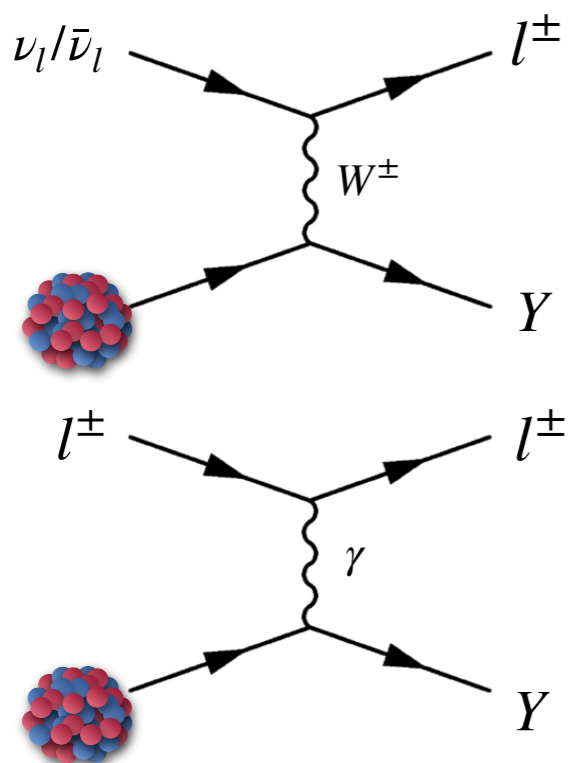
$$\frac{d^2\sigma}{d\Omega_e d\omega}$$



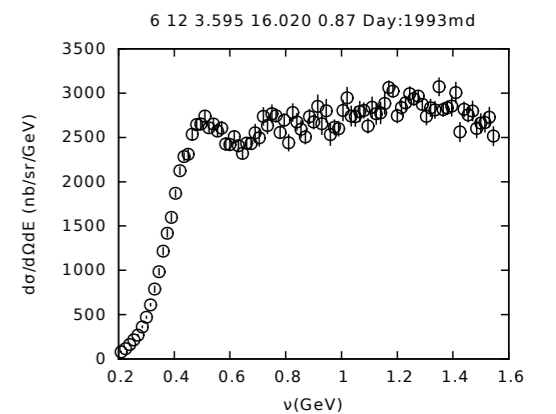
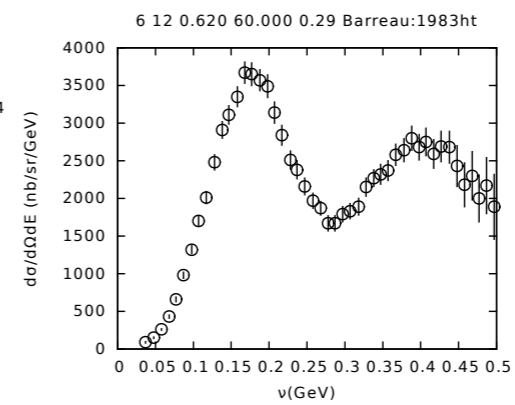
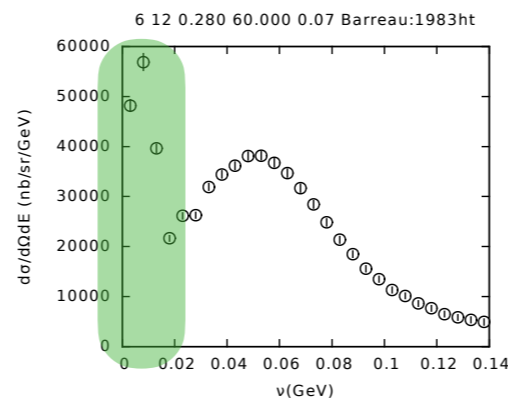
ν scattering



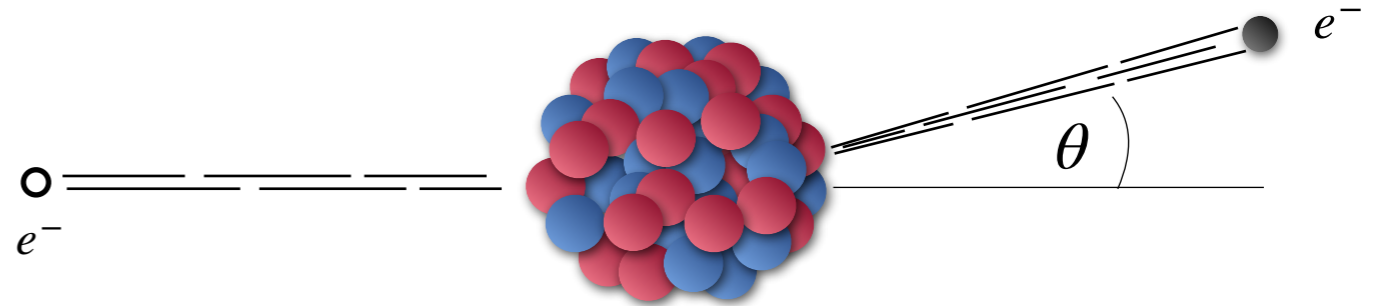
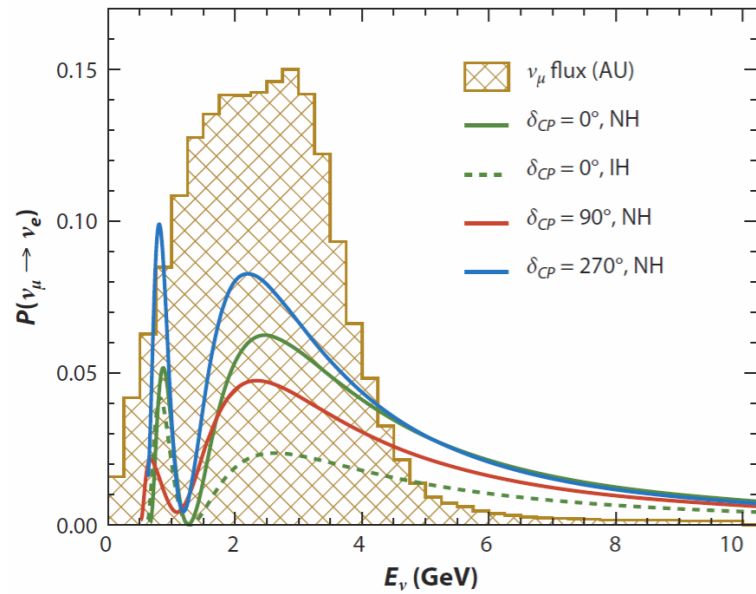
ANALOGY between **electron** and **neutrino** scattering



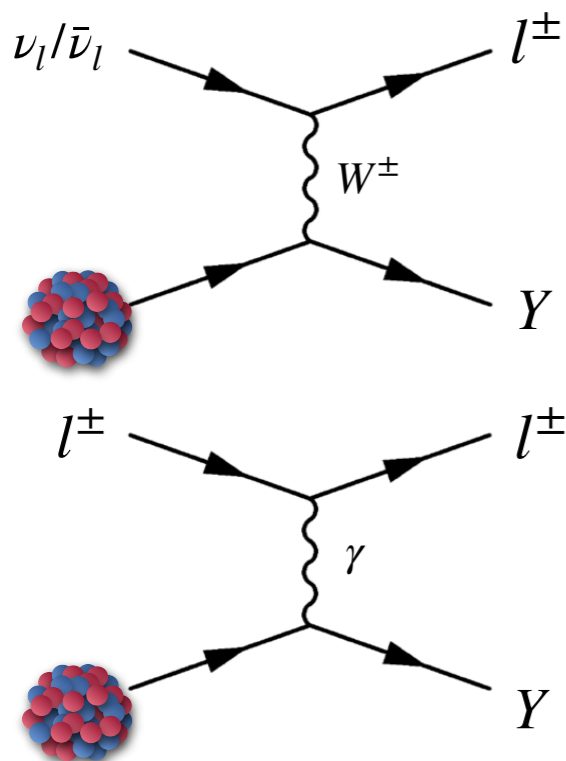
$$\frac{d^2\sigma}{d\Omega_e d\omega}$$



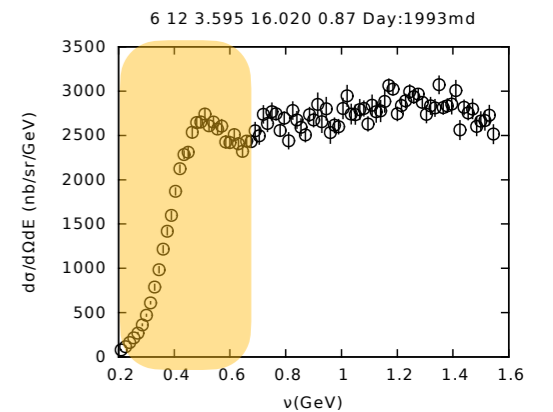
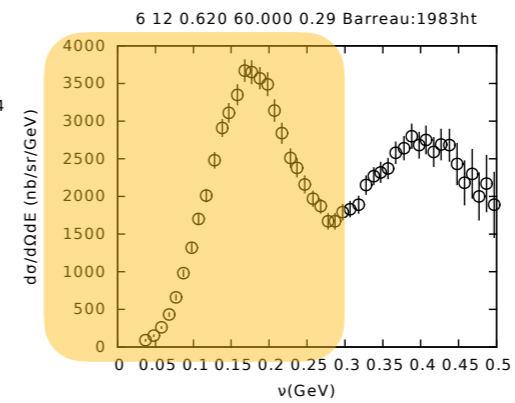
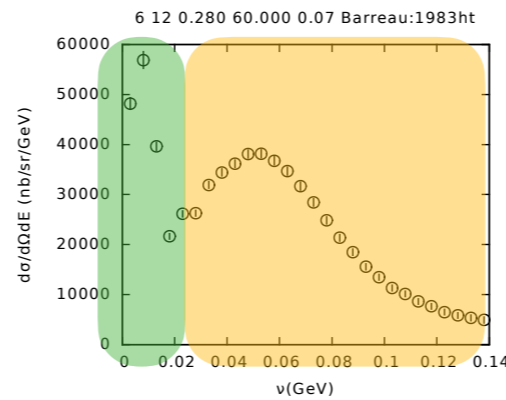
ν scattering



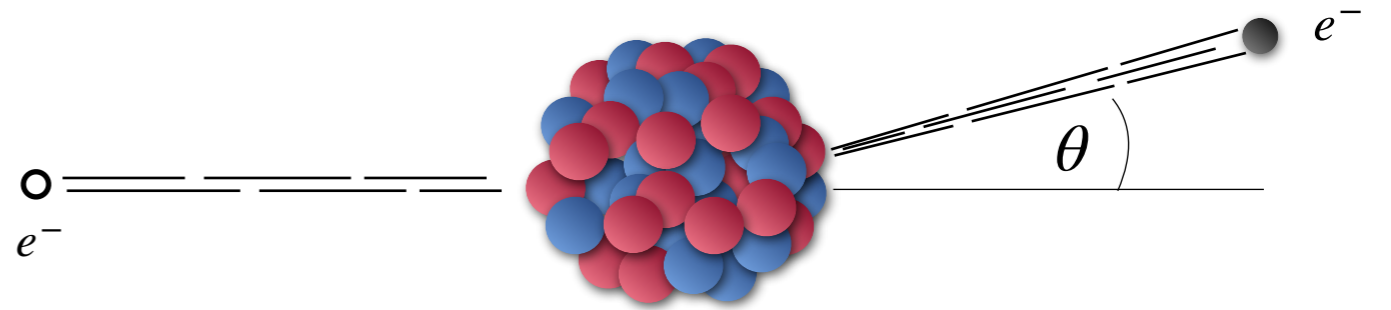
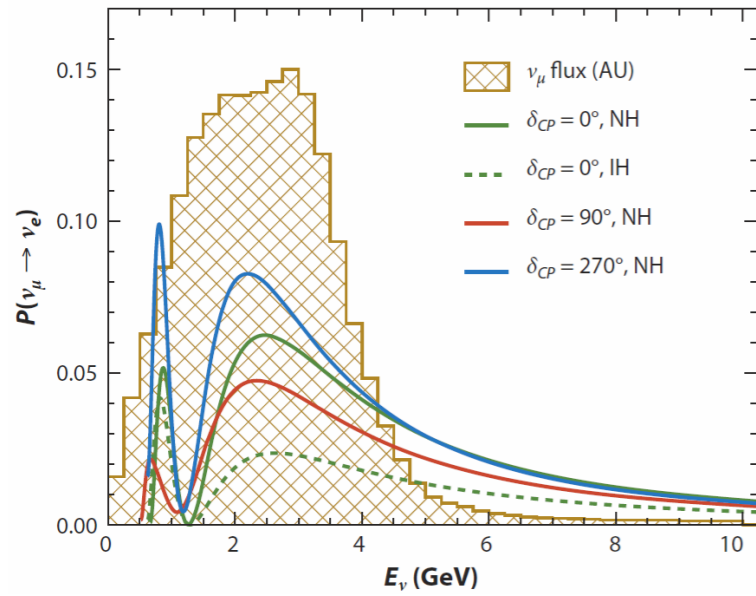
ANALOGY between **electron** and **neutrino** scattering



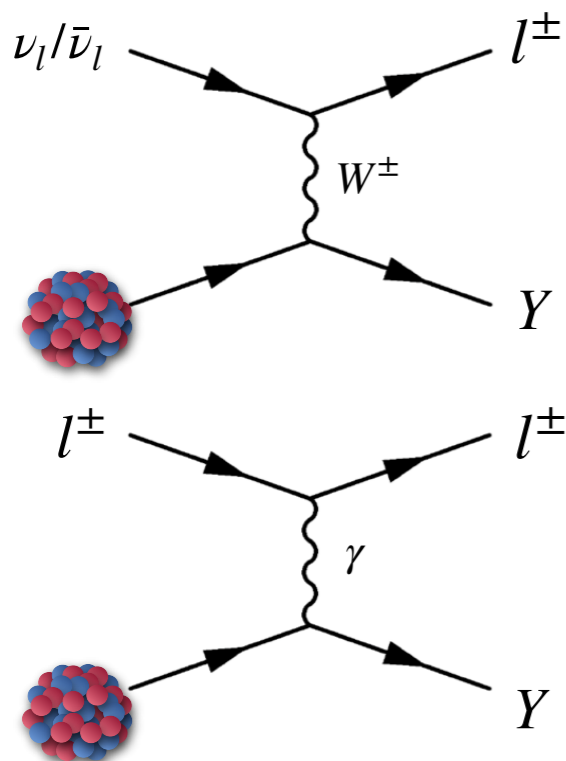
$$\frac{d^2\sigma}{d\Omega_e d\omega}$$



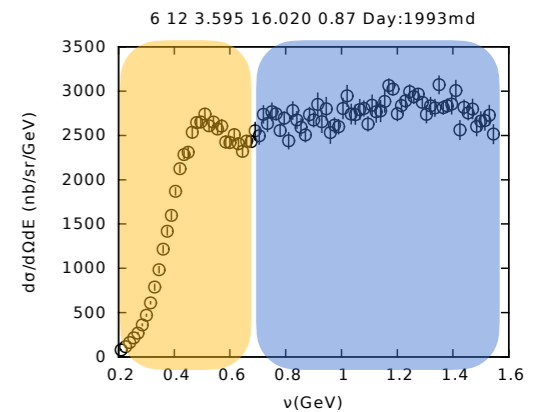
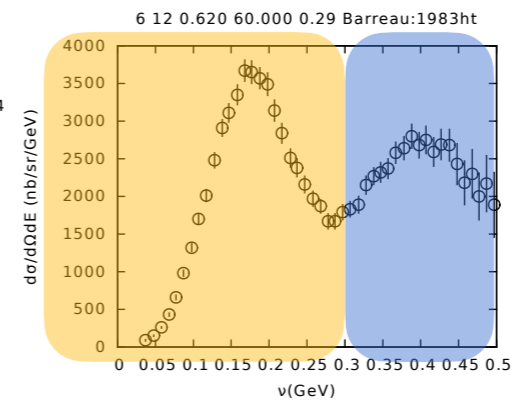
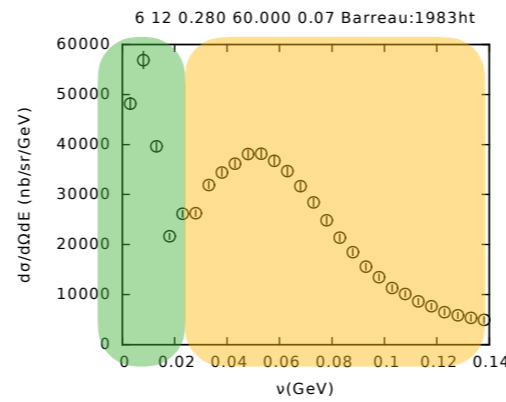
ν scattering



