# Testing the Universality of Nuclear Short-Range Correlations

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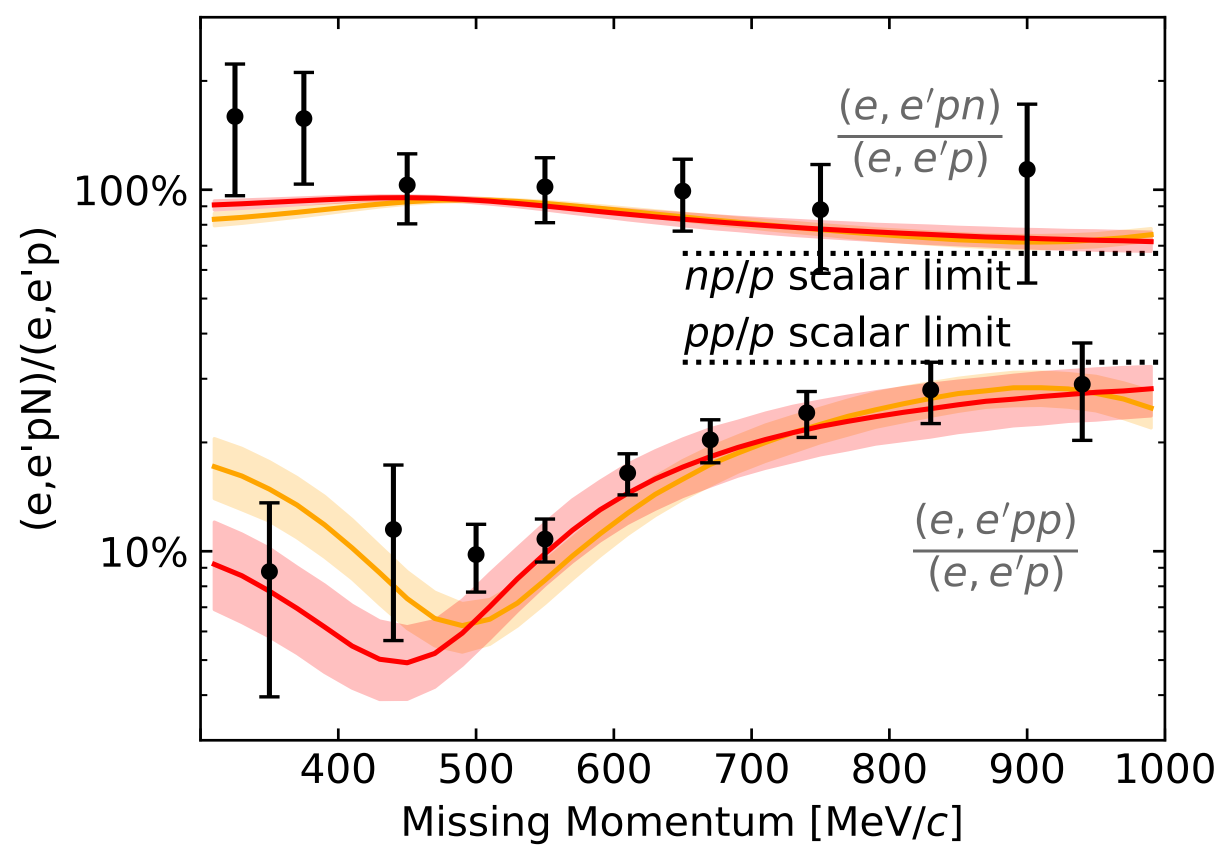
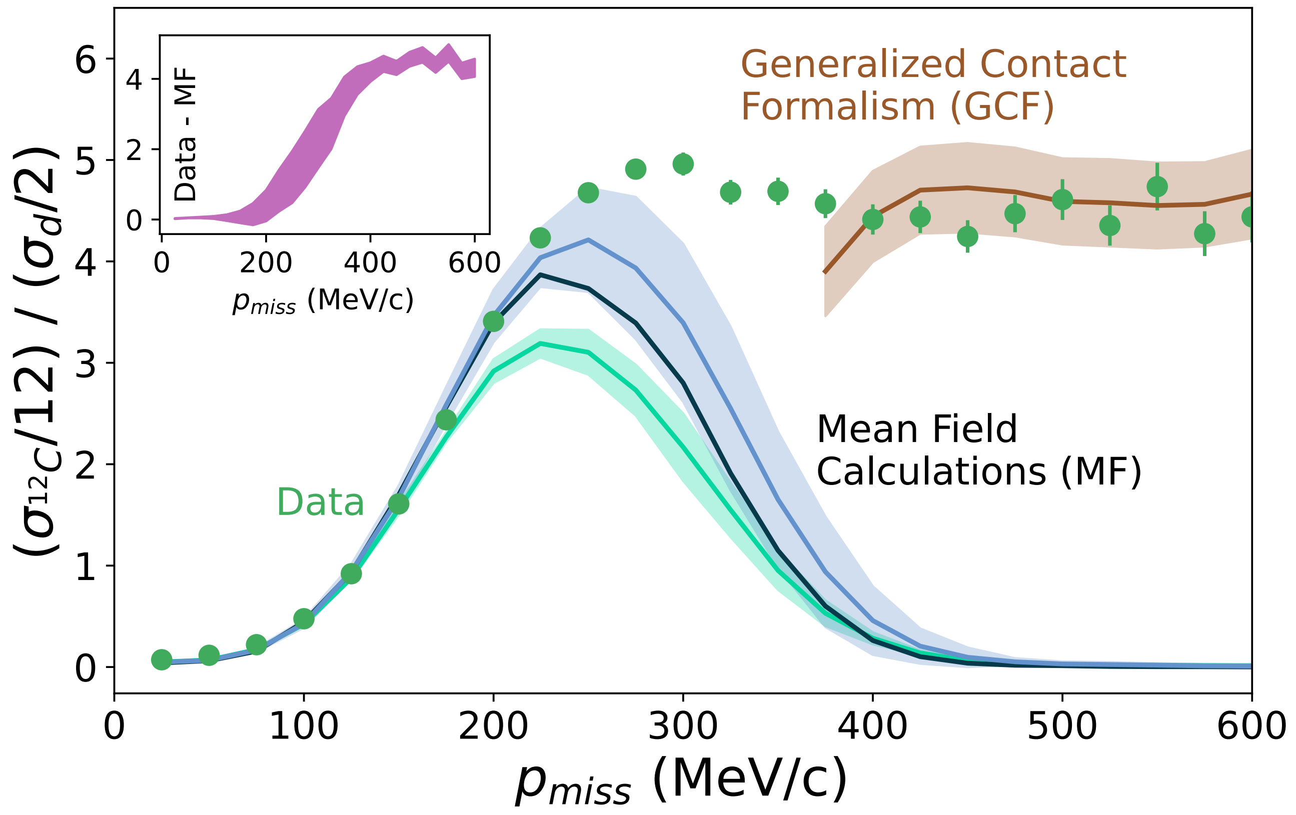
# What do we know about SRCs?

- Compose 10-20% of the nucleus
- Dominate high-momentum states
- Predominantly neutron-proton pairs
- Universal momentum distributions across nuclei




**PRC 2023**

**Nature Physics 2021**

**Nature Physics 2021**

**PLB 2021**

**PRC Lett 2021**

**Nature 2020**

**PLB 2020**

**PRL 2019**

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**Nature 2018**

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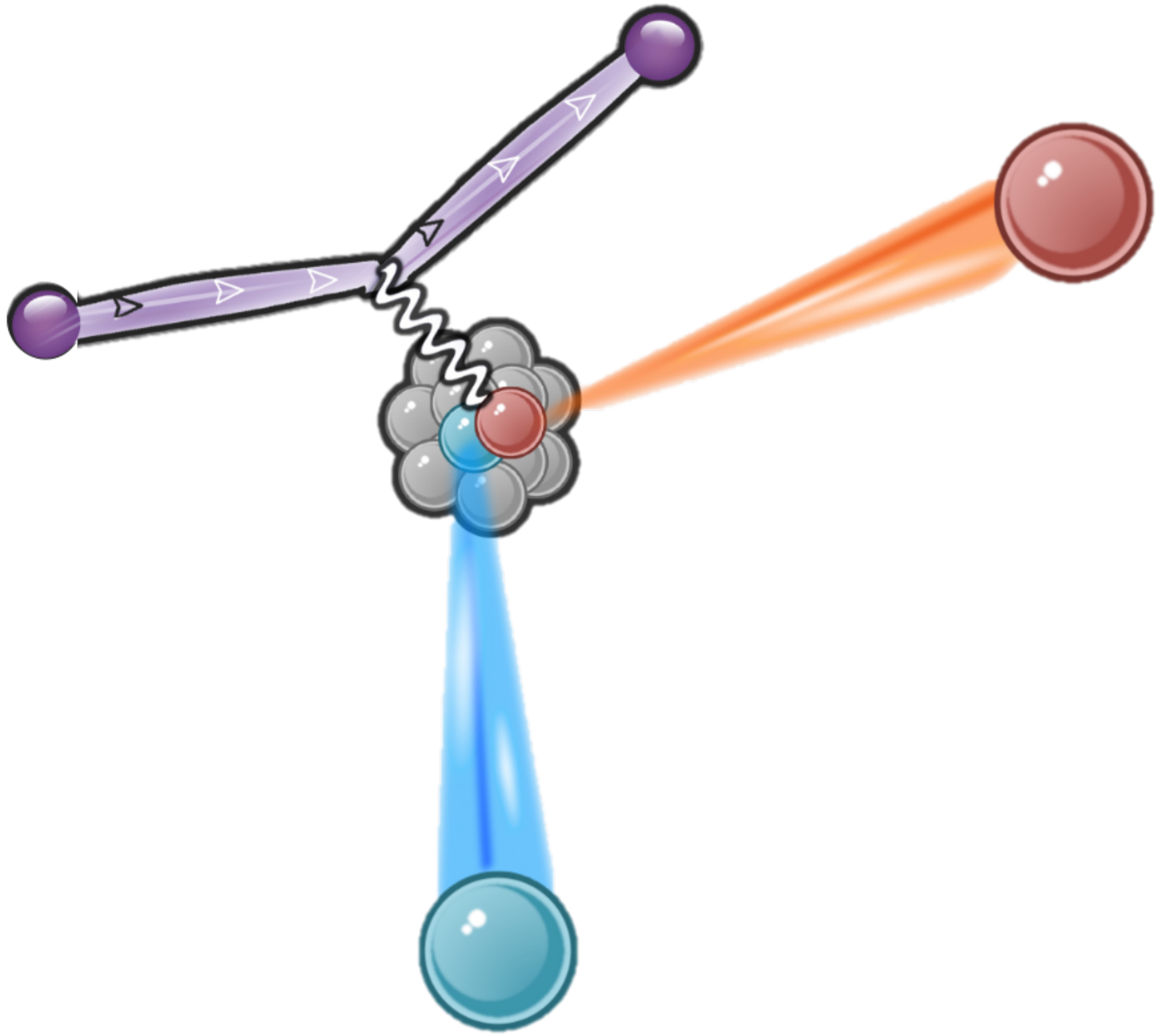
# Interpreting SRC results requires two things:

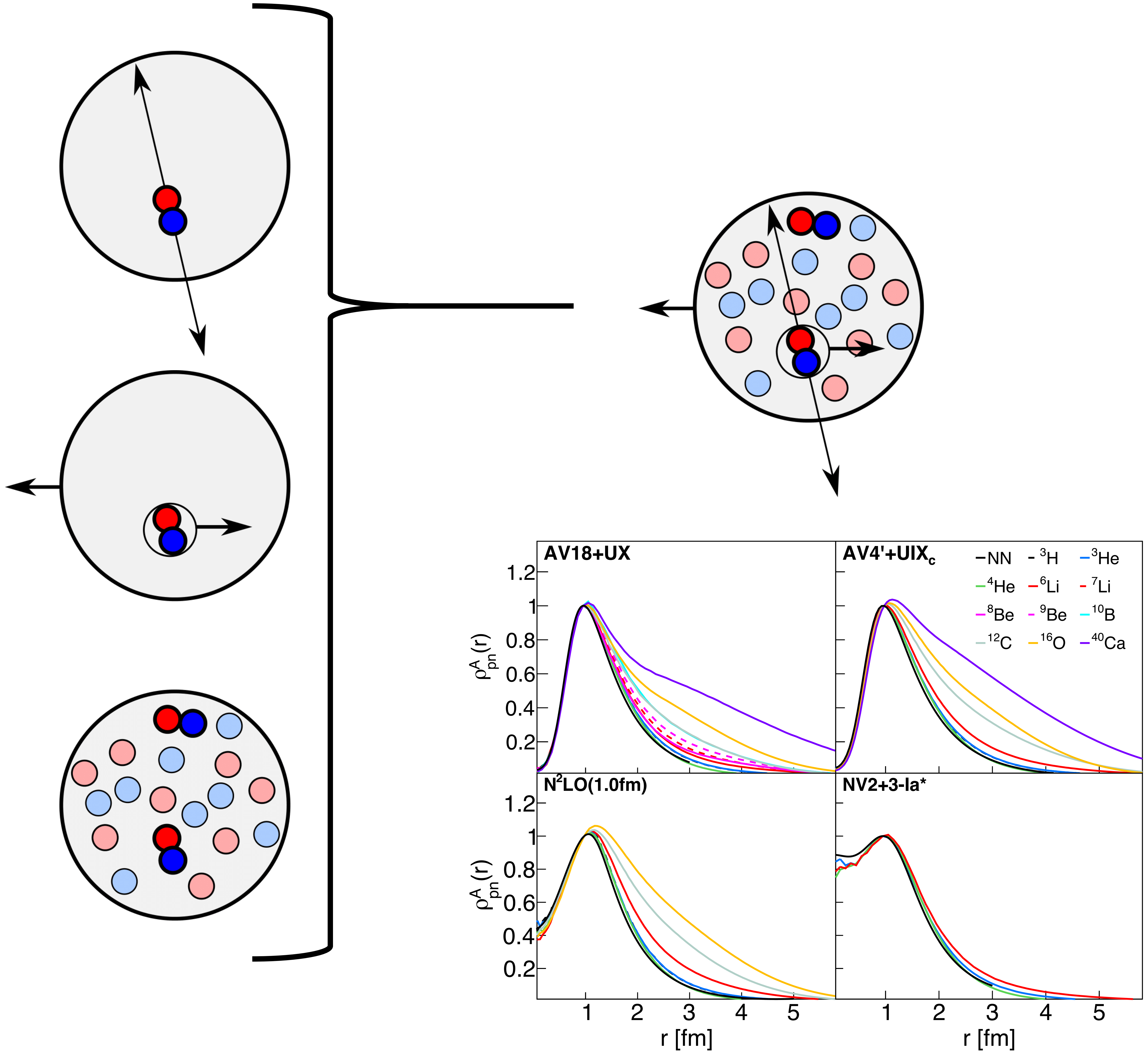
1. Clean measurements of SRC breakup using two-nucleon knockout



# Interpreting SRC results requires two things:

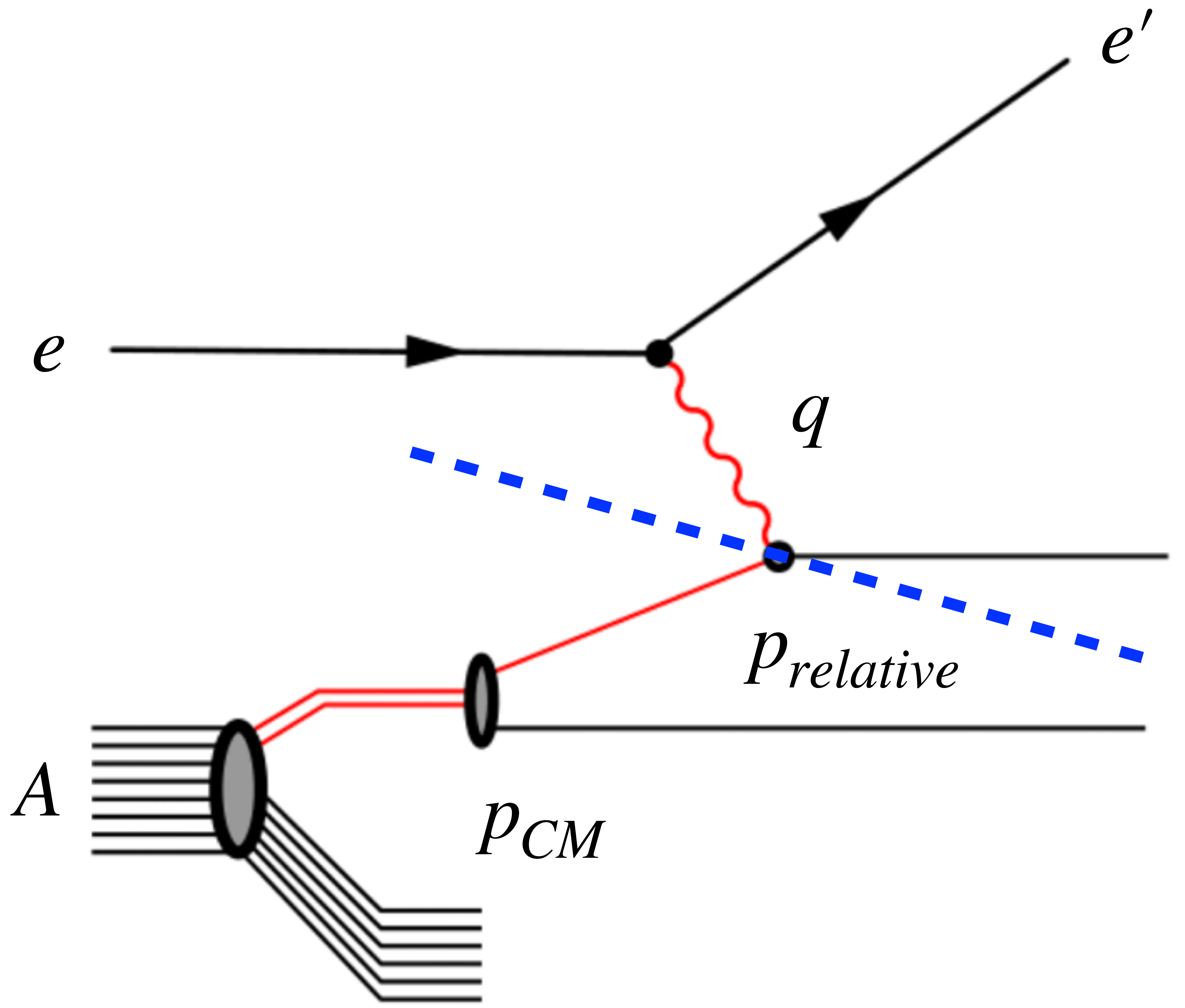
1. Clean measurements of SRC breakup using two-nucleon knockout

2. Model of the SRC component of the nuclear ground-state




**Cruz-Torres et al., Nature Physics (2021)**
Weiss et al., Phys. Lett. B 780 (2018)
Weiss, Bazak, Barnea, Phys. Rev. C 92 (2015)
Tropiano et al., Phys. Rev. C 104, 034311 (2021)
Lynn et al., JPG 47, 045109 (2020)
Chen, Detmold, Lynn, Schwenk, PRL 119 (2017)
Ryckebusch et al., Phys. Lett. B 792, 21 (2019)
Ciofi and Simula, Phys. Rev. C 53, 1689 (1996)

# Data and theory can be compared using high-resolution "Plane Wave Impulse Approximation" framework

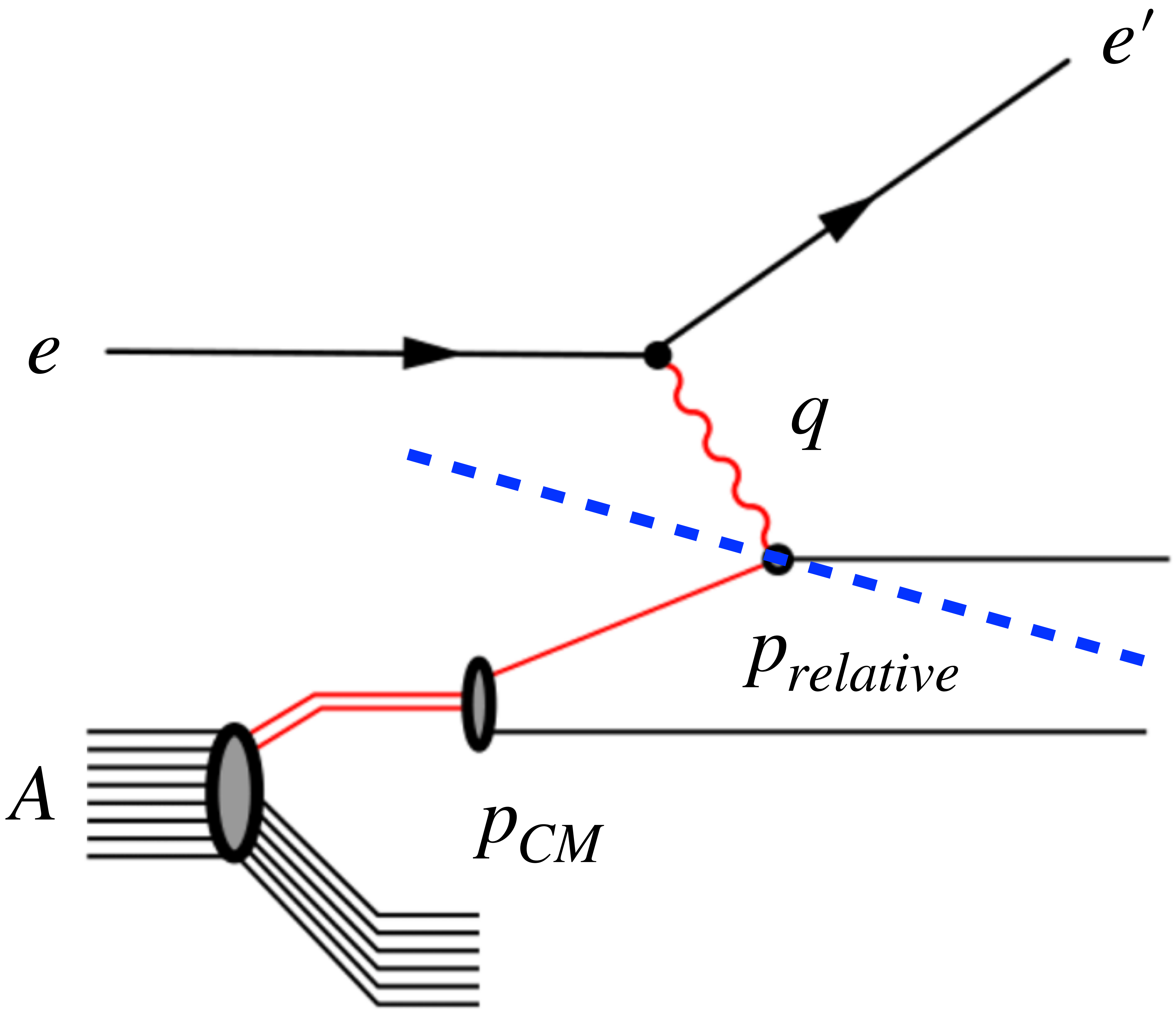



$$\sigma = \sigma_{e,N}(q) \times S(p_i, p_{rec})$$

**Reaction**

**Ground-State**

# PWIA relies on factorization between reaction and ground-state

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- 1-body operator
- Kinematics- and probe- dependent

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- 2-body dynamics
- Universal

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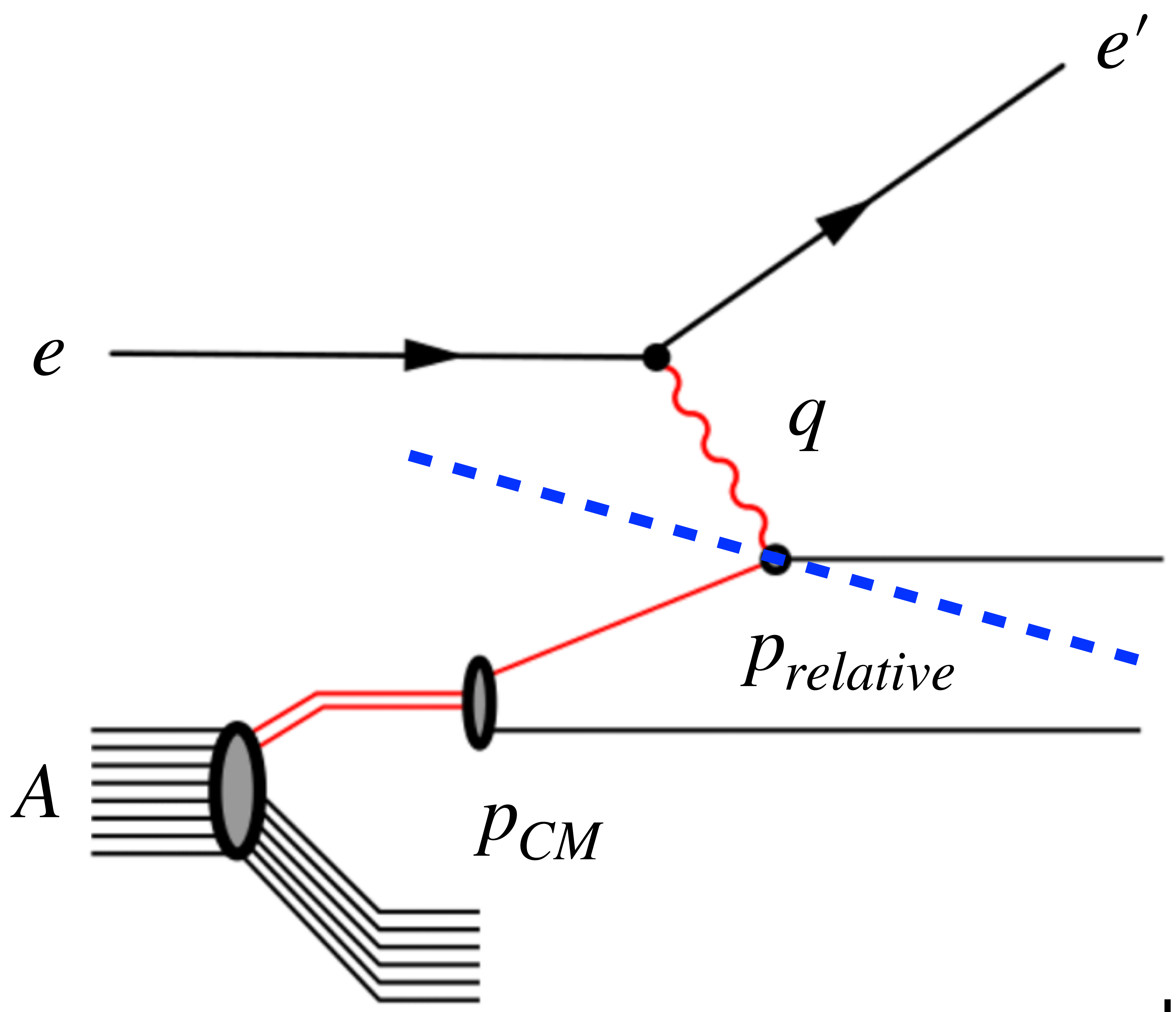


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How do we test this assumption?

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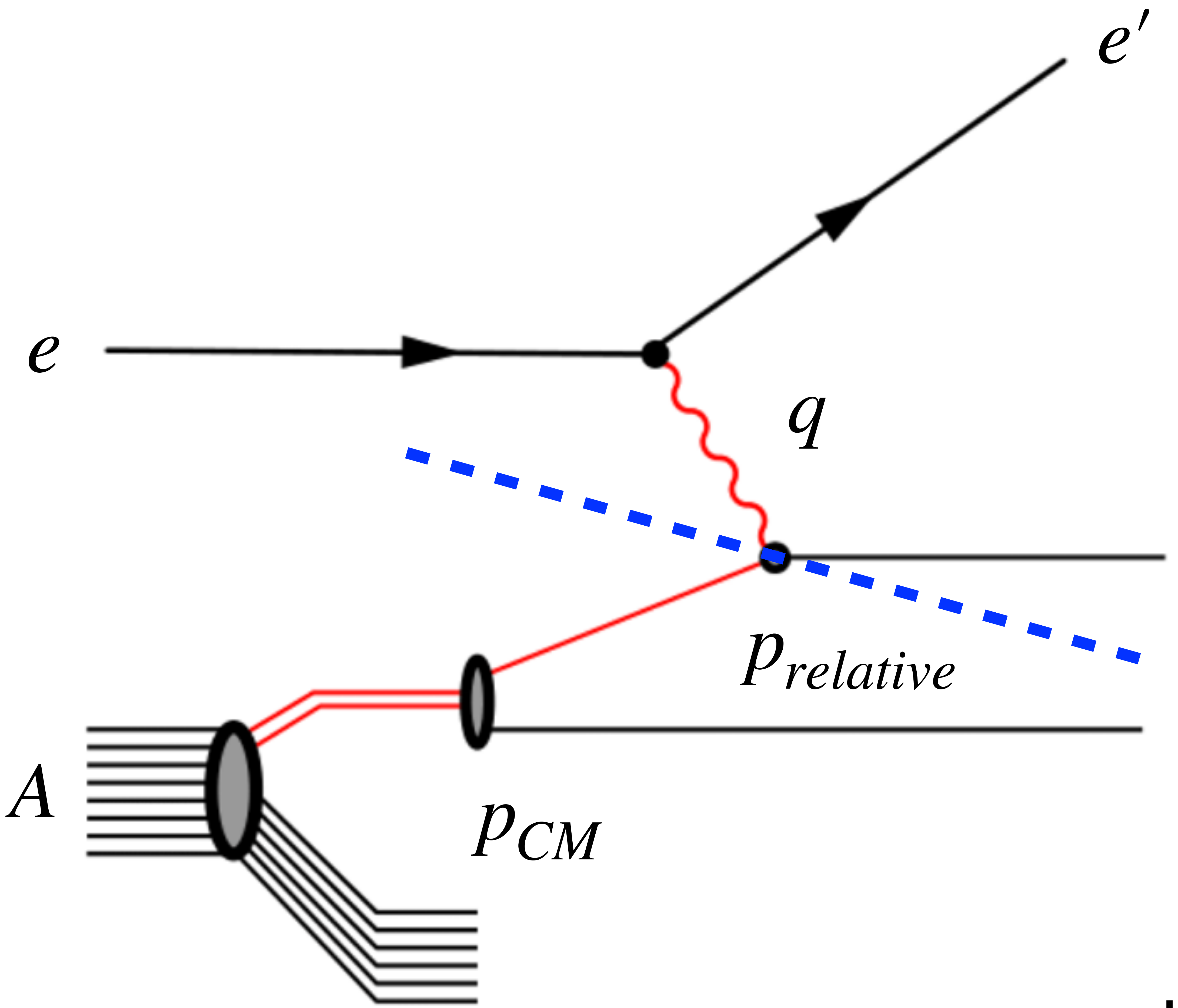


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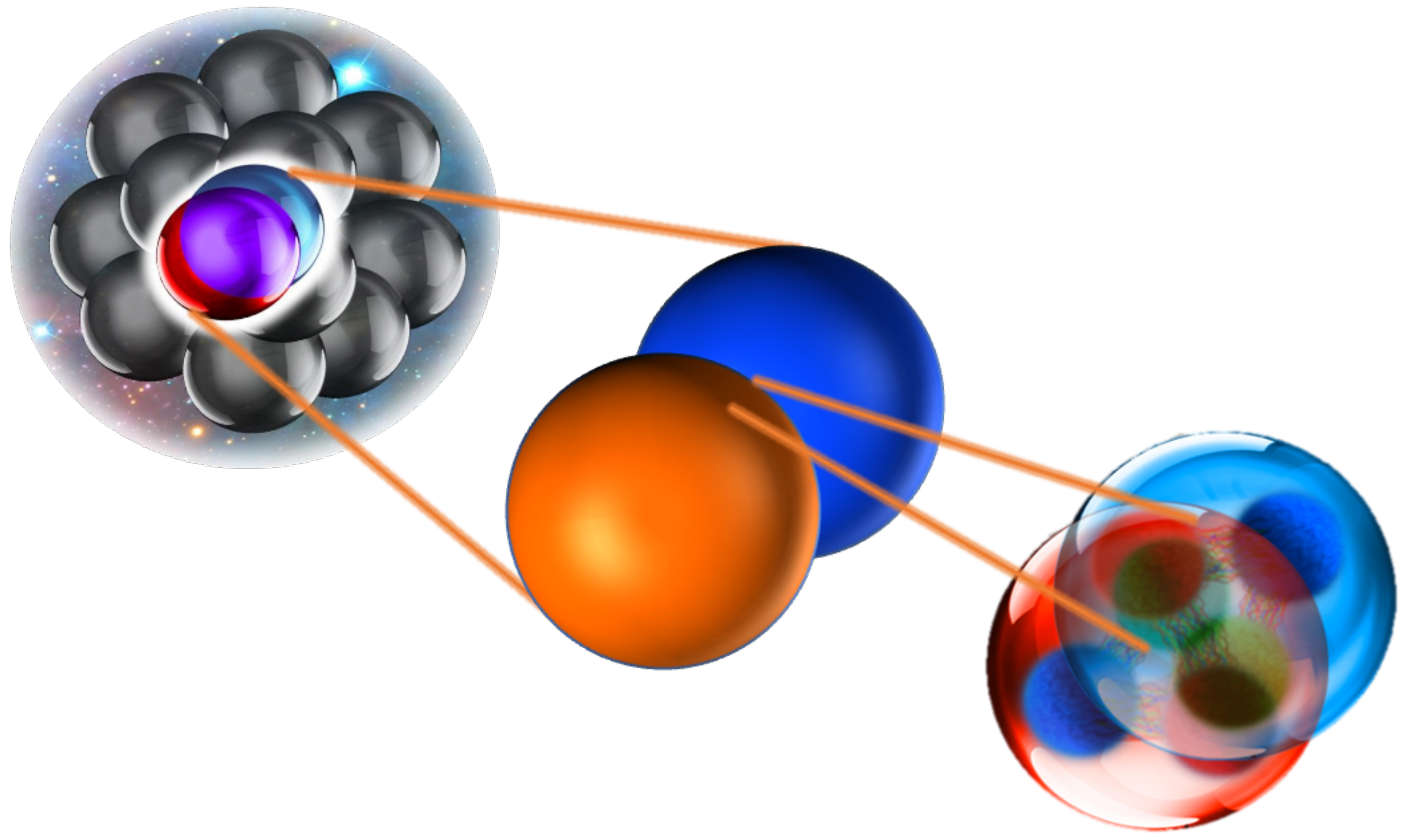
How do we test this assumption?

