Jefferson Lab
Thomas Jefferson National Accelerator Facility

First Measurement of Near- and Sub-Threshold J/ψ Photoproduction off Nuclei

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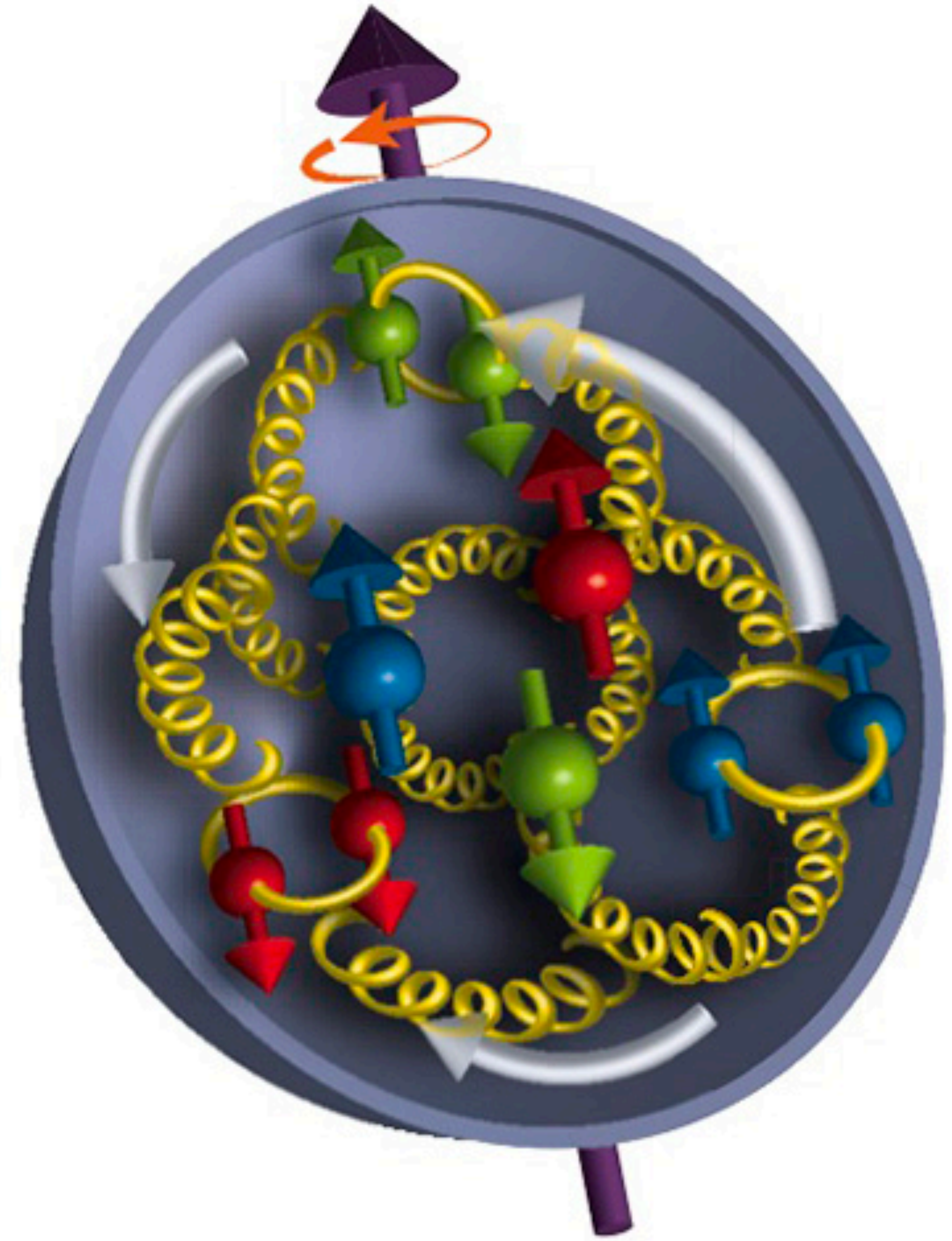
LNS
Laboratory for Nuclear Science

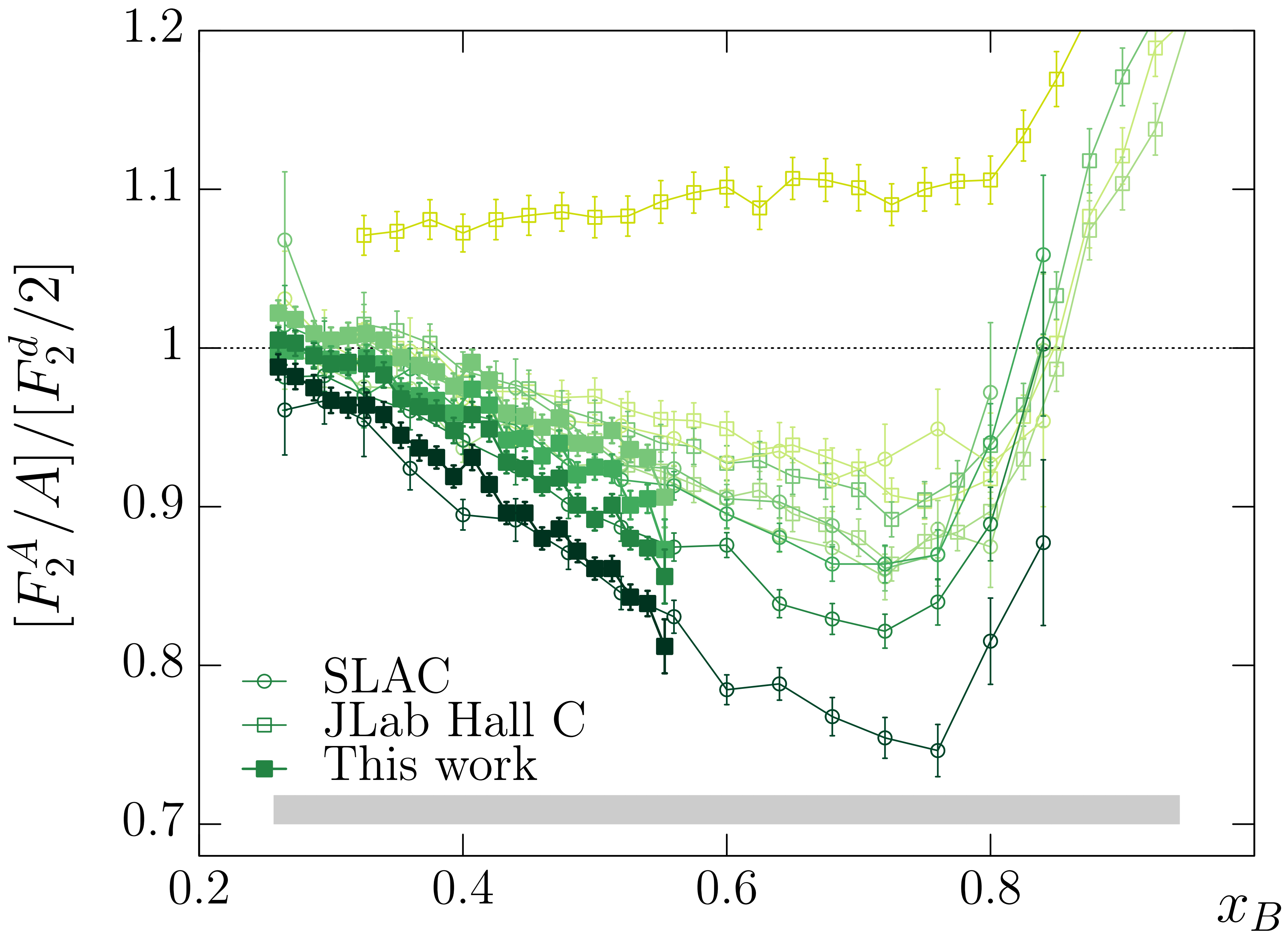
Slides stolen from Jackson Pybus

Proton structure emerges from QCD dynamics

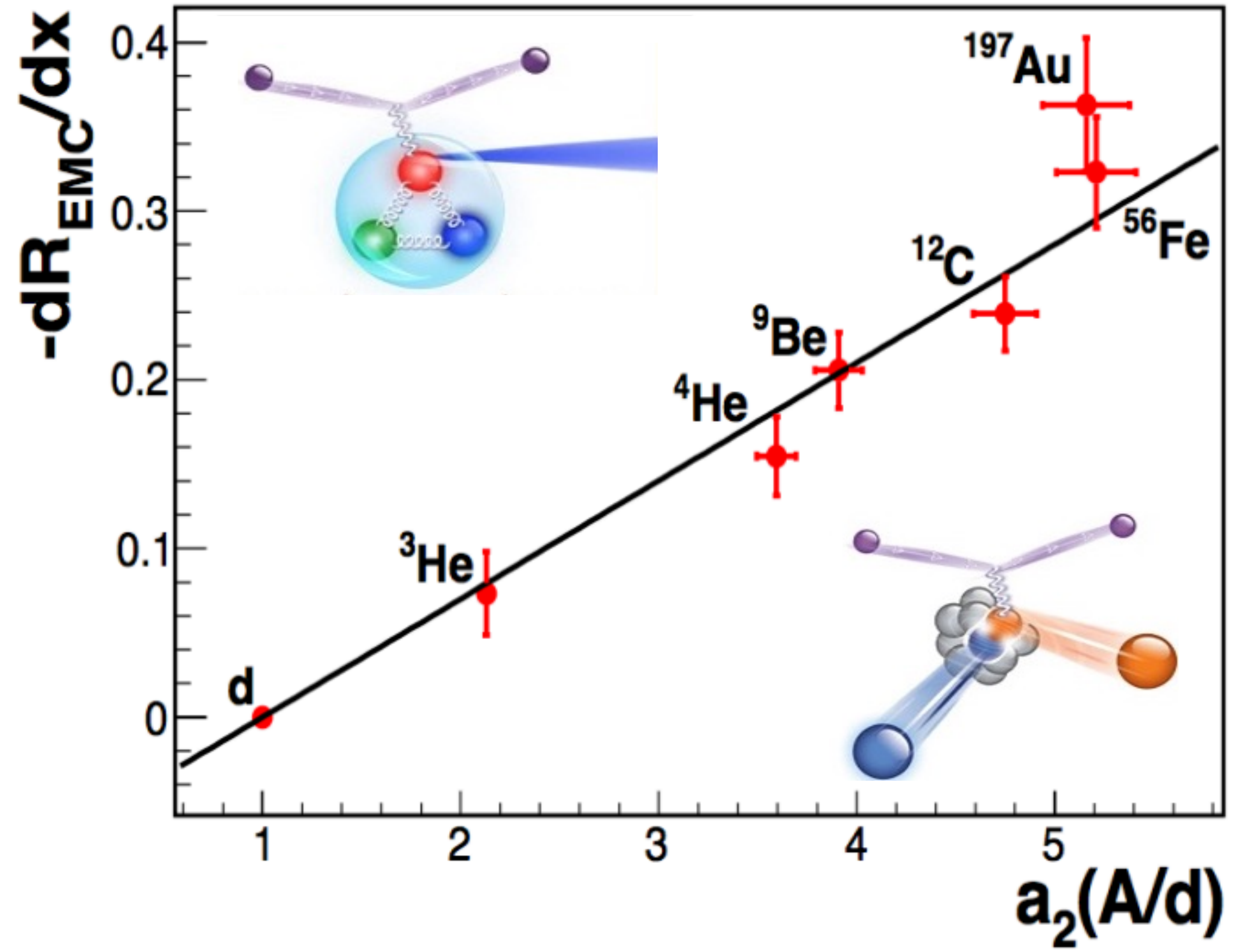
- Proton mass: **938 MeV**
- Higgs contribution to proton mass: **~10 MeV**
- Details of QCD dynamics drive proton structure
- Large fraction of proton mass and spin carried by massless gluons



EMC Effect: Modification of quark content in nuclei



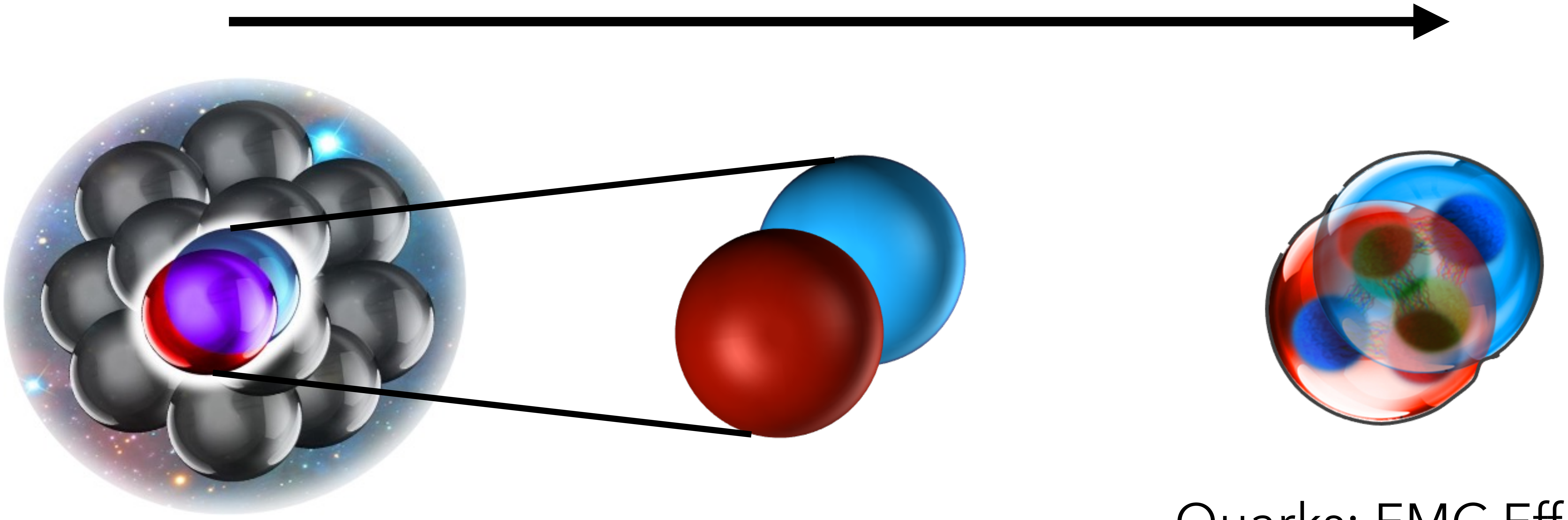
Fewer high-momentum quarks in nuclei



EMC effect correlated with SRCs

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

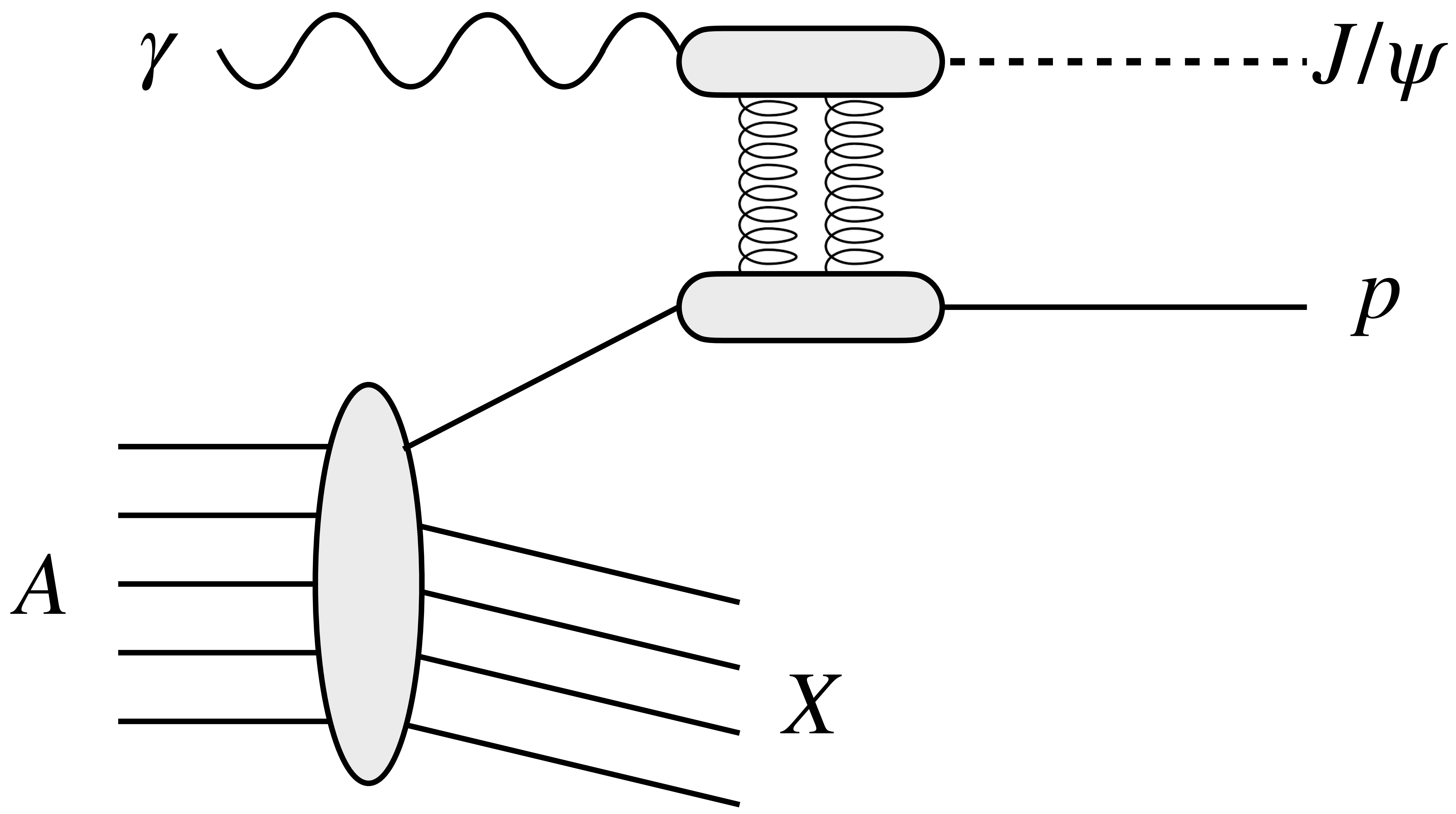
How do nuclear systems impact gluon dynamics?



Quarks: EMC Effect

Gluons: **?**

Photoproduction of J/ψ from bound protons



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

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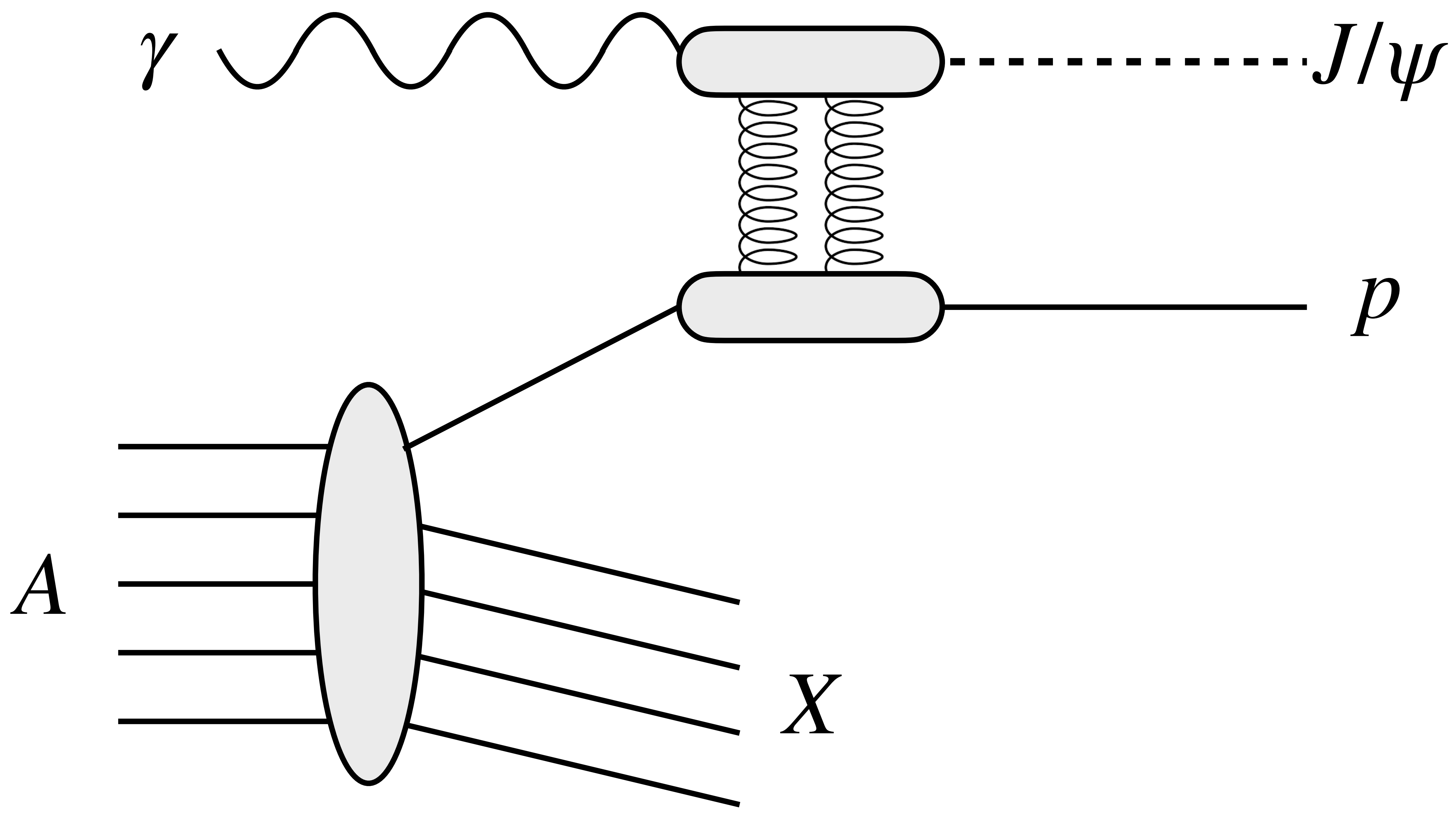

