Pion production on the nucleus: a big mess and a nice opportunity

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MITP Workshop, Mainz, Germany.
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Overview

Part 1. Constraining the nucleon structure in argon.

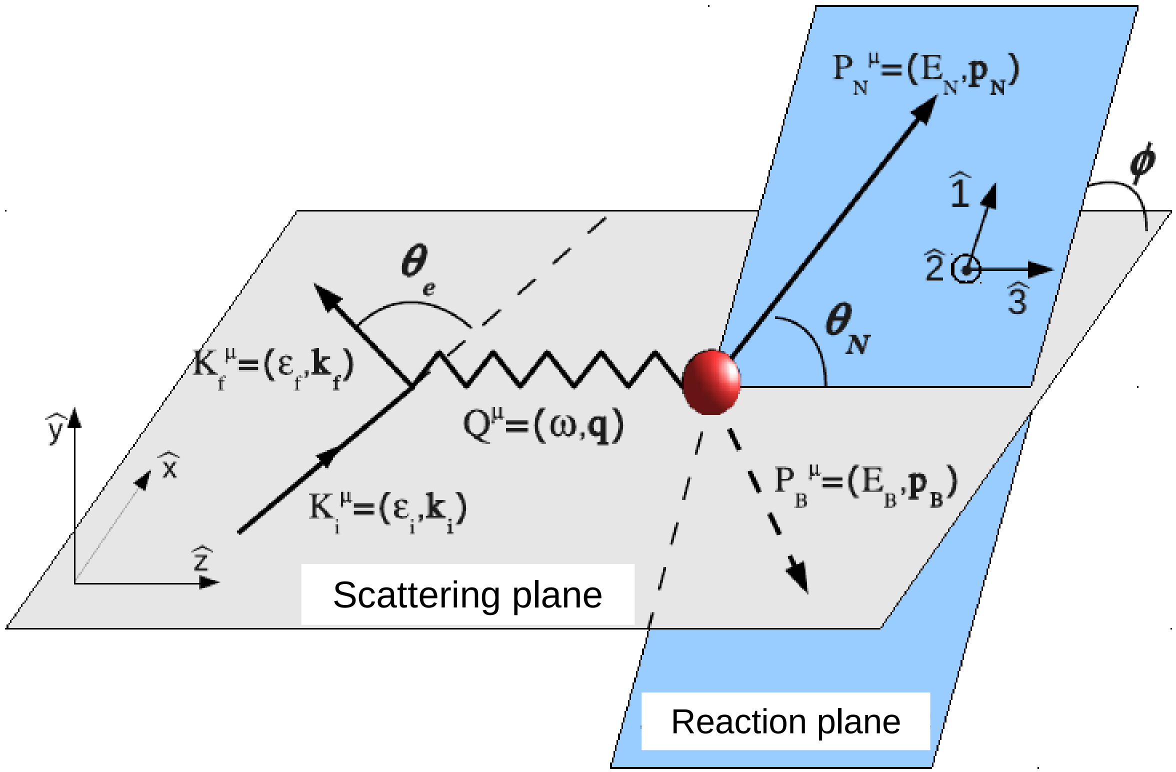
Part 2. Constraining the “pion absorption”.

Part 3. On the modeling.

PART 1:

Constraining the nucleon structure in ^{40}Ar

(e,e'p) experiments



$$\frac{d^6\sigma}{dE_{e'}\, d\Omega_{e'}\, dE_{p'}\, d\Omega_{p'}} = K\sigma_{ep} S(E_m, p_m)\,,$$

$$S^{exp}(E_m, p_m) = \frac{d^6\sigma}{dE_{e'}\, d\Omega_{e'}\, dE_{p'}\, d\Omega_{p'}} \Big/ K\sigma_{ep}^{cc1}$$

https://doi.org/10.1103/PhysRevC.32.1787

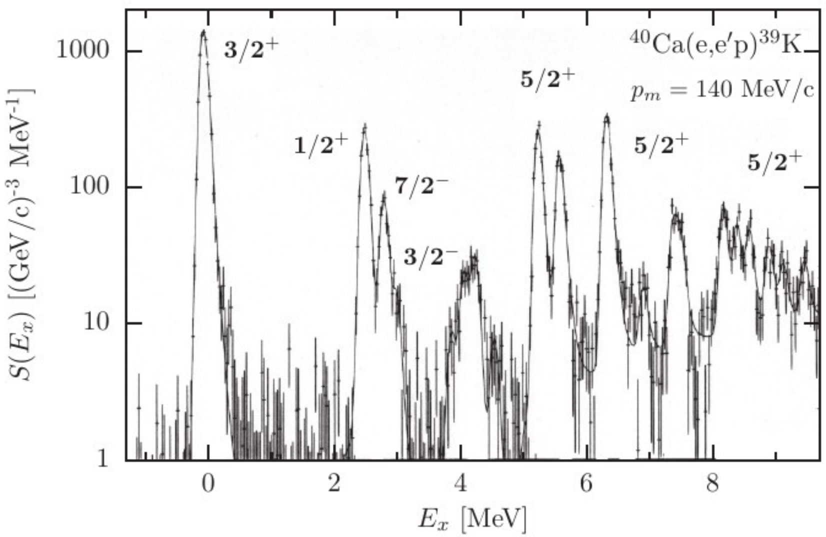


FIG. 1. Radiatively unfolded excitation-energy spectrum for the reaction ^{40}Ca$(e, e'p)$ at missing momentum 140 MeV/c, showing the well-resolved transitions to the $J^\pi = 3/2^+$ ground state and $1/2^+$ first excited state in ^{39}K. Above $E_x = 5$ MeV several transitions to states with mostly $J^\pi = 5/2^+$ are identified. The peak at $E_x \approx 4$ MeV results from the reaction ^{16}O$(e, e'p)^{15}N_{g.s.}$ due to oxygen contamination in the target. The curve is a multiple Gaussian fit to the data.

Nuclear Physics A480 (1988) 547-572

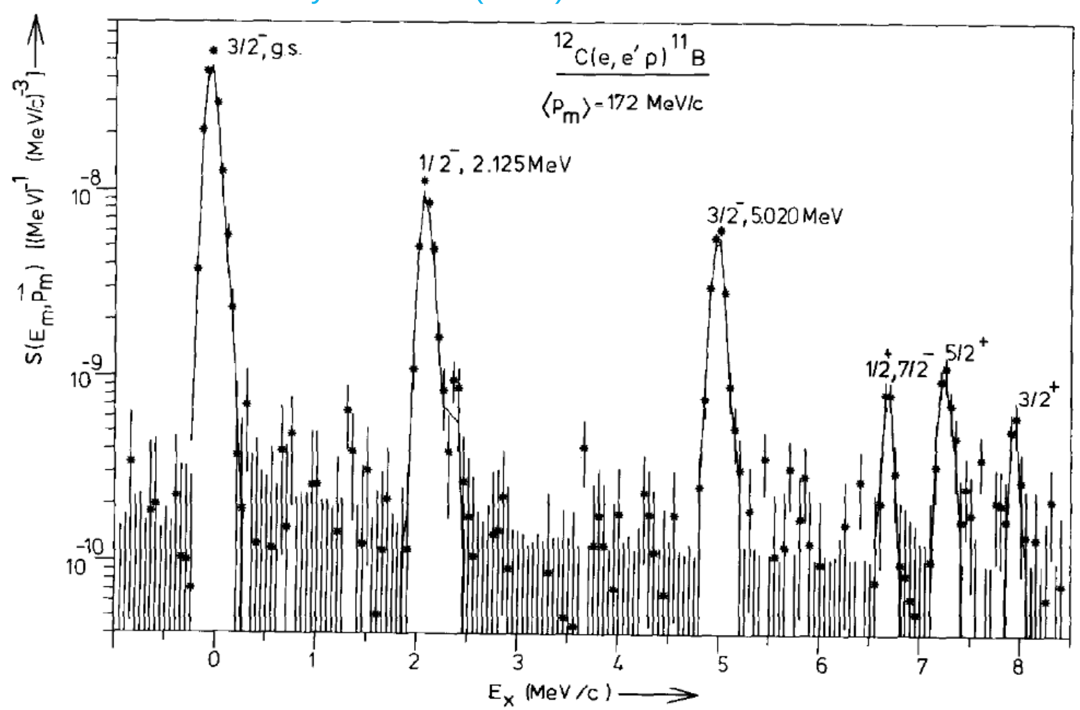


Fig. 1. Excitation-energy spectrum of the ^{12}C(e, e'p)^{11}B reaction at $E_0 = 284.5$ MeV. The central value of the missing momentum is 172 MeV/c.

Nuclear Physics A480 (1988) 547-572

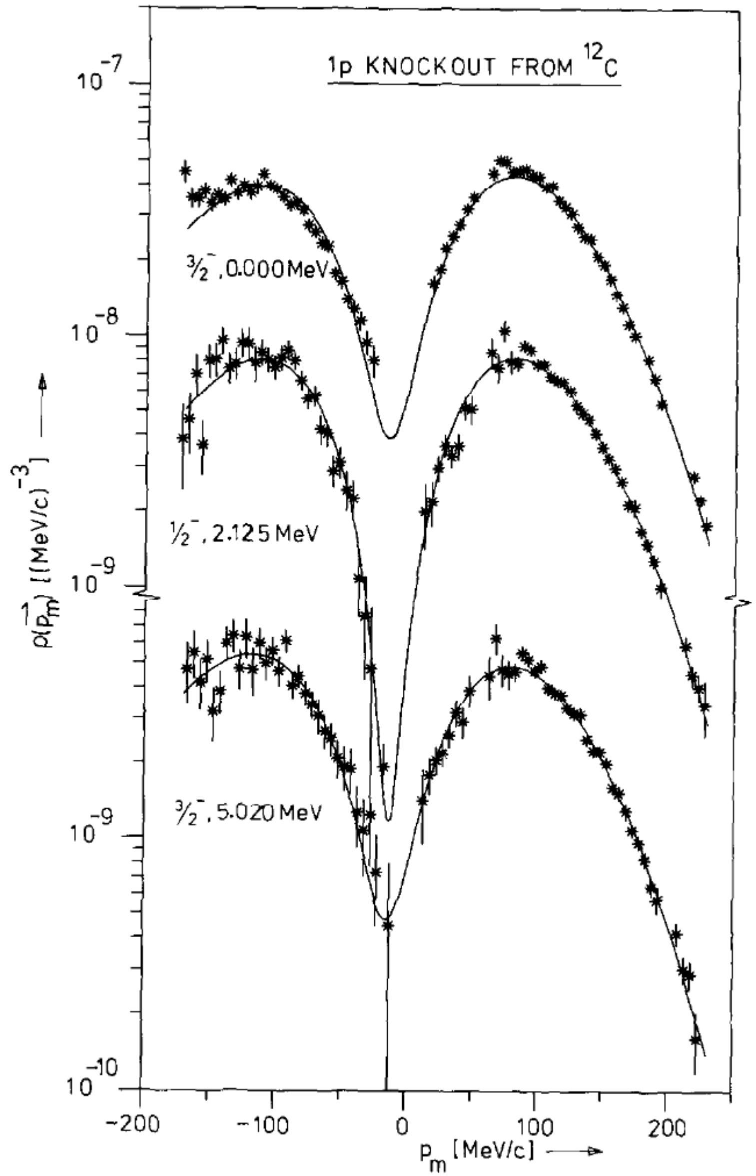


Fig. 11. Momentum distributions for 1p knockout from ^{12}C leading to the $\frac{3}{2}^-$ ground state, the $\frac{1}{2}^-$ state at 2.125 MeV and the $\frac{3}{2}^-$ state at 5.020 MeV in ^{11}B. The curves represent DWIA calculations employing the MCO potential. The fitted parameters are listed in table 6 (after a correction for the omitted couplings using table 5).

10.1103/PhysRevC.70.034606

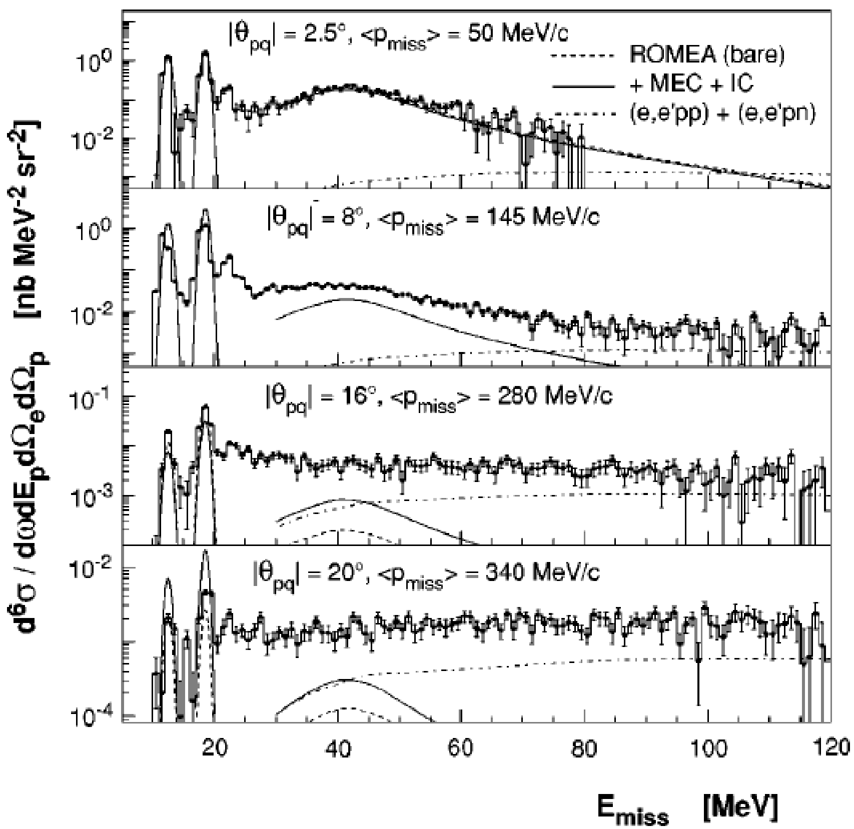


FIG. 21. Data from this work together with ROMEA calculations by the Ghent Group for the E_{miss}-dependence of the cross section obtained at E_{beam}=2.442 GeV. The data are the averaged cross section measured on either side of **q** at each θ_{pq}. Normalization factors of 0.6, 0.7, and 1.0 have been used for the $1p_{1/2}$-, $1p_{3/2}$-, and $1s_{1/2}$-states, respectively. Uncertainties are statistical and, on average, there is an additional ±5.9% systematic uncertainty associated with the data. Also shown are calculations by the Ghent Group for the $(e,e'pN)$ contribution.

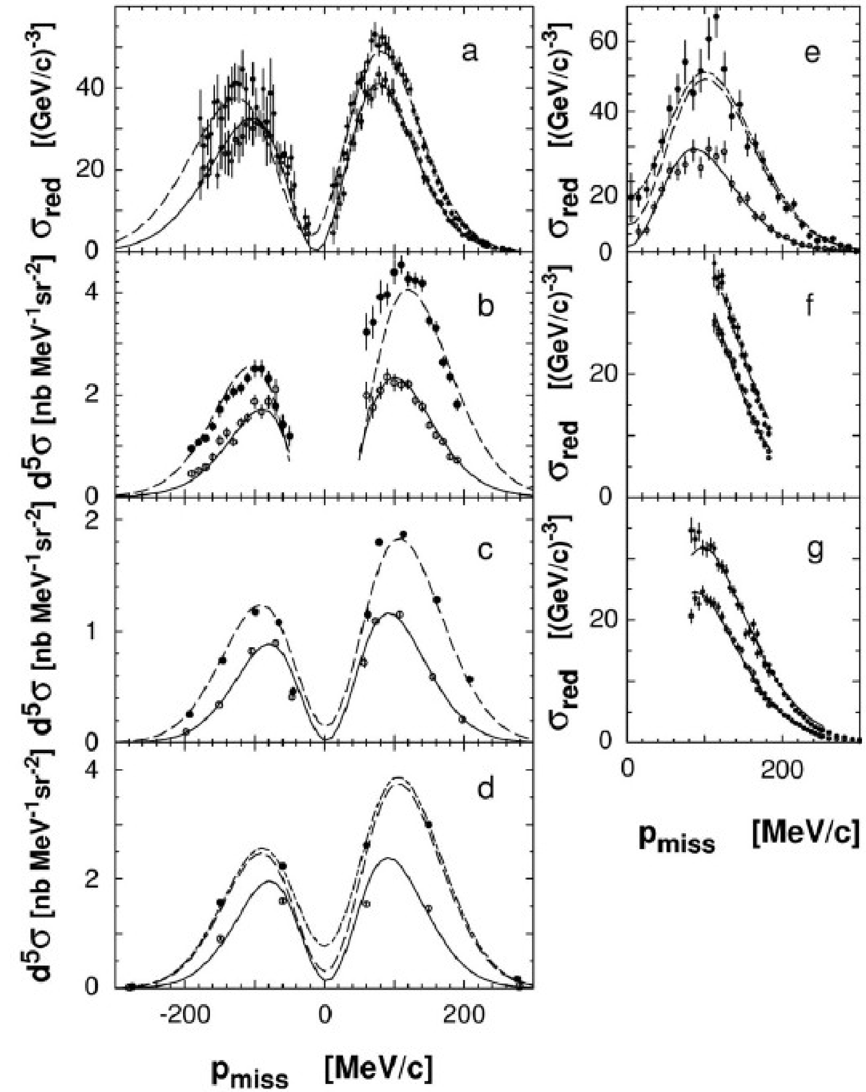


FIG. 24. Fits to various $^{16}O(e,e'p)$ data sets based on the HS bound-nucleon wave function and the EDAD1 optical potential. See Table IX for the key to the dataset labels. Open points and solid lines pertain to the $1p_{1/2}$-state, while points and dashed lines pertain to the $1p_{3/2}$-state. The dashed-dotted lines include the contributions of the positive parity $2s_{1/2}1d_{5/2}$-doublet to the $1p_{3/2}$-state. Panel (d) shows the data from this work.

https://arxiv.org/abs/2504.09972

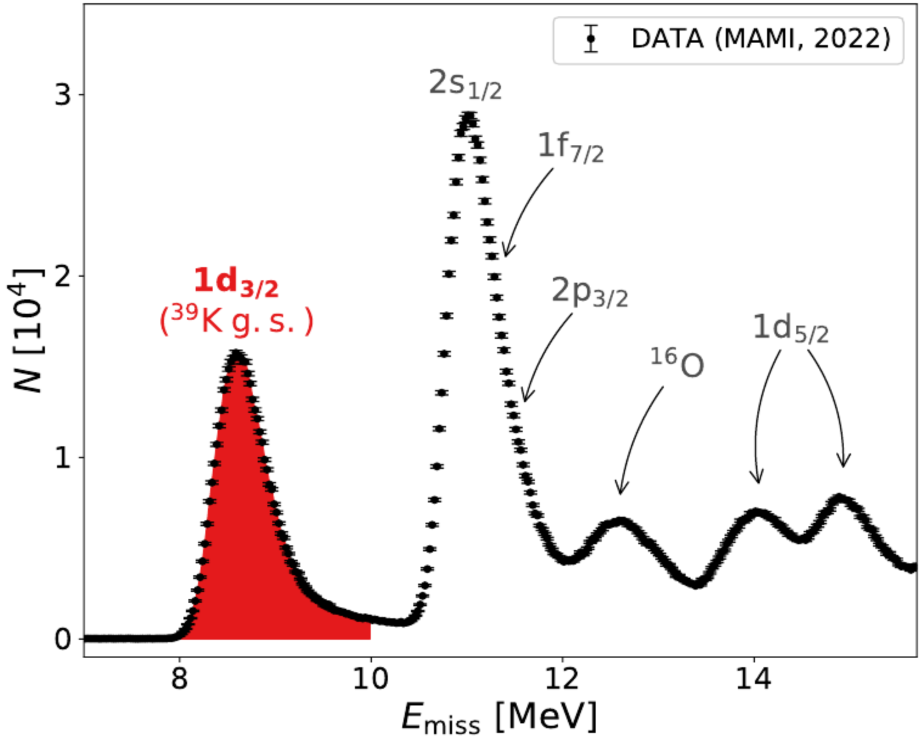


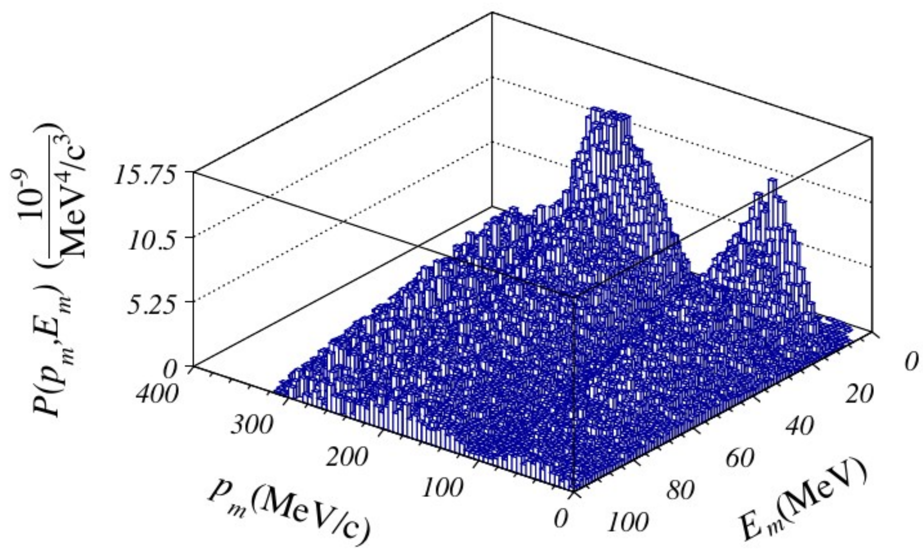
Figure 2: Missing-energy spectrum of the proton knockout from the ^{40}Ca target. Marked is also a peak associated with oxygen contamination due to the target oxidation.