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

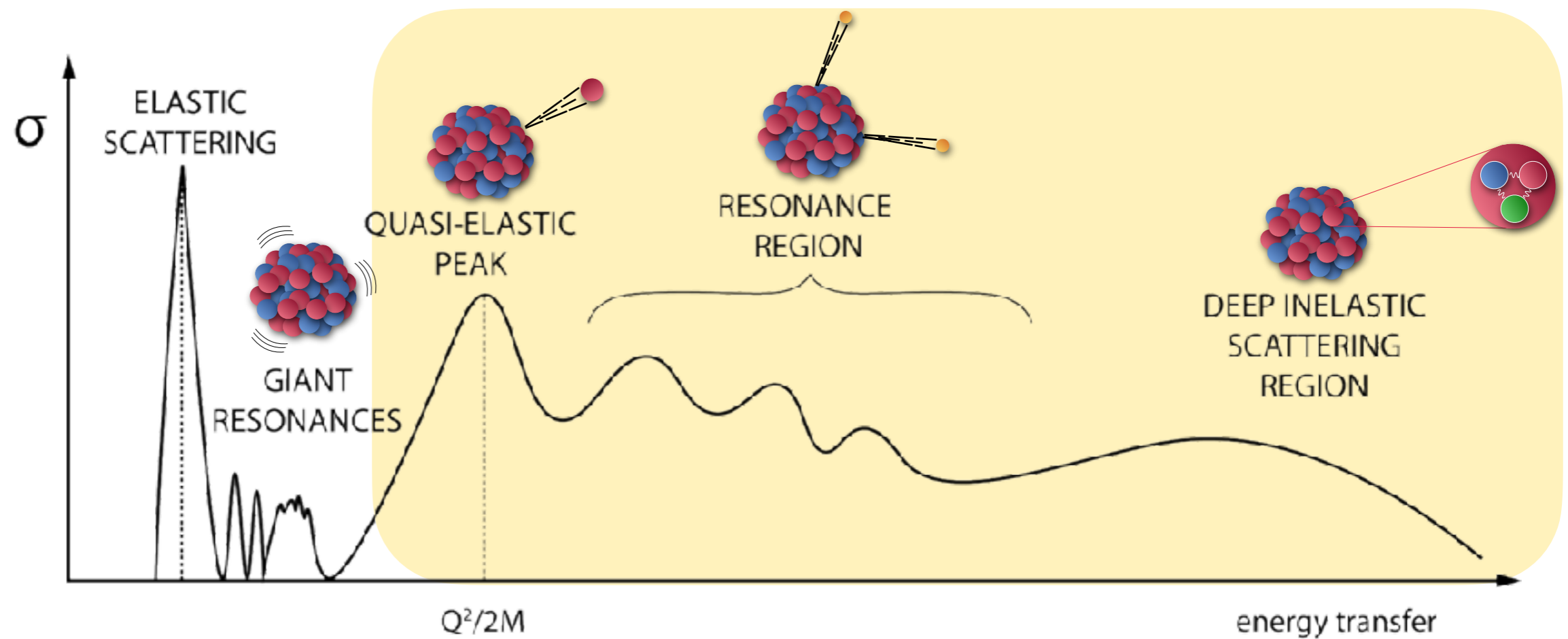


$$\frac{d^2\sigma}{d\Omega_e d\omega}$$



Motivation

Electroweak nuclear responses



Motivation

Electroweak nuclear responses



Elastic scattering:
CEvNS

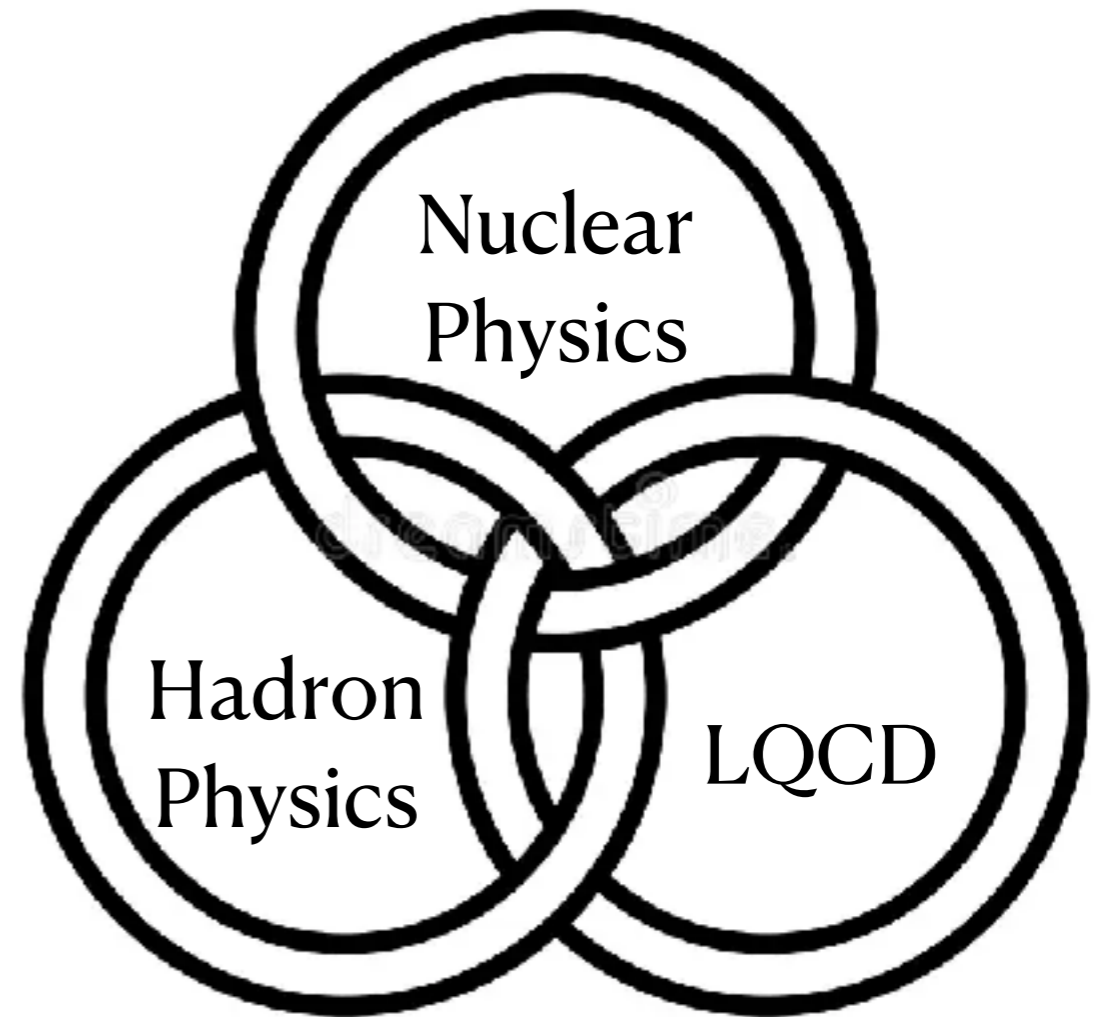
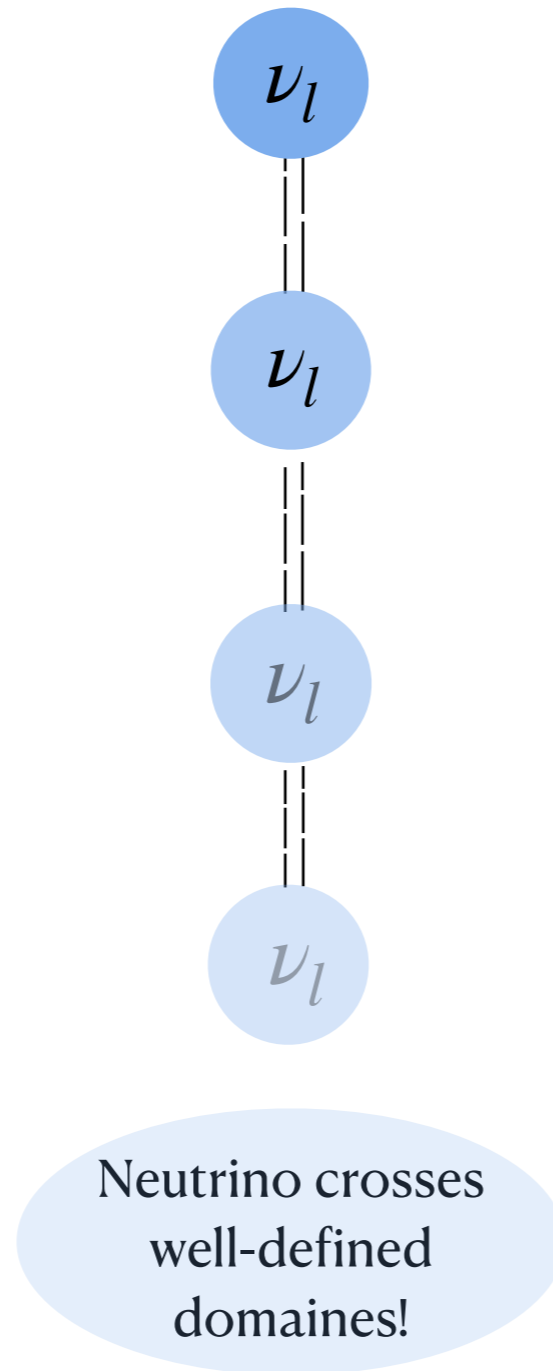
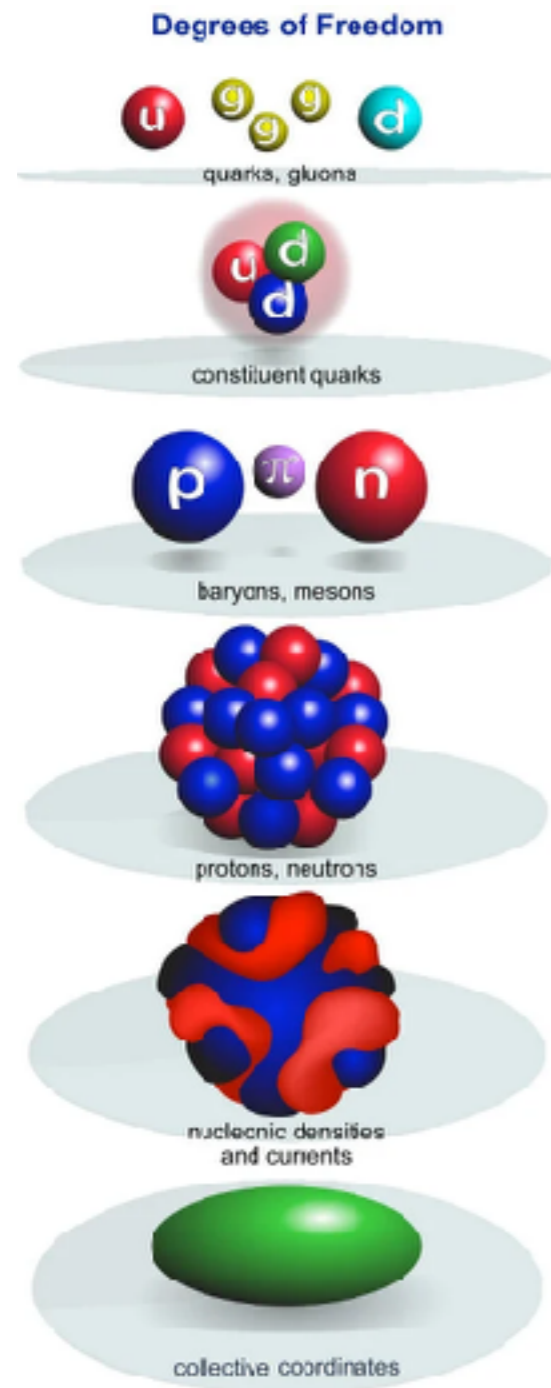
e.g. Supernovae
neutrinos

Long-baseline experiments

Monday talks:
J.D. Hakenmueller
S. Hedges

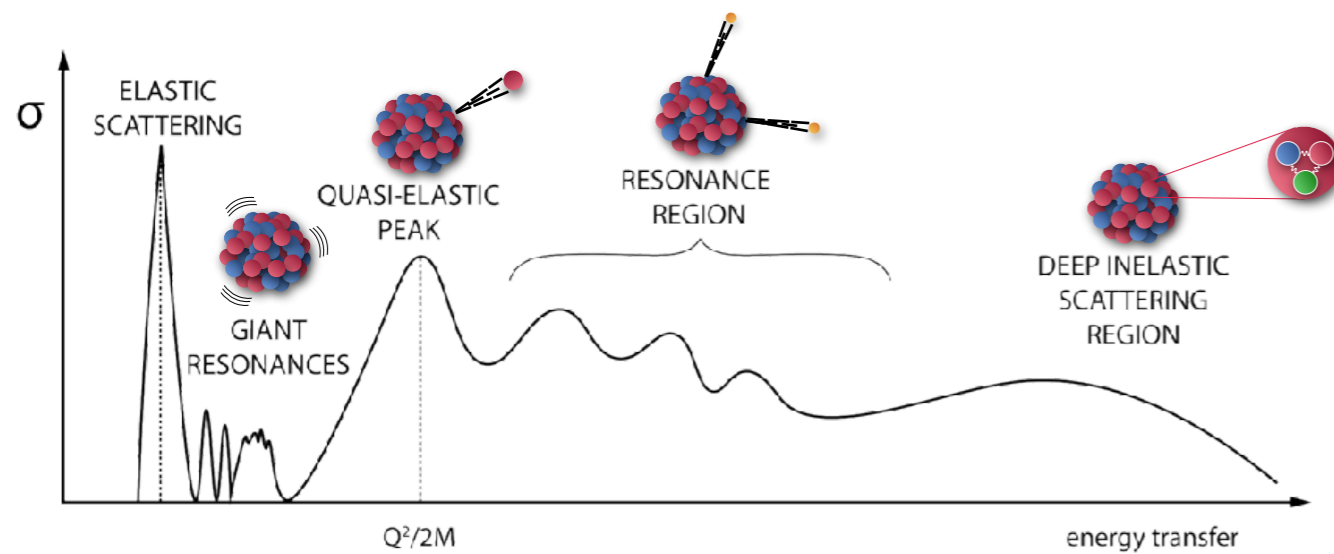
Thursday talks:
J. Beacom
H. Sekiya

Energy scales



Nuclear responses — inclusive cross-section

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



Nuclear responses — inclusive cross-section

Cross-section

$$\sigma \propto$$

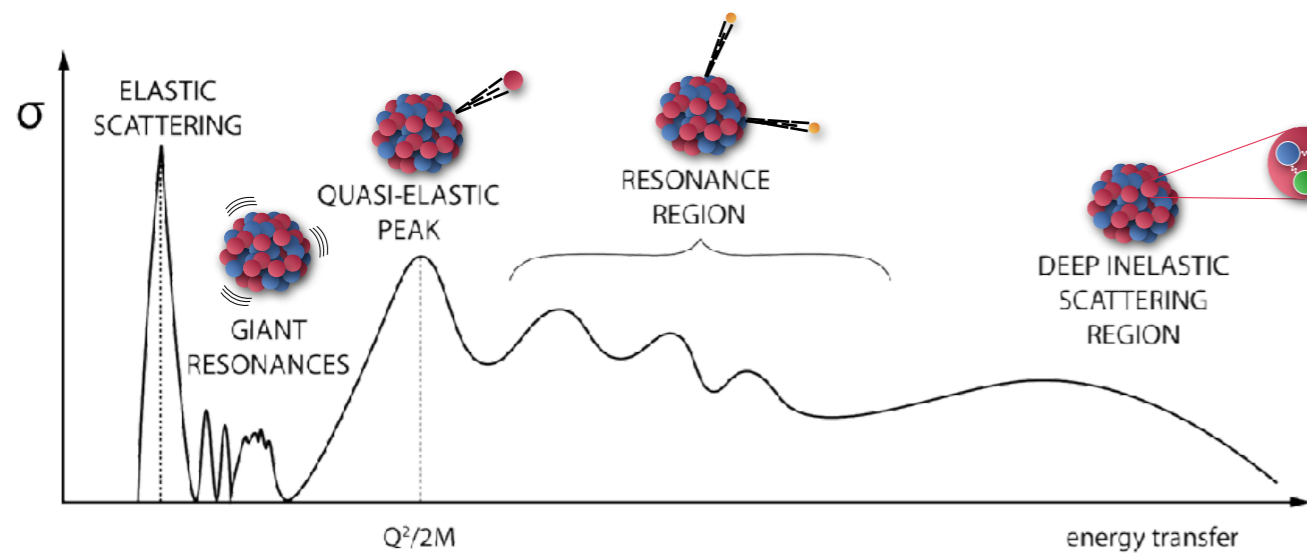
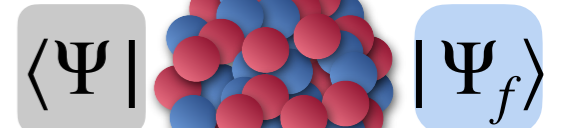
$$L^{\mu\nu}$$

$$R_{\mu\nu}$$

lepton tensor



nuclear responses



Nuclear responses — inclusive cross-section

Cross-section

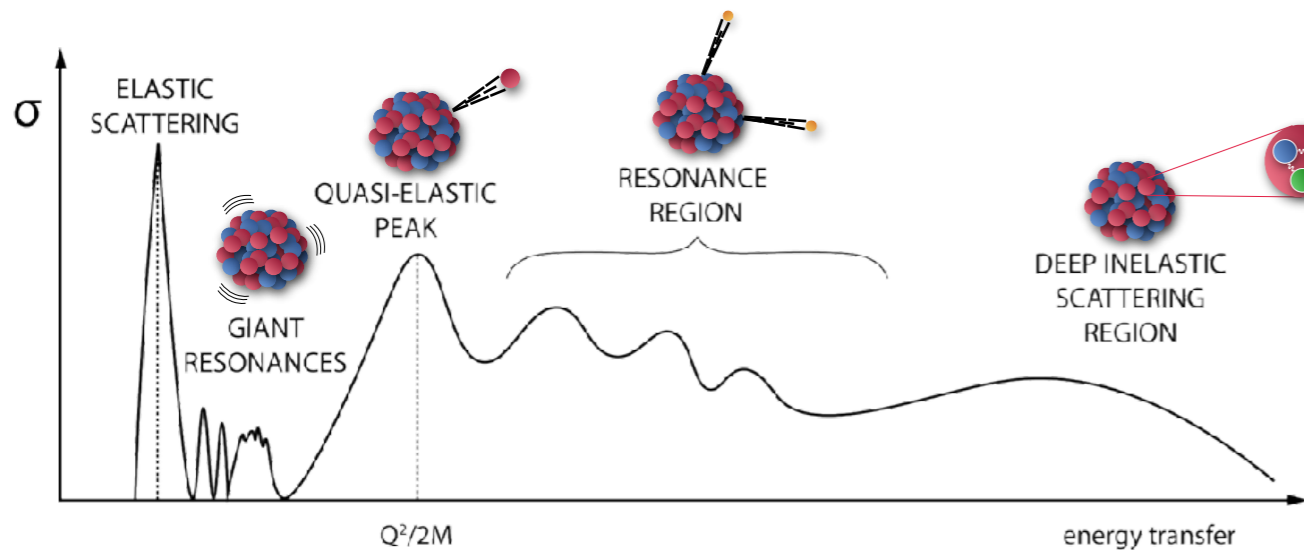
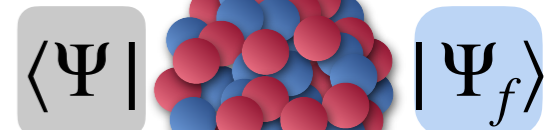
$\sigma \propto$

$$L^{\mu\nu} R_{\mu\nu}$$

lepton tensor



nuclear responses



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

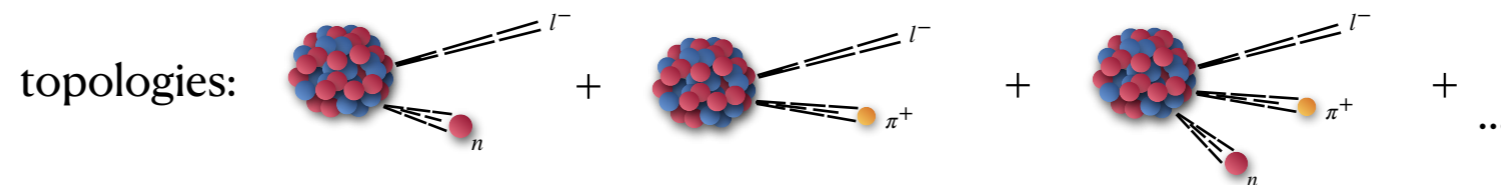
Challenging sum over
continuum spectrum

Challenges

Exclusive processes

- Inclusive cross-section (final lepton observed):

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

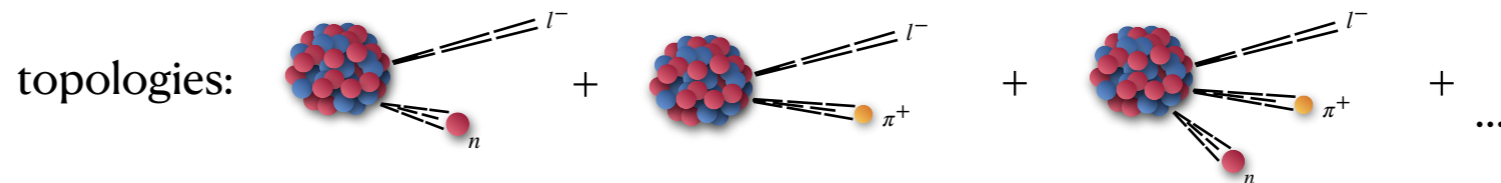


Challenges

Exclusive processes

- Inclusive cross-section (final lepton observed):

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



- Semi-exclusive observables (final lepton + hadrons observed):

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

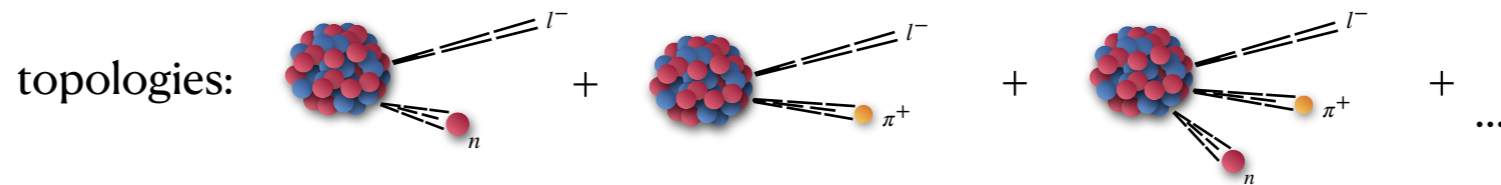
- Each topology treated separately
- Relativistic processes
- Mostly nucleons + pions production

Challenges

Exclusive processes

- Inclusive cross-section (final lepton observed):

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



- Semi-exclusive observables (final lepton + hadrons observed):

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

THIS IS NEEDED BY
EXPERIMENTS

- Each topology treated separately
- Relativistic processes
- Mostly nucleons + pions production

Monte Carlo event generators

Experiment-focused generators

Meet the needs of current oscillation experiments



[Eur. Phys. J. Spec. Top. 230, 4449 \(2021\)](#)

C++. Primary generator for Fermilab experiments. Largest group (still just a handful of active developers). Ambitions to be the universal platform.

