Probing nuclear short-range correlations with real photons at JLab

Tim Kolar

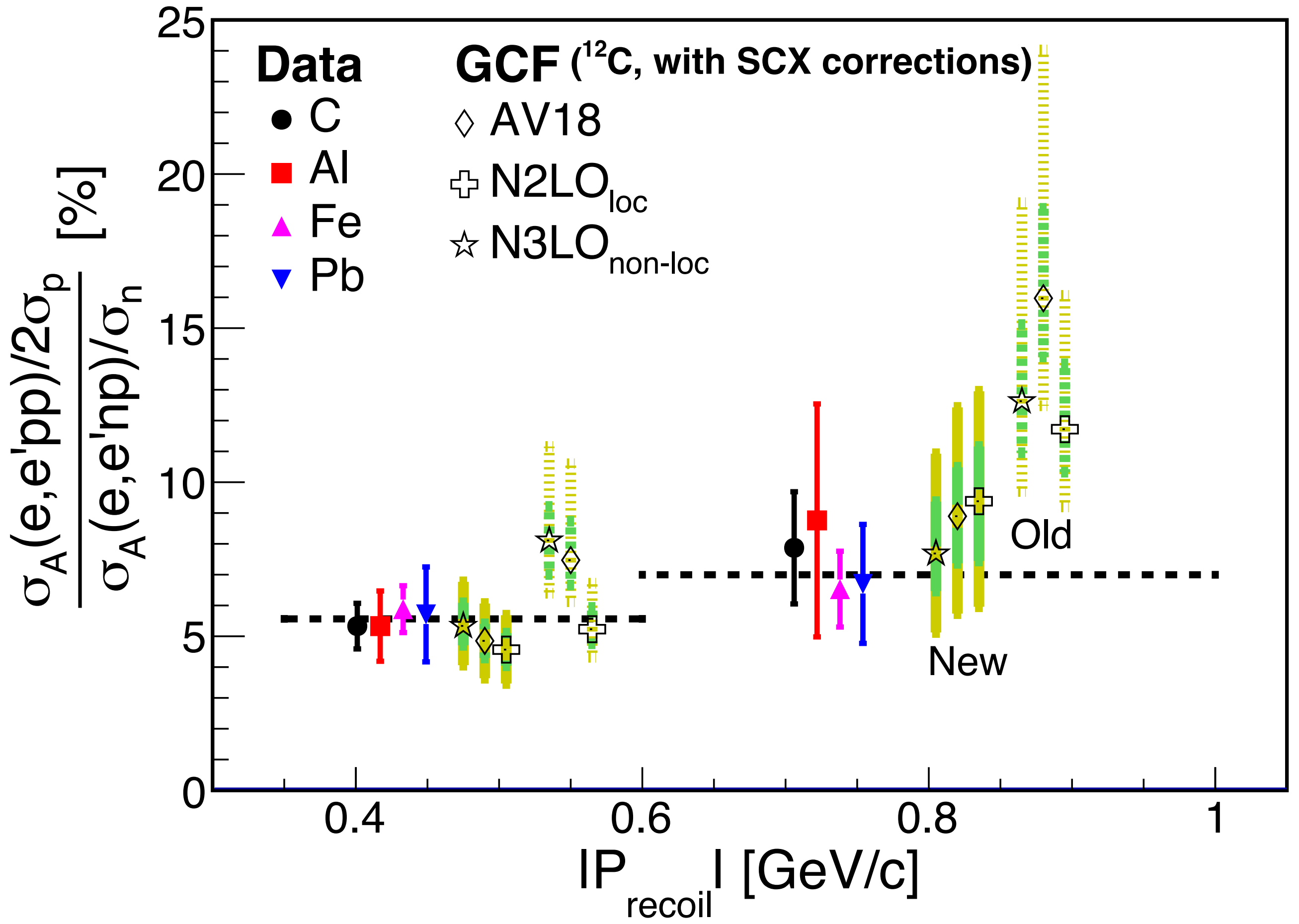
GHP 2023, Minneapolis

April 13, 2023

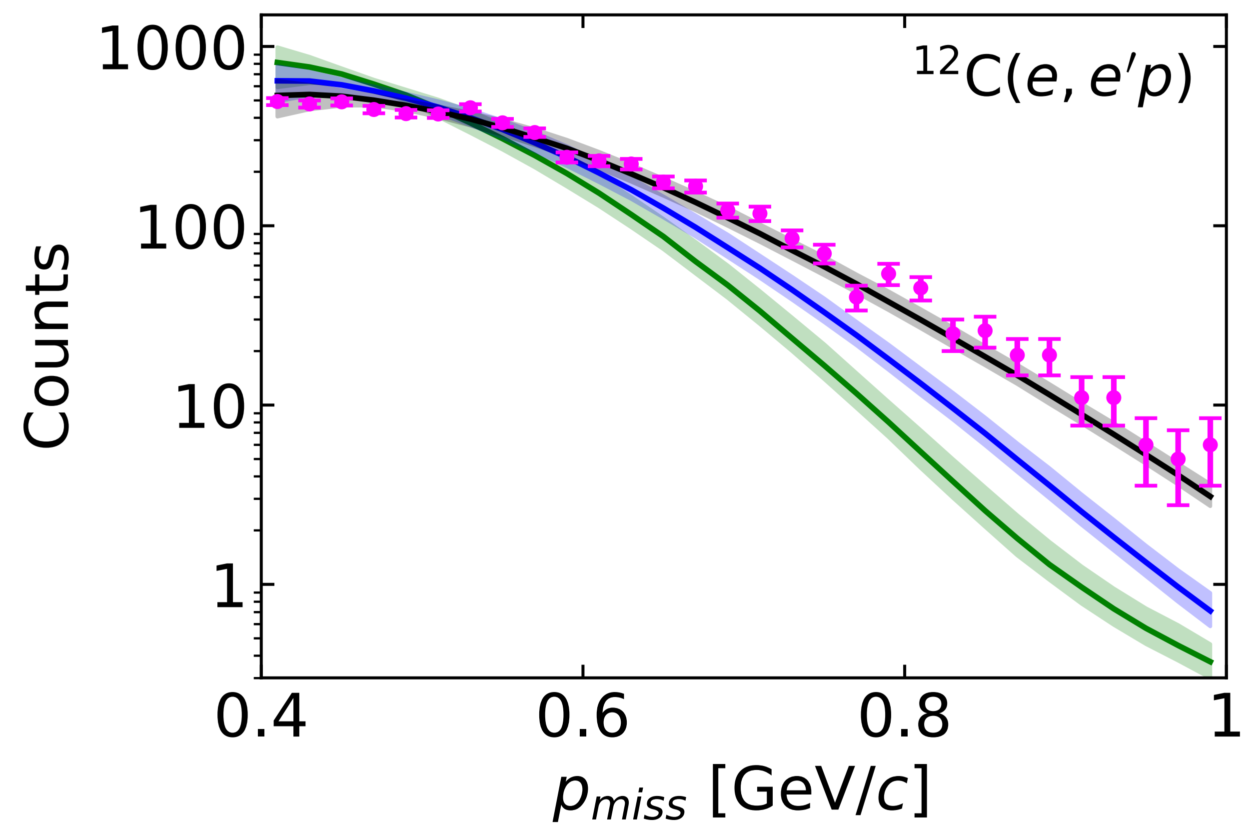
TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Plethora of recent electron scattering results SRCs

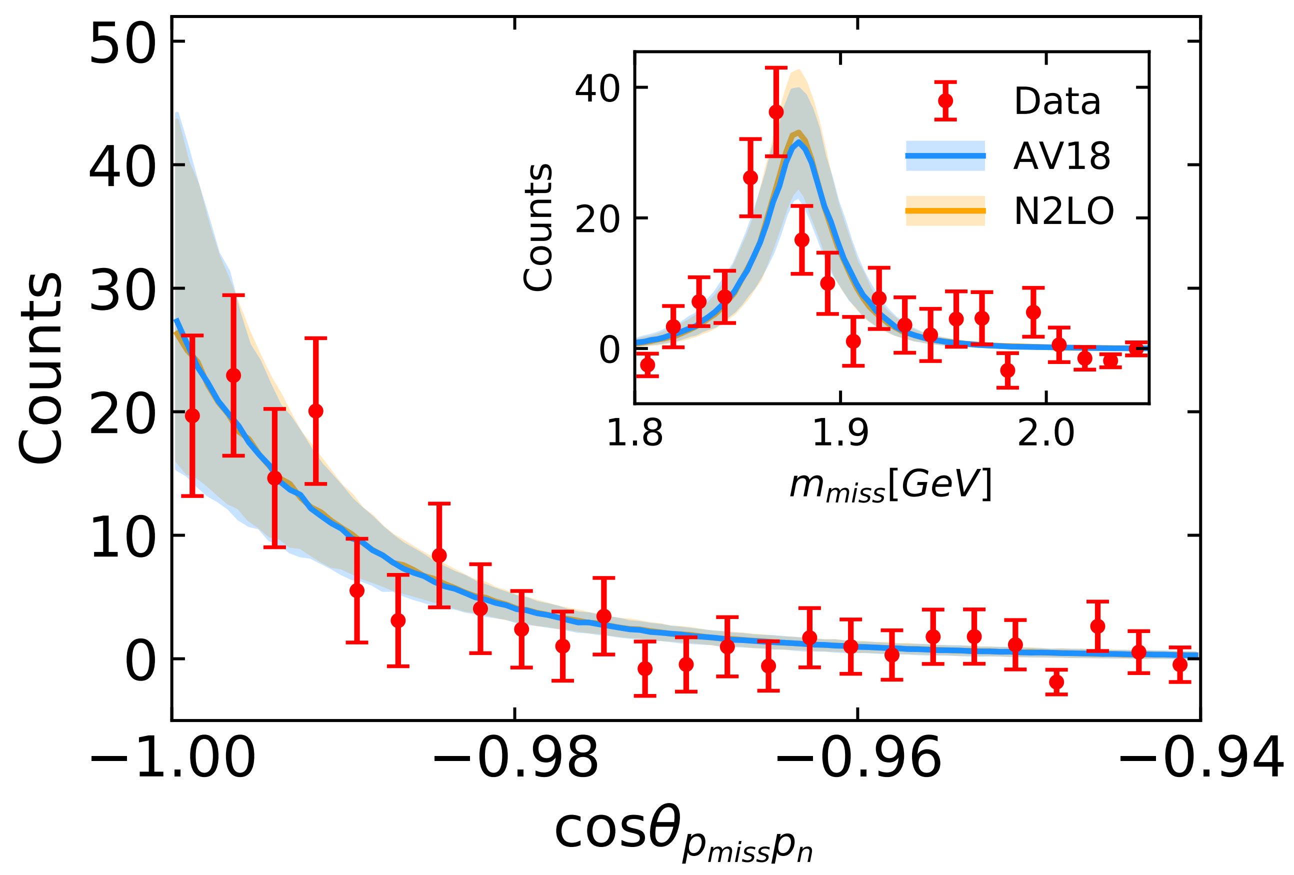
PRL 122, 172502 (2019)



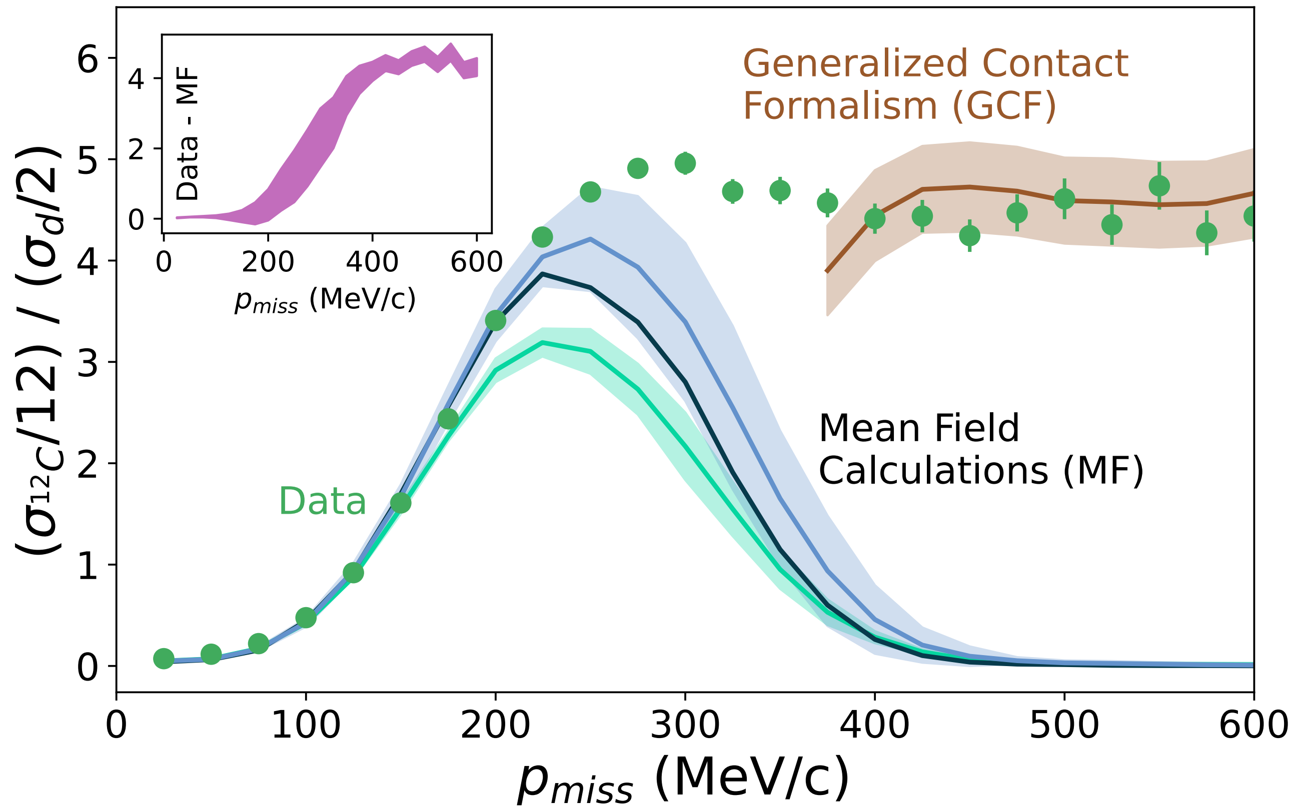
Nature 578, 540 (2020)



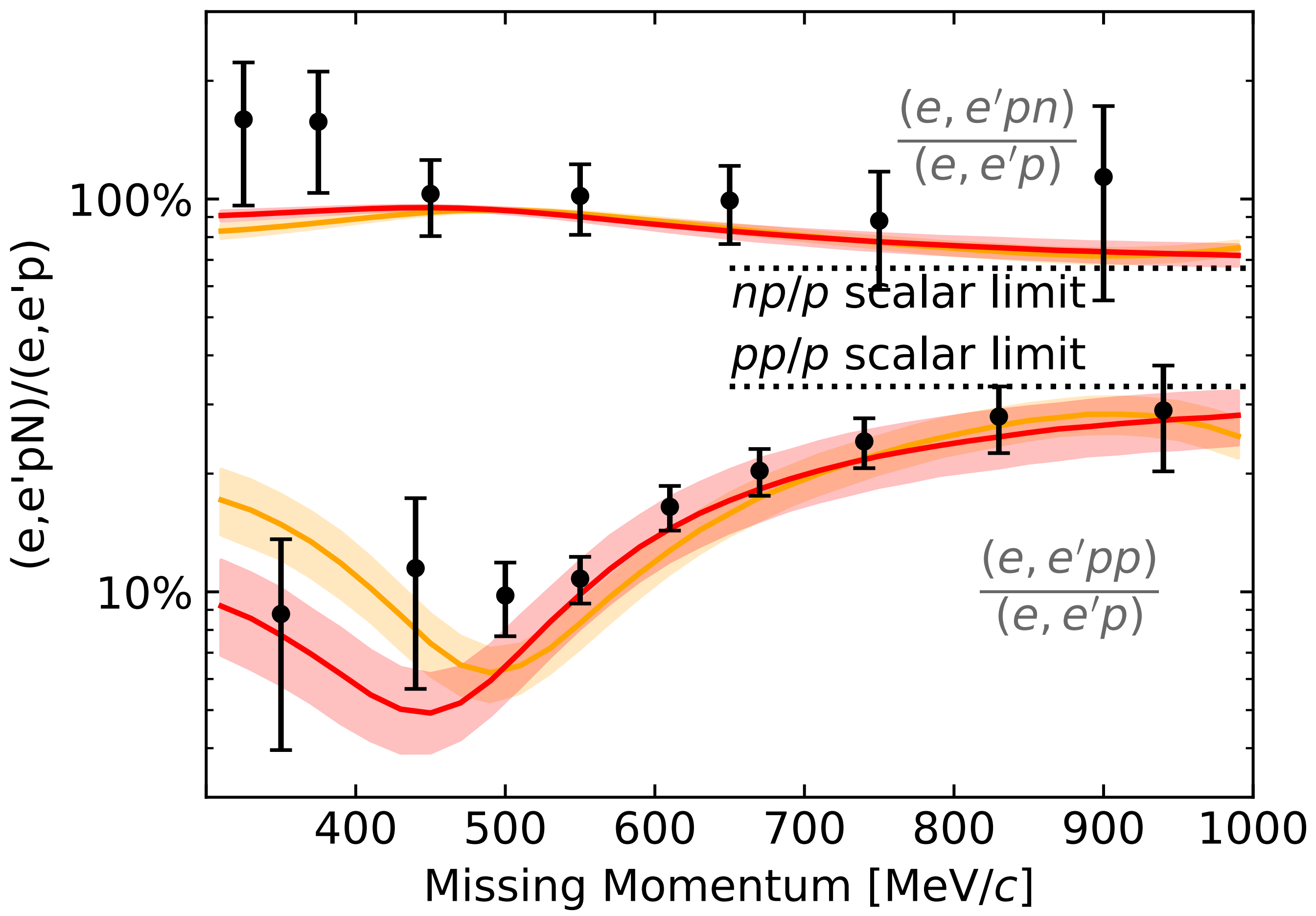
PLB 805, 135429 (2020)



arXiv: 2209.01492 (2022)



PLB 820, 136523 (2021)



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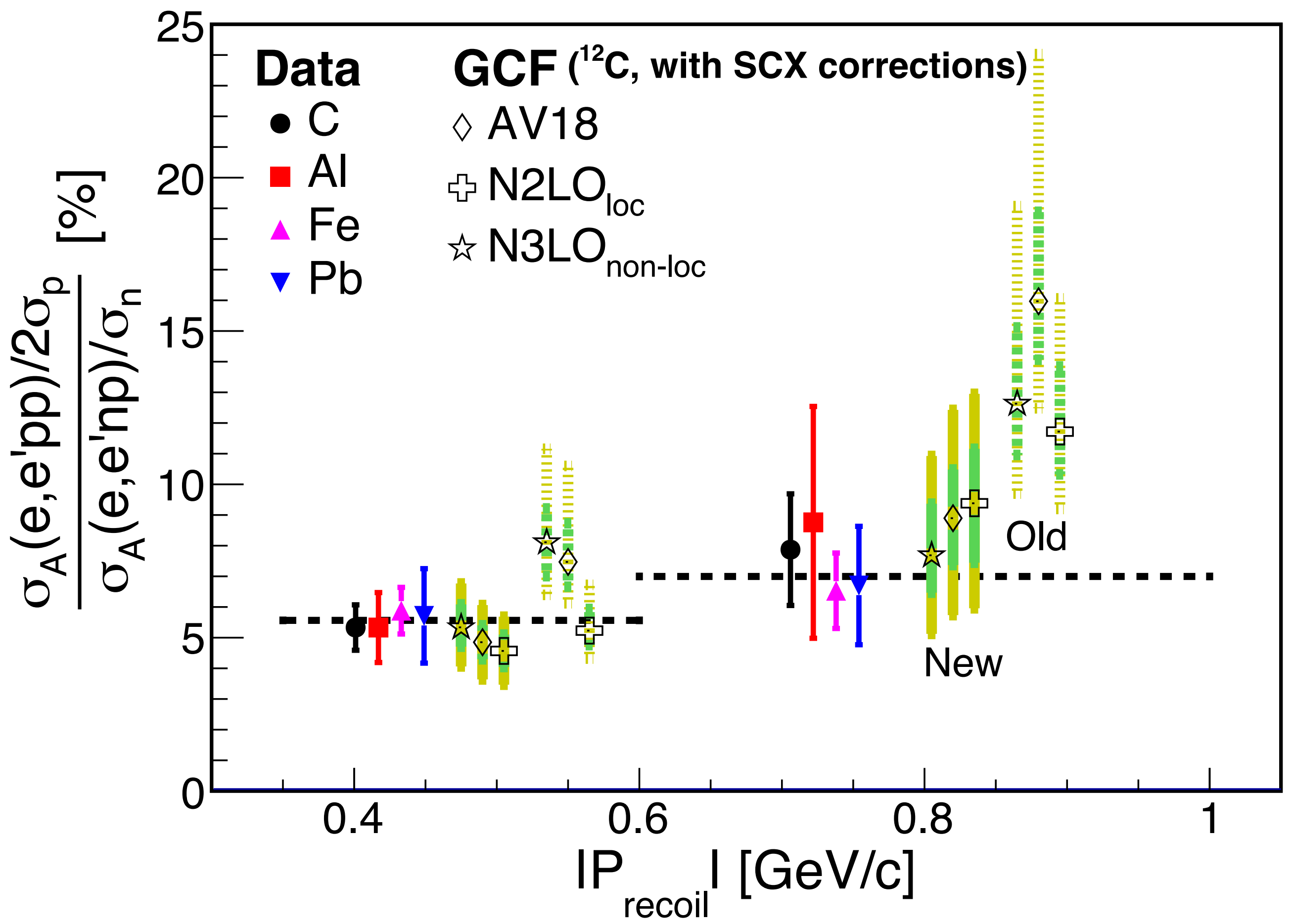

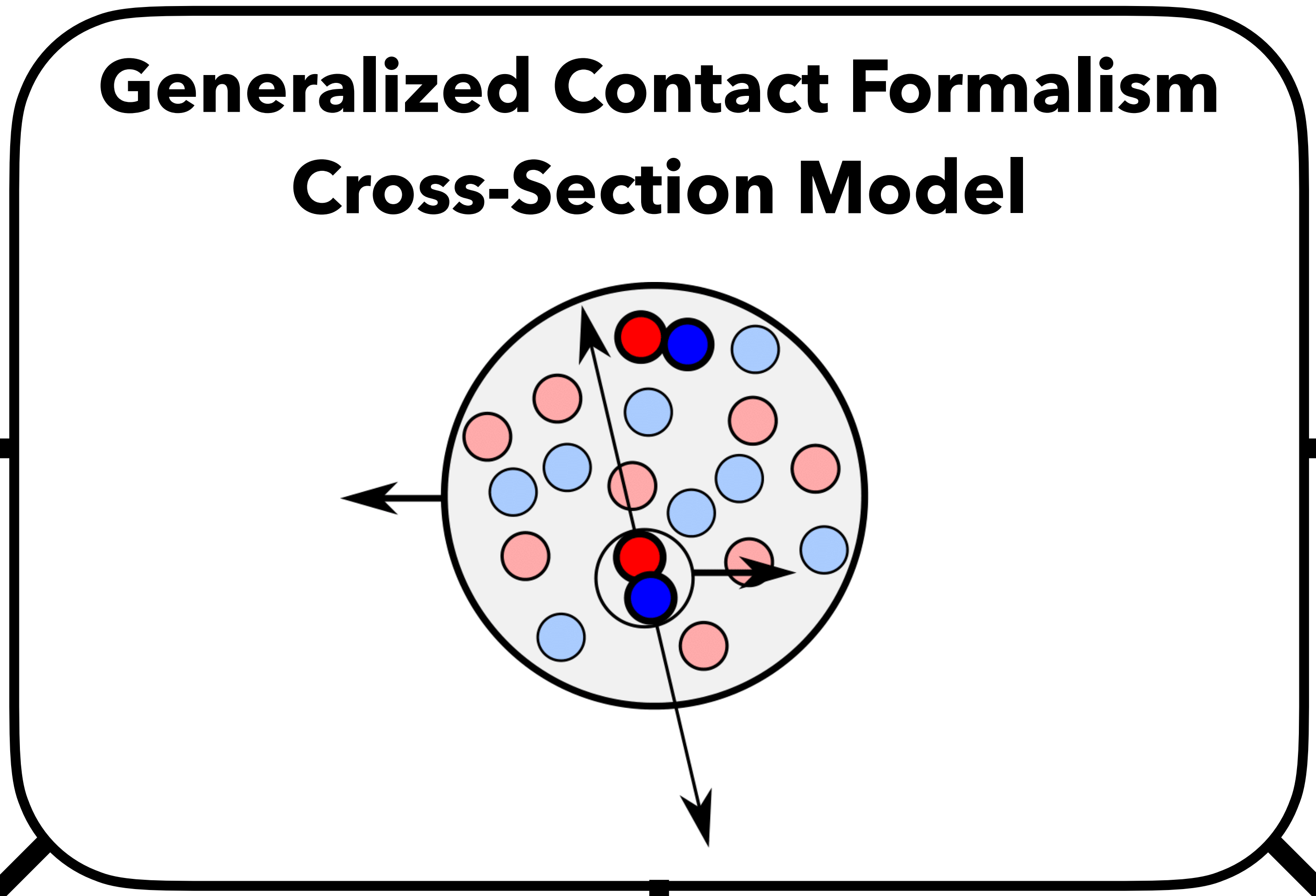

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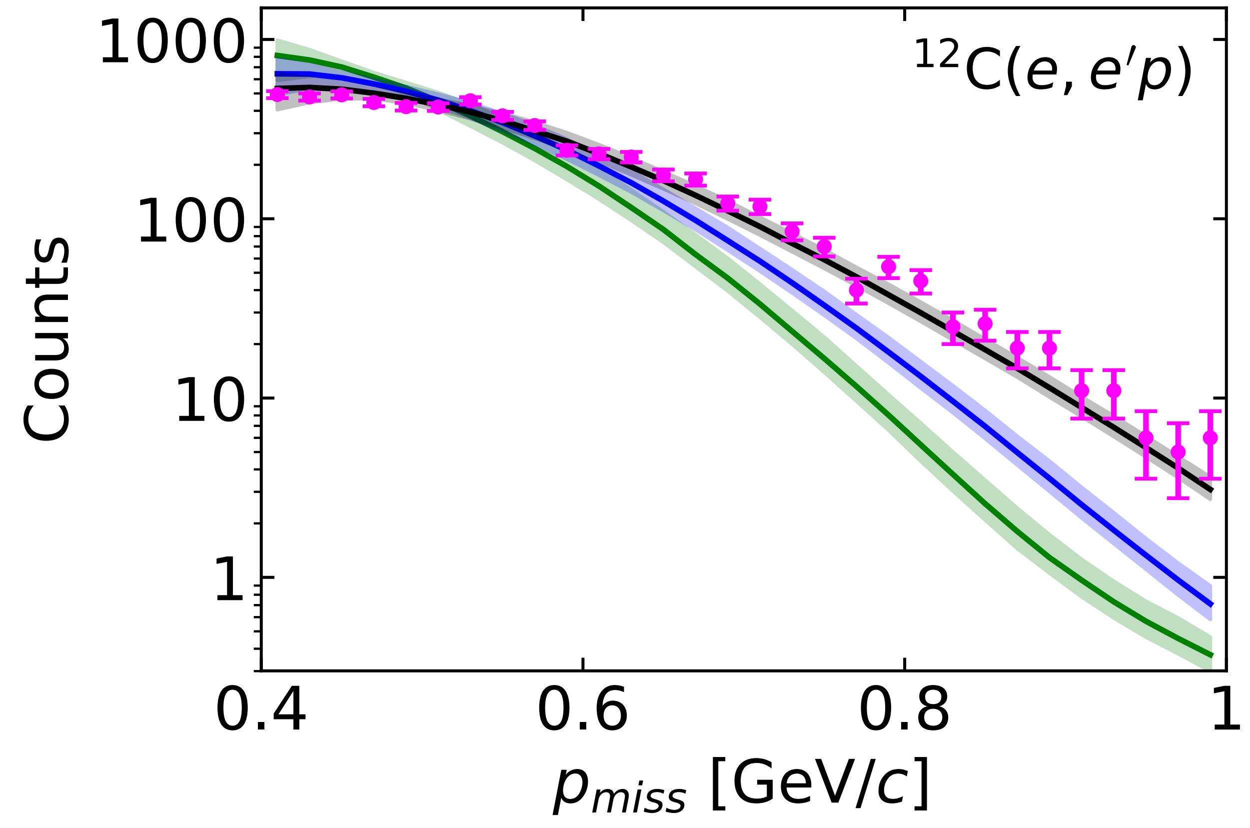

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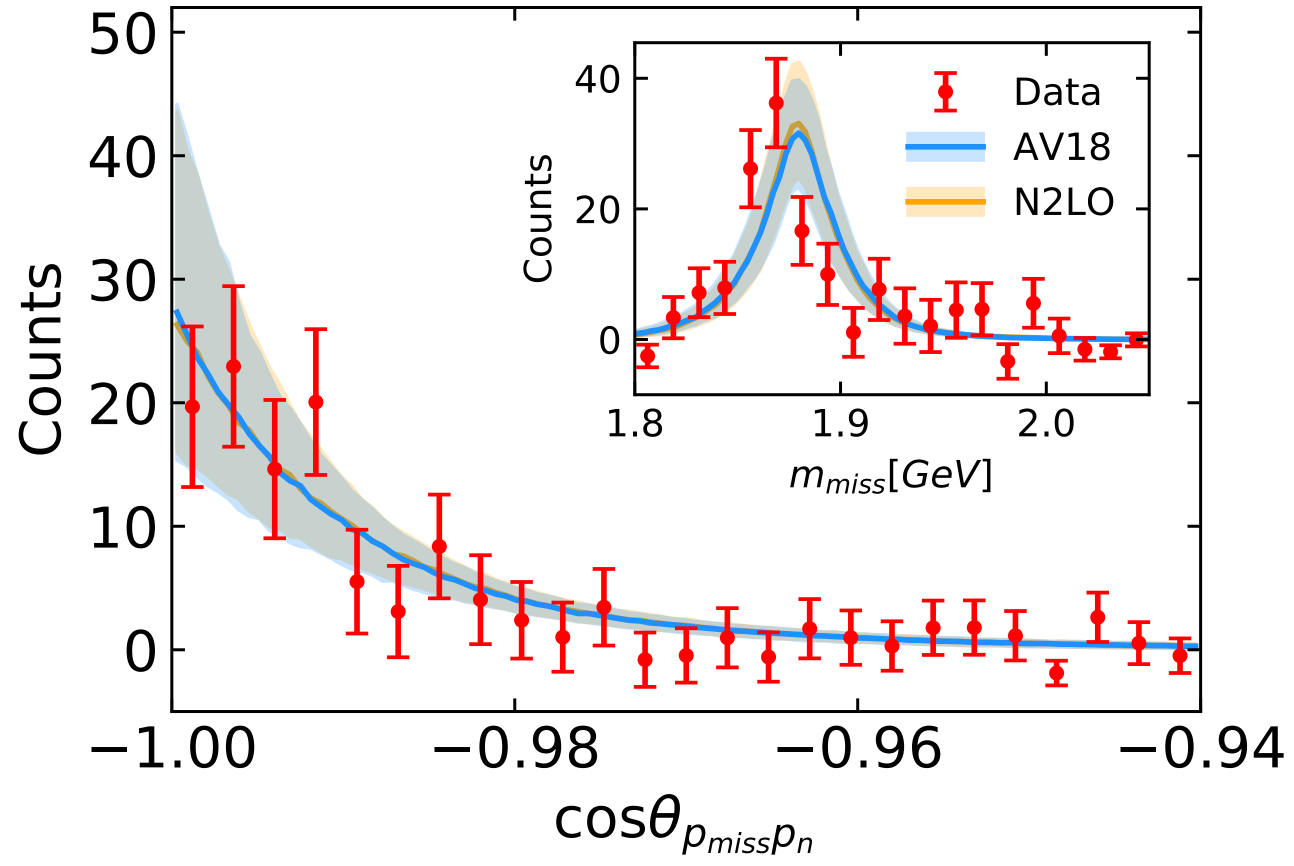

