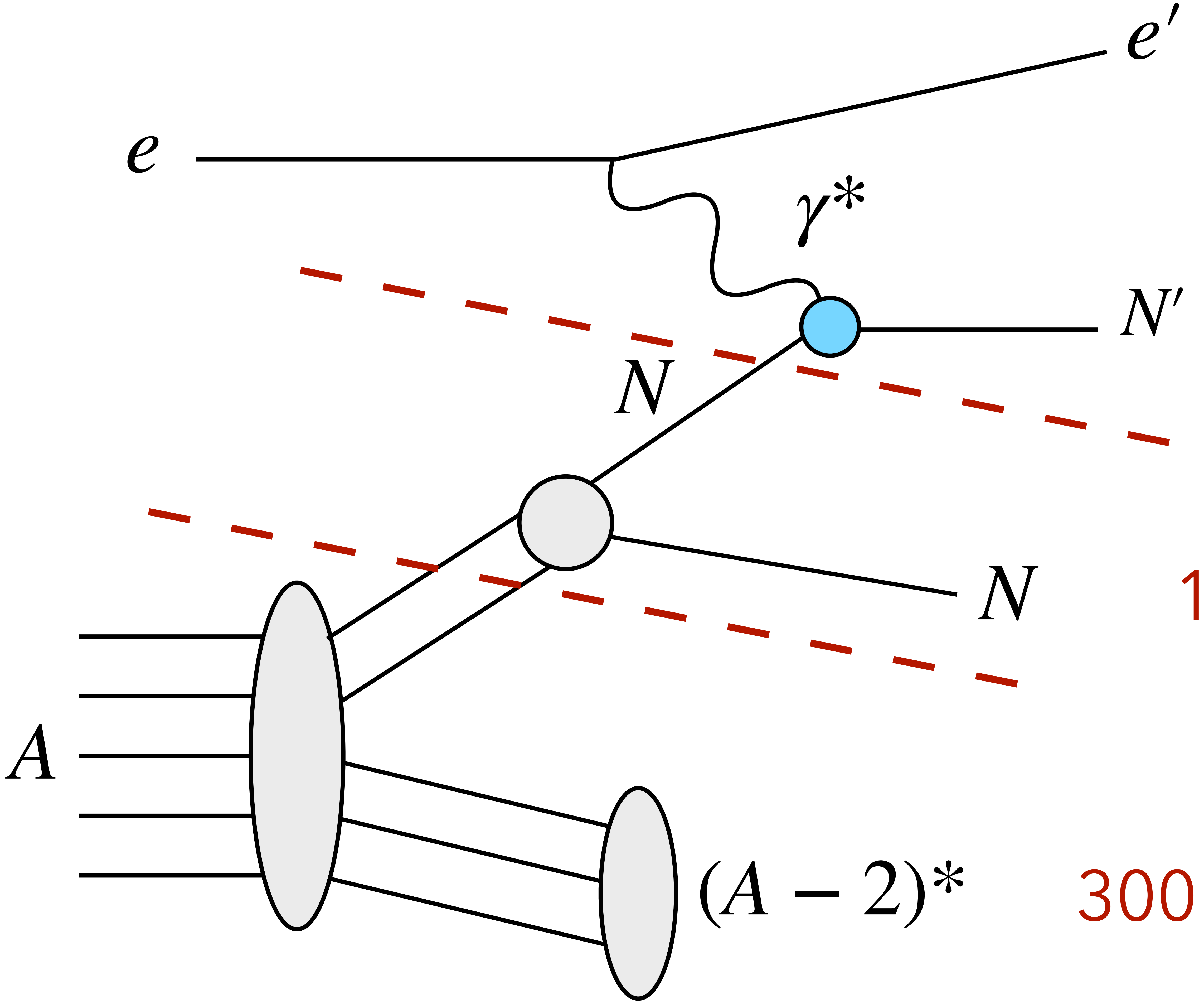
Probing SRCs with high-energy photonuclear reactions at GlueX

Jackson Pybus

Plane-wave SRC breakup 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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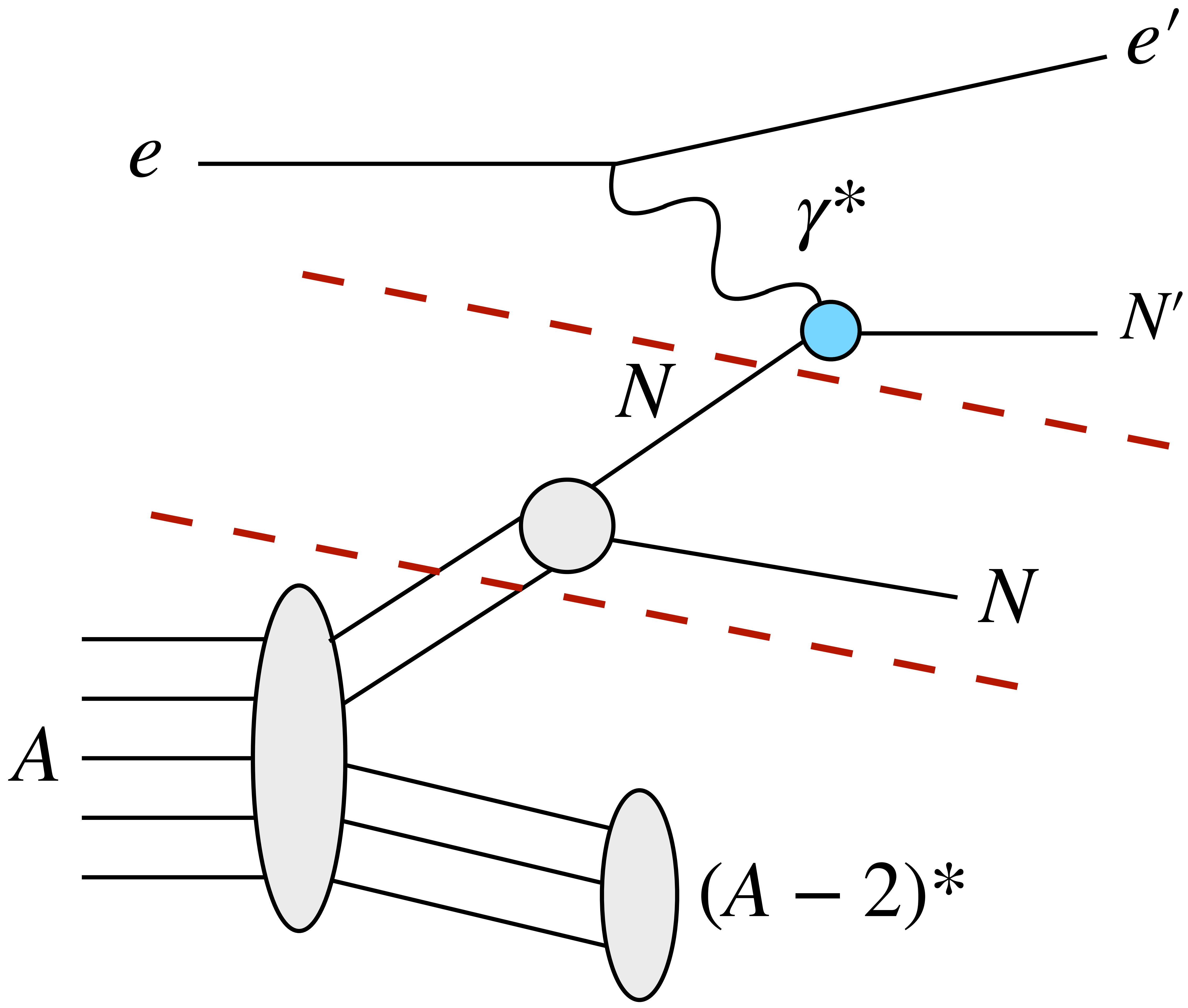

$$\sigma_{SRC} \sim K \cdot \sigma_{eN} \cdot S(p_i, p_{spec})$$

$$S \sim C_{NN} \cdot |\phi(k_{rel})|^2 \cdot n(p_{CM})$$

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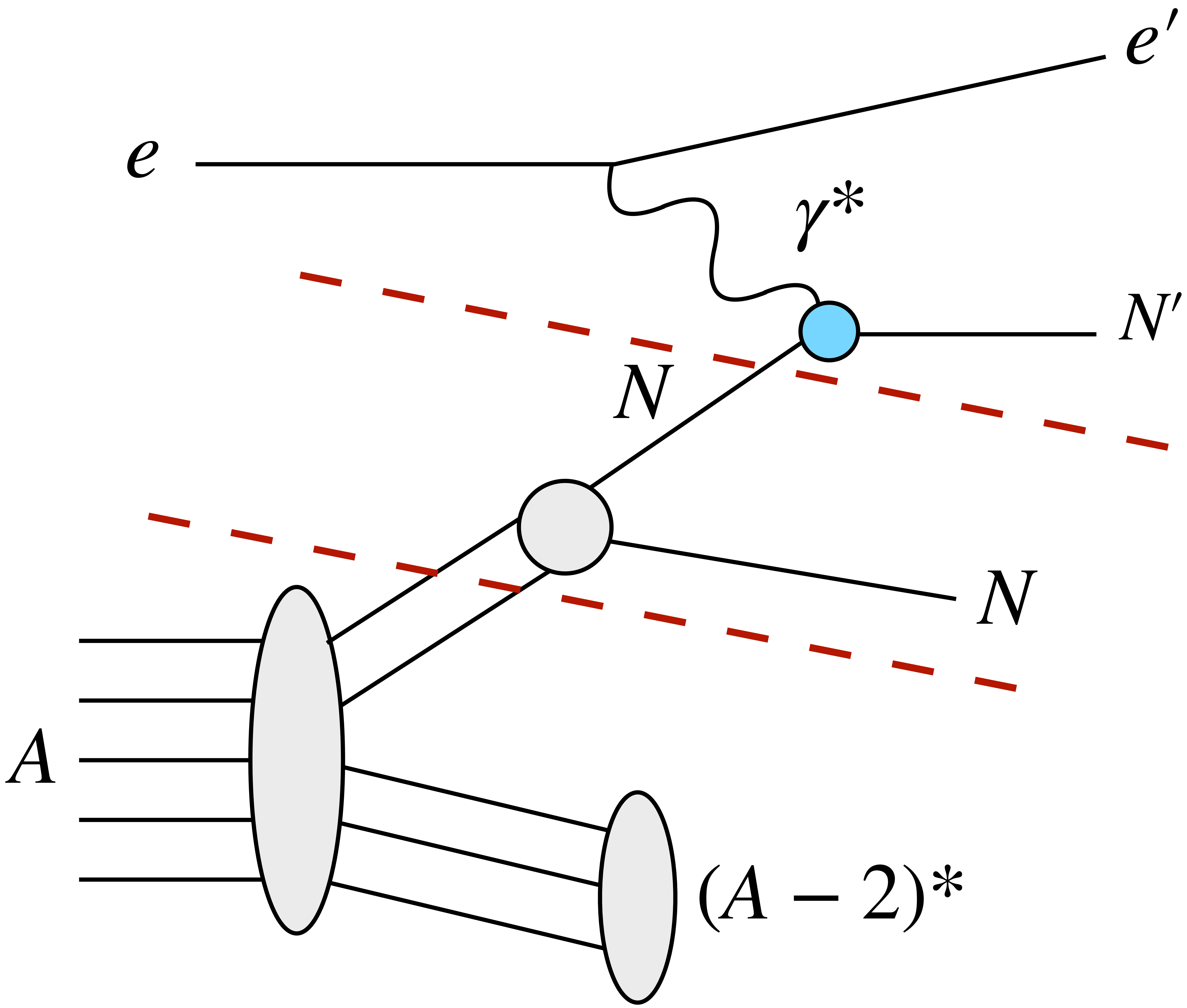

?

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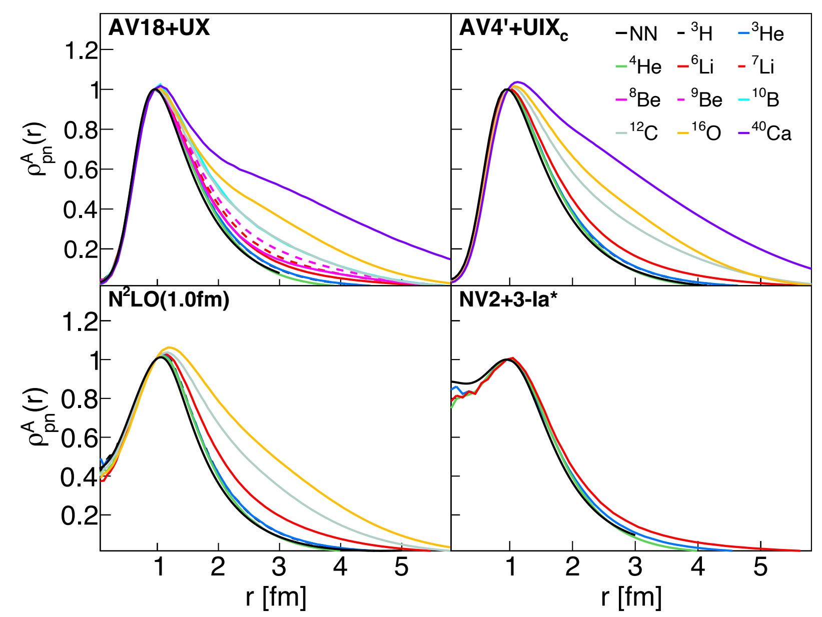
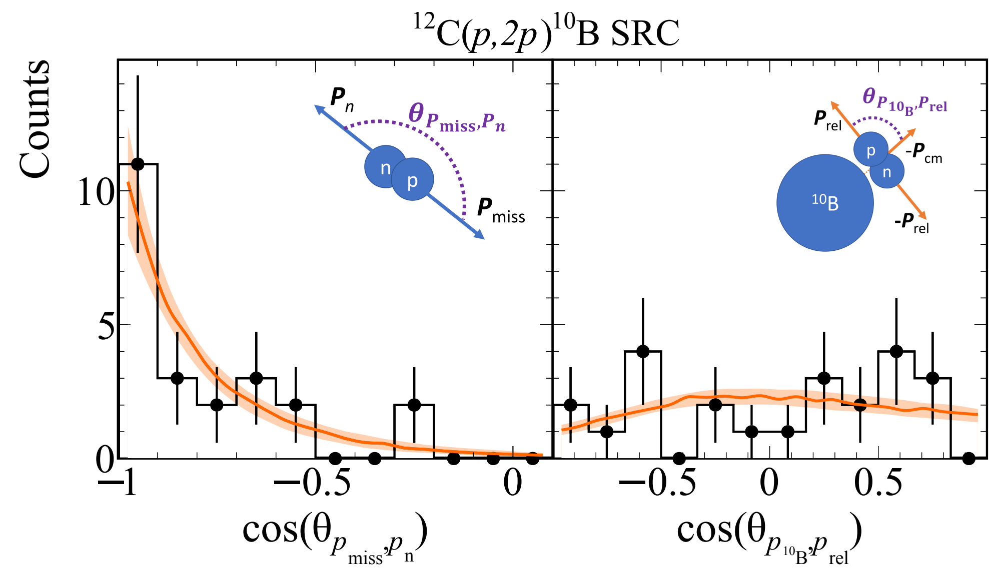
Nature Physics 17, 306 (2021)



Nature Physics 17, 693 (2021)



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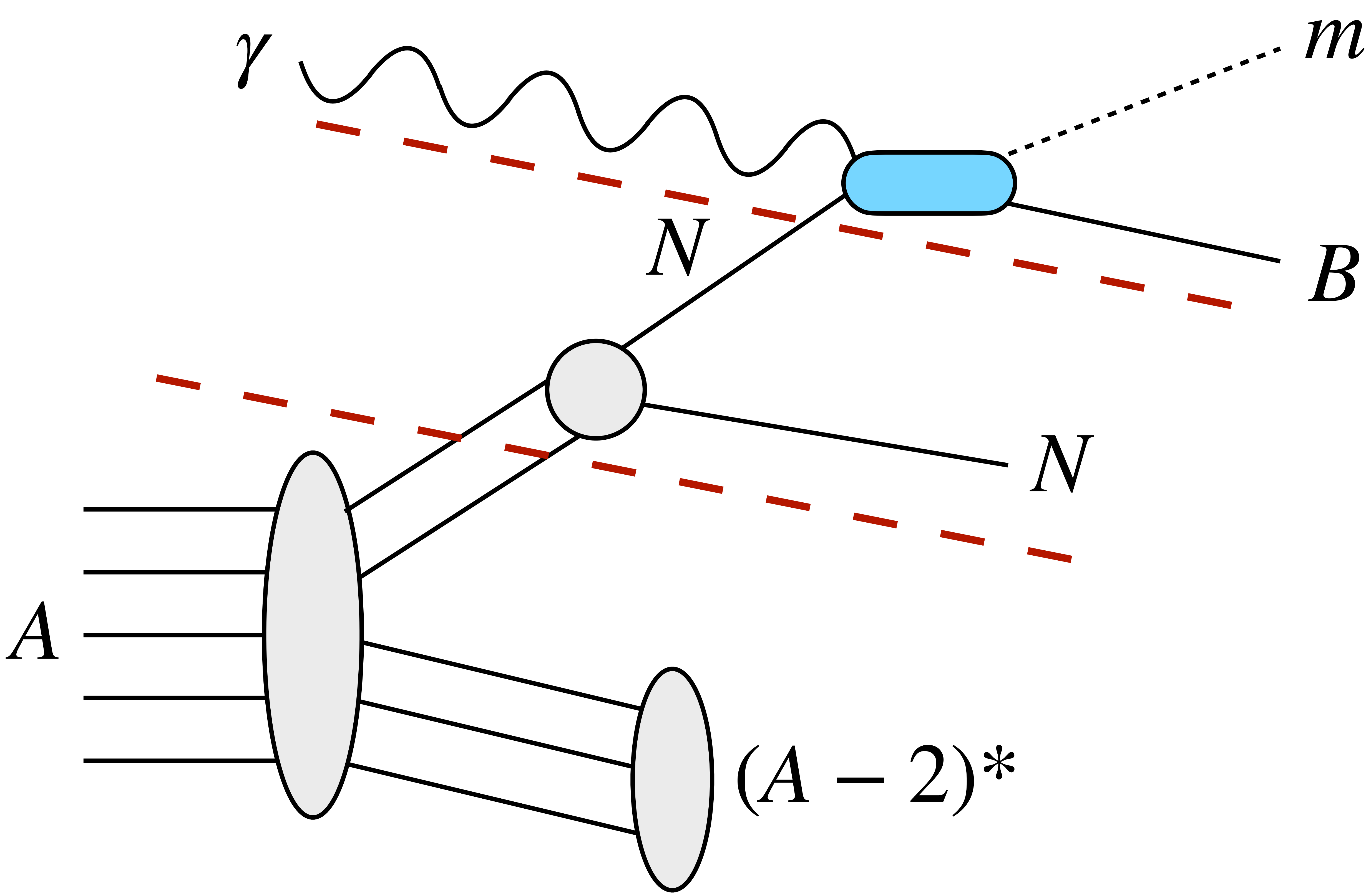

$\sigma(\gamma N \to mB)$

$\updownarrow$

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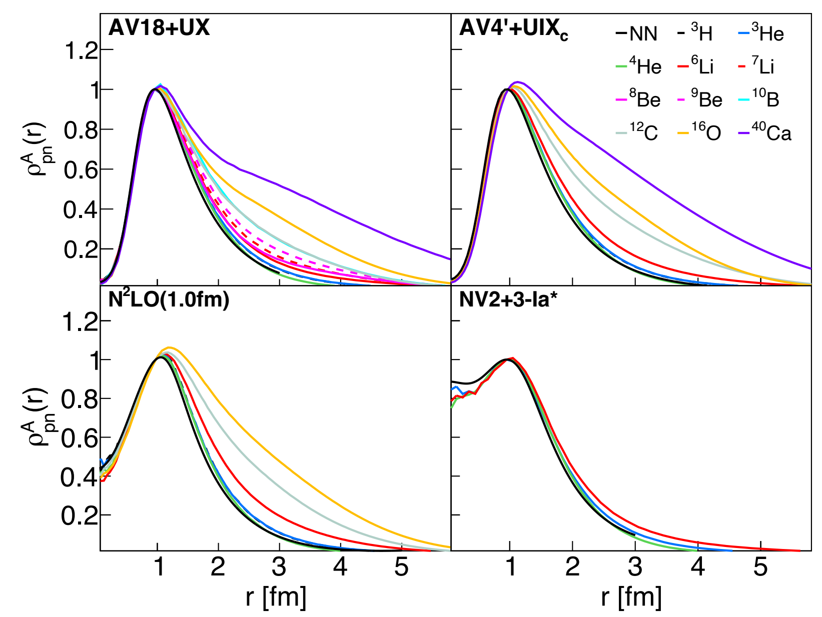

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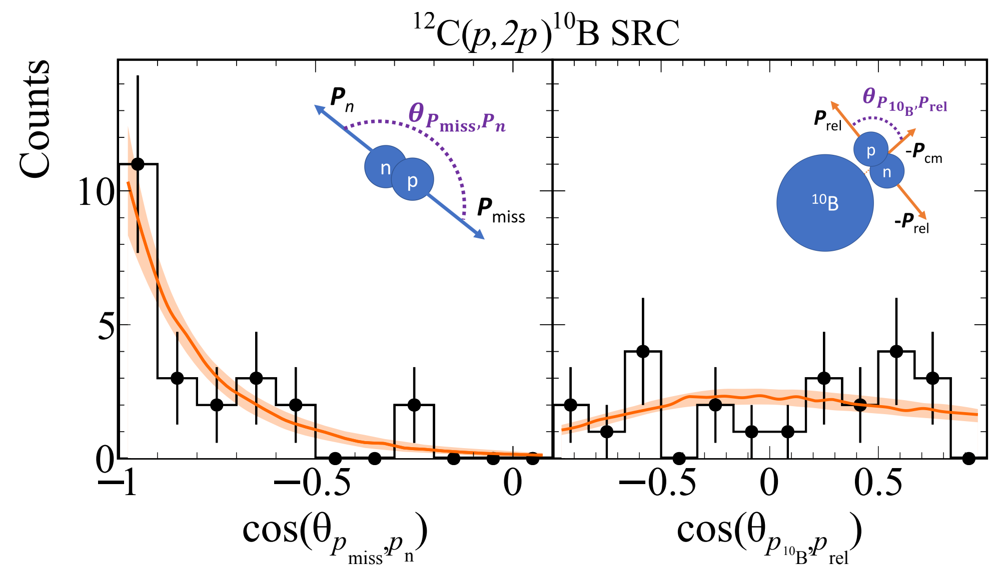
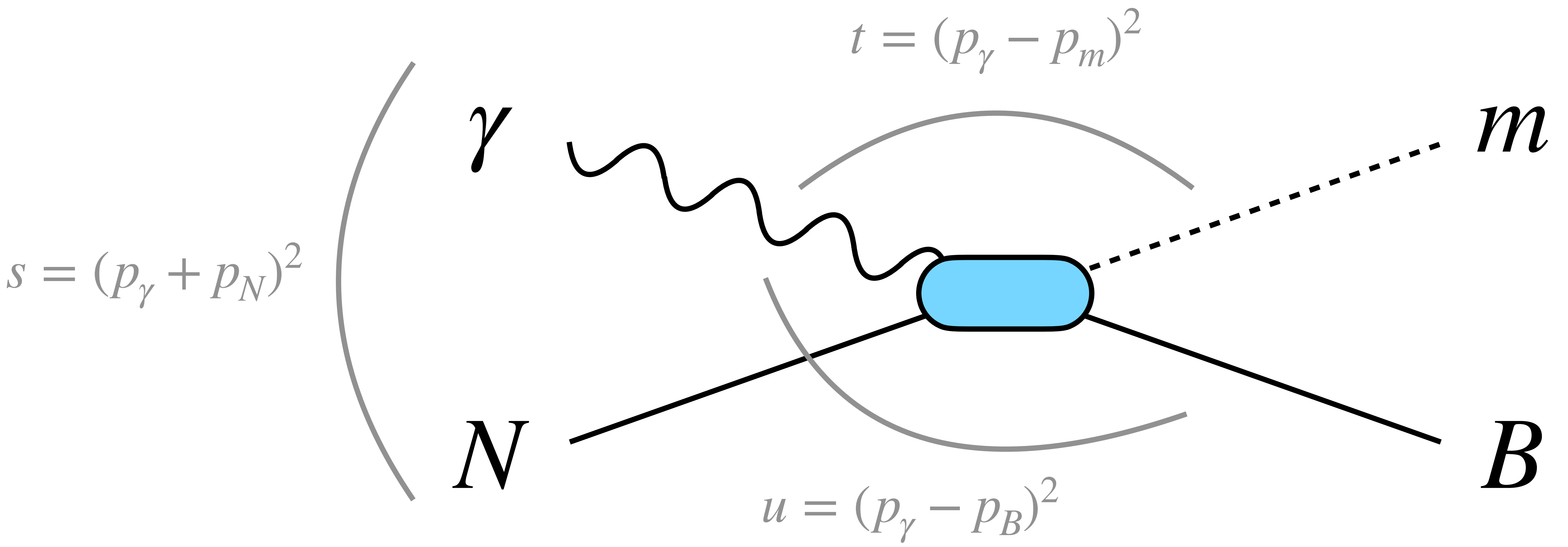
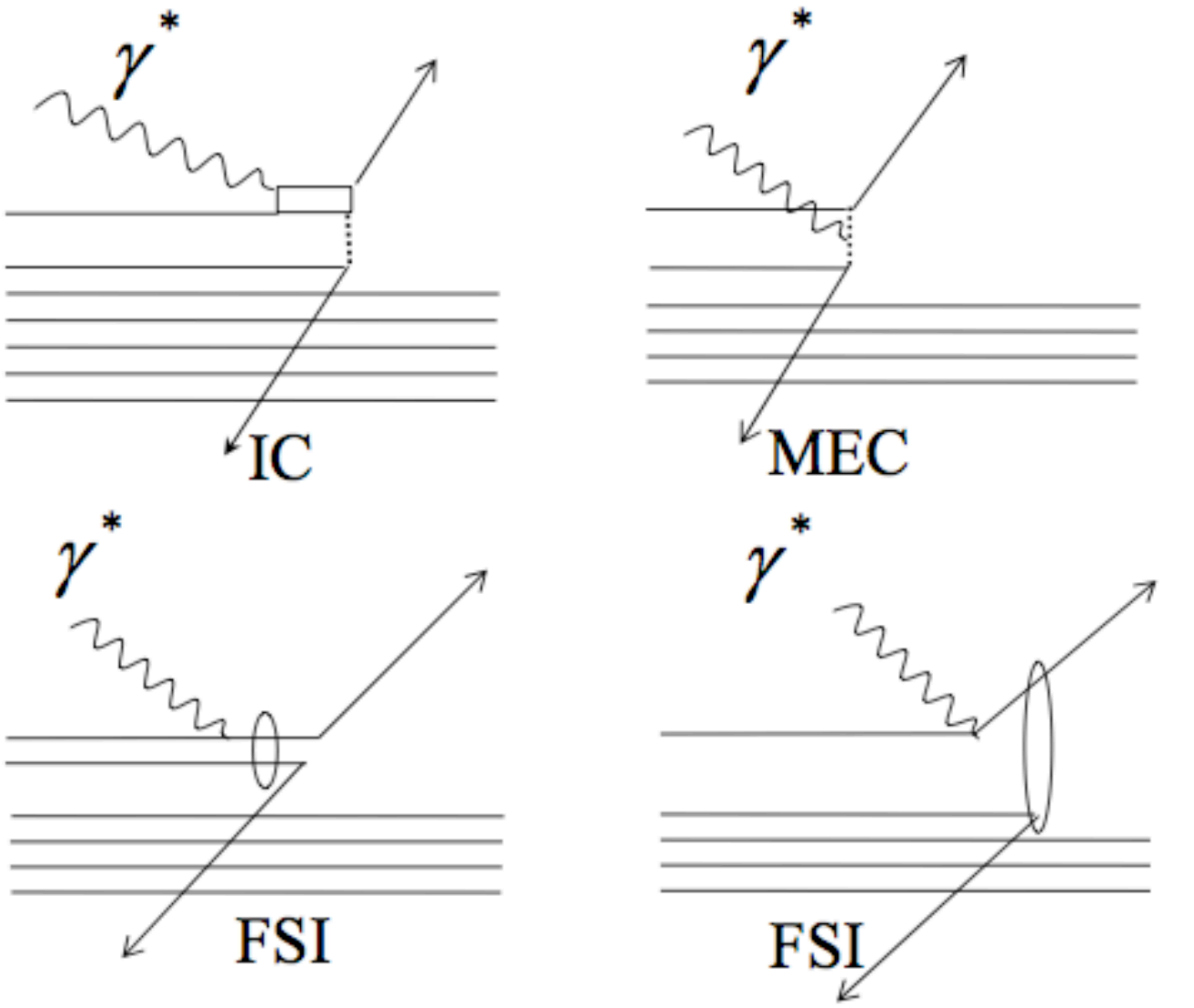


Meson photoproduction

- Often a tool for hadron spectroscopy; can also be used as a probe of high-resolution nuclear structure
- Exclusive 2-body process:
  - $\gamma + N \rightarrow m + B$
- Can occur through s, t, u-channel exchanges
- Cross section weighted by constituent counting rules: $\frac{d\sigma}{dt}|_{\theta=90^\circ} \propto s^{-7}$