PHYSICAL REVIEW D **105,** 112002 (2022)

Determination of the argon spectral function from $(e, e'p)$ data

L. Jiang,[1] A. M. Ankowski,[2] D. Abrams,[3] L. Gu,[1] B. Aljawrneh,[4] S. Alsalmi,[5] J. Bane,[6] A. Batz,[7] S. Barcus,[7] M. Barroso,[8] V. Bellini,[9] O. Benhar,[10] J. Bericic,[11] D. Biswas,[12] A. Camsonne,[11] J. Castellanos,[13] J.-P. Chen,[11] M. E. Christy,[12] K. Craycraft,[6] R. Cruz-Torres,[14] H. Dai,[1] D. Day,[3] A. Dirican,[15] S.-C. Dusa,[11] E. Fuchey,[16] T. Gautam,[12] C. Giusti,[17] J. Gomez,[11,*] C. Gu,[18] T. J. Hague,[19] J.-O. Hansen,[11] F. Hauenstein,[20] D. W. Higinbotham,[11] C. Hyde,[20] Z. Jerzyk,[21] C. Keppel,[11] S. Li,[22] R. Lindgren,[3] H. Liu,[23] C. Mariani,[1,†] R. E. McClellan,[11] D. Meekins,[11] R. Michaels,[11] M. Mihovilovic,[24] M. Murphy,[1] D. Nguyen,[3] M. Nycz,[19] L. Ou,[14] B. Pandey,[12] V. Pandey,[1,‡] K. Park,[11] G. Perera,[3] A. J. R. Puckett,[16] S. N. Santiesteban,[22] S. Širca,[25,24] T. Su,[19] L. Tang,[12] Y. Tian,[26] N. Ton,[3] B. Wojtsekhowski,[11] S. Wood,[11] Z. Ye,[27] and J. Zhang[3]

(Jefferson Lab Hall A Collaboration)



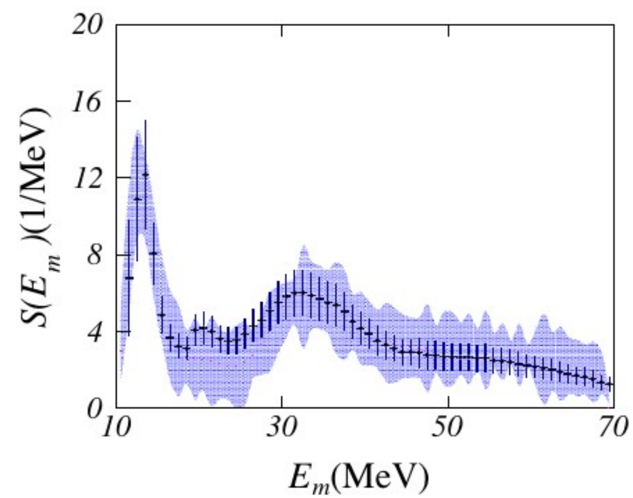


FIG. 10. Reduced cross section as function of missing energy and missing momentum.

That was for the protons, but what about the neutrons?

That was for the protons, but what about the neutrons?

One could do

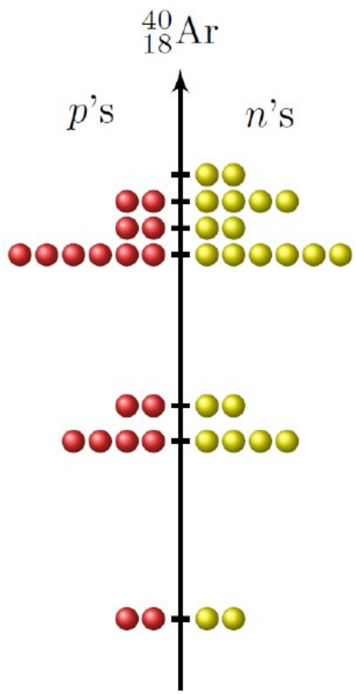
$^{40}Ar(e,e'n)$

but... there are some issues with detecting neutrons

Determination of the neutron structure of Argon 40
Needed for the neutrino programe: MicroBooNE, DUNE, SBND, others.

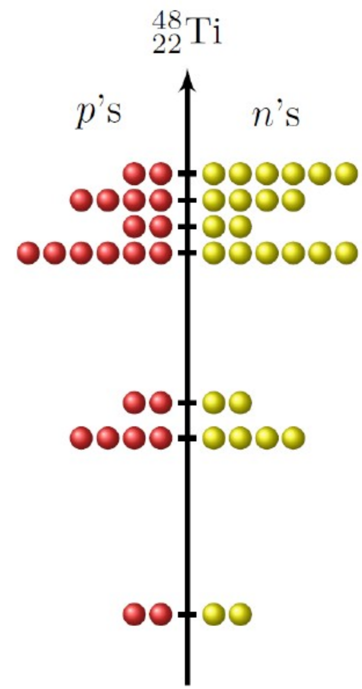
Energy levels

Slide from Ankowski talk, Workshop@ECT* 2024



^{40}Ar neutrons		^{48}Ti 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



Determination of the neutron structure of Argon 40
Needed for the neutrino programe: MicroBooNE, DUNE, SBND, others.

PHYSICAL REVIEW D 107, 012005 (2023)
Determination of the titanium spectral function from (e,e'p) data

TABLE V. Results of the χ^2 minimization using the missing-energy distributions for different cases. We repeat the fit with different priors, and without including the correlated part of the SF. For every state α, we extract the spectroscopic factor S_α and occupational number N_α, assuming independent particle model and total spectroscopic strength. We report at the end also the number of degrees of freedom (d.o.f.), and the χ^2 per d.o.f.

		All priors	w/o p_m	w/o corr
α	N_α		S_α	
$1f_{7/2}$	2	1.53 ± 0.25	1.55 ± 0.28	1.24 ± 0.22
$1d_{3/2}$	4	2.79 ± 0.37	3.15 ± 0.54	3.21 ± 0.37
$2s_{1/2}$	2	2.00 ± 0.11	1.78 ± 0.46	2.03 ± 0.11
$1d_{5/2}$	6	2.25 ± 0.16	2.34 ± 0.19	3.57 ± 0.29
$1p_{1/2}$	2	2.00 ± 0.20	1.80 ± 0.27	2.09 ± 0.19
$1p_{3/2}$	4	2.90 ± 0.20	2.92 ± 0.20	4.07 ± 0.15
$1s_{1/2}$	2	2.14 ± 0.10	2.56 ± 0.30	2.14 ± 0.11
Corr	0	4.71 ± 0.31	4.21 ± 0.46	Excluded
$\sum_\alpha S_\alpha$		20.32 ± 0.65	20.30 ± 1.03	18.33 ± 0.59
d.o.f.		121	153	125
χ^2/d.o.f.		0.95	0.71	1.23

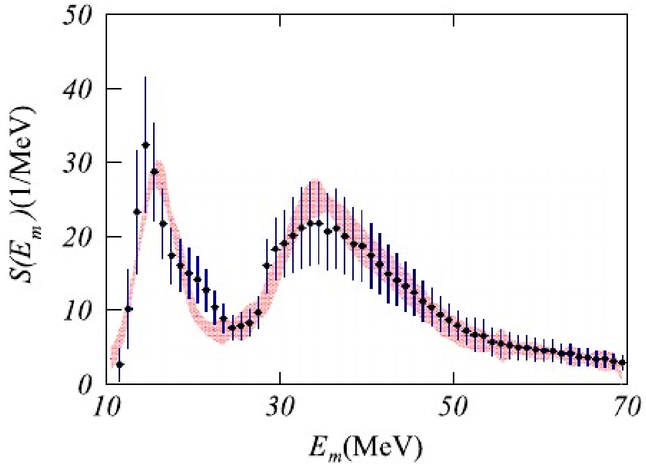
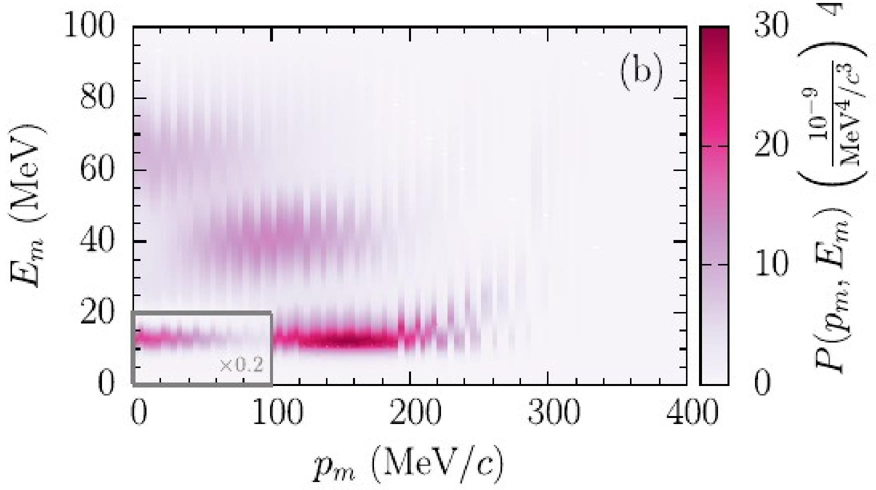


FIG. 3. Missing-energy distributions obtained for natural titanium for $130 < p_m < 260$ MeV/c. The red band indicates the final fit results, including the full error uncertainties.



CAN WE DO SOMETHING ELSE?

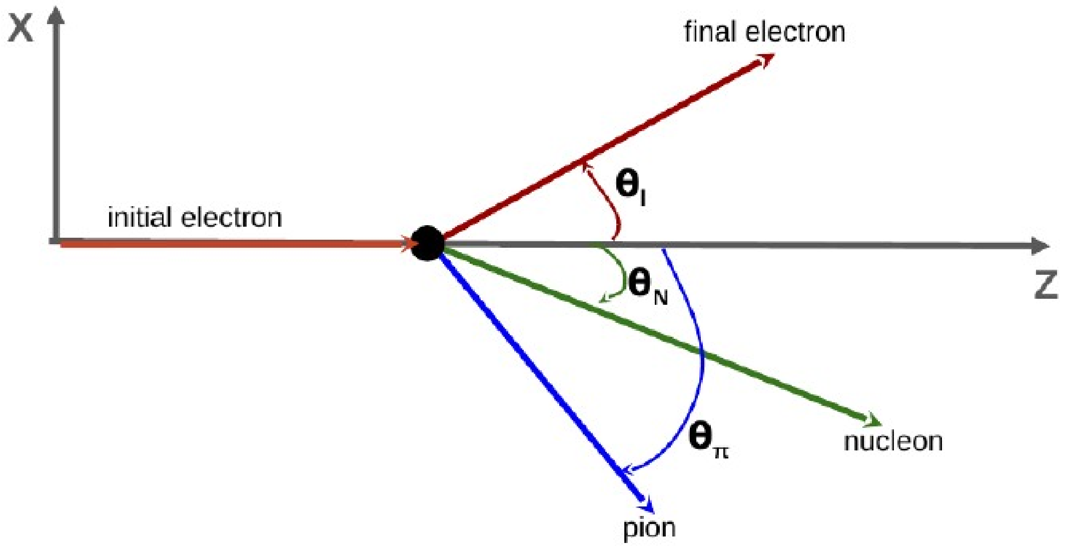
(Remember, they didn't measure neutrons in argon 40 but protons in titanium 48.)

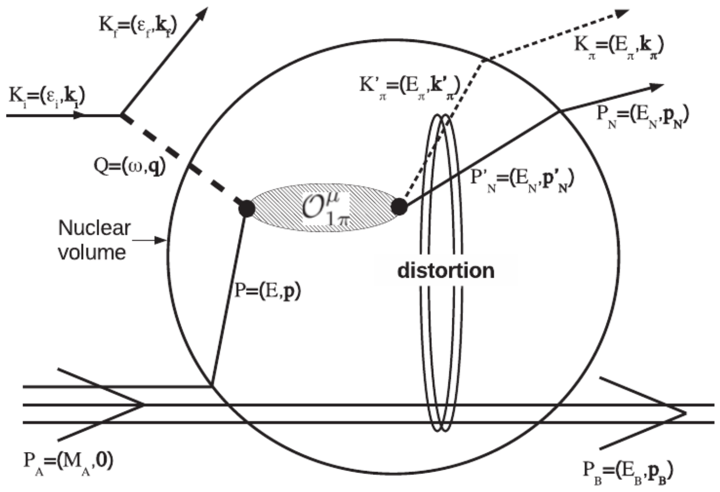
CAN WE DO SOMETHING ELSE?

YES!

TRIPLE COINCIDENCE EXPERIMENT @ MAMI

$$e + n \longrightarrow e' + p + \pi^-$$





ADVANTAGES

1. One probes neutrons of argon directly (instead of using a proxy nucleus like 48Ti)

2. There is no need to detect neutrons

DIS-ADVANTAGES

1. Modeling pion production is more difficult than quasielastic

2. This is a triple-coincidence experiment: statistics

ADVANTAGES

1. One probes neutrons of argon directly
(instead of using a proxy nucleus like 48Ti)

2. There is no need to detect neutrons

~~DIS-ADVANTAGES~~
CHALLENGES and OPPORTUNITIES

1. Modeling pion production is more difficult than quasielastic

2. This is a triple-coincidence experiment: statistics

In summary, there are three spectrometers with the following specifications for the maximum momenta of the particle, and momentum and angular acceptances [12]:

- Spectrometer A: $p_{max} = 735$ MeV, $\Delta p/p = 20\%$, $\Omega = 28$ msr (horizontal 100 mrad, vertical 70 mrad, or in degrees: horizontal 7.73 deg, vertical 4 deg).
- Spectrometer B: $p_{max} = 870$ MeV, $\Delta p/p = 15\%$, $\Omega = 5.6$ msr (horizontal 20 mrad, vertical 70 mrad, or in degrees: horizontal 1.15 deg, vertical 4 deg).
- Spectrometer C: $p_{max} = 551$ MeV, $\Delta p/p = 25\%$, $\Omega = 28$ msr (horizontal 100 mrad, vertical 70 mrad, or in degrees: horizontal 7.73 deg, vertical 4 deg).

[12] K. Blomqvist et al.,
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 403, 263 (1998).

K. Blomqvist et al.,

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 403, 263 (1998).

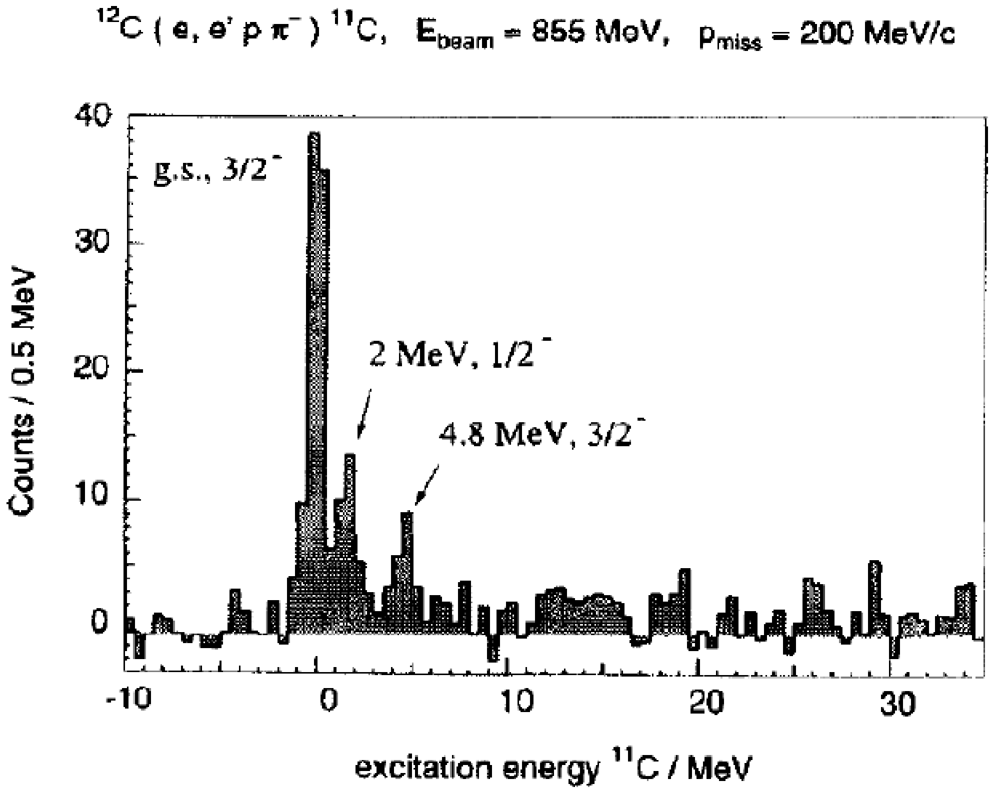


Fig. 32. Spectrum of the triple coincidence reaction $^{12}C(e, e'p\pi^-)$ in the Δ resonance region as a function of the excitation energy of the residual nucleus ^{11}C.