# Two ways to examine reaction-dependence:

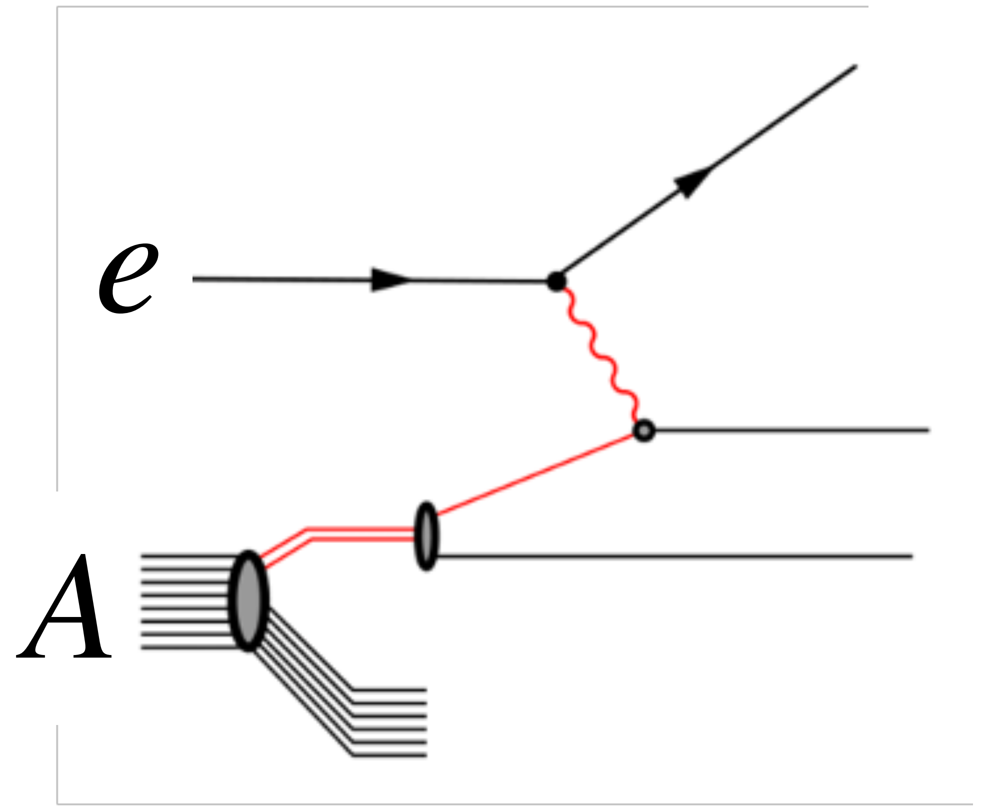
## Scale

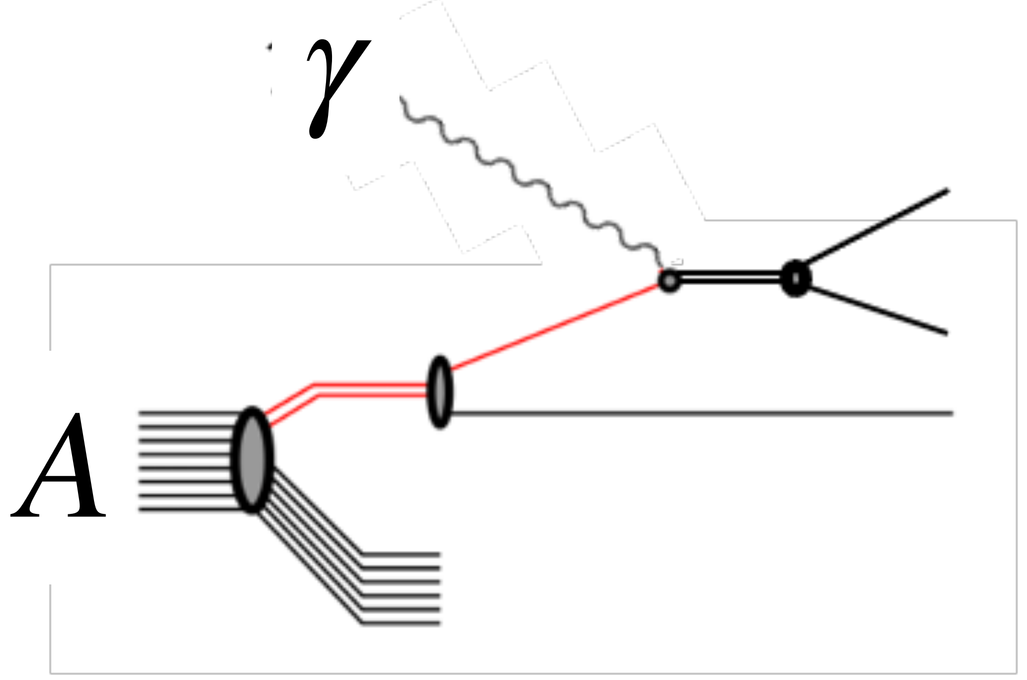


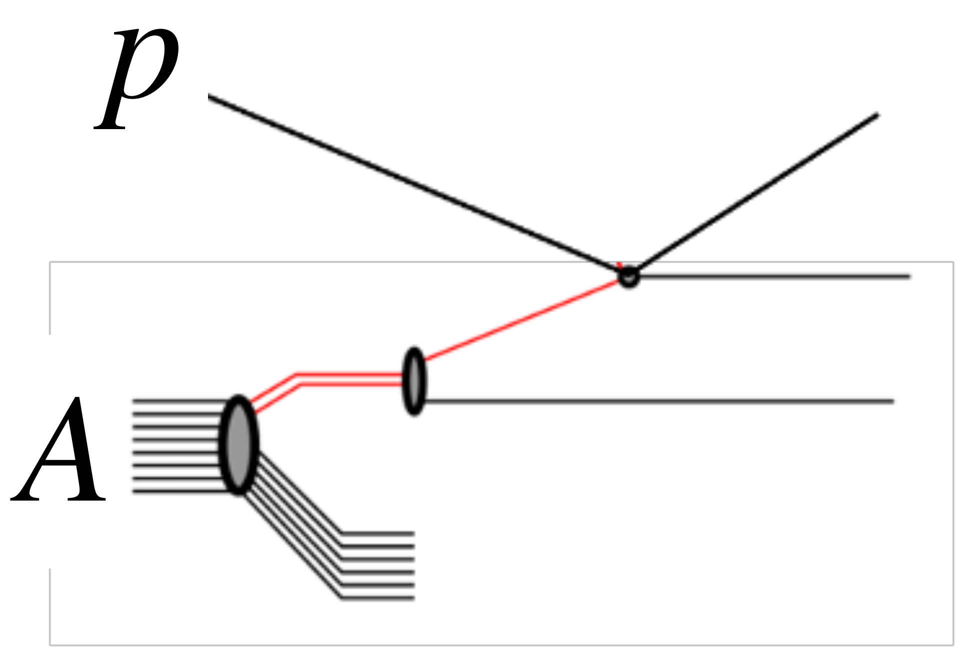
Change the resolution **scale** of the reaction by looking at dependence on momentum transfer $Q^2$, $|t|$

## Probe

Compare different reactions using different **probes**: Electron-scattering, Proton-scattering, Photoproduction



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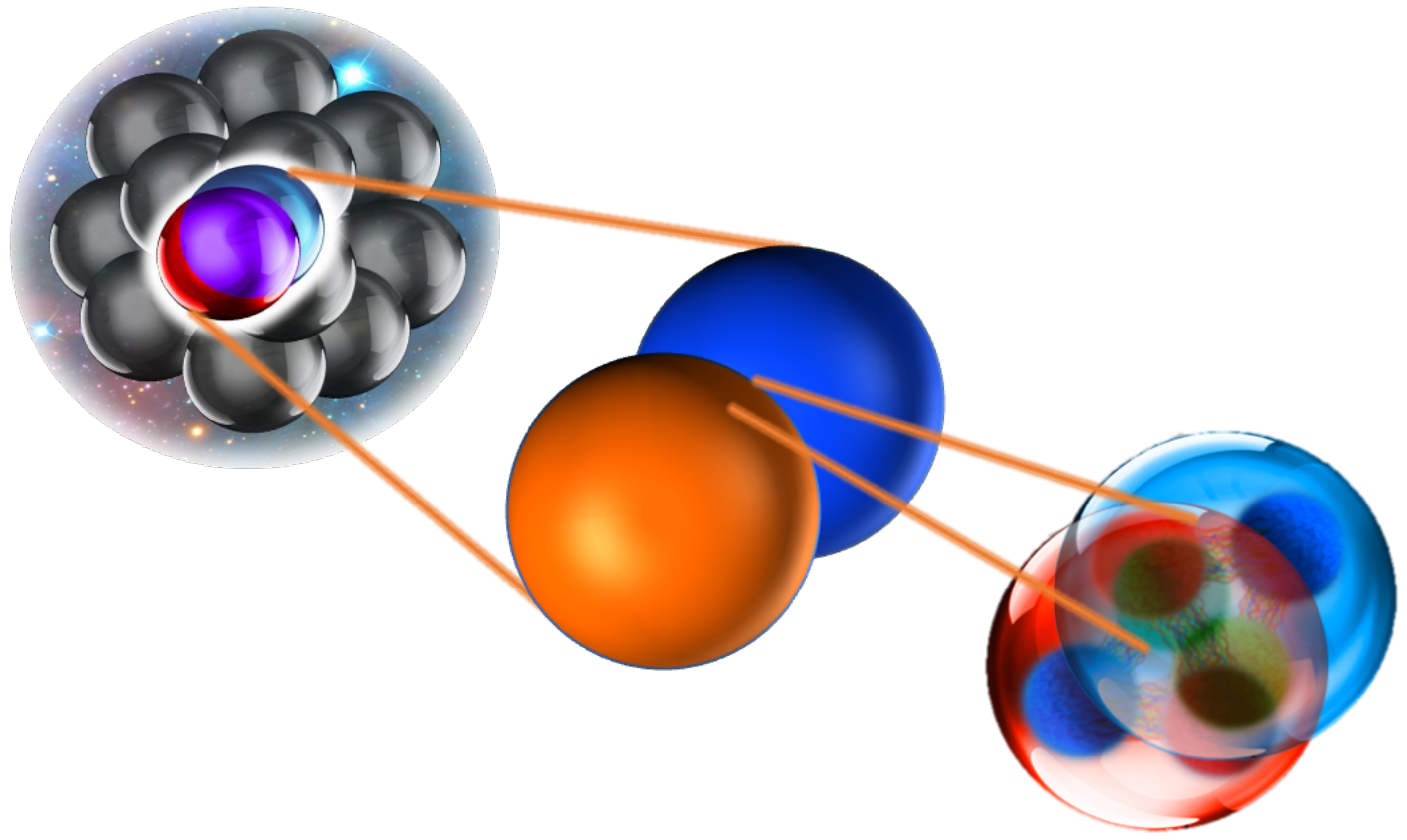

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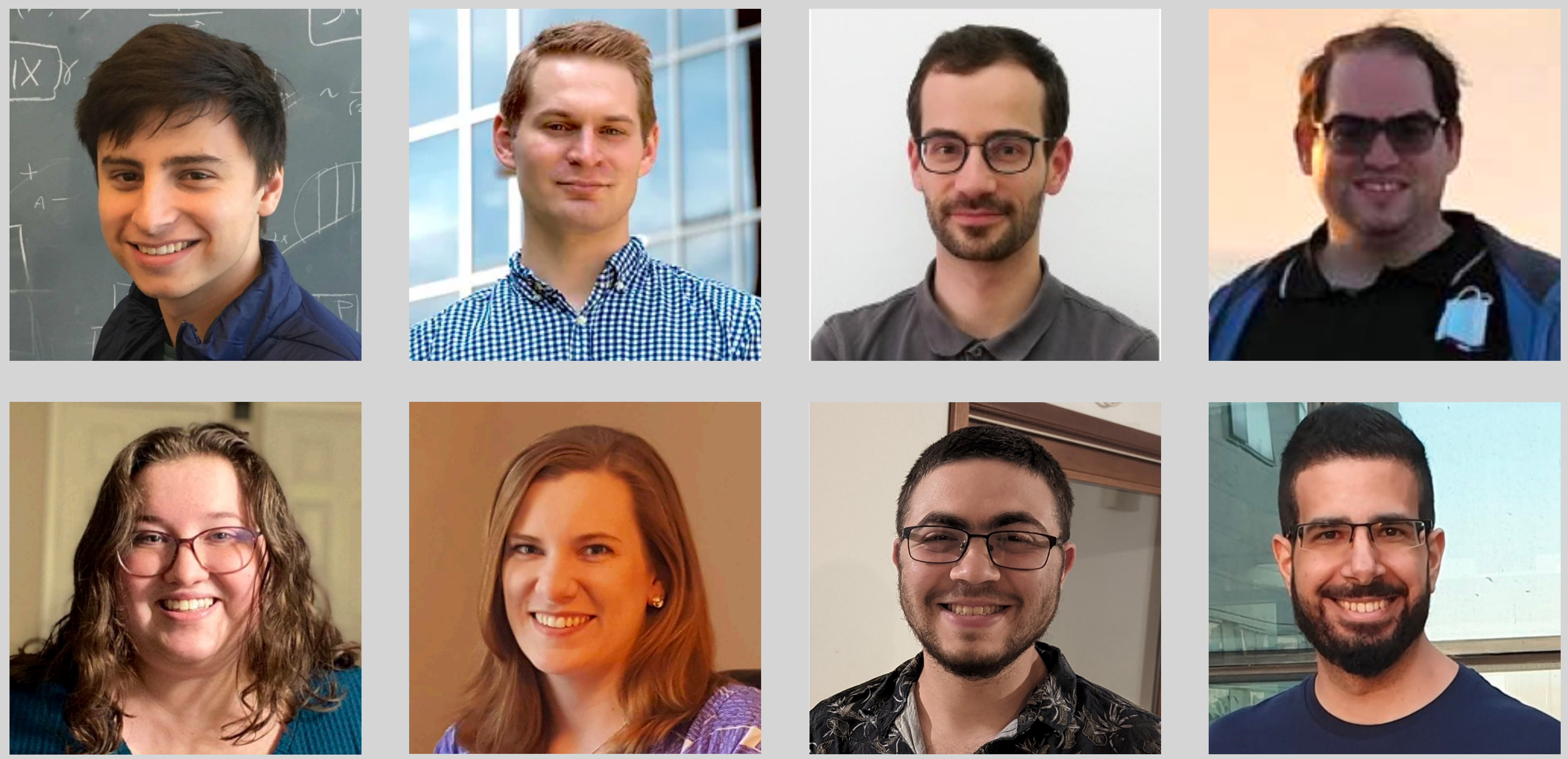
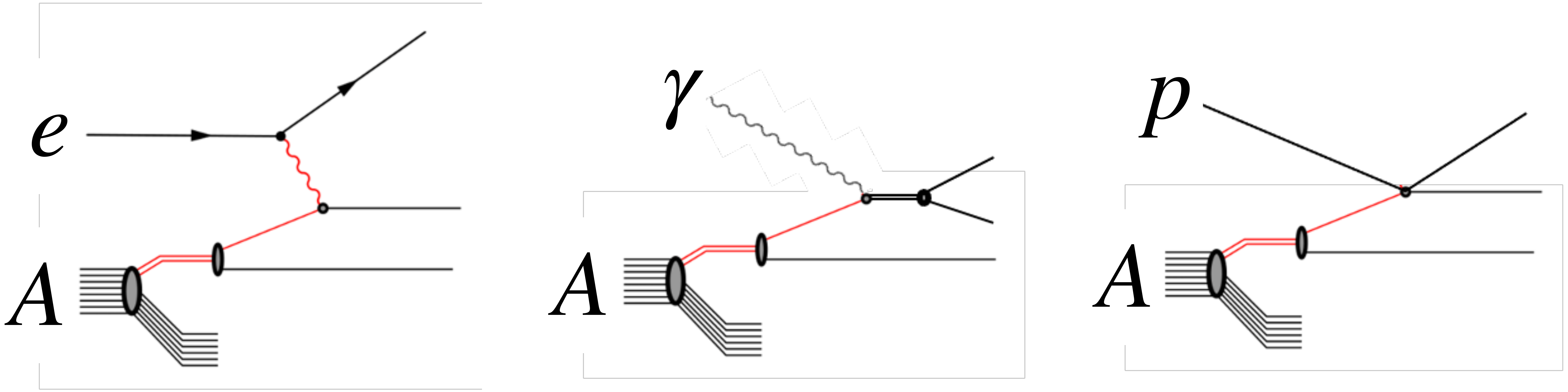


See previous talk by Justin Estee

# Probe Dependence of SRCs



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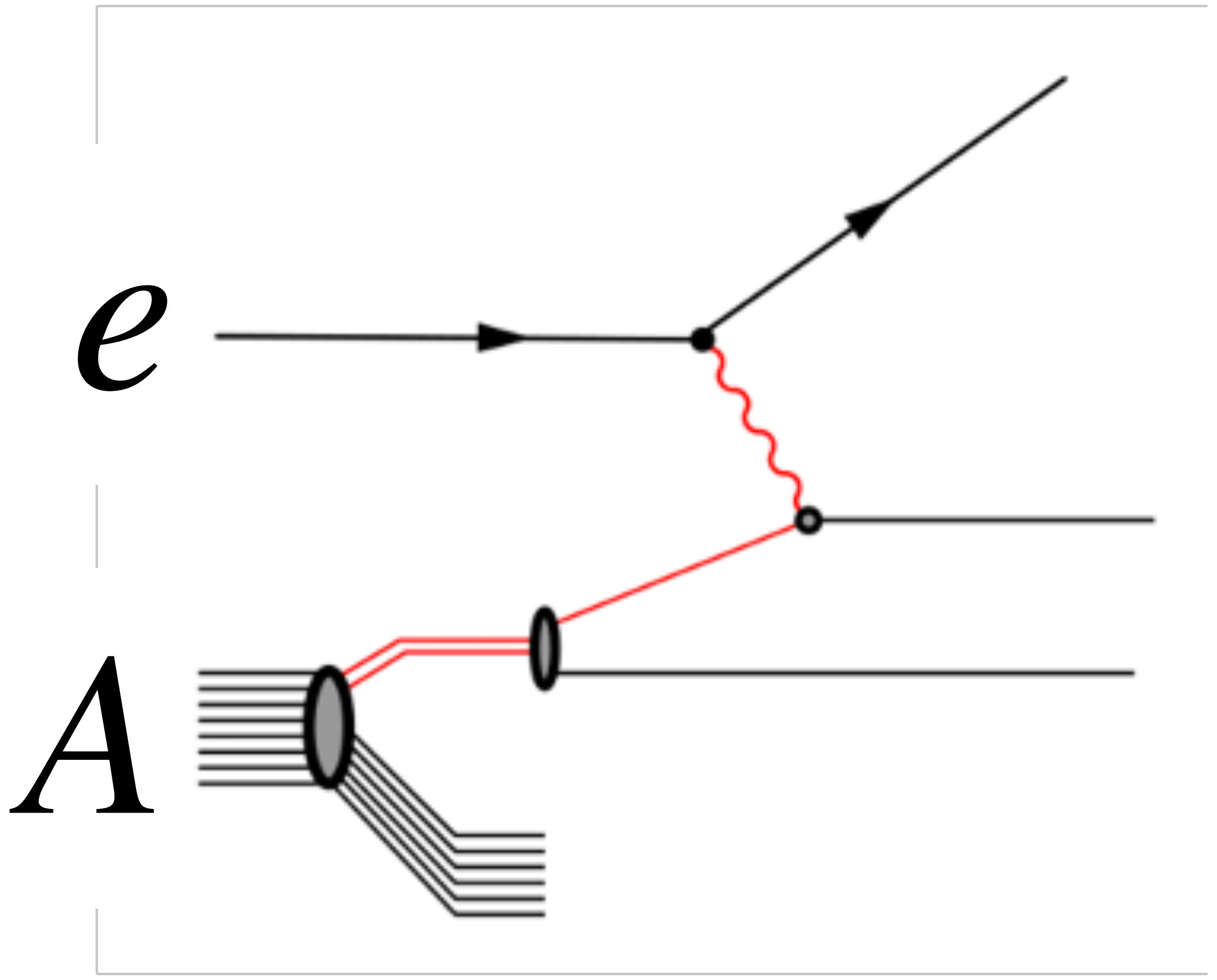