NEUT (no official logo)

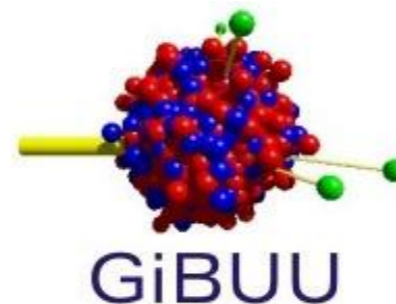


[Eur. Phys. J. Spec. Top. 230, 4469 \(2021\)](#)

C++/Fortran. Primary generator for J-PARC experiments (T2K, Super-K, Hyper-K). Not yet fully open source.

Theory-focused generators

Aid theoretical investigations of neutrino scattering



[J. Phys. G: Nucl. Part. Phys. 46 113001 \(2019\)](#)

Fortran. Supports neutrino projectiles as part of larger framework. Most sophisticated FSI model. Limited infrastructure (no geometry handling, etc.)

NuWro



[Nucl. Phys. Proc. Suppl. 229-232, 499 \(2012\)](#)

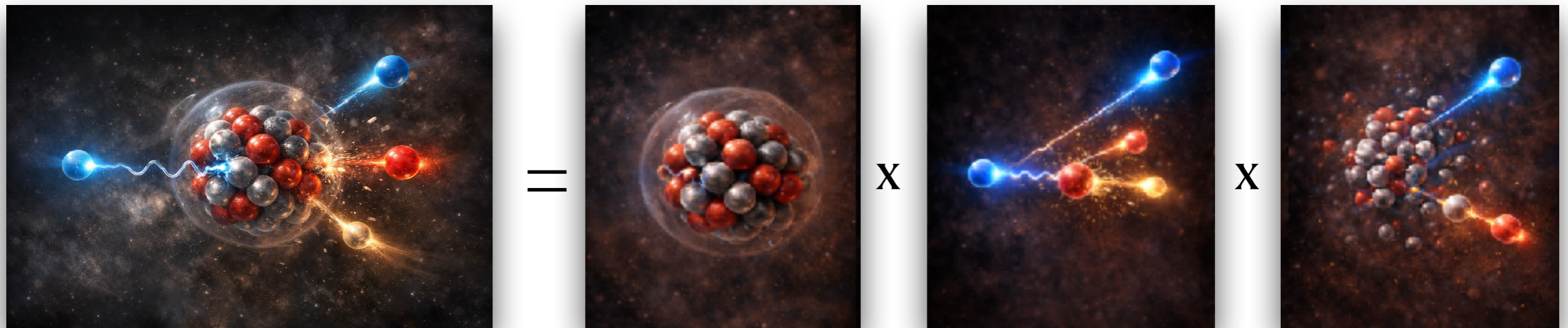
C++. Many model options, often the first adopter of new theory developments from the literature.



[Phys. Rev. D 107 \(2023\) no.3, 033007](#)

C++. Based on factorisation via spectral functions. Validated for electron scattering.

Towards semi-exclusive cross-sections



Process factorised:

Initial nuclear
state

Primary vertex
of interaction

Final state
interactions

- Each scattering event is obtained as a two-step process:
 - **Primary interaction vertex** (hadrons produced at some point in nucleus)
 - **Intra-nuclear cascade**
- This factorisation assumes **impulse approximation**

This factorisation is assumed by Monte Carlo event generators

Towards semi-exclusive cross-sections



Process factorised:

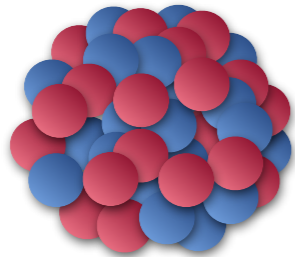
- Each scattering event is factorised into:
 - **Primary interaction** (point in nucleus)
 - **Intra-nuclear cascade**
- This factorisation assumes **impulse approximation**



This factorisation is assumed by Monte Carlo event generators

“Ab initio” nuclear theory

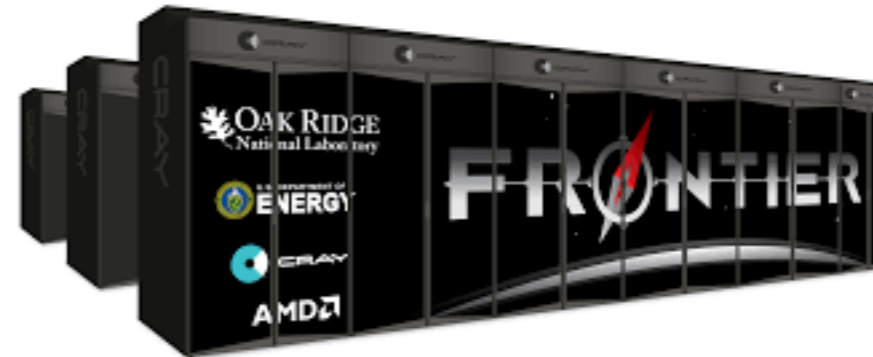
nucleons —
degrees of
freedom



$$\mathcal{H} |\Psi\rangle = E |\Psi\rangle$$

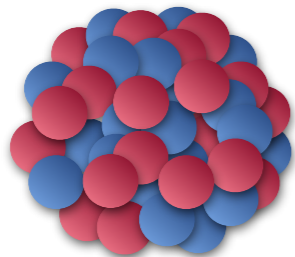
$$\mathcal{H} = \sum_{i=1}^A t_{kin} + \sum_{i>j=1}^A v_{ij} + \sum_{i>j>k=1}^A v_{ijk} + \dots$$

Many-body methods to get realistic
correlated nuclear wave functions $|\Psi\rangle$



“Ab initio” nuclear theory

nucleons —
degrees of
freedom



$$\mathcal{H} |\Psi\rangle = E |\Psi\rangle$$

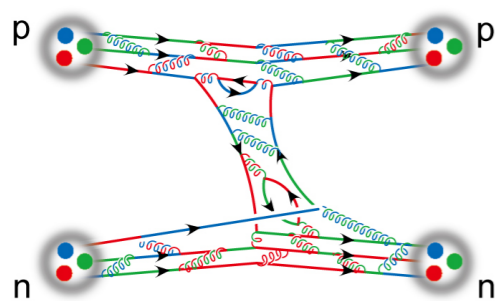
$$\mathcal{H} = \sum_{i=1}^A t_{kin} + \sum_{i>j=1}^A v_{ij} + \sum_{i>j>k=1}^A v_{ijk} + \dots$$

Many-body methods to get realistic
correlated nuclear wave functions $|\Psi\rangle$



Nuclear force rooted in the fundamental theory of QCD + consistent **electroweak currents**

Quantum Chromodynamics



Chiral Effective Field Theory

	NN	3N	4N
LO (Q/Λ_χ) ⁰			
NLO (Q/Λ_χ) ²			
NNLO (Q/Λ_χ) ³			
N ³ LO (Q/Λ_χ) ⁴			

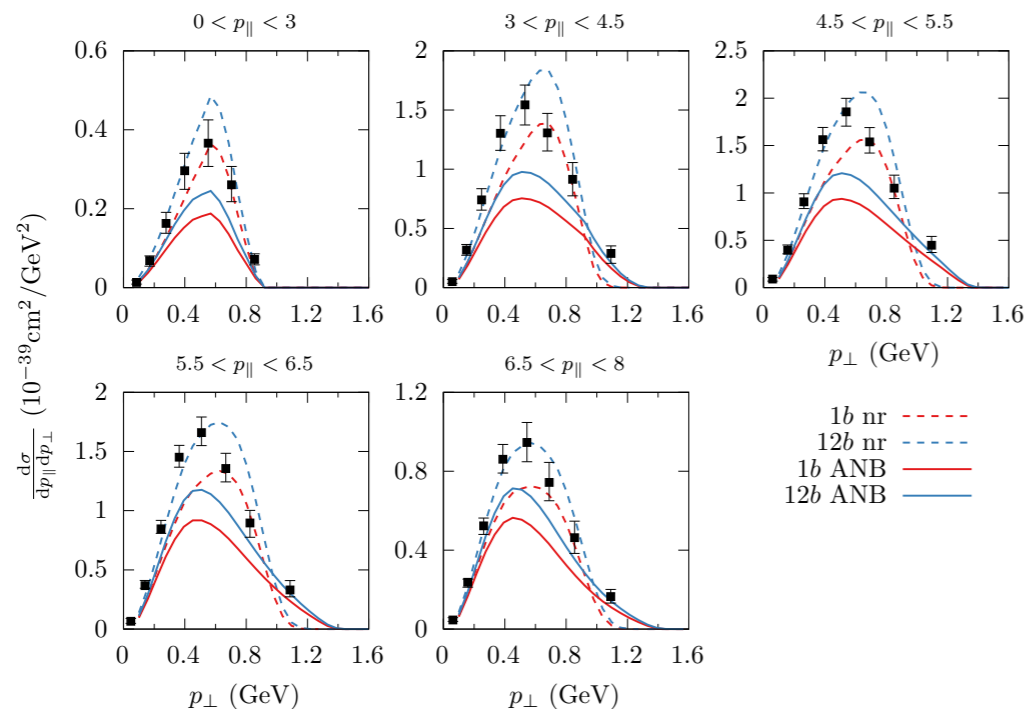
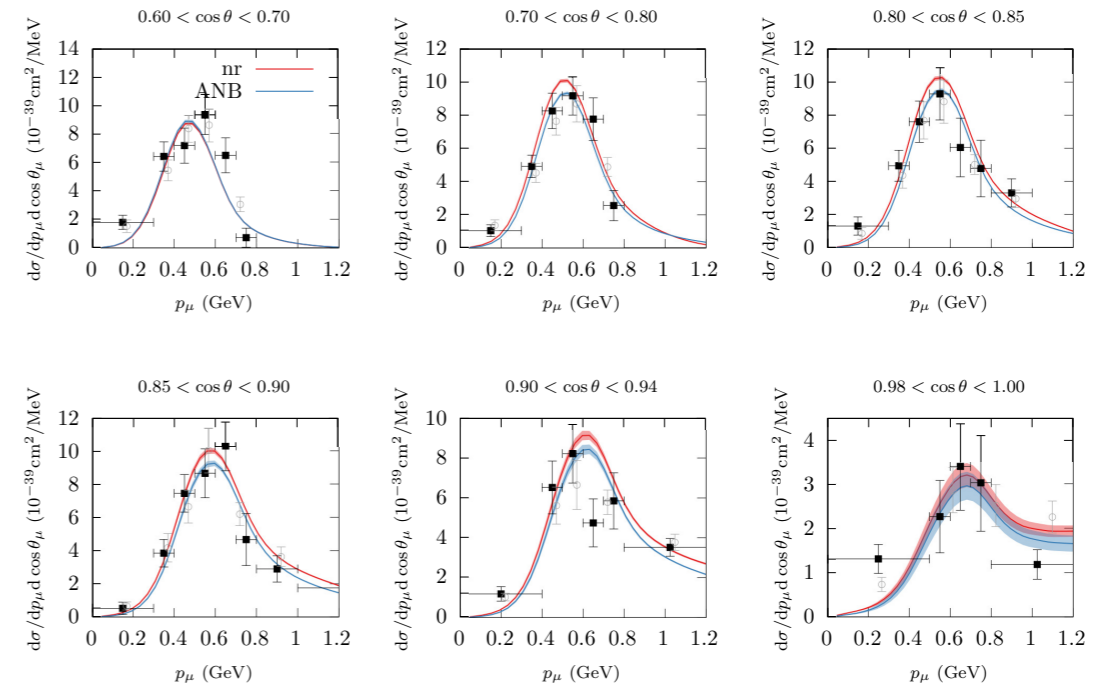
Nuclei & nuclear matter



Scattering on ^{12}C

Laplace integral transform + Green function Monte Carlo

- Employing $\text{Av18}+\text{UIX}$ nuclear potential
- Comparisons to T2K, MiniBooNE, Minerva data



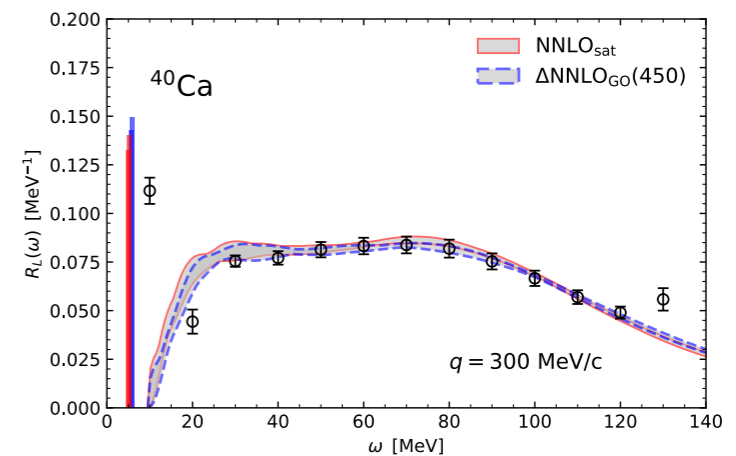
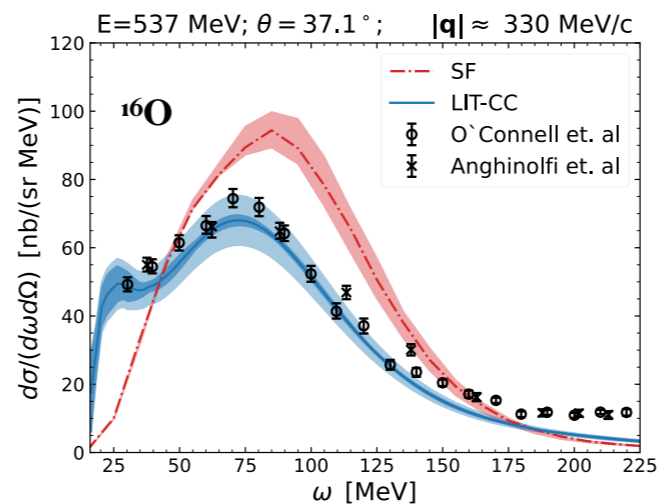
↑good agreement with T2K data

←Extreme (relativistic) kinematics for Minerva

Scattering on ^{16}O and ^{40}Ca

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

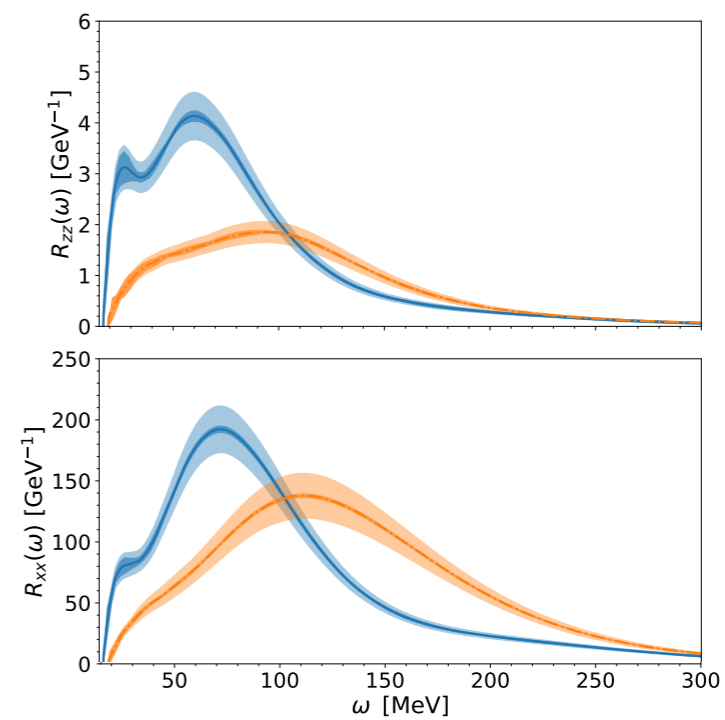
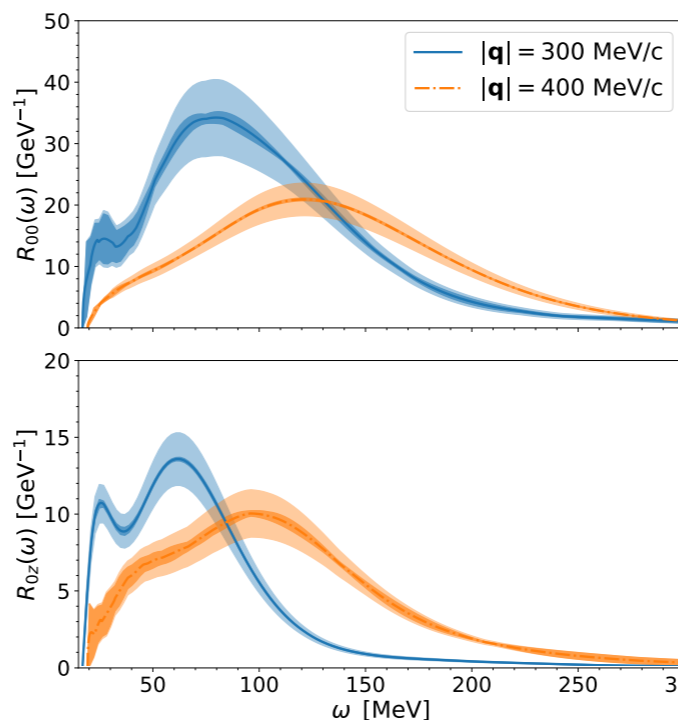
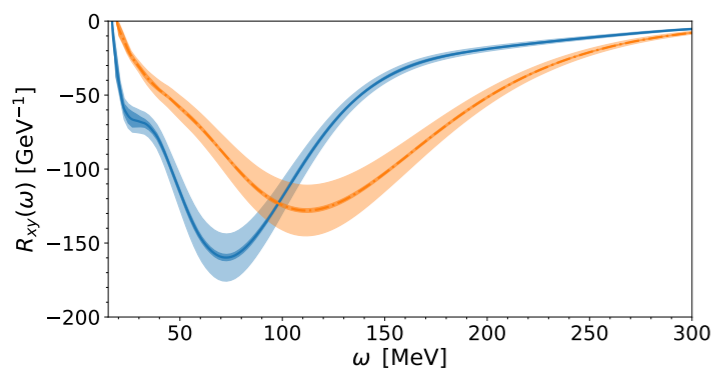
Benchmark with
electron scattering
on ^{16}O and ^{40}Ca



B.Acharya, JES, et al. *Phys. Rev. Lett.* 134.202501 (2025)

JES, B. Acharya, et al. *Phys. Rev. Lett.* 127 (2021) 7, 072501

Predictions for neutrino
scattering on ^{16}O



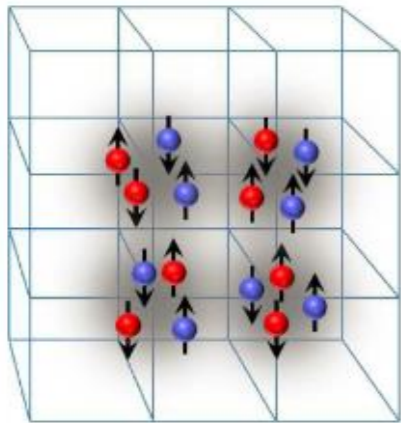
$$15 \quad \left. \frac{d\sigma}{dE'd\Omega} \right|_{\nu/\bar{\nu}} = \sigma_0 \left(v_{00}R_{00} + v_{0z}R_{0z} + v_{zz}R_{zz} + v_T R_T \pm v_{xy}R_{xy} \right)$$

