Electron scattering for accurate neutrino cross sections

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based on A.M.A. and Alex Friedland, arXiv:1908.XXXXX

Precision Investigations of the Neutrino Sector (PINS 2019)
SLAC, July 14–17, 2019

Outline

1) **Introduction**

- Accurate neutrino-energy reconstruction requires accurate estimate of the cross sections
- Which reaction mechanisms are relevant for long-baseline experiments?
- MC generators must be tested against electron data

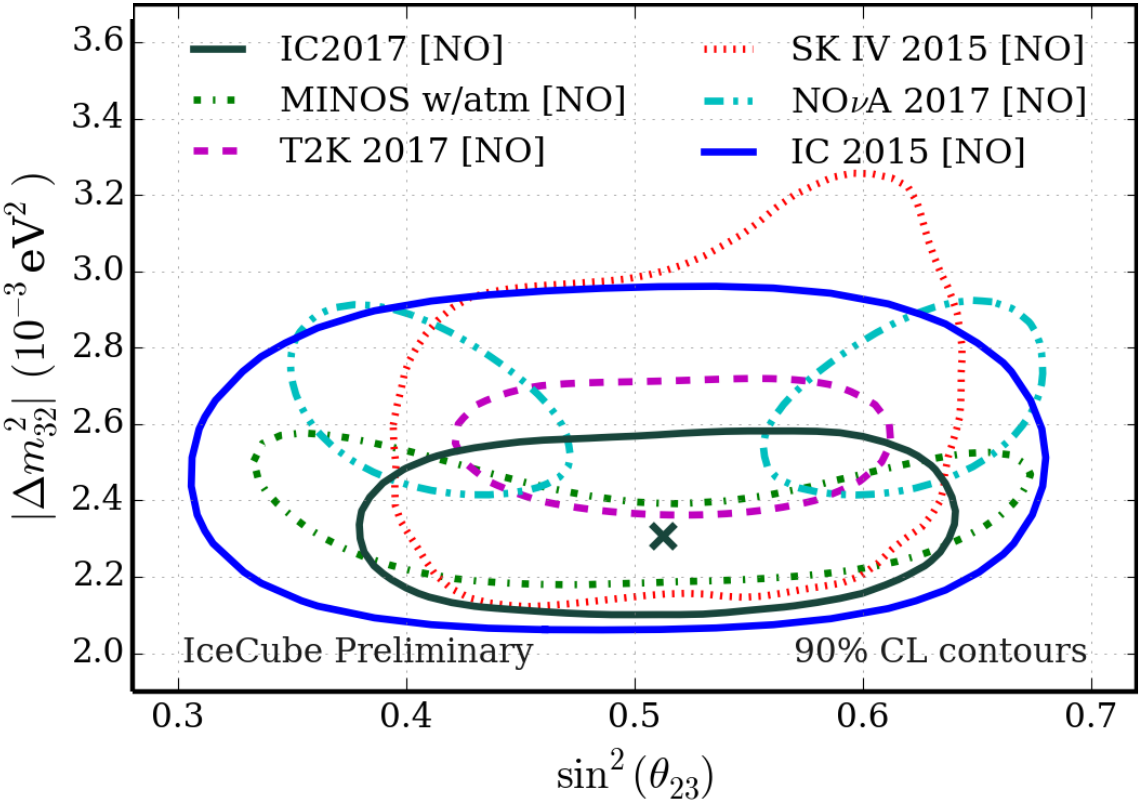
2) **Assessing the accuracy of GENIE**

- Examples of comparisons to electron-scattering data
- Global picture

3) **Summary**

Introduction

Current precision



J. Hignight (IceCube), APS April Meeting, 2017

Precision of energy reconstruction

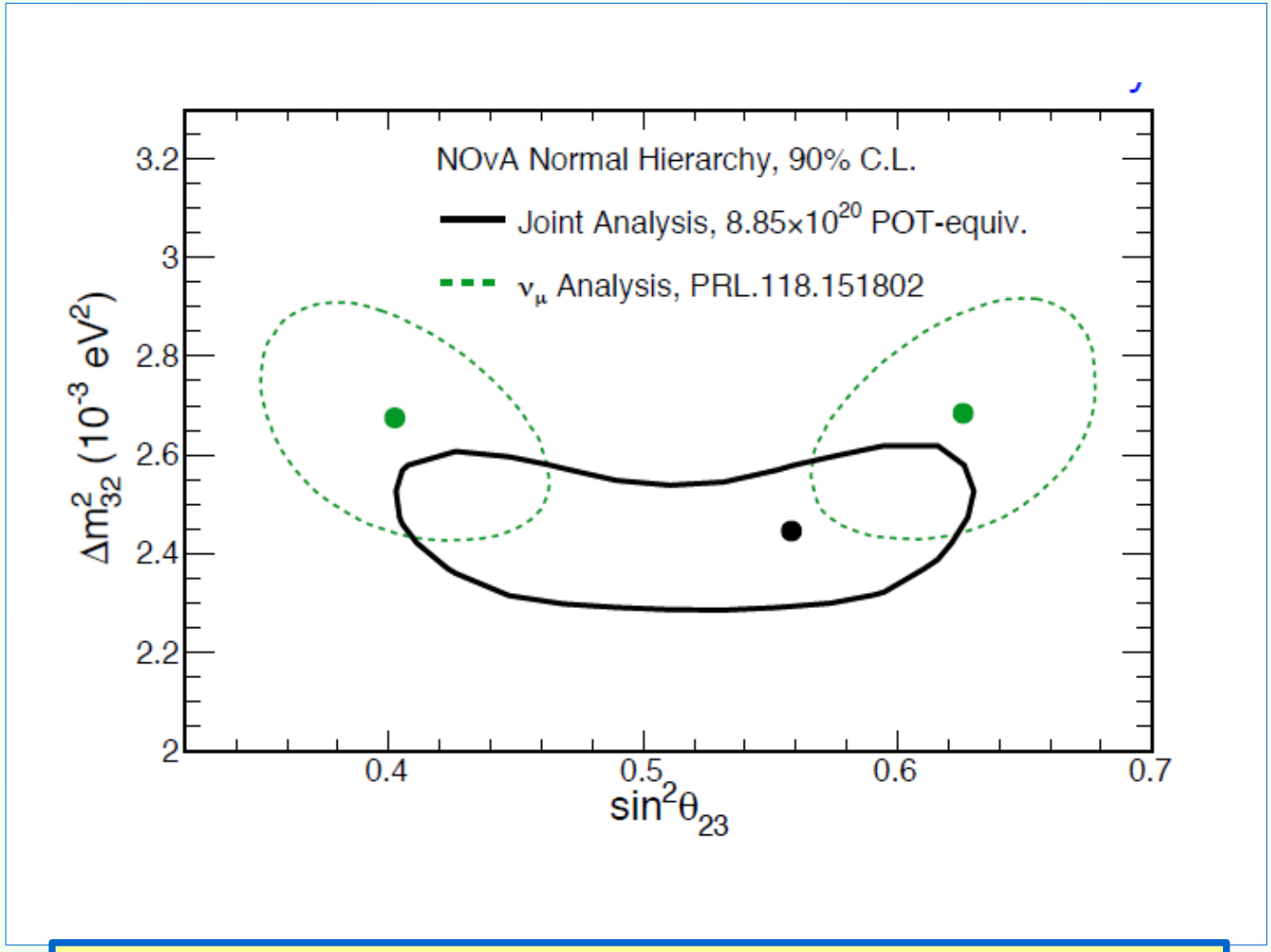
TABLE VIII. 1 σ confidence intervals for physics parameters in the normal mass hierarchy.

Parameter (units)	1 σ interval(s)
Δm^2_{32} ($10^{-3}\mathrm{eV}^2/c^4$)	[2.37,2.52]
$\sin^2\theta_{23}$	[0.43, 0.51] and [0.52, 0.60]
δ_{CP} (π)	[0, 0.12] and [0.91, 2]

Acero *et al.* (NOvA), PRD **98**, 032012 (2018)

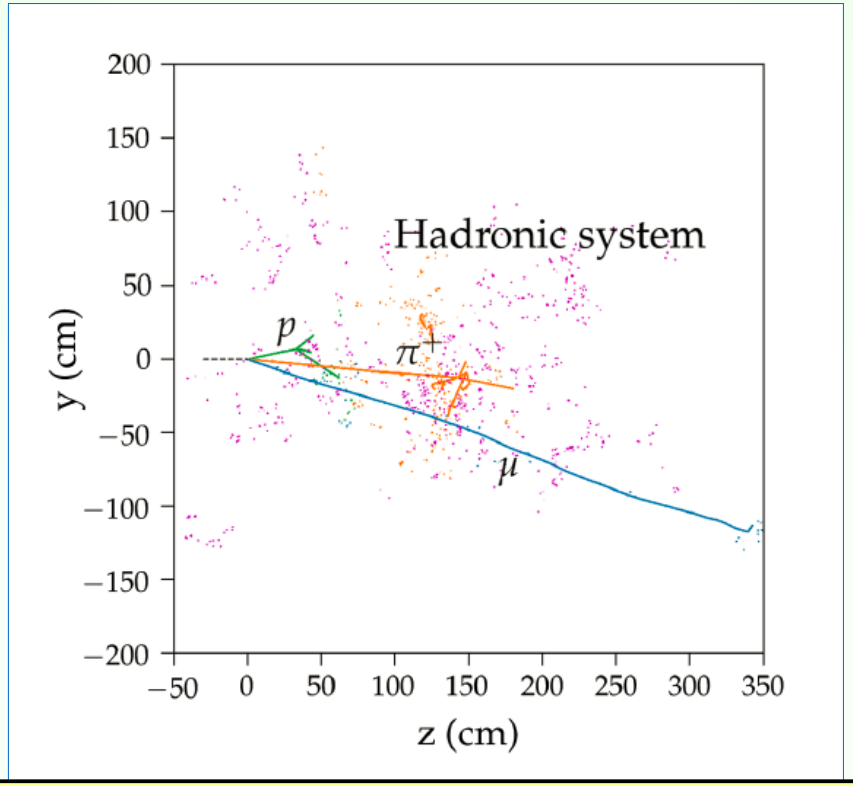
- In NOvA (~2 GeV), 3% uncertainty means $\mathcal{O}$(60 MeV).
- DUNE aims at uncertainties < 1% meaning $\mathcal{O}$(25 MeV) precision of energy reconstruction.

Precision of energy reconstruction



A. Radovic (NOvA), JETP Jan 12, 2018

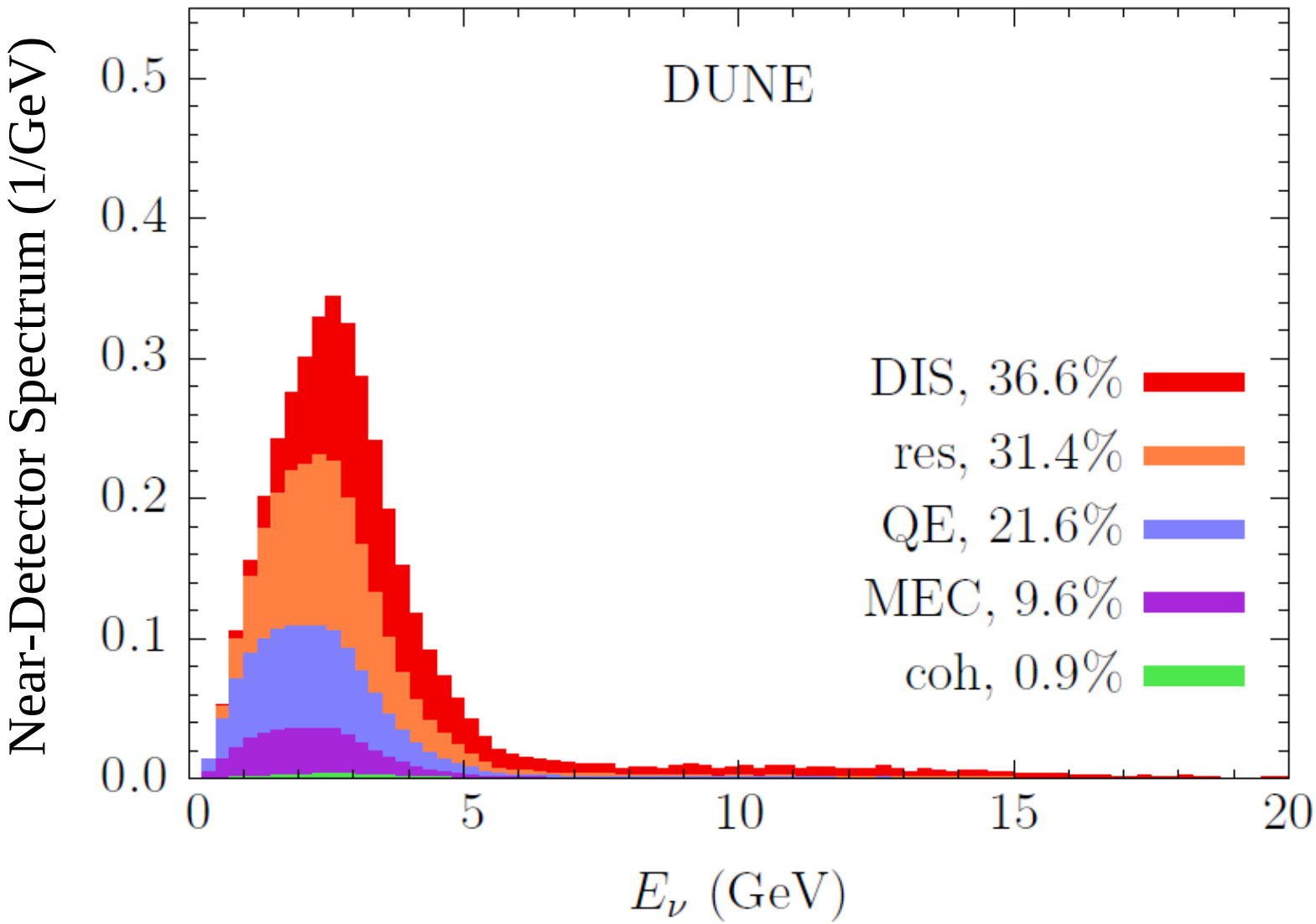
Monte Carlo generators



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.

Which cross sections are relevant?



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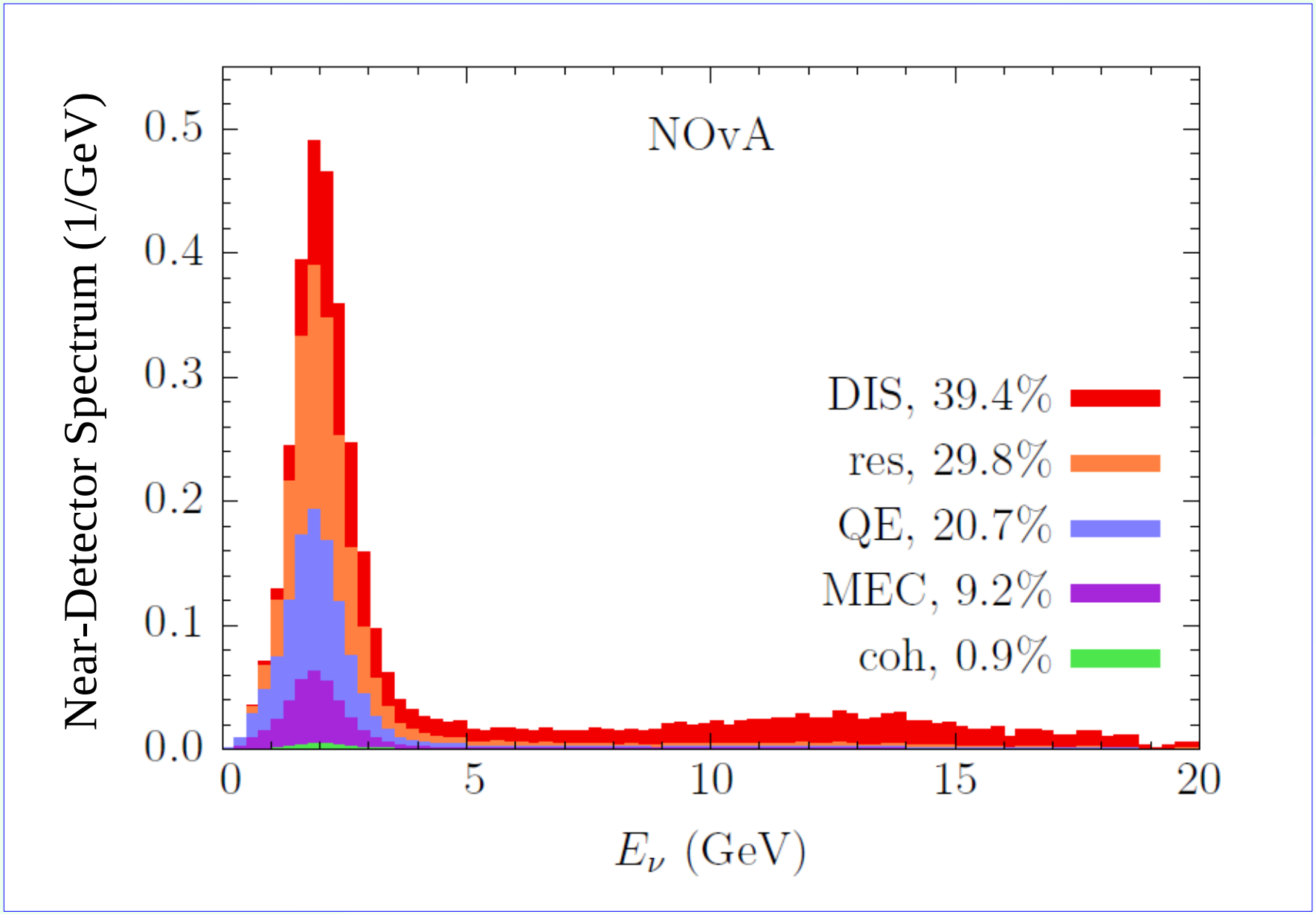
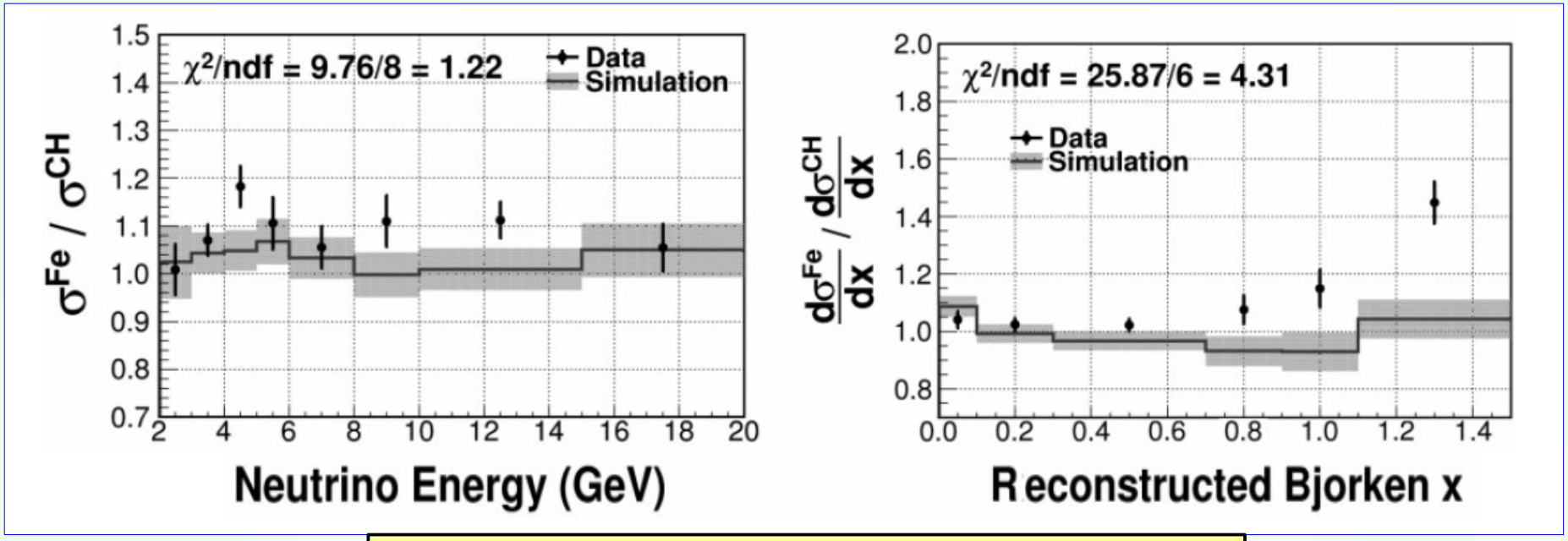


Which channels are problematic?



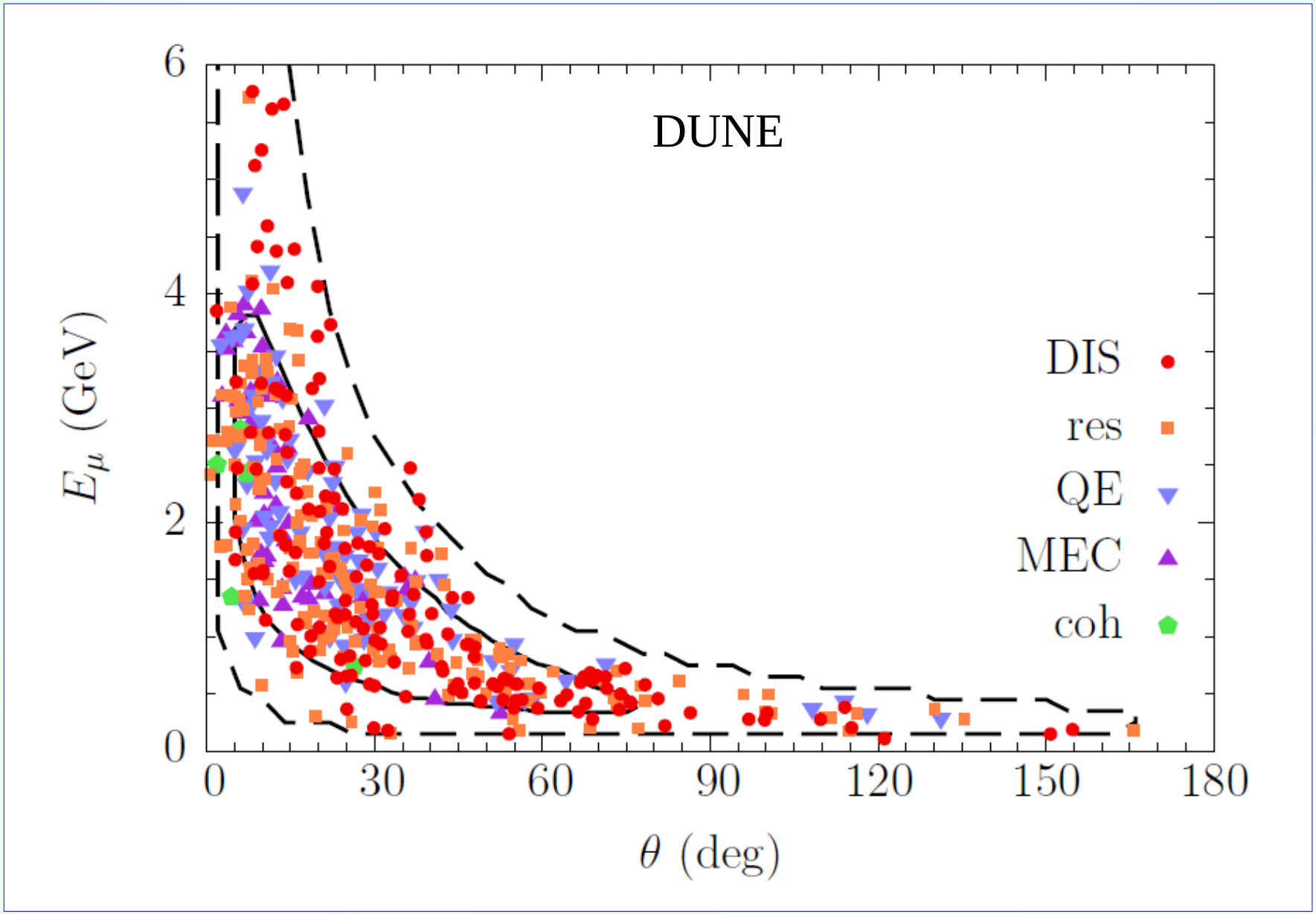
Tice *et al.* (MINERvA), PRL **112**, 231801 (2014)

"Simulation reproduces these measurements within roughly **10%**."

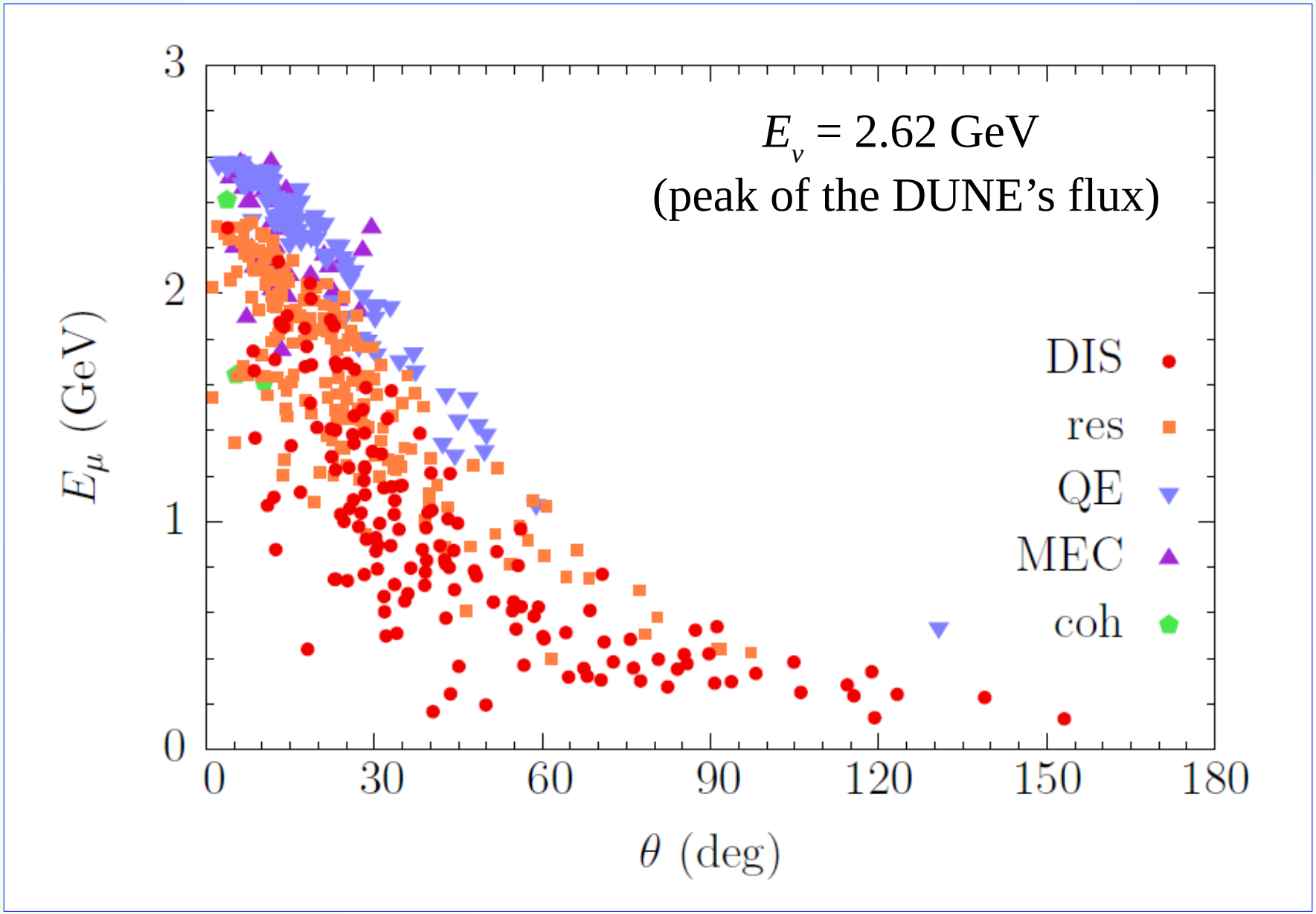
"The array of nuclear models available ... give similar results for these cross section ratios, **none of which is confirmed by the data**."