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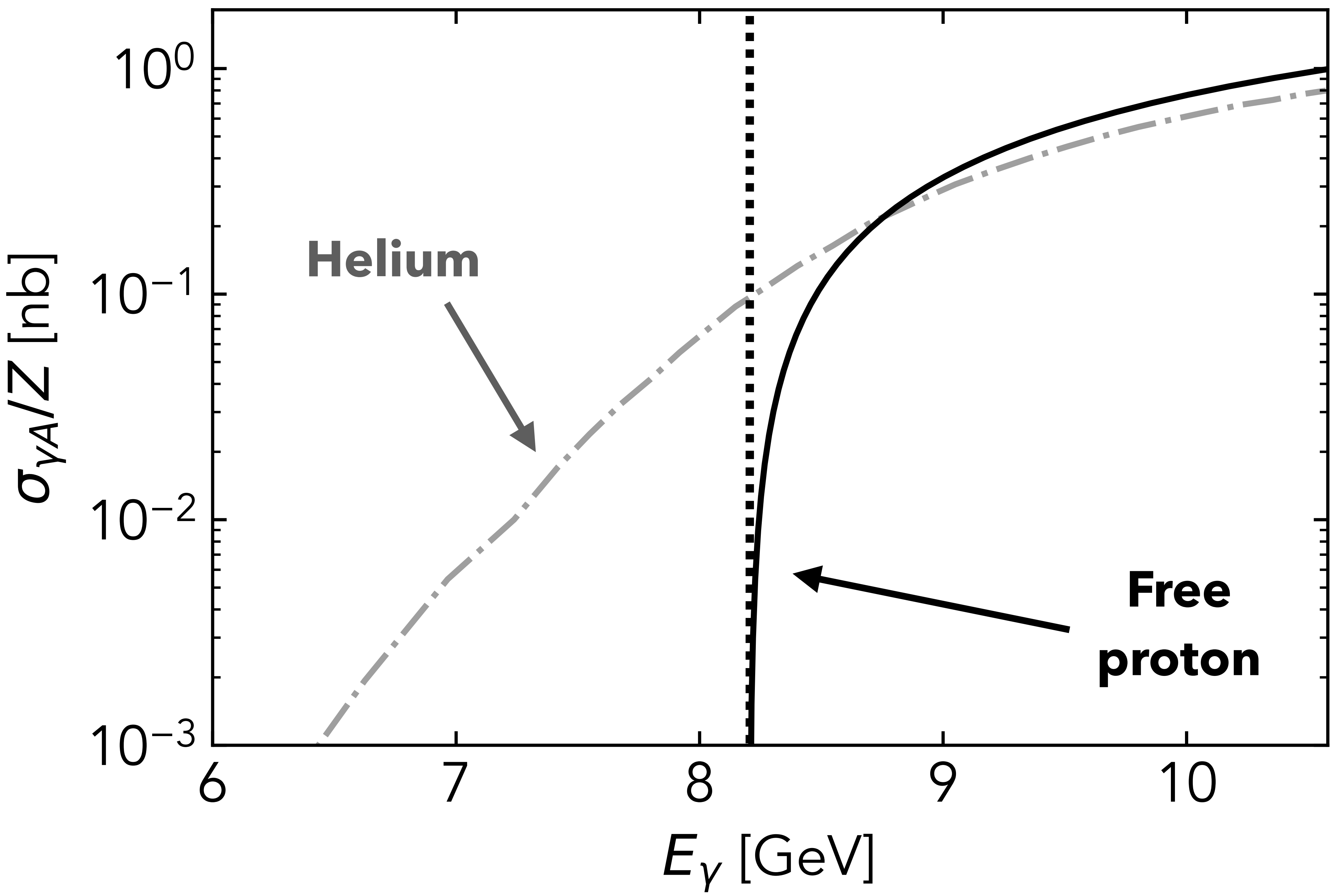

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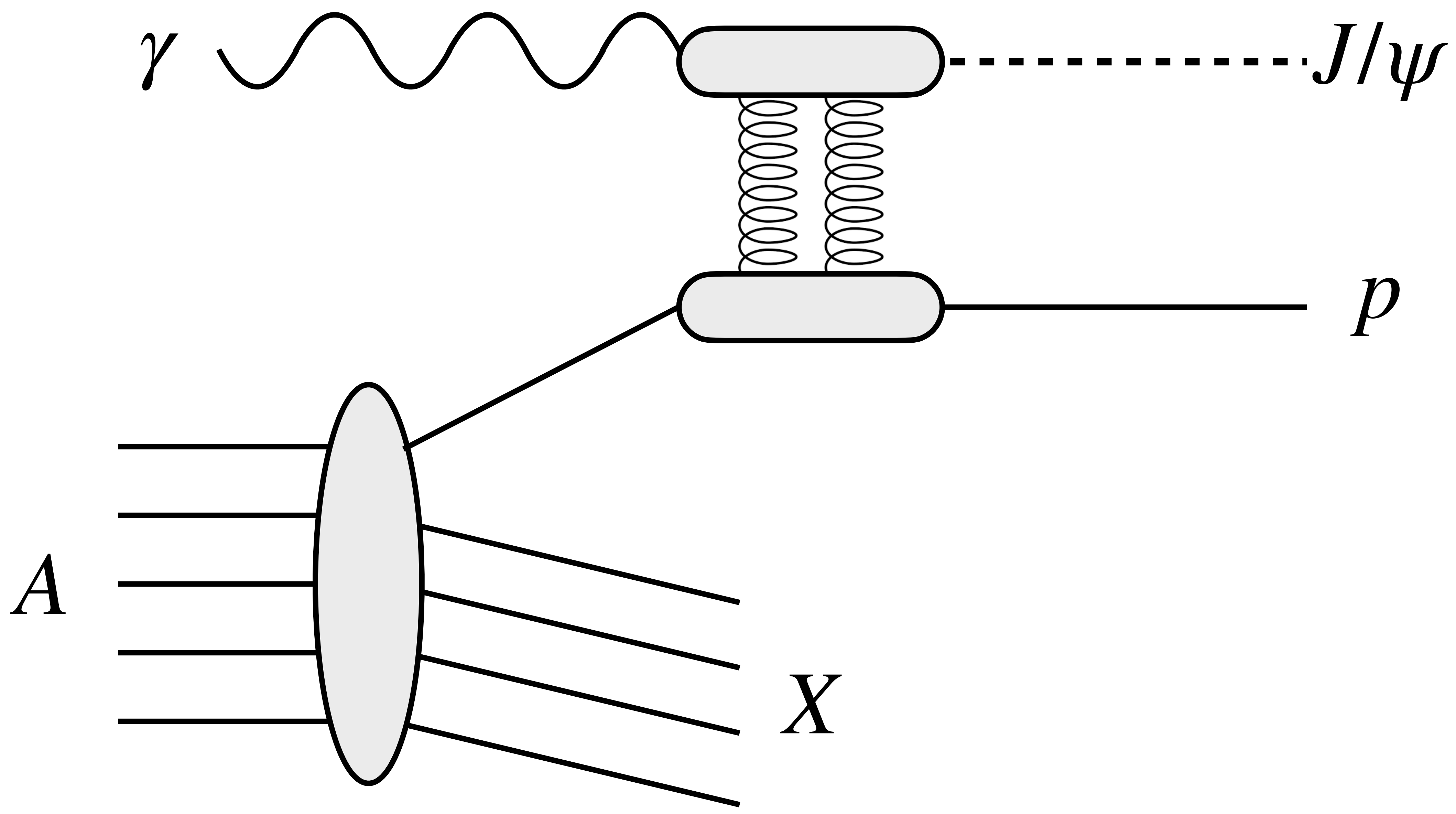

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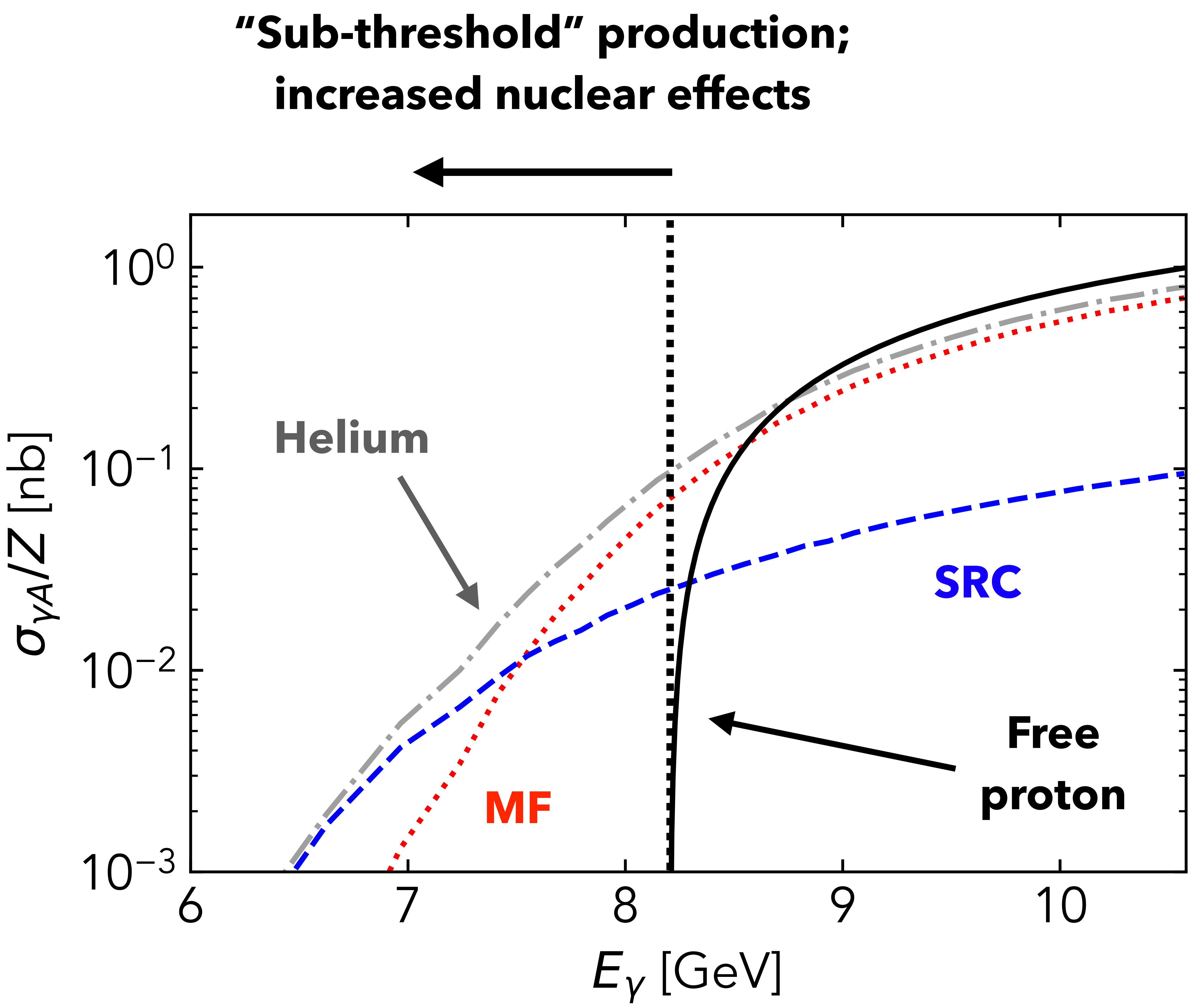
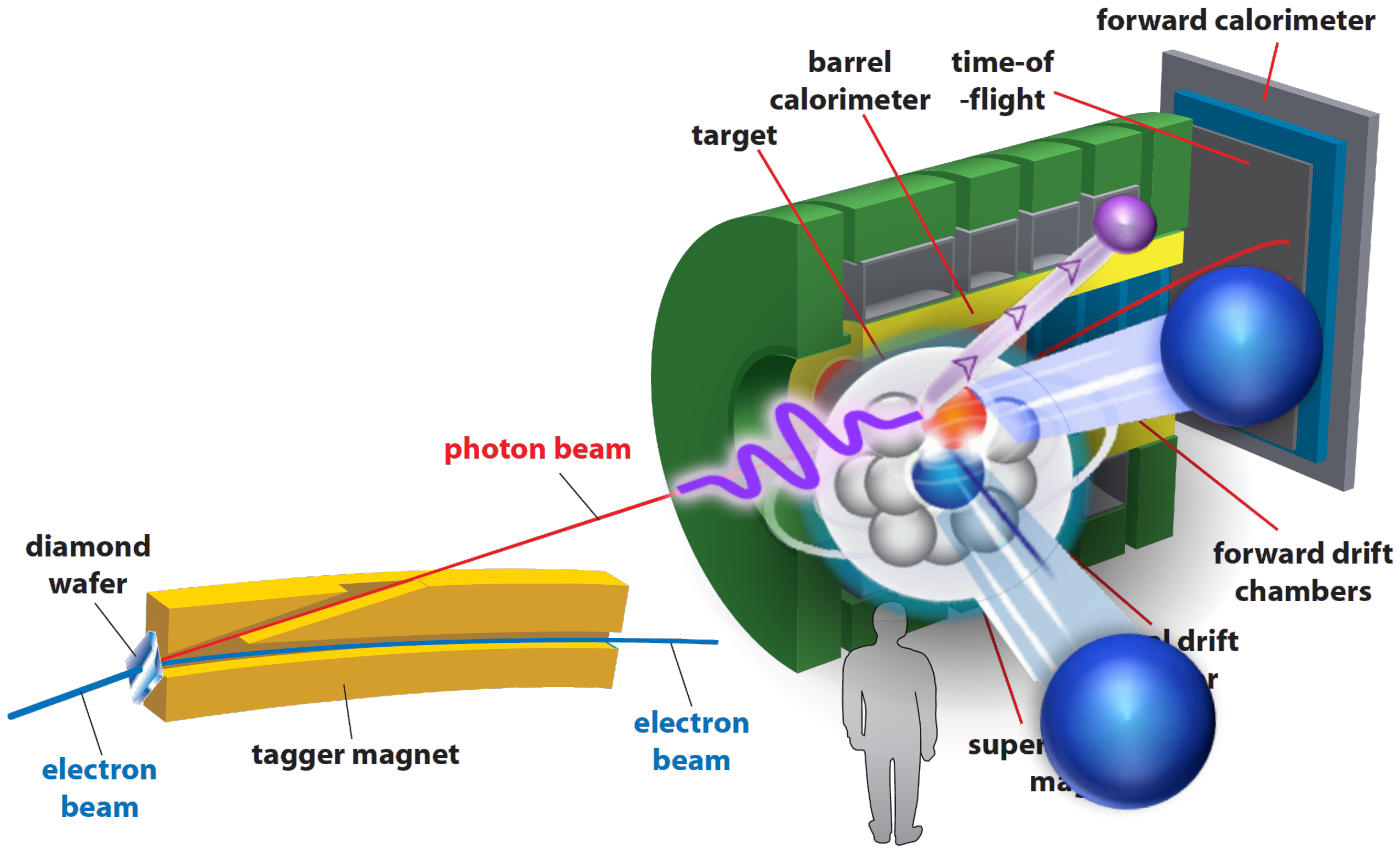
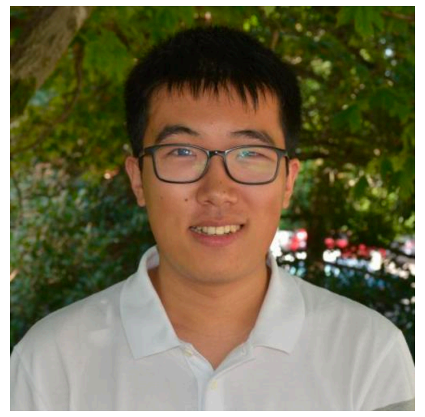


Hall D SRC-CT Experiment



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

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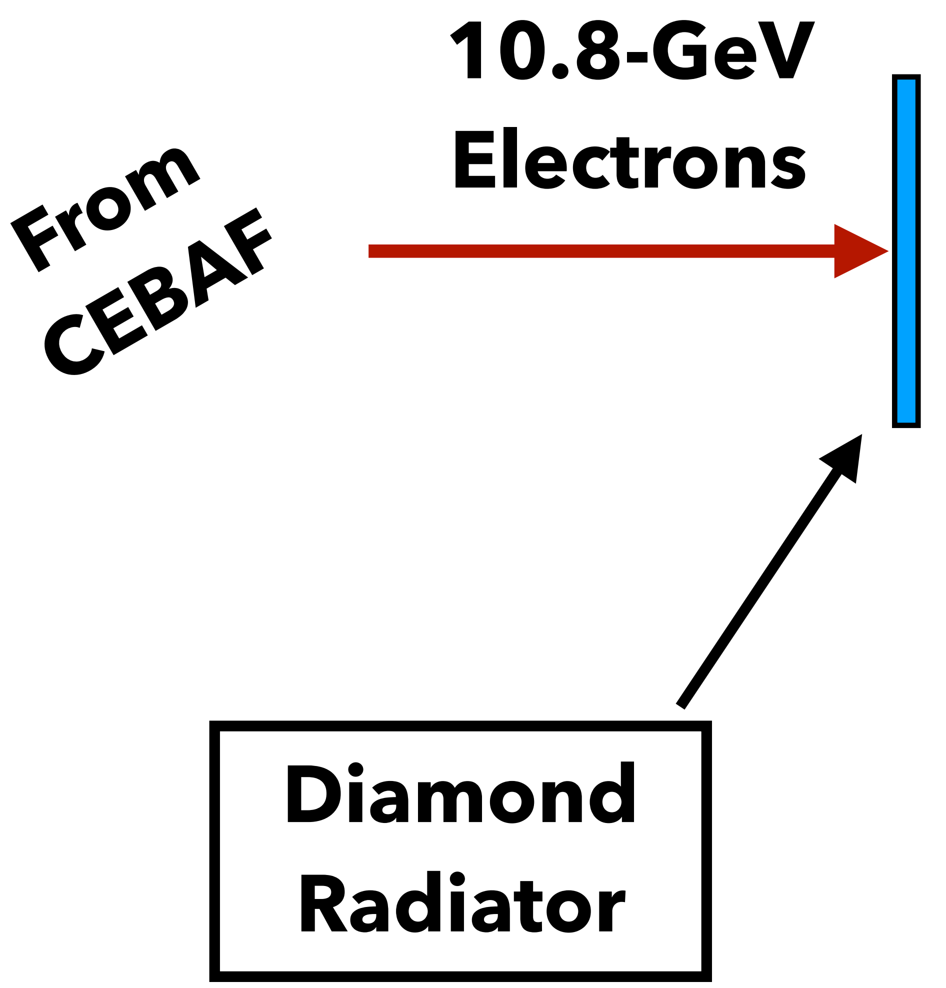
Hall D Tagged Photon Beam



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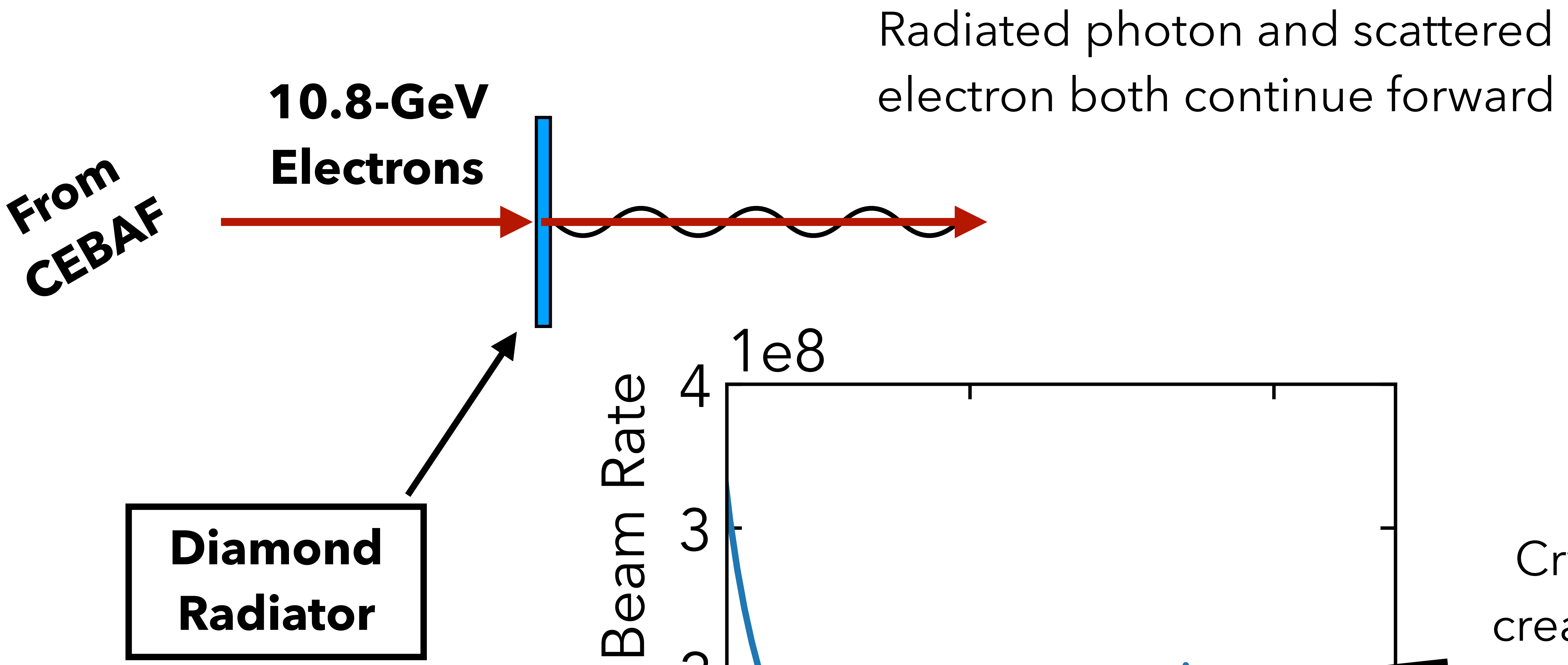