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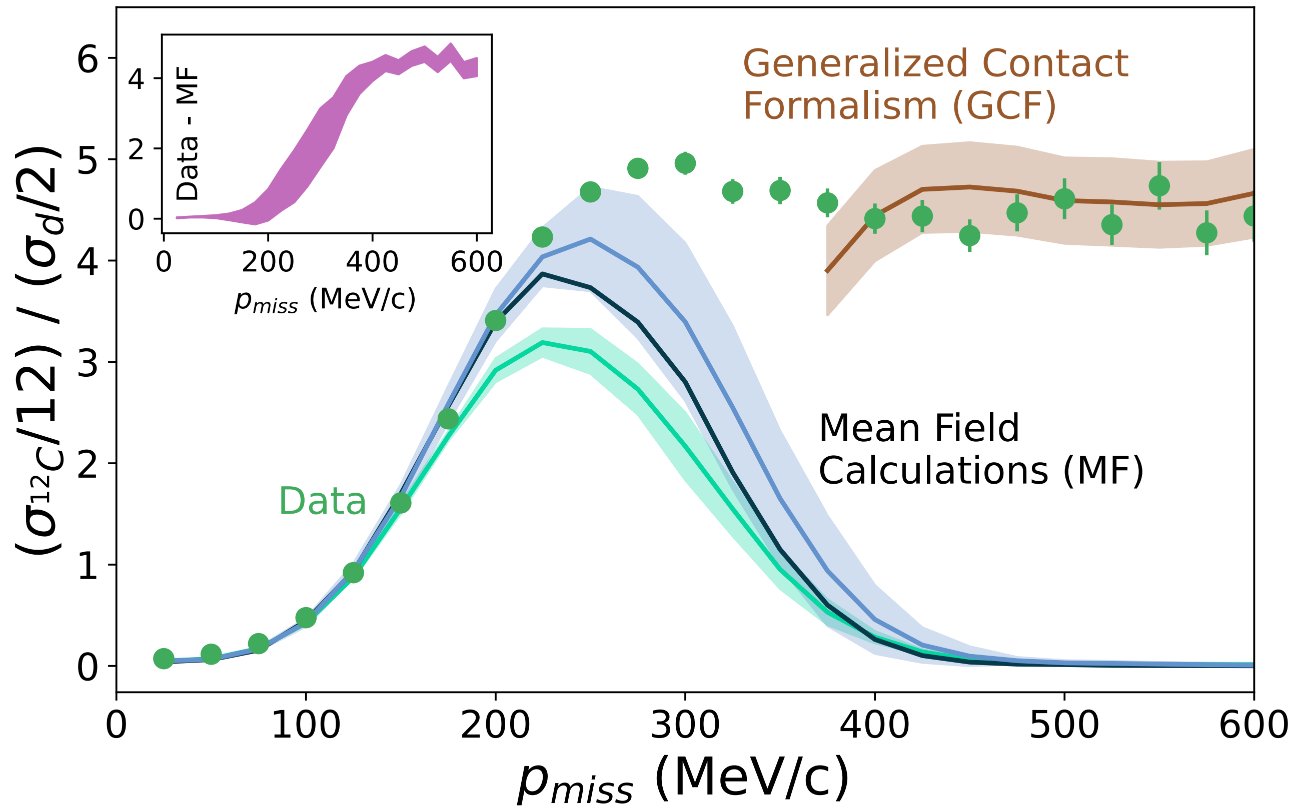

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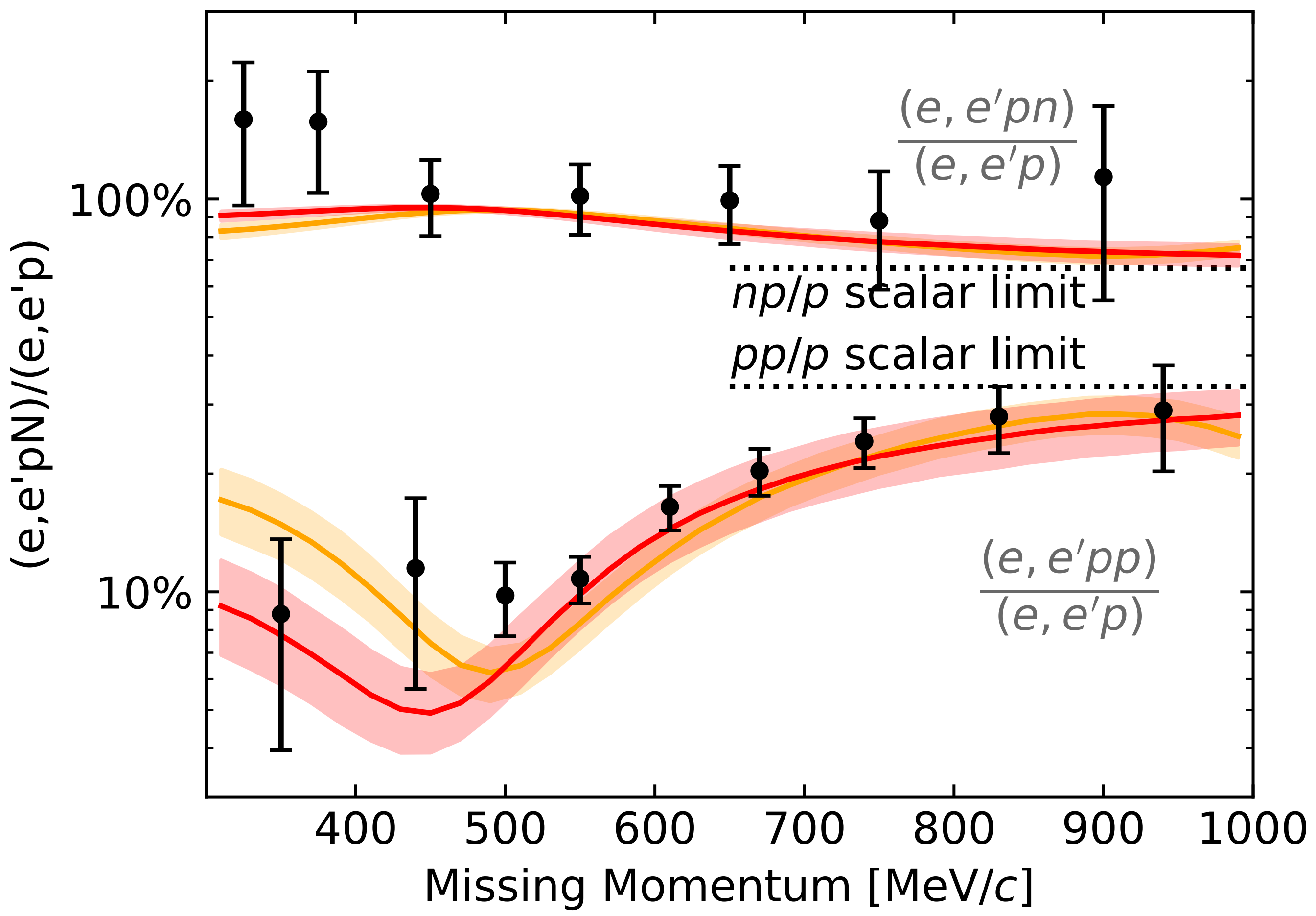
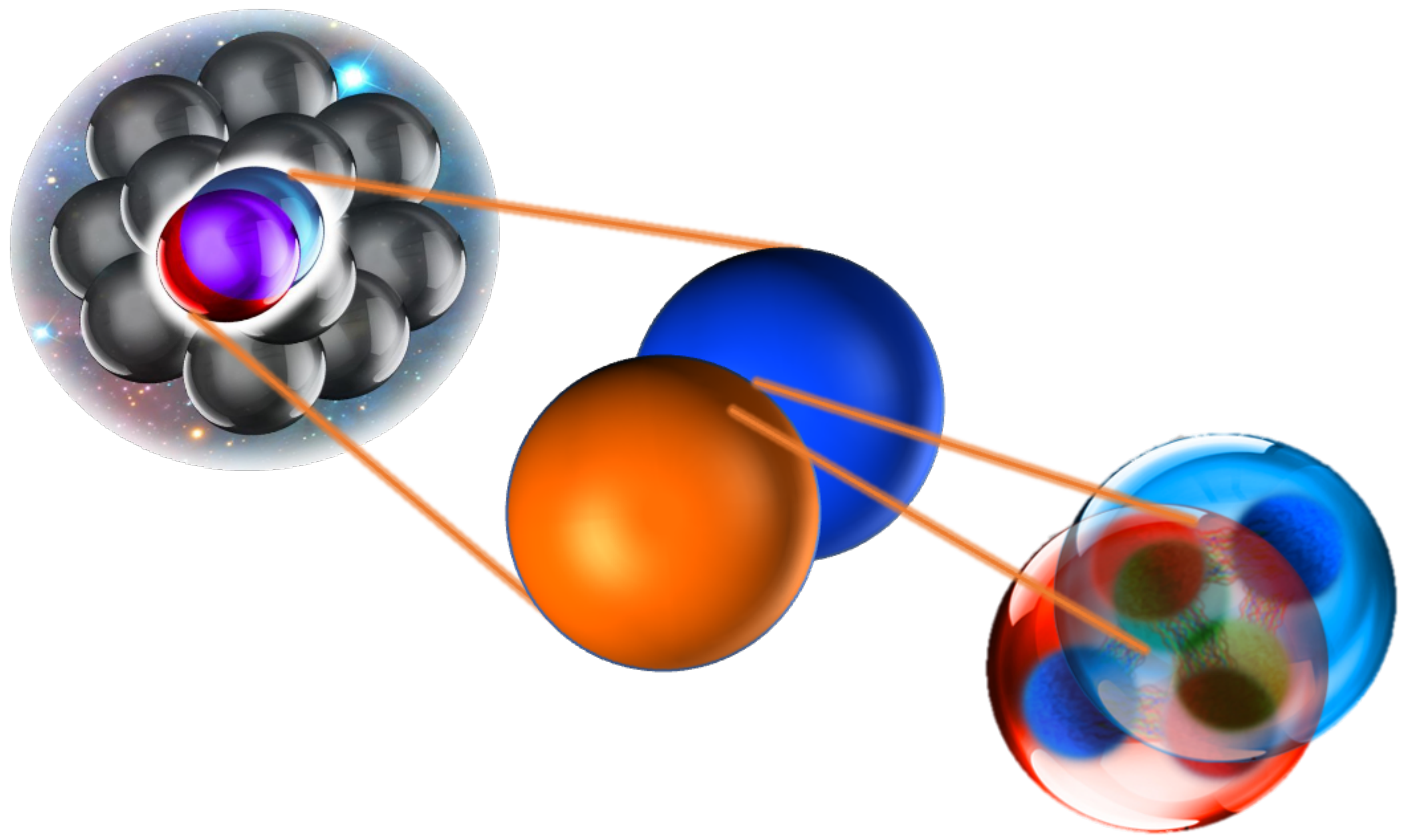


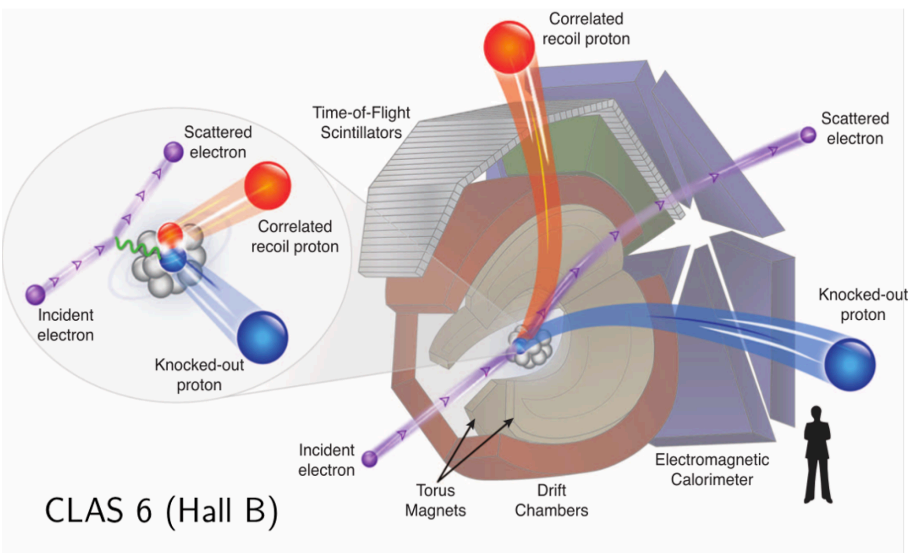
Scale & Probe Independence of SRC Observables

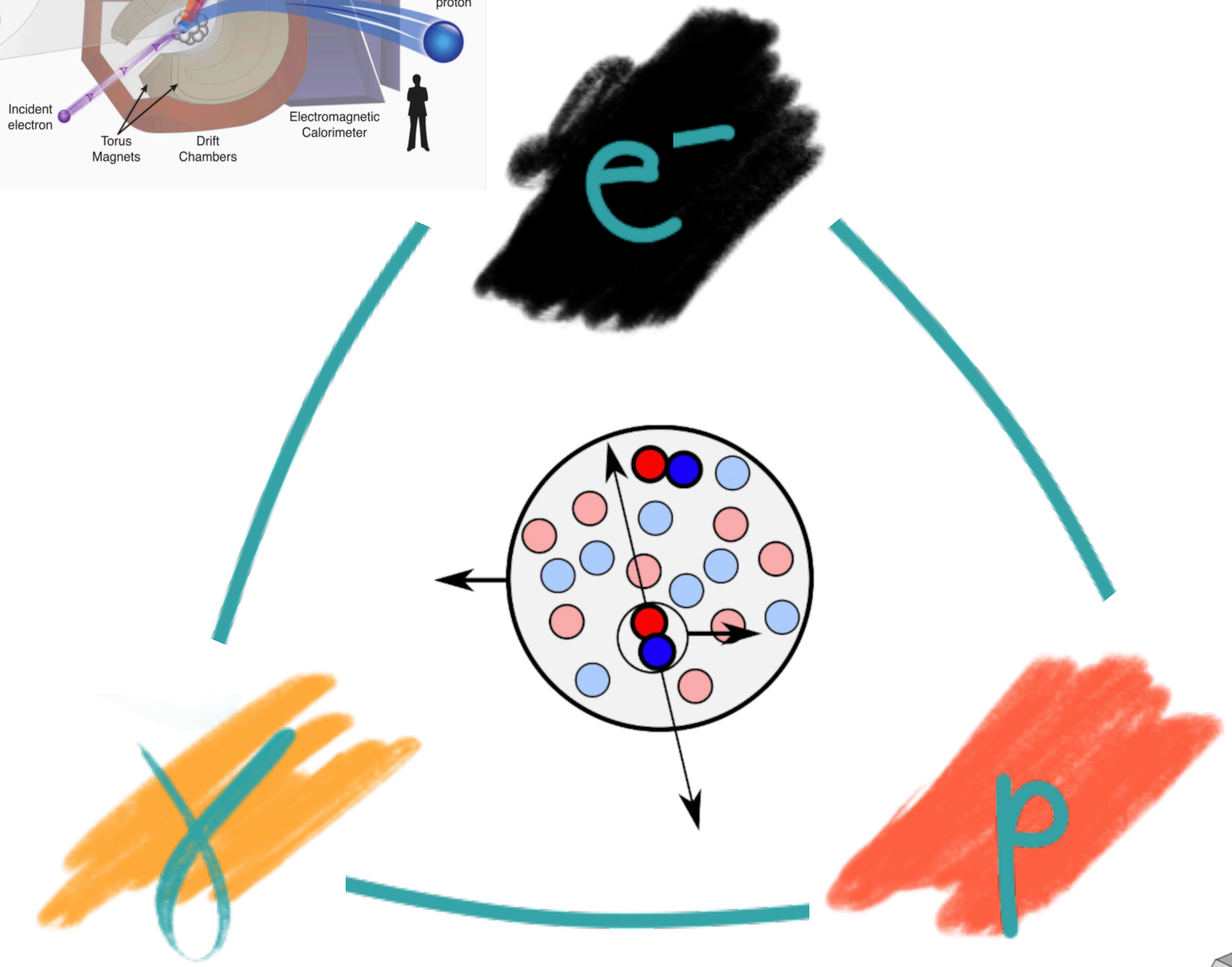
SCALE

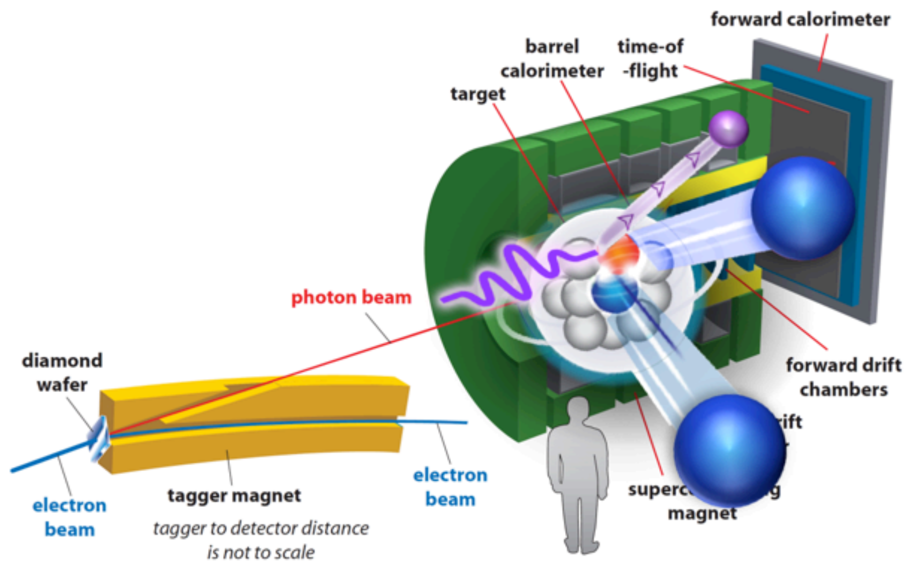


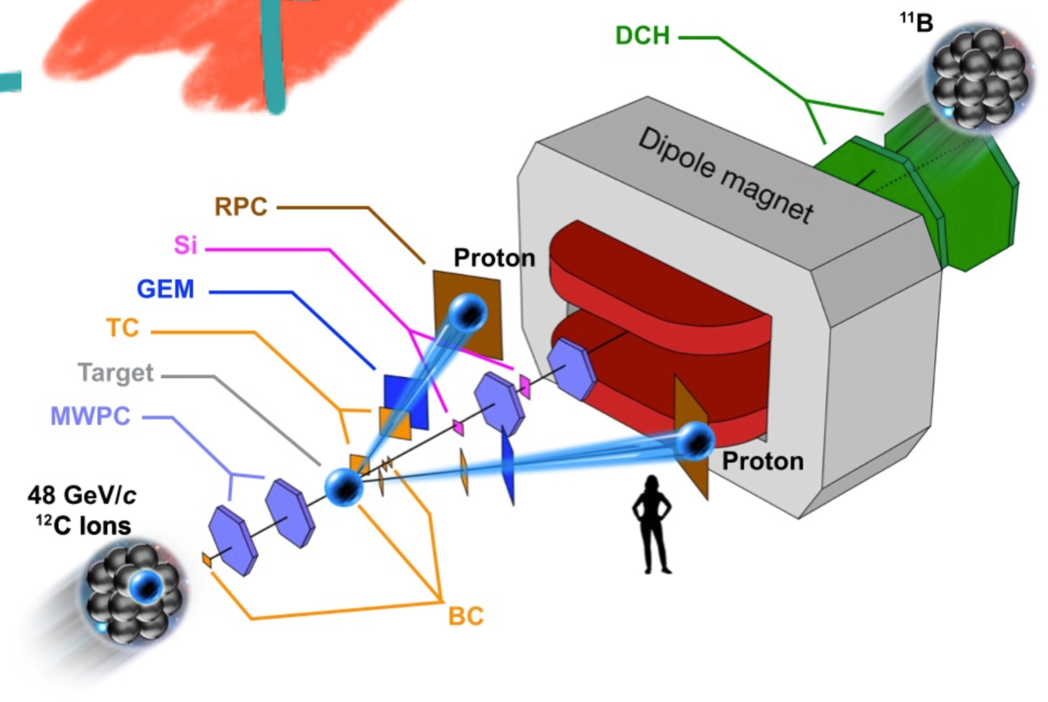
Probing SRCs with large range of momentum transfer
q (electrons) or t (photons)

PROBE

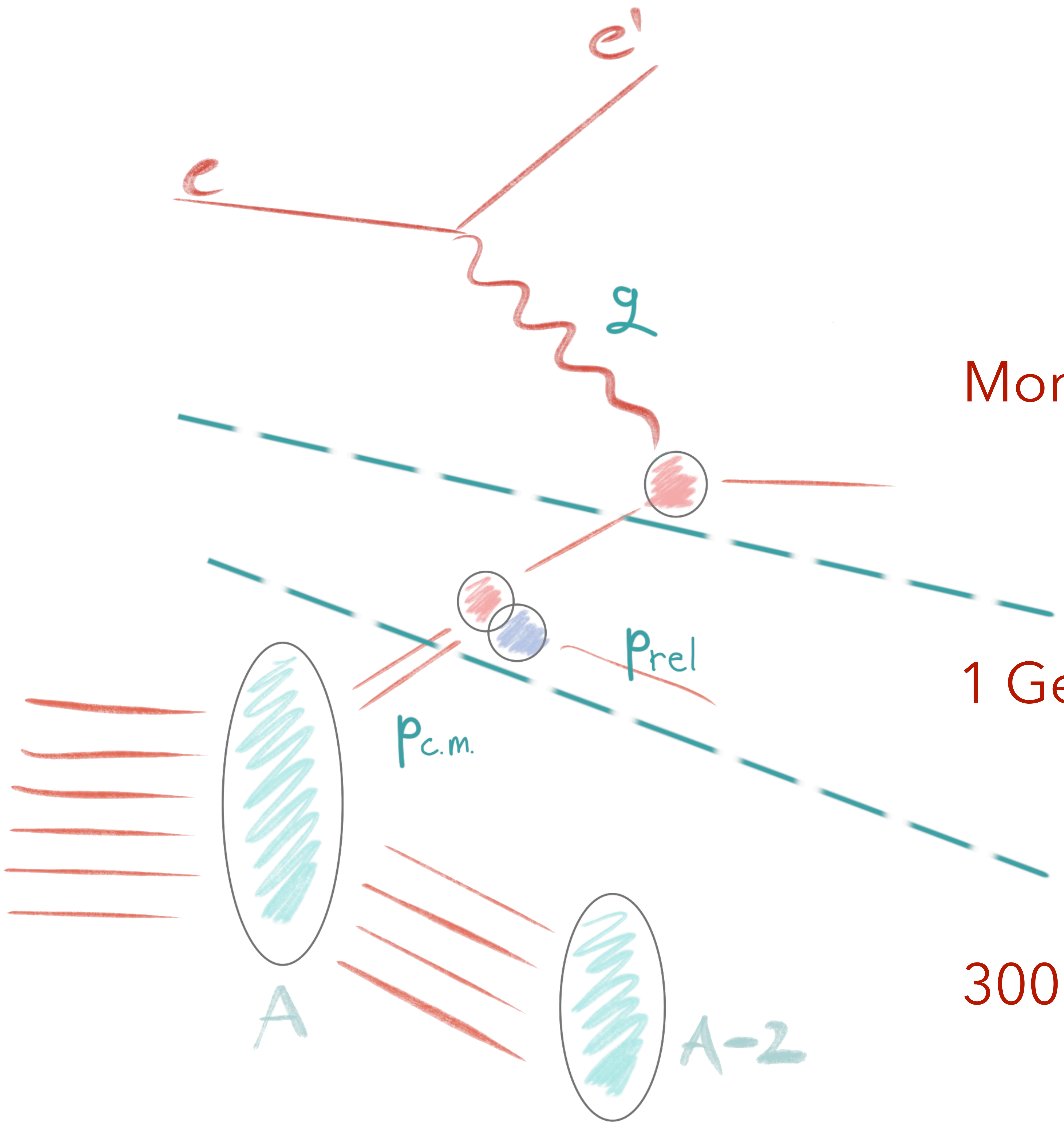








GCF relies on two factorization scales



Momentum transfer $\gtrsim$ 1 GeV

1 GeV $\gtrsim$ Relative momentum $\gtrsim$ 300 MeV

300 MeV $\gtrsim$ Center-of-mass momentum

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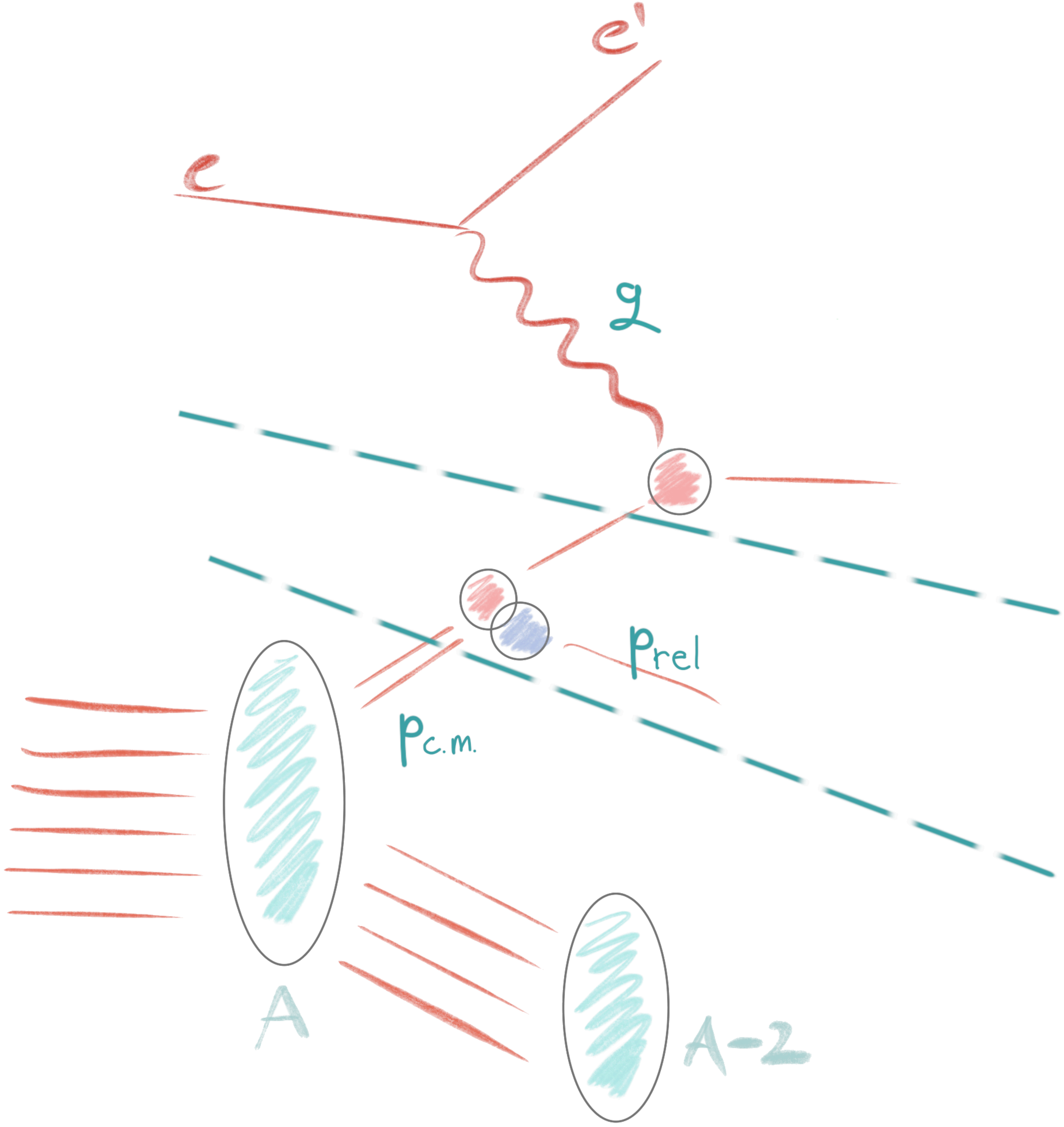
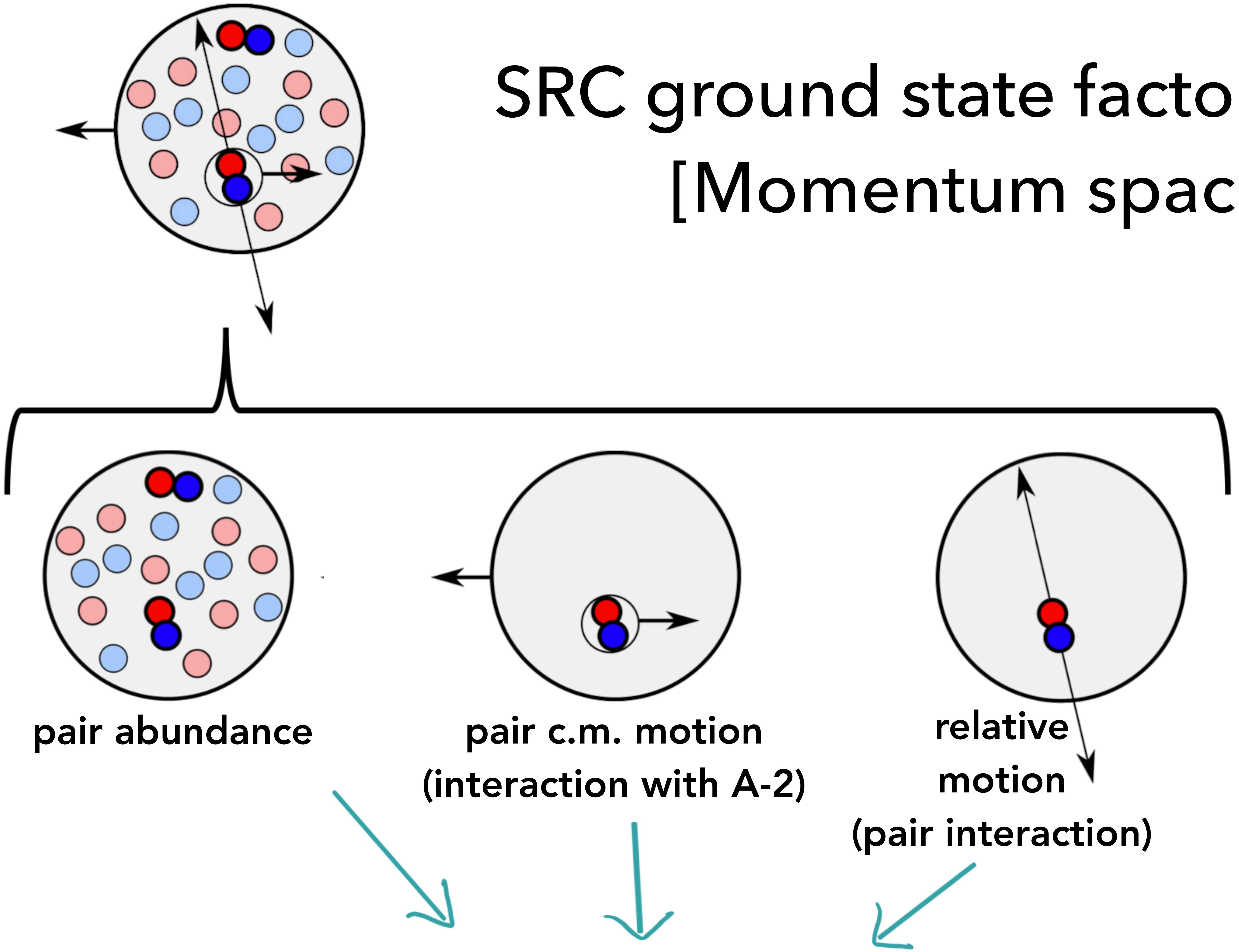


$$\sigma_{SRC} \sim K \cdot \sigma_{eN} \cdot S(p_i, p_{spec})$$

$$S \sim \sum_{\alpha} C^{\alpha}_{NN} \cdot n(p_{\text{c.m.}}) \cdot |\phi(p_{\text{rel}})|^2$$

SRC ground state factorization [Momentum space]



