

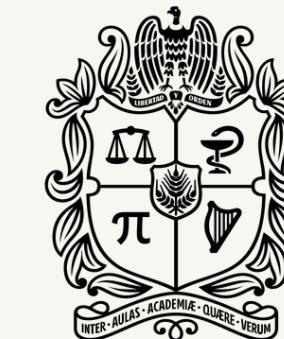
# Tensions between theory and experiment on final state interactions with neutrinos

Villa de Leyva, Colombia - November 29th 2022

**Camilo Cortés Parra<sup>1</sup>**  
**Juan Villamil Santiago<sup>1</sup>**  
**Diego Milanés Carreño<sup>1</sup>**  
**Enrique Arrieta Díaz<sup>2</sup>**

<sup>1</sup>Universidad Nacional de Colombia

<sup>2</sup>Universidad del Magdalena



UNIVERSIDAD  
**NACIONAL**  
DE COLOMBIA

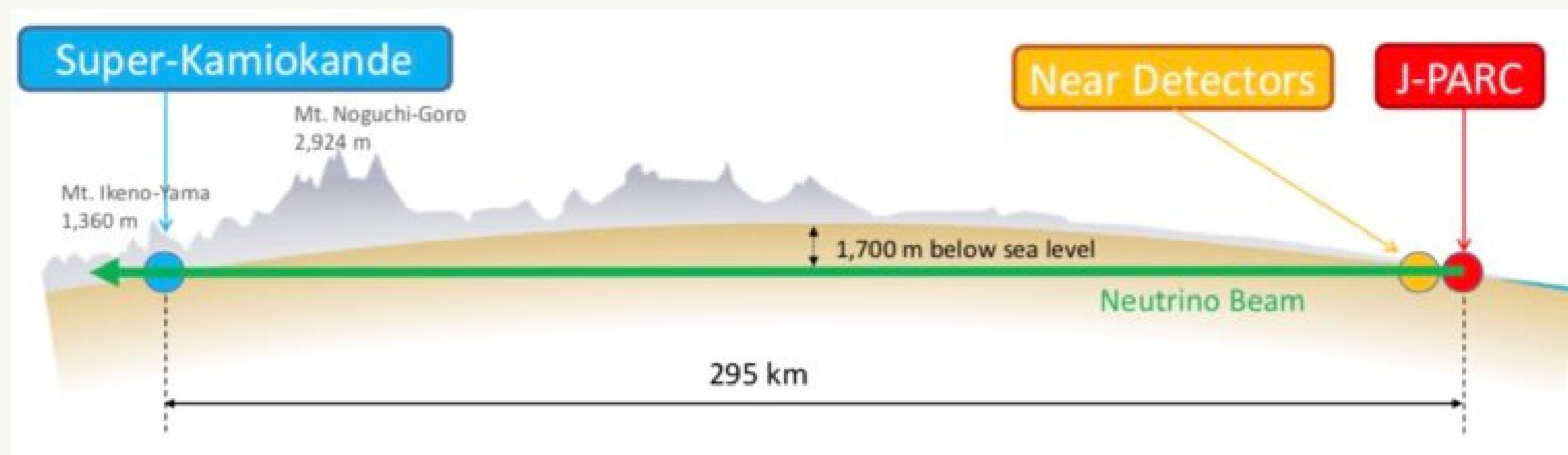