"**More theoretical work is needed to correctly model nuclear effects in neutrino interactions, from the QE to the DIS regime.**"

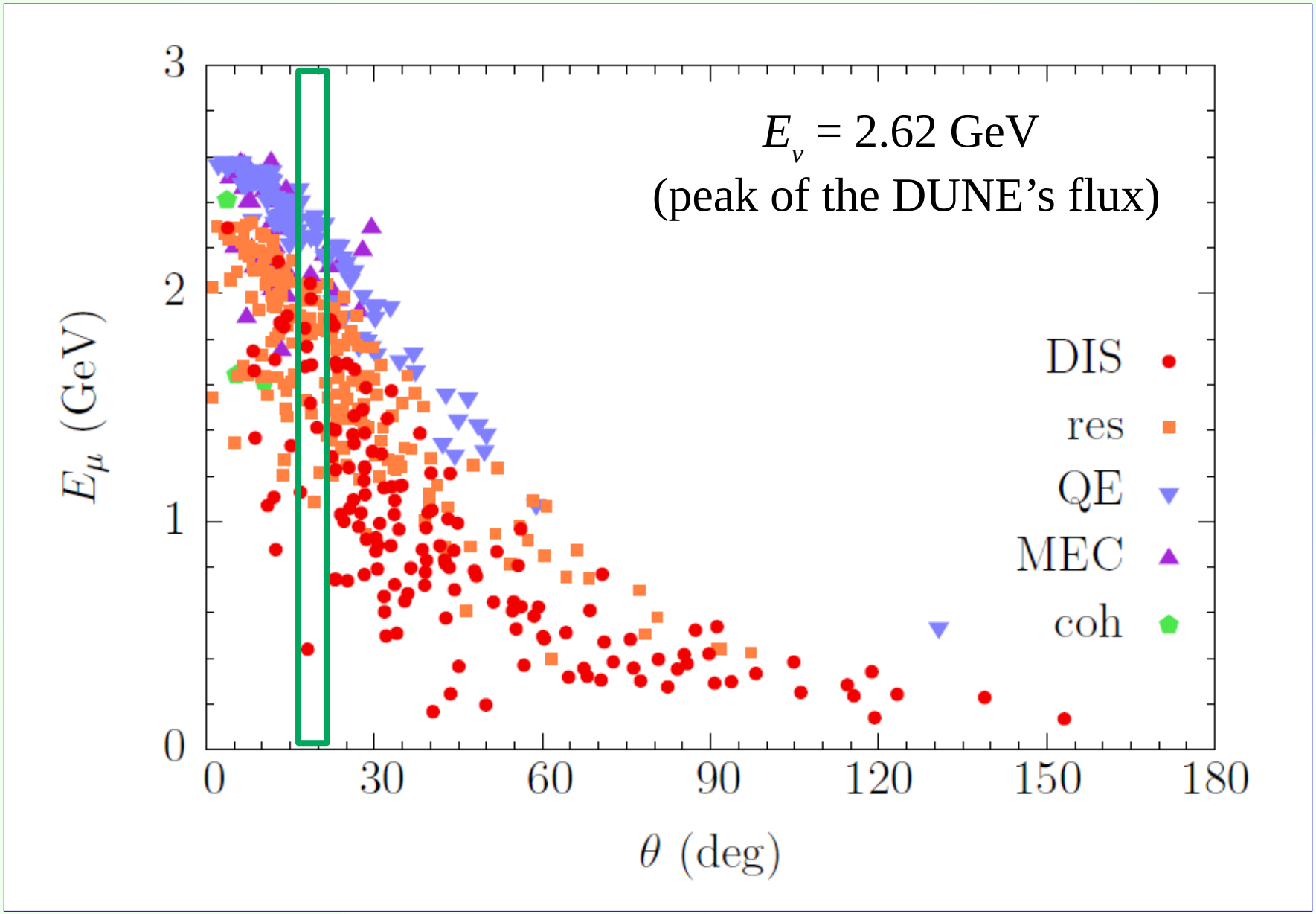
Muon kinematics mixes channels



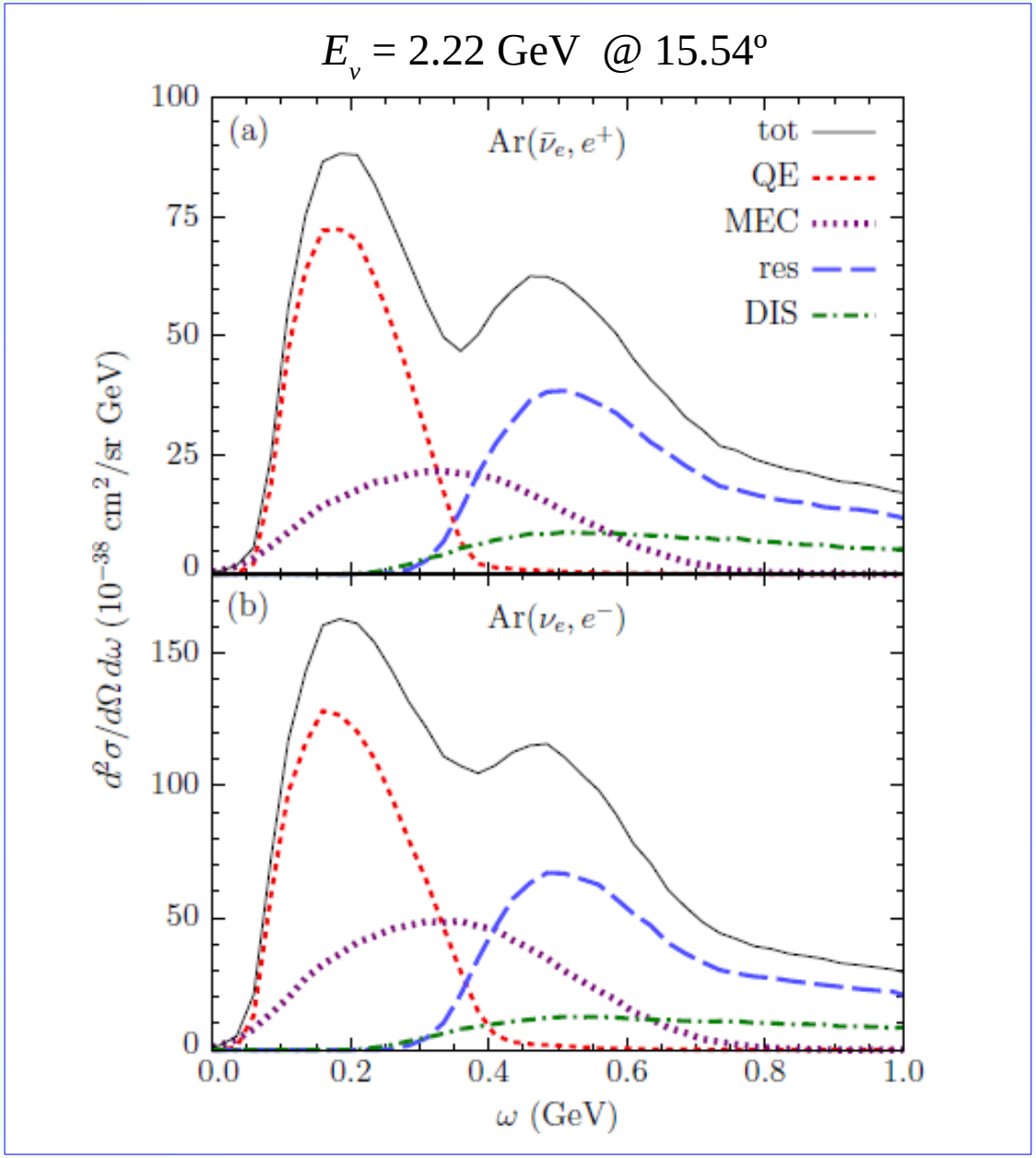
Monoenergetic beam



Monoenergetic beam



Double differential cross sections



Impulse approximation

For scattering in a given angle, neutrinos and electrons differ only due to the **elementary cross sections**.

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

Electron-scattering data allow us to test both the vector contribution to the neutrino cross sections and nuclear effects.

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

"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 non-perturbative 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)

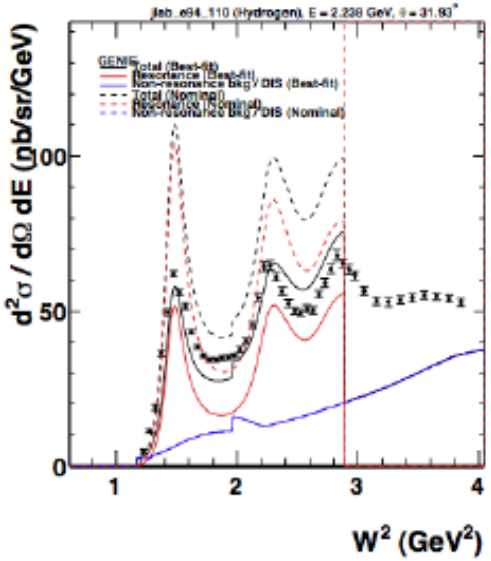
Scope of this talk

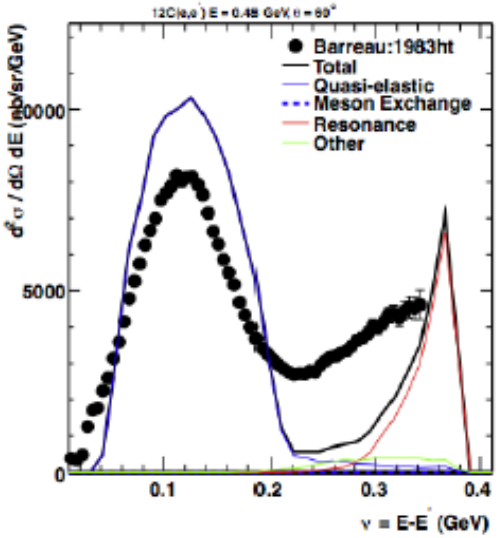
- What is the accuracy of GENIE at the DUNE's kinematics?
- Which channels are most problematic?
- Do the observed discrepancies follow a pattern?
- What is the origin of these issues? Do they affect neutrino simulations?

Validation running GENIE in electron mode

Not run as part of the validation procedure just yet. Tools exists for plotting $d^2\sigma/dE'd\Omega$ for Hydrogen/Deuterium (gvld_e_res_xsec, based on GENIE cross-section model) and for nuclear targets (gvld_e_qel_xsec, based on GENIE samples in electron mode).

Example plots:

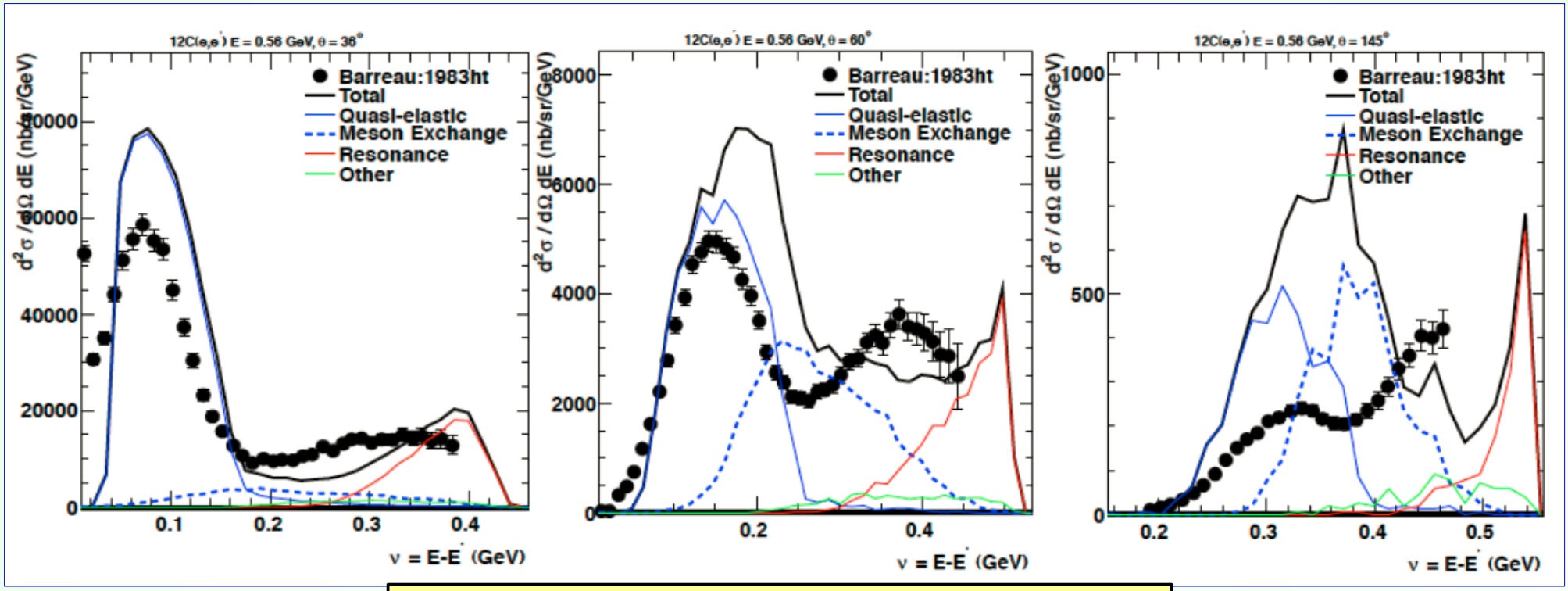




Well designed.
Enormous amounts of differential cross-section data (O(100k) data points).
Programs also support fitting (see top left plot).
Some bug somewhere affects non-QE component for nuclear targets.
Some awkwardness with hardcoded Q^2 cutoffs requires code recompilation for running the electron mode.
Both issues on my plate, never gets done...,

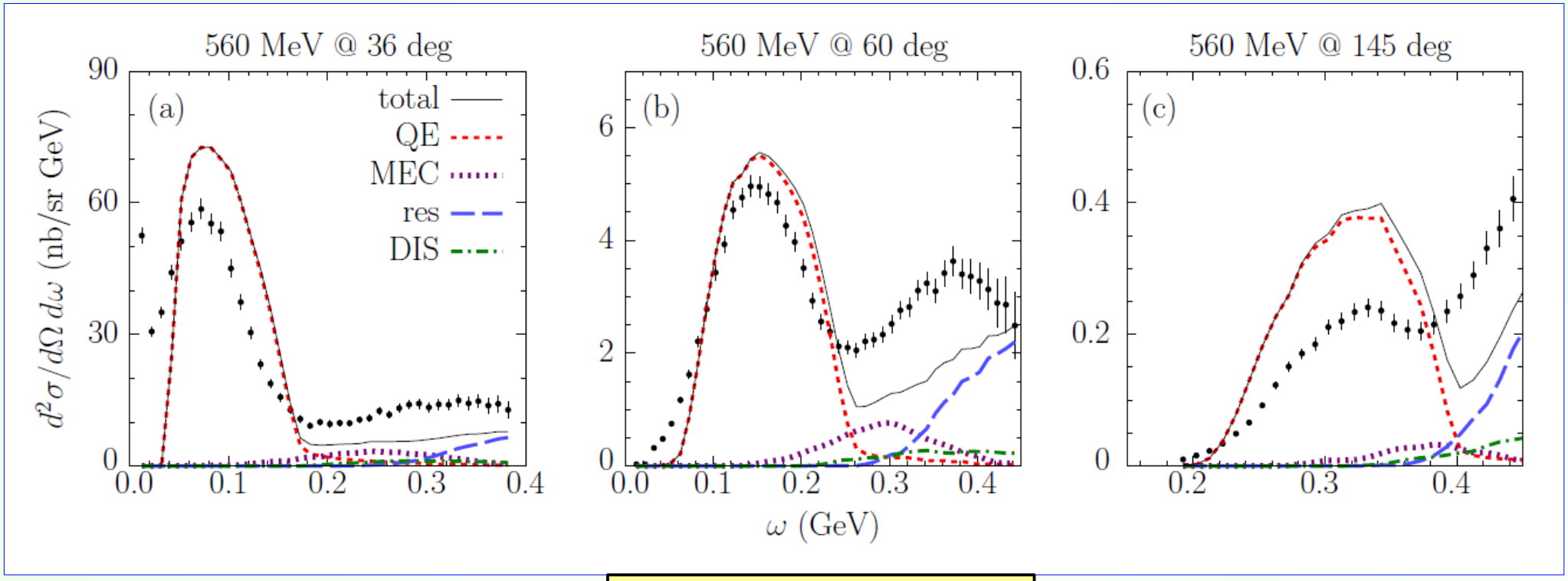
C. Andreopoulos, Dec 2013
http://projects-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=2927
Tools added to v. 2.6 (Mar '10) removed from v. 2.12 (Oct '16)

Past efforts



T. Katori @ NuInt2012
AIP Conf. Proc. **1663**,030001 (2015)

GENIE 2.12

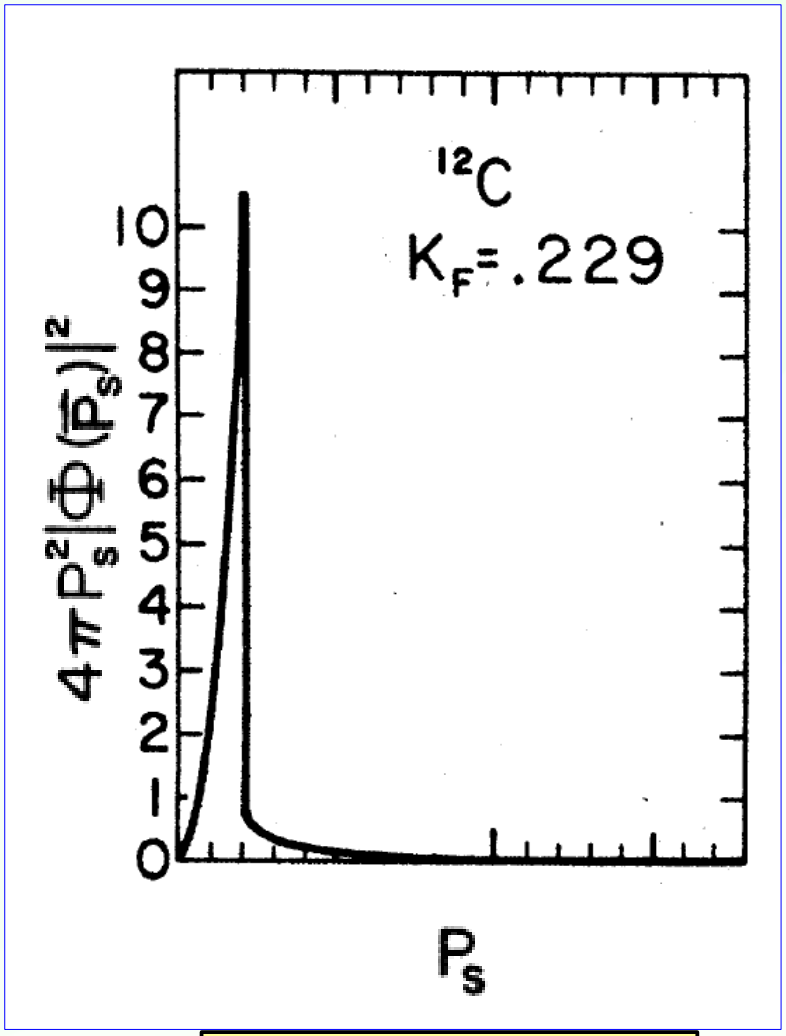


A.M.A. & Alex Friedland, arXiv:1908.XXXXX

GENIE in a nutshell

Nuclear model: relativistic Fermi gas of Bodek & Ritchie

- Nucleus treated as a fragment of noninteracting infinite nuclear matter of constant density. Translational invariance: eigenstates have definite momenta
- High momentum tail added to the momentum distribution
- No off shell effects



Bodek & Ritchie, PRD **23**, 1070 (1981)

GENIE in a nutshell

Quasielastic (QE) interactions

- Constant binding energy subtracted from the total energy of particles in the final state

- Llewellyn-Smith (Rosenbluth) formula for neutrinos (electrons). Parameters fitted to deuteron data.

Meson-exchange currents (MEC)

- Phenomenological Dytman approach [Katori, arXiv:1304.6014] developed to describe the neutrino data from MiniBooNE

GENIE in a nutshell

Pion production

- Resonance excitation in the framework of the model of Rein and Sehgal (16 resonances with parameters from PDG, *no interference between them*)

Deep-inelastic scattering (DIS)

- Implementation of the model of Bodek and Yang.
  DIS is the only mechanism of interaction for $W > 1.7$ GeV, used also to calculate nonresonant background for lower invariant hadronic masses.

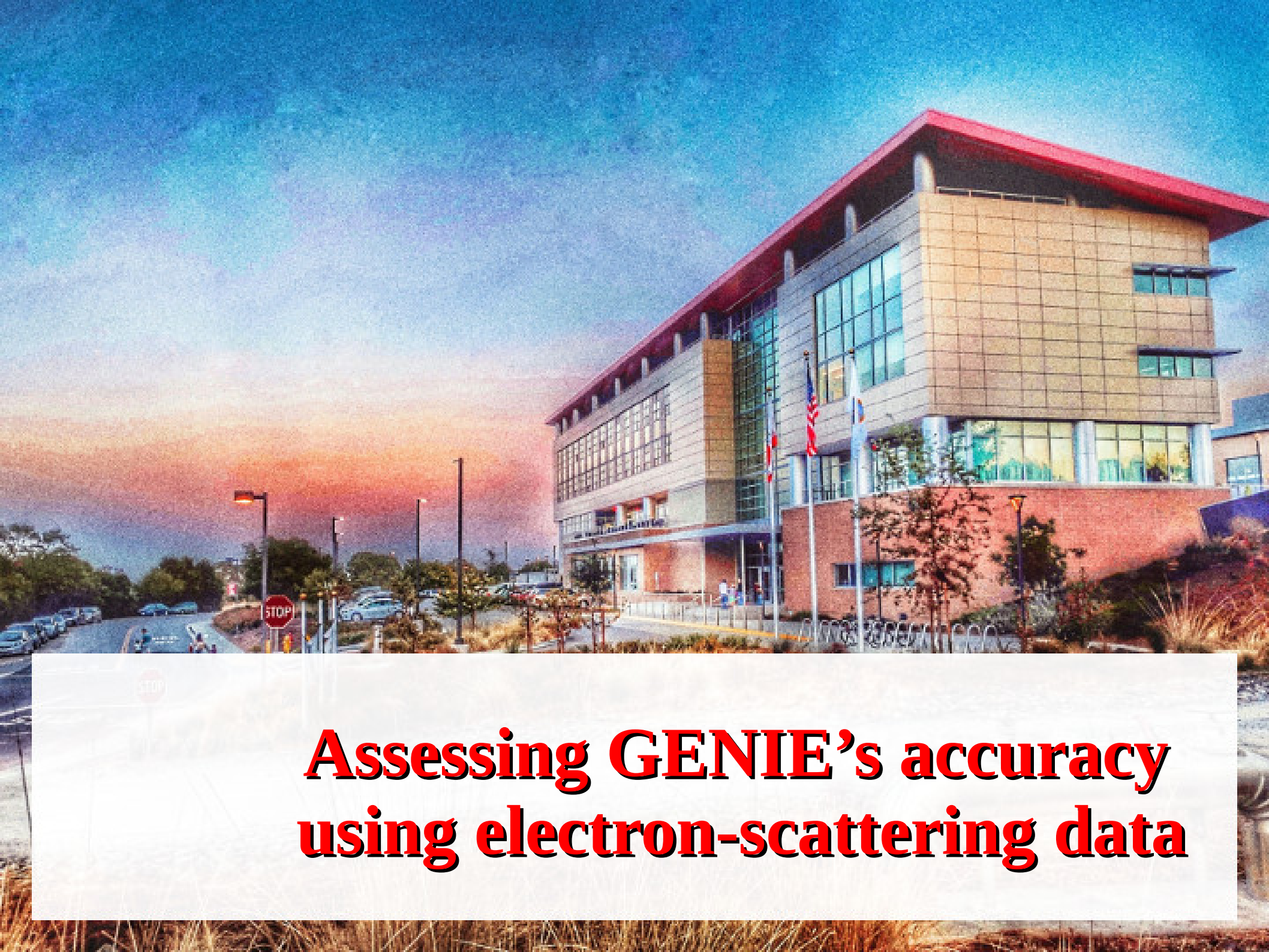
GENIE in a nutshell

- 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

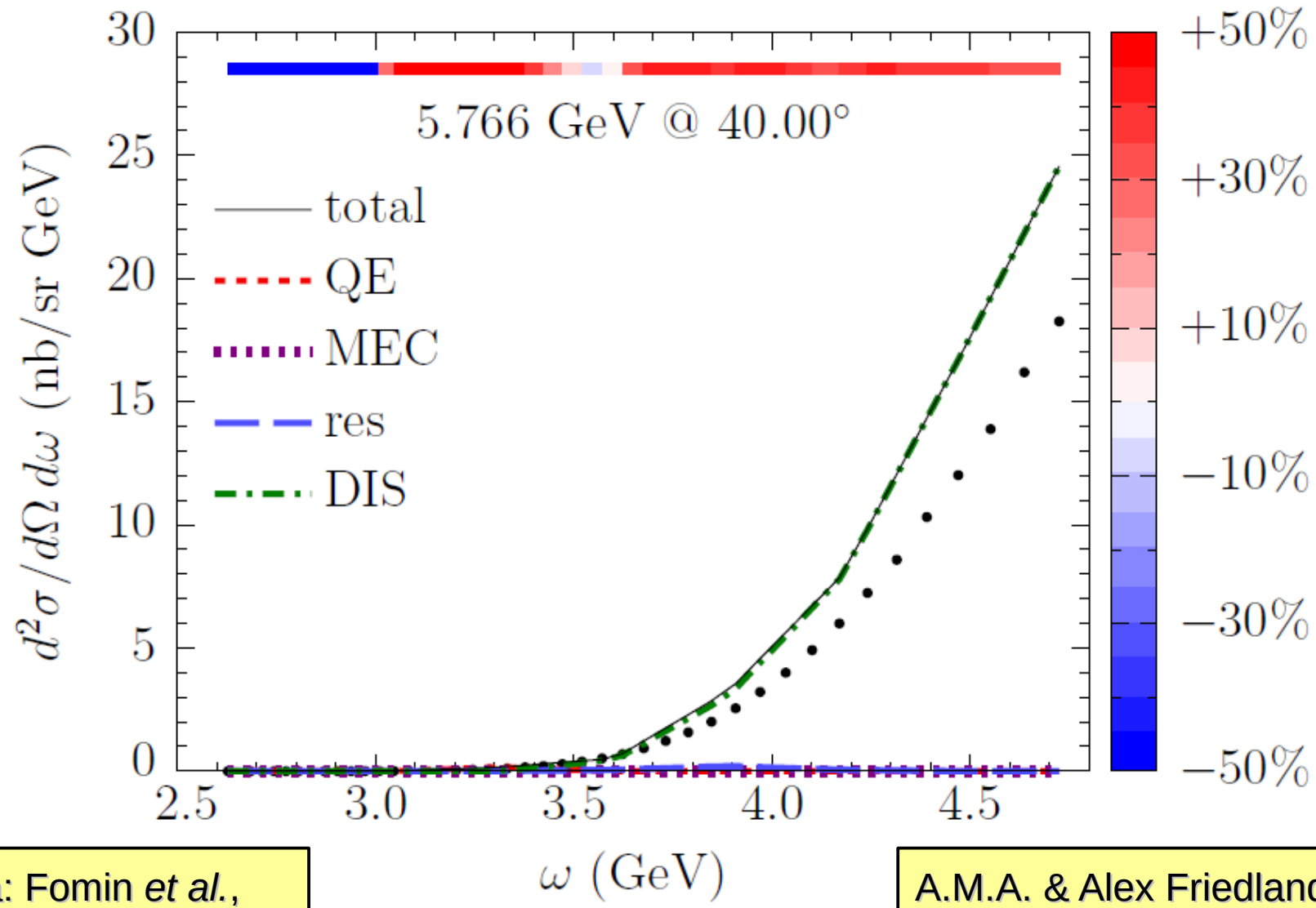
- From the mission statement:

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



Assessing GENIE's accuracy using electron-scattering data

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

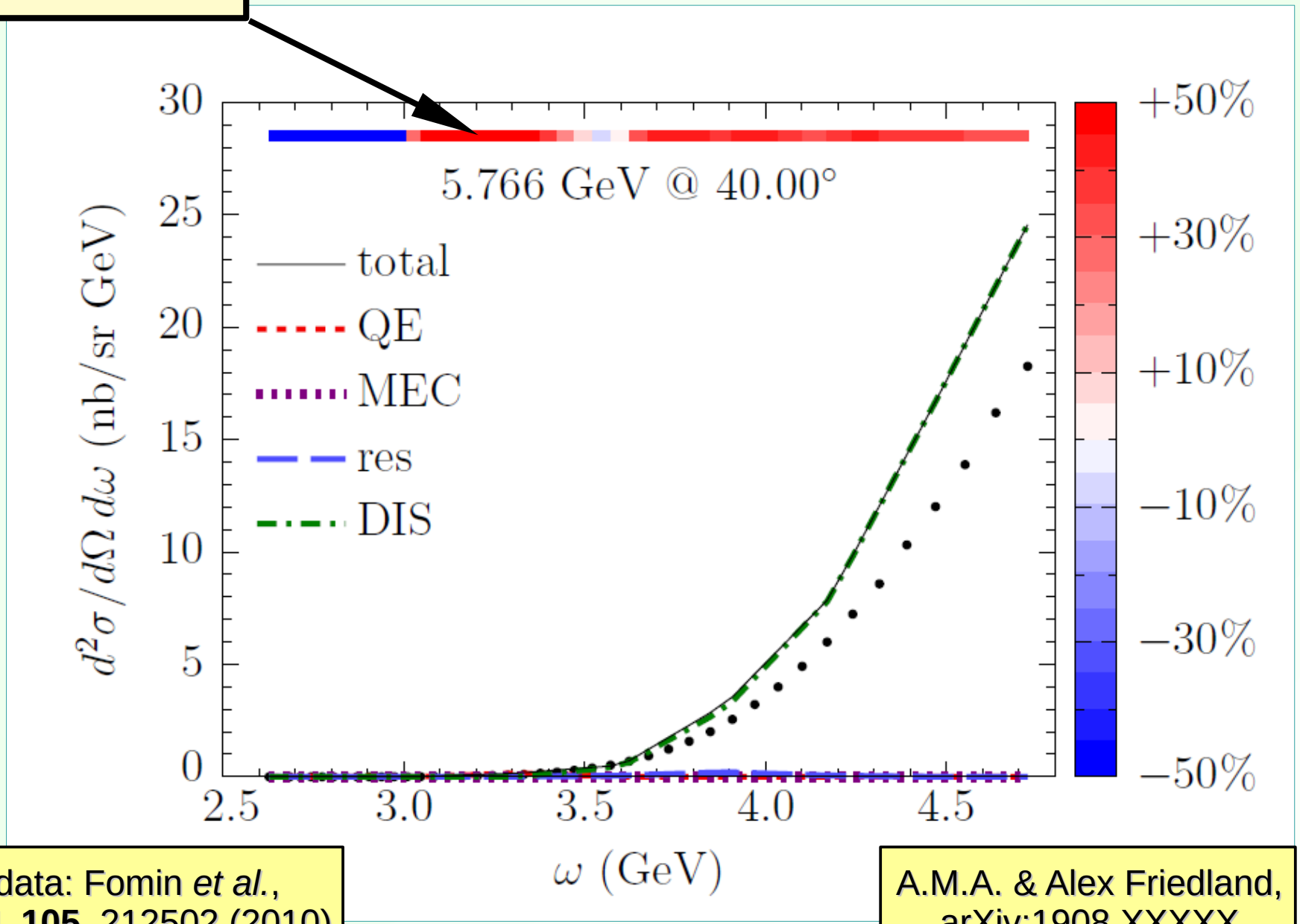


data: Fomin *et al.*, PRL **105**, 212502 (2010)

A.M.A. & Alex Friedland, arXiv:1908.XXXXX

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

GENIE – data
data



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PRL **105**, 212502 (2010)

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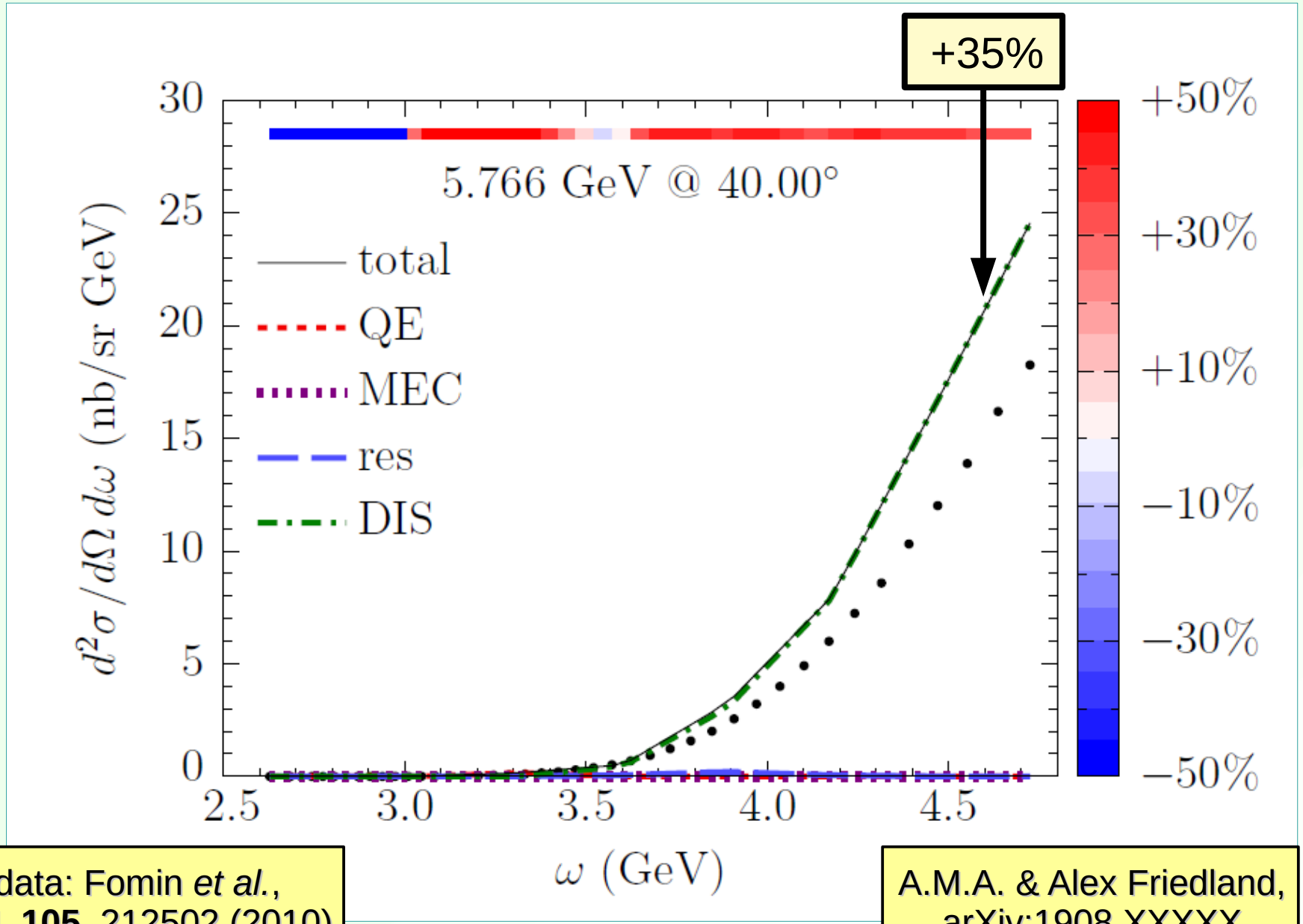

