Neutrino Cross Sections and Interactions

Neutrino University

2021 Summer Undergraduate Lecture Series

Fermilab

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Neutrinos are abundant

Produced at various sources with different energies

Interacting only via the weak force - very rarely

Measuring neutrino interactions in massive detectors

Neutrino Cross Sections and Interactions

Today:

What is the probability for neutrino interactions to happen?

What is a cross section?

Why is it so important in neutrino physics?

The nuclear target

Possible neutrino nuclei interactions

Final State interactions

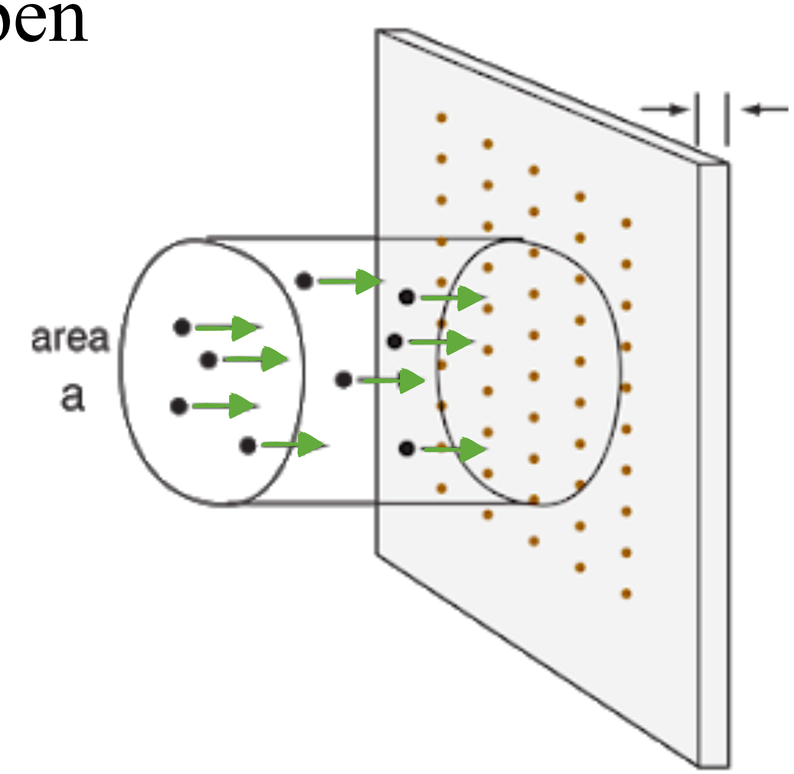
Some examples for neutrino cross section measurements

How can we estimate those cross sections?

How can we improve?

Cross Section

Cross section, σ, is a measure for a process to happen



Experimentally, it depends on:

The process itself

The experiments condition.

$$R = \sigma \mathcal{L}$$

$$\sigma = \frac{R}{\mathcal{L}}$$

Rate - Number of interactions per unit time

Luminosity - depends on beam and target

$$\mathcal{L} = \Phi N_{targets}$$

Incoming flux

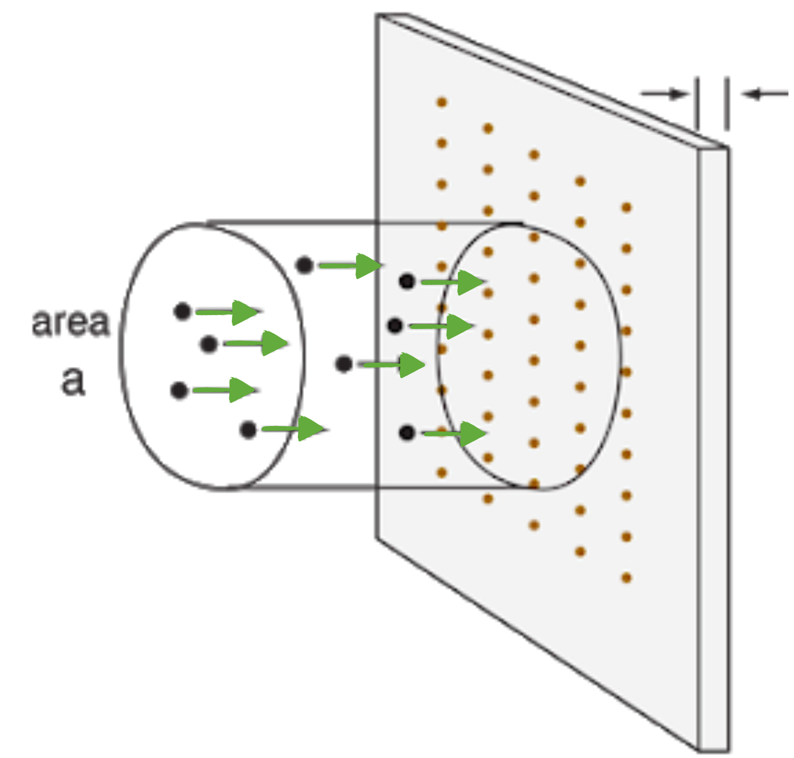
$$L = \int \mathcal{L} dt$$

Integrated luminosity [1/Area]

Integrated Cross Section

Integrated cross section

$$\sigma = \int \frac{R}{\mathcal{L}} dt = \frac{N}{L}^{\text{scatter}}$$

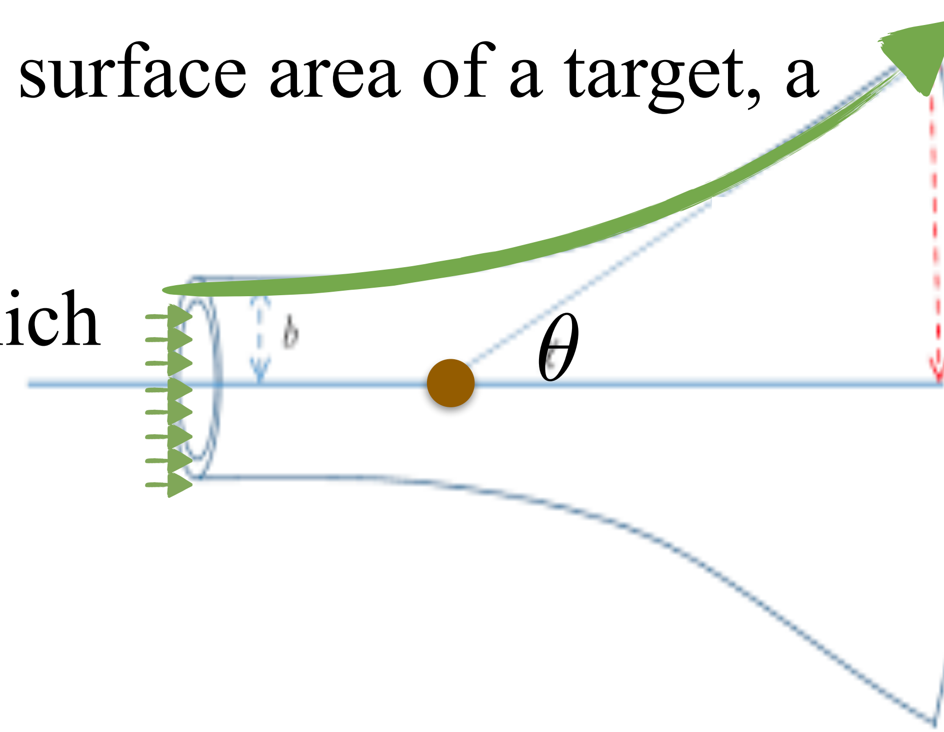


σ has units area: cm^2 or barn (1 br = 1E-24 cm^2)

σ is also: Lorentz invariant, additive $\sigma_{tot} = \sum_i \sigma_i$

Classically, σ can be interpreted as the effective surface area of a target, a

Or the area around the target particle within which the incident particles will interact with target.



Differential Cross Section

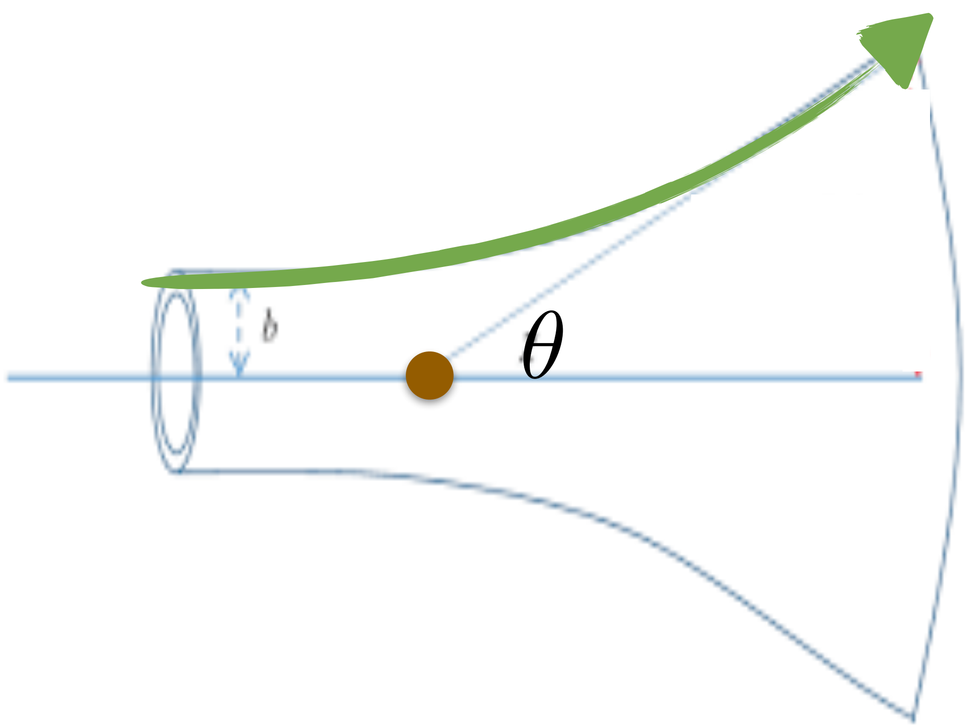
$$\frac{d\sigma}{dX_n} = \frac{N}{L\Delta_n}$$

Δ - bin width (product of bin widths)

For example: $$\frac{d\sigma}{dp_l}$$

$$\frac{d\sigma}{dcos(\theta_l)}$$

$$\frac{d\sigma}{d\Omega}$$



Differential Cross Section - in real life

$$\frac{d\sigma}{dX_n} = \frac{N_n^{\text{on}} - N_n^{\text{off}} - B_n}{\eta_n^{\mu} \cdot \Phi_n \cdot N_{\text{targets}} \cdot \Delta_n}$$

N^{on} - # of events in beam-on data

N^{off} - # of events in beam-off data

DATA

B_n - Background

η_n^{μ} - Effective detection efficiency

MC

N_{targets} - number of scattering nuclei

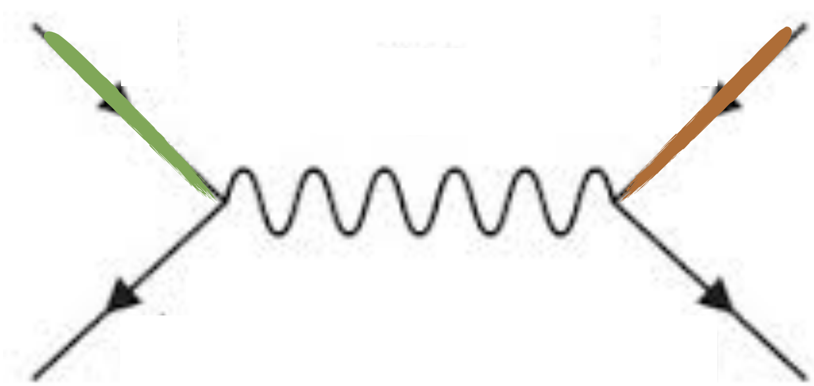
ϕ_{ν} - neutrino flux

Δ - bin width (product of bin widths)

constants

Fermi golden rule

For any process. the rate is proportional to:



$$R \propto |M_{if}|^2 \rho$$

Density of states

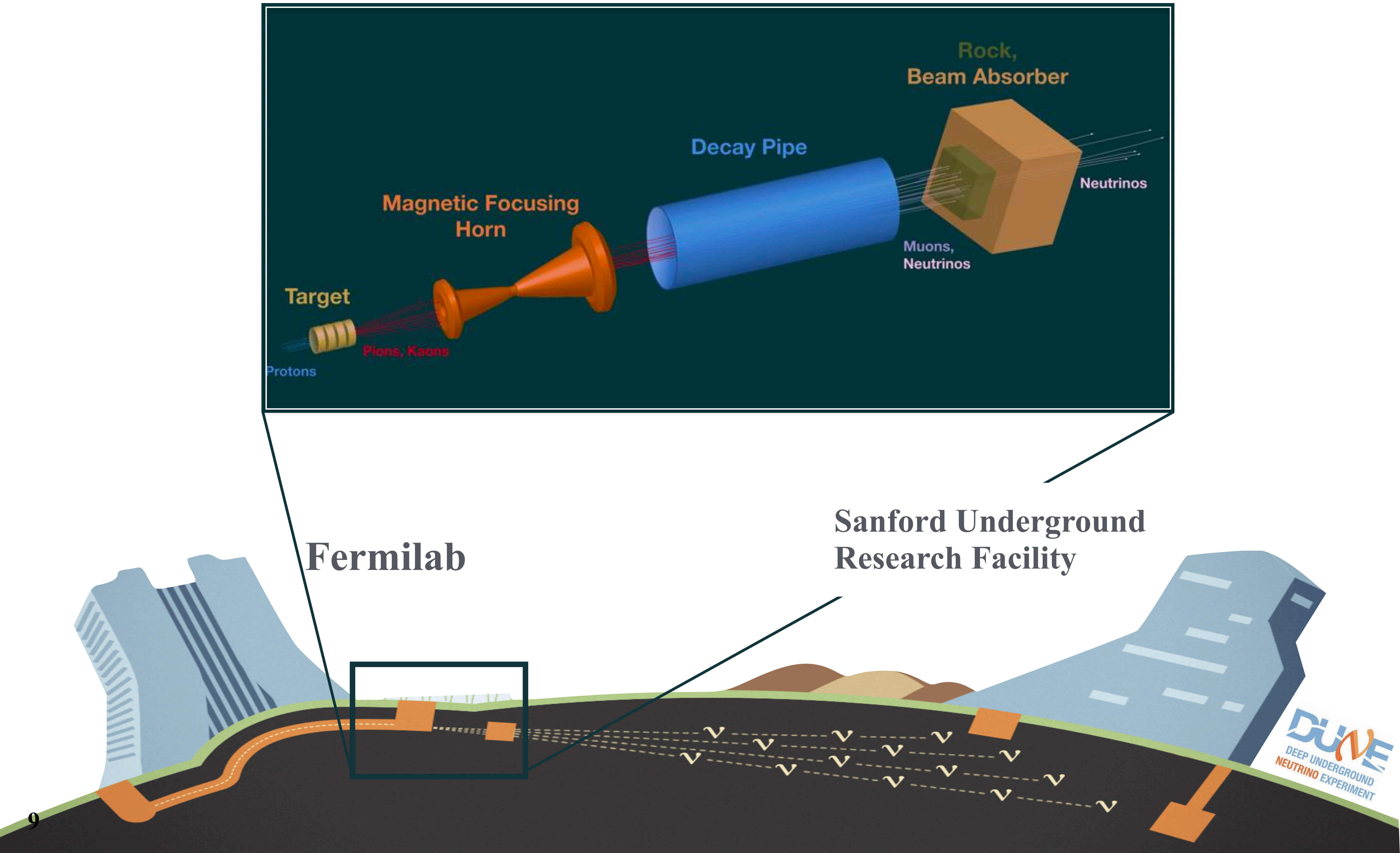
Matrix element

$$M_{if} = \langle \psi_f | V(\vec{r}) | \psi_i \rangle = \int \psi_f^* \mathcal{H} \psi_i d\tau$$

Calculable in perturbation theory

For more see: Quarks and Leptons, Halzen & Martin p79

Beam flux and Targets in Neutrino Physics



flux and n targets - in Neutrino Physics

Counting POT - Protons On Target

For example Fermilab BNB $O(10^{21})$ POTs per year

µBooNE $\Phi = 3.15769 \times 10^{10} \text{cm}^{-2}$ per year

Nuclei target with high A. Example Argon $Z = 18$, $A = 40$

Neutrino is dimensionless wrt to atomic nuclei $R_A = 1.2\ A^{1/3}$ fm

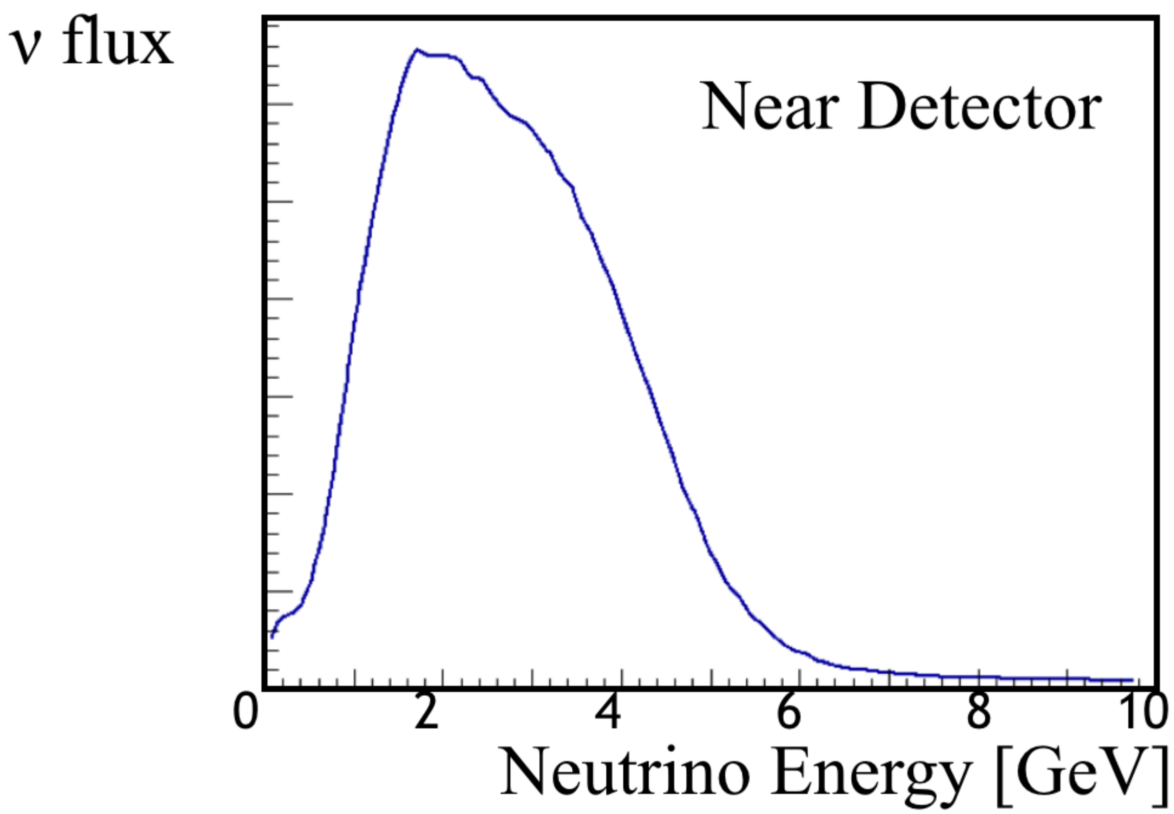
Detectors are measured in tons (or tons in fiducial volume)

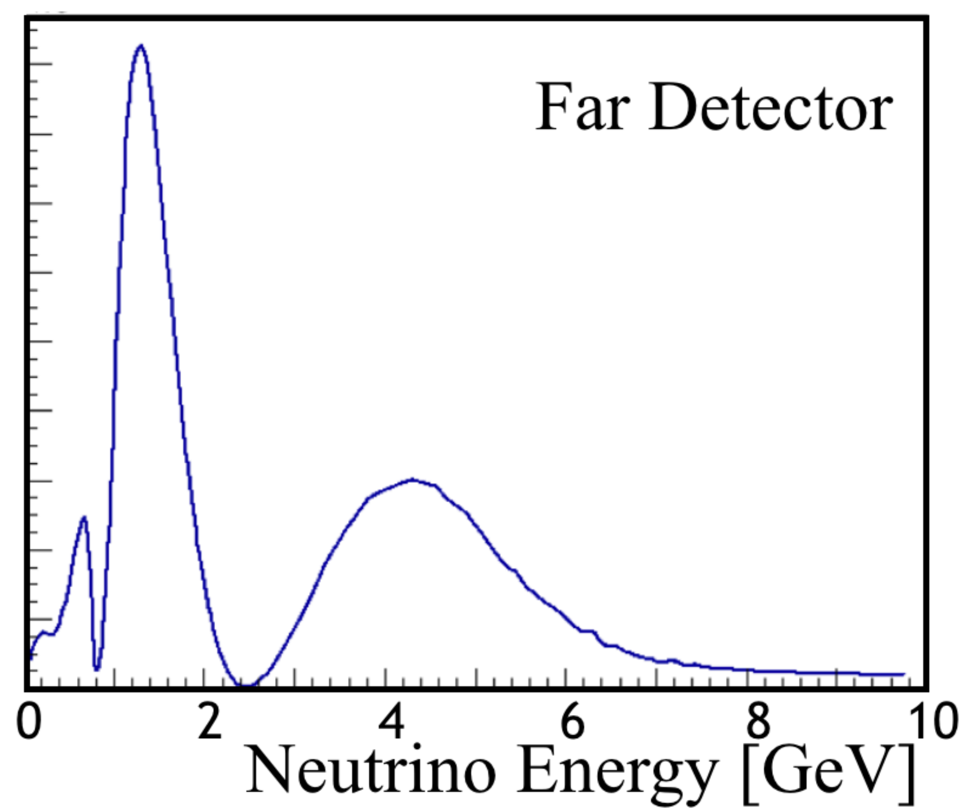
For example µBooNE $N_{targets} = \rho_{Ar} V N_A / m_{mol} = 1.203 \times 10^{30}$