7th Colombian Meeting on High Energy Physics

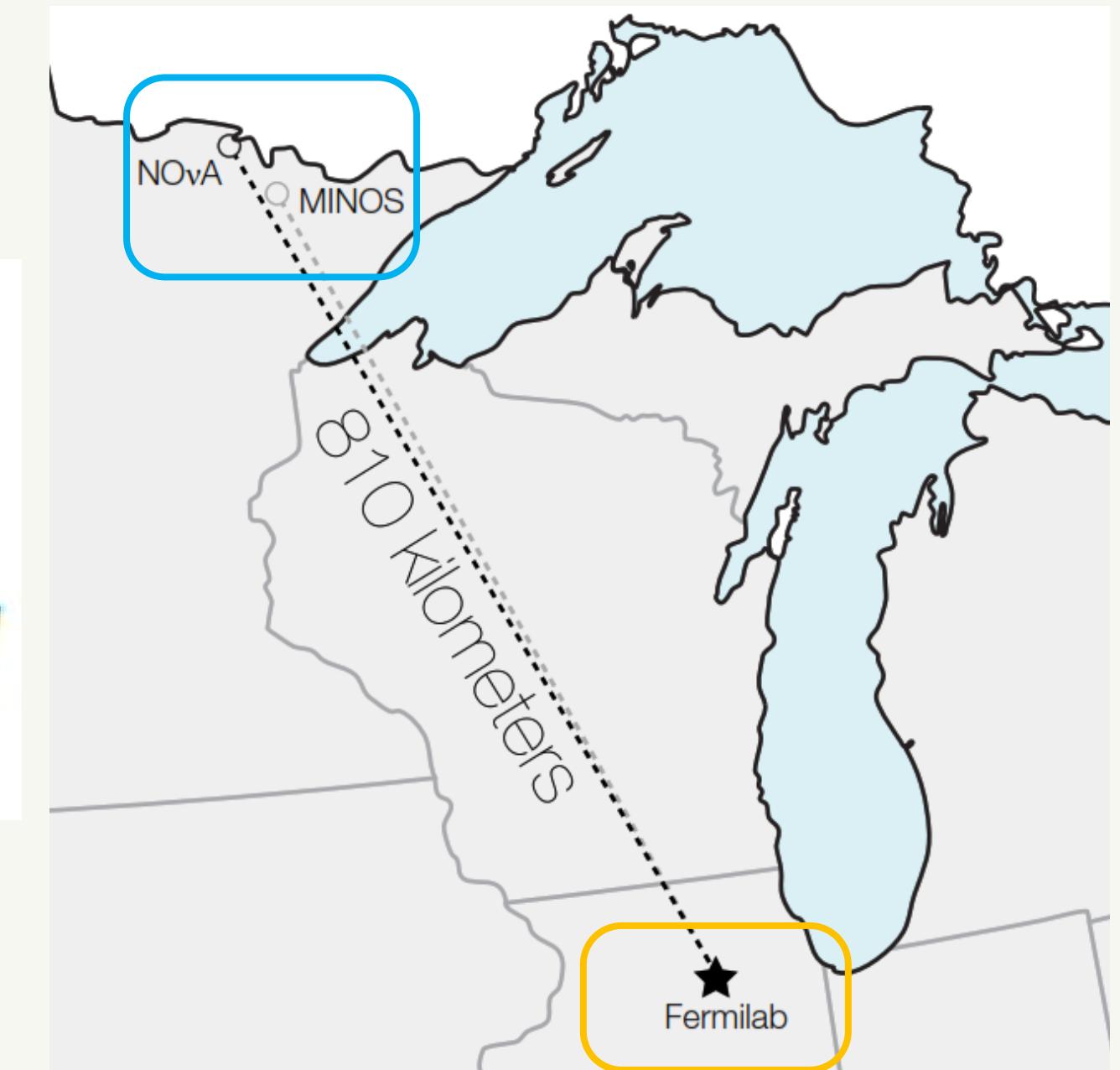
# Introduction

## >> Long-Baseline Neutrino Experiments: Two-detector design

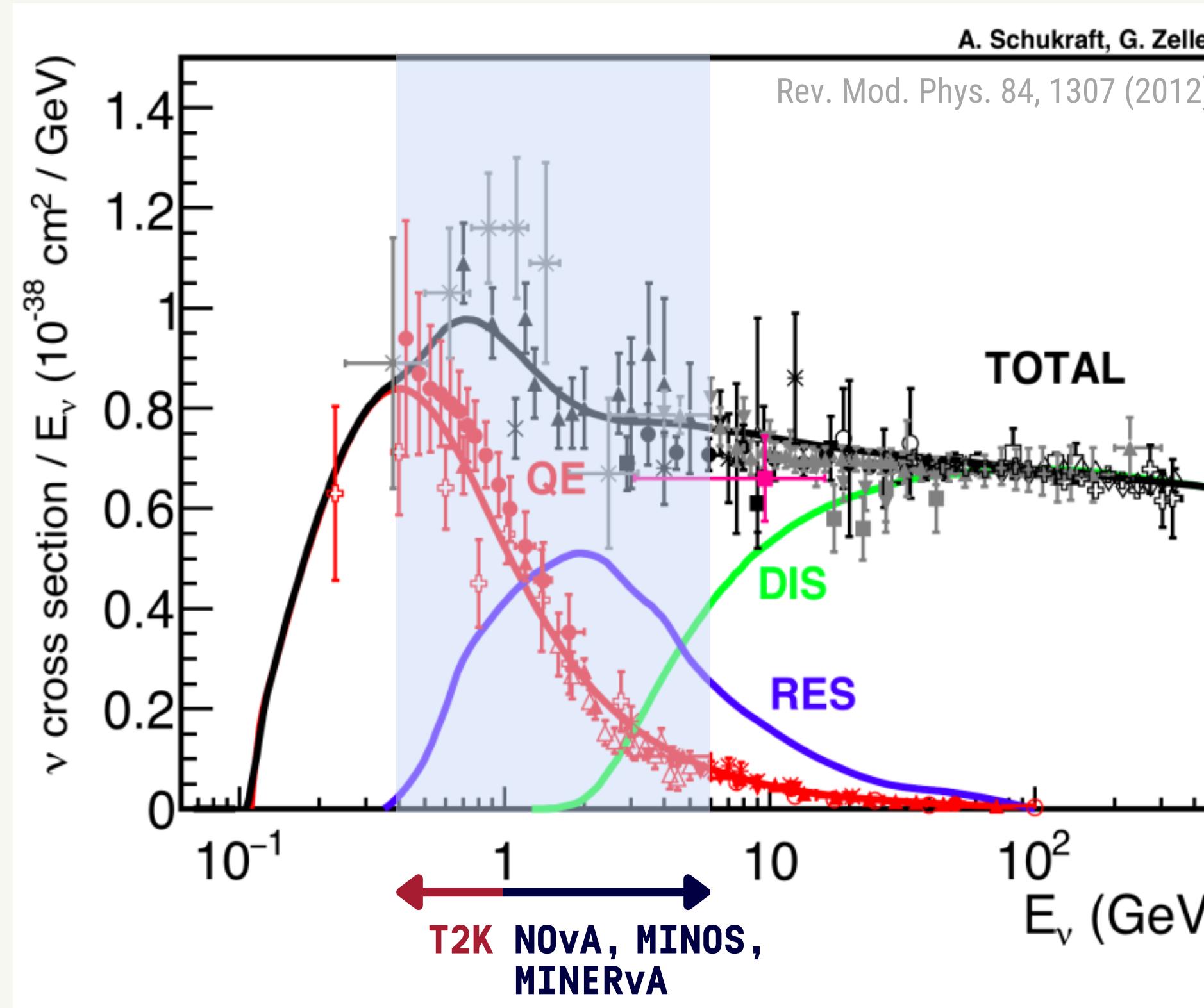
- **Near Detector (ND)**
- **Far Detector (FD)**



ND data are used to adjust FD predictions  
and constrain systematic uncertainties



# Introduction



>>> Primary neutrino interactions:

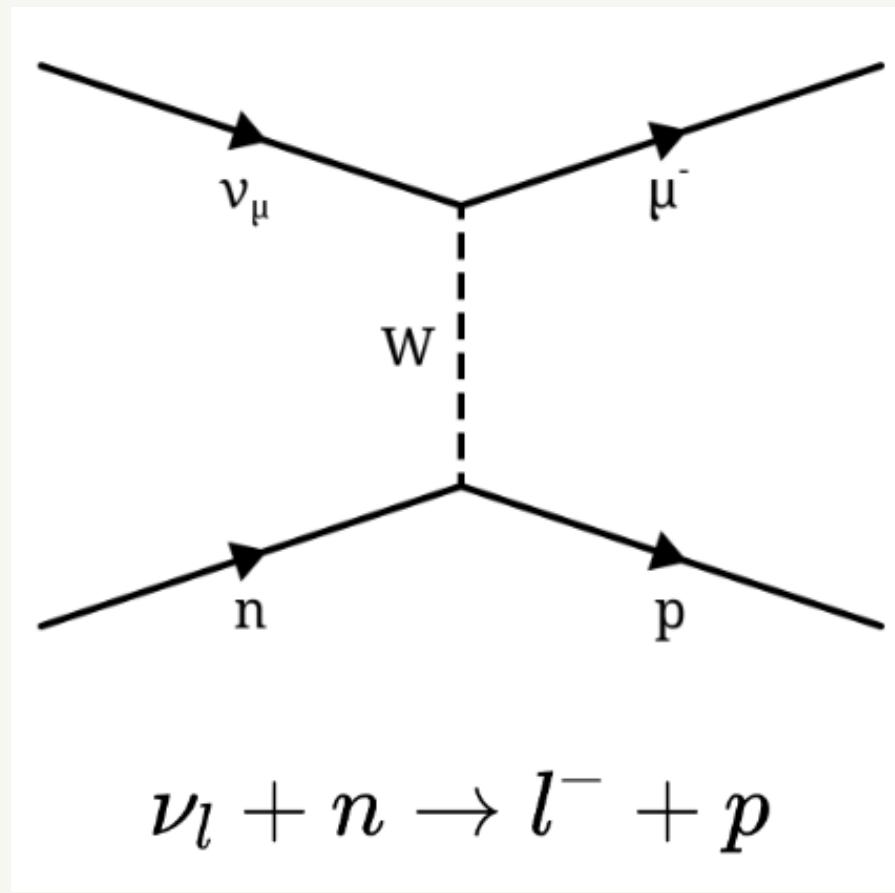
- Quasi Elastic (QE)
- Single Meson Resonance (RES)
- Deep Inelastic Scattering (DIS)