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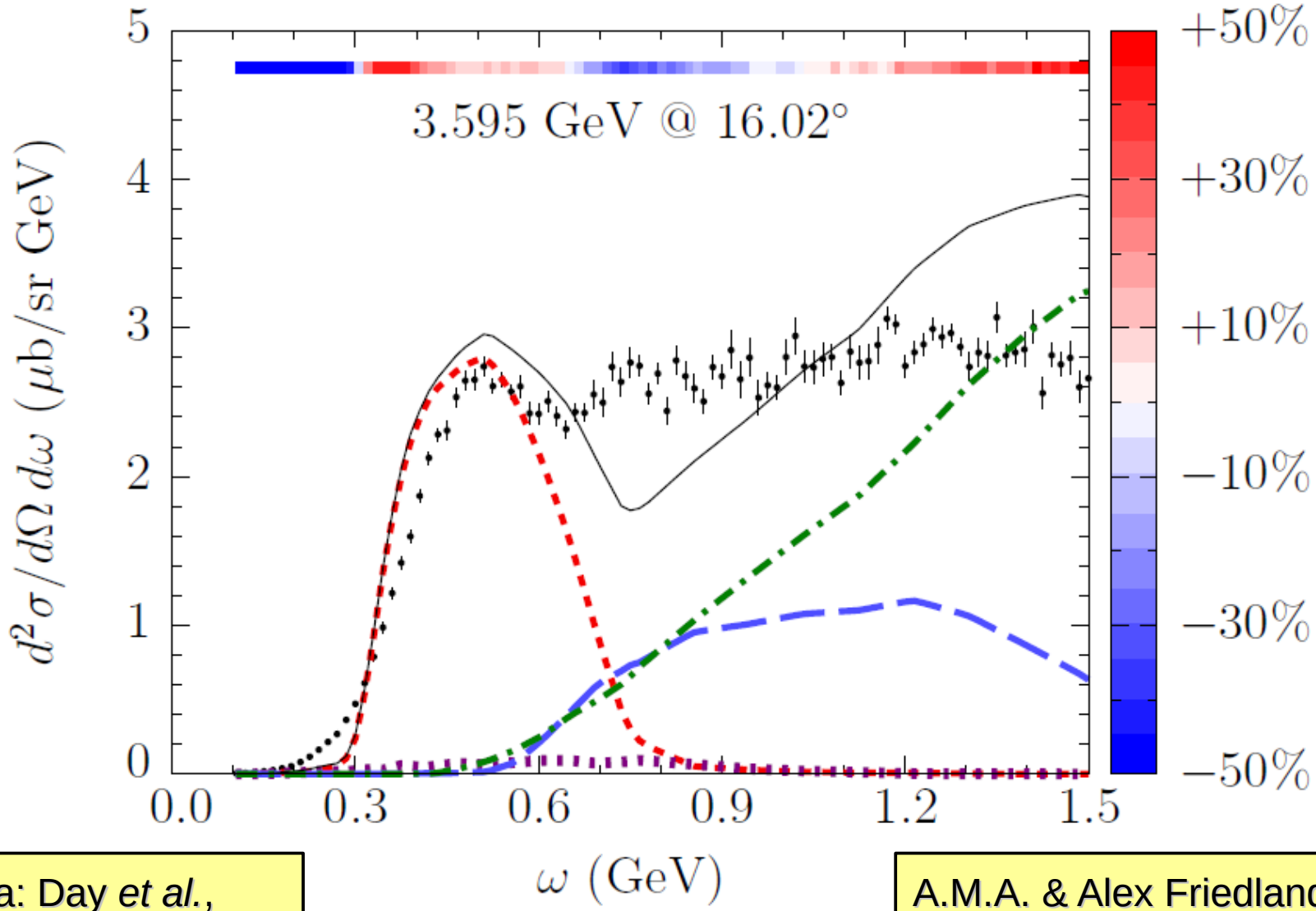

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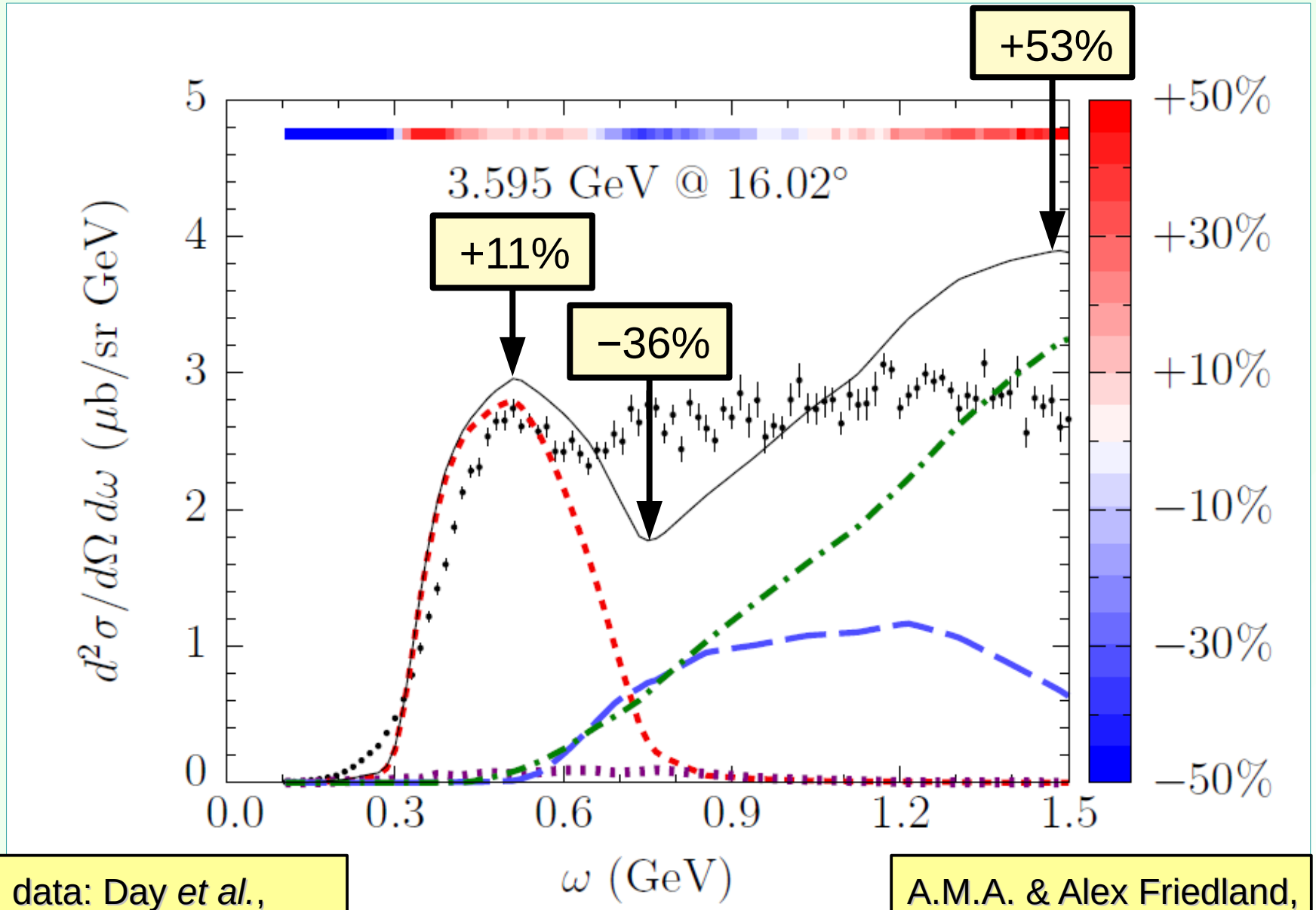

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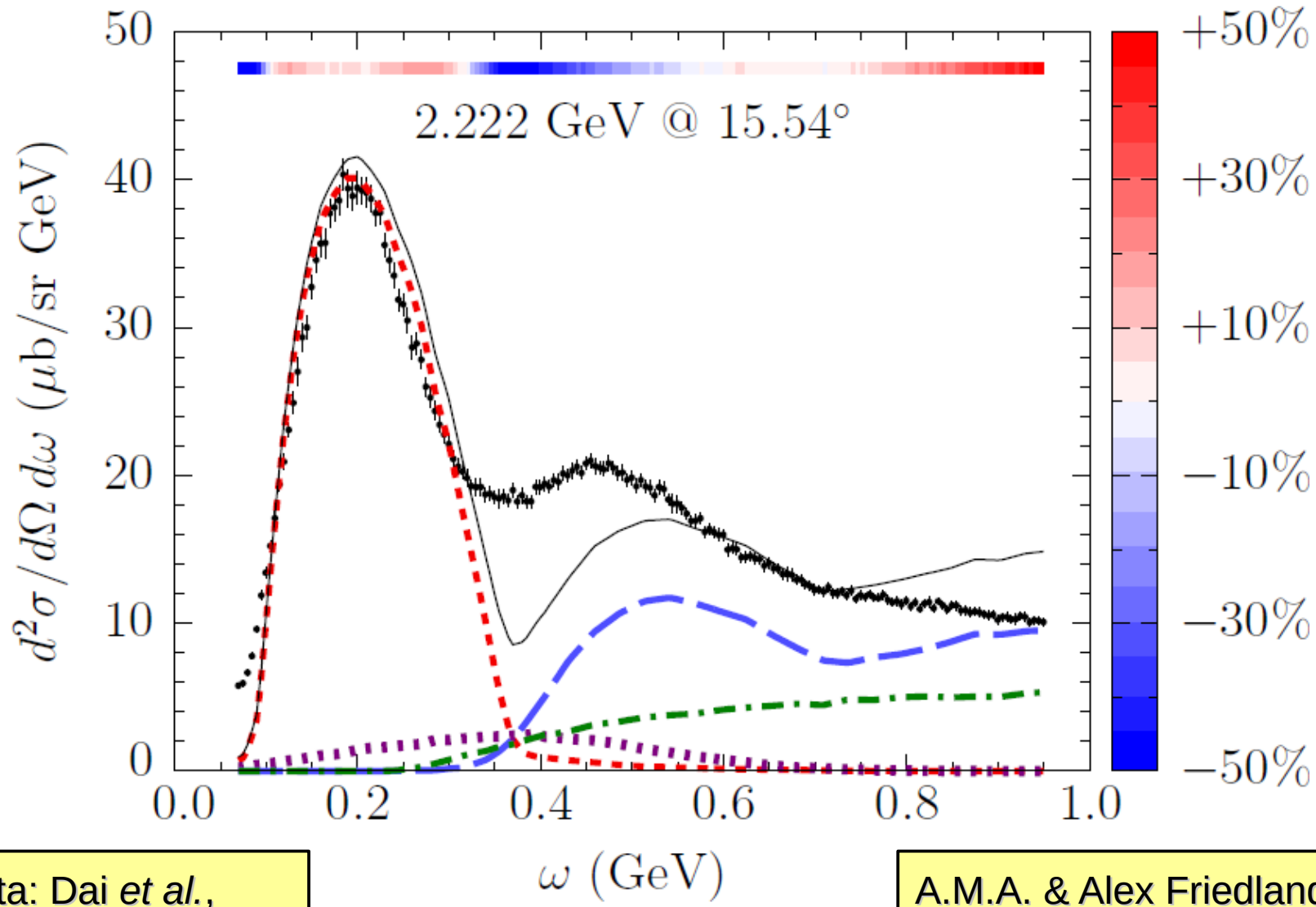

data: Dai *et al.*,
PRC **98**, 014617 (2018)

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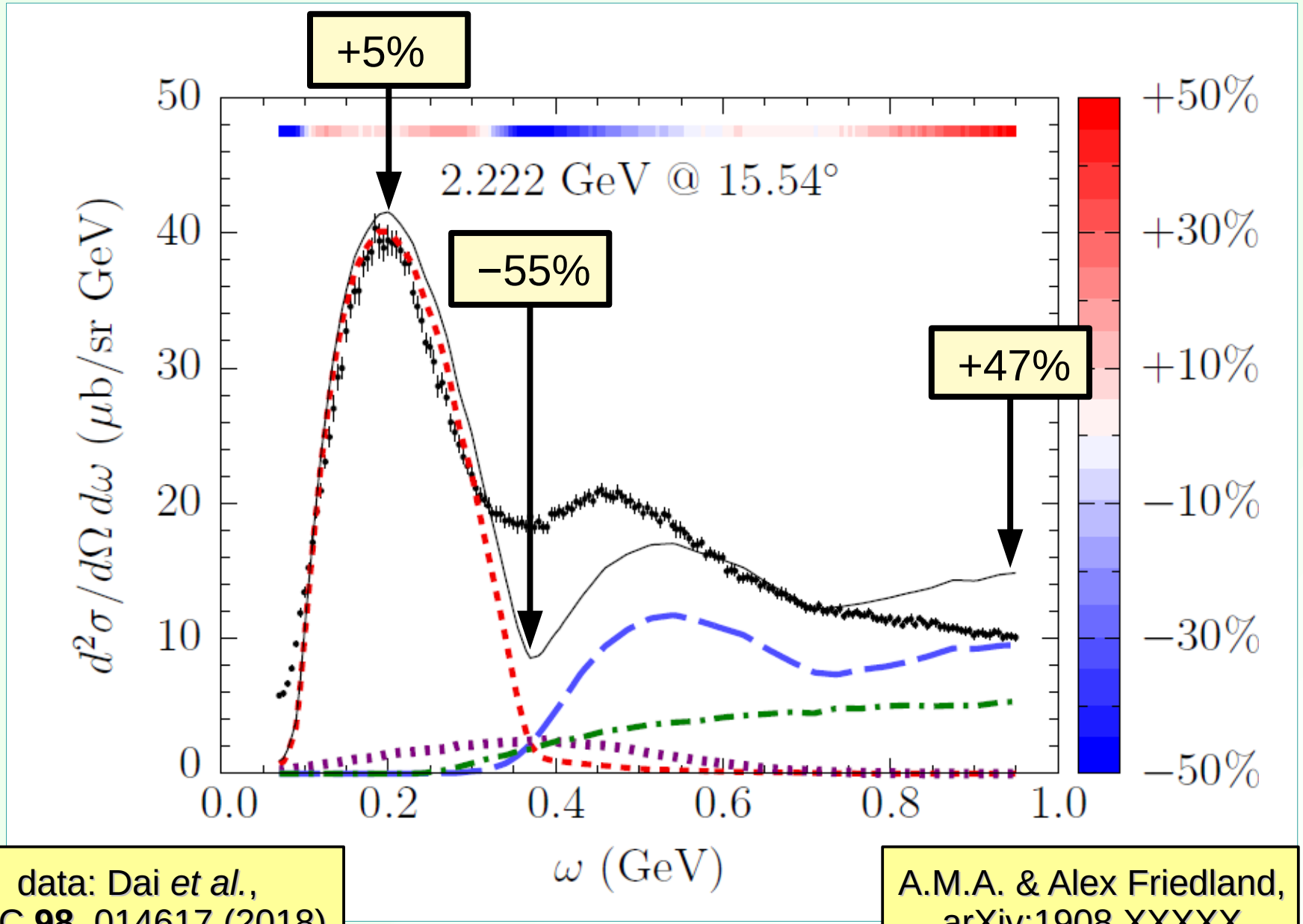
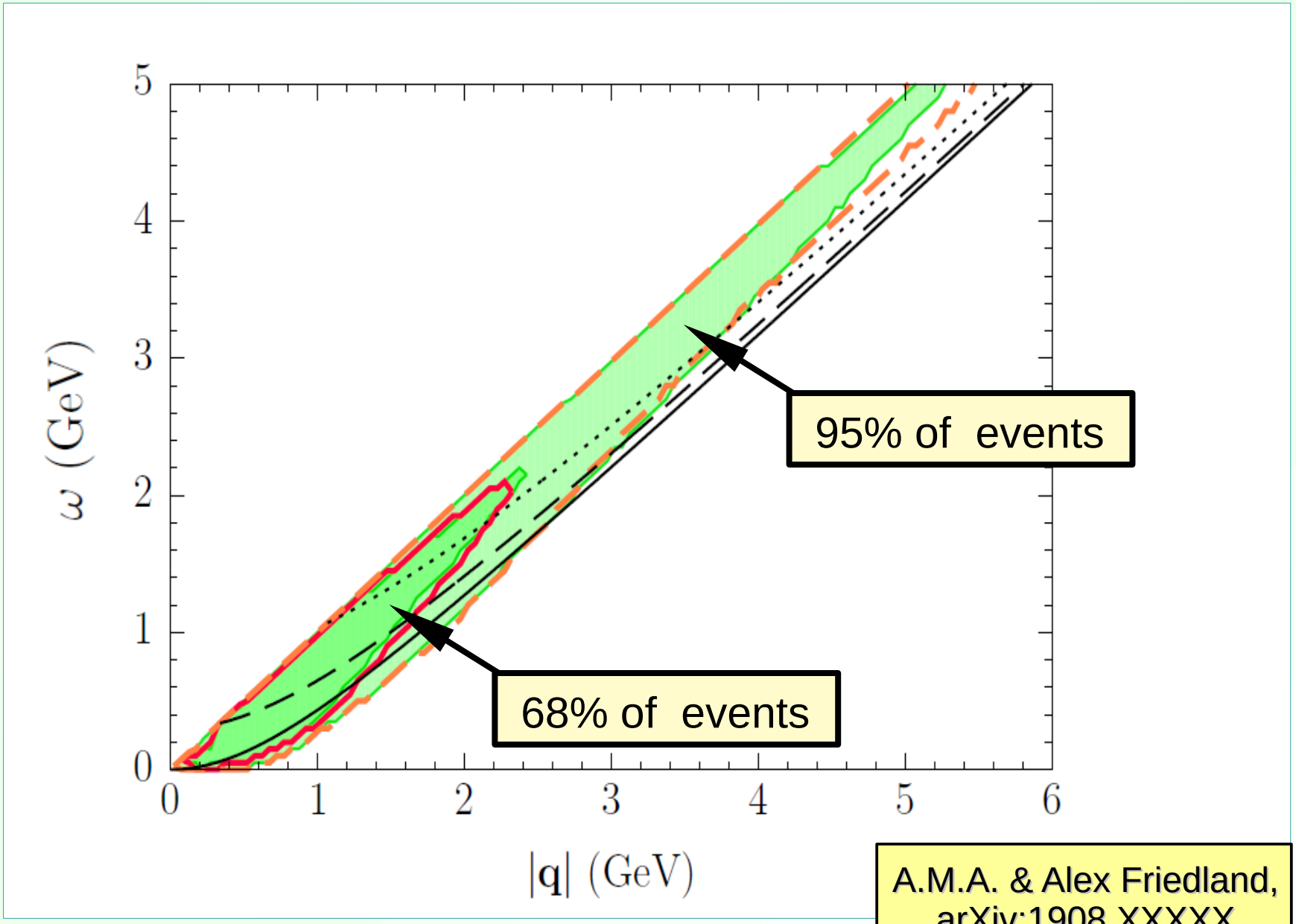


data: Dai *et al.*,
PRC **98**, 014617 (2018)

A.M.A. & Alex Friedland,
arXiv:1908.XXXXX

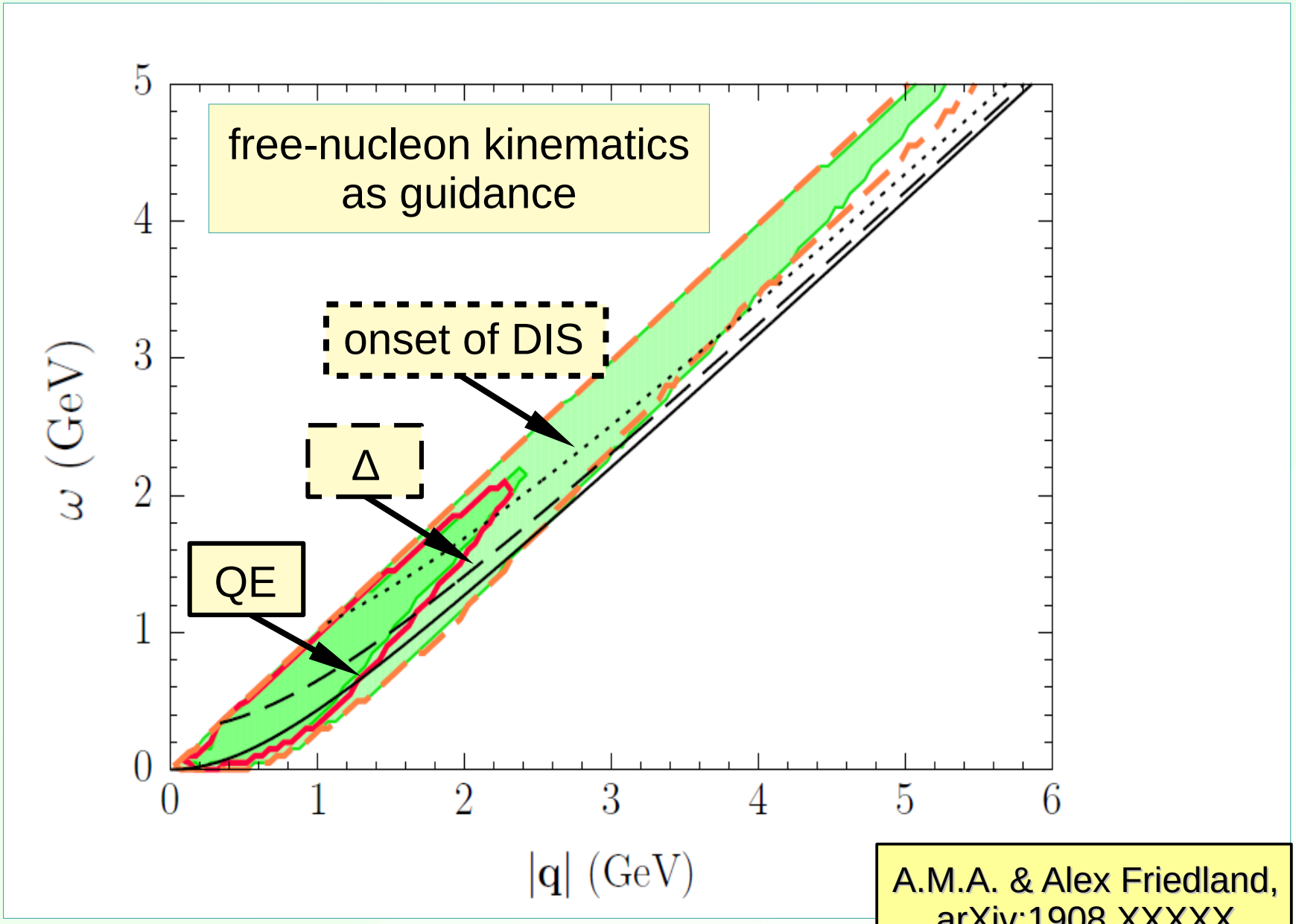
Assessing GENIE's accuracy: global picture

DUNE vs. NOvA



A.M.A. & Alex Friedland, arXiv:1908.XXXXX

DUNE vs. NOvA



A.M.A. & Alex Friedland,
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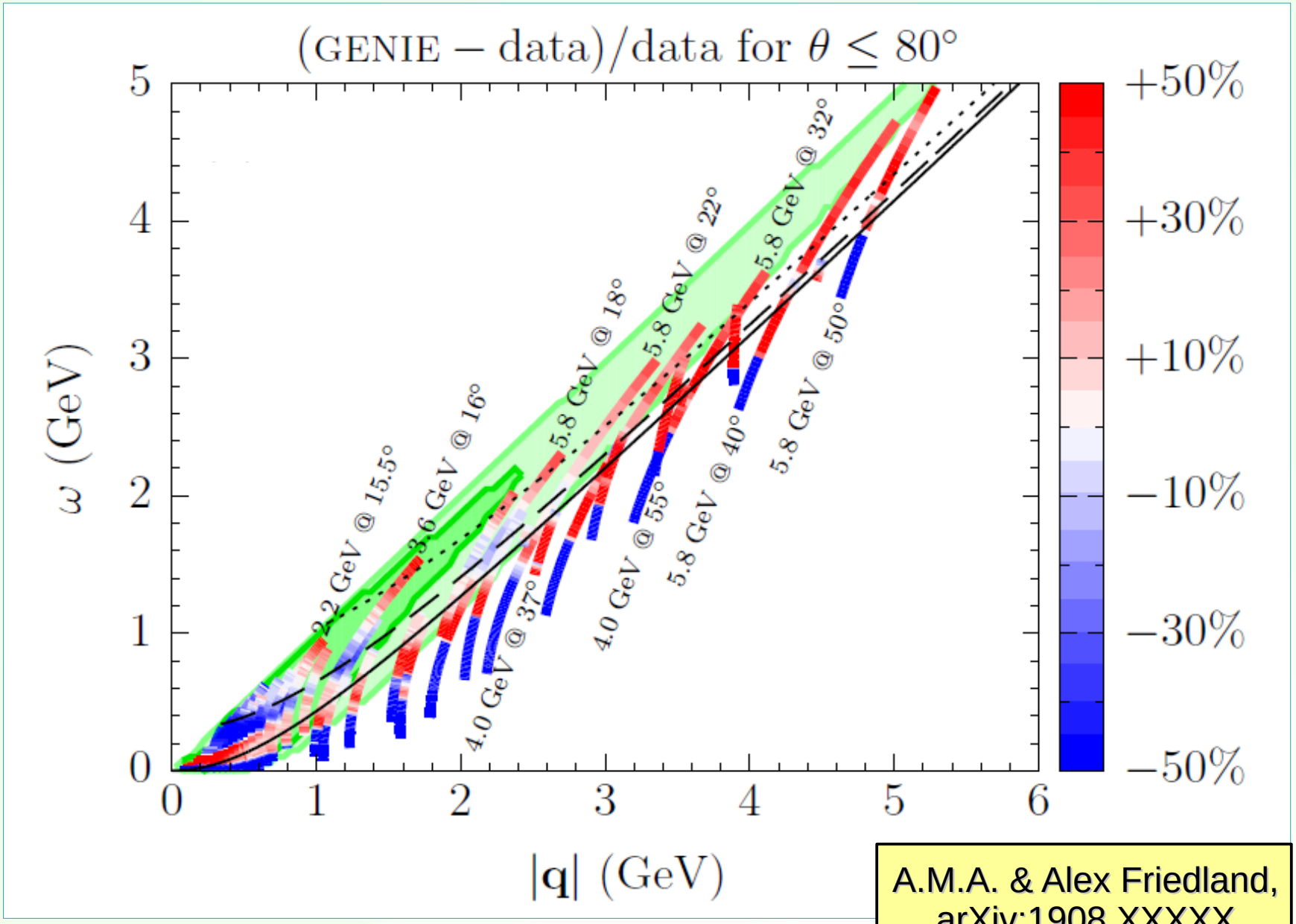
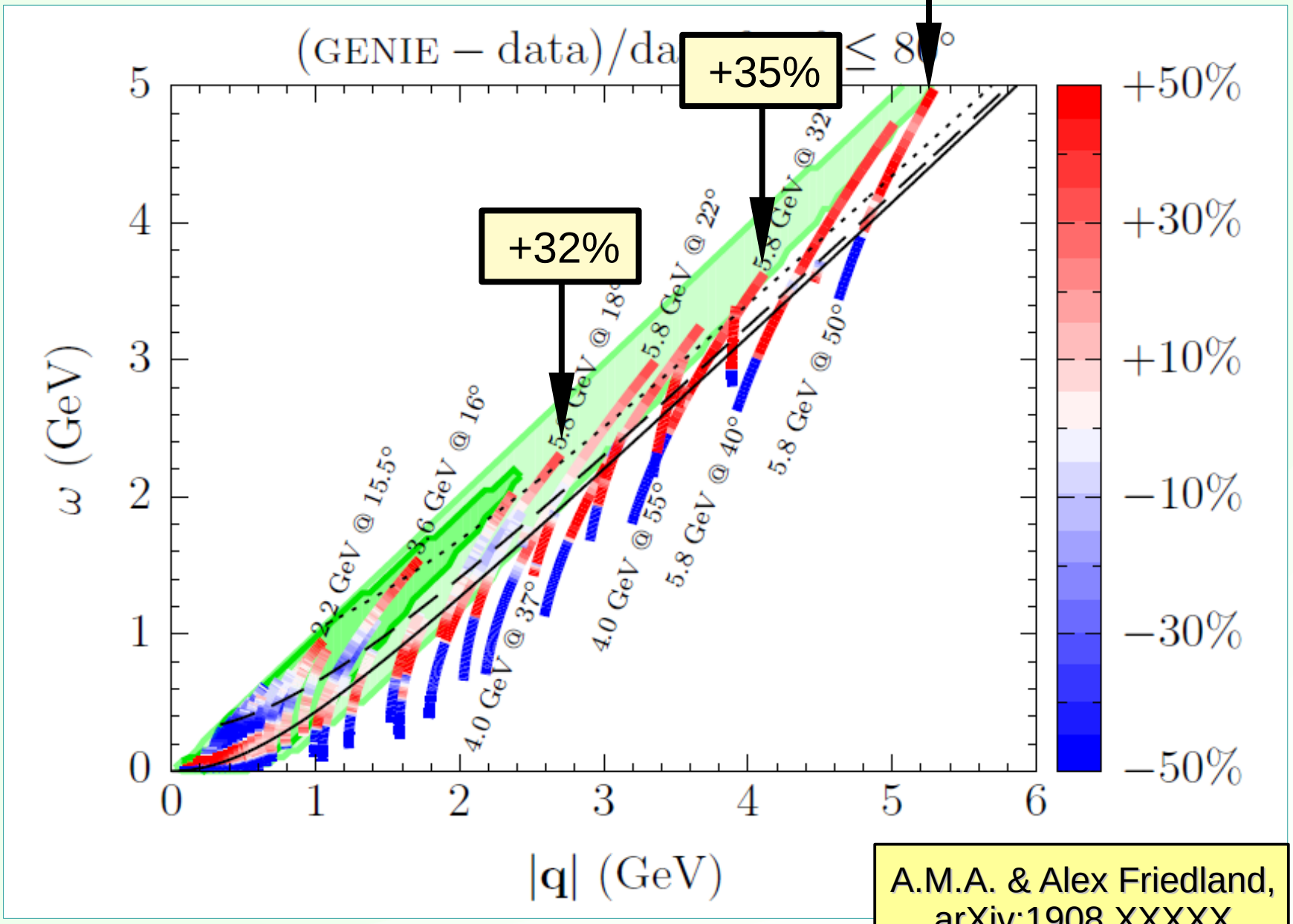


