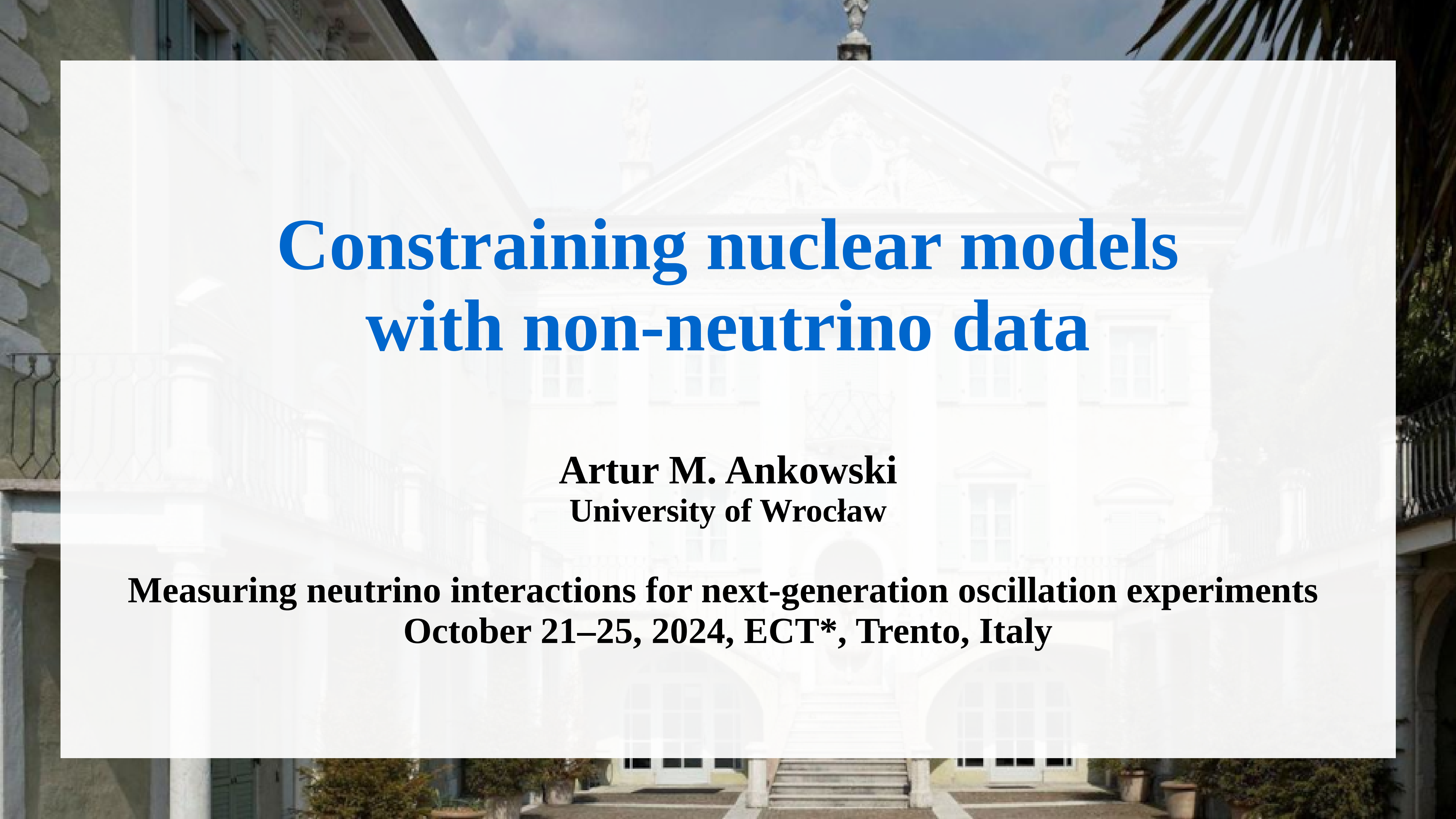


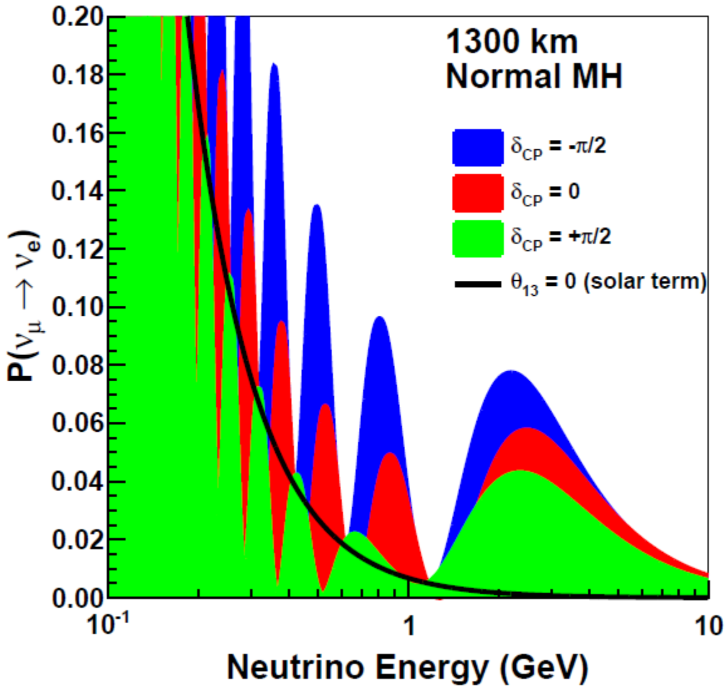
Constraining nuclear models with non-neutrino data

Artur M. Ankowski
University of Wrocław

Measuring neutrino interactions for next-generation oscillation experiments
October 21–25, 2024, ECT*, Trento, Italy

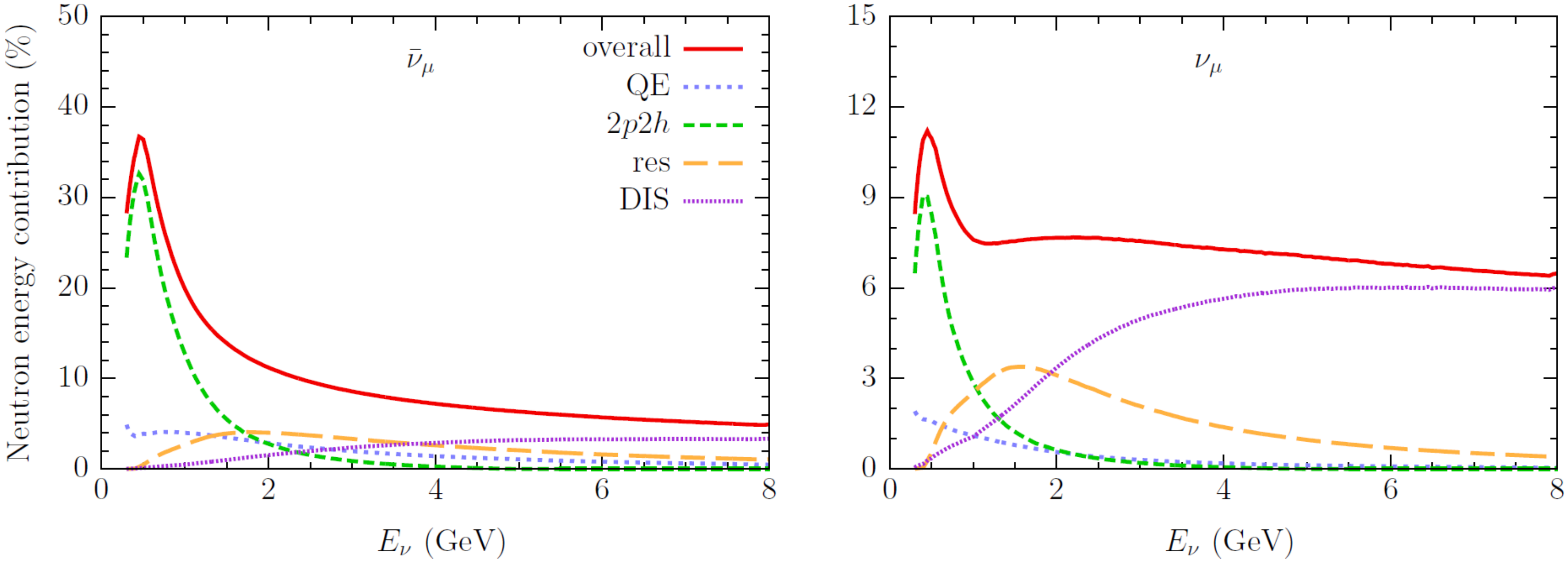
MC Generators in accelerator neutrino physics

- 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**.



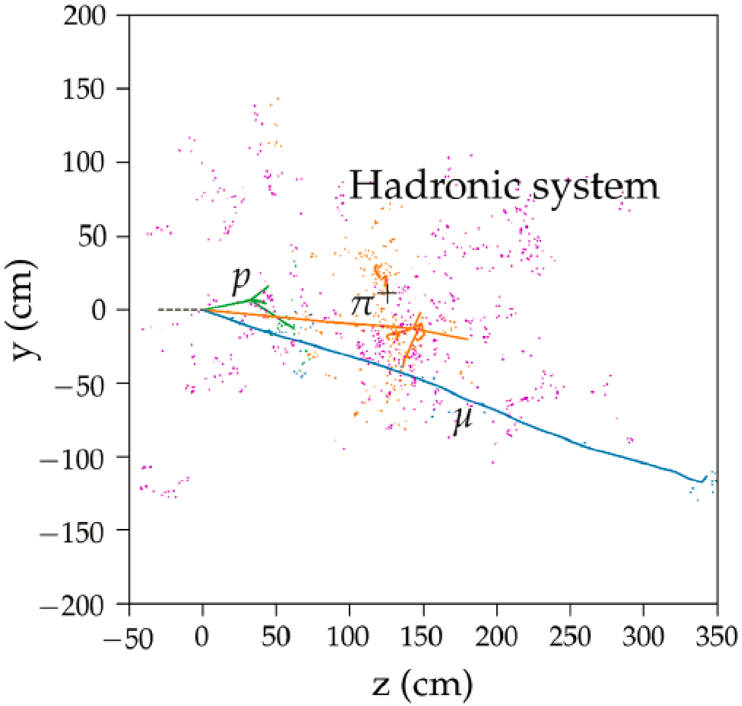
DUNE Collaboration, arXiv:1512.06148

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.

Are neutrino data sufficient?

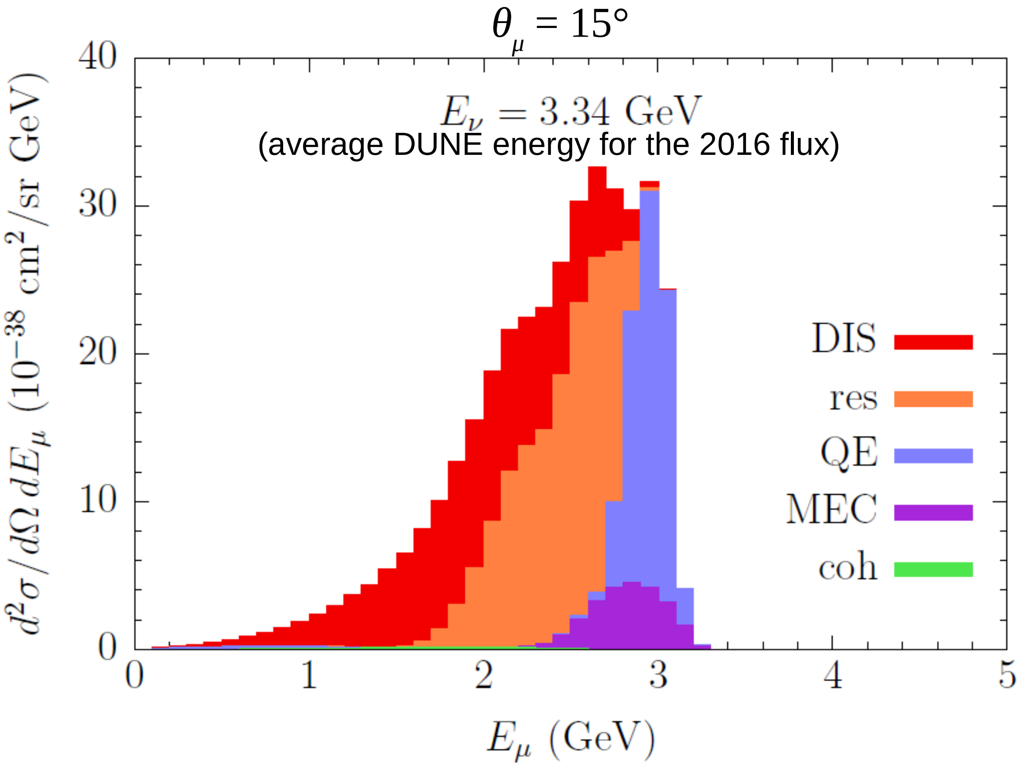
"... fitting to individual MINERvA pion production channels [$1\pi^{\pm}$ and $N\pi^{\pm}$ for ν_μ, and $1\pi^0$ for ν_μ and $\bar{\nu}_\mu$] produces **different best-fit parameters** ..."

"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)

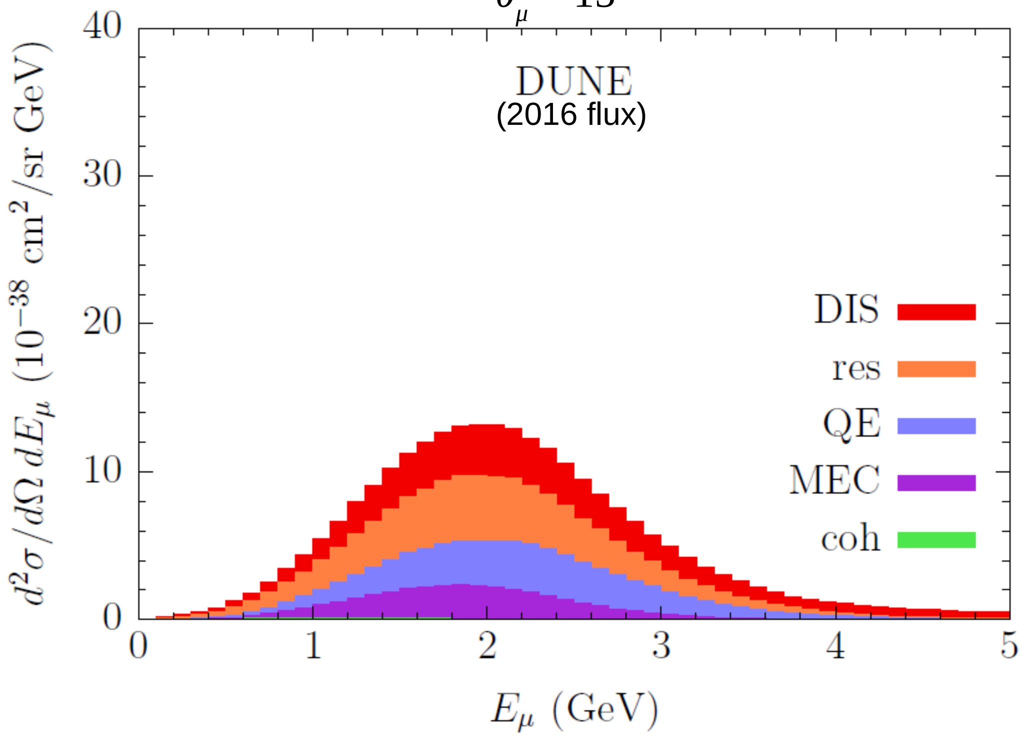
Neutrino double differential cross section



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

Neutrino double differential cross section

$\theta_\mu = 15°$



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

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 ($\varrho = 0.16/\mathrm{fm}^3$)

- ν's: ~6.3×10^{12} fm

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

- p's: ~3.5 fm

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

- γ's: ~310 fm

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

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

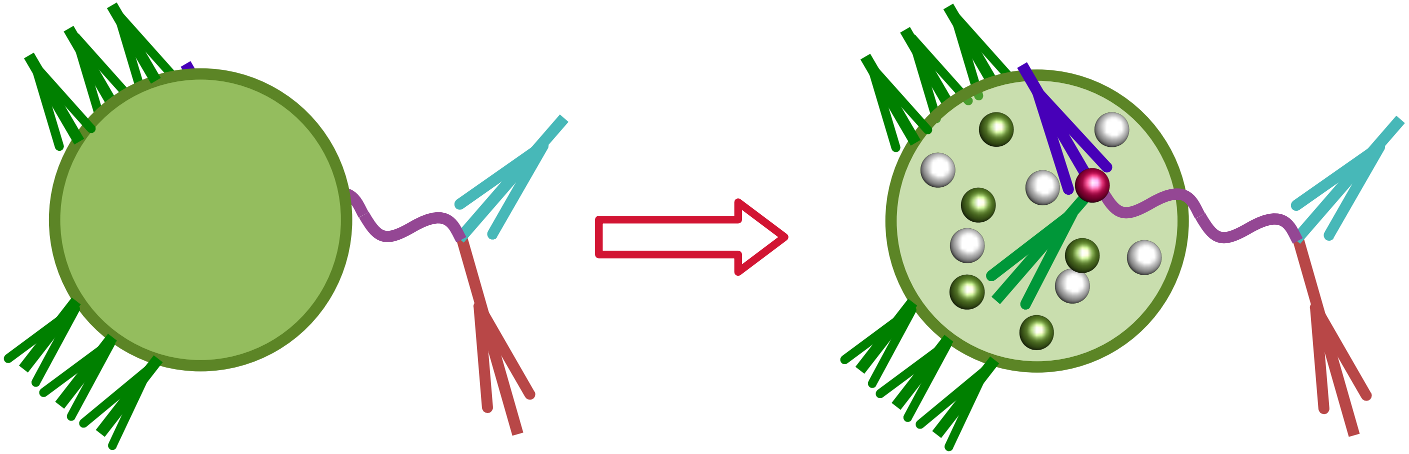
  assuming $\sigma = 0.01/A$ mb [QE @ 1.3 GeV, $\theta \geq 12°$, see Baran *et al.*, PRL 61, 400 (1988)]

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

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).