Responses from ab initio

- **Reliable** at lower momentum transfers
- **Uncertainty quantification**
- Relevant for **benchmarks**
- Currently **inclusive** cross-sections
- Currently **no pion** degrees of freedom
- **Non-relativistic** description

Possible way forward

Nuclear simulations on lattice



- Lattice EFT

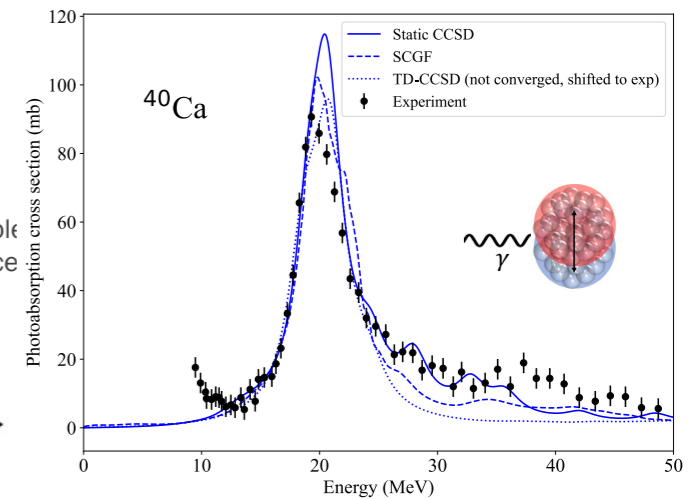
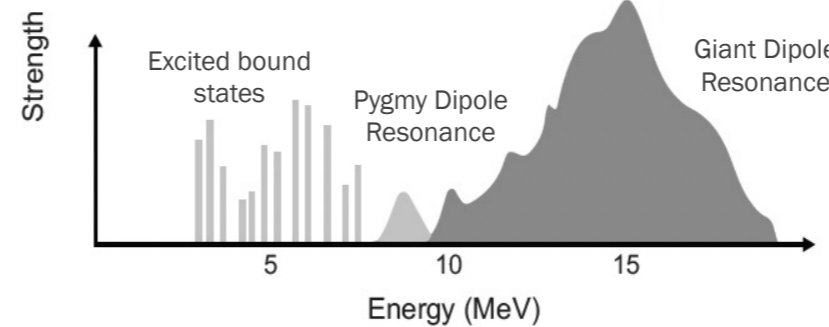
D. Lee, Ann.Rev.Nucl.Part.Sci. 75 (2025) 1, 109-128

- NuLattice

M. Rothman et al., Eur.Phys.J.A 62 (2026) 2, 28

Real-time nuclear dynamics

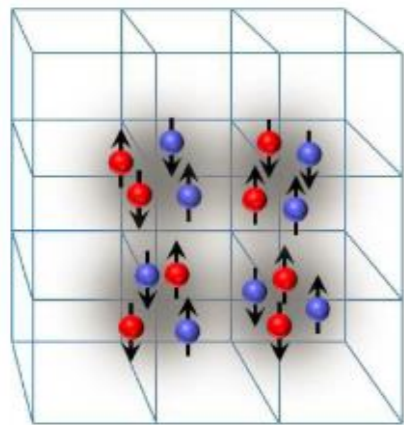
$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = \hat{H} |\Psi(t)\rangle$$



F. Bonaiti et al., Phys. Rev. C 113, 024312 (2026)

Possible way forward

Nuclear simulations on lattice



- Lattice EFT

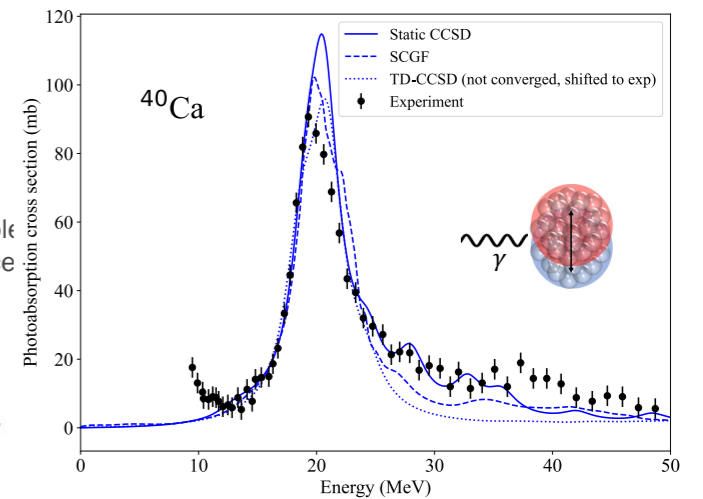
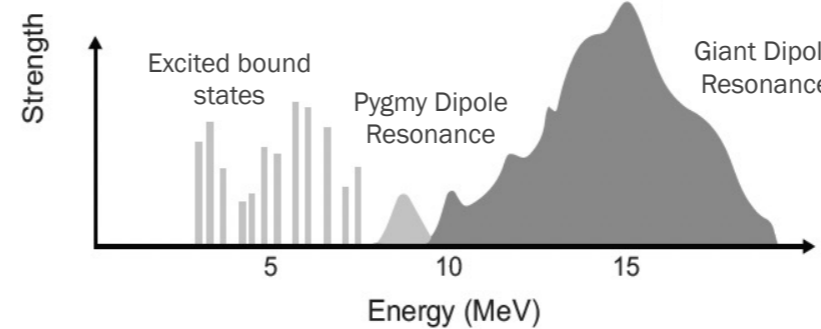
D. Lee, Ann.Rev.Nucl.Part.Sci. 75 (2025) 1, 109-128

- NuLattice

M. Rothman et al., Eur.Phys.J.A 62 (2026) 2, 28

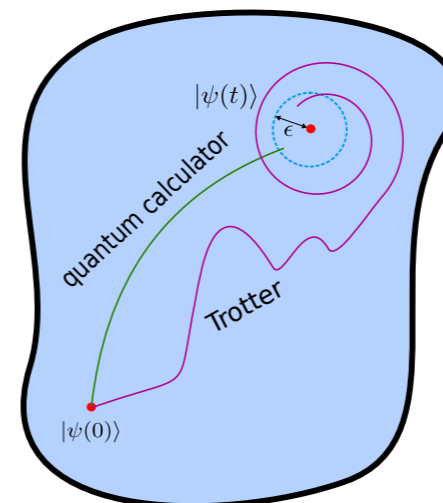
Real-time nuclear dynamics

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = \hat{H} |\Psi(t)\rangle$$



F. Bonaiti et al., Phys. Rev. C 113, 024312 (2026)

Quantum simulations of atomic nuclei



A. Roggero et al., Phys.Rev.D 101 (2020) 7, 074038

C.Kane talk @ INT-26-1

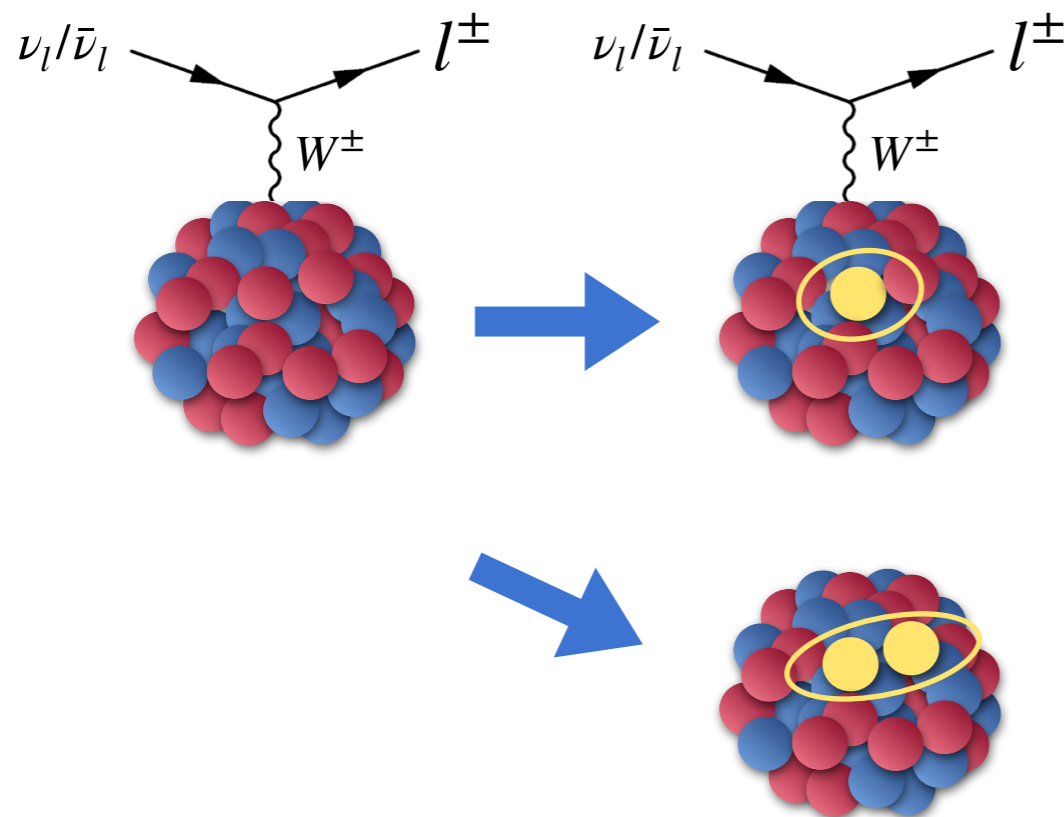
Ab initio + factorisation

- **Reliable** at lower momentum transfers
- **Uncertainty quantification**
- Relevant for **benchmarks**
- Currently **inclusive** cross-sections
- Currently **no pion** degrees of freedom
- **Non-relativistic** description

Ab initio + factorisation

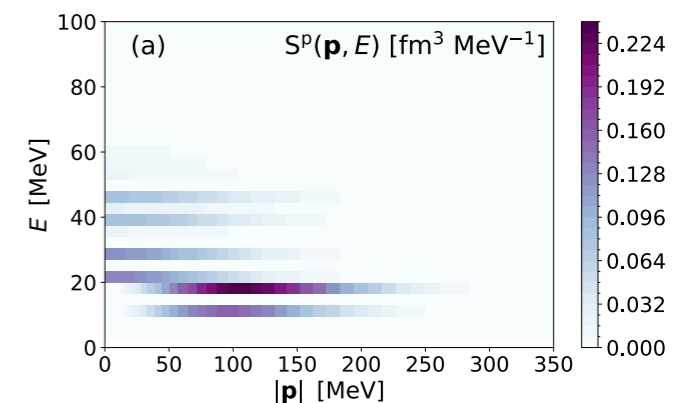
- **Reliable** at lower momentum transfers
- **Uncertainty quantification**
- Relevant for **benchmarks**

- Currently **inclusive** cross-sections
- Currently **no pion** degrees of freedom
- **Non-relativistic** description



Spectral
function

Short time
approximation

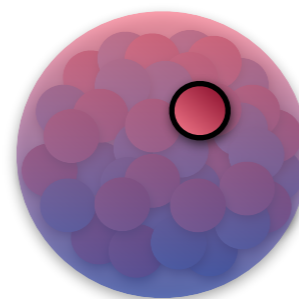
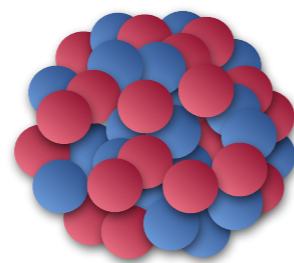


*Distribution of nucleon's momentum —
removal energy in the nucleus ground state*

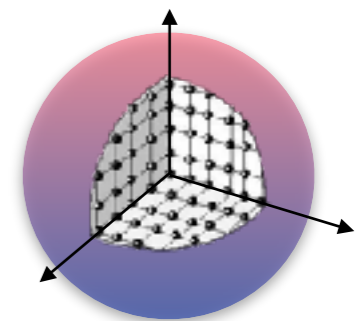
From ab initio to pheno

- **Reliable** at lower momentum transfers
- **Uncertainty quantification**
- Relevant for **benchmarks**

- Currently **inclusive** cross-sections
- Currently **no pion** degrees of freedom
- **Non-relativistic** description



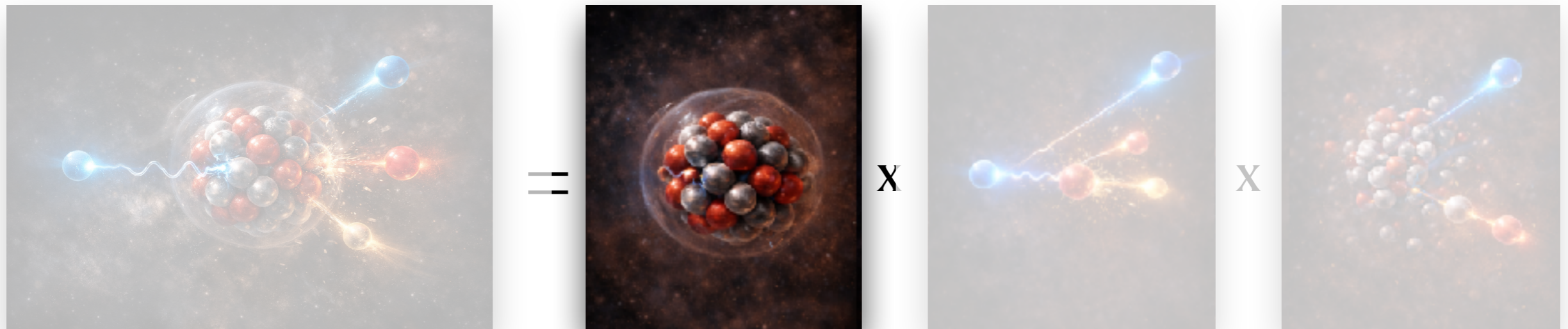
Mean-field
(Hartree-Fock)



Fermi Gas model

+ phenomenological add-on's
to account for missing physics

Factorisation

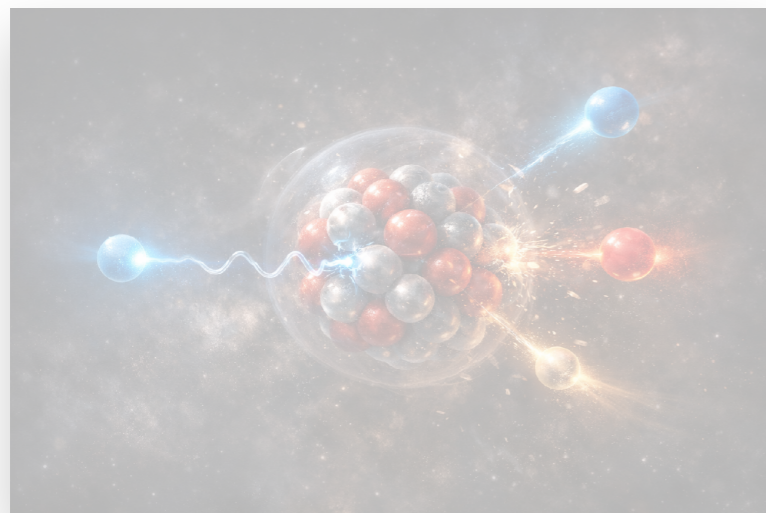


Initial nuclear
state

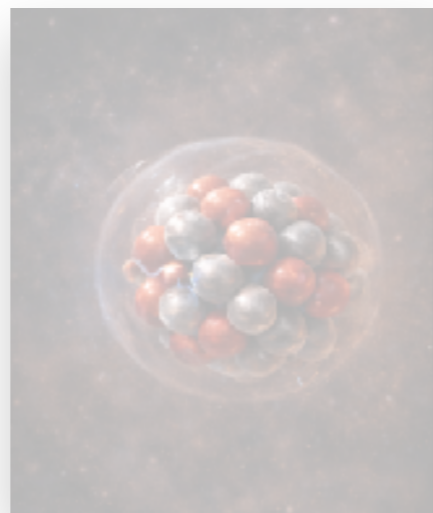
Primary vertex
of interaction

Final state
interactions

Factorisation



=



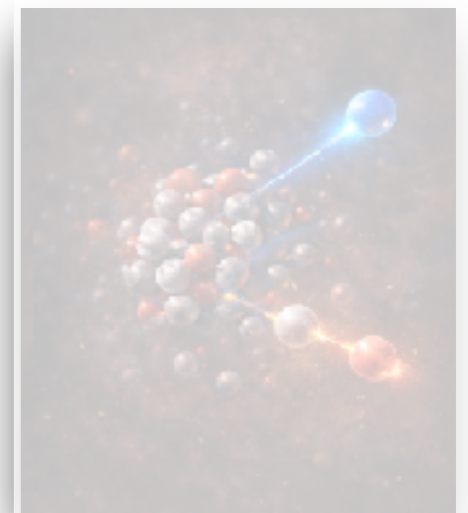
Initial nuclear state

X



Primary vertex of interaction

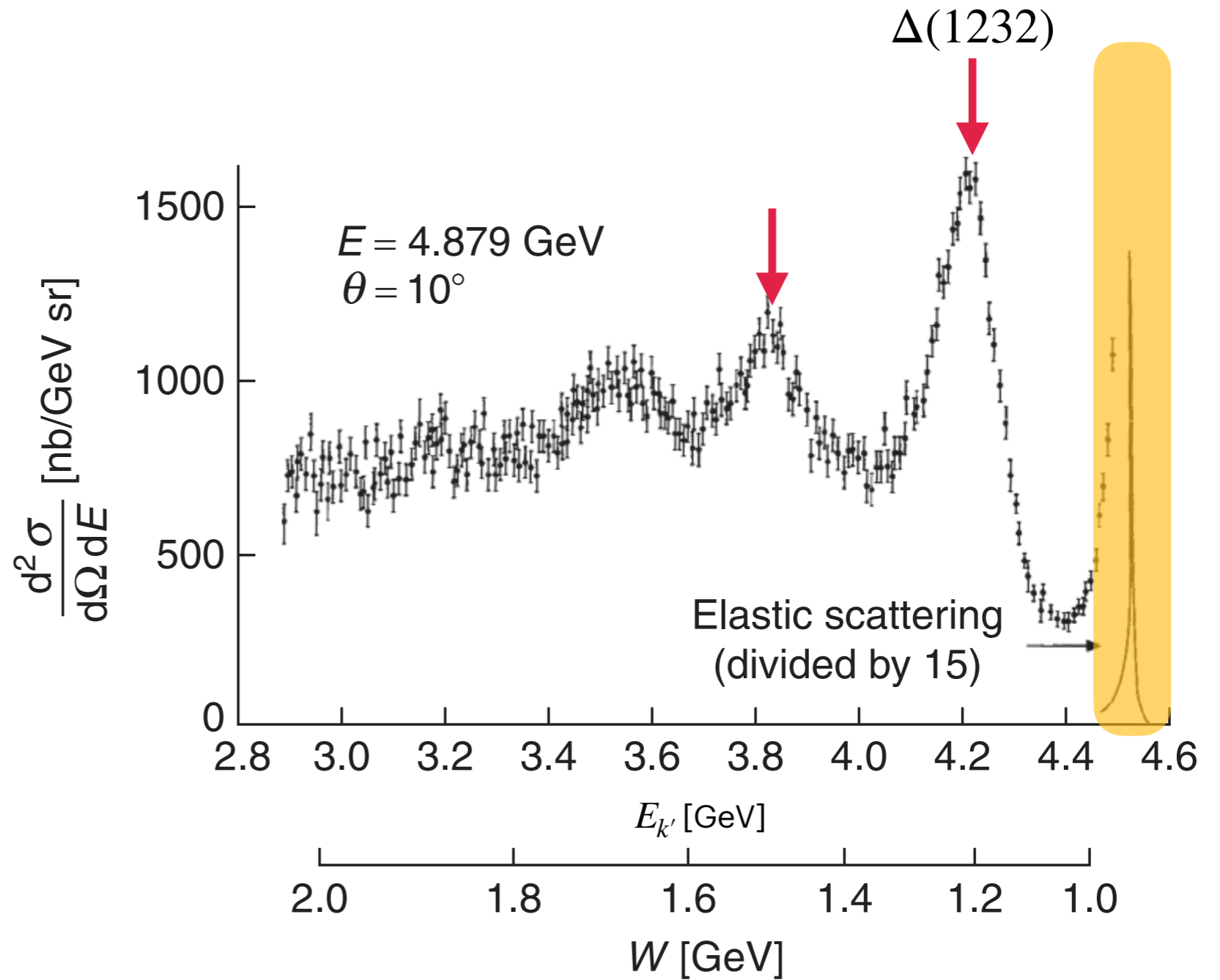
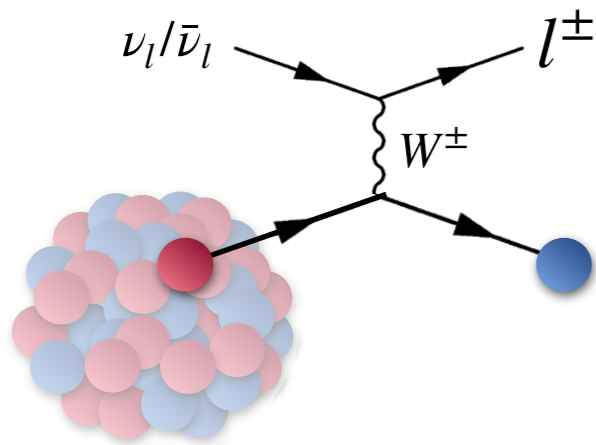
X



