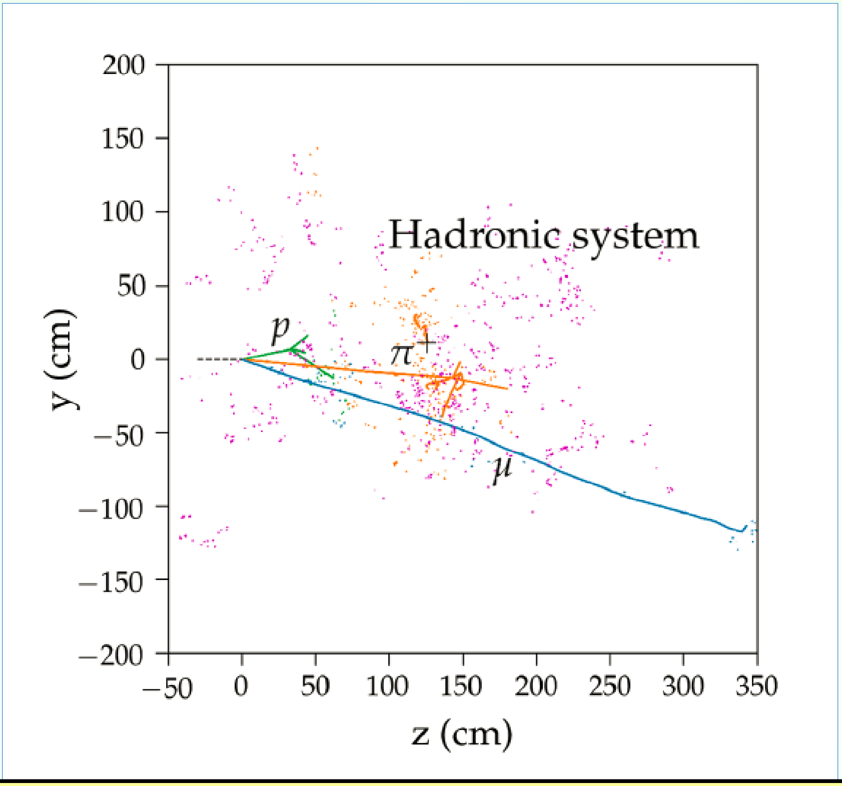
Assessing the accuracy of GENIE with electron-scattering data

Artur M. Ankowski

based on
A. M. A. and Alexander Friedland, PRD 102, 053001 (2020)

New Directions in Neutrino-Nucleus Scattering, March 15-18, 2021

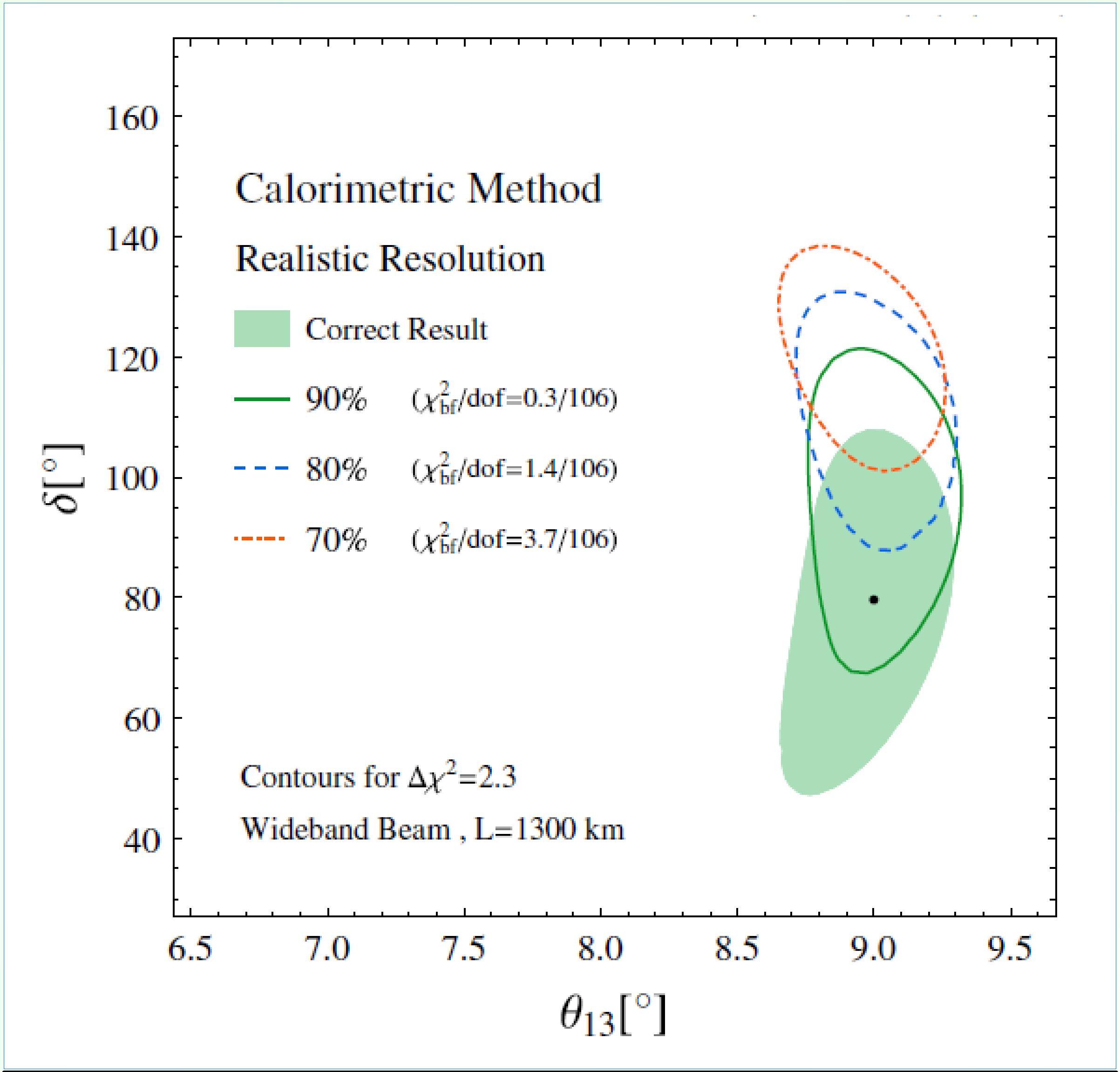
Monte Carlo generators



A. Friedland & S. W. Li, PRD **99**, 036009 (2019)

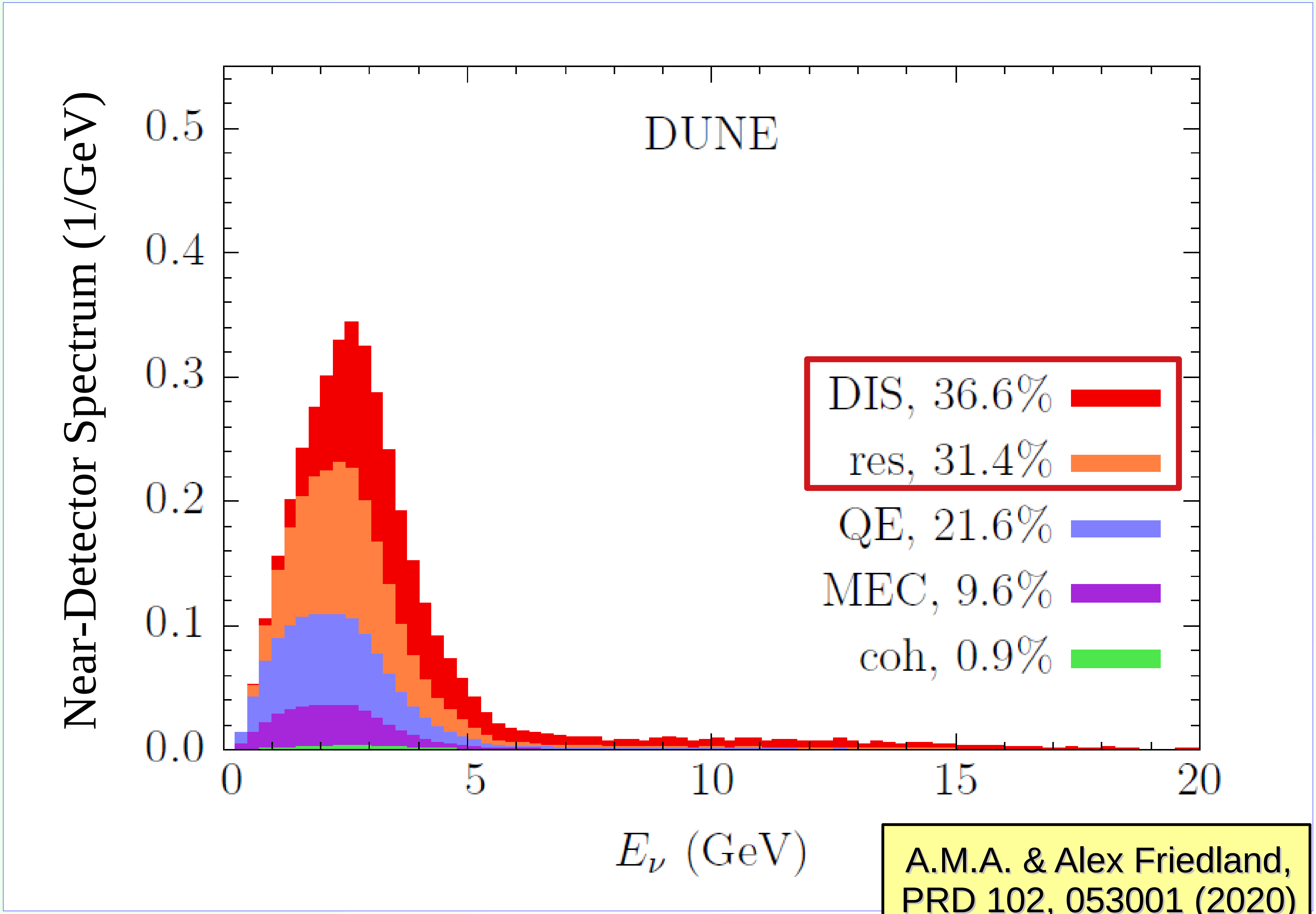
- Visible energy needs to be translated to the true energy using a Monte Carlo simulation.
- Accuracy of the energy reconstruction depends on the accuracy of the simulation.

Missing energy



A.M.A. P. Coloma, P. Huber, C. Mariani & E. Vagnoni, PRD **92**, 091301(R) (2015)

Which cross sections are relevant?



A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

Idea of our analysis

- Benchmark of GENIE against a broad set of inclusive electron scattering data to understand **which channels are most problematic for DUNE**
(3,446 for carbon and 5,928 for other targets)

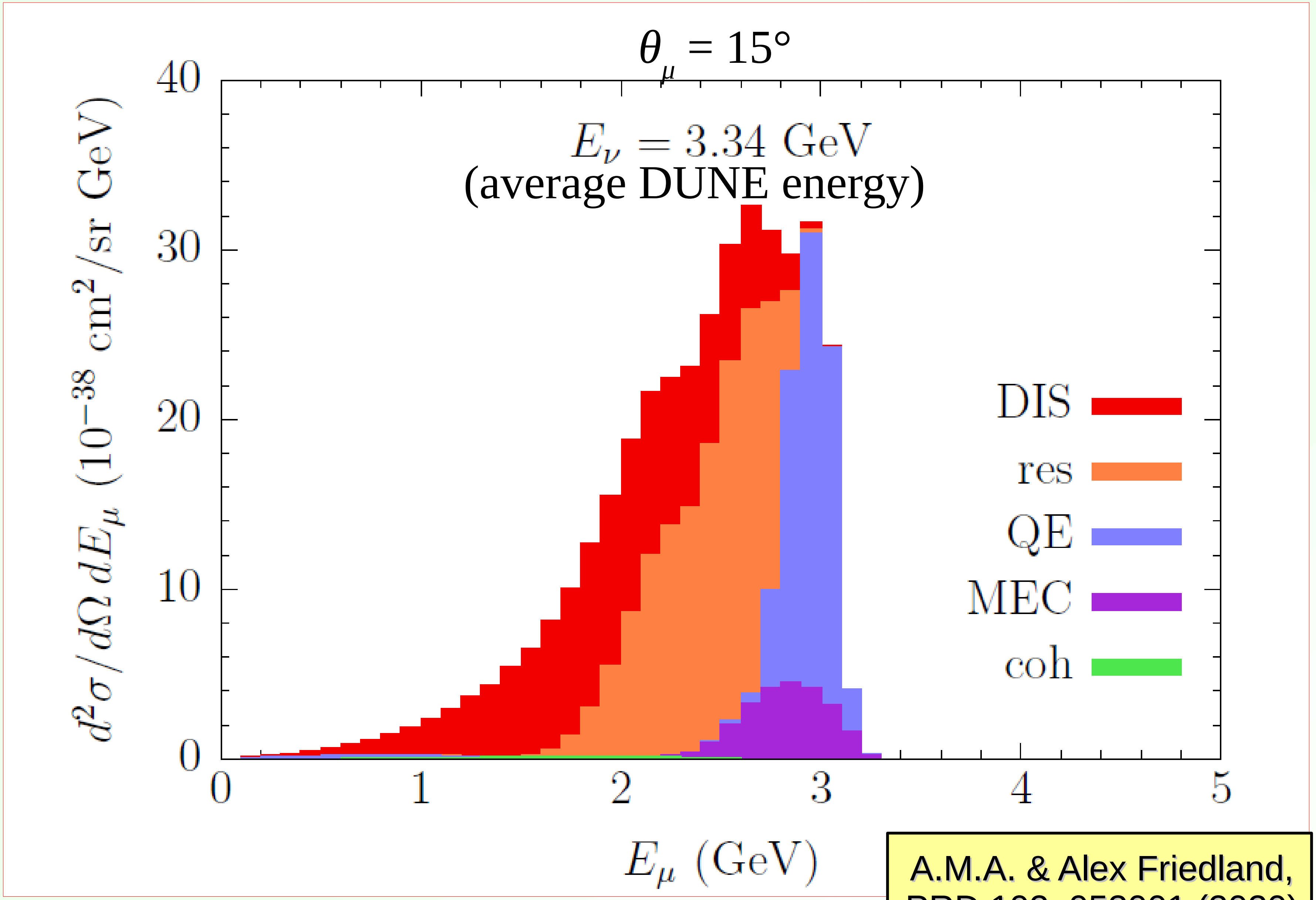
- Check if the discrepancies follow a pattern & **understand their origin**