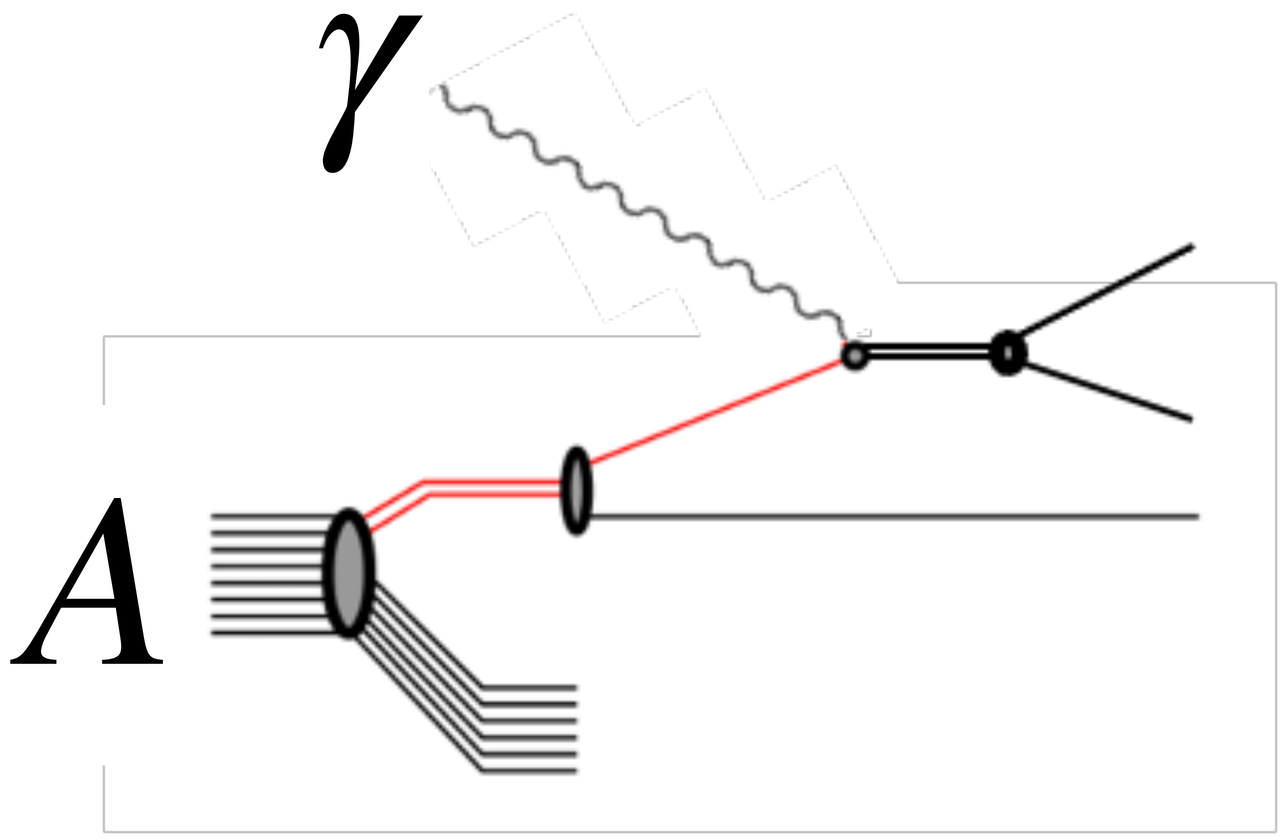


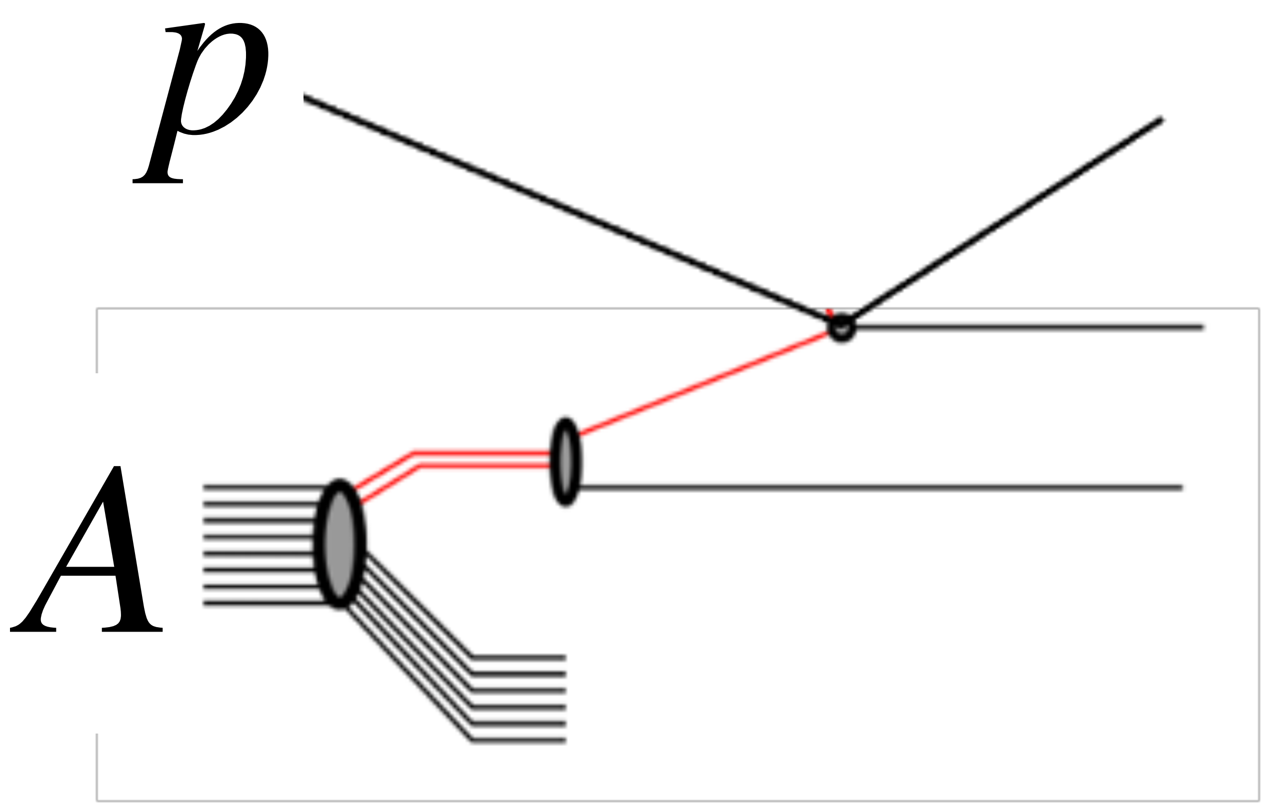


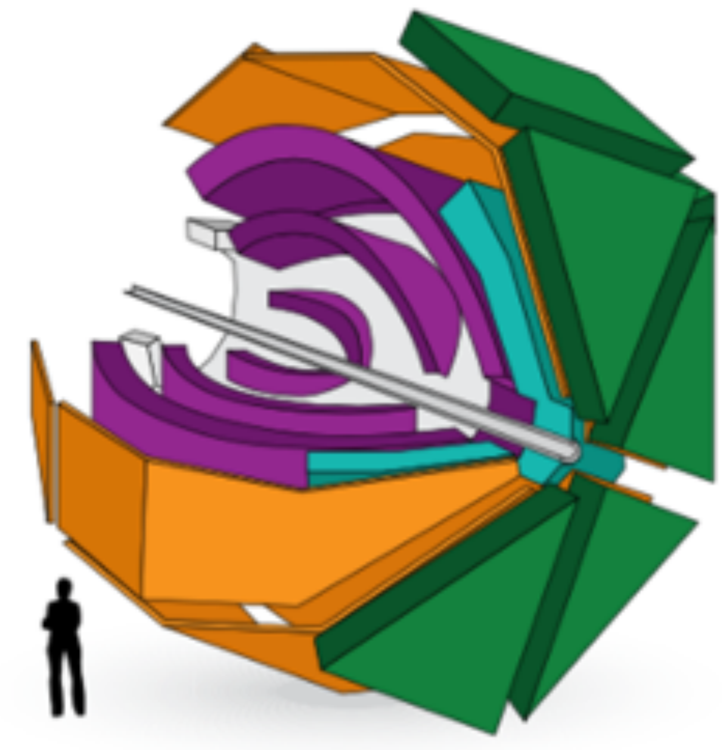

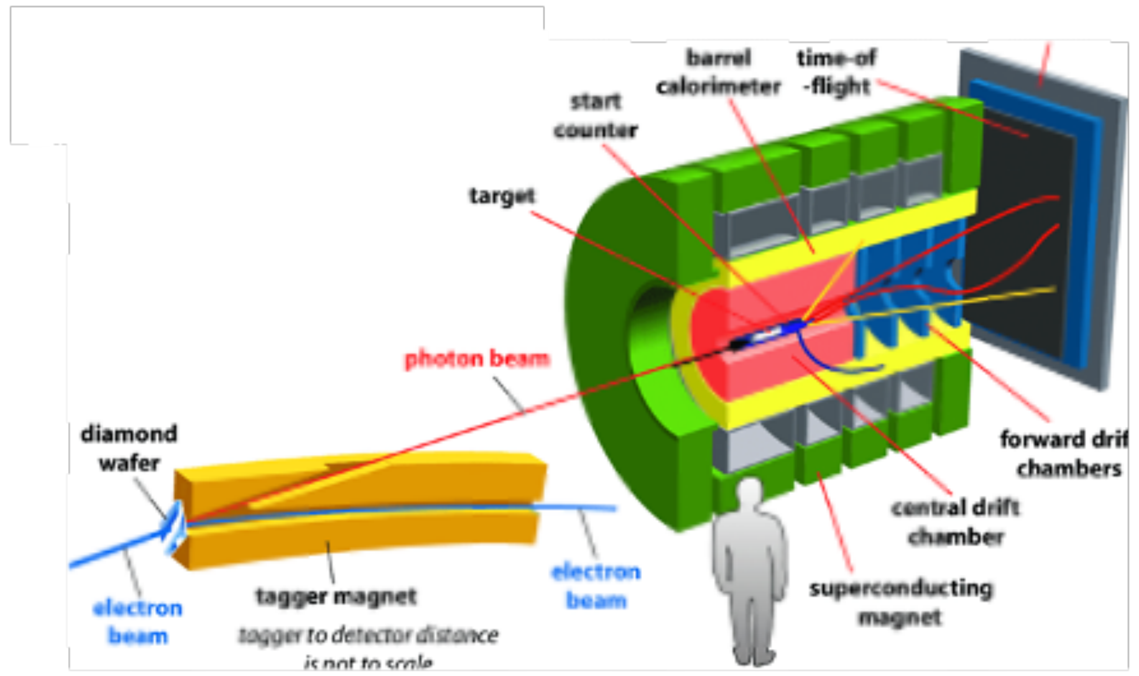


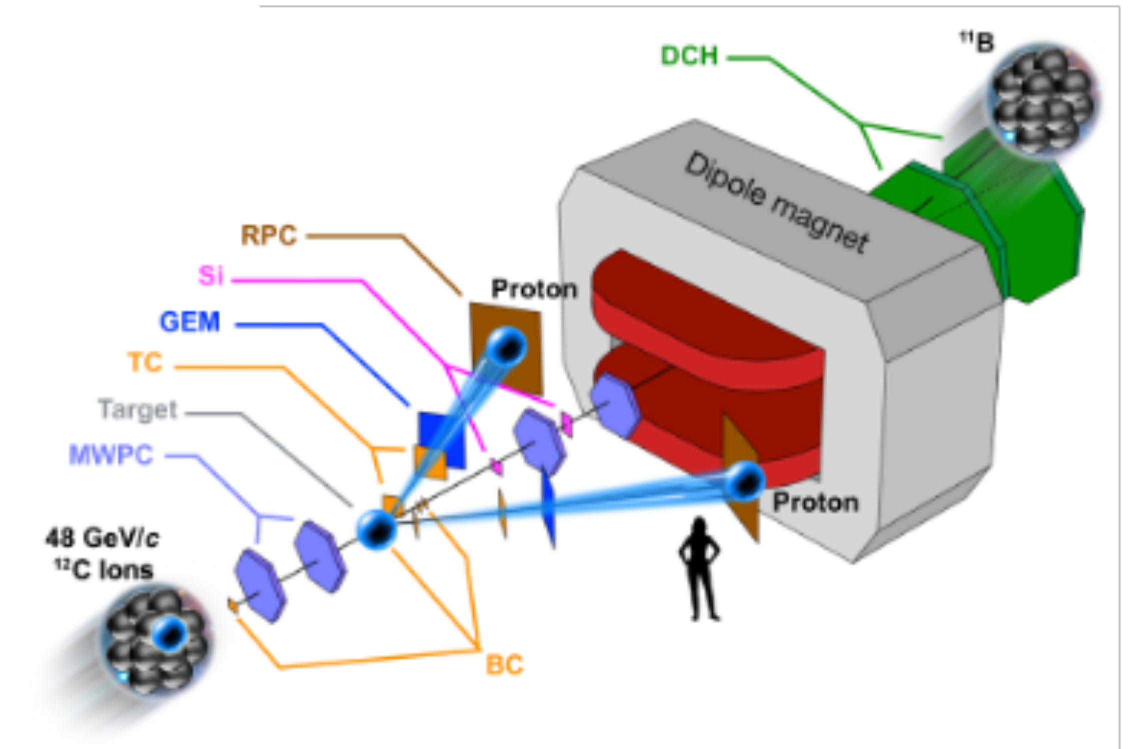

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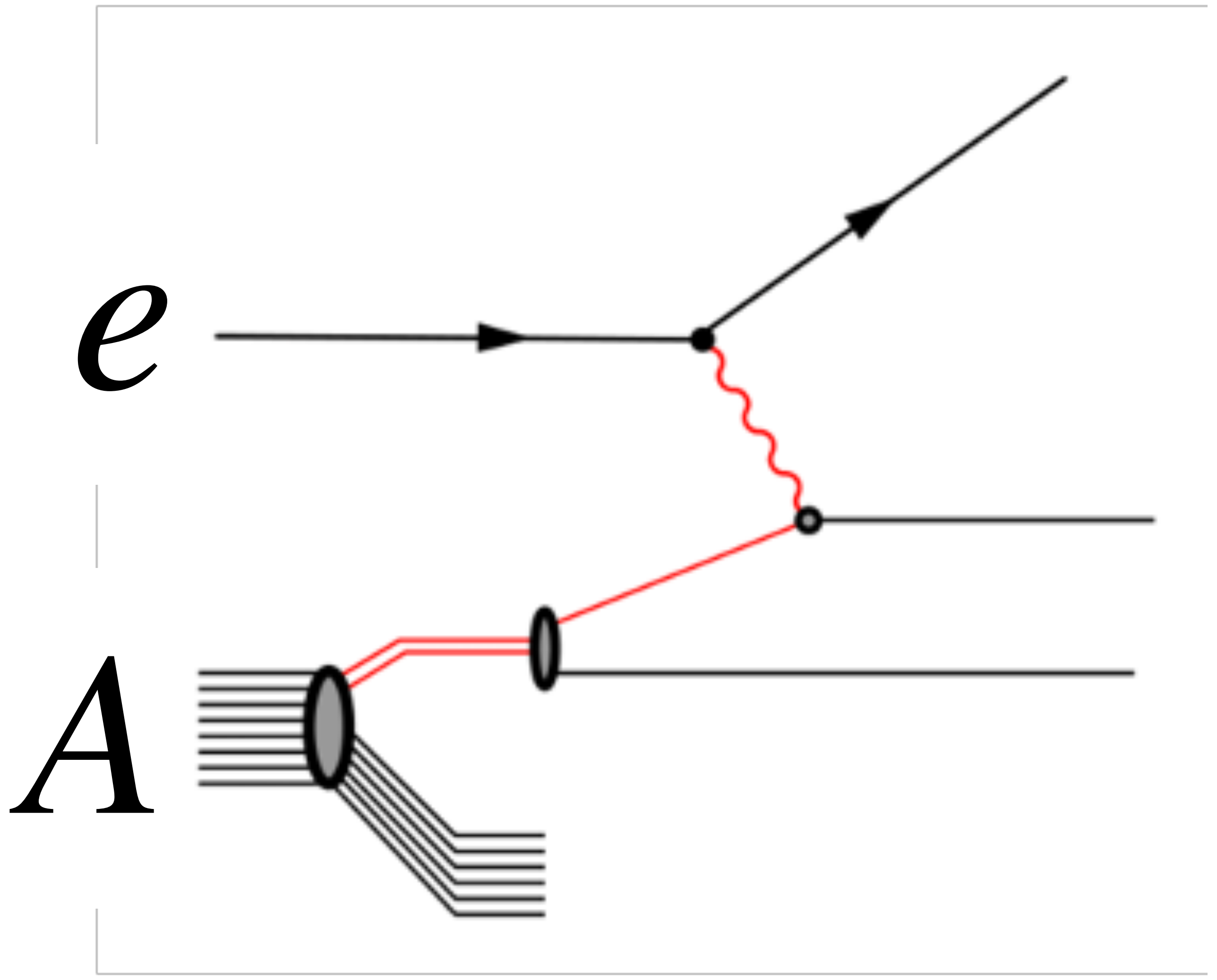
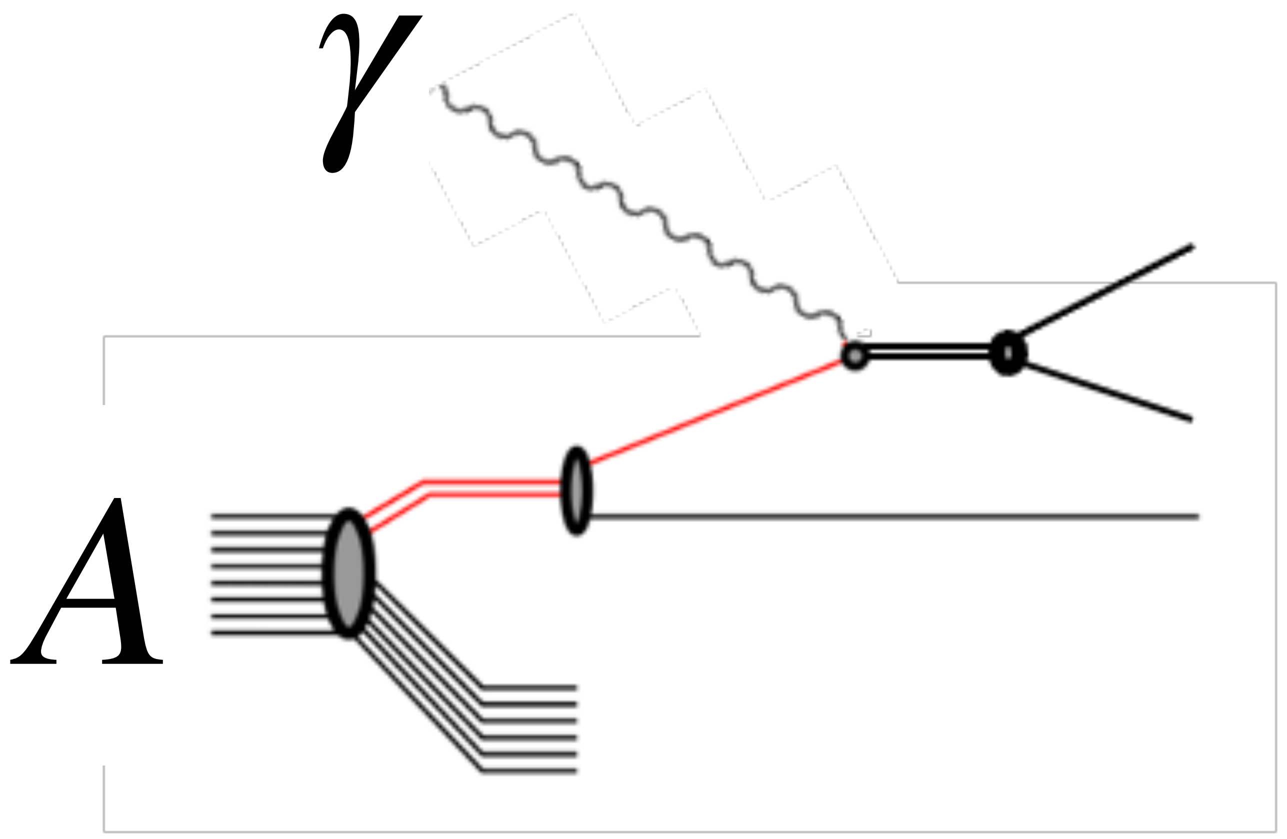
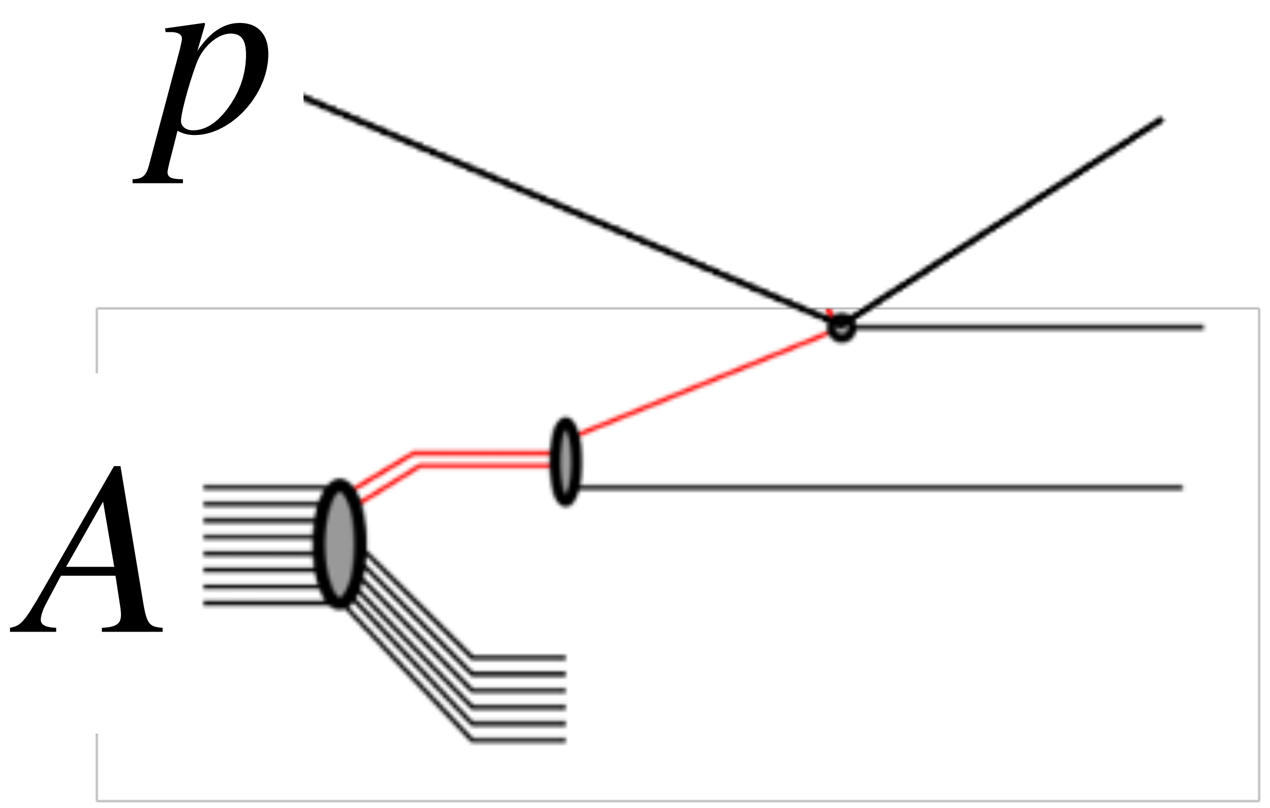
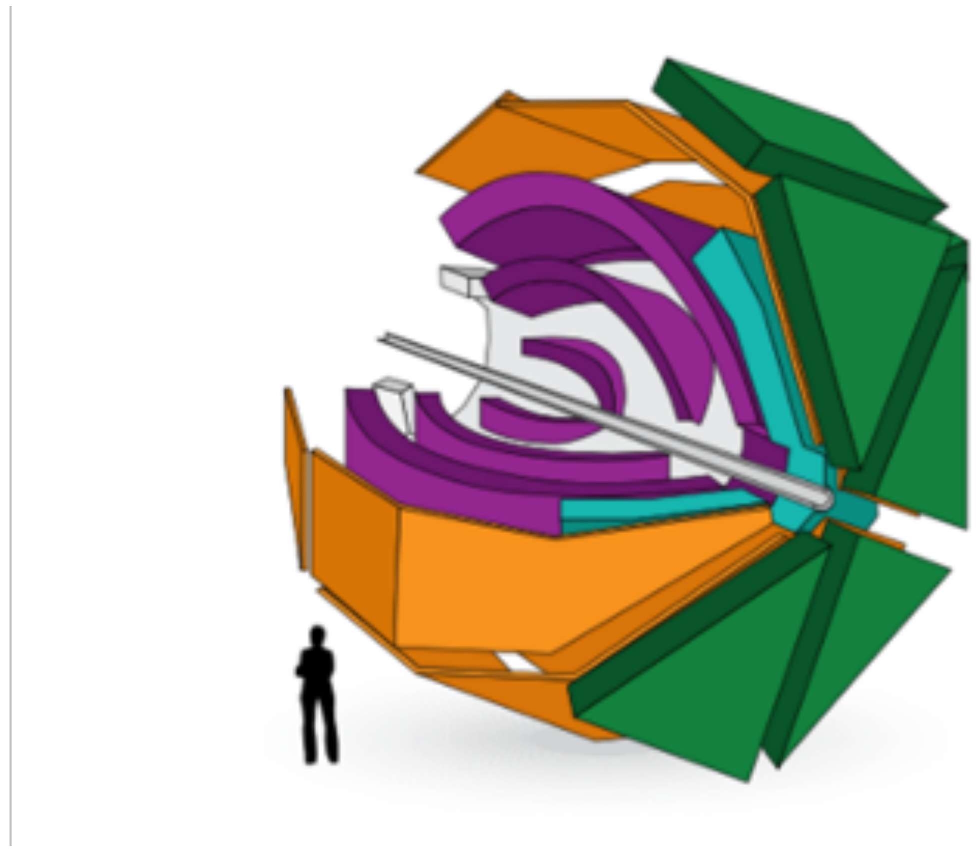
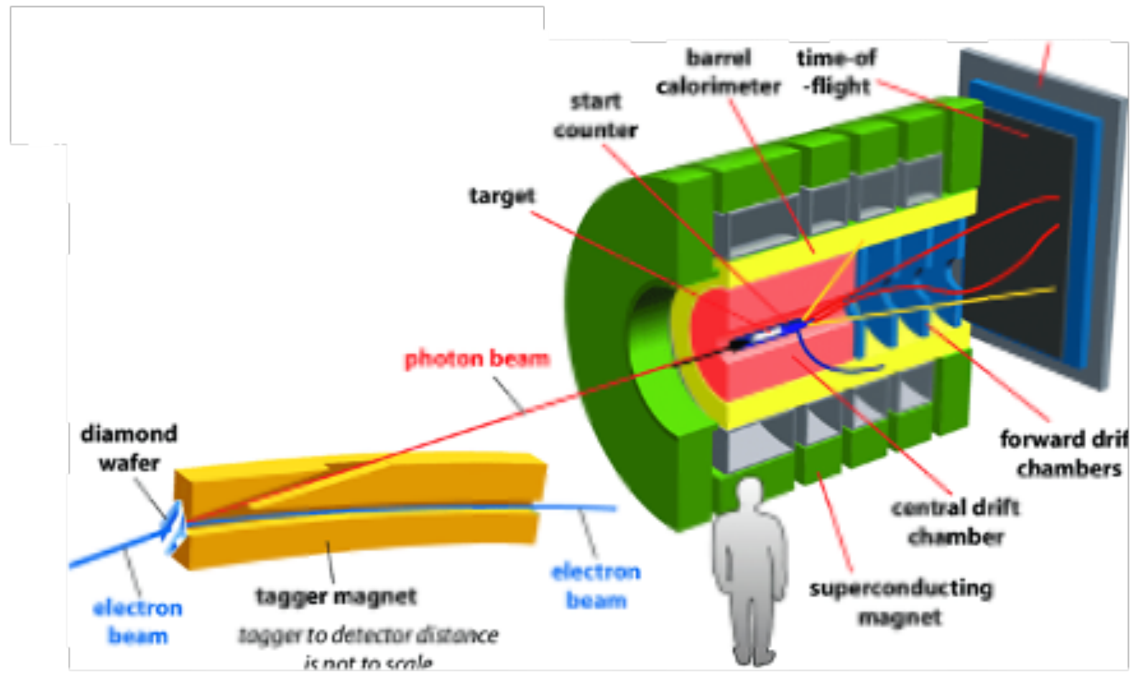
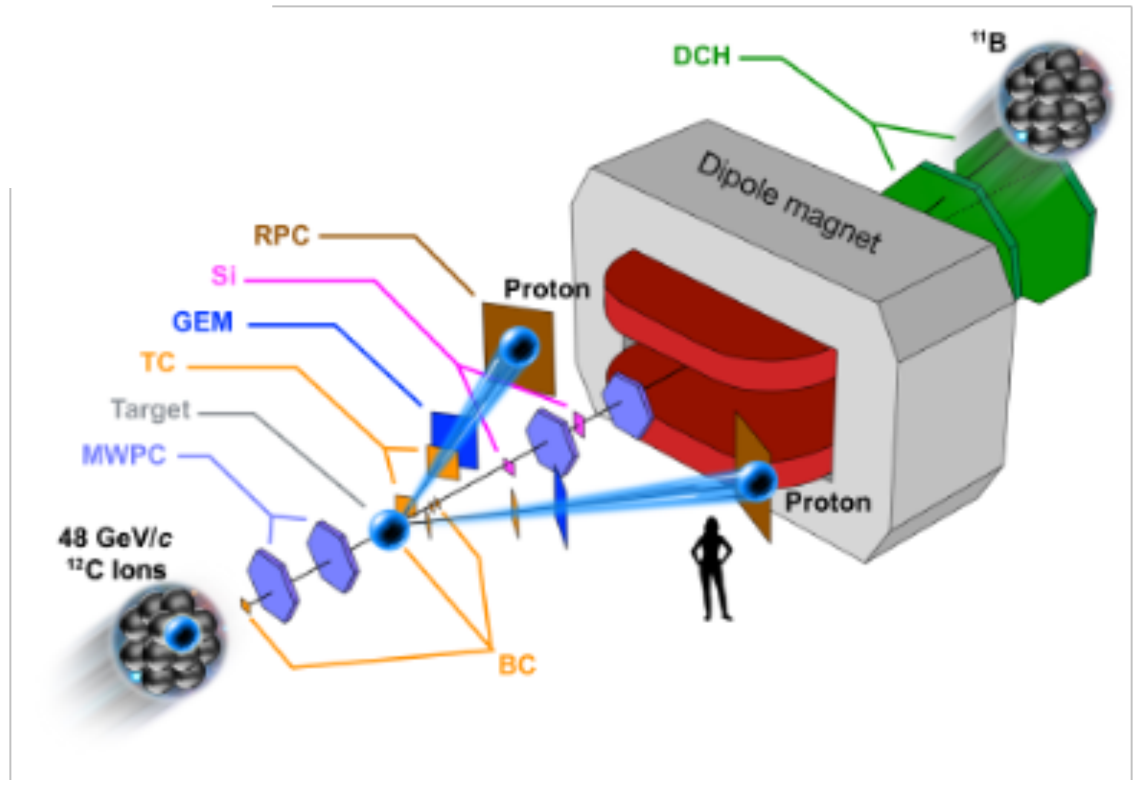


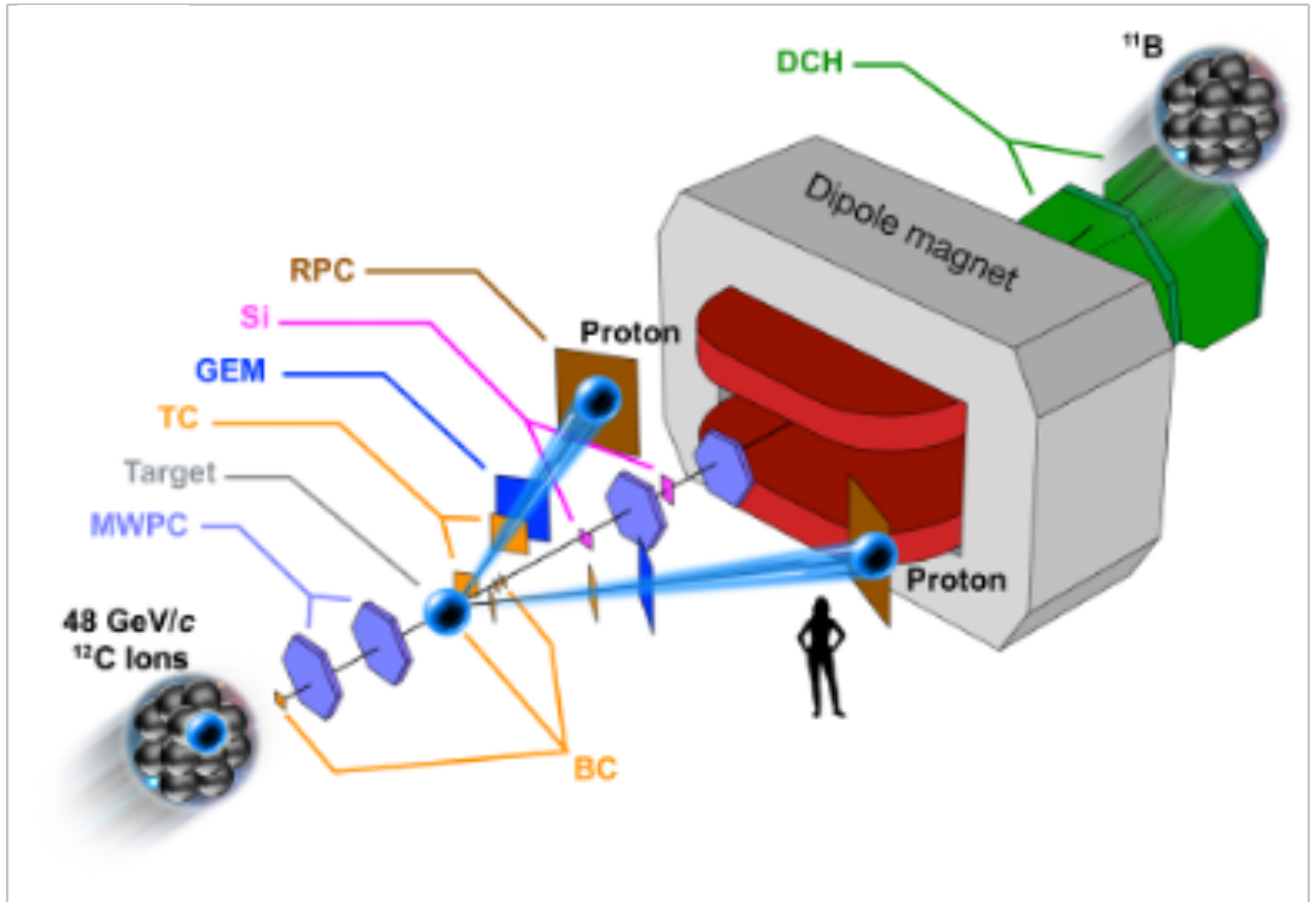





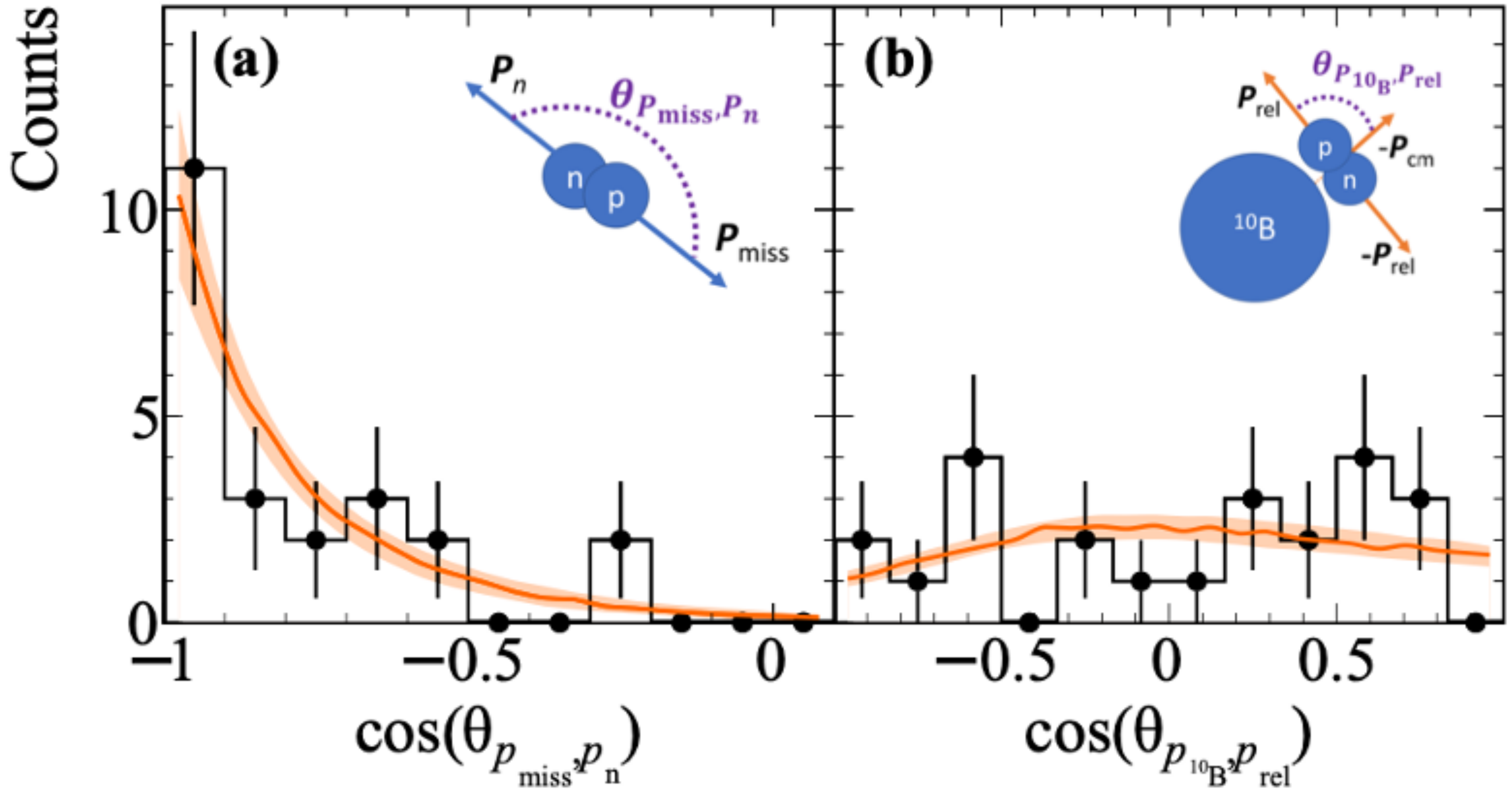



# Hadron-scattering measurements of SRCs

- Inverse-kinematics measurement at Joint Institute for Nuclear Research in Dubna
- $^{12}C$ ions incident on hydrogen target
- Spectrometer measured final-state protons, nuclear fragments
- Allows reconstruction of nuclear final-state in SRC breakup scattering



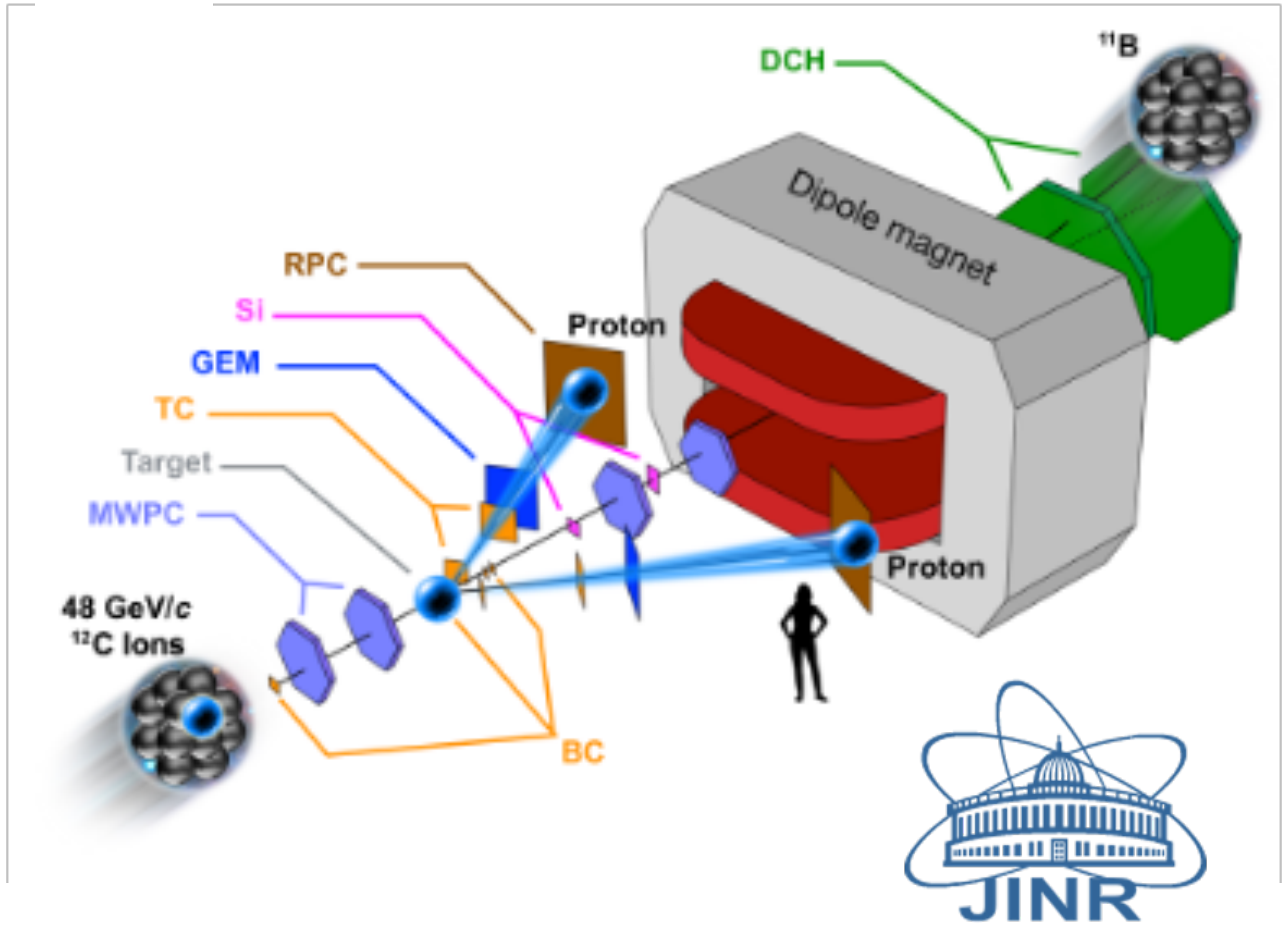
# Experimental evidence for SRC scale-separation



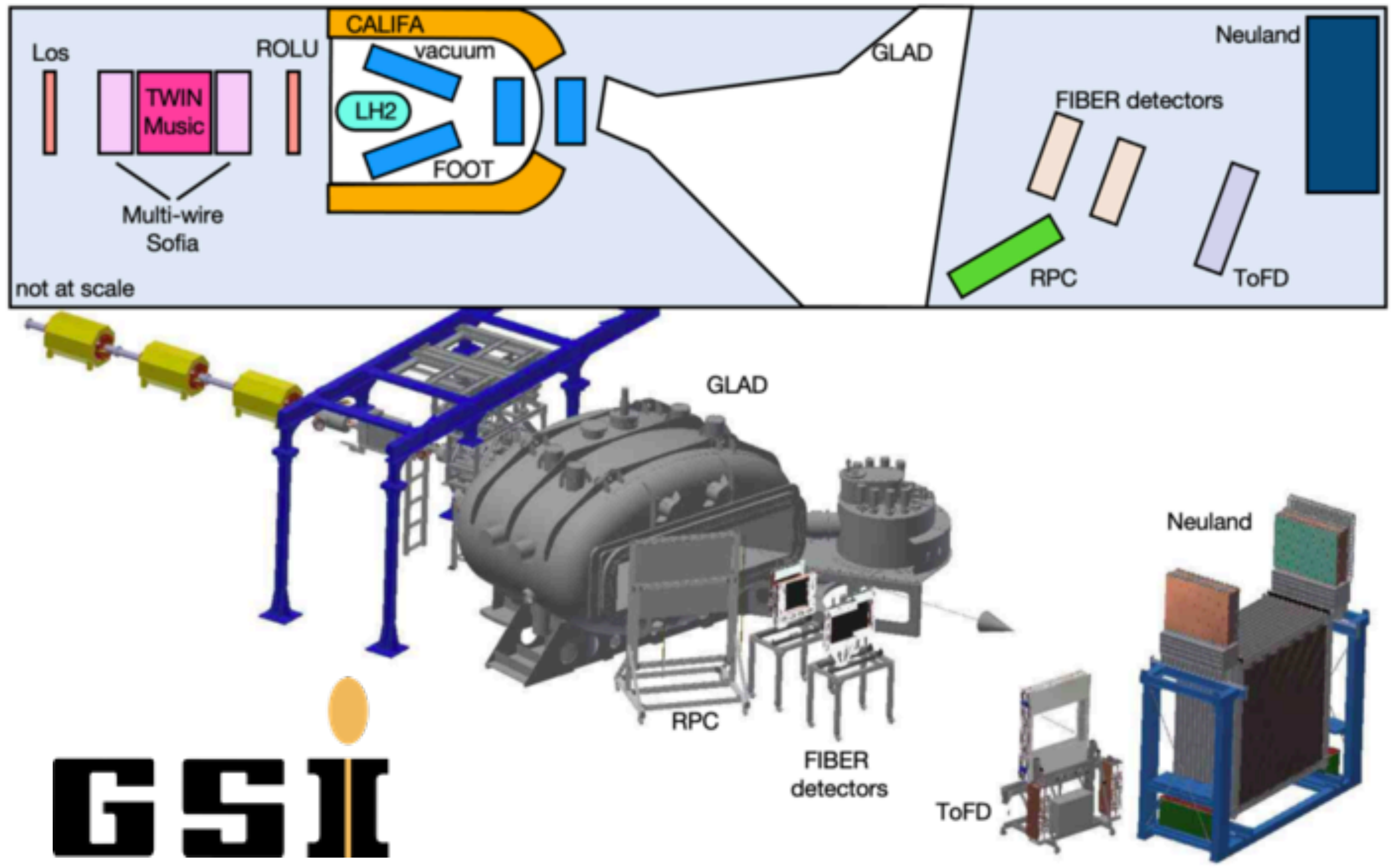

M. Patsyuk et al, Nature Physics (2021)

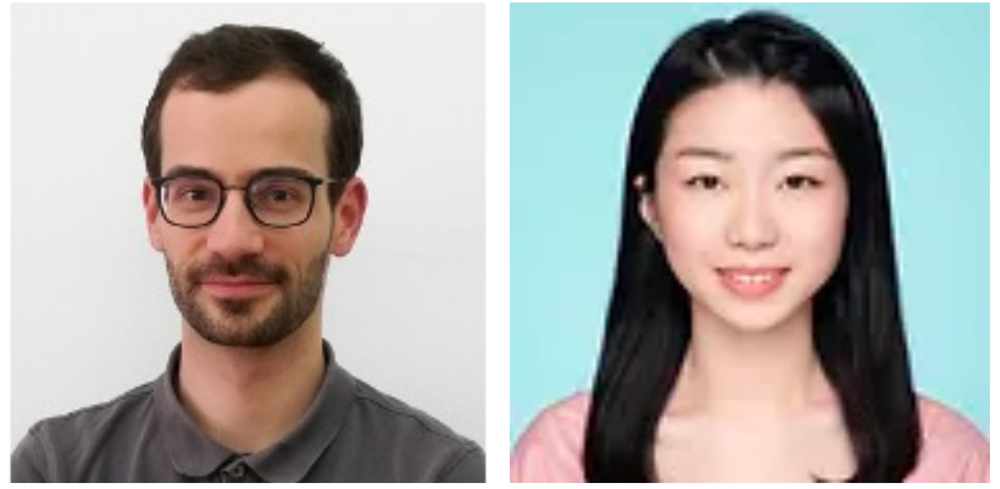
# Next generation of ion-beam SRC studies underway

