Phenomenological Chiral Perturbation Theory for Neutrino Event Generators

Miša Toman, Mareen Hoppe, Joshua Isaacson, Zara Jones, Shirley Li

Coming soon to arXiv

Motivation

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- Neutrino experiments
  - T2K
  - NOVA
  - DUNE

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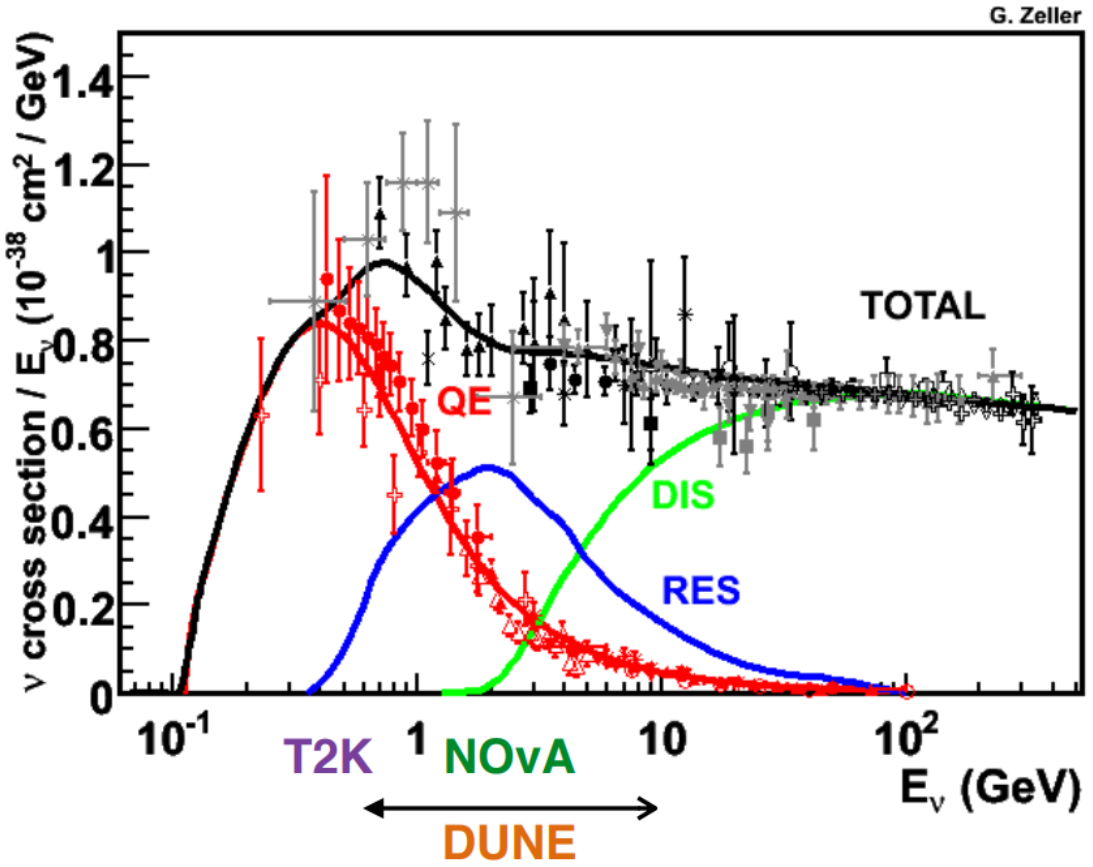

J. A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

Minerba Betancourt, Neutrino Cross sections, NPC Neutrino University 2016

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  - NOVA
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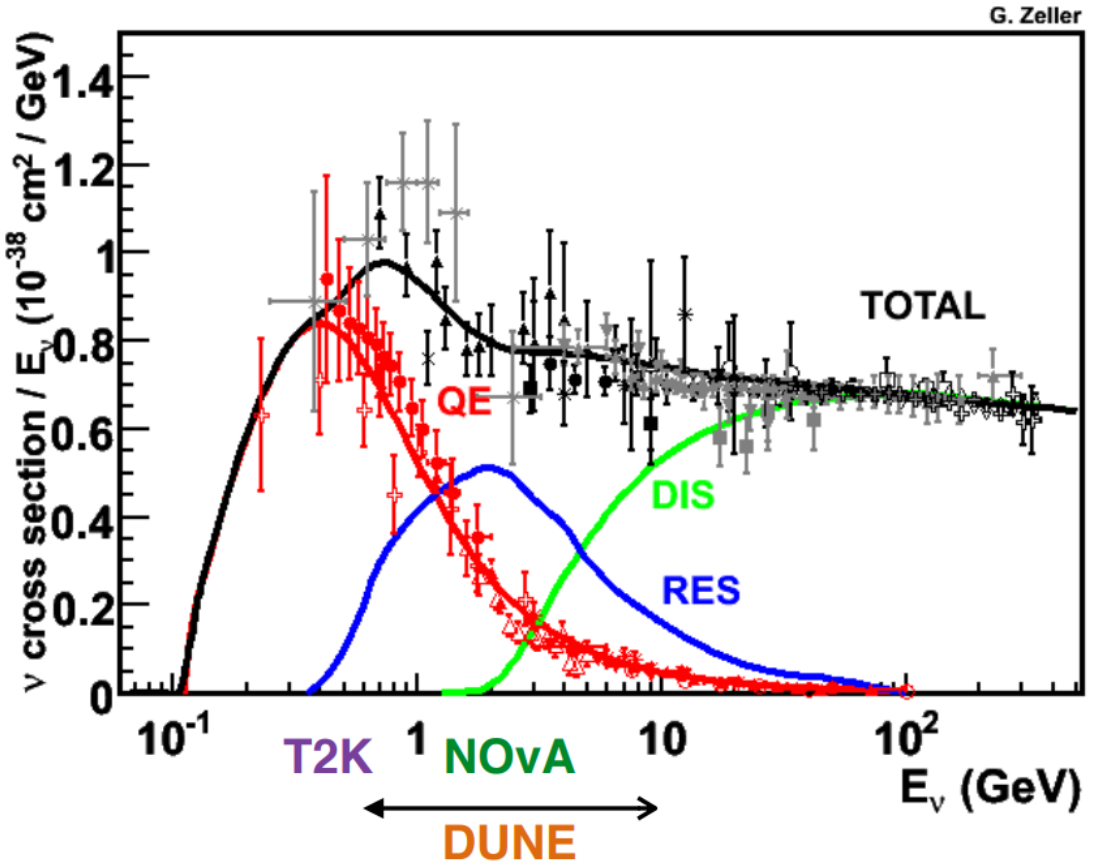
- Complex neutrino-nucleus interactions



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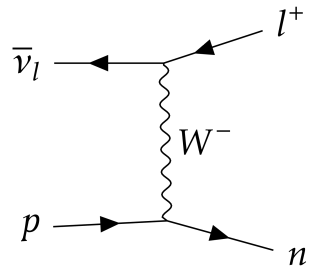
Neutrino interaction landscape

J. A. Formaggio, G. P. Zeller 2012, From eV to EeV: Neutrino cross sections across energy scales

Neutrino interaction landscape

Quasi Elastic (QE)



100 MeV 1 GeV 10 GeV

E_ν

[J. A. Formaggio, G. P. Zeller 2012, From eV to EeV: Neutrino cross sections across energy scales]

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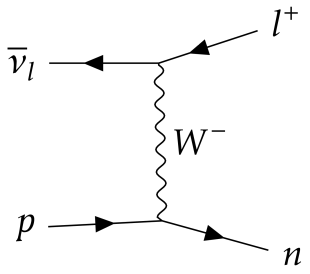
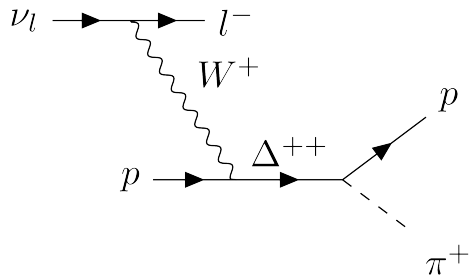
Quasi Elastic (QE)

Resonance production (RES)