- Offer directions for **possible improvements**

A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

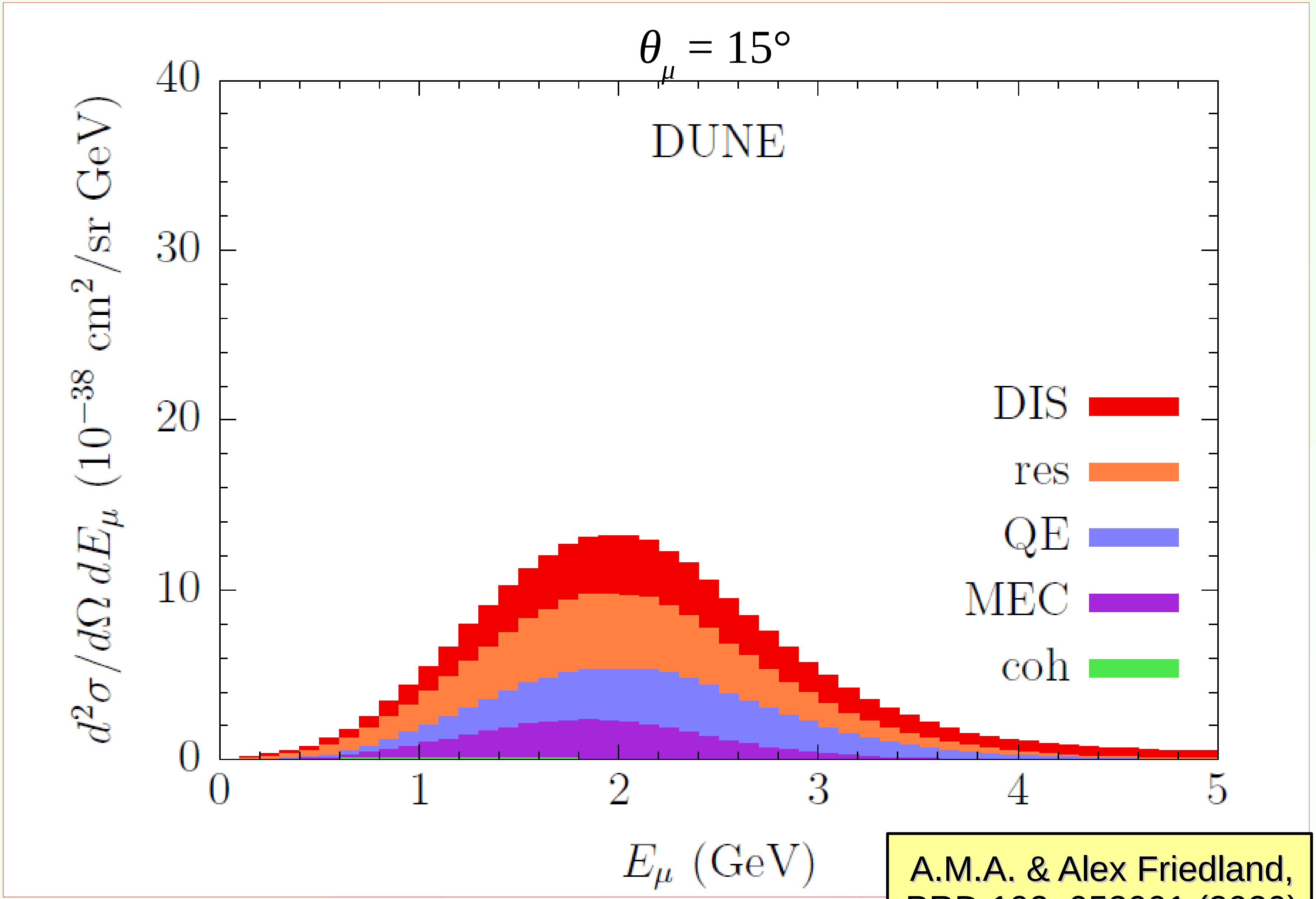
Introduction

Double differential cross sections



A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

Double differential cross sections

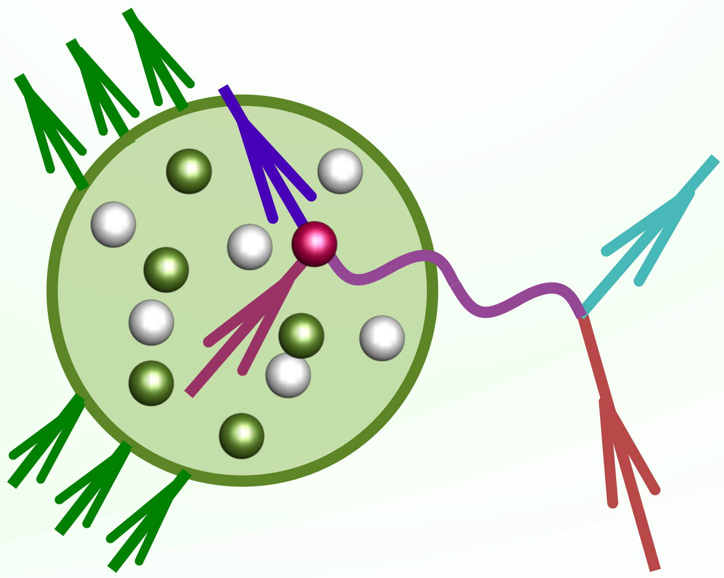


A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

Impulse approximation

For scattering in a given angle and energy, *ν*'s and *e*'s differ almost exclusively due to the **elementary cross sections**.

In neutrino scattering, uncertainties come from (i) nuclear effects and (ii) interaction dynamics (vector & axial contributions).

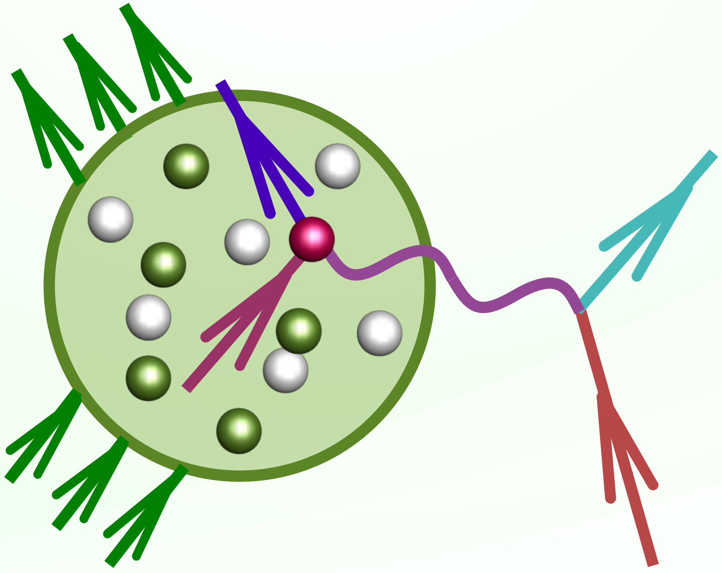


Impulse approximation

Electron-scattering data can provide information on

- the vector contributions to neutrino cross sections
- nuclear effects (ground state properties, transparency, FSI)
- hadronization

Detailed discussion in A.M.A. A. Friedland, S. W. Li, O. Moreno, P. Schuster, N. Toro & N. Tran, PRD 101, 053004 (2020)



GENIE in a nutshell

- Generator of choice for all ongoing Fermilab-based neutrino experiments, used also by T2K

- **Not tuned to electron-scattering data**
  In principle, an opportunity to determine various systematic uncertainties

- From the mission statement:

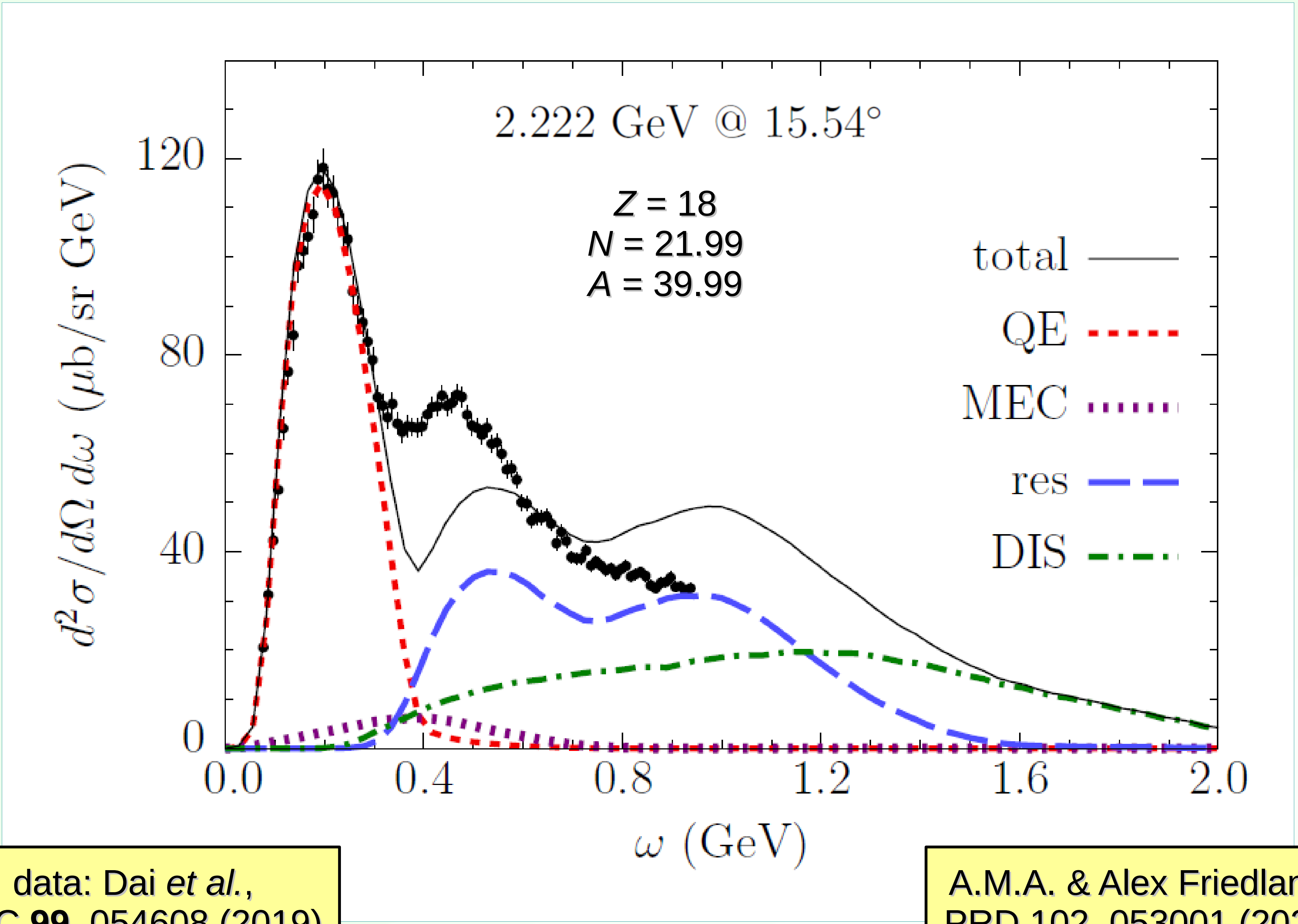
"The GENIE Collaboration shall provide electron-nucleus, hadron-nucleus and nucleon decay generators in the **same physics framework** as the neutrino-nucleus generator."

GENIE 2 in a nutshell

- **Nuclear model**: relativistic Fermi gas of Bodek & Ritchie **('81)**
- **Quasielastic** interactions: Llewellyn-Smith (Rosenbluth) formula for neutrinos (electrons). Parameters fitted to deuteron data. **('72)**
- **Meson-exchange currents**: Phenomenological Dytman approach developed to fit the MiniBooNE ν data **('13)**
- **Resonance excitation**: model of Rein and Sehgal (16 resonances with updated parameters) **('81)**
- **Deep-inelastic scattering**: model of Bodek and Yang, used also to calculate nonresonant background for lower invariant hadronic masses $W < 1.7$ GeV. **('05)**

Comparisons with electron-scattering data

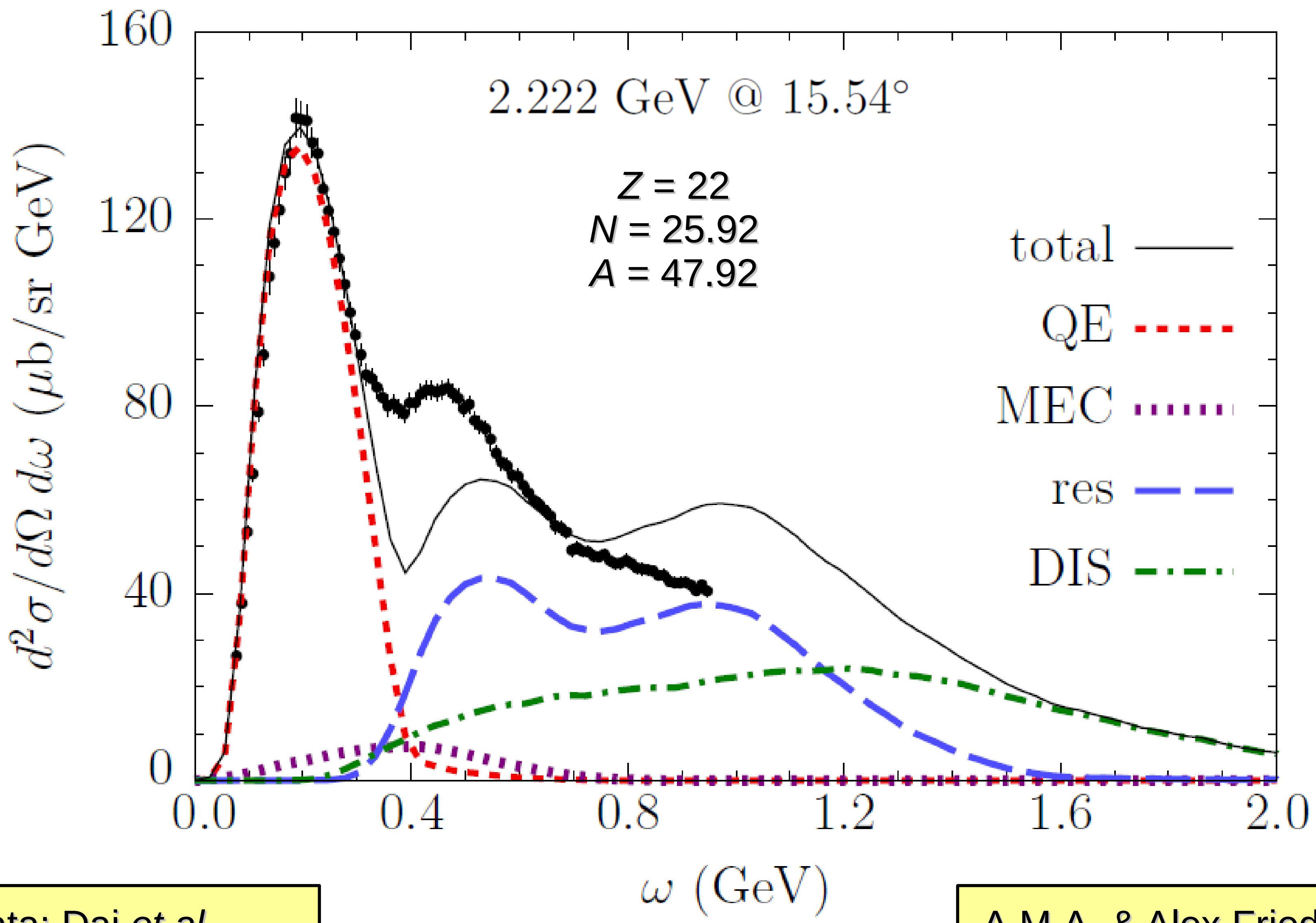
Ar(e, e') in GENIE



data: Dai *et al.*, PRC **99**, 054608 (2019)

