STUDYING FINAL STATE INTERACTIONS WITH NEUTRINO EXPERIMENTS

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INTRODUCTION

- Motivation
- What are Final State Interactions (FSI)?
- Why are FSI important in neutrino oscillations experiments?
- The role of FSI models in neutrino interactions simulators
- Progress by neutrino experiments on FSI model tuning
- Final remarks

WHAT ARE FSI

- Neutrinos are studied via their interactions with matter
  - Neutrino detectors are made of various nuclei: Hydrogen, Helium, Carbon, Oxygen, Iron, Lead
  - Nuclei are busy quantum beasts

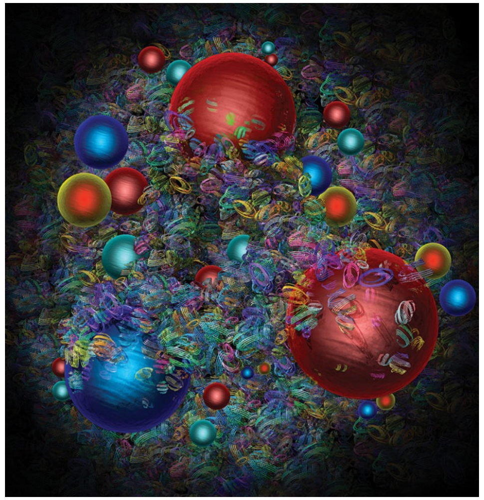
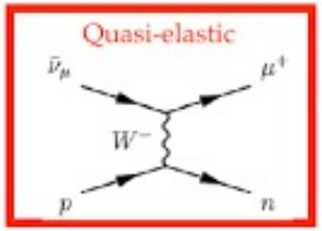


Image by CERN

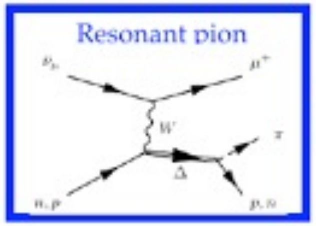
- Neutrino interactions inside nuclei are more than meets the eye (basics)

Charged Current

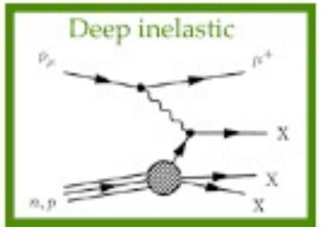
  - Quasi – elastic (QE) $\quad v_l + n \rightarrow l^- + p$
  - Resonant pion production (Res) $\quad v_l + N \rightarrow l^- + \Delta$, $\Delta \rightarrow \pi + N$
  - Deep inelastic (DIS) $\quad v_l + N \rightarrow l^- + X$
  - Most relevant neutrino – nuclei primary interactions



QE



RES



DIS

WHAT ARE FSI

- Are QE, Res or DIS observed by neutrino detectors?
  - RHS of the interactions
  - Particles detected