1. Choose a particular lepton kinematic

+ We want large single-pion production cross section

+ We want small contribution from other reaction channels

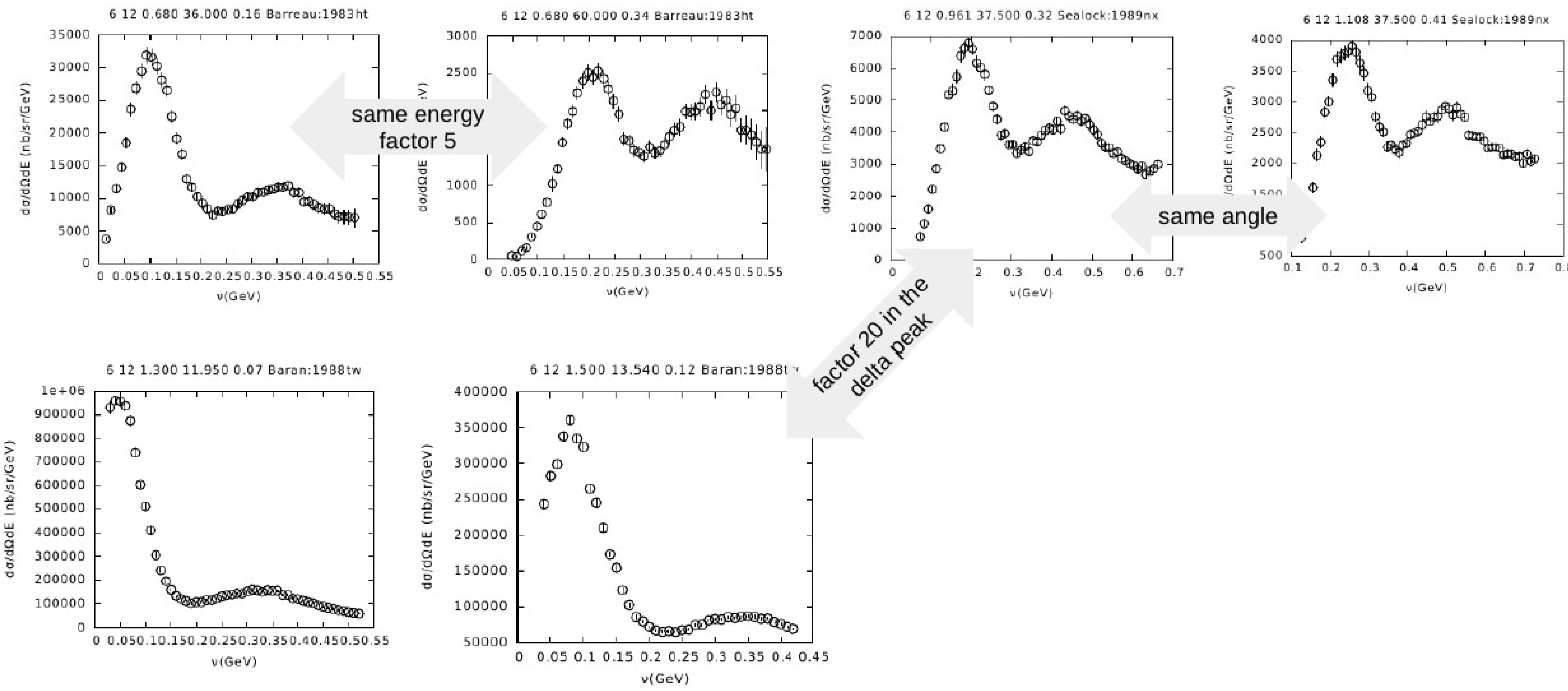


FIG. 5. A few selected (e, e') datasets to show how the cross section changes with the energy and scattering angle.

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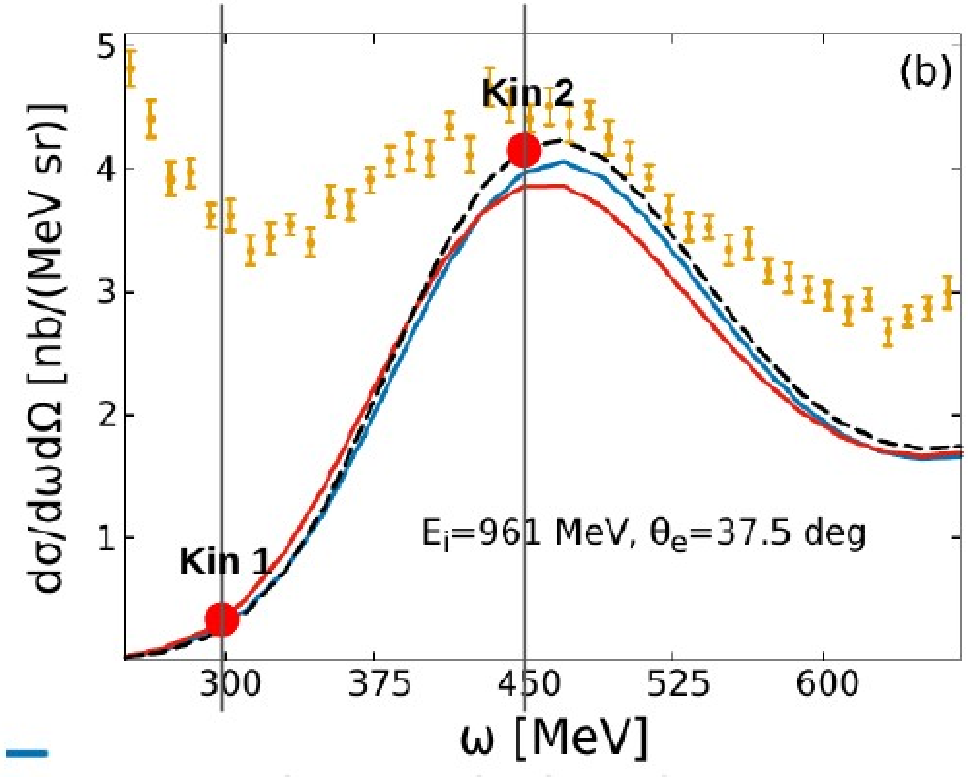
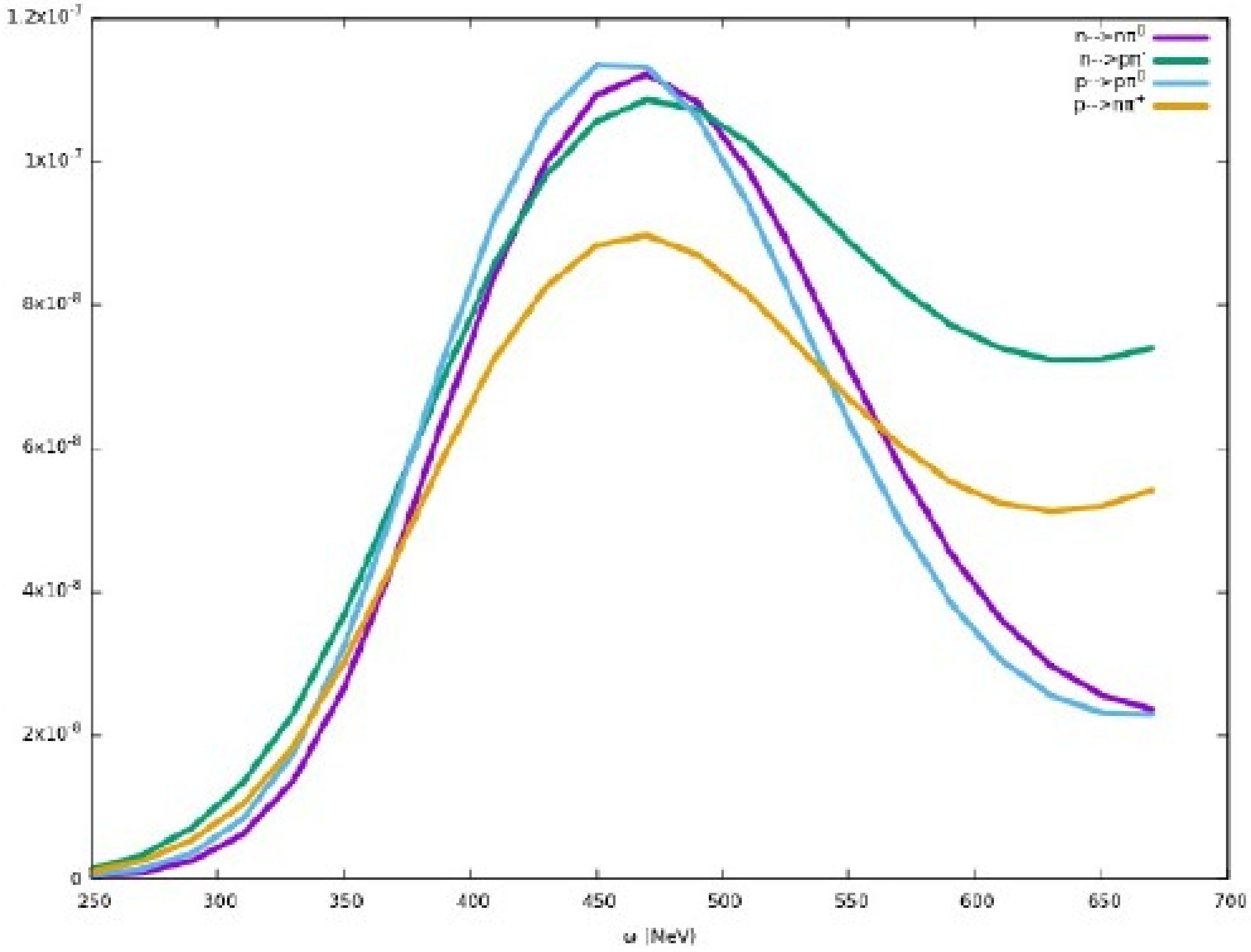


Inclusive $^{12}C(e,e')$ data compared with some model predictions for single-pion production

Kin 1: just above 1pi "threshold"
+ little contribution from delta (so ChPT describes the process)
+ so NO medium modification of resonances
+ but Large contribution from other reaction channels

Kin 2: delta peak
+ below 2pi "threshold"
+ SPP cross section is maximum

Ei=961 MeV, thetal=37.5 deg



2. Where do we put the hadron detectors?

2. Where do we put the hadron detectors?

+ We want large cross section

+ We want small backgrounds

Sources of backgrounds:

+ **Inelastic final-state interactions**: we can minimize them by placing the detectors where the nucleon and pion transparency are maximal

+ **Other reaction channels** leading to the same signal in the detectors
  ++ production of π^0 followed by charge exchange
  ++ pion production on a two nucleon pair
  ++ two-pion production
  ++ others

Making **cuts in missing energy (E_m)** and **missing momentum (p_m)** helps eliminate backgrounds a lot.

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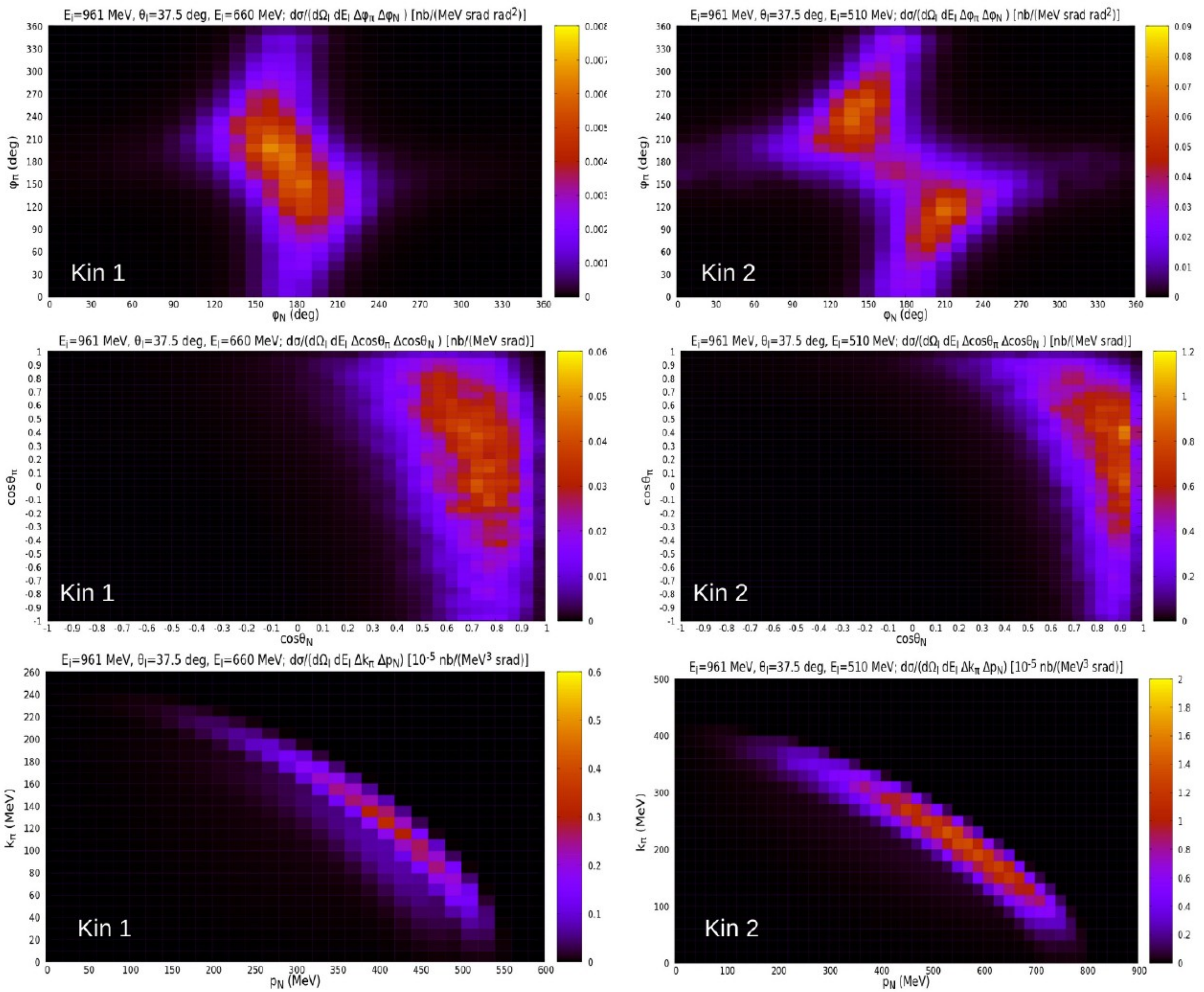


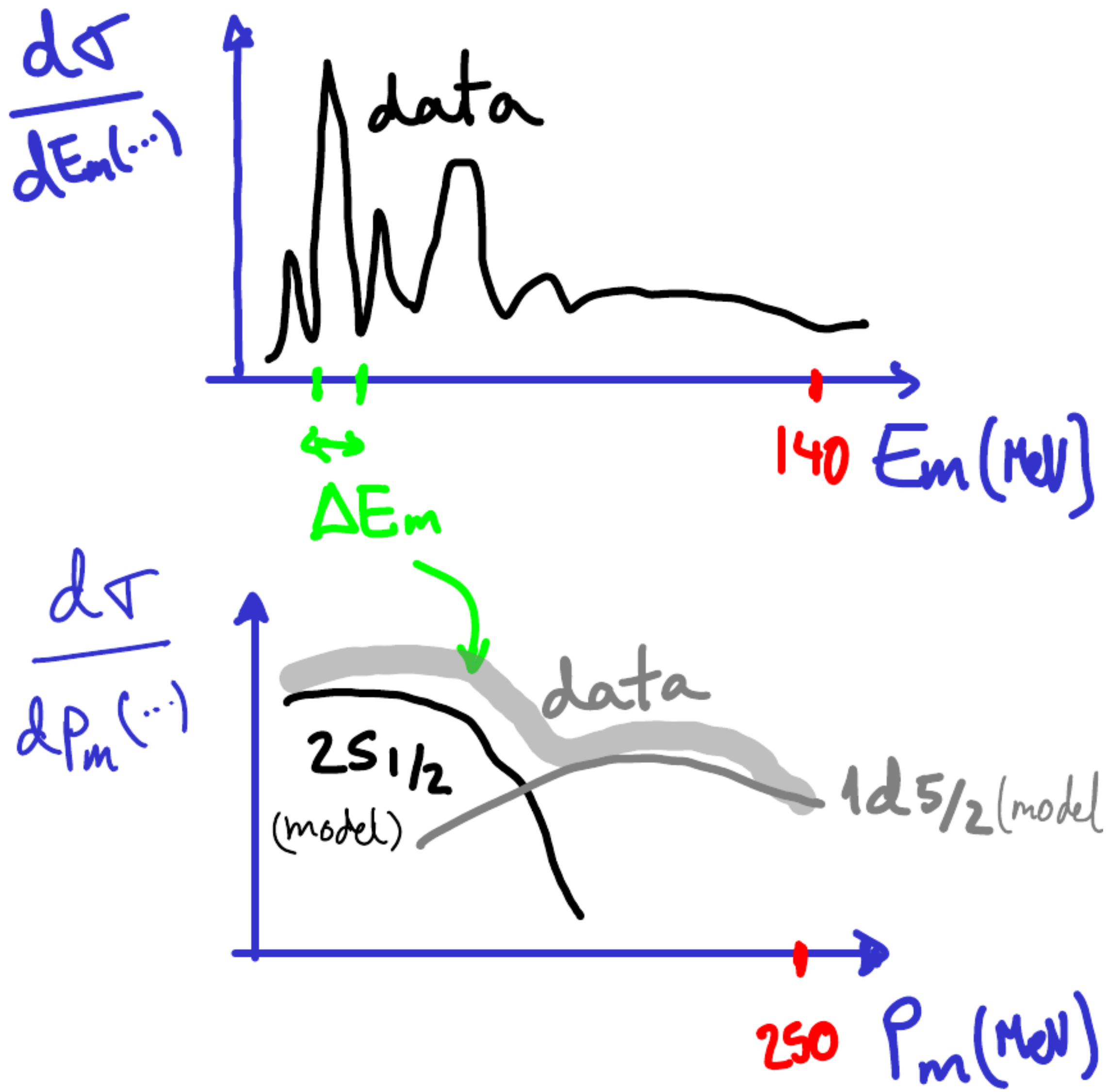
FIG. 8. Five differential cross sections in terms of different combinations of hadron variables. First row: azimuthal angles of the proton and pion. Middle row: scattering angles of the proton and pion. Bottom row: proton and pion momenta.

3. Then, what?

3. Then, what?

We (try to) identify the peaks.

$$E_m = \omega - T_p - E_\pi - T_R$$



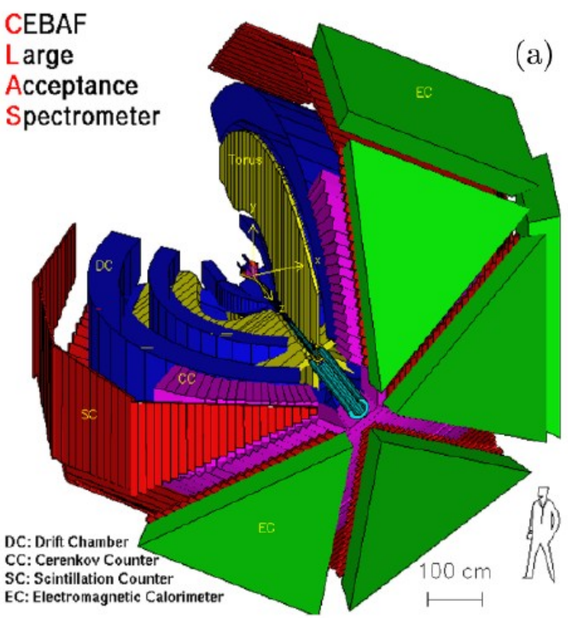
TRIPLE COINCIDENCE EXPERIMENT @ CLAS

CLAS detector

Electron-beam energy reconstruction for neutrino oscillation measurements
Nature | Vol 599 | 25 November 2021 | 565

son Lab). We detected electrons with energy $E_e \geq 0.4$, 0.55 and 1.1 GeV for $E_{\text{beam}} = 1.159$, 2.257 and 4.453 GeV, respectively, and angles $15° \leq \theta_e \leq 45°$; hadrons with momenta above 150 to 300 MeV/c and $10–20° \leq \theta_h \leq 140°$; and photons with energy $E_\gamma \geq 300$ MeV. These hadron detection thresh-

We detected protons with momenta $p_p \geq 300$ MeV/c and angles $\theta_p \geq 10°$, charged pions with momenta $p_\pi \geq 150$ MeV/c and angles $\theta_{\pi^+} \geq 10°$ and $\theta_{\pi^-} \geq 22°$, and photons with energy $E_\gamma \geq 300$ MeV and $8° \leq \theta_\gamma \leq 45°$. We applied separate fiducial cuts for electrons, π^-, positive



where the detection efficiency was constant and close to one. We also determined the minimum electron angle (as a function of electron momentum p) for each beam energy as:

$$\theta_e^{1.1} \geq 17° + \frac{7°}{p\ [\text{GeV}]}, \quad (12)$$

$$\theta_e^{2.2} \geq 16° + \frac{10.5°}{p\ [\text{GeV}]}, \quad (13)$$

$$\theta_e^{4.4} \geq 13.5° + \frac{15°}{p\ [\text{GeV}]}, \quad (14)$$

and the minimum π^- angle as

$$\theta_{\pi^-}^{1.1} \geq 17° + \frac{4°}{p\ [\text{GeV}]},$$

and

$$\theta_{\pi^-}^{2.2,4.4} \geq 25° + \frac{7°}{p\ [\text{GeV}]},$$

for $p_{\pi^-} < 0.35$ GeV/c and

$$\theta_{\pi^-}^{2.2,4.4} \geq 16° + \frac{10°}{p\ [\text{GeV}]}$$

for $p_{\pi^-} \geq 0.35$ GeV/c. The minimum π^+ and proton angle was $\theta > 12°$ for all datasets and momenta.