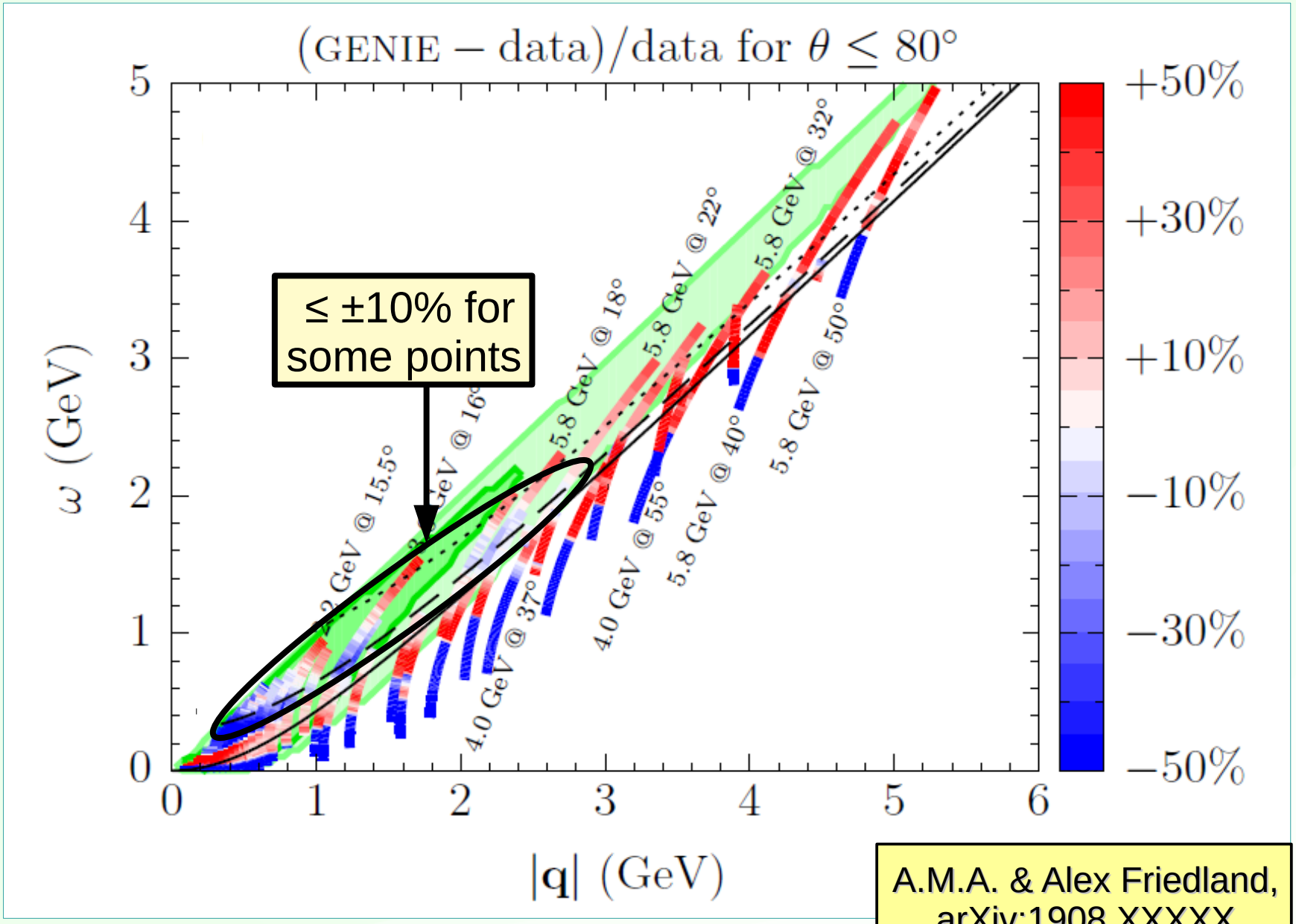
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

DIS



A.M.A. & Alex Friedland, arXiv:1908.XXXXX

Tail of the Δ resonance



A.M.A. & Alex Friedland, arXiv:1908.XXXXX

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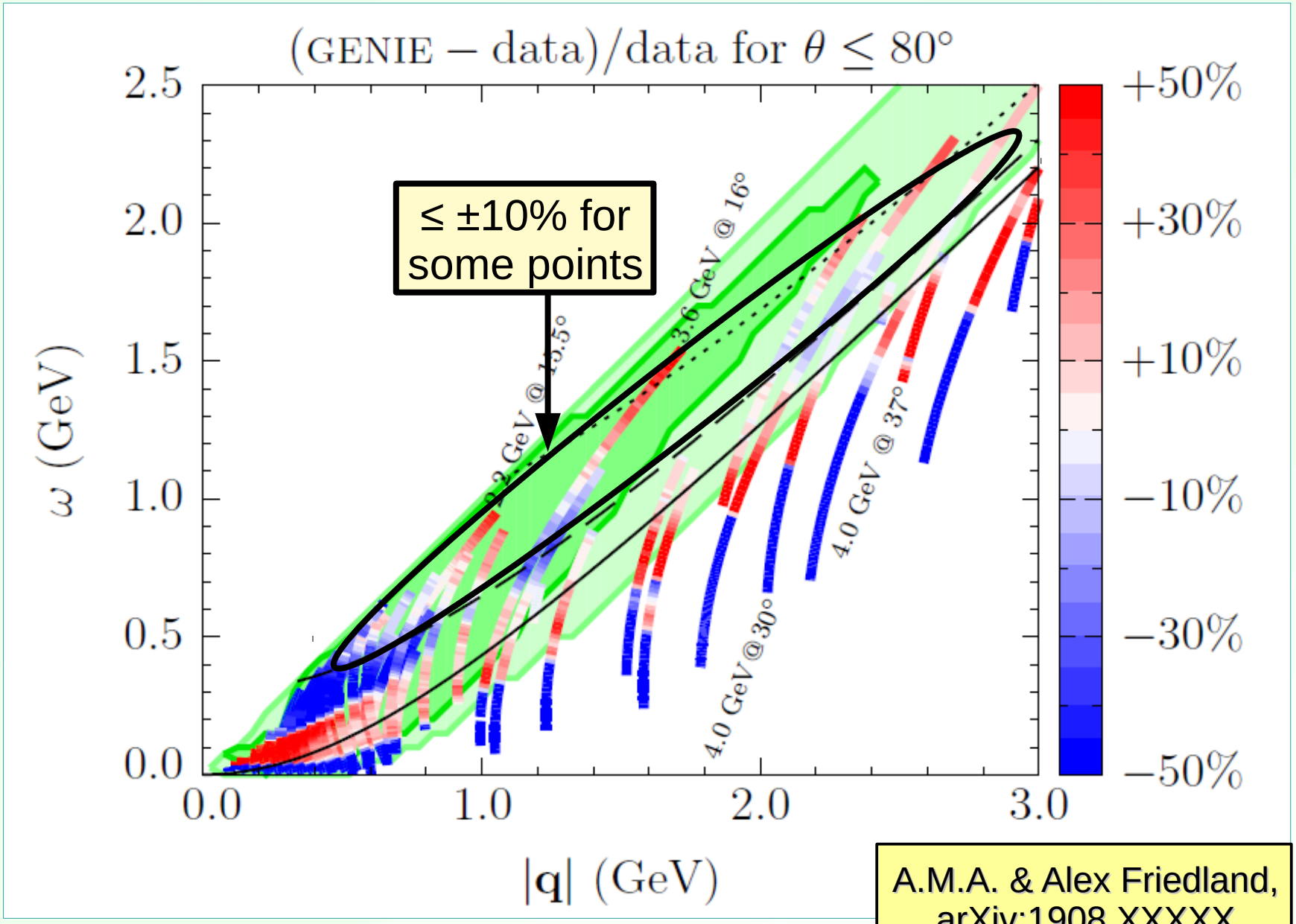
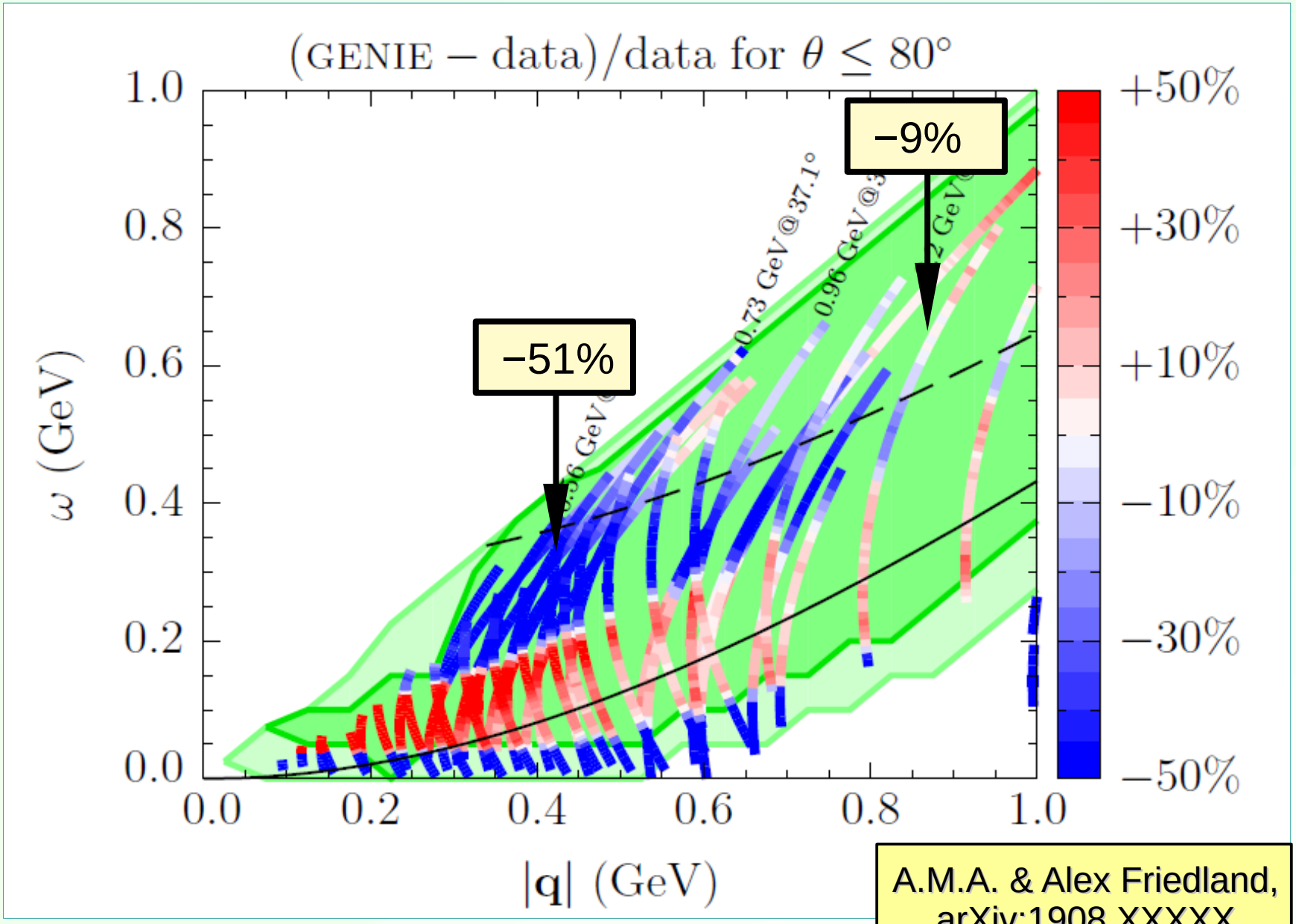


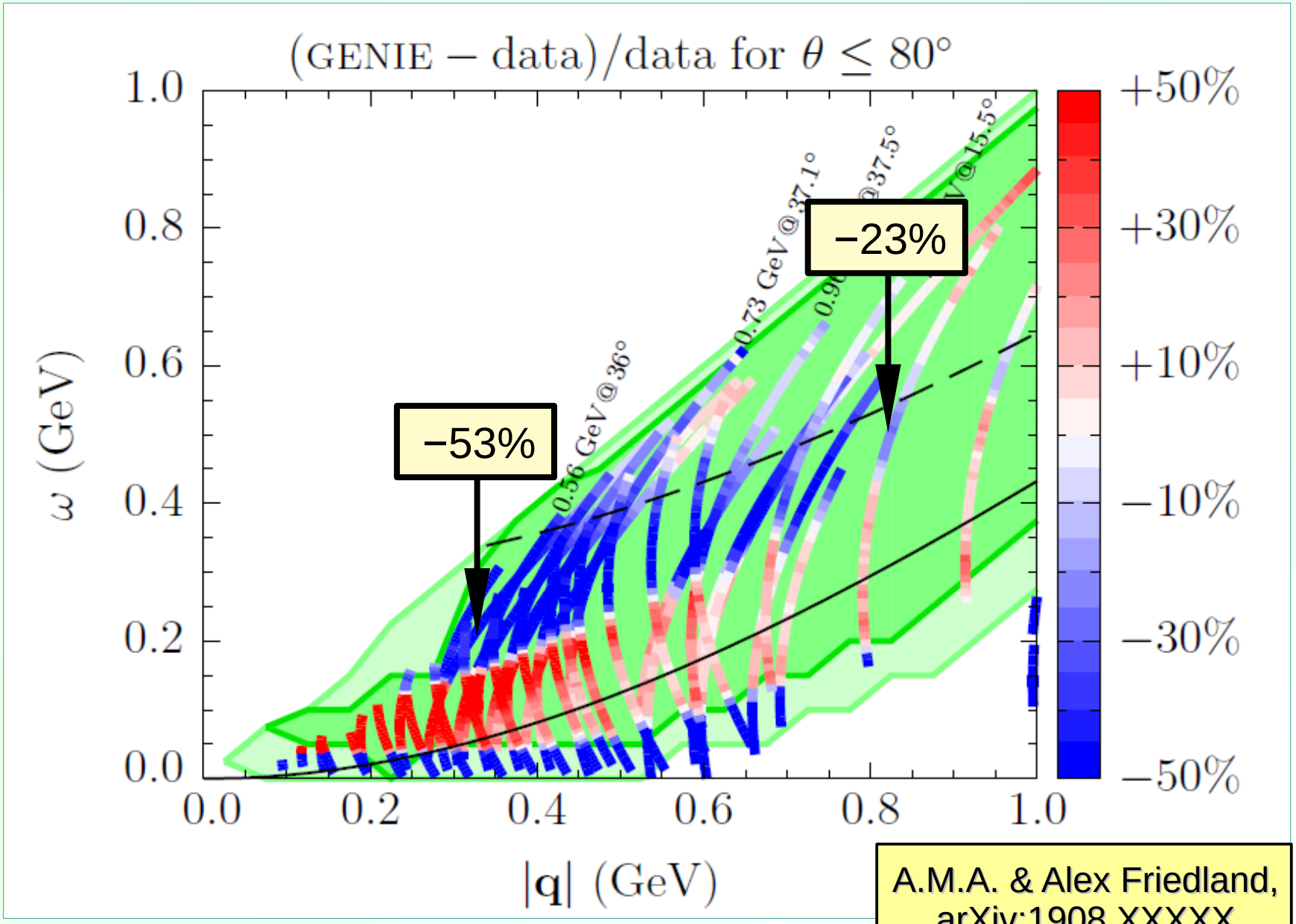
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

Δ resonance



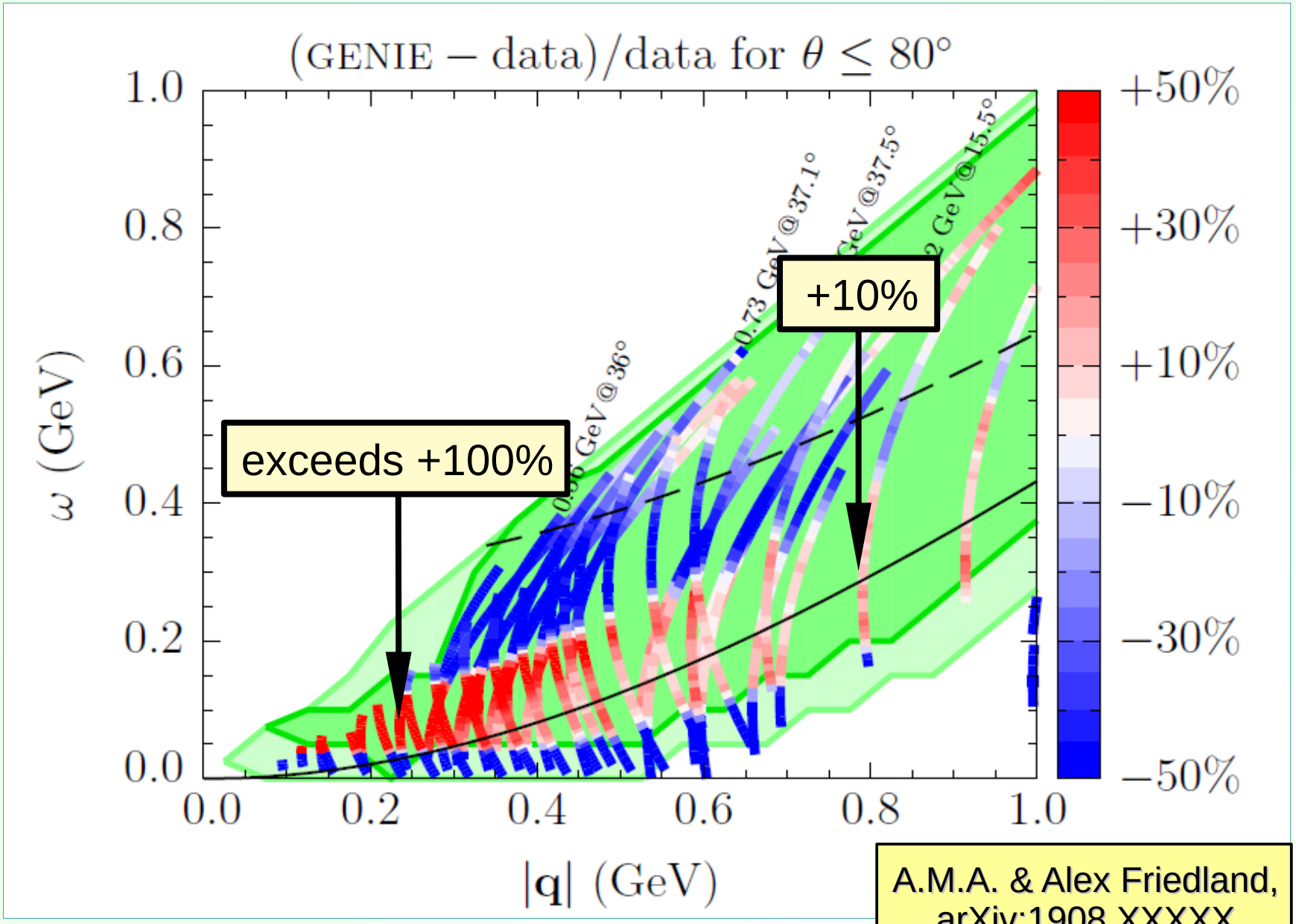
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

Dip region



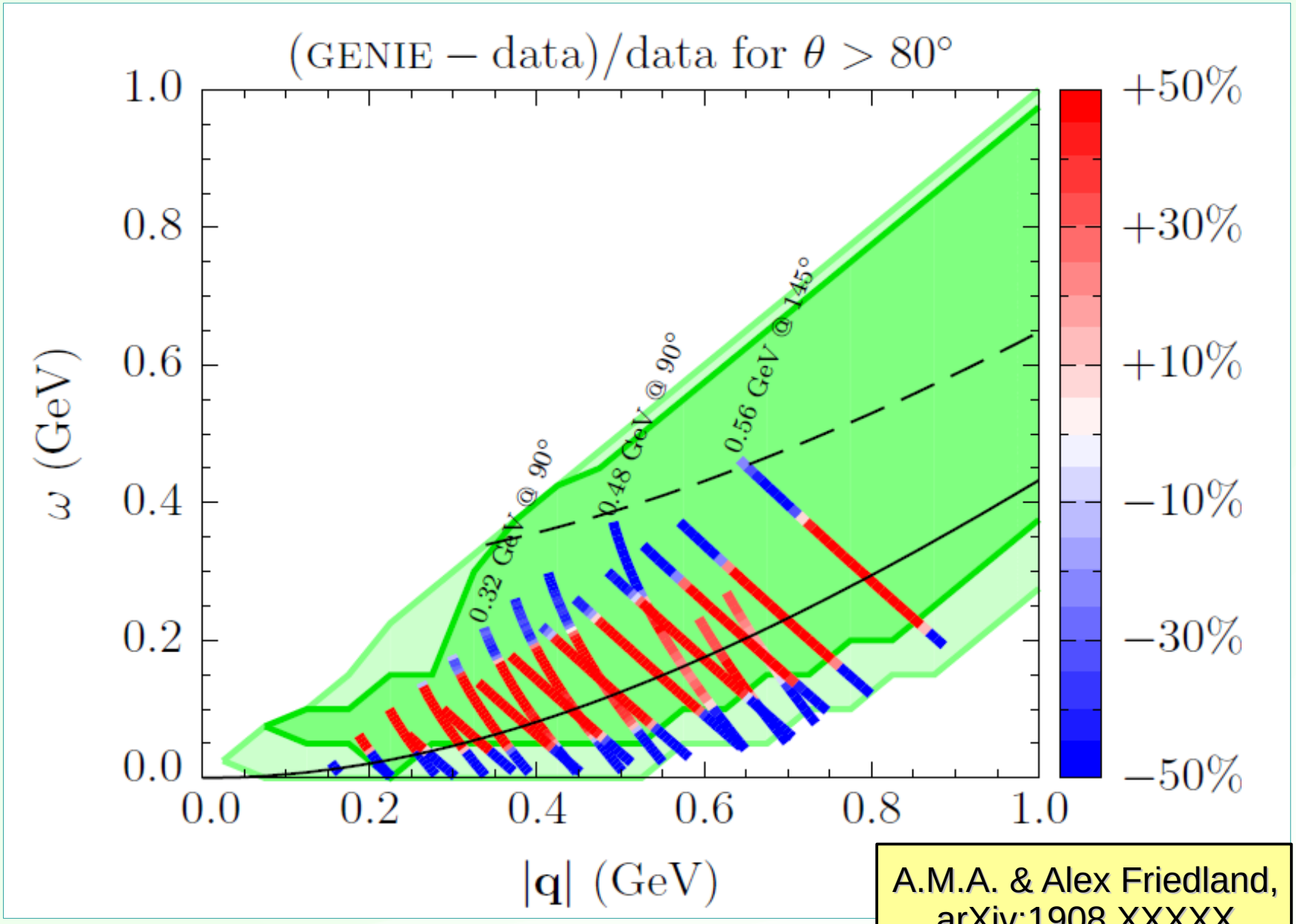
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

Quasielastic



A.M.A. & Alex Friedland, arXiv:1908.XXXXX

Quasielastic



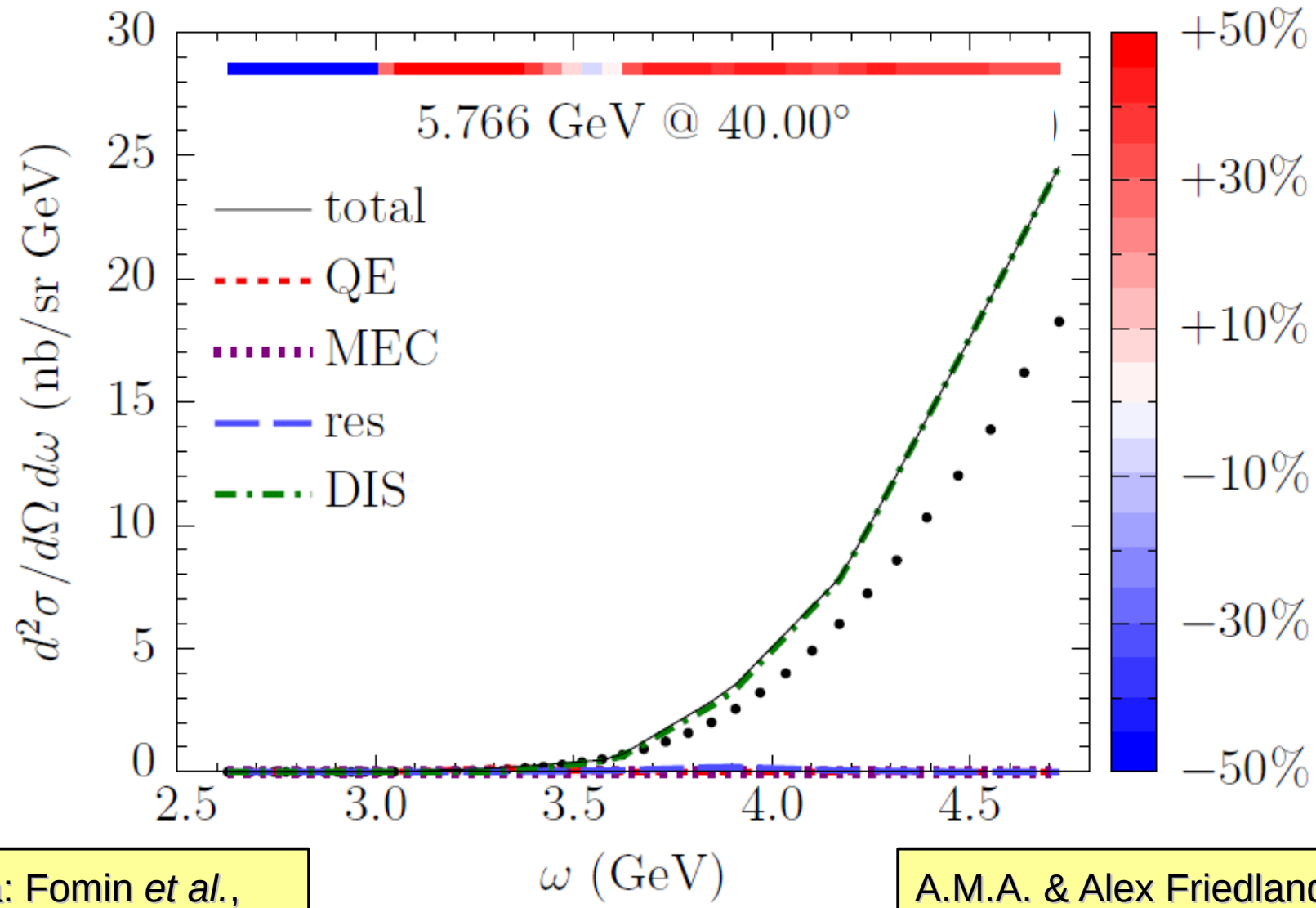
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

Global picture

- DIS cross section **overestimated** by 30–50%, higher resonances too high as well.
- Delta resonance **underestimated** (10–50%), but its tail is described *very well at some kinematics* (~10%)
- Dip region **underestimated** (20–50%)
- Quasielastic peak **overestimated** by more than 100% at low energies, but much better agreement (~10%) for the data available at 2 GeV.
- Discrepancies increase with increasing scattering angle.

