Short-Range Nuclear Structure: Beyond JLab Electron-Scattering

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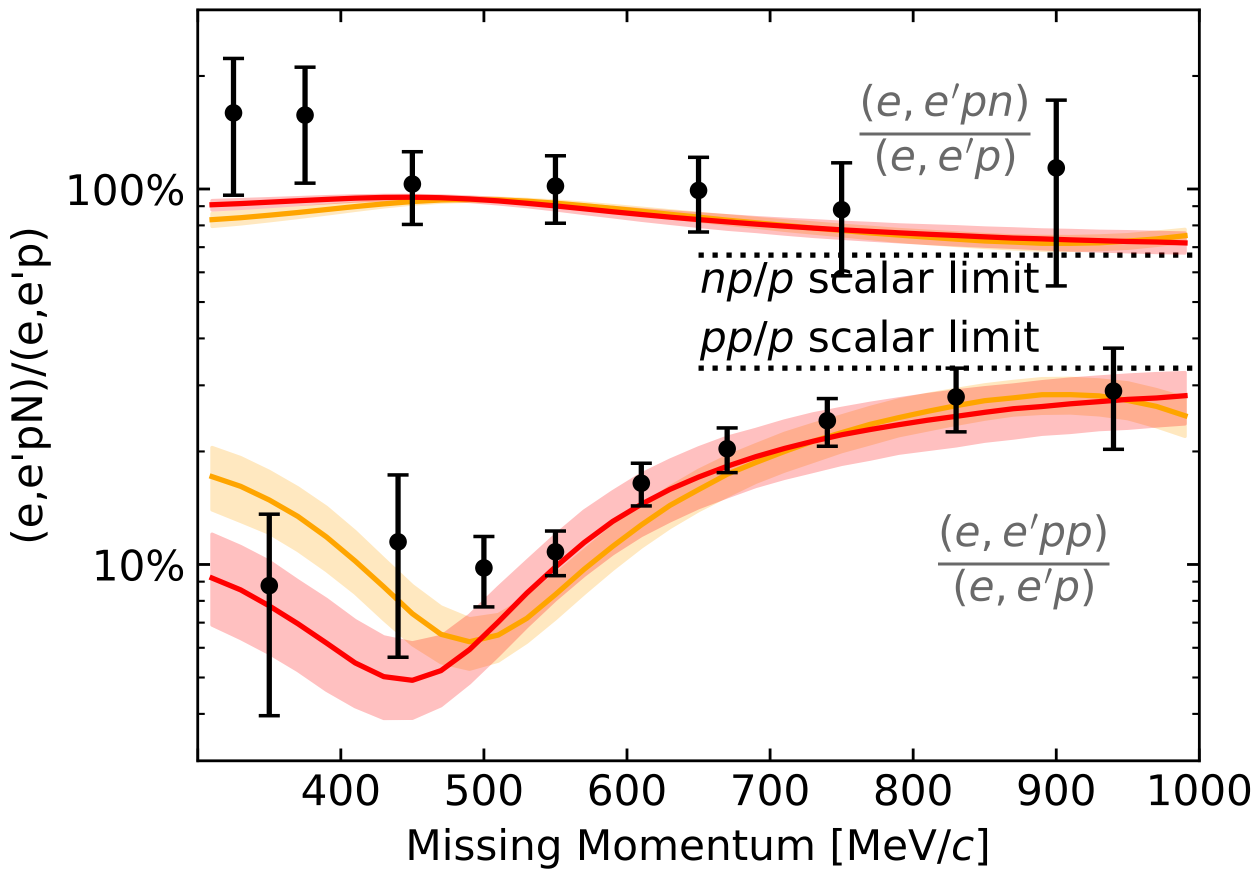
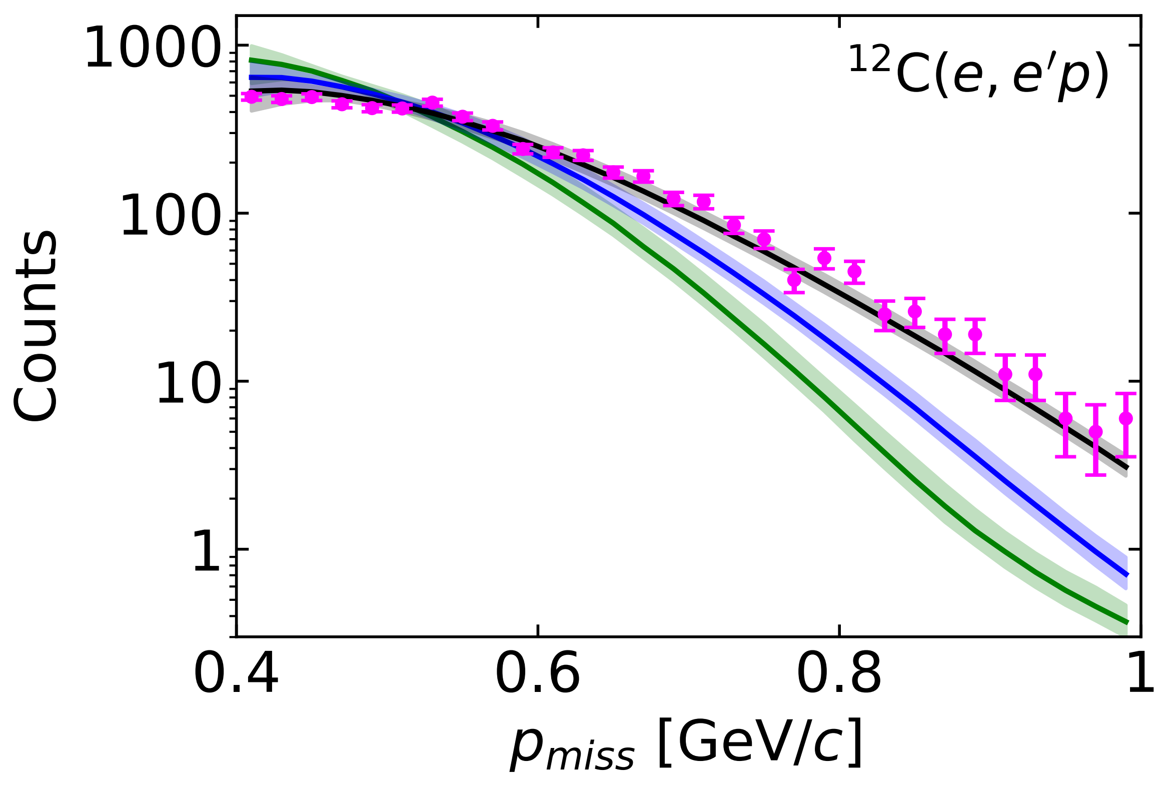
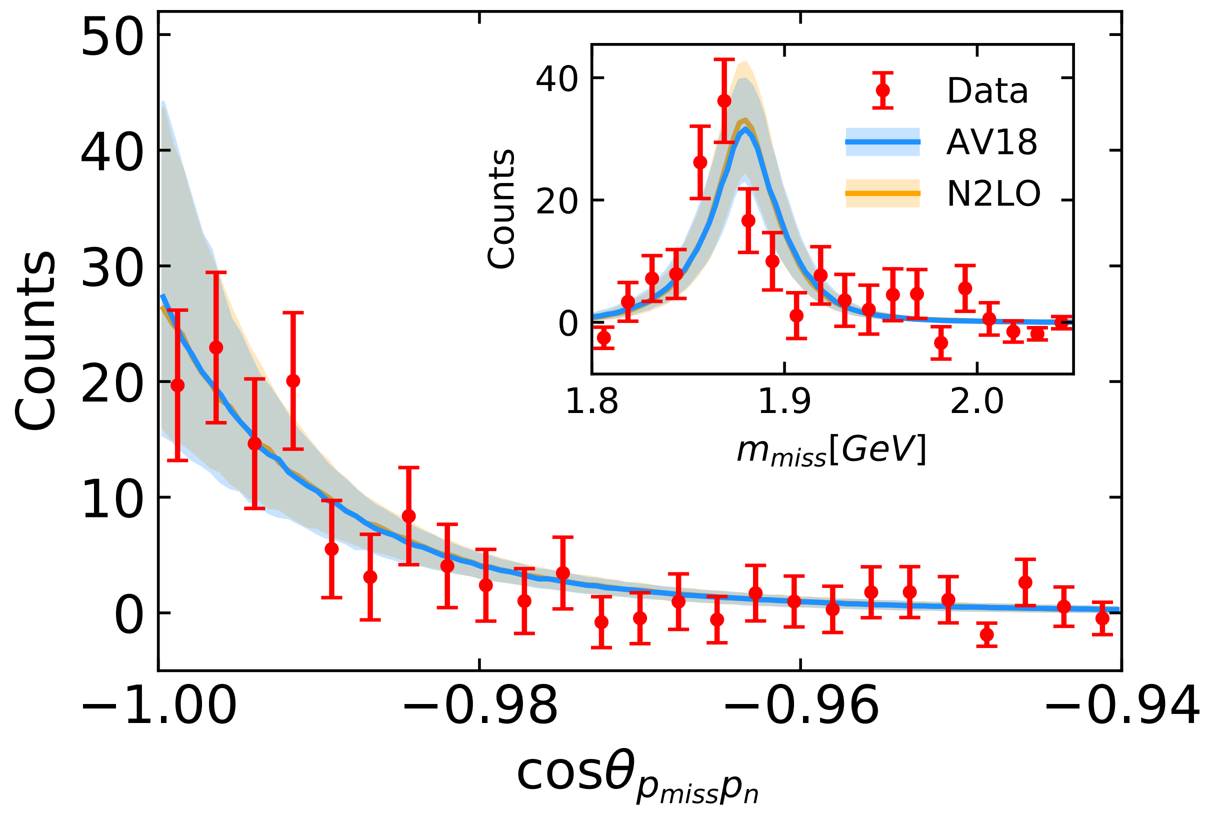
Directors' Fellow, Los Alamos National Laboratory

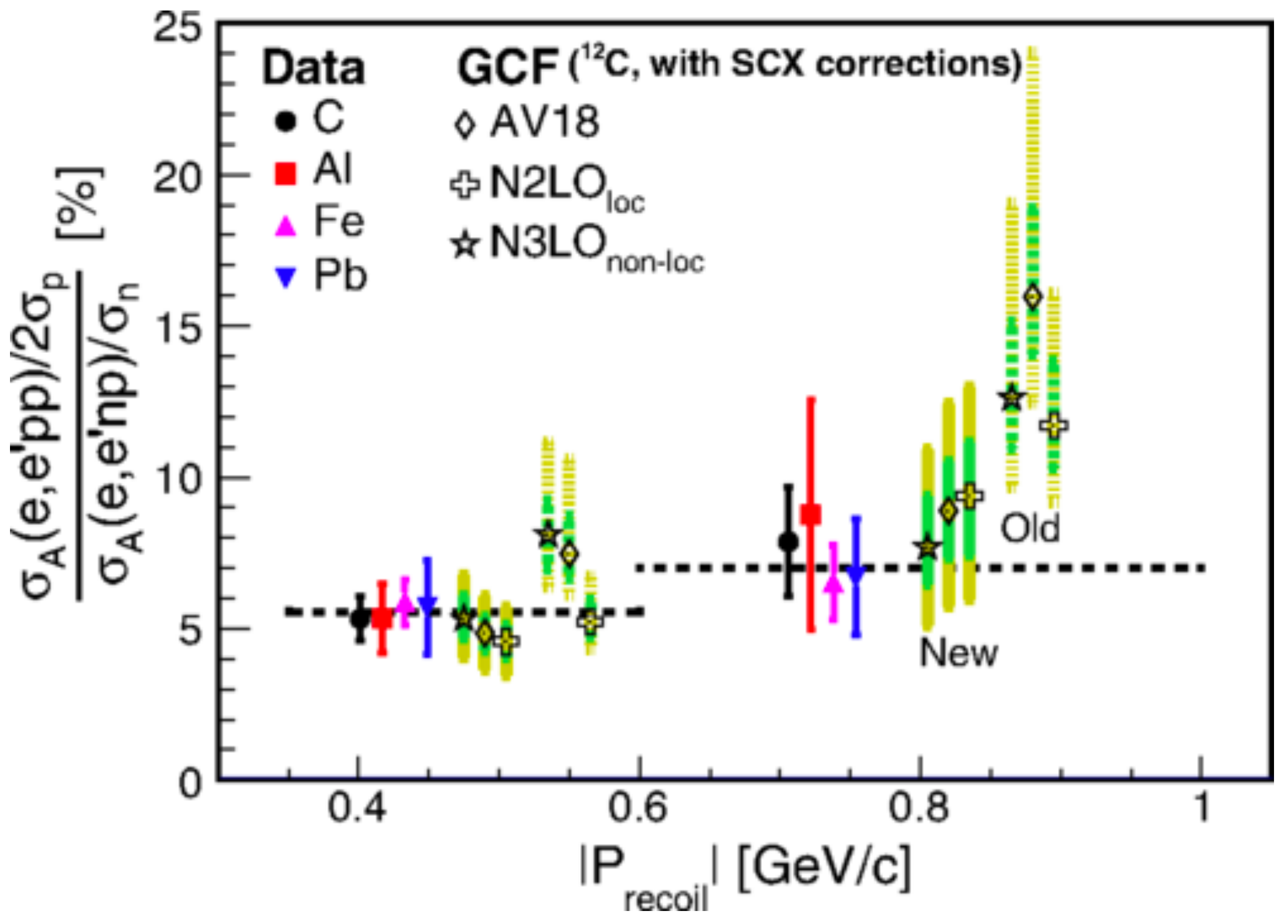
"Light-ion physics in the EIC era"
June 2025, Florida International University, Miami, FL

GCF analysis connect scattering data to ground-state SRC properties



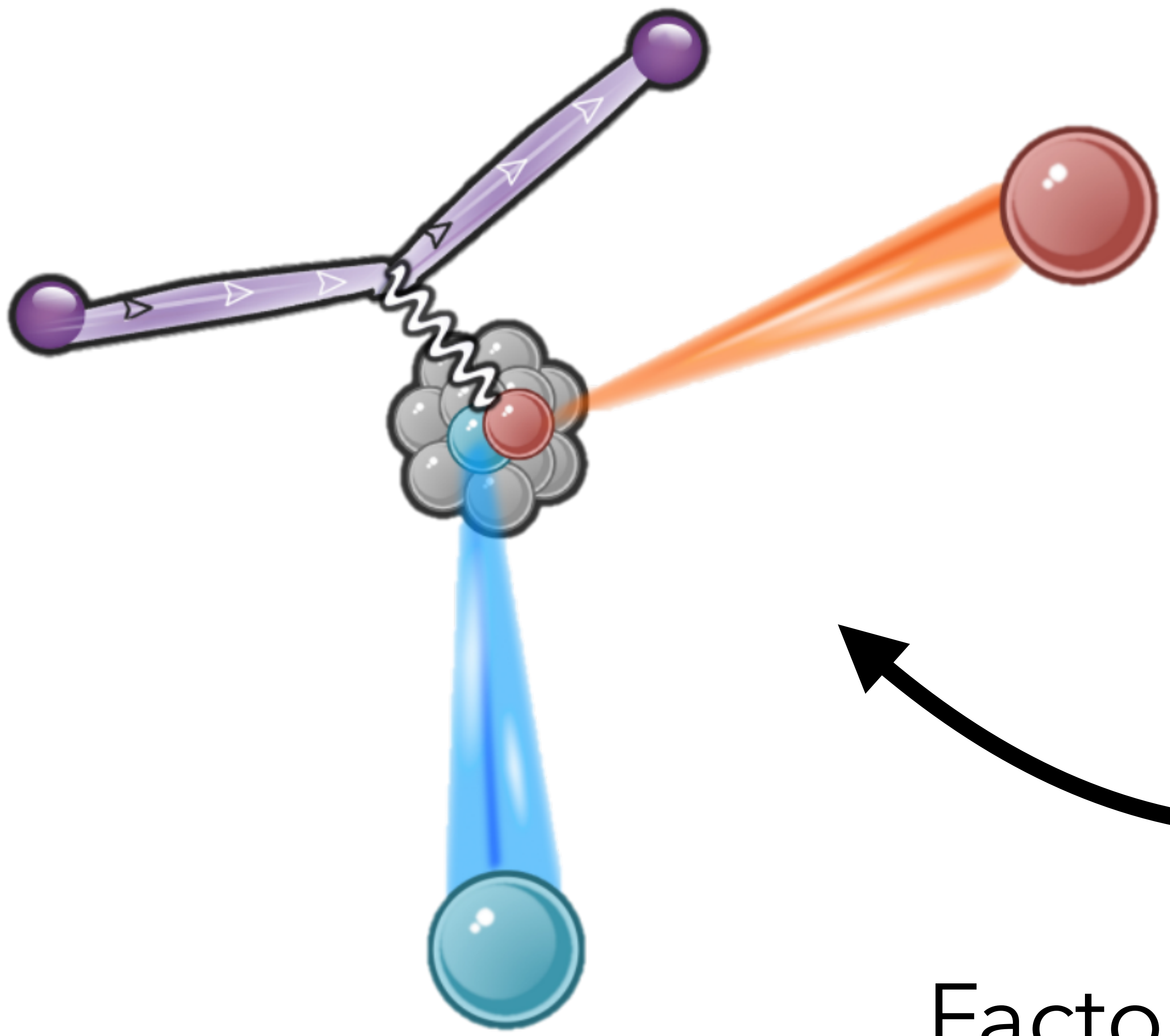


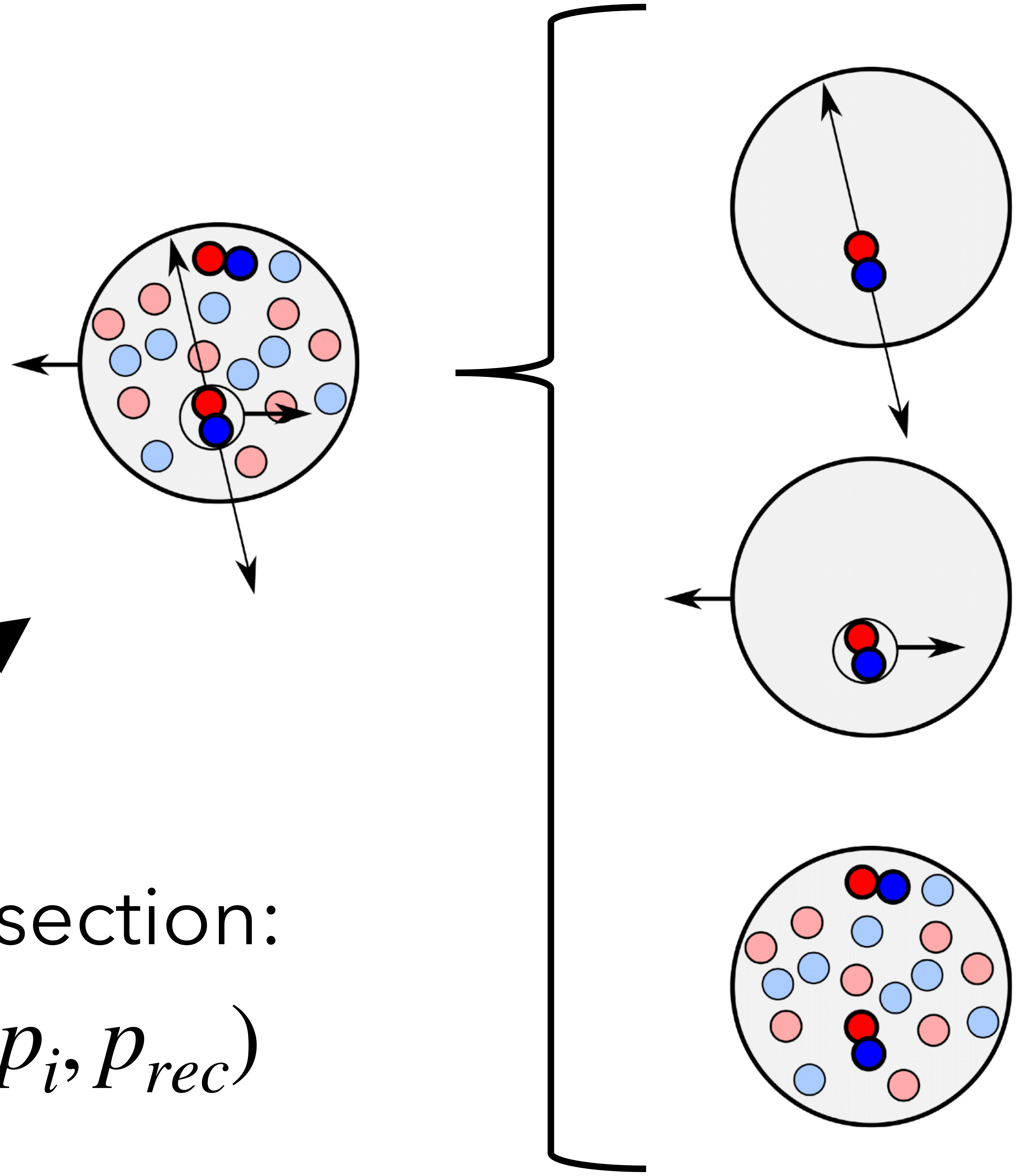




Duer et al. PRL 2019
Schmidt et al. Nature 2020
Pybus et al. PLB 2020
Weiss et al. PRC 2021
Korover et al. PLB 2021

Relies on connection between electron scattering data and nuclear ground-state

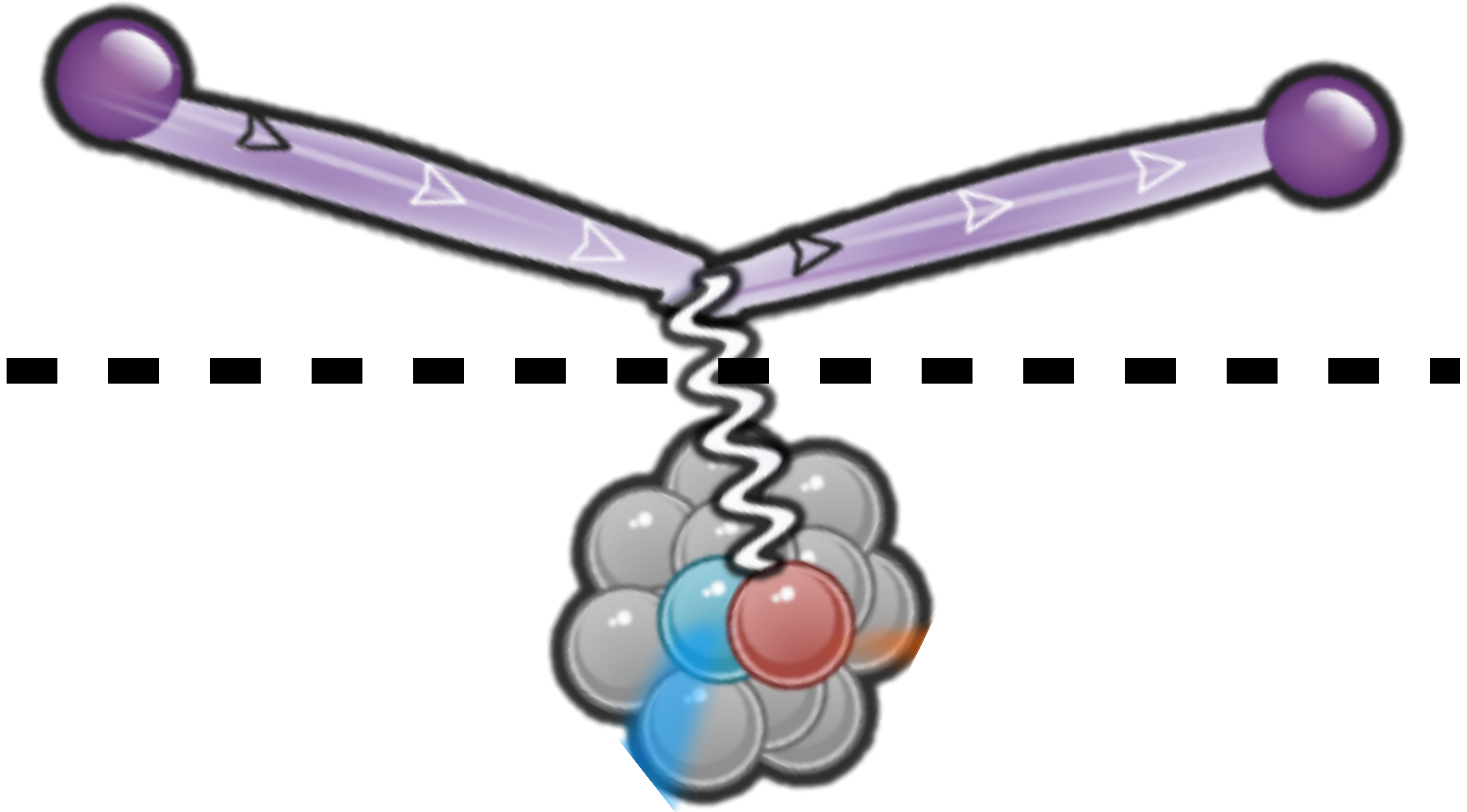




Factorized cross section:

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

Ground-state interpretation requires establishing plane-wave factorization!

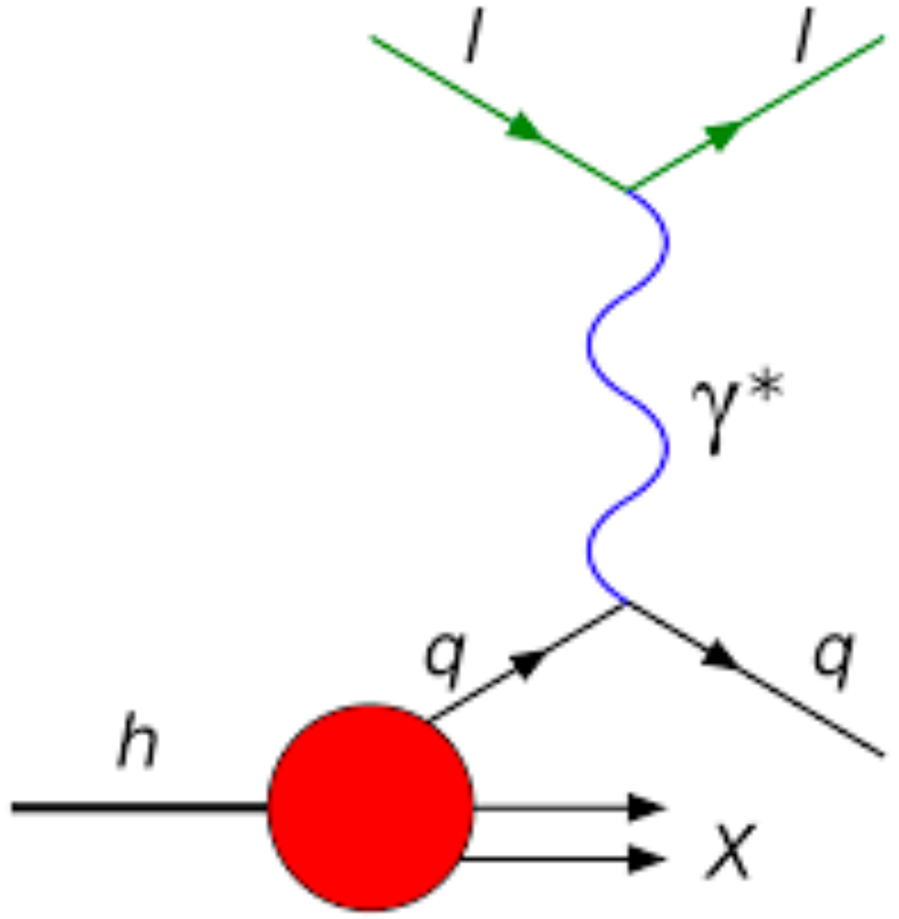


High-energy **Reaction**

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

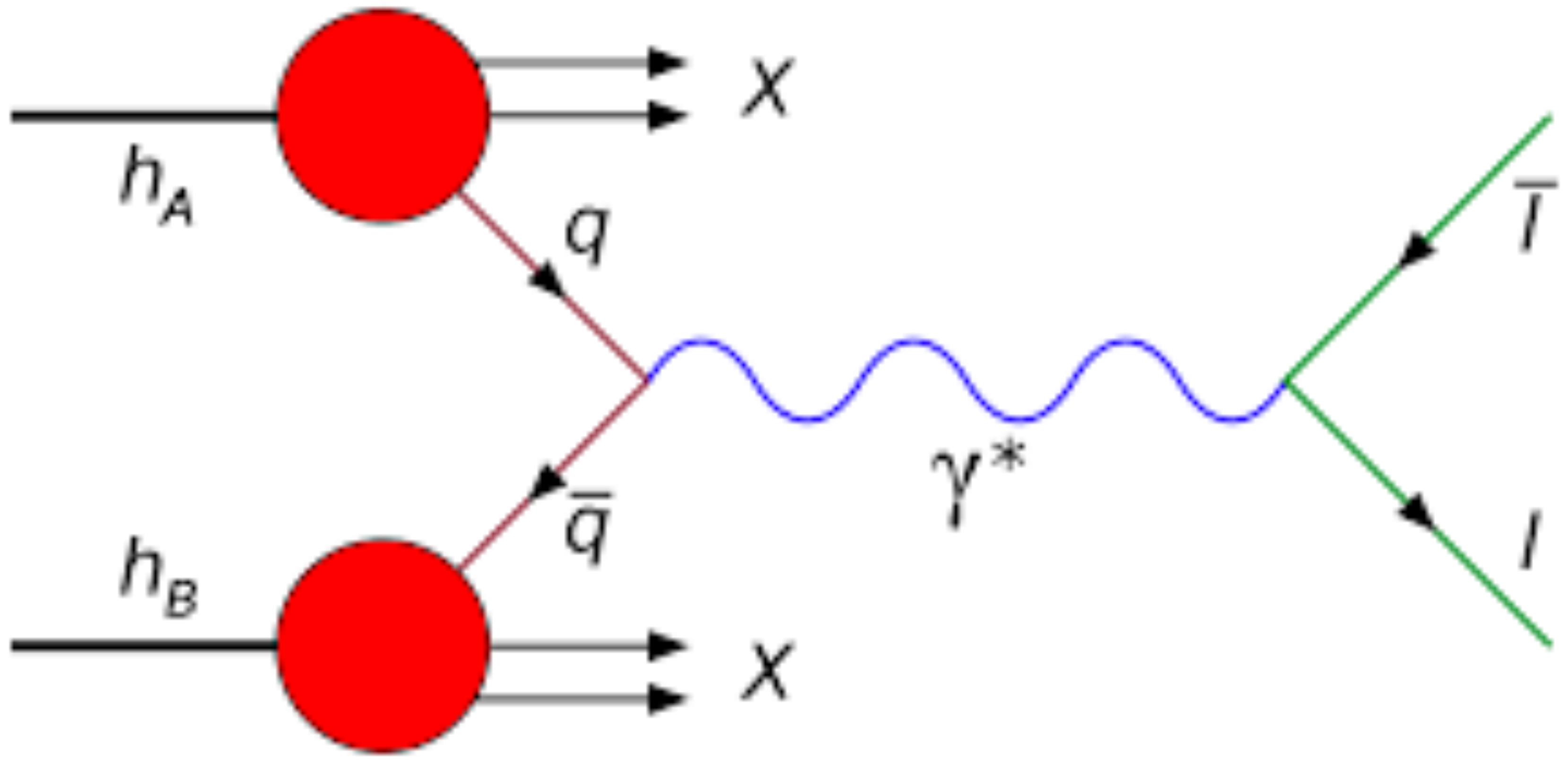
Low-energy **Ground-State**

Example: PDF Universality

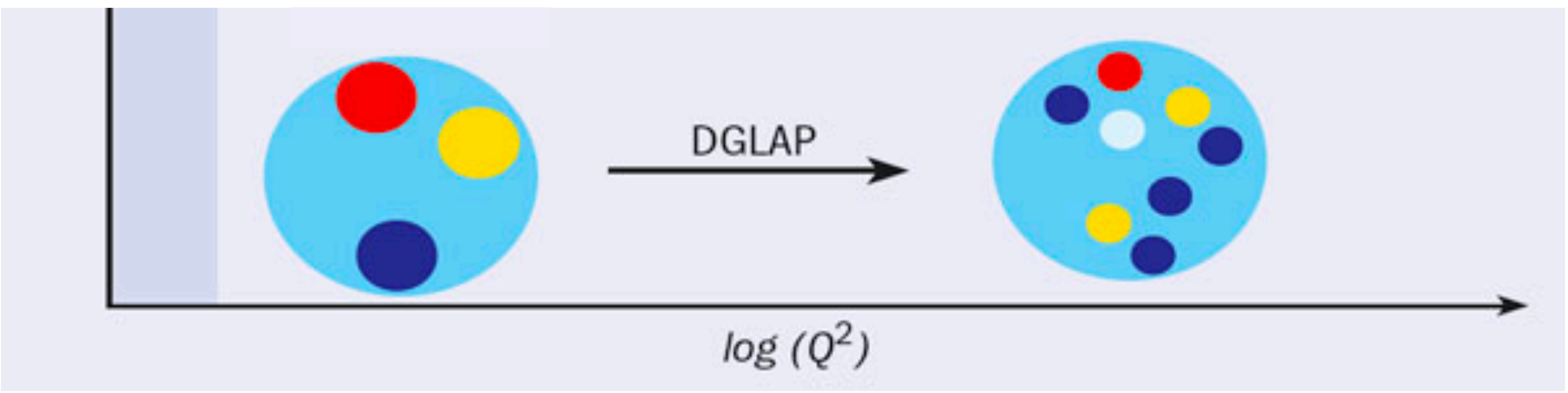


Deep-Inelastic Scattering

vs



Drell-Yan

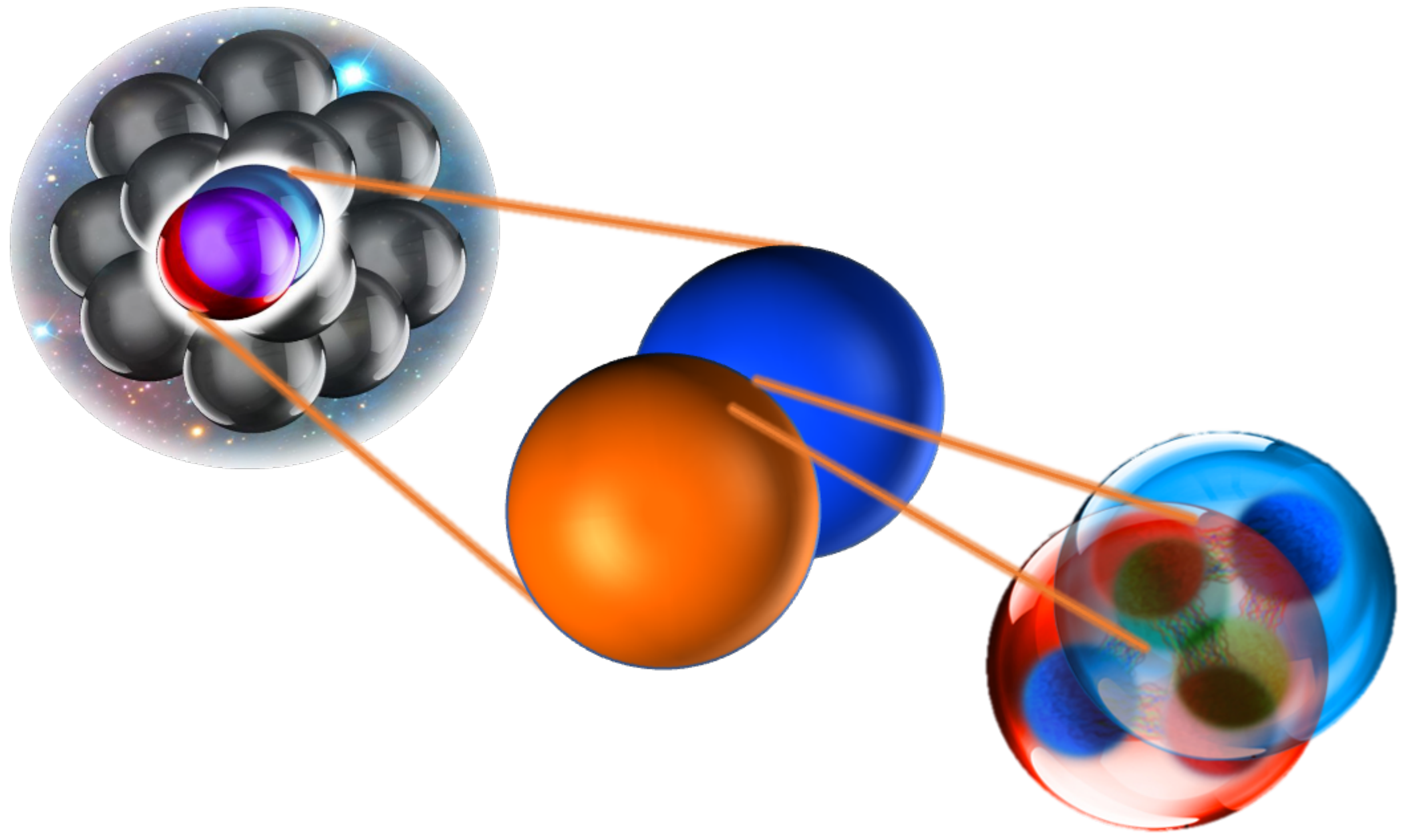


+ Q^2-evolution from DGLAP

= Universal framework for measuring parton structure of the proton

Two ways to examine reaction-dependence:

Scale



Q^2, $|t|$ change the resolution **scale**

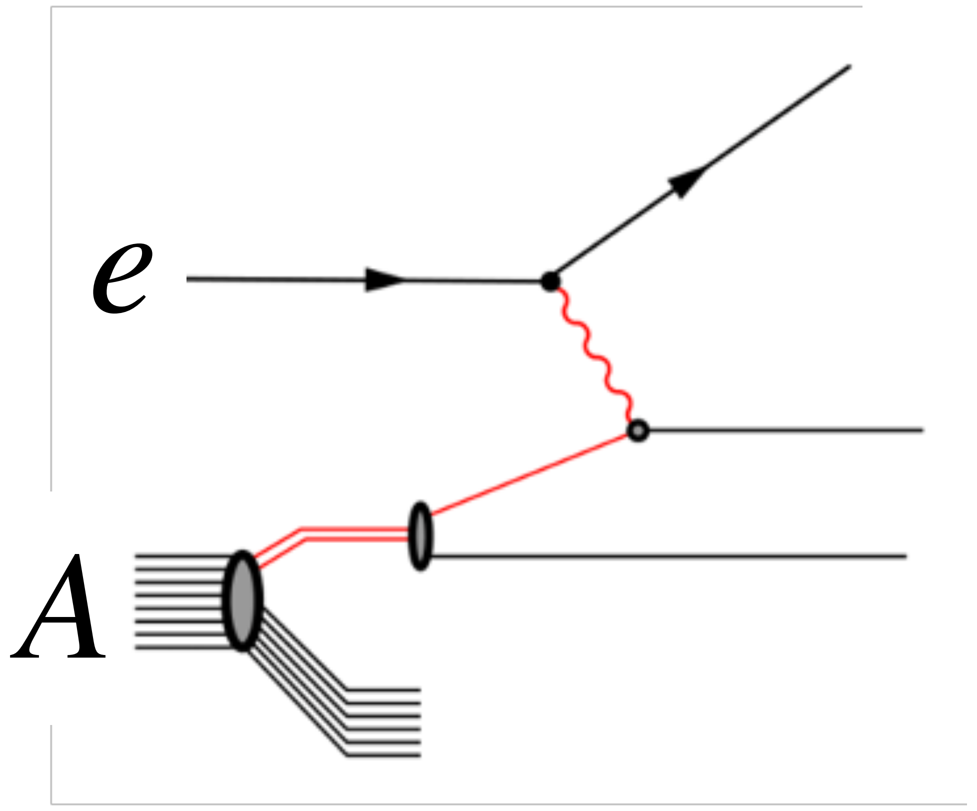
Probe

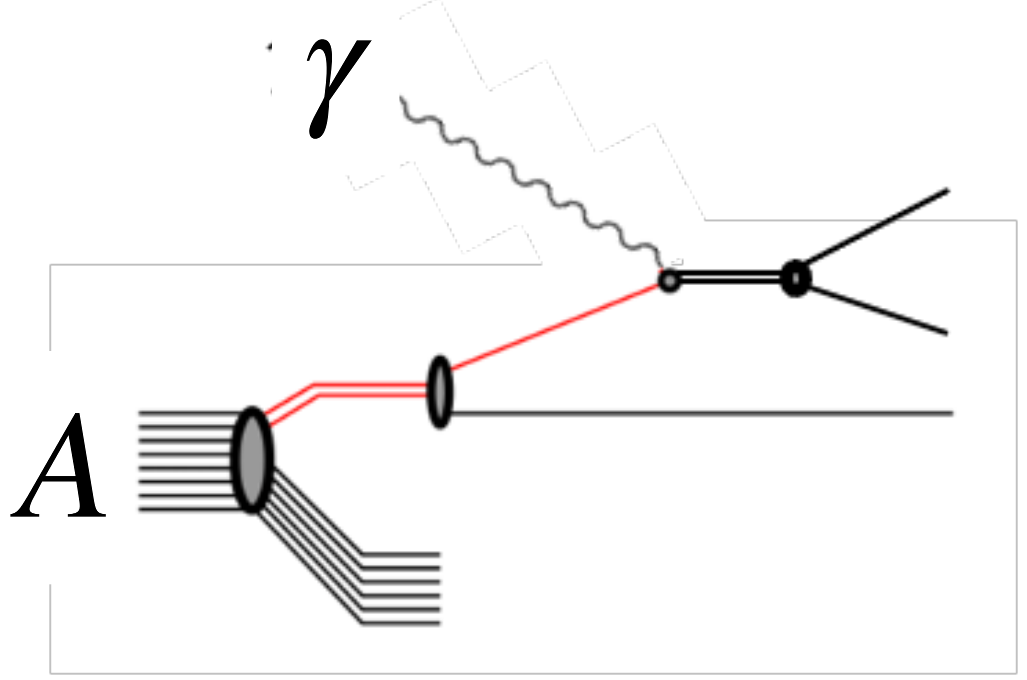
Different **probes**:

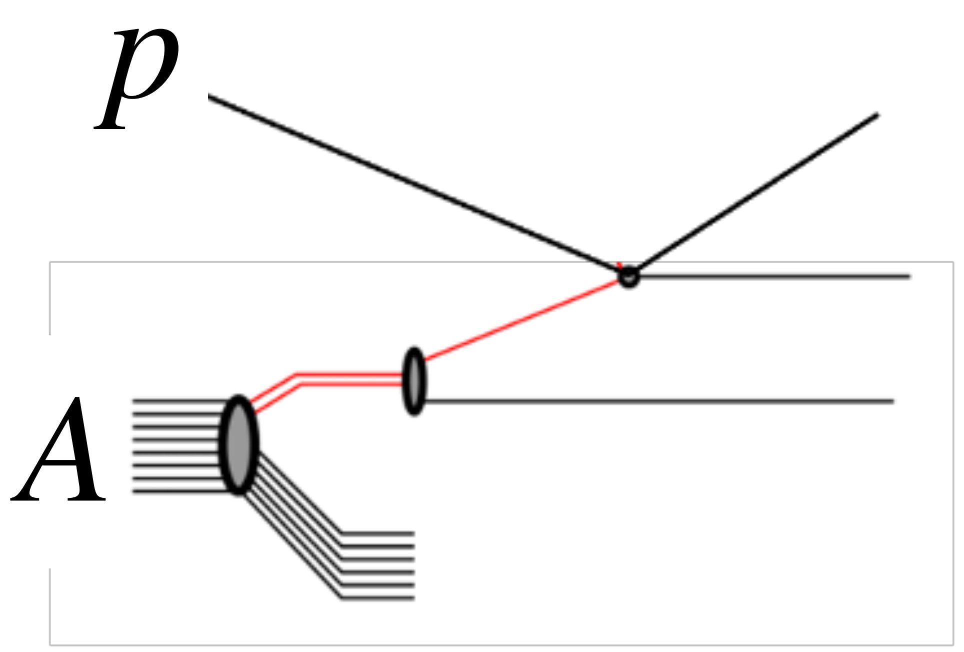
Electromagnetic (e^-),

Hadronic (p, A),

Photonuclear (γ)







Two ways to examine reaction-dependence:

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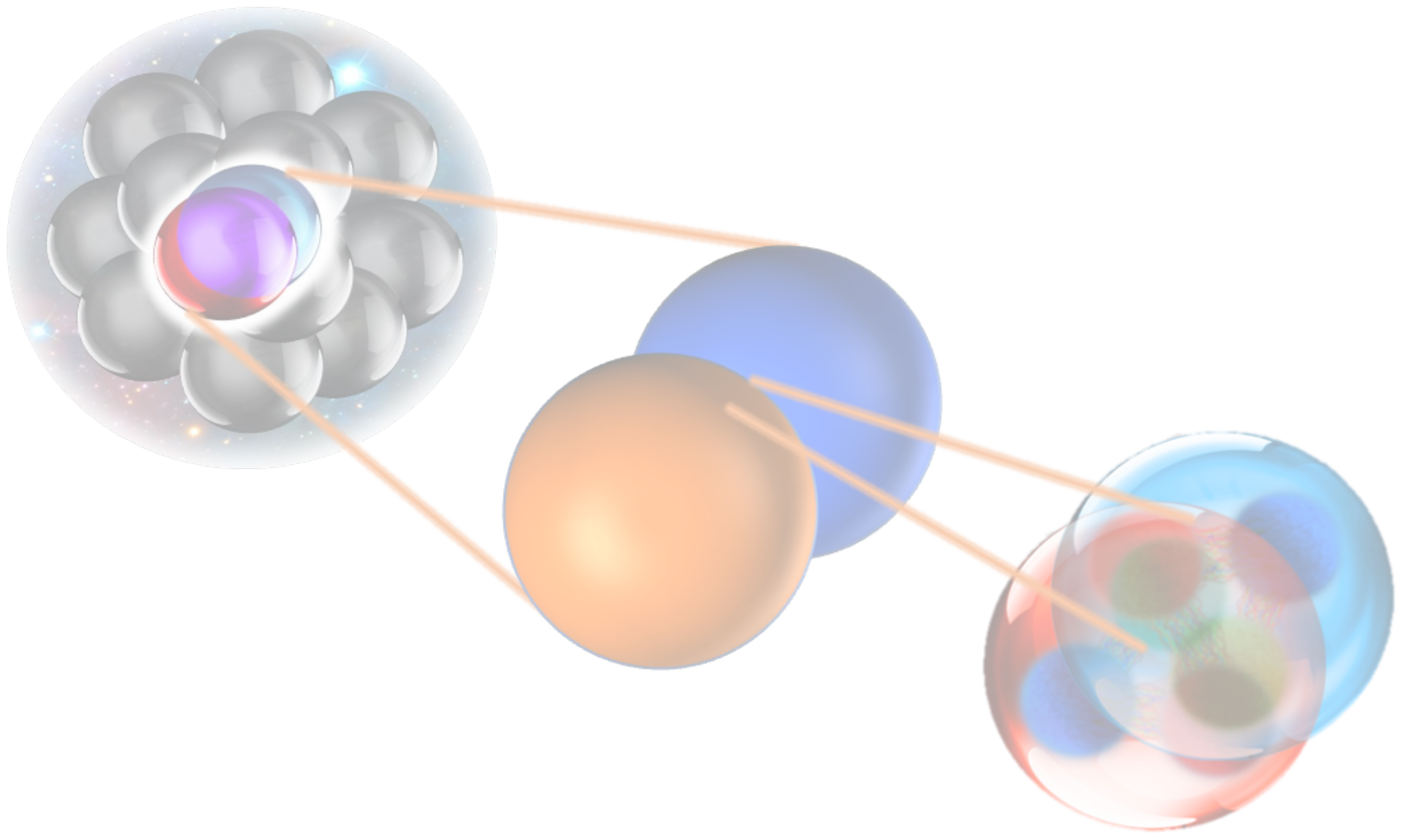