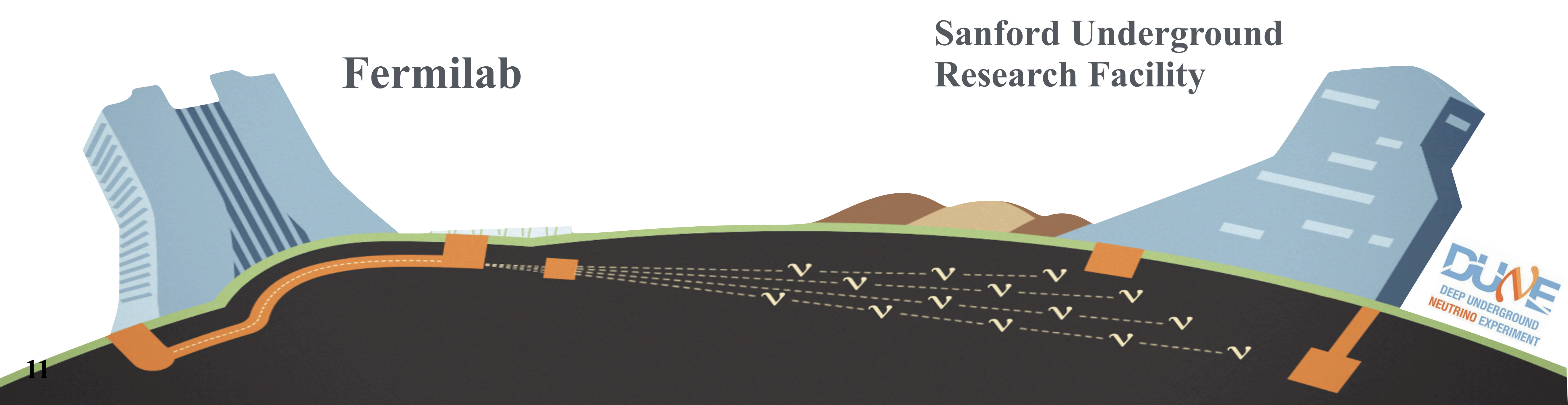
DUNE Additional orders of magnitude

Cross Section - Charged Current neutrino interaction on Argon $O(10^{-38}\ \text{cm}^2)$

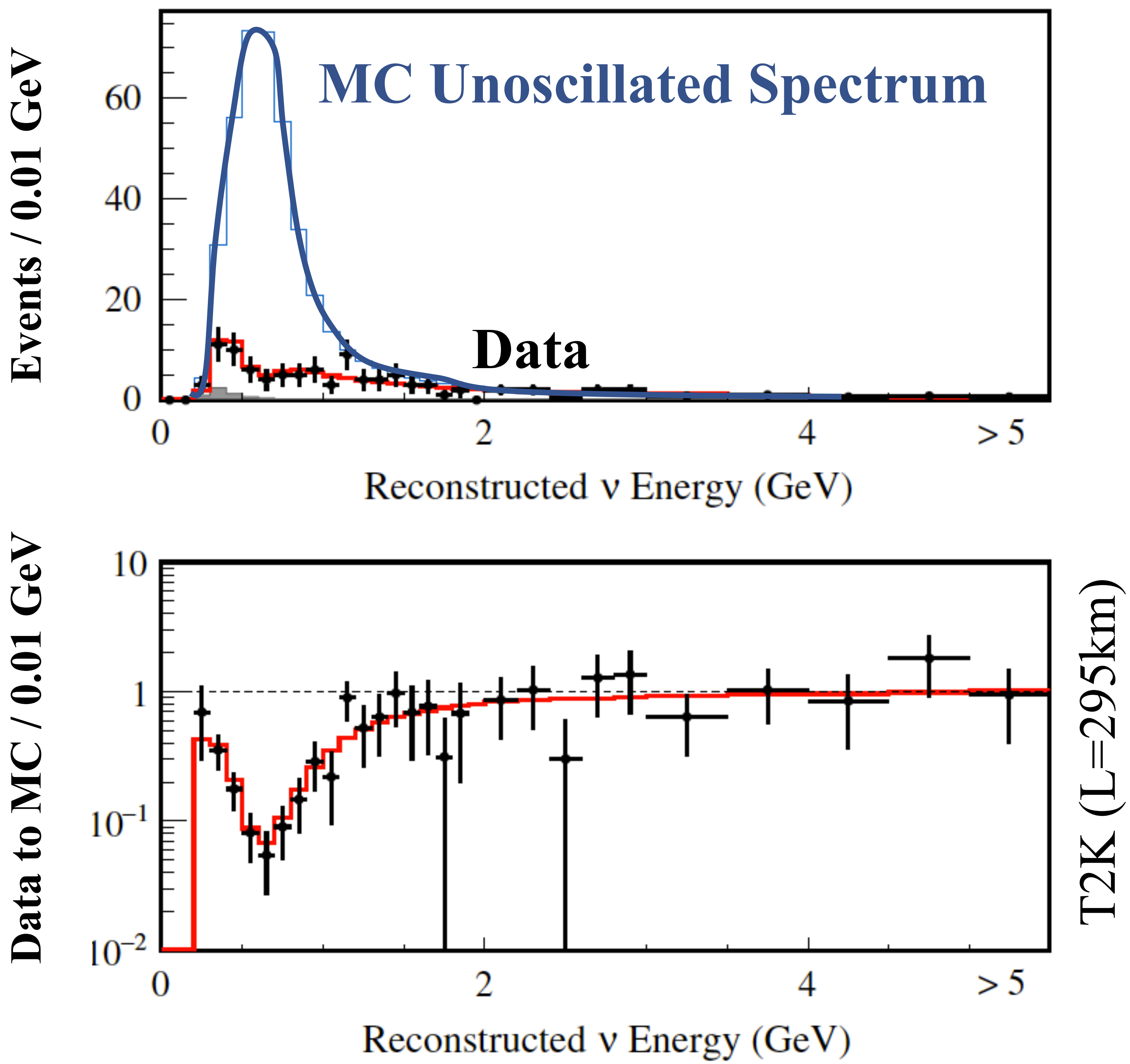
Why Cross Section is important when oscillations







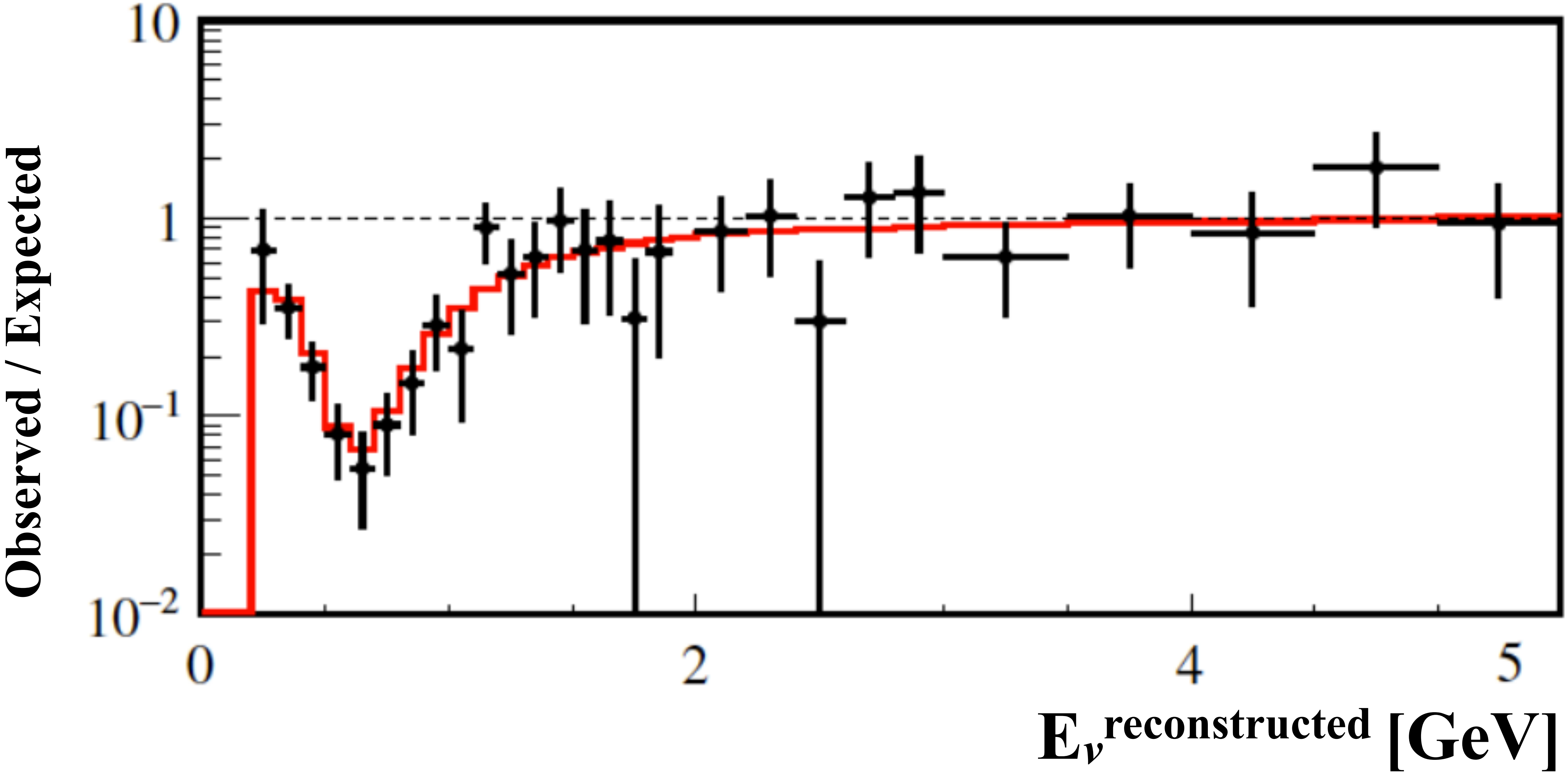
Oscillations Require incoming E_ν Reconstruction



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

Oscillations Require incoming E_ν Reconstruction

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



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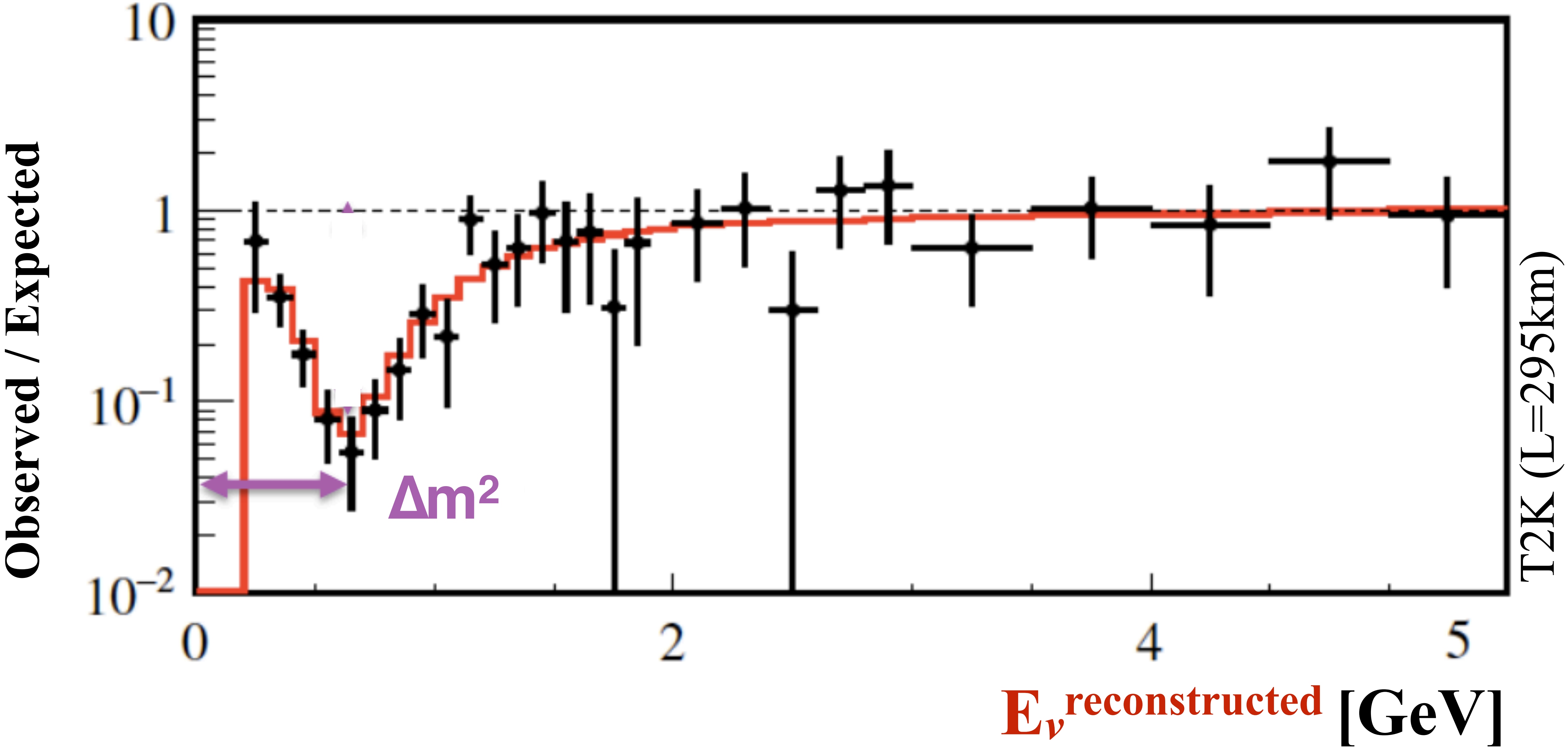

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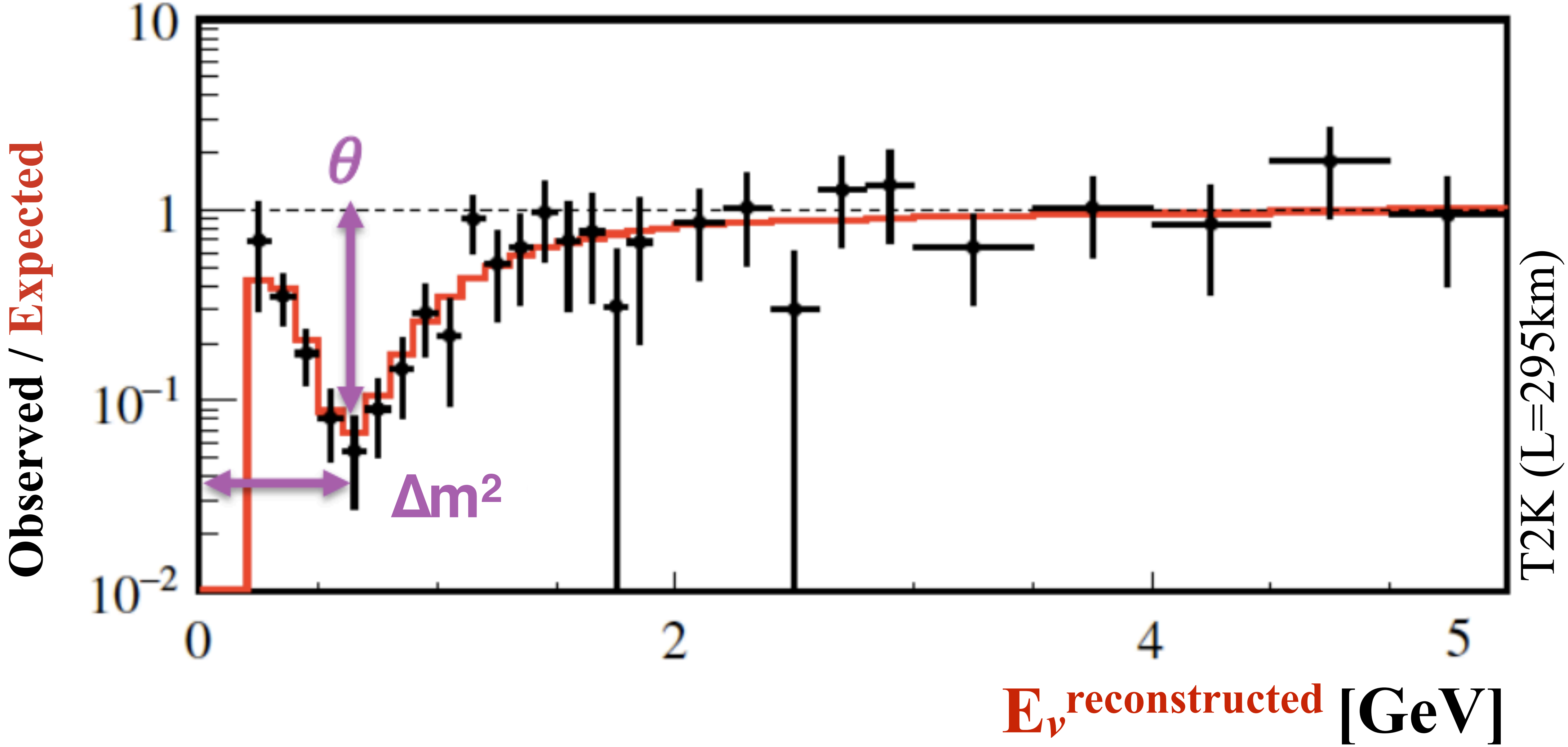

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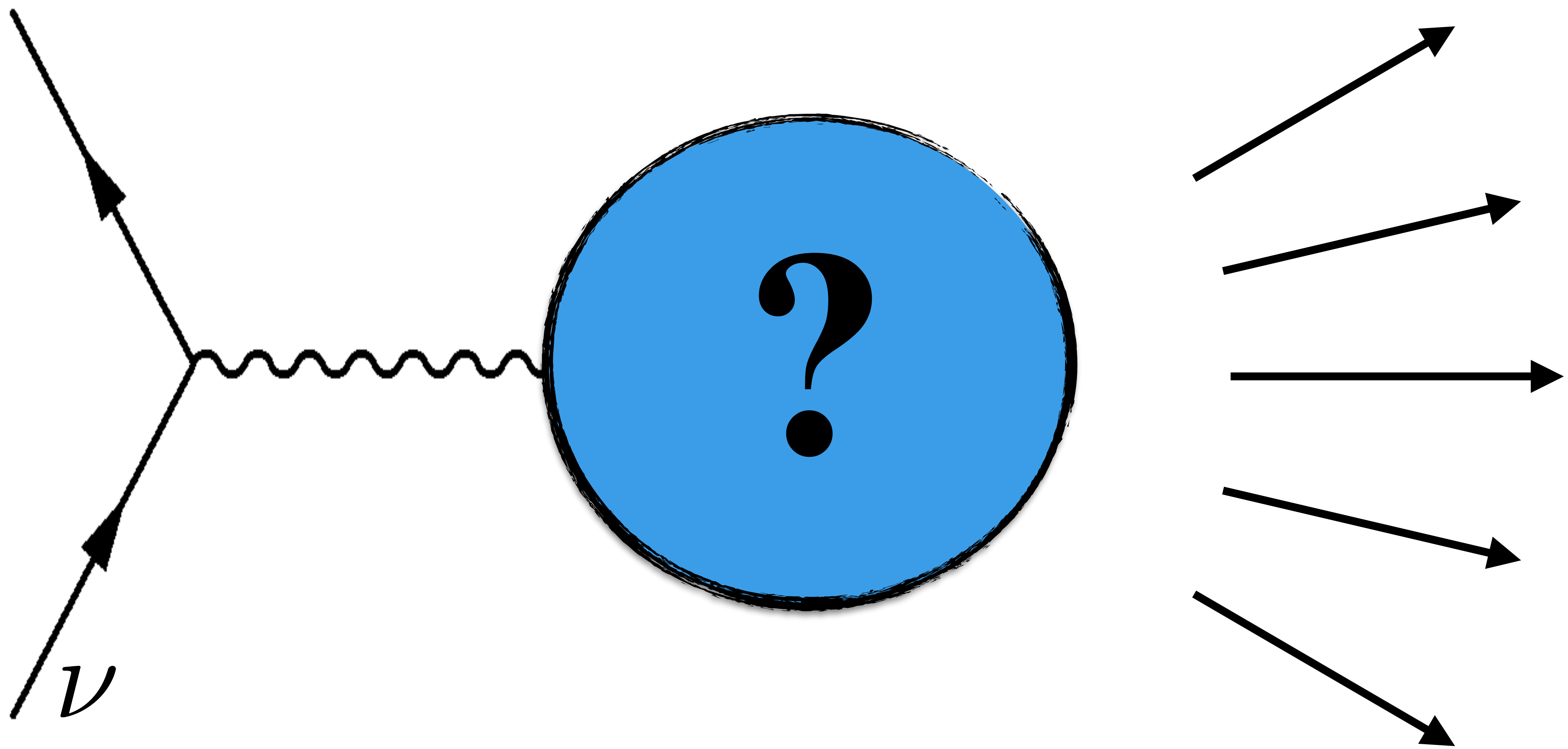
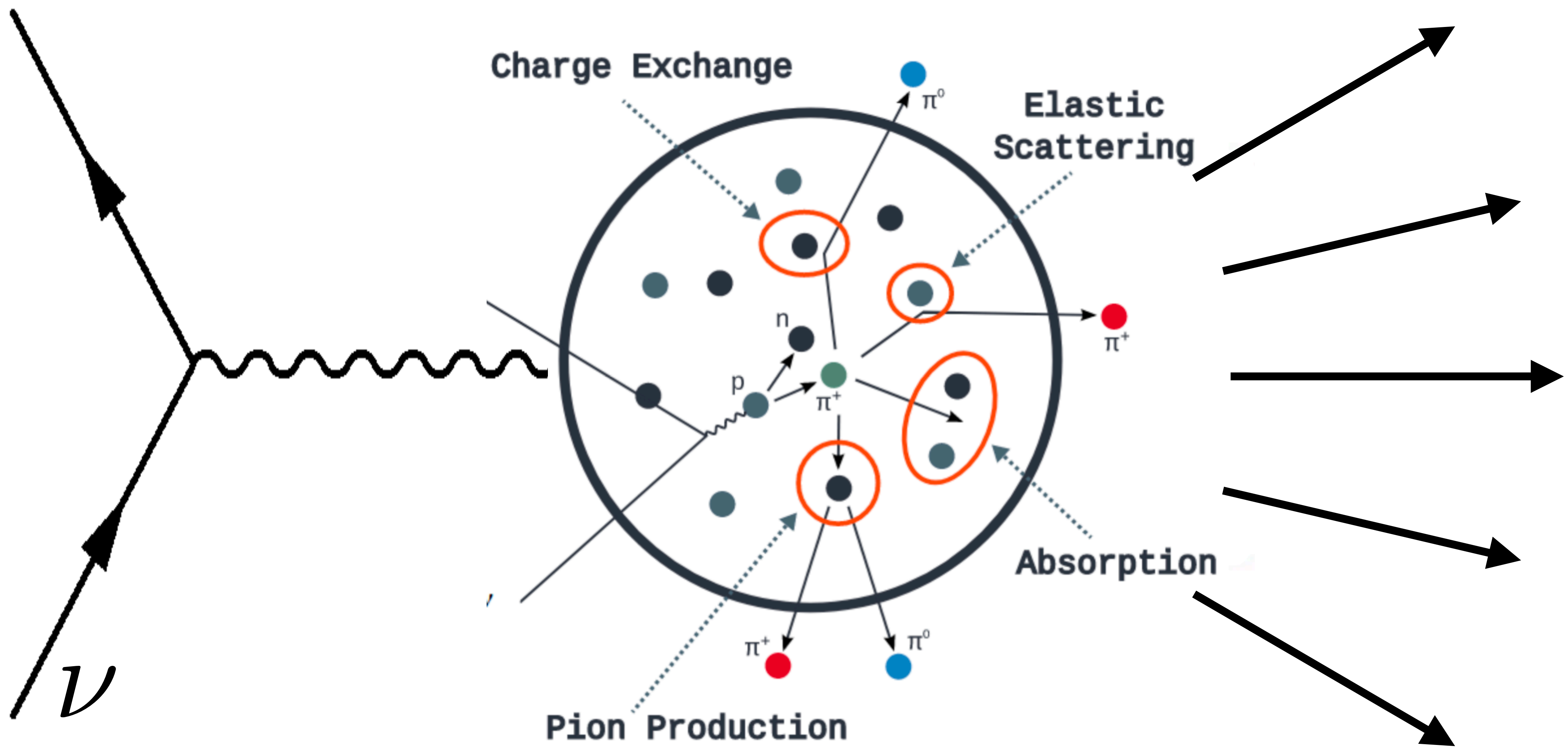
Detecting neutrino interaction



$$E_\nu = \Sigma\, E_{\text{outgoing particles}}$$

Detecting neutrino interaction



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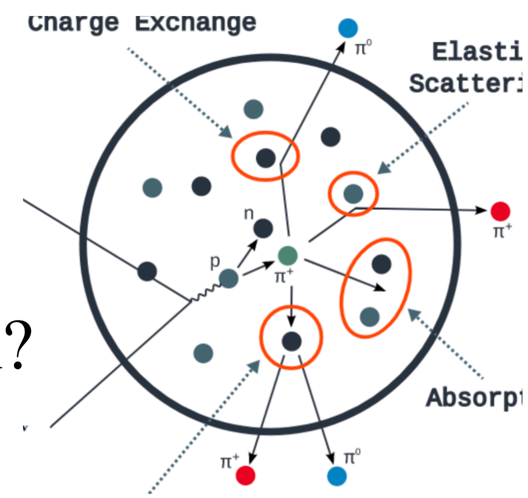
The nuclei



