Precise neutrino-oscillation experiments require accurate Monte Carlo simulations

Artur M. Ankowski
SLAC National Accelerator Laboratory

based on A.M.A. and Alex Friedland, arXiv:1905.XXXXX

Fermilab, May 9, 2019

Outline

1) **Introduction**

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

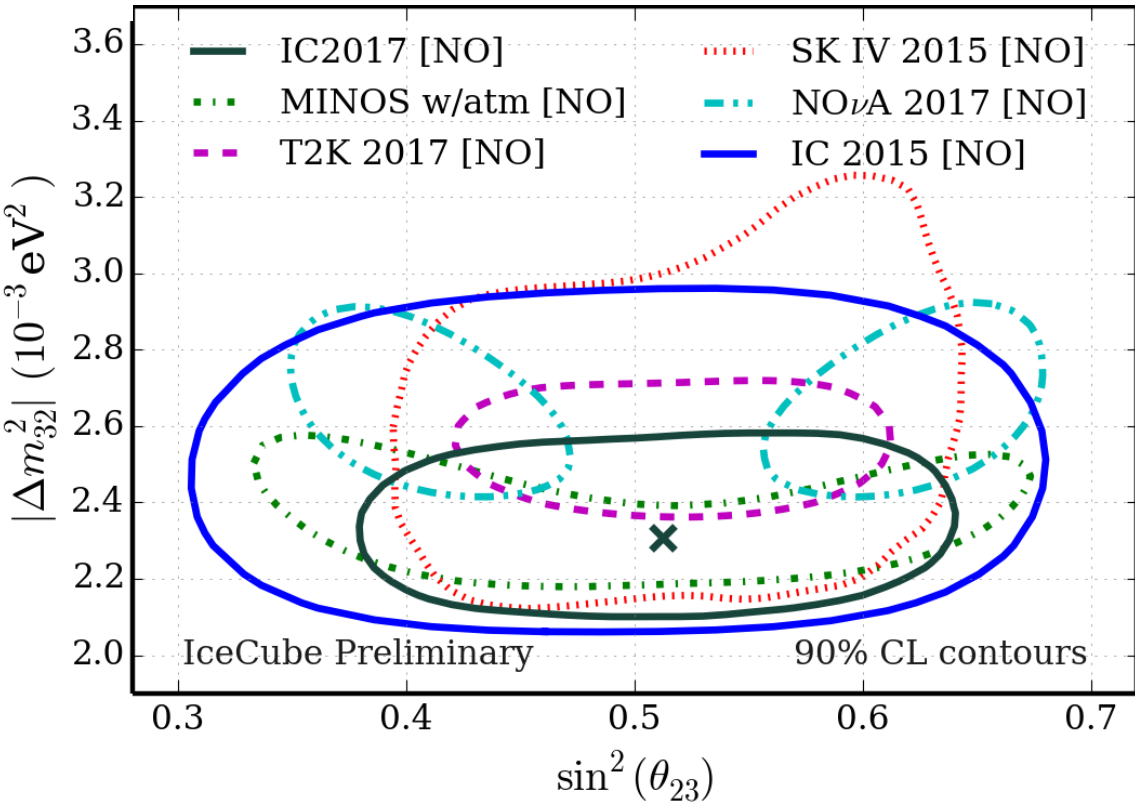
2) **Assessing the accuracy of GENIE**

- 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

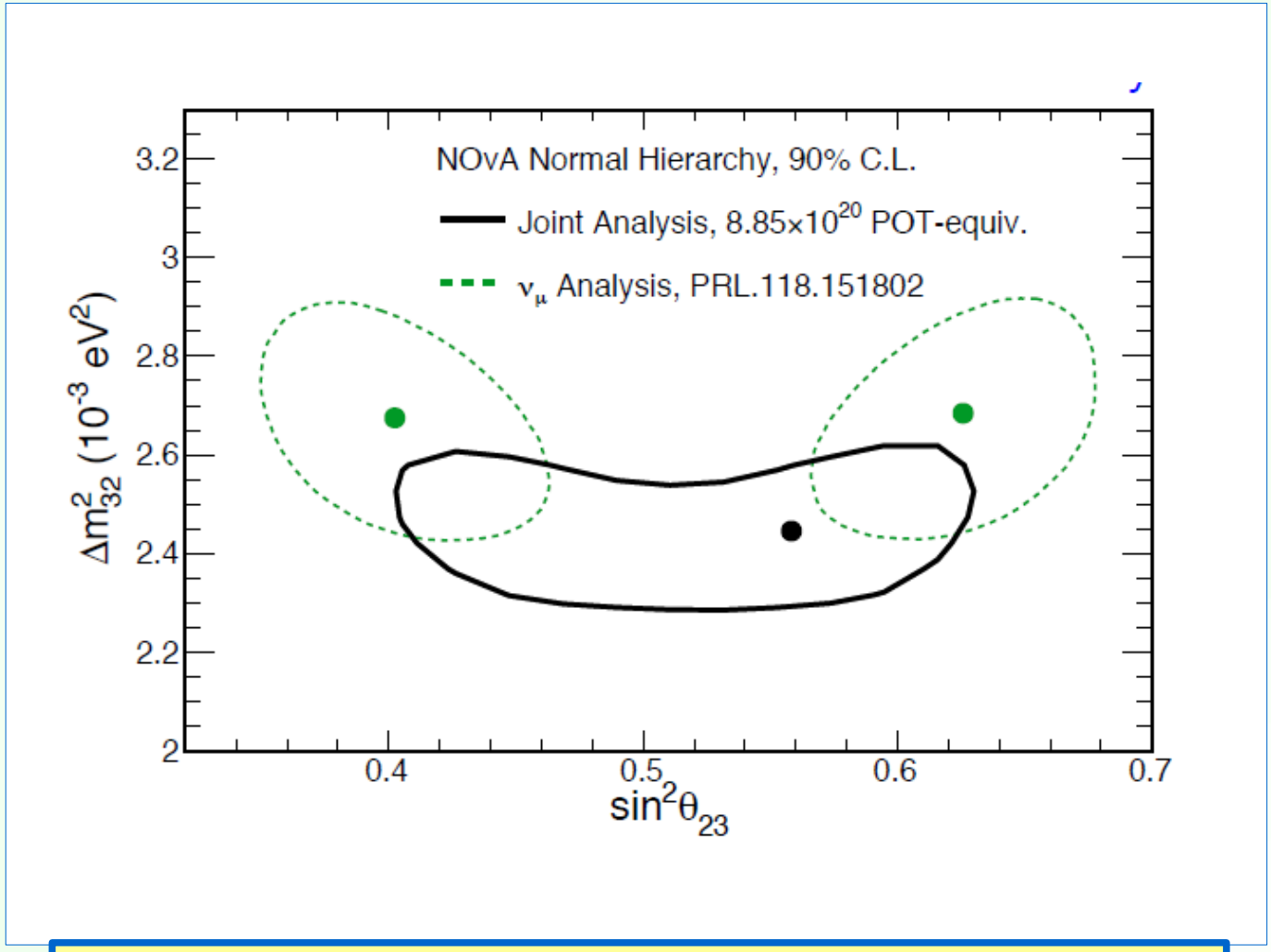
TABLE VIII. 1 σ confidence intervals for physics parameters in the normal mass hierarchy.

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)

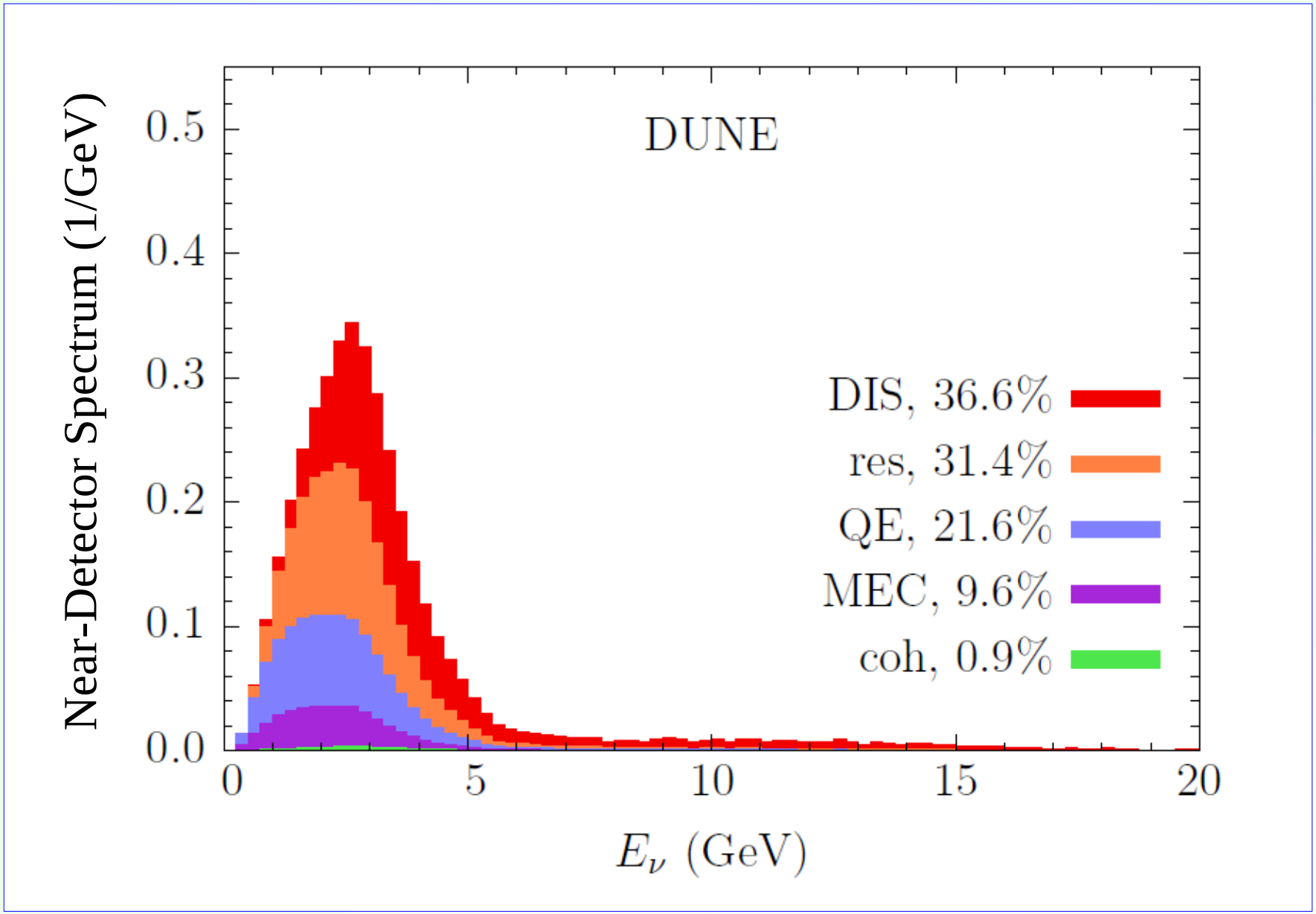
- In NOvA (~2 GeV), 3% uncertainty means $\mathcal{O}$(60 MeV).
- DUNE aims at uncertainties < 1% meaning $\mathcal{O}$(25 MeV) precision of energy reconstruction.

Precision of energy reconstruction

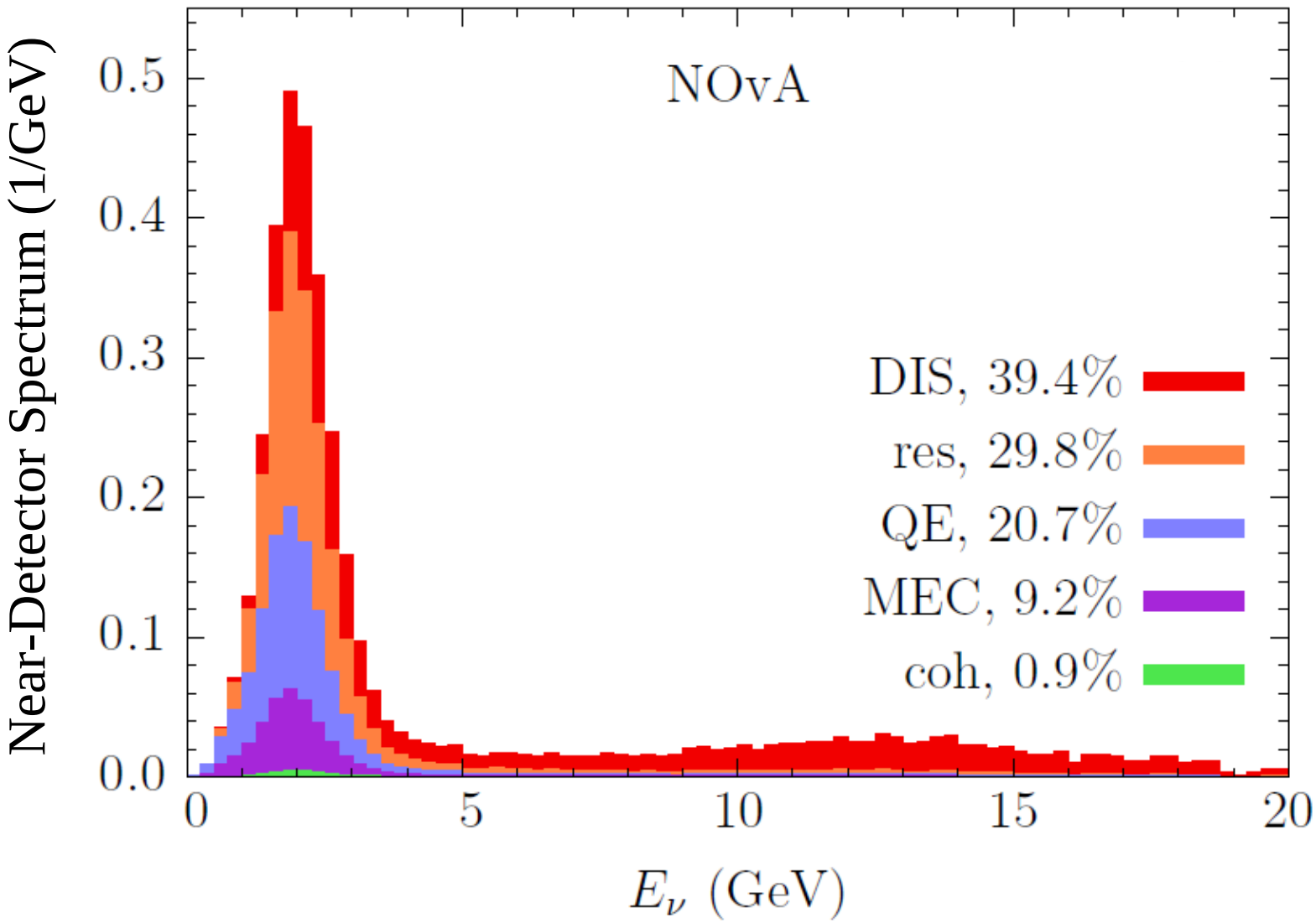


A. Radovic (NOvA), JETP Jan 12, 2018

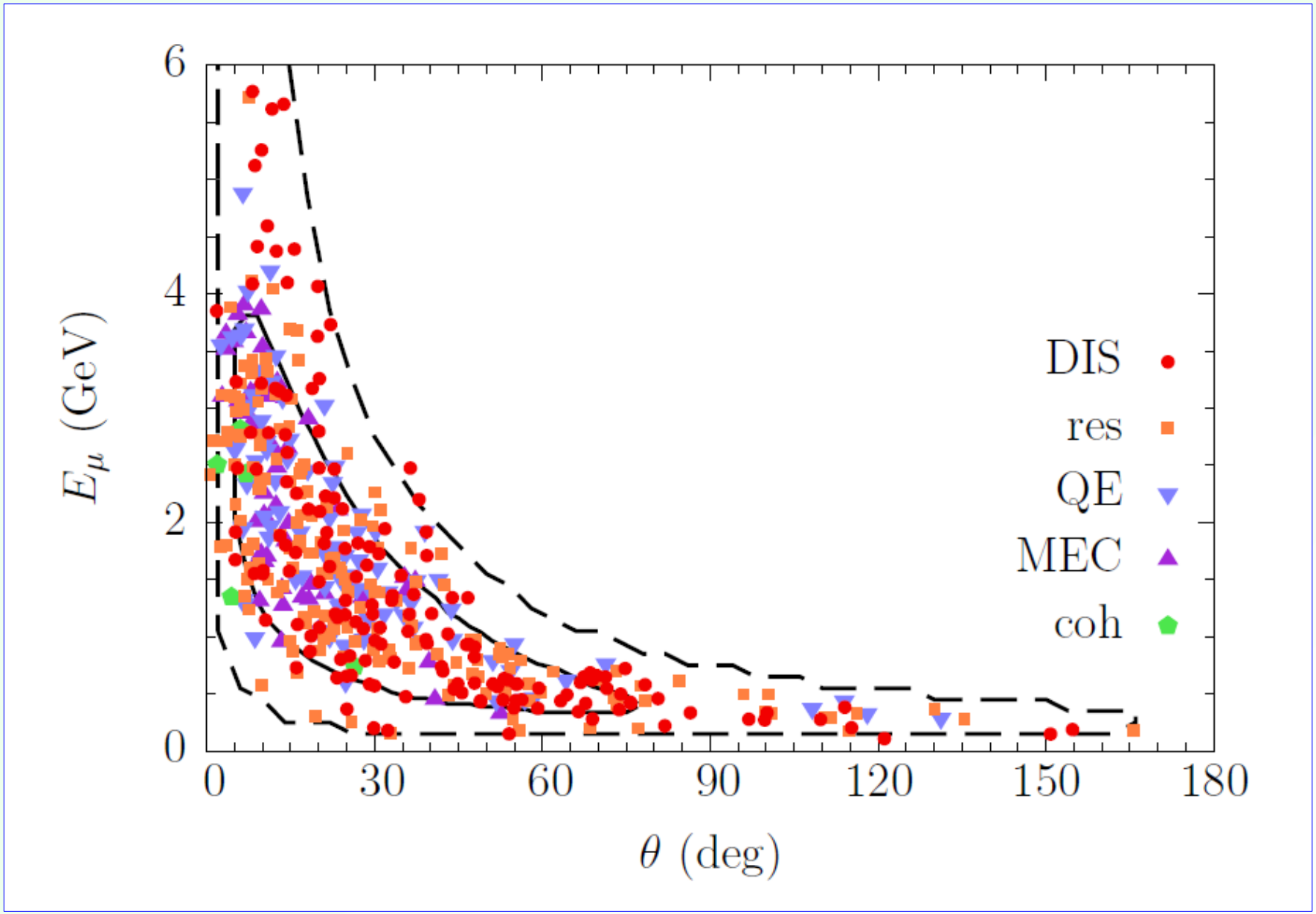
Which cross sections are relevant?



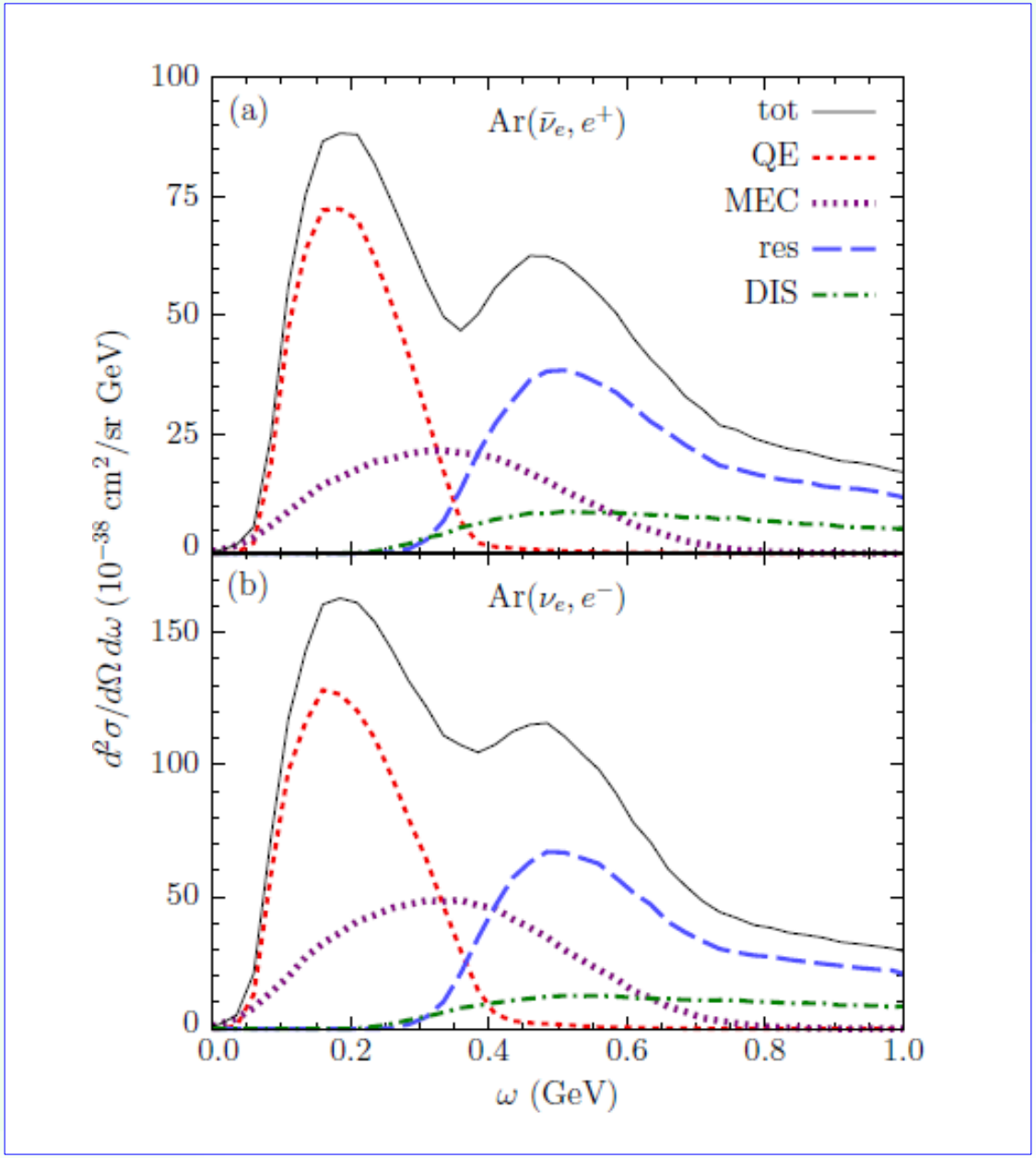
Which cross sections are relevant?