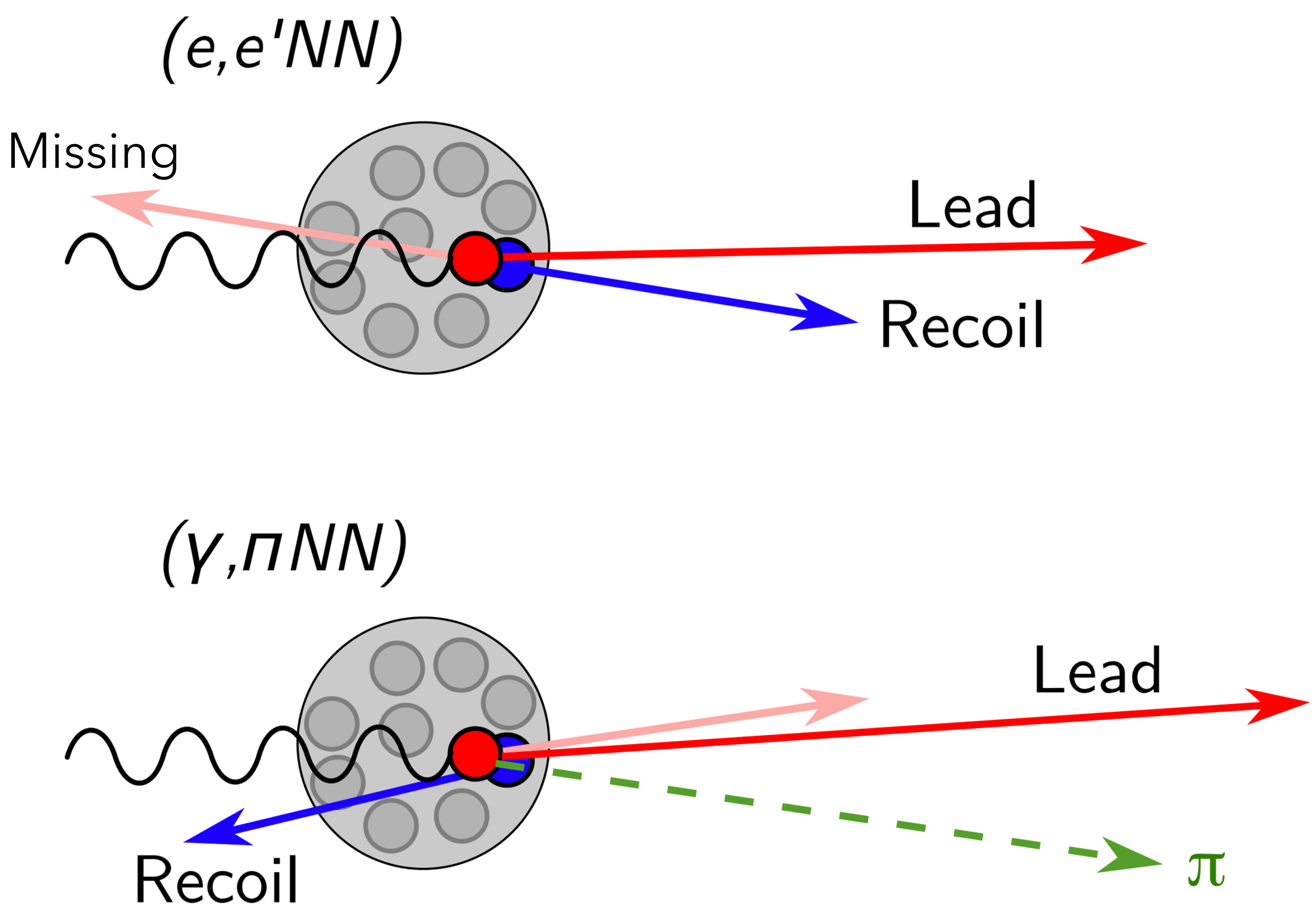


Electron-scattering reaction mechanisms complicate interpretation of data

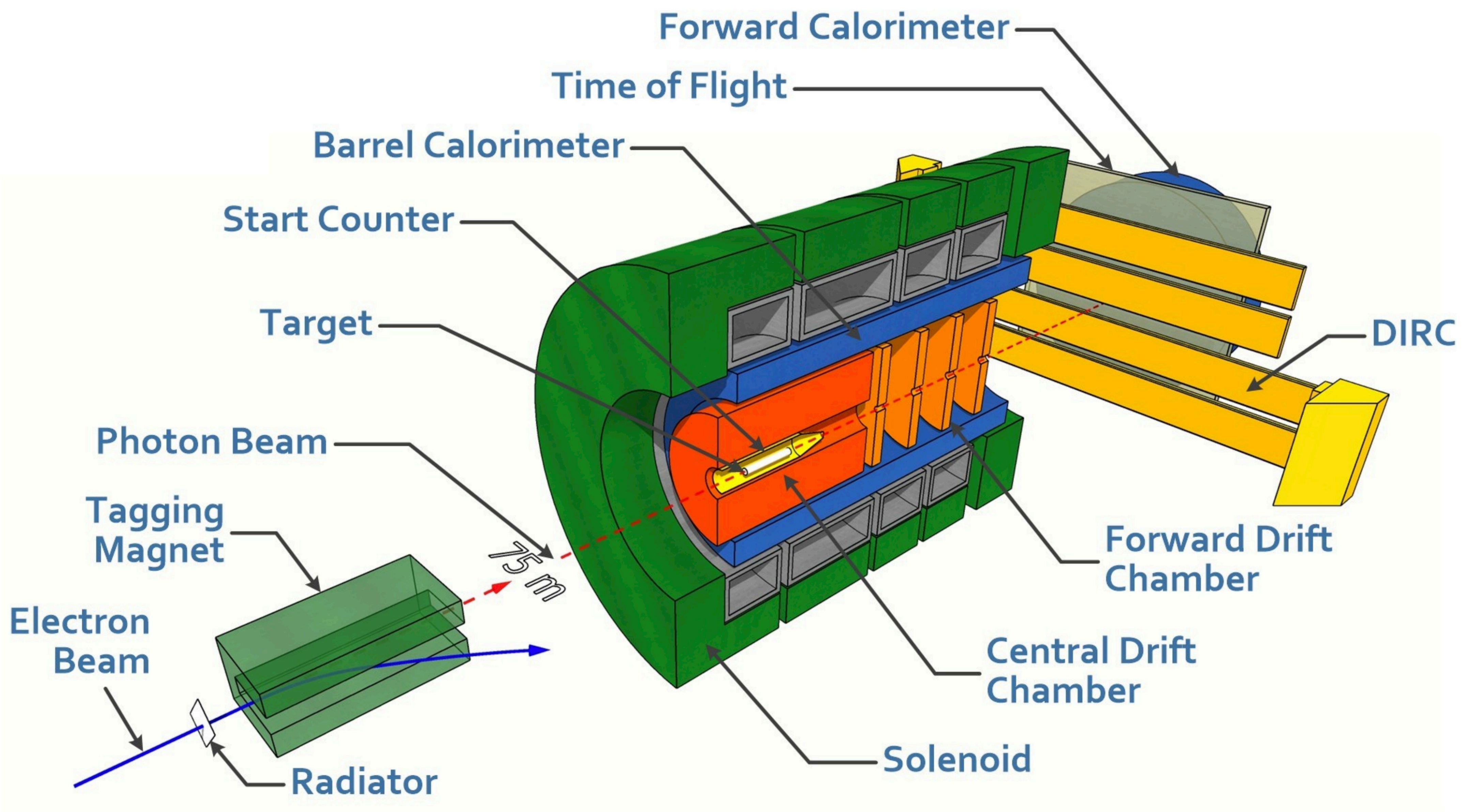


Photoproduction reaction mechanisms differ significantly from electron-scattering

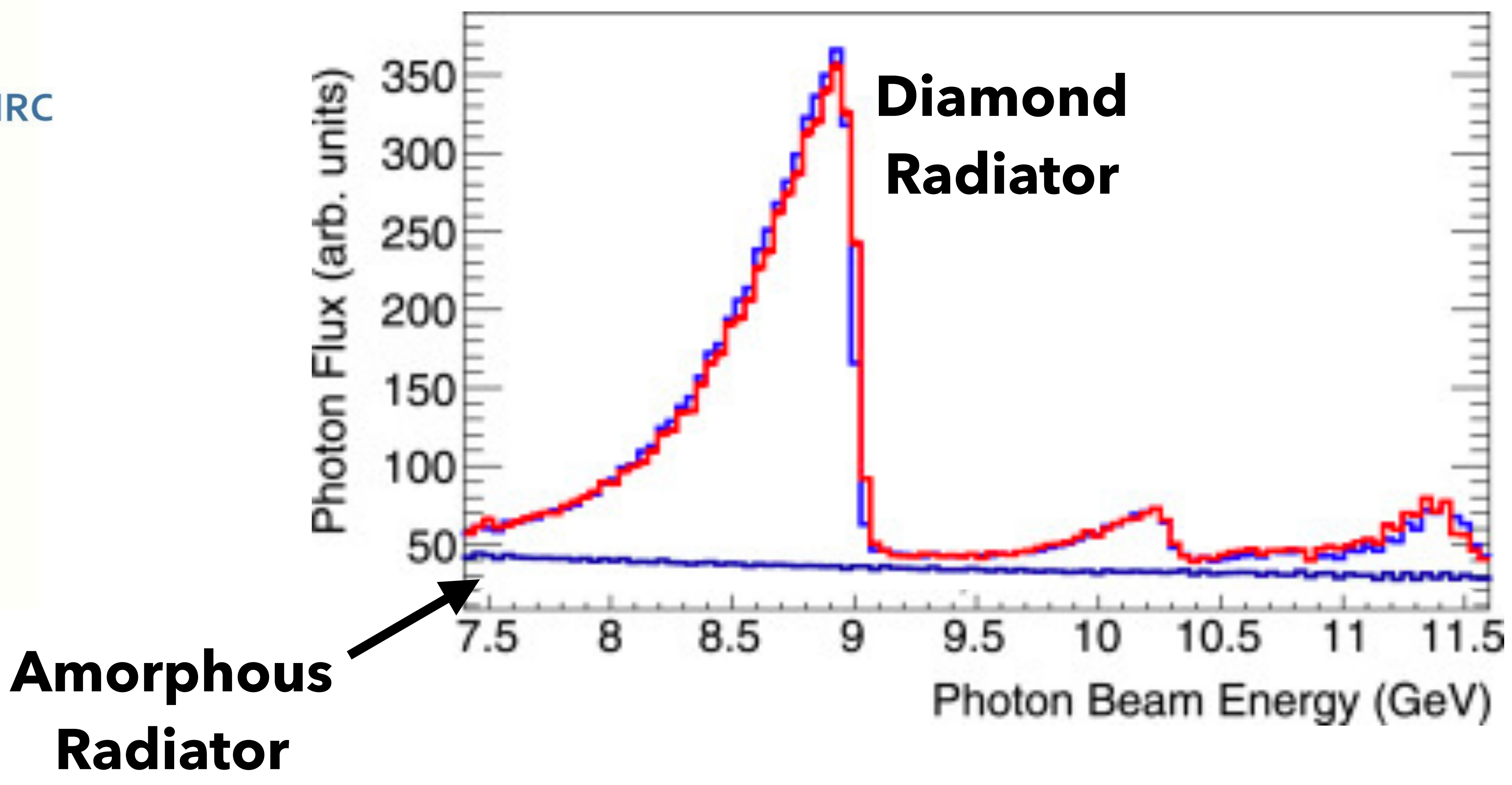
- No substantial radiative effects
- Kinematics prefer parallel kinematics, not antiparallel
  - Different effects of final-state interactions
- Different sensitivity to meson-exchange currents
- Less inelastic background
- Can give access to neutrons through charge-exchange channels



Experimental Setup



- 10.8 GeV electron beam incident on diamond radiator



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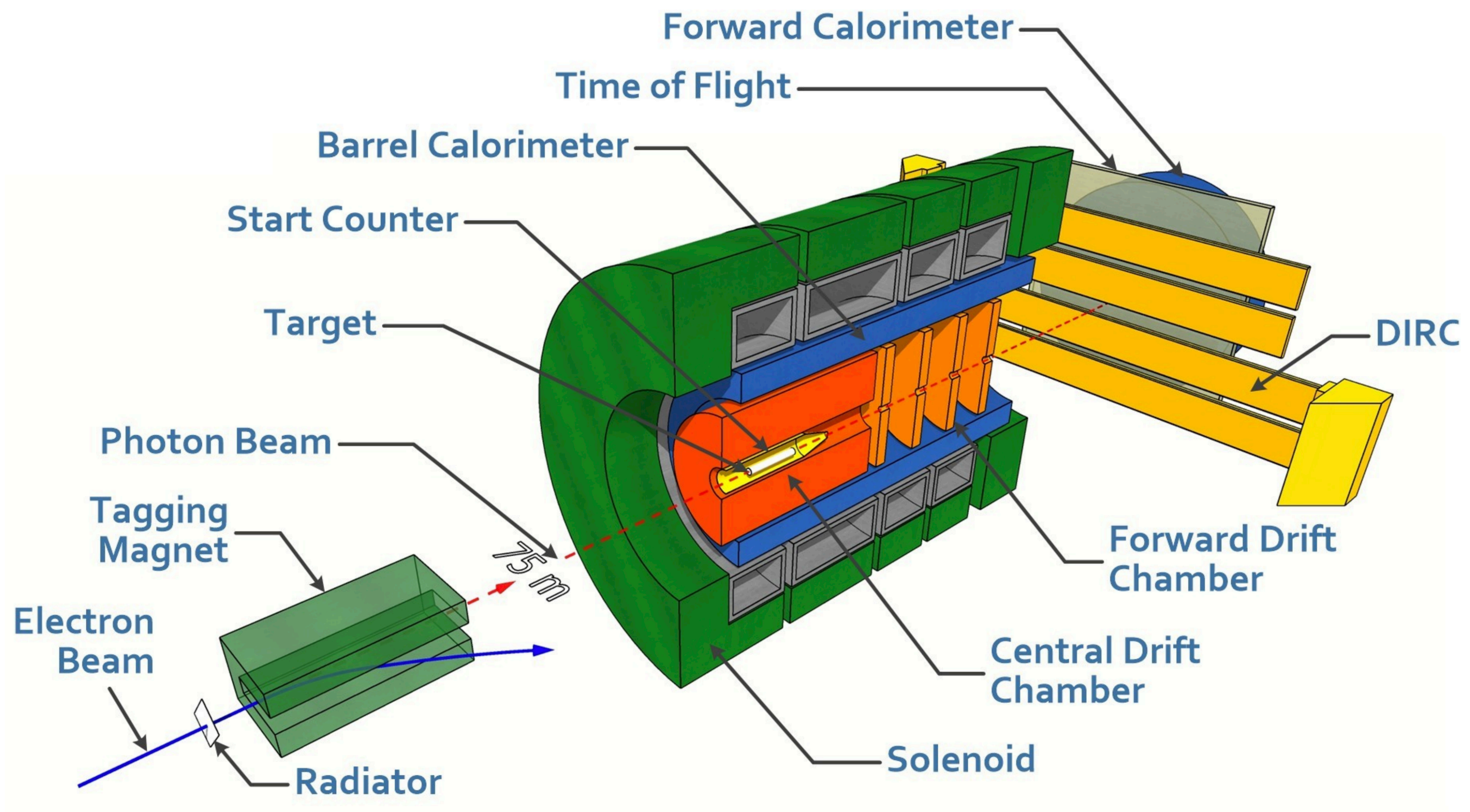

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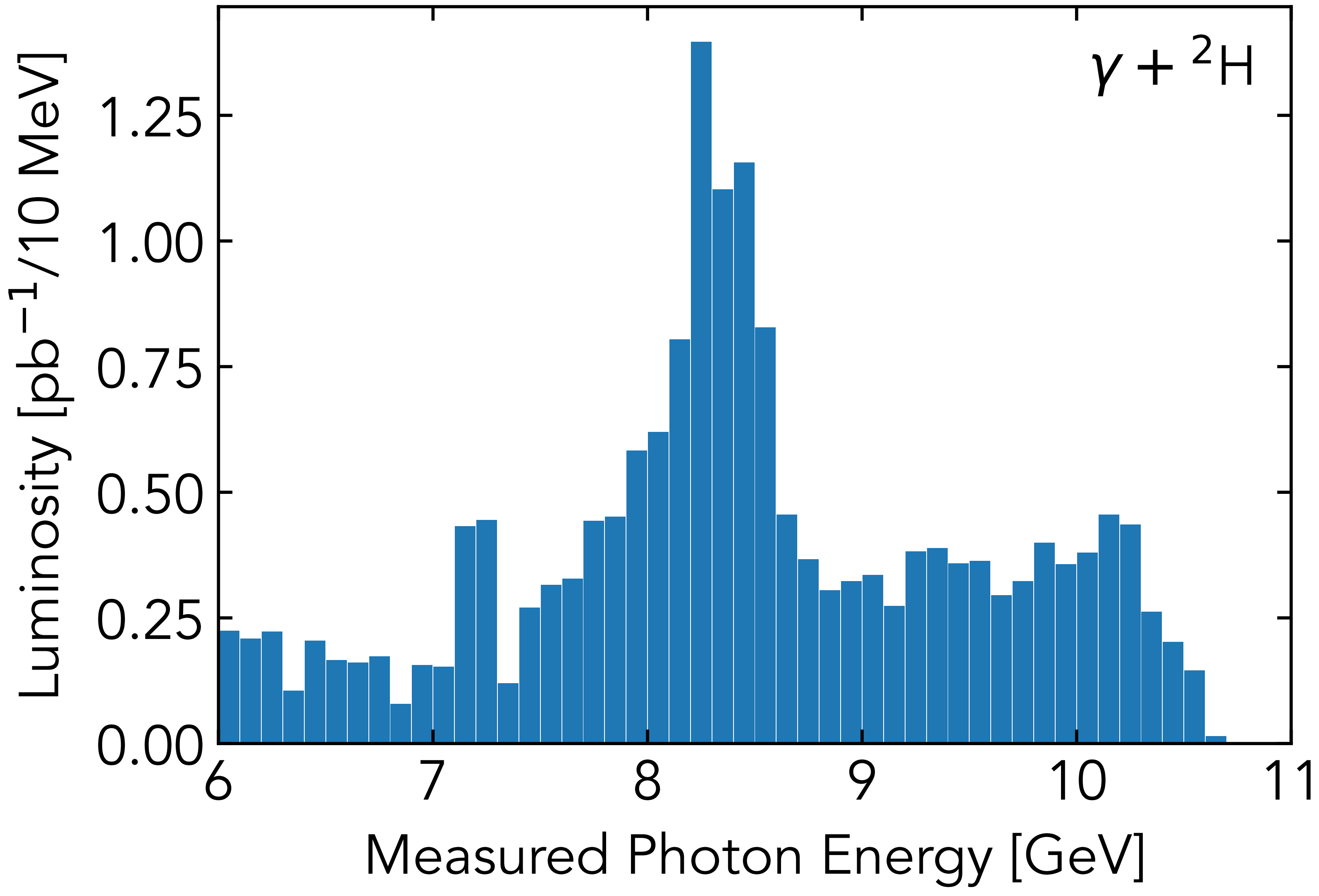

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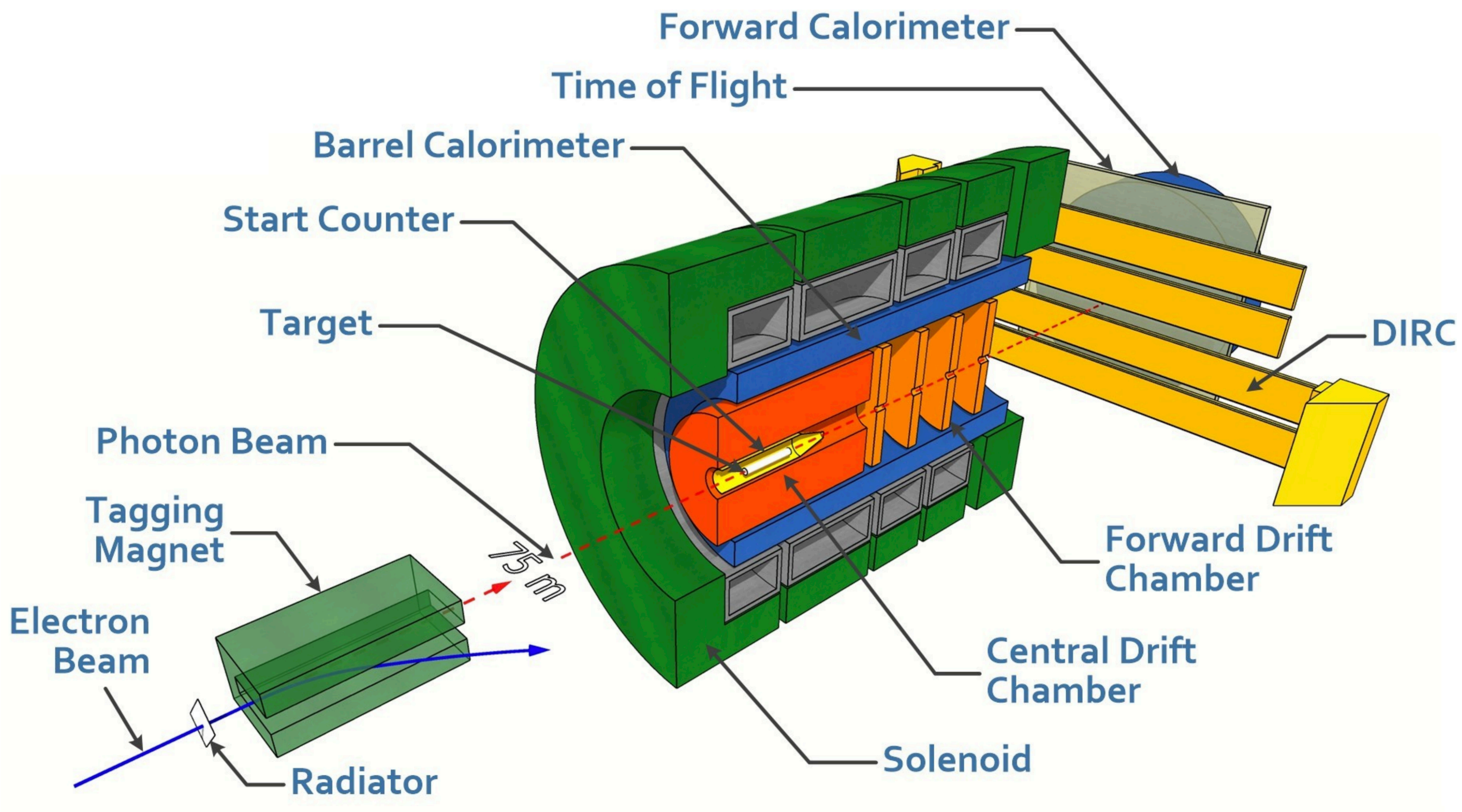

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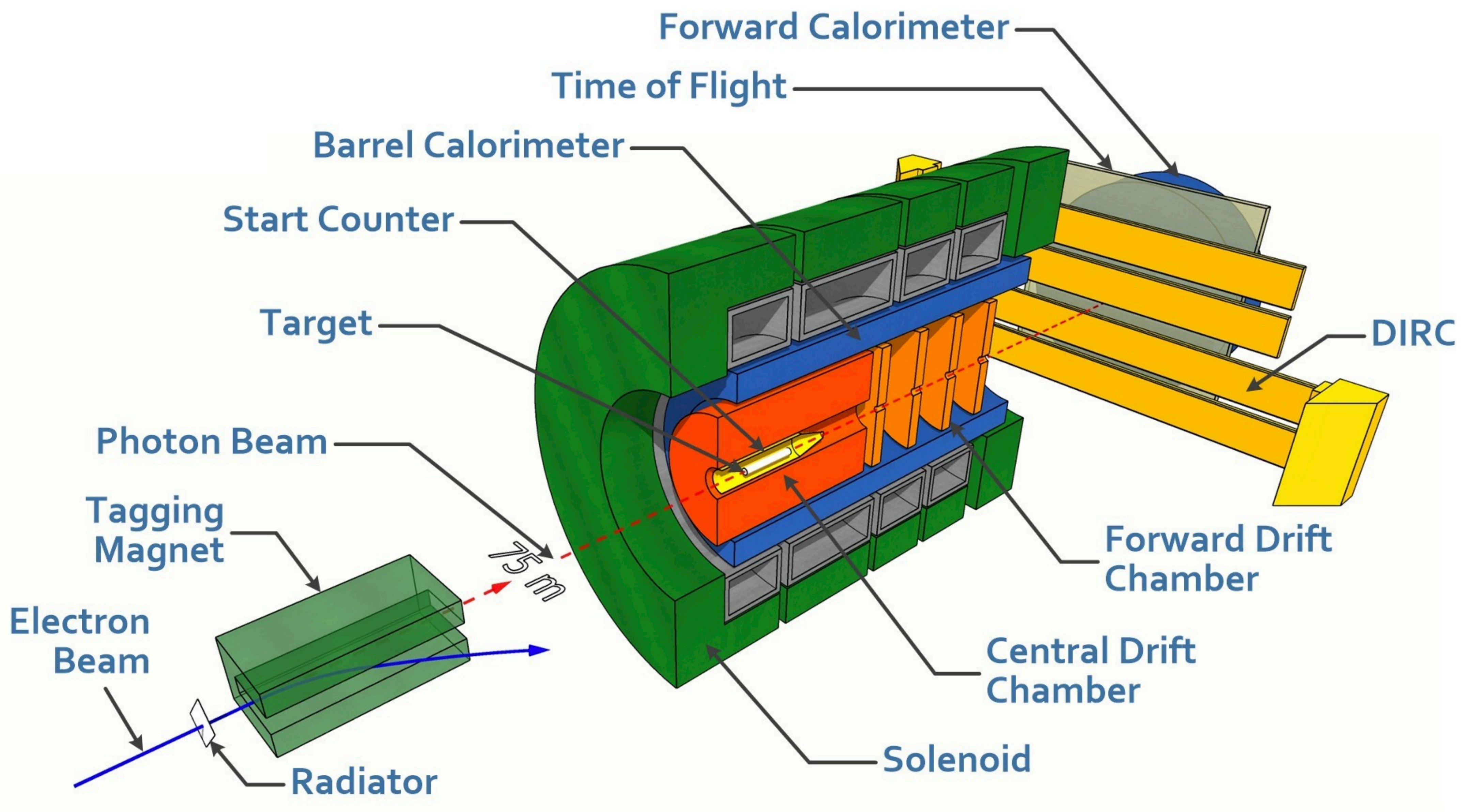

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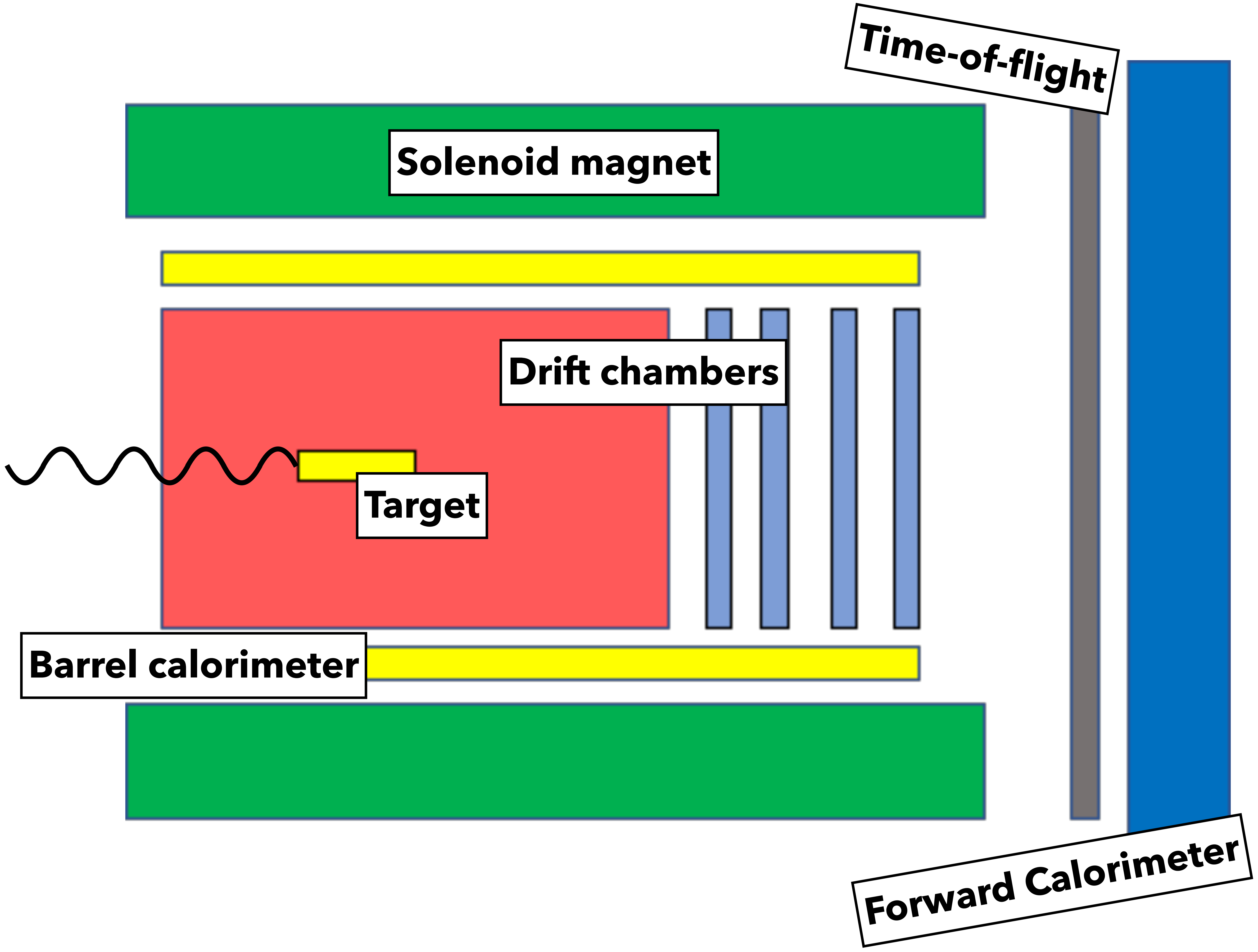
- Final-state particles detected in large-acceptance GlueX detector

GlueX Spectrometer



- Large-acceptance detector
- Solenoidal magnet:
  - Good p_T resolution
  - Poor p_z resolution
- Time-of-flight allows particle identification for forward-going charged particles
- Calorimeters allows good acceptance and reconstruction of final-state photons

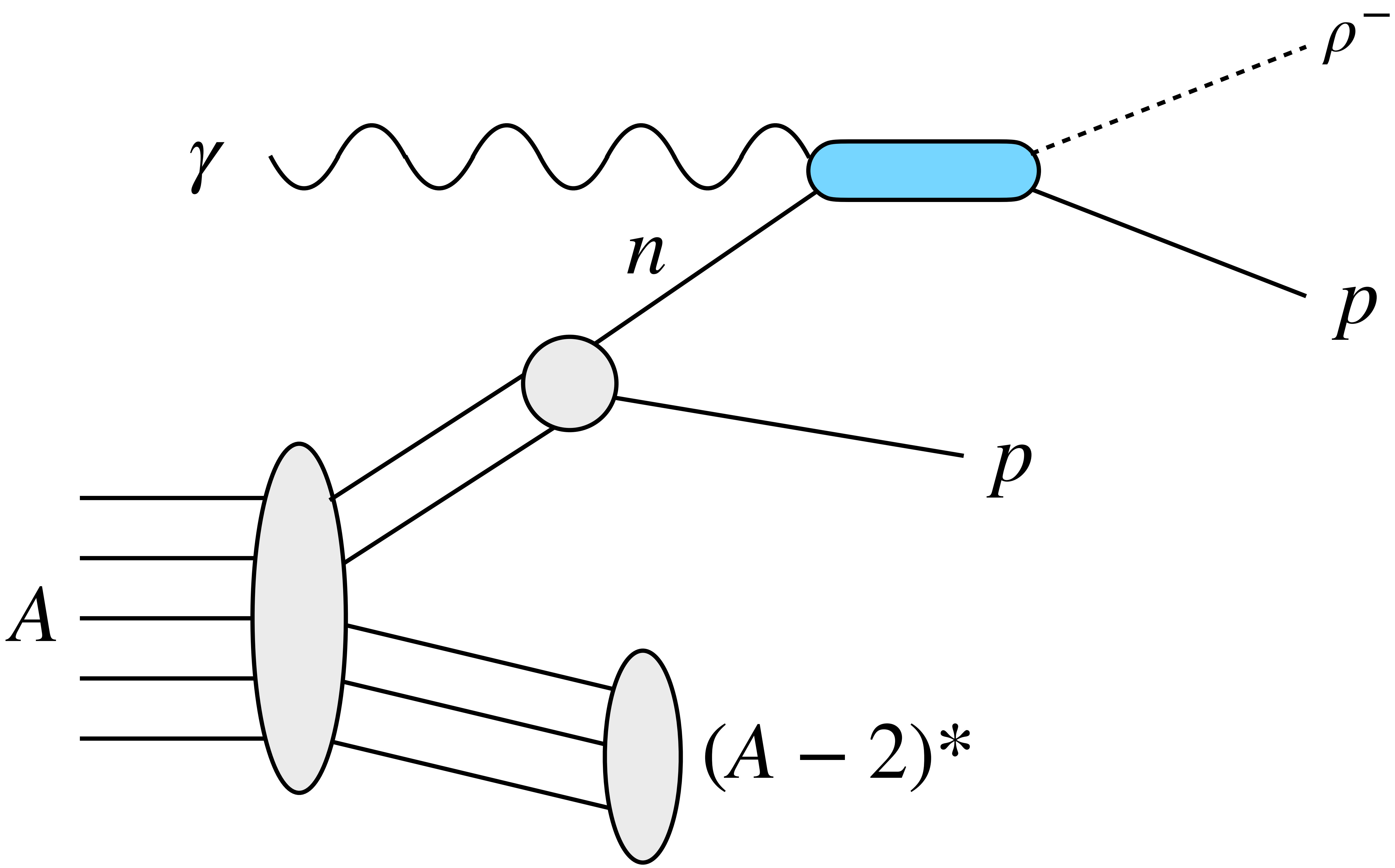
Fall 2021 Data

Target	Days of Beam	Luminosity (E_γ > 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