  Not necessarily the same

$$\nu_l + n \rightarrow l^- + p$$

$$\nu_l + N \rightarrow l^- + \Delta$$

$$\Delta \rightarrow \pi + N$$

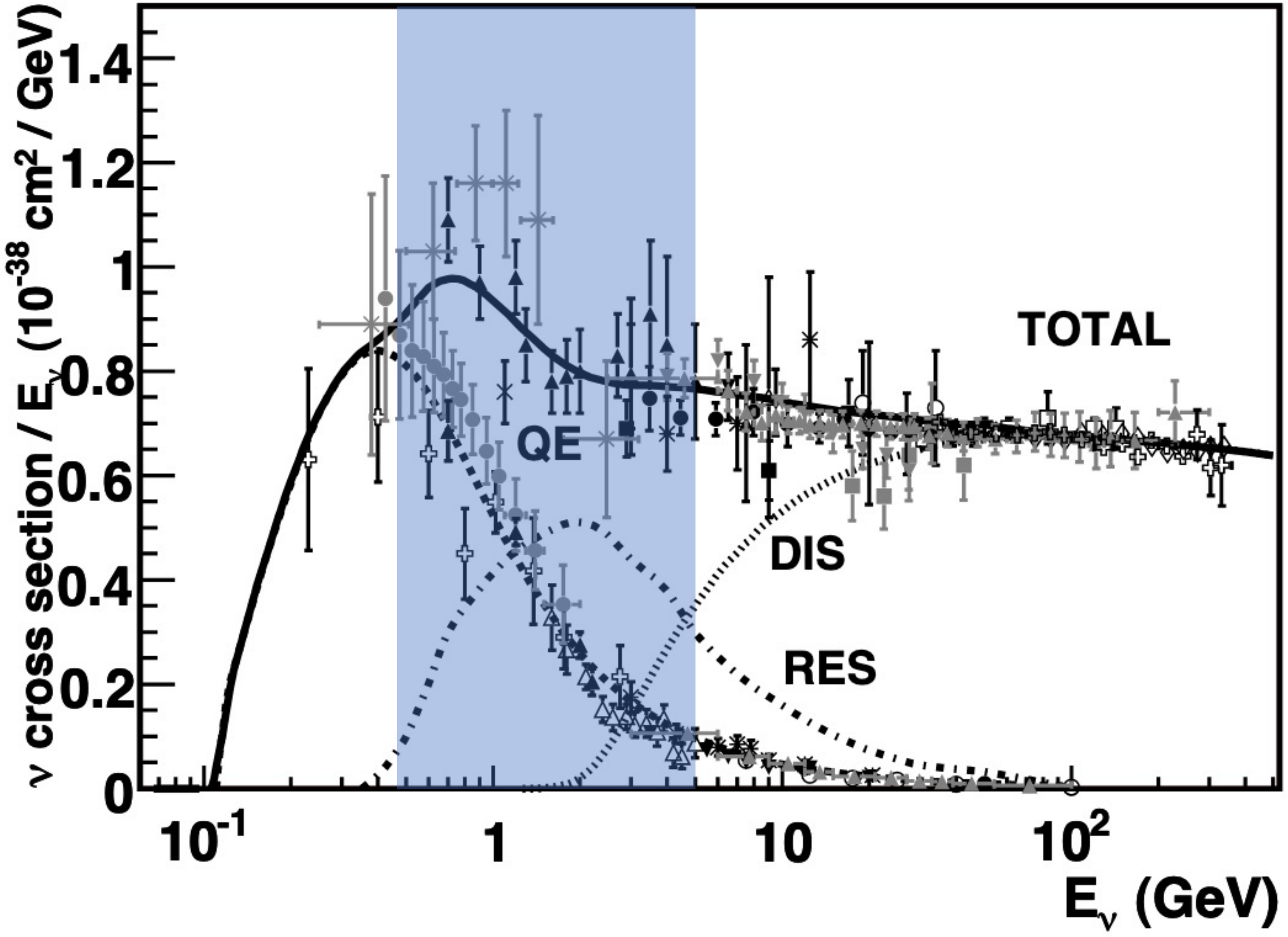
$$\nu_l + N \rightarrow l^- + X$$

- RHS particles could
  - Have secondary interactions inside the nucleus
    - Be absorbed by the nucleus
    - Create additional particles
  - Exit the nucleus and be invisible for detectors (*e.g.* no charge, low energy)
- The FSI output is what neutrino detectors observe