Muon kinematics mixes channels



Double differential cross sections

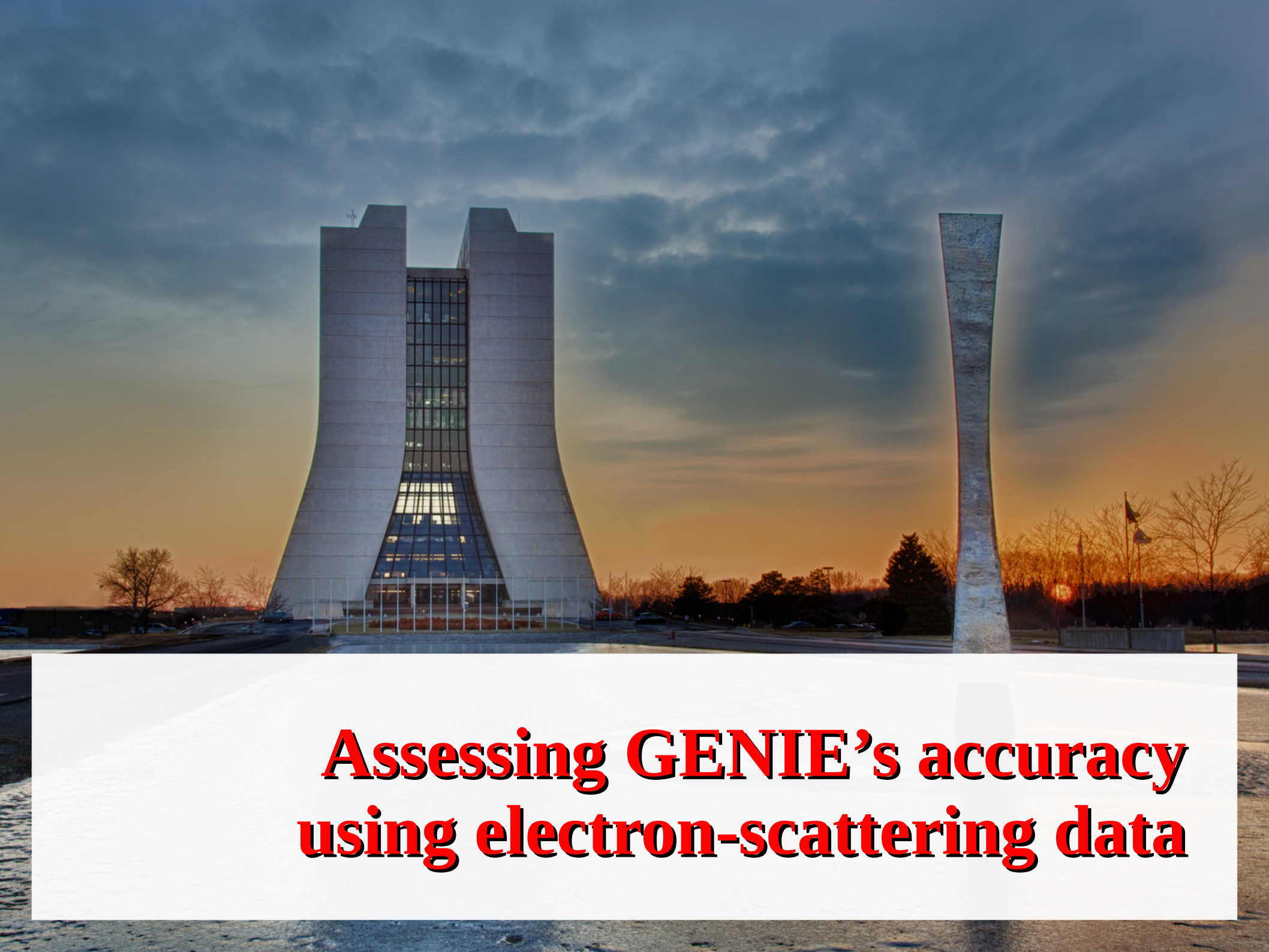


Impulse approximation

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

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

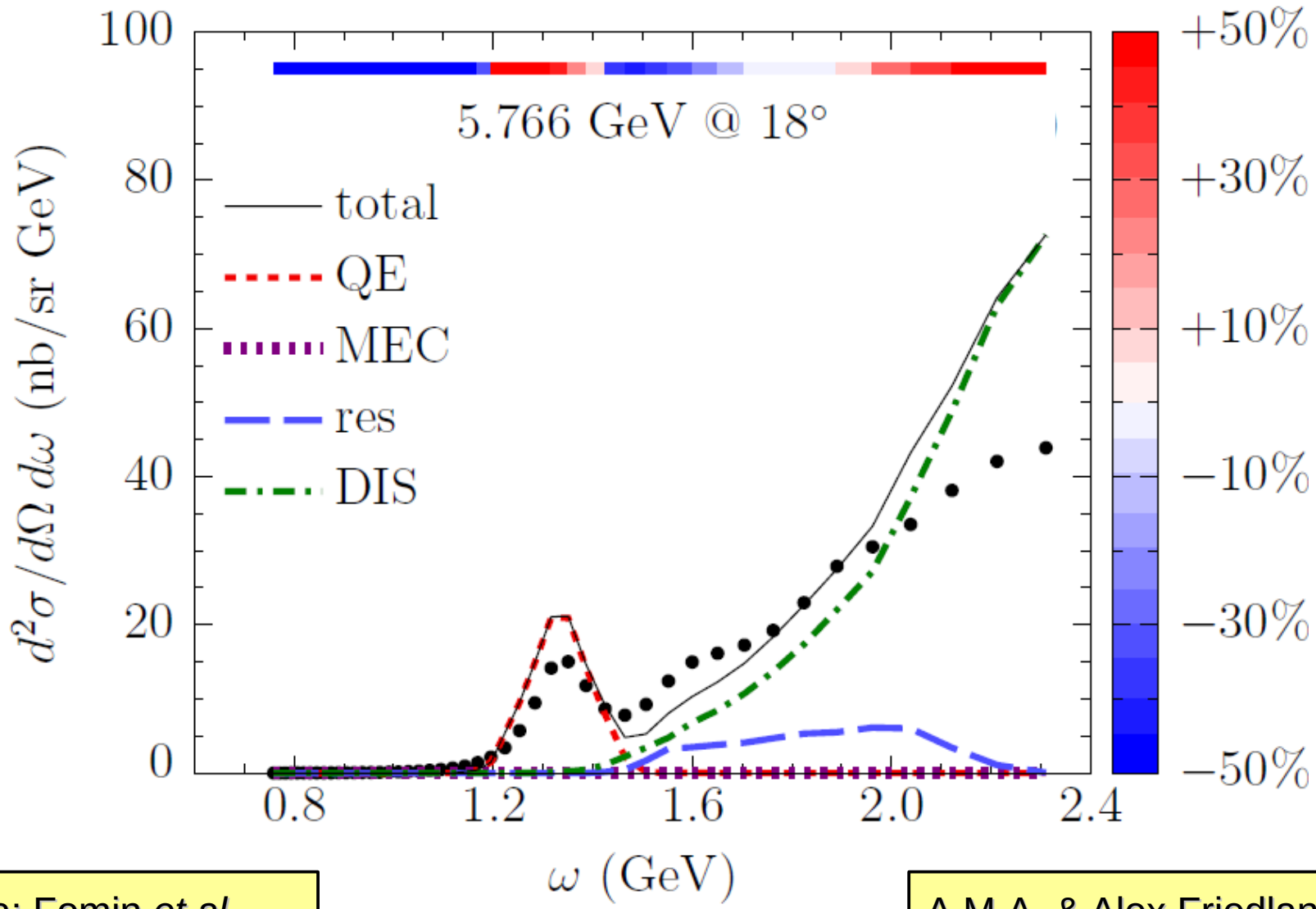


Assessing GENIE's accuracy using electron-scattering data

GENIE

- Nuclear model: relativistic Fermi gas of Bodek and Ritchie
- Quasielastic according to Llewellyn-Smith for neutrinos and Rosenbluth for electrons, phenomenological MEC
- Resonant pion production in the framework of the model of Rein and Sehgal (16 resonances from PDG, no interference)
- Nonresonant pion production (deep-inelastic scattering or DIS) in the model of Bodek and Yang is the only mechanism of interaction for $W > 1.7$ GeV, used also to calculate nonresonant background for lower invariant hadronic masses
- Generator of choice for many neutrino experiments. Not tuned to electrons, but treats them as neutrinos.

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

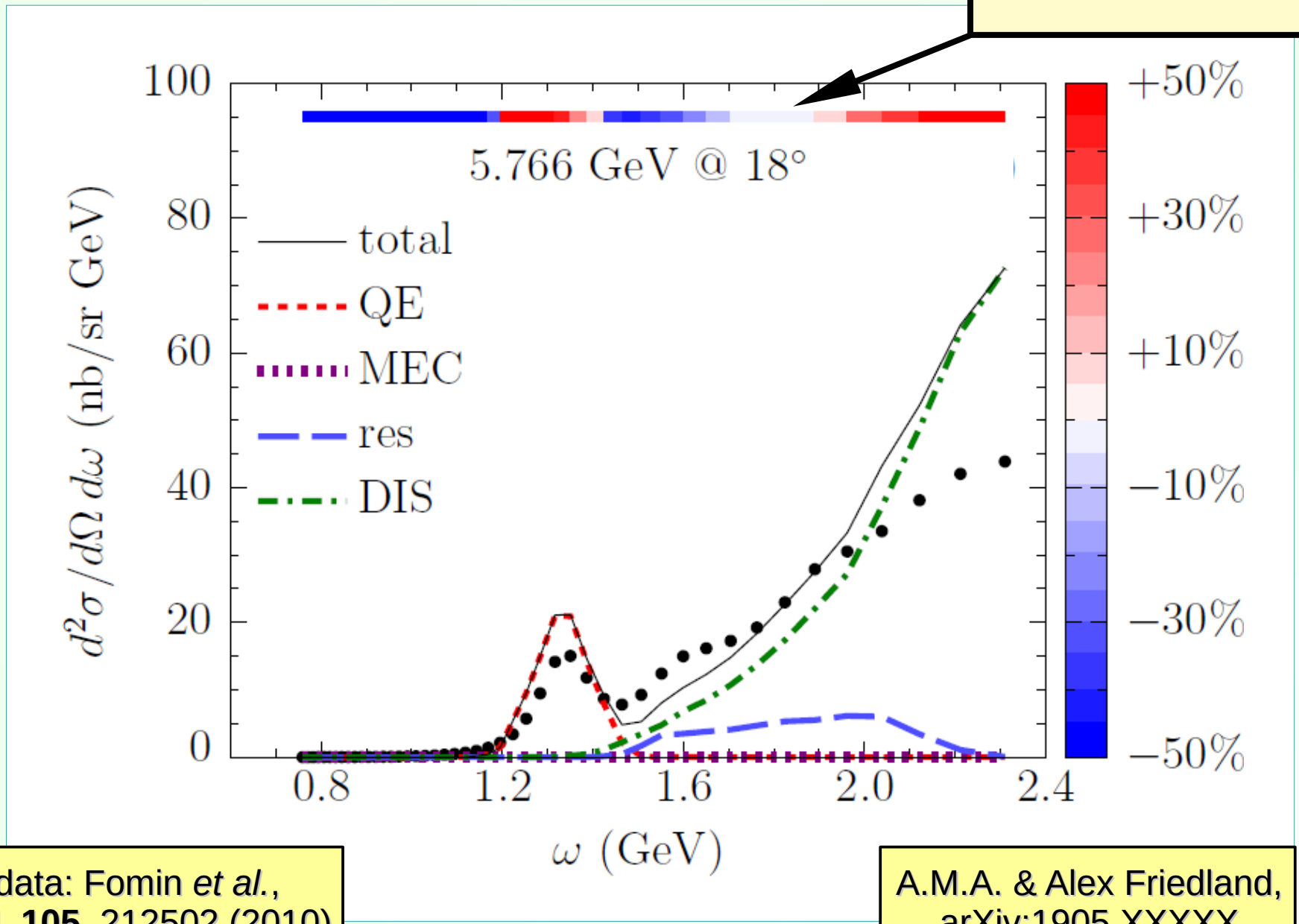


data: Fomin *et al.*, PRL **105**, 212502 (2010)

A.M.A. & Alex Friedland, arXiv:1905.XXXXX

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

GENIE – data
data



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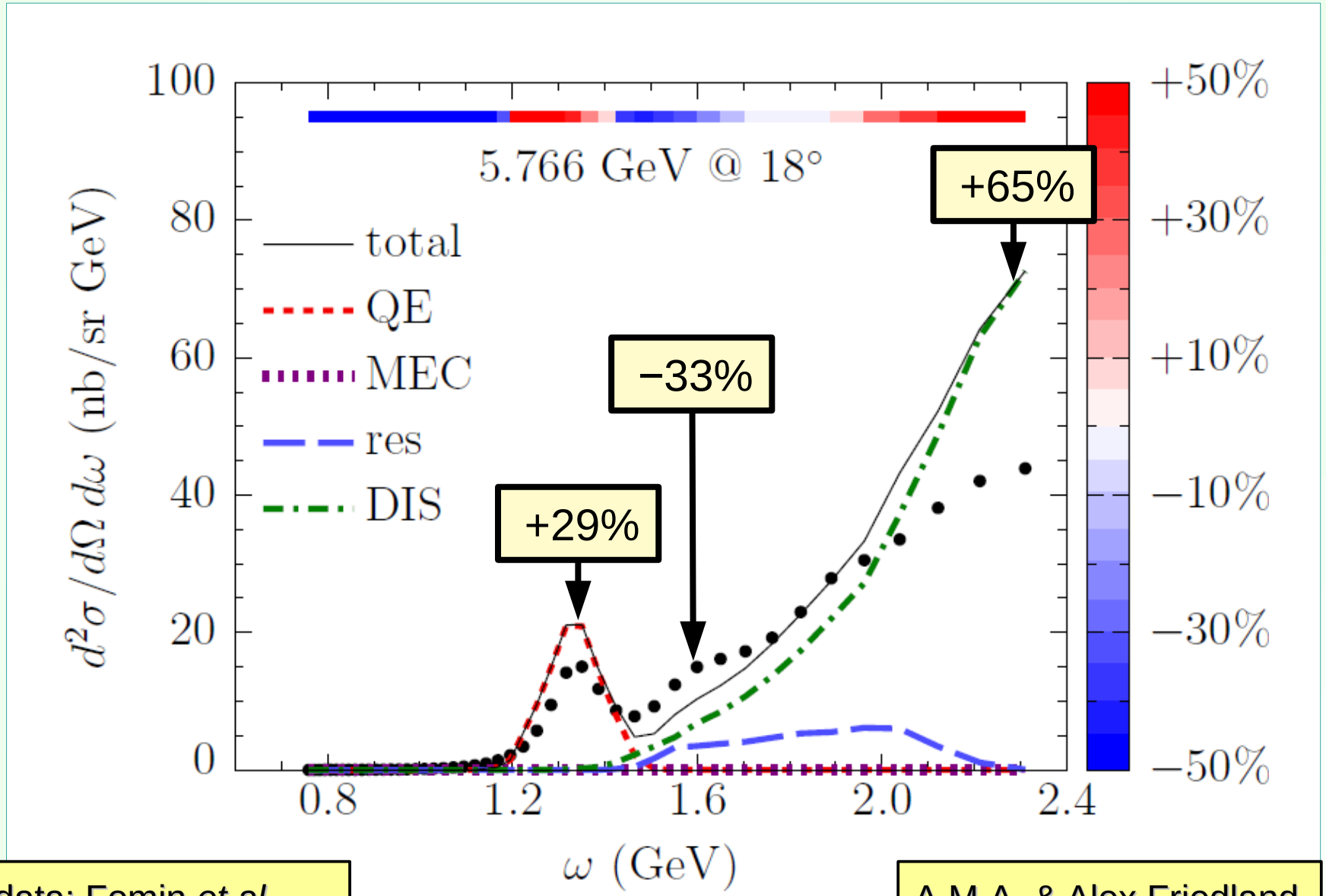
D(*e*, *e*') in GENIE



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

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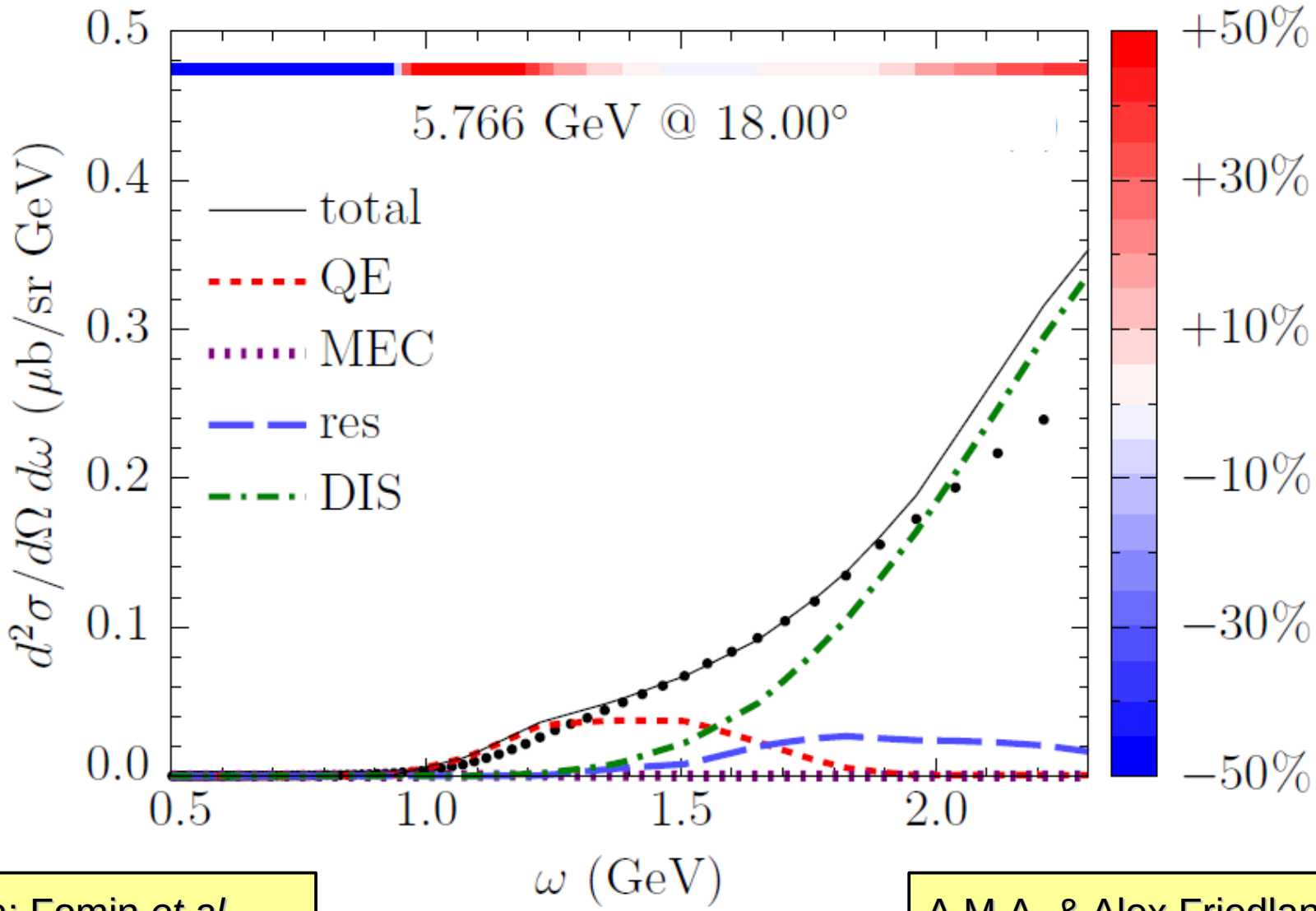
C(*e*, *e*') in GENIE



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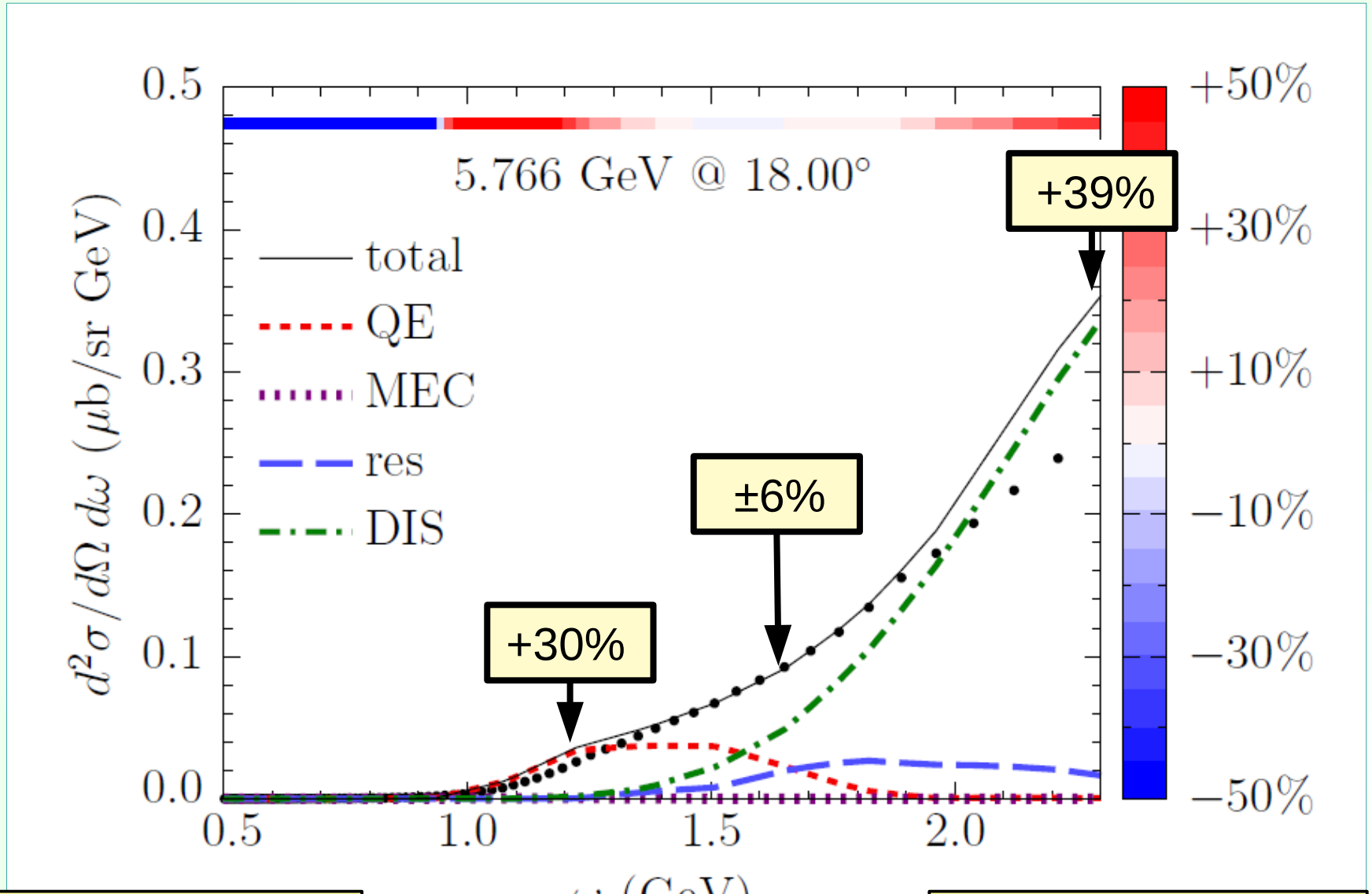
C(*e*, *e*') in GENIE



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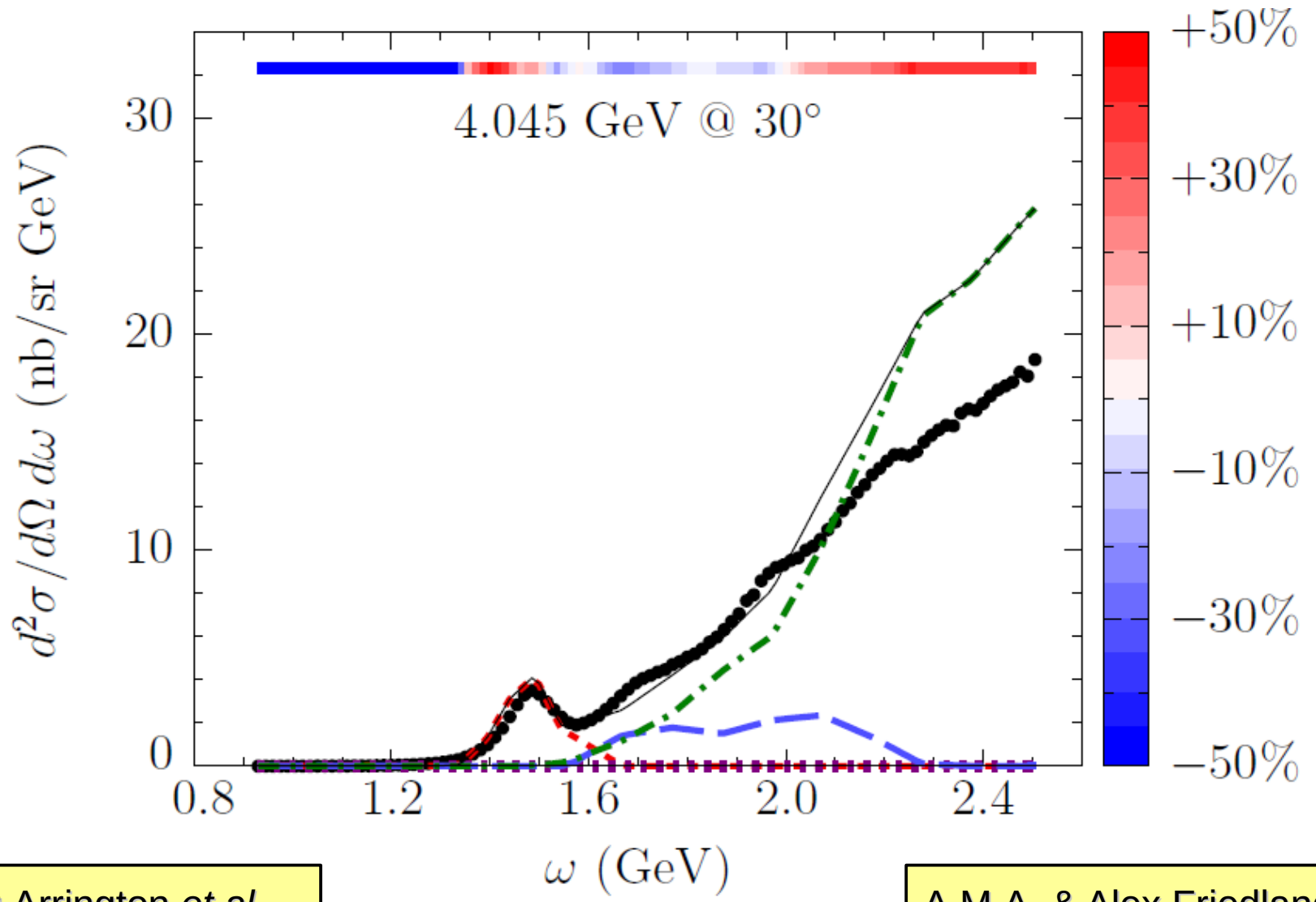
D(*e*, *e*’) in GENIE



data: Arrington *et al.*, PRL **82**, 2056 (1999)

