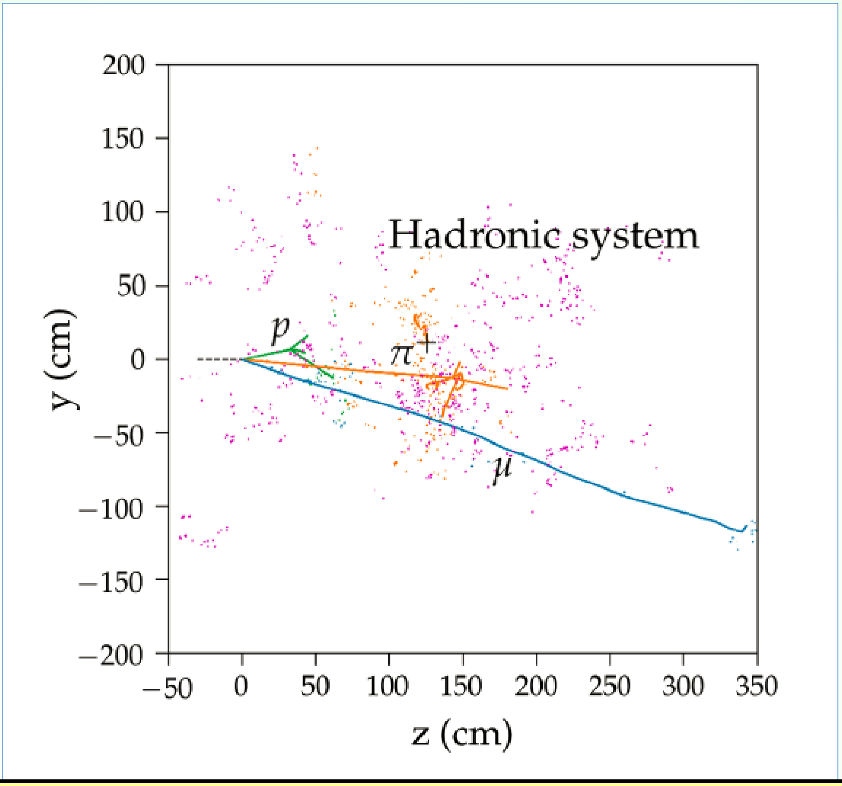
Assessing the accuracy of GENIE with electron-scattering data

Artur M. Ankowski

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

IPPP Topical Meeting on Physics with High-Brightness Stored Muon Beams
February 10-11, 2021

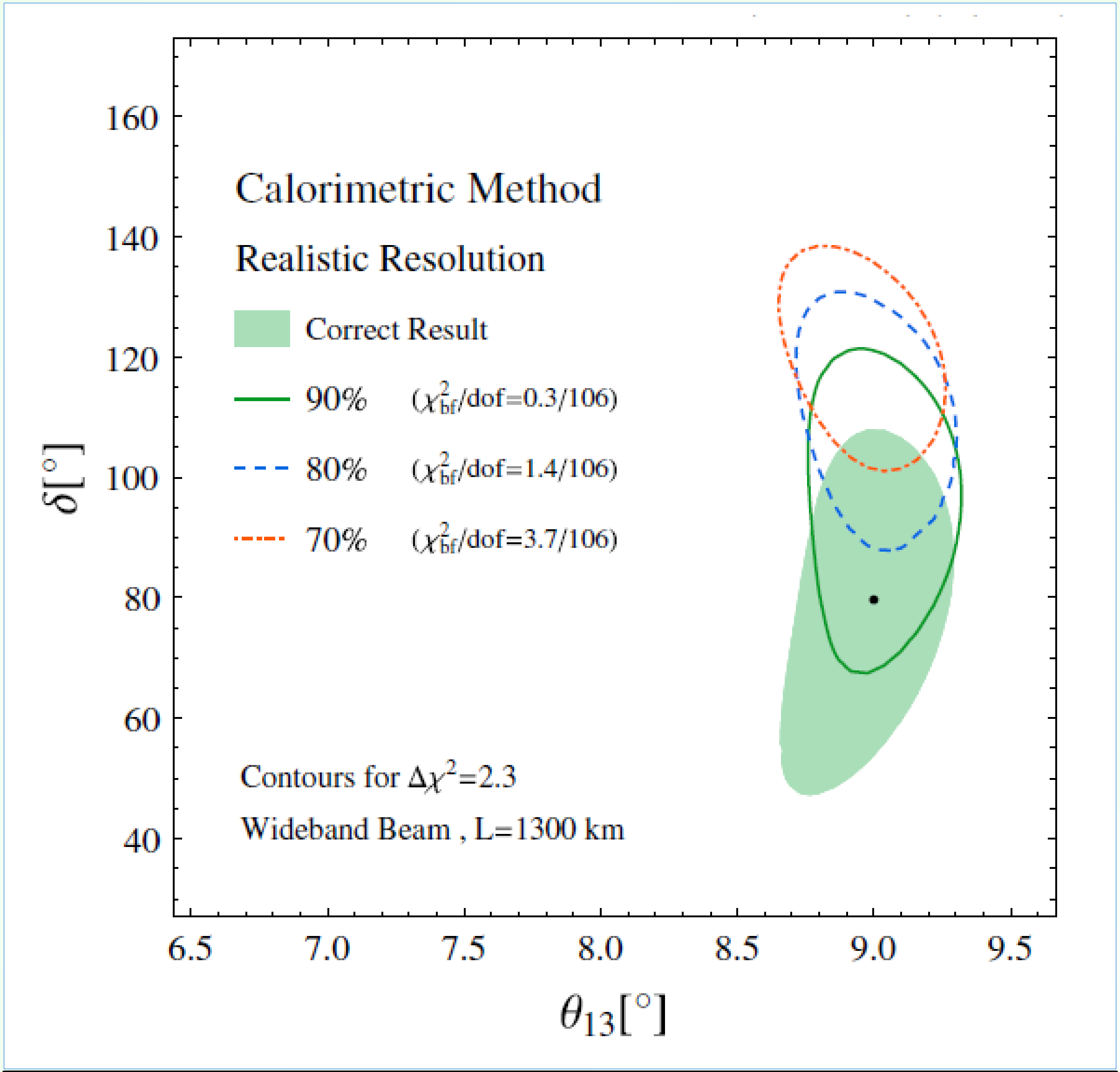
Monte Carlo generators



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

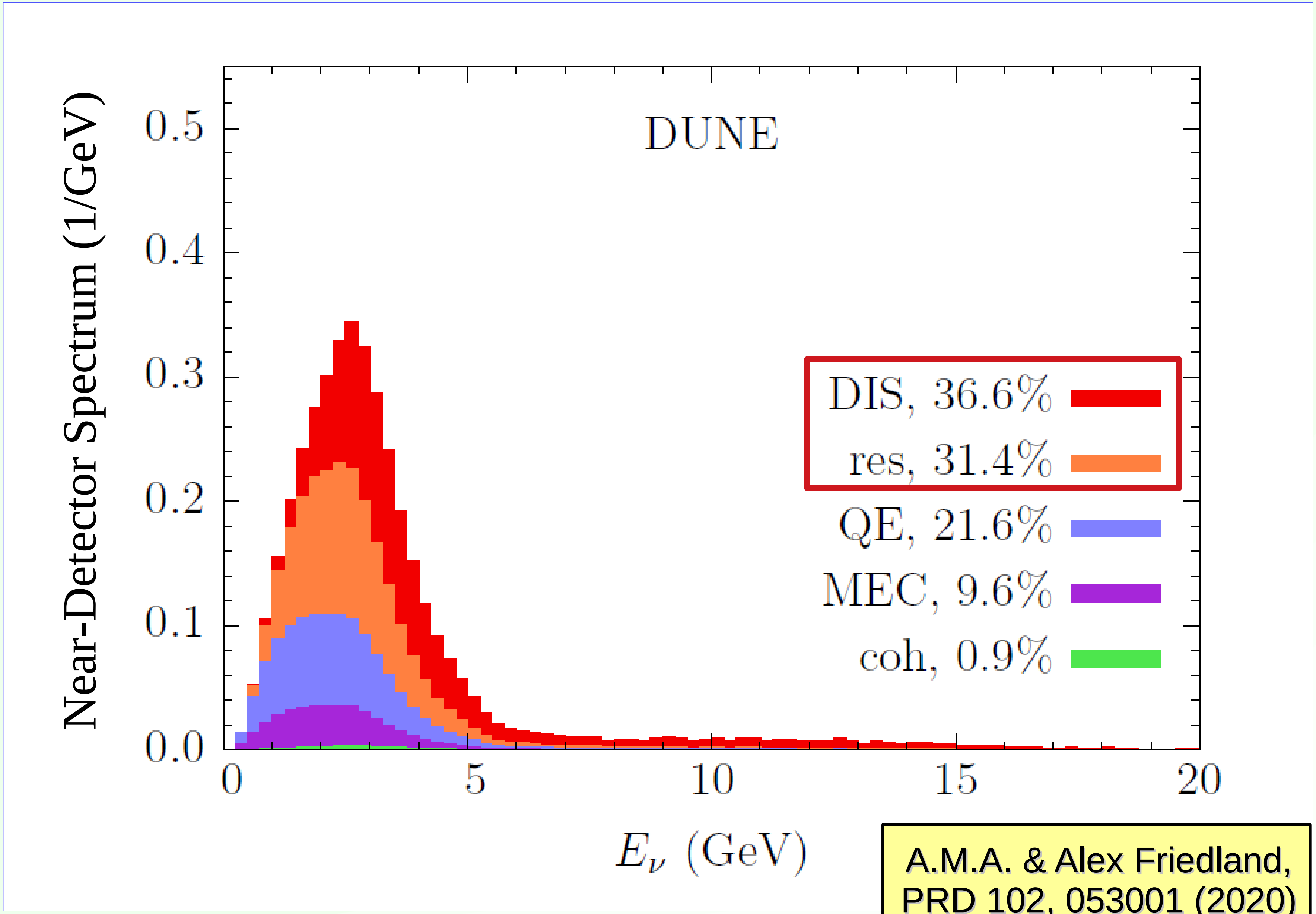
- Visible energy needs to be translated to the true energy using a Monte Carlo simulation.
- Accuracy of the energy reconstruction depends on the accuracy of the simulation.

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)

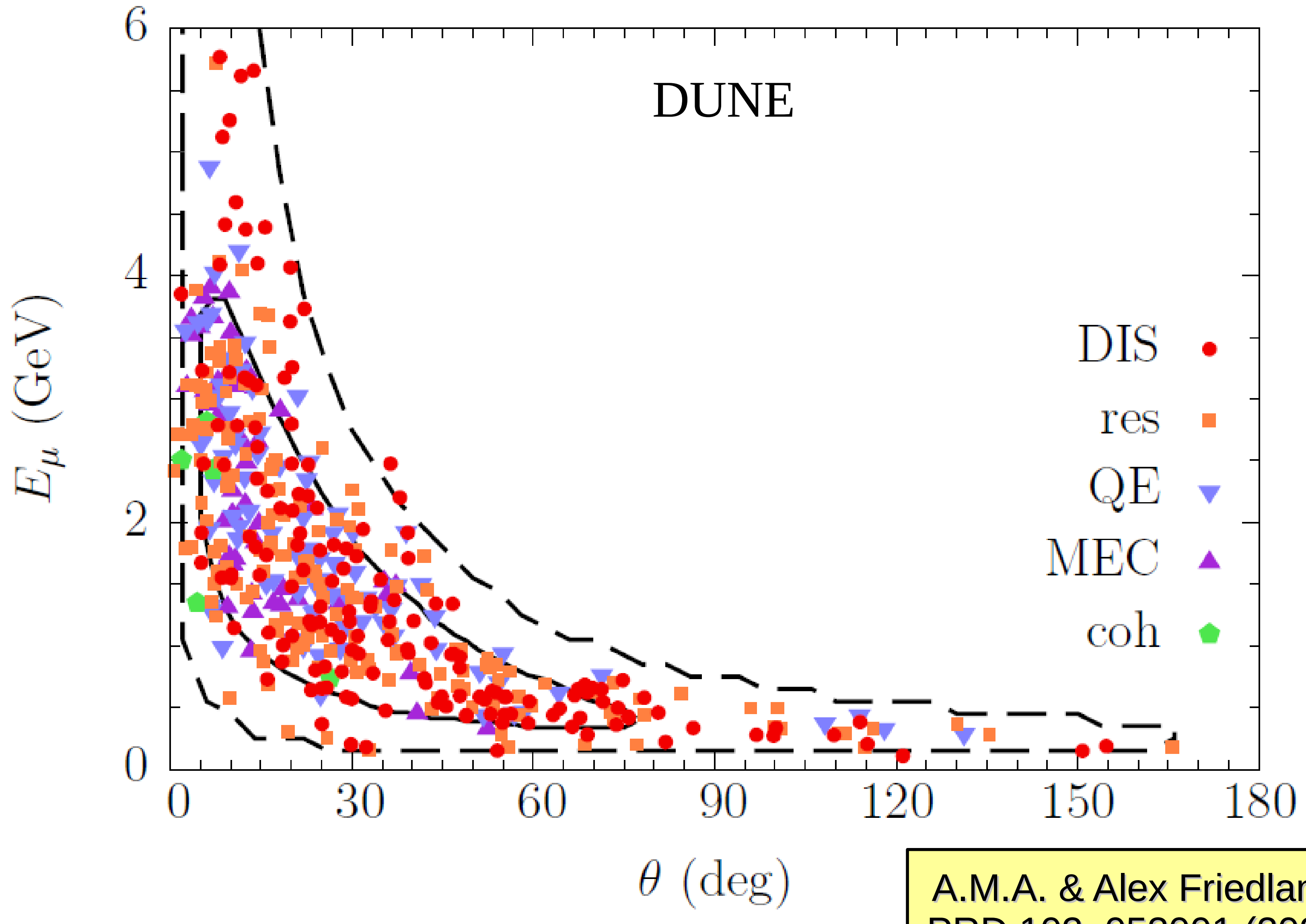
- Check if the discrepancies follow a pattern & **understand their origin**