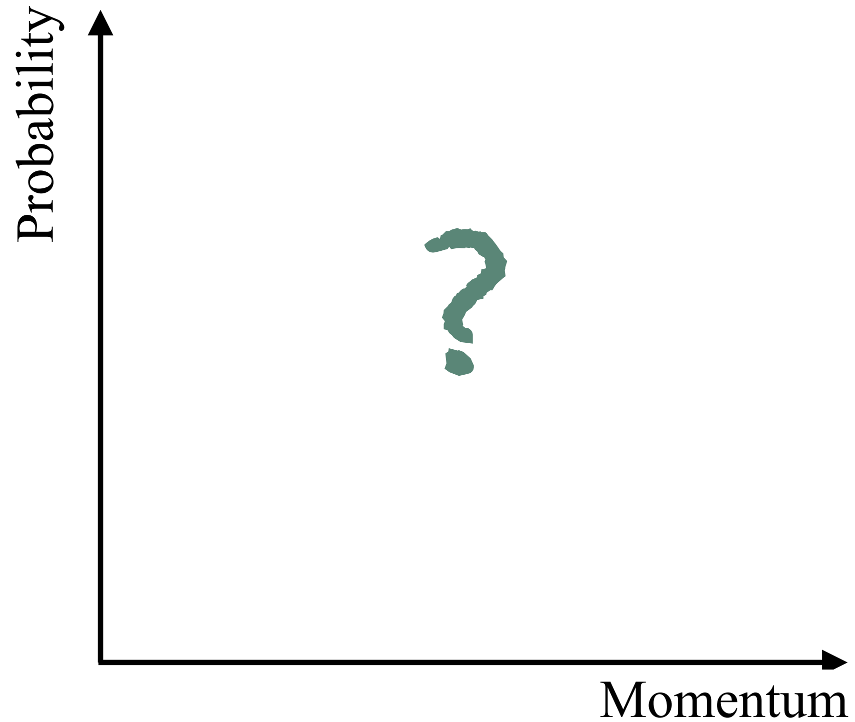
The atom is made out of nucleons

How are they interacting with one another?

What is their initial state? Their momentum distribution? their motion?

Important to understand the initial state to understand final state

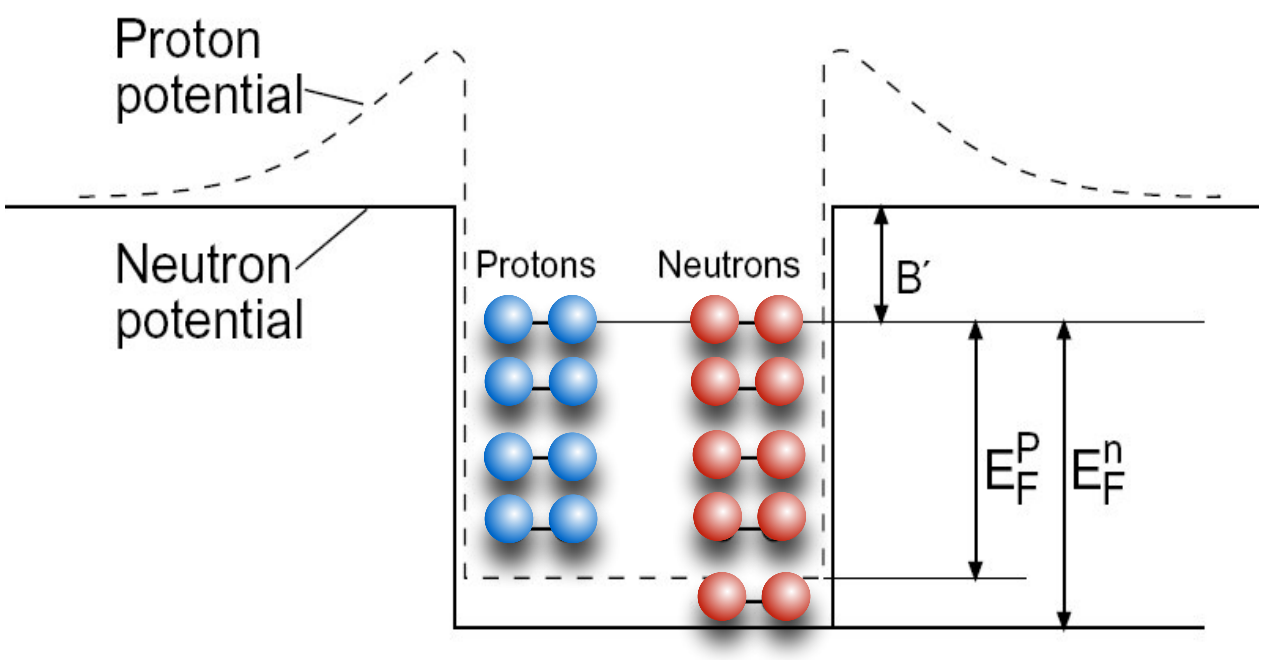
Historically been studied by bombarding by electrons or other hadrons and measuring their final state



Initial State - Fermi Gas Model

Simplest model

- No interactions between nucleons
- Moving freely inside the nucleus volume (potential well).
- Using Pauli exclusion principle (only two 1/2 spin fermions in each energy state)

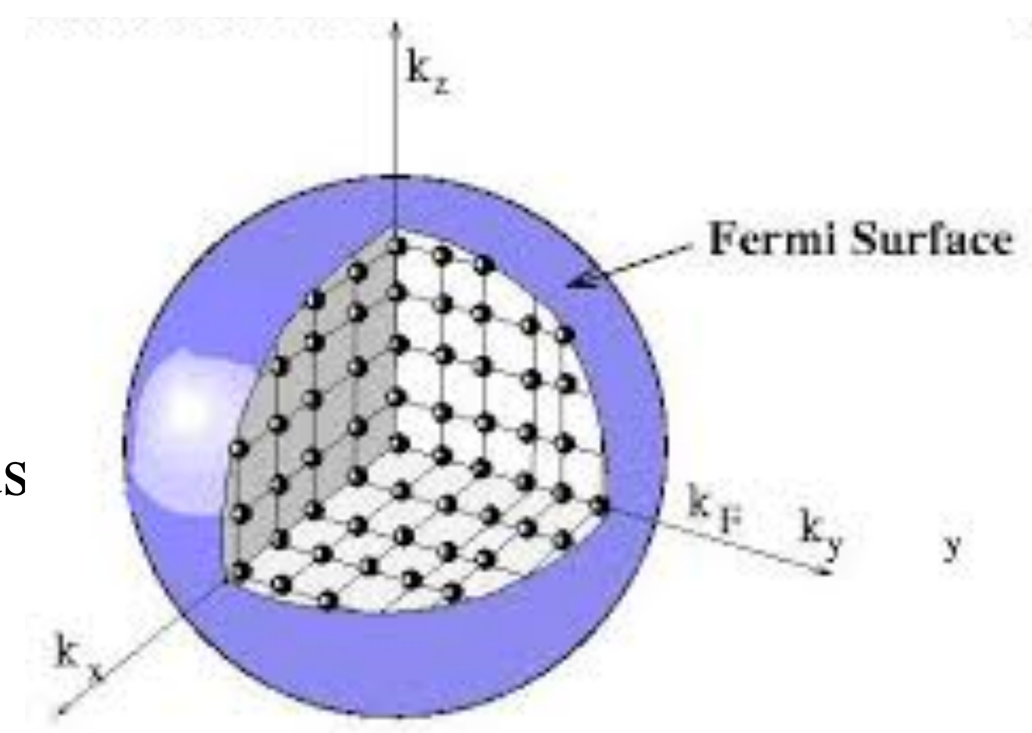


Fermi energy (E_F)

The highest occupied state energy

Binding energy (B/E_B)

Energy required to separate a nucleon from nucleus



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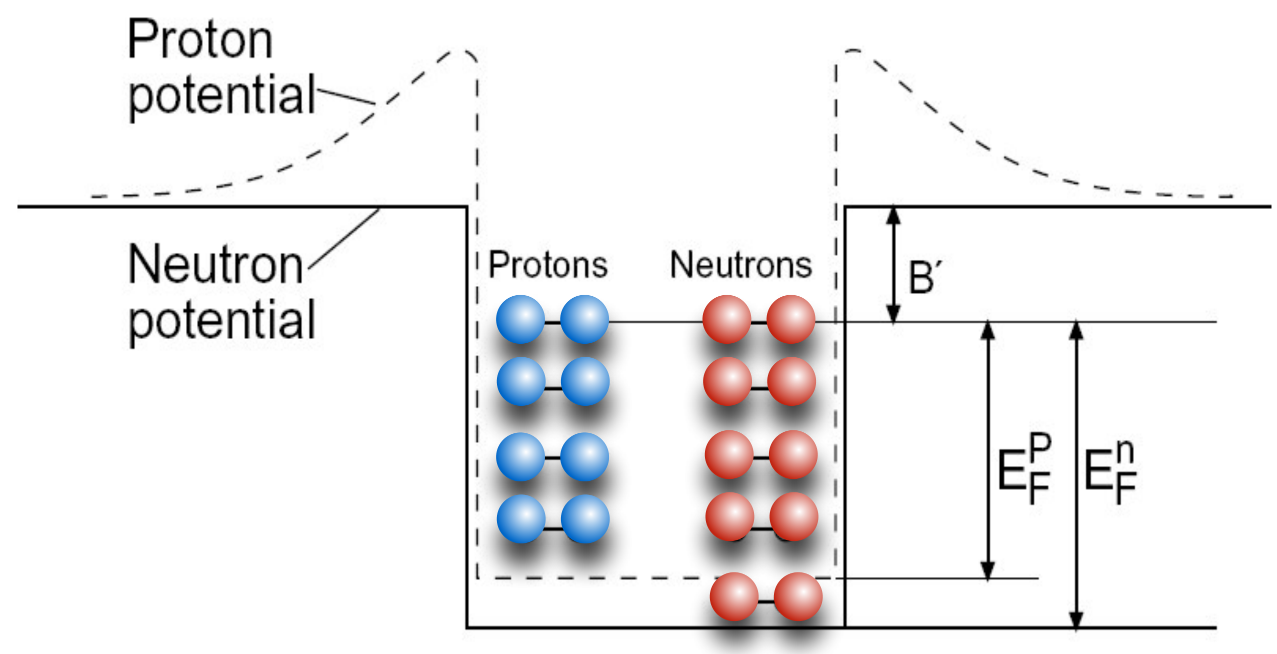

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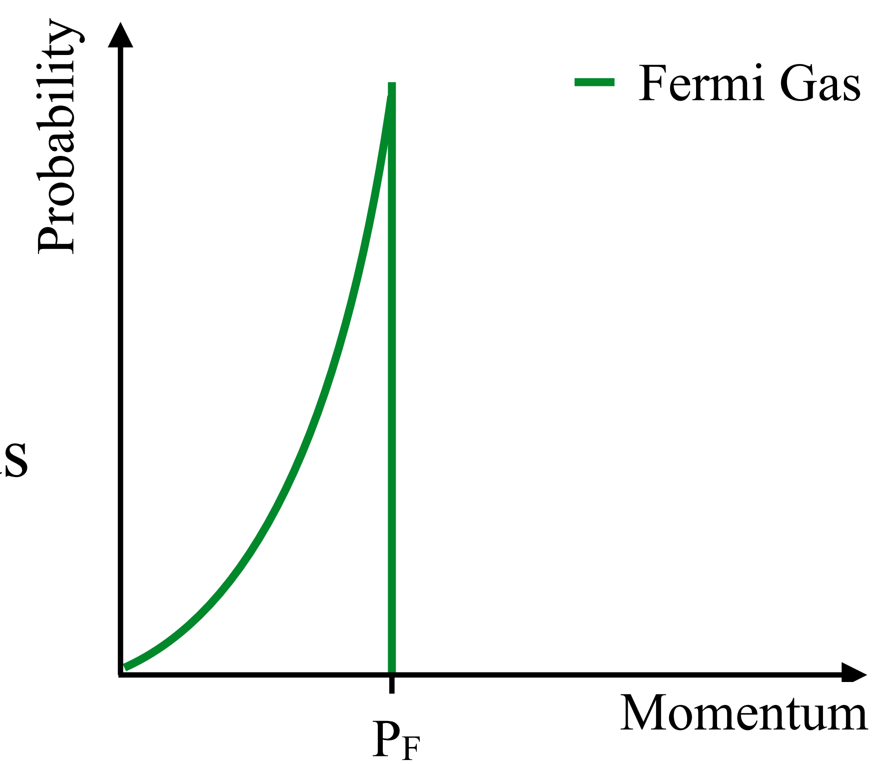
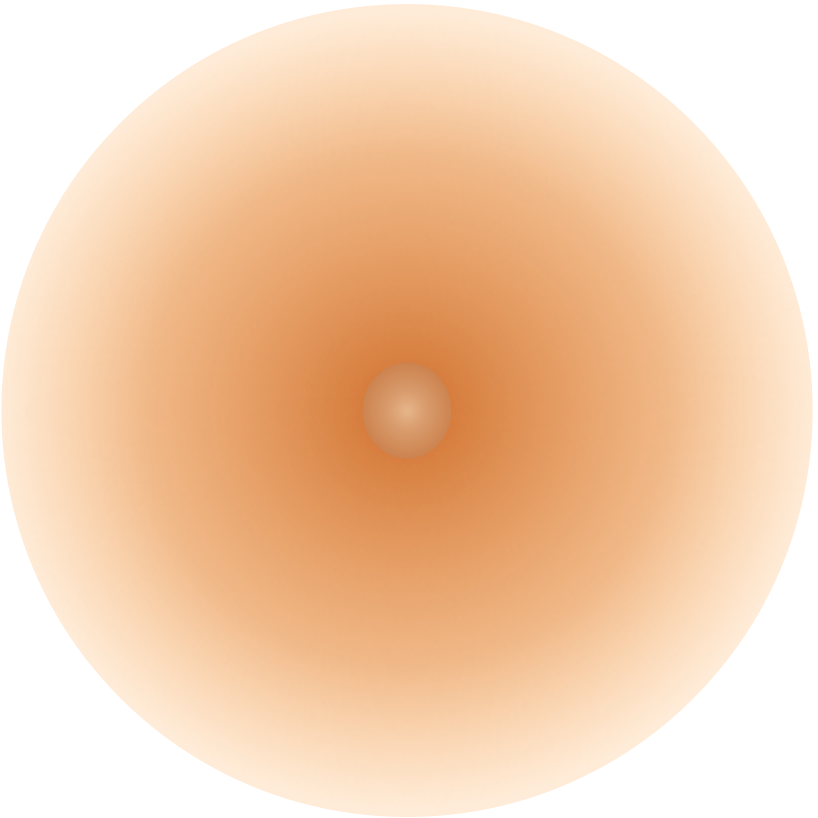


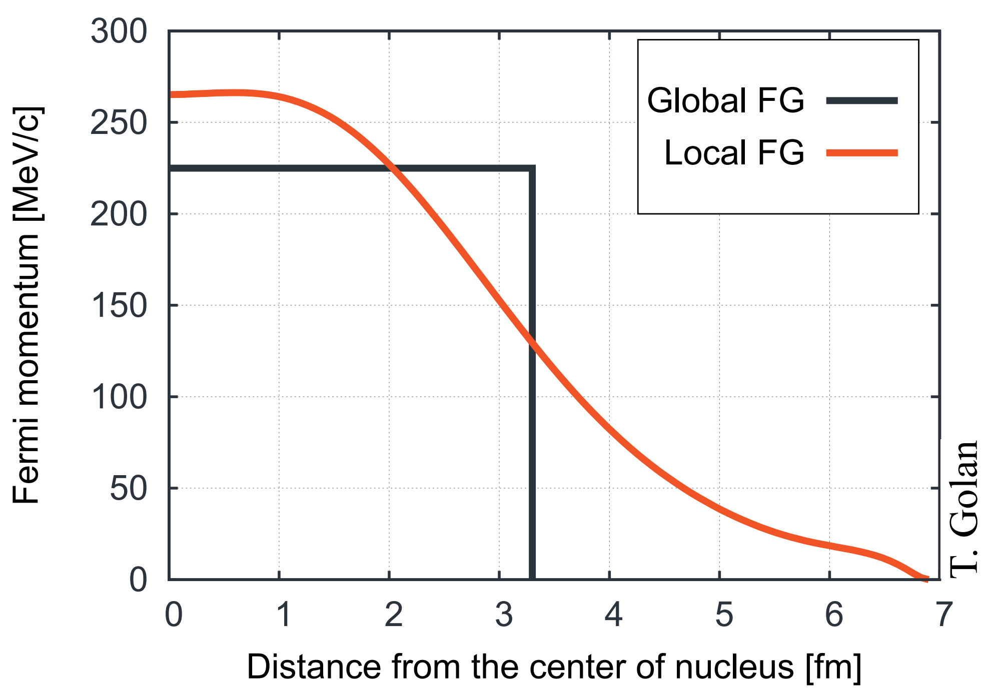
Initial State - Local Fermi Gas Model

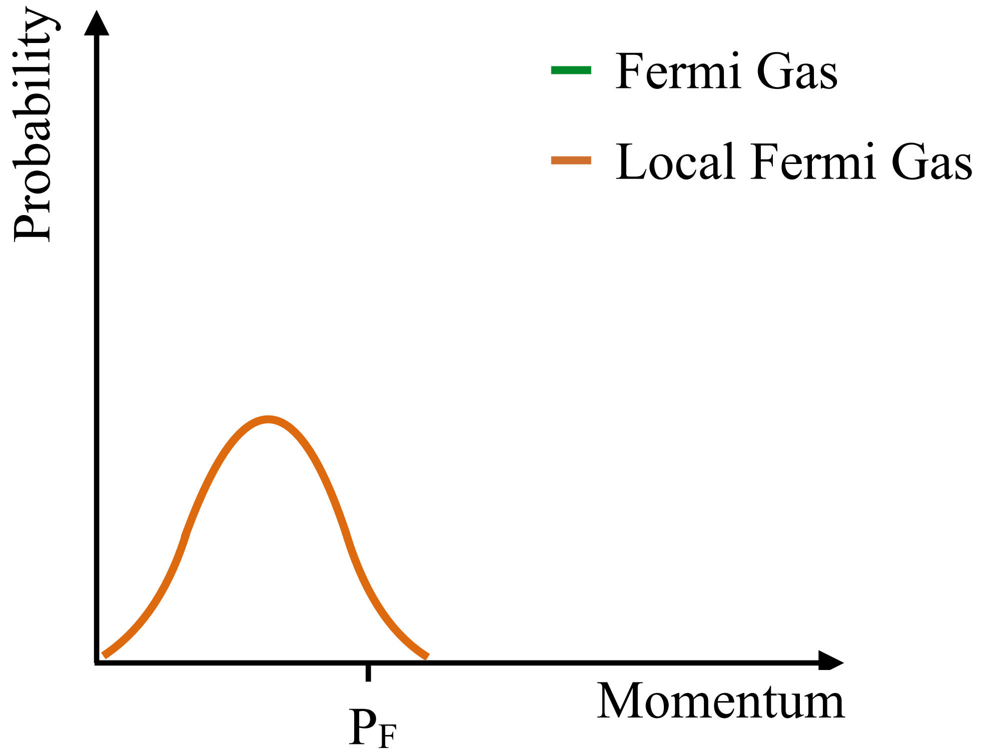
Taking into account the nucleons spherically symmetric density ρ(r)



Most likely to find a nucleon at around 2.5 fm from the center

Fermi momentum is also dependent on r





For more: Theory of Quasi-Elastic Neutrino Scattering on Nuclei, Cheryl E. Patrick

Initial State - Shell Model

Nucleons are moving freely but subject to a radial potential V(r).