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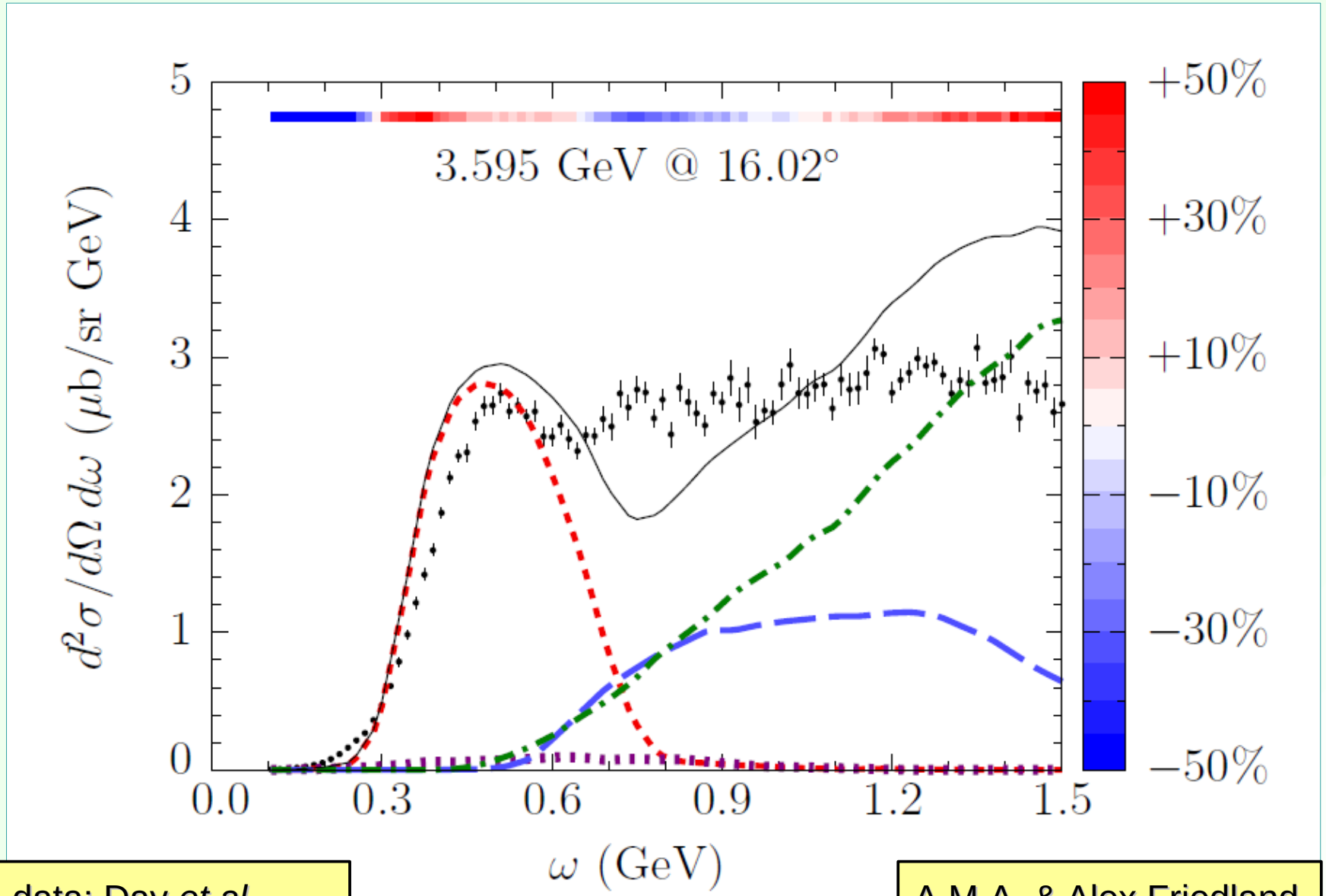
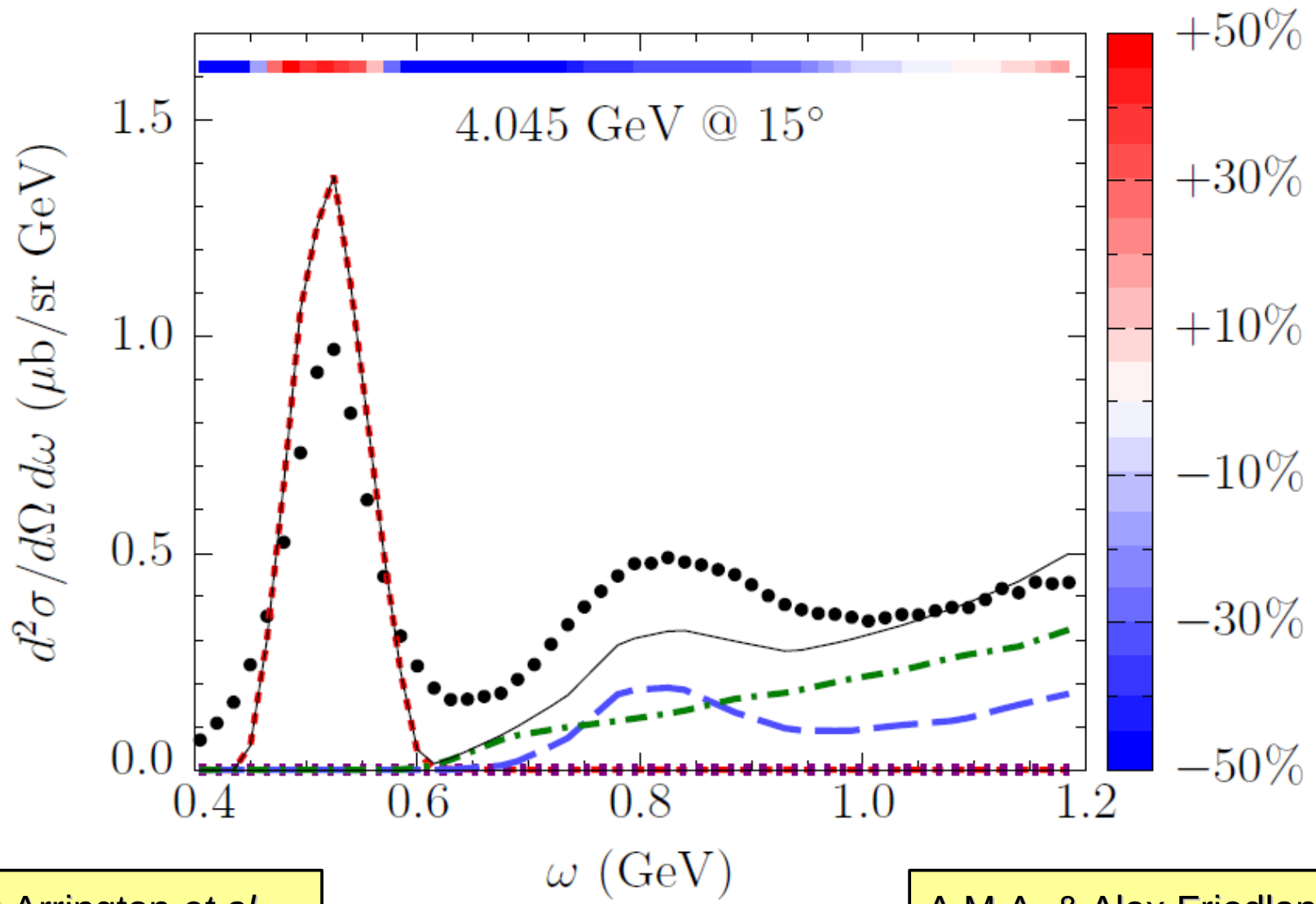


data: Day *et al.*, PRD **48**, 1849 (1993)

A.M.A. & Alex Friedland, arXiv:1905.XXXXX

D(*e*, *e*’) in GENIE



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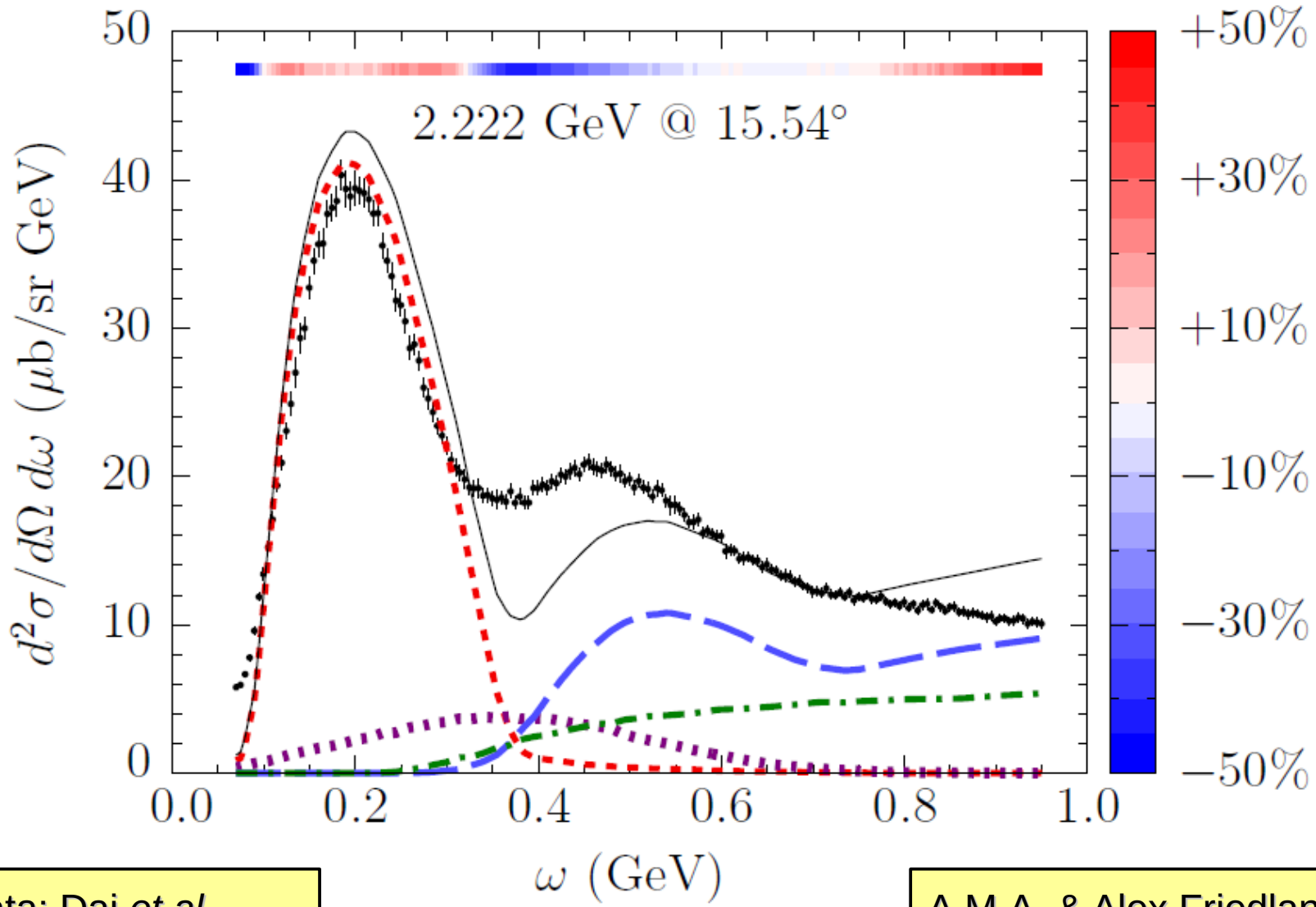
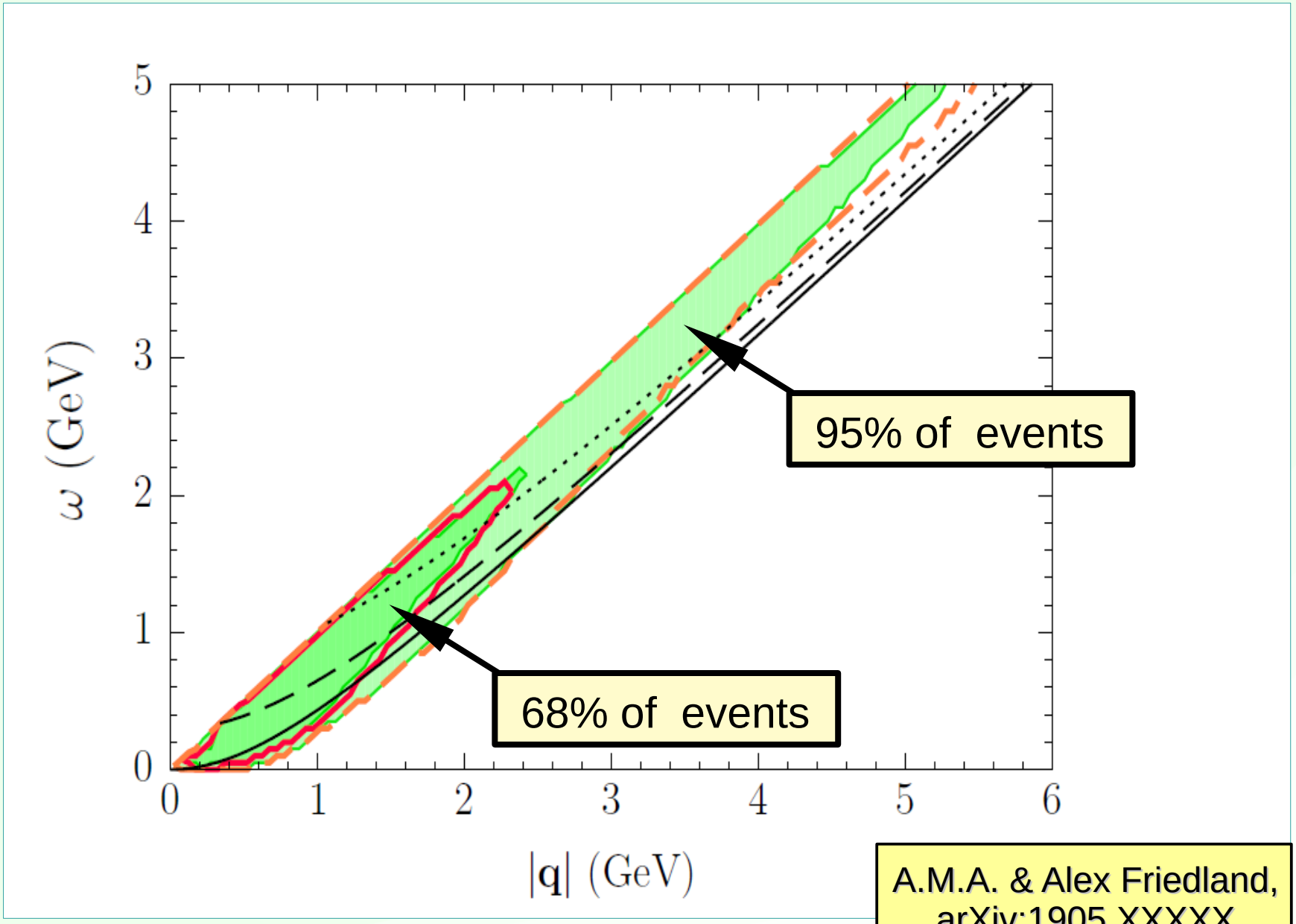


data: Dai *et al.*,
PRC **98**, 014617 (2018)

A.M.A. & Alex Friedland,
arXiv:1905.XXXXX

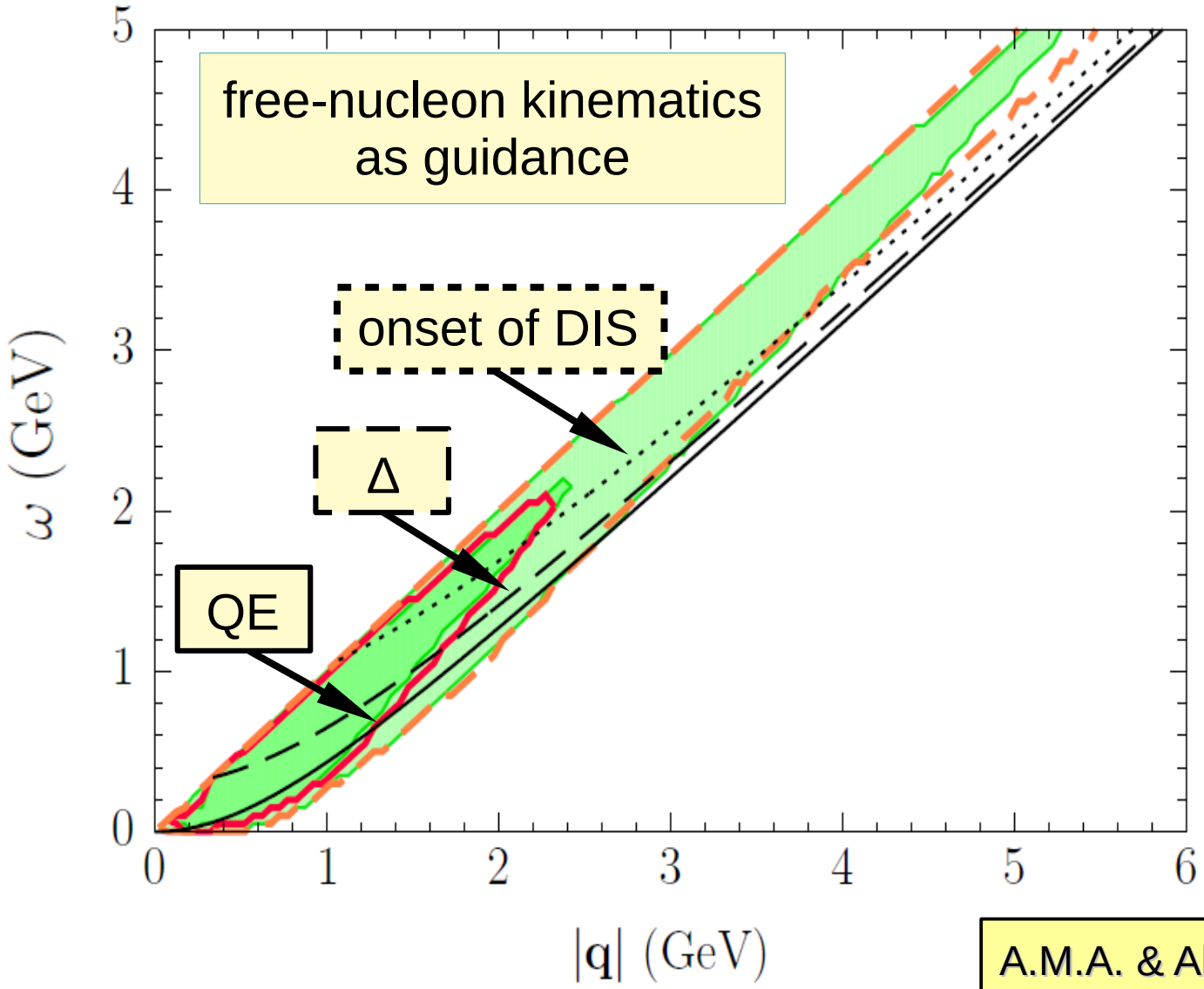
Assessing GENIE's accuracy: global picture from electron data

DUNE vs. NOvA



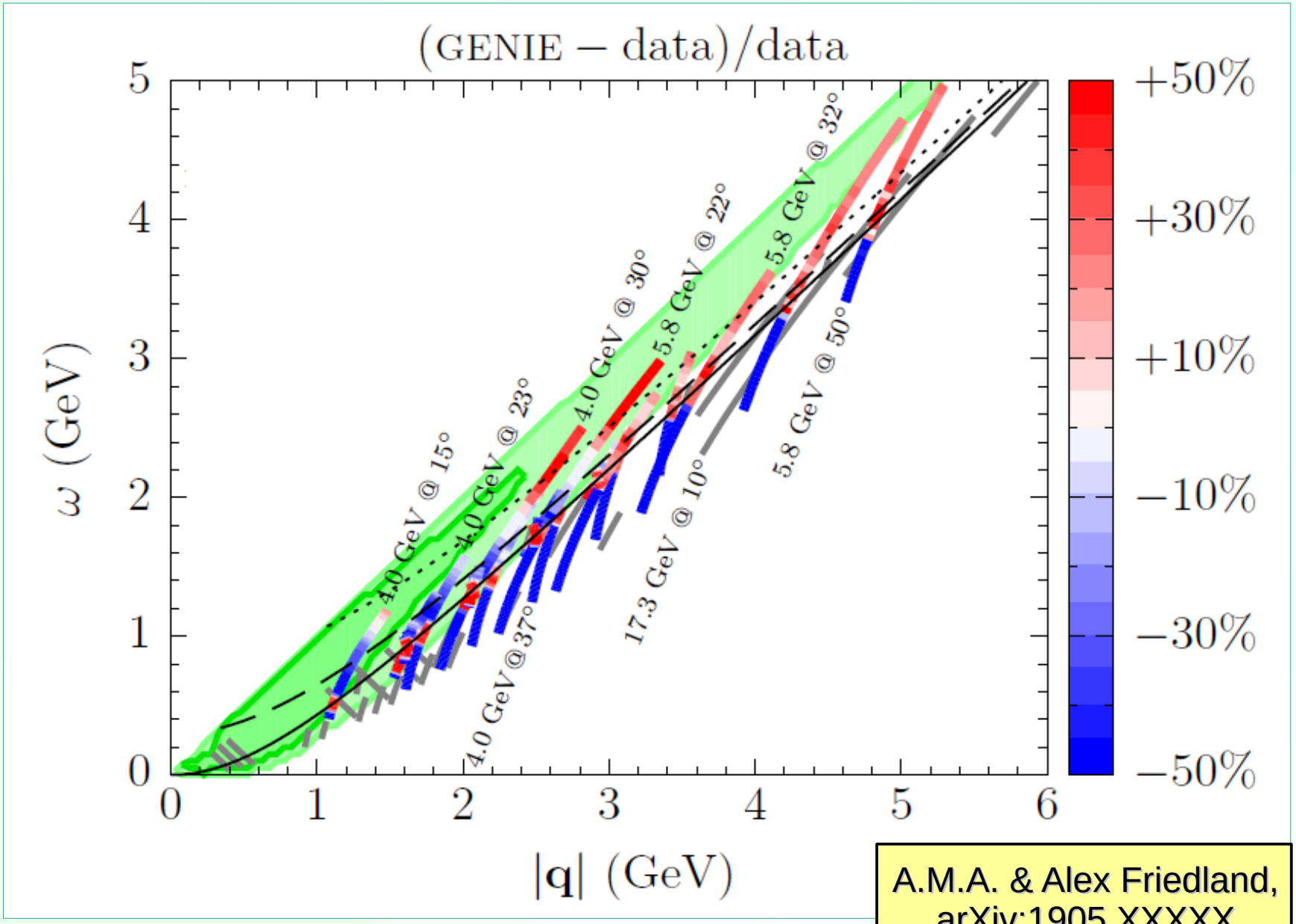
A.M.A. & Alex Friedland, arXiv:1905.XXXXX