Neutrino experiments must identify primary interaction from FSI

- Neutrino charged current cross sections

arXiv: 1305.7513



Neutrino oscillations:
Precise number of initial neutrinos

Accurate knowledge of cross sections:
Crucial for counting events

- Most neutrino oscillations experiments: $E_\nu = [0.5,5]GeV$

FSI IMPORTANCE

Neutrino Experiments

- Systematic uncertainties > statistical uncertainties

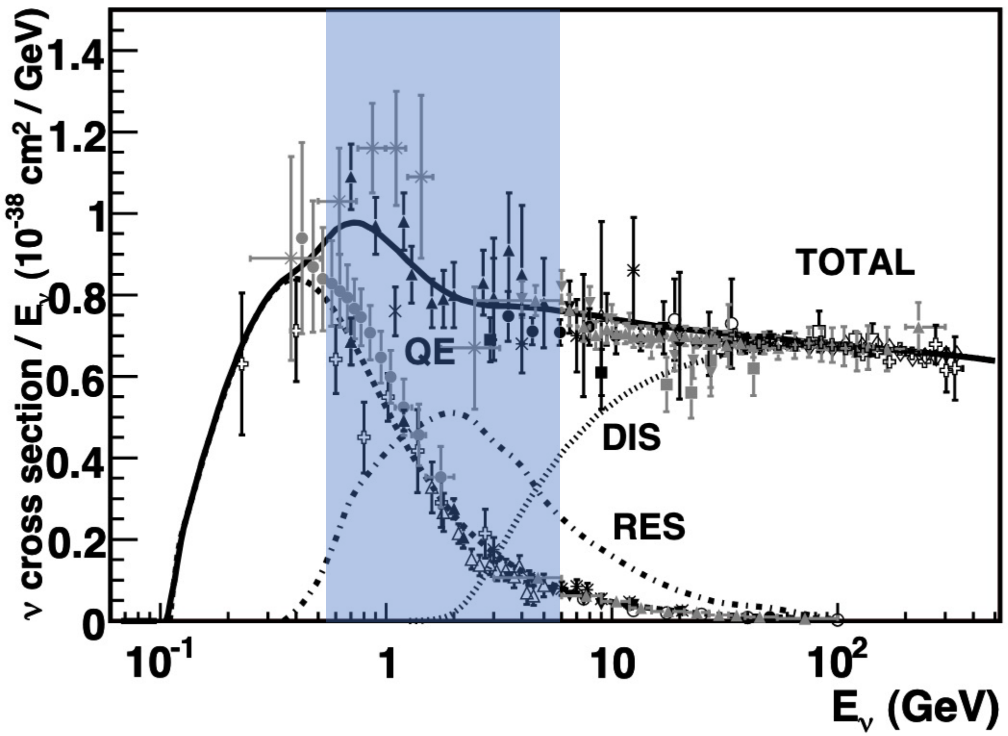
  Cross section uncertainties are large

- Neutrino oscillations experiments
  - Two detectors: Near (ND) and Far (FD)
    - ND constrains flux & interaction cross sections
    - FD observes neutrinos after oscillations
  - Rely on simulations (theory) for ND constrains on FD
    - Model dependent

  Experimental results ahead of theoretical models

- Neutrino – nuclei interactions around 1 GeV are challenging
  - To describe theoretically
  - To measure experimentally