Q^2, $|t|$ change the resolution **scale**

Probe

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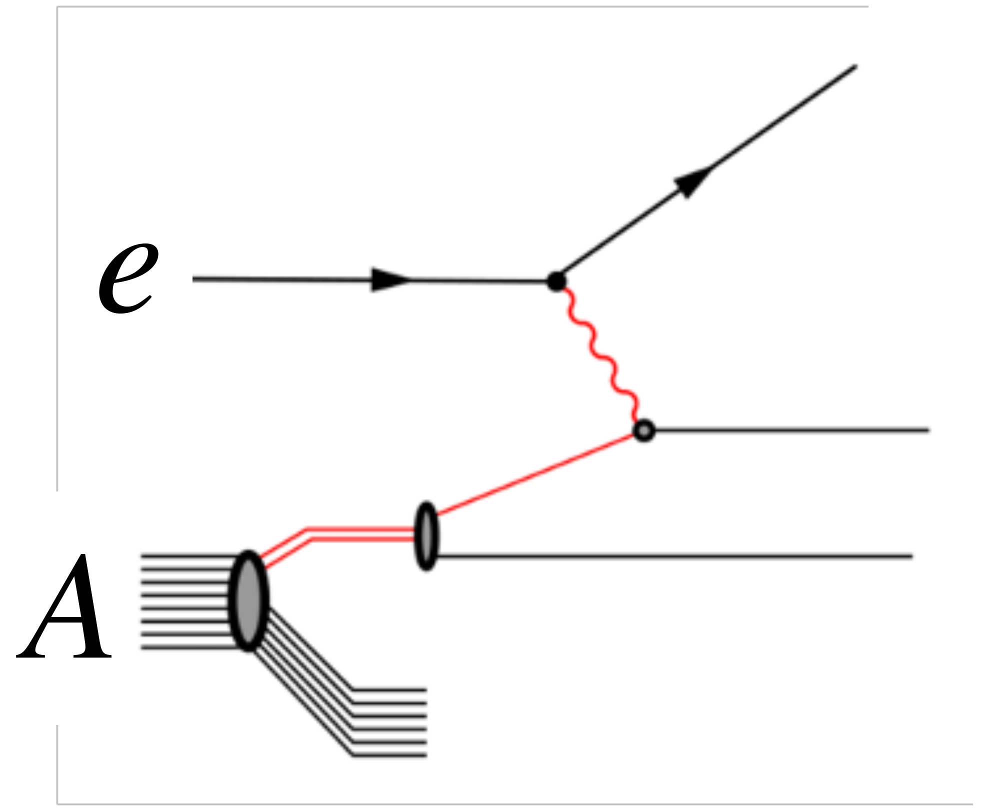
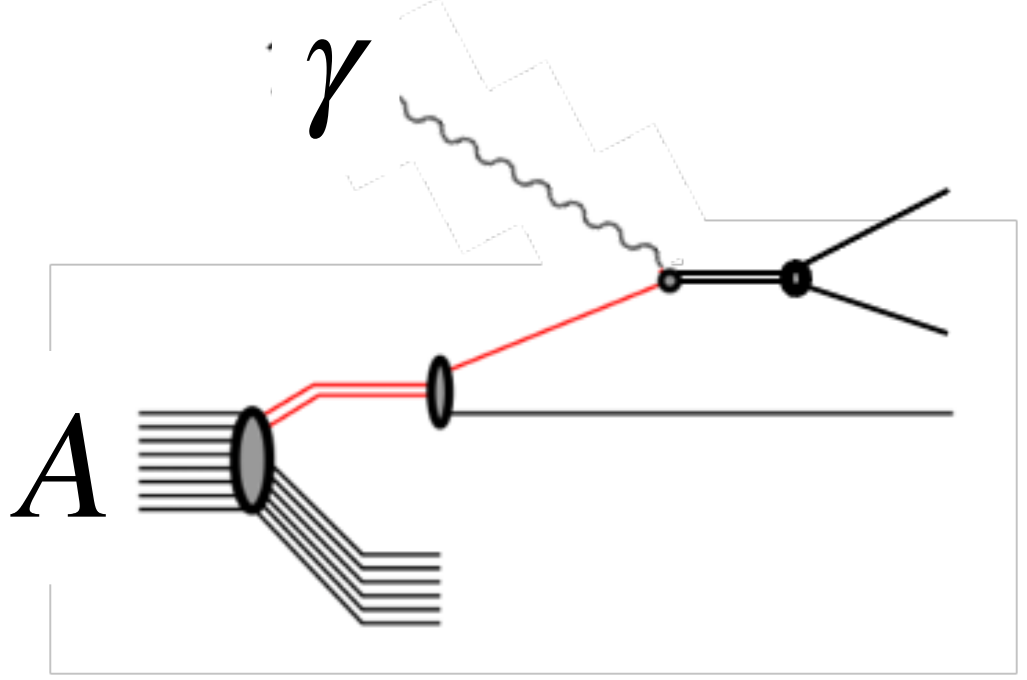
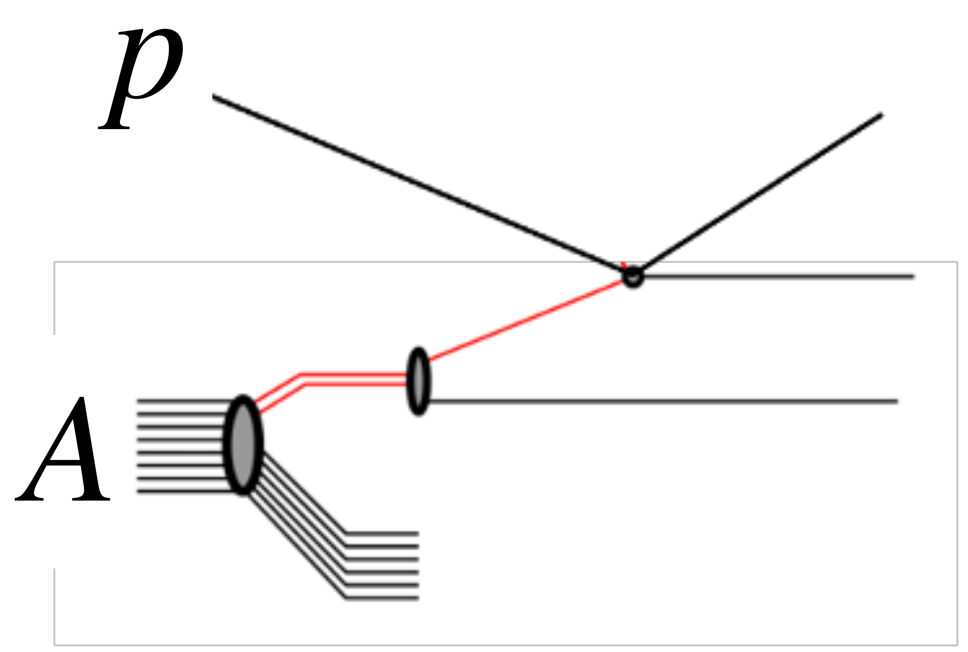
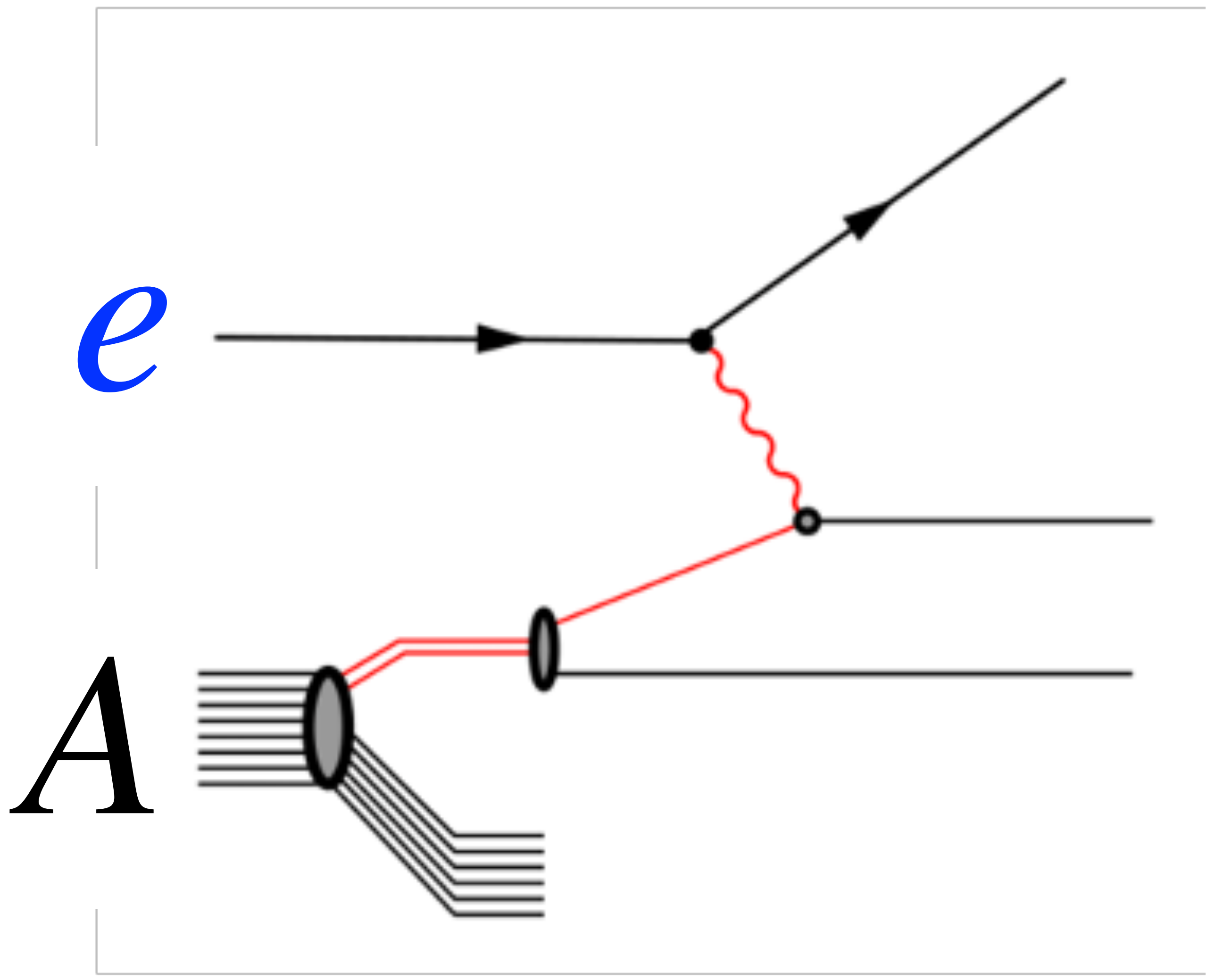
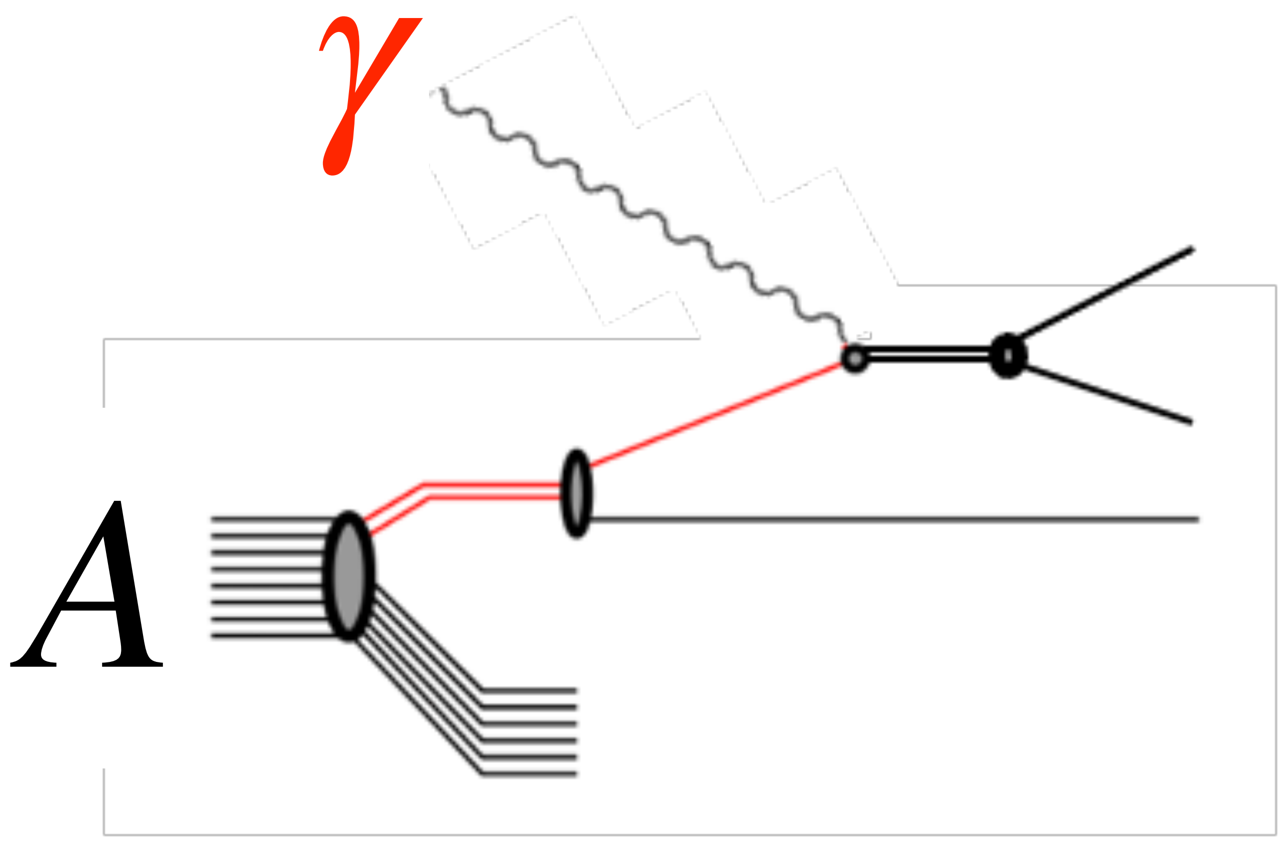


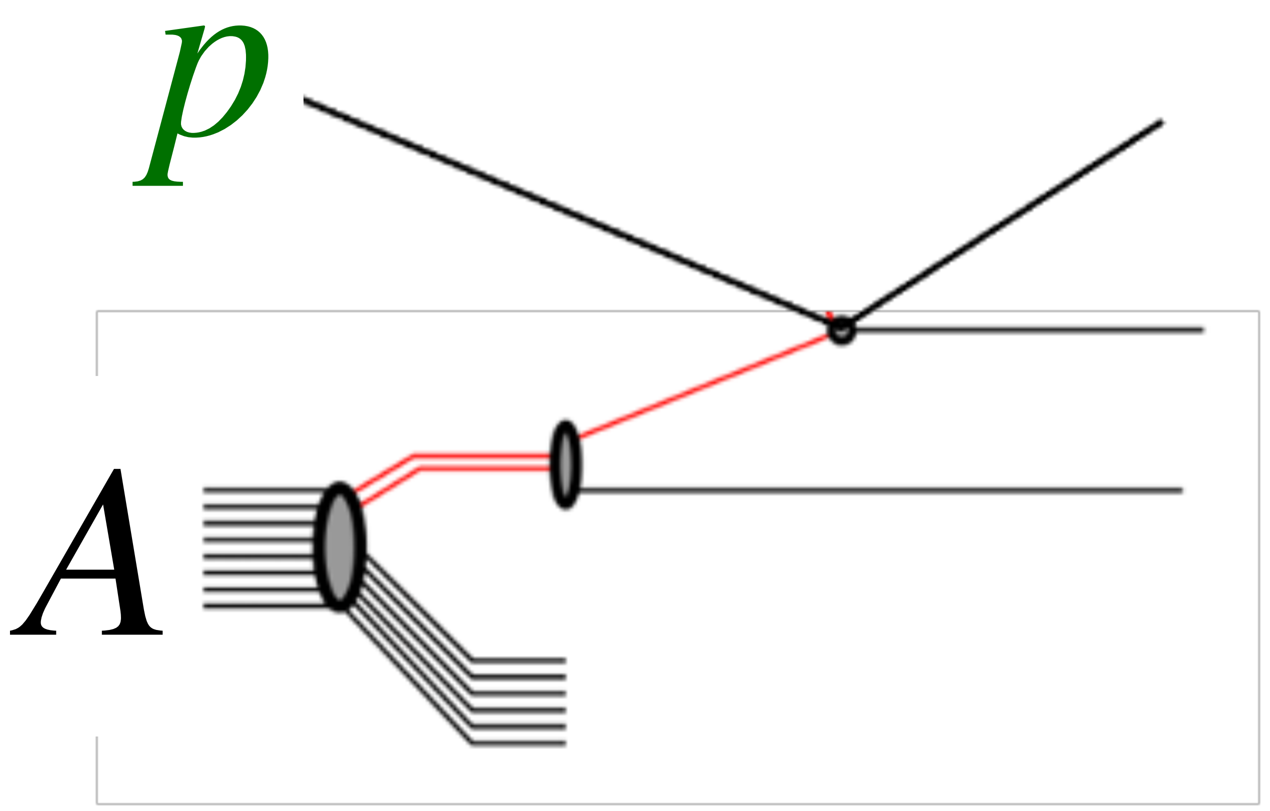




Probe Dependence of SRCs







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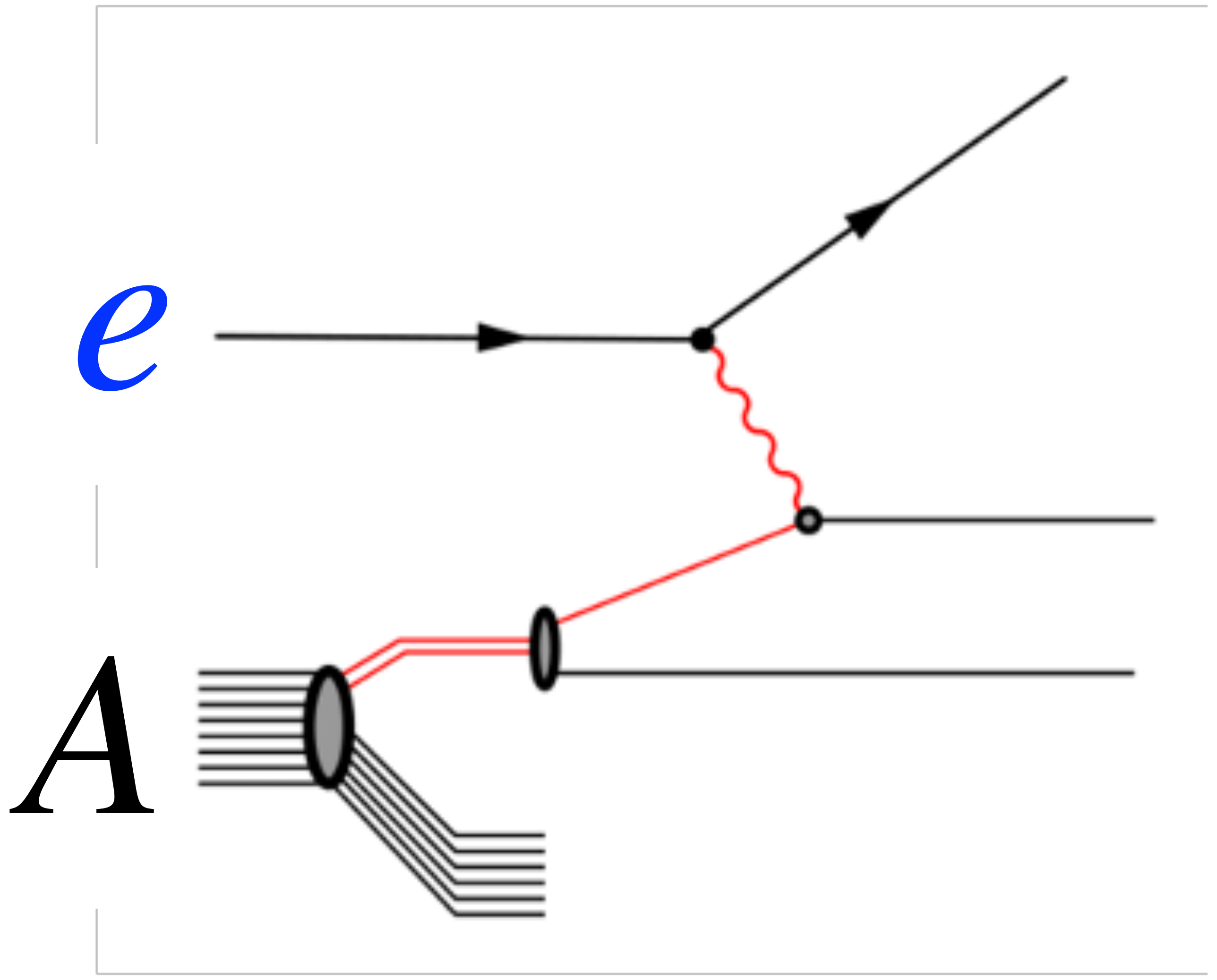
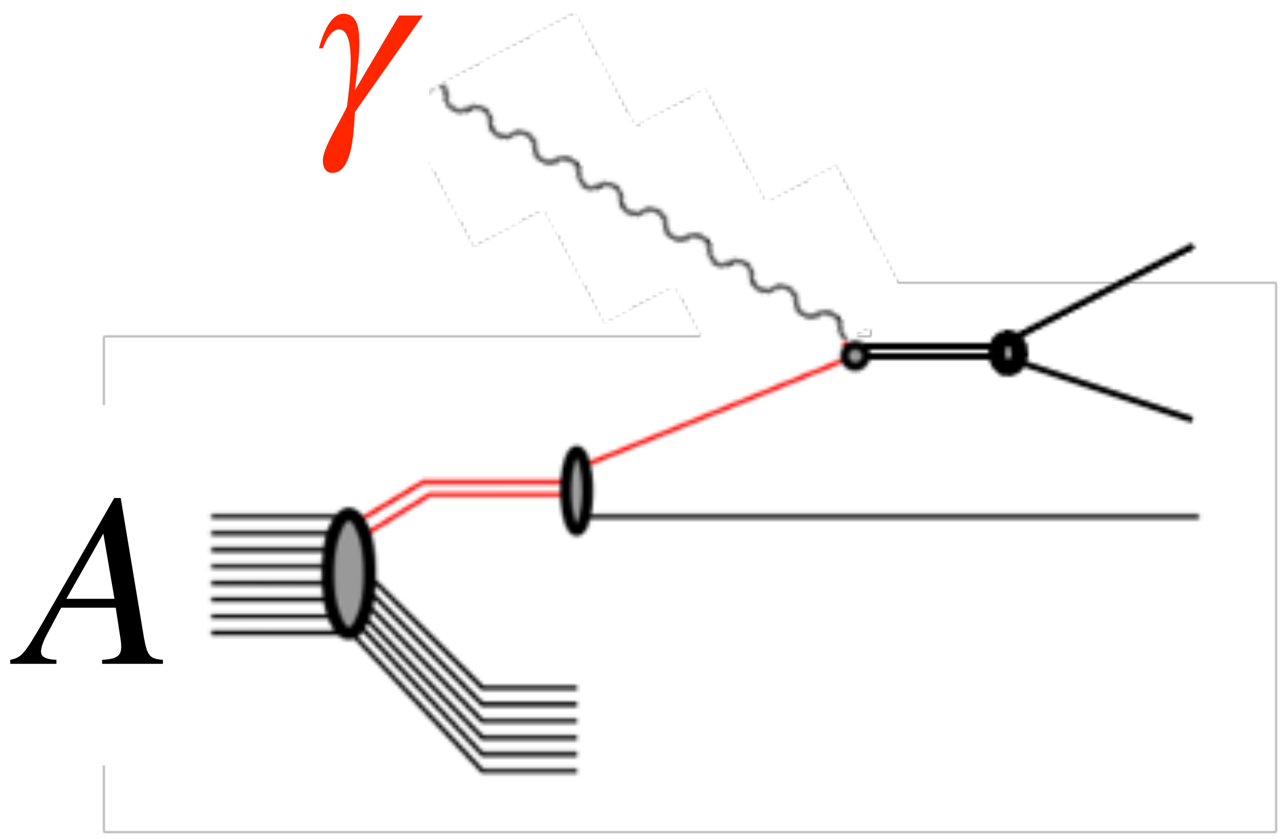
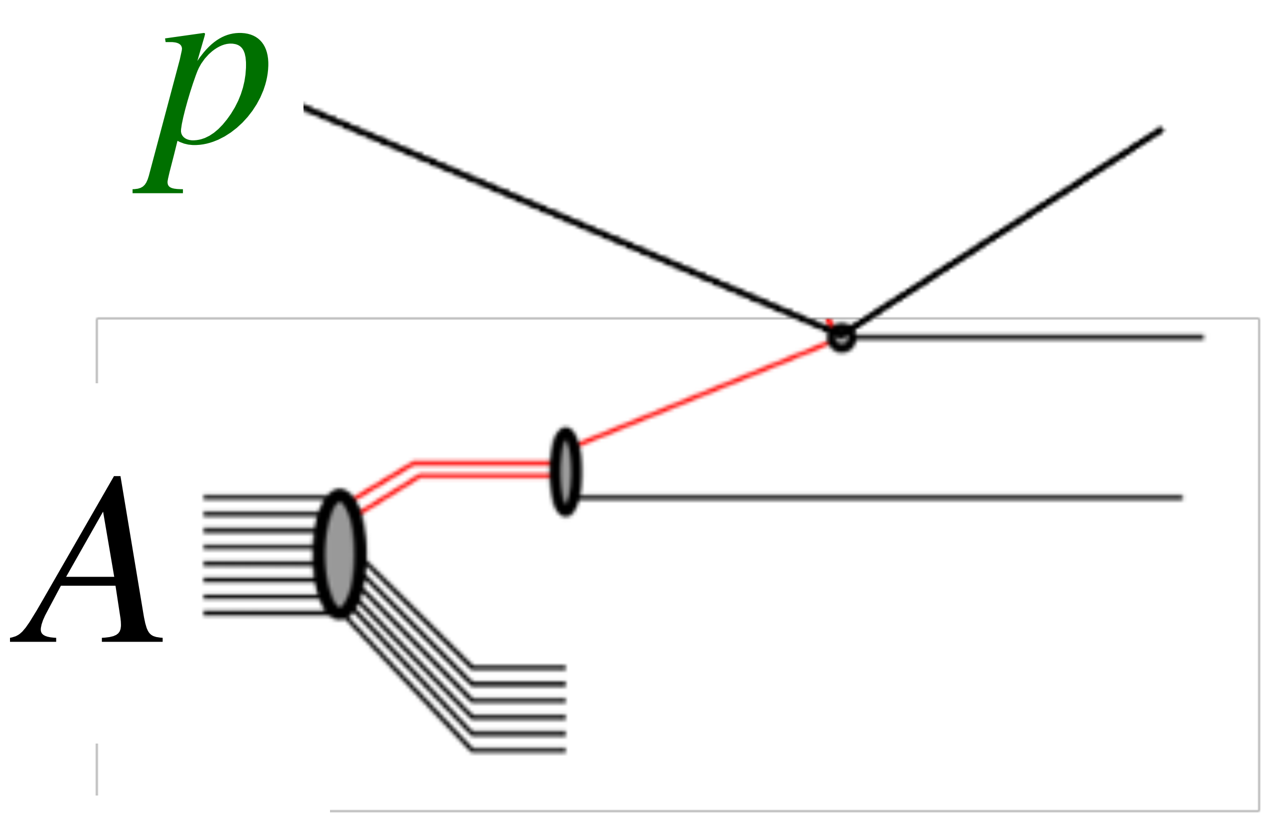
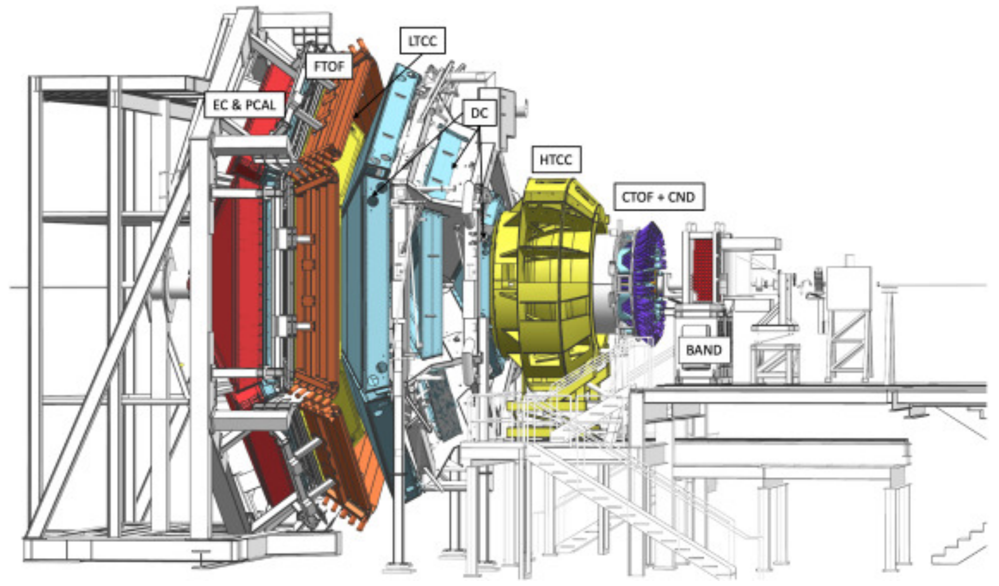
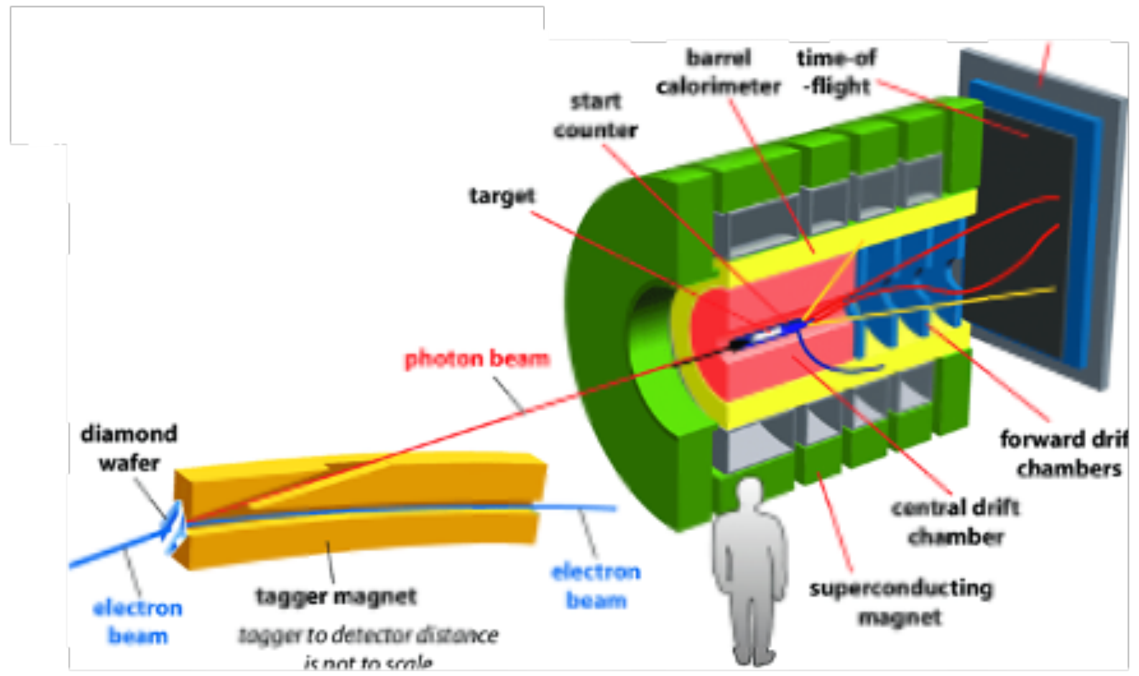




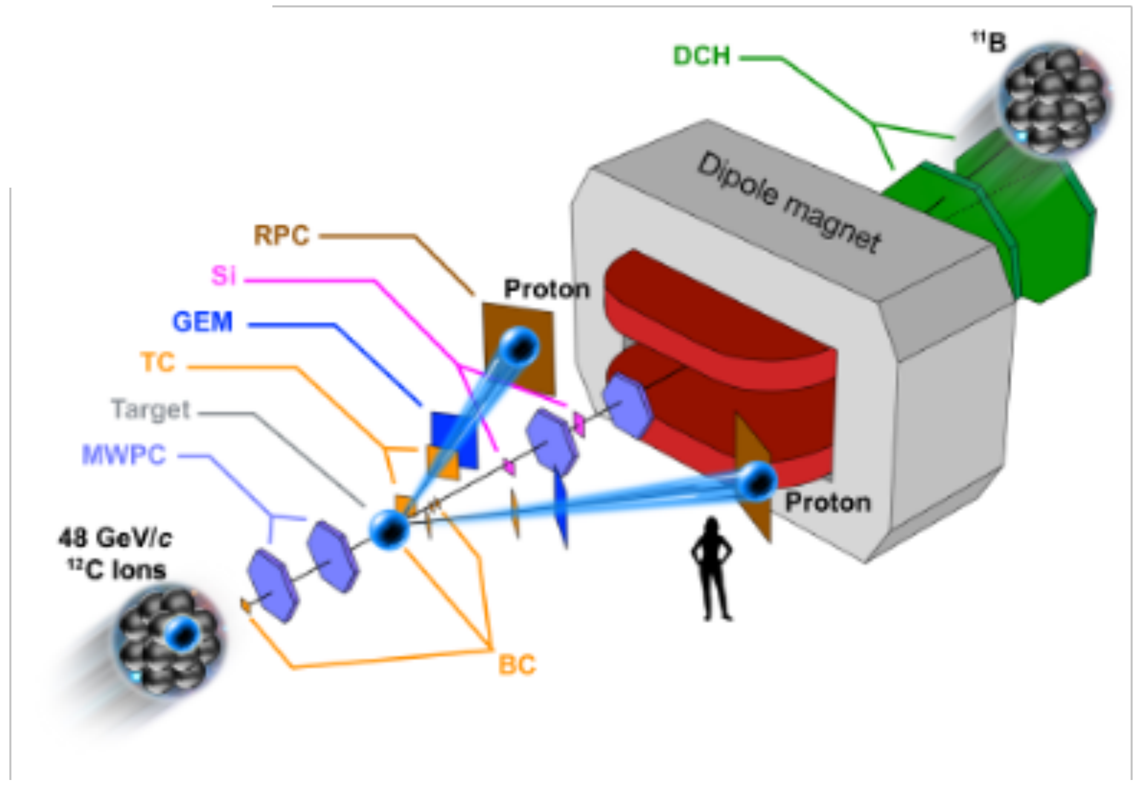




CLAS12

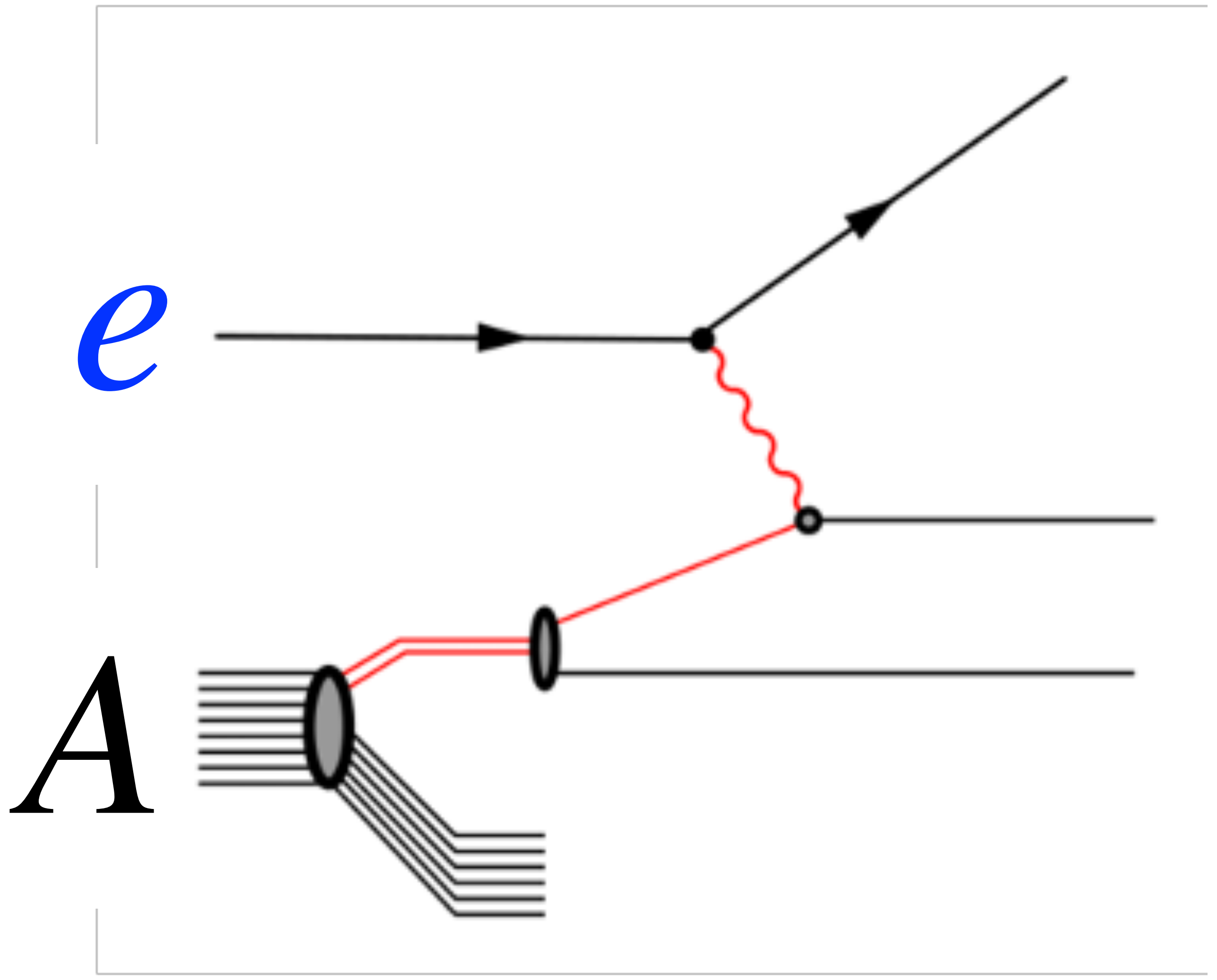


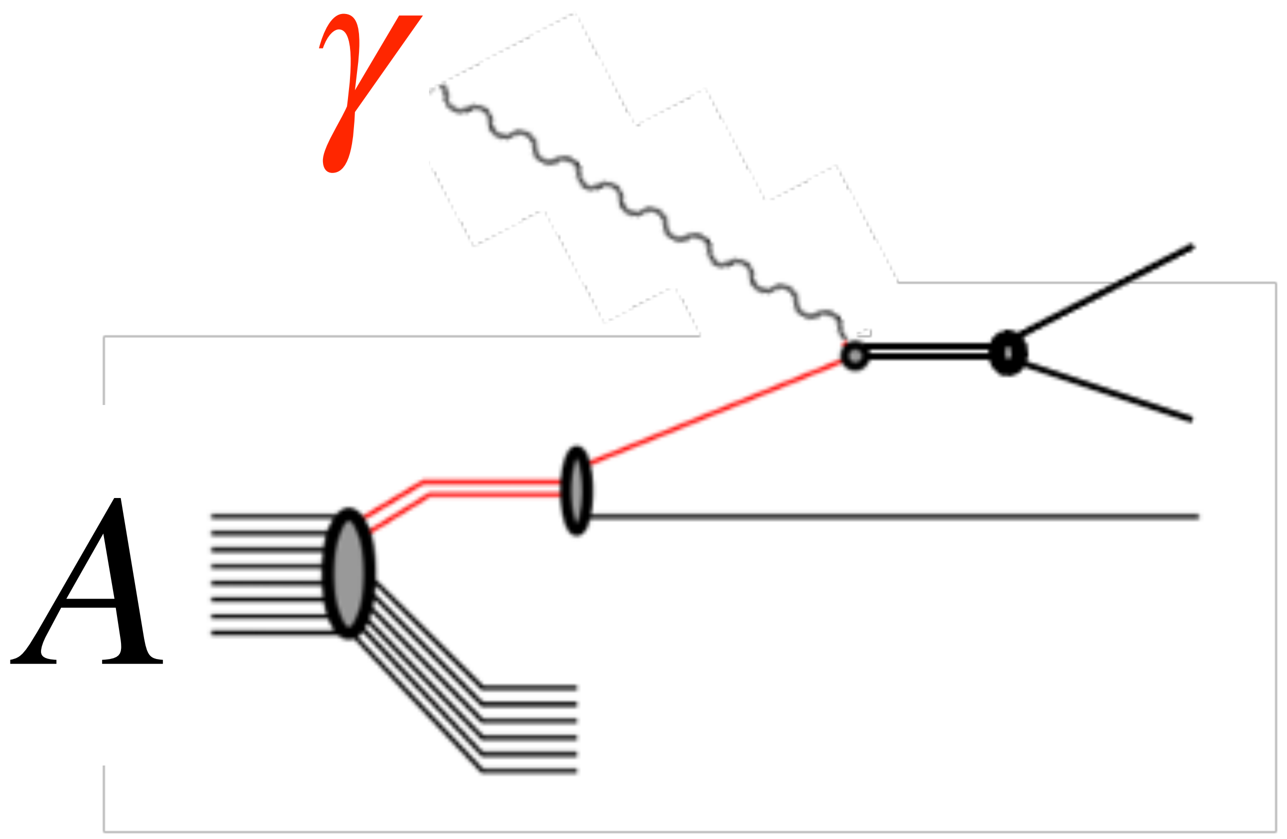
GlueX

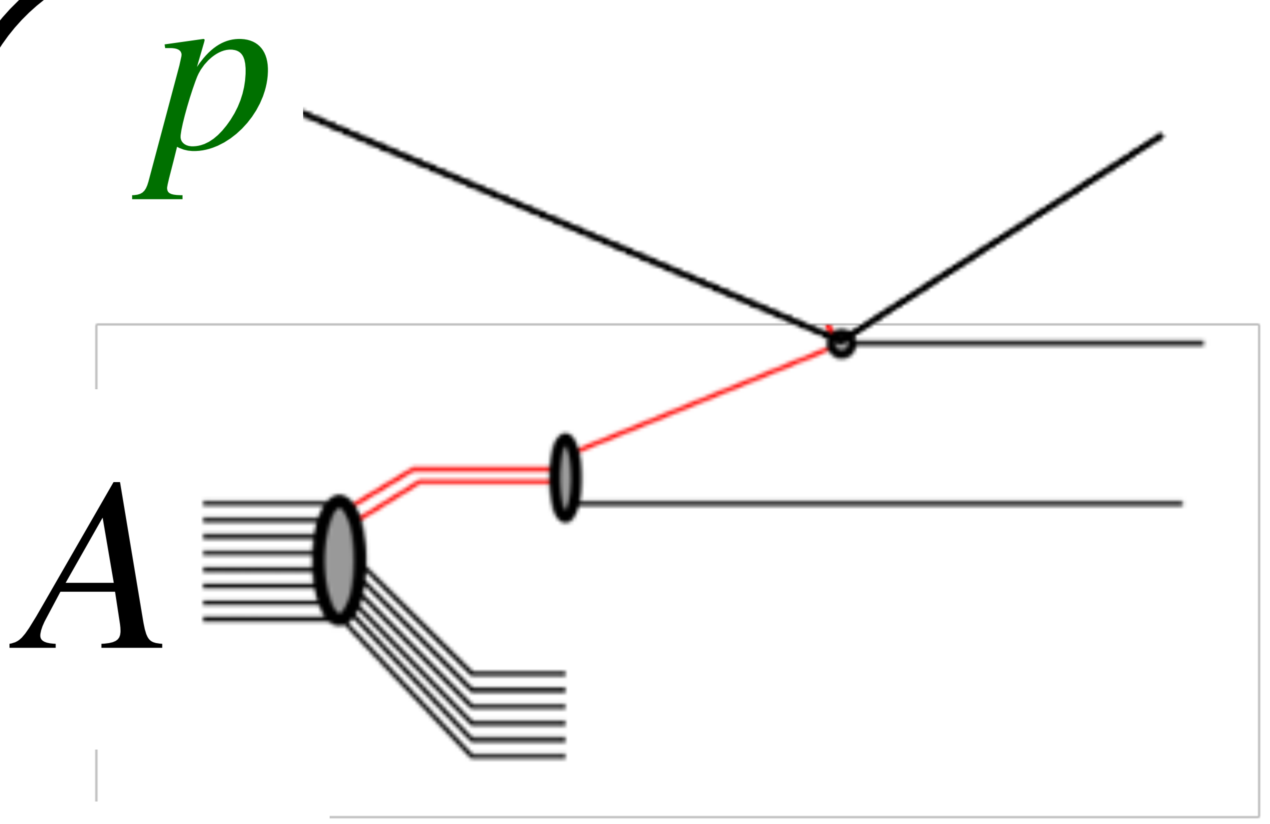


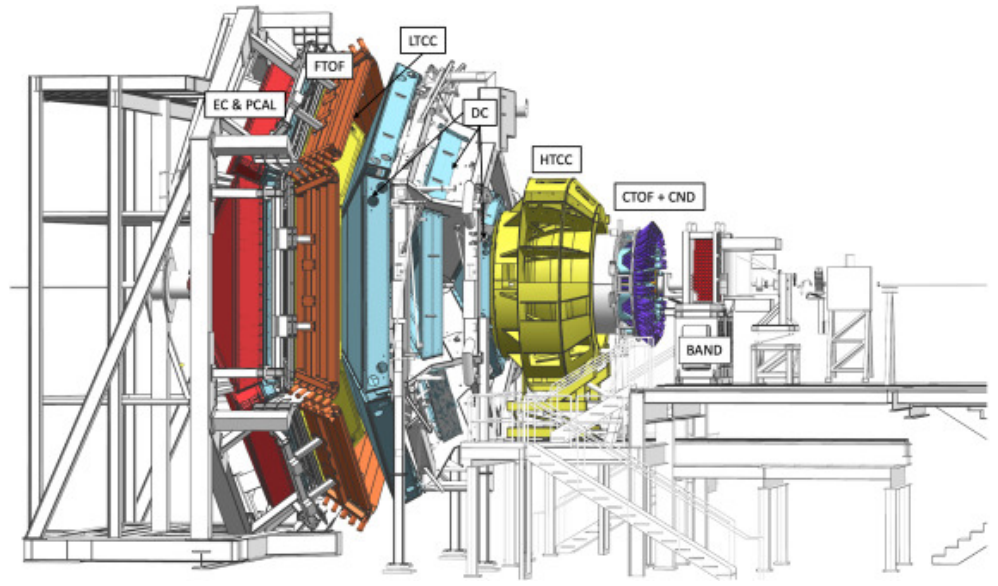
BM@N / R3B

Probe Dependence of SRCs









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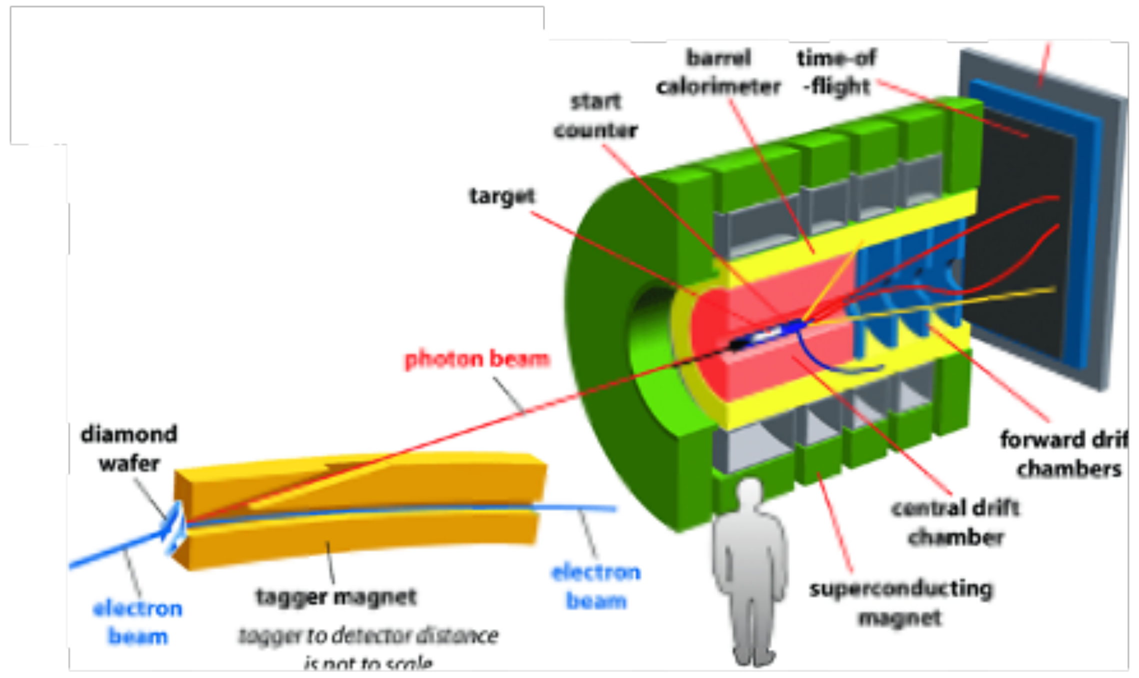

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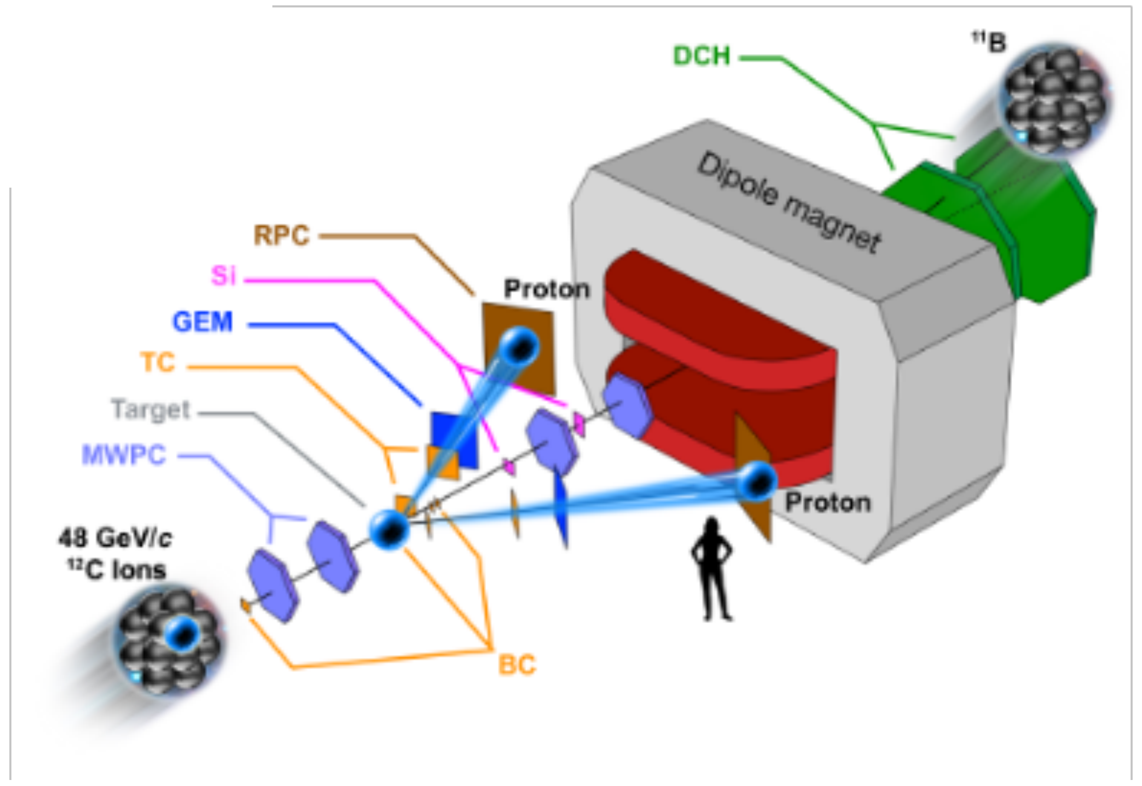
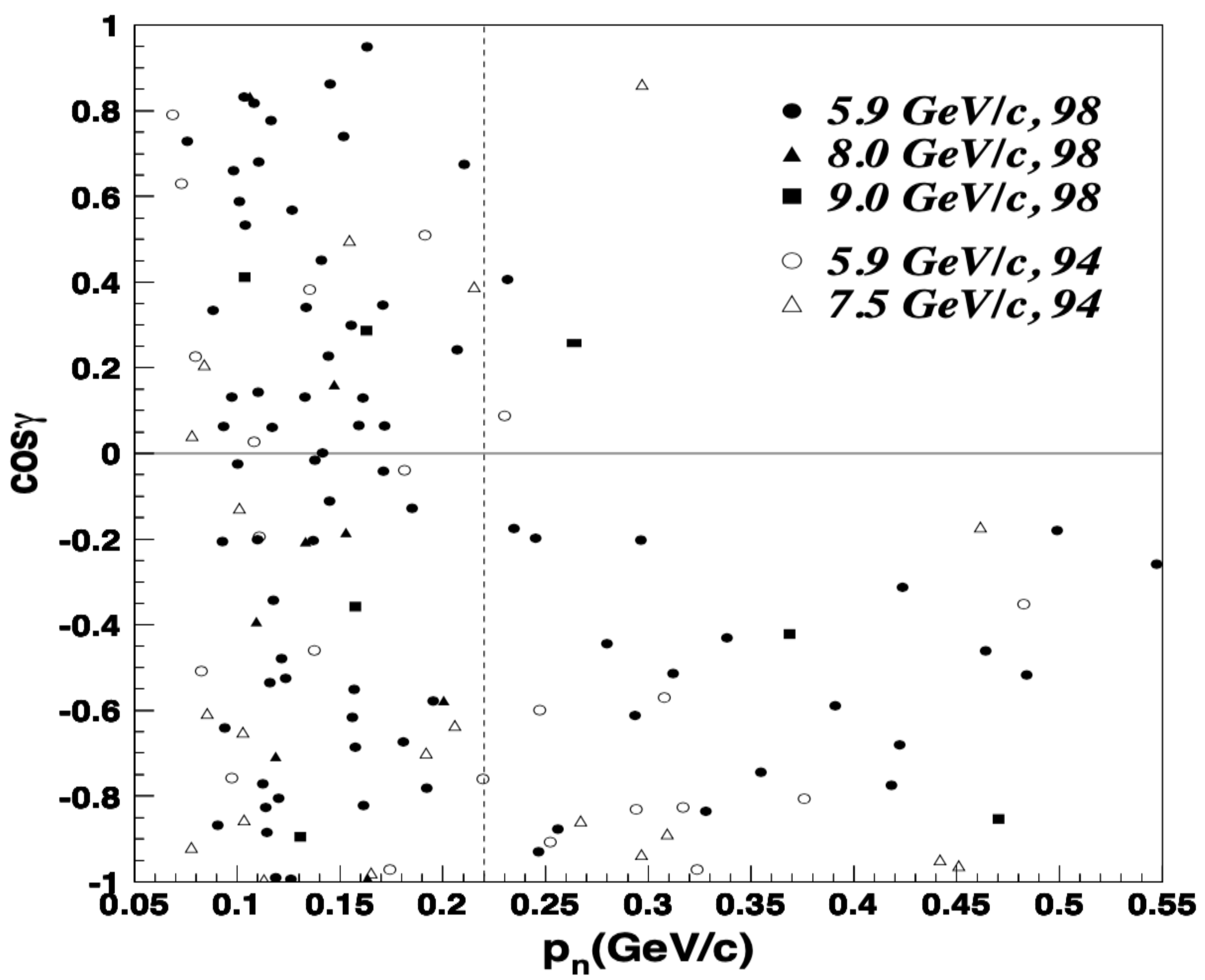