# Neutrino Interactions

>> Primary neutrino interactions inside nuclei:

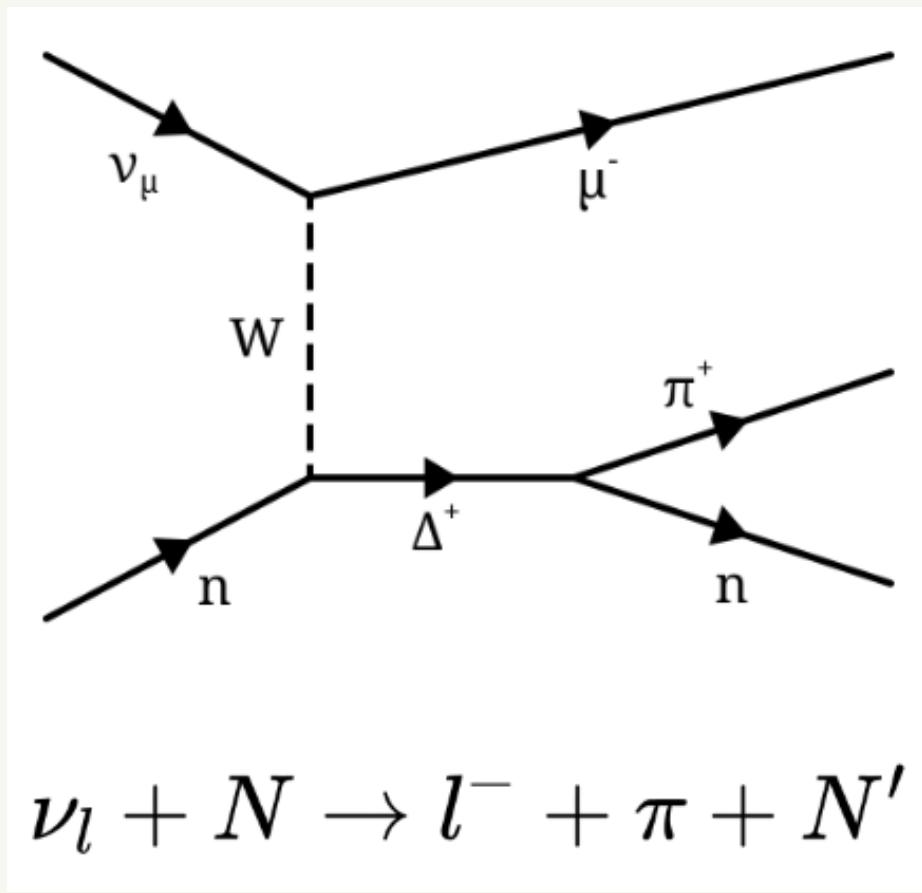
## Quasi-Elastic

Nucleon changes,  
but doesn't break up



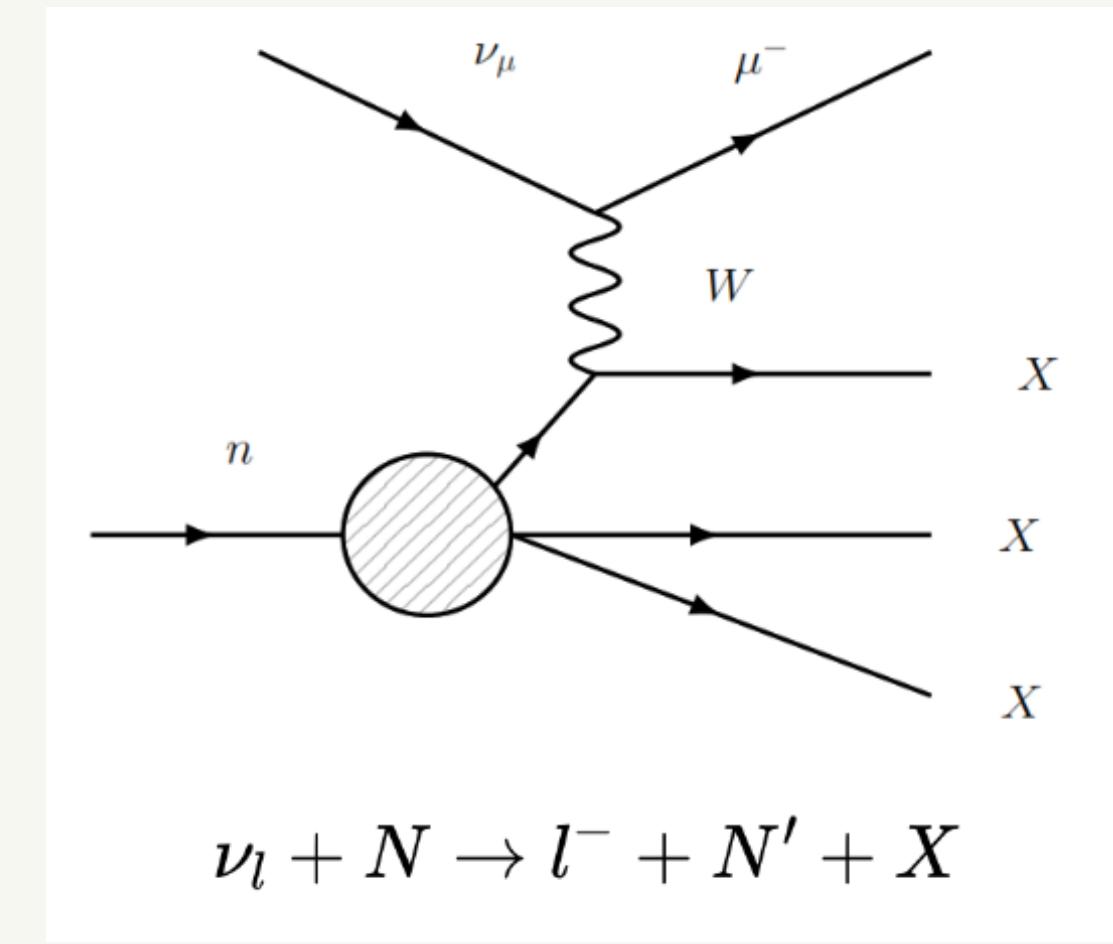
## Single Meson Resonance

Nucleon excites to  
resonance state



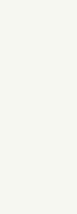
