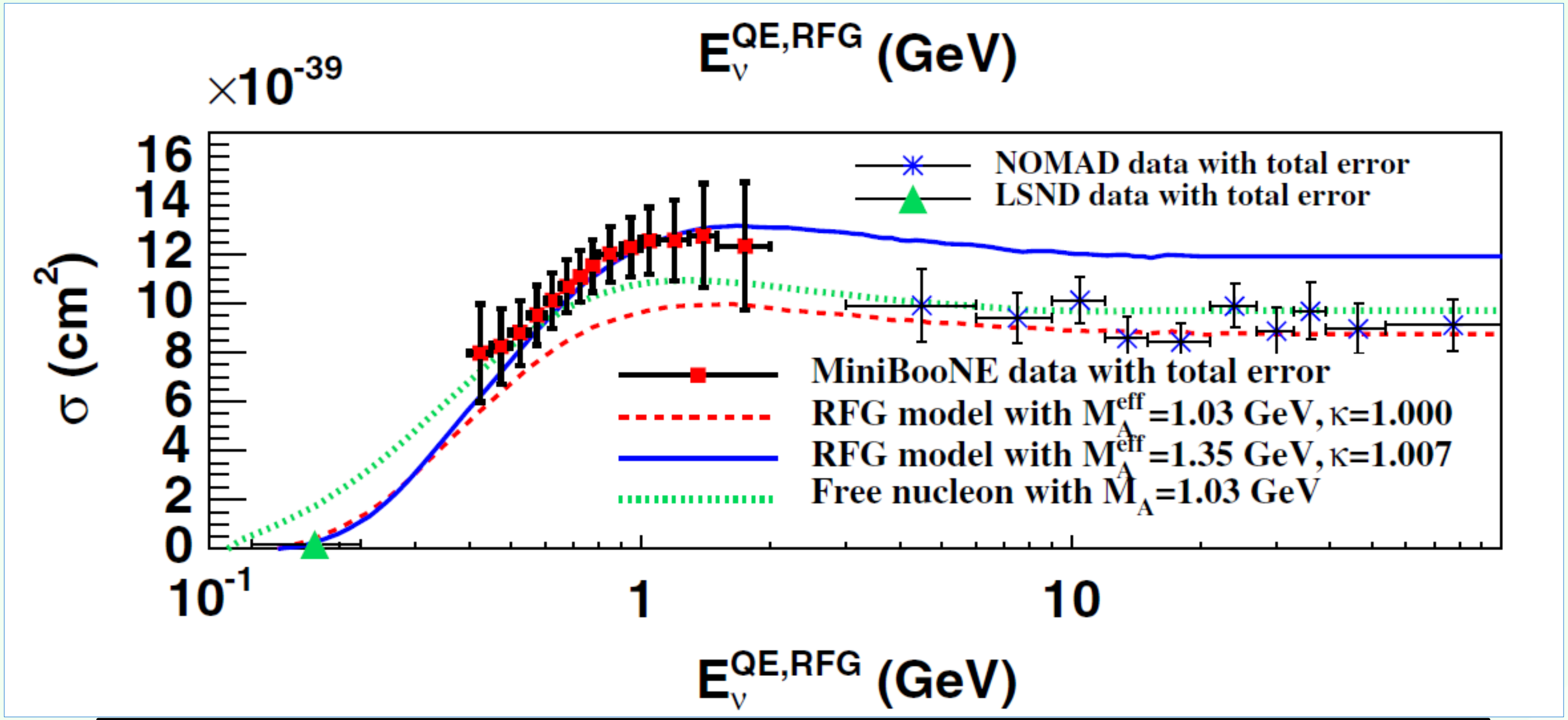
# Assessing the accuracy of GENIE with electron-scattering data

**Artur M. Ankowski**

**based on**
**A. M. A. and Alexander Friedland, arXiv:2006.11944**

**SLACmass neutrino meeting, July 1, 2020**

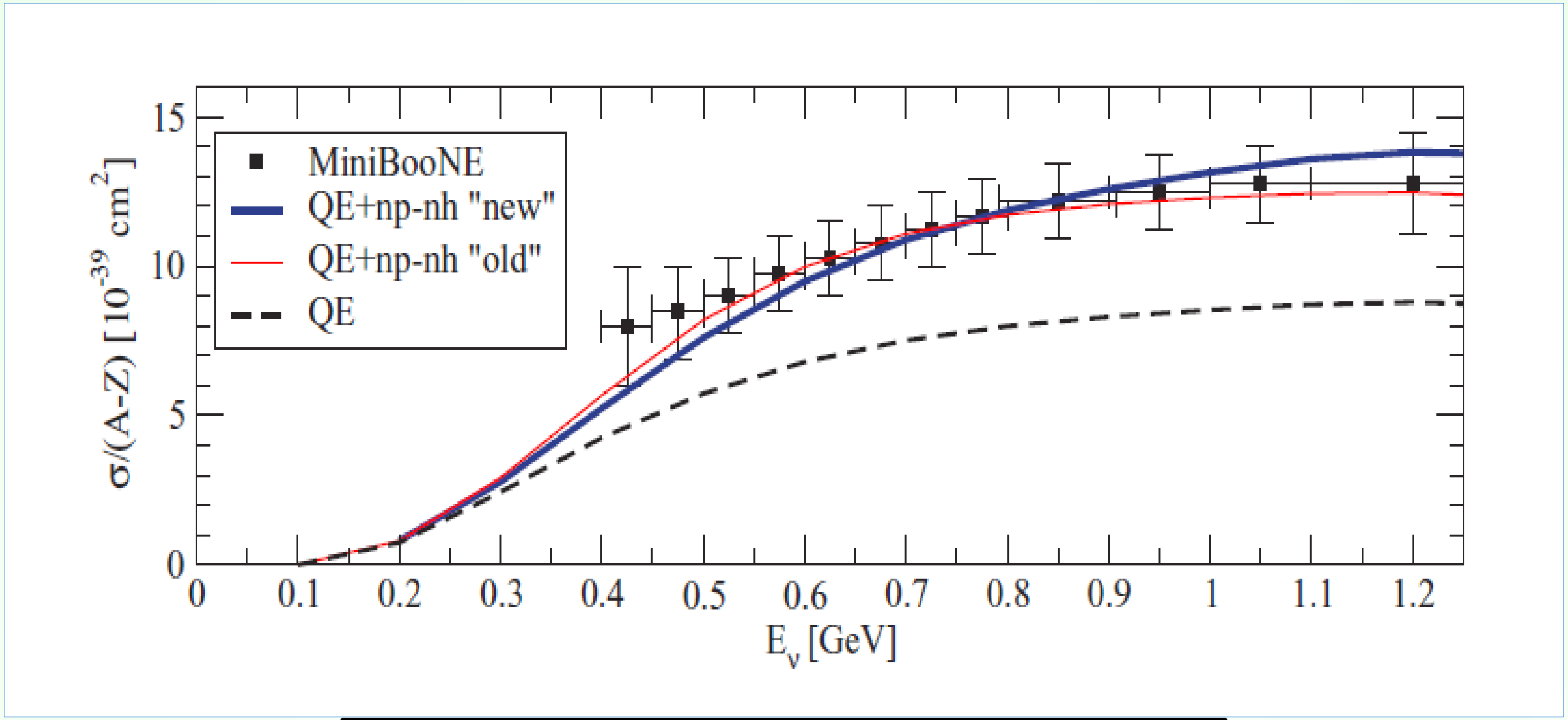
# MiniBooNE @ NuInt09




A. A. Aguilar-Arevalo *et al.* (MiniBooNE), PRD **81**, 092005 (2010)

- Shape of the $Q^2$ distrib. gives $M_A$ = 1.35 ± 0.17 GeV
- Cross section higher than for free nucleons (assuming $M_A$ = 1.03 GeV)

# Martini *et al.*



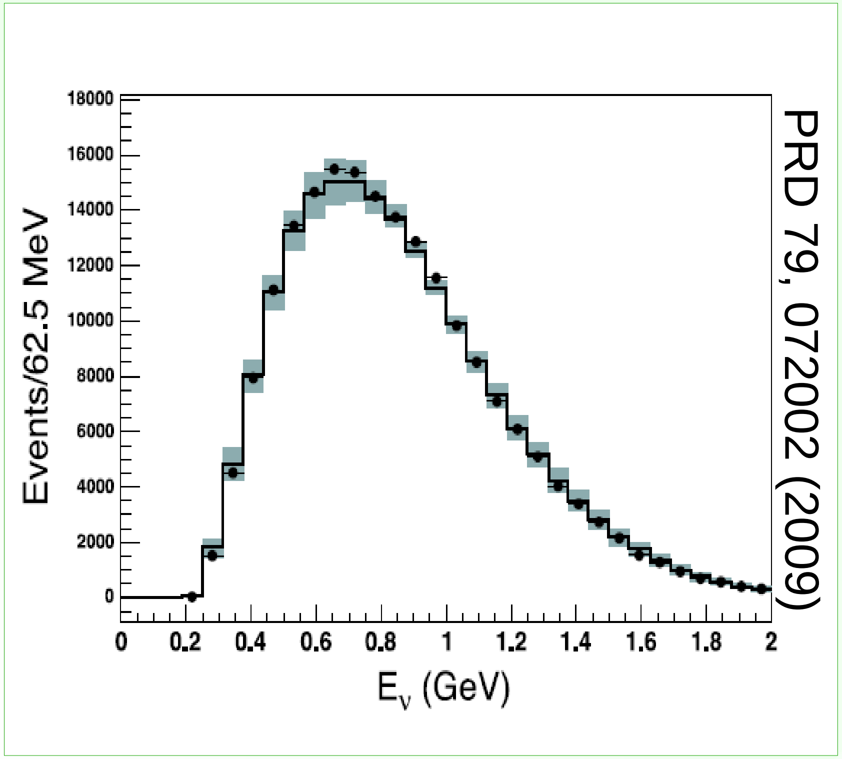

M. Martini *et al.*, PRC **80**, 065501 (2009)

- Formalism of Marteau (1999)
- **"A distinct feature of our approach, and one of our significant results, is the large 2p-2h component."**

# MiniBooNE

30 publications

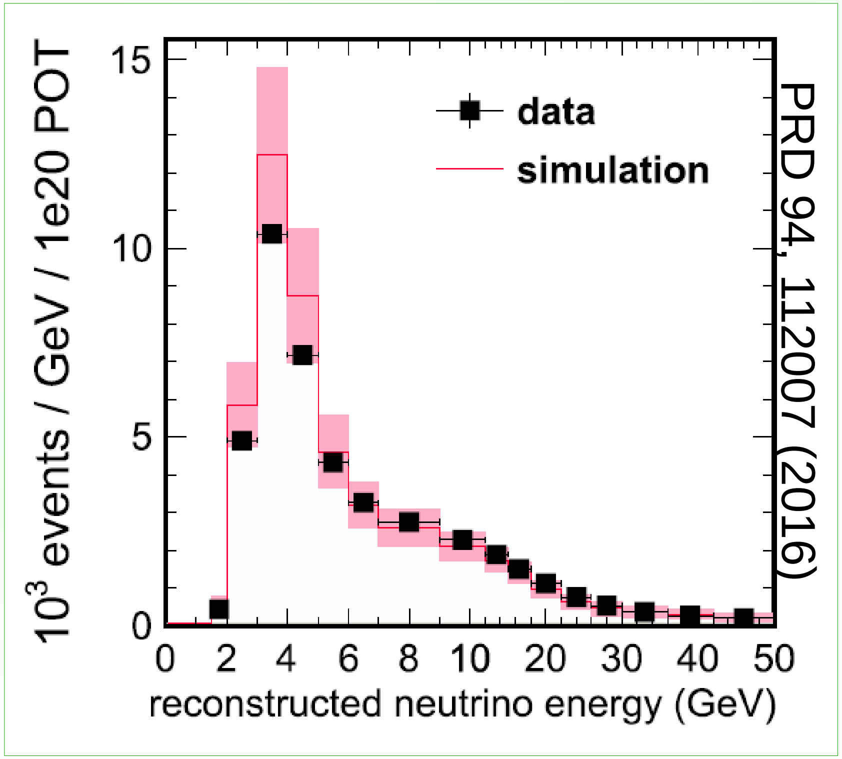
(7 on quasielastic channel)



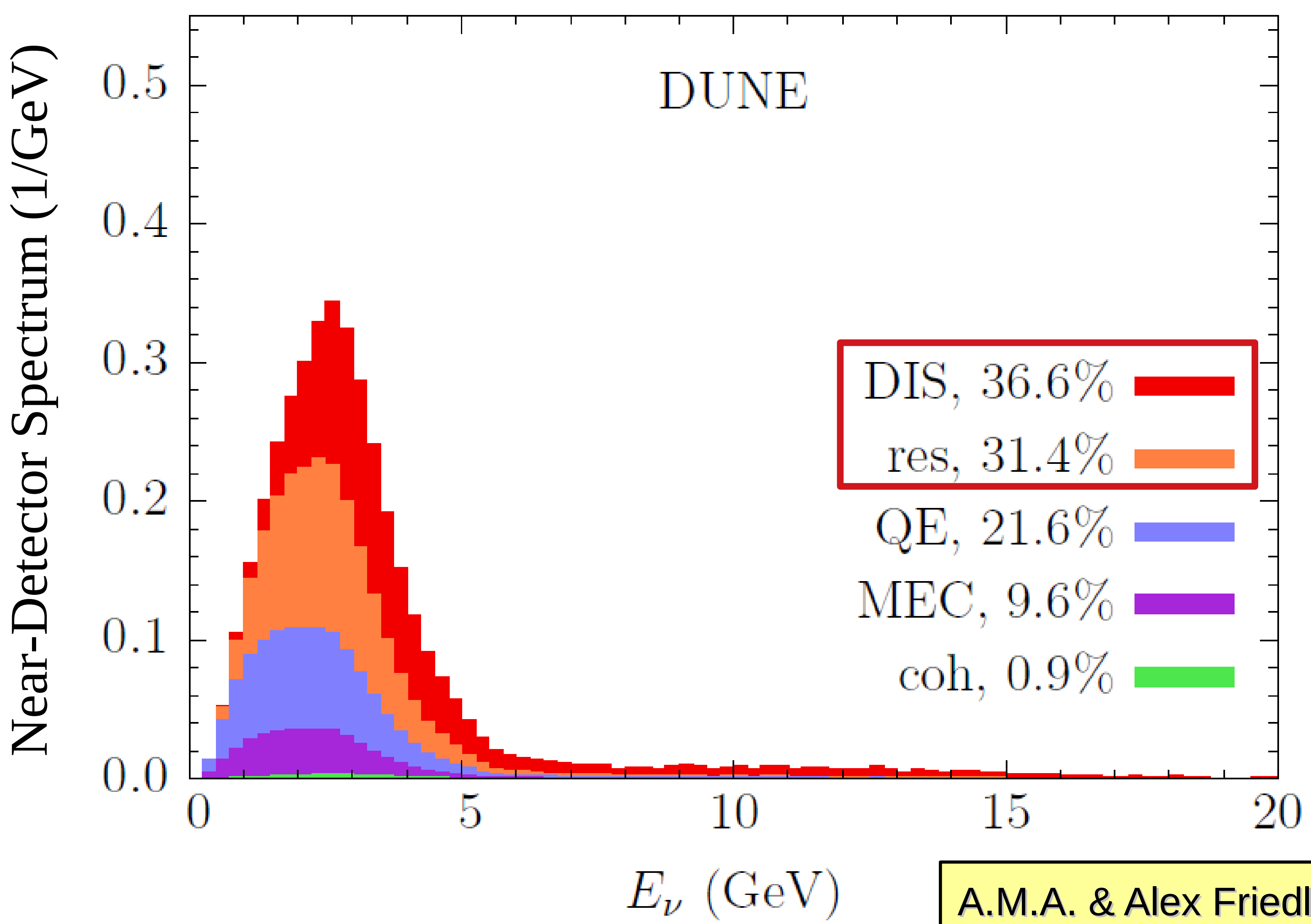

# MINERvA

40 publications

(10 on quasielastic channel,
7 on deep-inelastic/inclusive scattering)

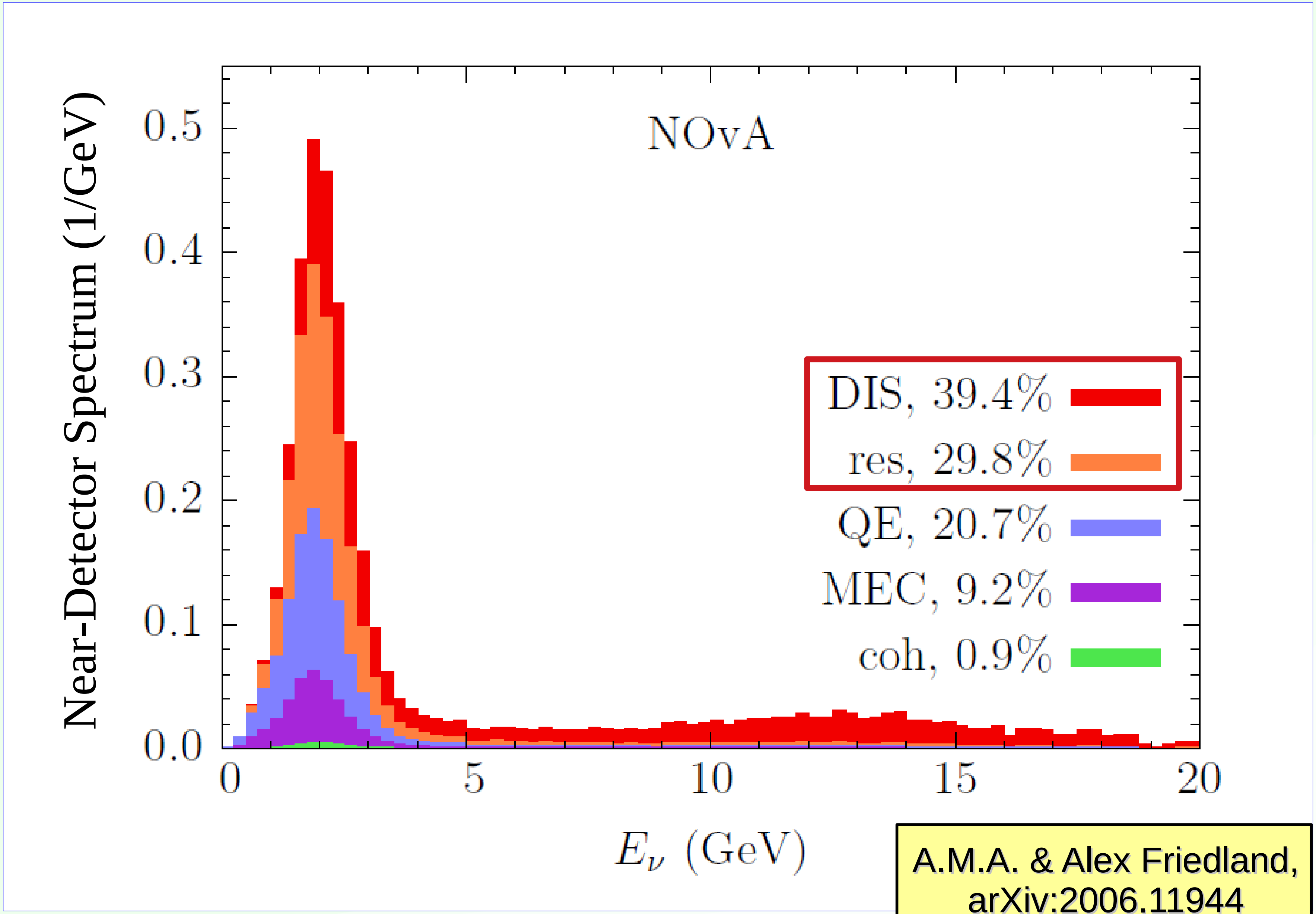


# Which cross sections are relevant?




A.M.A. & Alex Friedland, arXiv:2006.11944

# Which cross sections are relevant?




A.M.A. & Alex Friedland, arXiv:2006.11944

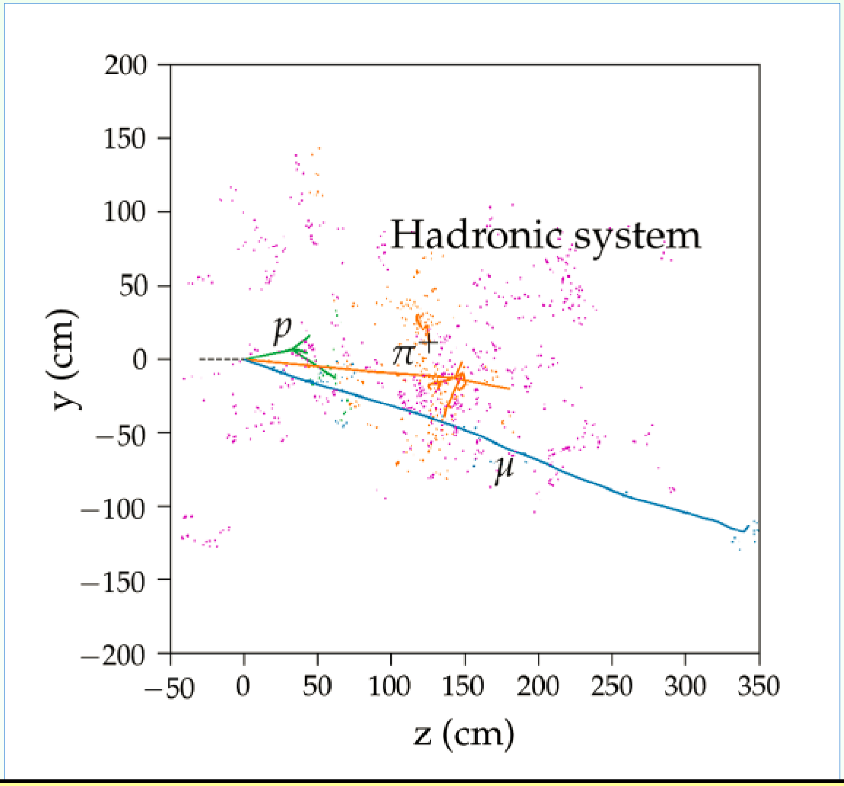
# P. Stowell *et al.* (MINERvA), PRD 100, 072005 (2019)

"… **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."