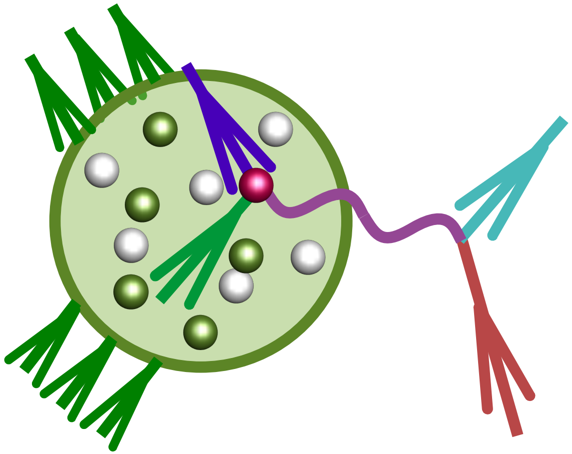
Impulse approximation

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

average over the initial nucleon state

nucleon cross section

final-state interactions



Electrons and neutrinos

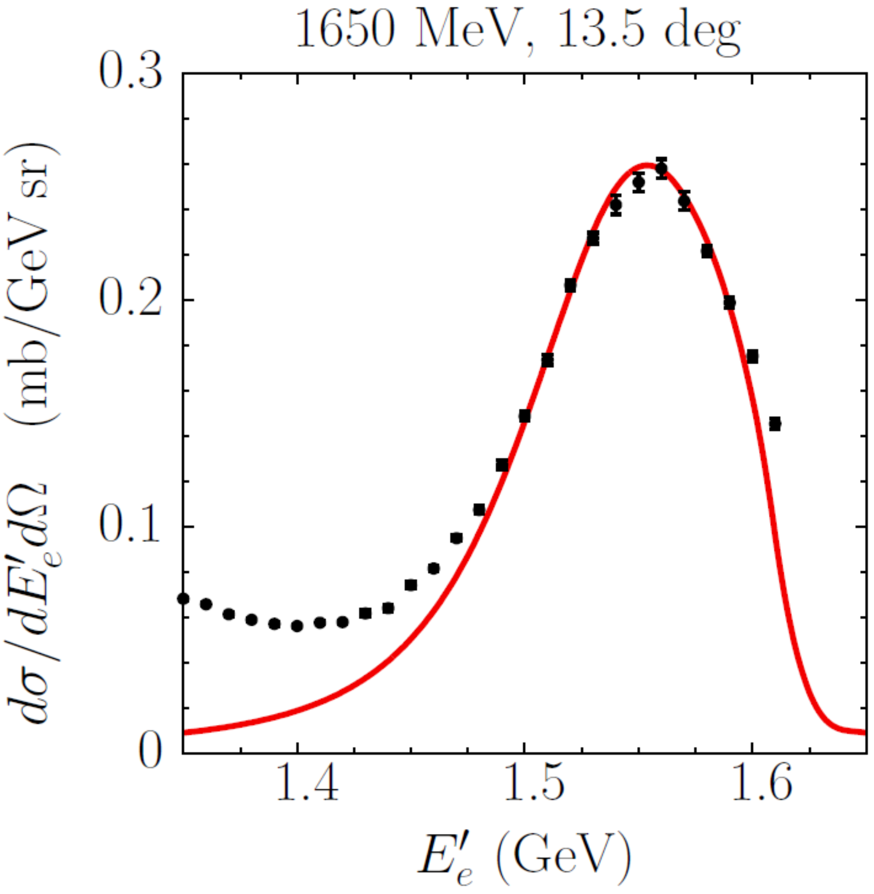
For scattering in a given angle and energy, *ν*'s and *e*'s differ almost exclusively due to the elementary cross sections.

Electron-scattering data can provide information on

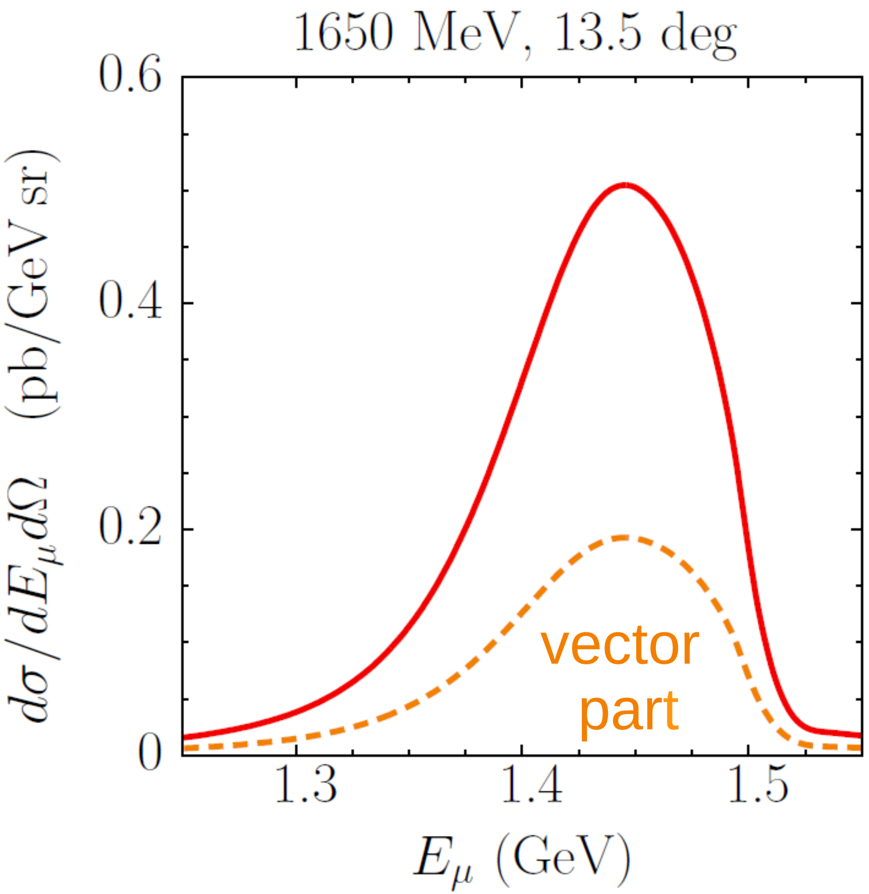
- the vector contributions to elementary neutrino cross sections
- proton and neutron spectral functions (Ar & Ti targets)
- hadronization (H & D targets)
- final-state interactions (Ar & Ti + H & D targets)

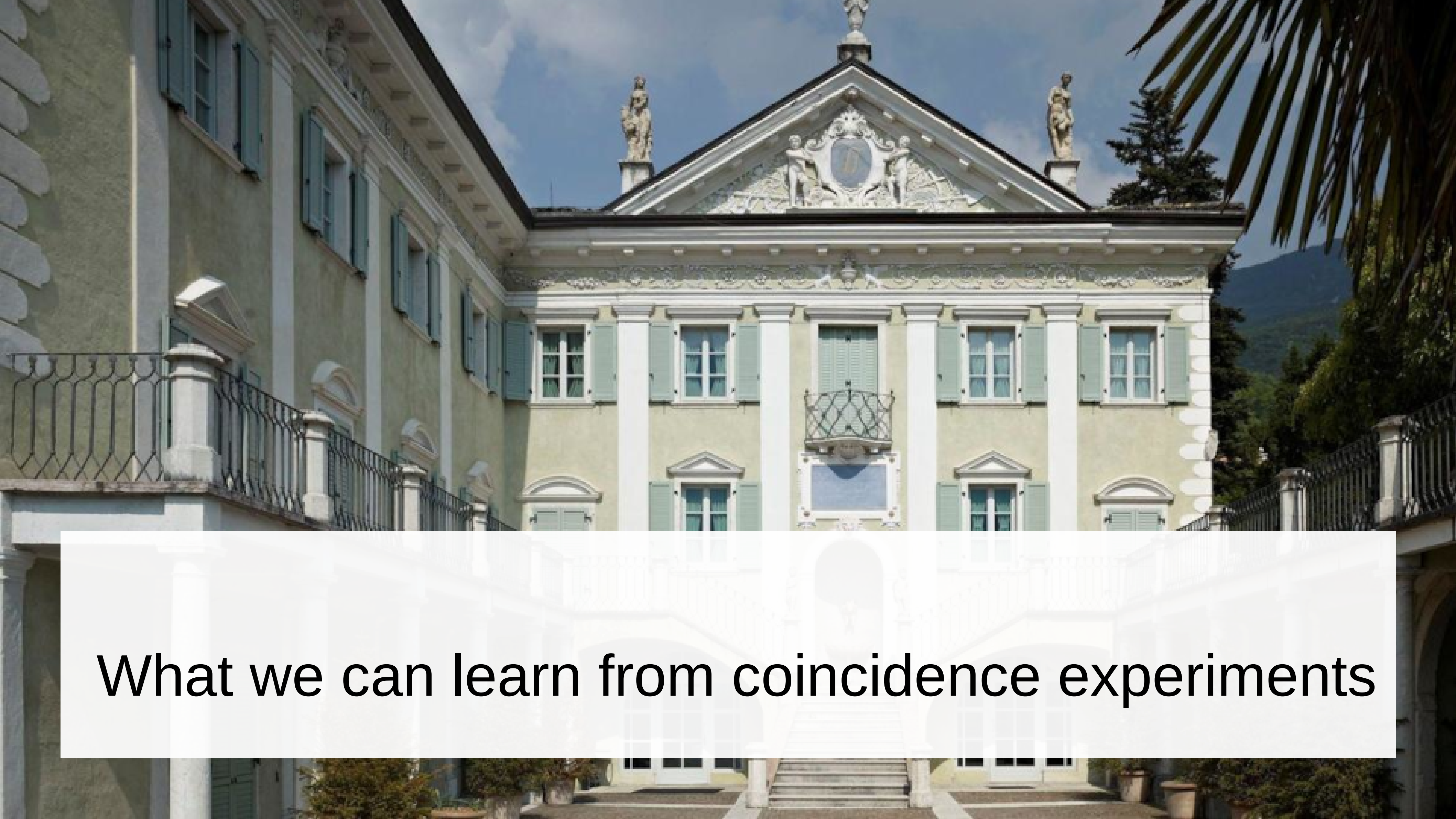
Electron data allow MC validation, reduction of systematic uncertainties, as well as their rigorous determination.

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



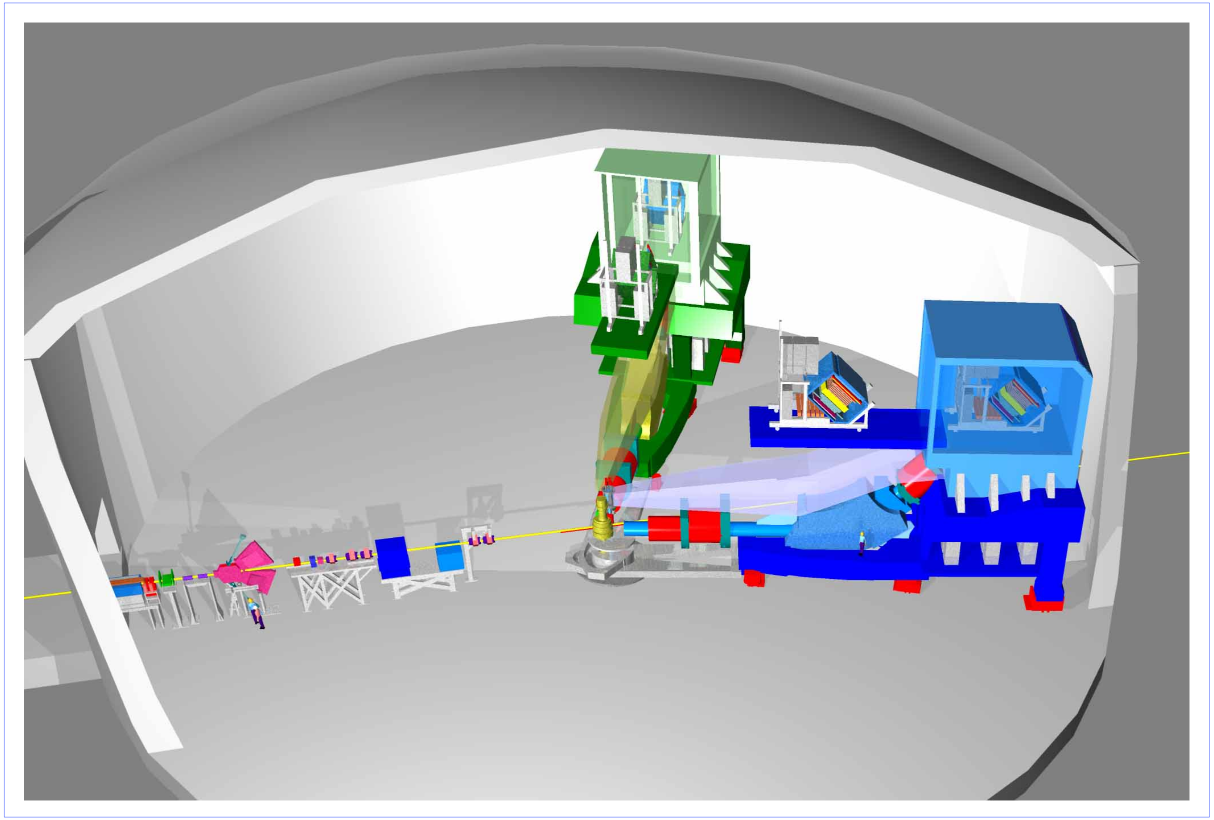
muon neutrinos



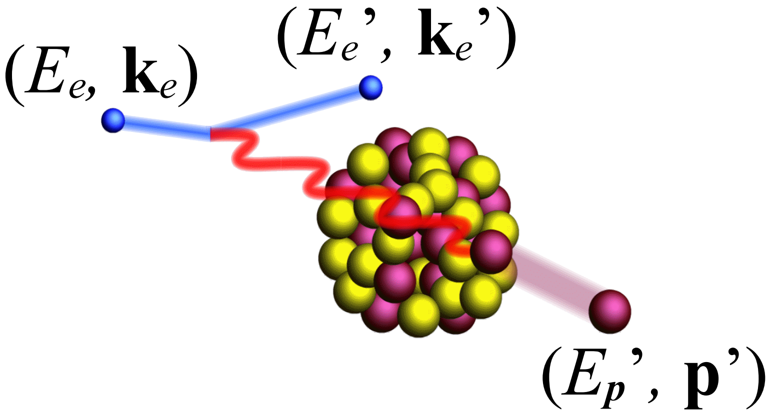


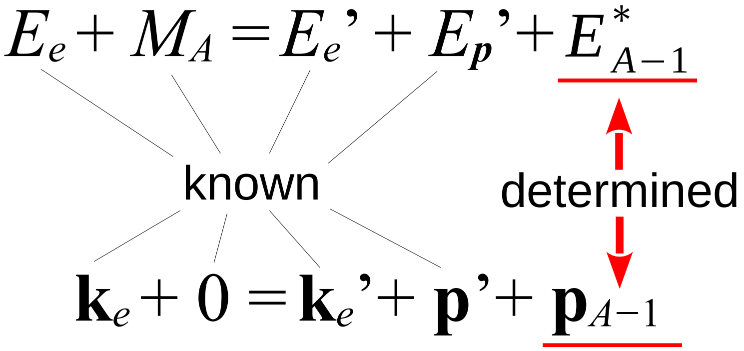
What we can learn from coincidence experiments

Coincidence experiments



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,

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

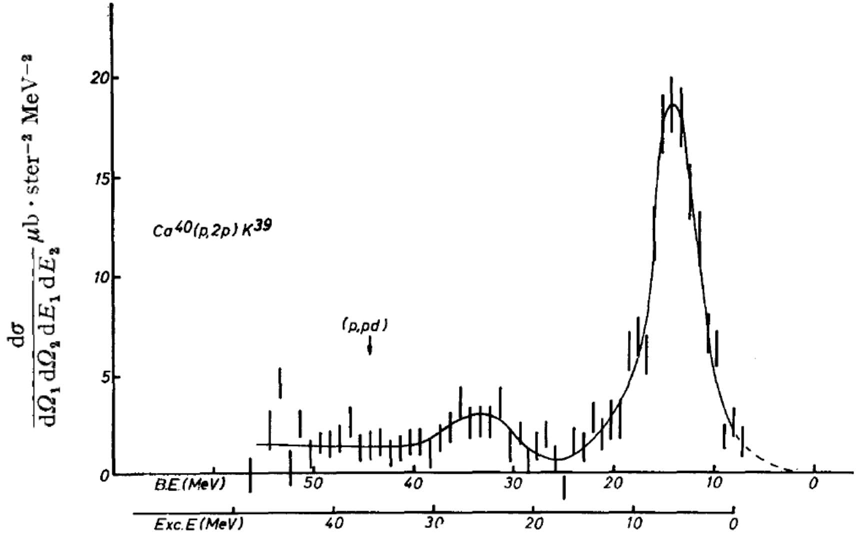
$E_m - E_{\mathrm{thr}}$ is the excitation energy of ^{39}Cl