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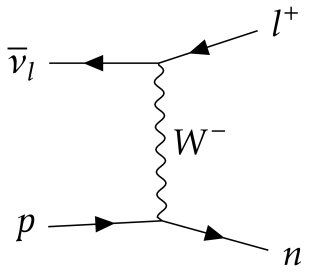
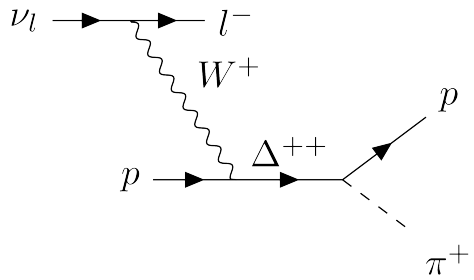
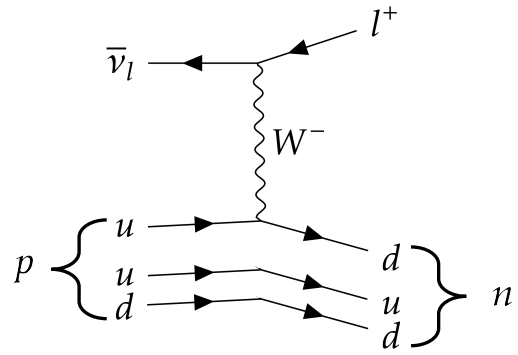
Deep Inelastic Scattering (DIS)







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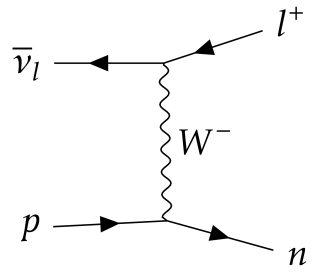

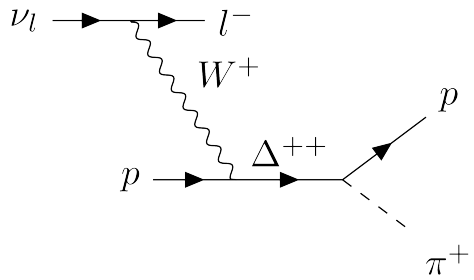

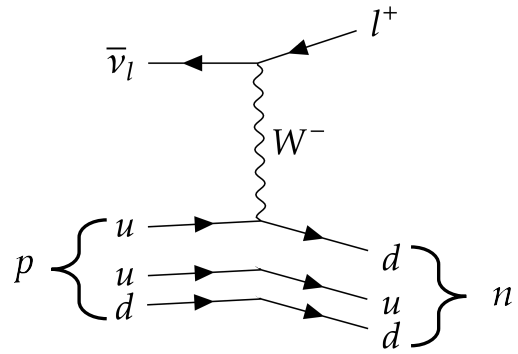

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Neutrino interaction landscape

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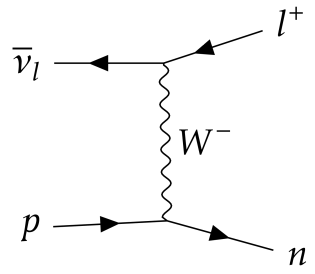
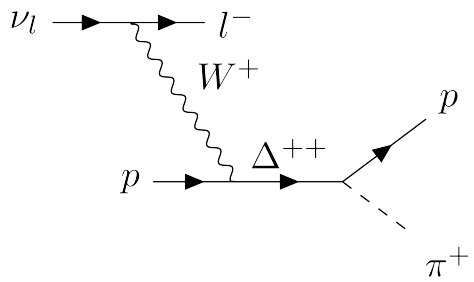
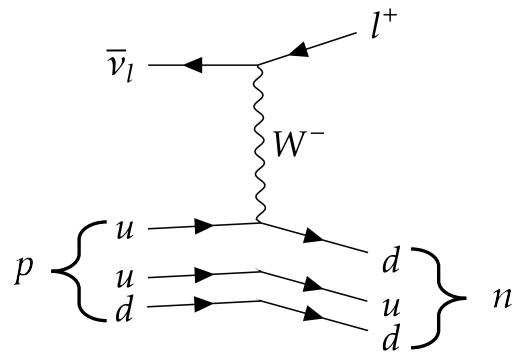
Shallow Inelastic Scattering (SIS)







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Neutrino-nucleus scattering event generation

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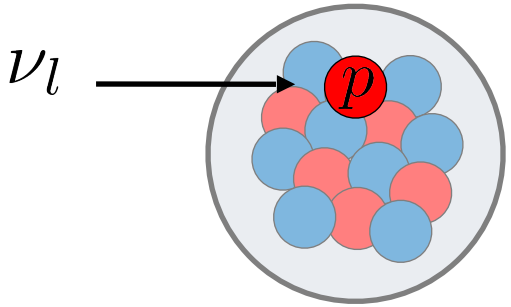
Initial state modeling



- Momentum distribution
- Spectral function

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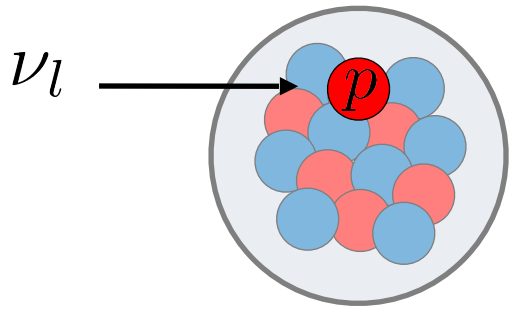

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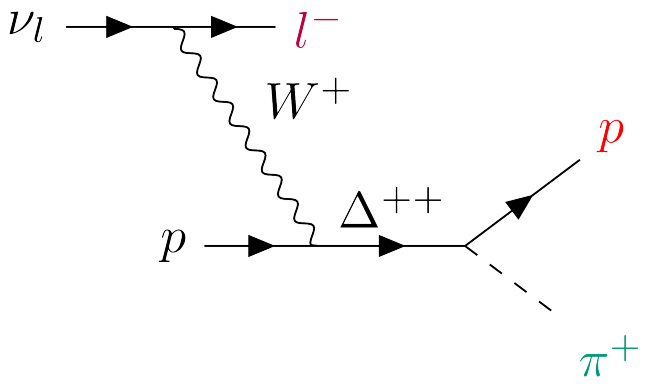
Hard Scattering Matrix Element



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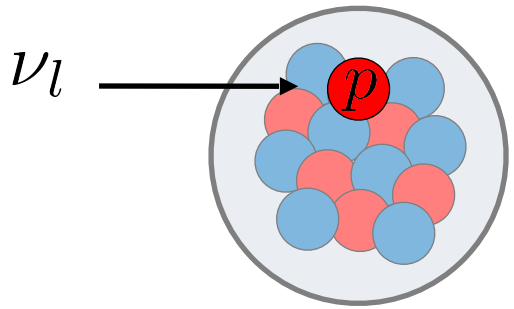

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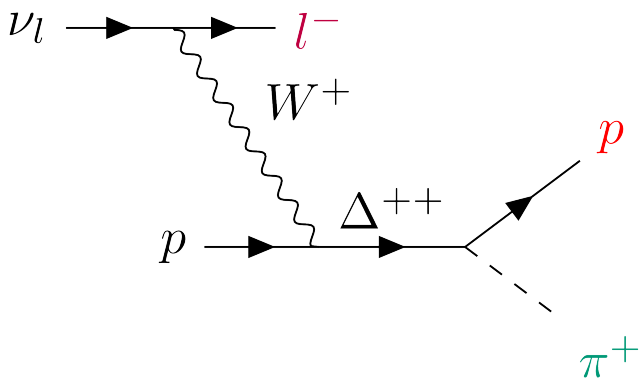

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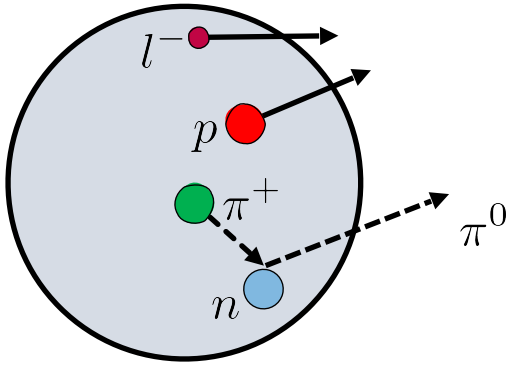
Final State Interactions (FSI)



