How neutrino physics can benefit from electron-scattering measurements

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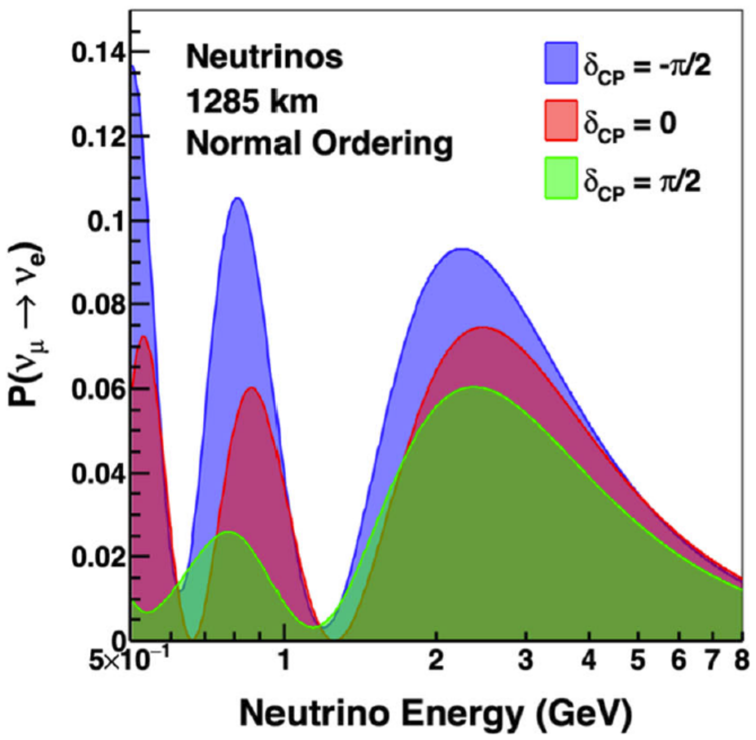
July 20, 2026

MC Generators in accelerator neutrino physics

- Main goal: extract the ν & $\bar{\nu}$ oscillation probabilities.
- Polychromatic beams, neutrino energy reconstructed from visible energy deposited by interaction products.
- Monte Carlo essential to account for the missing energy, near-far flux differences, backgrounds etc.
- For example, in DUNE, the average energy is 3.926 and 4.208 GeV (unoscillated spectrum) in the near and far detector, respectively (2021 fluxes).
- Accuracy of simulations translates into the accuracy of the extracted oscillation parameters.
- We are no longer after O (1) effects, **without reliable cross sections we cannot succeed**.



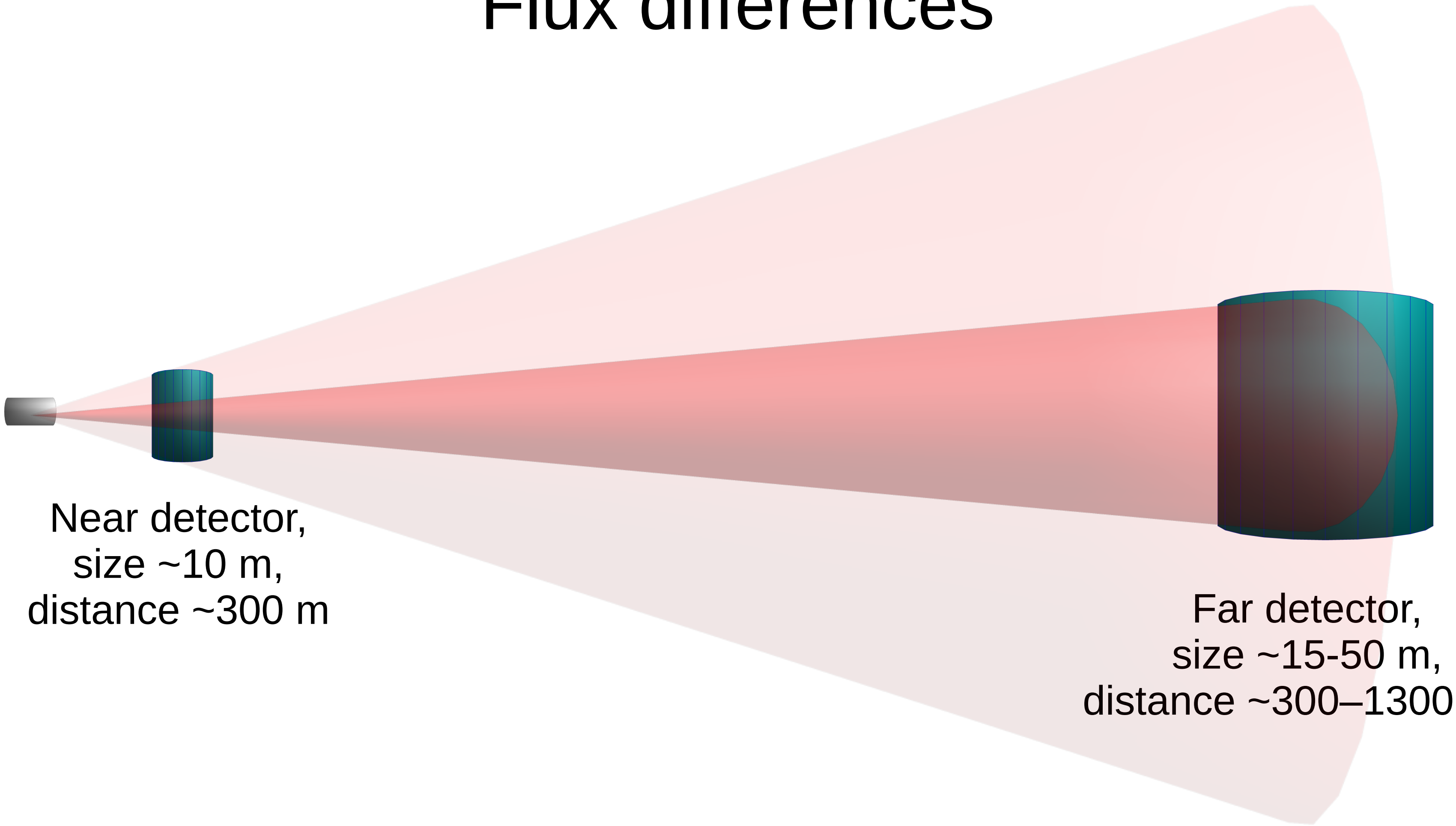
DUNE Collaboration, arXiv:2006.16043

Flux differences

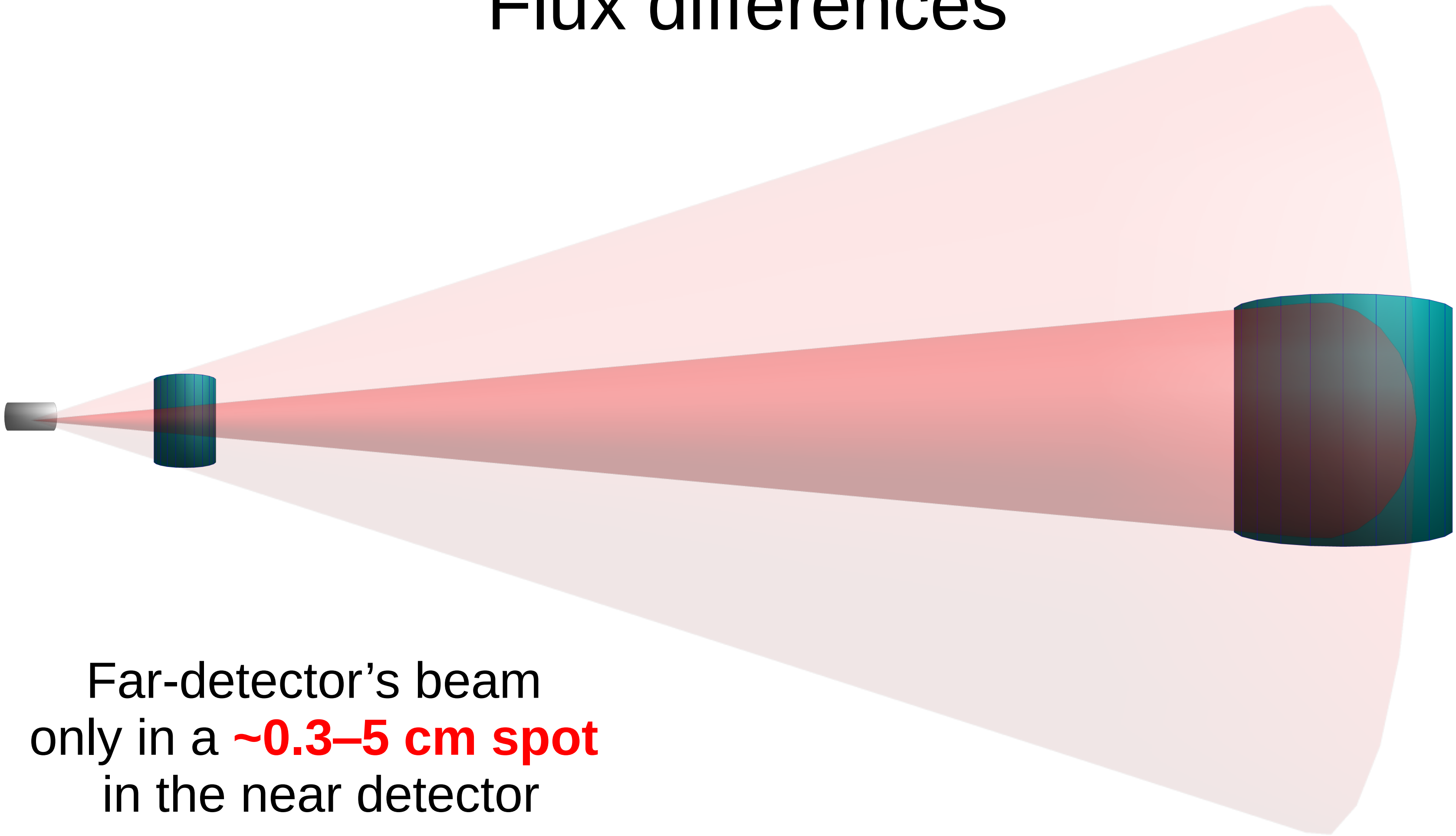
Near detector,
size ~10 m,
distance ~300 m

Far detector,
size ~15-50 m,
distance ~300–1300 km

Flux differences

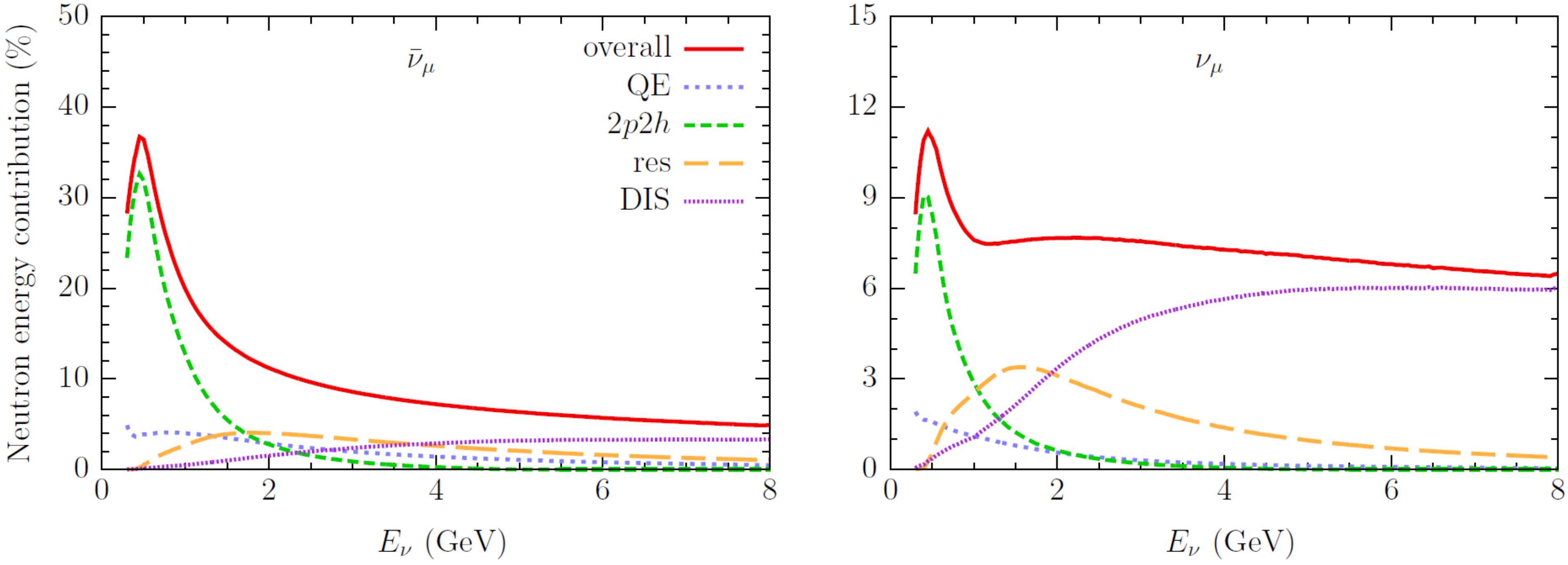


Flux differences



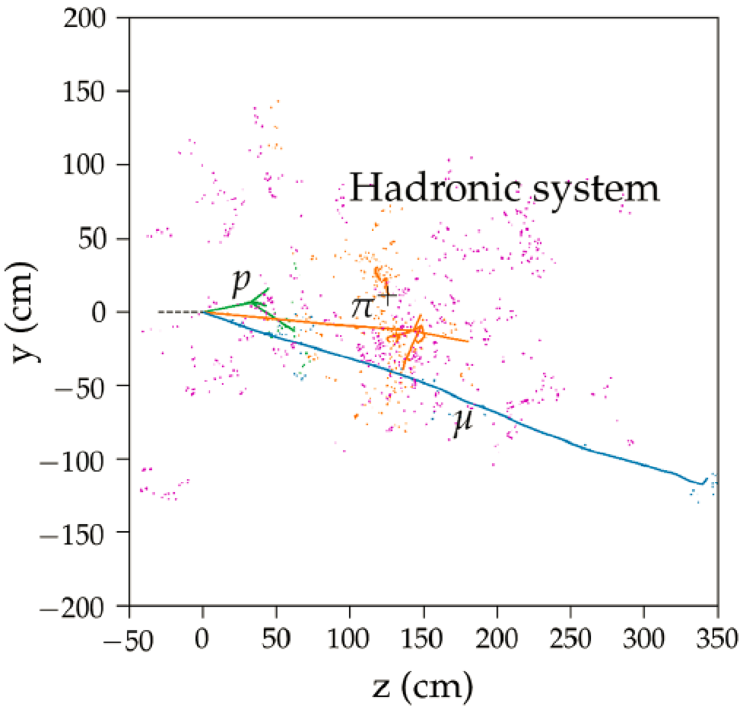
Far-detector’s beam
only in a **~0.3–5 cm spot**
in the near detector

Neutron energy contribution



A.M.A. *et al.*, PRD 92, 073014 (2015)

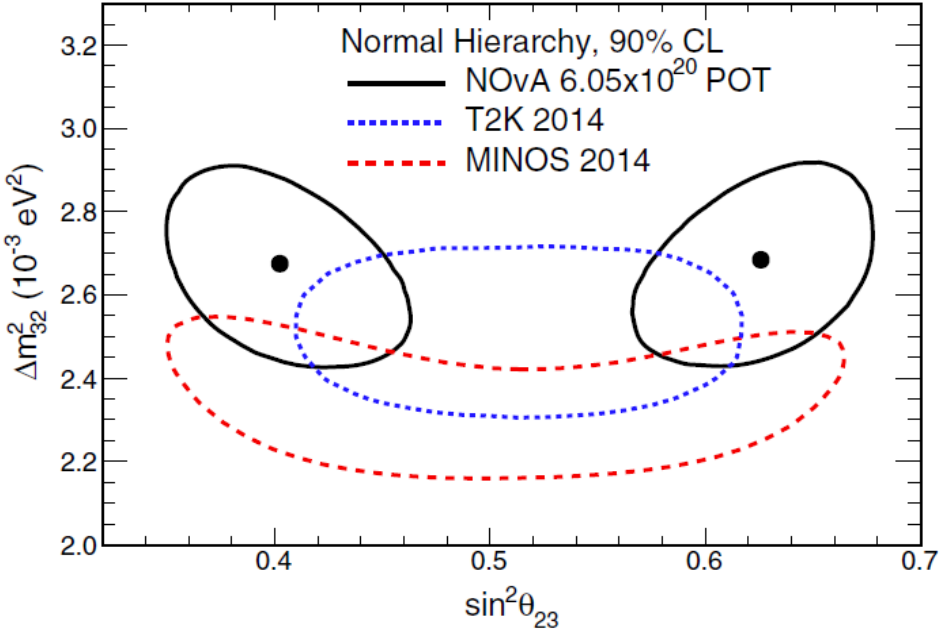
LAr potential for accurate energy reconstruction



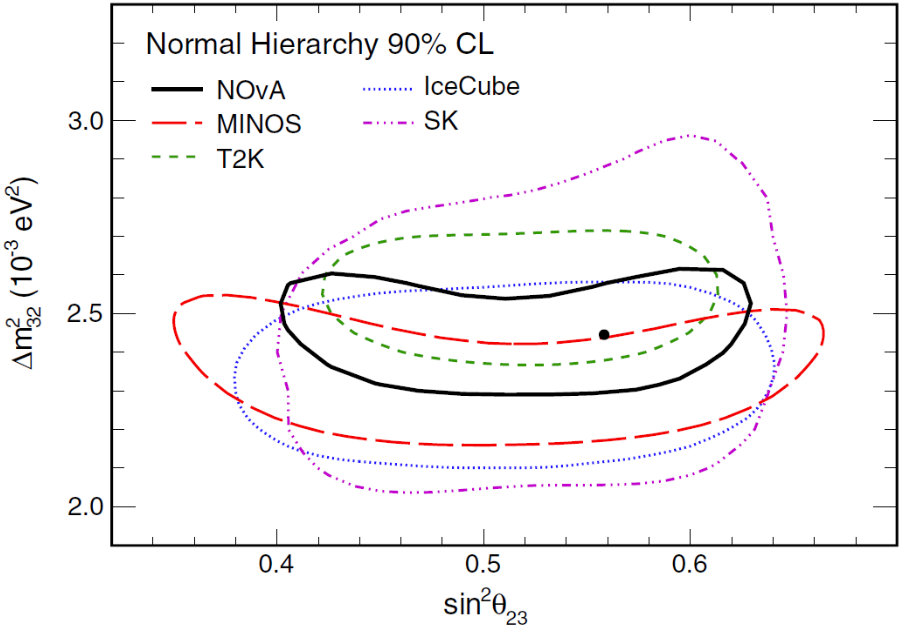
A. Friedland & S.W. Li, PRD 99, 036009 (2019)

Multiply differential cross sections required for energy reconstruction

Concrete example: NOvA



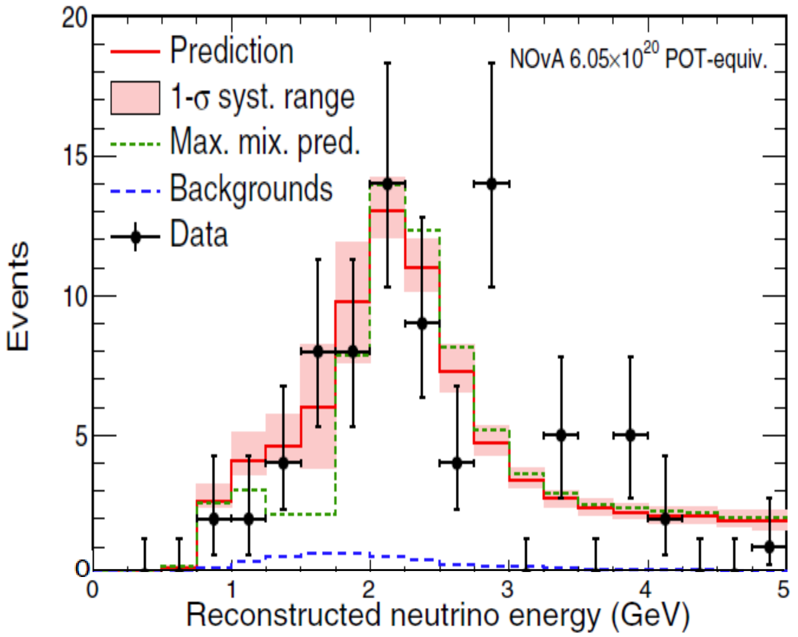
Acero *et al.* (NOvA), PRL 118, 151802 (2017)



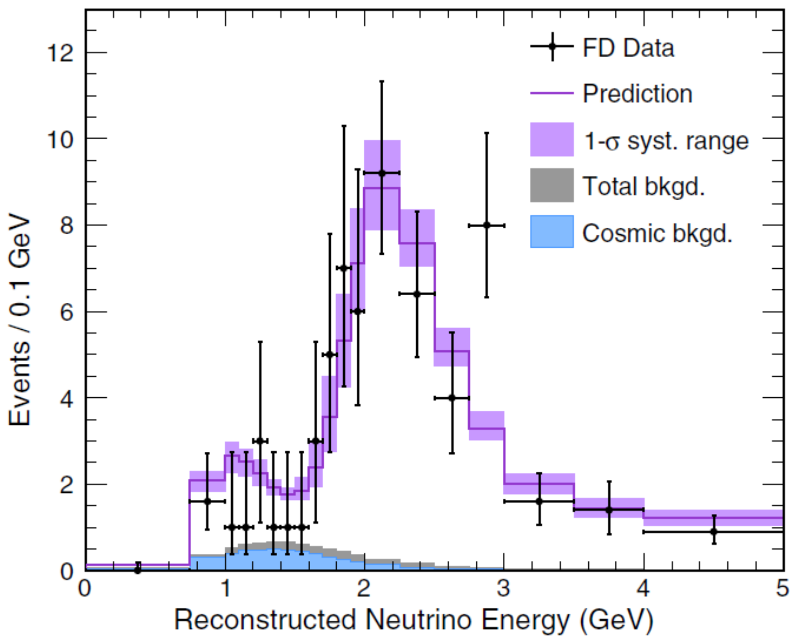
Acero *et al.* (NOvA), PRD 98, 032012 (2018)

"This change was caused by three changes ... The largest effect was due to new simulations and calibrations."

Concrete example: NOvA



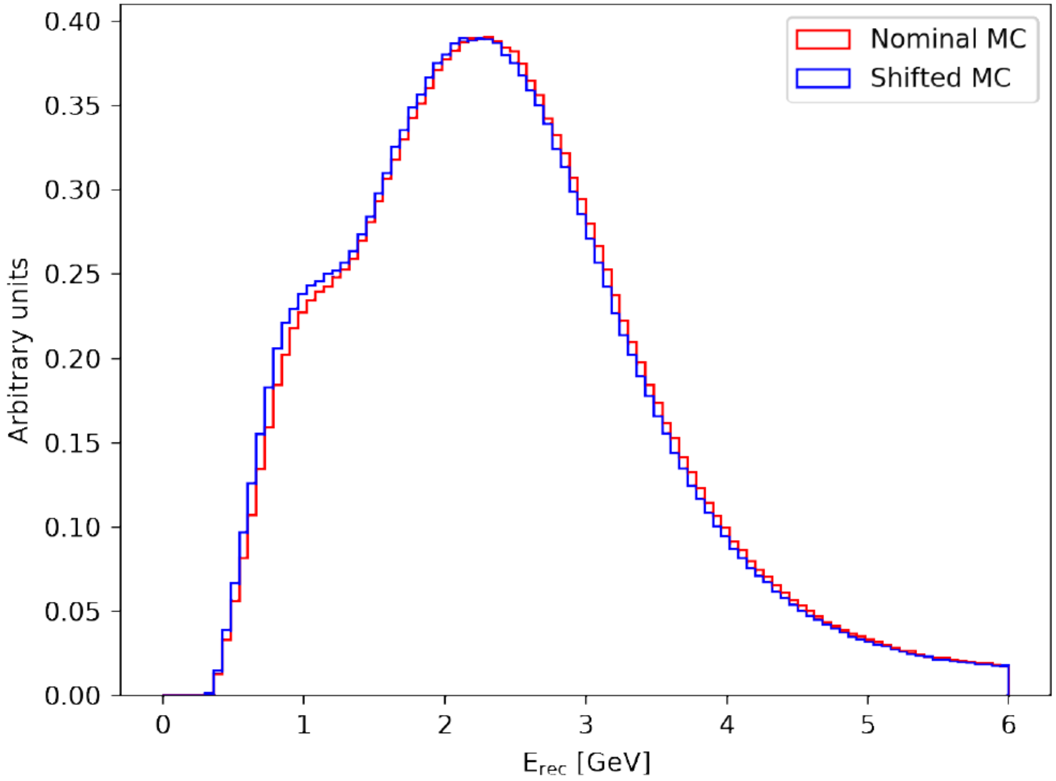
Acero *et al.* (NOvA), PRL 118, 151802 (2017)

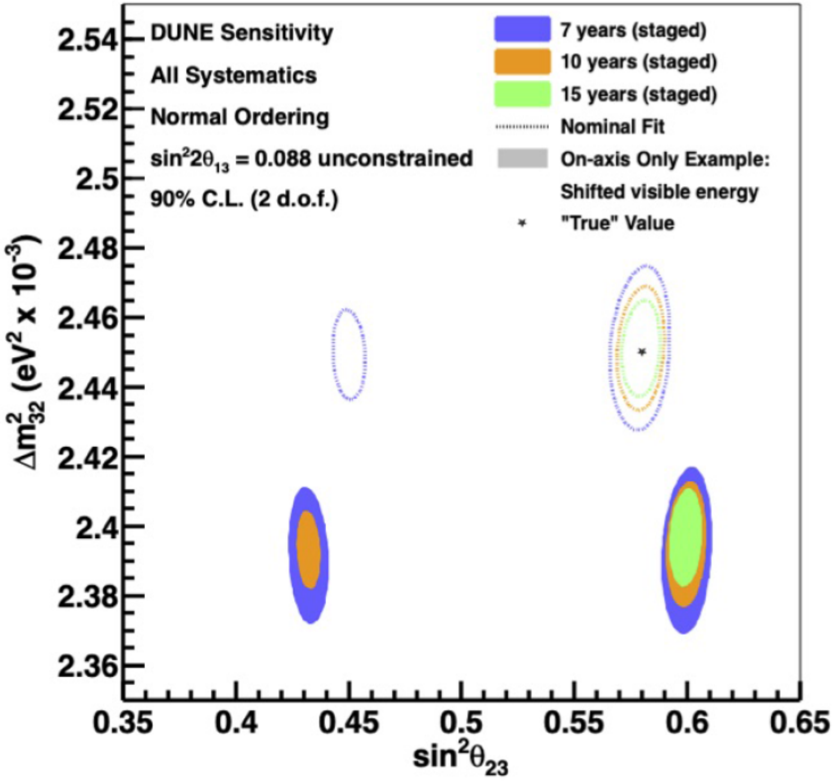


Acero *et al.* (NOvA), PRD 98, 032012 (2018)

"This change was caused by three changes ... The largest effect was due to new simulations and calibrations."

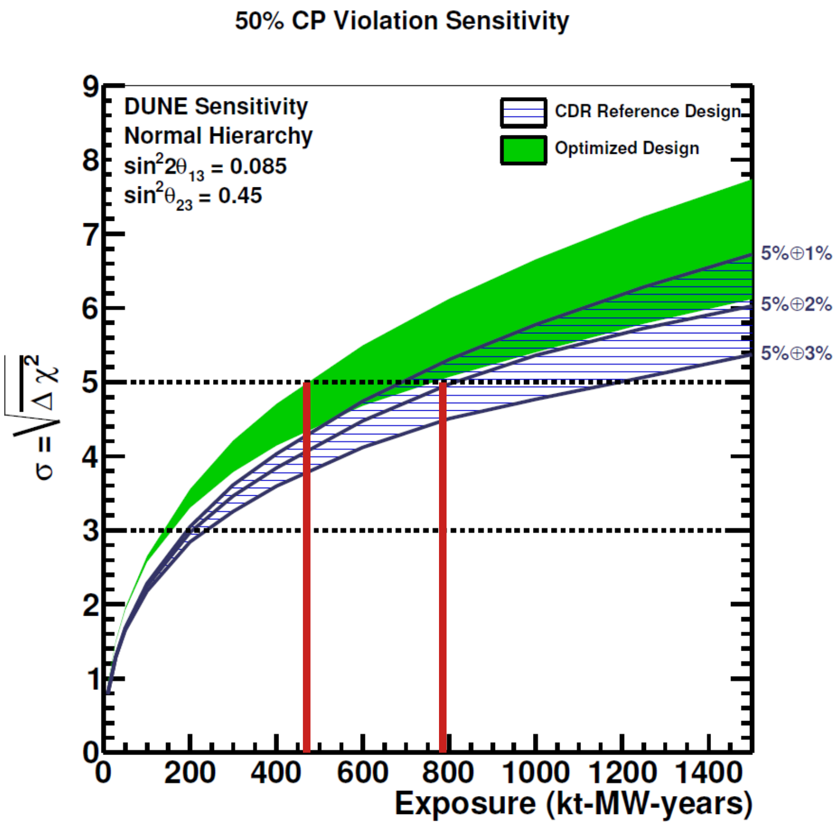
Hypothetical scenario from the DUNE ND CDR



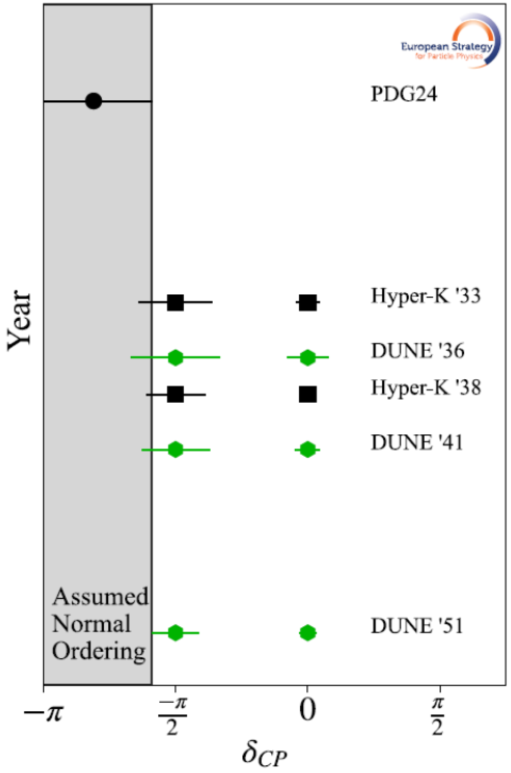


DUNE Collaboration, arXiv:arXiv:2103.13910
see also A.M.A *et al.*, PRD 92, 091301(R) (2015)

Impact of cross-section precision



DUNE Collaboration, arXiv:1512.06148



de Blas et al., arXiv:2511.03883

Are neutrino data sufficient?