BM@N / R3B

n-p Short-Range Correlations from $(p, 2p + n)$ Measurements

A. Tang,[1] J.W. Watson,[1] J. Aclander,[2] J. Alster,[2] G. Asryan,[4,3] Y. Averichev,[8] D. Barton,[4] V. Baturin,[6,5] N. Bukhtoyarova,[4,5] A. Carroll,[4] S. Gushue,[4] S. Heppelmann,[6] A. Leksanov,[6] Y. Makdisi,[4] A. Malki,[2] E. Minina,[6] I. Navon,[2] H. Nicholson,[7] A. Ogawa,[6] Yu. Panebratsev,[8] E. Piasetzky,[2] A. Schetkovsky,[6,5] S. Shimanskiy,[8] and D. Zhalov[6]



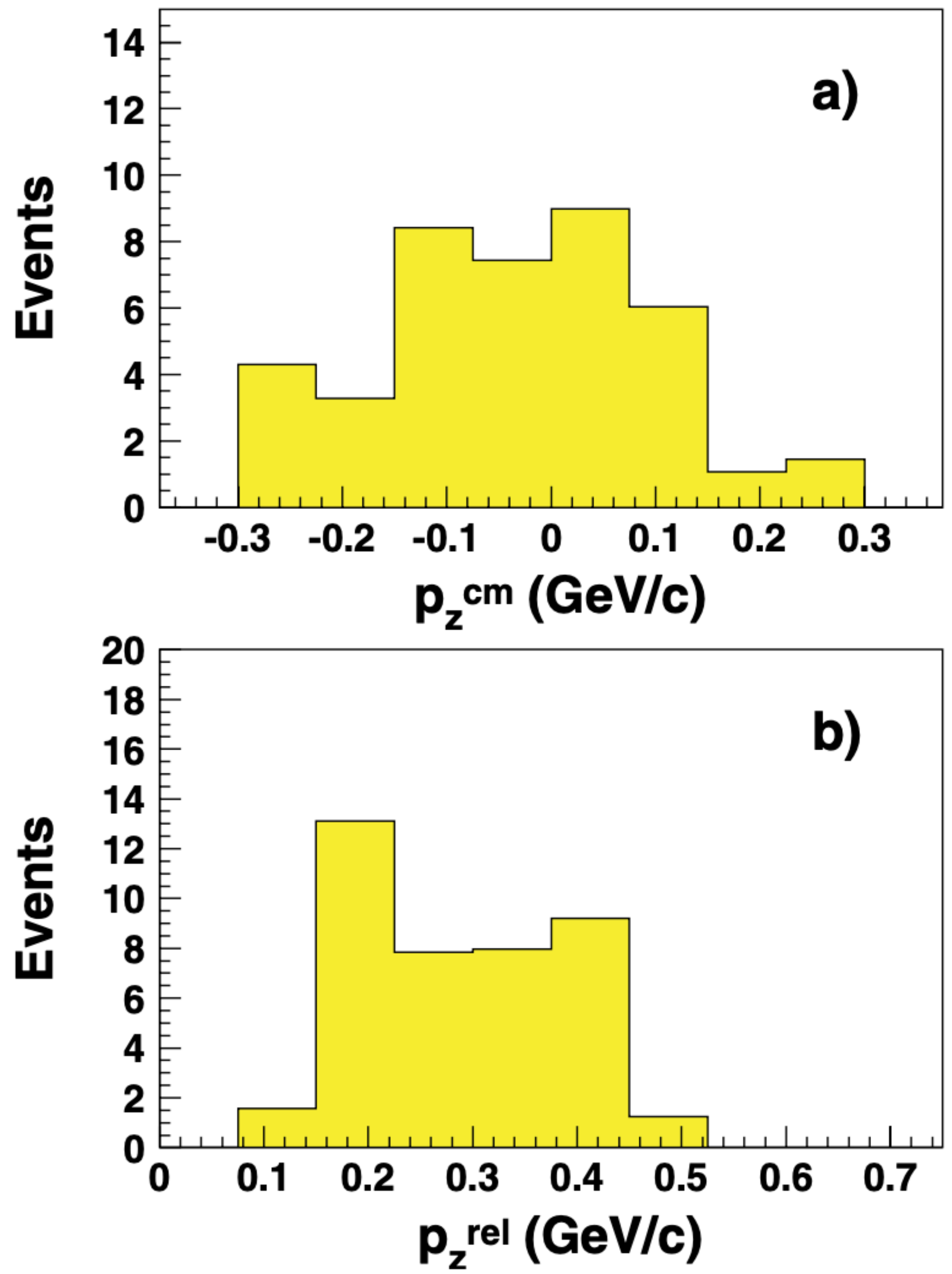
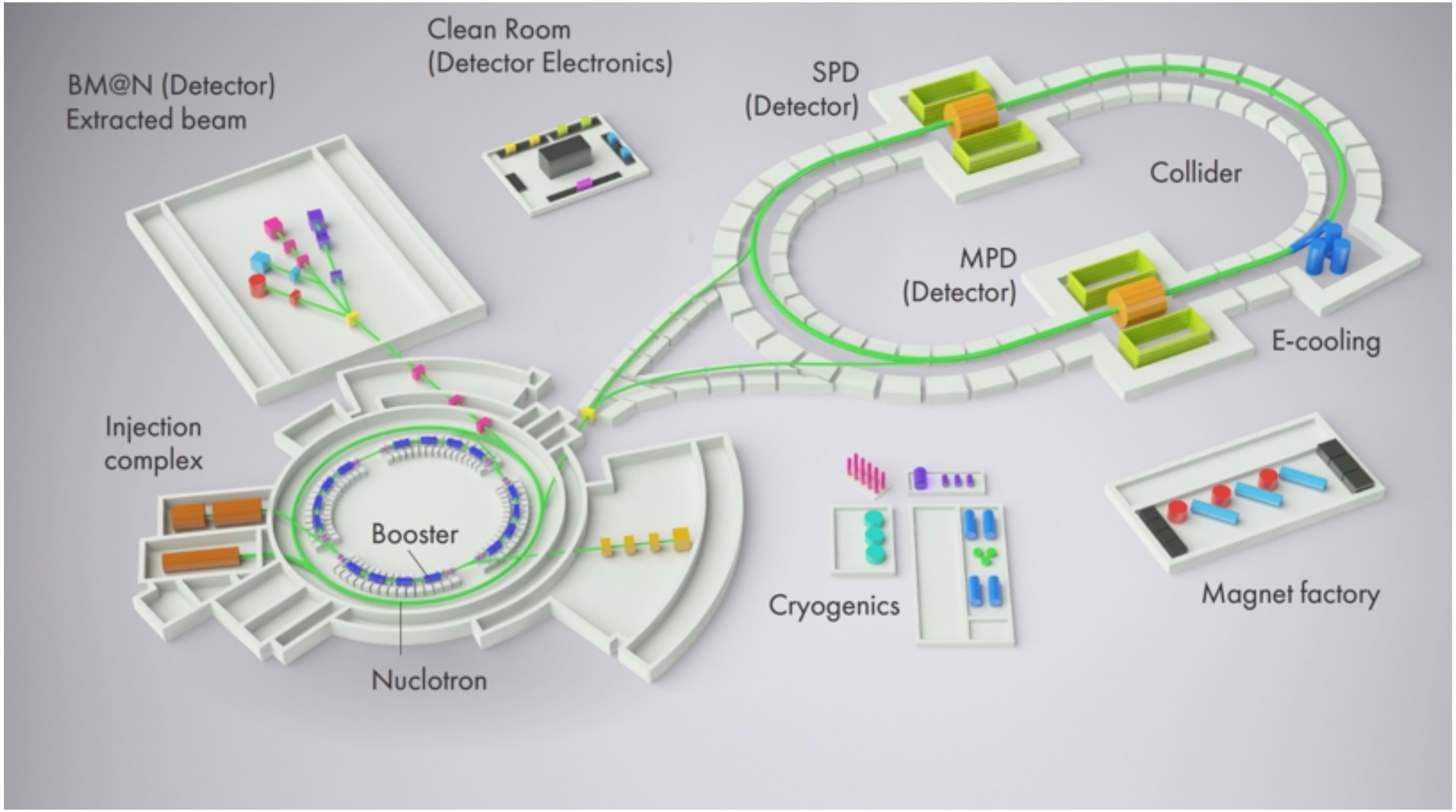


FIG. 4 (color online). Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for ^{12}C$(p, 2p + n)$ events. Each event has been s-weighted, as described in the text.

High-Energy Ion Beam @ JINR Nuclotron



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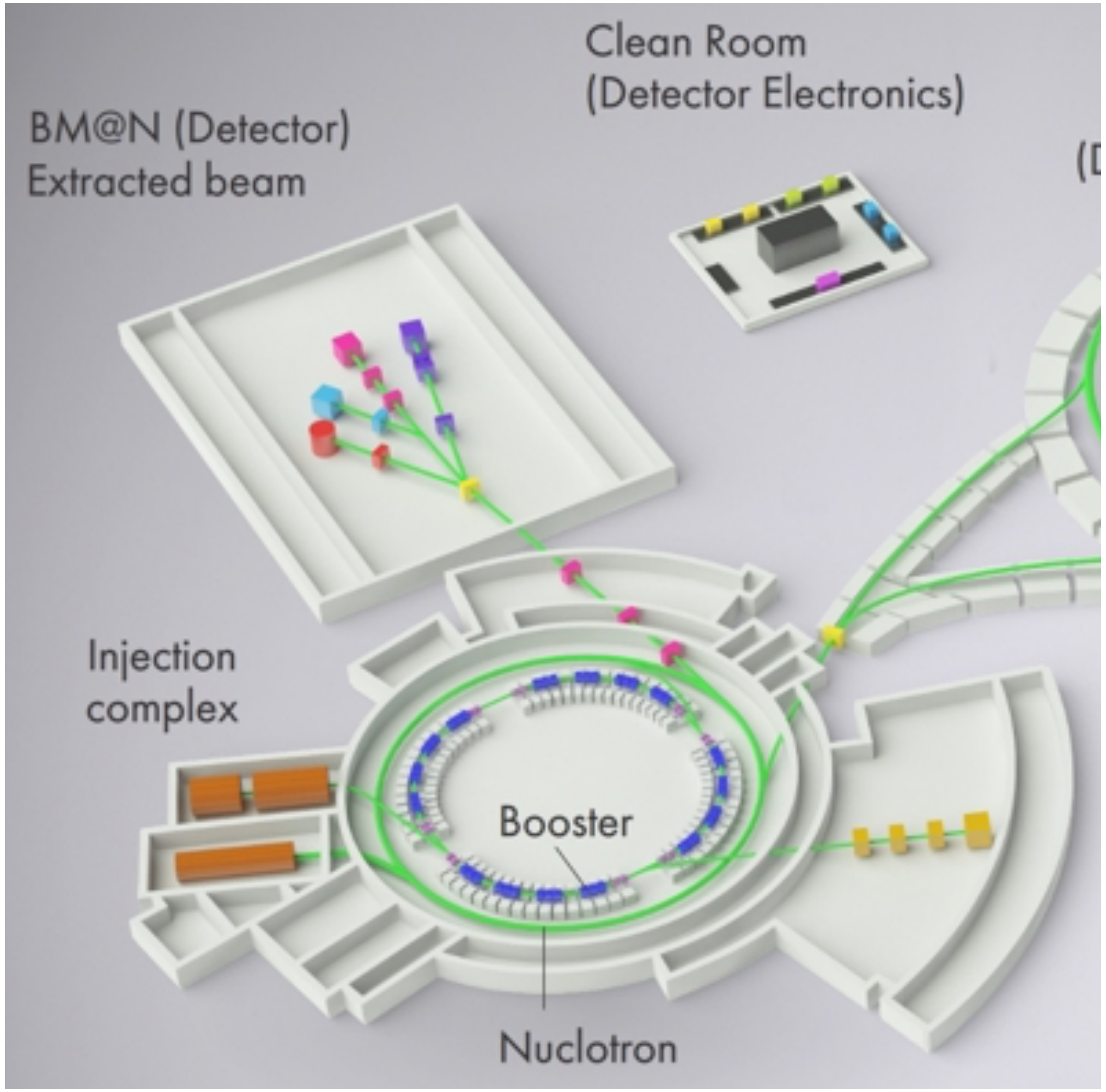
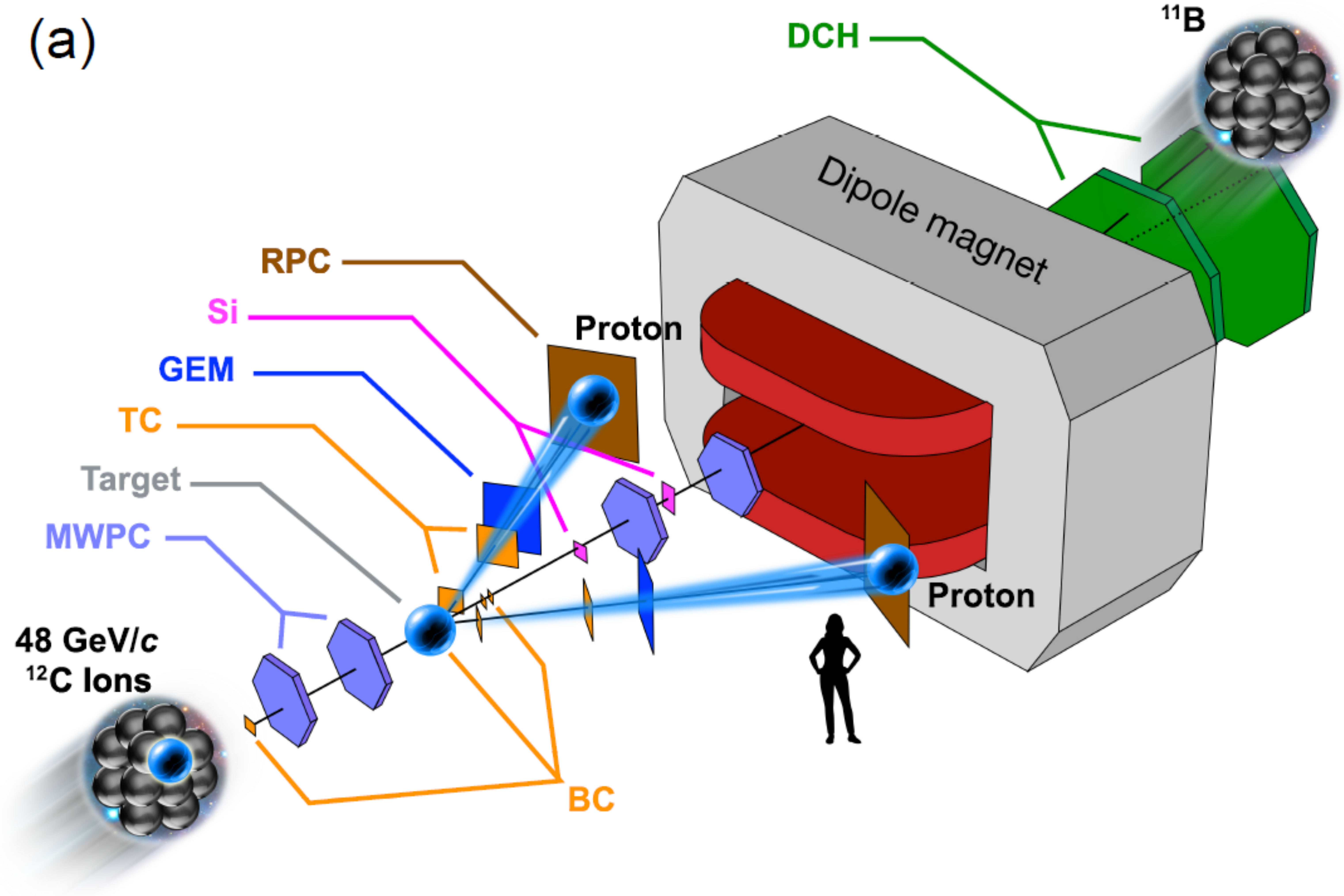


SRC @ BM@N



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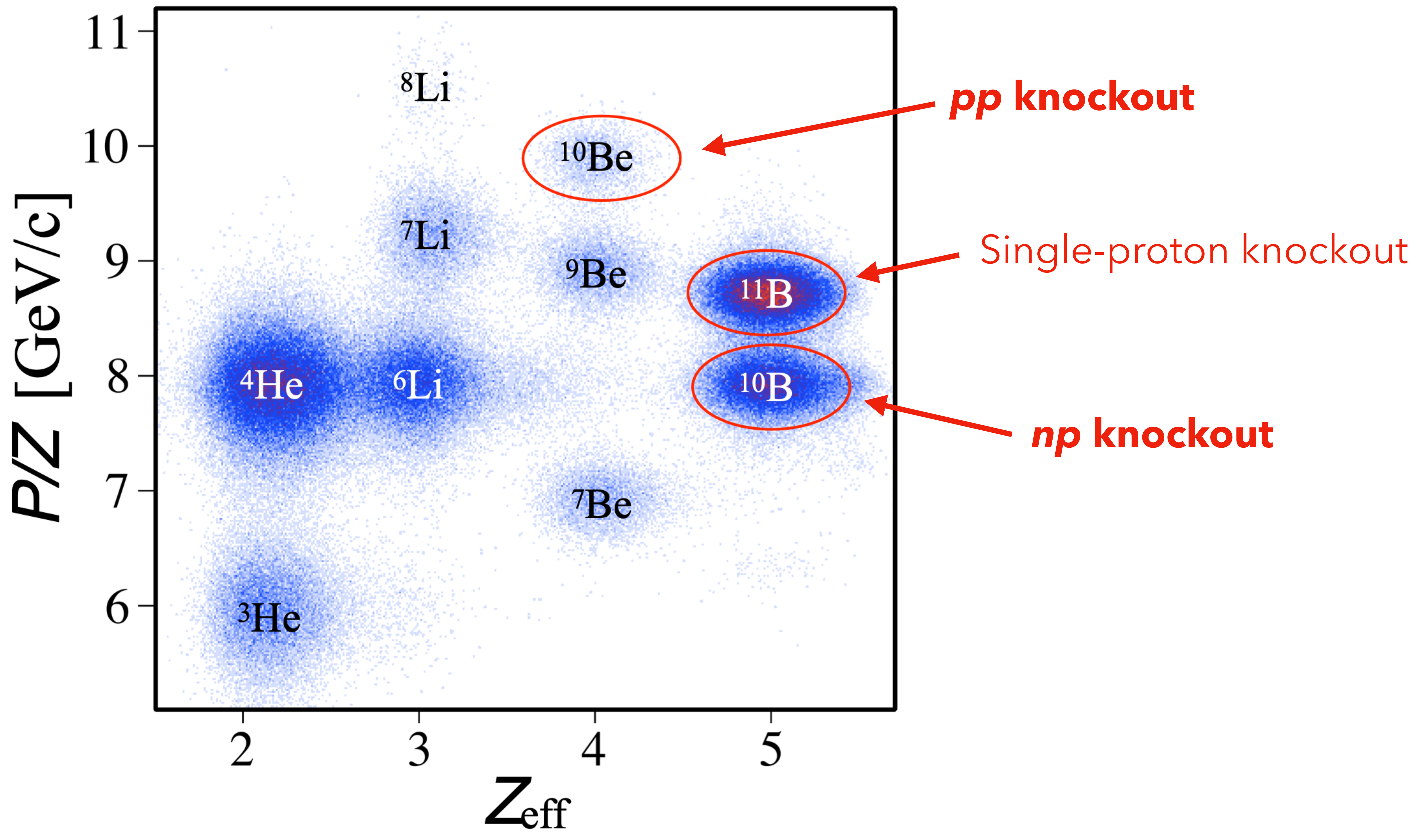
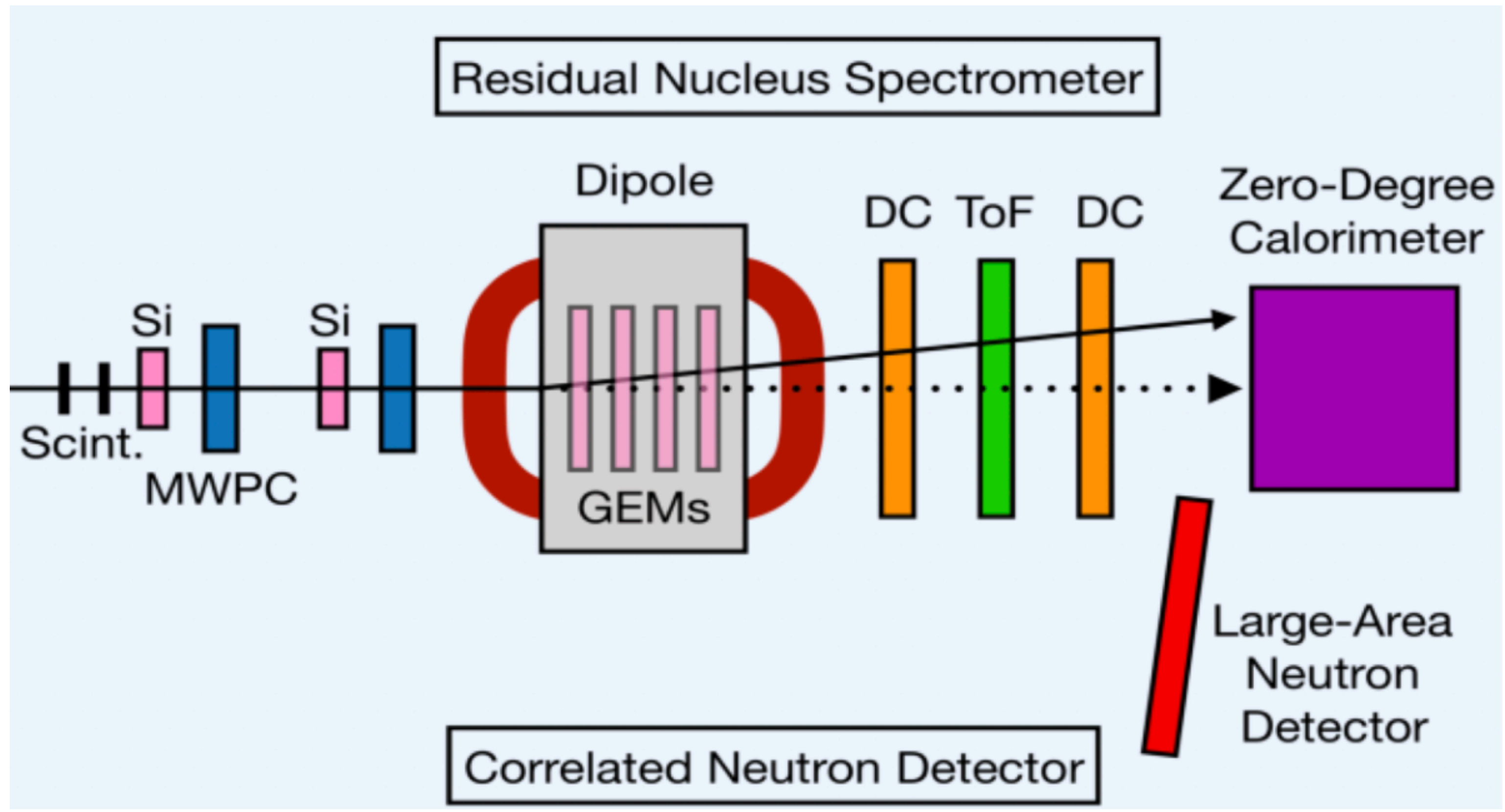
Fragment identification –





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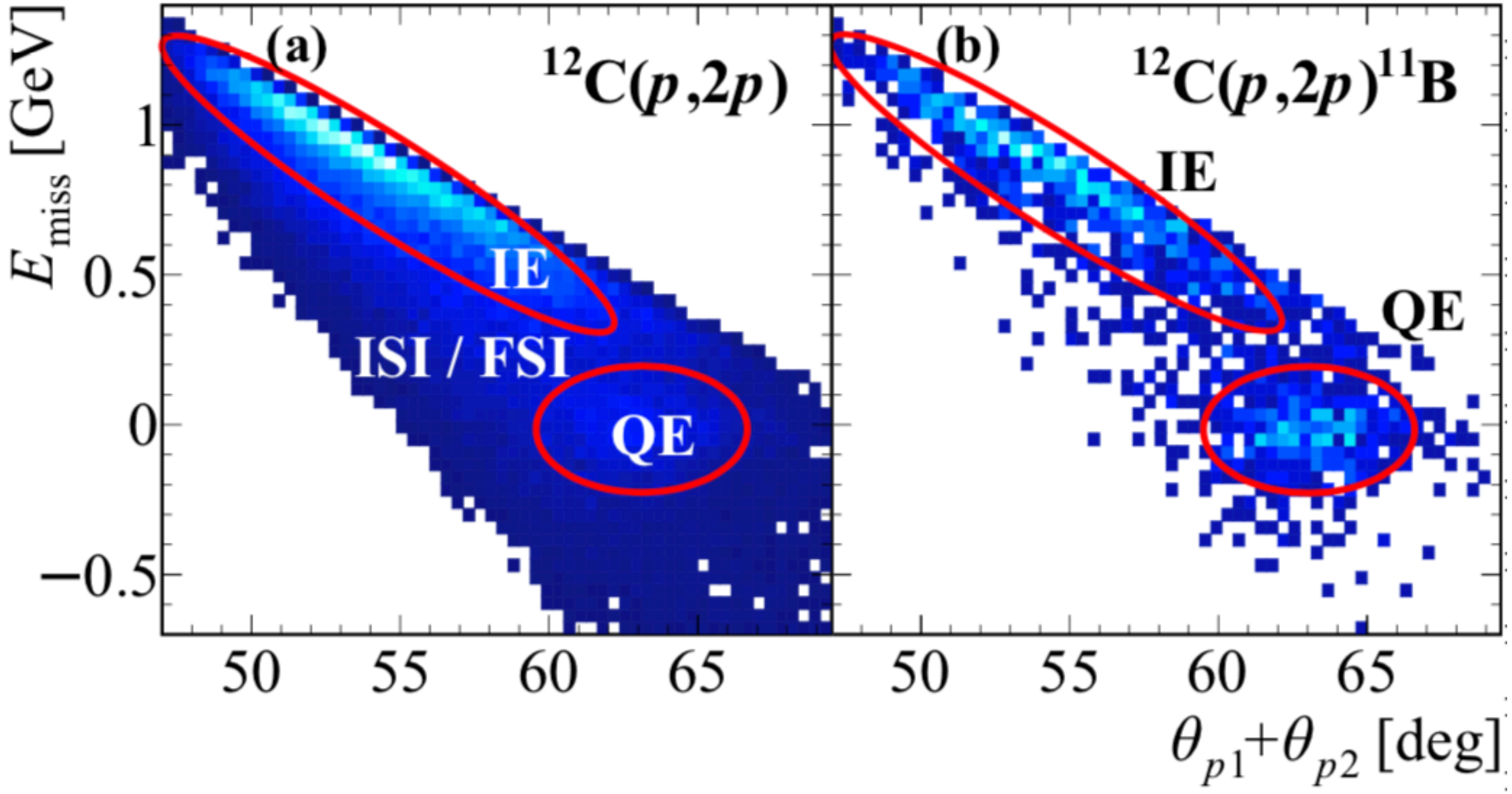
$(p,2p)$: Quasi-Free Scattering



Tagging on residual nucleus kills FSI contributions!

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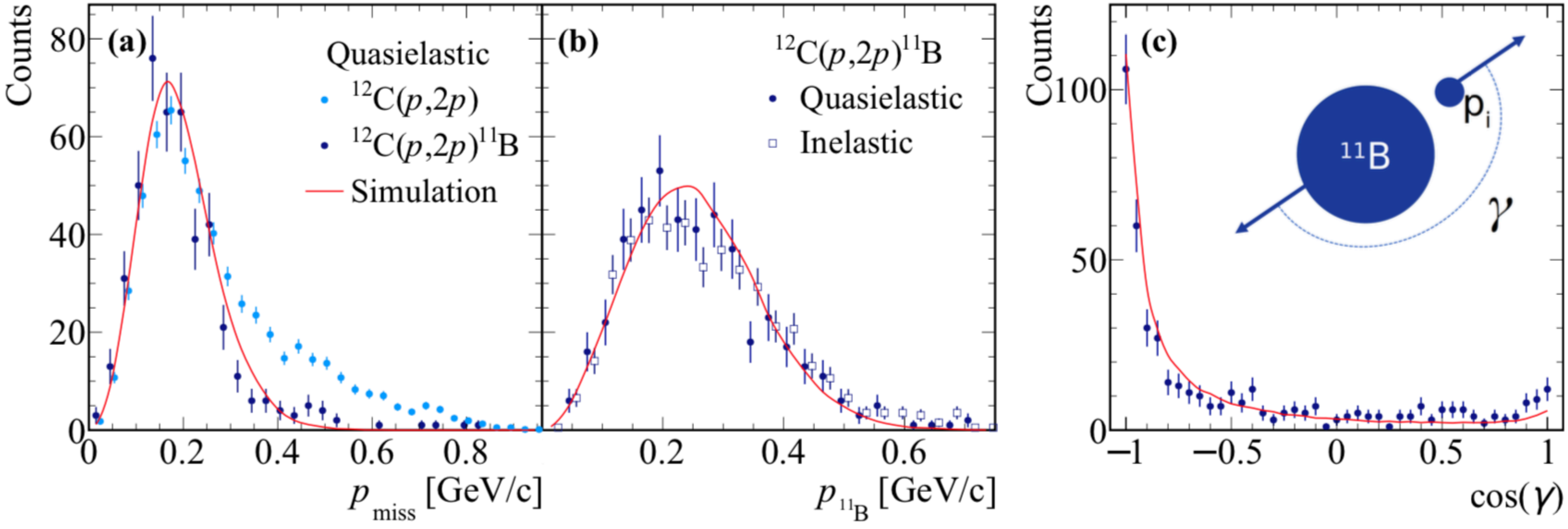
Single-nucleon knockout spectrum matches theory to high precision



But only ~40% of $(p,2p)$ quasielastic events have ^{11}B fragment

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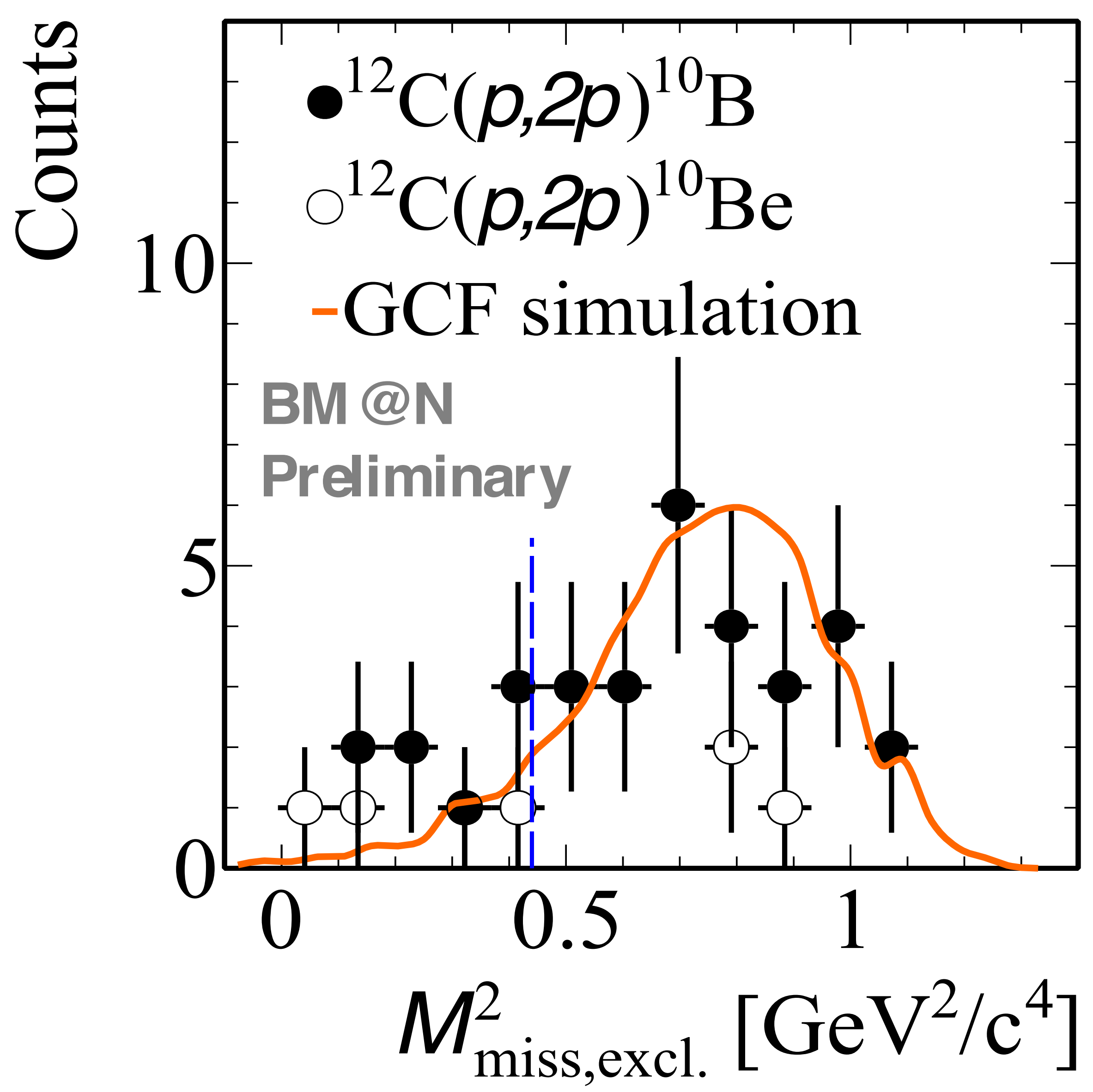
Looking for SRCs

Selection Cuts:

- Inclusive $(p,2p)$ + ^{10}B or ^{10}Be
- $p_{miss} > 350$ MeV/c
- $-100 < E_{miss} < 240$ MeV
- In-plane $2p$ opening angle $> 63°$
- $m_{miss} > 420$ MeV^2/c^2

Only few % of relevant $(p,2p)$ events have ^{10}B or ^{10}Be fragments

Missing mass consistent with a nucleon



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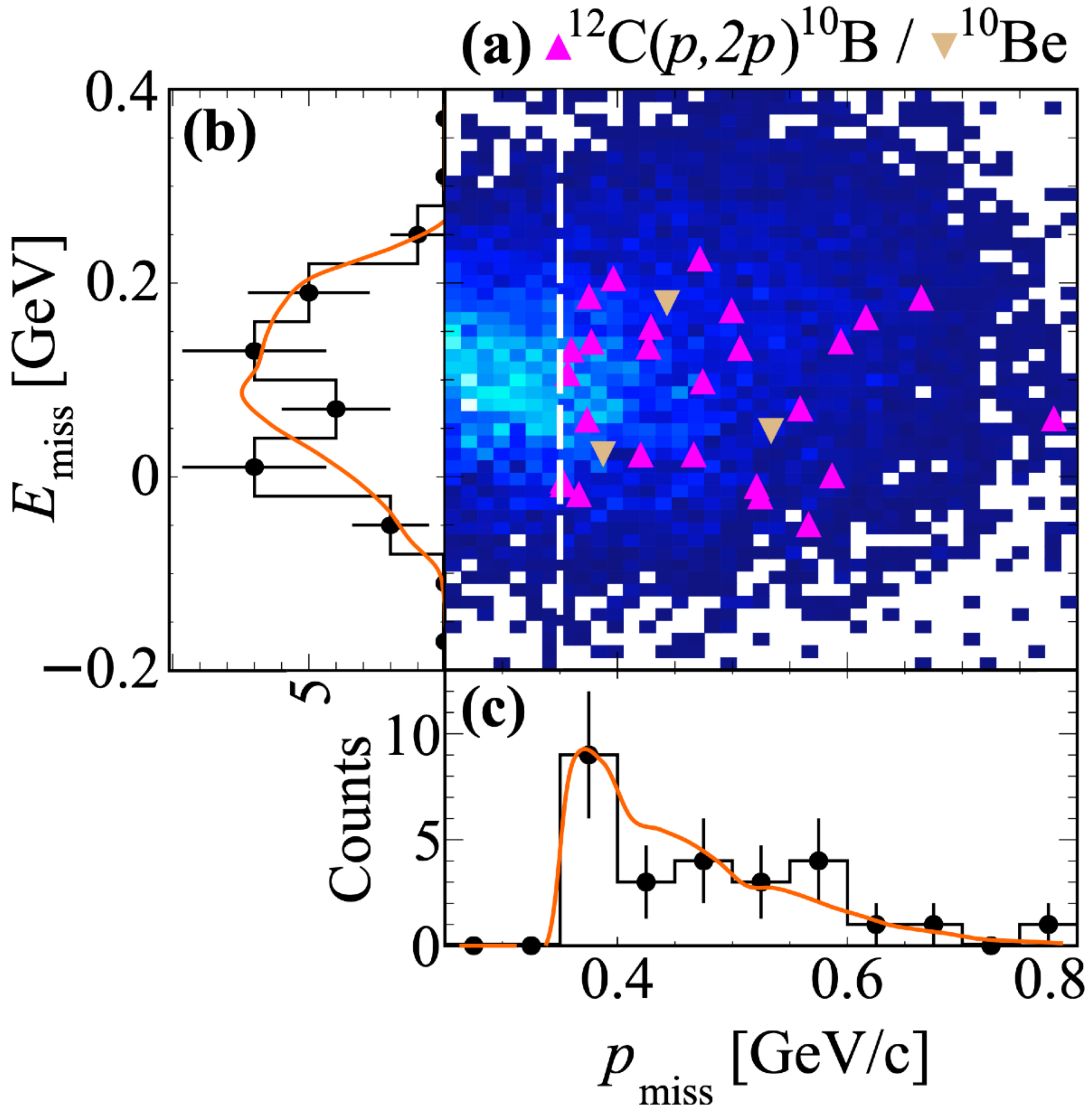
NP-SRC dominance

26 ^{10}B events

3 ^{10}Be events

→ *np* pair dominance



Possible contamination:

- **^{11}B + FSI nucleon knockout?**
  Would result in #^{10}B ~ #^{10}Be

- **QE mean-field events with excited ^{11}B?**
  Estimated maximum contribution 5 (^{10}B) and 2 (^{10}Be) events

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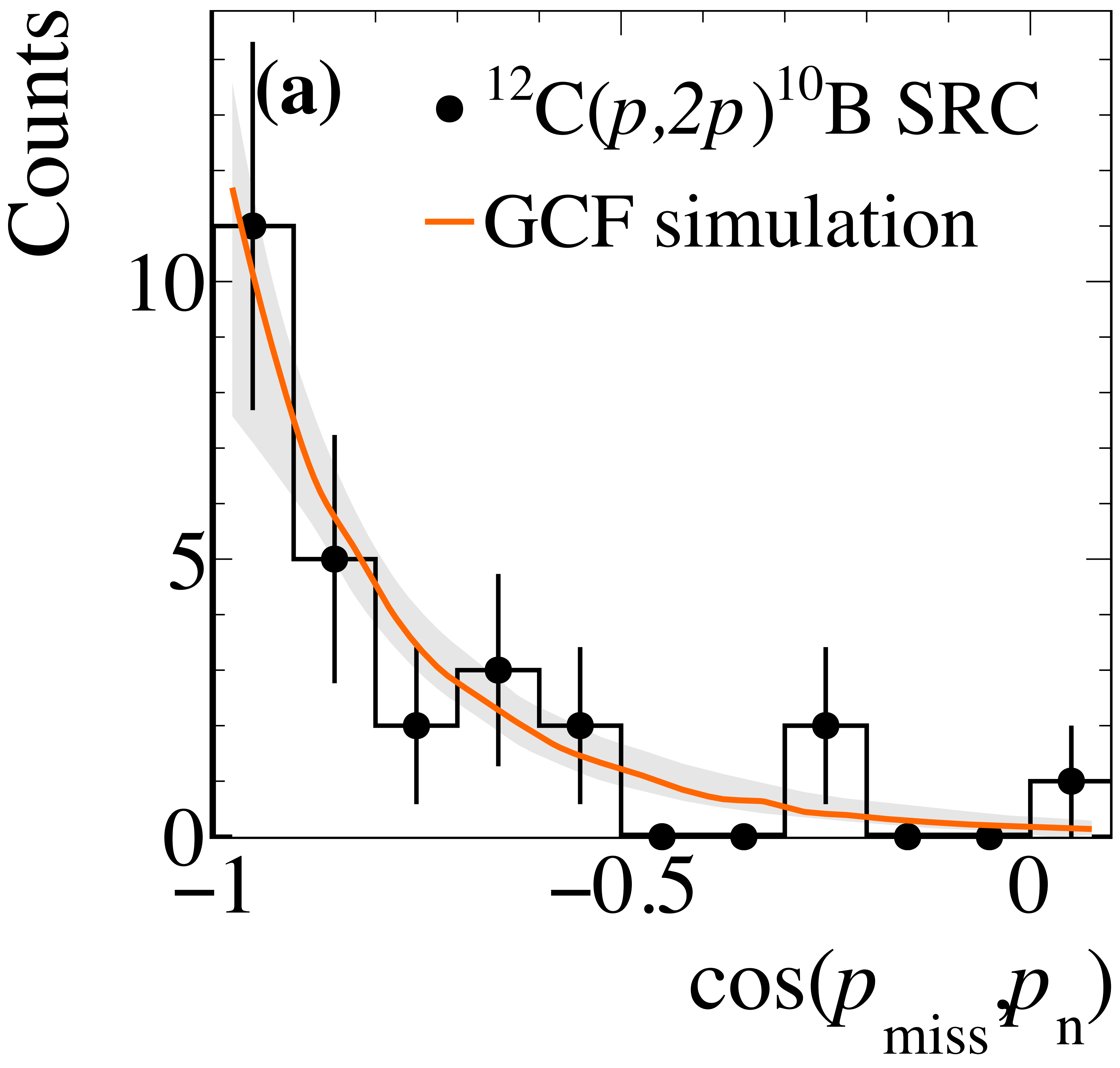
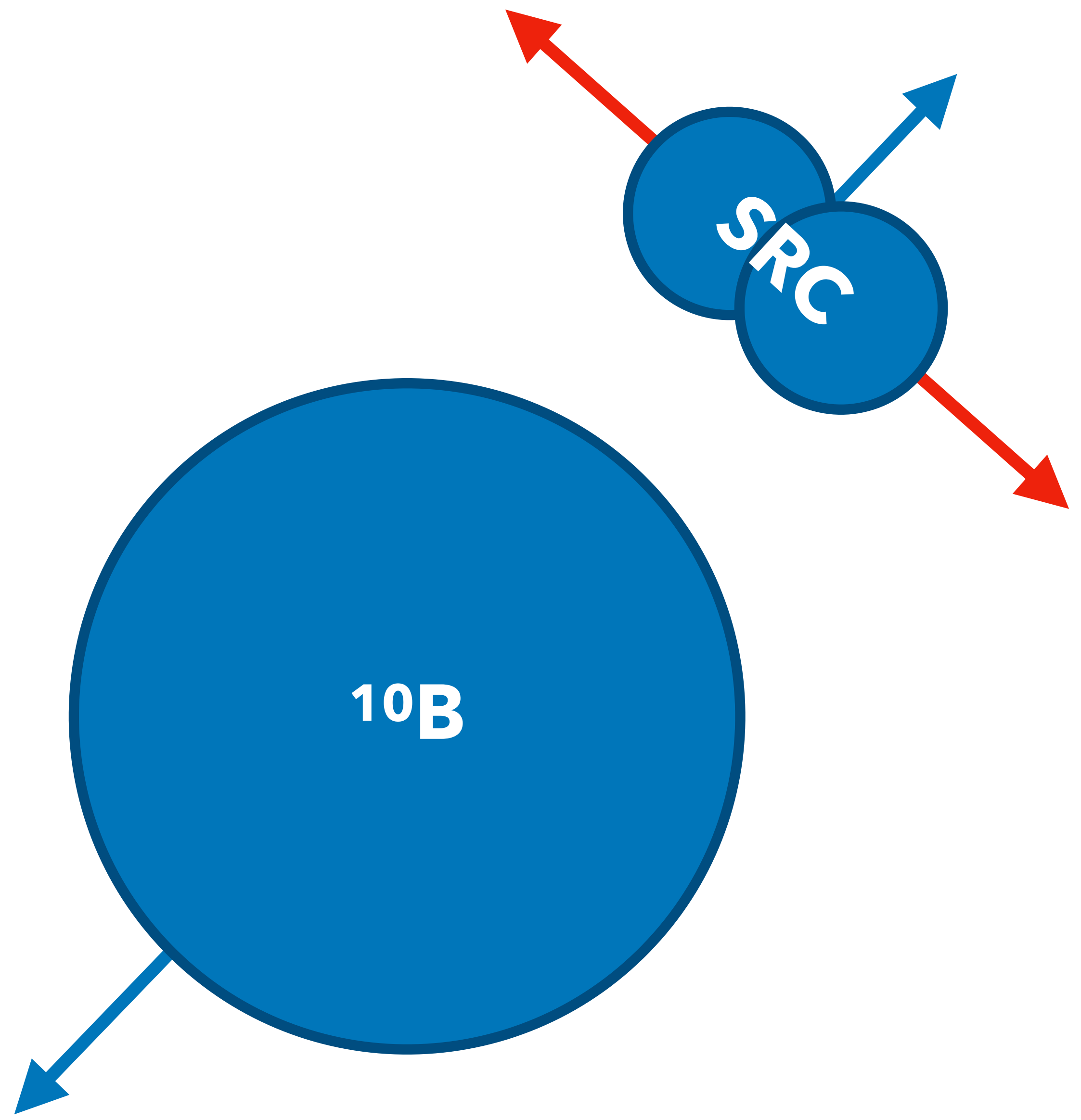
SRC nucleons show back-to-back correlation





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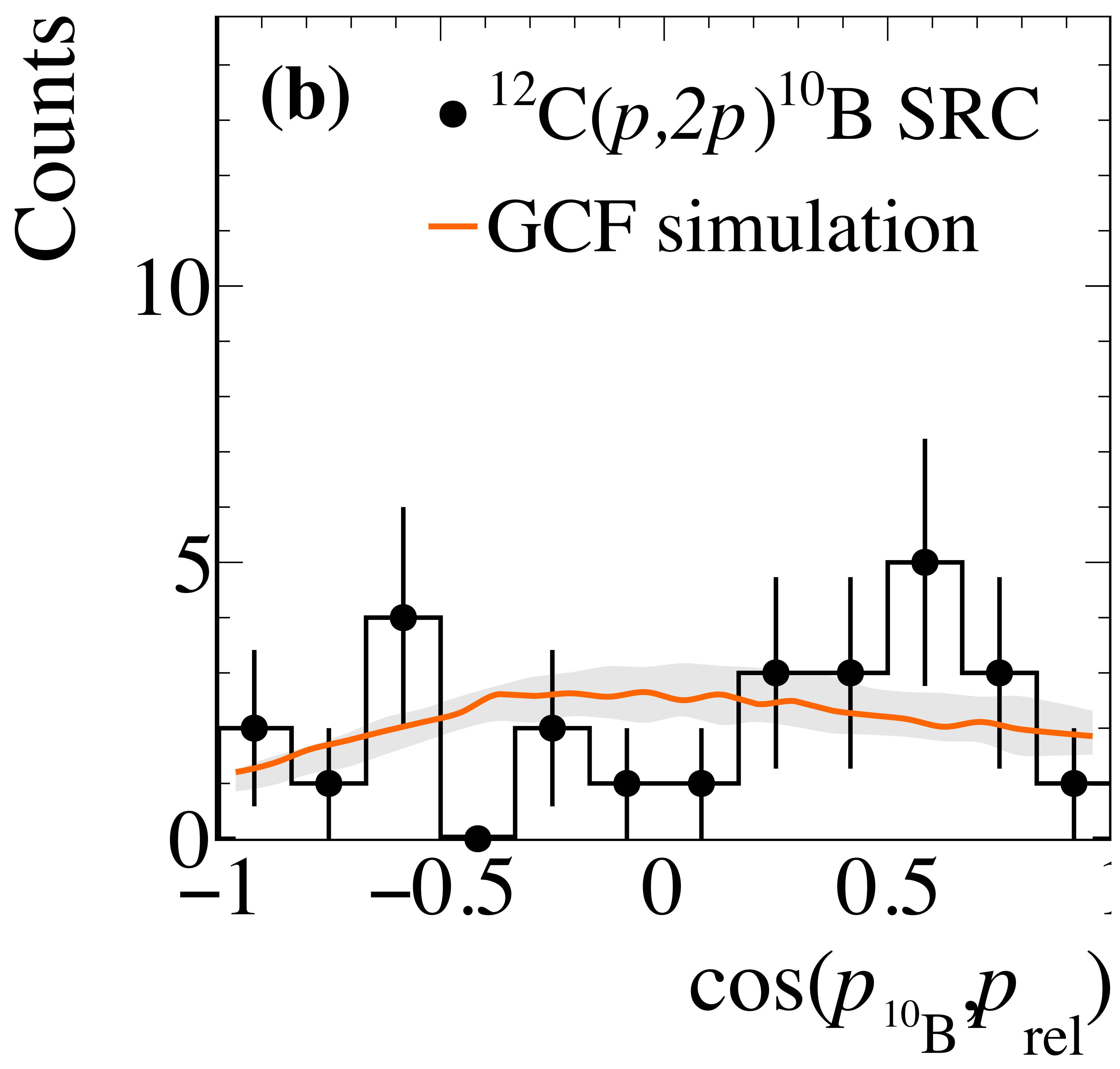
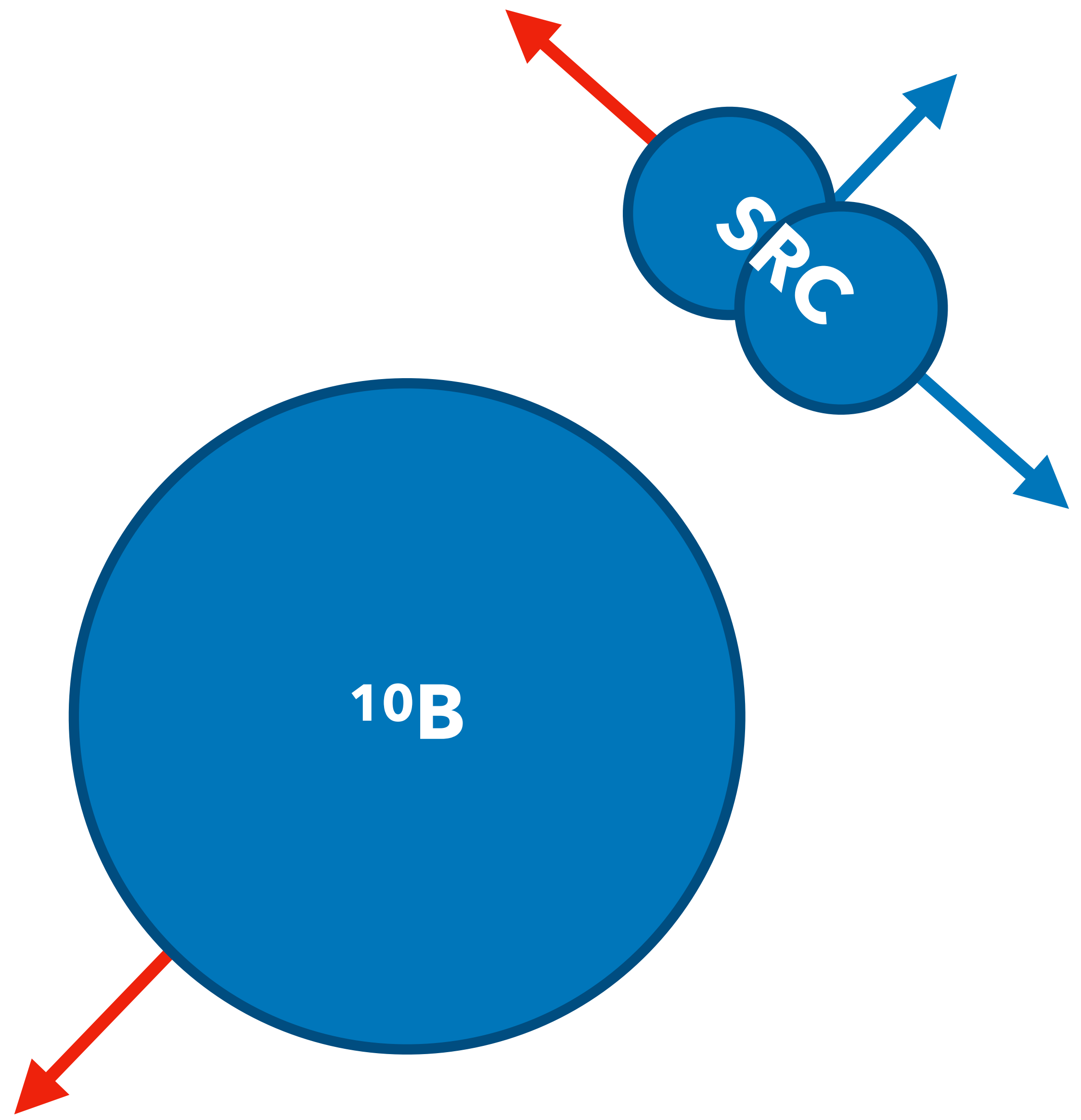
SRCs de-correlate from the rest of the nucleus!