## Deep Inelastic Scattering

Nucleon breaks up



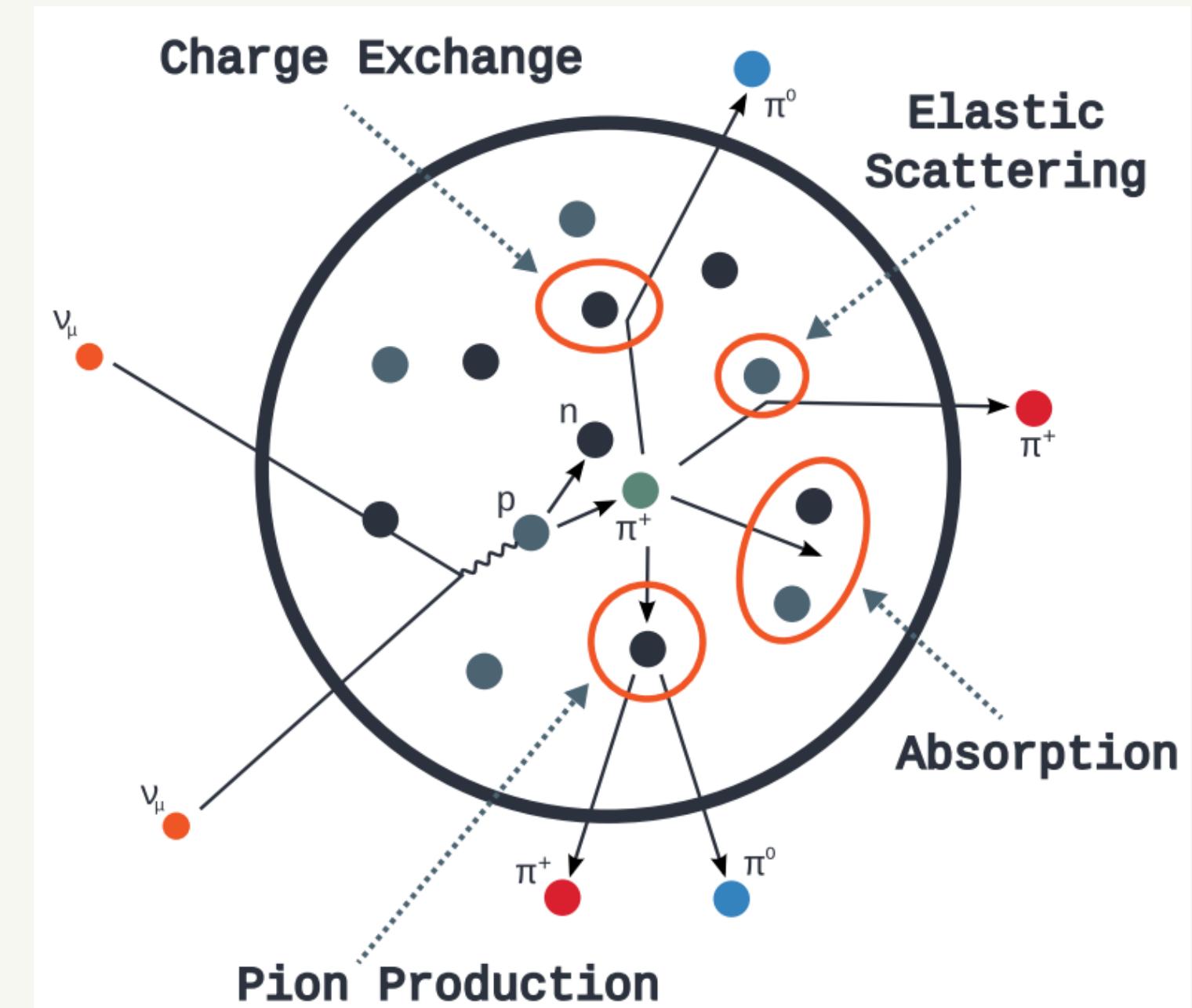
# Final State Interactions

>>> What does a neutrino detector observe?

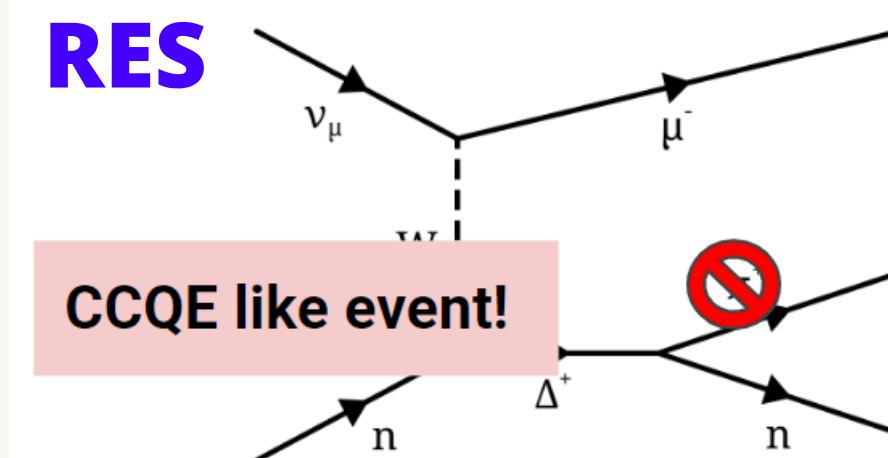


## Final State Interactions:

Hadrons produced in a primary interaction re-interact with other nucleons before they escape the nucleus