Assessing GENIE's accuracy: origin of the discrepancies

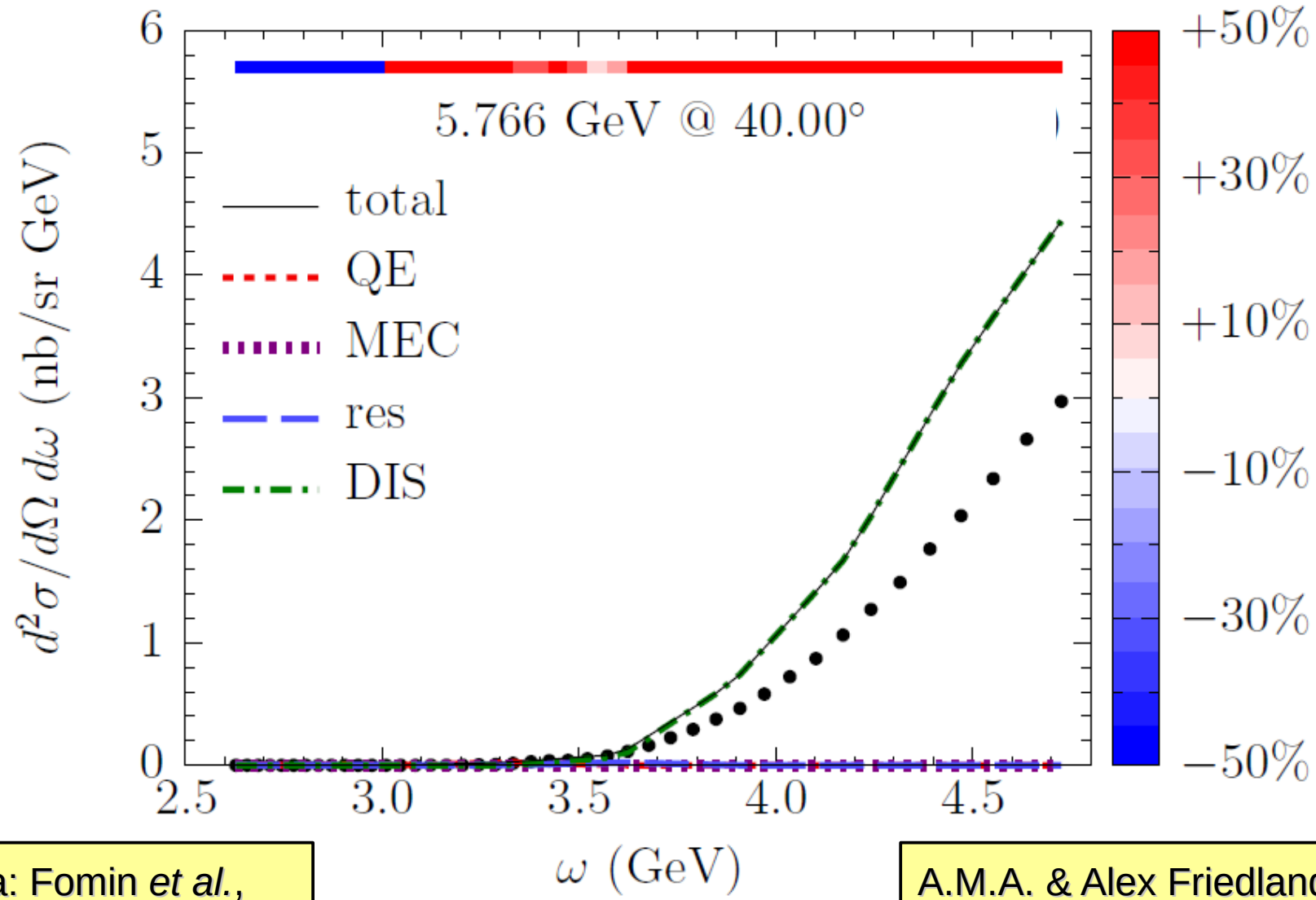
C(*e*, *e*') in GENIE



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

A.M.A. & Alex Friedland, arXiv:1908.XXXXX

D(*e*, *e*’) in GENIE



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

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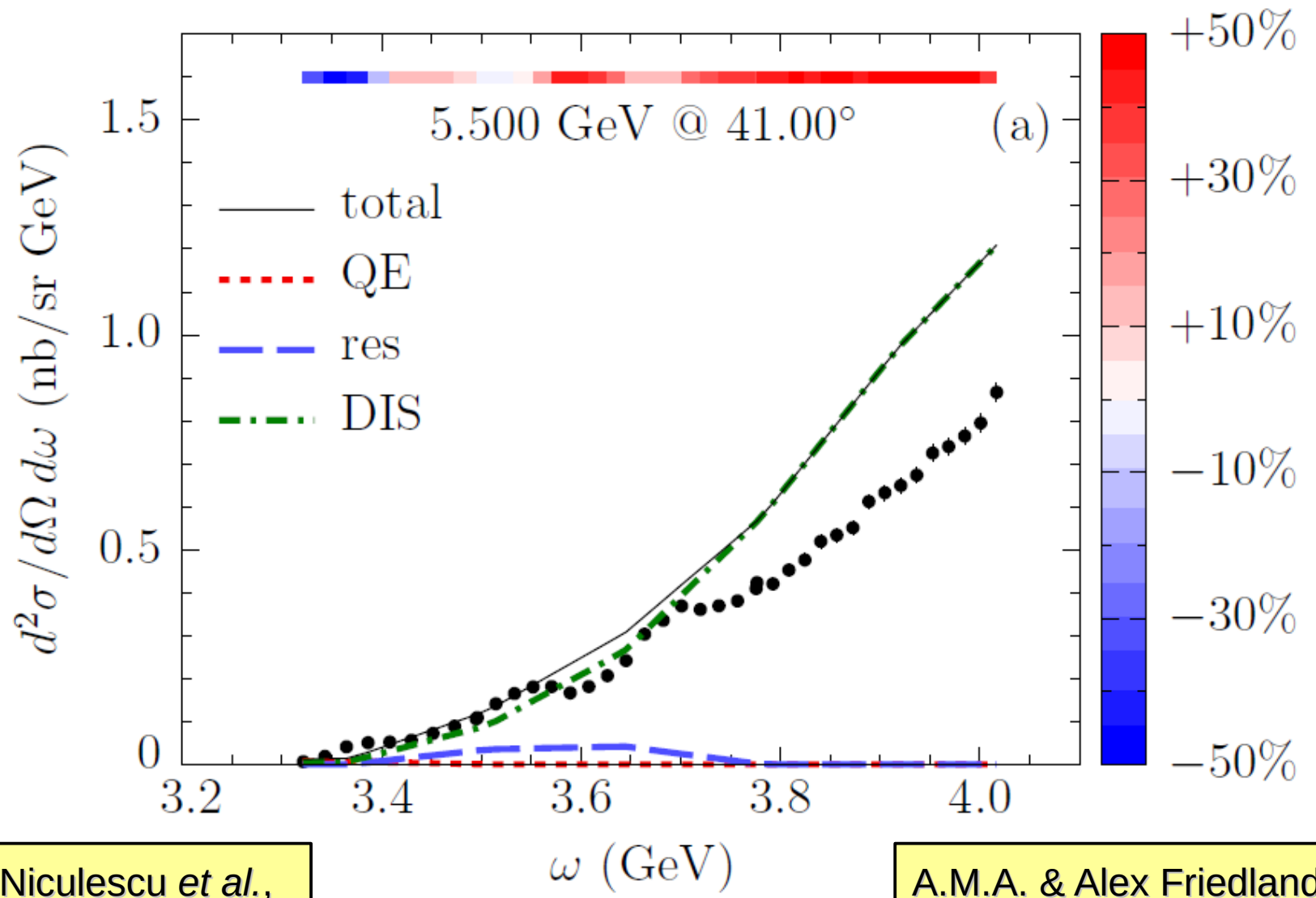
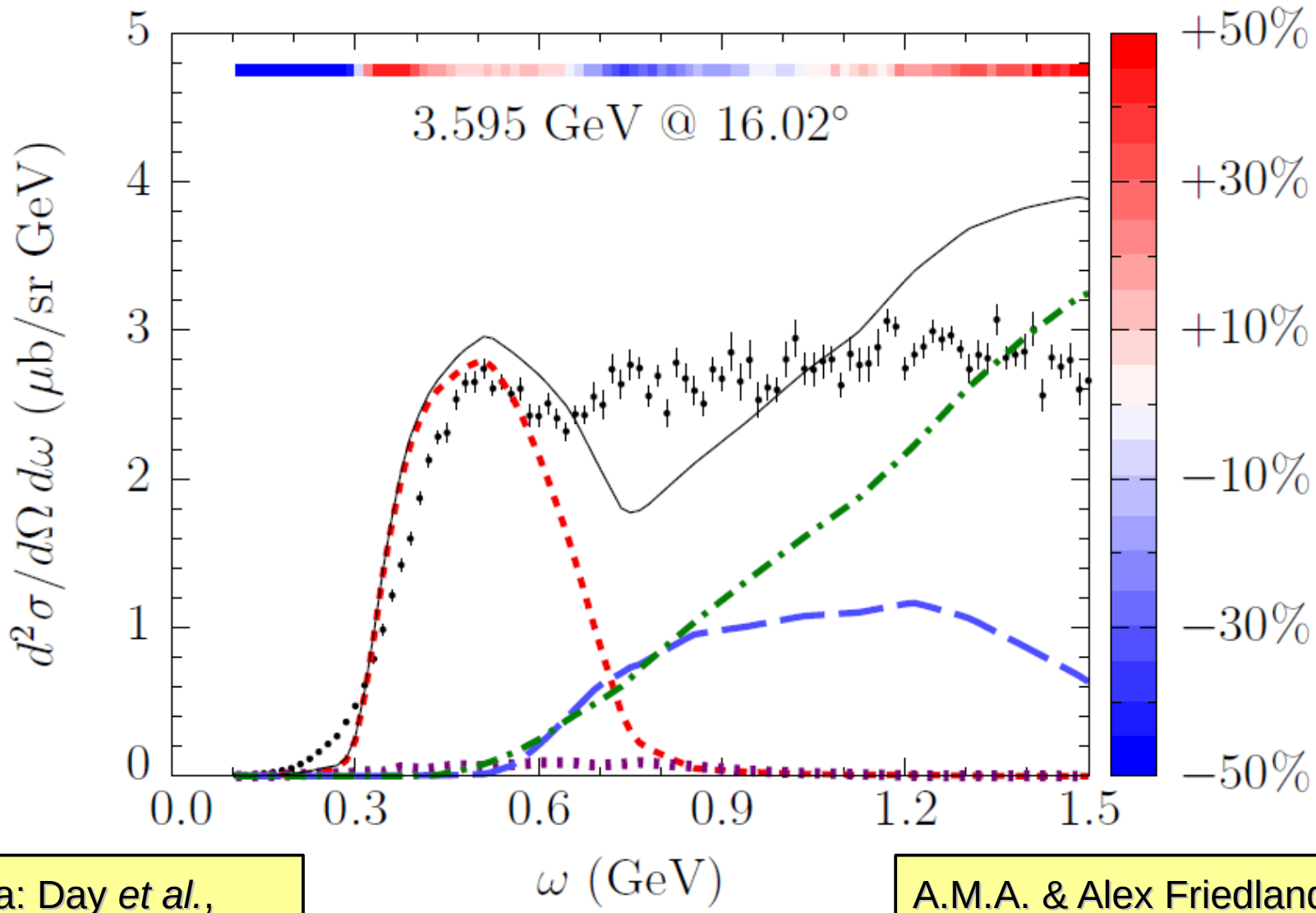
H(*e*, *e*') in GENIE



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

A.M.A. & Alex Friedland, arXiv:1908.XXXXX

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



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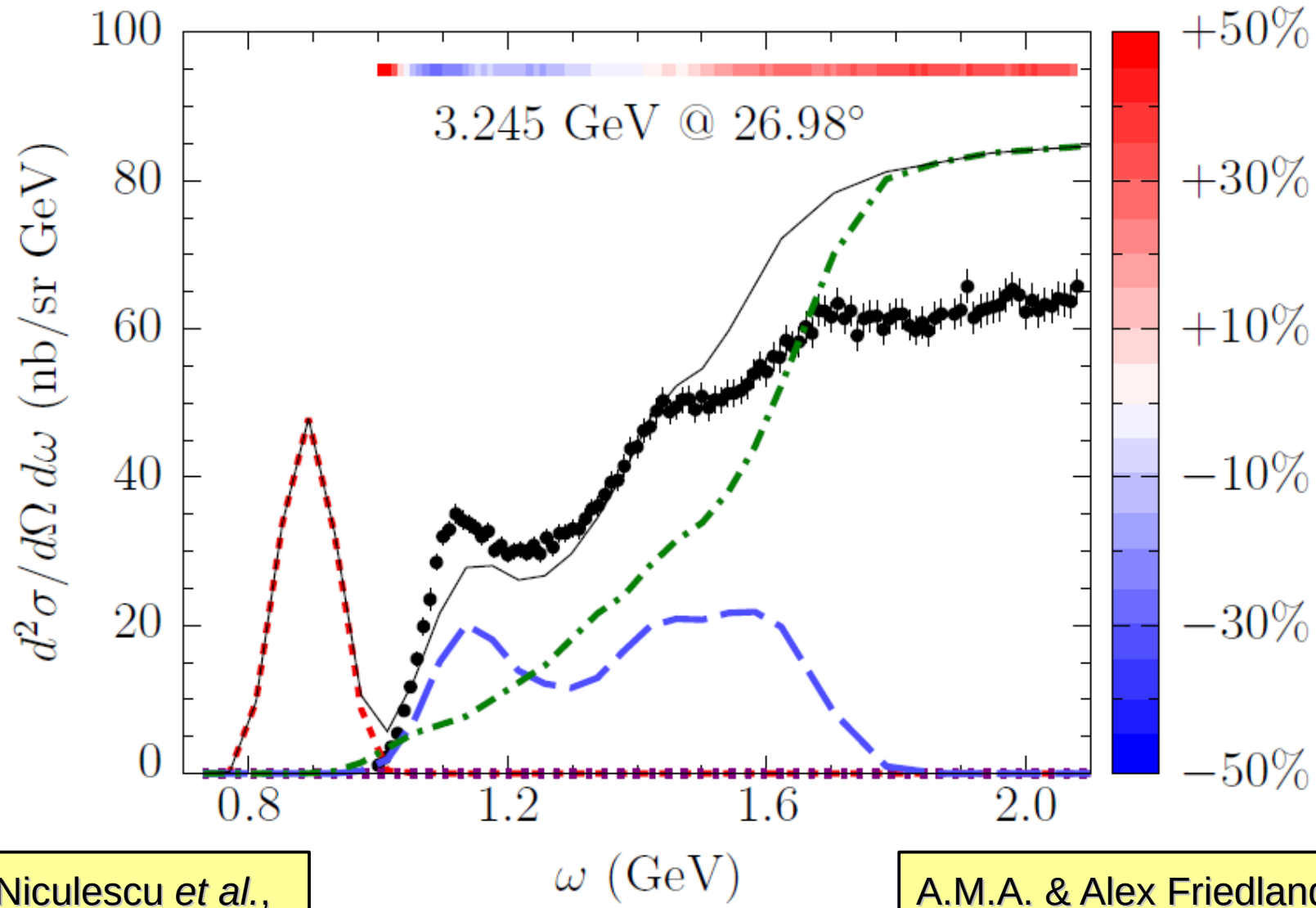

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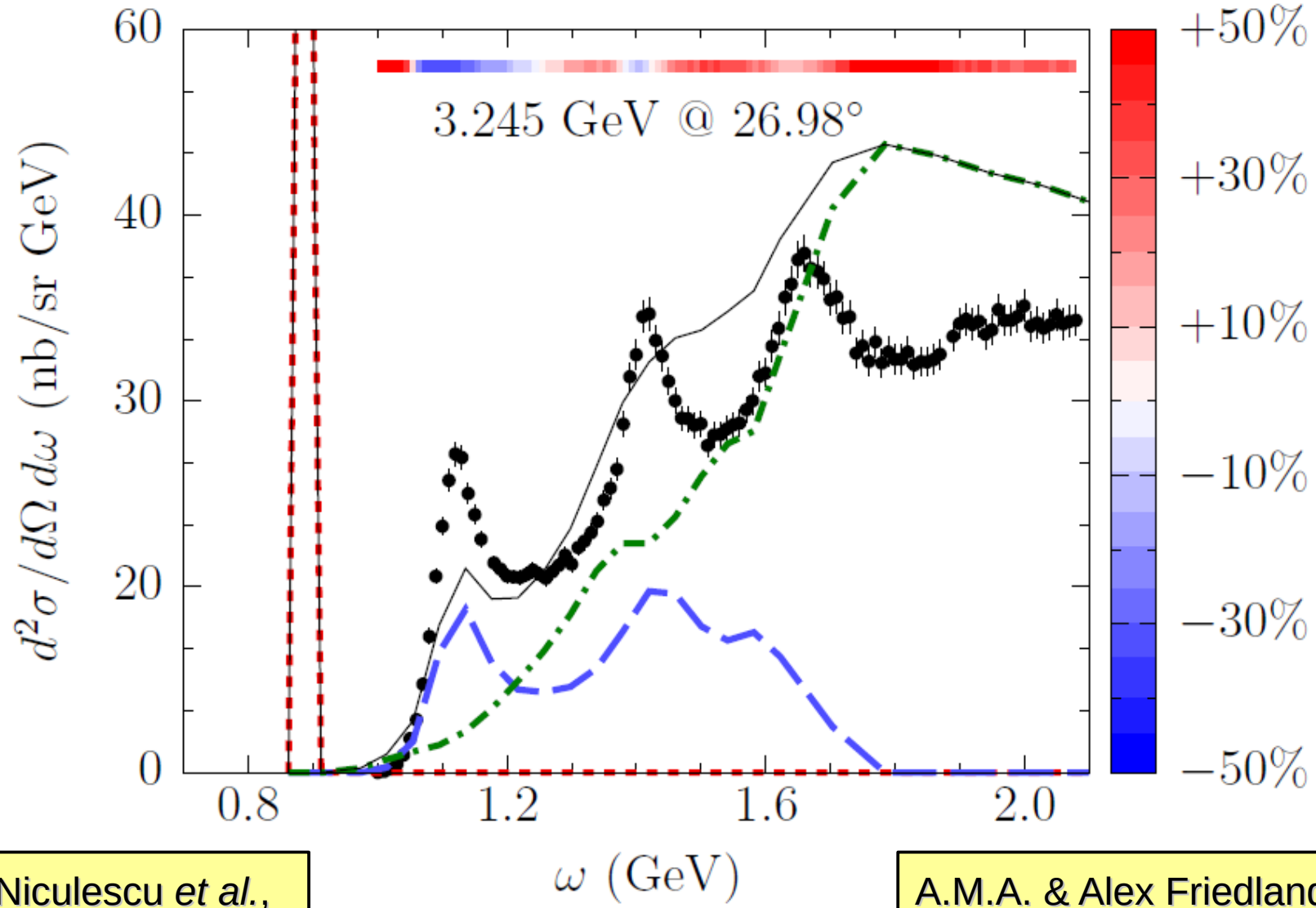

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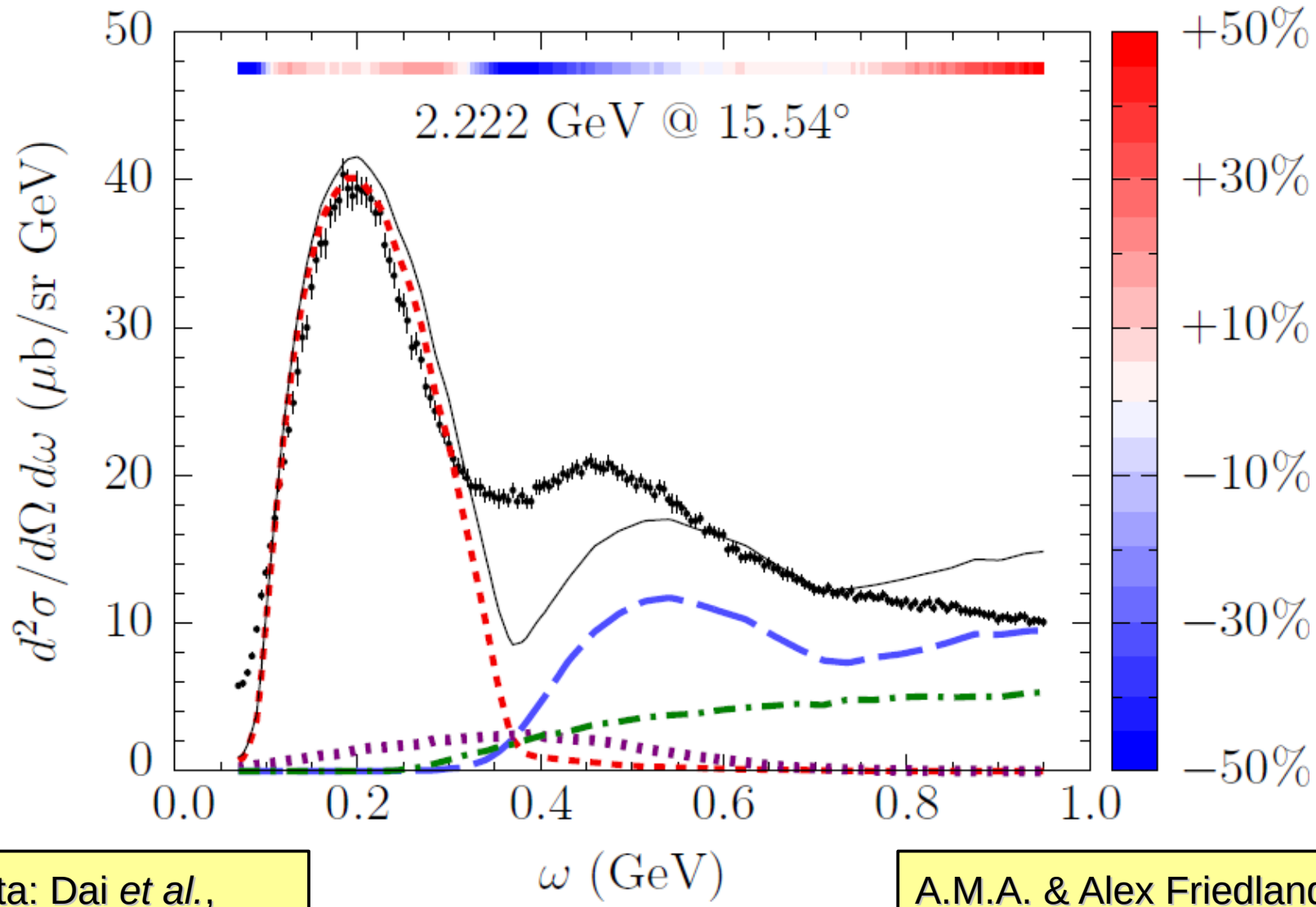

data: Dai *et al.*,
PRC **98**, 014617 (2018)

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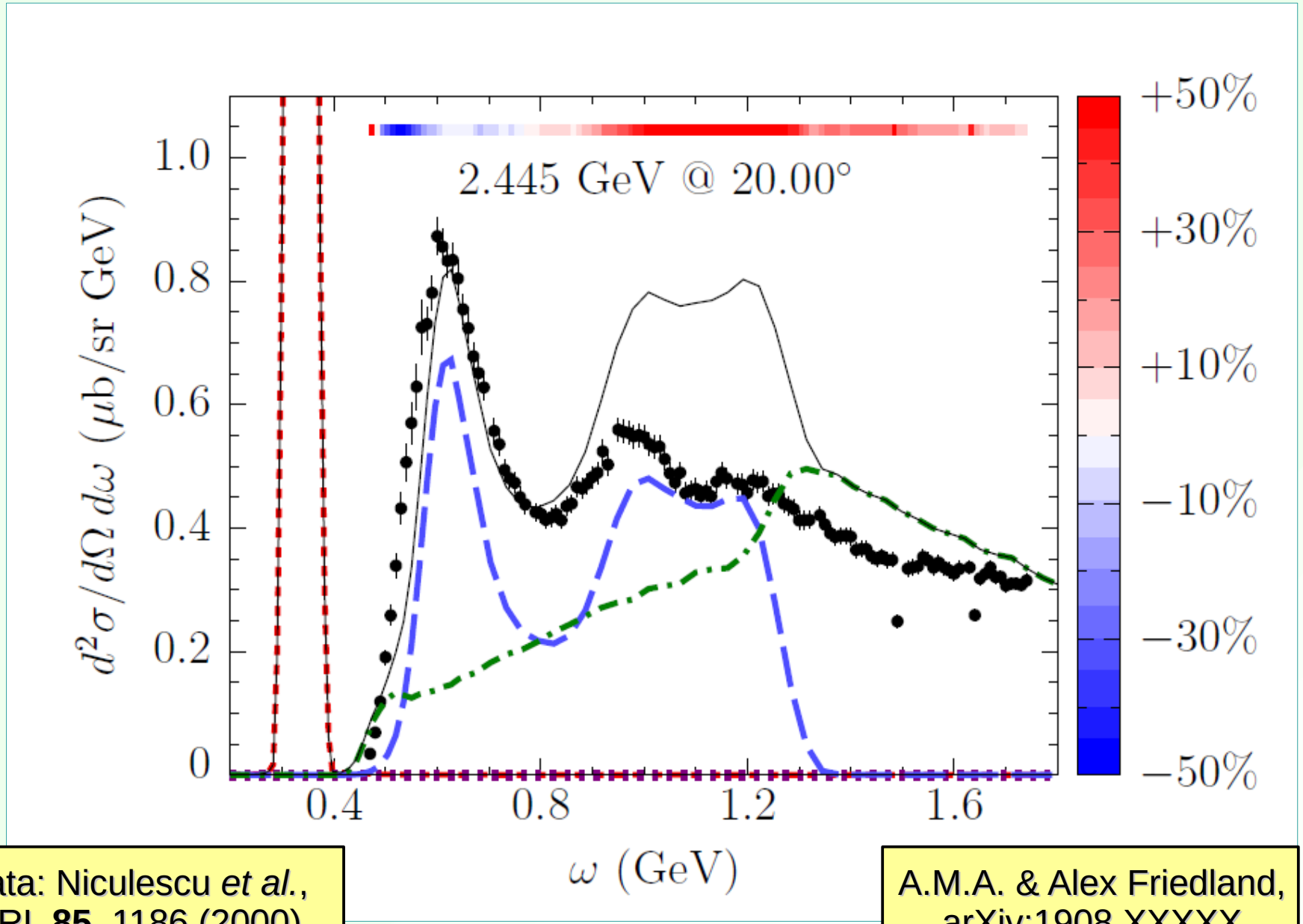
arXiv:1908.XXXXX

D(*e*, *e*’) in GENIE



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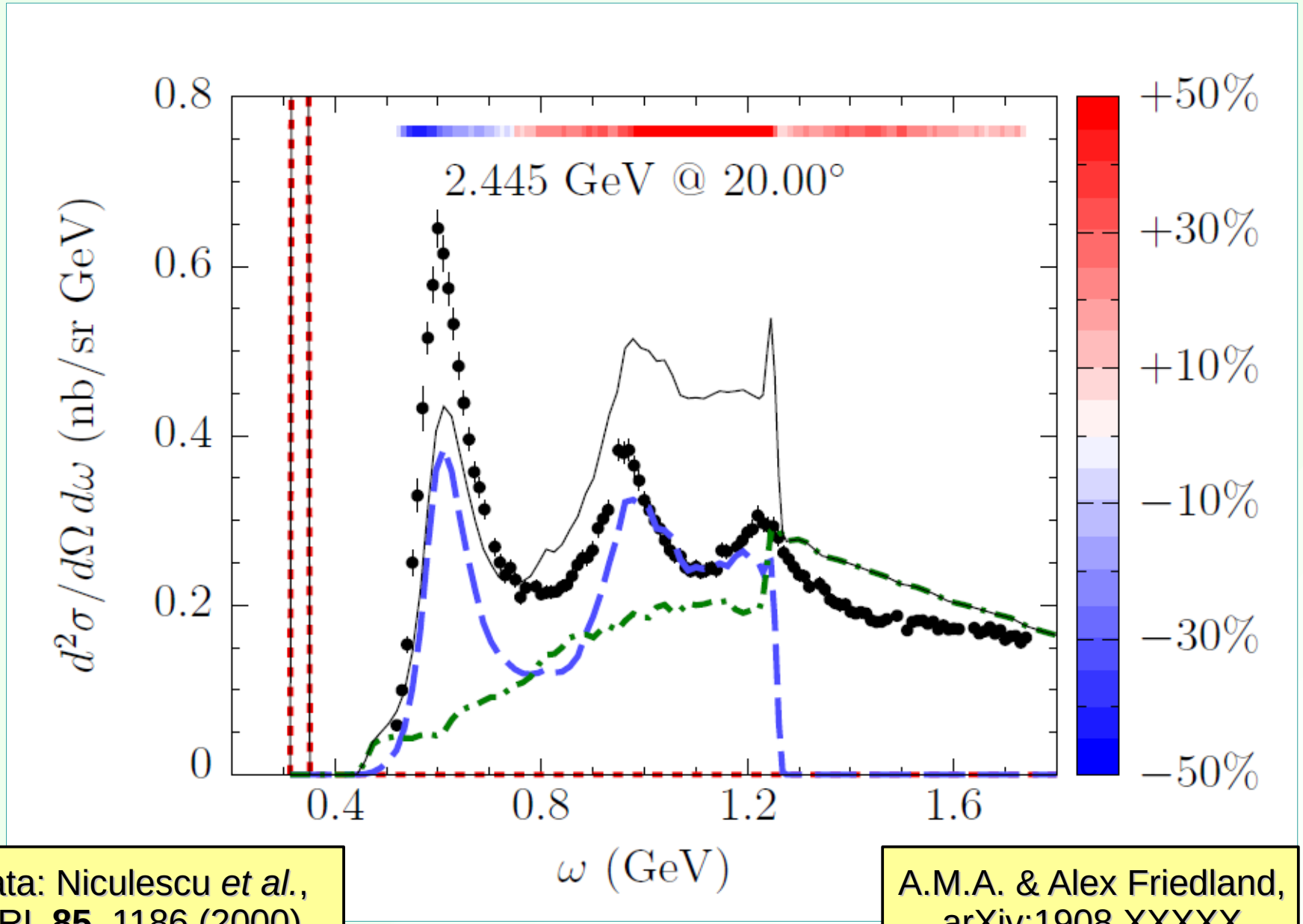
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

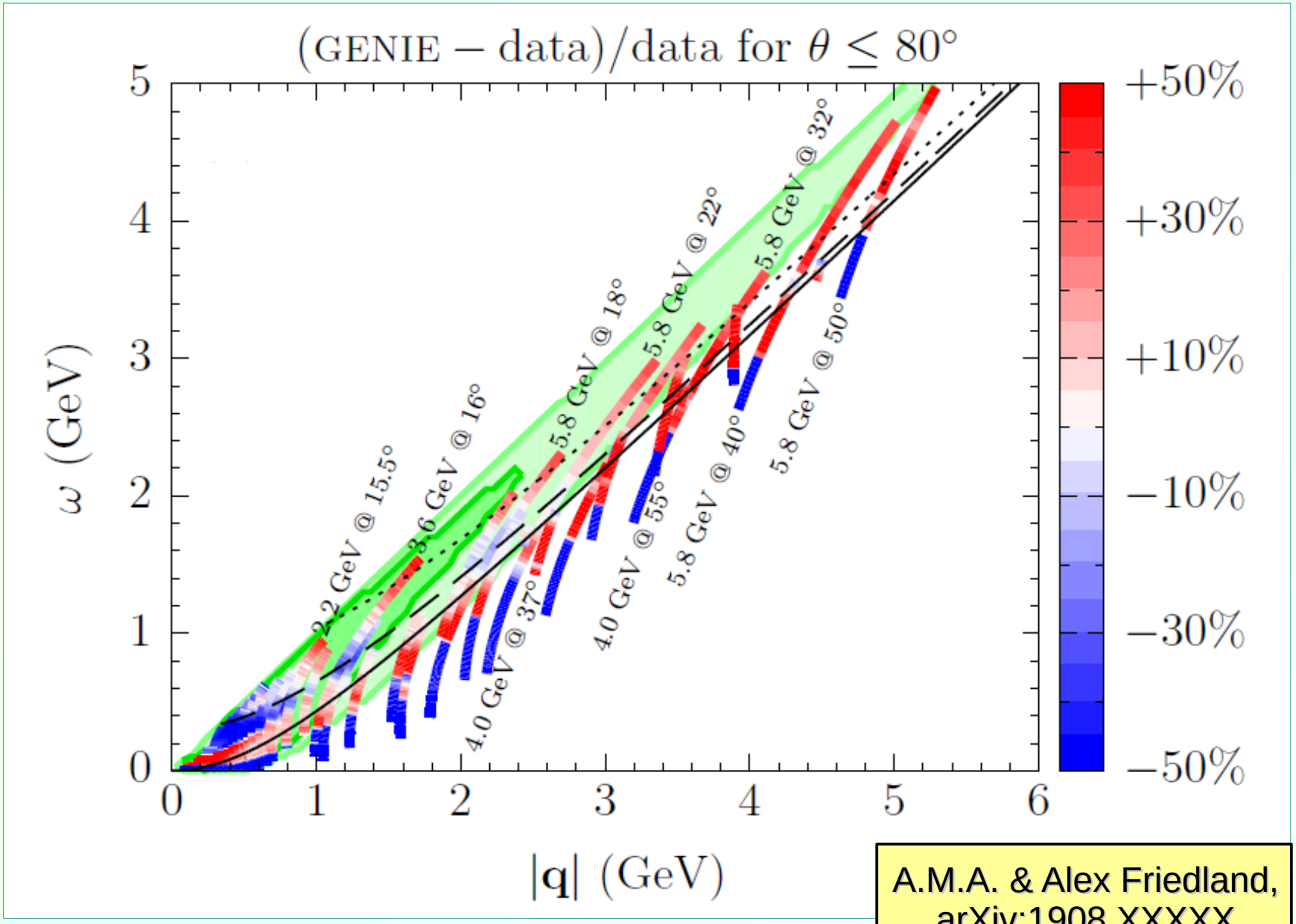
H(*e*, *e*') in GENIE



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

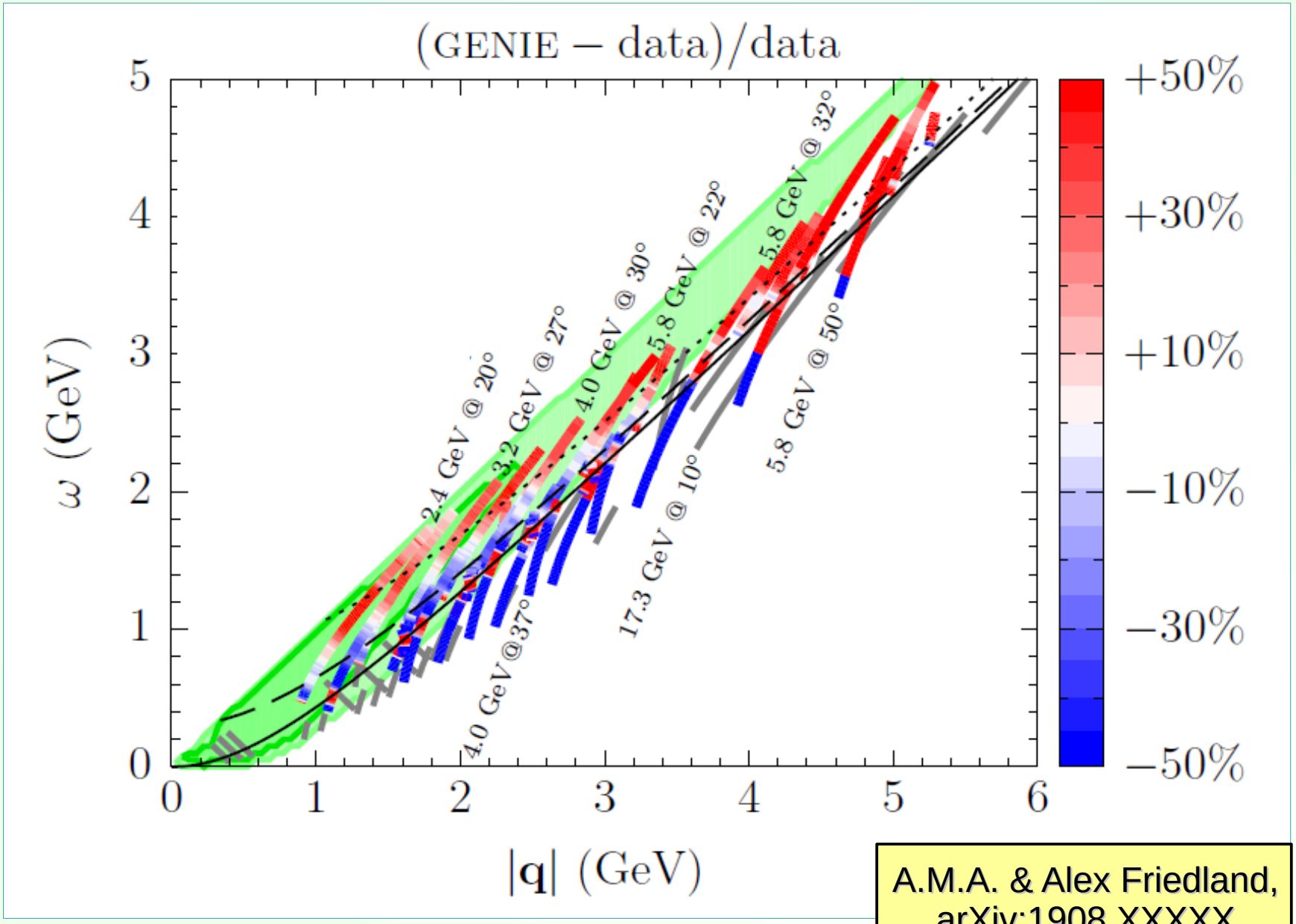
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