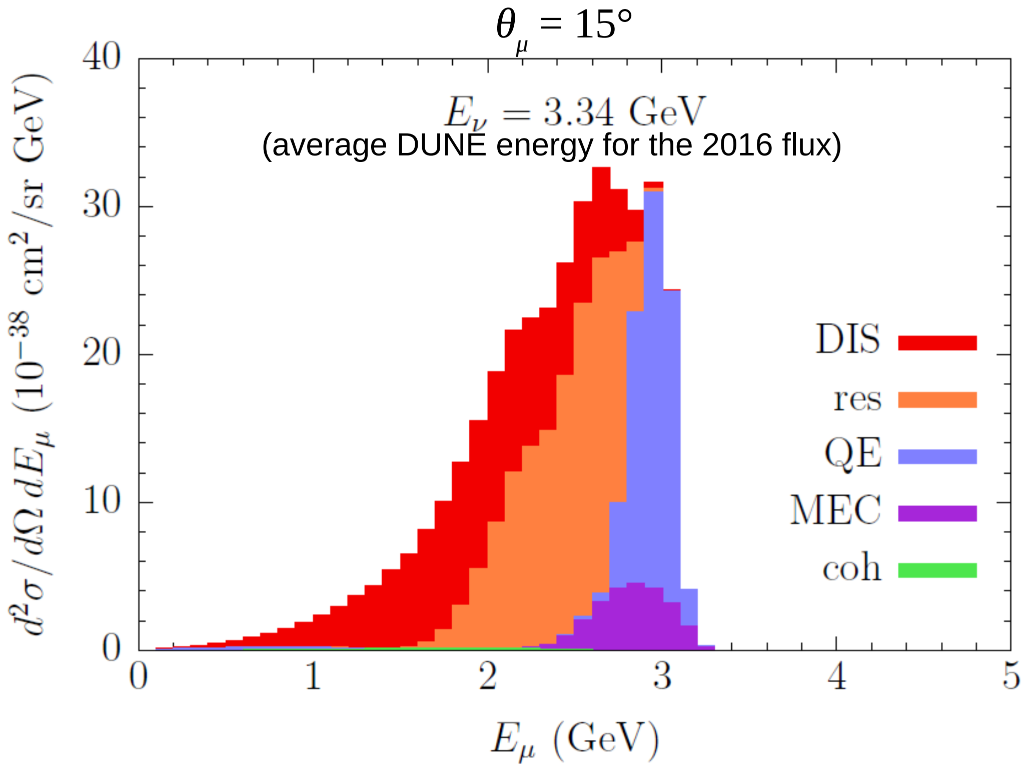
"… fitting to individual MINERvA pion production channels [$1\pi^{\pm}$ and $N\pi^{\pm}$ for ν_μ, and $1\pi^0$ for ν_μ and $\bar{\nu}_\mu$] produces **different best-fit parameters** …"

"Because the four channels cover different kinematic regions and contain different physics, it is **difficult to pinpoint the origin of the discrepancy** …"

"The main conclusion … is that current **neutrino experiments** … **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."

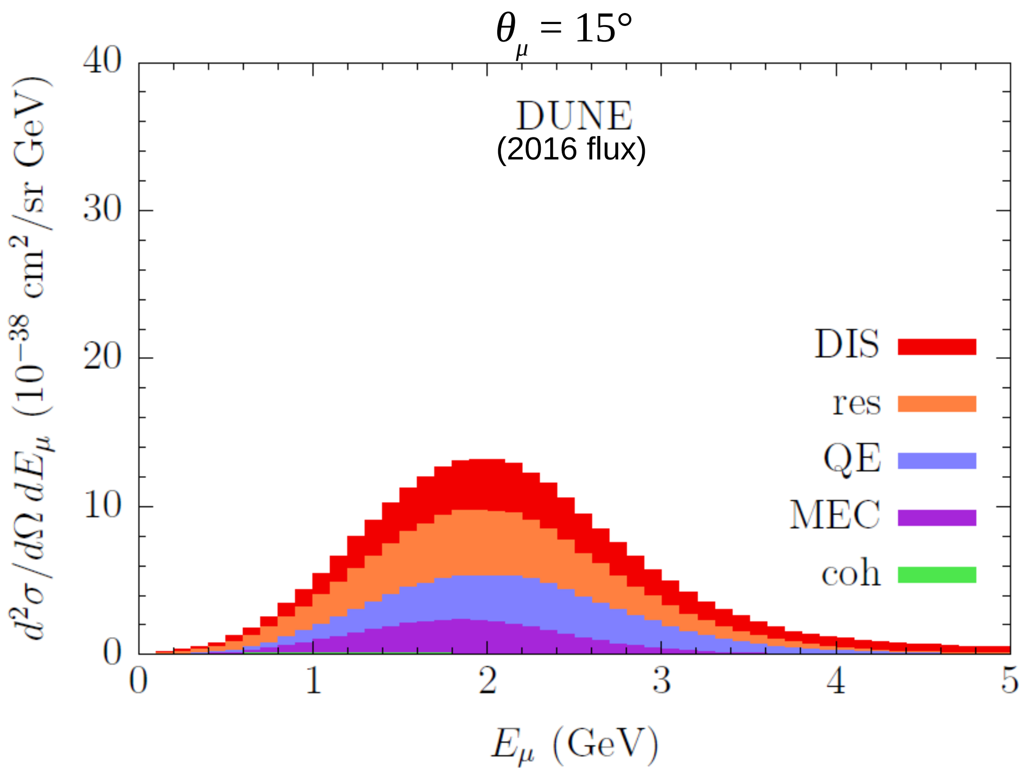
P. Stowell *et al*. (MINERvA), PRD 100, 072005 (2019)

Neutrino double differential cross section



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

Neutrino double differential cross section

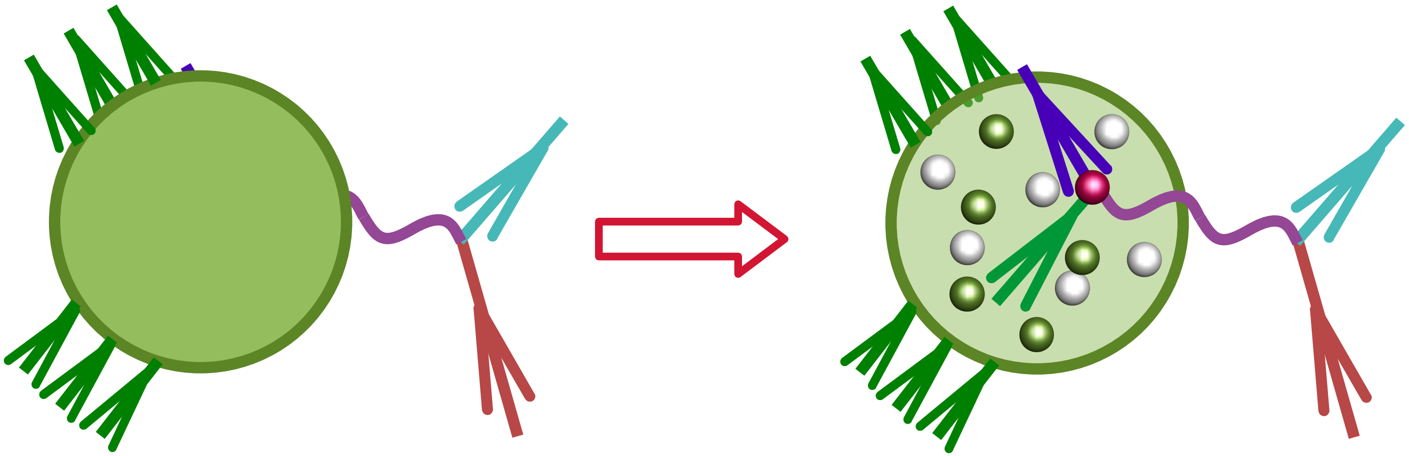


A.M.A. & A. Friedland, PRD 102, 053001 (2020)

Impulse approximation

At relevant kinematics, the dominant process of neutrino-nucleus interaction is **scattering off a single nucleon**, with the remaining nucleons acting as a spectator system.

This description is valid when the momentum transfer $|\mathbf{q}|$ is high enough ($|\mathbf{q}| \gtrsim 200$ MeV).



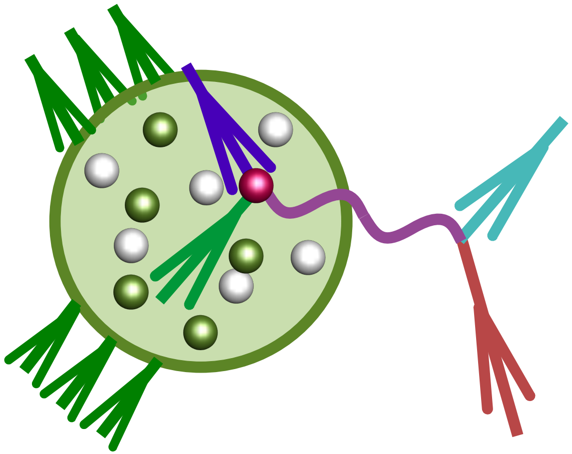
Impulse approximation

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

average over the initial nucleon state

nucleon cross section

final-state interactions



Electrons and neutrinos

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

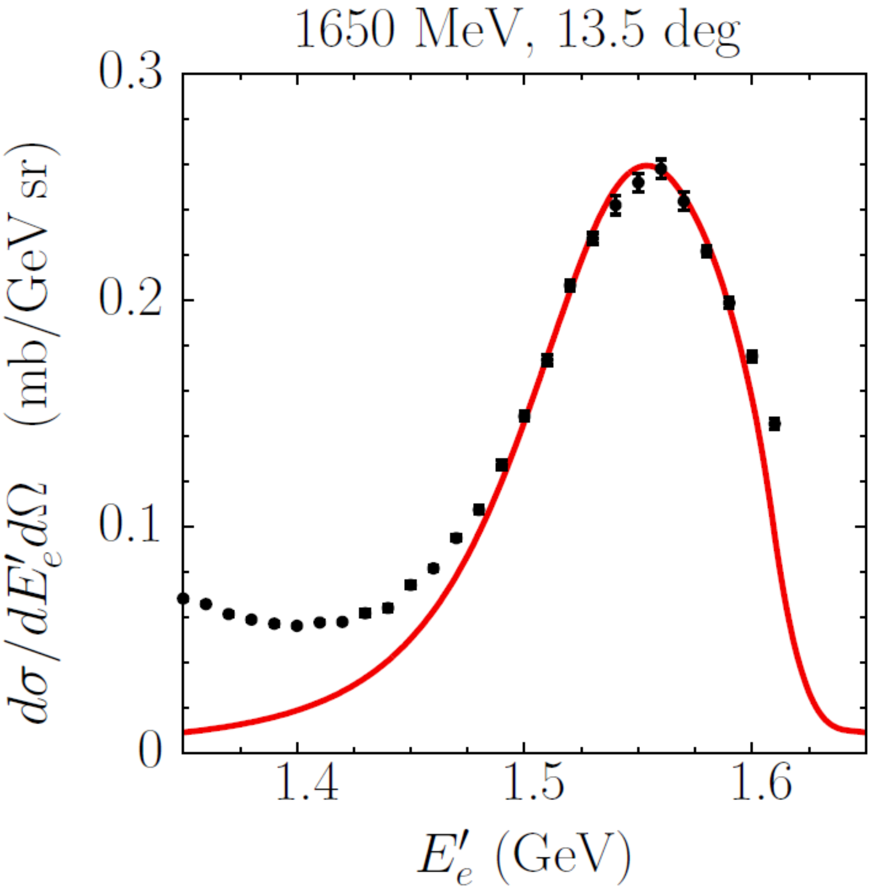
Electron-scattering data can provide information on

- the vector contributions to elementary neutrino cross sections
- proton and neutron spectral functions (Ar & Ti targets)
- hadronization (H & D targets)
- final-state interactions (Ar & Ti + H & D targets)

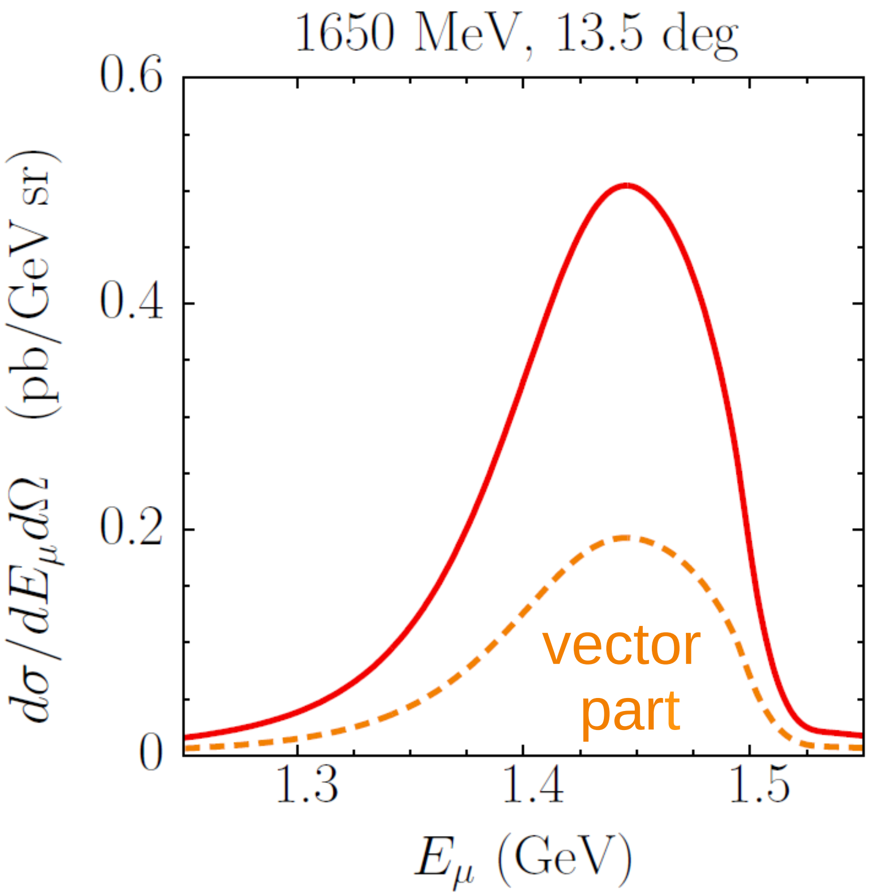
Electron data allow MC validation, reduction of systematic uncertainties, as well as their rigorous determination.

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

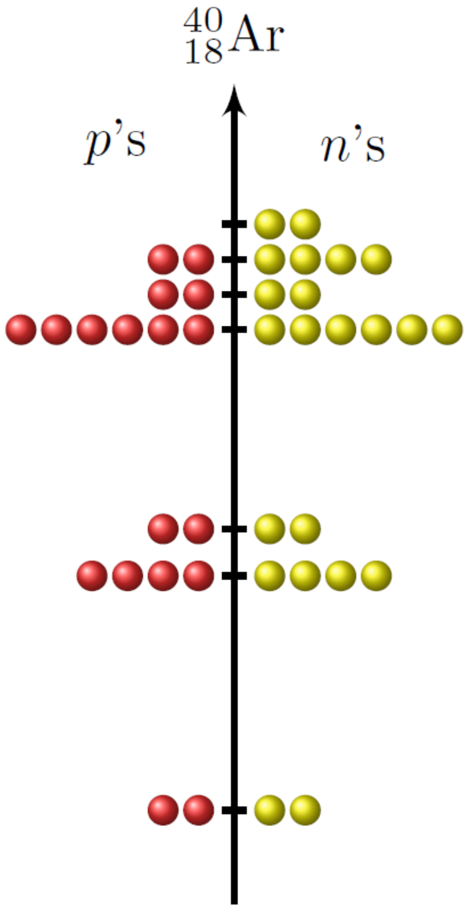
electrons

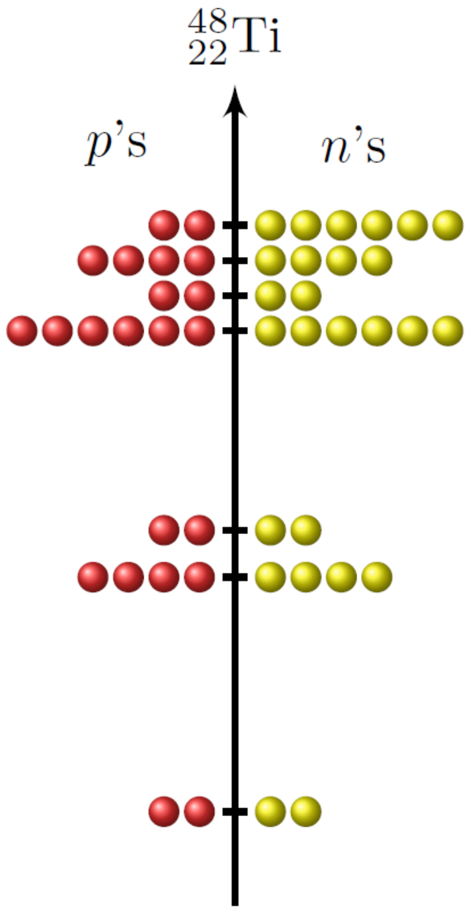


muon neutrinos



Why titanium?





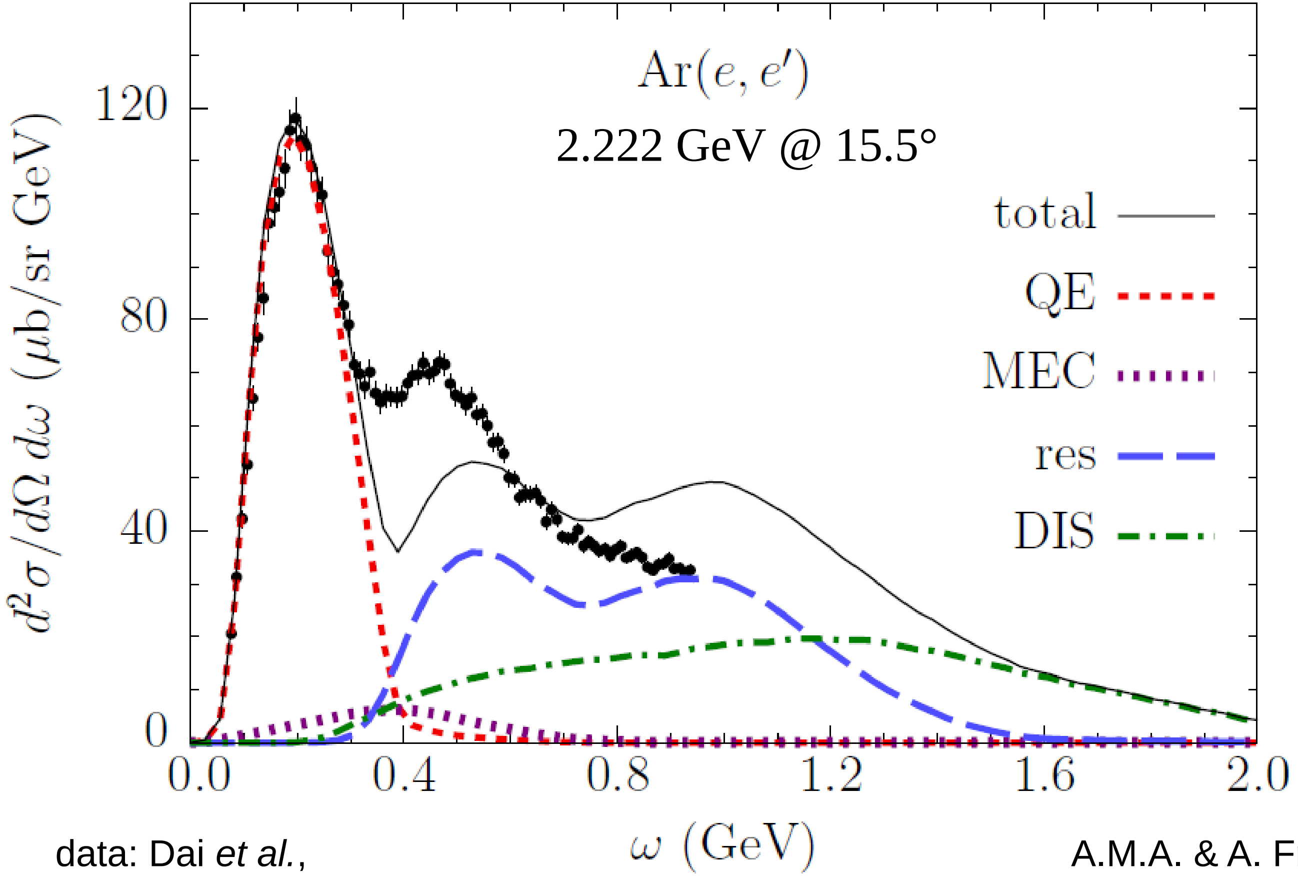
GENIE in a nutshell

The MC generator most broadly used in neutrino physics, including DUNE studies.

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.”

- Nuclear model: Fermi gas (in version 2: Bodek & Ritchie ‘81)
- Quasielastic (Rosenbluth ‘50, Llewellyn-Smith ‘72)
  + MEC (Lightbody & O’Connell ‘88, Dytman ‘13)
- Resonance excitation (Rein & Sehgal ‘81)
- Deep-inelastic scattering (Bodek & Yang ‘05)

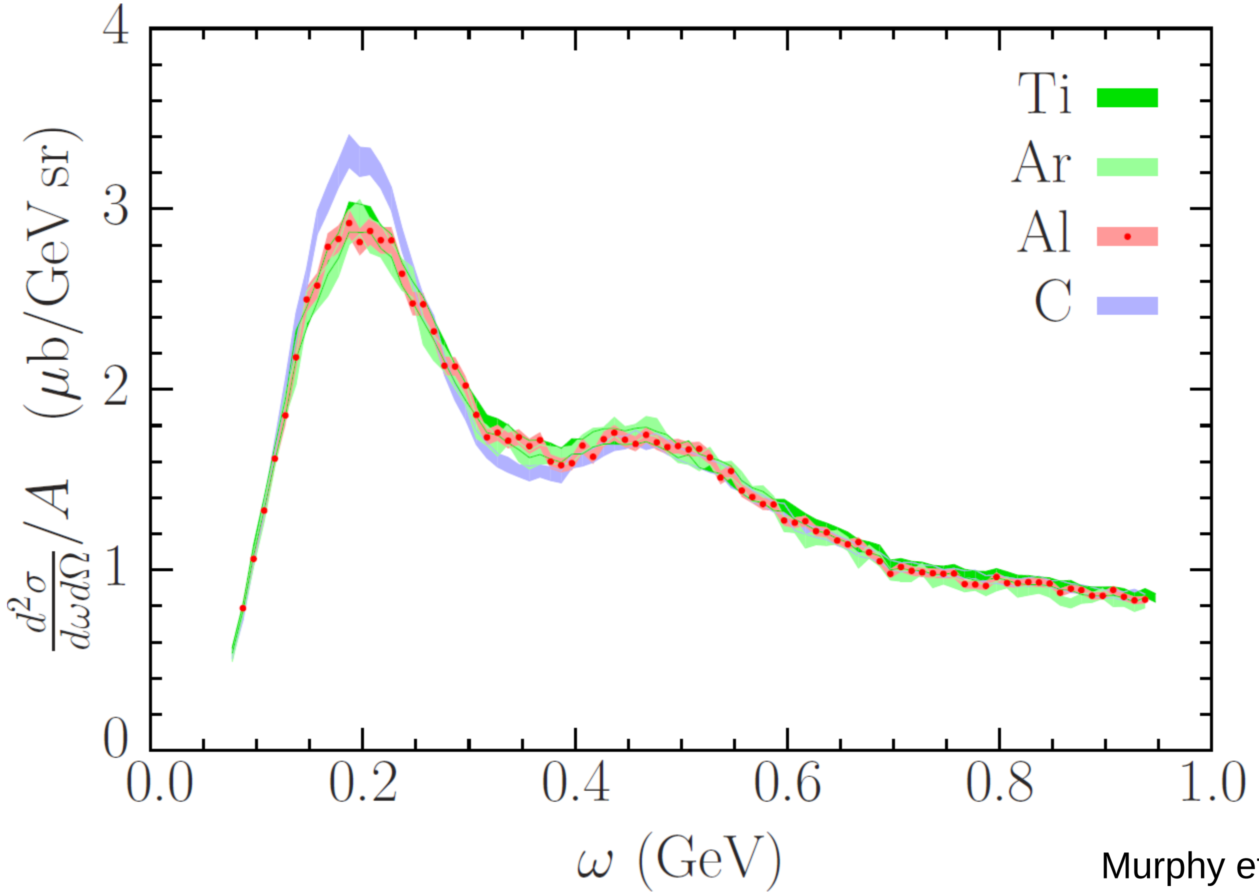
Electron scattering on argon



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

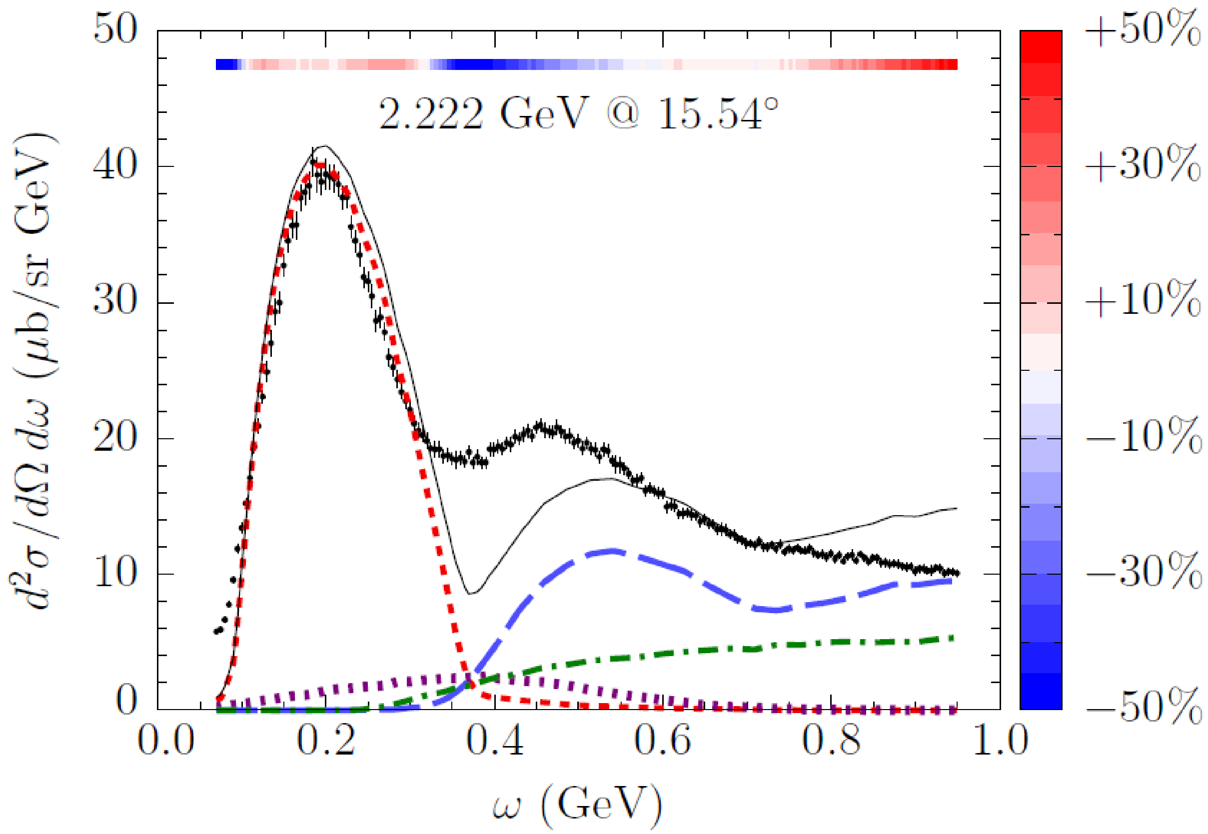
A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

A-dependence of the inclusive data



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

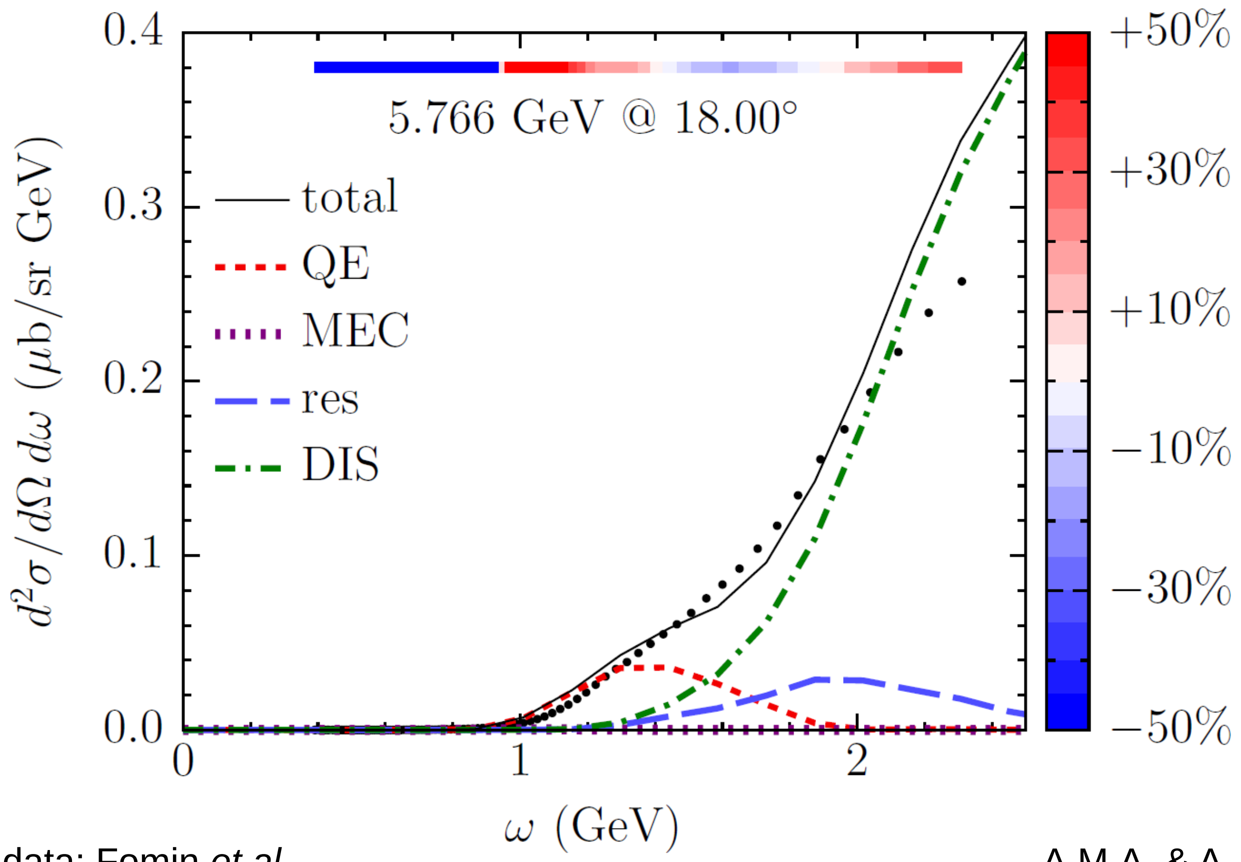
Electron scattering on carbon



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

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

How well do we know inelastic cross sections?