**JINR, Dubna**




**GSI, Frankfurt**



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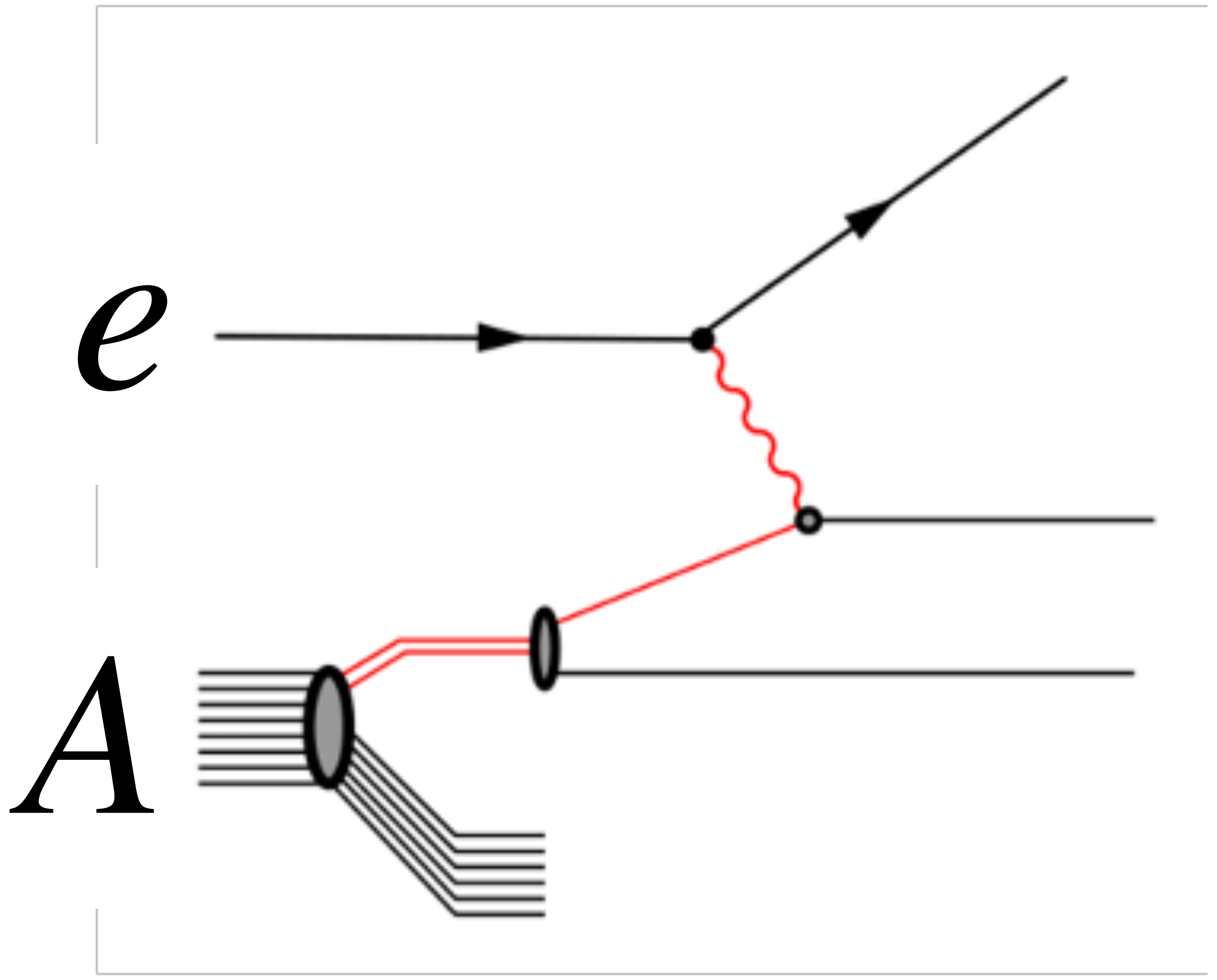
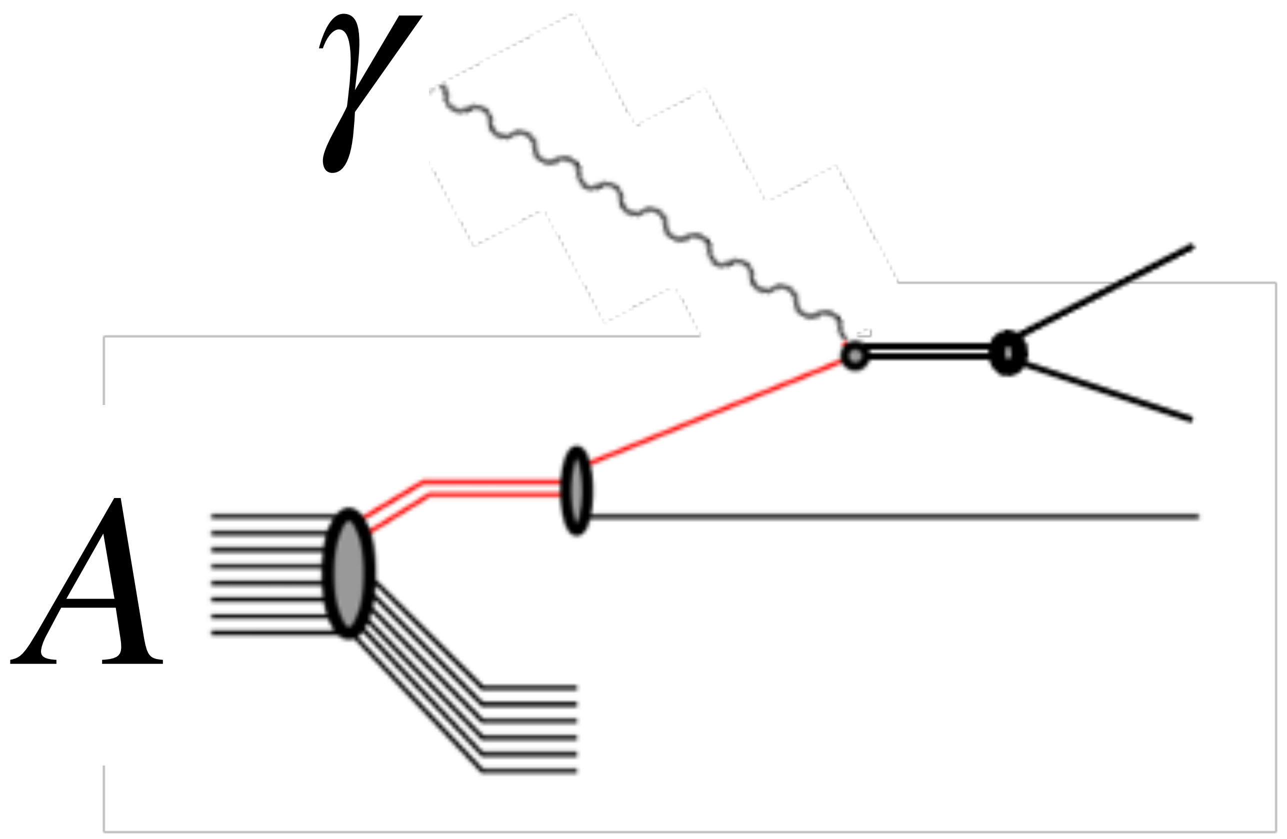
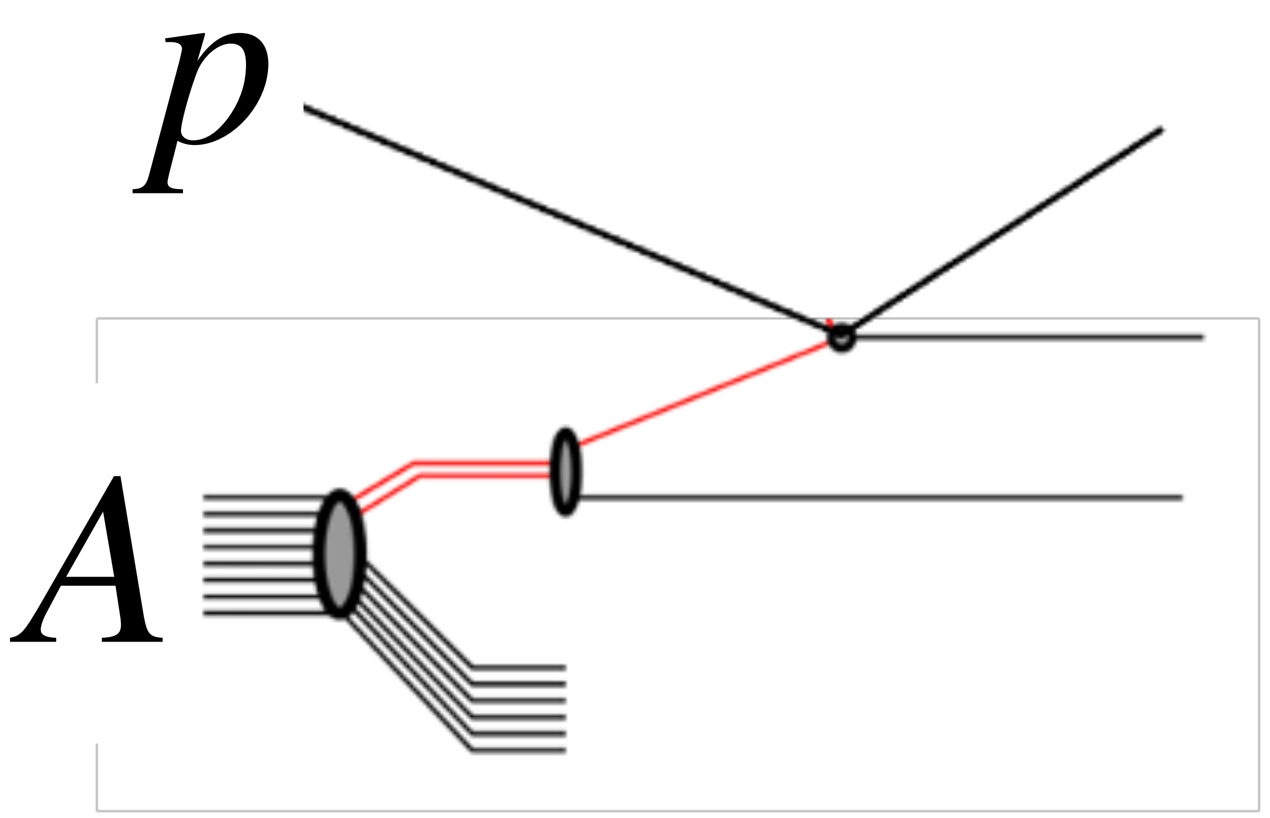
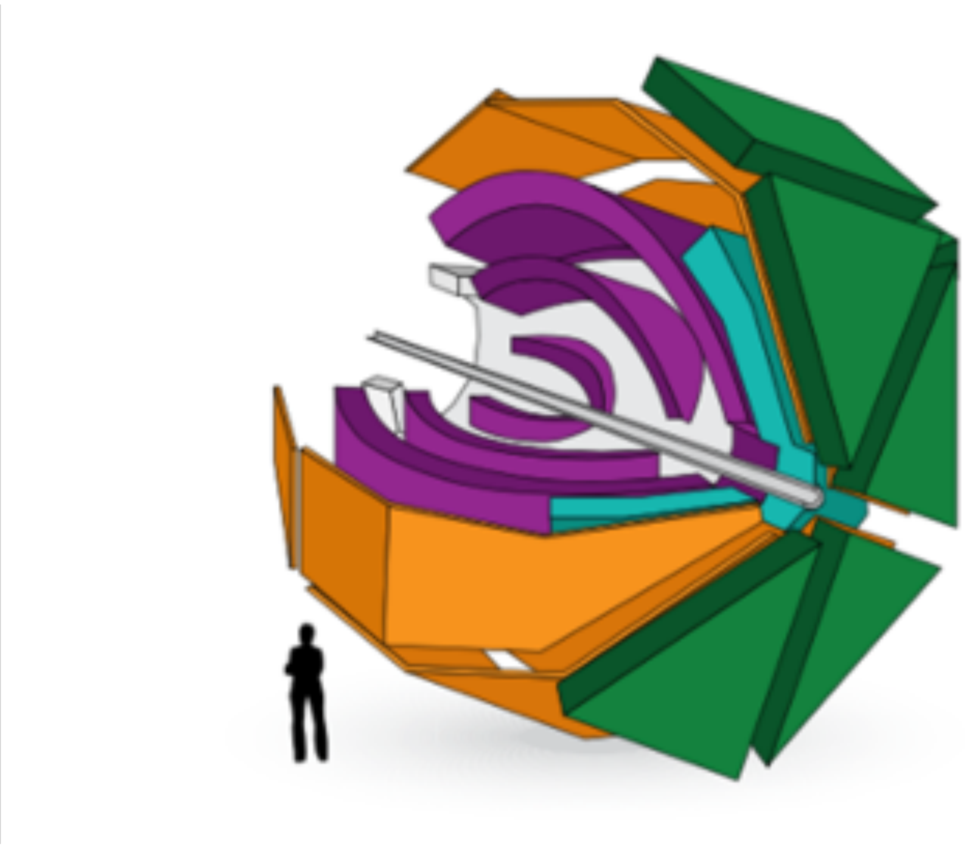
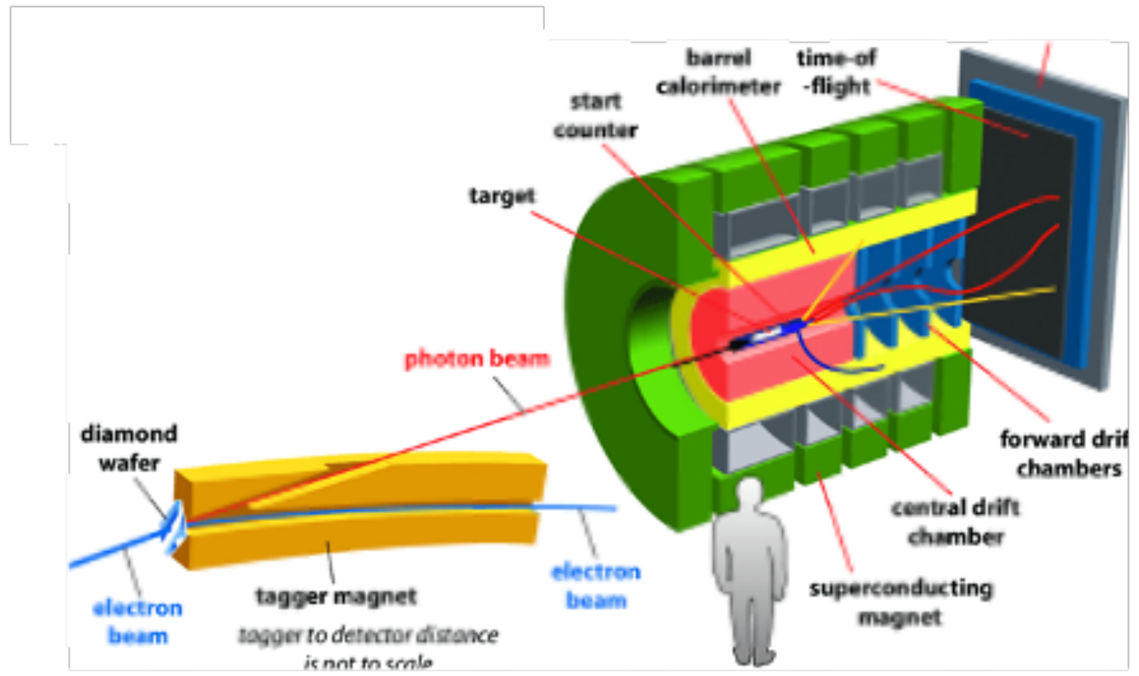
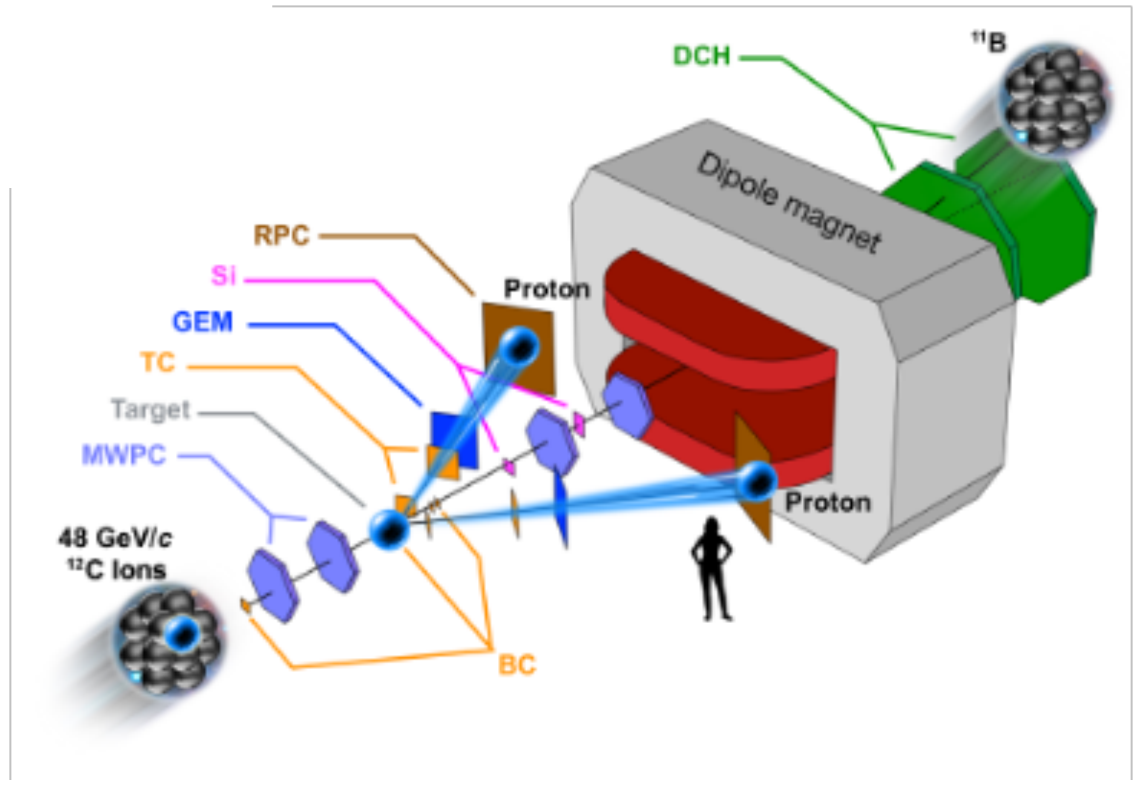


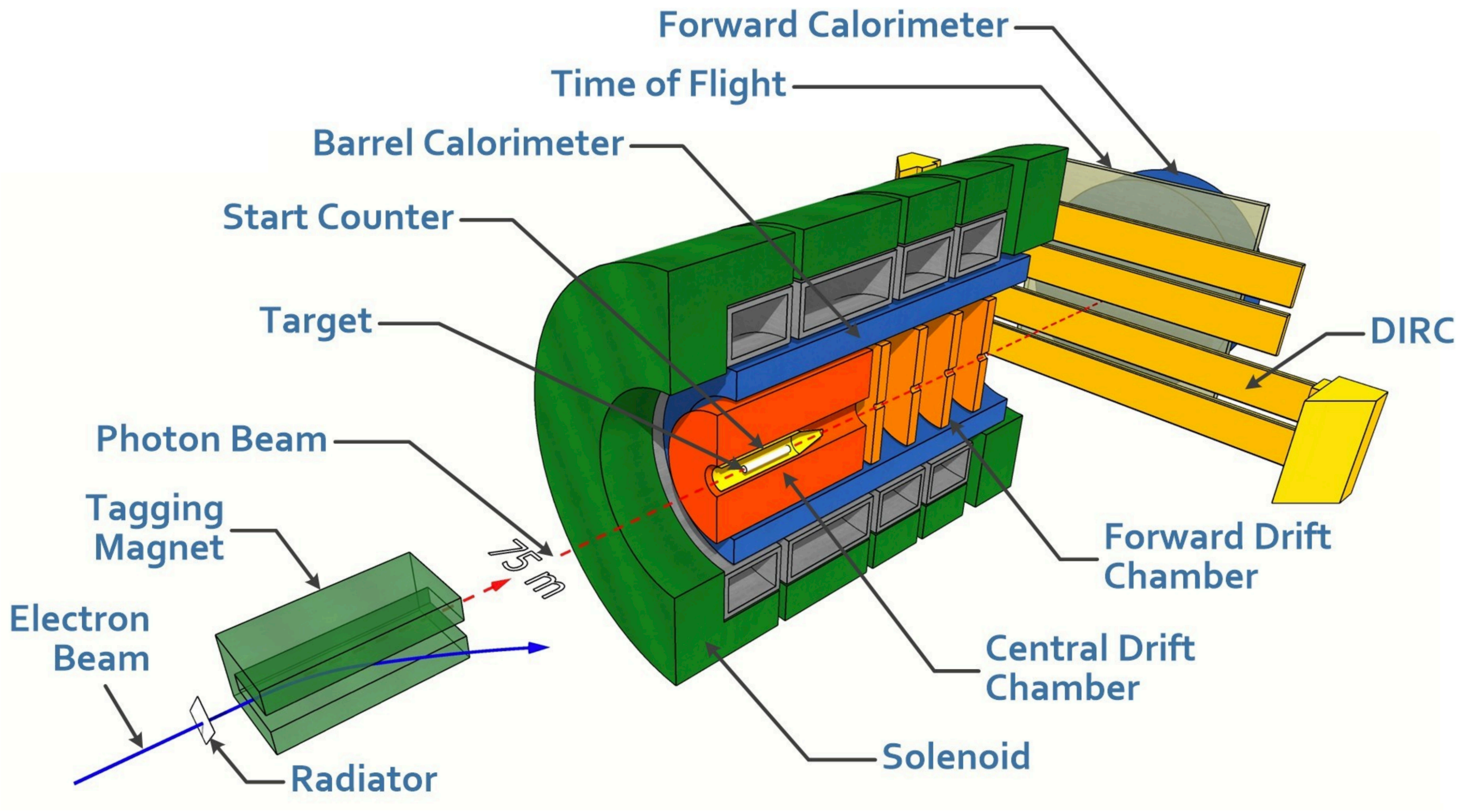





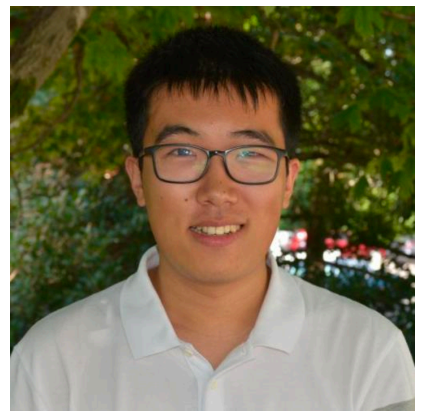



# SRC Photoproduction in Hall D




**E12-19-003**

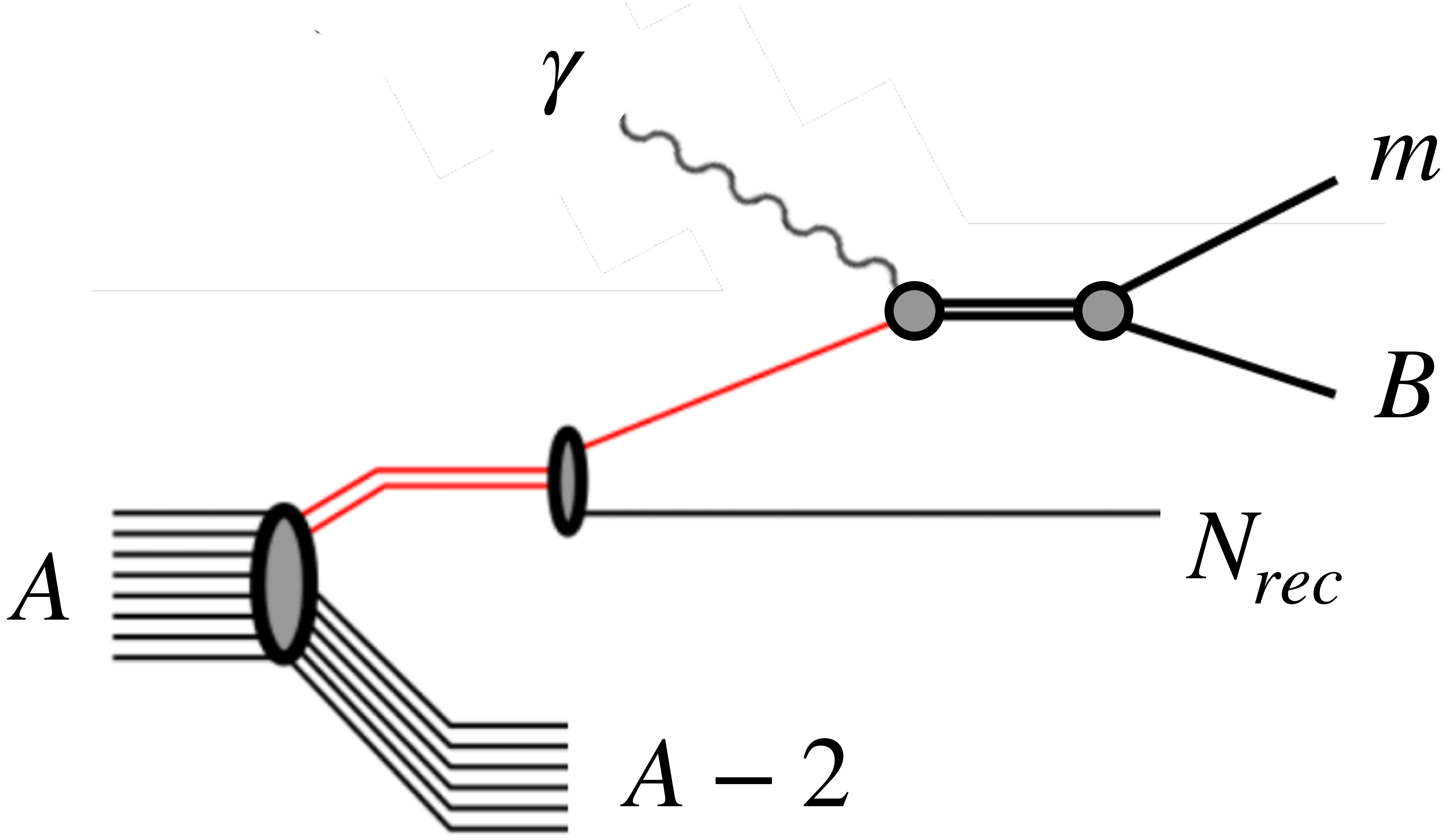
- Data taken in Fall 2021
- 10.8 GeV electron beam incident on diamond radiator
- Photon emitted via coherent bremsstrahlung; scattered electron tagged
- Real photon incident on nuclear targets: $^{2}$H, $^{4}$He, $^{12}$C
- Final-state particles detected in large-acceptance GlueX spectrometer

      . . .

See Phoebe's poster outside for more details

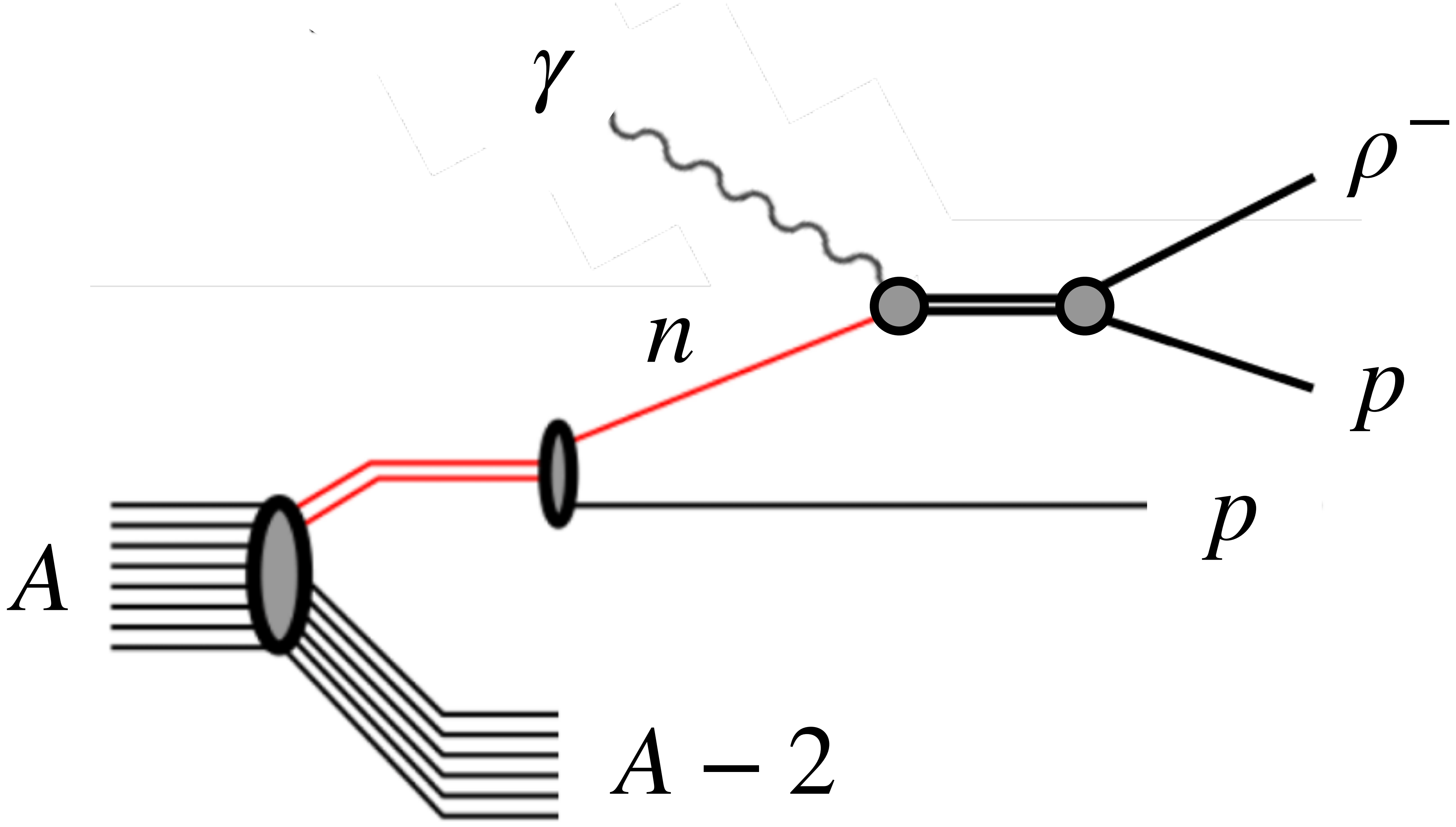
# SRC Photoproduction in Hall D

- Quasi-elastic photoproduction: hard photon-nucleon interaction
- Many meson+baryon final-states are possible



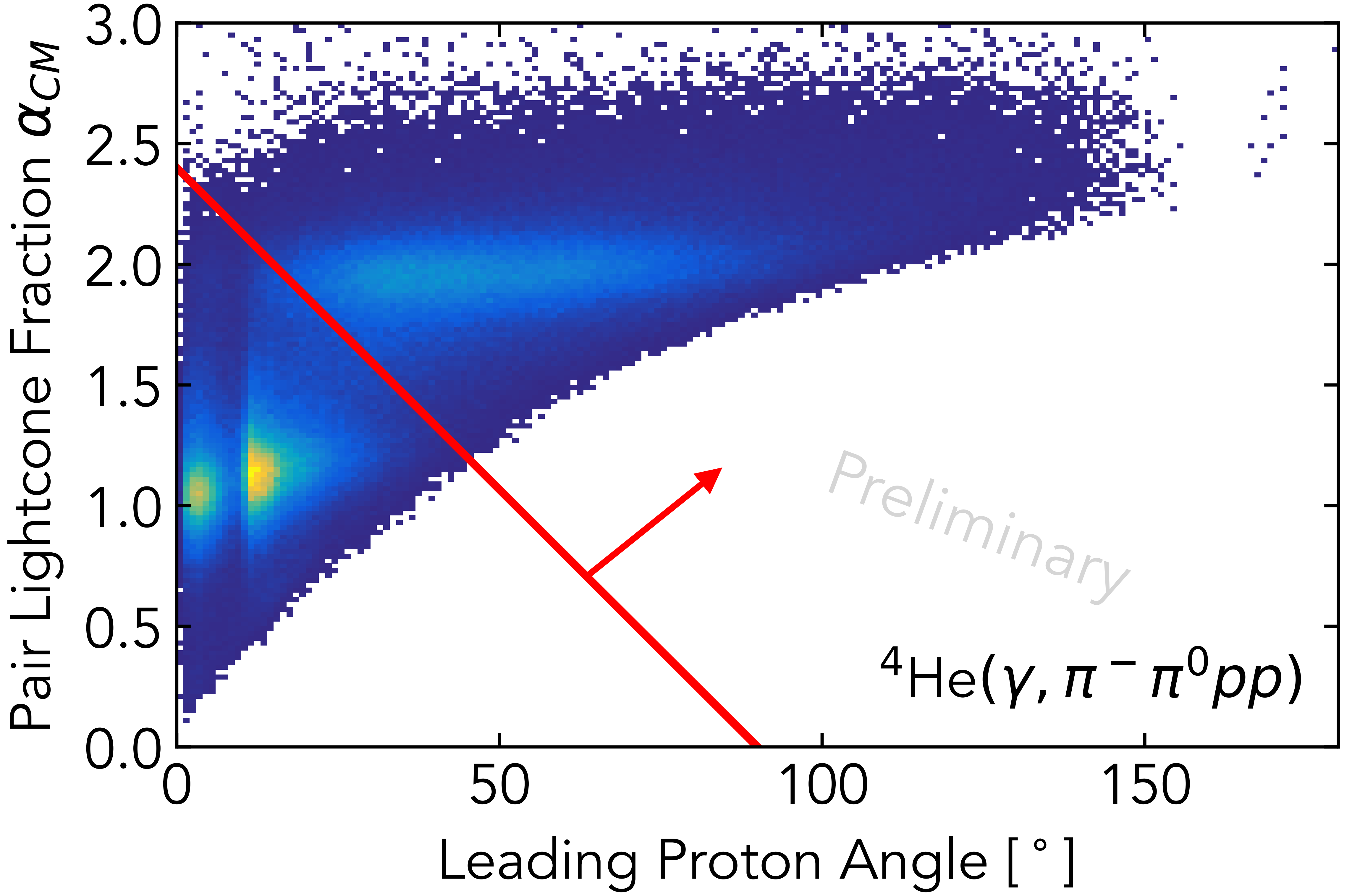
# SRC Photoproduction in Hall D

- Quasi-elastic photoproduction: hard photon-nucleon interaction
- Many meson+baryon final-states are possible
- $\rho^-$ photoproduction:
  - Initial-state neutron
  - Distinctive topology with $\rho^- \to \pi^- \pi^0$ decay
- Exclusive detection of $(\gamma, \rho^- pp)$