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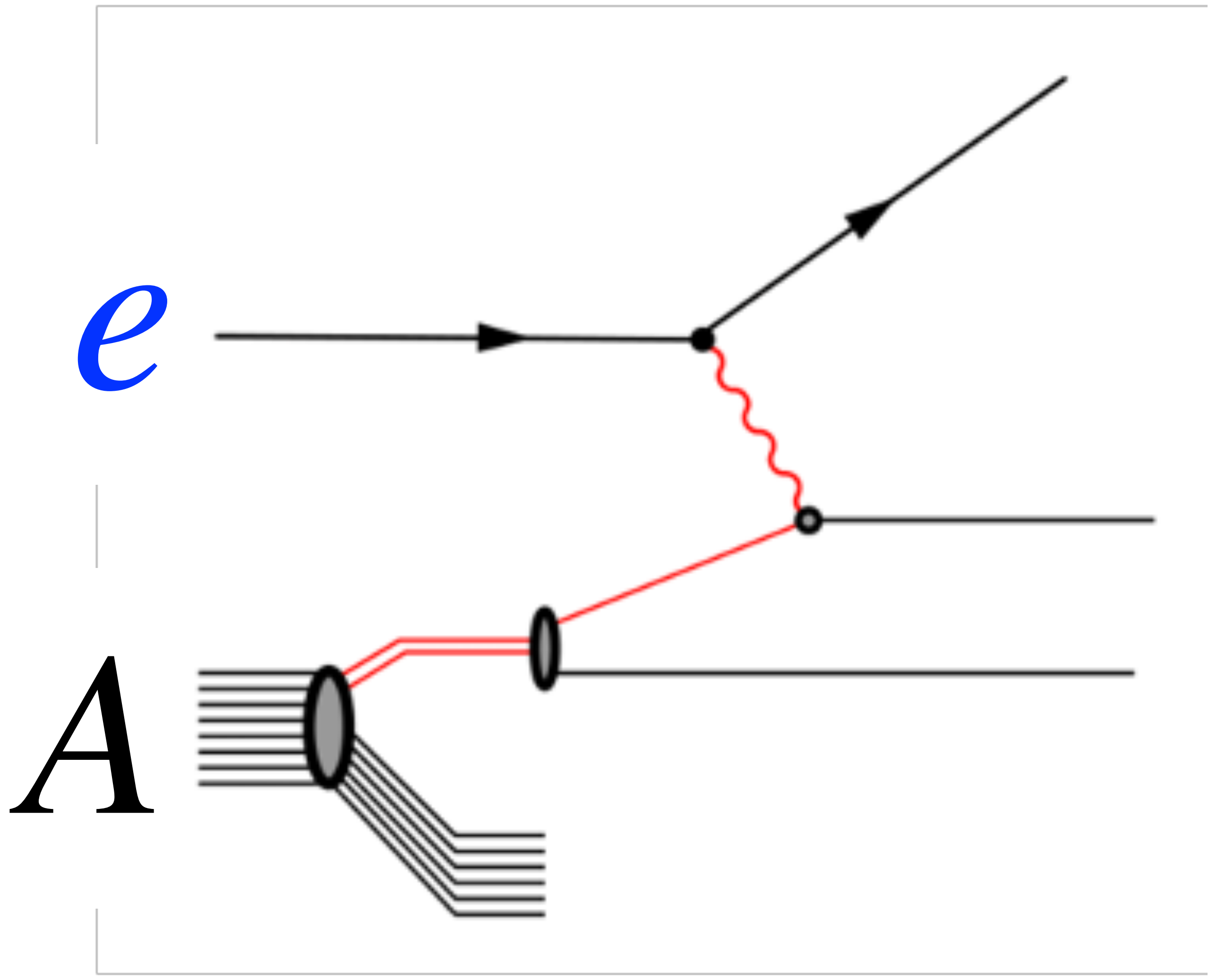
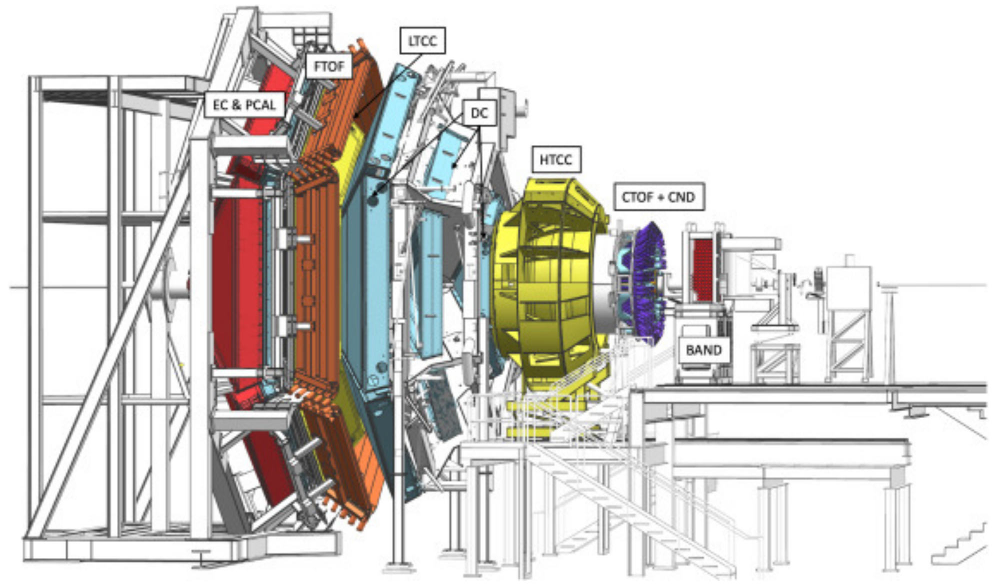
Probe Dependence of SRCs





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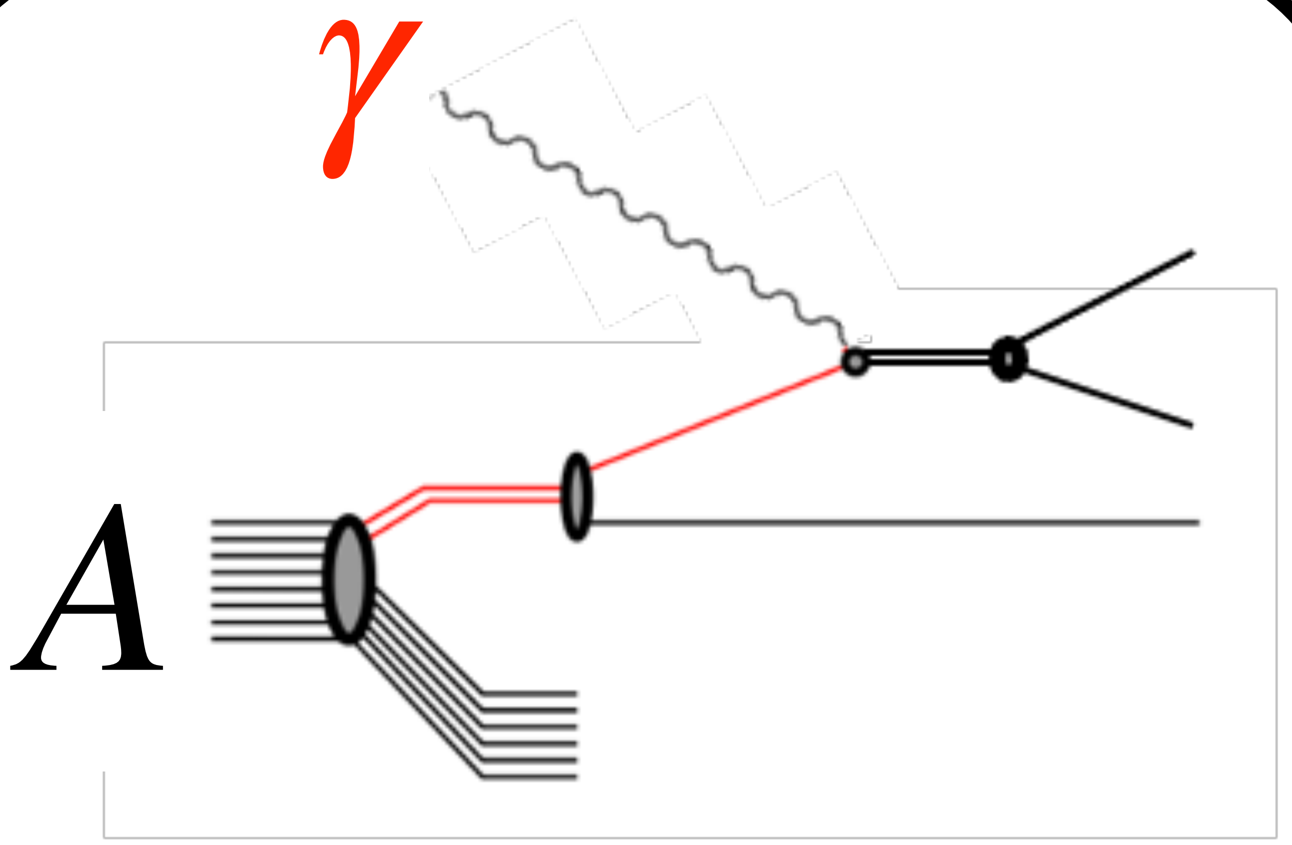

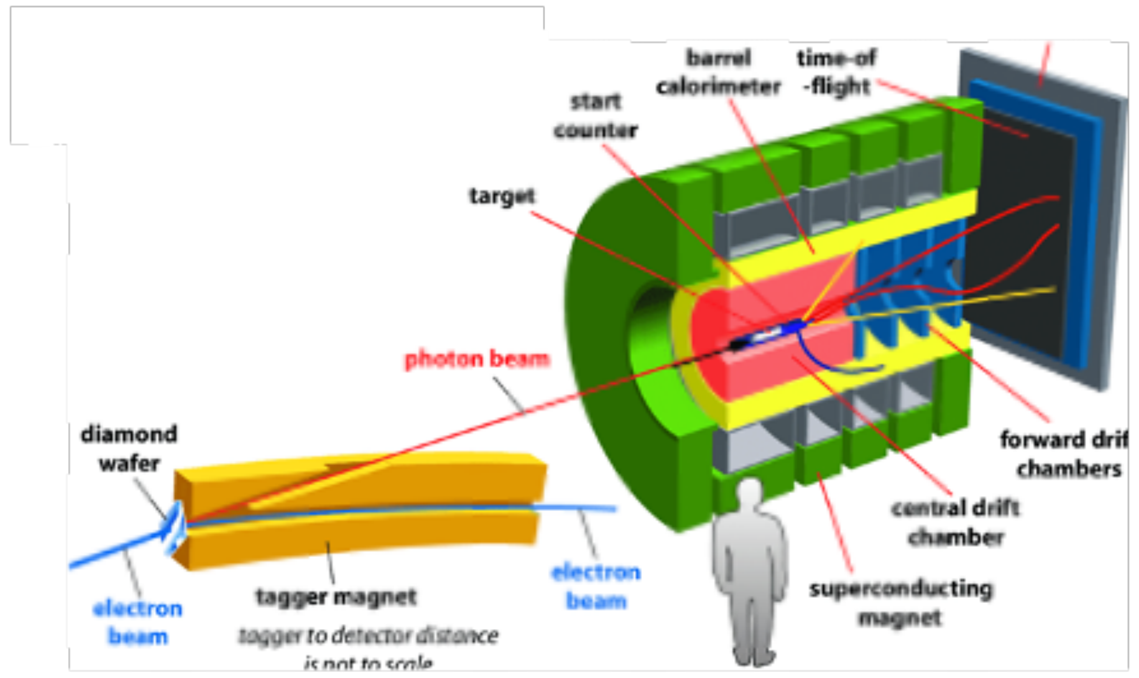

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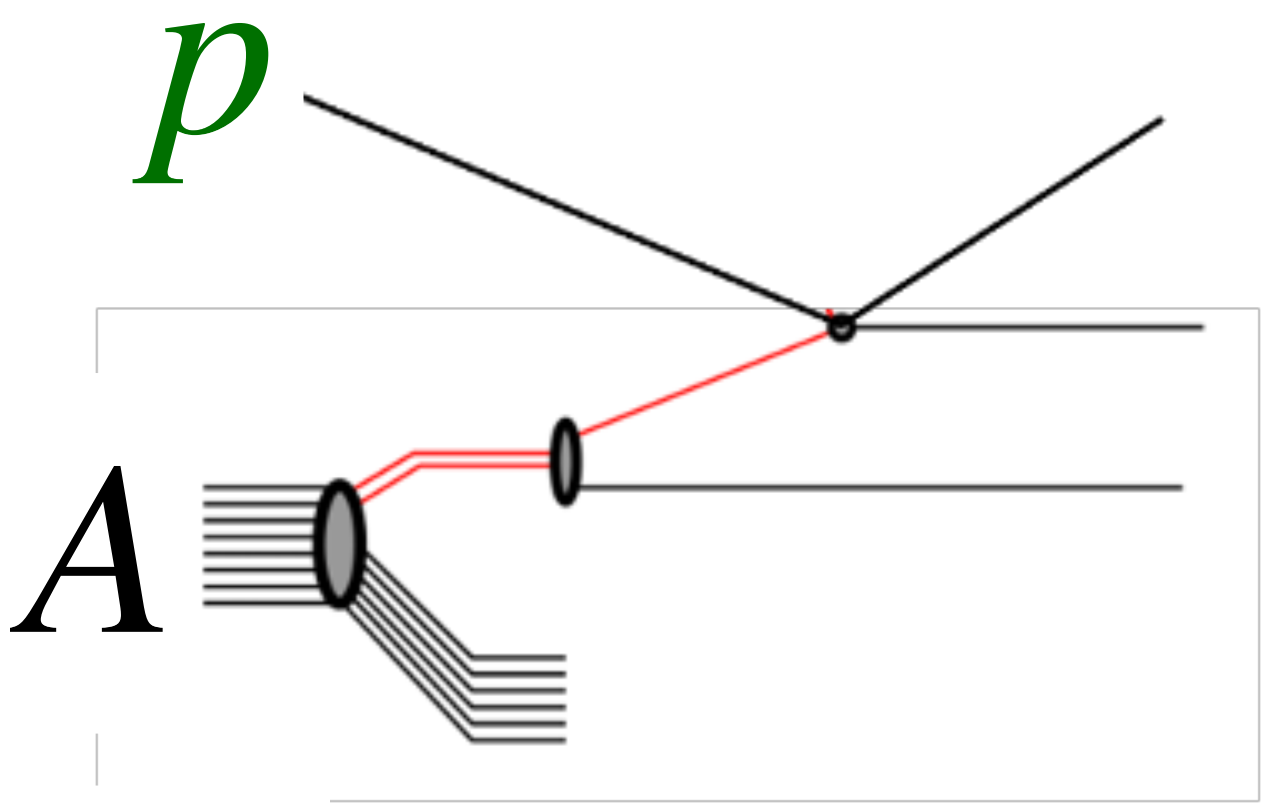

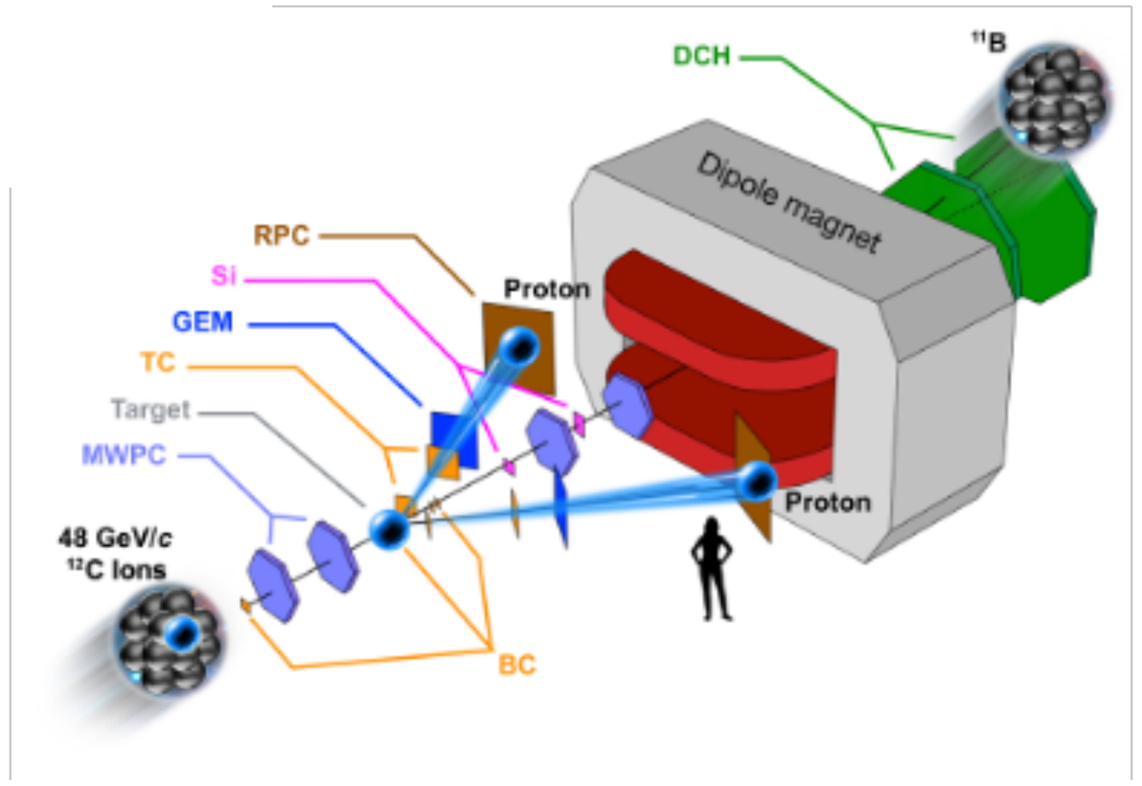

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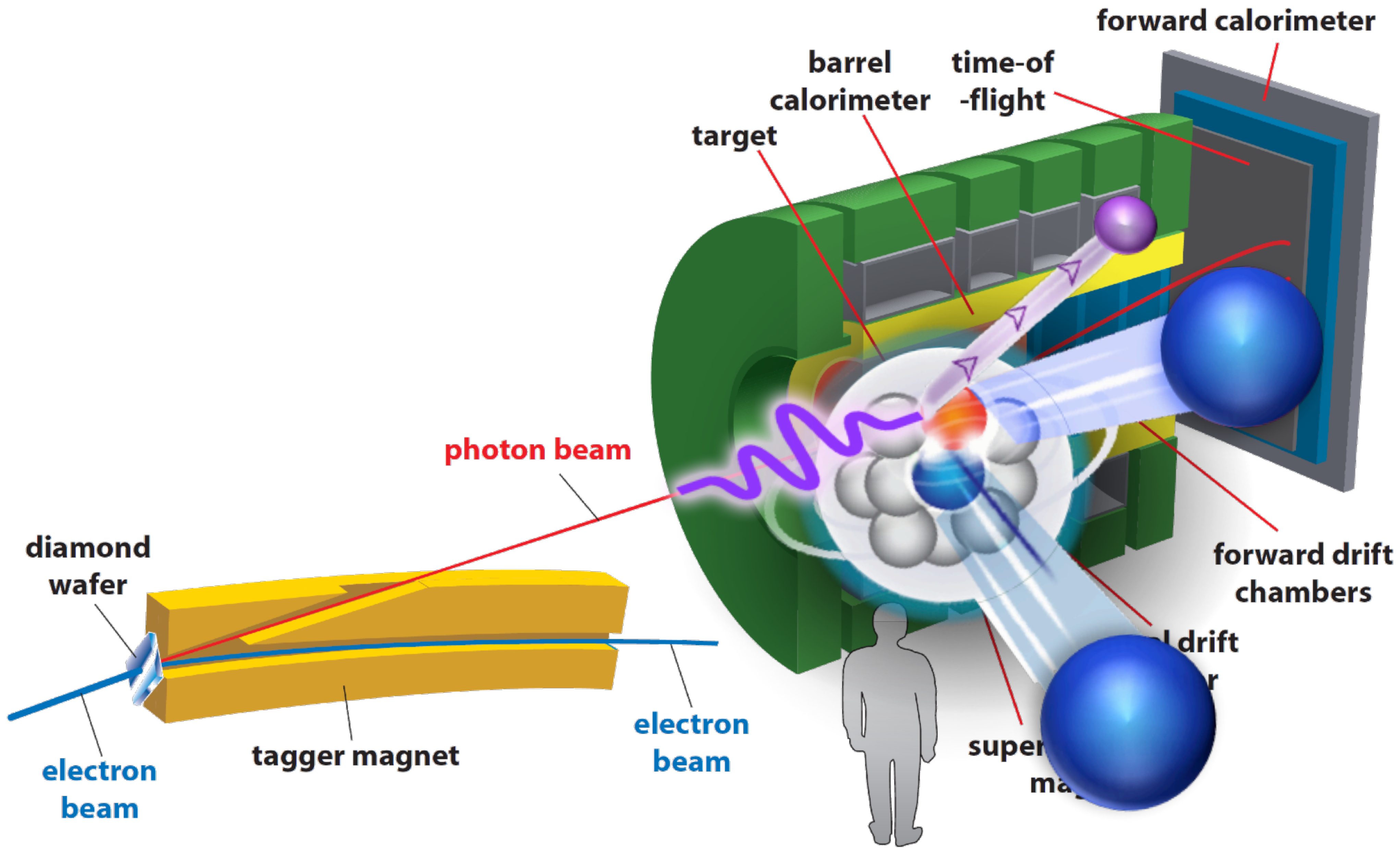
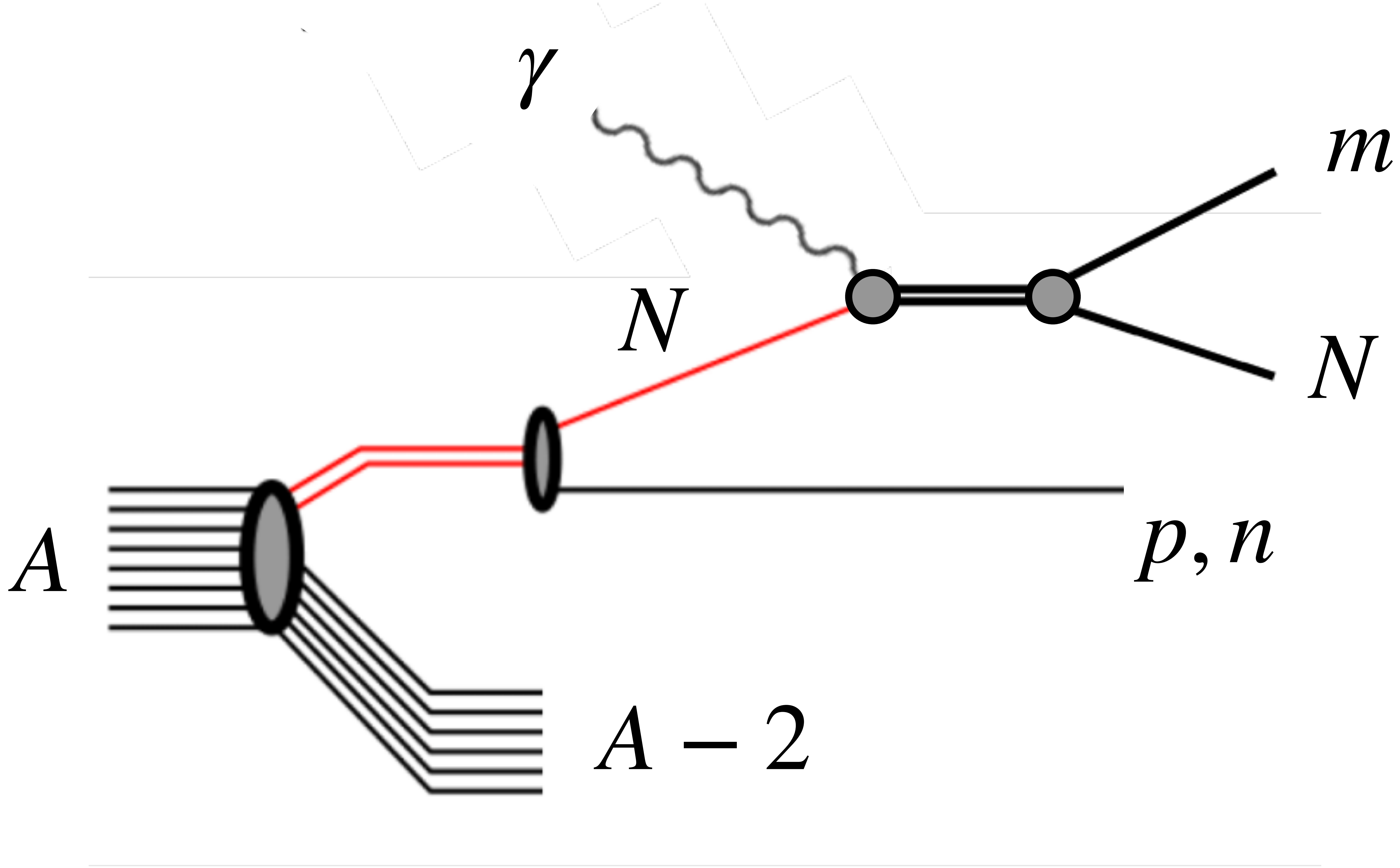
Hall D SRC-CT Experiment



- Dedicated high-energy photonuclear measurement
- 10.8-GeV electron beam – energy-tagged coherent bremsstrahlung
- ~40-day measurement of targets ^{2}H, ^{4}He, ^{12}C
- Final-state particles detected in large-acceptance GlueX spectrometer

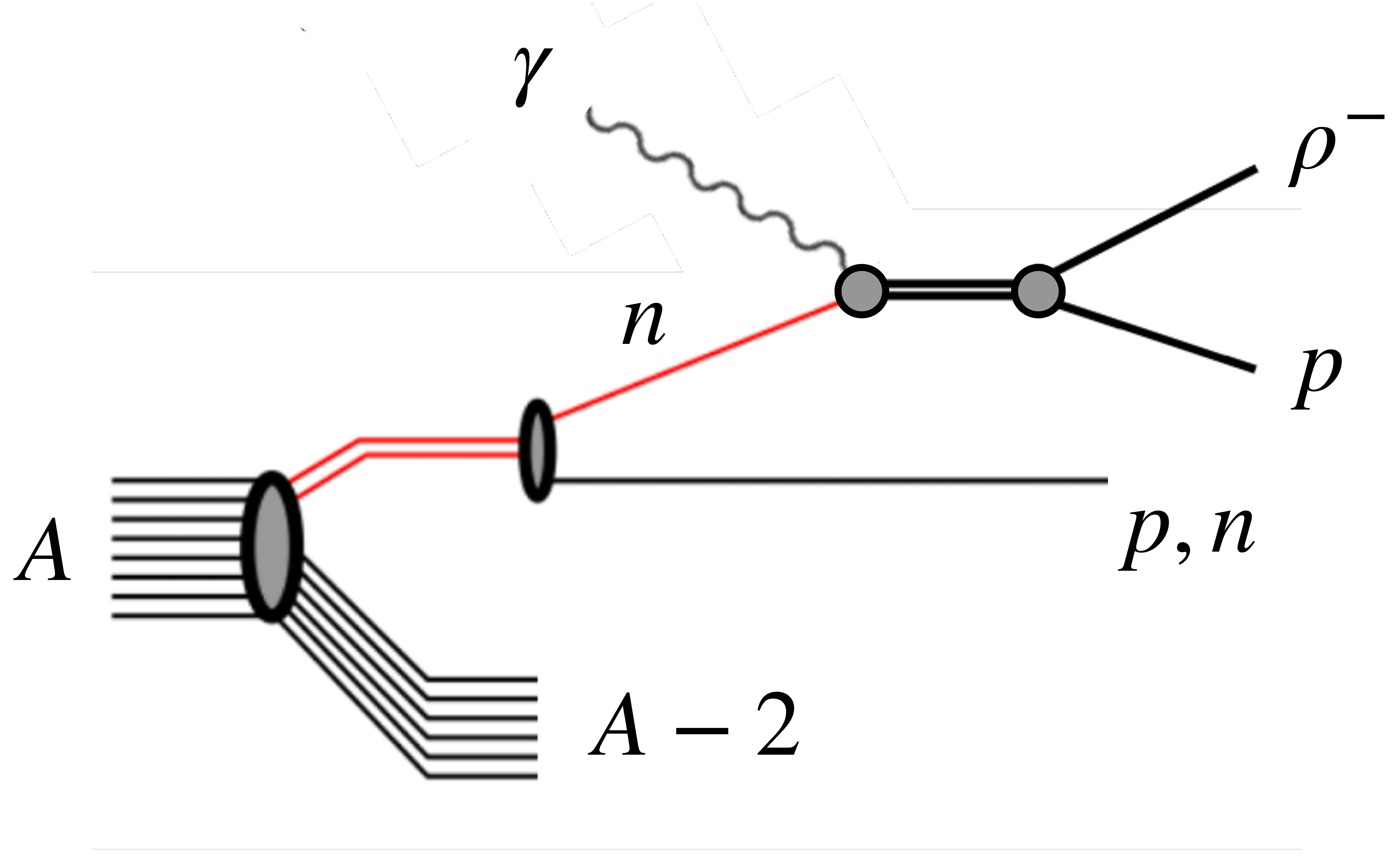
SRC Photoproduction in Hall D

- Quasi-elastic photoproduction: hard photon-nucleon interaction



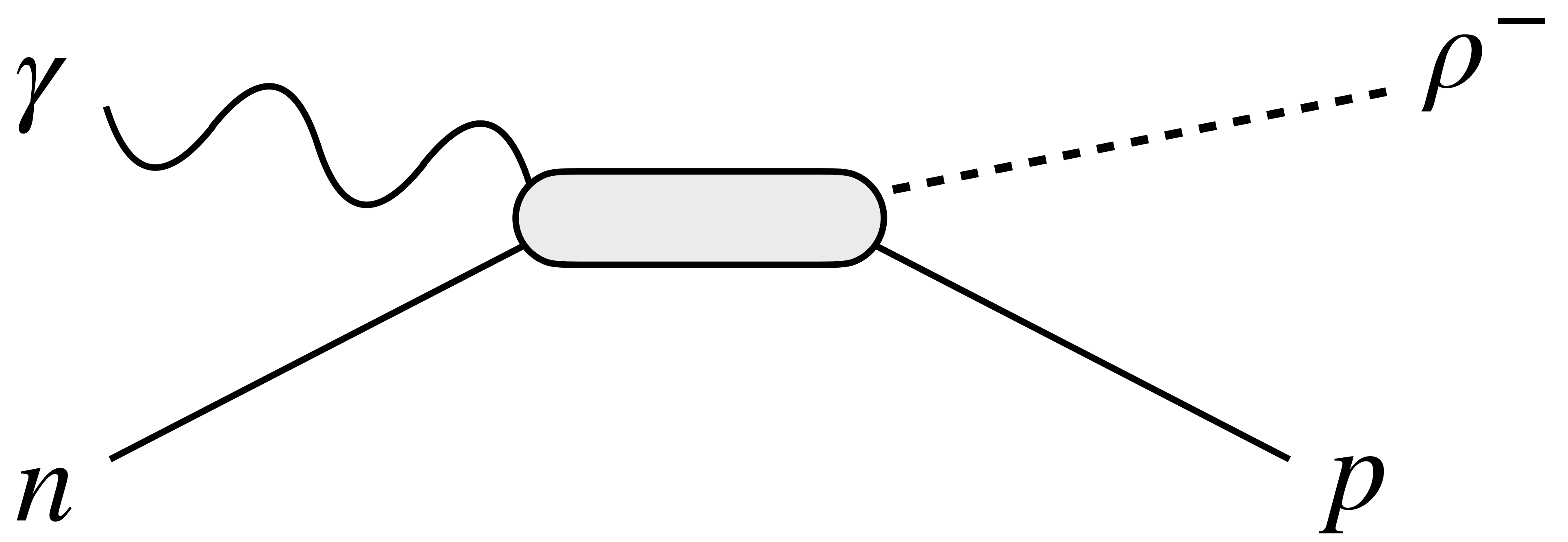
SRC Photoproduction in Hall D

- Quasi-elastic photoproduction: hard photon-nucleon interaction
- ρ^- photoproduction:
  - Initial-state neutron
  - Distinctive $\rho^- \to \pi^-\pi^0$ decay
- Measurements of $(\gamma, \rho^- p)$ and $(\gamma, \rho^- pp)$



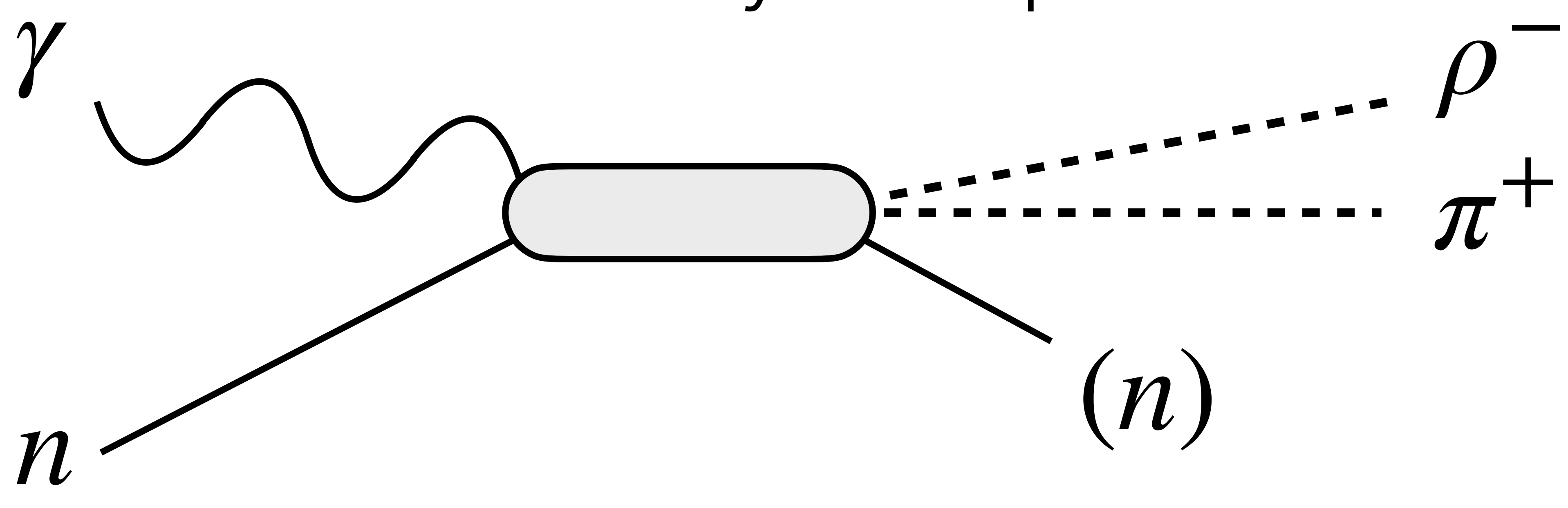
SRC Event Selection

Signal Process: $\gamma n \to \rho^- p$



Background: $\gamma n \to \rho^- \pi^+ n$

Misidentify π^+ as proton



Inclusive variables:

- Momentum-transfer: $t_M = (p_\gamma - p_M)^2$
- Invariant mass: $W_M^2 = (p_\gamma + p_N - p_M)^2 \sim m_N^2$
- Scaling variable: $\zeta_M \equiv \dfrac{-t_M}{2m_N(E_\gamma - E_M)} \sim 1$

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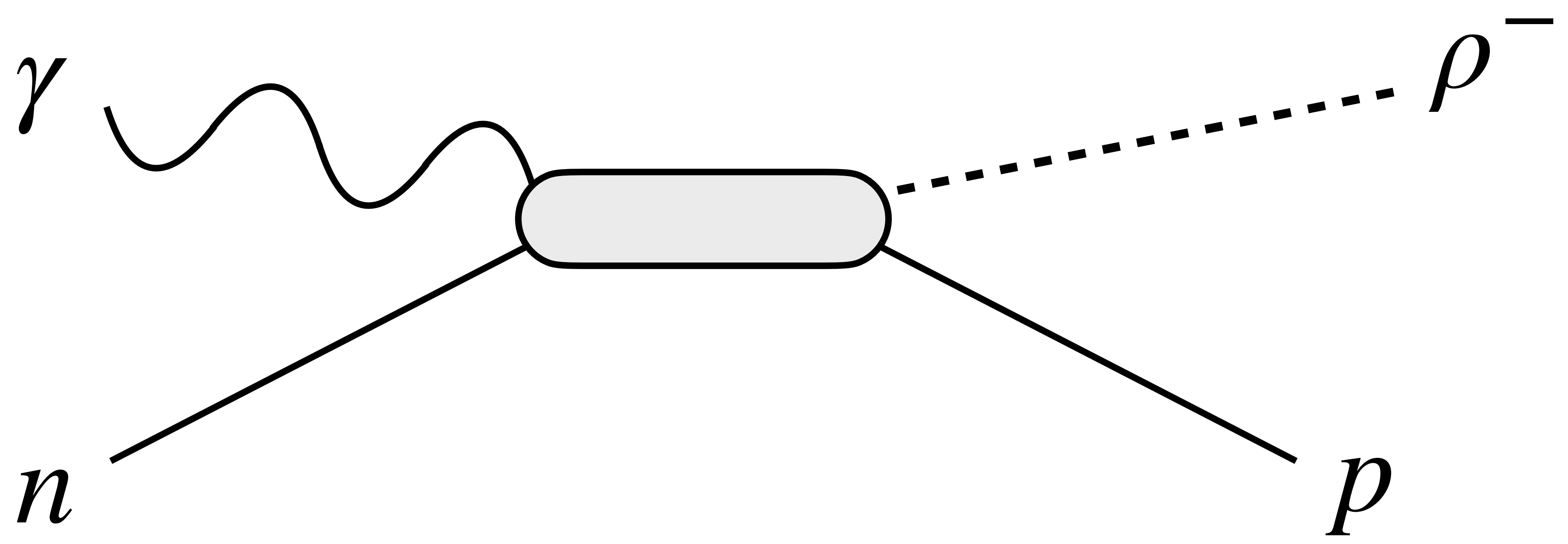

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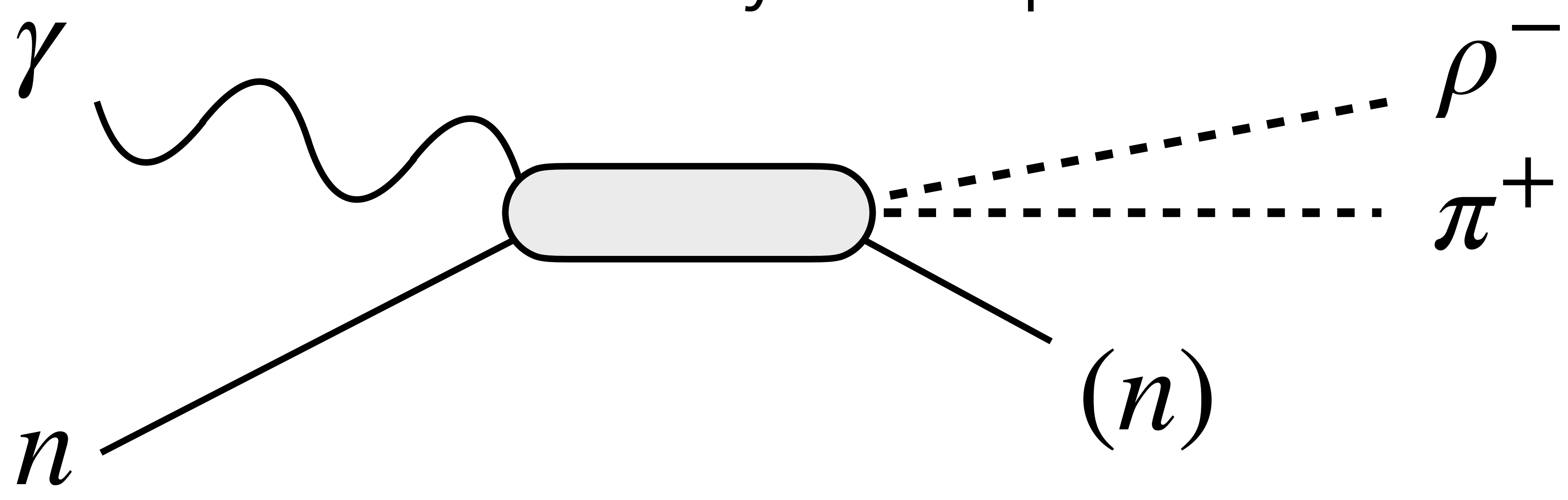

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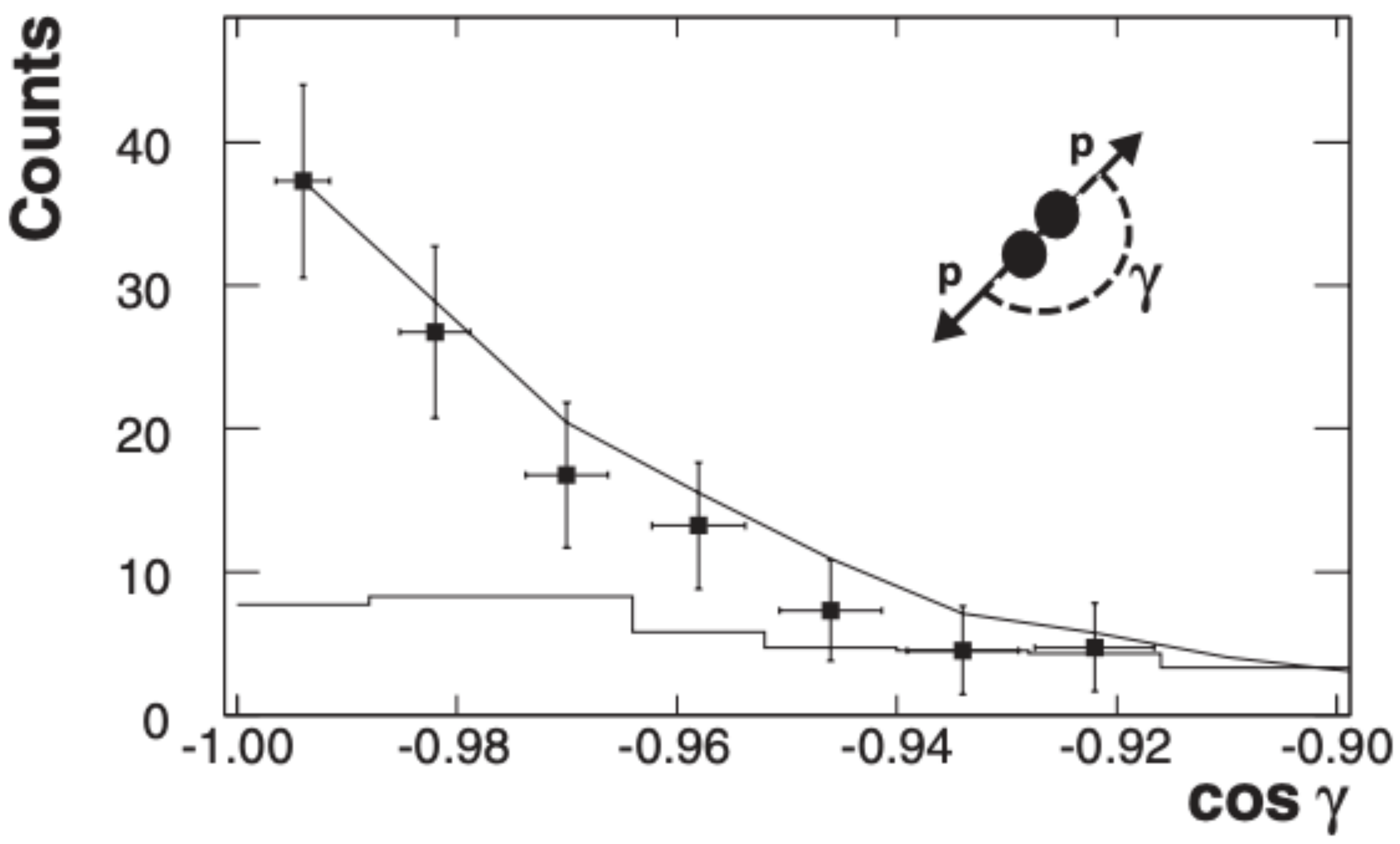
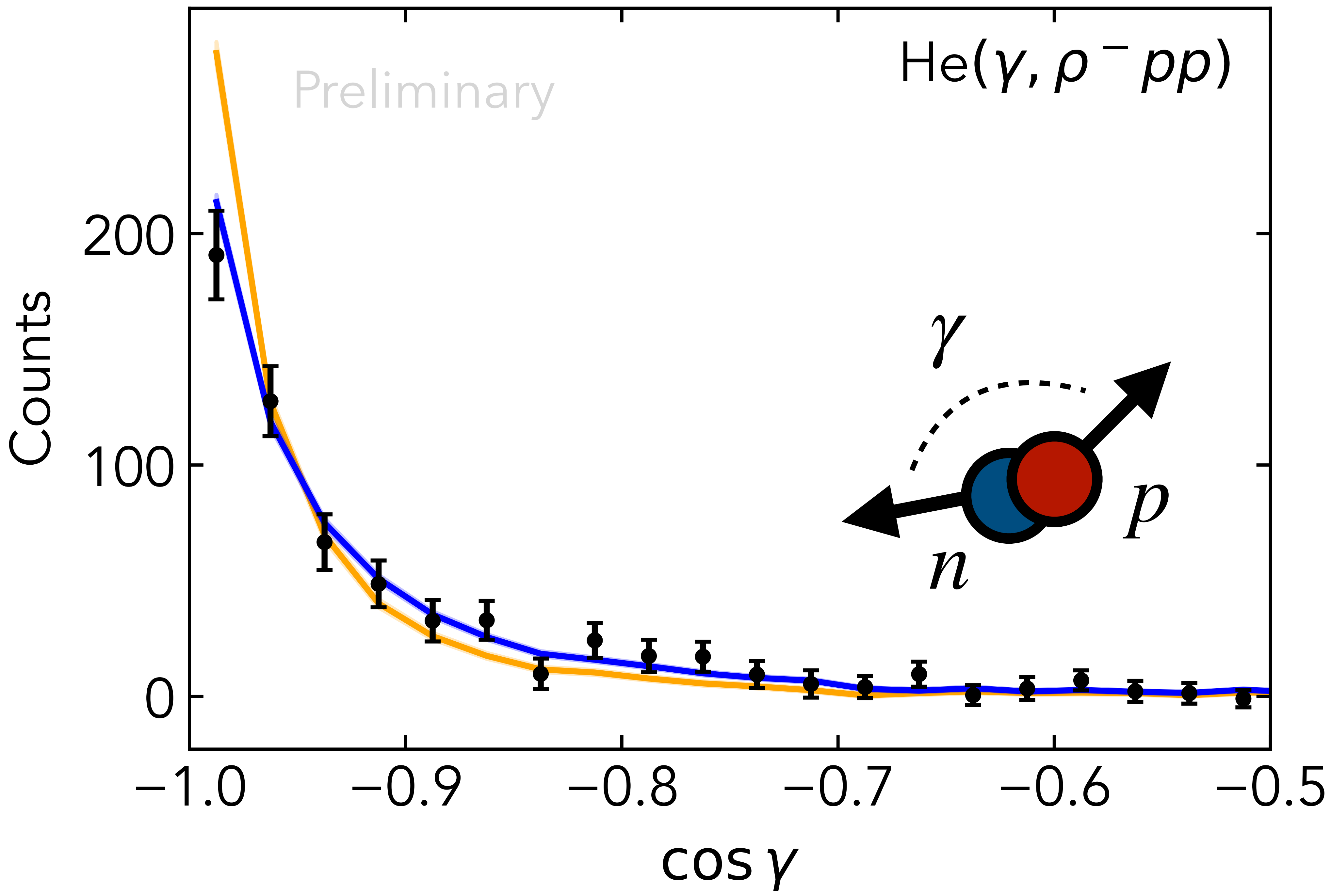
New photoproduction variables balance **PID**, **resolution**, and **kinematic** considerations to identify SRC signal