Without final state interactions

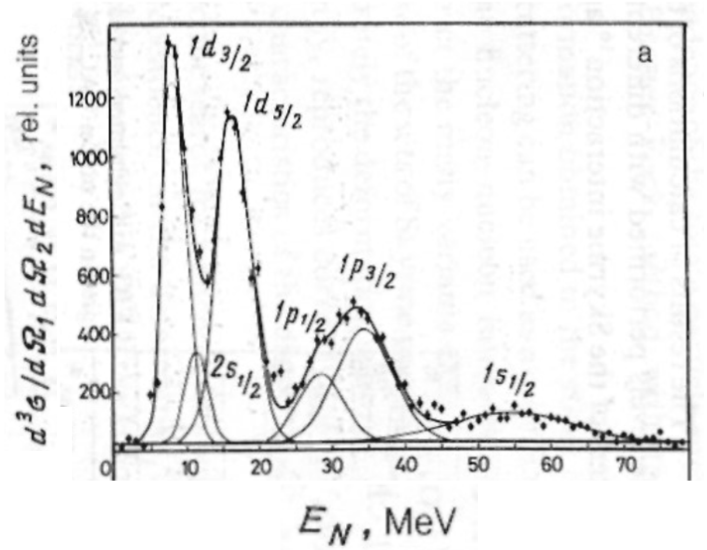
$$-\,\mathbf{p}_{A-1} = \mathbf{p}_m$$

is the initial proton momentum

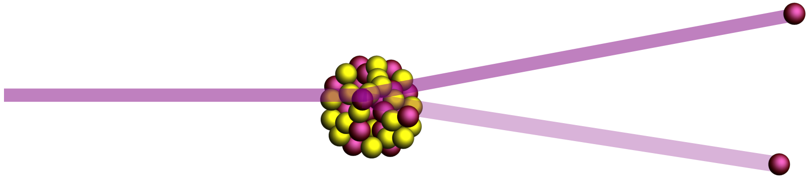
Proton coincidence scattering

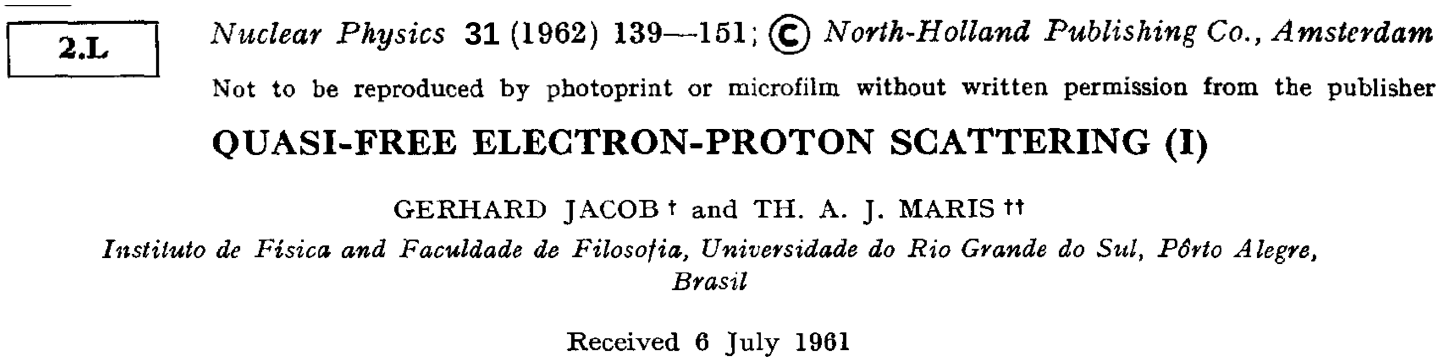


Tyren *et al.*, NP 7, 10 (1958)



Volkov *et al.*, SJNP 52, 848 (1990)





2.L

Nuclear Physics **31** (1962) 139—151; © *North-Holland Publishing Co., Amsterdam*

QUASI-FREE ELECTRON-PROTON SCATTERING (I)

GERHARD JACOB † and TH. A. J. MARIS ††

Instituto de Física and Faculdade de Filosofia, Universidade do Rio Grande do Sul, Pôrto Alegre, Brasil

Received 6 July 1961

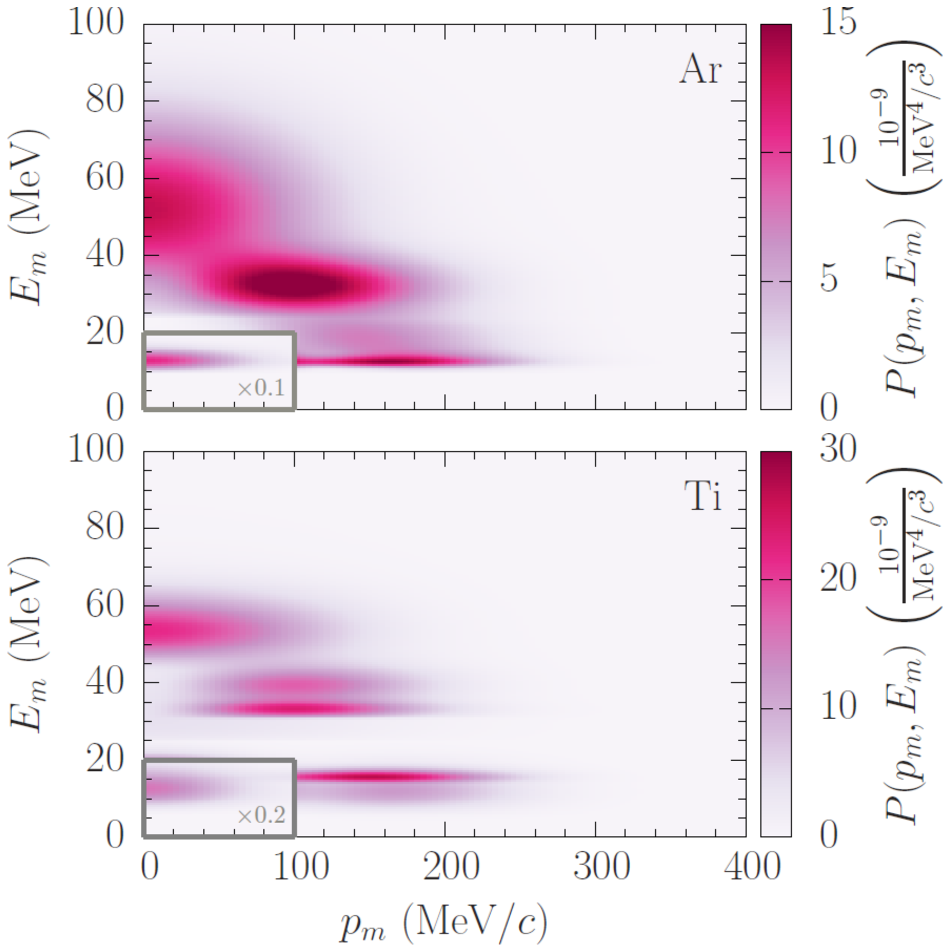
"… quasi-free **(e,e′p) scattering should offer a clear advantage over the (p,2p) processes**. … In a quasi-free (e,e′p) scattering event only the outgoing proton has an appreciable chance of being absorbed in the nucleus. Therefore surface interactions are much less accentuated than in the (p,2p) scattering and **the contributions of the inner shells relatively to those of the upper shell will be much larger**, especially for medium or heavy nuclei."

"The electron-proton angular correlation distributions would, for light and medium nuclei, nearly directly give **the momentum distributions of the separate shells**."

^{40}Ar(*e*,*e'p*) and ^{40}Ti(*e*,*e'p*) in JLab

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

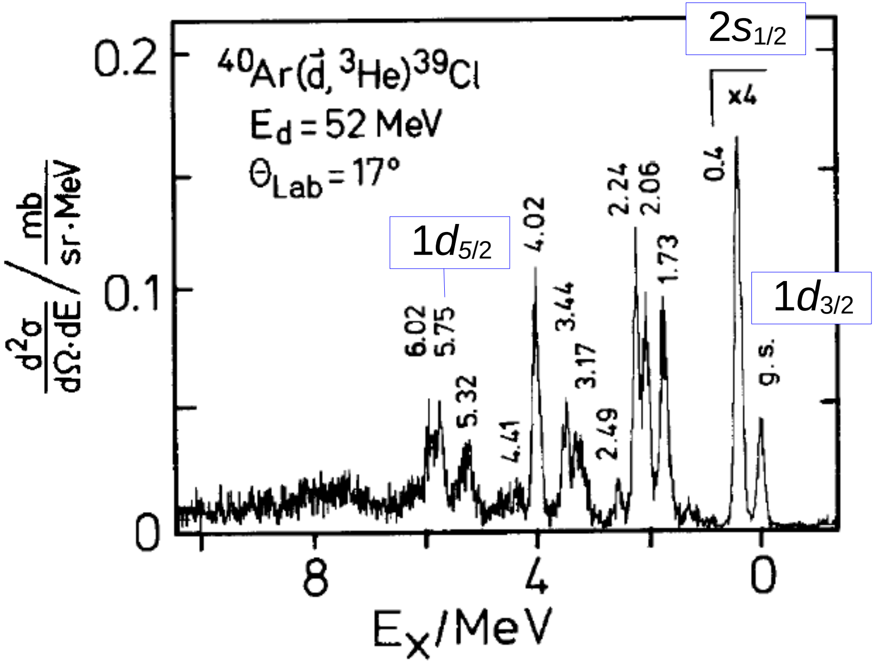
- Beam energy 2222 MeV
- $0 \leq p_m \leq 300$ (250) MeV for Ar (Ti)
- $12 \leq E_x \leq 80$ MeV, resolution 6–7 MeV
- Priors from hadronic experiments essential to identify contributions



$^{40}\mathrm{Ar}(\vec{d}, {}^{3}\mathrm{He})^{39}\mathrm{Cl}$ 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 $1d$ shells, the spectroscopic factors exceed the IPSM expectations
- No uncertainties assigned

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



Energy levels of protons in ^{40}Ar

- $(1d_{3/2})^{-1}$ energy from the difference between the ^{40}Ar and ^{39}Cl masses, correcting for the extra m_e,

  12.5286744 ± 0.0017316 MeV

  Wang *et al.*, Chin. Phys. C 41 (2017) 030002

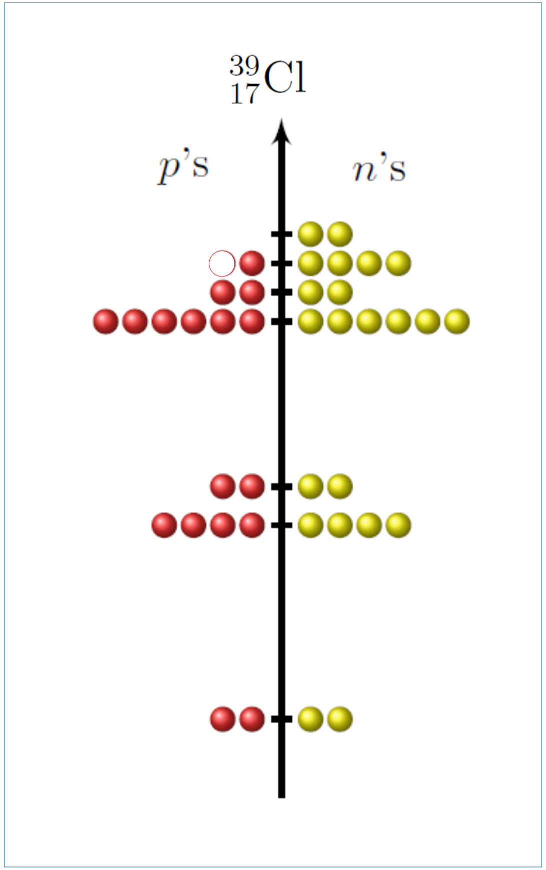
- $(2s_{1/2})^{-1}$ energy from the results of Mairle *et al.*, its uncertainty dominated by that of the ^{39}Cl mass 1.716 keV,

  12.9250944 ± 0.0017331 MeV

  Chen, Nucl. Data Sheets 149 (2018) 1

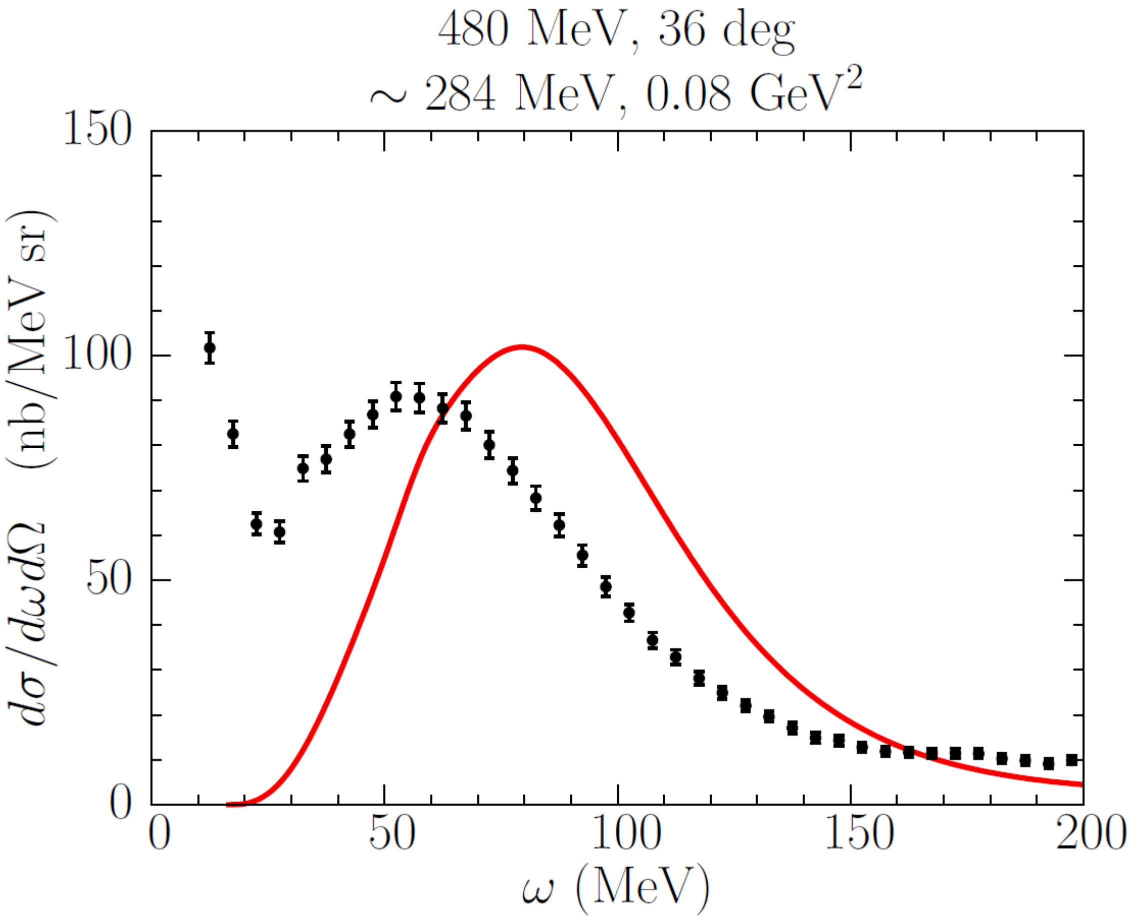
- $(1d_{5/2})^{-1}$ energy uncertainty dominated by that of the E_x value

  18.2286744 ± 0.0150996 MeV



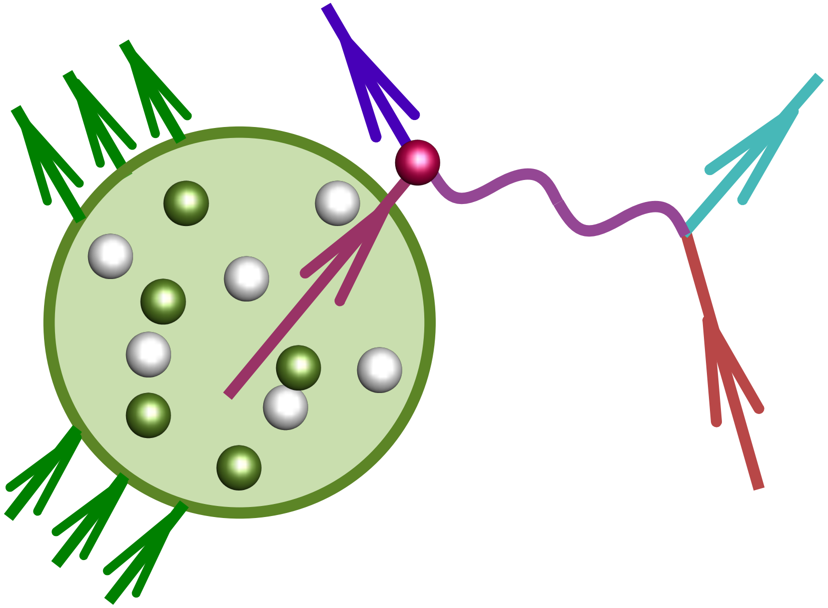
What we can learn from inclusive experiments

What is missing?