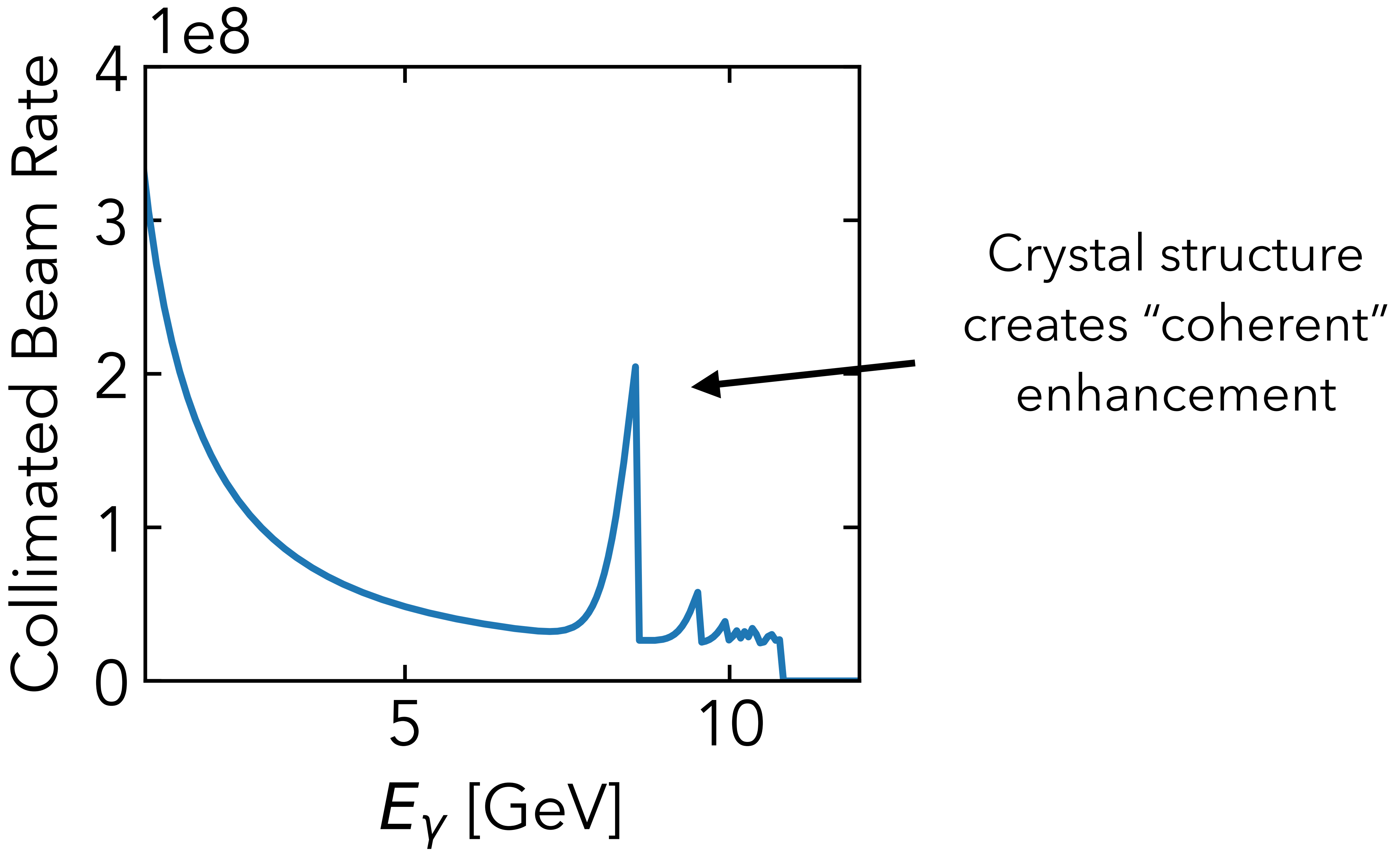

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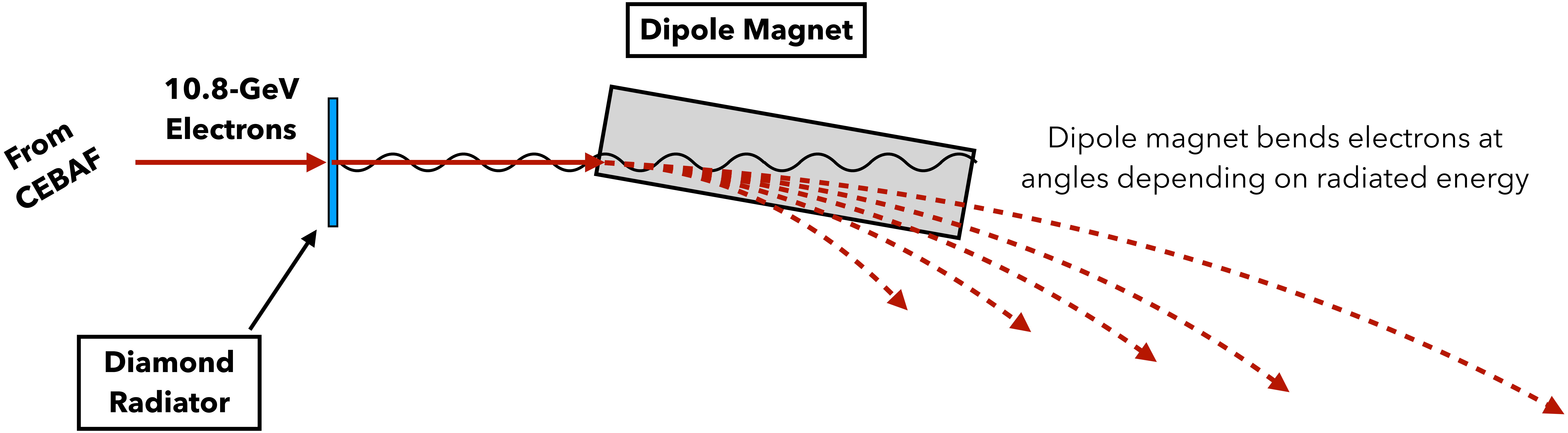
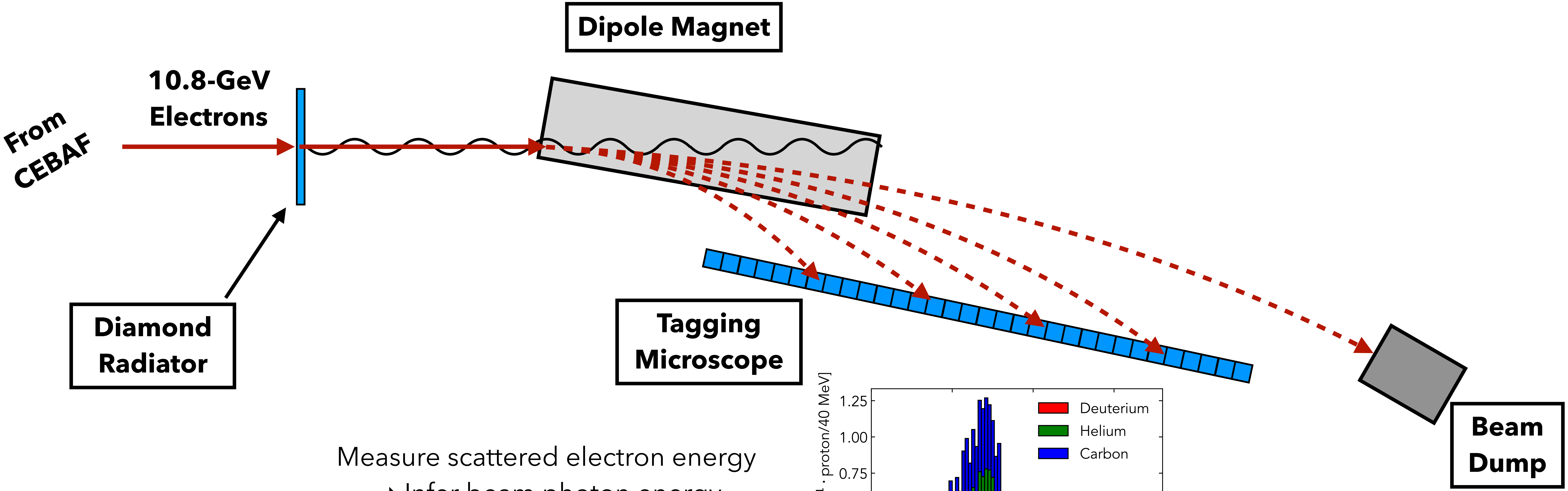
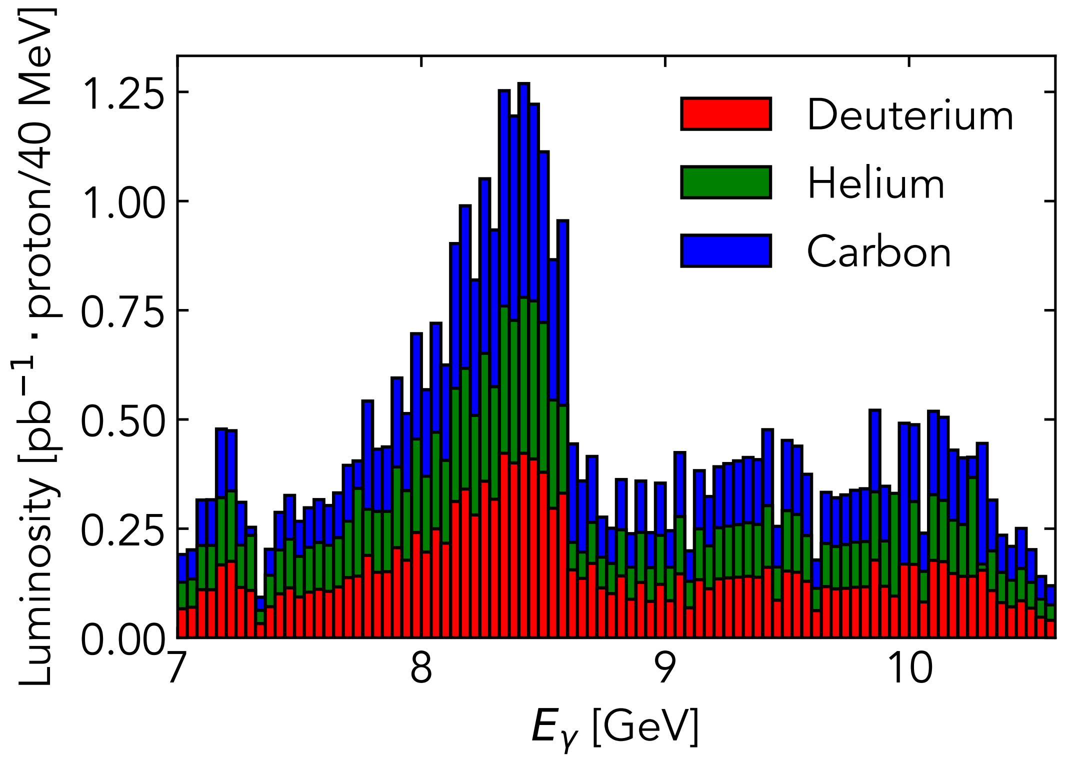


Dipole magnet bends electrons at angles depending on radiated energy

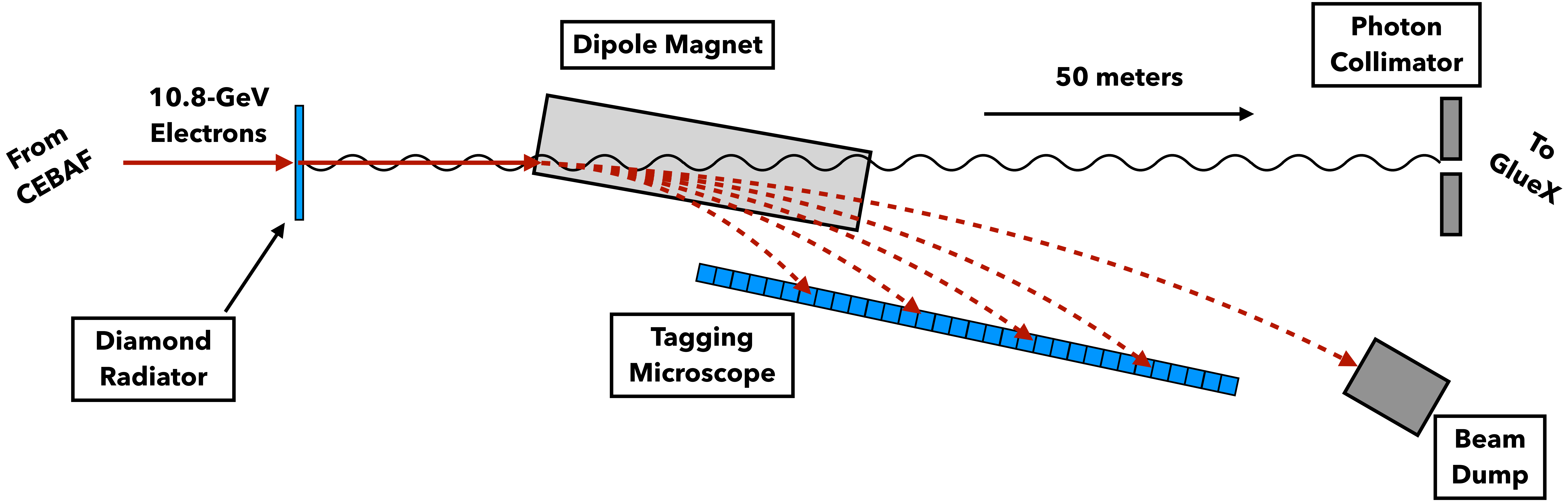
Hall D Tagged Photon Beam



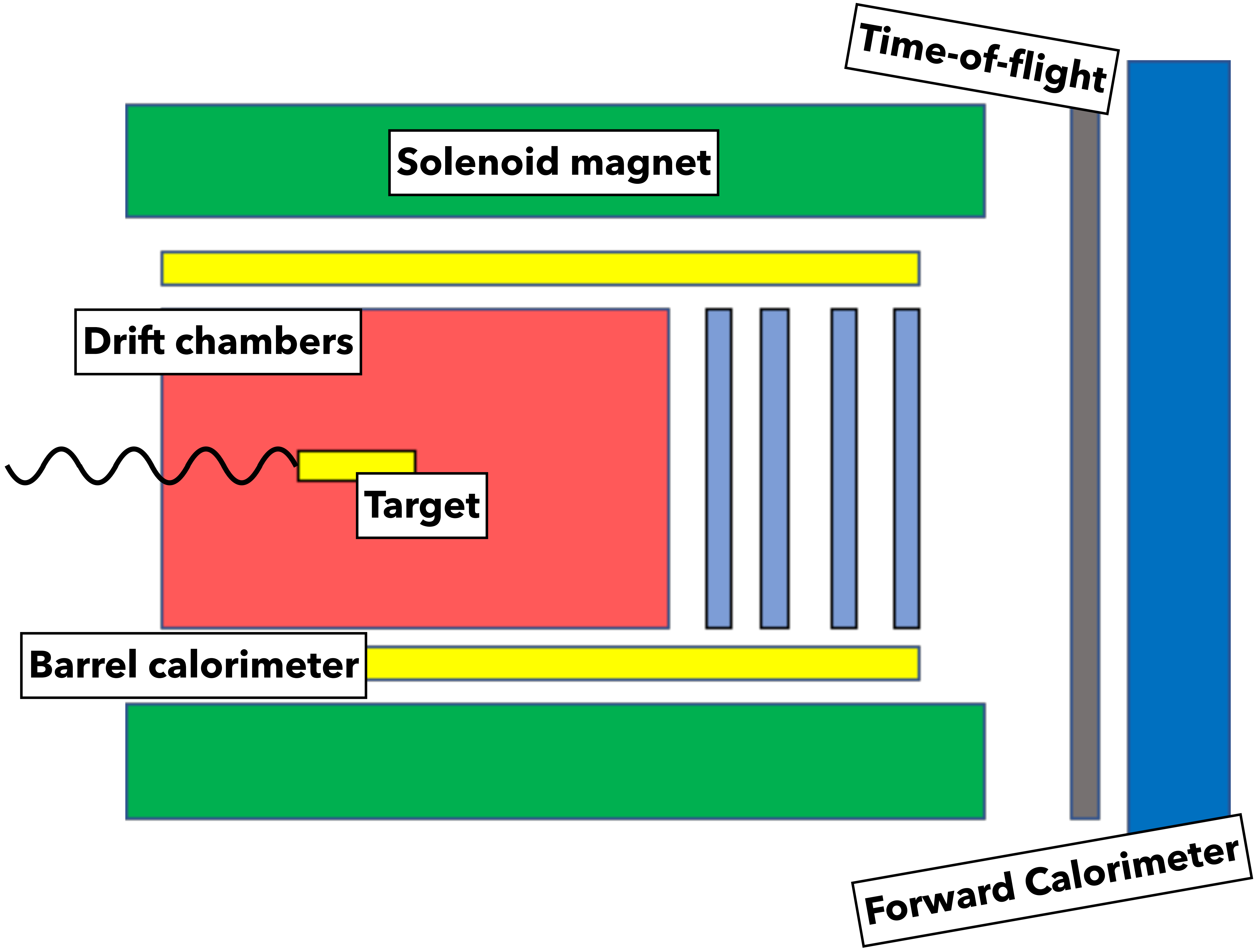
Measure scattered electron energy
→ Infer beam photon energy



Hall D Tagged Photon Beam

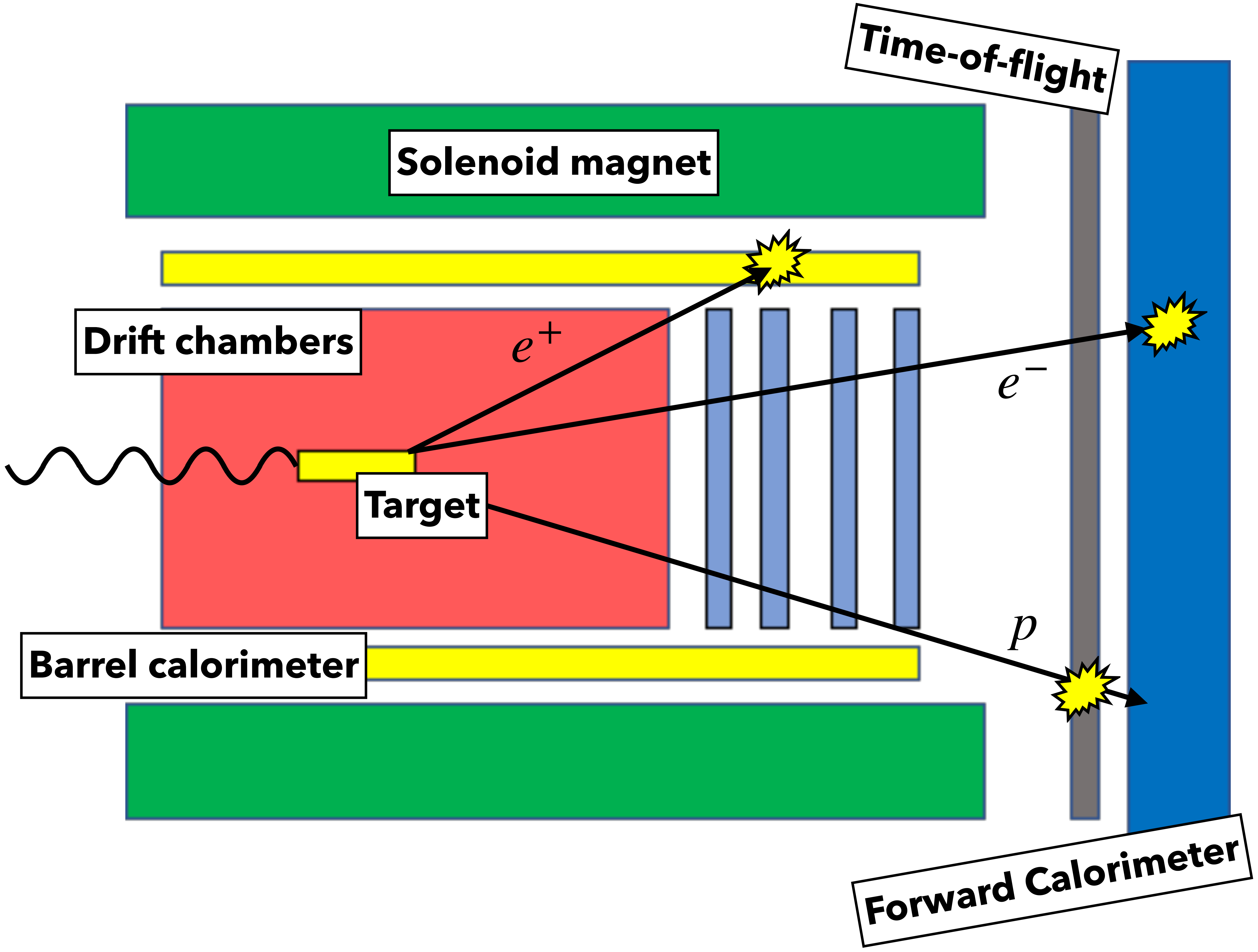


GlueX Spectrometer



- 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 identification of leptons