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

Ti(*e*, *e*’) in GENIE



data: Dai *et al.*, PRC **98**, 014617 (2018)

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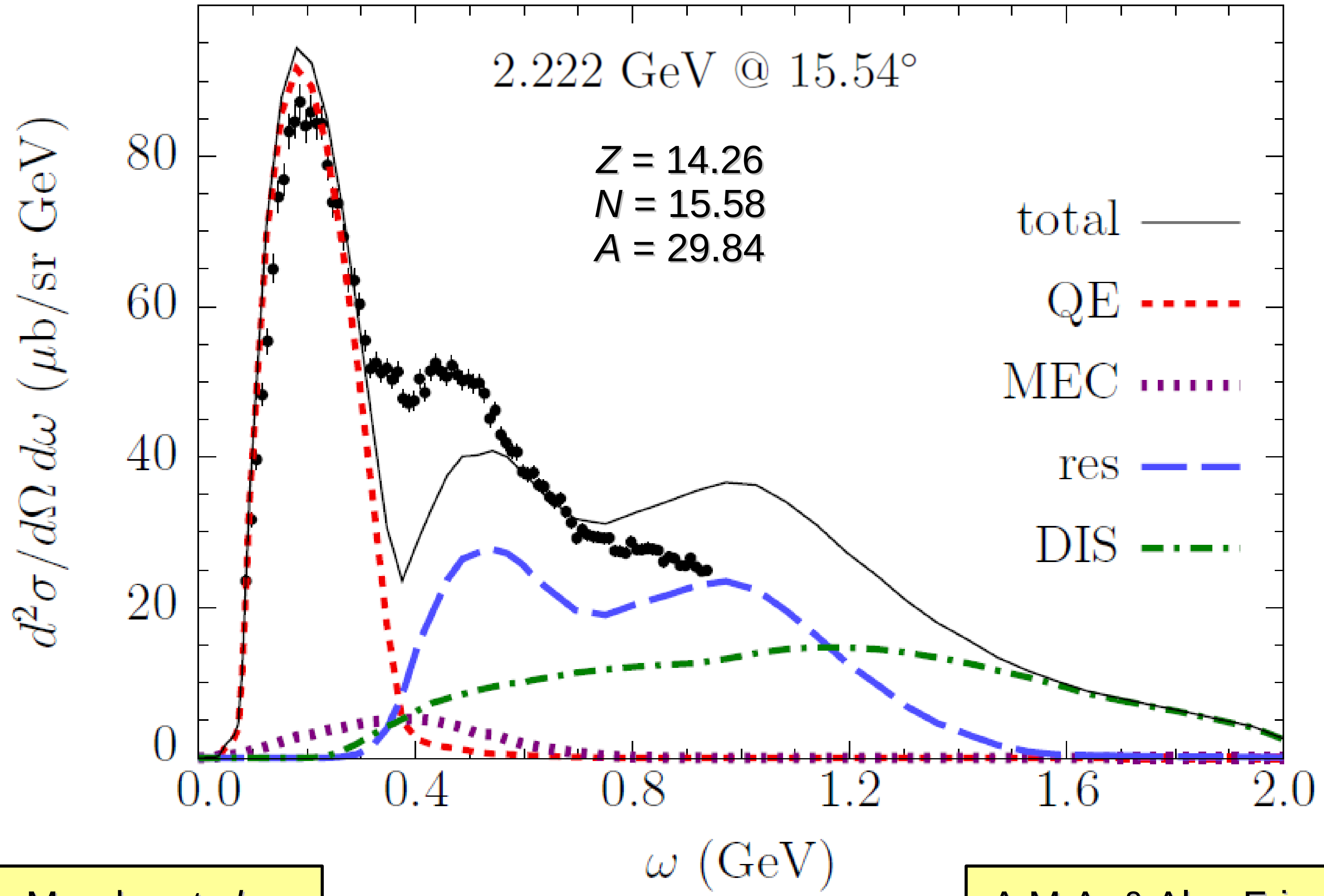
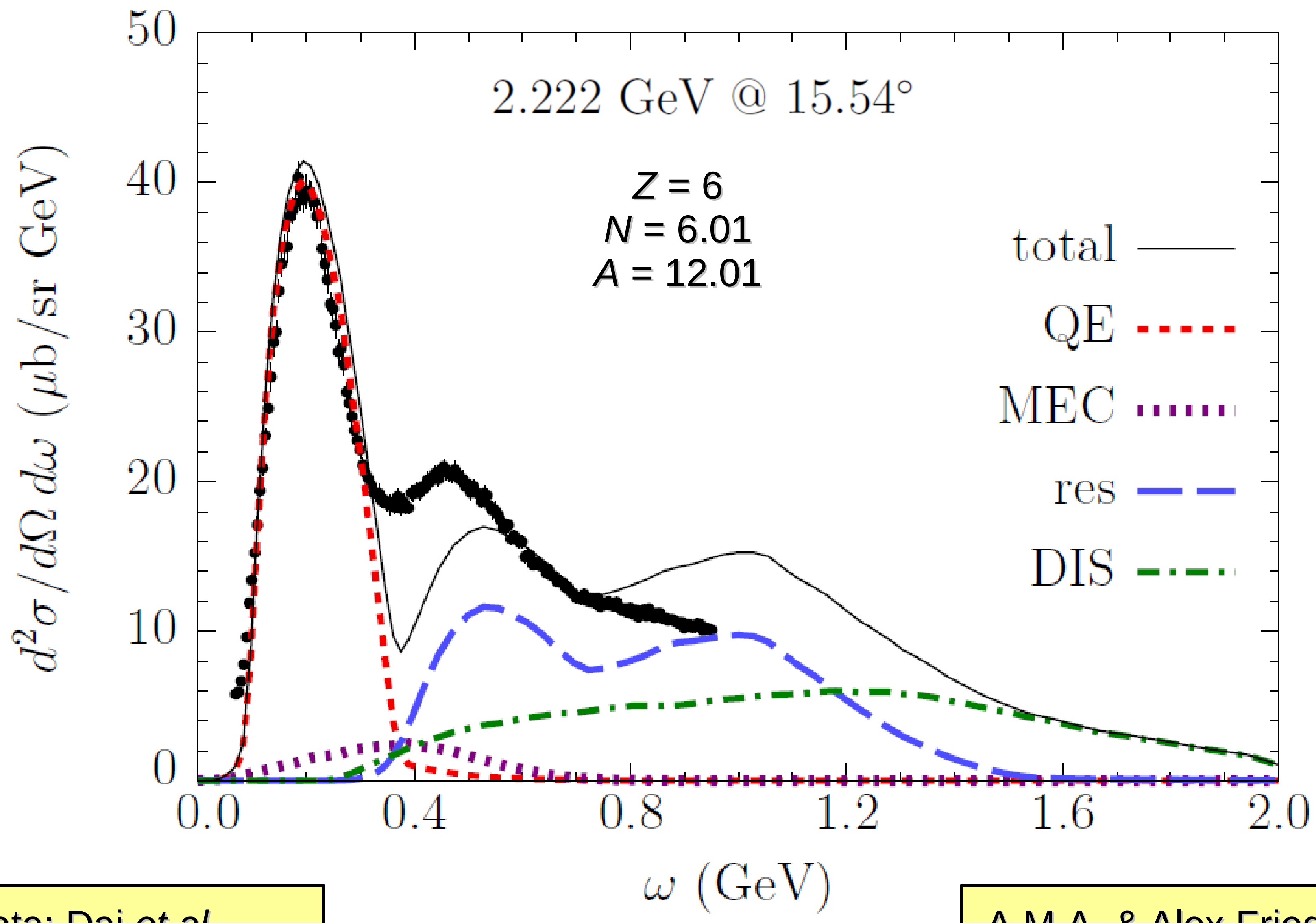
Al-7075(*e*, *e*') in GENIE



data: Murphy *et al.*, PRC **100**, 054606 (2018)

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

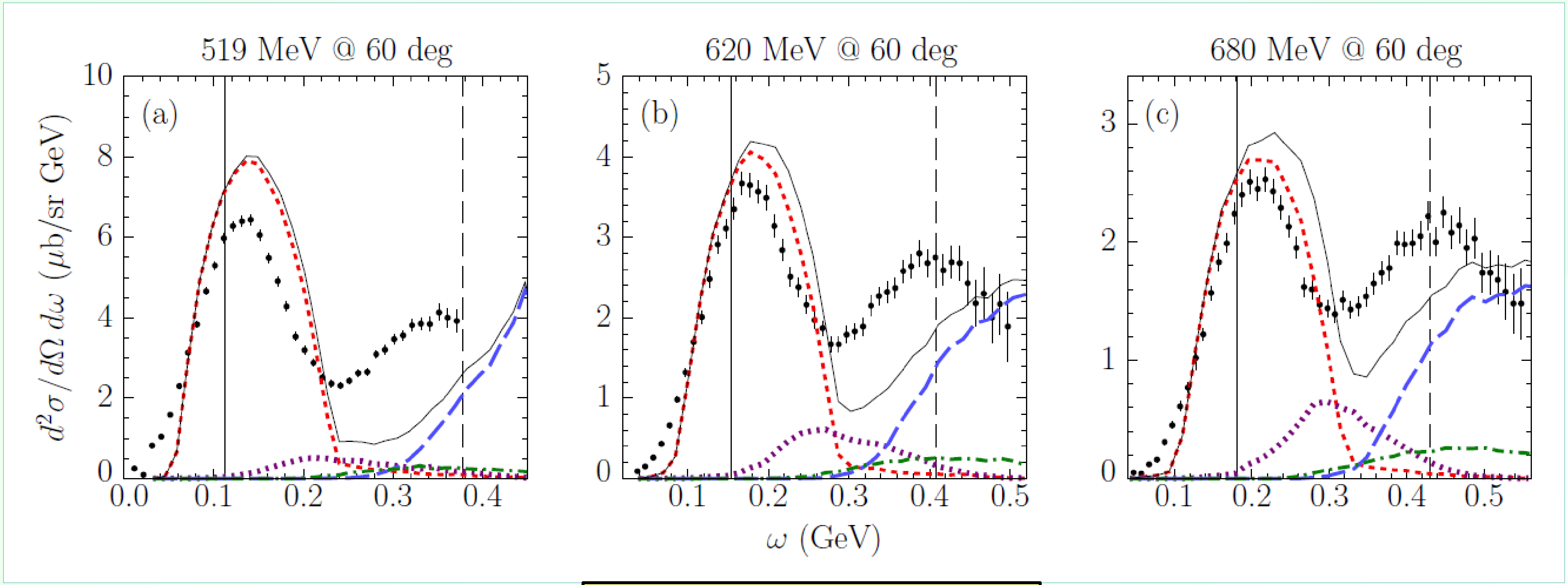
C(*e*, *e*’) in GENIE



data: Dai *et al.*, PRC **98**, 014617 (2018)

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

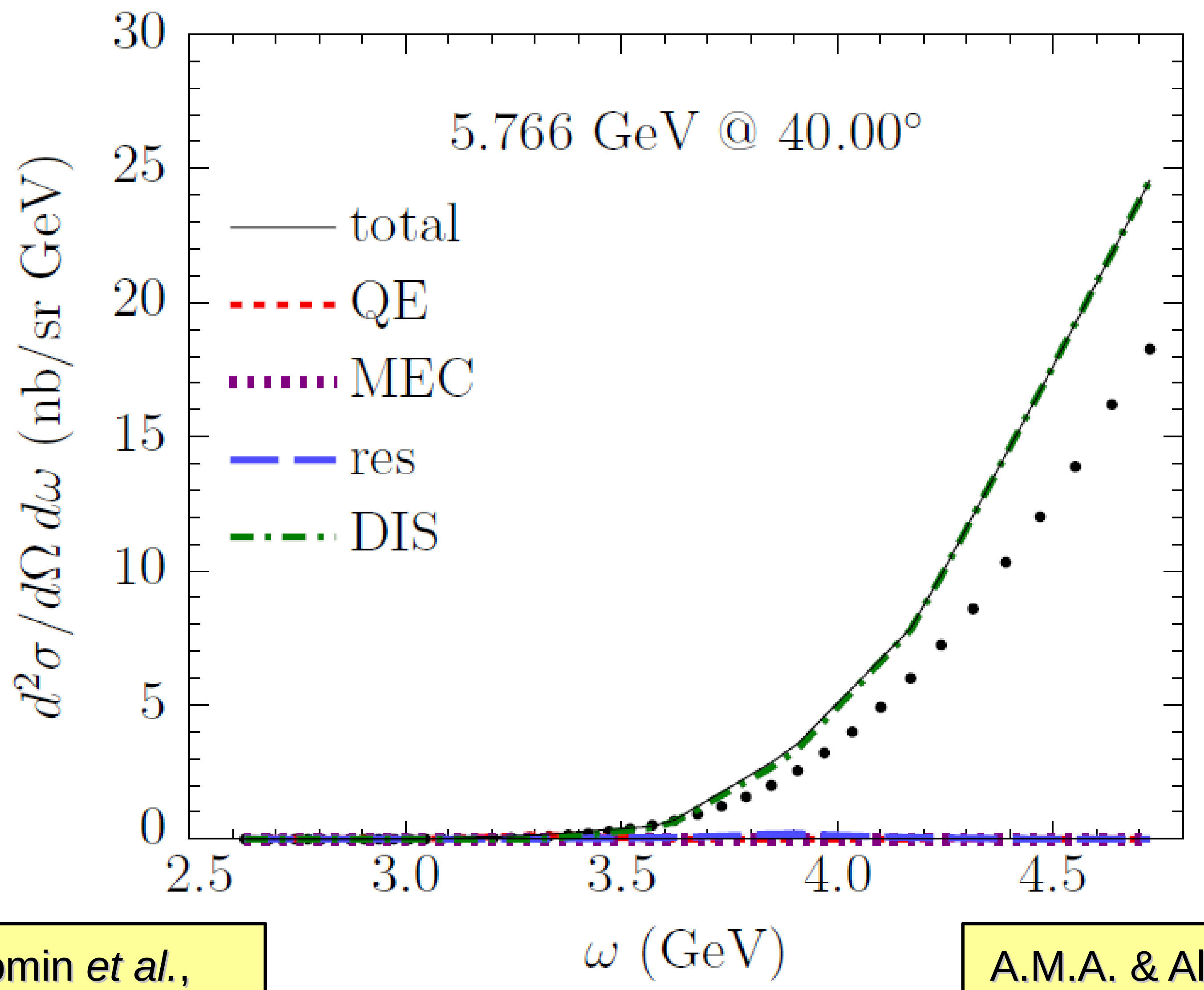
C(*e*, *e'*) in GENIE



data: Barreau *et al.*,
NPA **402**, 515 (1983)