- Intra nuclear cascade (INC)

Neutrino-nucleus scattering event generation

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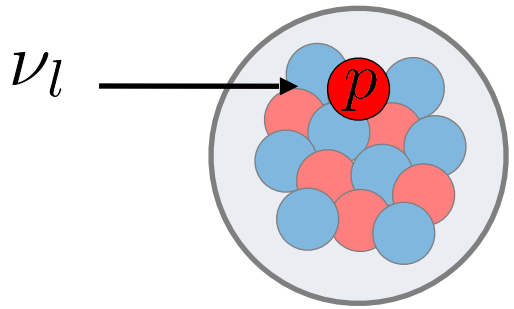

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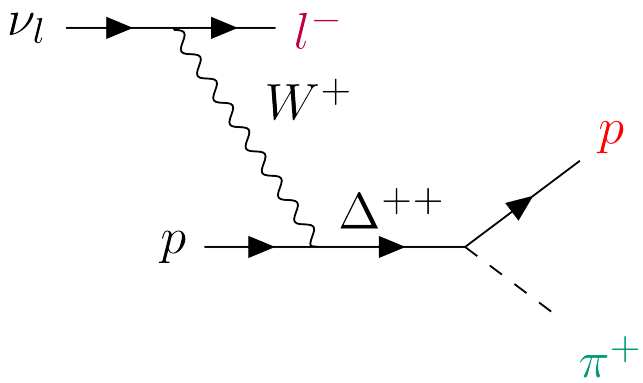

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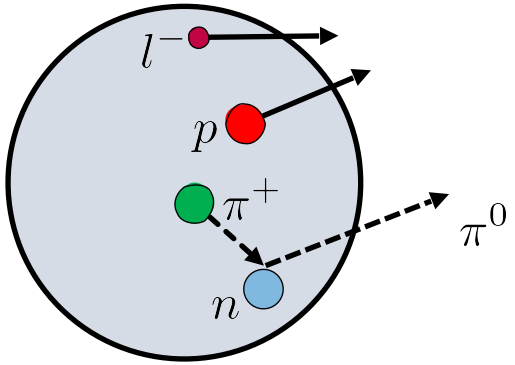

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1. S. Dytman et al 2021, Comparison of validation methods of FSI
2. A. Nikolakopoulos et al 2024, FSI in neutrino-induced proton knockout from argon

Chiral Perturbation Theory (ChiPT)

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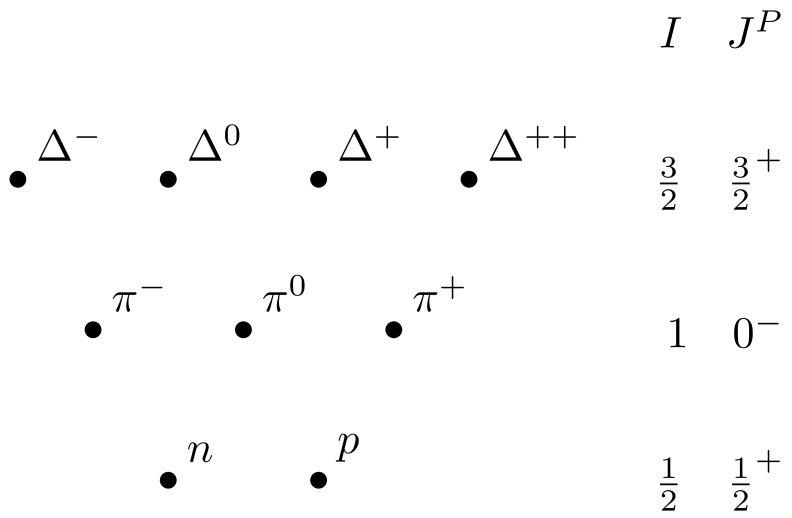

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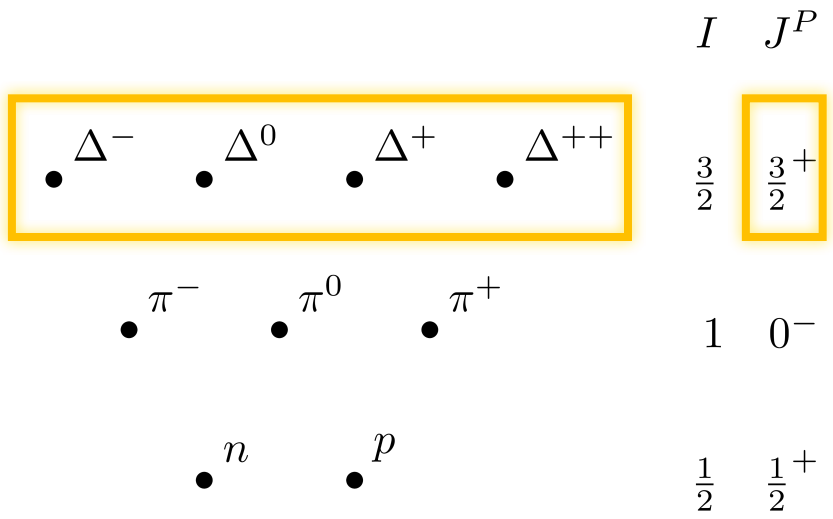

Spin 3/2 interactions

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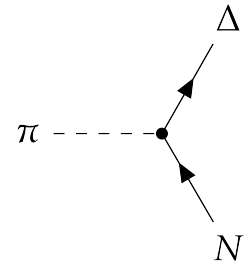

[C. Fernandez-Ramırez, E. Moya de Guerra, J.M. Udıas c, 2006, Effective Lagrangian Approach to pion photoproduction from the nucleon]

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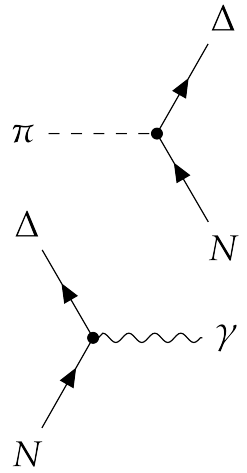

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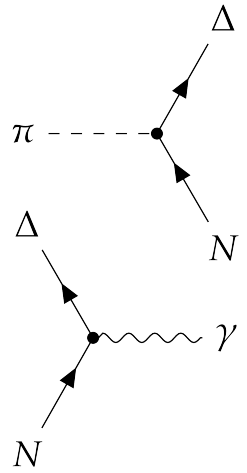
- Vertices available in literature but not systematically used for neutrino event generation



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Phenomenological ChiPT

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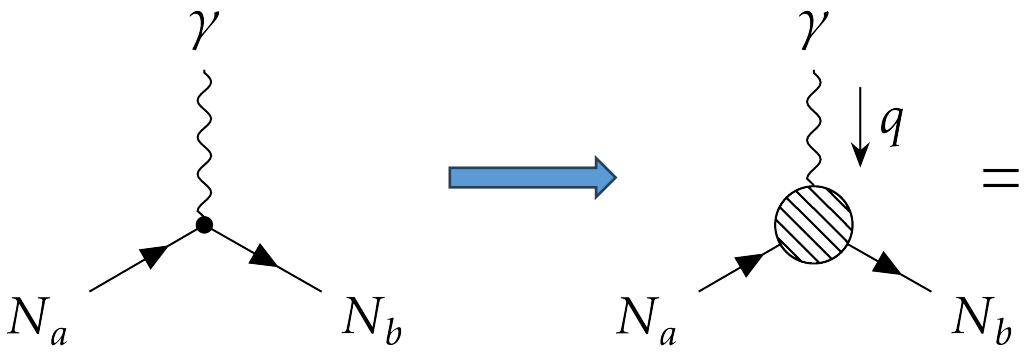
- Why phenomenological?