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

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

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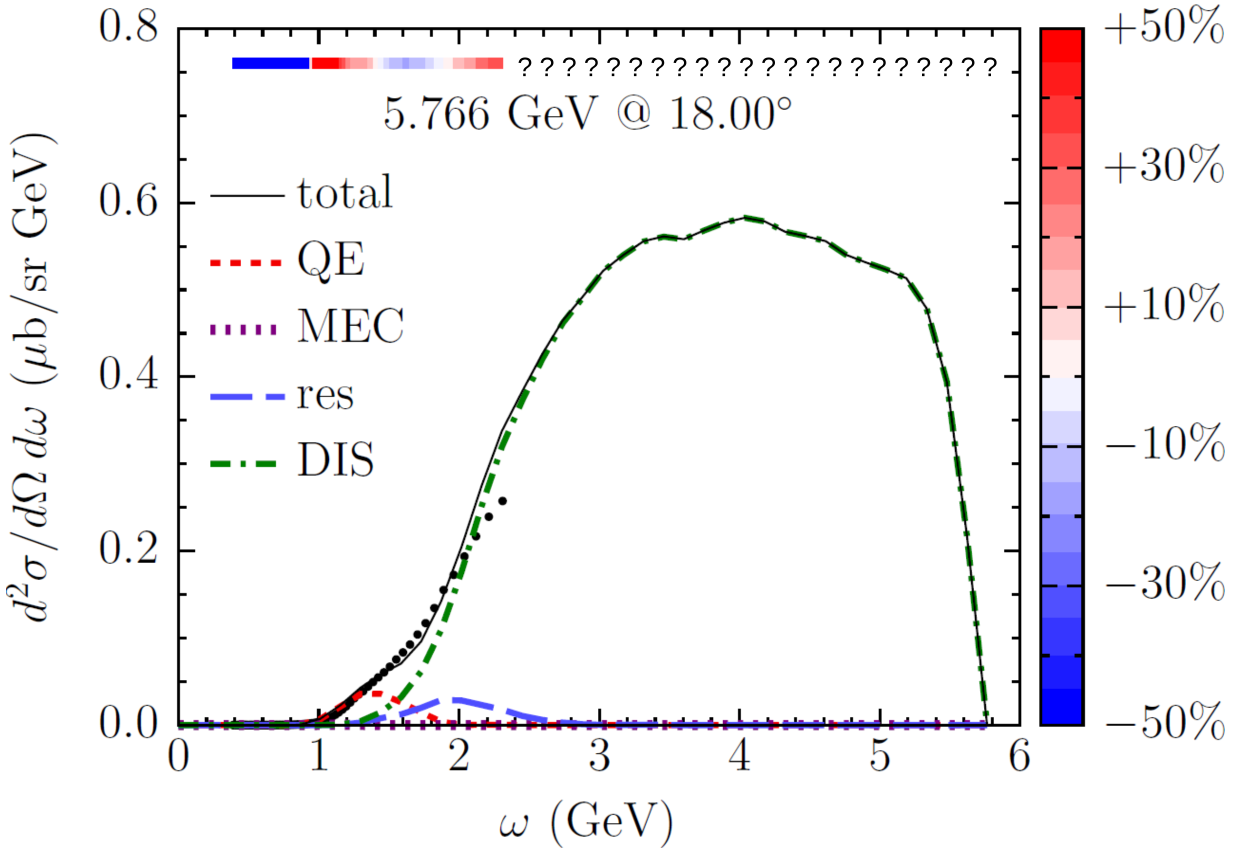
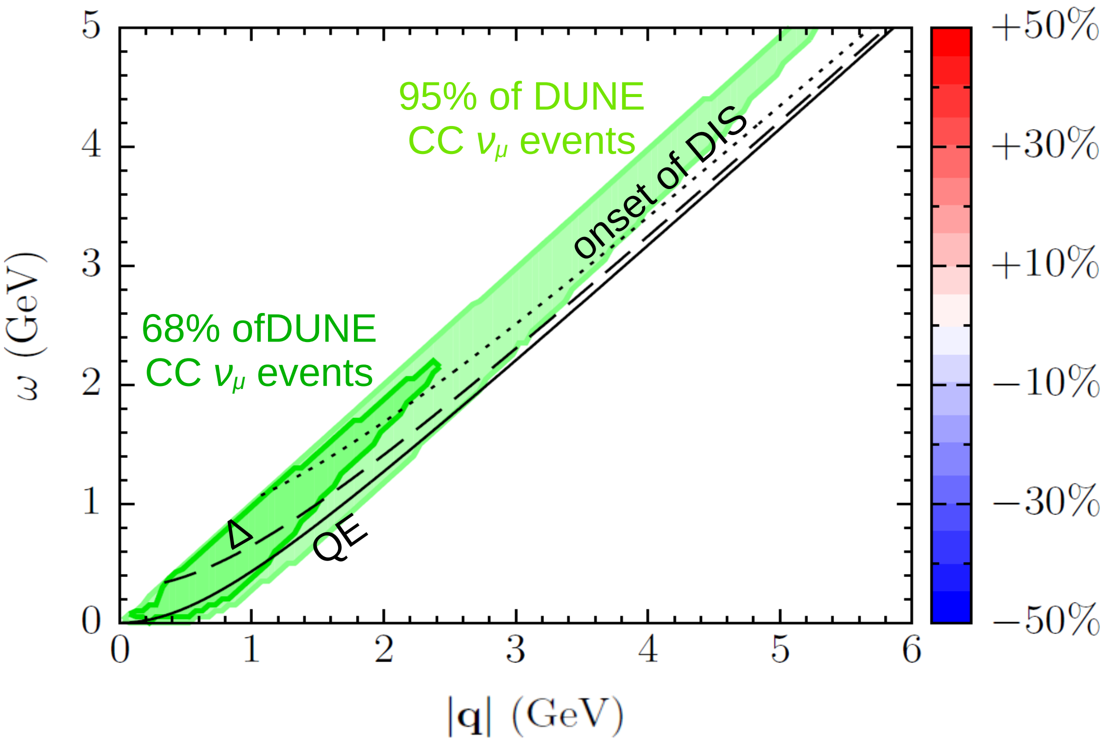


A.M.A. & A. Friedland, PRD 102, 053001 (2020)

Are these issues general and relevant?



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

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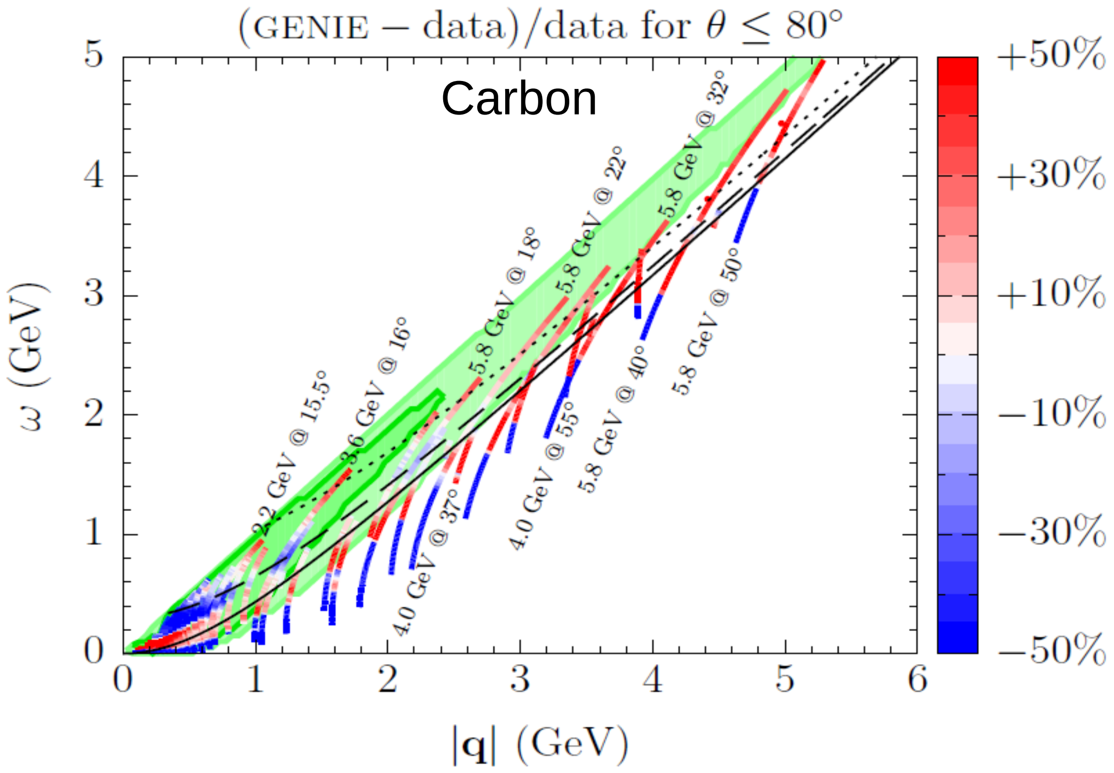
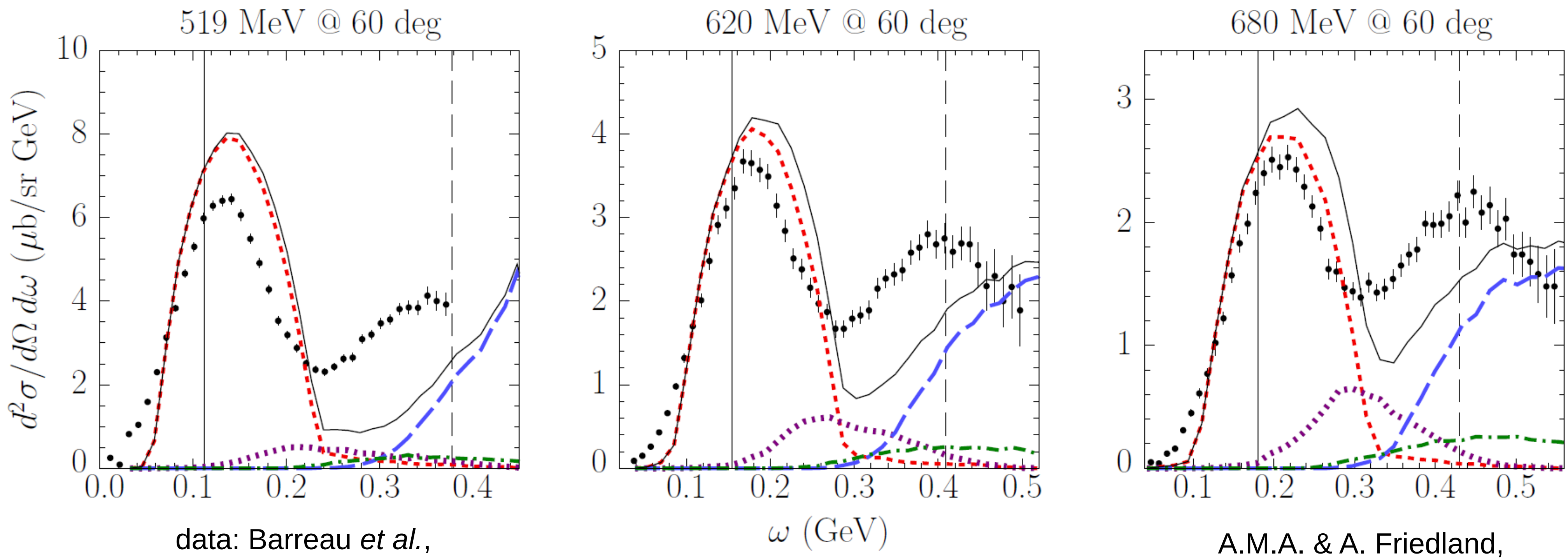


A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

Low energies



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

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

Kinematic energy reconstruction

In quasielastic scattering on free nucleons, $\nu + p \rightarrow l + n$ and $\nu + n \rightarrow l + p$, we can infer the neutrino energy from the charged lepton's kinematics.

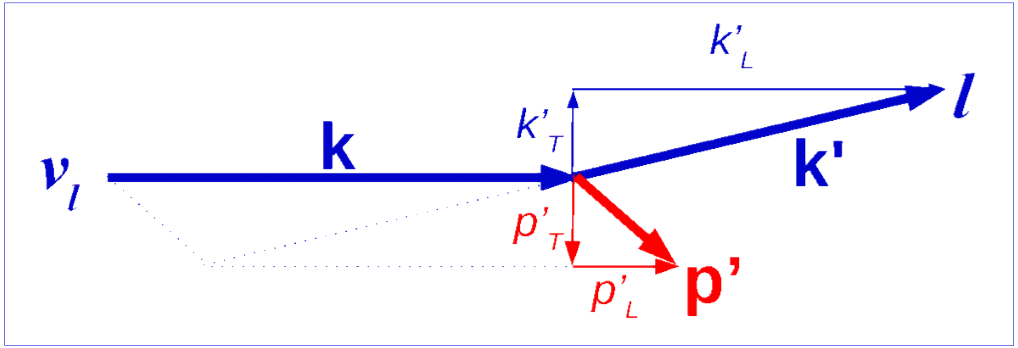
Energy conservation:

$$E_\nu + M = E_l + \sqrt{M^2 + p'^2_L + p'^2_T}$$

Momentum conservation:

$$E_\nu = |k'|\cos\theta + p_L'$$

$$0 = |k'|\sin\theta + p_T'$$



Therefore

$$E_\nu = \frac{2ME_l + m^2}{2\left(M - E_l + |k'|\cos\theta\right)}$$

Kinematic energy reconstruction

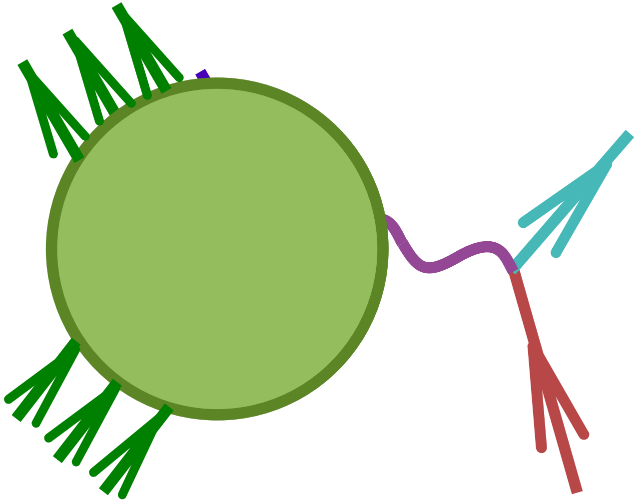
$$E_\nu = \frac{2(M-\epsilon)E_l + m^2 + M^2 - (M-\epsilon)^2}{2[(M-\epsilon) - E_l + |k'|\cos\theta]}$$

- Applicable only to charged-current quasielastic events
- Based on the lepton kinematics only
- No need to reconstruct hadrons
- *What is the separation energy ϵ value?*

Thought experiment: unknown monochromatic beam

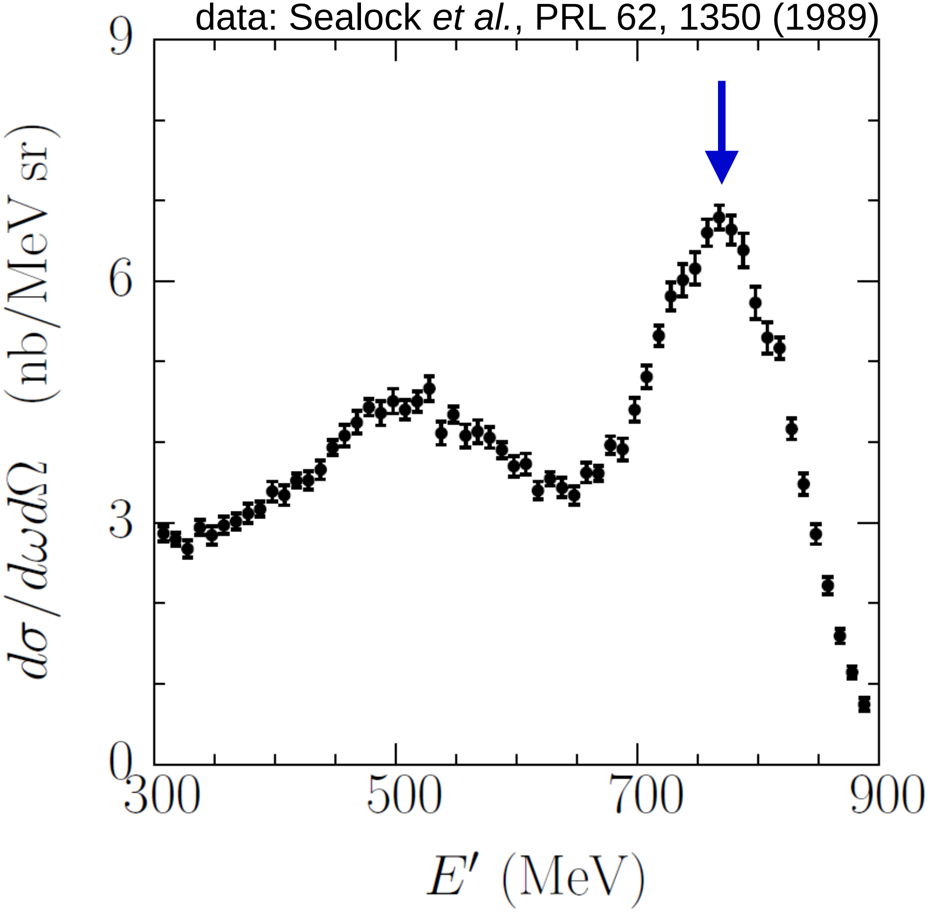
Consider the simplest (unrealistic) case: the beam is monochromatic but its energy is unknown and has to be reconstructed

A.M.A., PoS(NuFact2014)004



“Unknown” monochromatic electron beam

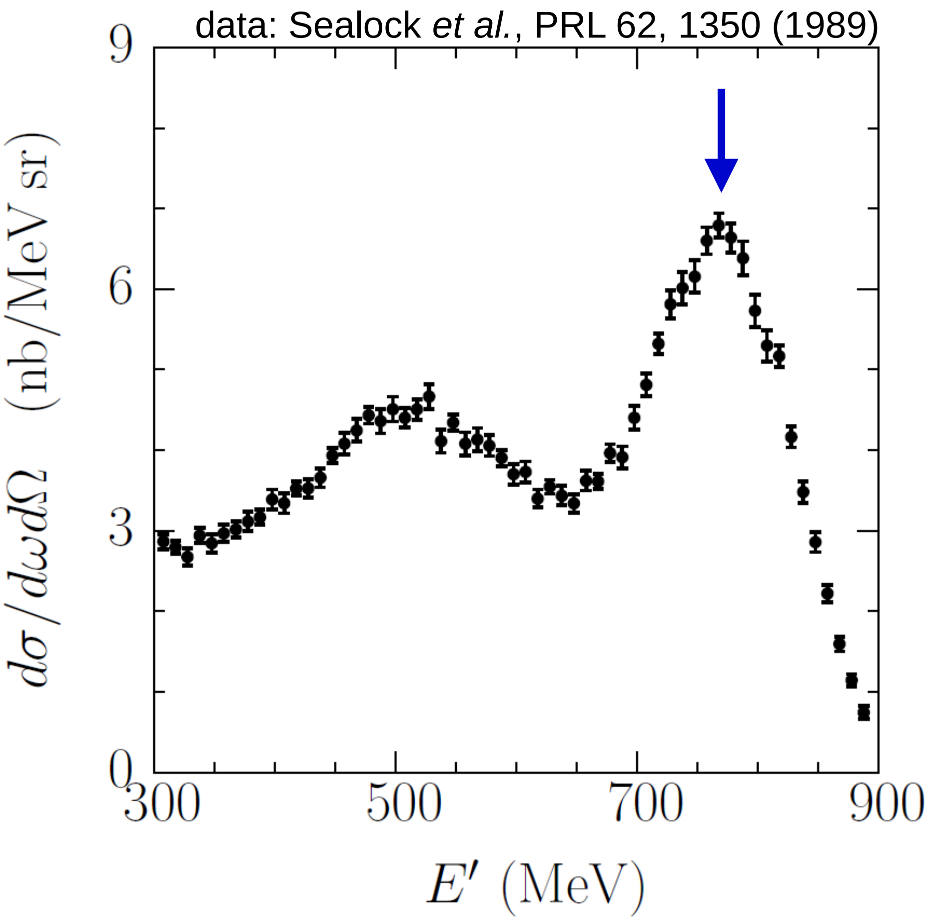
data: Sealock *et al.*, PRL 62, 1350 (1989)



quasielastic peak:
θ = 37.5 deg
E' = 768 MeV
$\Delta E'$ = 5 MeV

A.M.A., PoS(NuFact2014)004

“Unknown” monochromatic electron beam



quasielastic peak:
θ = 37.5 deg
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for ϵ = 25 MeV:
E = 960 MeV
ΔE= 7 MeV

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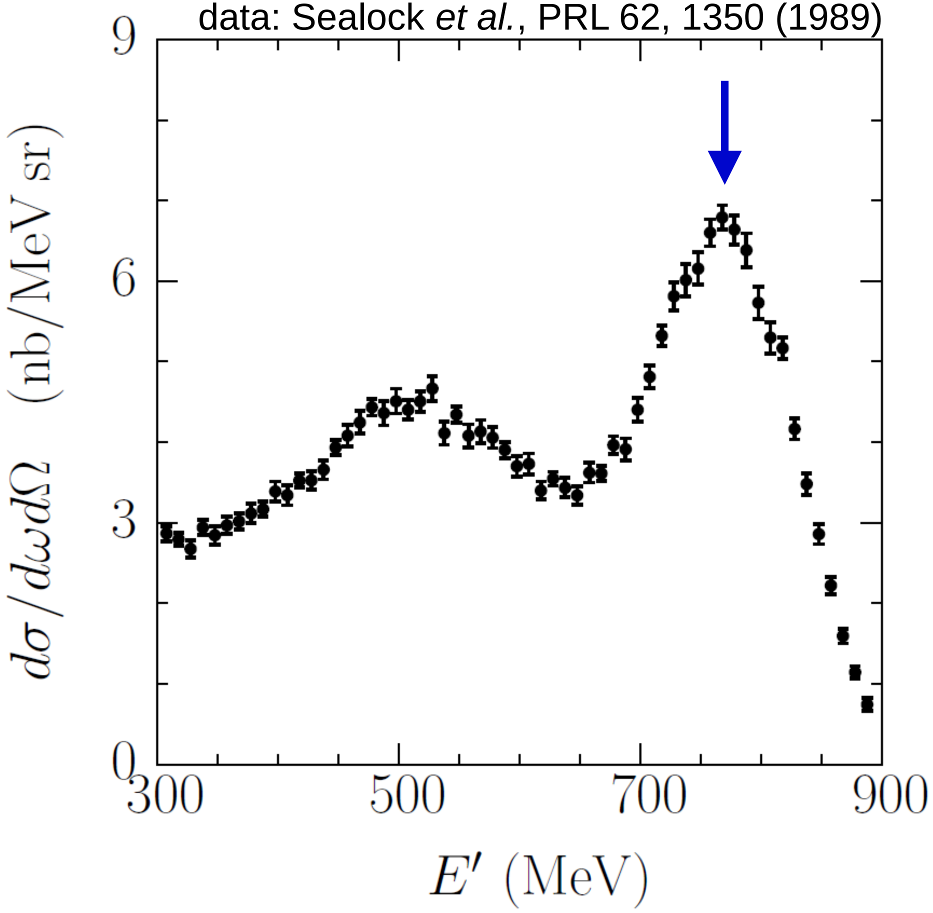