# SRC Event Selection

- Diffractive background cut



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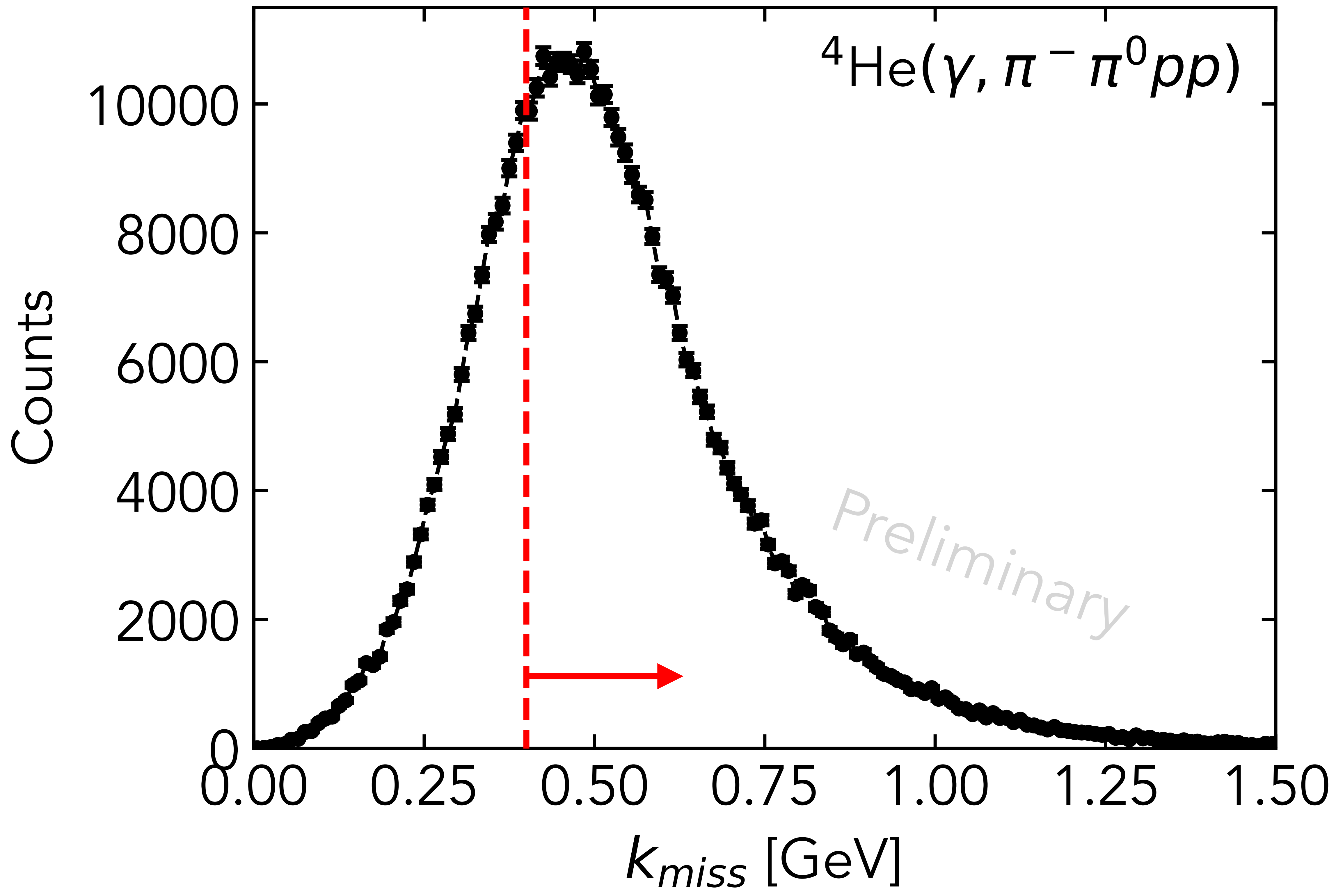

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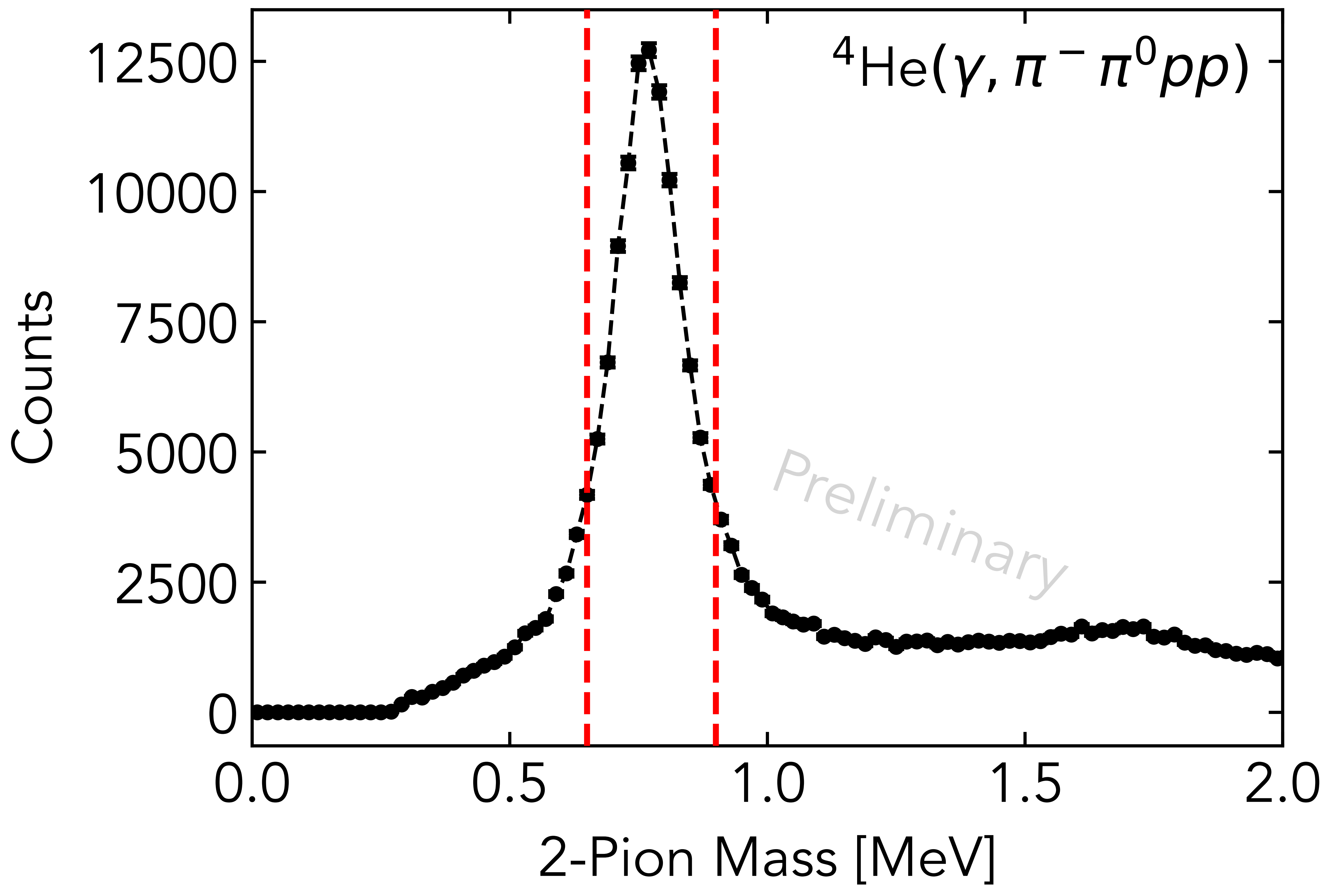
- Diffractive background cut
- High relative momentum cut
- Cut on rho meson mass



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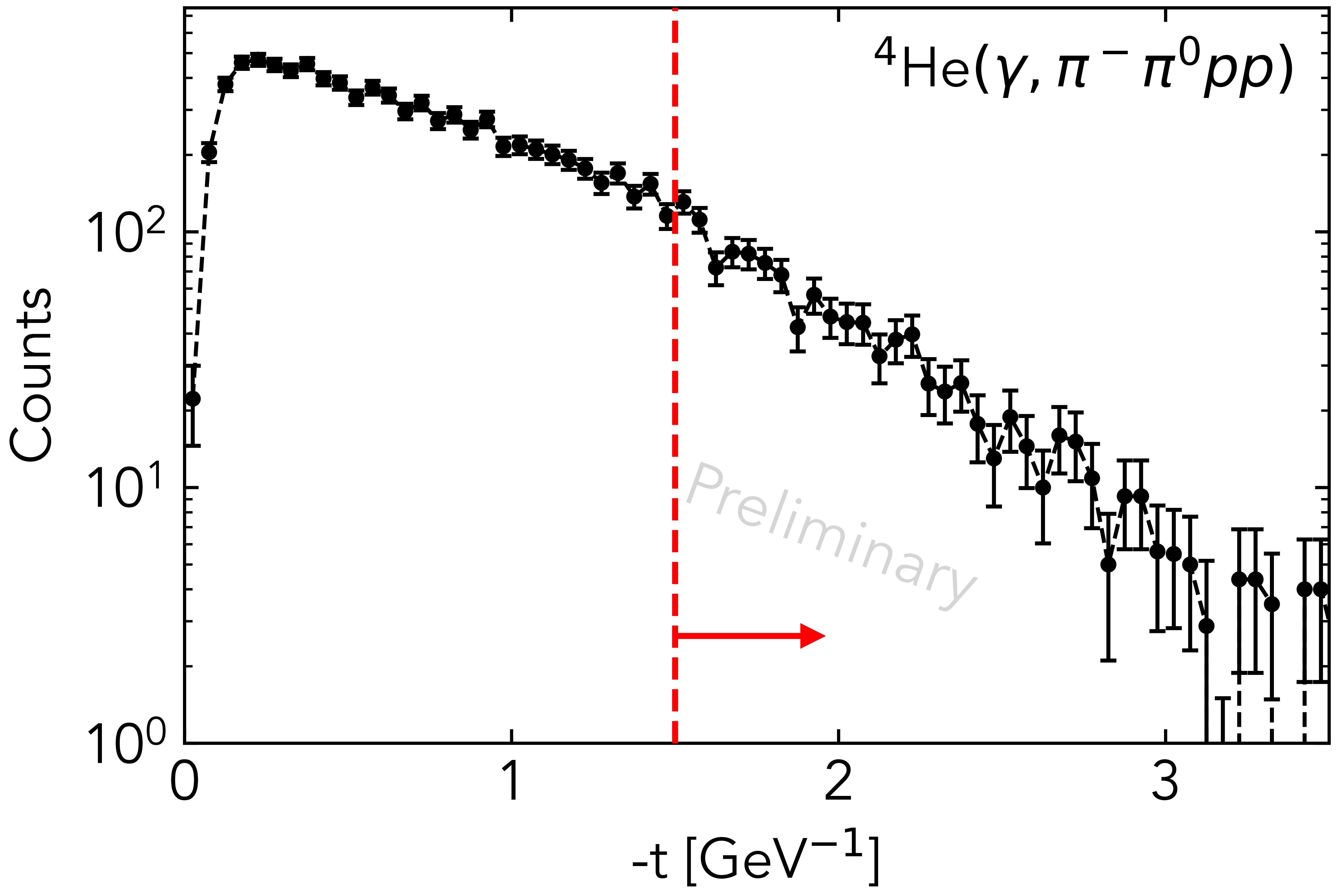
- High momentum-transfer $|t|, |u| > 1.5$ GeV$^2$



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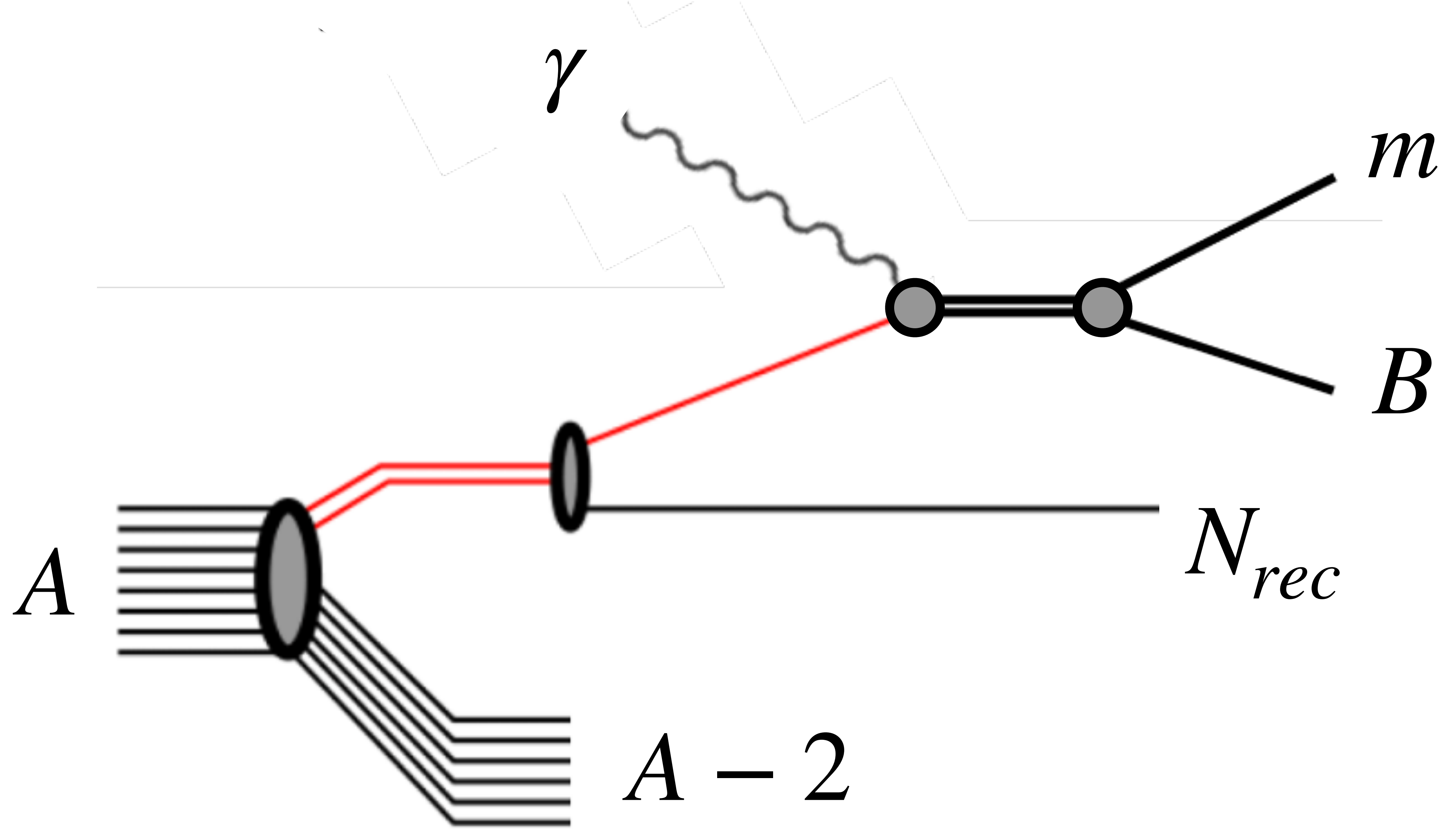
- **Compare with PWIA+GCF calculations**

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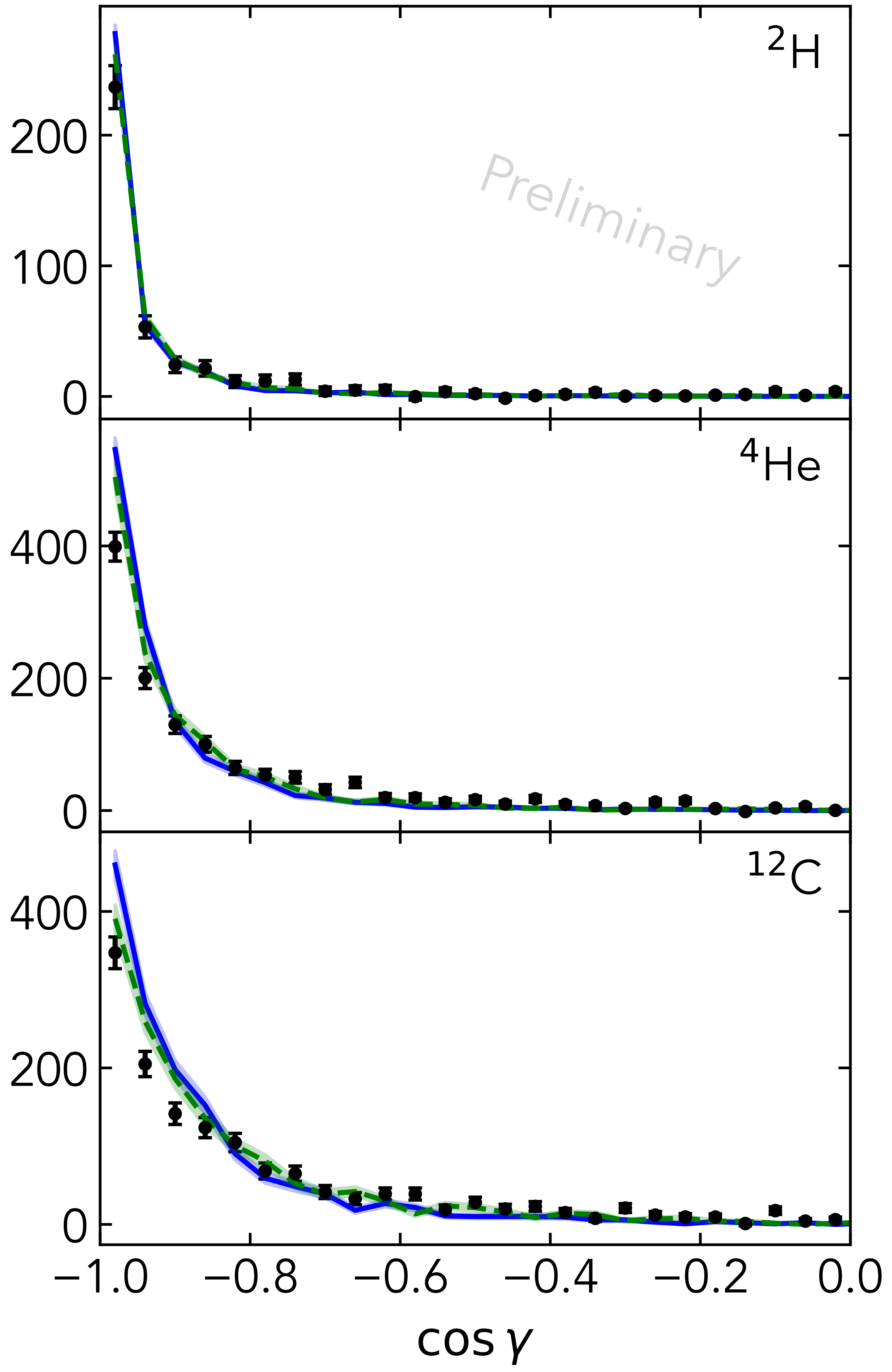
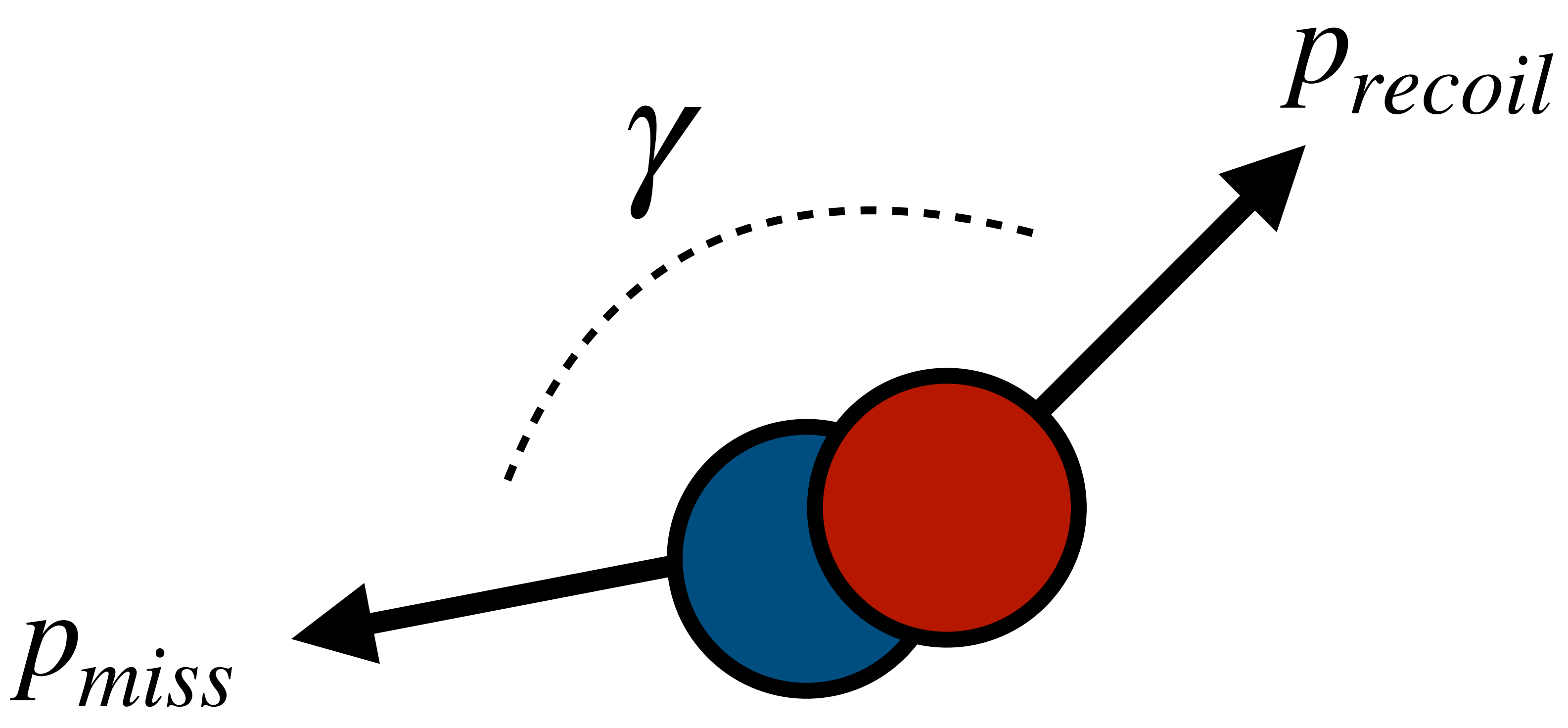
A. Schmidt et al, Nature (2020)
J. R. Pybus et al, PLB (2020)
I. Korover et al, PLB (2021)

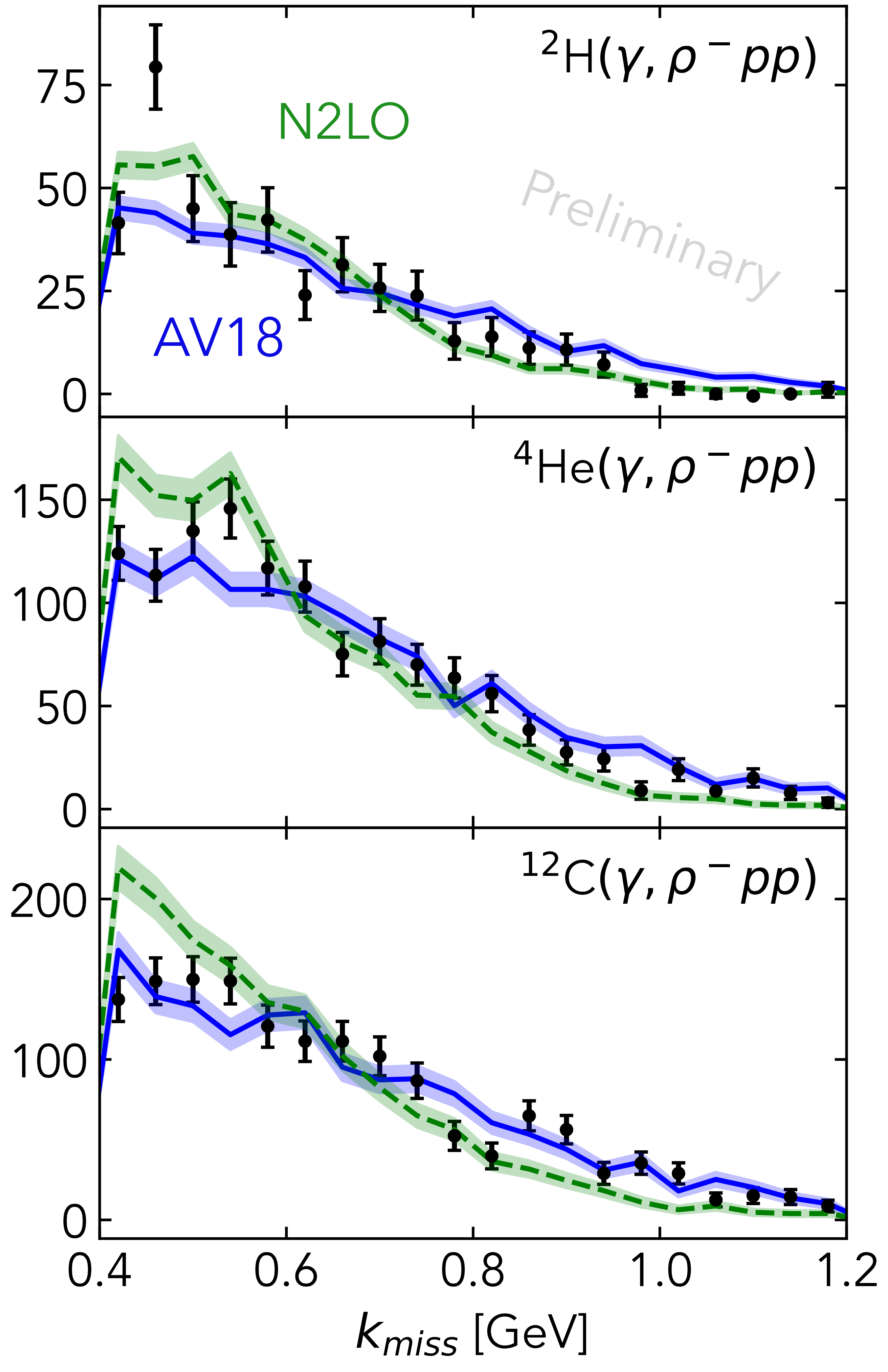
# SRC Pair Opening Angle



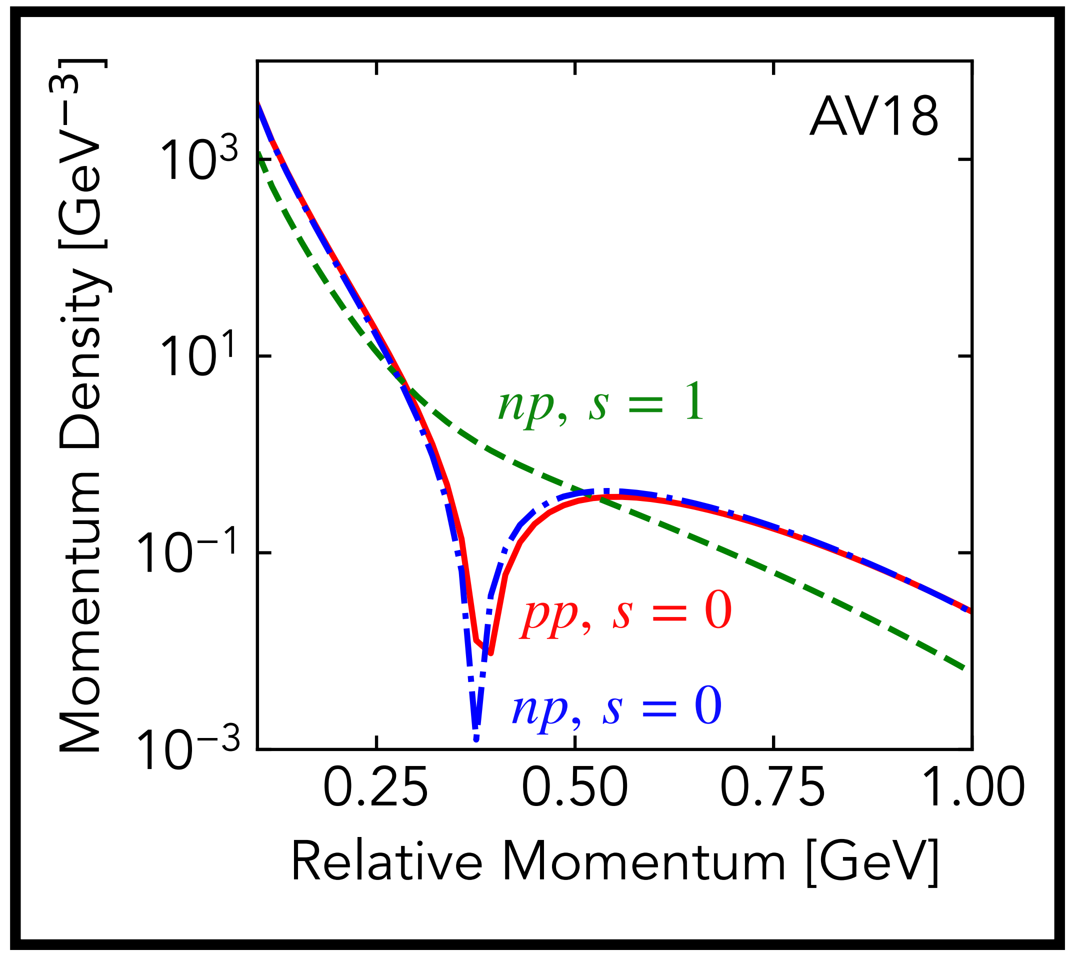

- Reconstruct angle between initial-state neutron and spectator proton
- All nuclei show clear back-to-back correlation

# Initial Neutron Momentum

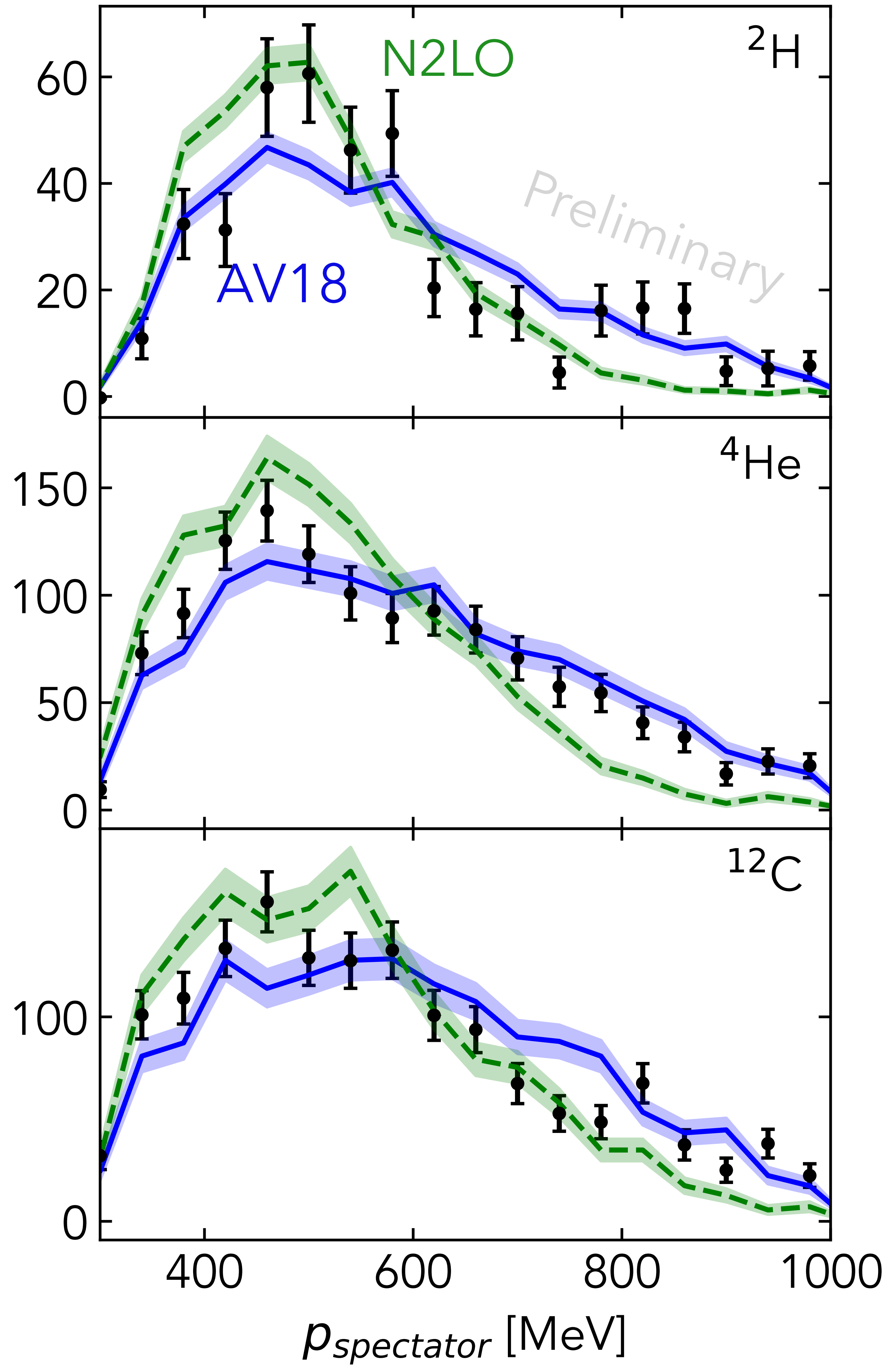



- Initial neutron momentum sensitive to short-distance NN interaction
- Momentum distributions well-described
- Agreement with AV18 predictions similar to that for electron-scattering data