SRC studies using exclusive $A(\gamma, \rho^- pp)$ production

$(\gamma n \to \rho^- p)$ Reaction

- Measure exclusive SRC breakup, with final-state $(\pi^-\pi^0 pp)$
- Distinctive topology and exclusive detection helps to reduce background
- We require:
  - PWIA predictions
  - Clean SRC breakup data



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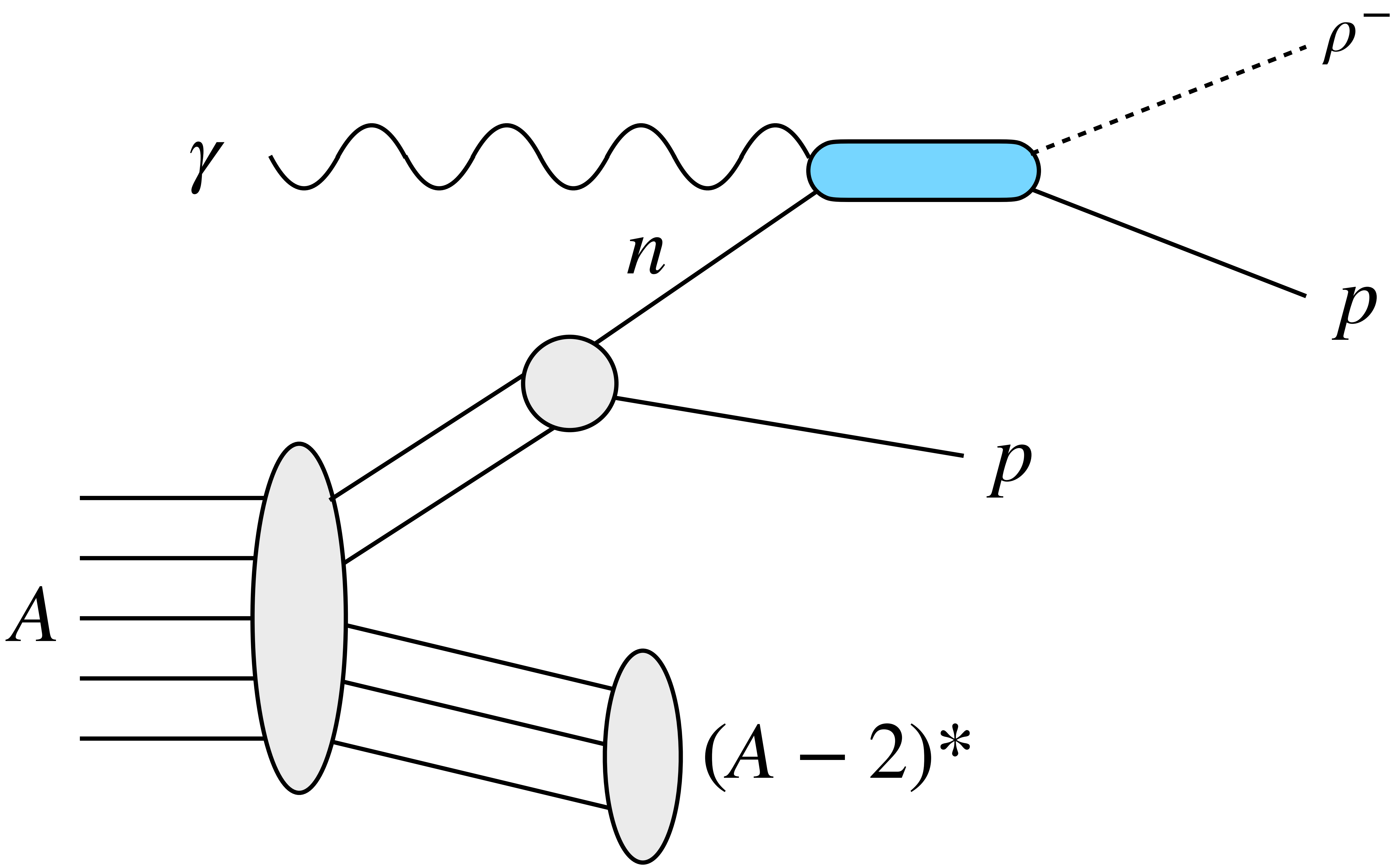
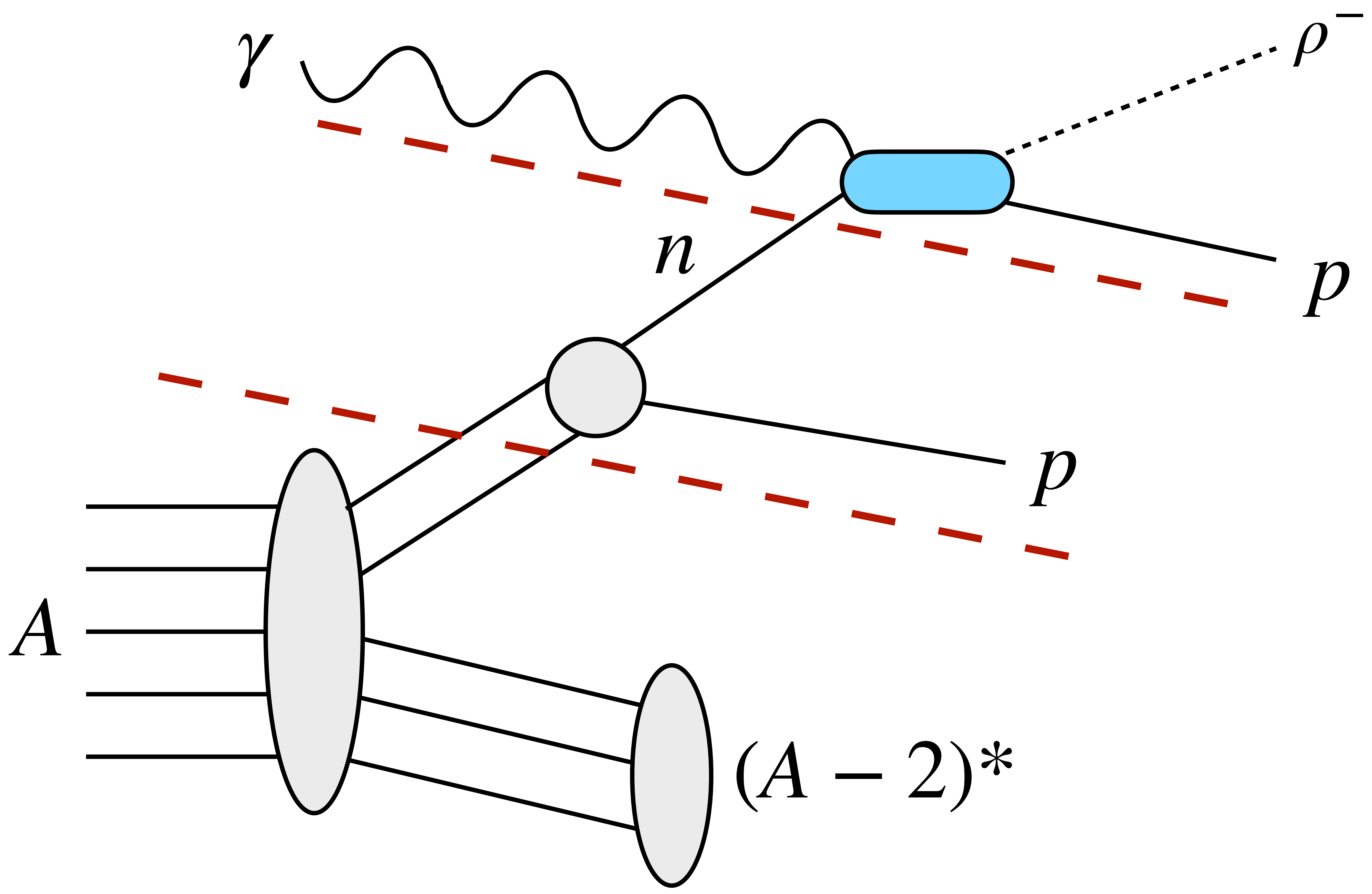


Plane-wave SRC Cross Section

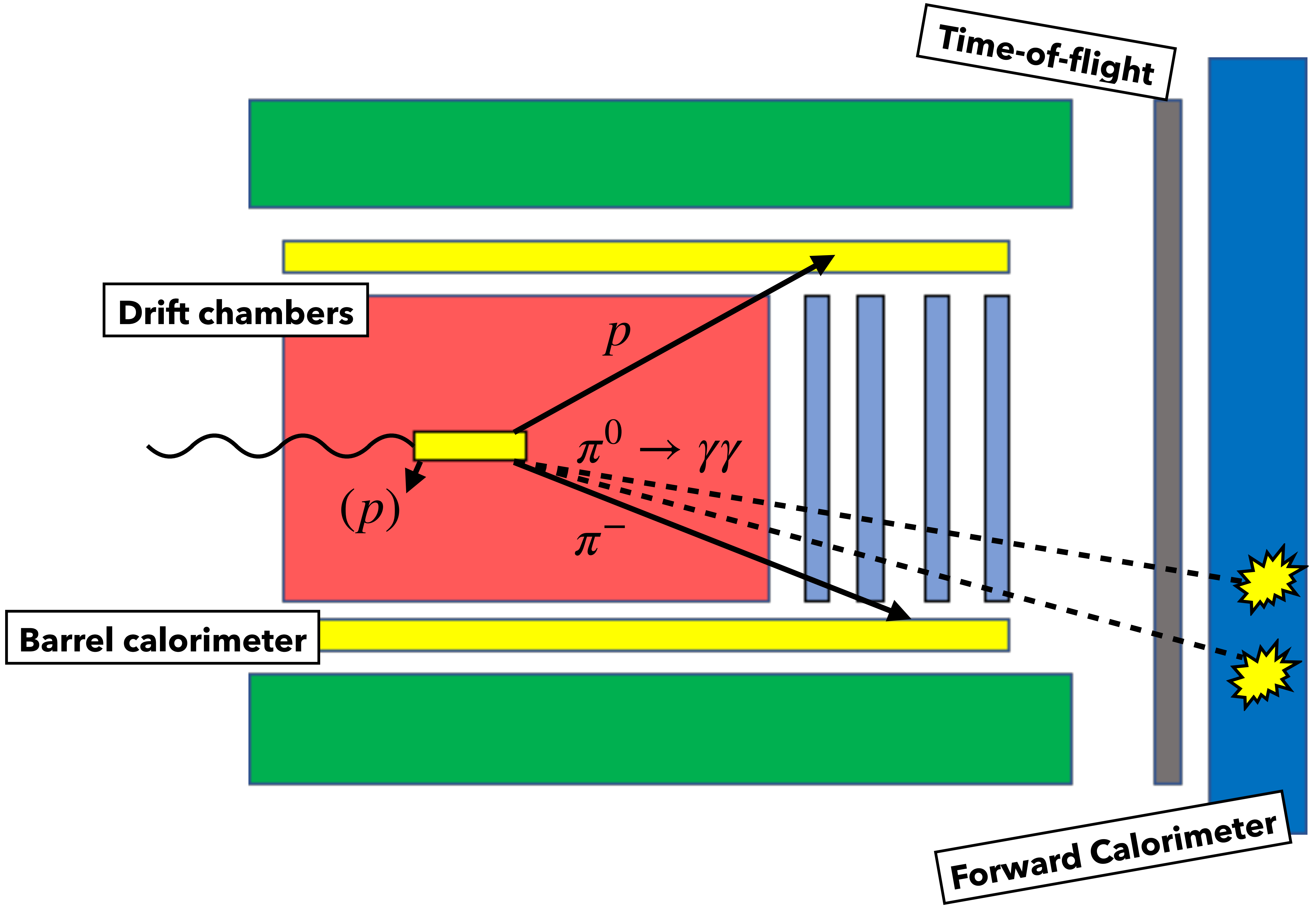


$$\sigma_{SRC} \sim K \cdot \sigma(\gamma n \to \rho^- p) \cdot S(p_i, p_{spec})$$

- We require a single-body operator to input to our plane-wave model
- Deuterium data allows us to extract the shape of this cross section for quasi-free neutrons

Measuring $\gamma n \to \rho^- p$ from deuterium

- Detect photon showers in calorimeters, charged particles in drift chambers



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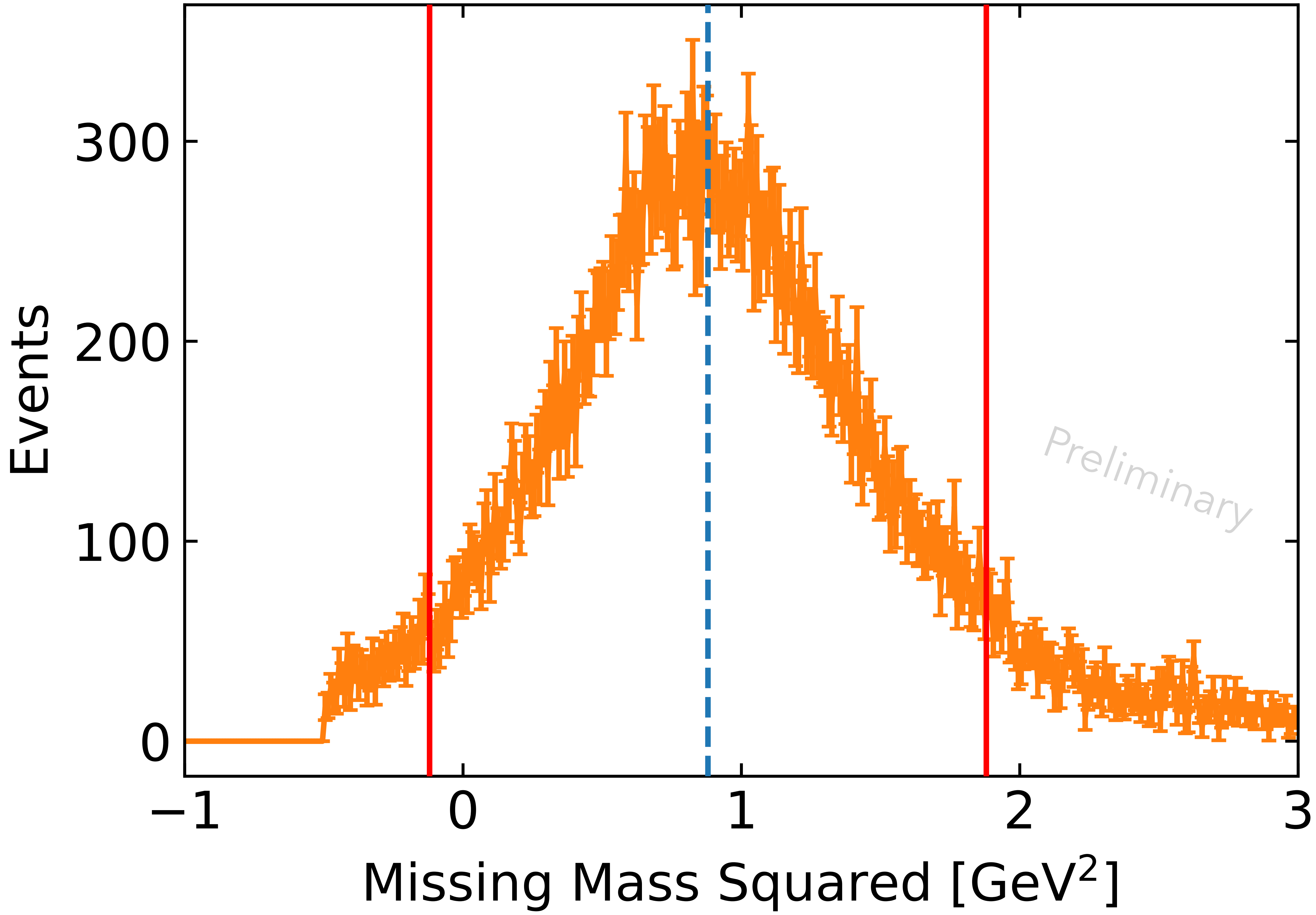

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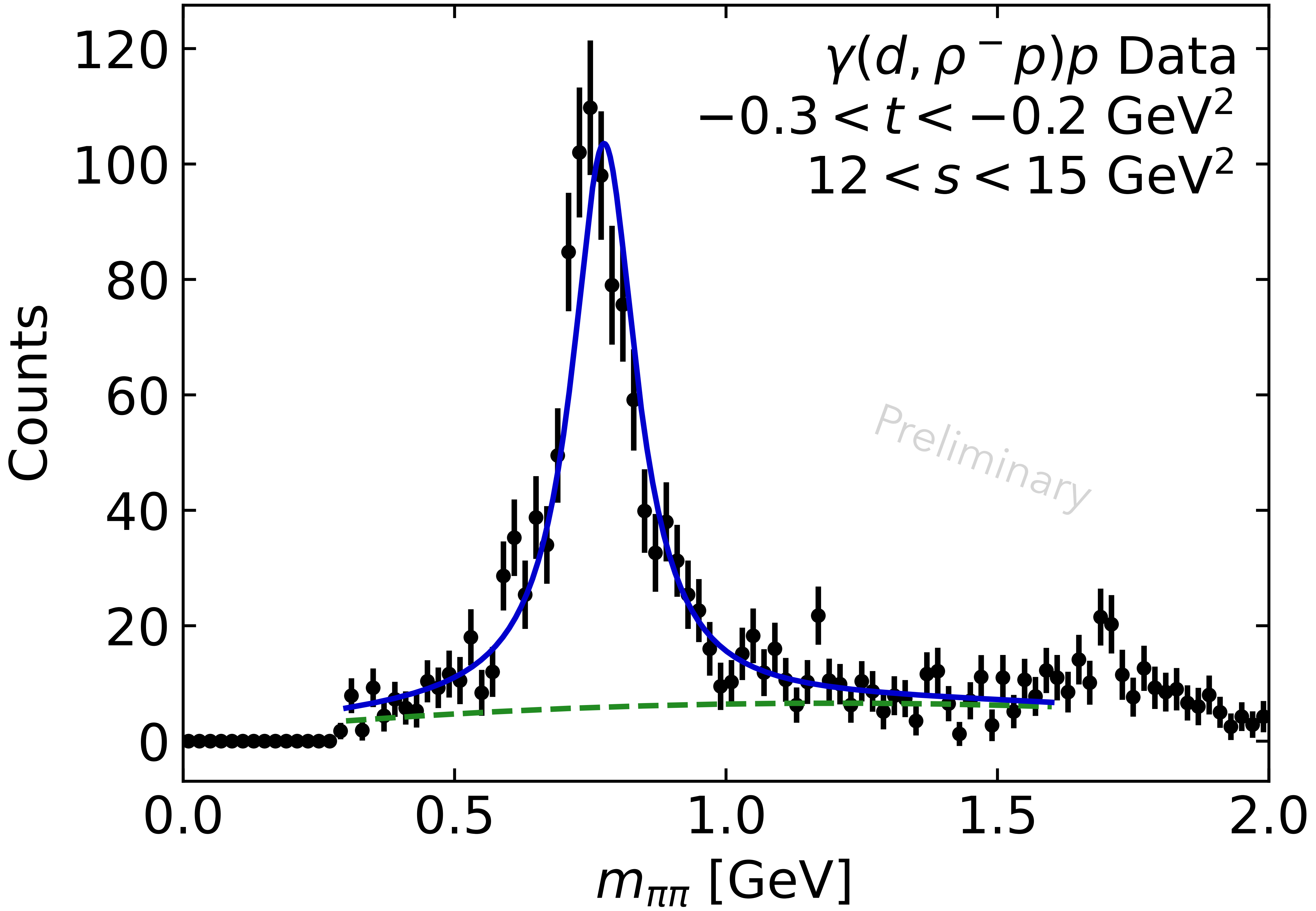
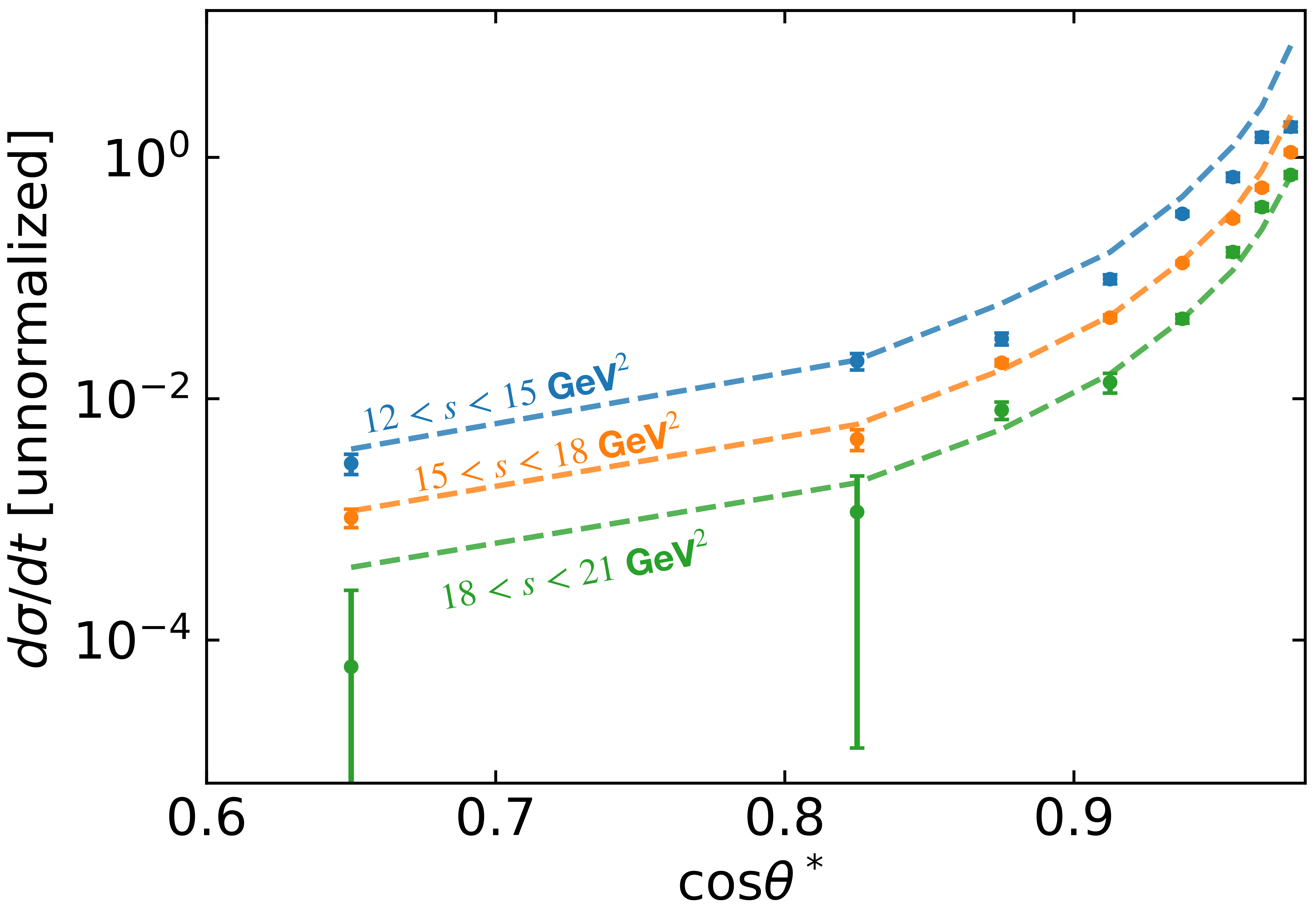


Measuring $\gamma n \to \rho^- p$ from deuterium

- Detect photon showers in calorimeters, charged particles in drift chambers
- In quasi-free case, spectator proton is low momentum, but missing mass can be restricted
- Invariant mass of 2-pion system used to determine ρ^- yields
- Comparison to phase-space generator allows extraction of cross section shape



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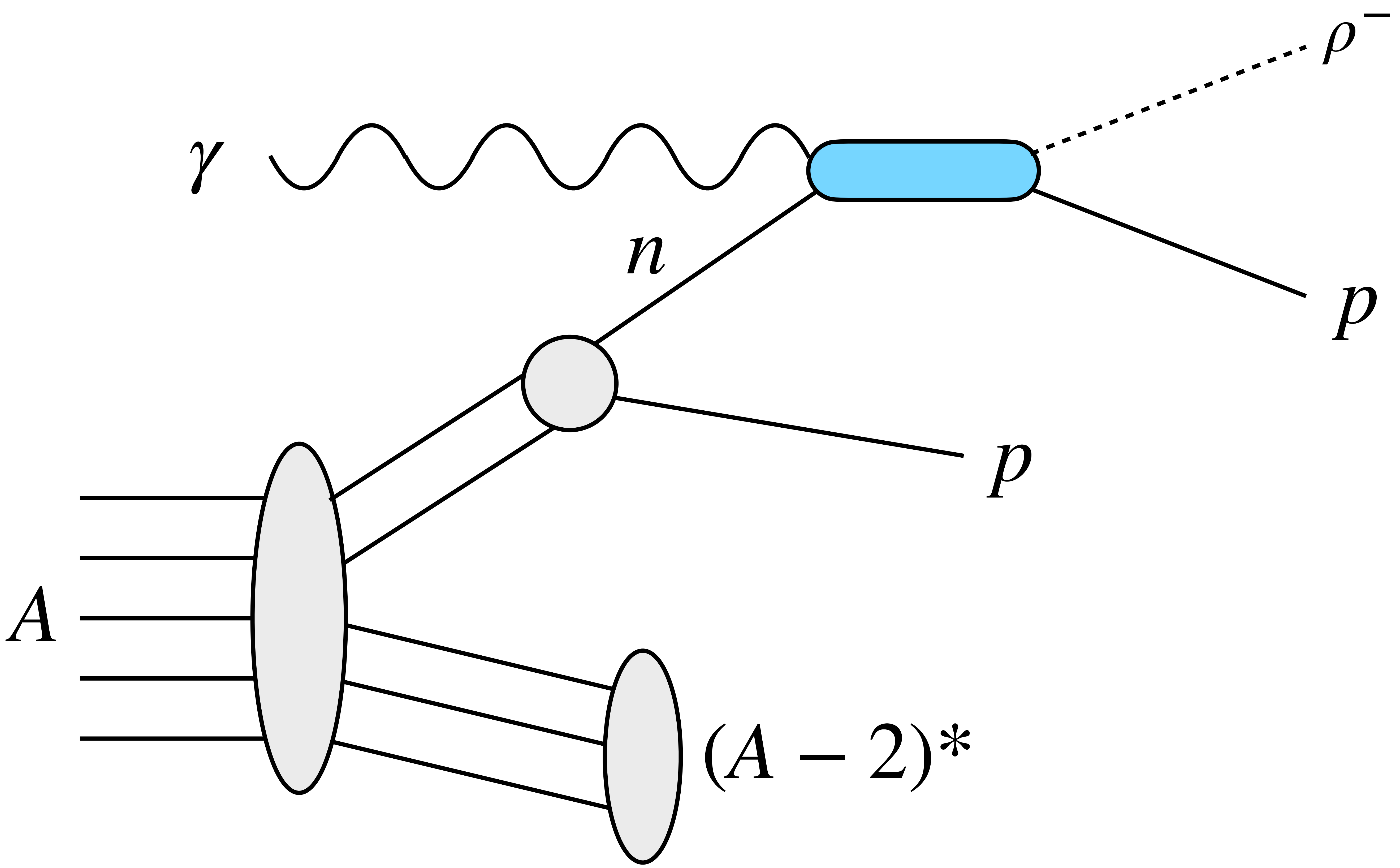
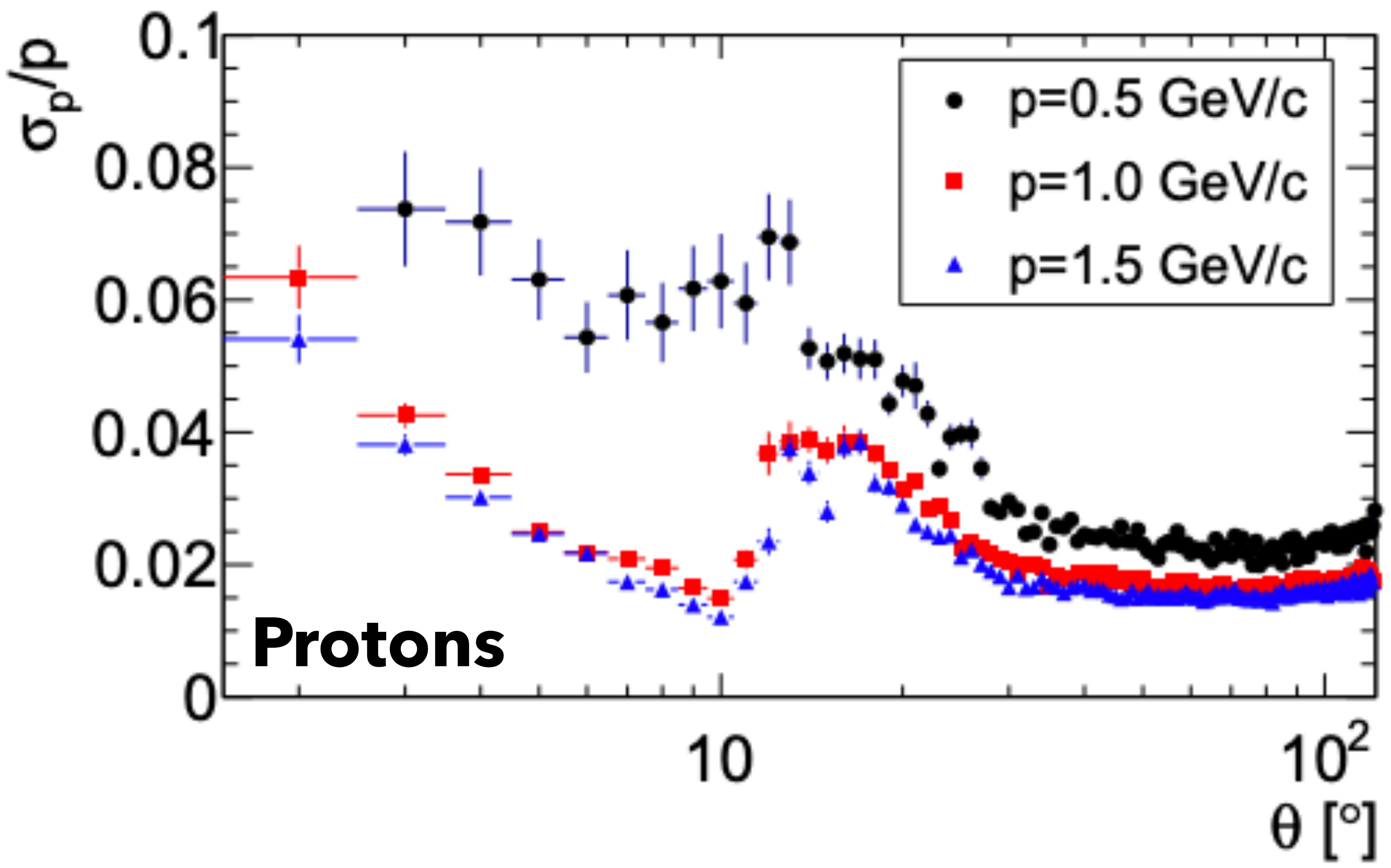
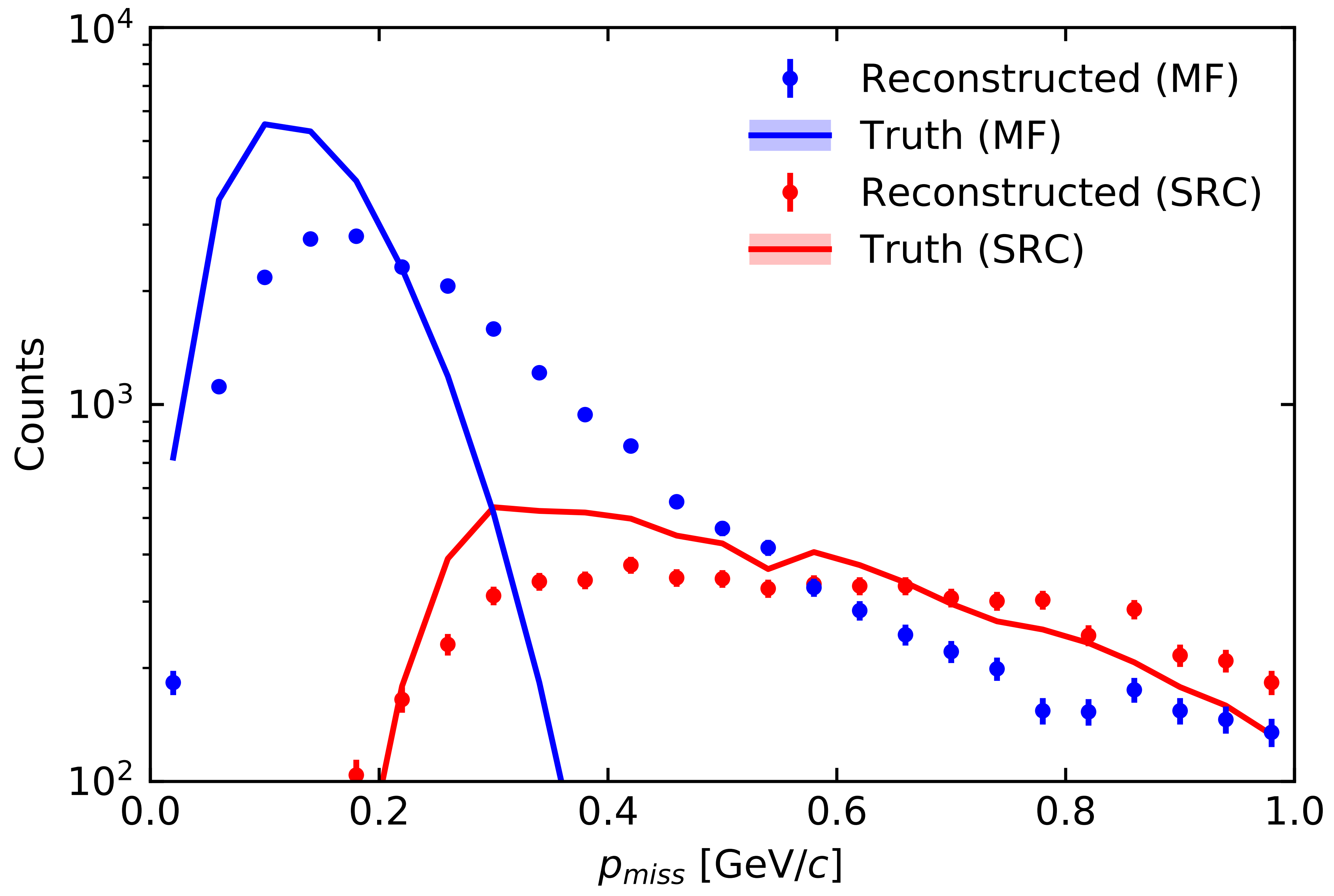