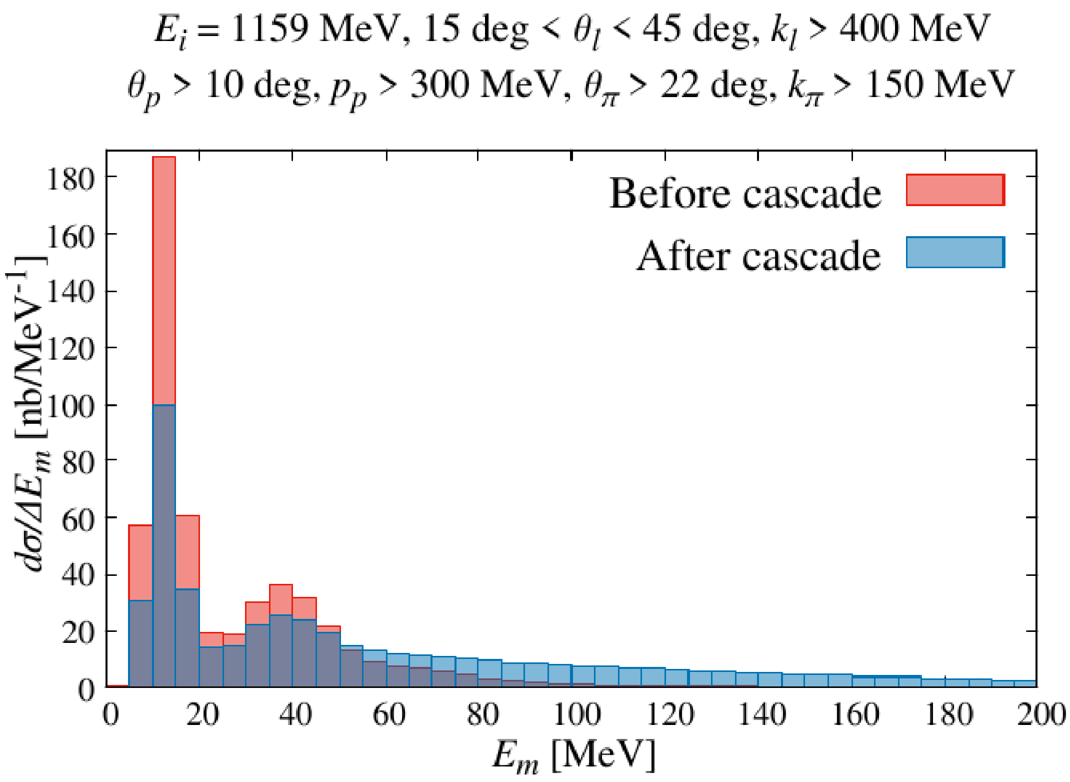


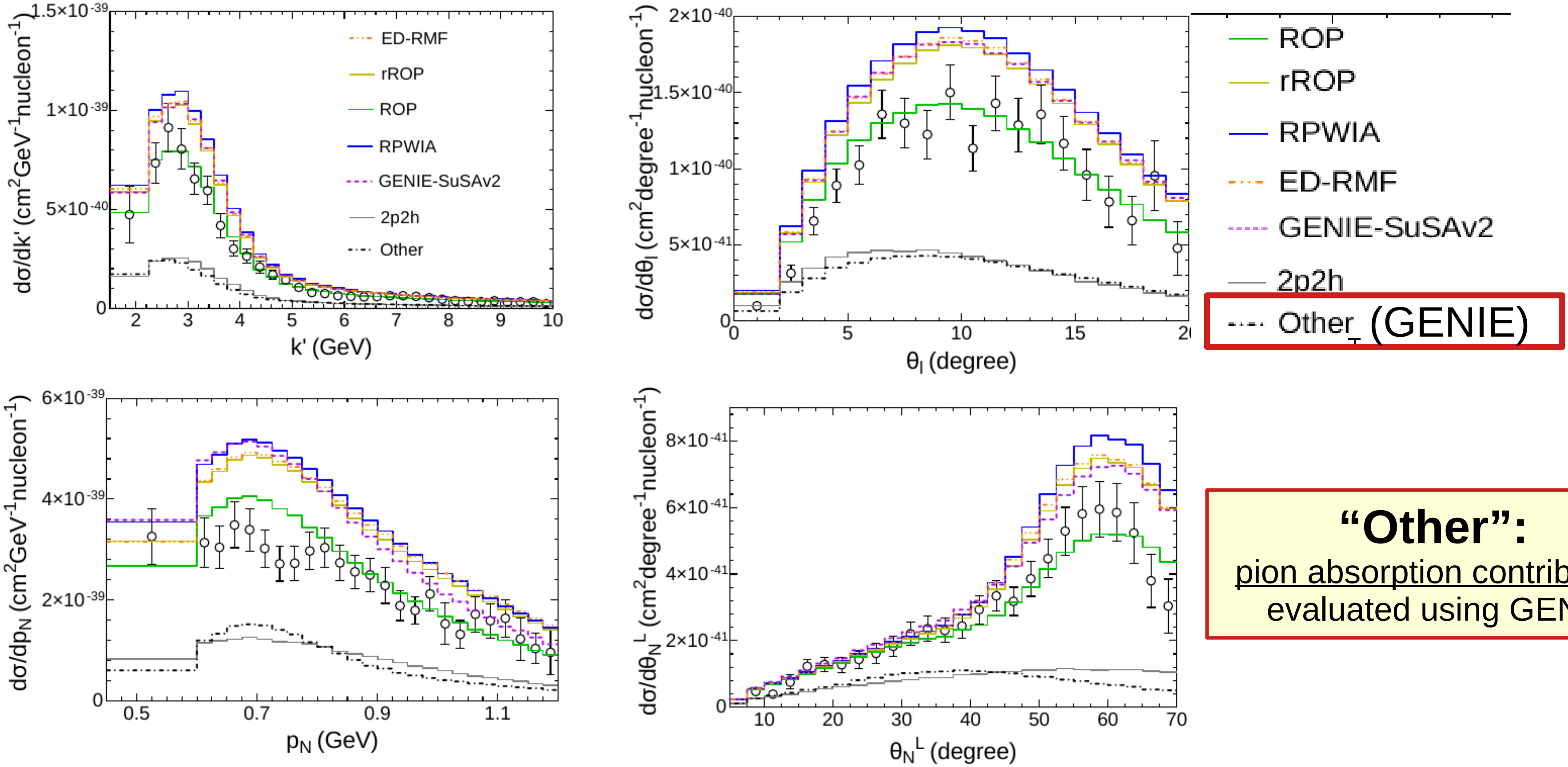
FIG. 14. $^{40}\mathrm{Ar}(e, e'p\pi^-)$ cross section as a function of missing energy using the CLAS kinematics and acceptances.

PART 2:

Constraining the “pion absorption”

MINERνA no-pion ν_μ-^{12}C cross section

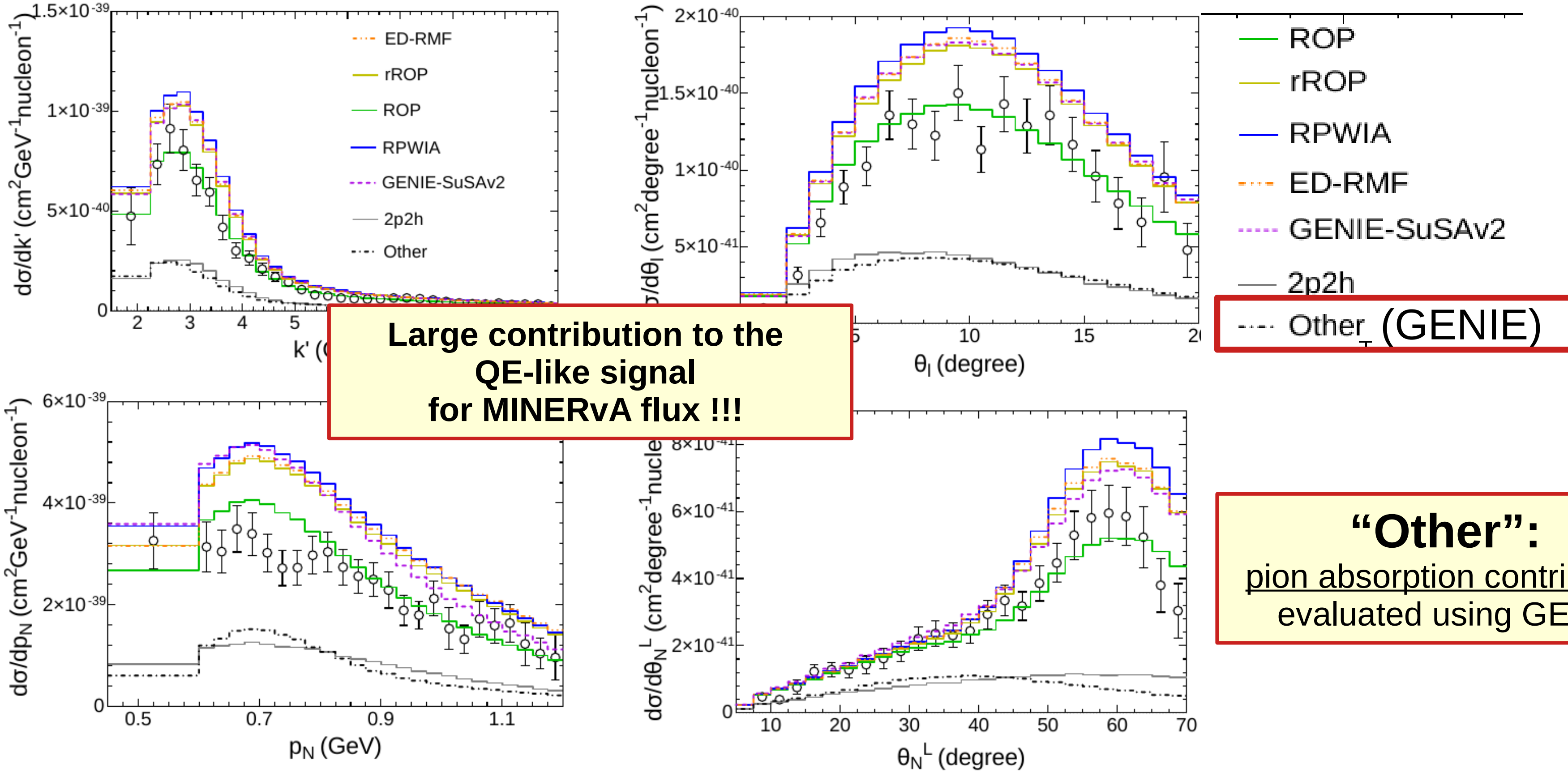
Franco-Patino et al. (2022), https://doi.org/10.1103/PhysRevD.106.113005



"Other":
pion absorption contribution
evaluated using GENIE

MINERνA no-pion ν_μ-^{12}C cross section

Franco-Patino et al. (2022), https://doi.org/10.1103/PhysRevD.106.113005



Large contribution to the QE-like signal for MINERνA flux !!!

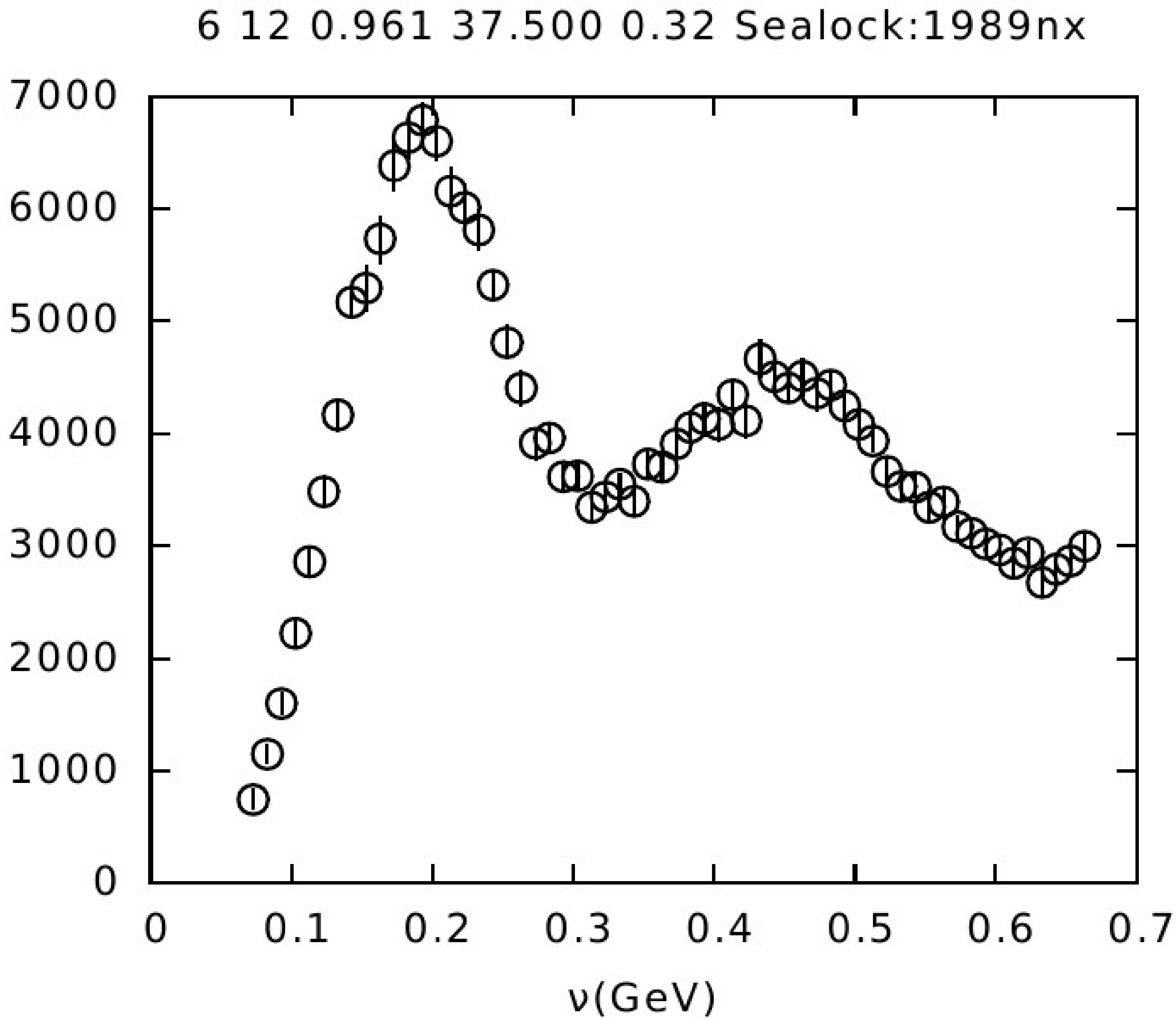
“Other”:
pion absorption contribution evaluated using GENIE

What does it really mean
“**pion absorption**” ?

In reality, there never was a real pion.

Can **experiments constrain** this important **(model-dependent)** contribution to the zero pion signal ?

$^{12}C(e,e')$



6 12 0.961 37.500 0.32 Sealock:1989nx
7000
6000
5000
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3000
2000
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0
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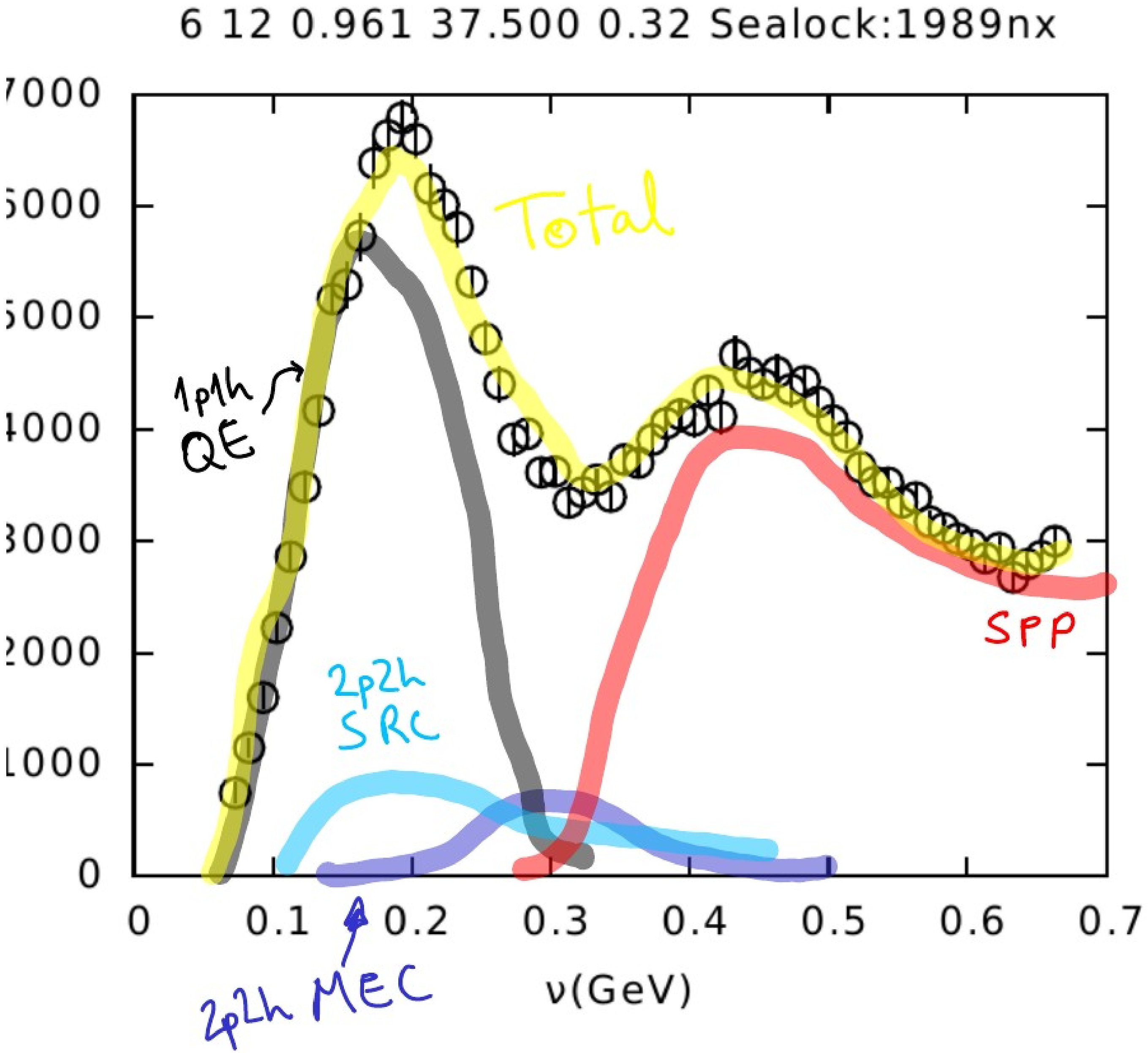
0.2
0.3
0.4
0.5
0.6
0.7
ν(GeV)