- Offer directions for **possible improvements**

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

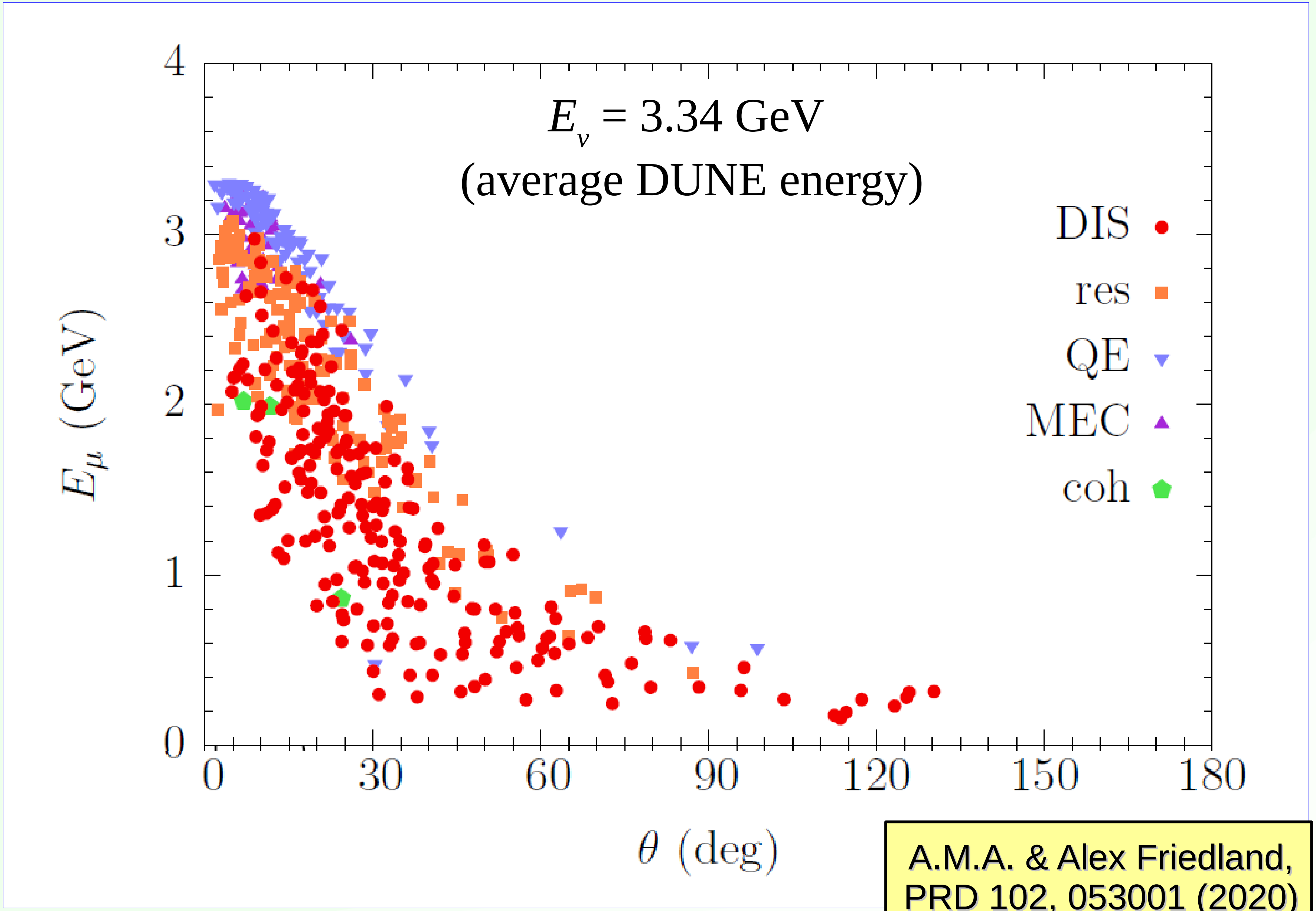
Introduction

Muon kinematics mixes channels



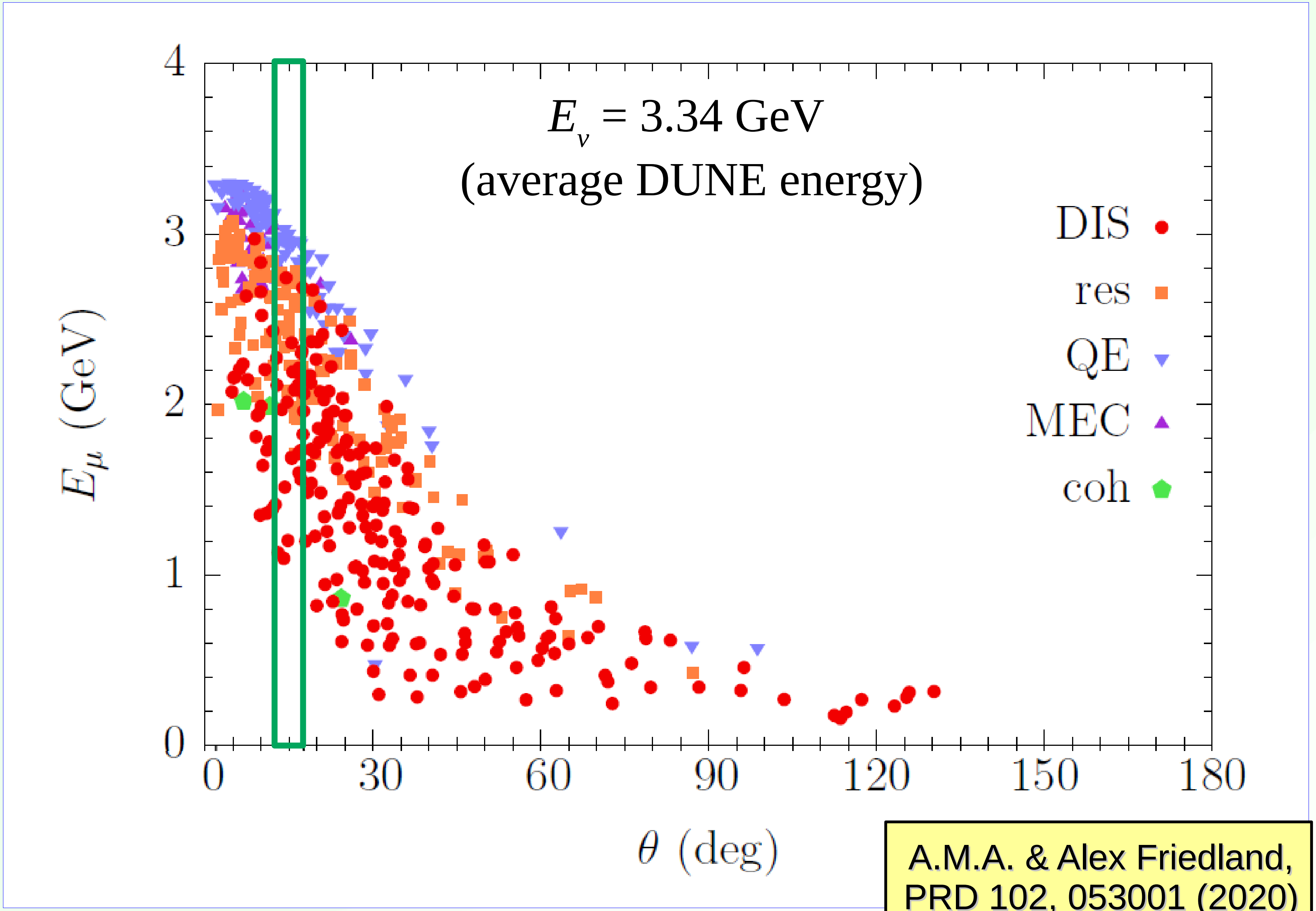
A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

Monoenergetic beam



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

Monoenergetic beam



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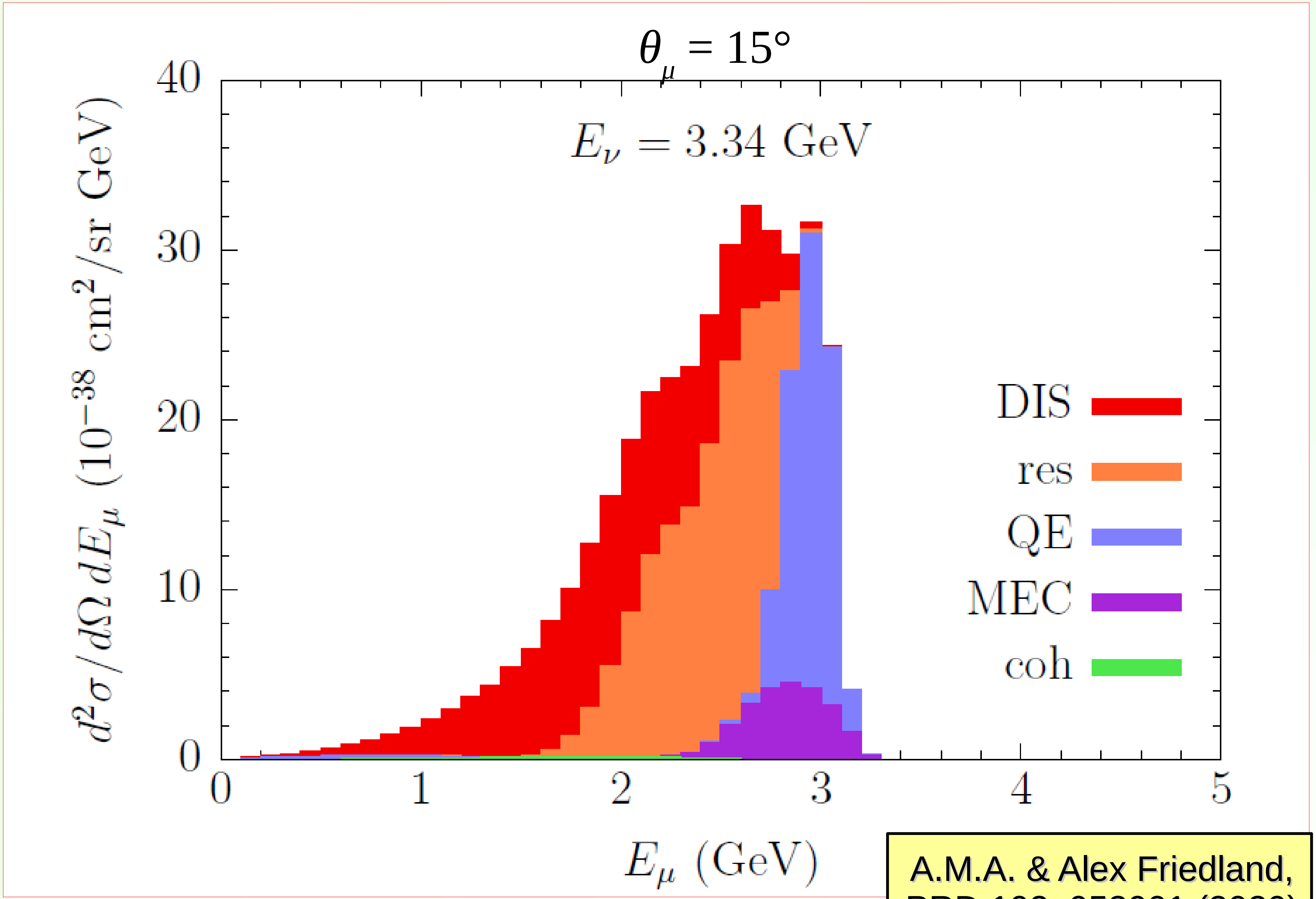
Double differential cross sections



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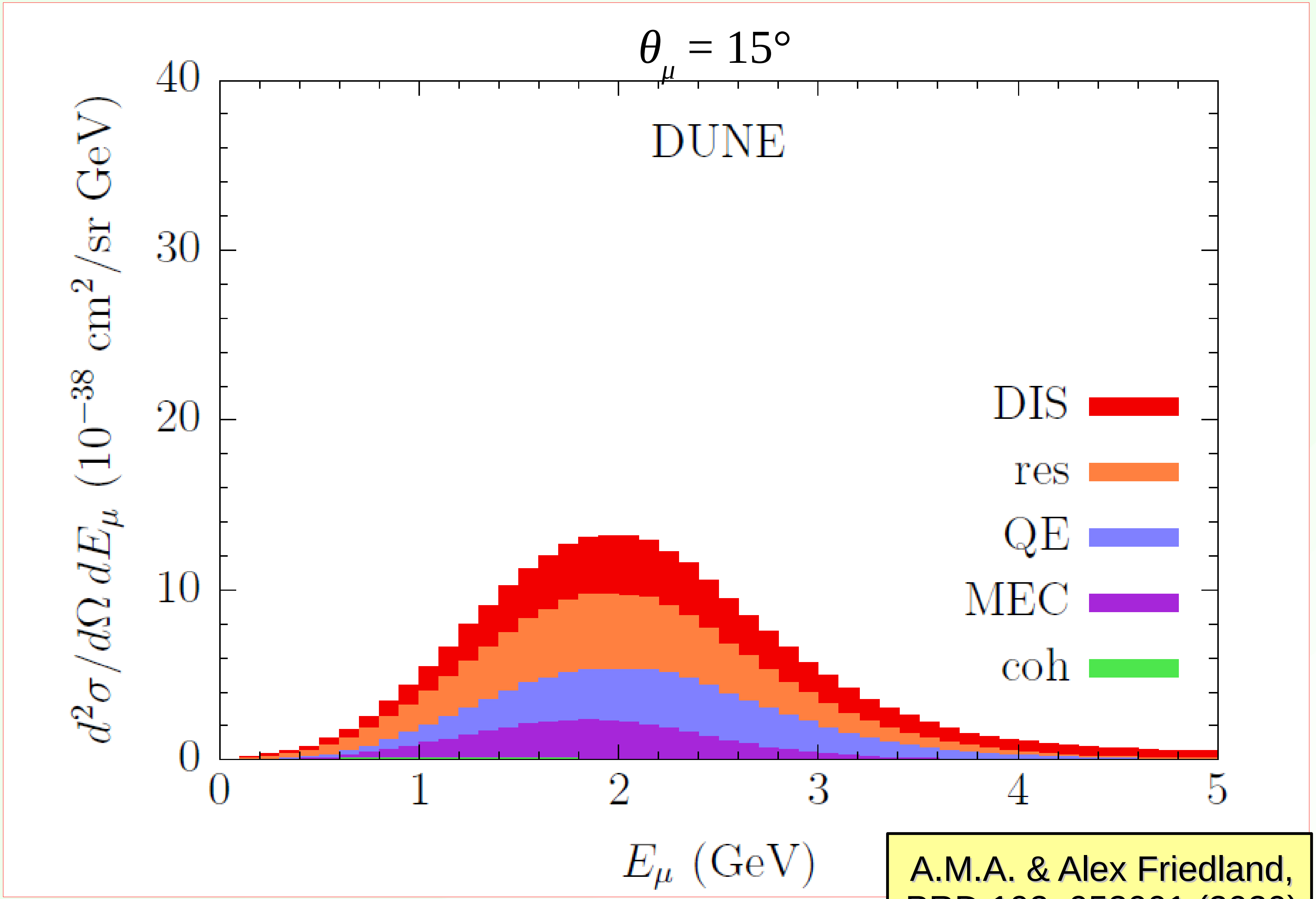
Double differential cross sections



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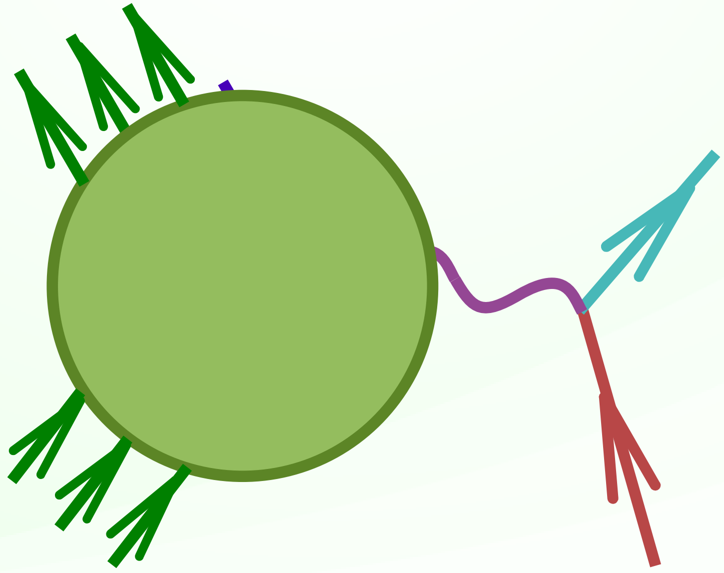
Impulse approximation

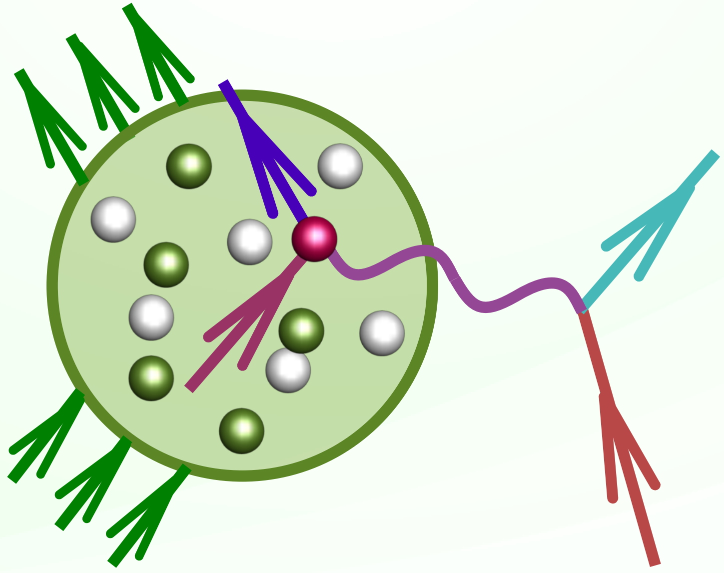
Assumption: the dominant process of lepton-nucleus interaction is **scattering off a single nucleon**, with the remaining nucleons acting as a spectator system.