A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

C(*e*, *e*’) in GENIE



data: Fomin *et al.*, PRL **105**, 212502 (2010)

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

Findings for complex nuclei

- In the **quasielastic** peak GENIE works best (some implementation issues observed), but the contribution of **meson-exchange currents** worsens it for higher energy transfers

- **Delta peak** position is not correct, strength underestimated

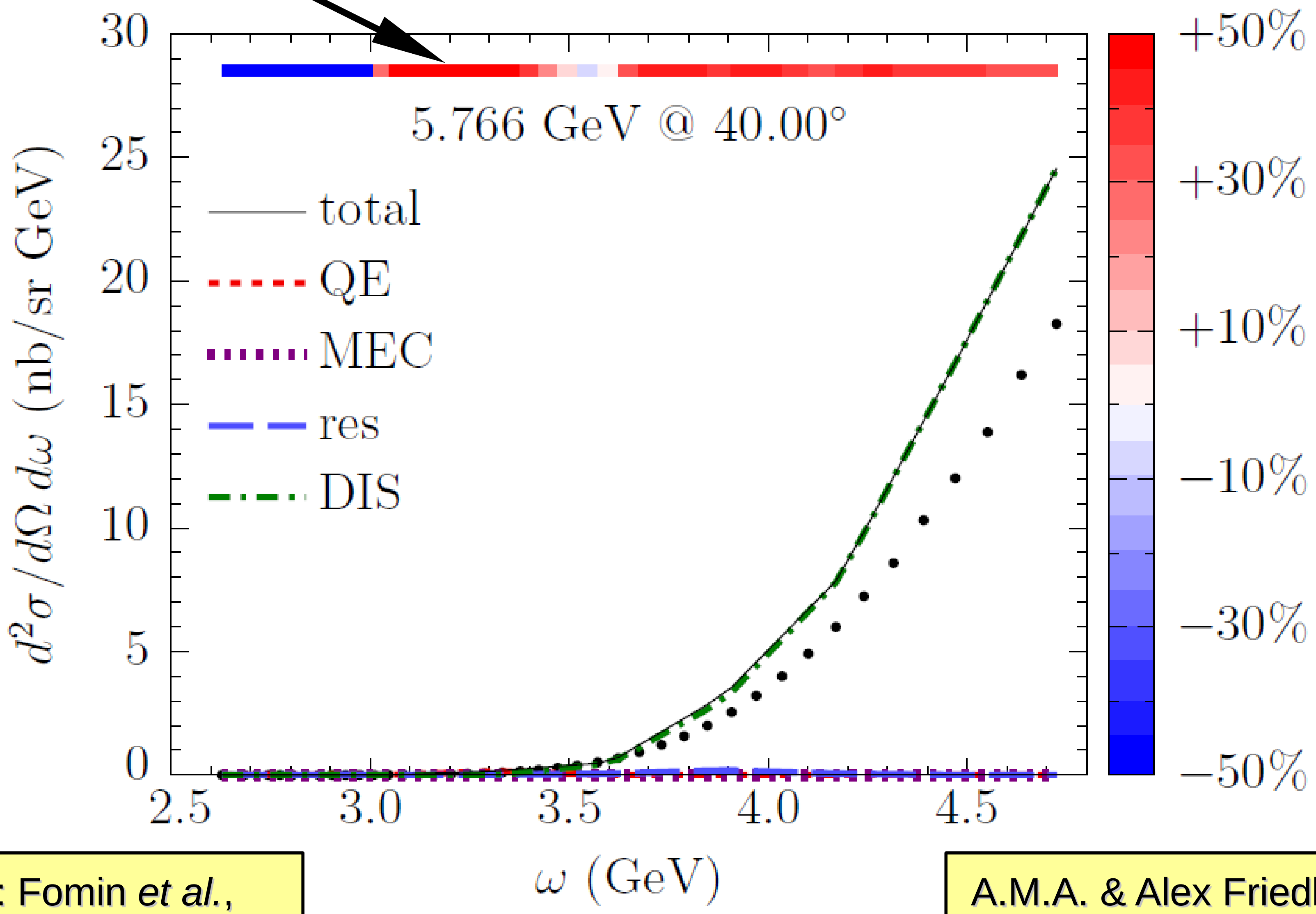
- **Higher resonances** not visible in data, clearly overestimated in GENIE

- **Deep-inelastic scattering** is significantly overestimated

What are the origins of these issues?

C(*e*, *e*’) in GENIE

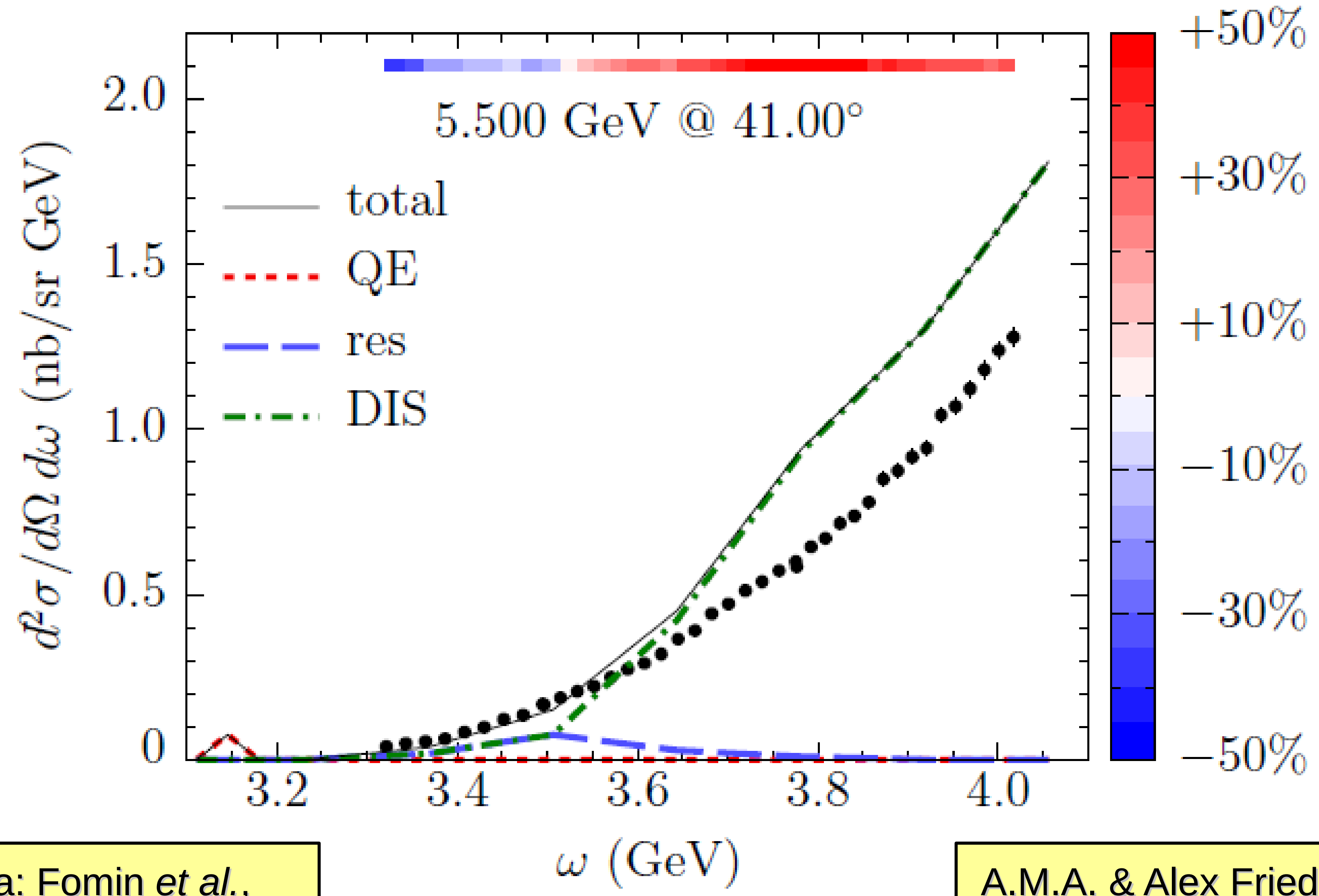
$\frac{\text{GENIE} - \text{data}}{\text{data}}$



data: Fomin *et al.*, PRL **105**, 212502 (2010)

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

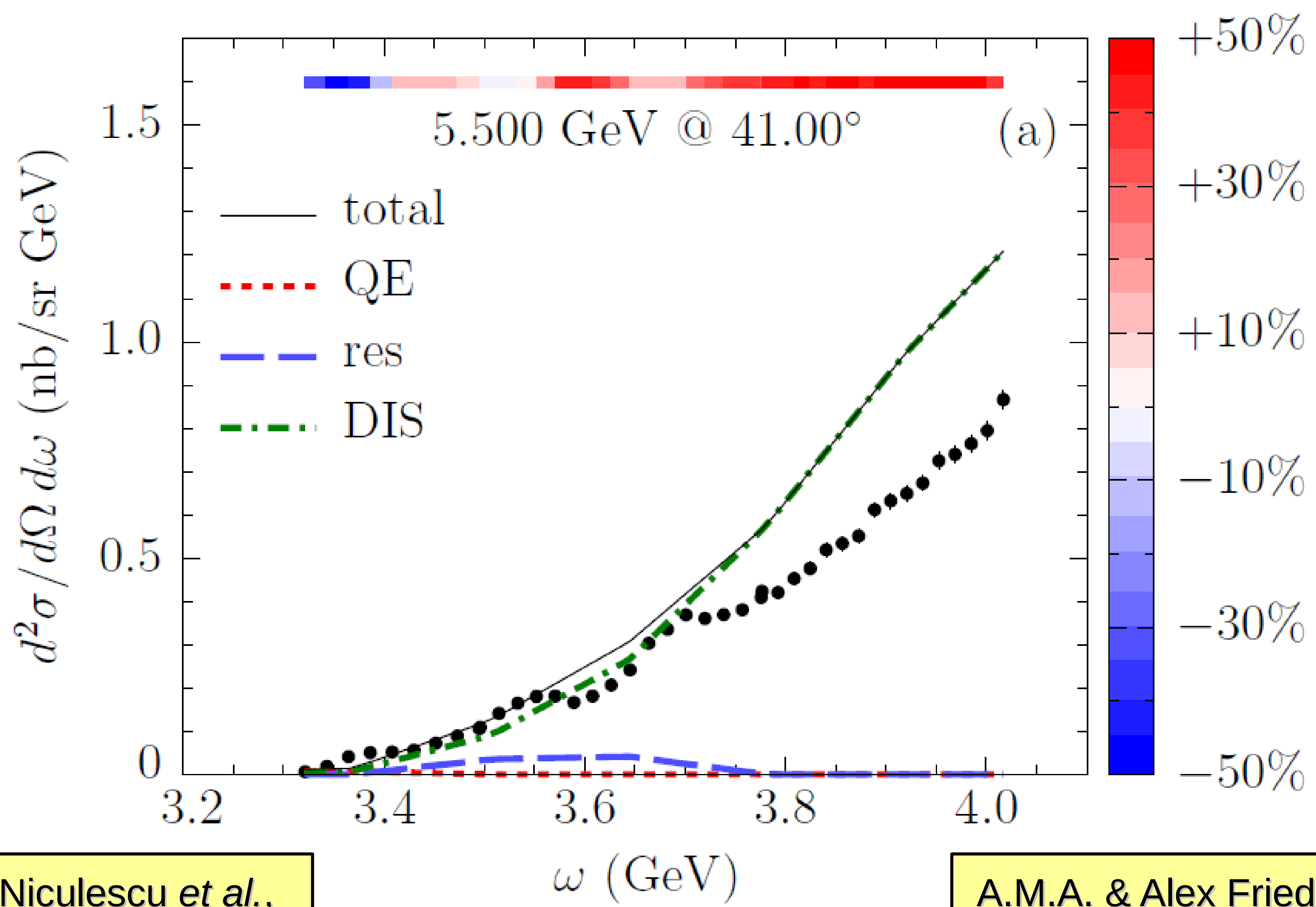
D(*e*, *e*’) in GENIE



data: Fomin *et al.*, PRL **105**, 212502 (2010)