Detector resolution limits missing momentum reconstruction





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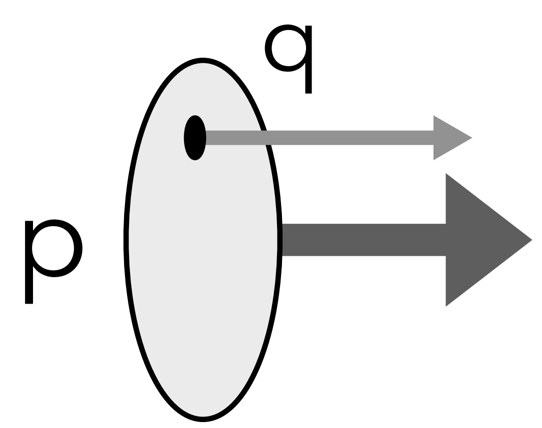
Analysis on the light-front

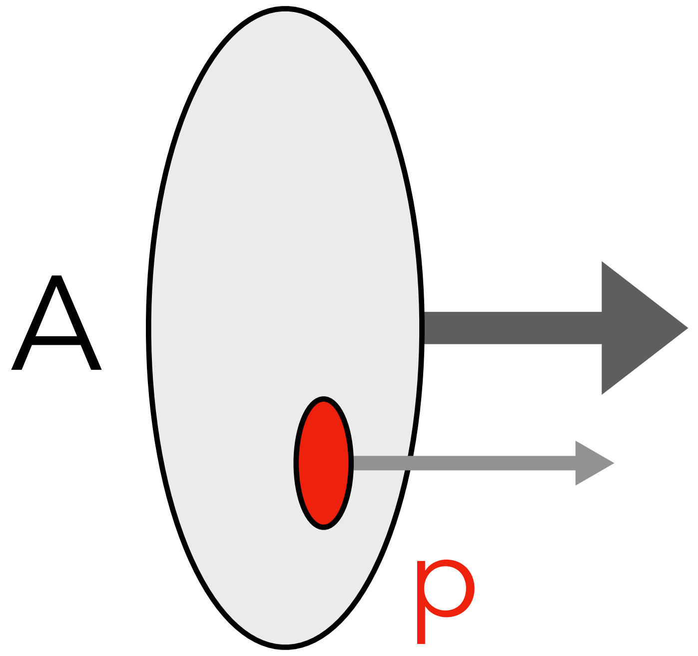
Parton in Hadron



Parton momentum fraction

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

Nucleon in Nucleus

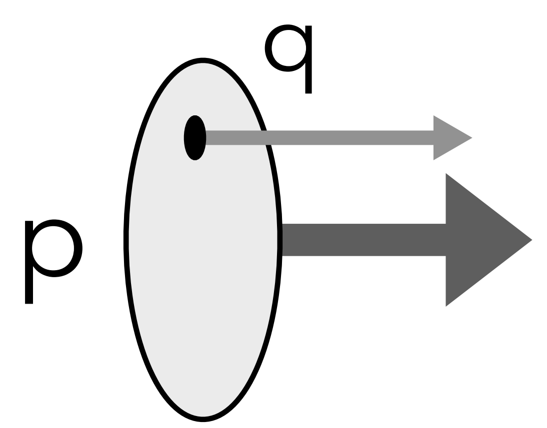


Nucleon momentum fraction

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

Analysis on the light-front

Parton in Hadron



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Light-front variables mitigate resolution effects

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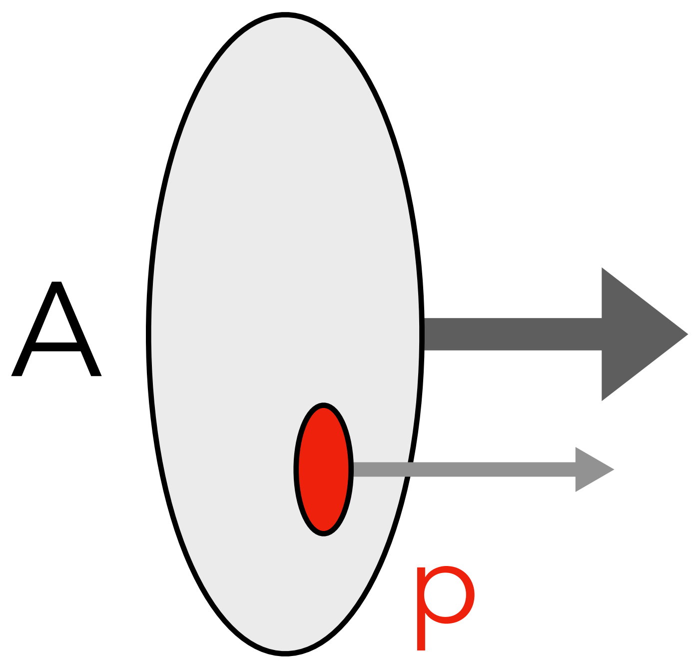

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Analysis on the light-front

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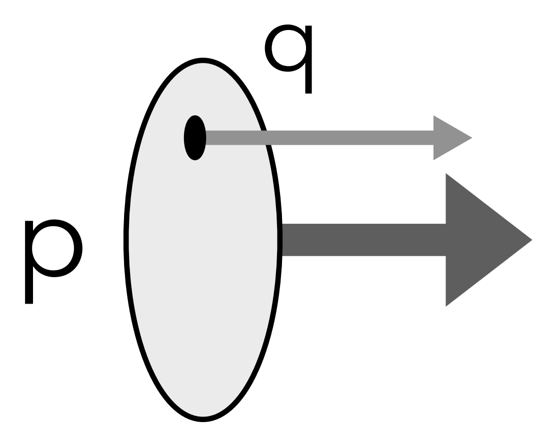

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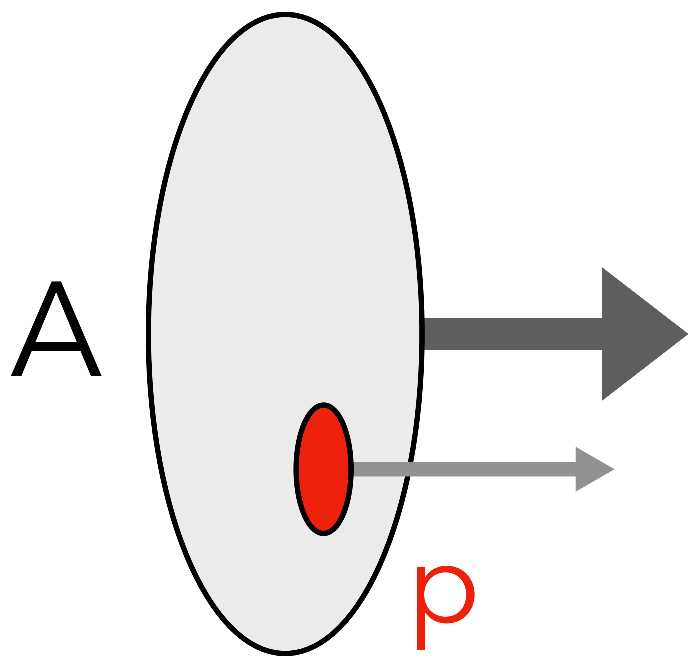


Nucleon momentum fraction

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

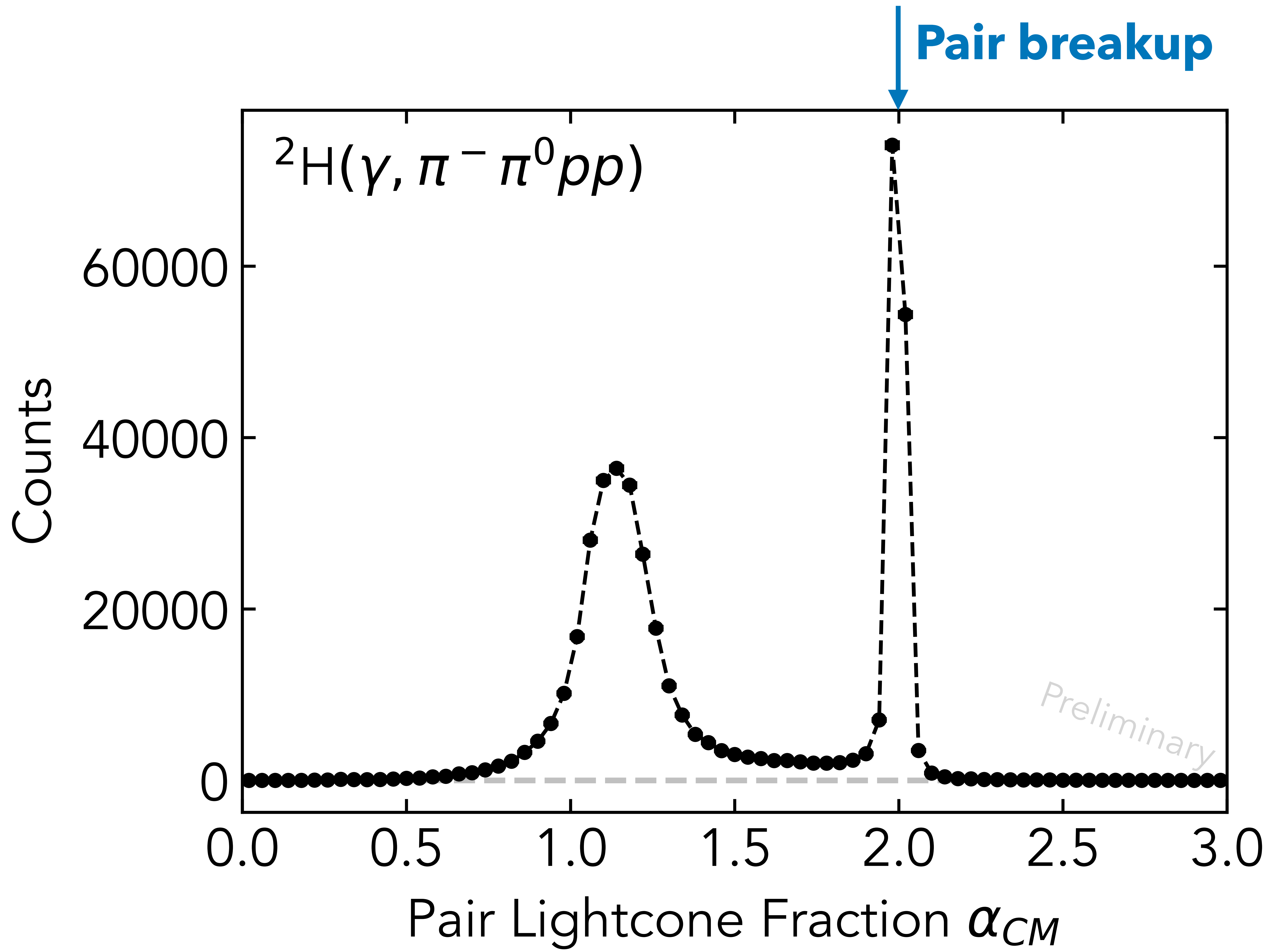
Low-momentum nucleon

$$\alpha_N \sim 1$$

Standing nucleon pair

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

Exclusive deuteron breakup clear in data



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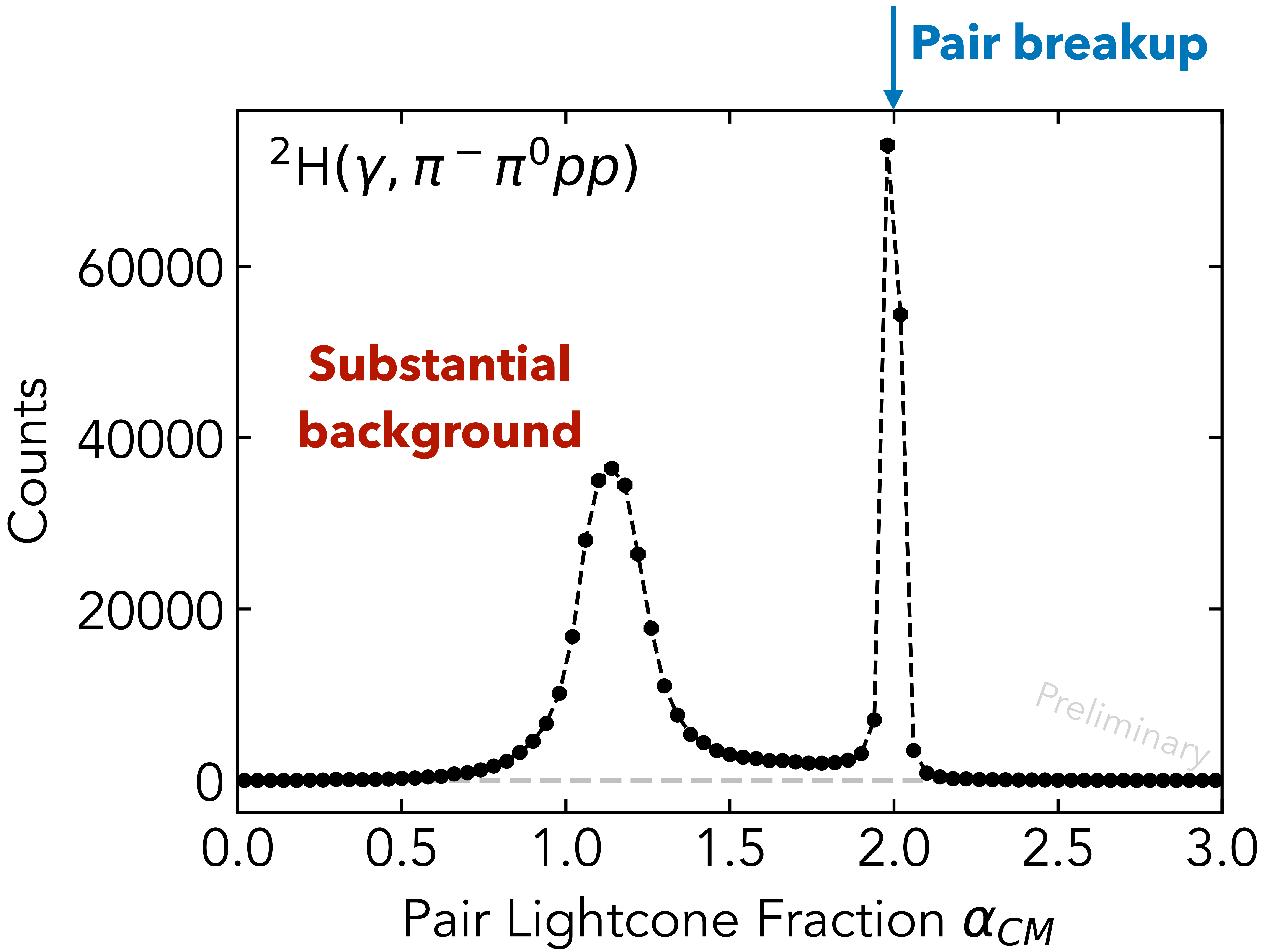
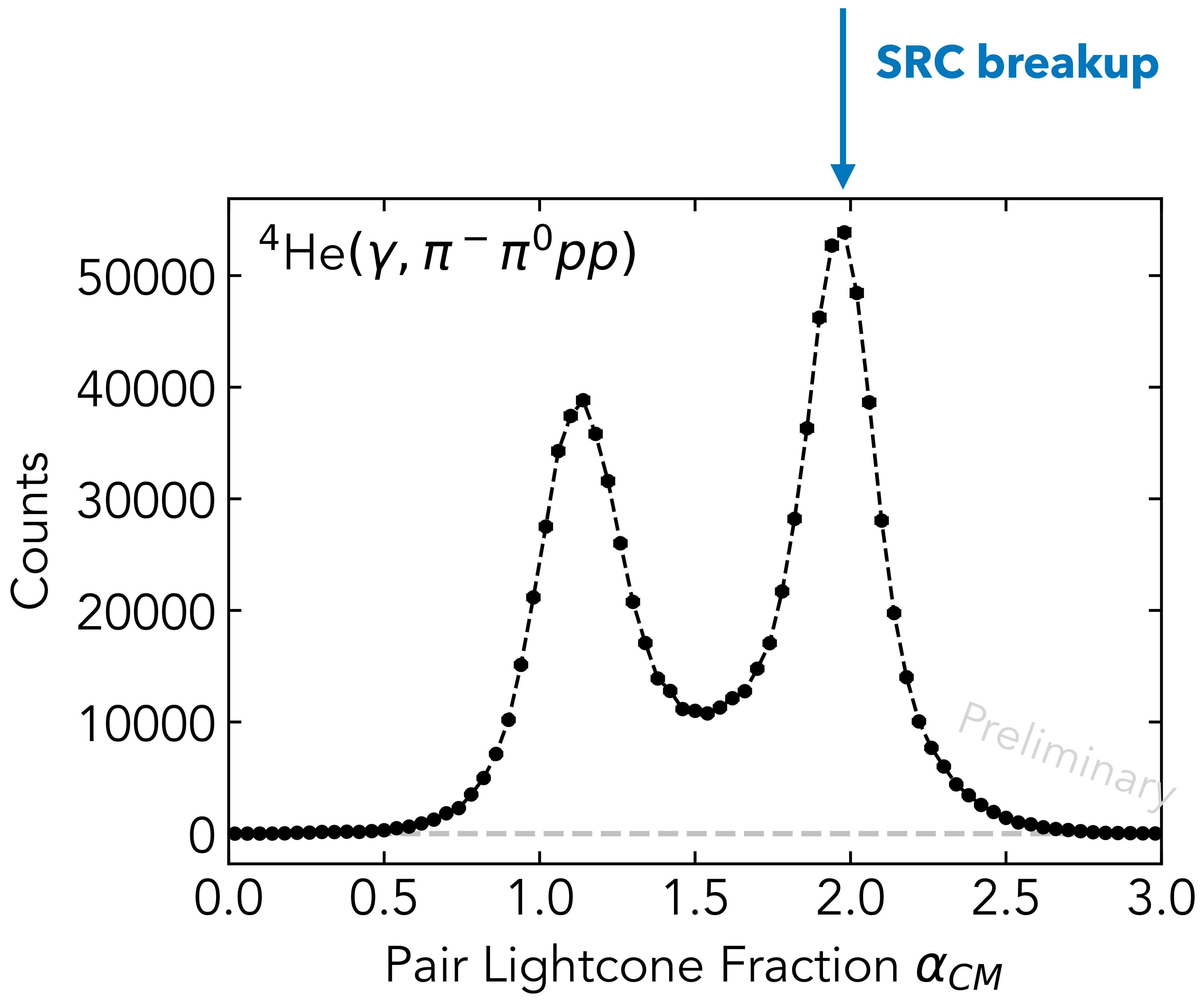
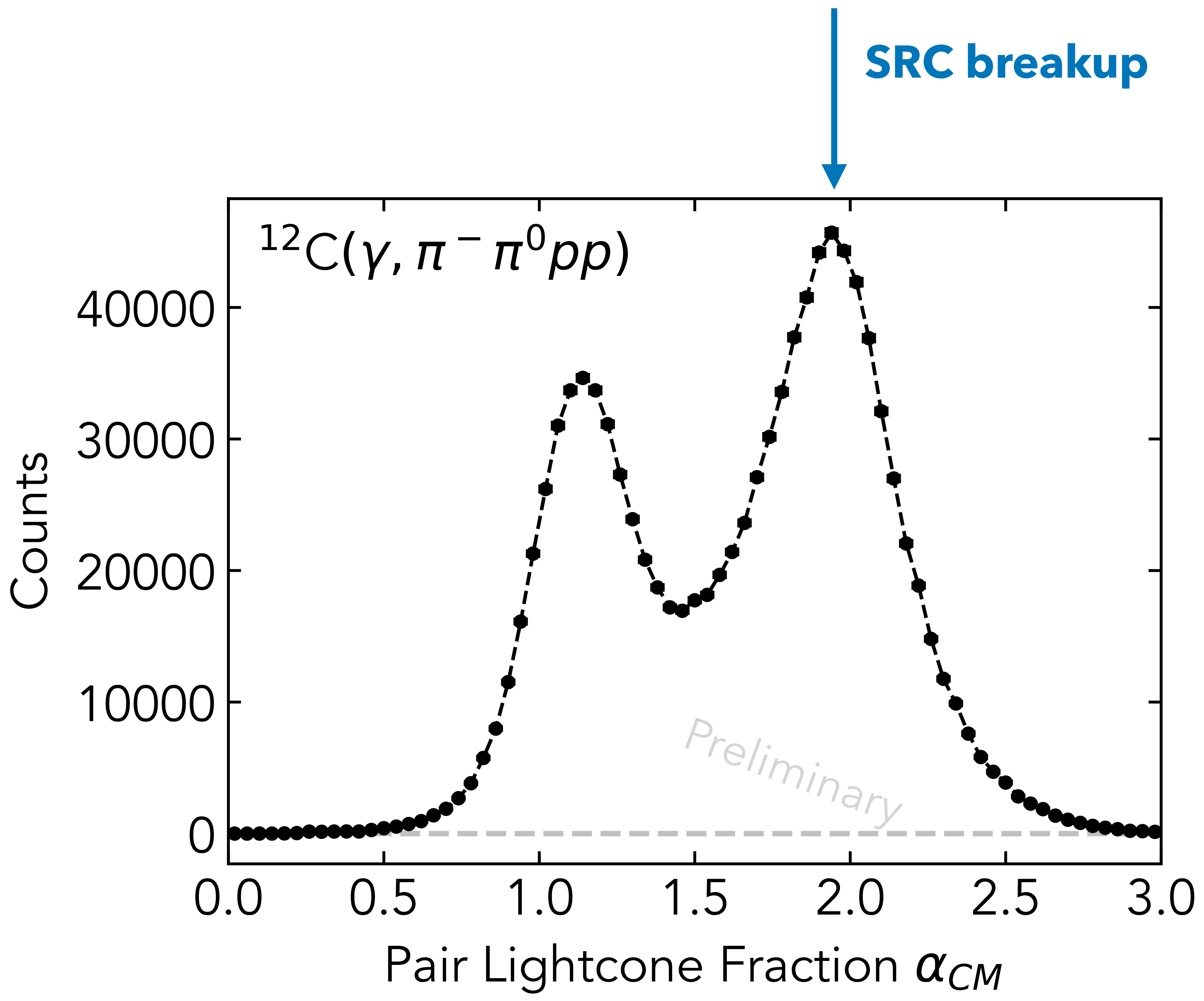