Phenomenological ChiPT

- Why phenomenological?
- Systematically replace vertices with form factors



$$= e\left(F_1(Q^2)\gamma^\mu + F_2(Q^2)\,\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}\right)\delta_{ab}$$

Event generation with Achilles

J. Isaacson, S. Höche, D. L. Gutierrez, N. Rocco, 2022 A novel event generator for the automated simulation of neutrino scattering
J. Isaacson et al, 2022, ACHILLES: A novel event generator for electron- and neutrino-nucleus scattering

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- **A CHI**cago**L**and **L**epton **E**vent **S**imulator

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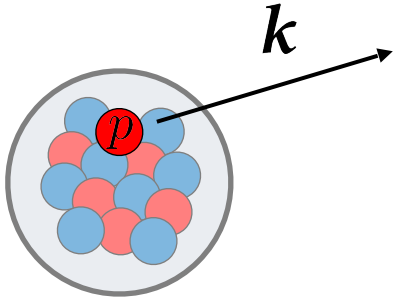

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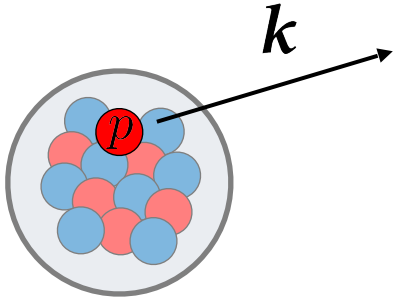

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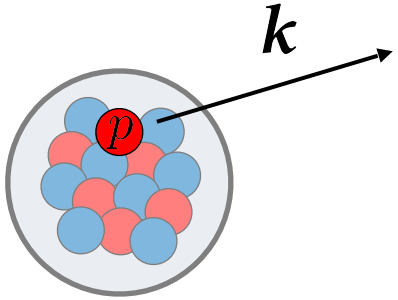

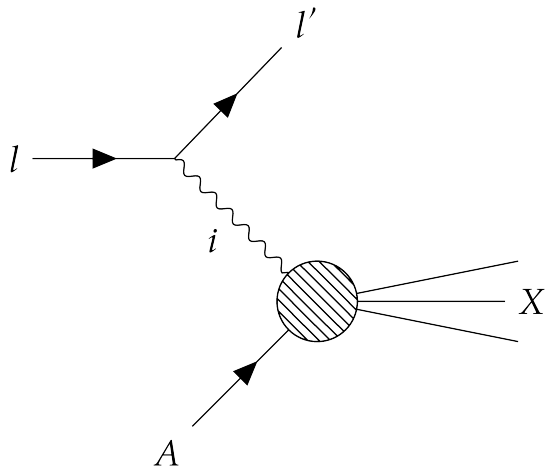

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \left| \sum_{i=\gamma,Z,W} L_\mu^{(i)} W^{(i)\mu} \right|^2$$

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Hard Scattering Matrix Element

J. Isaacson et al, 2026, Single pion-production and pion propagation in Achilles

L. Darme, C. Degrande et al UFO - The Universal FeynRules Output

Hard Scattering Matrix Element

- **D**ynamically **C**oupled **C**hannels $N, \pi, \Delta, K, \Lambda, \Sigma$

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Results (work in progress)

Data: R. M. Sealock et al. 1989

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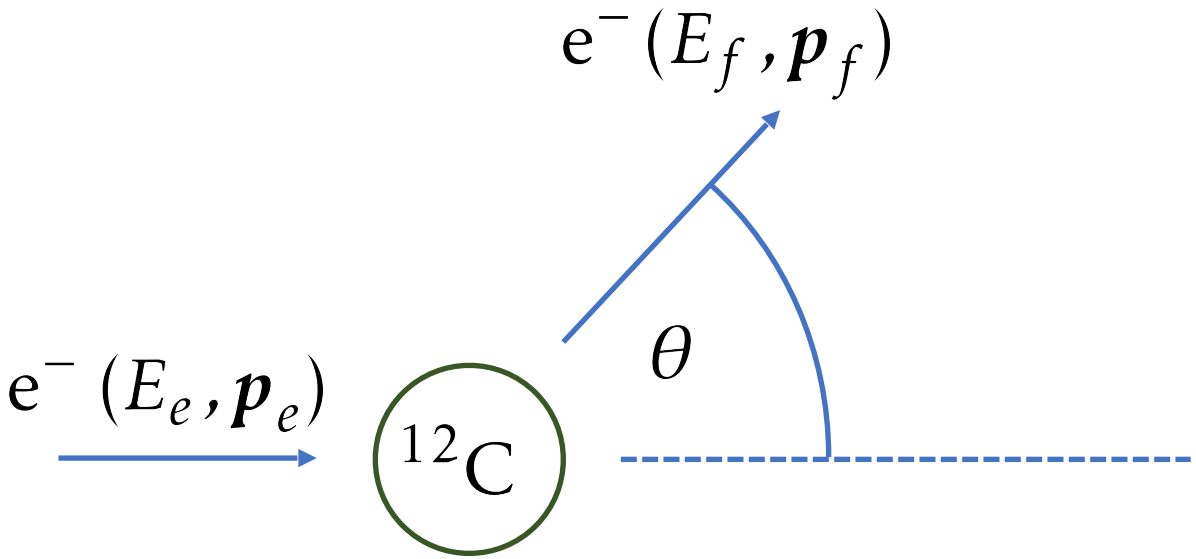

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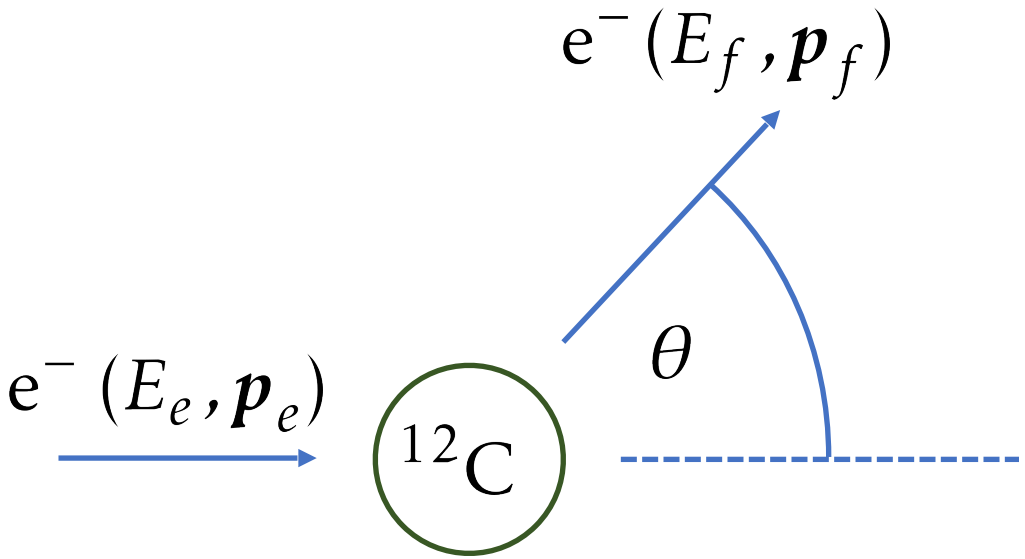