Harmonic Oscillator:

$$V(r) = \frac{1}{2} m\omega r^2$$

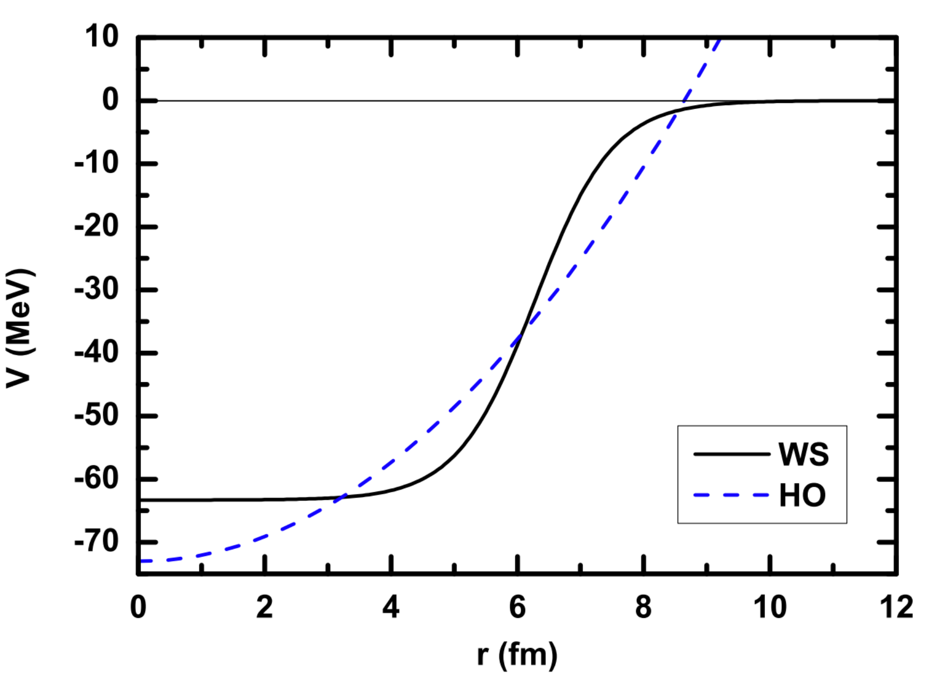
Wood Saxon:

$$V(r) = \frac{V_0}{1 + e^{\frac{r-R}{a}}}$$

Enables prediction of stable nuclei

Also smearing the momentum distribution

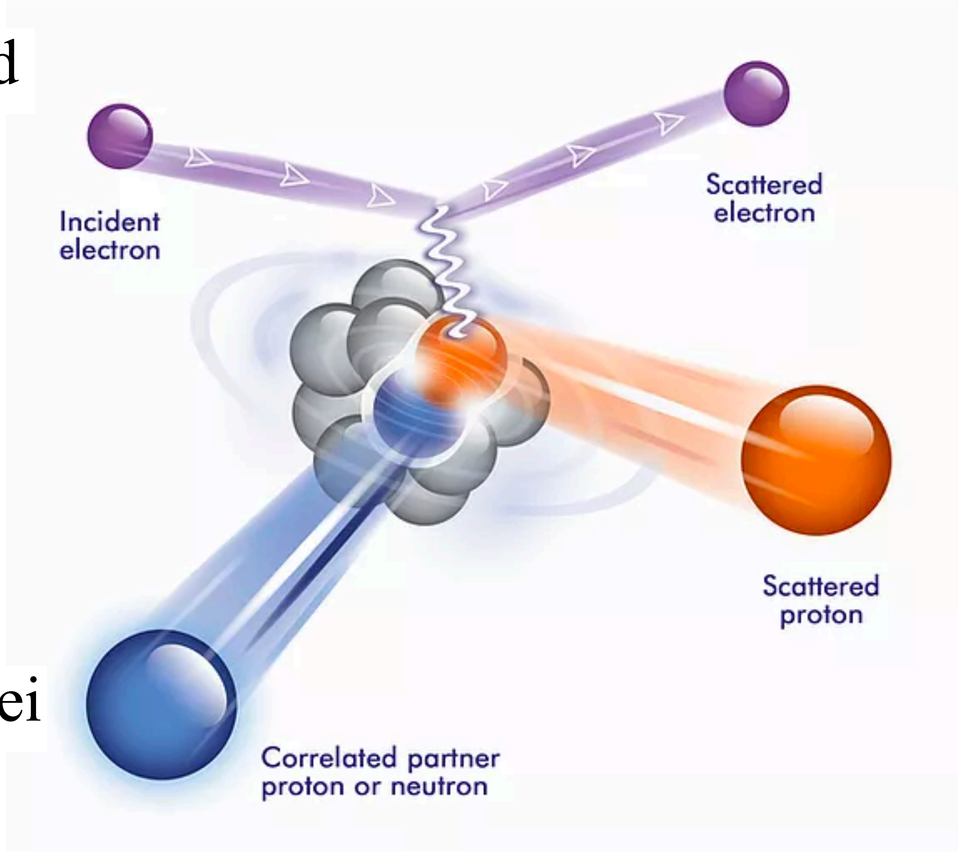
J.E Amaro, et al. Eur.Phys.J.A26:307-309,2005



Physical Review C 87(1):014334

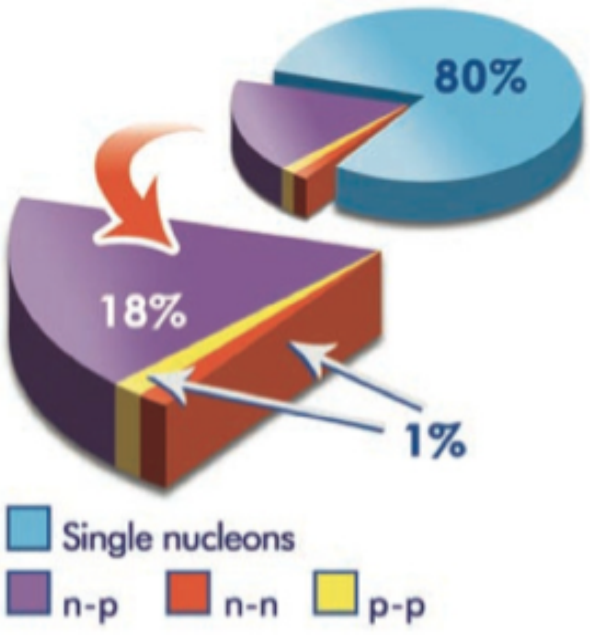
Initial State - Short Range Correlations SRC

Electron scattering experiments detected along with a knocked out nucleon also a recoil one



SRC pairs are two close nucleons with high relative momentum, low center of mass momentum

Experiments have confirmed 20% of nucleons in various nuclei occupy a high momentum tail consists mainly of 2N SRC



O. Hen et al. Science 364 (2014) 614, E. Piasetzky et al. PRL (2006)

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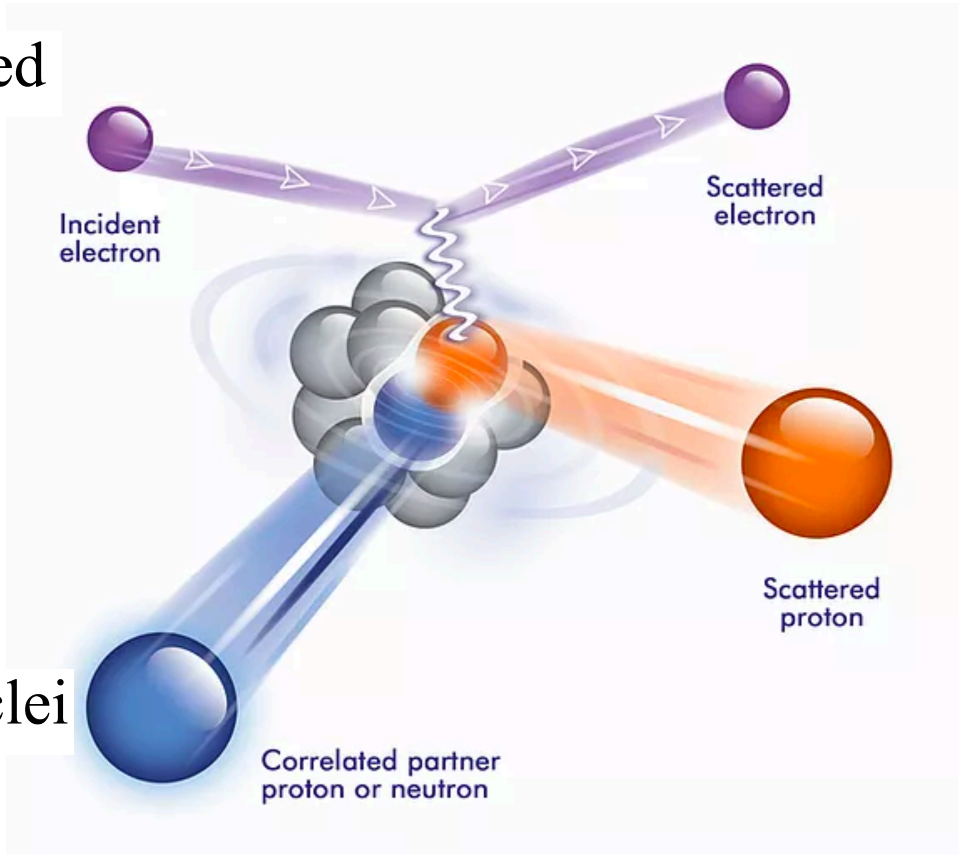

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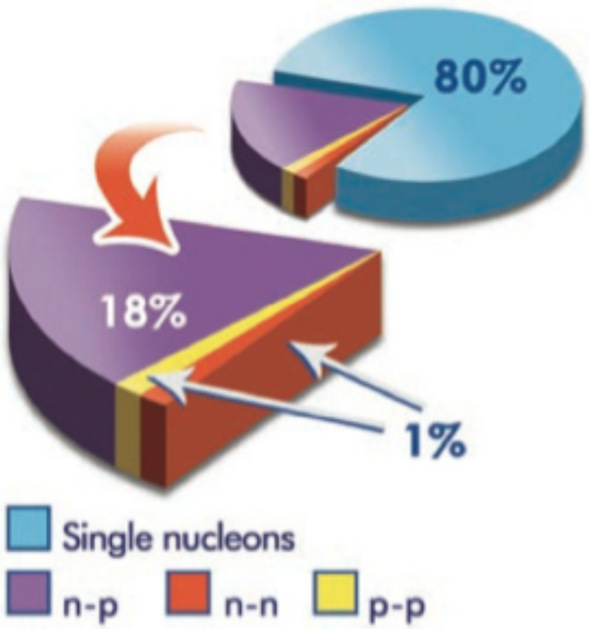
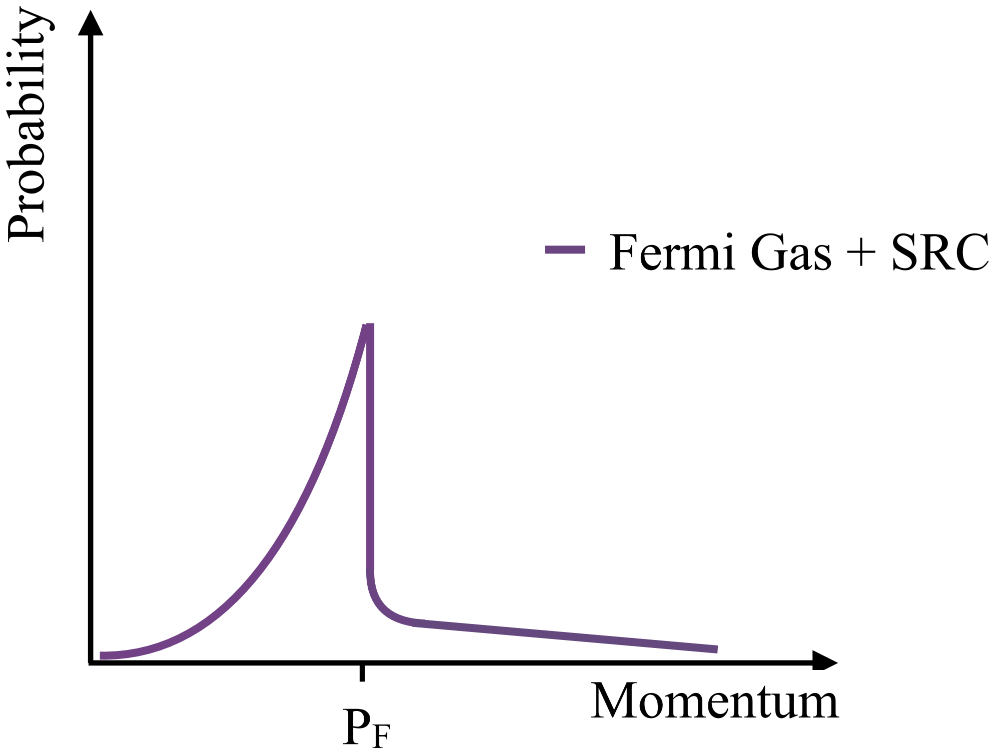




O. Hen et al. Science 364 (2014) 614, E. Piasetzky et al. PRL (2006)

Initial State - Spectral Function

The nuclear spectral function for specific nuclei

Based on (e, e'p) data + theoretical nuclear matter calculations in the Local Density Approximation (LDA)

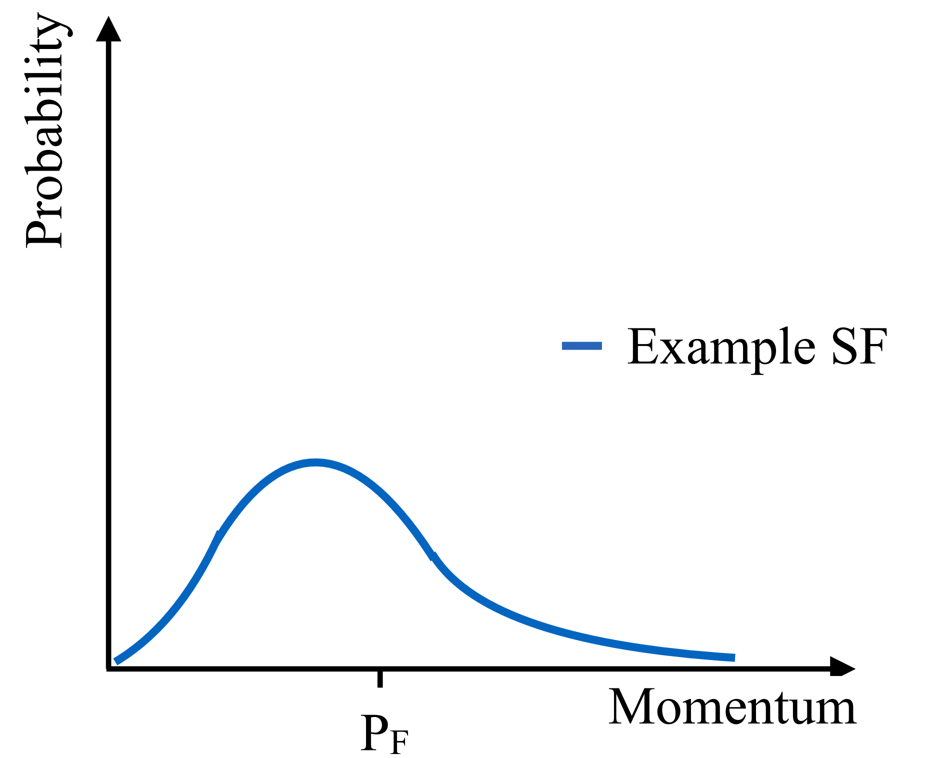
Accounting for SRC leading to high momentum tail

Available for He, C, O

The spectral function formalism used to get the probability of removing a nucleon of momentum k leaving the residual system with excitation energy E.

Can be calculated by the matrix element accounting for

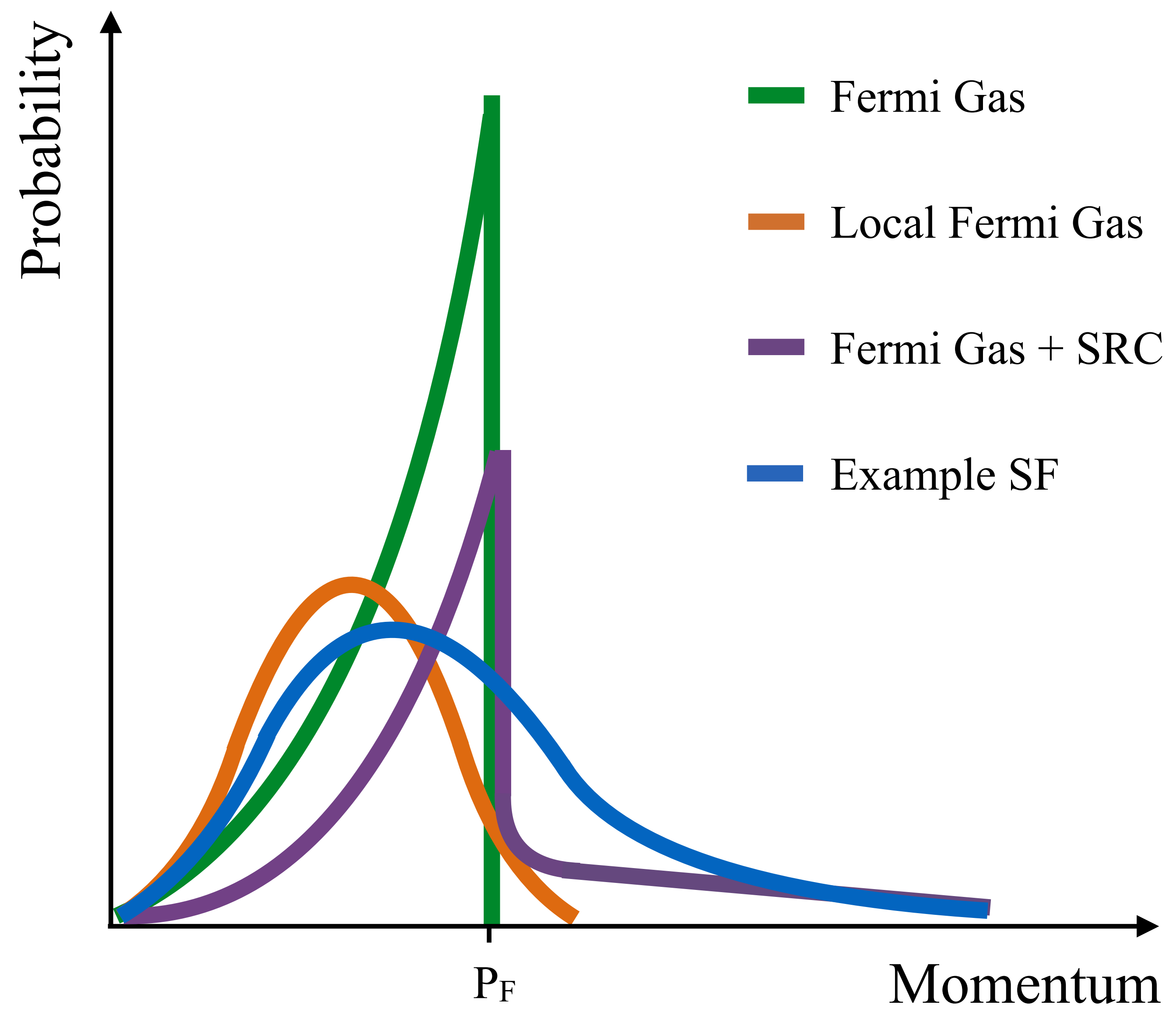
$$H = \sum_i \frac{p_i}{2m} + \sum_{i<j} V_{i,j} + \sum_{i<j<k} V_{i,j,k} + \cdots$$



O. Benhar, A. Fabrocini, and S. Fantoni, Nucl. Phys. A505, 267 (1989).

Initial State - Summary

Each Model gives a different prediction to the nucleons' momentum distribution

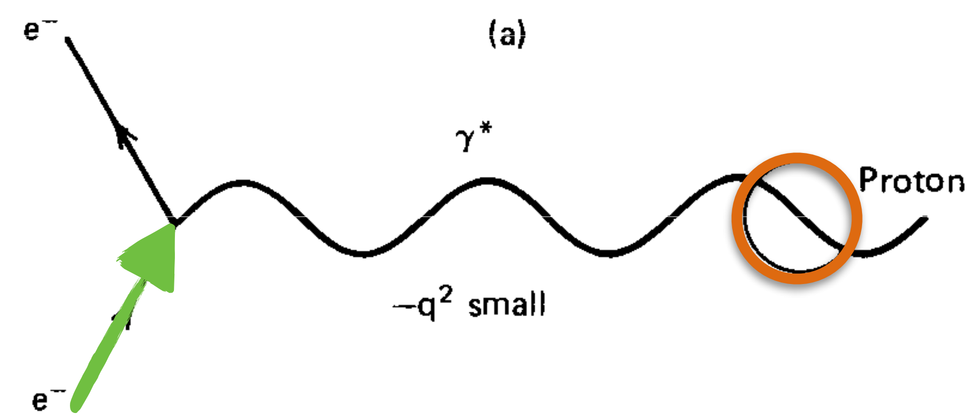


Probing the target structure

The interaction depends on the mediator energy (the energy transfer - ω)

At λ >> r

Scattering from a point like spin-less particle.