Exclusive SRC breakup in nuclei

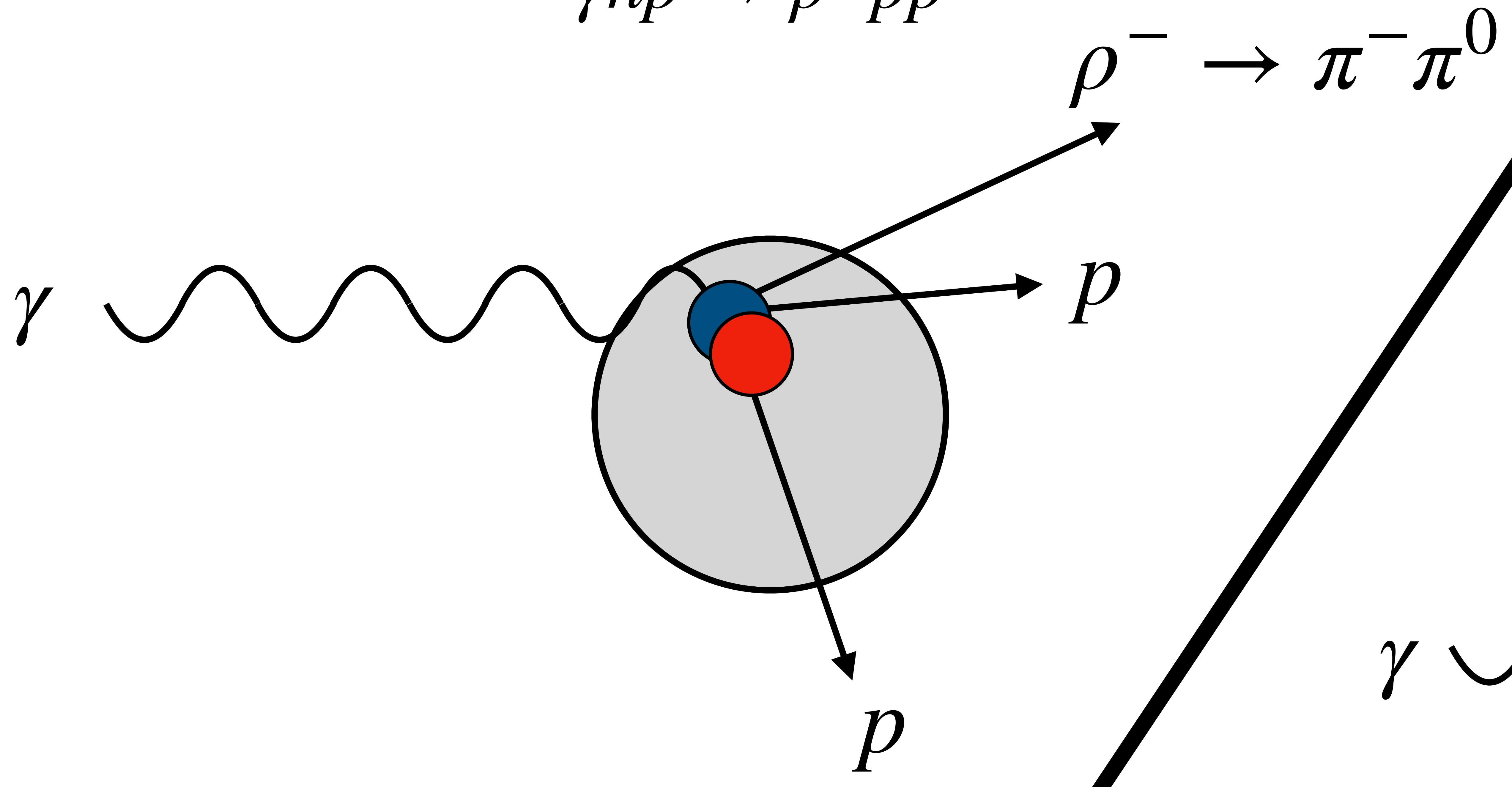




Background Separation

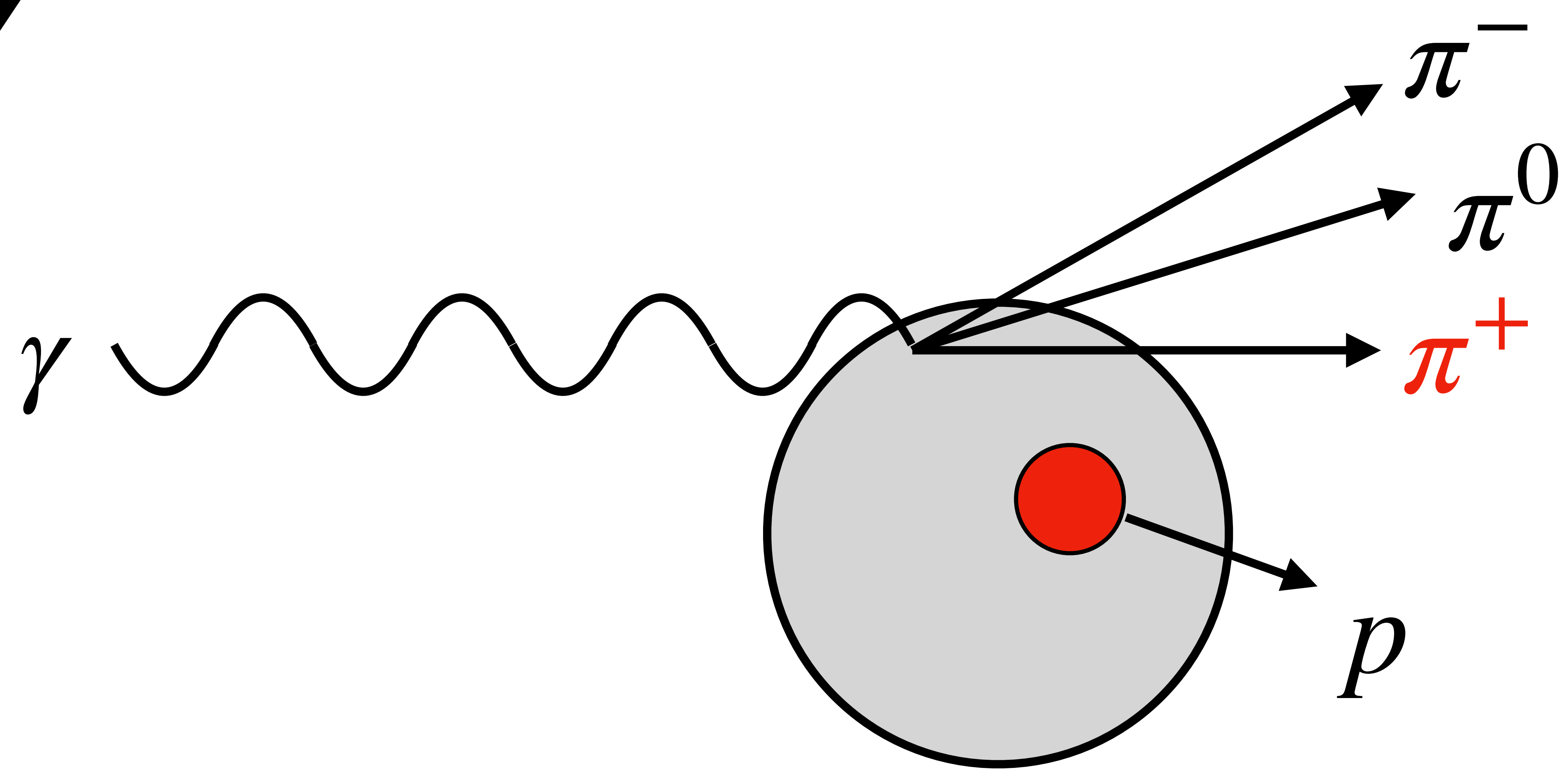
Signal process:

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

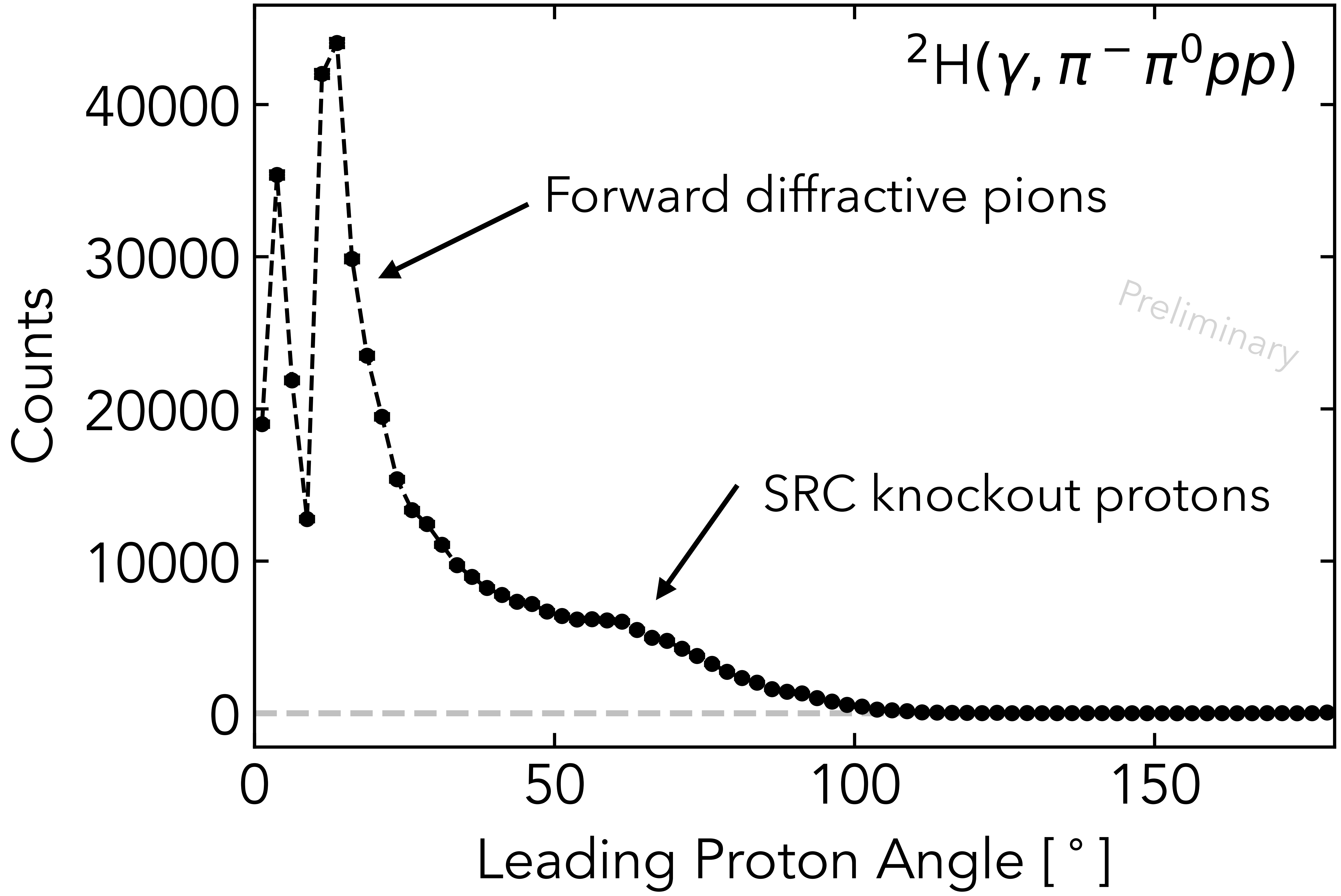


Largest Background

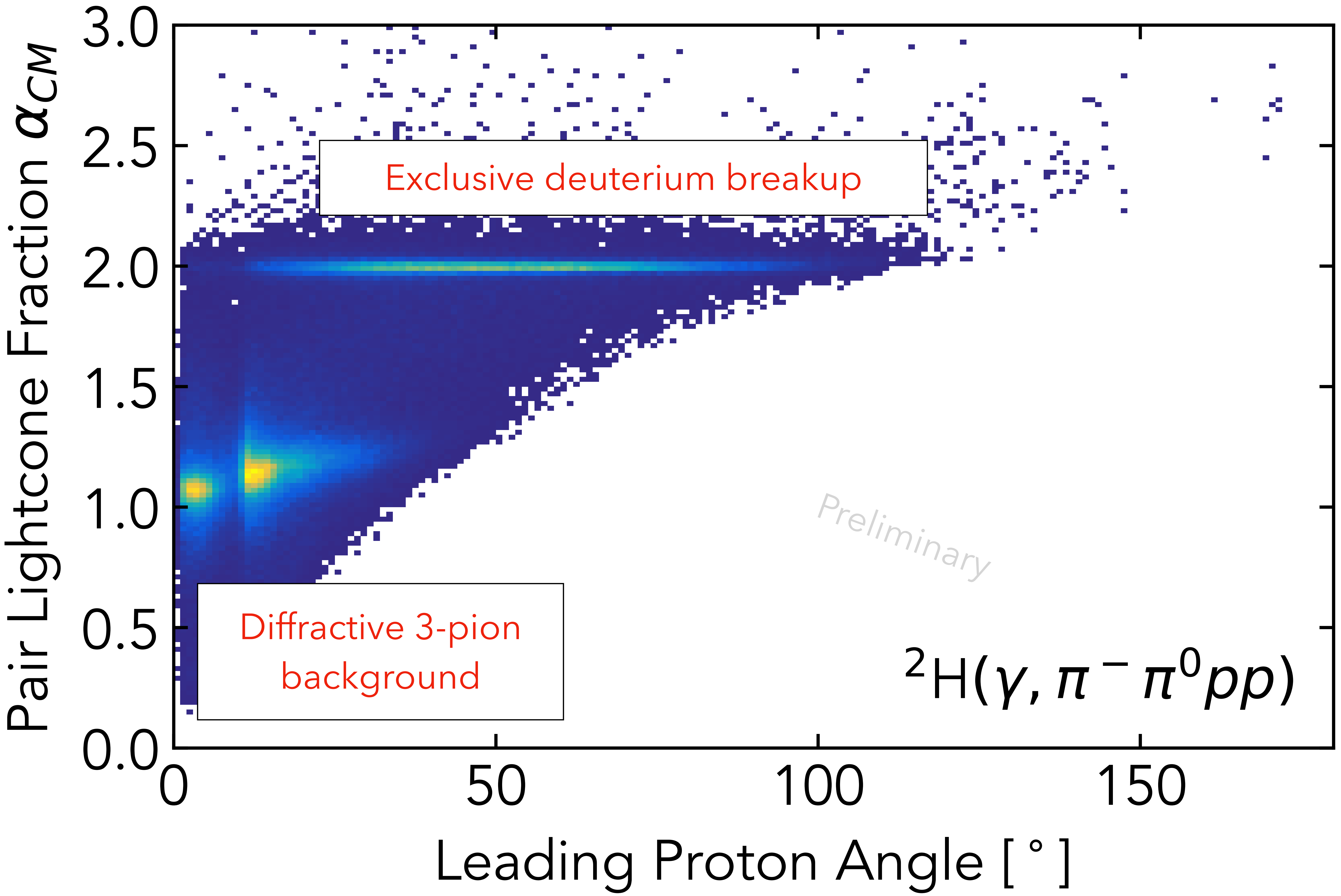
$\gamma A \to \pi^+\pi^-\pi^0 p(X)$



Diffractive pion production kinematics



Combining these identifiers helps us to isolate exclusive deuterium events for $(\gamma d \rightarrow \pi^{-}\pi^{0}pp)$



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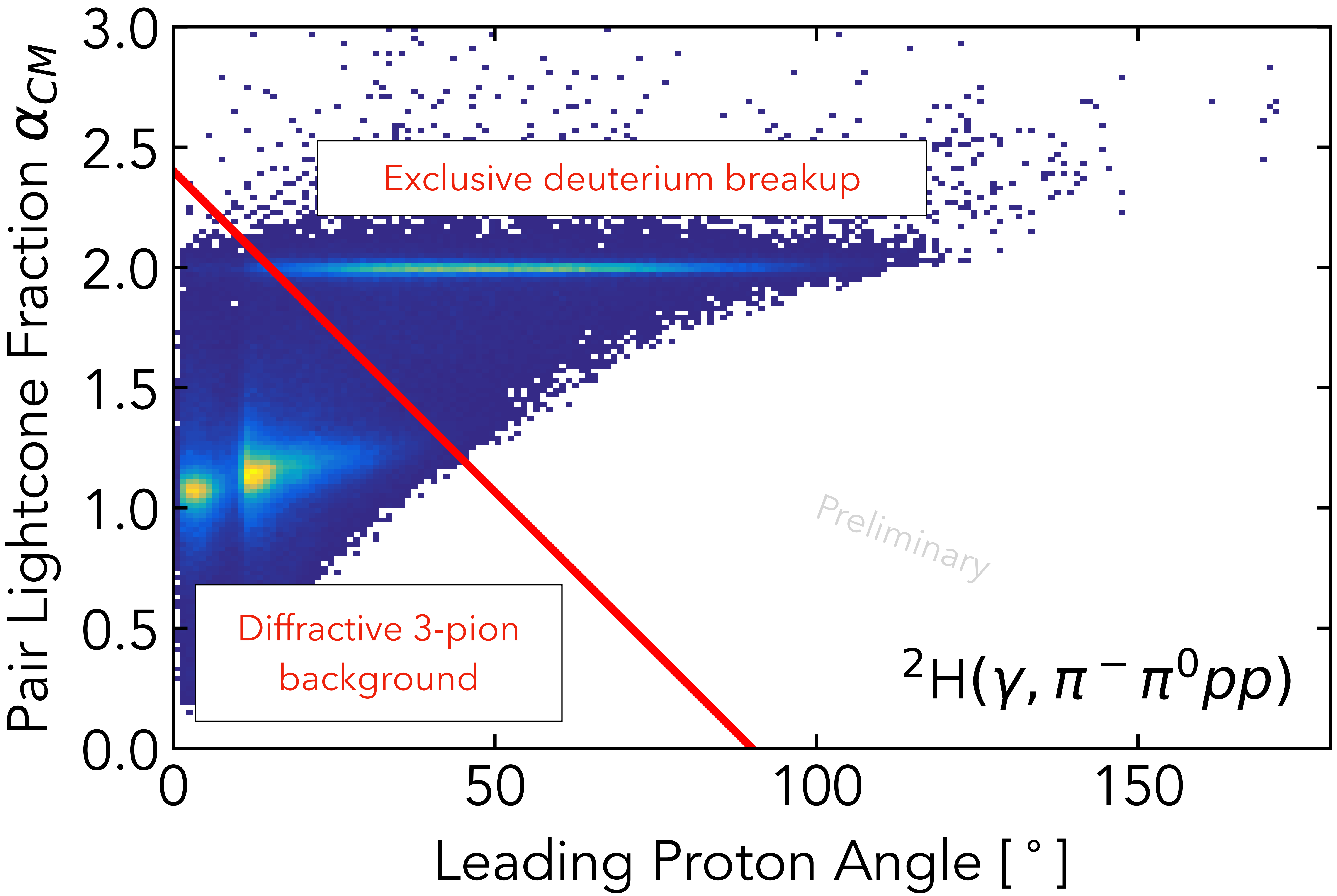
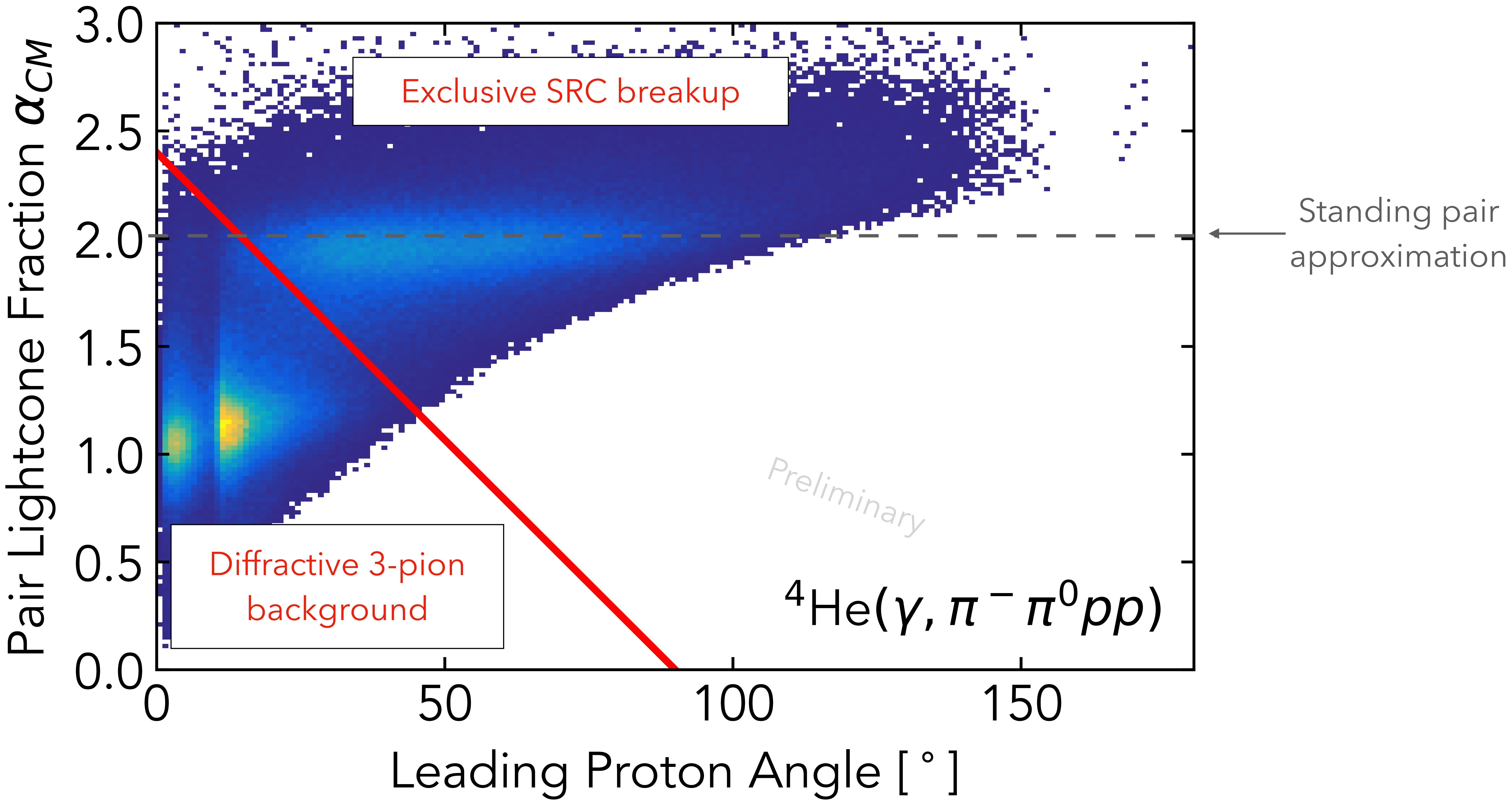
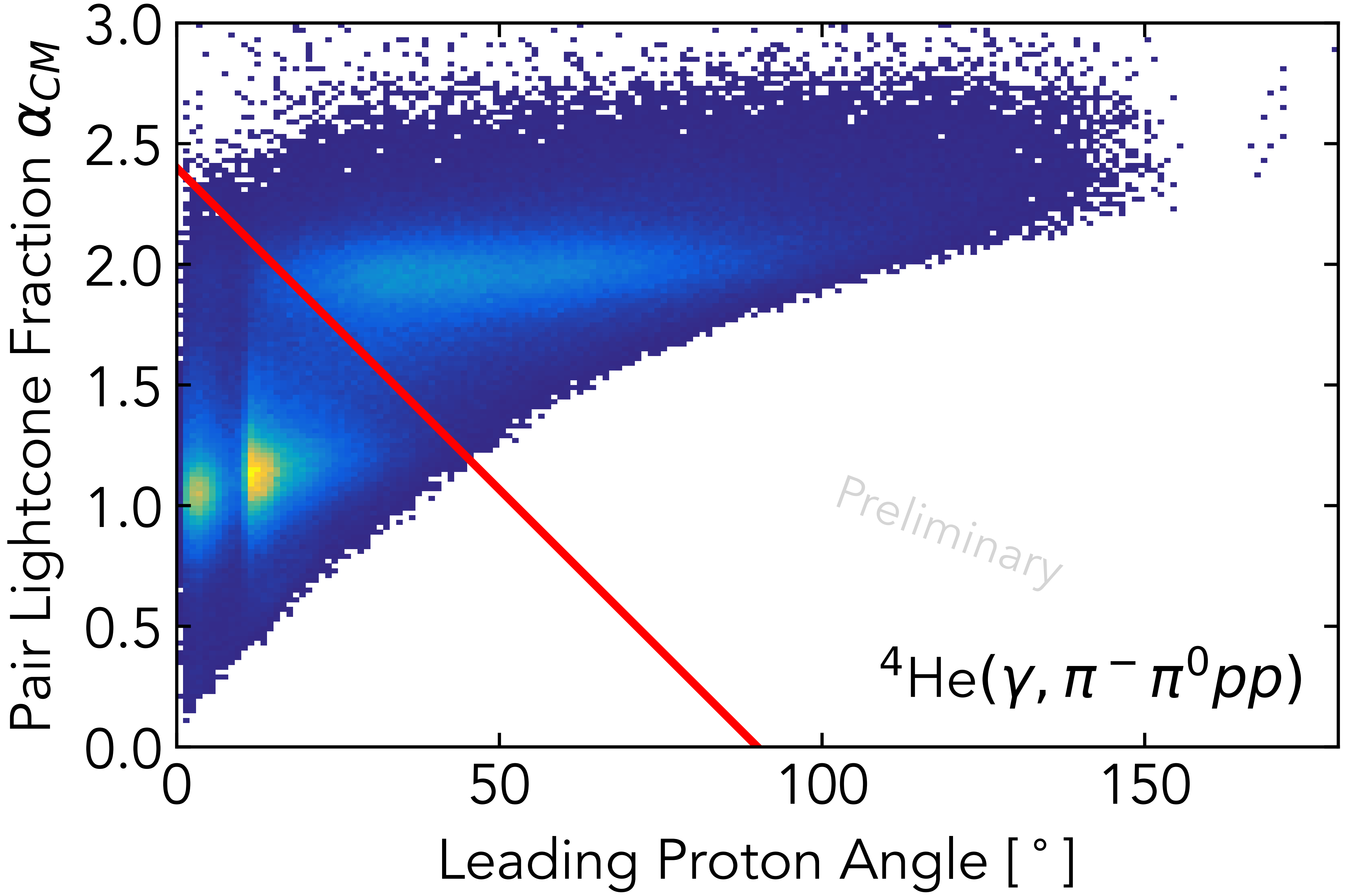


SRC events more spread out but still clear in data



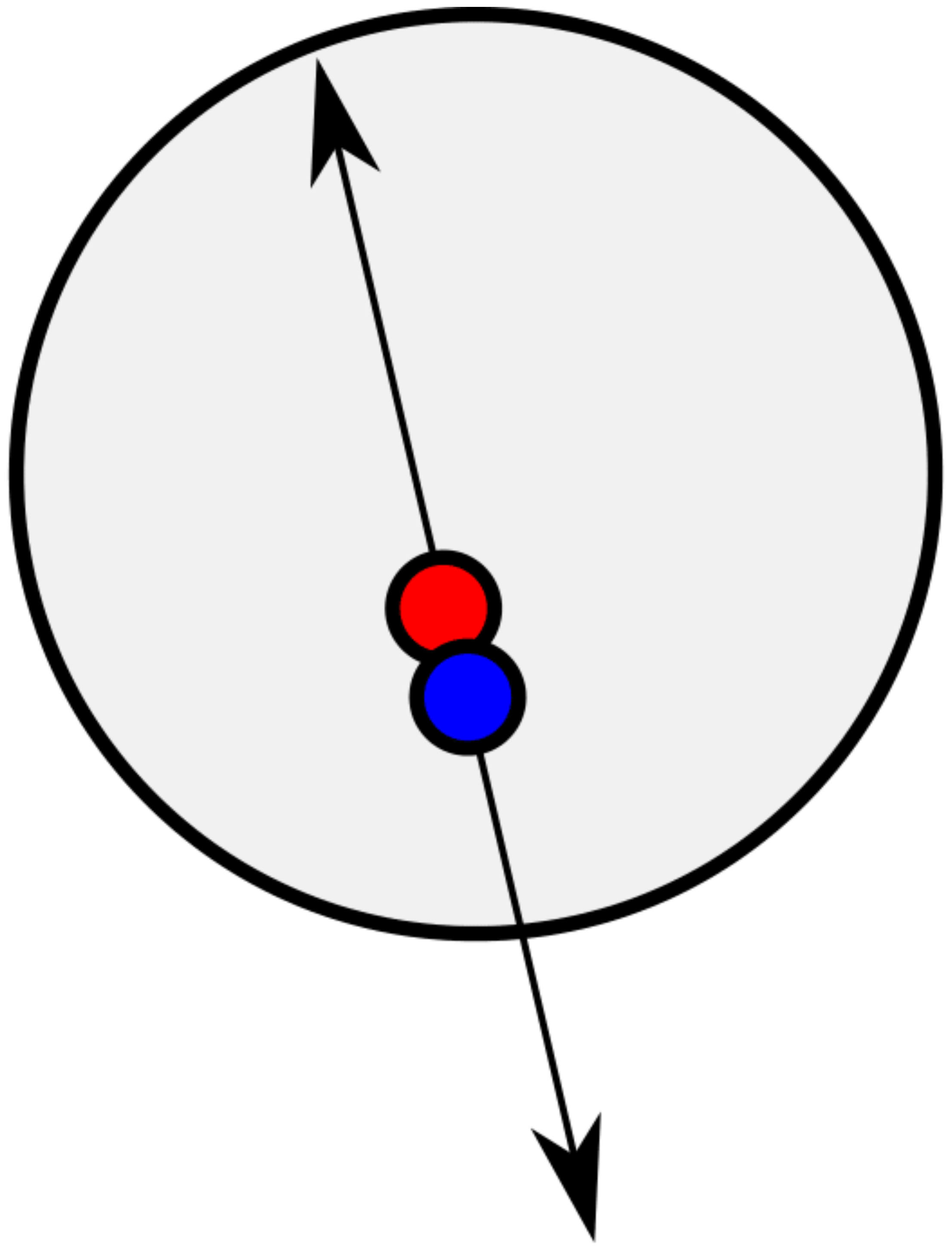
Comparison with PWIA calculations

- Diffractive background cut



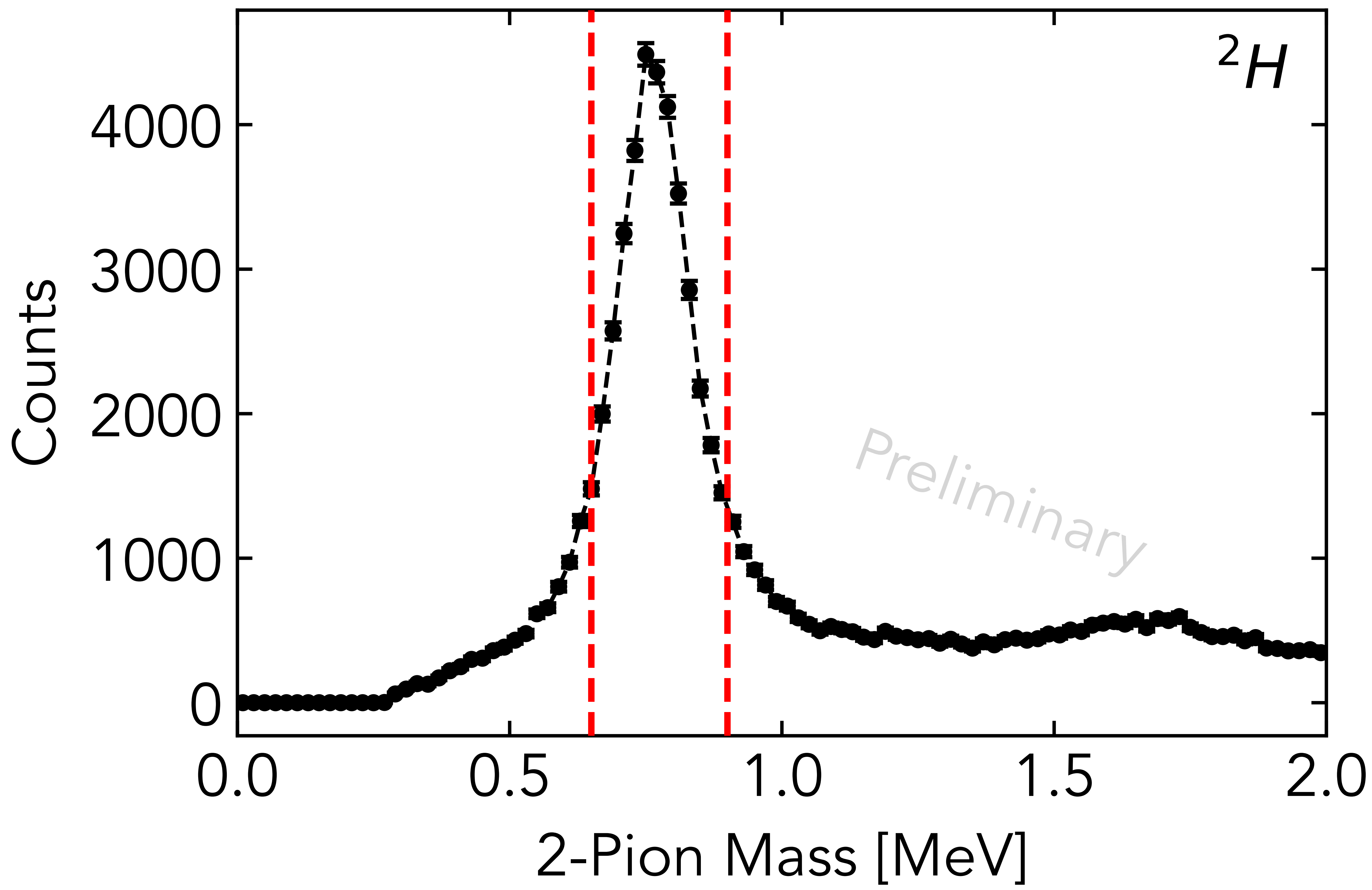
Comparison with PWIA calculations

- Diffractive background cut
- High relative momentum cut



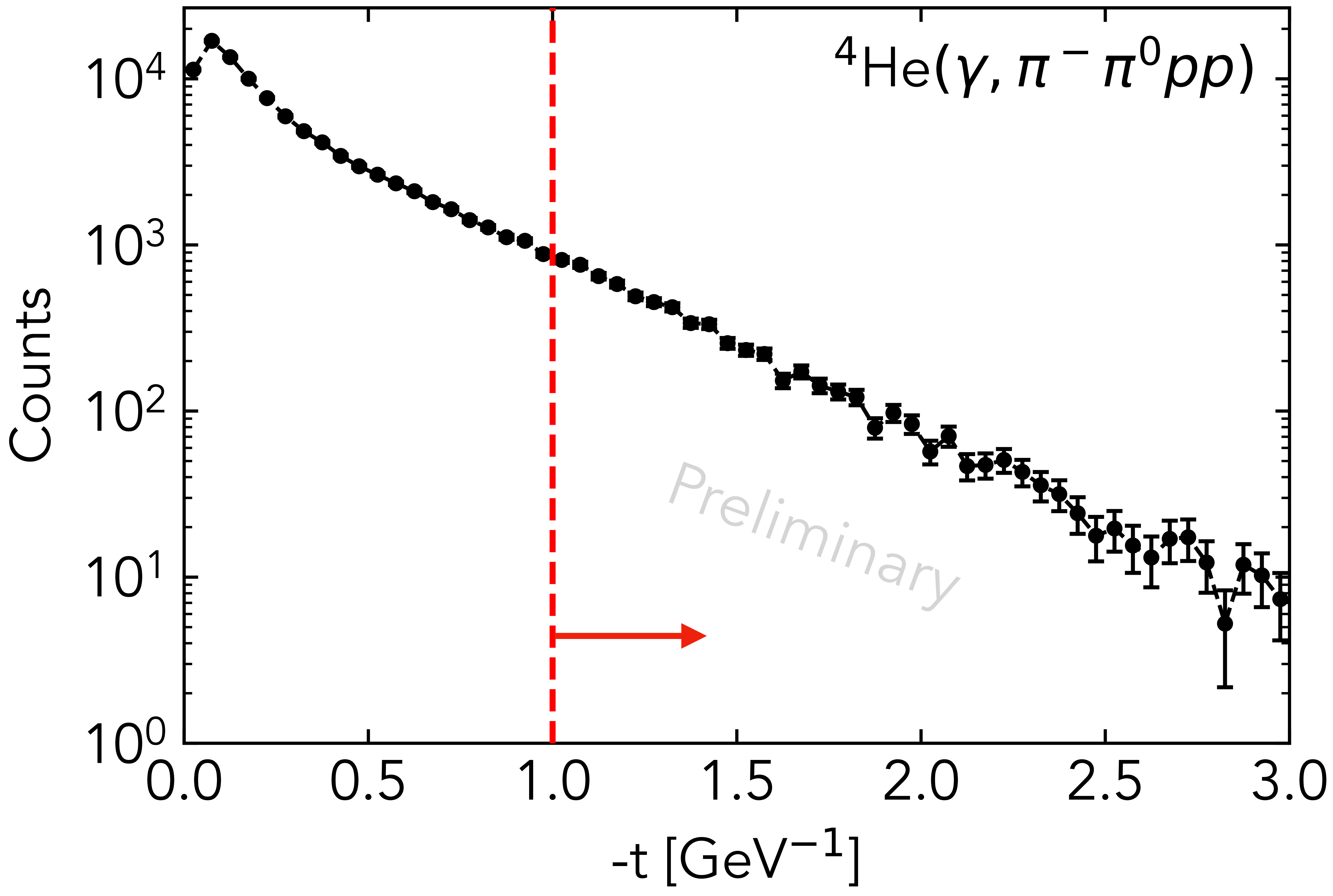
Comparison with PWIA calculations

- Diffractive background cut
- High relative momentum cut
- Cut on rho meson mass