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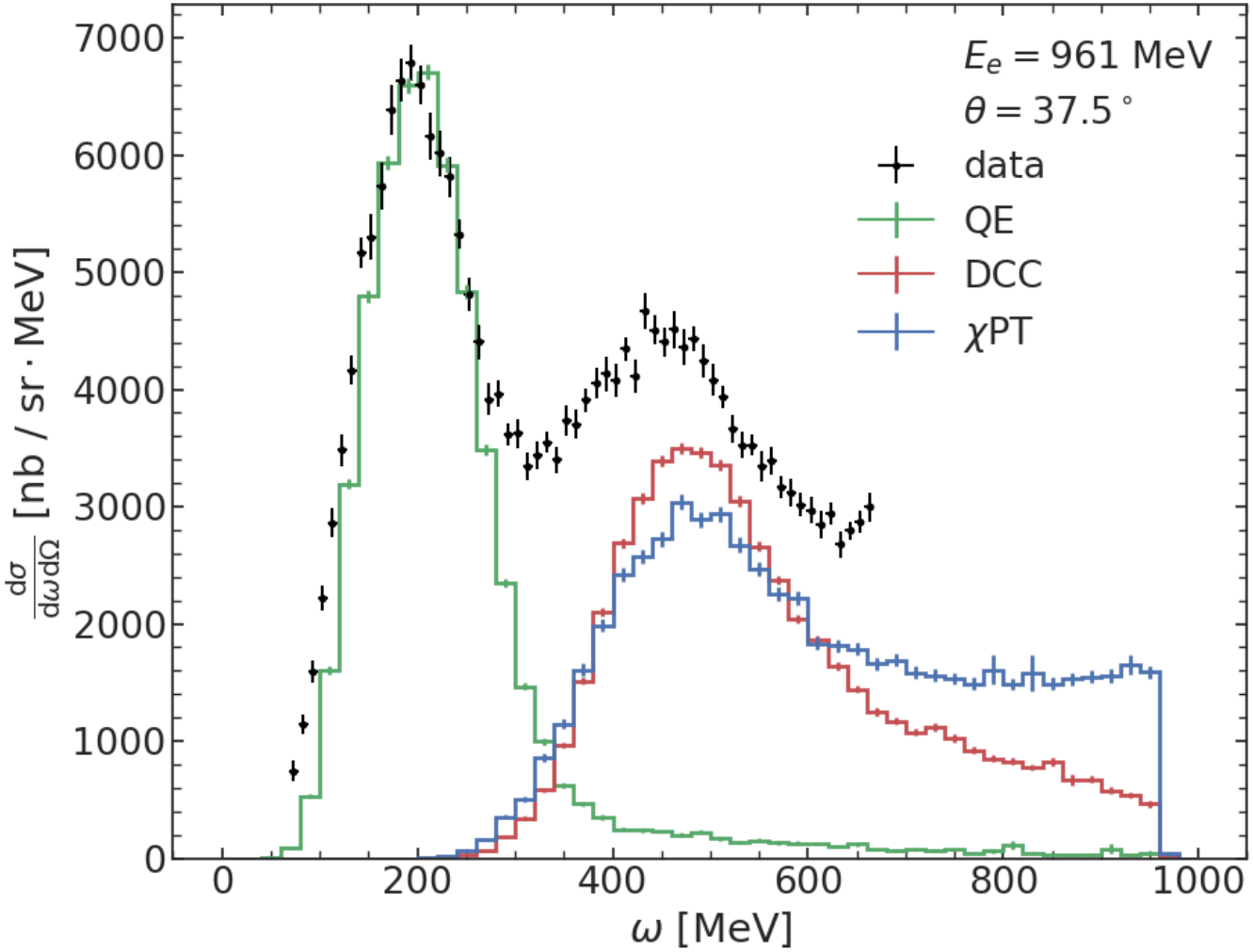

Data: [R. M. Sealock et al. 1989]

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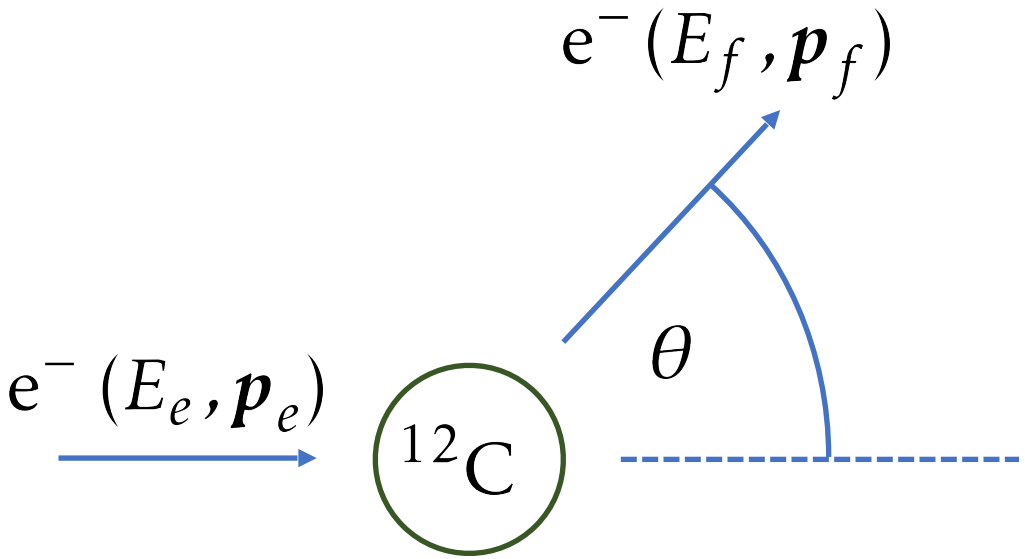
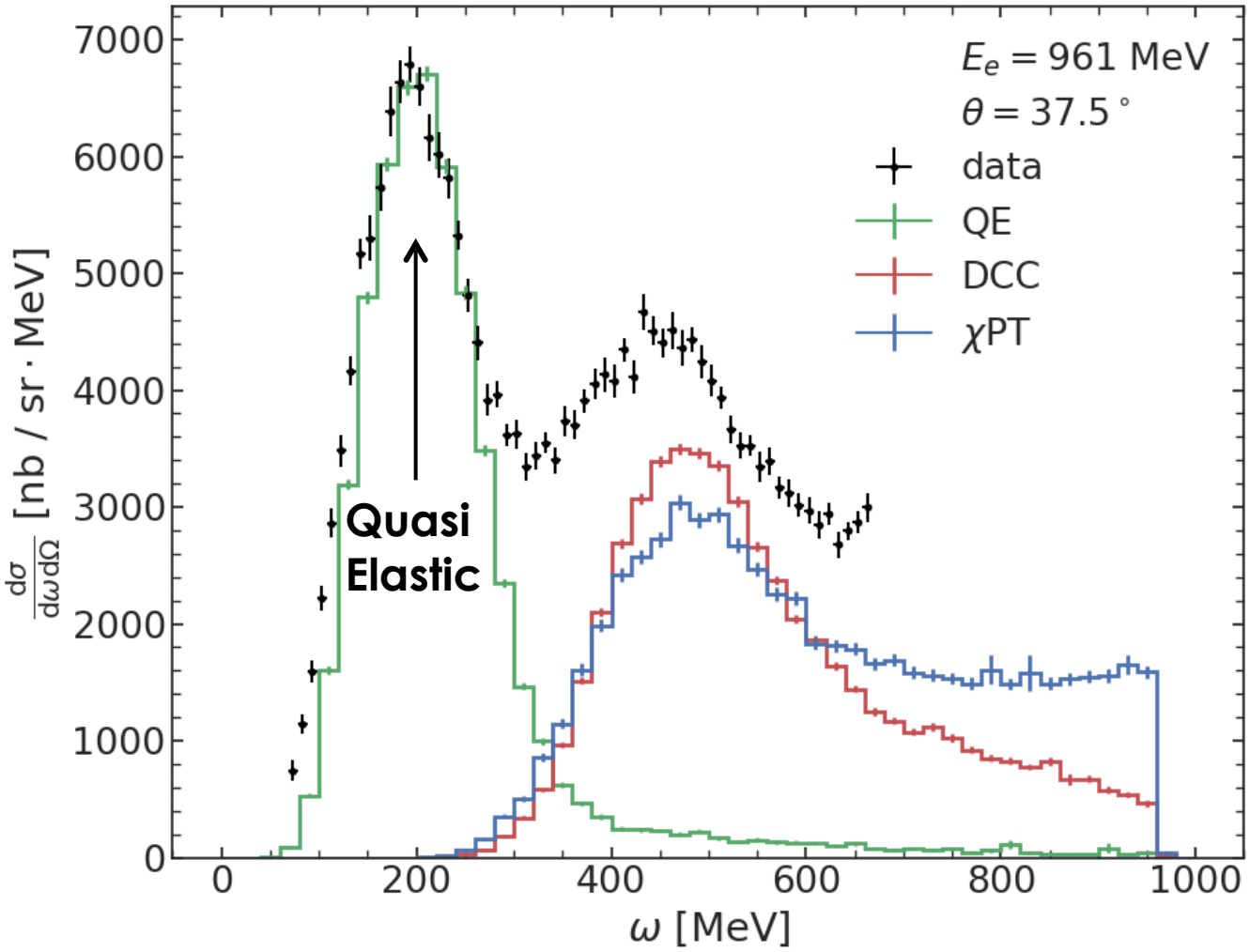