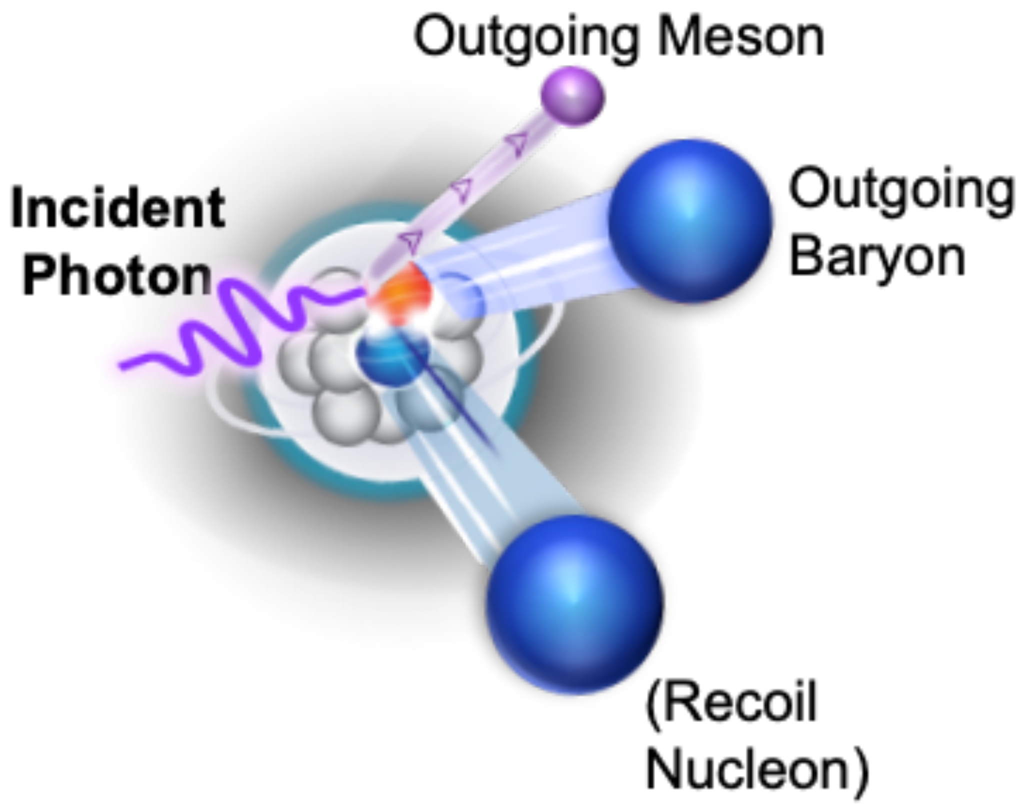
Pybus et al. preliminary

Observation of SRCs in photoproduction



PRL 2007
Back-to-back correlation in
$(e, e'pp)$ @ Hall A





$\gamma np \rightarrow \rho^- pp$
@ Hall D

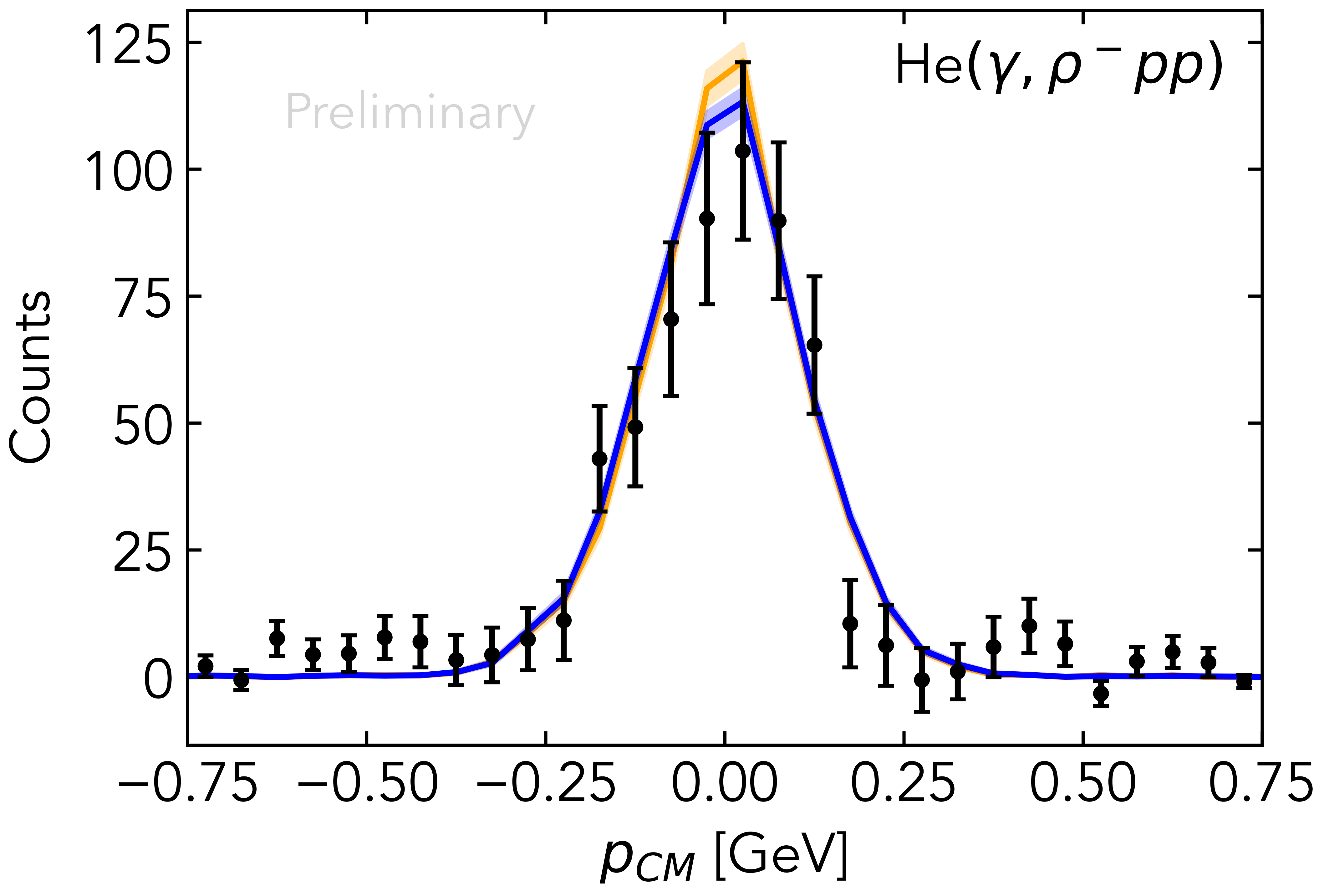
Pybus et al. preliminary

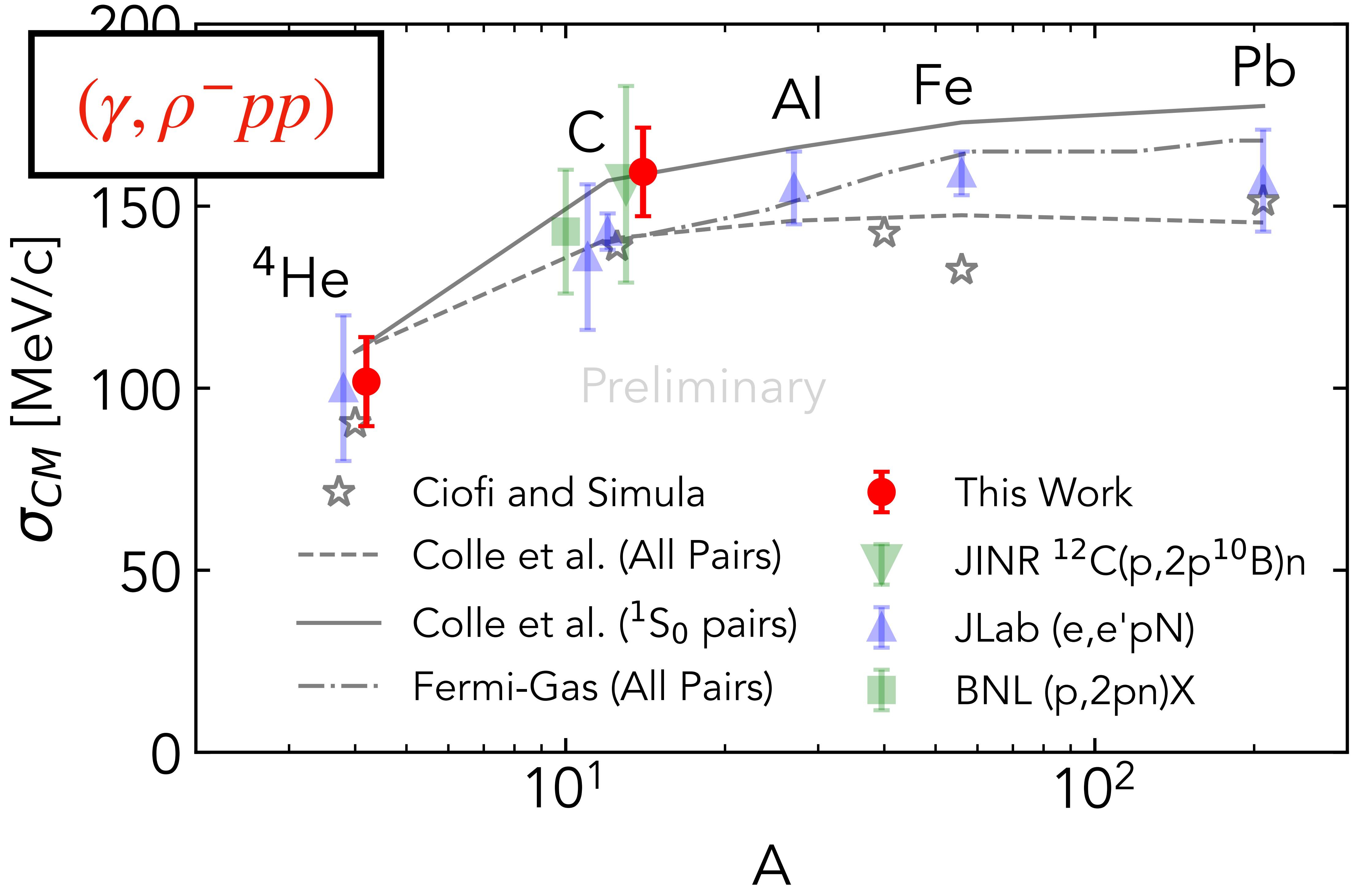
SRC Center-of-Mass Motion

e^-: **PRL (2018)**

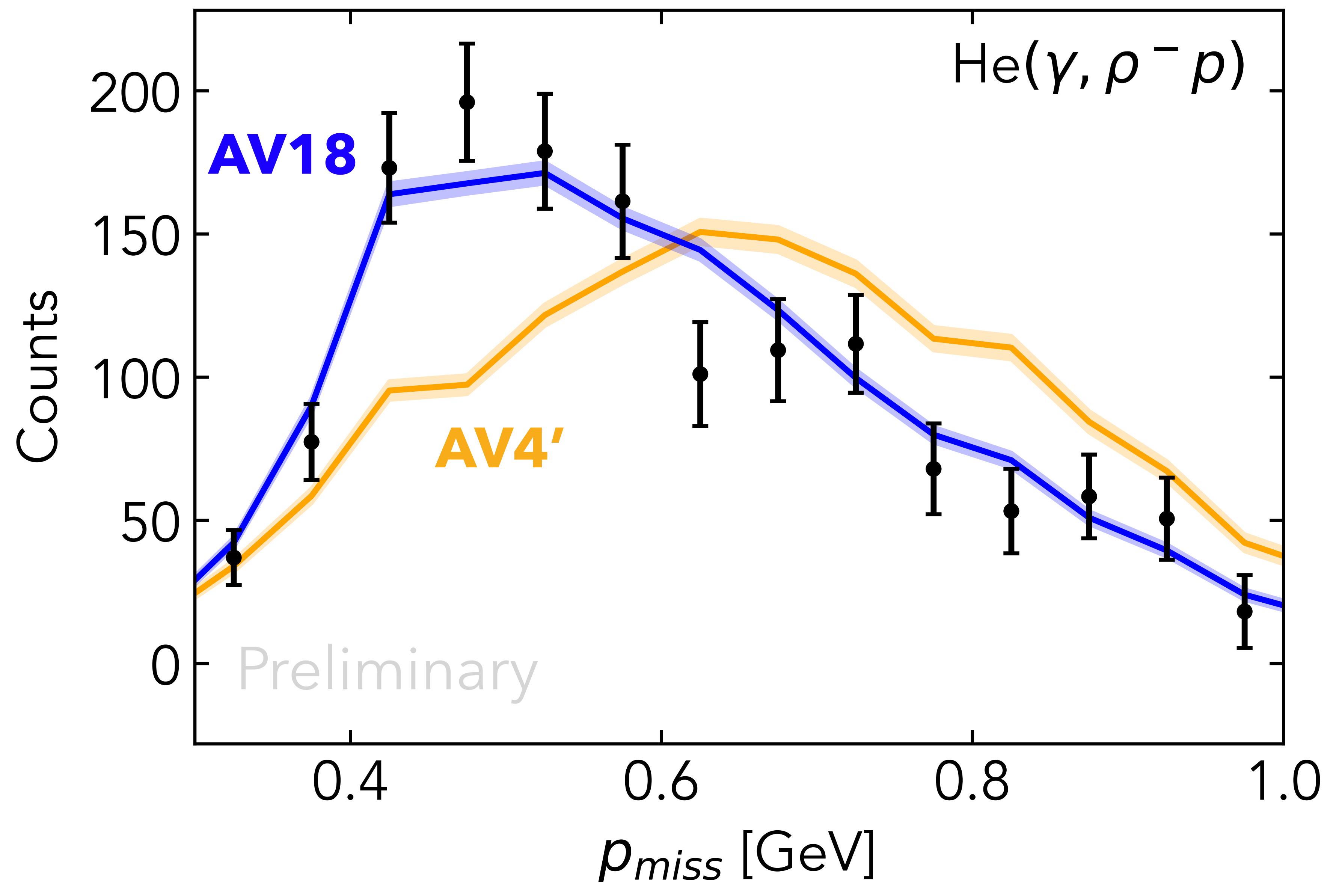
p: **Nature Physics (2021)**

γ: **SRC-CT (2024)**





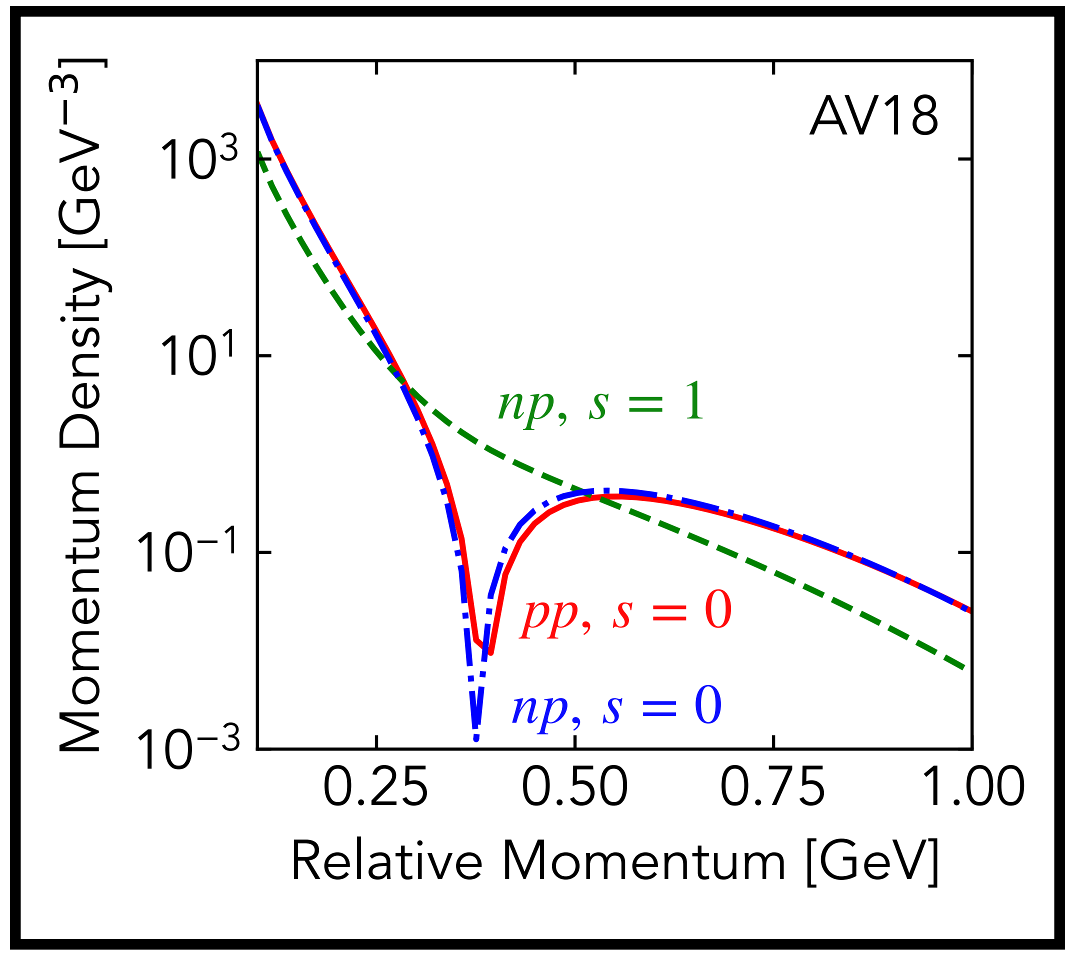
Data connect to ab-initio theory at high momentum; Distinguish realistic and unrealistic models

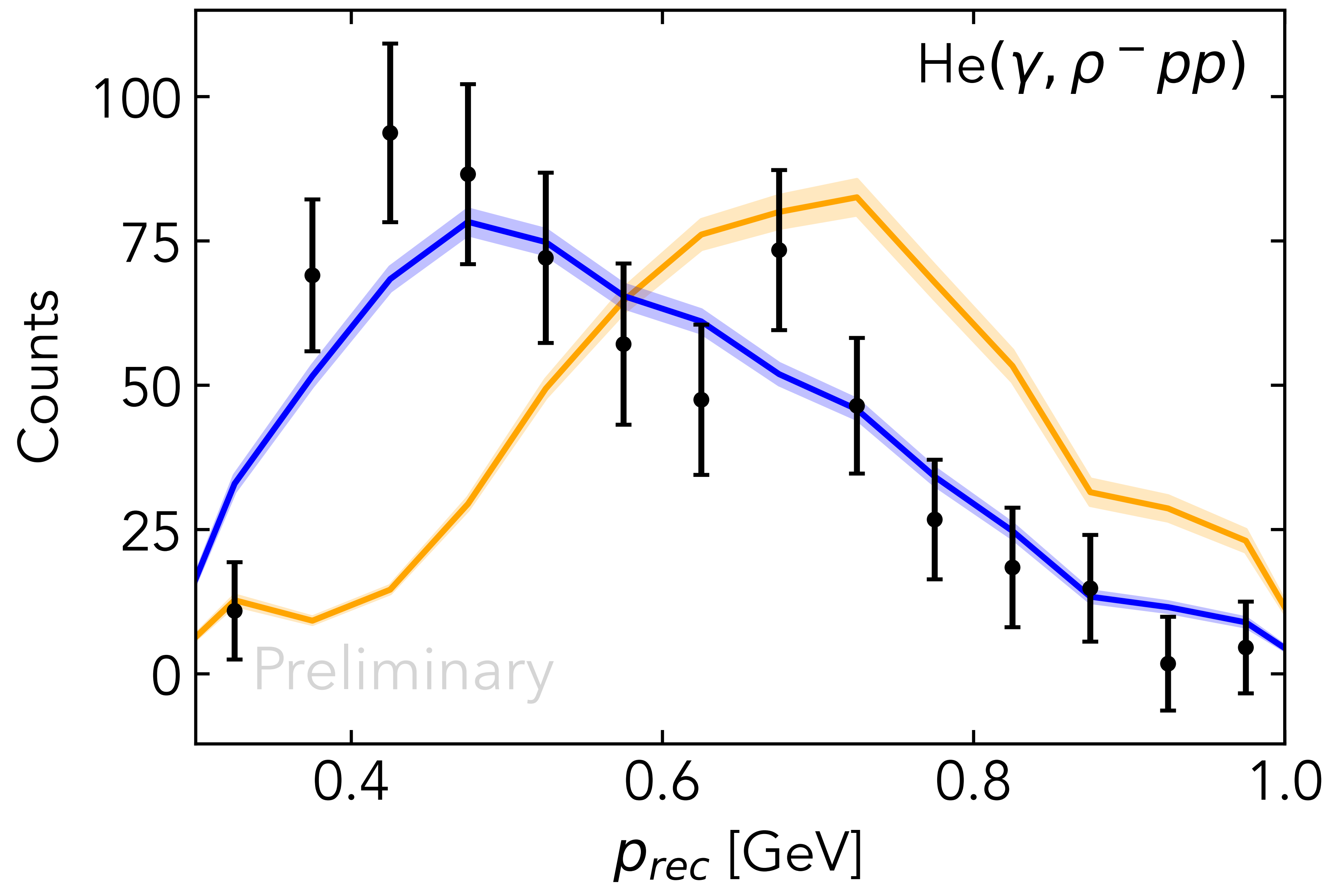


Initial neutron momentum

Inferred from momentum conservation

NN Interaction



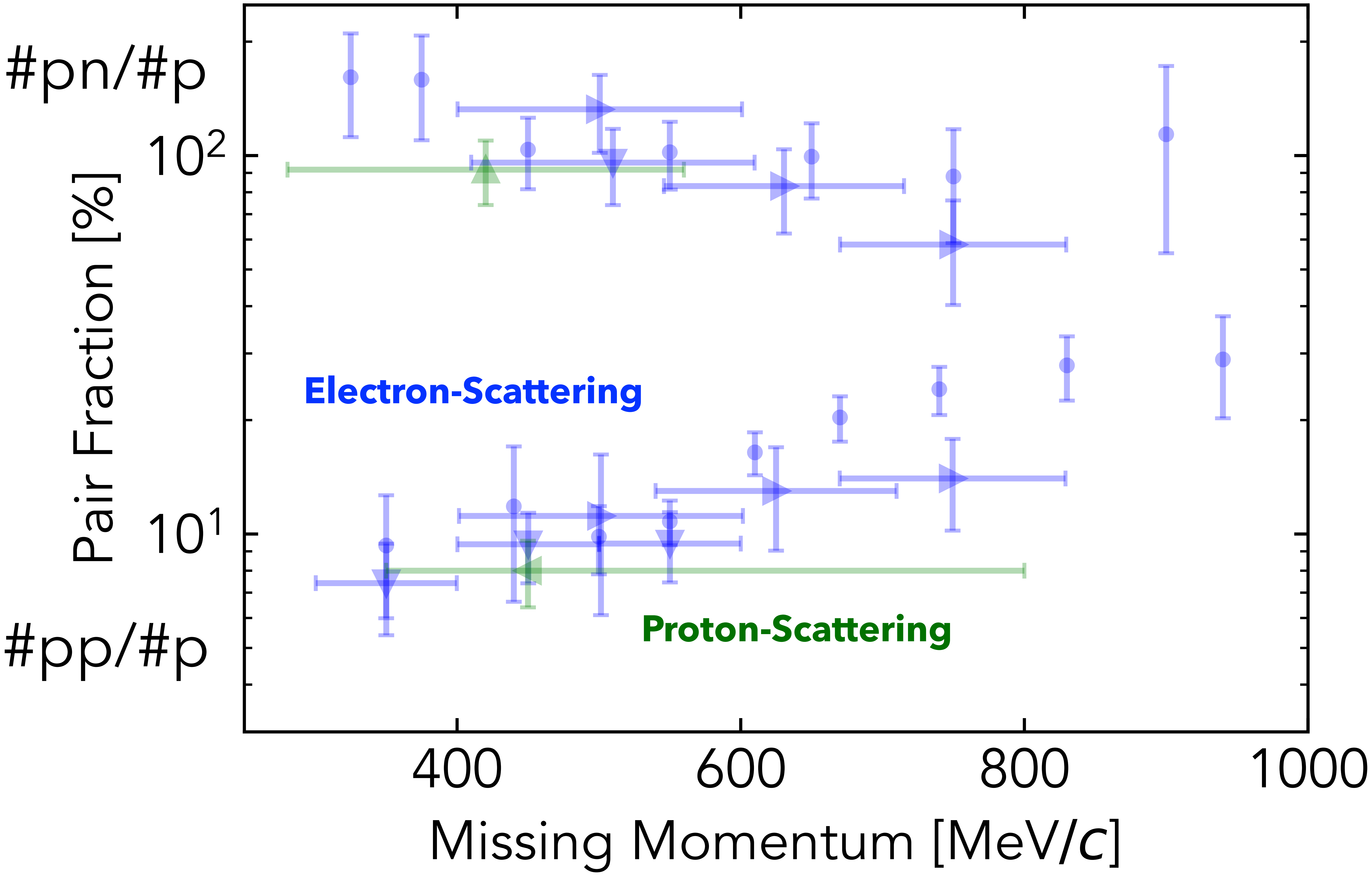


Initial recoil proton momentum

Directly measured

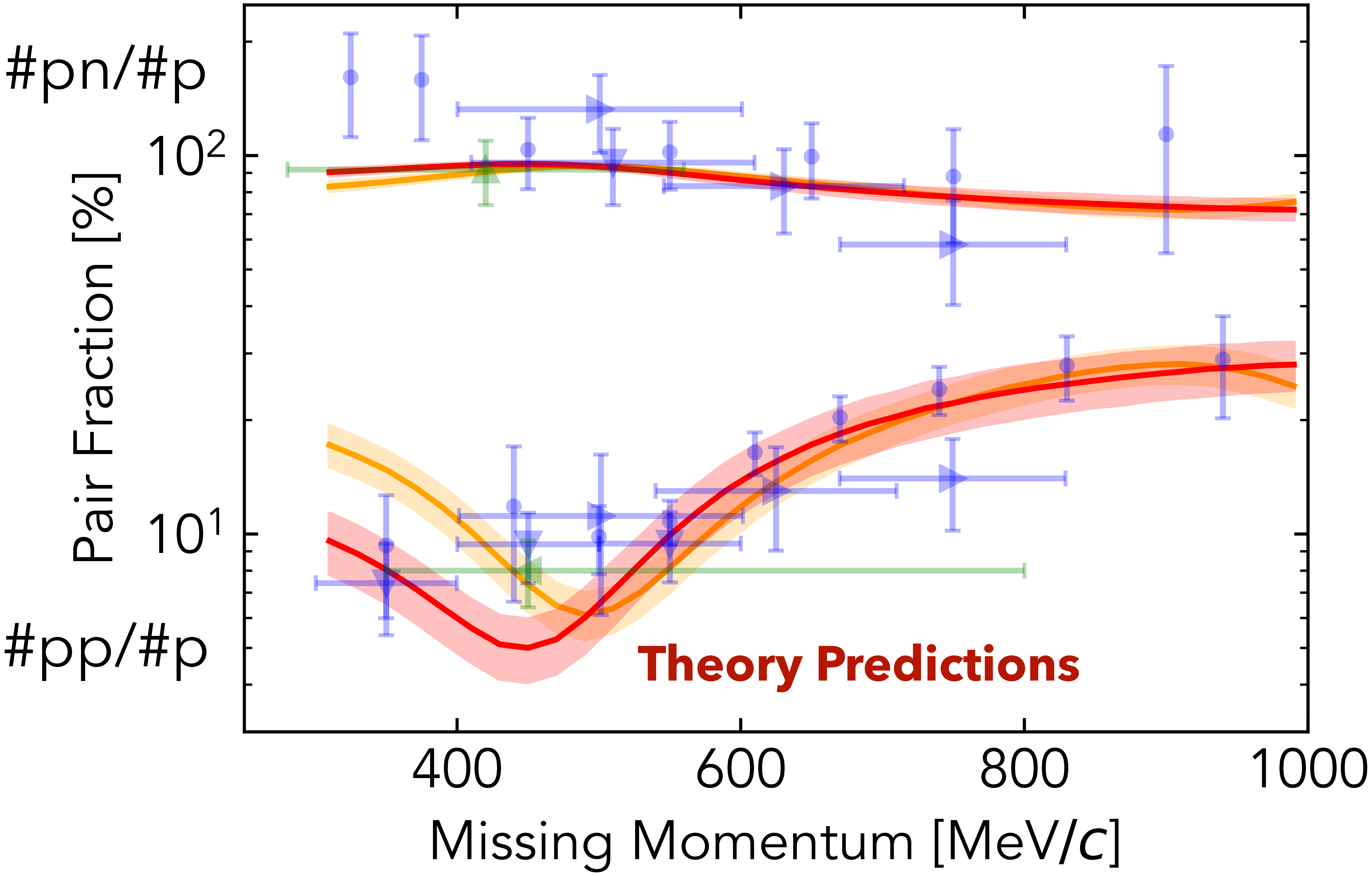
Pybus et al. preliminary

SRC Isospin Structure



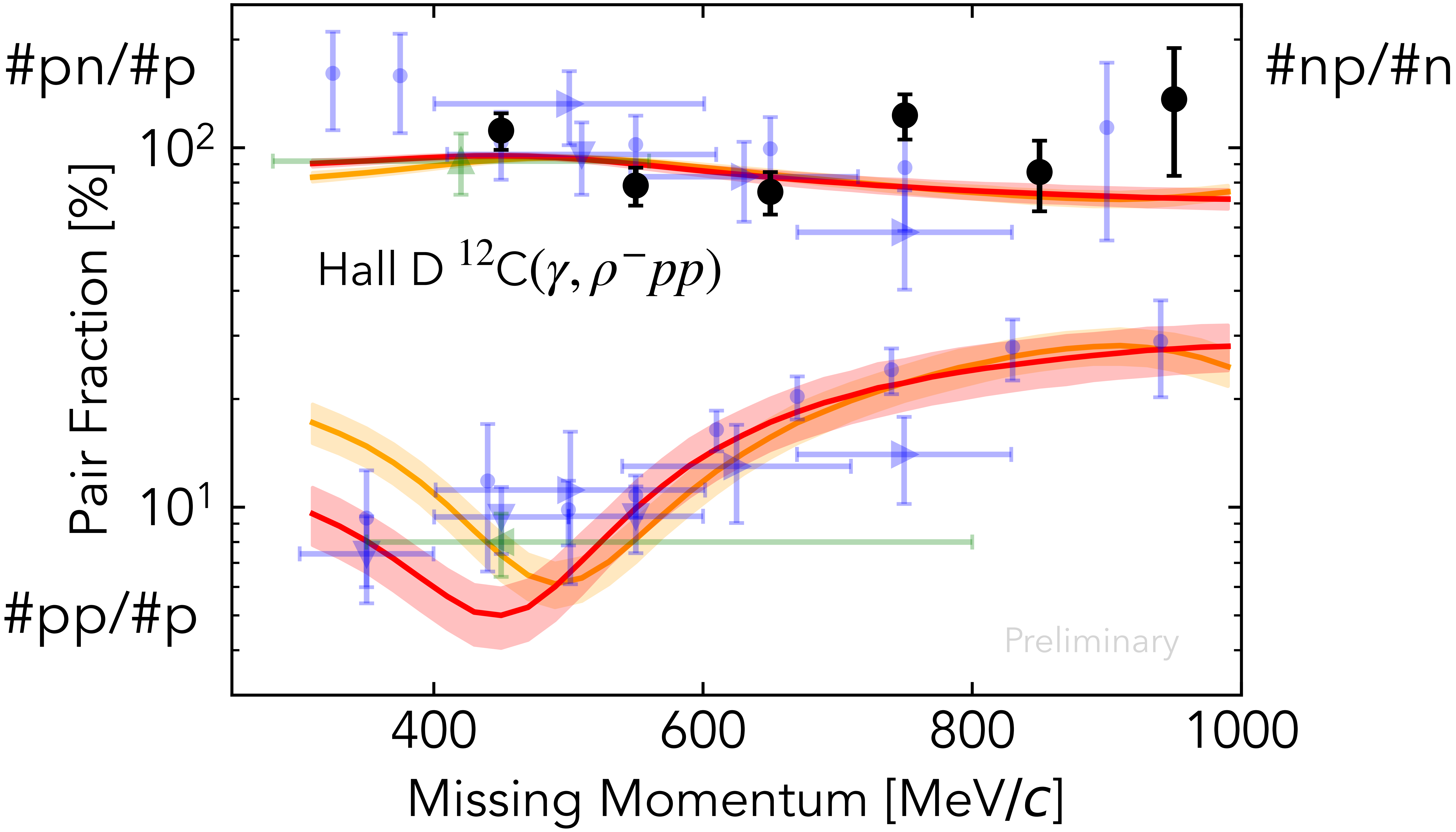
Pybus et al. preliminary

SRC Isospin Structure



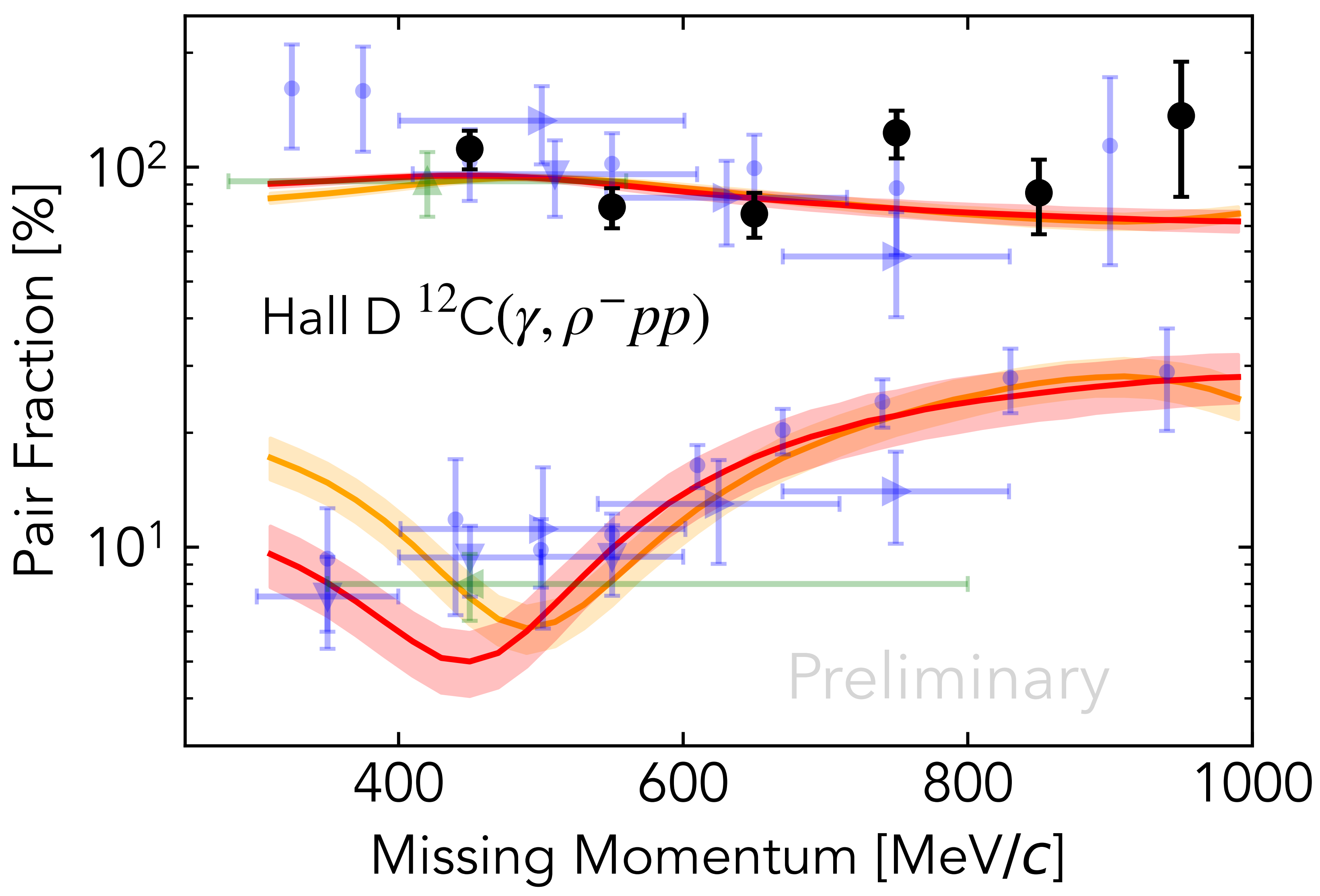
Pybus et al. preliminary

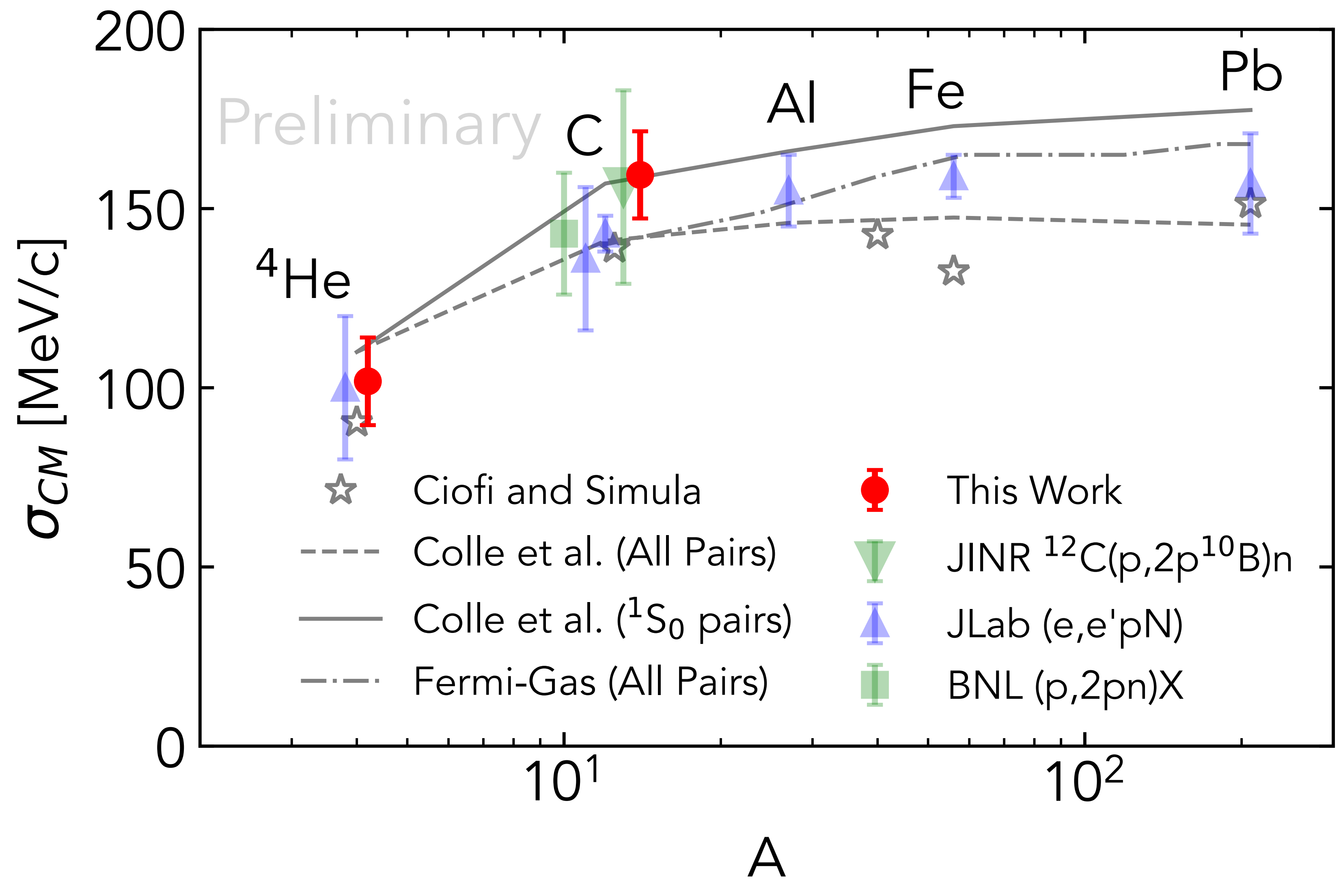
SRC Isospin Structure



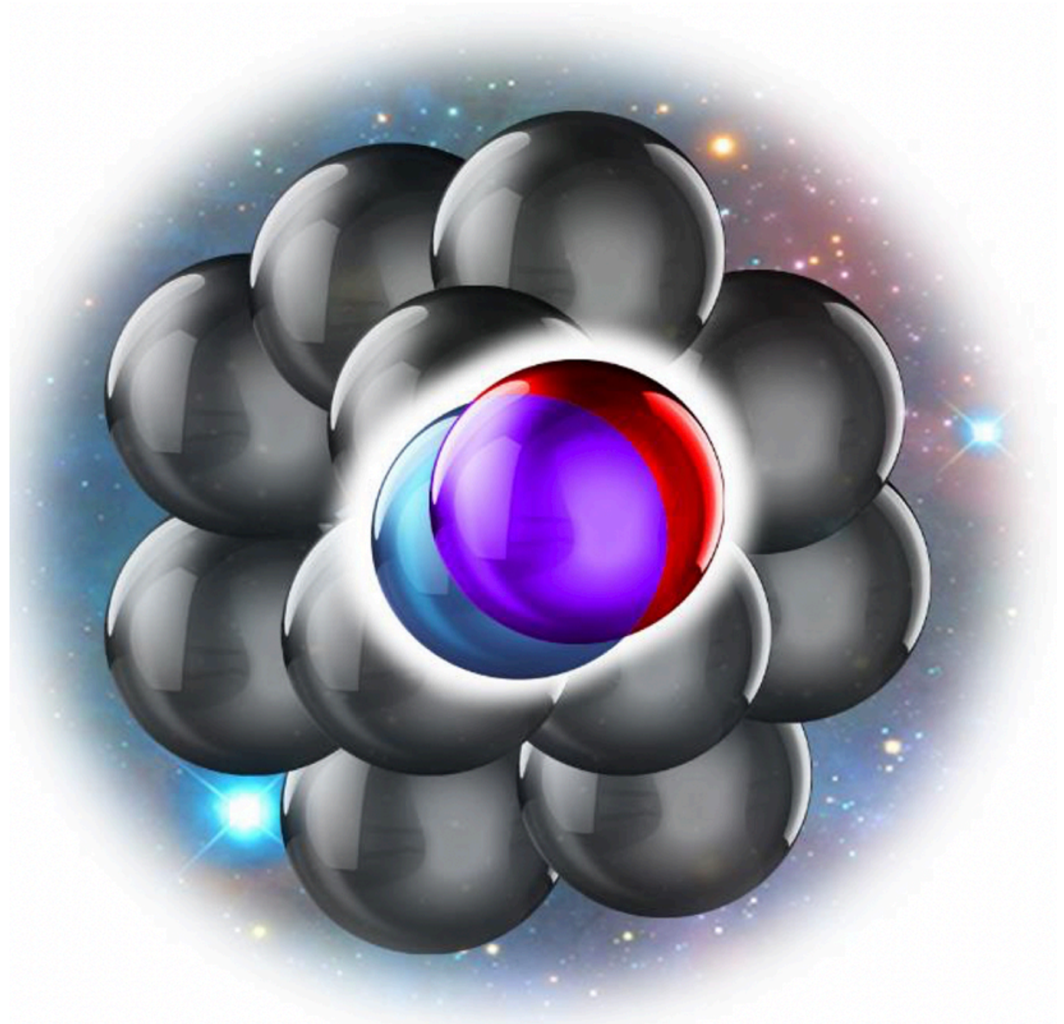
Pybus et al. preliminary

Consistency with theory points to universal picture of the nuclear ground-state!