Comparison with PWIA calculations

- Diffractive background cut
- High relative momentum cut
- Cut on rho meson mass
- High momentum-transfer $|t|, |u| > 1$ GeV^2



Comparison with PWIA calculations

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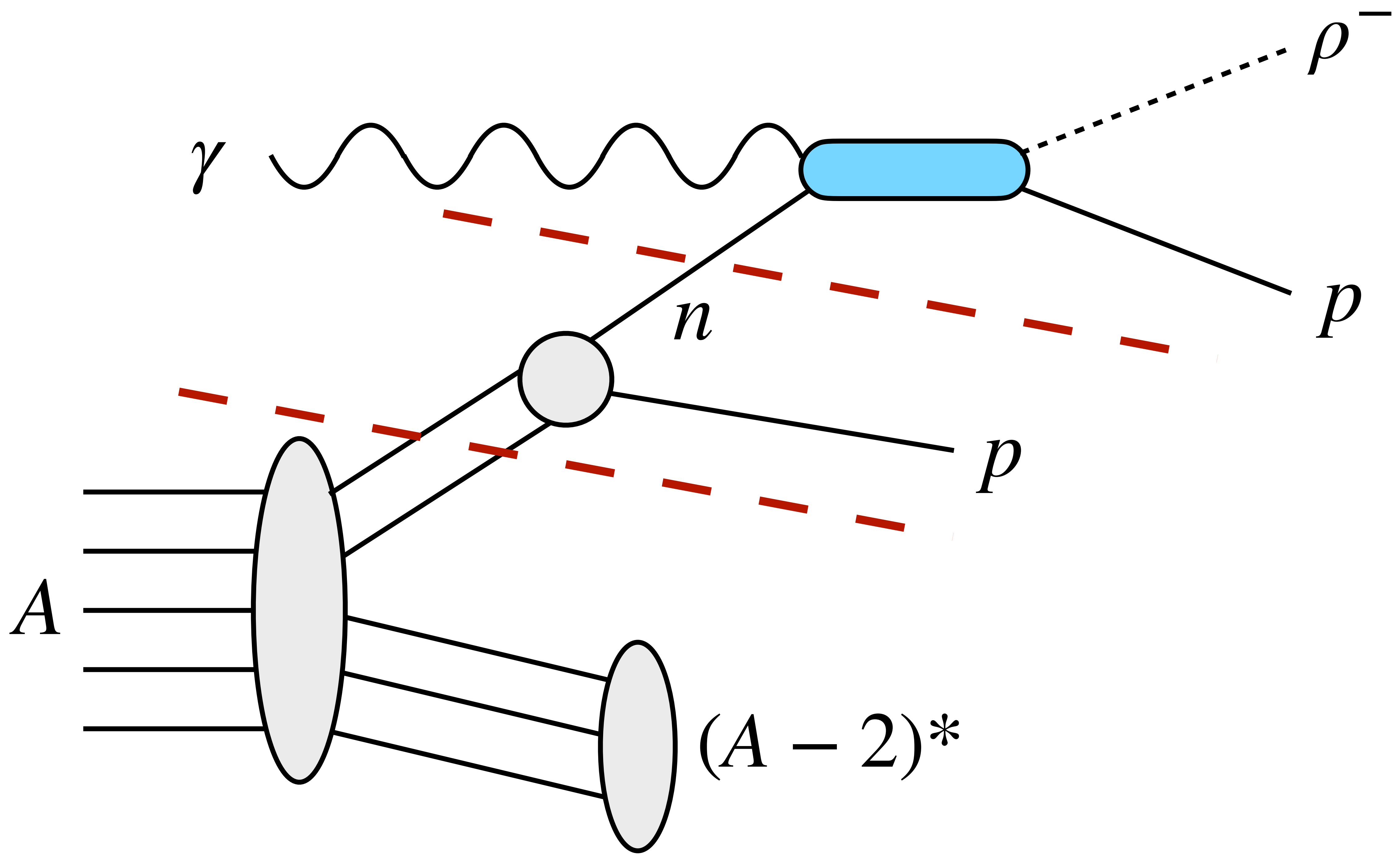
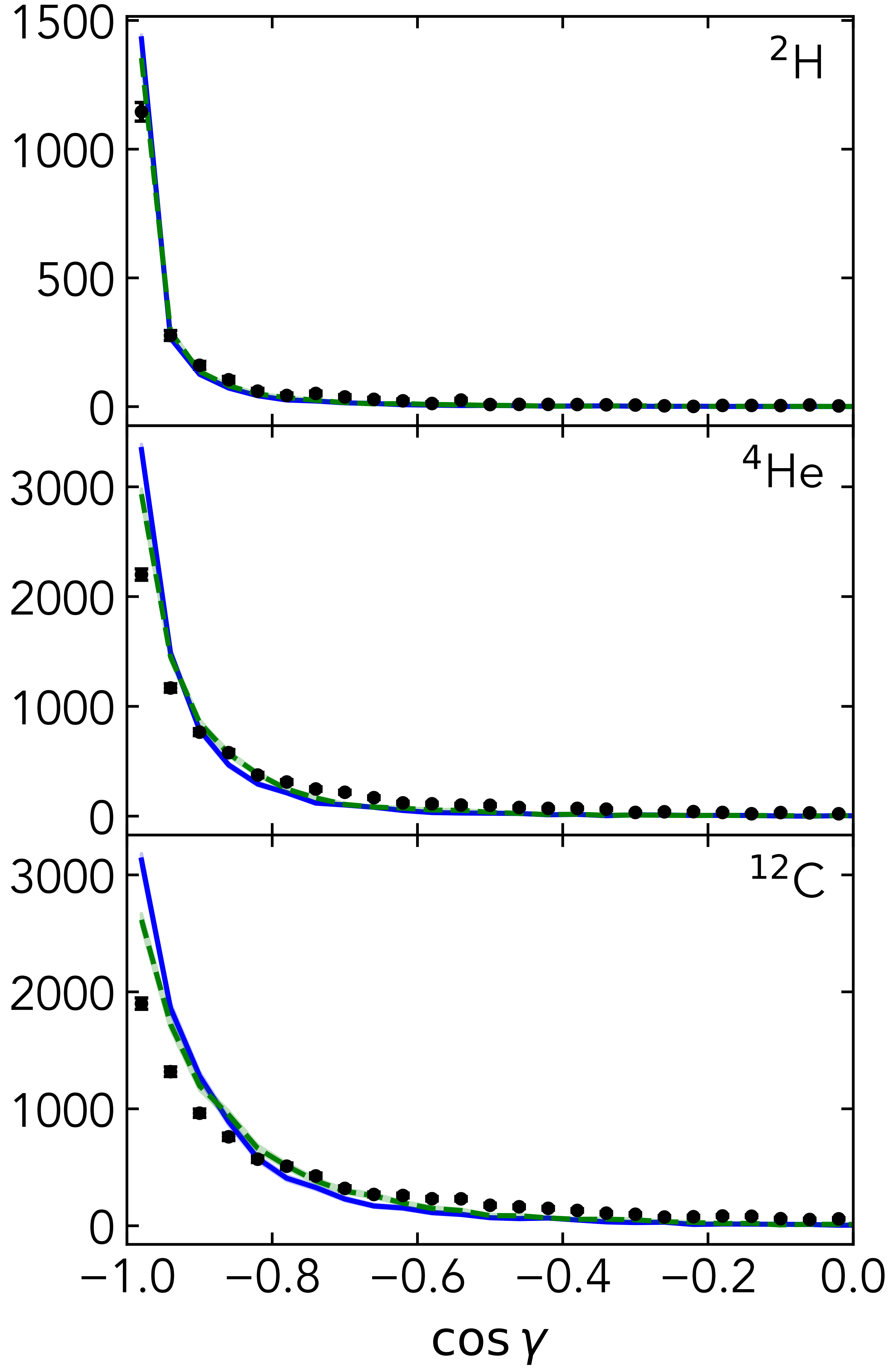
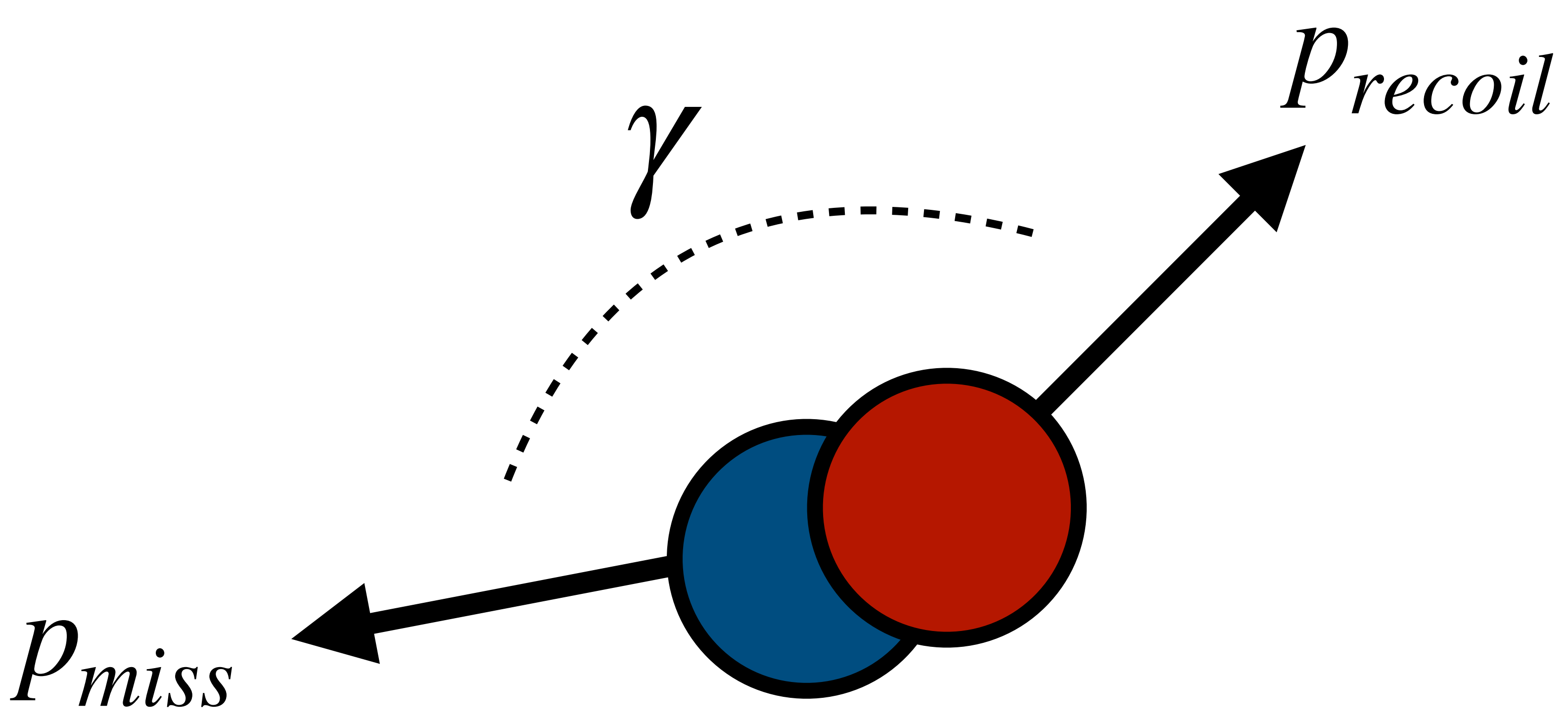
- High momentum-transfer $|t|, |u| > 1$ GeV^2
- **Compare with GCF calculations**



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

SRC Pair Opening Angle





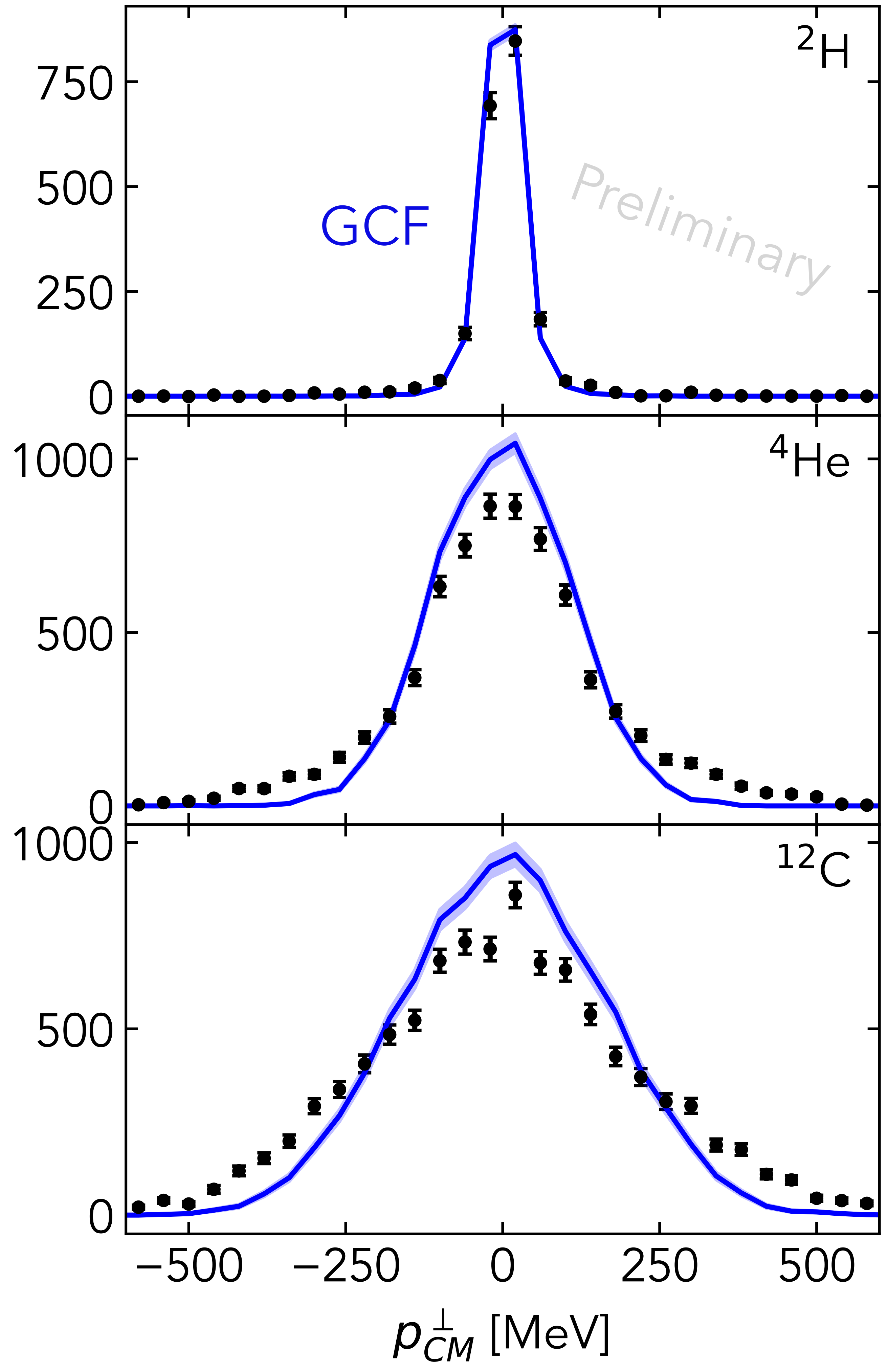
- Reconstruct angle between initial-state neutron and spectator proton
- All nuclei show clear back-to-back correlation

SRC Center-of-Mass Momentum

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

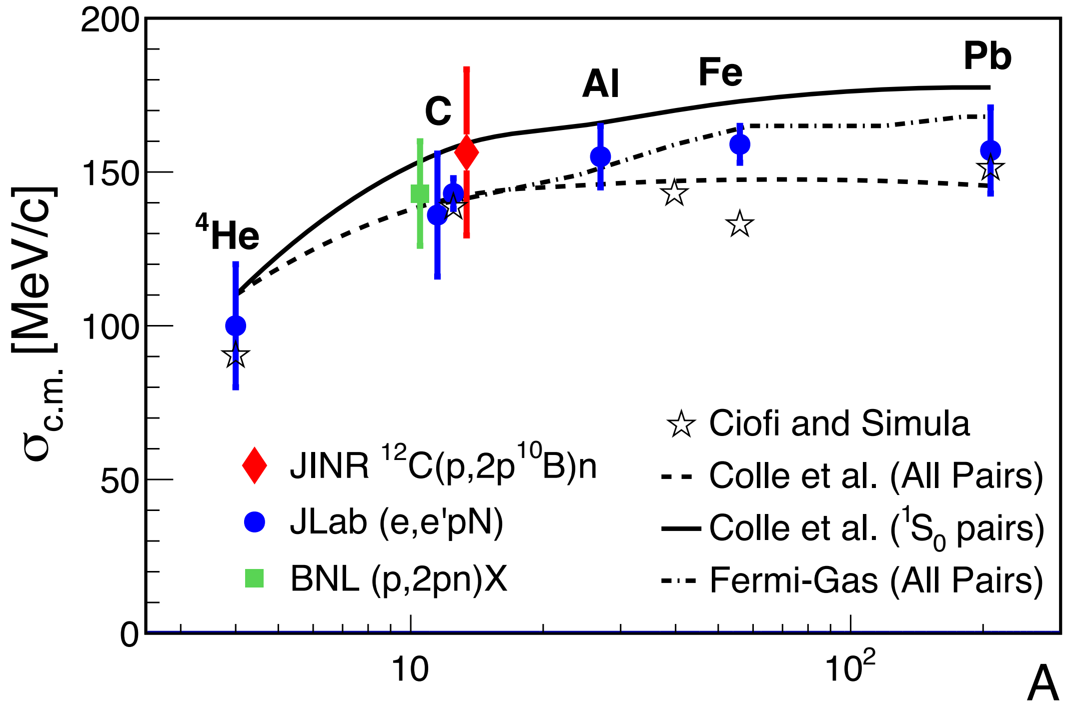
$\sigma_{CM} = 100$ MeV

$\sigma_{CM} = 150$ MeV

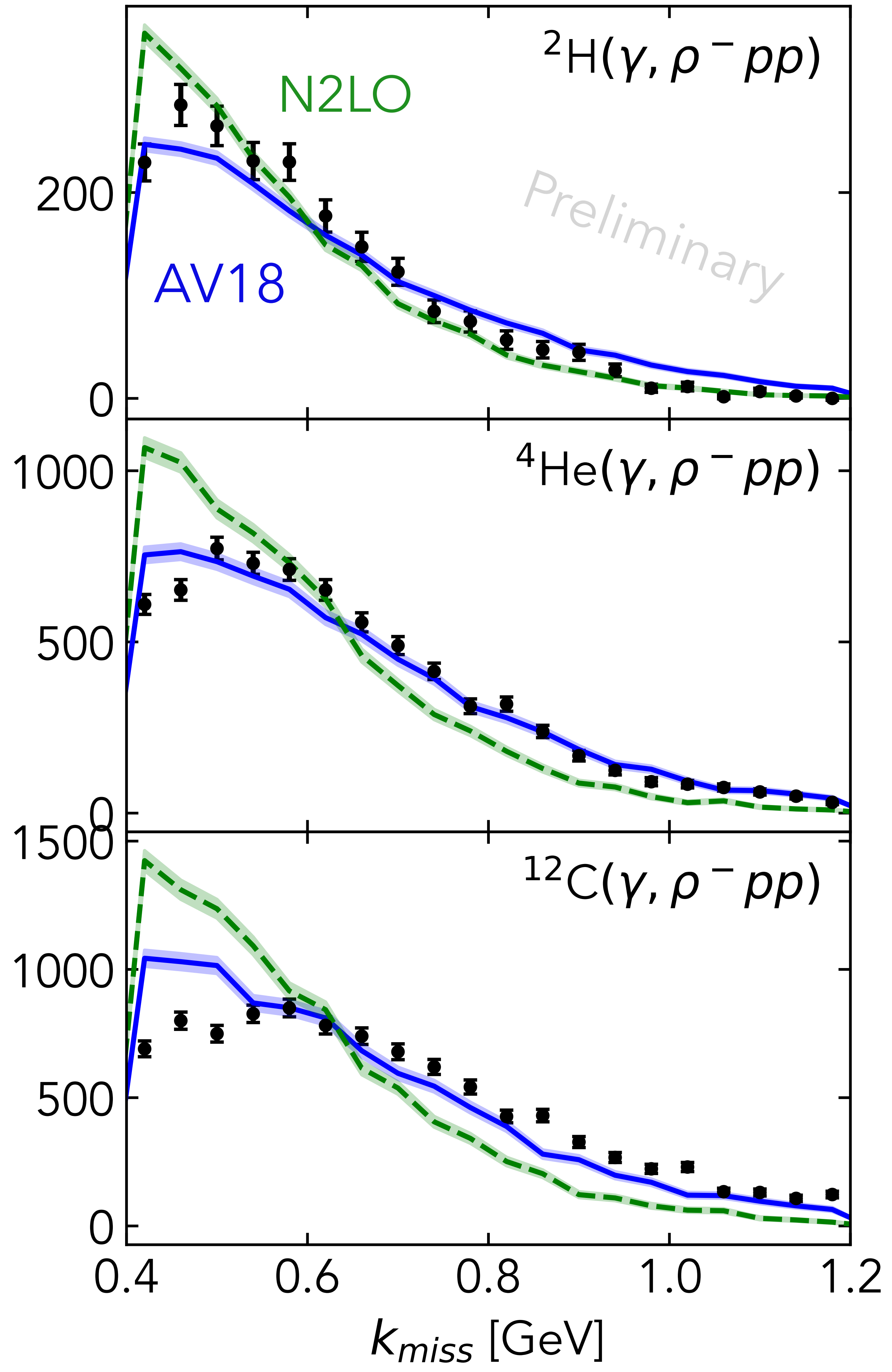


- Transverse component of center-of-mass momentum used to limit FSI and cross section effects
- General trend with A agrees with current measurements, but precise value needs to be extracted and compared

GCF Input

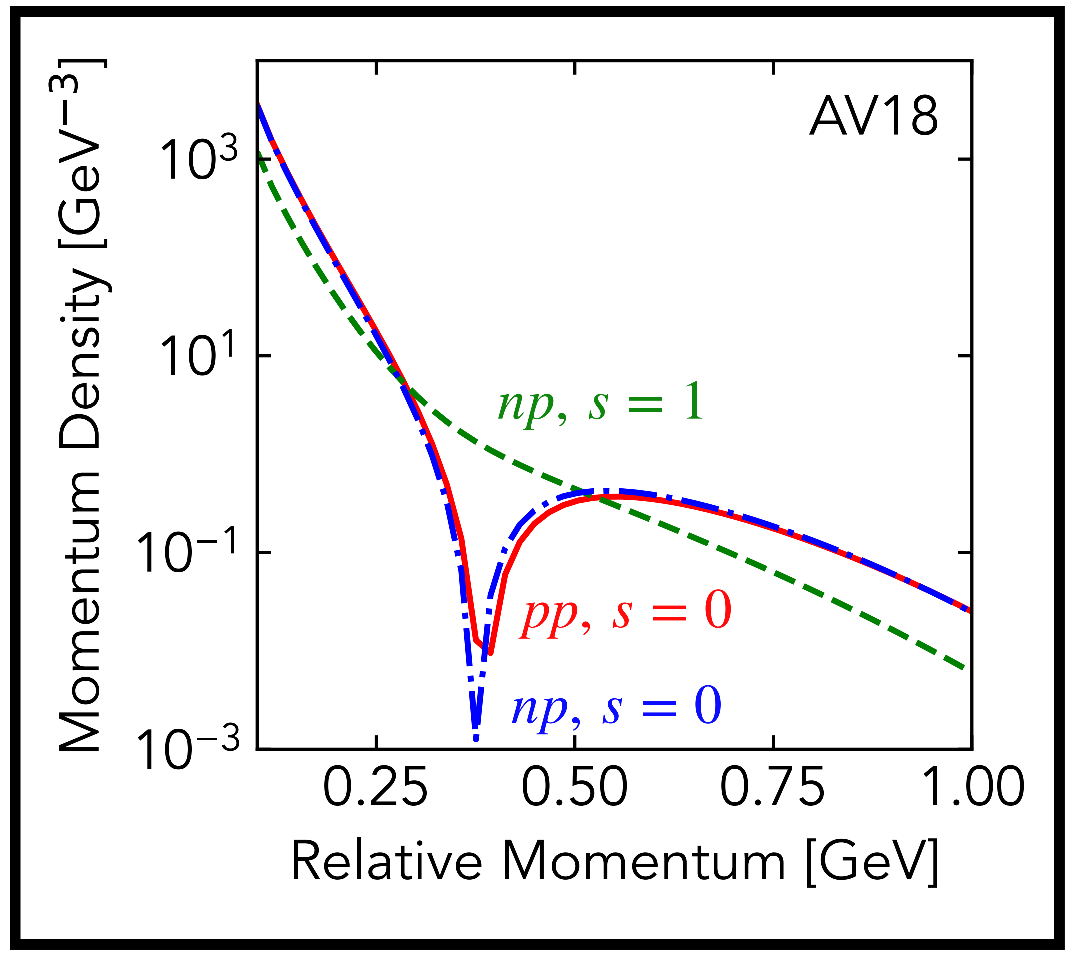


Initial Neutron Momentum (Proxy)

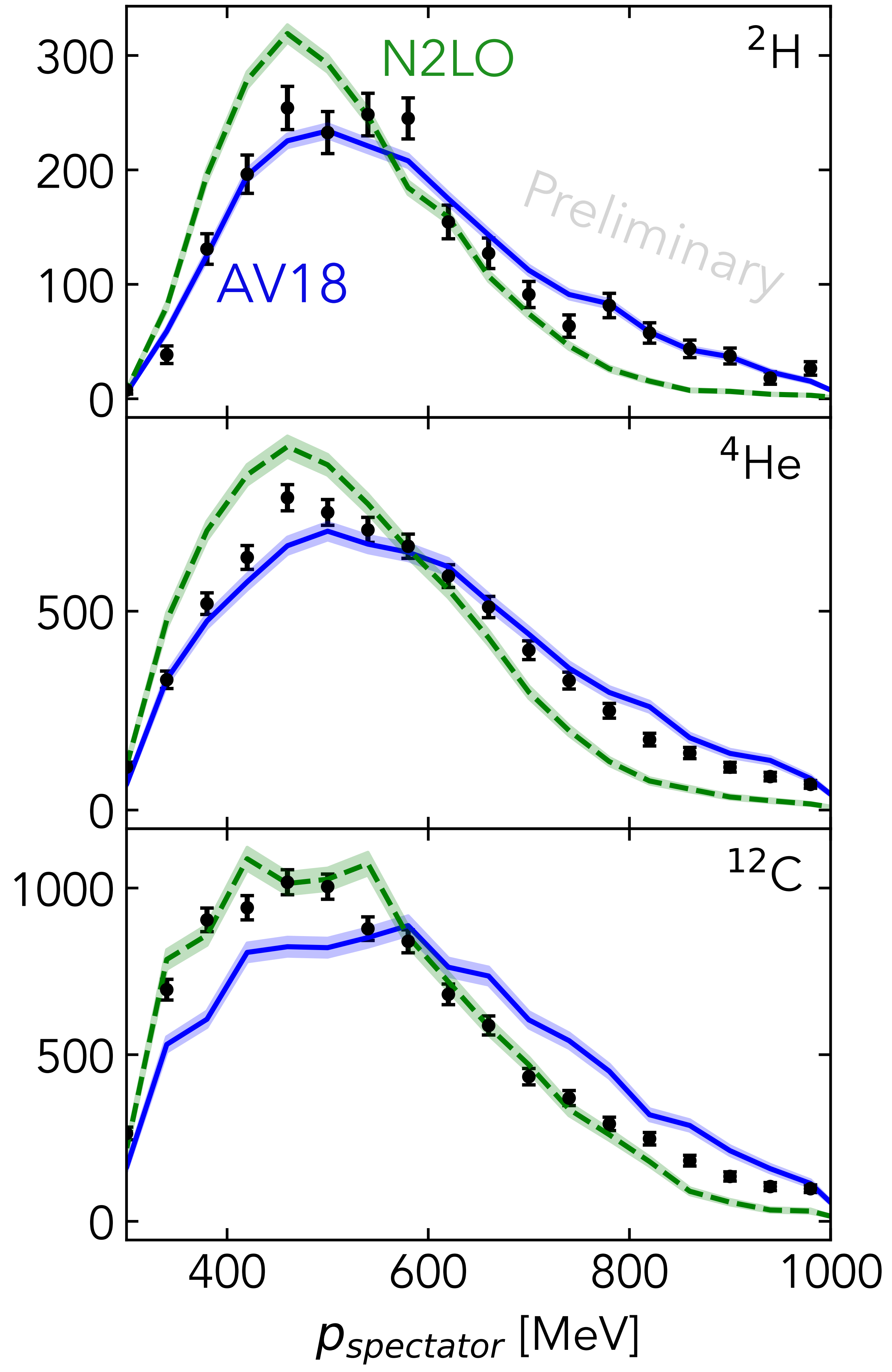


- Initial neutron momentum sensitive to short-distance NN interaction
- Momentum distributions well-described
- Agreement with AV18 predictions similar to that for electron-scattering data