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

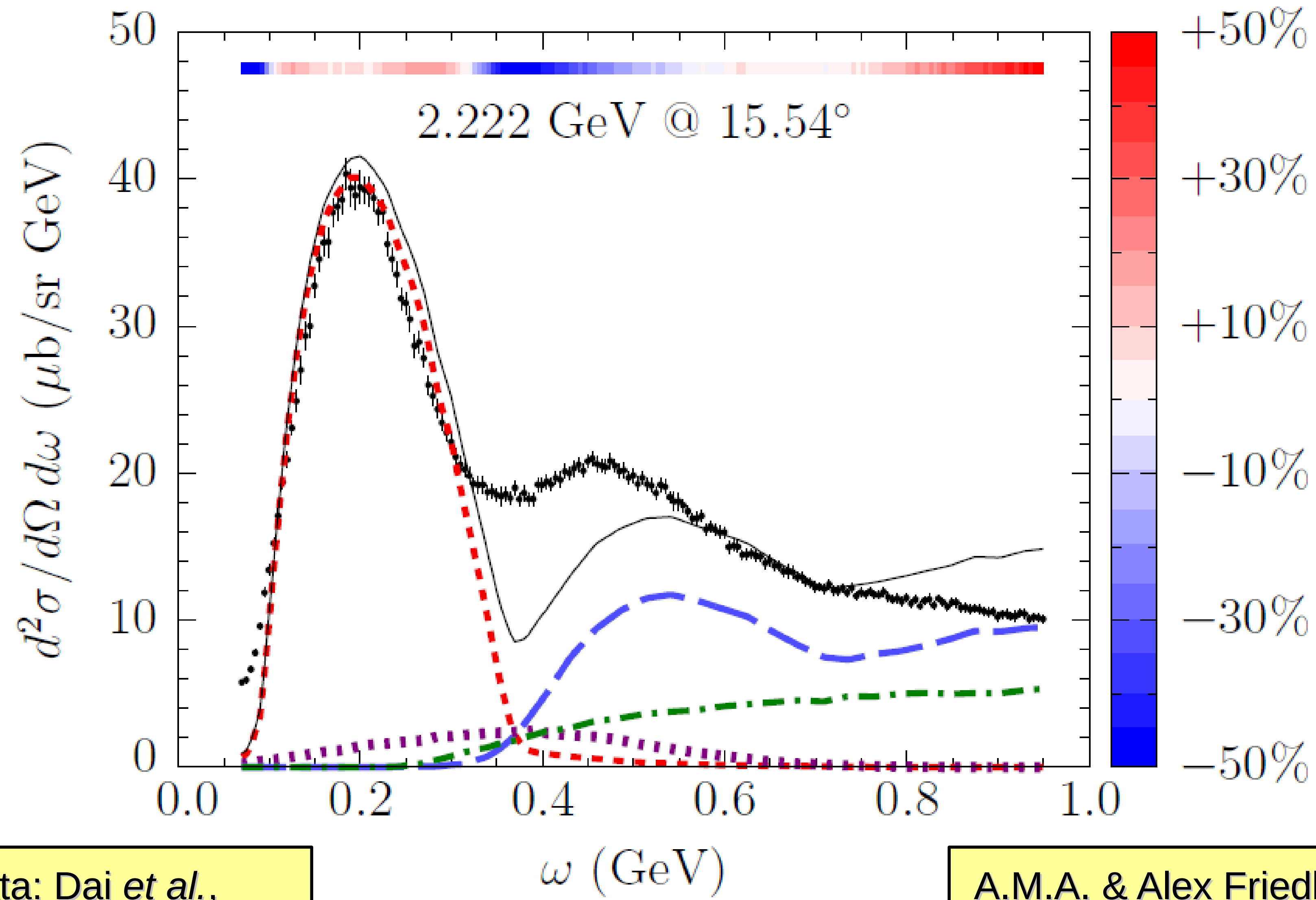
H(*e*, *e*’) in GENIE



data: Niculescu *et al.*, PRL **85**, 1186 (2000)

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

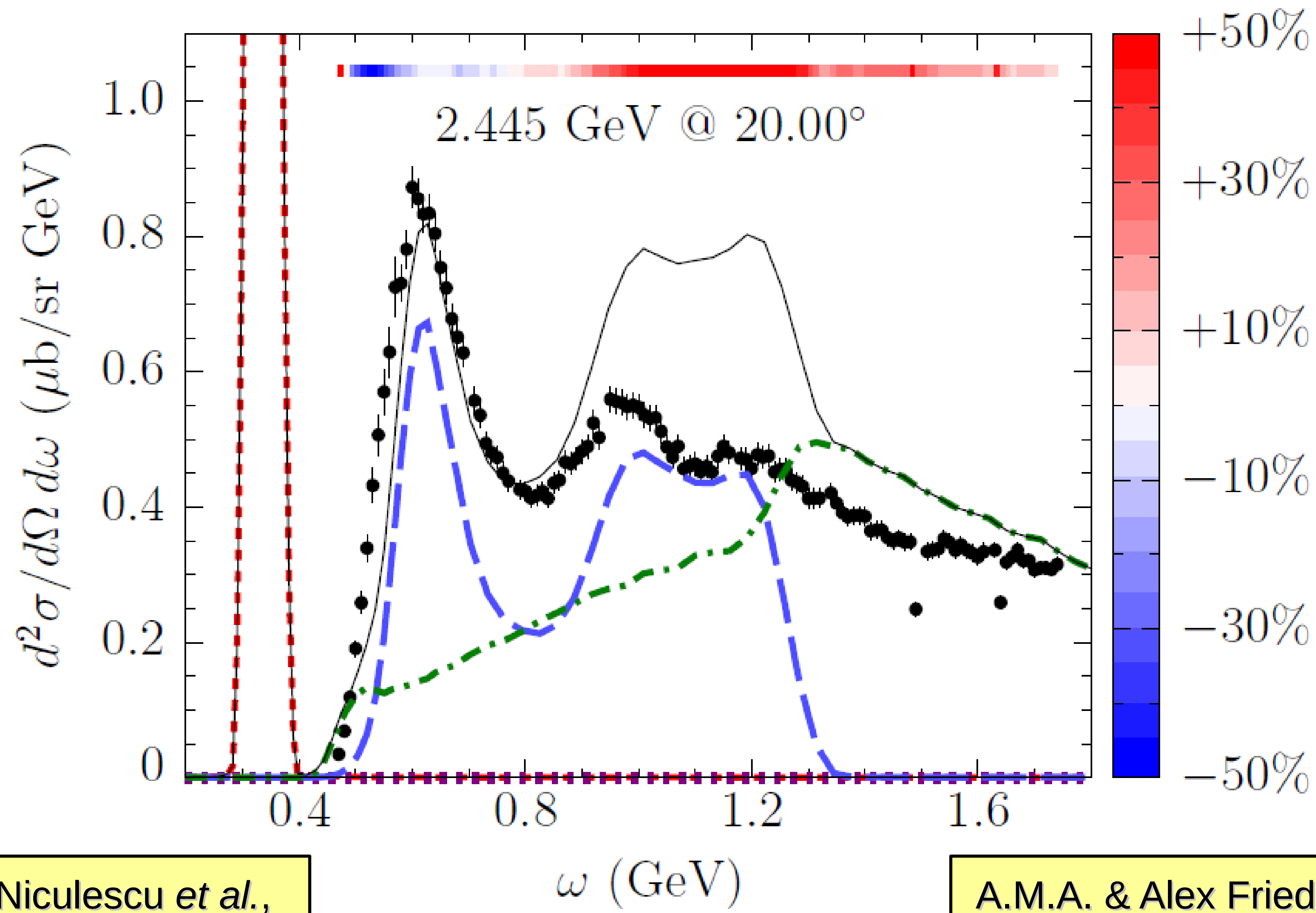
C(*e*, *e'*) in GENIE



data: Dai *et al.*, PRC **98**, 014617 (2018)

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

D(*e*, *e*') in GENIE



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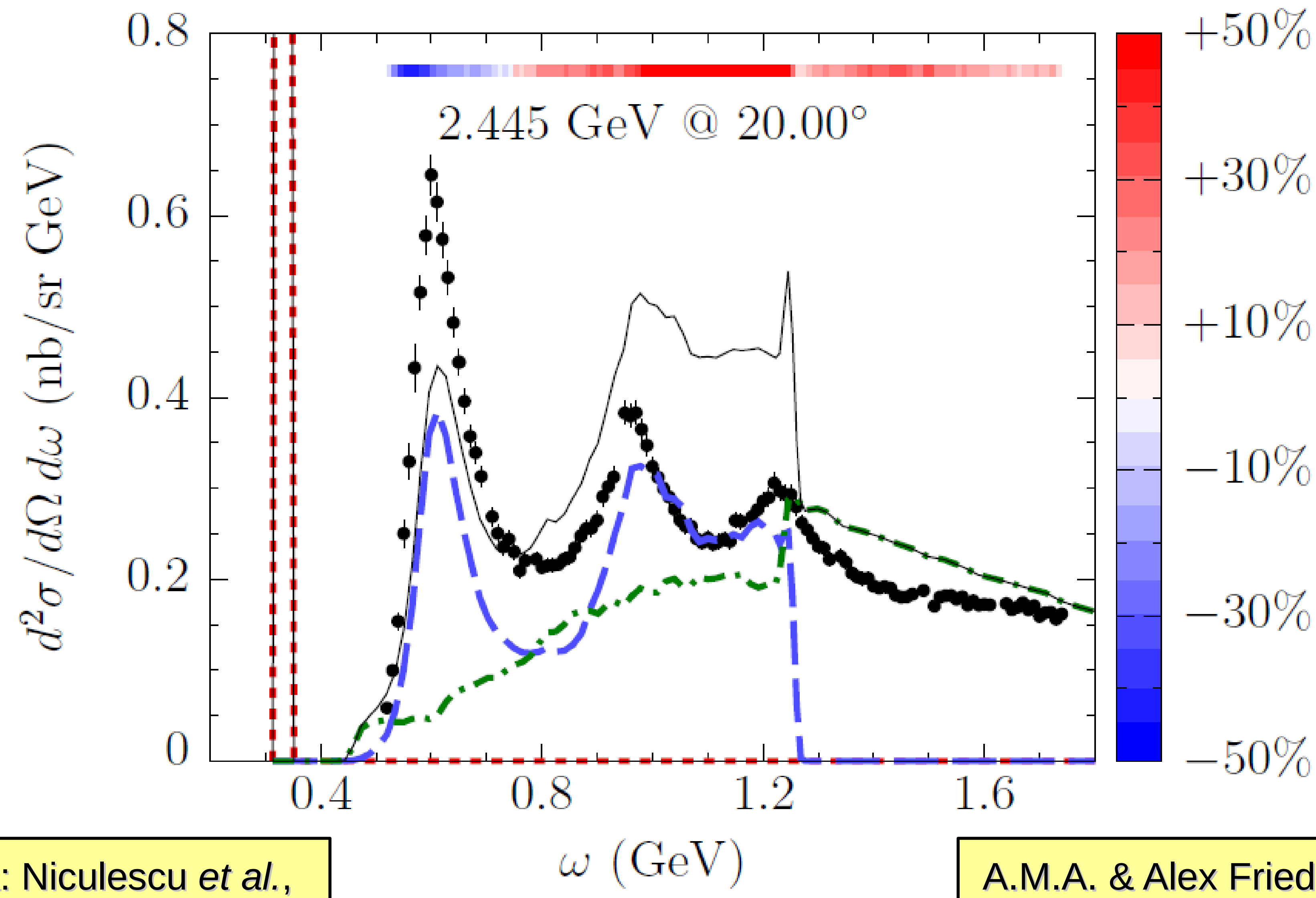
H(*e*, *e*’) in GENIE



data: Niculescu *et al.*, PRL **85**, 1186 (2000)

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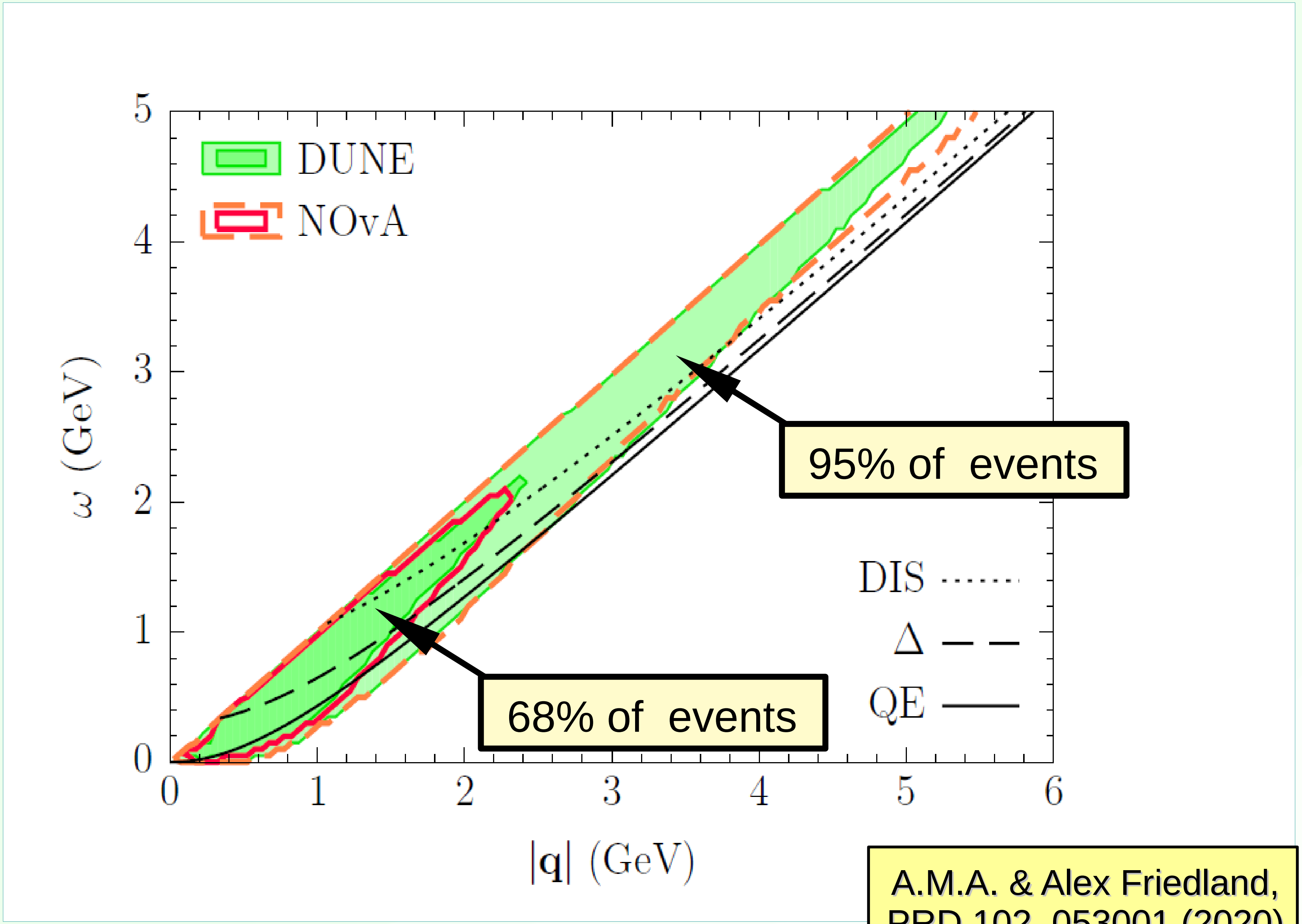
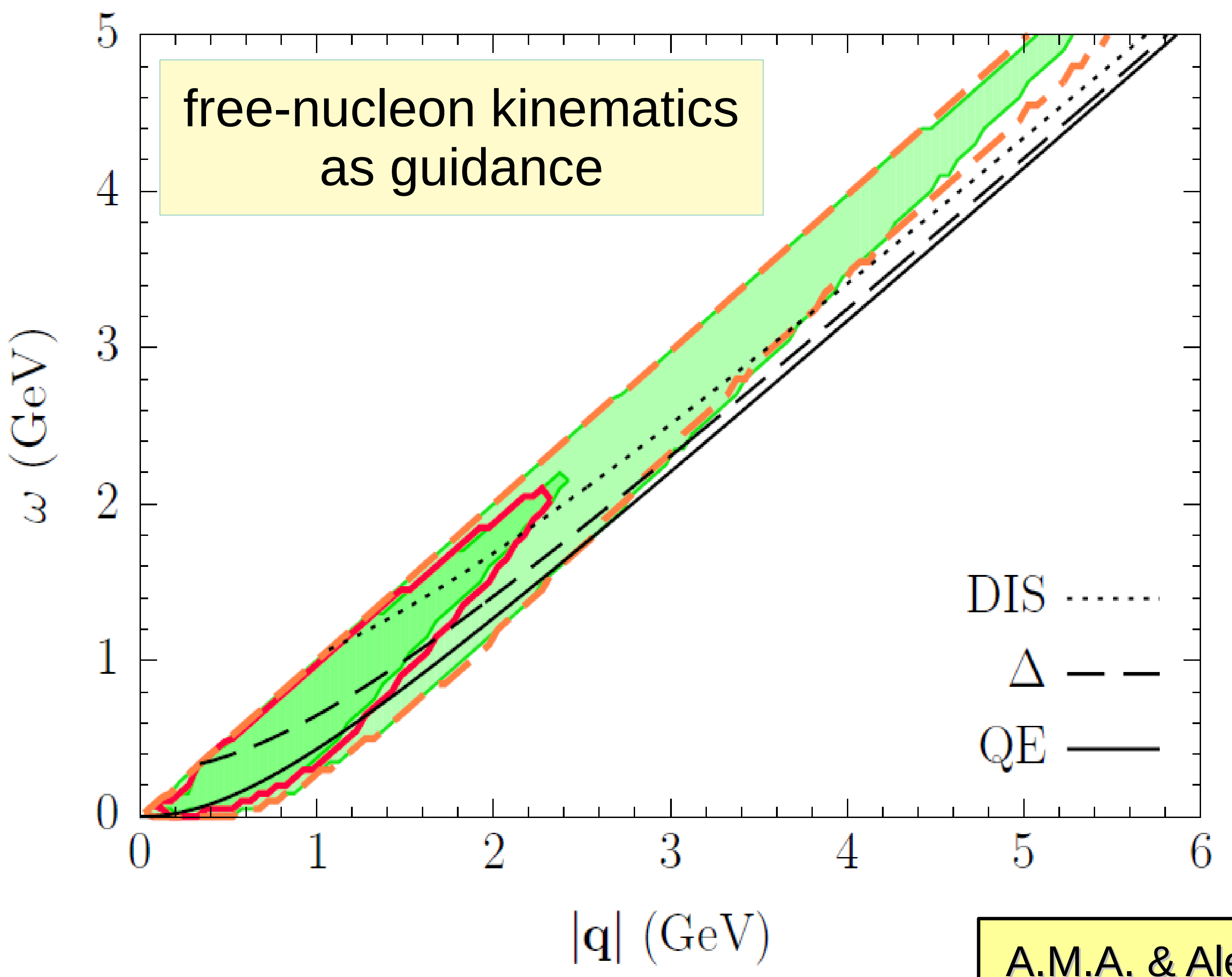
Are these issues general?