Impulse approximation

Assumption: the dominant process of lepton-nucleus interaction is **scattering off a single nucleon**, with the remaining nucleons acting as a spectator system.

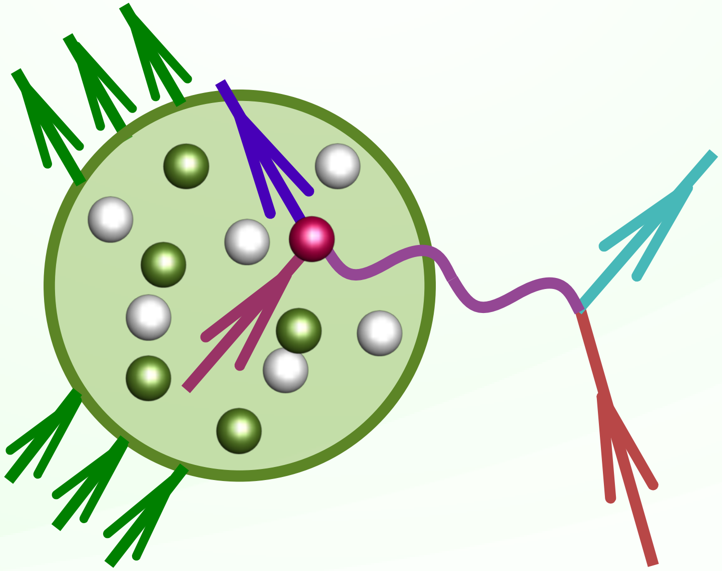
It is valid when the momentum transfer |**q**| is high enough, as the probe's spatial resolution is ~1/|**q**|.



Impulse approximation

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

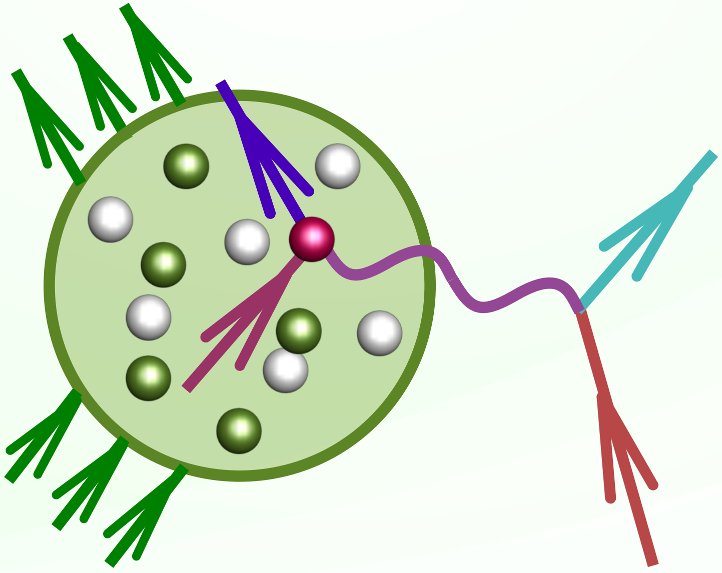
In neutrino scattering, uncertainties come from (i) nuclear effects and (ii) interaction dynamics (vector & axial contributions).



Impulse approximation

Electron-scattering data can provide information on the vector contribution to the neutrino cross sections, nuclear effects, and hadronization [*Detailed discussion in A.M.A. A. Friedland, S. W. Li, O. Moreno, P. Schuster, N. Toro & N. Tran,* PRD 101, 053004 (2020)].

It is **highly improbable** that theoretical approaches unable to reproduce *(e,e')* data would describe nuclear effects in neutrino interactions at similar kinematics.



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:

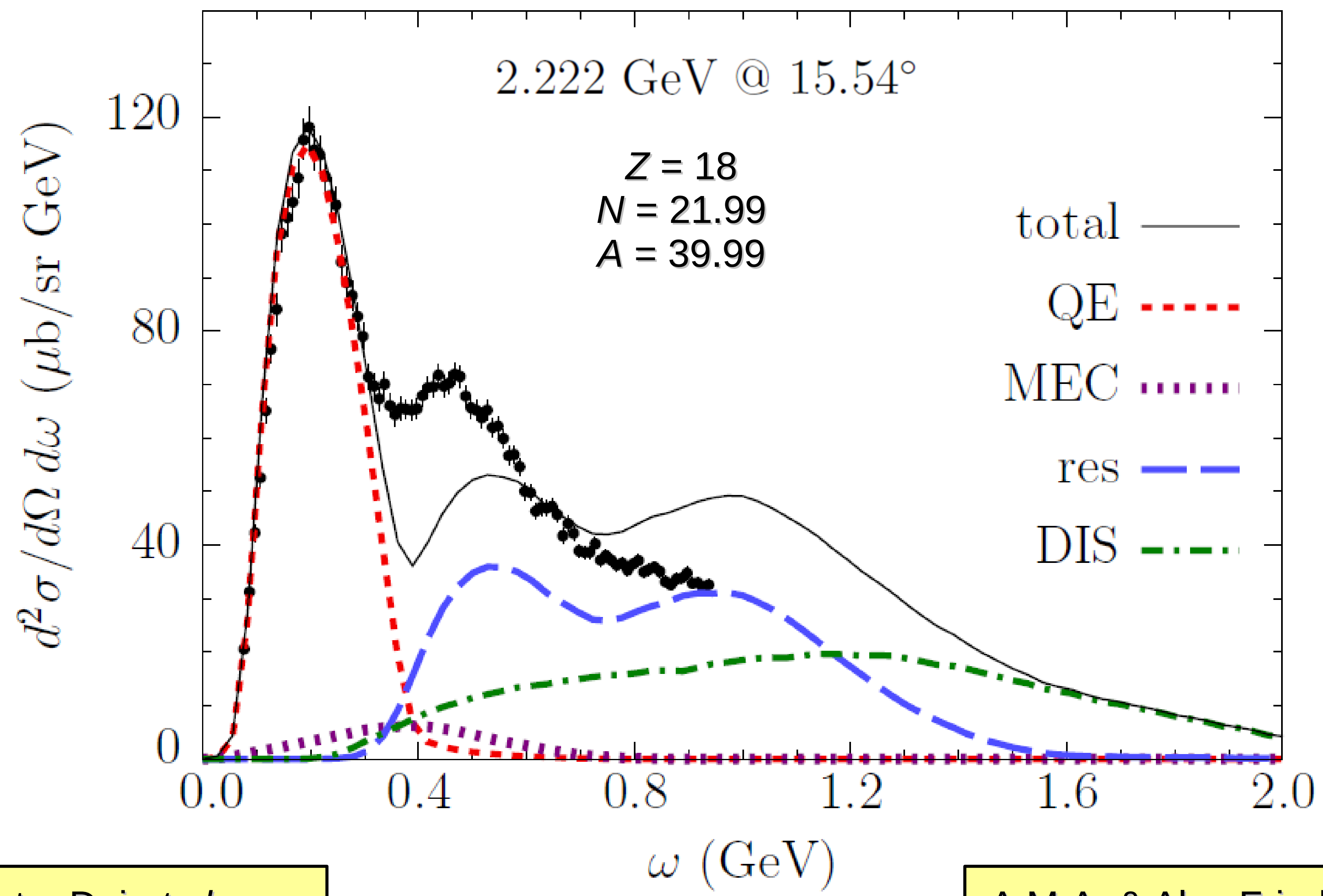
"The GENIE Collaboration shall provide electron-nucleus, hadron-nucleus and nucleon decay generators in the **same physics framework** as the neutrino-nucleus generator."

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

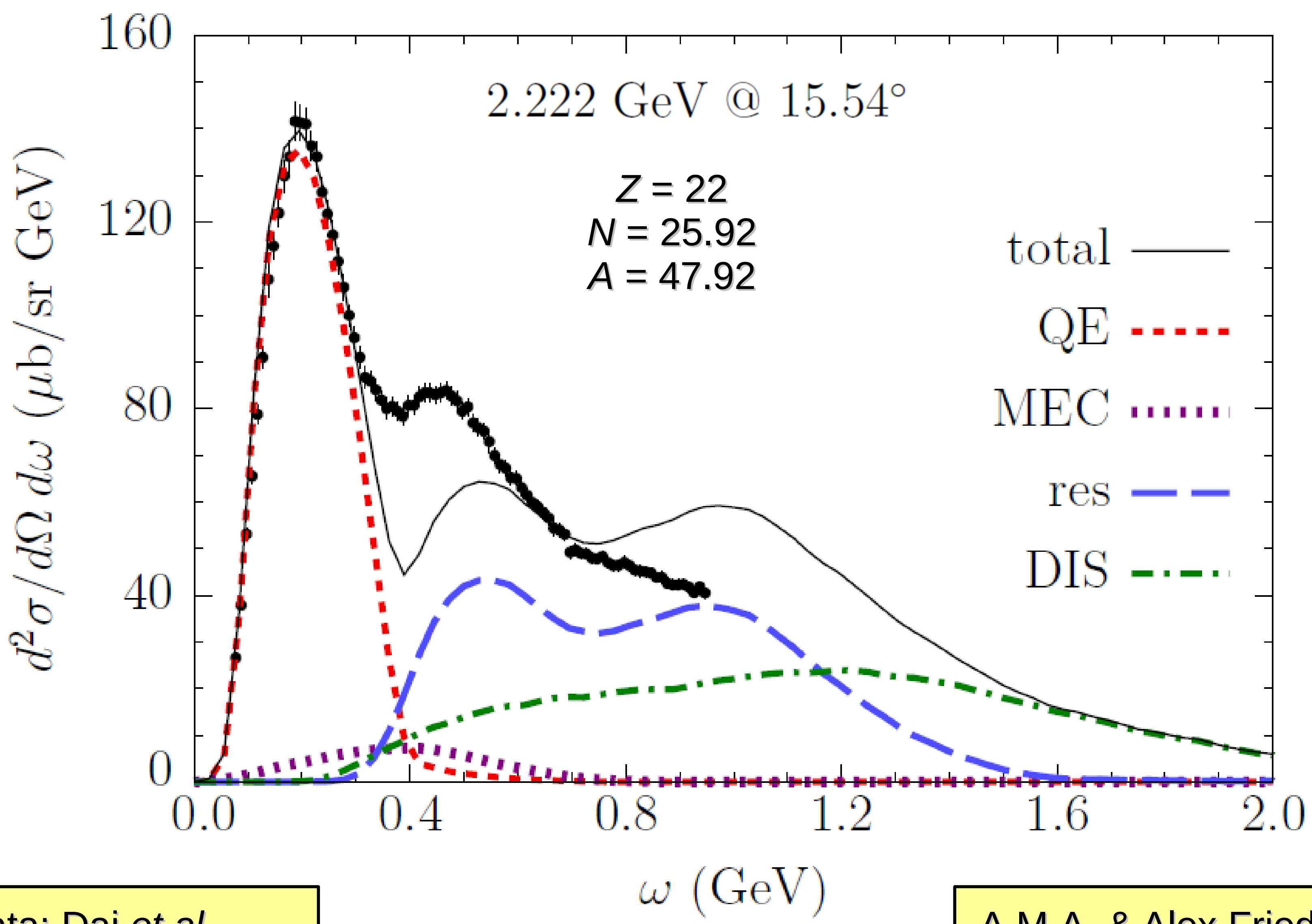
Ar(e, e') in GENIE



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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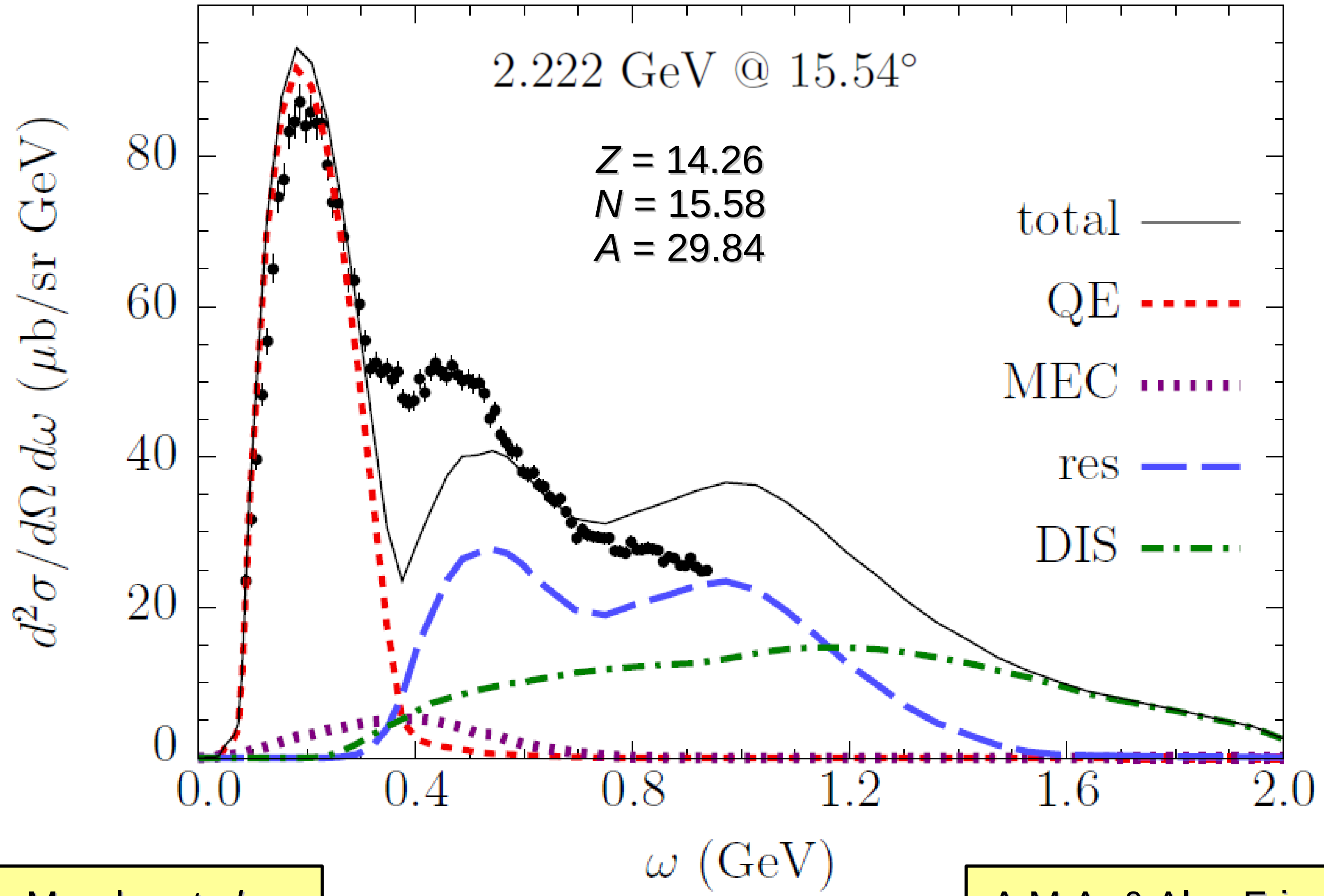
Al-7075(*e*, *e*’) in GENIE