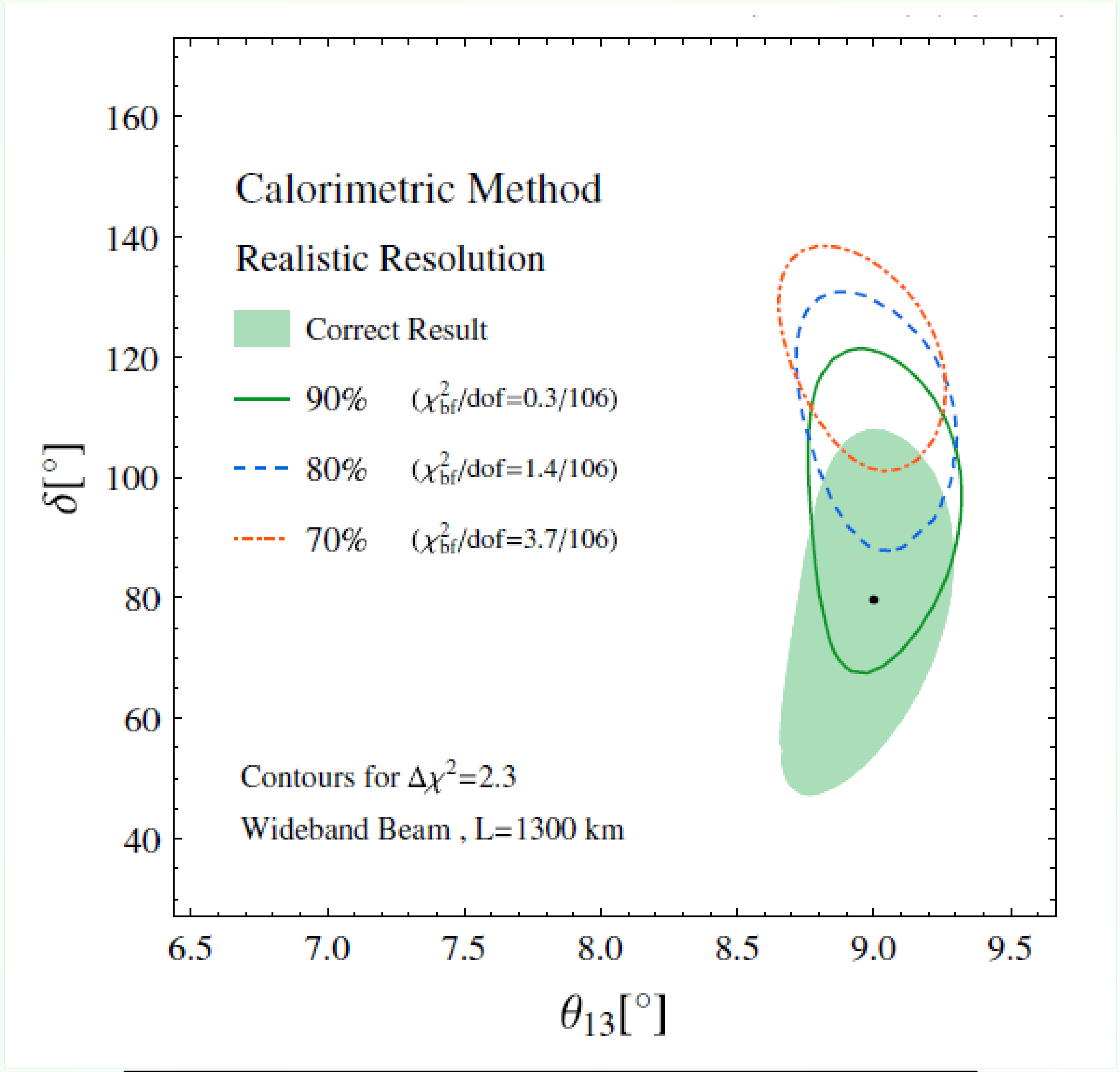
# Monte Carlo generators




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. *et al.*, PRD **92**, 091301(R) (2015)

"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.**"

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

# 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, arXiv:2006.11944

# 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:

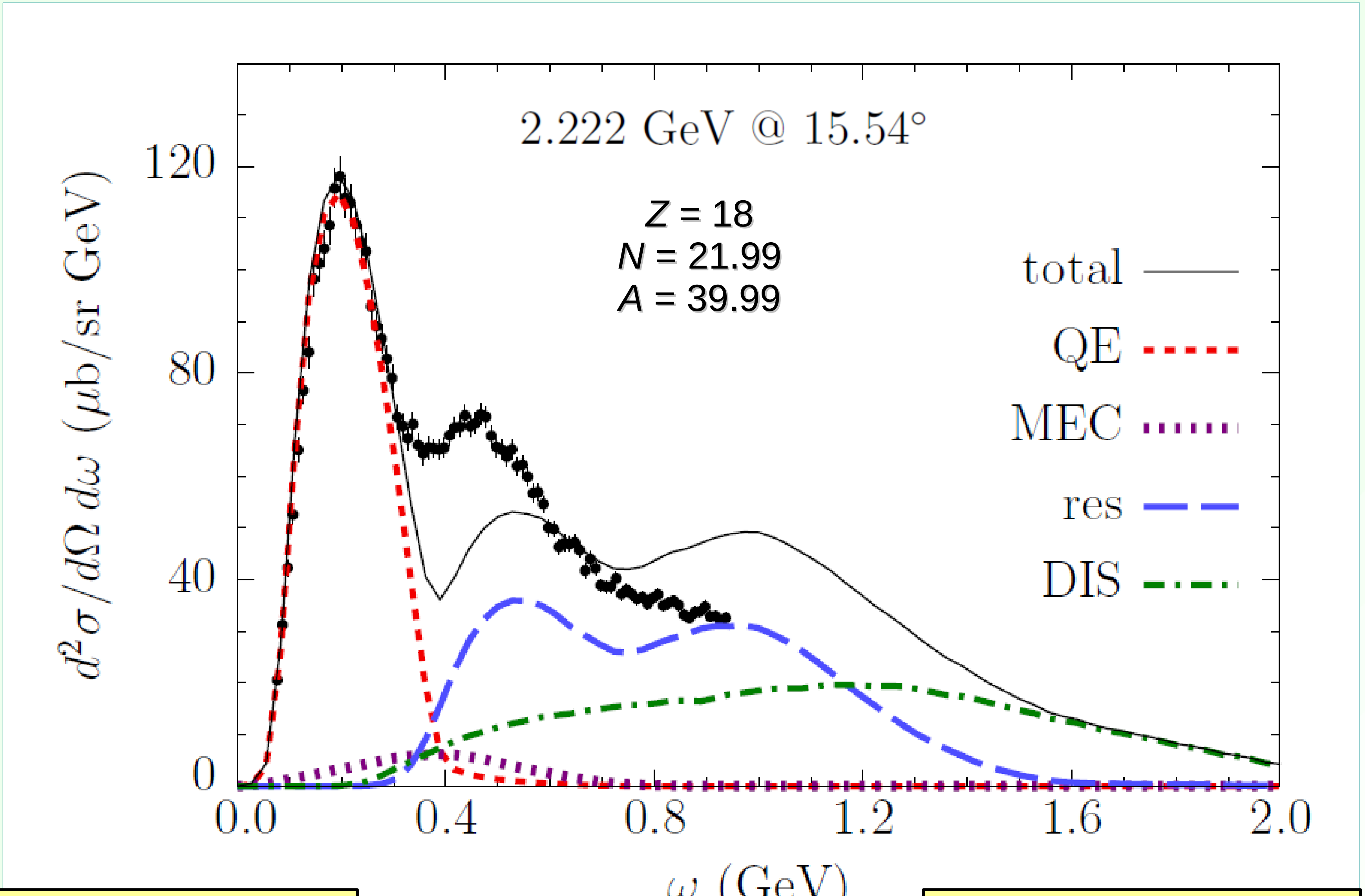
"The GENIE Collaboration shall provide electron-nucleus, hadron-nucleus and nucleon decay generators in the **same physics framework** as the neutrino-nucleus generator."