DUNE vs. NOvA



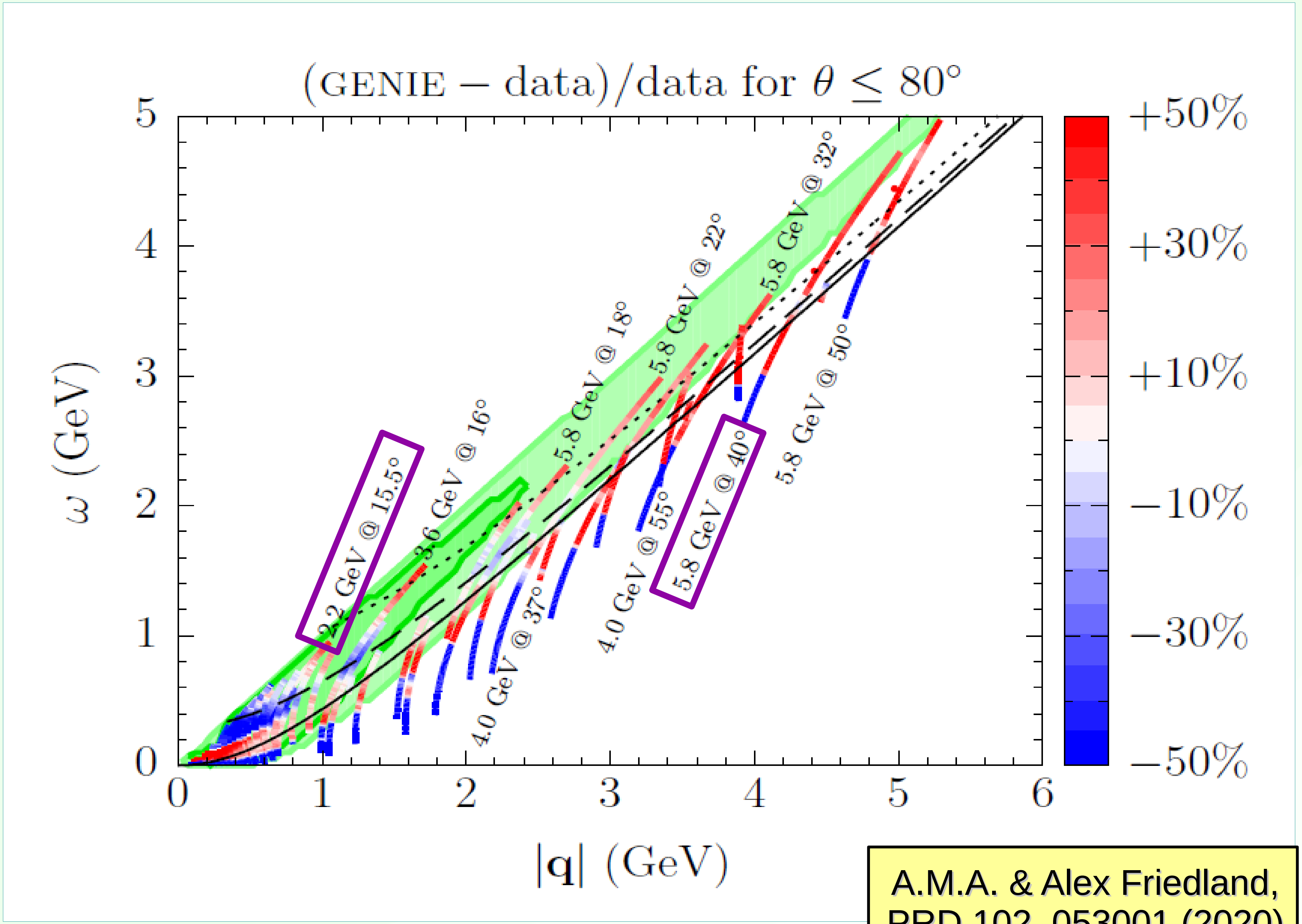
A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

DUNE vs. NOvA



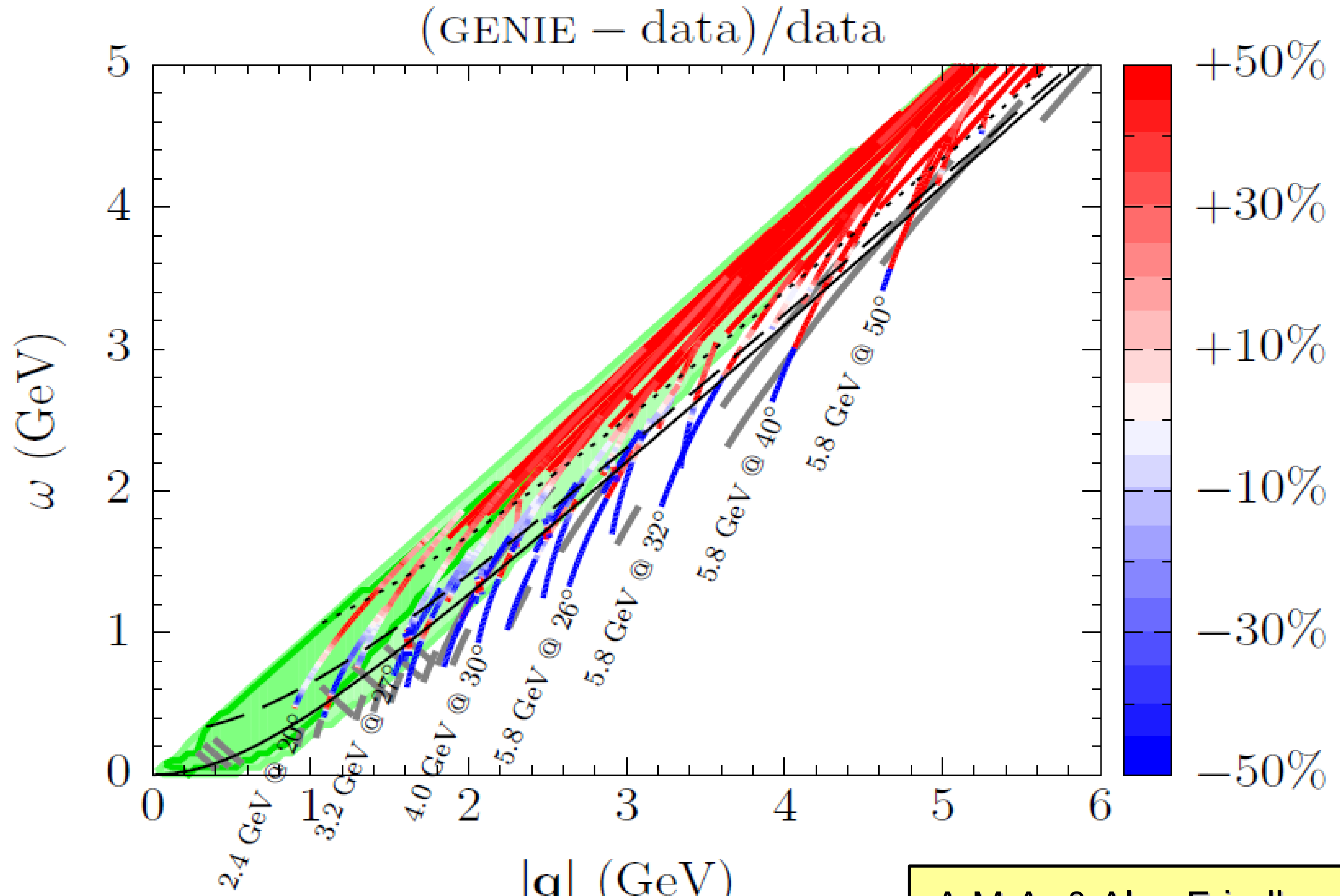
A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

C(*e*, *e*’) in GENIE



A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

D(*e*, *e*’) in GENIE



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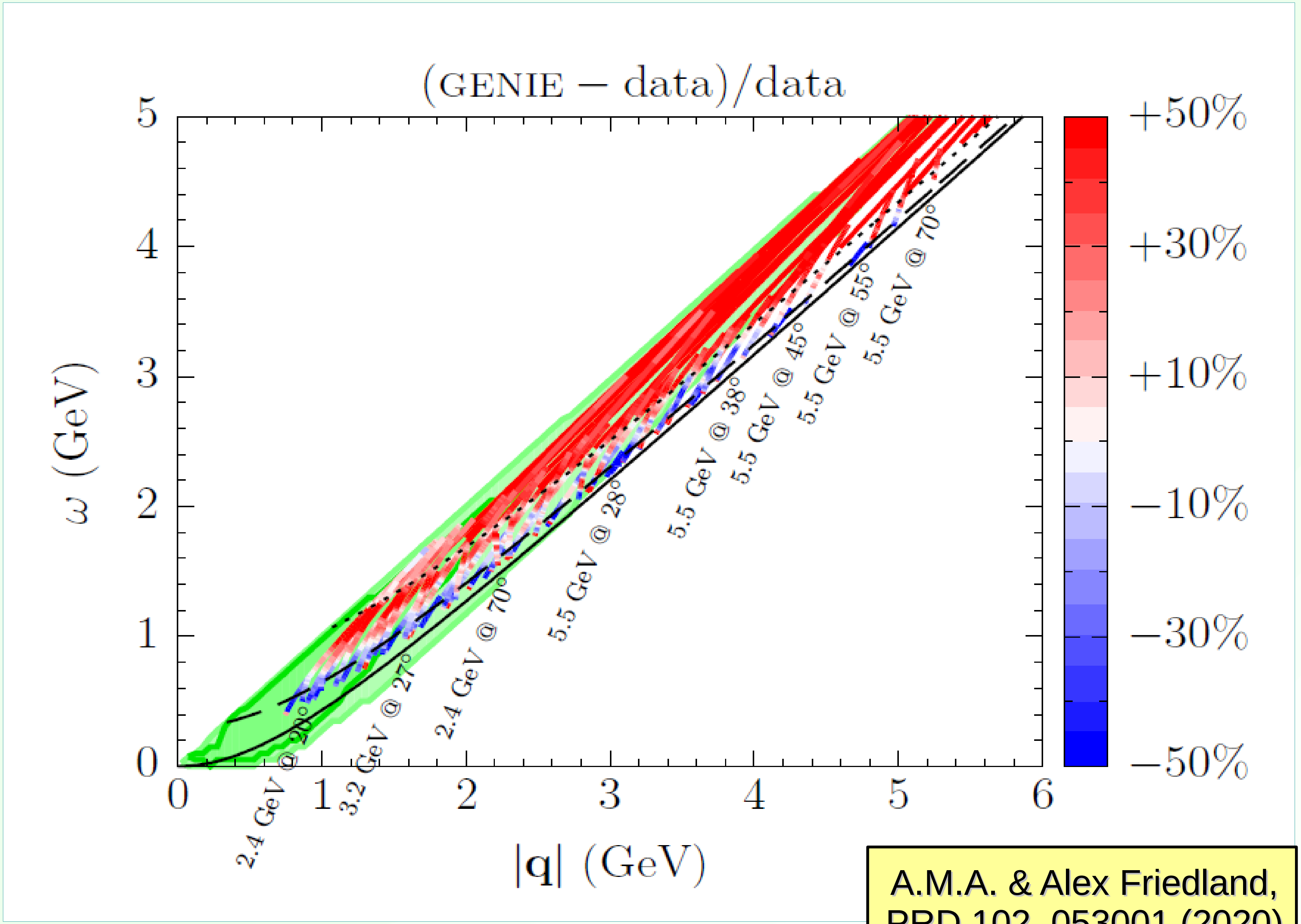


A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

Findings for light targets

- **Delta peak** position is correct, strength underestimated more for proton than for deuteron. Better model necessary.