arXiv: 1305.7513

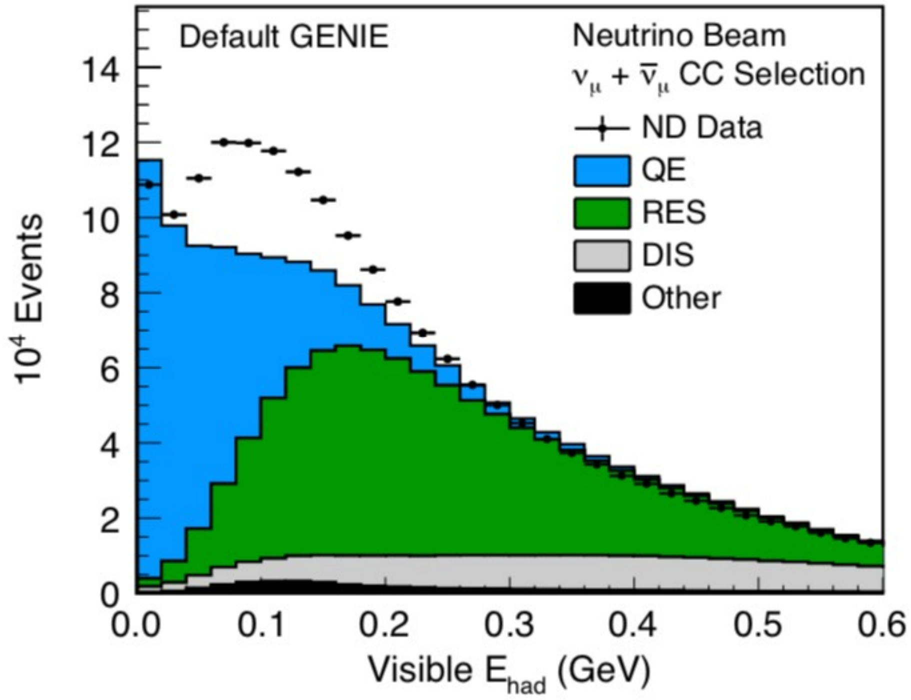


- Neutrino experiments rely on simulations to develop analysis tools
  - Neutrino flux (*e.g.* Fluka, Nucl. Data Sheets 120, 211 (2014))
  - Interactions (*e.g.* GENIE, Nucl. Instrum. Methods Phys. Res., Sect. A 614, 87 (2010))
  - Detectors (*e.g.* GEANT4, Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003))
- Interactions simulators built upon
  - Initial nuclear state
    - Global relativistic Fermi gas (RFG) (Nucl. Phys. B43, 605 (1972))
    - High momentum tail: short – range nuclear interactions (Science 320, 1476 (2008))
  - Hard scatter
    - QE (Phys. Rept. 3, 261 (1972))
    - Res (Annals Phys. 133, 79 (1981))
    - DIS (arXiv:hep-ex/0308007, Eur. Phys. J. C63, 1 (2009))
  - Reinteractions of resulting particles with nuclear medium

Effective cascade model (AIP Conf. Proc. 896, 178 (2007))

- Renowned theoretical models are in tension with latest data

NOvA: *Eur. Phys. J. C* **80,** 1119 (2020)



- Traditional QE now understood better
  - Meson Exchange Currents (MEC)
    Phys. Rev. D88, 113007 (2013)

$$\nu_l + N \rightarrow l^- + X$$

Meson

N'

- Simulators allow for tuning of various processes
  - Each allowed variation must be understood
    - Individually
    - Collectively
- Neutrino experiments are tuning simulators to better represent the data
- Theoreticians are seeking novel models to better represent the data

Active research area

- MEC is currently the focus of the discussion

QE – like interactions

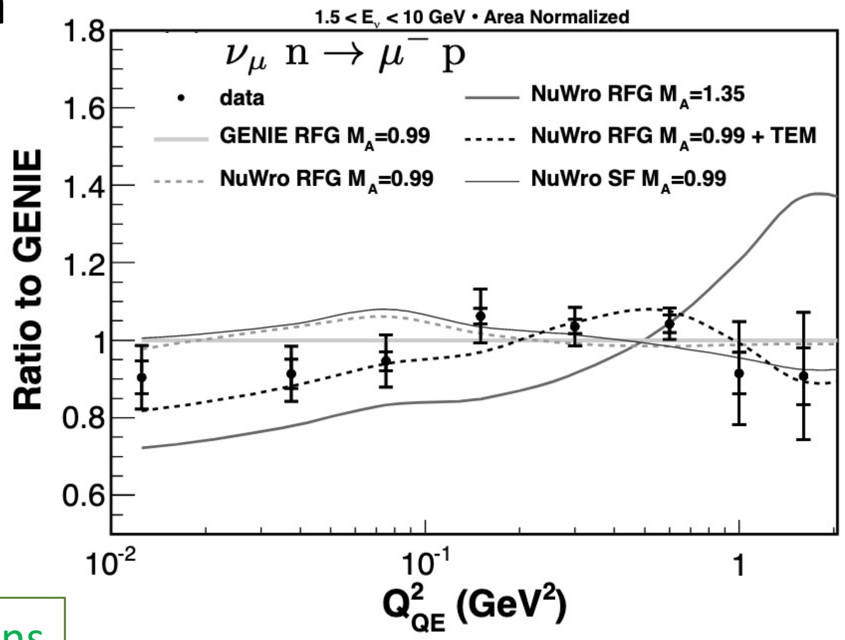
- Renowned theoretical models are in tension with latest data
- QE – like cross section measurements leading the quest
  - Simulated Q^2_{QE} parameterized by V – A mass: M_A
  - Data favors a Transverse Enhancement Model (TEM)