DUNE vs. NOvA



A.M.A. & Alex Friedland,
arXiv:1905.XXXXX

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



A.M.A. & Alex Friedland, arXiv:1905.XXXXX

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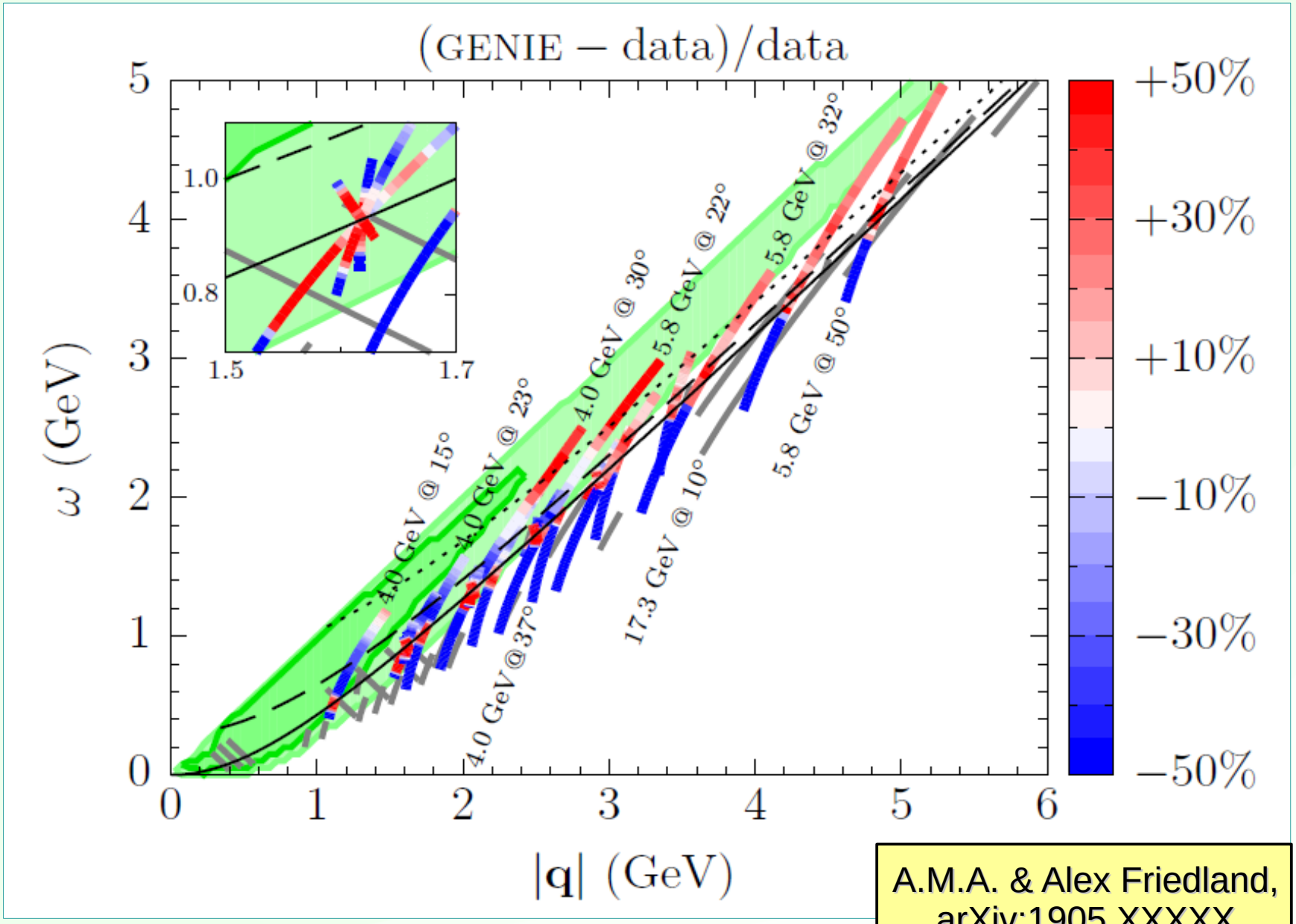

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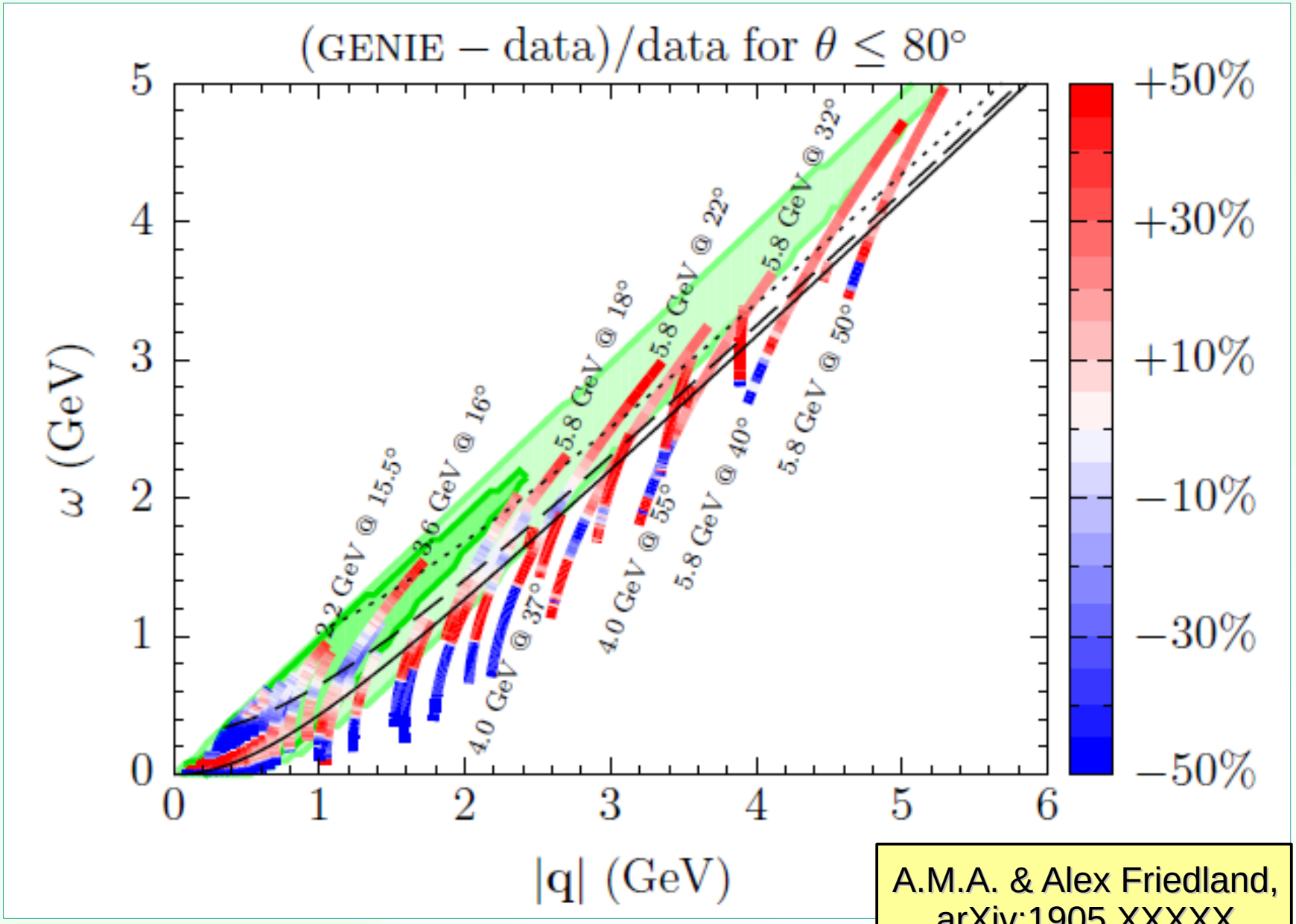

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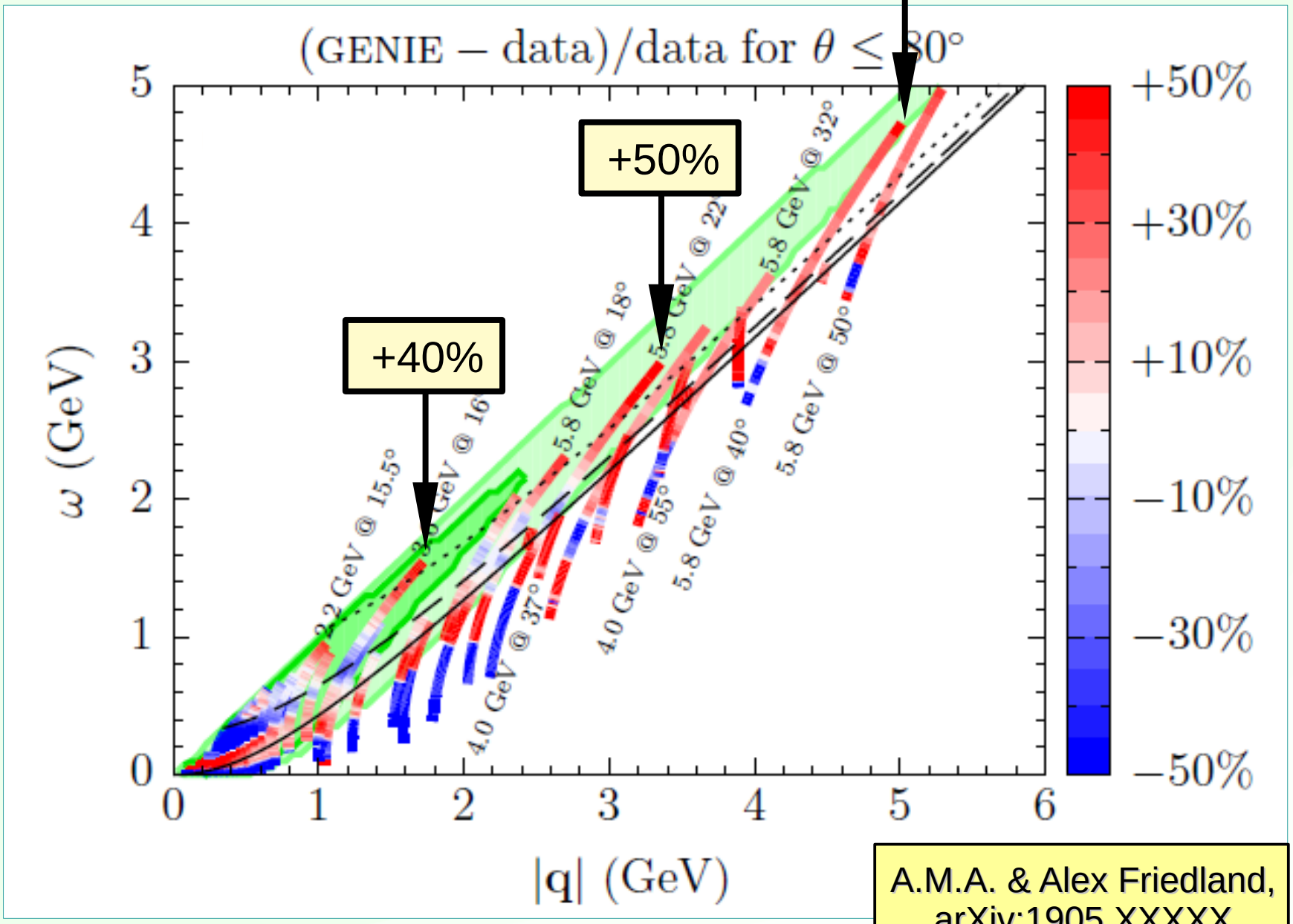
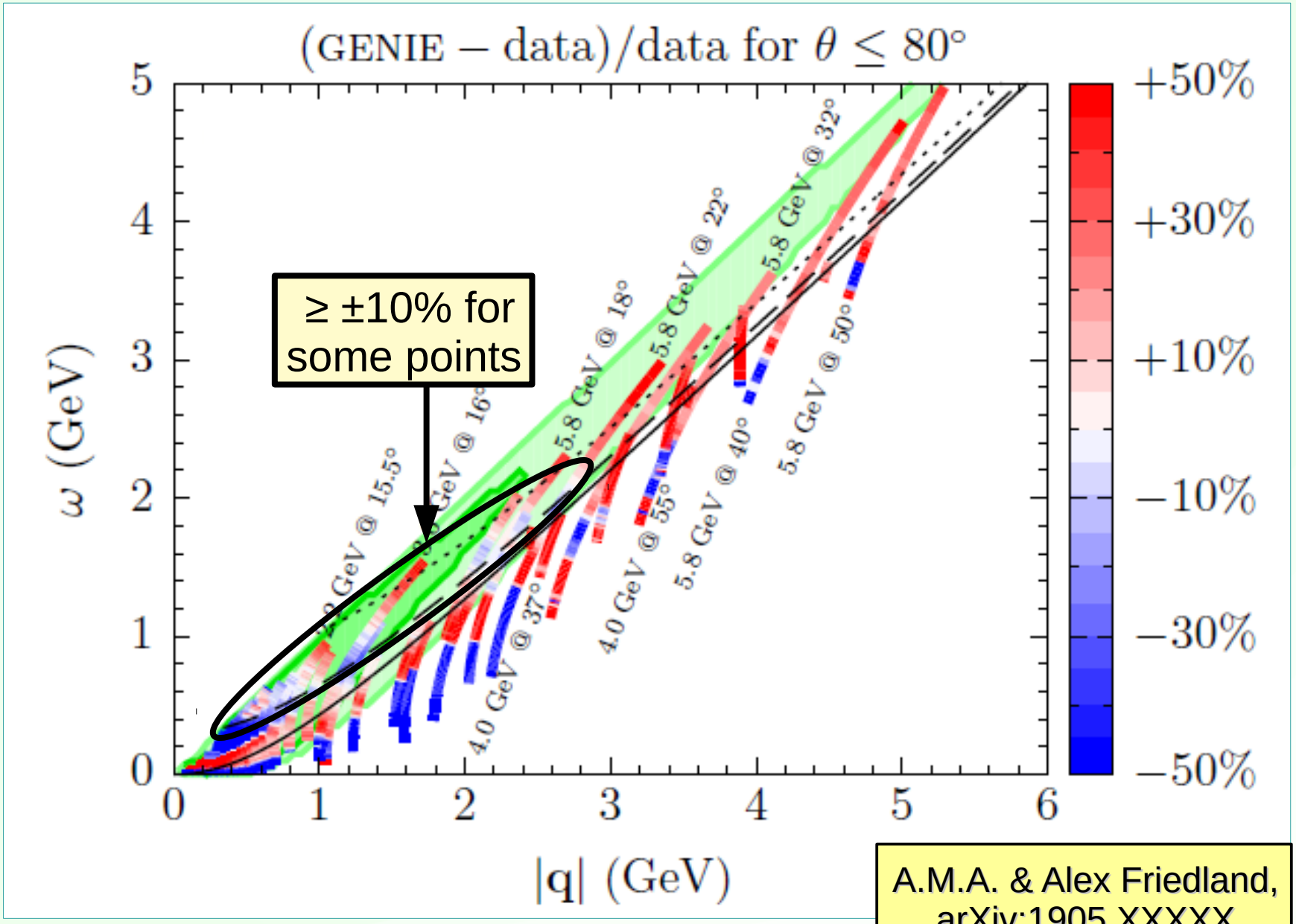
DIS



A.M.A. & Alex Friedland, arXiv:1905.XXXXX

Res/DIS transition



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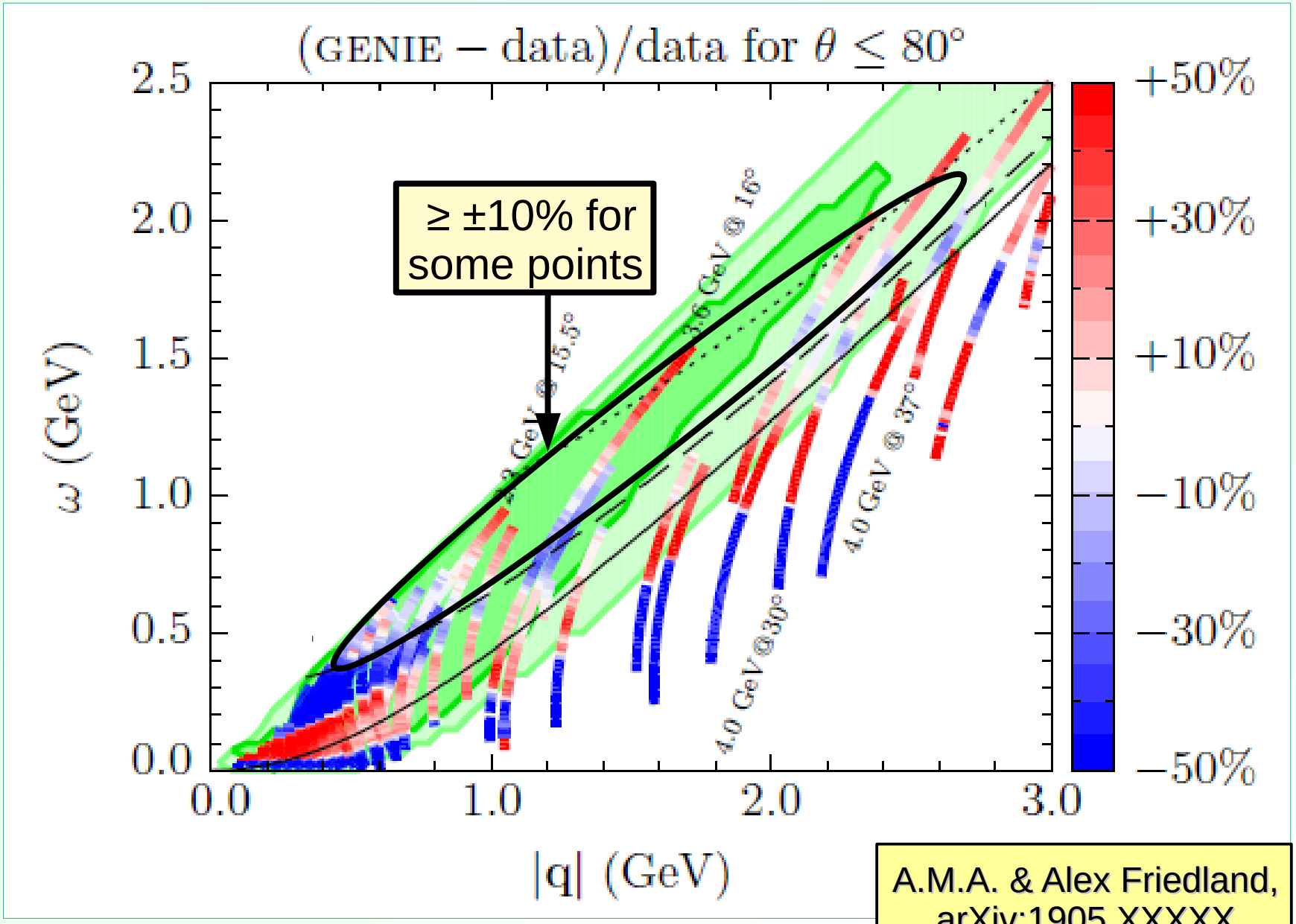
Res/DIS transition



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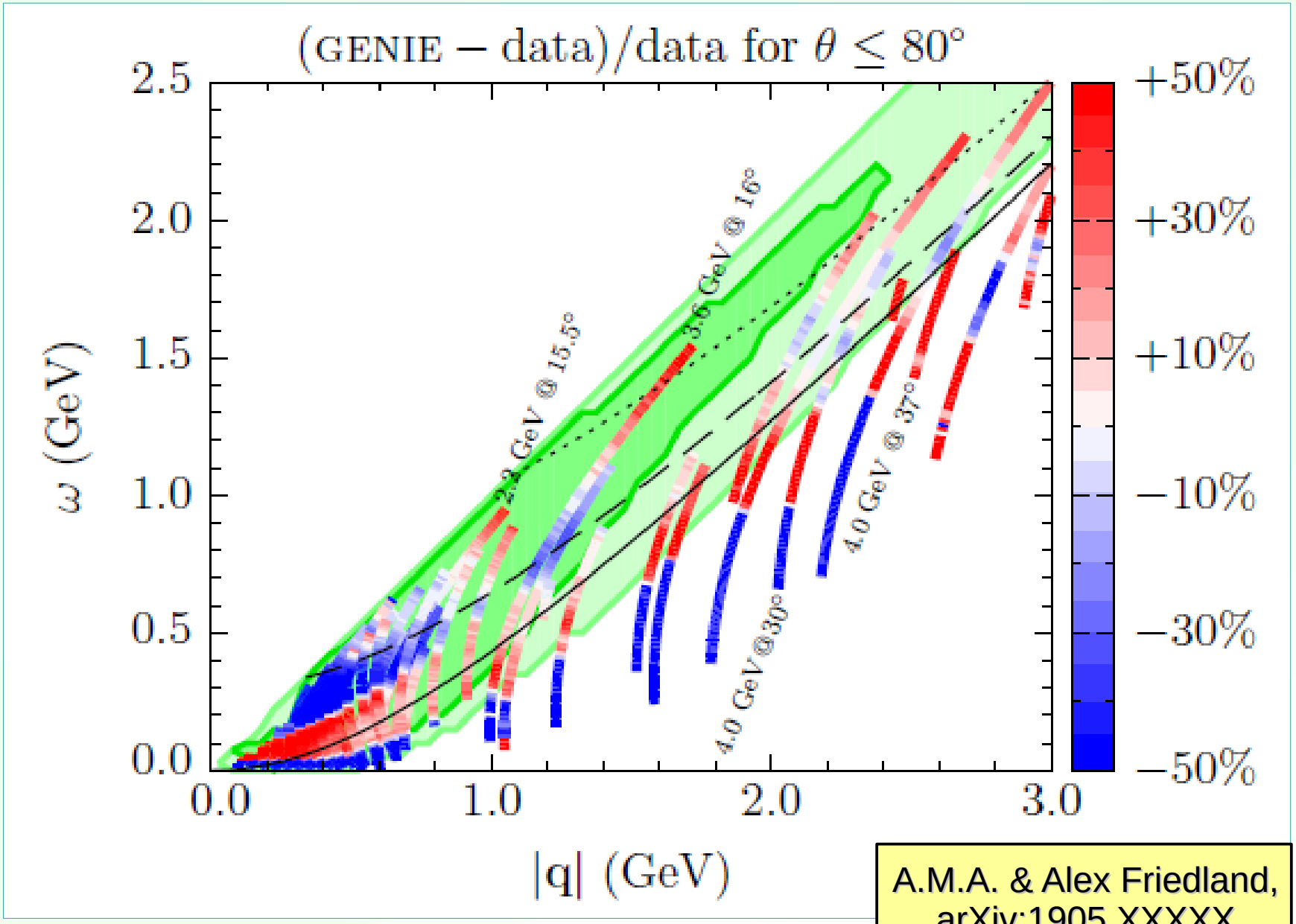
Res/DIS transition