Final state interactions

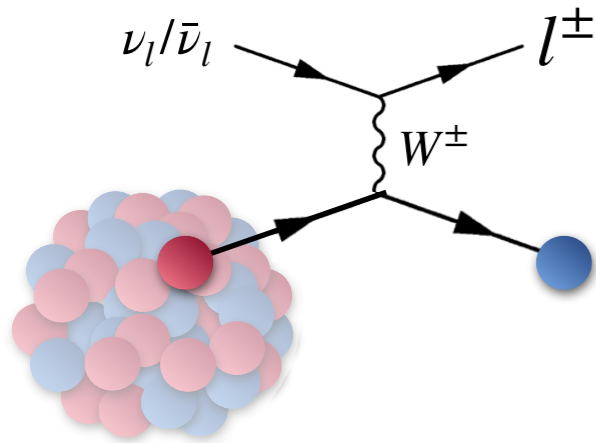
Interaction channels

Quasi-elastic

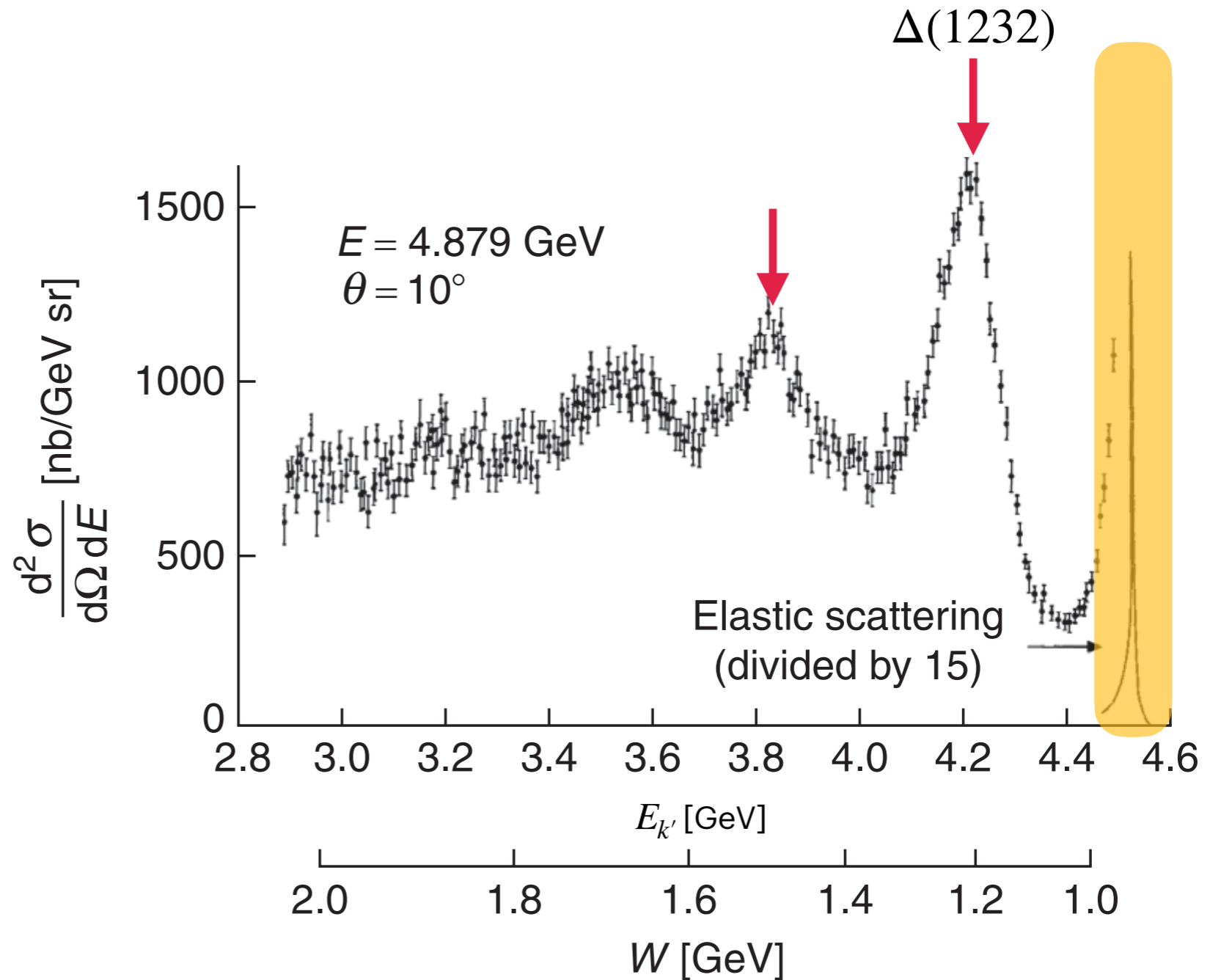


Interaction channels

Quasi-elastic

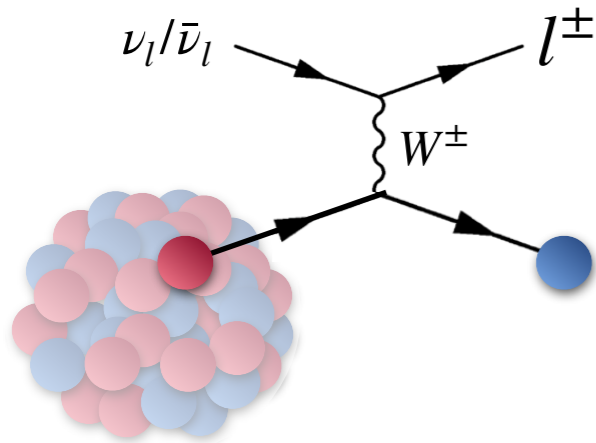


✓ Relatively well understood

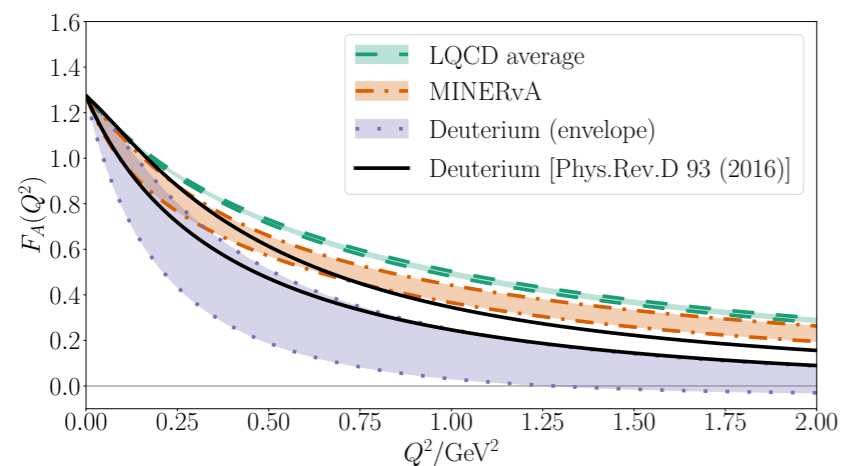


Interaction channels

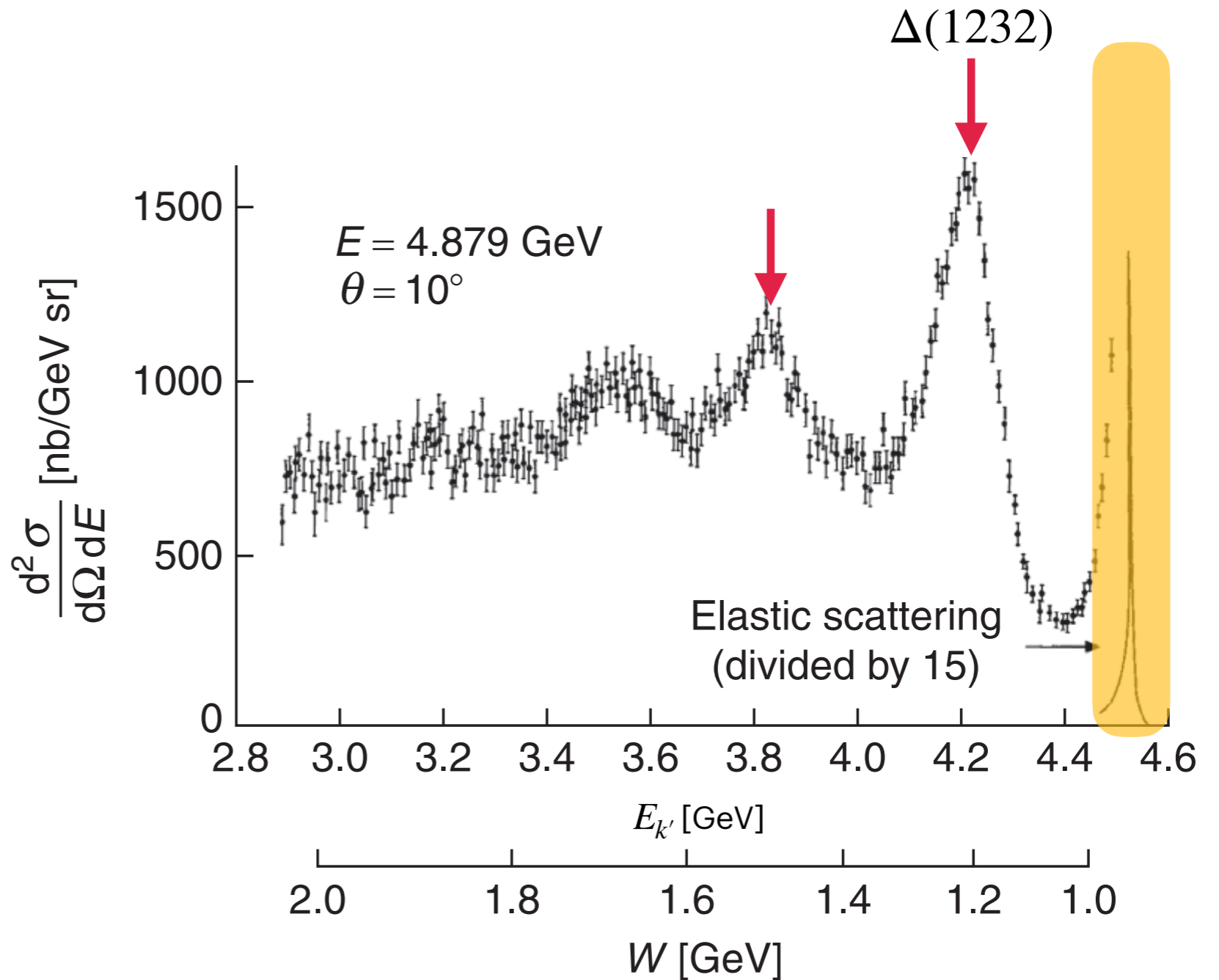
Quasi-elastic



- ✓ Relatively well understood
- ✓ Axial form-factor from LQCD & measured by MINERvA

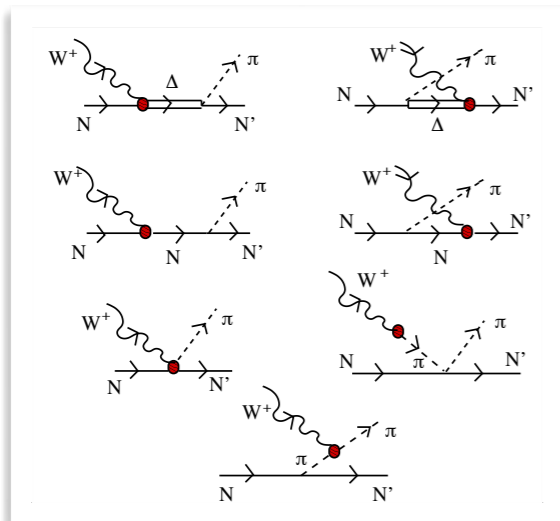
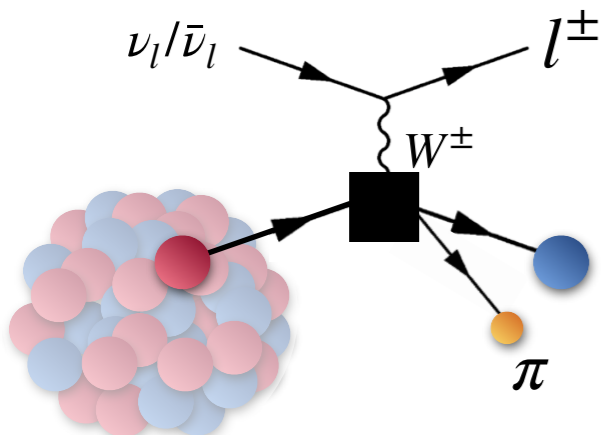


A. Meyer, arXiv: 2601.02676

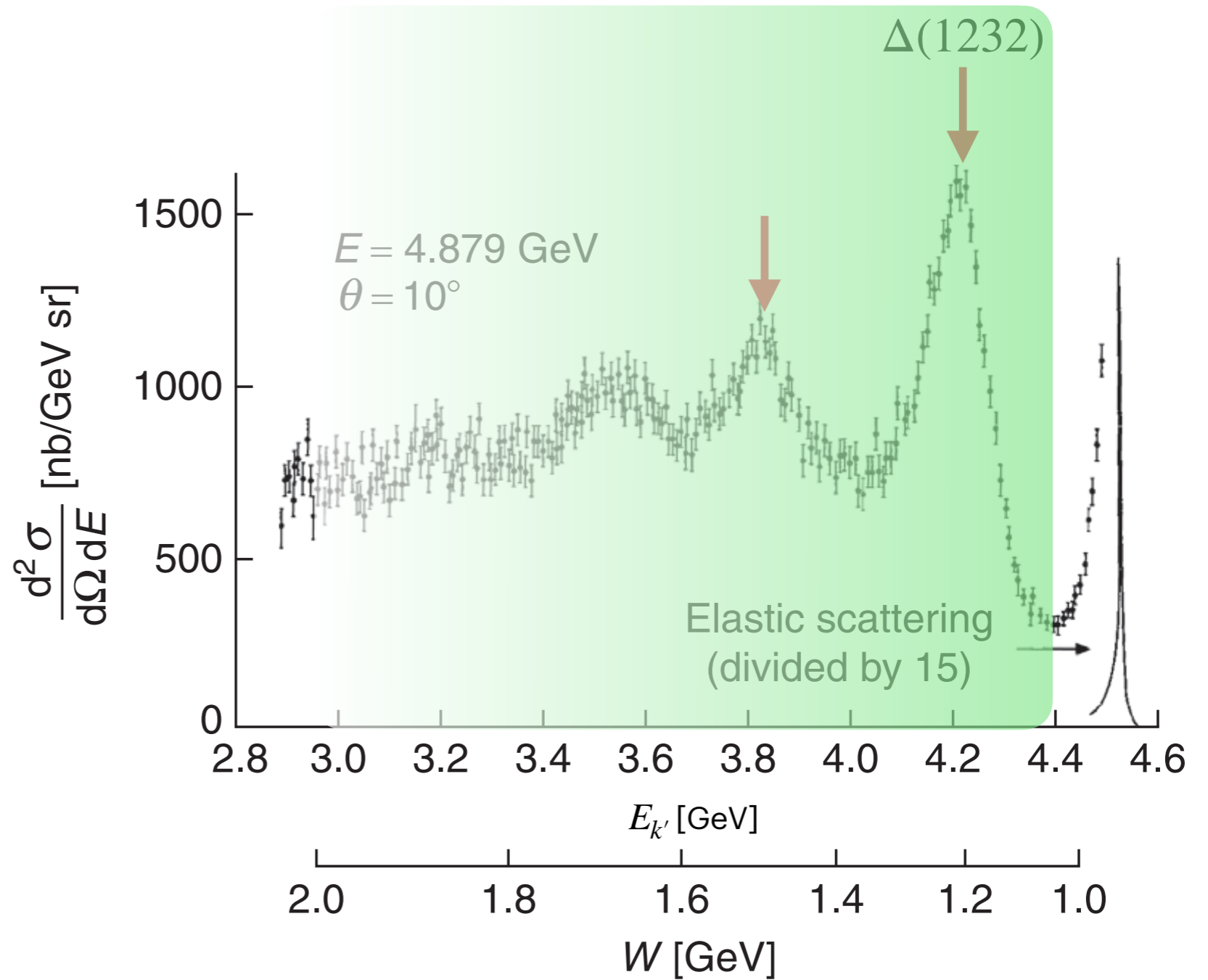


Interaction channels

Pion(s) production

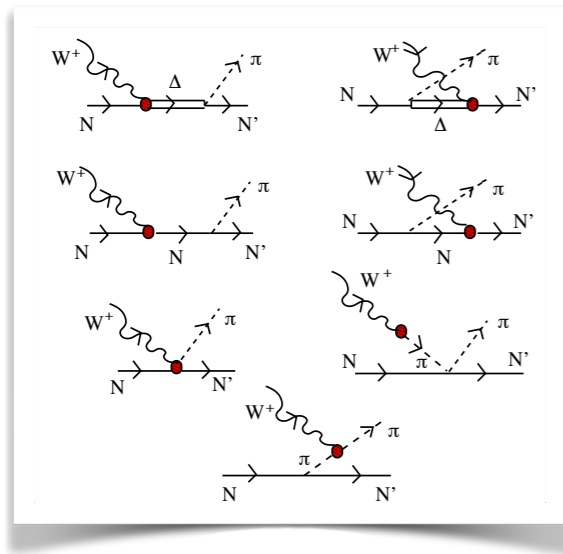
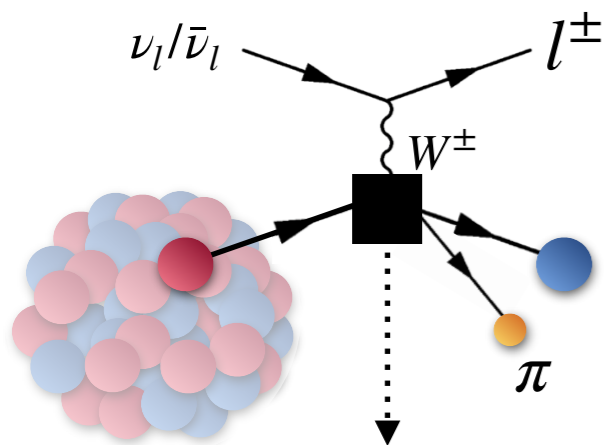


Over 30% of all events in DUNE!



