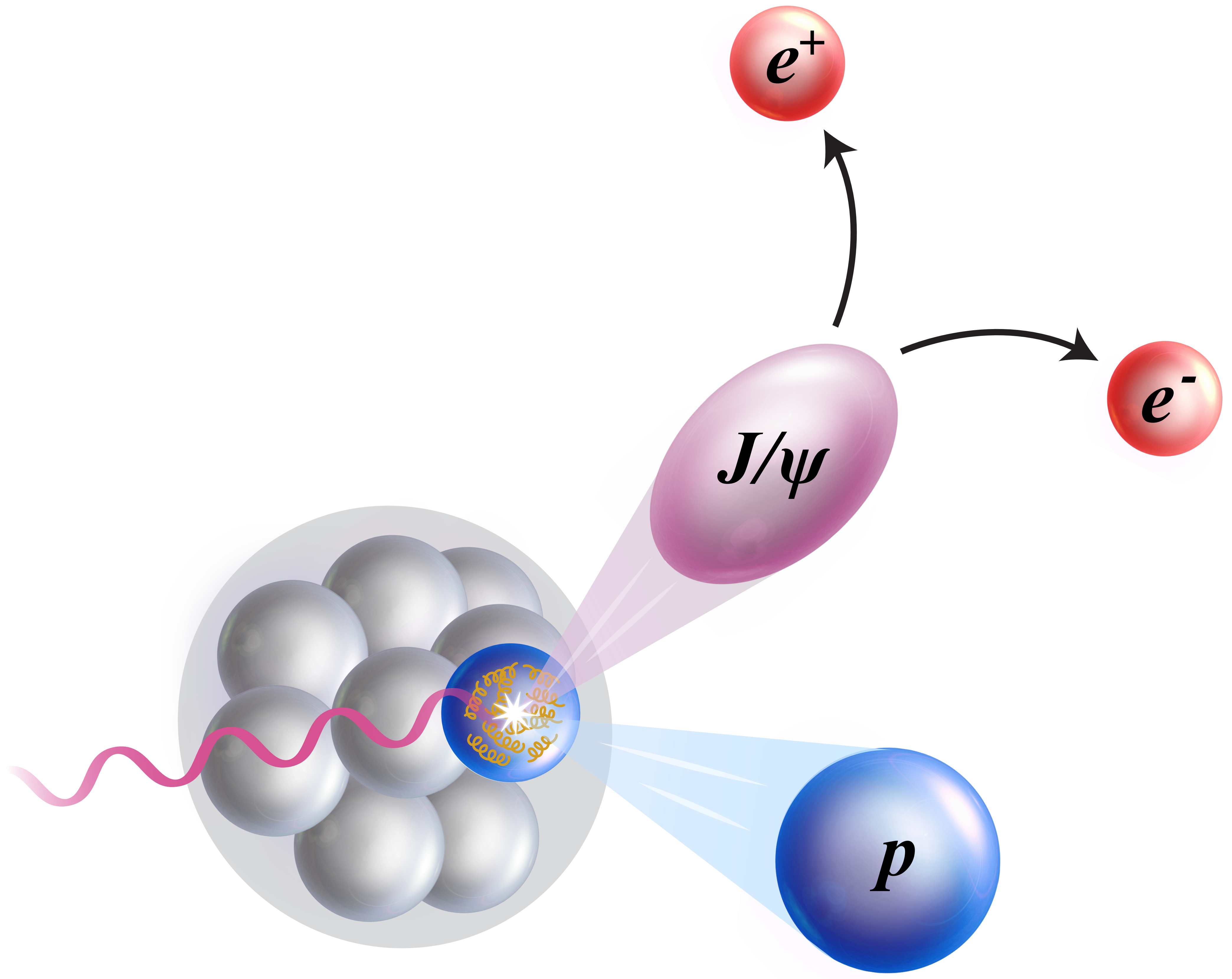
Threshold J/ψ Photoproduction as a Probe of Nuclear Gluon Structure

PR12-25-002 Spokespersons:

D. Dutta (MSU),
H. Gao (Duke)
O. Hen (MIT),
I. Korover (TAU),
T. Kolar (JSI),
J. R. Pybus (LANL),
A. Schmidt (GWU),
A. Somov (JLab),
H. Szumila-Vance (FIU)



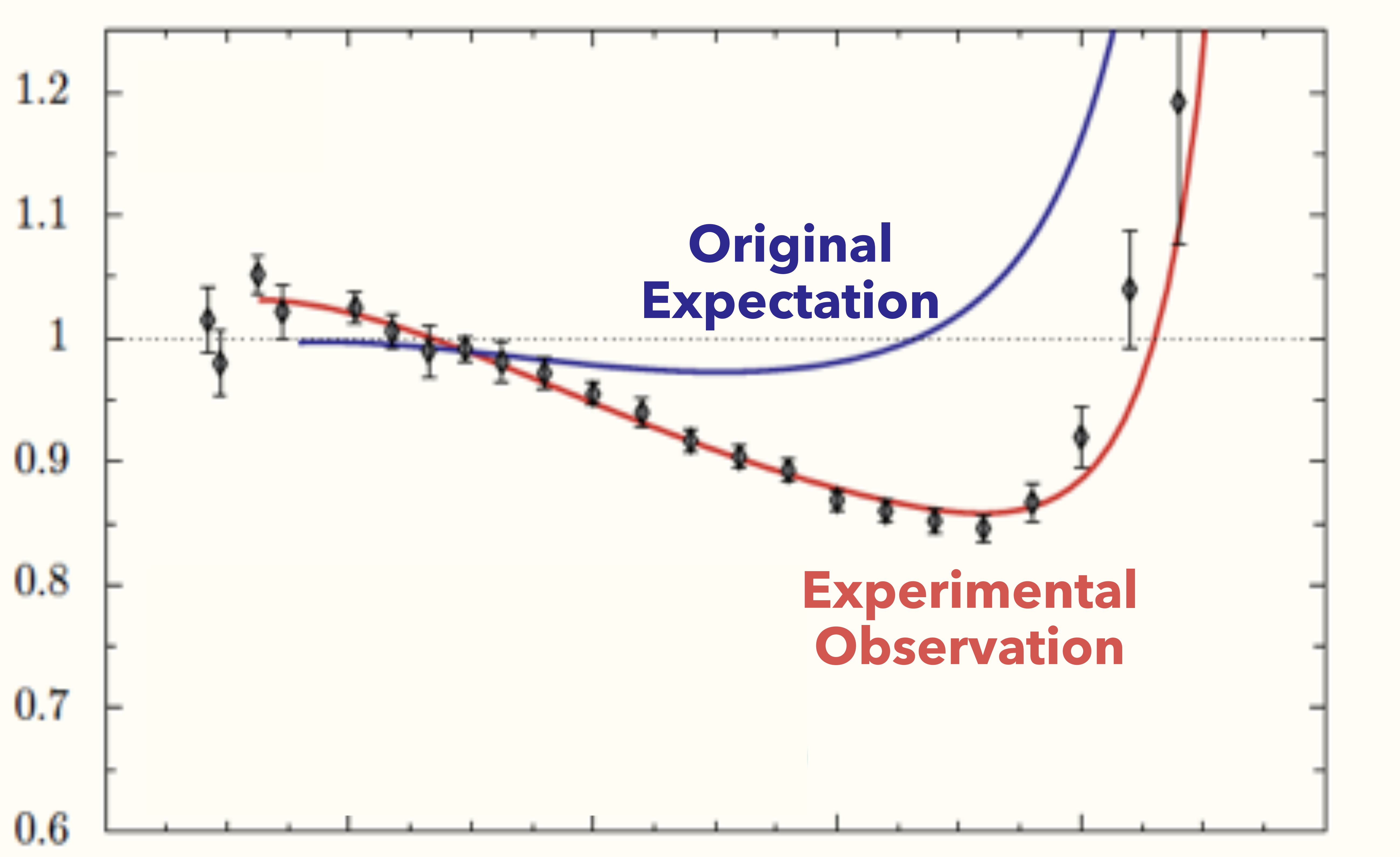
"We hope that, working together, we will achieve a deep understanding of **quarks and gluons**, and precisely how they form **all nuclear matter.**"

–Founding Director Hermann Grunder

Nuclear partons $\neq$

A $\times$ Nucleon partons

Quarks: EMC Effect



Iron / Deuterium Structure Function

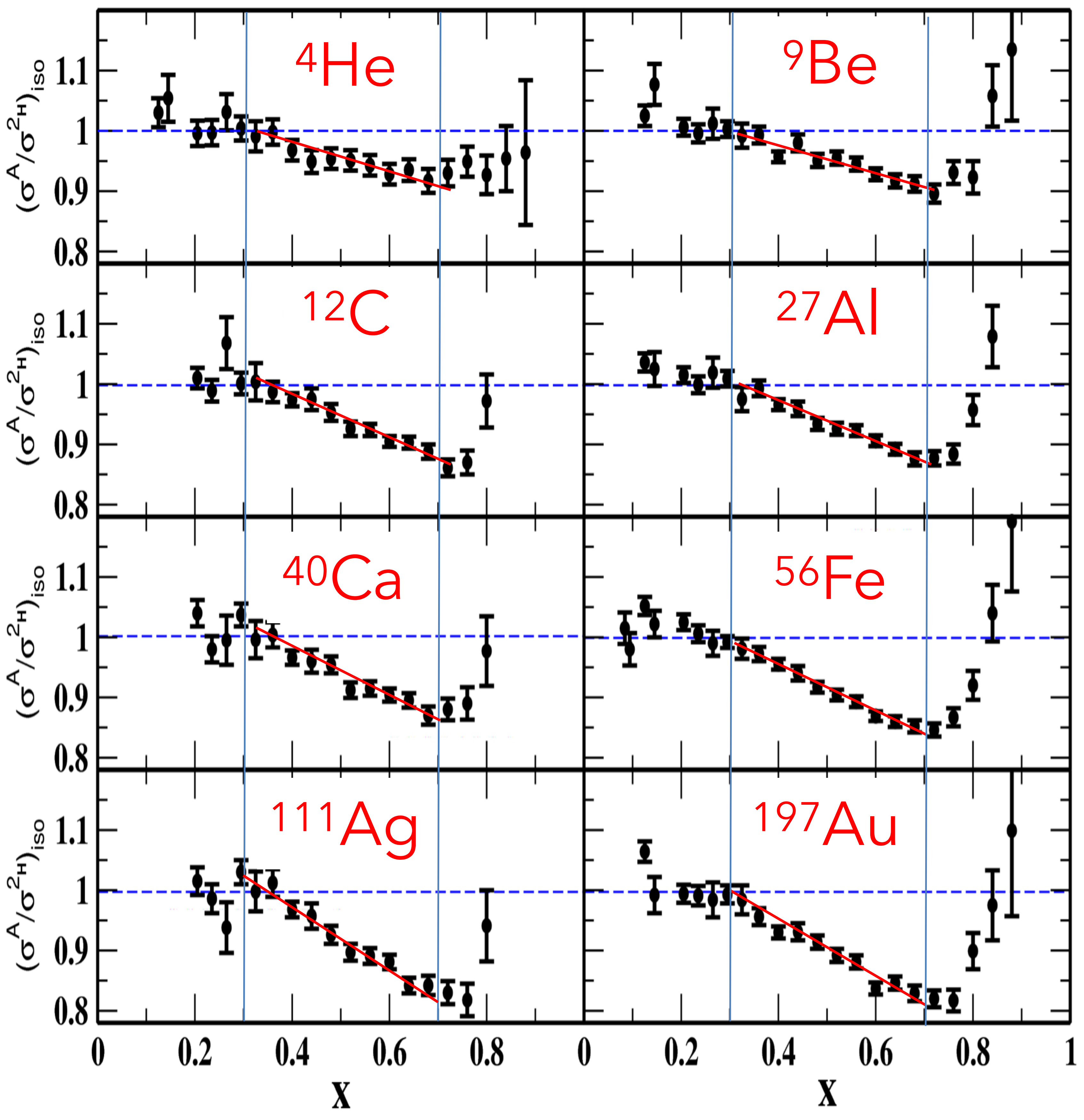
0 0.2 0.4 0.6 0.8 1

x_B

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)

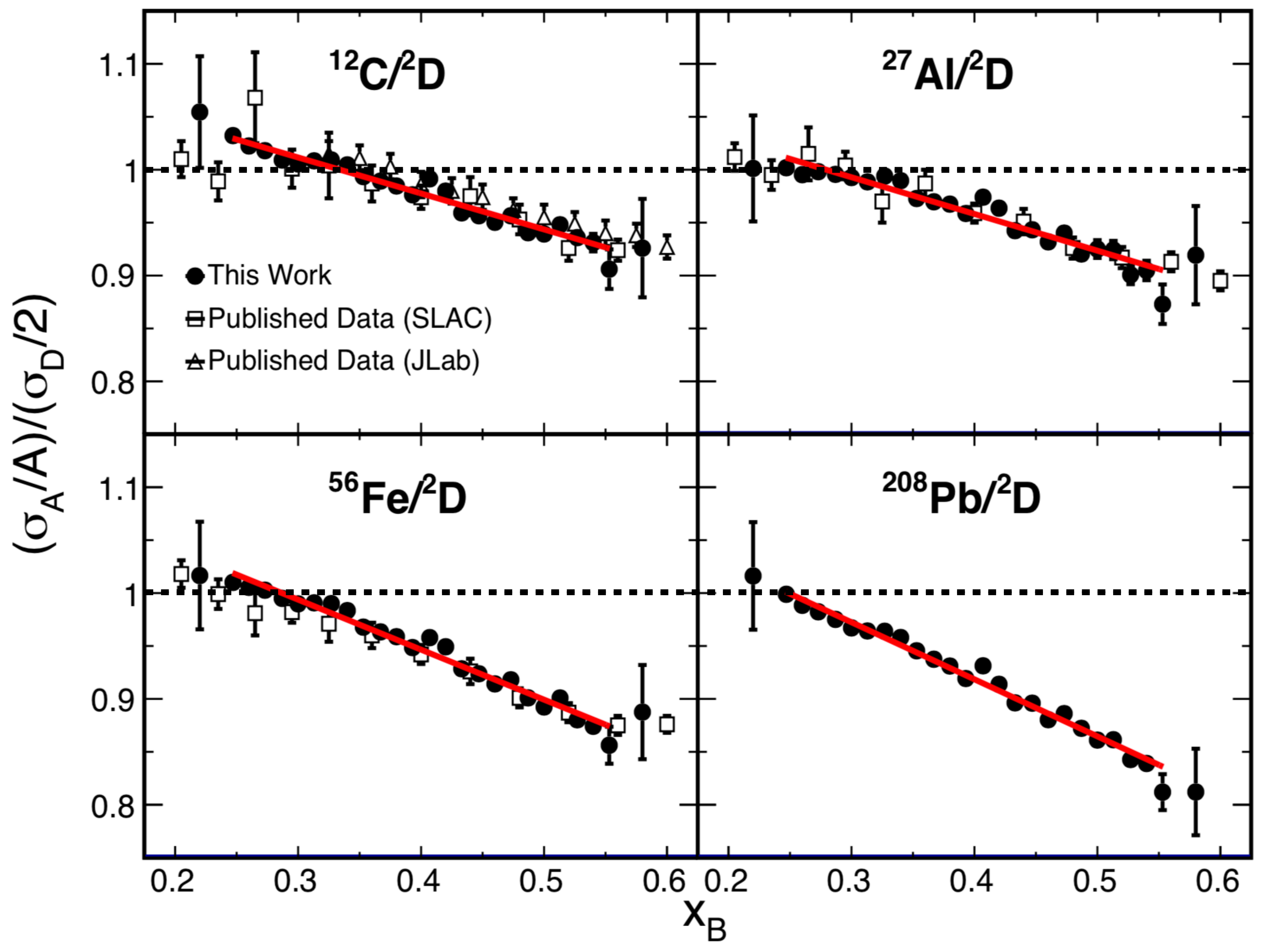
Universal Growth Across Nuclei

SLAC



Gomez et al. PRD (1994)

JLab

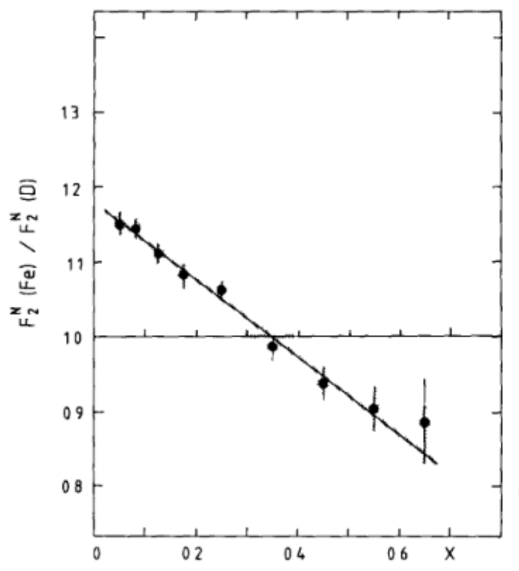


Schmookler et al. Nature (2021)

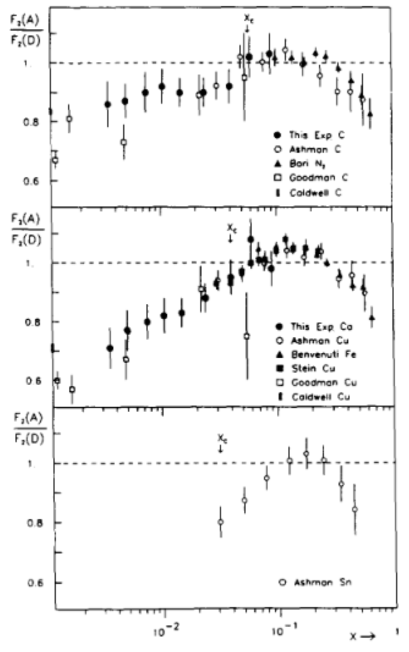
Over 40 Years of Steady Progress

80s - 90s: Observation & Exploration

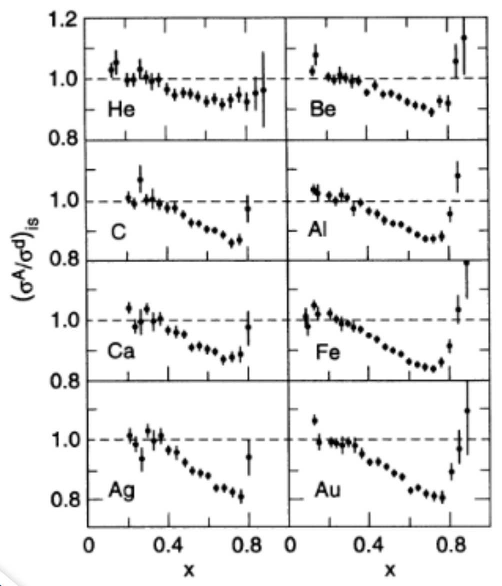
Aubert et al. PLB (1983)



Ashman et al. PLB (1988),
Aachen et al. PLB (1988)



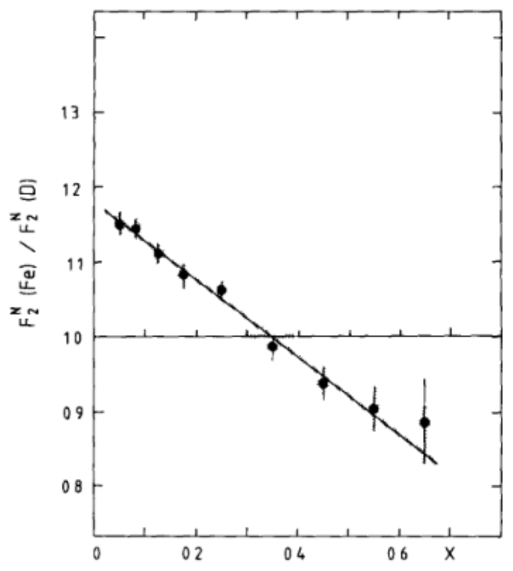
Gomez et al. PRD (1994)



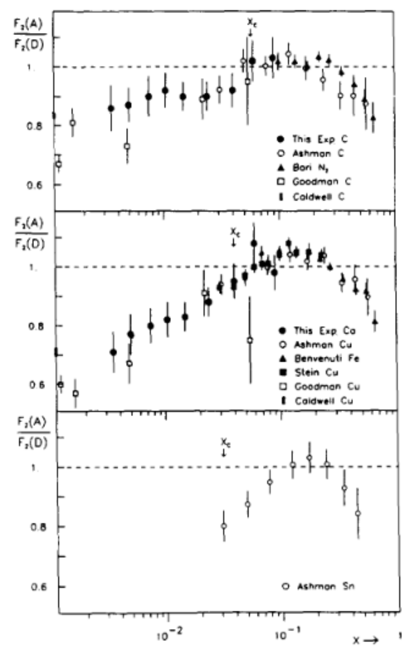
1983 → 1988 → 1994

2000s: JLab Precision Data

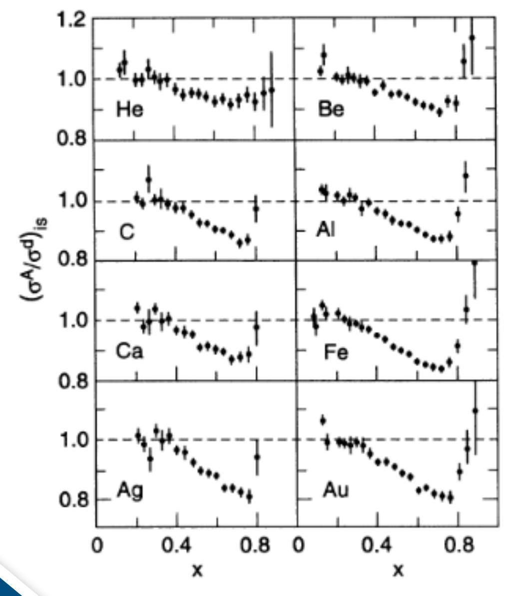
Aubert et al. PLB (1983)



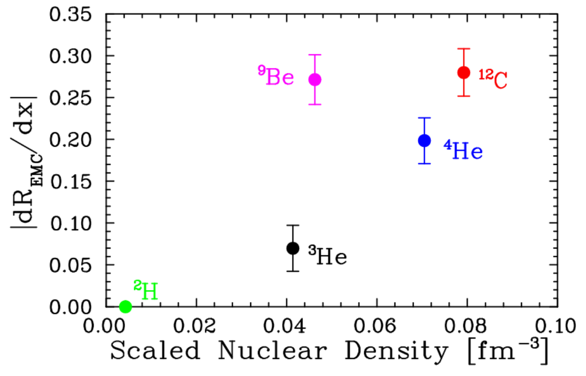
Ashman et al. PLB (1988),
Aachen et al. PLB (1988)



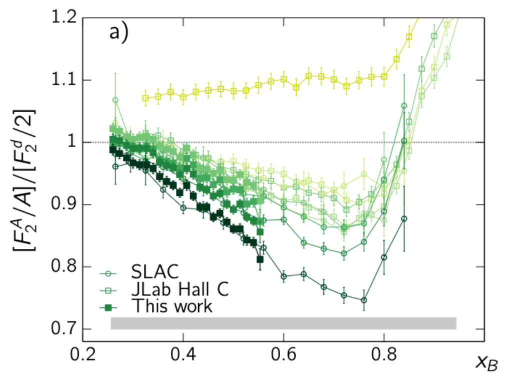
Gomez et al. PRD (1994)

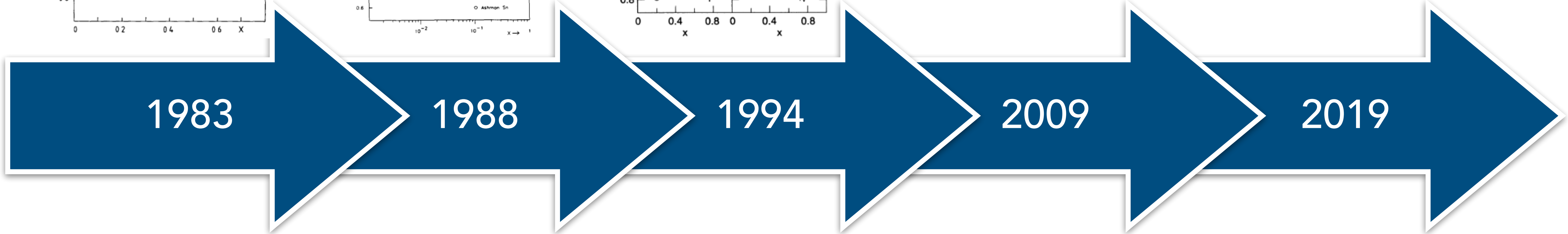


Seely et al. PRL (2009)

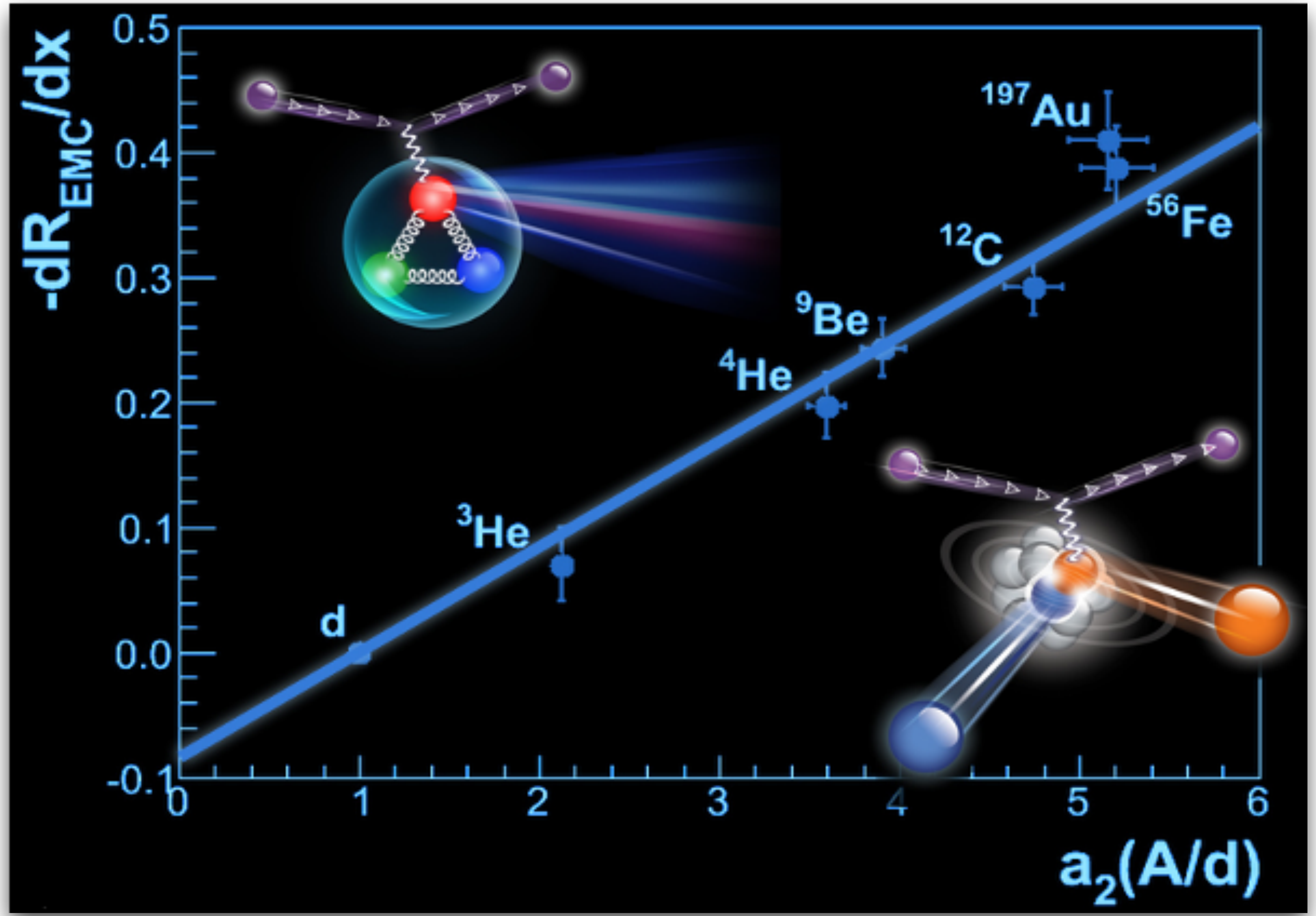


Schmookler et al. Nature (2019)

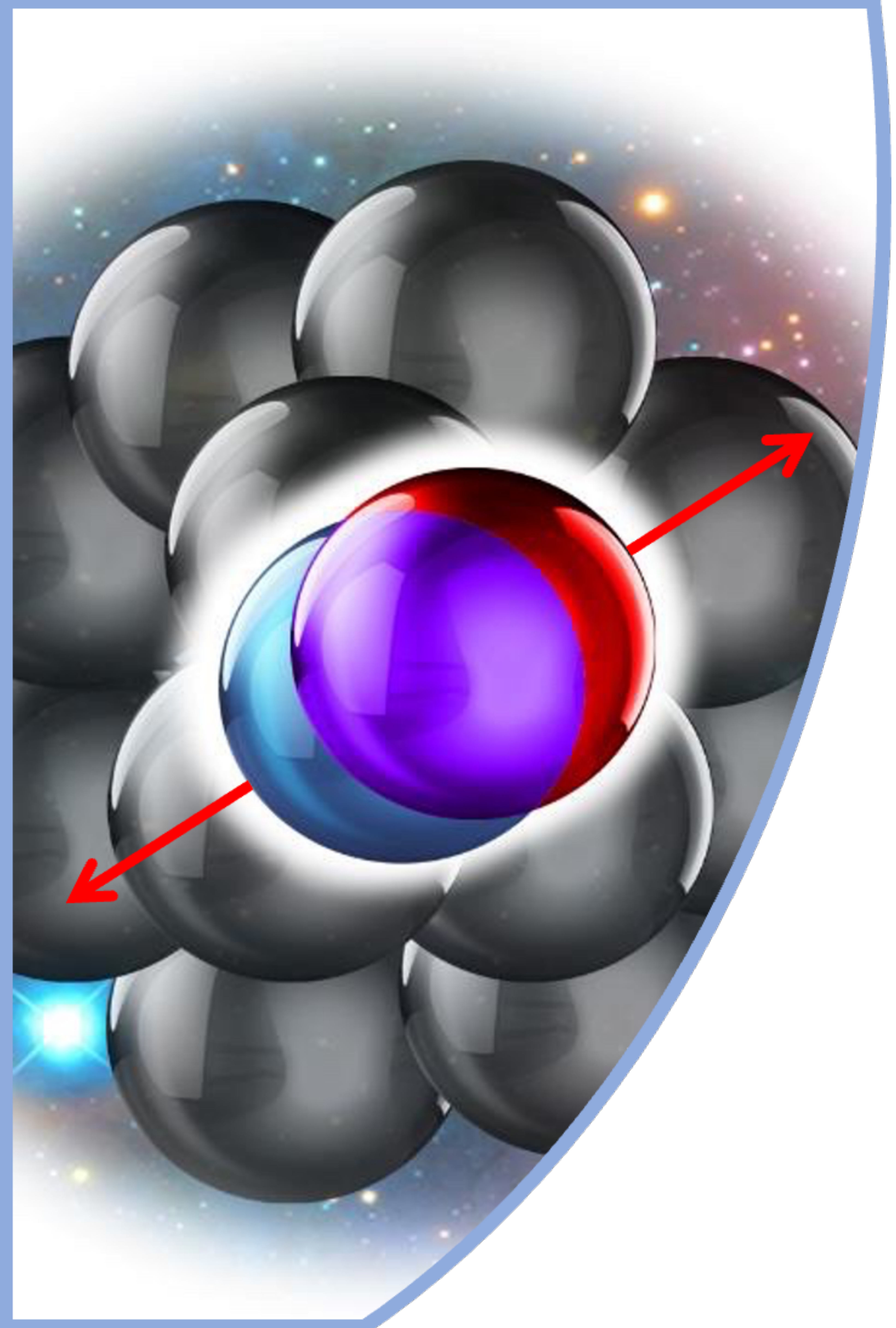




2011: EMC-SRC Correlation

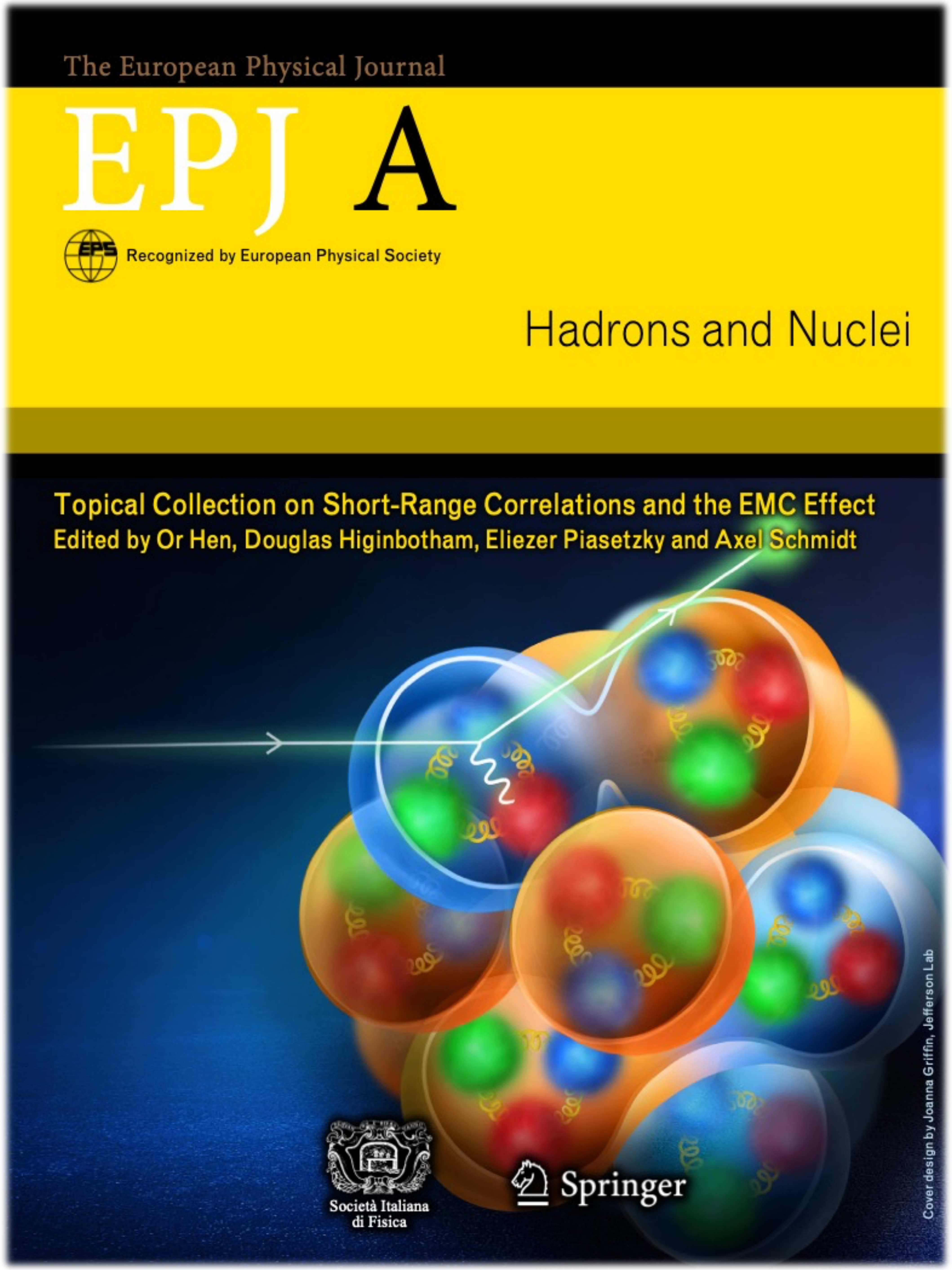


Nature (2019); RMP (2017); IJMPE (2013); PRC (2012); PRL (2011)



Interlude: Short-Range Correlations

Fluctuations of close-proximity nucleon pairs



Isospin Structure:
- Phys. Rev. Lett. 122, 172502 (2019)
- Nature 560, 617 (2018)
- Science 346, 614 (2014)
- Phys. Rev. Lett. 113, 022501 (2014)