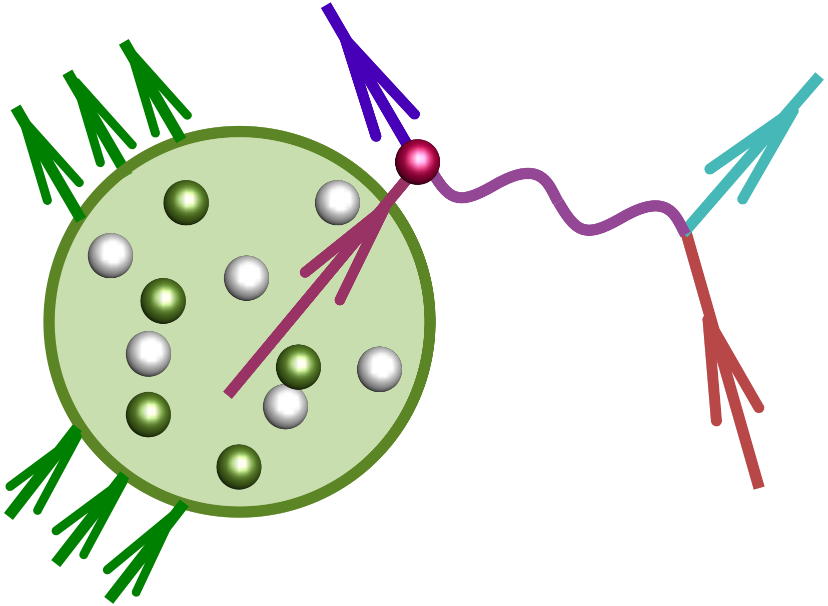
Energy conservation

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

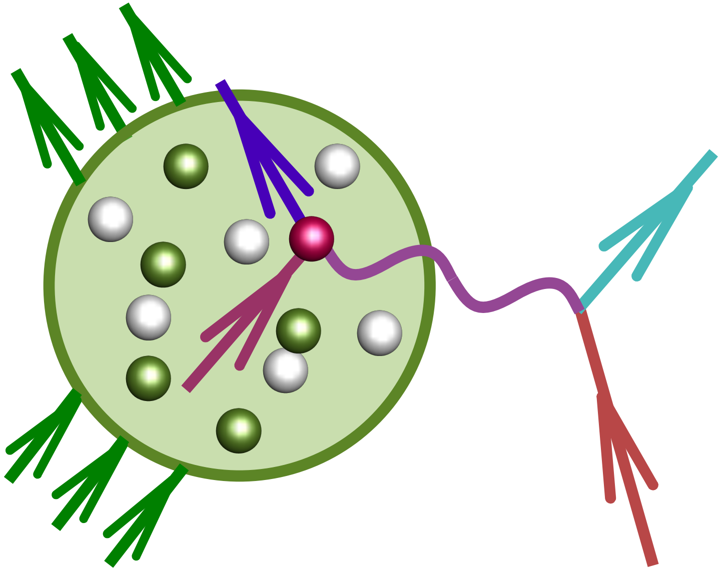


Energy conservation

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

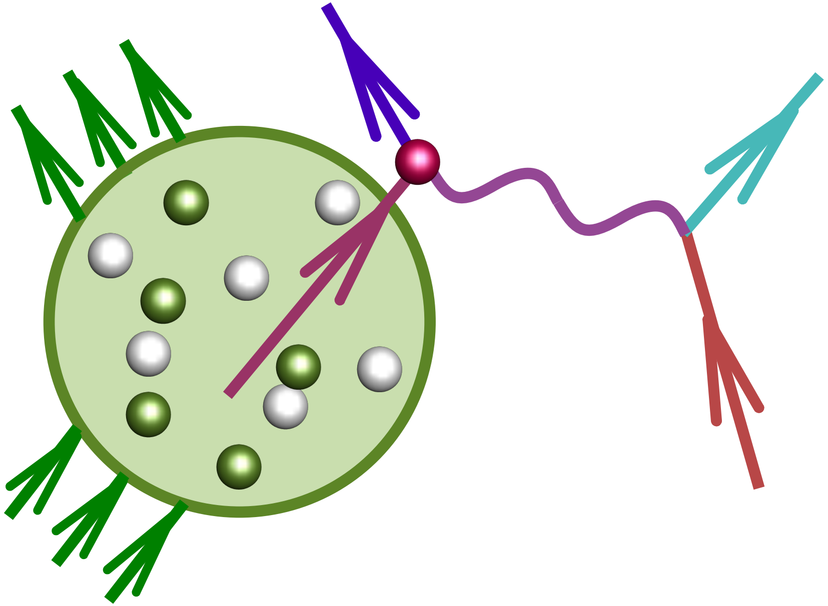


$$E_\nu + M_A = E_\mu + E_{A-1} + E_{p'} + U_V(p')$$

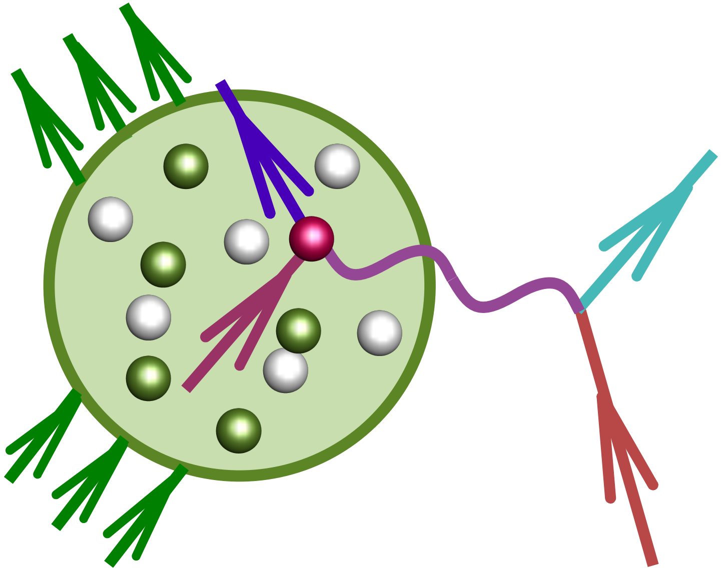


Energy conservation

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



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



Final-state interactions

The convolution approach,

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

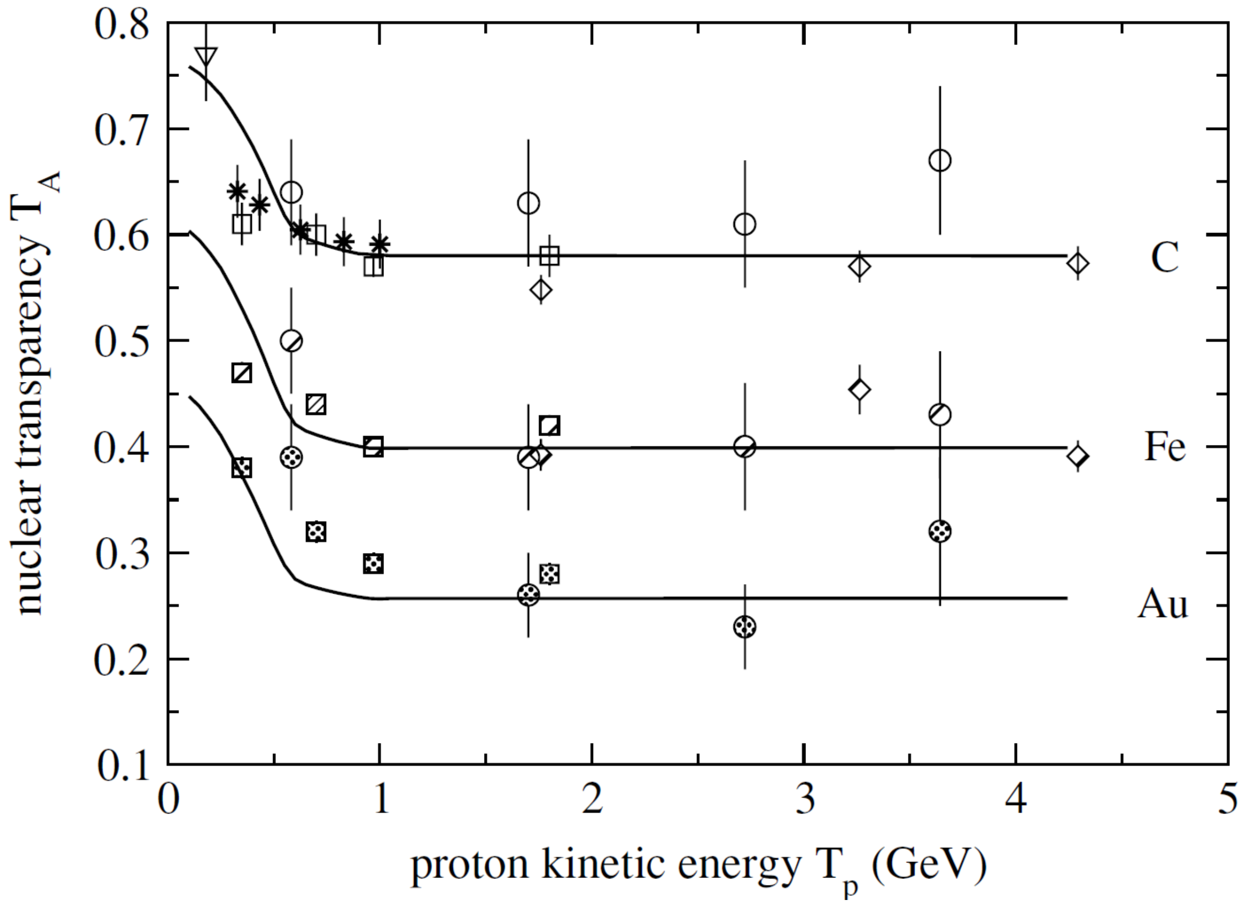
with the folding function

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

and nuclear transparency T_A.

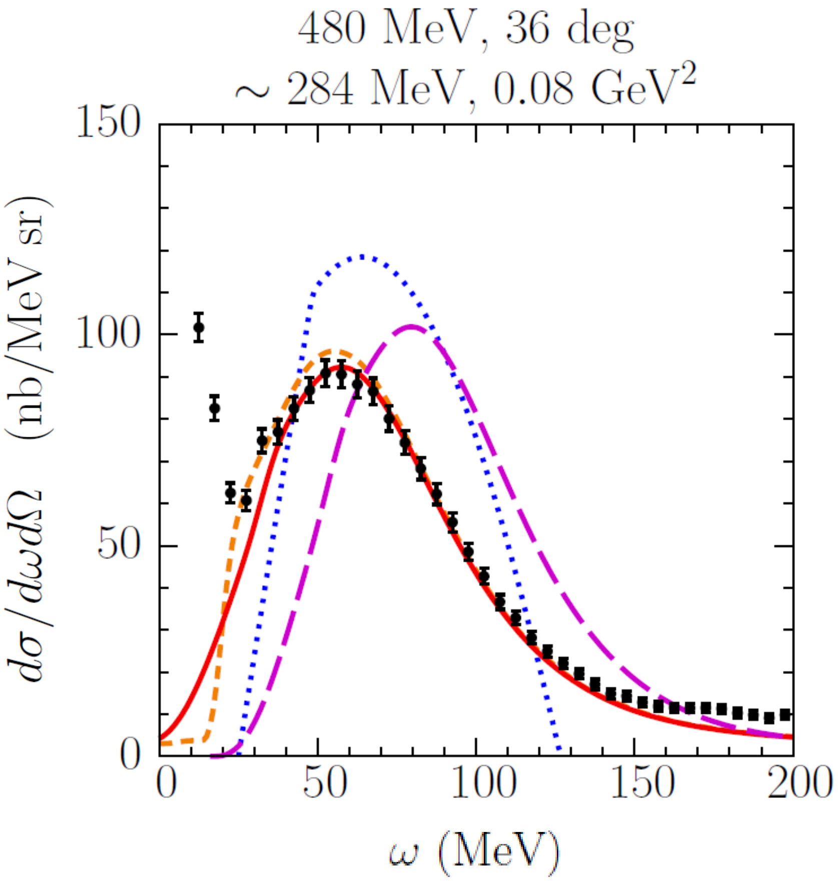
O. Benhar, PRC 87, 024606 (2013)

Nuclear transparency



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

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



RFG

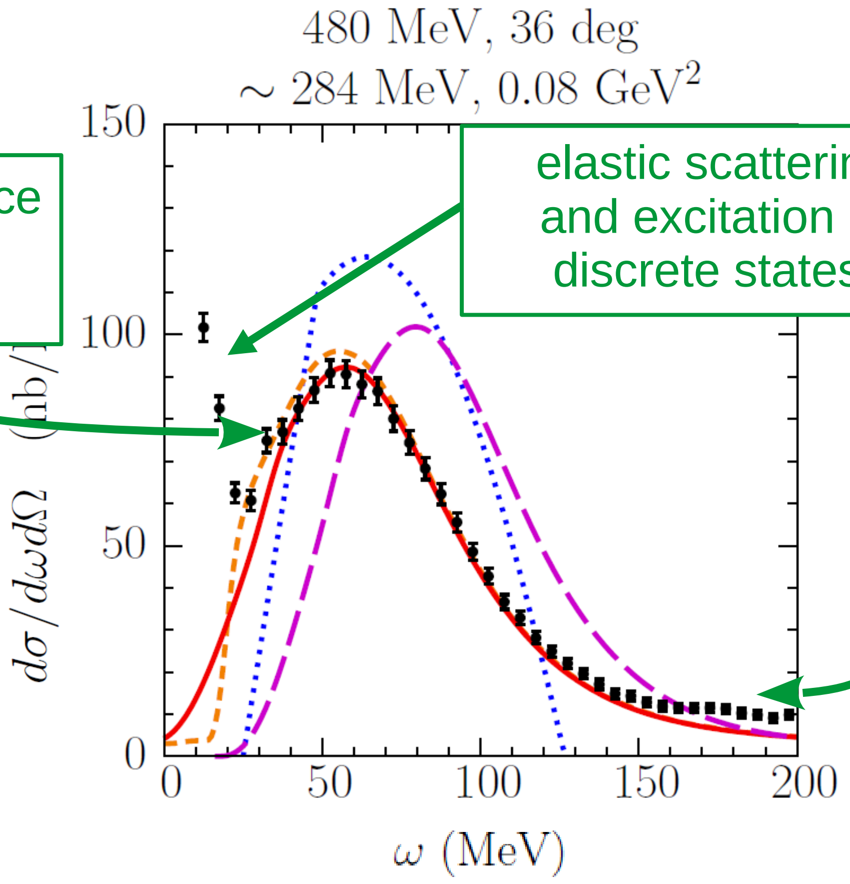
SF w/o FSI

SF w/ FSI,
LDA treatment
of Pauli blocking

SF w/ FSI,
step function

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

What is not included?



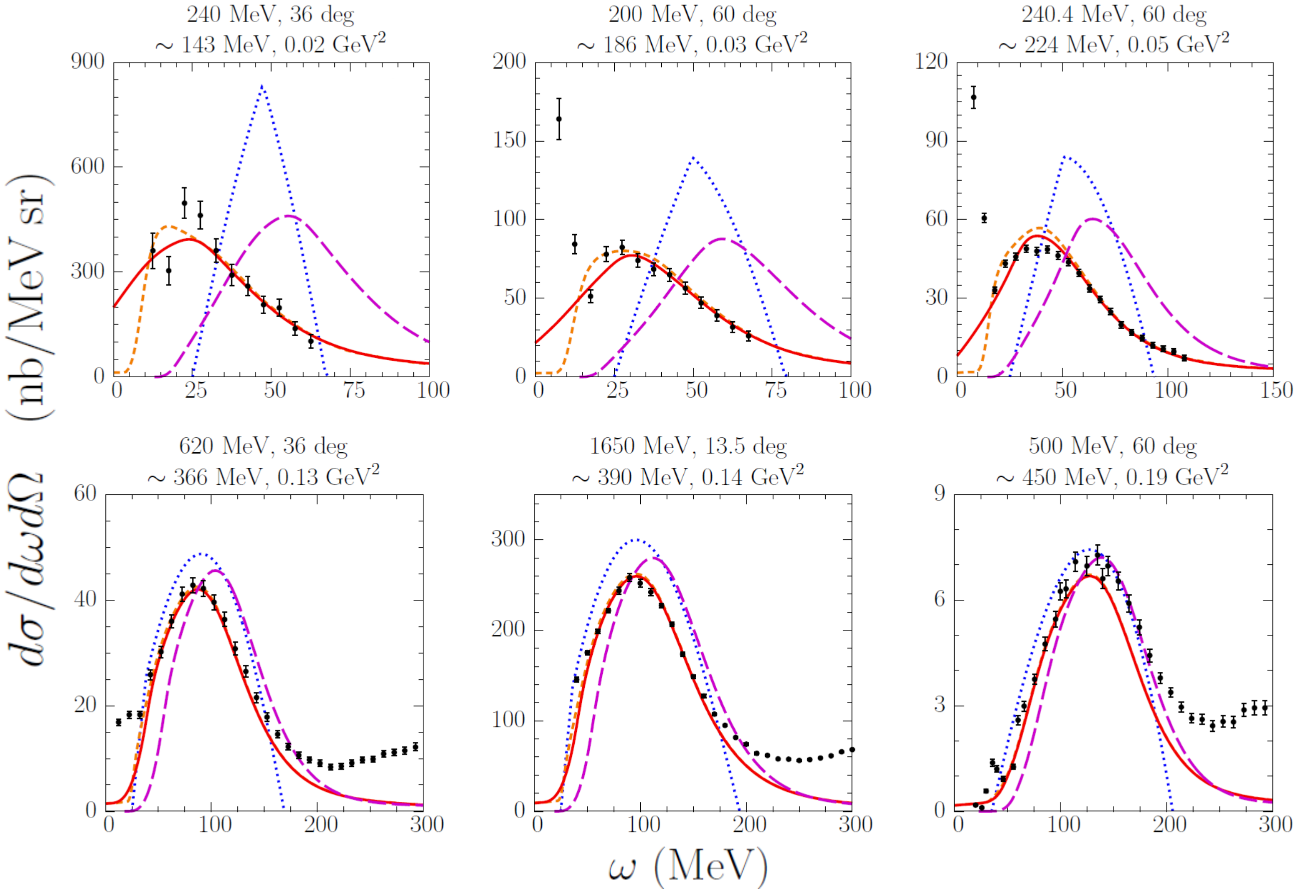
dipole resonance
$E_x = 22.6$ MeV
$\Gamma = 3.2$ MeV