Incoherent $A(\gamma, J/\psi\ p)X$



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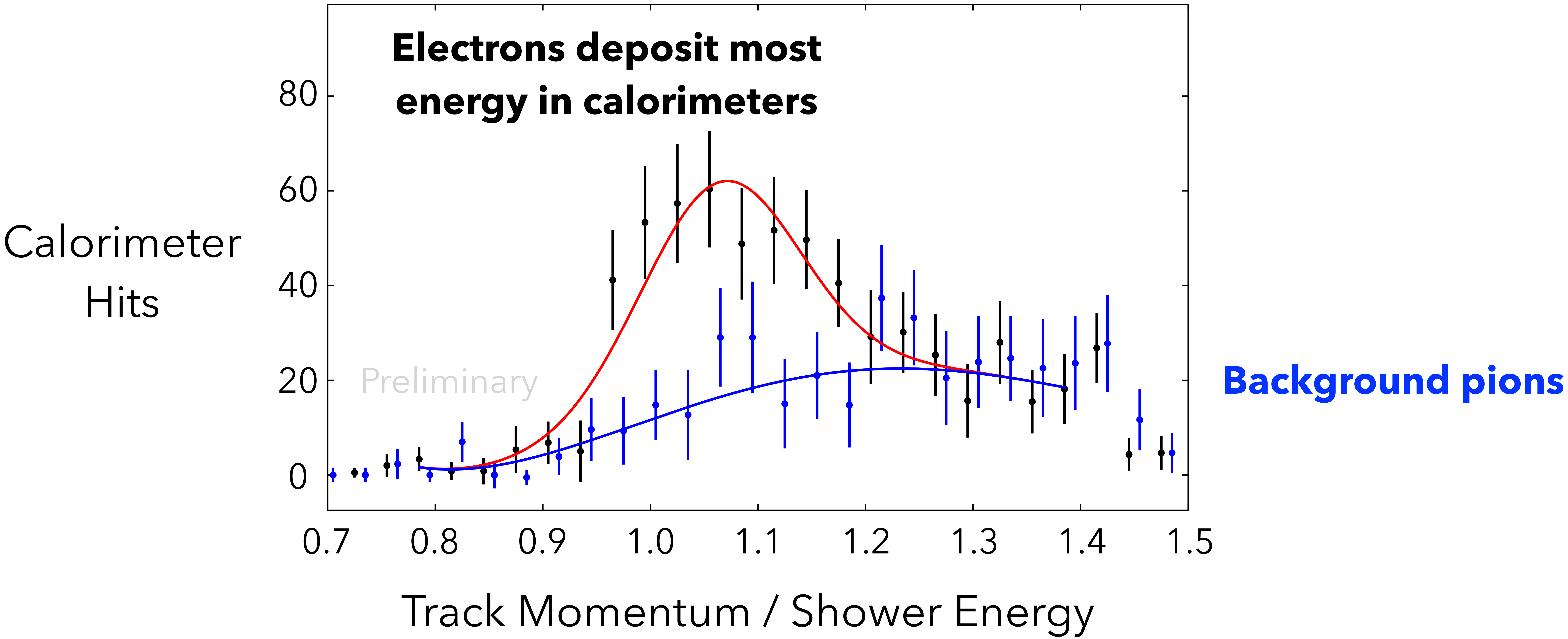
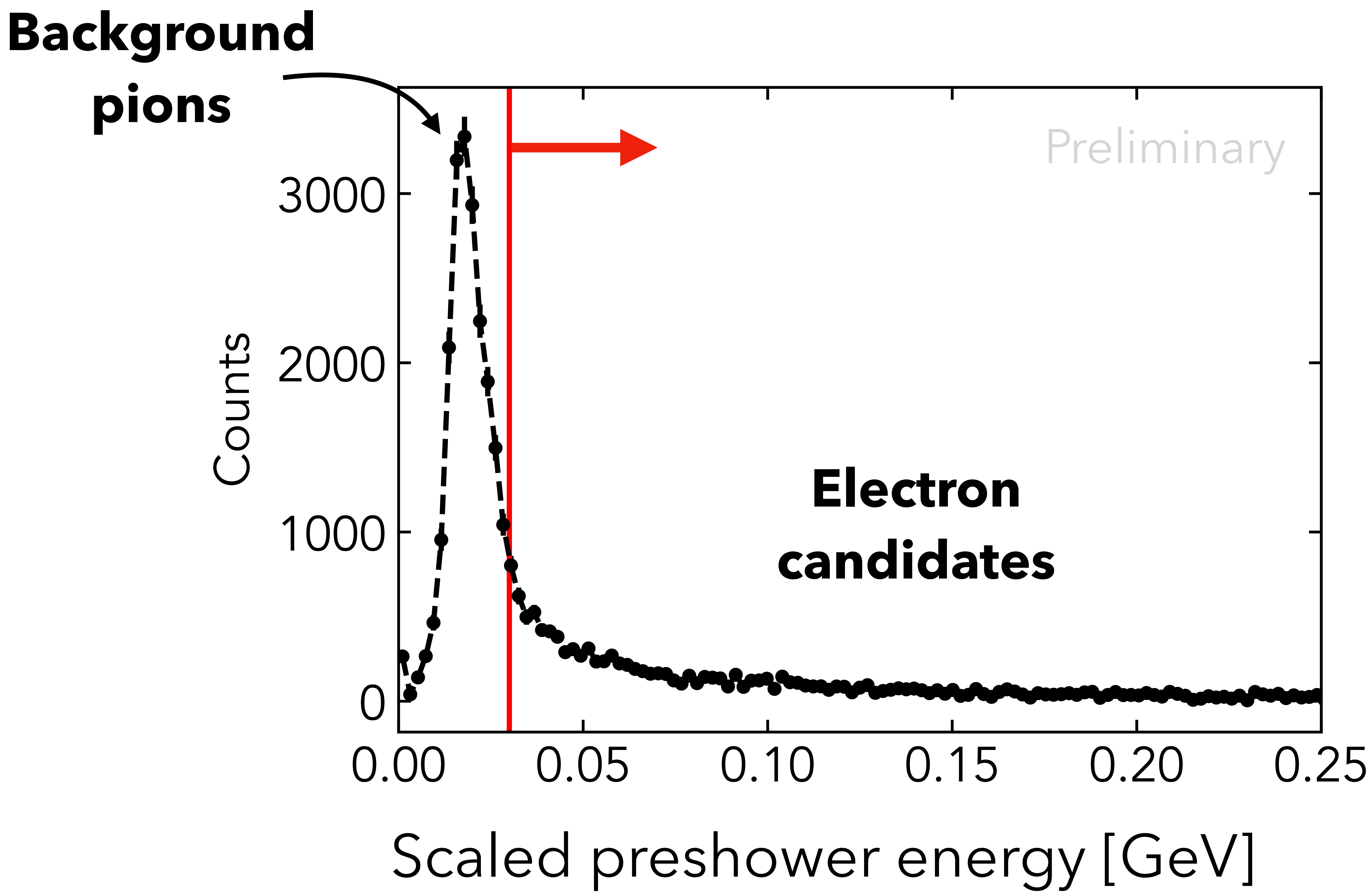
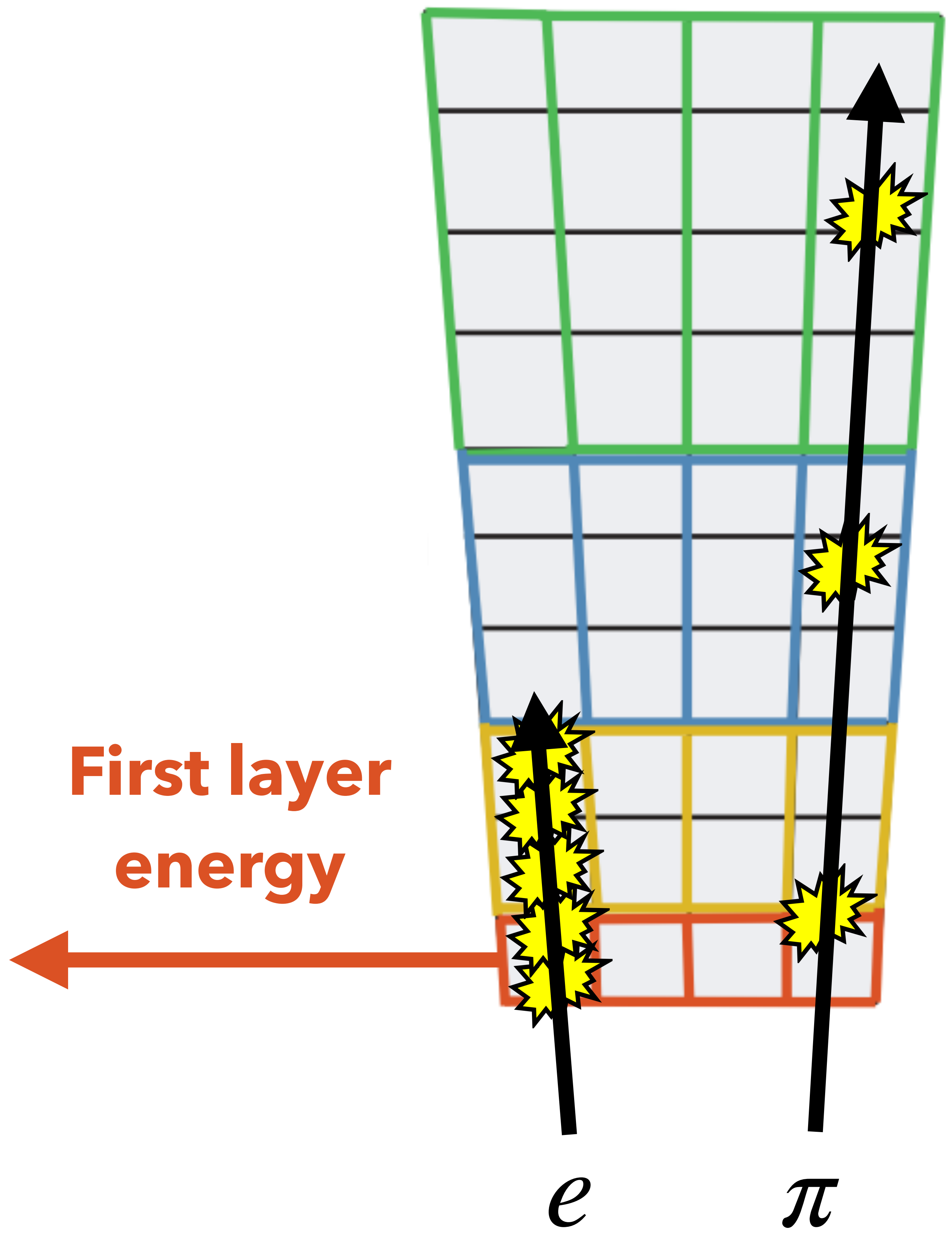
Calorimetry allows for e/π separation

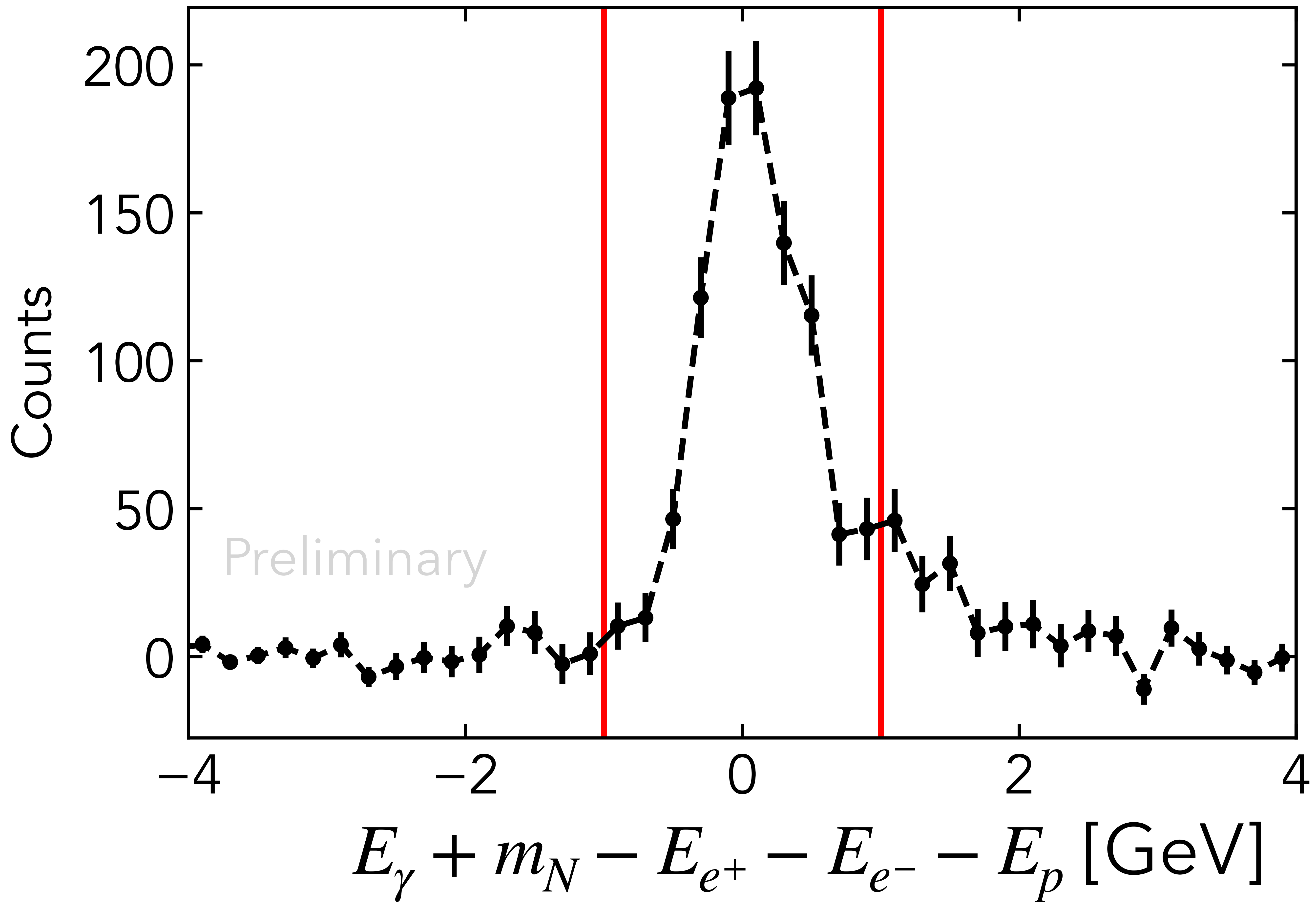


Barrel calorimeter can measure shower evolution



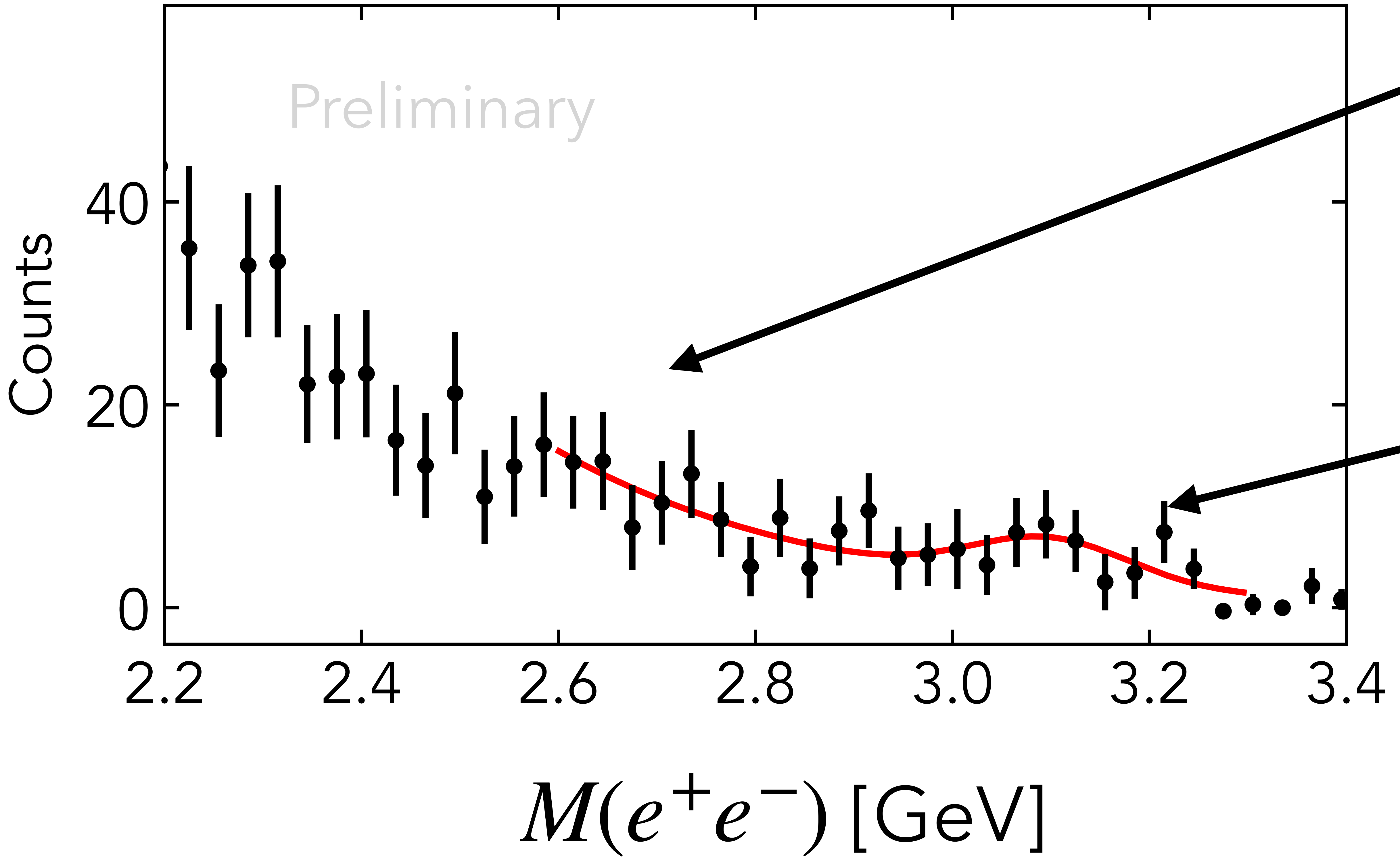


Use photon energy to check "elasticity"



Still hard to resolve J/ψ!

$\gamma\mathrm{C} \to e^+e^-p(X)$

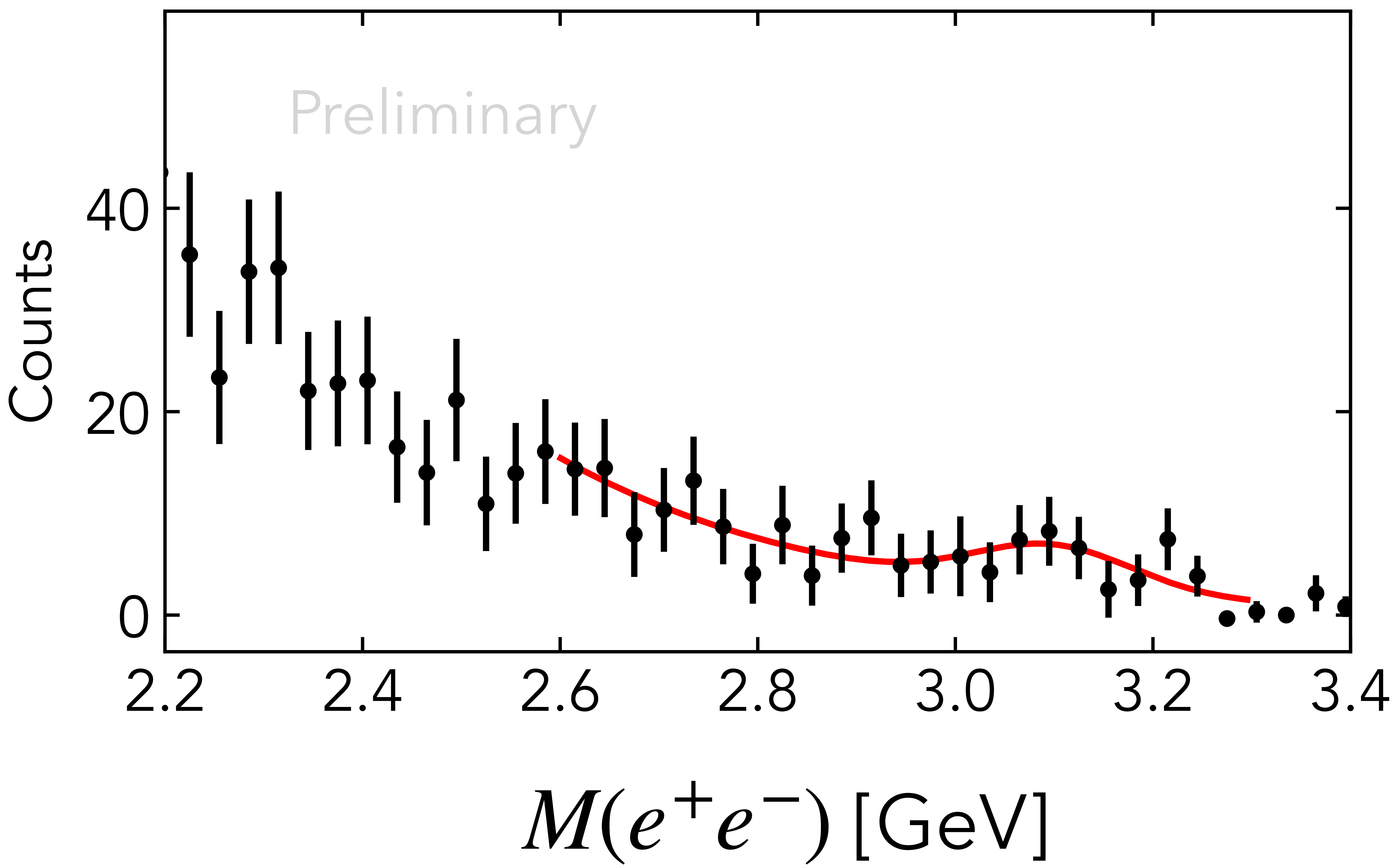


Sizable e^+e^- and $\pi^+\pi^-$ background obscures J/ψ peak

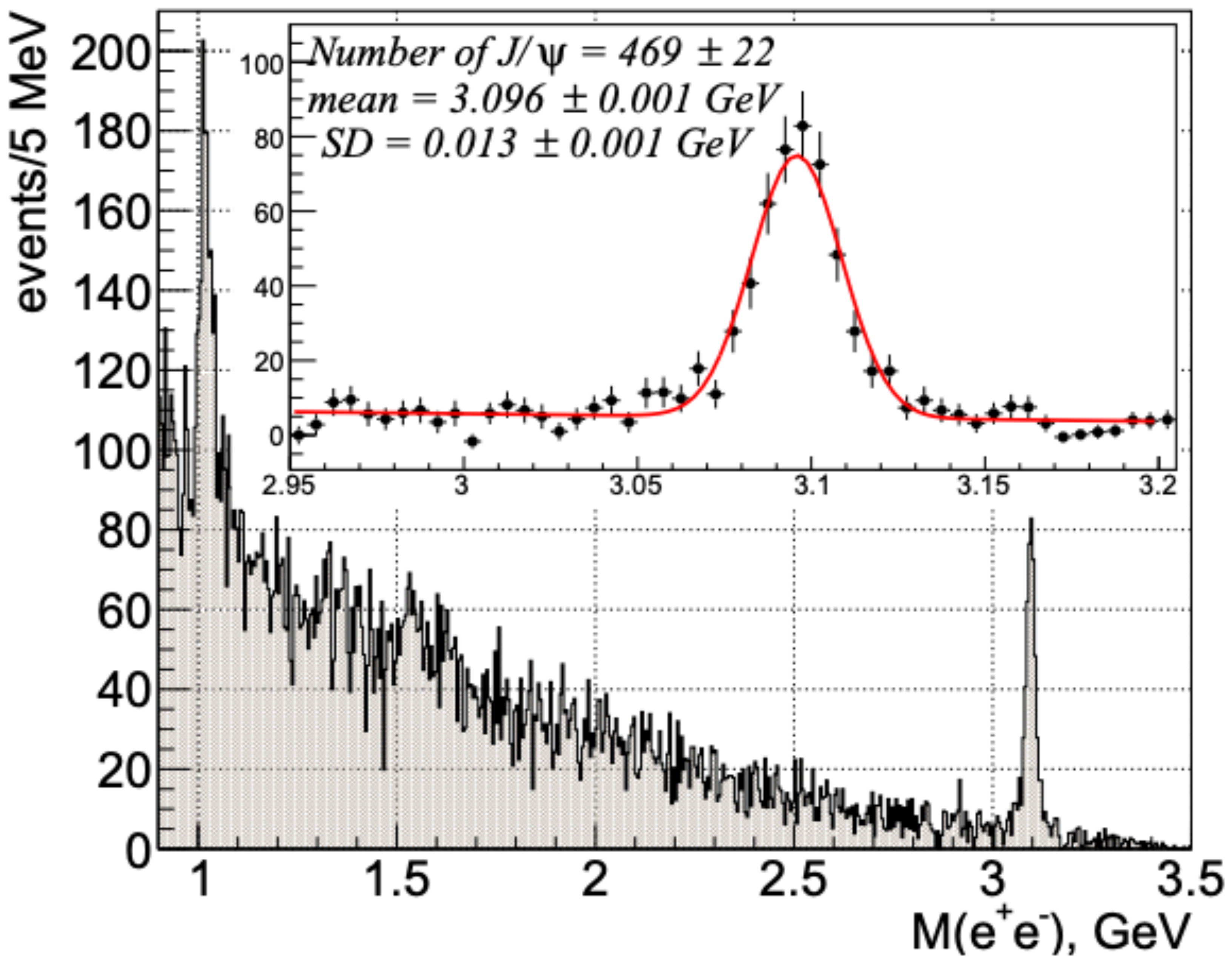
$J/\psi \to e^+e^-$ invariant mass poorly resolved

Still hard to resolve J/ψ!