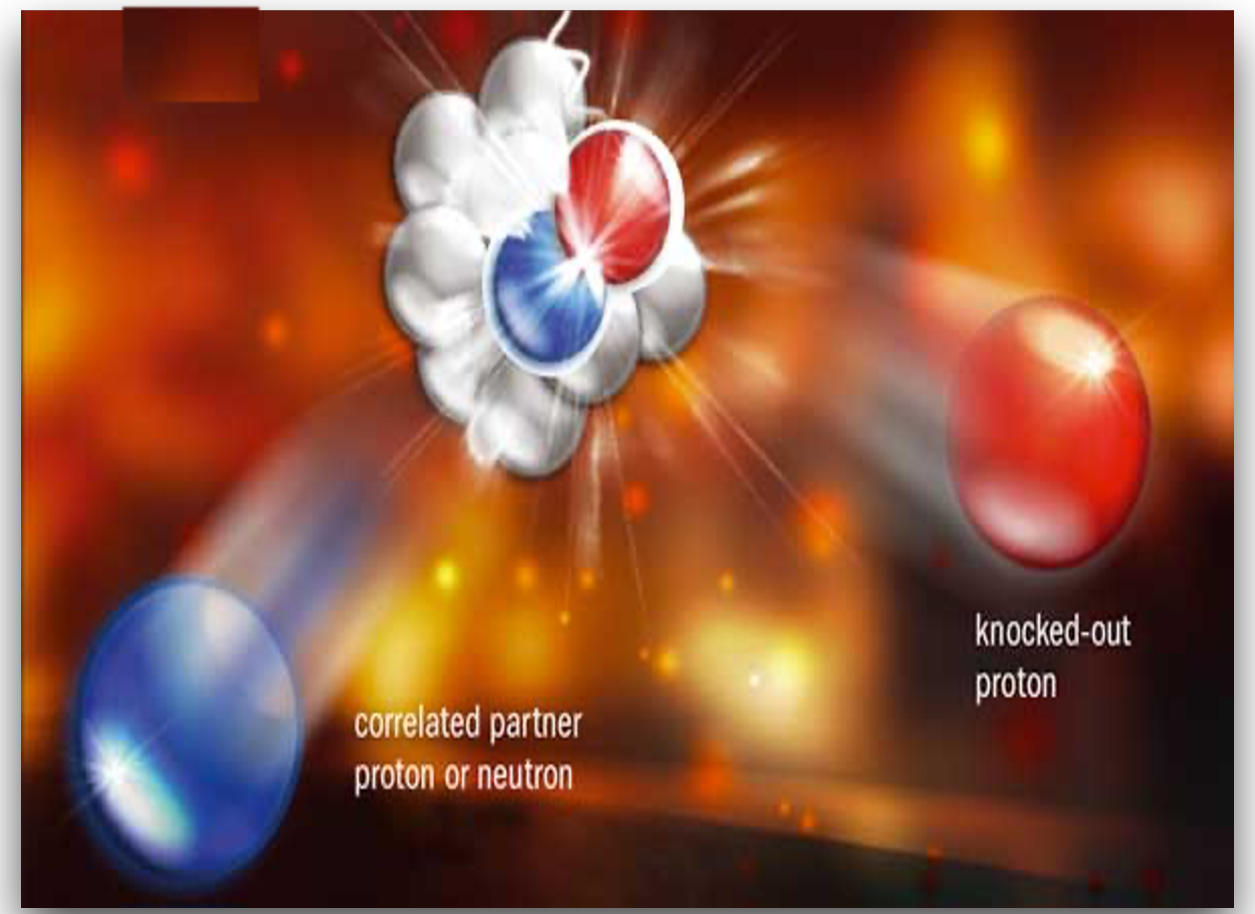
C.M. Motion:
- Phys. Rev. Lett. 121, 092501 (2018)

Hard-Reaction Dynamics:
- Nature Physics 17, 693 (2021)
- Phys. Lett. B 797, 134792 (2019)
- Phys. Lett. B 722, 63 (2013)

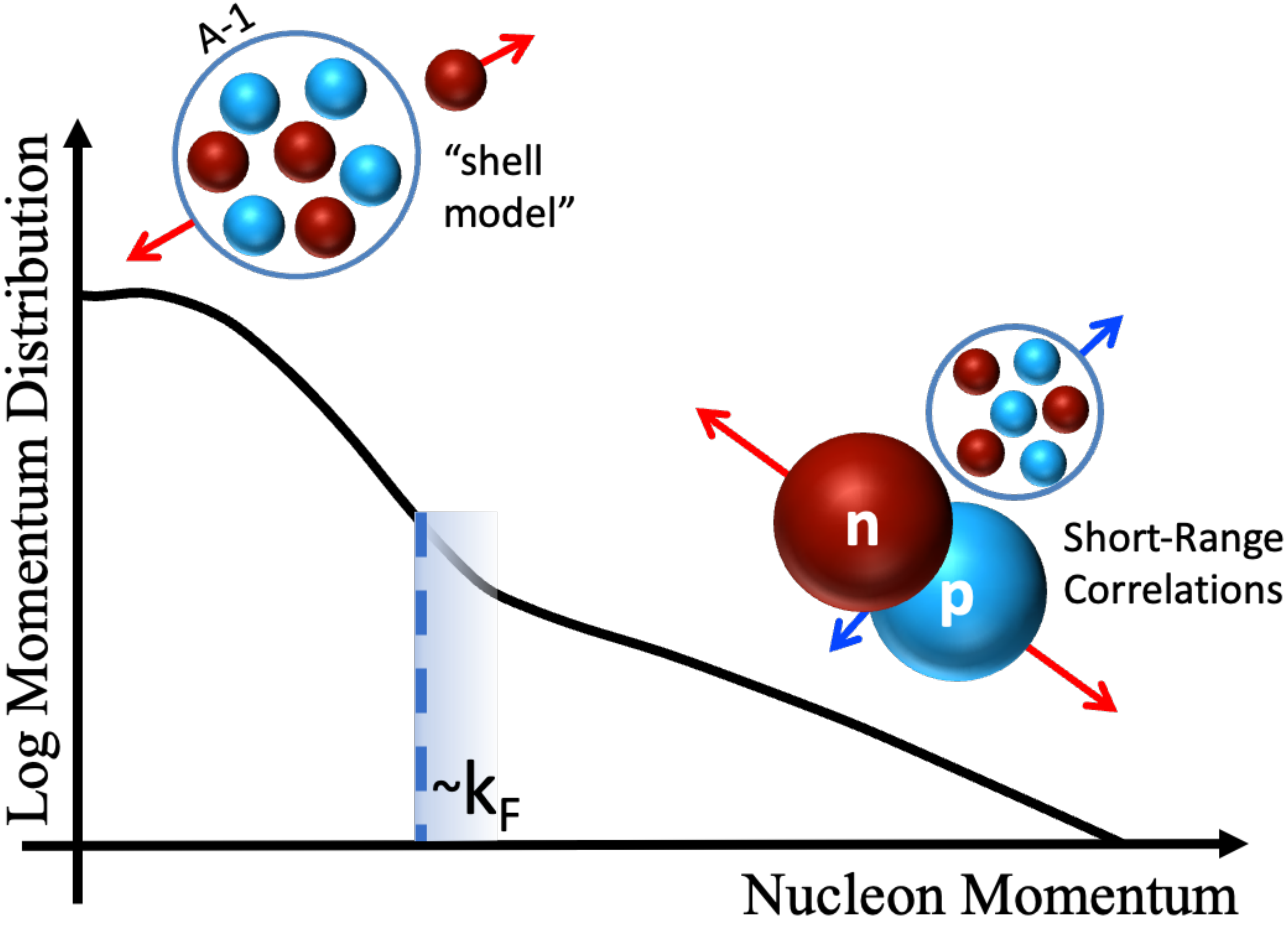
Nuclei / Nuclear Matter Properties:
- Phys. Lett. B 800, 135110 (2020)
- Phys. Lett. B 793, 360 (2019)
- Phys. Lett. B 785, 304 (2018)
- Phys. Rev. C 91, 025803 (2015)

Effective Theory:
- Nature Physics 17, 306 (2021)
- Phys. Lett. B 805, 135429 (2020)
- Phys. Lett. B 791, 242 (2019)

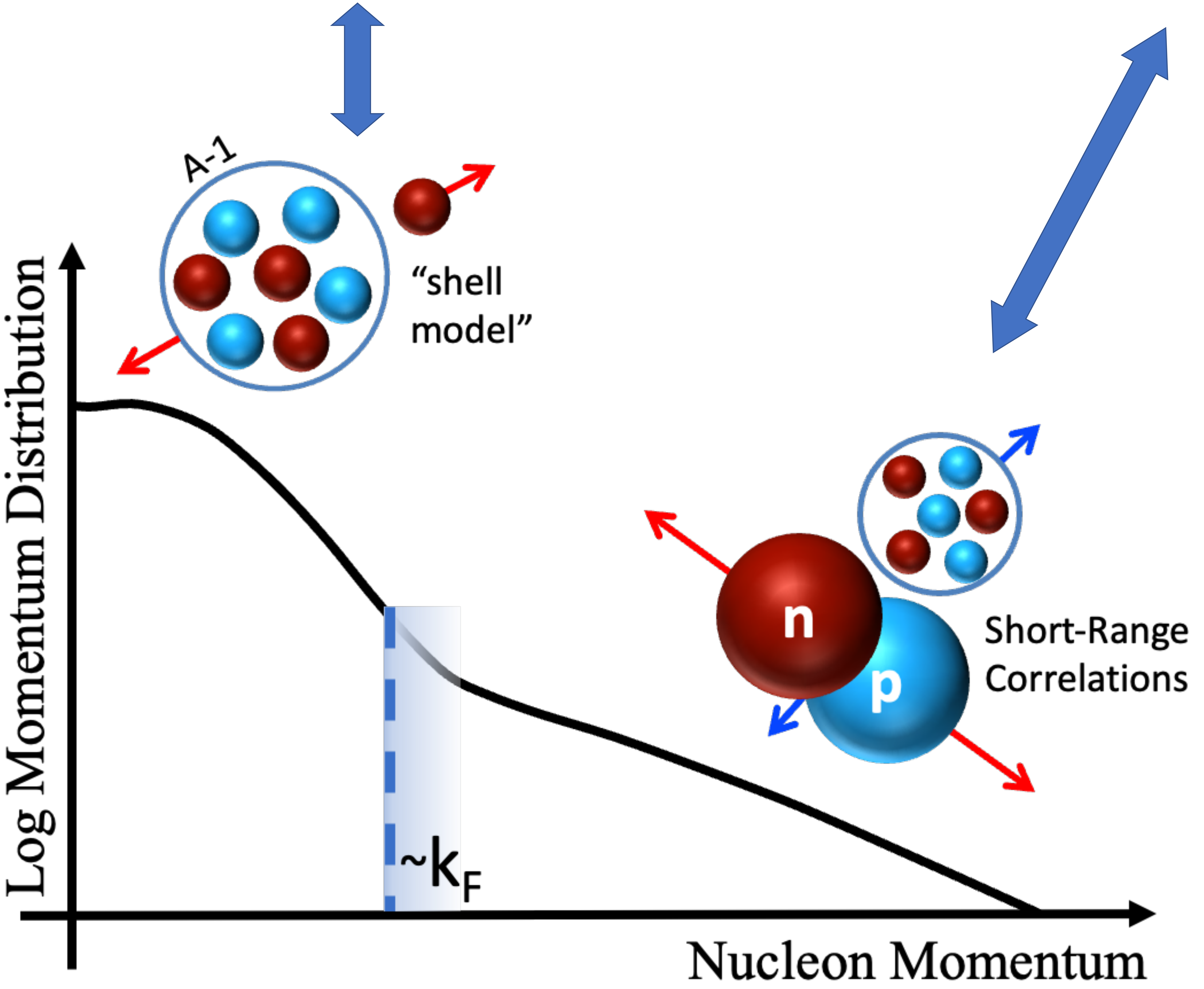
Quantum Numbers, Mass, Asymmetry Dependence:
- Phys. Rev. C 103, L031301 (2023)
- Phys. Lett. B 780, 211 (2018)
- PRC 92, 024604 (2015)
- PRC 92, 045205 (2015)



The Two-Phased Nucleus

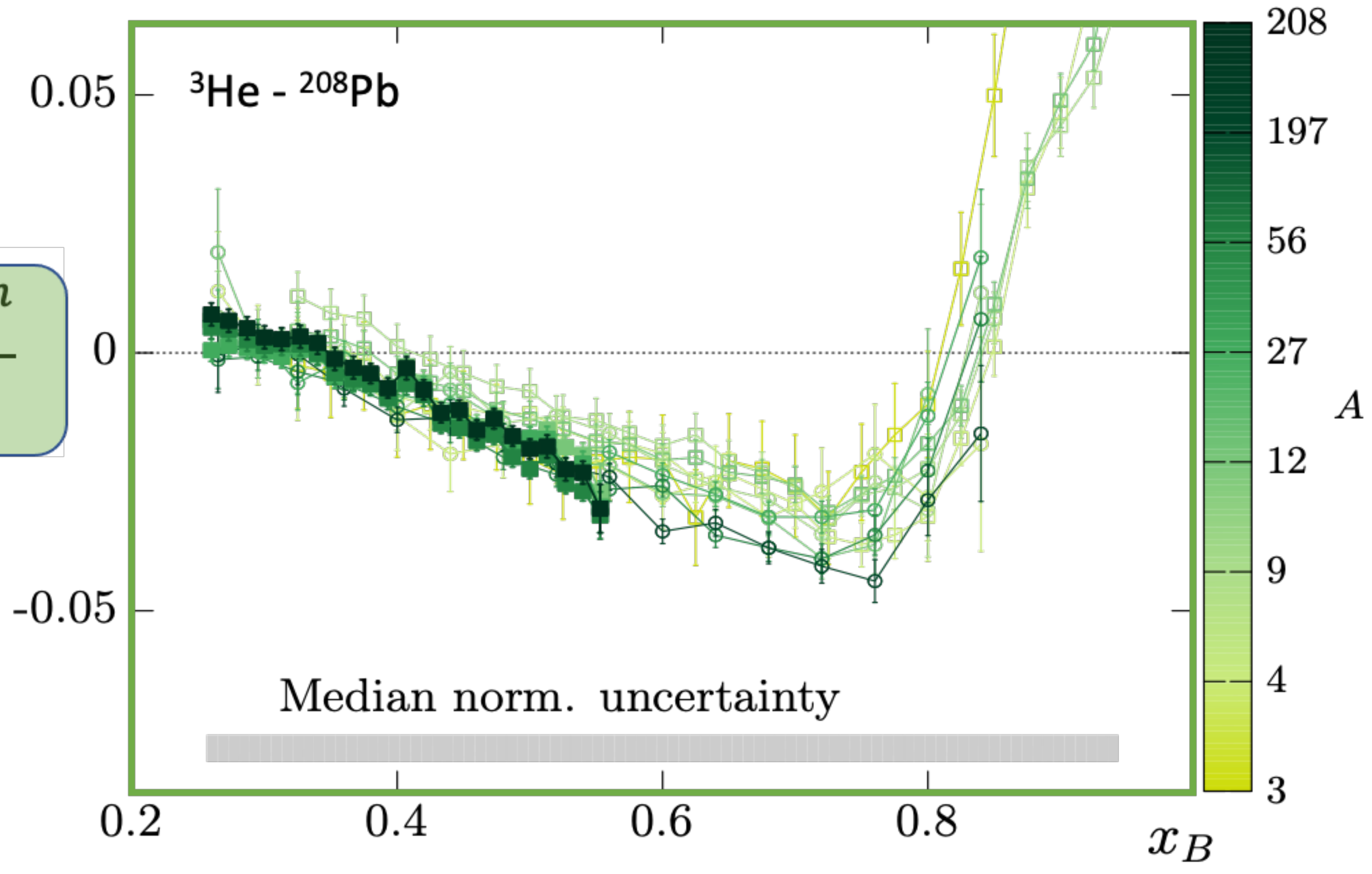


Bound = 'quasi Free' + Modified SRCs



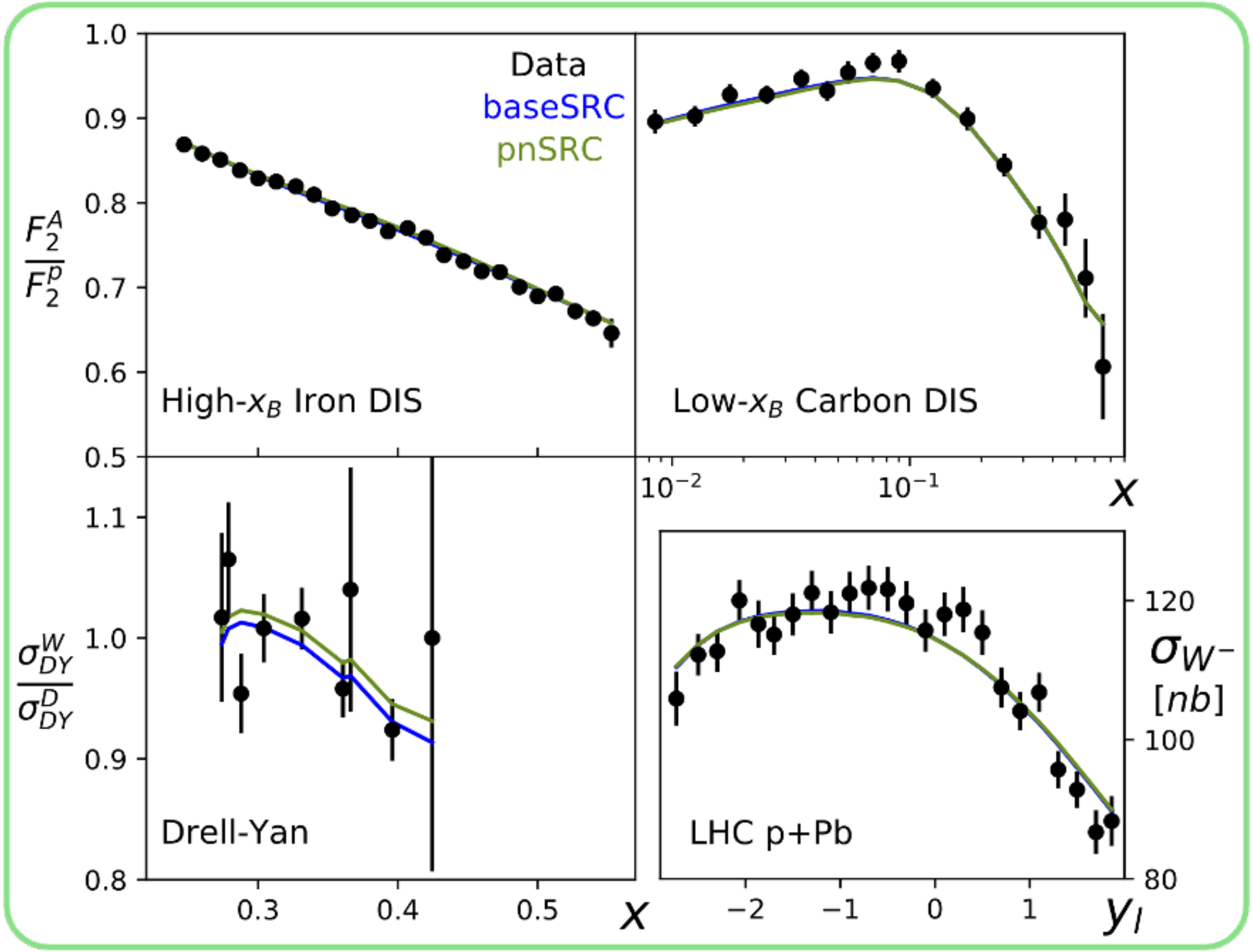
SRCs experience *universal* modification

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



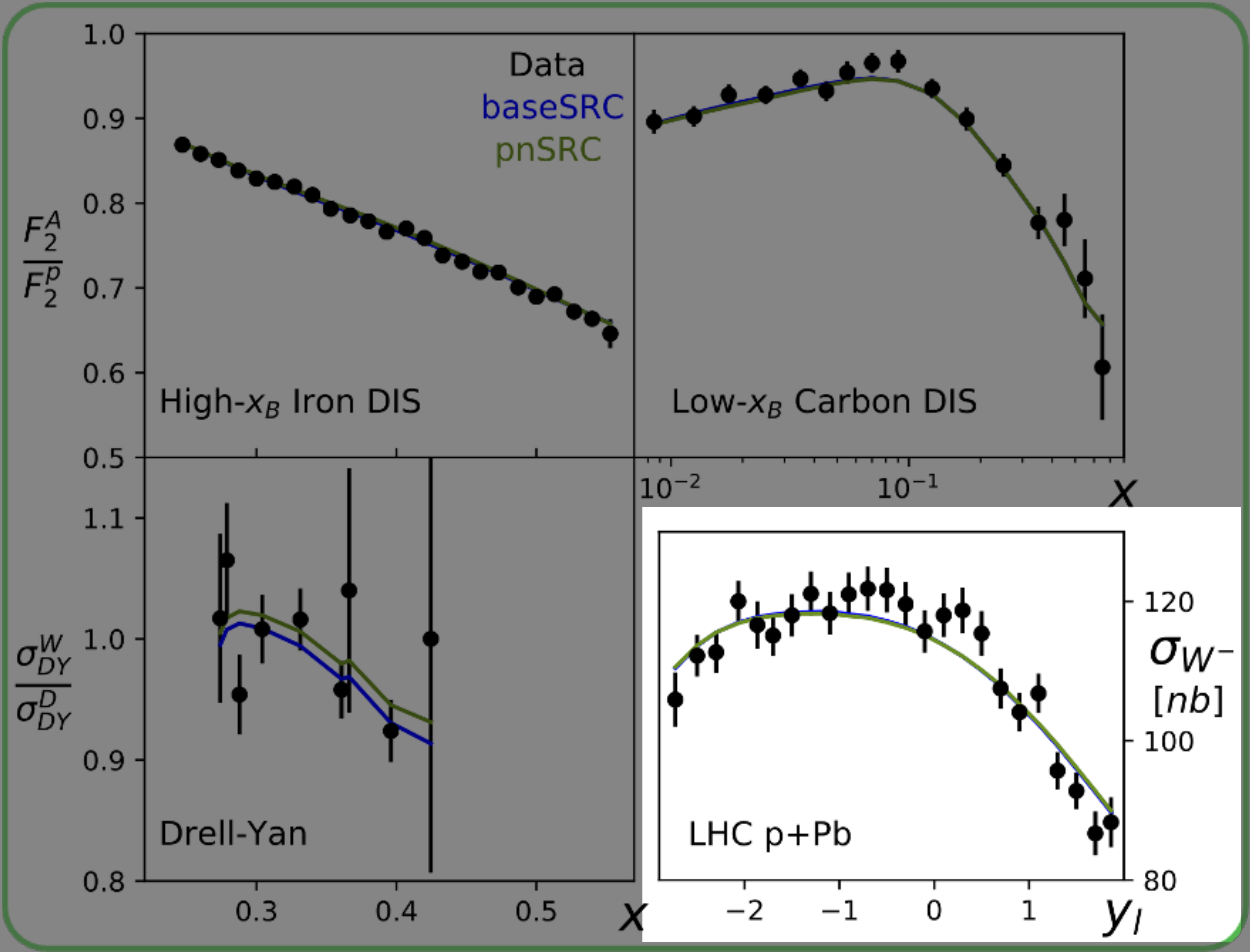
Schmookler et al. Nature (2021)

Global analysis of nPDF data under SRC nuclear-structure framework



Denniston et al. PRL (2024)

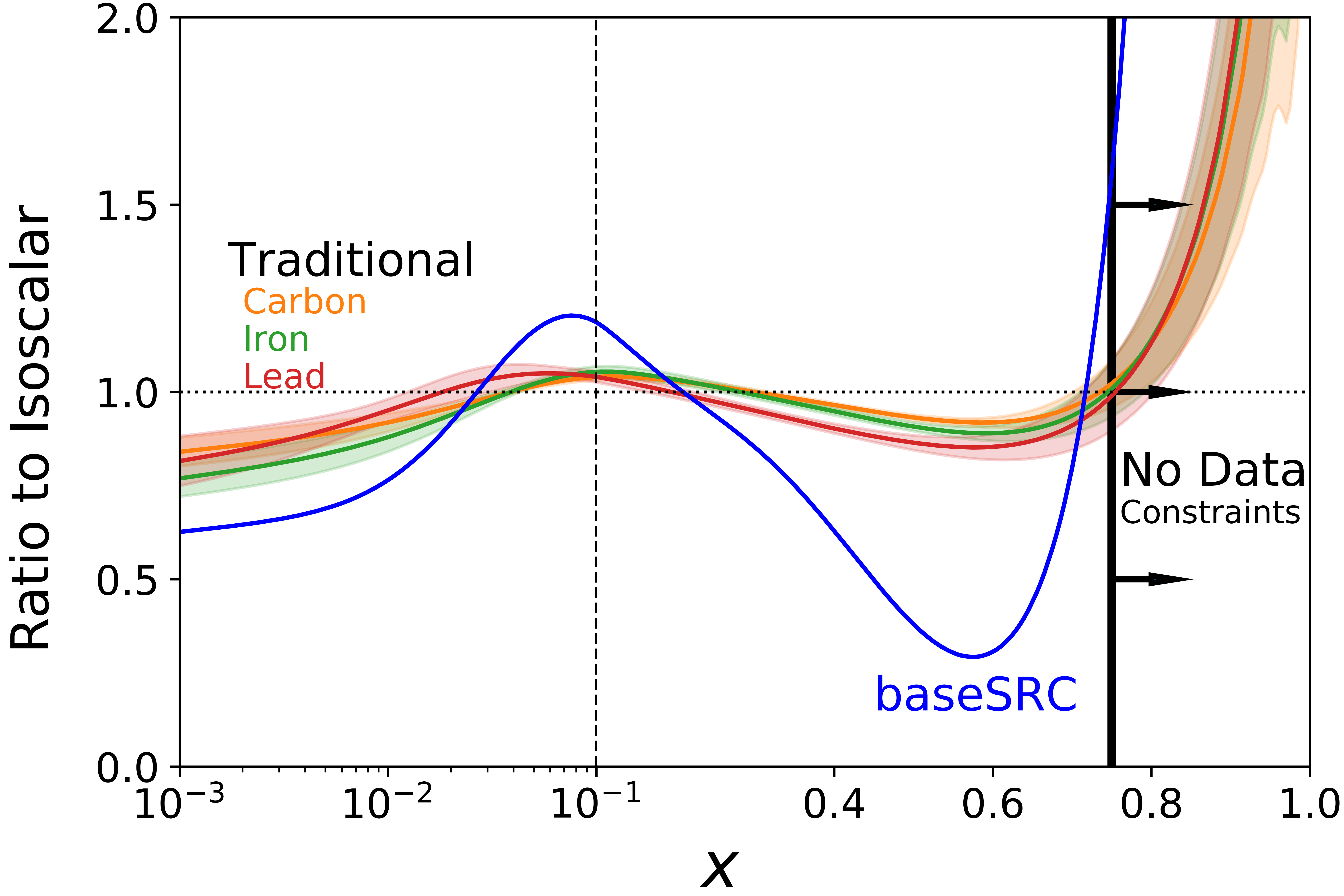
Global analysis of nPDF data under SRC nuclear-structure framework

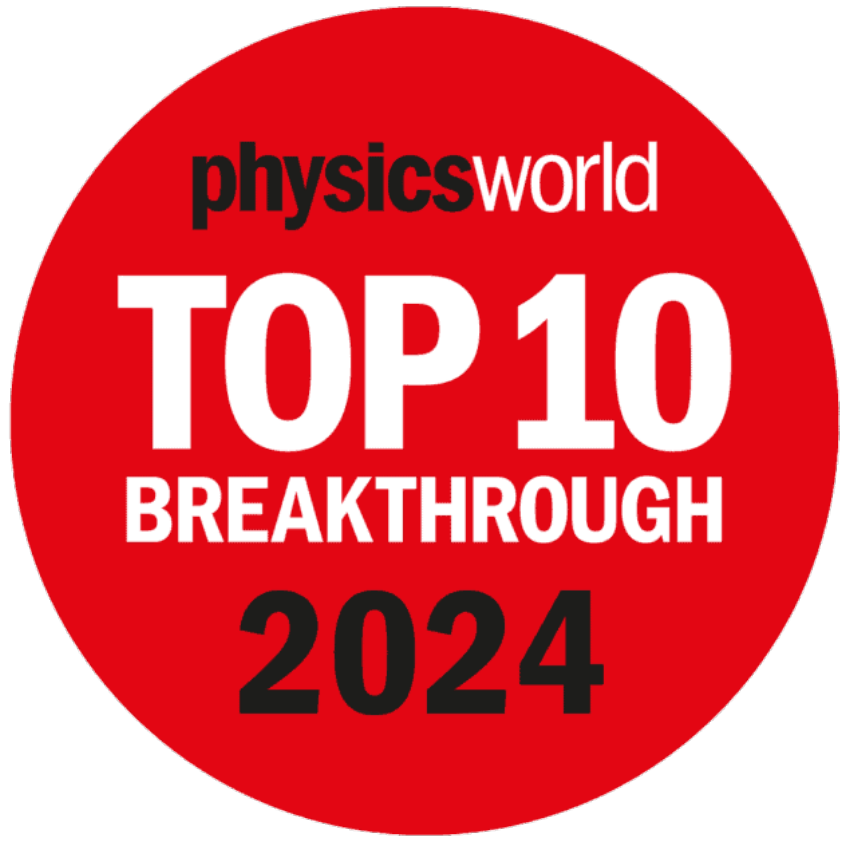


physicsworld TOP 10 BREAKTHROUGH 2024

Denniston et al. PRL (2024)

Global analysis of nPDF data under SRC nuclear-structure framework

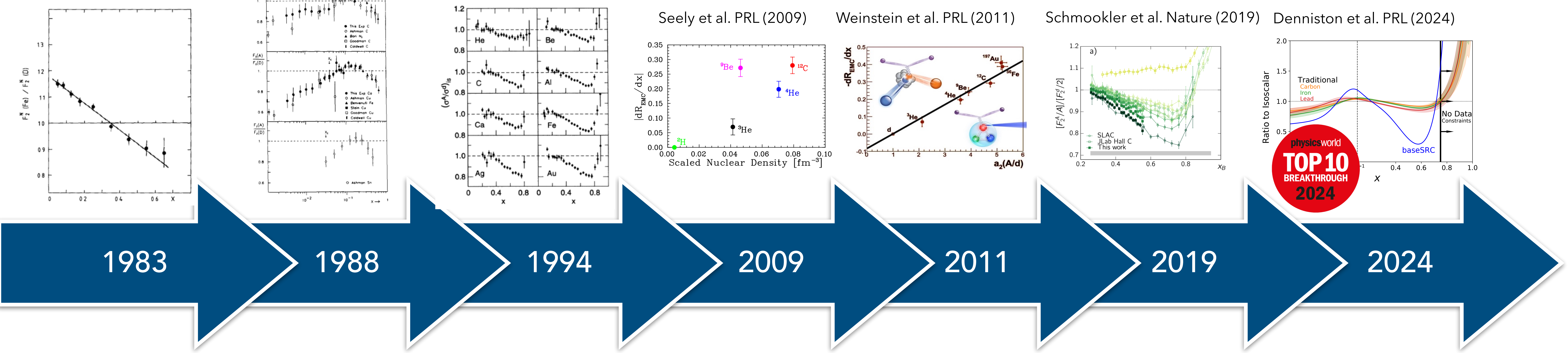




Denniston et al. PRL (2024)

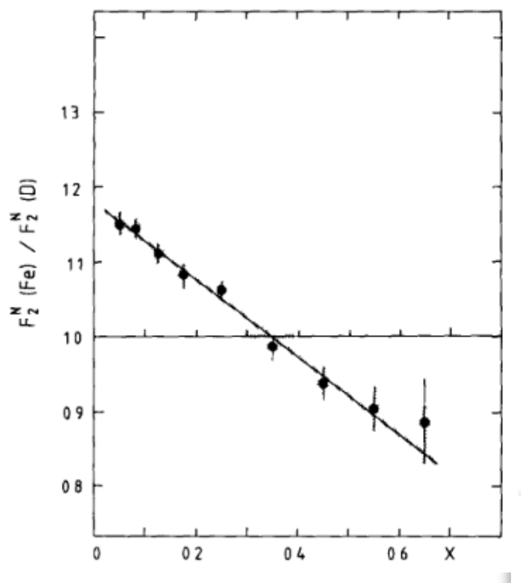
Today: New nuclear-particle bridge!