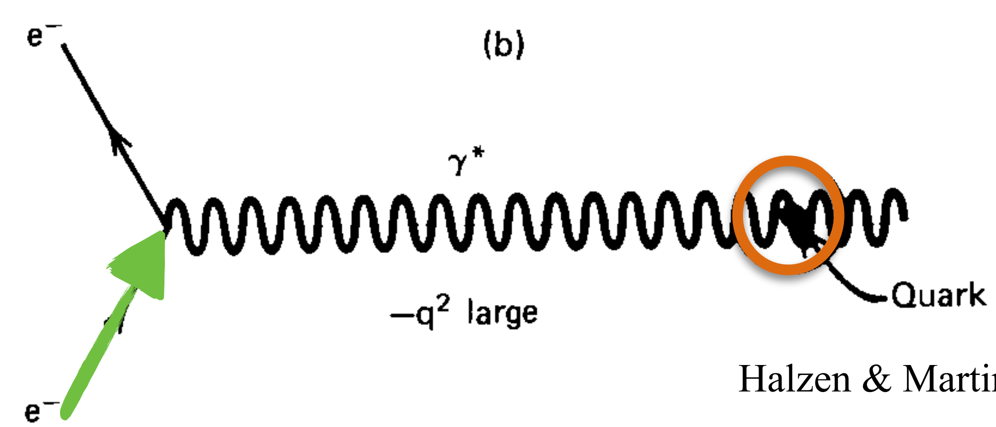


At low energies λ ~r

Scattering from a charged object - various possible interactions

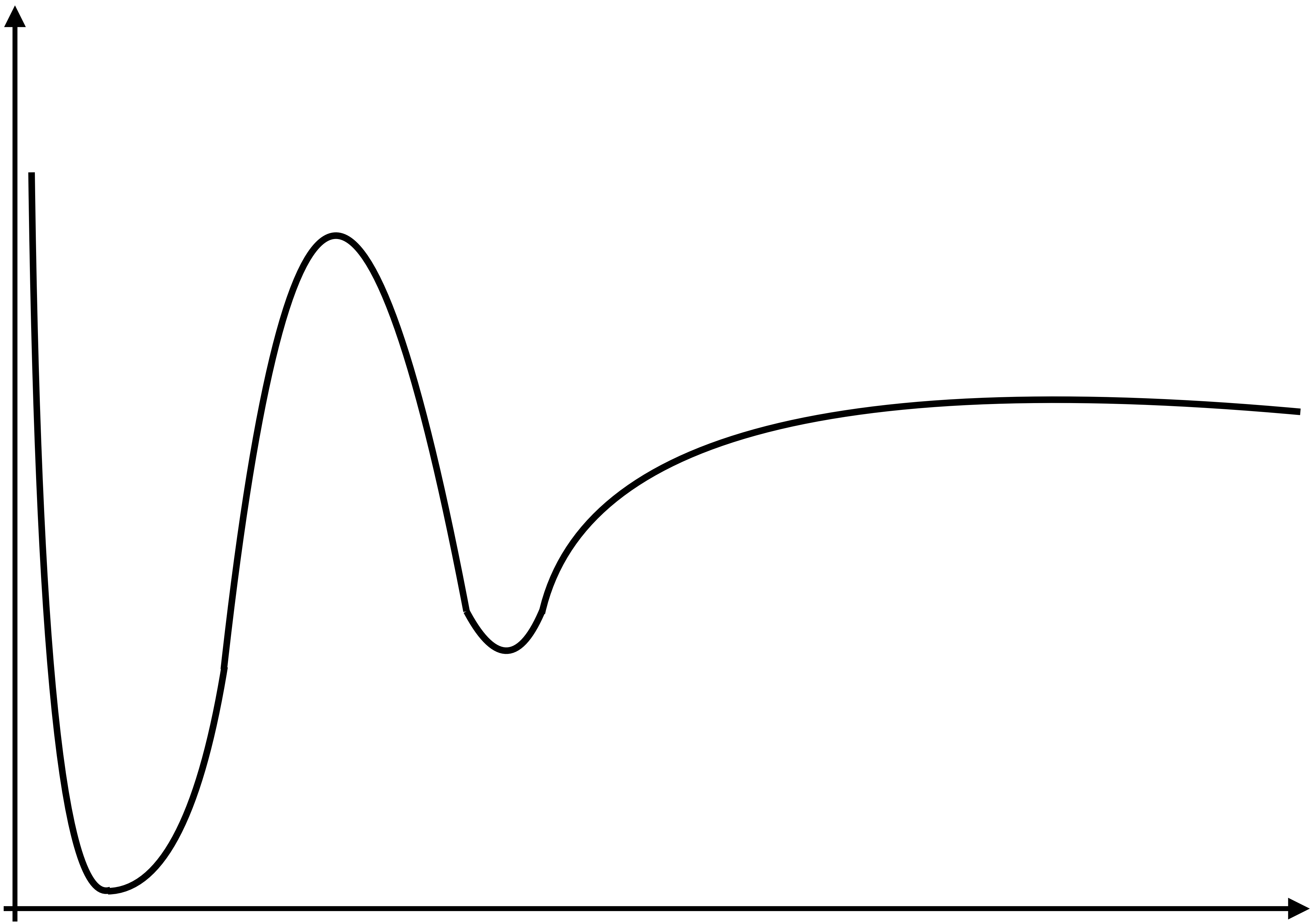
At high energies λ < r

Scattering from target constituents - various possible interactions



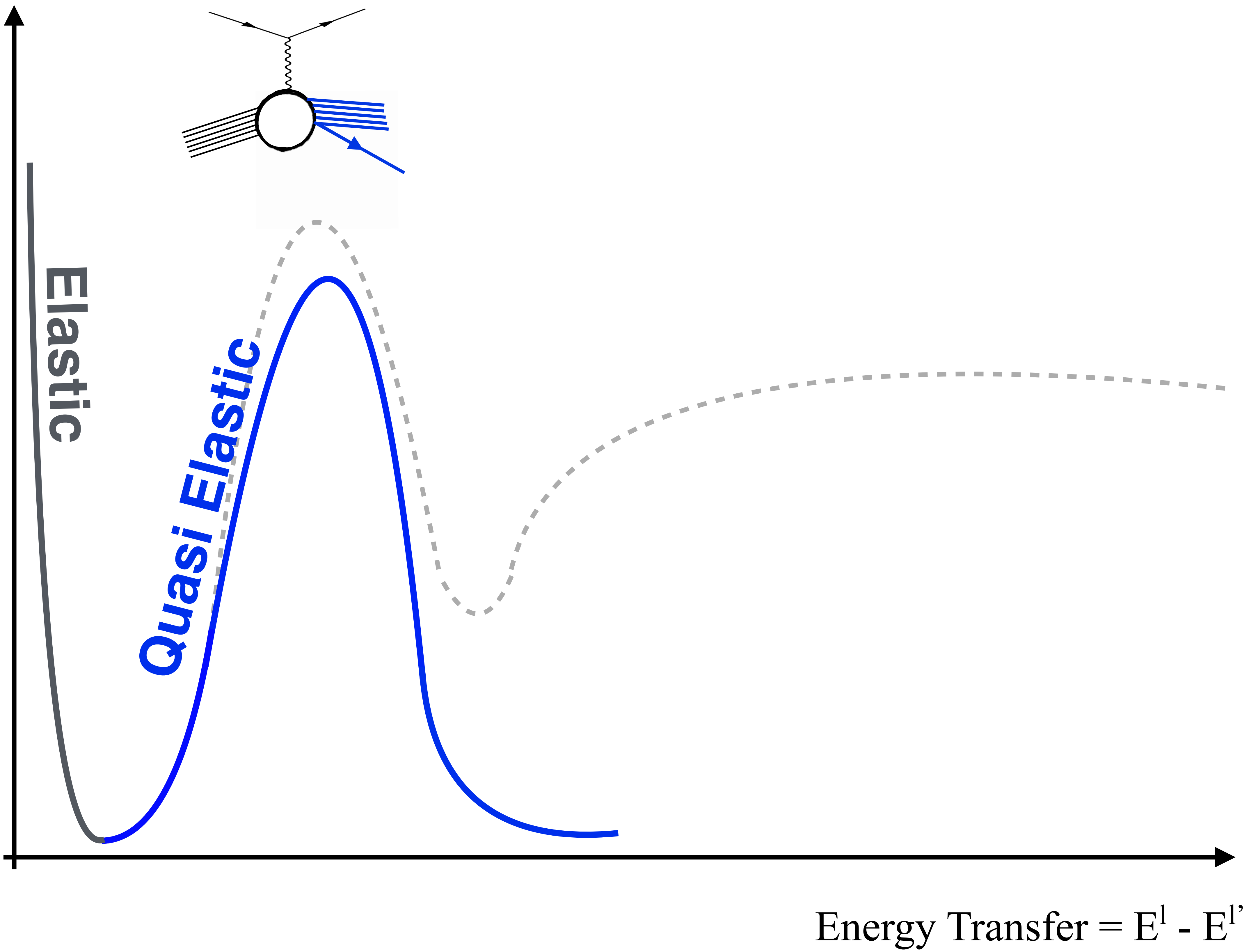
Halzen & Martin

lepton - nuclei interaction processes



Energy Transfer = $E^{l} - E^{l'}$

lepton - nuclei interaction processes



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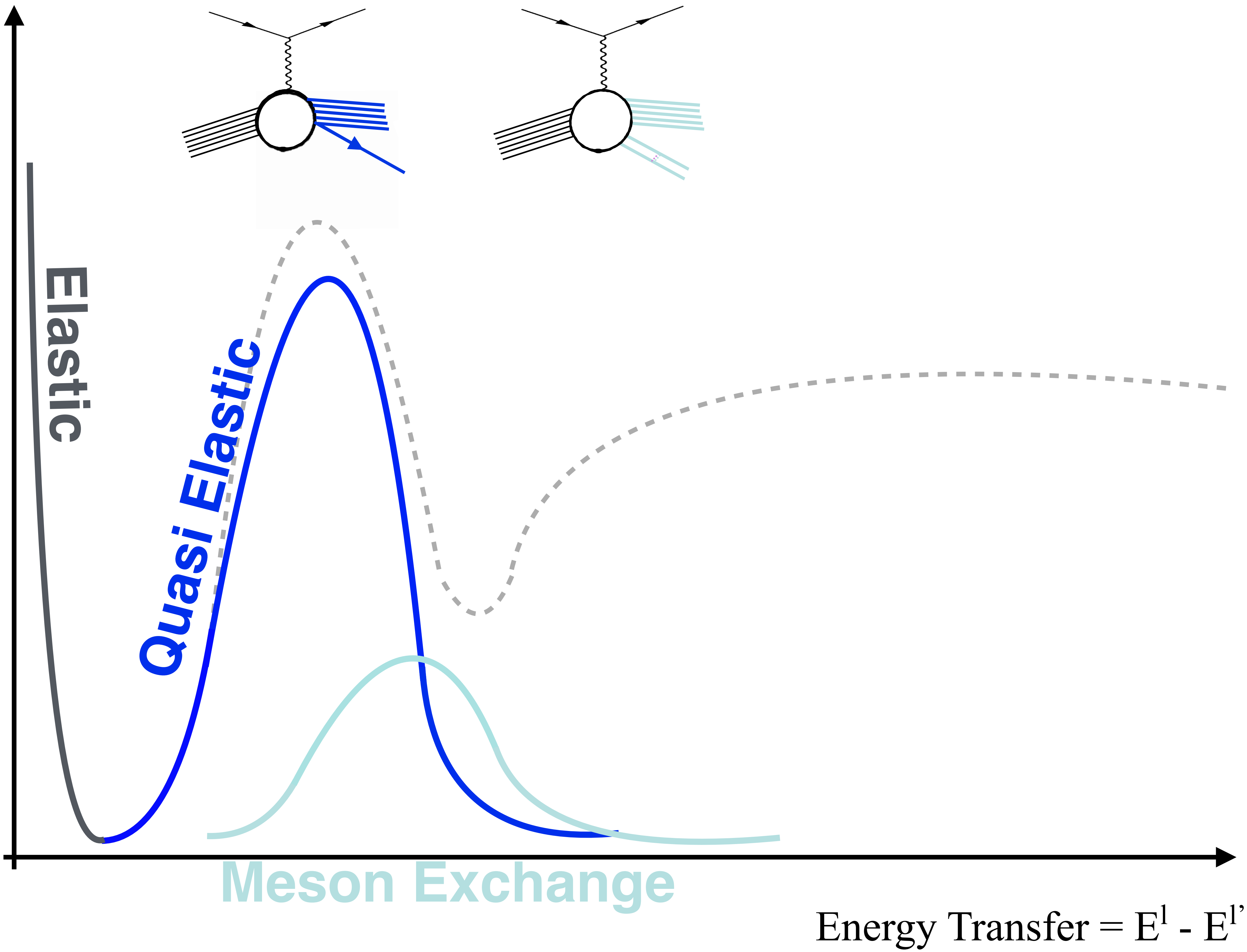

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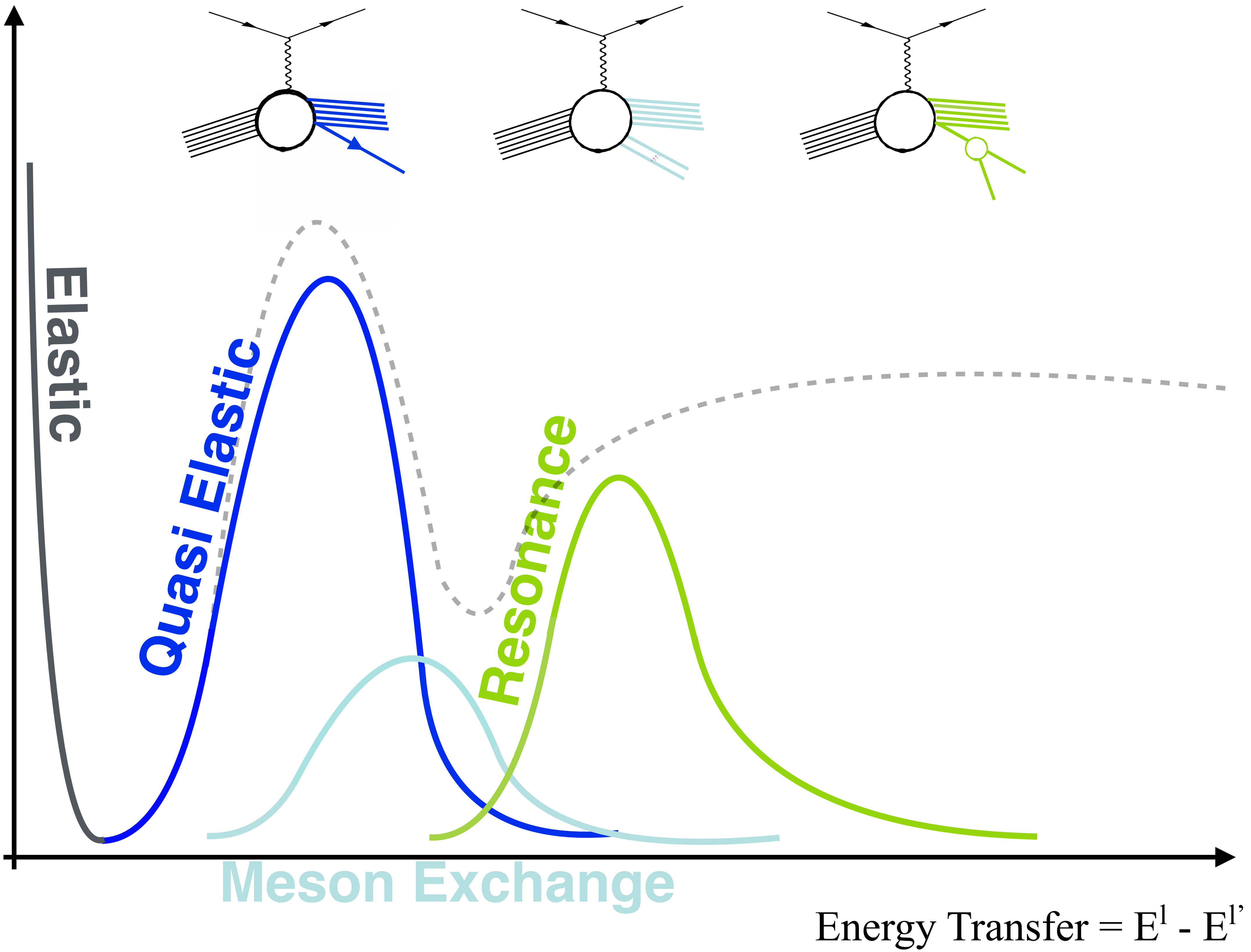

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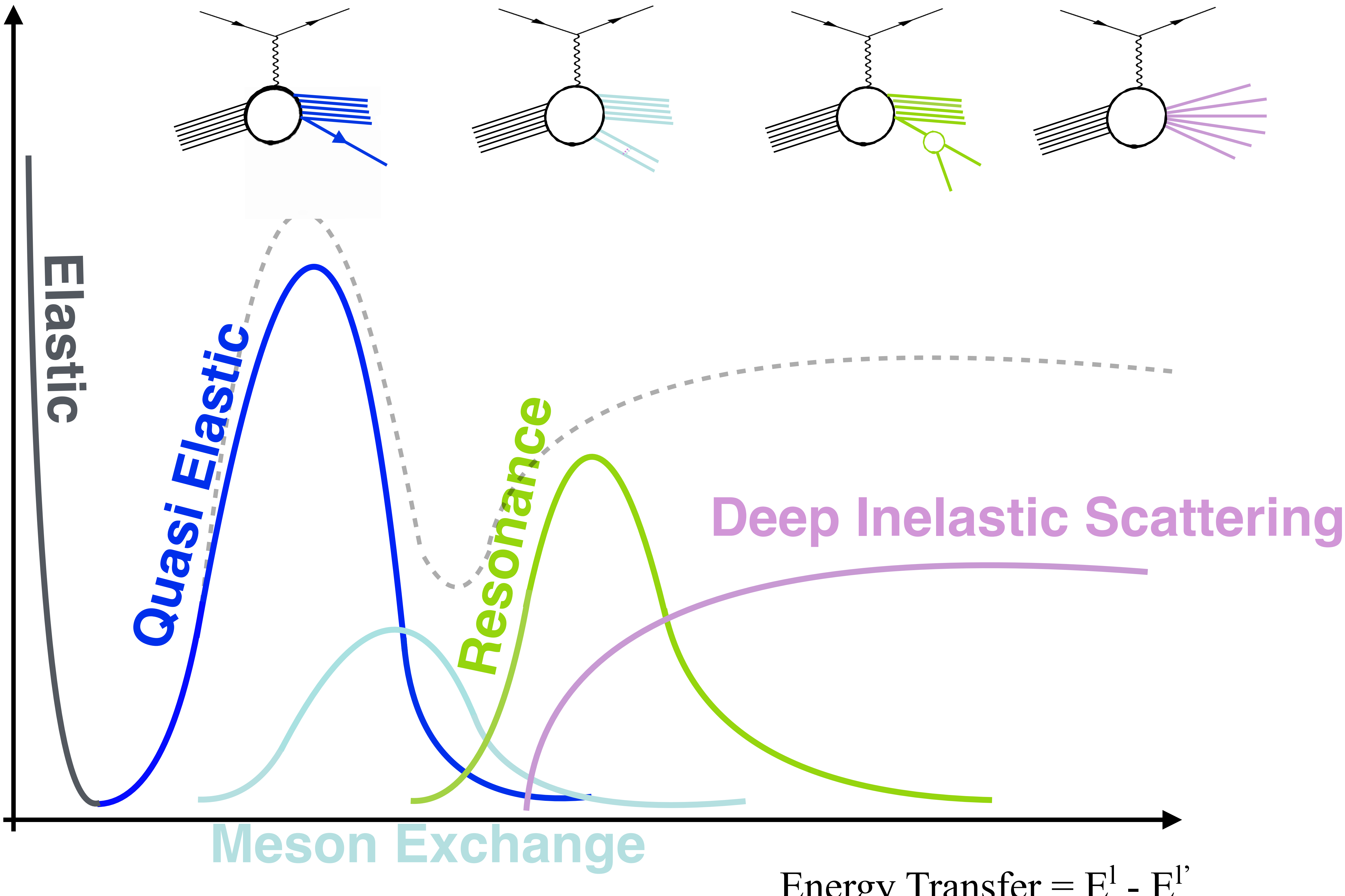


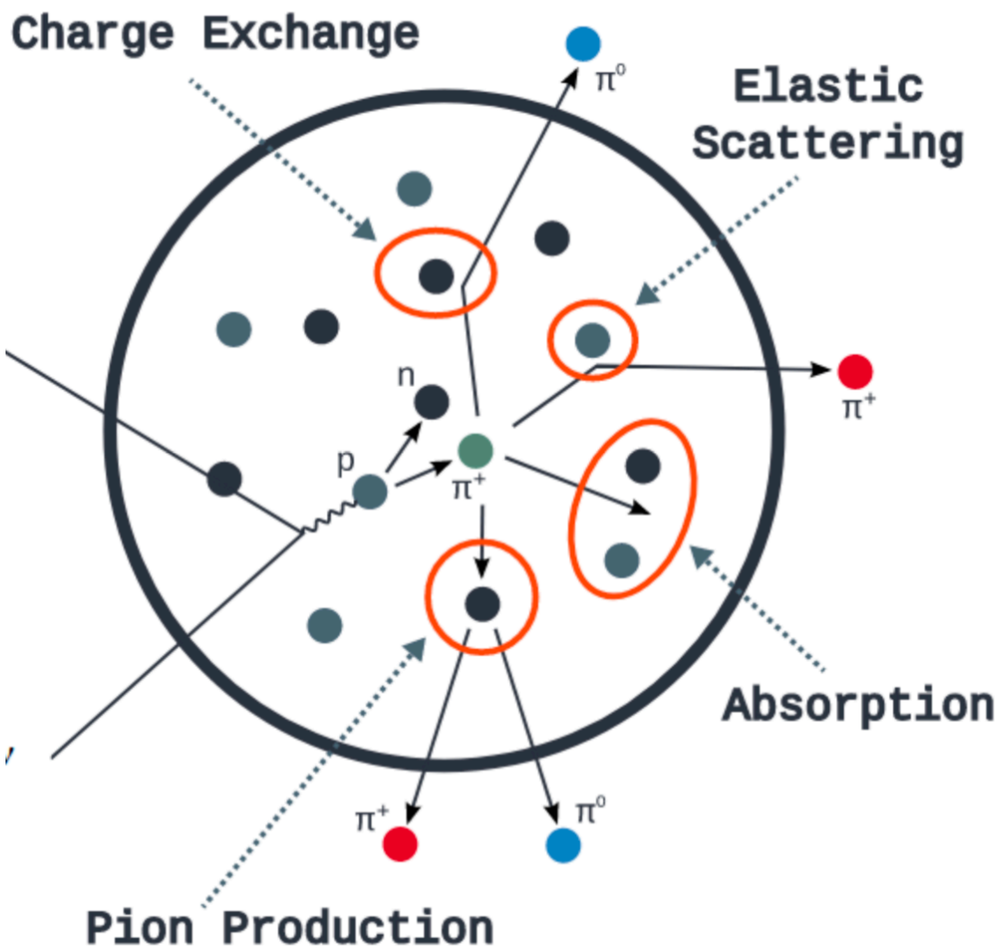
Final State Interactions (FSI)

Interaction happened inside the nucleus

The final state particles still need to get out of it, but undergo FSI

Complex elastic/inelastic scattering with other nucleons.

Hadrons can also be absorbed or produced



Final State Interactions (FSI) - Models

Intra-nuclear cascade Model or the “billiard balls” model

- Each particle is moving classically along a straight line.