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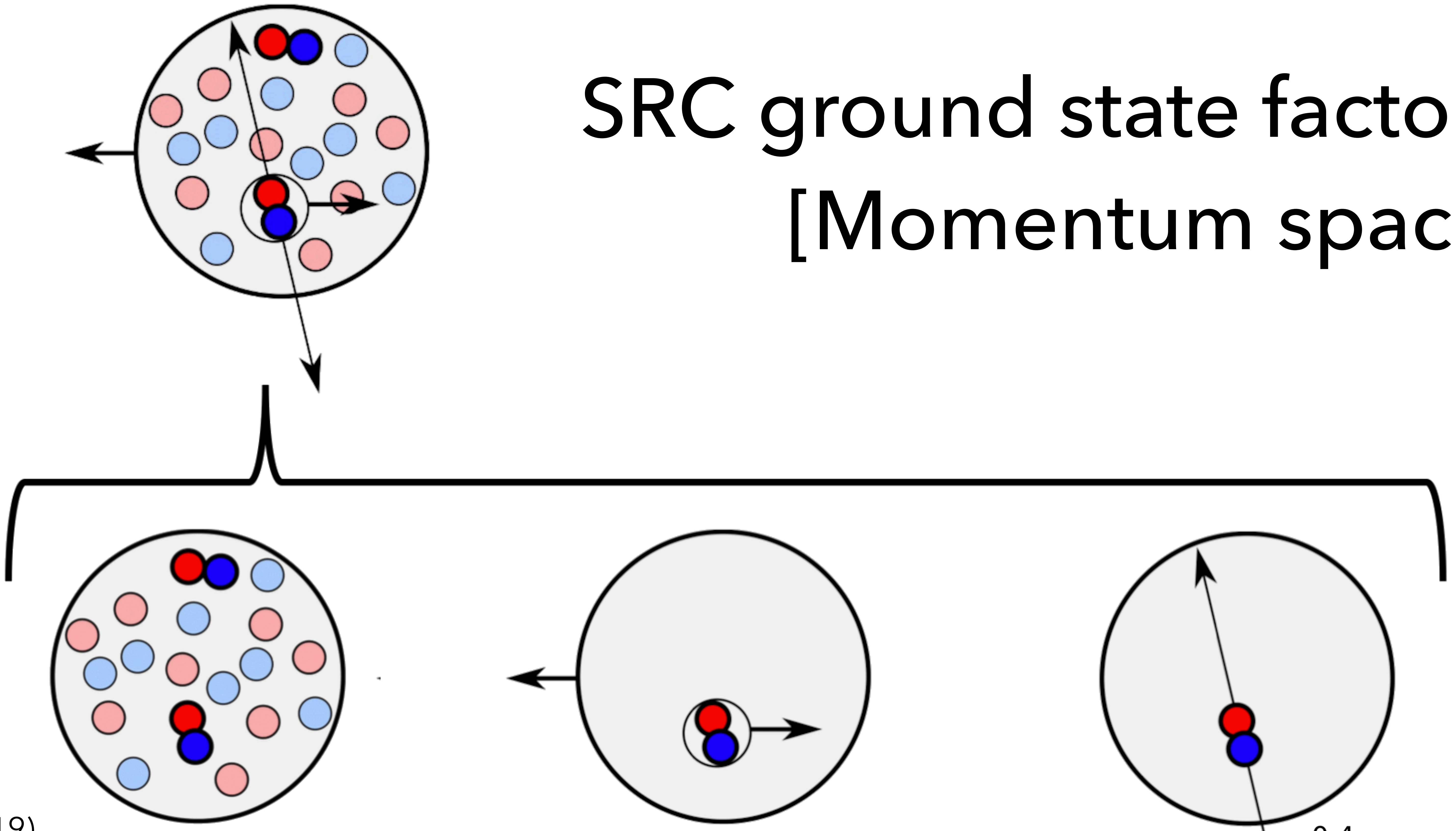
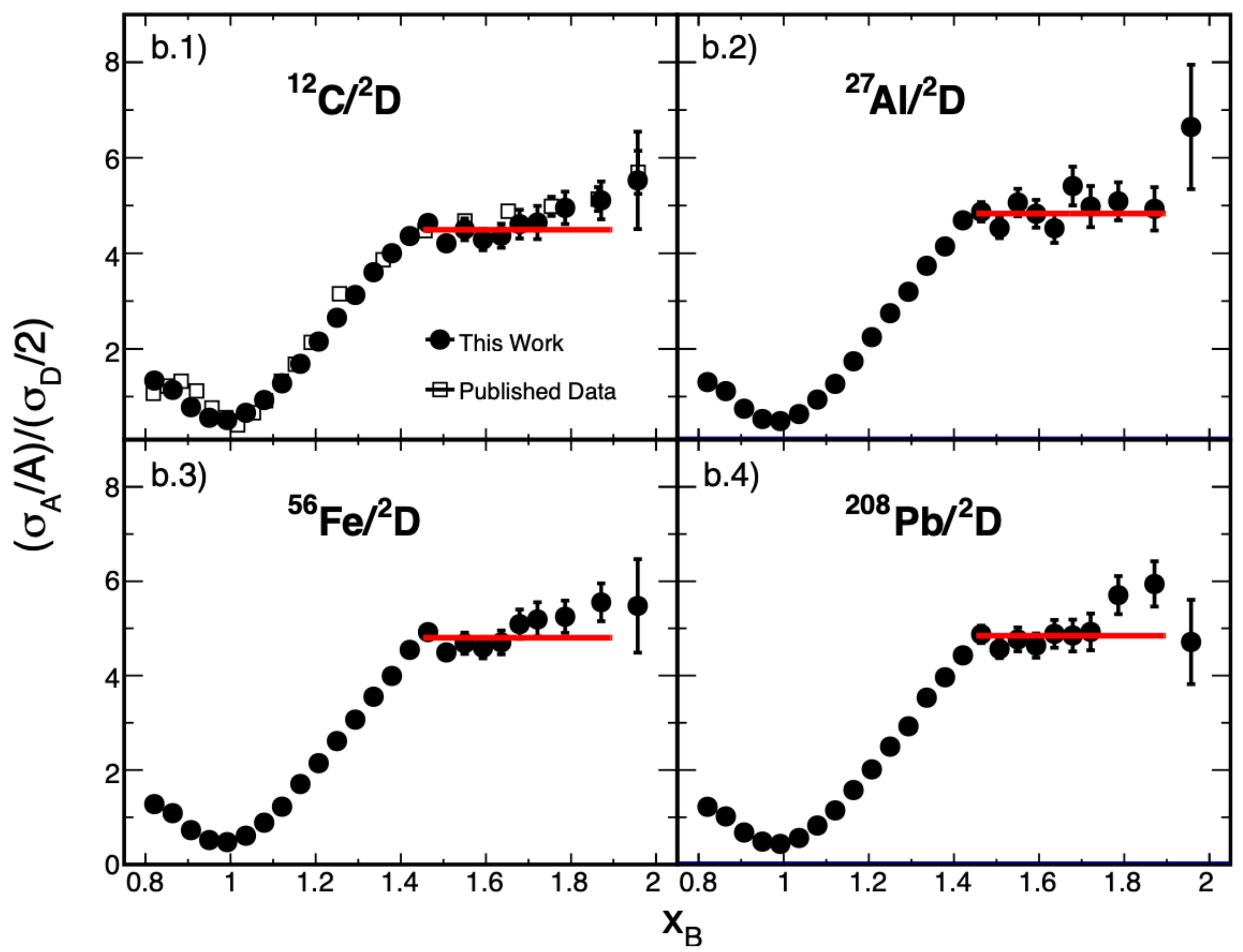
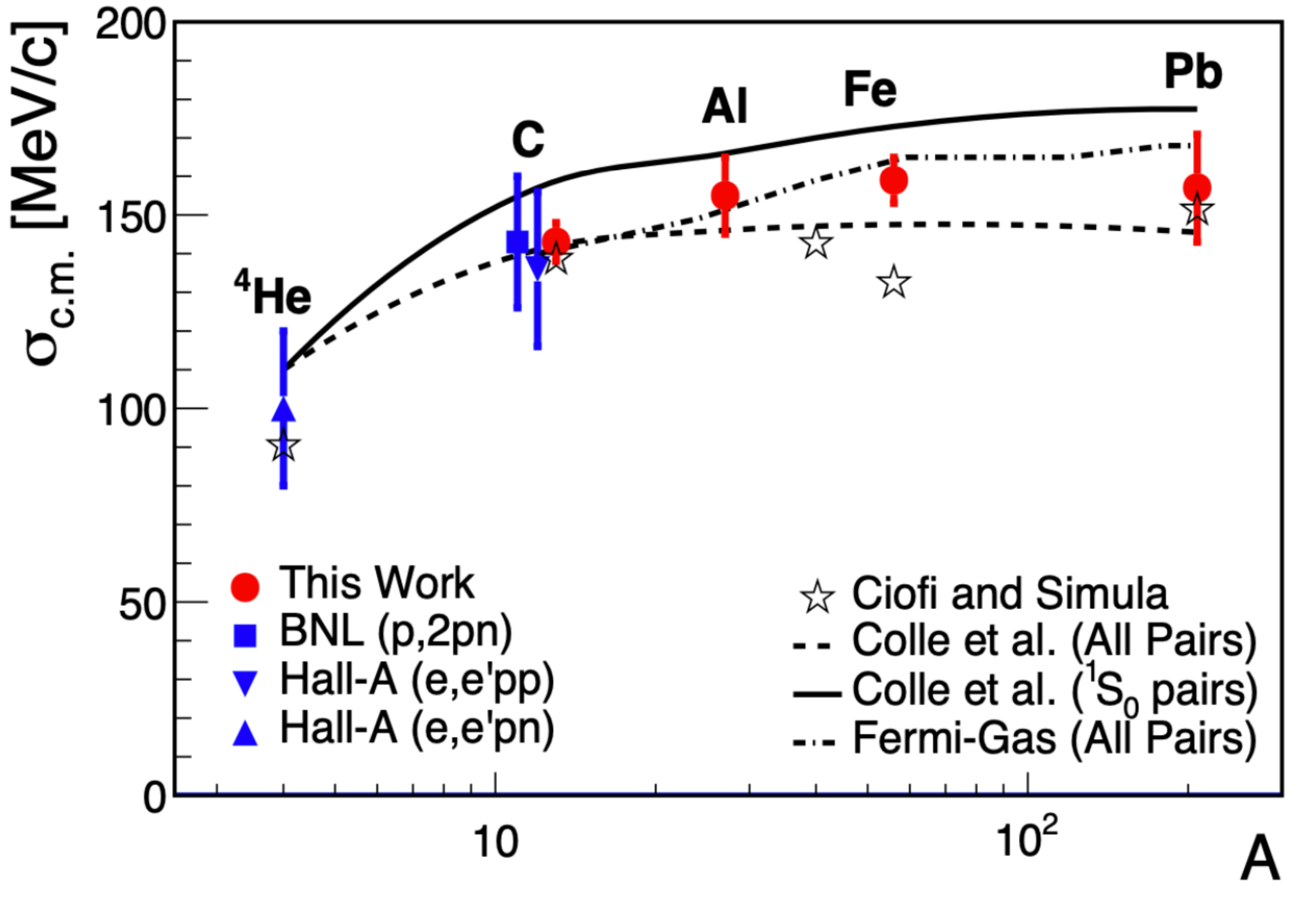


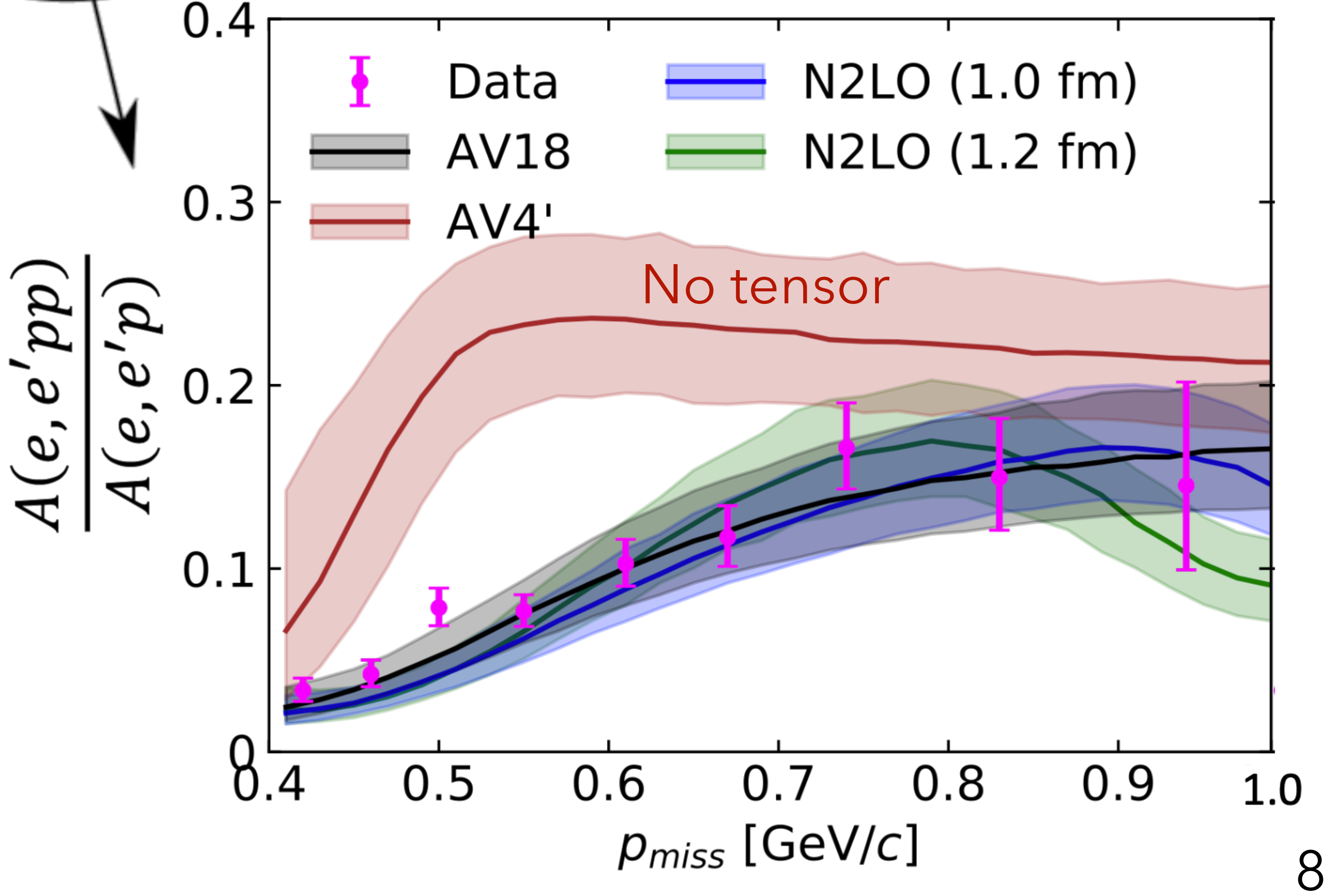
Schmookler, Nature (2019)



Cohen, PRL (2018)



Schmidt, Nature (2020)



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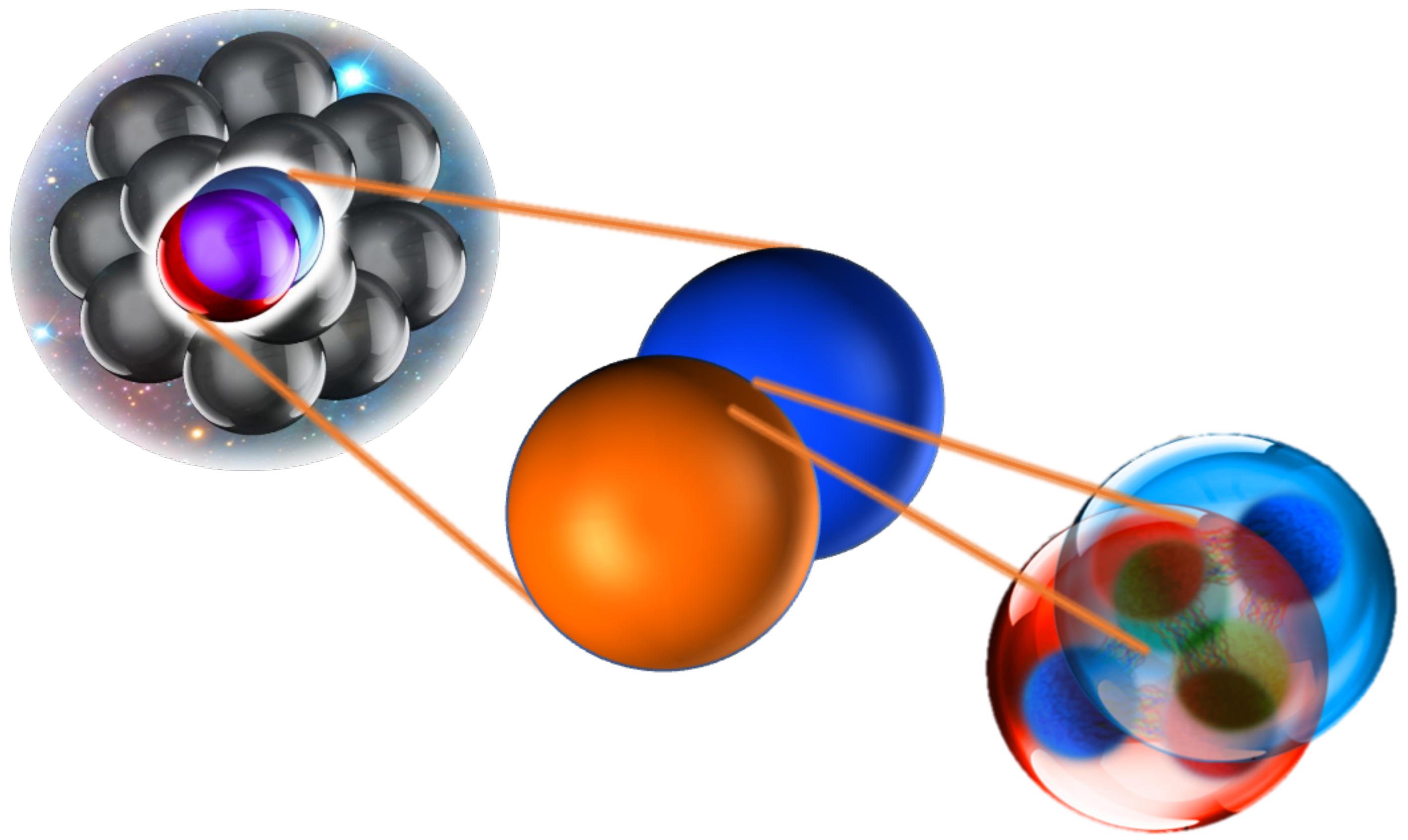
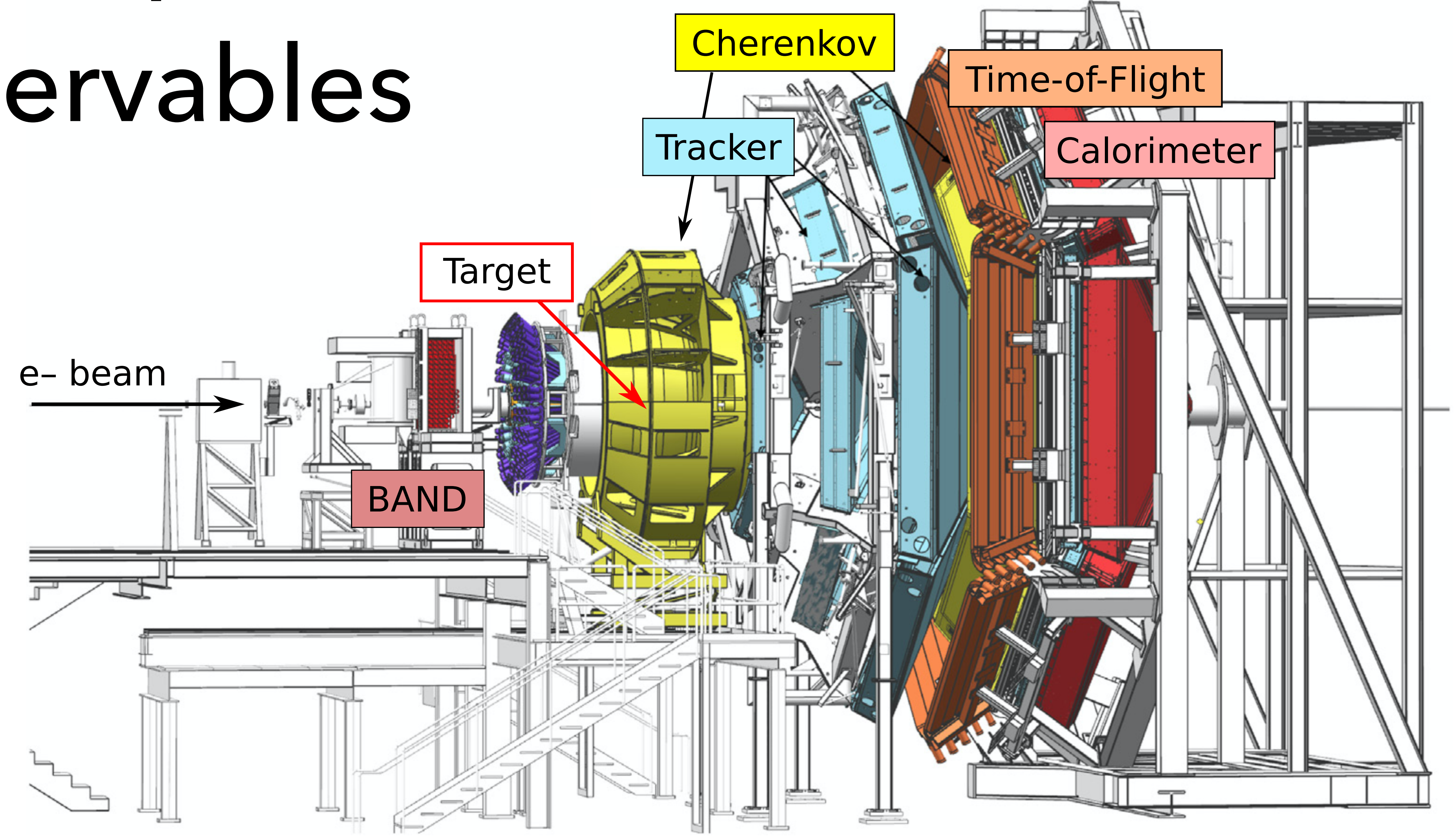
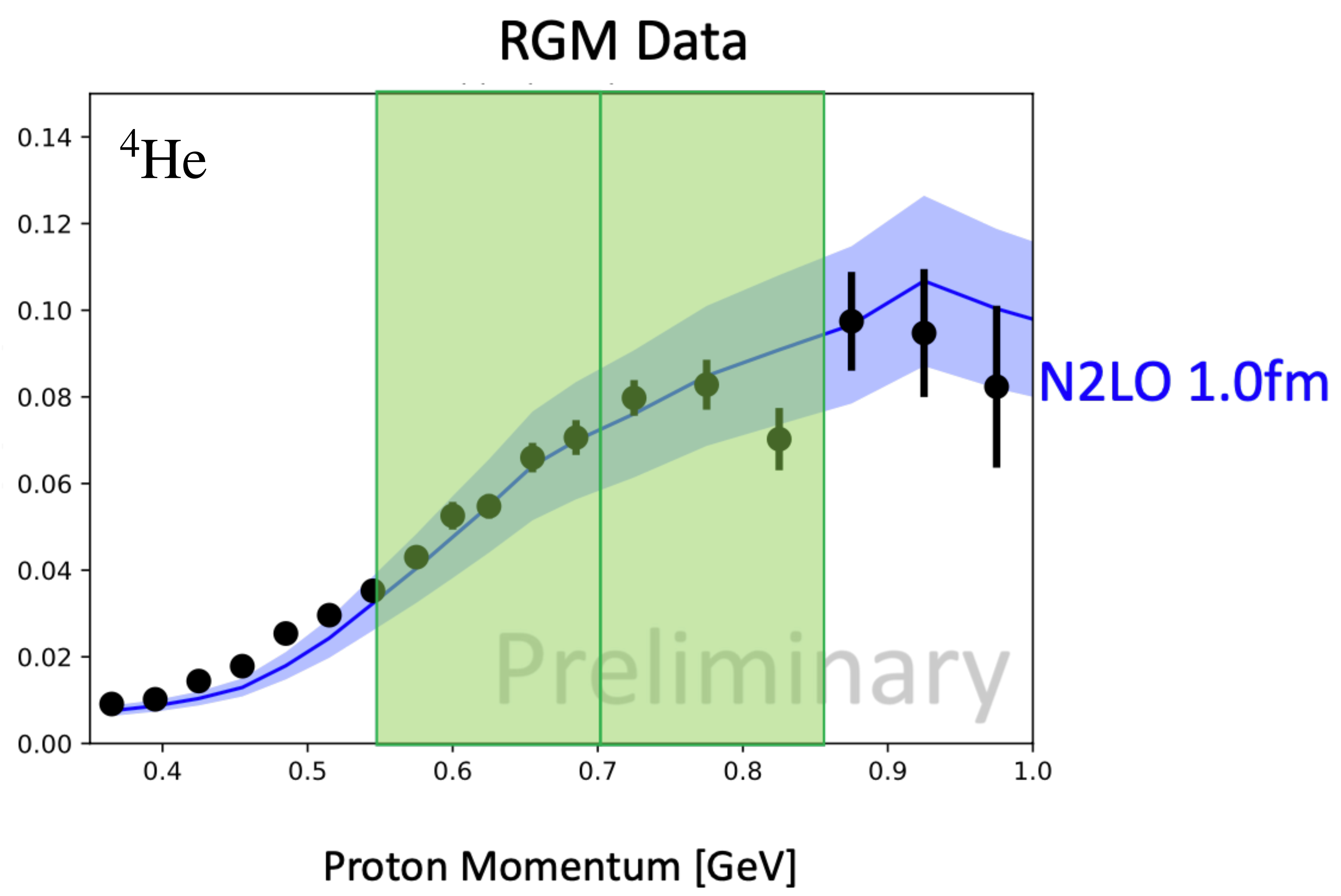




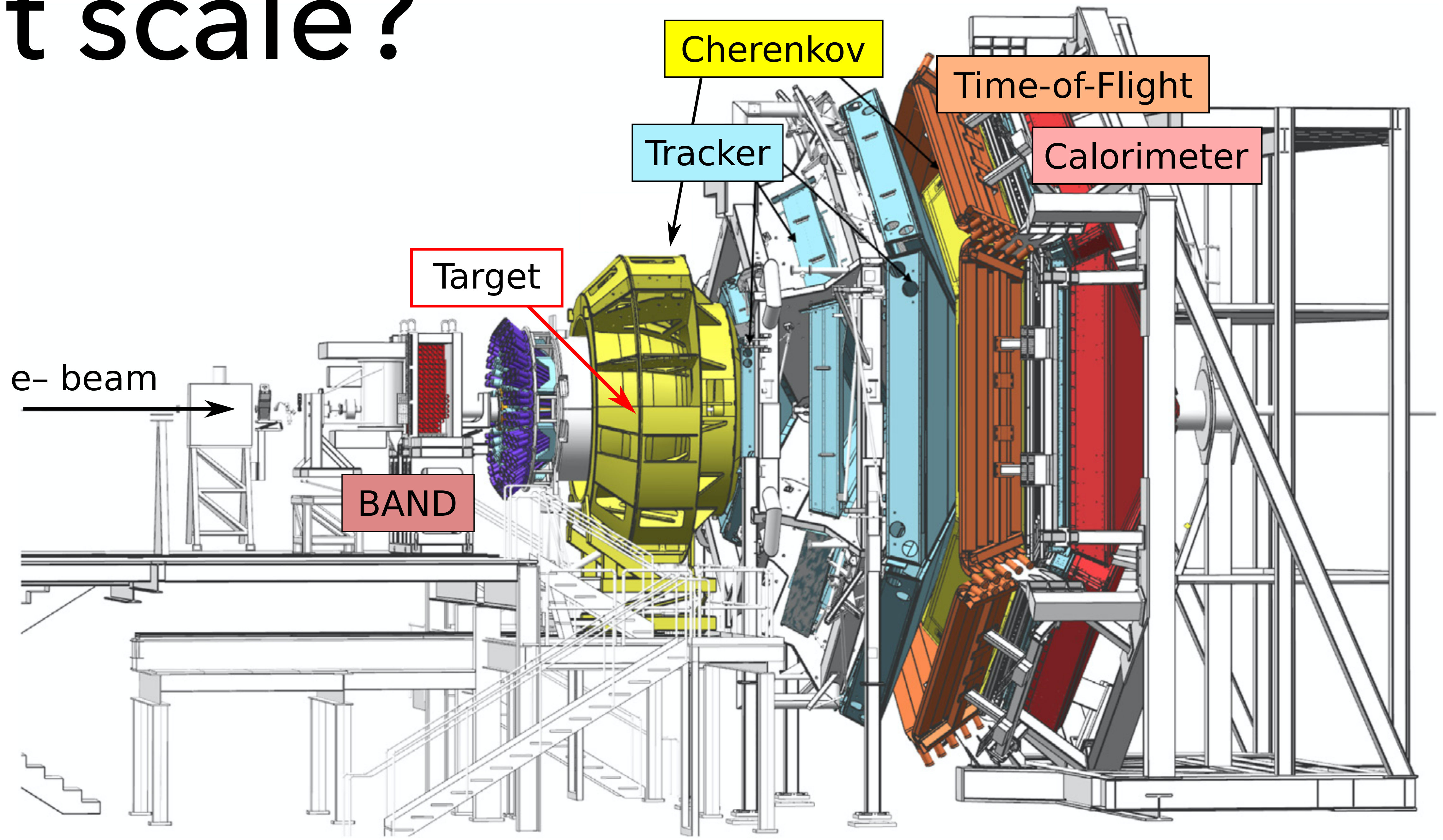
RGM@hallB (JLab) provides the best SRC statistics yet (electron scattering)

- going from ~400 events to ~15000 events (combined ^{4}He, ^{12}C, ^{40}Ca)

But, does it scale?



$$\frac{A(e,e'pp)}{A(e,e'p)}$$



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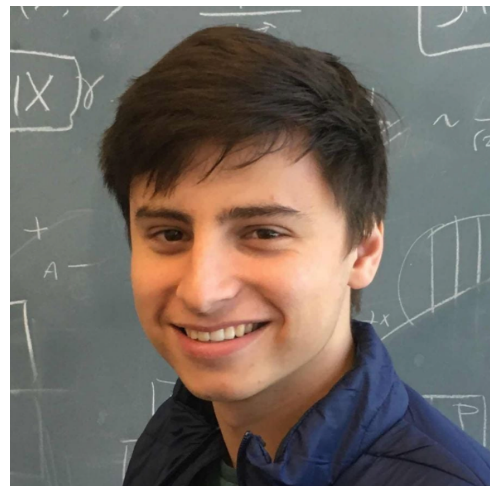

Work done by Andrew Denniston (MIT)

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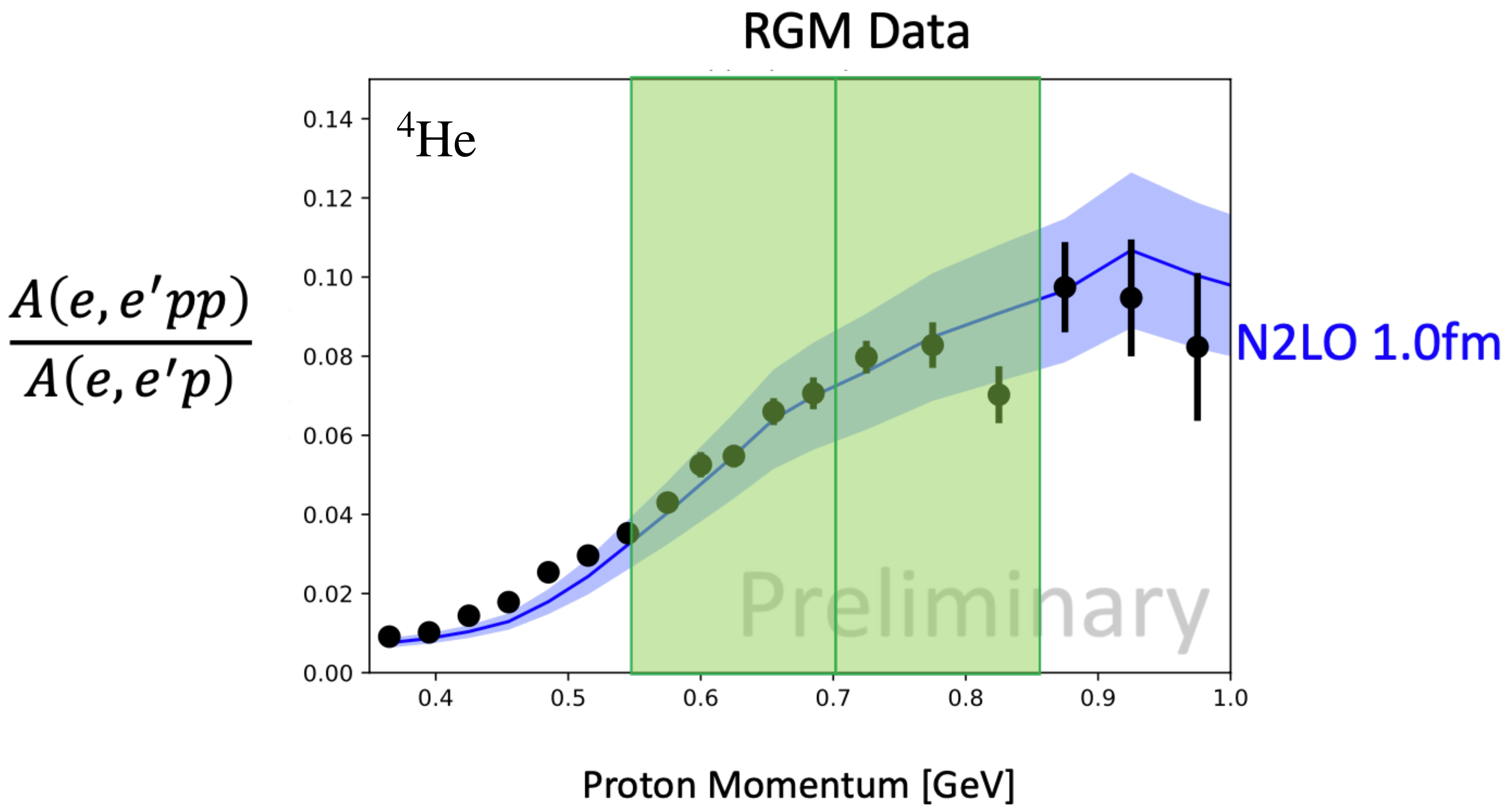