Aubert et al. PLB (1983)
Ashman et al. PLB (1988),
Aachen et al. PLB (1988)
Gomez et al. PRD (1994)
Seely et al. PRL (2009)
Weinstein et al. PRL (2011)
Schmookler et al. Nature (2019)
Denniston et al. PRL (2024)

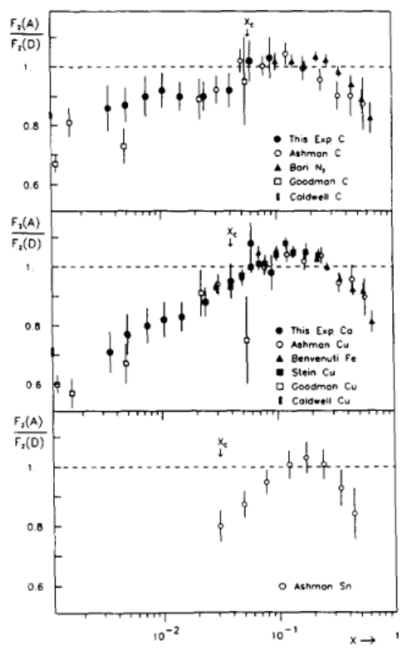


+ New Observables @ JLab & EIC

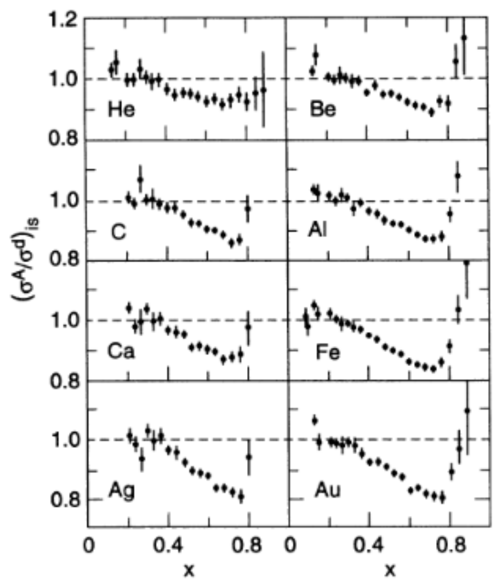
Aubert et al. PLB (1983)



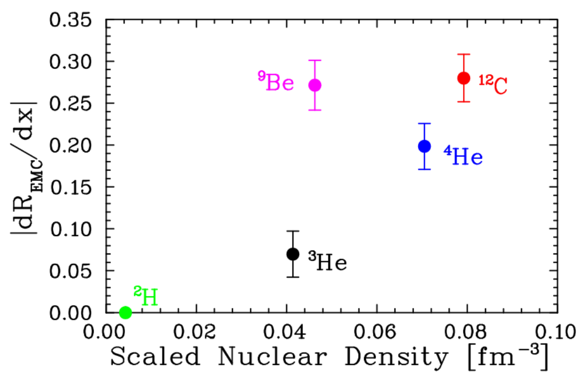
Ashman et al. PLB (1988),
Aachen et al. PLB (1988)



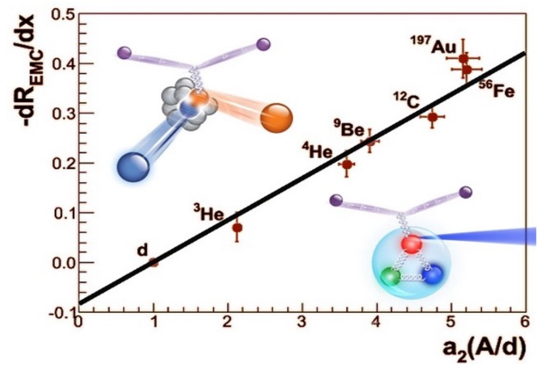
Gomez et al. PRD (1994)



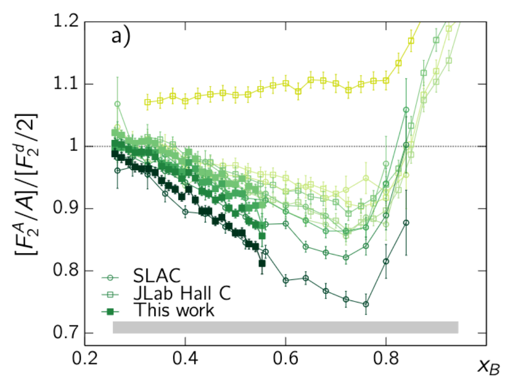
Seely et al. PRL (2009)



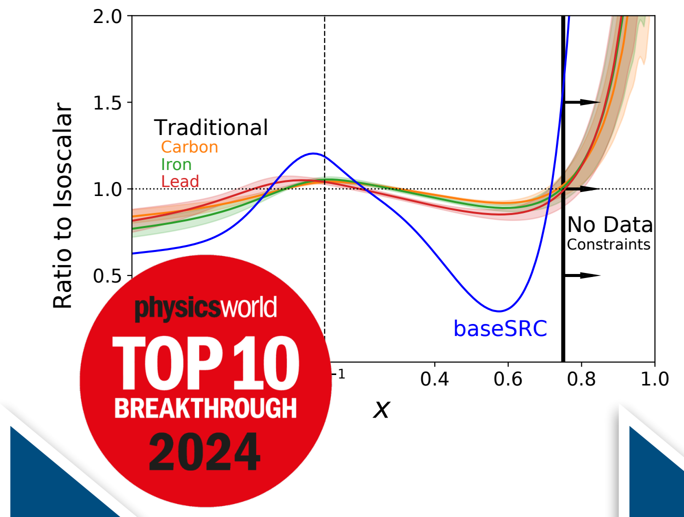
Weinstein et al. PRL (2011)



Schmookler et al. Nature (2019)



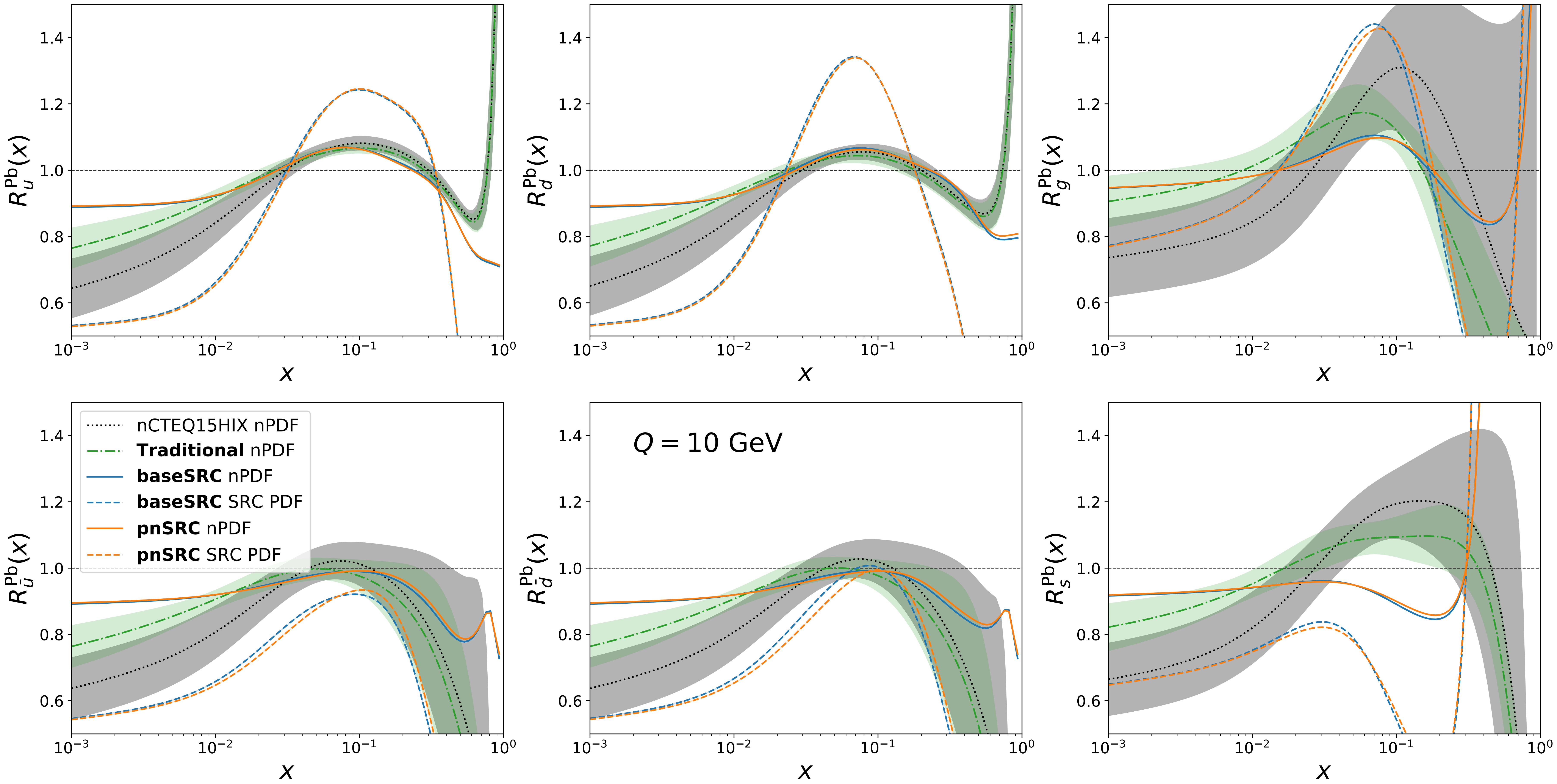
Denniston et al. PRL (2024)



1983 → 1988 → 1994 → 2009 → 2011 → 2019 → 2024 → Present

- **Precision nuclear dependence (E12-10-008, E12-06-105)**
- **Spectator-tagging (BAND, ALERT, LAD)**
- **Polarized EMC Effect (E12-14-001)**

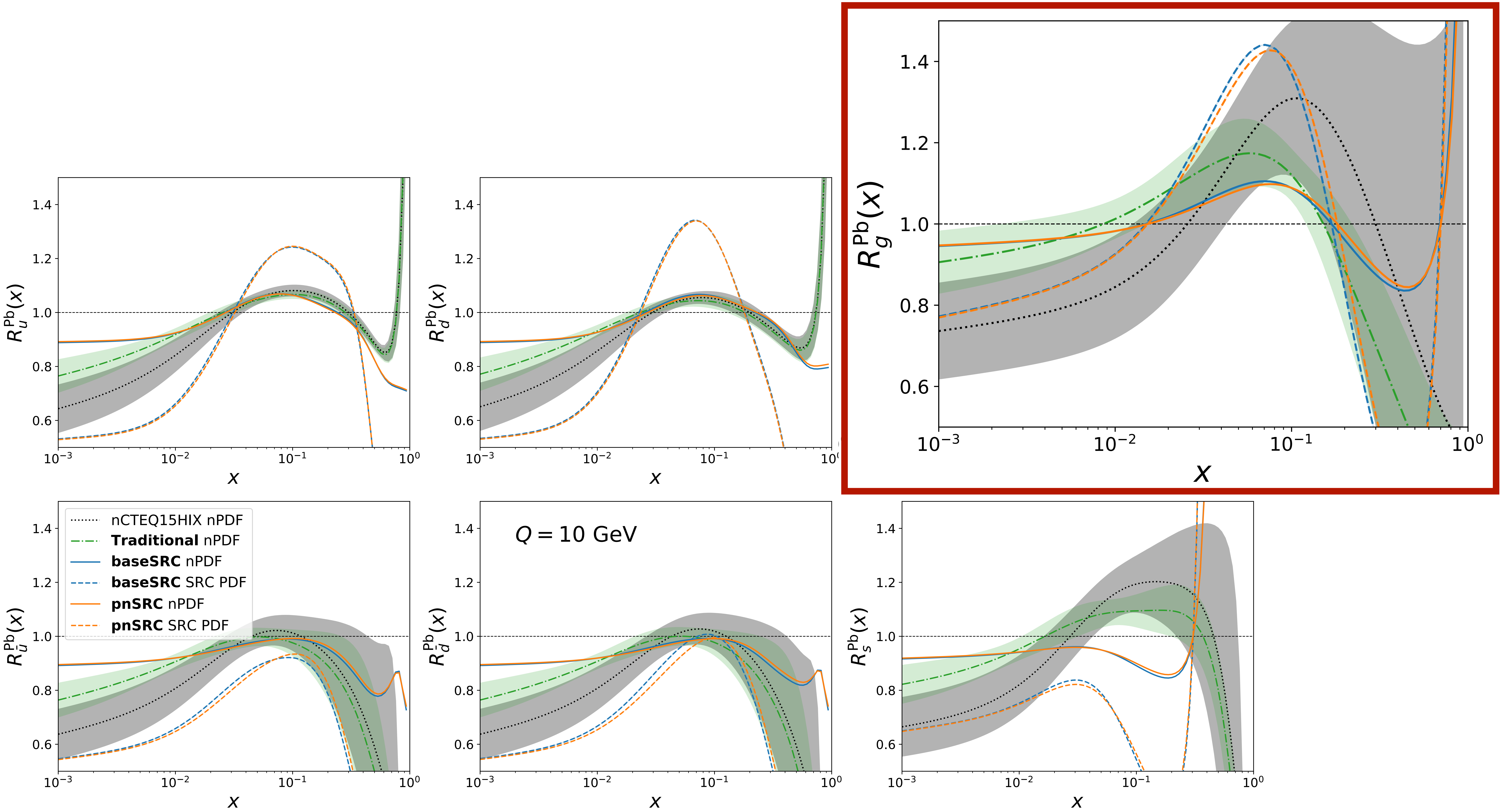
Working to understand the full partonic structure of nuclei



physicsworld TOP 10 BREAKTHROUGH 2024

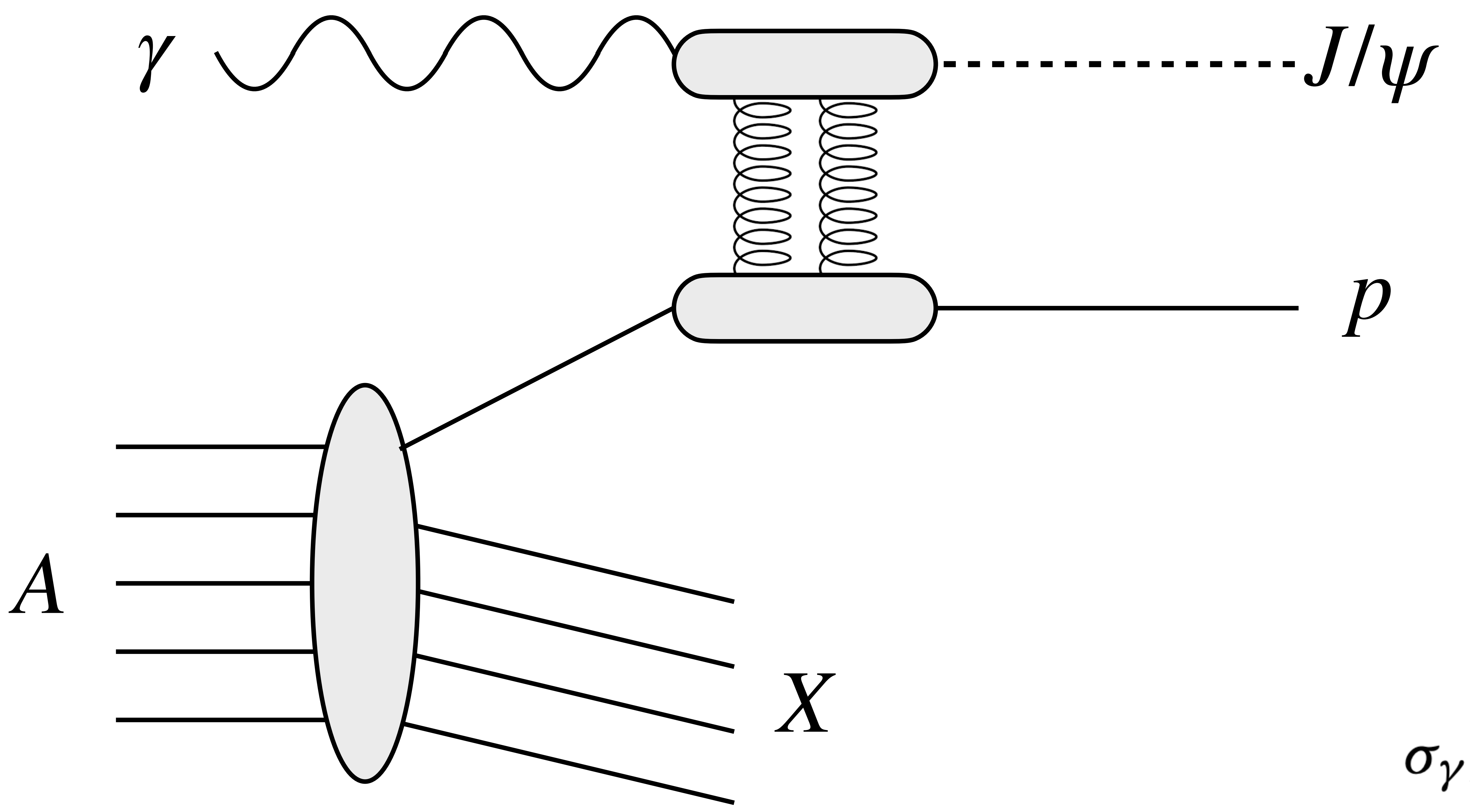
Denniston et al. PRL (2024)

But... High-x Gluons lag behind!

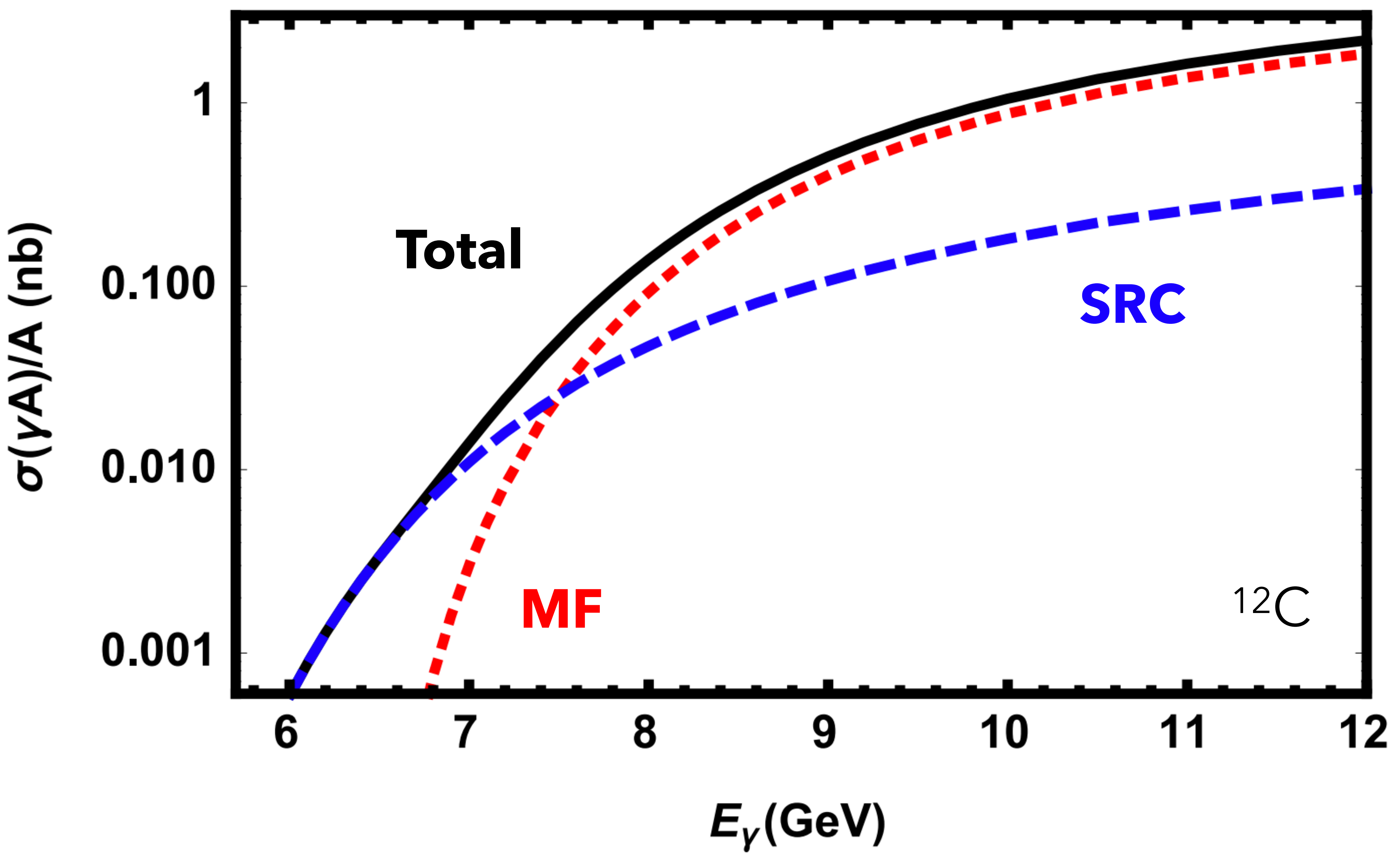


Denniston et al. PRL (2024)

Proposal: Gluonic Probes of SRC Structure



Y. Hatta et al, PLB 2020



$$\sigma_{\gamma A} = A \int d^3k d\epsilon \, \rho_A(k,\epsilon) \widetilde{\mathcal{F}}(k,\epsilon) \sigma_{\gamma p}(W_{\gamma p'})$$

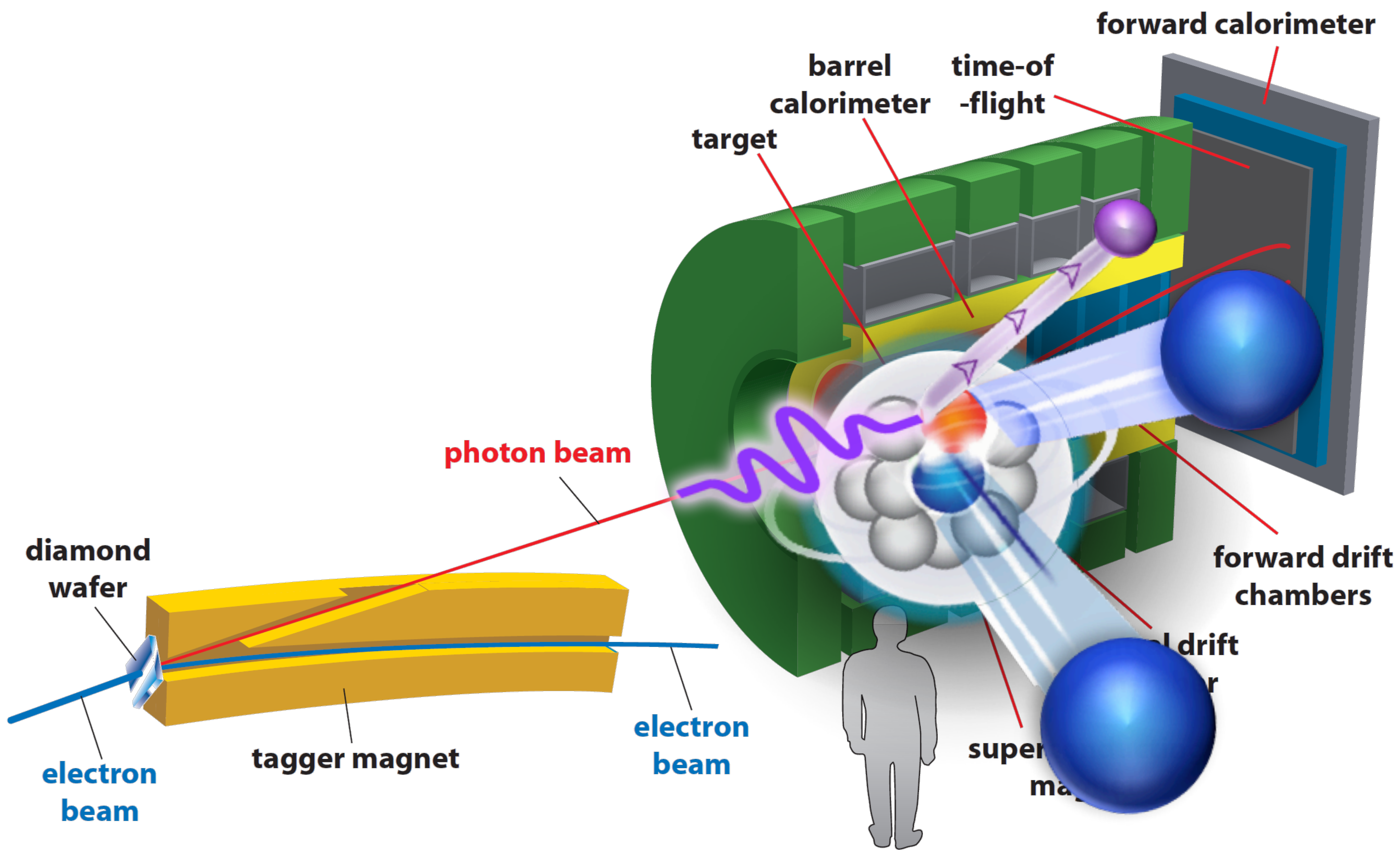
Spectral function (MF + SRC) — $\rho_A(k,\epsilon)$

Flux factor — $\widetilde{\mathcal{F}}(k,\epsilon)$

Free-proton cross section — $\sigma_{\gamma p}(W_{\gamma p'})$

First Observation: Hall D SRC-CT Experiment

- Late 2021: First Hall D nuclear target run
- ^{2}H, ^{4}He, ^{12}C targets with GlueX spectrometer
- **15 PAC days, B+ rating**
- Publications: Phys. Rev. Lett Editors' Suggestion; Phys. Lett. B; Multiple analyses entering final review
- 2 Ph.D. theses complete; 3 ongoing!

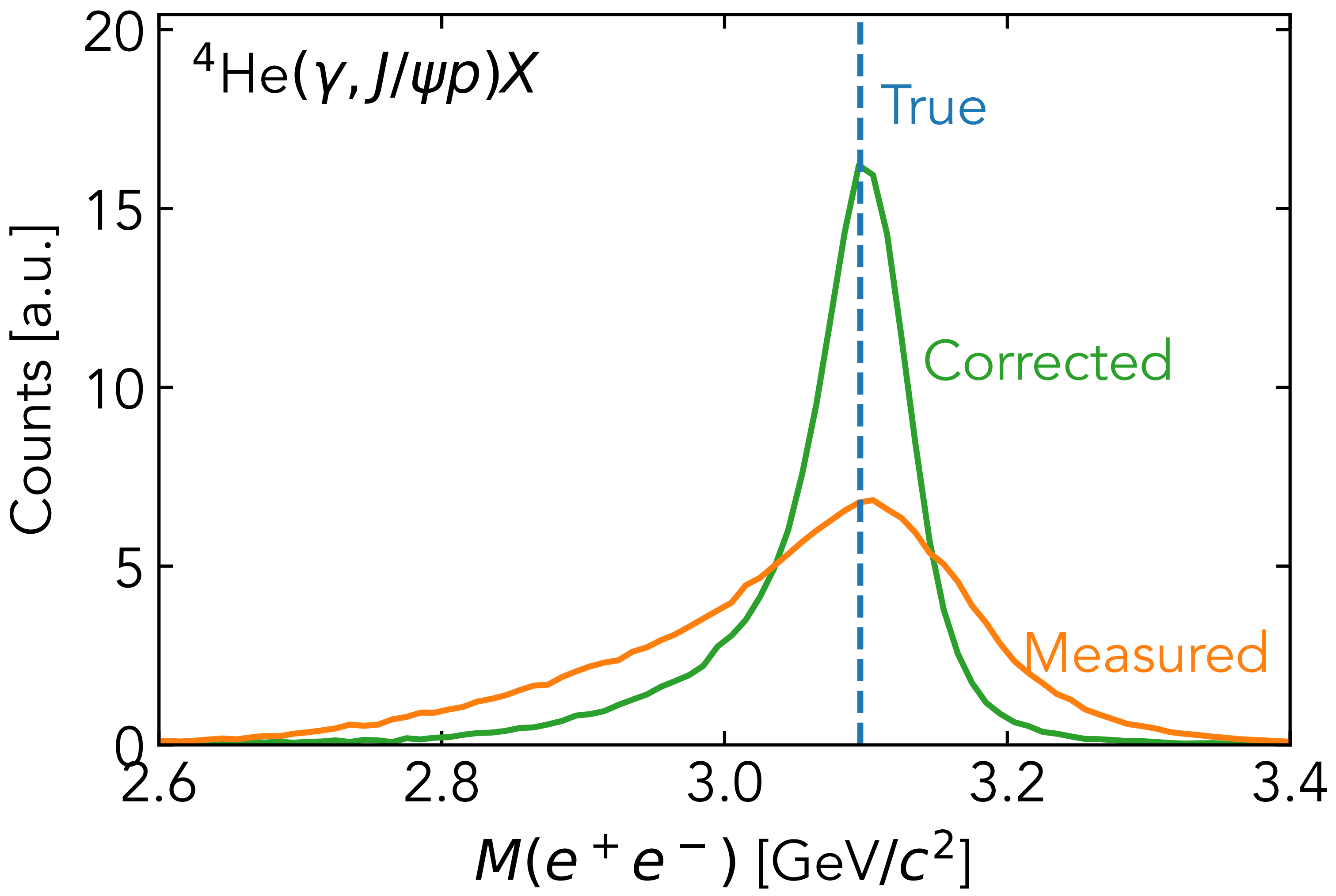


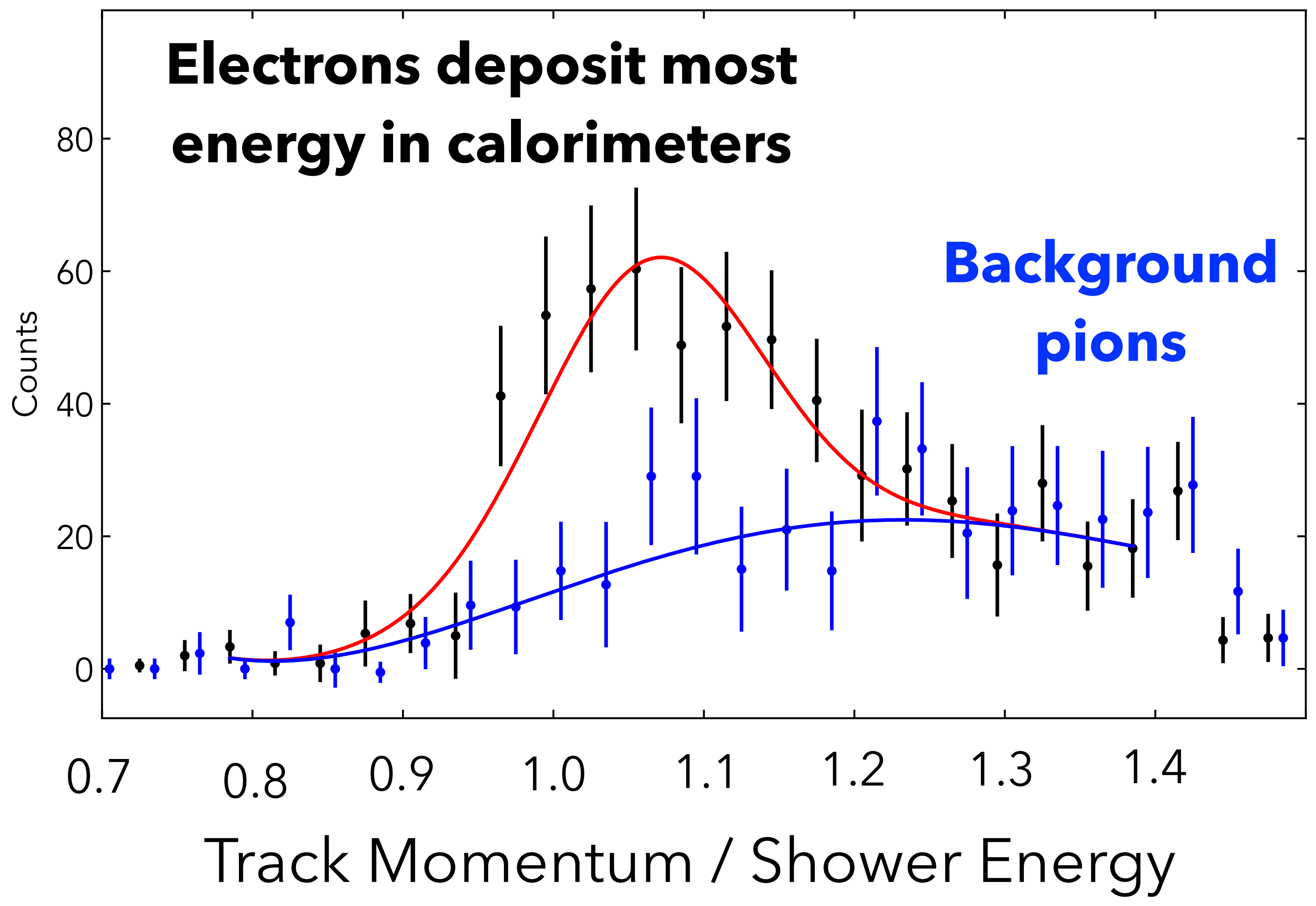
Isolating $A(\gamma, J/\psi\ p)$ events from photonuclear data

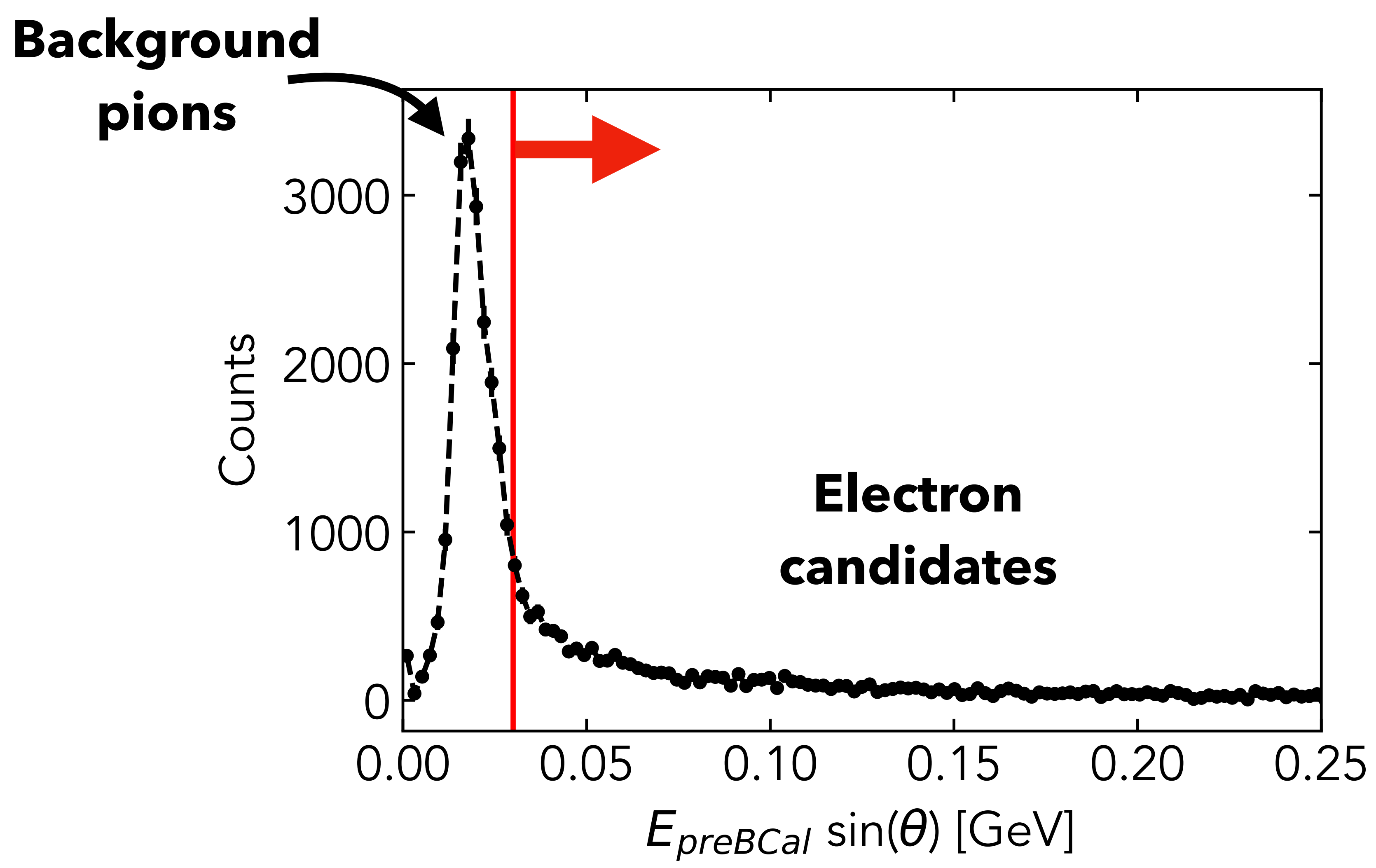
- Elasticity: $|E_{miss} - m_N| < 1$ GeV
- Exclusivity: veto extra detector activity
- $J/\psi \rightarrow e^+e^-$ isolated using light-front mass variable, fit to mass spectrum to select signal:

Lepton identification:

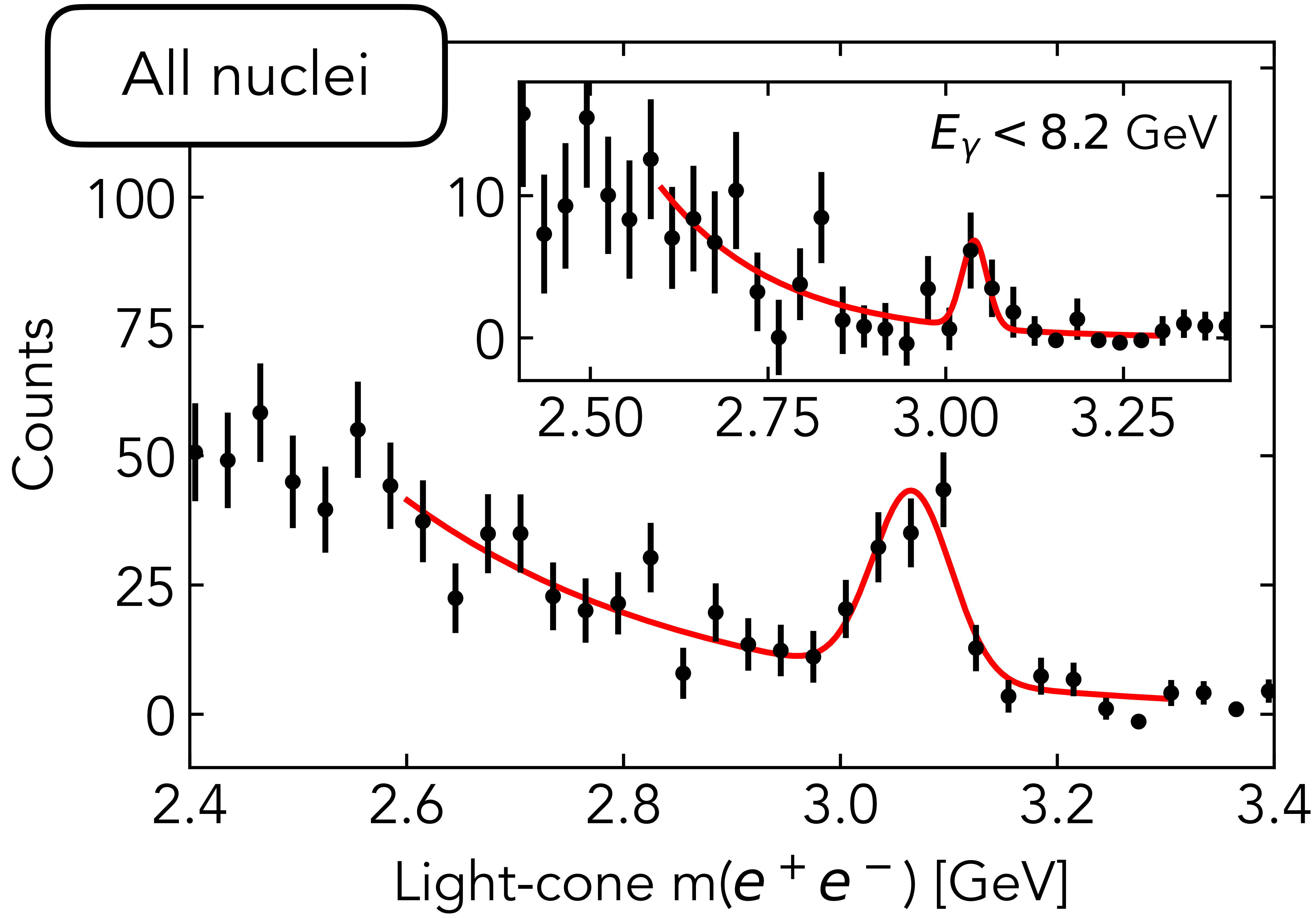
- Total calorimeter energy deposition
- Calorimeter shower evolution





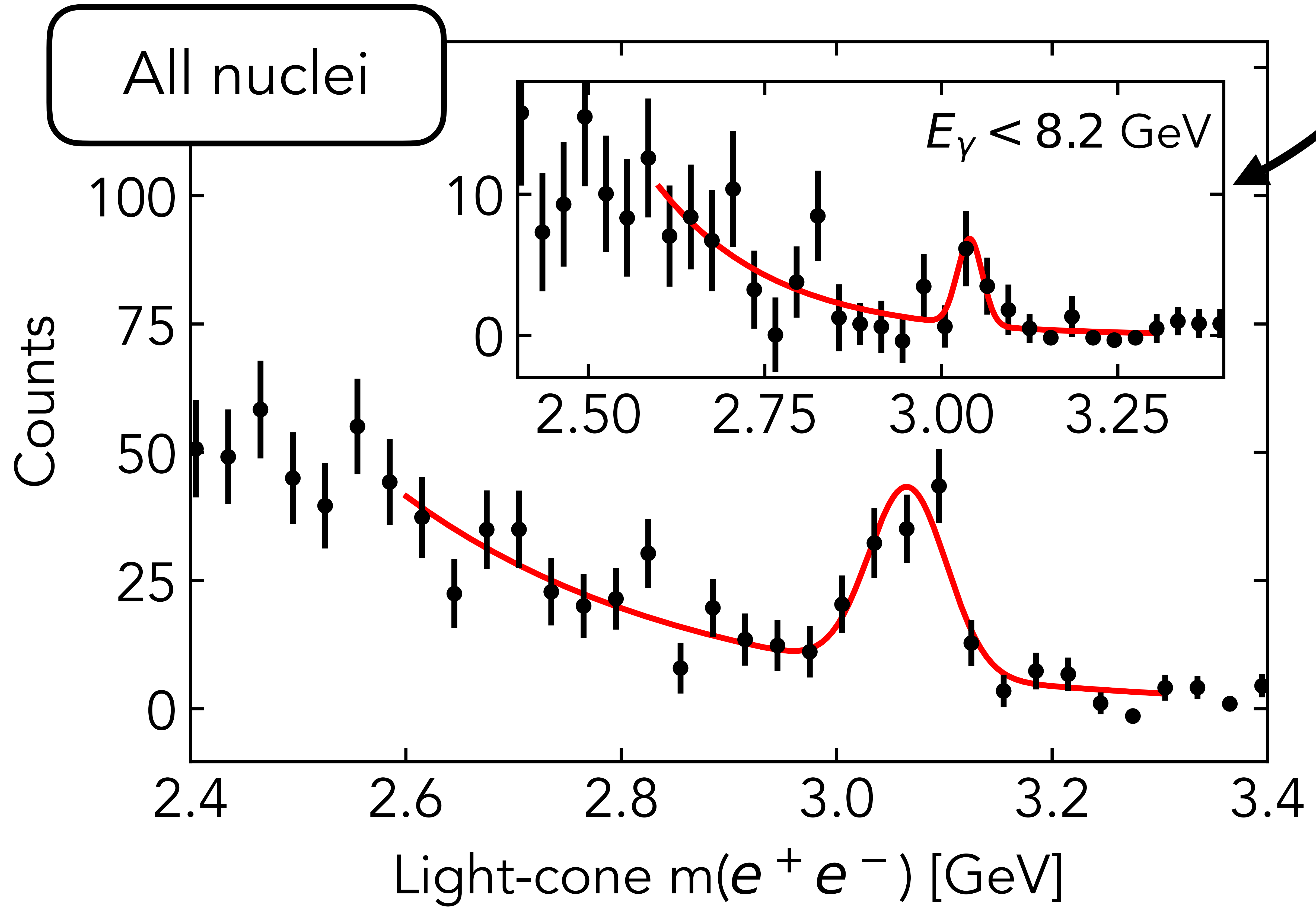


Successful J/ψ observation!