**GCF Input**

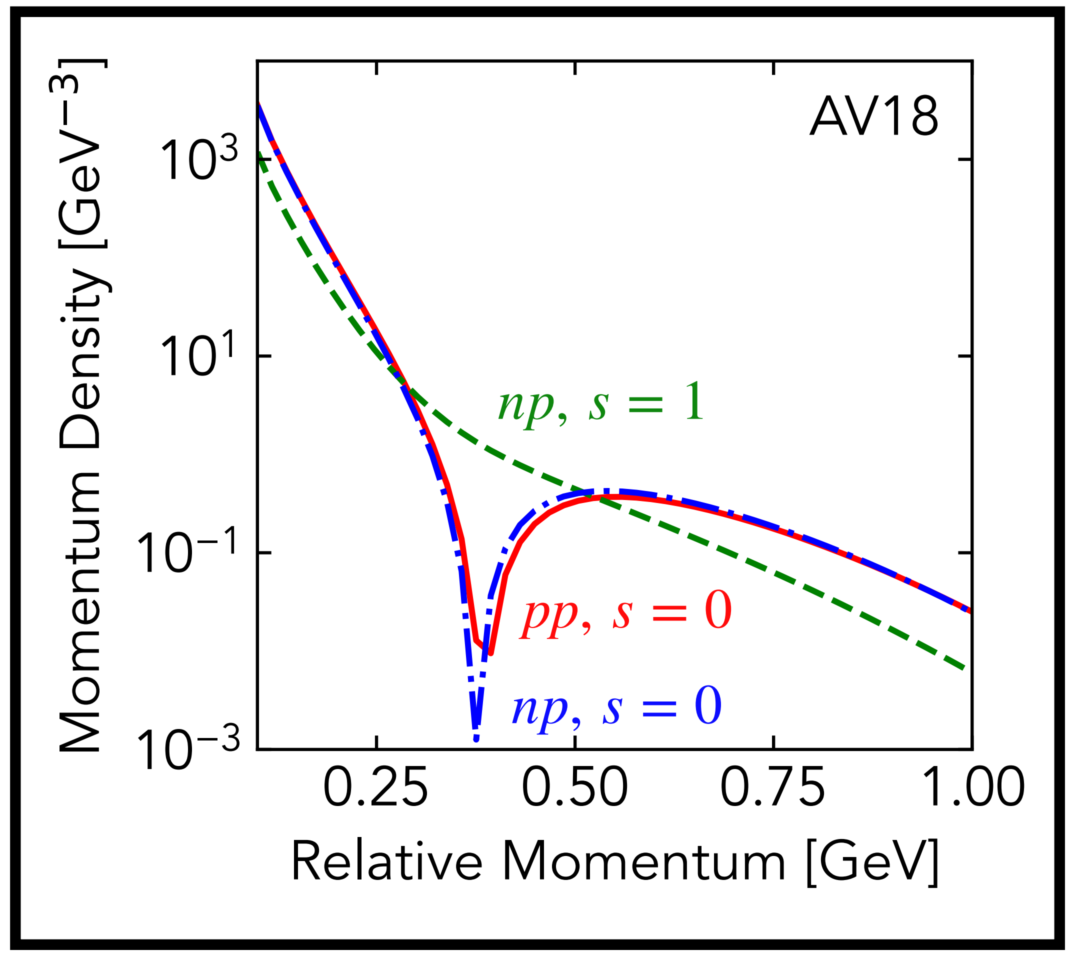


# Spectator Proton Momentum

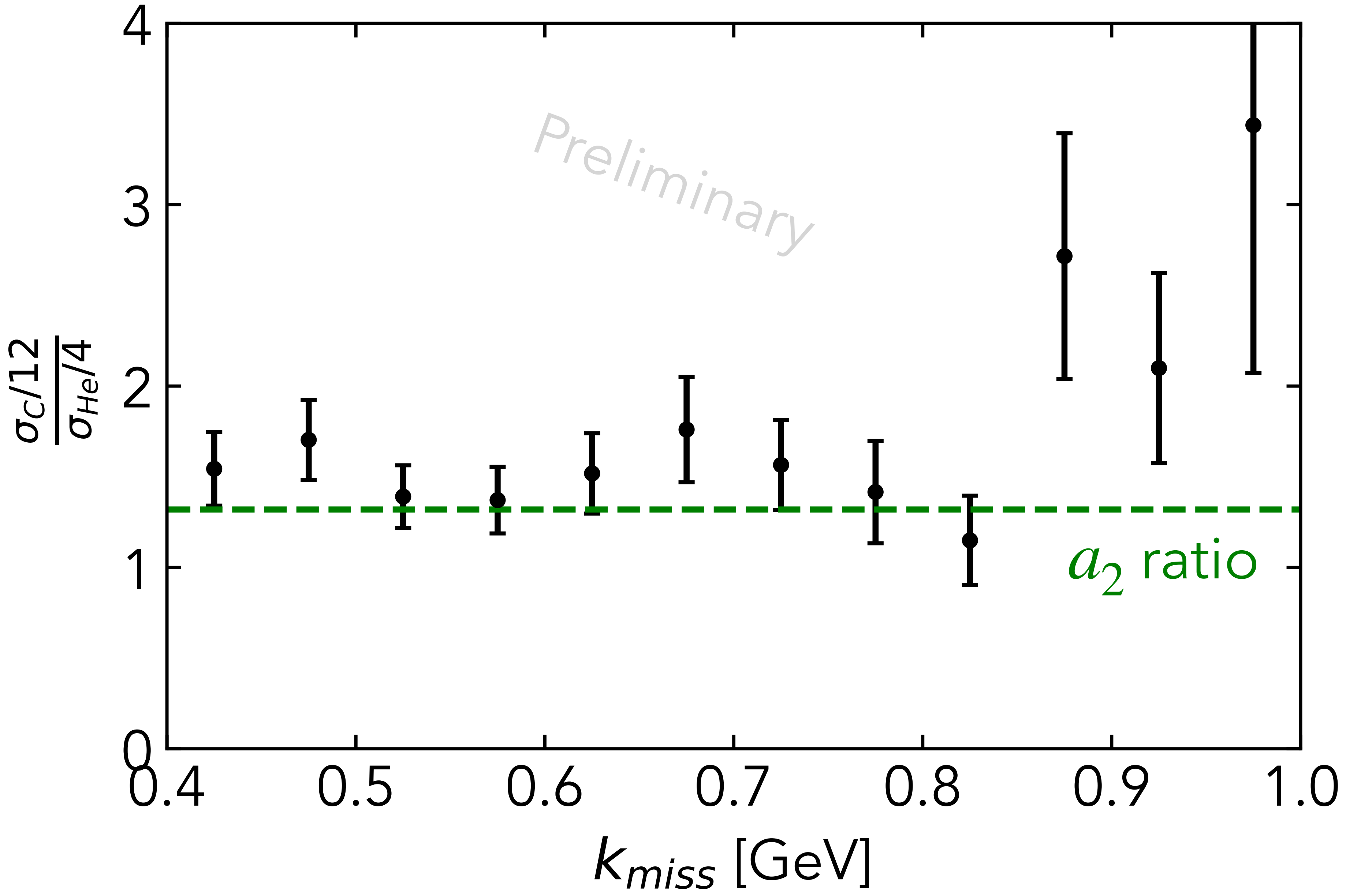



- Spectator momentum also well-reconstructed but may be subject to rescattering
- Calculation of FSI using cascade models can help identify regions of large FSI

**GCF Input**



# SRC Abundances




- Compare momentum distributions to confirm scaling across nuclei
- Data is corrected for nuclear transparency (~20% normalization uncertainty)
- Data for helium and carbon show scaling across large momentum range and agree with $a_2$ predictions
- Data ratio with deuterium also consistent with measured $a_2$

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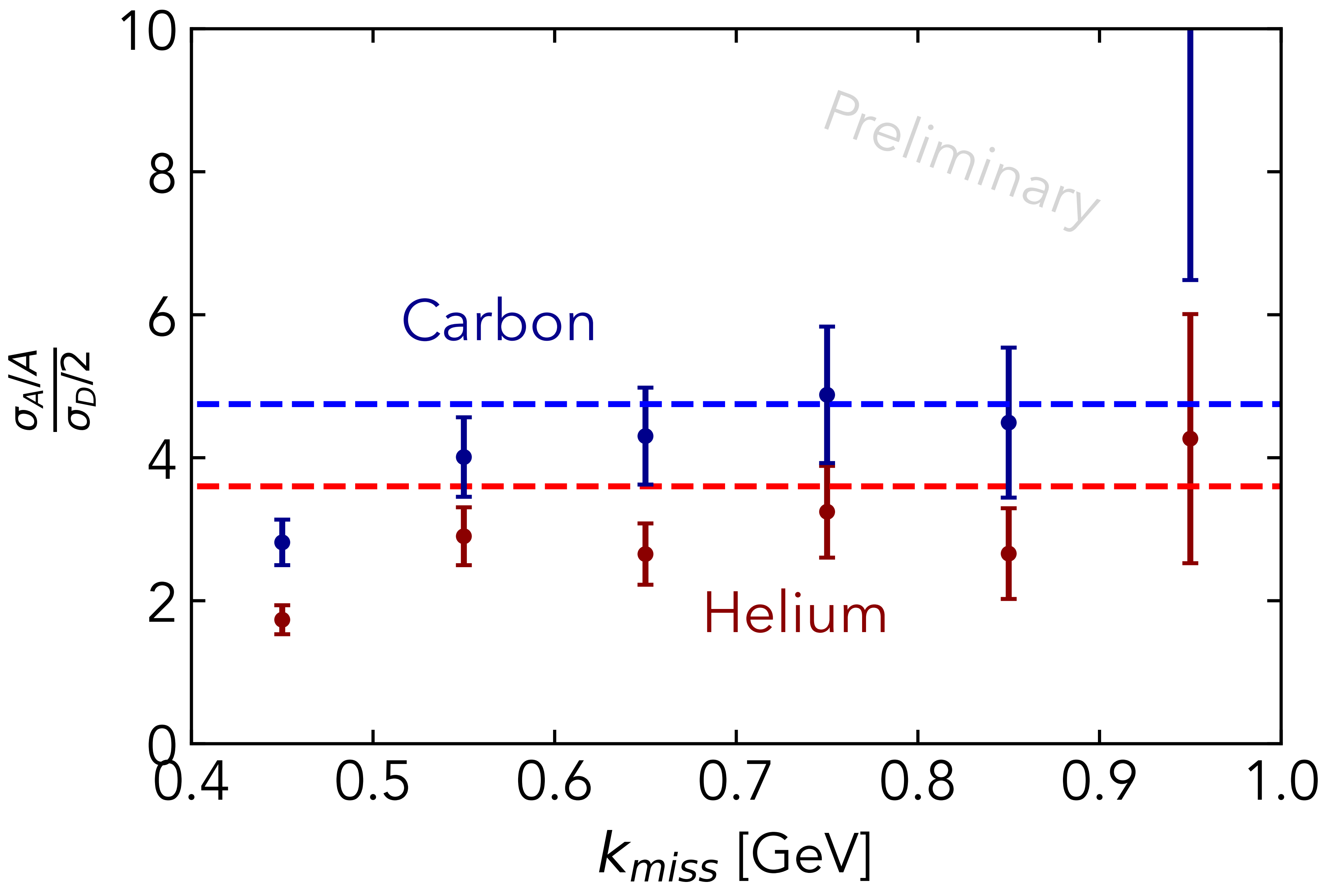


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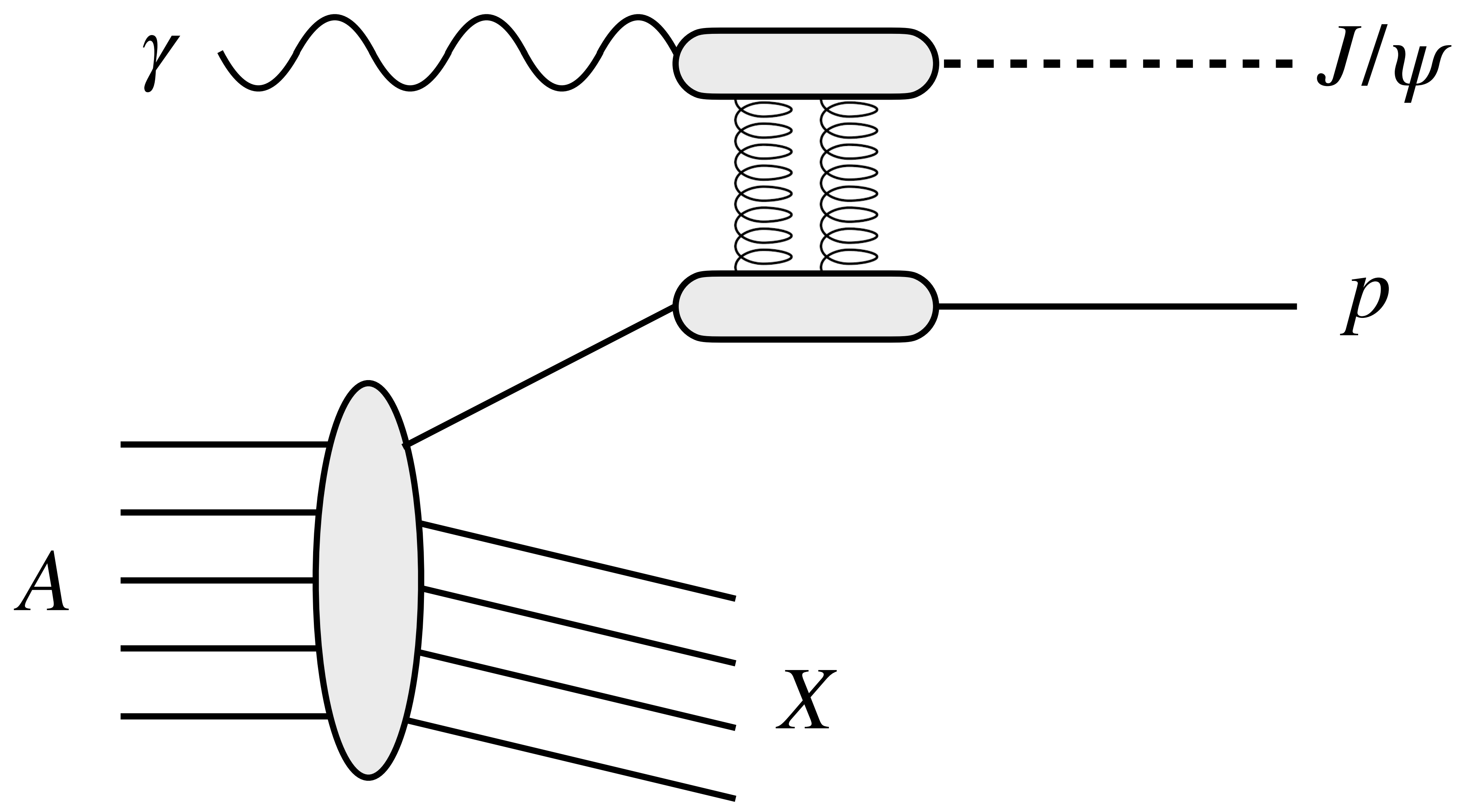
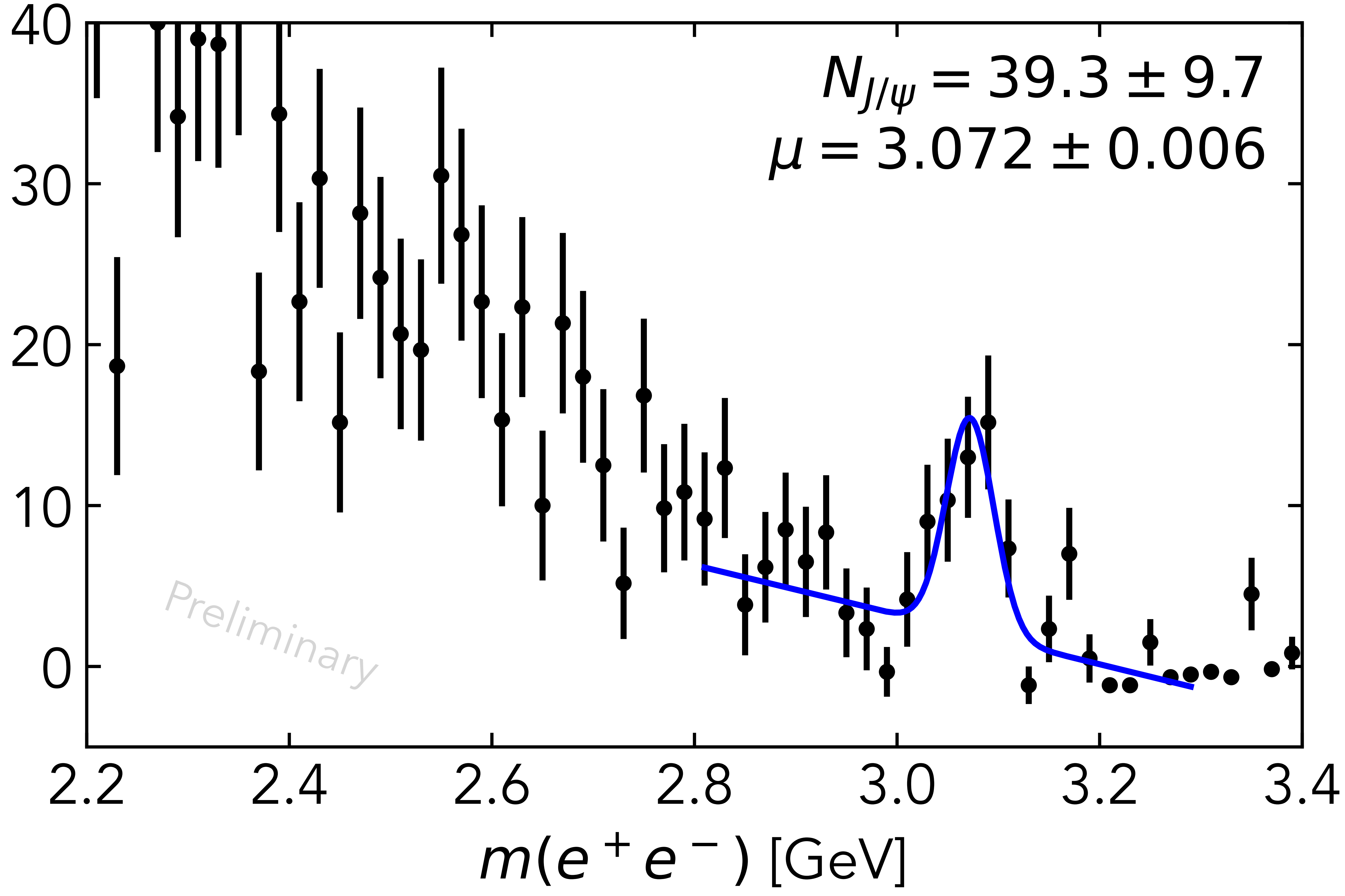
# Outlook for Hall D Nuclear Measurement