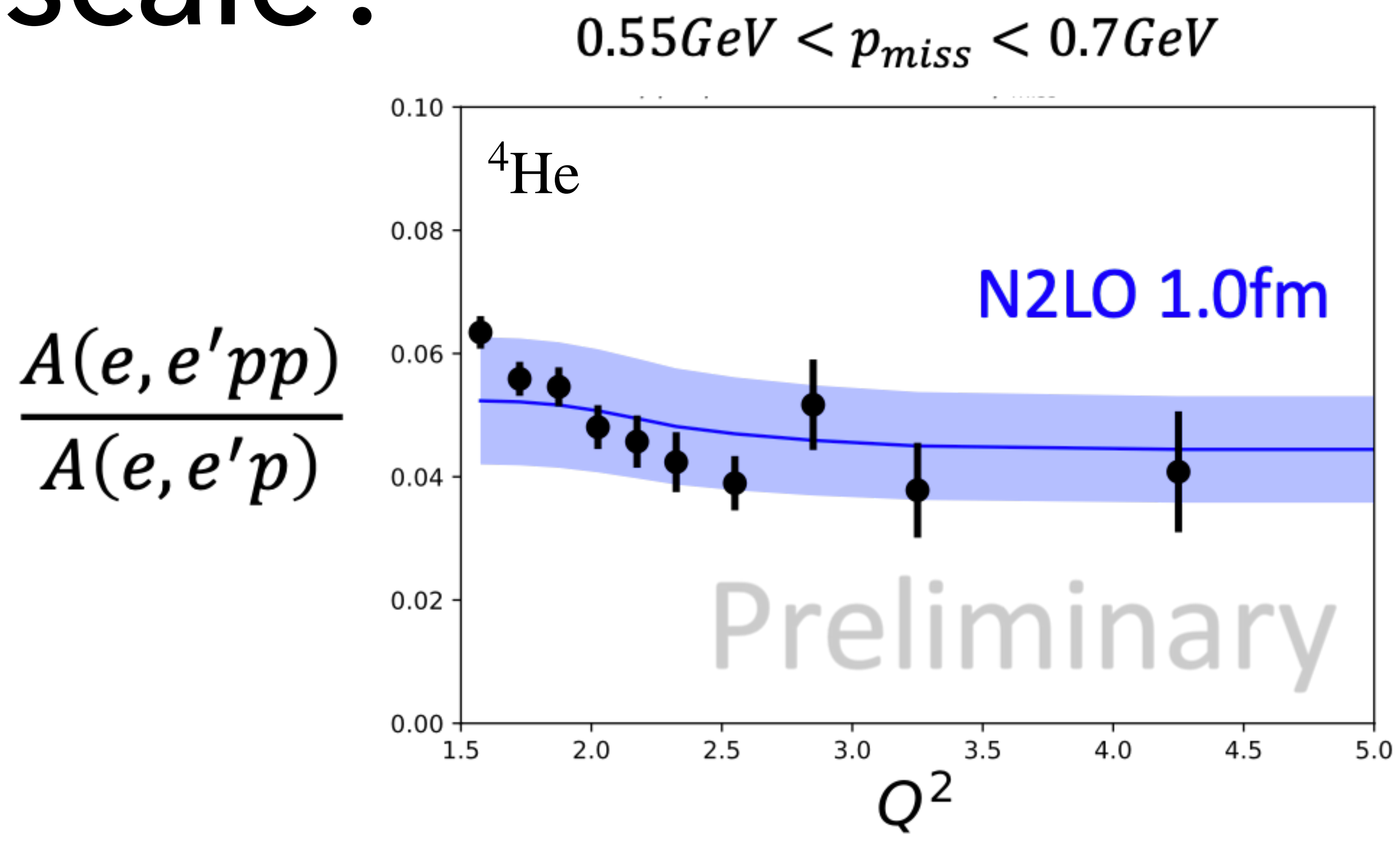

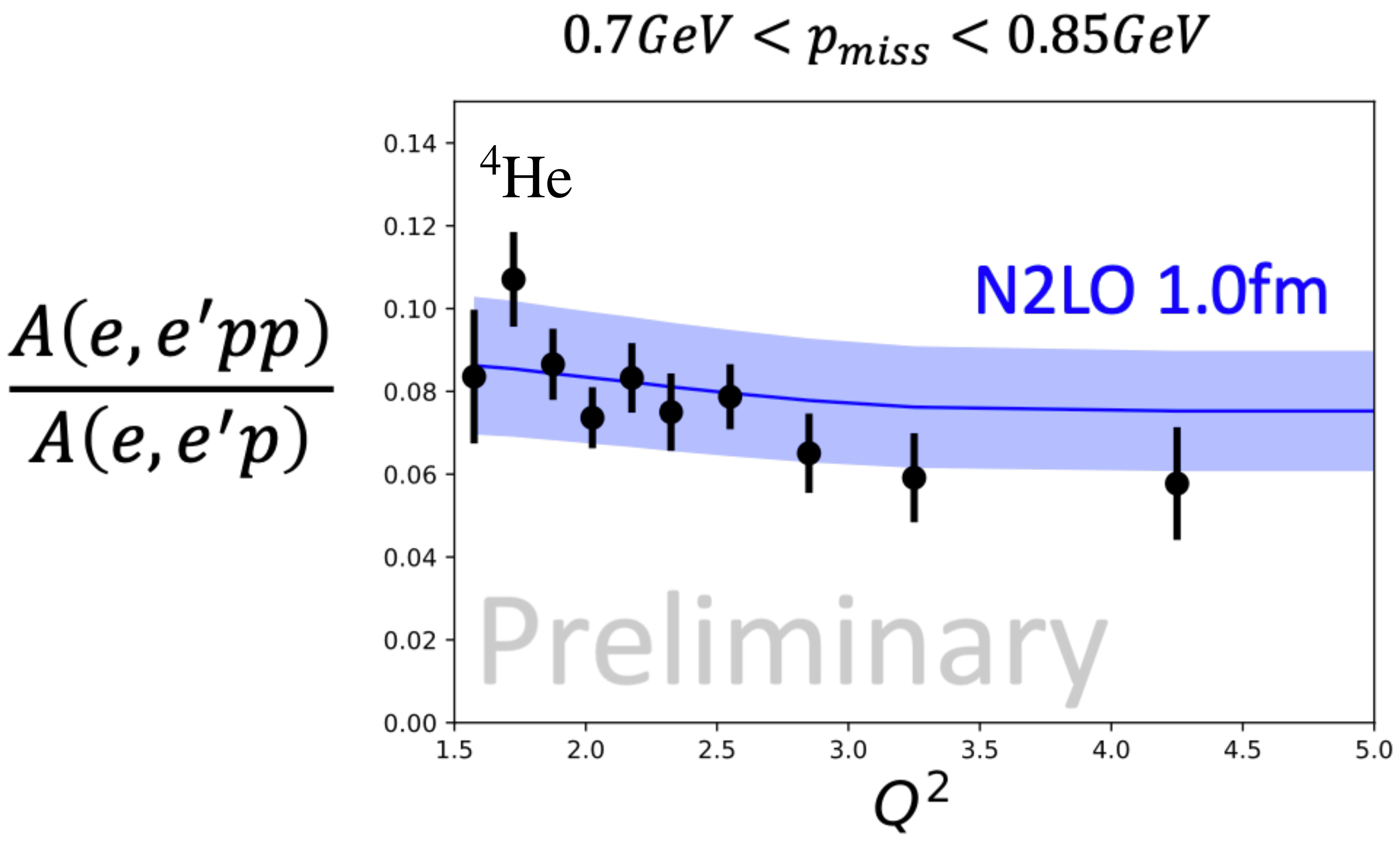

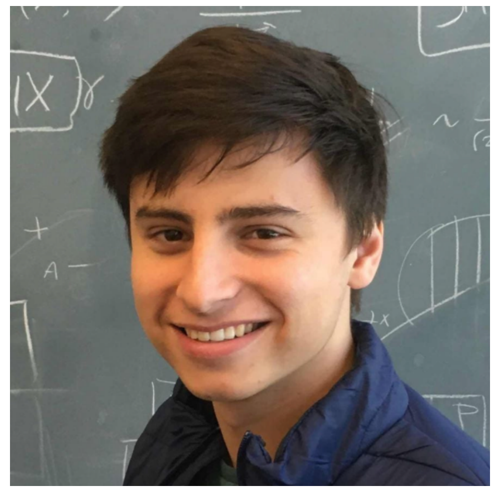

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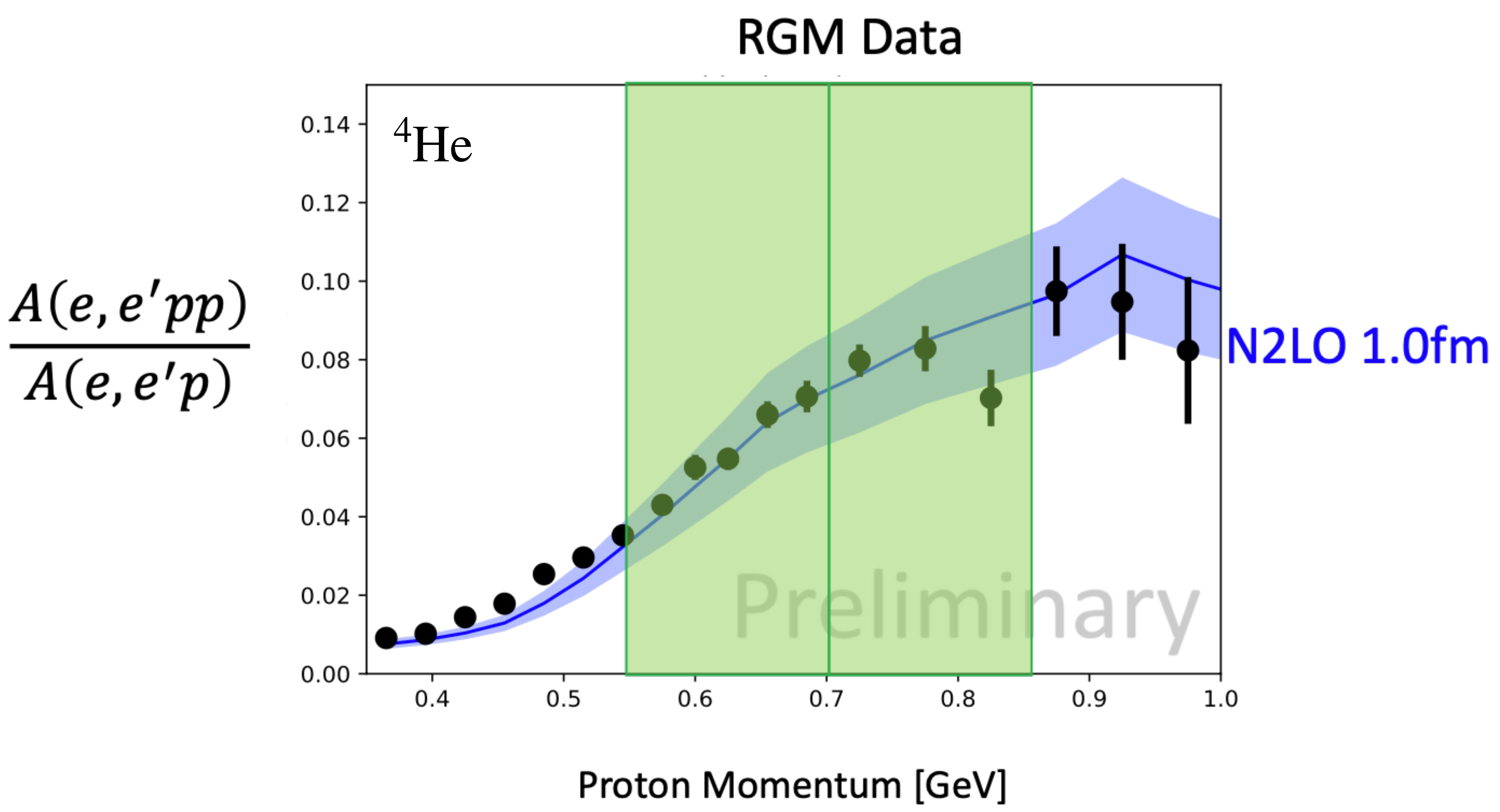

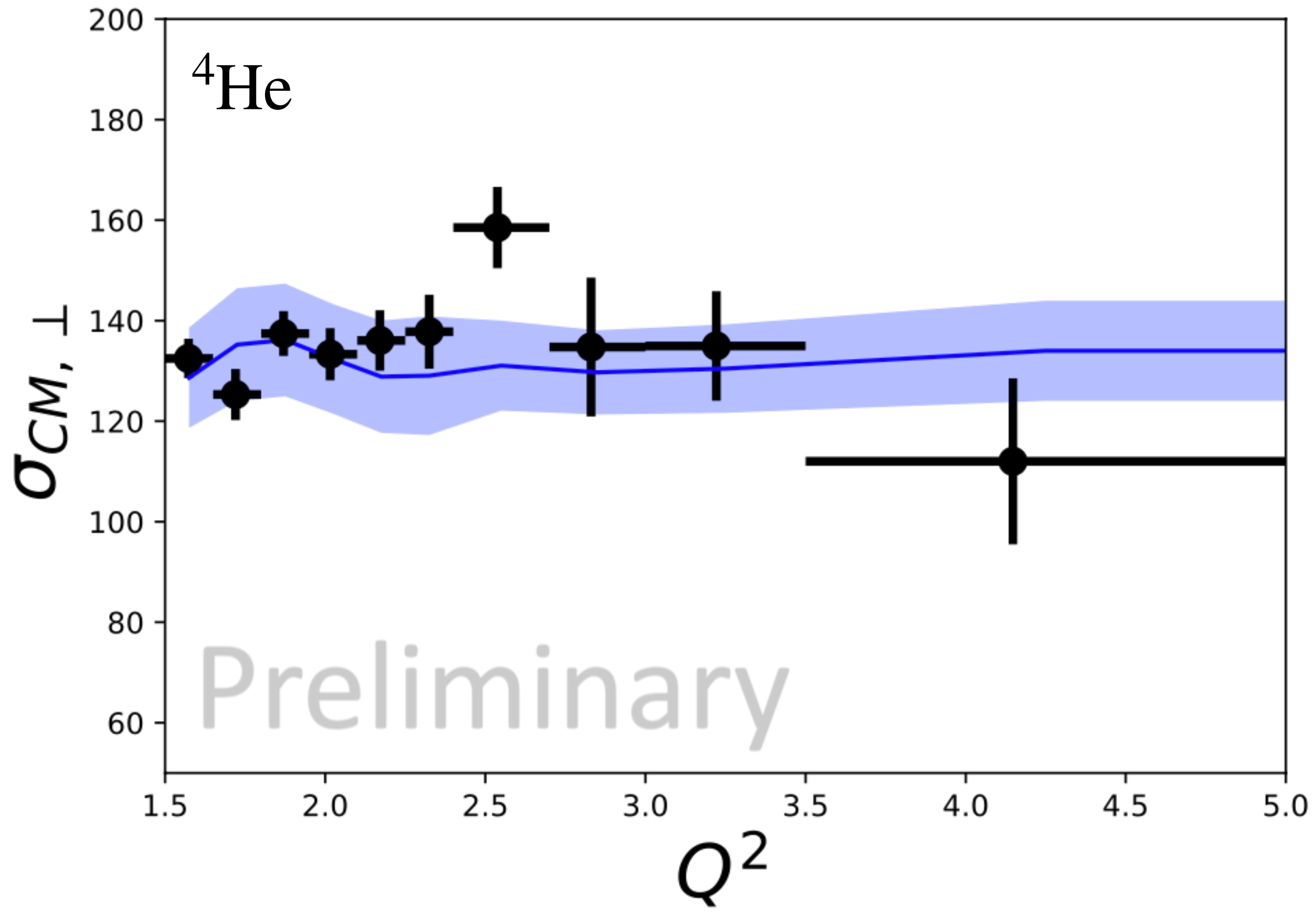

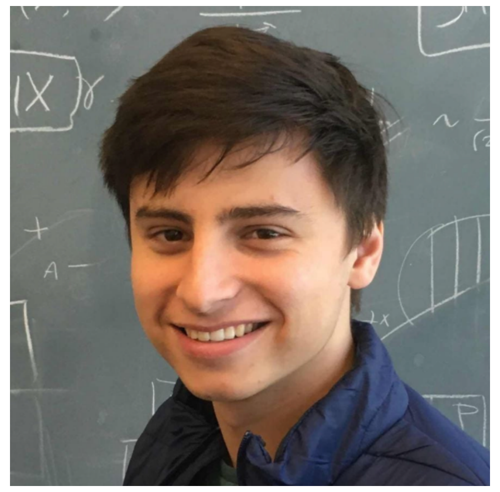

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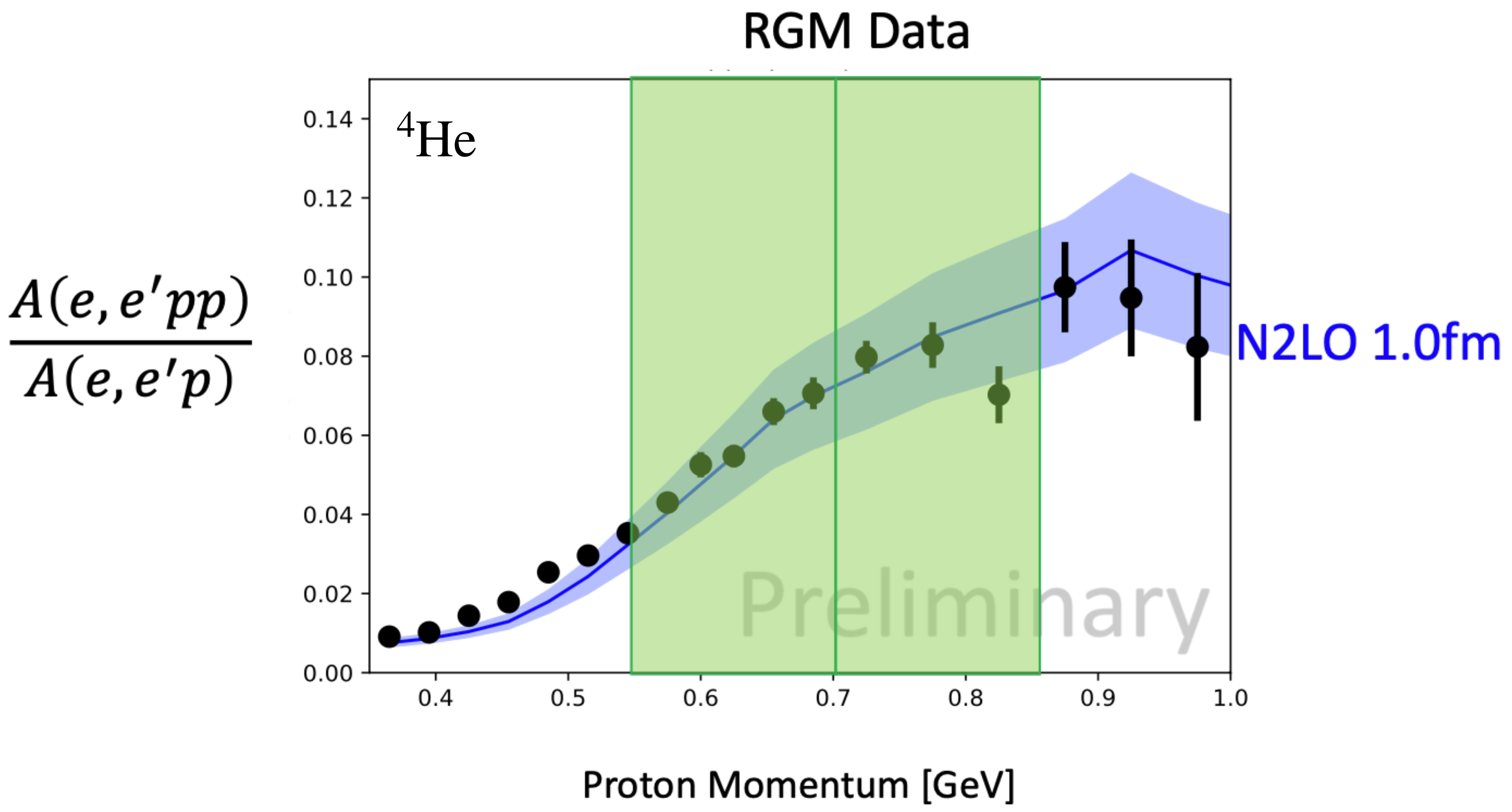

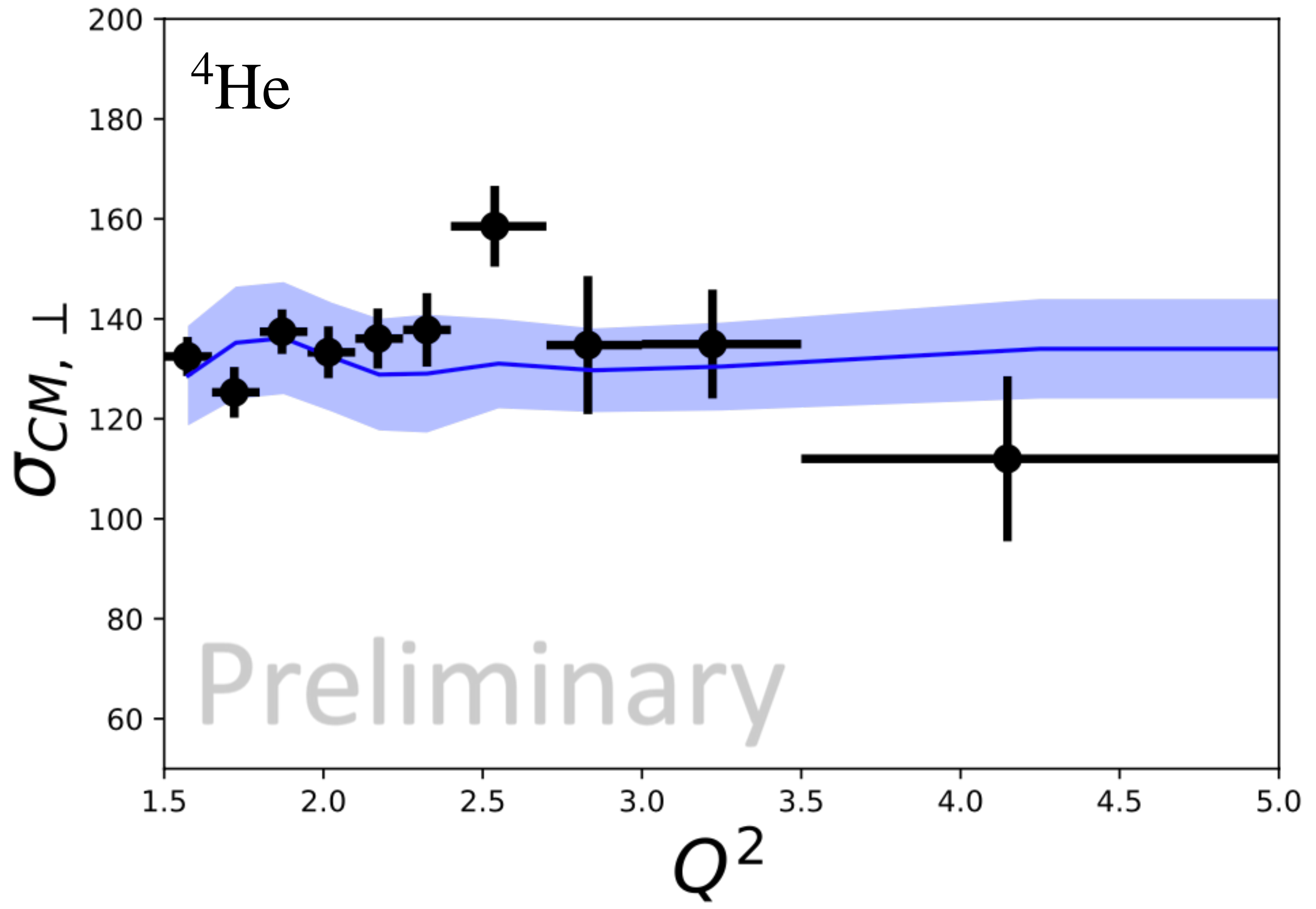

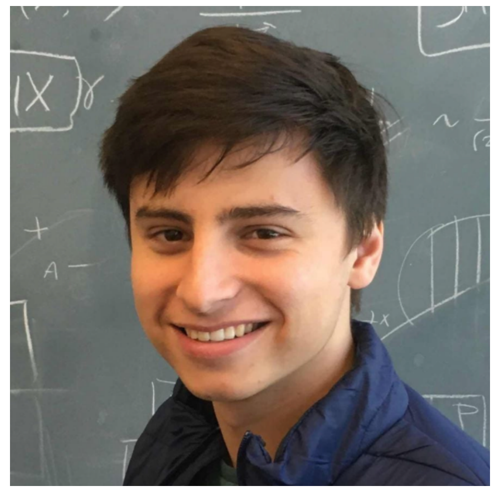

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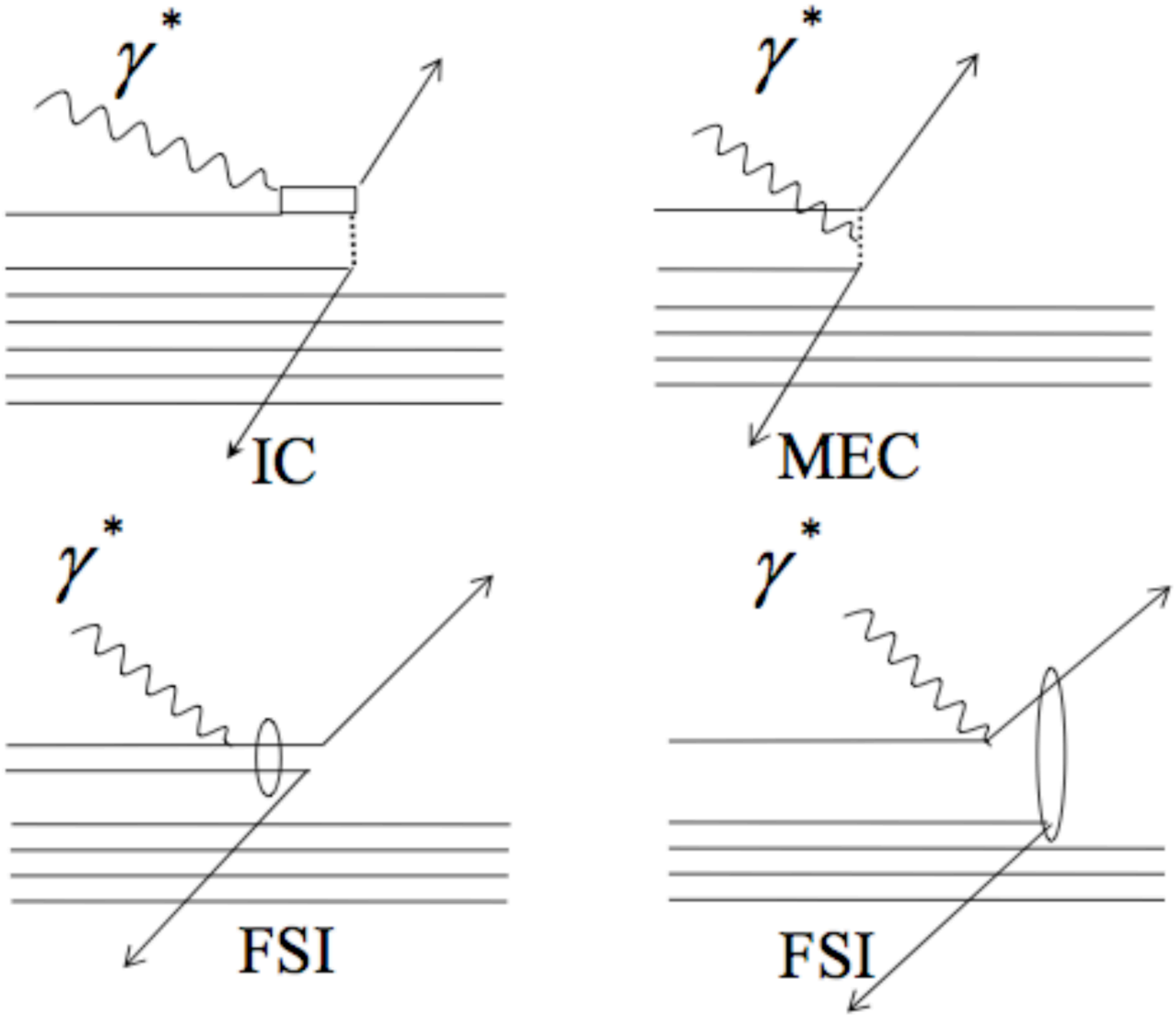
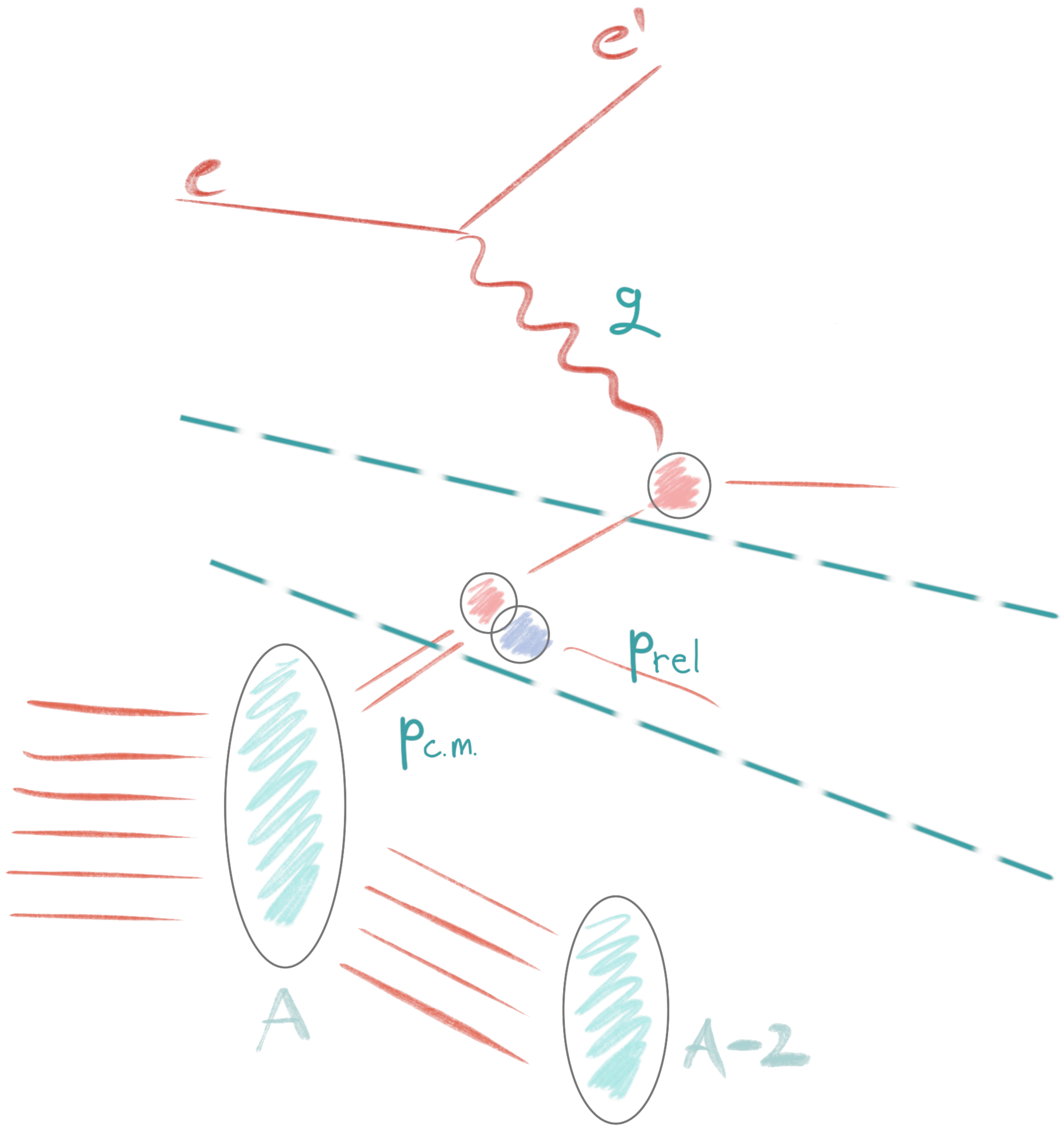
YES IT DOES!