- It has a probability to pass a mean free path λ without interacting: $\exp(-\lambda/\lambda')$; $\lambda' = 1/\sigma\rho$

$\sigma_{\pi prod}$ $\sigma_{elastic}$ $\sigma_{inelastic}$ σ_{abs}

hN intranuke:

Many possible interactions

Calculated cross sections for each process

Adding particles and interactions until leaving nuclei (full cascade)

hA intranuke:

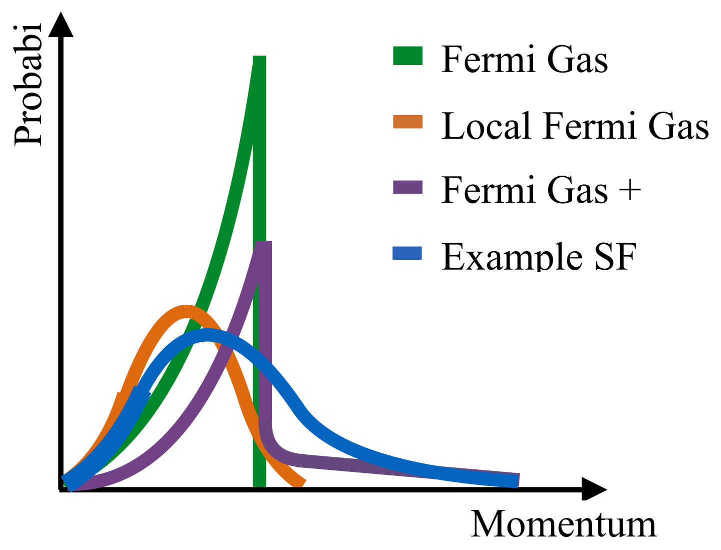
One “effective” interaction

tuned do hadron-nucleus data

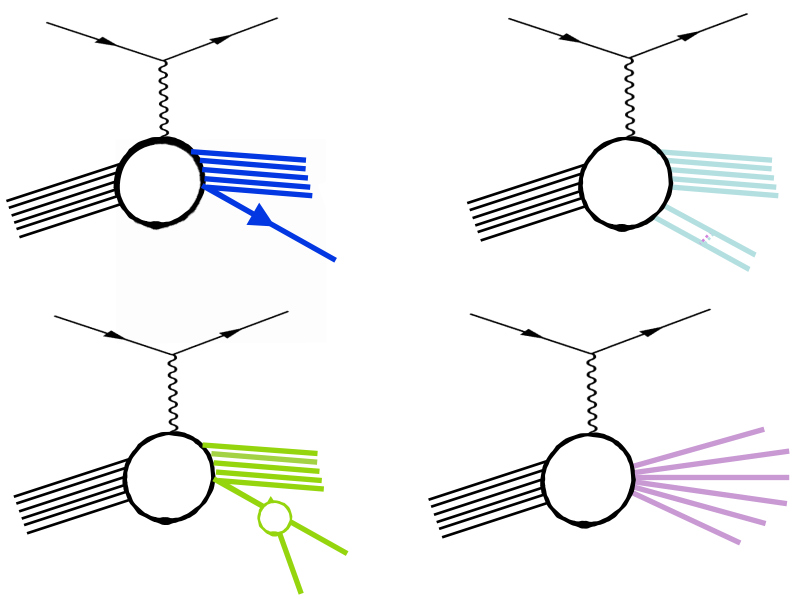
Parameters (λ,σ) are reweightable

Quick Summary

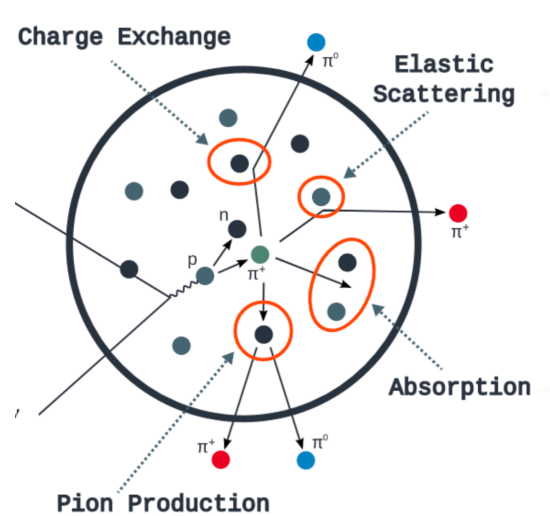
Nuclear Initial State



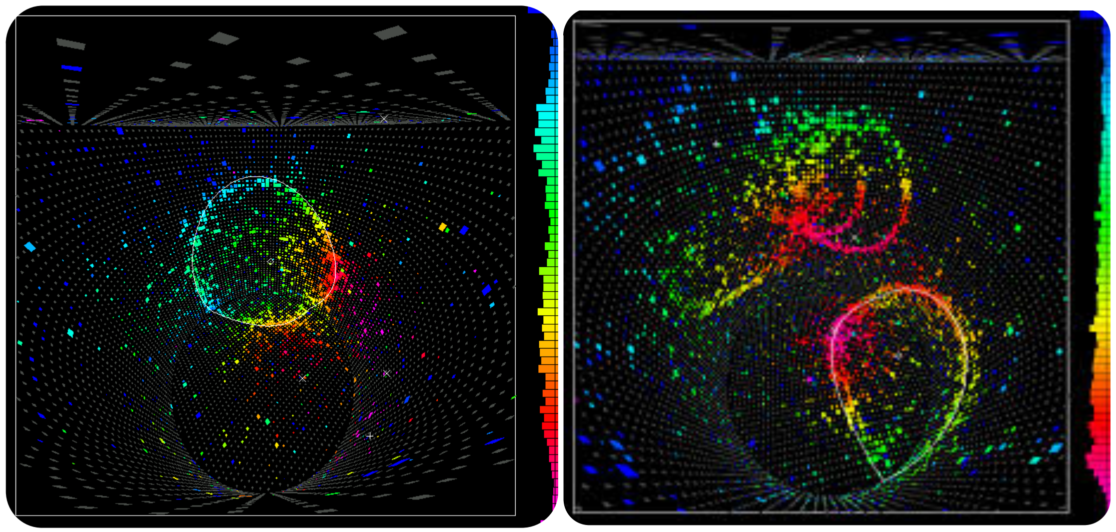
Interaction processes



Final state interactions



Incoming neutrino Energy Reconstruction



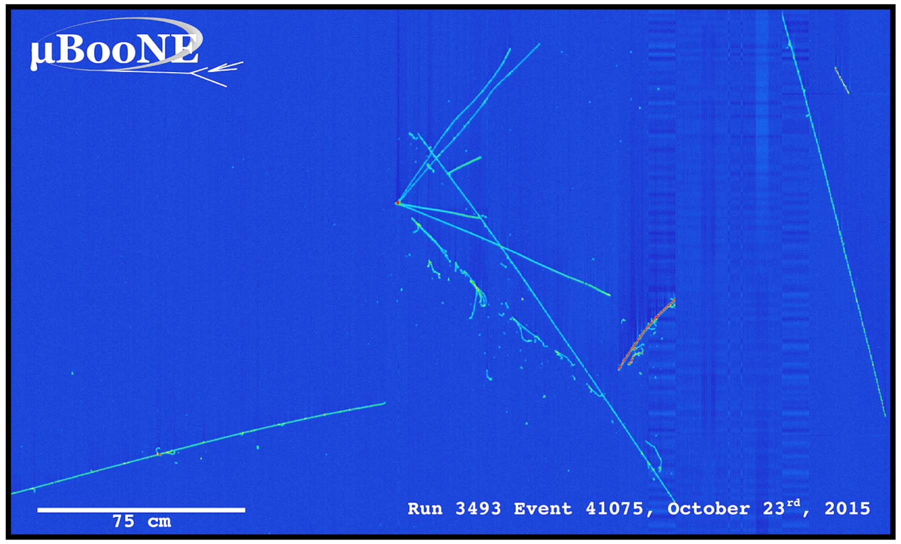
Cherenkov detectors:

Assuming QE interaction

Using solely the final state lepton

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|cos\theta)}$$

ϵ is the nucleon separation energy



Tracking detectors:

Need good hadronic reconstruction

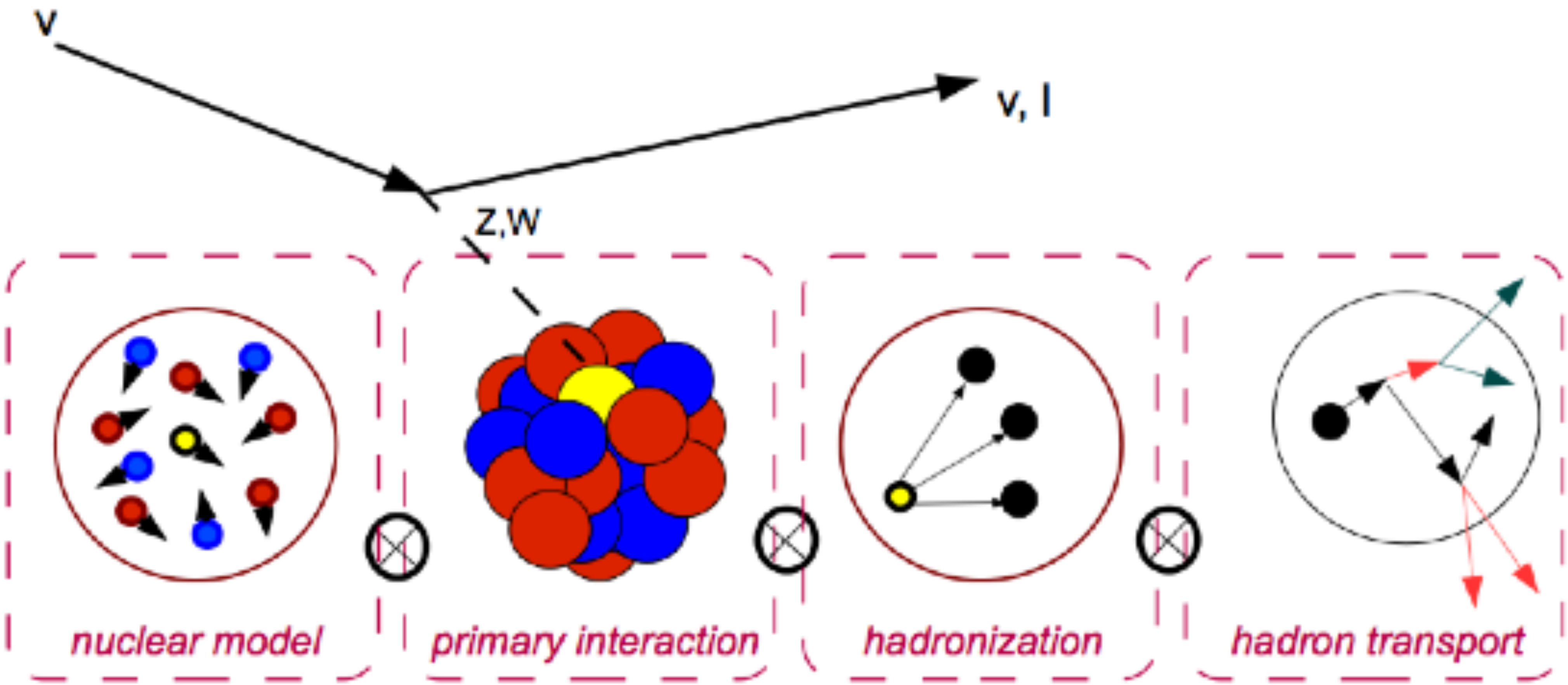
$$E_{\rm cal} = E_l + E_p^{\rm kin} + \epsilon$$

Modelling can significantly effect our interpretation of the measurement

Event Generators to the Rescue

Monte Carlo event generators are used to predict backgrounds and efficiency

Using a factorisation scheme



Event Generators to the Rescue

Monte Carlo event generators are used to predict backgrounds and efficiency

NEUT

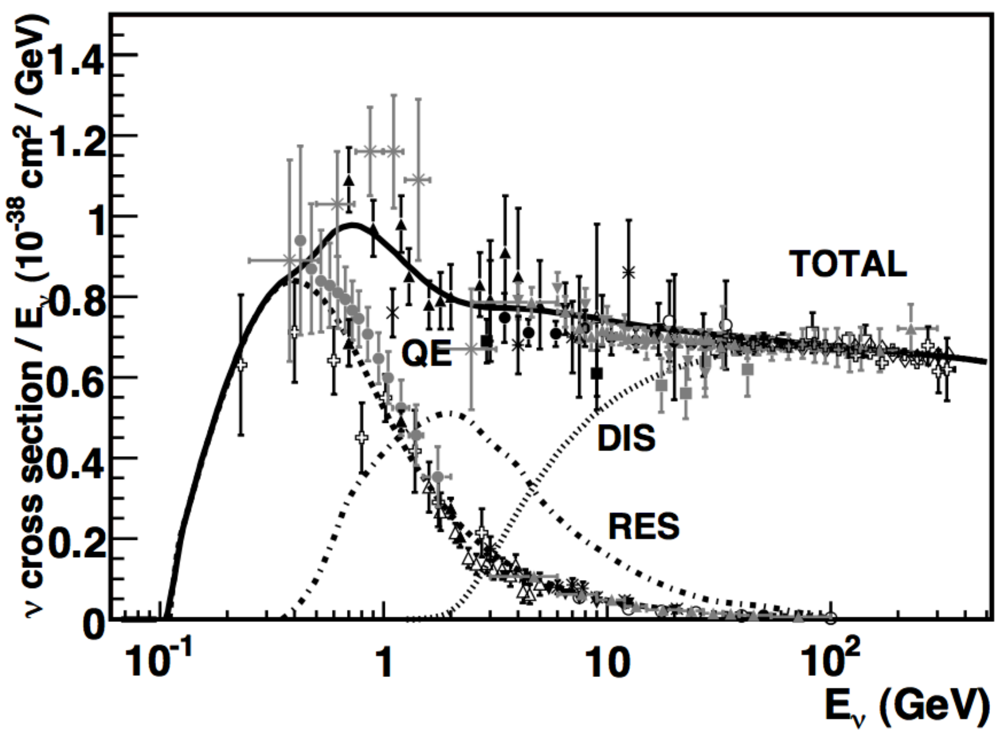
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

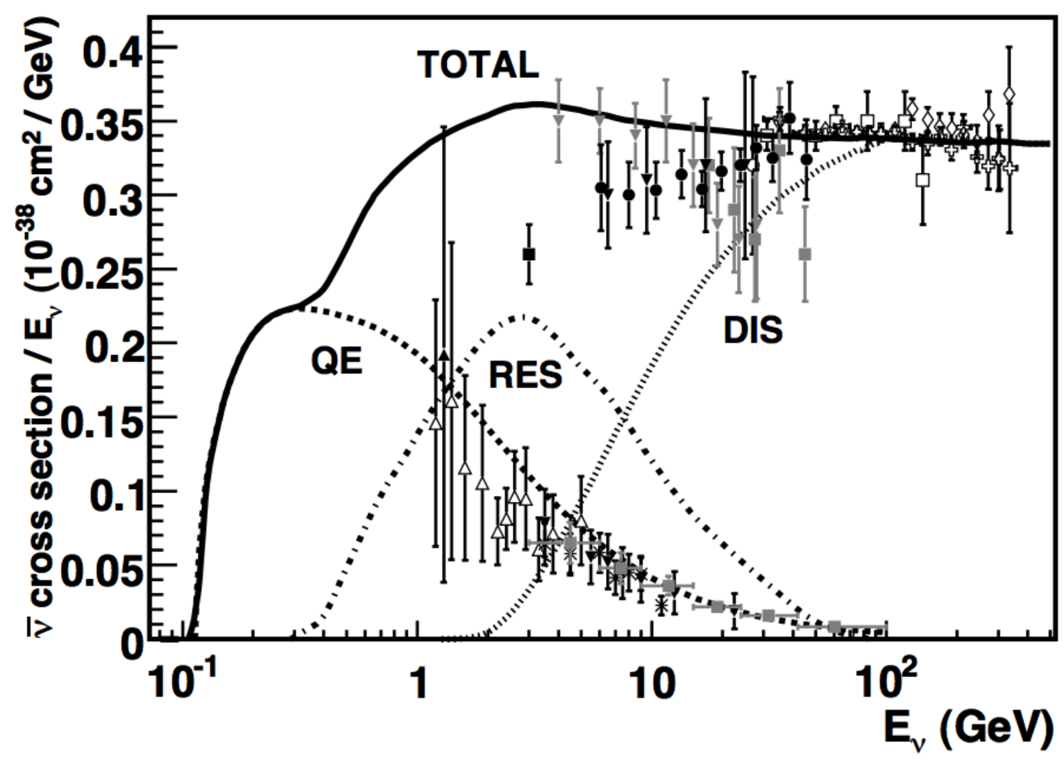
Genie

FLUKA

- Each Generator has many free parameters (many dozens)
- Many can be reweighed tuned to data
- Note, tuning to neutrino data (with specific target and energy) is not necessarily applicable to your experiment.
- External constraints are needed

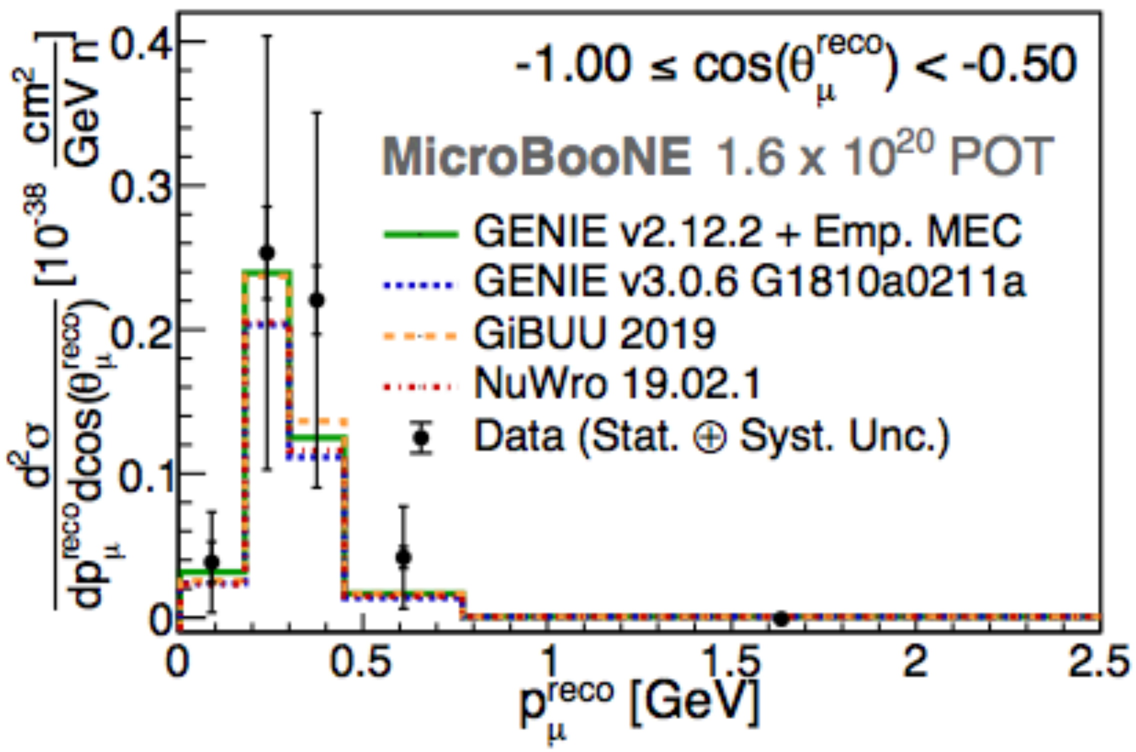
Neutrino Cross Section

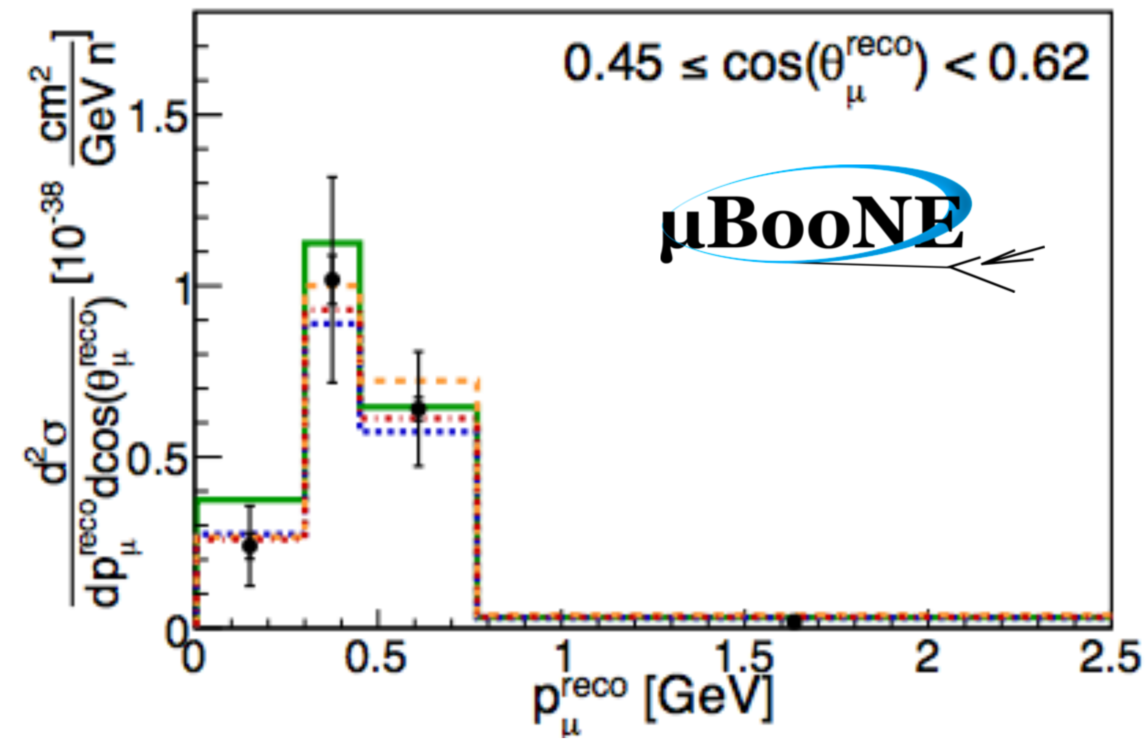




J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)