Interaction channels

Pion(s) production



- **@nucleon** level: various (sophisticated) models of meson production

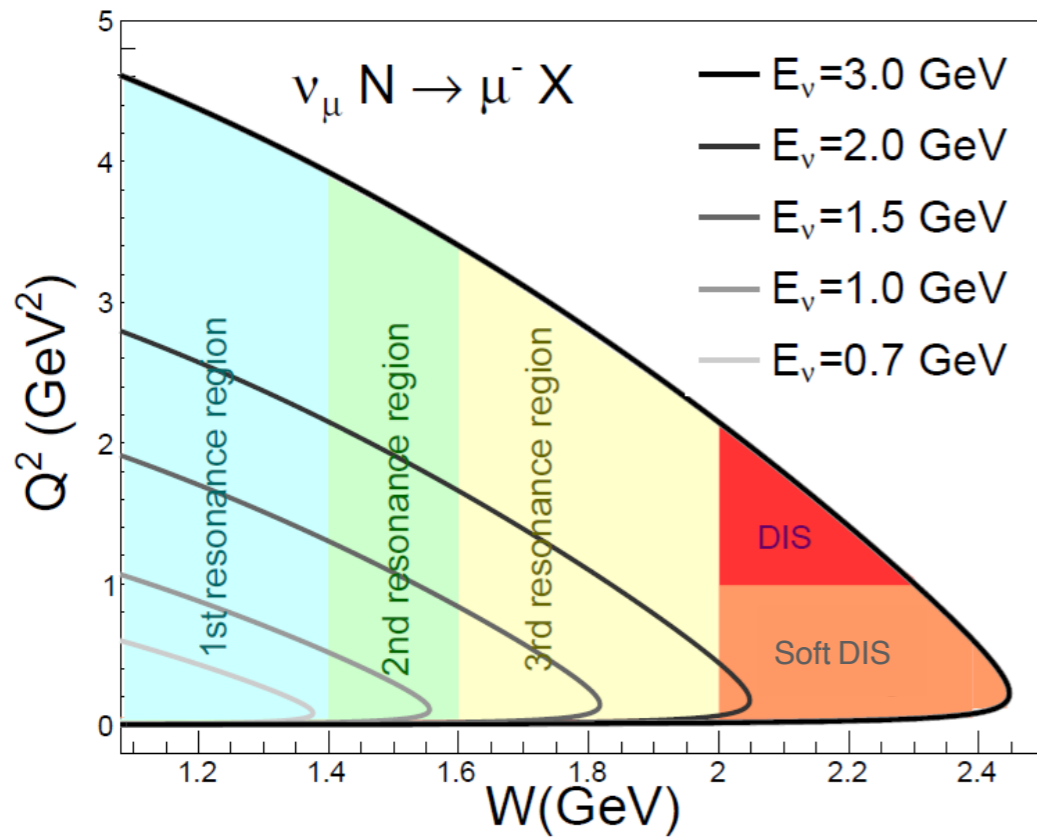
- ANL-Osaka DCC (*dynamical coupled channels*), *Julich-Bonn*
- MAID07, SAID ("*unitary isobar model*")
- *HNV model*

- Axial form factors poorly known
- **@nucleus**: less theoretical expertise

L. L. Salcedo, E. Oset, et al. Nucl. Phys. A 484, 557 (1988).

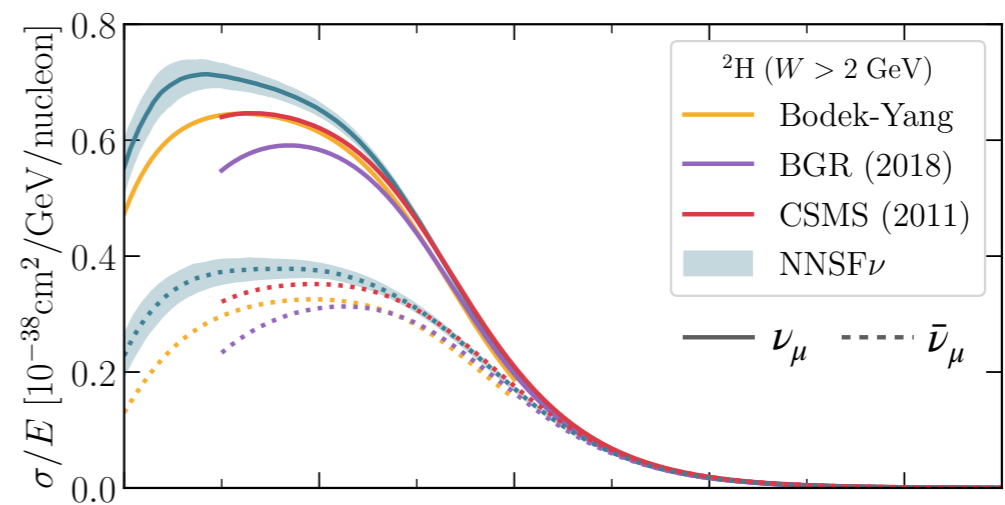
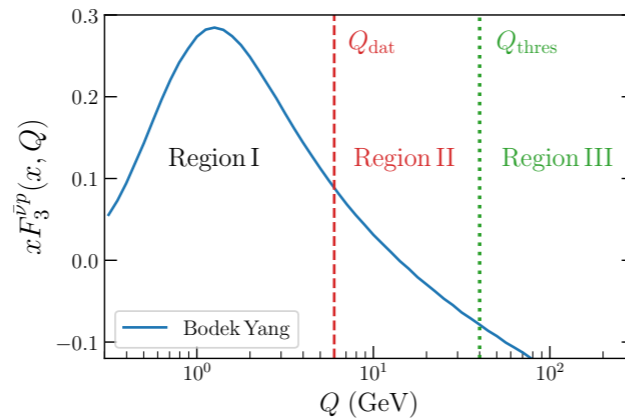
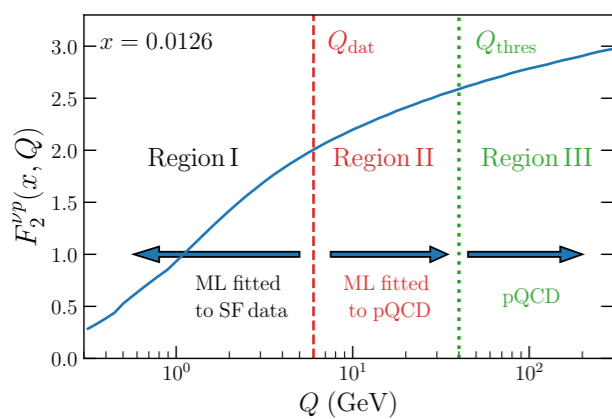
Over 30% of all events in DUNE!

Interaction channels



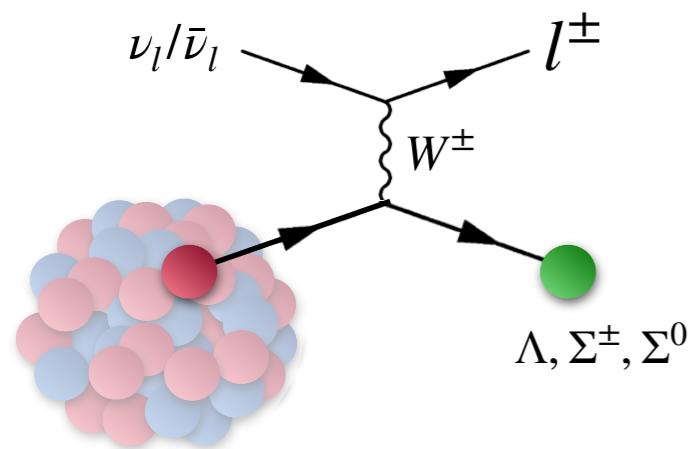
$$\frac{d^2\sigma^{\nu A}(x, Q^2, y)}{dx dy} = \frac{G_F^2 s / 2\pi}{(1 + Q^2/m_W^2)^2} \left[(1-y) F_2^{\nu A}(x, Q^2) + y^2 x F_1^{\nu A}(x, Q^2) + y \left(1 - \frac{y}{2}\right) x F_3^{\nu A}(x, Q^2) \right]$$

- DIS – perturbative QCD
- Parametrization in terms of **structure functions** $F_1^{\nu A}, F_2^{\nu A}, F_3^{\nu A}$.
- Recent phenomenological fit using ML

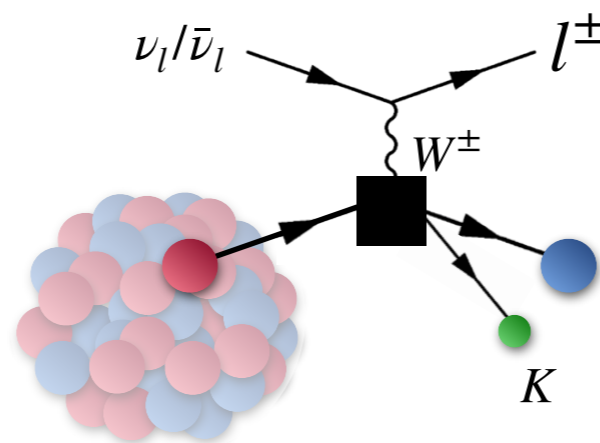


Interaction channels

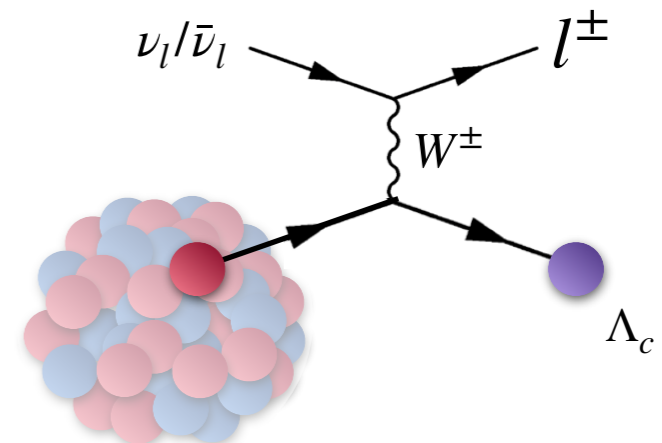
Rare processes



Hyperon production:
 $N \rightarrow \Lambda, \Sigma^\pm, \Sigma^0 (+\pi)$



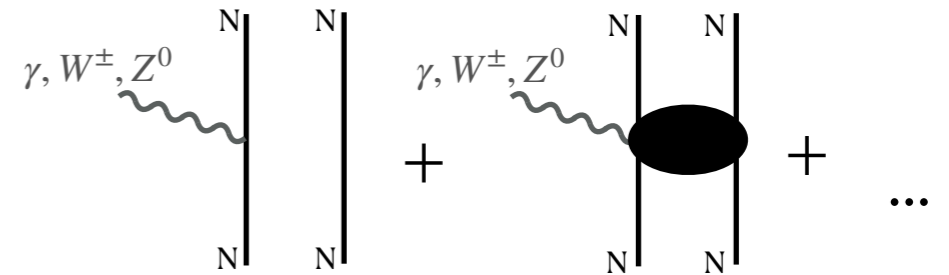
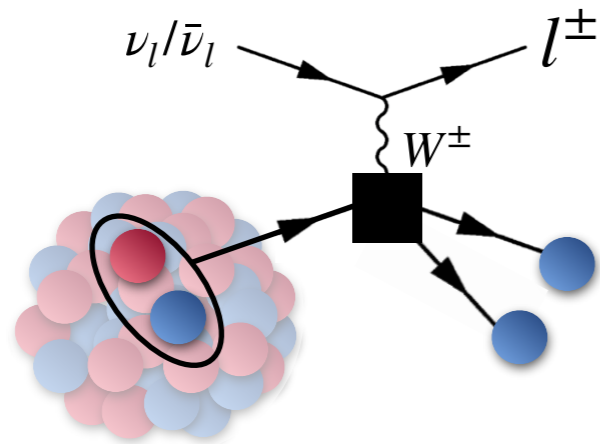
Kaon production



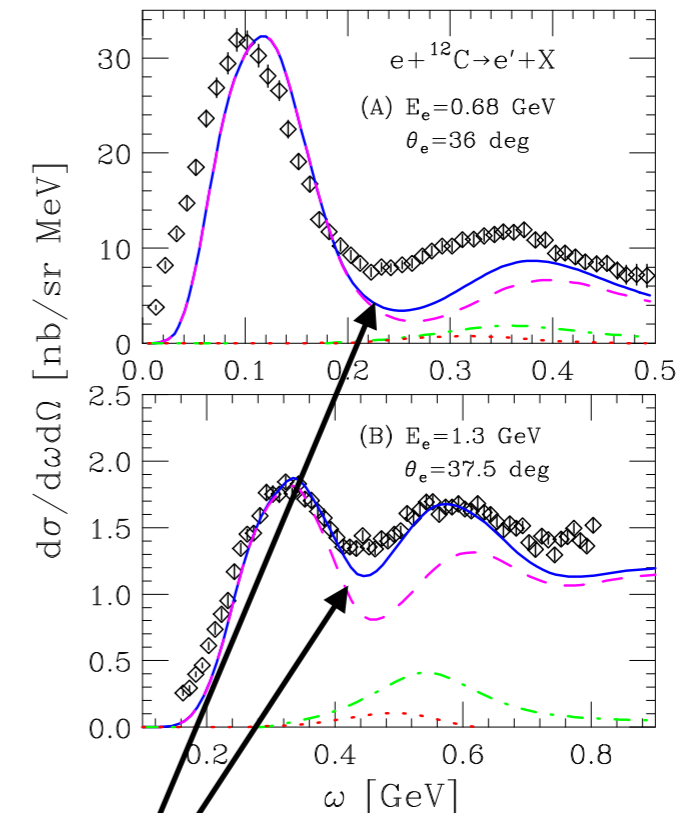
Charm hyperon production:
 $n \rightarrow \Lambda_c$

- ✓ Strangeness, charm production: $W^- u \rightarrow s, d \rightarrow c$
- ✓ suppressed by $V_{us} = 0.23$
- ✓ Heavier hadrons — smaller model space
- ✓ Nuclear properties of these hadrons poorly known

2-body mechanism



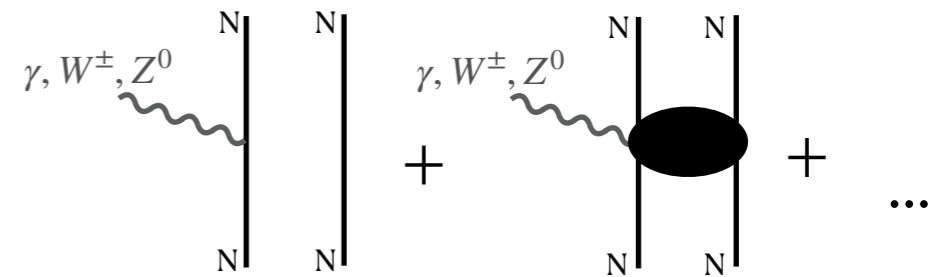
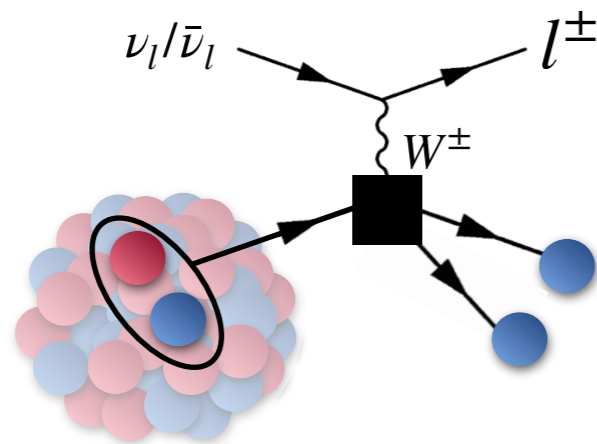
- Scattering on a pair of correlated nucleons, modelled as **meson exchange currents**



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

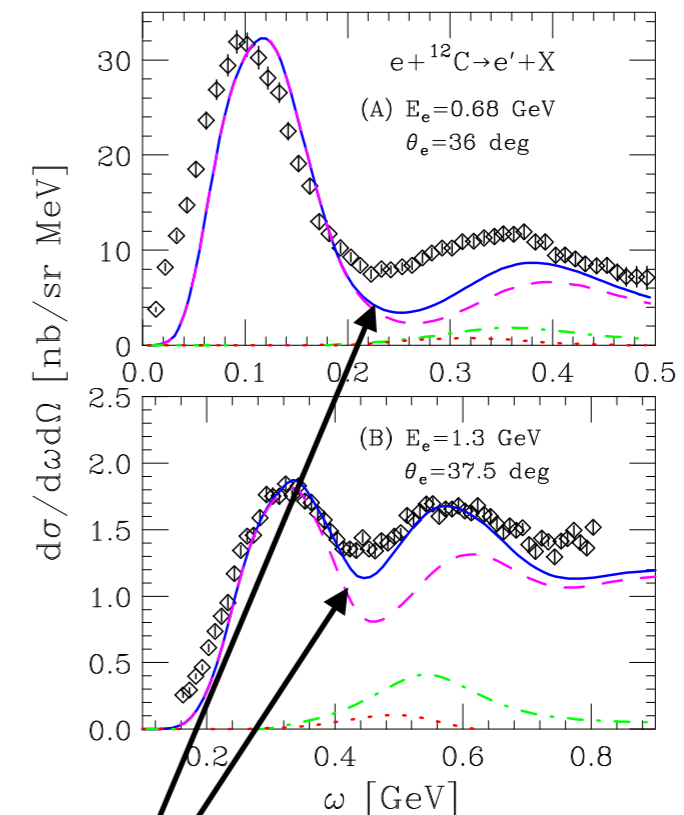
DIP region

2-body mechanism



- Scattering on a pair of correlated nucleons, modelled as **meson exchange currents**
- A lot of theoretical activity within many models:
 - Spectral function, Valencia model, Fermi Gas, relativistic mean-field, Ghent mean-field, super scaling...

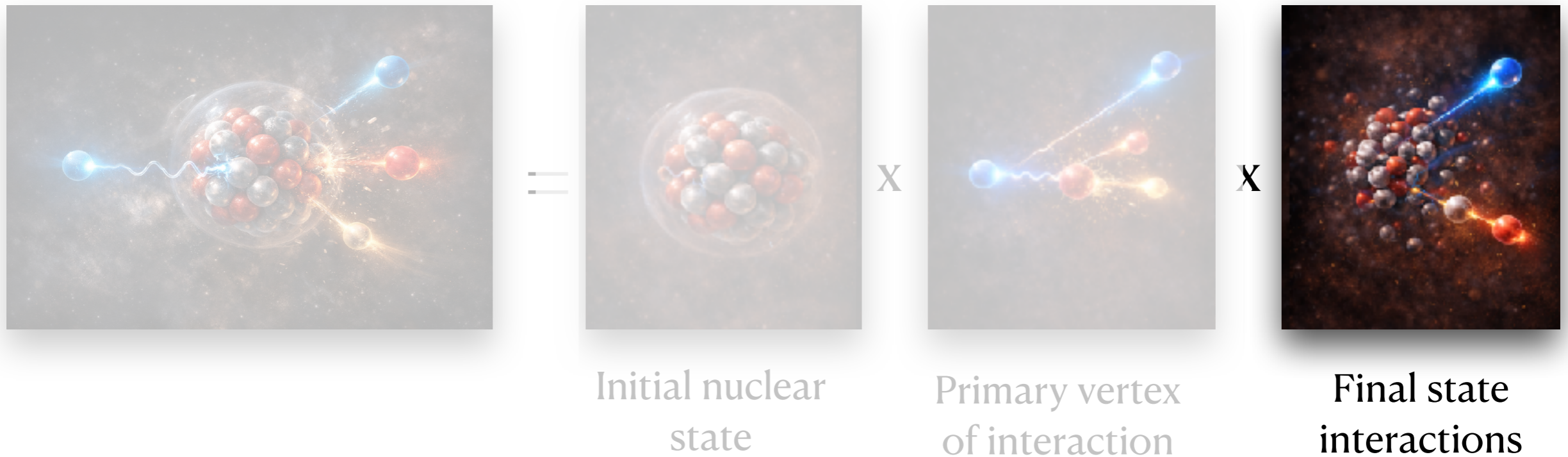
- A.Lovato, N.Rocco, et al *Phys.Rev.C* 112 (2025) 4, 045501
- JES., J. Nieves *Phys.Rev.C* 111 (2025) 2, 025502
- P.R.Casale et al. *Phys.Rev.C* 112 (2025) 6, 065502
- T. Franco-Munoz, J.-McKean et al. arXiv:2605.00756
- ...