Do we trust electrons?



different reaction mechanisms can complicate interpretation of data



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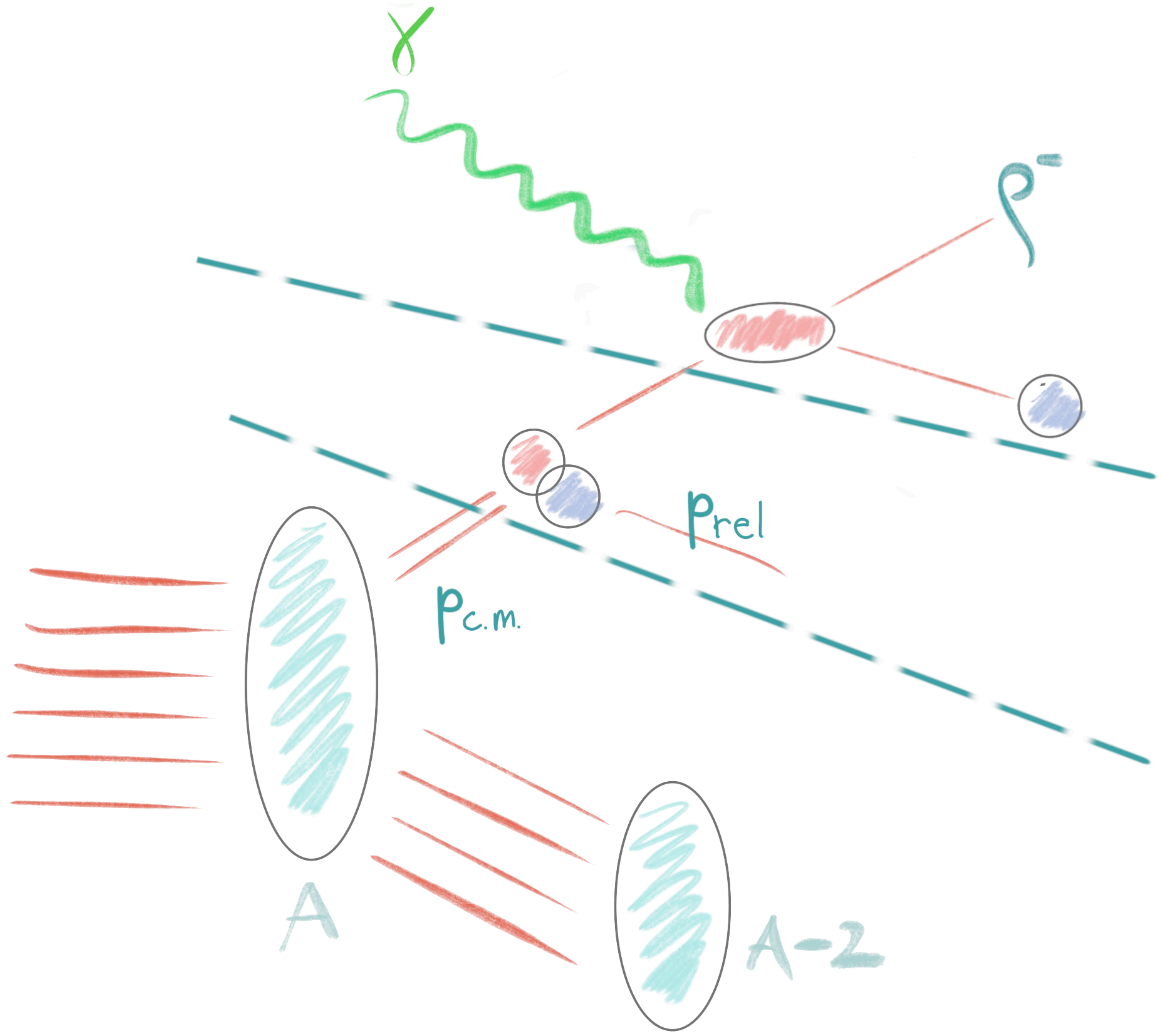
is GCF factorization probe independent?



$\sigma(\gamma n \rightarrow \rho^- p)$

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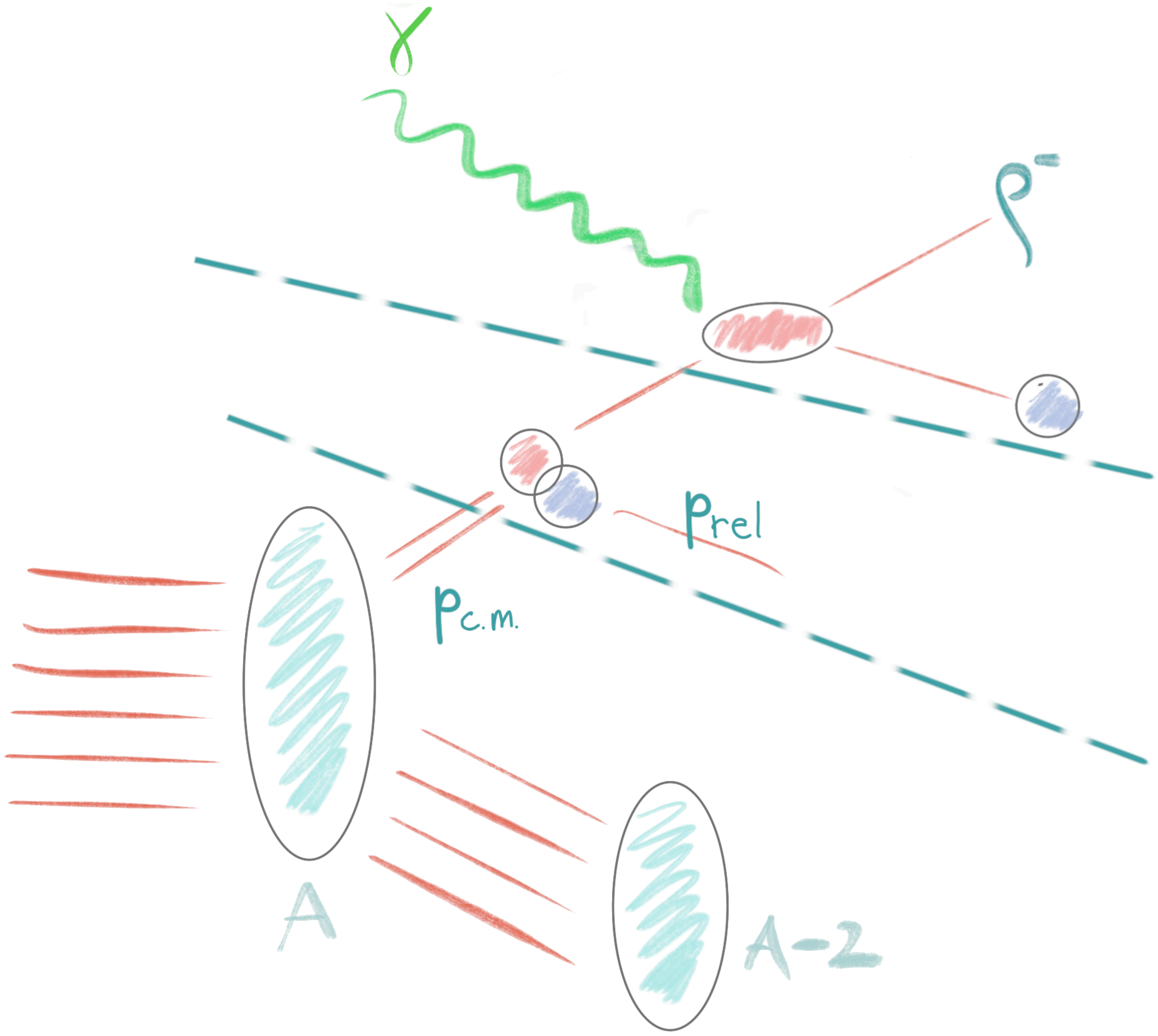

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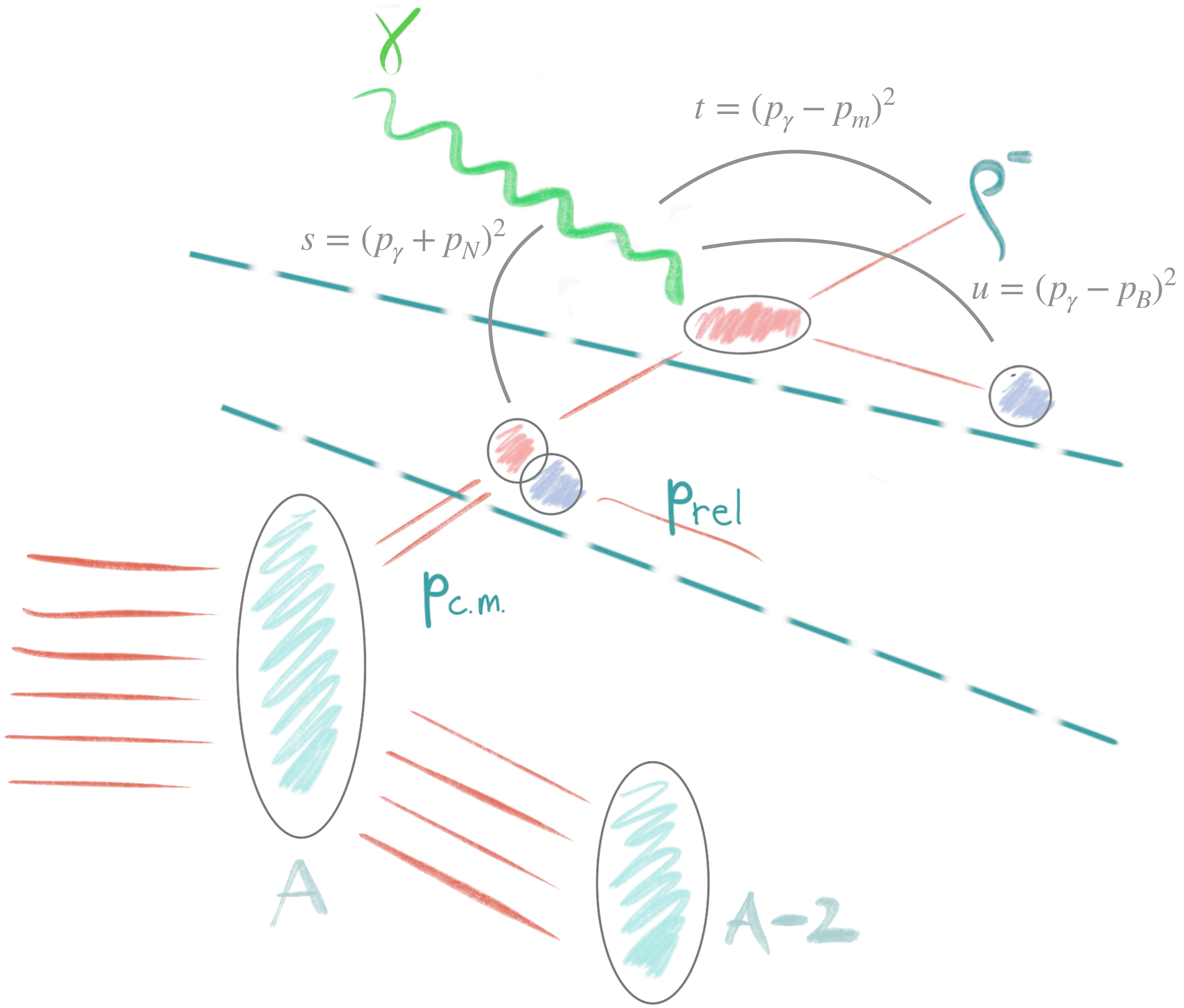
should not change

Many reactions avilable

γp			γn		
$\gamma p \to \pi^0 p$	$\gamma p \to \rho^0 p$	$\gamma p \to \eta p$	$\gamma n \to \pi^0 n$	$\gamma n \to \rho^- p$	$\gamma n \to \eta n$
$\gamma p \to \pi^+ n$	$\gamma p \to \rho^+ n$	$\gamma p \to \omega p$	$\gamma n \to \pi^- p$		$\gamma n \to \omega n$
$\gamma p \to \pi^- \Delta^{++}$	$\gamma p \to K^+ \Lambda^0$	$\gamma p \to \phi p$		$\gamma n \to K^0 \Lambda^0$	$\gamma n \to \phi n$
$\gamma p \to \pi^0 \Delta^+$	$\gamma p \to K^+ \Sigma^0$	$\gamma p \to J/\psi p$	$\gamma n \to \pi^- \Delta^+$	$\gamma n \to K^0 \Sigma^0$	$\gamma n \to J/\psi n$
$\gamma p \to \pi^+ \Delta^0$	$\gamma p \to K^0 \Sigma^+$			$\gamma n \to K^+ \Sigma^-$	

- charge exchange gives us easy access to pn pairs
- ρ^- invariant mass reconstruction helps reduce background (unlike π^-channel)

Advantages of ρ^- photoproduction

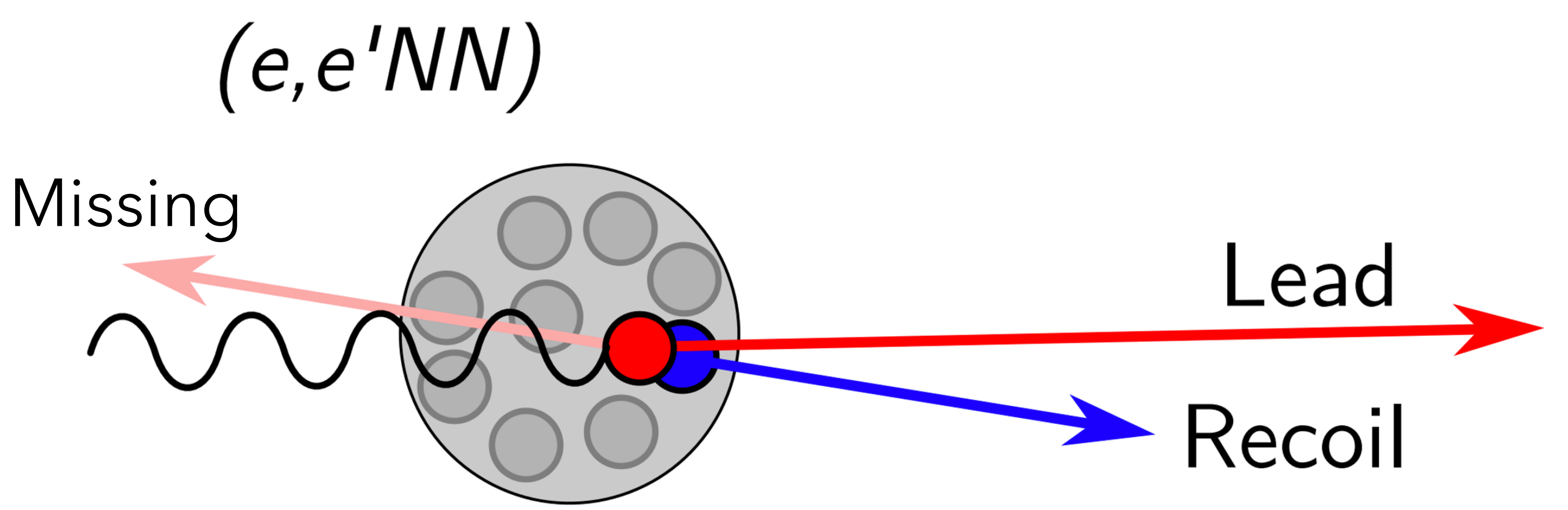


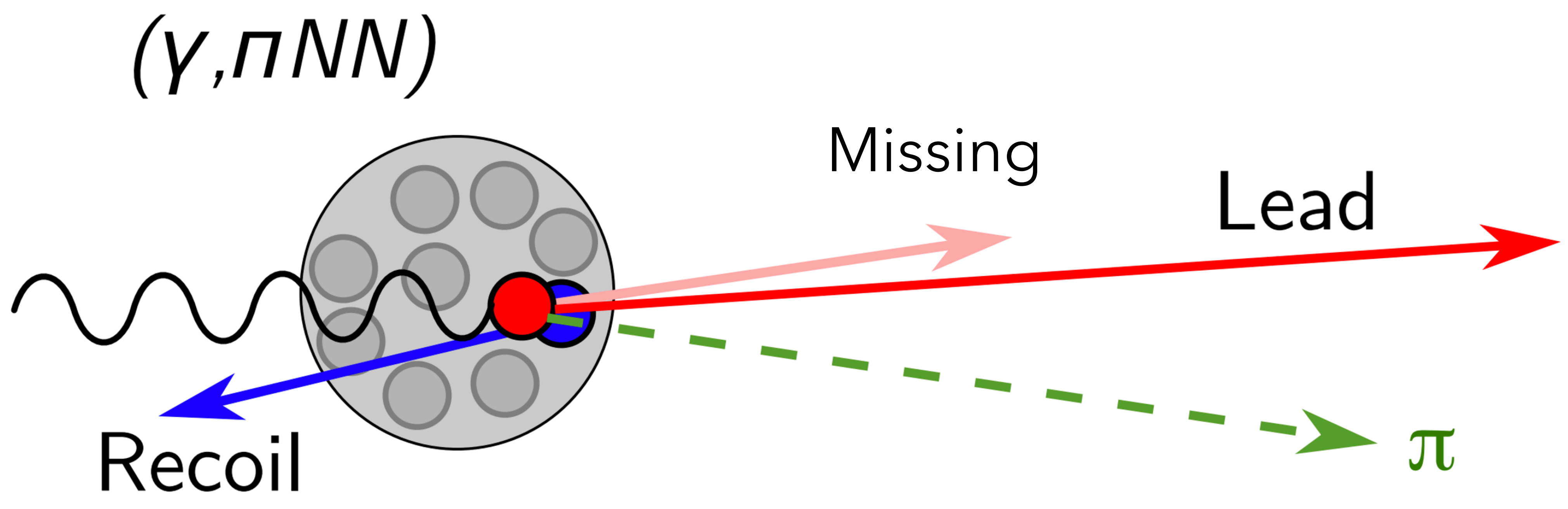
- Can occur through s, t, u-channel exchanges
- final-state $(\pi^-\pi^0 pp)$ has limited background
- Distinctive topology and exclusive detection helps to reduce background
- $(\gamma n \rightarrow \rho^- p)$ provides clean channel for probing SRC structure

Photoproduction reaction mechanisms differ significantly from electron-scattering

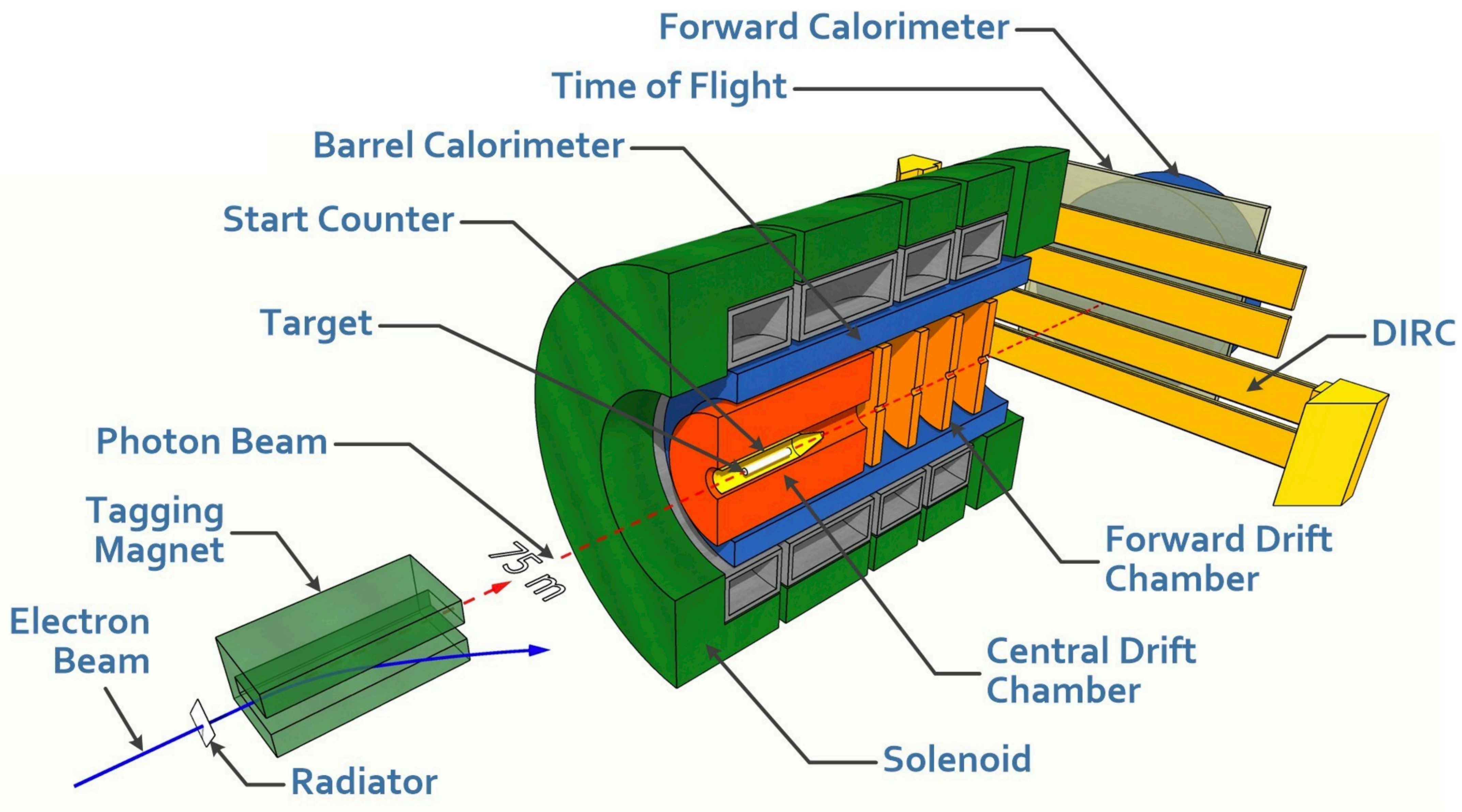
- No substantial radiative effects
- Kinematics prefer parallel kinematics, not antiparallel

  → Different effects of final-state interactions
- Different sensitivity to meson-exchange currents
- Less inelastic background





Experiment @ Hall D (JLab)



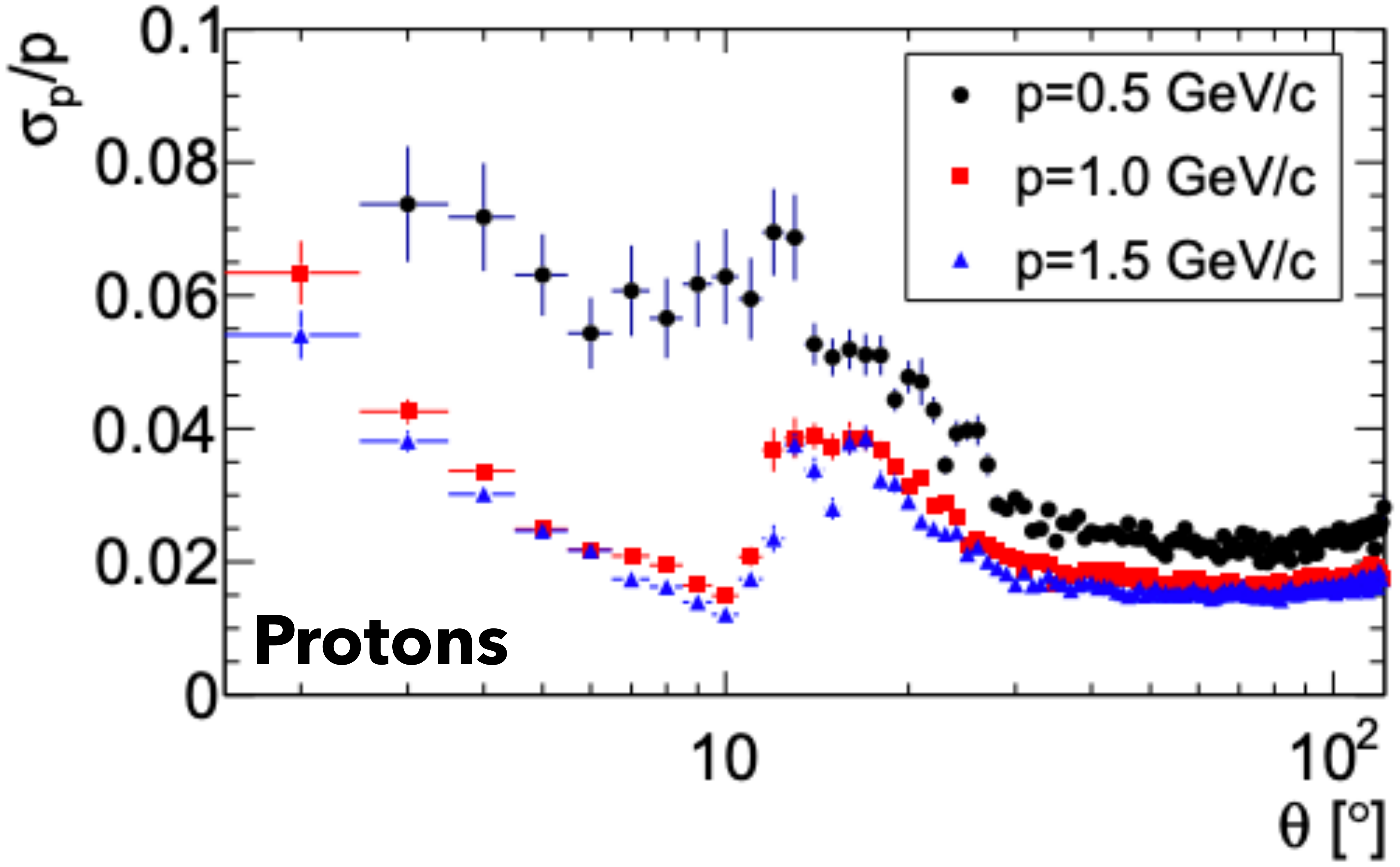
- 10.8 GeV electron beam incident on diamond radiator
- Photon emitted via coherent bremsstrahlung; scattered electron tagged
- Real photon incident on nuclear targets: ^{2}H, ^{4}He, ^{12}C
- Final-state particles detected in large-acceptance GlueX detector

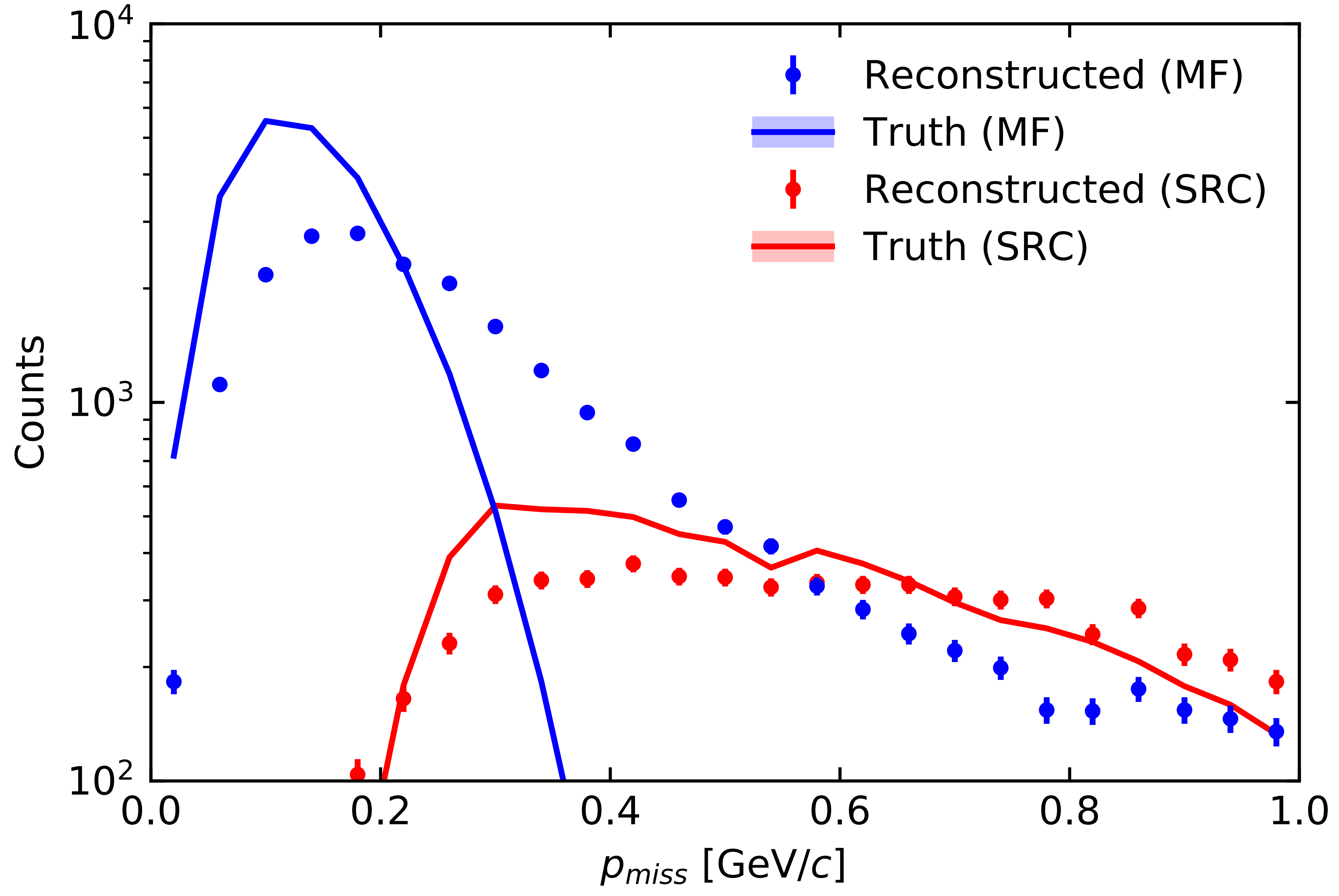
Experiment @ Hall D (JLab)

Target	Days of Beam	Luminosity ($E_\gamma > 6$ GeV)
Deuterium	4	18.0 nucleus · pb-1
Helium-4	10	16.7 nucleus · pb-1
Carbon-12	14	8.6 nucleus · pb-1

Downsides

- limited momentum resolution → affects p_{miss} reconstruction



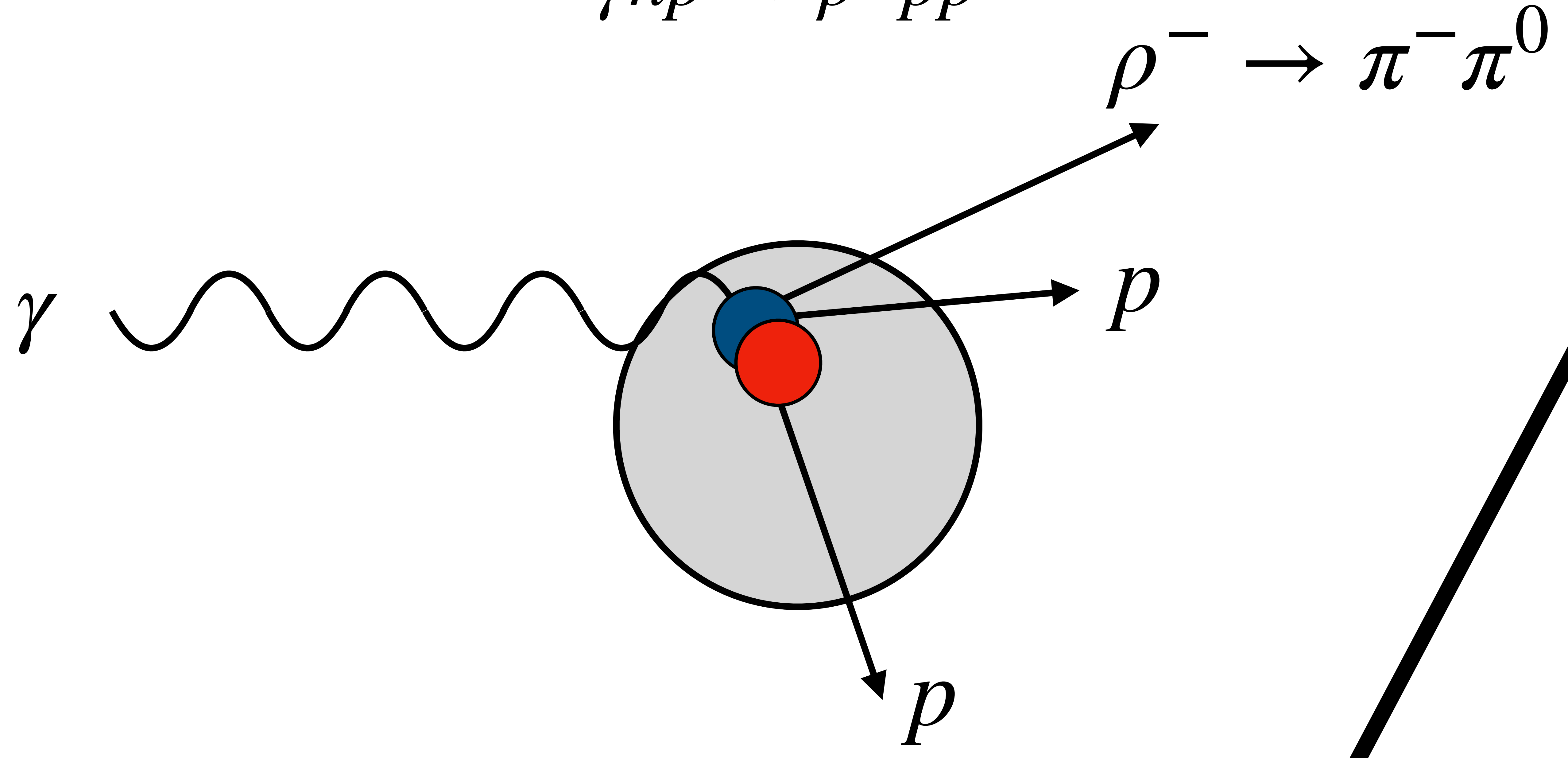


Downsides

- Bad detector resolution
- Background reactions

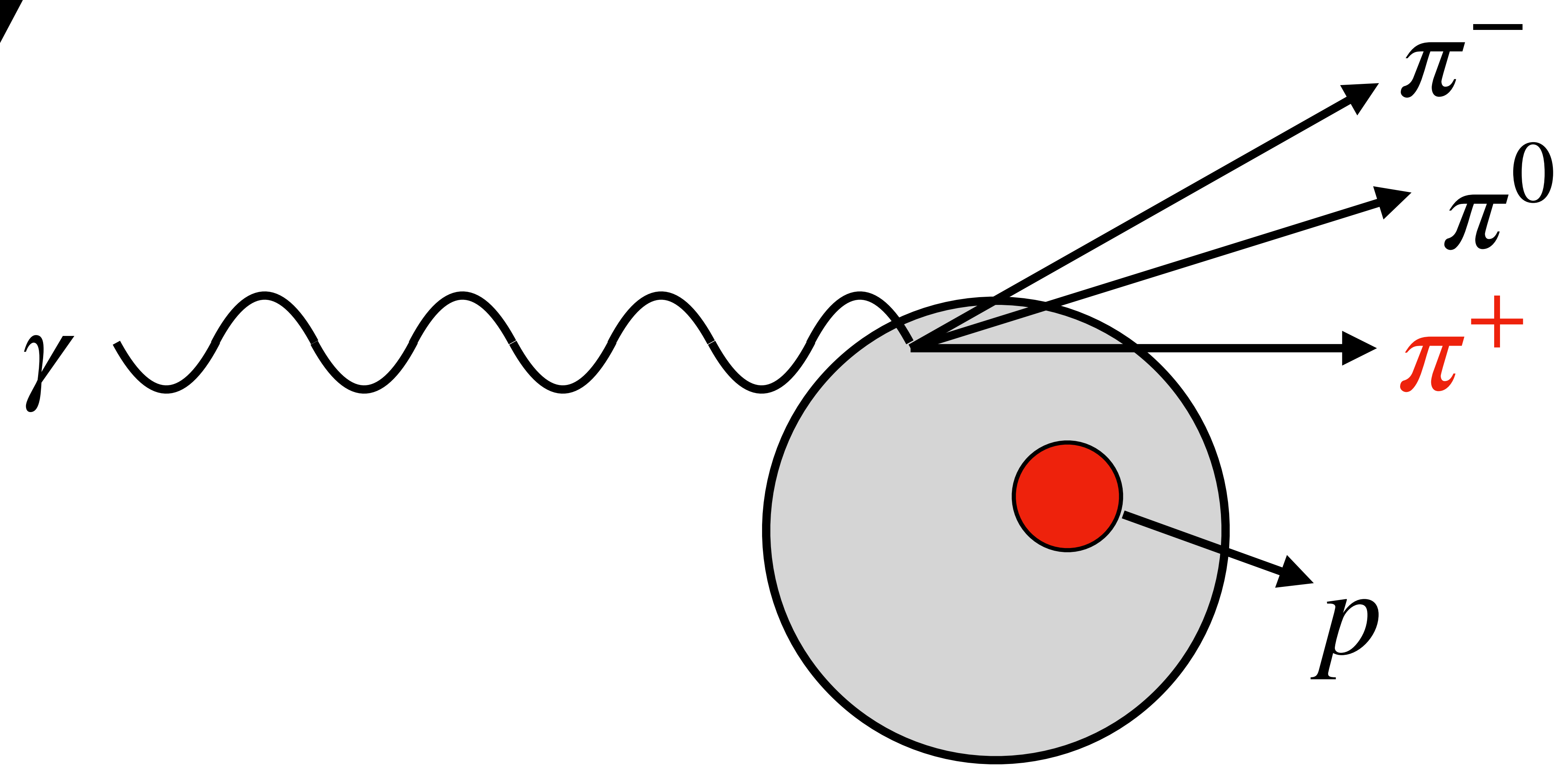
Signal process:

$\gamma np \to \rho^- pp$

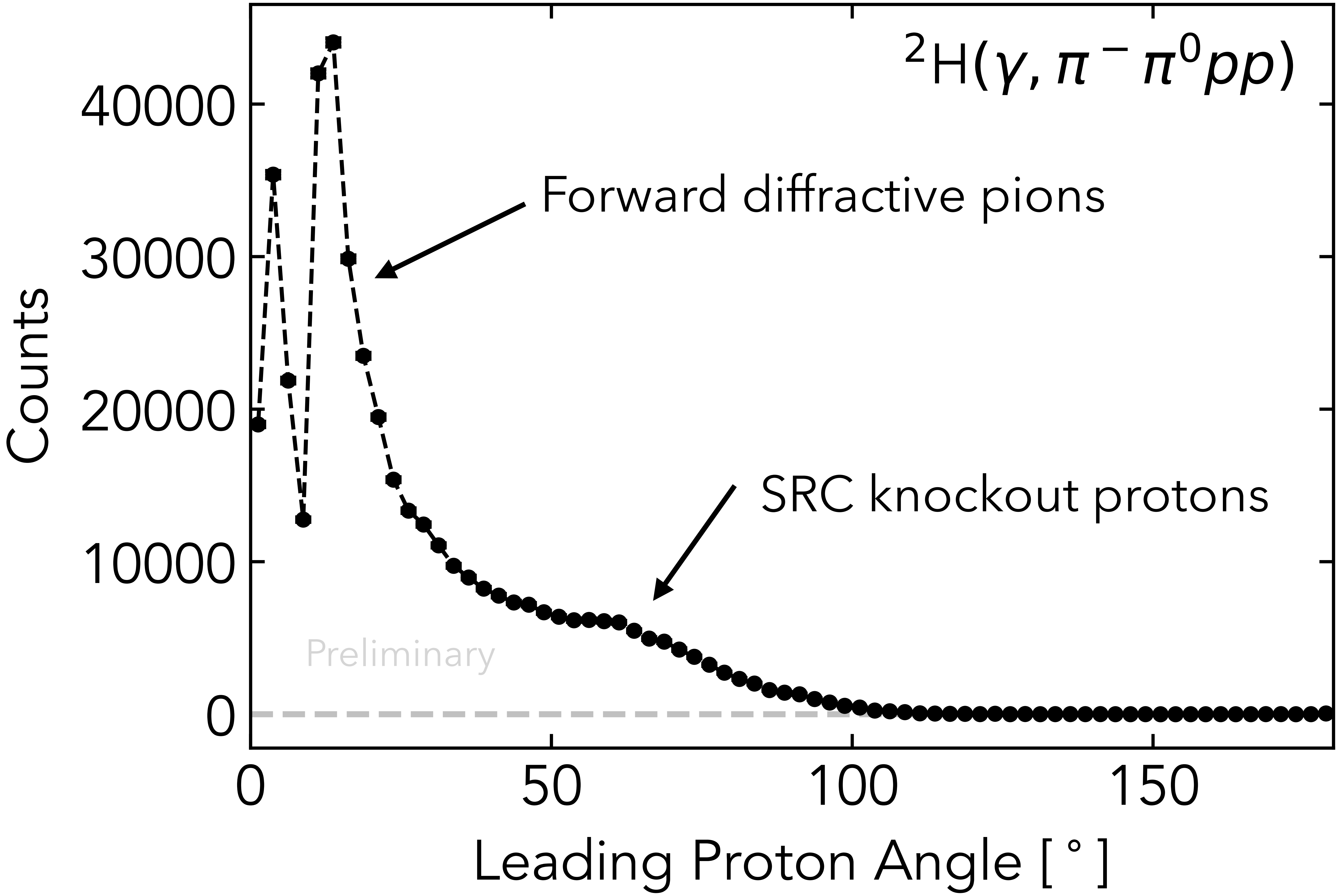


Largest Background

$\gamma A \to \pi^+ \pi^- \pi^0 p(X)$



Diffractive pion production backround



Can't separate SRCs from BG

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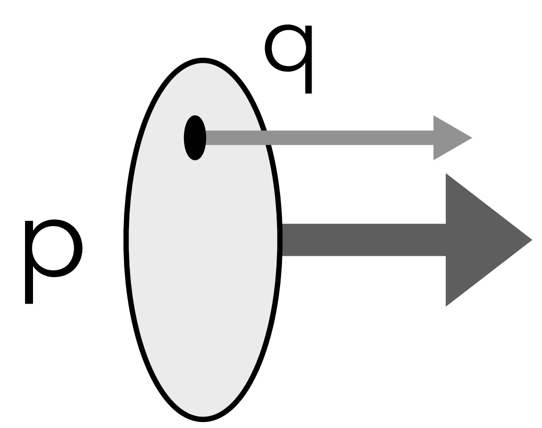
Analysis on the light-front

Parton in Hadron

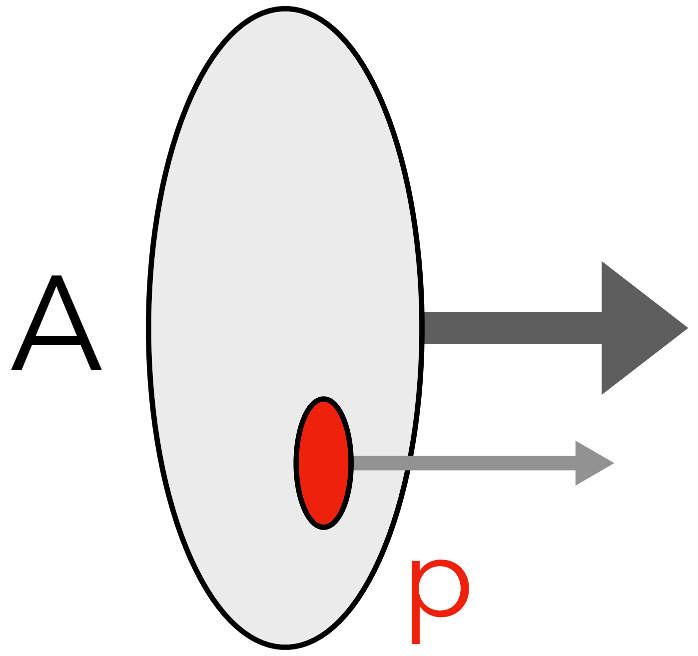


Parton momentum fraction

$$x_B = \frac{Q^2}{2p_N \cdot q} \rightarrow \frac{E_q - p_q^z}{E_N - p_N^z}$$

Light-front variables mitigate resolution effects

Nucleon in Nucleus

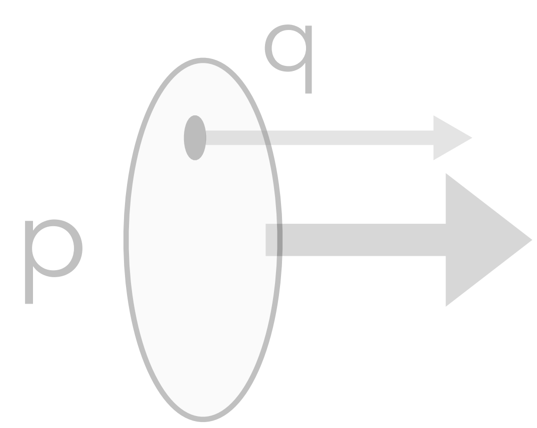


Nucleon momentum fraction

$$\alpha_N \equiv A \frac{E_N - p_N^z}{E_A - p_A^z}$$

Light-front → better resolution

Parton in Hadron



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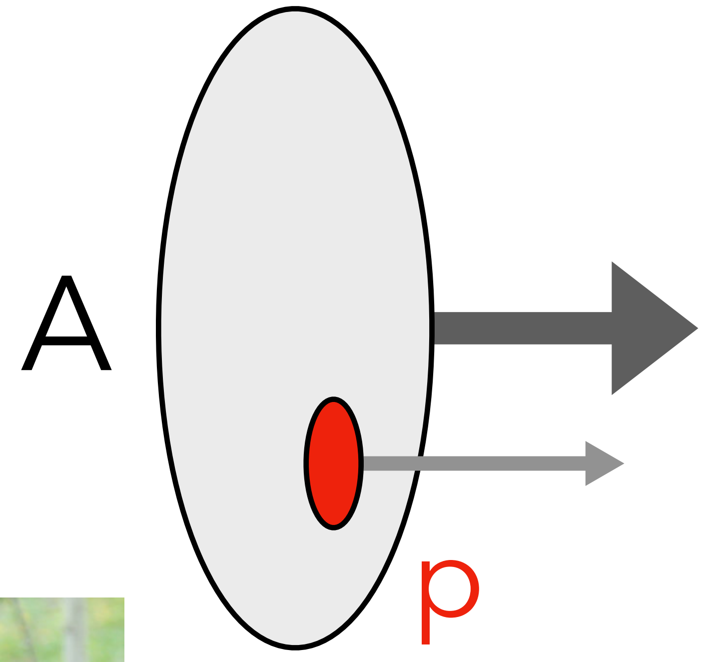


Nucleon momentum fraction

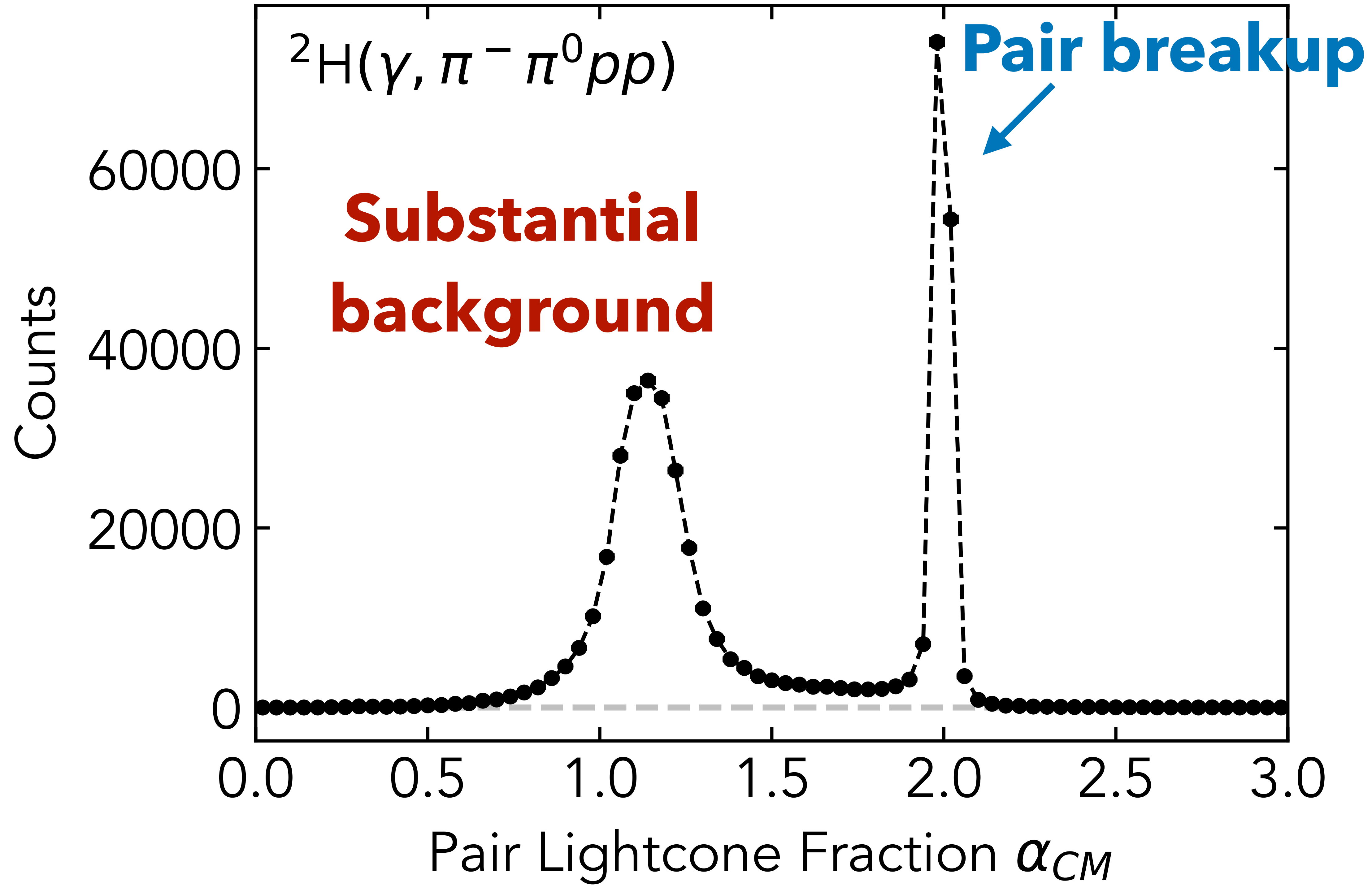
$$\alpha_N \equiv A \frac{E_N - p_N^z}{E_A - p_A^z}$$

→ Low-momentum nucleon

$$\alpha_N \sim 1$$

→ Standing nucleon pair

$$\alpha_1 + \alpha_2 \equiv \alpha_{CM} \sim 2$$



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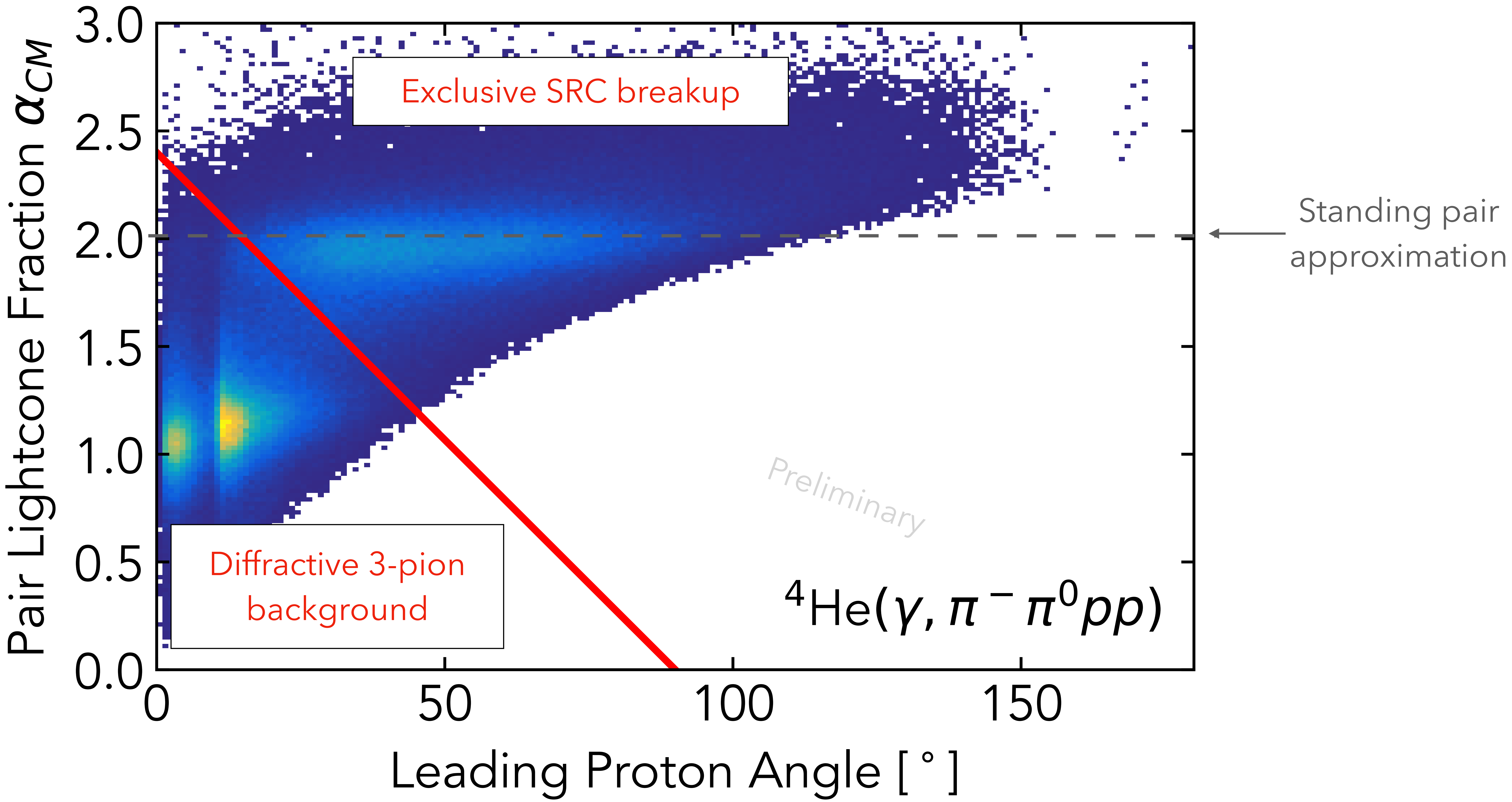
SRC events more spread out but still clear in data



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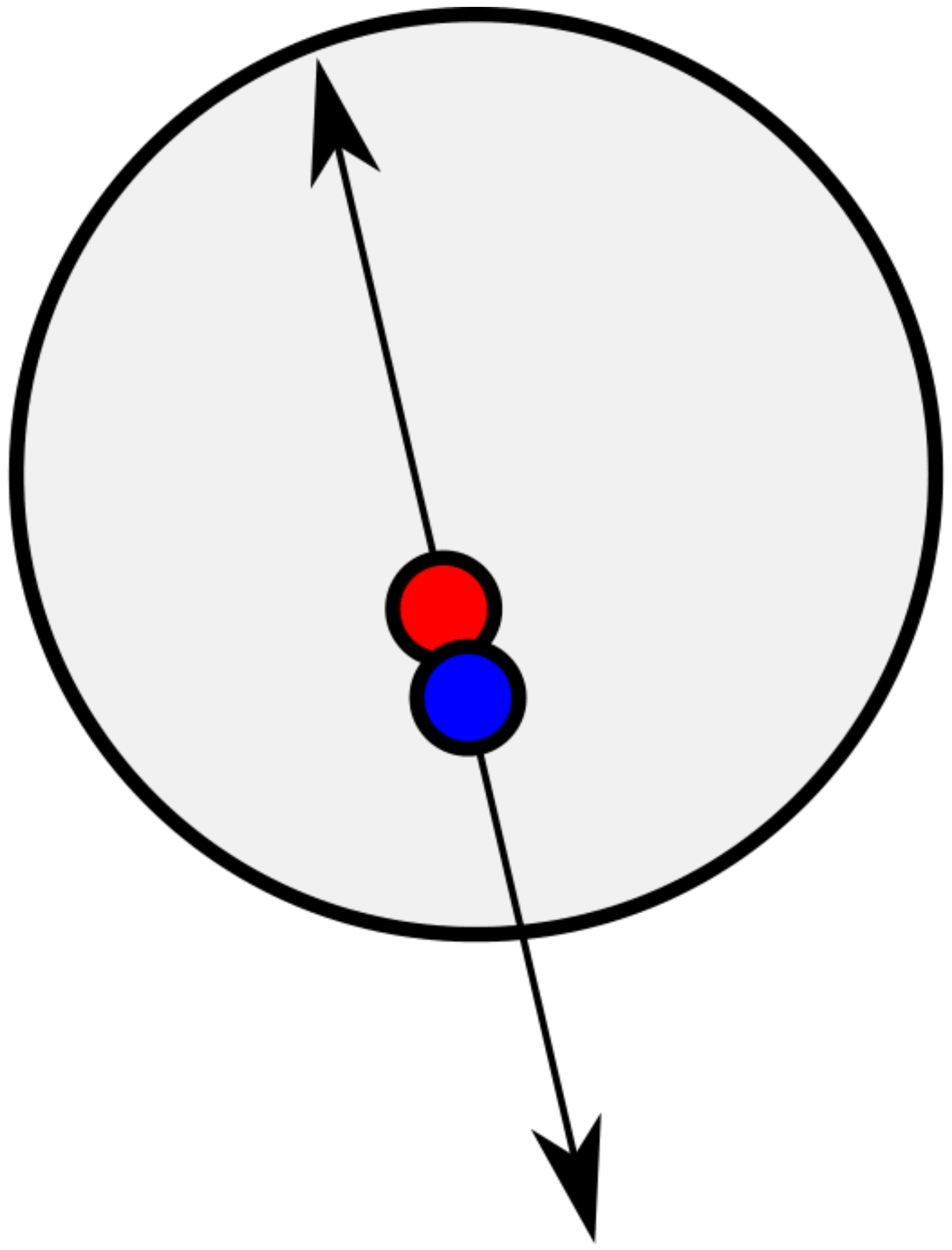
Comparison with GCF calculations

- Diffractive background cut
- High relative momentum cut



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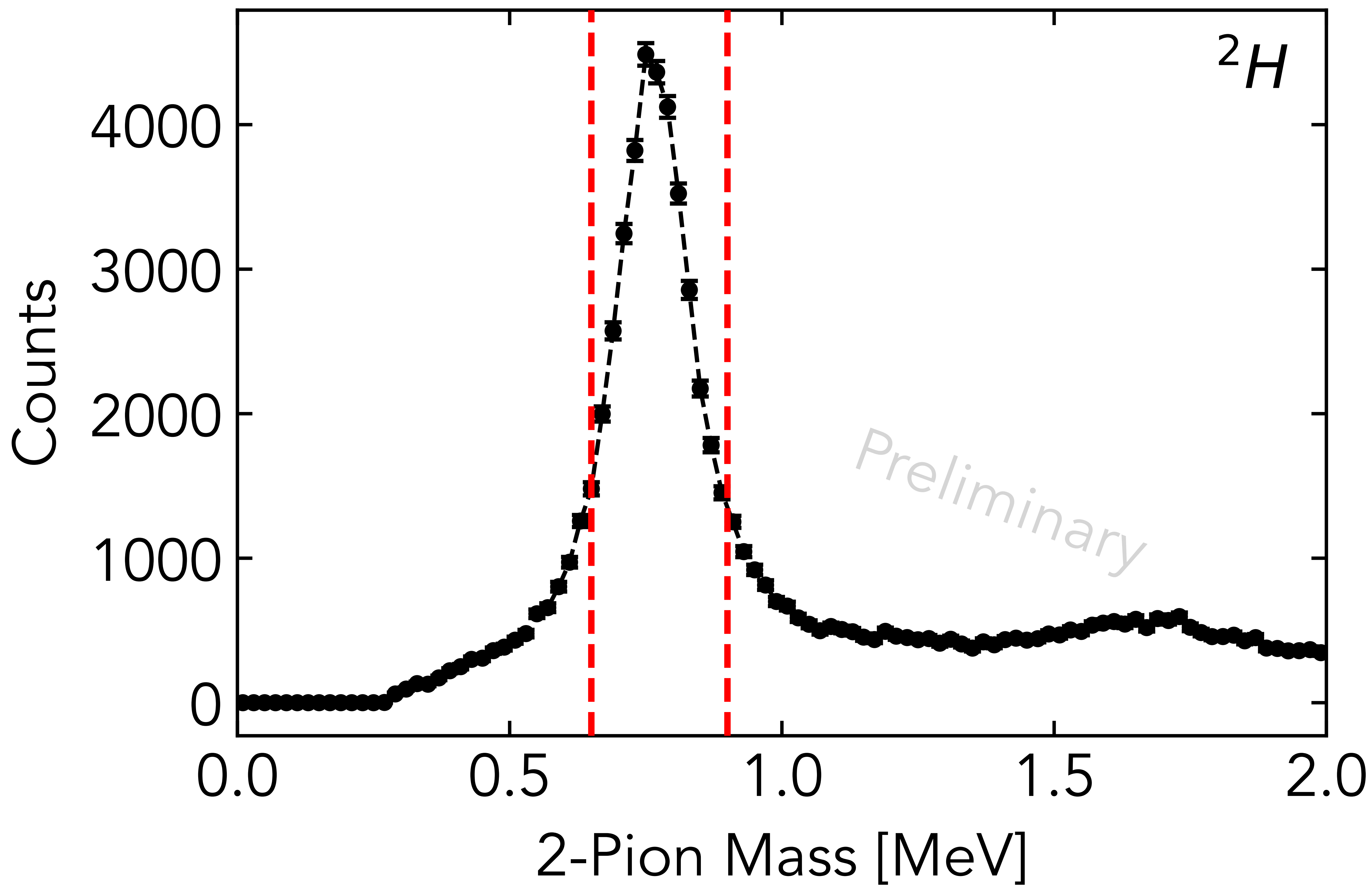
- Cut on rho meson mass



Work done by
Jackson R. Pybus (MIT)

Comparison with GCF calculations

- Diffractive background cut
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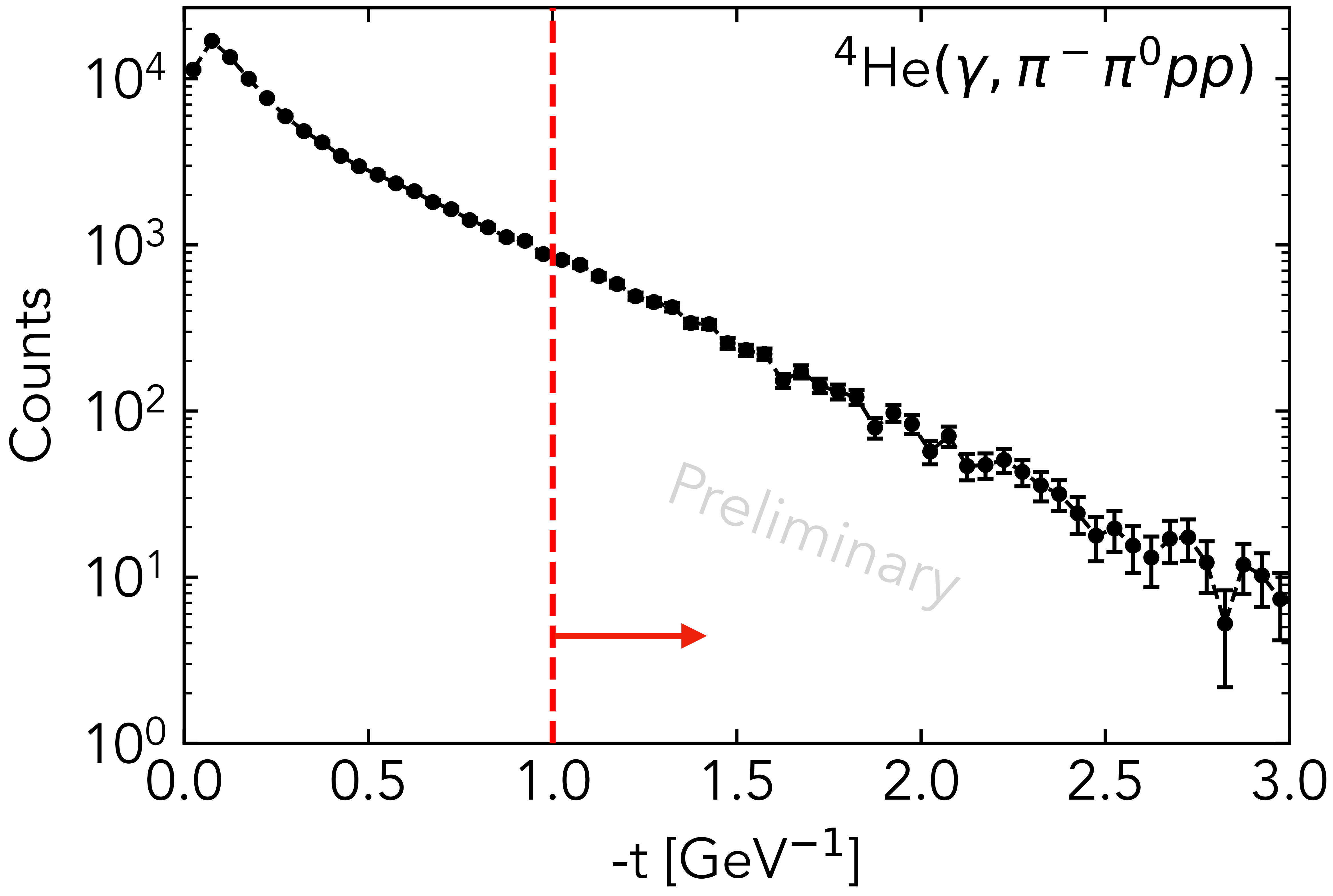
- High momentum-transfer $|t|, |u| > 1$ GeV^2