# GENIE in a nutshell

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


# Comparisons with electron-scattering data

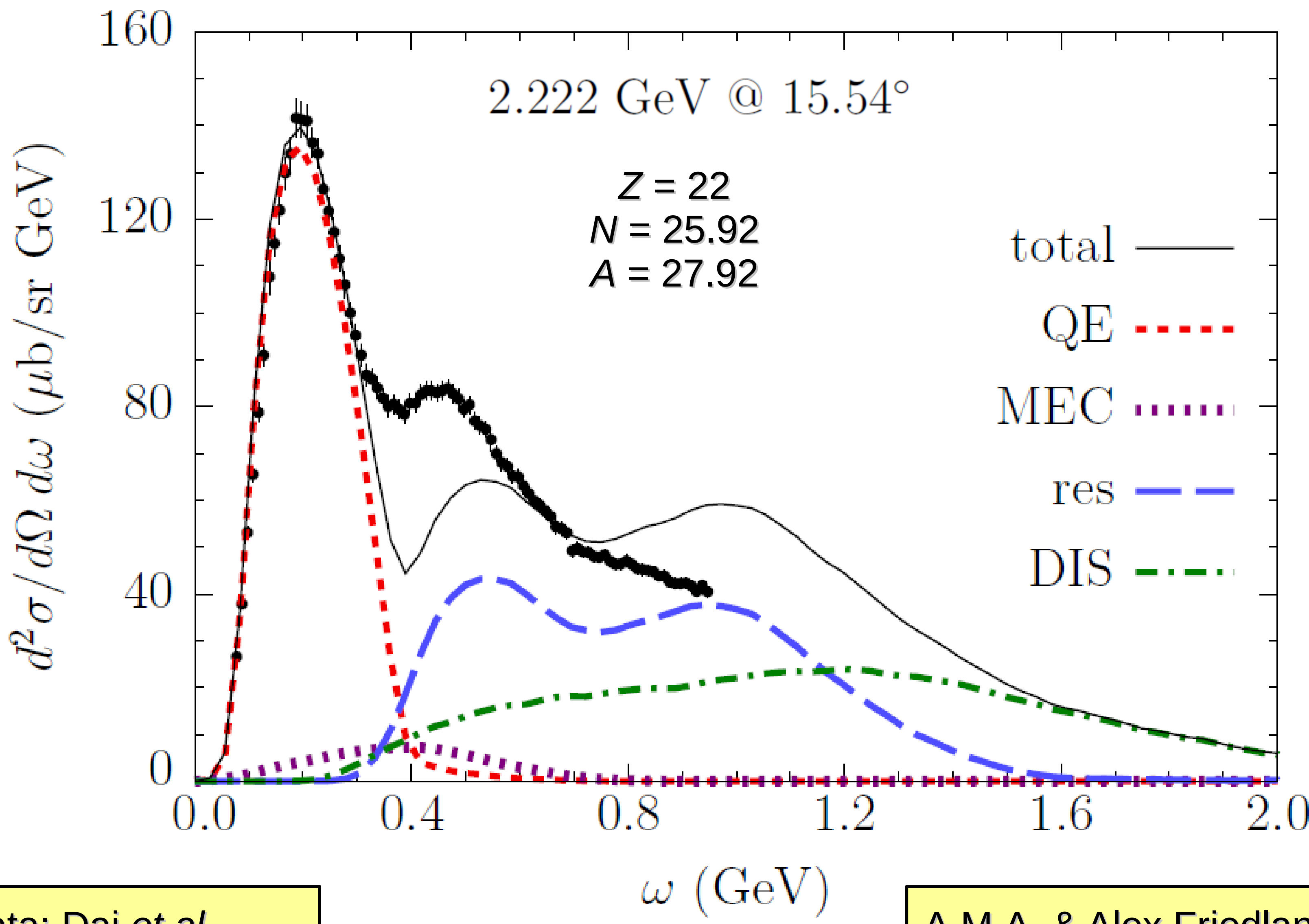
# Ar($e$, $e$') in GENIE




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

A.M.A. & Alex Friedland, arXiv:2006.11944

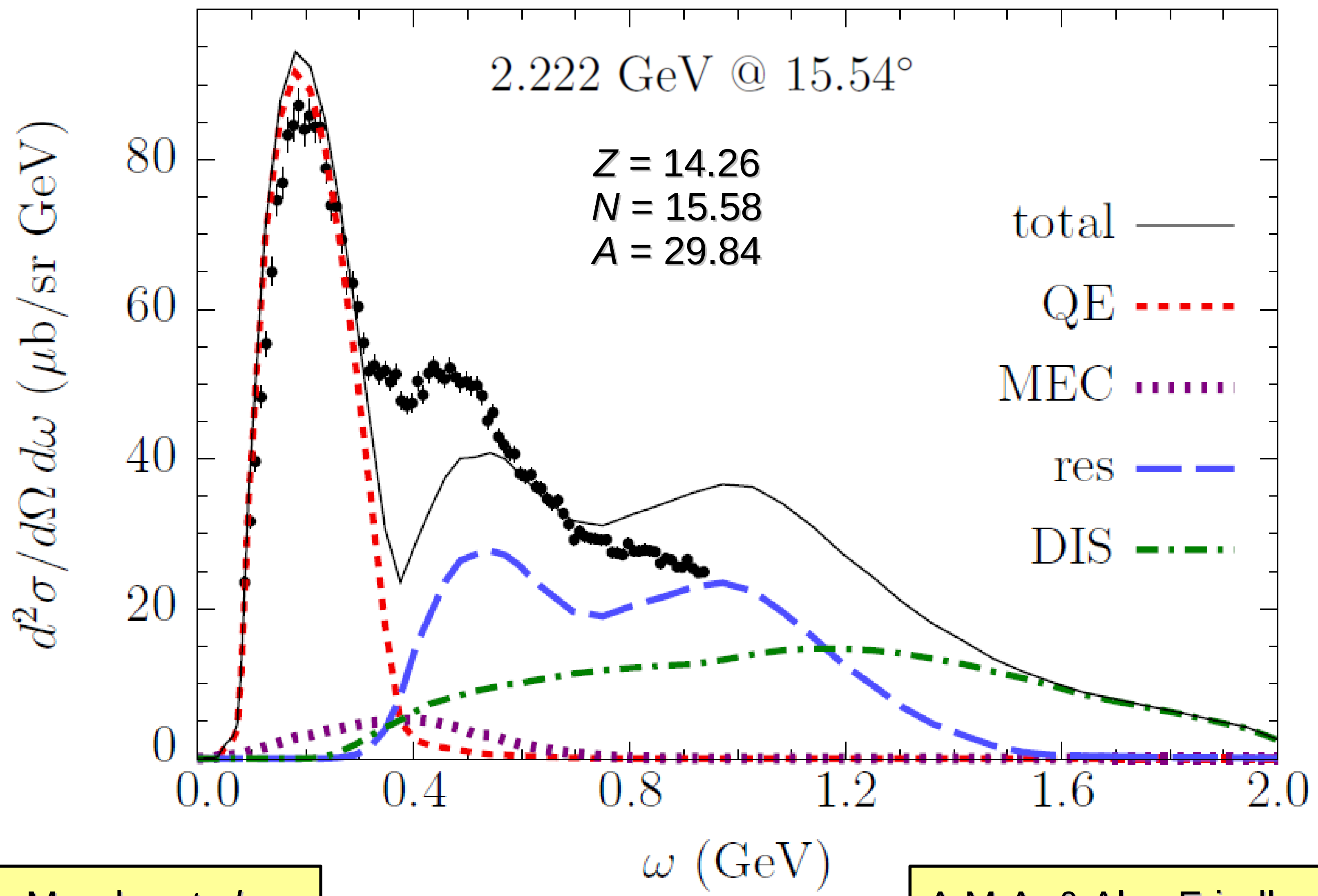
# Ti(*e*, *e*') in GENIE




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

A.M.A. & Alex Friedland,
arXiv:2006.11944

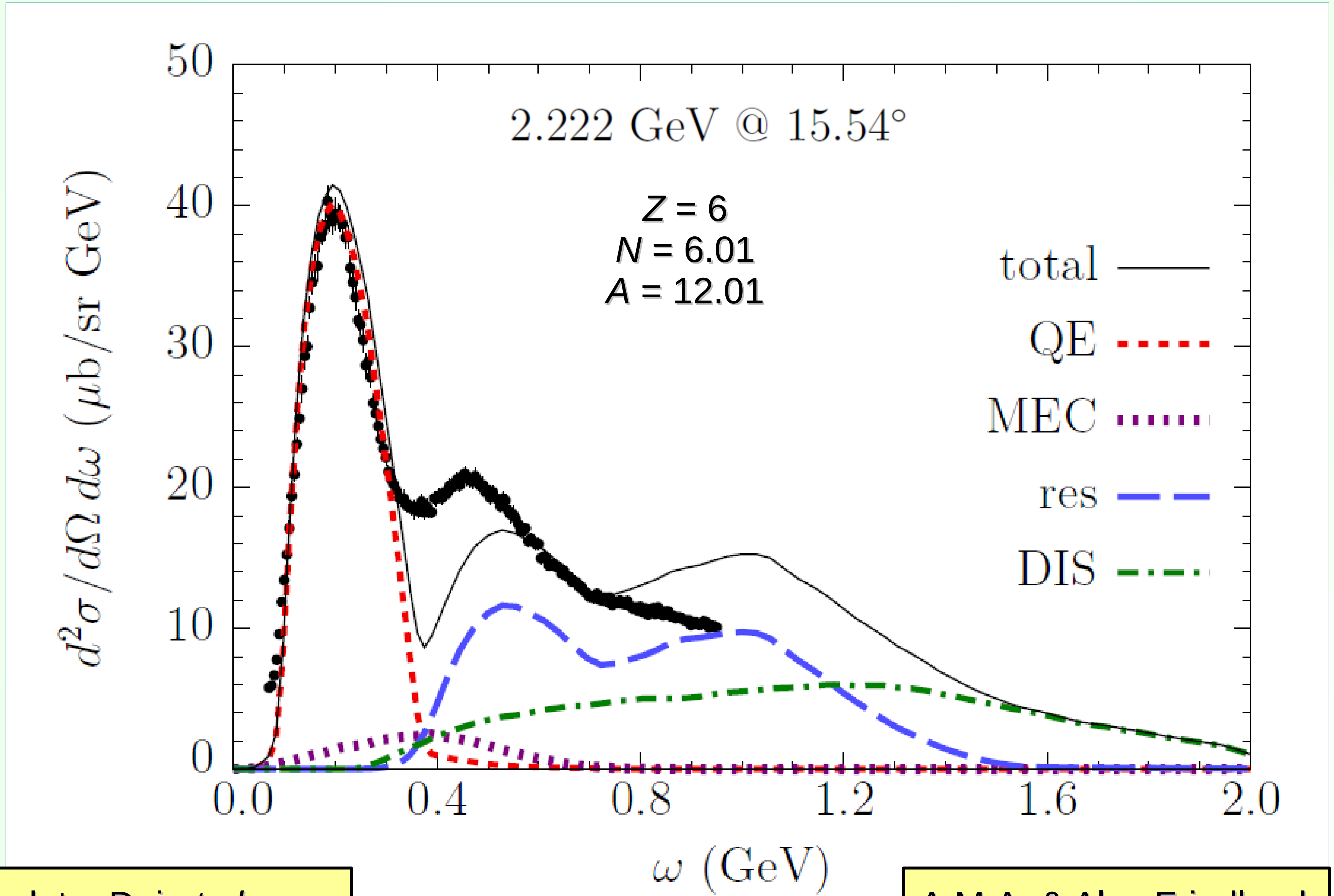
# Al-7075(*e*, *e*') in GENIE




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

A.M.A. & Alex Friedland,
arXiv:2006.11944

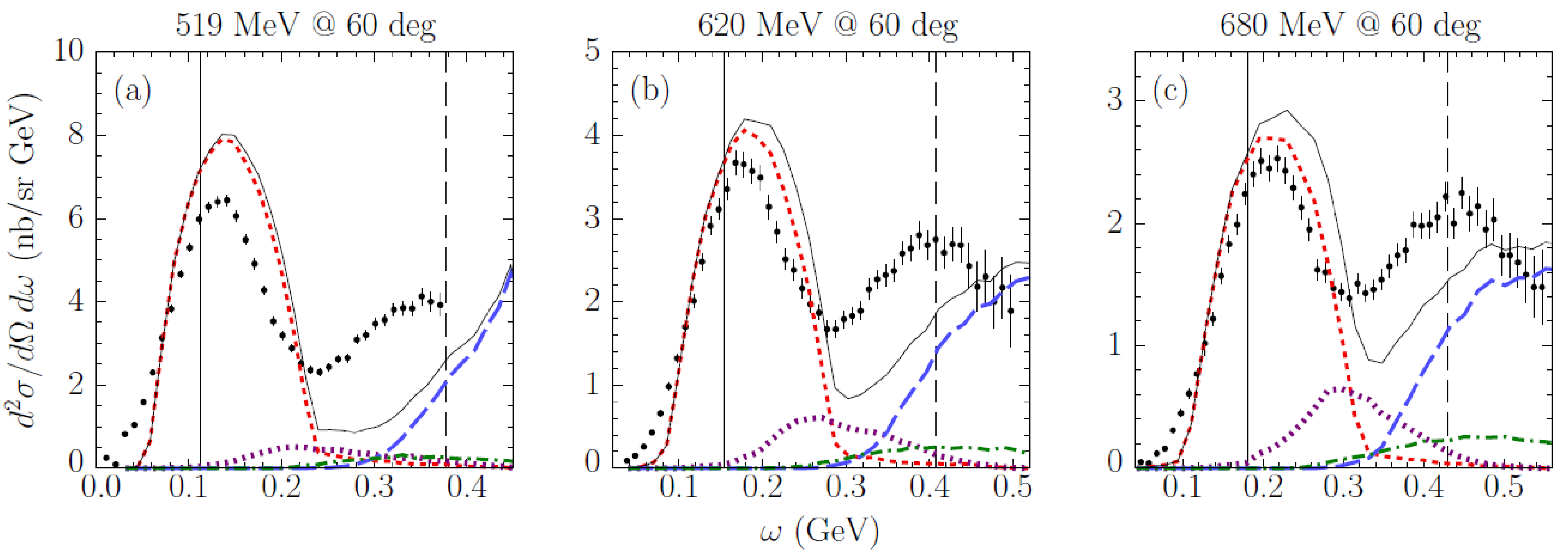
# C(*e*, *e*’) in GENIE




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

A.M.A. & Alex Friedland,
arXiv:2006.11944

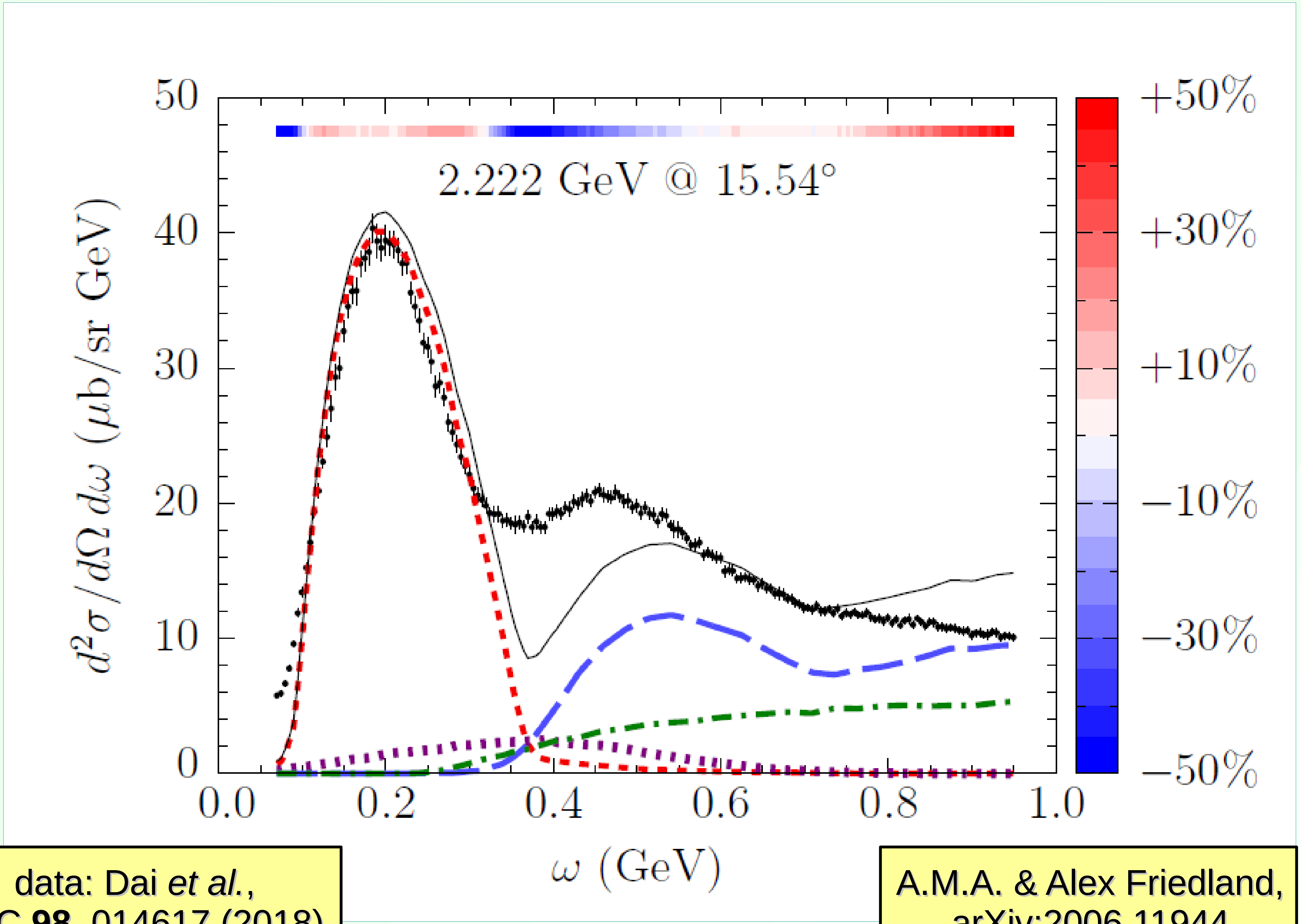
# C(*e*, *e*') in GENIE




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

A.M.A. & Alex Friedland, arXiv:2006.11944

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

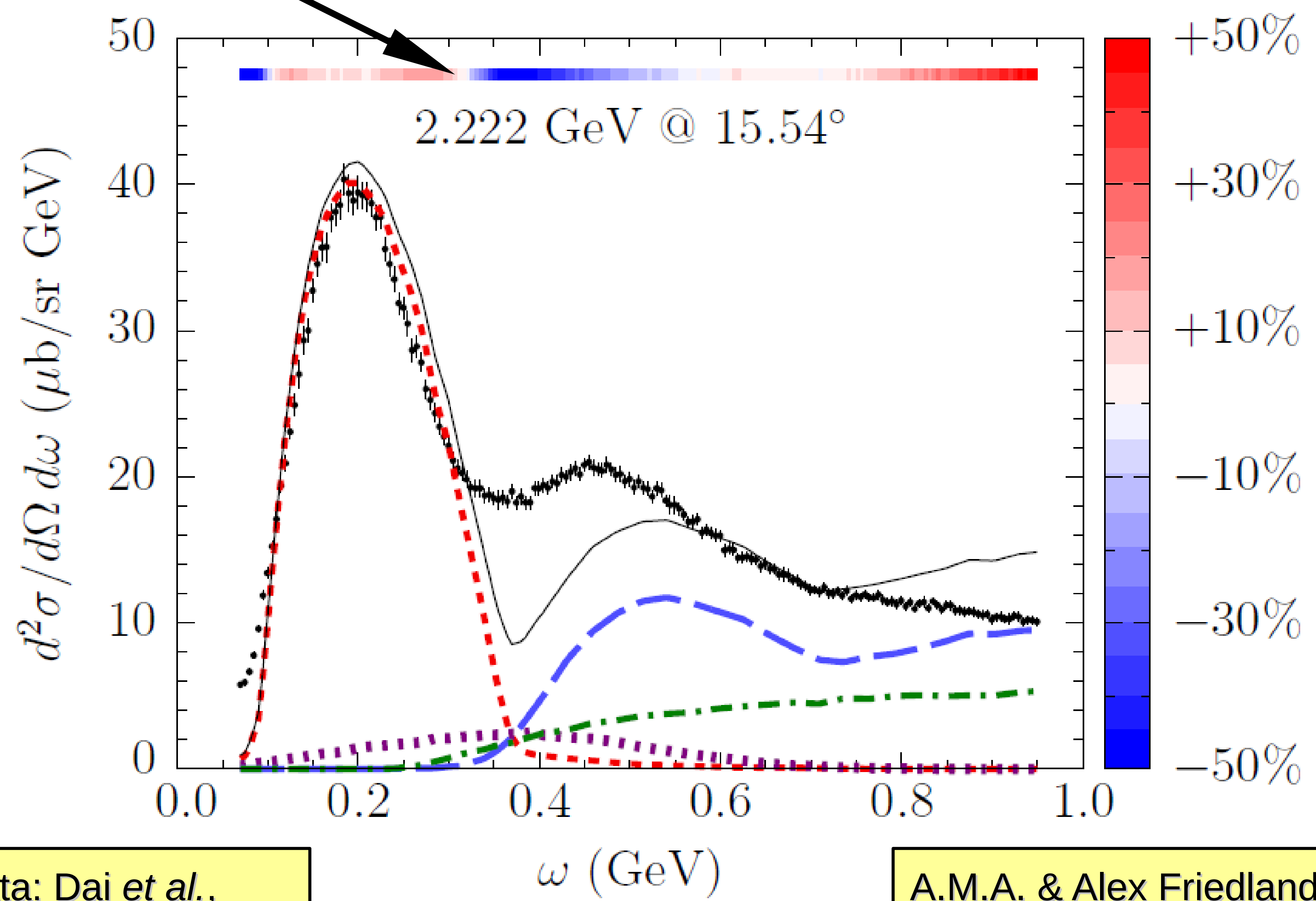



data: Dai *et al.*, PRC **98**, 014617 (2018)

A.M.A. & Alex Friedland, arXiv:2006.11944

# C(*e*, *e*’) in GENIE

GENIE – data
data




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

A.M.A. & Alex Friedland,
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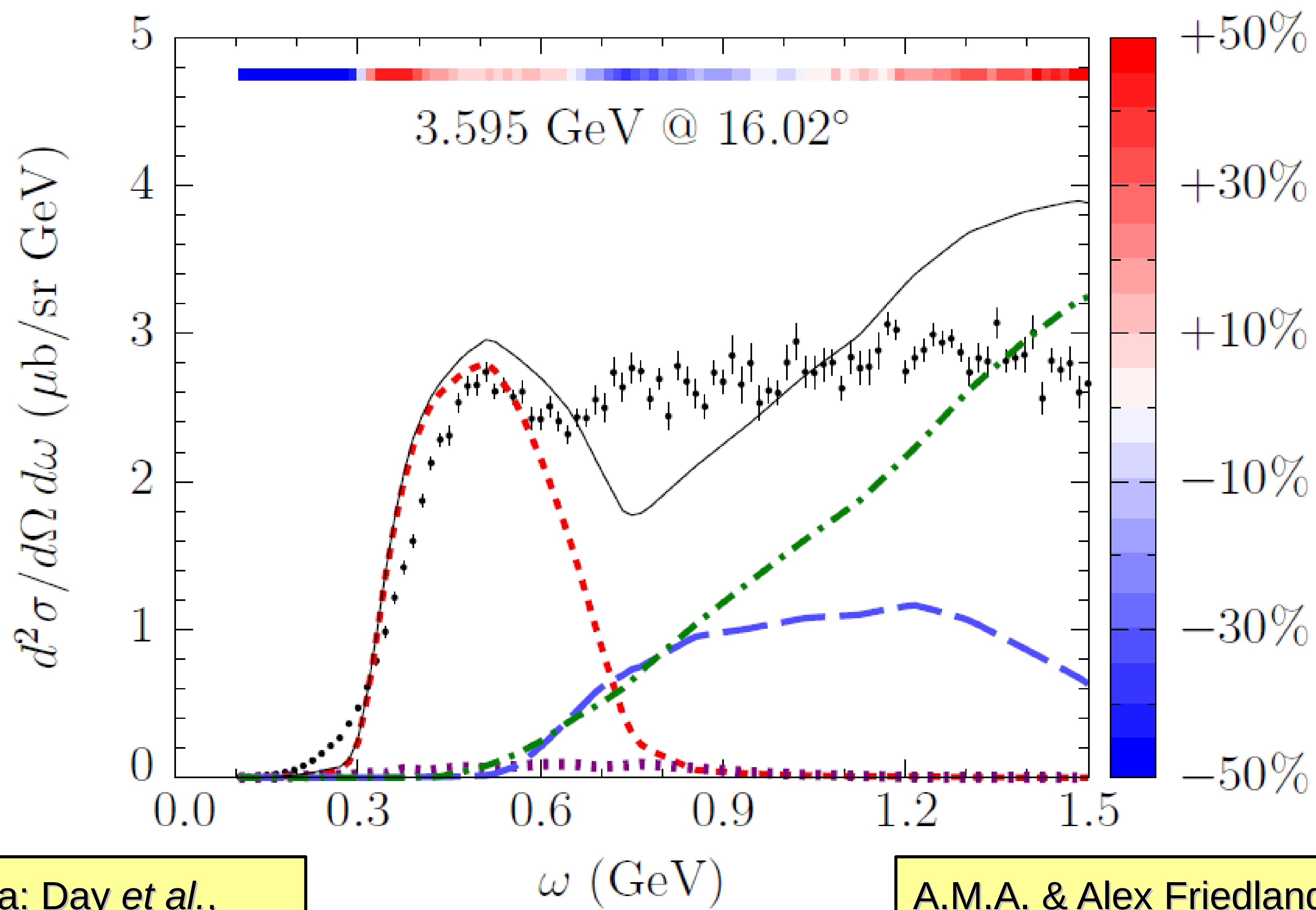
# C(*e*, *e*’) in GENIE