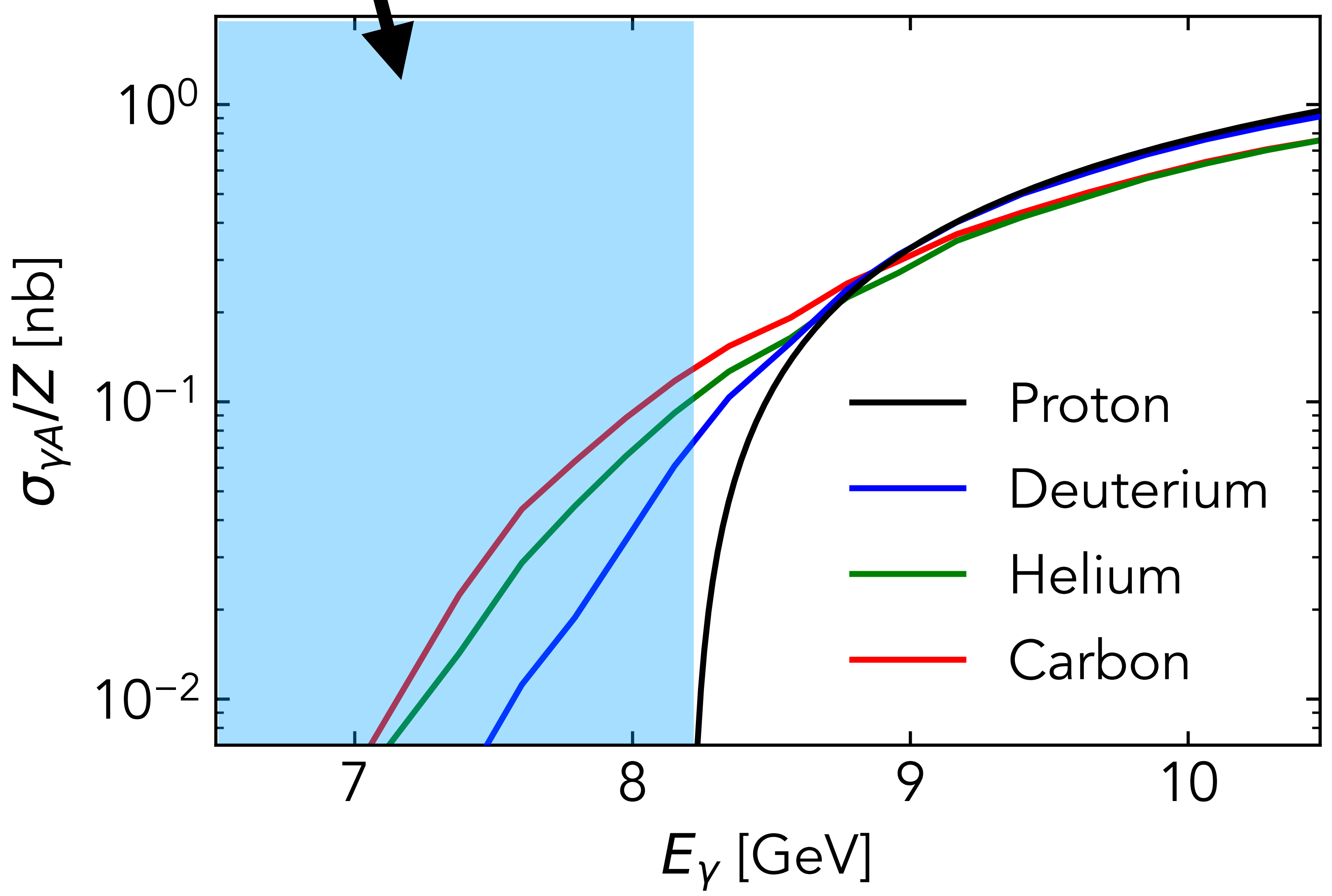


Pybus et al. PRL (2025)

Successful J/ψ observation!

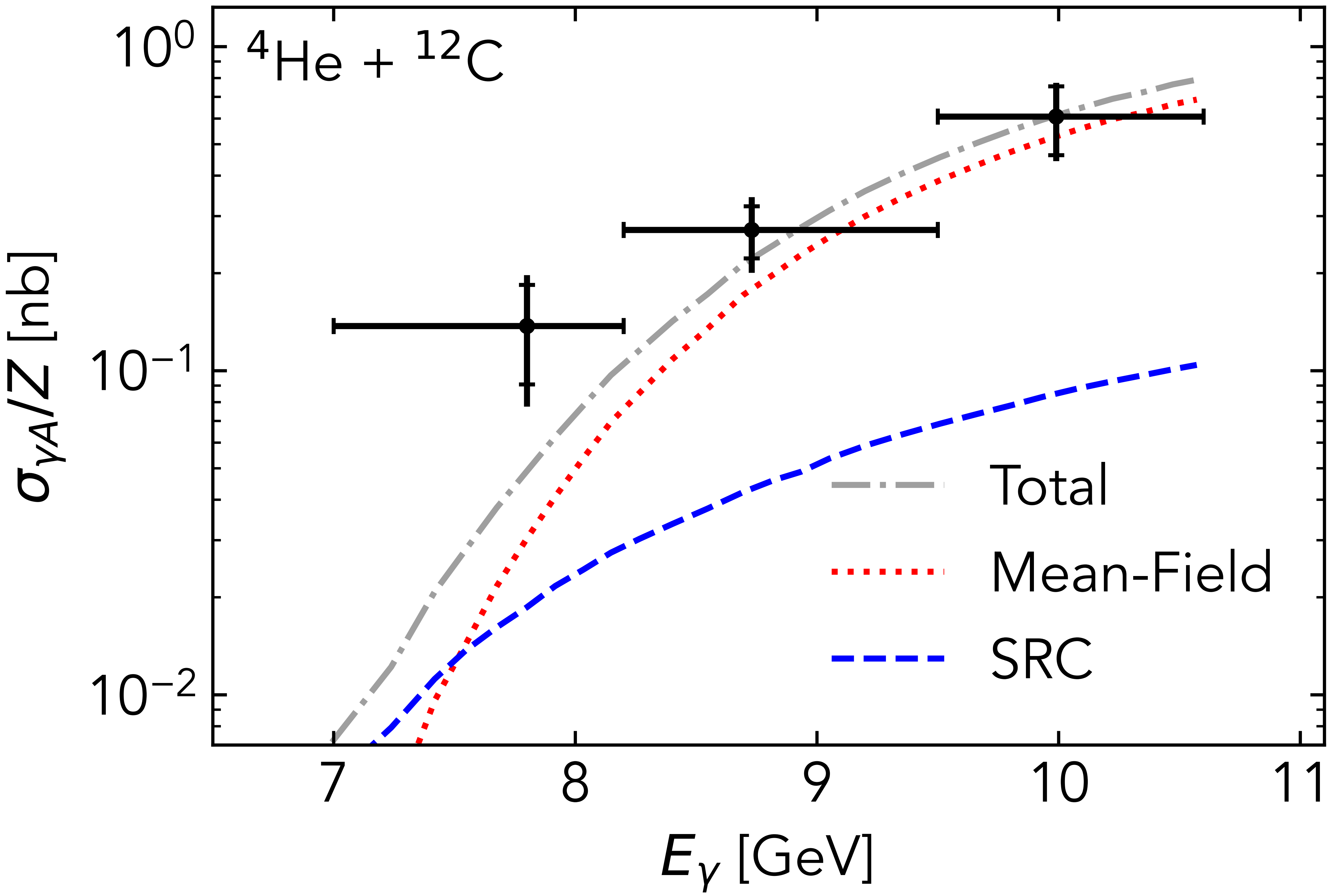


Subthreshold!



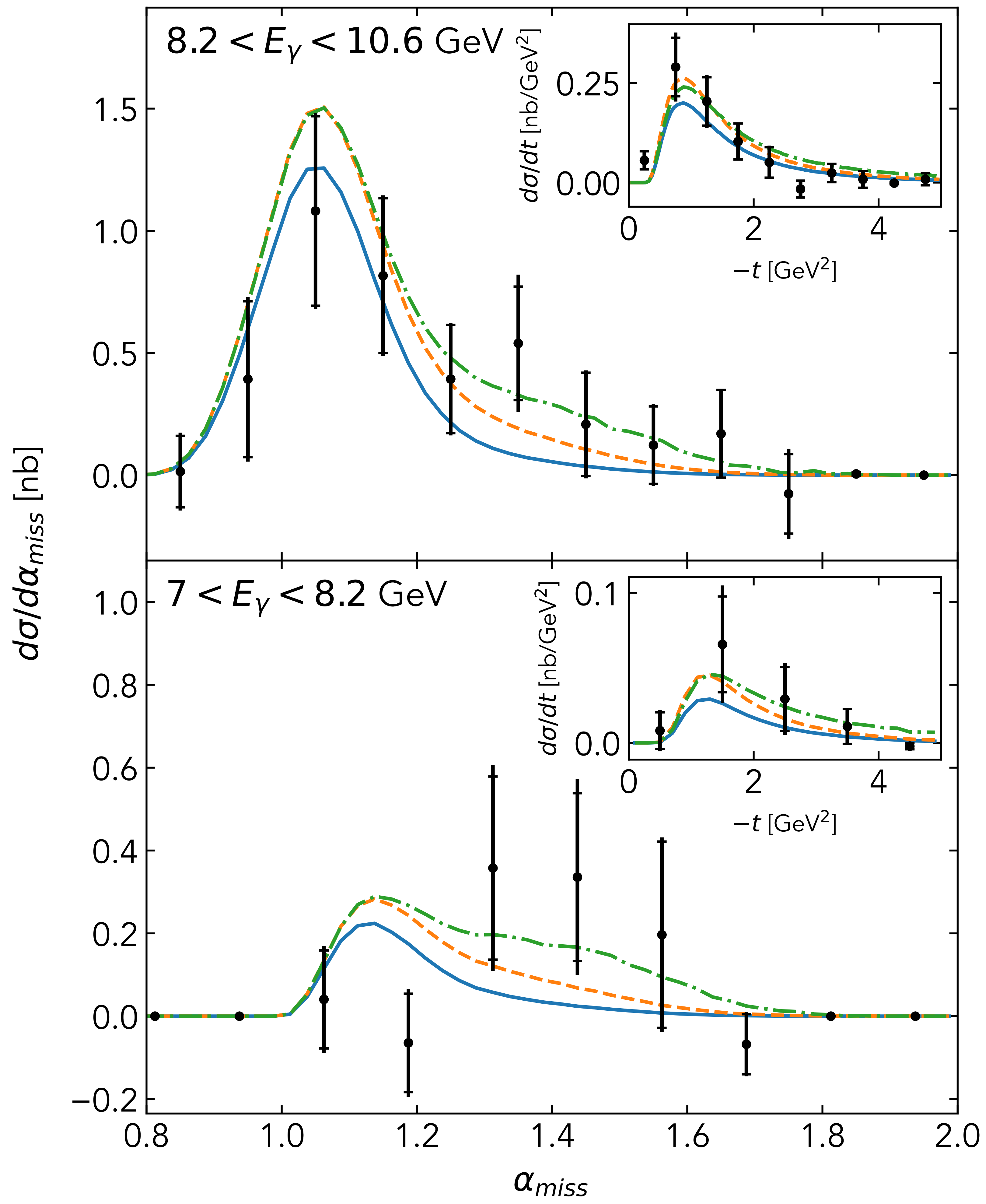
Pybus et al. PRL (2025)

Absolute Cross-Section Extraction



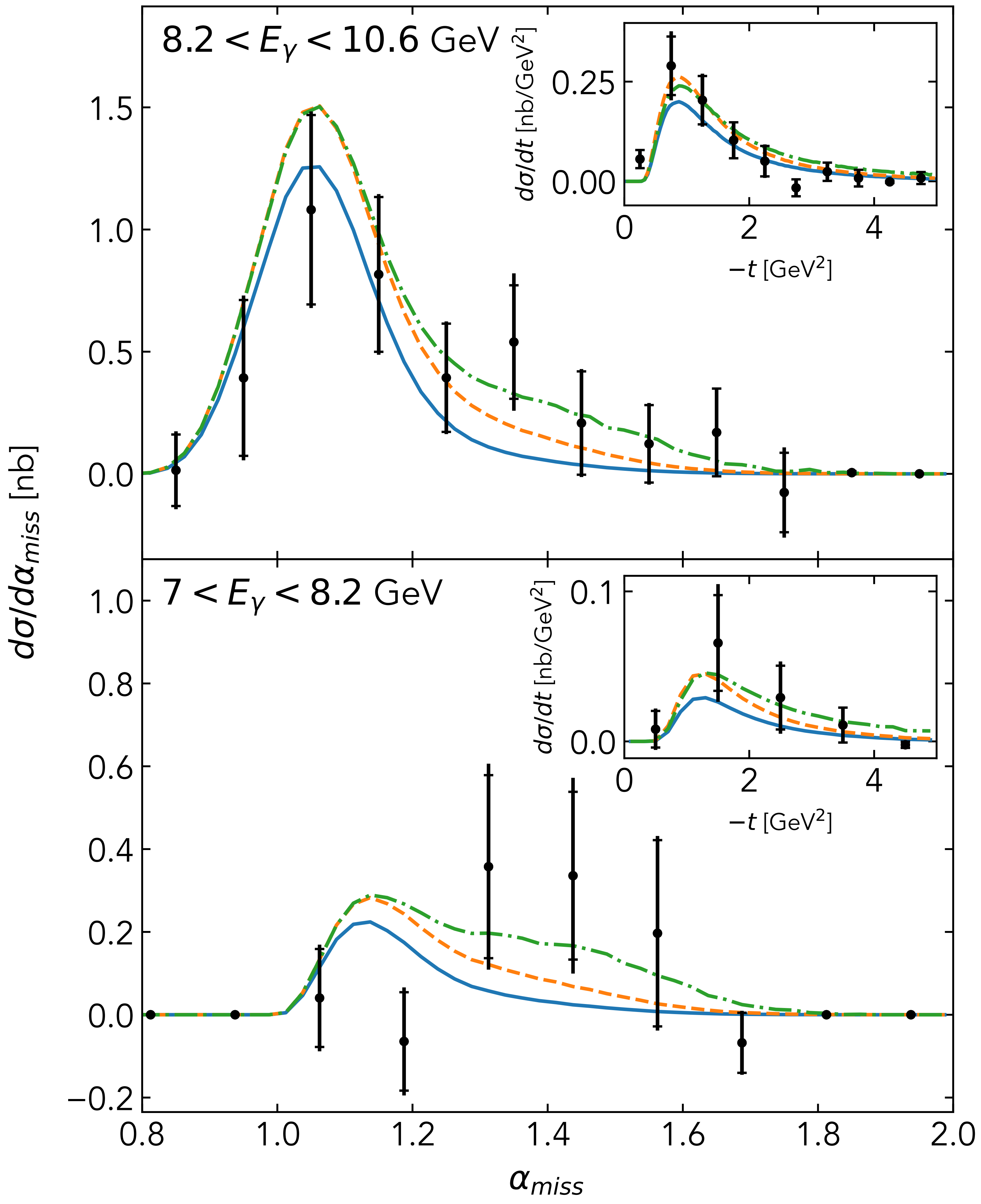
Pybus et al. PRL (2025)

Suggesting gluon modification



Pybus et al. PRL (2025)

Suggesting gluon modification



$$\sigma_{\gamma A} = A \int d^3k d\epsilon \rho_A(k,\epsilon) \widetilde{\mathcal{F}}(k,\epsilon) \sigma_{\gamma p}(W_{\gamma p'})$$

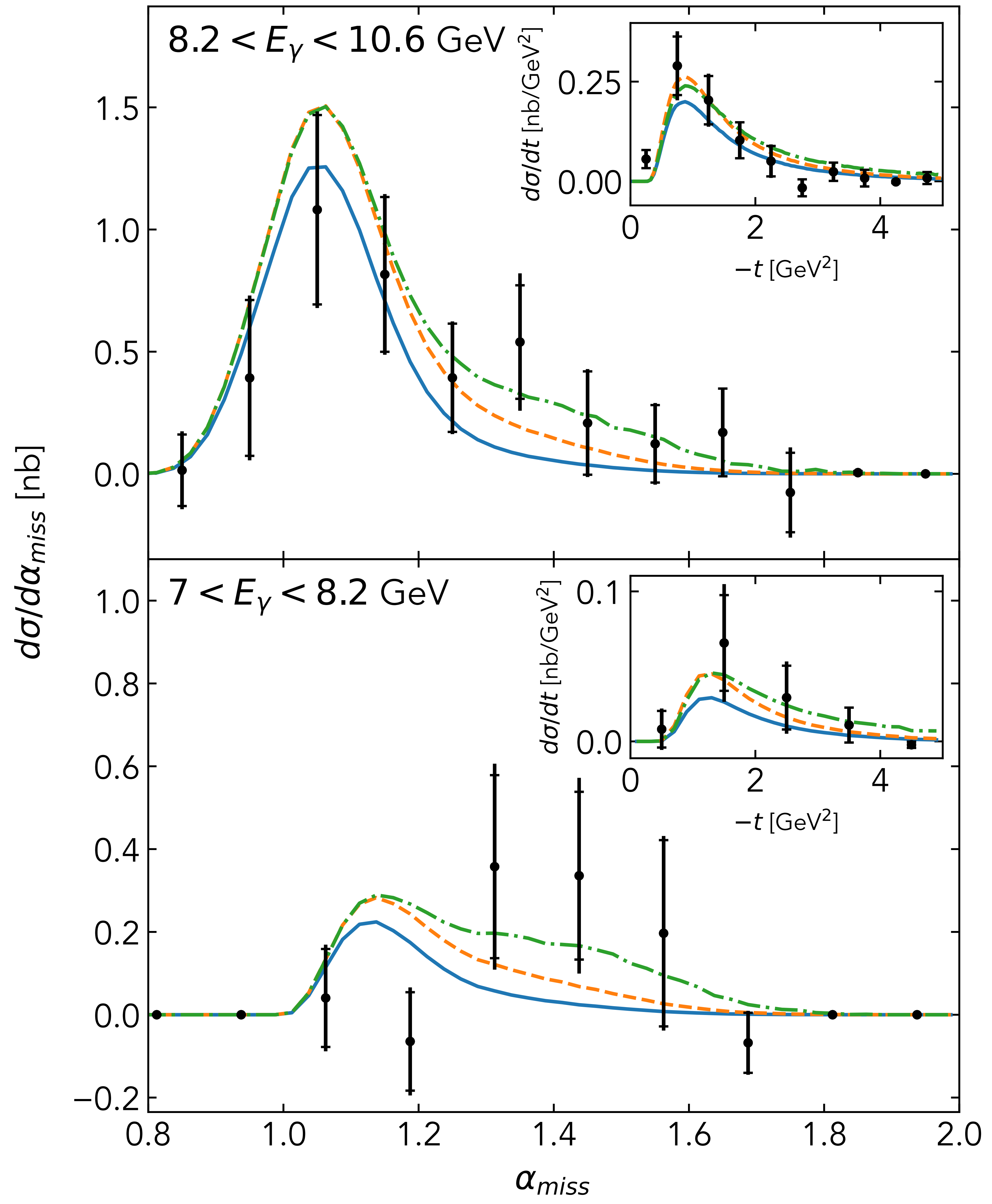
$$\frac{d\sigma}{dt}(\gamma p \to J/\psi p) = \left.\frac{d\sigma}{dt}\right|_{t=0}(s_{\gamma p}) \times F^2(t)$$

Forward cross section

Gravitational form factor

Pybus et al. PRL (2025)

Suggesting gluon modification



$$\sigma_{\gamma A} = A \int d^3k d\epsilon \rho_A(k,\epsilon)\widetilde{\mathcal{F}}(k,\epsilon)\sigma_{\gamma p}(W_{\gamma p'})$$

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

Forward cross section

Gravitational form factor

Plane-wave

Modified density

Modified form factor

Smaller proton?

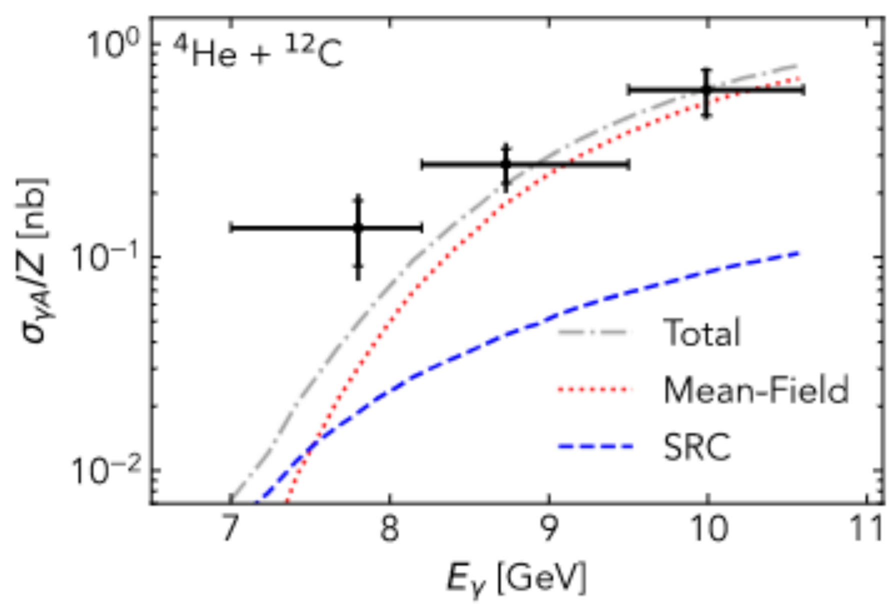
Denser proton?

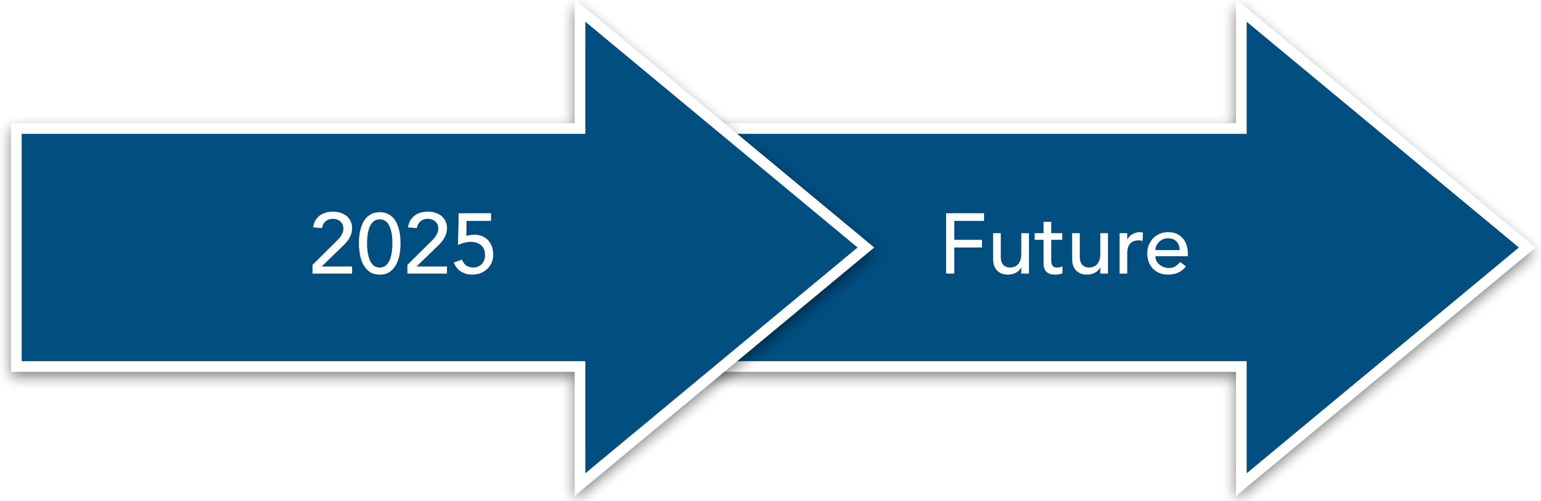
Multi-nucleon interactions?

Pybus et al. PRL (2025)

Nuclear Gluons are **40 years** behind quarks @ large x

We need to catch up!





PR12-25-002:

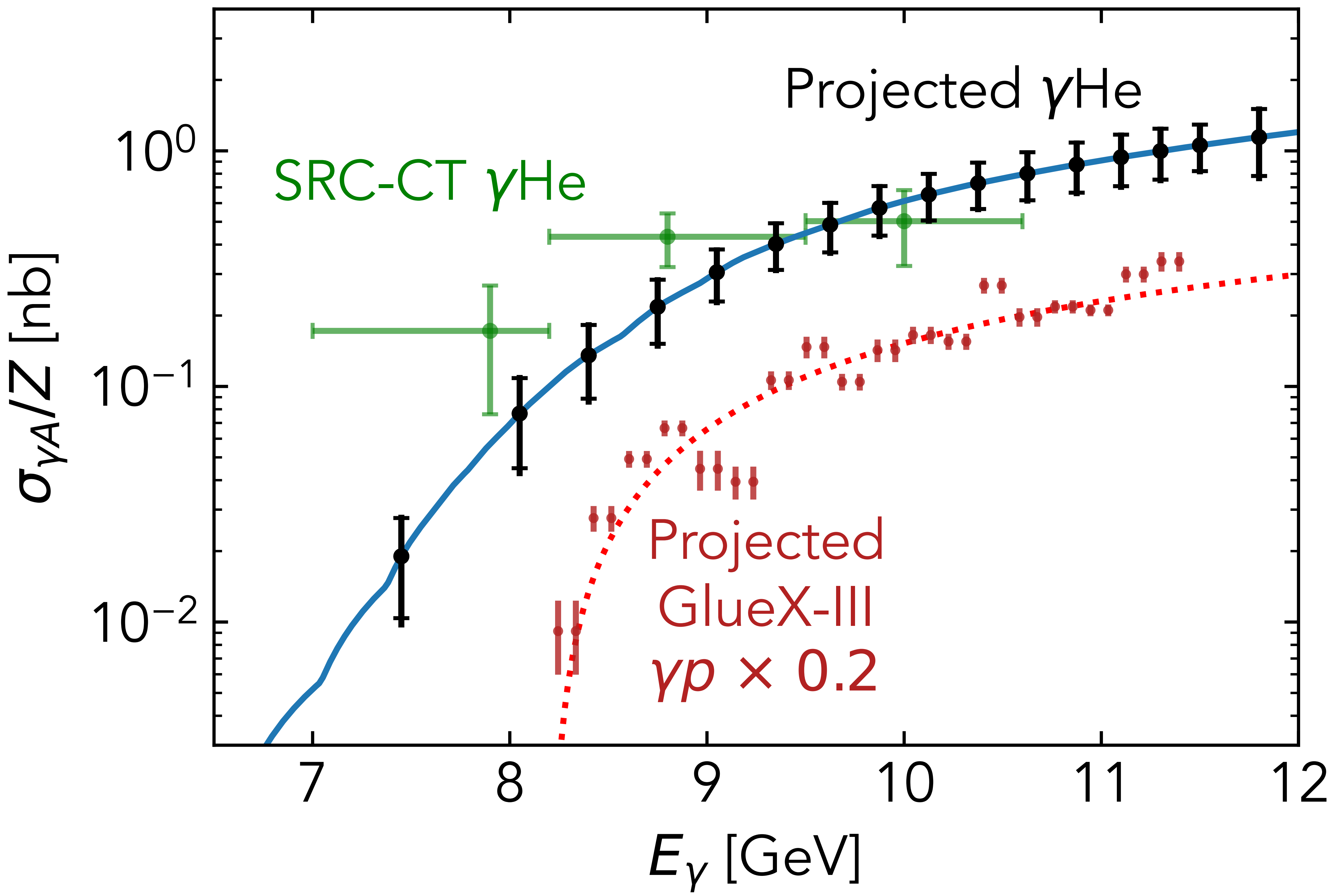
Proposed measurement of ^{4}He

can constrain mechanisms of J/ψ production from nuclei at threshold

80 PAC days measurement of 4He

~600 J/ψ events

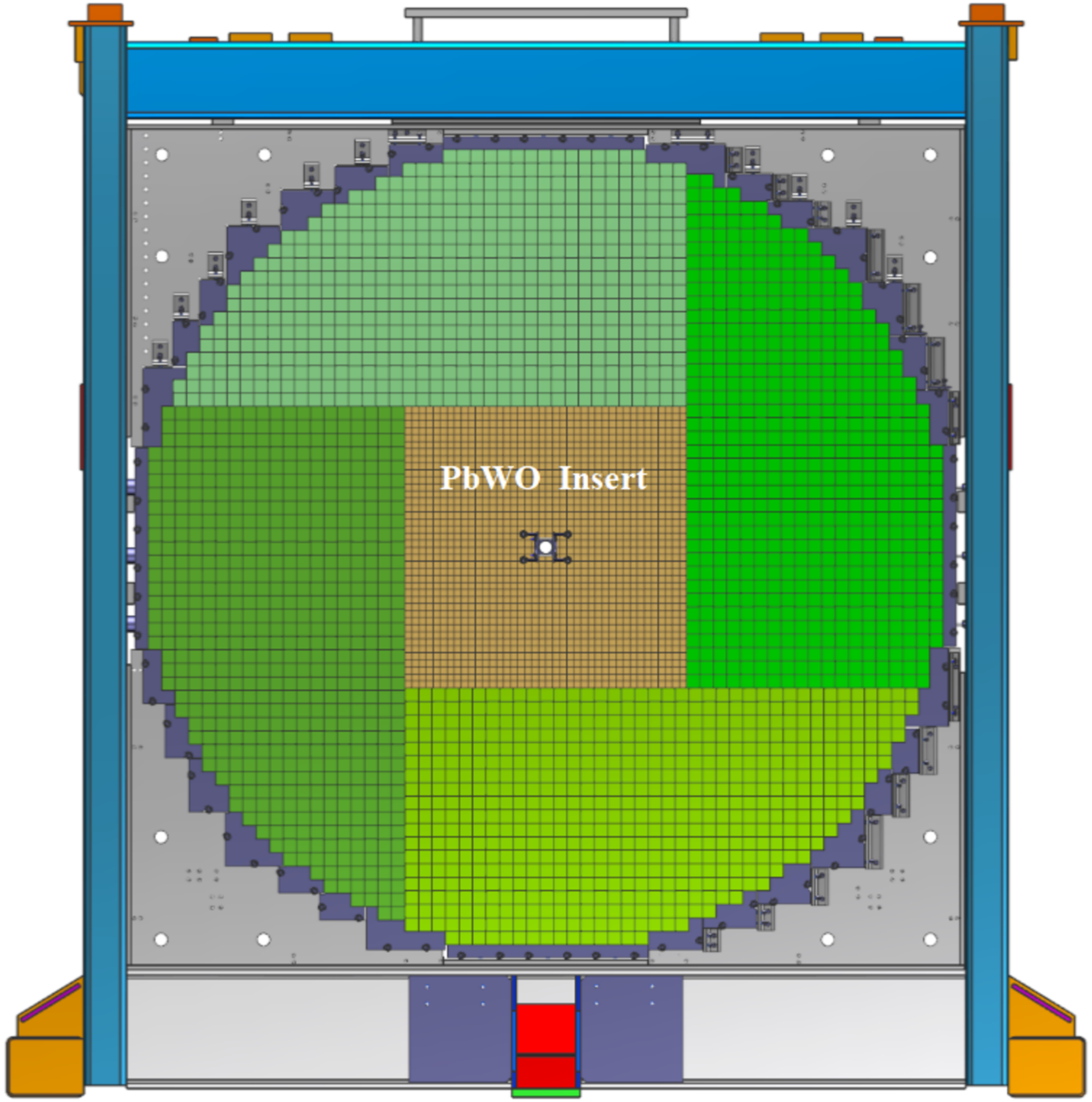
Measure cross section across full energy range and kinematics



PR12-25-002

- Signal channel: quasi-elastic ^{4}He$(\gamma, J/\psi\ p)$
- Lepton identification using calorimetry and new forward upgrades (FCAL, TRD)
  - Full selection criteria detailed in PRL
- Primary backgrounds: incoherent $\pi^+\pi^-$ production and Bethe-Heitler e^+e^-
- Point-to-point systematic uncertainties primarily from cut-dependence and J/ψ yield extraction
- J/ψ signal and nuclear kinematics isolated using light-front observables
- Differential measurement planned; dependence on E_γ, t, α_{miss}, p_t

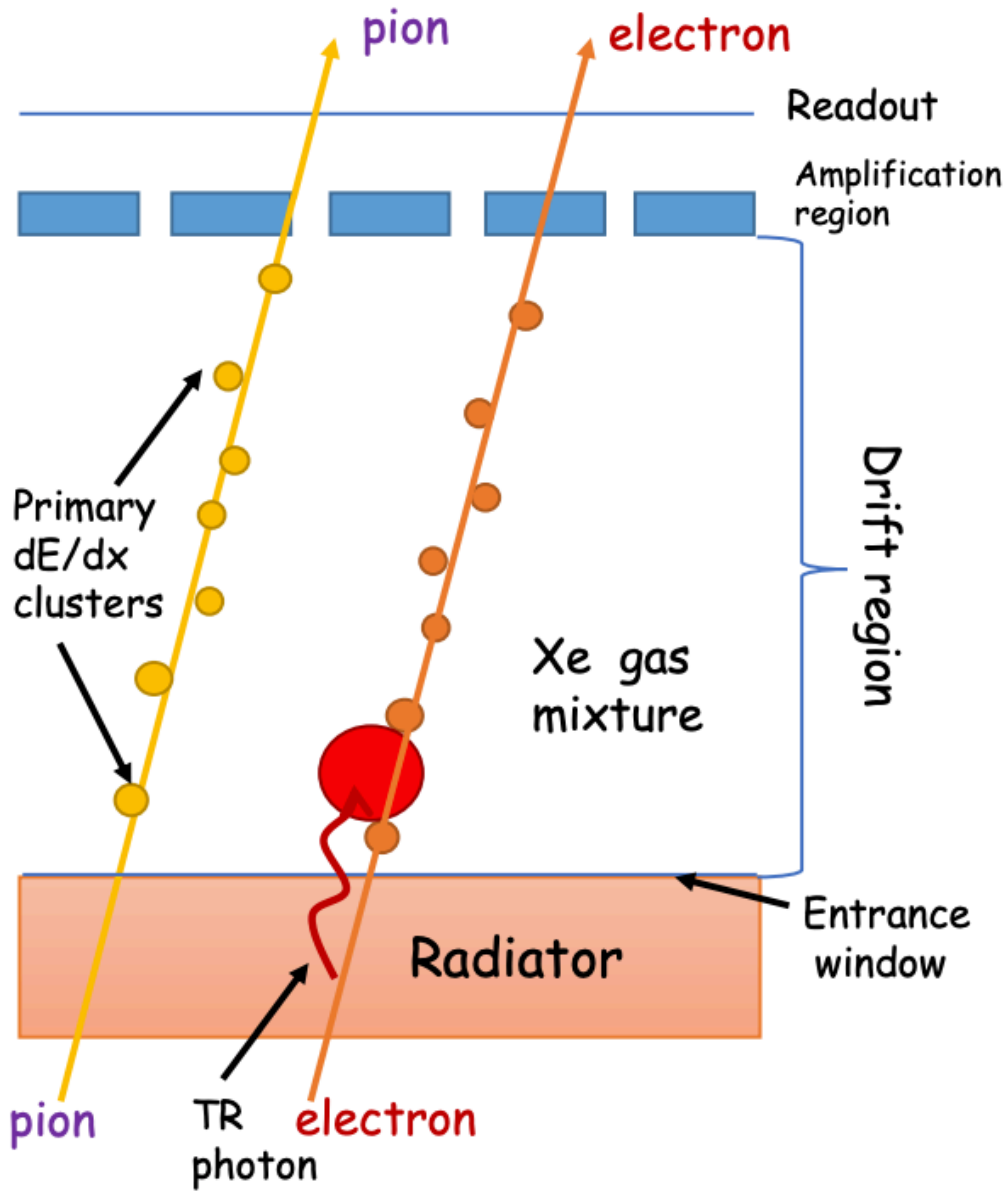
Forward calorimeter can measure shower evolution