$\gamma\mathrm{C} \to e^+e^-p(X)$

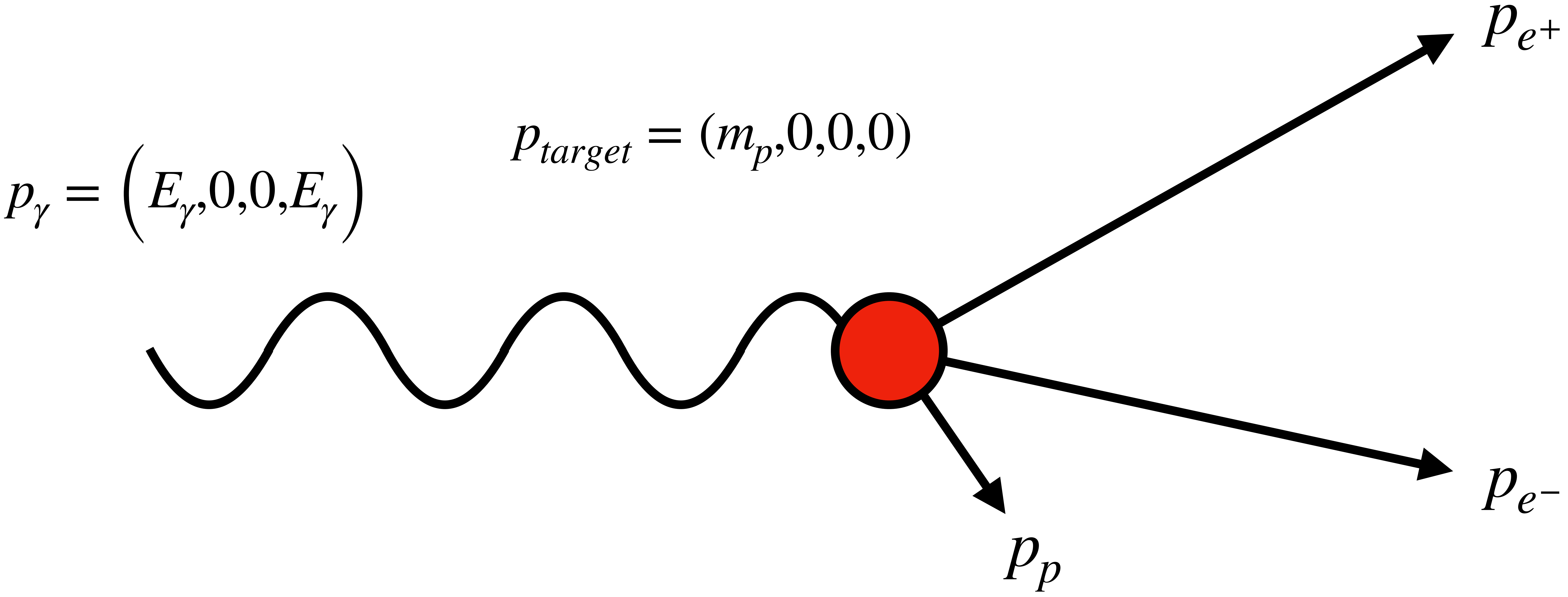


Compare with GlueX result for $\gamma p \to J/\psi p$



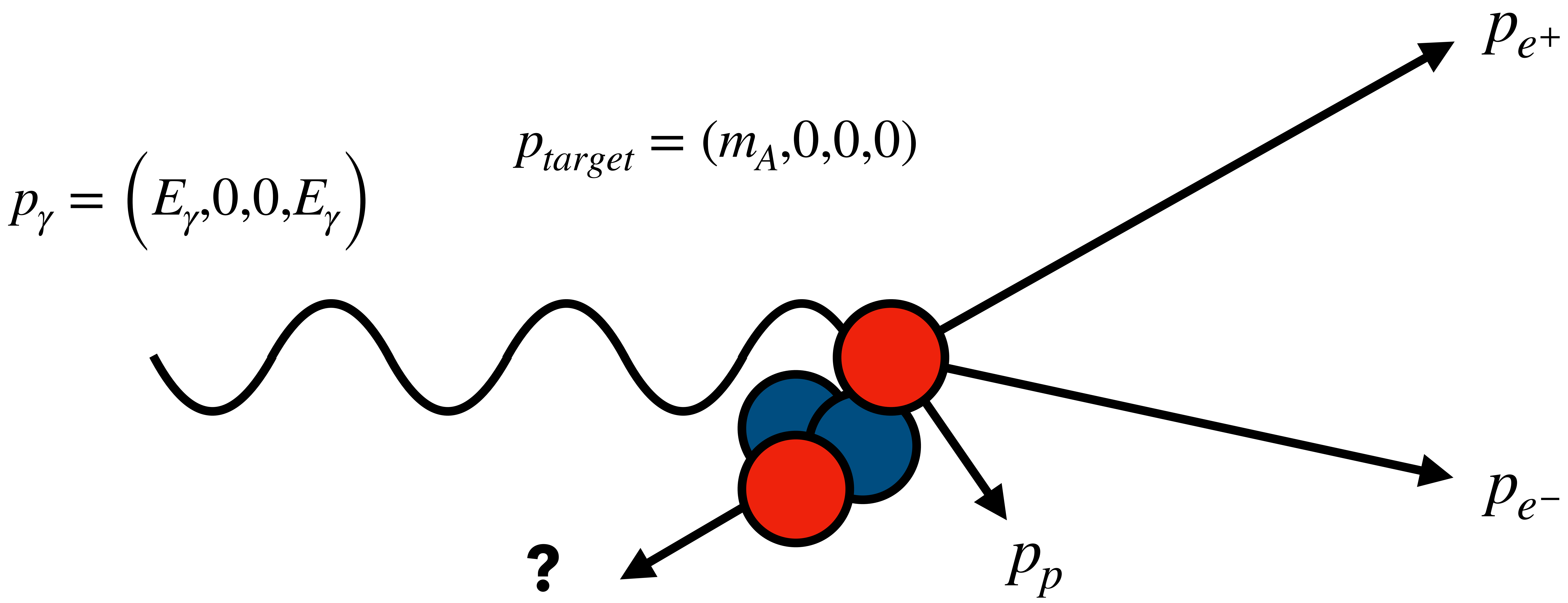
Ali et al. PRL (2019)

Standard GlueX hydrogen running uses kinematic fitting



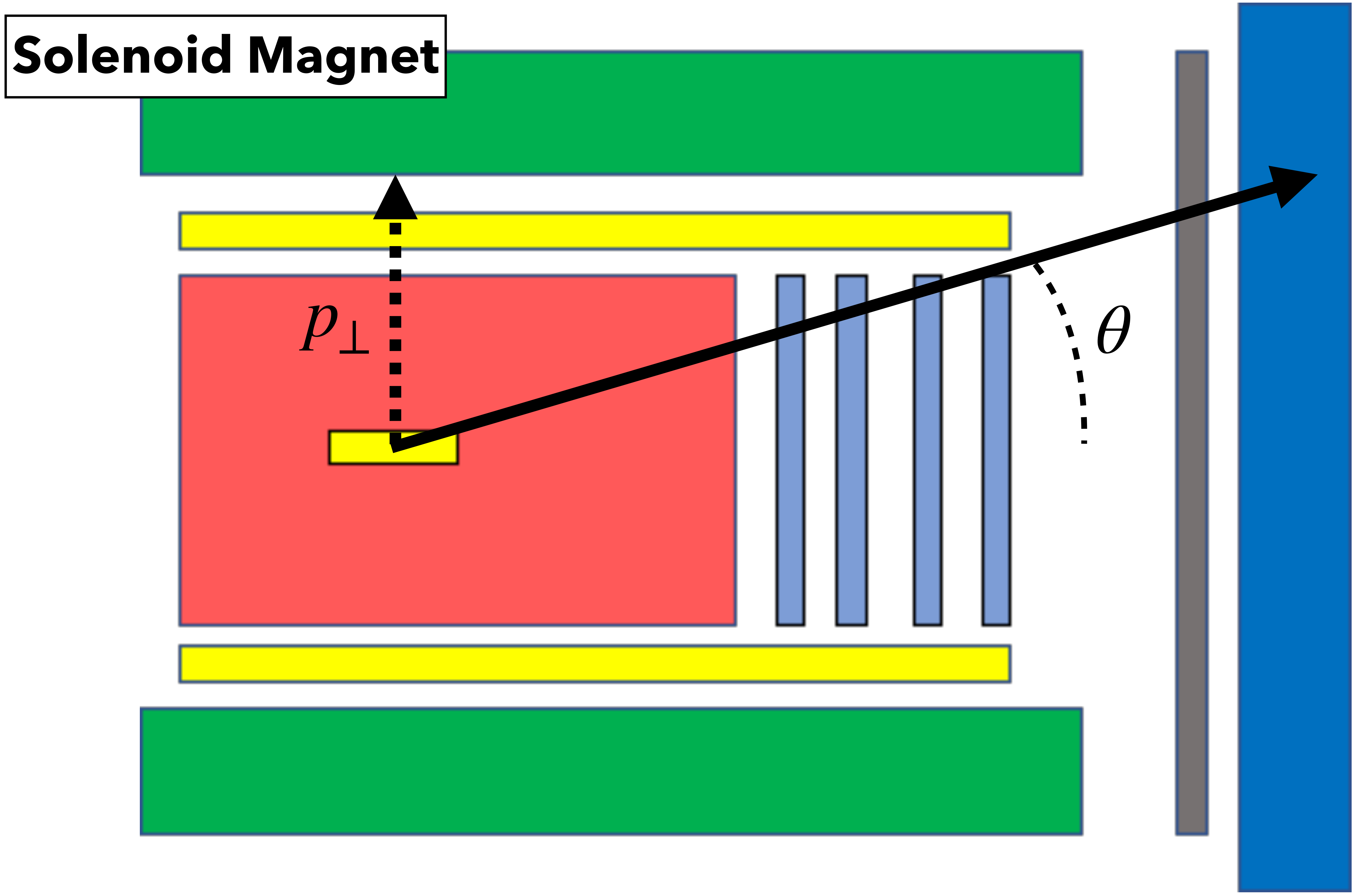
Conservation of 4-momentum → Improved resolution on final-state momentum

Standard GlueX hydrogen running uses kinematic fitting



~~Conservation of 4-momentum~~ ⟶ **Poor resolution!**

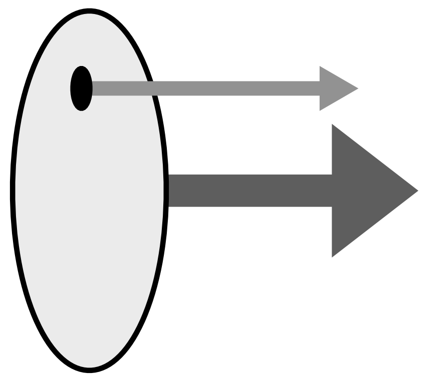
Momentum measurement in GlueX



- Solenoid magnet – measure $p_\perp$ and θ
- **Measurement on p_Z poor for forward, high-momentum particles**
- Resolution of final-state dominated by forward particles carrying most of the photon energy

Analysis on the light-front

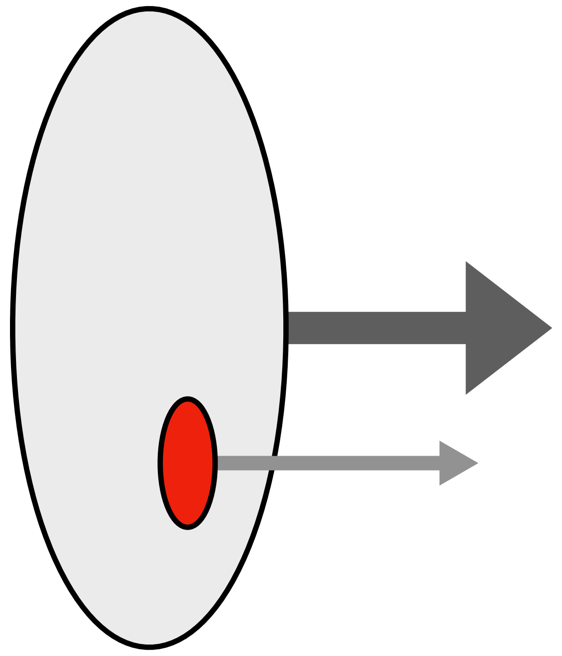
Parton in Hadron



Parton momentum fraction

$$x_B$$

Nucleon in Nucleus

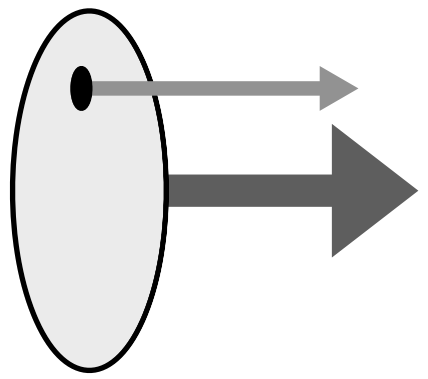


Nucleon momentum fraction

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

Analysis on the light-front

Parton in Hadron

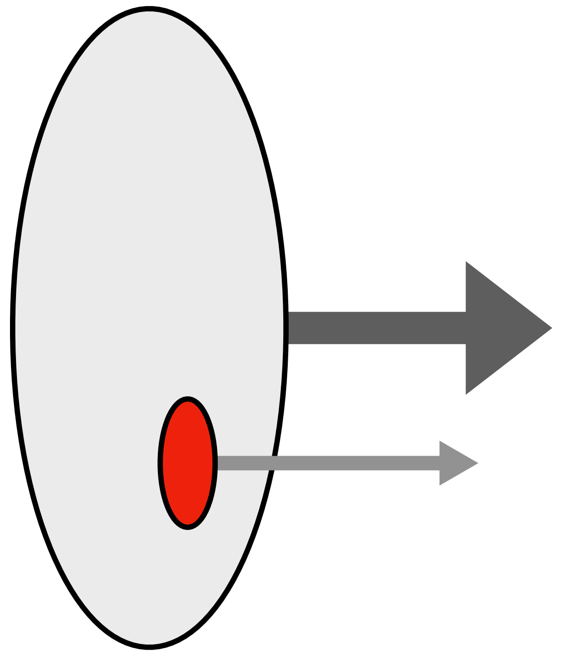


Parton momentum fraction

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 $|\alpha_N - 1|$

Reformulate invariant mass using light-front variables

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

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

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

Well-reconstructed

$$p^- = E - p_z$$

Cancellation of resolution effects

Poorly-reconstructed

$$p^+ = E + p_z$$

Enhancement of resolution effects

Well-reconstructed

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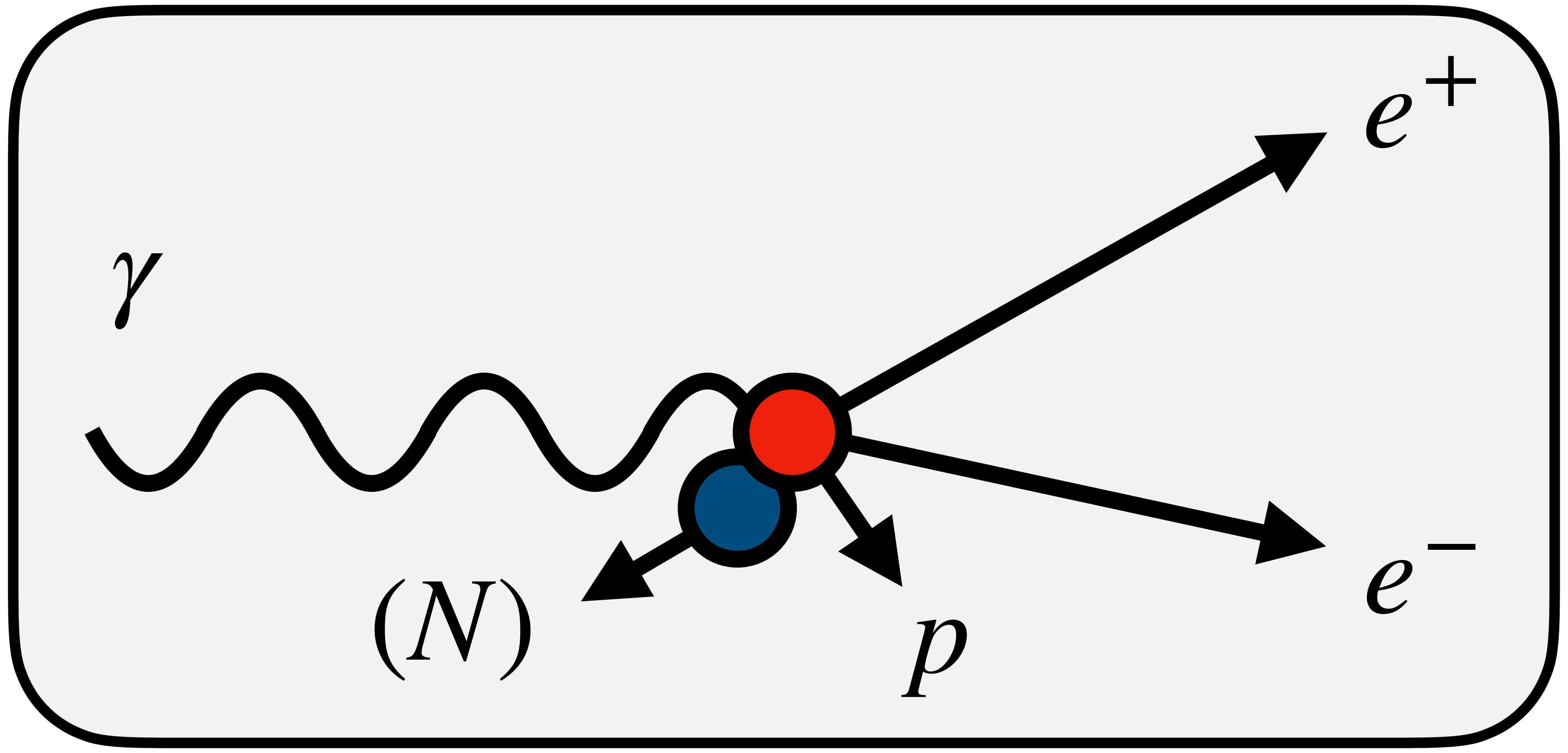
$$p_\gamma + p_{2N} = p_{e^+} + p_{e^-} + p_p + p_N$$

Assume recoil 4-momentum carried by single nucleon



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

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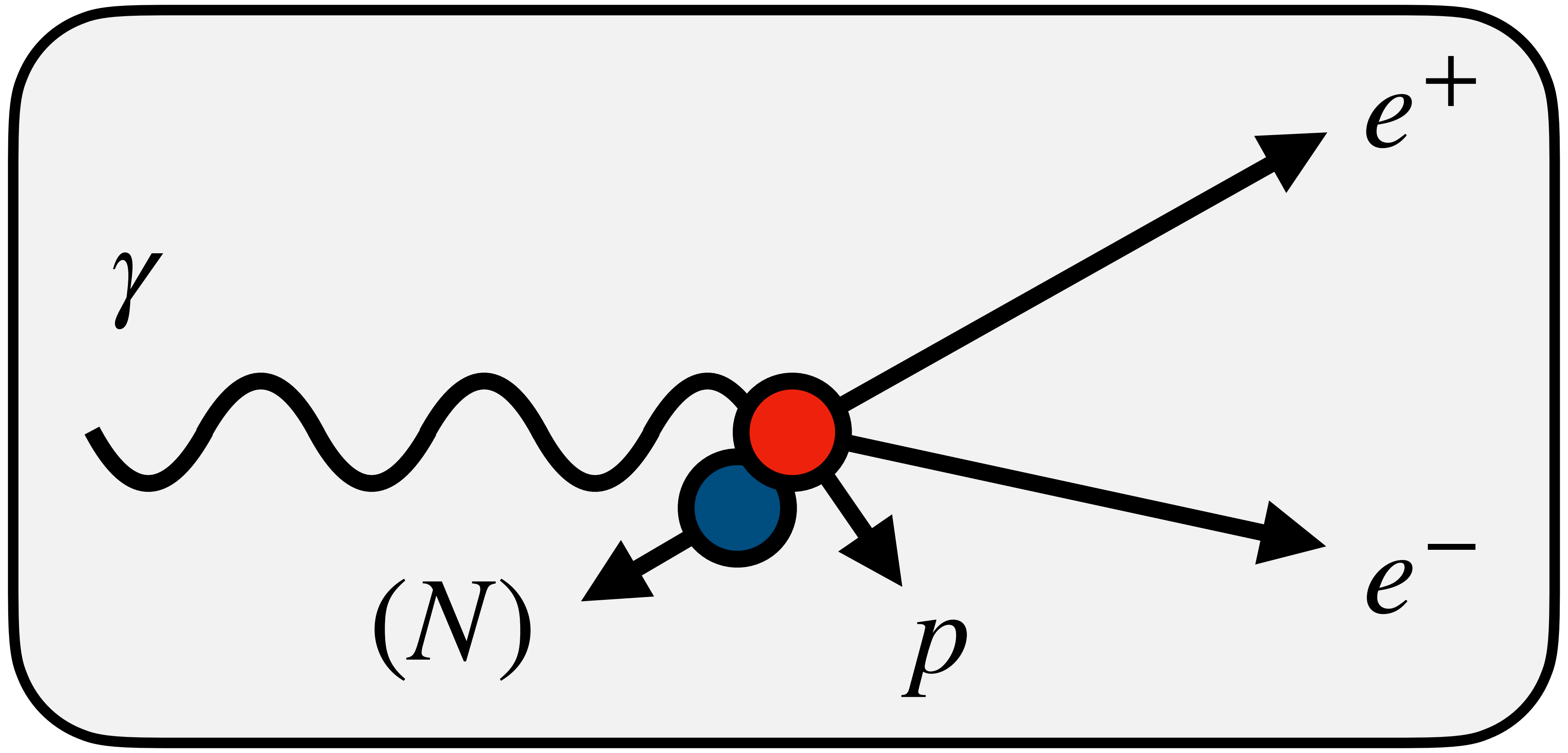