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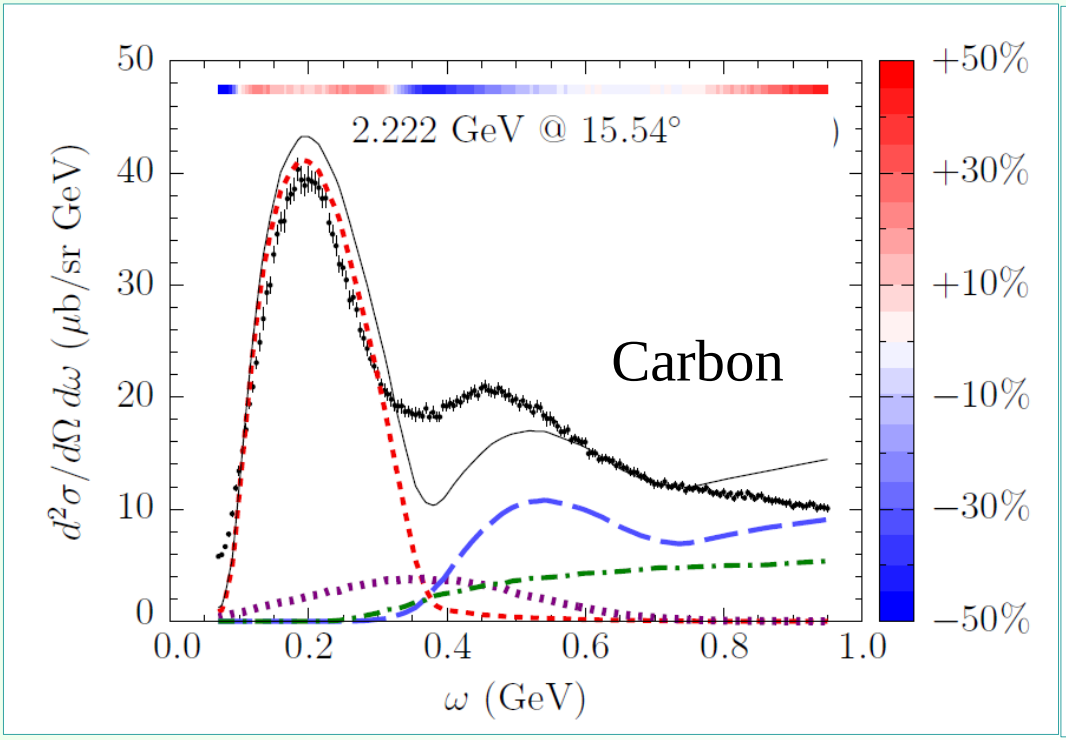
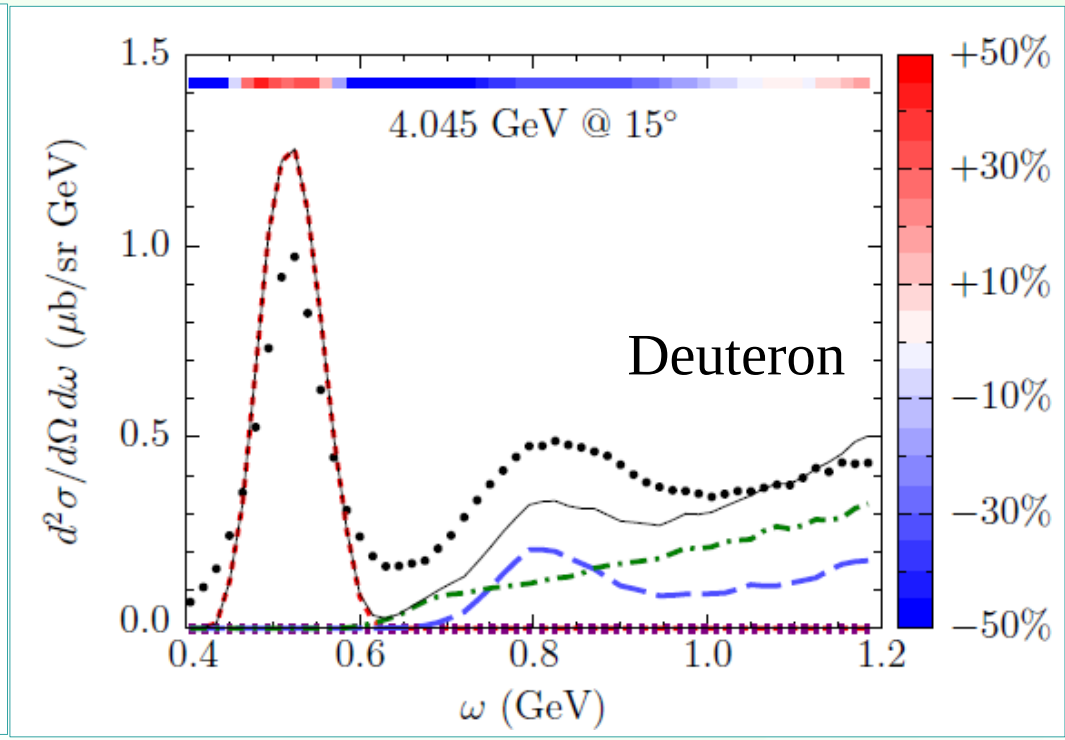
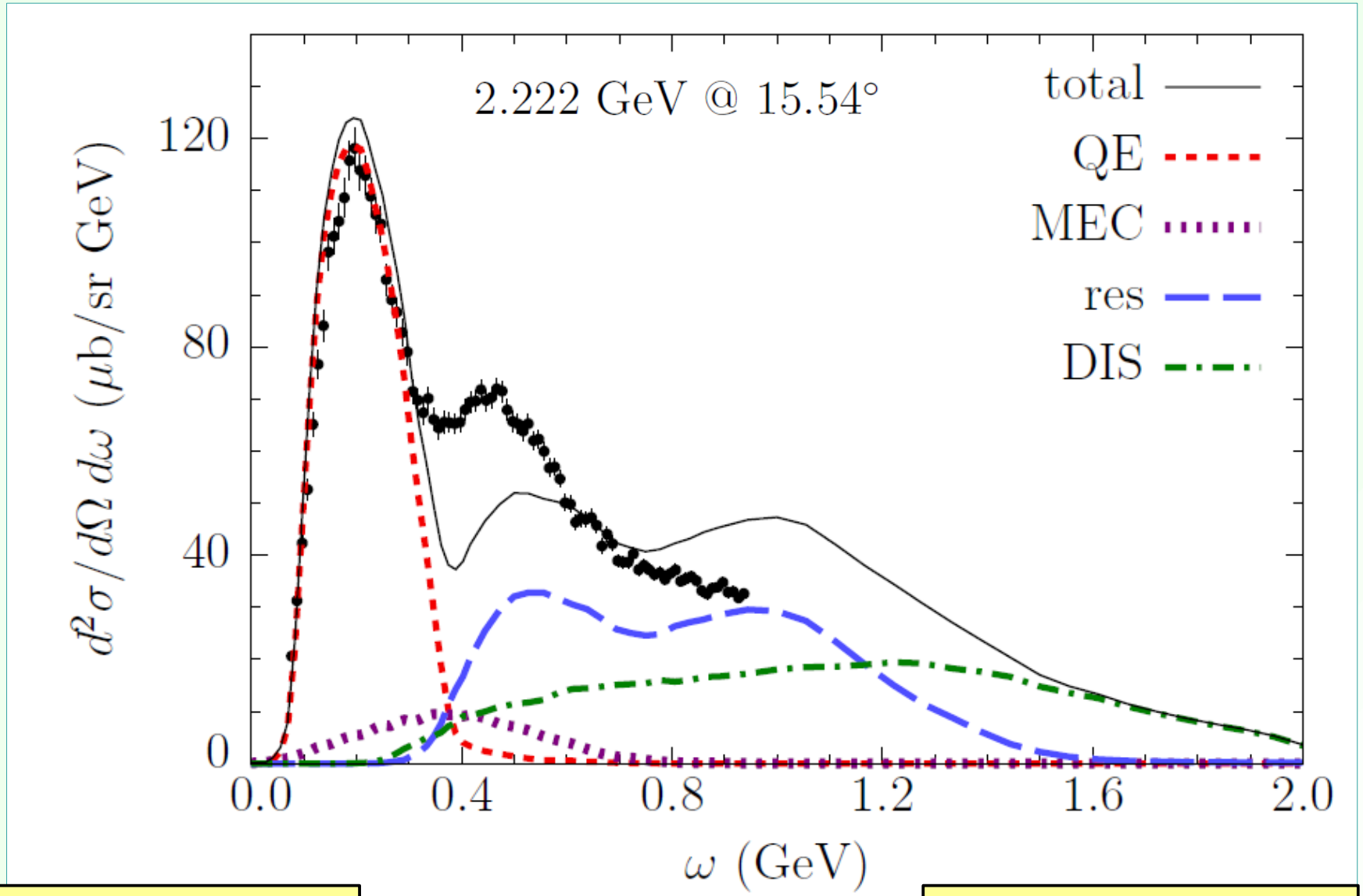




- Fermi motion broadens Δ and higher resonances, leading to **accidental cancellation** of under- and overestimation.
- Present for C, much smaller for Ar and Ti, absent for D.
- Higher resonances—visible in GENIE, not in C(*e, e'*) data.

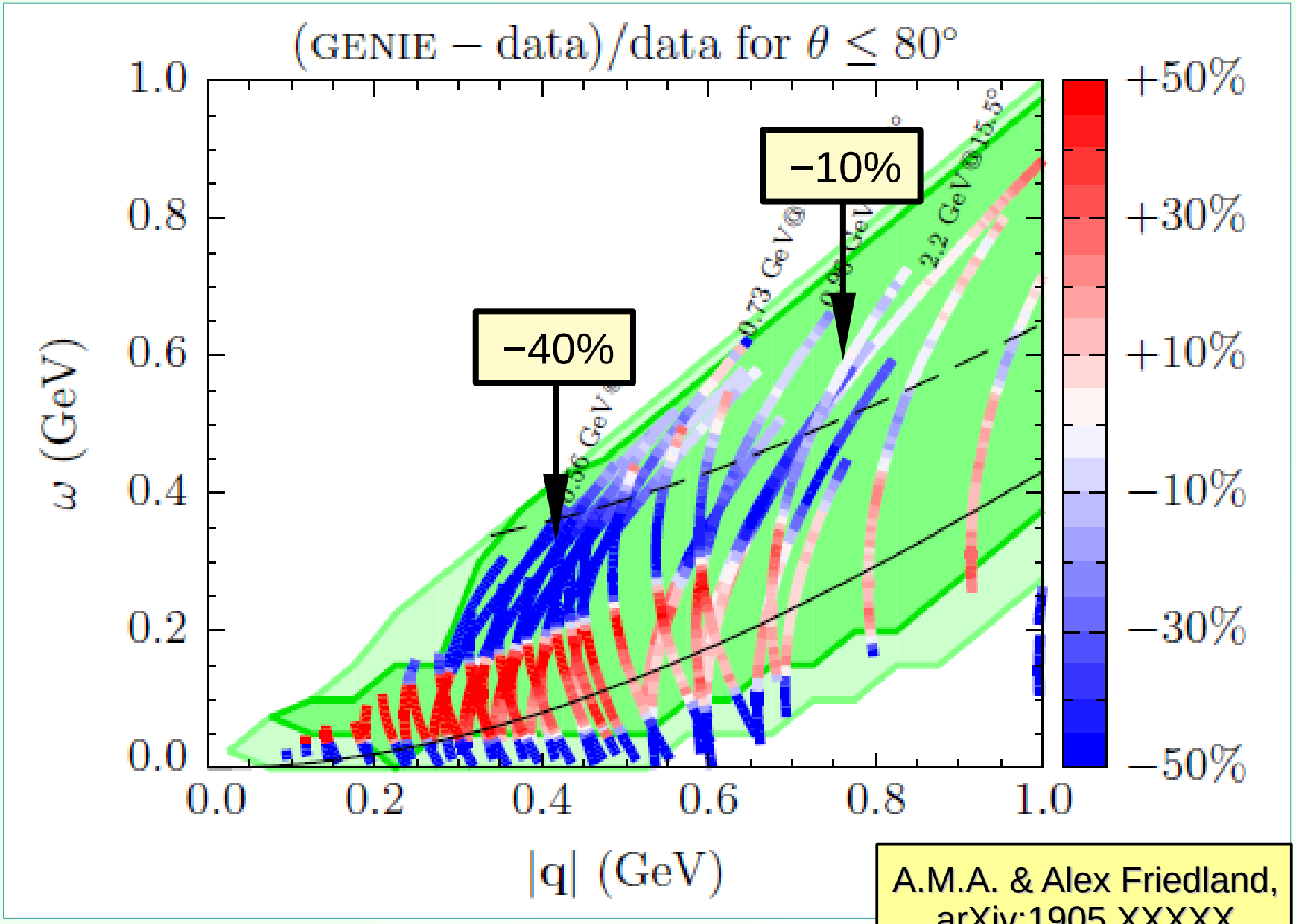
Ar(*e*, *e*') in GENIE



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

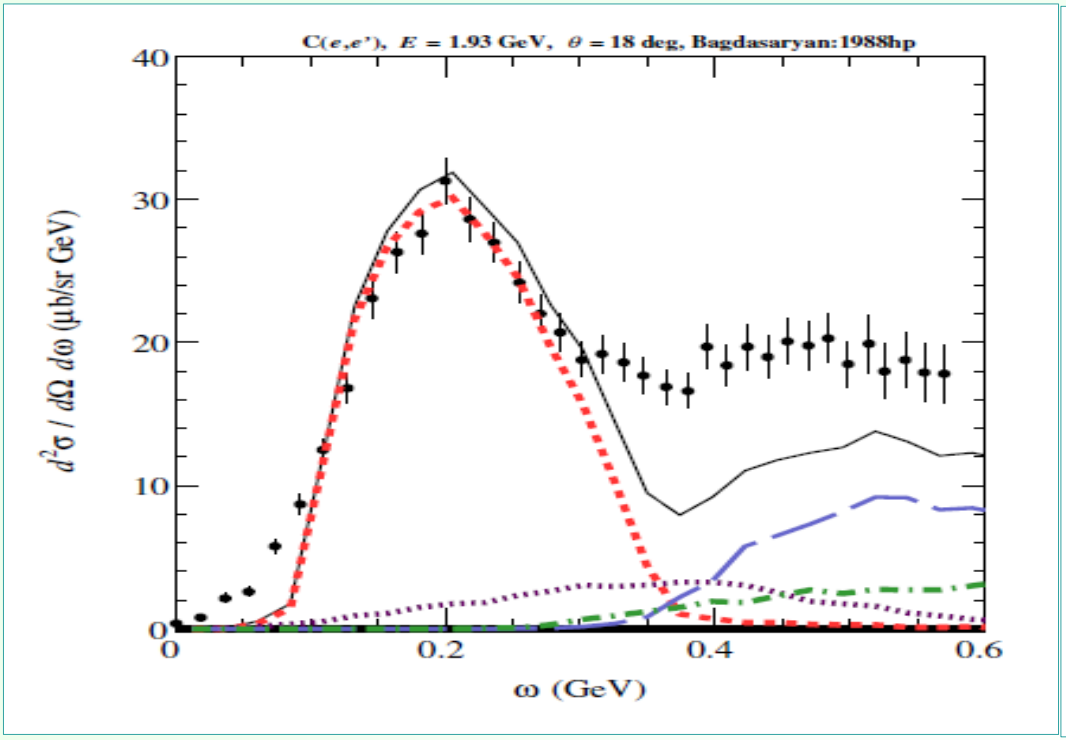
A.M.A. & Alex Friedland,
arXiv:1905.XXXXX

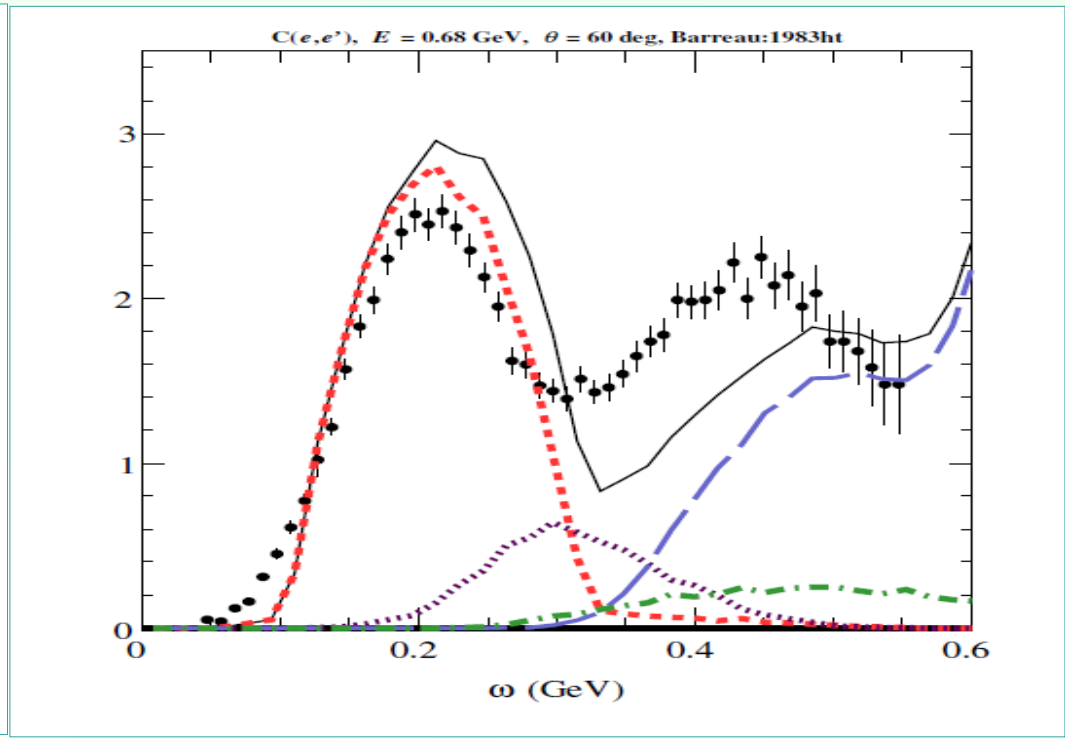
Δ resonance



A.M.A. & Alex Friedland, arXiv:1905.XXXXX

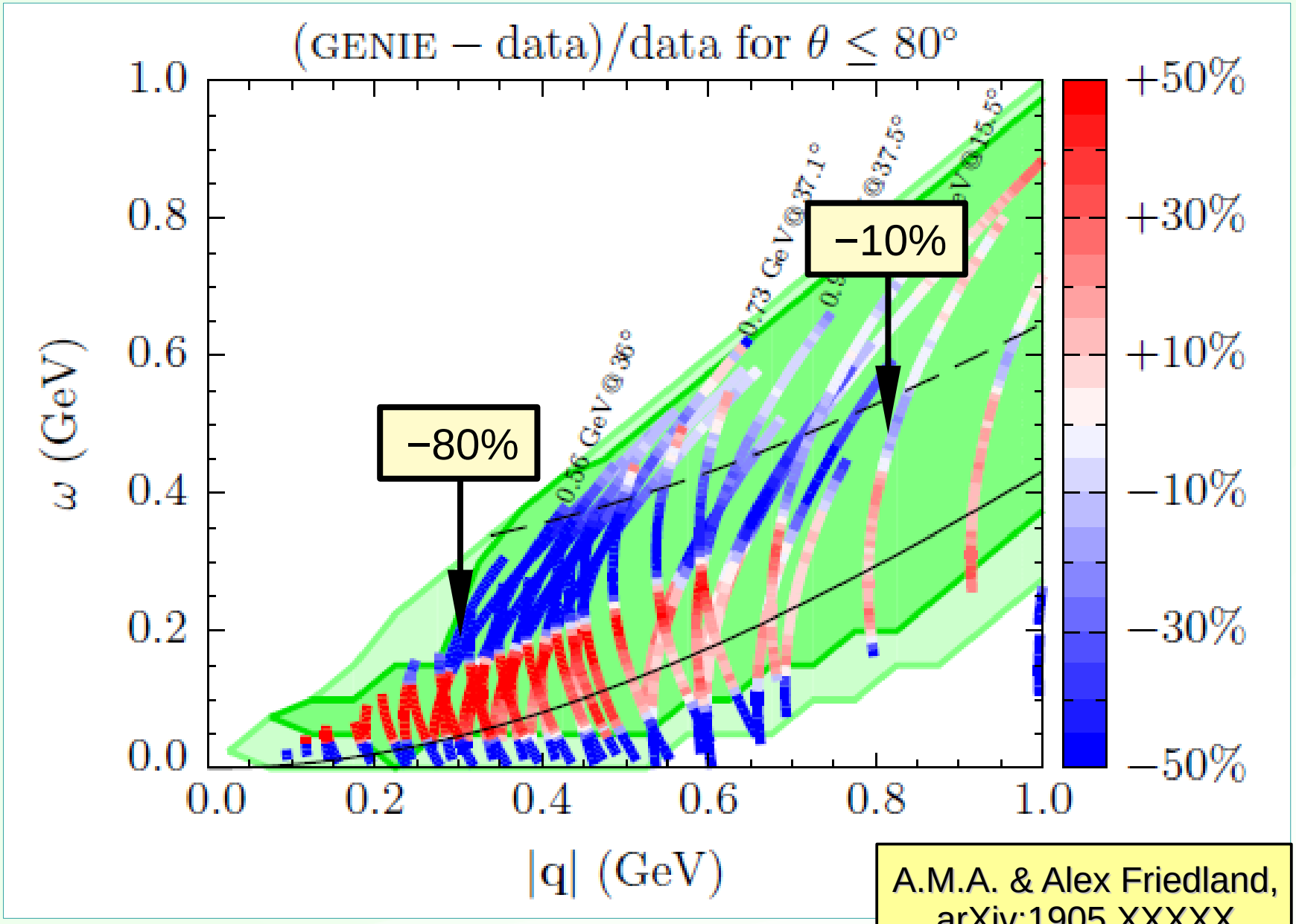
Δ resonance





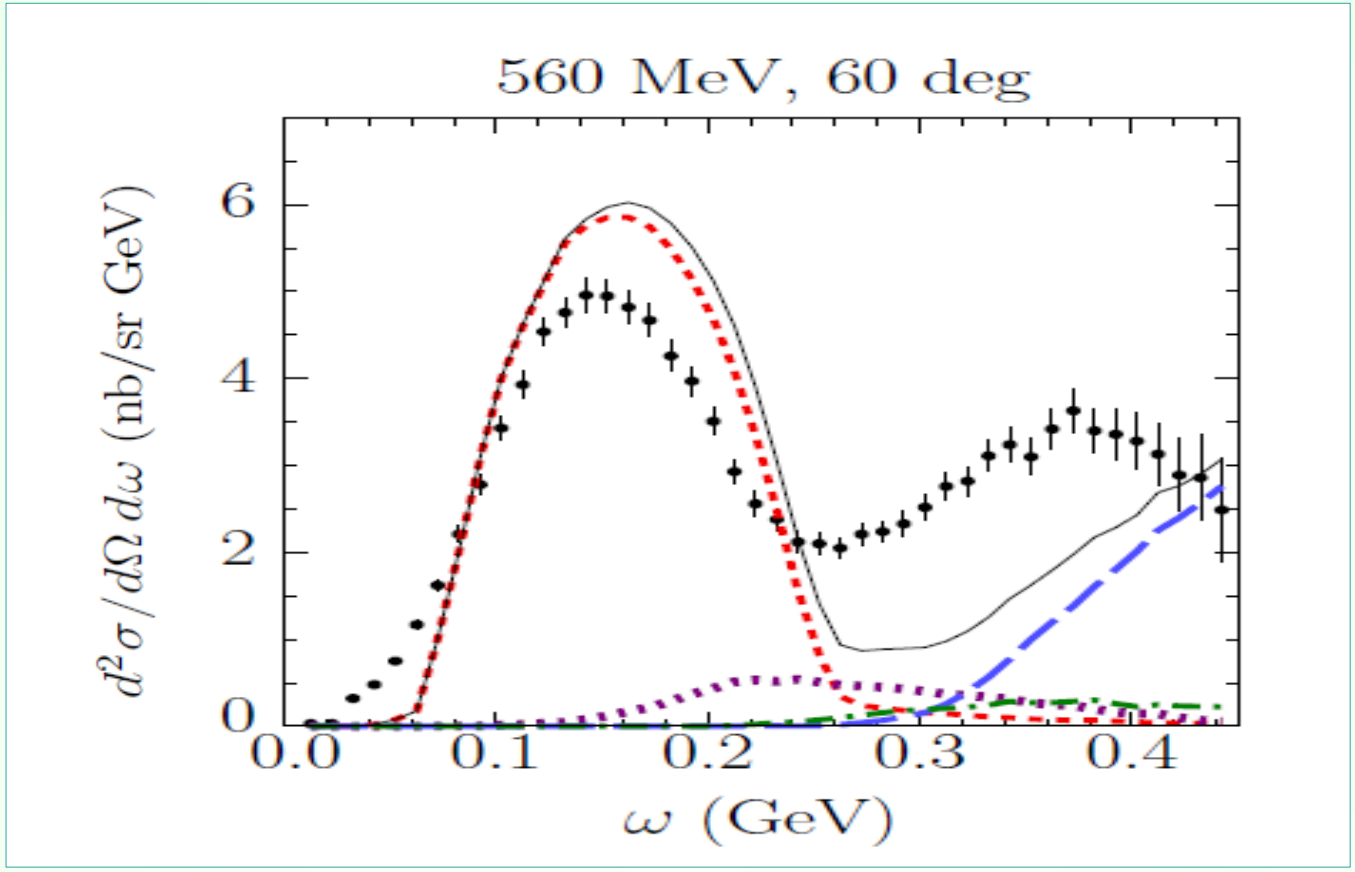
- For |q| > 1 GeV, Δ cannot be clearly distinguished in data.
- Discrepancy decreases with |q| increasing: −40% at 0.4 GeV and −10% at 0.8 GeV.
- Δ position wrong by **~100 MeV**: pions too hard.