- **Higher resonances** clearly overestimated in GENIE, (double counting and lack of interference). Conceptual problem.

- **Deep-inelastic scattering** significantly overestimated, also for the data used to construct the approach of Bodek & Yang. Implementation issue.

- Note that GENIE is tuned to deuteron data.

Conclusions in a nutshell

- Electron scattering data present a great opportunity to test MC generators and quantify systematic uncertainties for the neutrino-oscillation analysis

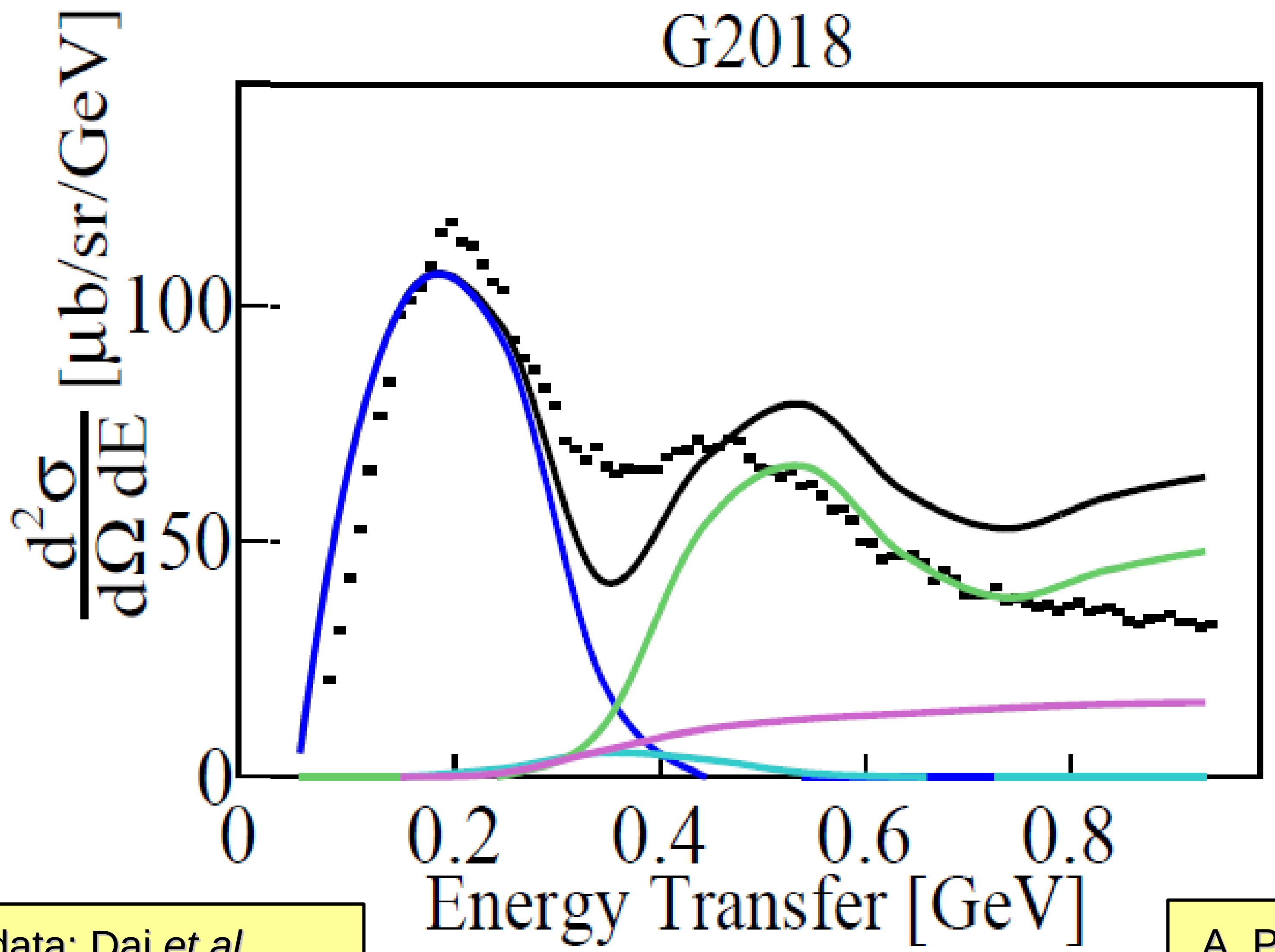
- Several sources of discrepancy identified, possible remedies discussed (implementation improvements, model updates, theory developments)

- Contrary to common believe, the most important issues are not related to MEC but to pion production, especially in deep-inelastic regime

- We strongly encourage publication of the cross sections extracted from available data and collecting new, inclusive and exclusive, ones.

Backup slides

Ar(*e*, *e*’) in GENIE 3



data: Dai *et al.*,
PRC **99**, 054608 (2019)

A. Papadopolou,
arXiv:2009.07228

H. Gallagher,
AIP Conf. Proc. **698,** 153 (2004)

"Neutrino interactions in the energy range of interest to current and near-future experiments (1 to 10 GeV), pose particular problems. In this energy range, bridging the perturbative and nonperturbative pictures of the nucleon, a variety of scattering mechanisms are important.

...

The models incorporated into neutrino simulations at these energies have been tuned primarily to this bubble chamber data. This data is not sufficient to completely constrain the models, particularly with regards to the simulation of nuclear effects. **A logical place to turn for guidance are electron scattering experiments.**"

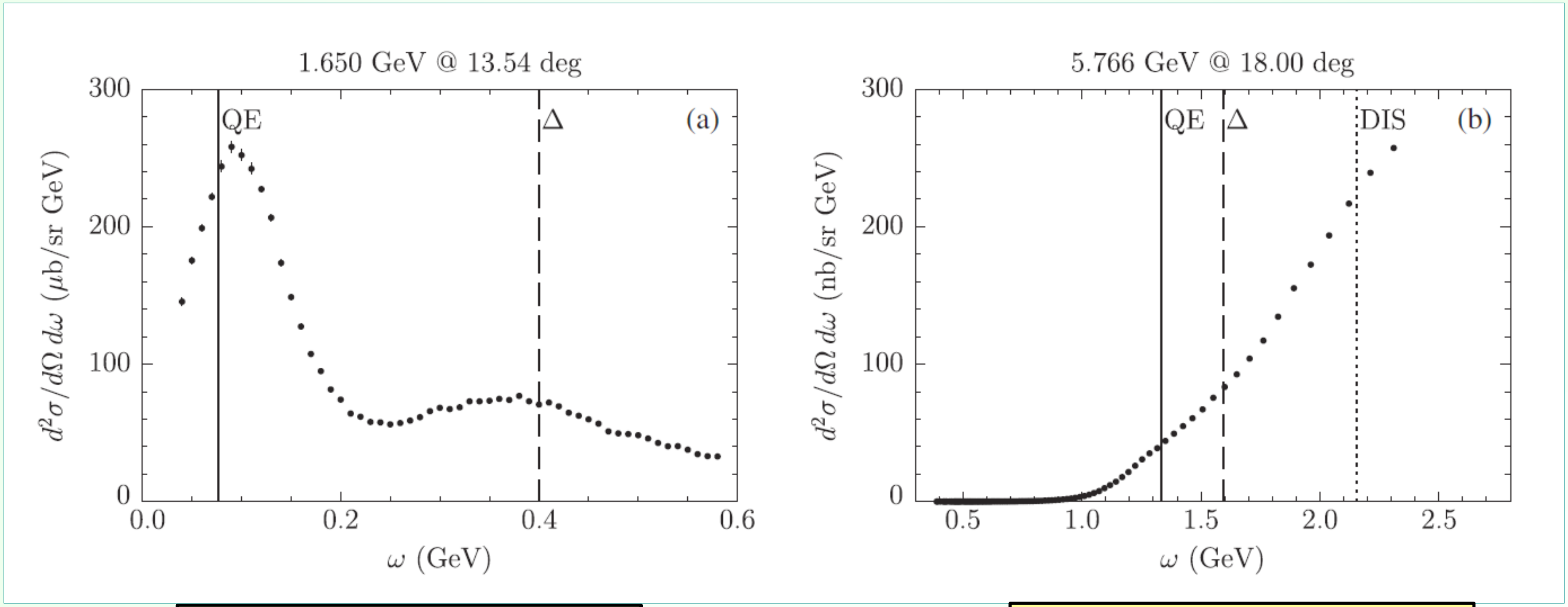
P. Stowell *et al.* (MINERvA), PRD **100**, 072005 (2019)

"… **fitting to individual MINERvA pion production channels** [$\nu_\mu CC1\pi^\pm$, $\nu_\mu CCN\pi^\pm$, $\nu_\mu CC1\pi^0$, and $\overline{\nu}_\mu CC1\pi^0$] **produces different best-fit parameters** …"

"Because the four channels cover different kinematic regions and contain different physics, it is **difficult to pinpoint the origin of the discrepancy** between the model and the different MINERvA datasets."

"The main conclusion of this work is that current **neutrino experiments operating in the few-GeV region should think critically about single pion production** models and uncertainties, as the Monte Carlo models which are currently widely used in the field are unable to explain multiple datasets, even when they are from a single experiment."

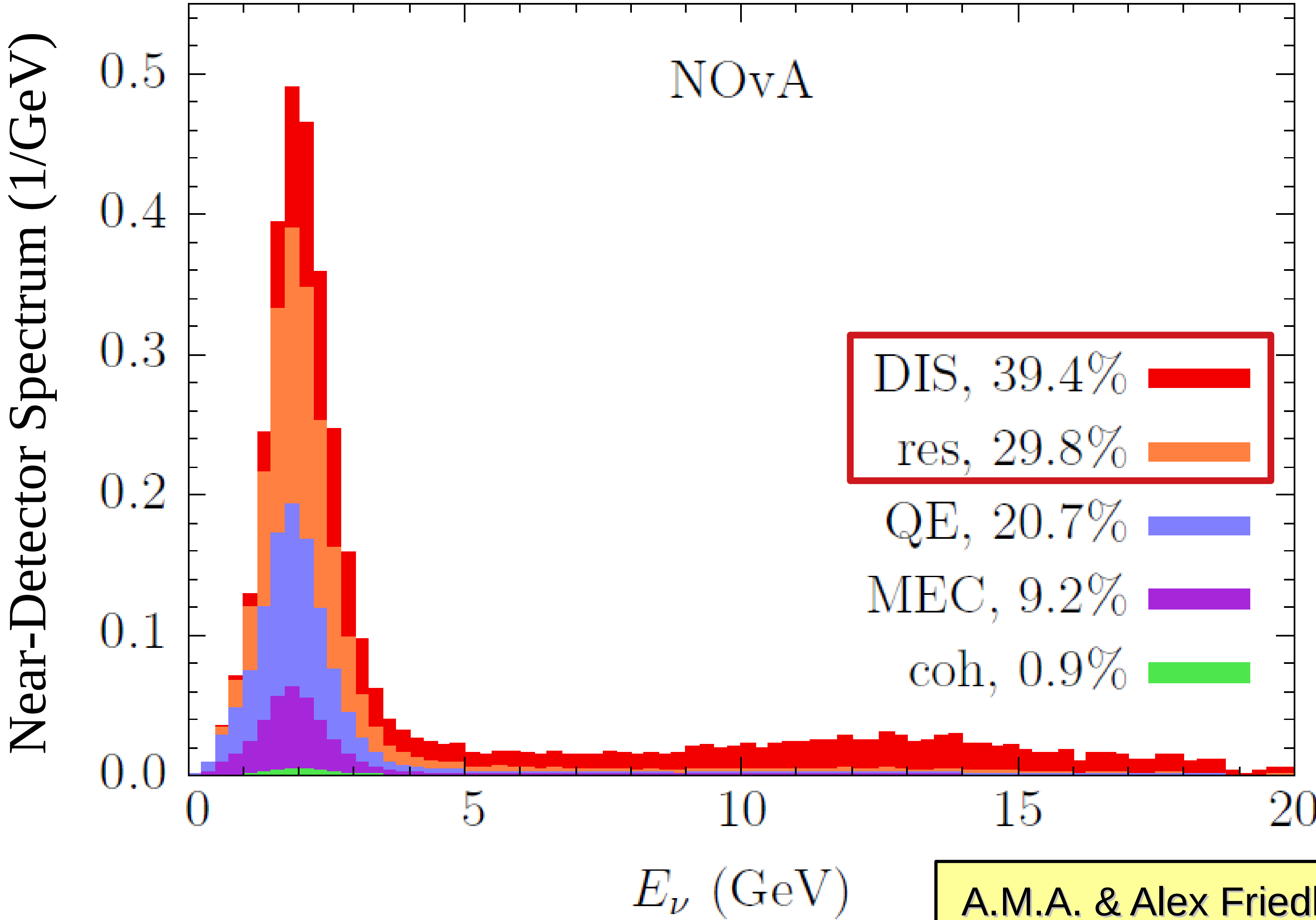
Double differential cross sections



Baran *et al.*,
PRL **61**, 400 (1988)

Fomin *et al.*,
PRL **105**, 212502 (2010)

Which cross sections are relevant?