- 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

# New Measurement: Threshold $J/\psi$ from Nuclei

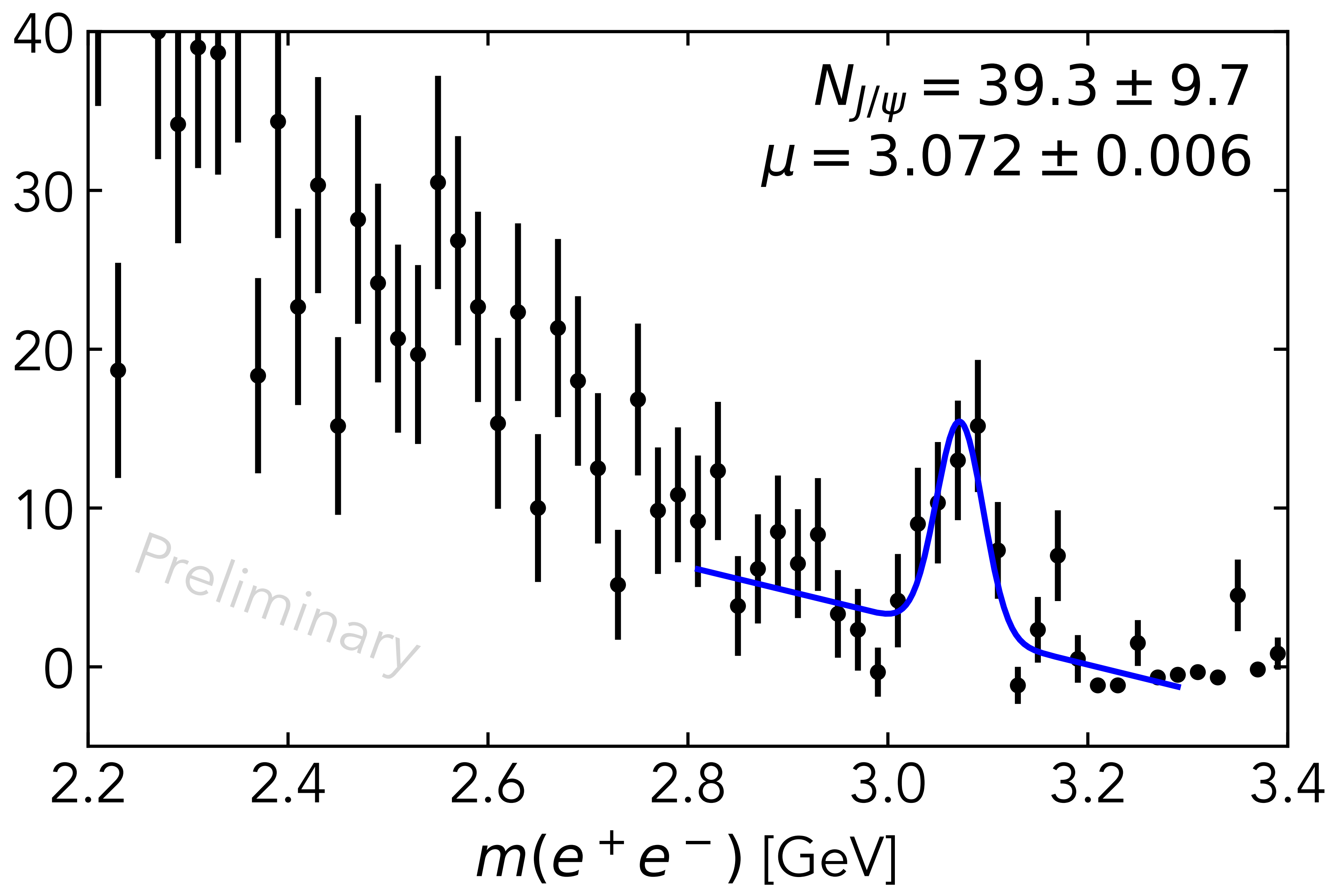



$\gamma\,^4\text{He} \to e^+e^-pX$

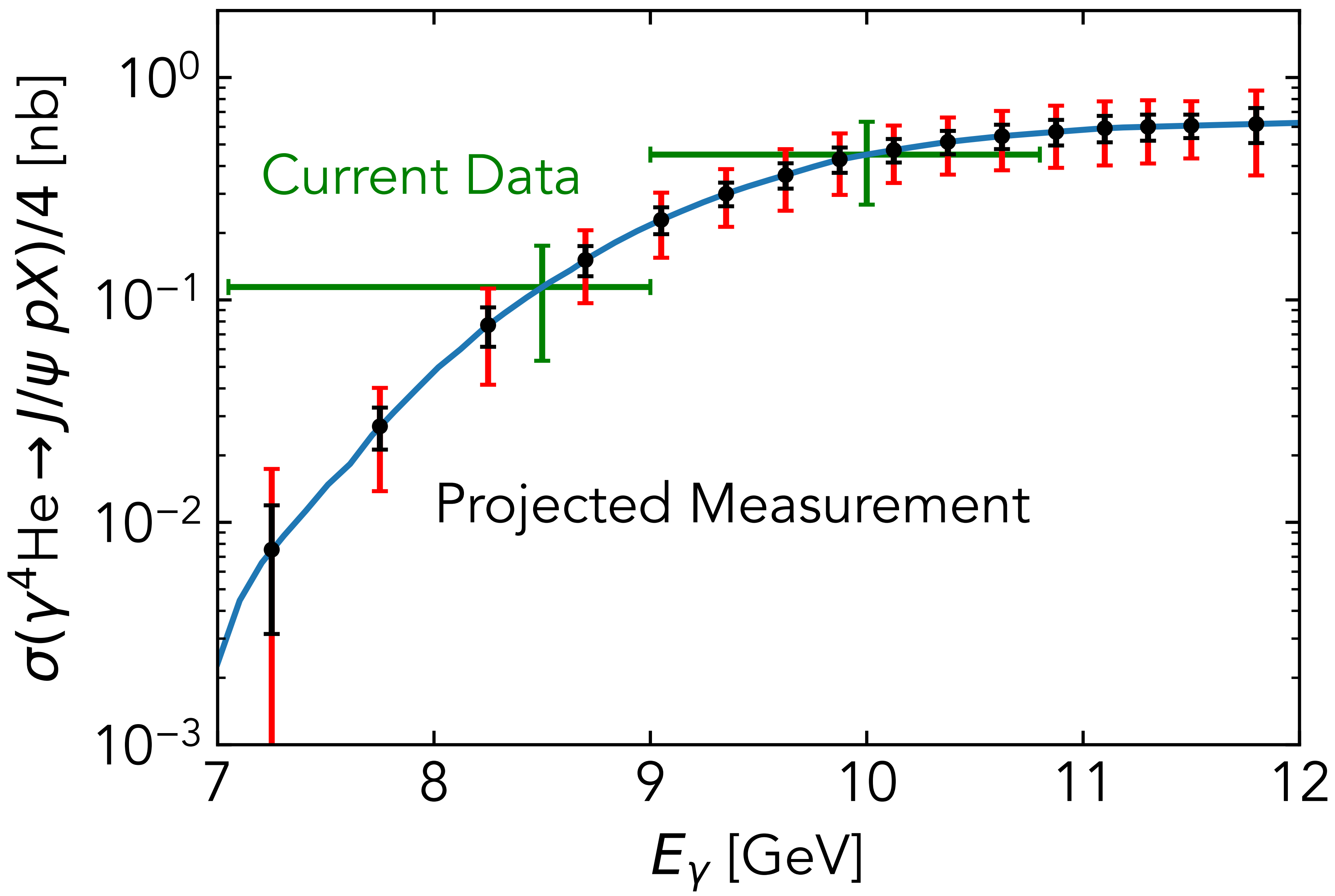



# Submitted proposal would allow order-of-magnitude better measurement of $J/\psi$ photoproduction from $^4$He

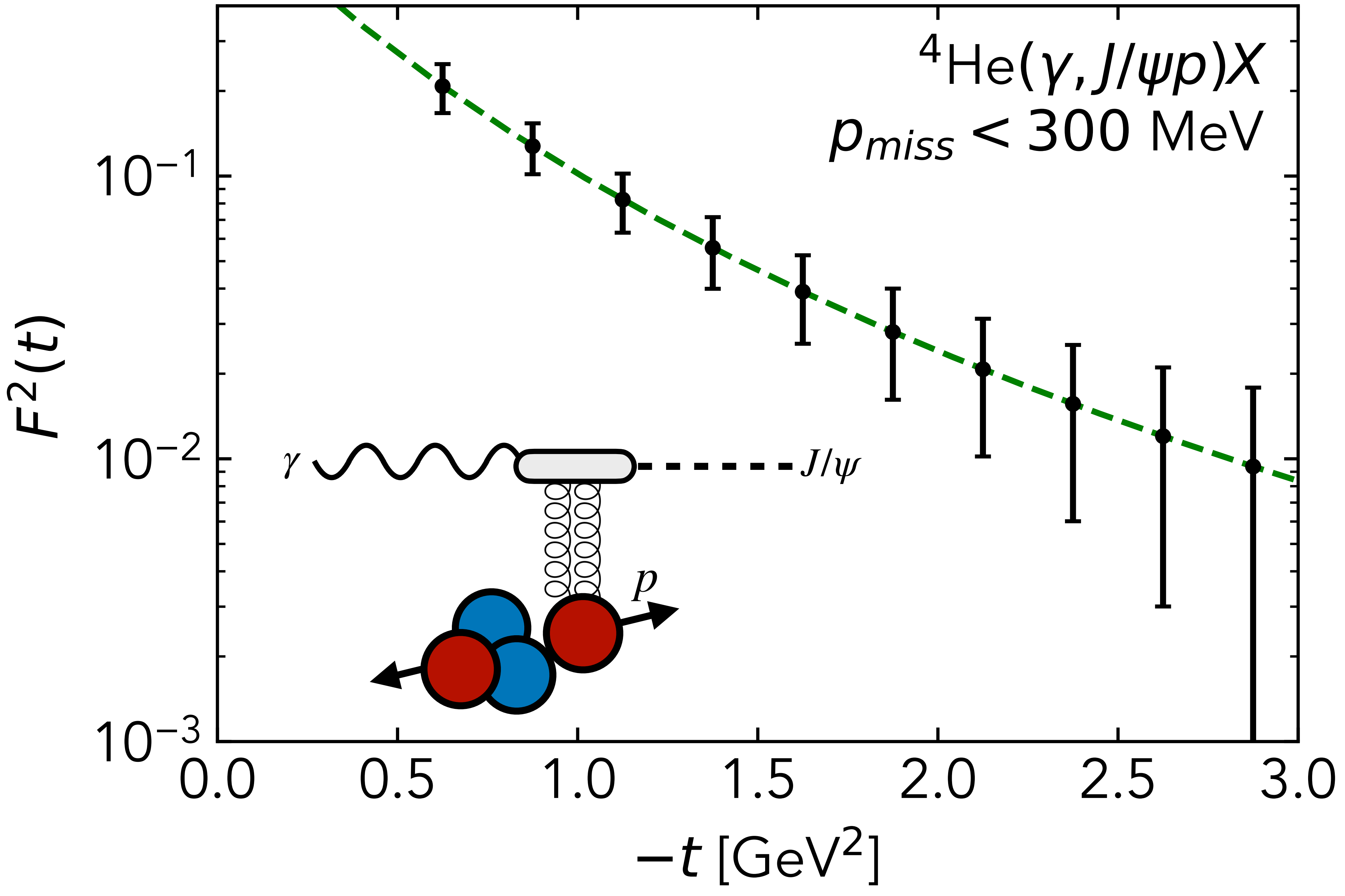
Current $^4$He Data from E12-19-003

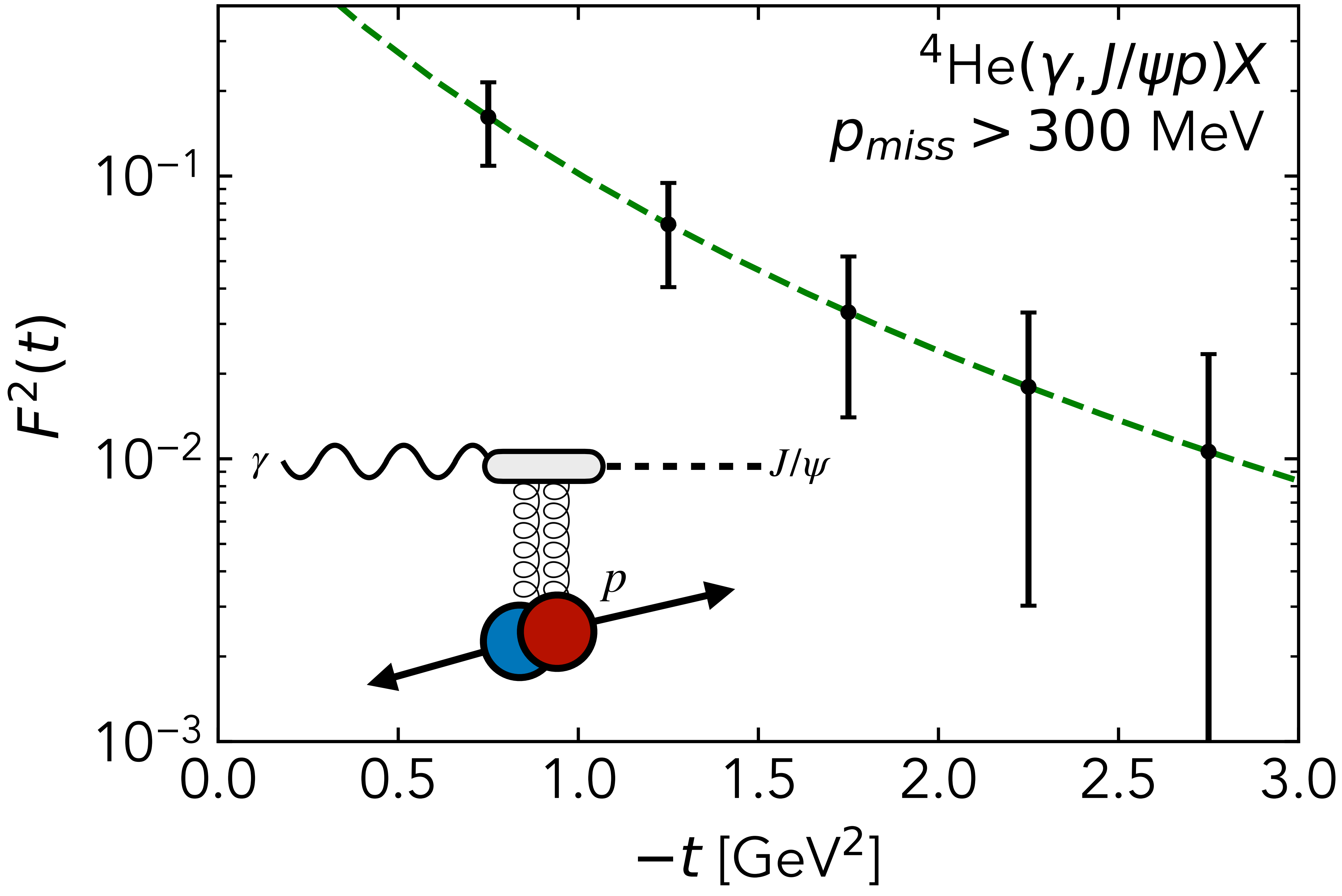



New Hall D Proposal **PR12-23-009**




# First gluonic probe of correlated nucleons?



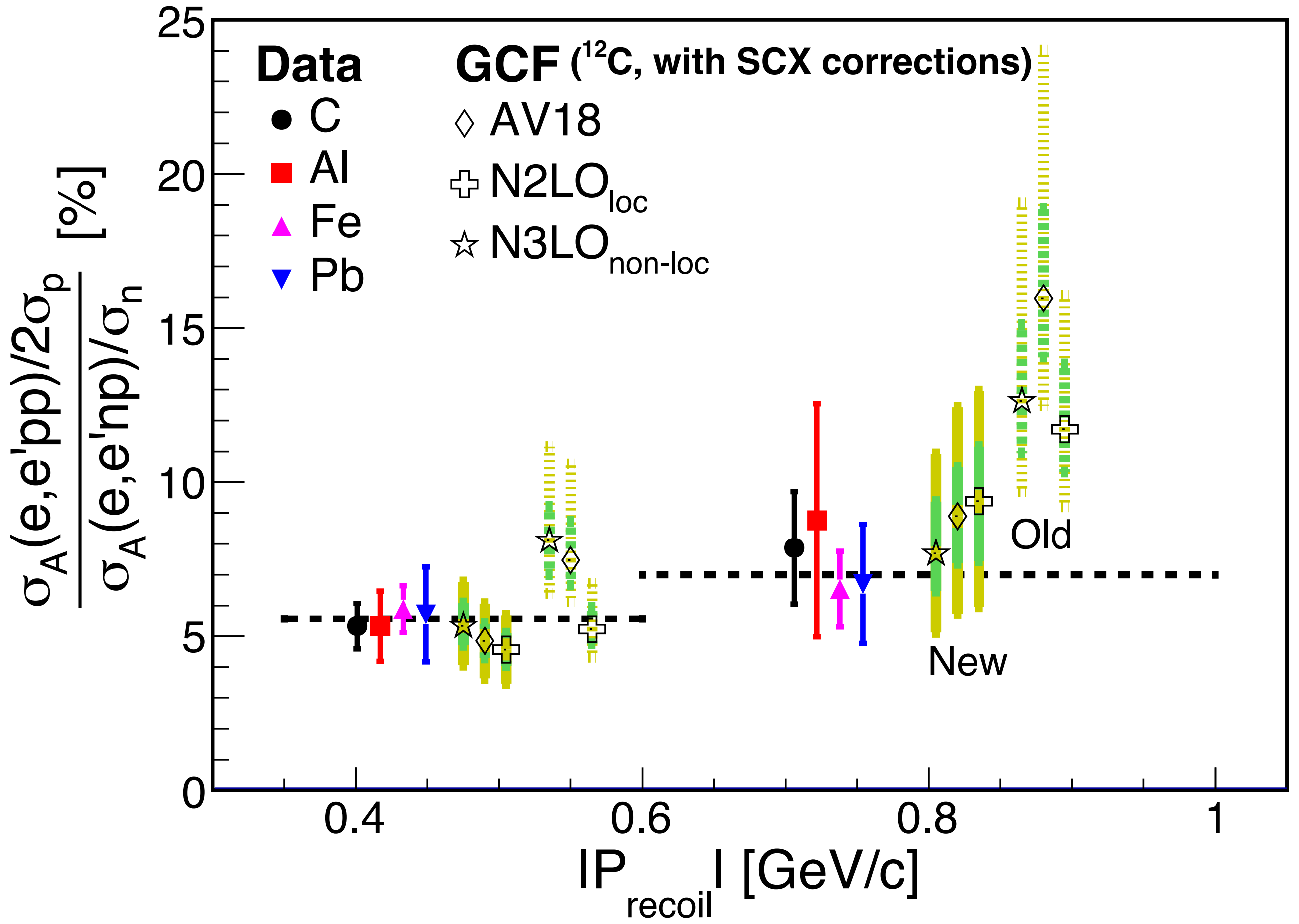




New Hall D Proposal **PR12-23-009**

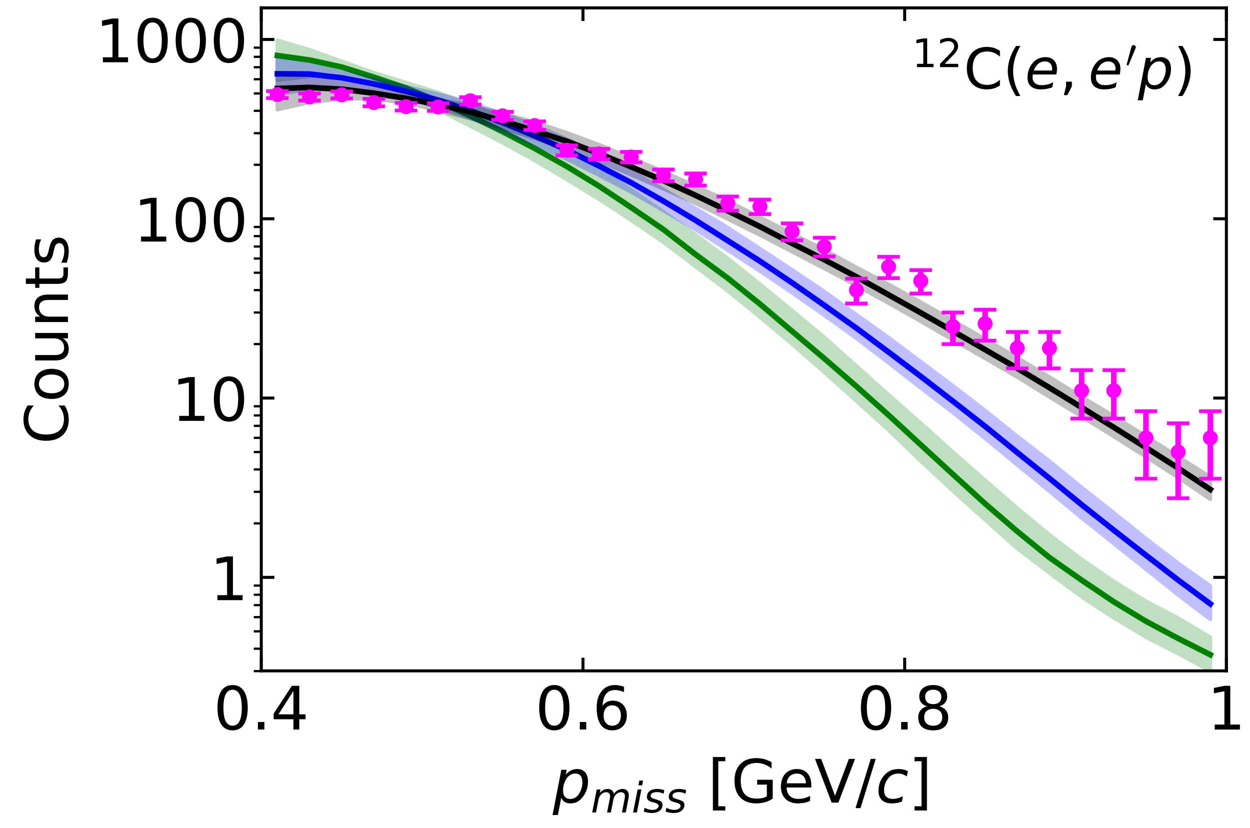
# Backup Slides

# Many recent results in quantitative study of SRCs

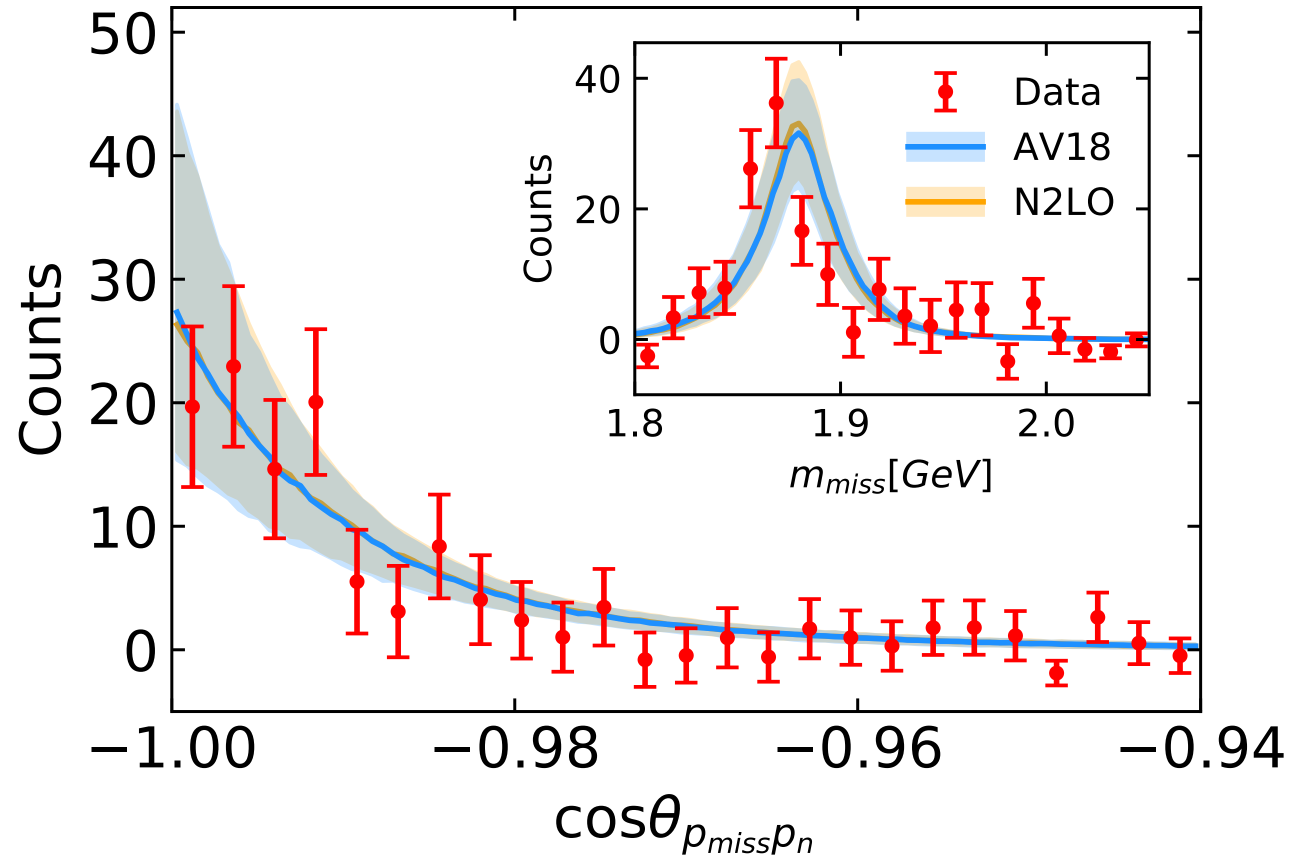
**PRL 122, 172502 (2019)**



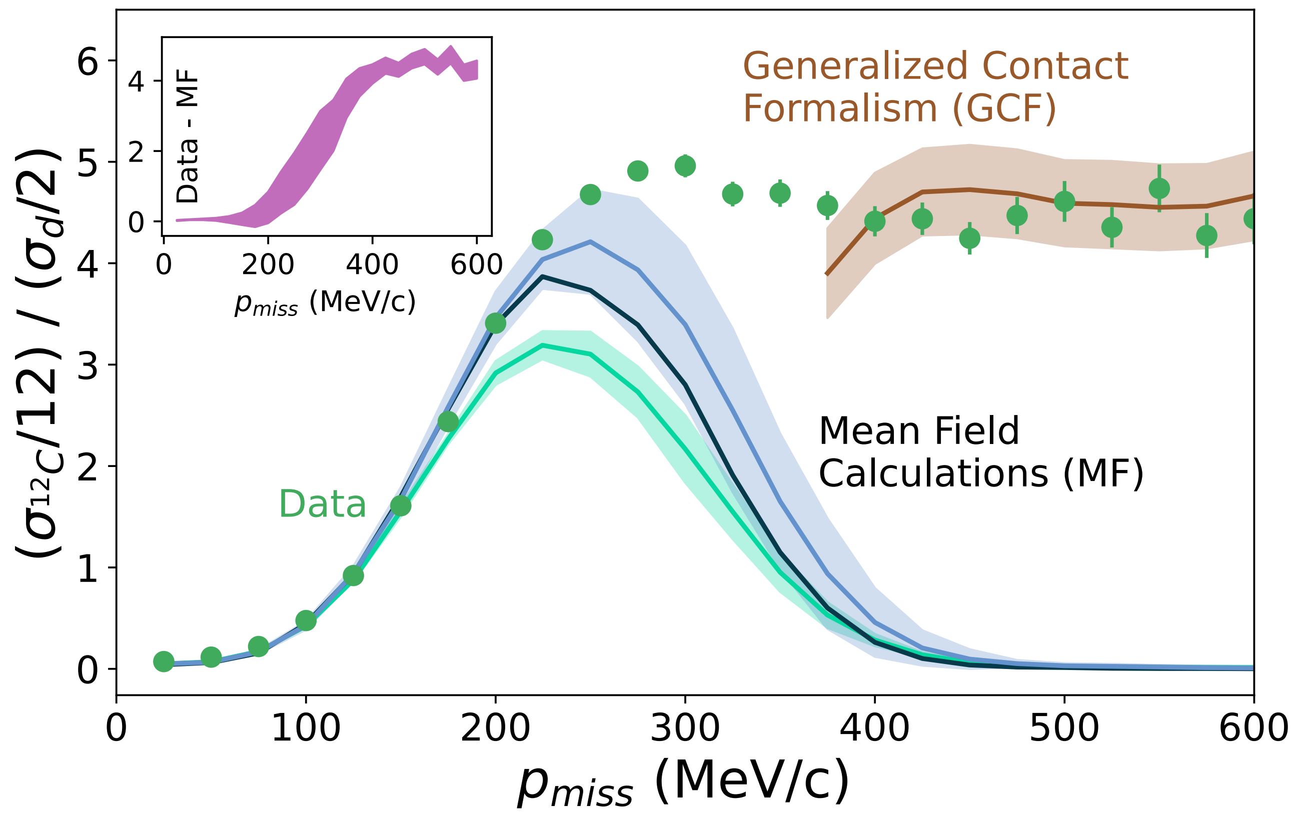

**Nature 578, 540 (2020)**



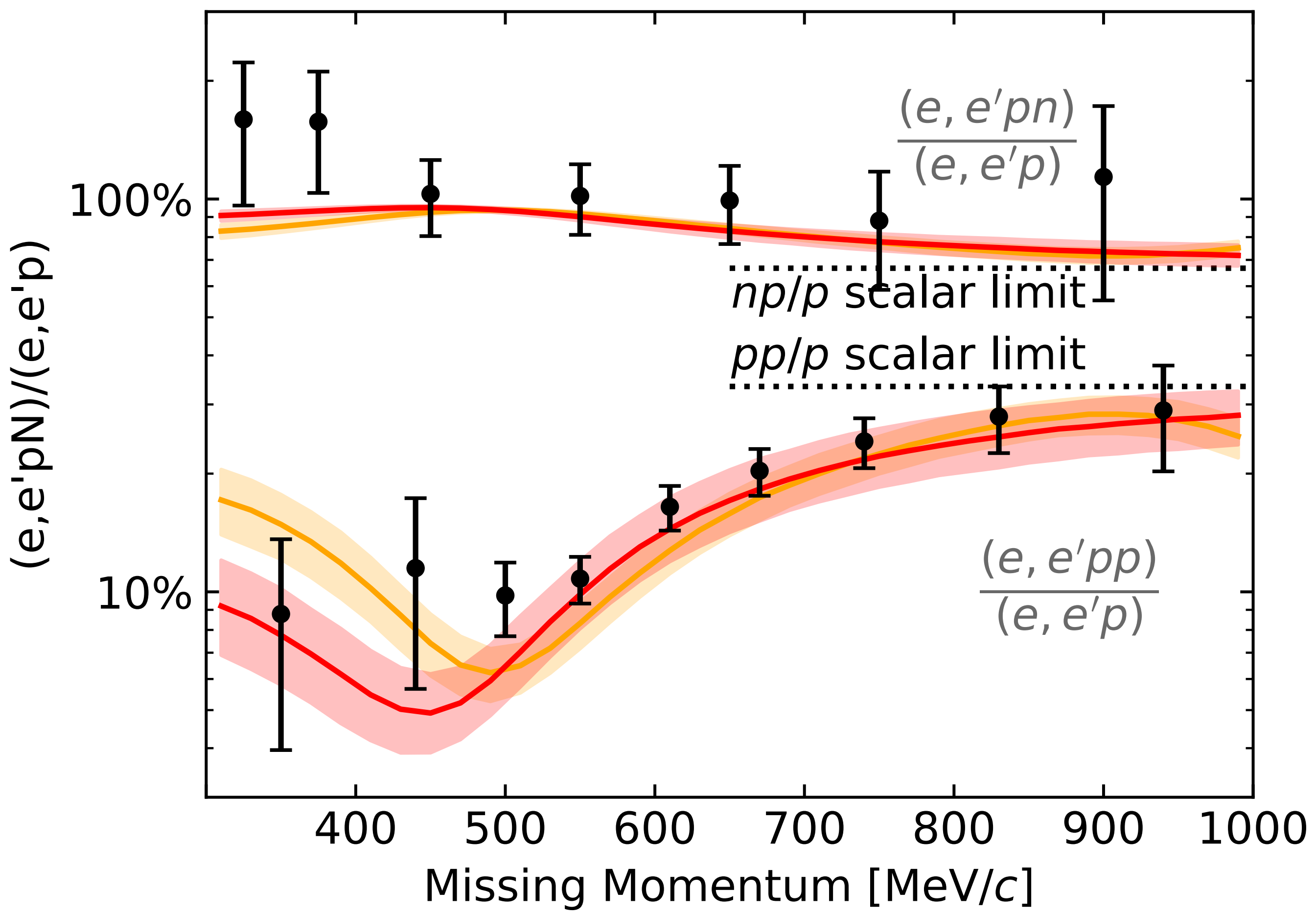

**PLB 805, 135429 (2020)**




**PRC 107, L061301 (2023)**

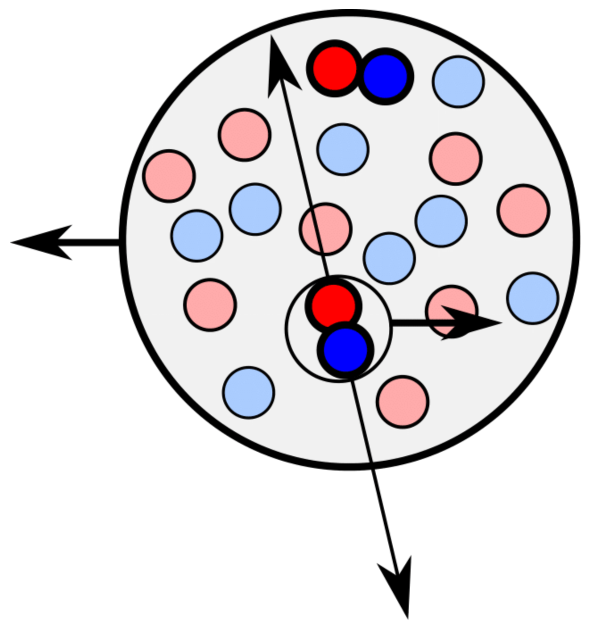



**PLB 820, 136523 (2021)**

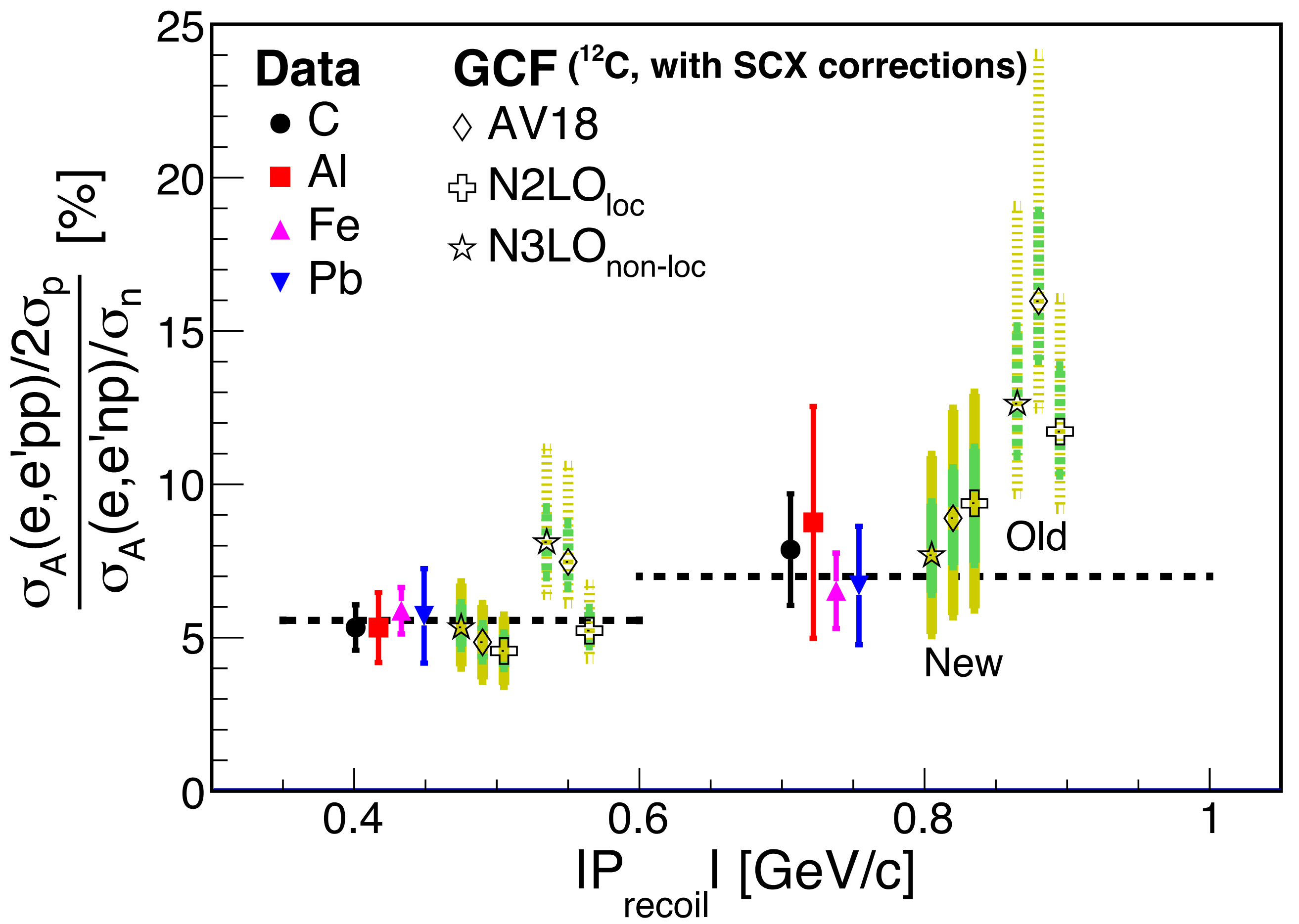


# Many recent results in quantitative study of SRCs

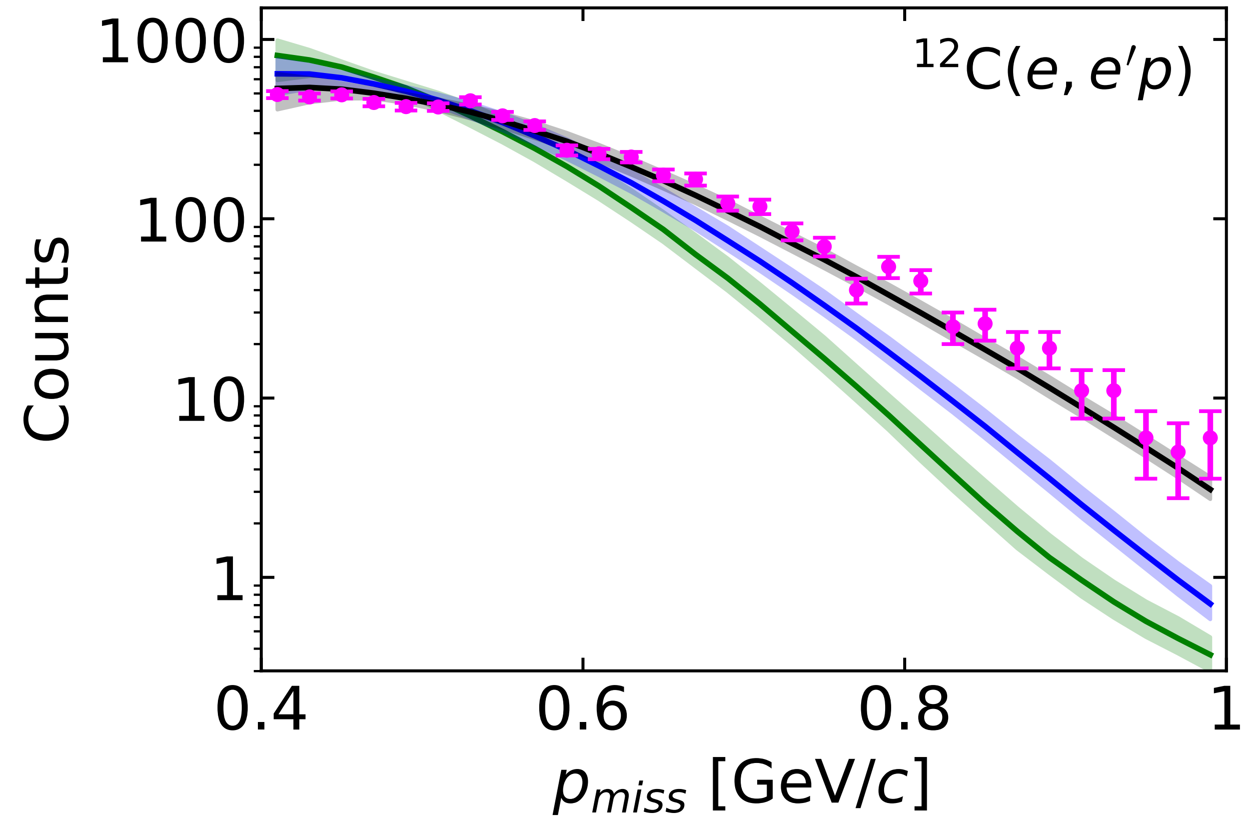
**Generalized Contact Formalism Cross-Section Model**



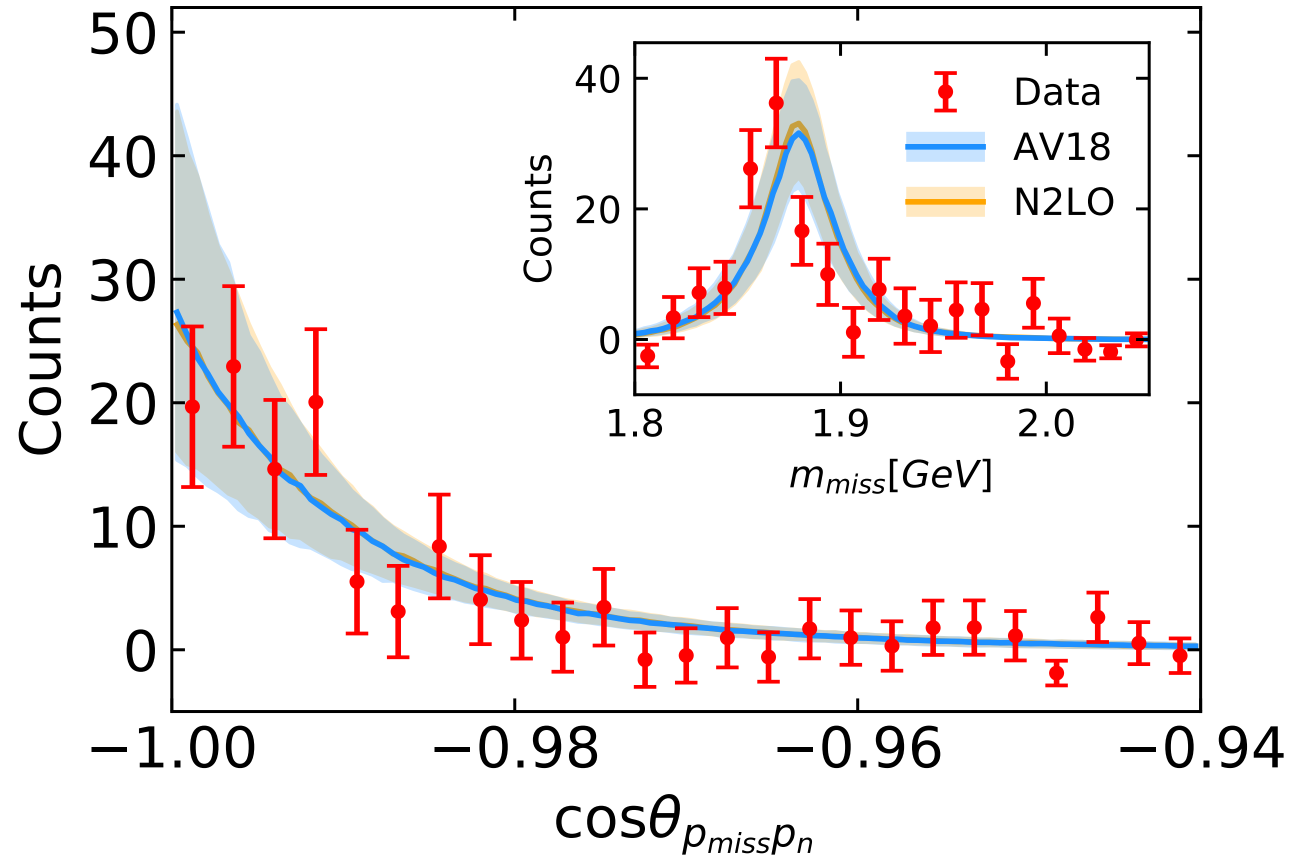
**PRL 122, 172502 (2019)**



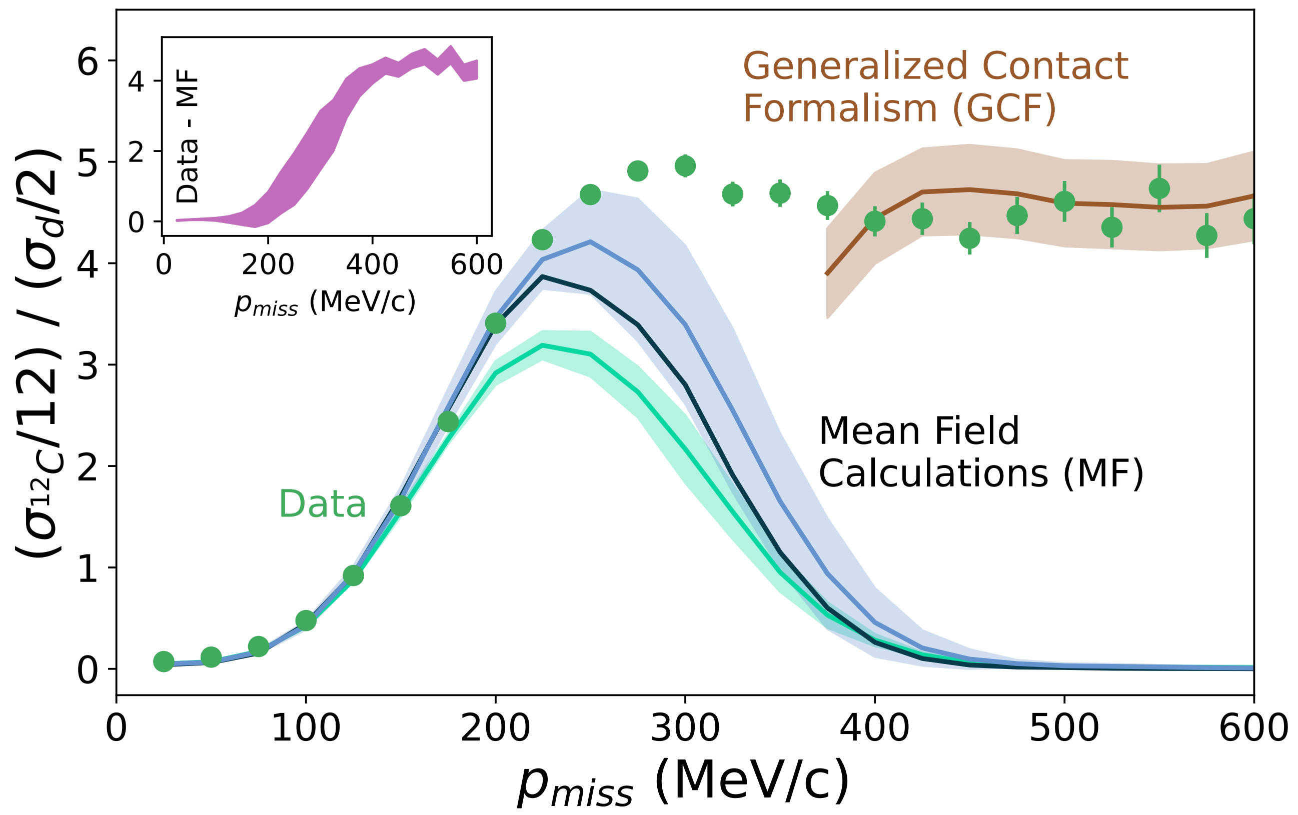

**Nature 578, 540 (2020)**




**PLB 805, 135429 (2020)**




**PRC 107, L061301 (2023)**

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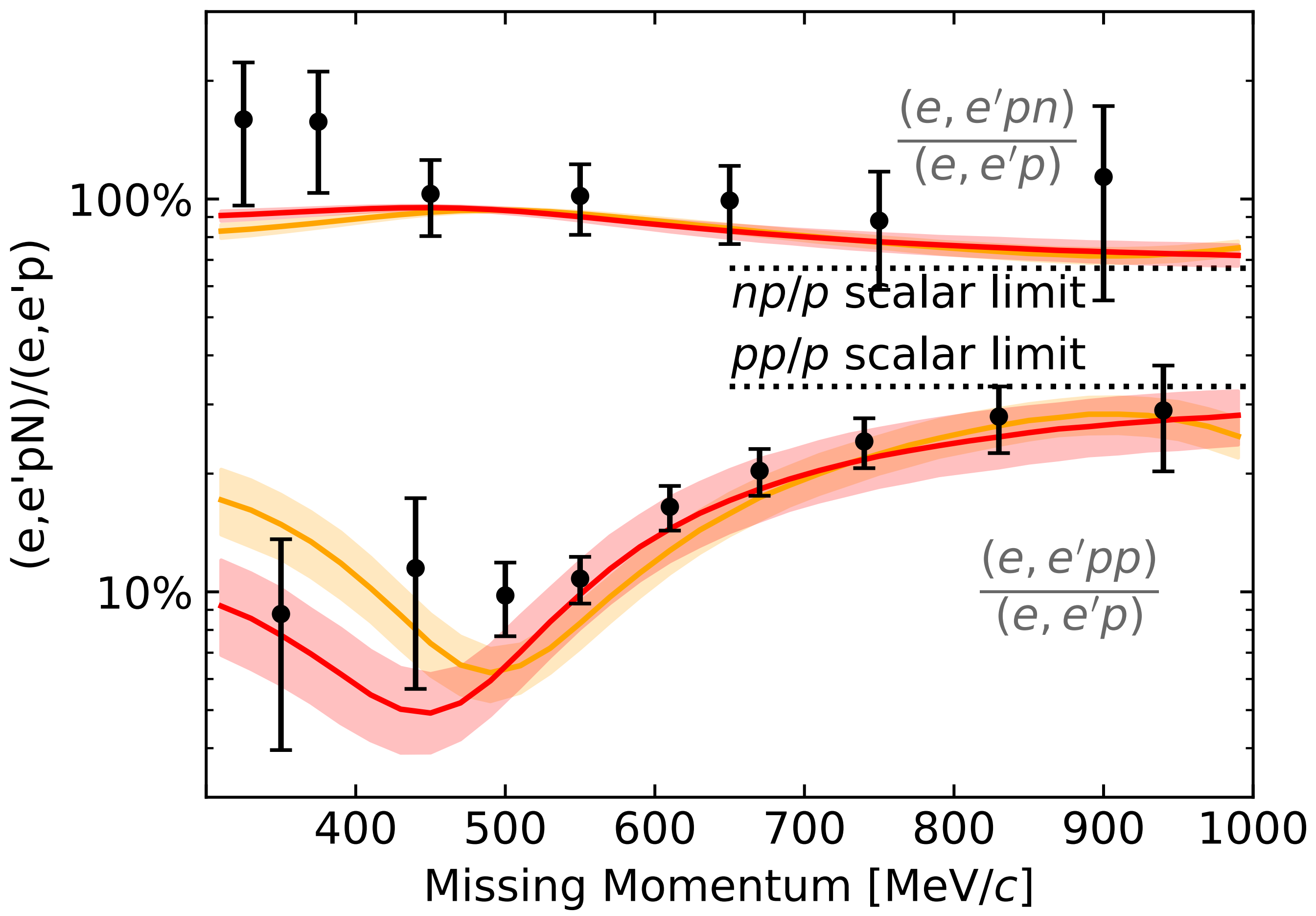
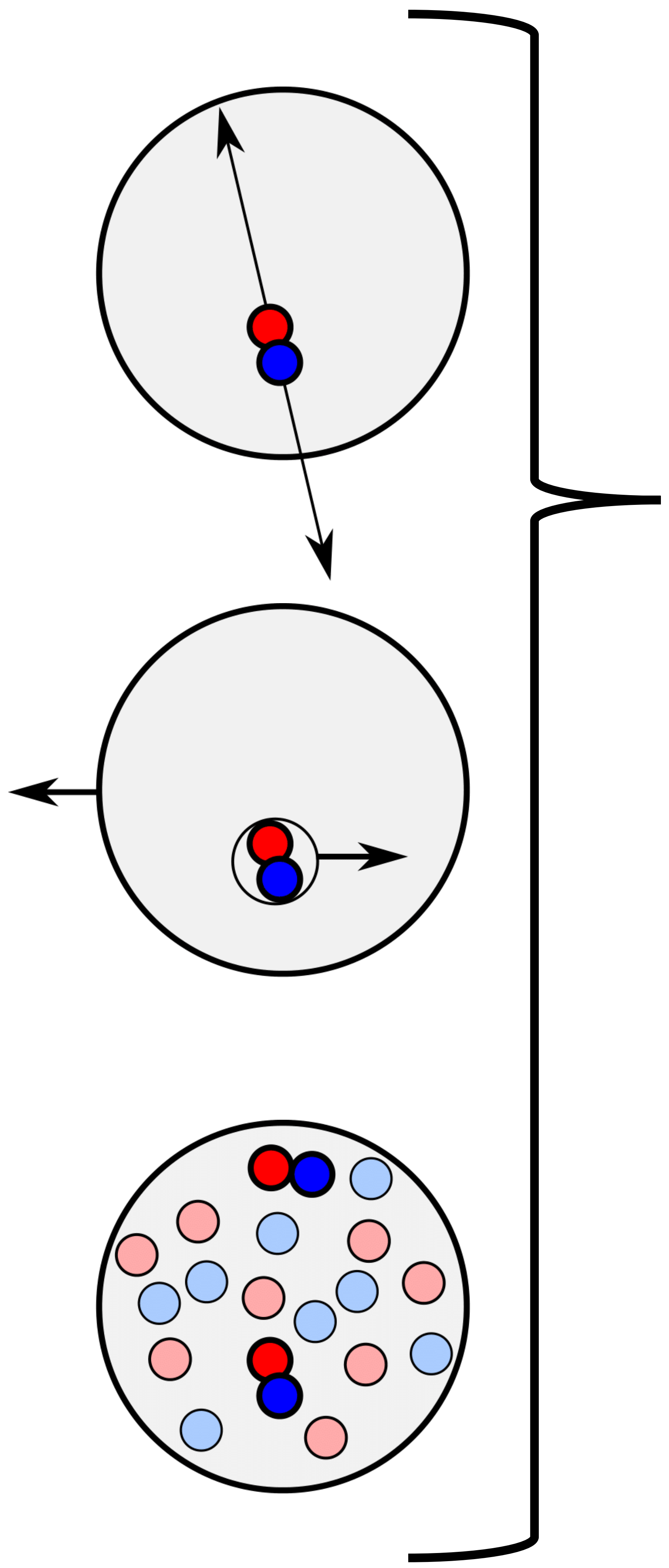