$^{12}C(e,e')$



6 12 0.961 37.500 0.32 Sealock:1989nx
7000
6000
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1000
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0.1
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0.3
0.4
0.5
0.6
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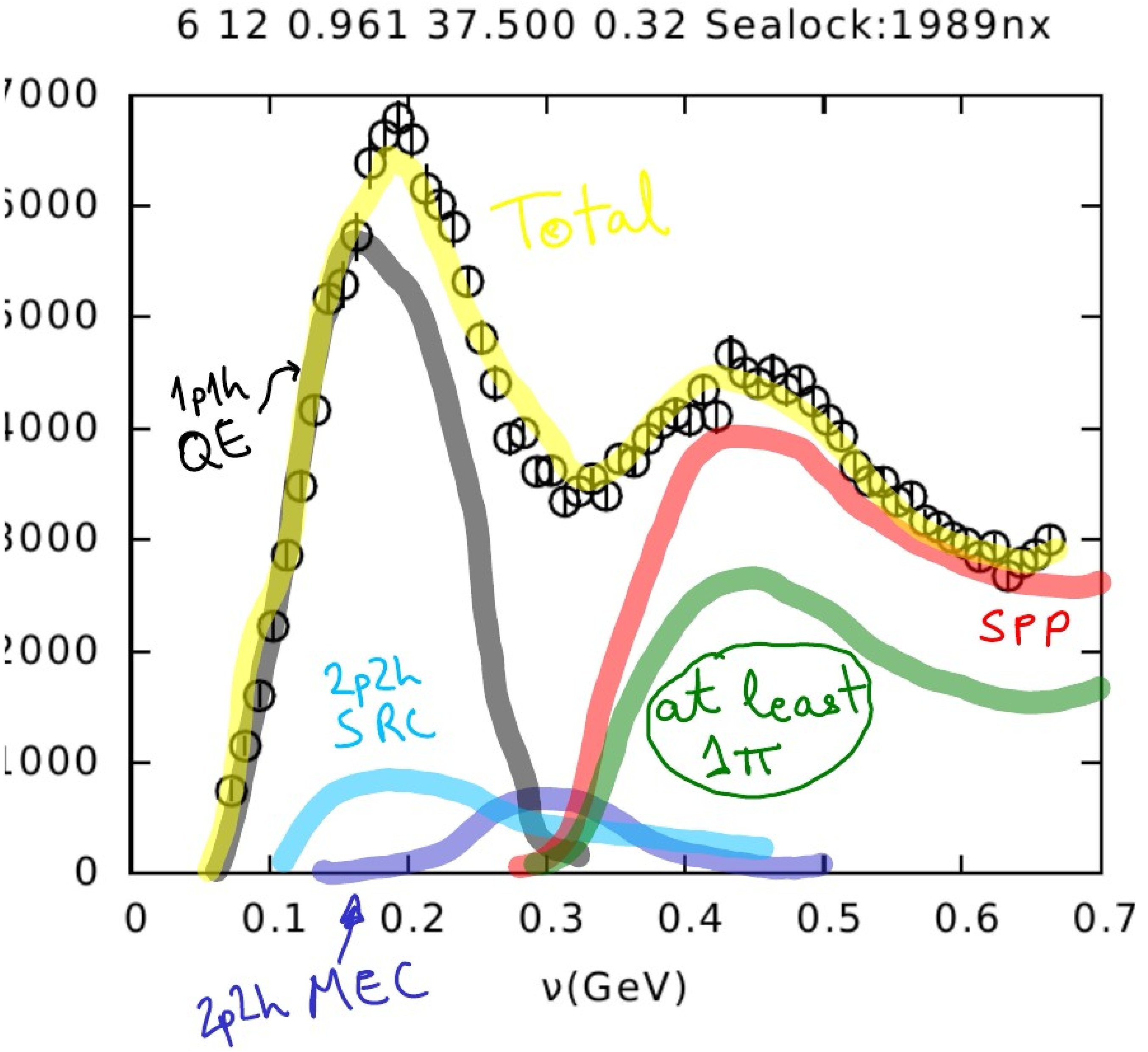
ν(GeV)
Total
1p1h
QE
2p2h
SRC
SPP
2p2h MEC

$^{12}C(e,e')$


6 12 0.961 37.500 0.32 Sealock:1989nx
7000
6000
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0.1
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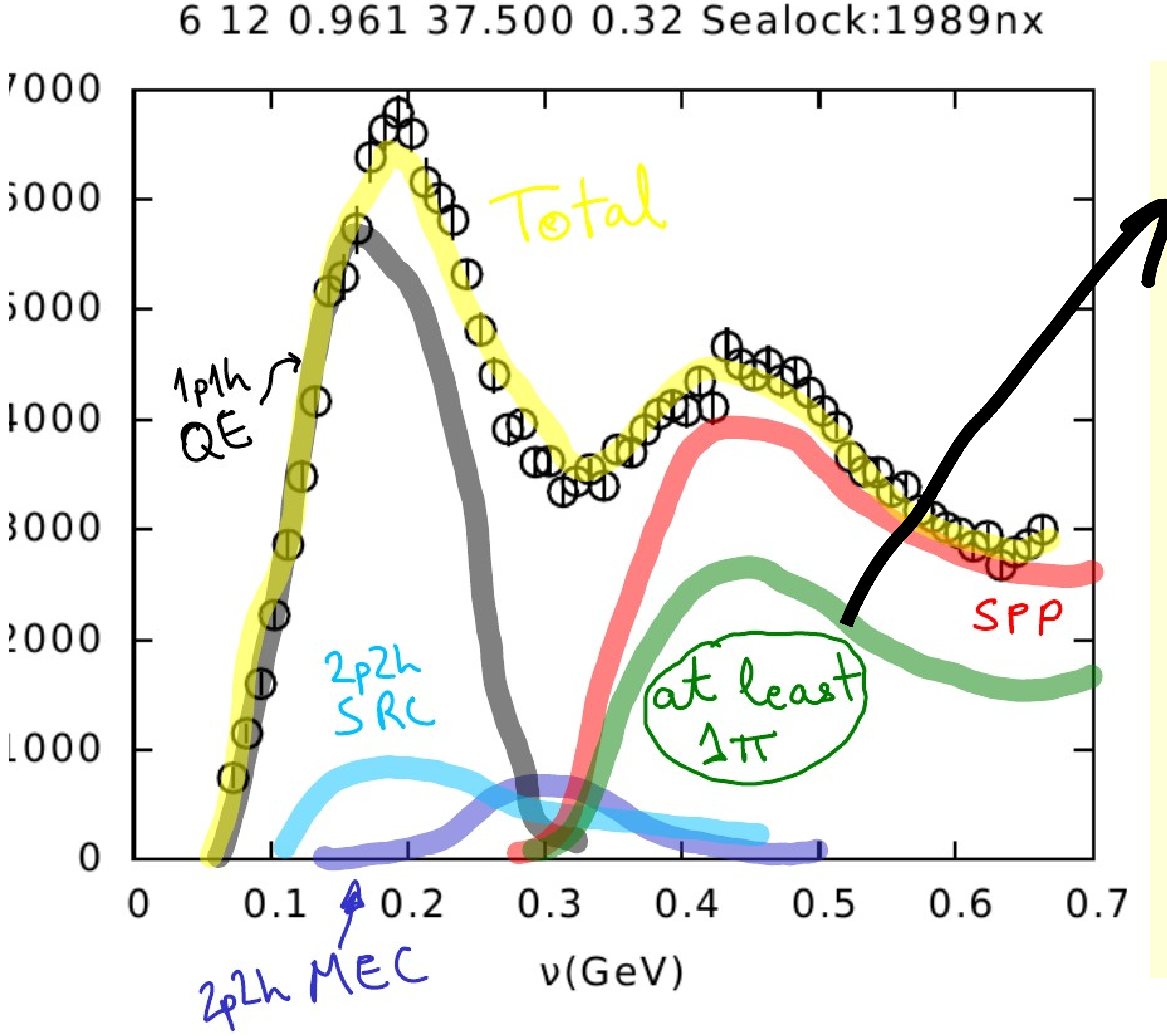
0.3
0.4
0.5
0.6
0.7
ν(GeV)
Total
1p1h
QE
2p2h
SRC
2p2h MEC
at least
1π
SPP

$^{12}C(e,e')$

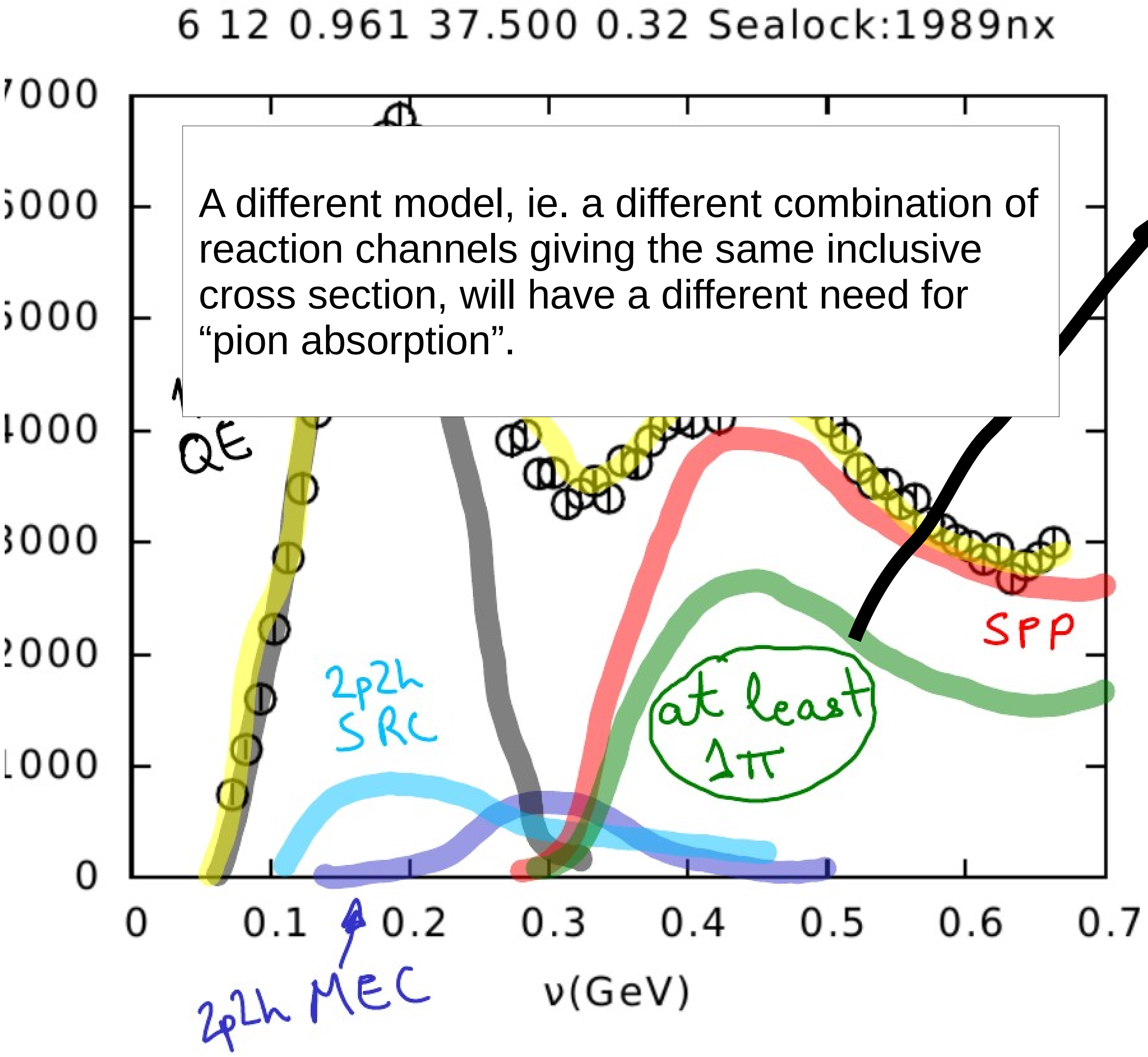


The green curve is the exp. data we want.

The other lines are model predictions.

The difference between the red and the green curves is **"pion absorption", within this particular model.**

$^{12}C(e,e')$



A different model, ie. a different combination of reaction channels giving the same inclusive cross section, will have a different need for "pion absorption".

The green curve is the exp. data we want.

The other lines are model predictions.

The difference between the red and the green curves is **"pion absorption", within this particular model**.

+ Delta propagator in the MEC 2p2h: Full vs real ??

+ In medium modifications of the delta in the SPP contribution

+ In medium modifications of the delta in the MEC 2p2h contribution

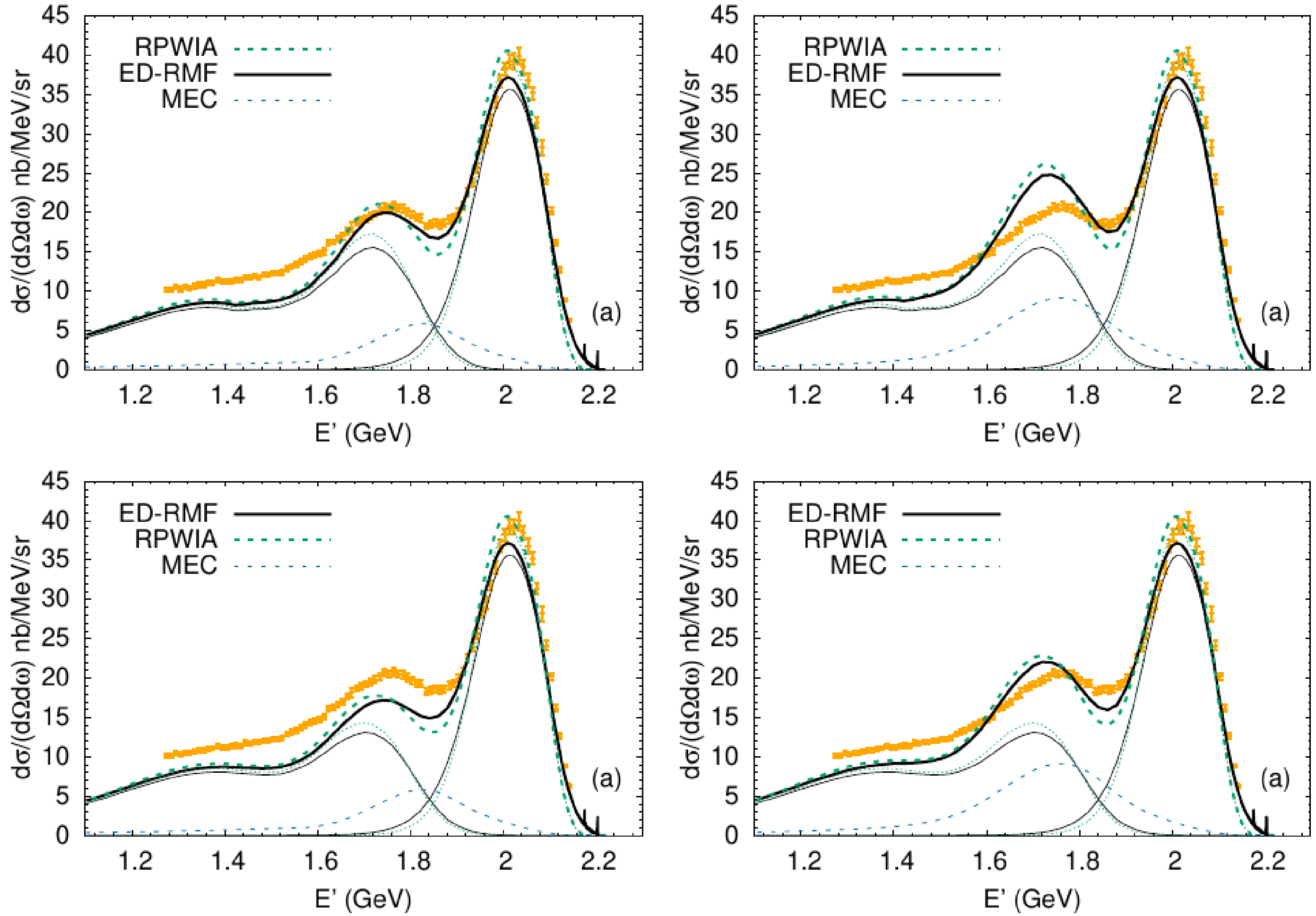
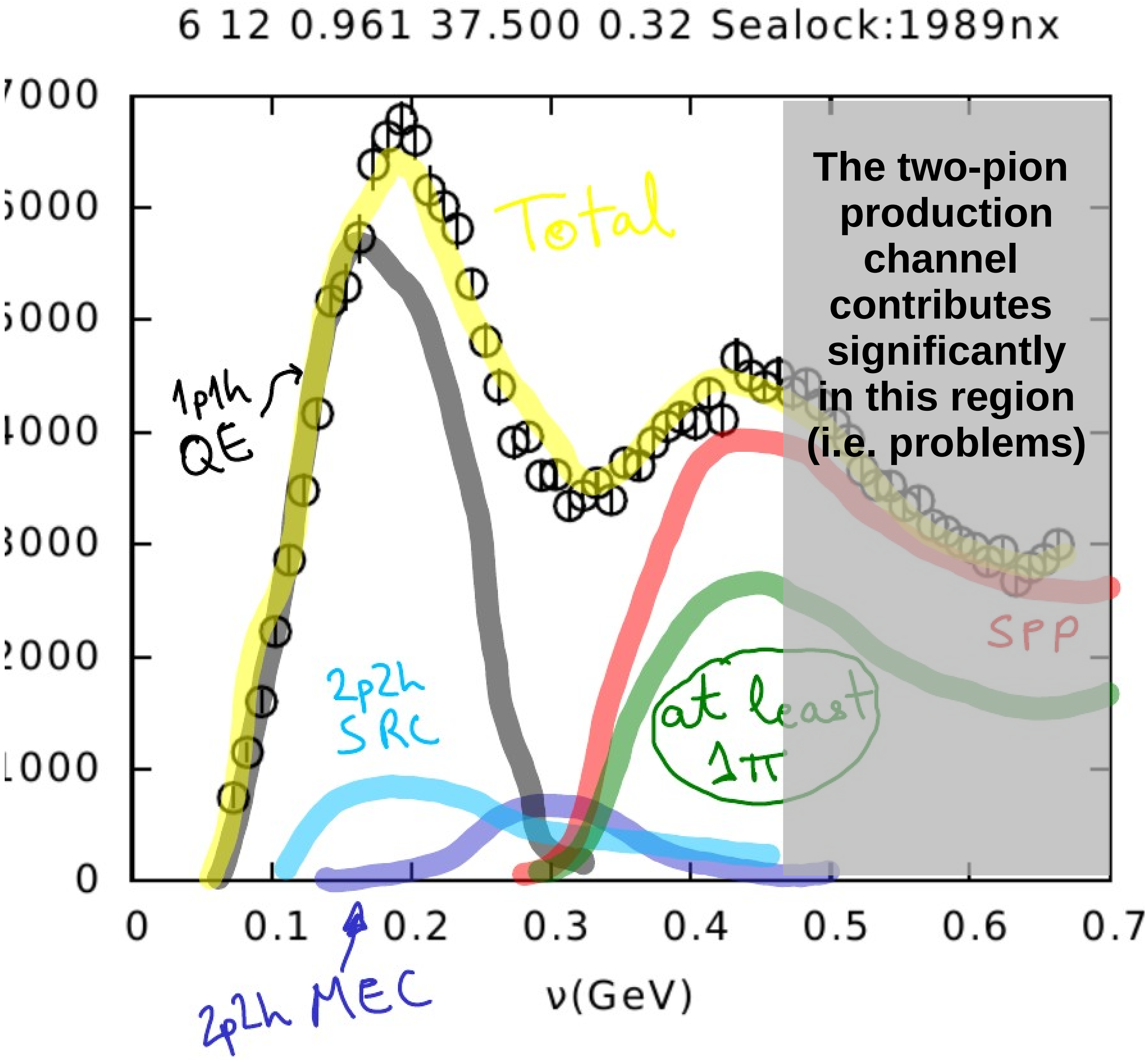


FIG. 1: Left panels are the results with only the real part of the delta propagator in the MEC contribution. Right panels are the results with the full delta propagator in the MEC. Top panels are the results without medium-modification in the delta-decay width in the SPP contribution. Bottom panels are the results including medium-modification in the delta-decay width in the SPP (see text for details). The QE response is the same in the four panels.