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

A.M.A. & Alex Friedland,
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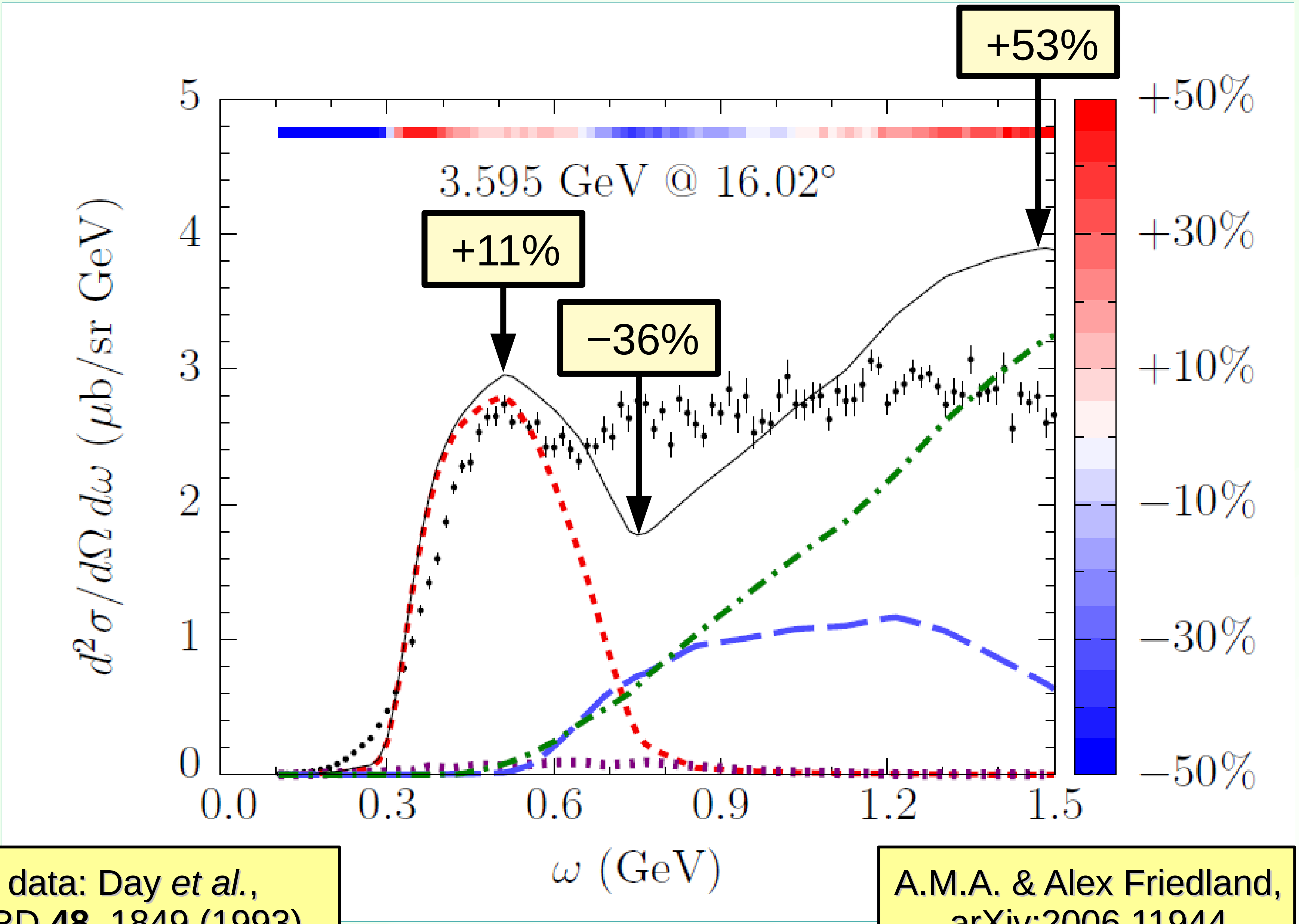
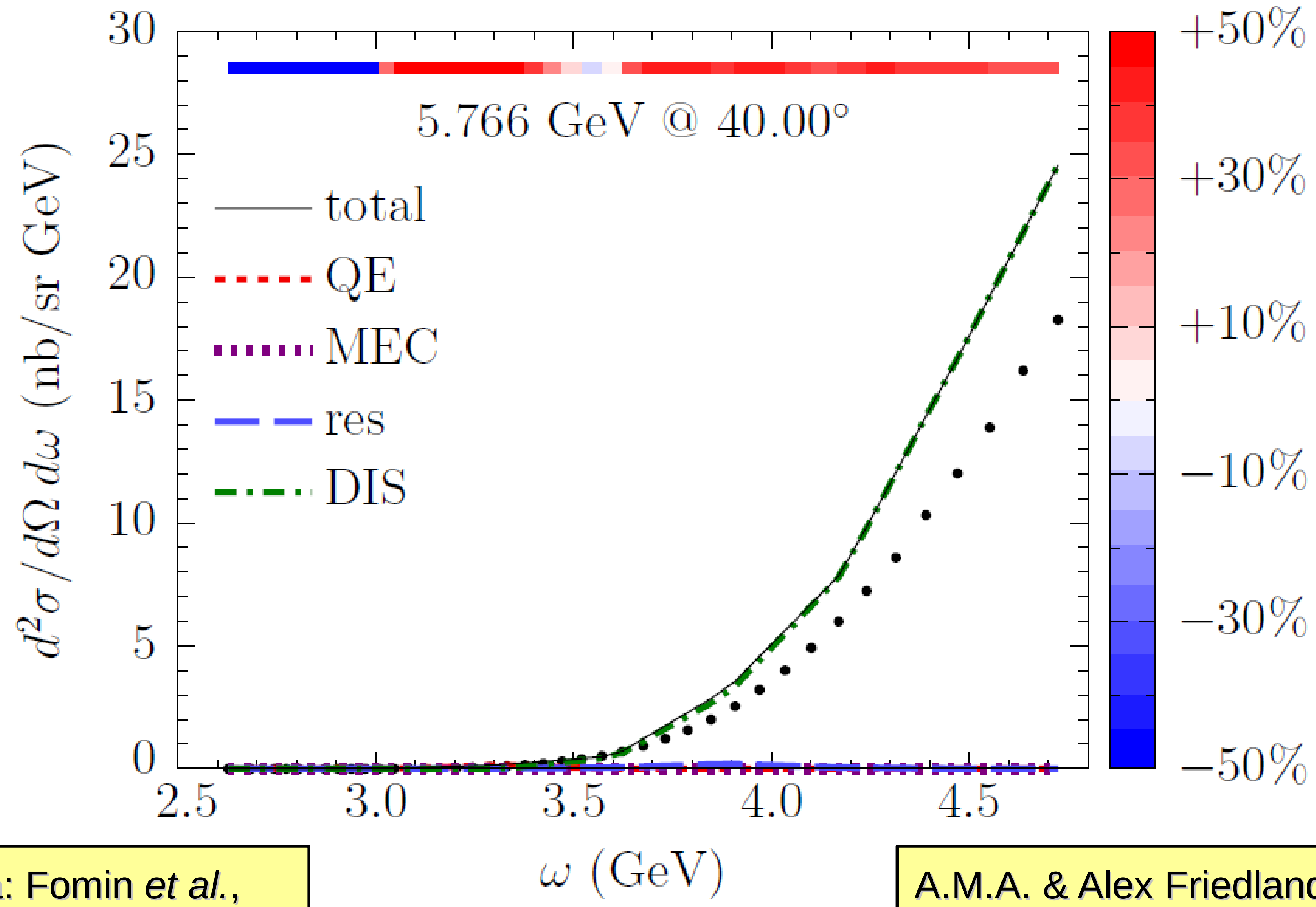
# C(*e*, *e*’) in GENIE




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

A.M.A. & Alex Friedland,
arXiv:2006.11944

# C(*e*, *e*’) in GENIE

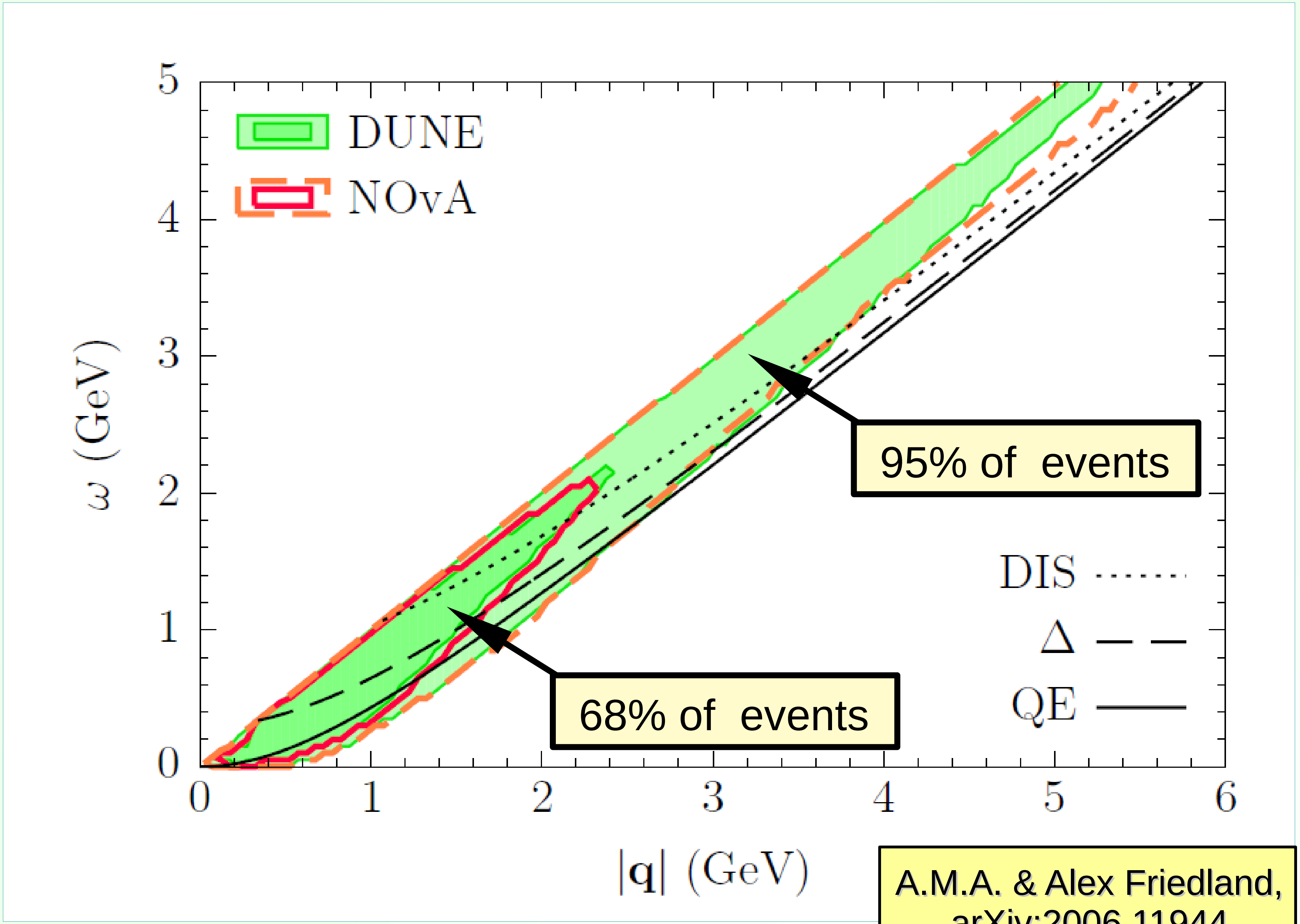



data: Fomin *et al.*, PRL **105**, 212502 (2010)

A.M.A. & Alex Friedland, arXiv:2006.11944

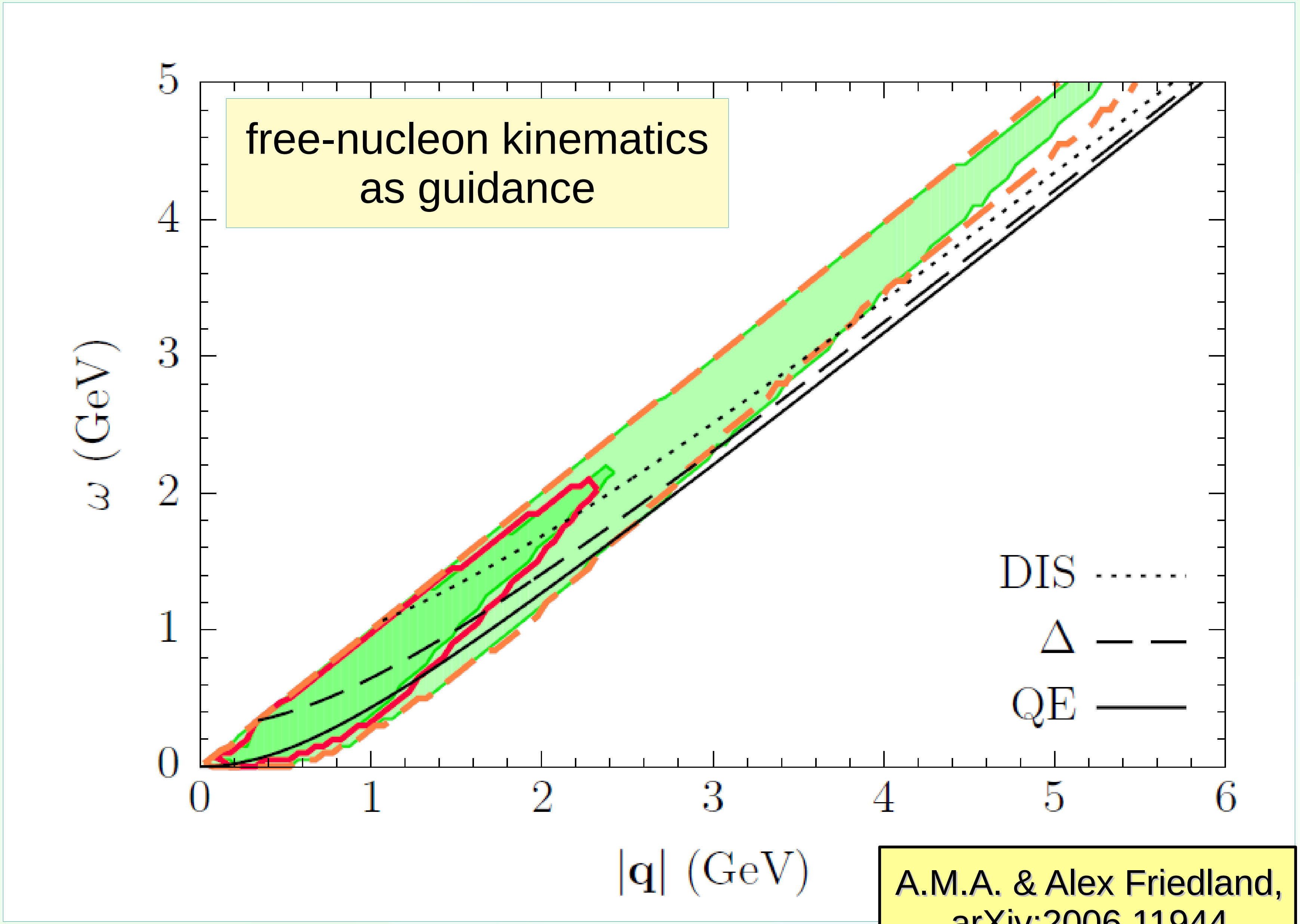

# Are these issues general?

# DUNE vs. NOvA




A.M.A. & Alex Friedland, arXiv:2006.11944

# DUNE vs. NOvA




A.M.A. & Alex Friedland,
arXiv:2006.11944

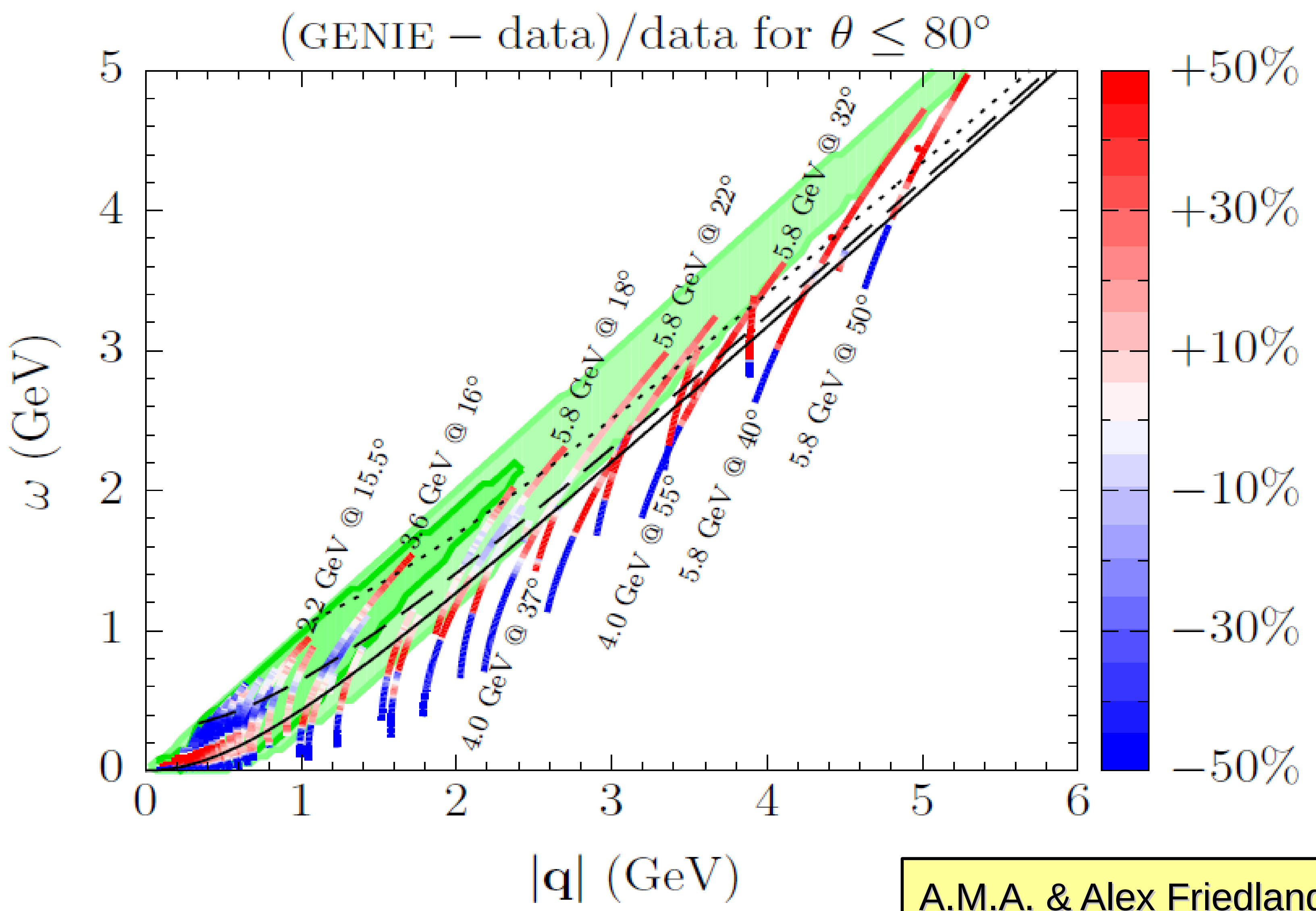
# C(*e*, *e*’) data

TABLE I. Summary of the cross sections extracted for inclusive electron scattering off carbon. Symbol “Y” marks the datasets considered in this analysis.

| Year | Lab | Energy (GeV) | Angle (deg) | Point number | Incl. here | Ref. |
|---|---|---|---|---|---|---|
| 1974 | HEPL | 0.50 | 60.0 | 35 | Y | [27] |
| 1983 | Saclay | 0.12–0.68 | 36.0–145.0 | 1,397 | Y | [5] |
| 1987 | Bates | 0.54 | 37.1 | N/A | | [28] |
| 1987 | Bates | 0.73 | 37.1 | 54 | Y | [28] |
| 1988 | Yerev. | 1.93, 2.13 | 16.0, 18.0 | 134 | Y | [29] |
| 1988 | SLAC | 0.65 | 33.0, 53.0 | N/A | | [10] |
| 1988 | SLAC | 1.30–1.65 | 11.95–13.54 | 263 | Y | [10] |
| 1989 | SLAC | 0.96–1.50 | 37.5 | 250 | Y | [30] |
| 1993 | SLAC | 2.02–3.60 | 15.02–30.01 | 316 | Y | [31] |
| 1994 | SLAC | 12.1–17.3 | 12.8–15.9 | 7 | Y | [32] |
| 1995 | SLAC | 2.02–5.12 | 35.51–56.64 | 56 | Y | [33] |
| 1998 | JLab | 4.05 | 15.0–74.0 | 398 | Y | [34, 35] |
| 2010 | JLab | 5.77 | 18.0–50.0 | 359 | Y | [11, 12] |
| 2018 | JLab | 2.22 | 15.54 | 177 | Y | [22] |