$$\omega = E_e - E_f$$



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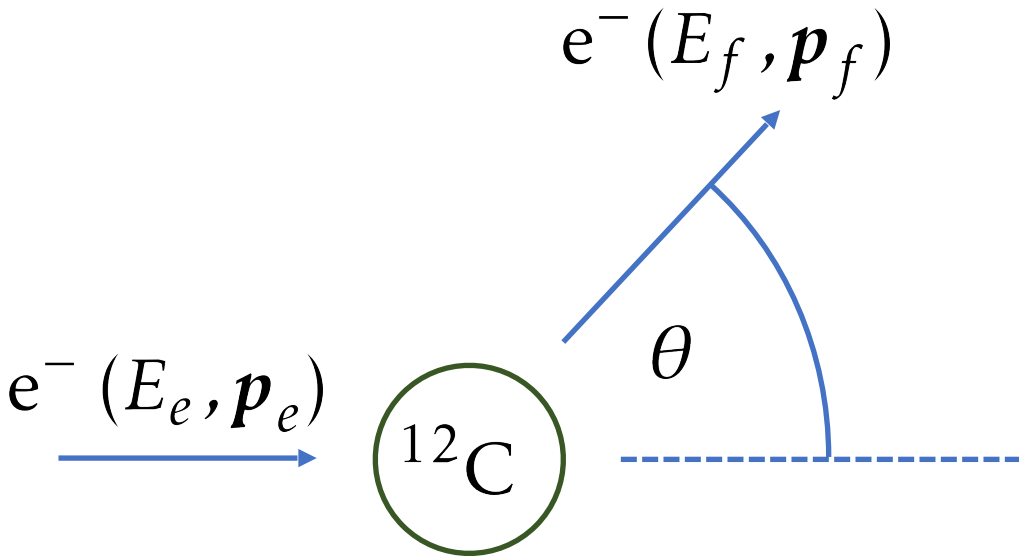

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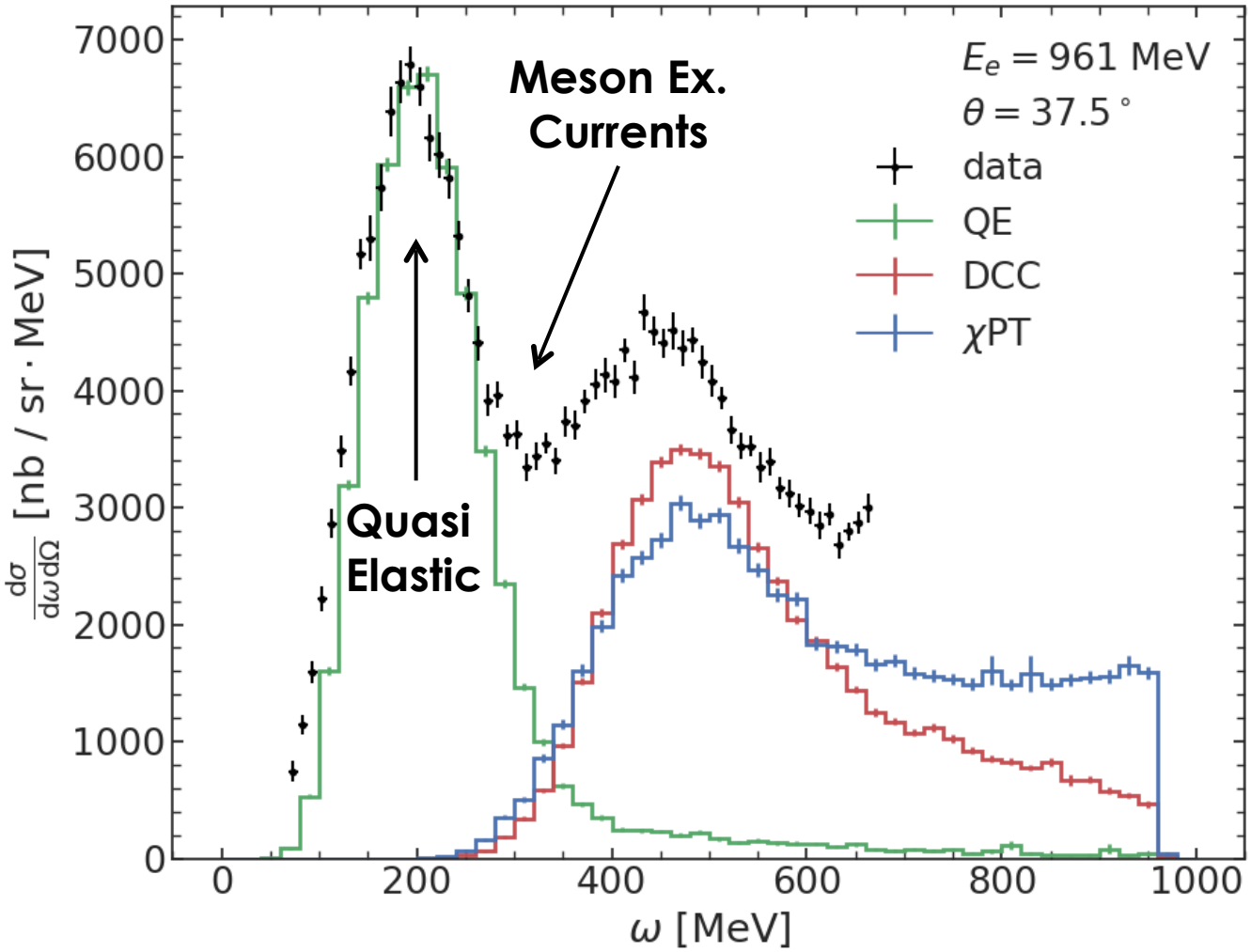

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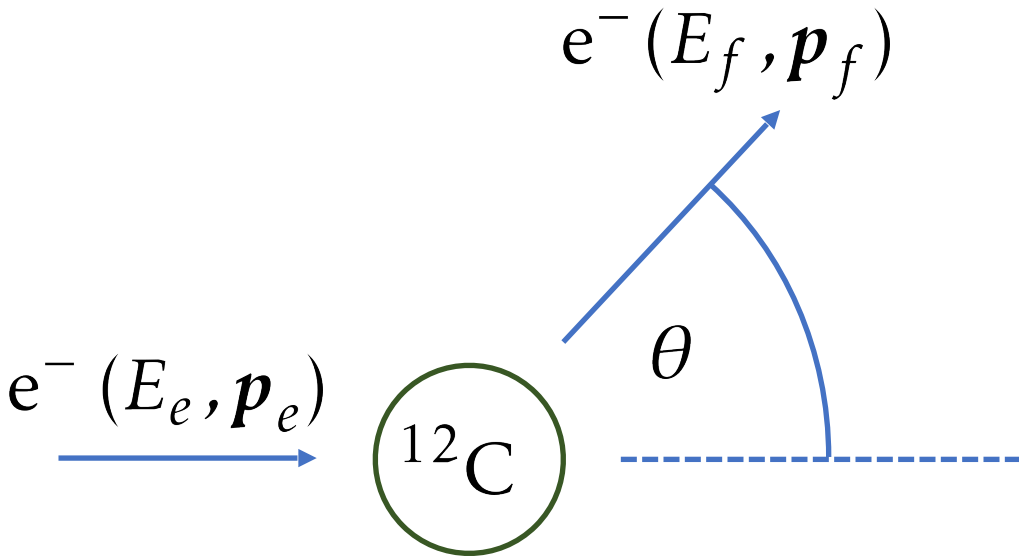