Photons

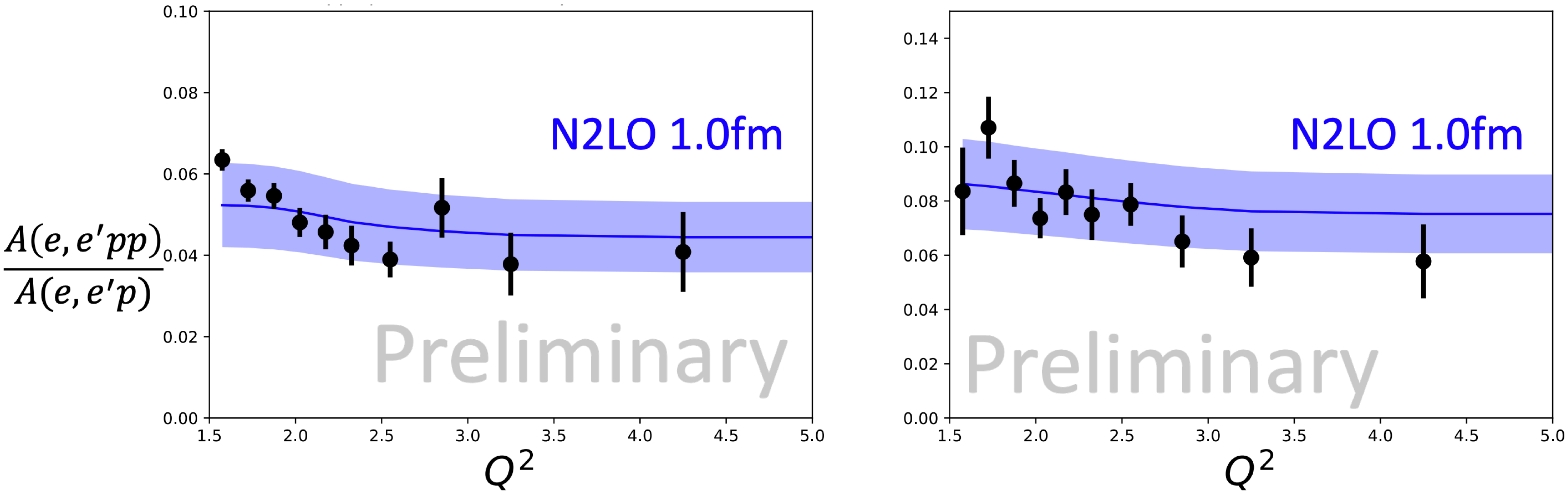


Electrons

Protons

Pybus et al. preliminary

New CLAS12 data point to resolution-independent SRC properties

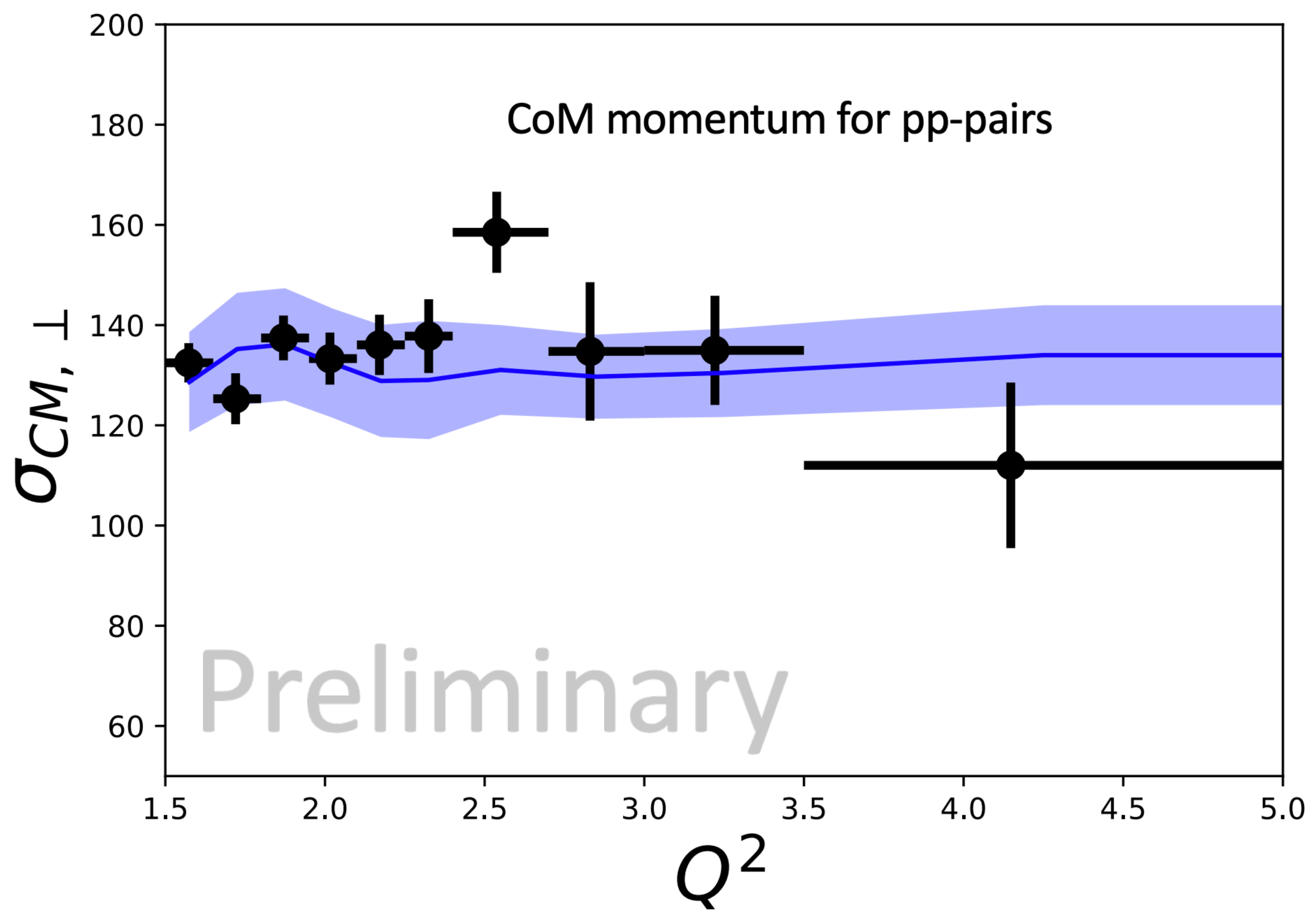


p_{miss}: 550 – 700 MeV/c

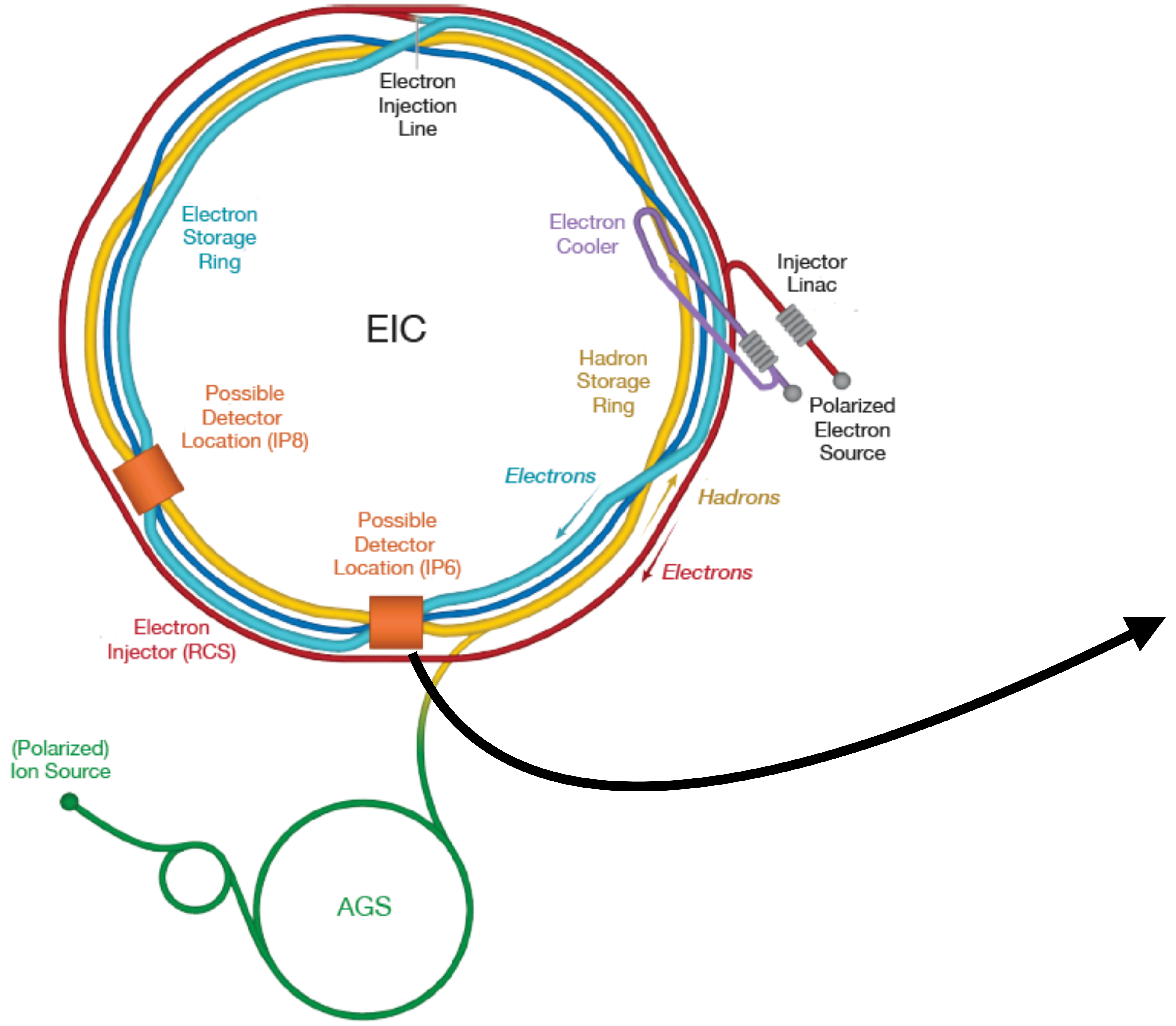
p_{miss}: 700 – 850 MeV/c

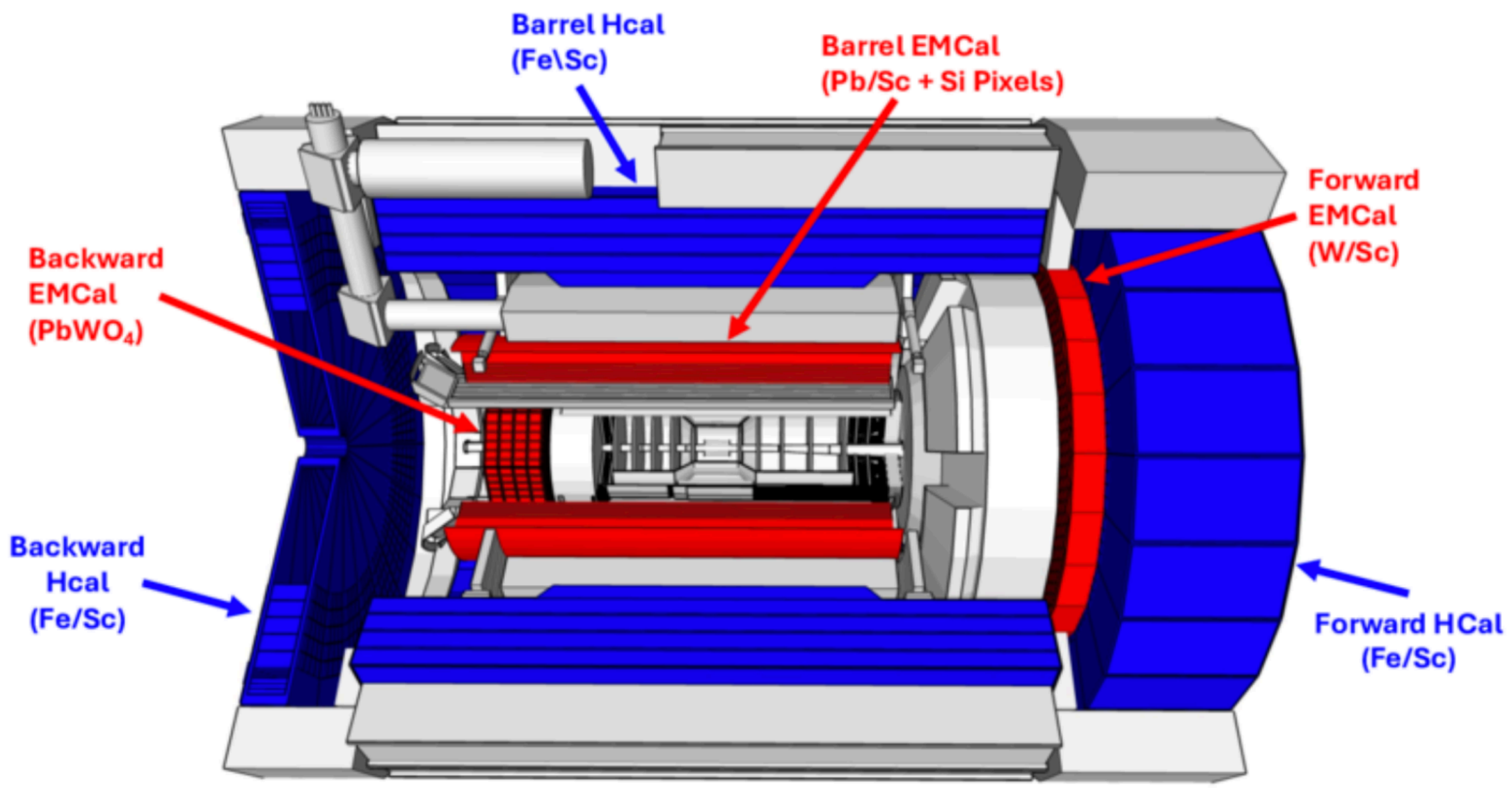
Denniston et al. preliminary

New CLAS12 data point to resolution-independent SRC properties



EIC – Measuring SRCs in a collider setting

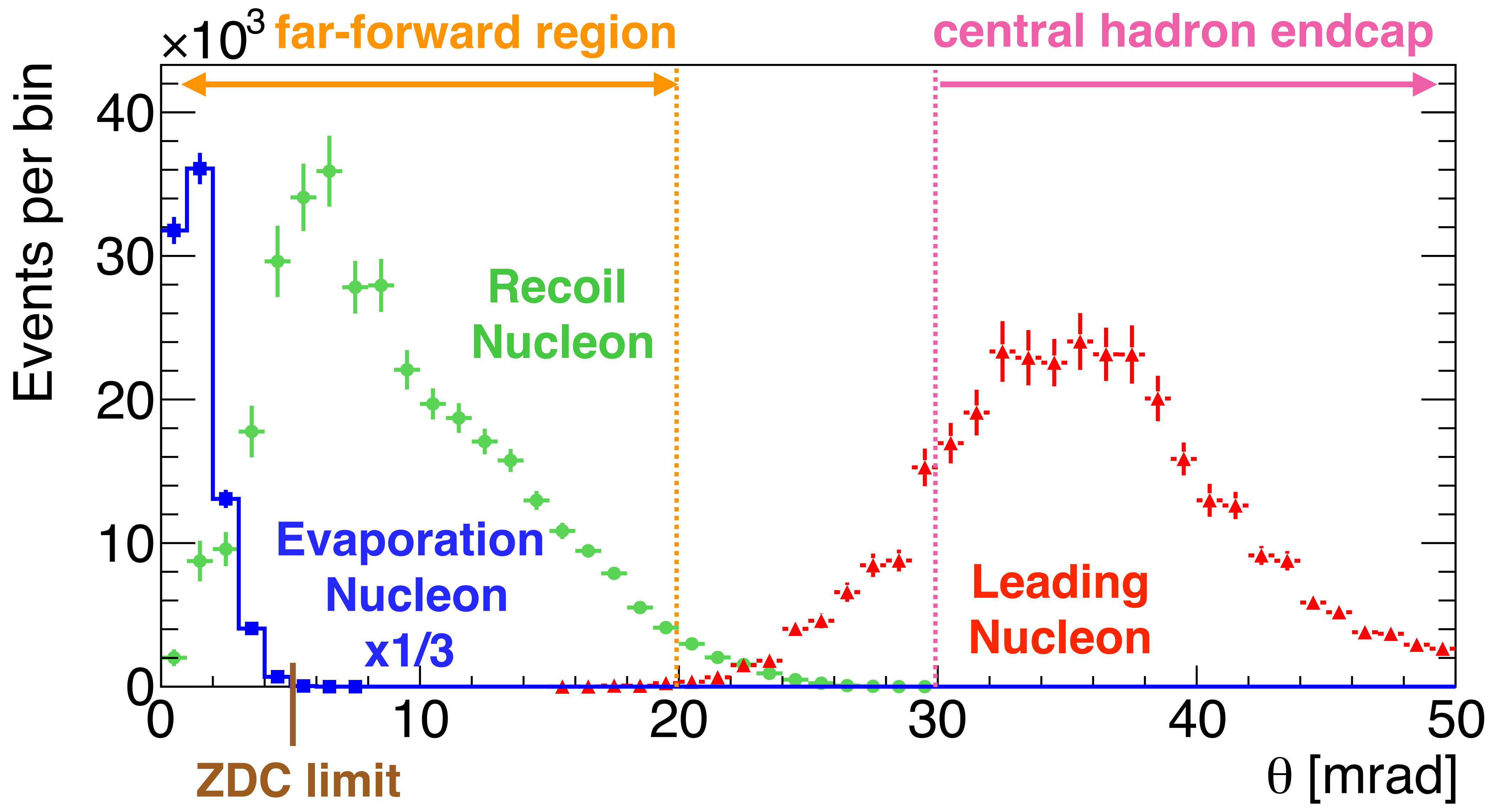




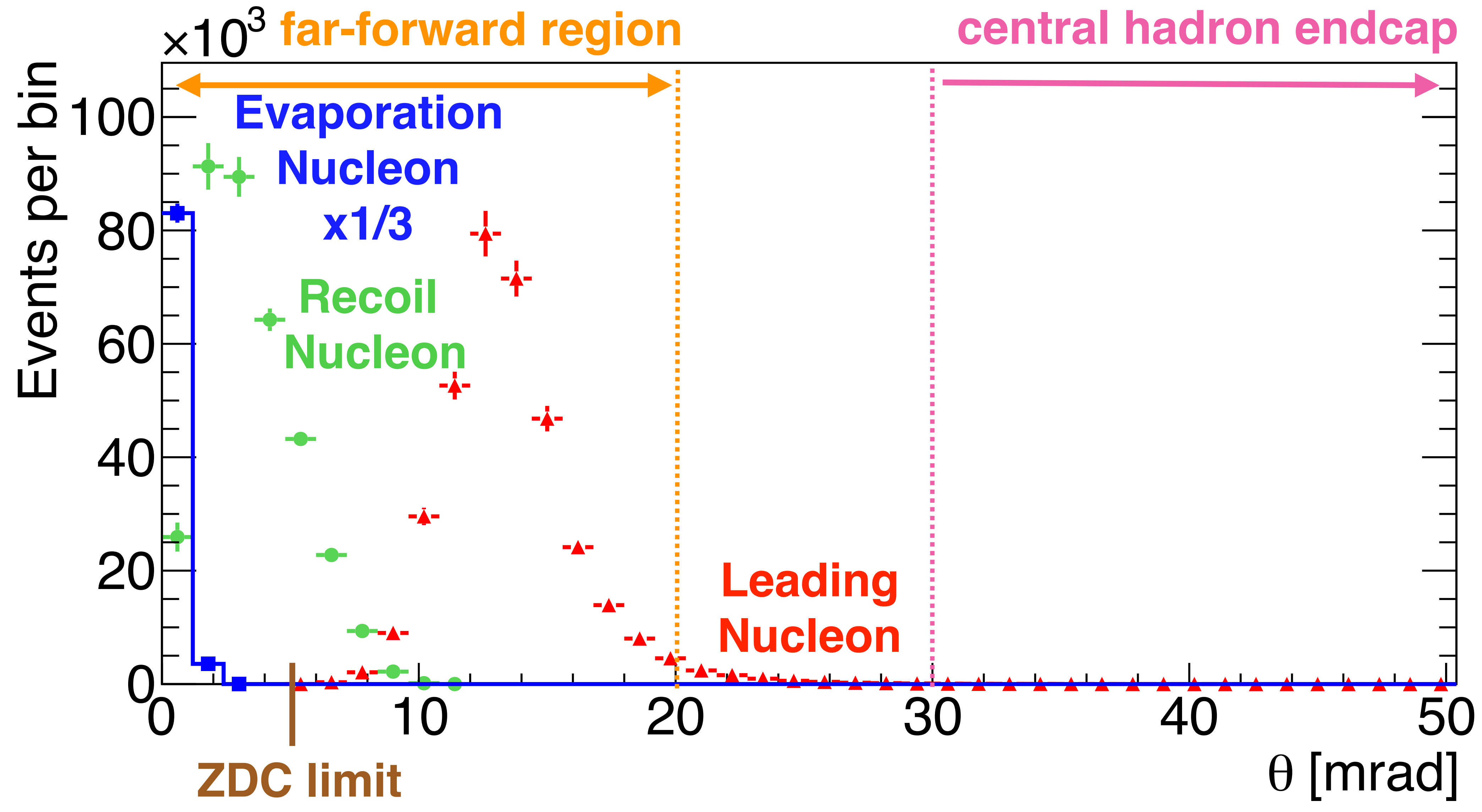
Two-nucleon knockout will have different kinematics

EIC $(e, e'pp)$ Kinematics

5x41 GeV



10x110 GeV

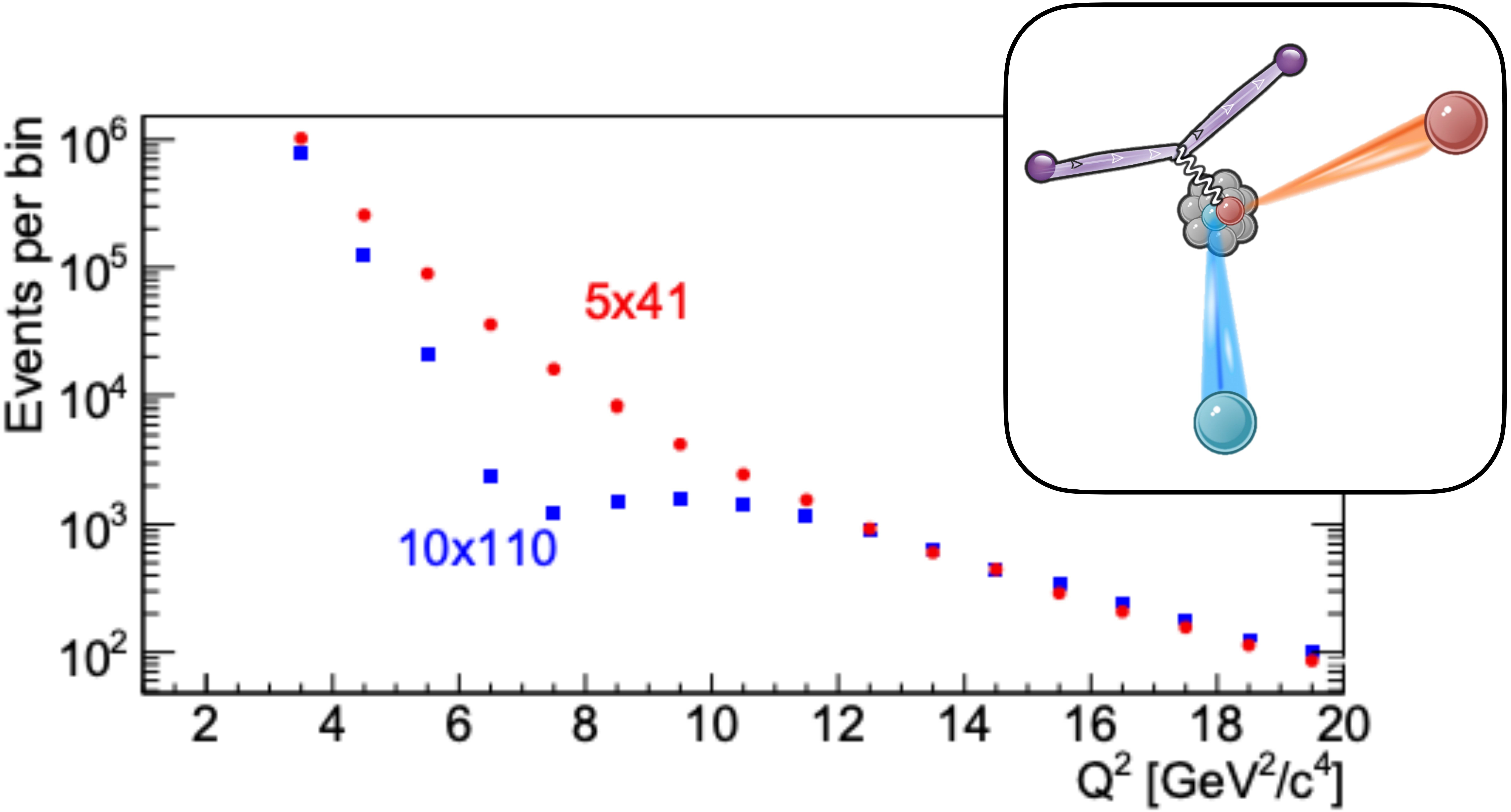


Knocked-out protons all go into very forward kinematics

Good far-forward resolution and acceptance key for performing such nuclear measurements!

Hauenstein et al. PRC (2022)

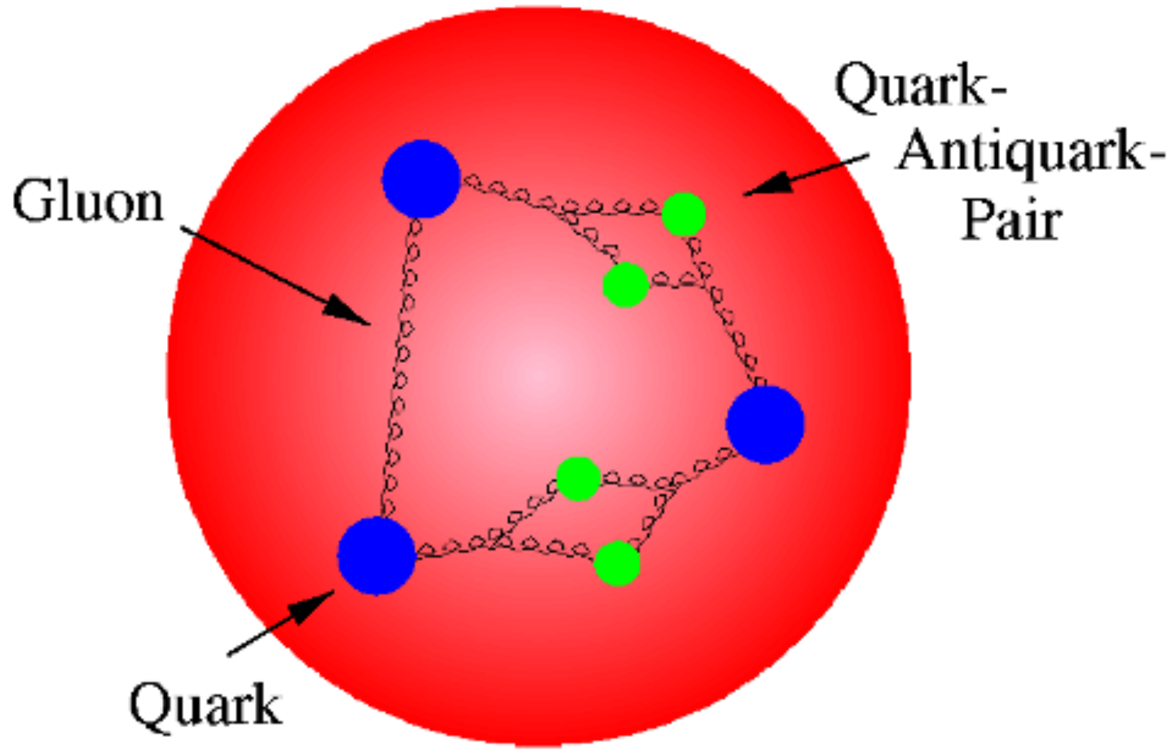
EIC energies → Robust test of resolution-dependence

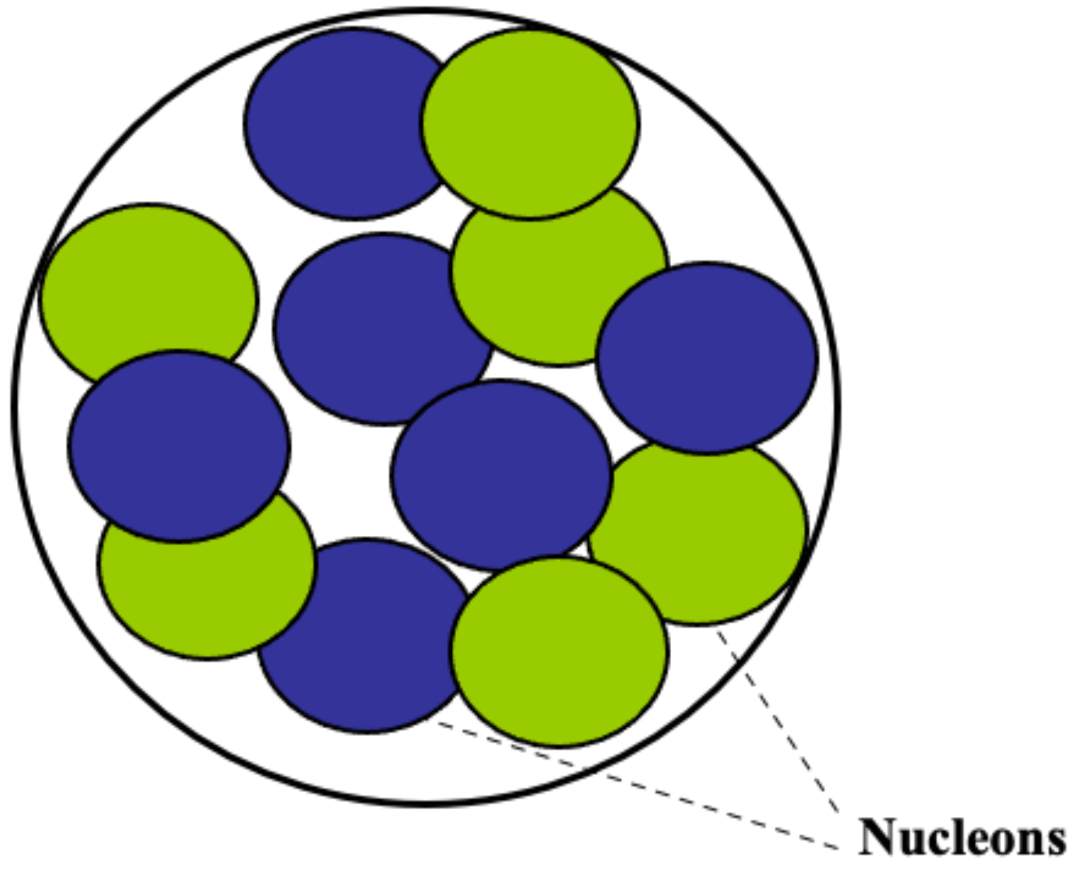


Nuclear **ground-state** features should be independent of momentum-transfer

Hauenstein et al. PRC (2022)

DIS from the Nucleus





DIS scale: tens of GeV

- Incident energies
- Energy transfers
- Invariant masses

Nuclear scale: less than 10 MeV

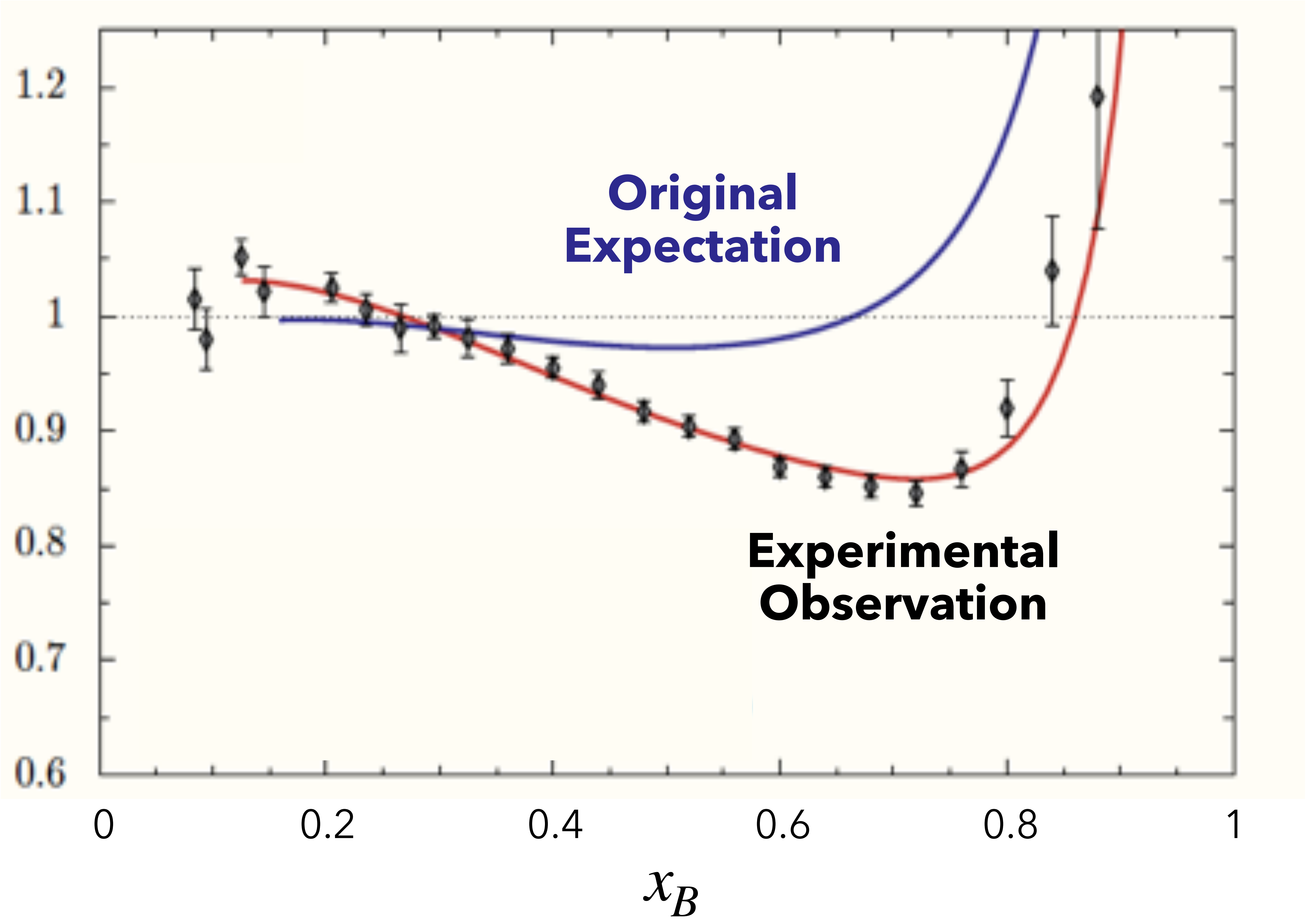
- Nucleon binding energy

Naive expectation:

DIS off a bound nucleon = DIS off a free nucleon

The EMC Effect

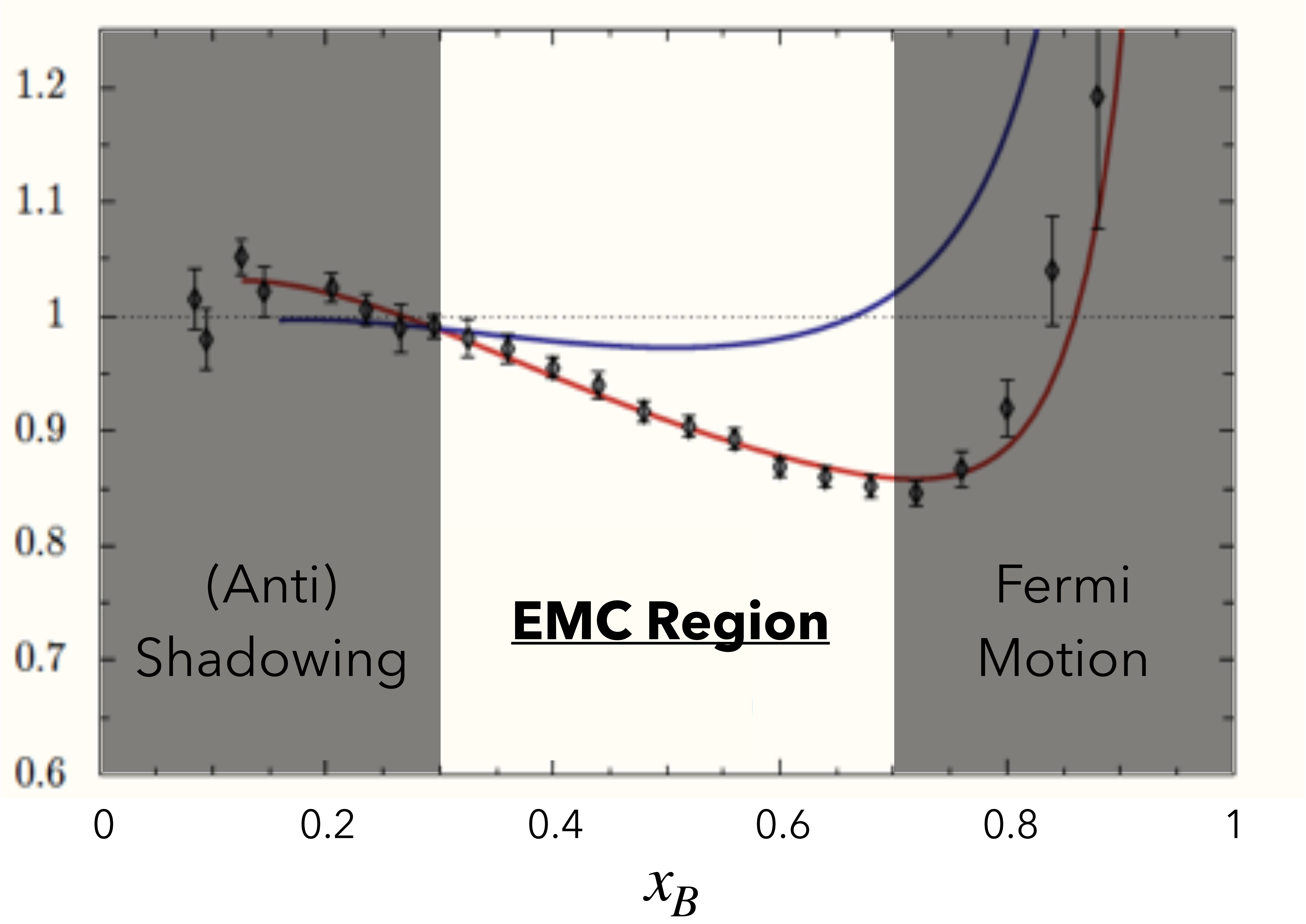
Iron / Deuterium Structure Function



Aubert et al., PLB (1983); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Nature (2019)

The EMC Effect

Iron / Deuterium Structure Function



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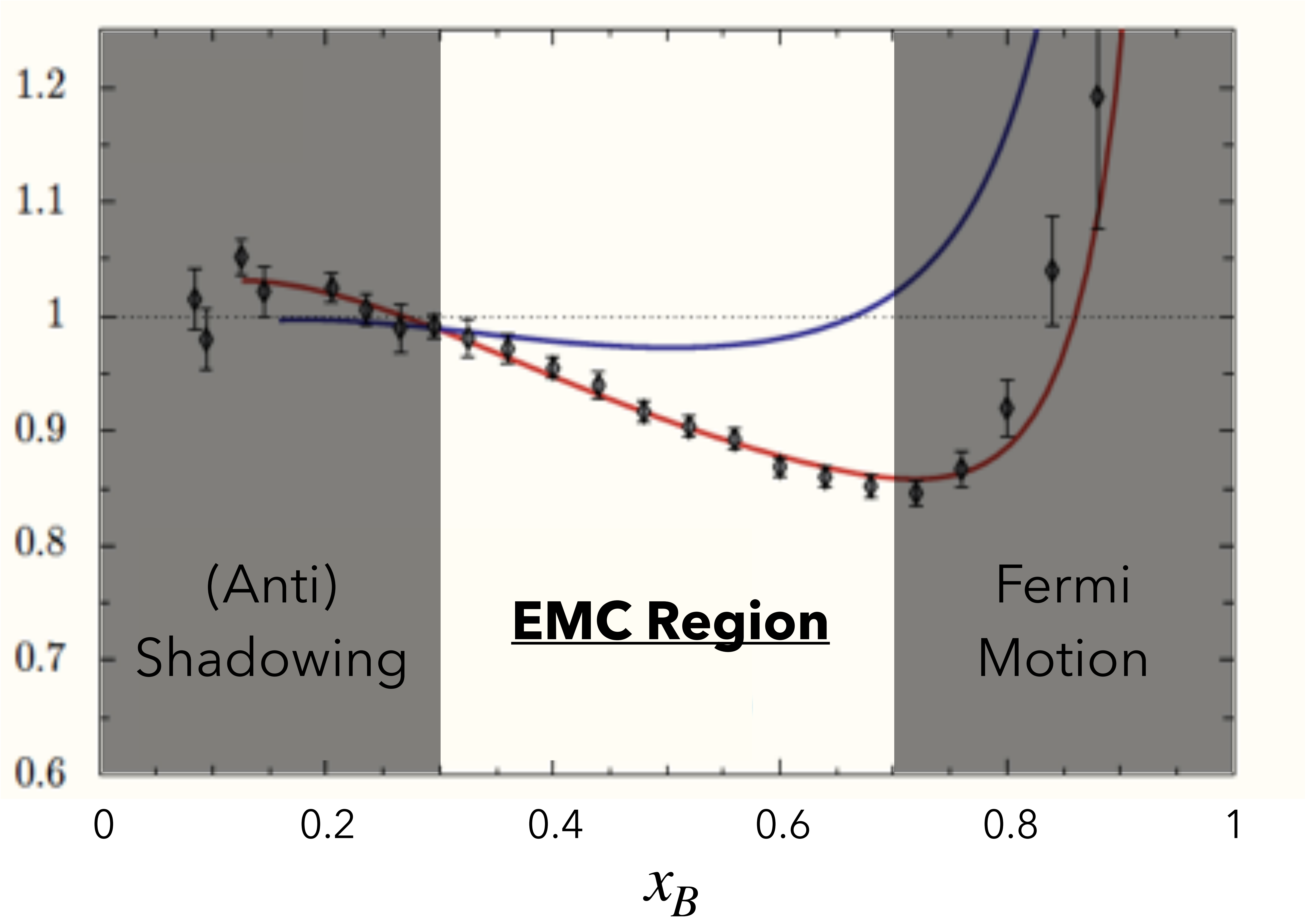
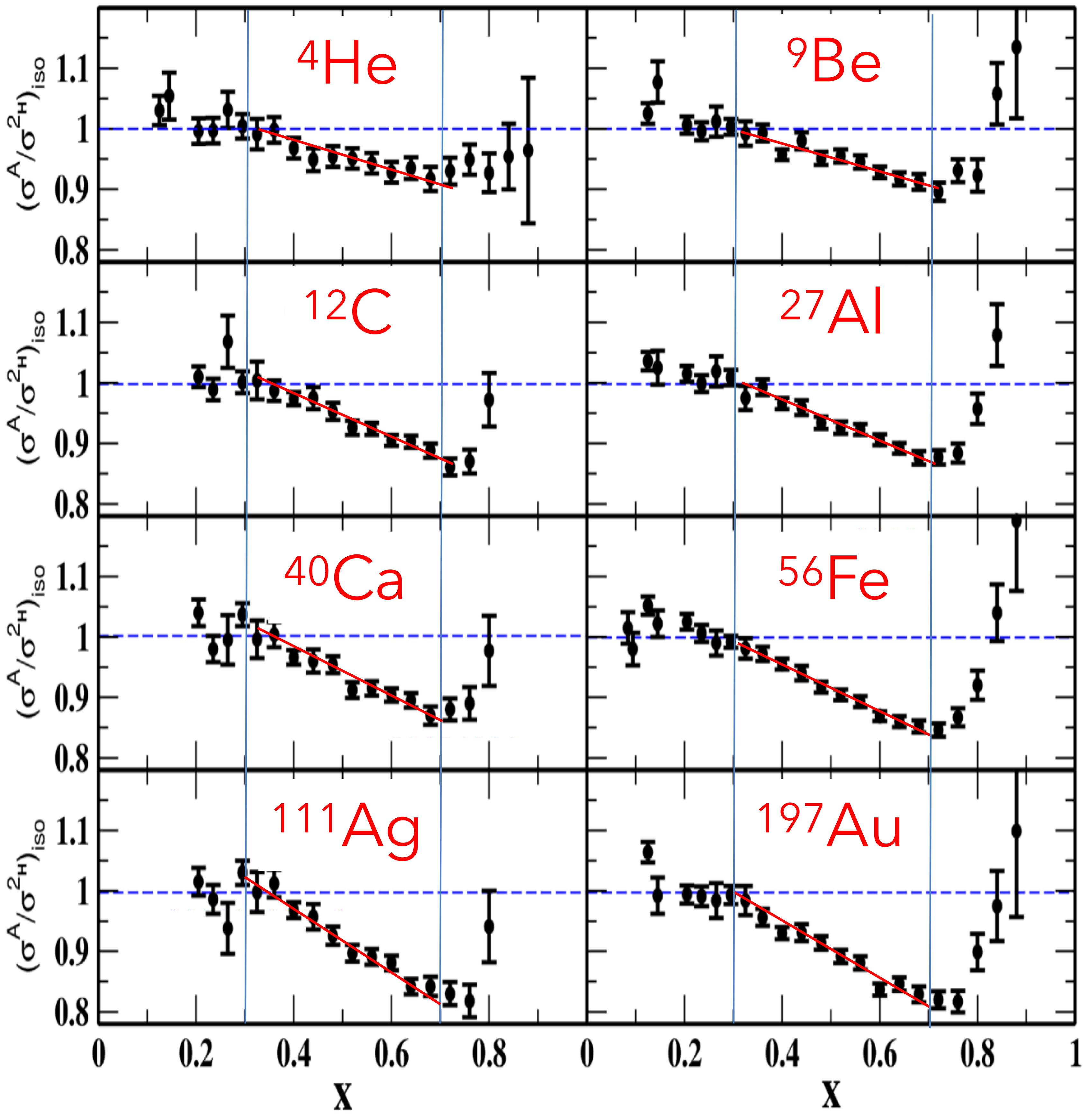


Aubert et al., PLB (1983); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Nature (2019)

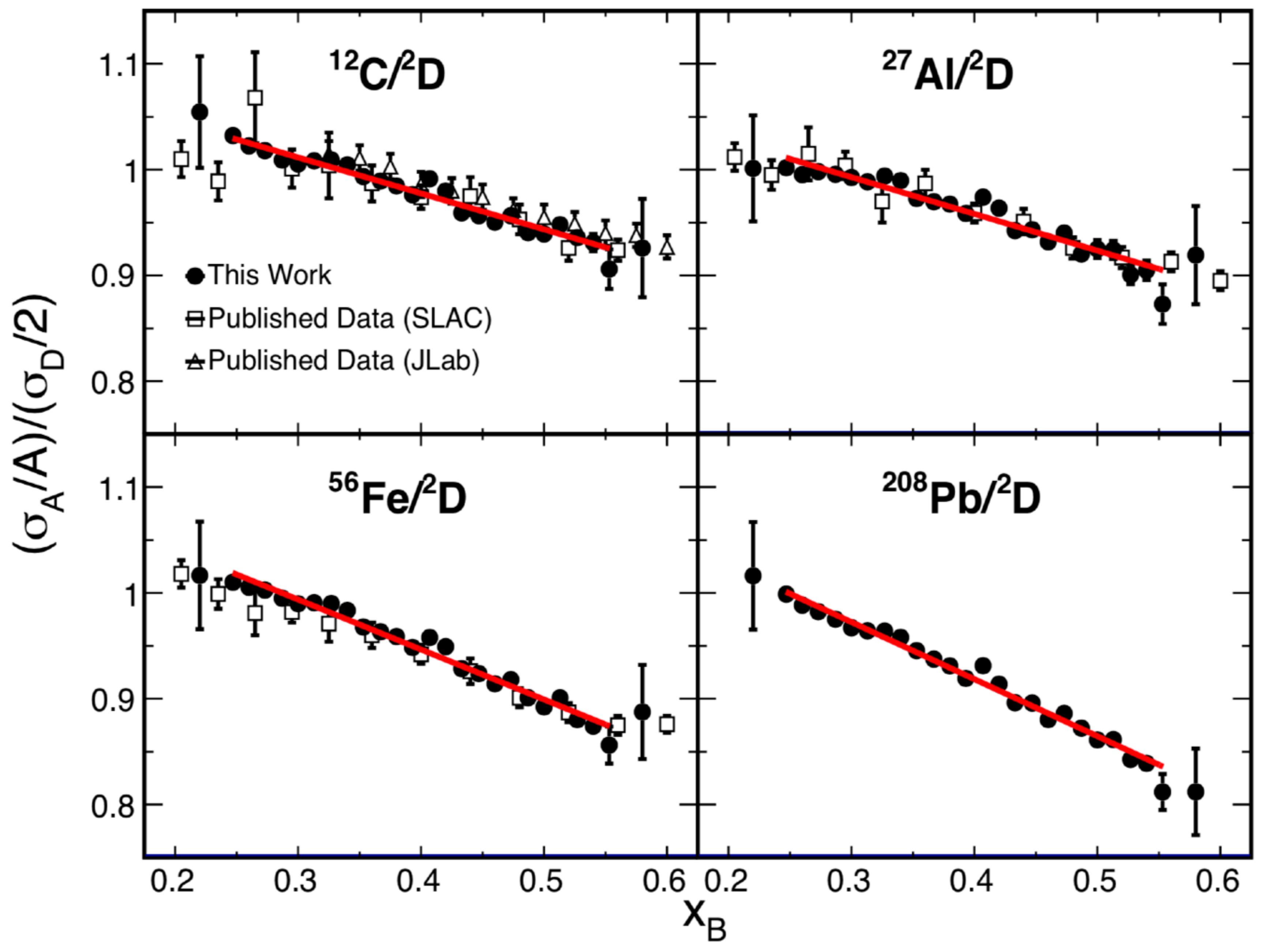
Partons in bound nucleons are substantially modified!