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



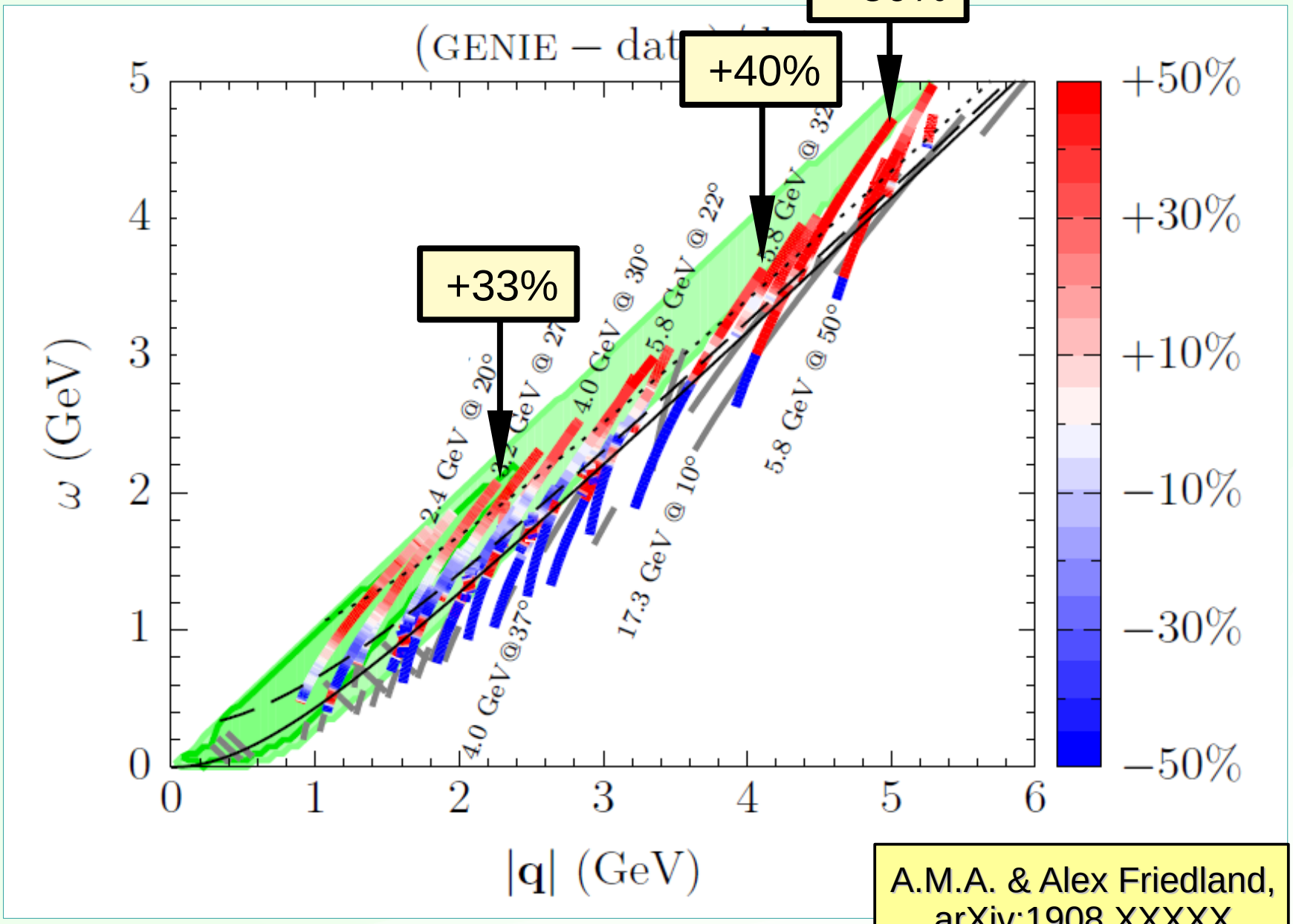
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

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



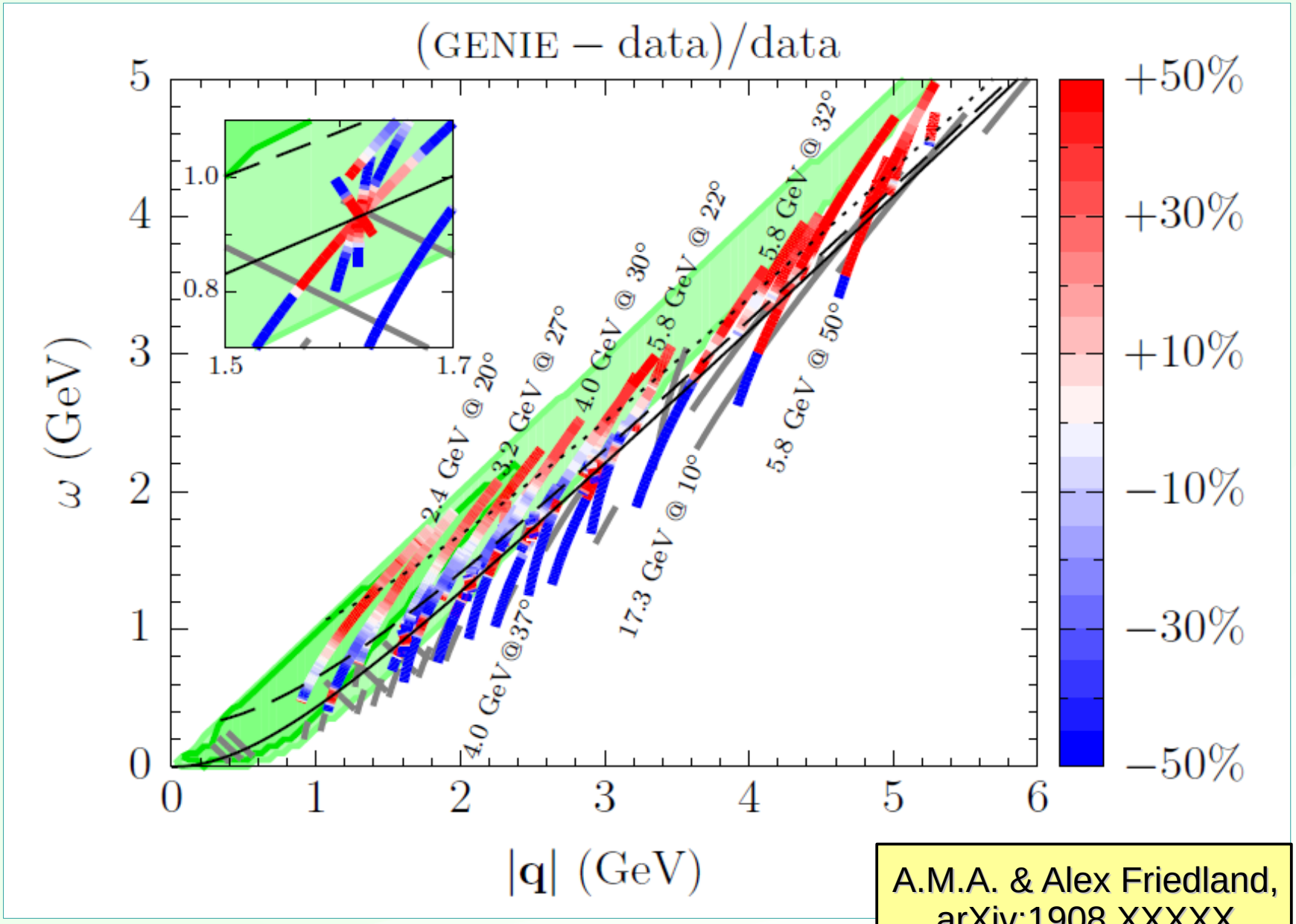
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

DIS



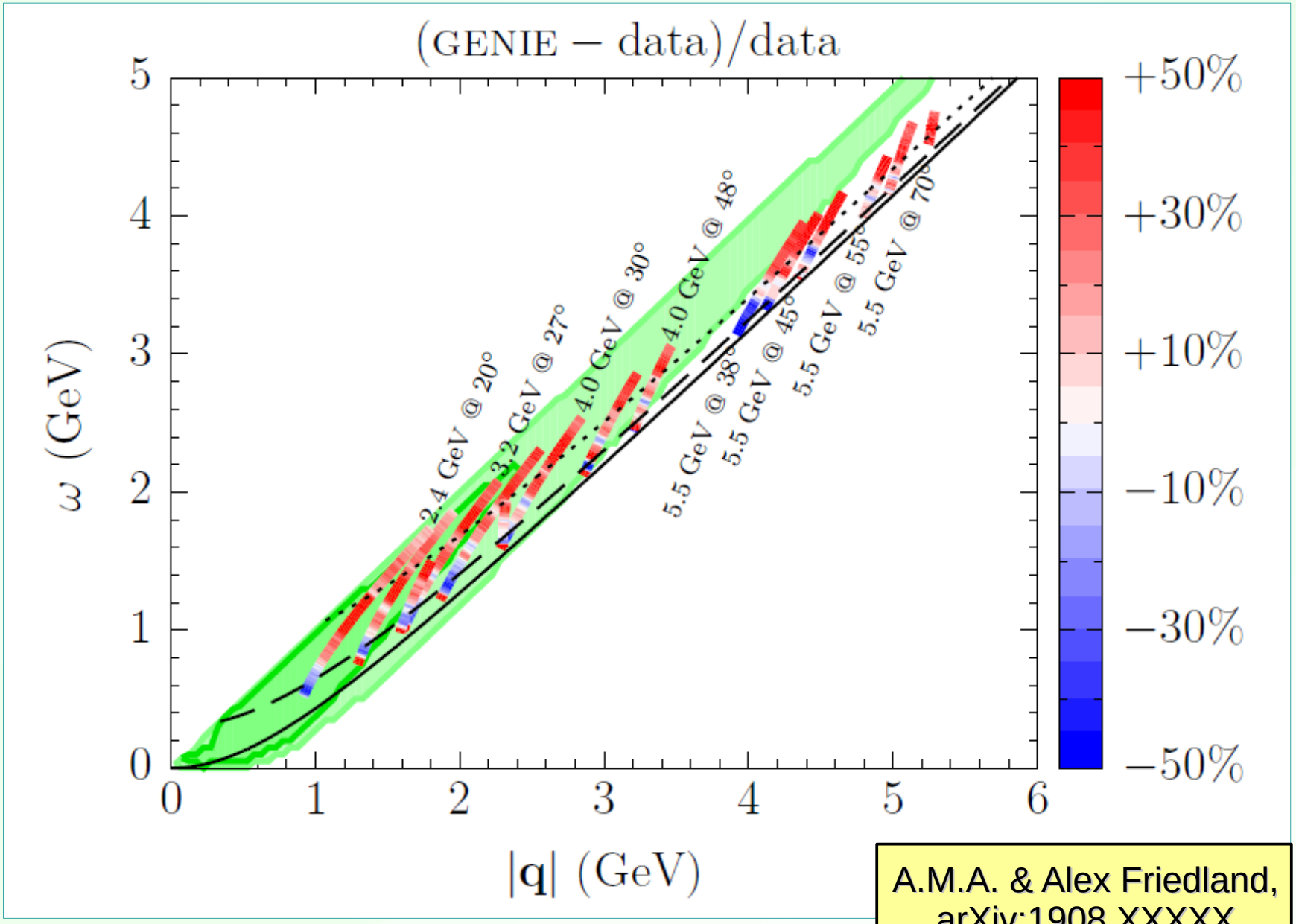
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

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



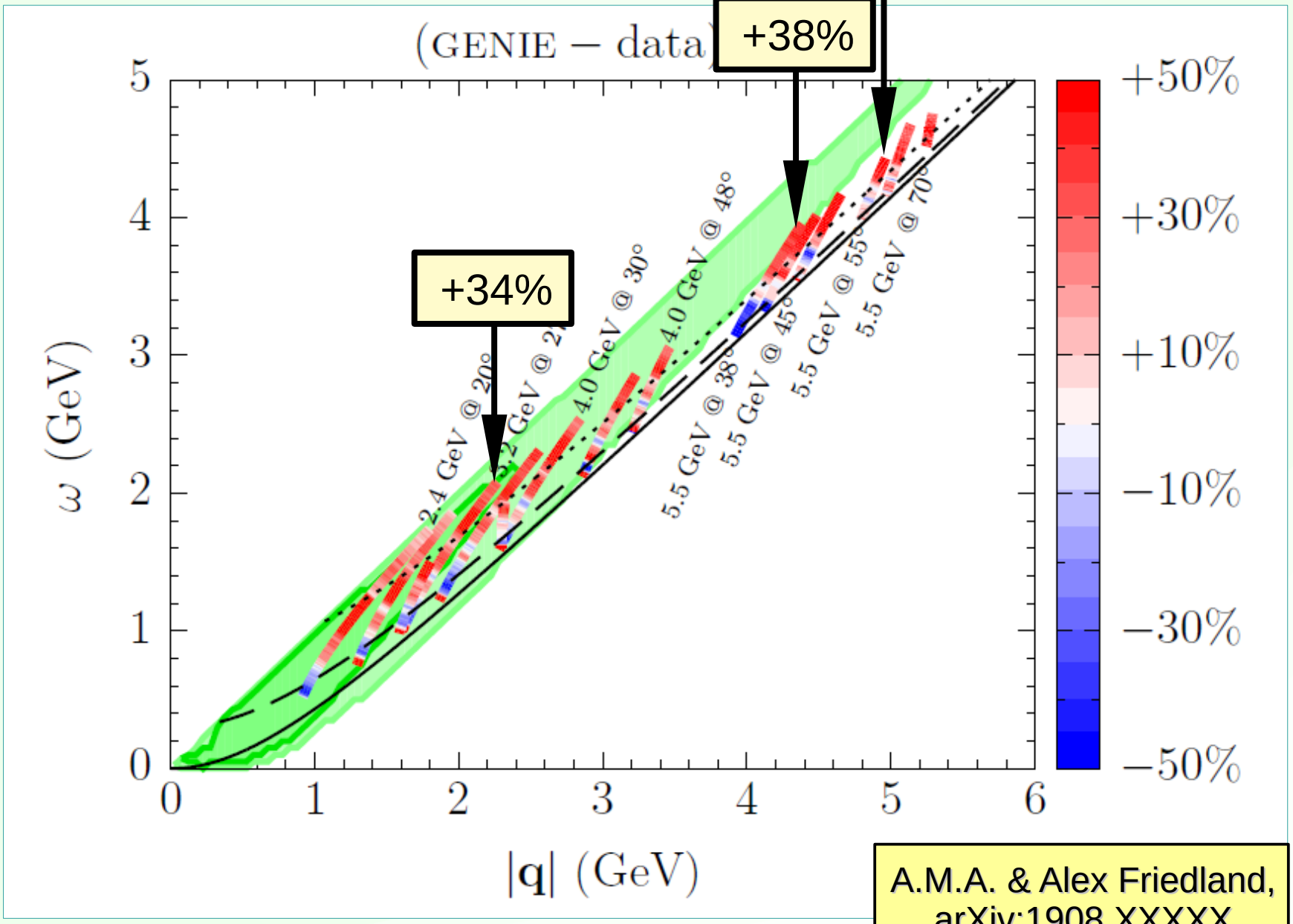
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

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



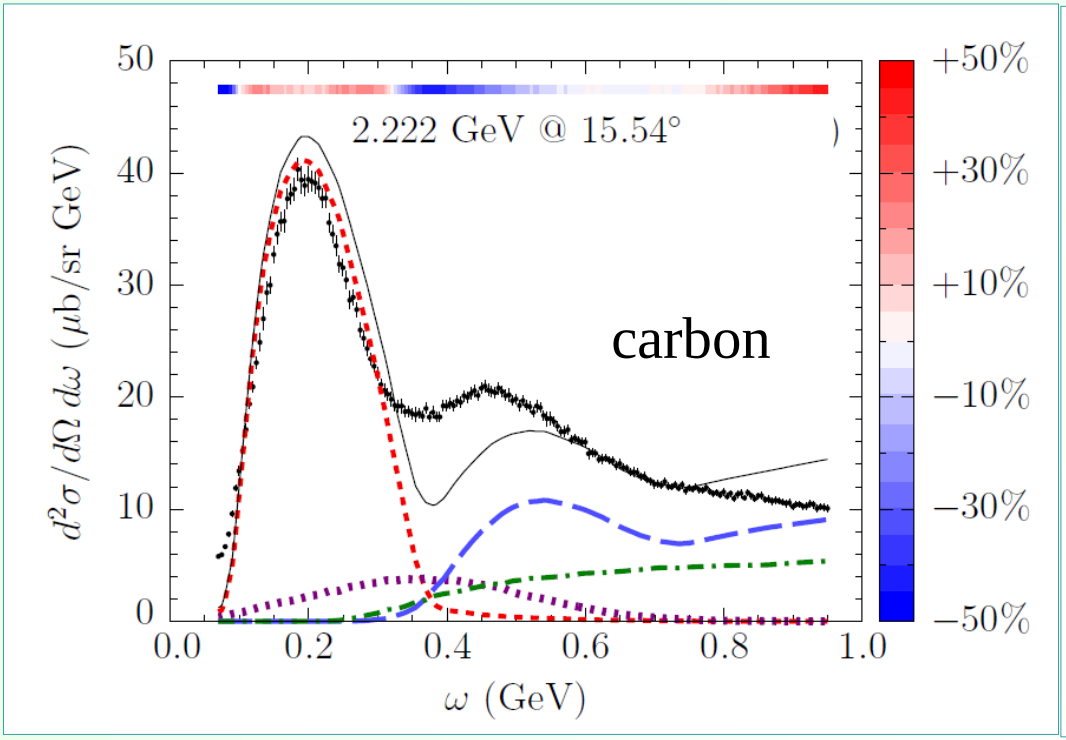
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

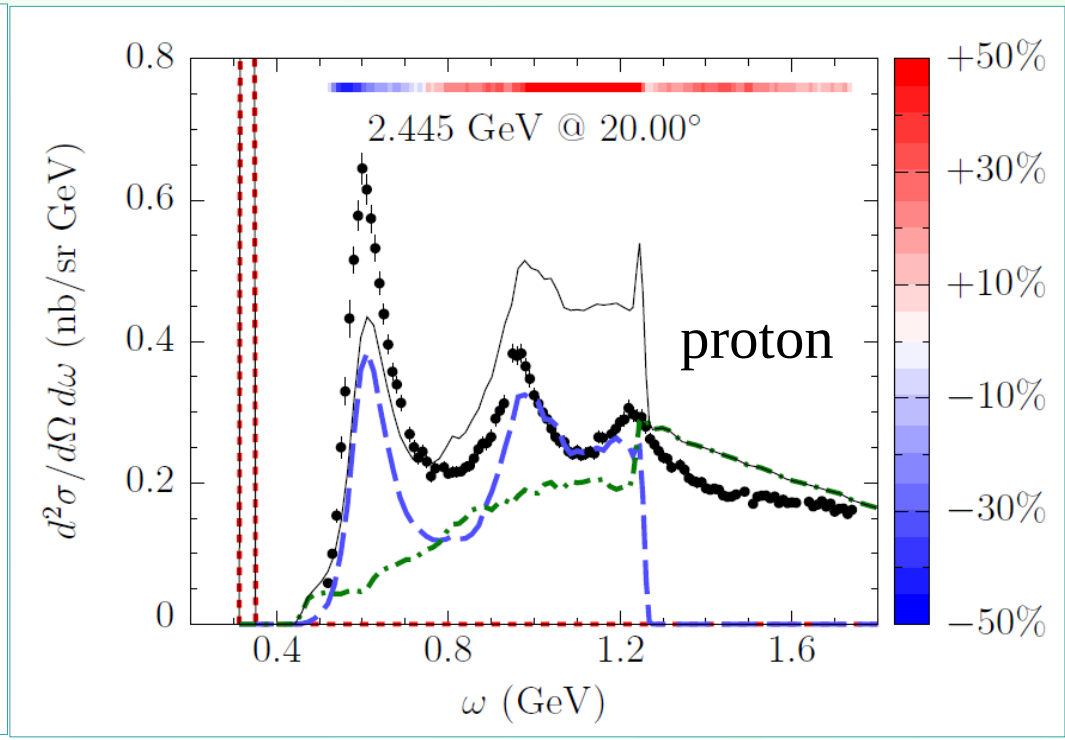
H(*e*, *e*') in GENIE



A.M.A. & Alex Friedland, arXiv:1908.XXXXX

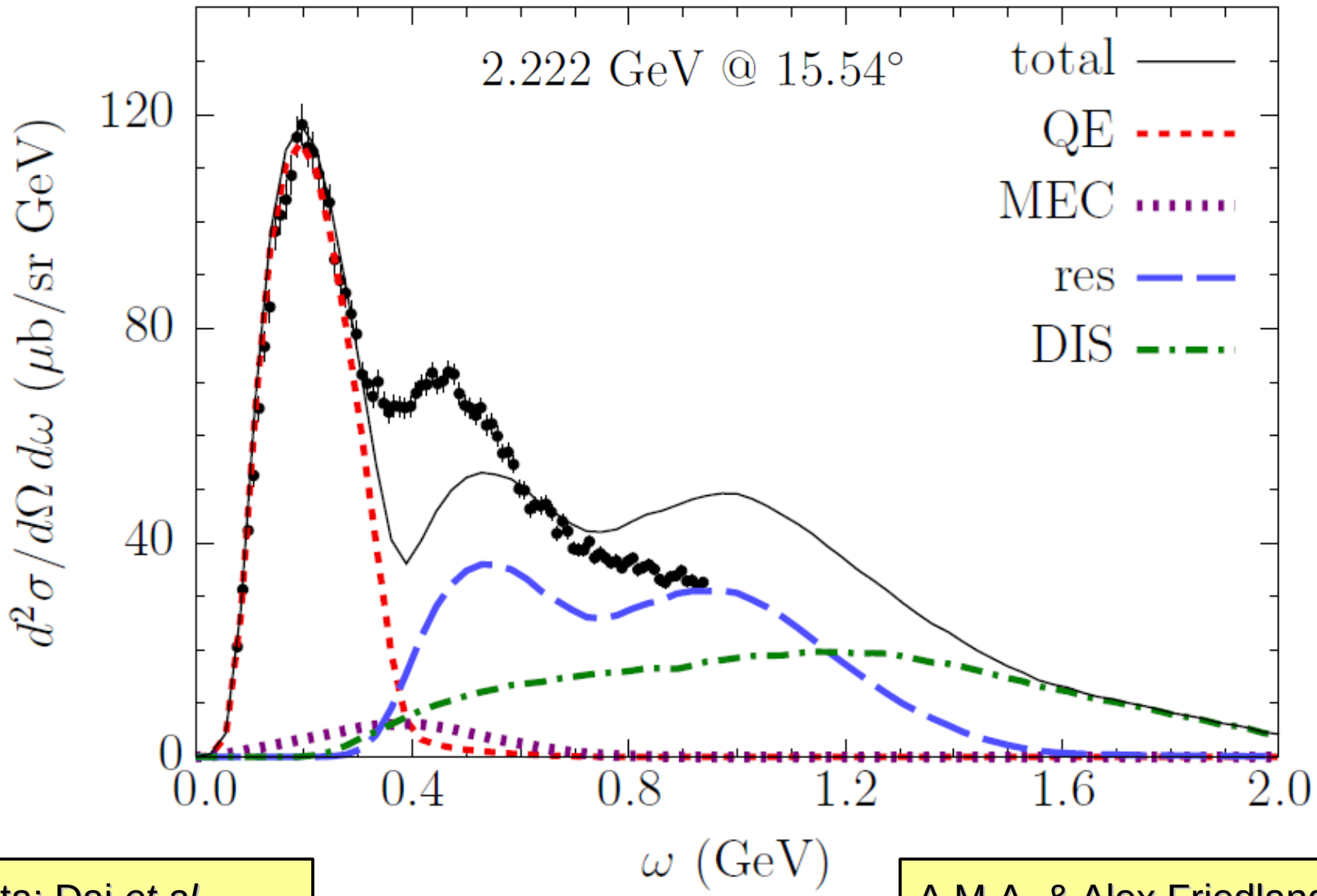
Resonances





- Higher resonances are clearly overestimated: visible in GENIE but not in (*e*, *e'*) data for $A \geq 12$.
- Fermi motion broadens higher resonances, likely accidentally improving the agreement in the Δ tail.

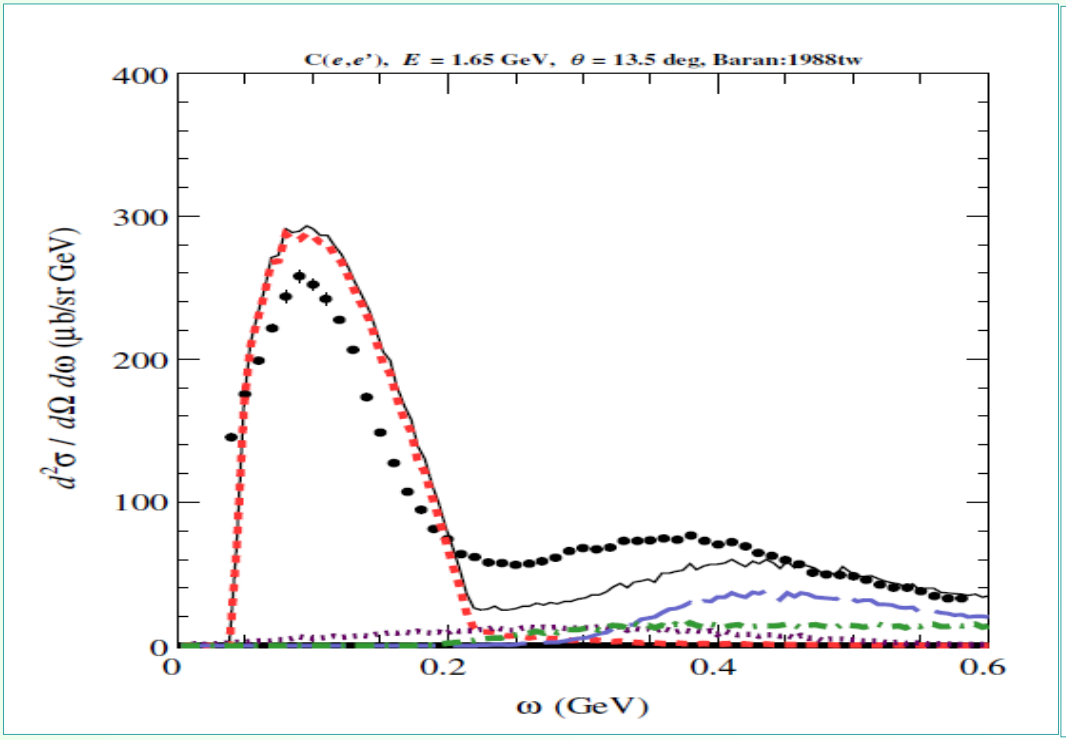
Ar(*e*, *e*') in GENIE

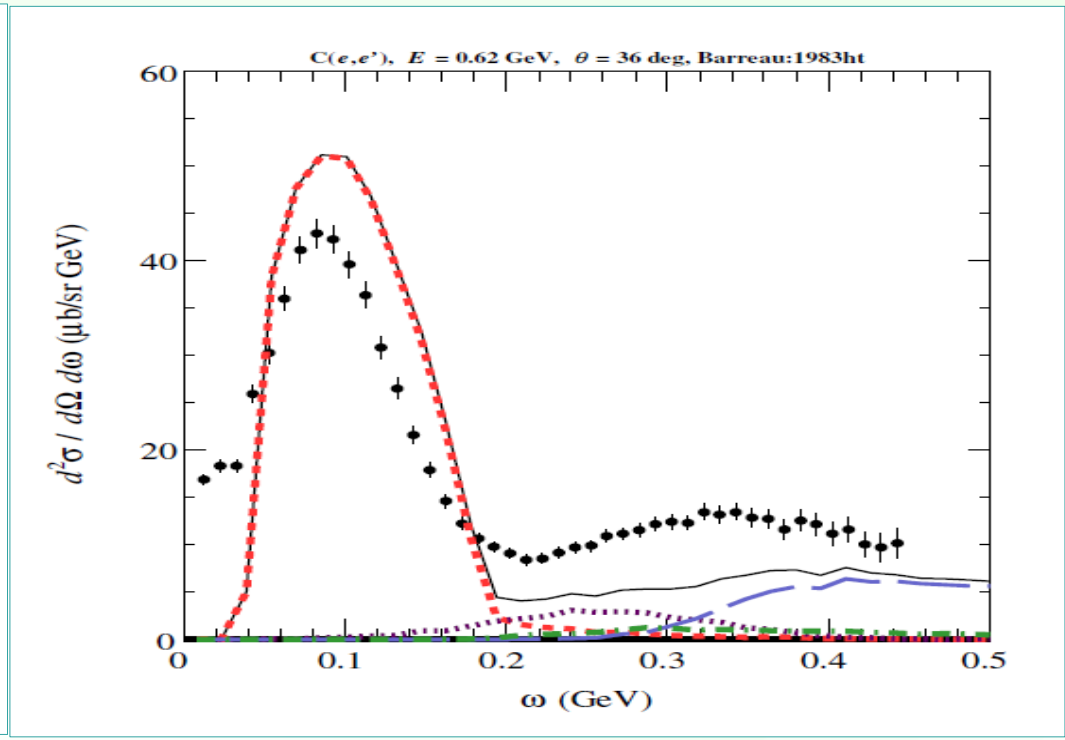


data: Dai *et al.*,
PRC **99**, 054608 (2019)