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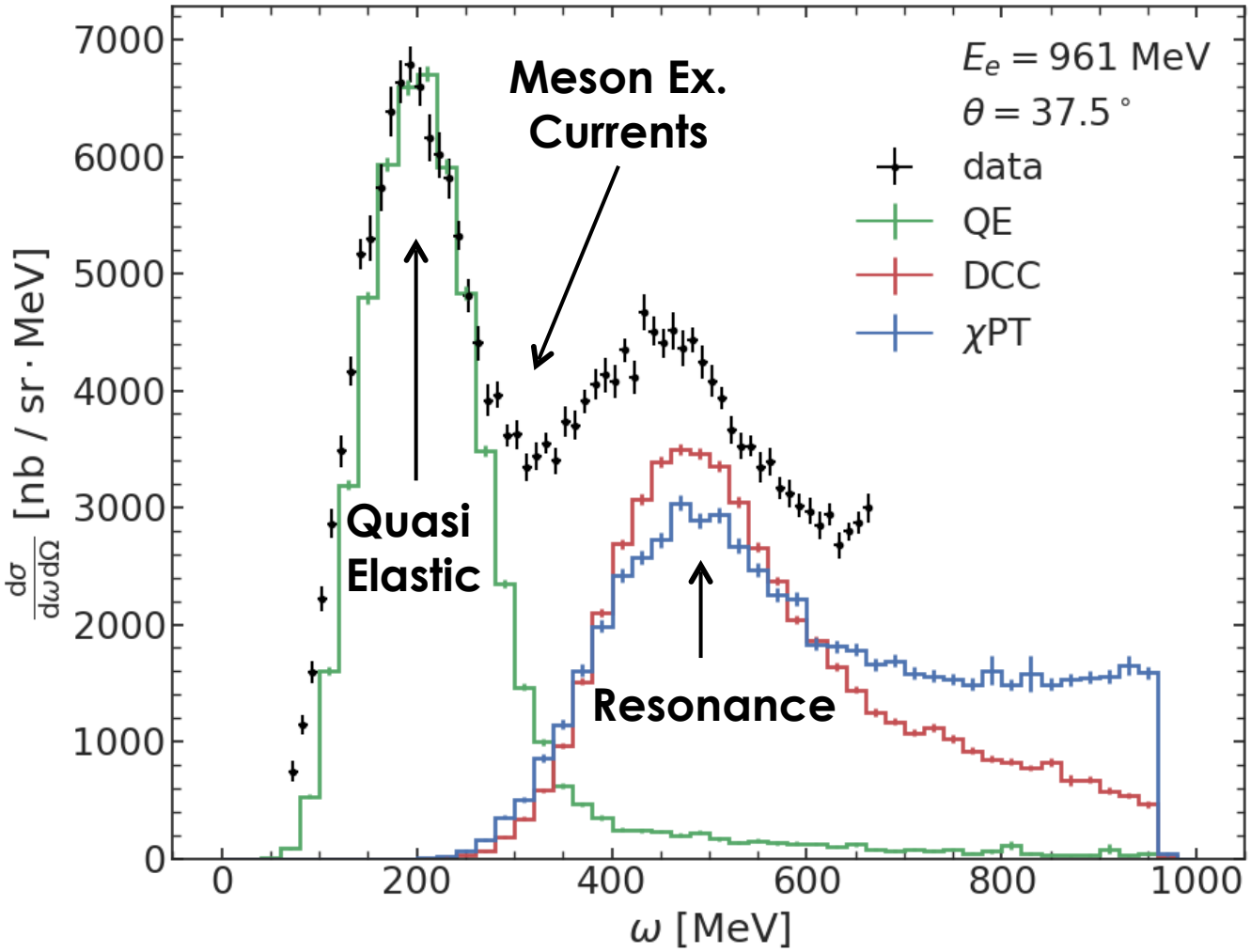

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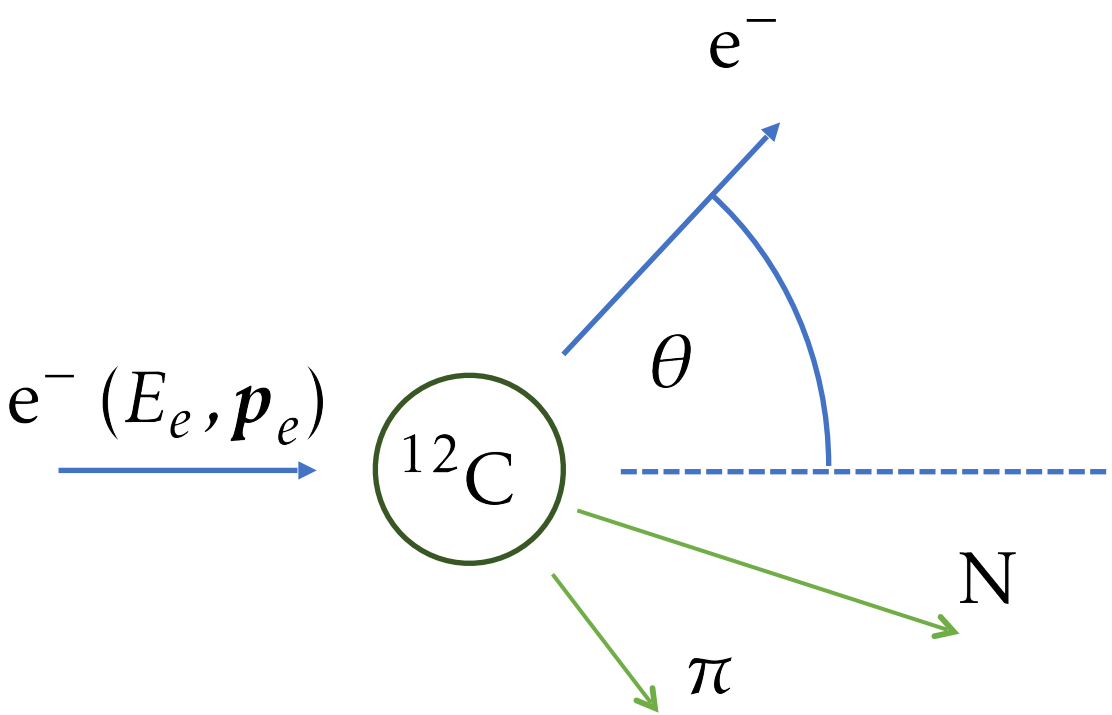
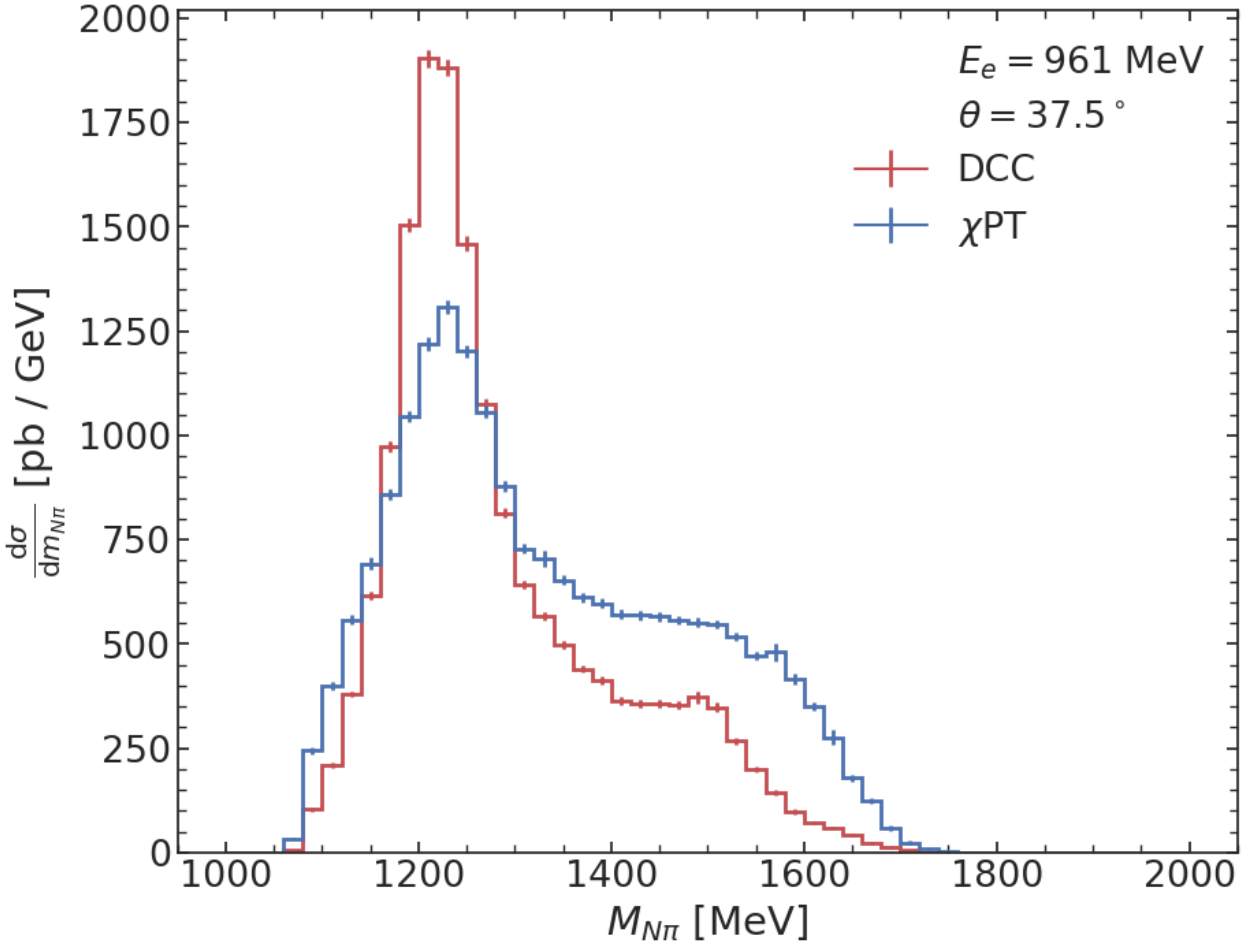