Global EMC Data

SLAC

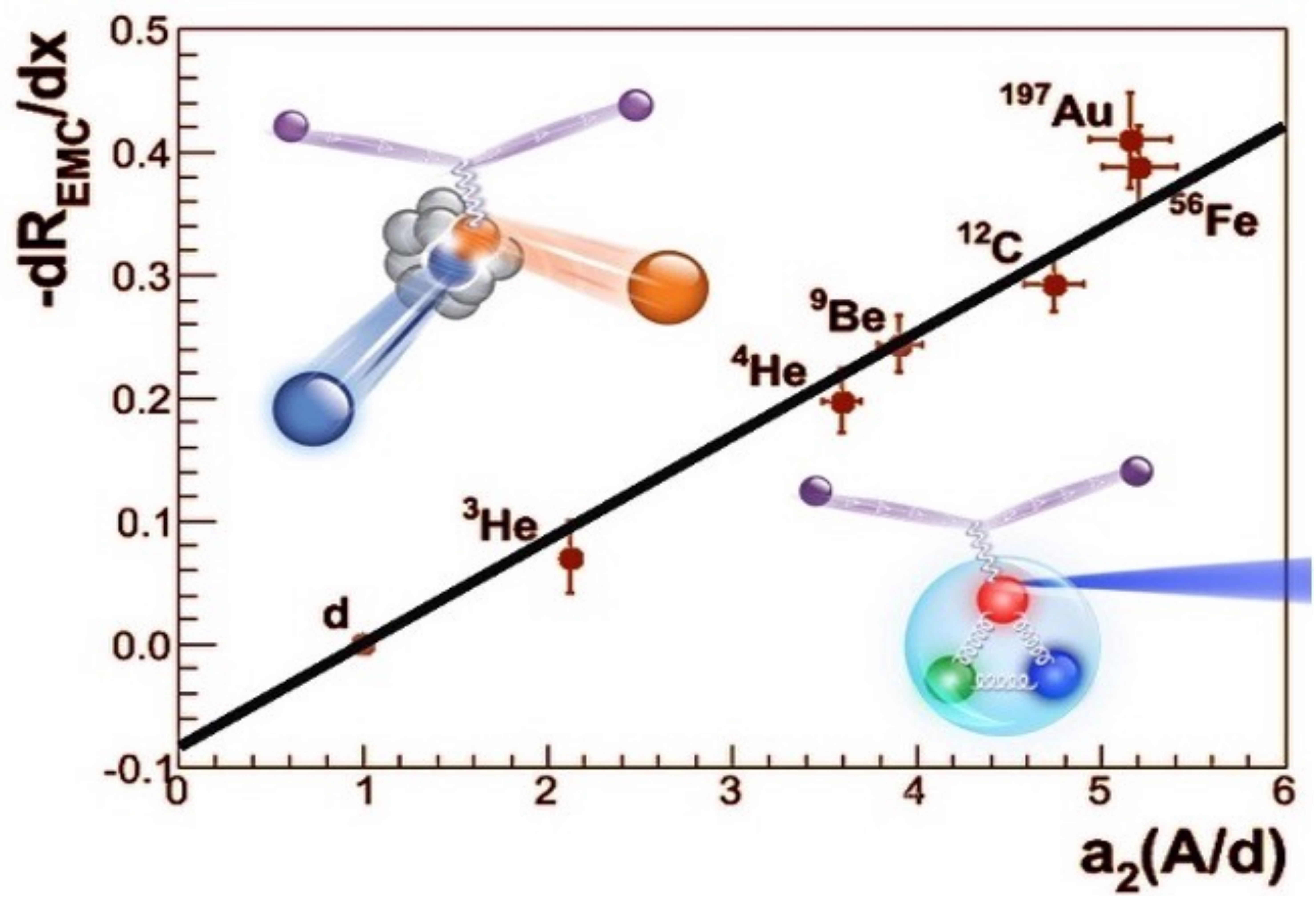


JLab



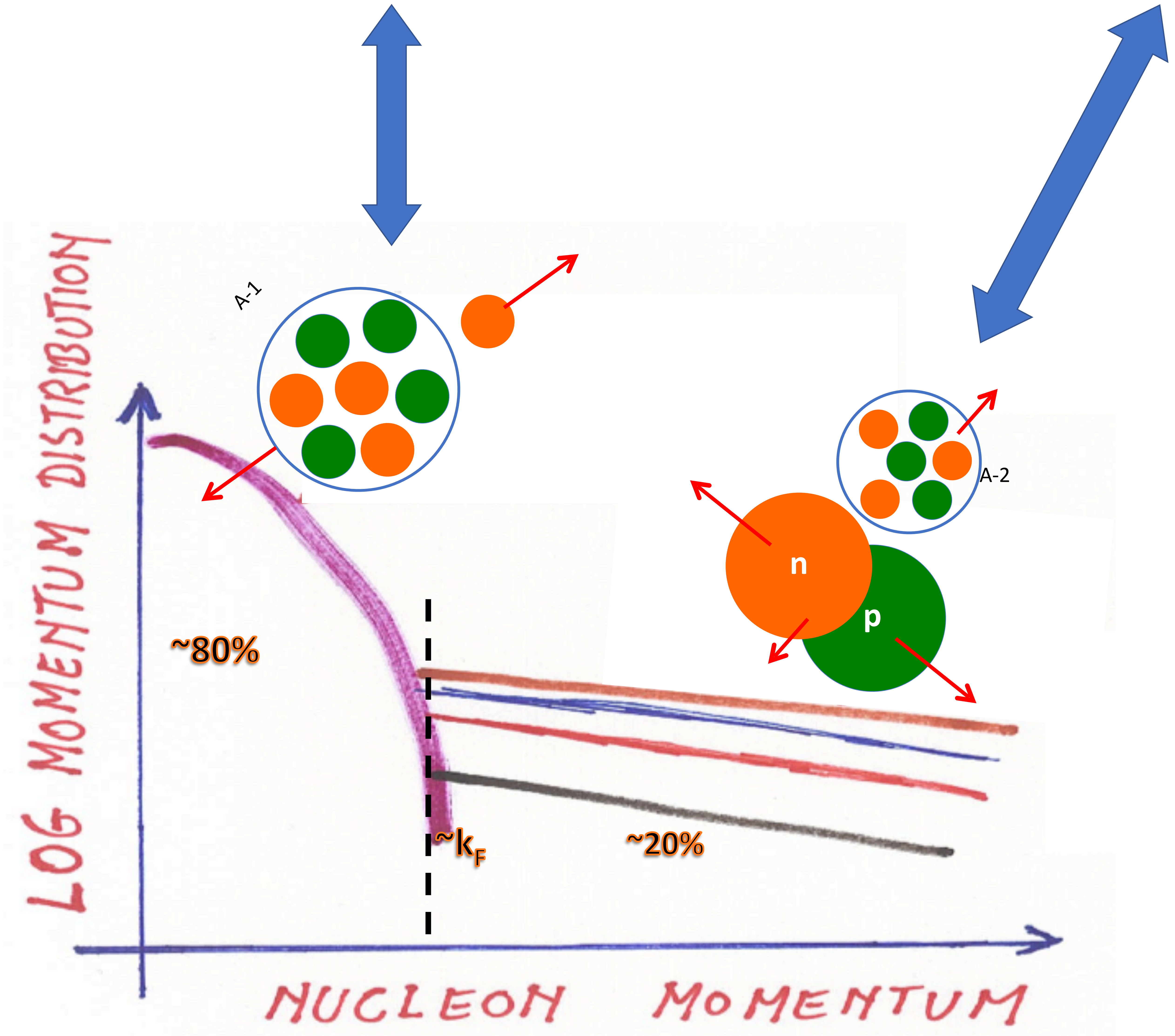
Gomez et al. PRD (1994)
Schmookler et al. Nature (2021)

EMC-SRC Correlation



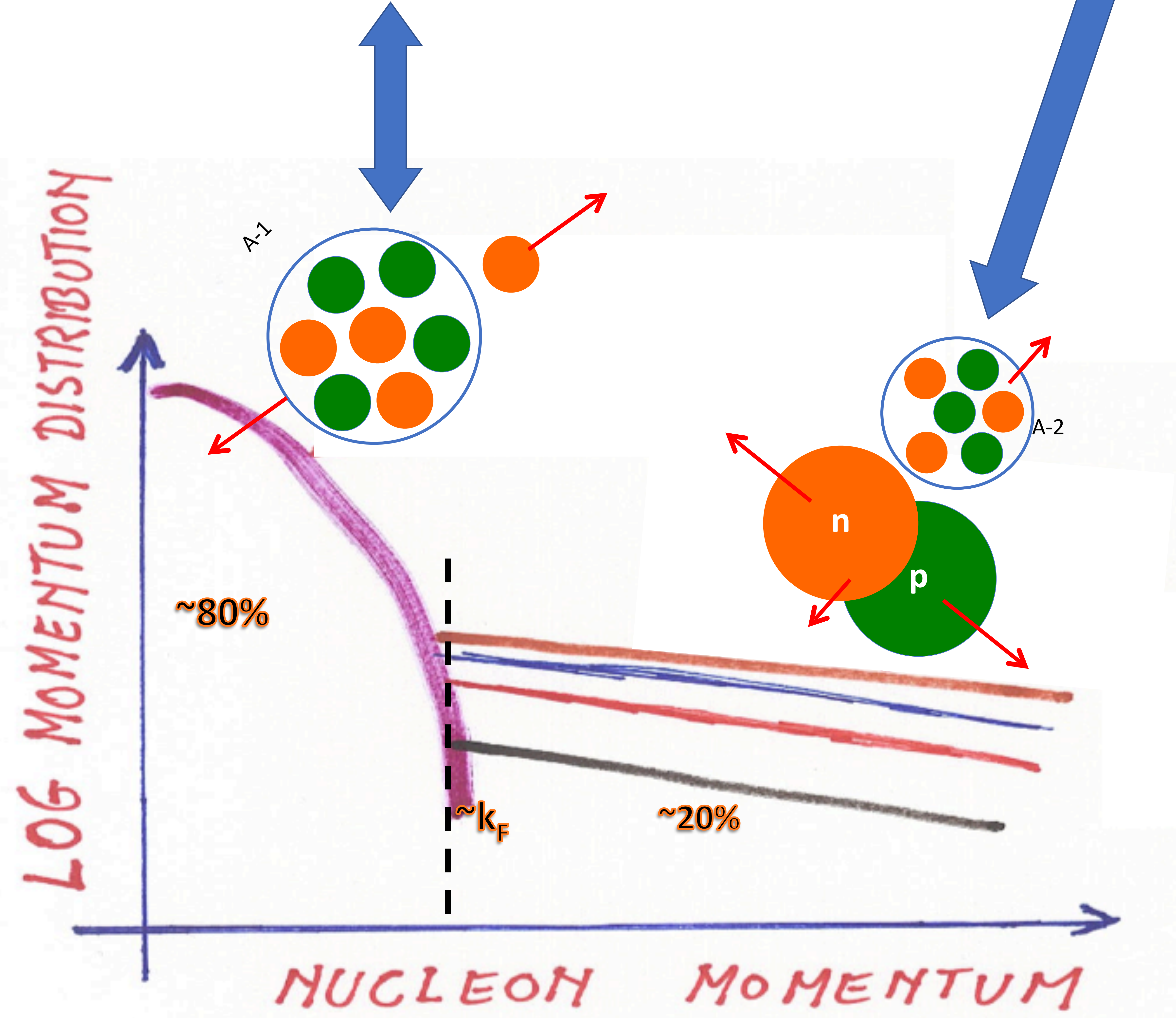
Nature (2019); RMP (2017); IJMPE (2013); PRC (2012); PRL (2011)

Bound = 'quasi Free' + Modified SRCs



Bound = 'quasi Free' + Modified SRCs

$$F_2^A = \left(Z - n_{SRC}^A\right) F_2^p + \left(N - n_{SRC}^A\right) F_2^n + n_{SRC}^A\left(F_2^{p*} + F_2^{n*}\right)$$



Bound = 'quasi Free' + Modified SRCs

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A\left(\Delta F_2^p + \Delta F_2^n\right)$$

$$F_2^d = F_2^p + F_2^n + n_{SRC}^d\left(\Delta F_2^p + \Delta F_2^n\right)$$

$$\frac{F_2^A}{F_2^d} = (Z - N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right) n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}$$

Schmookler et al. Nature (2021)

Bound = 'quasi Free' + Modified SRCs

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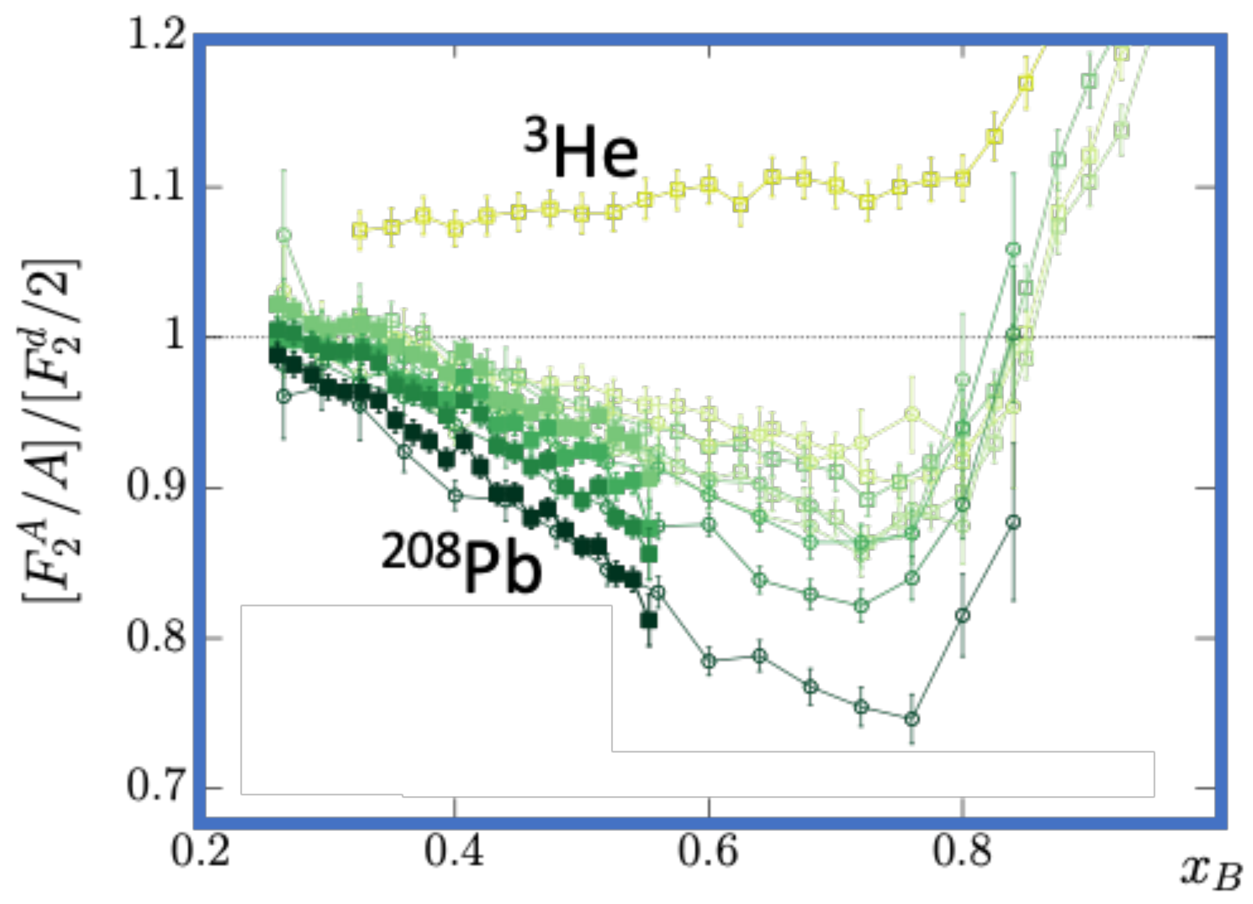
✓ **EMC**



Schmookler et al. Nature (2021)

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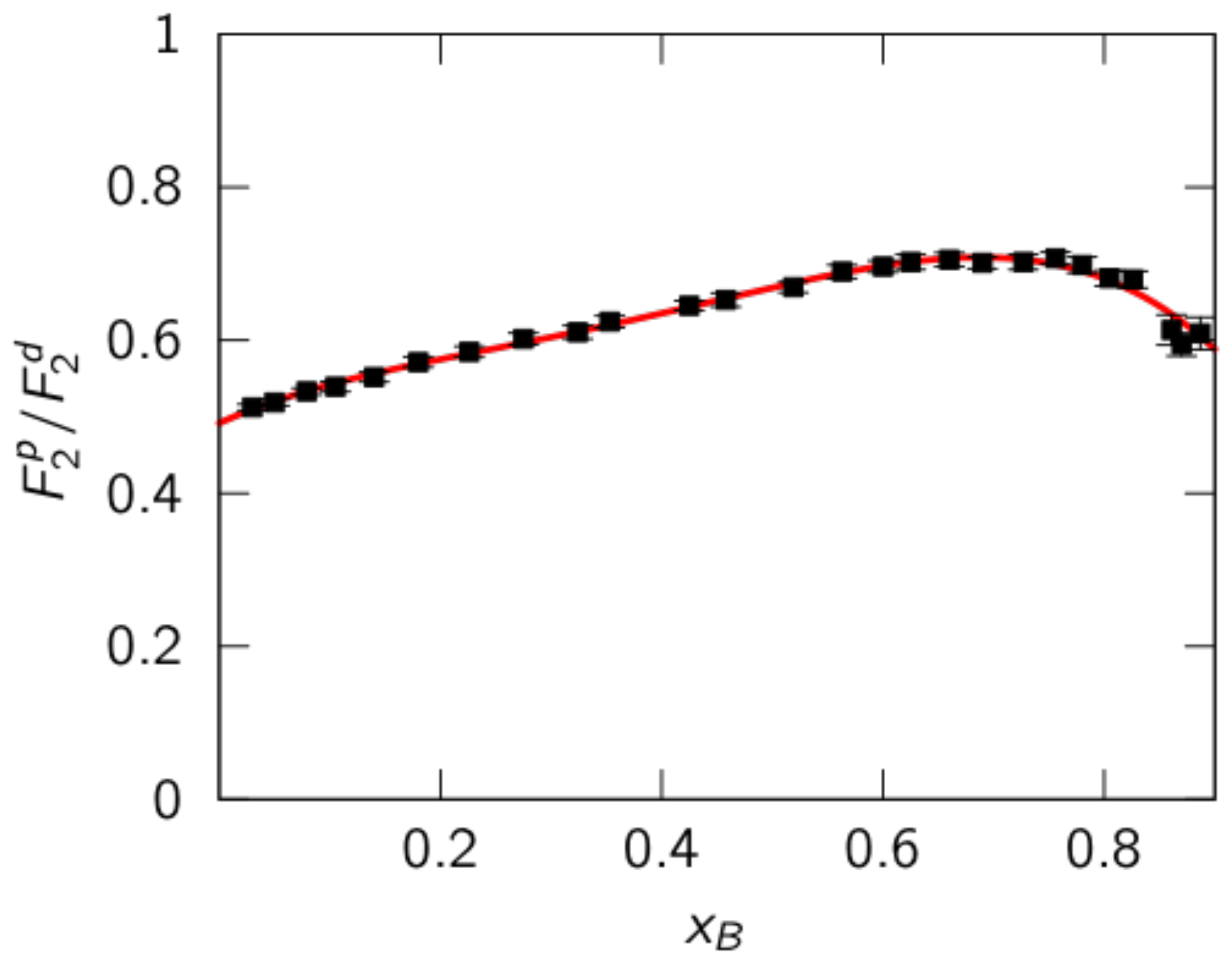
✓ EMC ✓ DIS



Schmookler et al. Nature (2021)

Bound = 'quasi Free' + Modified SRCs

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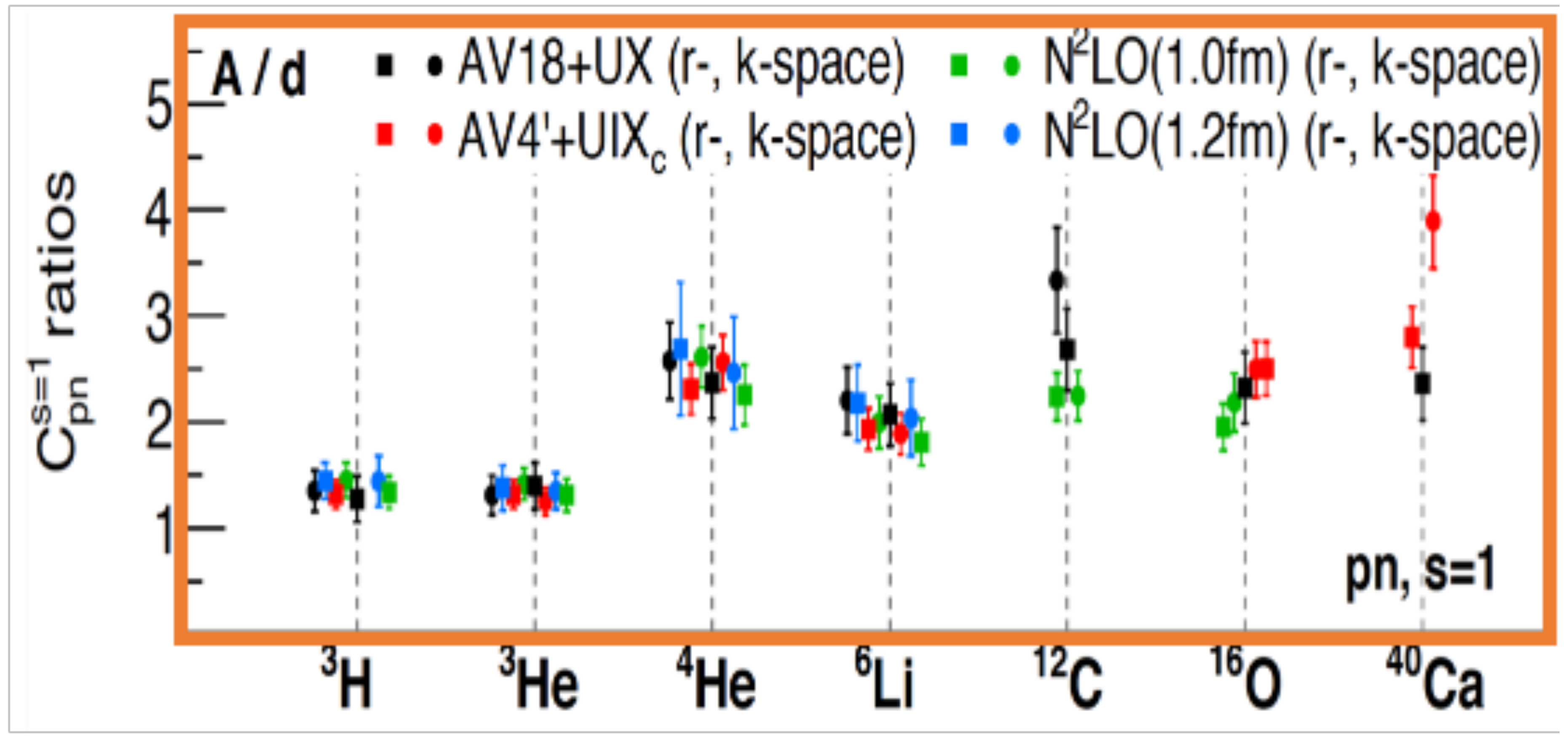
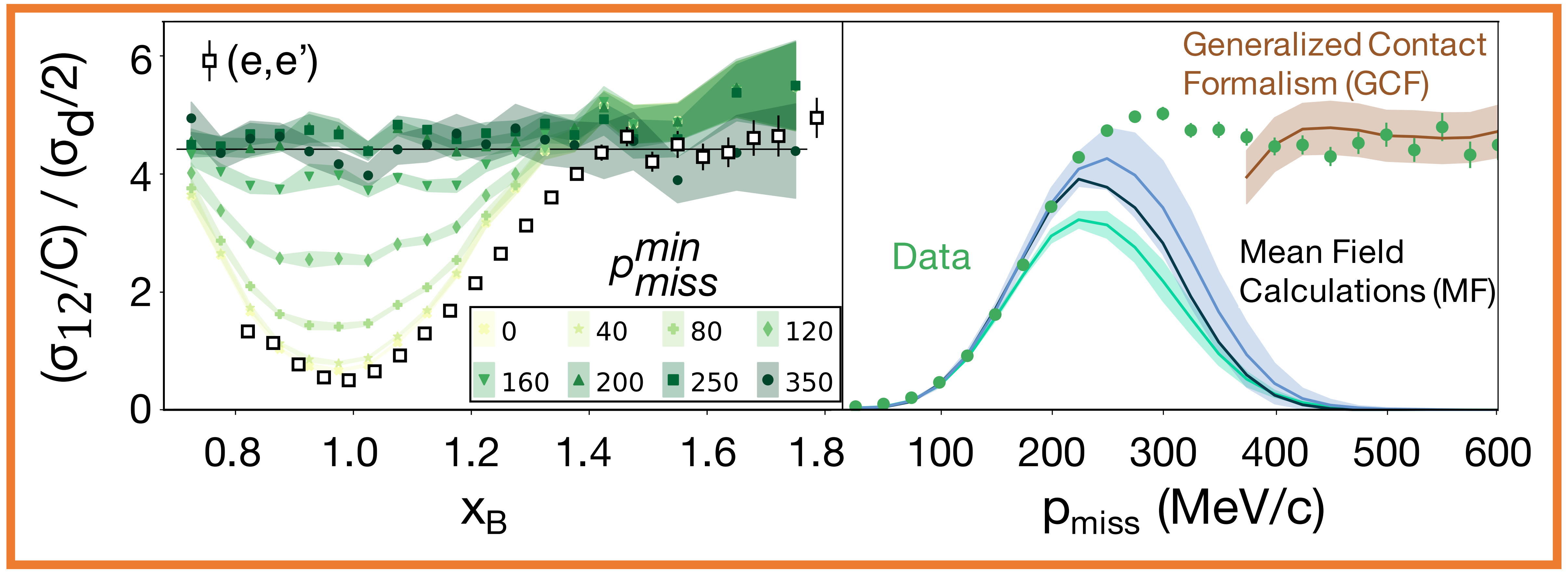
✓ EMC ✓ DIS ✓ QE / Ab-Initio





Schmookler et al. Nature (2021)

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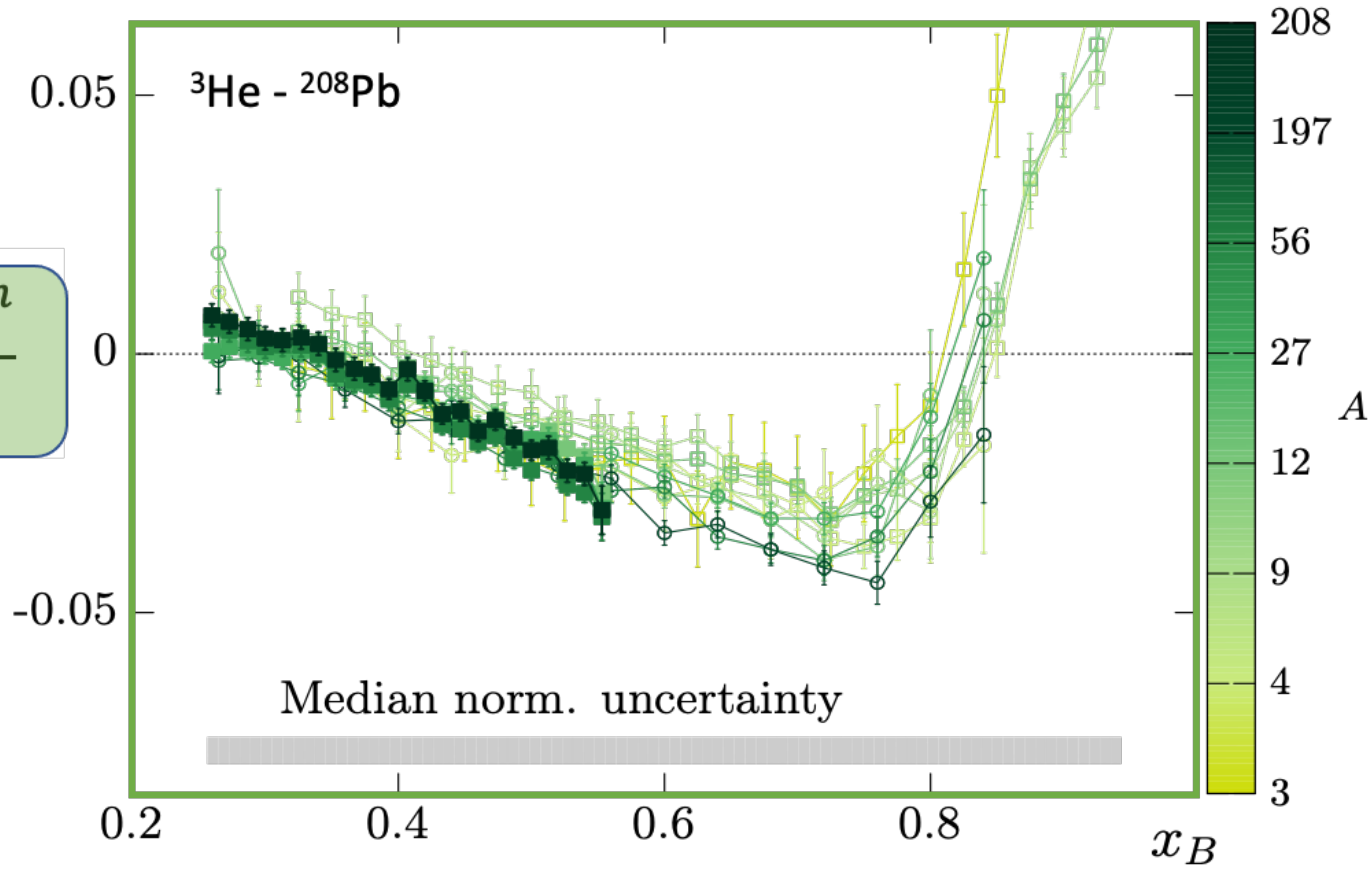
✓ EMC ✓ DIS ✓ QE / Ab-Initio Universal?

Schmookler et al. Nature (2021)

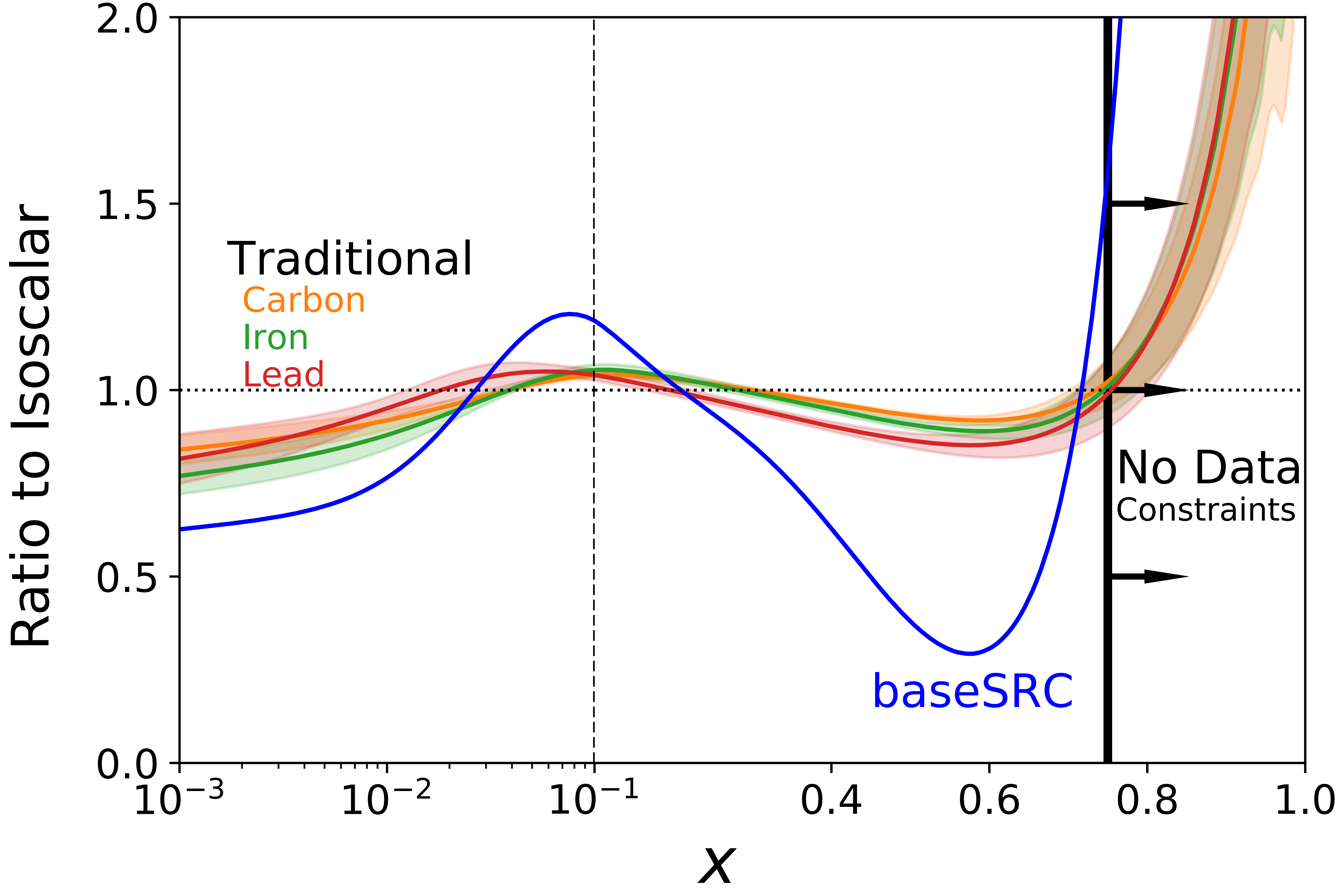
SRCs experience *universal* modification

$$n_{SRC}^{d}\frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}$$



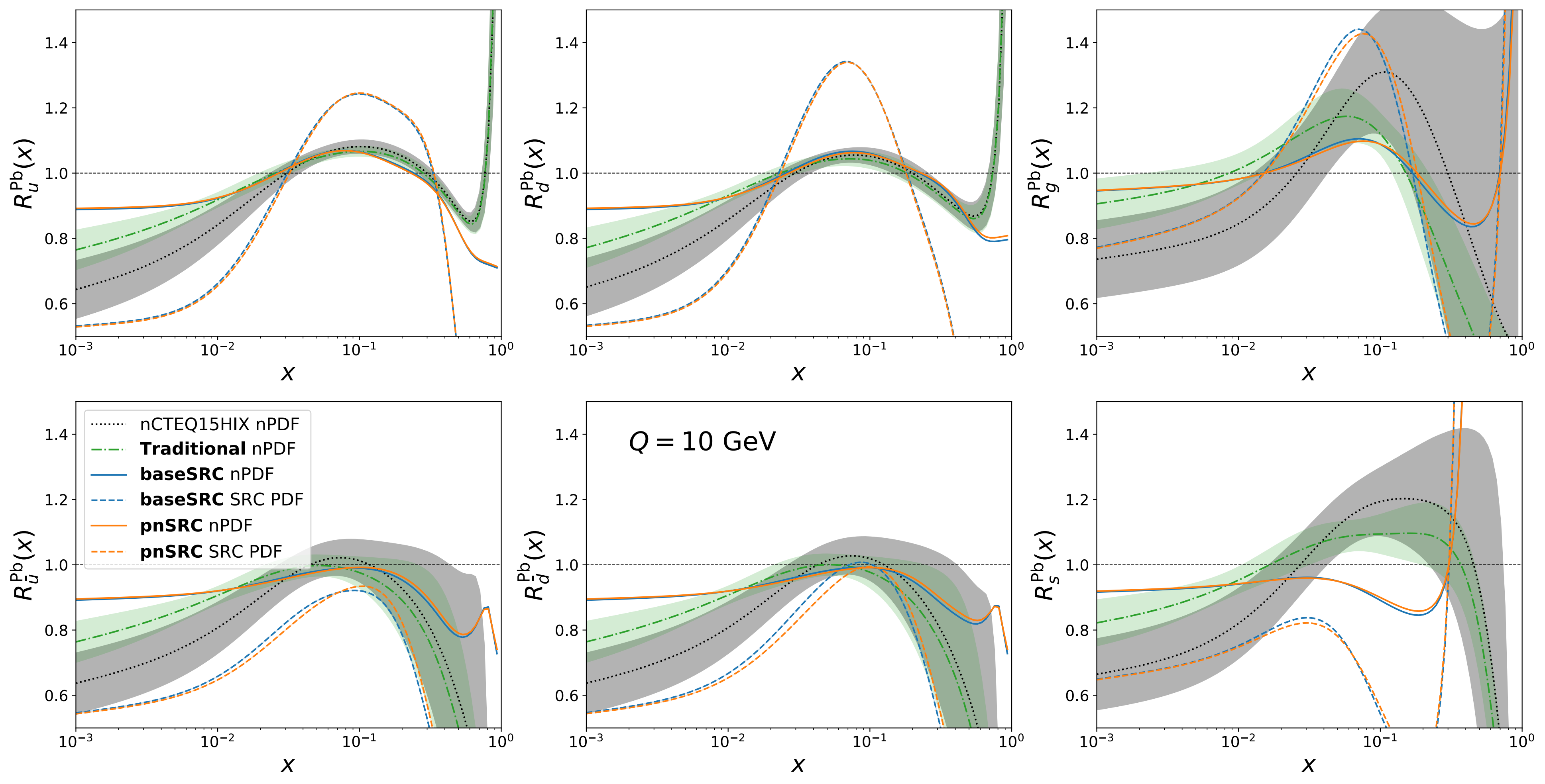
Schmookler et al. Nature (2021)

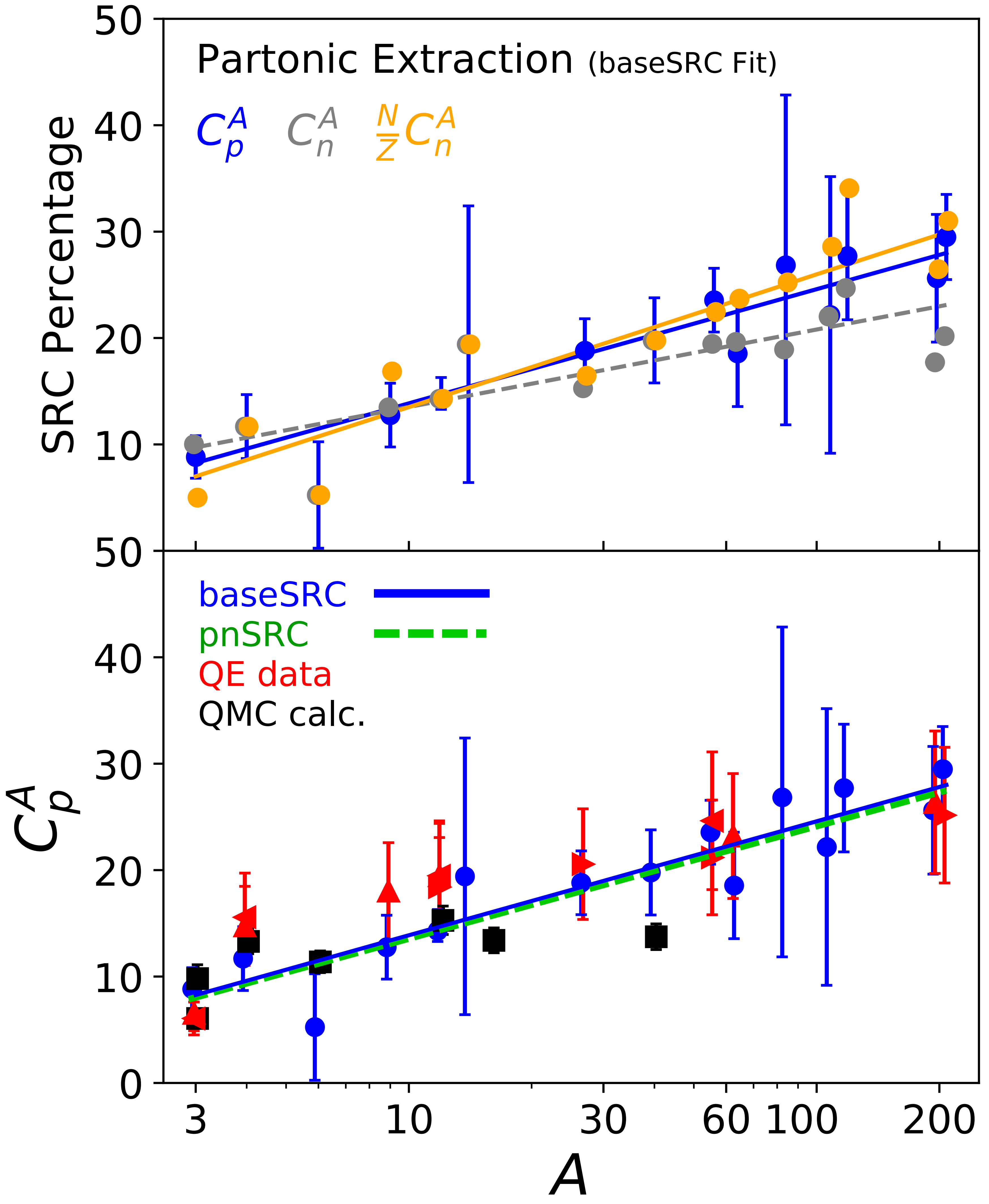
Global analysis of nPDF data under SRC-modified framework



Denniston et al. PRL (2024)

SRC abundance from *partonic* data?

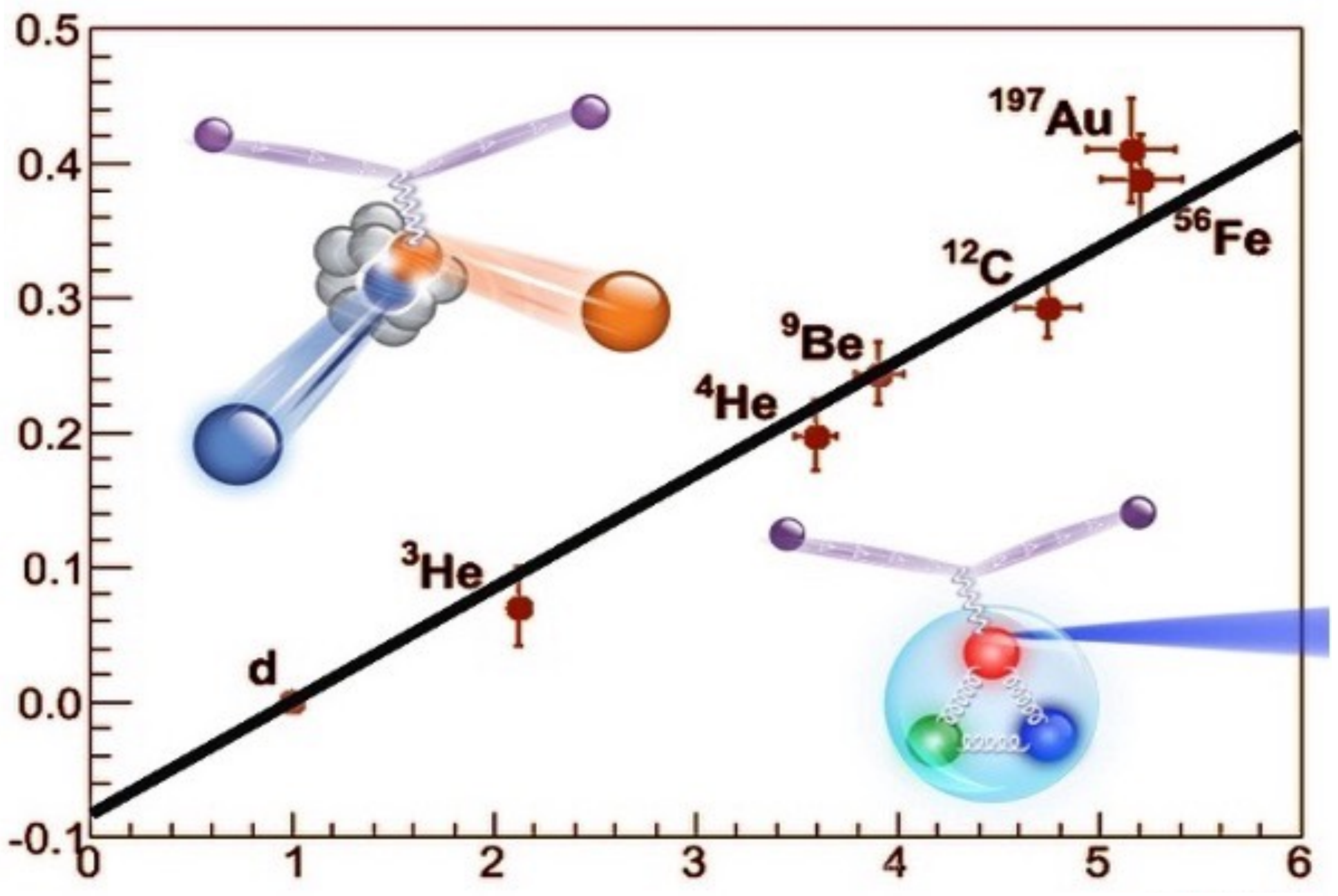




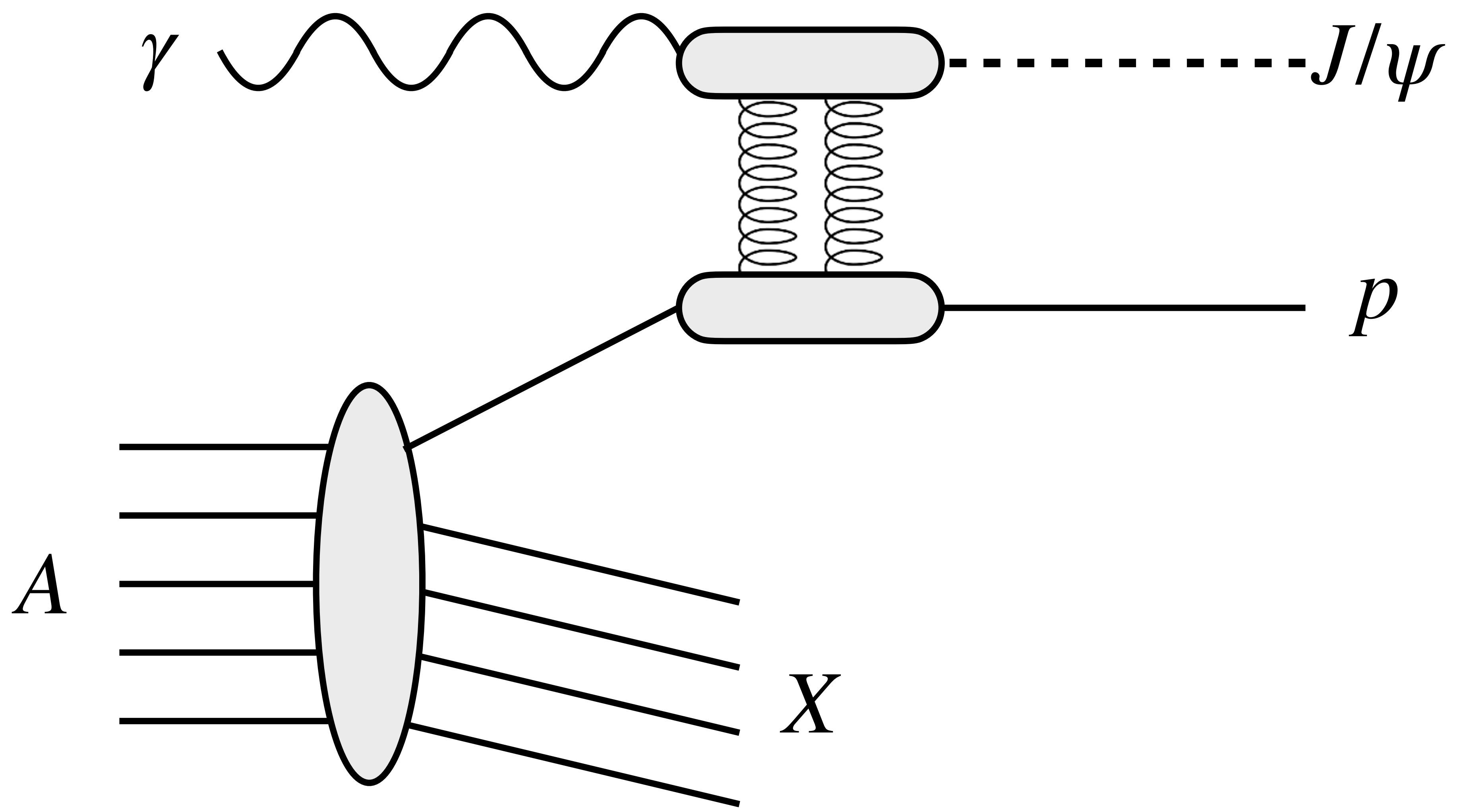
Theory, quasi-elastic, partonic data
→ consistent SRC abundances!