elastic scattering and excitation of discrete states

pion production and 2-body currents

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

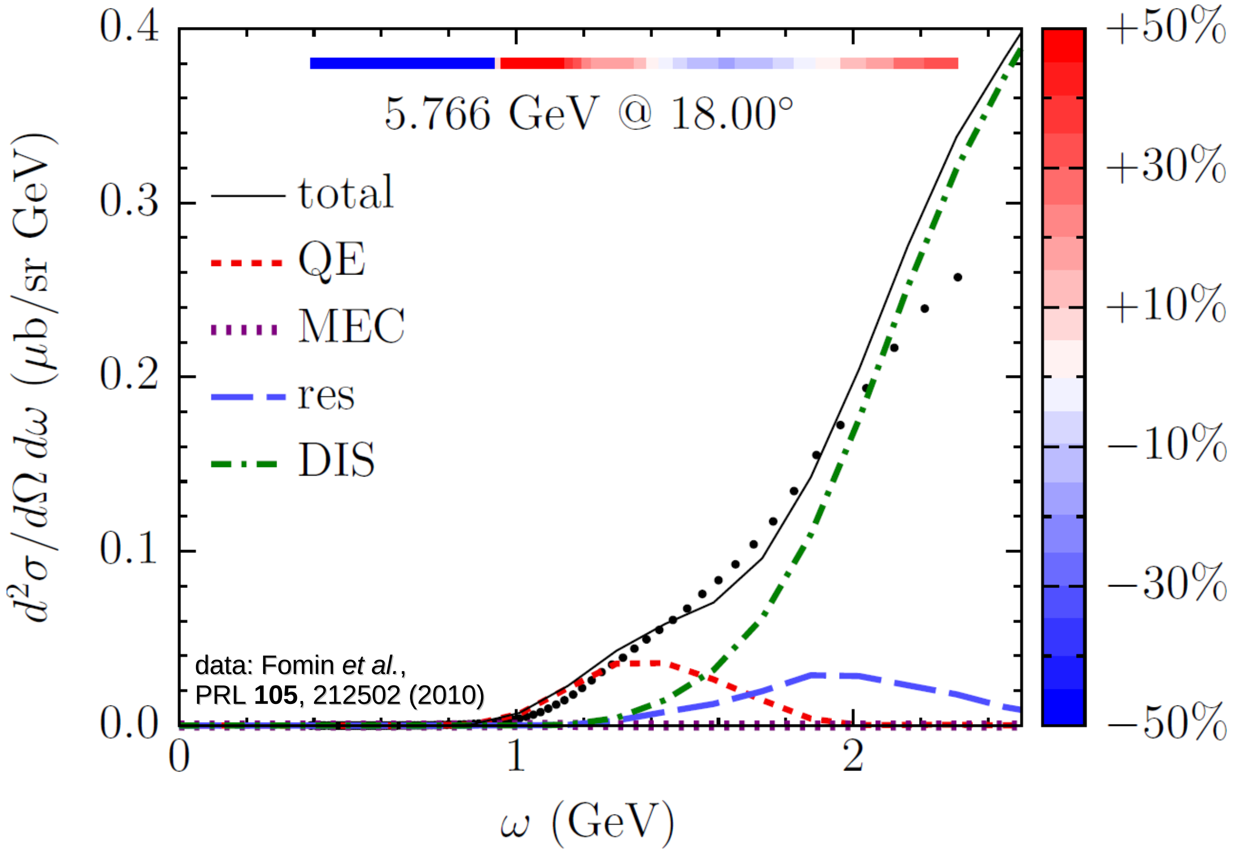
Realistic description of the nucleus: C(*e*,*e'*)



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

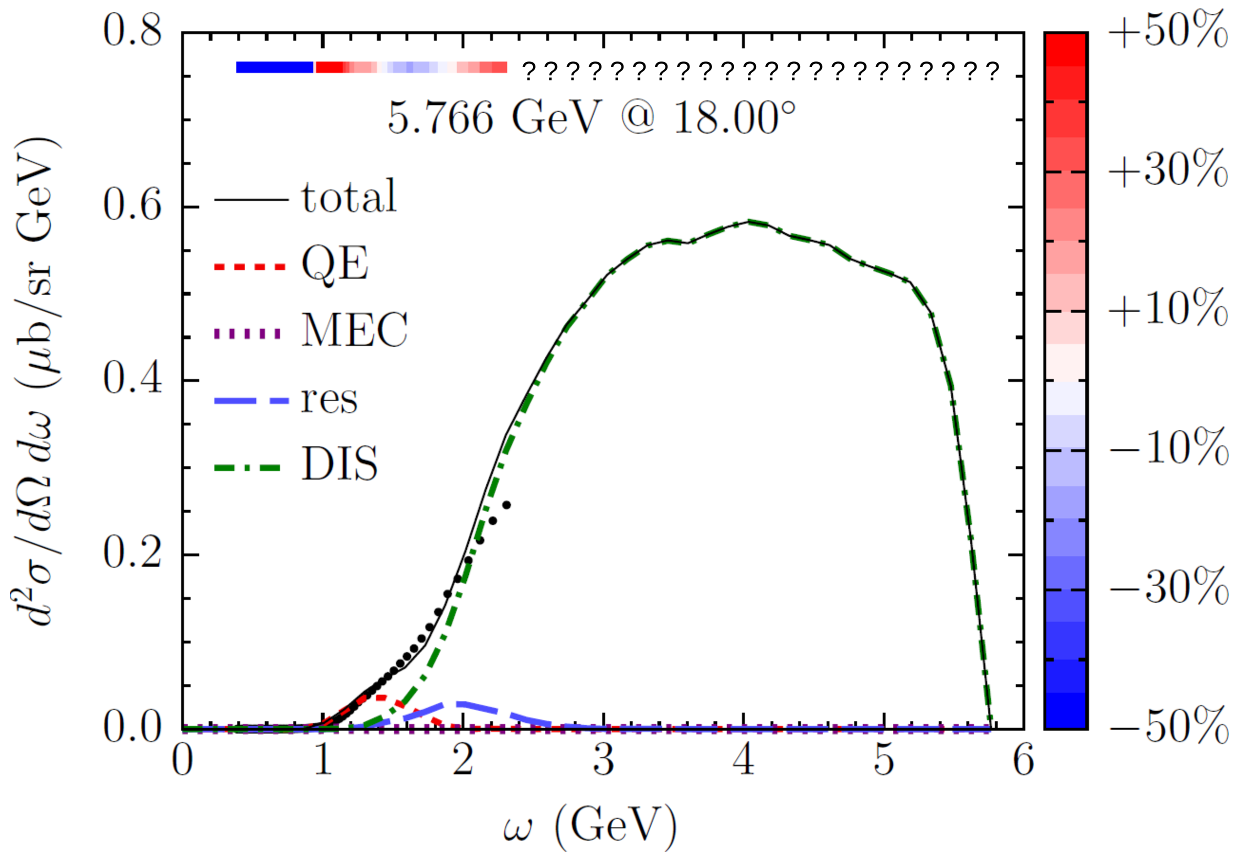
How we can identify the gaps in our knowledge

How well do we know inelastic cross sections?



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

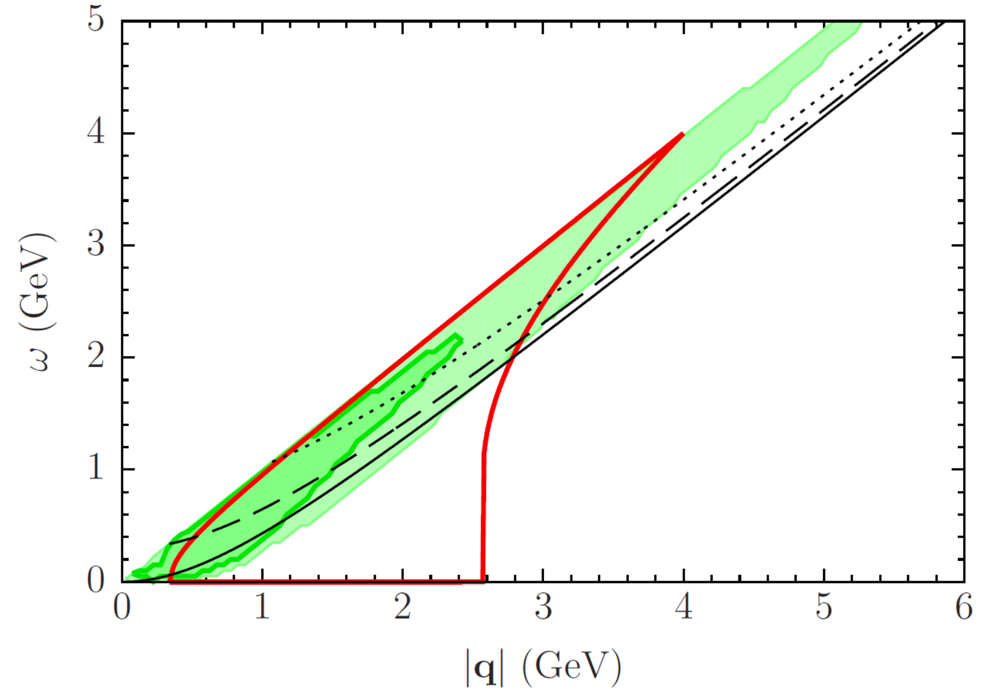
How well do we know inelastic cross sections?



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

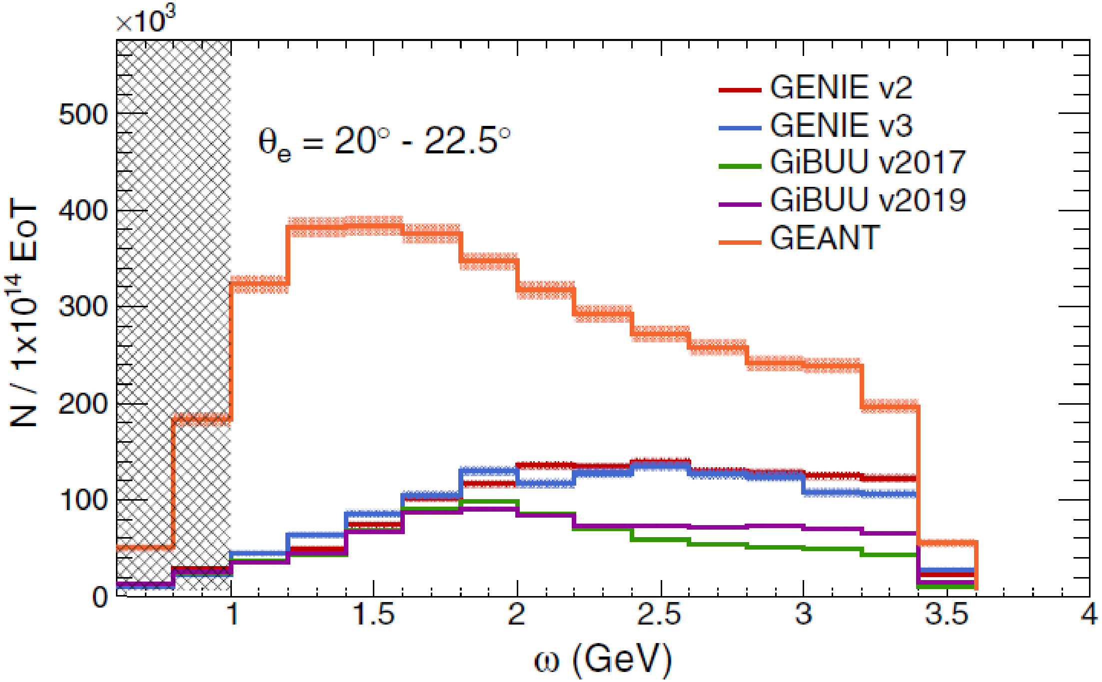
Light Dark Matter Experiment (LDMX)

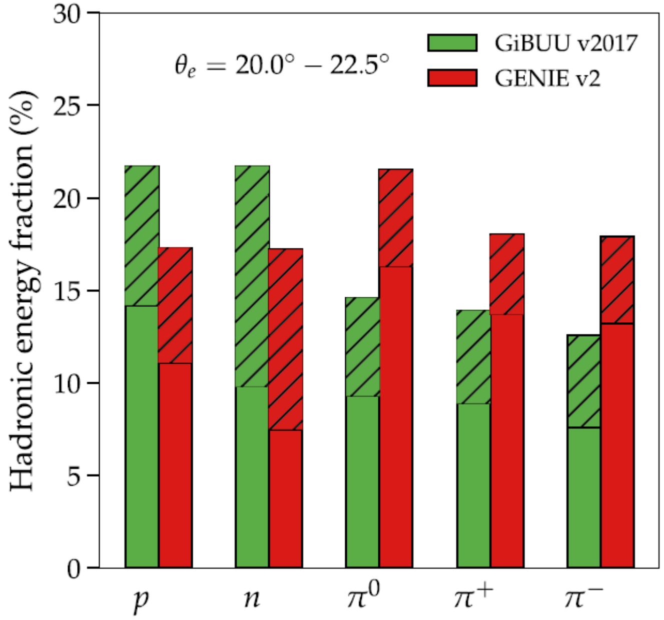
- Search for sub-GeV dark matter
- Expected signal: high-missing momentum
- Huge statistics (10^{14} electrons on target in 6 months)
- Detector coverage and hermeticity for hadrons is essential
- Beam energy 4 GeV



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

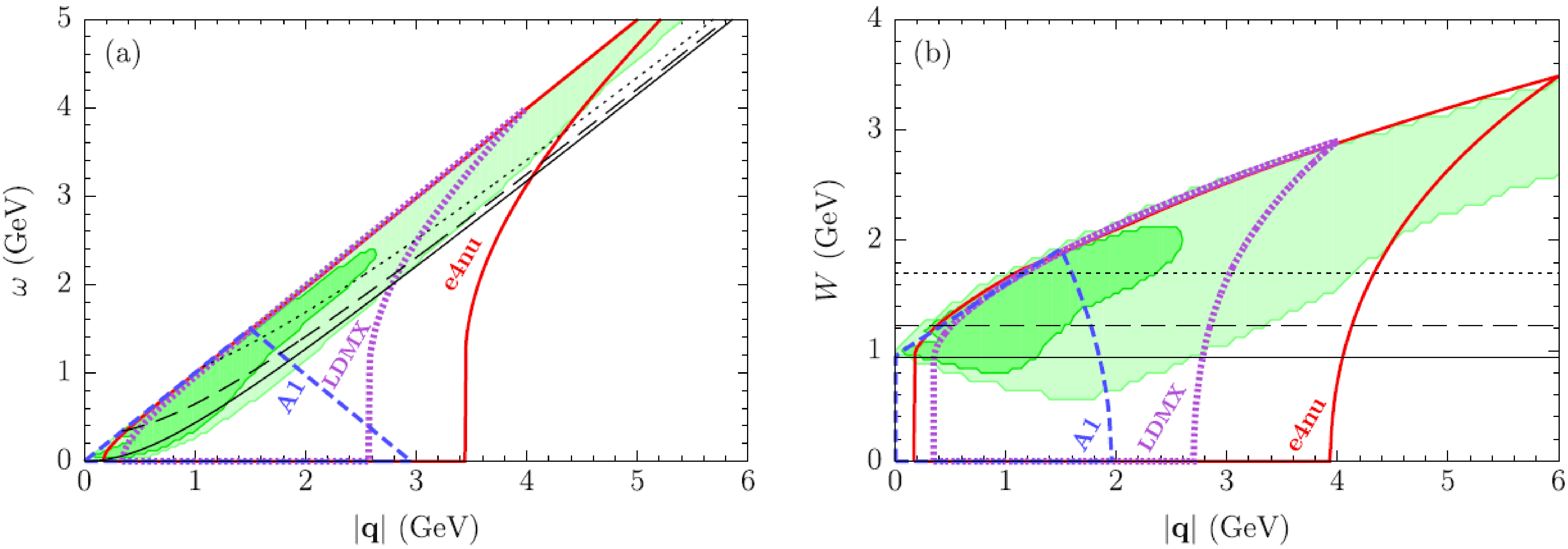
Light Dark Matter Experiment (LDMX)





- Opportunity to measure inclusive and exclusive cross sections
- Spectra of protons, pions, and neutrons could be measured
- Possible studies of hadronization and FSI, if targets can be swapped

Future Experiments



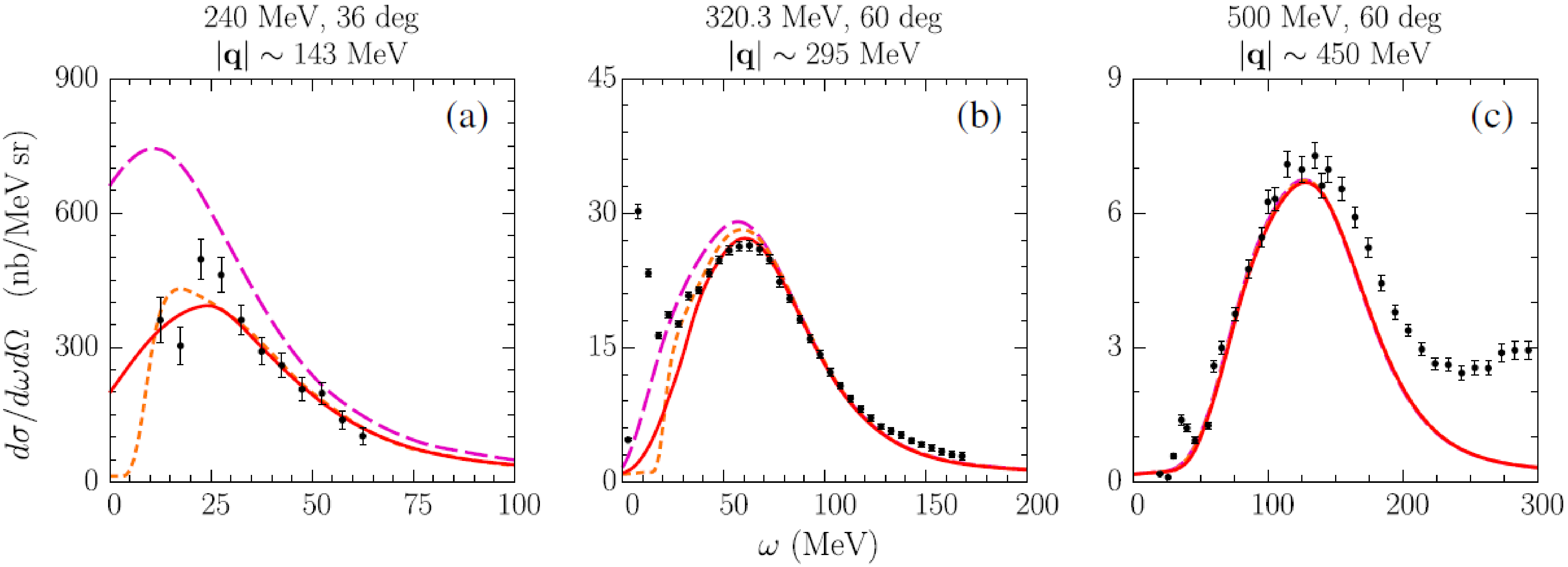
A.M.A. *et al.*, JPG 50 (2023) 120501

Summary

- The success of the neutrino-oscillation program (DUNE and Hyper-Kamiokande) requires reliable cross sections.
- Coincidence *(e, e’p)* experiments are optimal to determine the SFs.
- Inclusive *(e, e’)* cross sections can inform us on
  - FSI effects (Pauli blocking, real OP, cross-section broadening),
  - the vector contributions to neutrino cross sections,
  - consistency of the nuclear model in the transition regimes,
  - systematic uncertainty of our model.
- Exclusive cross sections for hadrons, especially neutron multiplicities and spectra for argon. Ti*(e,e’p)* may be a simple way forward.