    From MEC

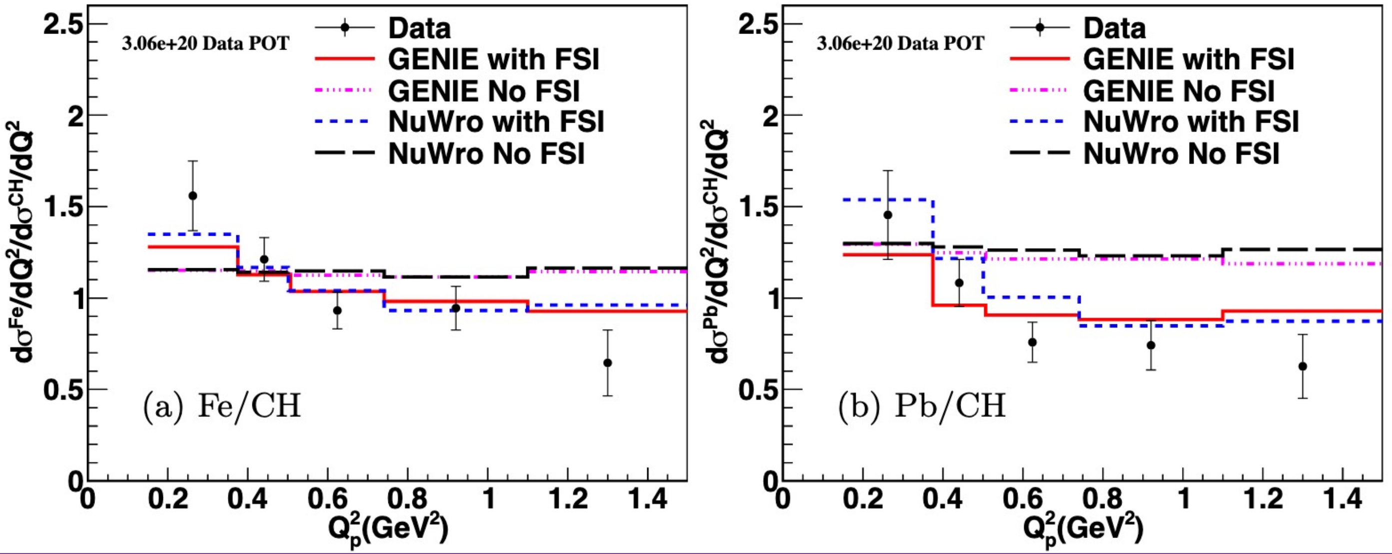
    - Corrections to the magnetic form factors

      Bound nucleons
  - Backgrounds from FSI
    - Primary π absorbed in nucleus
  - 0π events part of QE – like signal