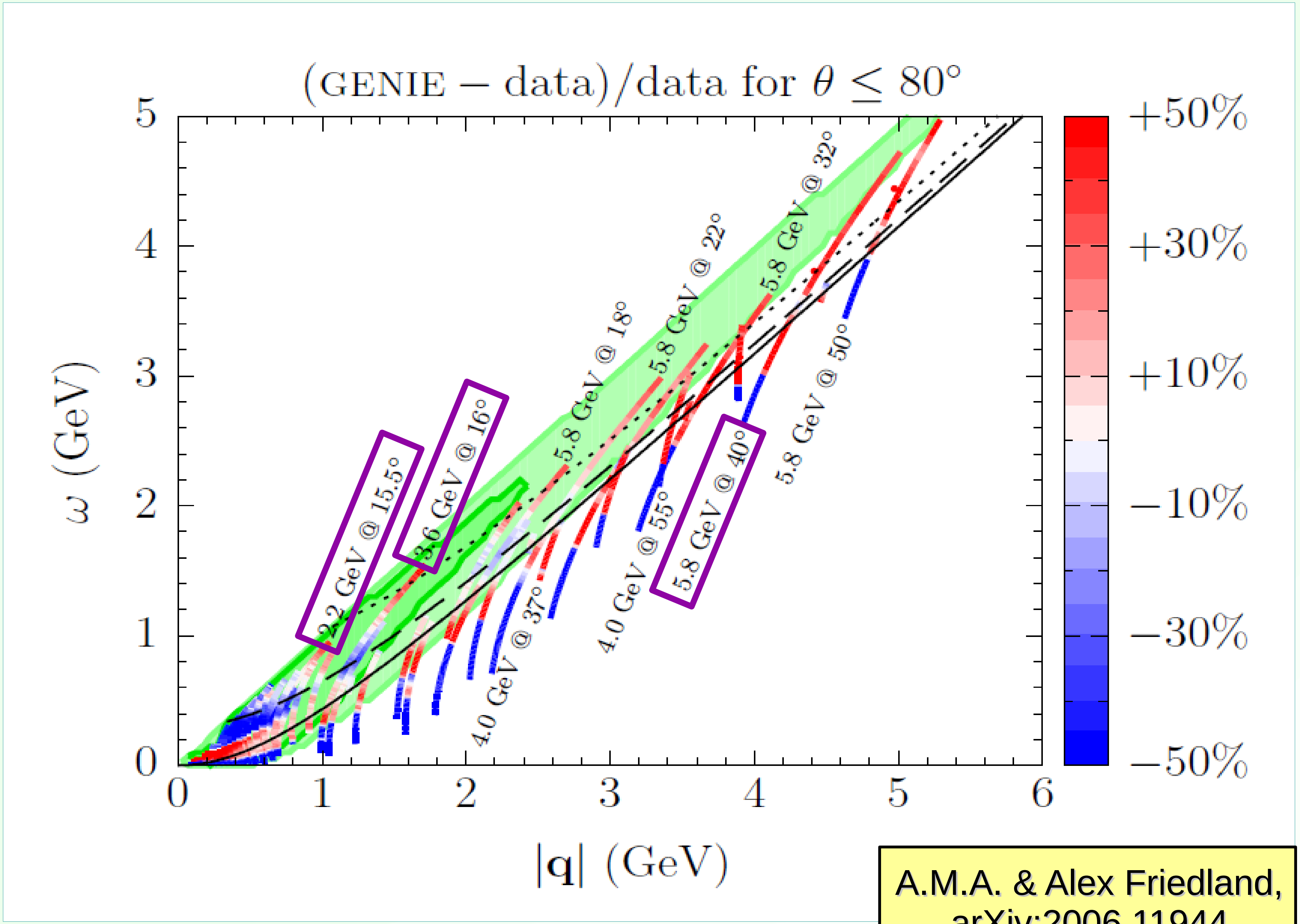
3,446 points

# C(*e*, *e*’) in GENIE




A.M.A. & Alex Friedland, arXiv:2006.11944

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



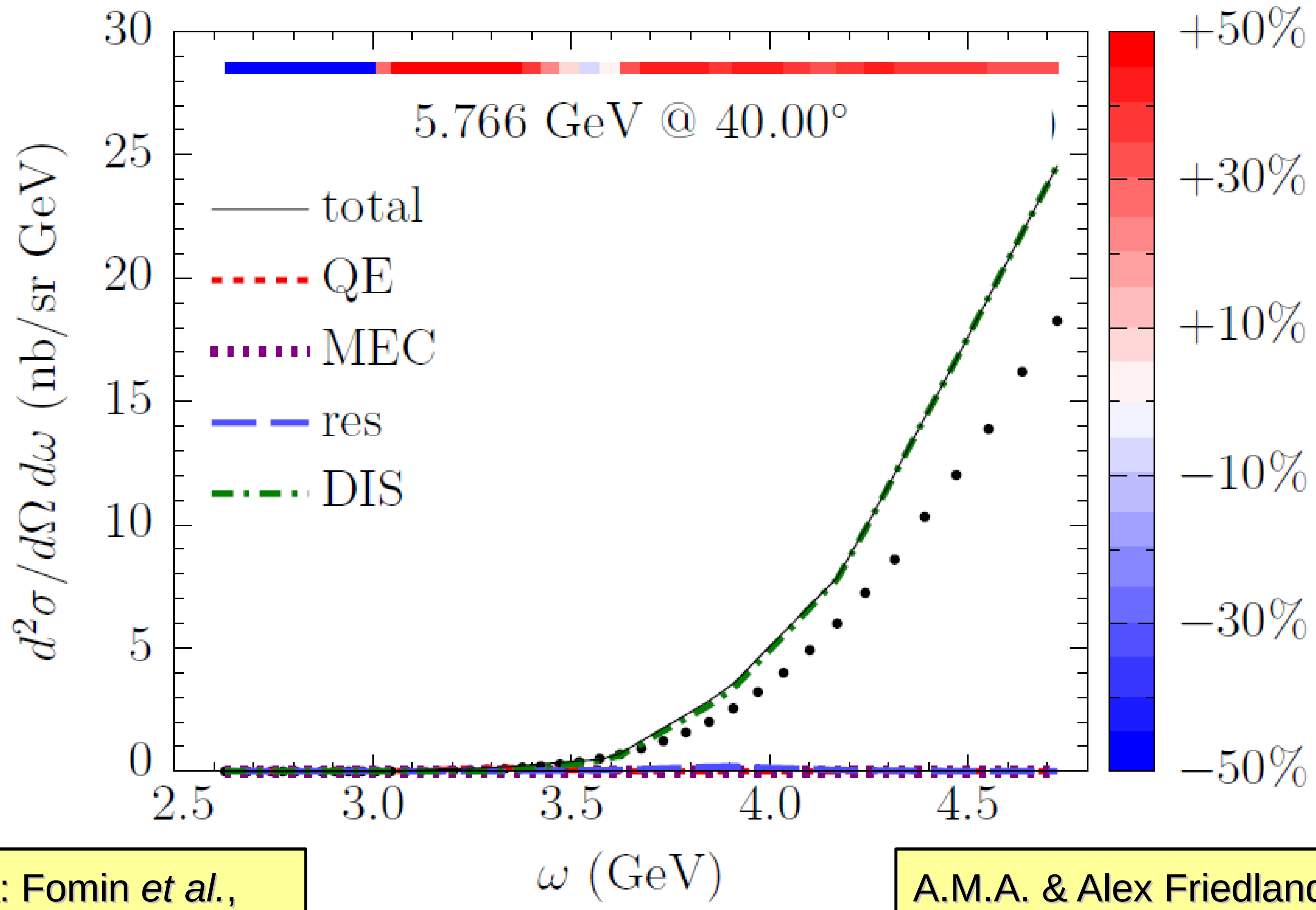

A.M.A. & Alex Friedland, arXiv:2006.11944

# Findings for carbon

- 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?