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

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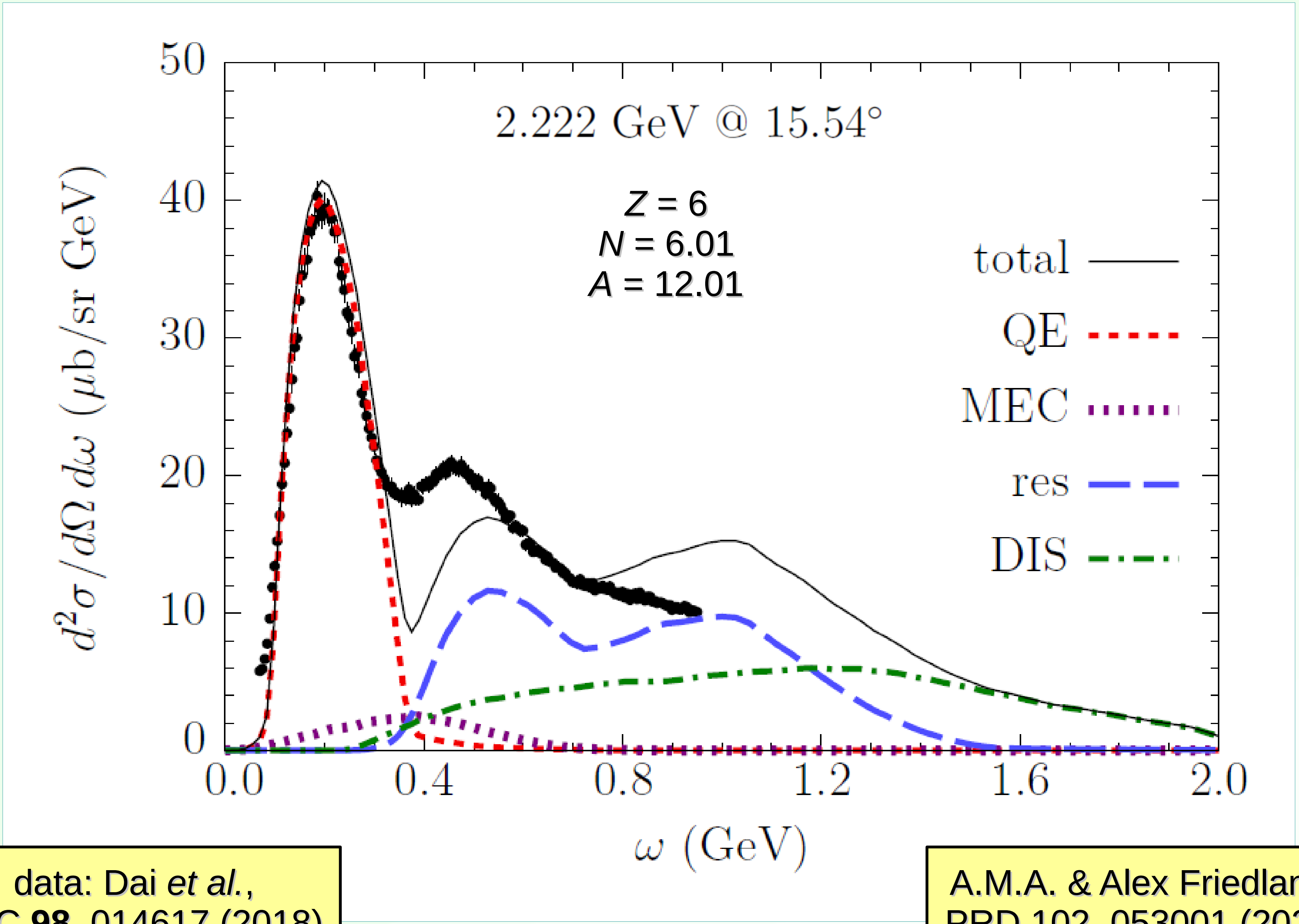
C(*e*, *e*’) in GENIE



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

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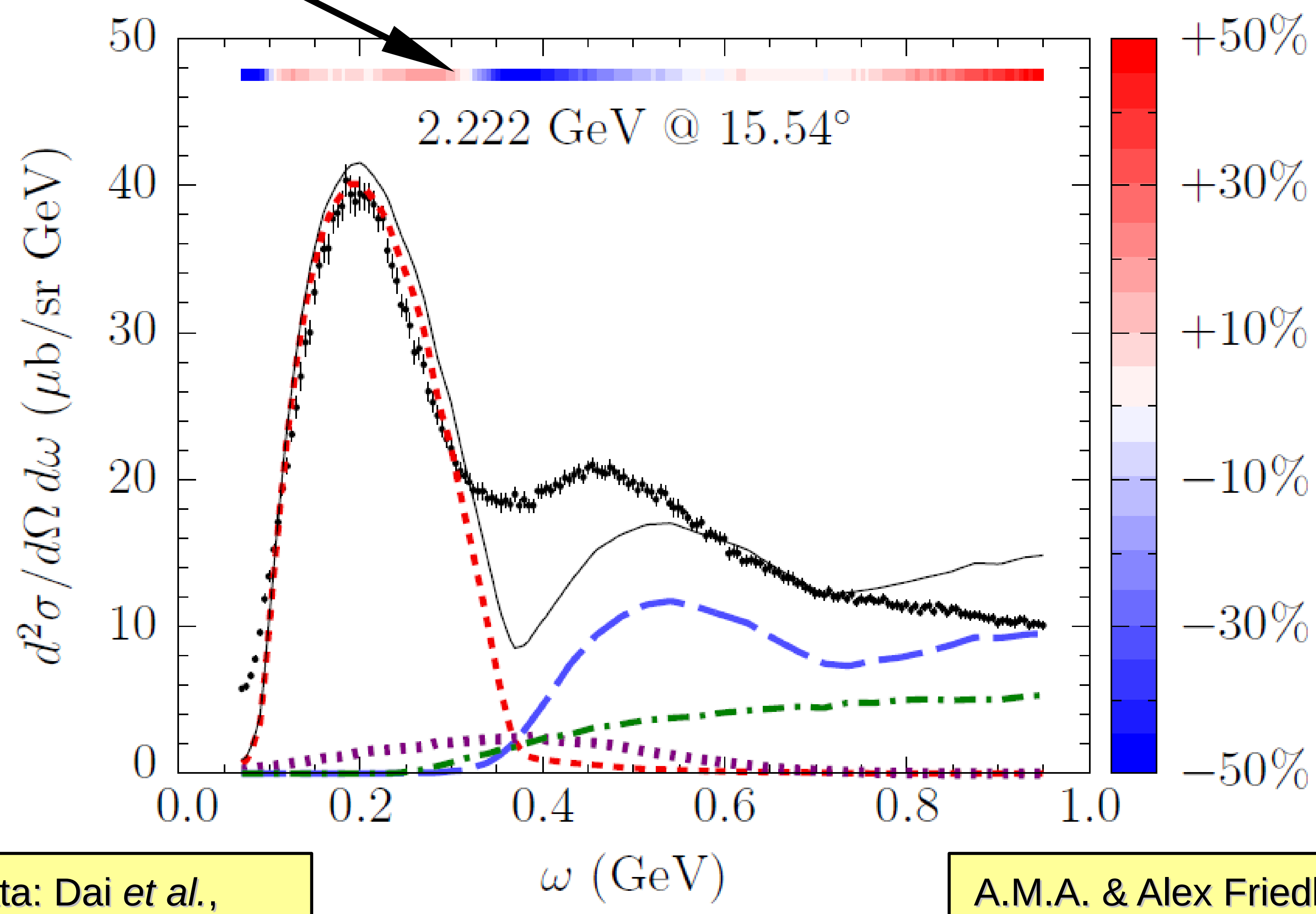
C(*e*, *e*’) in GENIE

GENIE – data
data



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

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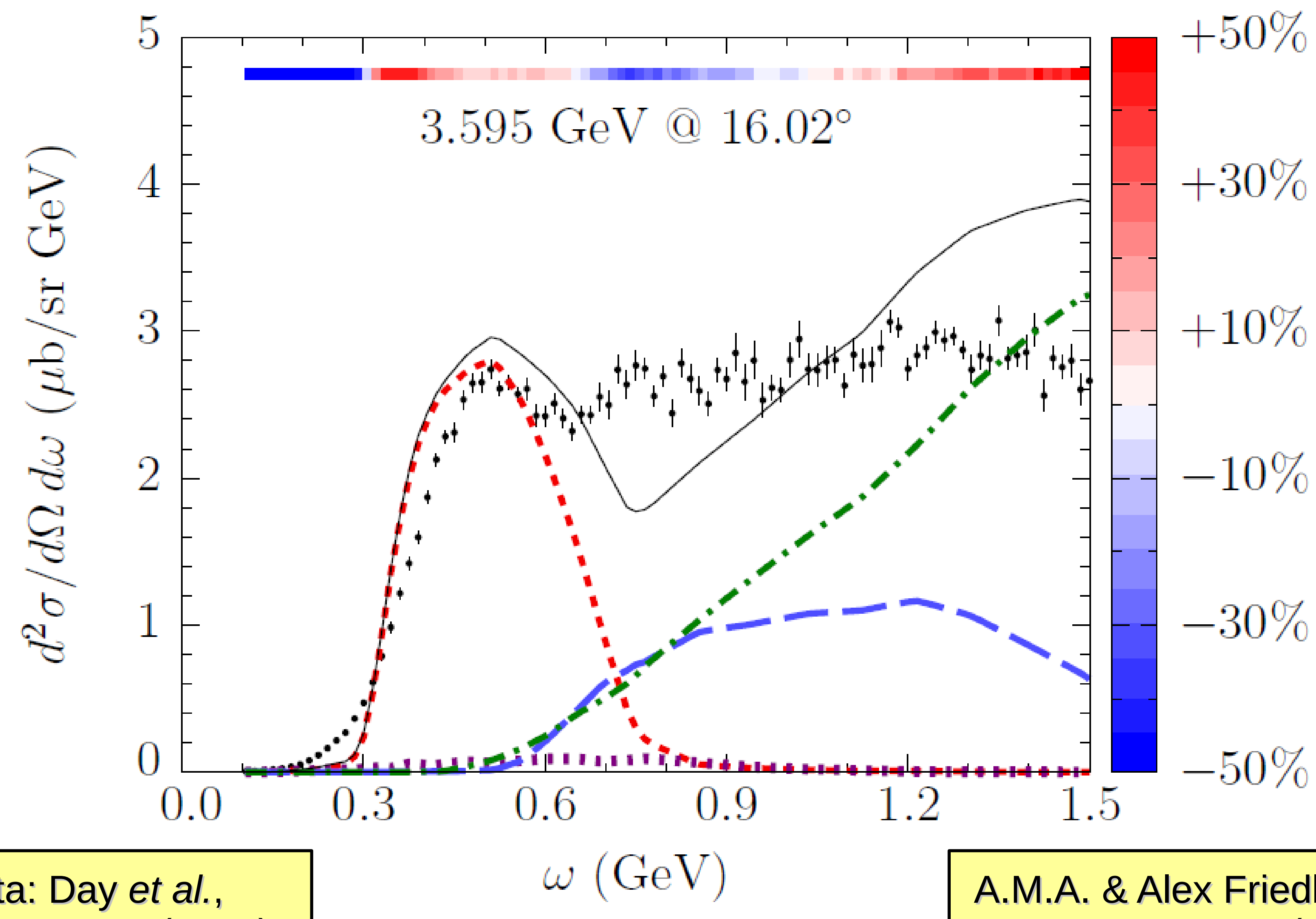
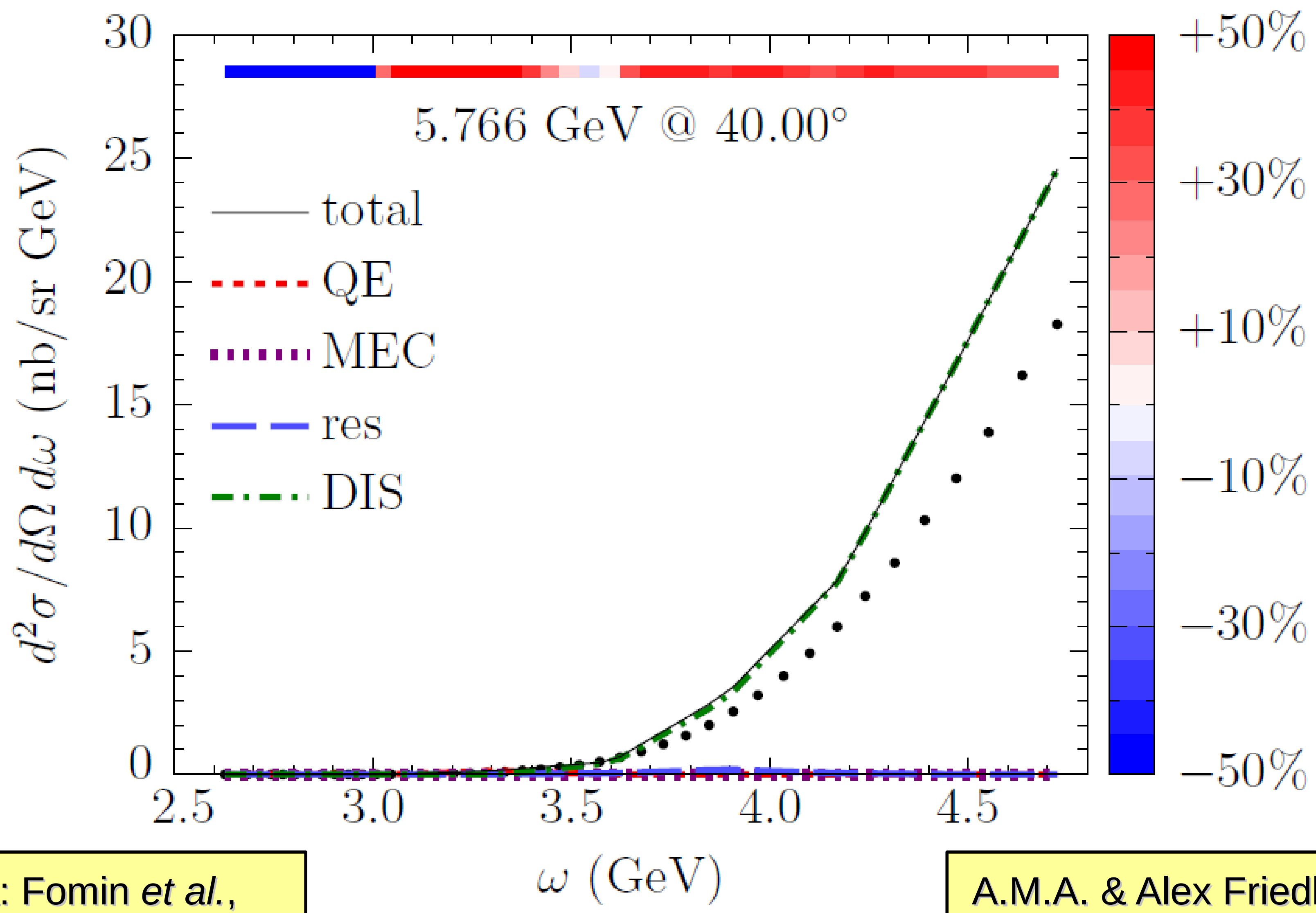
C(*e*, *e*’) in GENIE



data: Day *et al.*,
PRD **48**, 1849 (1993)