MINERvA: *arXiv:2107.02064*



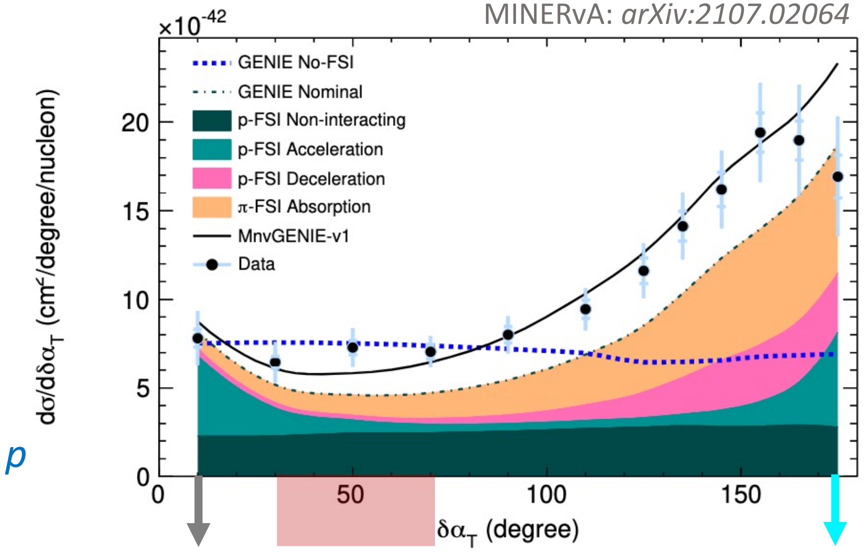
Phys. Rev. Lett., vol. 119,no. 8, p. 082001, 2017



FSI MODELS

- Transverse kinematic imbalance in charged currents
  - Muon transverse angle: $\delta\alpha_T$, sensitive to
    - FSI
    - Missing particles unaccounted momentum { π, Correlated p }
  - No – FSI flat region → isotropic Fermi motion
  - Deceleration region for energy dissipating processes (particle absorption)
  - Accelerating region for accelerating FSI (mainly protons)

MINERvA: *arXiv:2107.02064*



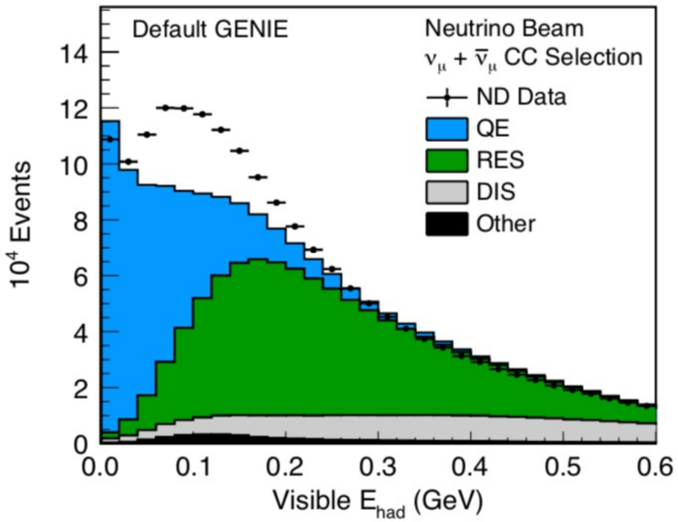
$\delta\alpha_T = 0°$ $\delta\alpha_T = 180°$

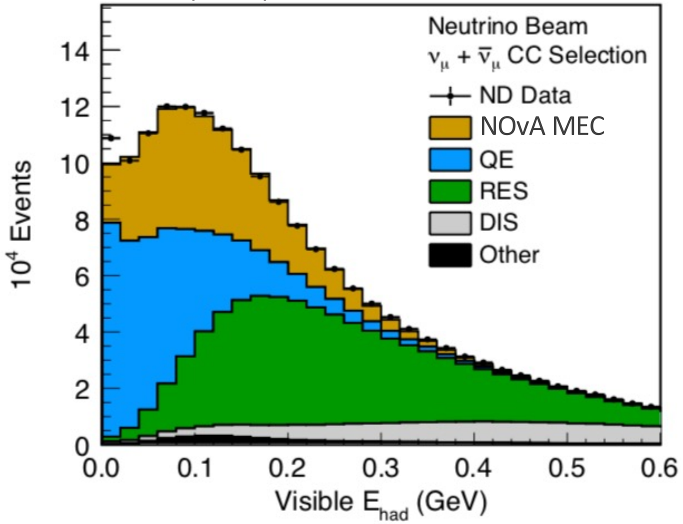
- MnvGENIE {
  - Minimizes cross section dependence on neutrino energy
  - Initial and final states effects directly probed
  - Described data within uncertainties