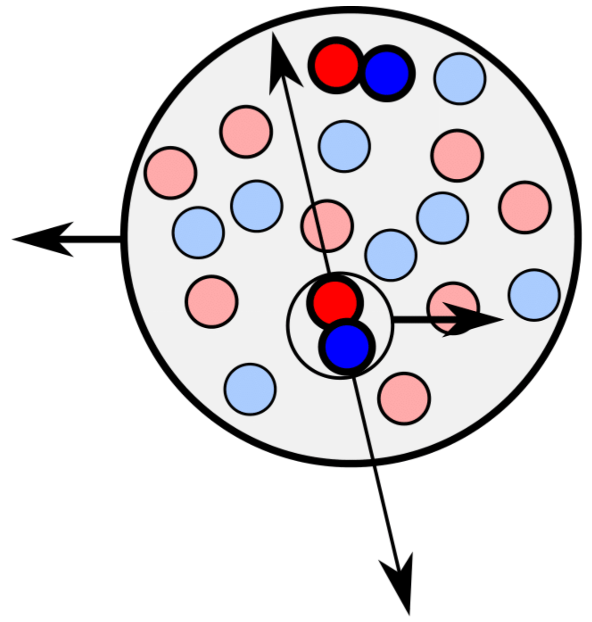
# Generalized Contact Formalism:
# Factorized model for SRCs in the nuclear ground state

Pair interaction

Center-of-mass

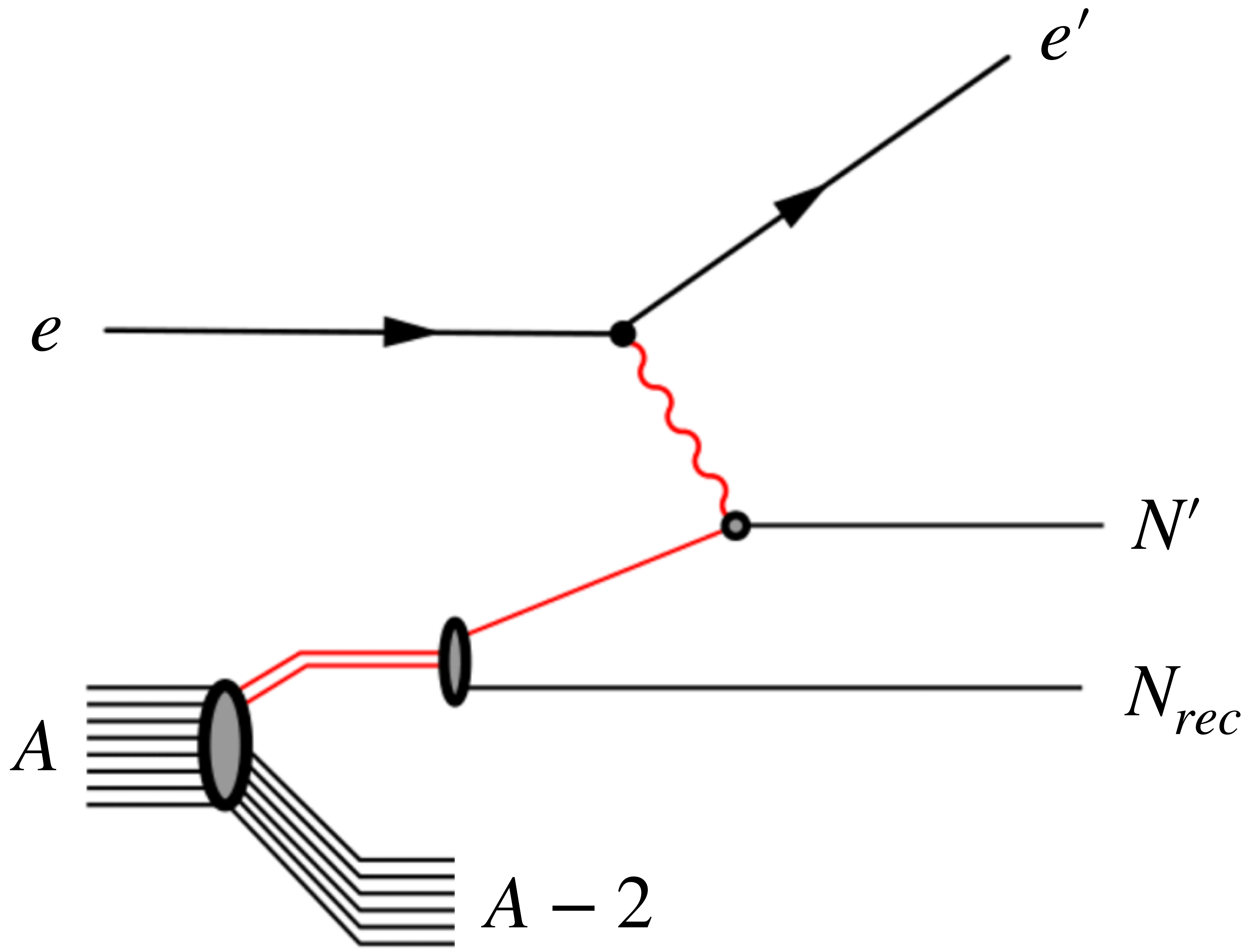
SRC abundance



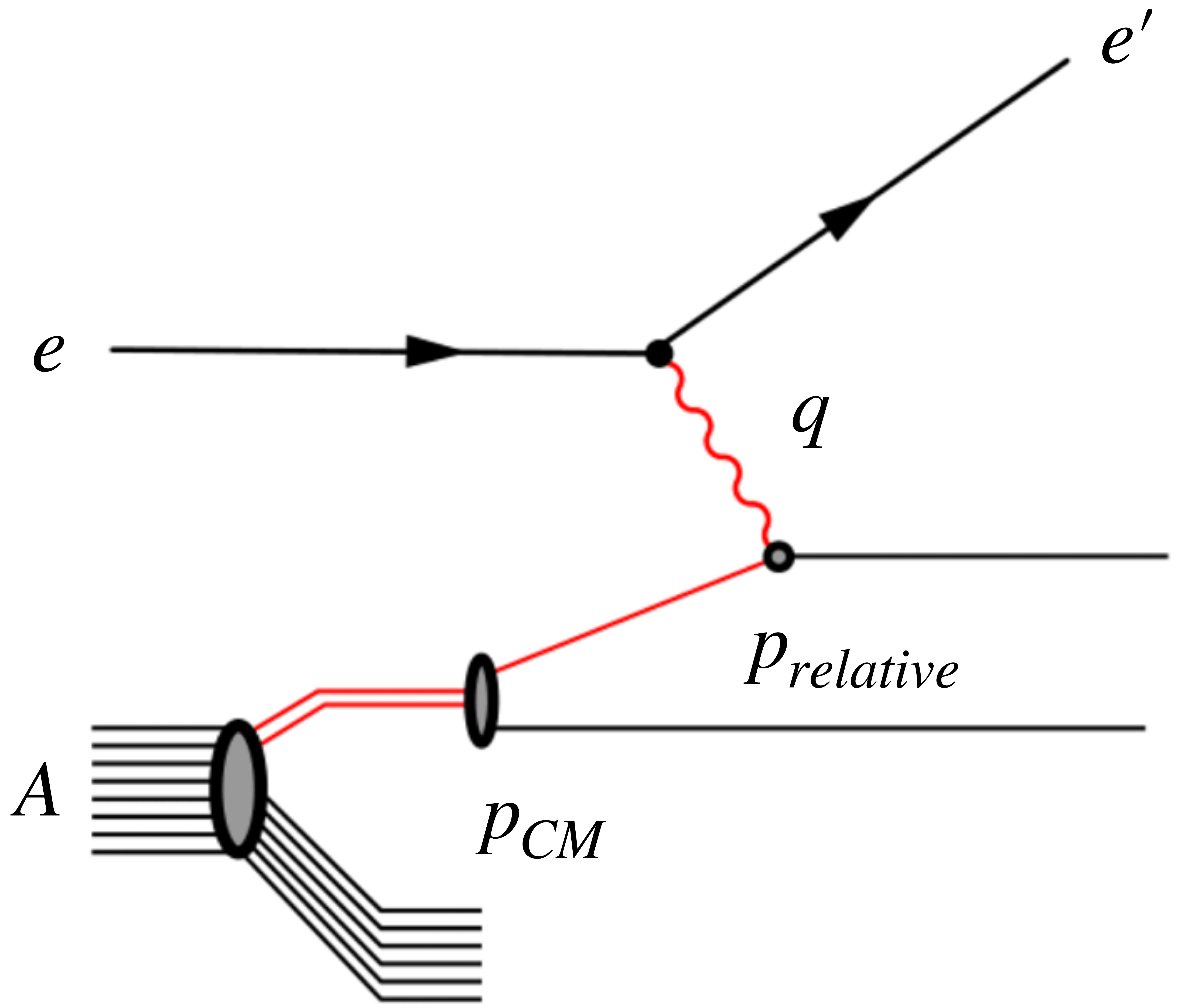


Factorized
**Spectral Function**

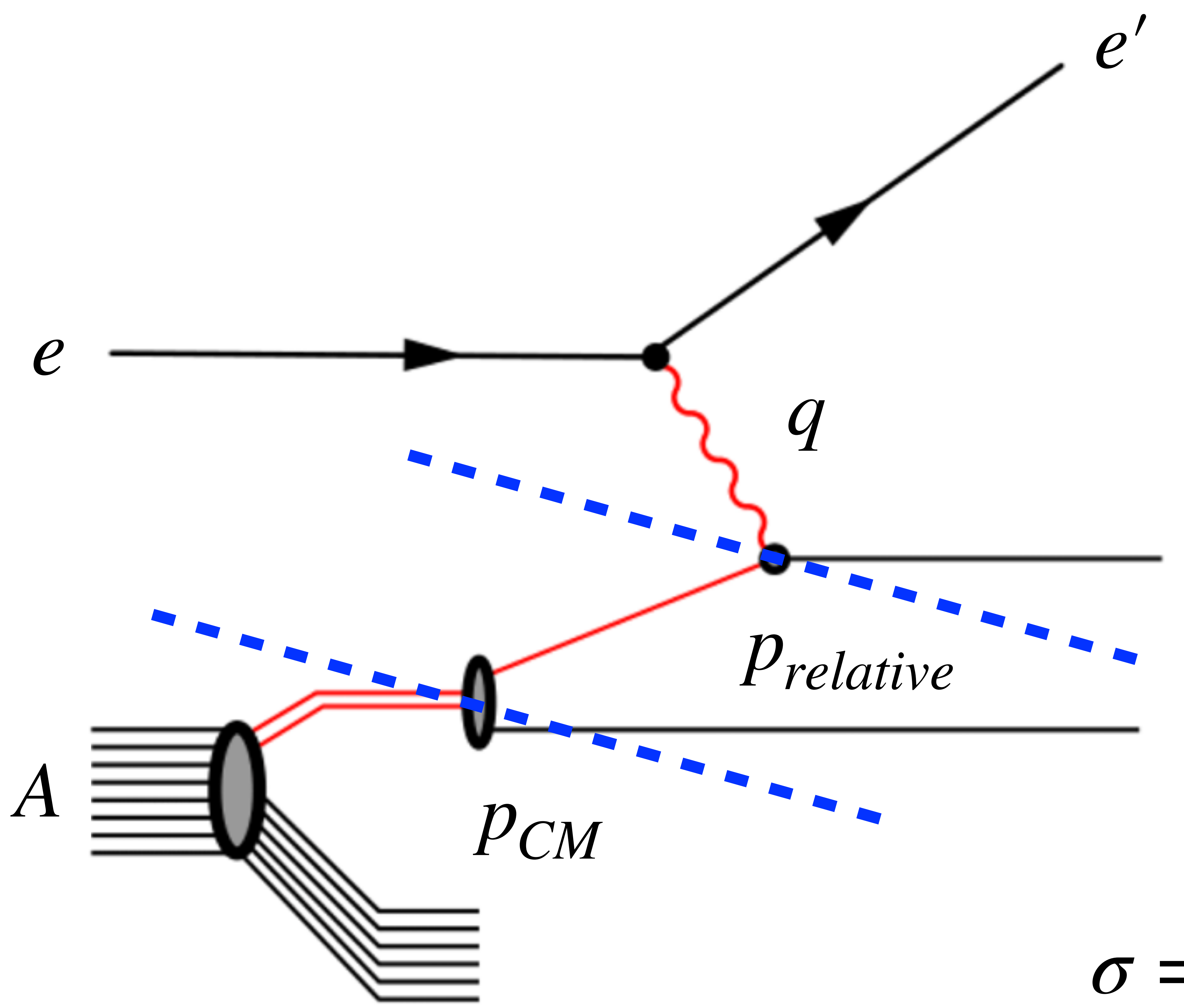
# Ground-state model can be combined with **"Plane-Wave Impulse Approximation"**



# Ground-state model can be combined with **"Plane-Wave Impulse Approximation"**



# Ground-state model can be combined with **"Plane-Wave Impulse Approximation"**

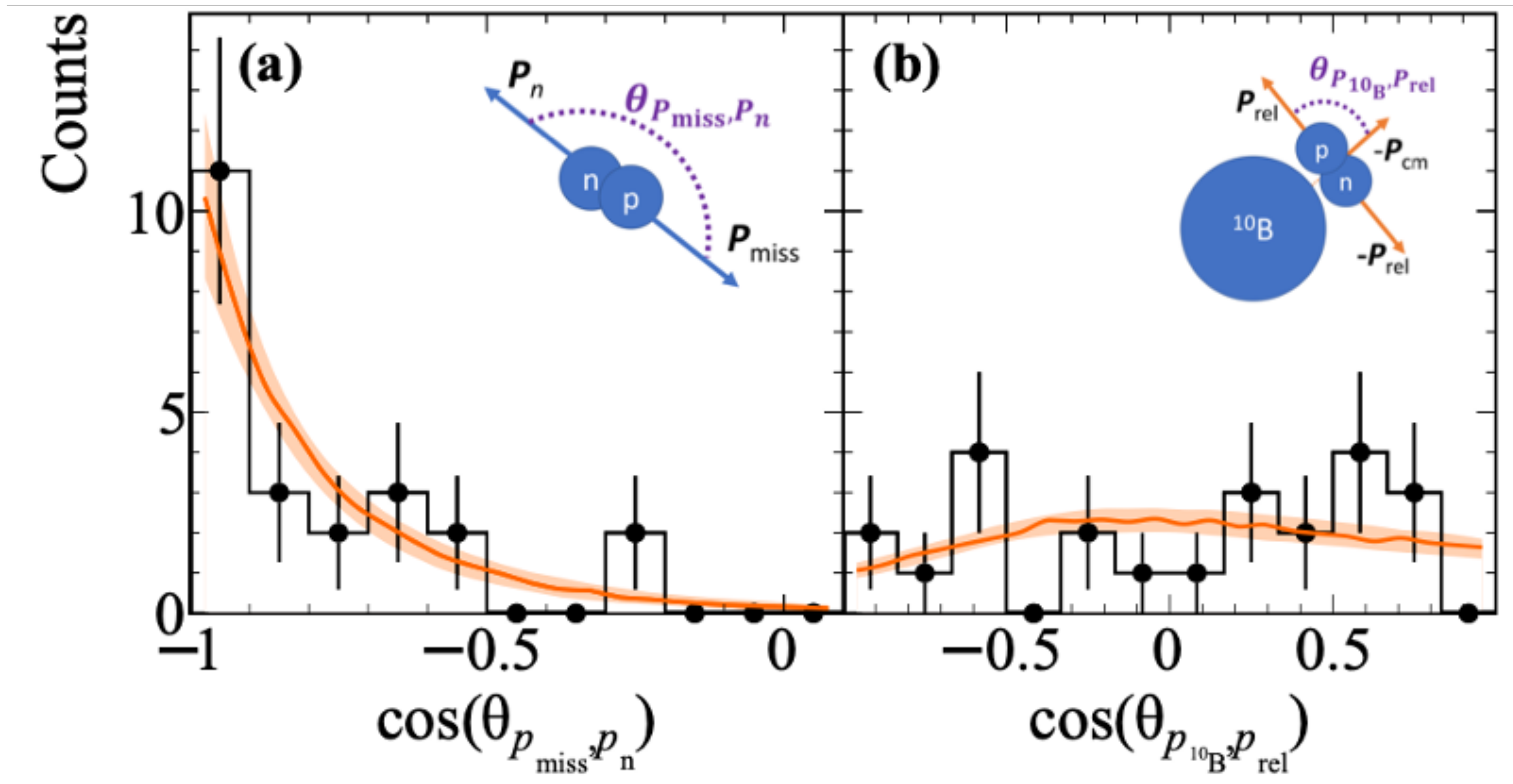



$$q > p_{relative} > p_{CM}$$

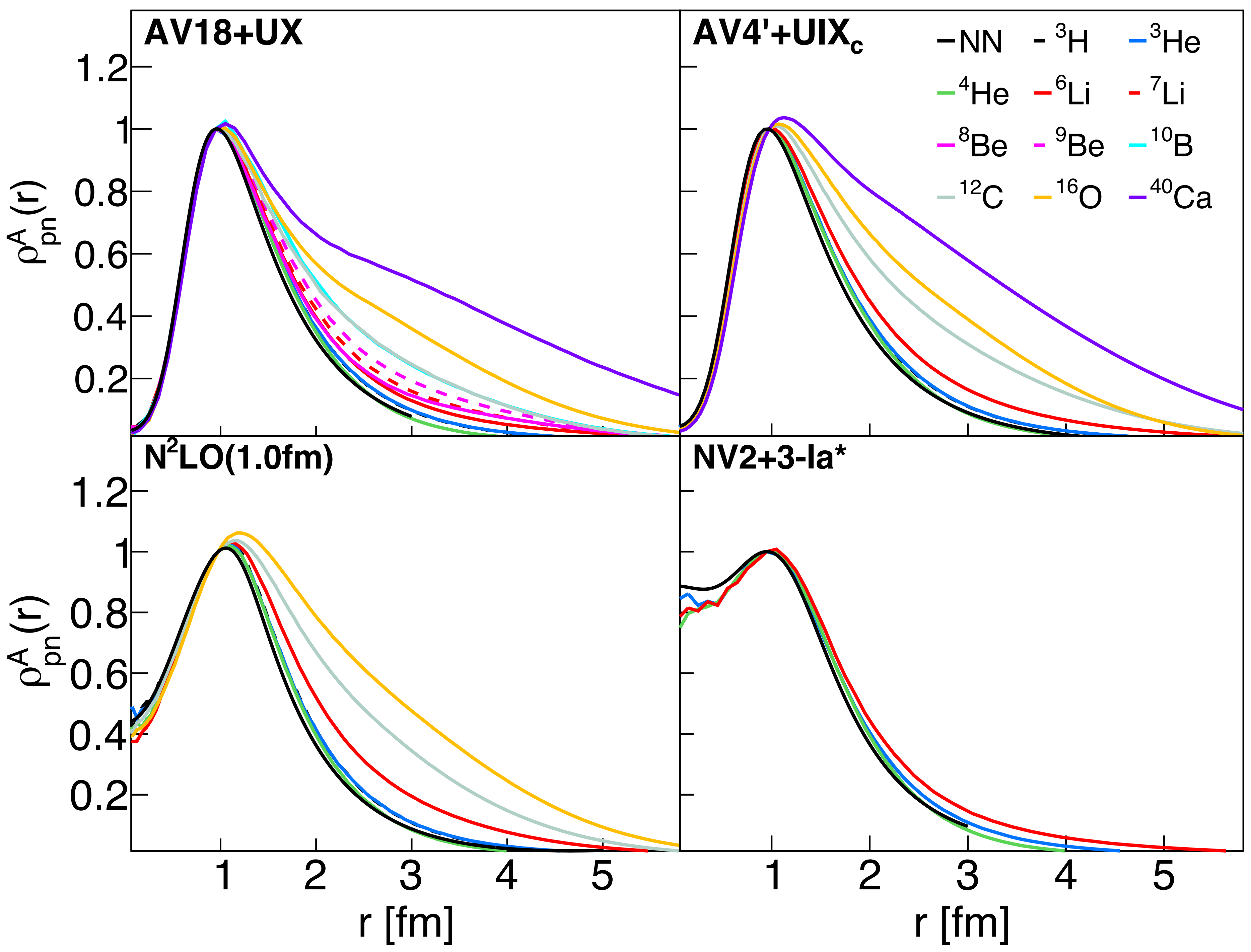
$$\sigma = \sigma_{e,N}(q) \sum_{\alpha} C^{\alpha} \, | \phi(p_{relative}) |^2 n(p_{CM})$$

# Internal scale separation of SRCs on good footing:

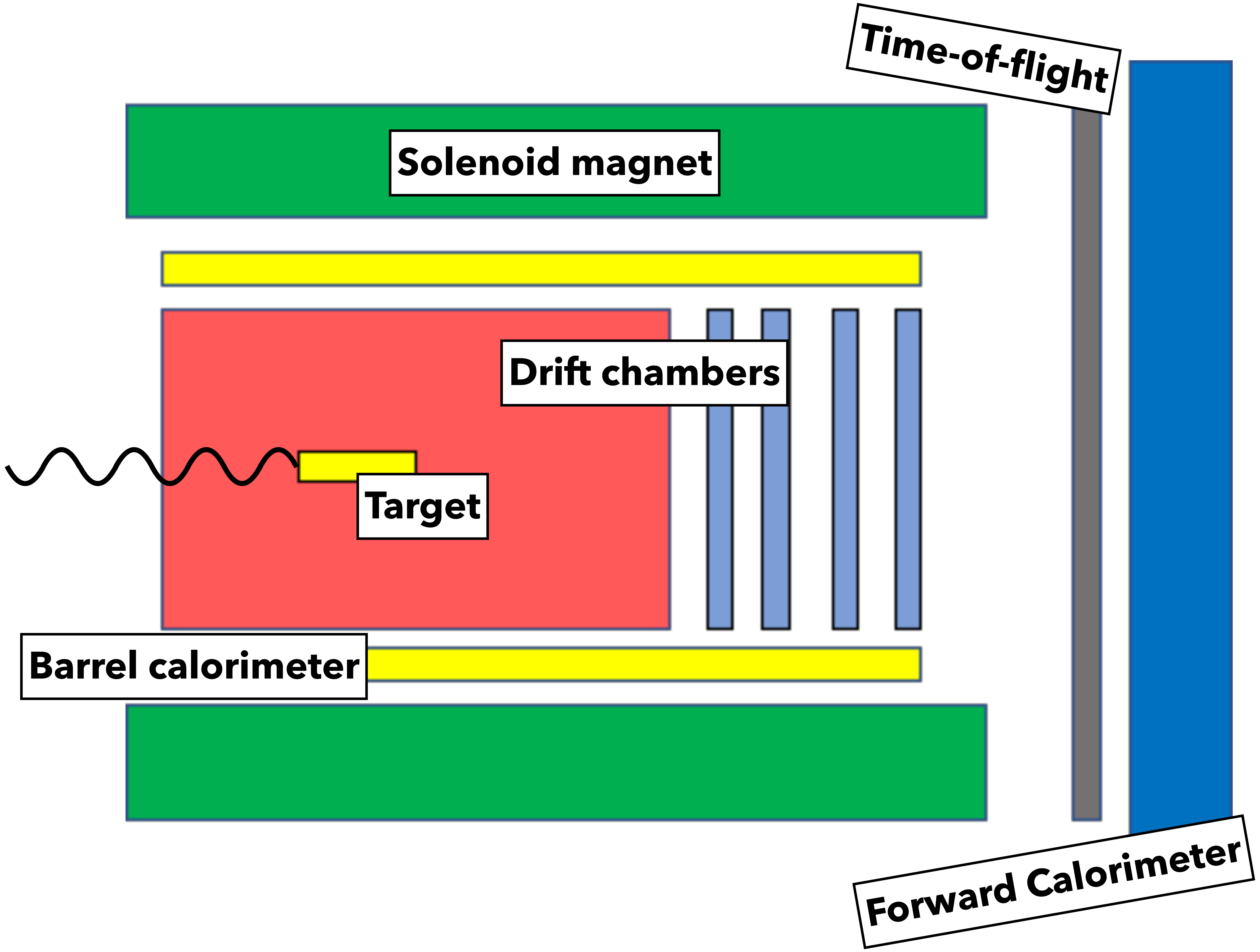
**Nature Physics 17, 667 (2021)**




**Nature Physics 17, 306 (2021)**

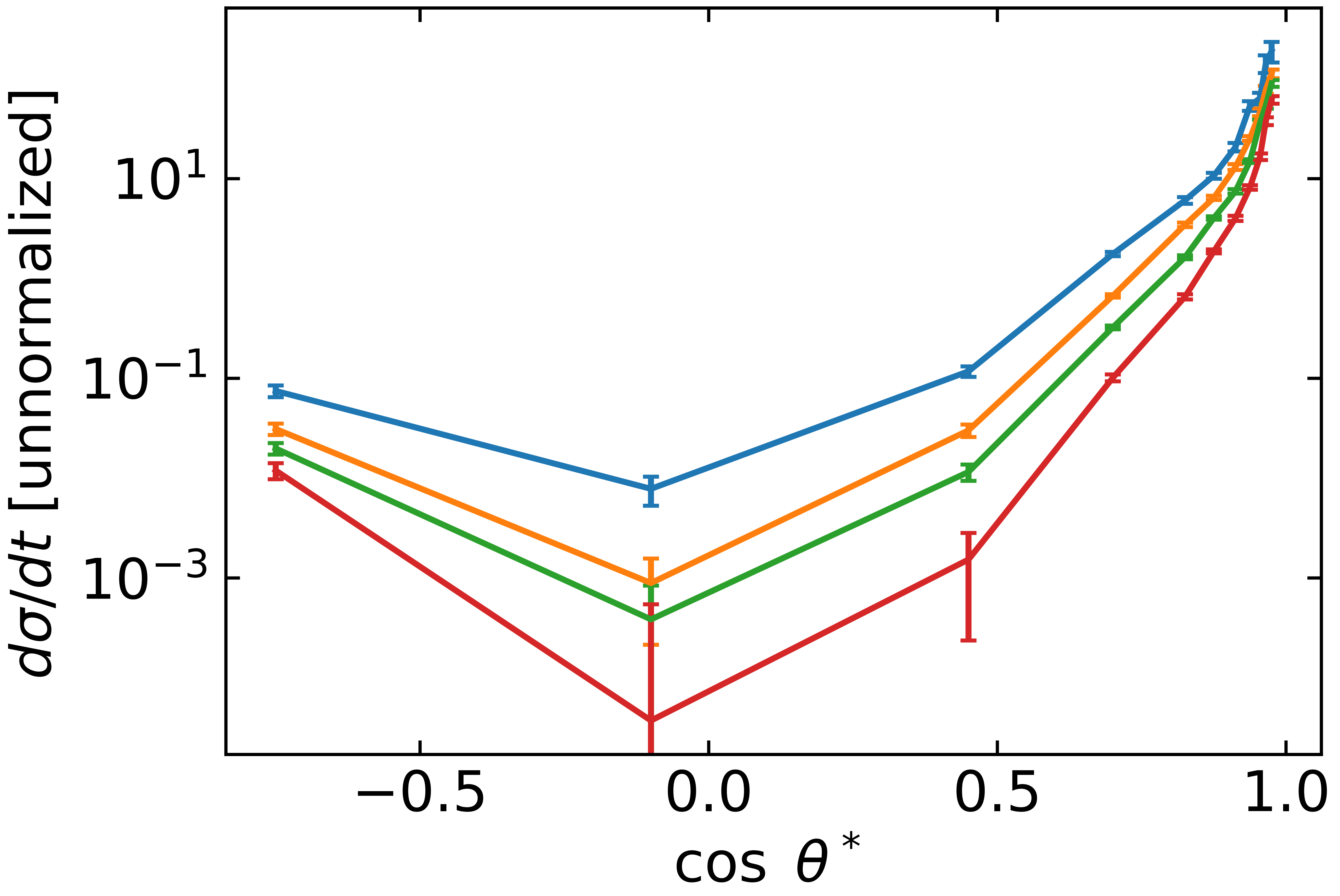


# GlueX Spectrometer

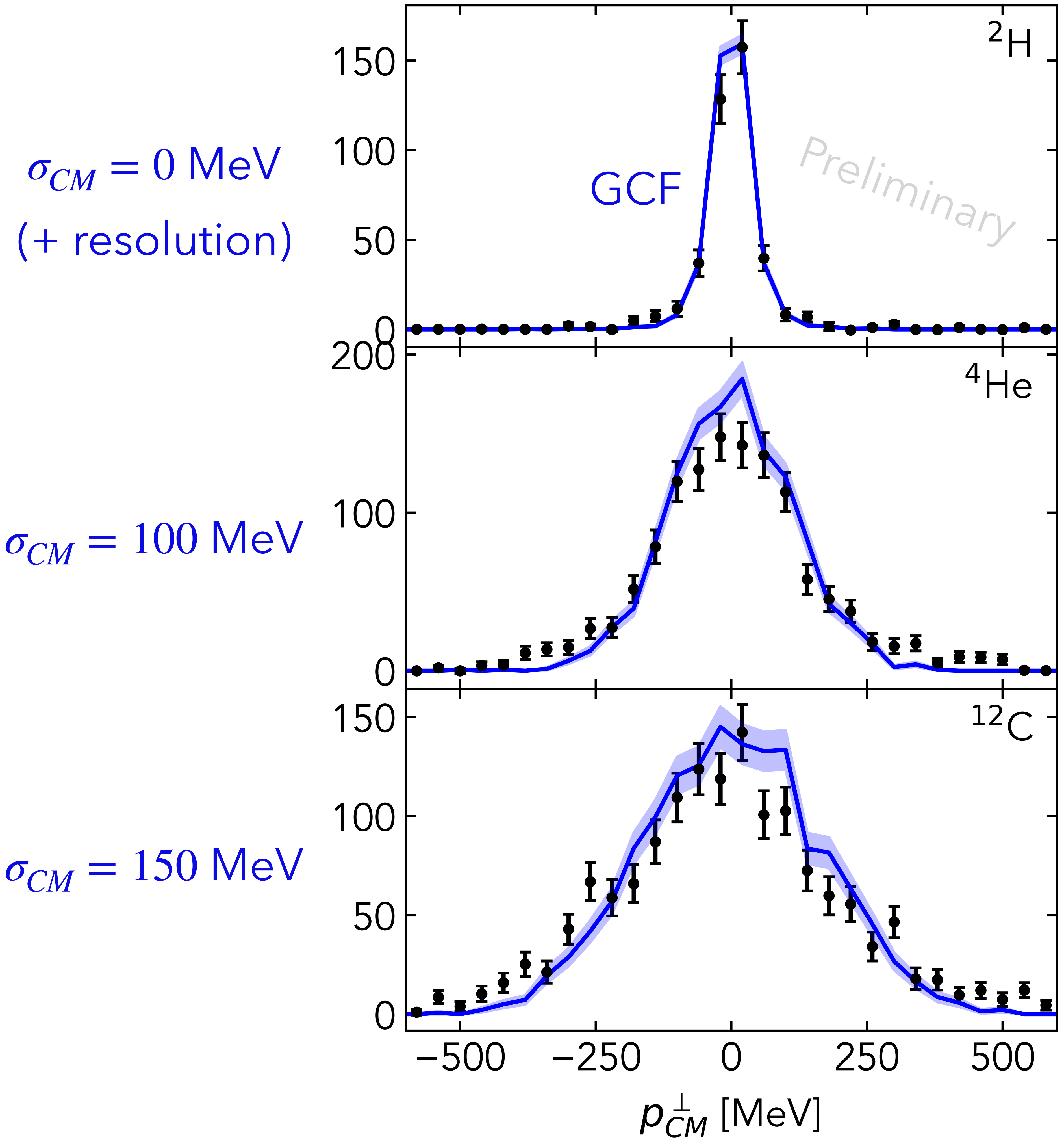



- Large-acceptance detector
- Solenoidal magnet:
  - Good $p_T$ resolution
  - Poor $p_z$ resolution
- Time-of-flight allows particle identification for forward-going charged particles
- Calorimeters allows good acceptance and reconstruction of final-state photons

# Cross section extraction for $\gamma n \rightarrow \rho^- p$



# SRC Center-of-Mass Momentum




- 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**