Dip region



A.M.A. & Alex Friedland, arXiv:1905.XXXXX

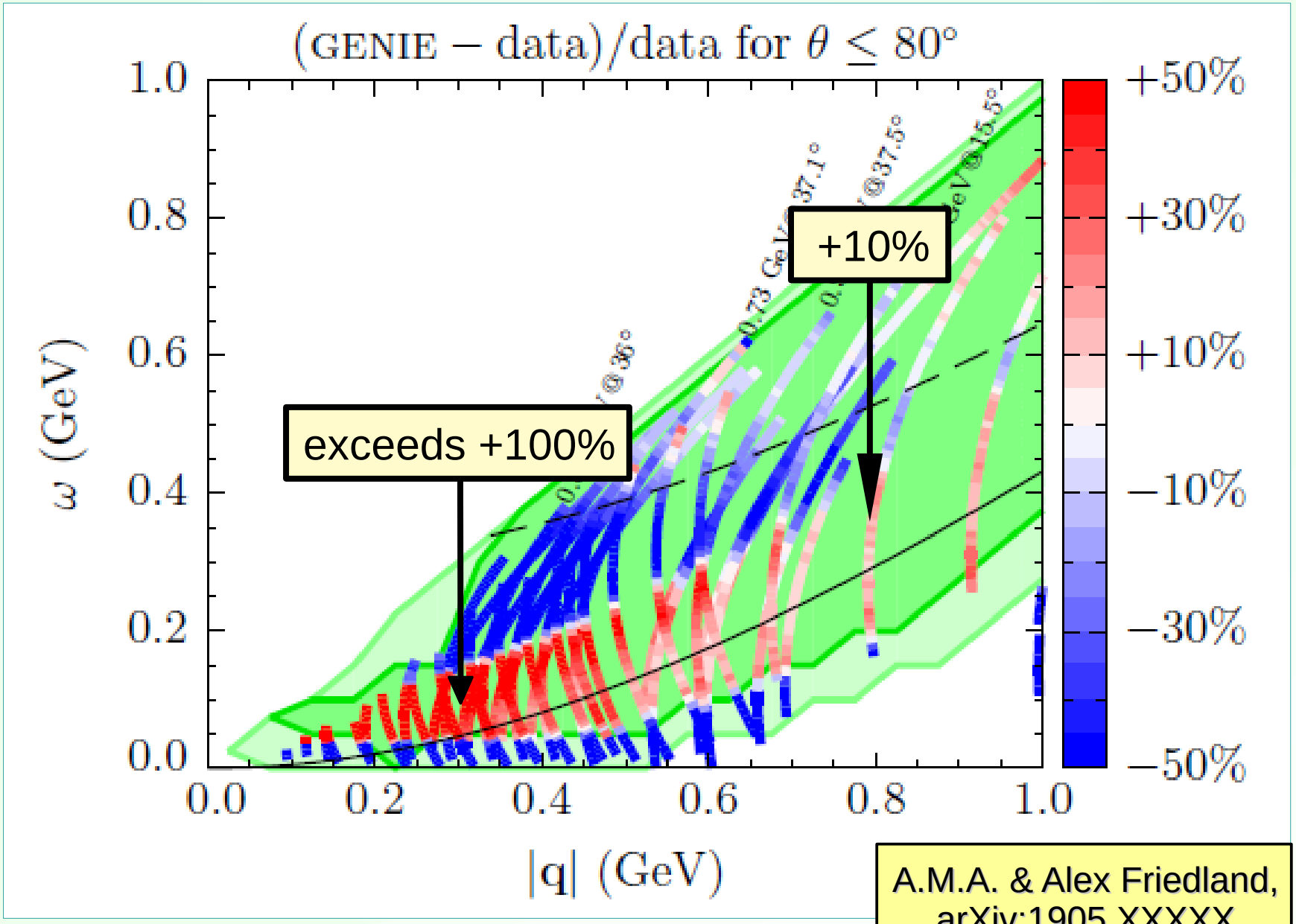
Dip region



- Dip-region discrepancy decreases with |q| increasing. Currently, its −80% at 0.3 GeV, −10% at 0.8 GeV, and −5% at 1.1 GeV.

- The discrepancy will decrease when Δ is reproduced.

QE



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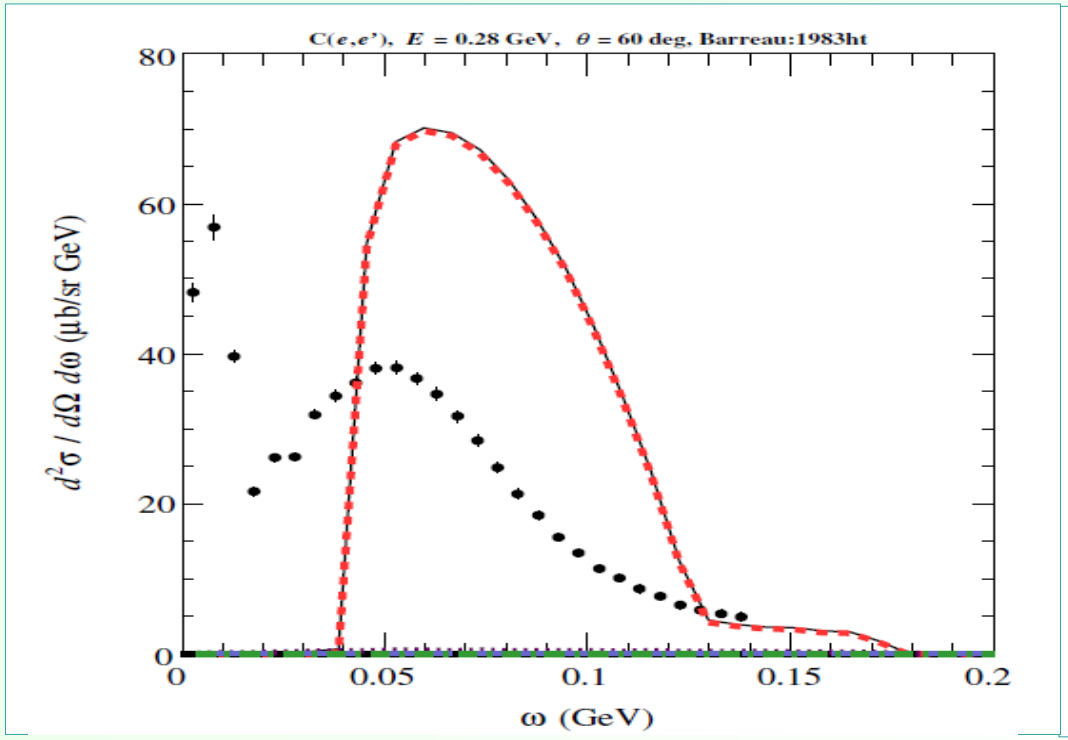
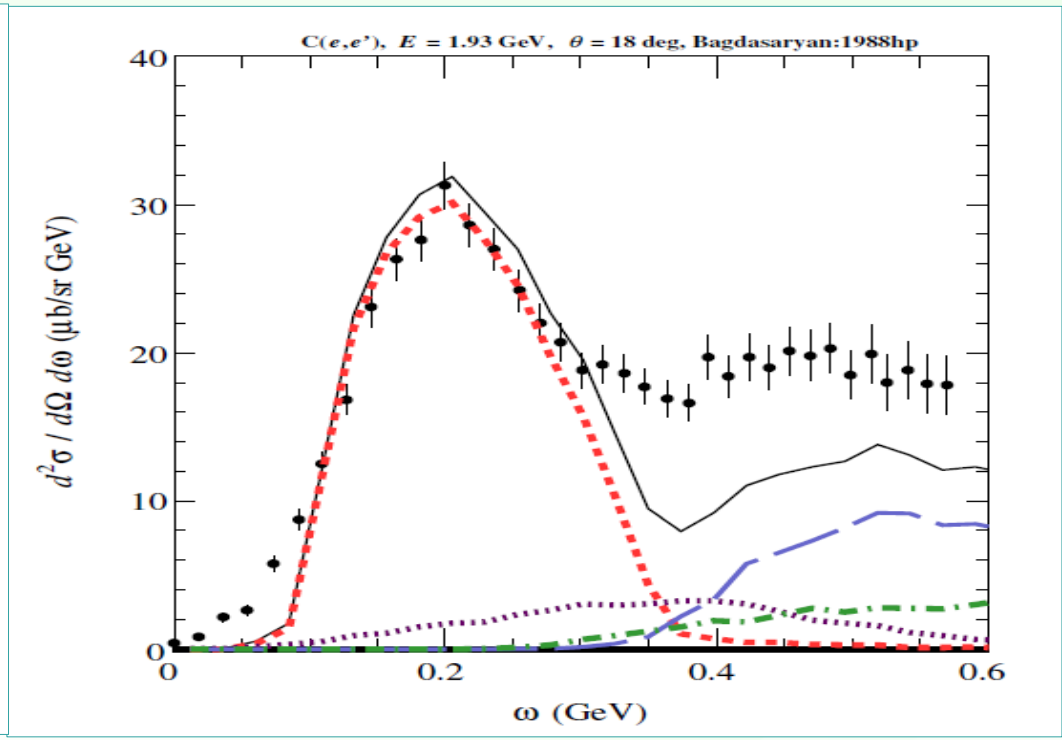
QE

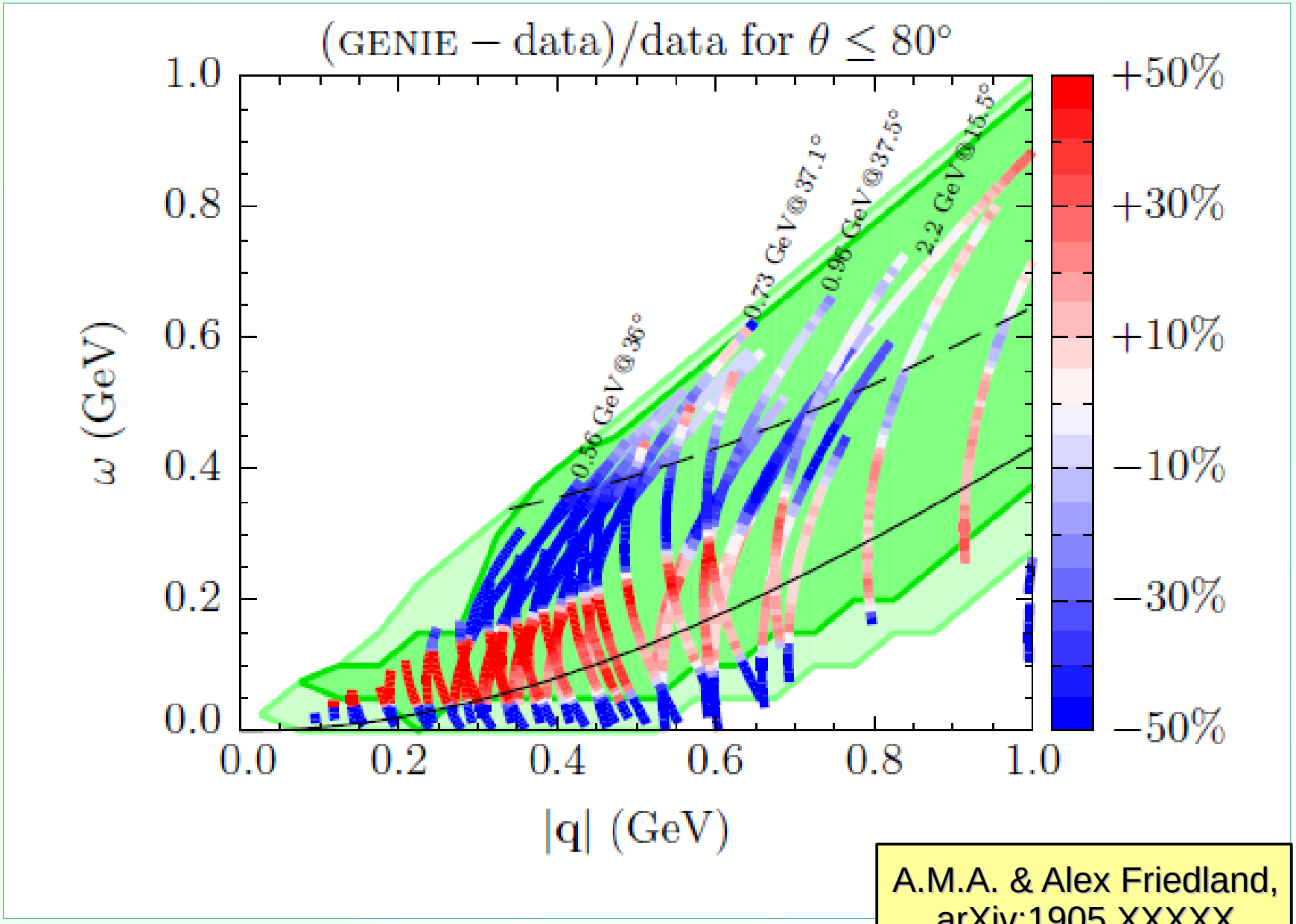




- Discrepancy decreases with |q| increasing: in the QE peak +500% at 0.2 GeV, +10% at 0.8 GeV, and +5% at 1.1 GeV. QE data for *E* = 2 GeV in **good agreement**.

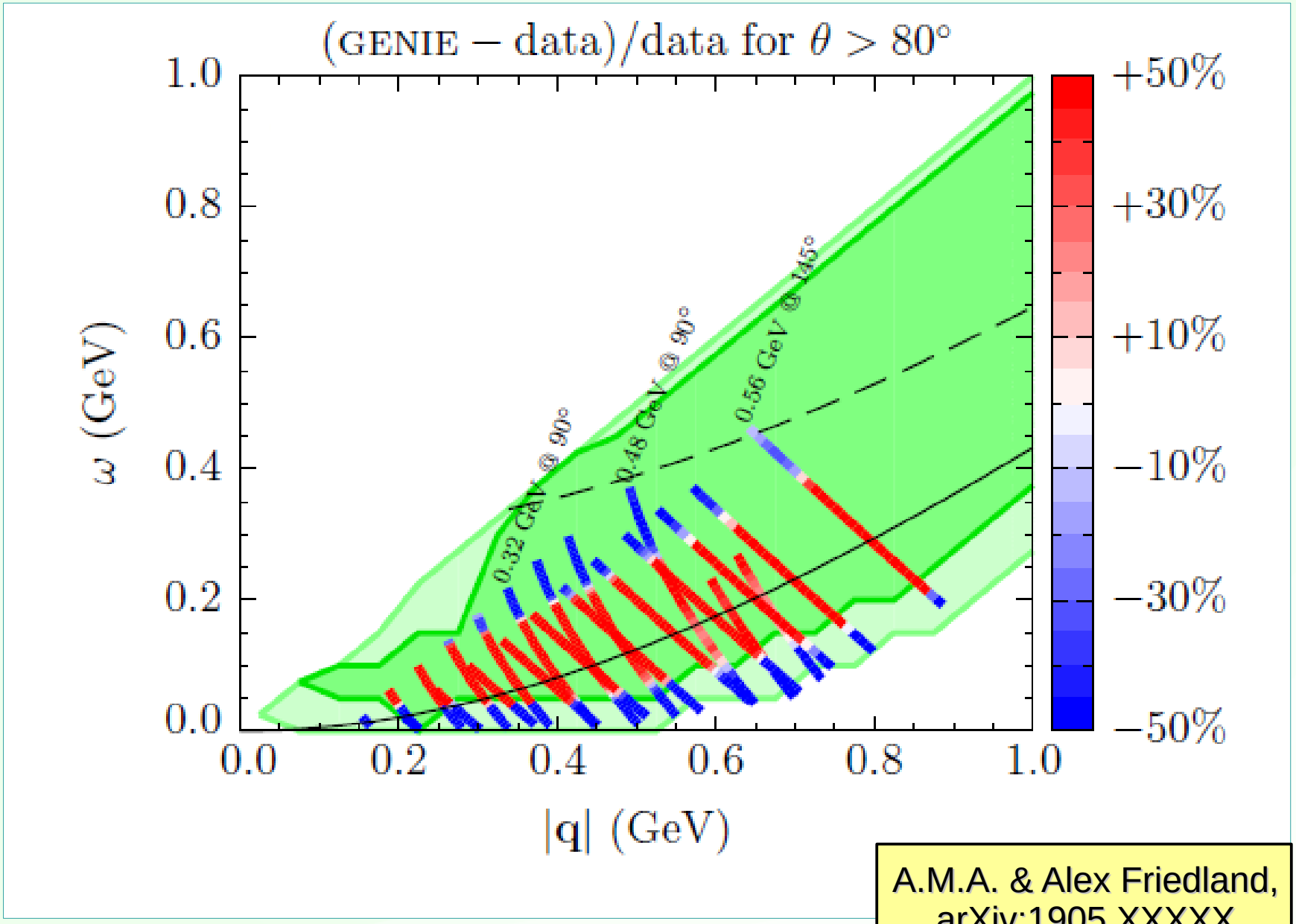
- MEC contribution **consistently worsens** the agreement in the QE peak: RFG parameters determined without it.

QE



A.M.A. & Alex Friedland, arXiv:1905.XXXXX

QE



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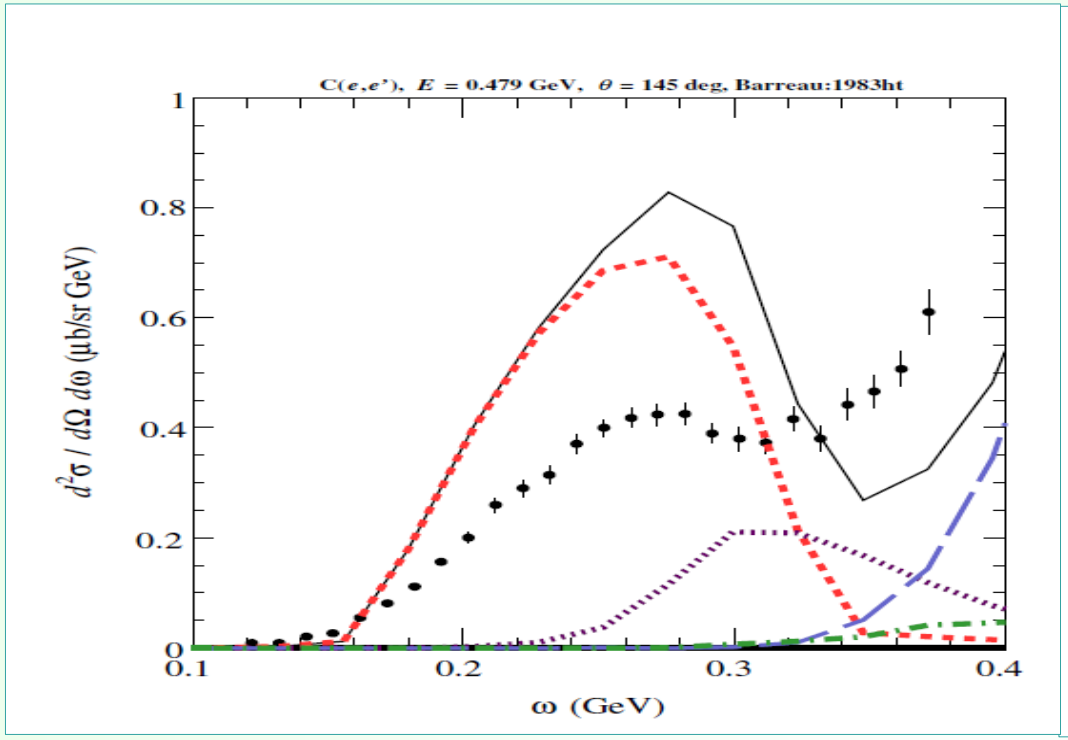
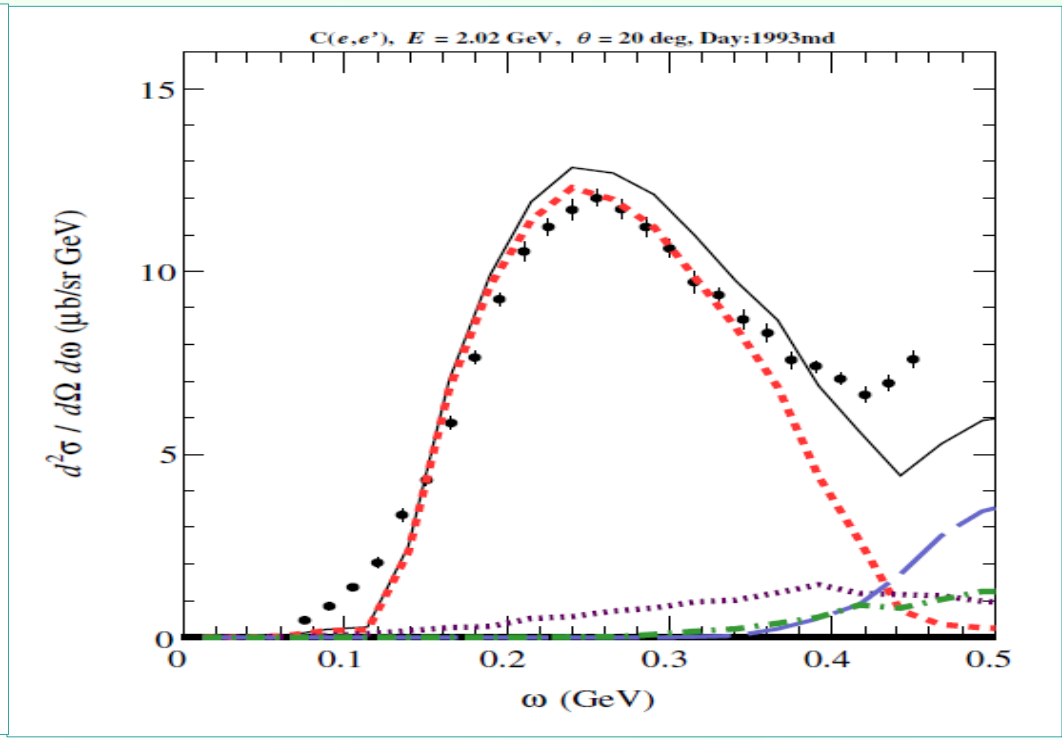
QE





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

- In the peak region, the discrepancy exceeds +100% in 9 out of 39 (16 out of 20) data sets for low (high) angles.

Summary

- Electron-scattering data give unique opportunity of assessing the accuracy of 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 expected to be too hard.

- Observed issues originate from elementary cross sections, **not nuclear model**.