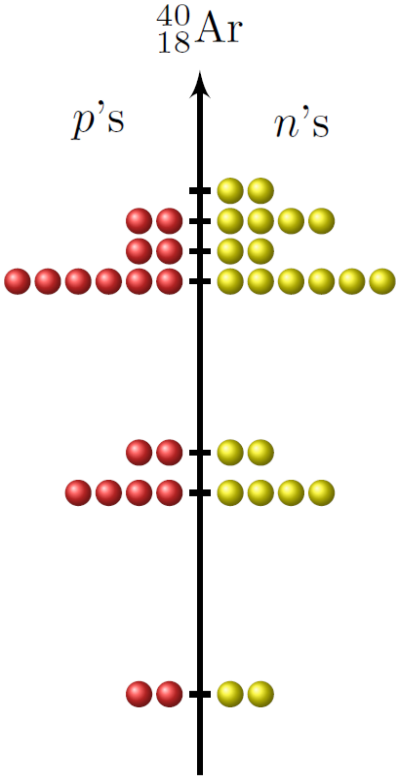
Thank you!

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



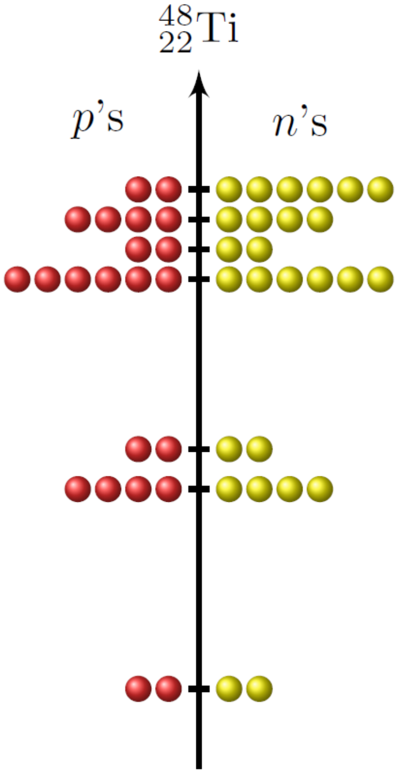
A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

Energy levels

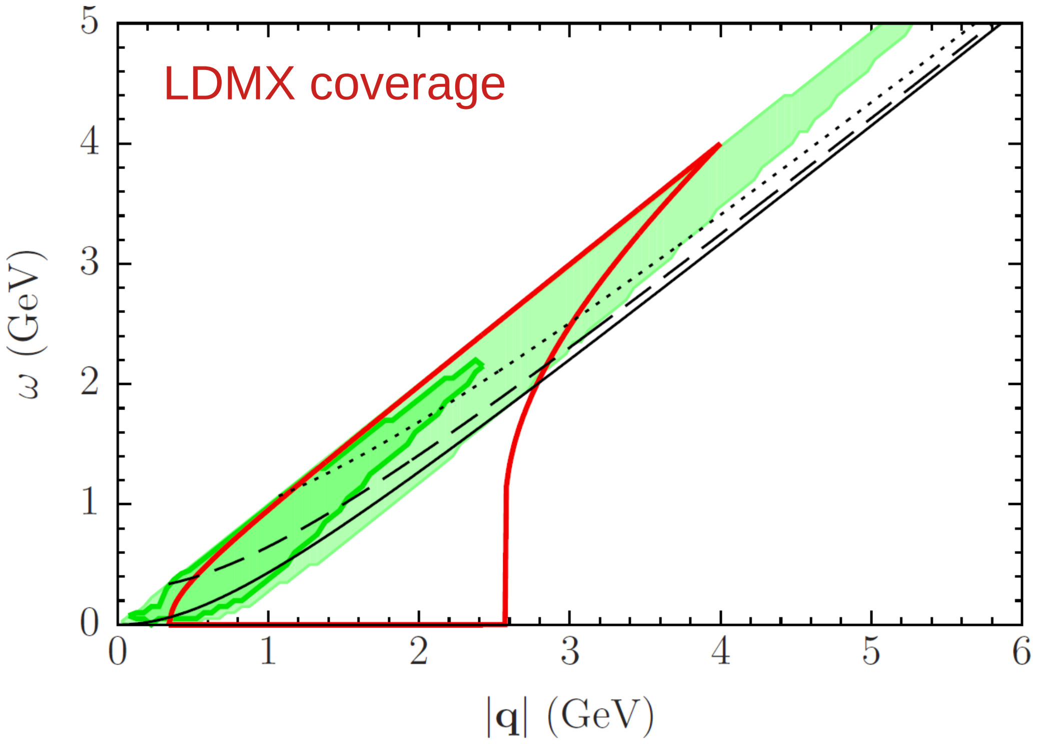


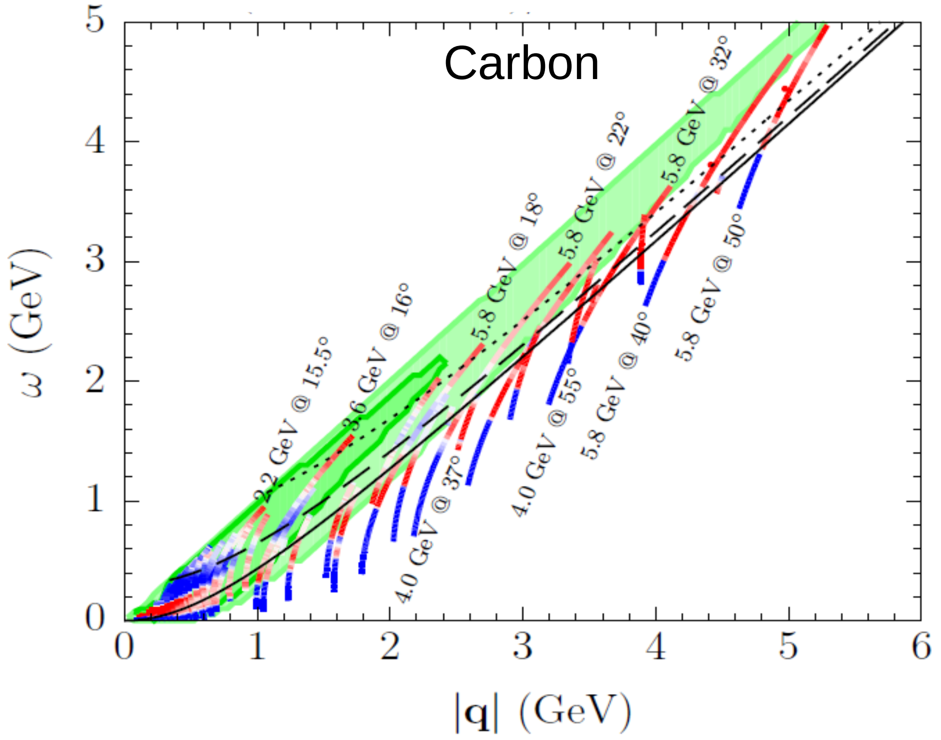
^{40}Ar		^{48}Ti
neutrons		protons
9.87	1f7/2	11.45
11.39	1d3/2	12.21
12.23	2s1/2	12.84
13.23	1d5/2	15.45

Agreement to 0.6–2.2 MeV

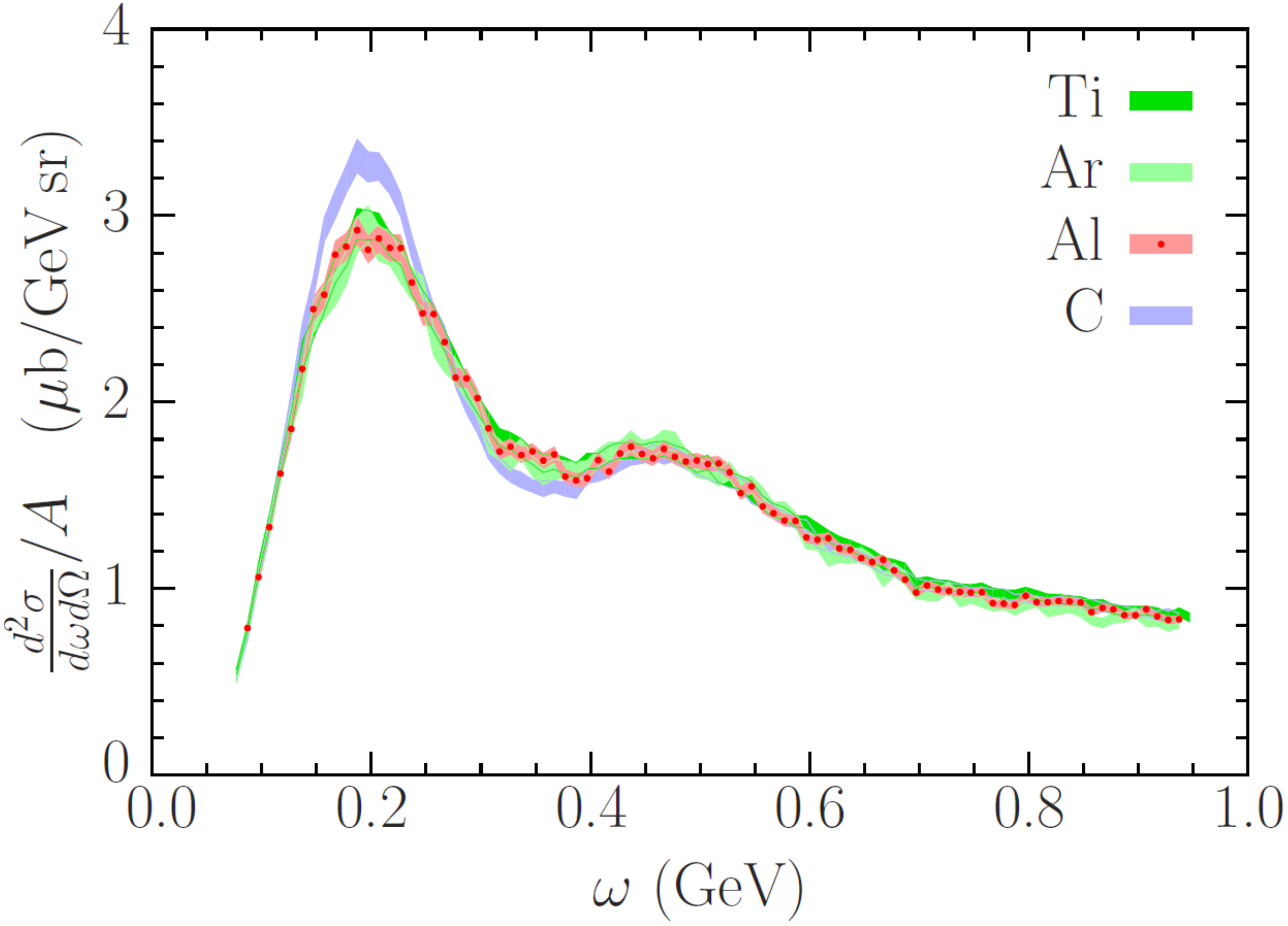


Light Dark Matter Experiment (LDMX)



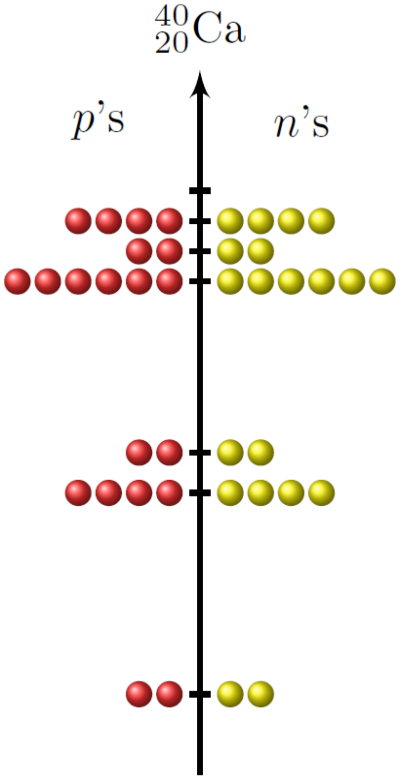


A-dependence of inclusive data



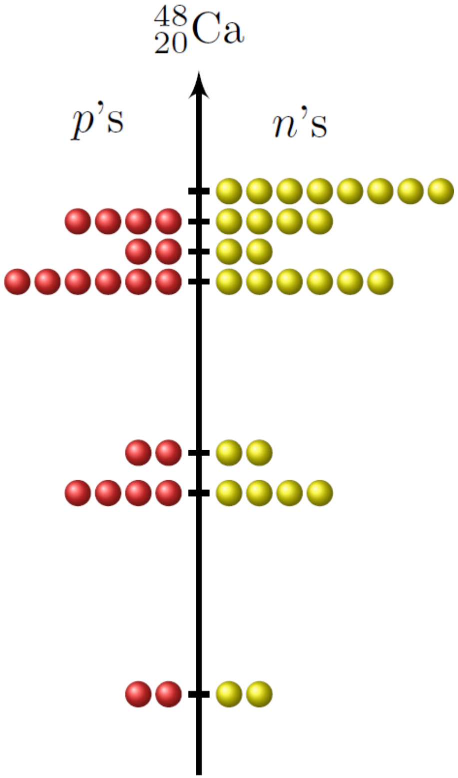
Murphy *et al.*, PRC 100, 054606 (2019)