GCF Input

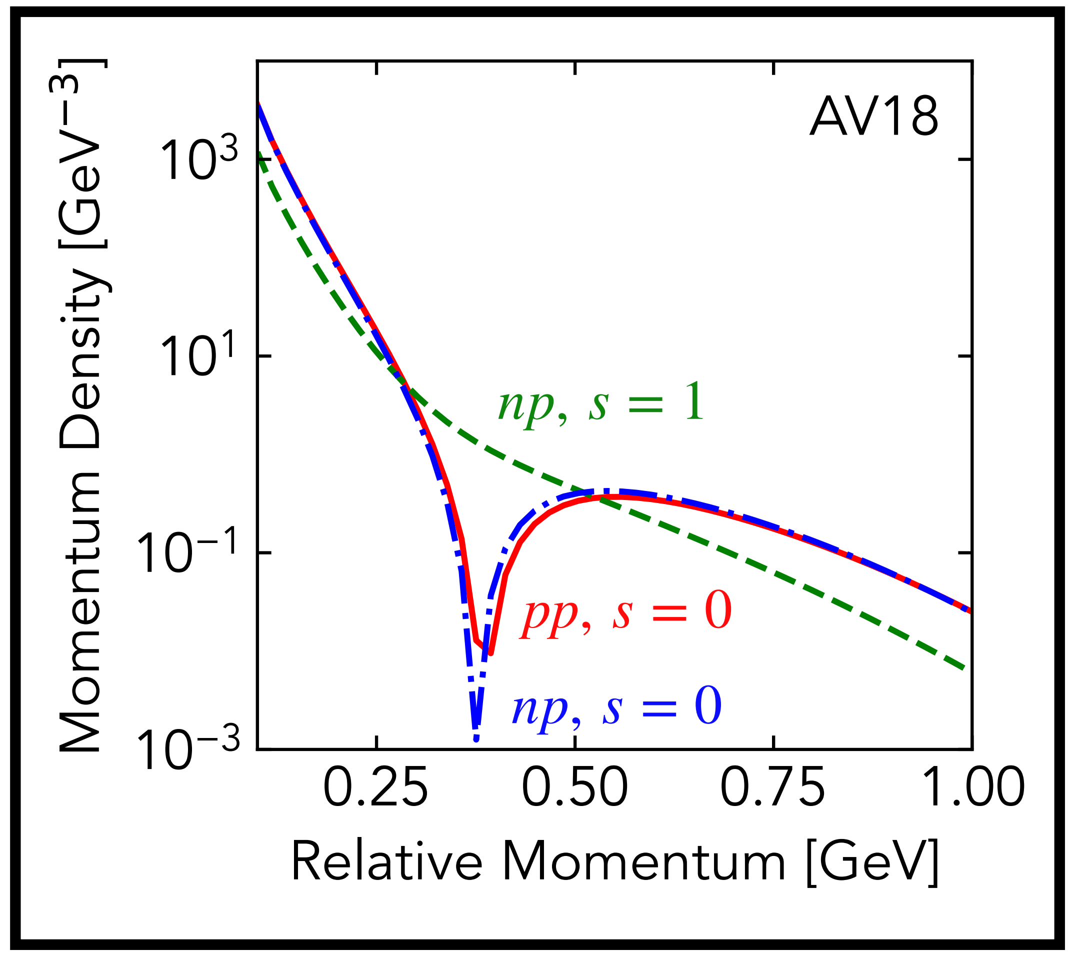


Initial Neutron Momentum (Proxy)



- 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



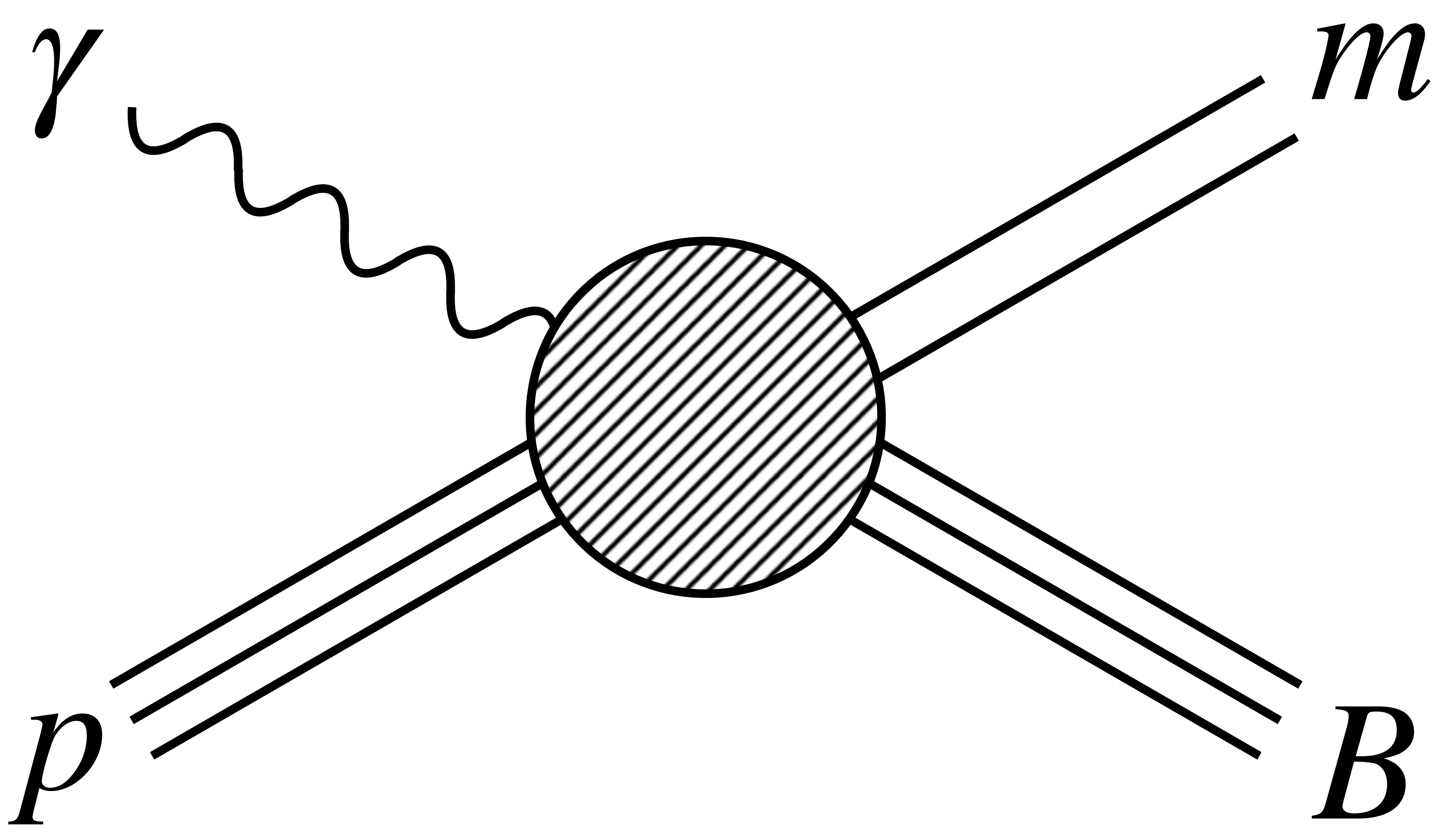
Outlook

- 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
- Complementary $(\rho^0 pp)$ channel allows access to pp pairs, enabling confirmation of isospin structure of SRCs
- Other ongoing projects: color transparency, neutron structure, medium modification

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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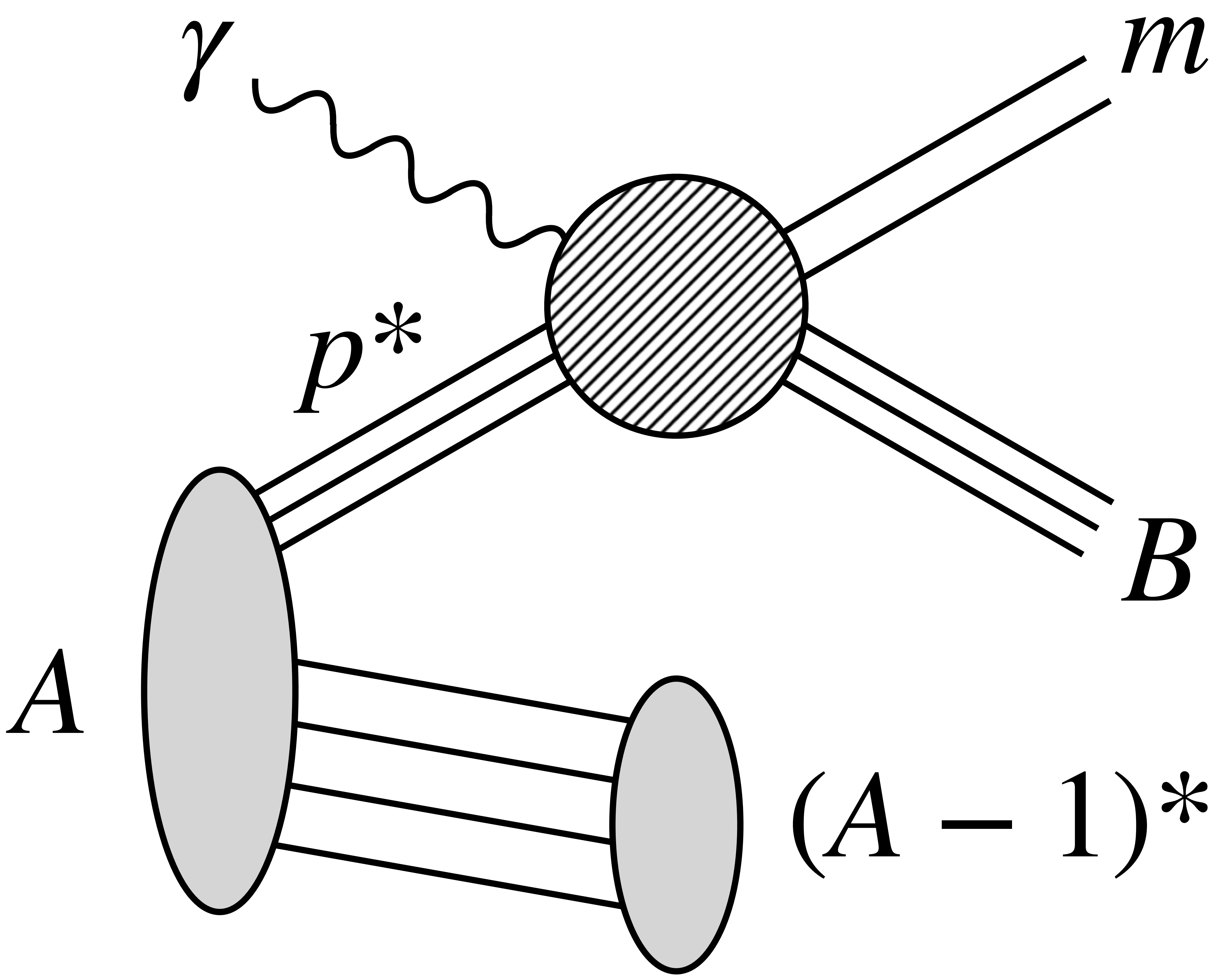
- Photoproduction channels have different sensitivity to proton Fock states



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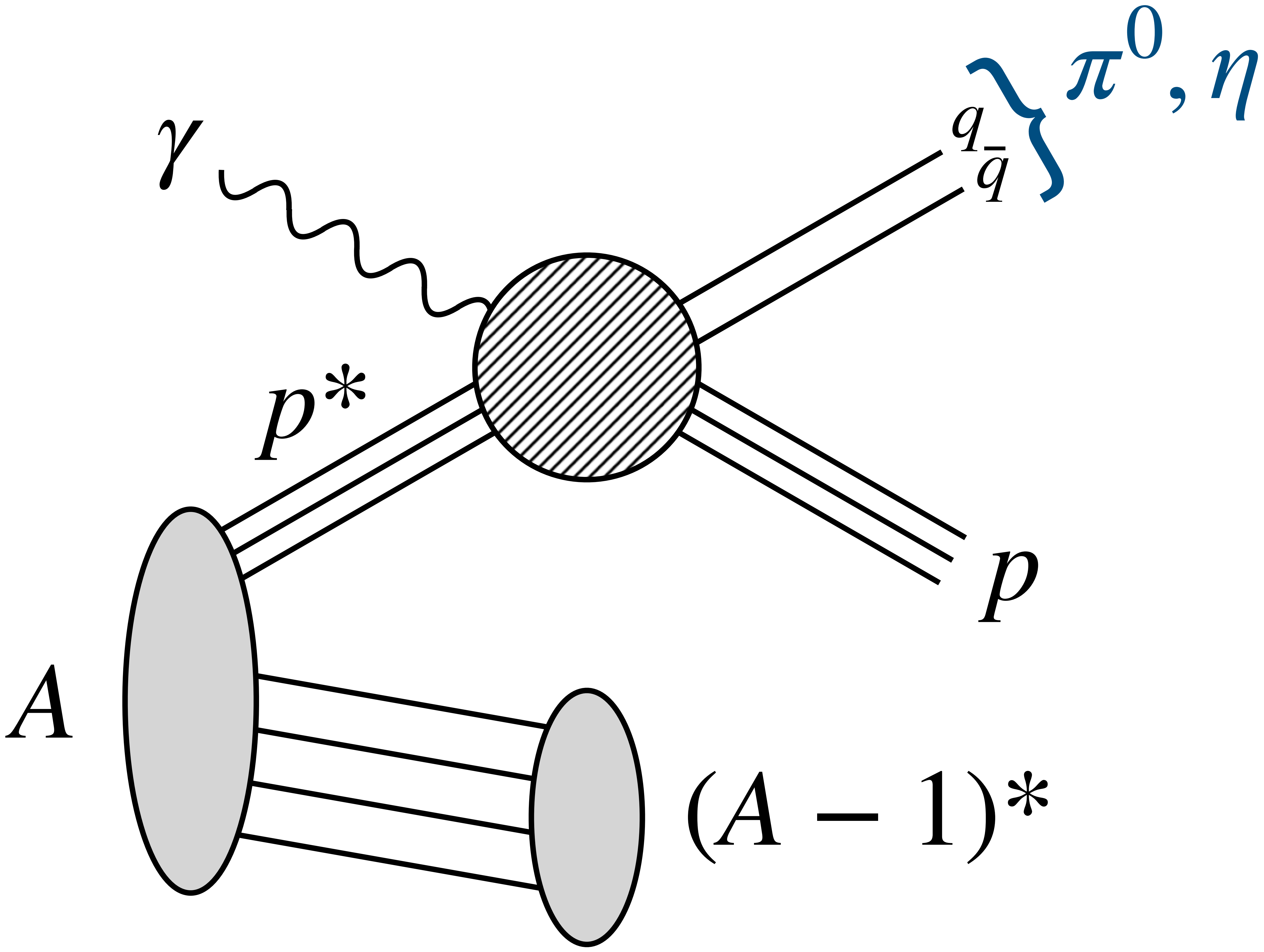

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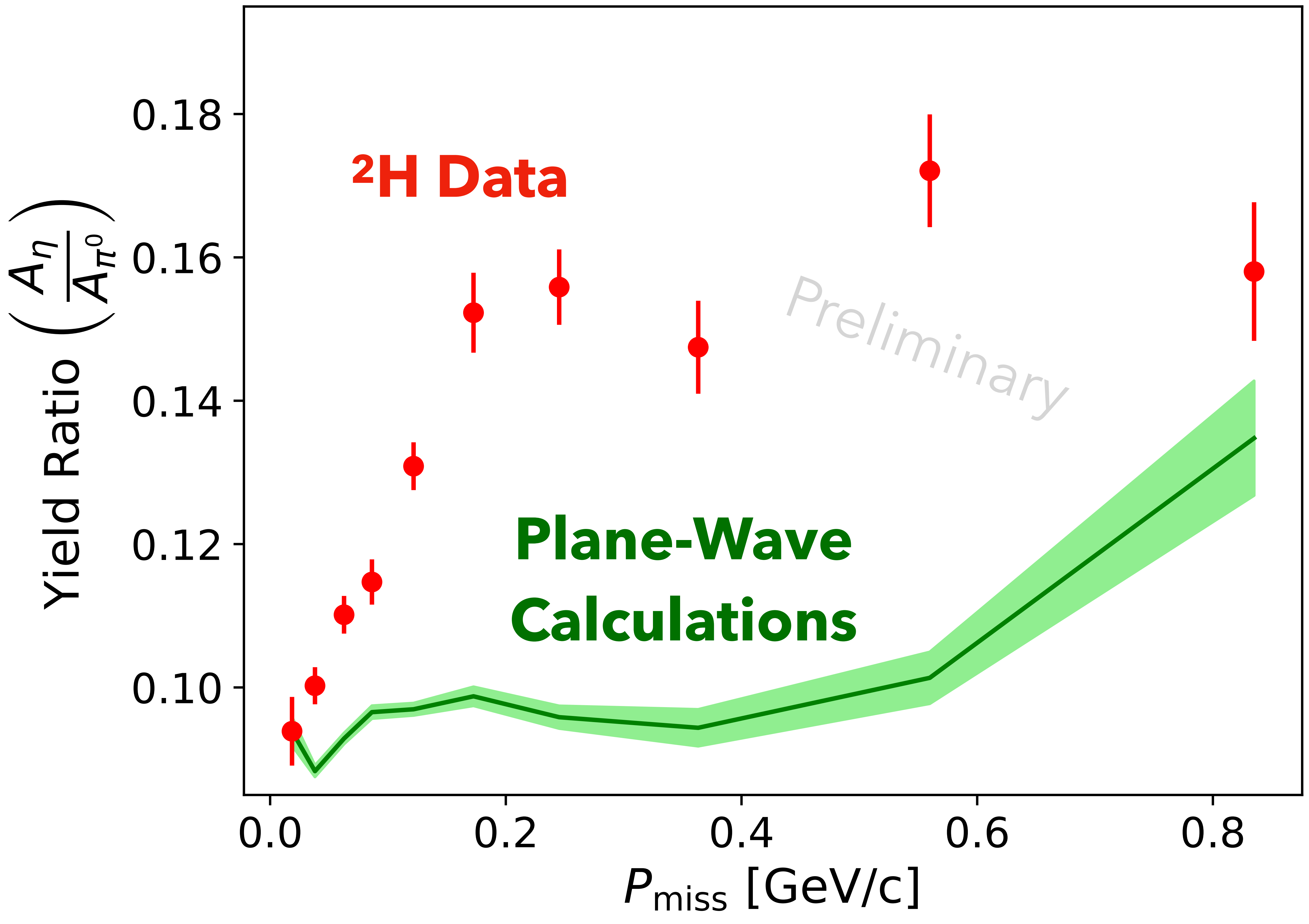
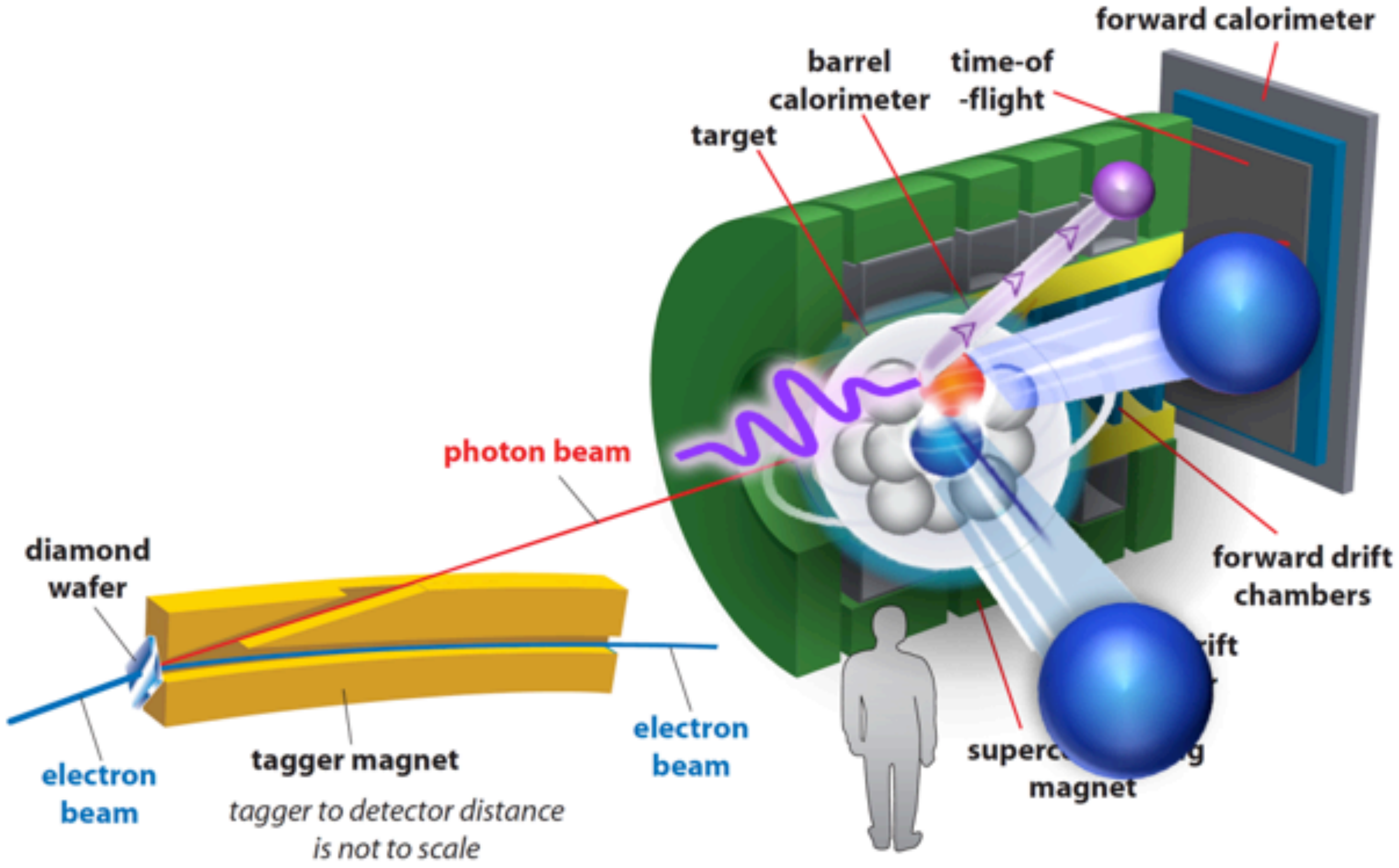


Conclusions

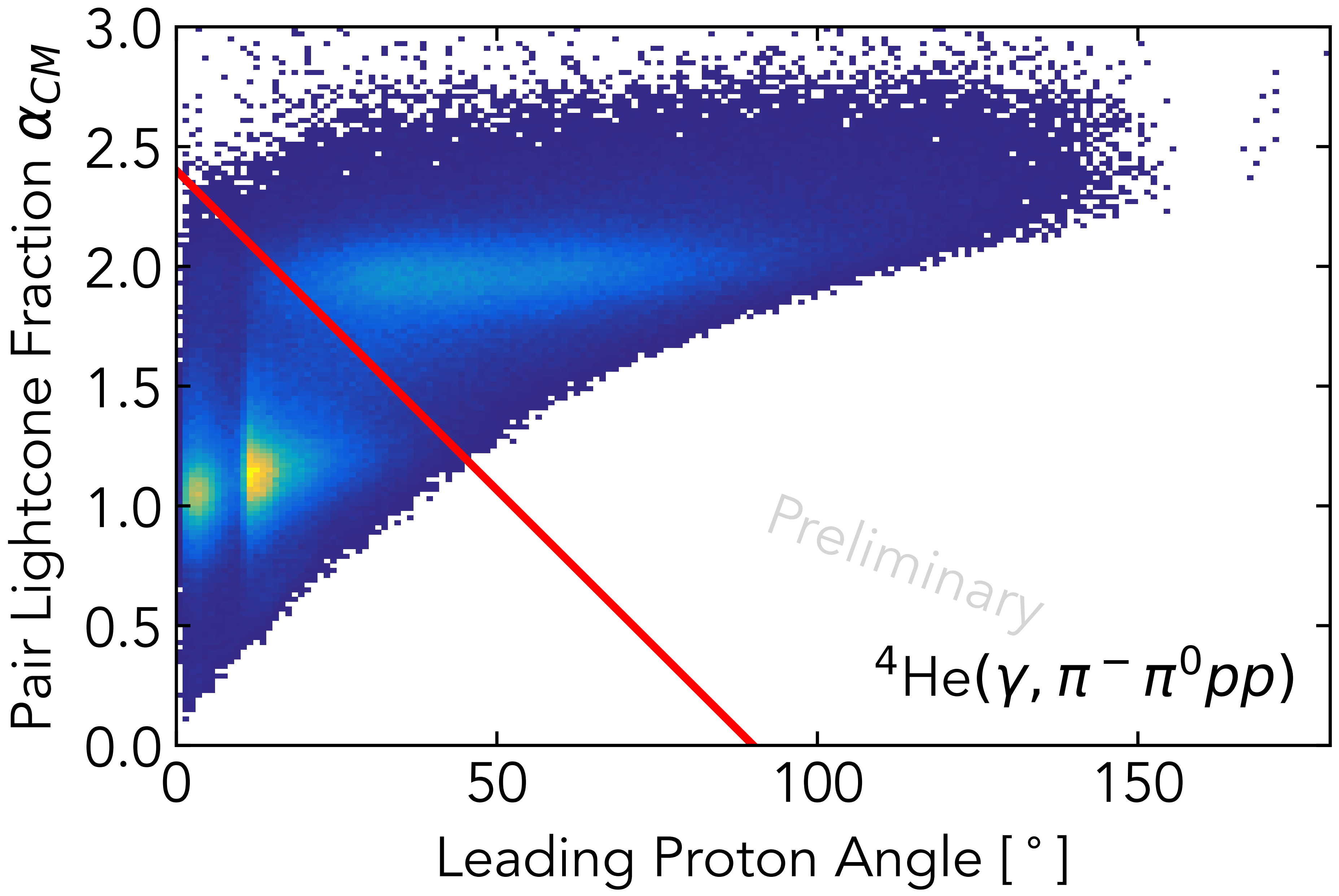
- New high-energy photonuclear data provides independent measure of nuclear SRC properties



Conclusions

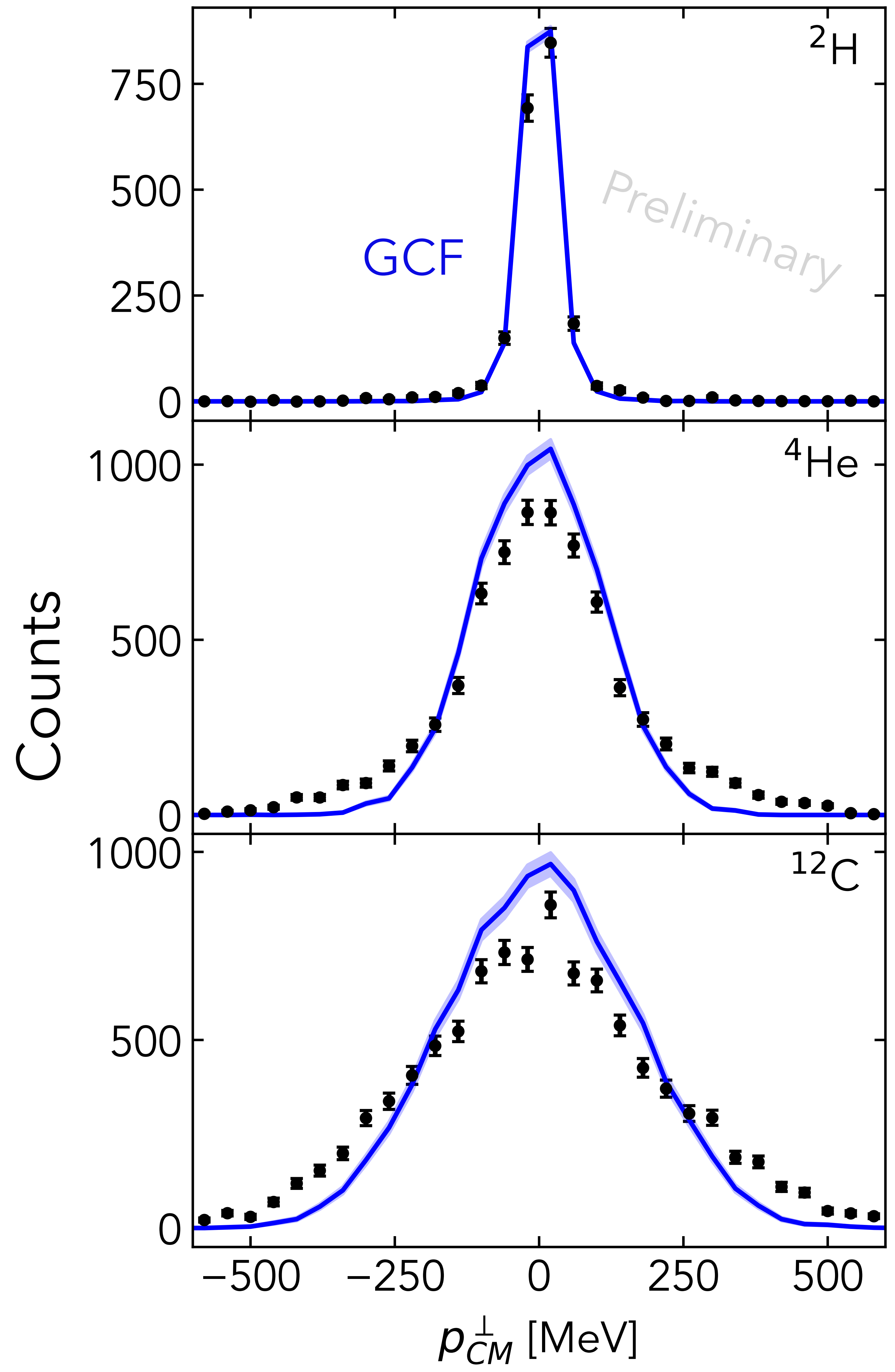
- New high-energy photonuclear data provides independent measure of nuclear SRC properties