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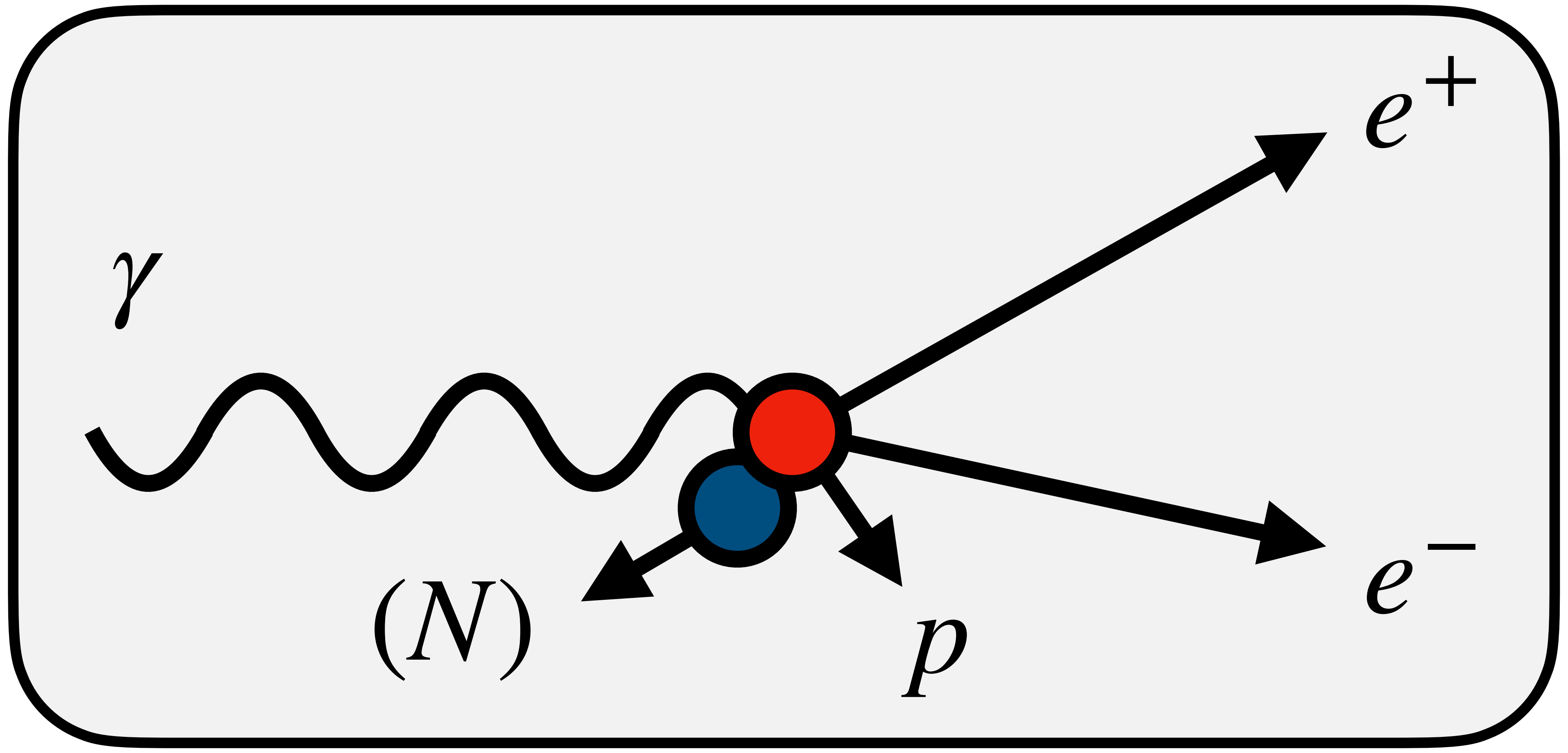
$$p_N^+ = \frac{p^2_{N,\perp} + m_N^2}{p_N^-}$$

Assume recoil 4-momentum carried by single nucleon



Reformulate invariant mass using light-front variables

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

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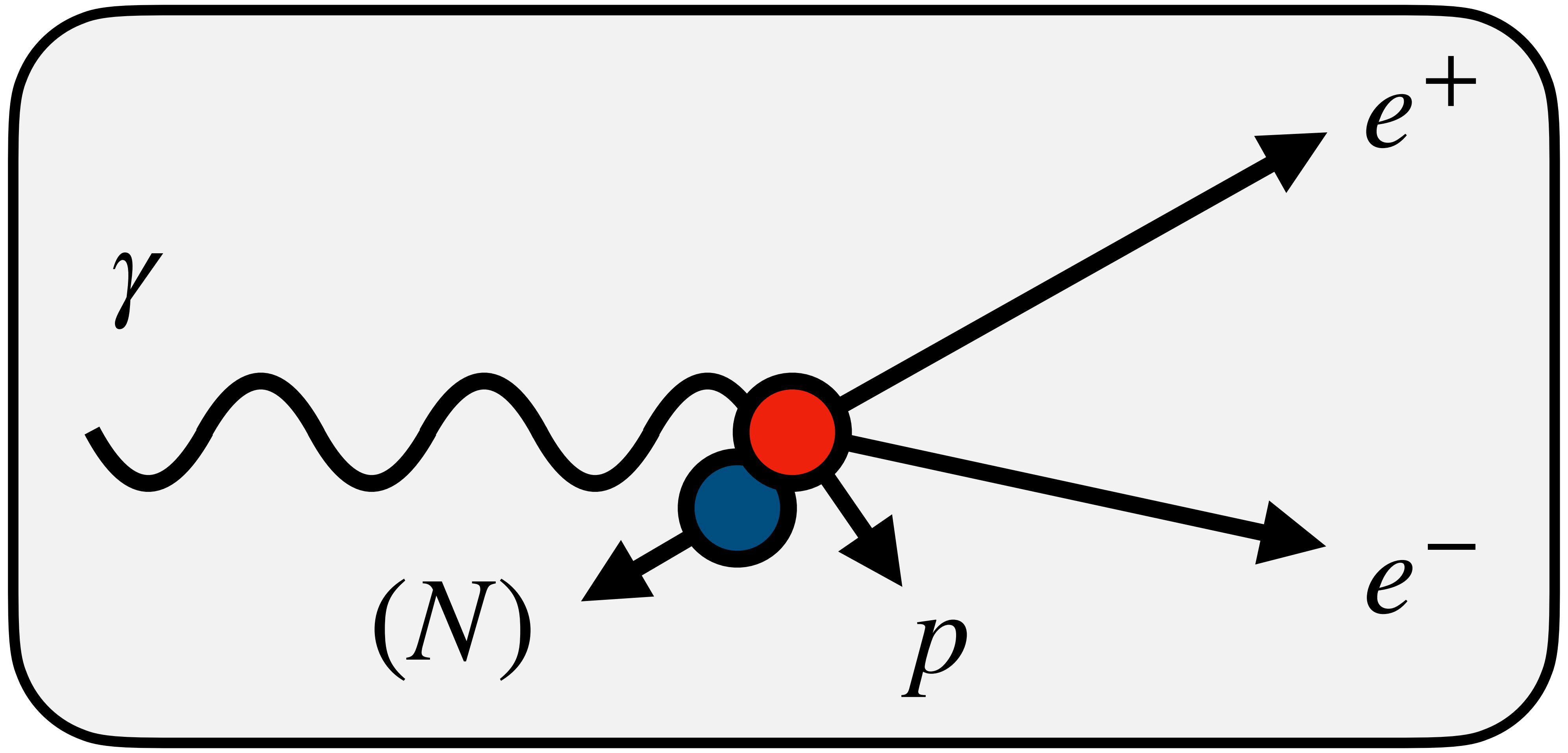
$$p_N^+ = \frac{p^2_{N,\perp} + m^2_N}{p^-_N}$$

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

Assume recoil 4-momentum carried by single nucleon



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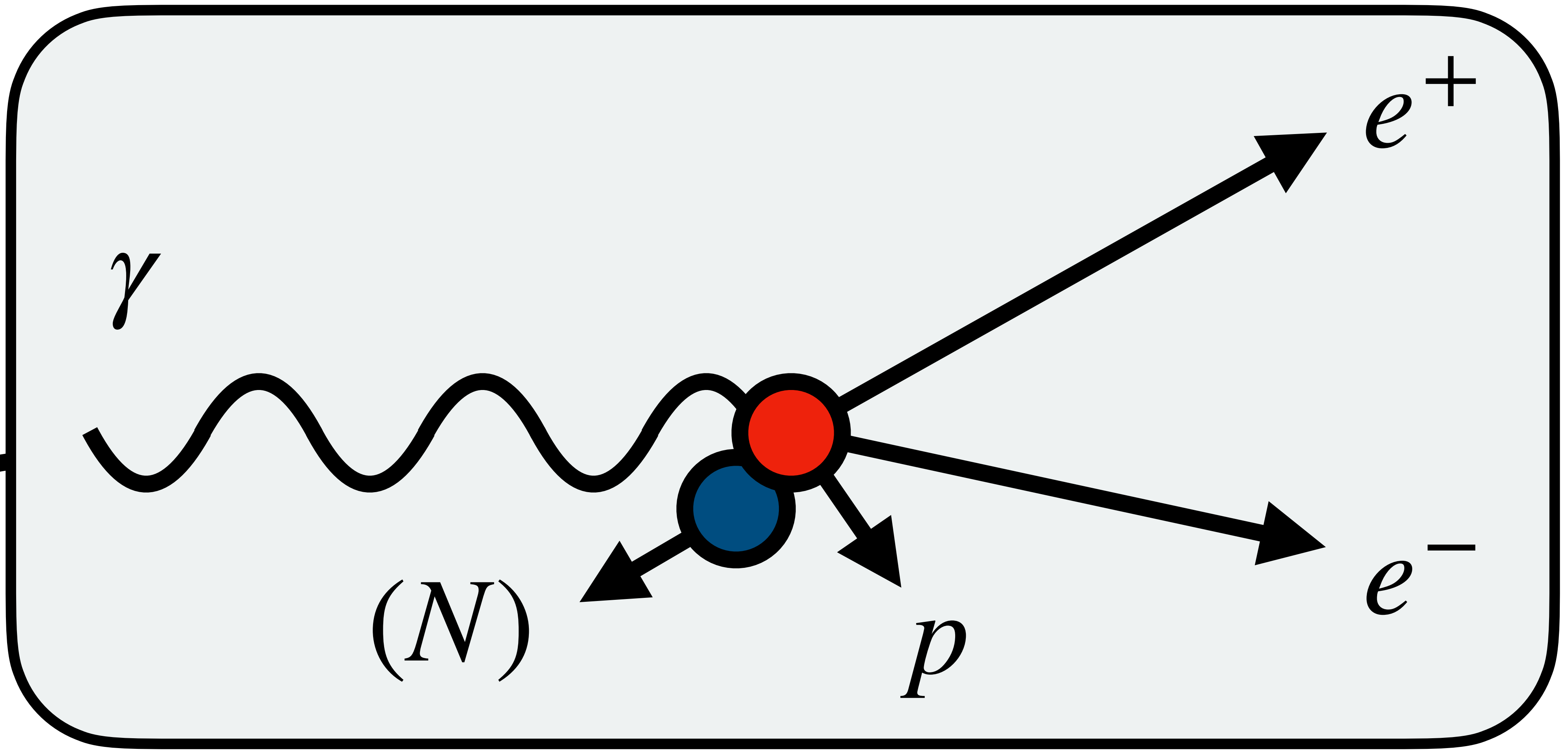
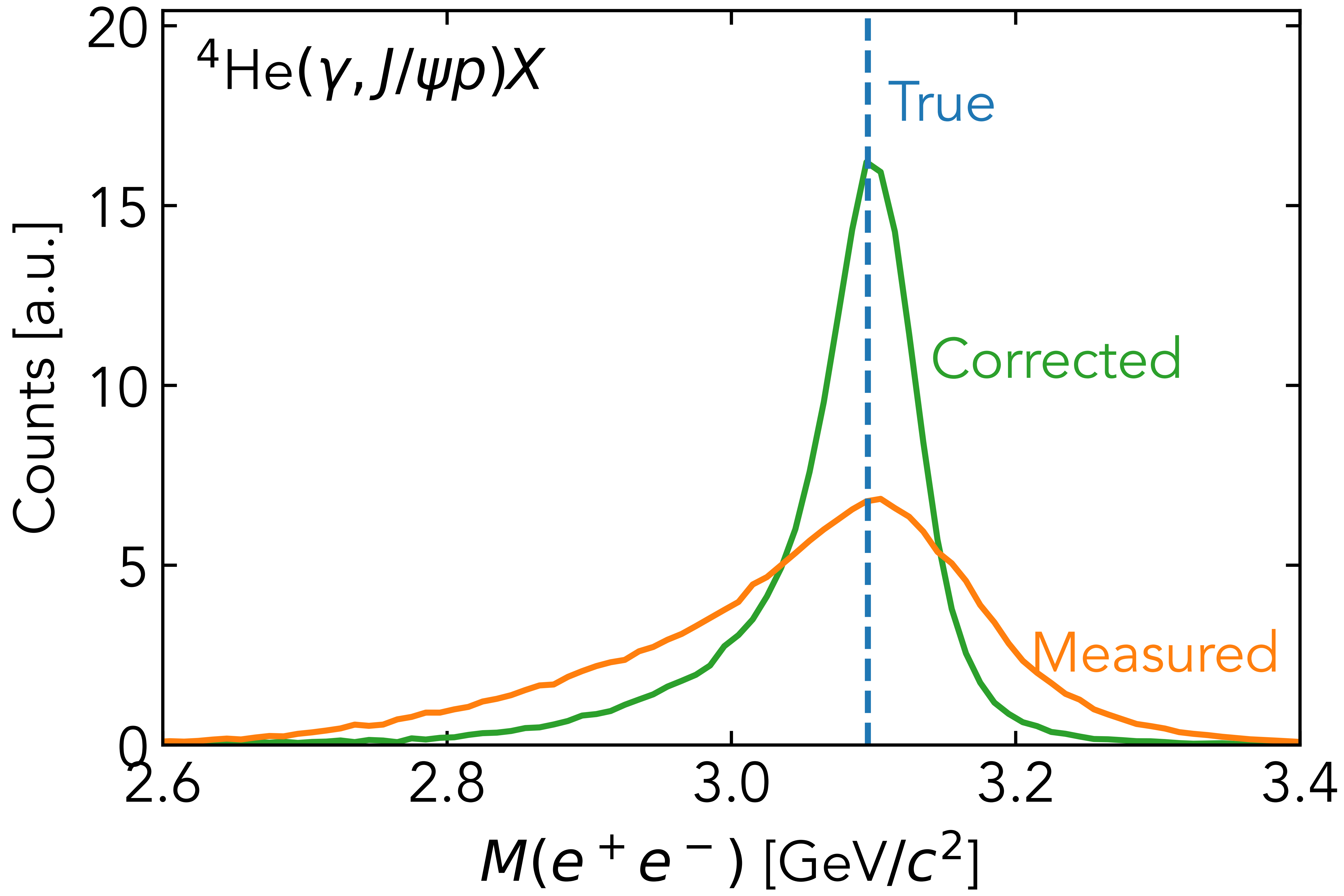
Assume recoil 4-momentum carried by single nucleon



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

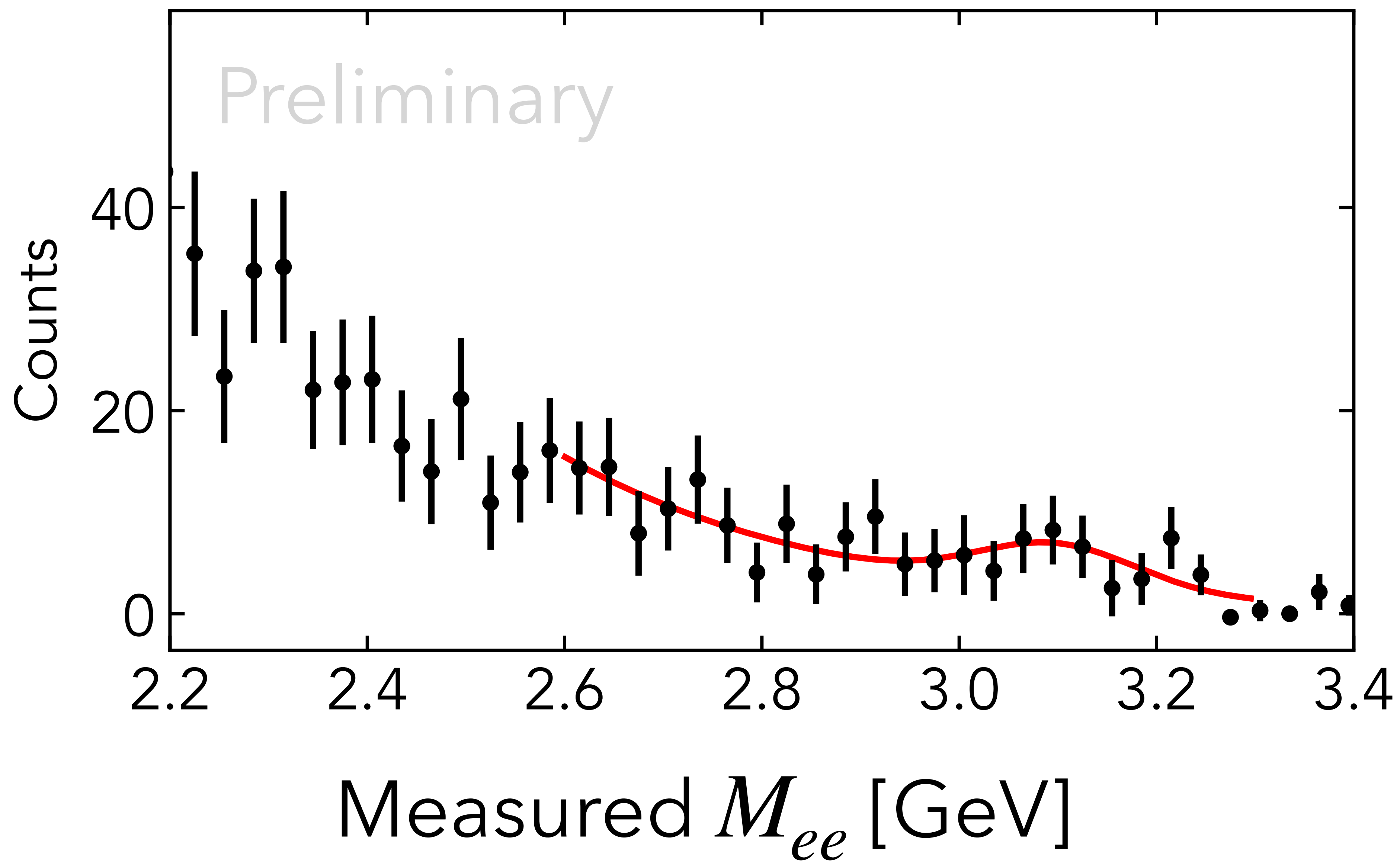
$$M^2_{e^+e^-} \approx (p^-_{e^+} + p^-_{e^-})\left(2E_\gamma + 2m_N - p^+_p - \frac{m_N^2 + p_{tot}^2}{2m_N - p^-_{tot}}\right) - (\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-})^2$$