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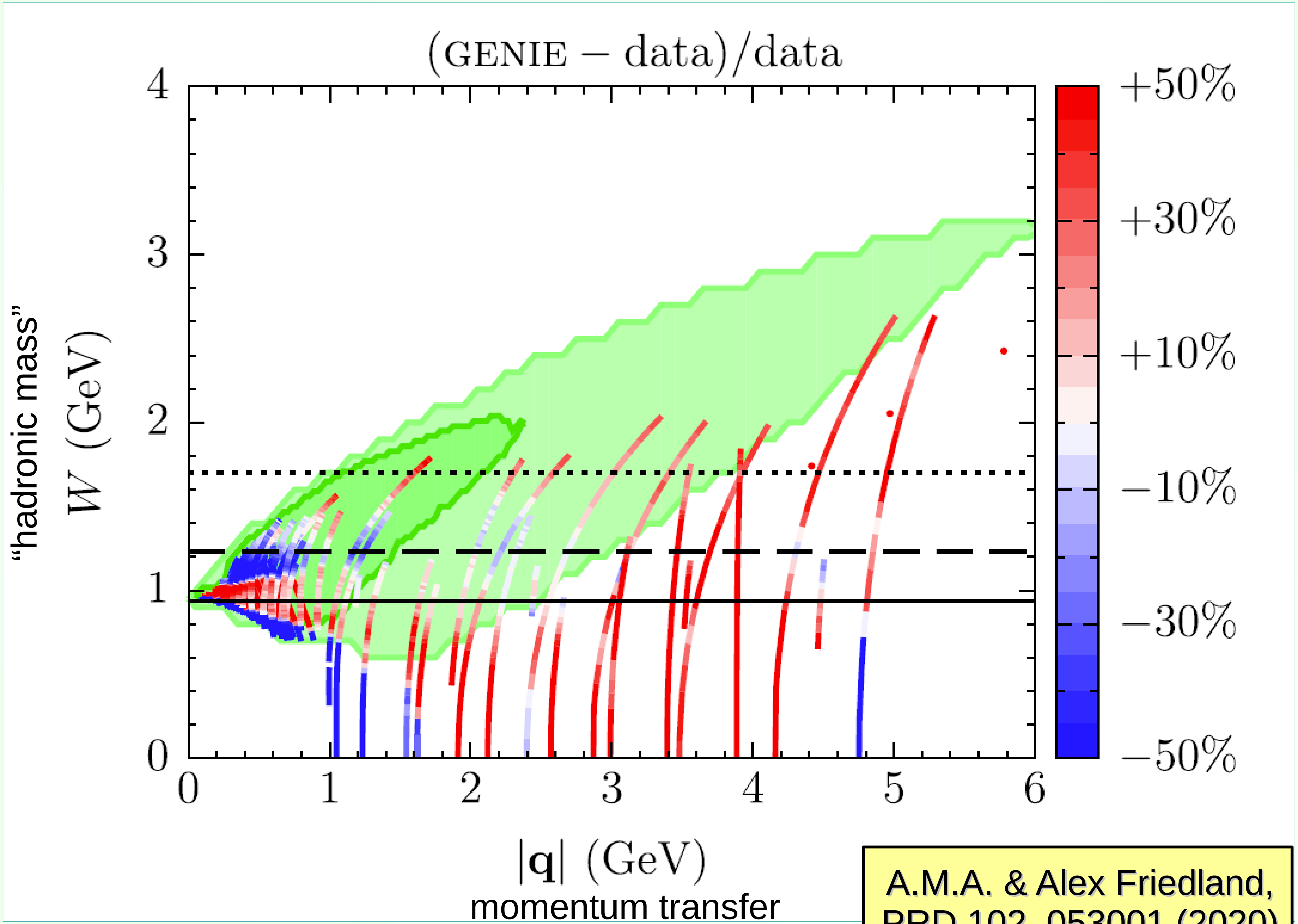
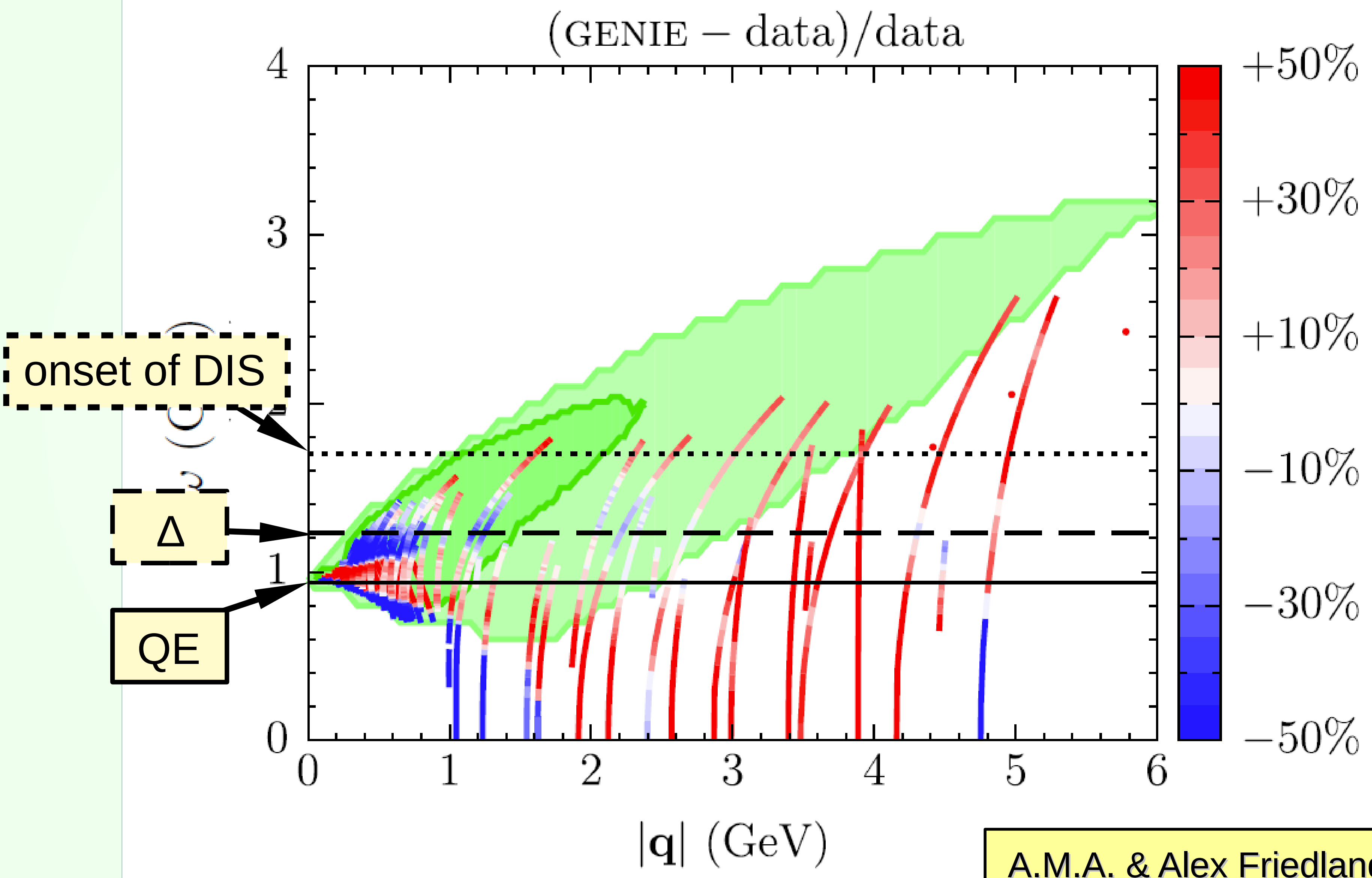
C(*e*, *e*’) in GENIE



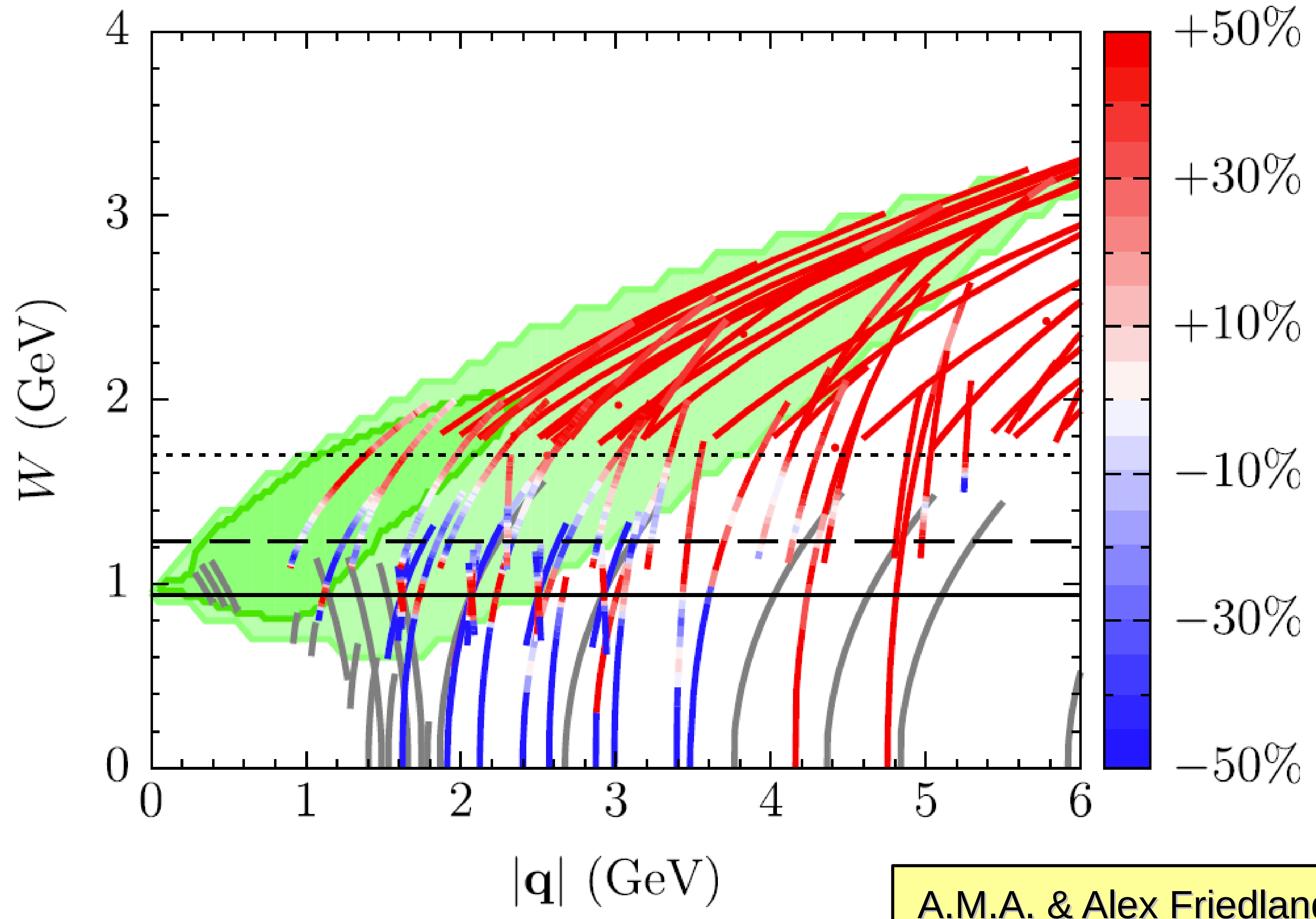
A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

C(*e*, *e*') in GENIE



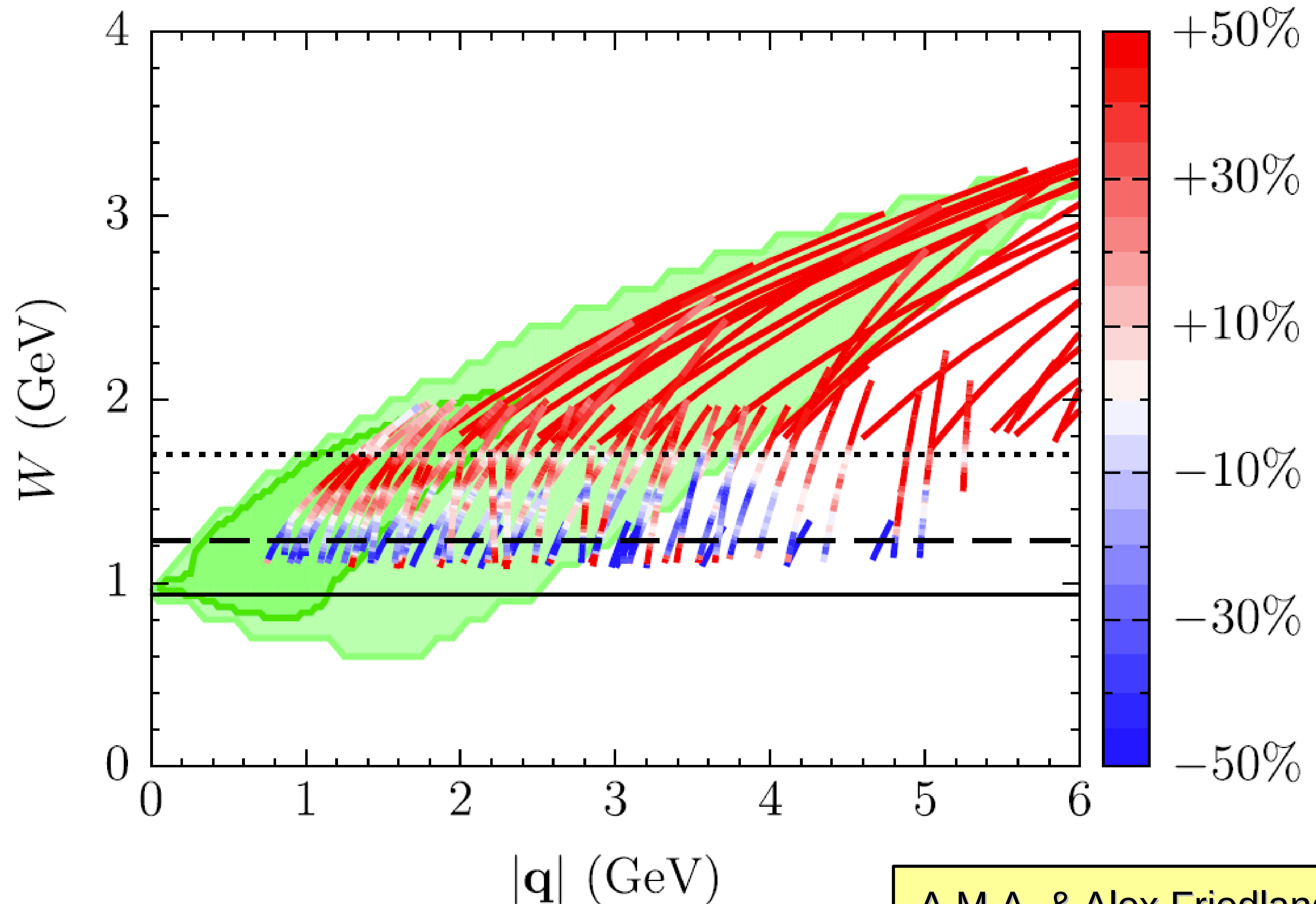
A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

D(*e*, *e'*) in GENIE



A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

H(*e*, *e*’) in GENIE



A.M.A. & Alex Friedland, PRD 102, 053001 (2020)