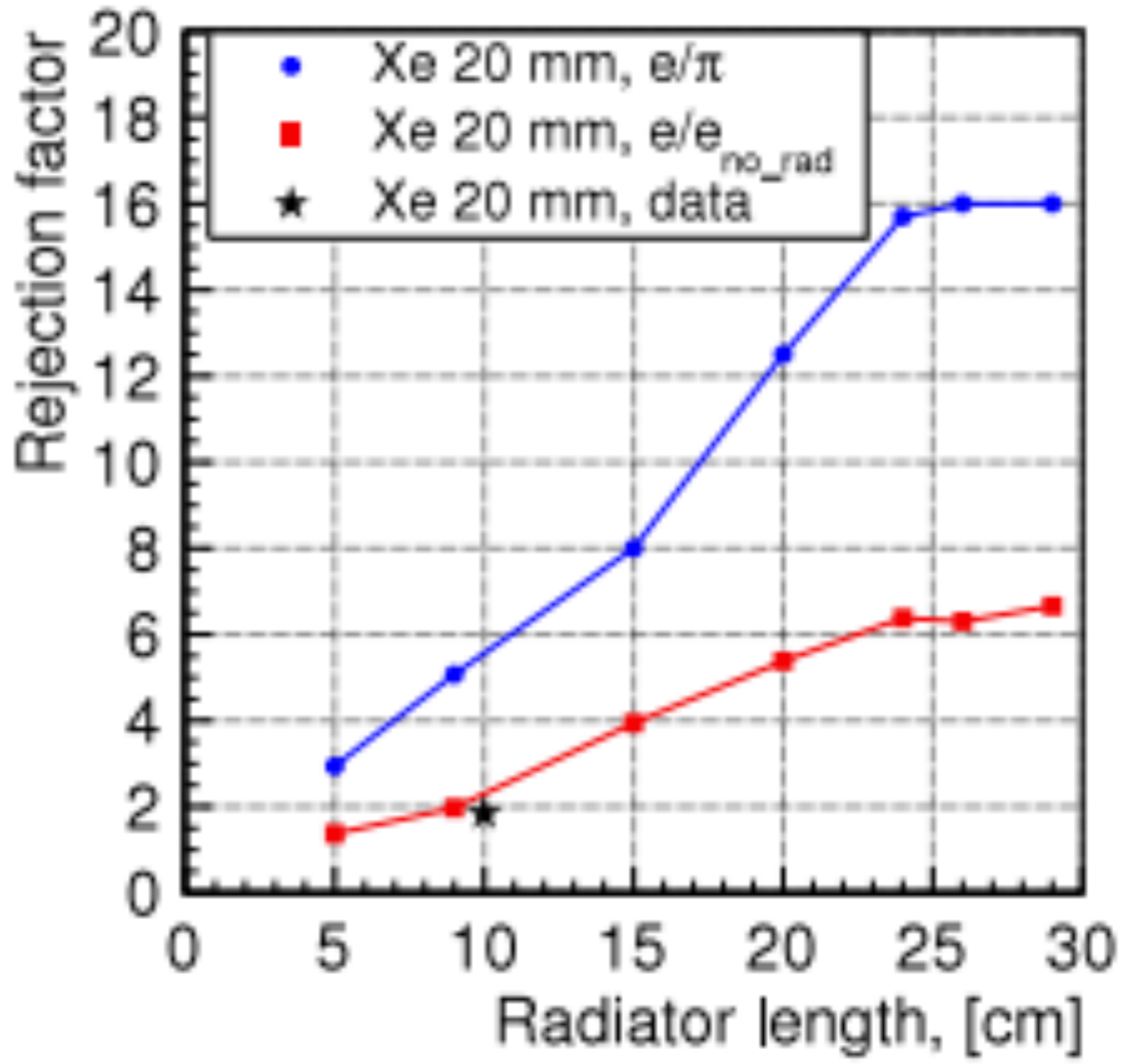
New $PbWO_4$ ECAL insert

- 2x improved energy and position resolution
- 4x improved granularity → improved shower shape, separates $e^{\pm}$ from $\pi^{\pm}$ within acceptance

GEM-TRD upgrade will improve $e^{\pm}/\pi^{\pm}$ separation

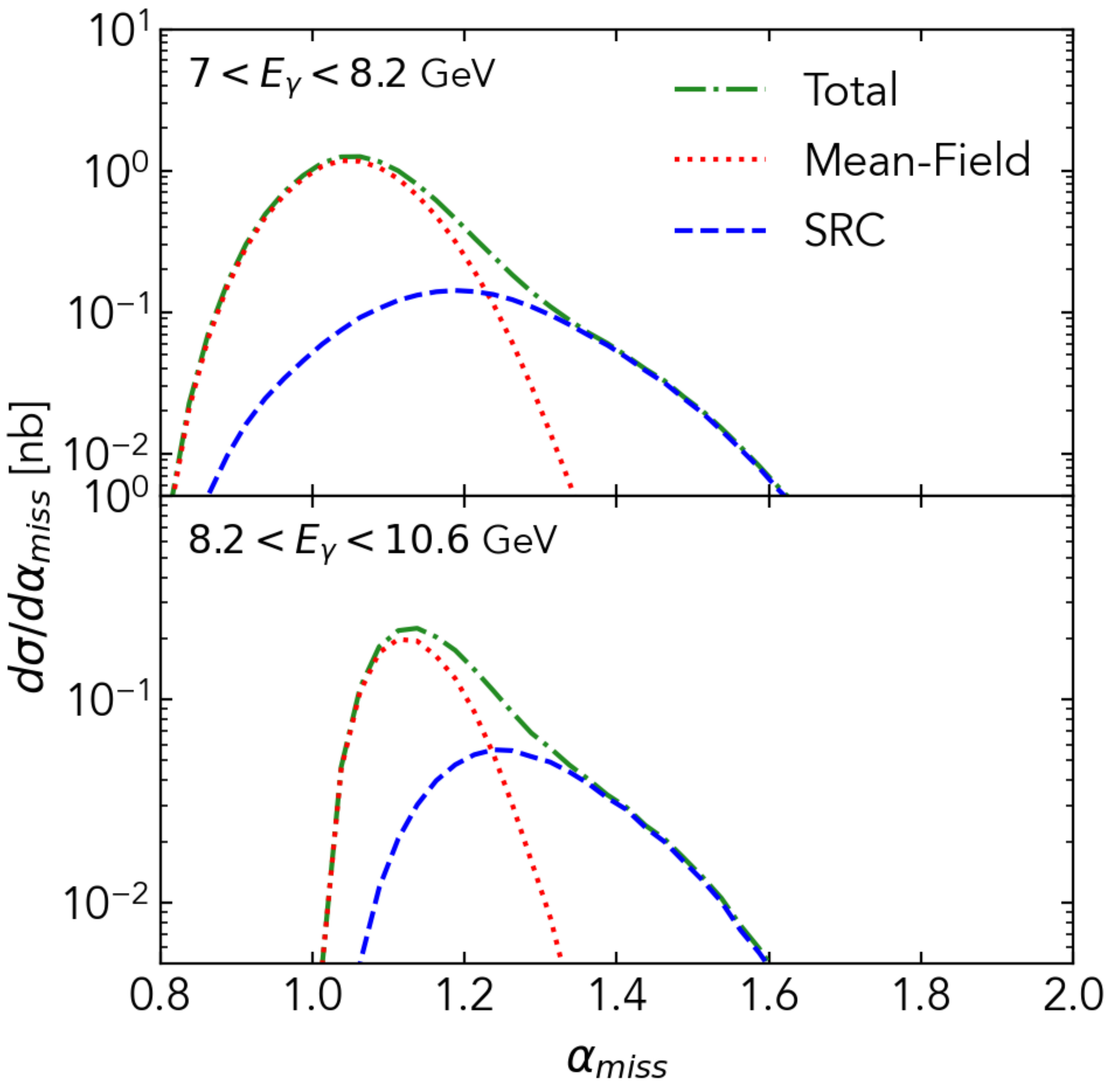


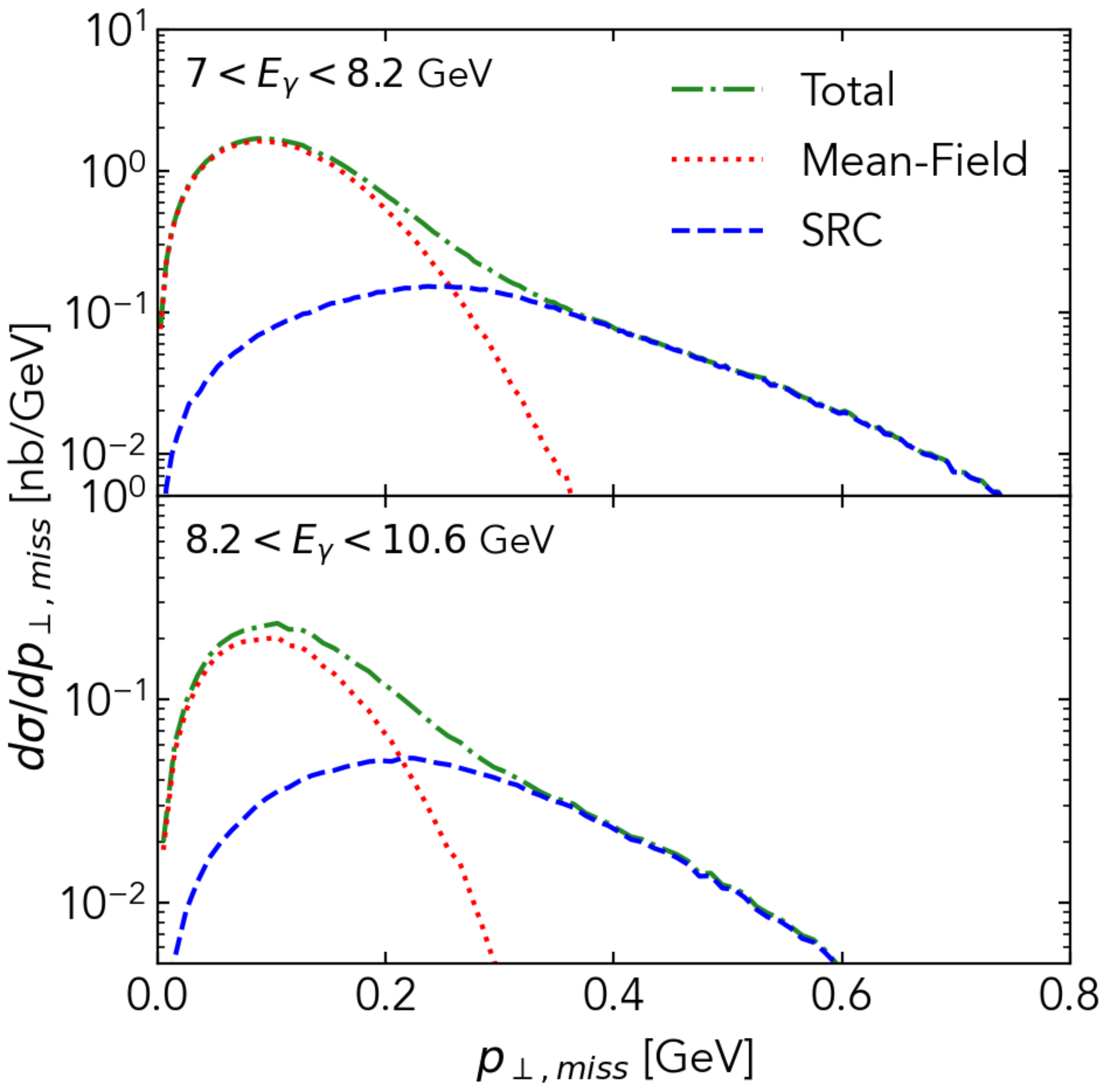
Barbosa et al. NIM (2019)



Planned 15-cm forward TRD provides ~10× $\pi^{\pm}$ rejection

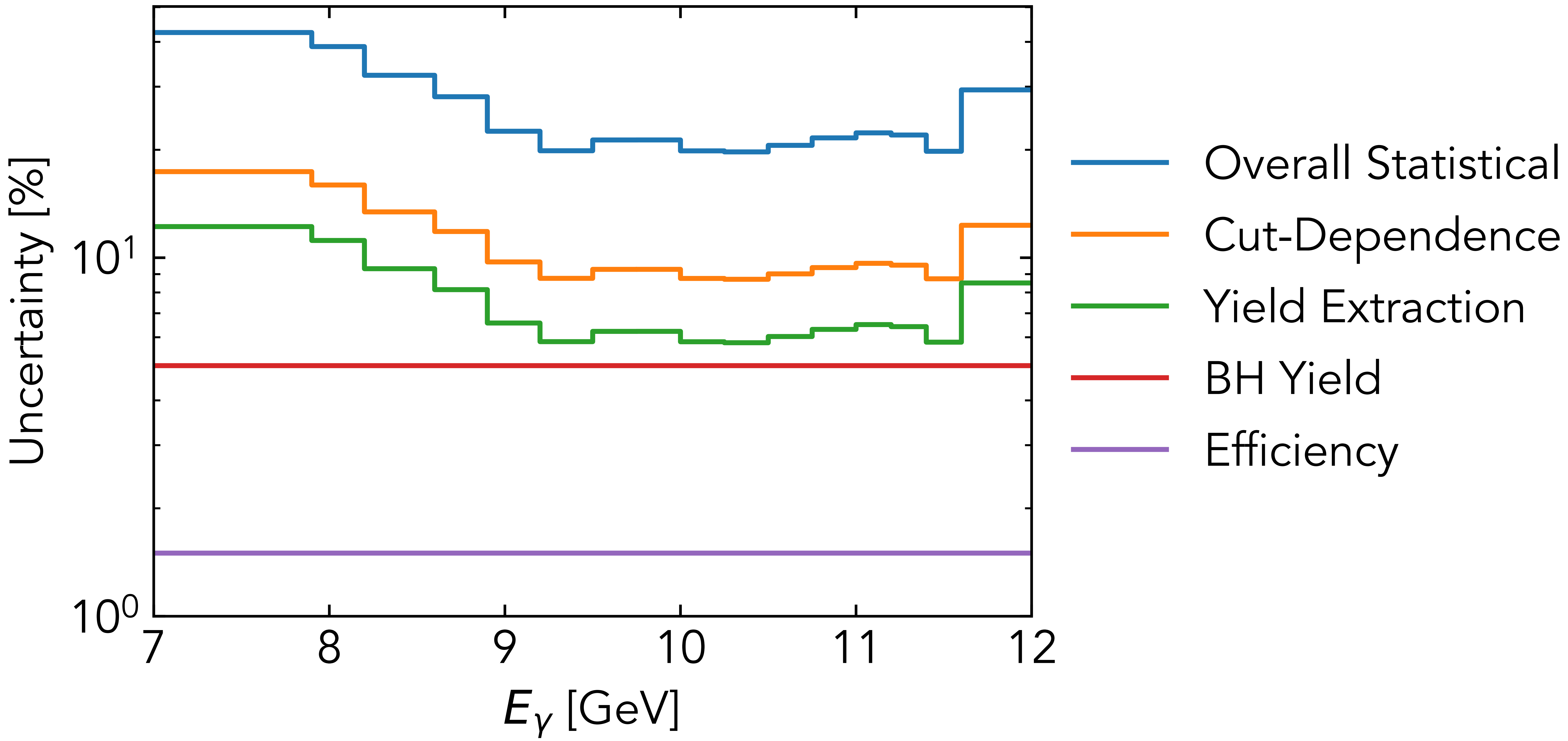
SRC can be isolated using light-front variables



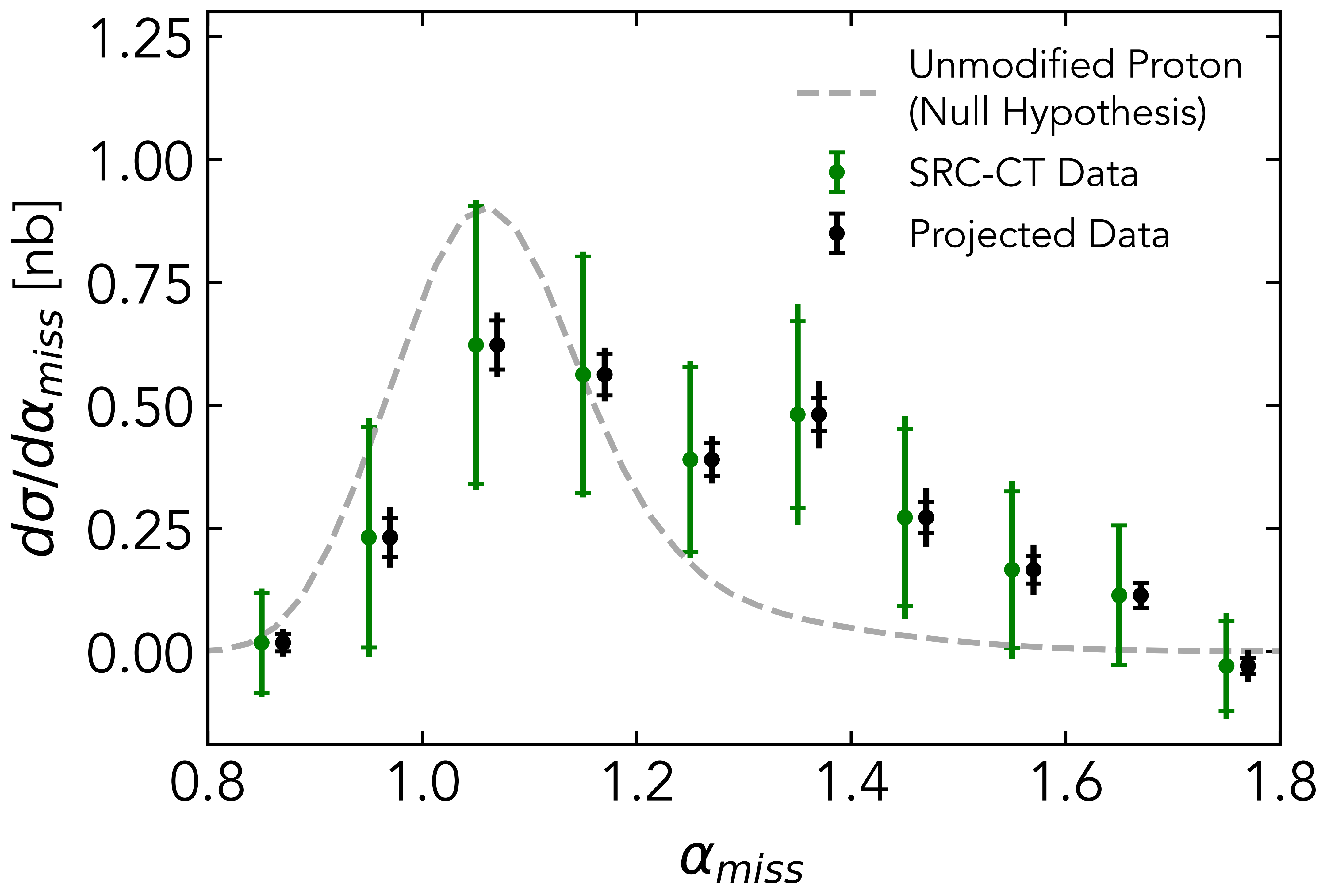


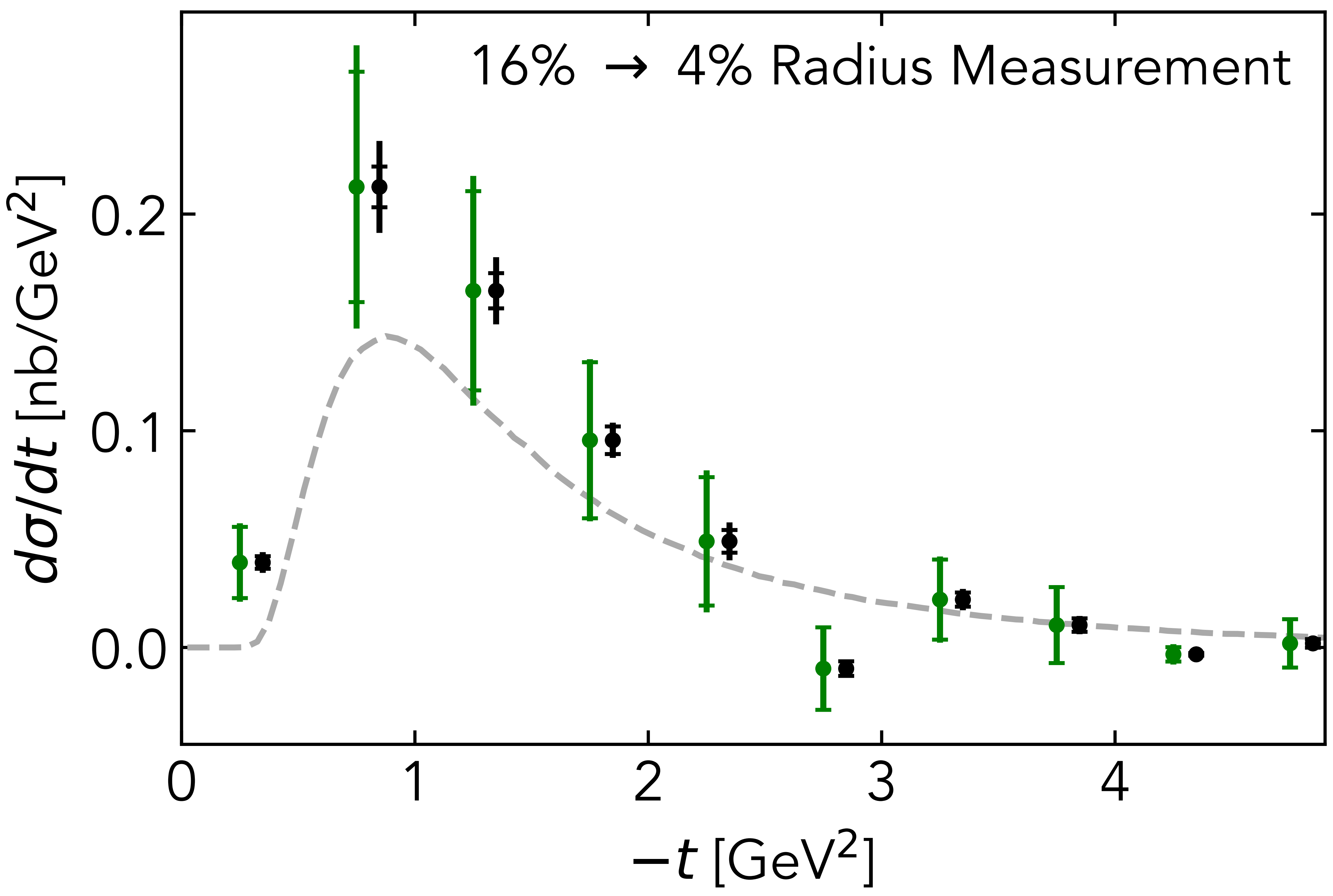
Detailed uncertainty study for J/ψ production

Projected uncertainties calculated using PRL data;
Measurement will be statistically-dominated

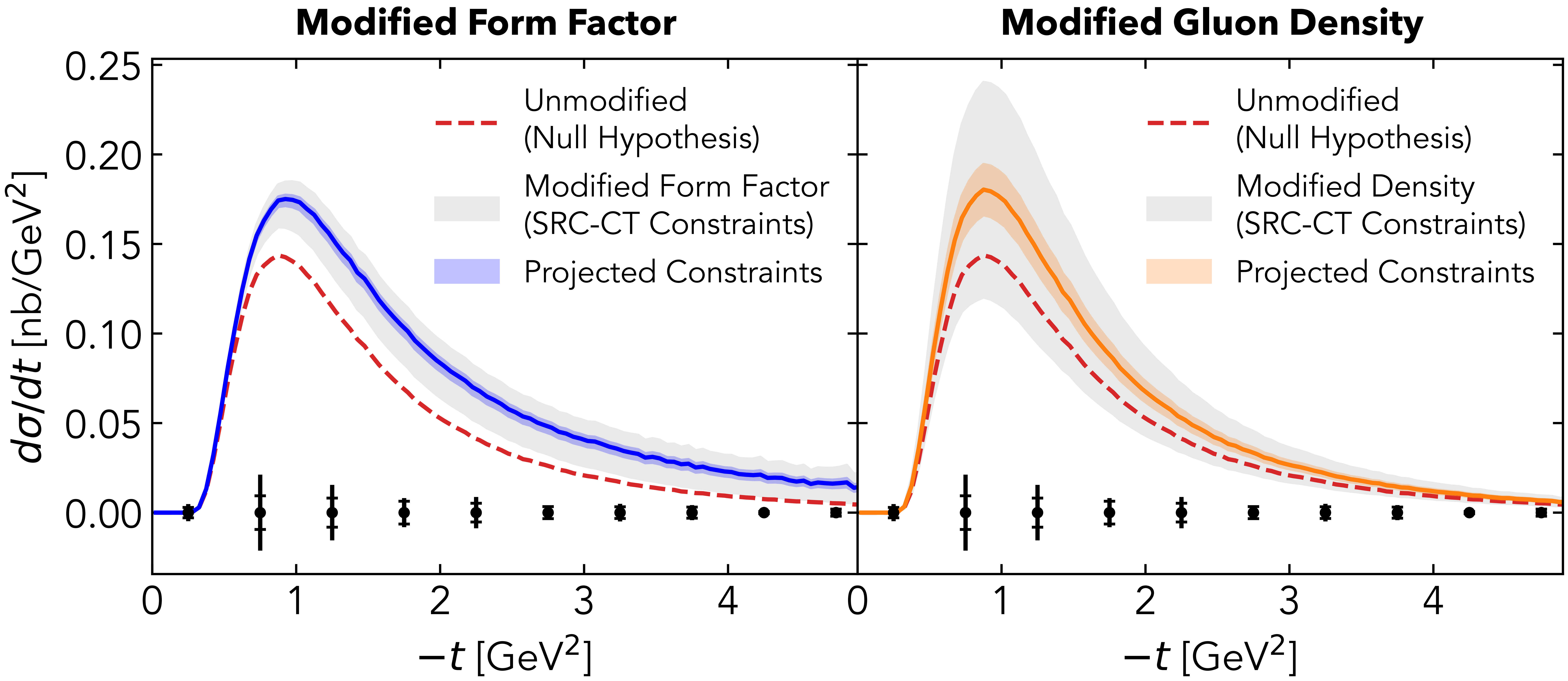


Precision Data

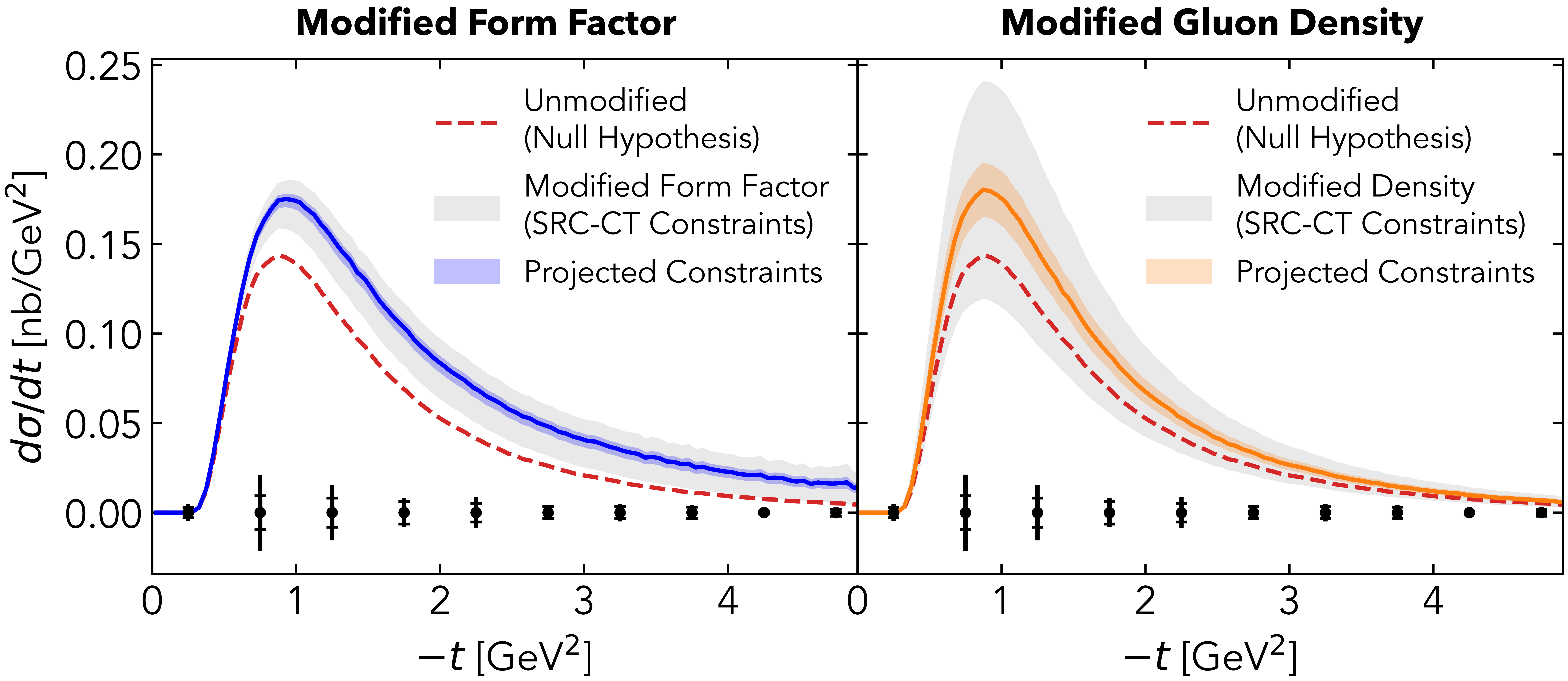




Separating + constraining modification hypotheses



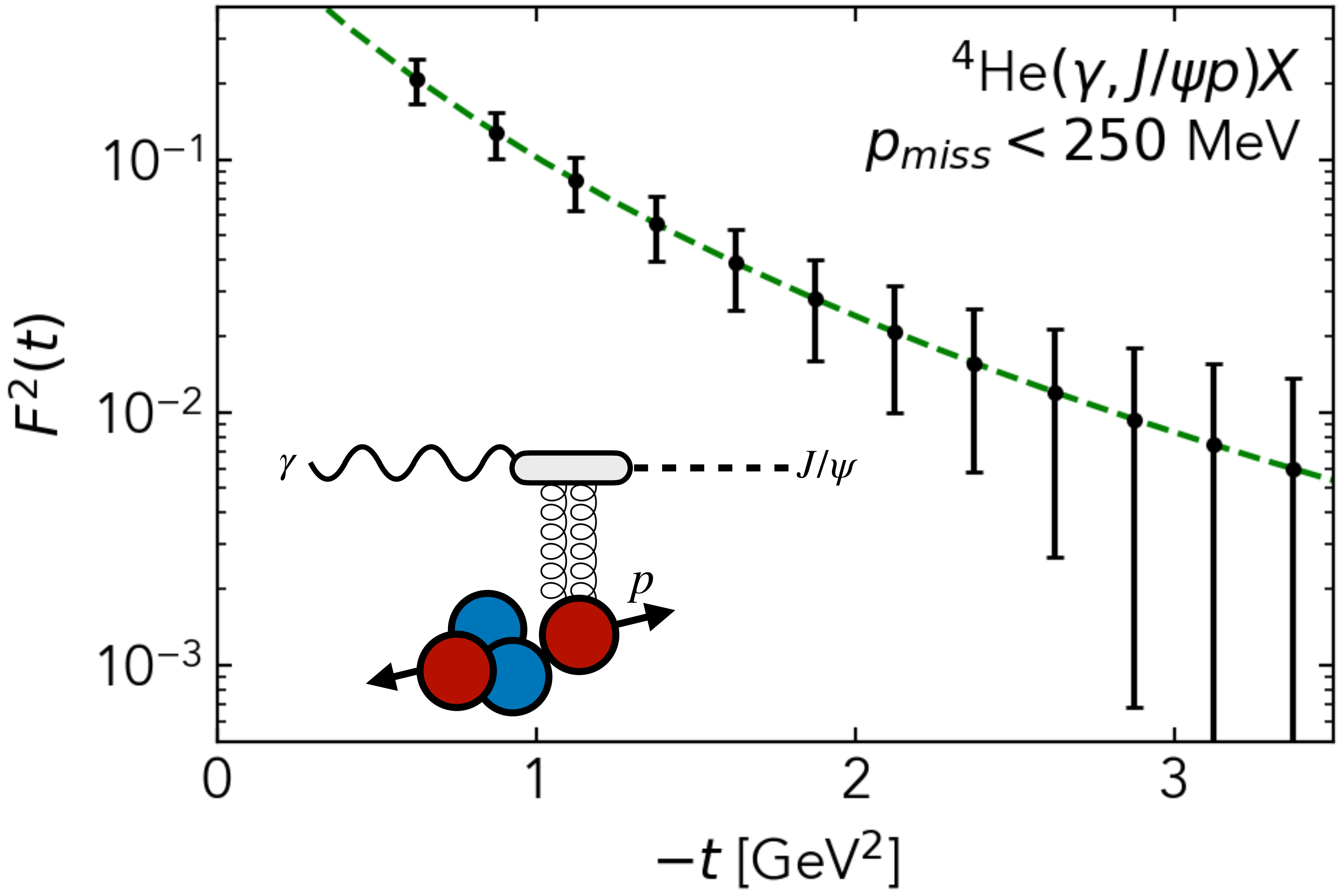
Separating + constraining modification hypotheses



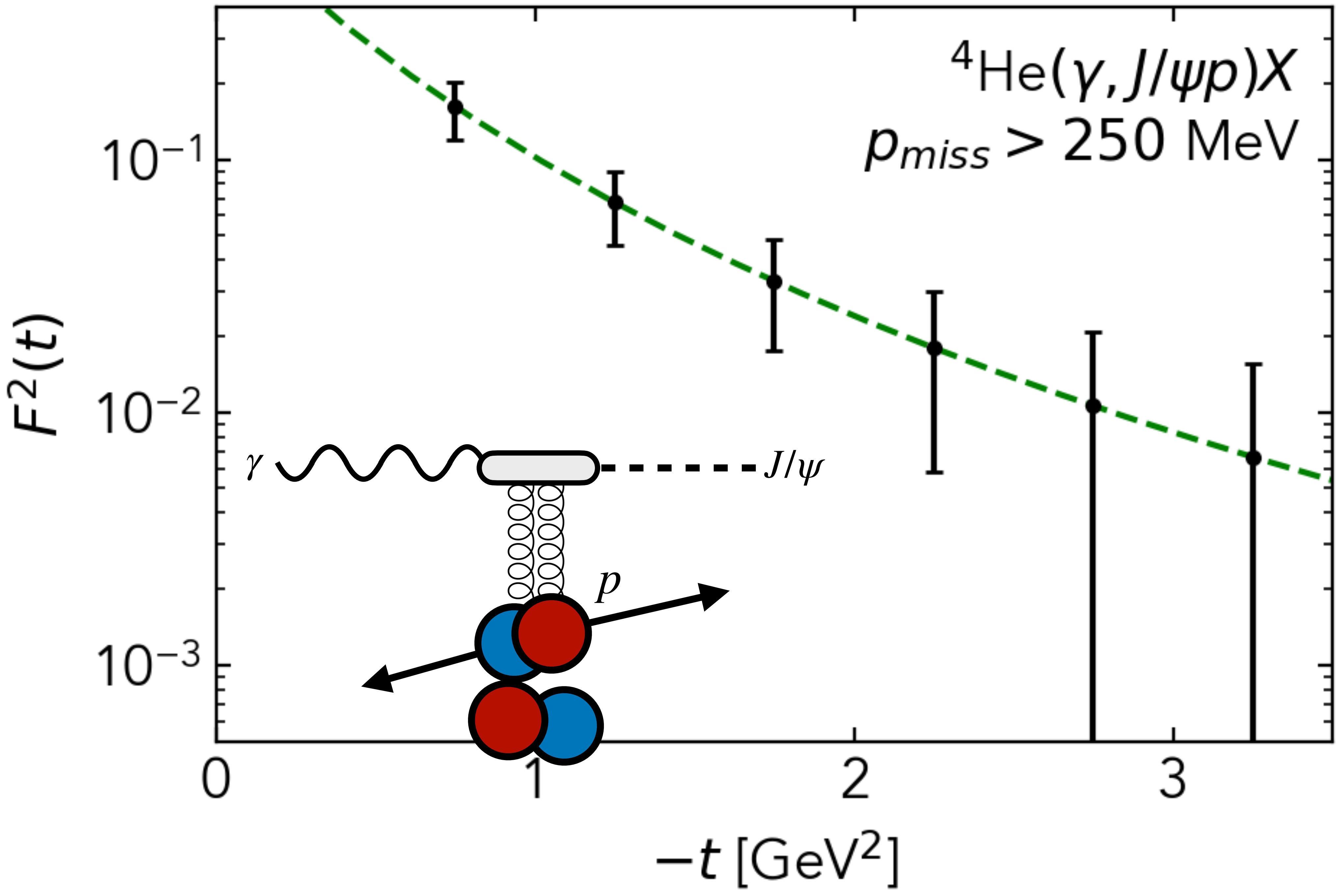
Deviation from "free proton expectation" can be established in a data driven manner!