Calcium isotopes



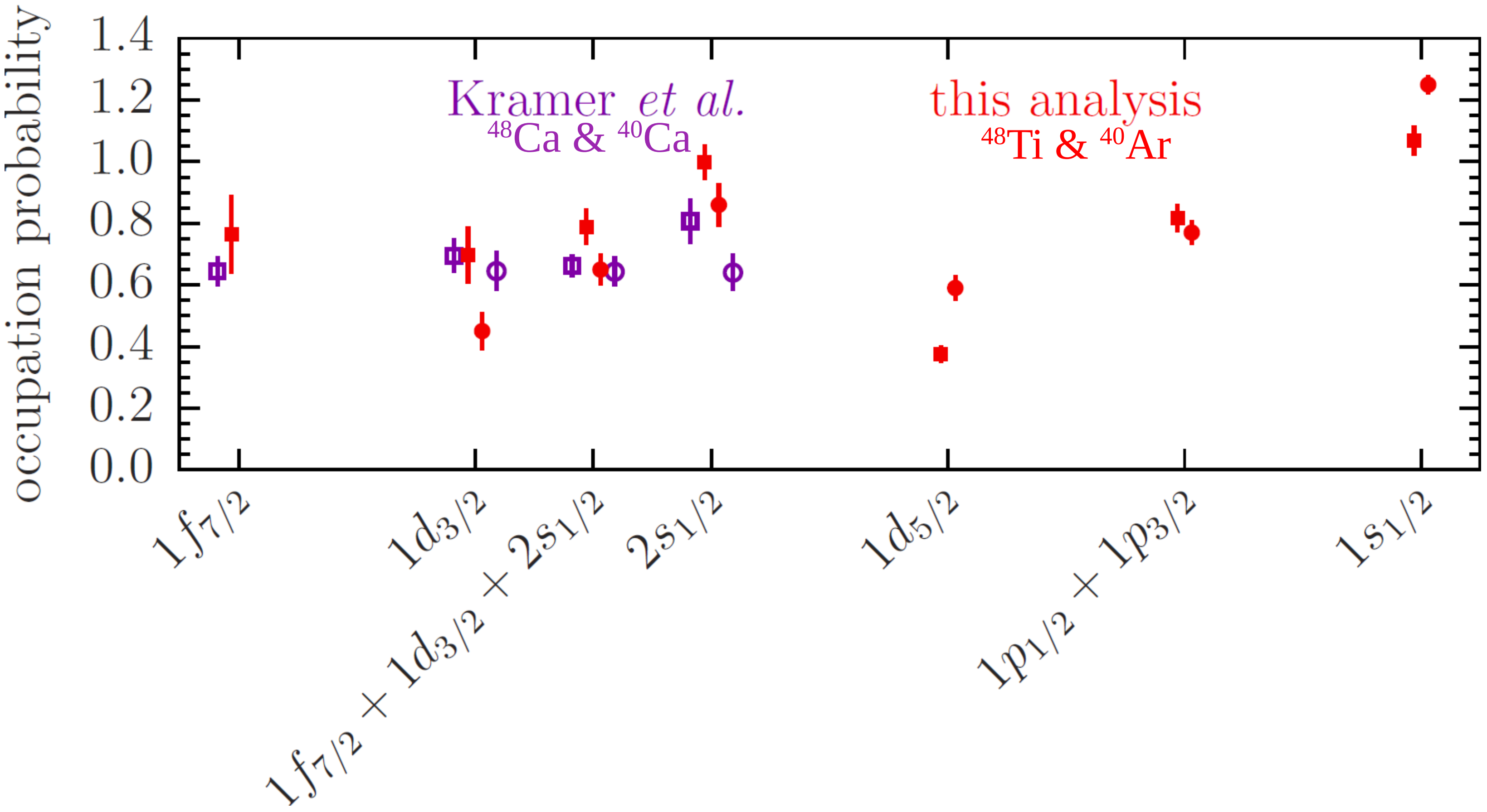
^{40}Ca		^{48}Ca
8.3(3)	1d3/2	16.8(3)
11.1(3)	2s1/2	17.1(3)
16.8(4)	1d5/2	23.9(7)

Kramer, Ph.D. thesis (1990)



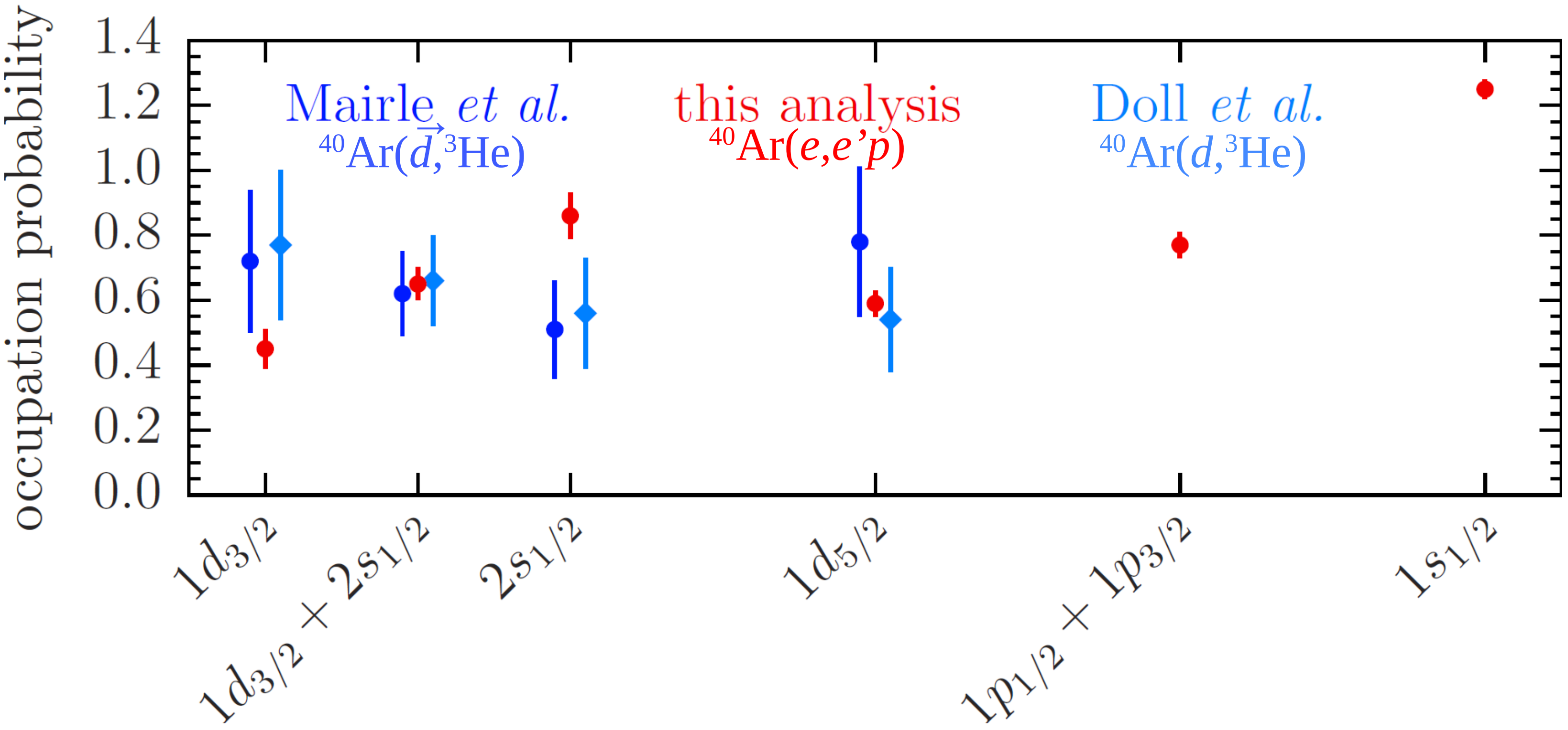
6–8.5 MeV differences

Occupation probability



Kramer *et al.* [Ph.D. thesis (1990)]: ~340–440-MeV electron beam at NIKHEF-K

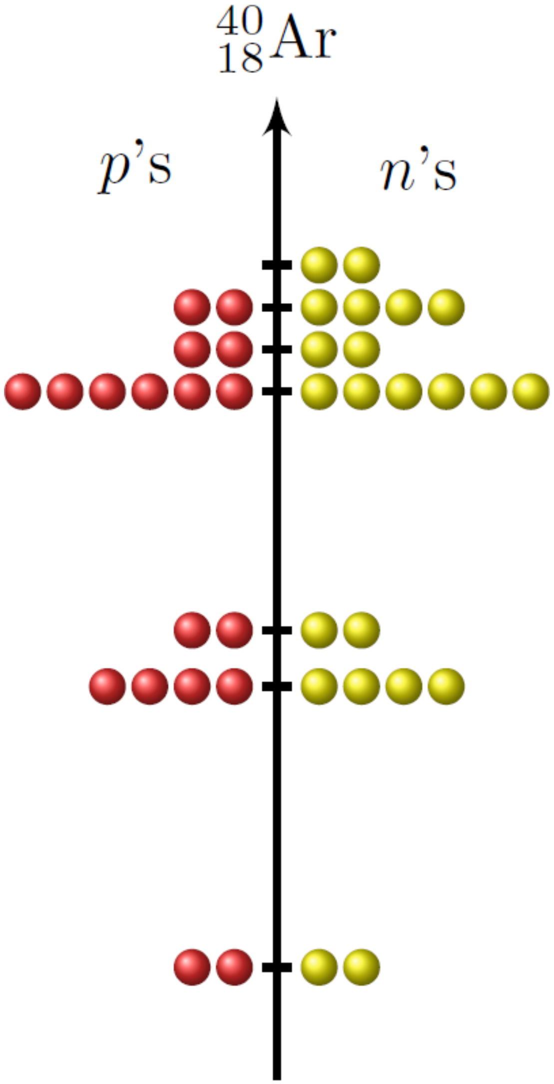
Occupation probability



52-MeV polarized [Mairle *et al.*, NPA **565**, 543 (1993); E_x < 9 MeV] and unpolarized [Doll *et al.*, NPA **230**, 329 (1974); **129**, 469 (1969); E_x < 7 MeV] deuteron beam at Karlsruhe

Kramer *et al.* [NPA **679**, 267 (2001)]: reanalysis of (d,^{3}He) experiments, $S_\alpha \rightarrow S_\alpha/1.5$

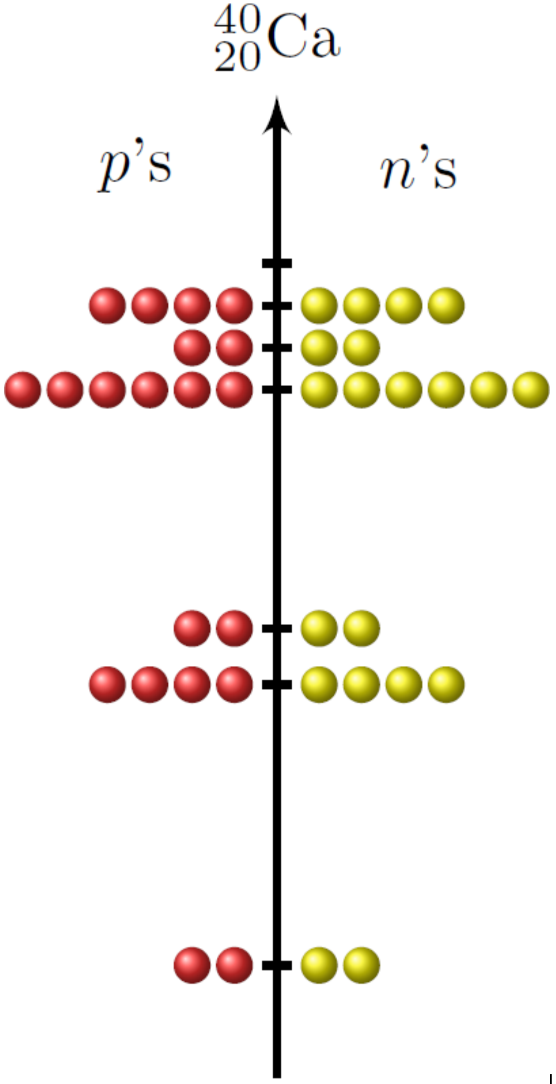
proton energy levels



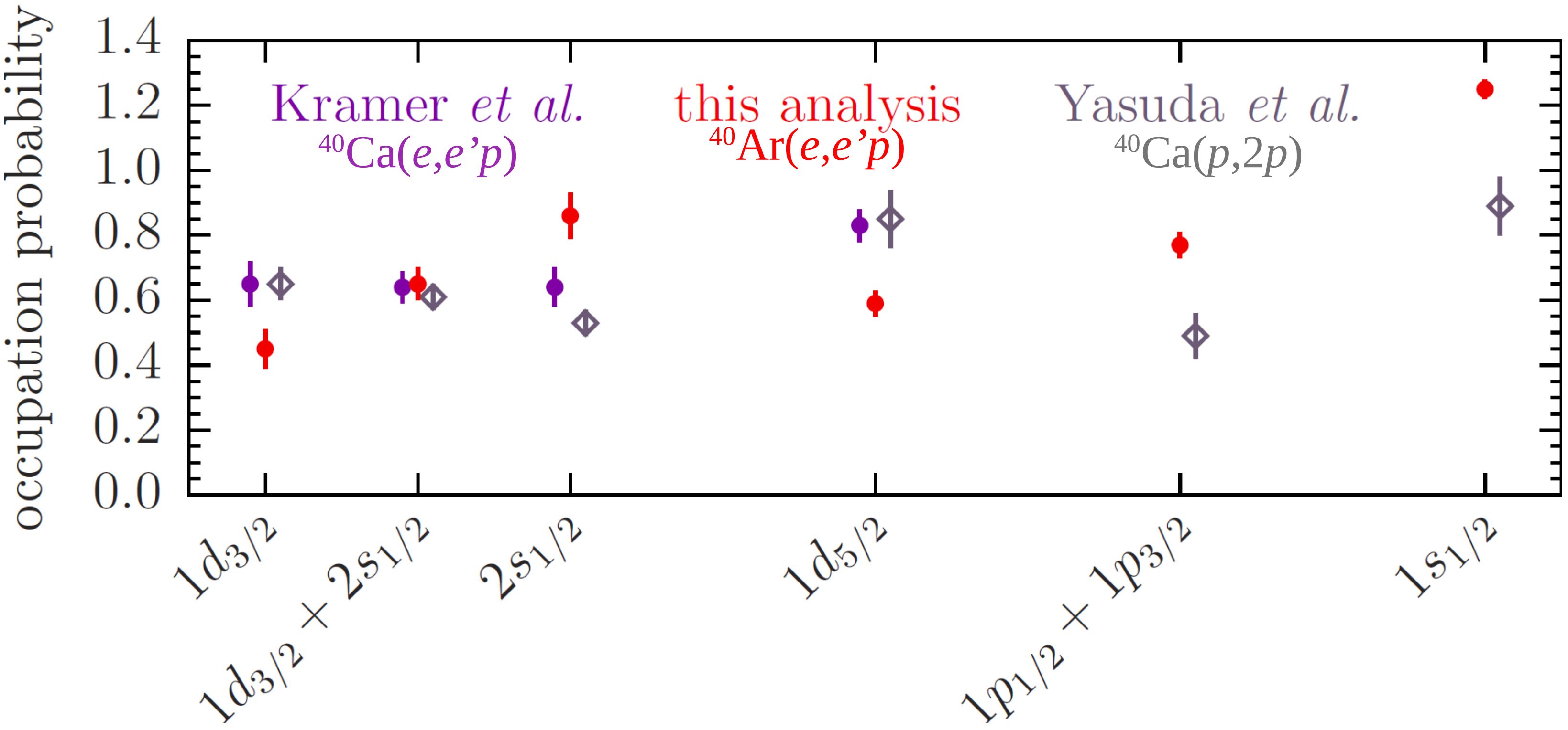
Ar		Ca
12.53(2)	1d3/2	8.5(1)
12.92(2)	2s1/2	11.0(1)
18.23(2)	1d5/2	15.7(1)
28.8(7)	1p1/2	29.8(7)
33.0(3)	1p3/2	34.7(3)
53.4(1.1)	1s1/2	53.6(7)

Jiang *et al.*,
PRD 105, 112002 (2022)

Volkov *et al.*
SJNP 52, 848 (1990)

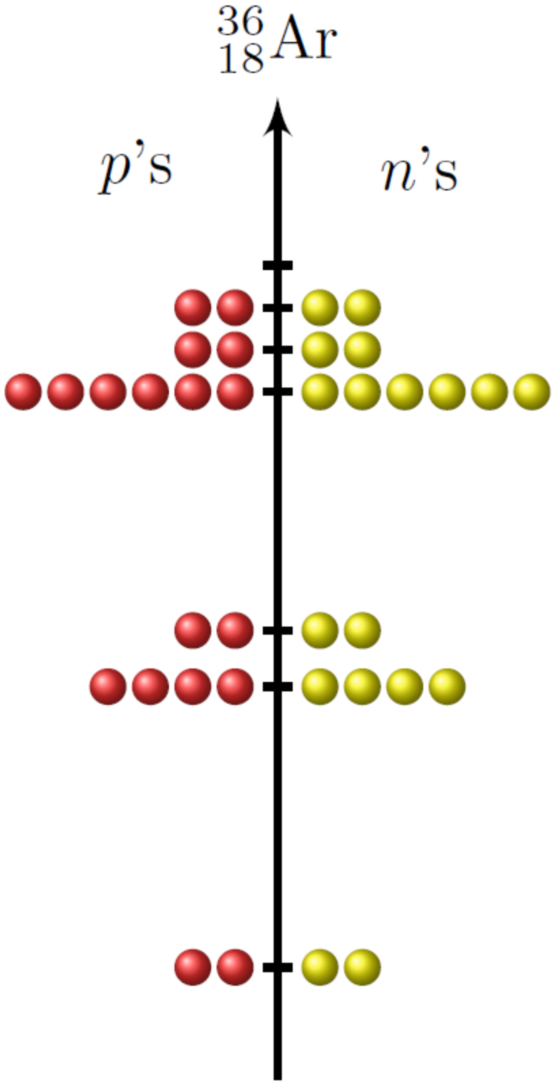


Occupation probability



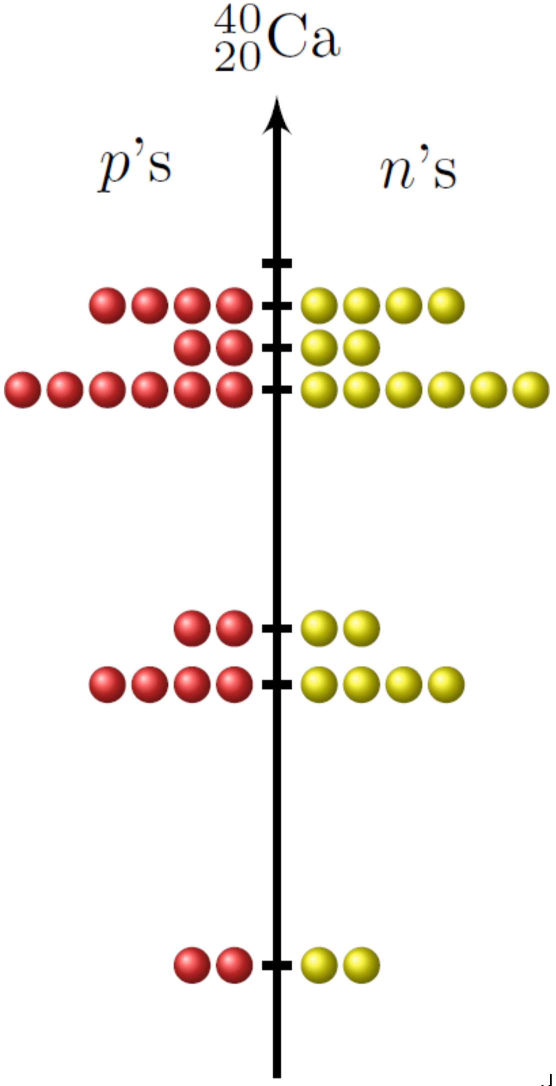
Kramer *et al.* [Ph.D. thesis (1990)]: ~340–440-MeV electron beam at NIKHEF-K