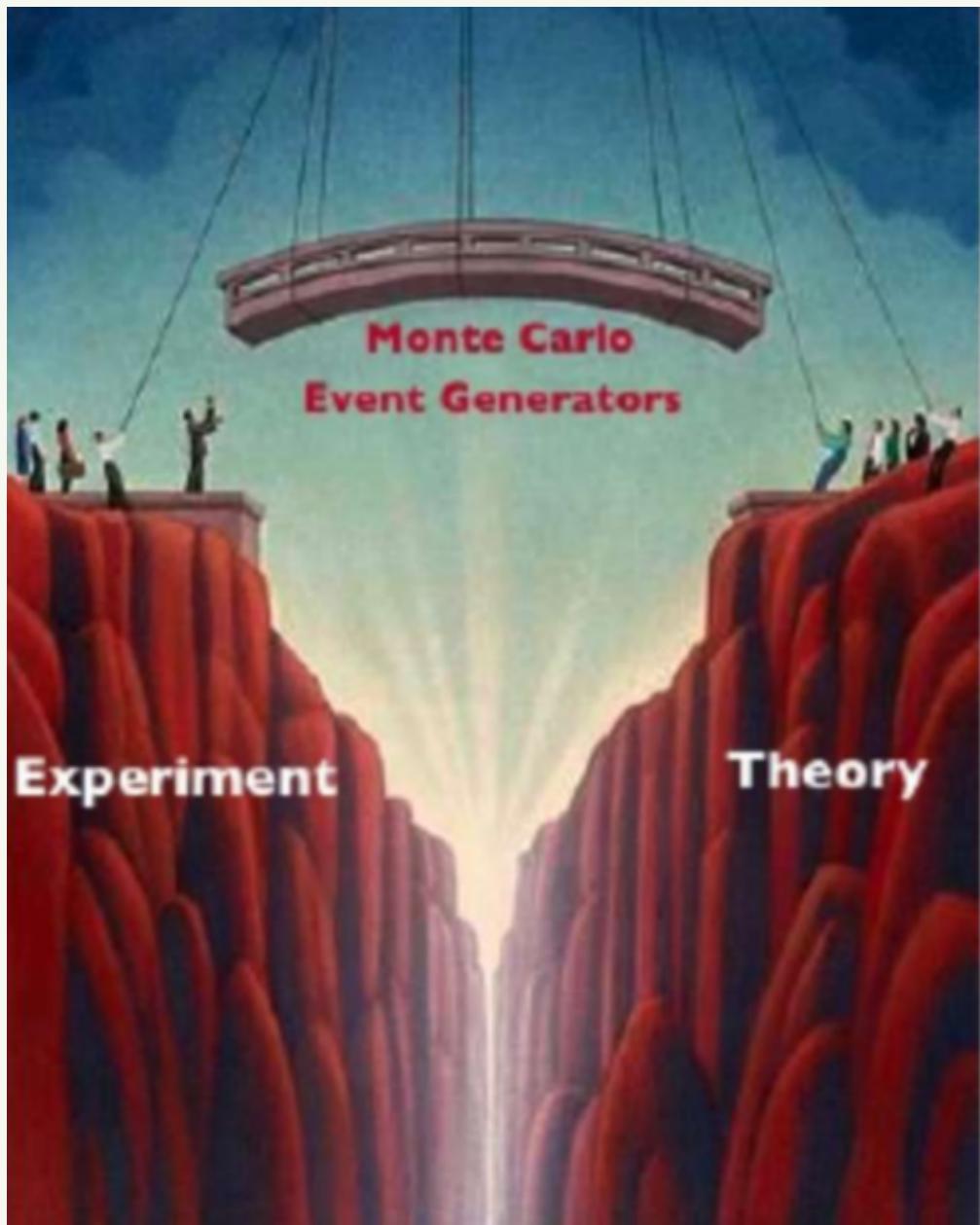


***Neutrino experiments must identify primary interactions from FSI***



# Simulation

>>> The neutrino interactions modeling is done by **Neutrino MC Event Generators**:

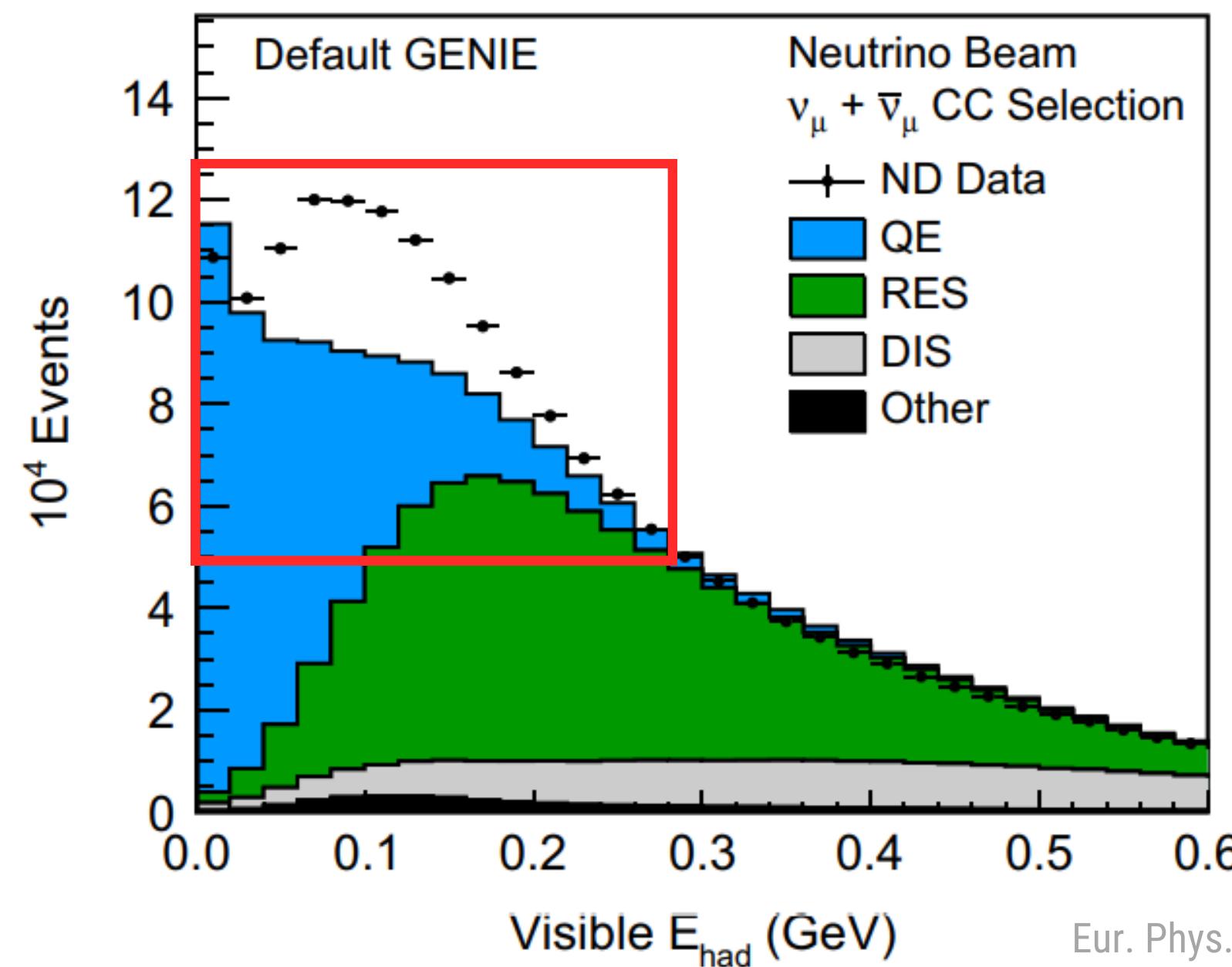


**GENIE 2.12.2:**

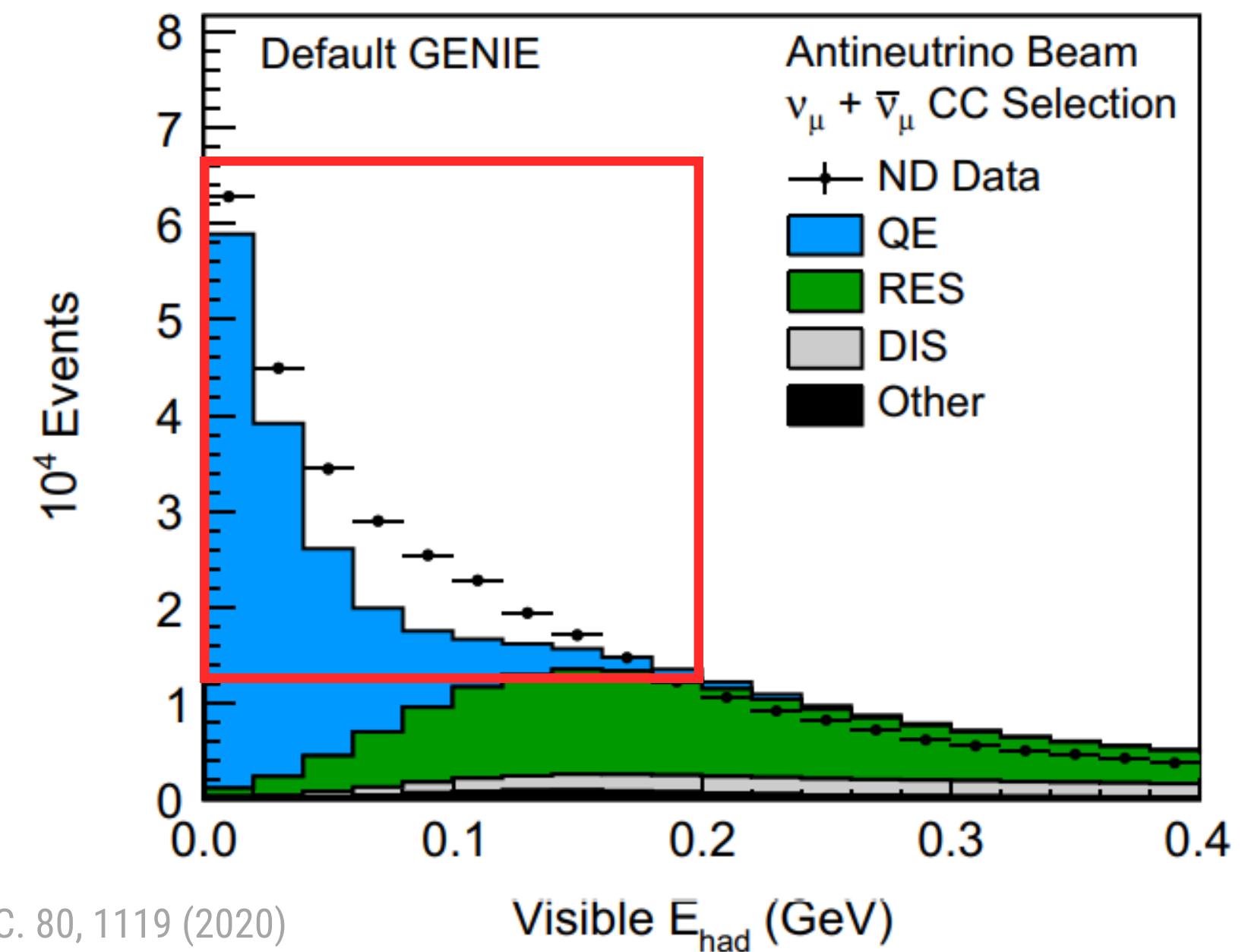
1. *Initial state*
2. *Hard scatter*
3. *Re-interactions (FSI)*

# Simulation vs Experiment

>>> NOvA: 25% underestimation by GENIE 2 in [50, 250] MeV



Eur. Phys. J. C. 80, 1119 (2020)