Separating mean-field / SRC gluon structure

~4% radius measurement



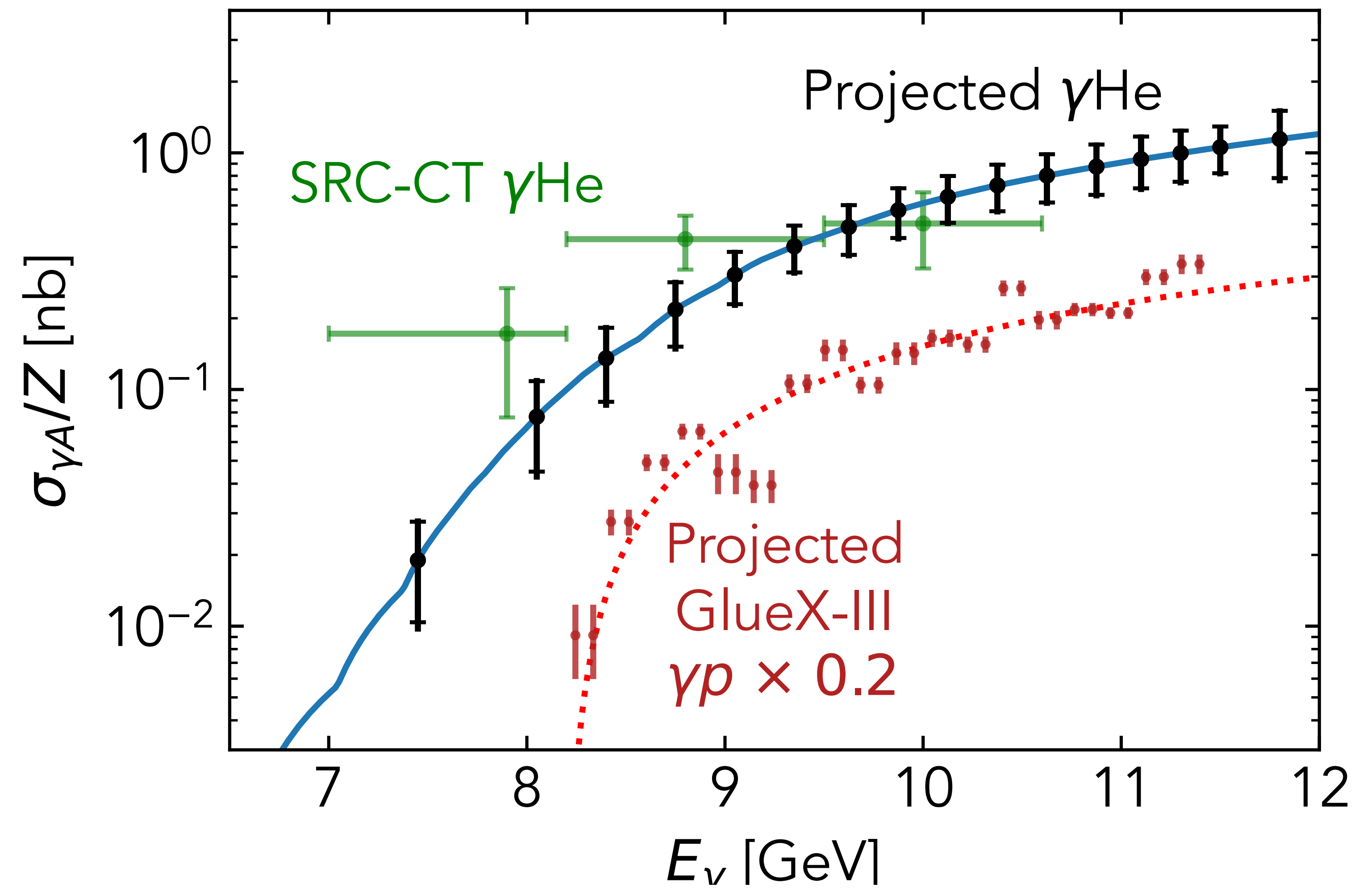
~10% radius measurement

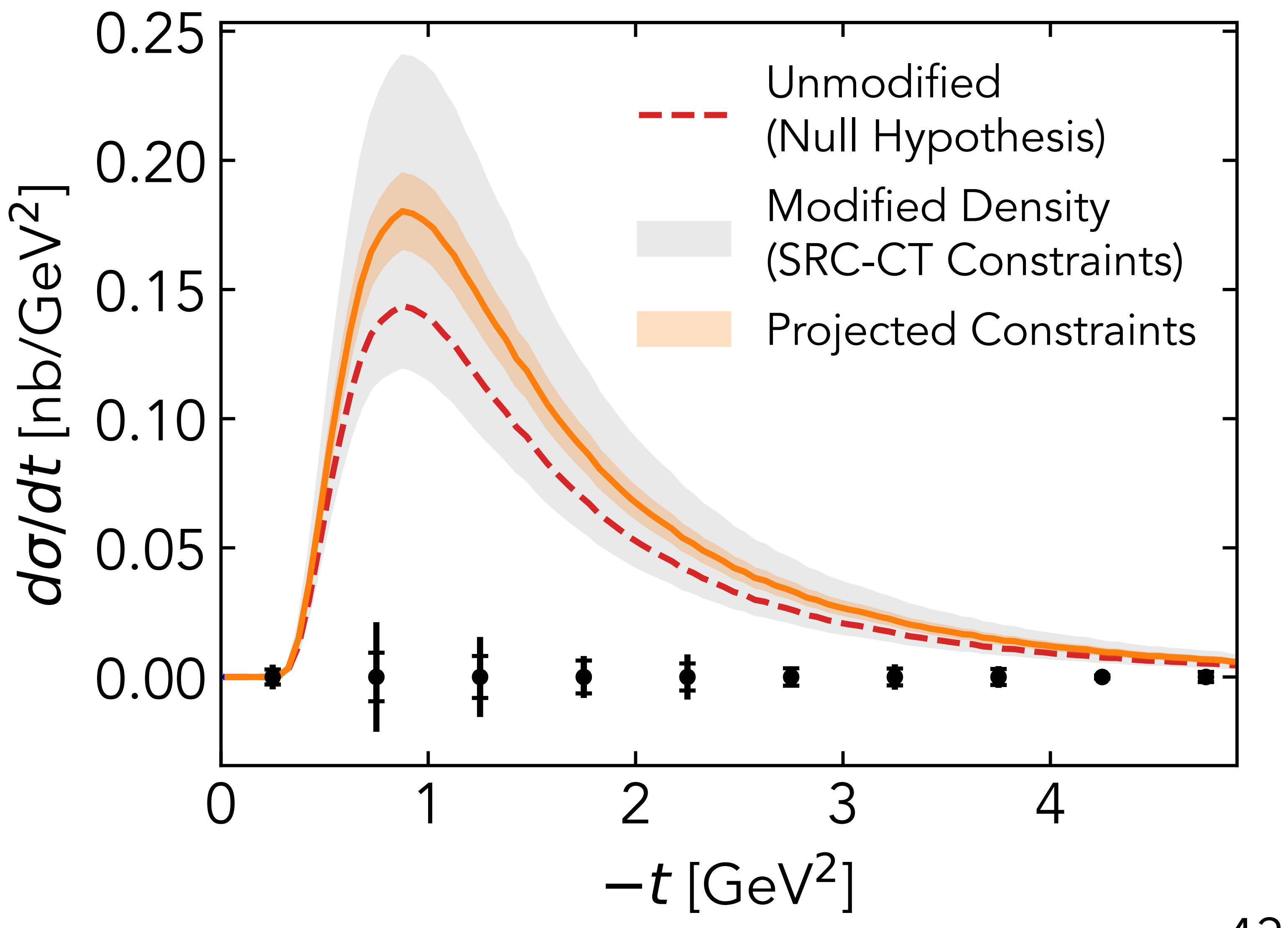


Double-differential measurements are key for separating out modification mechanisms → **Requires improved statistics**

Summary

- 85 PAC days: **helium-4** (80 days) + deuterium (5 days)
- Standard Hall D setup, as in our PRL run
- Diamond radiator, 8 GeV coherent photopeak
- Semi-inclusive photoproduction measurement:
  - J/ψ photoproduction from (γ, e^+e^-p)
- Expands program of previous E12-19-003 experiment





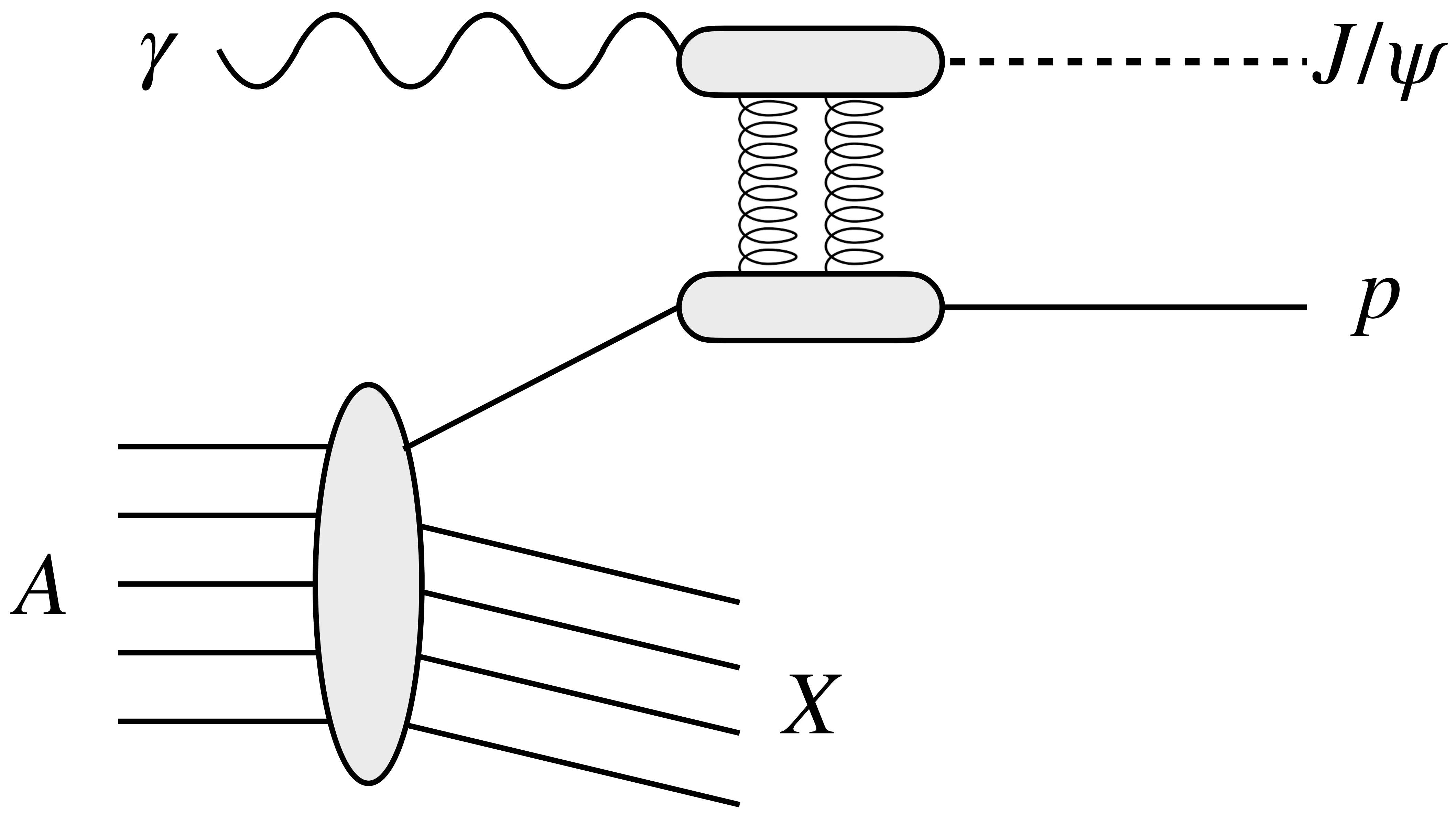
Phys. Rev. Lett Editors' Suggestion; Phys. Lett. B;
Multiple analyses in final review

Backup

Hall D Advantages

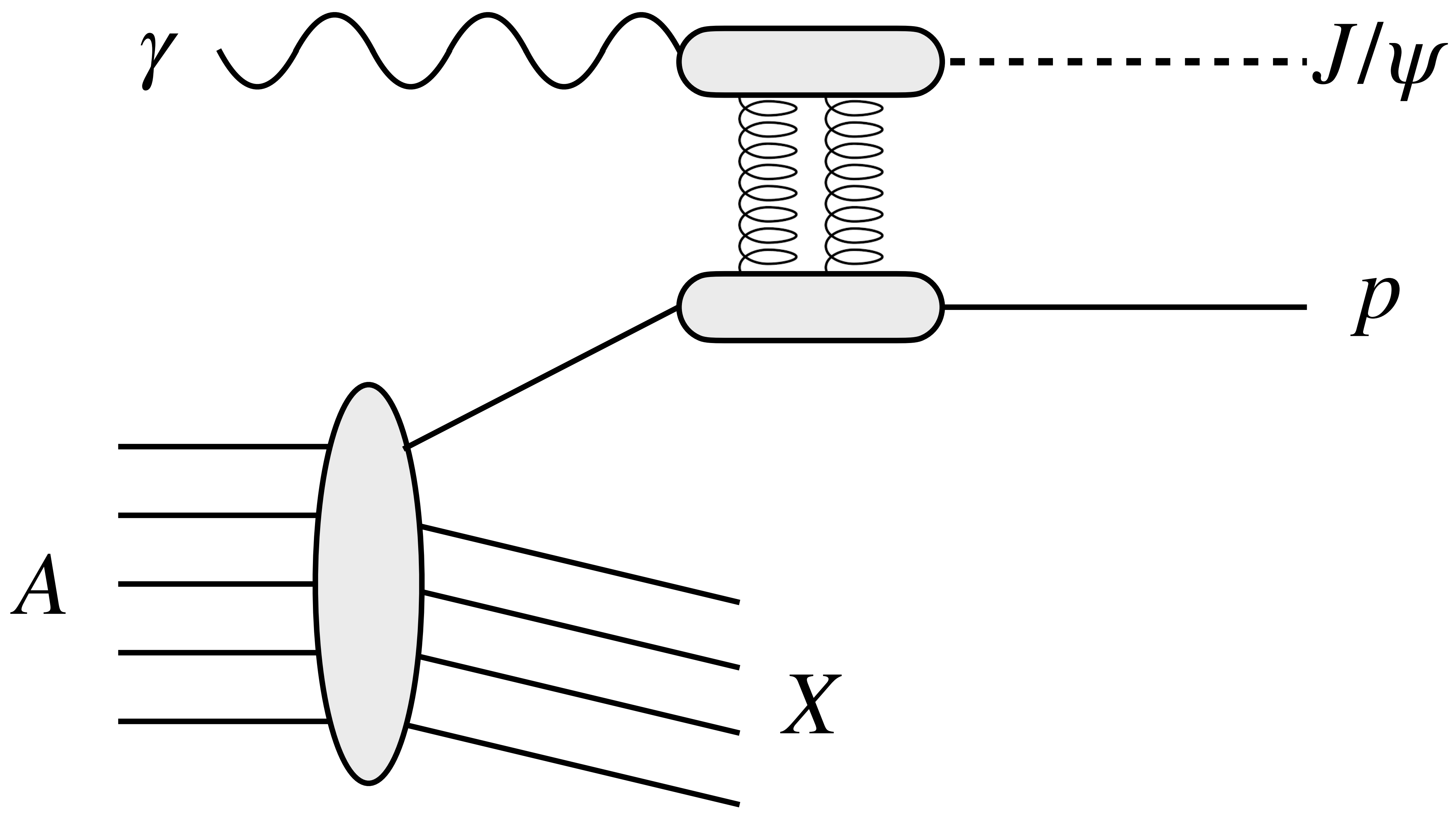
- Diamond radiator → tunable coherent bremsstrahlung spectrum
- Real photon beam → allows for comparison with significant free-proton data from GlueX
- High-resolution photon energy tagger
  - **Crucial** for definitive subthreshold measurement
- Large-acceptance GlueX spectrometer
  - Ability to measure 3+ final-state particles with large angular gaps

Photoproduction of J/ψ from bound protons

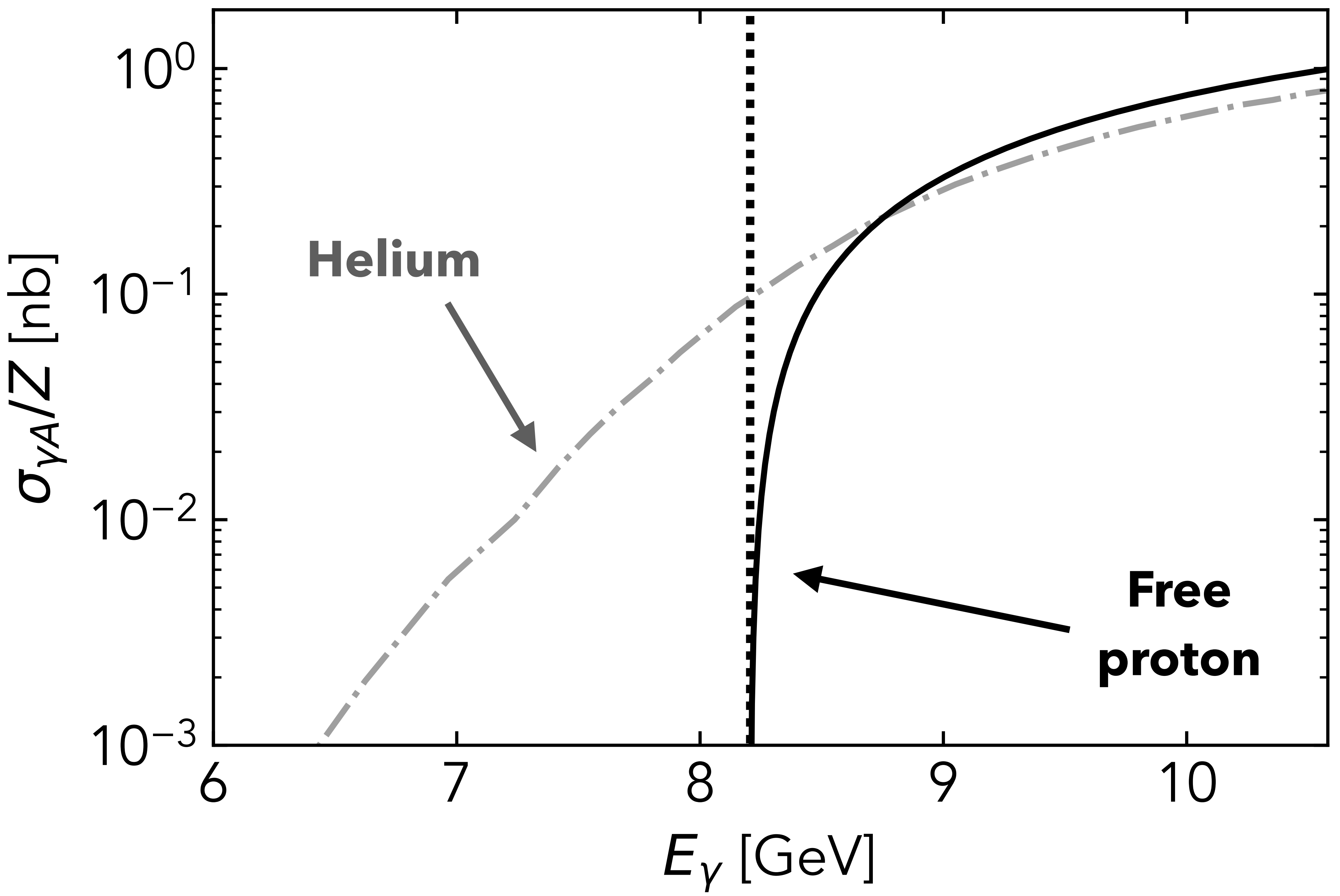


Incoherent J/ψ photoproduction near threshold sensitive to both nuclear and partonic effects

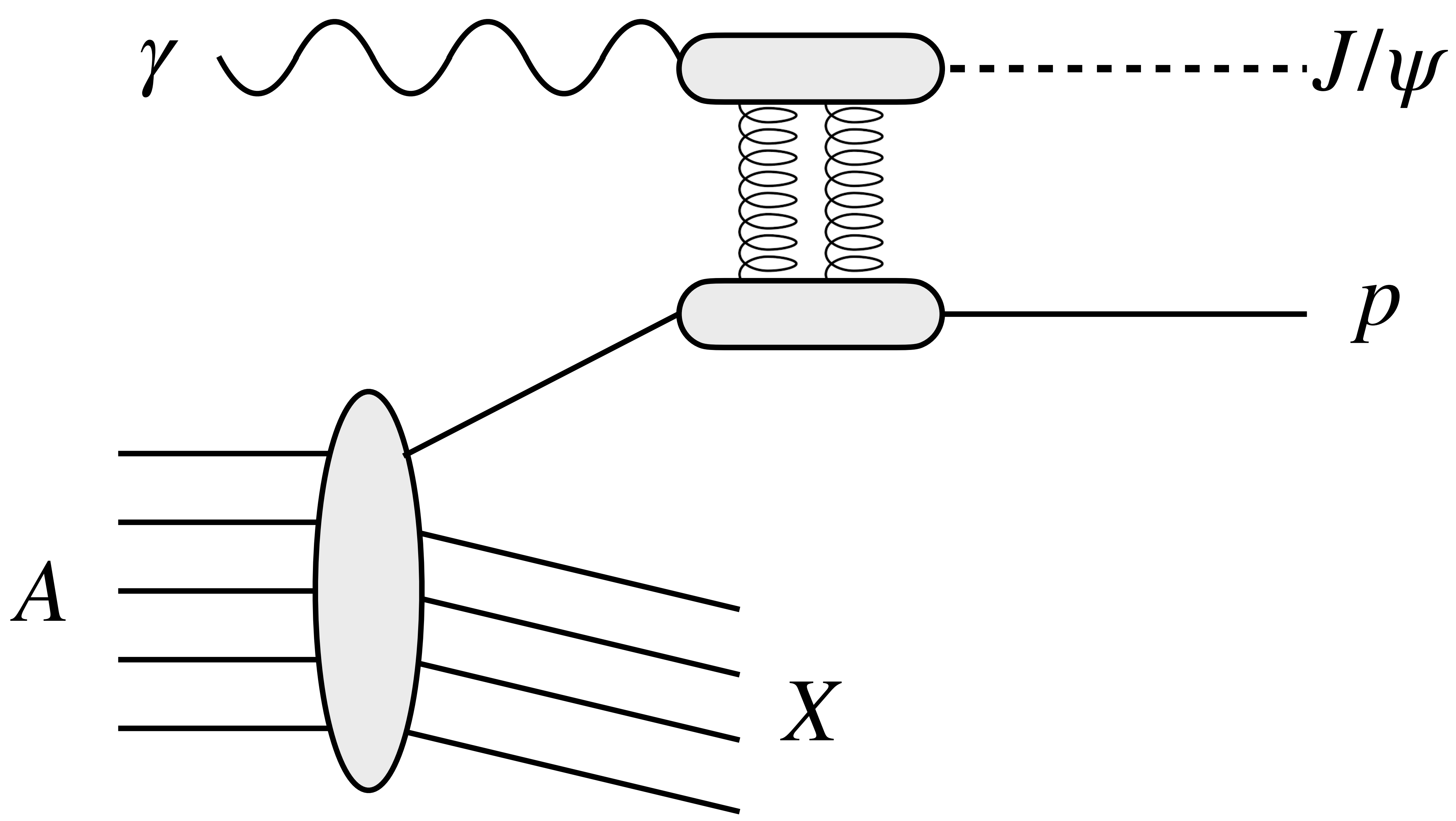
Photoproduction of J/ψ from bound protons



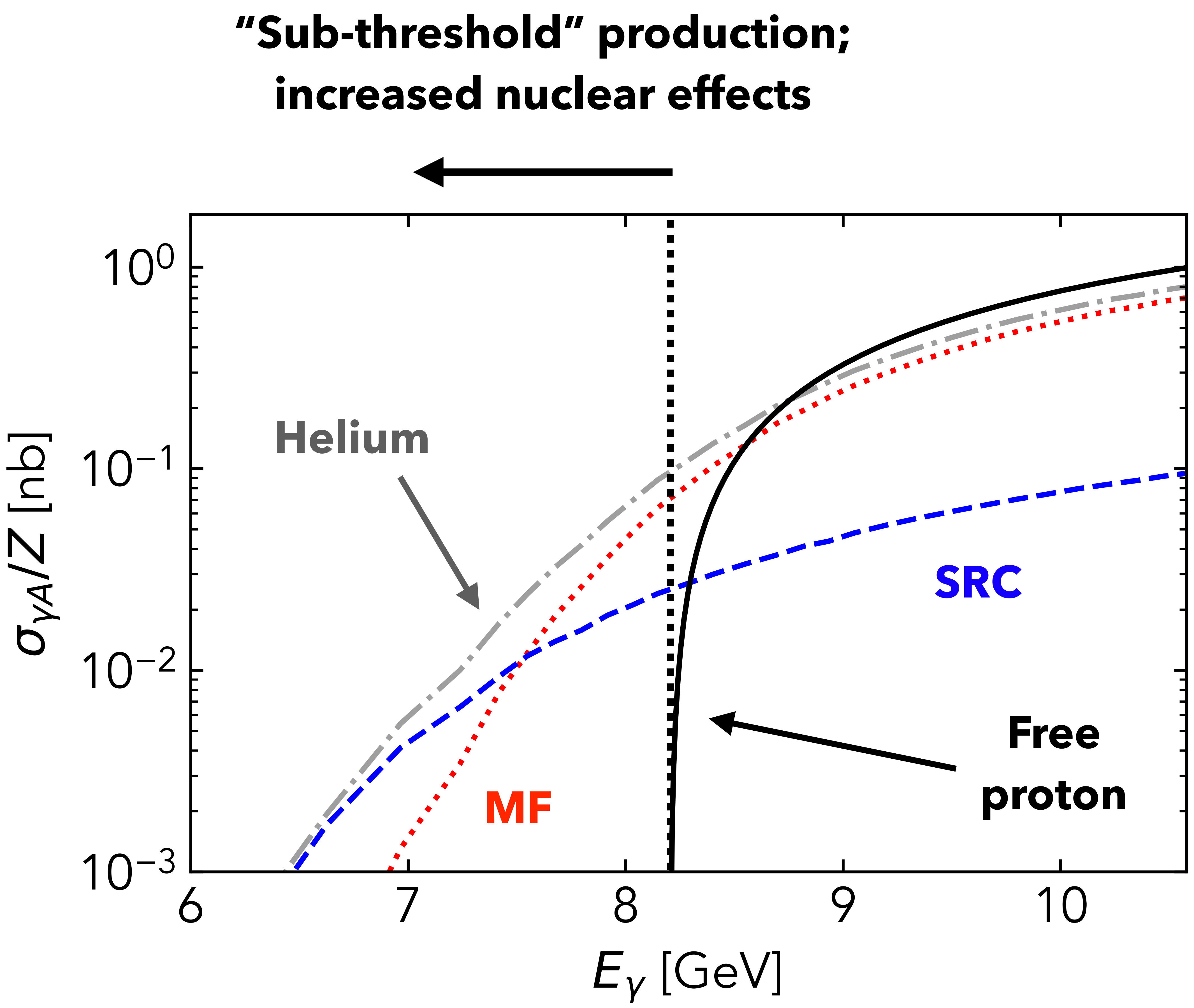
Incoherent J/ψ photoproduction near threshold sensitive to both nuclear and partonic effects



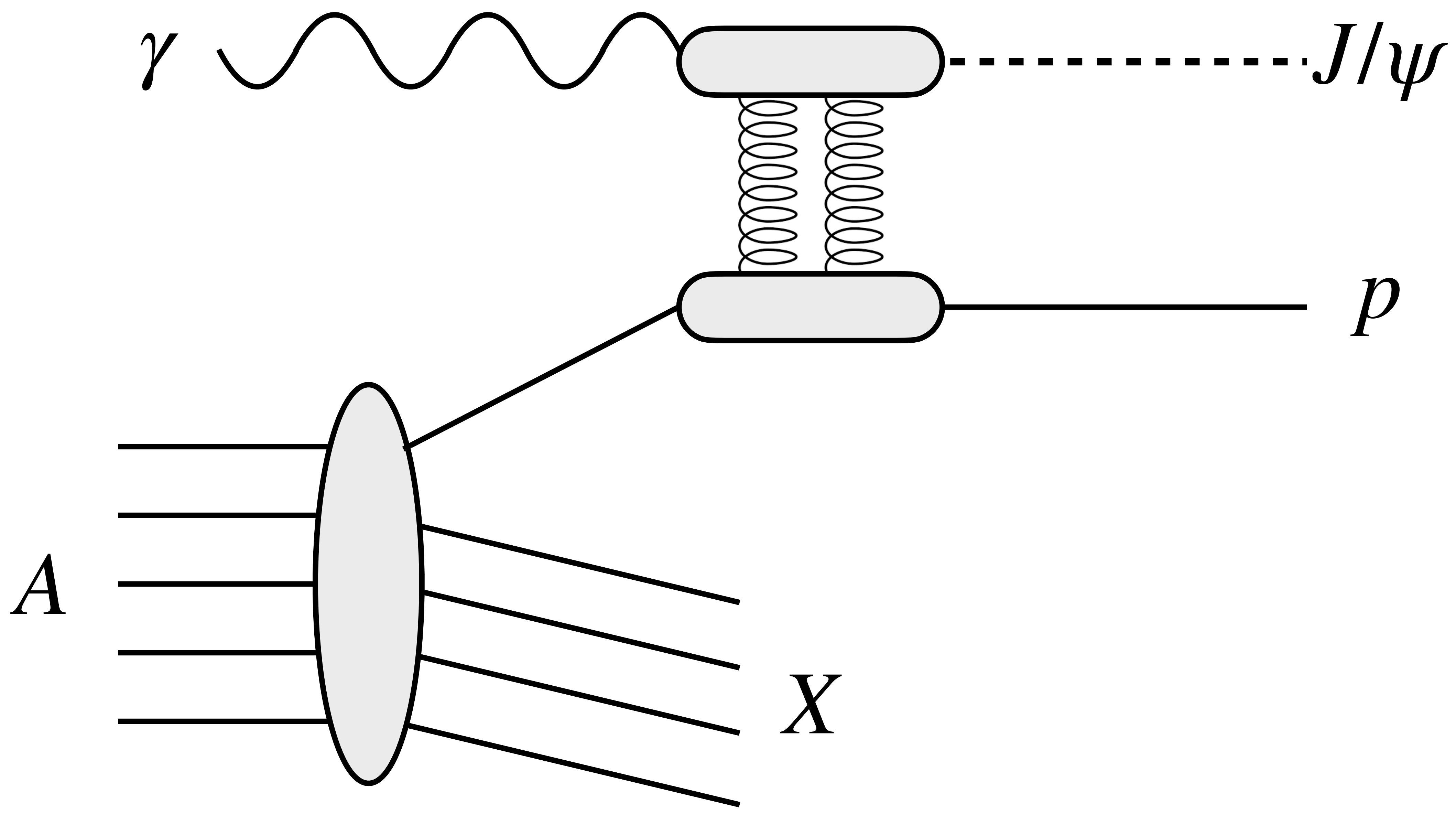
Photoproduction of J/ψ from bound protons



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

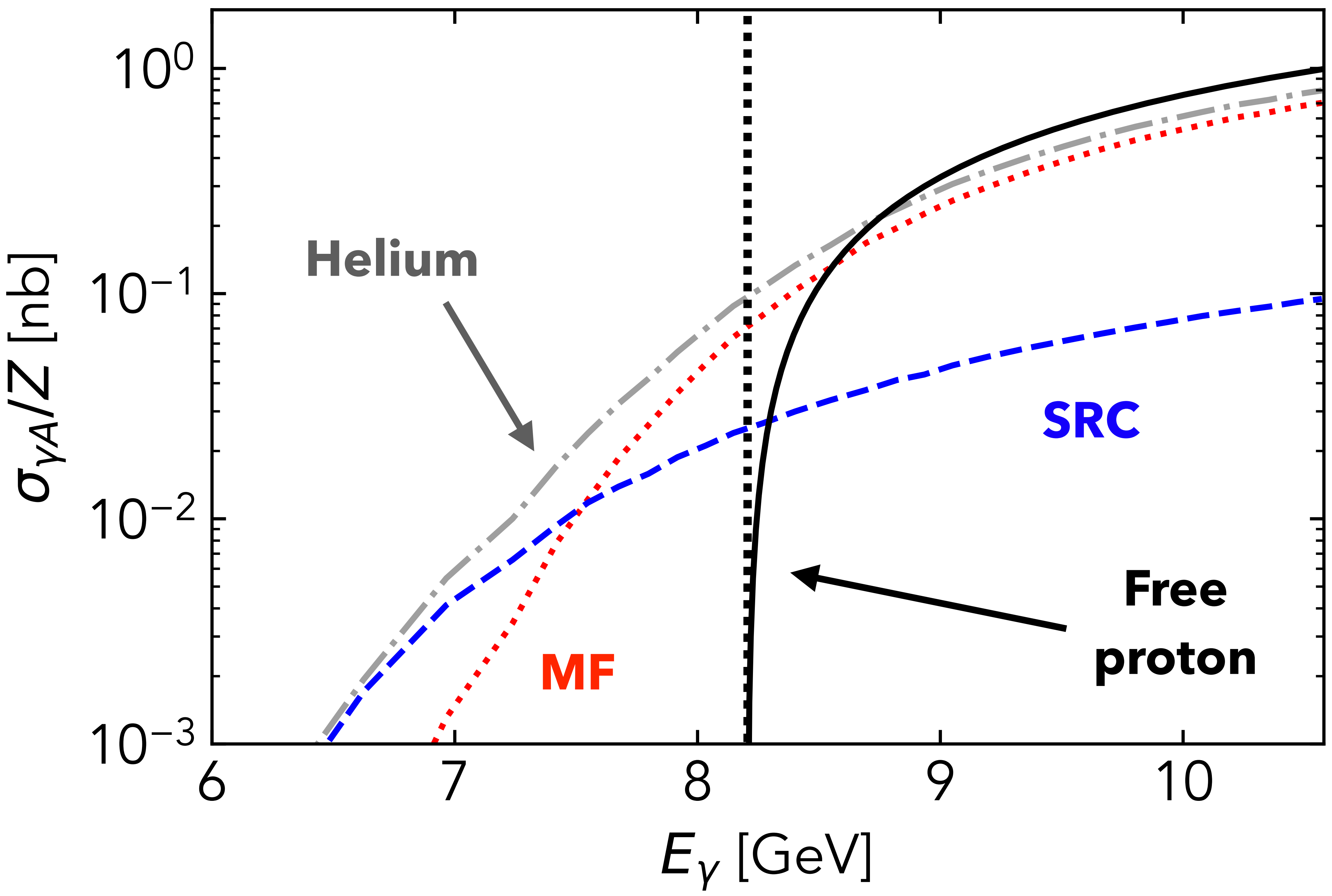


Photoproduction of J/ψ from bound protons

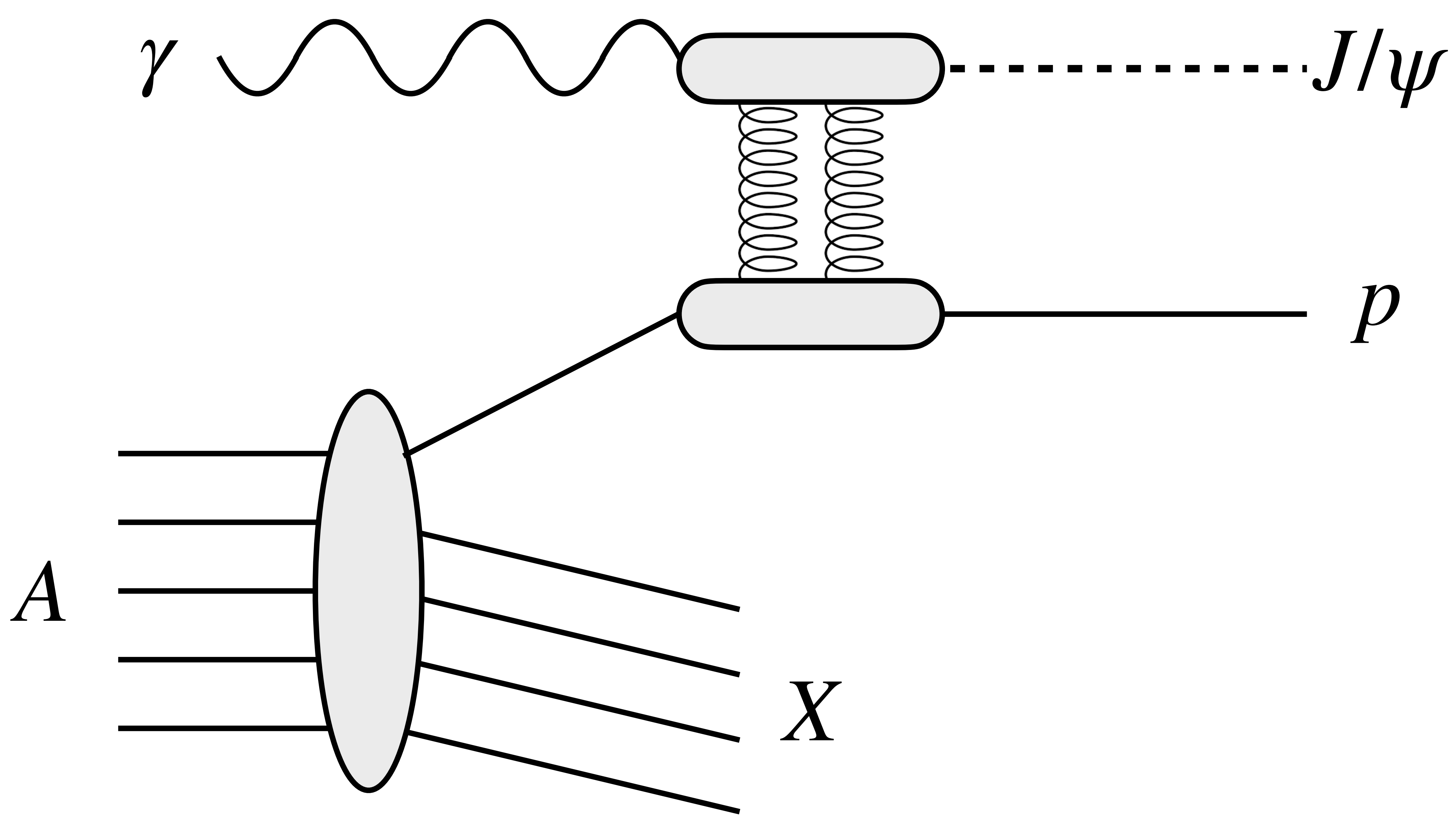


Incoherent J/ψ photoproduction near threshold sensitive to both nuclear and partonic effects