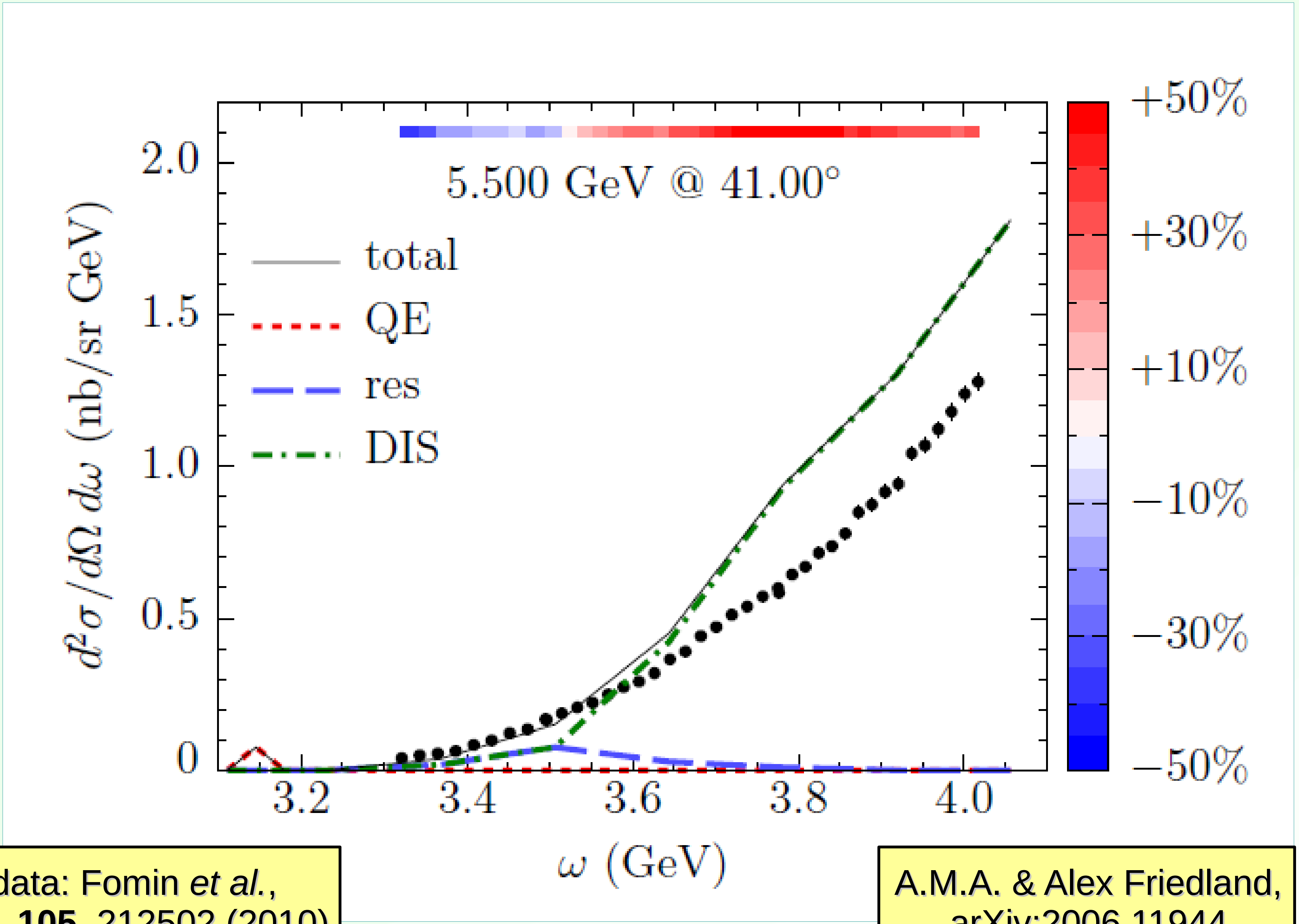
# C(*e*, *e*’) in GENIE




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

A.M.A. & Alex Friedland, arXiv:2006.11944

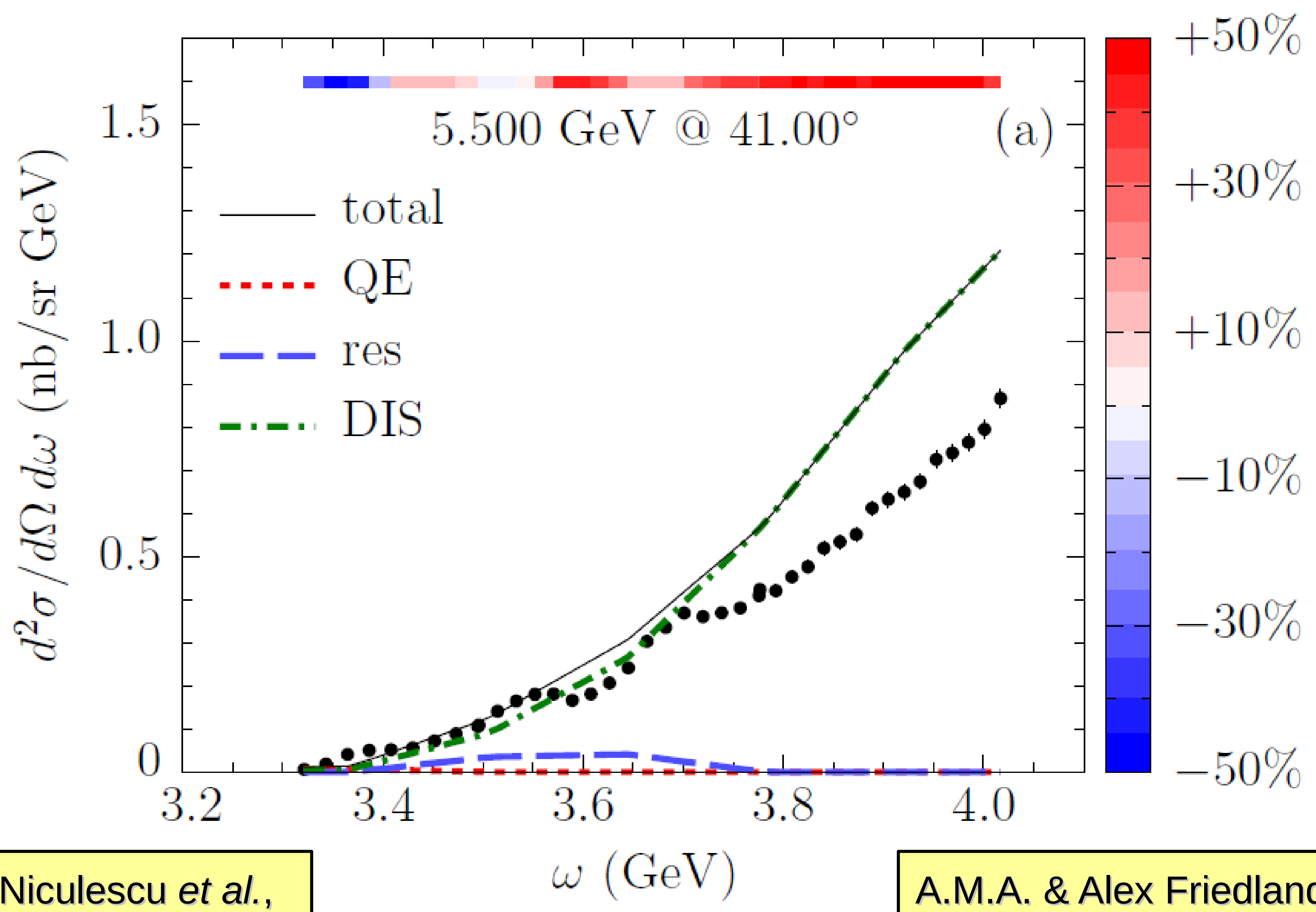
# D(*e*, *e*') in GENIE




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

A.M.A. & Alex Friedland,
arXiv:2006.11944

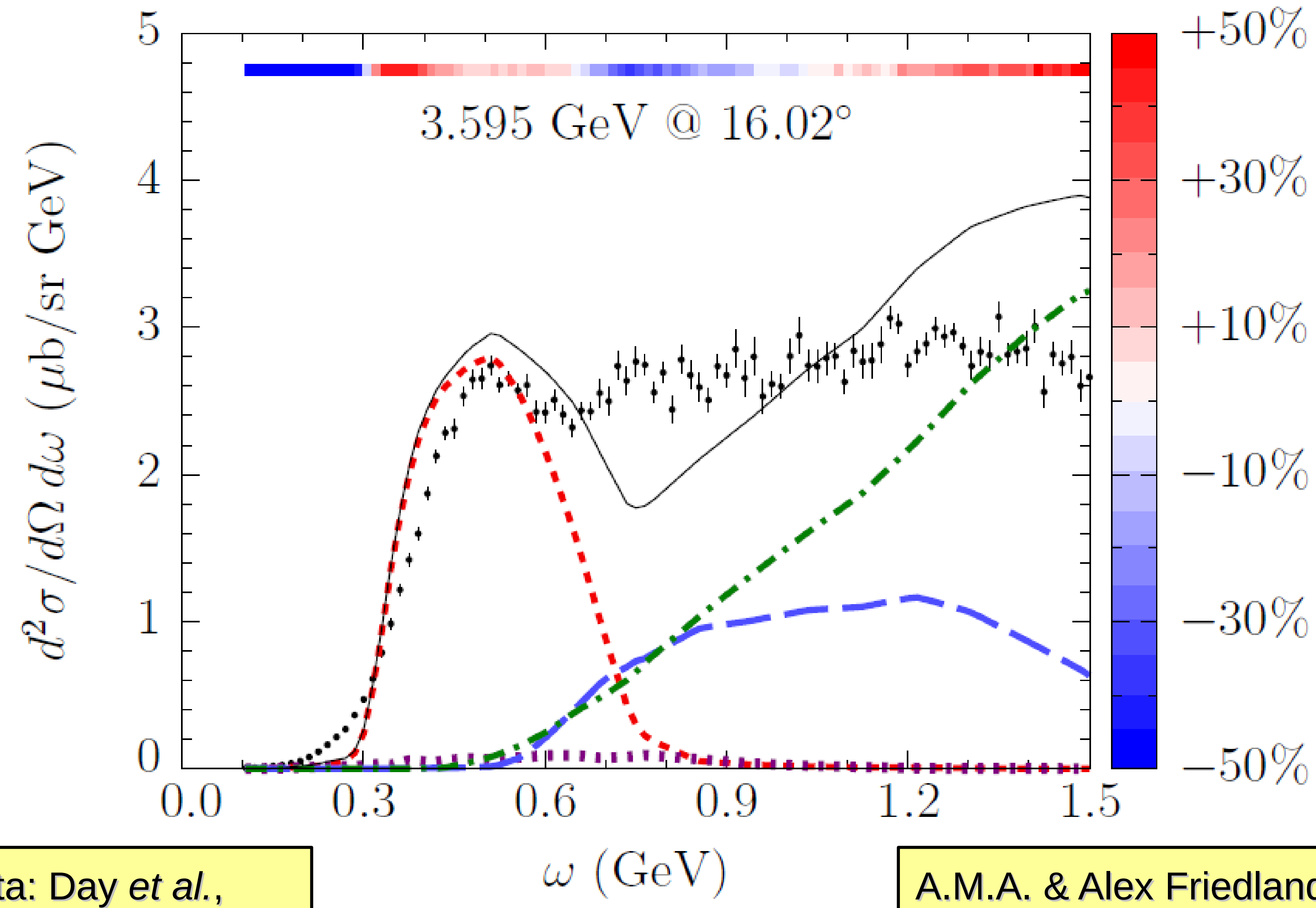
# H(*e*, *e*’) in GENIE




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

A.M.A. & Alex Friedland, arXiv:2006.11944

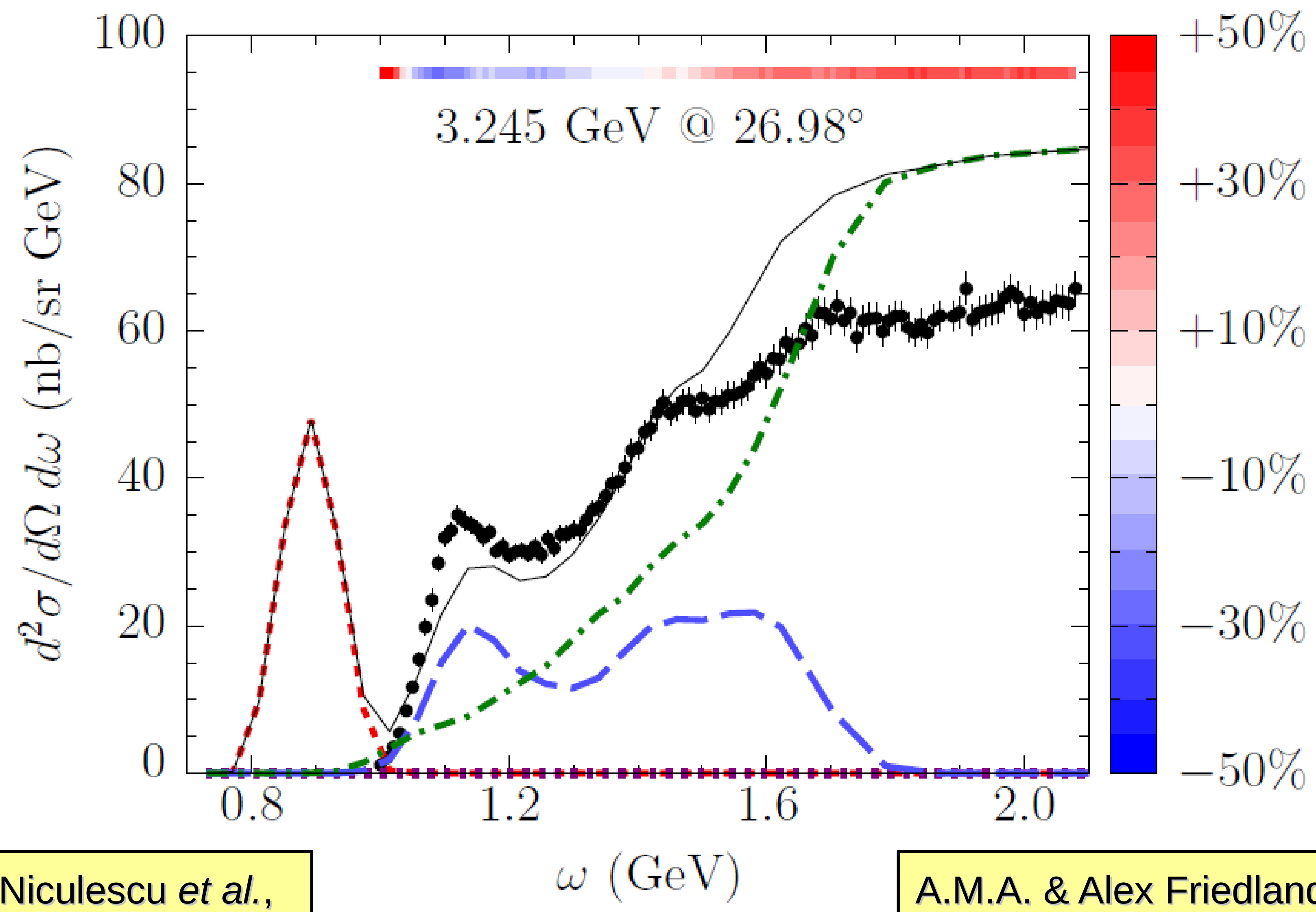
# C(*e*, *e*’) in GENIE




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

A.M.A. & Alex Friedland,
arXiv:2006.11944

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

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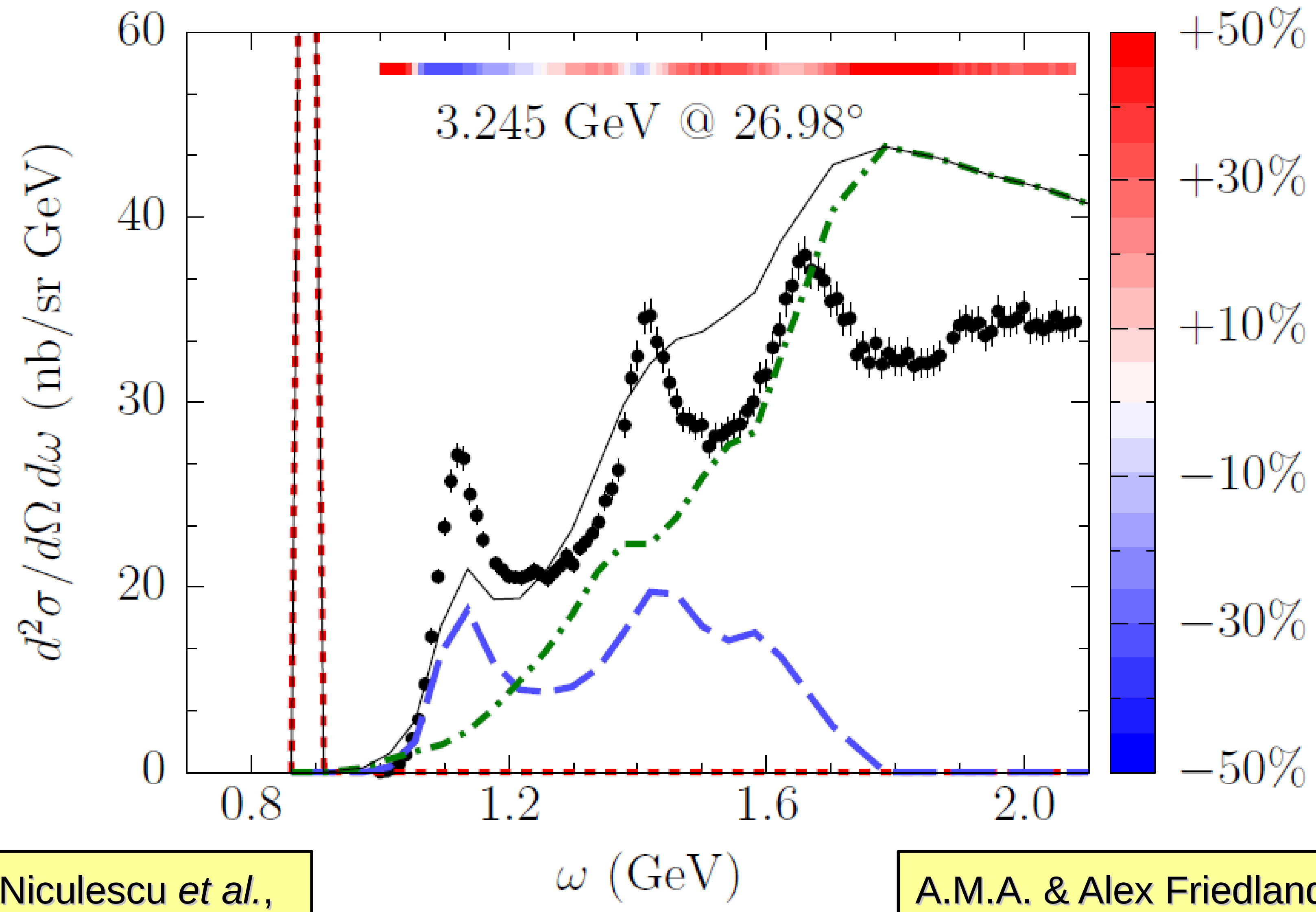


data: Niculescu *et al.*, PRL **85**, 1186 (2000)

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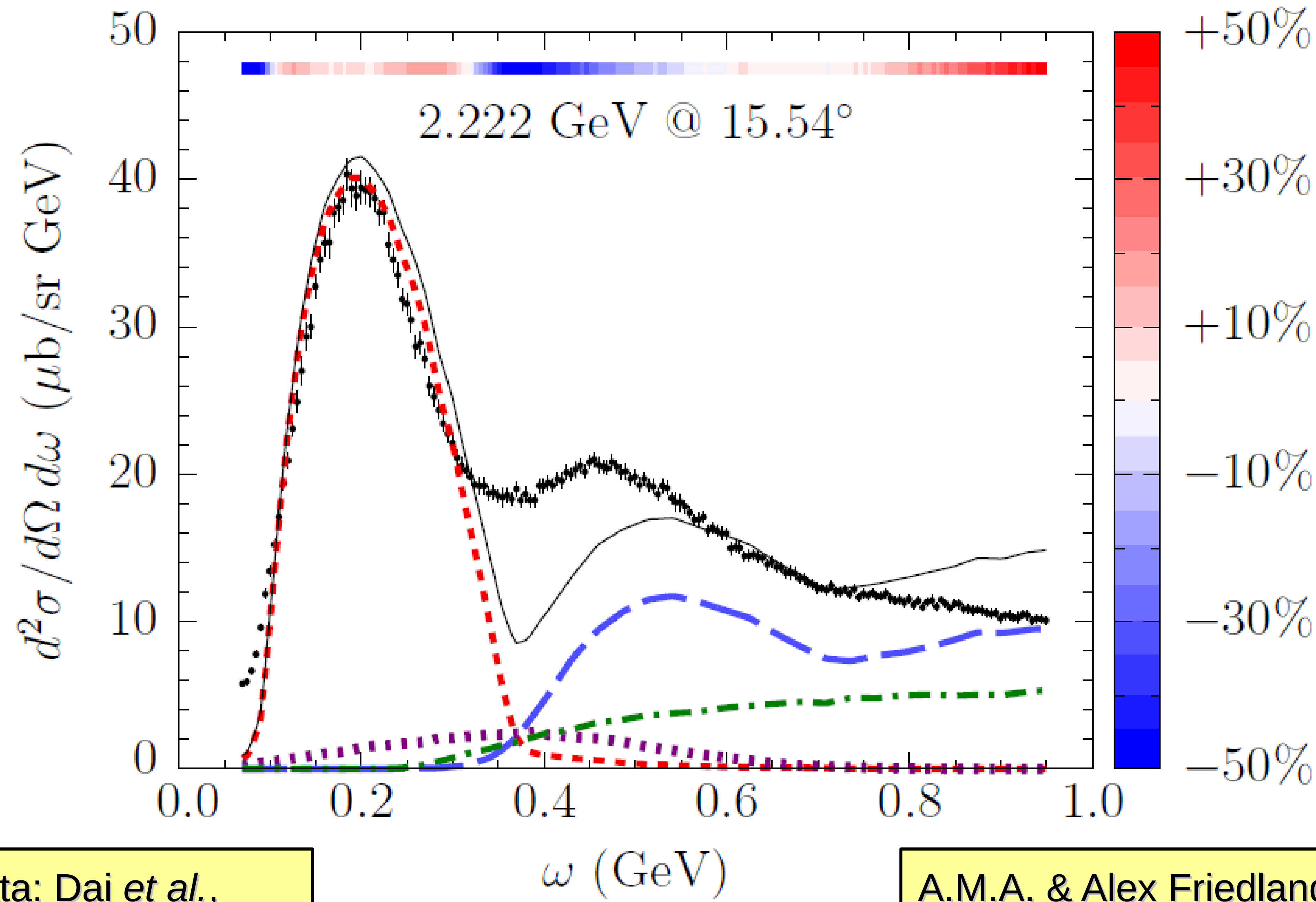
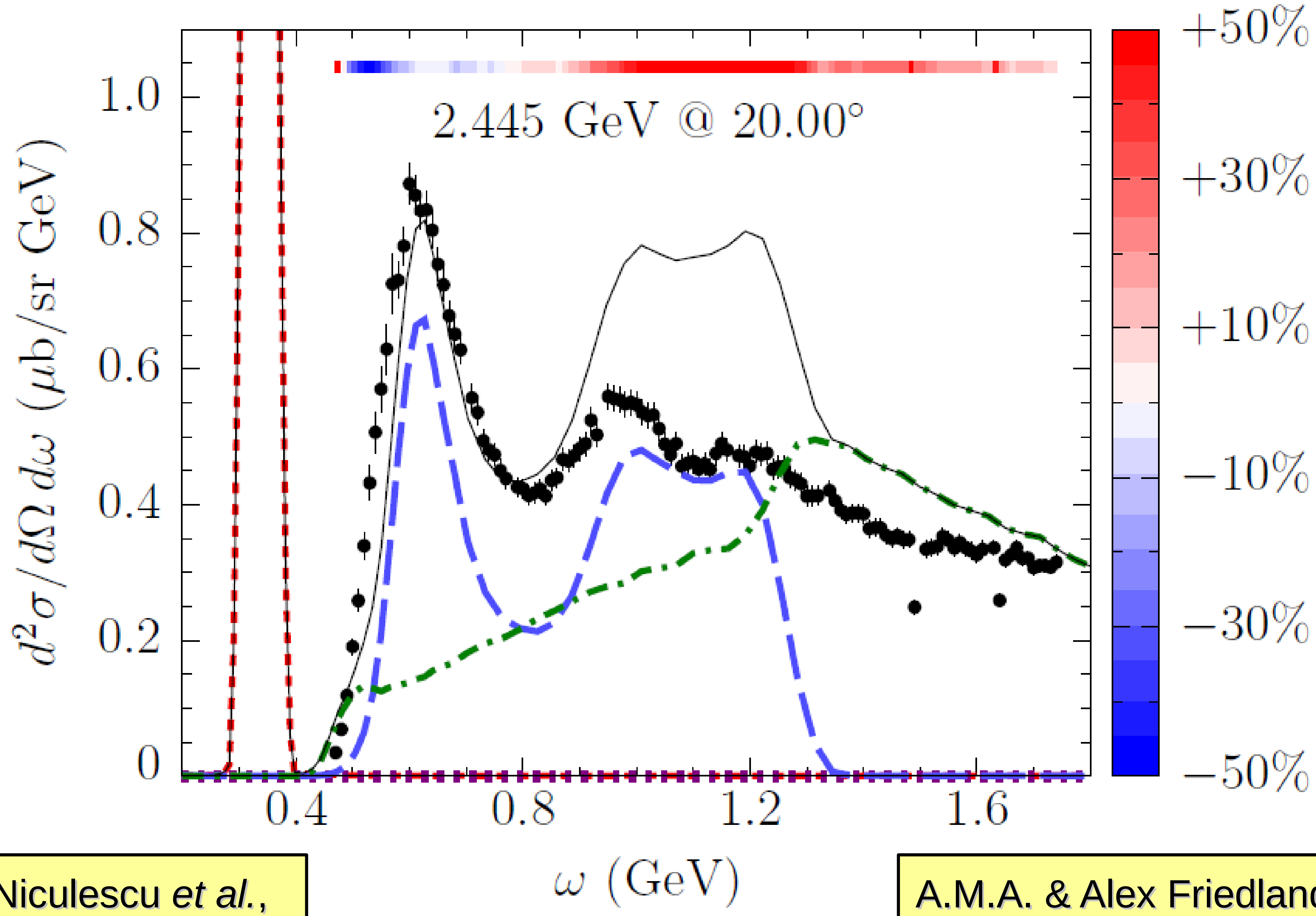



data: Dai *et al.*, PRC **98**, 014617 (2018)

A.M.A. & Alex Friedland, arXiv:2006.11944

# D(*e*, *e*’) in GENIE

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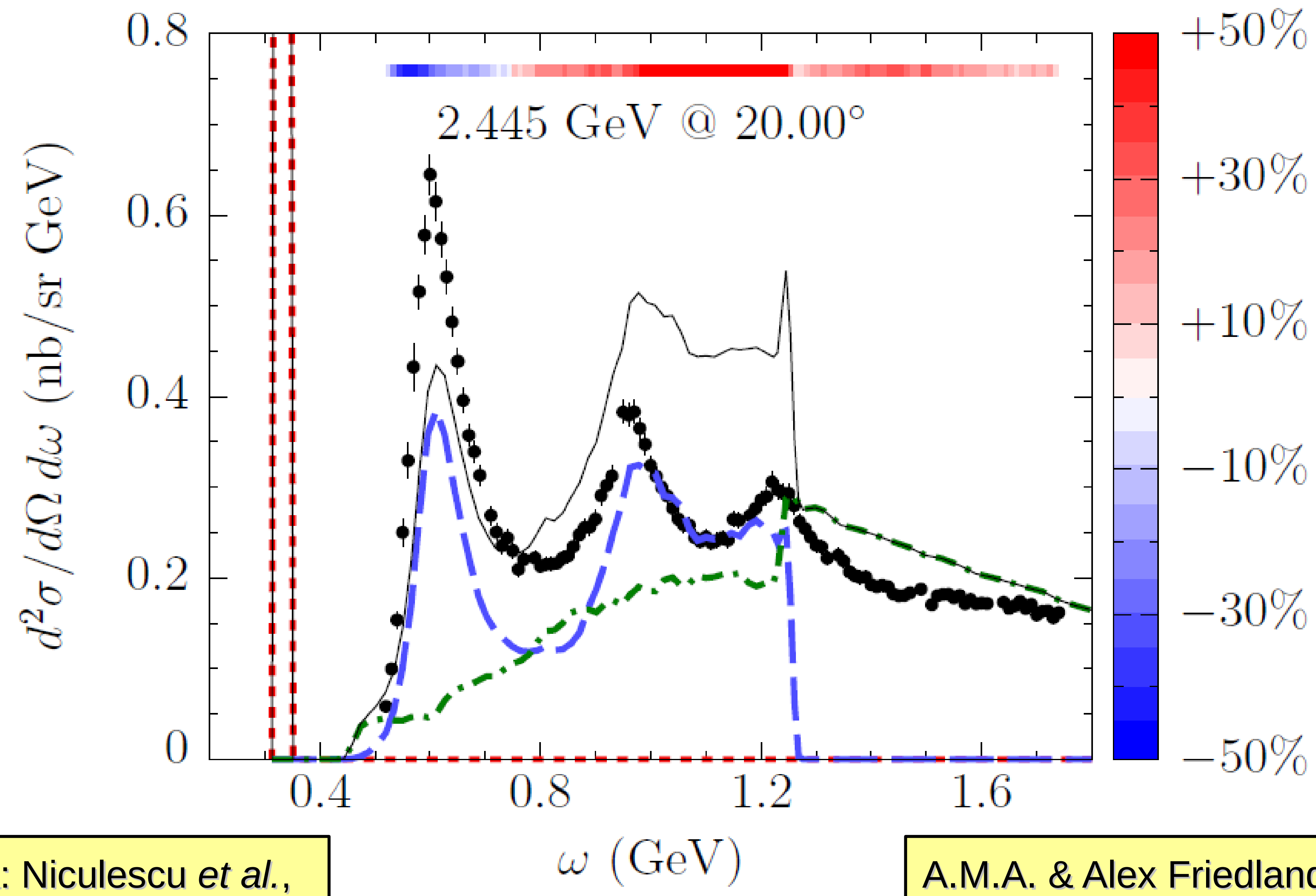


data: Niculescu *et al.*, PRL **85**, 1186 (2000)