GENIE MC reproduced ν inclusive data

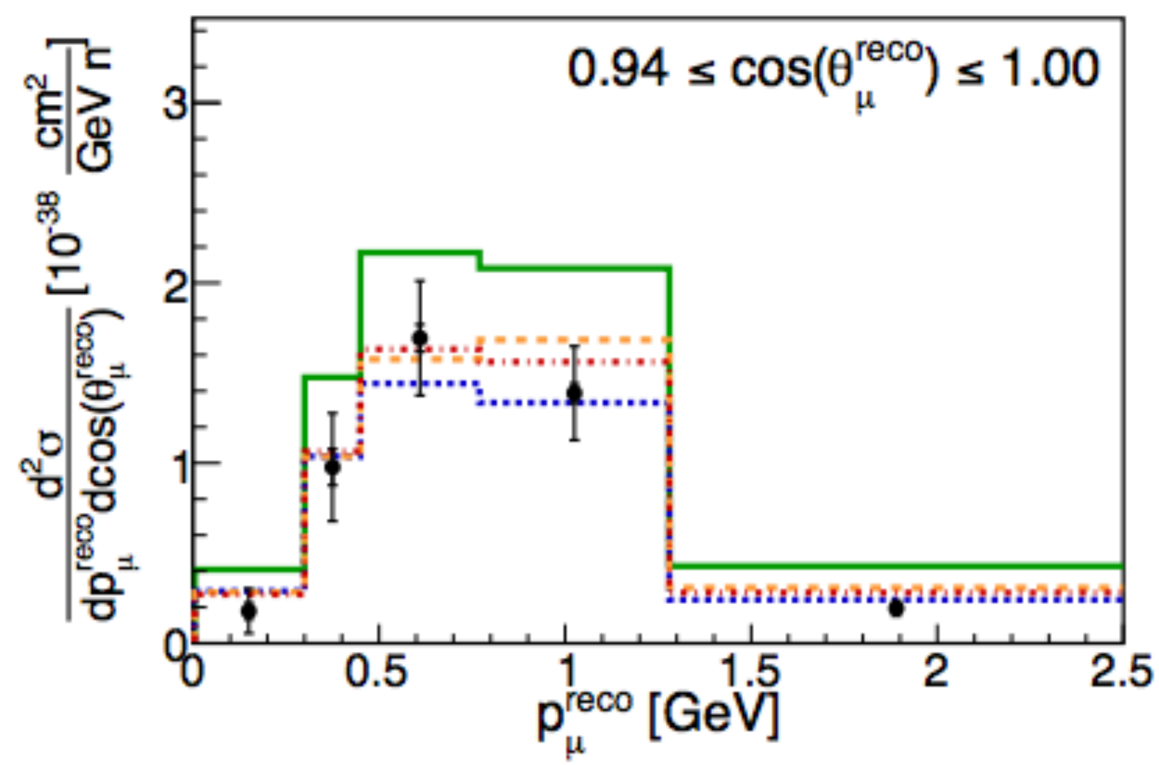




Genie

v3.0.6 tune G18_10a_02_11a

For more details see backup slides



Phys. Rev. Lett. 123, 131801 (2019)

CC0π1P or CCQE-like events

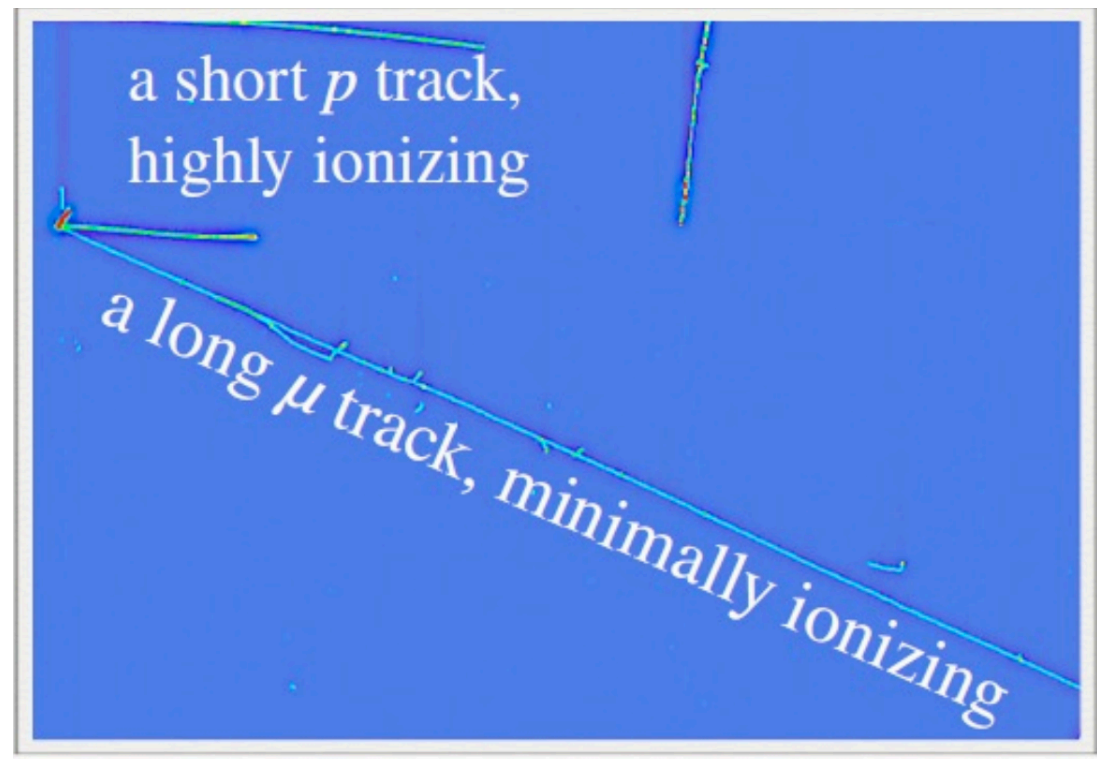
Vertex of 2 semi-contained tracks

(start within the fiducial volume)

one muon (**Pμ > 100 MeV/c**)

one proton (**Pp > 300 MeV/c**)

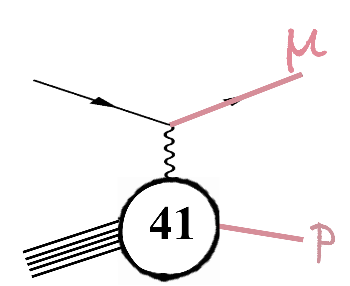
no π0 , no charged π (≥ 70 MeV/c)



Additional cuts on:

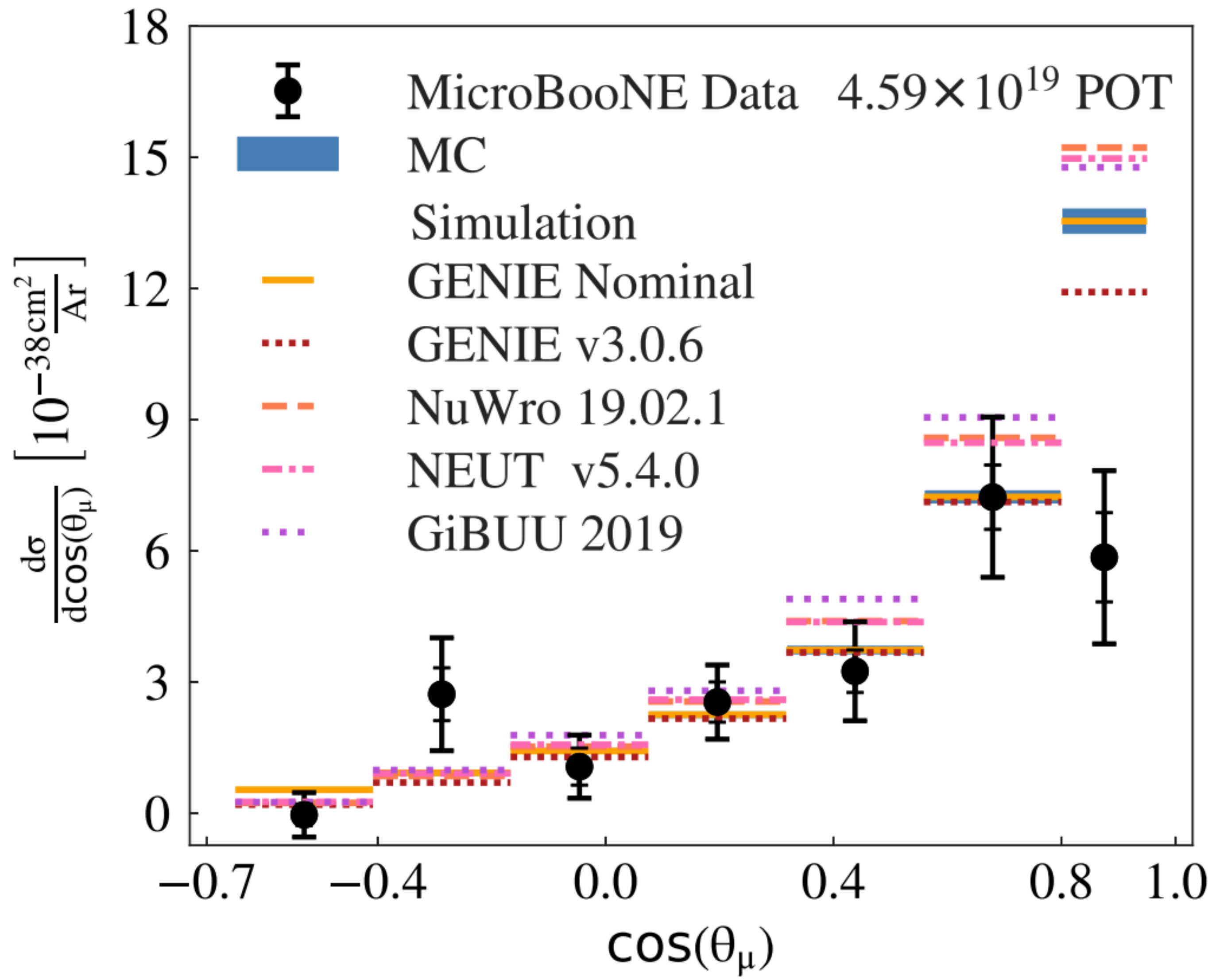
- To reduce cosmic contamination
  - $|\Delta\theta_{\mu p} - 90^{o}| < 55^{o}$
- To enhance QE contribution
  - $|\Delta\varphi_{\mu p} - 180^{o}| < 35^{o}$
  - $p_T = |\vec{p}_{T,\mu} + \vec{p}_{T,p}| < 350$ MeV/c

~84% CC1p0π (~81% CCQE) purity, 20% efficiency

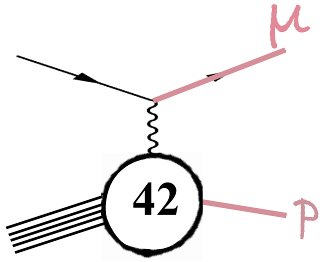


CC0π1P - CCQE-like events

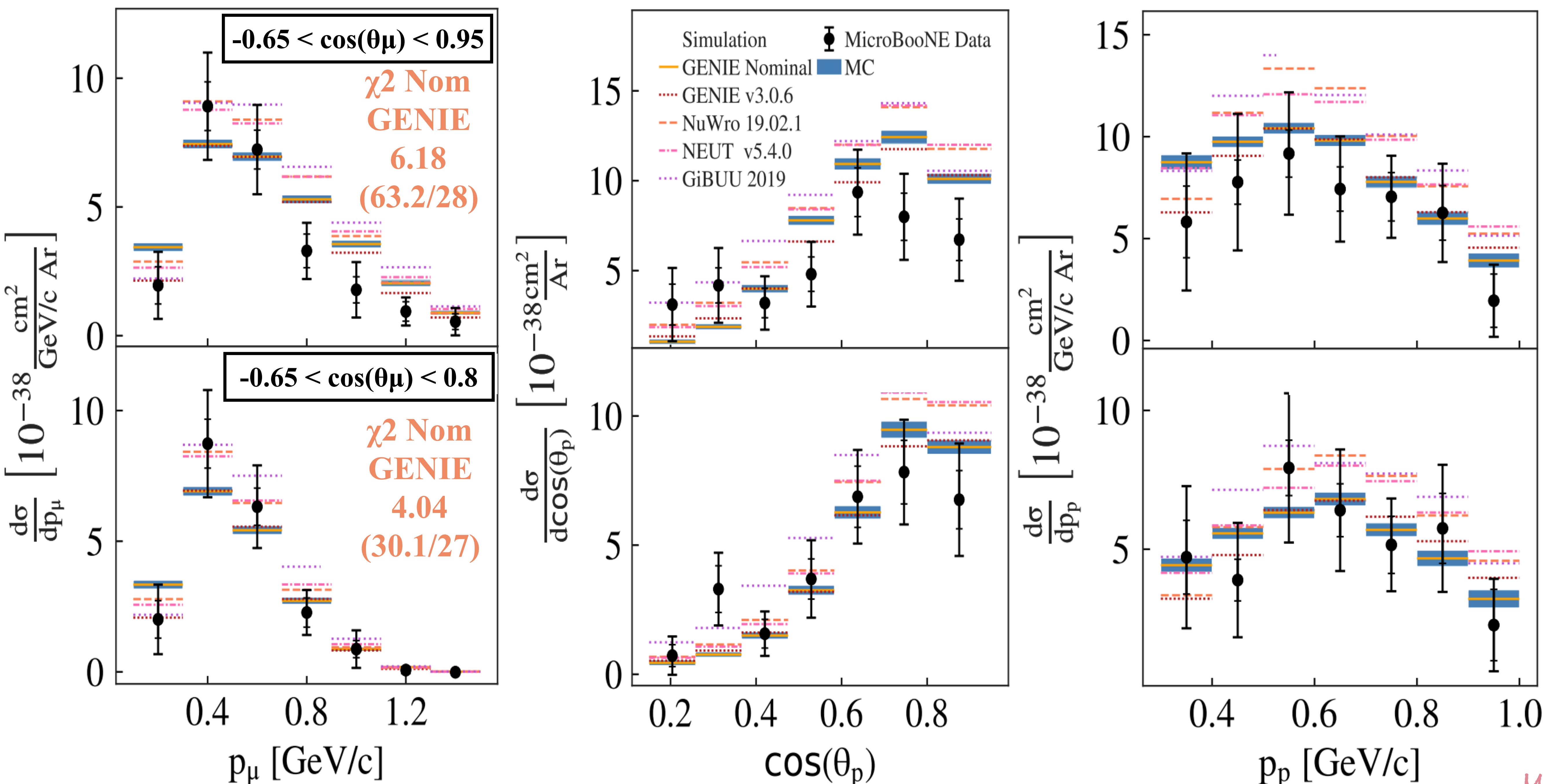
Overall agreement except for forward muon scattering angle



Phys Rev Lett. 125, 201803 (2020)

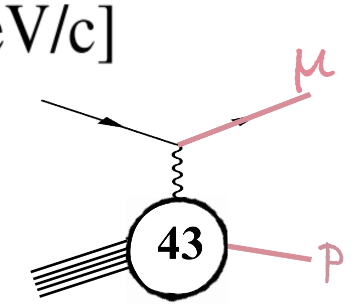


CC0π1P - CCQE-like events

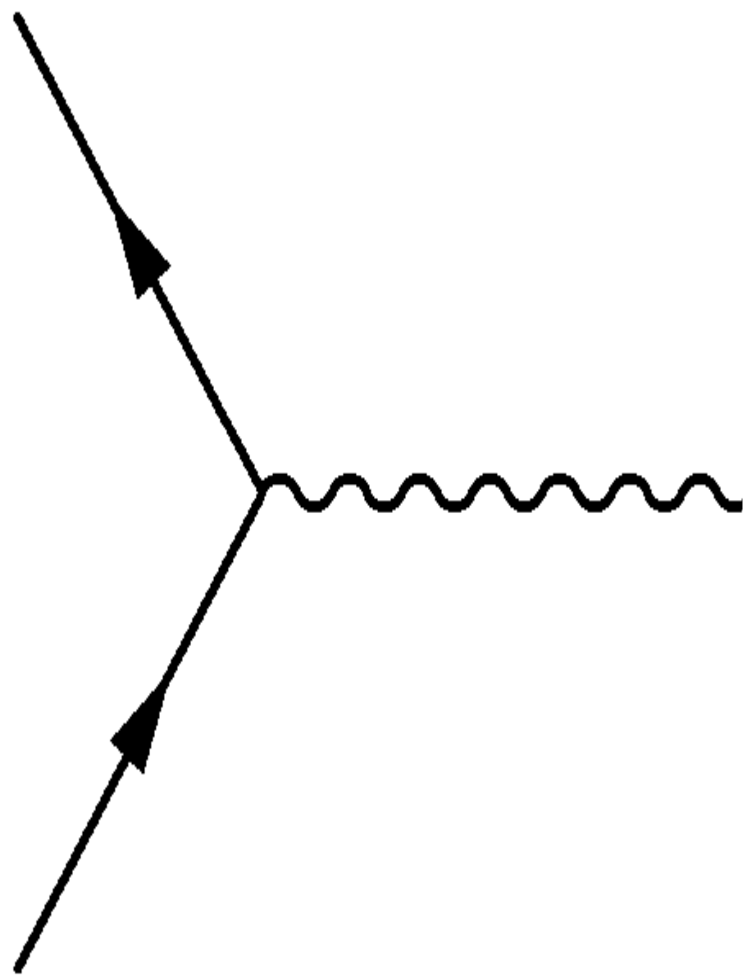


Significantly better agreement when excluding events with forward going muon

[Phys Rev Lett. 125, 201803 (2020)]



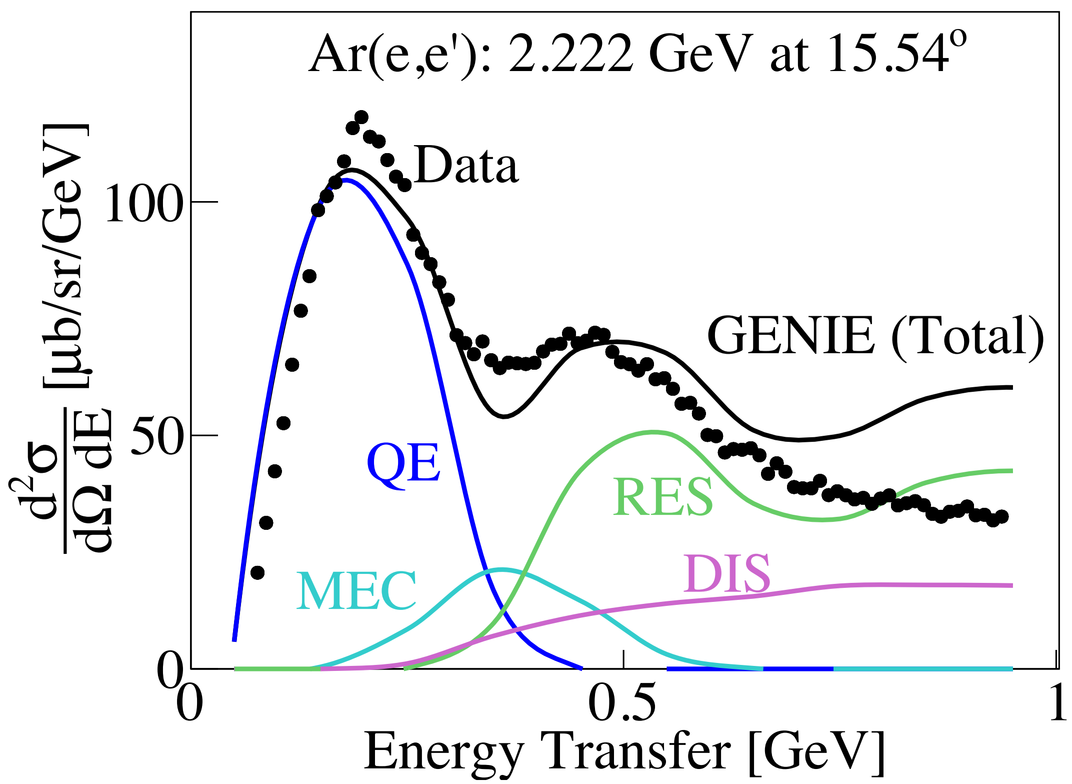
Using electrons to constrain models

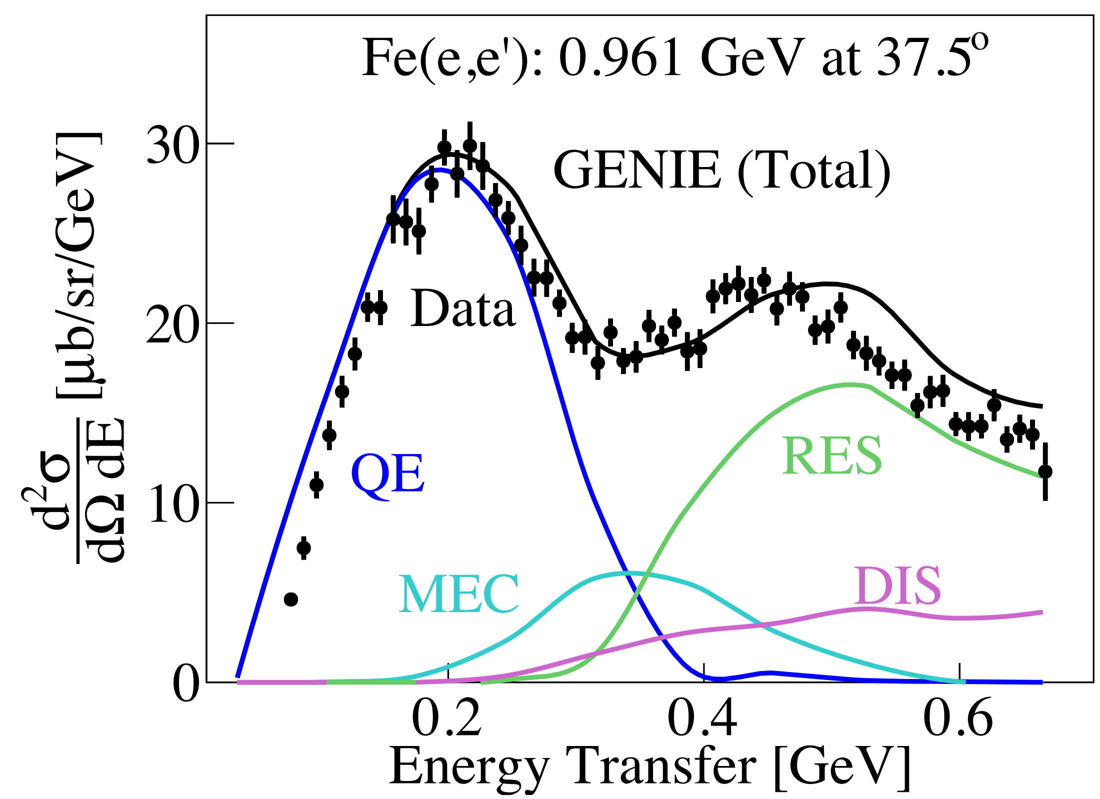


- Electrons and Neutrinos have:
  - Similar interactions
    - Vector vs. Vector + Axial Vector
  - Many identical nuclear effects
    - Ground state (spectral function)
    - Final state interactions