Simulation shows resolution improvement



New observable greatly improves signal-to-background

$\gamma\mathrm{C} \to e^+e^-p(X)$



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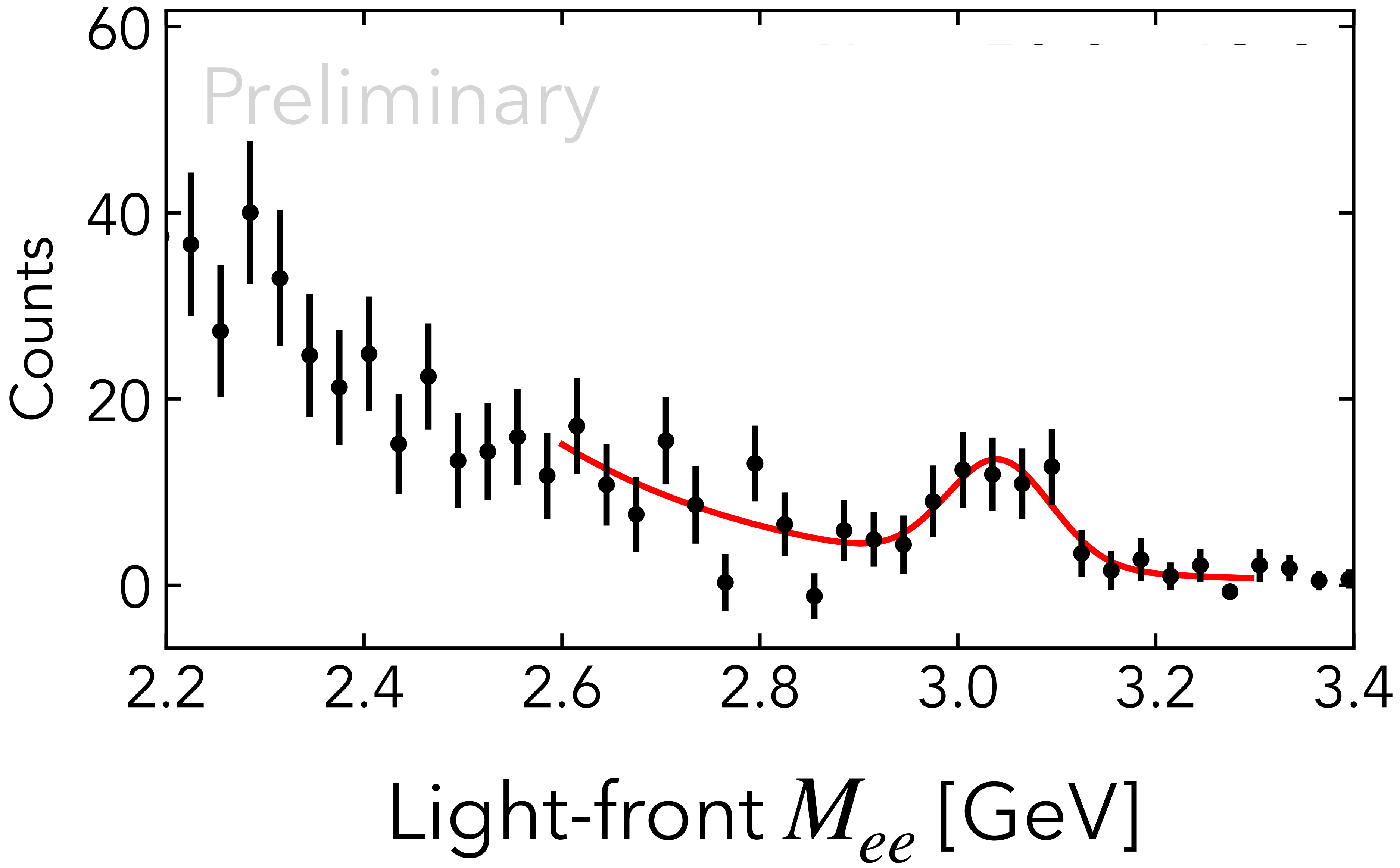
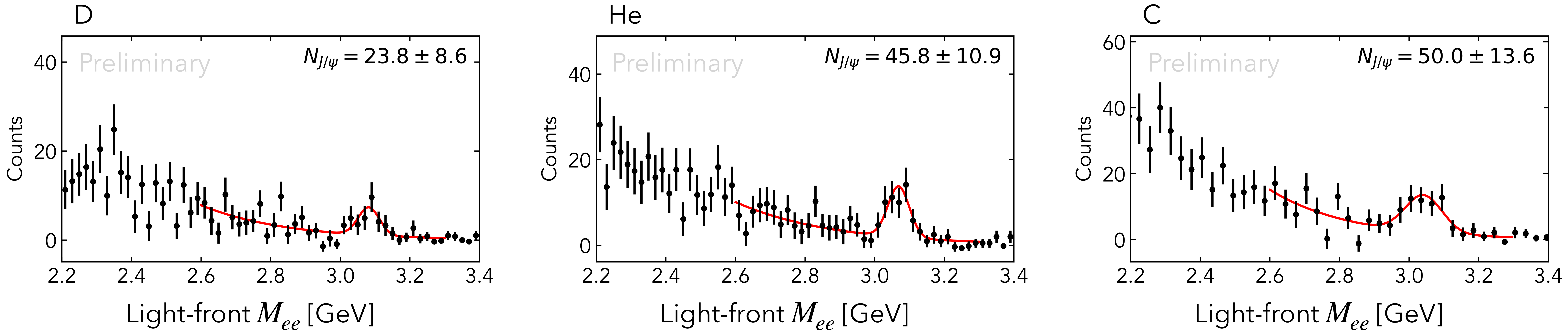
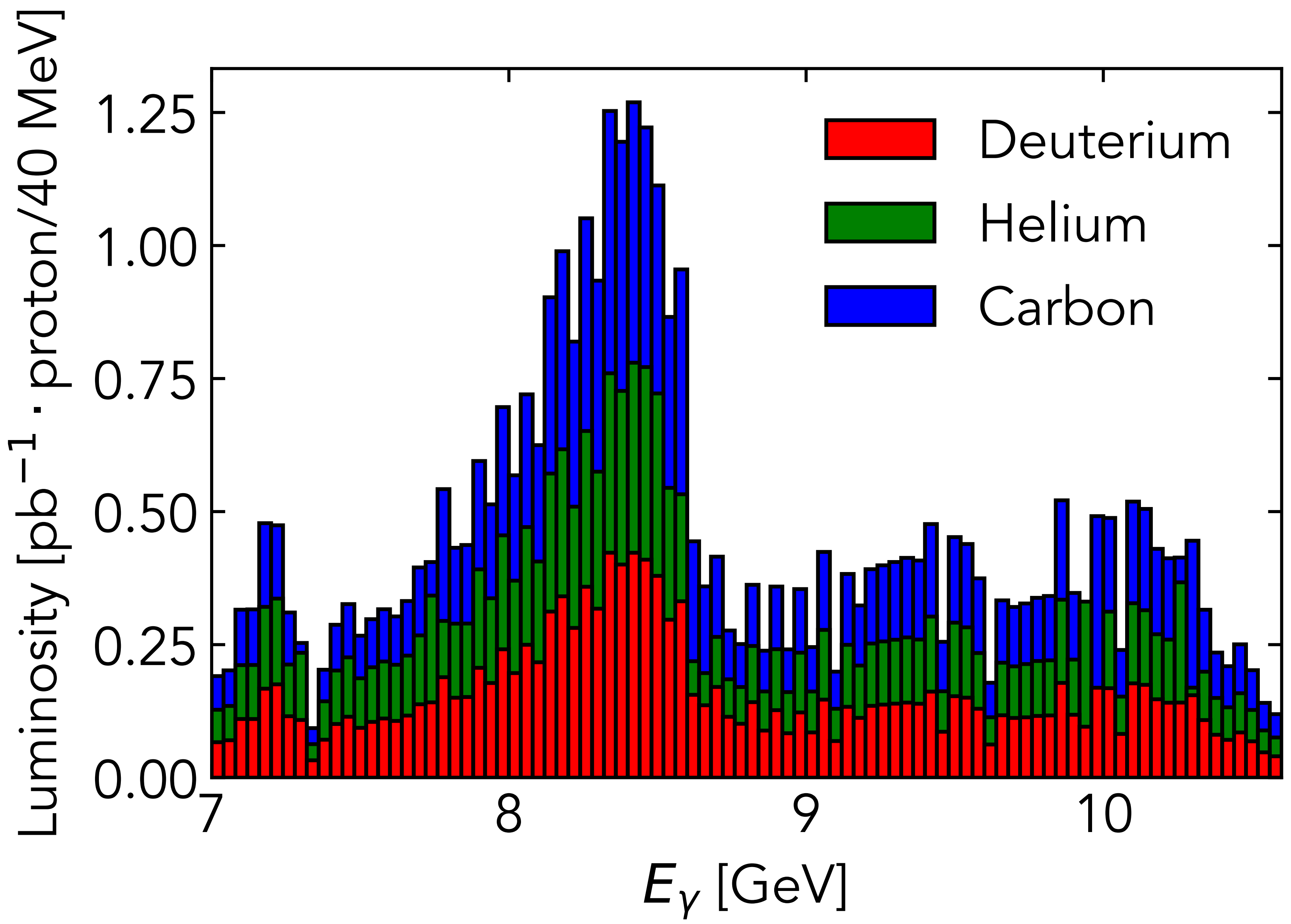


Invariant mass spectra show clear $J/\psi \to e^+e^-$ peaks



Cross section extraction



Yield from dilepton invariant mass fit

$$\sigma(E_\gamma) = \frac{Y_{J/\psi}(E_\gamma)}{\mathscr{L}(E_\gamma) \times \epsilon(E_\gamma) \times T_A \times \mathscr{B}(J/\psi \to e^+e^-)}$$

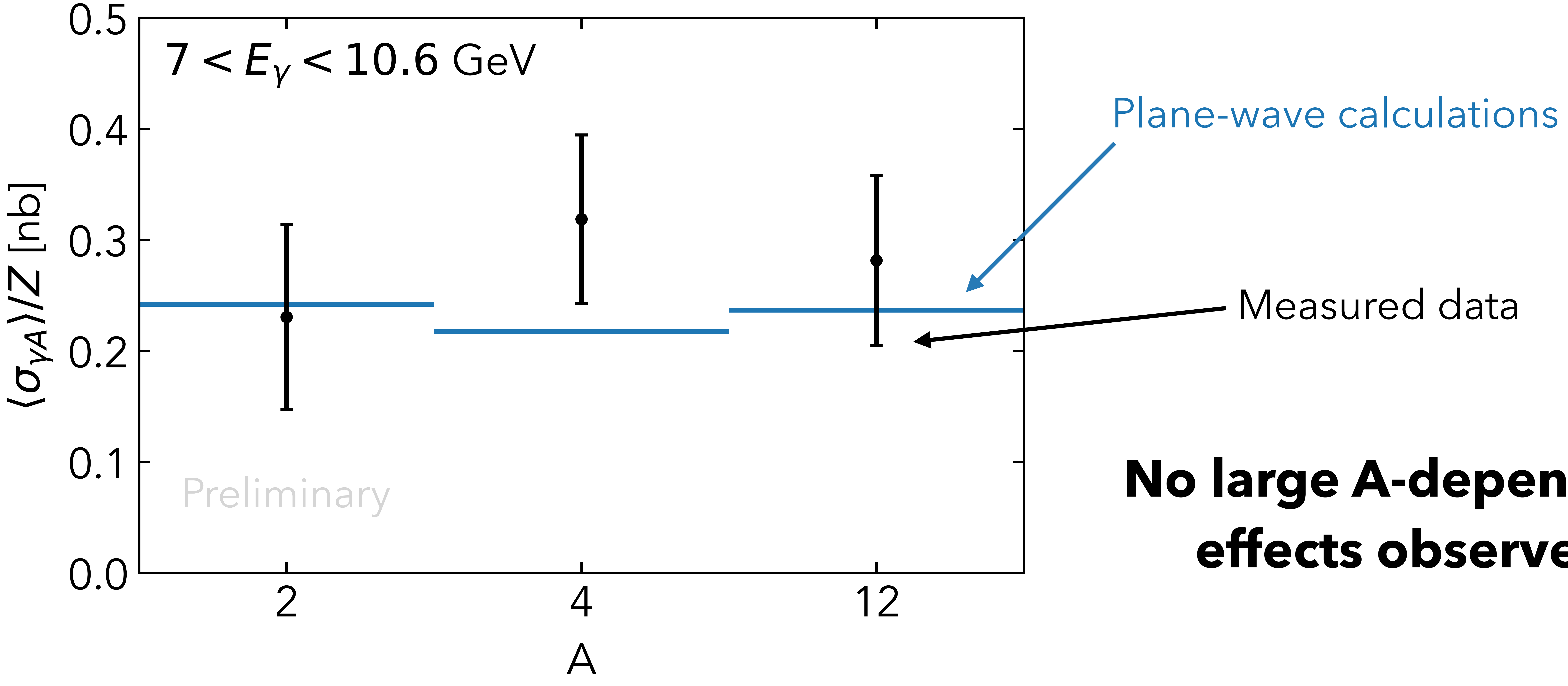
Luminosity from measured tagged photon flux

Efficiency from MC calculations

Proton nuclear transparency

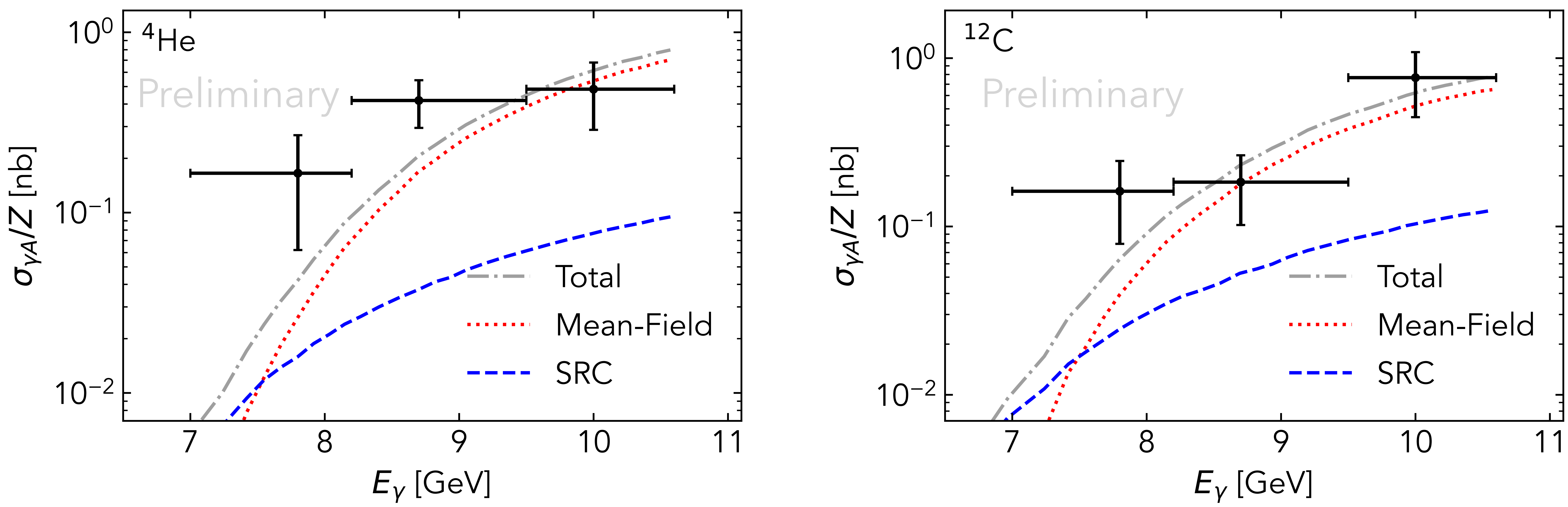
Branching fraction

Energy-averaged cross section compared across nuclei

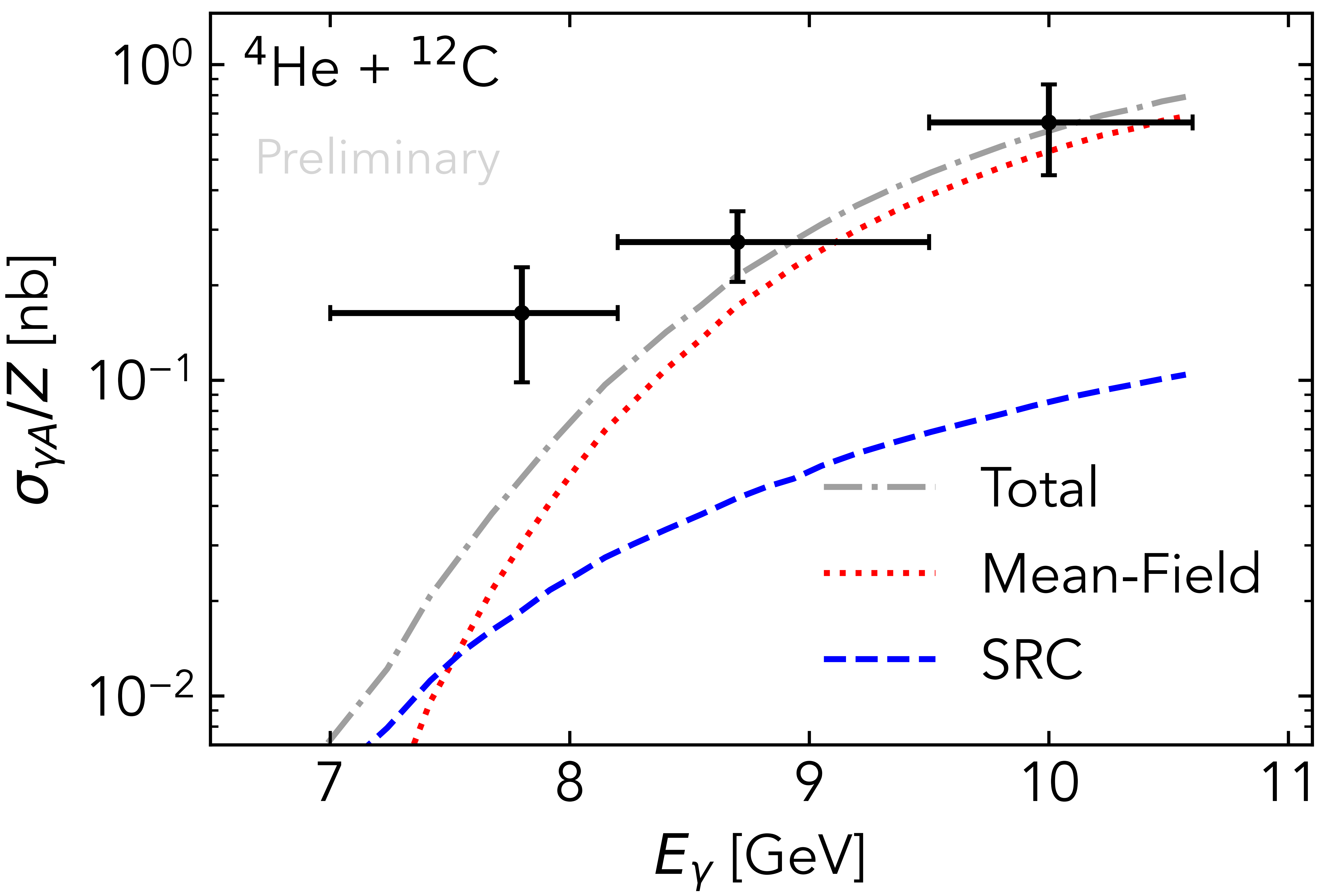


No large A-dependent effects observed

Cross section extracted as function of beam energy

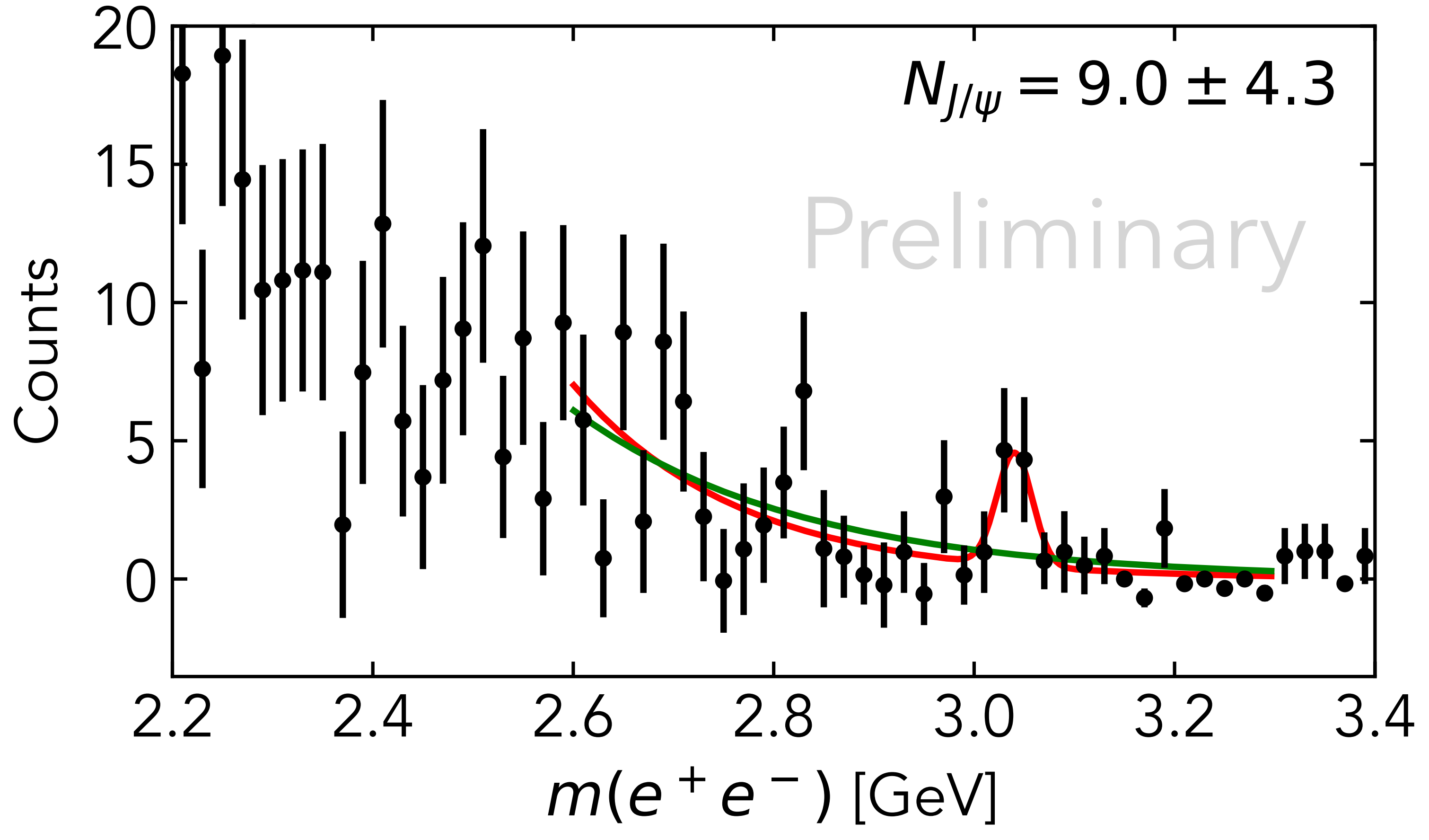


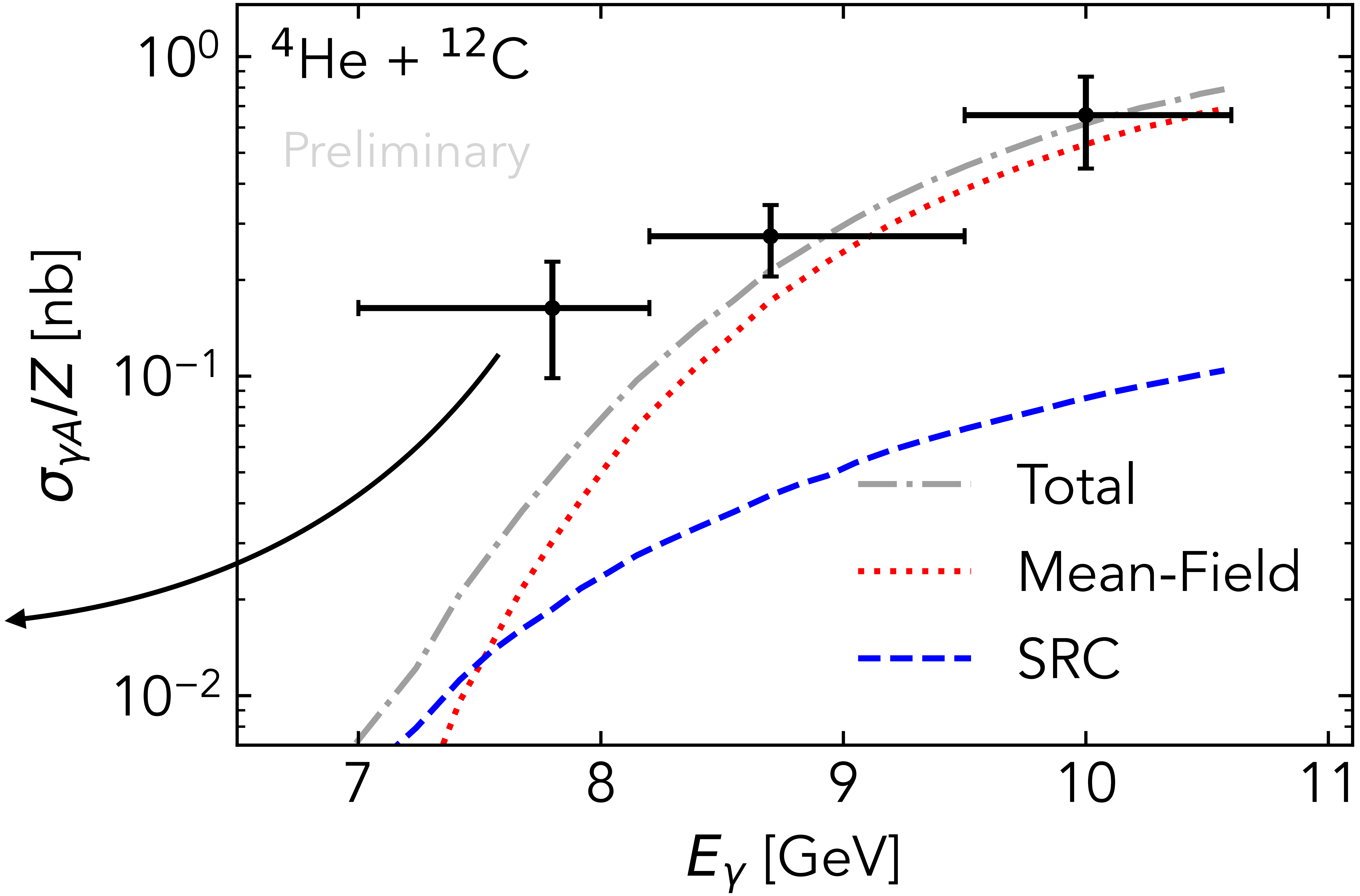
Combining nuclei improves precision



First observation of sub-threshold J/ψ!