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

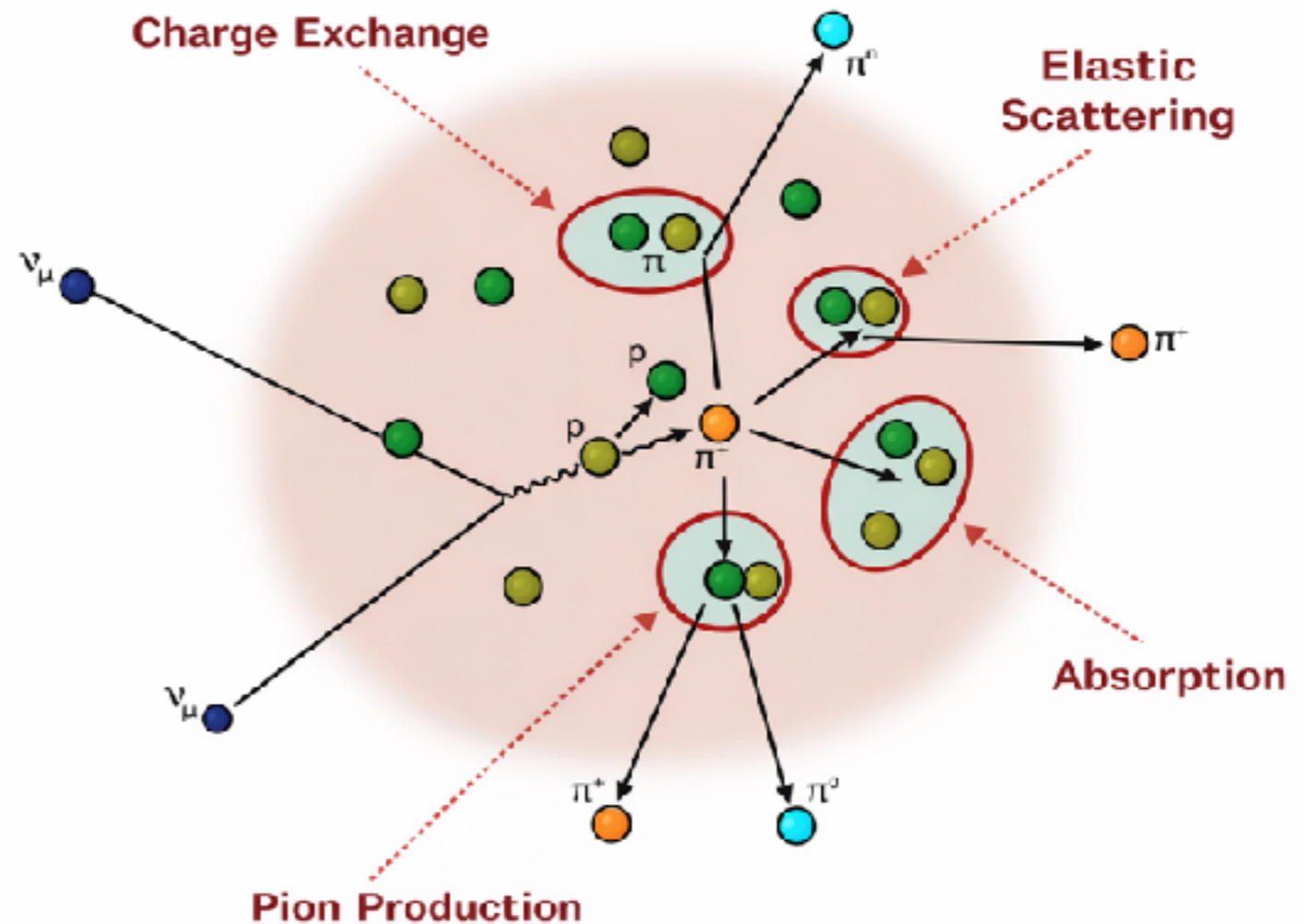
DIP region

Factorisation

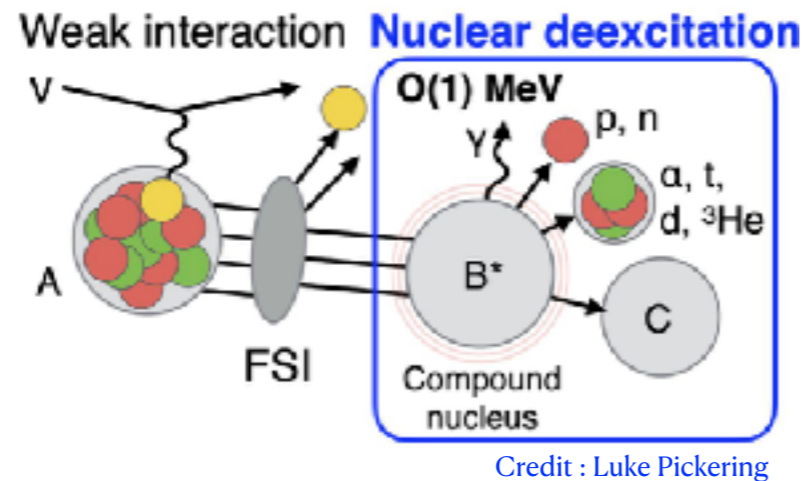
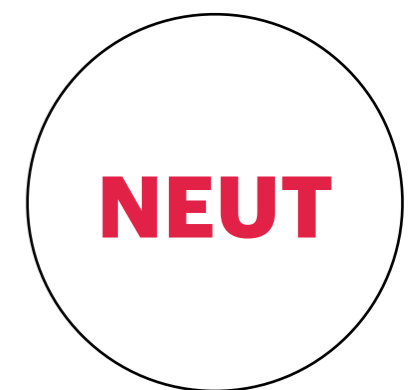


Intra-nuclear cascade

- **Transformation** from the initial configuration of hadrons to the final configuration, i.e. hadrons which leave the nucleus.
- Pions can:
 - Scatter elastically
 - Exchange charge
 - Be absorbed
 - Produce new pions (if enough energy)
- **Factorisation** (cascade does not impact the outgoing lepton)

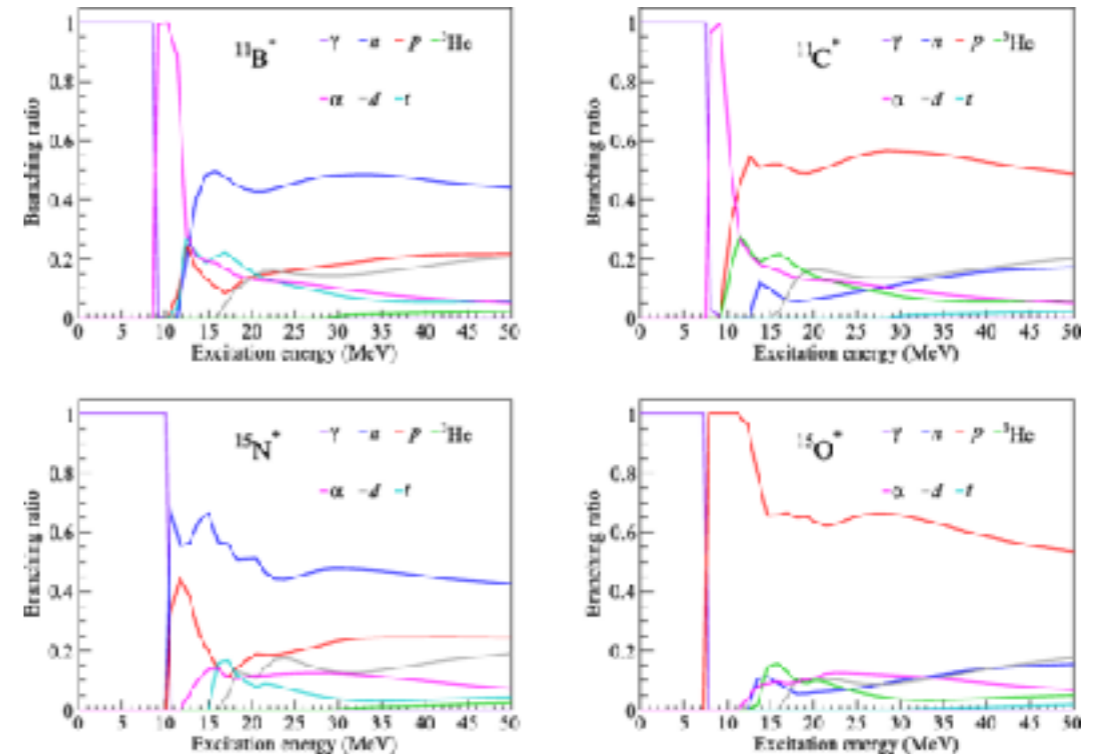


Nuclear de-excitations



Nuclear de-excitation model **NucDeEx**

- Nuclear deexcitation plays a significant role in neutron emissions associated with neutrino-nucleus interactions
- Uses TALYS model which simulates nuclear reactions below 200 MeV



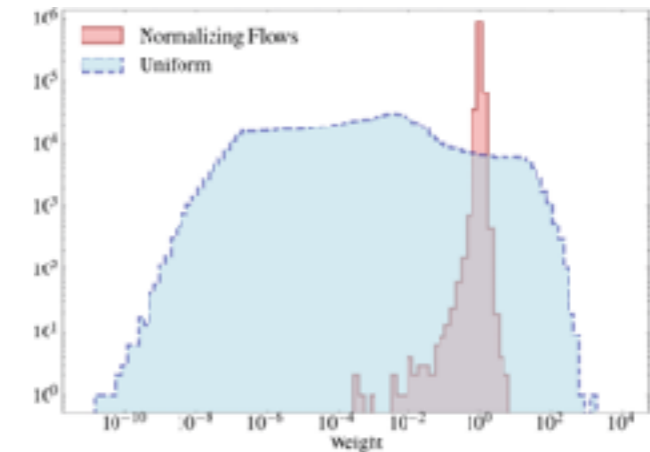
Branching ratios as a function of excitation energy calculated with TALYS

S. Abe, *Phys. Rev. D* 109, 036009 (2024)
 S. Abe, *Phys. Rev. D* 112, 112013 (2025)
 T2K, *Phys. Rev. D* 112, 032003 (2025)

Machine learning for cross-sections

- Implementation of more sophisticated models can benefit from ML techniques
- Use **normalizing flows** to generate surrogate cross sections that closely approximate those of the original model

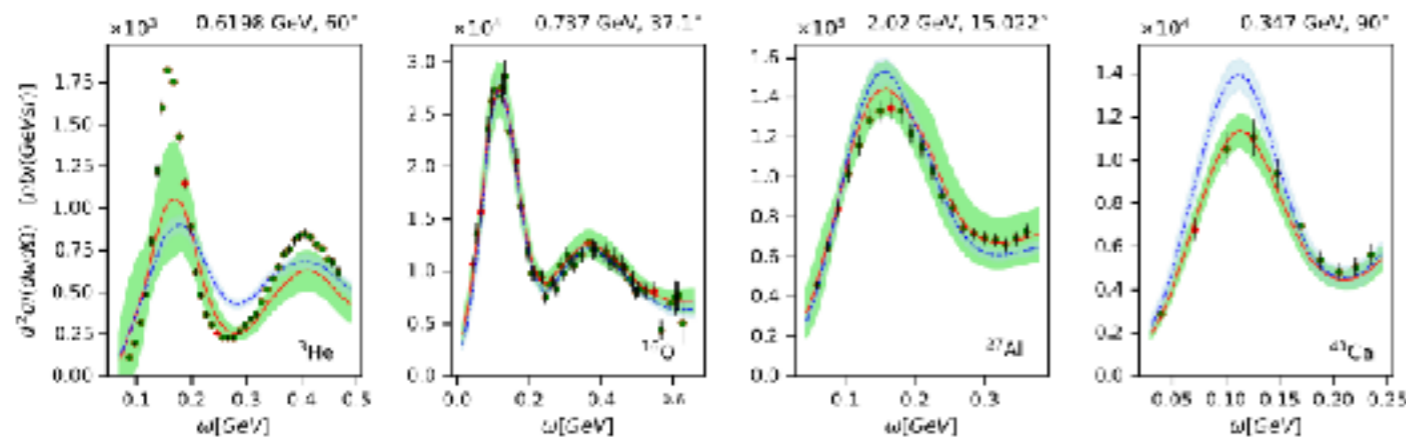
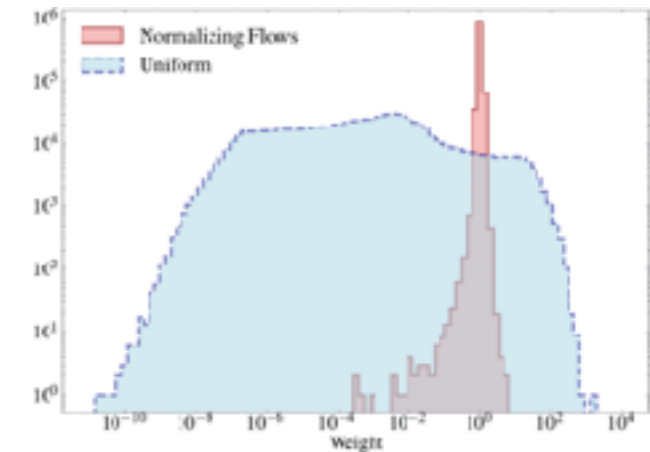
Mathias El Baz et al Phys. Rev D111 113001 (2025)



Machine learning for cross-sections

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Mathias El Baz et al Phys. Rev D111 113001 (2025)



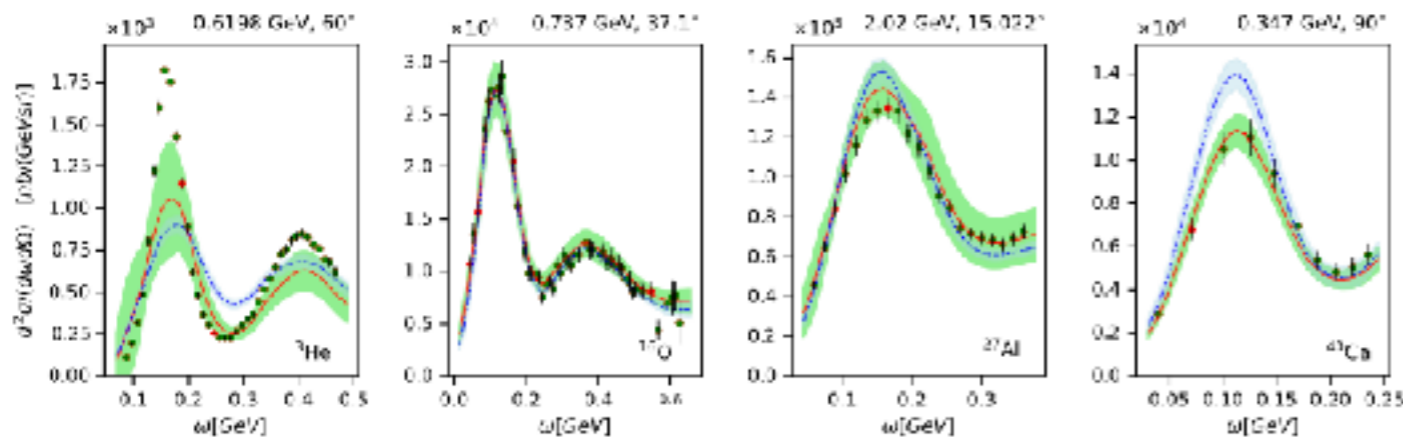
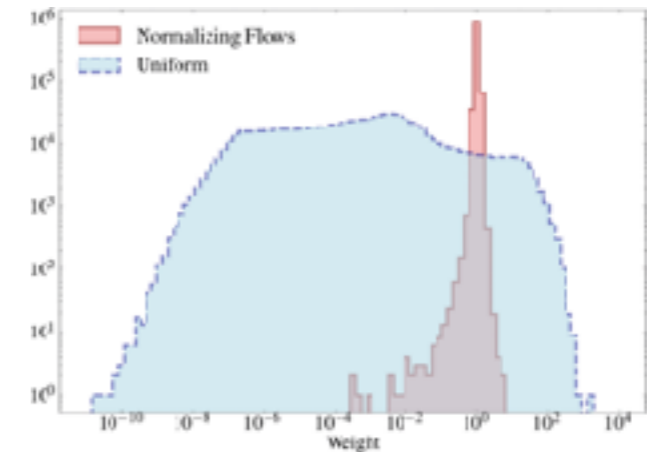
- Explore how to use electron scattering data to inform neutrino experiments using **transfer learning**
- Currently used only for electron scattering to transfer from ^{12}C to other targets

K. Graczyk et al. Phys. Rev. Lett. 135, 052502 (2025)

Machine learning for cross-sections

- Implementation of more sophisticated models can benefit from ML techniques
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Mathias El Baz et al Phys. Rev D111 113001 (2025)

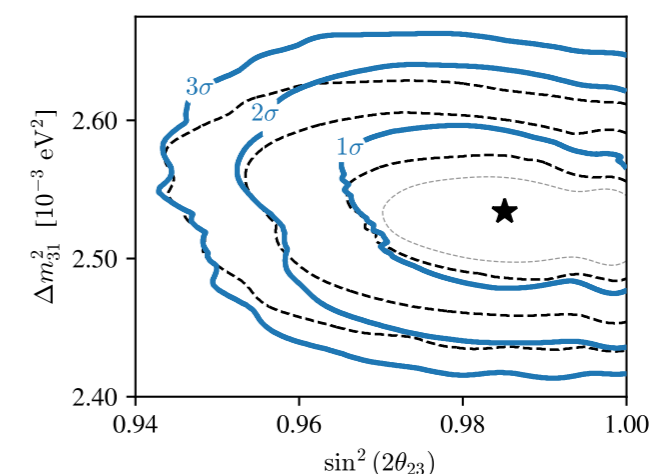


- Explore how to use electron scattering data to inform neutrino experiments using **transfer learning**
- Currently used only for electron scattering to transfer from ^{12}C to other targets

K. Graczyk et al. Phys. Rev. Lett. 135, 052502 (2025)

- Toy model analysis: neural network cross-section model trained on near detector data
- Oscillation analysis using this data-driven model

D. Hackett et al., Phys.Rev.D 112 (2025) 11, 113005



Summary

- Multi-scale problem which requires broad expertise
- Many developments:
 - **Theoretical** (2-body currents)
 - **Data-driven** (using available data on electron, neutrino, other probes)
 - **Numerical** (ML tools, model implementations to MC)
 - Including **de-excitation models** to MC generators
- To do: assessment of theoretical uncertainties



Thank you!