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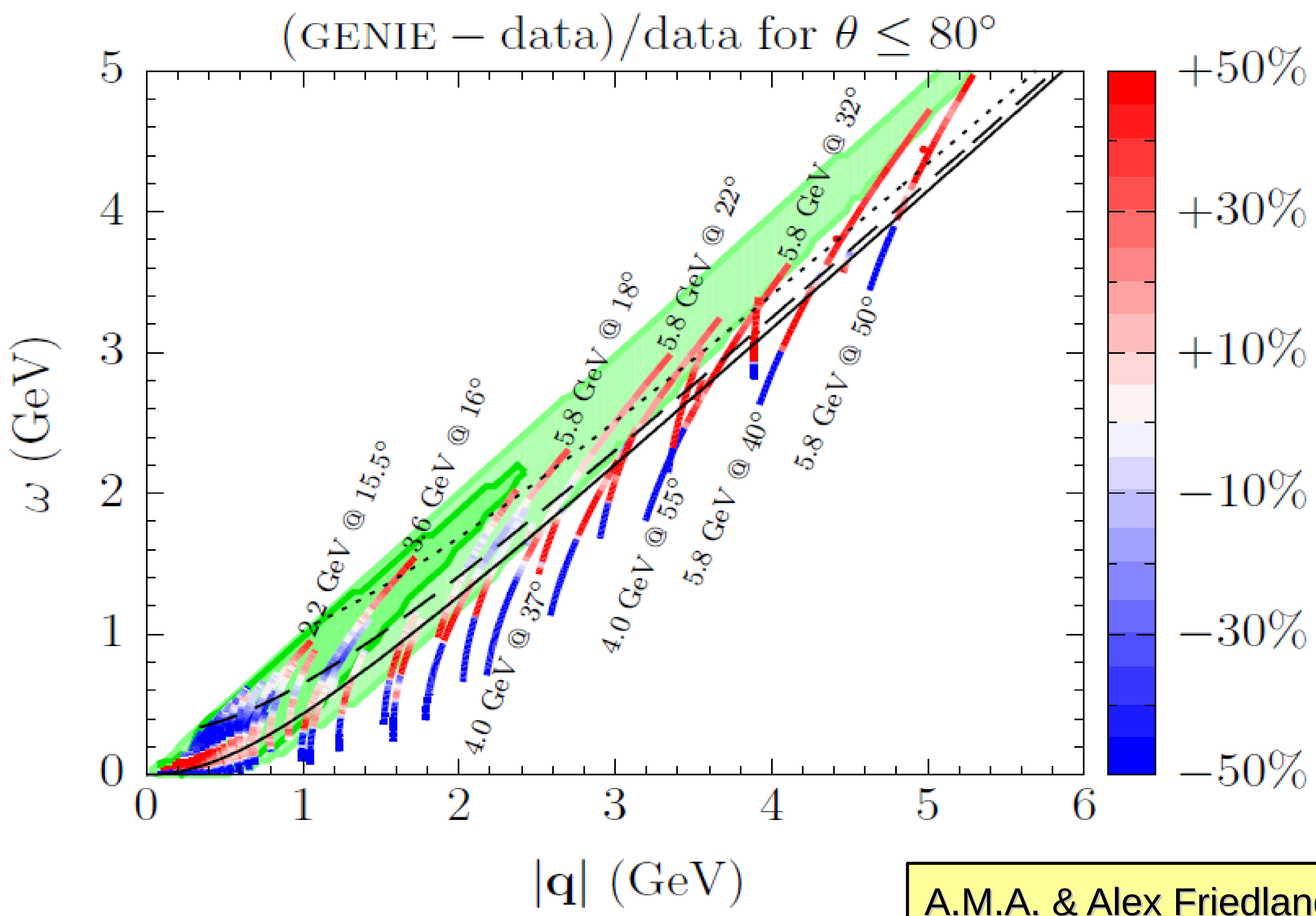
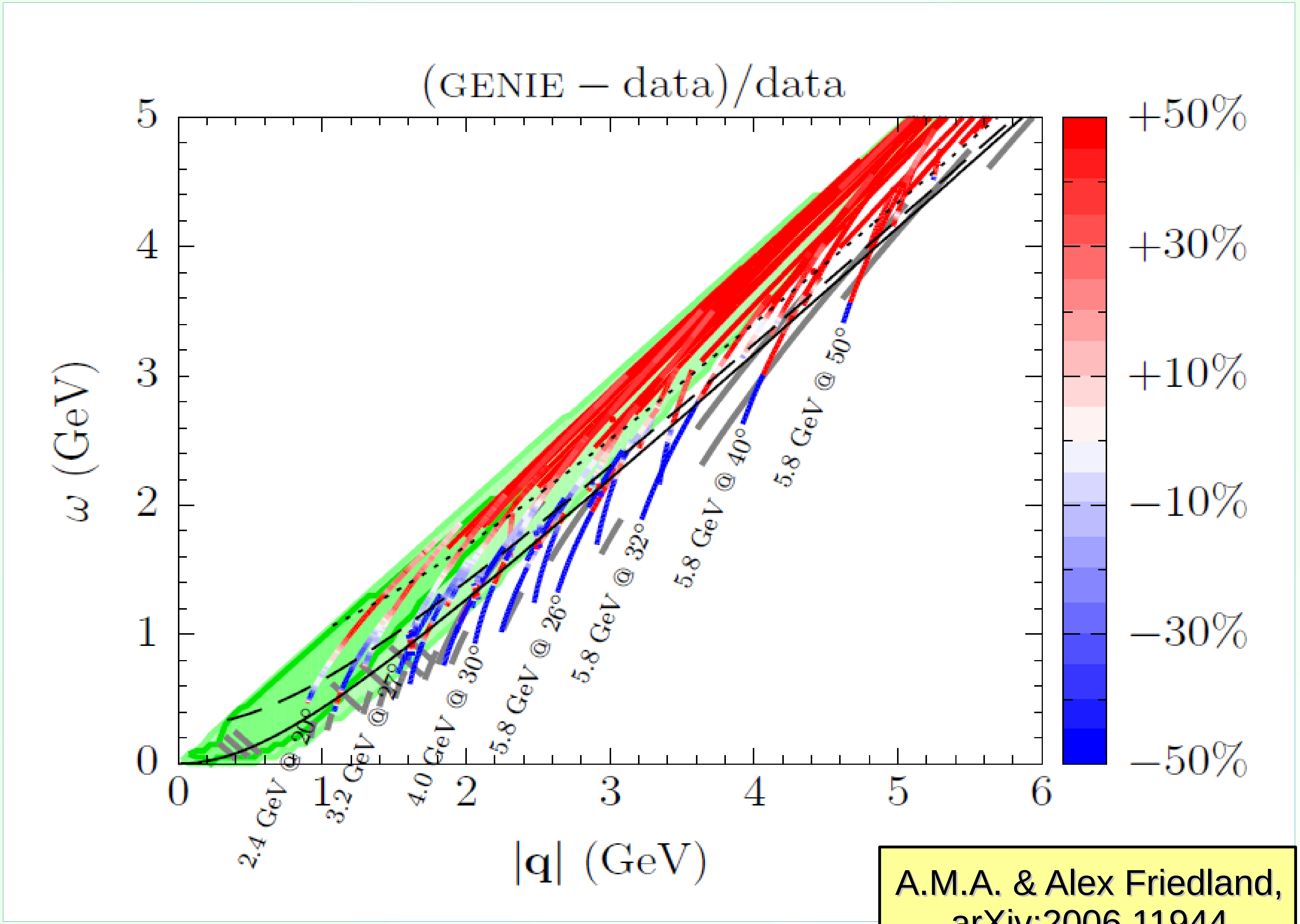


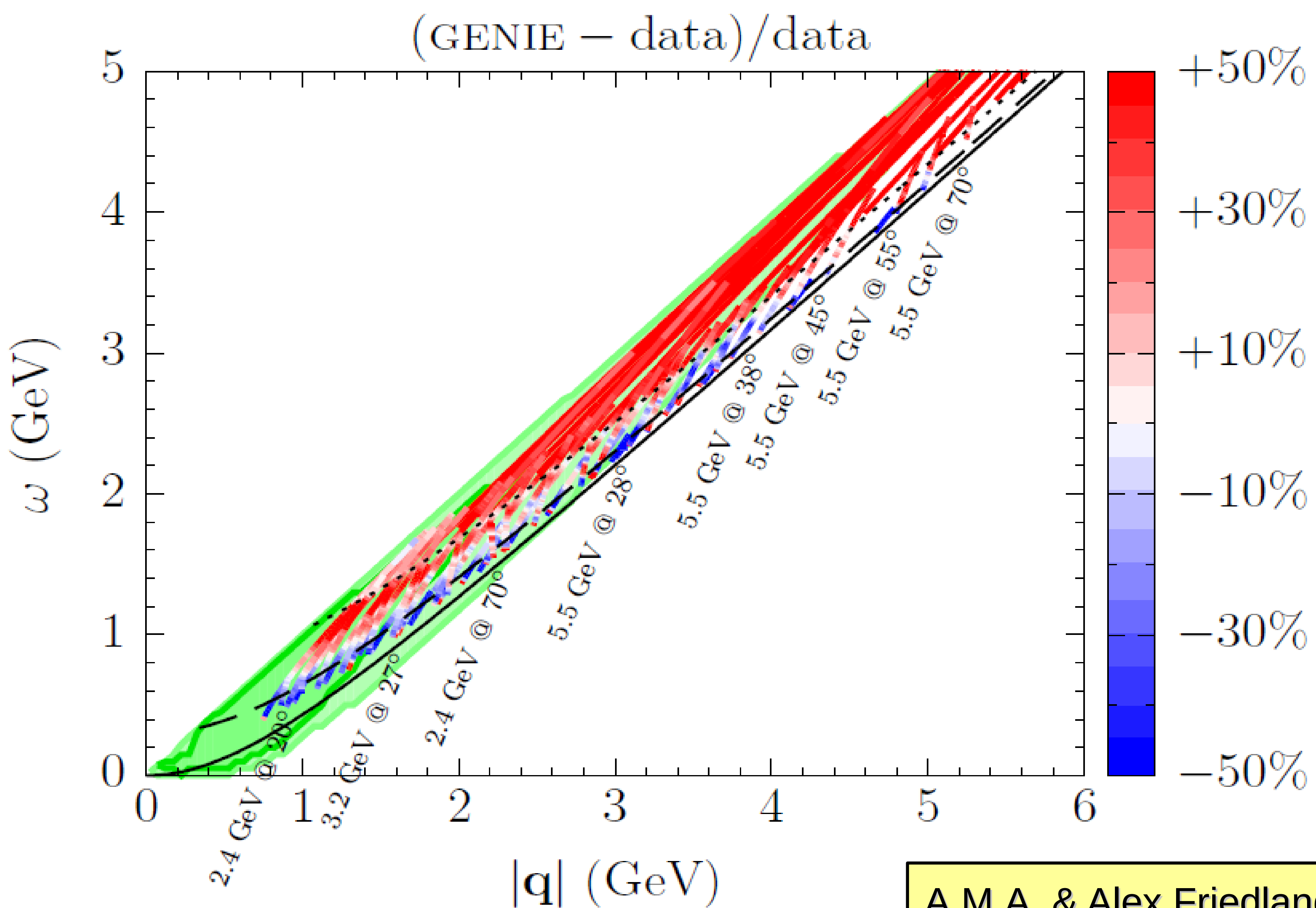

A.M.A. & Alex Friedland, arXiv:2006.11944

# D(*e*, *e*’) in GENIE




A.M.A. & Alex Friedland, arXiv:2006.11944

# H(*e*, *e*’) in GENIE




A.M.A. & Alex Friedland,
arXiv:2006.11944

# 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.

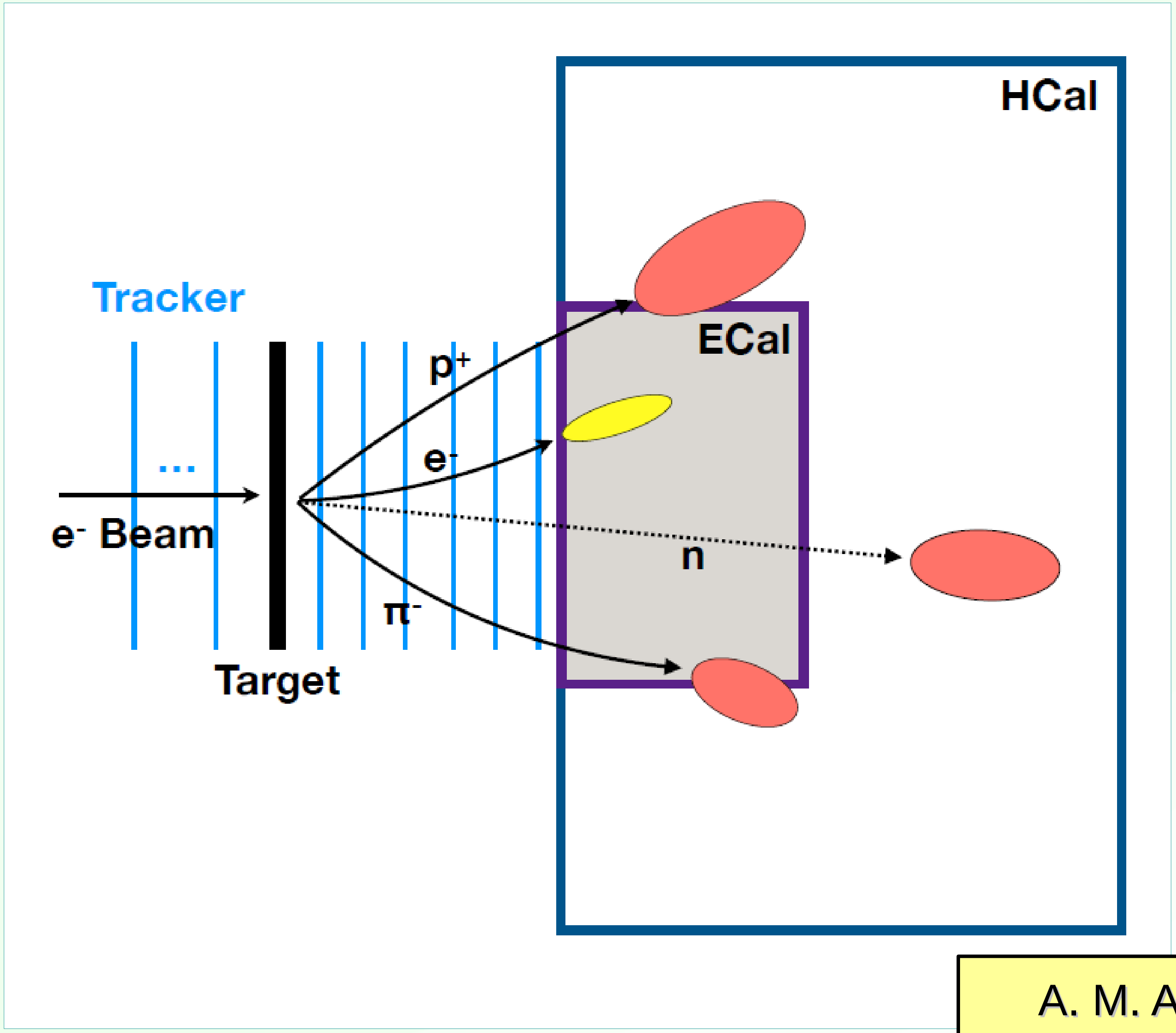
# Inclusive and exclusive cross sections for electron-nucleus scattering from LDMX

**Artur M. Ankowski**

**based on**
**A. M. A., Alexander Friedland, Shirley Weishi Li, Omar Moreno, Philip Schuster, Natalia Toro, and Nhan Tran, PRD 101, 053004 (2020)**

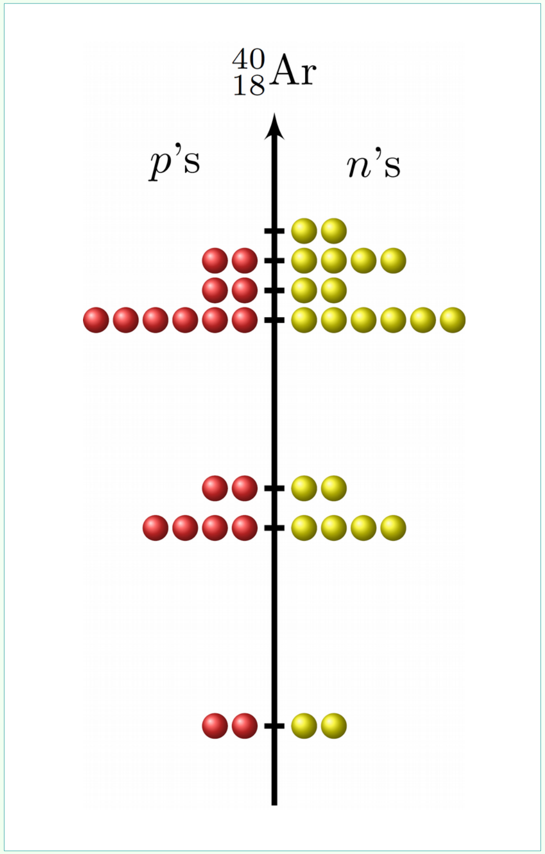
**SLACmass neutrino meeting, July 1, 2020**

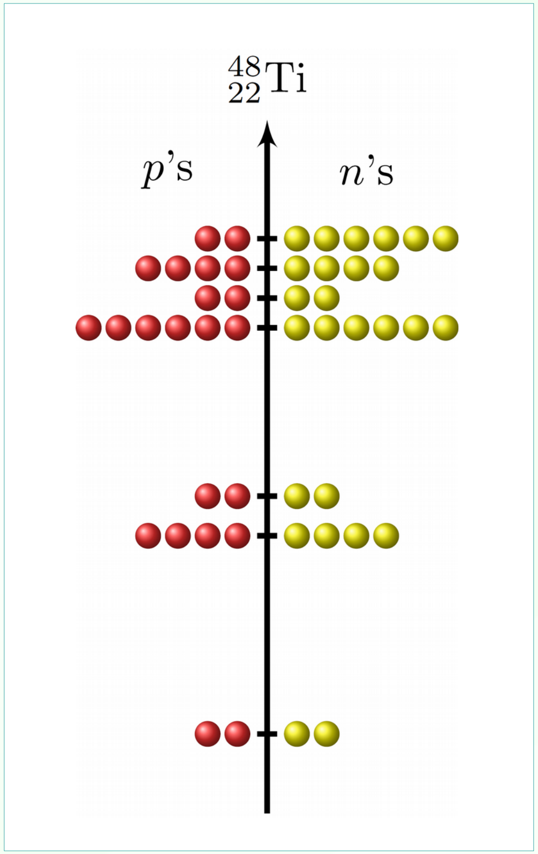
# Light Dark Matter eXperiment (LDMX)