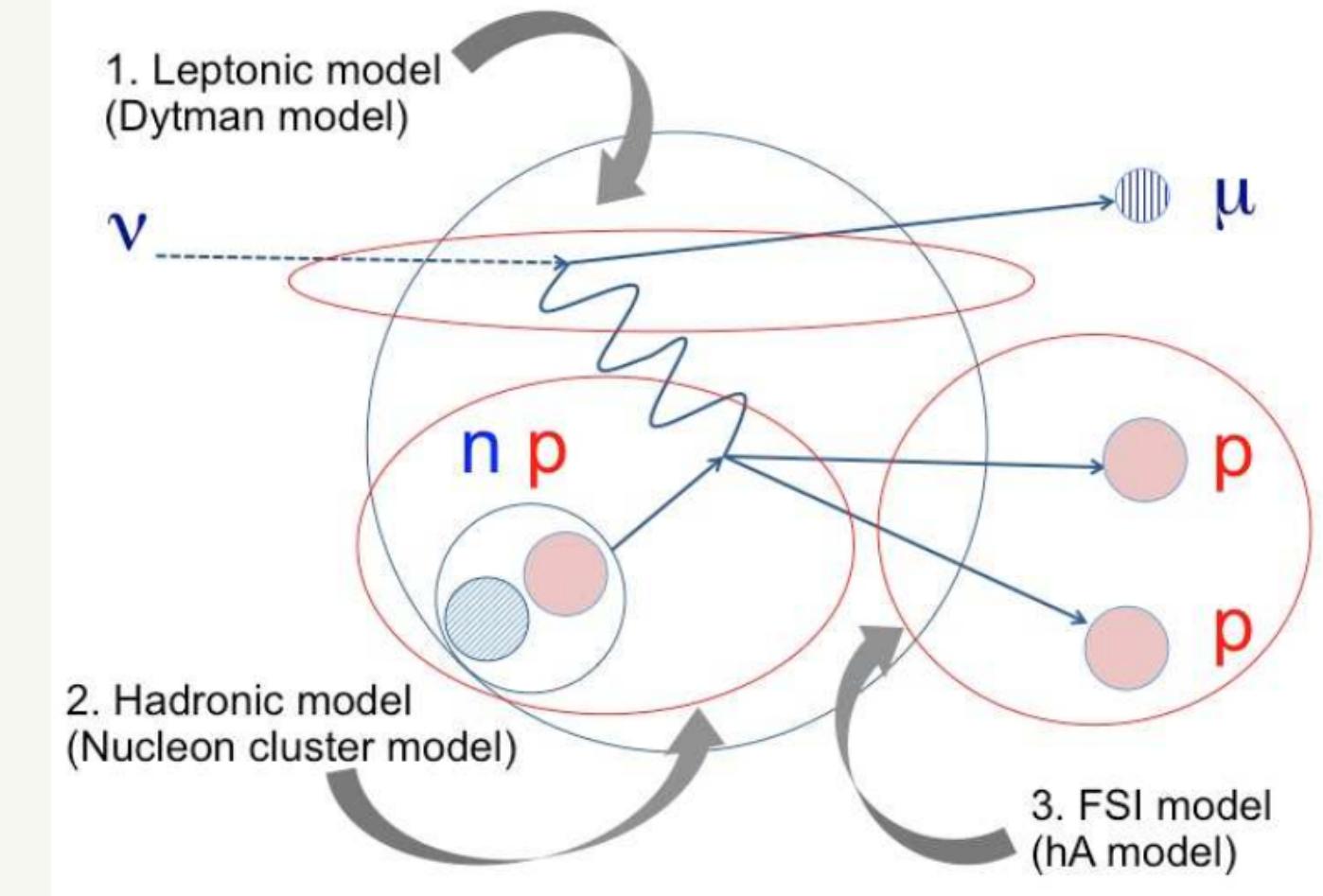
# Tuning Process

**Step 1: GENIE 2 modification incorporating new advances**



**Validation tasks**

**Step 2: Reshape and rescale the MEC component**

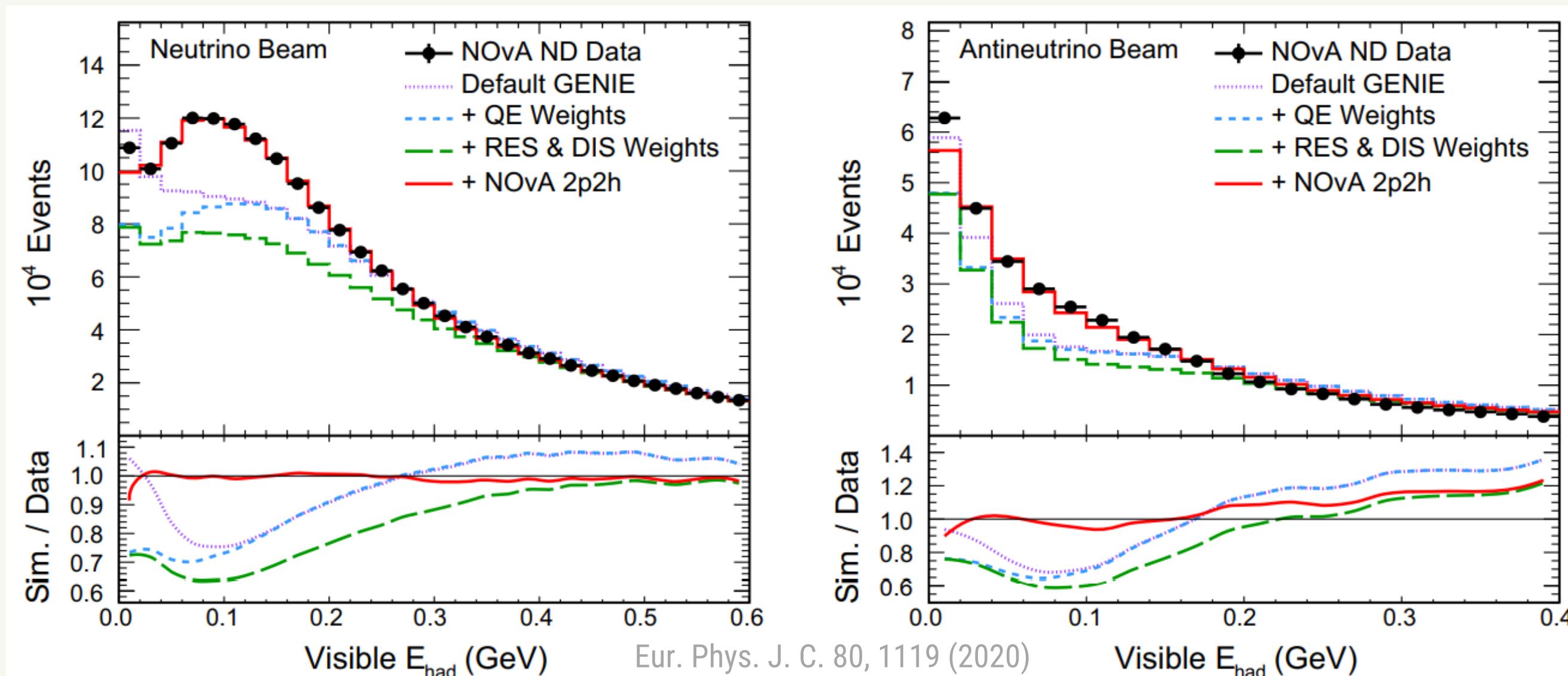


**>>> Meson Exchange Current (MEC)**  
***Quasi Elastic* like process**

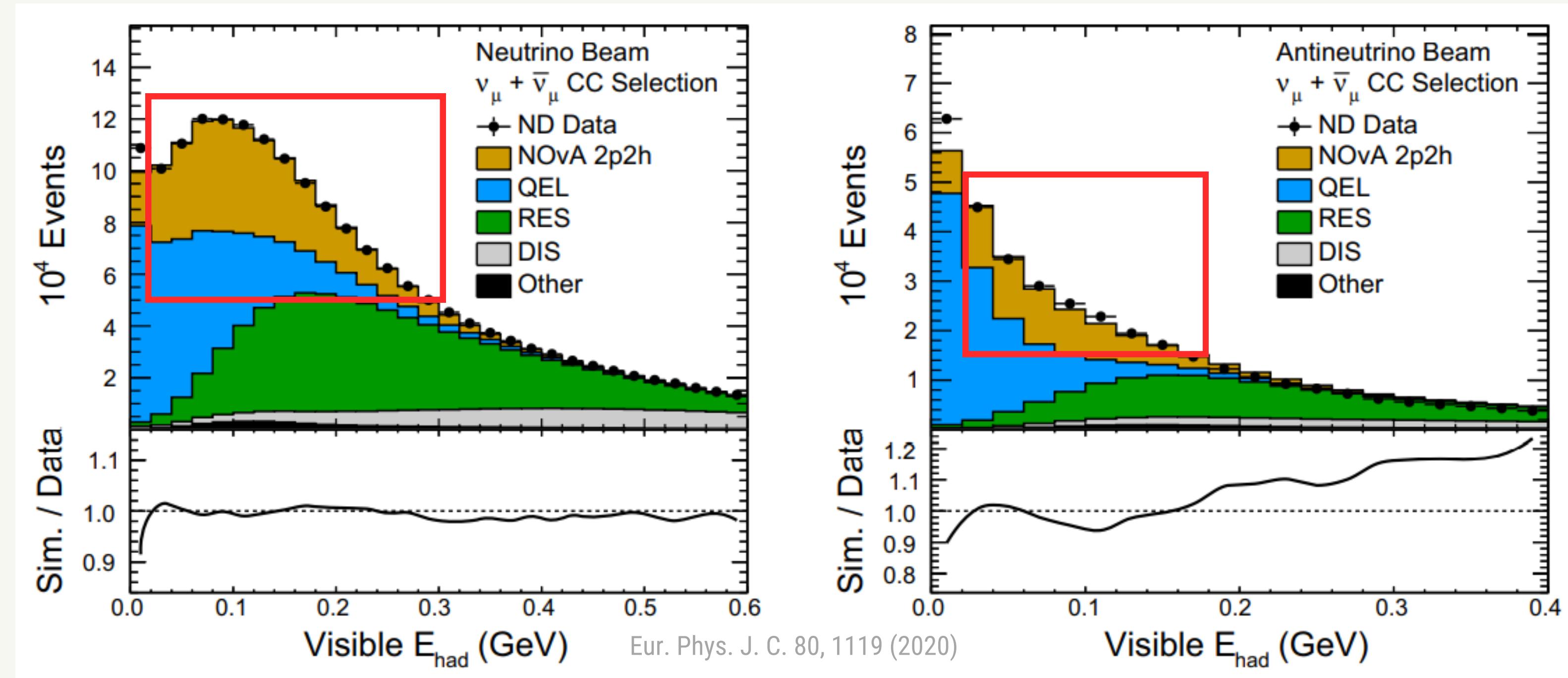
**2p2h effect!**

# Tuning Process: Does it look better?

- »» Change **CCQE  $M_A$**  from 0.99 to 1.04 GeV/c<sup>2</sup>
- »» **CCQE** nuclear models weights from **MINERvA**
- »» 57% reduction to soft **non-resonant single pion production** events from neutrinos
- »» Weights derived from **NOvA ND** data to Empirical **MEC** interactions



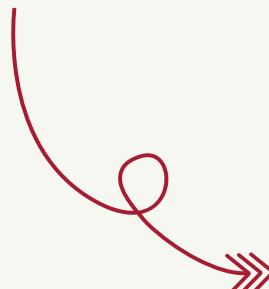
# Tuning Process: Does it look better?



>>> Significant contribution from NOvA Empirical **MEC** model via 2p2h interactions

# Outlook

- »» Precise neutrino measurements require precise knowledge of cross sections, final state interactions and nuclear effects.
- »» This is an **open** and **active** area of experimental and theoretical research!



***looking for improvements of this  
line of work in my master's research***

»» GENIE 3 is here!

PHYSICAL REVIEW D **104**, 072009 (2021)

## Neutrino-nucleon cross-section model tuning in GENIE v3

Júlia Tena-Vidal<sup>1,✉</sup>, Costas Andreopoulos,<sup>1,2</sup> Adi Ashkenazi,<sup>3</sup> Christopher Barry,<sup>1</sup> Steve Dennis,<sup>1,\*</sup> Steve Dytman,<sup>4</sup> Hugh Gallagher,<sup>5</sup> Steven Gardiner,<sup>6</sup> Walter Giele,<sup>6</sup> Robert Hatcher,<sup>5</sup> Or Hen,<sup>3</sup> Libo Jiang,<sup>4,†</sup> Igor D. Kakorin,<sup>7</sup> Konstantin S. Kuzmin,<sup>7</sup> Anselmo Meregaglia,<sup>8</sup> Vadim A. Naumov,<sup>7</sup> Afroditi Papadopoulou,<sup>3</sup> Gabriel Perdue,<sup>6</sup> Marco Roda<sup>10</sup>, Vladislav Syrotenko,<sup>5</sup> and Jeremy Wolcott<sup>5</sup>

(GENIE Collaboration)

PHYSICAL REVIEW D **105**, 012009 (2022)