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

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



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

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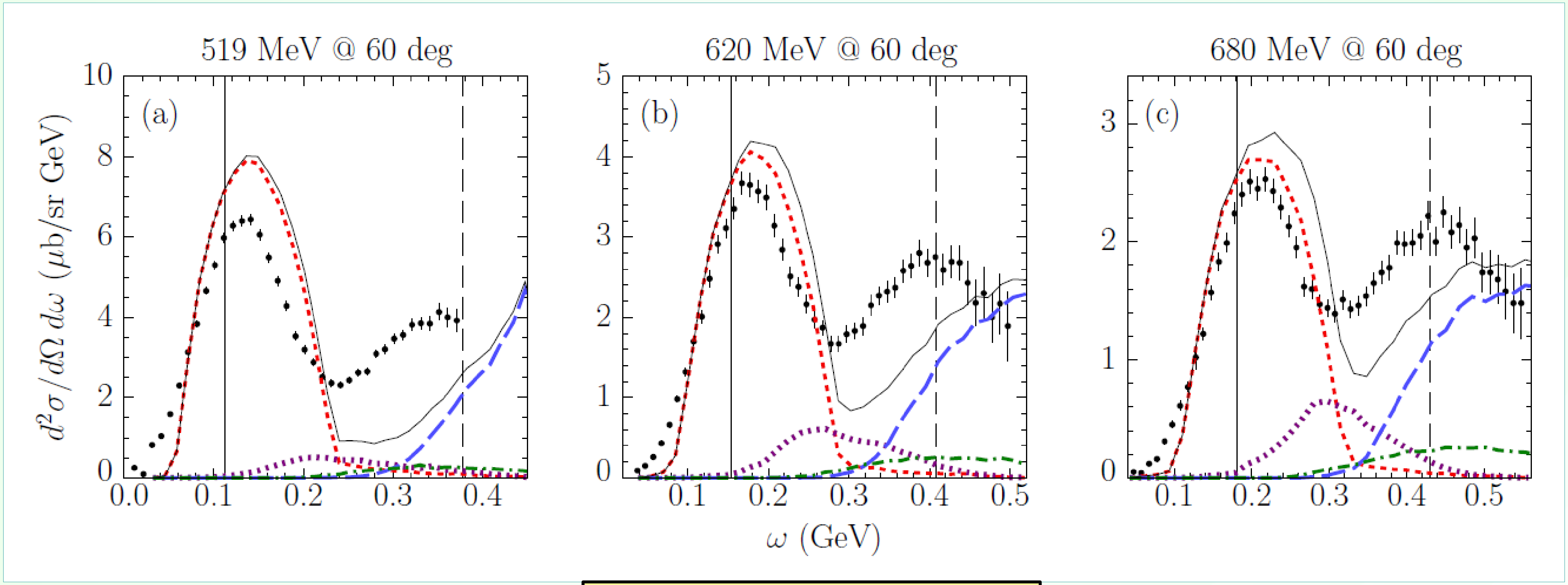
C(*e*, *e*’) in GENIE



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

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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

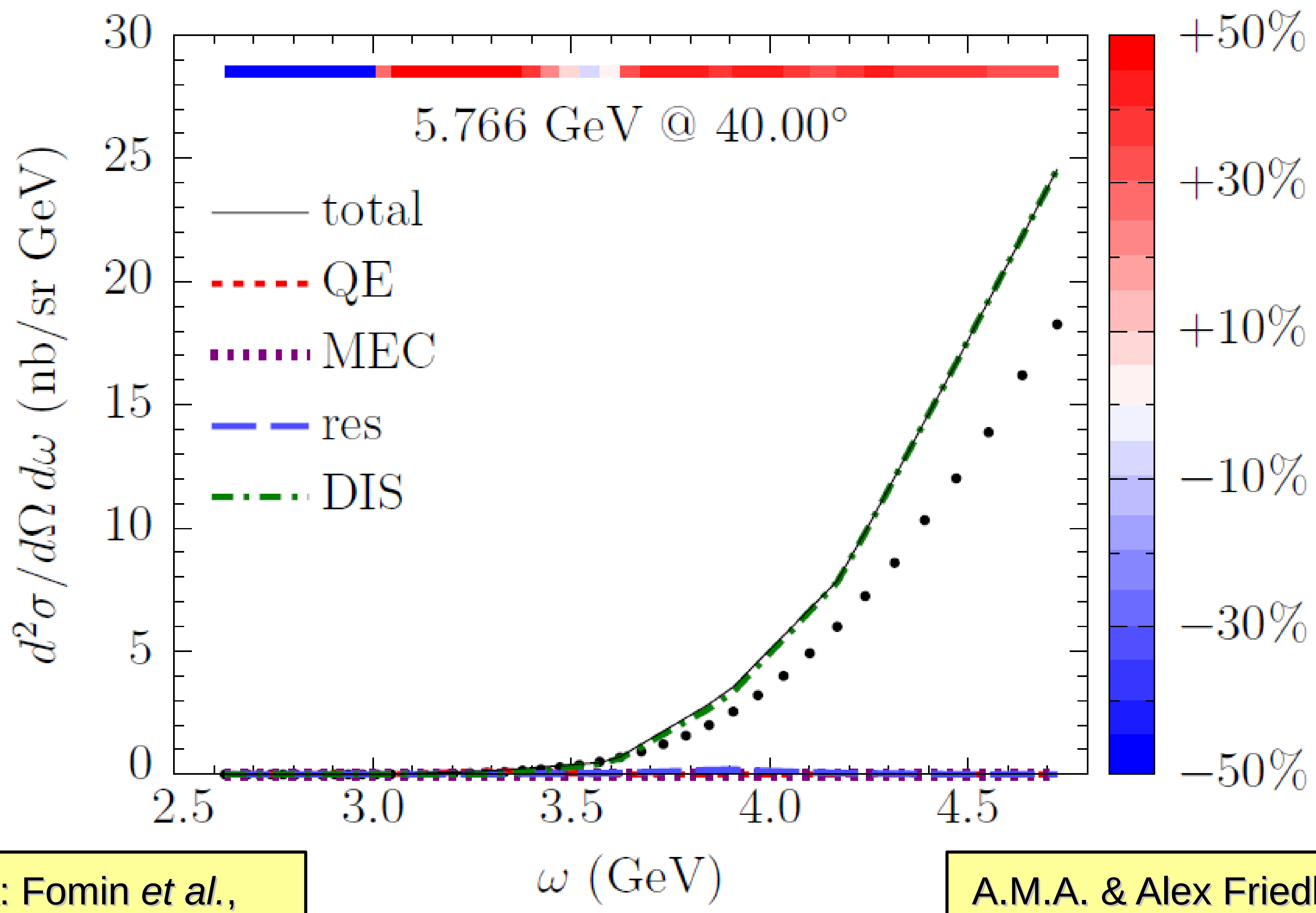
- **Delta peak** position is not correct, strength underestimated

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

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

What’s the origin of these issues?

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



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

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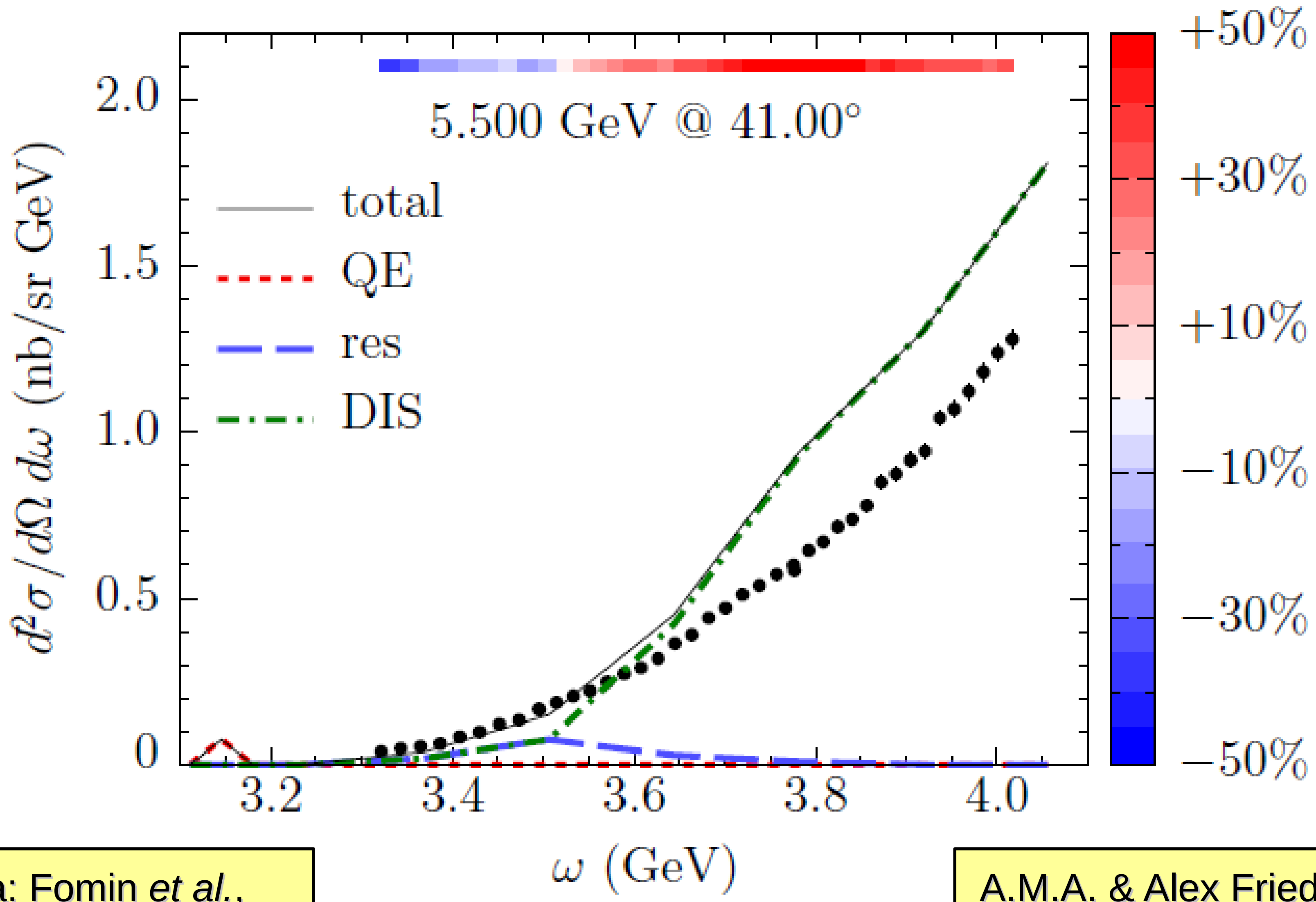
D(*e*, *e*’) in GENIE



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

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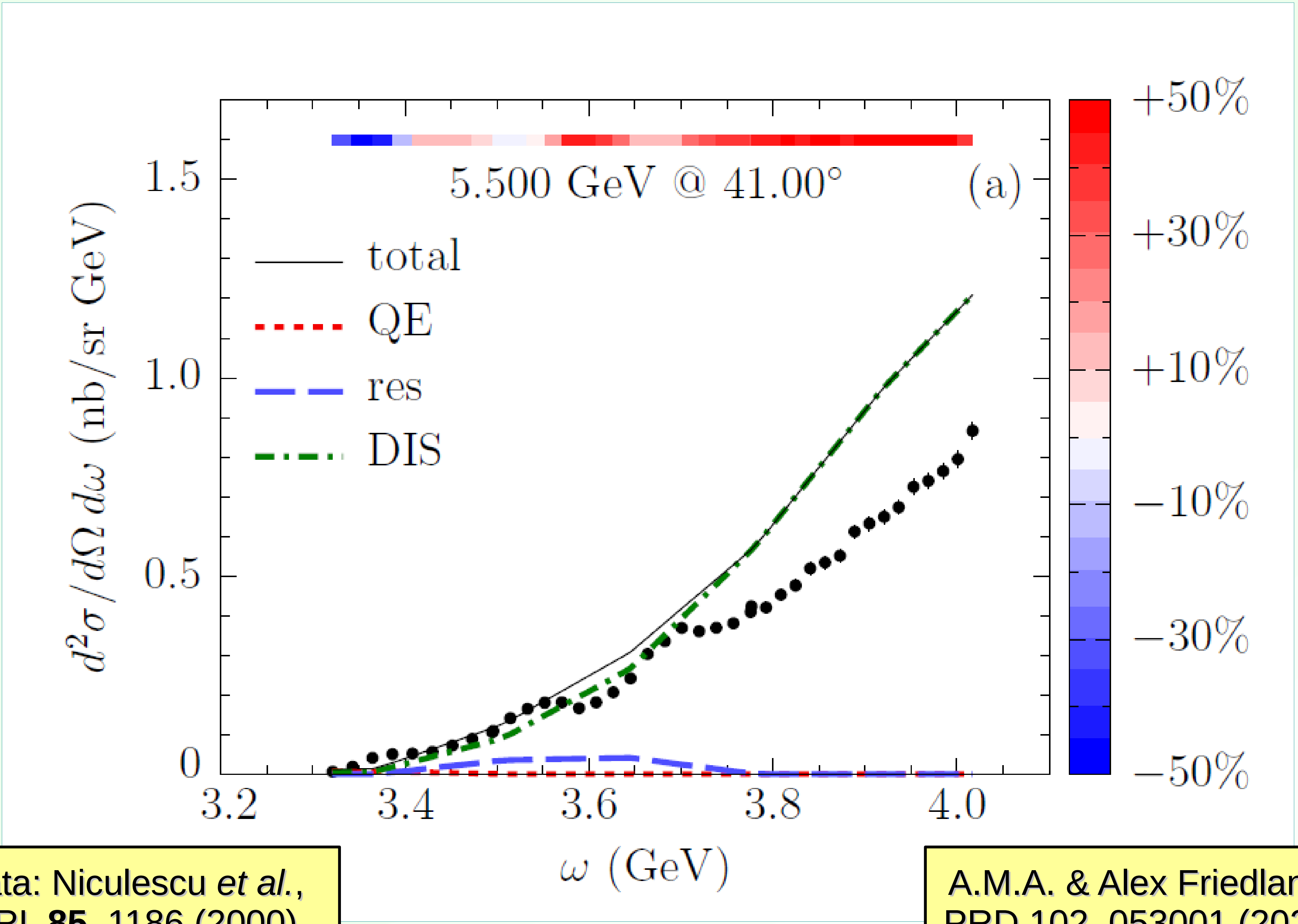
H(*e*, *e*’) in GENIE