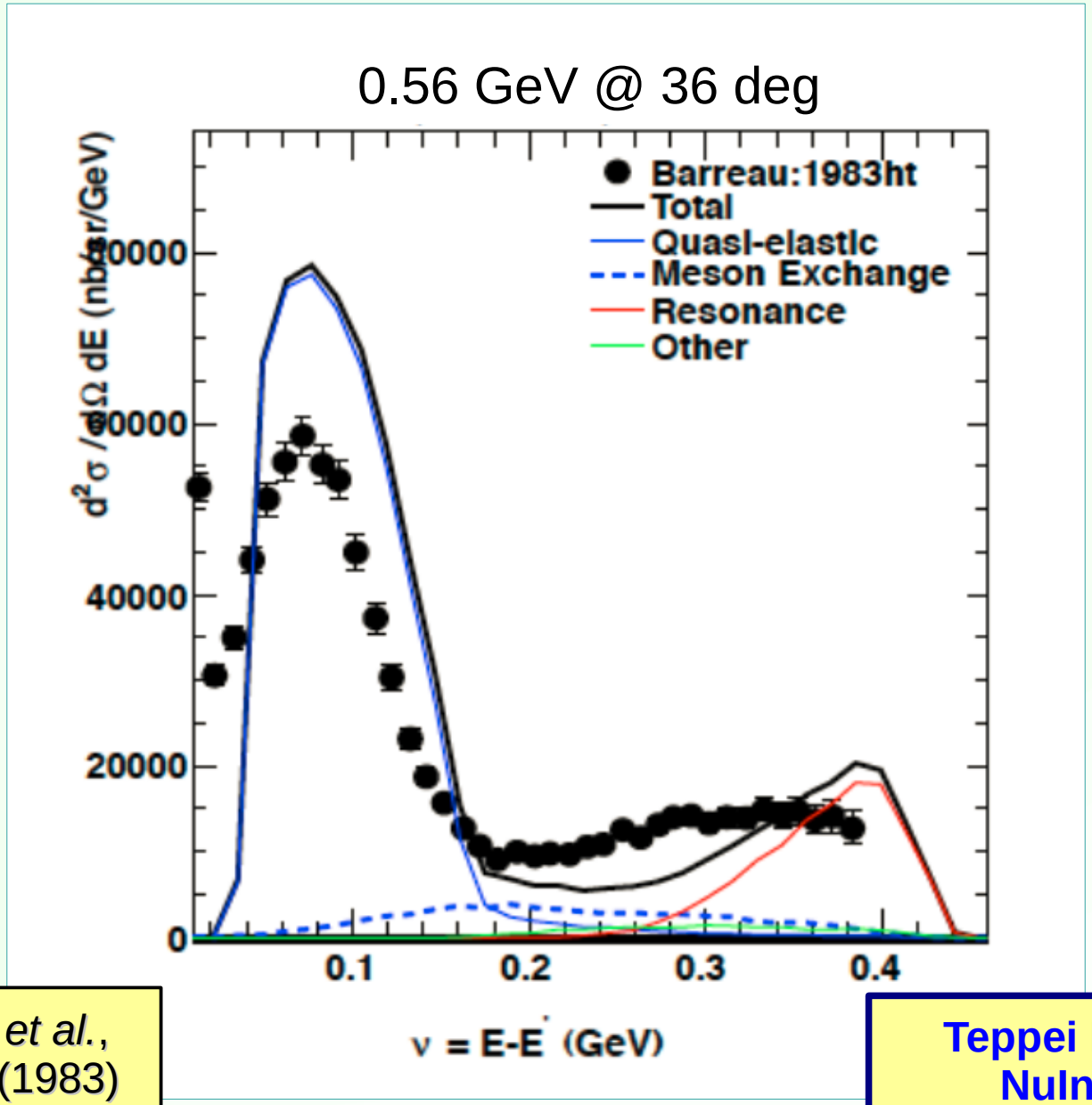
Backup slides

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.

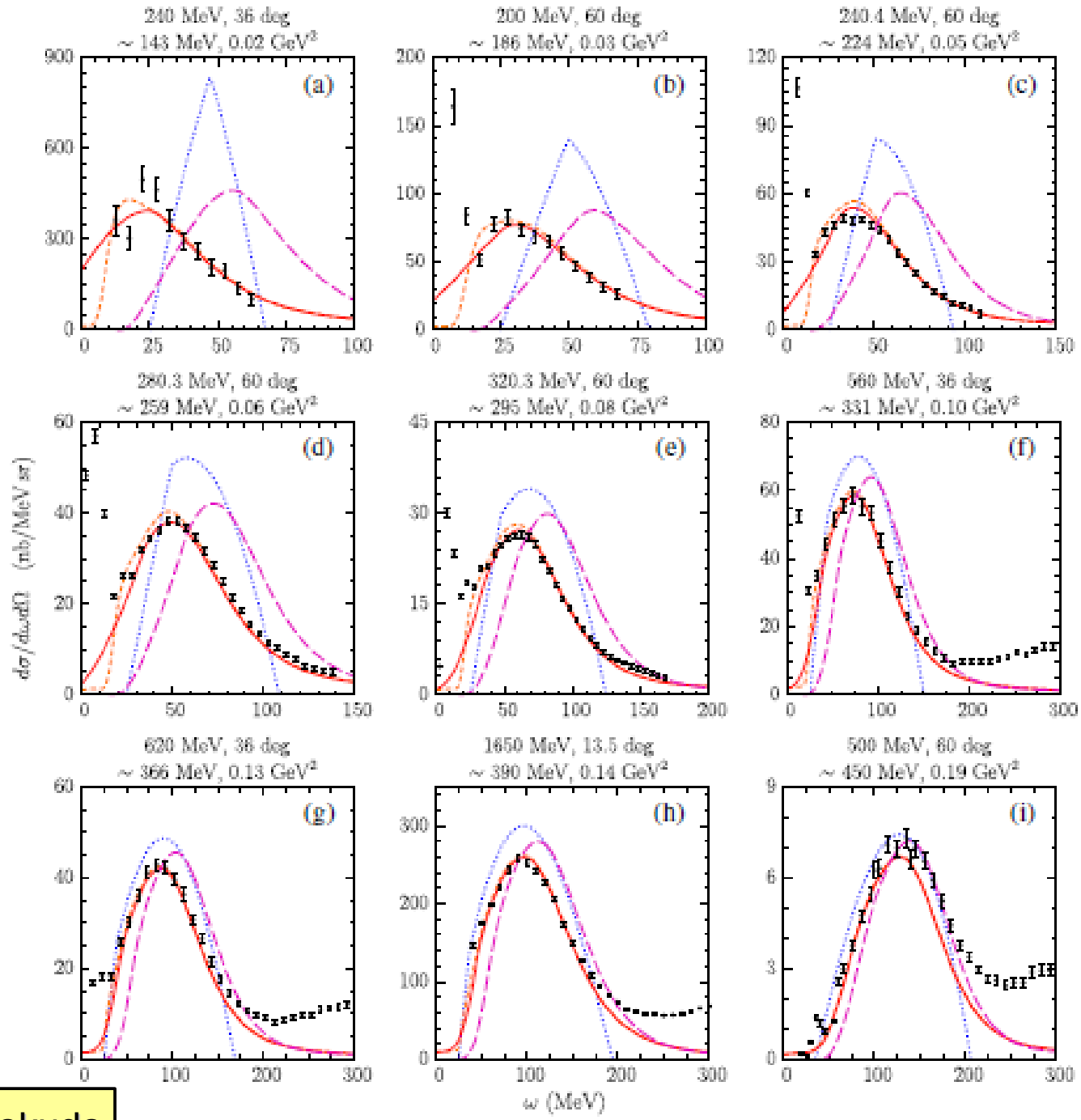
Acero *et al.* (NOvA), PRD **98**, 032012 (2018)

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



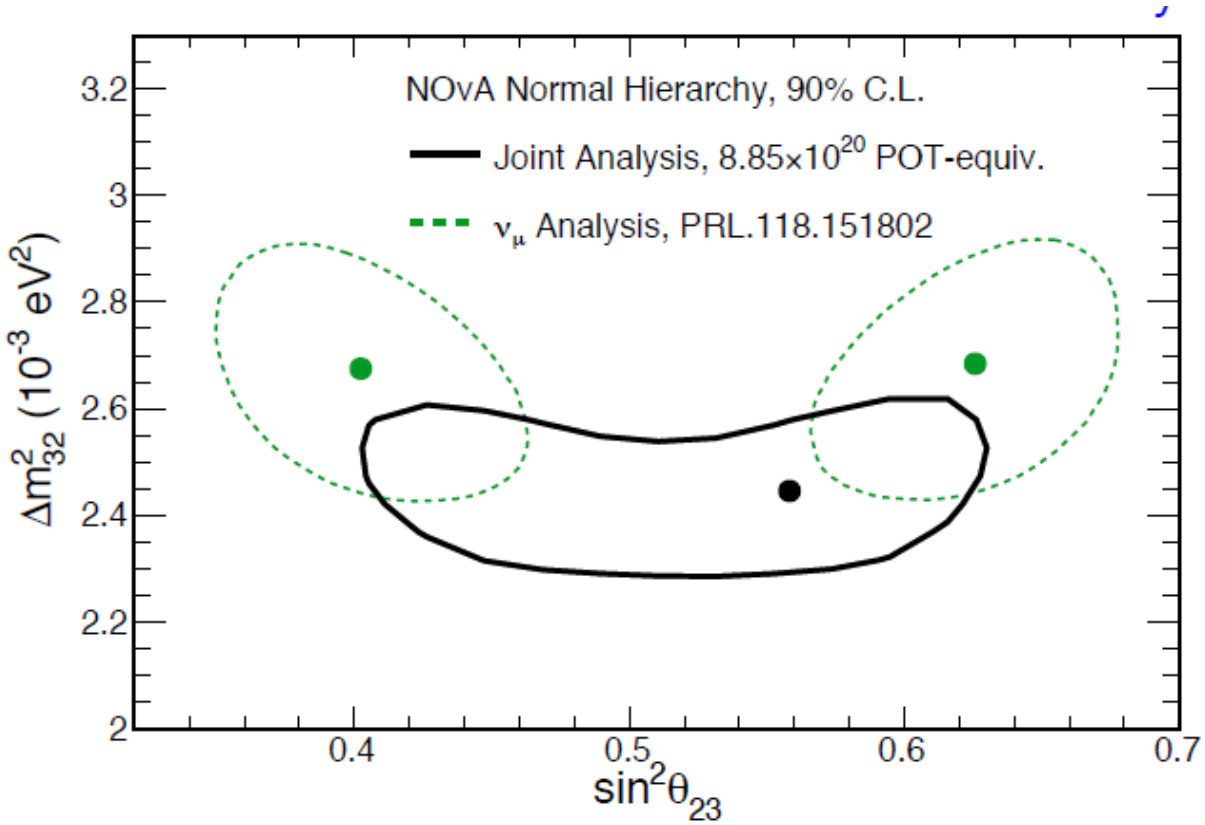
data: Barreau *et al.*, NPA **402**, 515 (1983)

Teppei Katori, NuInt'12



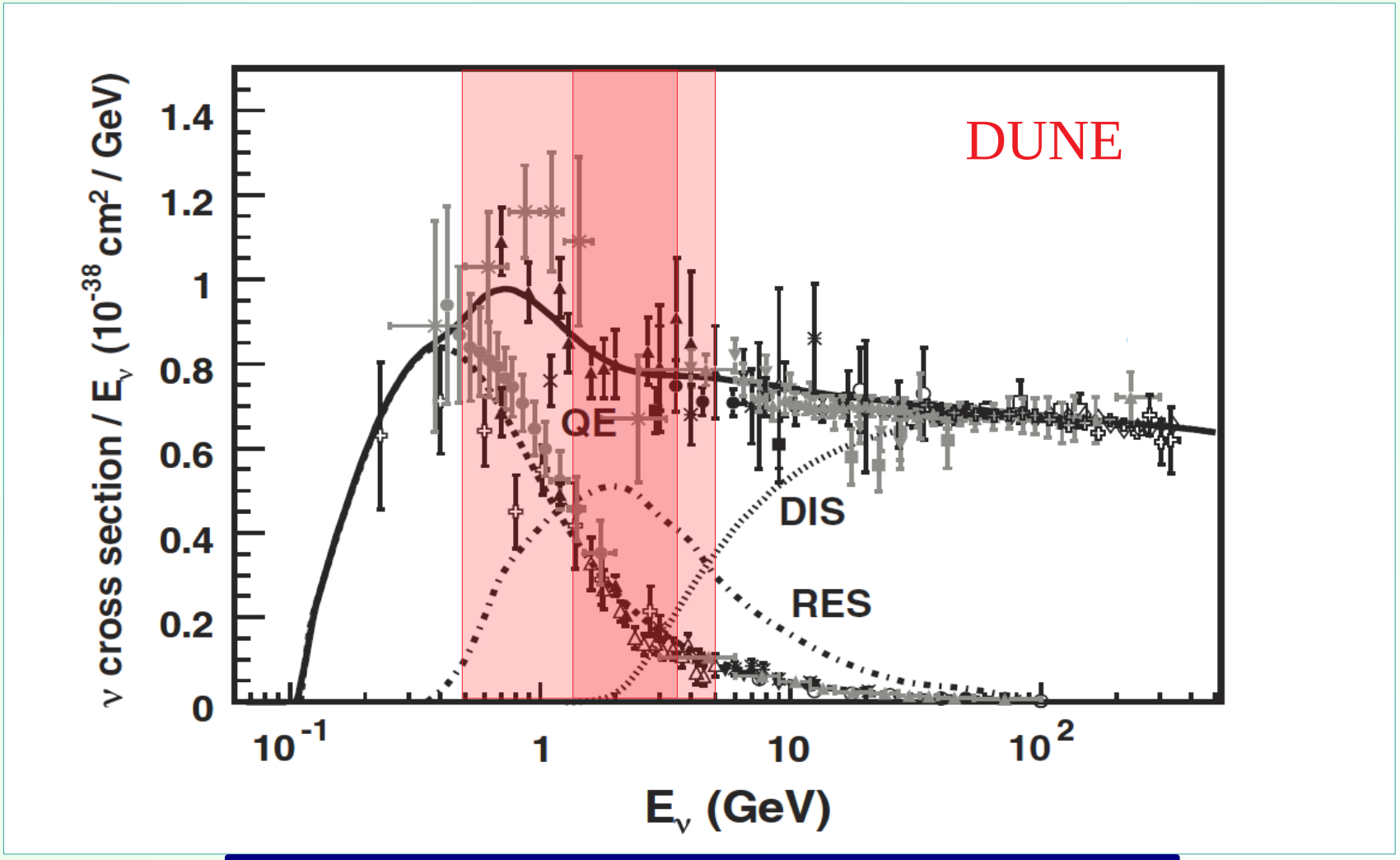
AMA, Benhar & Sakuda
PRD 91, 033005 (2015)

Current precision



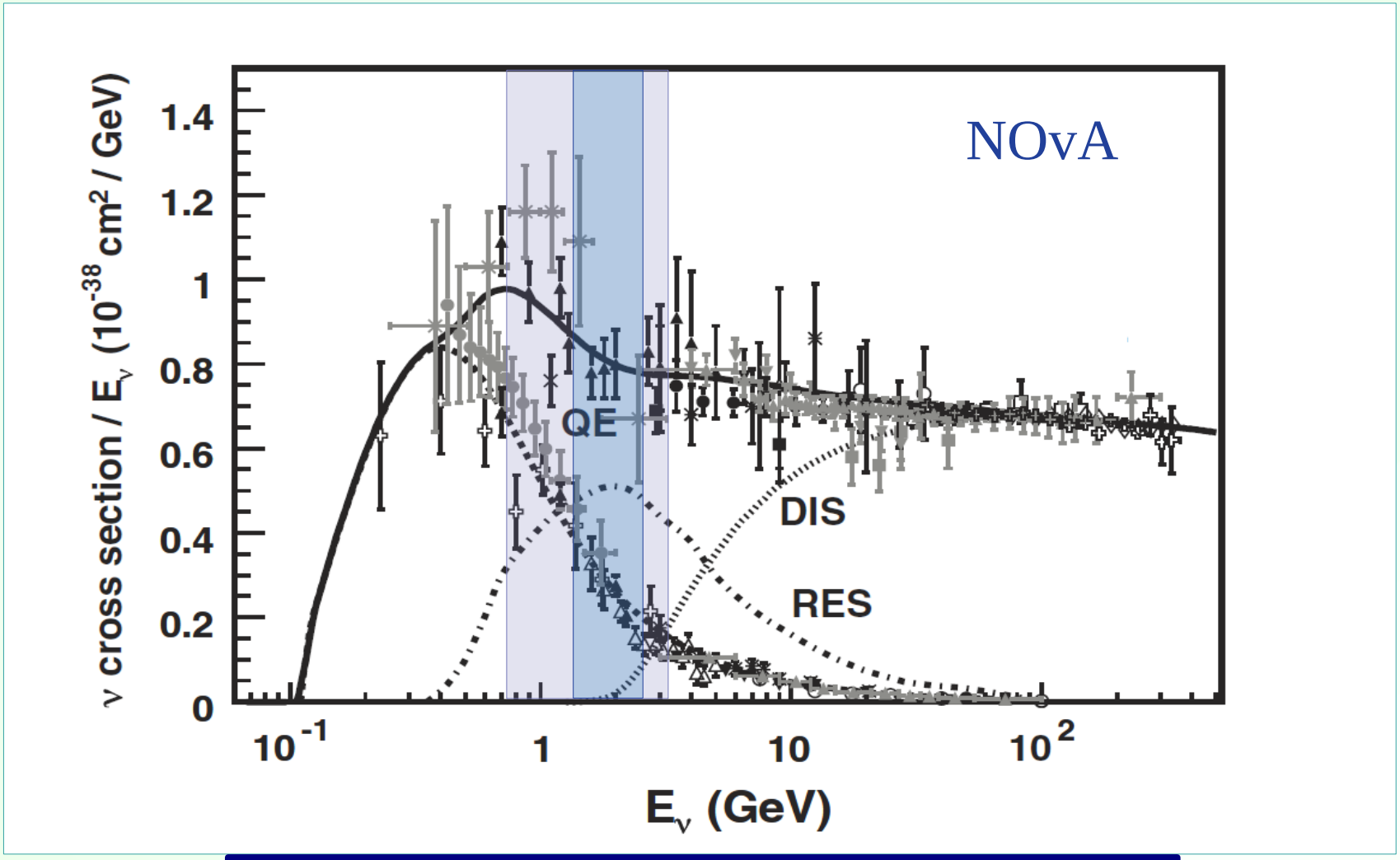
A. Radovic (NOvA),
JETP Jan 12, 2018

What energies are relevant?



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

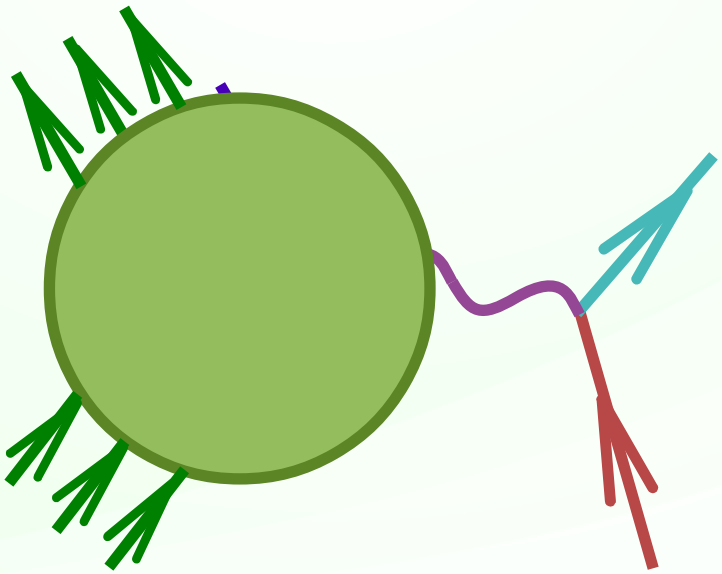
What energies are relevant?



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

Impulse approximation

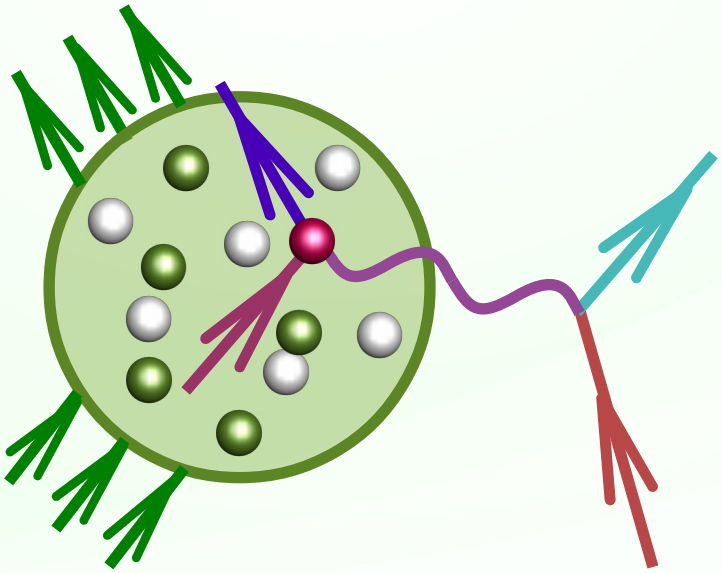
Assumption: the dominant process of lepton-nucleus interaction is **scattering off a single nucleon**, with the remaining nucleons acting as a spectator system.



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**|.