A.M.A. & Alex Friedland,
arXiv:1908.XXXXX

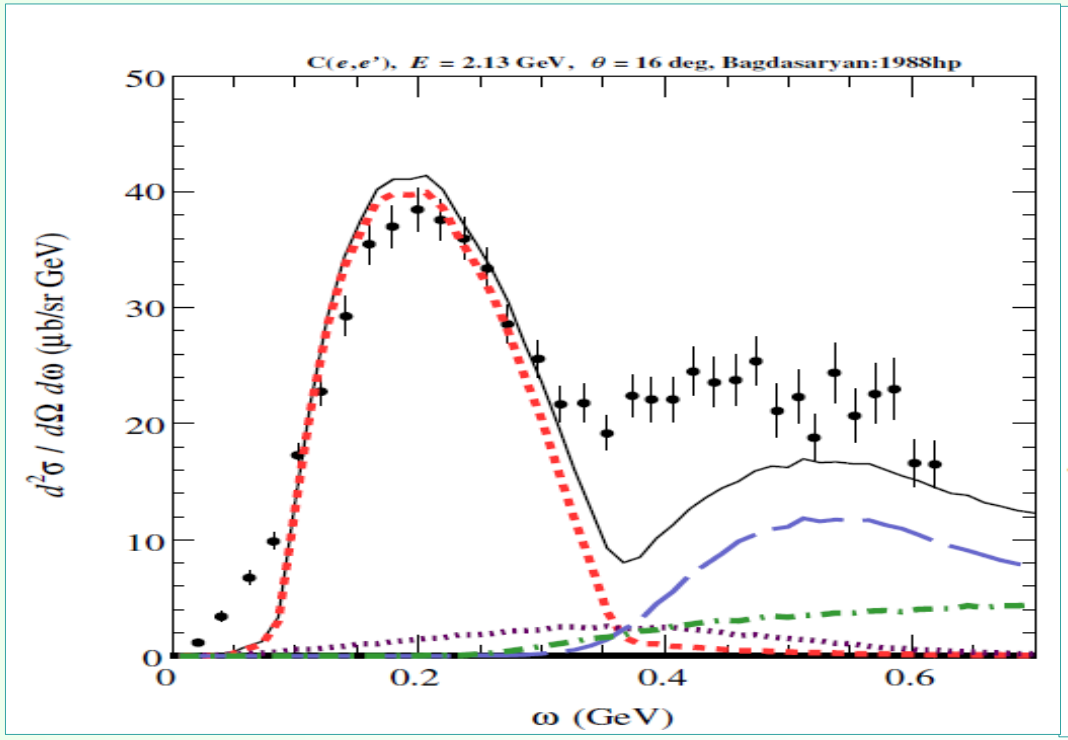
Δ resonance

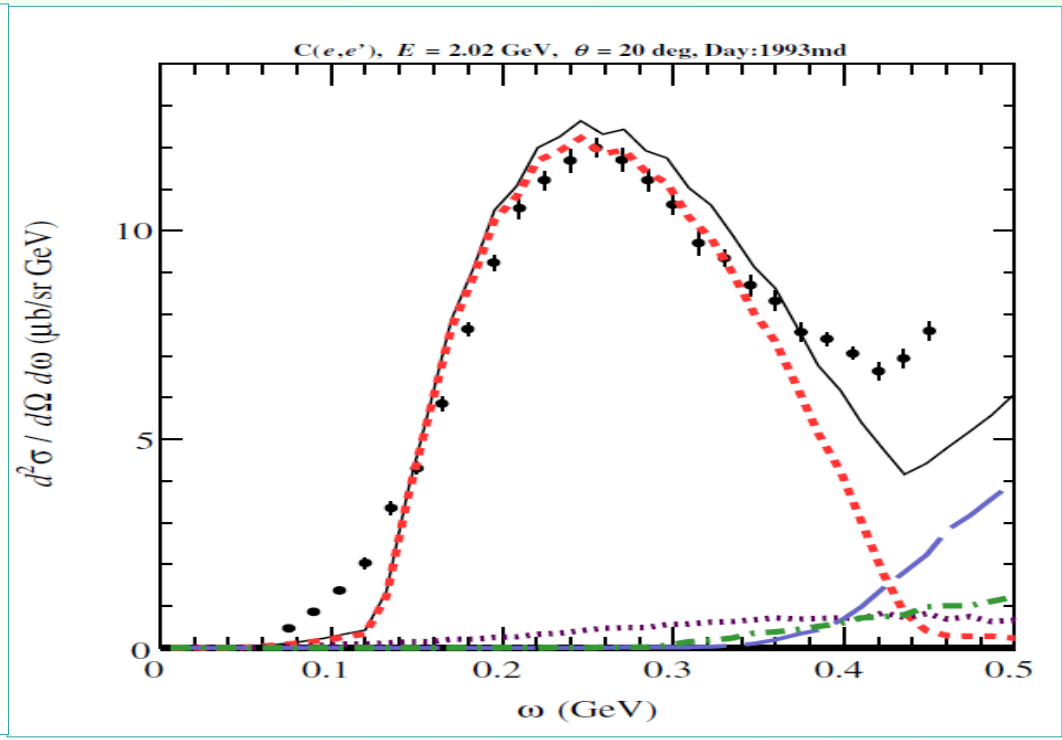




- For $|q| \lesssim 1$ GeV, Δ can be distinguished in data.
- Δ position wrong by **~50–100 MeV**: pions too hard.
- Correcting Δ position will improve the agreement in the dip region.

QE

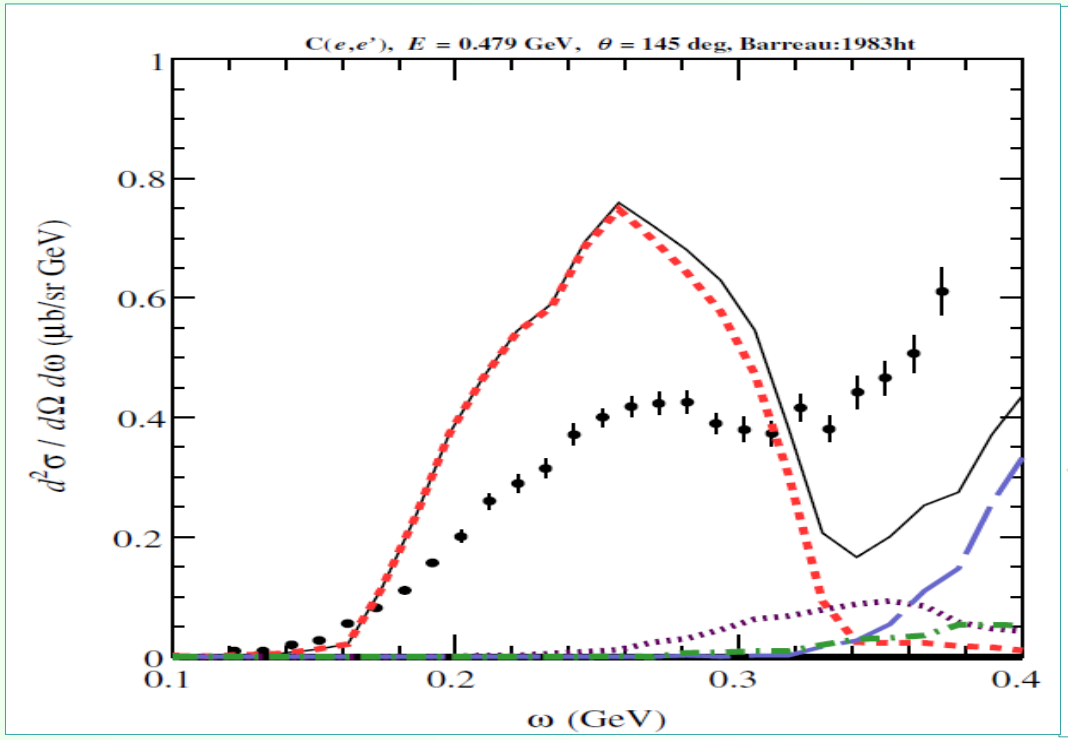


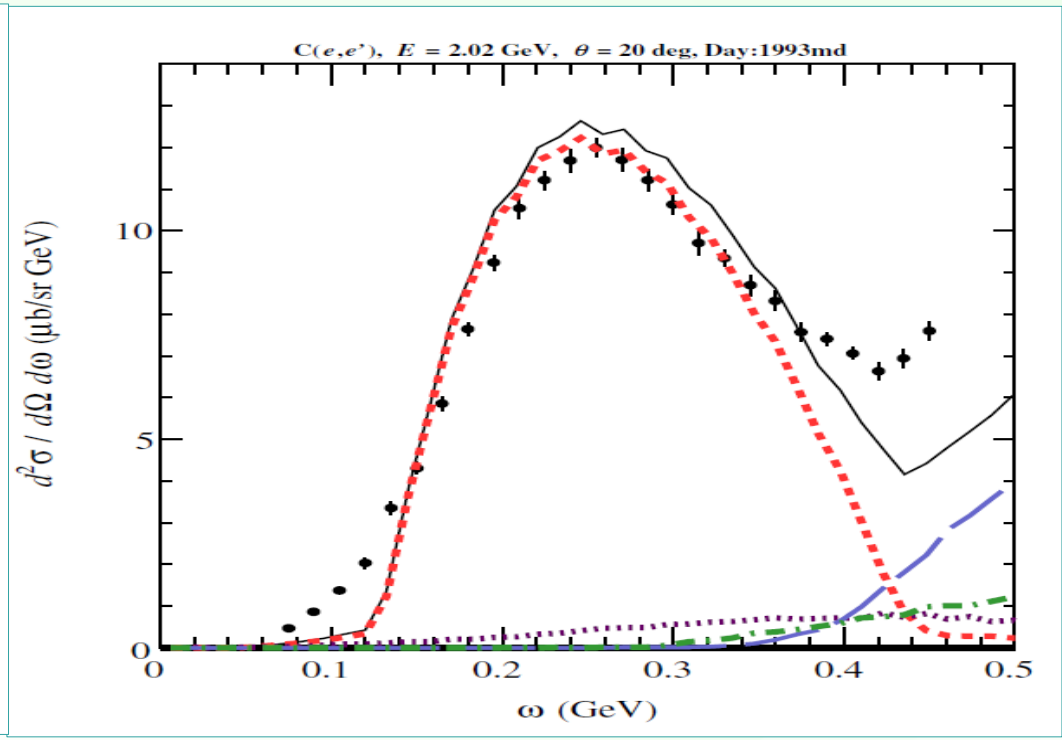


- Discrepancy decreases with |q| increasing.
  Available QE data for ~2 GeV beams in **good agreement**.

- MEC contribution **consistently worsens** the agreement in the QE peak: RFG parameters determined without it.

QE





Large differences in discrepancies between low and high scattering angles, for fixed energy and momentum transfers.

Summary

- Electron-scattering data give us unique opportunity of validating Monte Carlo generators **against data they were not tuned to**.

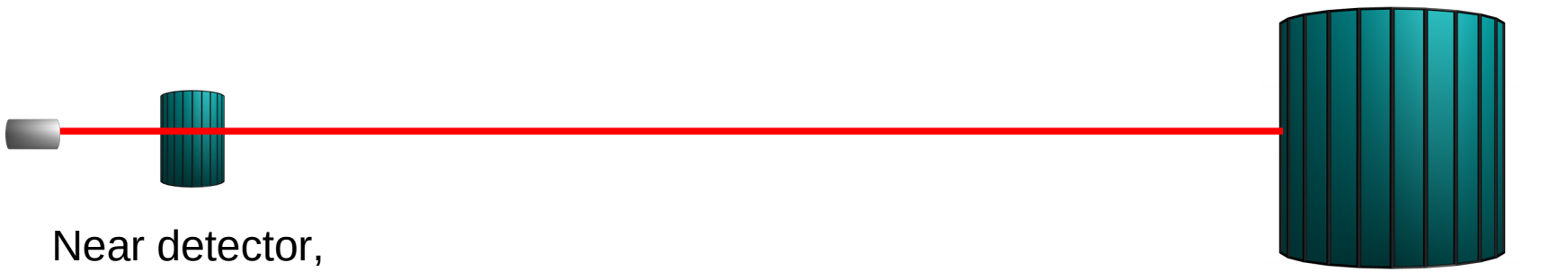
- We assessed accuracy of GENIE and found a consistent, global picture.

- In GENIE, quasielastic scattering works fine at ~2 GeV, but **improvements of pion production are called for**. Pion spectra from GENIE are expected to be too hard. Tunes to bubble-chamber data may have underestimated uncertainties.

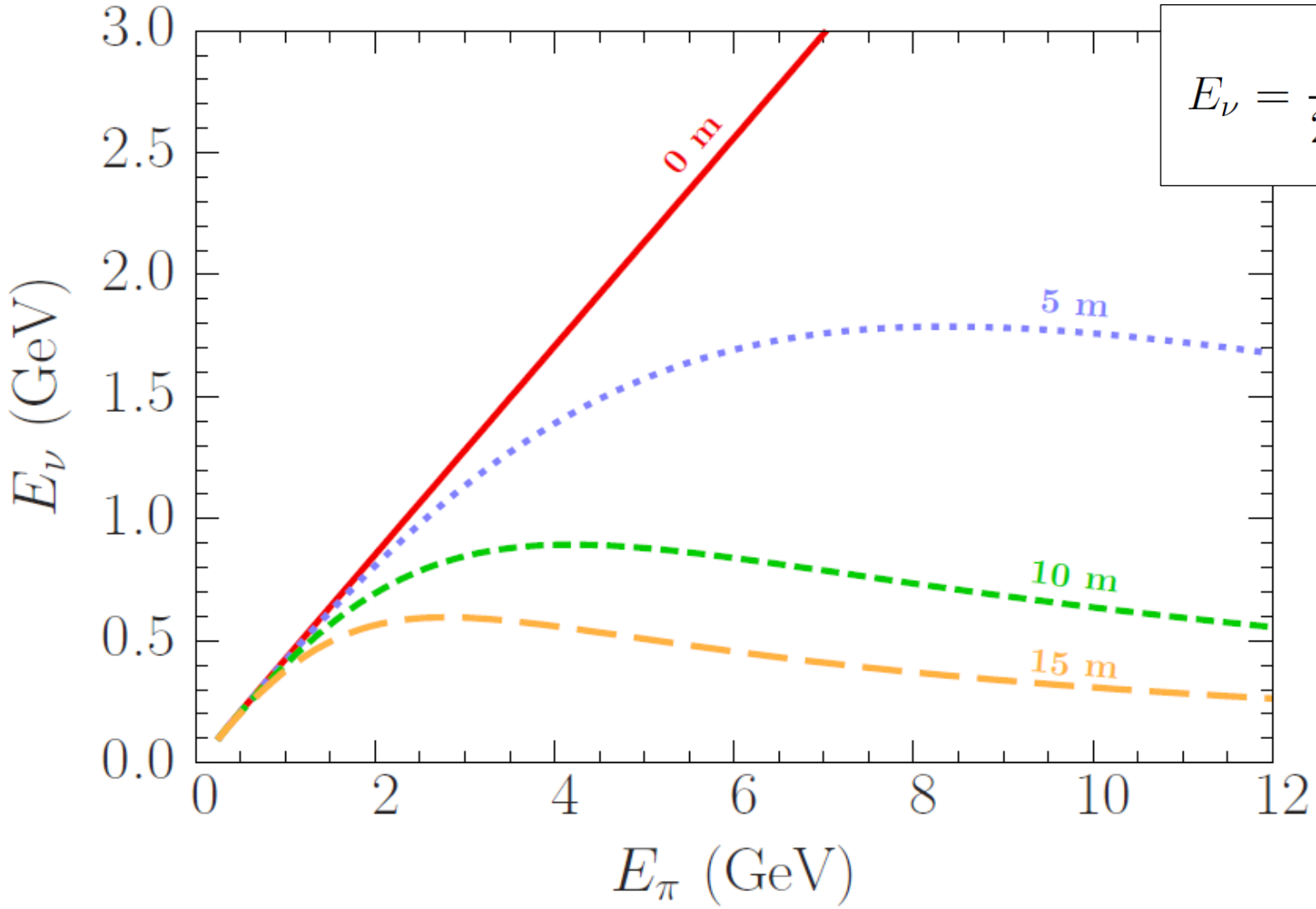
- Most of the observed issues with pion production **do not originate from nuclear model**, but from the elementary cross sections (physics or implementation).

Backup slides

Side remark: near detector



Flux's angular dependence @ ND



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - |\mathbf{p}_\pi| \cos\theta)}$$

ND @ 300 m,
off-axis distance

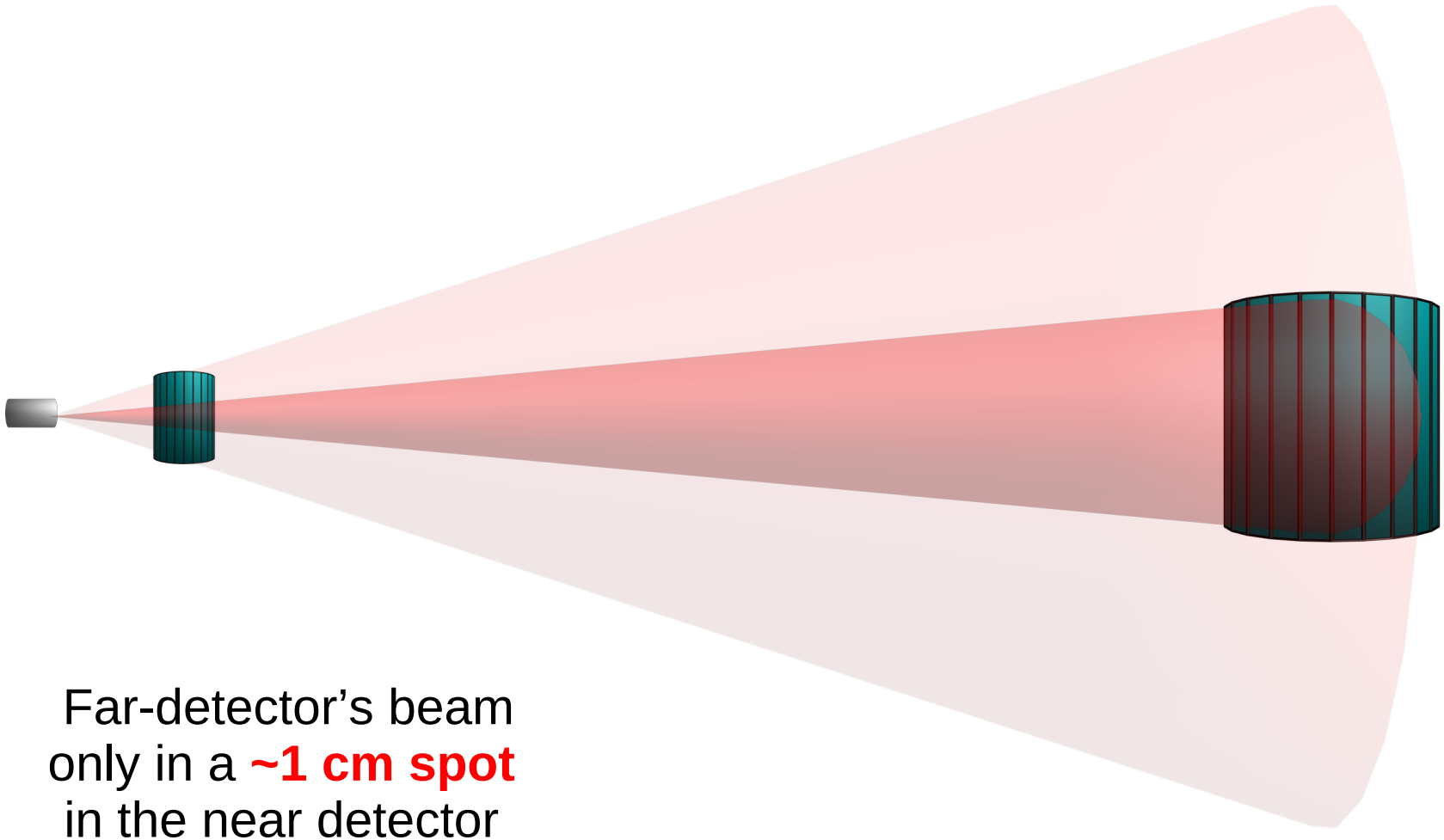
0 m → 0.00º

5 m → 0.96º

10 m → 1.91º

15 m → 2.87º

Side remark: near detector



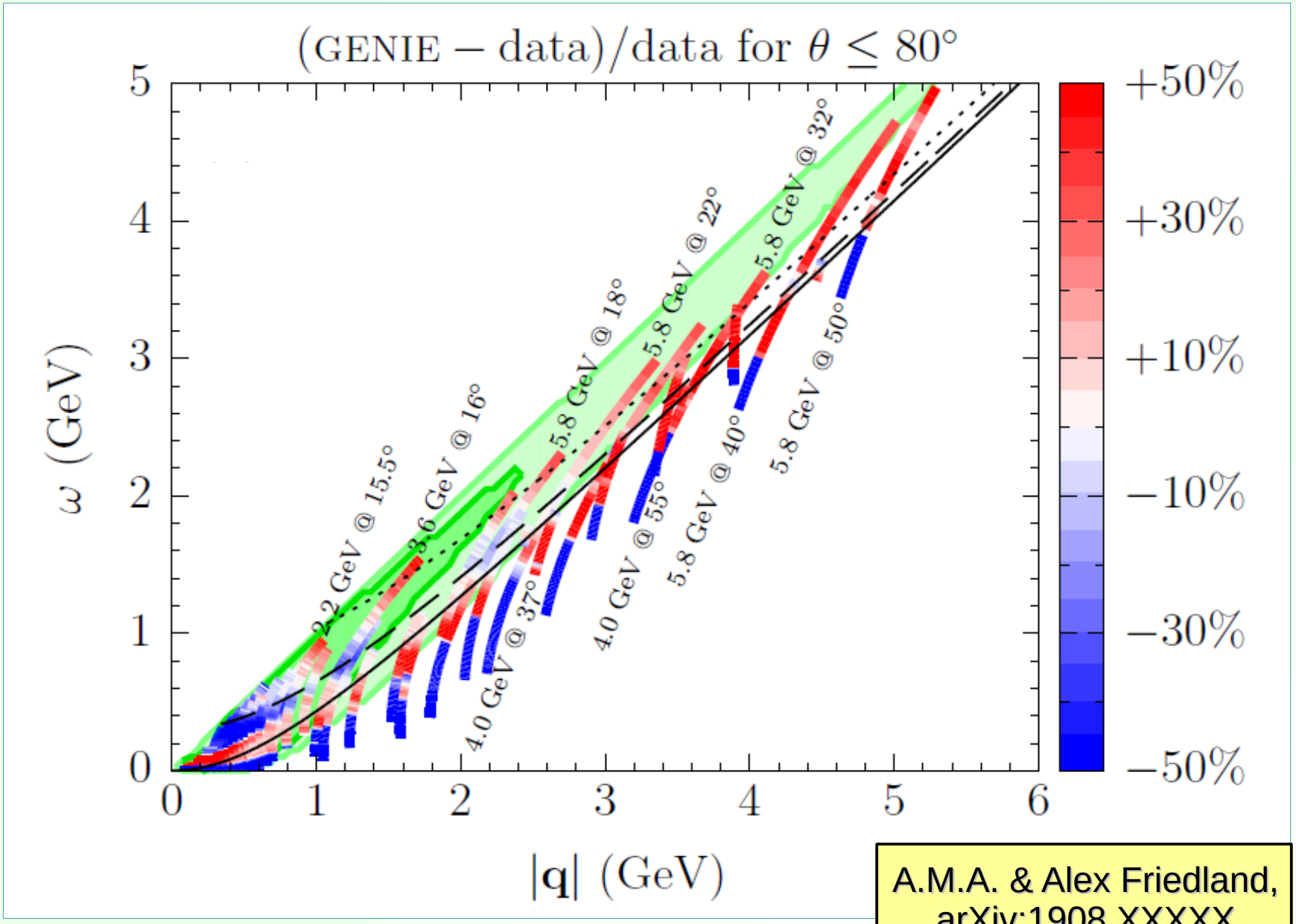
Far-detector's beam
only in a **~1 cm spot**
in the near detector

NOvA

- Rate of nonresonant single-pion production with $W < 1.7$ GeV reduced by 59%.
- Delta peak shifted by RPA.
- MEC increased by 20%.
- QE shifted and reduced at low |q| by RPA.

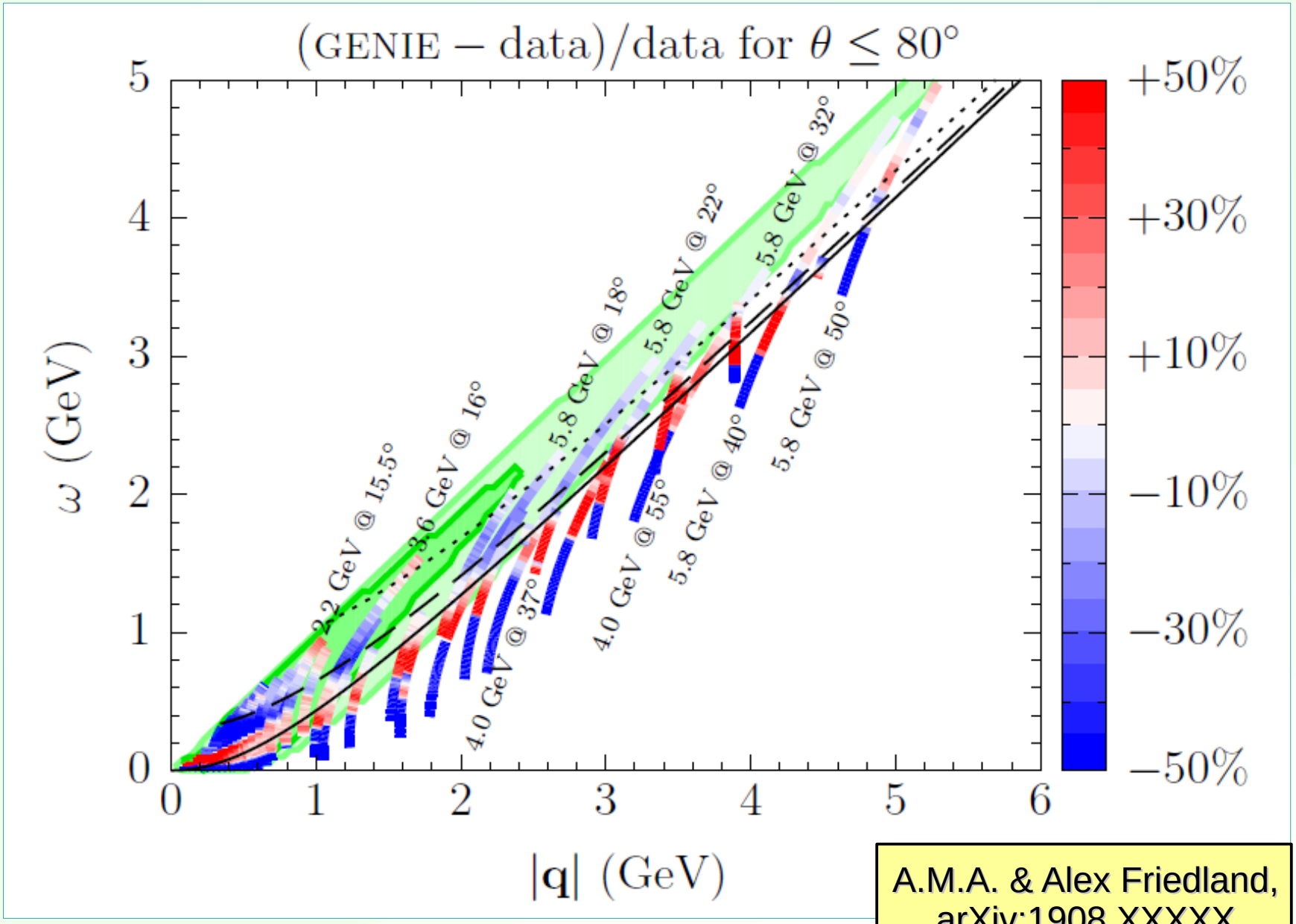
Acero *et al.* (NOvA), PRD **98**, 032012 (2018)

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



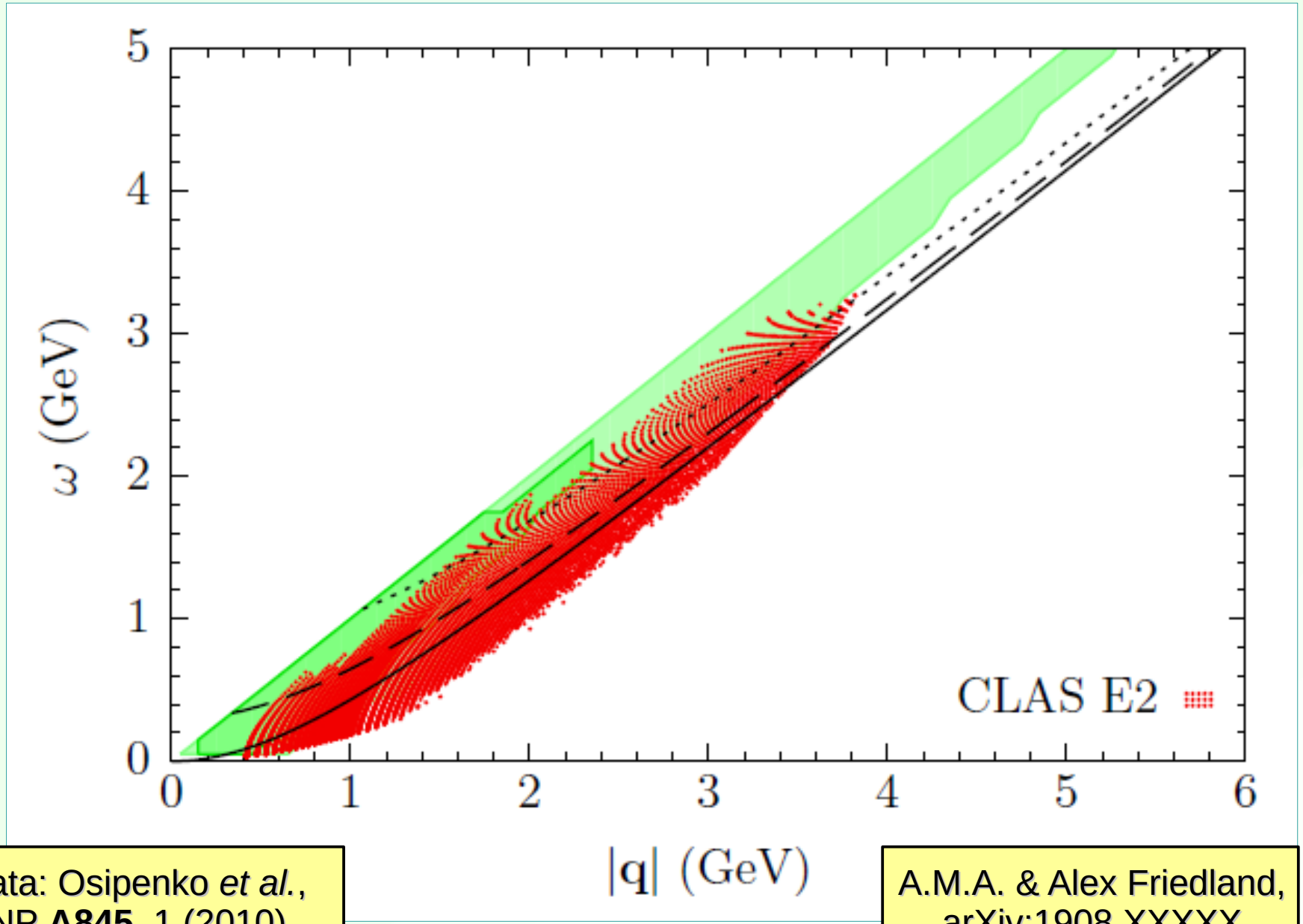
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