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

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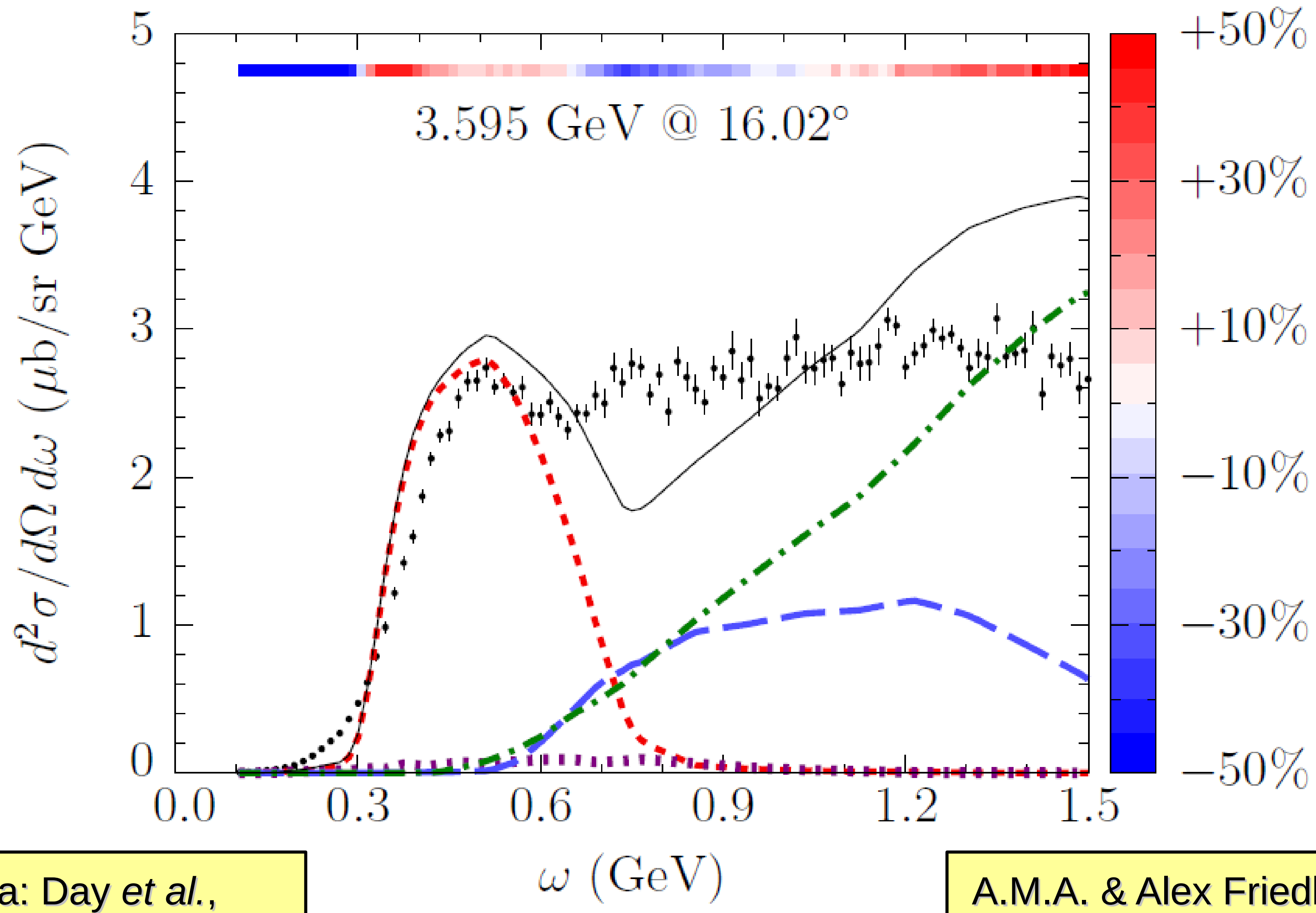
C(*e*, *e*’) in GENIE



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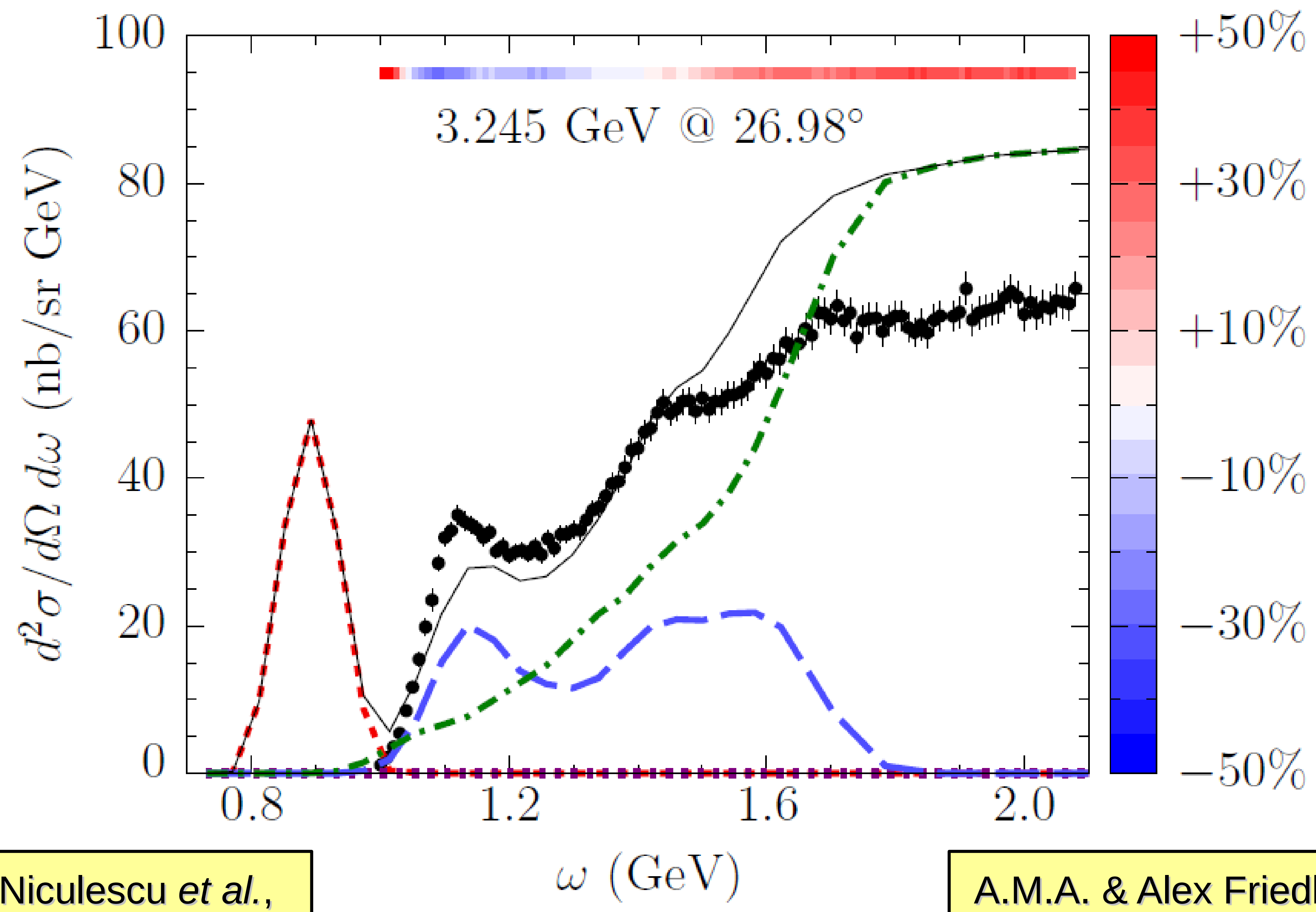
D(*e*, *e*’) in GENIE



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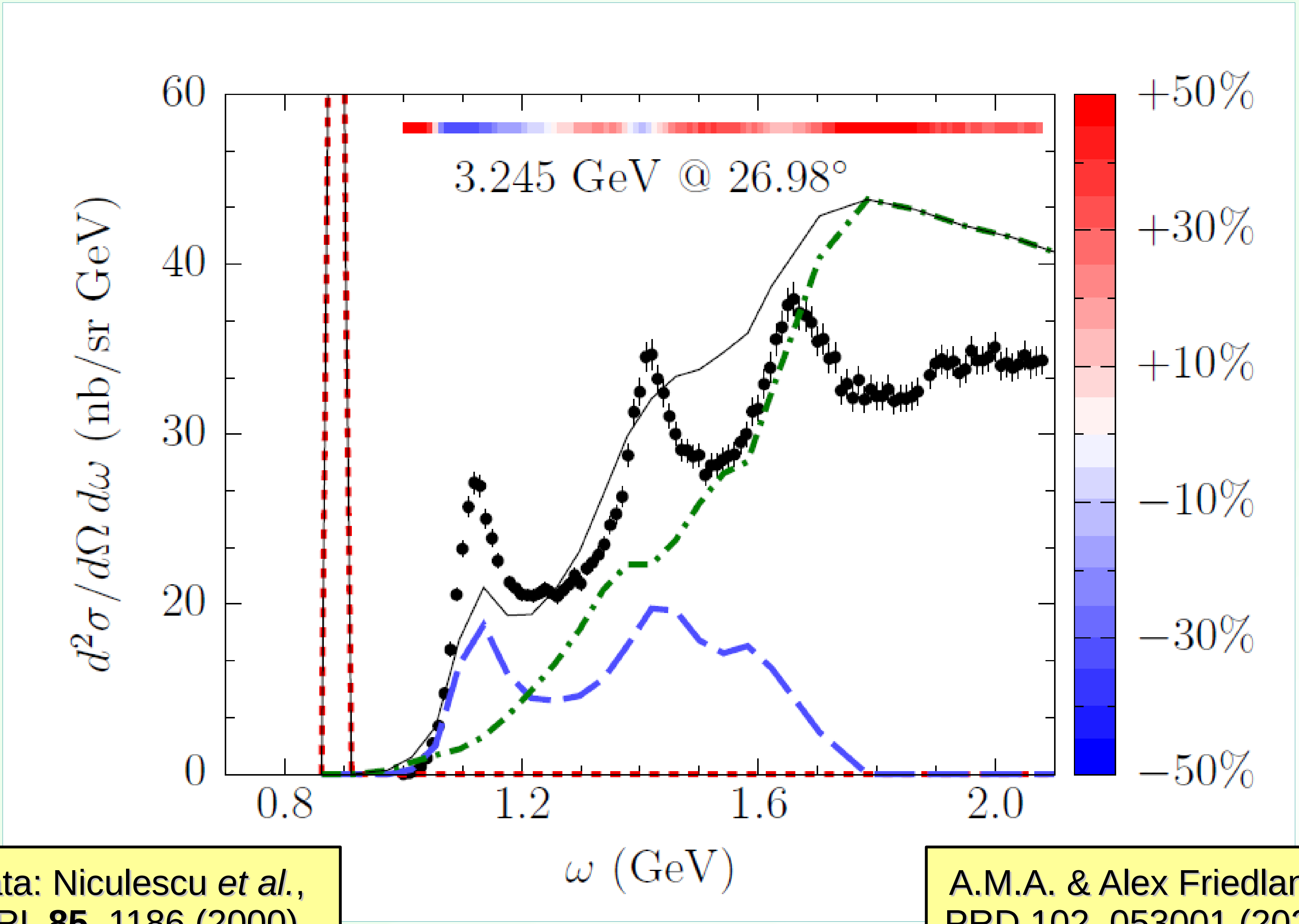

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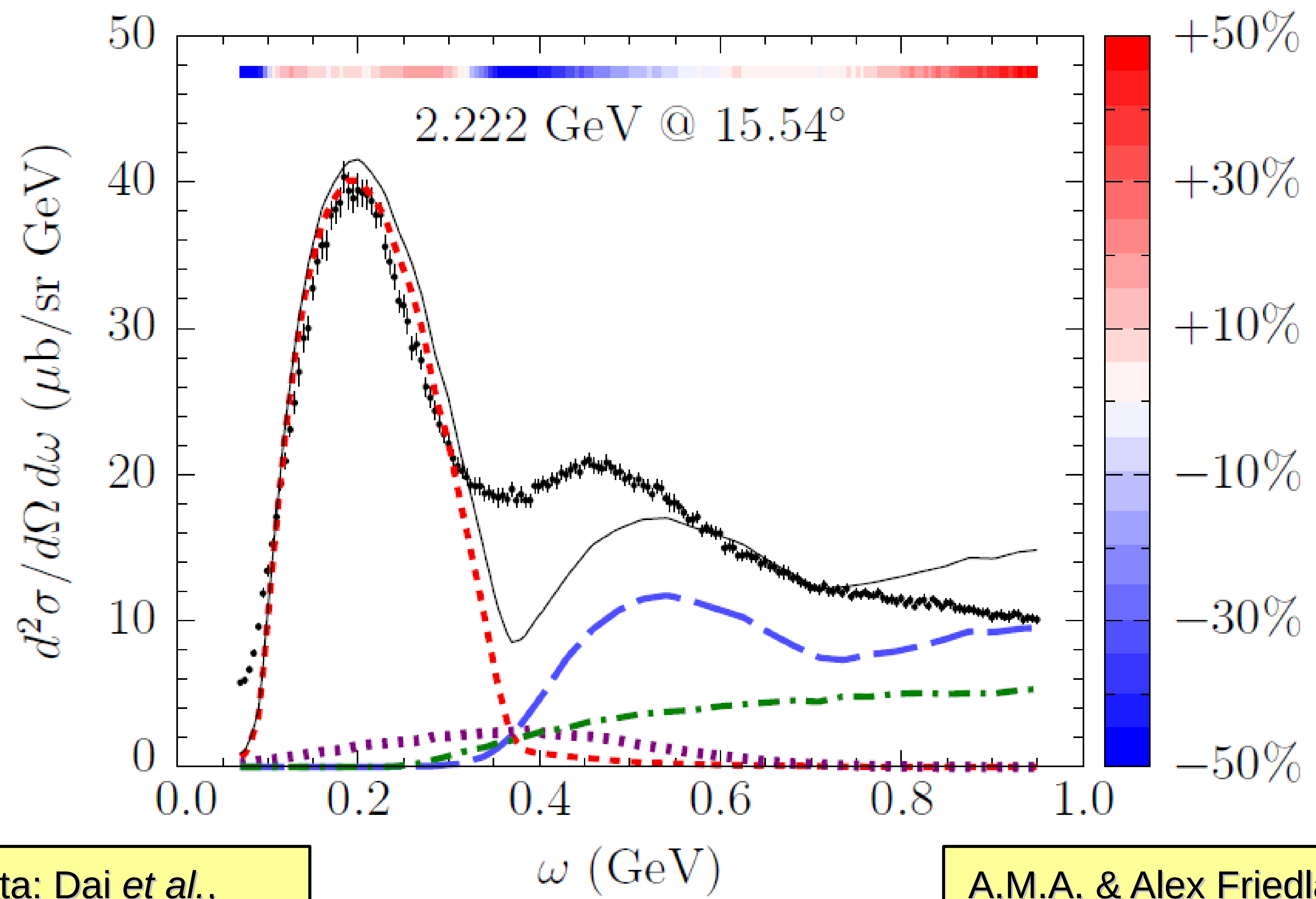