$$M^2_{N\pi} = (p_N + p_\pi)^2$$



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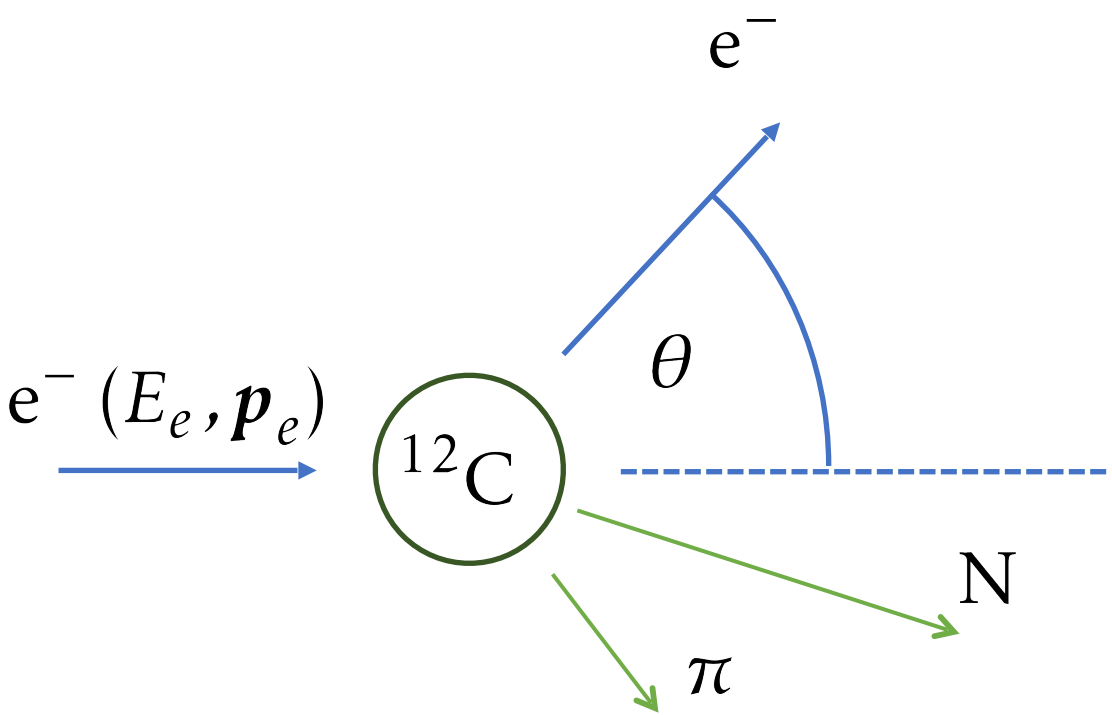

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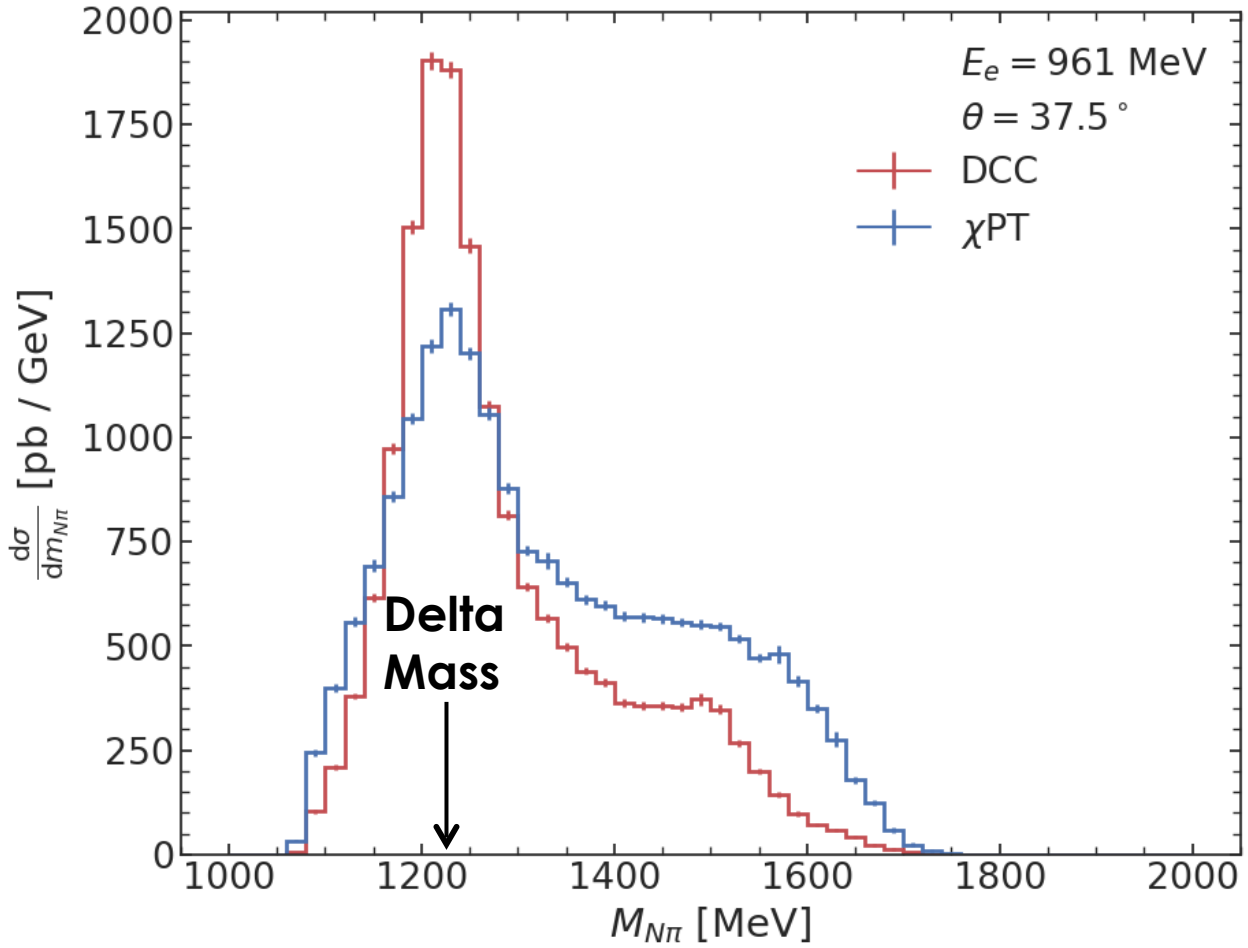

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- Goals:
  - Predict single pion production in neutrino experiments
  - Software package for the community

Thank you!