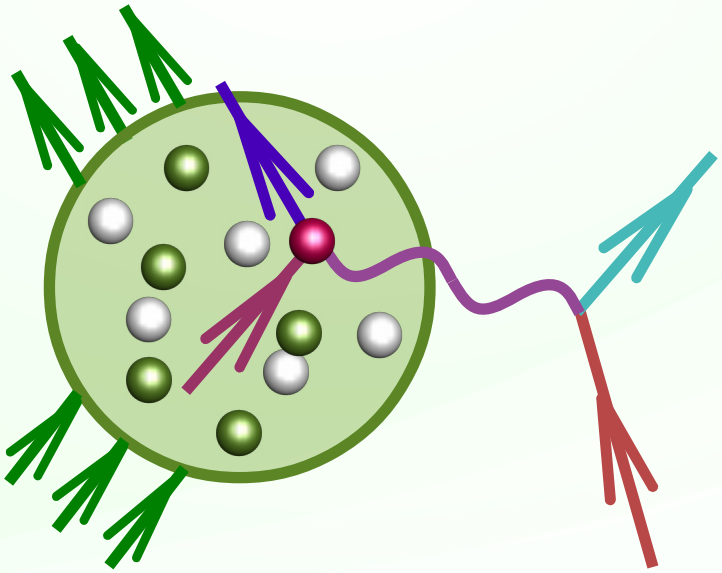
Impulse approximation

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

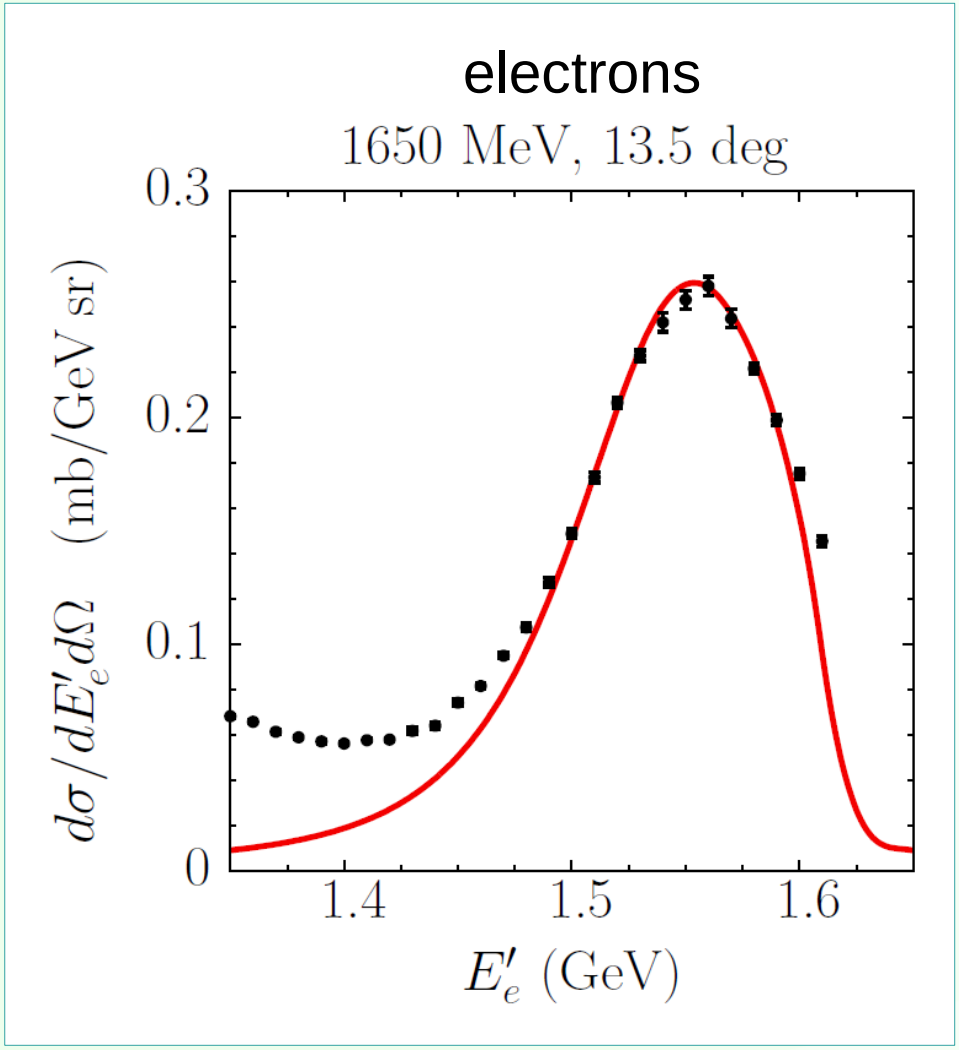
Hole spectral function

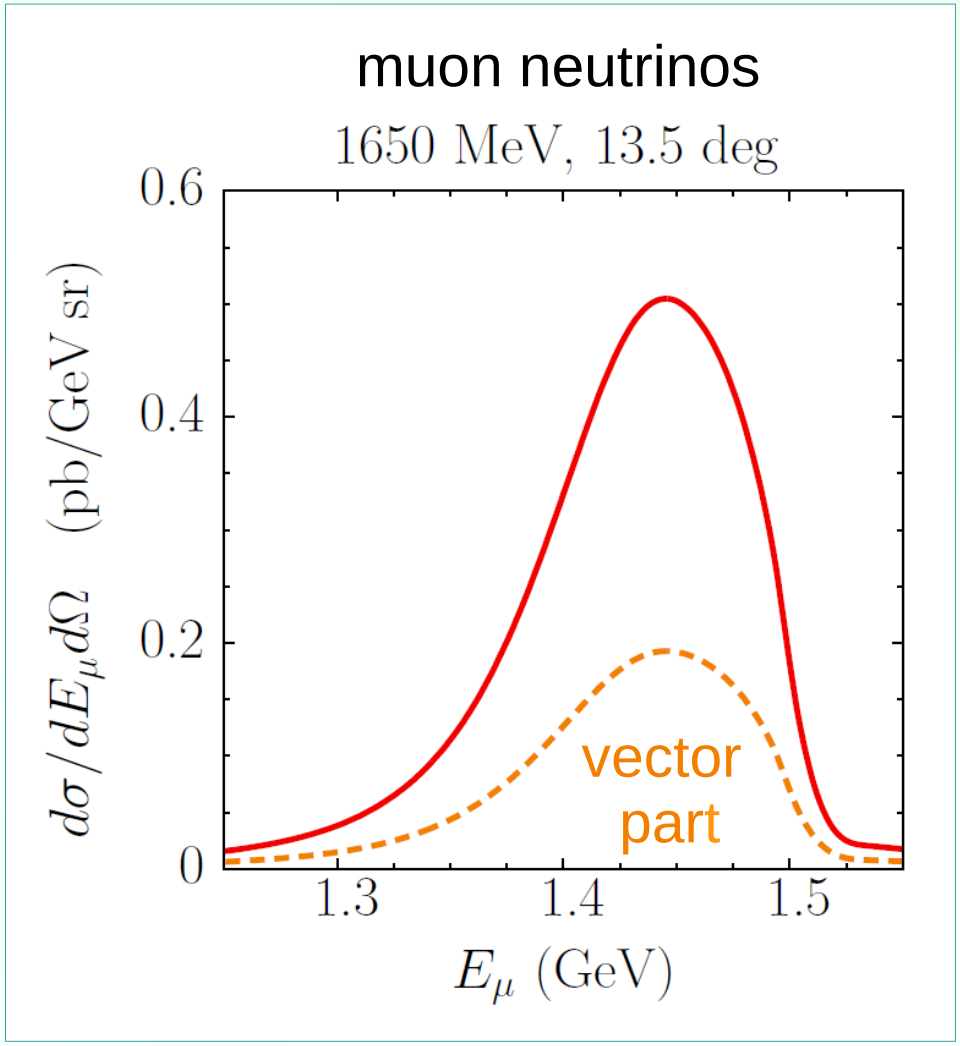
Elementary cross section

Particle spectral function

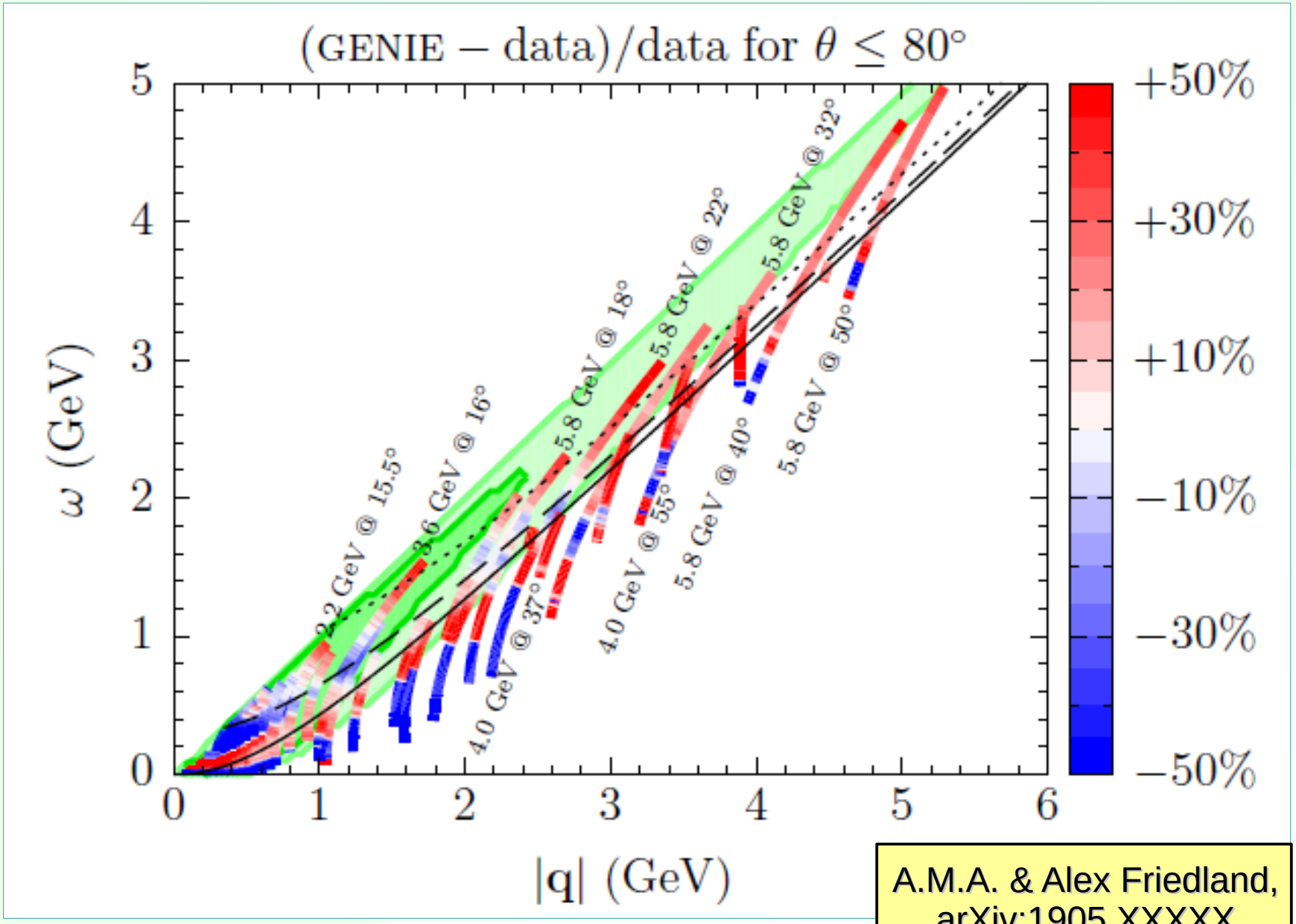


Much more than the vector part...



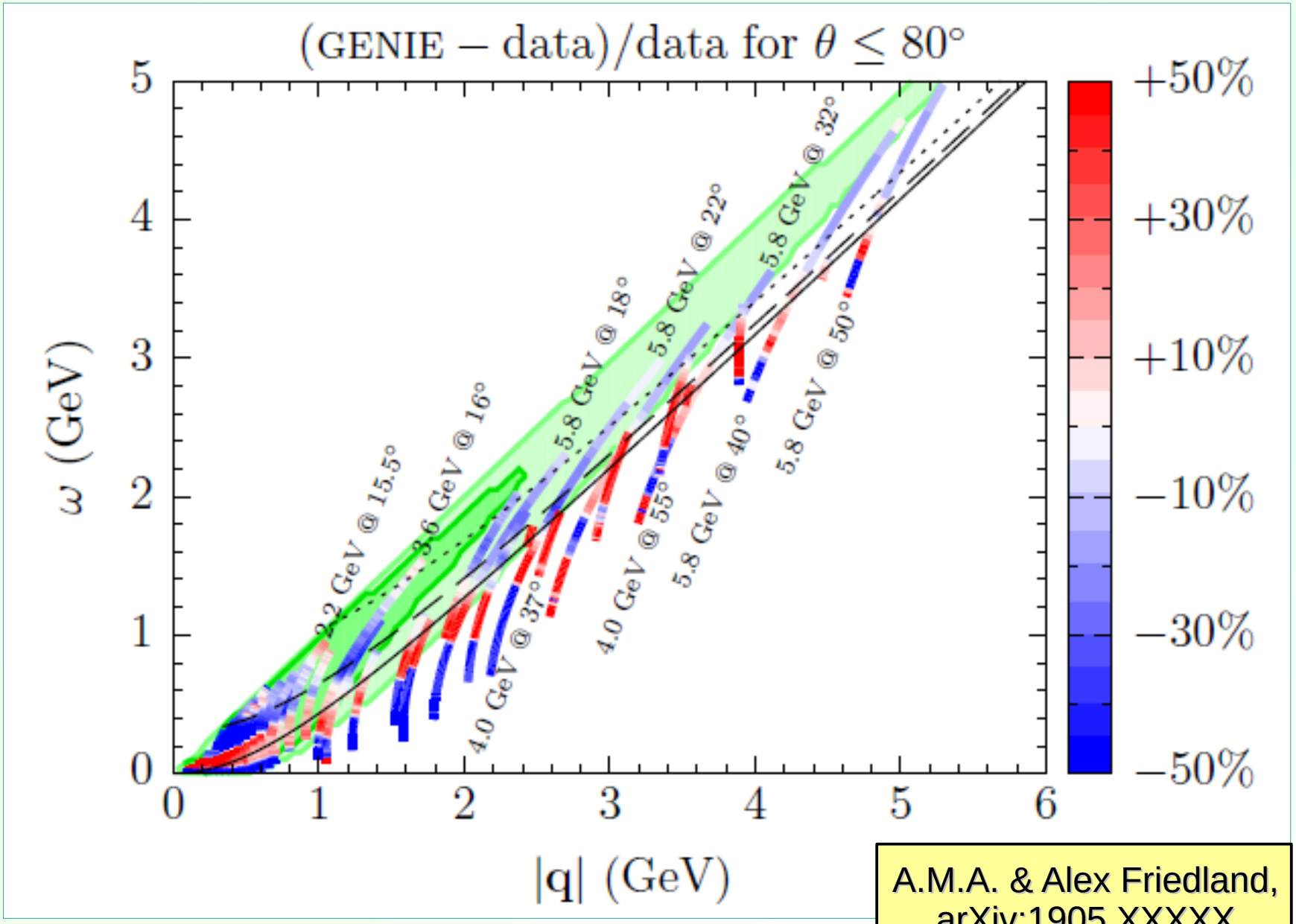


C(*e*, *e*') in GENIE



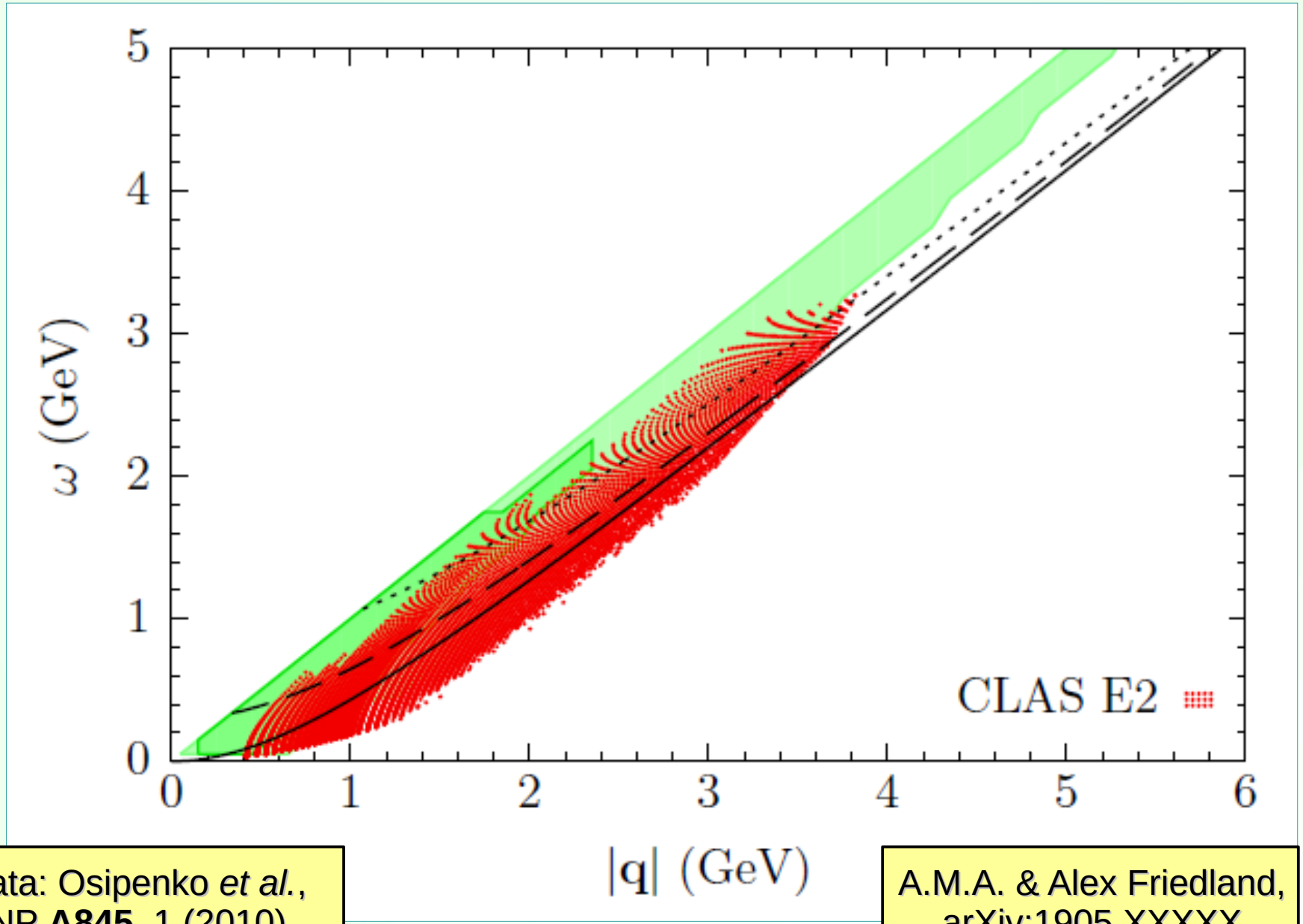
A.M.A. & Alex Friedland, arXiv:1905.XXXXX

DIS reduction by 35%



A.M.A. & Alex Friedland, arXiv:1905.XXXXX

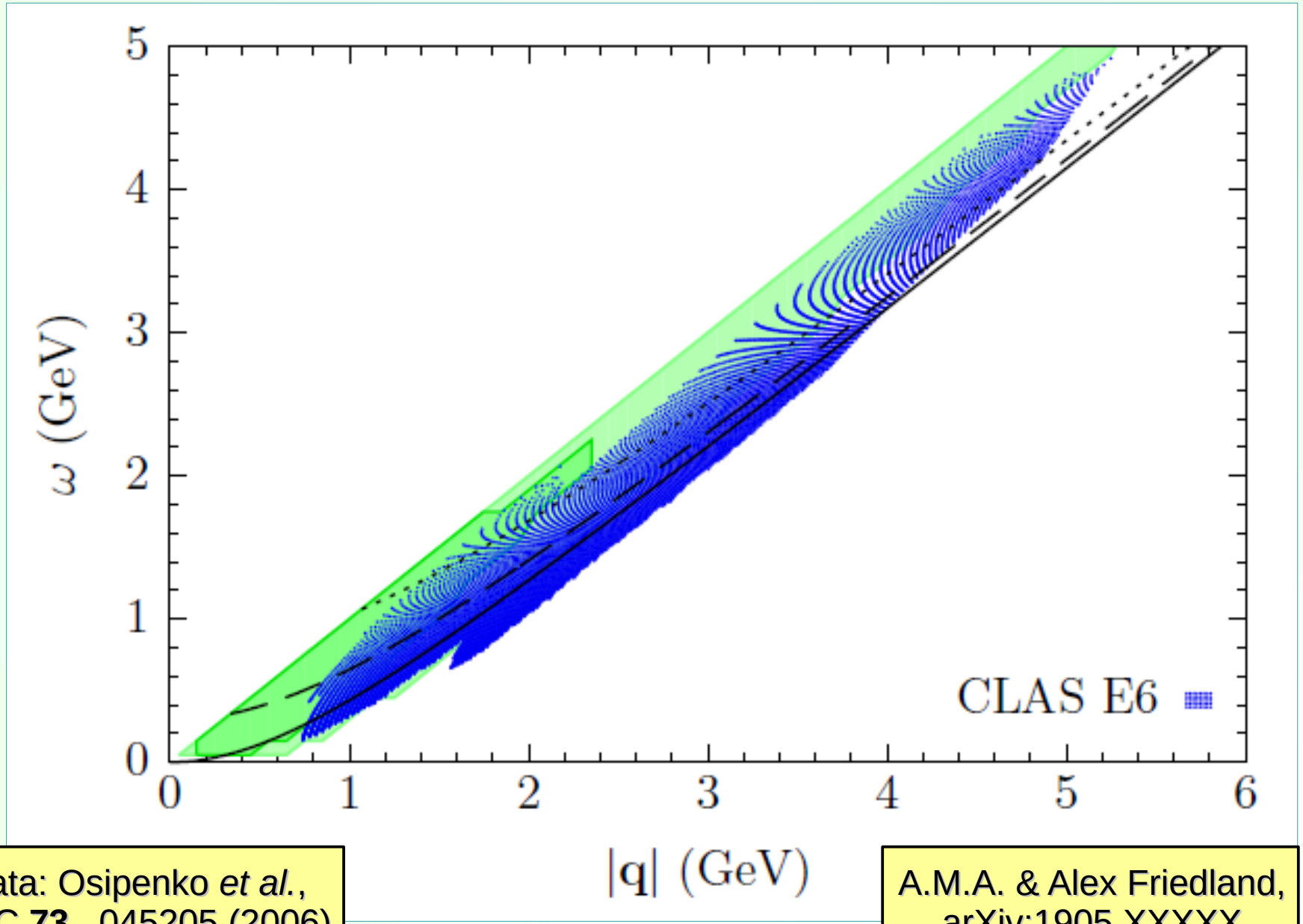
Kinematics covered in C(*e*, *e*')



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

A.M.A. & Alex Friedland, arXiv:1905.XXXXX

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



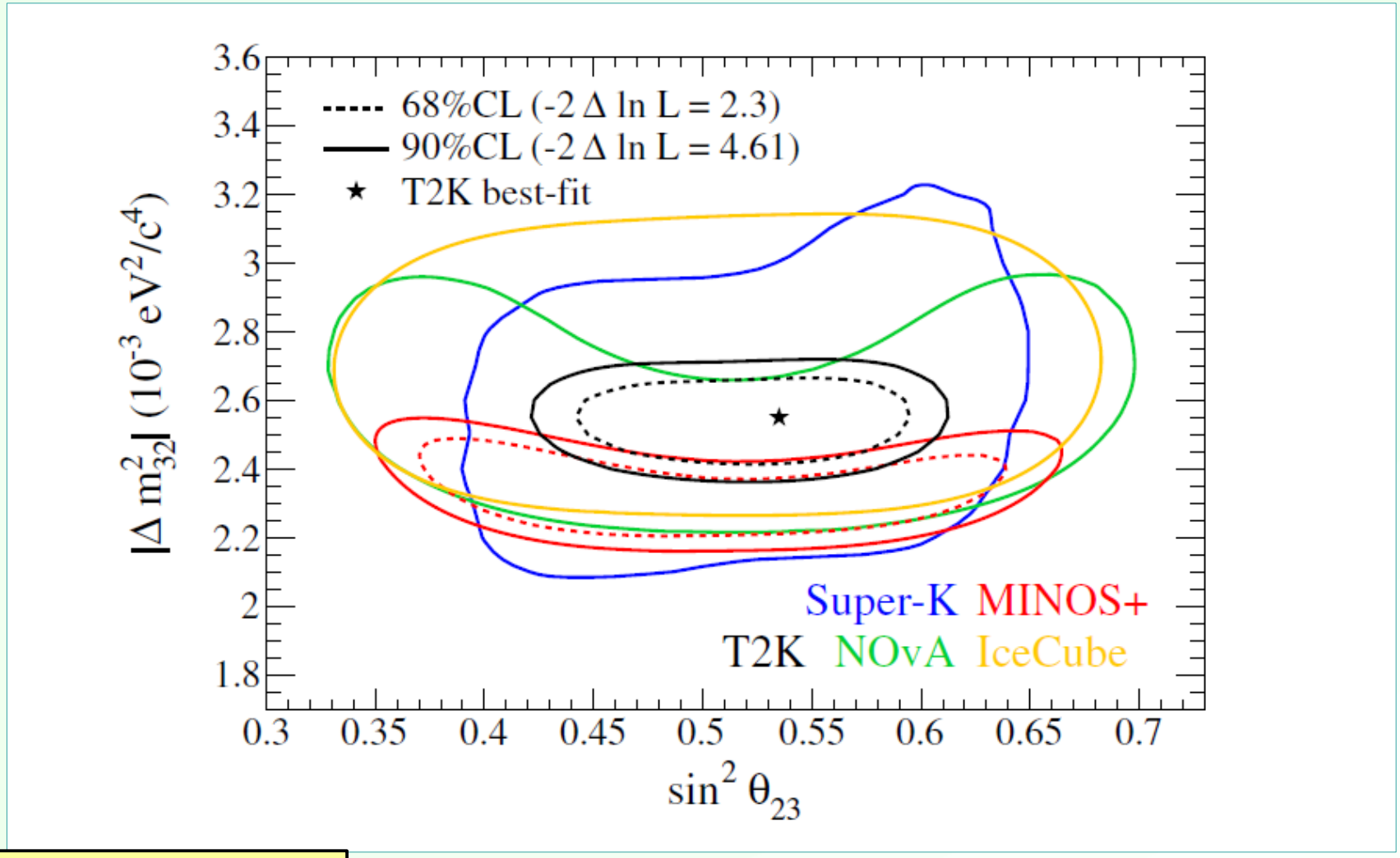
data: Osipenko *et al.*, PRC **73**, 045205 (2006)

A.M.A. & Alex Friedland, arXiv:1905.XXXXX

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)