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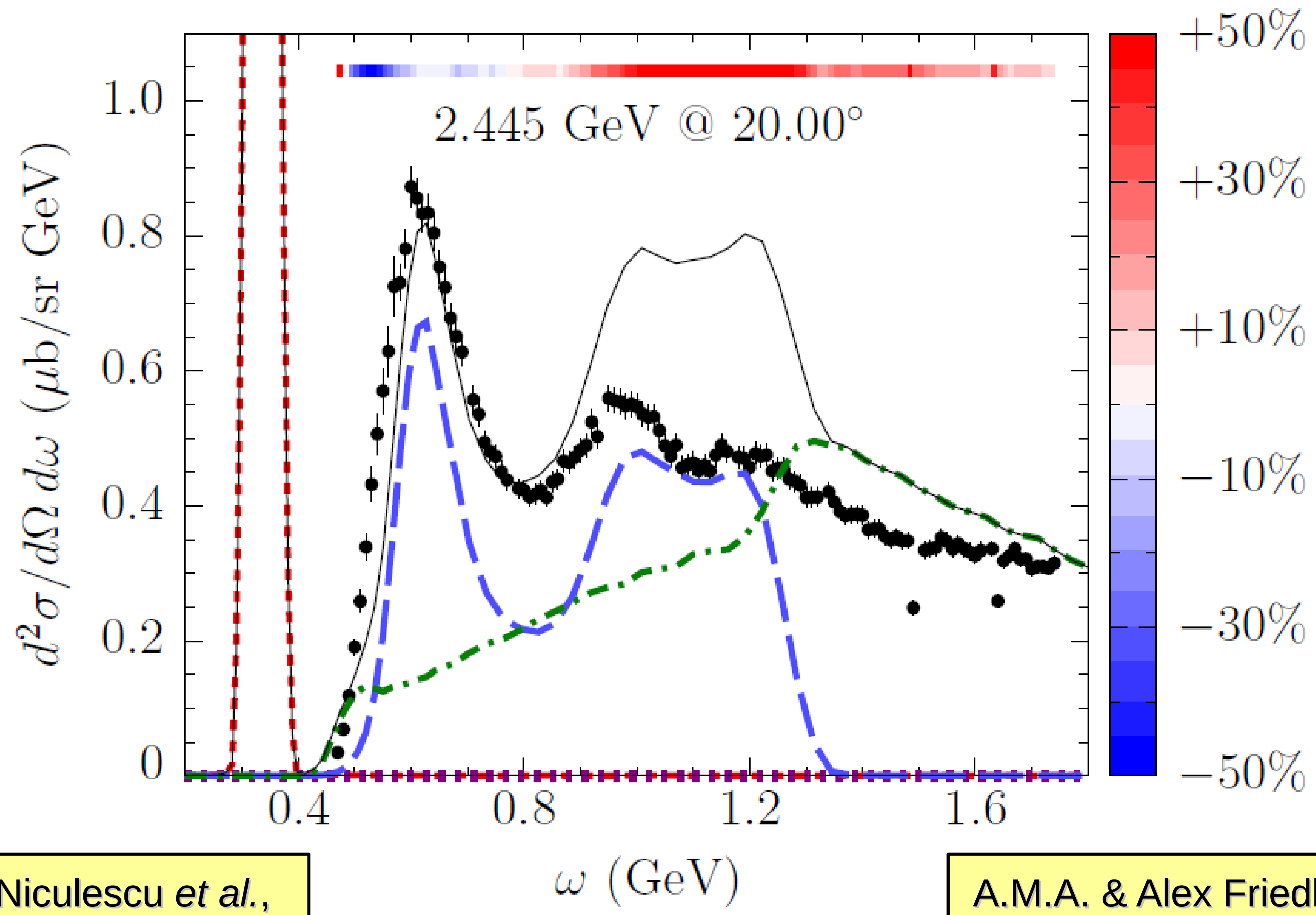

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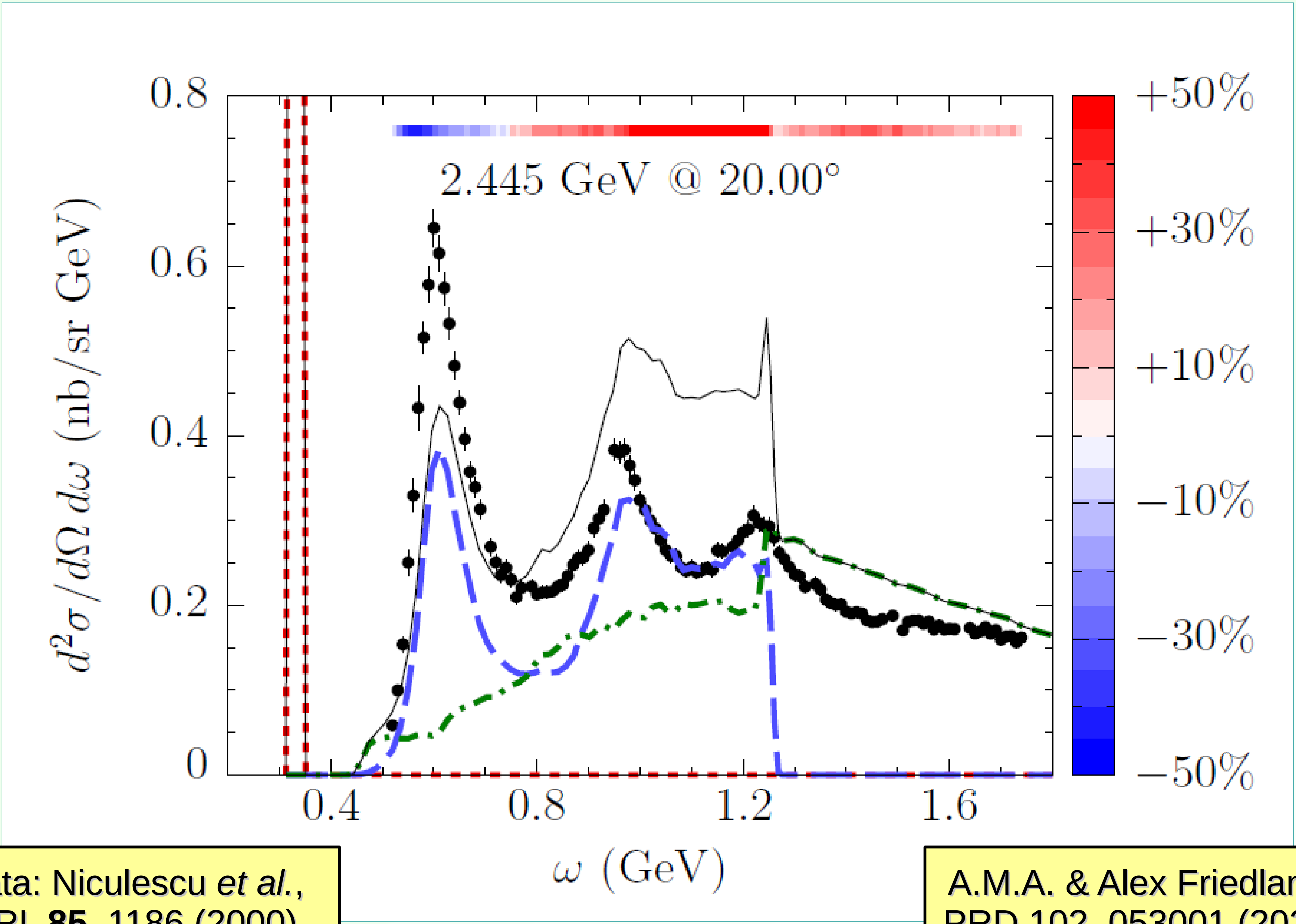
H(*e*, *e*’) in GENIE



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

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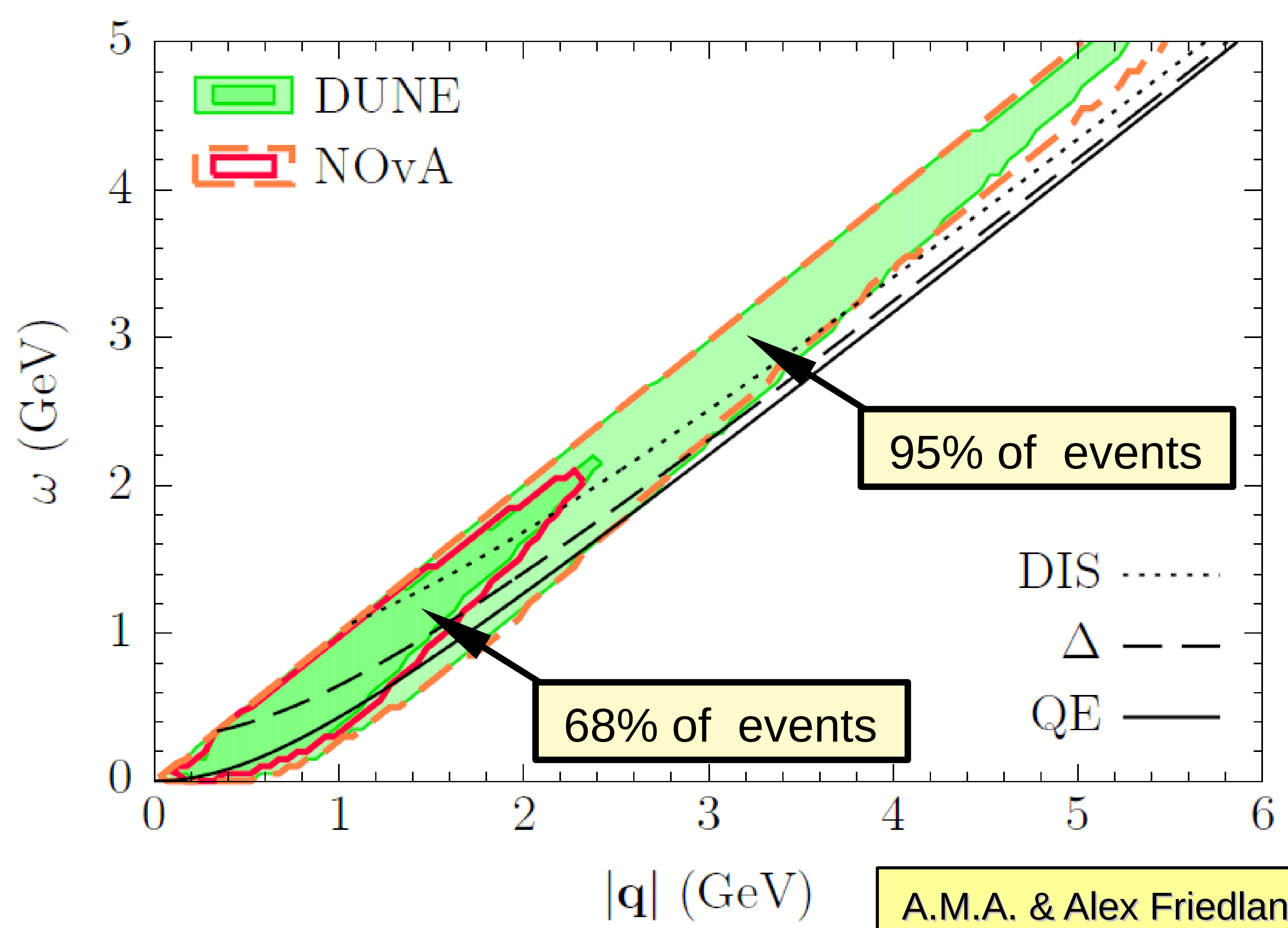
Are these issues general?

DUNE vs. NOvA



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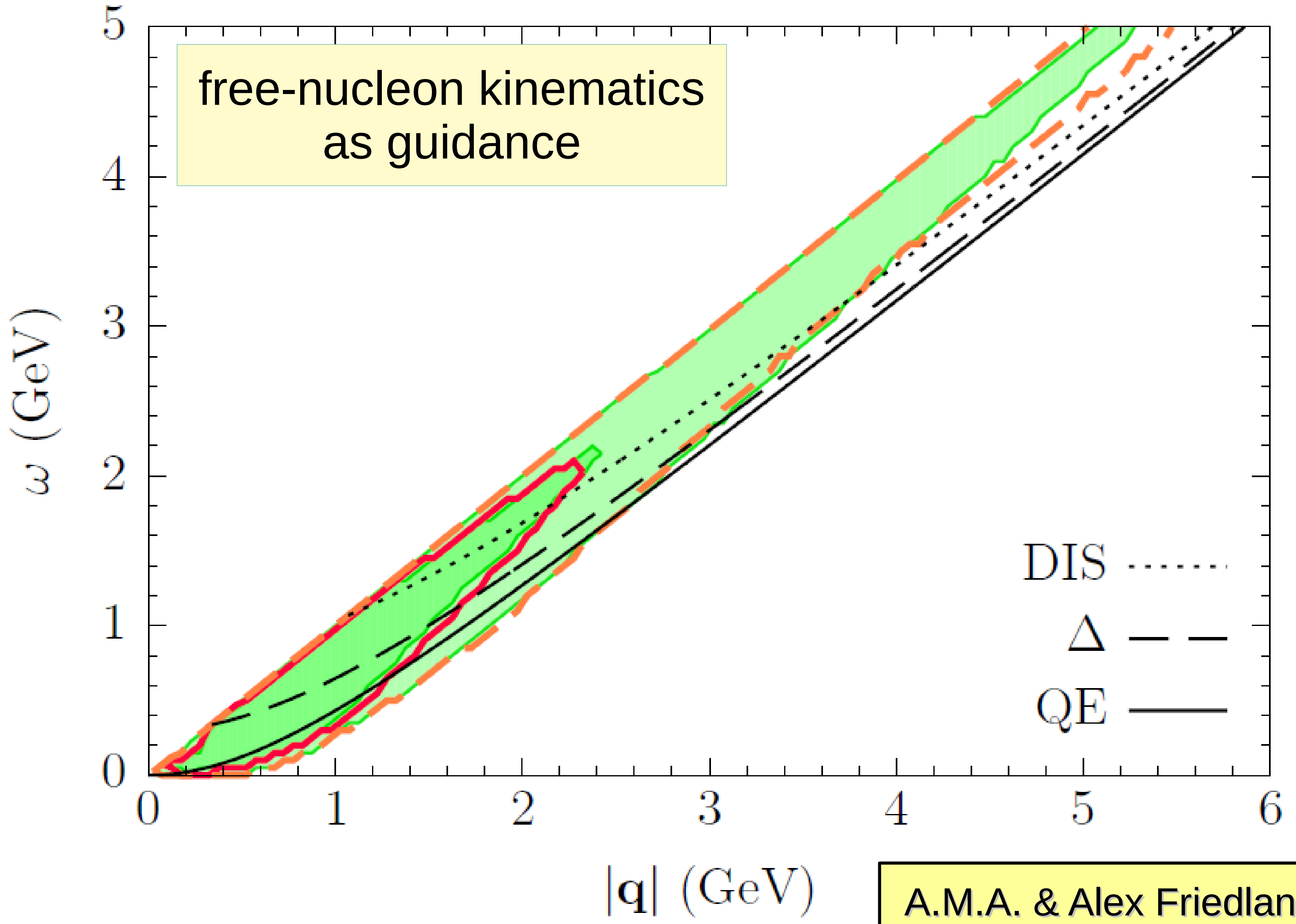
DUNE vs. NOvA