- SRC breakup events positively identified in data



Conclusions

- New high-energy photonuclear data provides independent measure of nuclear SRC properties
- SRC breakup events positively identified in data
- SRC properties so far consistent with electron-scattering results and theory calculations, but systematics need to be considered



Backup

“Internal” missing momentum k_{miss}

- “Internal” momentum defined in Frankfurt & Strikman 1981 Phys Rep.

$$k = \sqrt{\frac{m^2 + k_\perp^2}{\alpha(2-\alpha)} - m^2} \qquad \alpha = 1 + k_3/\sqrt{m^2 + k^2}\,.$$

- In the light-front deuteron model this variable controls the magnitude of the NN interaction between the nucleons

“Internal” missing momentum k_{miss}

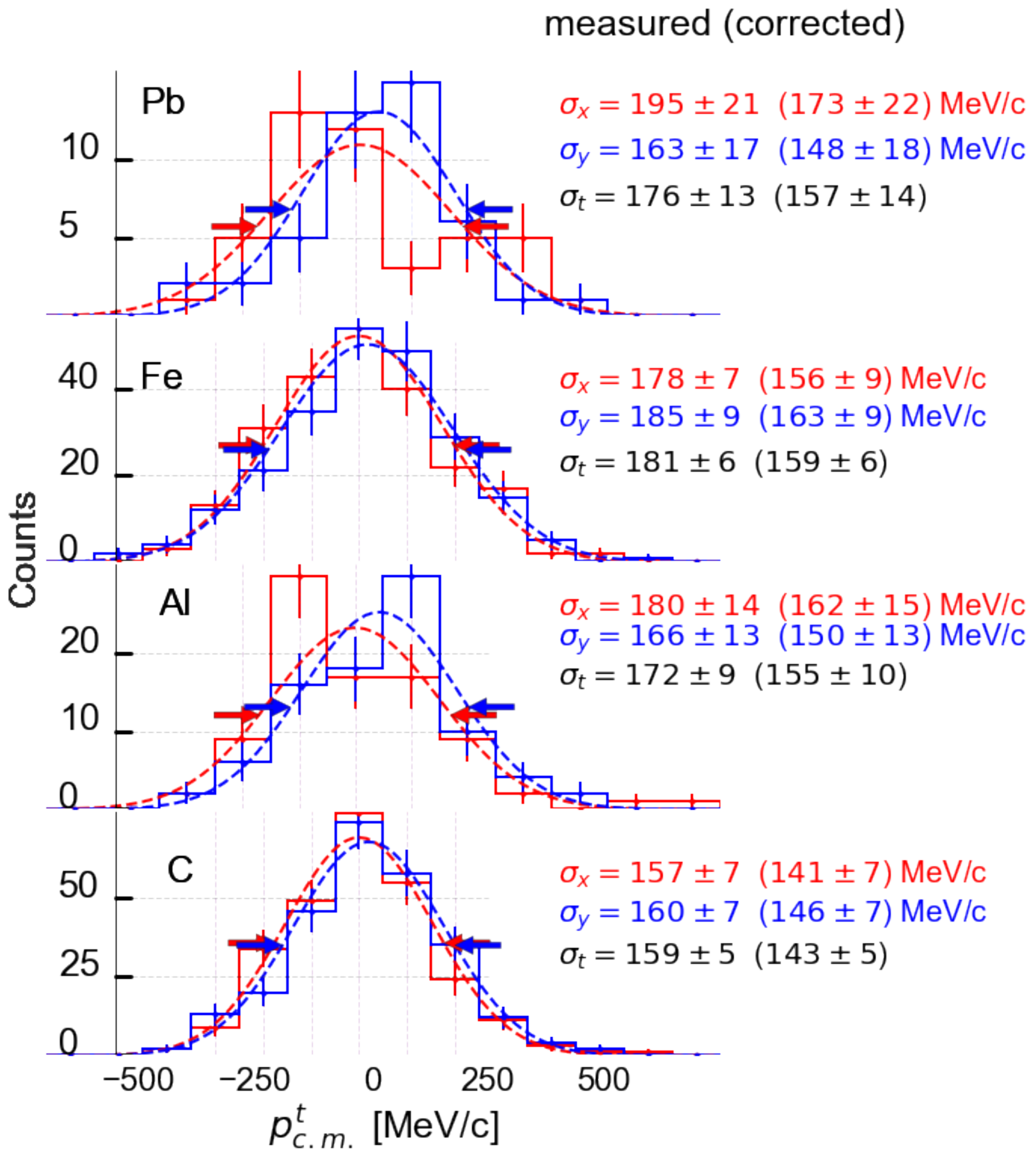
- Internal momentum can be calculated assuming a standing pair approximation, defining :

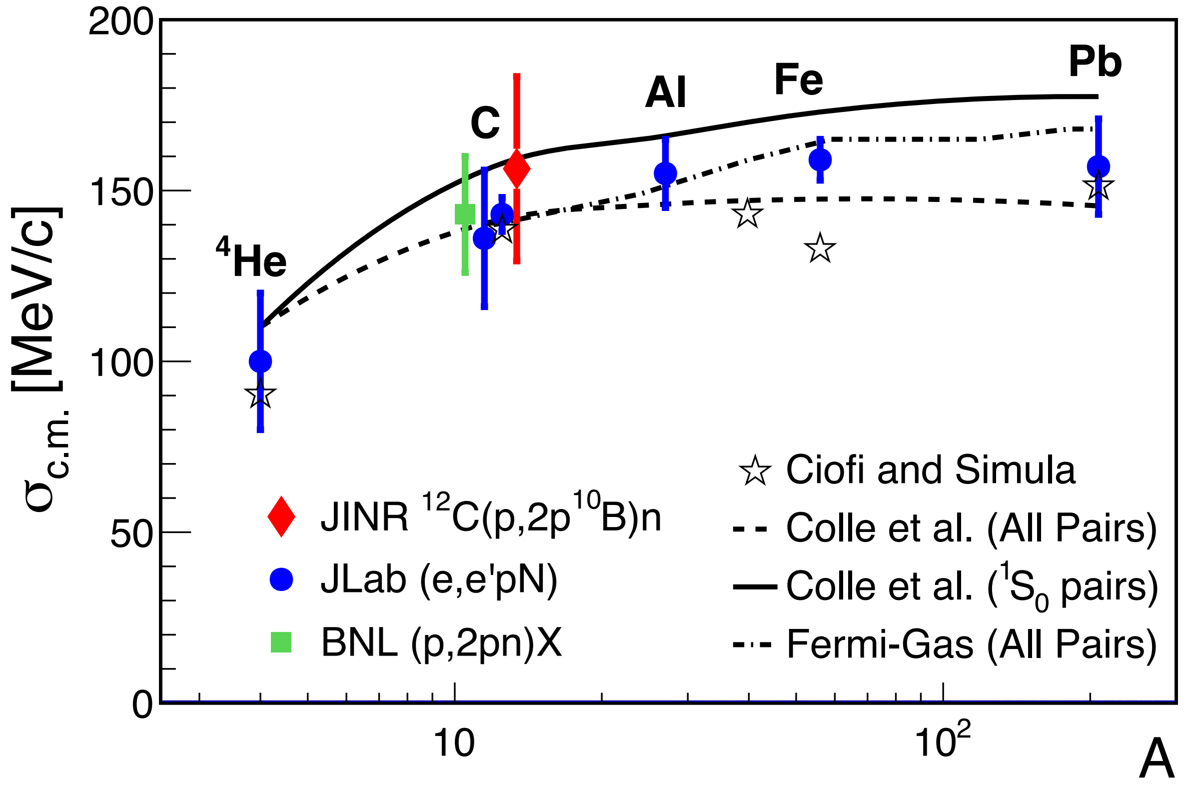
$$k_{miss} = m_N \sqrt{\frac{m_N^2 + p_{miss,\perp}^2}{p_{miss}^- \left(2m_N - p_{miss}^-\right)} - 1}$$

- This variable can be calculated using only quantities well-measured in the GlueX detector

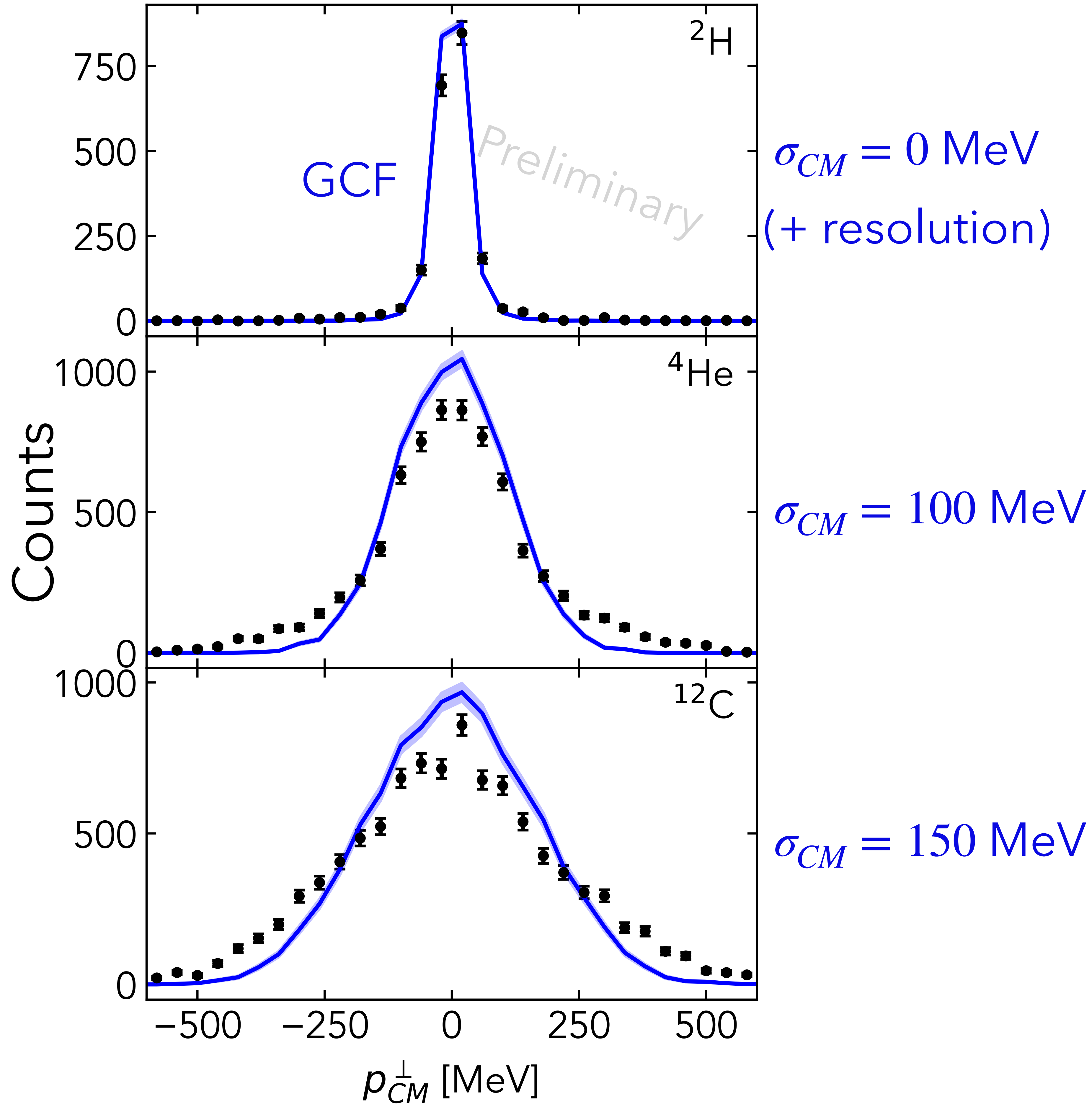
SRC center-of-mass motion consistent between probes

CM momentum width extracted from electron-scattering data





GCF shows consistency with photoproduction data



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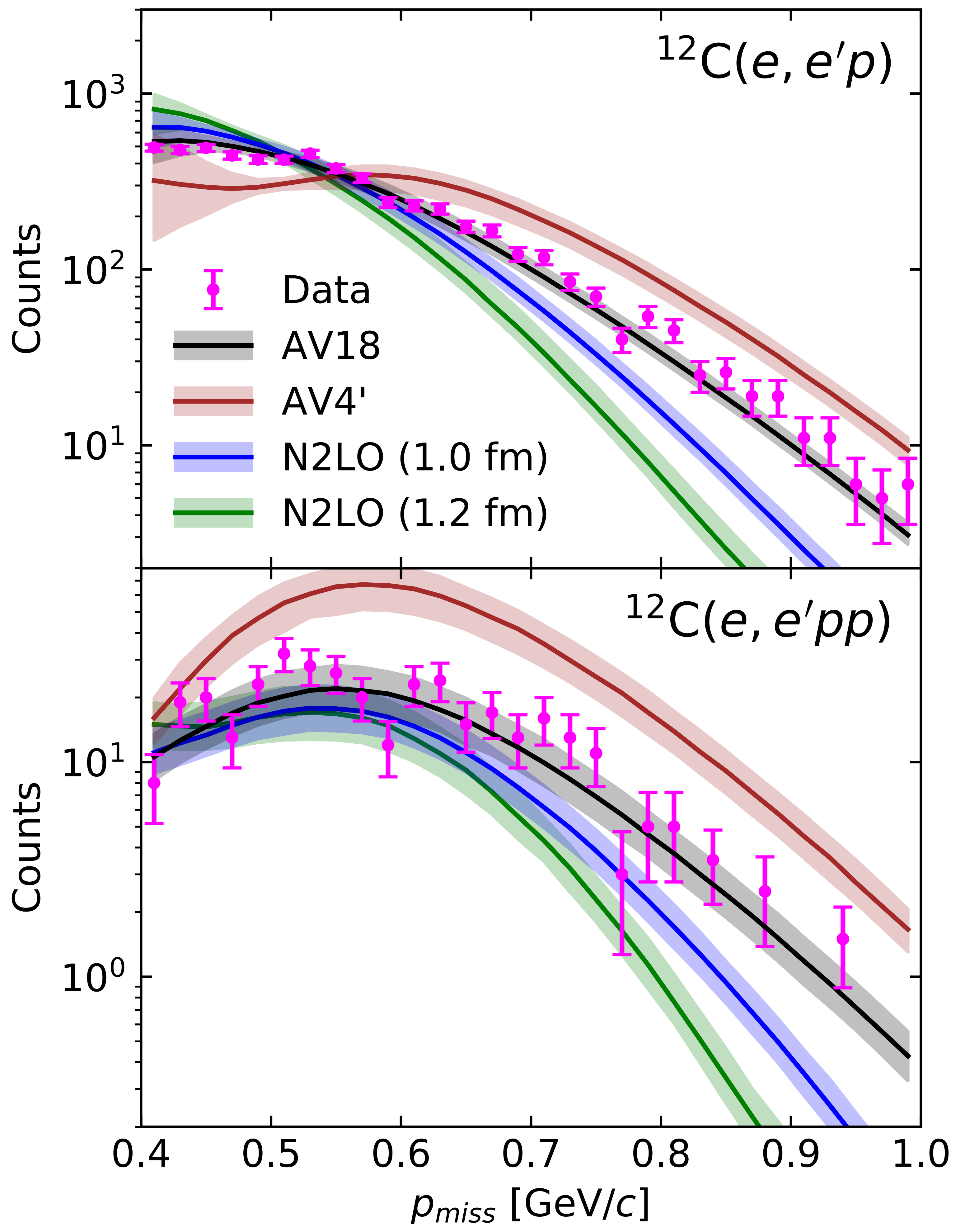
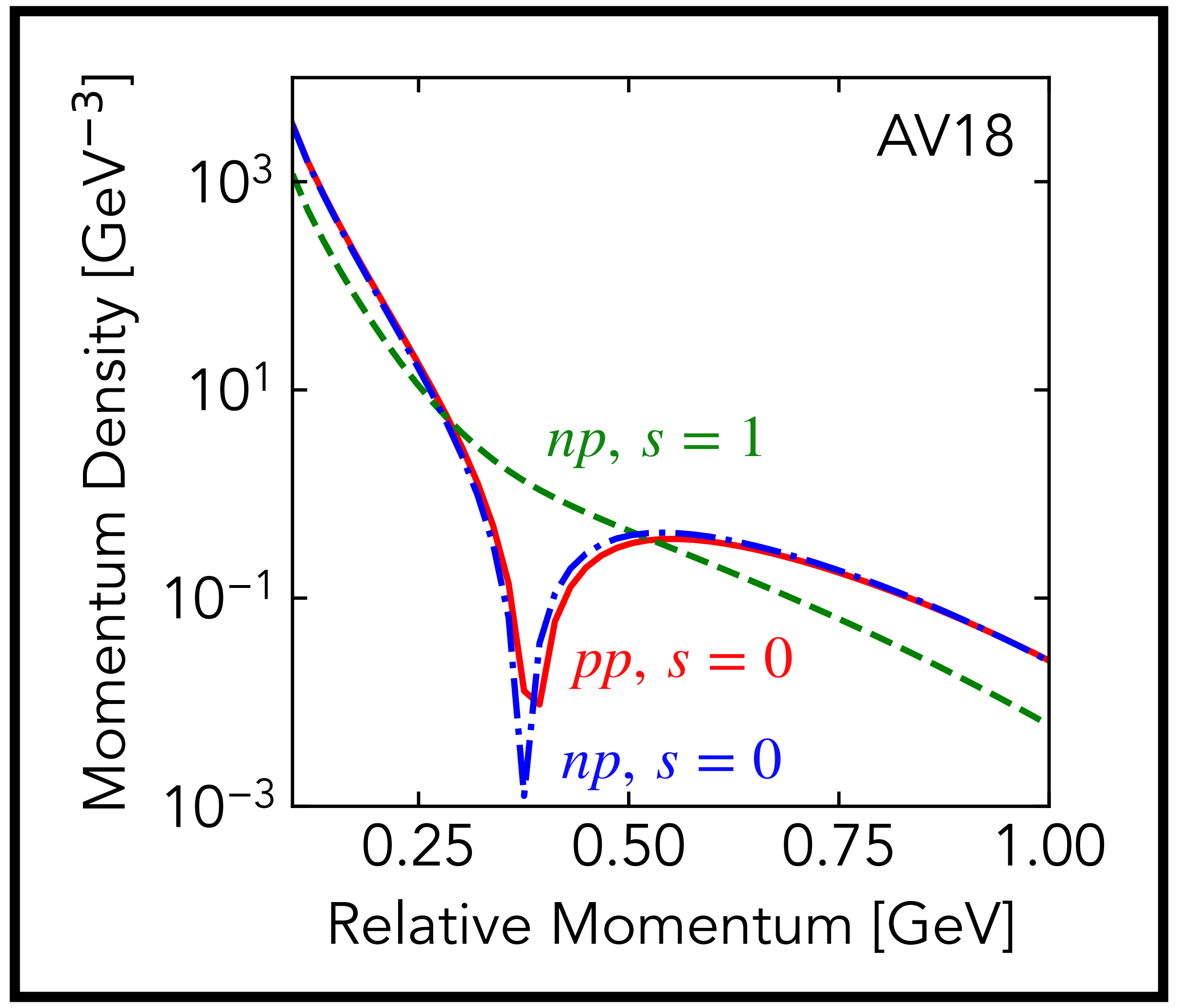
Neutron initial momentum sensitive to NN interaction

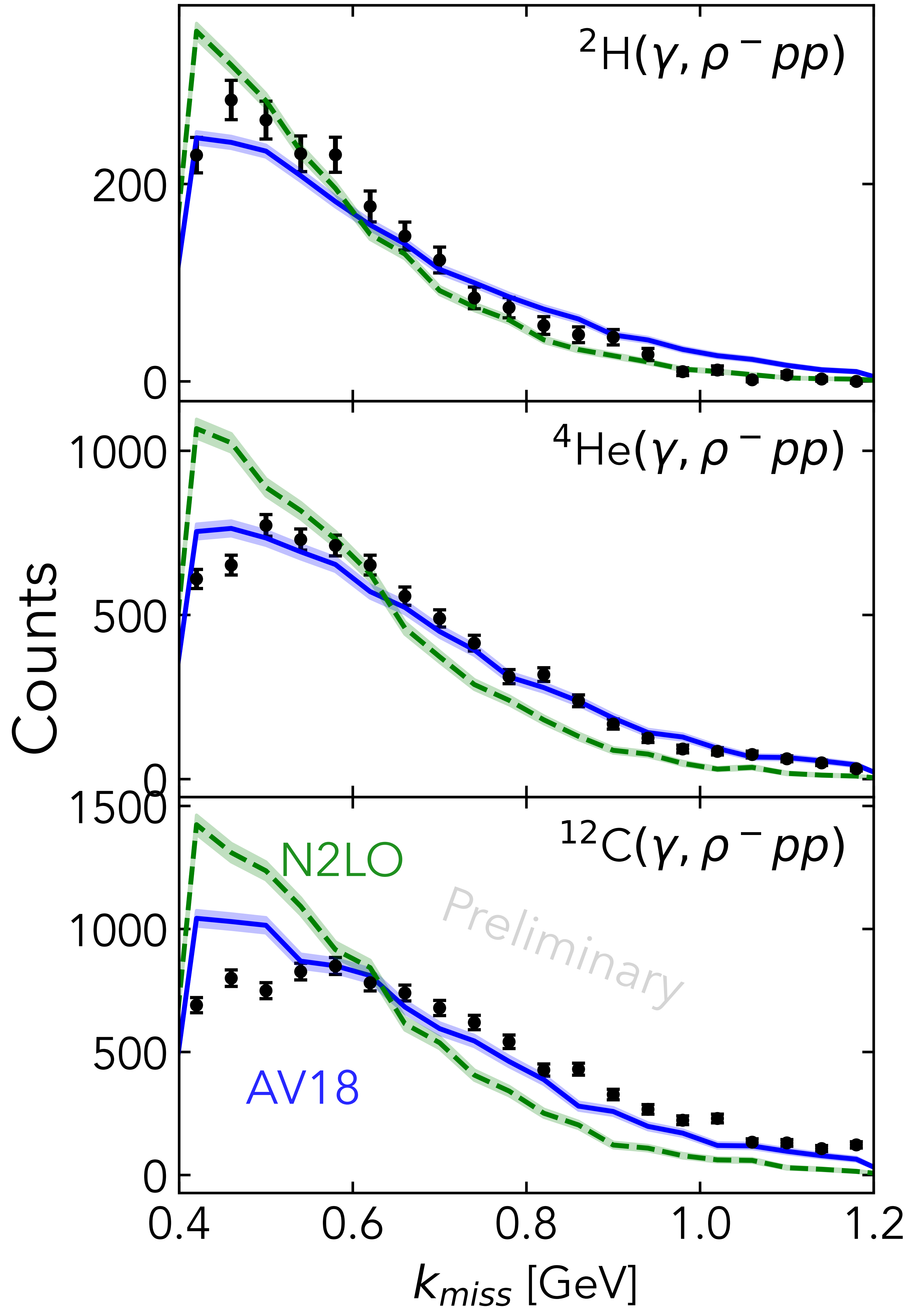
Electron Scattering



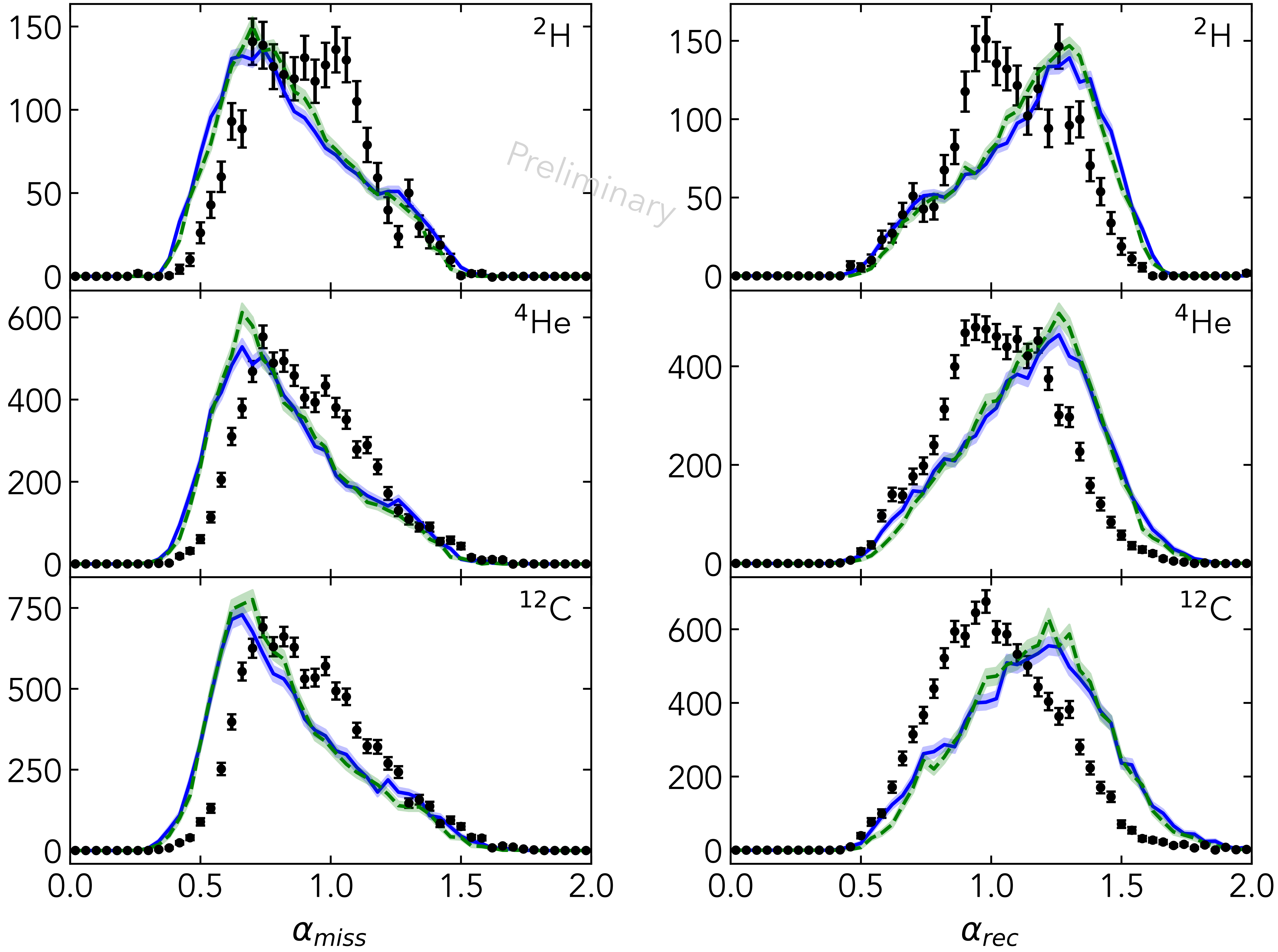


Theory calculations for pair internal momentum

Photon Scattering



Missing and Recoil Lightcone Fraction



- Distortion possible indication of incorrect γN cross section modeling
  - Strong cross section energy-dependence has large impact on α distributions
- FSI should also be considered as possible cause of distortion

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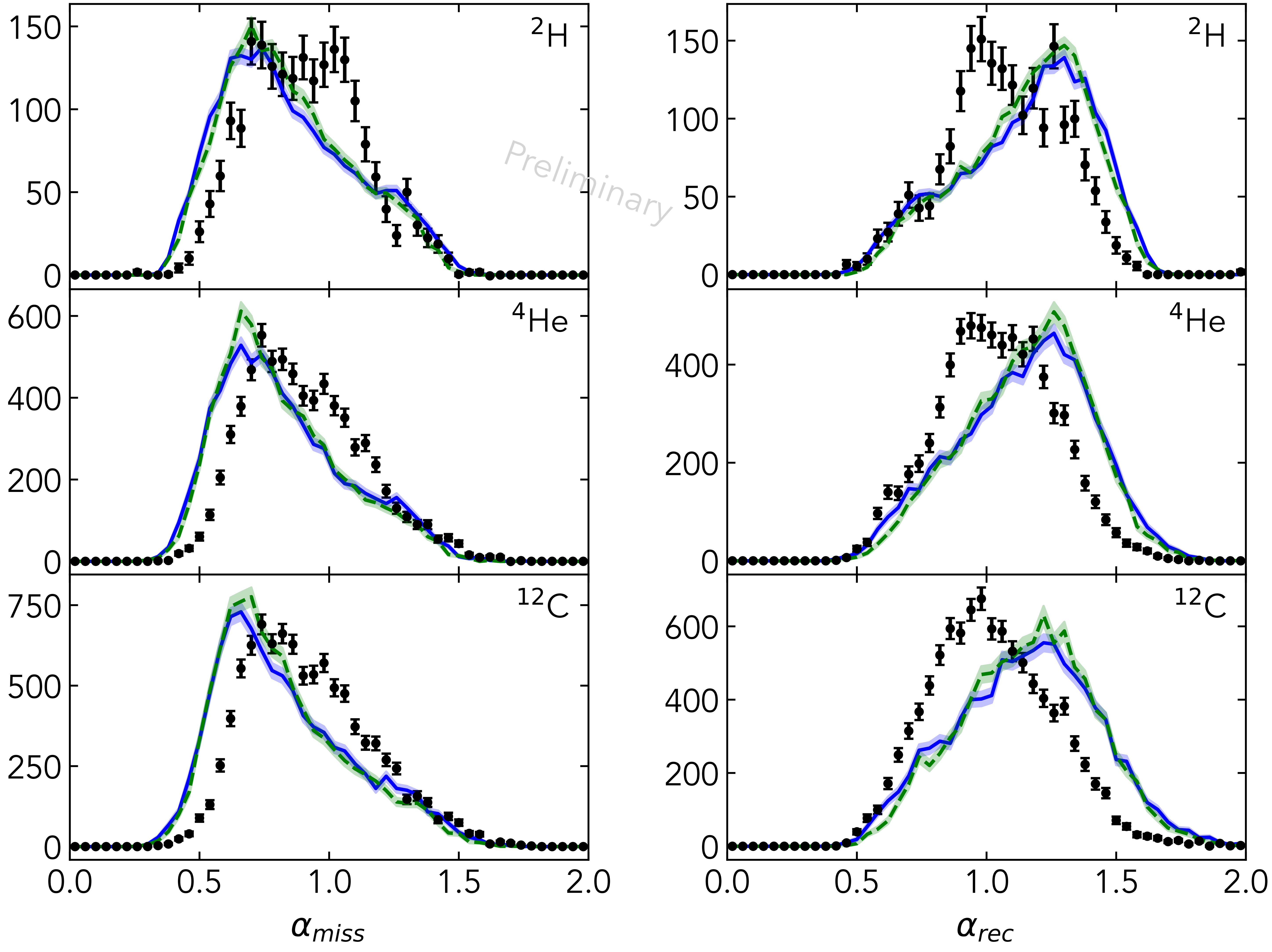

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