Electron beams have known energy

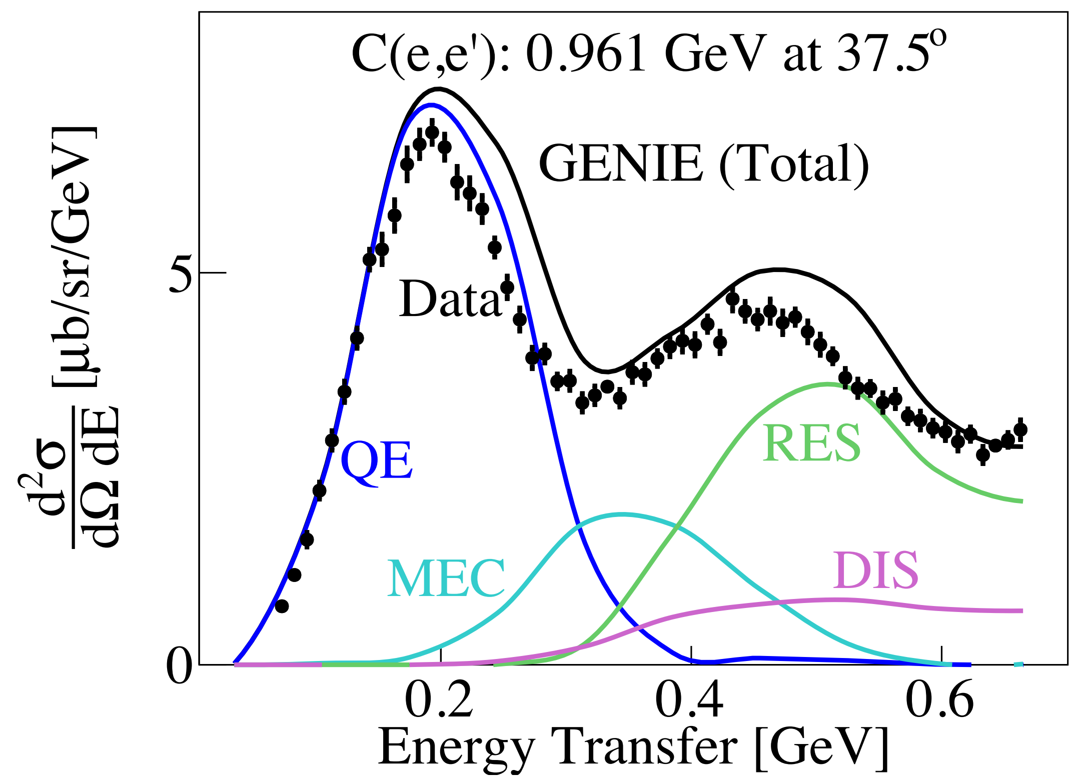
GENIE reproduced e inclusive data



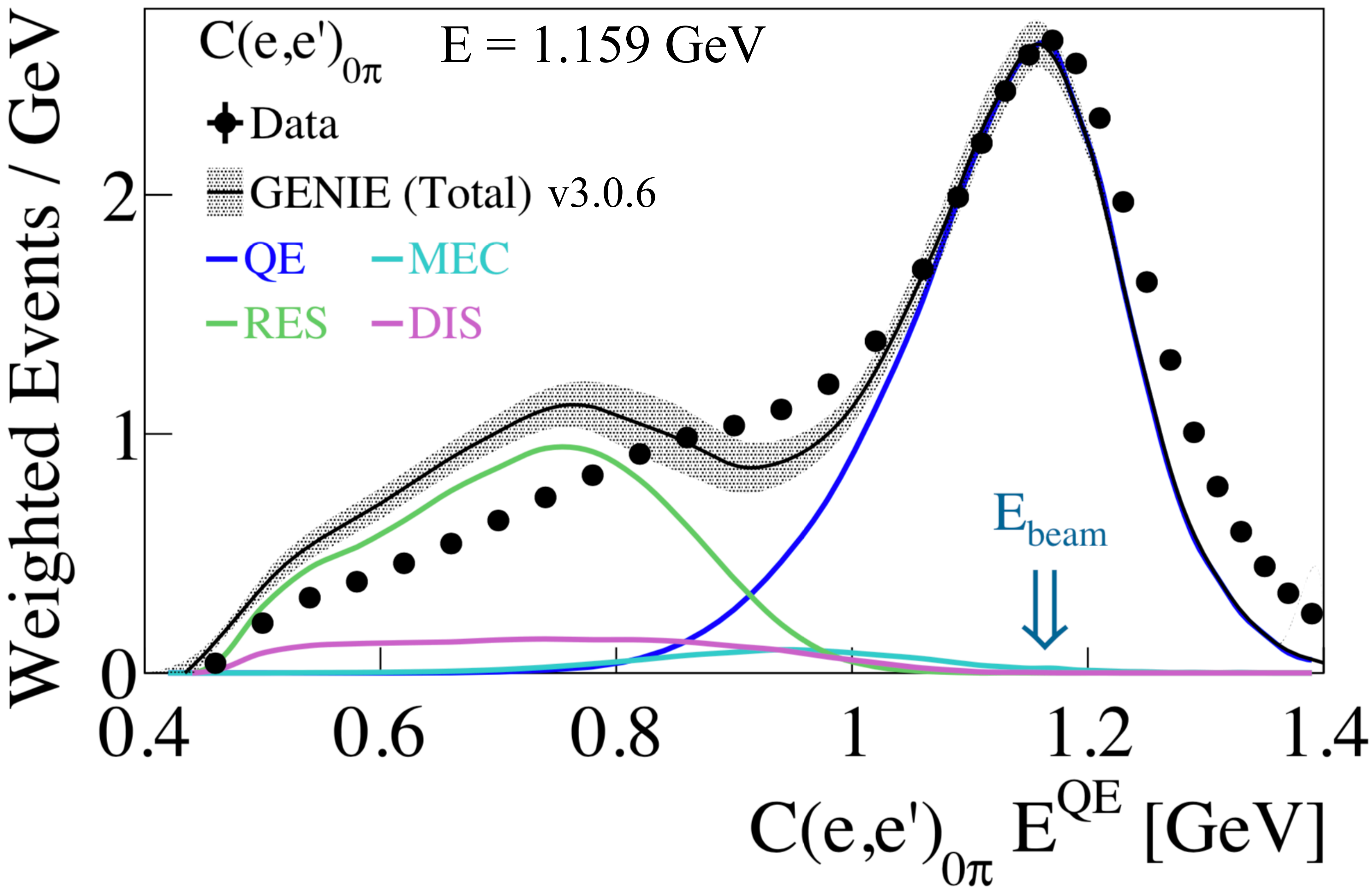


— v3.0.6 tune G18_10a_02_11a

A. Papadopoulou et al. Phys. Rev. D 103, 113003

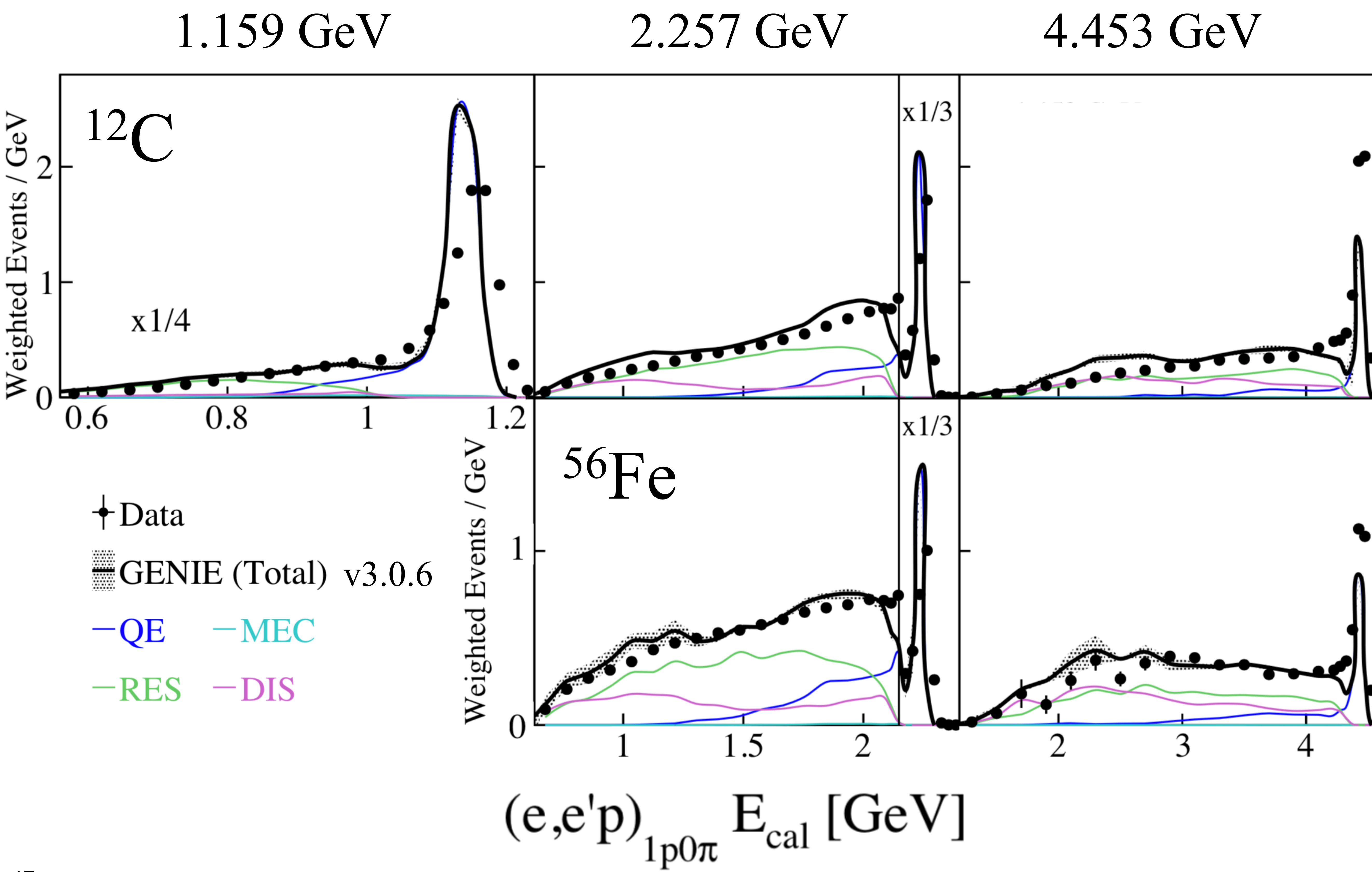


Disagreements between Data and MC

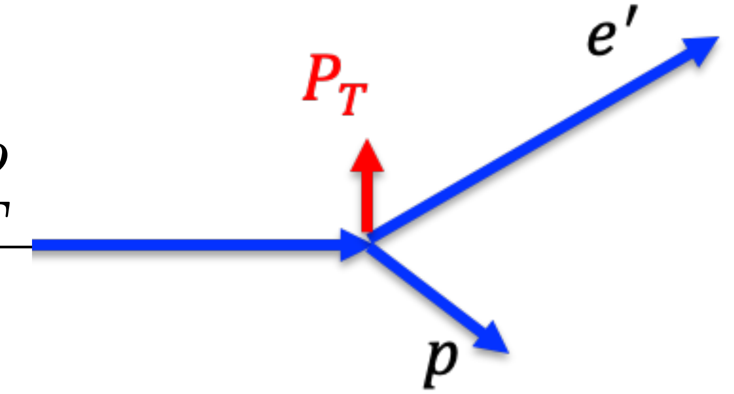


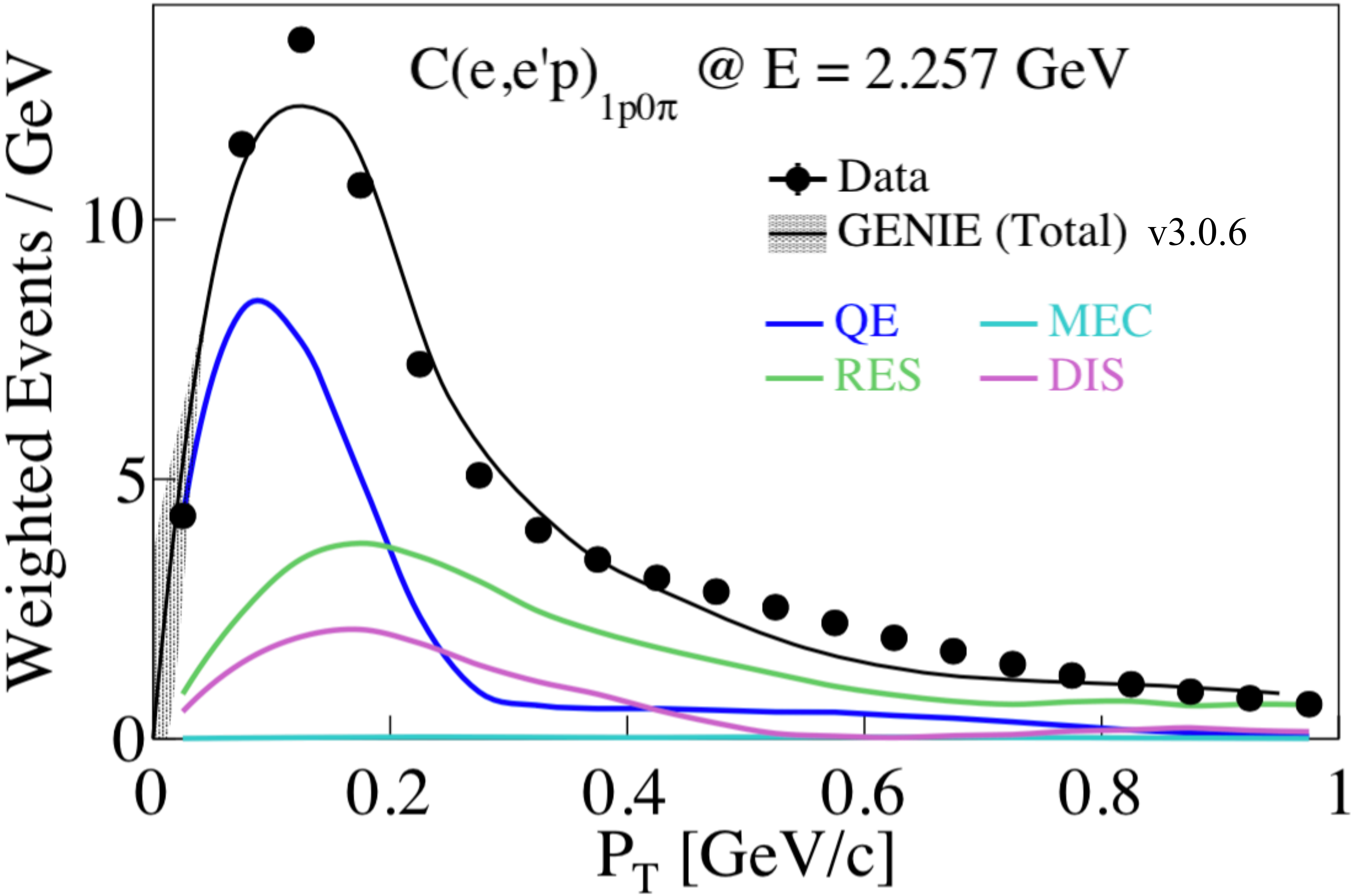
Peak width narrower in simulation due to model deficiencies

Disagreements between Data and MC

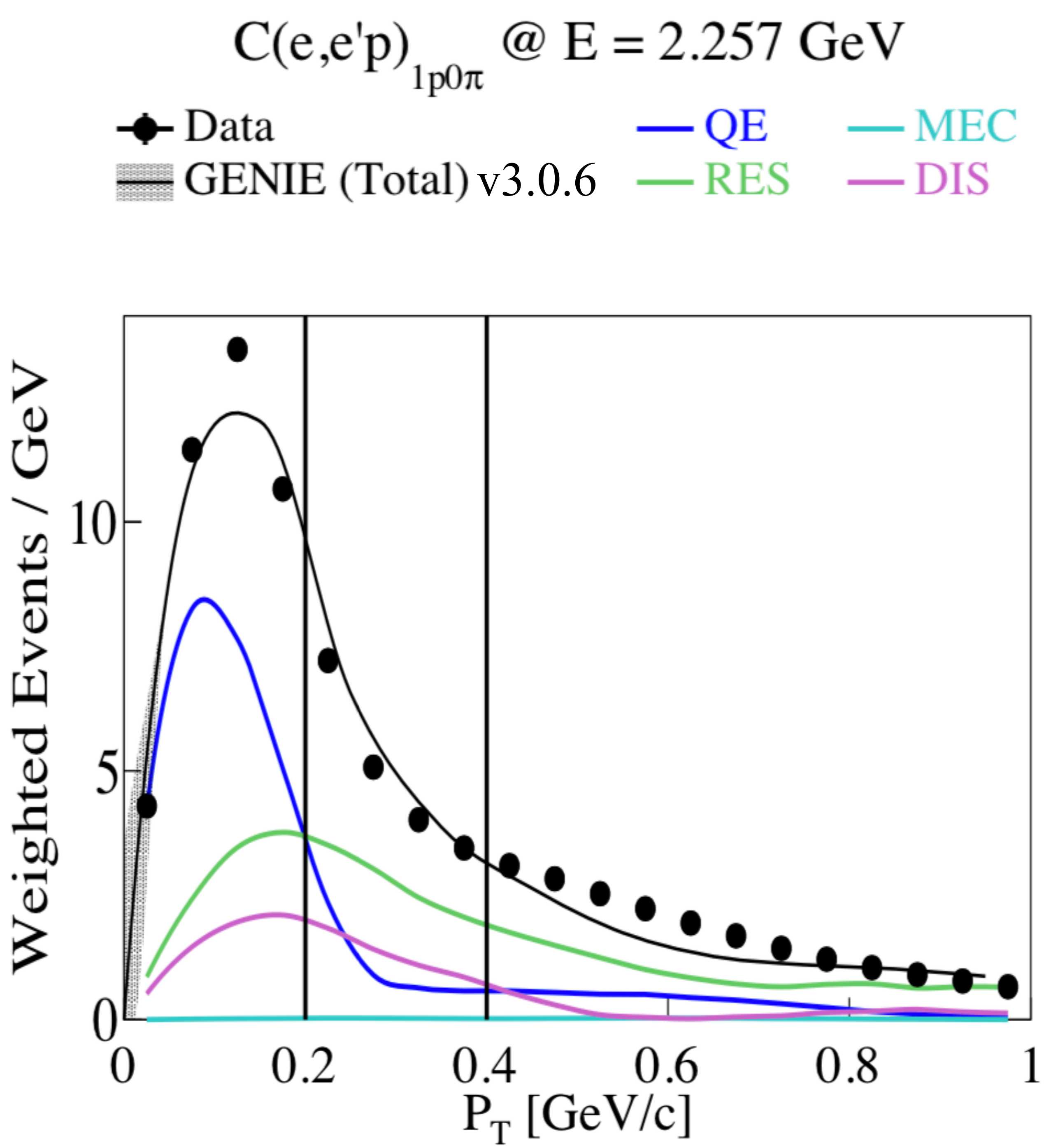


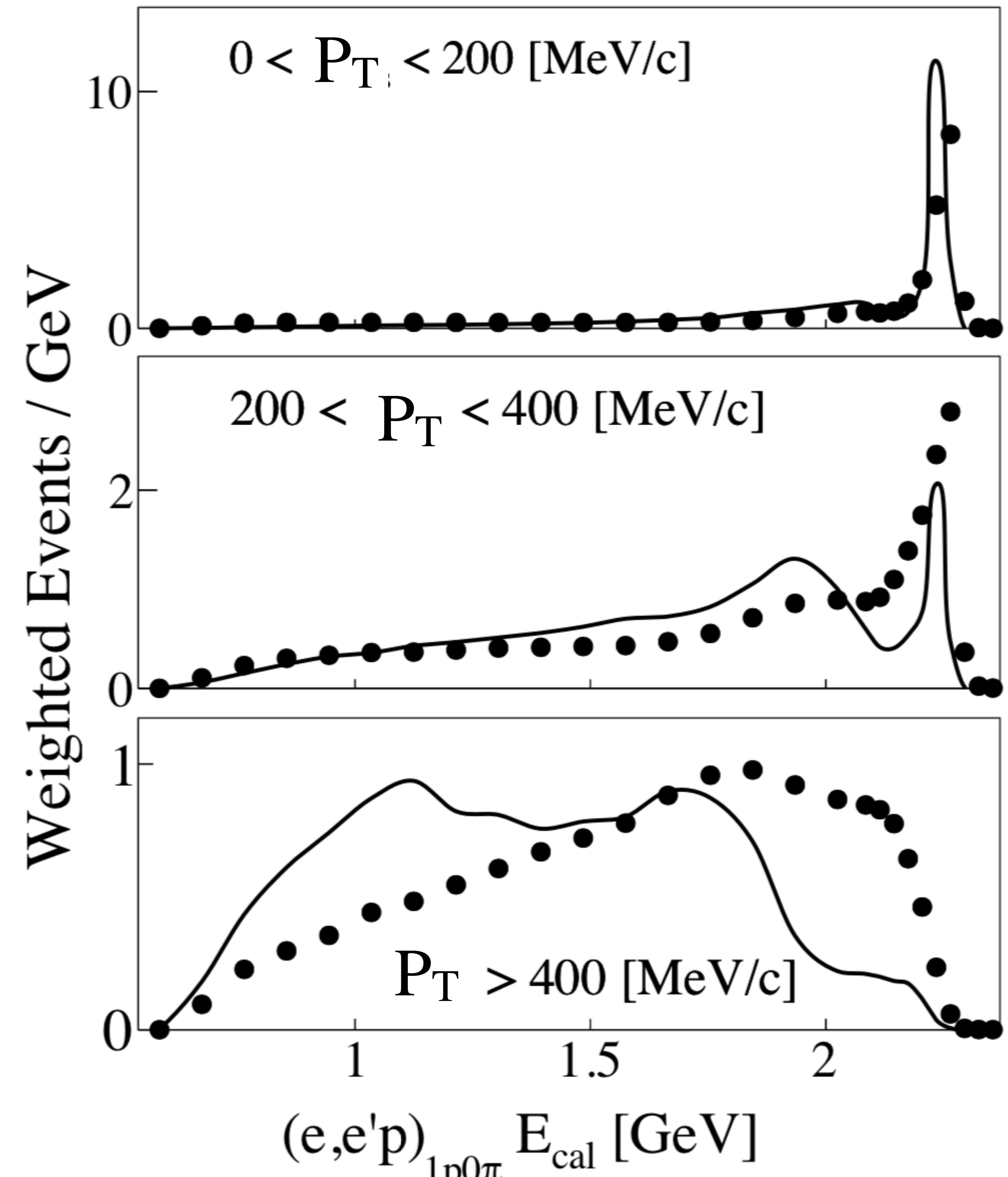
MC vs. (e,e'p) Data: $\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^{p}$





MC vs. (e,e'p) Data: $\vec{P_T} = \vec{P_T^{e'}} + \vec{P_T^{p}}$





Summary

Neutrino cross section are very challenging to measure and to predict!

Initial state, interaction processes and final state interaction, all could improve.

We rely on event generators, some still with semi-classical, or empirical models.

All models have many free parameters.

External data could be greatly used to constrain models and their uncertainties.

There's a lot of work - **join us!**

Thank you for your attention