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true value
E = 961 MeV

A.M.A., PoS(NuFact2014)004

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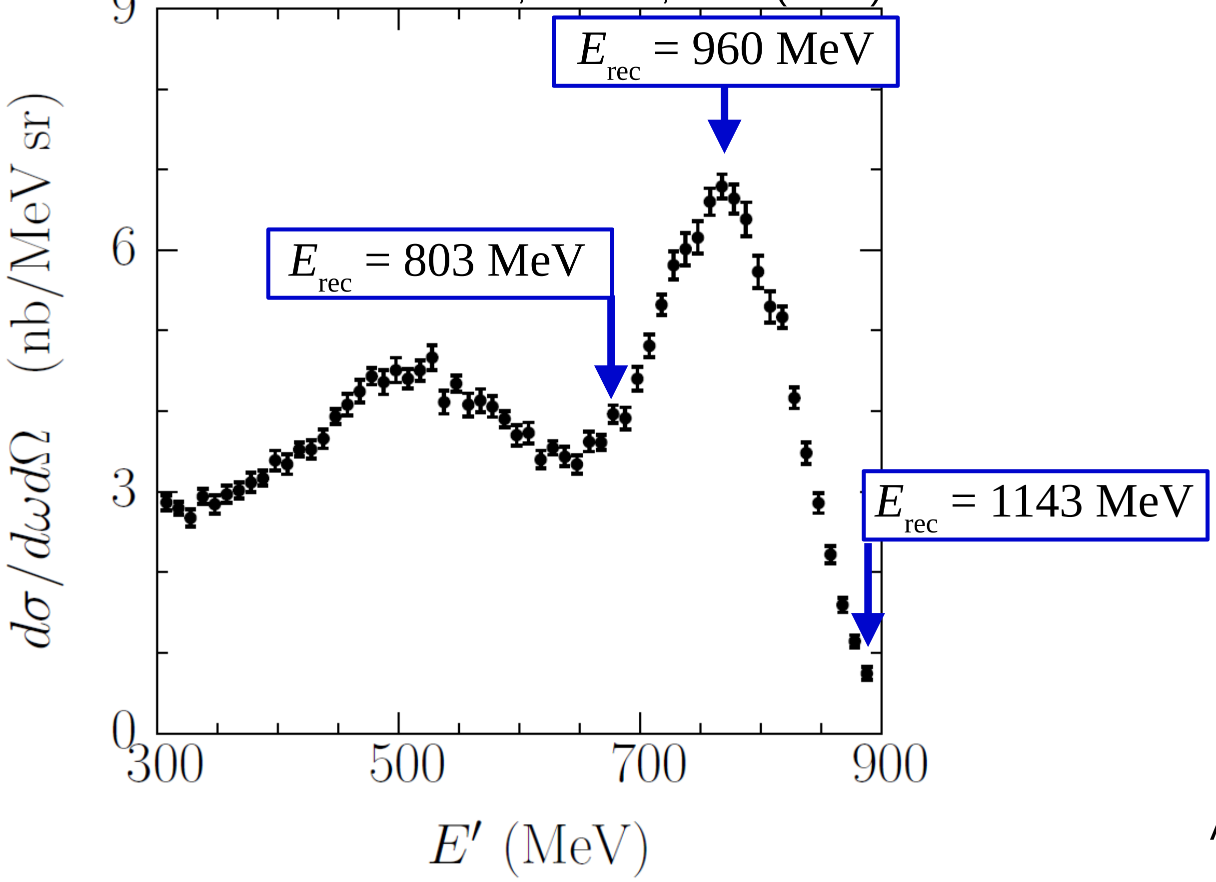

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true value
E = 961 MeV

A.M.A., PoS(NuFact2014)004

"Unknown" monochromatic electron beam

θ (deg)	37.5	37.5	37.1	36.0	36.0
E' (MeV)	976	768	615	487.5	287.5
$\Delta E'$ (MeV)	5	5	5	5	2.5

Assuming ϵ = 25 MeV:

rec. E	1285 ± 8	960 ± 7	741 ± 7	571 ± 6	333 ± 3
true E	1299	961	730	560	320

A.M.A., PoS(NuFact2014)004

"Unknown" monochromatic electron beam

θ (deg)	37.5	37.5	37.1	36.0	36.0
E' (MeV)	976	768	615	487.5	287.5
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What is the appropriate ϵ value?

true E	1299	961	730	560	320
ϵ	33 ± 5	26 ± 5	16 ± 5	16 ± 3	13 ± 3

A.M.A., PoS(NuFact2014)004

“Unknown” monochromatic electron beam

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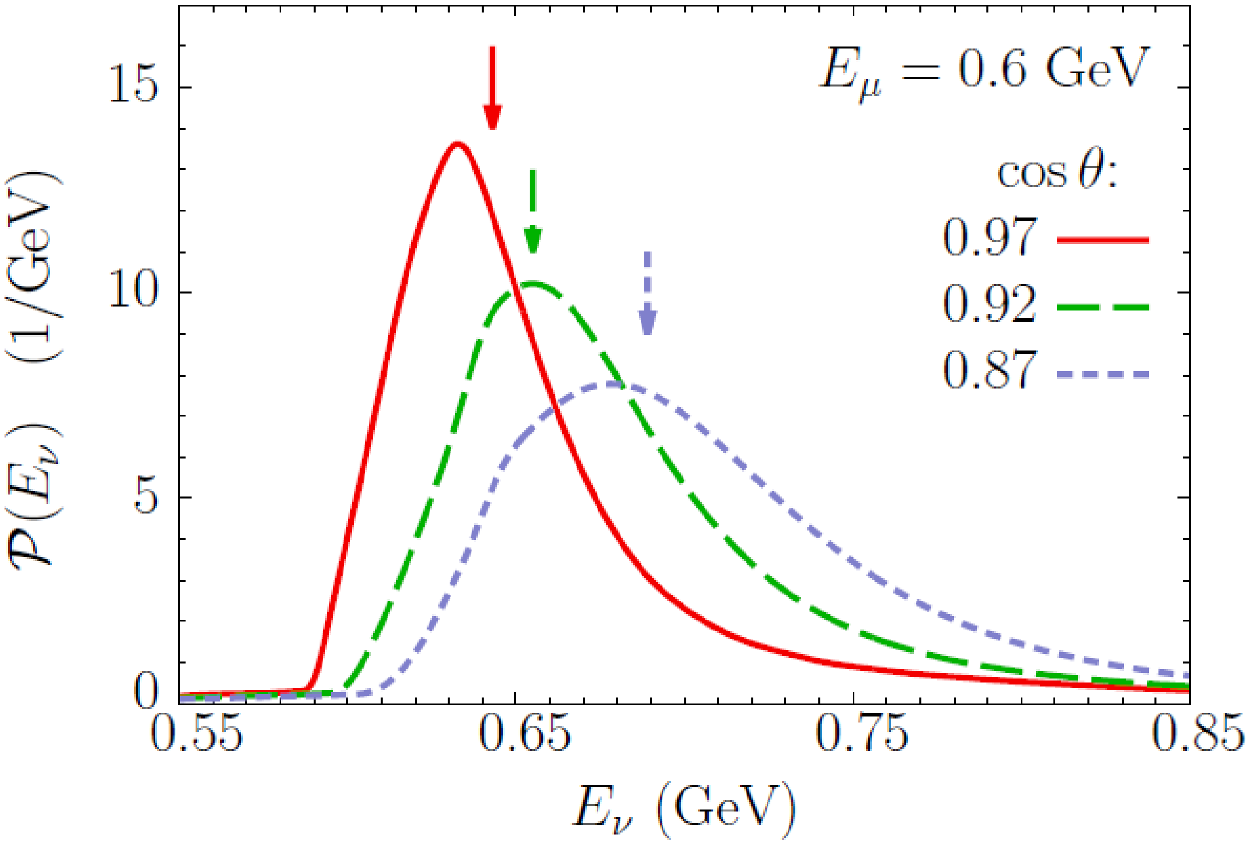
What is the appropriate ϵ value?

true E	1299	961	730	560	320
ϵ	33 ± 5	26 ± 5	16 ± 5	16 ± 3	13 ± 3

different E or different Q^2 or different θ → **different ϵ**

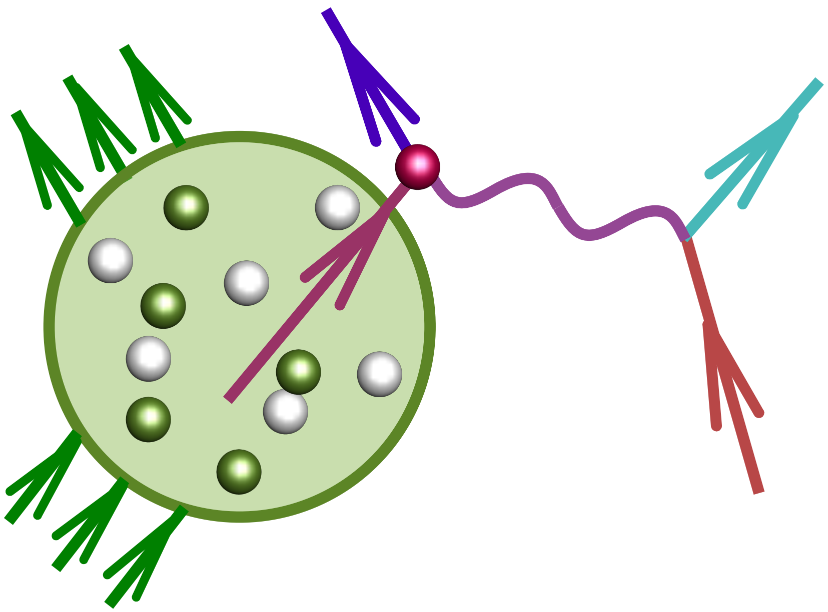
Realistic calculations vs E_{rec}



Cross-section physics drives energy reconstruction

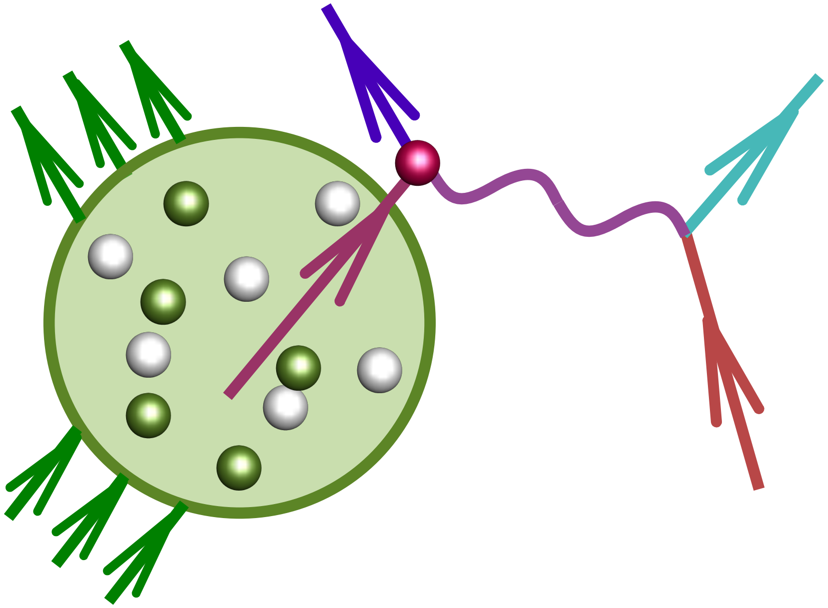
Energy conservation

$$E_\nu + M_A = E_\mu + E_{A-1} + E_{p'}$$

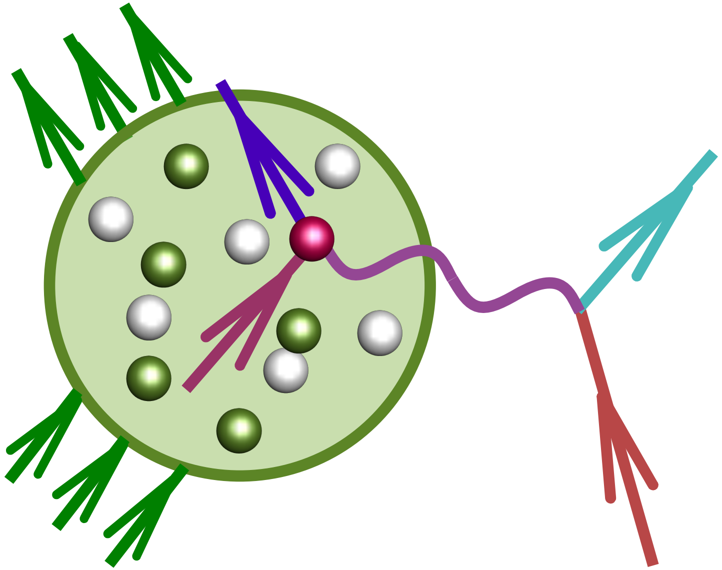


Energy conservation

$$E_\nu + M_A = E_\mu + E_{A-1} + E_{p'}$$



$$E_\nu + M_A = E_\mu + E_{A-1} + E_{p'} + U_V(p')$$



Energy conservation

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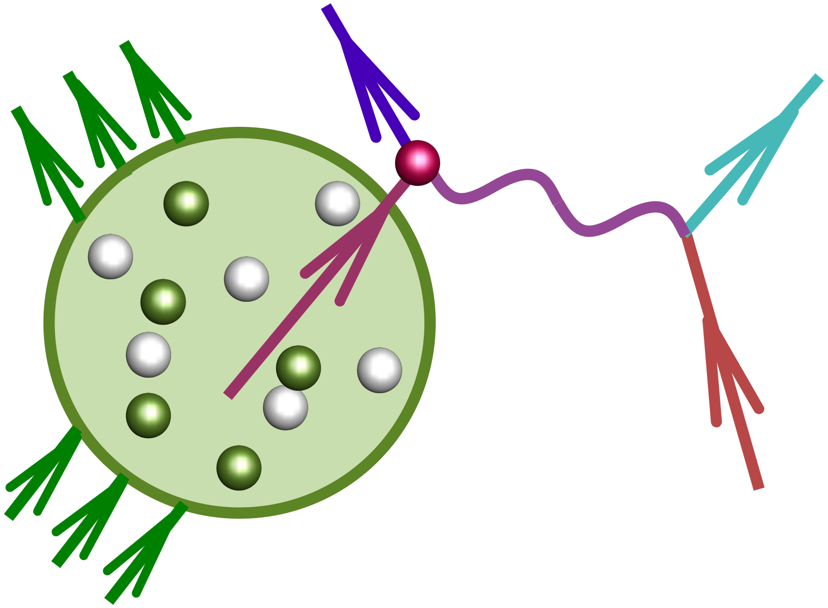
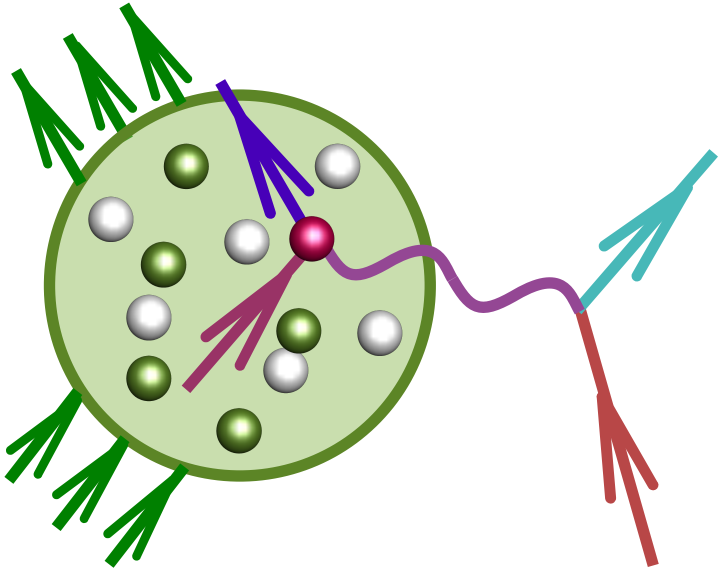


$$E_\nu + M_A \sim E_\mu + E_{A-1} + E_{p'} + U_V(p')$$



Final-state interactions

Soft interactions with the spectator system change the energy spectrum of the struck nucleon. When collisions happen, additional nucleons appear in the final states.

Those effects can be described using an optical potential

- the real part modifies the struck nucleon's energy spectrum, it is $\neq \sqrt{M^2 + p'^2}$
- the imaginary part introduces absorption of the struck nucleons and produces multiple hadrons in the final state (intranuclear cascade)

$$e^{iE_{p'}t} \rightarrow e^{i(E_{p'}+U)t} = e^{i(E_{p'}+U_V+iU_W)t} = e^{i(E_{p'}+U_V)t}\, e^{-U_W t}$$

Horikawa *et al.*, PRC 22, 1680 (1980)

Final-state interactions

The convolution approach,

$$\frac{d\sigma^{\mathrm{FSI}}}{d\omega d\Omega} = \int d\omega' f_{\mathbf{q}}(\omega - \omega' - U_V) \frac{d\sigma^{\mathrm{IA}}}{d\omega d\Omega}$$

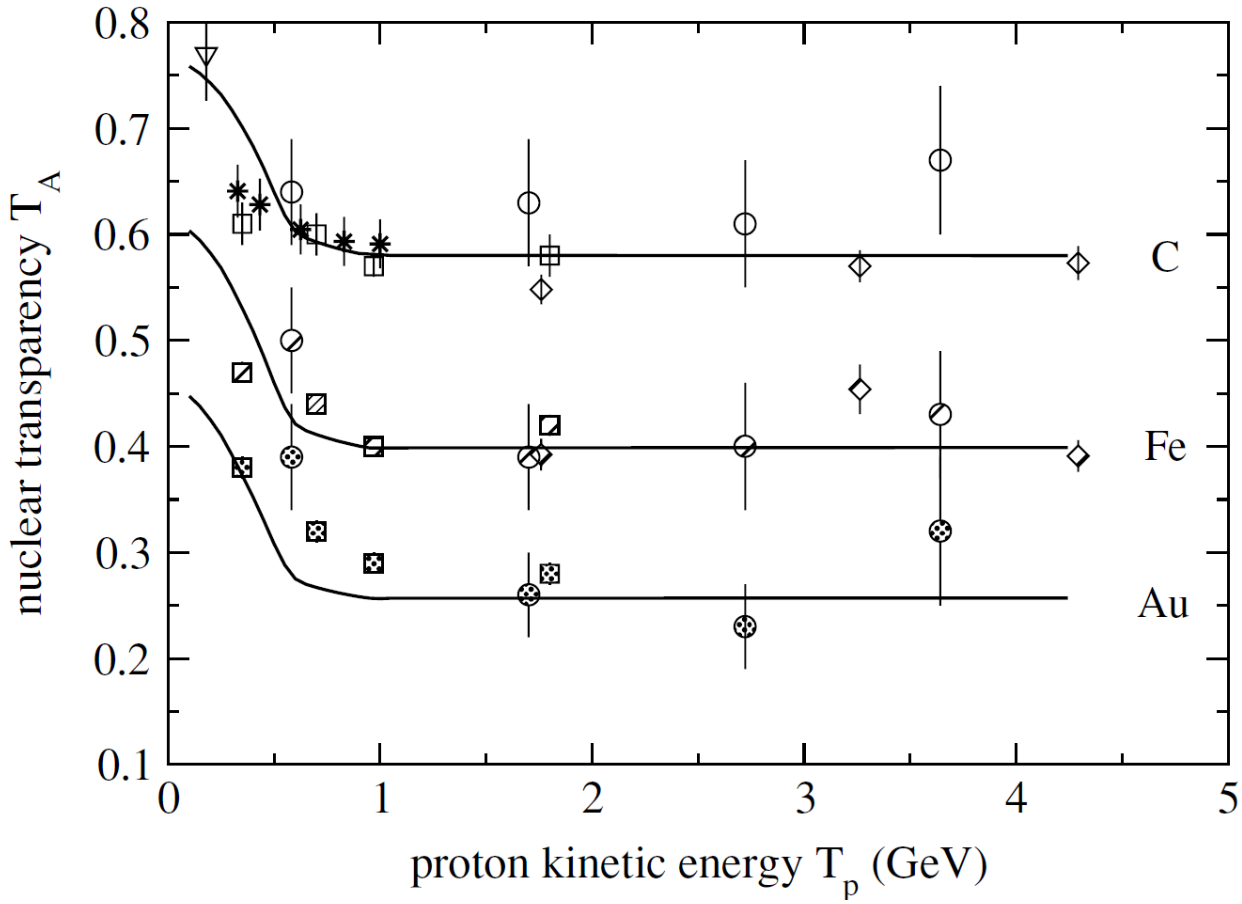
with the folding function

$$f_{\mathbf{q}}(\omega) = \delta(\omega)\sqrt{T_A} + (1 - \sqrt{T_A})F_{\mathbf{q}}(\omega)$$

and nuclear transparency T_A.

O. Benhar, PRC 87, 024606 (2013)

Nuclear transparency

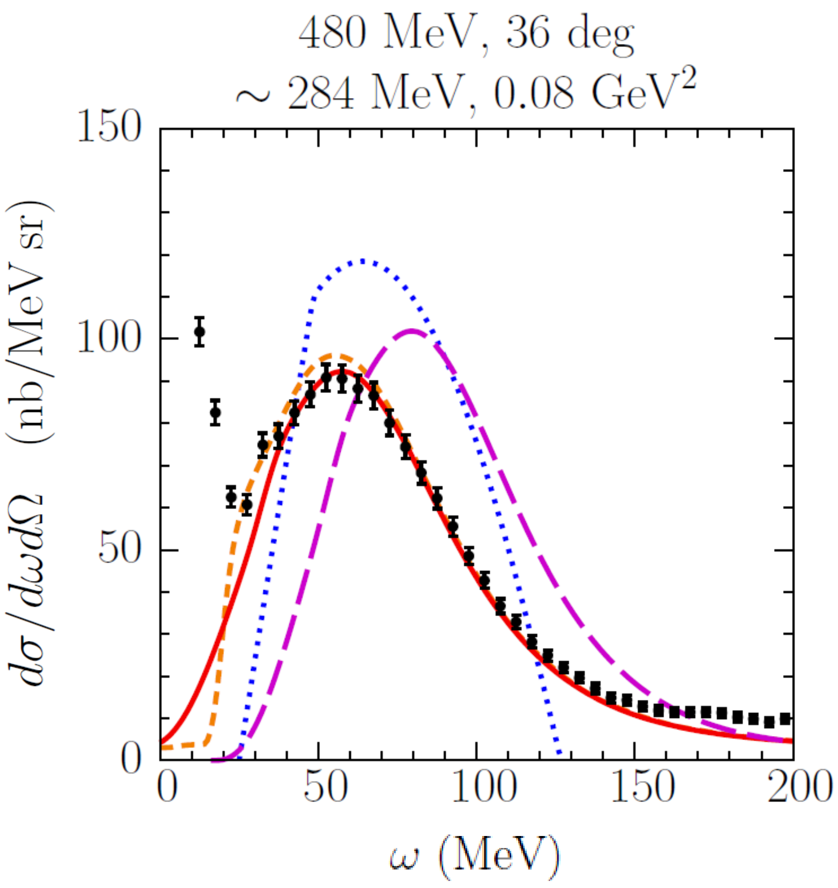


Rohe *et al.*, PRC 72, 054602 (2005)

Realistic description of the nucleus: C(*e*,*e*')

SF w/ FSI,
LDA treatment
of Pauli blocking

SF w/ FSI,
step function

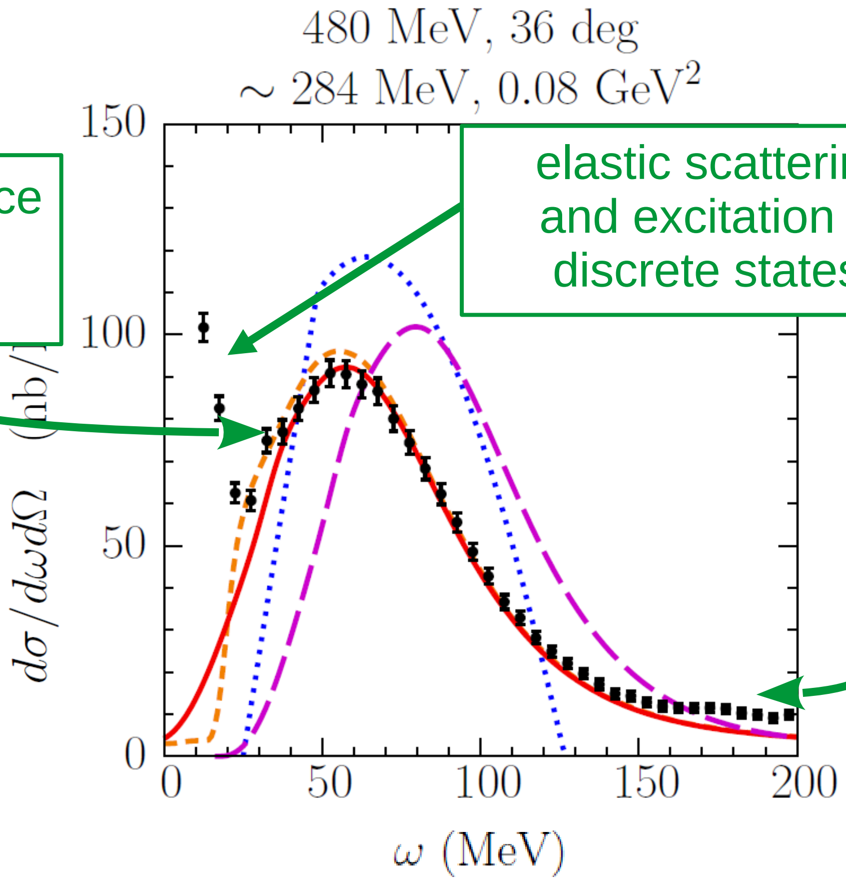


RFG

SF w/o FSI

A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

What is not included?



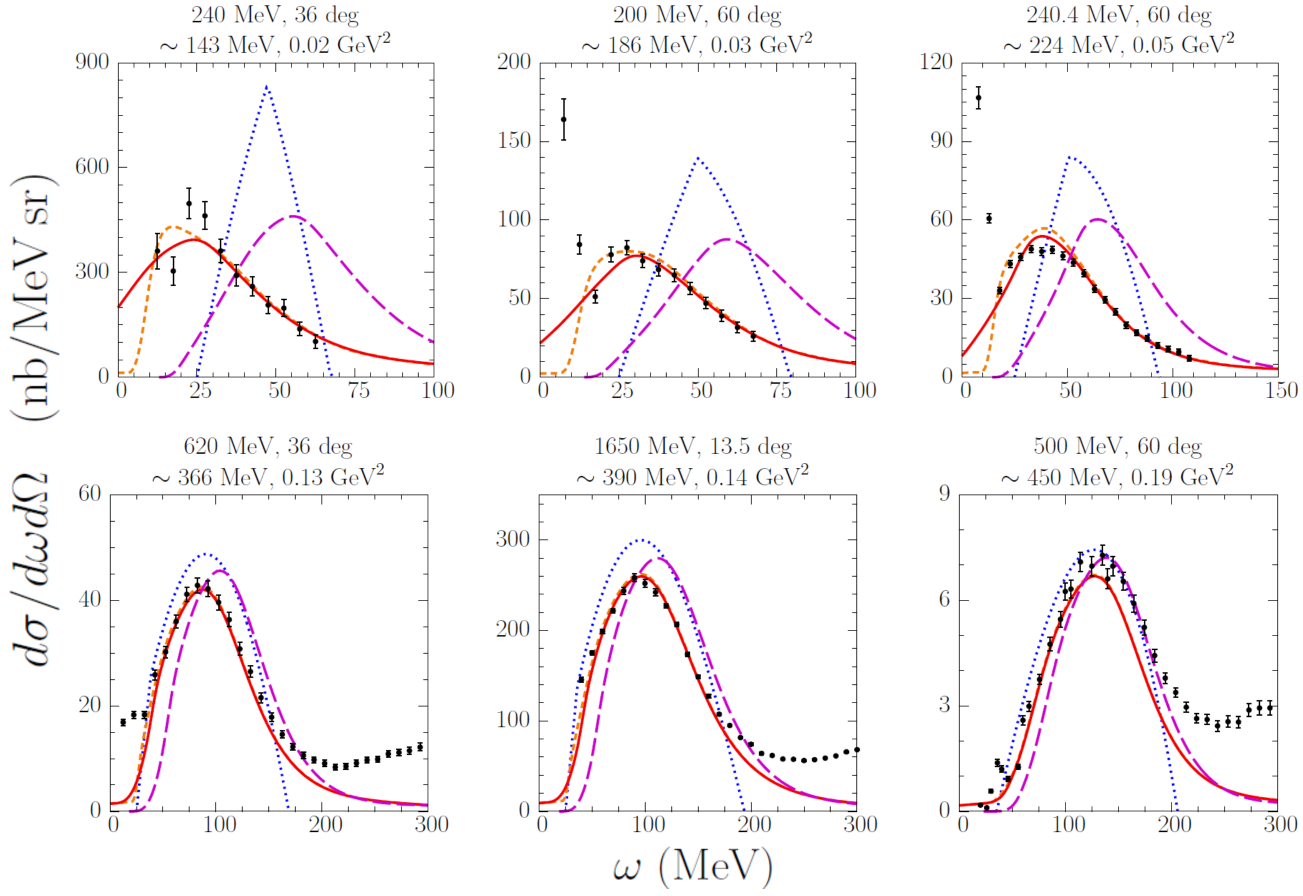
dipole resonance
$E_x = 22.6$ MeV
$\Gamma = 3.2$ MeV

elastic scattering and excitation of discrete states

pion production and 2-body currents

A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

Realistic description of the nucleus: C(*e*,*e*')