Yasuda *et al.* [Ph.D. thesis (2012)]: 392-MeV polarized proton beam at RCNP



proton energy levels

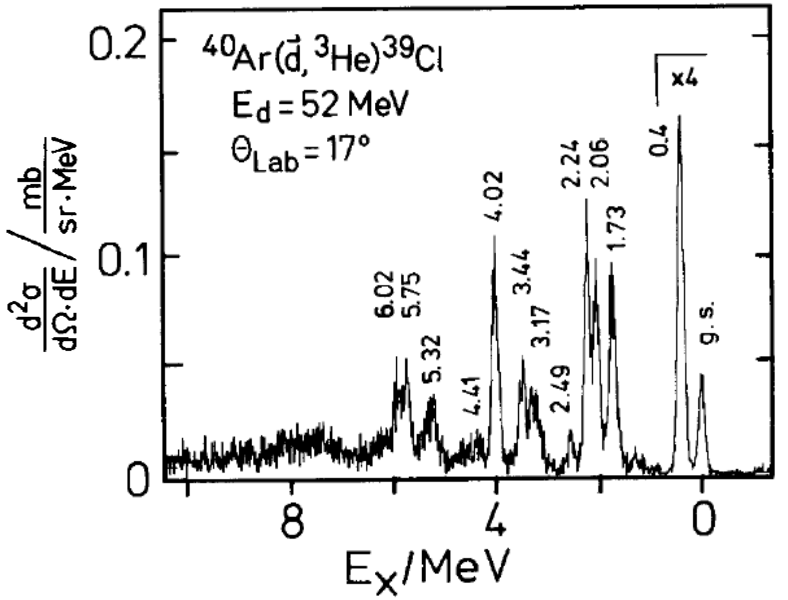
Ar		Ca
8.51	1d3/2	8.33
9.73	2s1/2	10.85
14.23	1d5/2	14.66
	1p1/2	
	1p3/2	
	1s1/2	



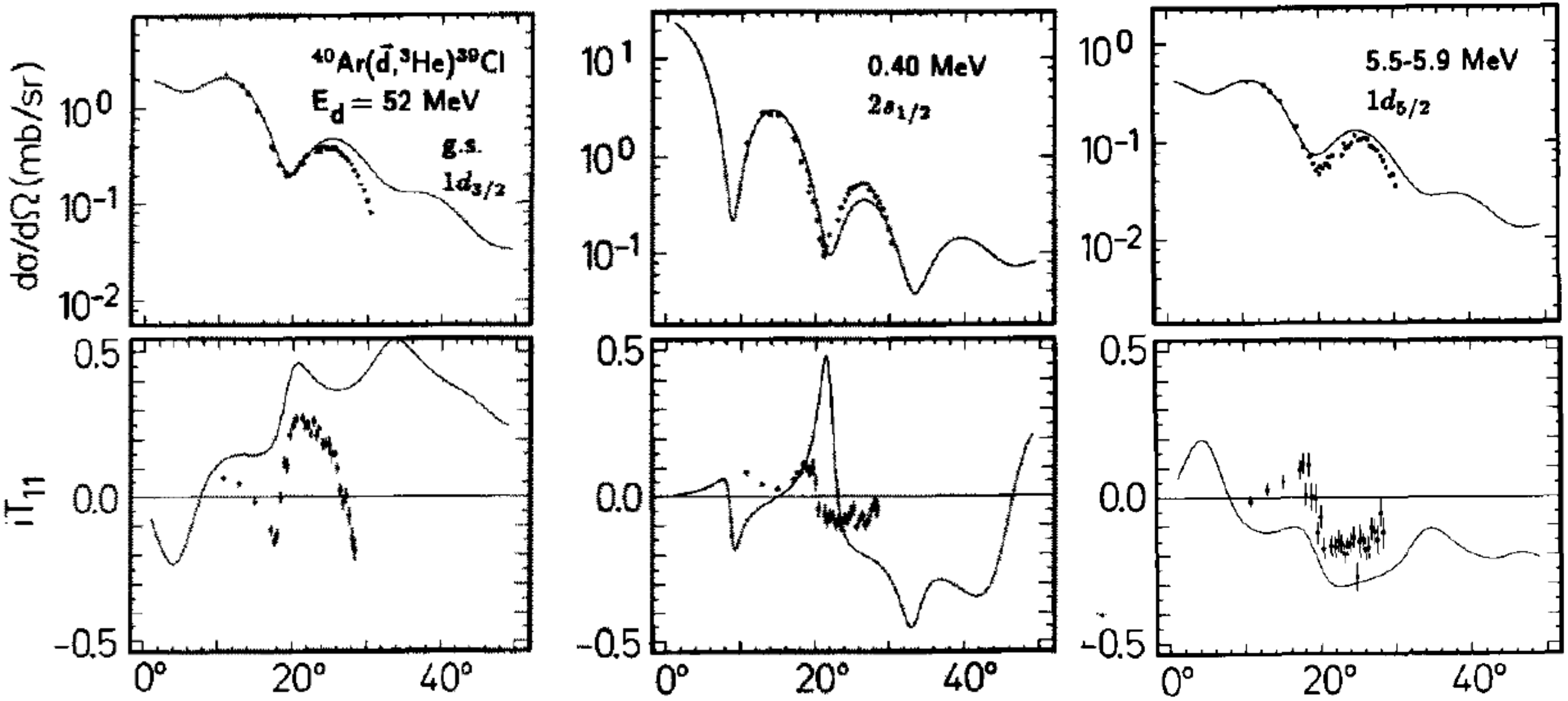
^{40}Ar($\vec{d}$, ^{3}He)^{39}Cl experiment by Mairle *et al.*

- 52-MeV polarized deuteron beam from the Karlsruhe cyclotrone
- Argon gas cell, 350 hPa
- Angular distributions for 10°–30° used to determine spectroscopic factors
- Excitation energies up to 9 MeV
- Spins determined from analyzing powers
- Energy resolution 0.13 MeV

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



^{40}Ar($\vec{d}$, ^{3}He)^{39}Cl experiment by Mairle *et al.*



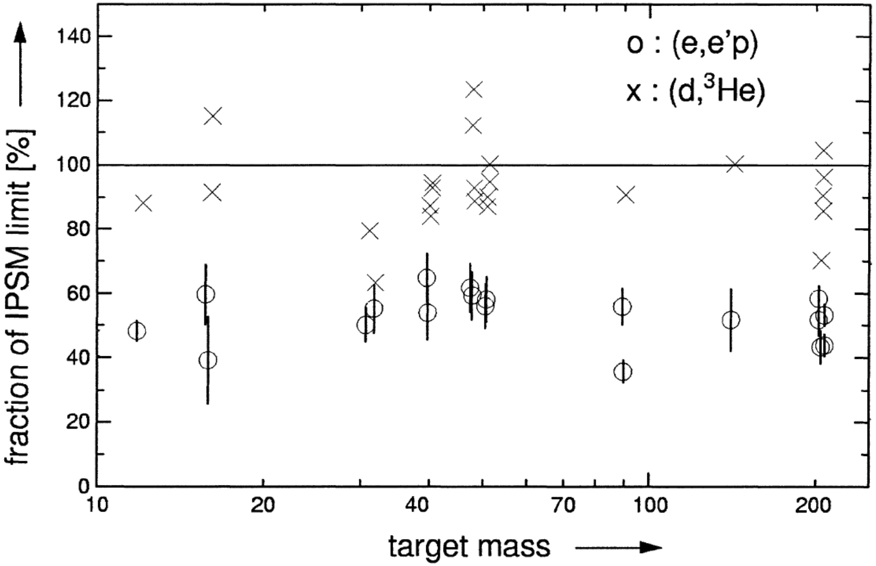
$^{40}\mathrm{Ar}(\vec{d}, {}^{3}\mathrm{He})^{39}\mathrm{Cl}$ experiment by Mairle *et al.*

- Spectroscopic factors for individual peaks for $E_x < 6$ MeV
- $1d_{5/2}$ strength measured over a broad range of excitation energies
- For the $1d$ shells, the spectroscopic factors exceed the IPSM expectations
- No uncertainties assigned

nlj	$\Sigma C^2 S(nlj)$
$1d_{3/2}$	2.17
$2s_{1/2}$	1.53
$1d_{5/2}$	7.03

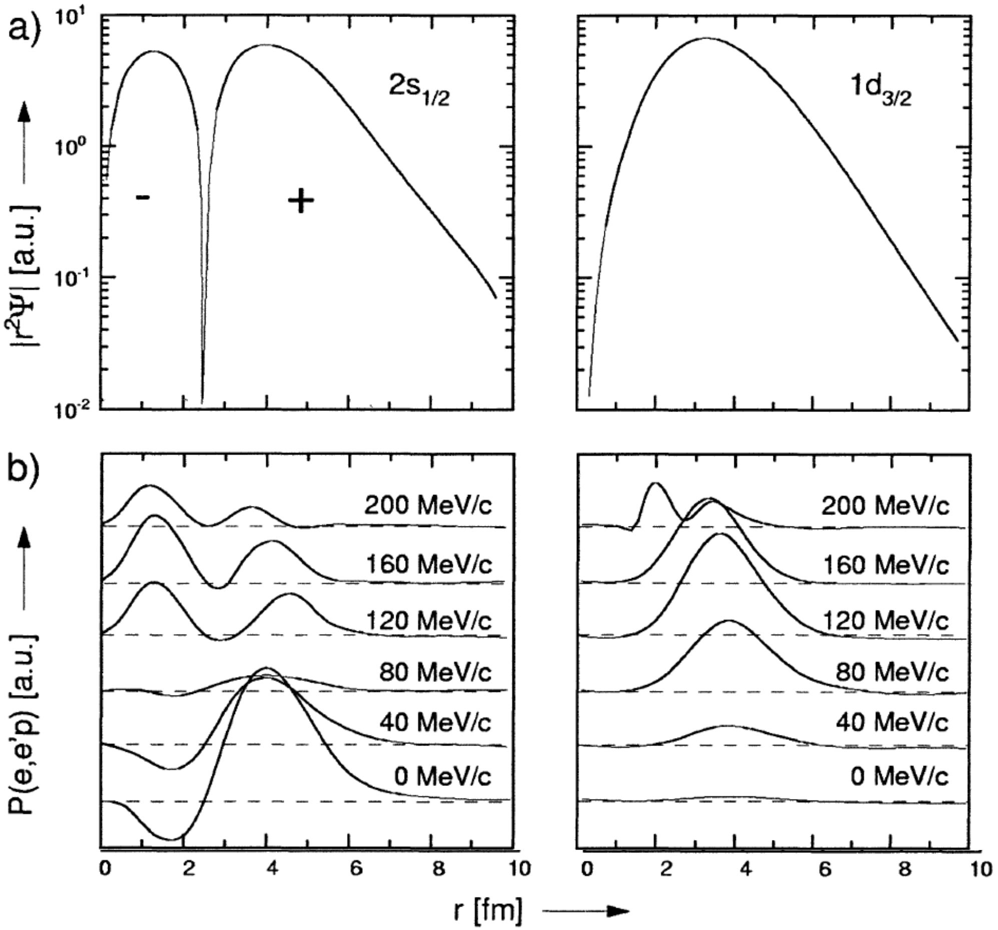
Puzzling difference between (*e*,*e'p*) and (*d*,^{3}He)

- Spectroscopic factors from (*e*,*e'p*) significantly below IPSM predictions
- (*d*,^{3}He) close to IPSM strengths
- Same behavior for across all *A*
- *What is the origin of the difference?*

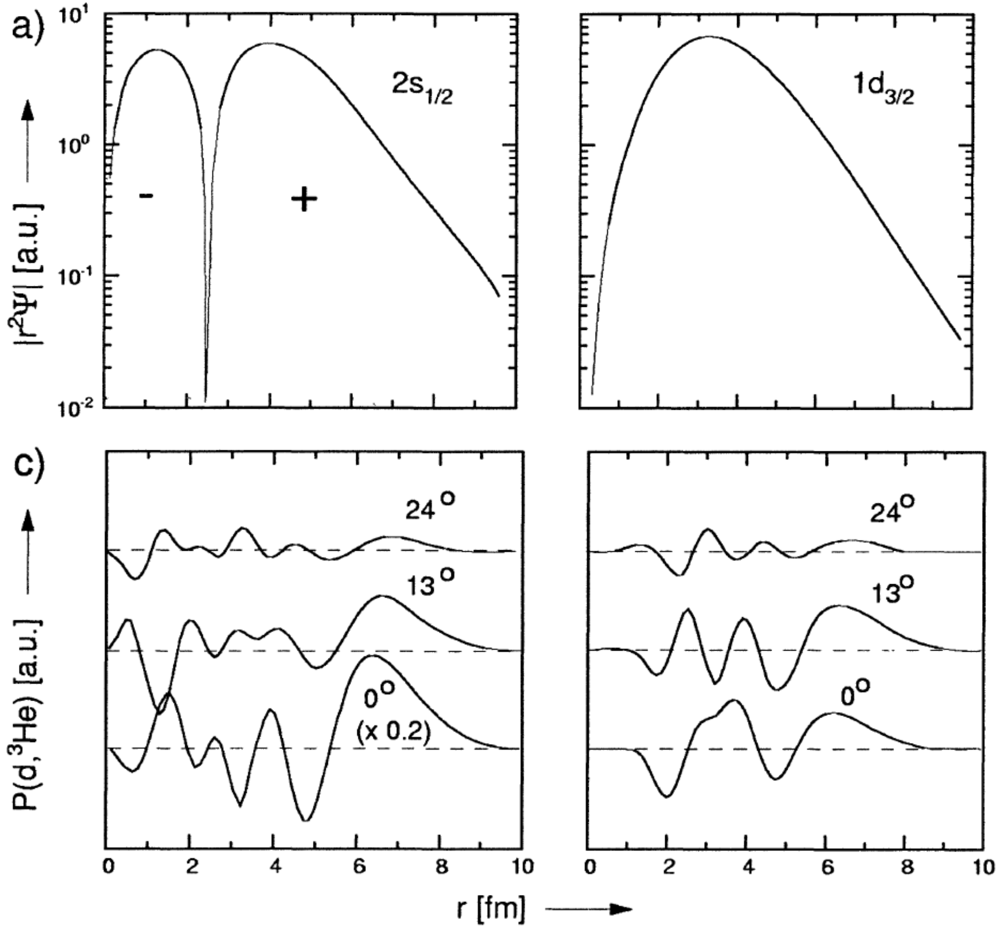


G.J. Kramer, H.P. Blok, & L. Lapikás, NPA 649, 267 (2001)

(*e*,*e’p*) experiments

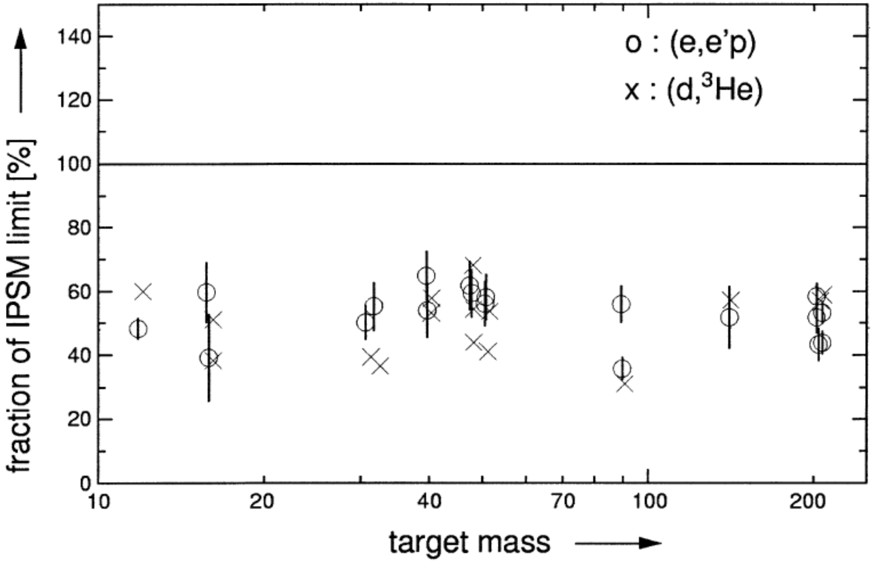


(d,^{3}He) experiments



Puzzling difference between (*e,e’p*) and (*d*,^{3}He)

- (*d*,^{3}He) is not sensitive to the wave functions inside the nucleus, probes only the exponential tails
- (*e,e’p*) probes the whole radial region
- Consistent spectroscopic factors extracted when the wave functions from (*e,e’p*) used in (*d*,^{3}He) analysis and finite range of interaction accounted for



G.J. Kramer, H.P. Blok, & L. Lapikás, NPA 649, 267 (2001)

Global analysis: (*d*,^{3}He) spectroscopic factors overestimated on average by 50%, assigned ~30% uncertainties.