DIS reduction by 28%



A.M.A. & Alex Friedland, arXiv:1908.XXXXX

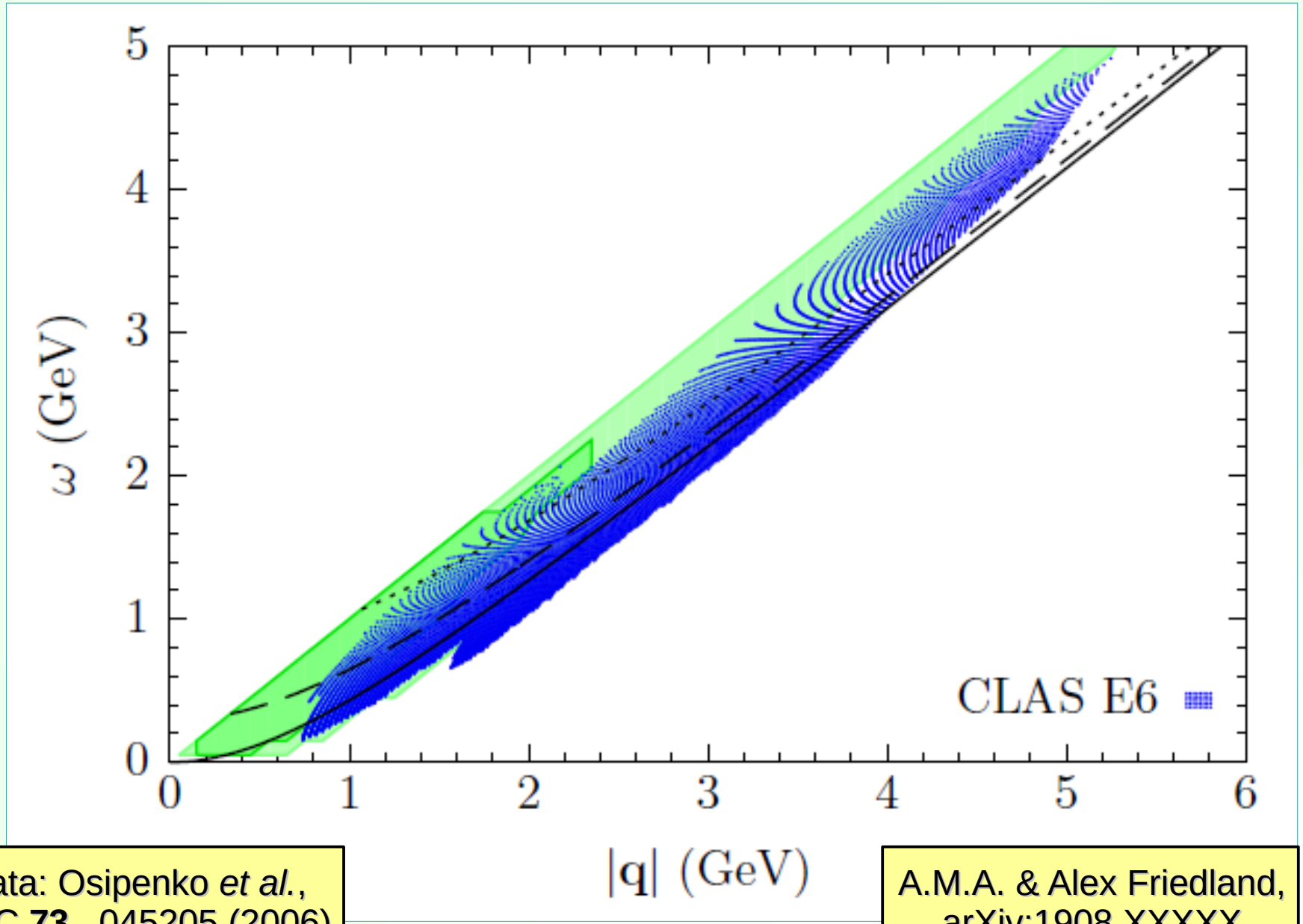
Kinematics covered in C(*e*, *e*')



data: Osipenko *et al.*, NP **A845**, 1 (2010)

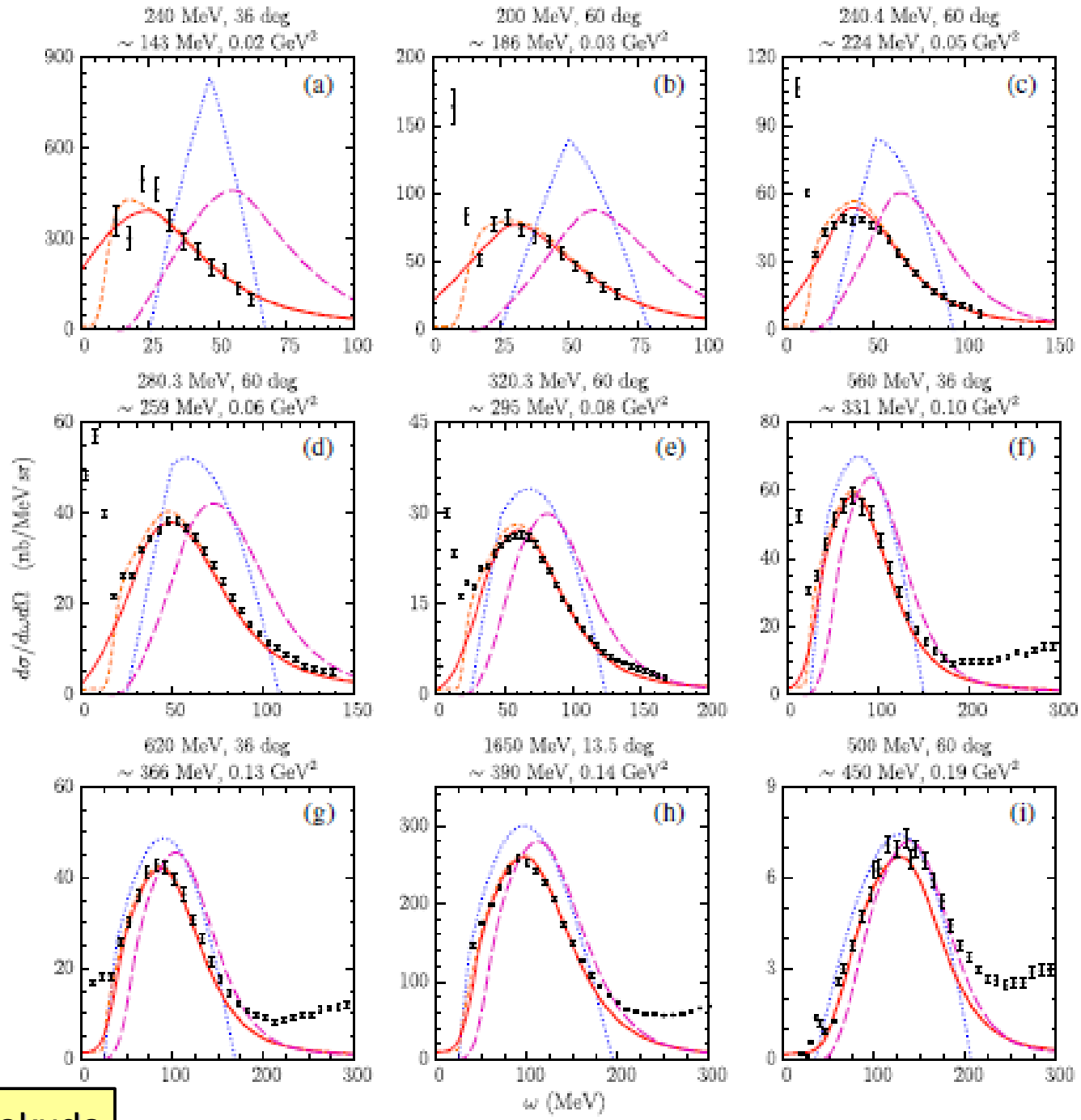
A.M.A. & Alex Friedland, arXiv:1908.XXXXX

Kinematics covered in D(*e*, *e*')



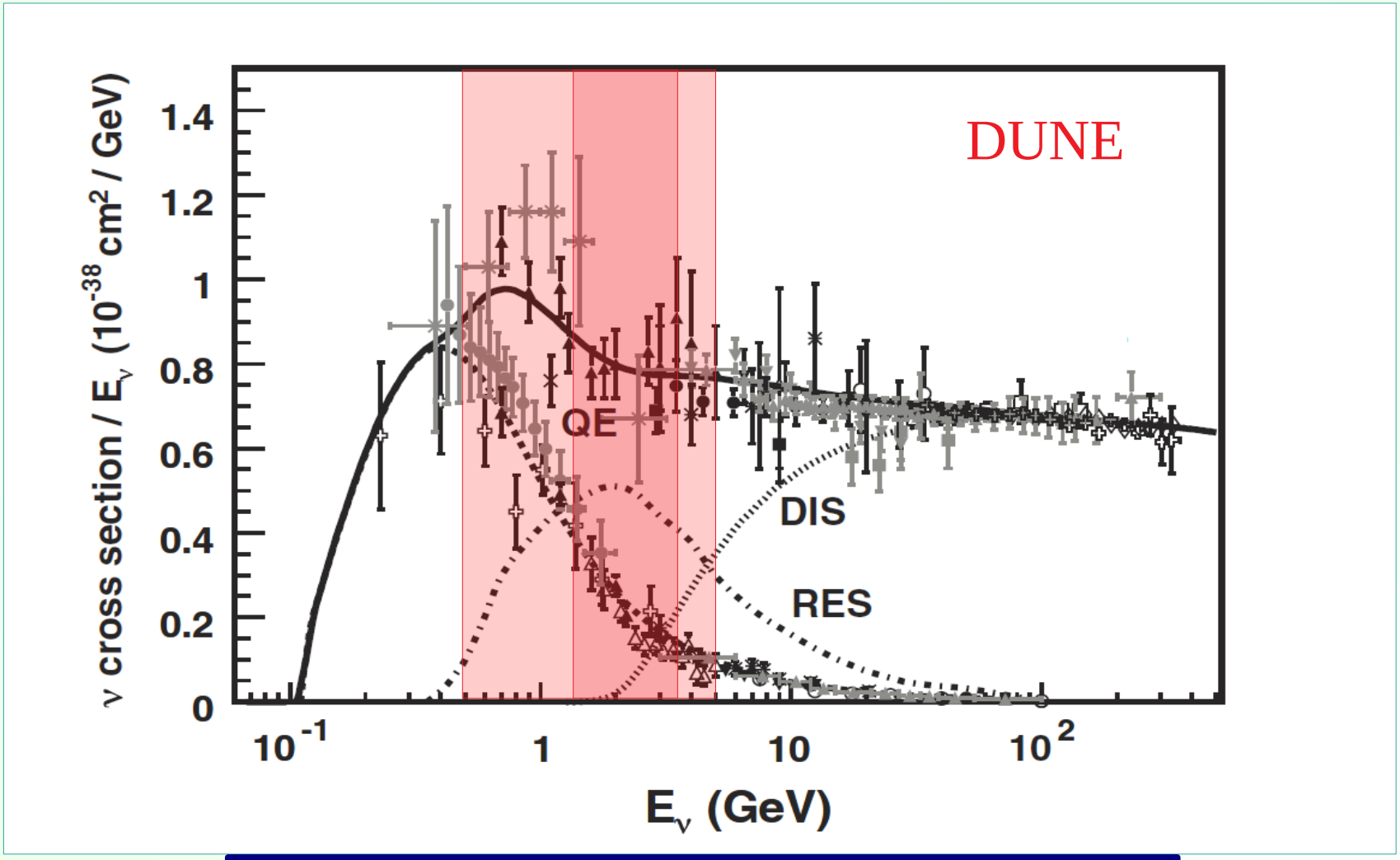
data: Osipenko *et al.*, PRC **73**, 045205 (2006)

A.M.A. & Alex Friedland, arXiv:1908.XXXXX



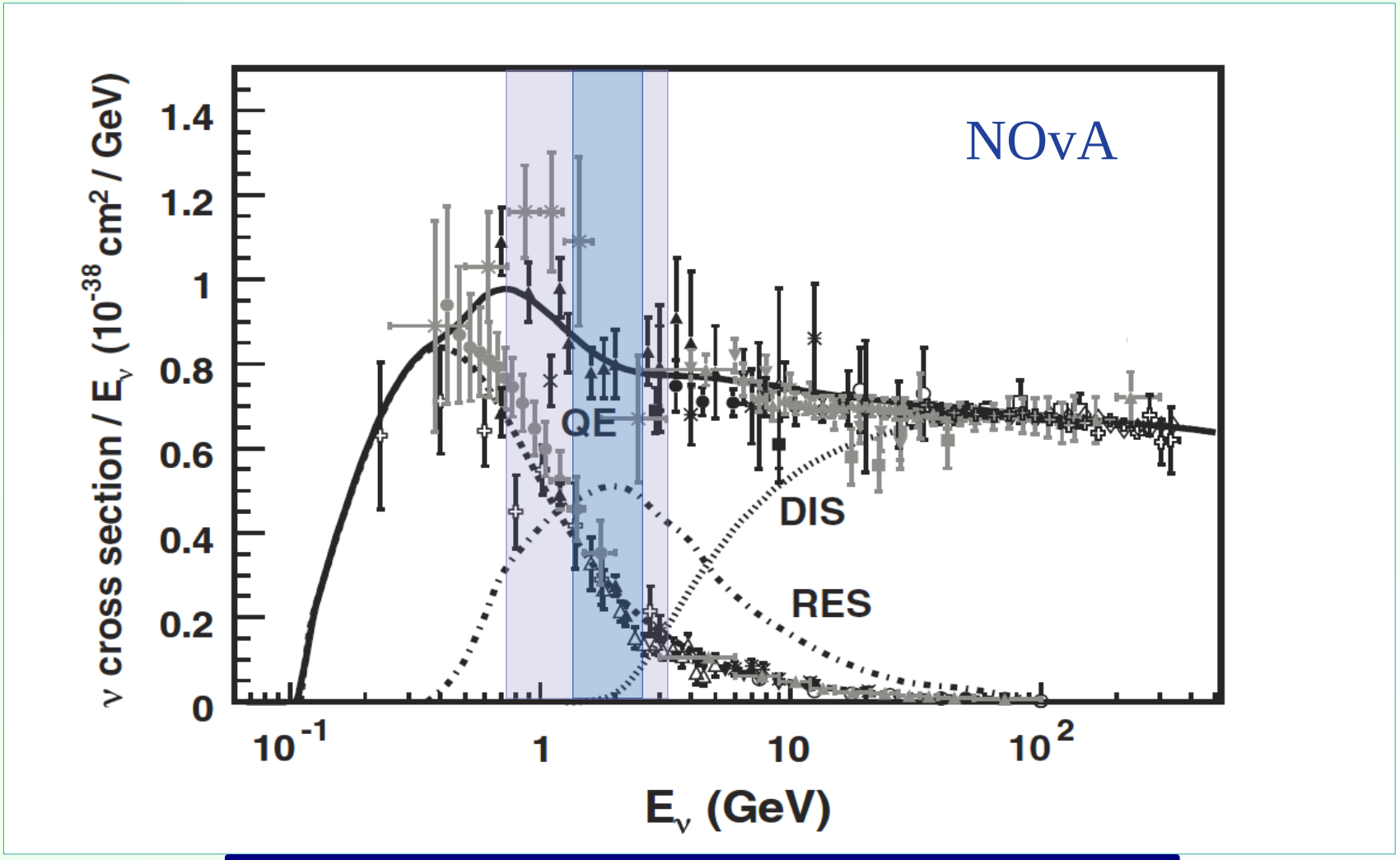
AMA, Benhar & Sakuda
PRD 91, 033005 (2015)

What energies are relevant?



adopted from
Formaggio & Zeller, RMP 84, 1307 (2013)

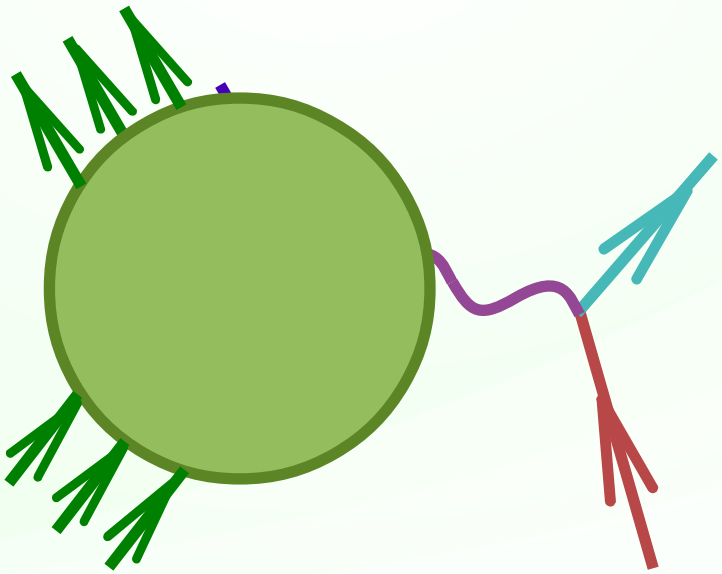
What energies are relevant?



adopted from
Formaggio & Zeller, RMP 84, 1307 (2013)

Impulse approximation

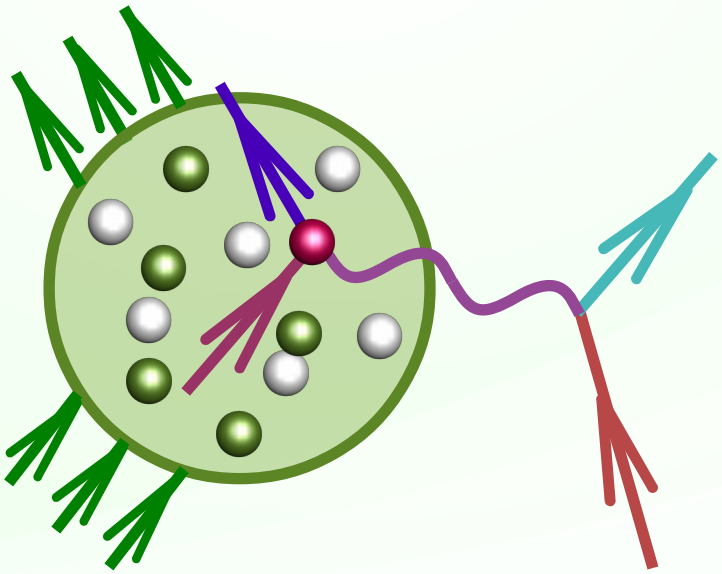
Assumption: the dominant process of lepton-nucleus interaction is **scattering off a single nucleon**, with the remaining nucleons acting as a spectator system.



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**|.



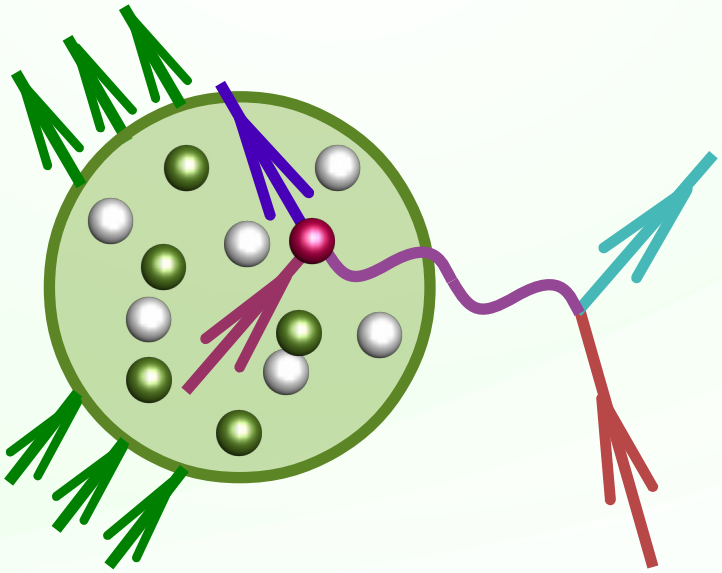
Impulse approximation

$$\frac{d\sigma_{\ell A}}{d\omega d\Omega} = \sum_N \int d\omega'\, d^3p\, dE\, P^N_{\rm hole}(\mathbf{p}, E)\, \frac{M}{E_{\mathbf{p}}} \frac{d\sigma^{\rm elem}_{\ell N}}{d\omega' d\Omega}\, P^N_{\rm part}(\mathbf{p}', \mathcal{T}', \omega')$$

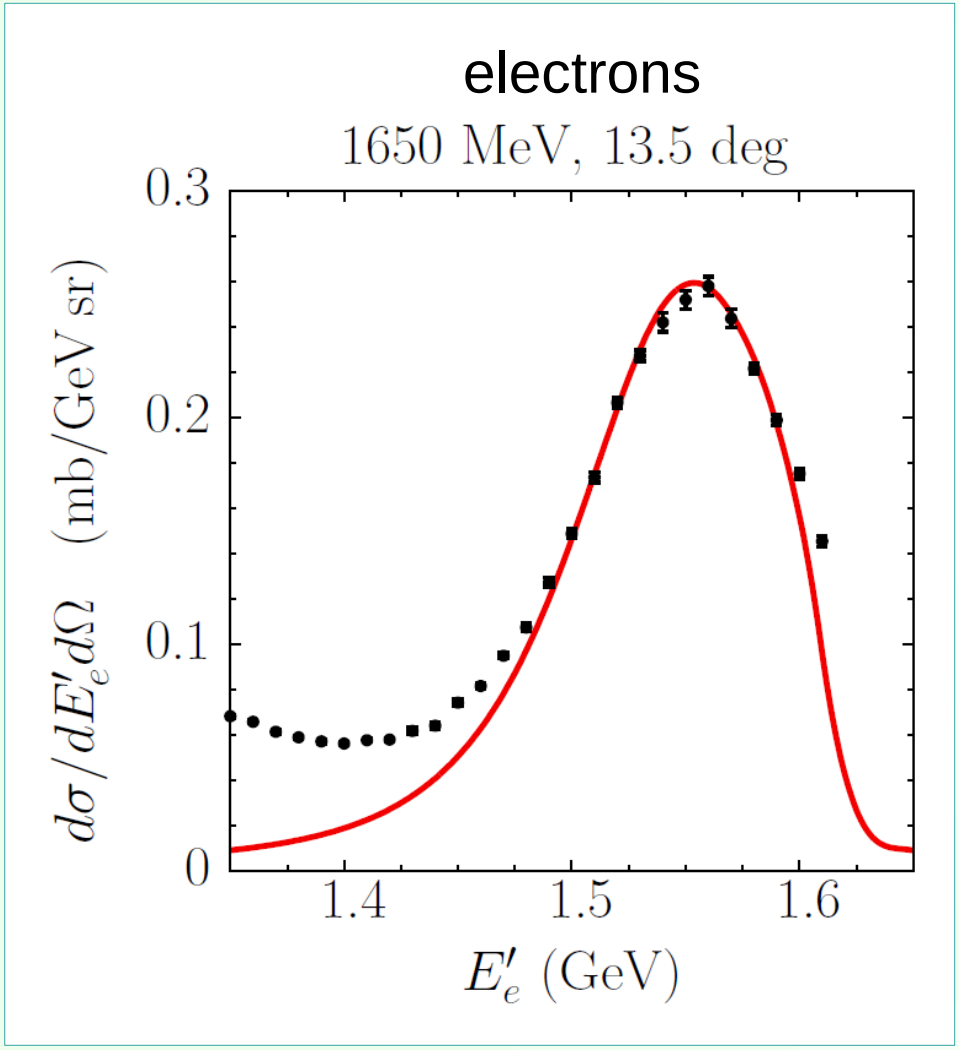
Hole spectral function

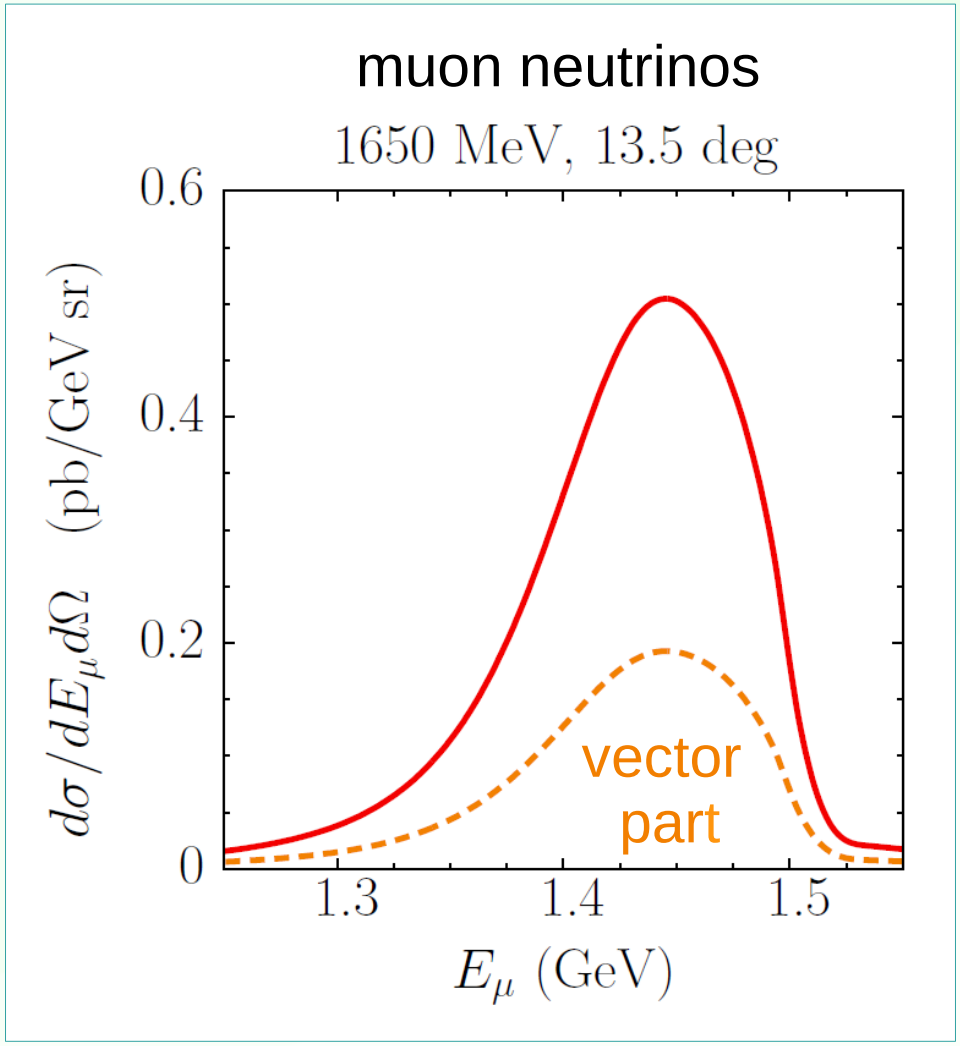
Elementary cross section

Particle spectral function



Much more than the vector part...

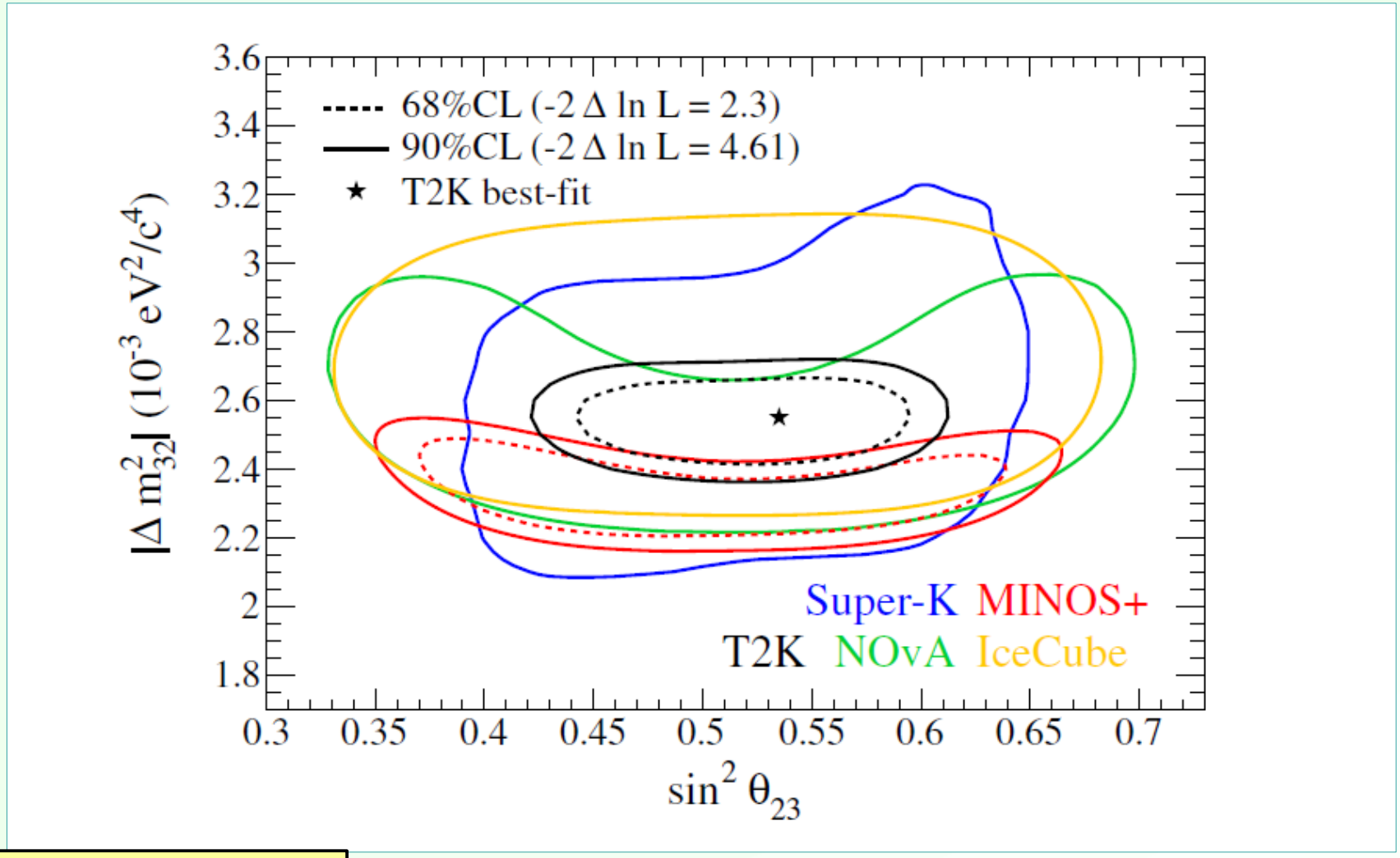




35% reduction of DIS in DUNE

channel	original contribution	reweighted contribution
QE	21.6%	24.8%
MEC	9.6%	11.0%
res	31.4%	36.0%
DIS	36.6%	27.2%
coh	0.9%	1.0%

Current precision



Abe *et al.* (T2K),
PRL **118**, 151801 (2017)