$^{12}C(e,e')$



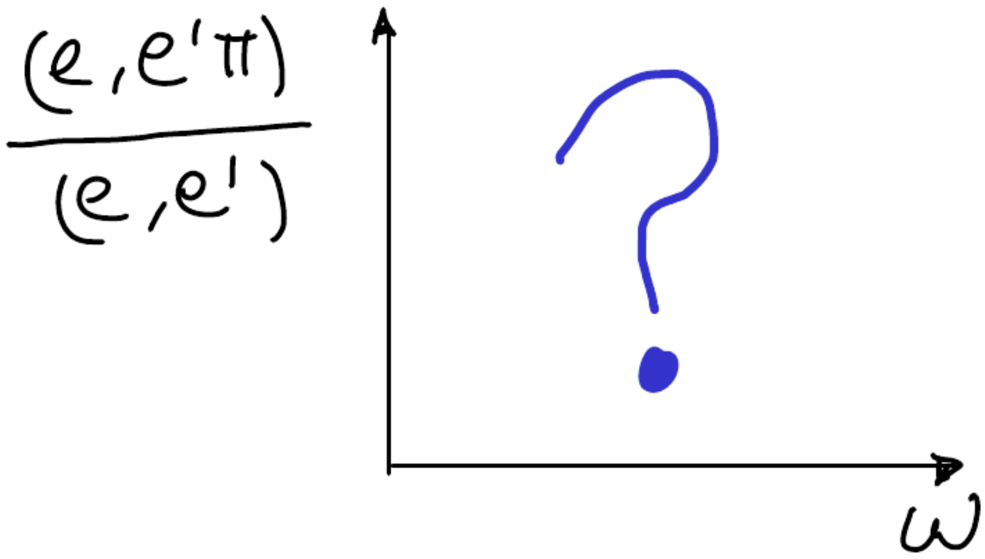
The green curve is the exp. data we want.

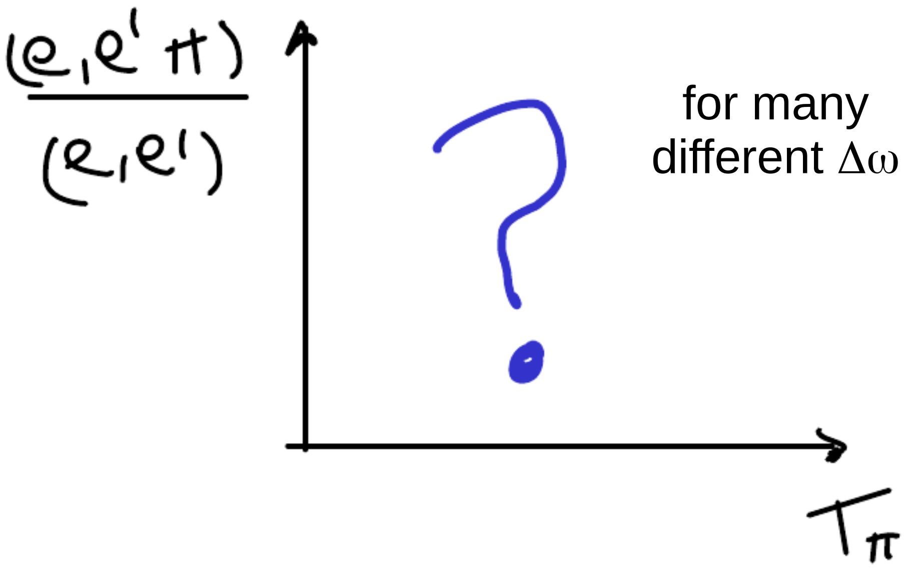
The other lines are your theory.

The difference between the red and the green curves is **"pion absorption", within this particular model**.

Incoming energy and
scattering angle fixed

We prefer cross sections
but if that is too difficult,
ratios of
“at least one pion” to
inclusive signal
are also fine.





for many
different Δω

Incoming energy and
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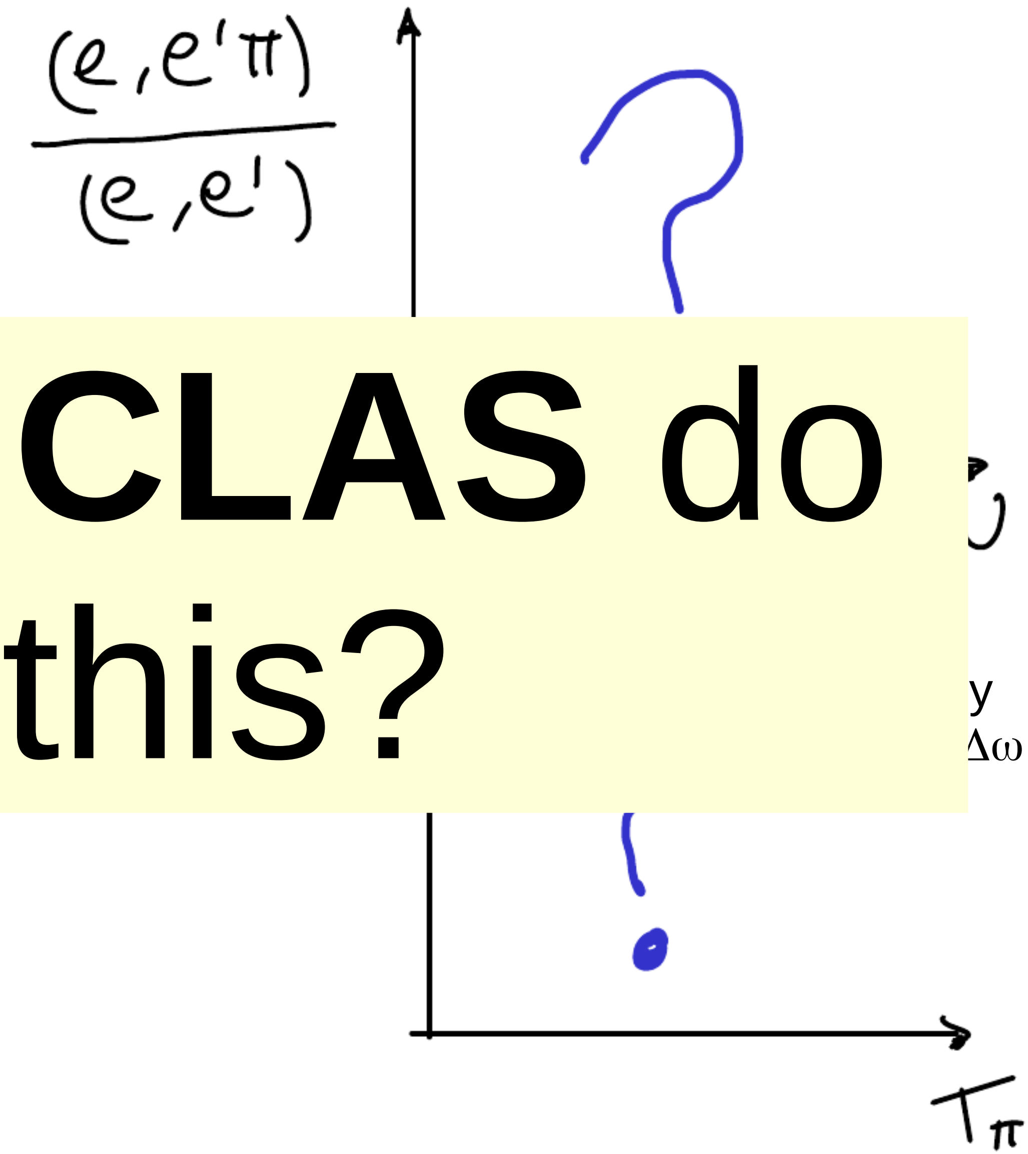

Can **CLAS** do this?

Incoming energy and
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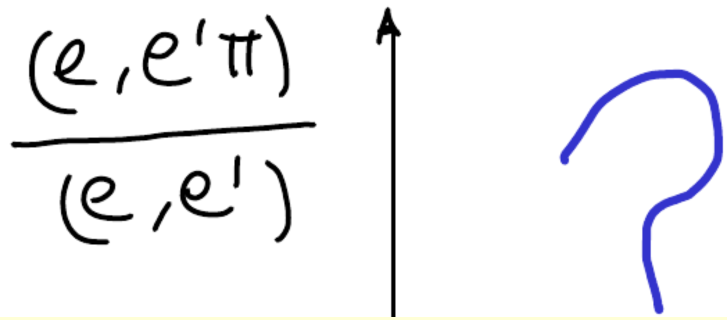
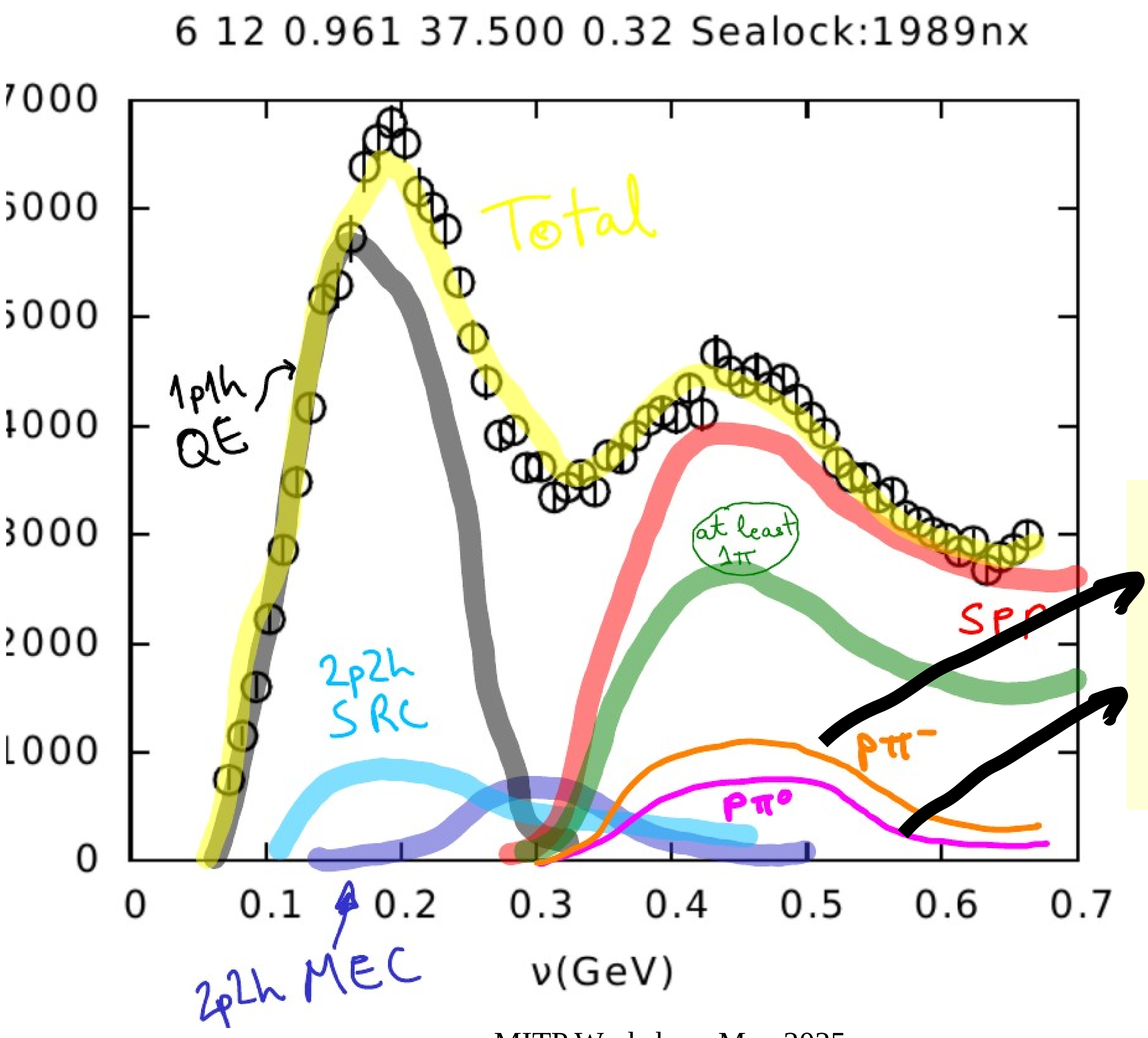


Can **CLAS** do this?
Adi’s talk yesterday!

If we keep dreaming...

If we keep dreaming...



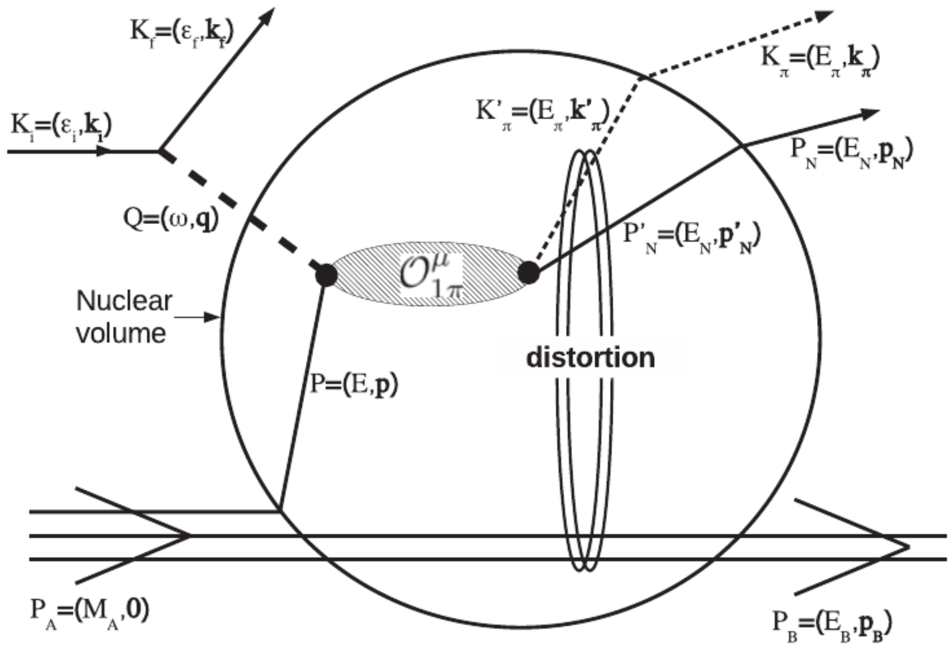
Single-pion production data separated in different channels would be even more useful to constrain models

Part 3:

On the modeling

$$e + n \longrightarrow e' + p + \pi^-$$

Single-Pion Production
(in the Impulse Approximation)



$$J^\mu_{\rm had} = \int d\mathbf{p} \int d\mathbf{p}'_N \overline{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)\phi^*_\pi(\mathbf{p}+\mathbf{q}-\mathbf{p}'_N, \mathbf{k}_\pi)\mathcal{O}_{1\pi}(Q, P'_N, P)\Psi_B(\mathbf{p})$$

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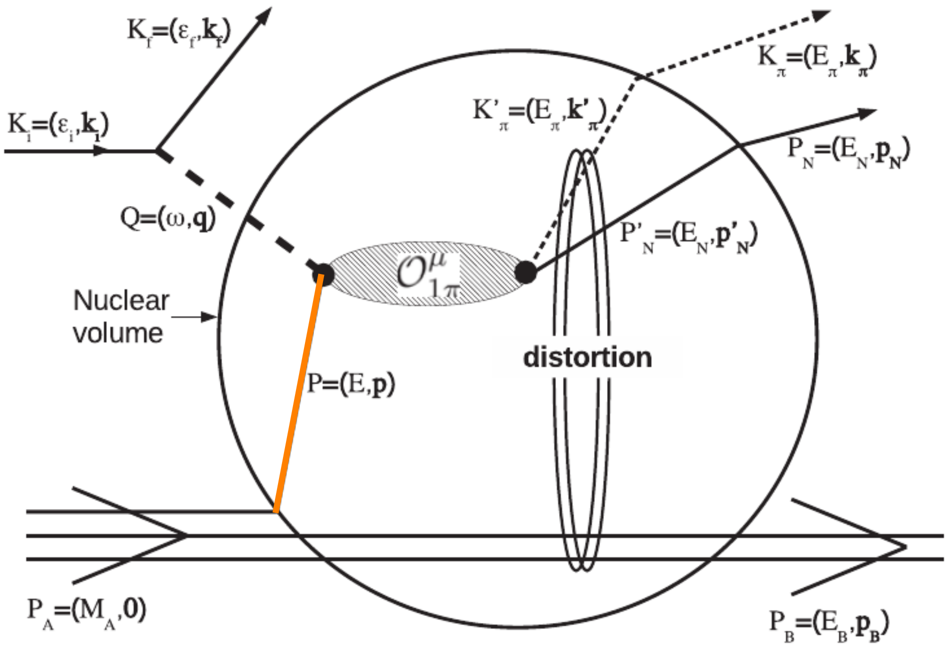

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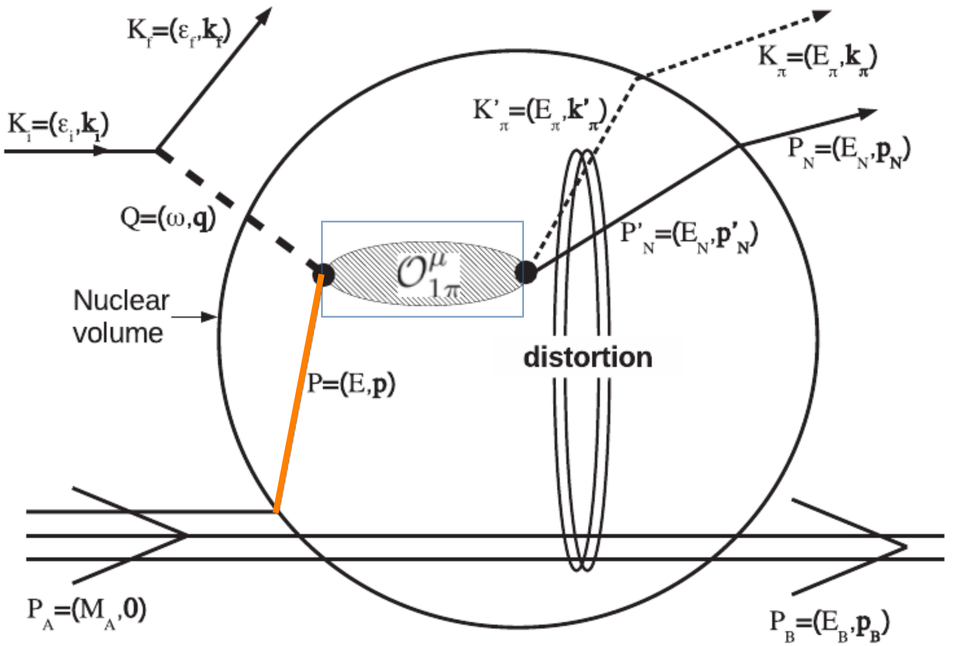