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



Photoproduction of J/ψ from bound protons



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

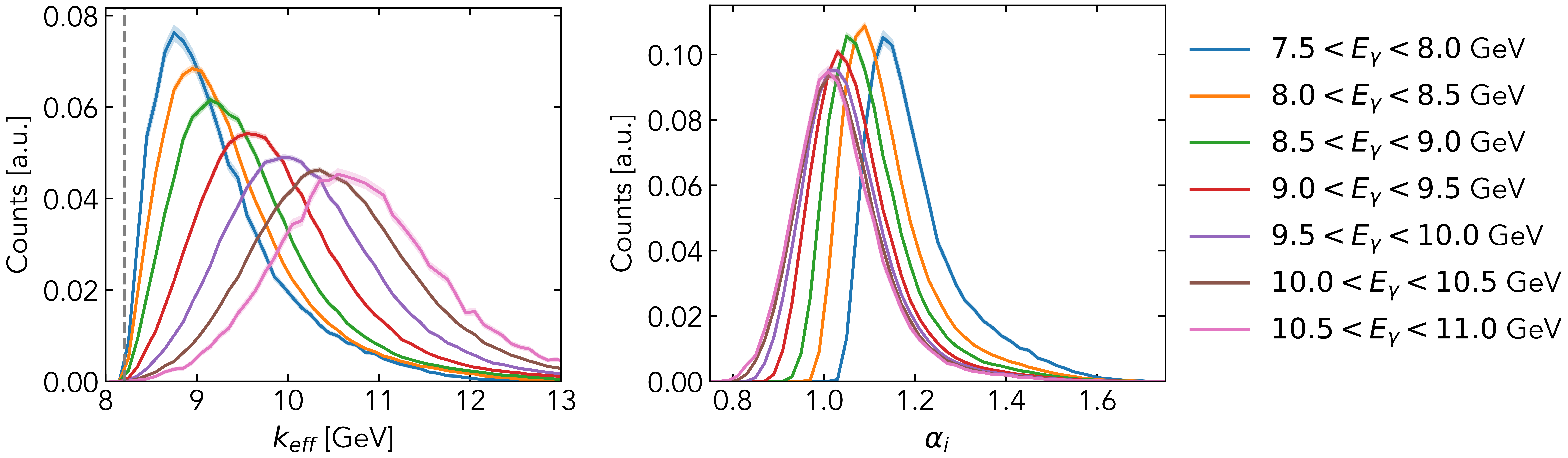
$$\frac{d\sigma(\gamma A \to J/\psi p X)}{dt d^3 p_{miss} dE_{miss}} = v_{\gamma i} \cdot \frac{d\sigma}{dt}(\gamma p \to J/\psi p) \cdot S(p_{miss}, E_{miss})$$

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

Forward cross section

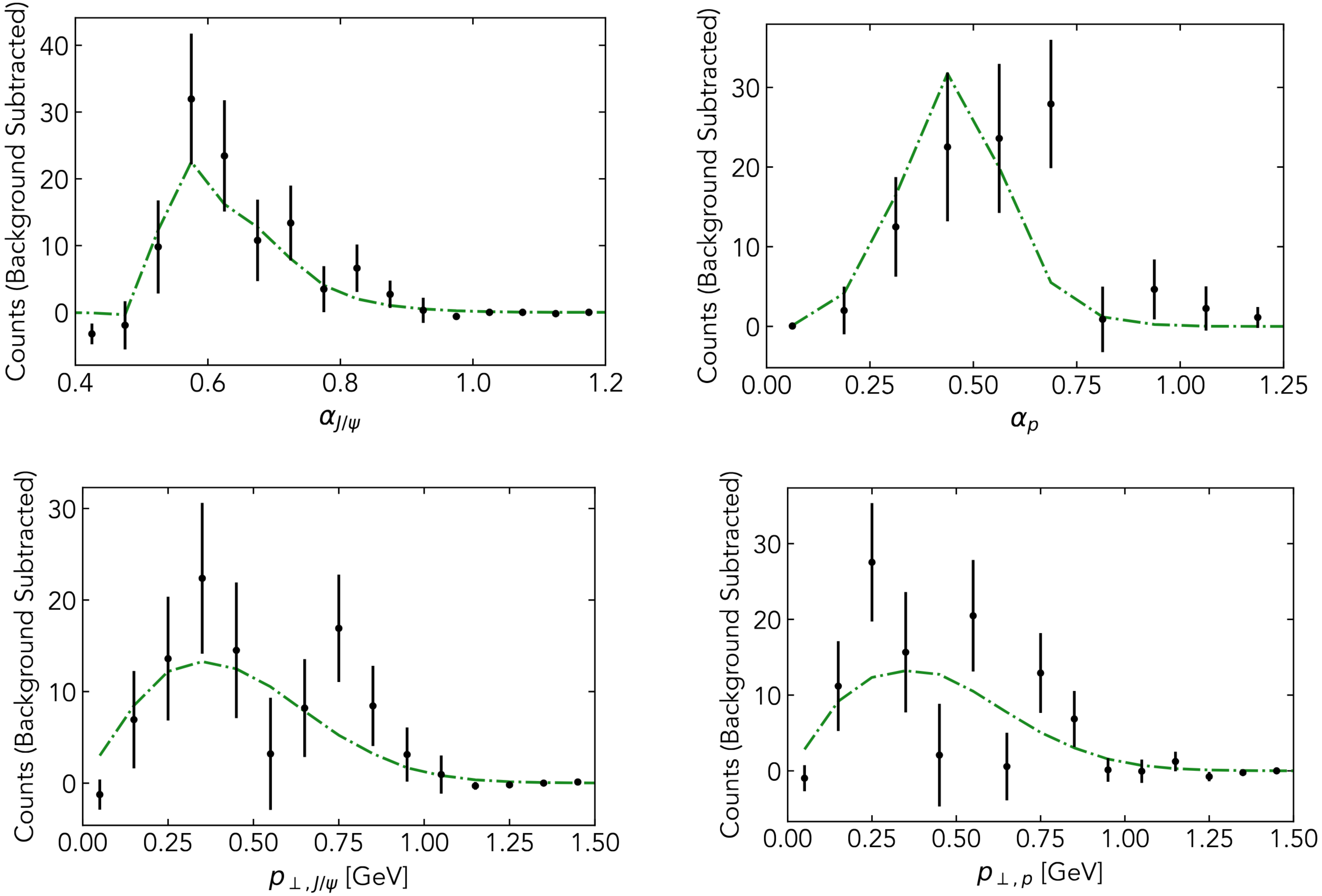
Gravitational form factor

Plane-wave cross-section sensitive to **integral** over free-proton cross section



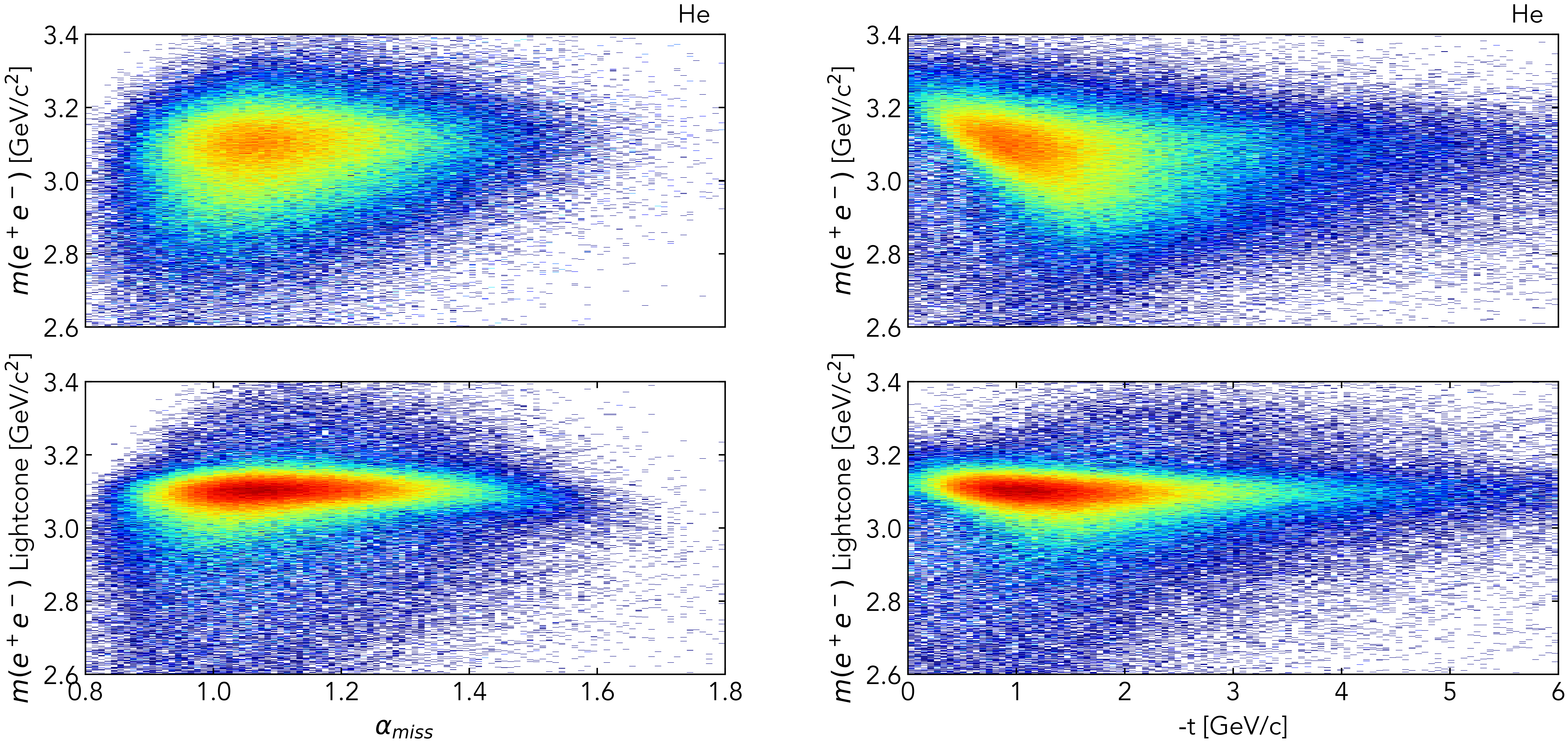
Modeling sub-threshold photoproduction does *not* require precision measurement of $E_\gamma \sim 8.2$ GeV cross section from the proton

Plane-wave simulations validated against existing data



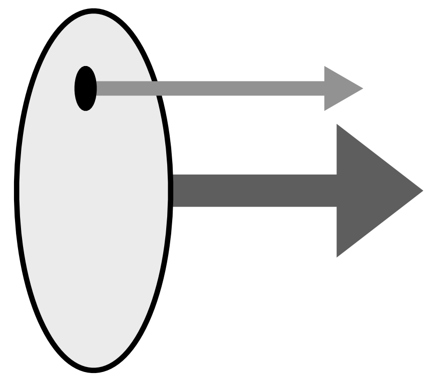
Pybus et al. PRL (2025)

Light-cone mass variable improves kinematic stability



Analysis on the light-front

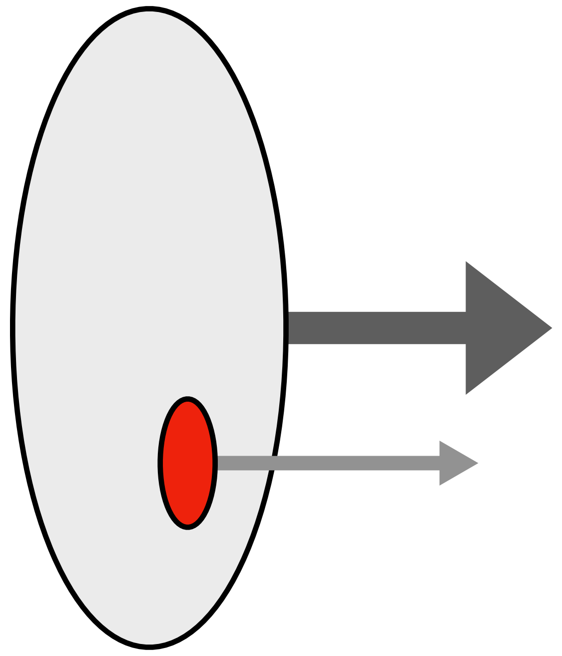
Parton in Hadron



Parton momentum fraction

$$x_B$$

Nucleon in Nucleus



Nucleon momentum fraction

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

Reformulate invariant mass using light-front variables

$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(p^+_{e^+} + p^+_{e^-}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

$$p^{\pm} = E \pm p_z$$

Reformulate invariant mass using light-front variables

$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(p^+_{e^+} + p^+_{e^-}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

$$p^{\pm} = E \pm p_z$$

Well-reconstructed

$$p^- = E - p_z$$

<u>Cancellation</u> of resolution effects

Poorly-reconstructed

$$p^+ = E + p_z$$

<u>Enhancement</u> of resolution effects

Well-reconstructed

Reformulate invariant mass using light-front variables

$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(p^+_{e^+} + p^+_{e^-}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

$$p^{\pm} = E \pm p_z$$

Well-reconstructed

$$p^- = E - p_z$$

Cancellation of resolution effects

Poorly-reconstructed

$$p^+ = E + p_z$$

Enhancement of resolution effects

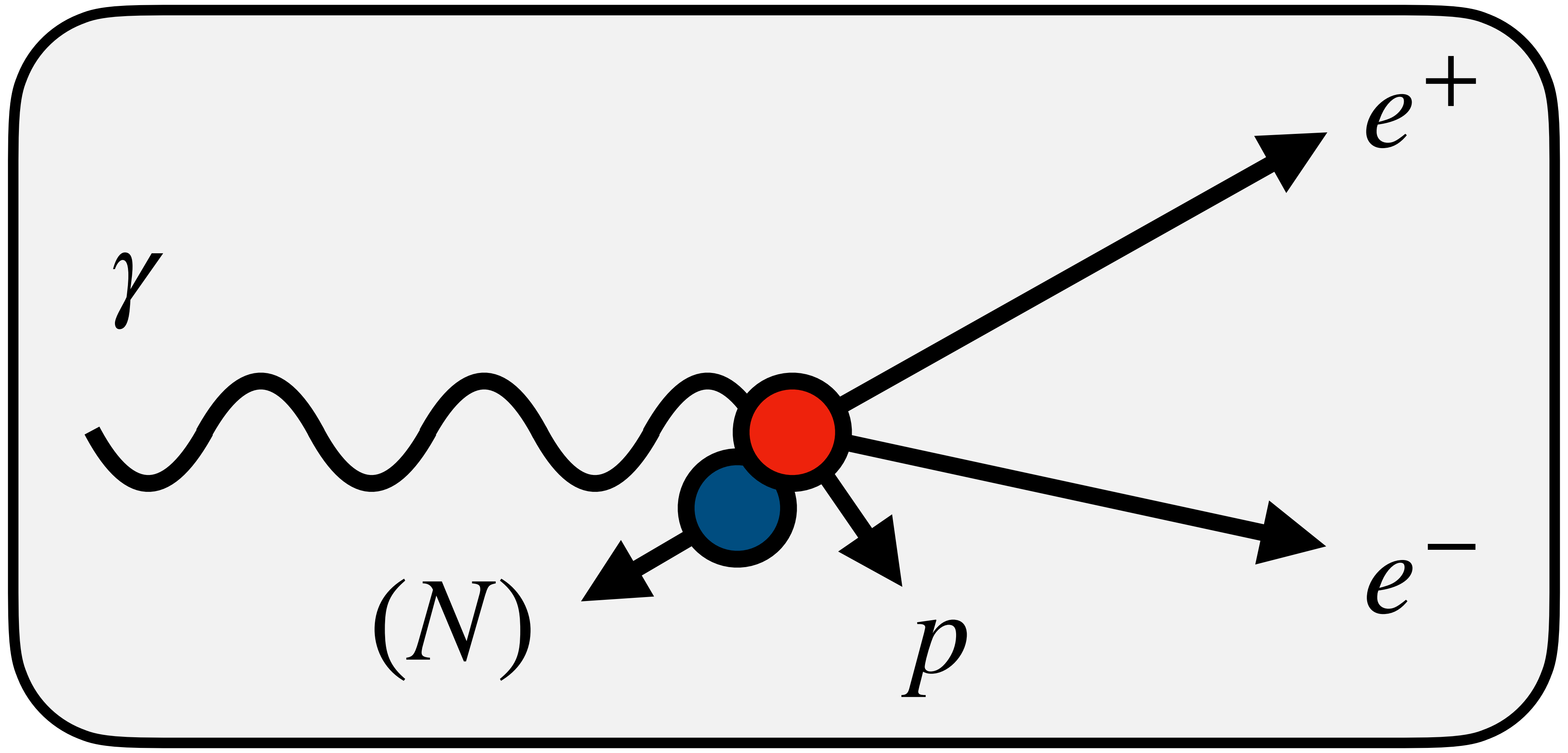
Well-reconstructed

Reformulate invariant mass using light-front variables

$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(p^+_{e^+} + p^+_{e^-}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

$$p_\gamma + p_{2N} = p_{e^+} + p_{e^-} + p_p + p_N$$

Assume recoil 4-momentum carried by single nucleon



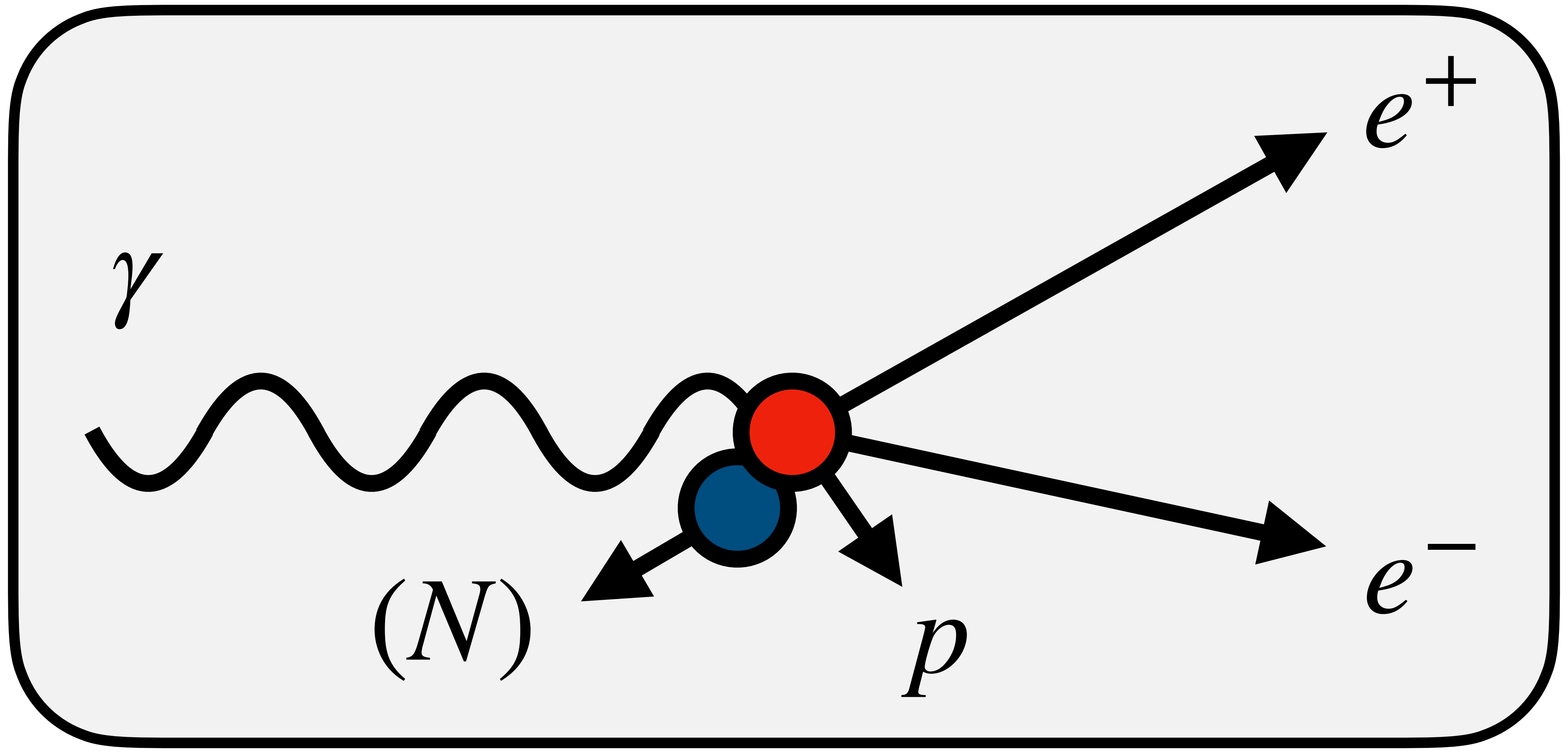
Reformulate invariant mass using light-front variables

$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(p^+_{e^+} + p^+_{e^-}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

$$p_\gamma + p_{2N} = p_{e^+} + p_{e^-} + p_p + p_N$$

$$p_N^{-,\perp} = p_\gamma^{-,\perp} + p_{2N}^{-,\perp} - p_{e^+}^{-,\perp} - p_{e^-}^{-,\perp} - p_p^{-,\perp}$$

Assume recoil 4-momentum carried by single nucleon



Reformulate invariant mass using light-front variables

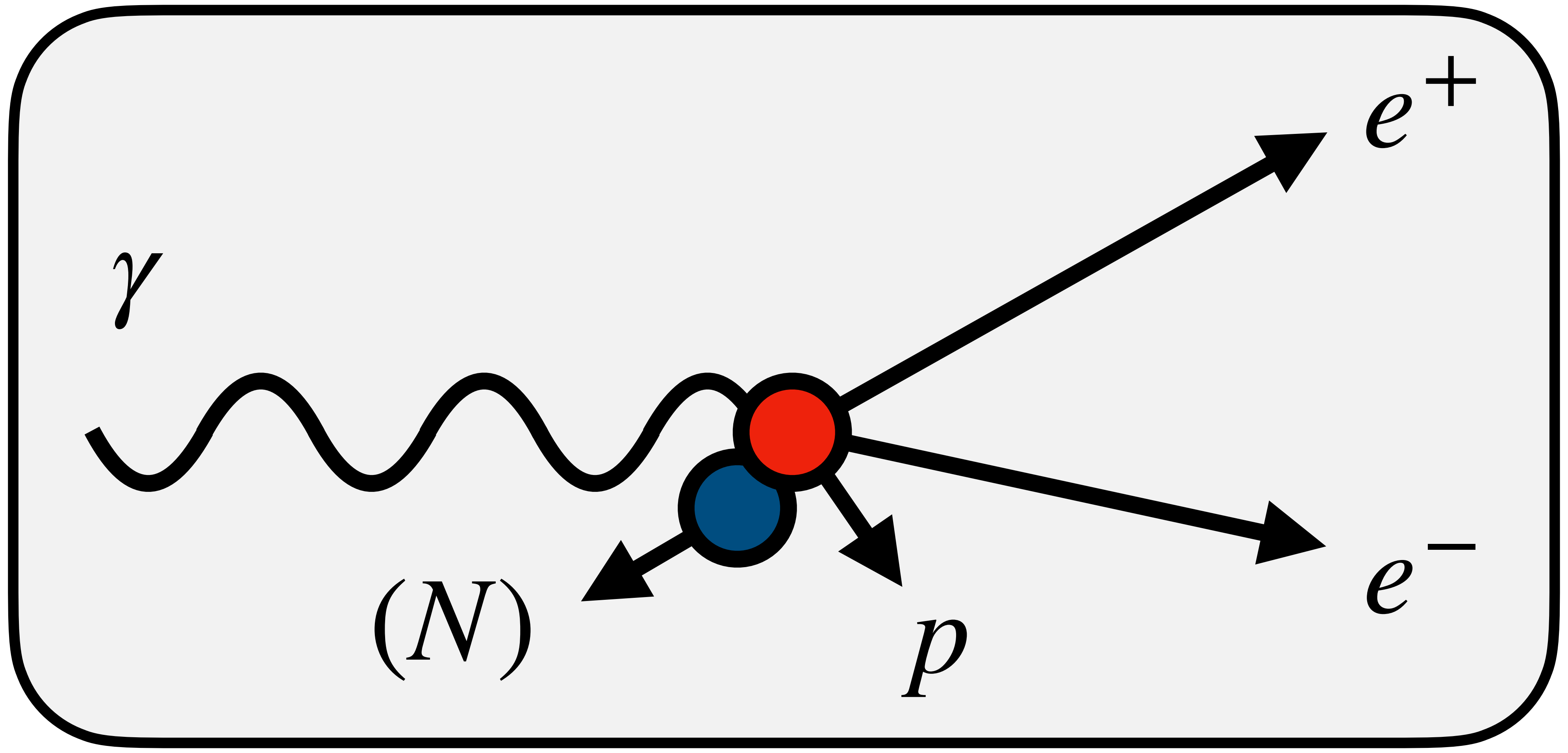
$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(p^+_{e^+} + p^+_{e^-}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

$$p_\gamma + p_{2N} = p_{e^+} + p_{e^-} + p_p + p_N$$

$$p_N^{-,\perp} = p_\gamma^{-,\perp} + p_{2N}^{-,\perp} - p_{e^+}^{-,\perp} - p_{e^-}^{-,\perp} - p_p^{-,\perp}$$

$$p_N^+ = \frac{p^2_{N,\perp} + m^2_N}{p^-_N}$$

Assume recoil 4-momentum carried by single nucleon



Reformulate invariant mass using light-front variables

$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(p^+_{e^+} + p^+_{e^-}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

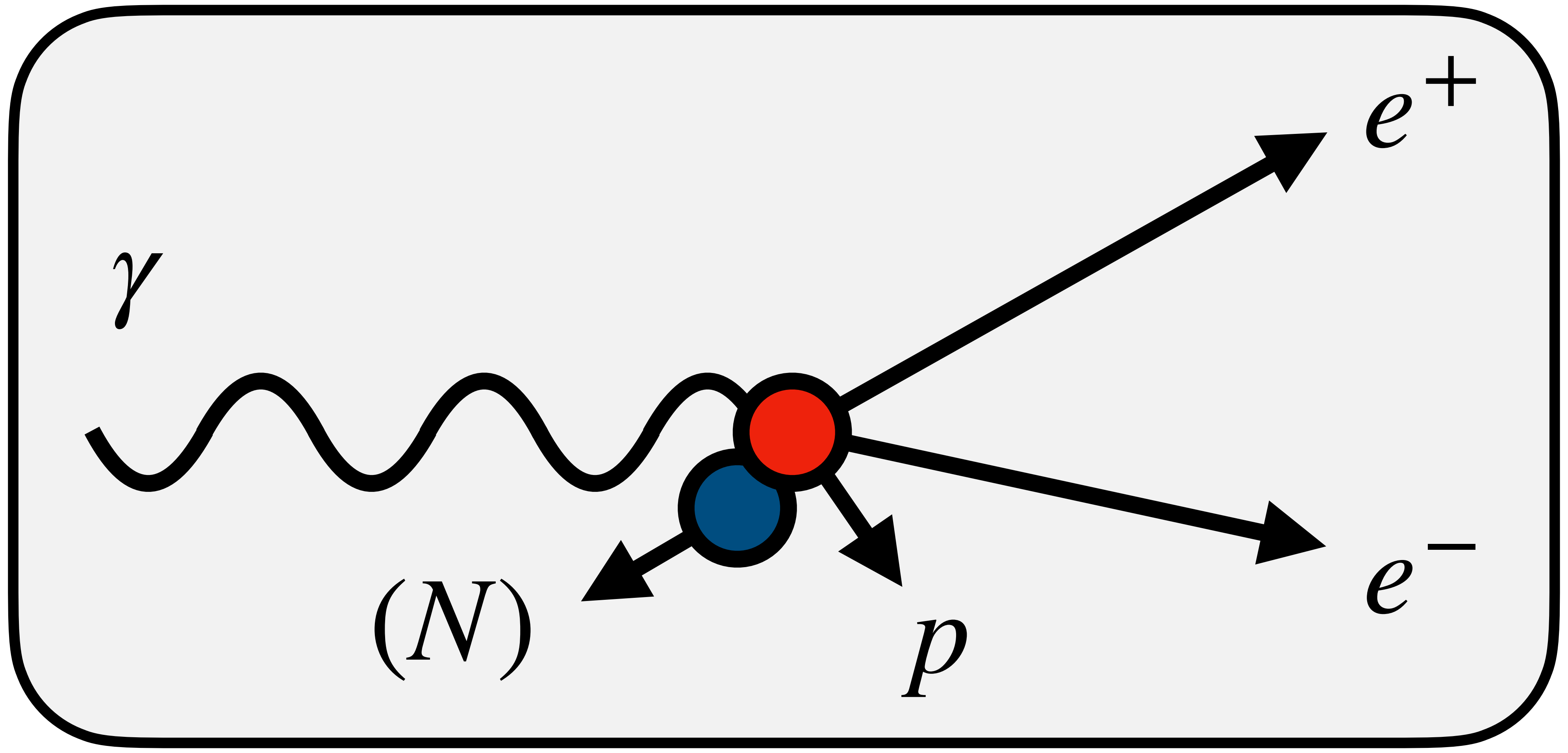
$$p_\gamma + p_{2N} = p_{e^+} + p_{e^-} + p_p + p_N$$

$$p_N^{-,\perp} = p_\gamma^{-,\perp} + p_{2N}^{-,\perp} - p_{e^+}^{-,\perp} - p_{e^-}^{-,\perp} - p_p^{-,\perp}$$

$$p_N^+ = \frac{p^2_{N,\perp} + m_N^2}{p_N^-}$$

$$p^+_{e^+} + p^+_{e^-} = p^+_\gamma + p^+_{2N} - p^+_p - p^+_N$$

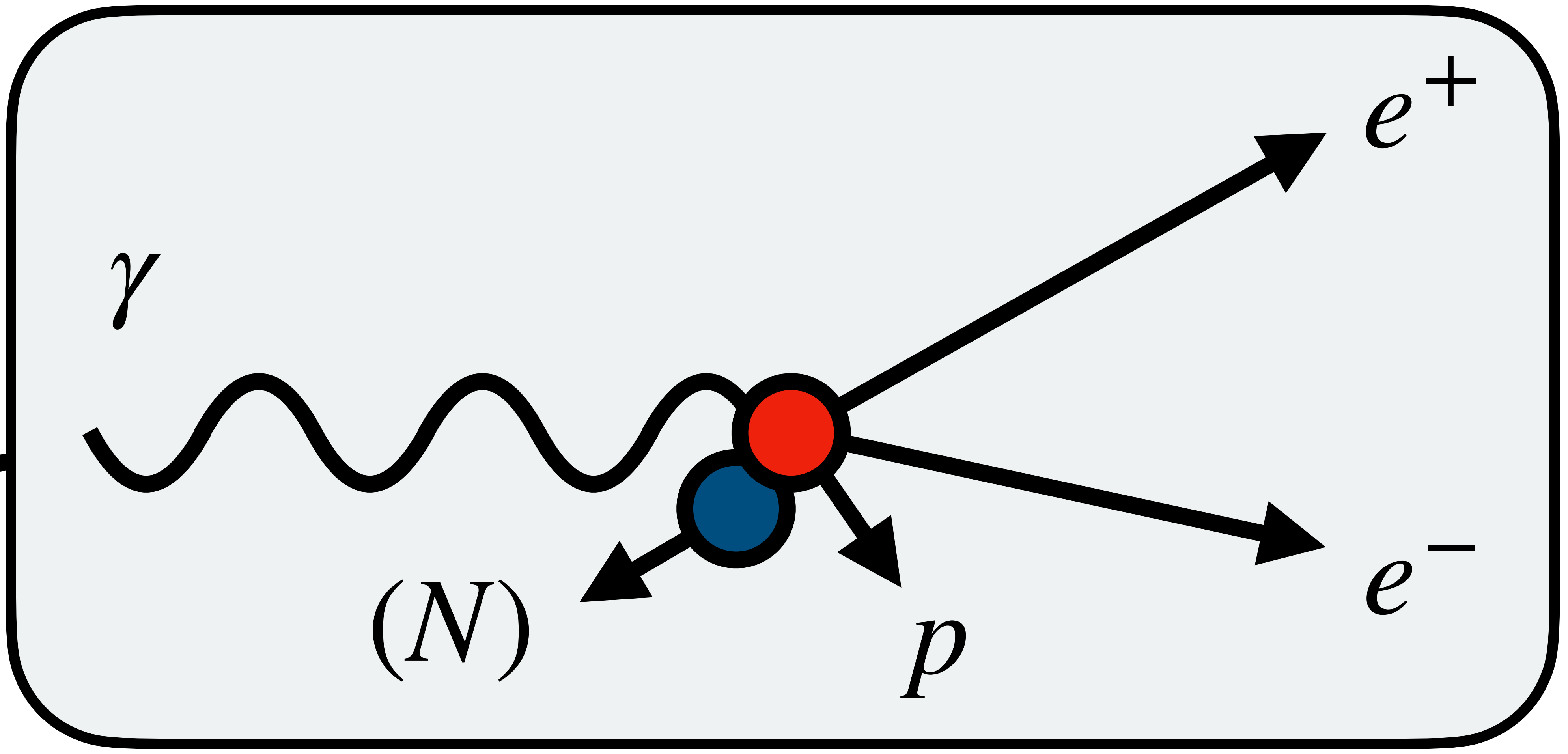
Assume recoil 4-momentum carried by single nucleon



Reformulate invariant mass using light-front variables

$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(p^+_{e^+} + p^+_{e^-}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