Gluonic Probes of SRCs

EMC Strength dR/dx



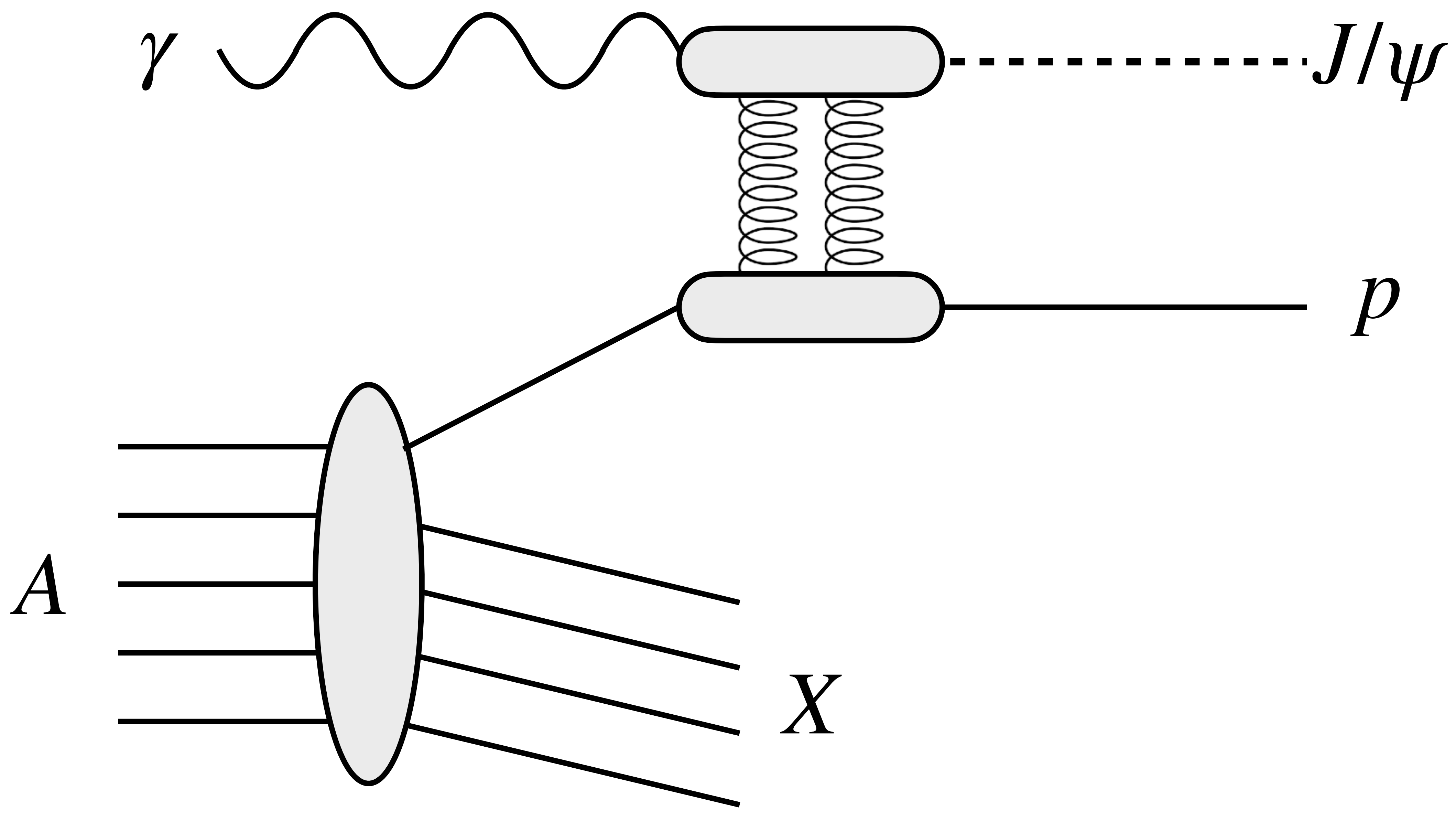
SRC Abundance a_2



Quarks in bound nucleons are known to be modified → Photoproduction of J/ψ can give insight to **gluons** in the bound proton

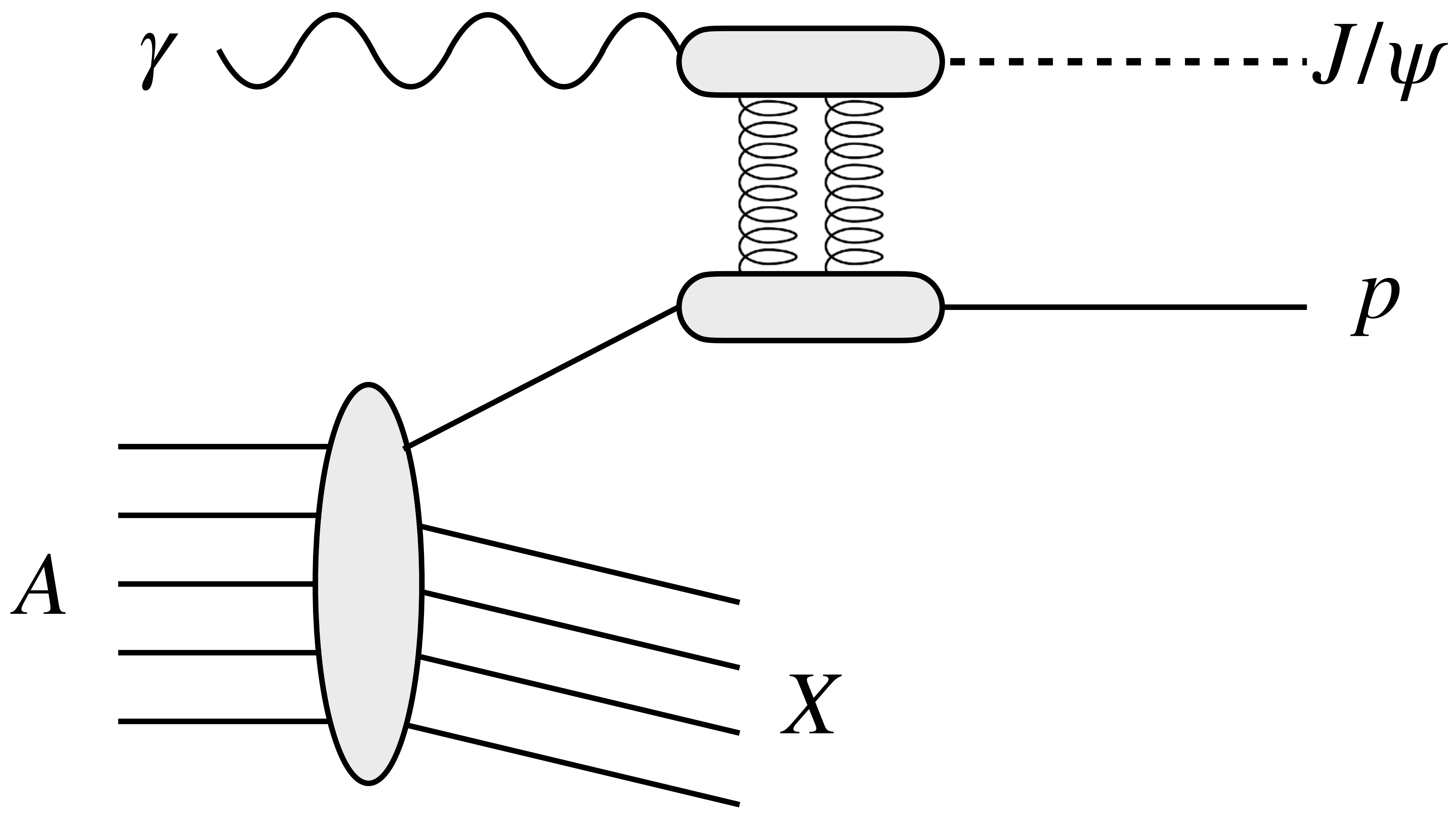
Nature (2019); RMP (2017); IJMPE (2013); PRC (2012); PRL (2011)

Photoproduction of J/ψ from bound protons

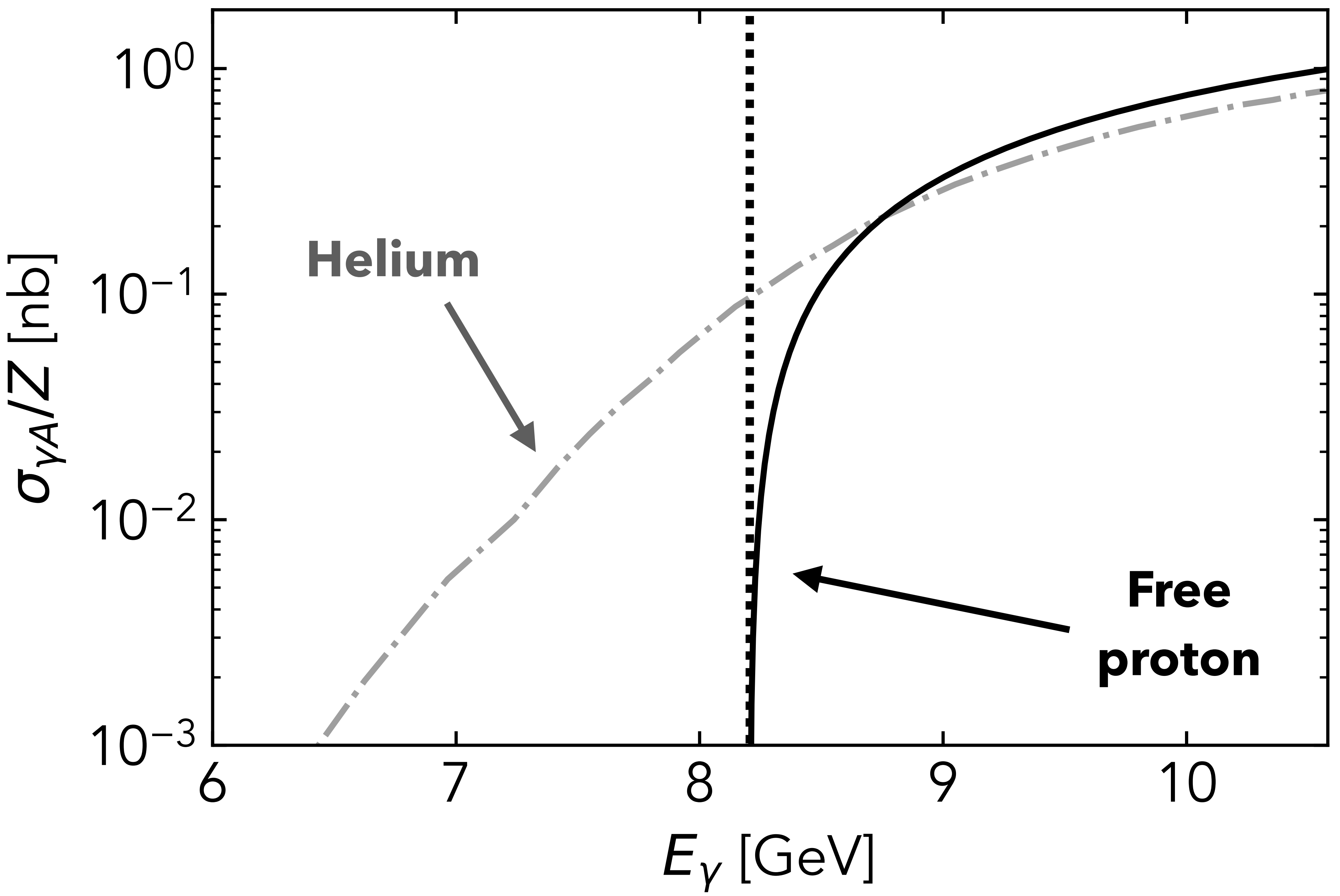


Incoherent J/ψ photoproduction near threshold sensitive to both nuclear and partonic effects

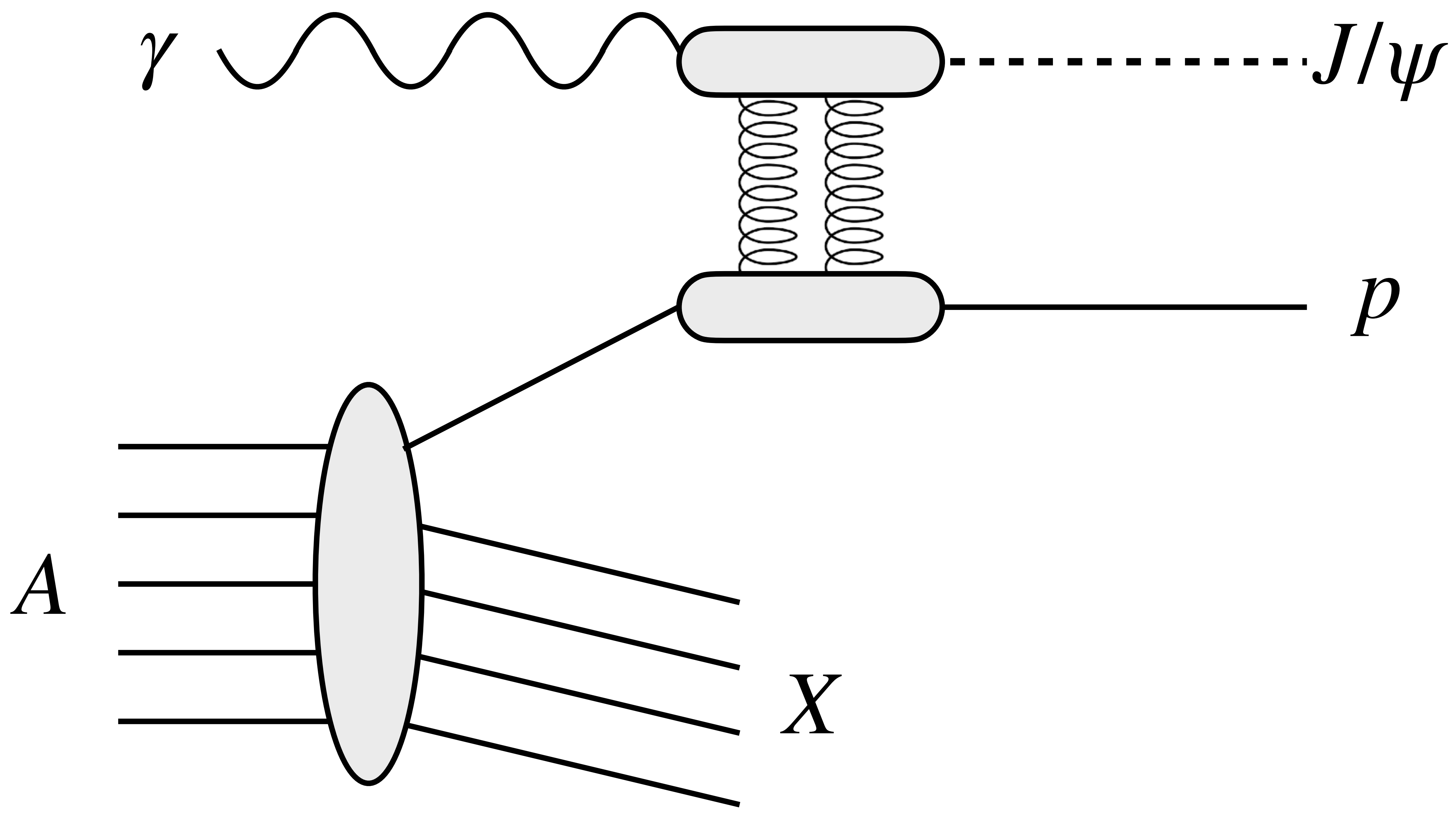
Photoproduction of J/ψ from bound protons



Incoherent J/ψ photoproduction near threshold sensitive to both nuclear and partonic effects

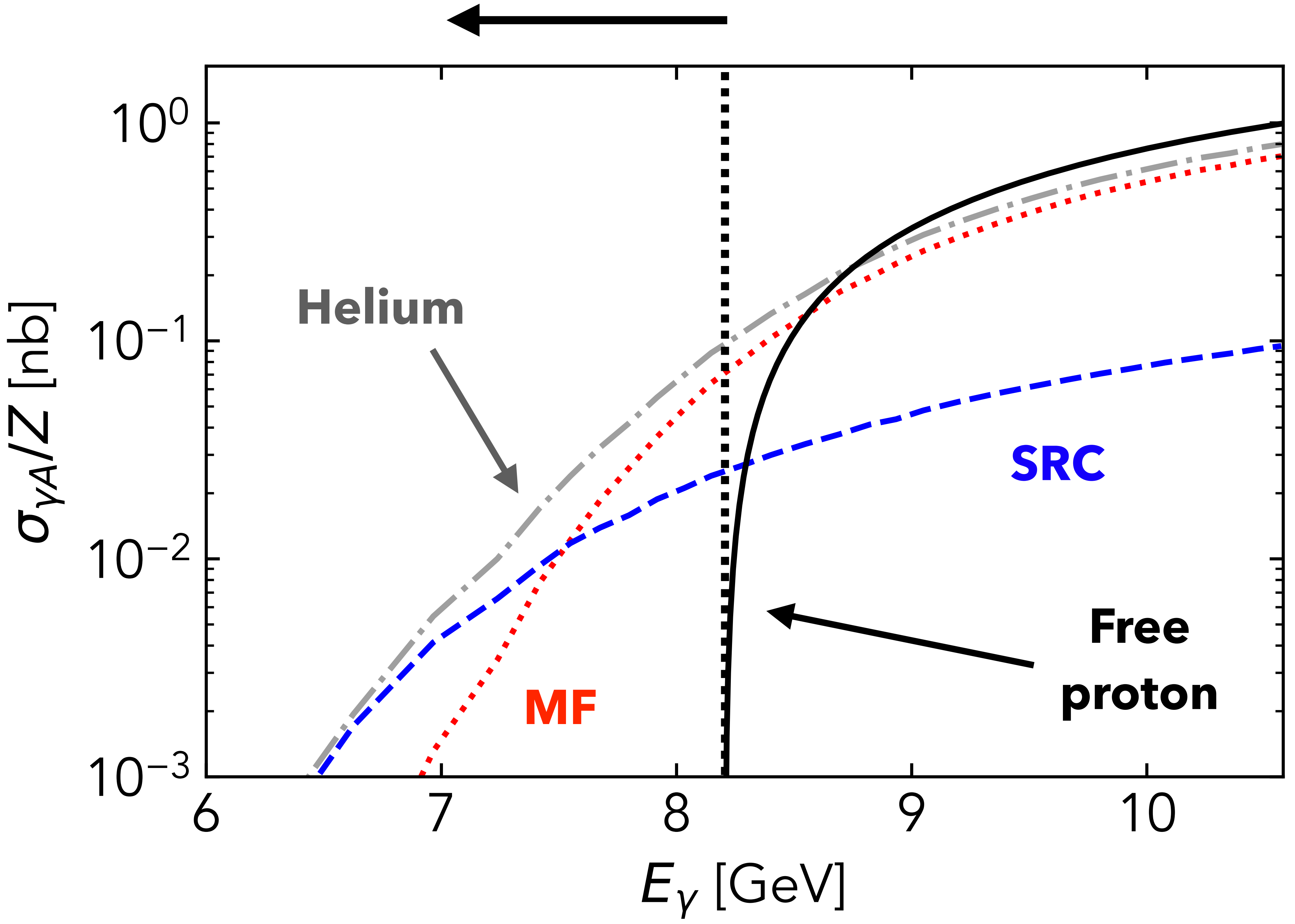


Photoproduction of J/ψ from bound protons

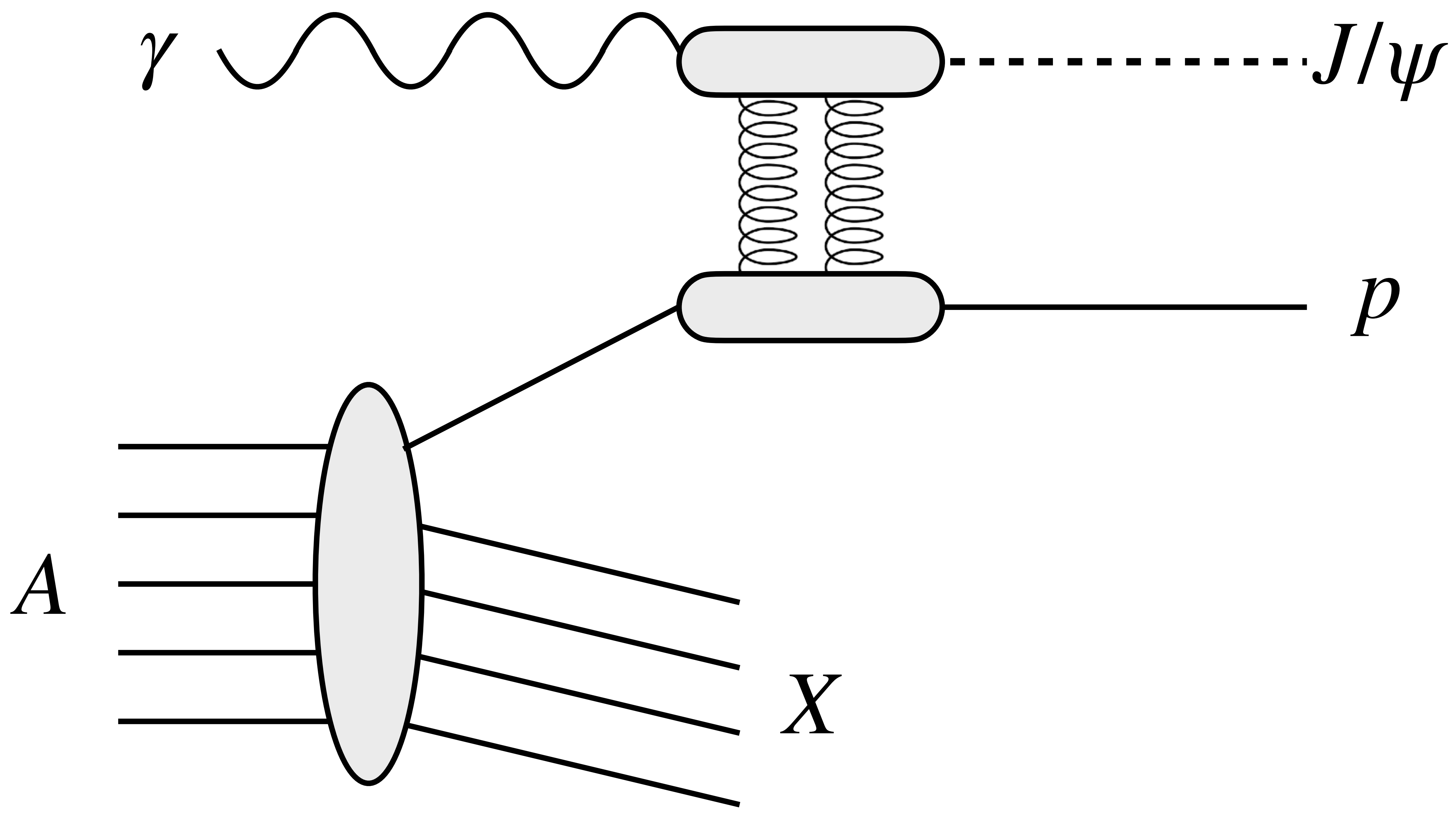


Incoherent J/ψ photoproduction near threshold sensitive to both nuclear and partonic effects

"Sub-threshold" production; increased nuclear effects

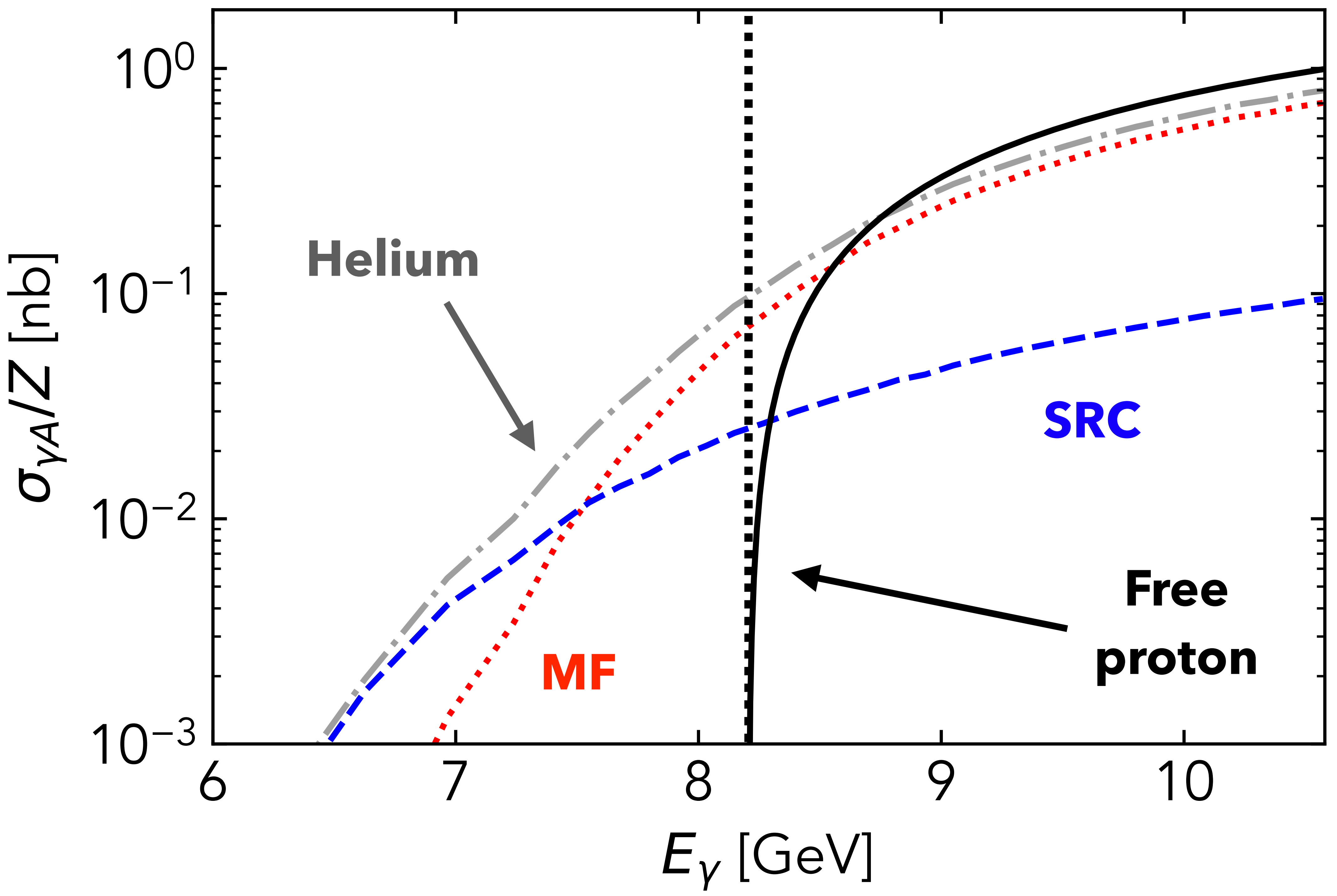


Photoproduction of J/ψ from bound protons

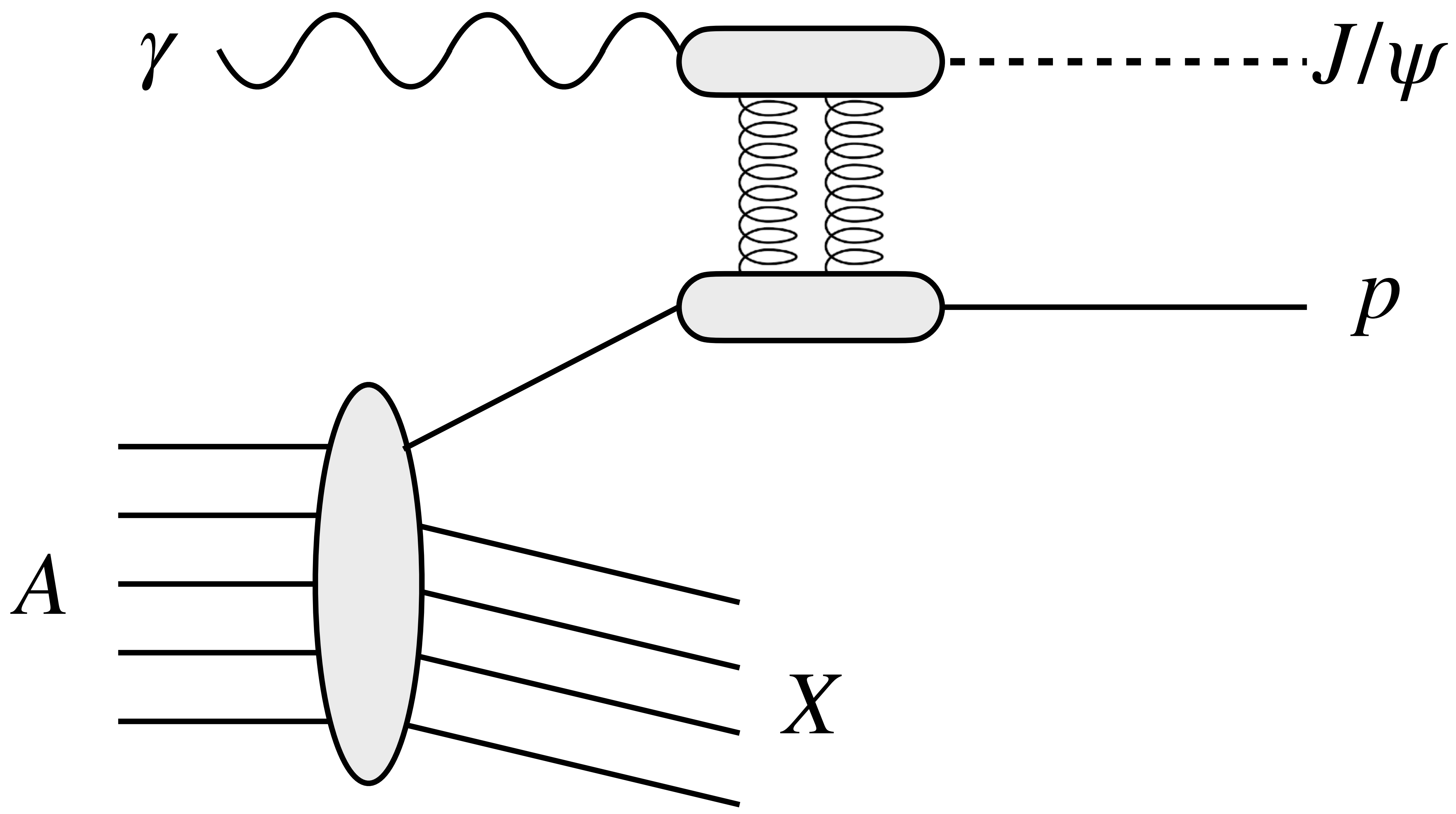


Incoherent J/ψ photoproduction near threshold sensitive to both nuclear and partonic effects

$$\frac{d\sigma(\gamma A \to J/\psi p X)}{dt d^3 p_{miss} dE_{miss}} = v_{\gamma i} \cdot \frac{d\sigma}{dt}(\gamma p \to J/\psi p) \cdot S(p_{miss}, E_{miss})$$



Photoproduction of J/ψ from bound protons



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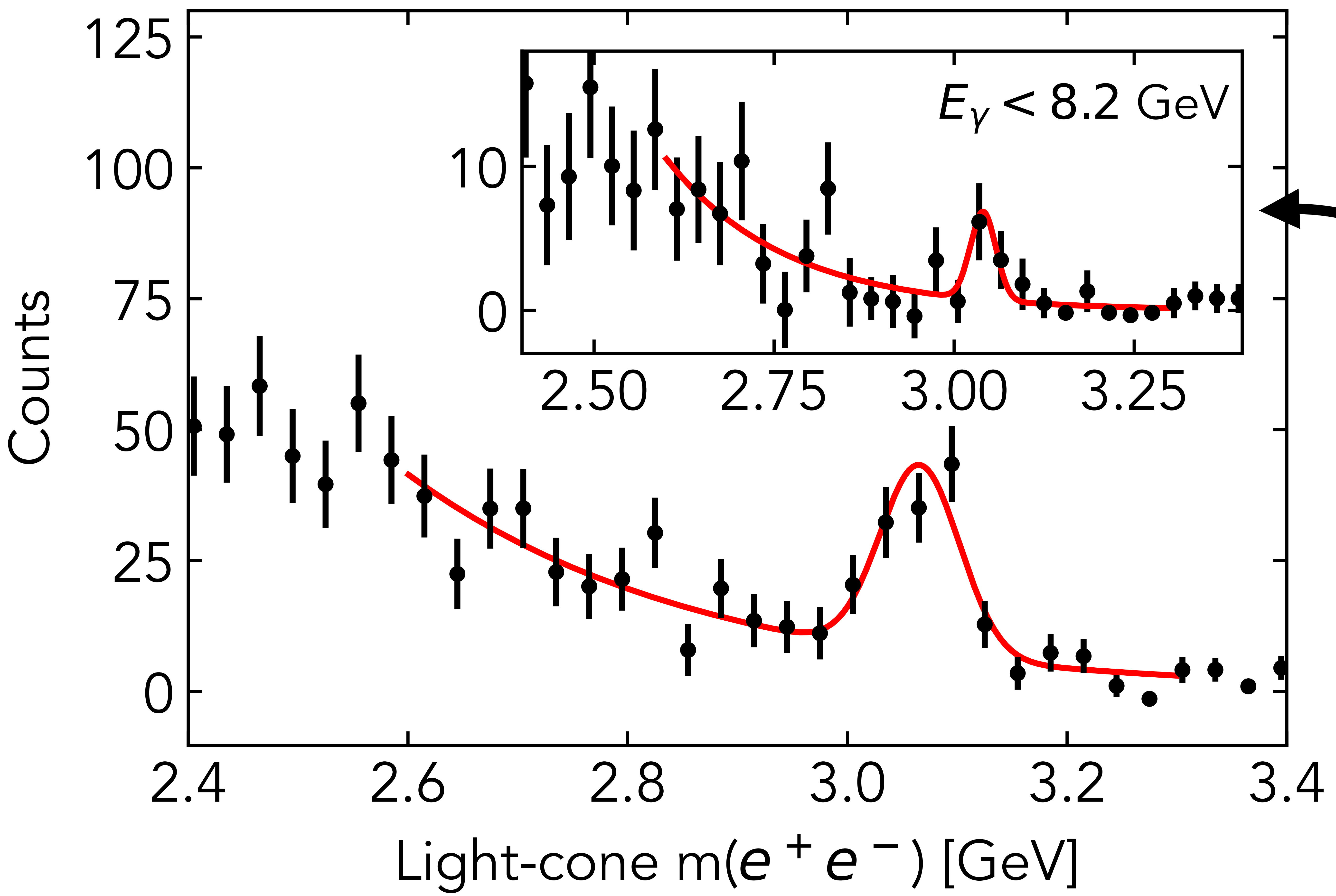
$$\frac{d\sigma}{dt}(\gamma p \to J/\psi p) = \left.\frac{d\sigma}{dt}\right|_{t=0}(s_{\gamma p}) \times F^2(t)$$

Forward cross section

Gravitational form factor

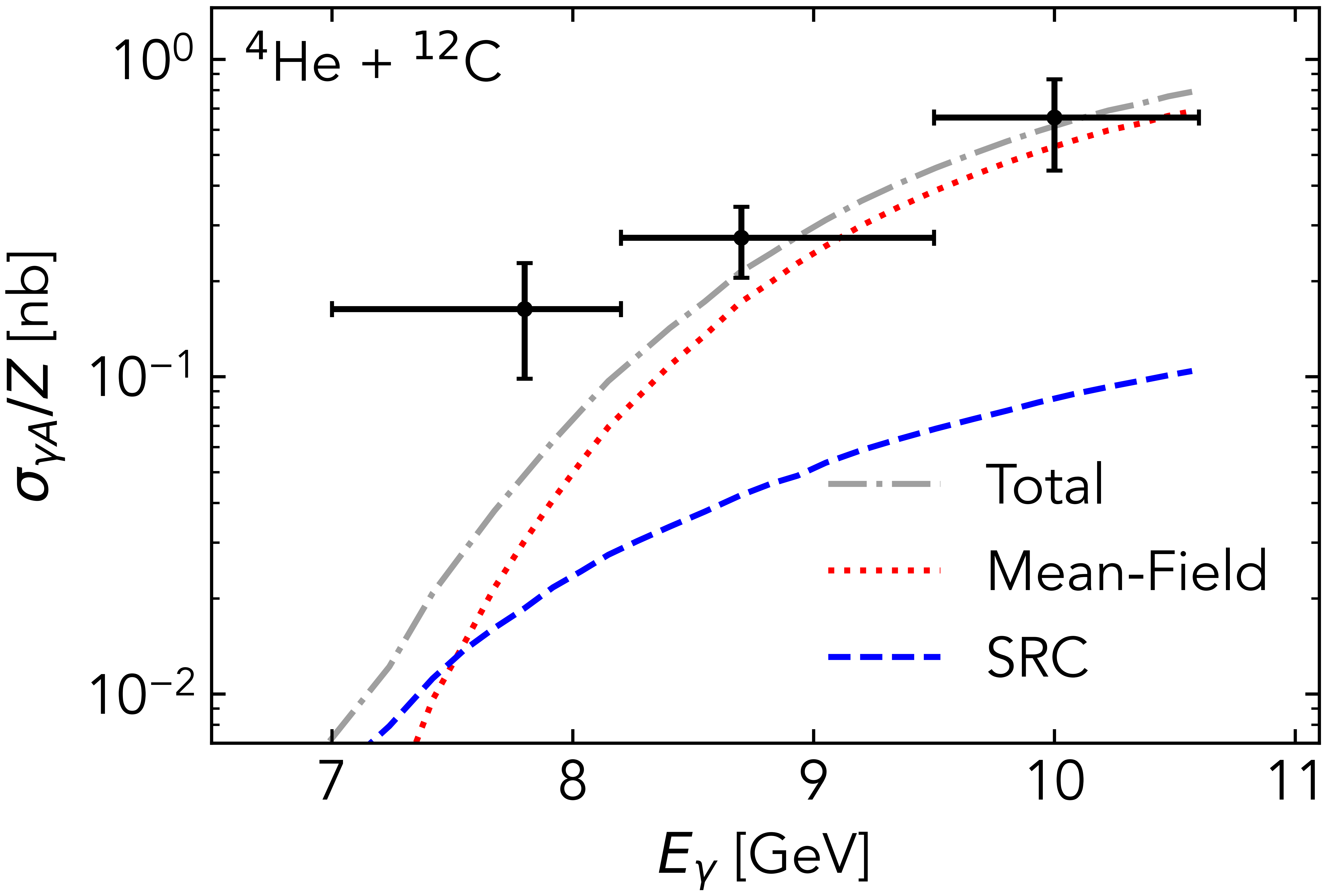
Invariant mass shows $J/\psi \rightarrow e^+e^-$ decay



Subthreshold J/ψ observation!

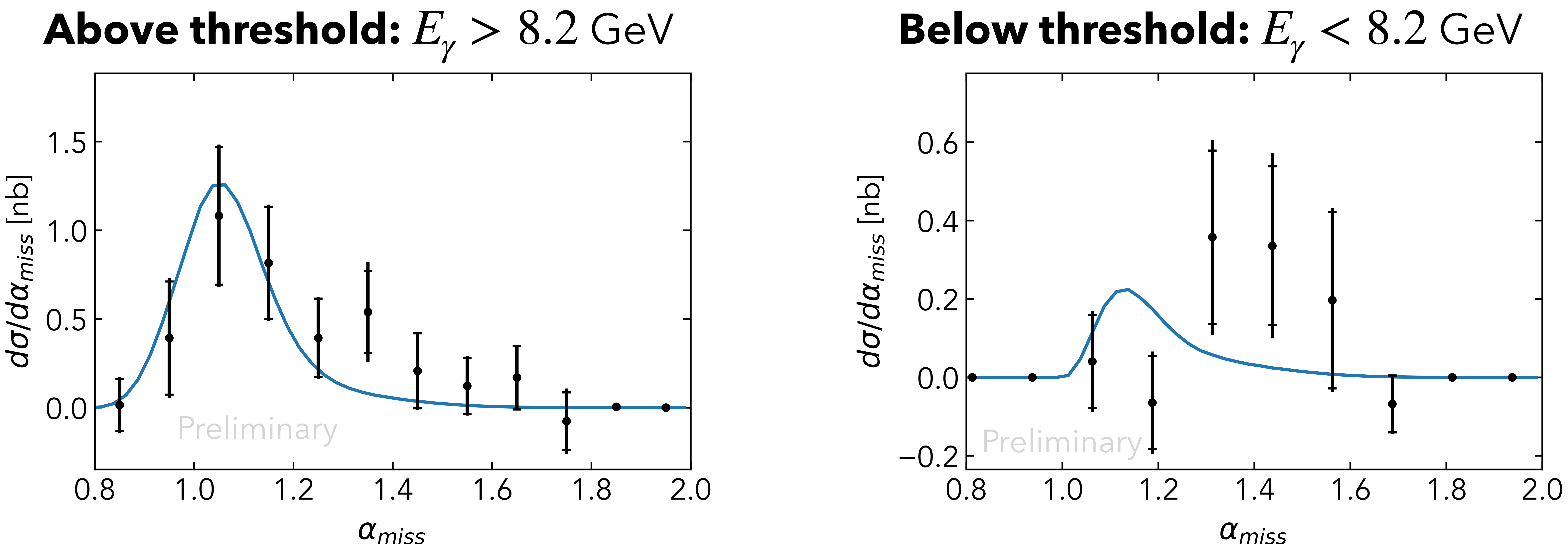
Pybus et al. PRL (2025)

Combined nuclear data → Enhanced subthreshold J/ψ?



Pybus et al. PRL (2025)

Kinematics give insight into reaction mechanisms



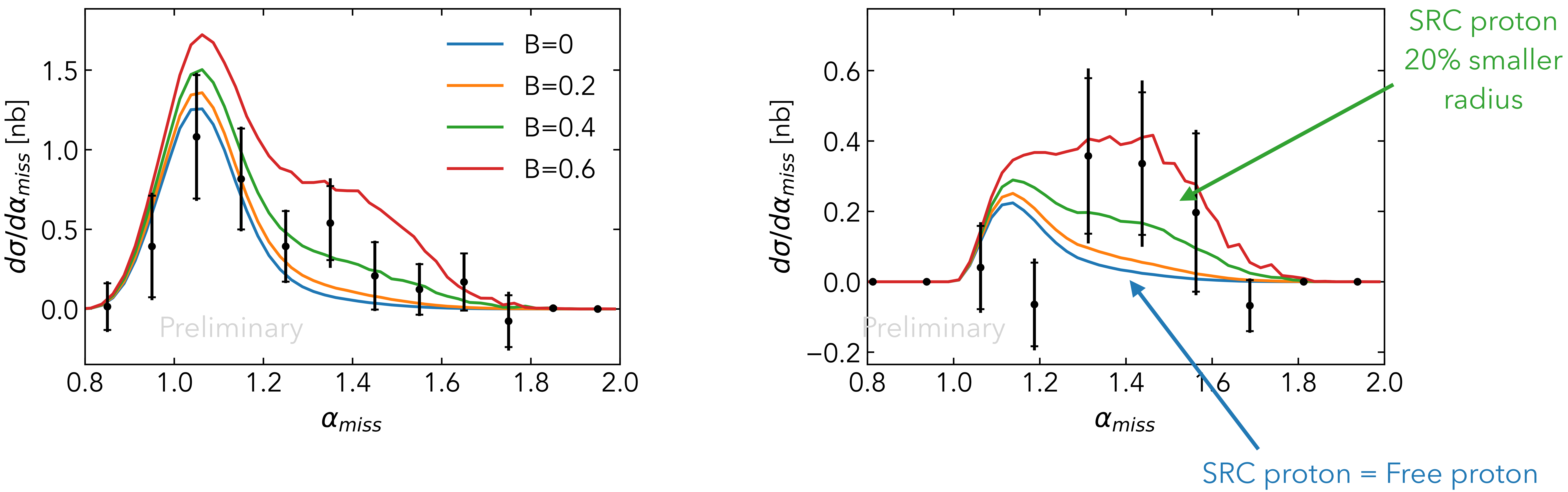
Lightcone momentum fraction $\alpha_{miss} = \dfrac{E_{miss} - p_{z,miss}}{m_A/A}$

Pybus et al. PRL (2025)

Smaller-size SRC proton could enhance large-α cross section

Above threshold: $E_\gamma > 8.2$ GeV

Below threshold: $E_\gamma < 8.2$ GeV



Modified gluon radius: $\langle r \rangle_g \to (1 + Bv)\langle r \rangle_g$

Pybus et al. PRL (2025)

Threshold J/ψ could also probe compact non-nucleonic states!

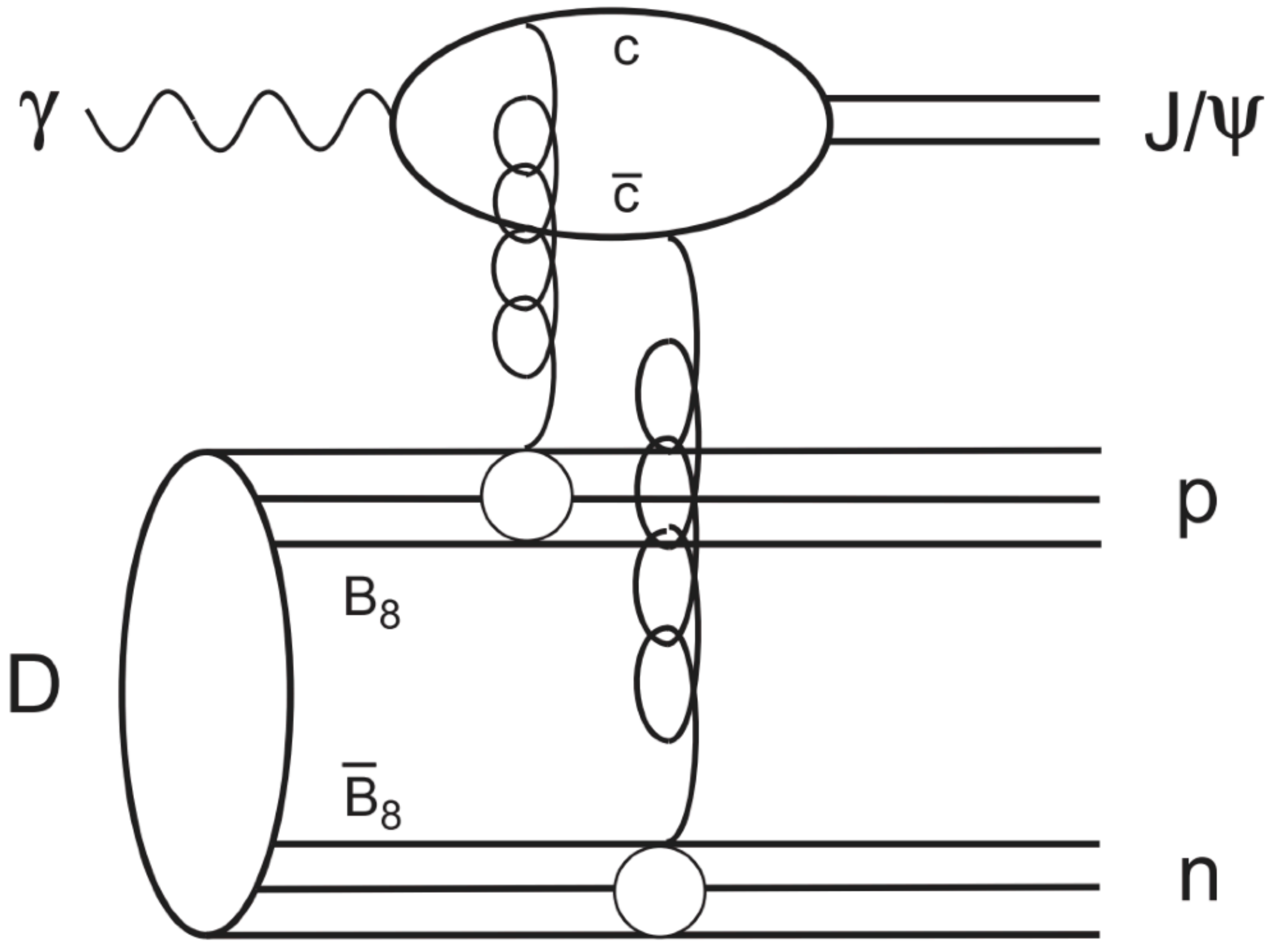
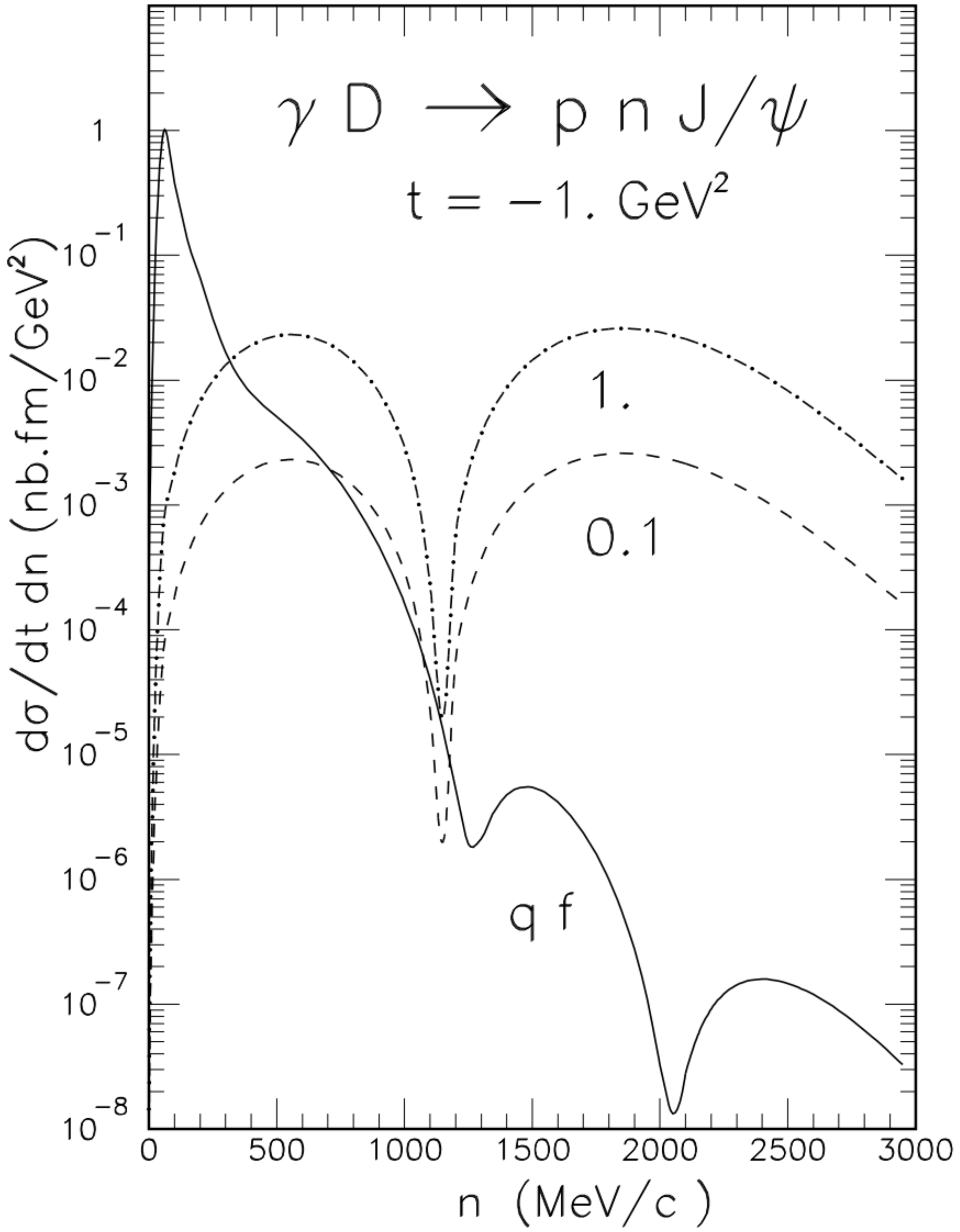


FIG. 4. The simplest diagram which reveals a hidden-color state in deuterium [18].

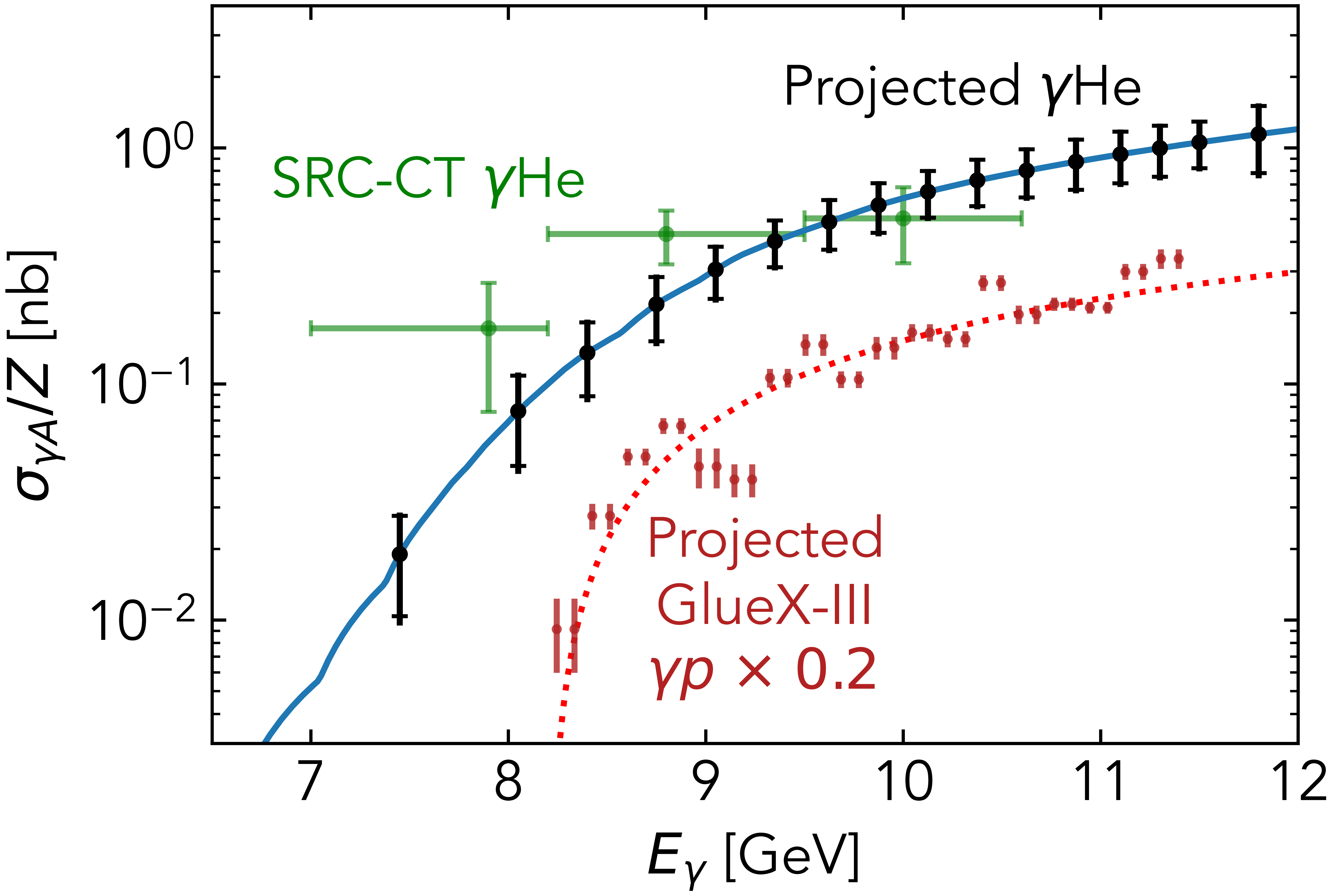


Small hidden-color fractions

Purely nucleonic system

Hoyer, NPA (1997)
Brodsky et al. PLB (2001)

Proposed measurement of 4He can constrain mechanisms of J/ψ production from nuclei at threshold



160-day measurement of a single nucleus; ~800 J/ψ production events

Measure cross section across full energy range and kinematics

Optimized radiator geometry maximizes measurement of sub-threshold production