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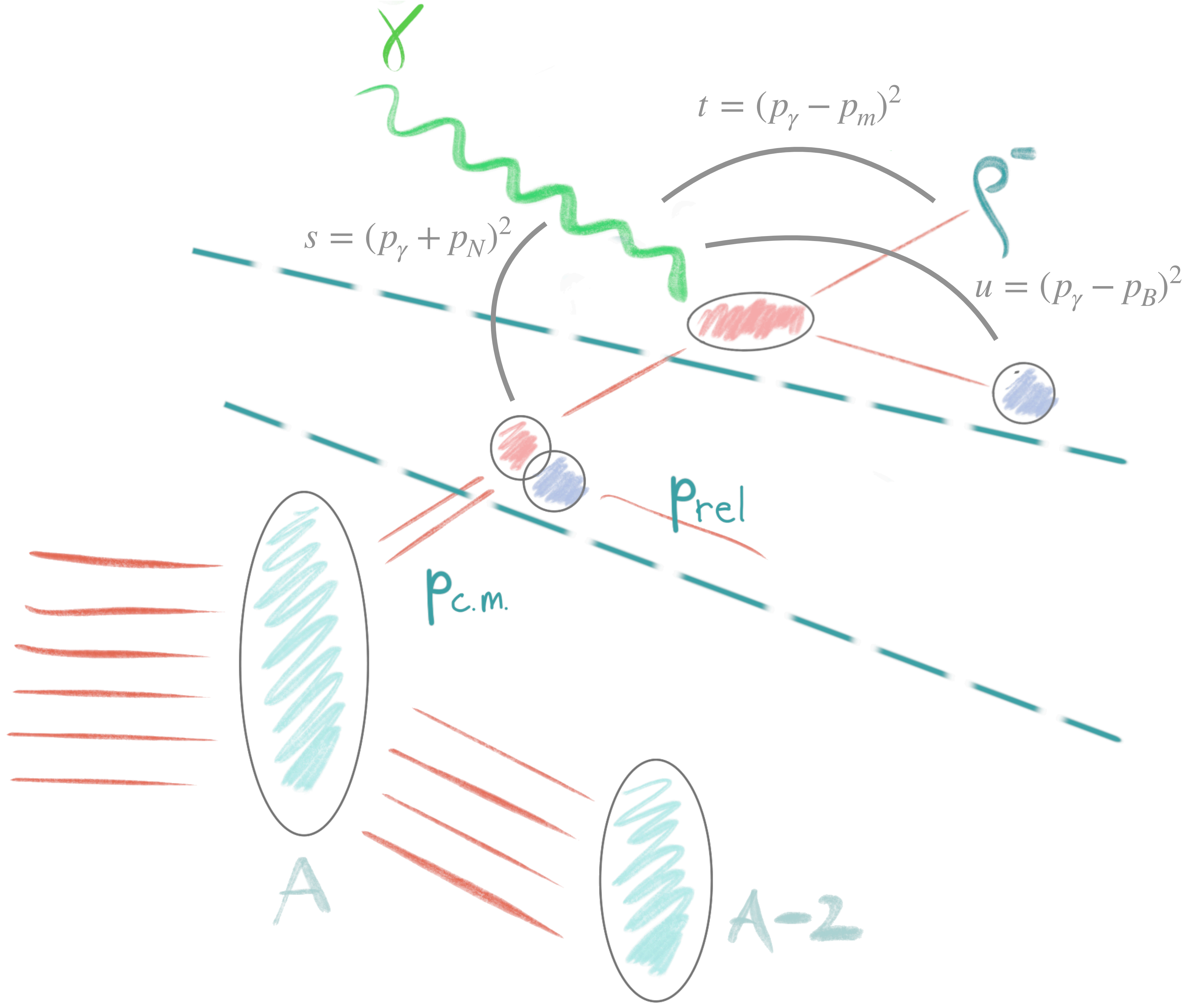
- **Compare with GCF calculations**



$$\sigma \sim K \cdot \sigma(\gamma n \to \rho^- p) \cdot S(p_i, p_{recoil})$$

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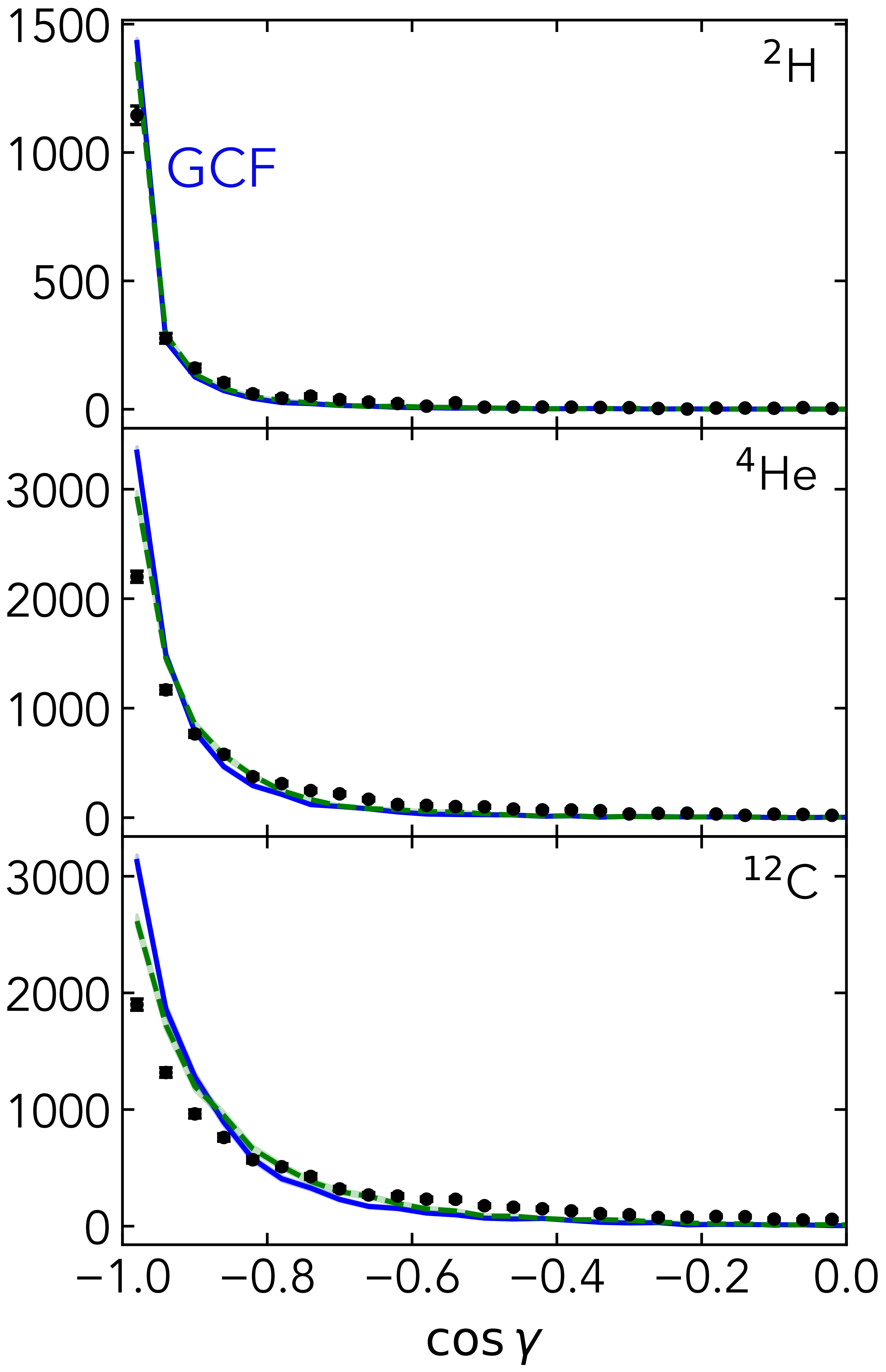
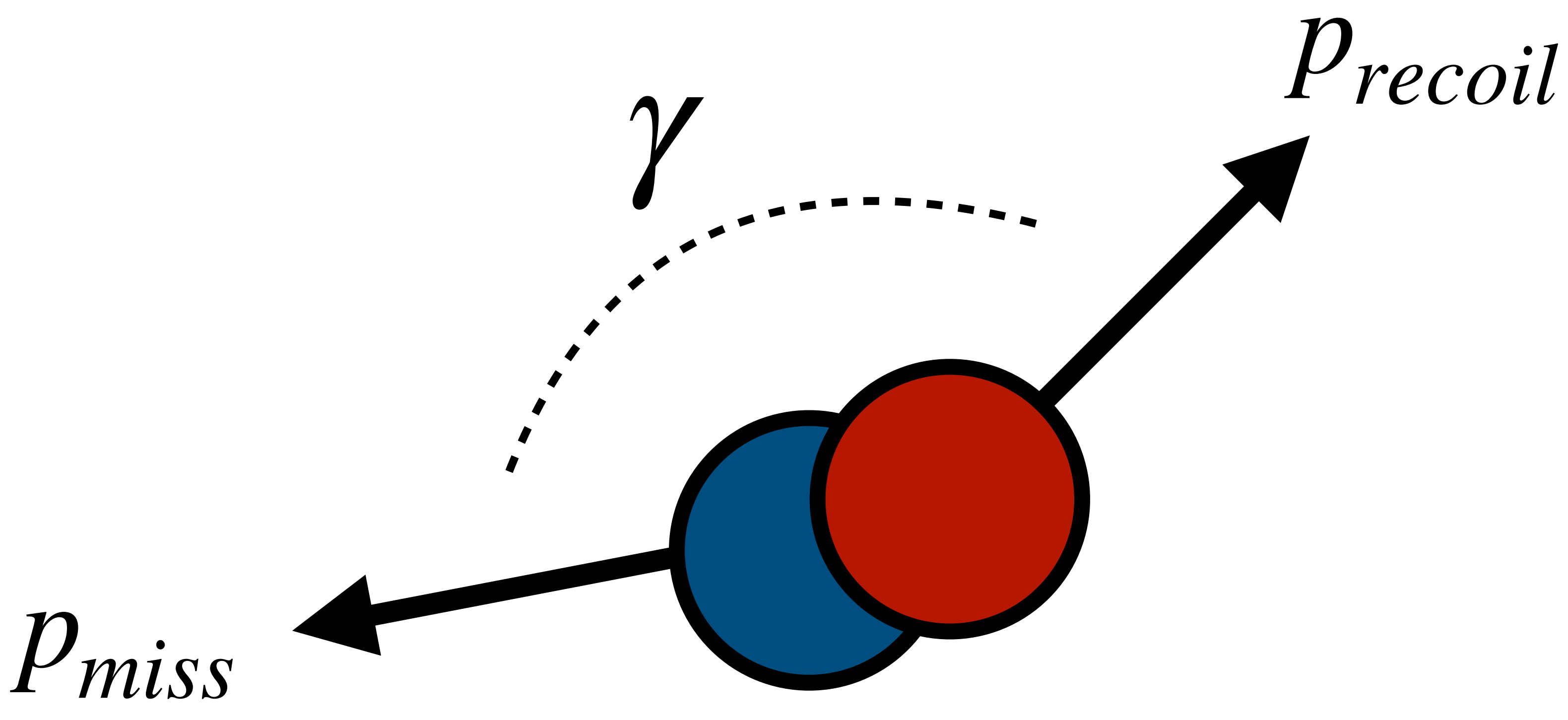
SRC Pair Opening Angle





- Reconstruct angle between initial-state neutron and spectator proton
- All nuclei show clear back-to-back correlation

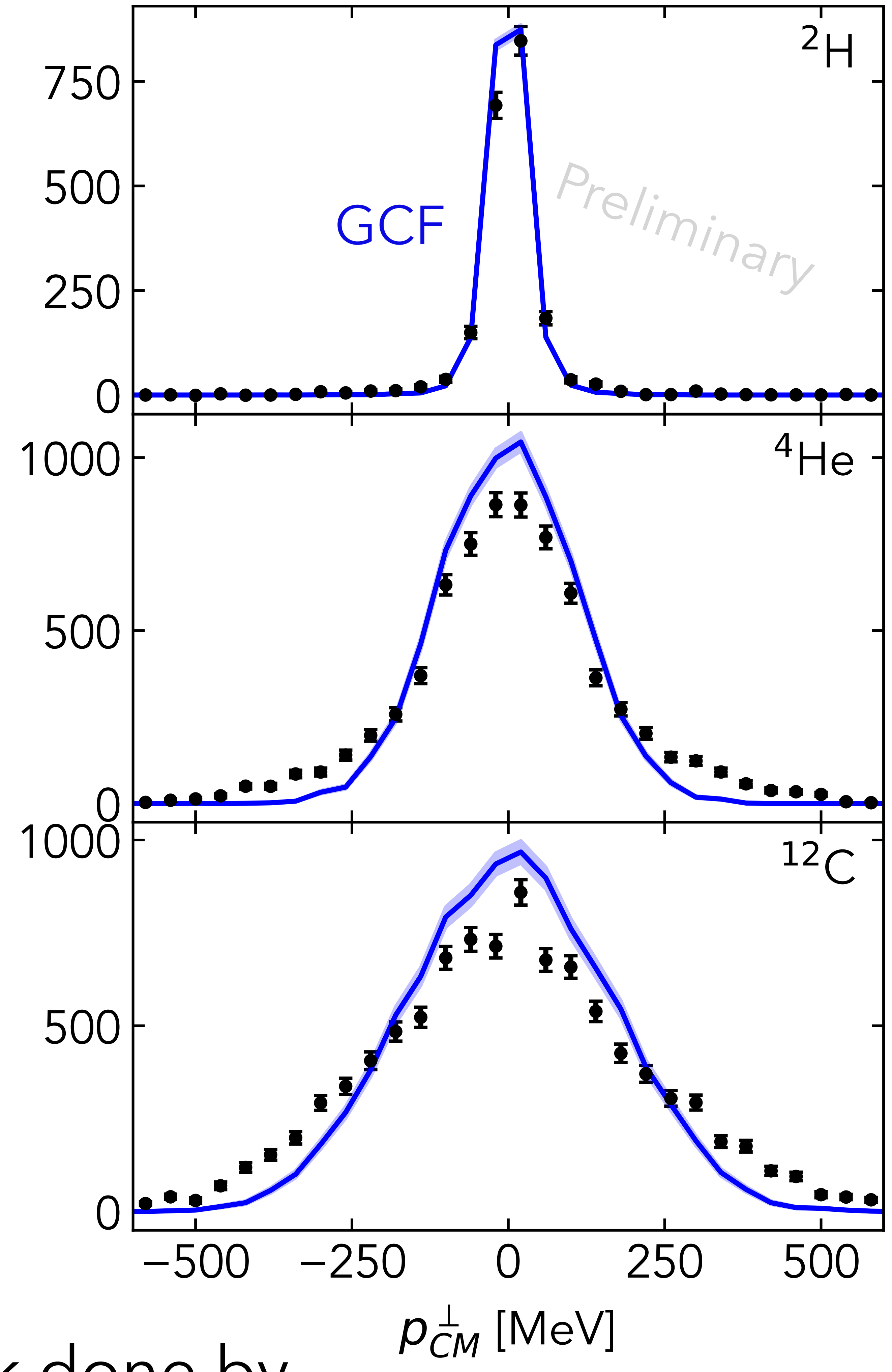
Work done by Jackson R. Pybus (MIT)

SRC Center-of-Mass Momentum

$\sigma_{CM} = 0$ MeV
(+ resolution)

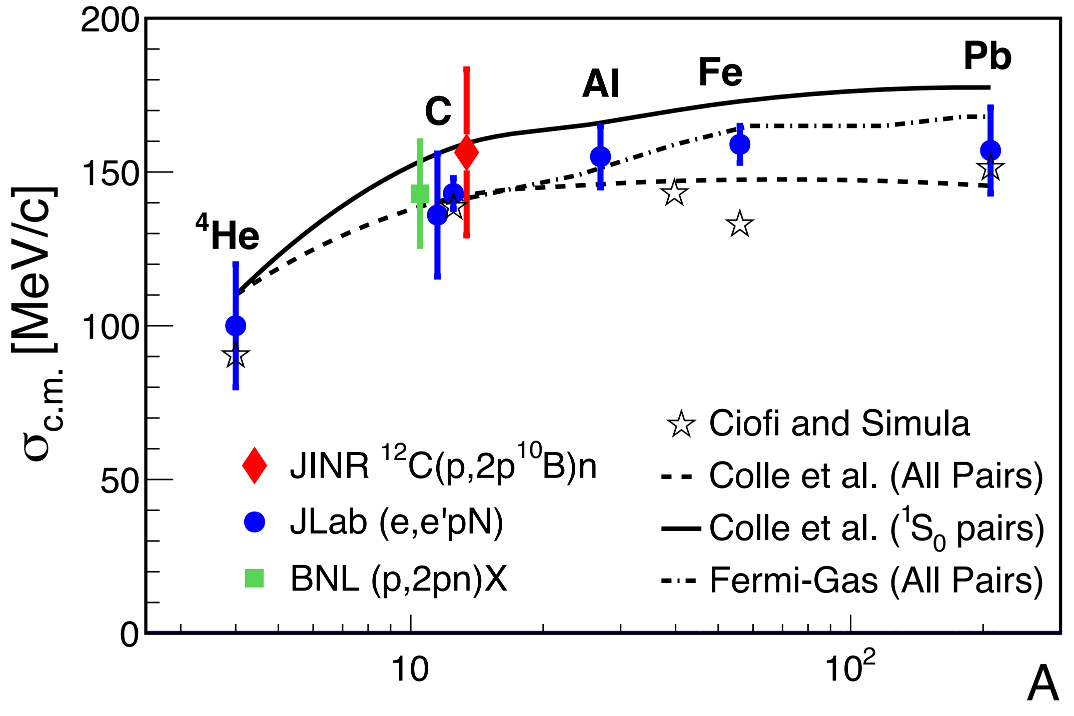
$\sigma_{CM} = 100$ MeV

$\sigma_{CM} = 150$ MeV



- Transverse component of center-of-mass momentum used to limit FSI and cross section effects
- General trend with A agrees with current measurements, but precise value needs to be extracted and compared

GCF Input



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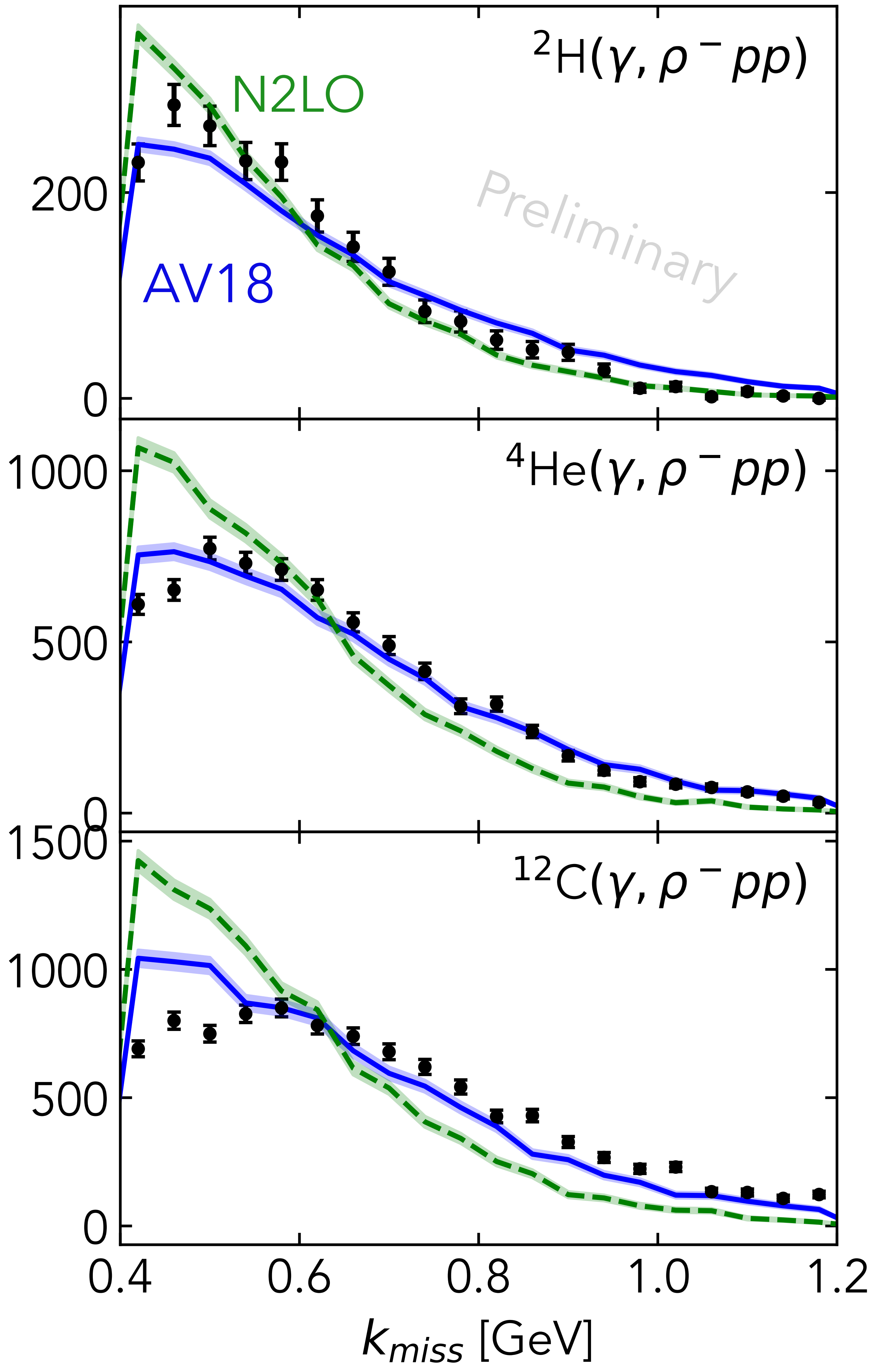
Initial Neutron Momentum (Proxy)



- Initial neutron momentum sensitive to short-distance NN interaction
- Momentum distributions well-described
- Agreement with AV18 predictions similar to that for electron-scattering data

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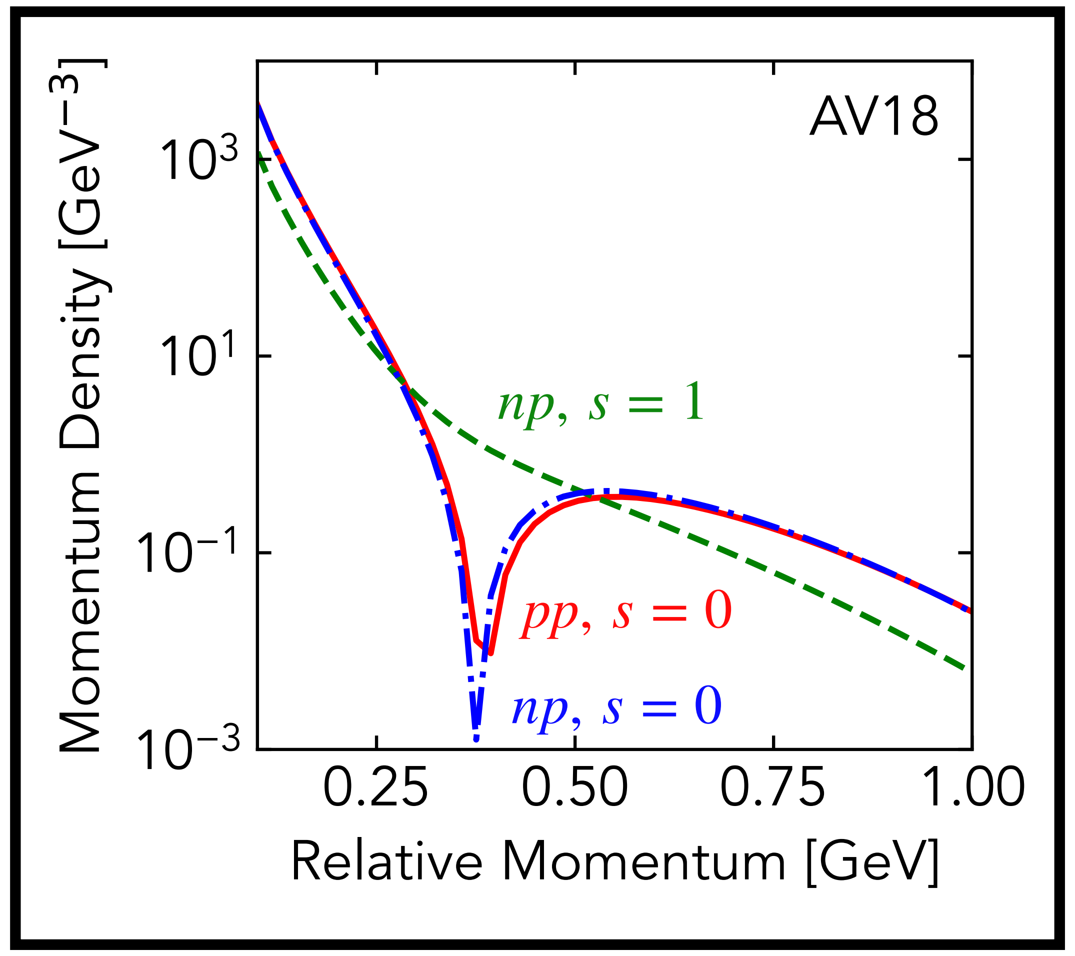
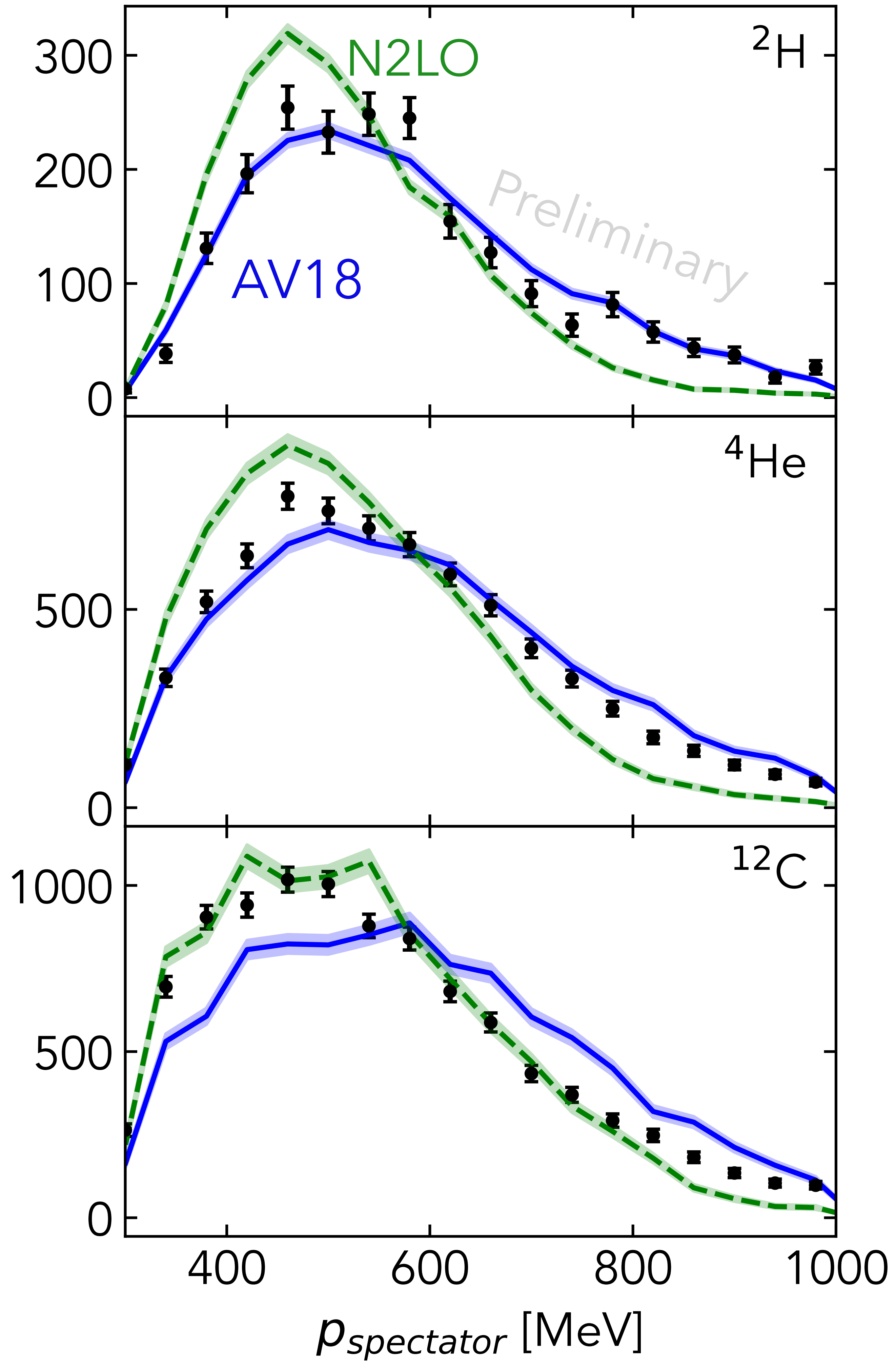
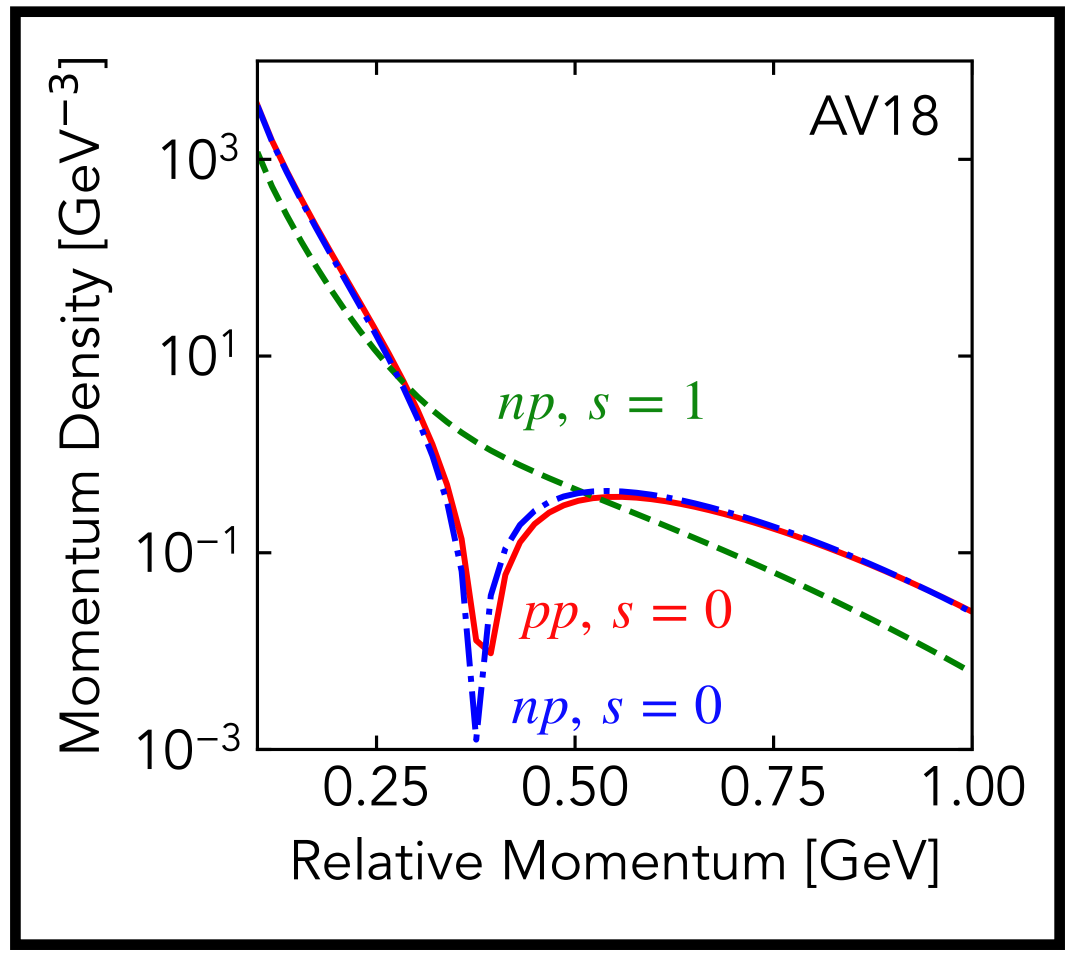


Recoil Proton Momentum



- Spectator momentum also well-reconstructed but shows possible signs of rescattering
- Calculation of FSI using cascade models can help identify regions of large FSI

GCF Input



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Outlook

- Further study of systematics necessary to complete comparison to plane-wave predictions

- Sensitivity to photoproduction cross section, understanding of FSI effects, impact of $|t|$ and $|u|$ cuts

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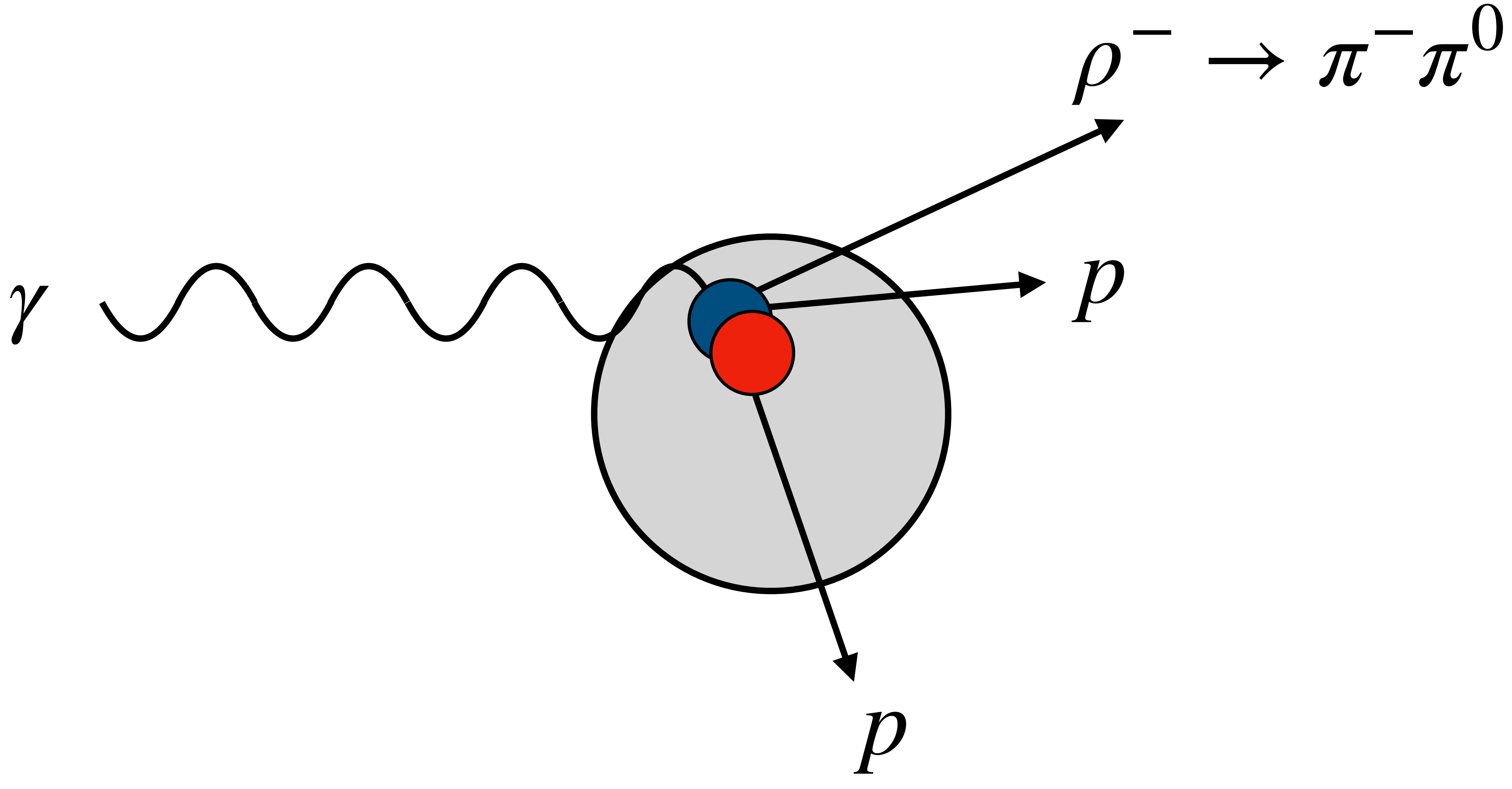
- Sensitivity to photoproduction cross section, understanding of FSI effects, impact of $|t|$ and $|u|$ cuts