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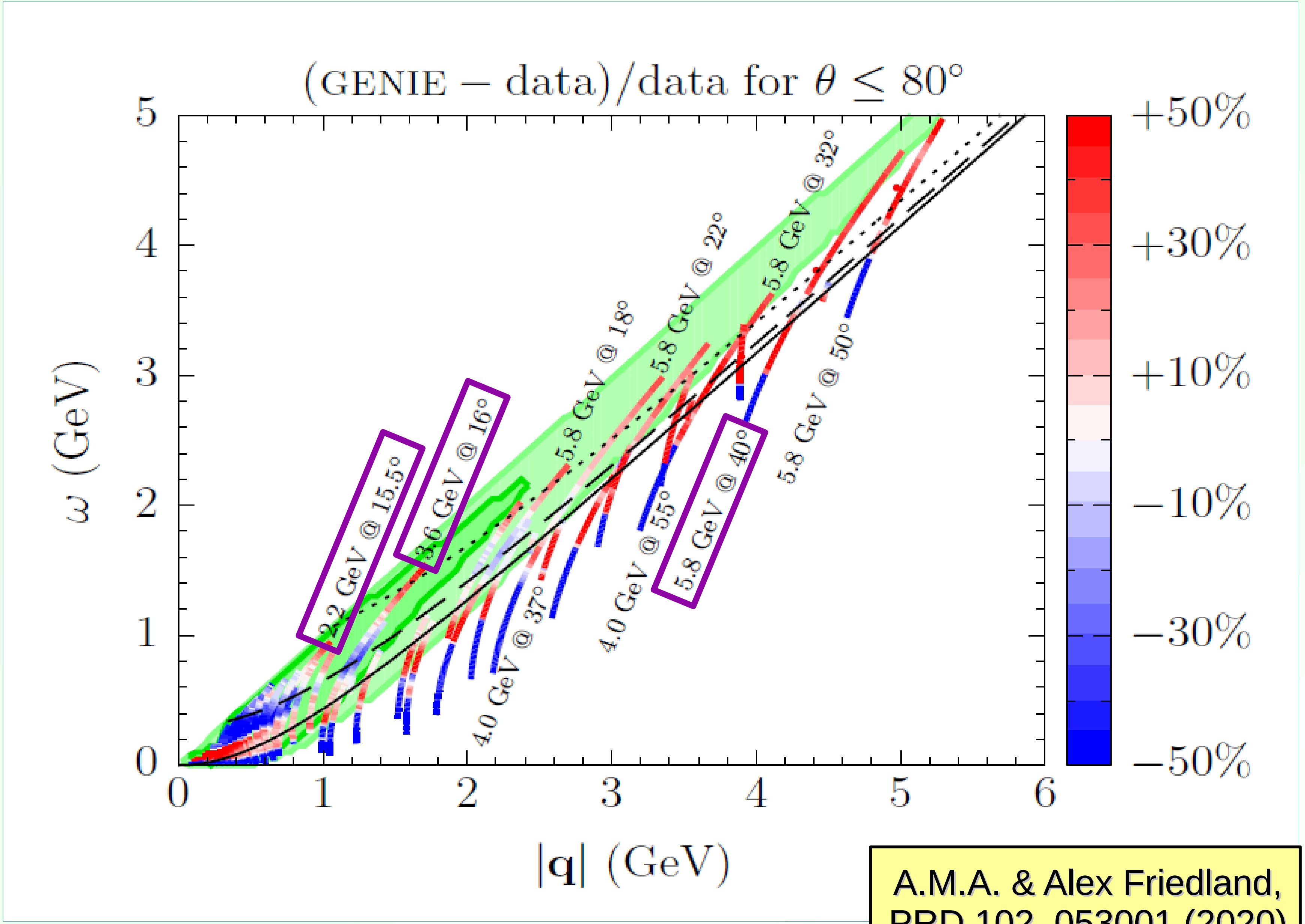
C(*e*, *e'*) in GENIE



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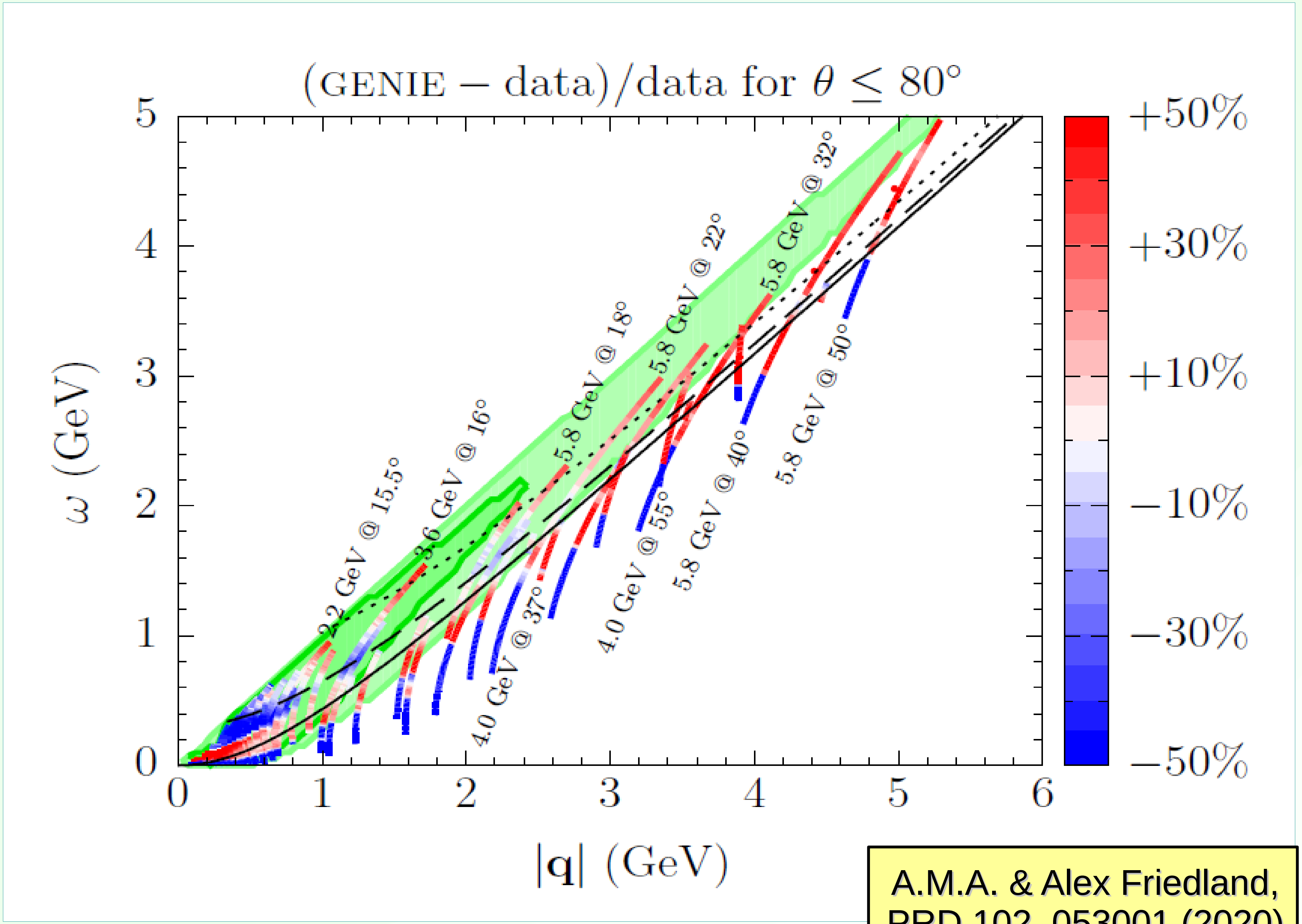

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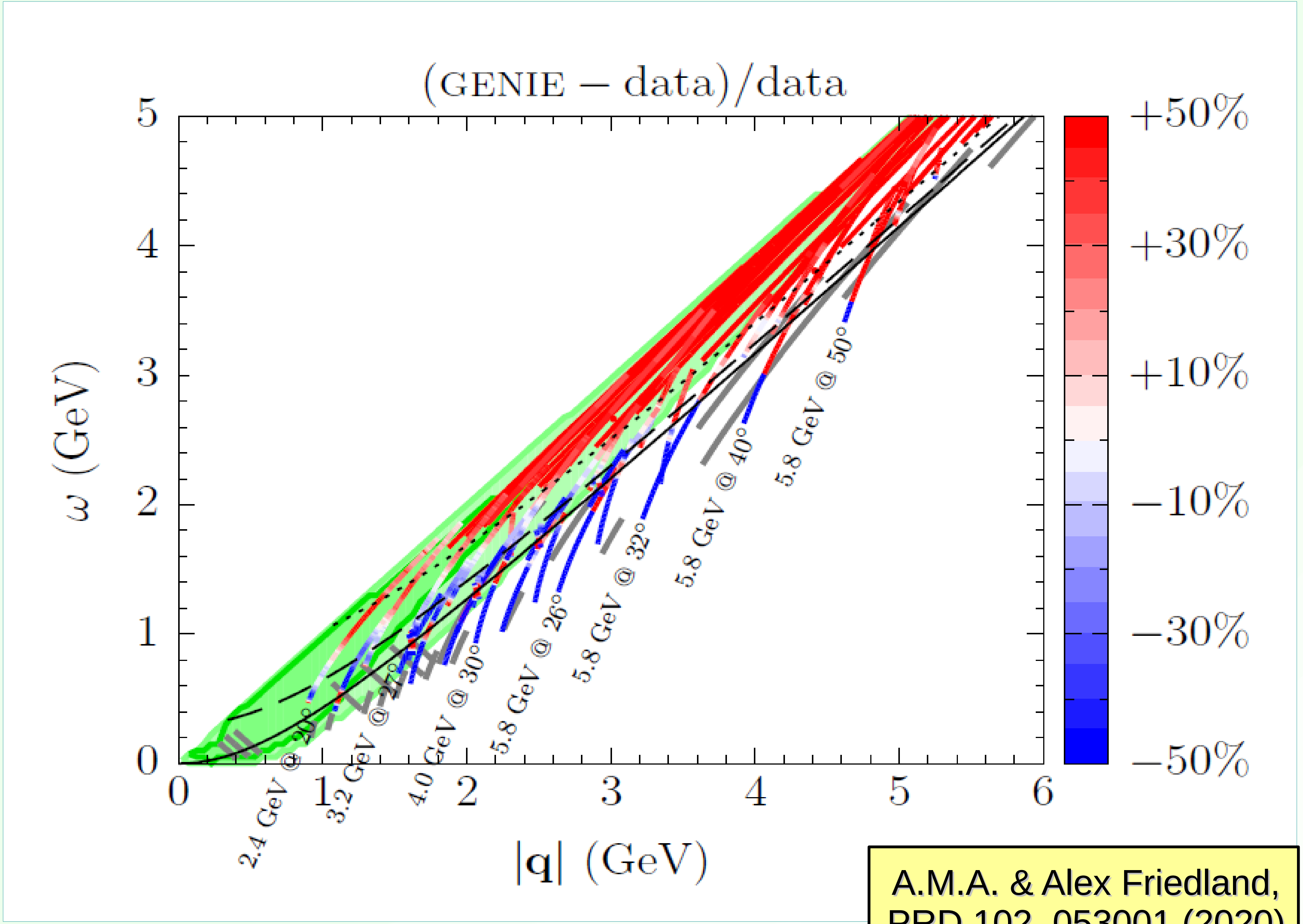

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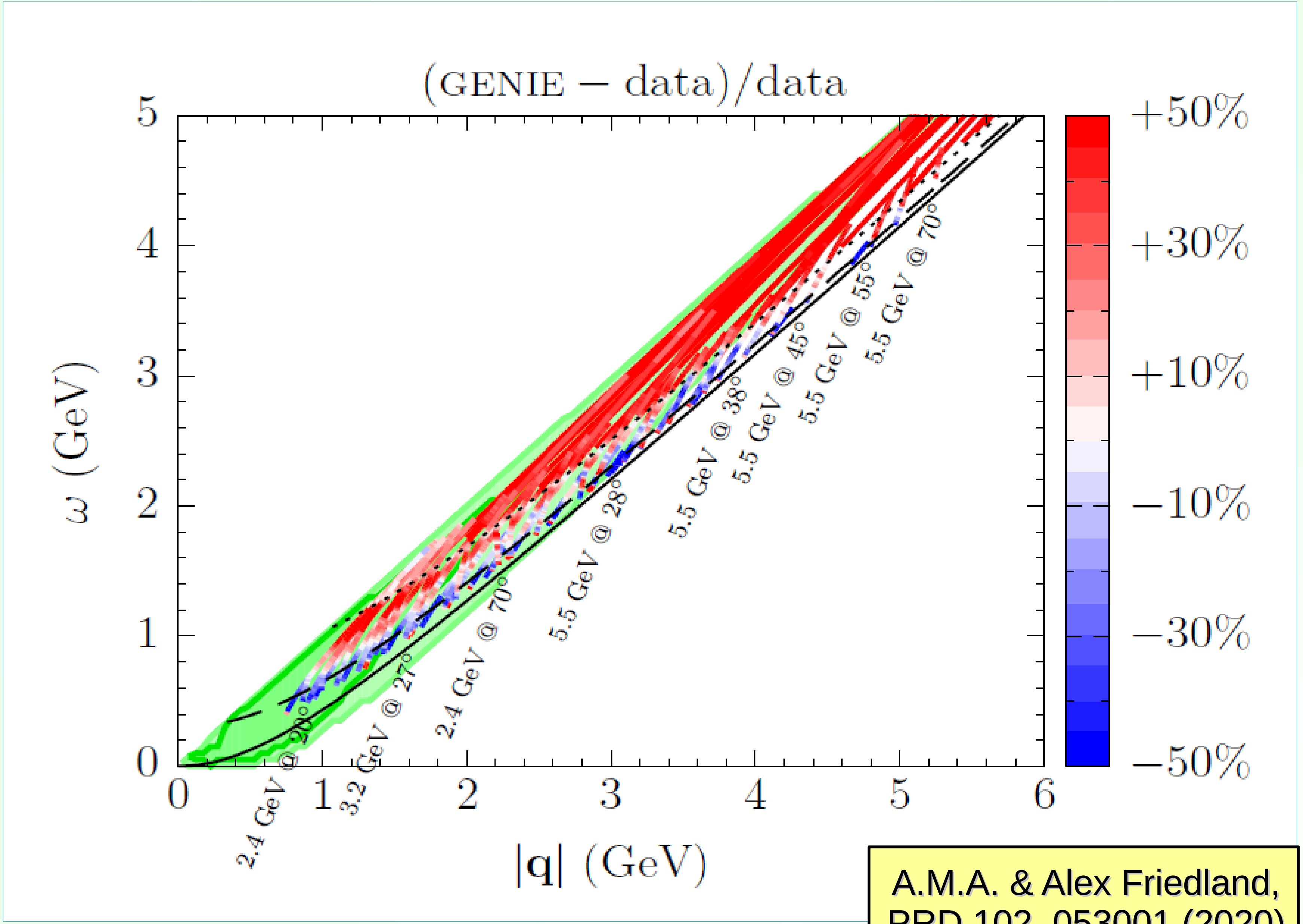

A.M.A. & Alex Friedland, PRD 102, 053001 (2020)

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.