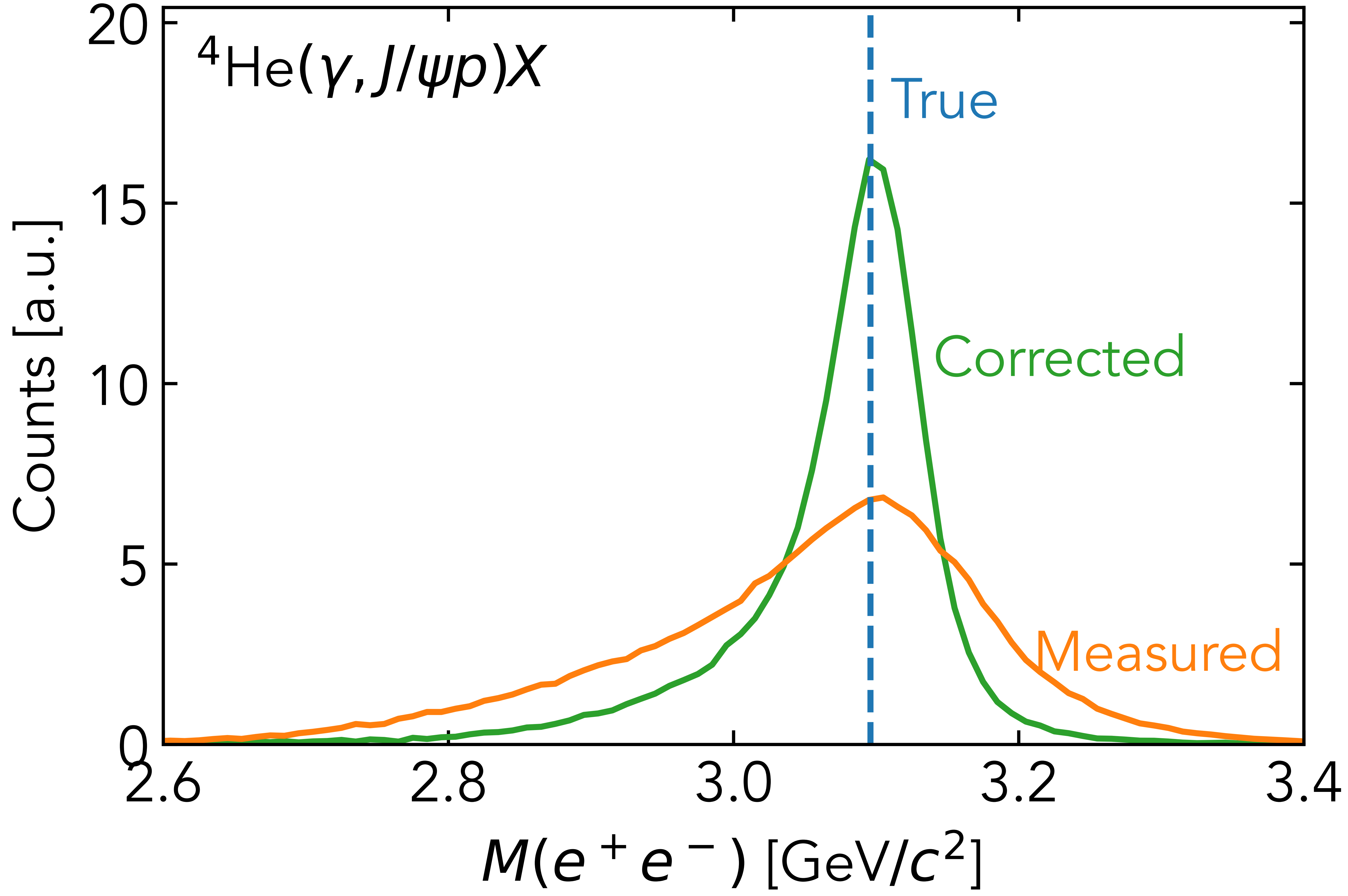
Assume recoil 4-momentum carried by single nucleon



Use photon and proton information to substitute for "plus" momentum

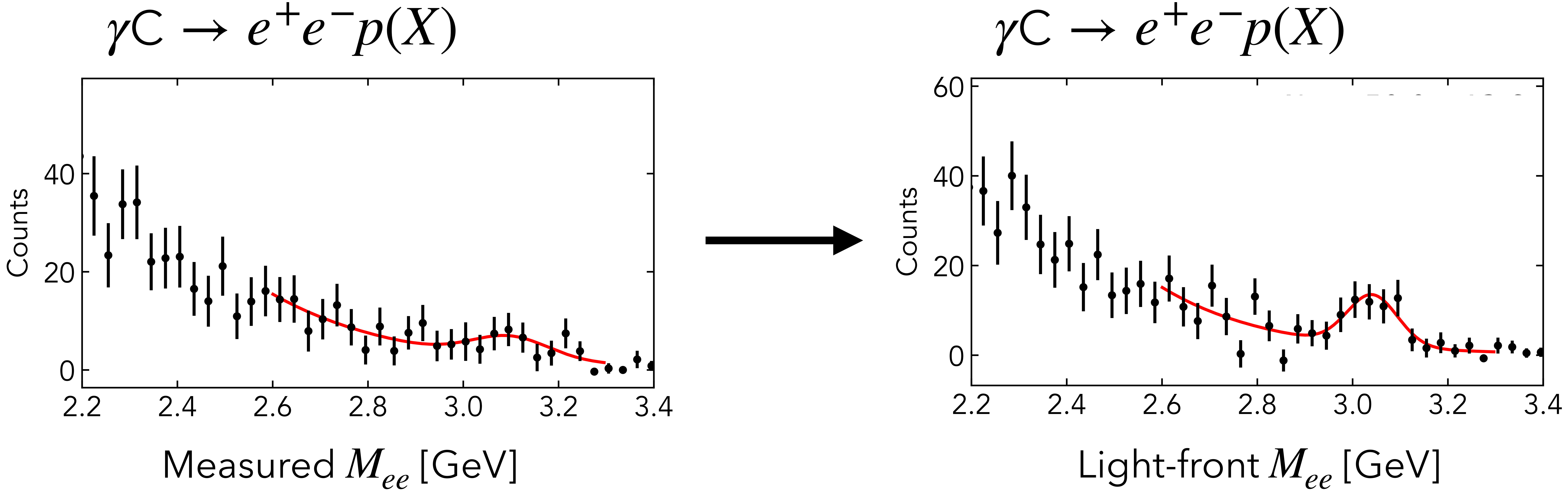
$$M^2_{e^+e^-} \approx \left(p^-_{e^+} + p^-_{e^-}\right)\left(2E_\gamma + 2m_N - p^+_p - \frac{m_N^2 + p_{tot}^2}{2m_N - p^-_{tot}}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

Simulation shows resolution improvement



Pybus et al. PRL (2025)

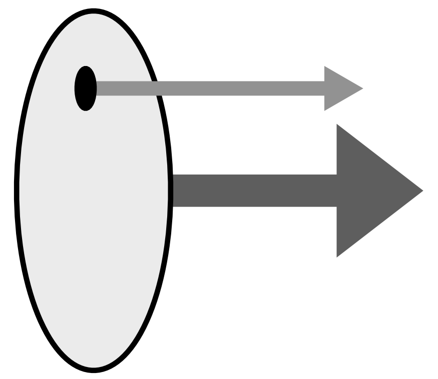
Careful selection of observables improves signal resolution



Pybus et al. PRL (2025)

Analysis on the light-front

Parton in Hadron

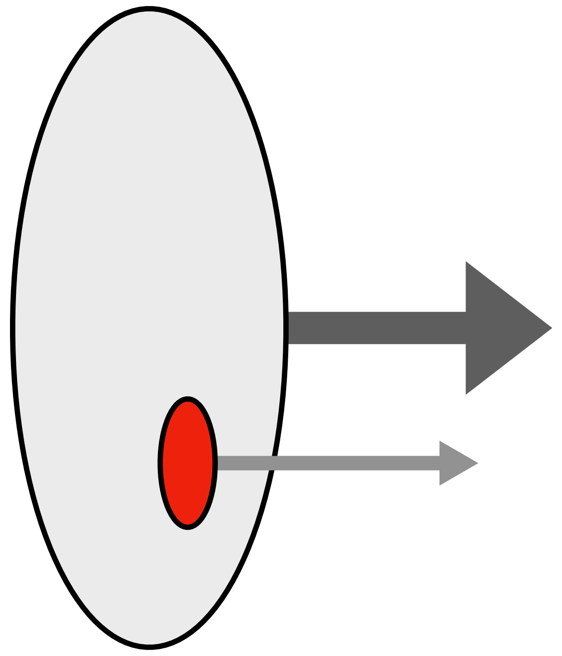


Parton momentum fraction

x_B

Light-front variables mitigate resolution effects

Nucleon in Nucleus



Nucleon momentum fraction

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

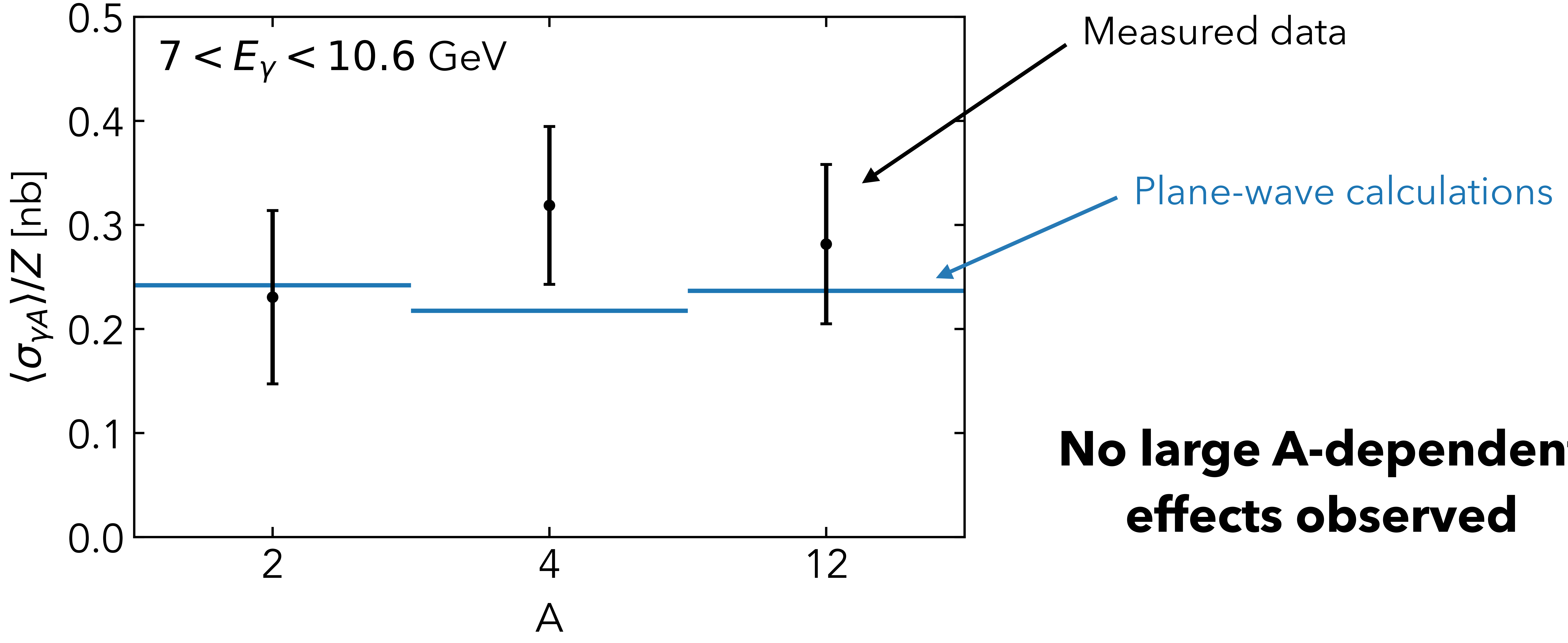
Low-momentum nucleon:

$\alpha_N \sim 1$

High-momentum nucleon:

Large $|\alpha_N - 1|$

Energy-averaged cross section across nuclei



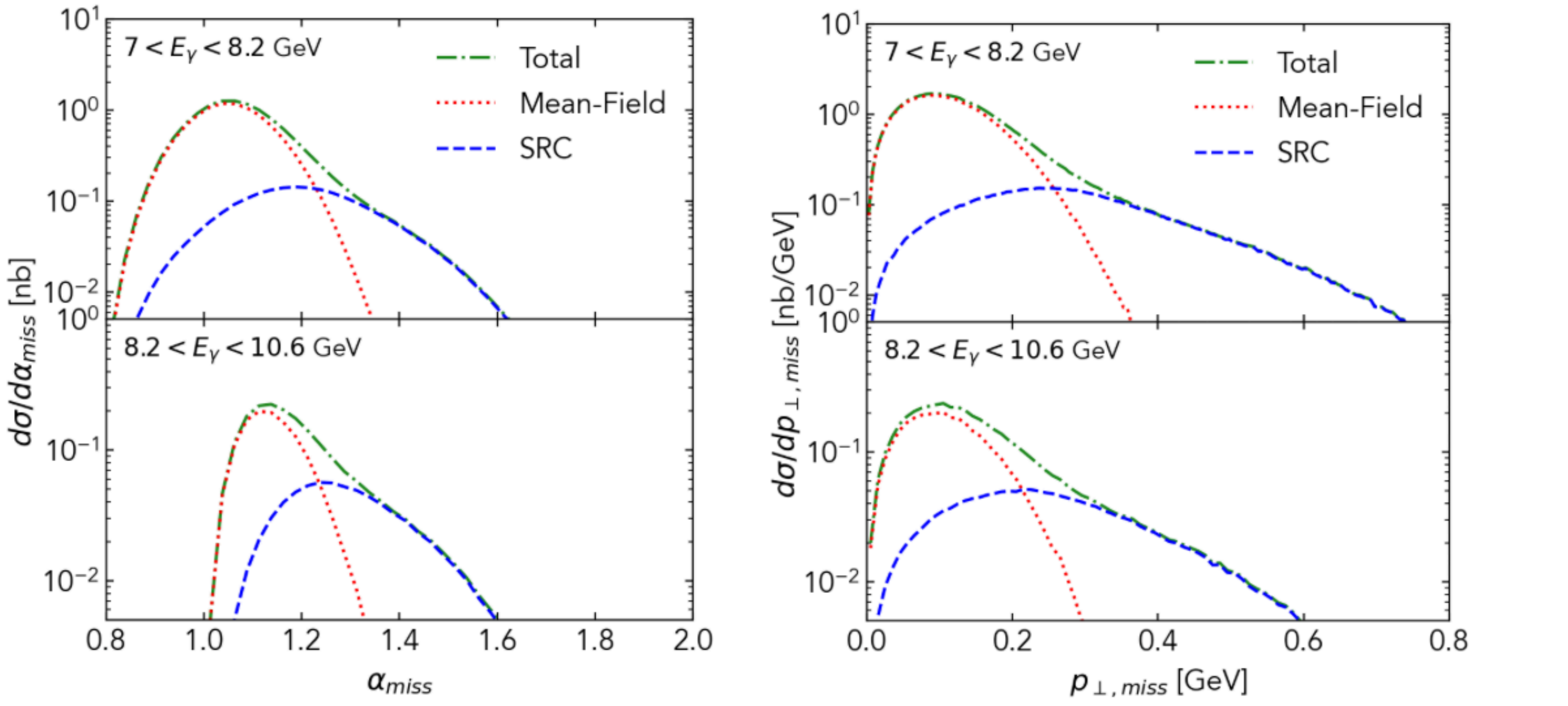
No large A-dependent effects observed

Pybus et al. PRL (2025)

PAC Readers Questions / Our Answers

> *In the new proposal to PAC53, there is strong emphasis on production from SRC nucleons (understandably so, since the SRC-EMC correlation in the quark sector was an important recent discovery by some of you). But how reliably can J/Psi production from SRC nucleons be identified in the proposed experiment?*
>
> *Namely, when comparing to the calculations shown in Fig. 3, even in the below-threshold bin more than half of the events are likely due to mean-field nucleons. It's not clear whether the statistics in the proposed future lowest bin will allow for a significantly better separation of SRC and mean field. Two related observations:*
>
> ** According to Fig. 9, the total uncertainty is expected to be 40% in the lowest bin, so roughly the same as the SRC contribution*

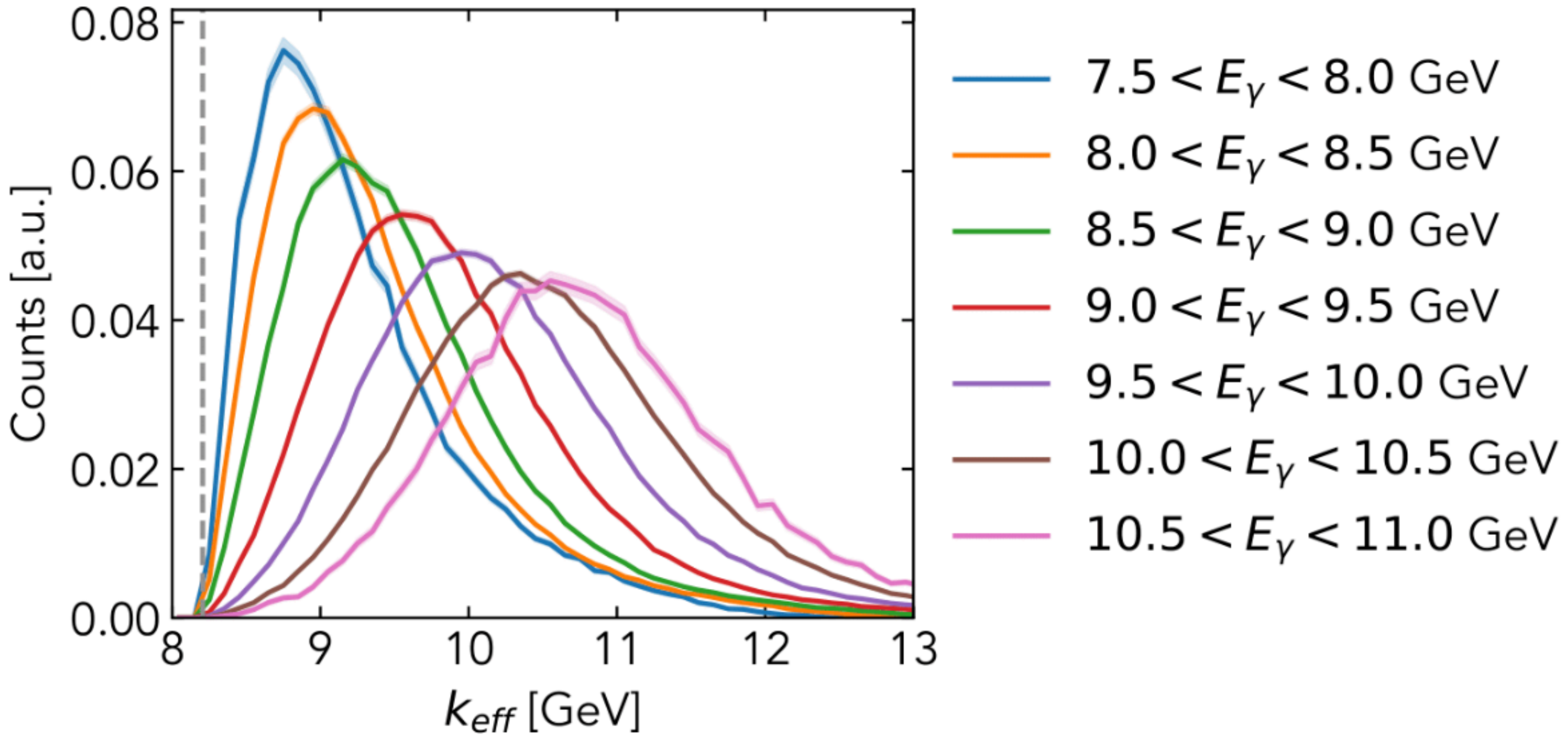
We apologize if Fig. 3 led to confusion. The readers are correct that beam photon energy cannot be used to separate between Mean-field and SRC-dominated regimes. The separation of SRC and mean-field contributions is performed using the measured missing light-cone momentum α_{miss} and transverse momentum p_T, requiring values above 1.3 and 300 MeV/c respectively to almost entirely exclude mean-field contribution:



Response Figure 1: Reaction cross-section as a function of missing light-cone momentum α_{miss} and transverse momentum p_T, separating contributions from interaction with mean-field and SRC nucleons. As can be seen, these measured kinematic variables allow separating mean-field and SRC contribution independently of the incoming photon beam energy.

> ** The (attached) TAC report observes that close to threshold, uncertainties in the GlueX measurement of free-proton J/Psi production are large. How will this impact the proposed experiment, which seems to rely on those results?*

While the result is sensitive to the free-proton cross-section near threshold, due to the impact on nuclear motion on the "effective" photon energy the dependence on the immediately-above-threshold energy is much smaller than one might naively expect. The attached plot (from our PRL Supplemental Materials) shows the effective photon energy, calculated from the center-of-mass energy of the final proton-J/psi system, in different bins of nucleus-frame photon energy. As can be seen, even below threshold the "effective" photon energy experienced from the perspective of the moving proton spans a wide range. We account for these effects of nuclear motion in the calculated cross-section, resulting in small sensitivity to k_eff<8.5 GeV. With the anticipated increase in precision from the GlueX-III run, the uncertainty on the plane-wave cross section from this input is expected to be on the level of a few percent even below threshold.



Response Figure 2: effective photon energy distribution entering the cross-section calculation for interaction with moving protons in 4He. As can be seen, nucleon motion effects lead to a wide effective distribution, reducing sensitivity to the measured free (stationary) proton cross-section at threshold.

> *As an aside, we note that proposals to PAC51 and PAC52 had "probing SRC" in the title. This proposal changes that to "probing nuclear gluon structure." Does this signal a shift in focus away from SRCs?*

The previous proposal had two distinct physics aims – gluon structure from J/Psi measurements and short-distance nuclear structure and interactions from SRC measurements. There has been rapid development in using J/Psi production near the threshold to probe the gluonic structure of the nucleon and nuclei, and JLab is becoming a leader in this area. The PRL from our pilot experiment demonstrated the uniqueness and importance of subthreshold J/Psi production and we want to explore and push this technique to the next level to probe the gluon structure. Therefore, this proposal is timely and focused on J/Psi studies, which are important for the 12 GeV physics program and studies at the EIC and beyond. As we complete analyses and publication of the original SRC experiment, we can extend those studies to this proposed experiment.

> *If the focus is now on gluon EMC effect, that's certainly fine. But how clearly is it connected to the EMC effect? There is no "EMC ratio" (nucleus-to-nucleon observable) proposed, or indeed any observable that would be plotted against Bjorken xB, correct?*
>
> *In this respect the next question would be whether the statistics of the calibration data on 2H would be sufficient for this. Compared to the pilot run, the ratio of running time with nuclear target and 2H target is much higher now. Can the existing data on 2H be combined with the new data?*

The Deuteron is used as a reference in EMC measurements as inclusive DIS is sensitive to both protons and neutrons. Here, by detecting the outgoing proton, we are sensitive to protons in 4He and the most relevant reference is the free-proton, 1H. The proposed 2H data is therefore largely used for calibration purposes.

4He / 1H ratios will always differ from unity due to ‘standard’ nuclear effects such as motion, and binding. Therefore, the way we look for modification effects is by comparing the 4He data with cross-section calculations that use as two key inputs the 1H cross-section data and 4He spectral function (to account for motion effects etc). The degree to which we can quantify deviations from this ‘trivial’ expectation is quantified in the proposal ‘results’ plots.

In addition, theoreticians will be able to utilize our data as input for global analyses. We (co-spokesperson Hen + colleagues) recently published such an analysis in PRL with the nCTEQ group, which examined the specific impact of SRCs. It was selected as one of Top 10 Physics breakthroughs in 2024 by Physics World Magazine. This analysis and similar works lack significant constraints on gluon structure and we will explore means to use the new data for added constraints.

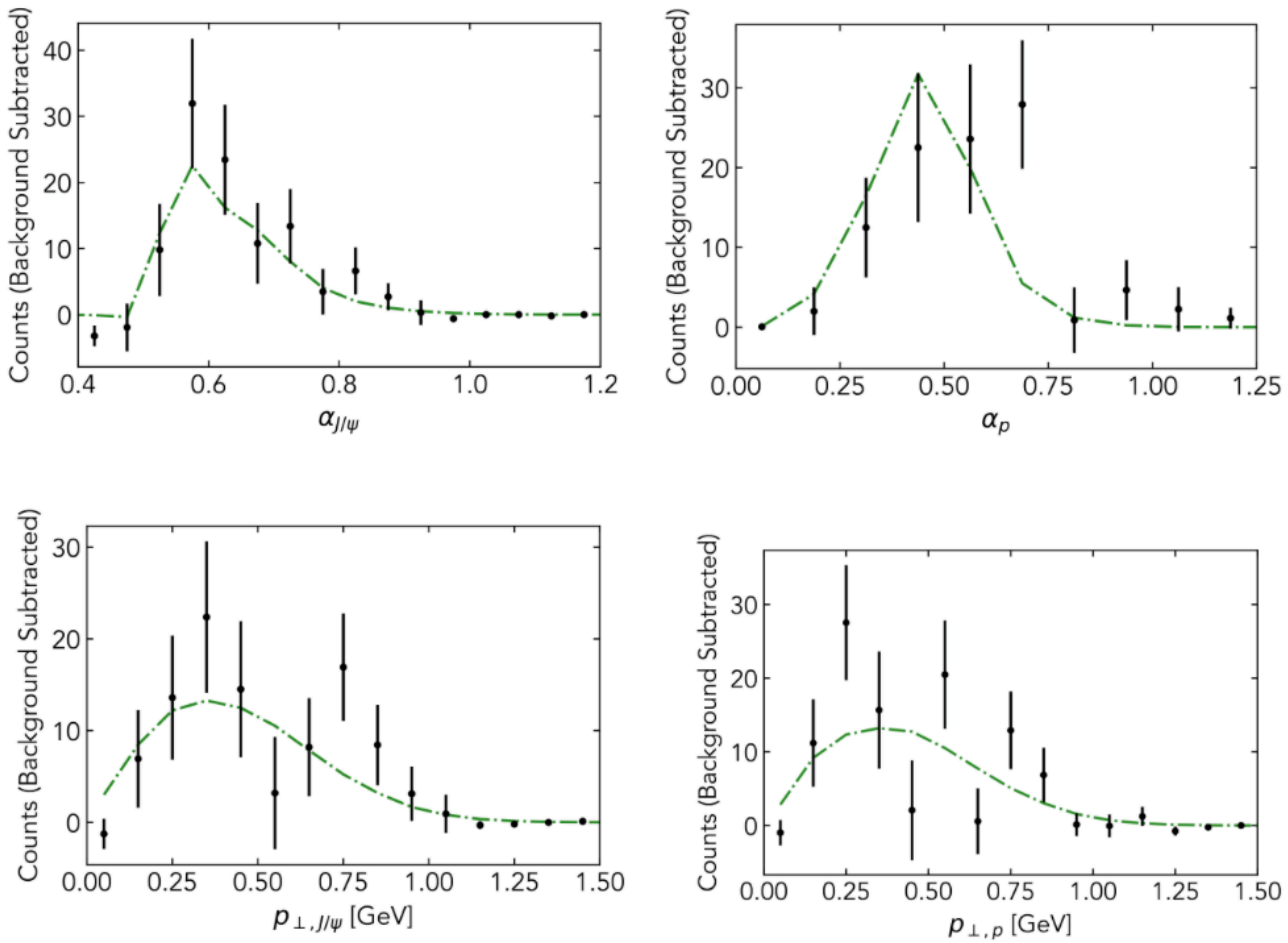
> *Then, we would welcome clarification regarding the sign of the already hinted effect - excess J/Psi production, as seen in PRL. If this is meant to be a hint of an EMC-like effect, which in the quark sector is a *suppression* of bound nucleon structure functions at moderate xB, wouldn't one expect suppression of J/Psi production as well?*
>
> *In more technical terms: explanations of the quark EMC effect involving bound-nucleon with negative virtuality v < 0 typically go like R_EMC = 1 + b v, with b > 0, while the SRC-CT effect published in the PRL appears to follow (1 - a v), again with a > 0 (see Eq. (9) in the PRL Supplement). Does this suggest a sort of "anti-EMC" effect in gluons?*

The readers are correct in identifying that the current data, which suggest an enhancement in the production of J/Psi from nuclei at high virtuality, seems to work in the opposite direction from the quark-section EMC effect which results in a depleted cross section. This is indeed a very intriguing and important result to clarify and interpret. The proposed data will have significantly improved ability to perform differential analysis, providing greater clarity about the mechanisms behind the observed effect.

We note that the predictions of various different hypotheses (several of which are discussed in the PRL in greater detail) become more clear and distinct when multiple kinematic variables (e.g., E_γ, t, pT, and αmiss) are examined simultaneously. The published results do not allow the desired detailed study, and this proposal is designed to address this deficiency allowing for detailed single- and double-differential cross-section measurements.

> *The distributions in Fig. 6 and Fig. 5 look very similar. Are these integrated over all photon energies? If so, one would expect SRC counts to be much smaller than mean-field ones. Were these plots perhaps generated with different (and arbitrary?) total luminosities? The legend indicating the correspondence between color and event counts is missing.*
>
> *Another question related to Figs. 5 and 6 is how well this agrees with measured data.*

As mentioned, the separation of SRC and Mean-Field components is performed using composite kinematic variables such as p_T and α_{miss}, which are shown above to be able to distinguish these contributions, rather than just the final-state particle momentum and angles. Proposal figures 5 and 6, which are integrated over all photon energies, show the readers the expected kinematics of the final-state particles as a means to understand the parts of the detector engaged by the measurement; as such, the normalization of each plot is arbitrary. These particular two-dimensional distributions were not compared to data, but the one-dimensional kinematics of the final-state proton and J/Psi were found to be overall consistent with data, as shown in the following figures.



Response Figure 3.

> *There are several questions on improvements of performances of detectors:*
> *- What was the signal-to-bgr ratio (SBR) in the J/psi region for the pilot run?*

The signal-to-background ratio in the pilot run in the J/psi region is approximately 1:1 when considering the 2-sigma region around the peak.

> *- Upgrade of FCal (p. 16): What is the status? How will it affect the efficiency (Fig. 7) and the SBR?*
> *- Forward TRD: It seems that this new detector component will greatly improve the measurement. What is the timescale of its realization and is this in line with the planned measurement? How will it affect efficiency and SBR? Or do the projections already include the upgrades?*

The FCAL upgrade was fully commissioned this spring and is operating as expected. Detector performance studies are currently underway. It covers an 80 cm × 80 cm region around the detector beamline and provides approximately a factor of two improvement in energy resolution compared to the lead-glass modules. As a result, it is expected to enhance electron/pion separation in the forward direction. However, only about 10% of leptons from J/ψ production (depending on the beam energy) are expected to be reconstructed in the new calorimeter.

TRD will have a more significant impact. Its construction is ongoing as per the PAC recommendation for the GlueX-III run:

> "The addition of the TRD will provide important additional performance enhancement of the GlueX detector and significantly improve the signal to background ratio in general."
> If this proposal is approved our collaboration is willing to join and support this effort to complete the TRD in advance of both measurements.

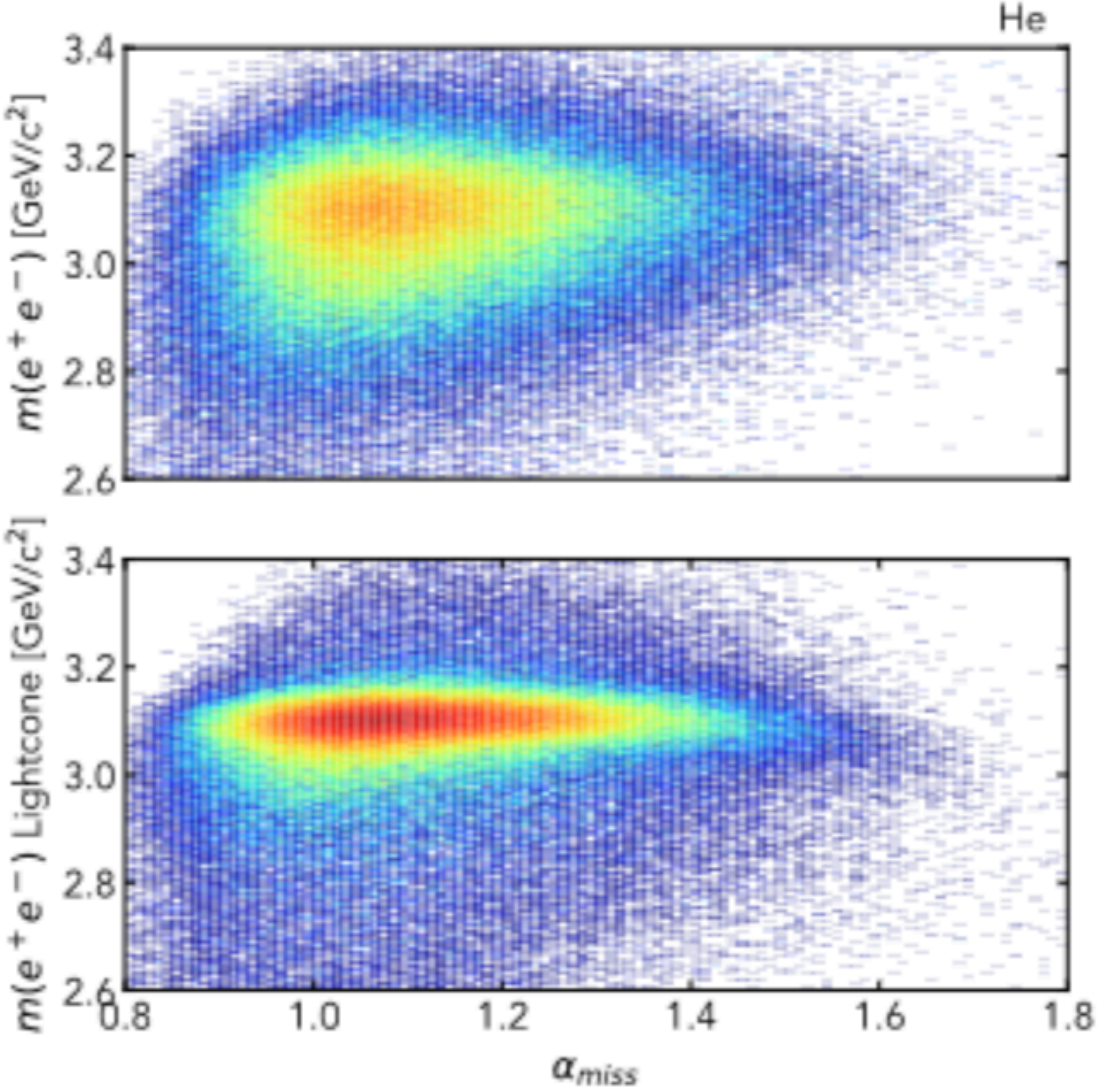
The proposal assumes the implementation of both the FCAL forward upgrade and the TRD. This is expected to reduce pion background by roughly a factor of 4, resulting in an estimated SBR of 4:1. If our proposal is approved, our collaboration will do everything within its capacity to support the successful realization and implementation of the new TRD detector.

> *- Maximum energy: It seems that a realistic value for the maximum beam energy is 11.7 GeV rather than 12 GeV. Does this affect the projections?*

The impact of this reduced electron beam energy is expected to be less than 10% for our overall J/psi yields, therefore having a minor impact on the overall measurement.

> *Comments on some TAC points would be welcome:*
>
> ** The parameter alpha_miss at small p_miss is related to the recoil mass. However, the kinematic constraint used effectively assumes that the recoil has nucleon mass. It's unclear how this assumption may affect the alpha_miss spectra.*

We understand the TAC and readers' concern that the assumptions used to reconstruct the J/psi mass could impact the distributions of variables of interest. This effect was studied in the Supplemental Material of the PRL, where it was found that the light-cone-reconstructed J/psi mass exhibited greater stability as a function of kinematics such as α_{miss}; see the plot below, taken from the published Supplemental Material, showing that the reconstruction of nuclear motion in simulated events can be more accurately resolved using the light-cone-based mass reconstruction. We note that other kinematic variables are reconstructed independently of kinematic assumptions, which are used exclusively for the purposes of performing signal/background separation.



Response Figure 4.

> ** The hidden-color study on p. 13 may require determining the momentum of the recoil neutron, perhaps using the missing-momentum technique.*

While the hidden color study of Brodsky et al. described the reaction in terms of the recoil nucleon momentum, the large relative momentum of such a correlated cluster pair can also be measured by examining the missing momentum, which we will study using the p_T and α_{miss} variables previously described.

> *In addition, the TAC question on manpower for a beamtime of 170 calendar days seems very relevant.*

We thank the readers for considering this point. This current proposal has an authorship list that is 40% larger than the proposal of the previous experiment, including over 50% more institutions. If approved, we expect even more involvement of the JLab community as the impact of the current data is raising more attention and this physics as a whole is becoming more central for the community and the lab.

In addition, we discussed this point with JLab management and were told that assuming the PAC approved the physics of this proposal, the shift staffing plan will be addressed as part of the Experimental Readiness Review process. This is the standard practice, which was implemented for other proposals who faced such needs (PRAD-II running in Hall-B etc.).

We thank the readers once more for their comments and detailed reading of our proposal and hope that our responses clarify and address any concerns with the proposal. We look forward to continued correspondence as needed. Please find below a copy of the TAC report with further details.