## Hadronization model tuning in GENIE v3

Júlia Tena-Vidal<sup>1,✉</sup>, Costas Andreopoulos,<sup>1,2</sup> Christopher Barry,<sup>1</sup> Steve Dennis,<sup>1,†</sup> Steve Dytman,<sup>3</sup> Hugh Gallagher,<sup>4</sup> Steven Gardiner,<sup>5</sup> Walter Giele,<sup>5</sup> Robert Hatcher,<sup>5</sup> Or Hen,<sup>6</sup> Igor D. Kakorin,<sup>7</sup> Konstantin S. Kuzmin,<sup>7,8</sup> Anselmo Meregaglia,<sup>9</sup> Vadim A. Naumov,<sup>7</sup> Afroditi Papadopoulou,<sup>6</sup> Marco Roda<sup>10</sup>, Vladislav Syrotenko,<sup>4</sup> and Jeremy Wolcott<sup>4</sup>

(GENIE Collaboration)

# Thank you for your interest!

*camacortespar@unal.edu.co*

# Backup

# Long-Baseline Neutrino Experiments

NOvA:



- $\langle E_\nu \rangle = 2.0 \text{ GeV}$
- $\langle E_{\bar{\nu}} \rangle = 2.0 \text{ GeV}$
- Neutrino target: CH<sub>2</sub>

MINERvA:



- $\langle E_\nu \rangle = 3.5 \text{ GeV (LE)} - 5.5 \text{ GeV (ME)}$
- $\langle E_{\bar{\nu}} \rangle = 3.5 \text{ GeV (LE)} - 5.5 \text{ GeV (ME)}$
- Neutrino target: He, CH, H<sub>2</sub>O, Fe, Pb

T2K:



- $\langle E_\nu \rangle = 0.6 \text{ GeV}$
- $\langle E_{\bar{\nu}} \rangle = 0.6 \text{ GeV}$
- Neutrino target: CH, H<sub>2</sub>O

# GENIE 2 [default]

## Initial State

- Global Relativistic Fermi Gas (RFG) model:  
High-momentum tail:  
  
short-range nuclear correlations.
- Nucl. Phys. B 43, 605 (1972).*  
*Phys. Rev. D 24, 1400 (1981).*  
*Science 320, 1476 (2008). arXiv:0908.1514.*

## Hard Scatter

- **QE:** *Phys. Rep. 3, 261 (1972).*
- **RES:** *Ann. Phys. 133, 79 (1981).*
- **DIS:**
  - Scaling formalism: *(2003). arXiv:hep-ex/0308007.*
  - Custom hadronization model: *Eur. Phys. J. C 63, 1 (2009). arXiv:0904.4043.*
  - PYTHIA 6: *JHEP 05, 026 (2006) arXiv:hep-ph/0603175.*

# GENIE 2 [default]

## Re-interactions (FSI)

- hA-INTRANUKE effective cascade model:

*AIP Conference Proceedings. 896, 178 (2007).*

## MEC models

- Empirical MEC:
- Valencia group model:

*AIP Conf. Proc. 1663, 030001 (2015), arXiv:1304.6014.*

*Phys. Rev. D88, 113007 (2013). arXiv:1307.8105.*