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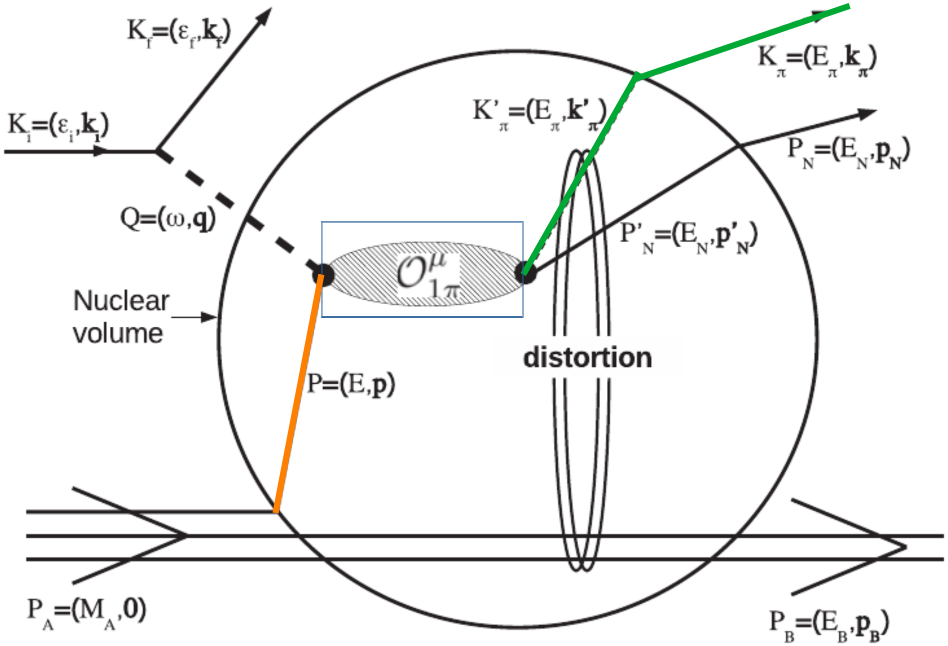

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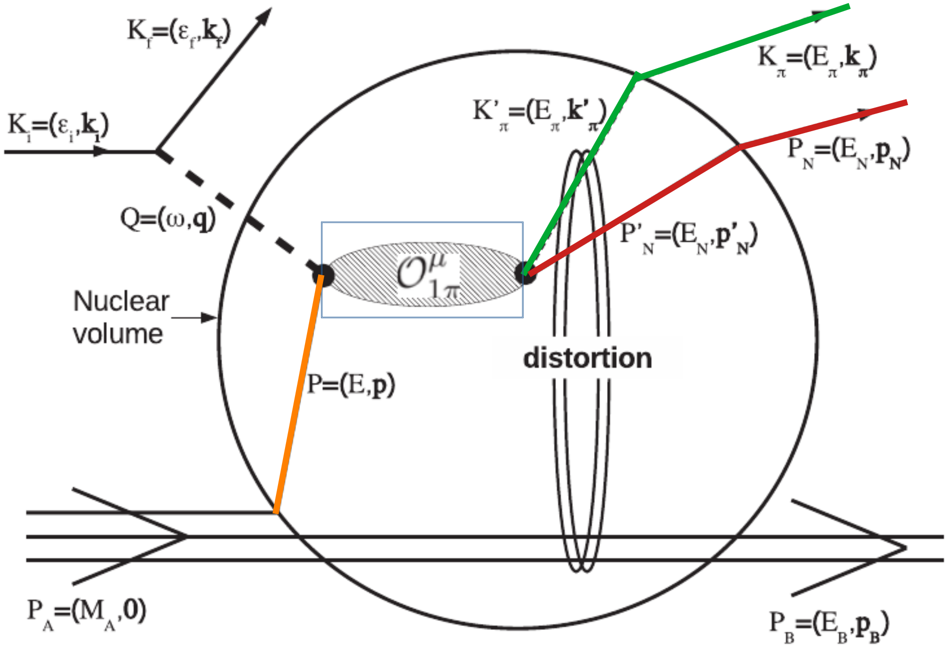

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Single-Pion Production

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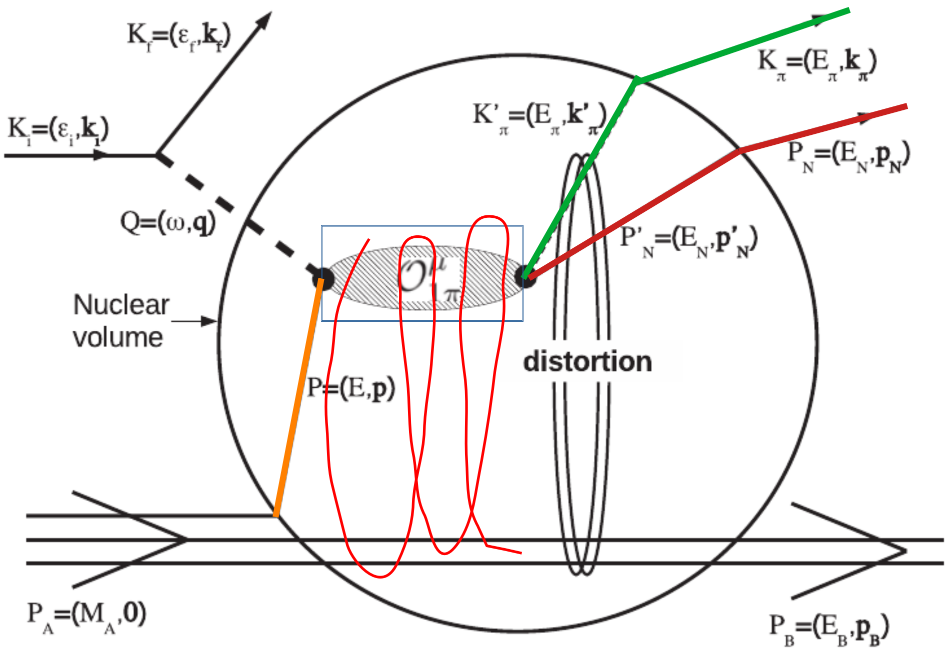


$$J^\mu_{\rm had} = \int d\mathbf{p} \int d\mathbf{p}'_N \overline{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N) \phi^*_\pi(\mathbf{p} + \mathbf{q} - \mathbf{p}'_N, \mathbf{k}_\pi) \mathcal{O}_{1\pi}(Q, P'_N, P) \Psi_B(\mathbf{p})$$

What is the best seed for a cascade?

What is the best seed for a cascade?

We believe a model based on the distorted wave approach is the best seed (currently in the market) for a cascade model:

+ it gives a fair description of the inclusive cross section

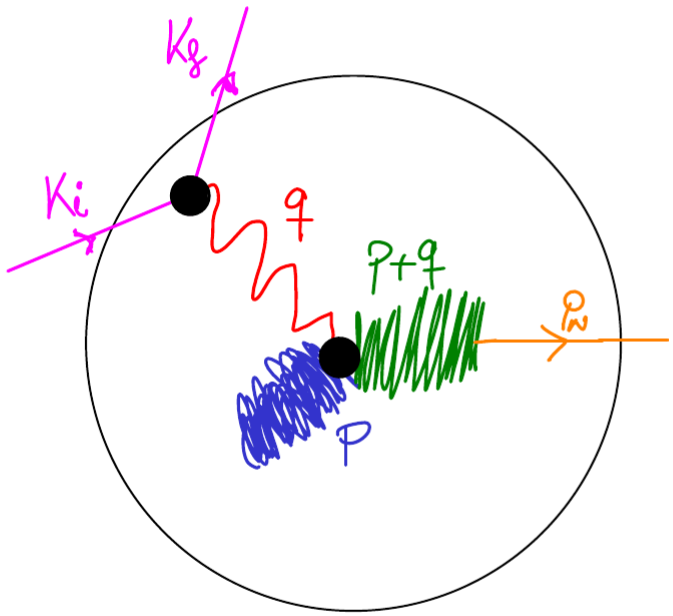
+ it provides information about the final nucleon

What about, **Double counting the FSI?**

I don’t think so…

https://doi.org/10.1103/PhysRevC.105.054603
https://doi.org/10.1103/PhysRevC.110.054611
https://arxiv.org/abs/2502.10629

$$J^{\mu}_{had} = \int d\mathbf{p}\, \overline{\Psi}_F(\mathbf{p}+\mathbf{q}, \mathbf{p}_N)\; \mathcal{O}^{\mu}_{\text{one body}}\; \Psi_B(\mathbf{p})$$



The **momentum of the nucleons** inside the nucleus is given by the wave functions (PDFs).

In other words: the nucleons do not have a momentum, but many. The nucleons do not have a wave length, but many. (That's why we average over them.)

$$J^{\mu}_{\rm had} = \int d\mathbf{r} \overline{\Psi}_F(\mathbf{r}, \mathbf{p}_N) \mathcal{O}^{\mu}_{one\ body} \Psi_B(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}}$$

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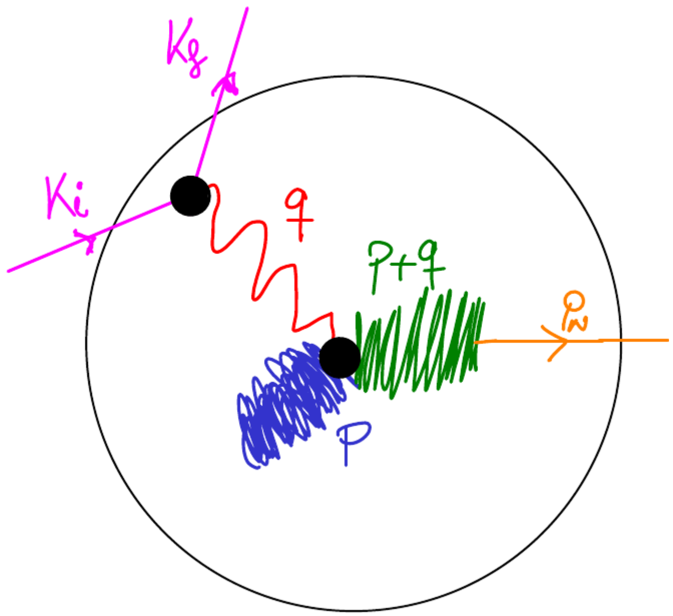

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Analogously **in coordinate space**: the nucleons are not in a particular point but in many at the same time, actually, in the whole nucleus. (That’s why we average over the whole nuclear volume.)

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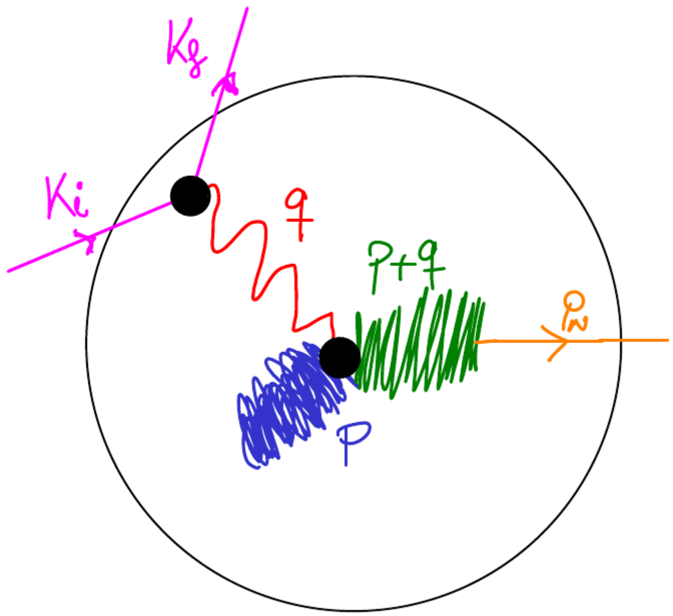

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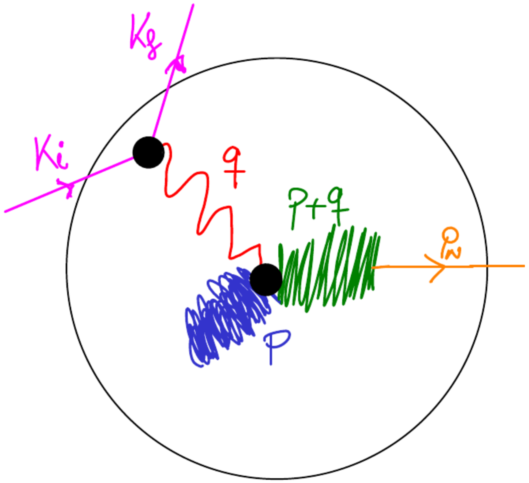
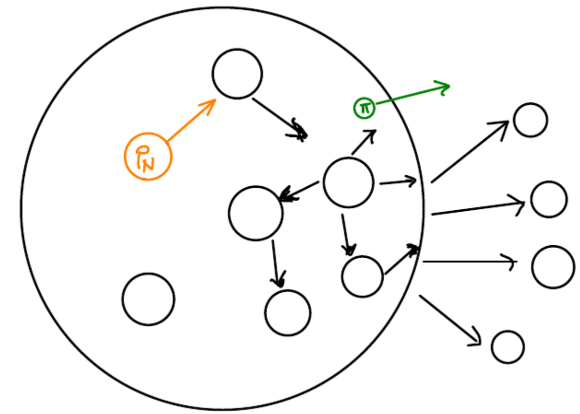
For the final nucleon, we know that its asymptotic momentum is $\mathbf{p}_N$. This is the momentum that one can measure in a detector **if and only if nothing else happens after the primary interaction**.



some time goes...



This happens first.

To describe this ALL INGREDIENTS discussed earlier are needed.

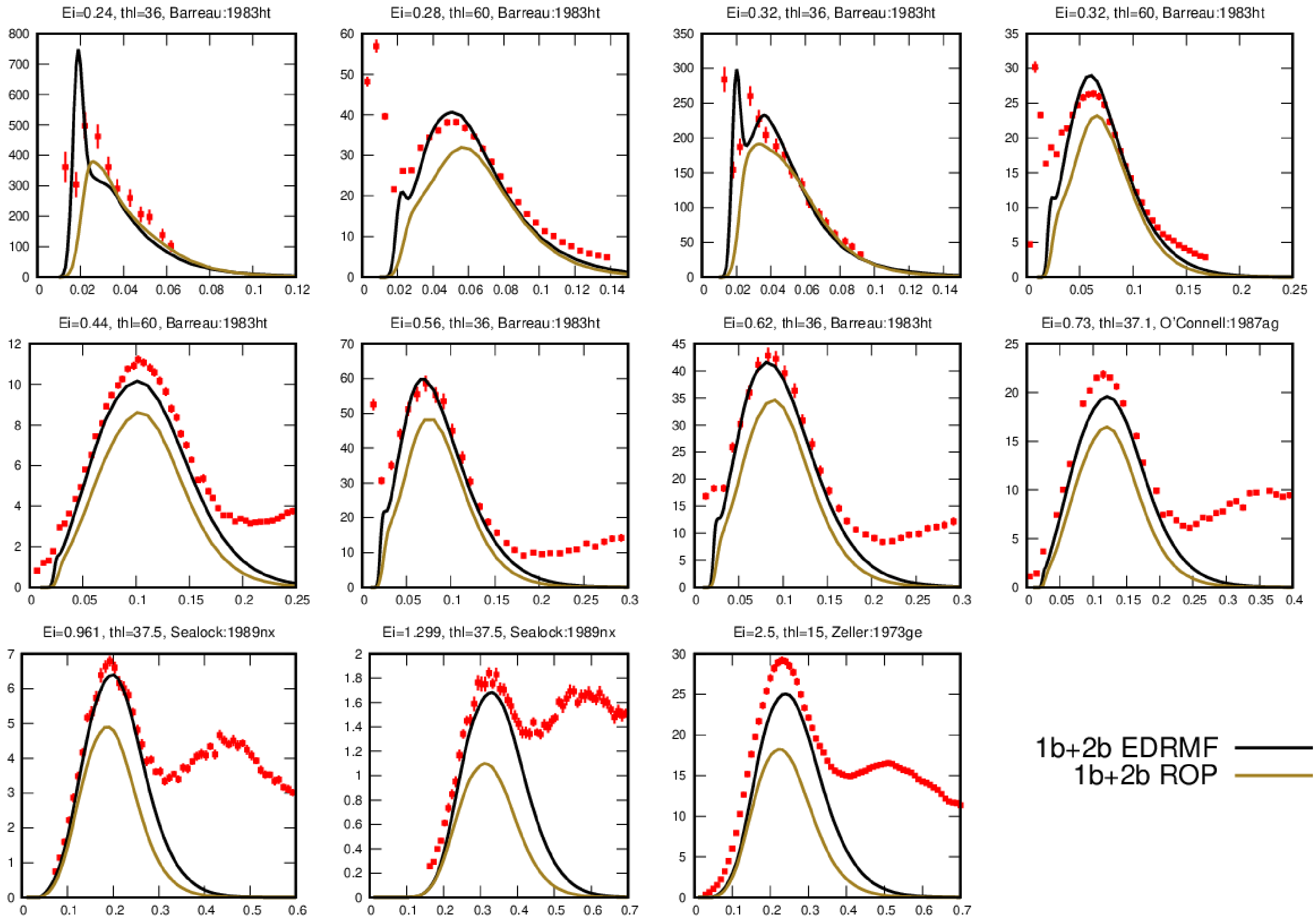
We use a RDWIA approach with only real potentials.

Then, re-scattering(s) can happen.

Hopefully, a cascade model is able to handle this.

Whatever happens here, the inclusive cross section remains the same.

(Elastic interactions should be avoided in the cascade, they were already included in the modeling of the primary interaction.)


Ei=0.24, thl=36, Barreau:1983ht
Ei=0.28, thl=60, Barreau:1983ht
Ei=0.32, thl=36, Barreau:1983ht
Ei=0.32, thl=60, Barreau:1983ht
Ei=0.44, thl=60, Barreau:1983ht
Ei=0.56, thl=36, Barreau:1983ht
Ei=0.62, thl=36, Barreau:1983ht
Ei=0.73, thl=37.1, O'Connell:1987ag
Ei=0.961, thl=37.5, Sealock:1989nx
Ei=1.299, thl=37.5, Sealock:1989nx
Ei=2.5, thl=15, Zeller:1973ge
1b+2b EDRMF
1b+2b ROP

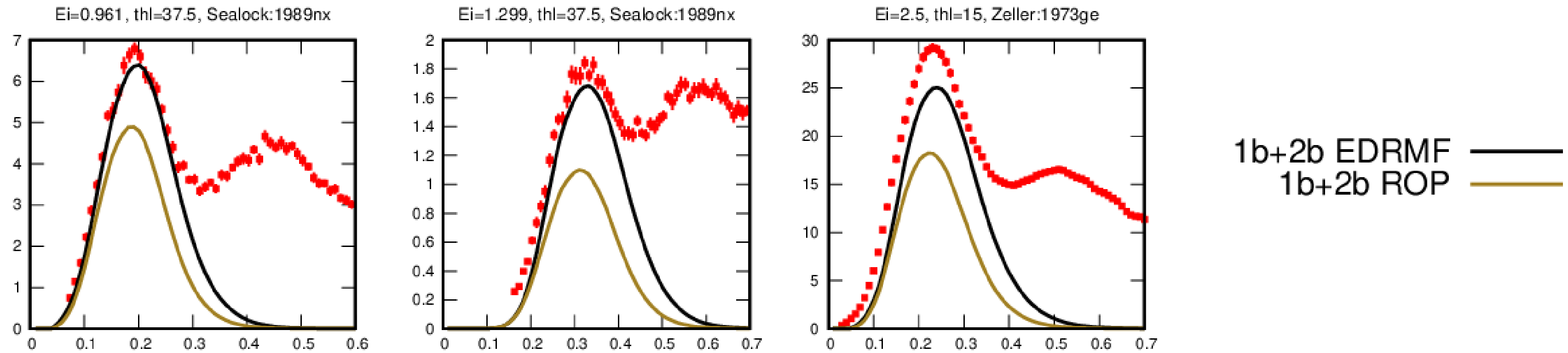
The **ROP** model uses a complex Relativistic Optical Potential (ROP).
The **EDRMF** model uses a real potential.

ROP predicts the cross section for the case in which the struck nucleon suffers only elastic final-state interactions (*): so the **final state consists in "the lepton + only one nucleon"**, the "Golden Channel" in neutrino experiments.

(*)In a MC generator, it corresponds to the case in which the nucleon propagates through the nucleus (using the intranuclear cascade model) without interacting at all. Useful to benchmark cascade models. https://arxiv.org/abs/2406.09244, https://doi.org/10.1103/PhysRevC.105.054603

Only a fraction of the strength corresponds to the "only one nucleon" case.

So… why the EDRMF approach works well for the inclusive?