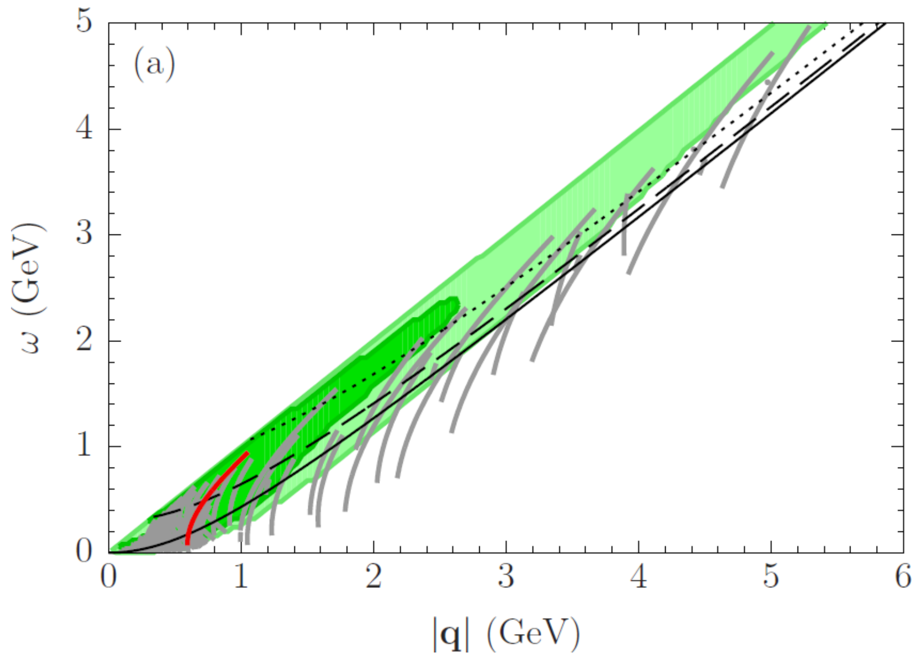
A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

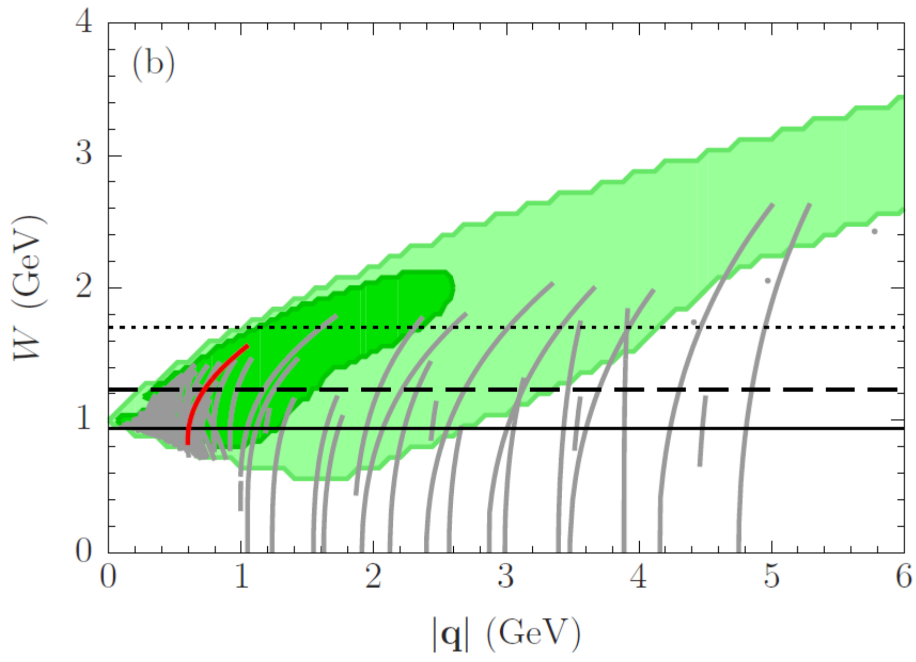
Physics probed by inclusive data

- Nuclear ground-state properties: govern the shape, normalization, and kinematic dependence of cross sections
- Shifts induced by final state interactions and Coulomb effects
- Nuclear transparency (indirectly)
- Underlying approximations: solving the nuclear many-body problem in the relativistic regime *always* involves simplifying assumptions
- Consistent treatment of transition regions

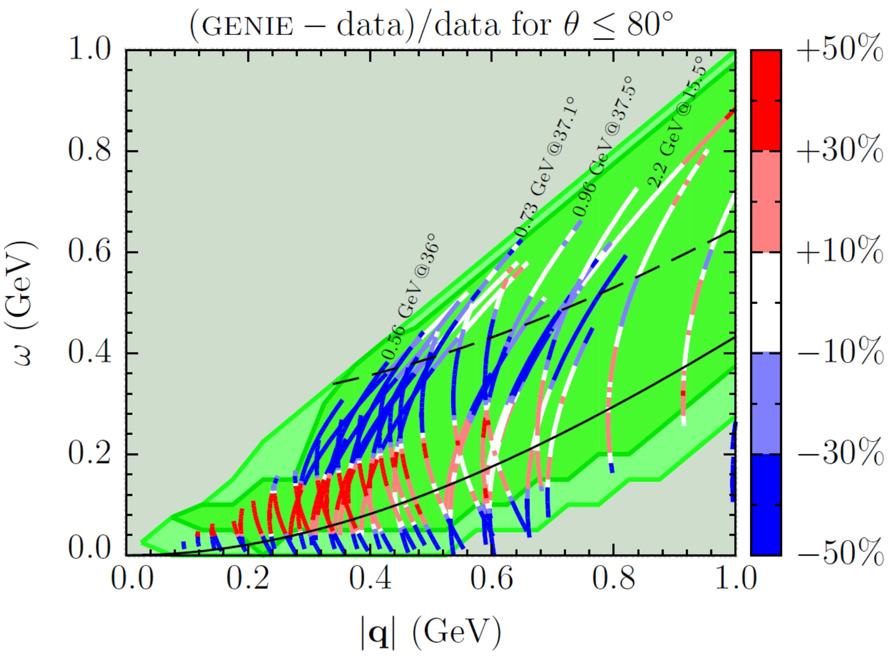
Accurate inclusive cross sections are a prerequisite for exclusive ones

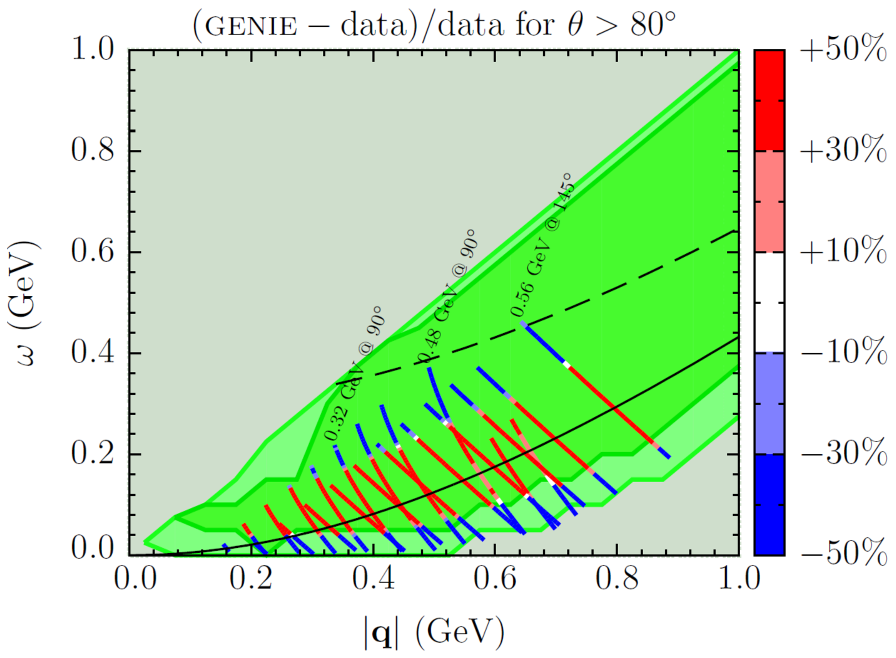
Inclusive data coverage: C vs Ar/Ti





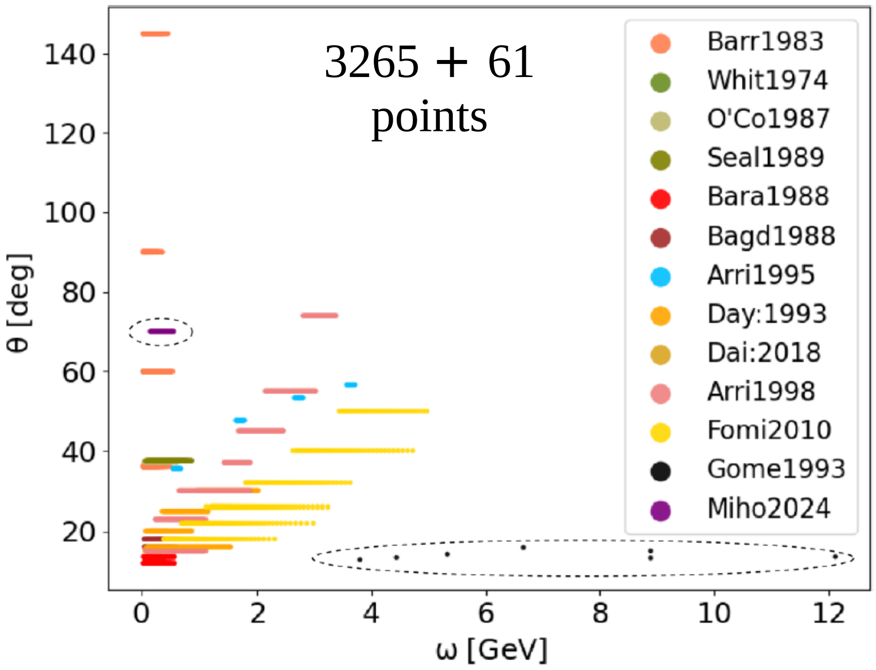
Is 2D coverage sufficient?

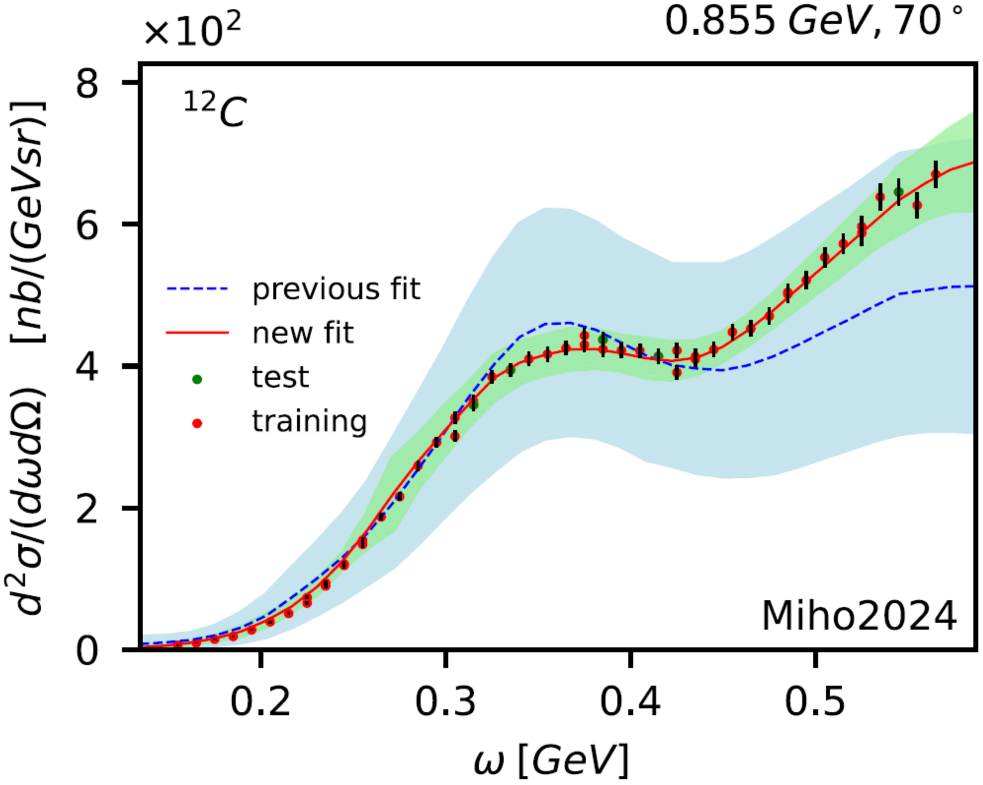




A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

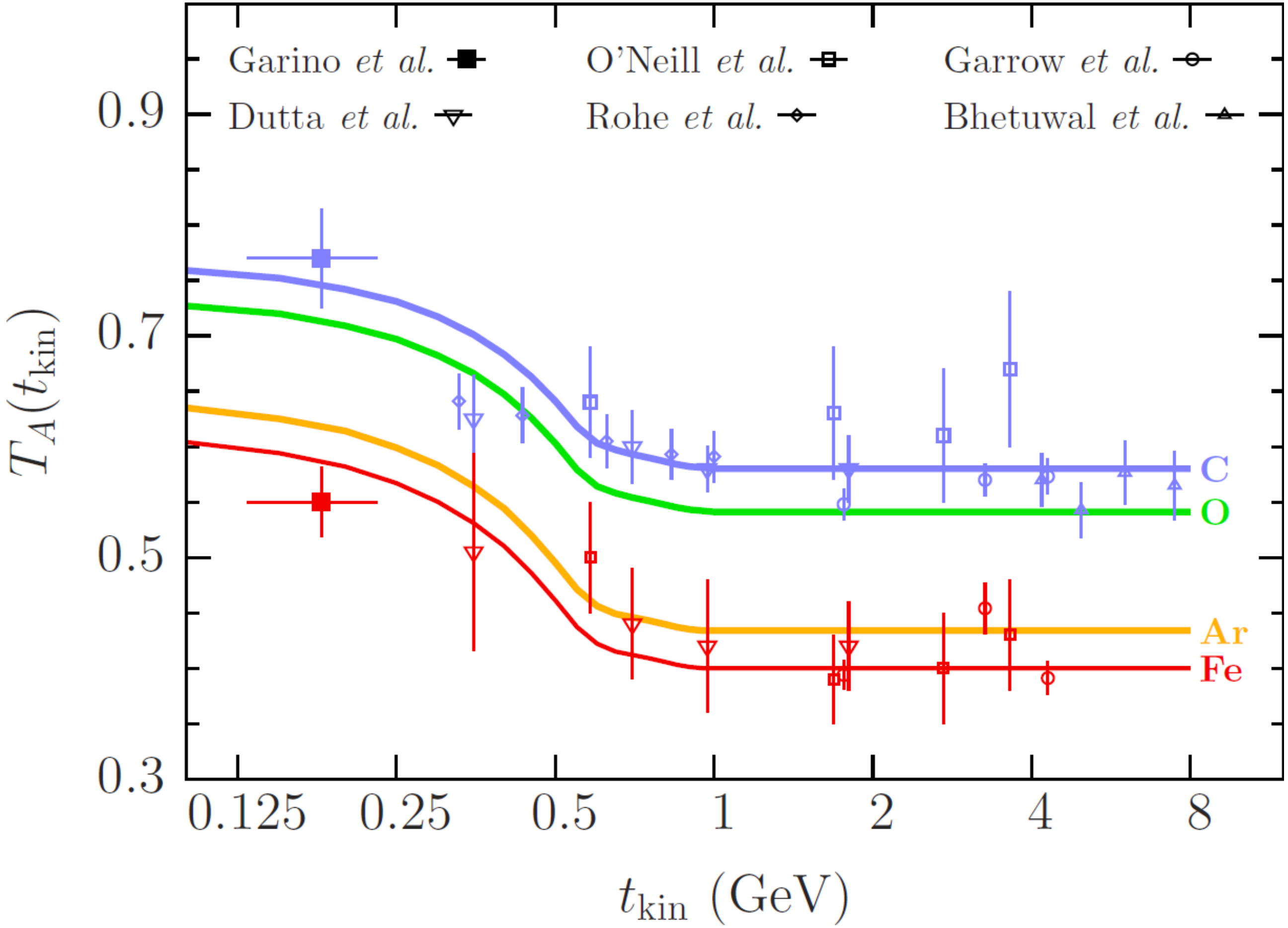
Importance of full coverage





B. Kowal *et al.*, PRC 112, 055504 (2025);
PRC 110, 025501 (2024)

Physics probed by (*e*,*e'p*) data: nuclear transparency



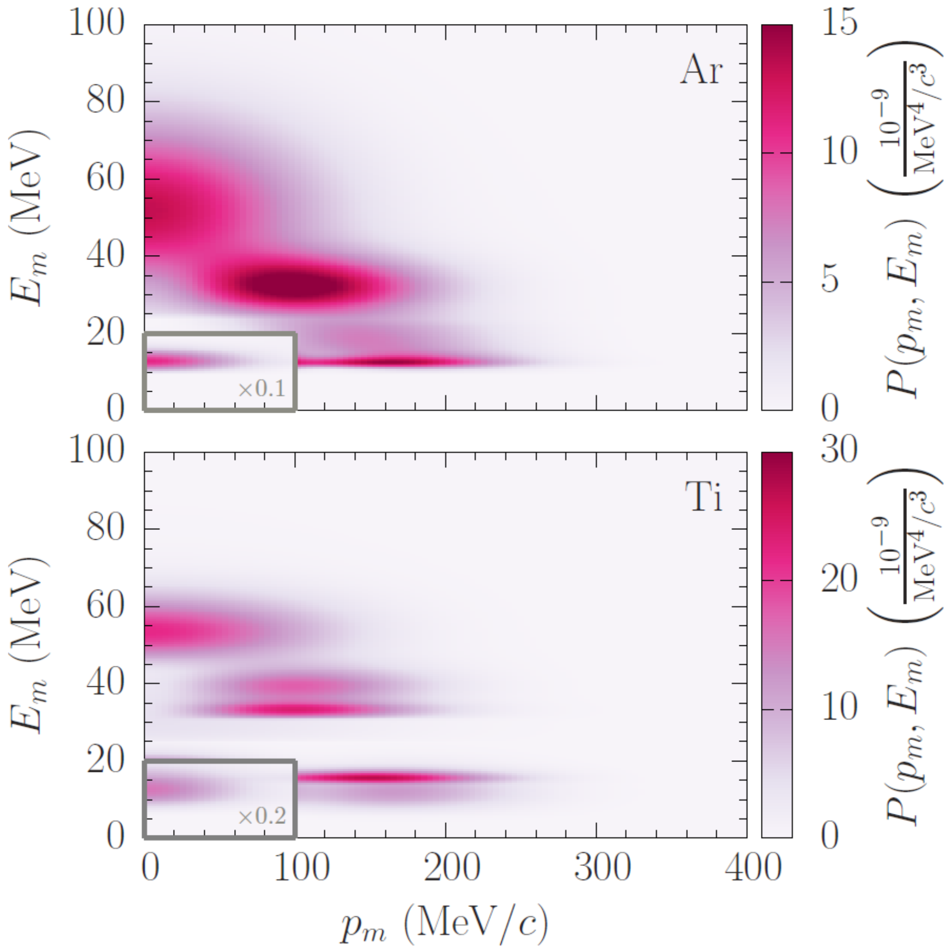
A.M.A. *et al*, arXiv:2508.10101

Spectral functions from Ar(*e*,*e'p*) and Ti(*e*,*e'p*)

L. Jiang *et al.*, PRD 105, 112002 (2022);
PRD 107, 012005 (2023)

- Beam energy 2222 MeV
- $0 \leq p_m \leq 300$ (250) MeV for Ar (Ti)
- $12 \leq E_x \leq 80$ MeV, resolution 6–7 MeV

Great opportunity to improve upon, especially with polarized beams.



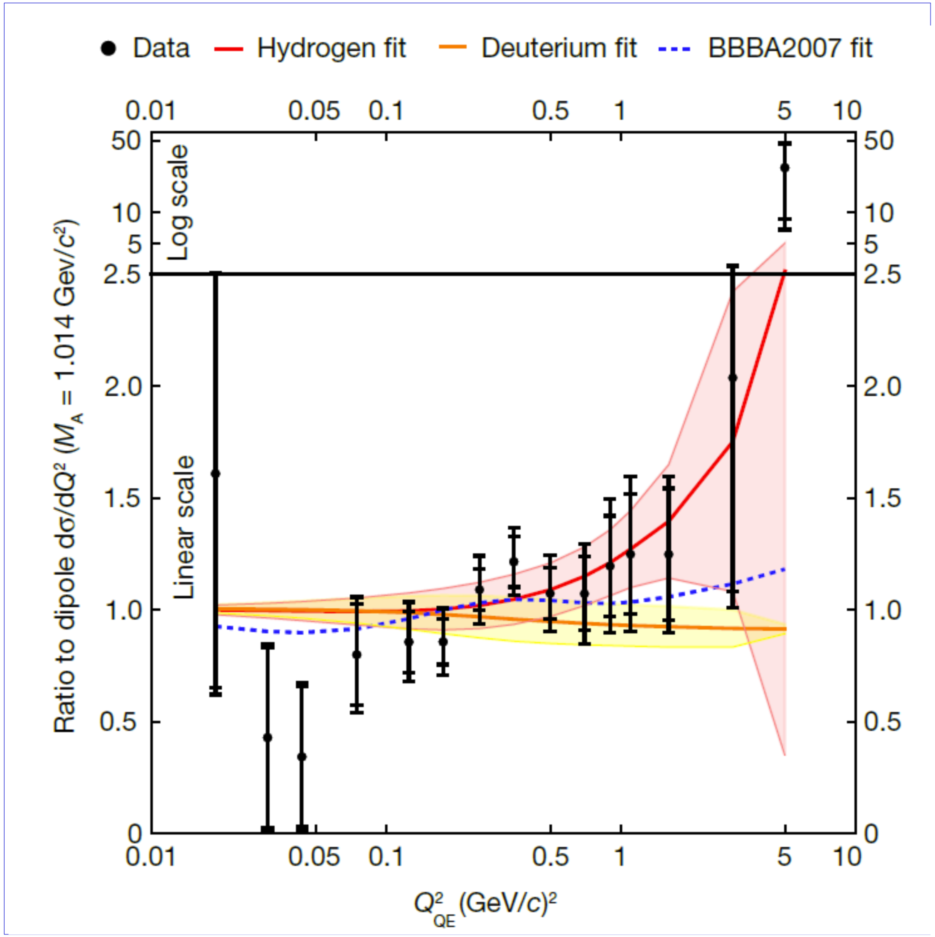
Exclusive measurements

- Neutrino energy reconstruction requires accurate predictions of exclusive final states
- Theory and Monte Carlo generators need experimental data on final state spectra, composition, and particle multiplicities
- The lower the hadron detection threshold, the better
- Ideally, the study would survey all channels

Handful of measurements available: any addition would be welcome; a systematic study could be a game changer.

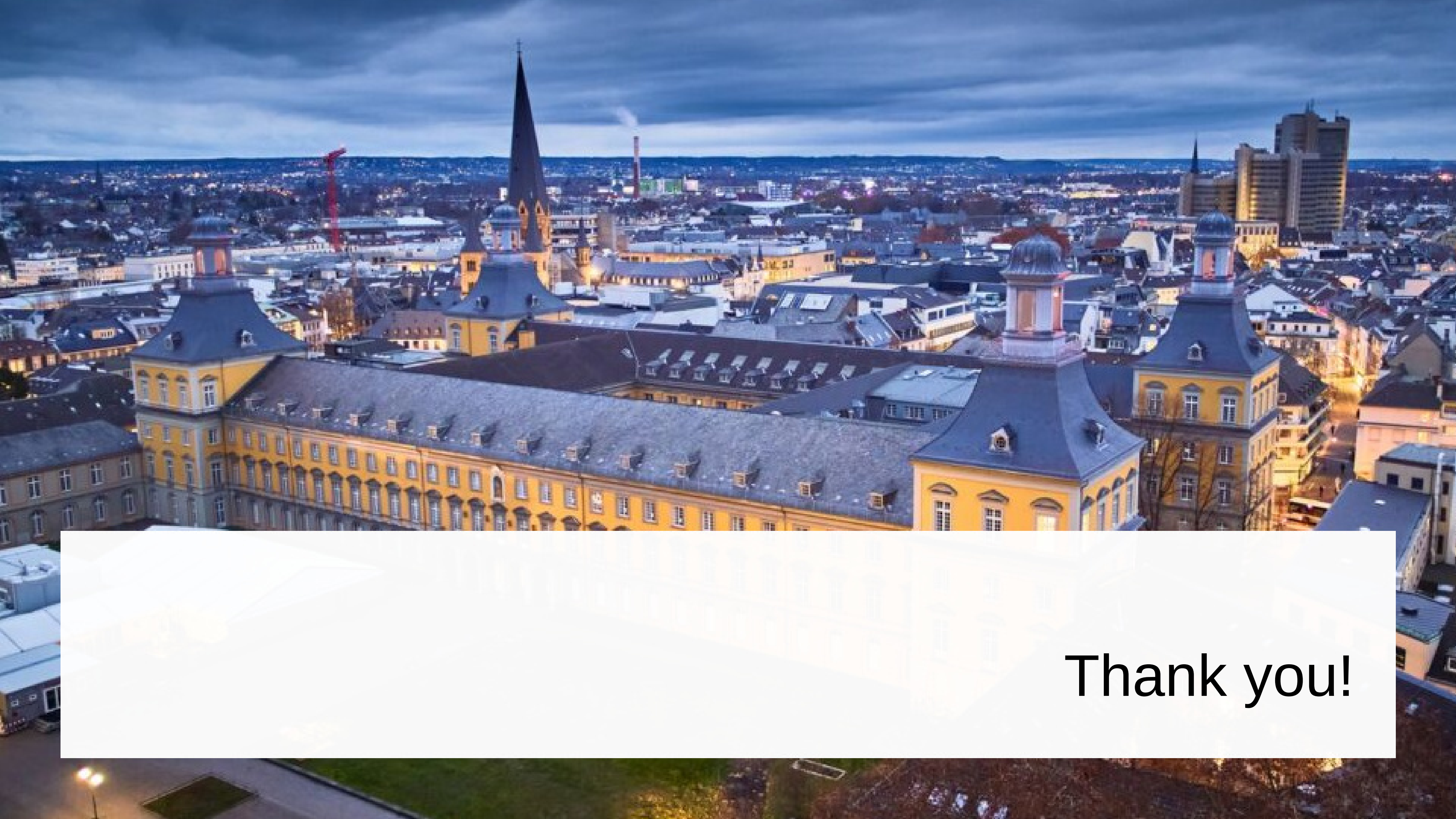
Axial form factor from $e + p \rightarrow \nu_e + n$

- Can only be measured in weak processes
- Dominant source of uncertainty in the QE channel, aside from nuclear effects
- Only occurs for negative polarization
- Measurement would require neutron energy and scattering angle capabilities, excellent background rejection
- Successful experiment would be a breakthrough



Summary

- The success of the long-baseline neutrino-oscillation program requires reliable cross sections.
- Inclusive *(e, e')* cross sections can inform us on
  - FSI effects (Pauli blocking, real OP, cross-section broadening),
  - consistency of the nuclear model in the transition regimes,
  - systematic uncertainty of our model.
- Coincidence *(e, e'p)* experiments are optimal to determine nuclear transparencies and spectral functions.
- Exclusive cross sections for hadrons, especially neutron multiplicities and spectra for argon. Ti*(e,e'p)* may be a simple way forward.
- The axial form factor could be measured in the $p(e,\nu_e)n$ process.



Thank you!

Puzzling results from K2K

Gran *et al.* (K2K), PRD 74, 052002 (2006)

- Beam energy peaked at ~1.2 GeV. Target: 70% H_2O, 22% Al, 8% CH
- From the shape analysis of ~6800 CC QE ν event Q^2_{rec} distribution for $Q^2_{rec} > 0.2$ GeV^2 the axial mass value of 1.20 ± 0.12 GeV was extracted
- “We do not assume that neutrino interactions on oxygen should be the same as for deuterium. In this sense, we have measured the effective M_A for oxygen. However, we find only a small effect on the shape of the Q^2 distribution for $Q^2 > 0.2$ $(\mathrm{GeV}/c)^2$ from known nuclear effects”

Puzzling results from MiniBooNE

Aguilar-Arevalo *et al.* (MiniBooNE), PRL 100, 032301 (2008)

- Motivated by the LSND anomaly, MiniBooNE remains an experiment that collected one of the highest statistics of (anti)neutrino events to date.
- Ratio of detected to predicted CCQE events was to predicted 1.21 ± 0.24.
- M_A value of 1.23 ± 0.24 GeV "may be incorporating nuclear effects not otherwise included in the RFG model."
- Considered Q^2 up to 2 GeV^2.
- Cross section at low Q^2 needs to be suppressed.

MINOS

Adamson *et al.* (MINOS), PRD 91, 012005 (2015).

- Beam energy between 1.5 and 6 GeV. The iron target.
- The shape analysis of the Q^2_{rec} distribution (up to 1.2 GeV^2) of ~123,000 CC QE ν events
- M_A value: $1.23^{+0.13}_{-0.09}$(fit)$^{+0.12}_{-0.15}$(syst) GeV

NOMAD

Lyubushkin *et al.* (NOMAD), Eur. Phys. J. C 63, 355 (2009)

- Beam energy between 3 and 100 GeV. The target dominated by carbon.