} Improved MEC modeling

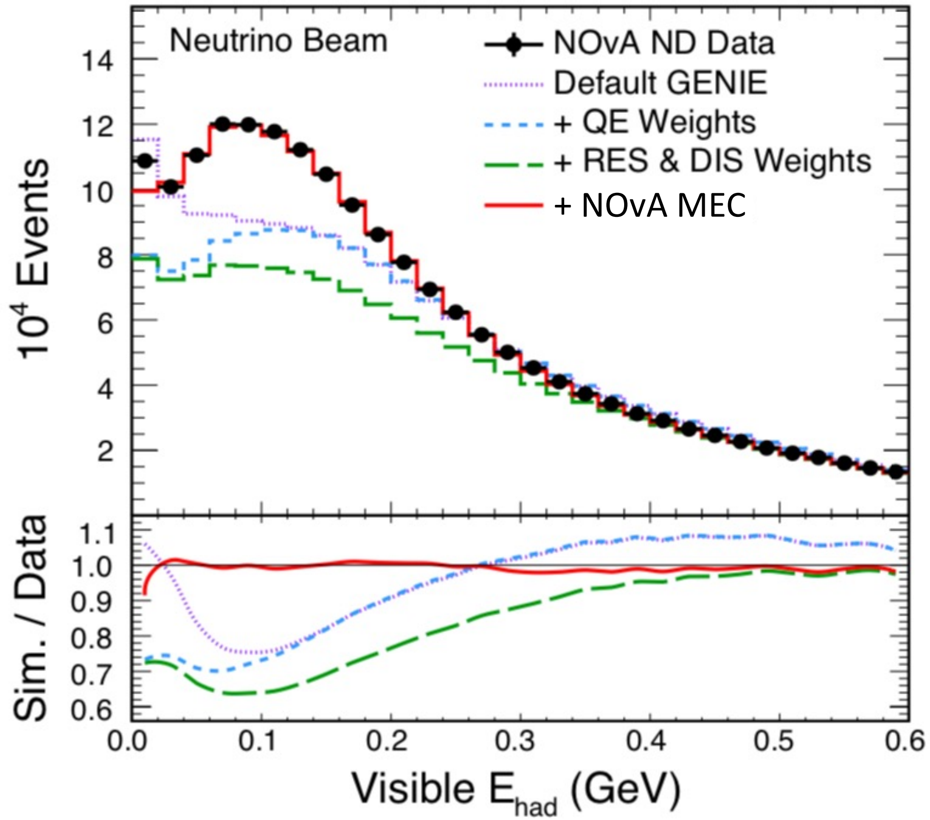
- Adjusting cross section models
  - Incorporate external data constraints
  - Empirical MEC model (NOvA MEC) Improvement!
    - $M_A = 0.99\,{}^{GeV}/_{c^2} \rightarrow M_A = 1.04\,{}^{GeV}/_{c^2}$
    - Nuclear weights from MINERvA
    - Reduction of non – resonant single pion

NOvA: *Eur. Phys. J. C* **80,** 1119 (2020)





NOvA: *Eur. Phys. J. C* **80,** 1119 (2020)



Default GENIE:
MEC events deficit
5% excess at low energies

FINAL REMARKS

- Neutrino experiments leading the quest for better FSI models
- Discoveries of novel processes challenge theoretical descriptions
- Improved simulations reduce cross section uncertainties on neutrino oscillations measurements
- Mixture of new results and model tuning are currently used
  - The goal: Theoretical descriptions of FSI from physics principles that reproduce the data
  - Active research area already producing promising results
- Opportunities for undergraduate and graduate students (or physicists) to contribute

THANK YOU!

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