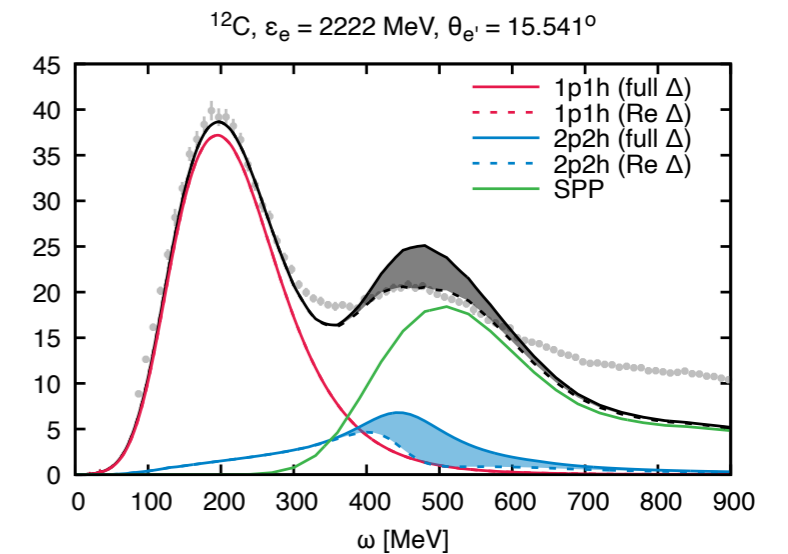
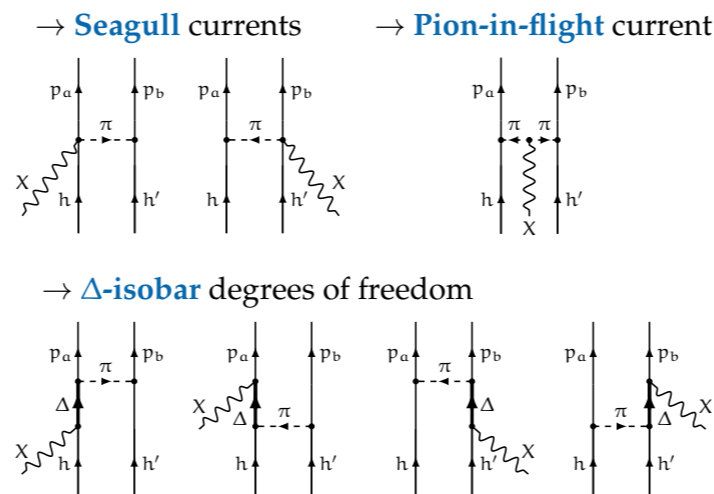
Backup

2p2h

Recent developments: mean-field approaches

Ghent group (Hartree-Fock)

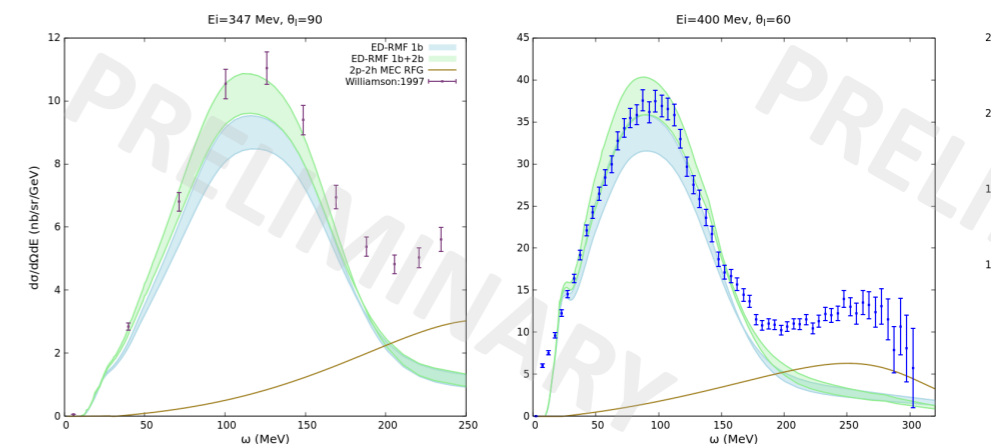
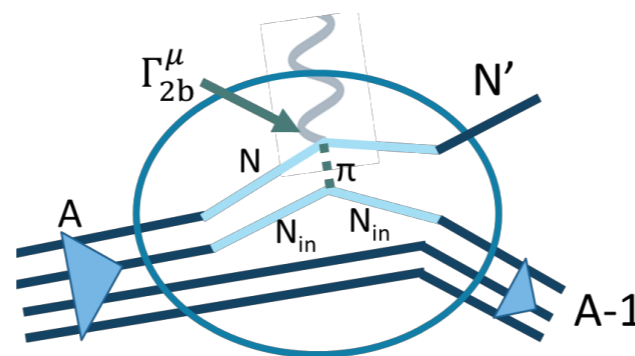
- Meson exchange currents
- Short-range correlations



(K. Niewczas, NuInt2024)

Relativistic mean-field

- Meson exchange currents in particle-hole excitations



(T. Franco Muñoz, NuInt2024)

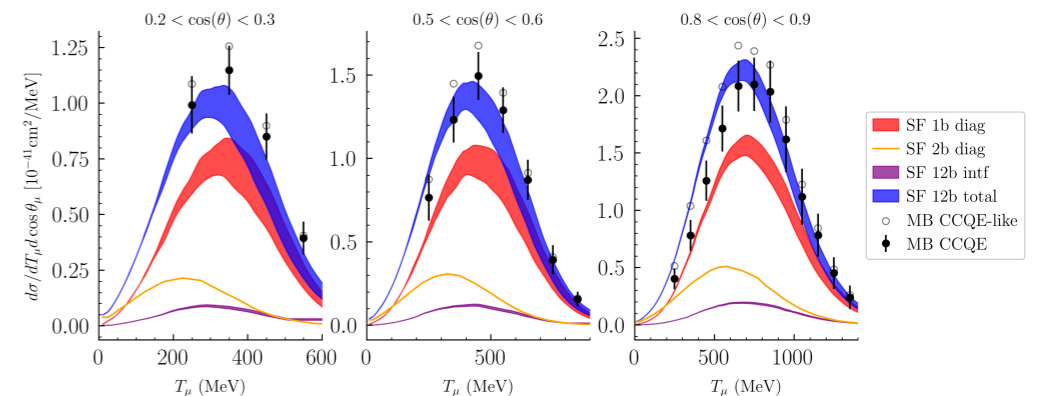
2p2h

Recent developments: results for neutrino scattering

Spectral function approach

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

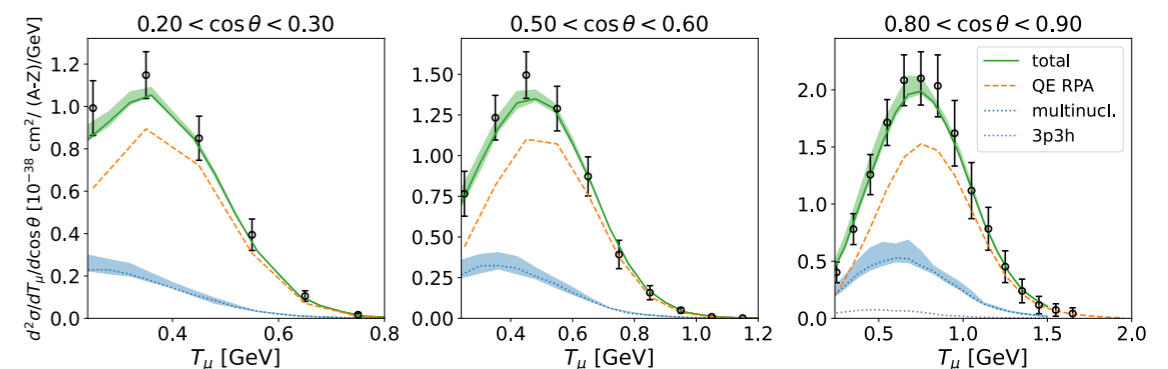
Comparison with MiniBooNE CCQE on 12C



A.Lovato, N.Rocco, et al *Phys.Rev.C* 112 (2025) 4, 045501

Valencia model

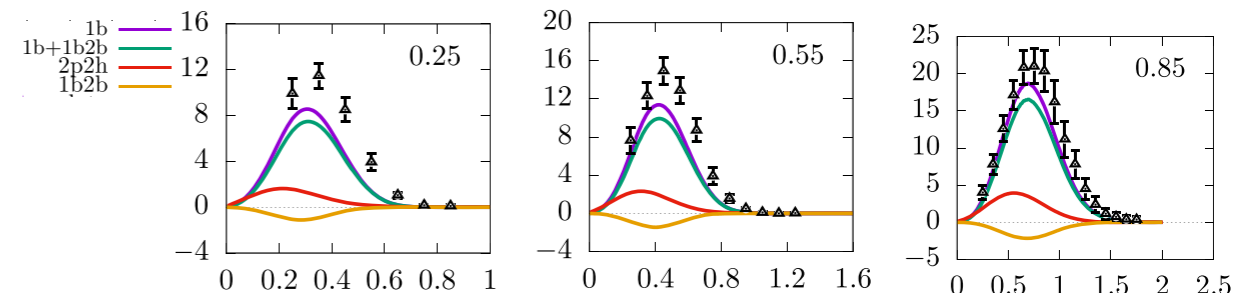
- Meson exchange current with effective interaction
- Uncertainty estimation: treatment of Δ self-energy



JES., J. Nieves *Phys.Rev.C* 111 (2025) 2, 025502

Relativistic mean-field + Short-range correlations

- Calculation of interference of 1-body and 2-body currents
- Next step: adding short-range correlations for neutrino scattering



P.R.Casale et al. *Phys.Rev.C* 112 (2025) 6, 065502

Axial form factor

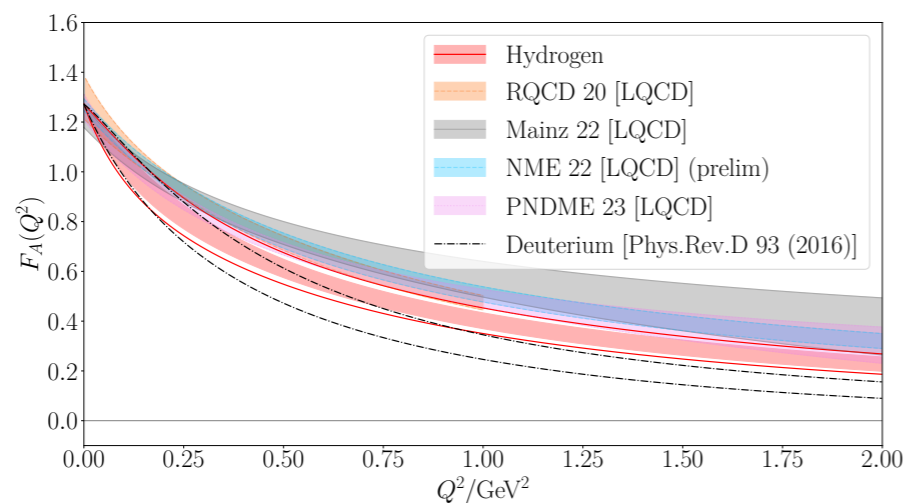
- Dipole ansatz

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

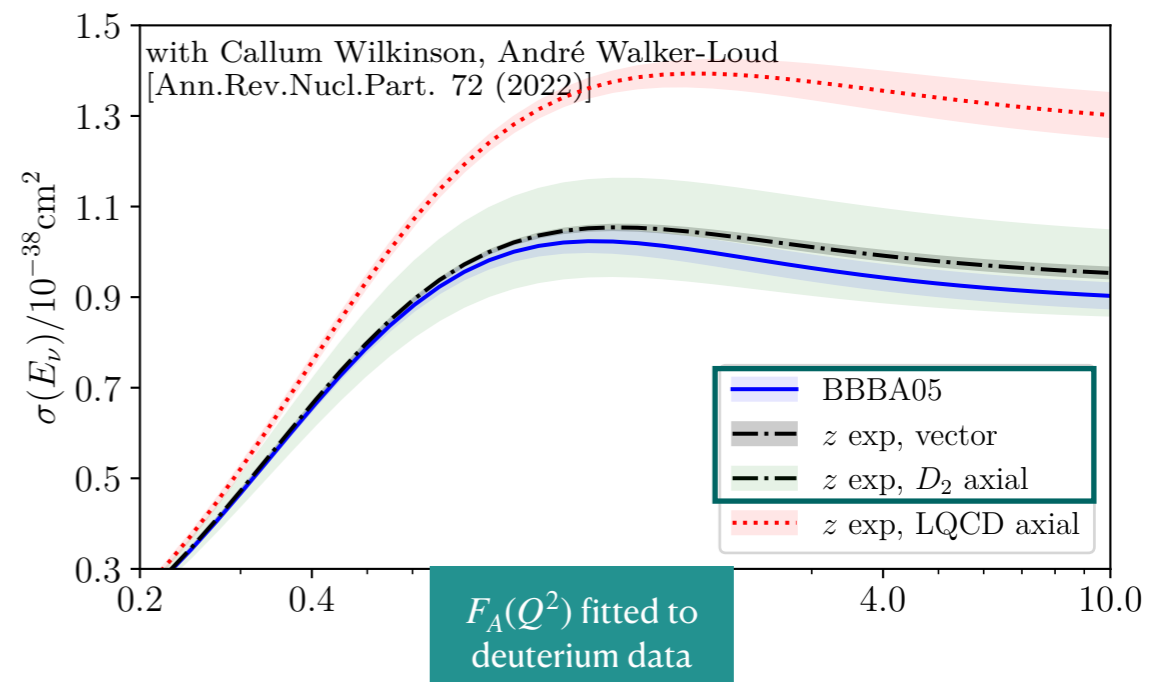
- Deuterium data: $m_A = 1014(14)$ MeV

- Recent results:

- LQCD calculations
- MINER ν A measurement on hydrogen (T. Cai et al. Nature 614, 48–53 (2023))



~ 30 % difference coming from the LQCD form-factor



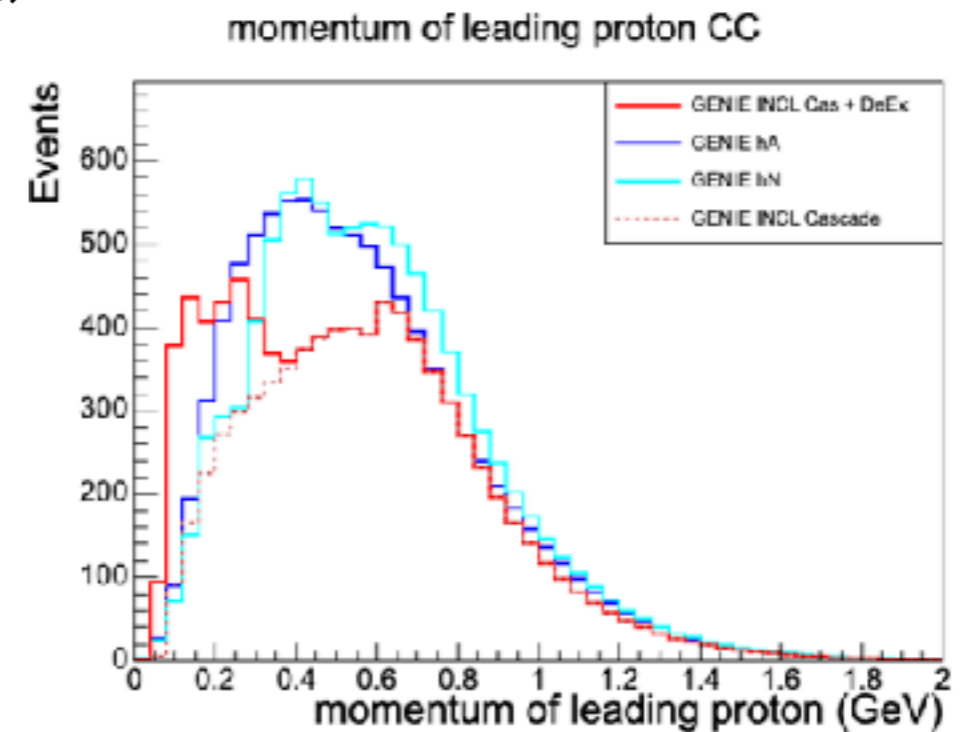
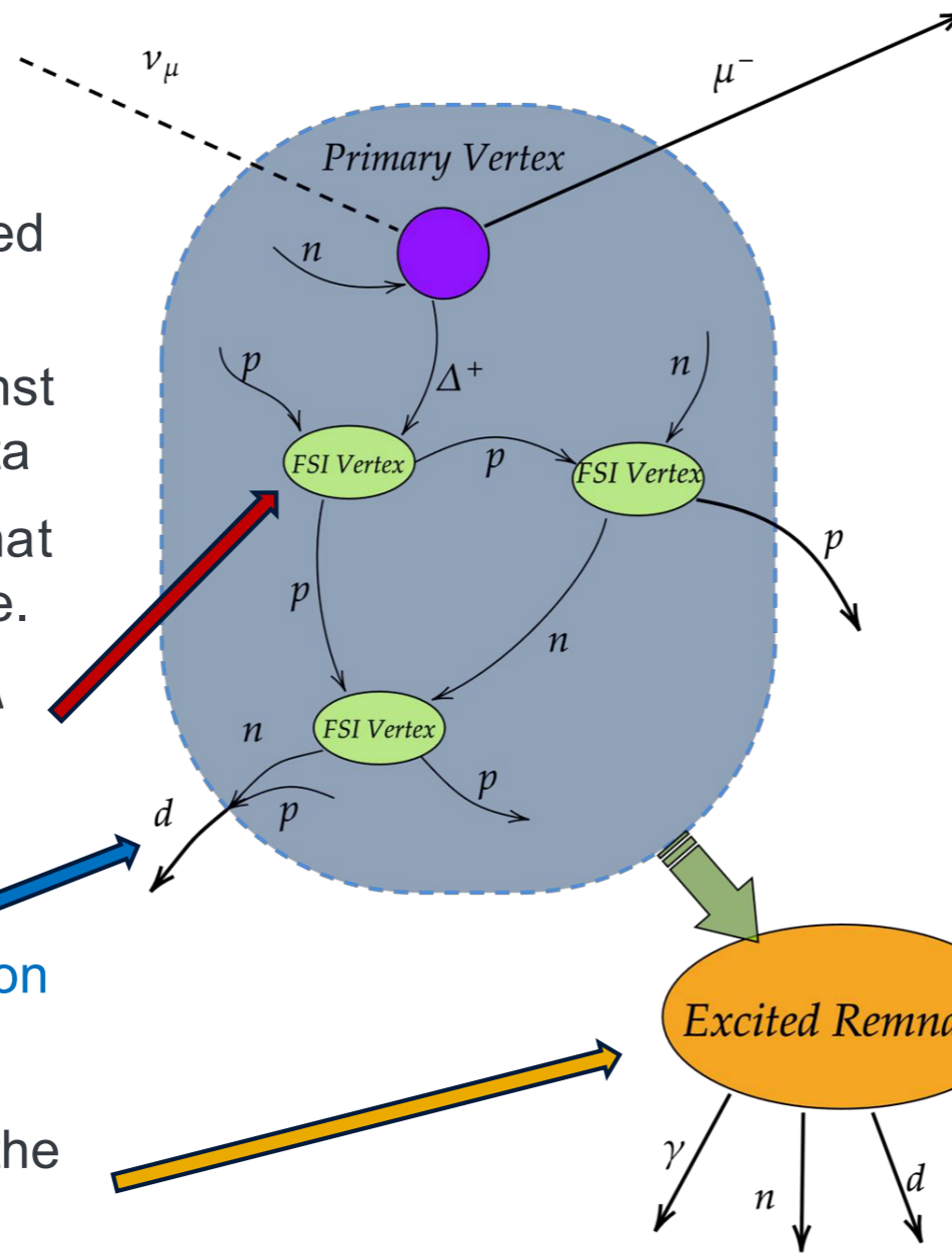
Ann.Rev.Nucl.Part.Sci. 72 (2022) 205-232

Alternative cascade model



INCL is an intranuclear cascade model developed in Liège.

- Primarily tested against hadron scattering data
- It includes features that GENIE does not have.
 - Δ re-scattering:** Δ collides with a nucleon
 - Multi-nucleon clusters production**
 - d, t, h, α
 - De-excitation** of the remnant nucleus



$\nu_\mu -^{40}\text{Ar}$ scattering with MicroBooNE flux