- Complementary $(\rho^0 pp)$ channel allows access to pp pairs, enabling confirmation of isospin structure of SRCs (P. Sharp, GWU)

- Other ongoing projects: color transparency (B. Devkota, MSU) , neutron structure (B. Yu, Duke), medium modification (T. Kolar, TAU)

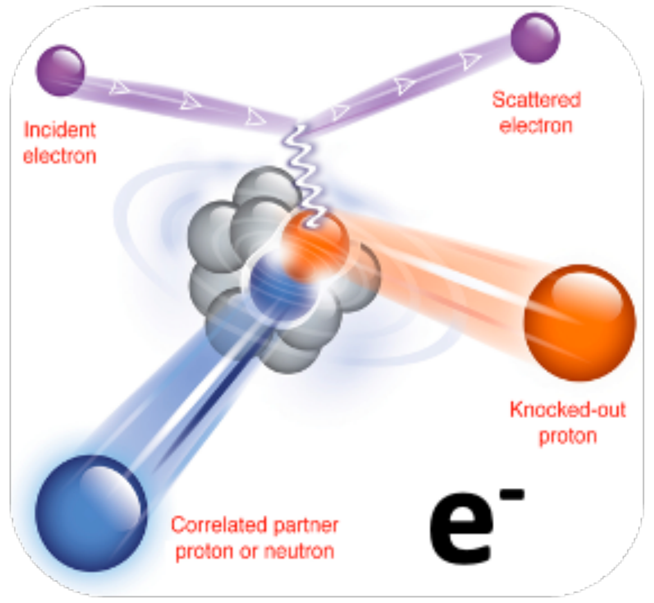
Conclusions

- New high-energy photonuclear data provides **independent measure** of nuclear SRC properties

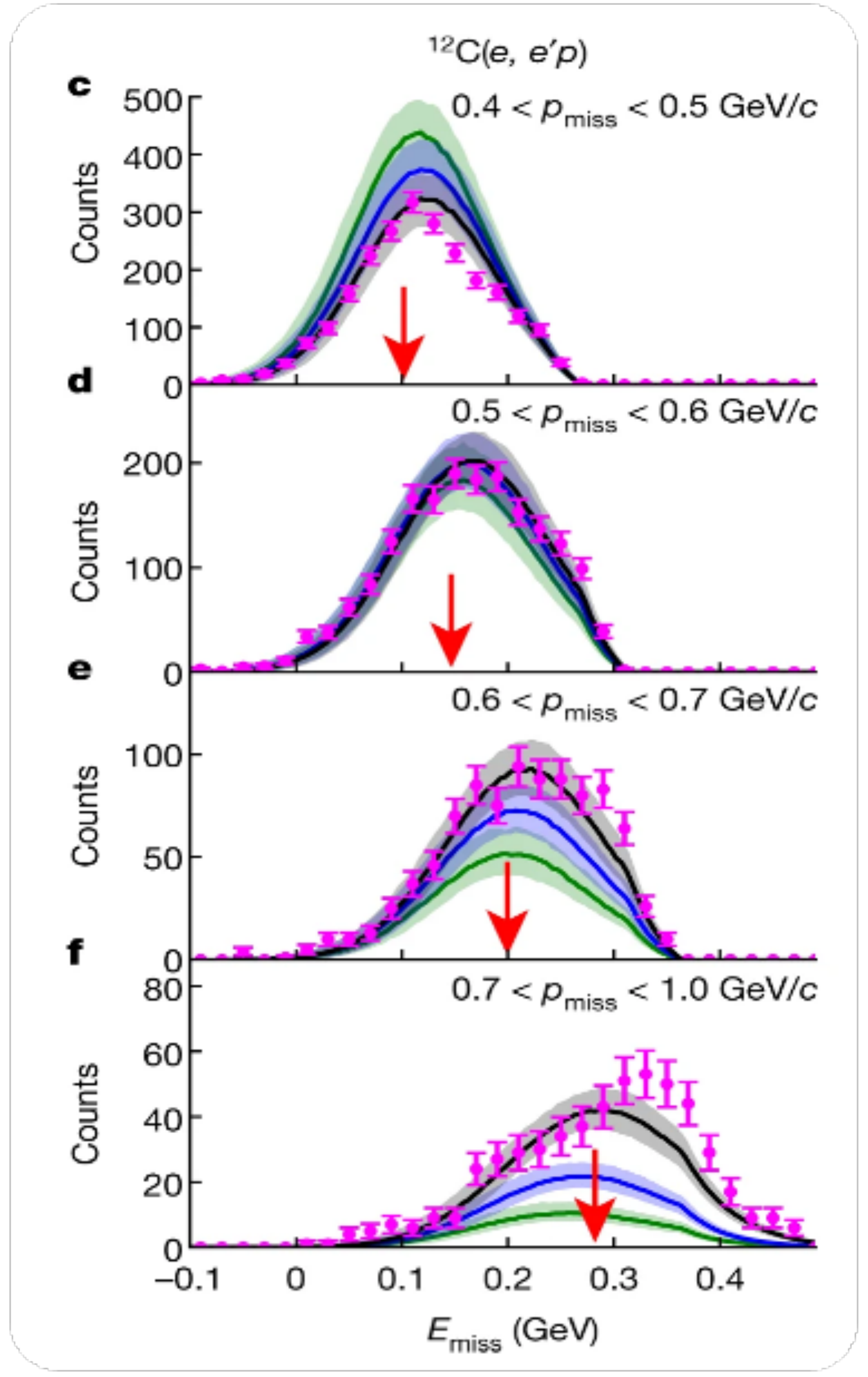


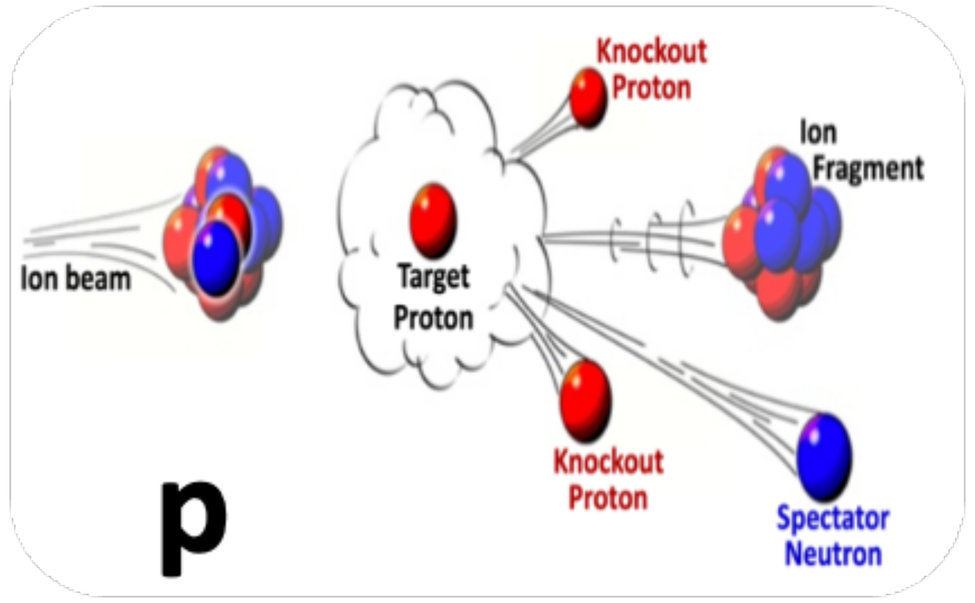
Conclusions

- New high-energy photonuclear data provides **independent measure** of nuclear SRC properties
- Together with recent inverse kinematics results we are on a good path to confirm **probe independence** of SRC observables

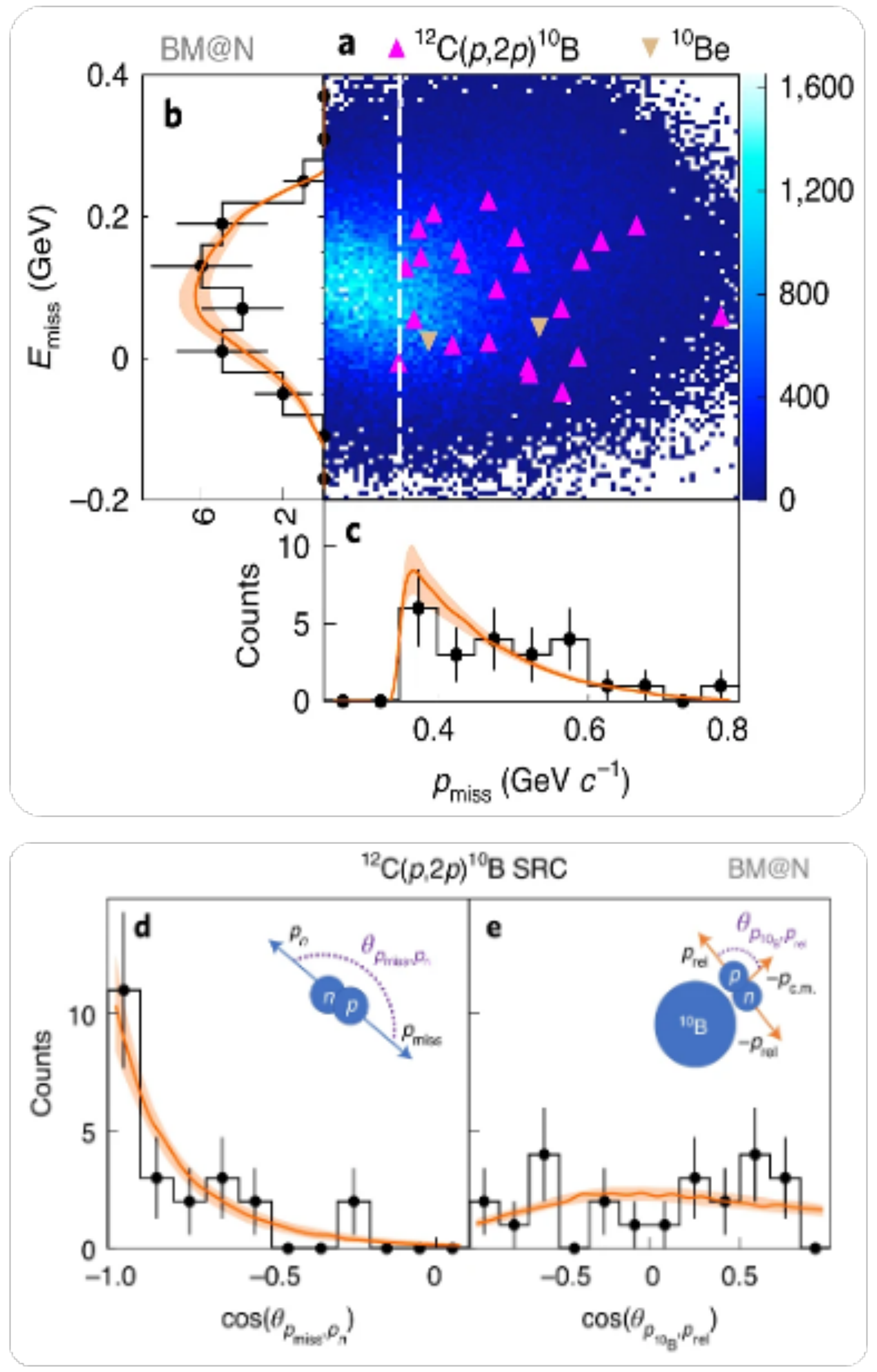


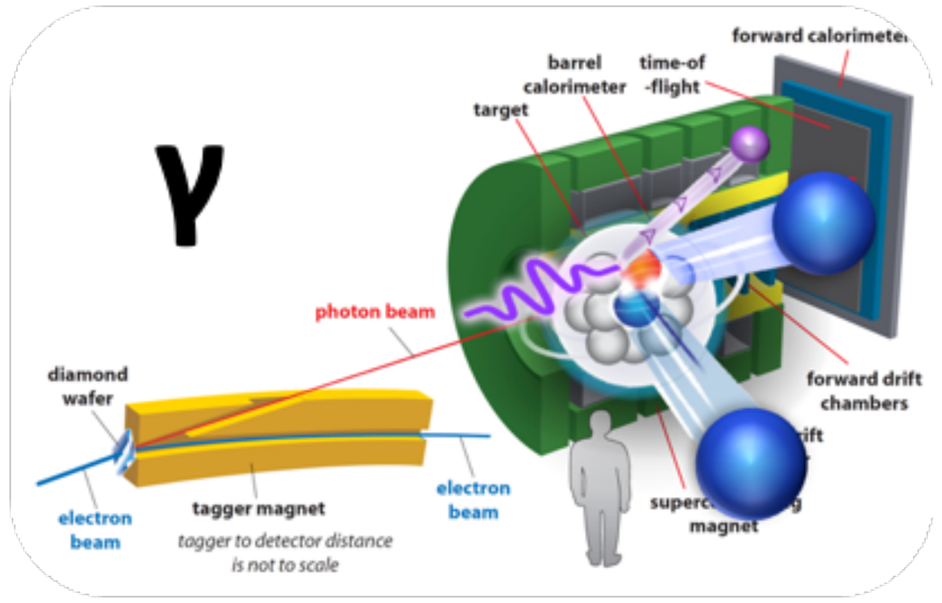
Nature '20



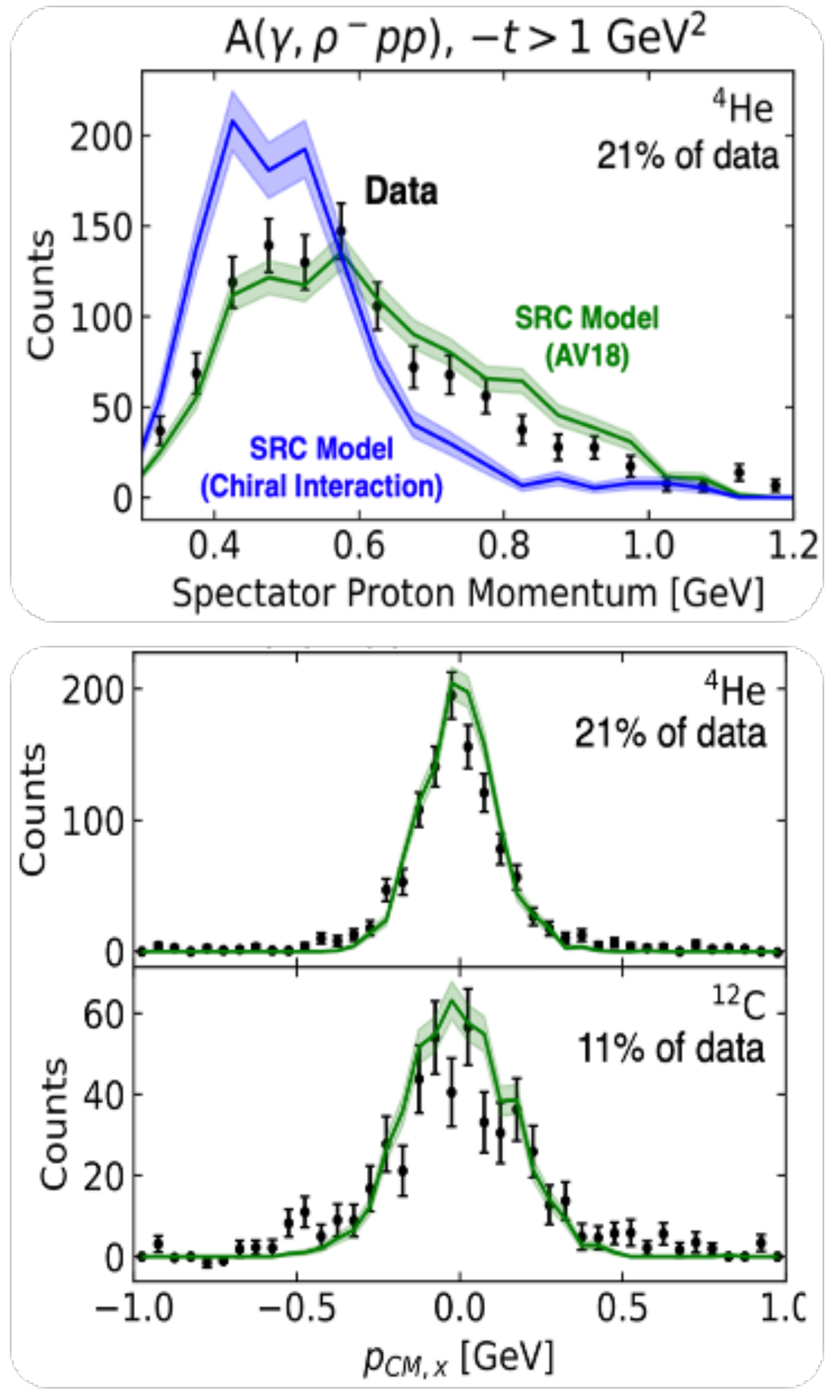


Nature Physics '21



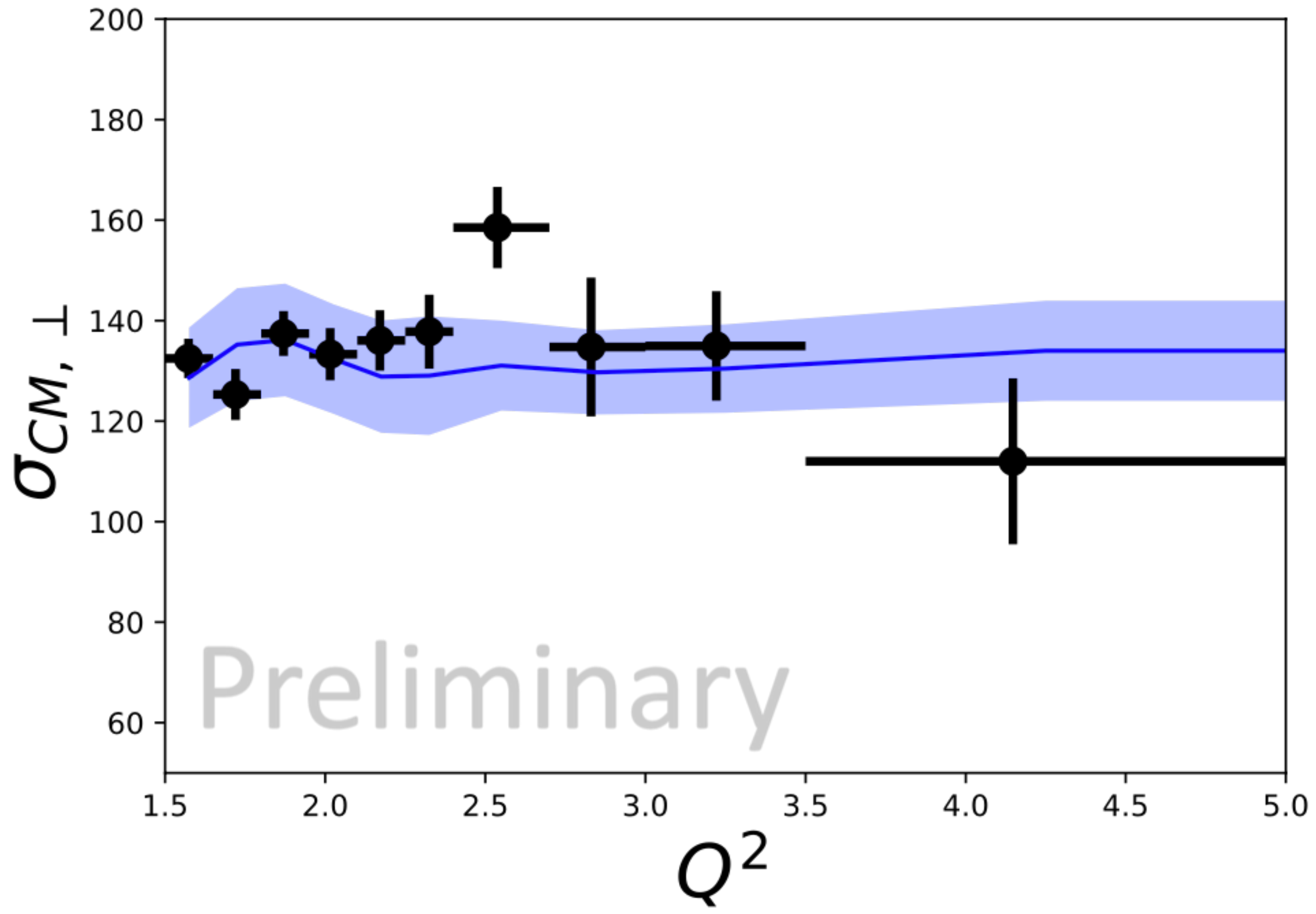


Brand new data!



Conclusions

- New high-energy photonuclear data provides **independent measure** of nuclear SRC properties
- Together with recent inverse kinematics results we are on a good path to confirm **probe independence** of SRC observables
- Good promises of **scale independence** with new high-statistics data from HallB@JLab

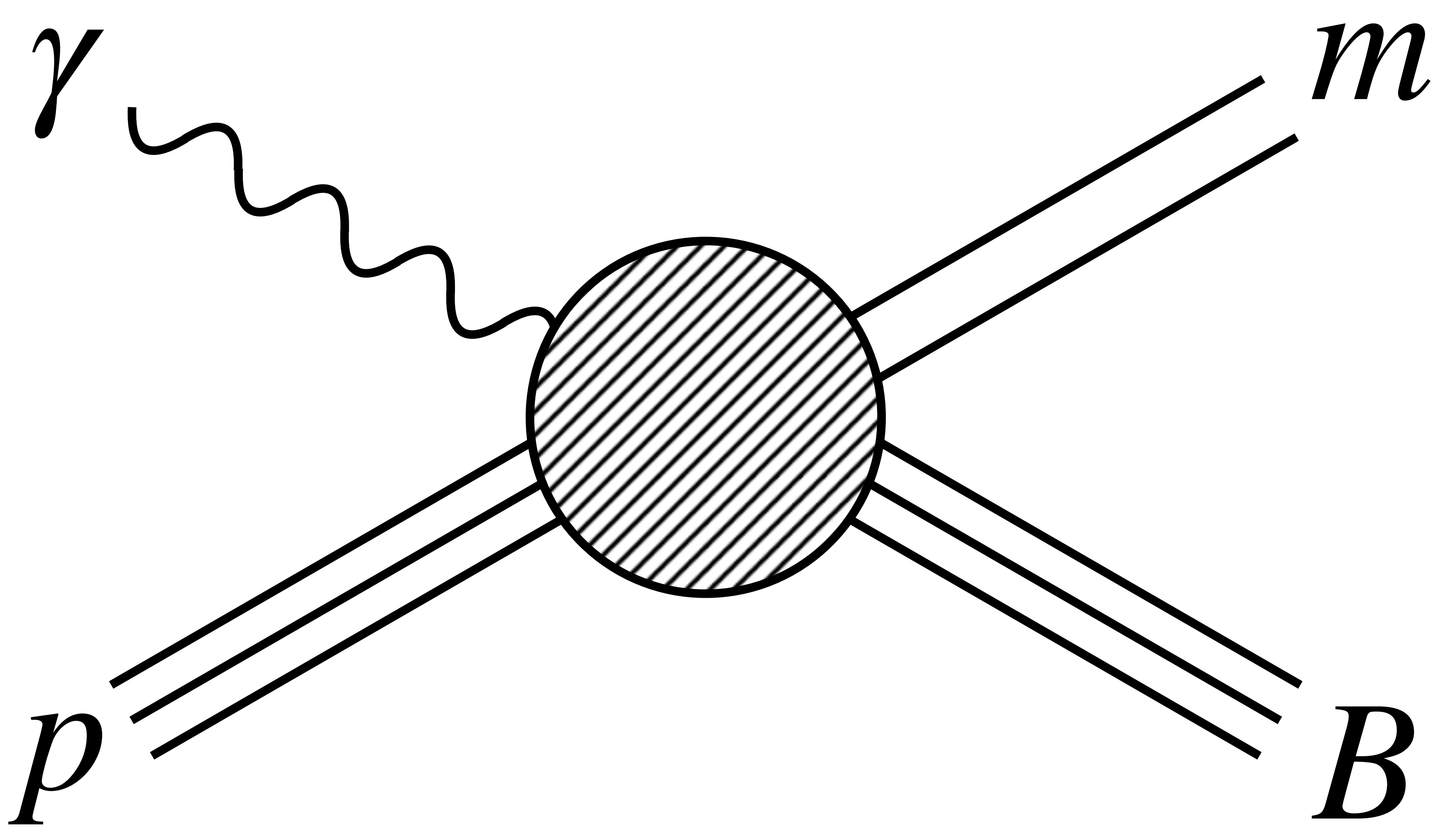


Backup Slides

Access to in-medium modification of photoproduction matrix elements

- Proton can be described as superposition of QCD Fock states:

$|\text{proton}\rangle = \alpha_{PLC}|\text{PLC}\rangle + \alpha_{3qg}|3qg\rangle + \alpha_{3qq\bar{q}}|3qq\bar{q}\rangle + \ldots$



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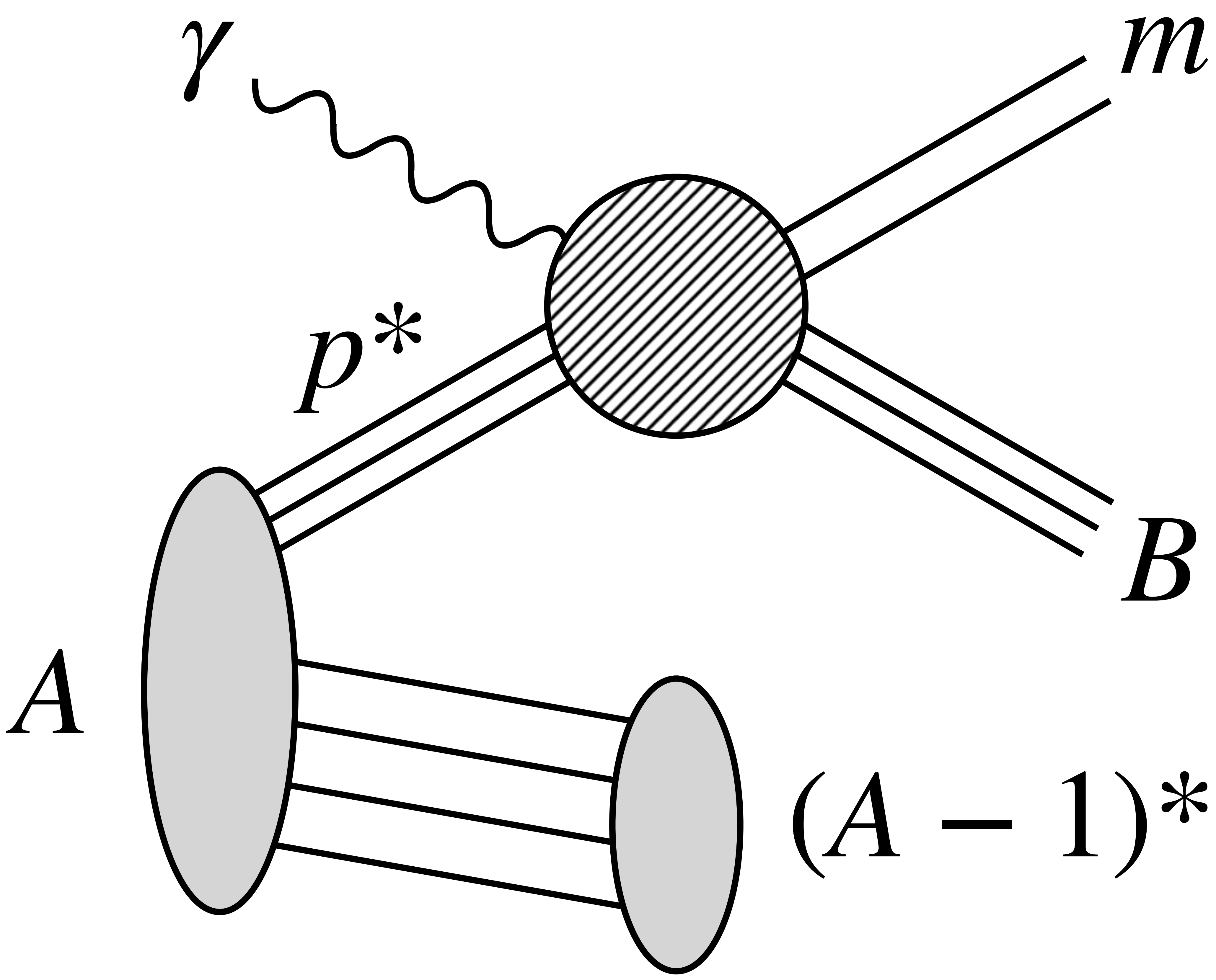
- Photoproduction channels have different sensitivity to proton Fock states



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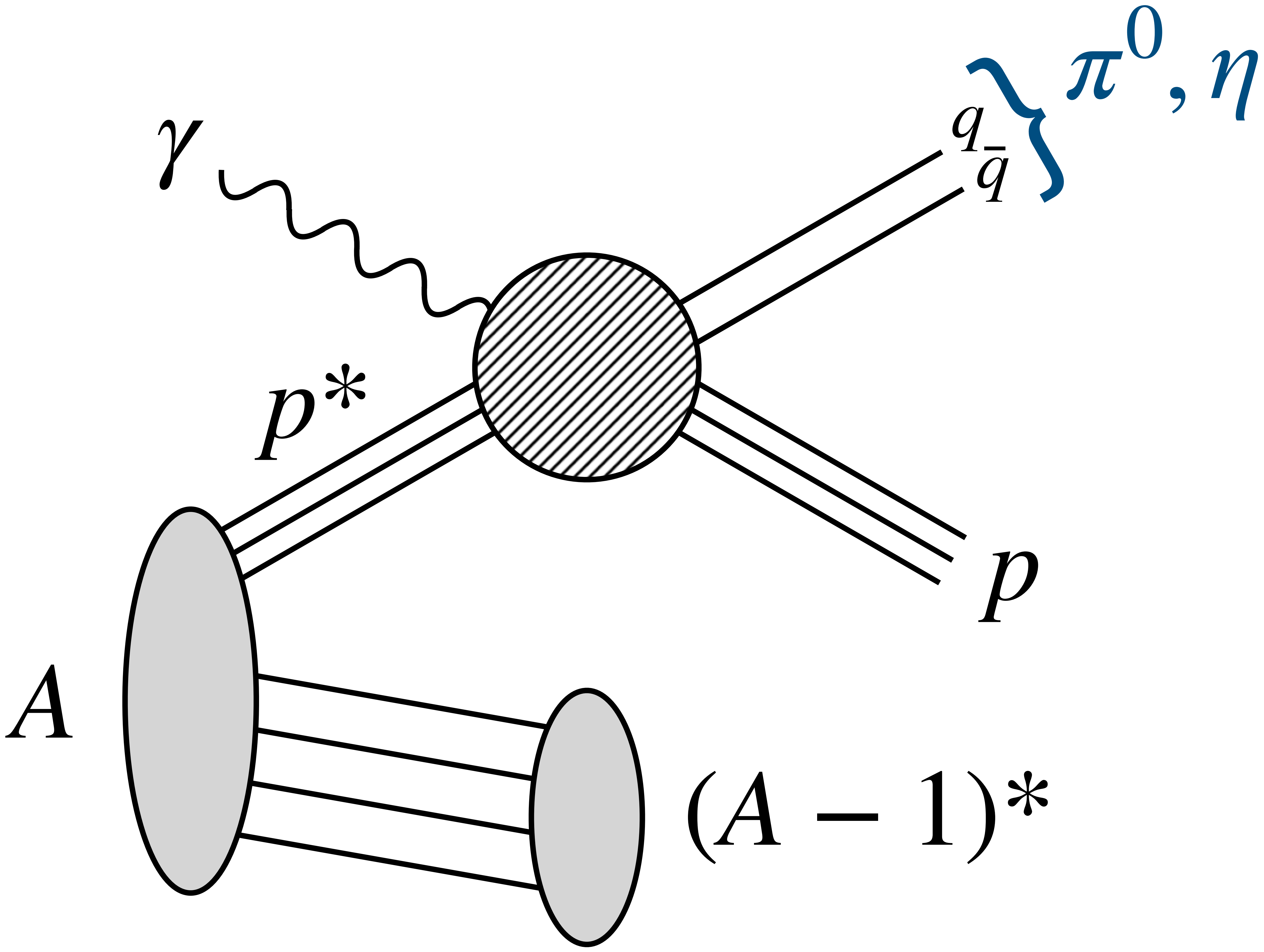

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