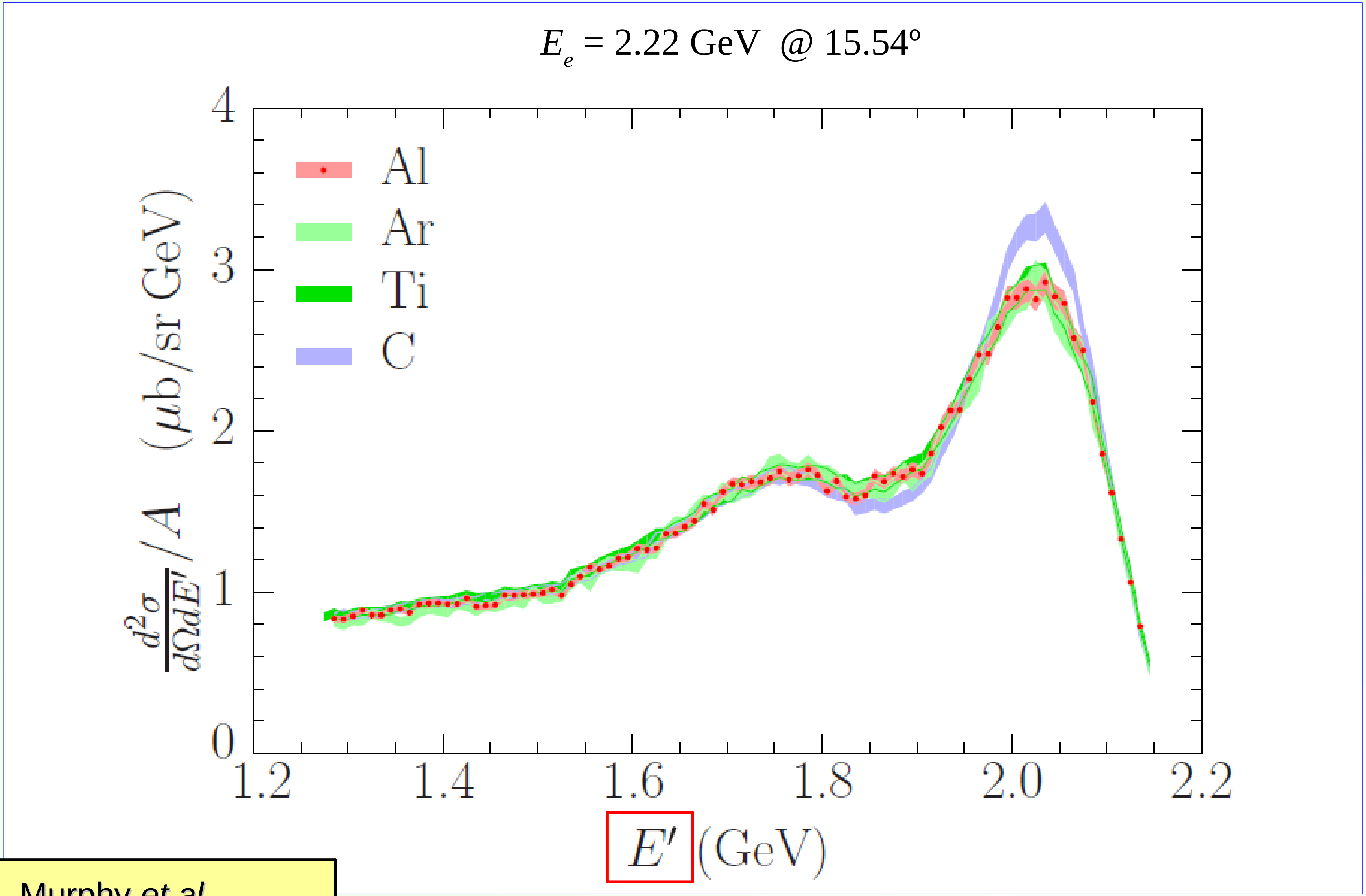

A. M. A. *et al.*, PRD 101, 053004 (2020)

# Argon vs. Titanium



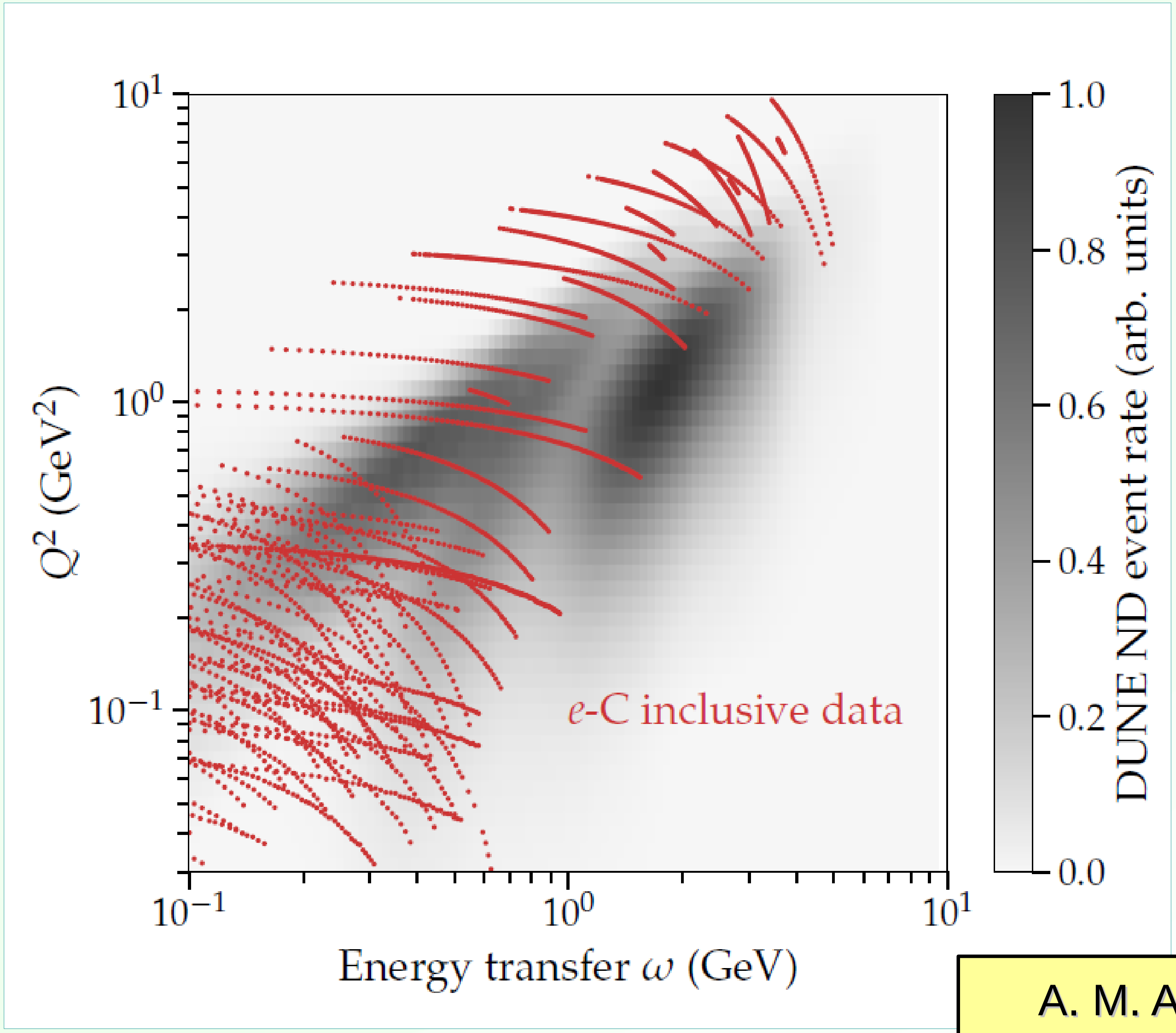



# Cross section's *A*-dependence




Murphy *et al.*,
PRC **100**, 054606 (2019)

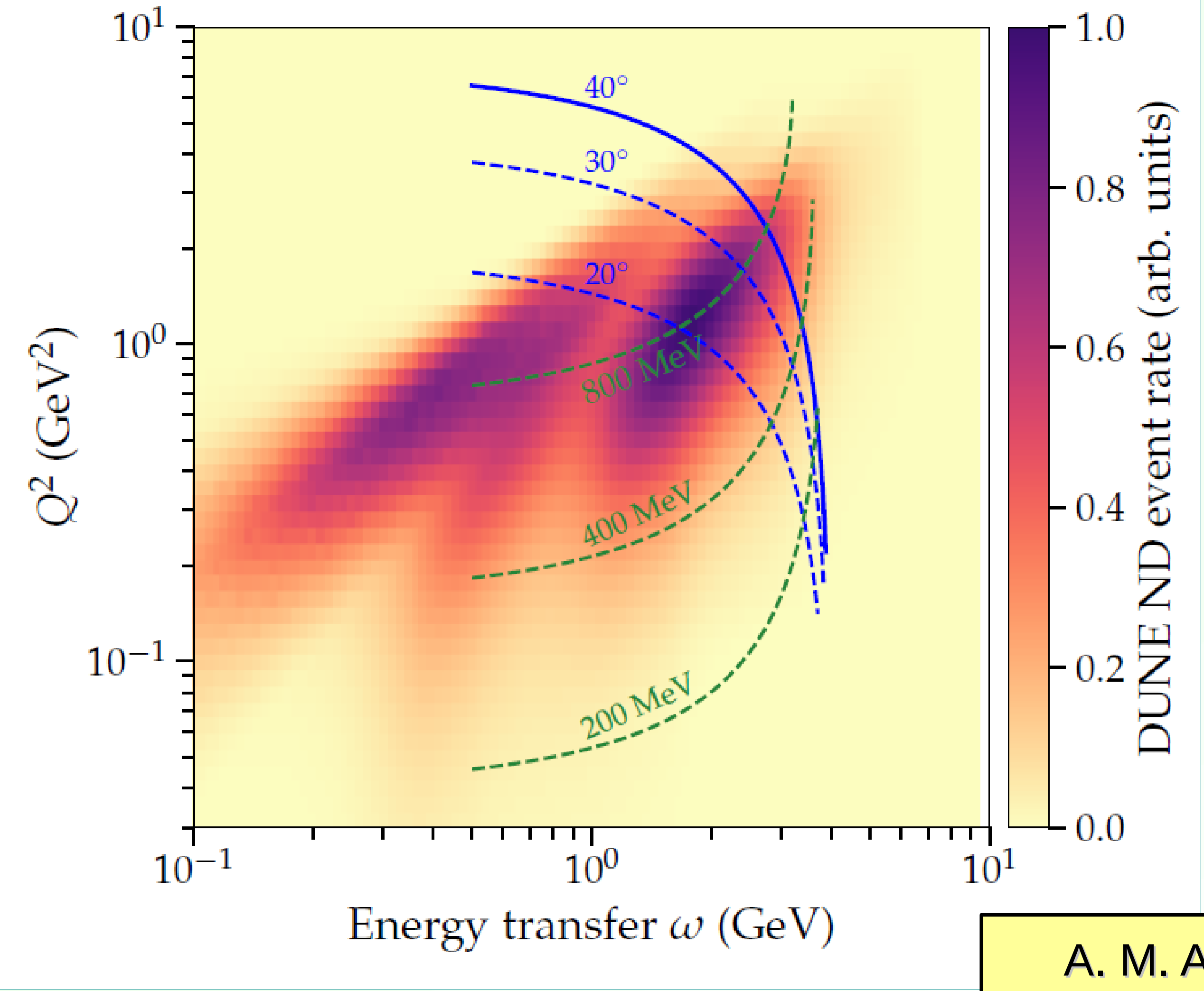
# Existing electron-scattering data




A. M. A. *et al.*,
PRD 101, 053004
(2020)

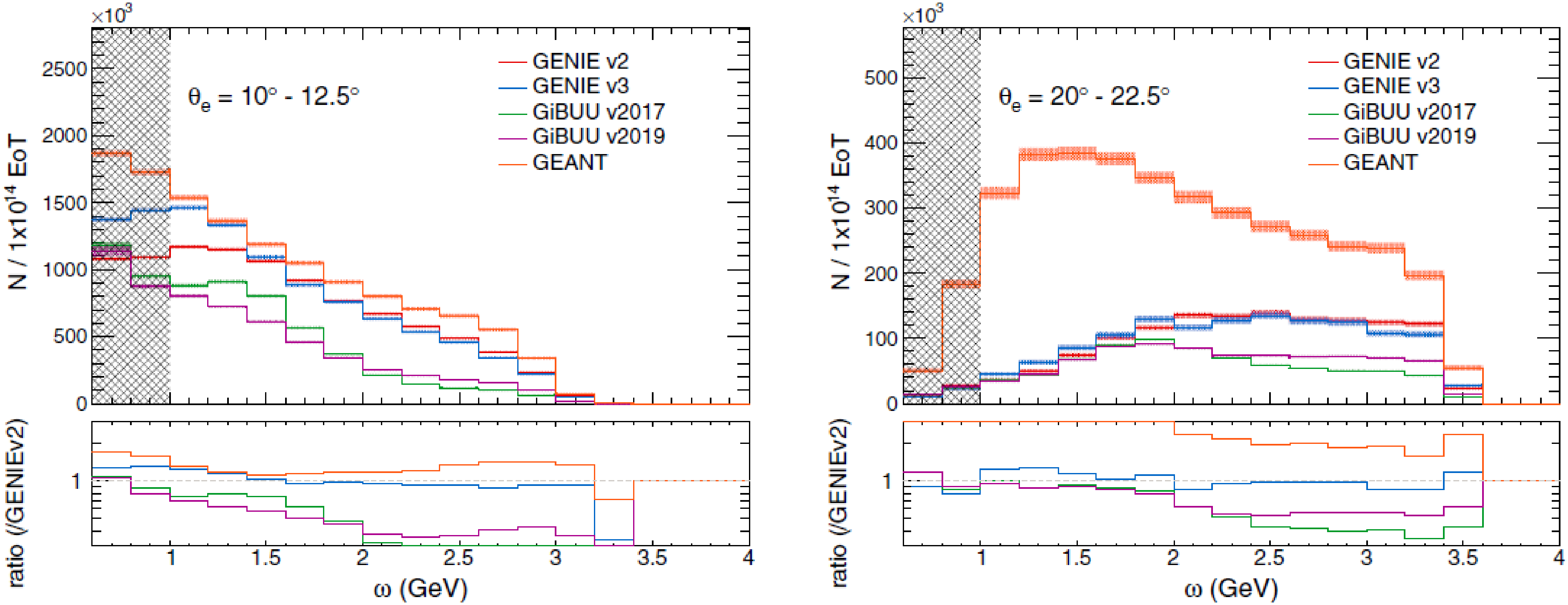
# Kinematics of LDMX & DUNE

**LDMX:** θ < 40°, $p_T$ > 10 MeV



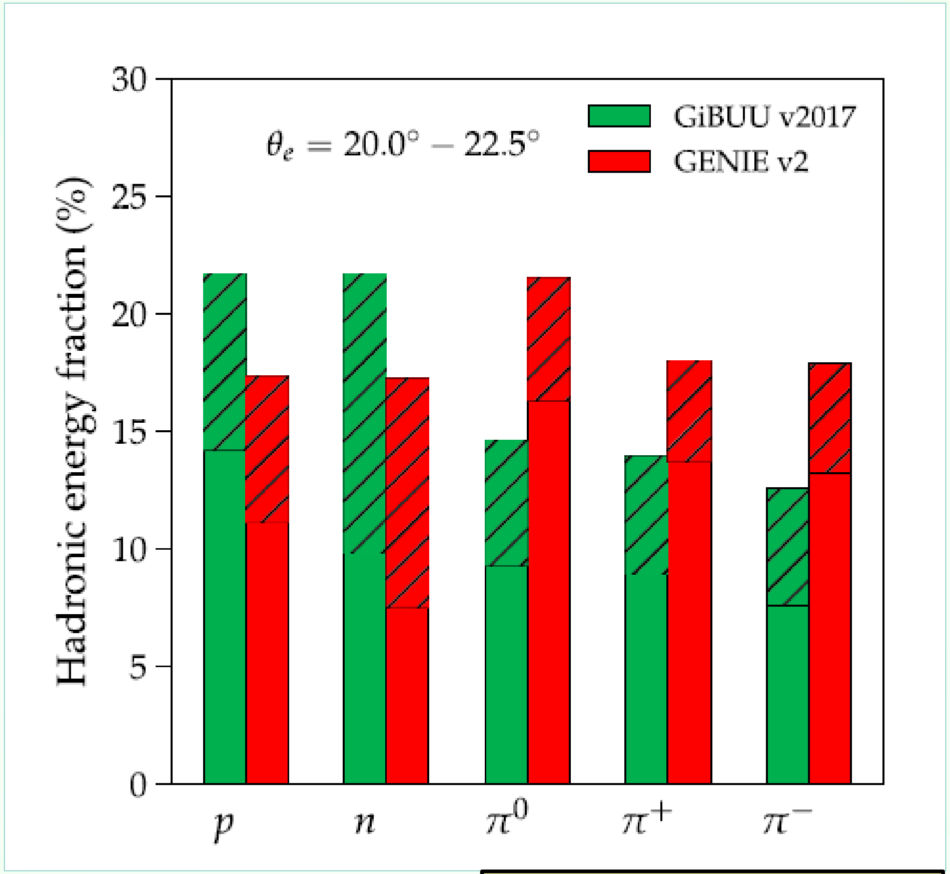

A. M. A. *et al.*, PRD 101, 053004 (2020)

# Inclusive cross sections



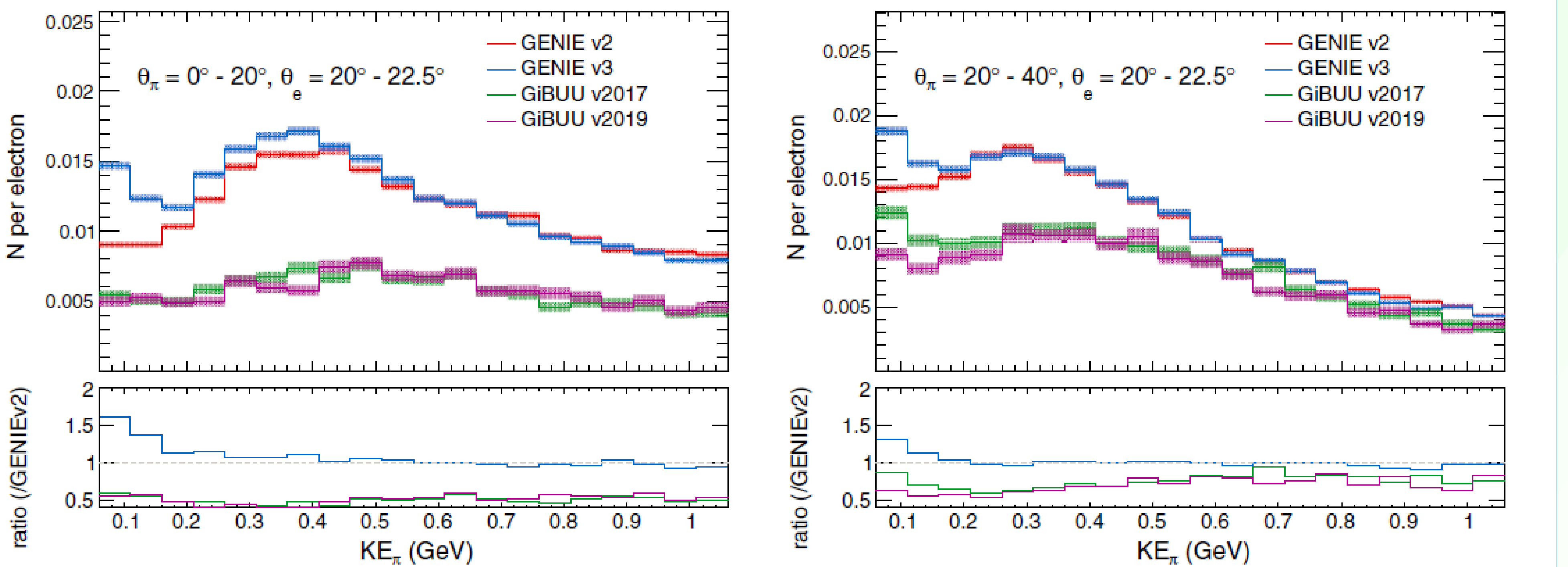

A. M. A. *et al.*, PRD 101, 053004 (2020)

# Exclusive cross sections



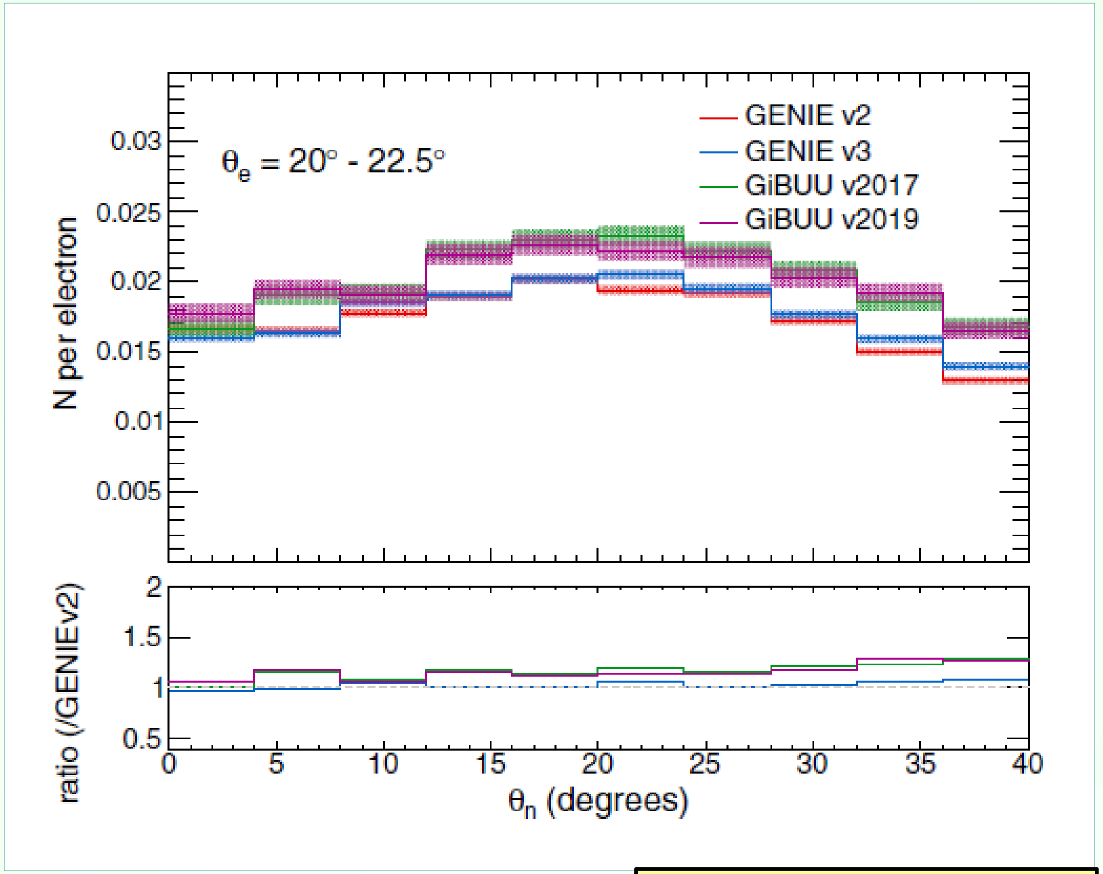

A. M. A. *et al.*, PRD 101, 053004 (2020)

# Exclusive pion production




A. M. A. *et al.*, PRD 101, 053004 (2020)

# Exclusive neutron knockout

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# Summary

- Accurate **exclusive** cross sections are essential for accurate neutrino energy reconstruction
- Electron-scattering data give **unique opportunity** of assessing the accuracy of Monte Carlo generators.
- At the DUNE kinematics, improvements of **pion production** are called for.
- Dark matter search in LDMX will provide invaluable data on **inclusive and exclusive** electron-scattering cross sections.
- Different targets possible, including **H, D, and Ar**

# Backup slides