- Based on the normalization of the total cross sections, corresponding to about 13,700 (2200) neutrino (antineutrino) events they obtained

  M_A = 1.05 ± 0.02 (stat) ± 0.06 (syst) GeV from CC QE ν events,
  M_A = 1.06 ± 0.07 (stat) ± 0.12 (syst) GeV from CC QE $\bar{\nu}$ events,

- From the the shape analysis of the Q^2_{rec} distribution for ~3400 two-track CC QE ν events

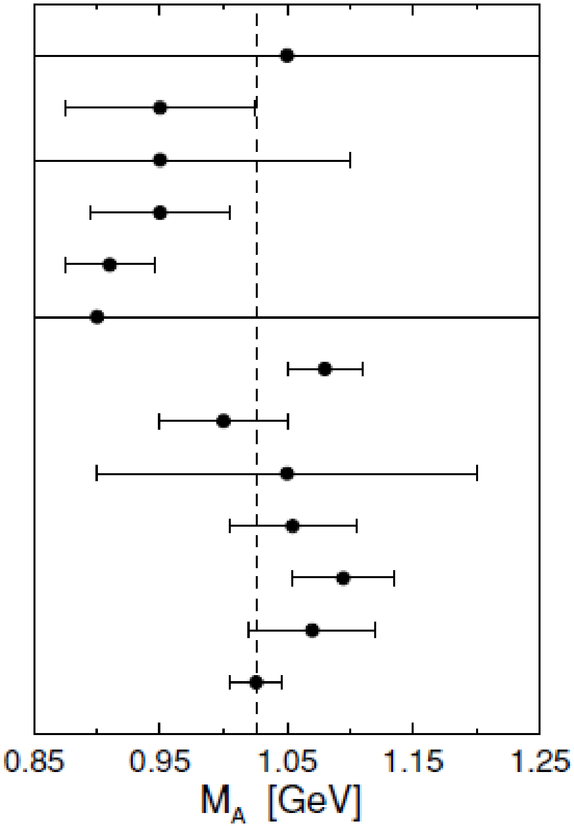
  M_A = 1.07 ± 0.06 (stat) ± 0.07 (syst) GeV

  considering $Q^2_{rec} < 4$ GeV^2.

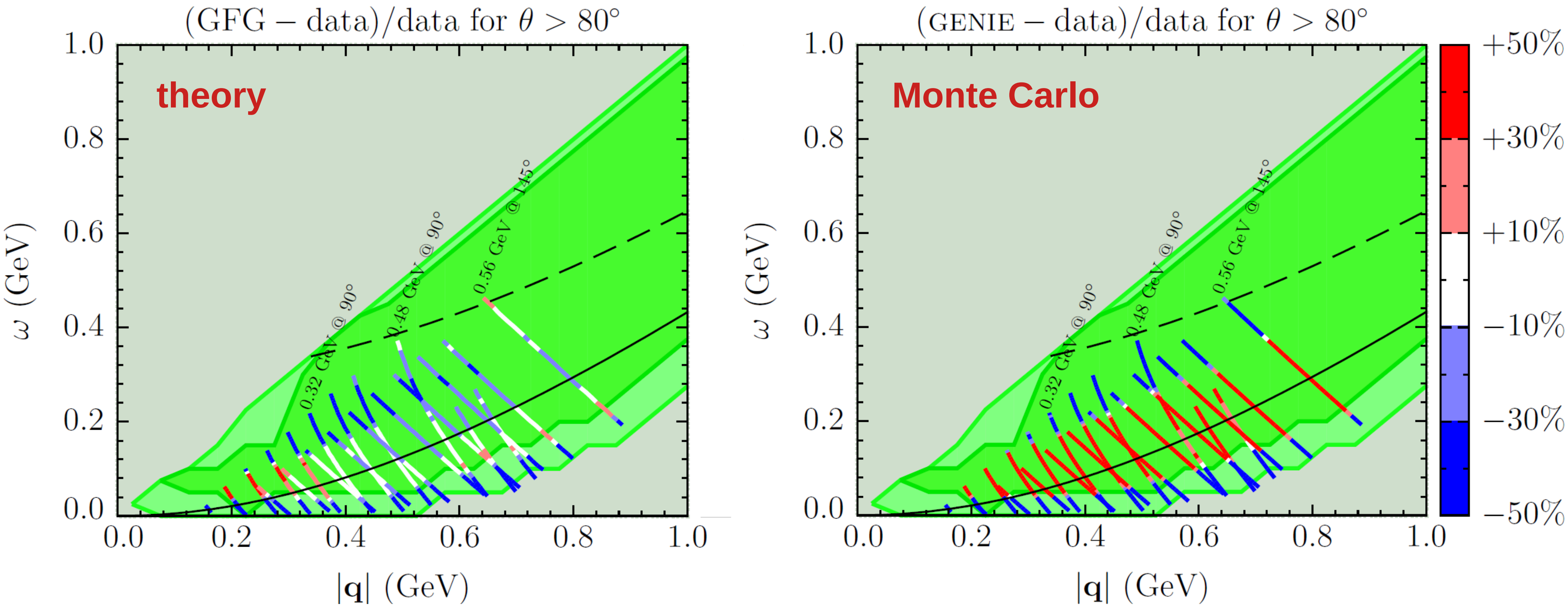
World average M_A value

Bernard, Elouadrhiri and Ulf-G Meißner, JPG 28, R1 (2002)

		target	stat.	
ν	CC	steel+scintillator	N/A	Argonne (1969)
ν	CC	D	166	Argonne (1973)
$\nu\&\bar{\nu}$	CC	freon: CF_3Br	1163	CERN (1977)
ν	CC	H & D	600	Argonne (1977)
$\bar{\nu}$	CC	propane	766	CERN (1979)
$\bar{\nu}$	NC	H	17	BNL (1980)
ν	CC	D	1138	BNL (1981)
ν	CC	D	1737	Argonne (1982)
ν	CC	D	362	Fermilab (1983)
$\nu\&\bar{\nu}$	NC	CH, Al	1727	BNL (1986)
ν	CC	CH, Al	2919	BNL (1987)
ν	CC	D	2538	BNL (1990)
				Average

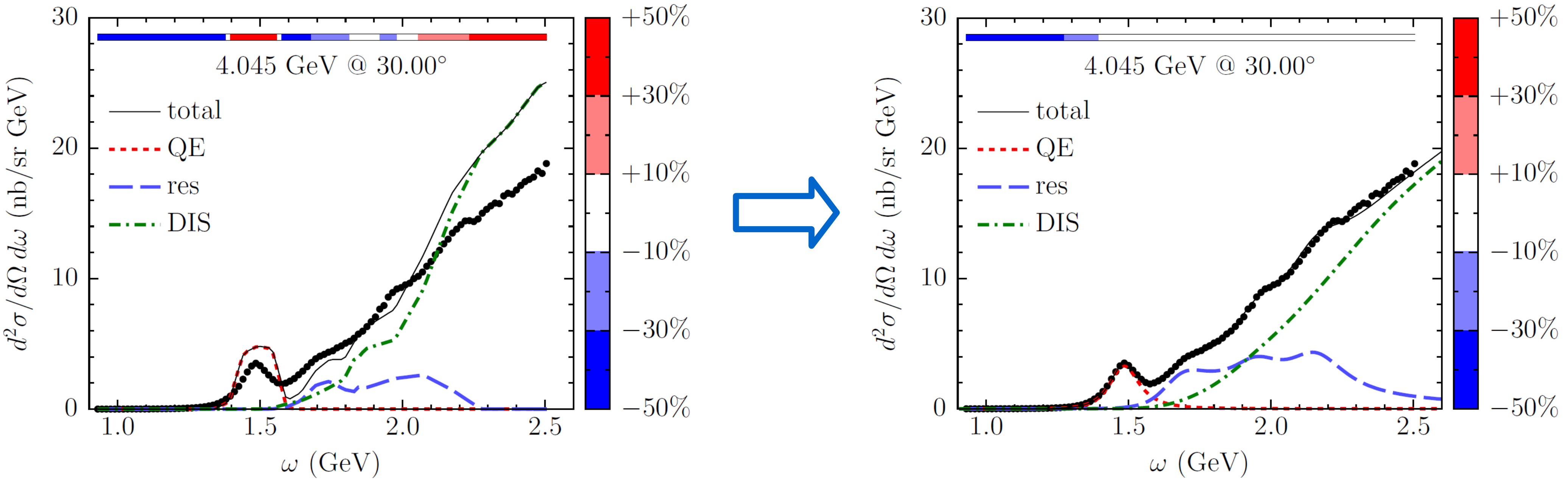


Are these issues expected?



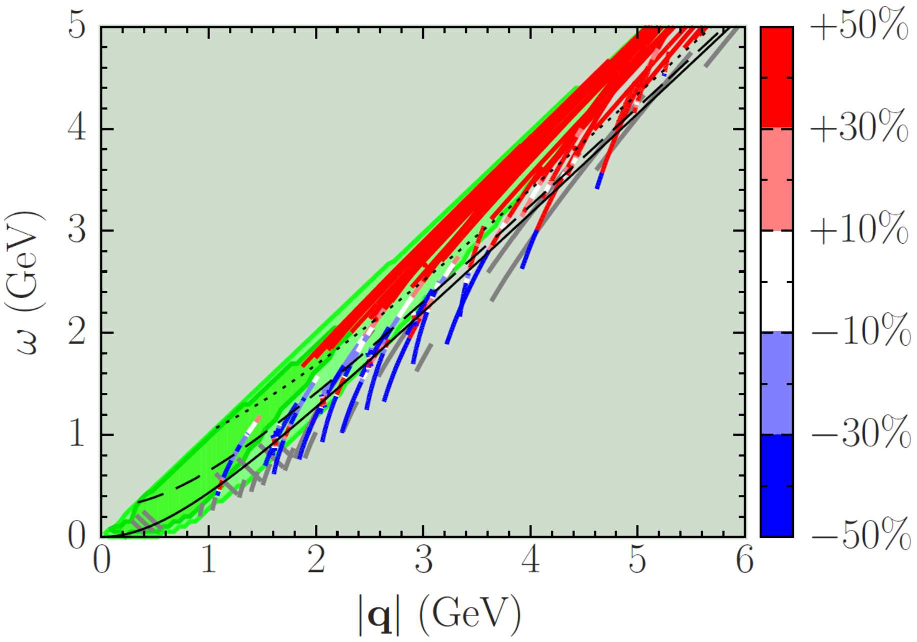
Relevant for T2K/Hyper-K, SBND, etc.

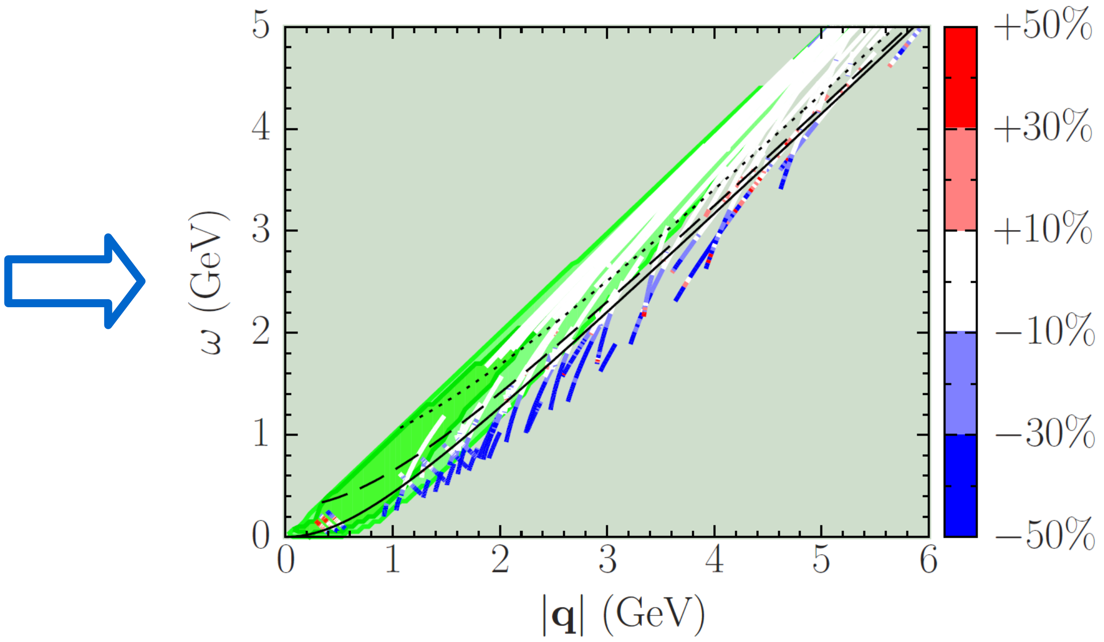
What can be done



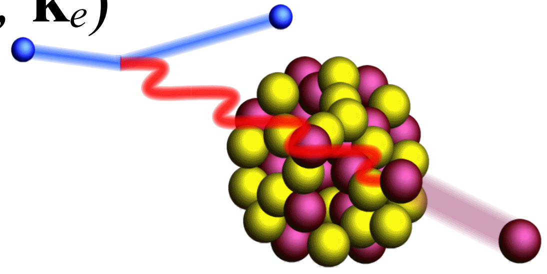
data: Arrington *et al.*, PRL **82**, 2056 (1999)

Update: what can be done





Missing energy E_m and missing momentum $\mathbf{p}_m$



$$E_e + M_A = E_e' + E_p' + \underline{E^*_{A-1}}$$

known | determined

$$\mathbf{k}_e + 0 = \mathbf{k}_e' + \mathbf{p}' + \underline{\mathbf{p}_{A-1}}$$

In general,

$$E^*_{A-1} = \sqrt{(M_A - M + E_m)^2 + p^2_{A-1}}$$

$E_m - E_{\text{thr}}$ is the excitation energy of ^{39}Cl

Without final state interactions

$$-\mathbf{p}_{A-1} = \mathbf{p}_m$$

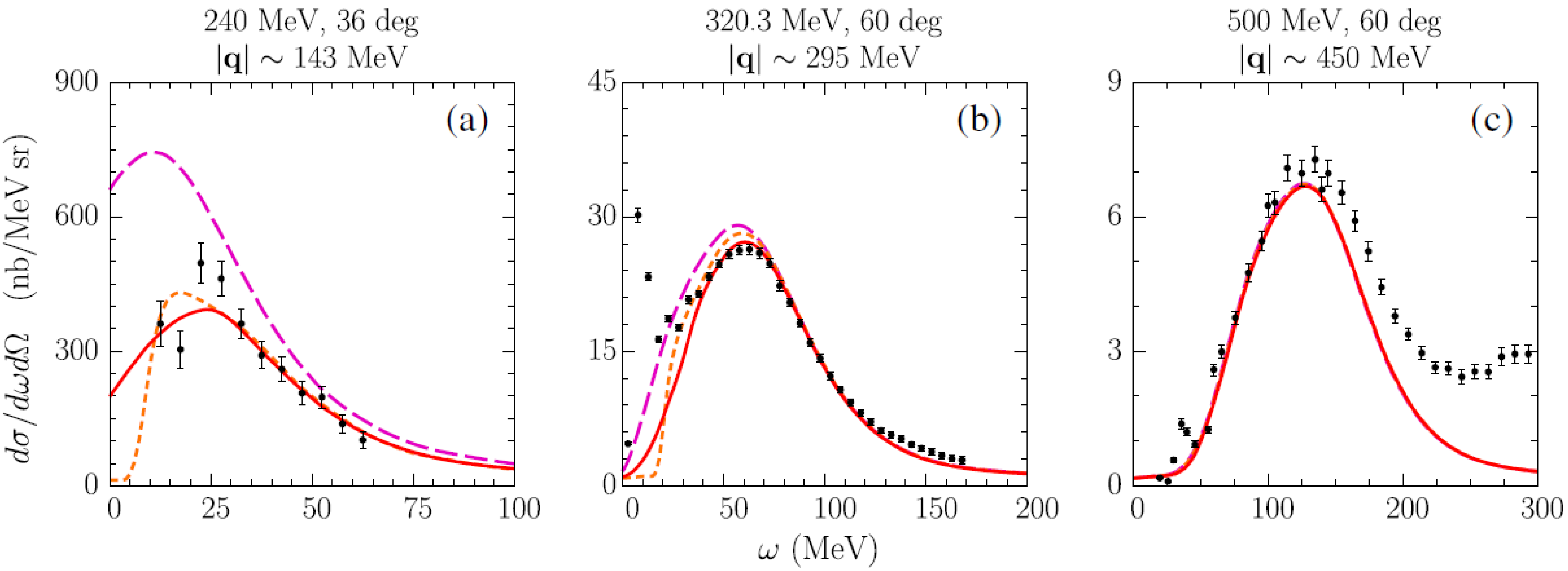
is the initial proton momentum

Findings for GENIE 2

- In the quasielastic peak GENIE works best (some implementation issues observed), but the contribution of meson-exchange currents worsens it for higher energy transfers.
- In complex nuclei, the Δ peak position is not correct. Nuclear implementation issue. Strength underestimated. Better pion production model necessary.
- Higher resonances clearly overestimated (double counting and lack of interference). Conceptual problem: no theory available.
- Deep-inelastic scattering significantly overestimated, also for the data used by Bodek & Yang. Implementation issue.

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

Realistic description of the nucleus: C(*e*,*e'*)



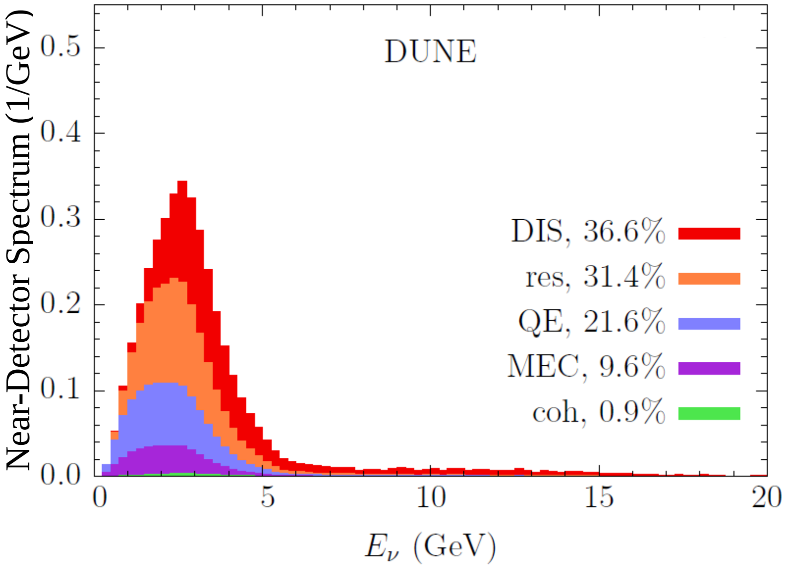
A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

Which cross sections deserve most attention?

Different channels contribute. To address the needs of DUNE we need to understand

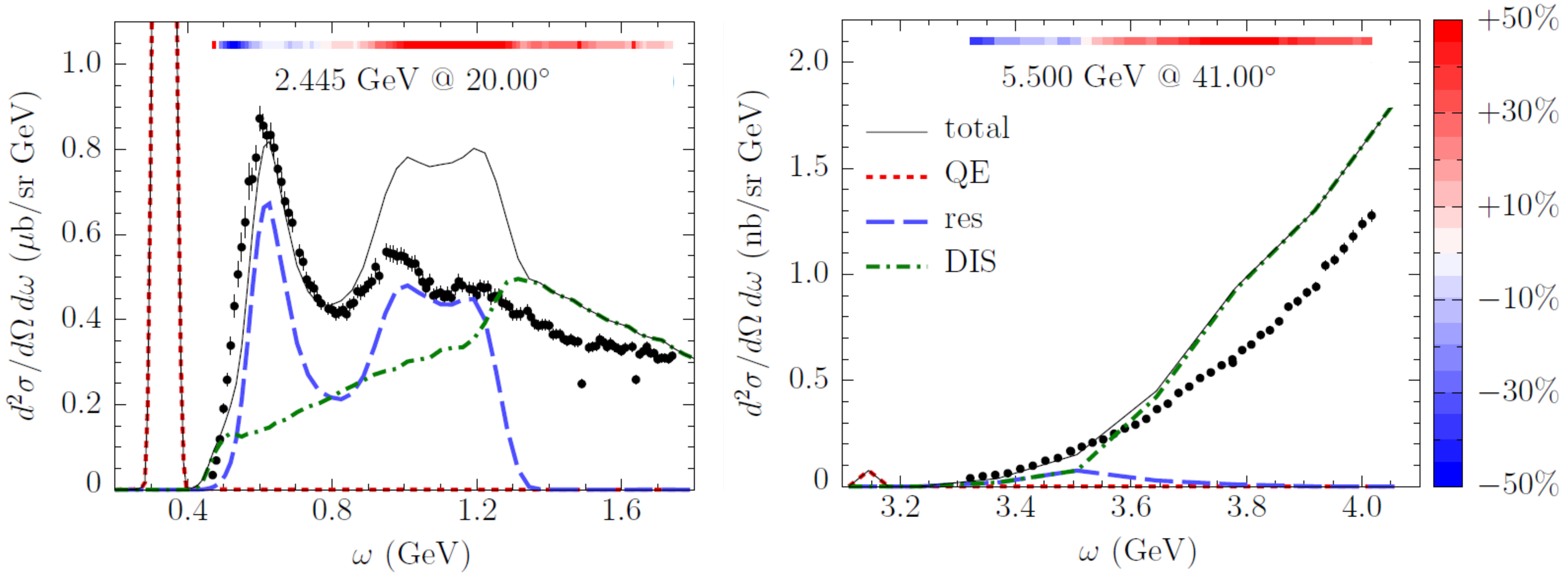
- which channels are most problematic?
- what are the origins of the discrepancies?
- what are possible improvements?

As e^{-}'s and ν's probe nuclei in a very similar way, we can use electron-scattering data to test our Monte Carlo generators.



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

Electron scattering on deuterium

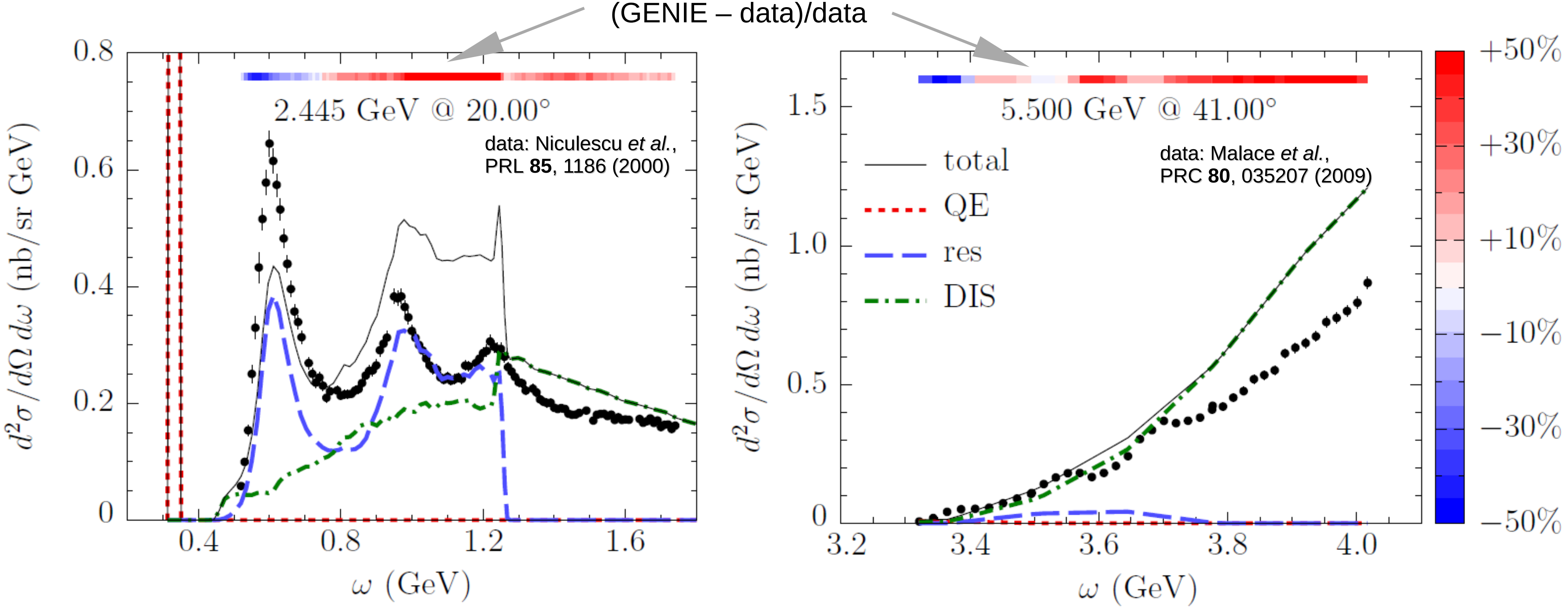


data: Niculescu *et al.*,
PRL **85**, 1186 (2000)

data: Malace *et al.*,
PRC **80**, 035207 (2009)

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

Electron scattering on hydrogen

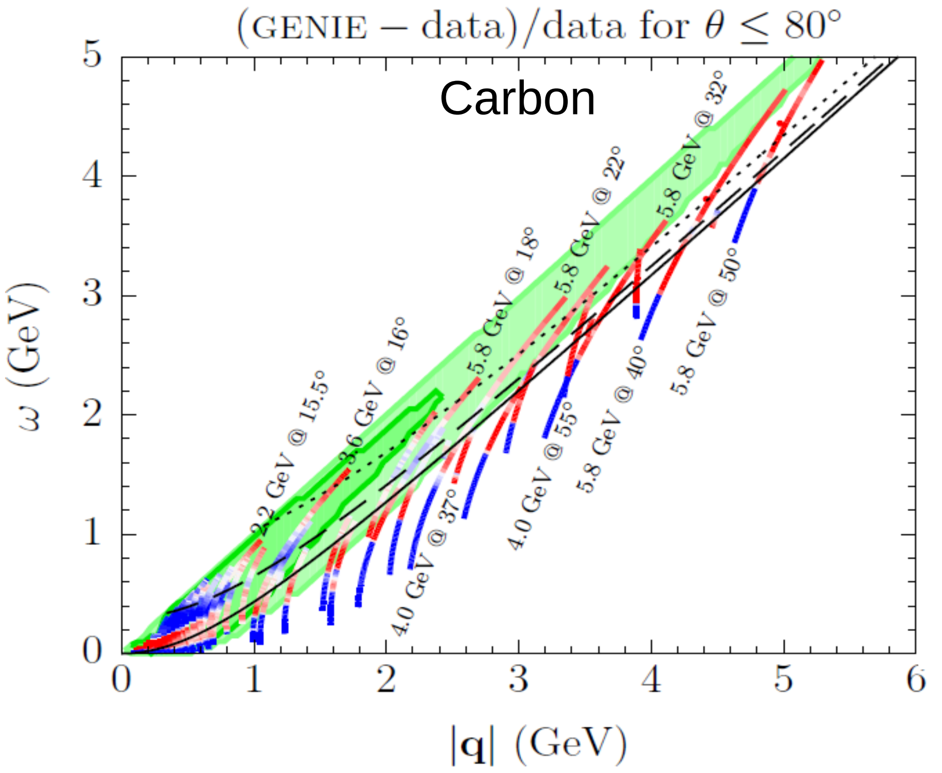


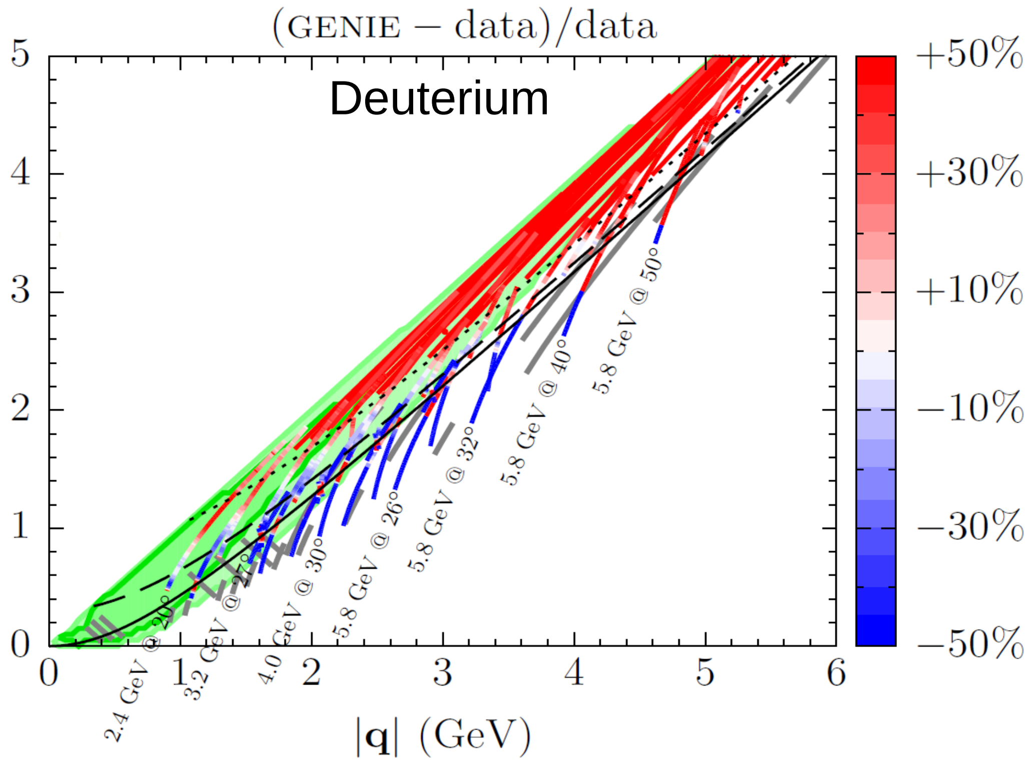
data: Niculescu *et al.*, PRL **85**, 1186 (2000)

data: Malace *et al.*, PRC **80**, 035207 (2009)

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

Are these issues general and relevant?