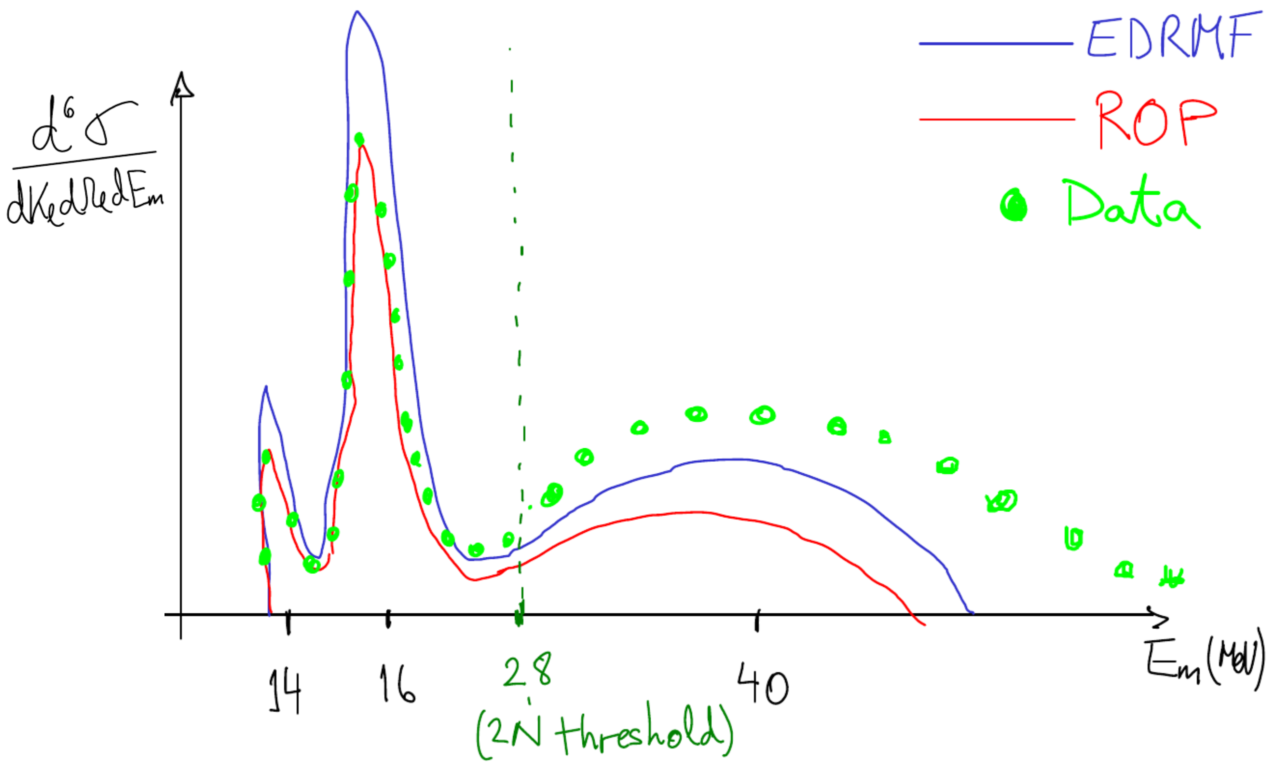


Fictitious experiment

$^{16}O(e,e'p)^{15}N$, integrated over the whole solid angle of the nucleon.

(And let's imagine that the only process that exists is QE scattering, so there is no MEC 2p-2h or SRC inducing 2p2h.)

What do we expect to see?



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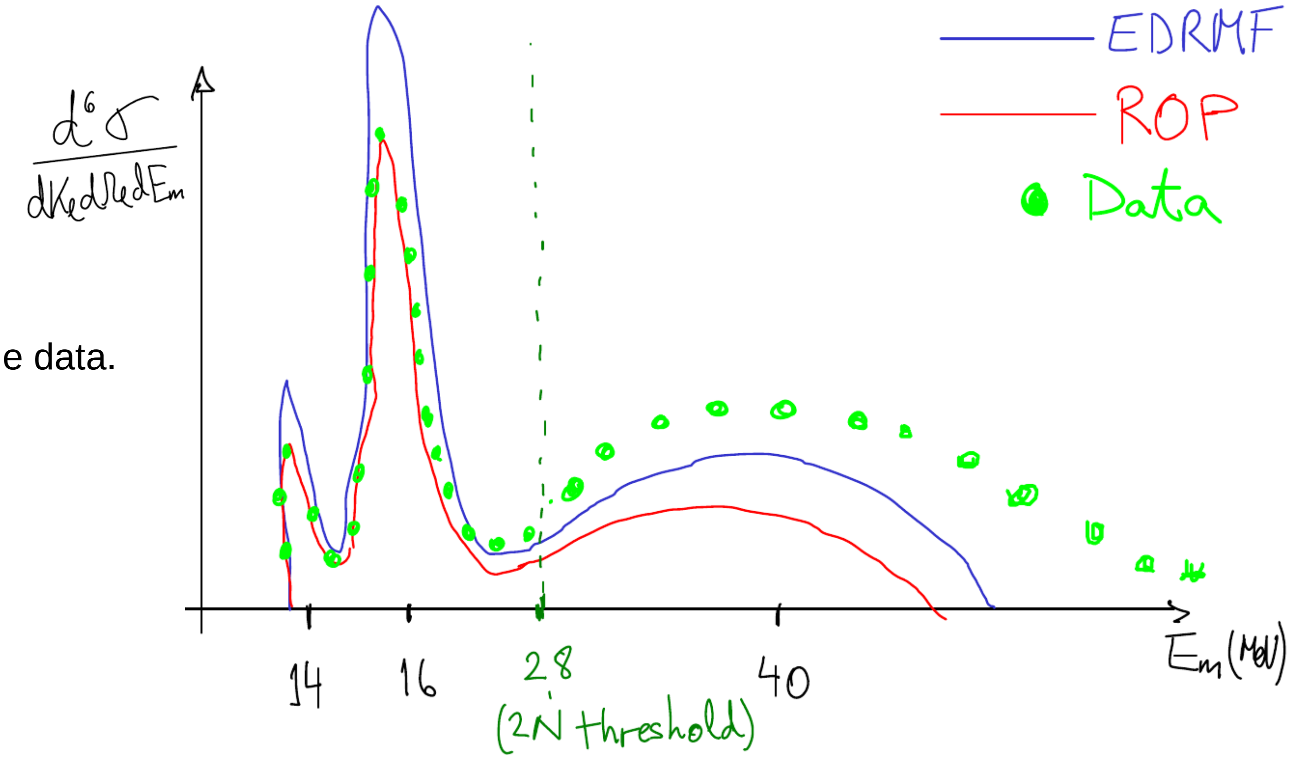

What do we expect to see?

1. Around 1p1h threshold: ROP matches the data. EDRMF overestimates them.

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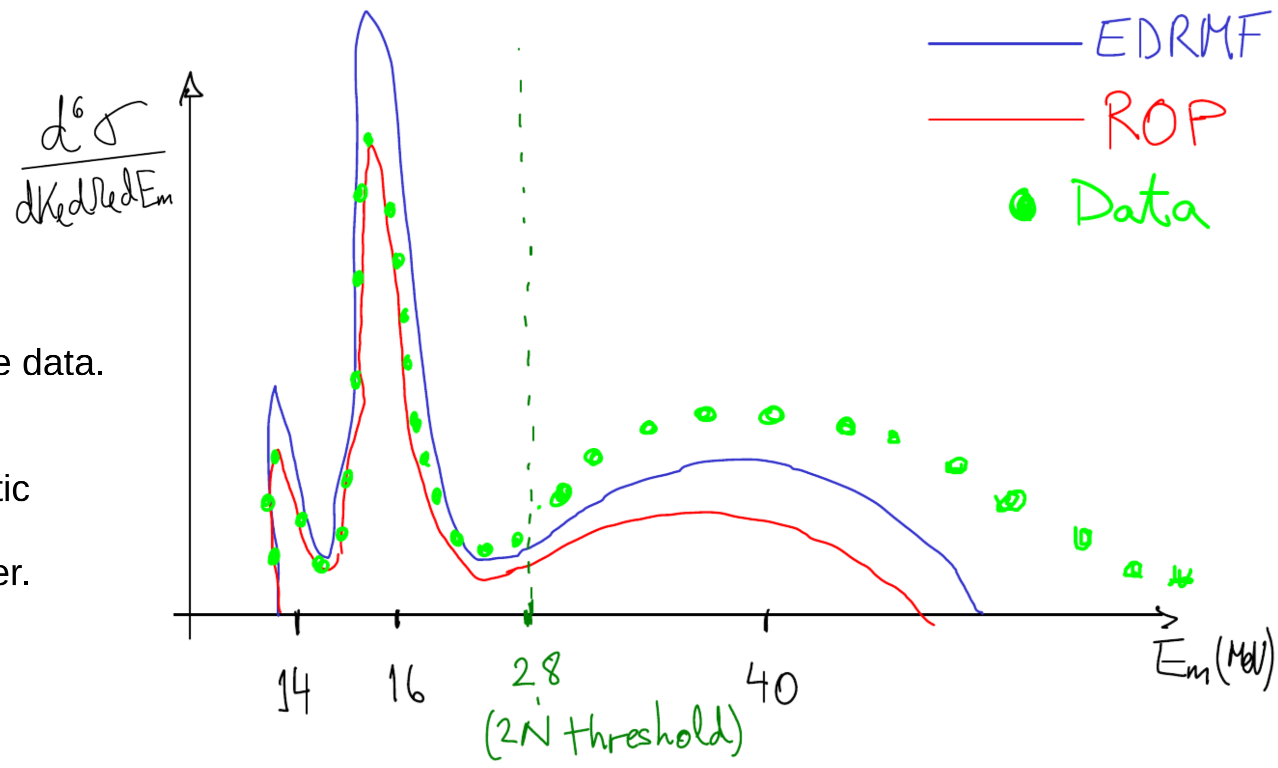
2. A bit beyond 1p1h threshold some inelastic channels have been opened: ROP starts to underestimate data. EDRMF is getting closer.



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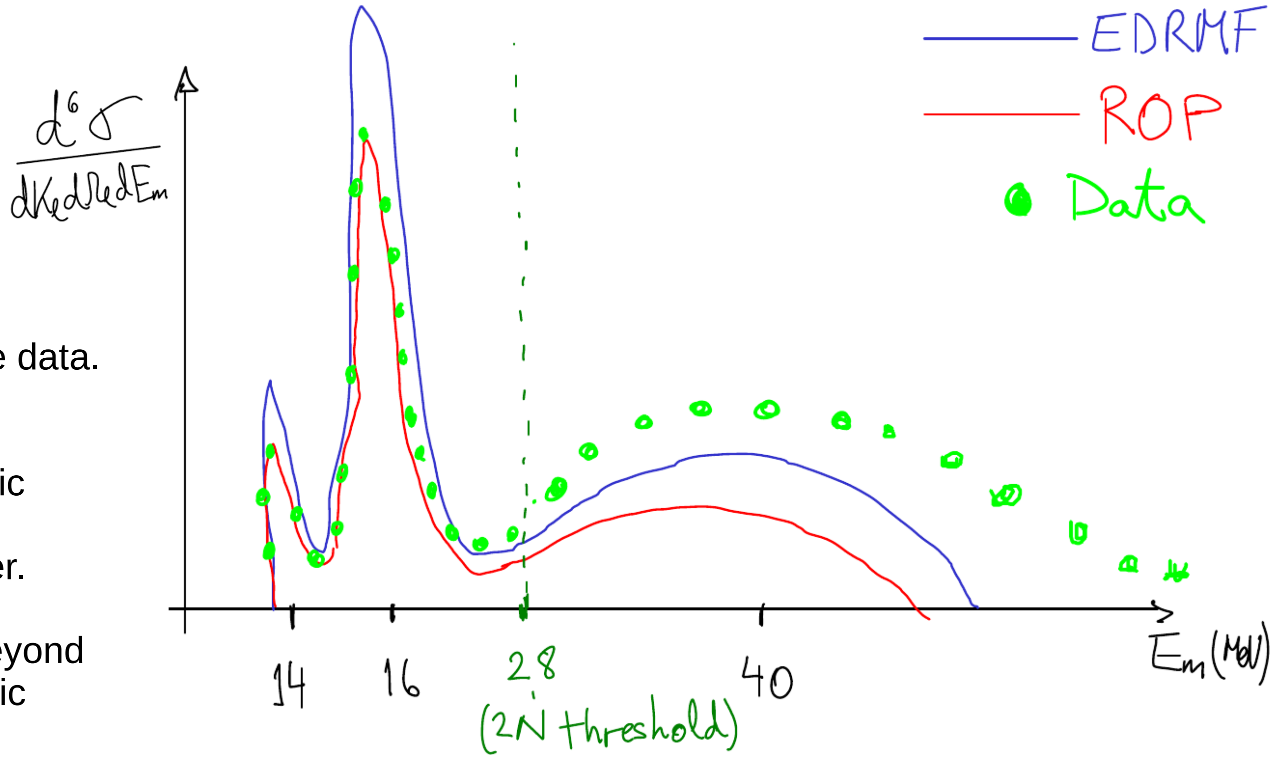

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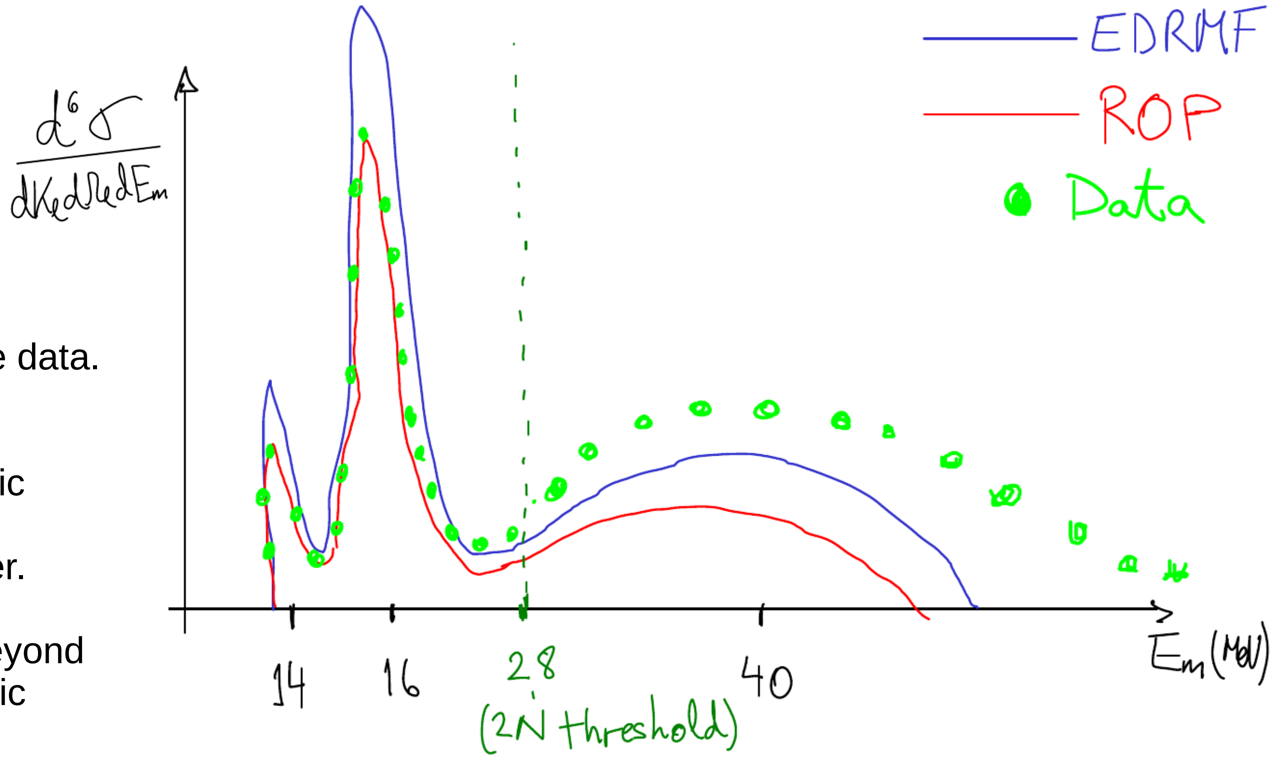

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4. If we integrate over E_m, (aka inclusive xs), the EDRMF value matches the data value.

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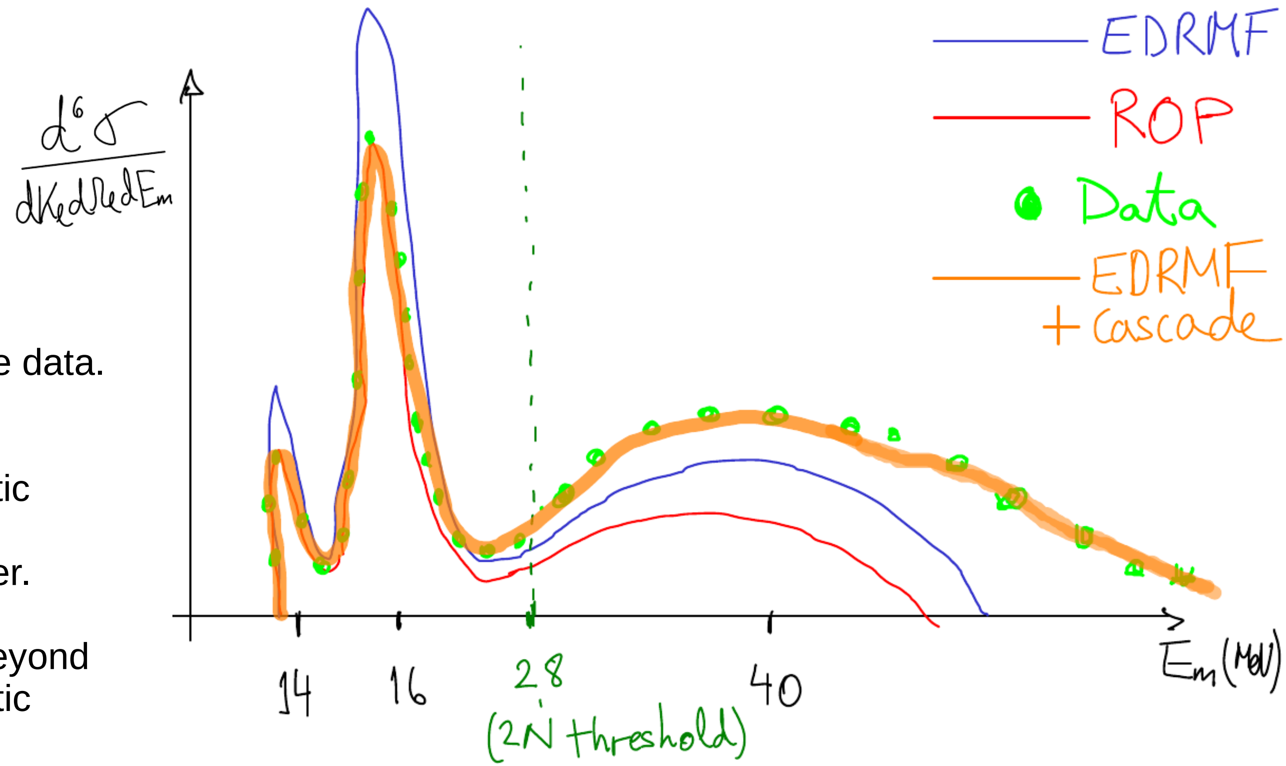

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5. EDRMF+cascade (hopefully) matches the data nicely.

SUMMARY

+ **MAMI** could make a triple coincidence experiment, $^{40}Ar(e,e'p\pi^-)$, to help constrain the **neutron structure in argon**, and other nuclei.

++ CLAS could do it as well, but backgrounds are expected to be larger

+ **CLAS** could help constrain the amount of the, so called, **“pion absorption”** in argon, and other nuclei.

+ In both cases, a good model for single-pion production, and related nuclear effects, is needed. These proposed experiments would feed, or trigger, theoretical developments.

+ On the modeling of nuclear effects:

++ A distorted wave approach to describe the initial interaction (both the pion and final nucleon are distorted waves, solution of the wave equation with real potentials).

++ An intranuclear cascade to handle inelastic FSI.