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

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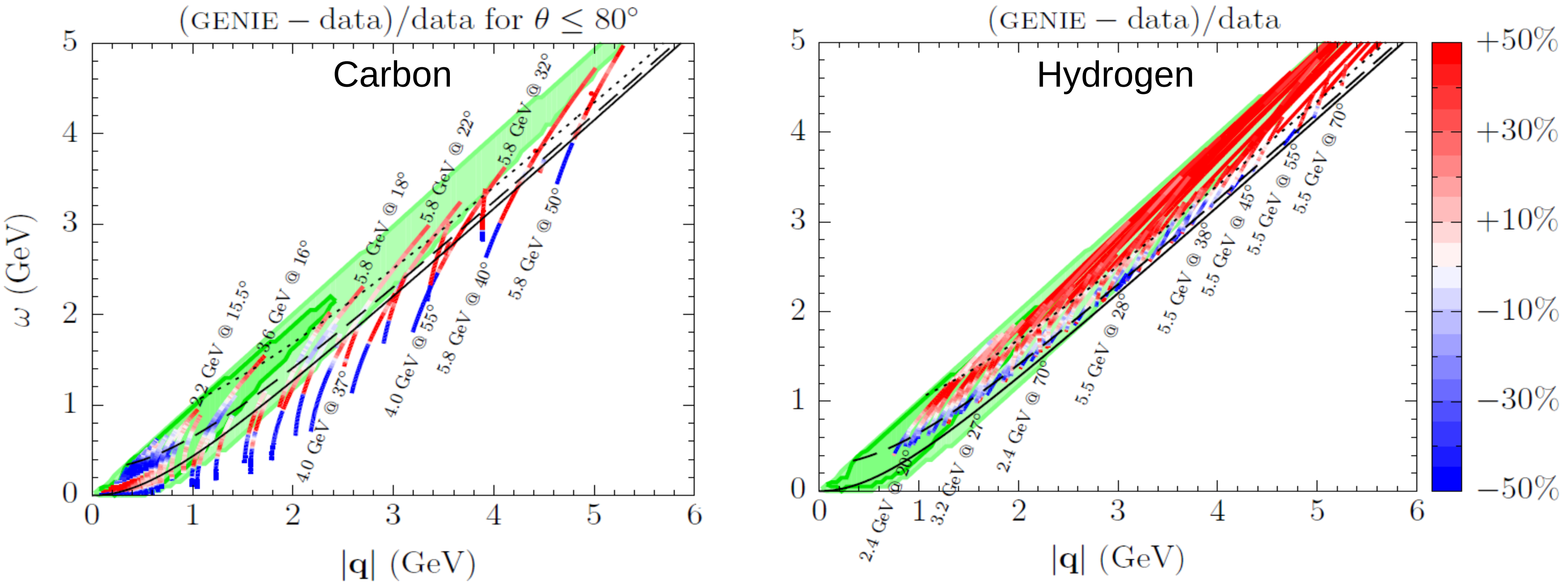
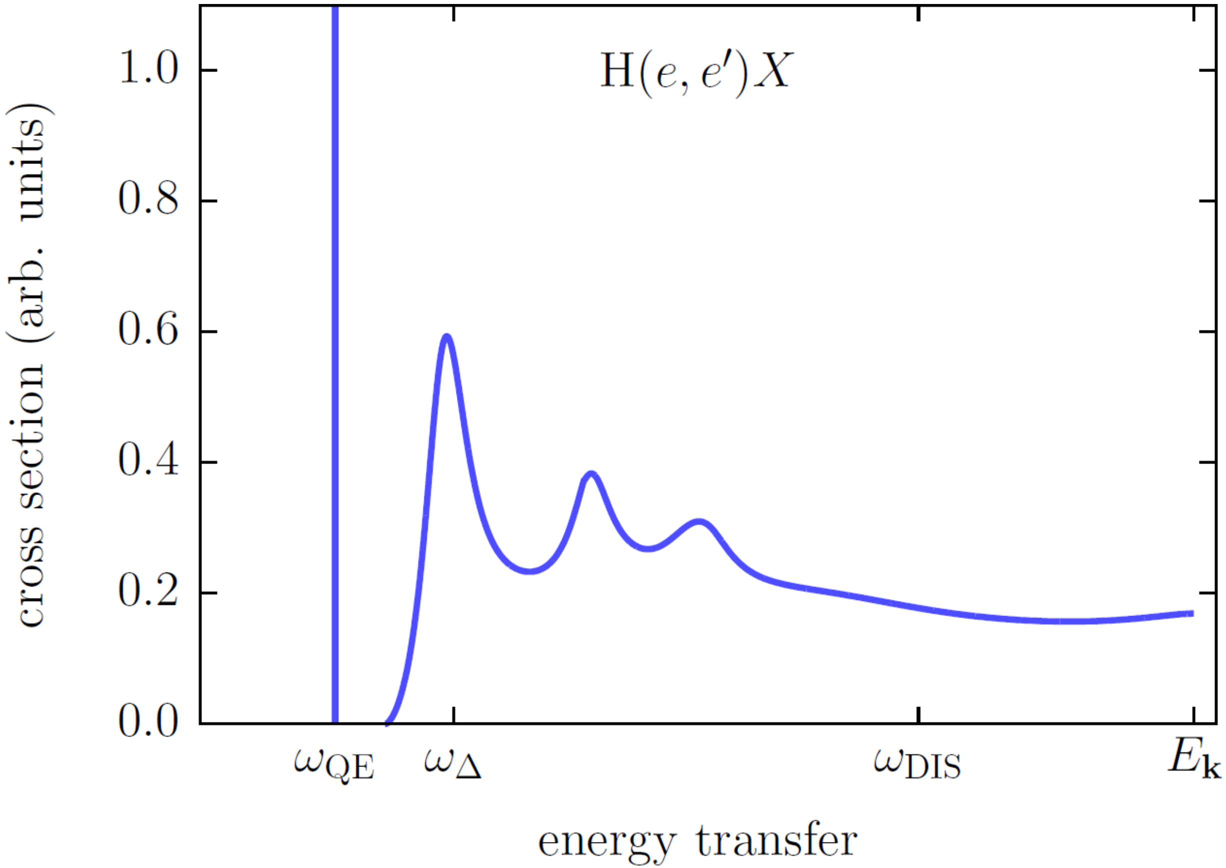
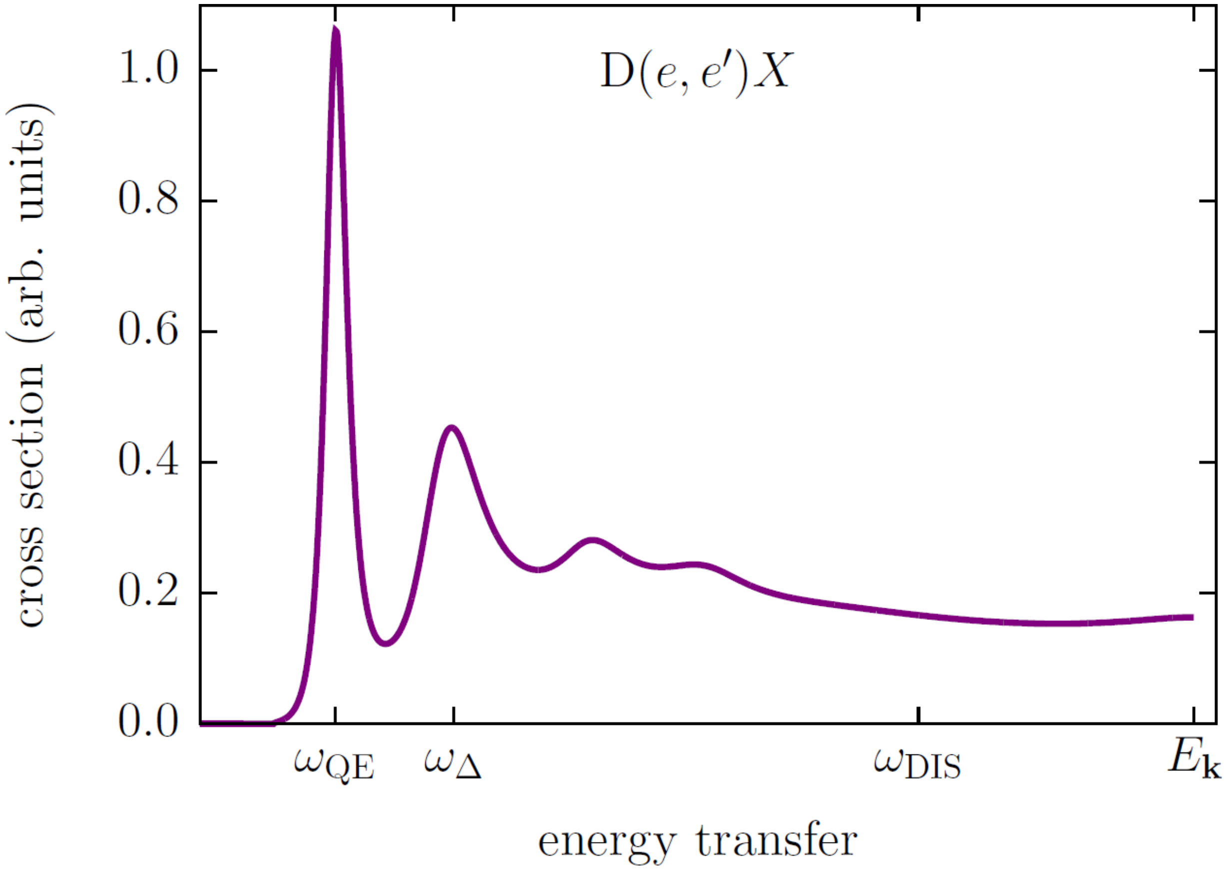


A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

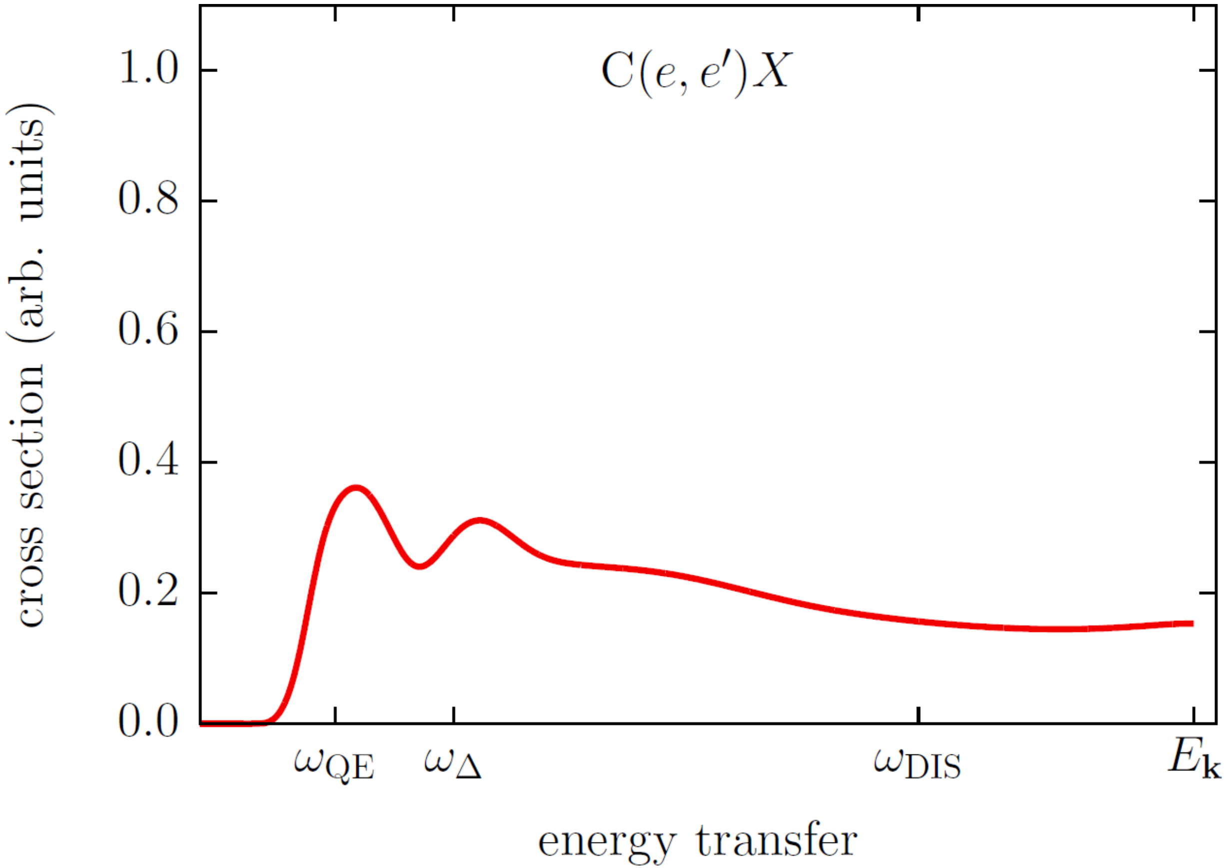
Double differential cross section



Double differential cross section



Double differential cross section



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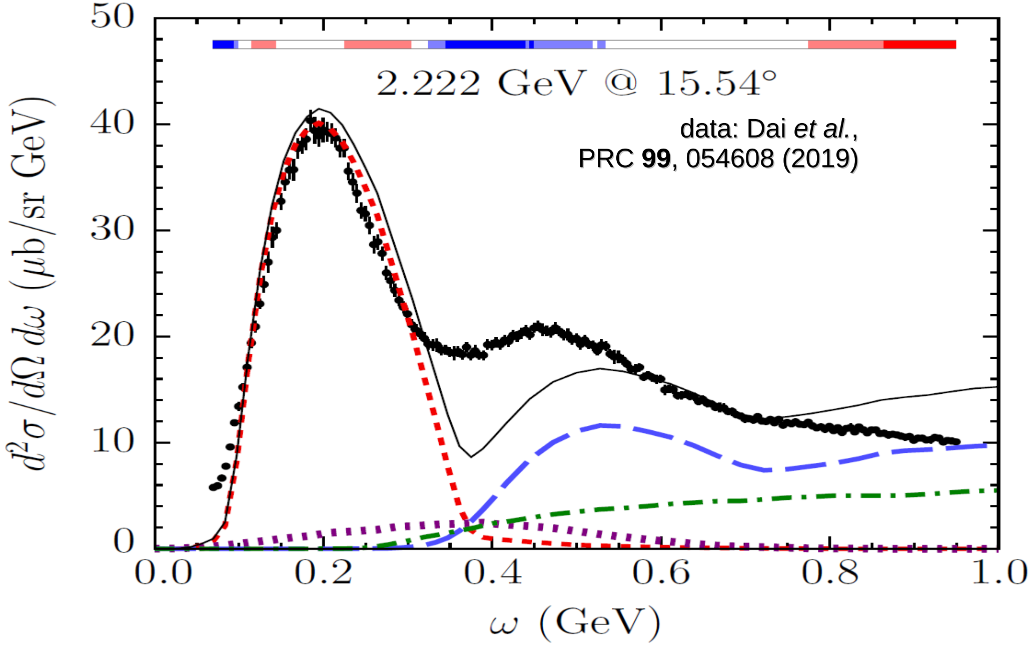
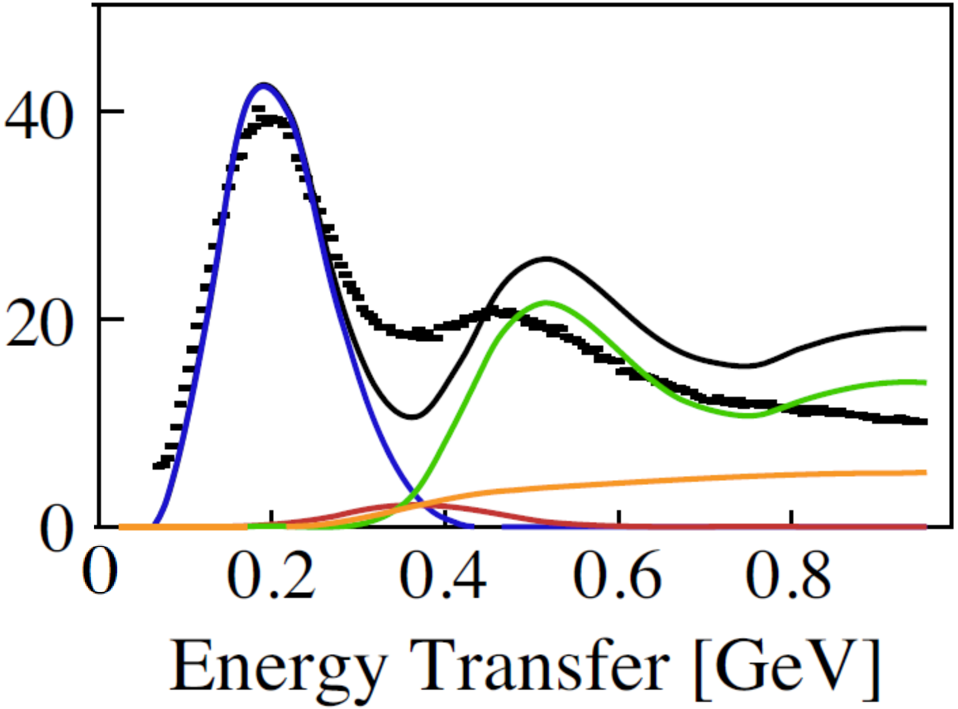
GENIE update

2.12

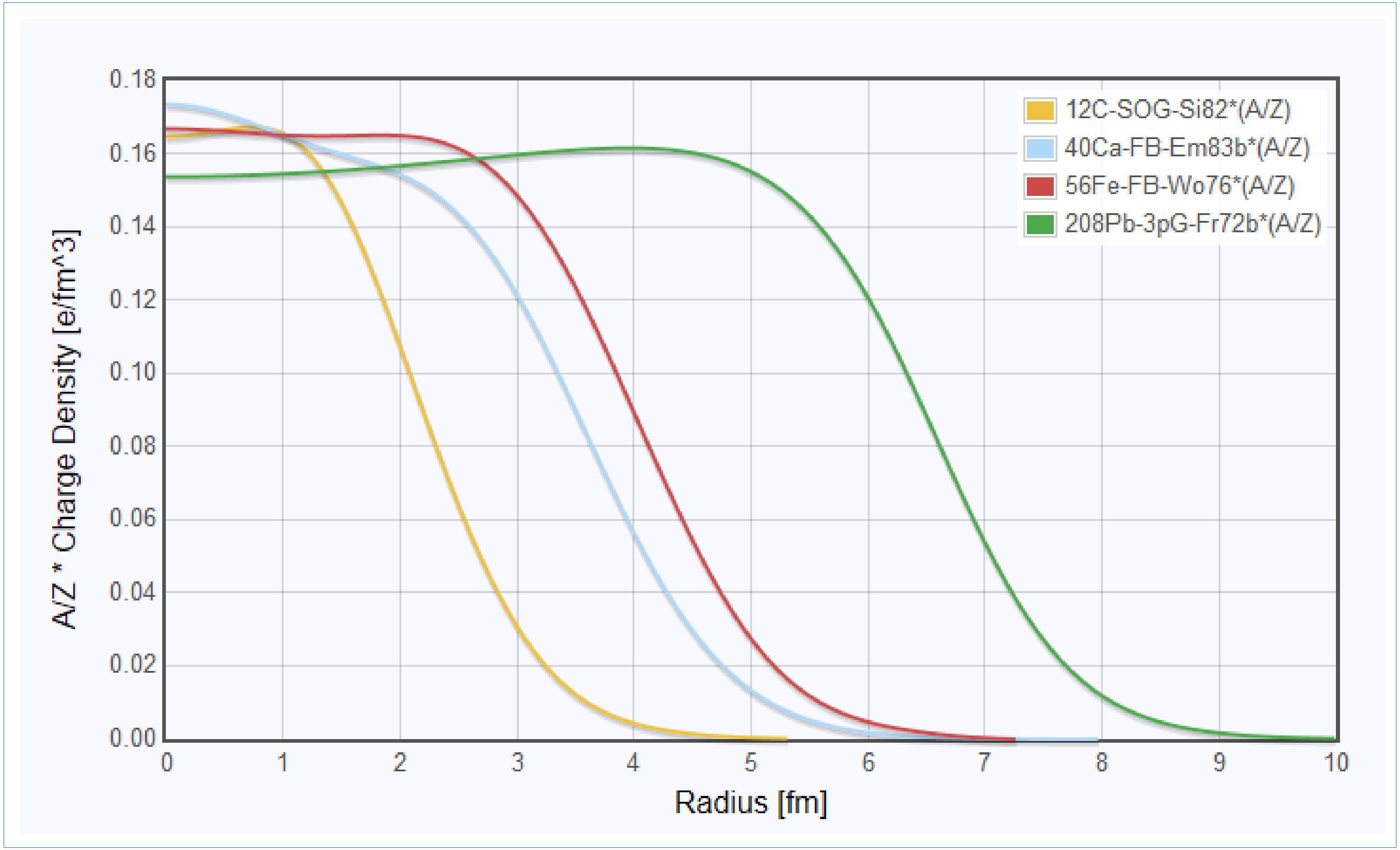


3.2



A. Papadopoulou *et al.*, PRD 103, 113003 (2021)

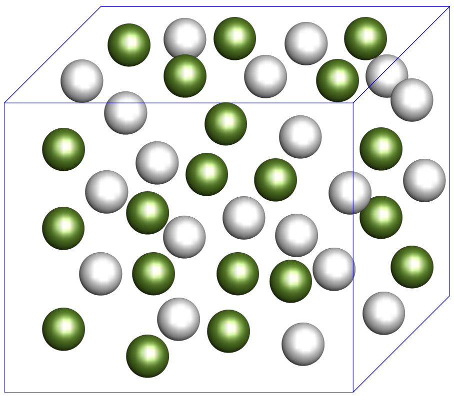
Charge density of nuclei



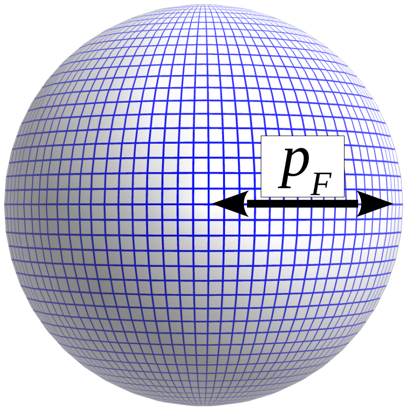
https://discovery.phys.virginia.edu/research/groups/ncd/index.html

Fermi gas

As fermions, nucleons occupy states up to the maximal momentum ('Fermi momentum'). In a constant potential, their energies are $E_p = \sqrt{M^2 + \boldsymbol{p}^2} - \epsilon$.

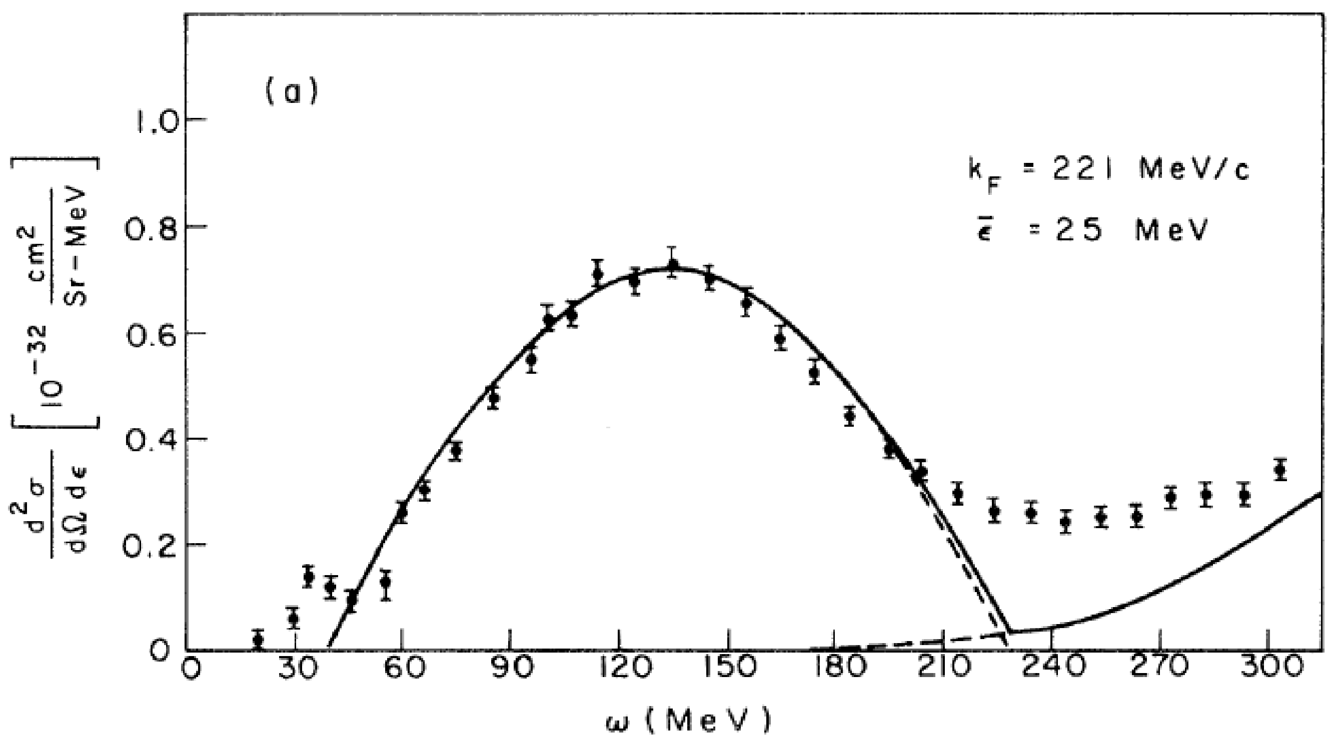


Coordinate space



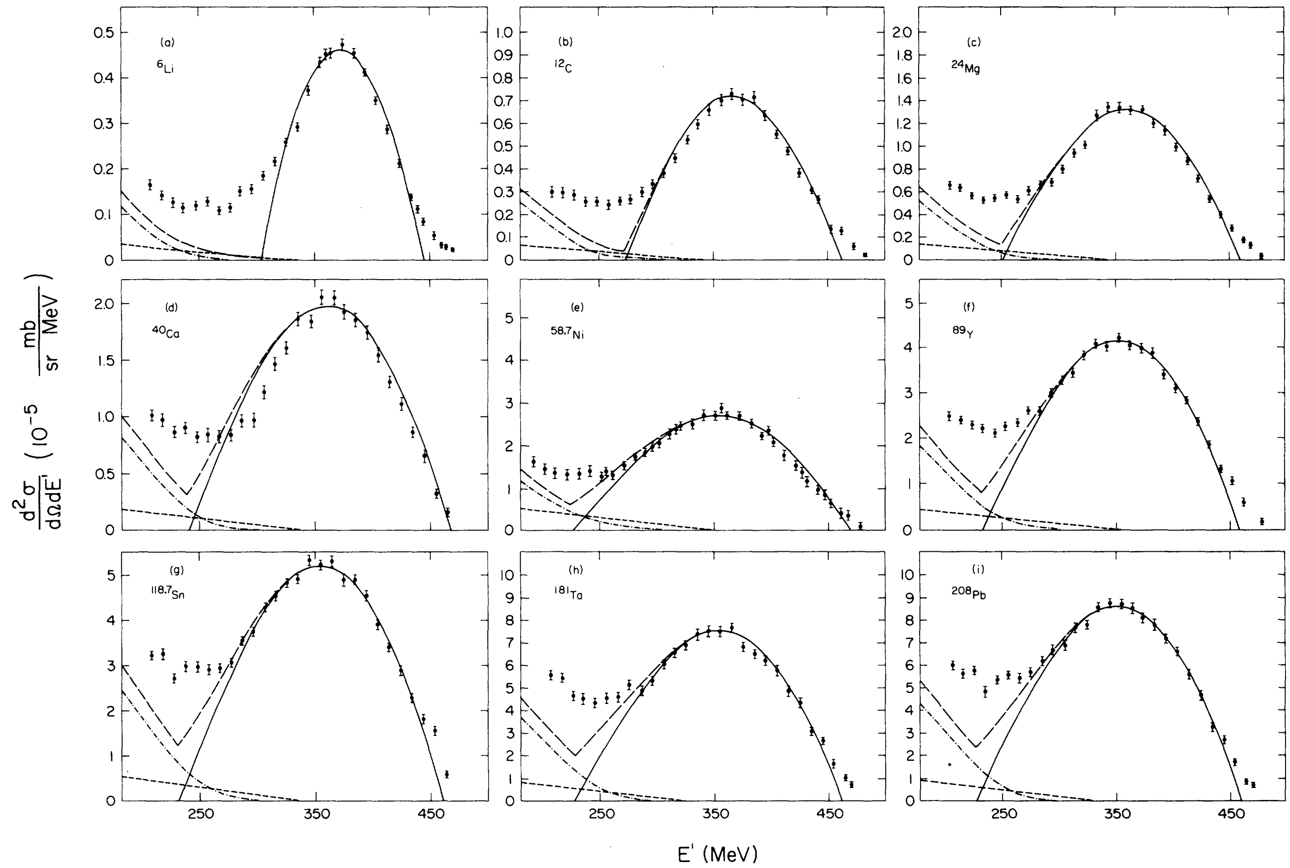
Momentum space

Electron scattering on carbon



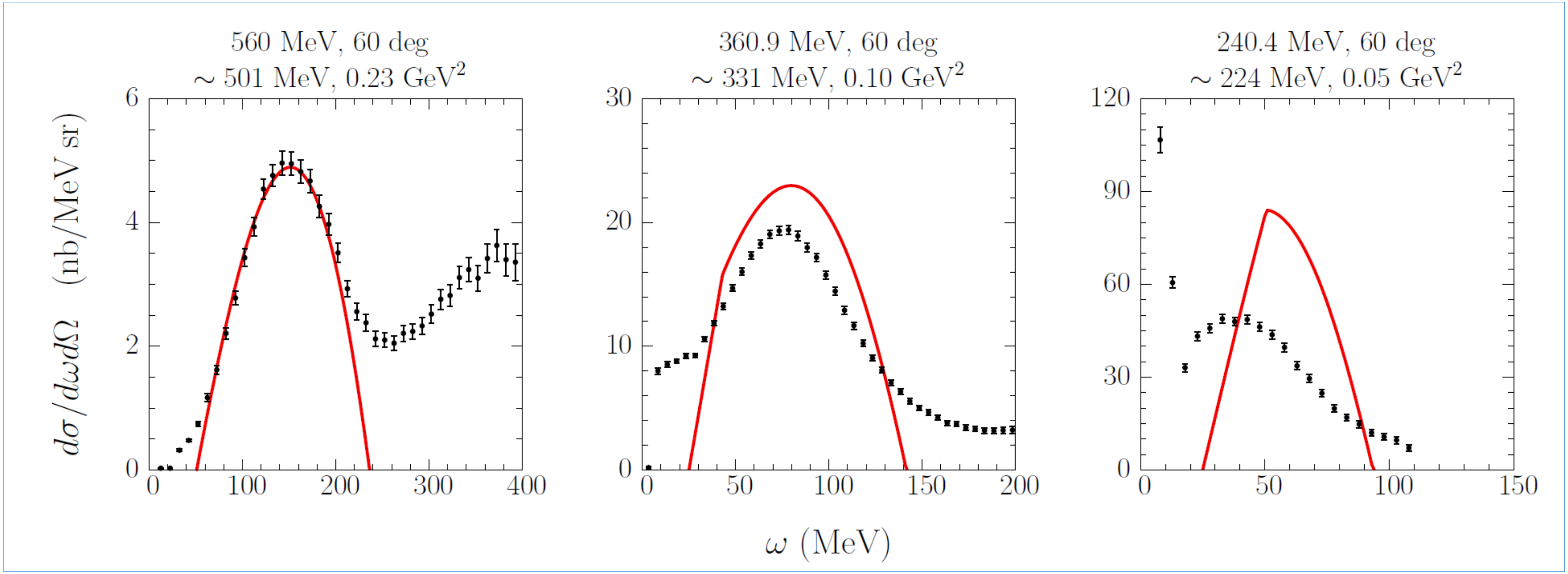
Moniz *et al.*, PRL 26, 445 (1971)

How about other targets?



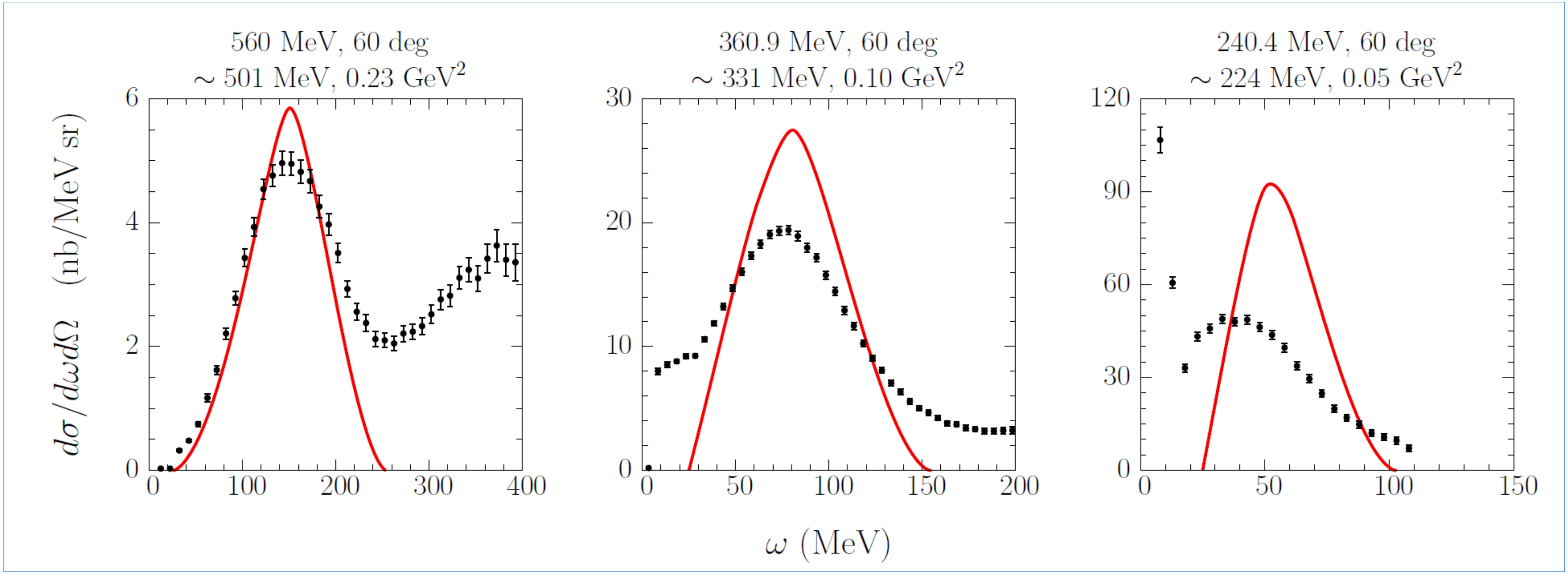
Whitney *et al.*, PRC 9, 2230 (1974)

How about other *kinematics*?



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

Local Fermi gas



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

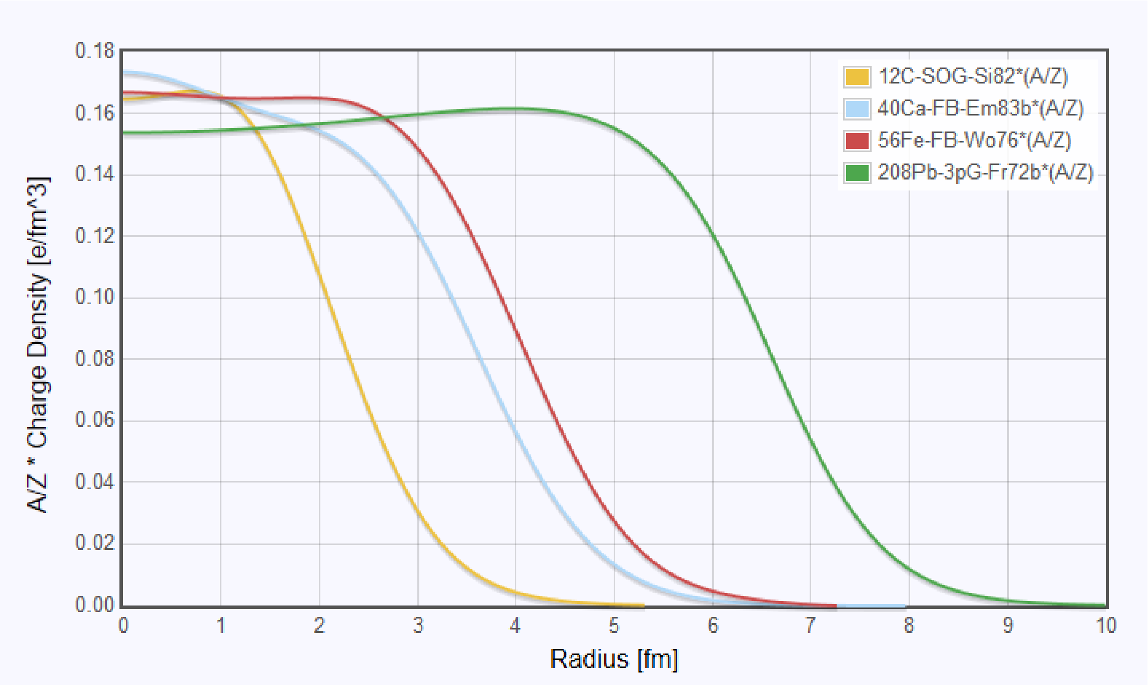
Shortcomings of the Fermi gas model

According to Whitney *et al.* (1974),

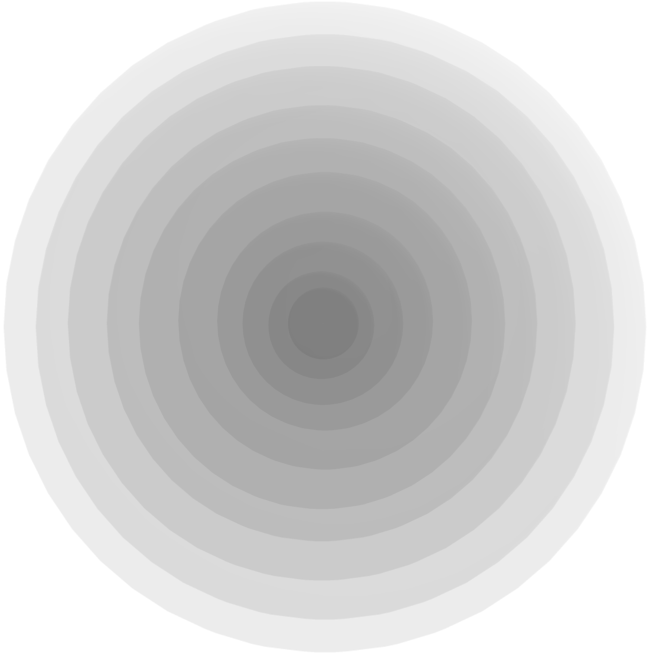
- nucleon-nucleon correlations are ignored
- final-state interactions are not accounted for
- oversimplified momentum distribution
- disregards finite-size effects (‘nuclear surface’)

Local Fermi gas

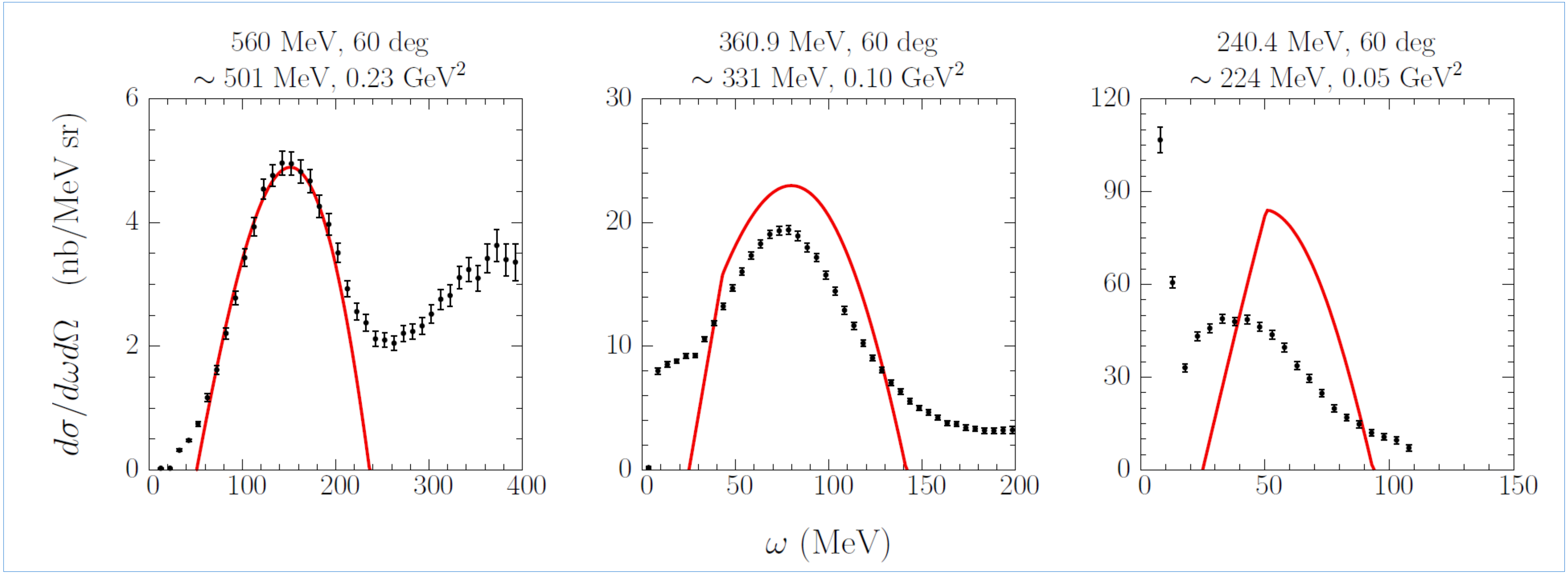
Perhaps we can approximate a spherically symmetric nucleus by a set of concentric spheres of a constant density?



https://discovery.phys.virginia.edu/research/groups/ncd/index.html



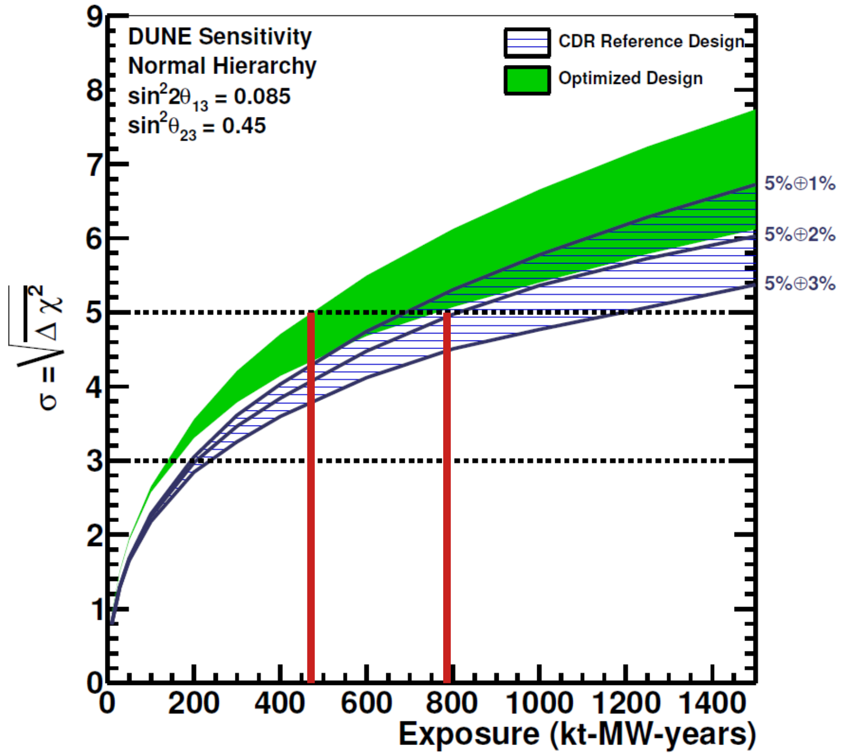
Global Fermi gas



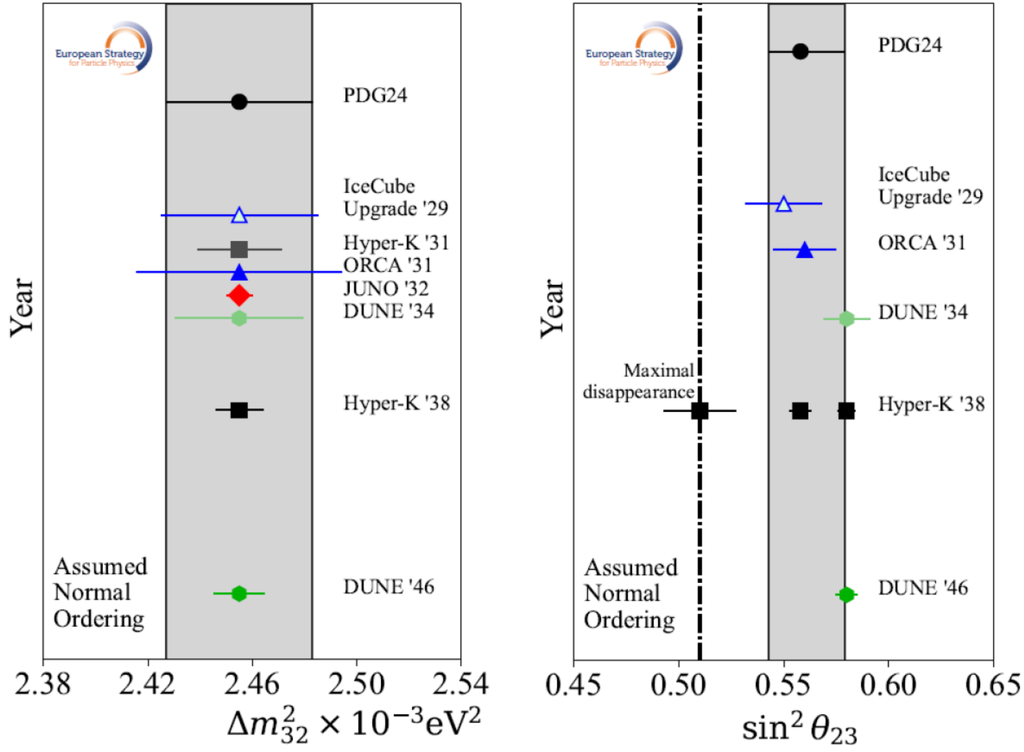
data: Barreau *et al.*, NPA 402, 515 (1983)

Impact of cross-section precision

50% CP Violation Sensitivity

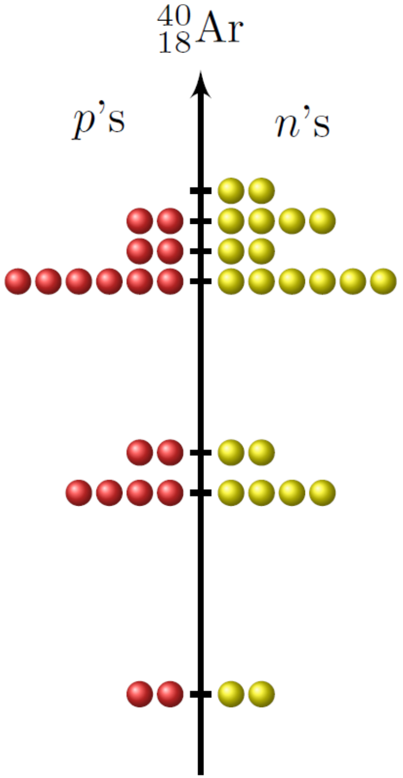


DUNE Collaboration,
arXiv:1512.06148



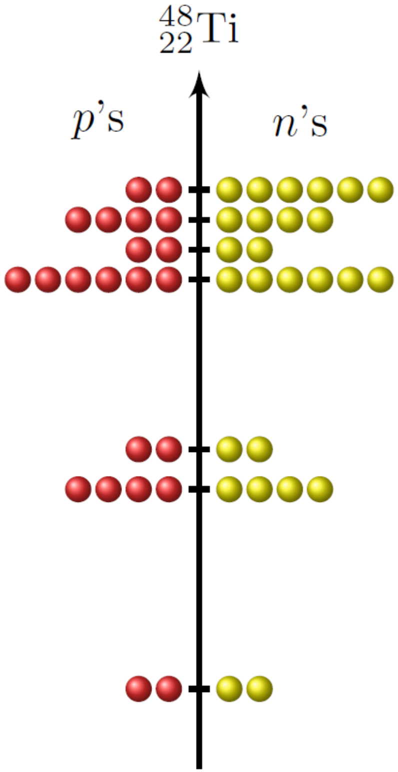
de Blas et al., arXiv:2511.03883

Energy levels

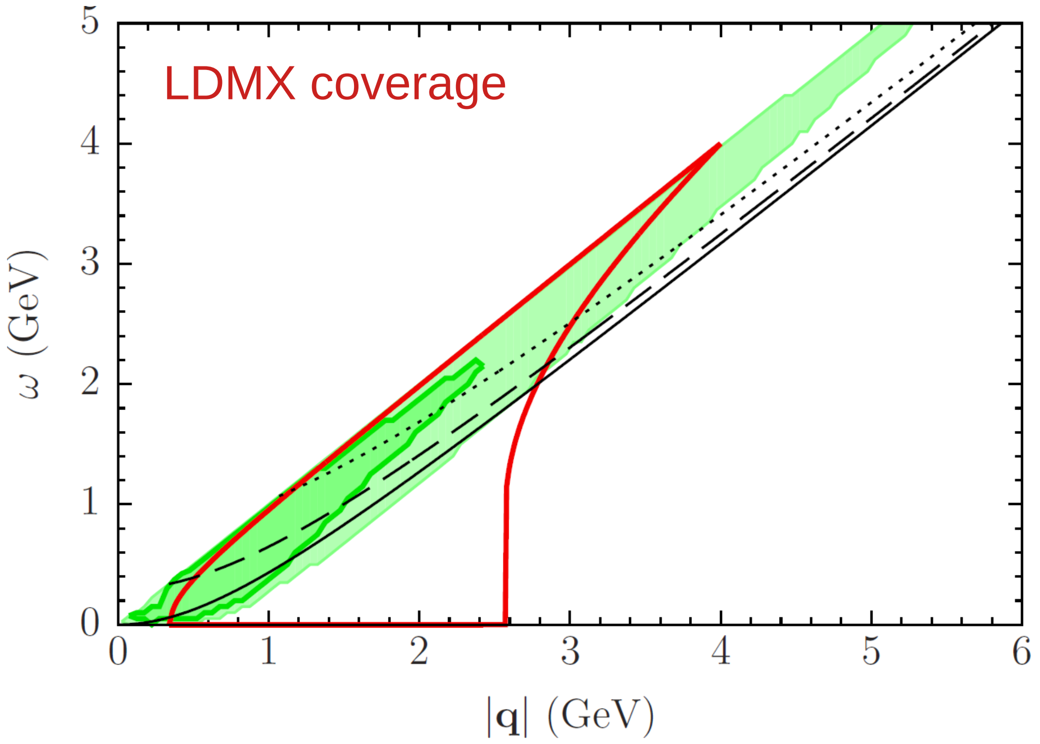


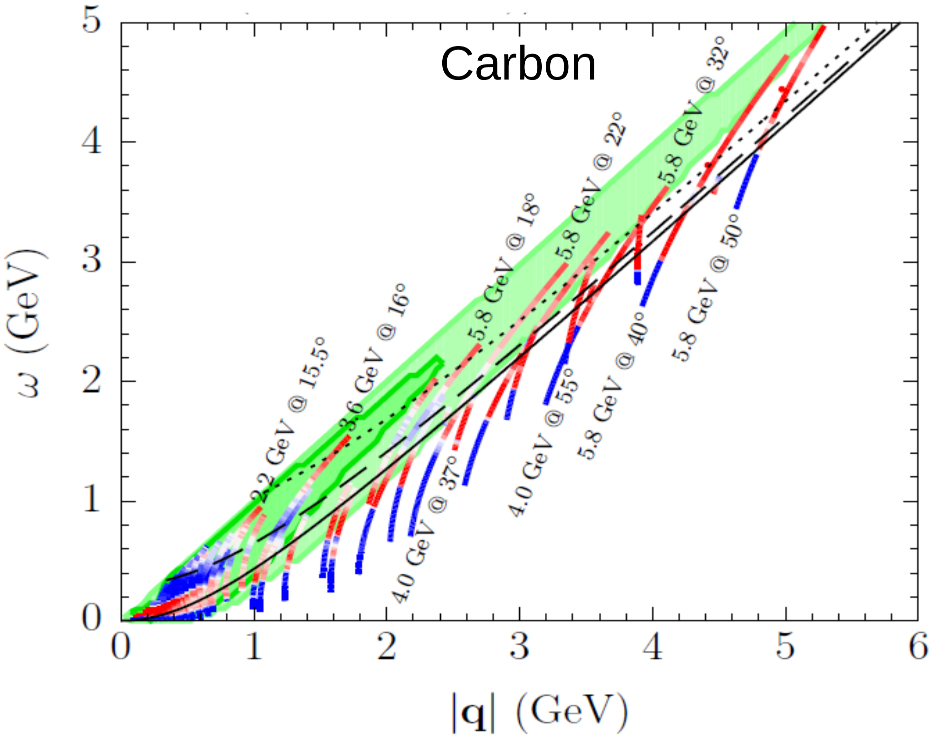
^{40}Ar		^{48}Ti
neutrons		protons
9.87	1f7/2	11.45
11.39	1d3/2	12.21
12.23	2s1/2	12.84
13.23	1d5/2	15.45

Agreement to 0.6–2.2 MeV



Light Dark Matter Experiment (LDMX)

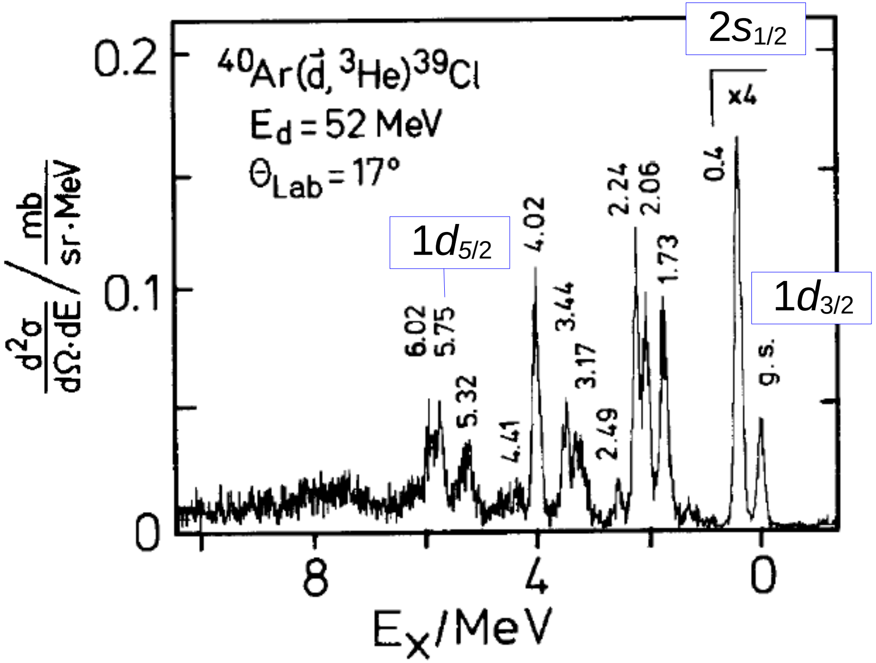




$^{40}Ar(\vec{d}, {}^{3}He)^{39}Cl$ experiment

- Polarized 52-MeV beam
- $0 \leq E_x \leq \sim 10$ MeV, resolution 0.13 MeV
- Spectroscopic factors for individual peaks for $E_x < 6$ MeV
- $1d_{5/2}$ strength measured over a broad range of excitation energies
- For the 1*d* shells, the spectroscopic factors exceed the IPSM expectations
- No uncertainties assigned

Mairle *et al.*, NPA 565, 543 (1993)



What data can we use to test our models?

- ν's interact weakly: tiny cross sections, probe the whole nuclear volume
- α, d, p, $\pi^{\pm}$'s interact strongly: huge cross sections, but only scatter on the nuclear surface
- γ's interact electromagnetically: small/large cross sections, probe the whole nuclear volume at $Q^2 = 0$
- e^{-}'s interact electromagnetically: small/large cross sections, probe the whole nuclear volume at any kinematics

Mean-free path

back of the envelope estimates

In nuclear matter at saturation density (ϱ = 0.16/fm^3)

- ν's: ~6.3 × 10^{12} fm

  assuming $\sigma = 10^{-38}$ cm^2

- p's: ~3.5 fm

  for E_{lab} = 300 MeV, Pandharipande & Piper, PRC 45, 791 (1992)

- γ's: ~310 fm

  assuming σ = 0.2 mb, E = 1 GeV [Bianchi *et al.*, PRC 54, 1688 (1996)]

- e^-'s: ~71,000 fm

  assuming $\sigma = 0.01/A$ mb [QE @ 1.3 GeV, $\theta \geq 12°$, see Baran *et al.*, PRL 61, 400 (1988)]

For reference, the RMS radius of ^{40}Ar is 3.42 fm and $\overline{\varrho}$ = 0.10/fm^3.