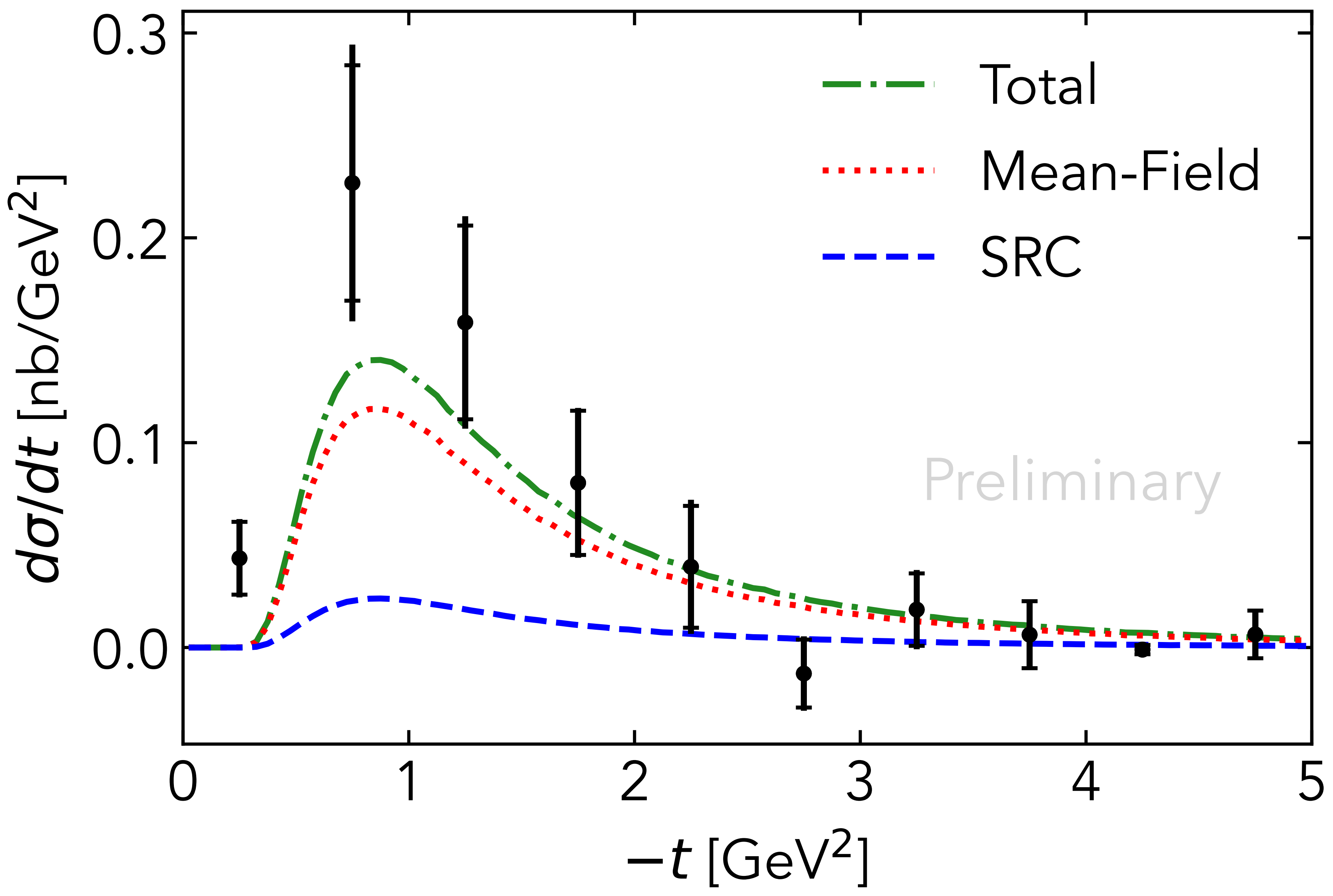
Subthreshold peak of J/ψ found to be statistically significant at >3σ



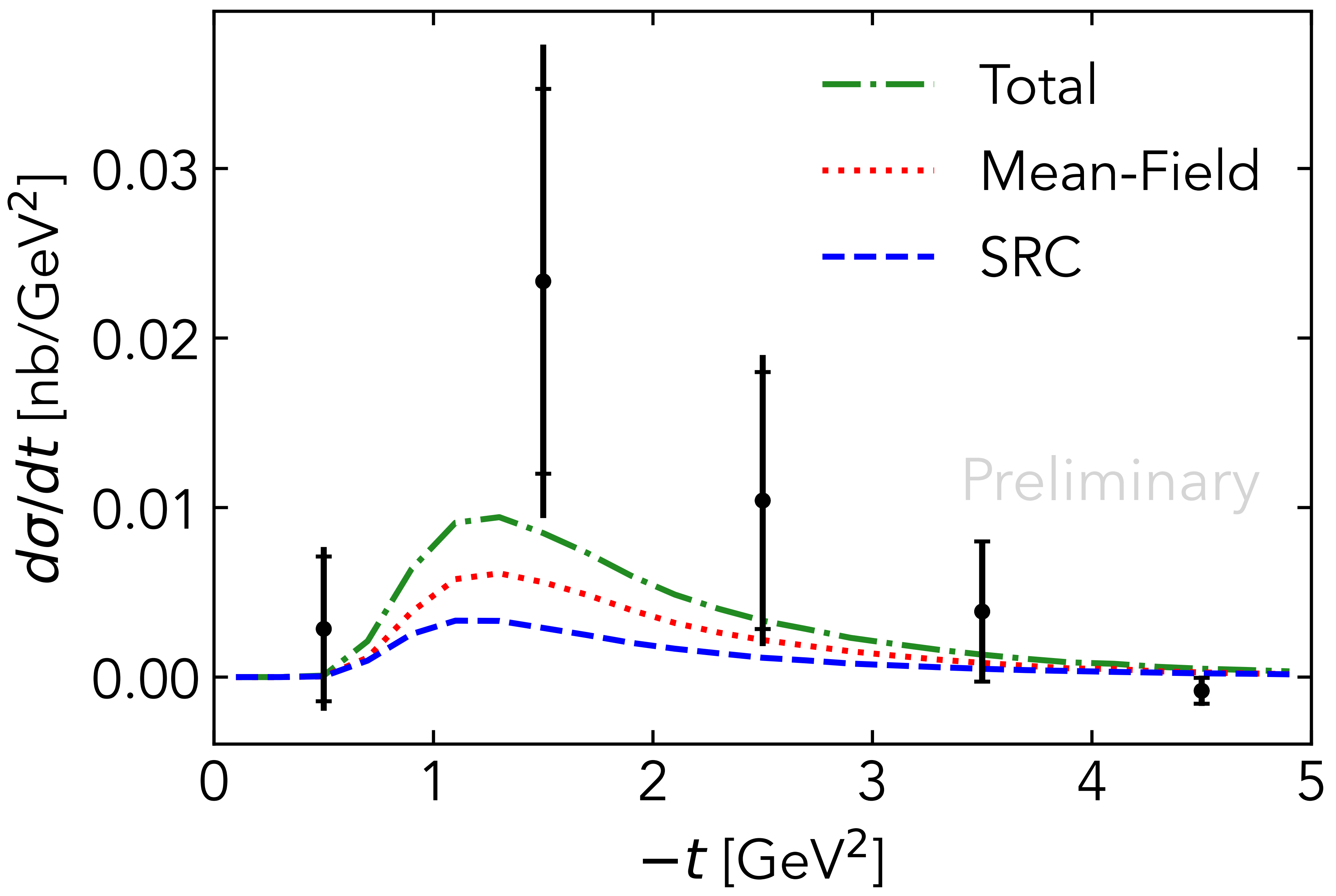


Kinematics give insight into reaction mechanisms

Above threshold: $E_\gamma > 8.2$ GeV



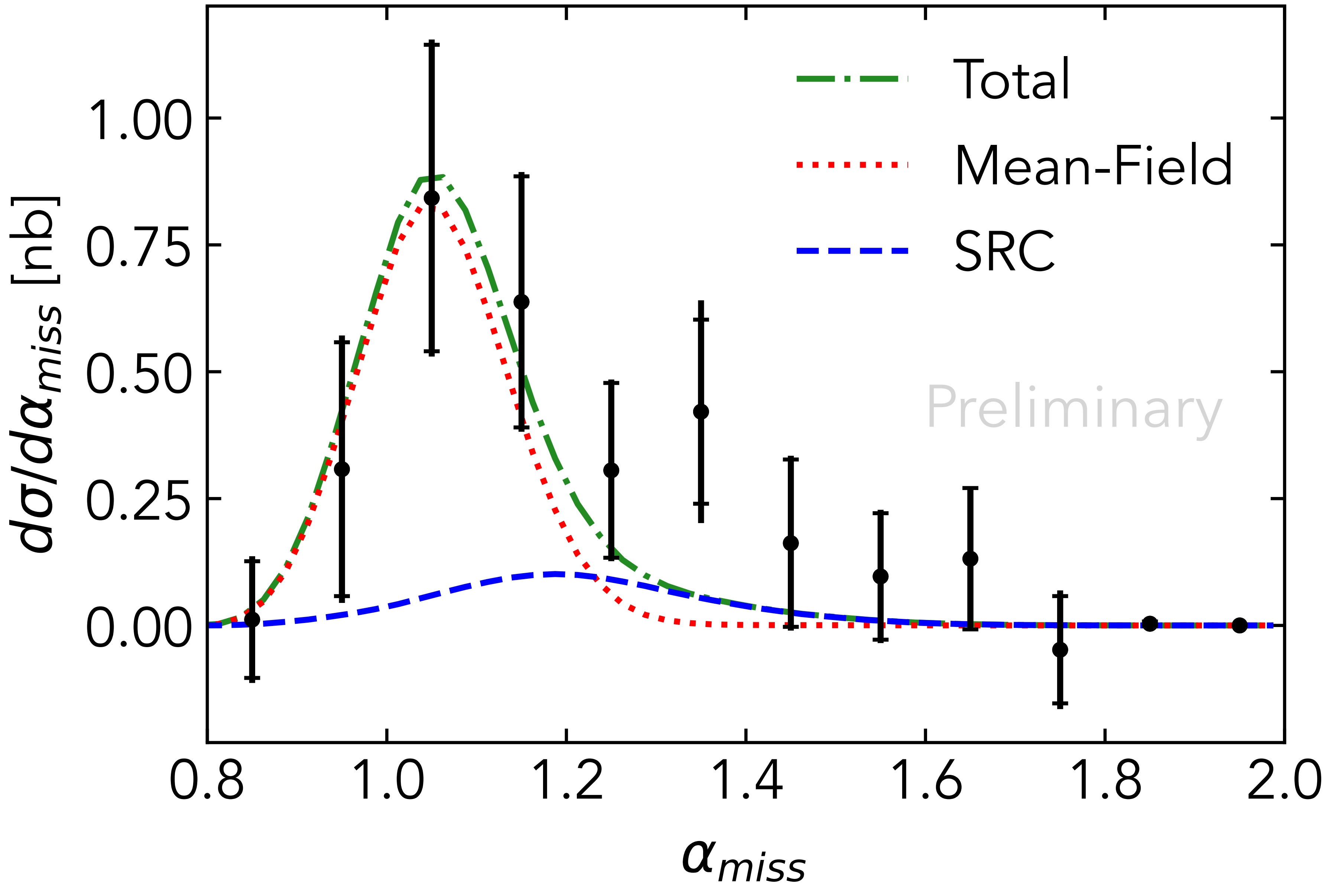
Below threshold: $E_\gamma < 8.2$ GeV



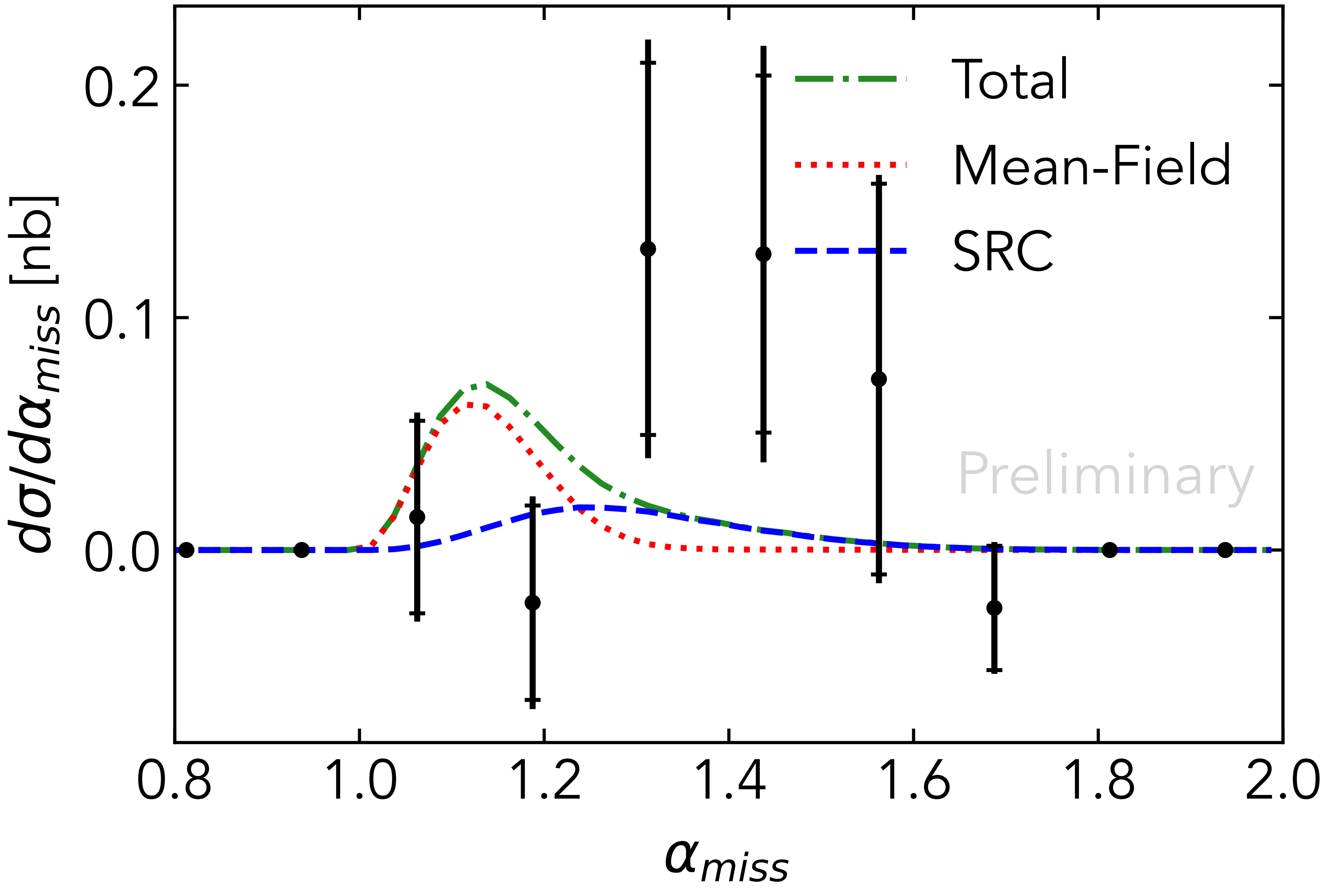
Momentum-transfer gives measure of reaction kinematics

Kinematics give insight into reaction mechanisms

Above threshold: $E_\gamma > 8.2$ GeV



Below threshold: $E_\gamma < 8.2$ GeV



Production of J/ψ below threshold energies shows larger than expected cross section, as well as distortion to larger α_{miss}

What could cause disagreement with plane-wave?

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

What could cause disagreement with plane-wave?

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Nuclear spectral function

What could cause disagreement with plane-wave?

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Nuclear spectral function ✓

What could cause disagreement with plane-wave?

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

Photon-proton interaction?

Nuclear spectral function ✓

Bound proton might not interact with color dipole same as free proton

How does the J/ψ interact with the proton?

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

Forward cross section; sensitive to gluon density at

$$x \approx \frac{m_{J/\psi}^2}{s_{\gamma p} - m_N^2}$$

Gravitational form factor with dipole parameterization

$$F(t) = \frac{1}{\left(1 - t/\Lambda^2\right)^2}$$

Gives mass radius $\langle r_m \rangle = \frac{\sqrt{12}}{\Lambda}$

Two ways to modify the proton

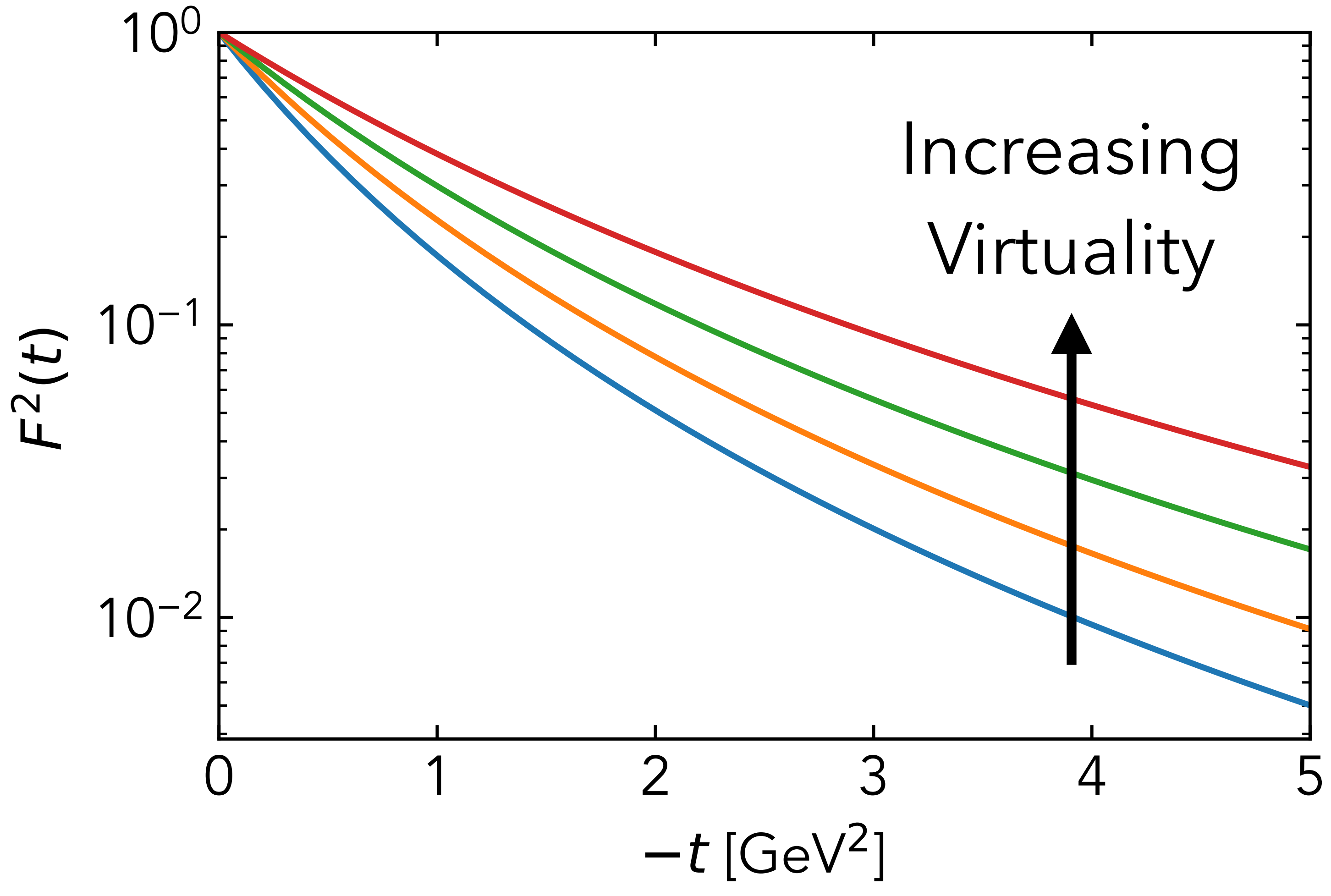
1. Bound protons have **greater** gluon density:

$$\left.\frac{d\sigma}{dt}\right|_{t=0} \to (1 - Av) \times \left.\frac{d\sigma}{dt}\right|_{t=0}$$

2. Bound protons have **smaller** mass radius:

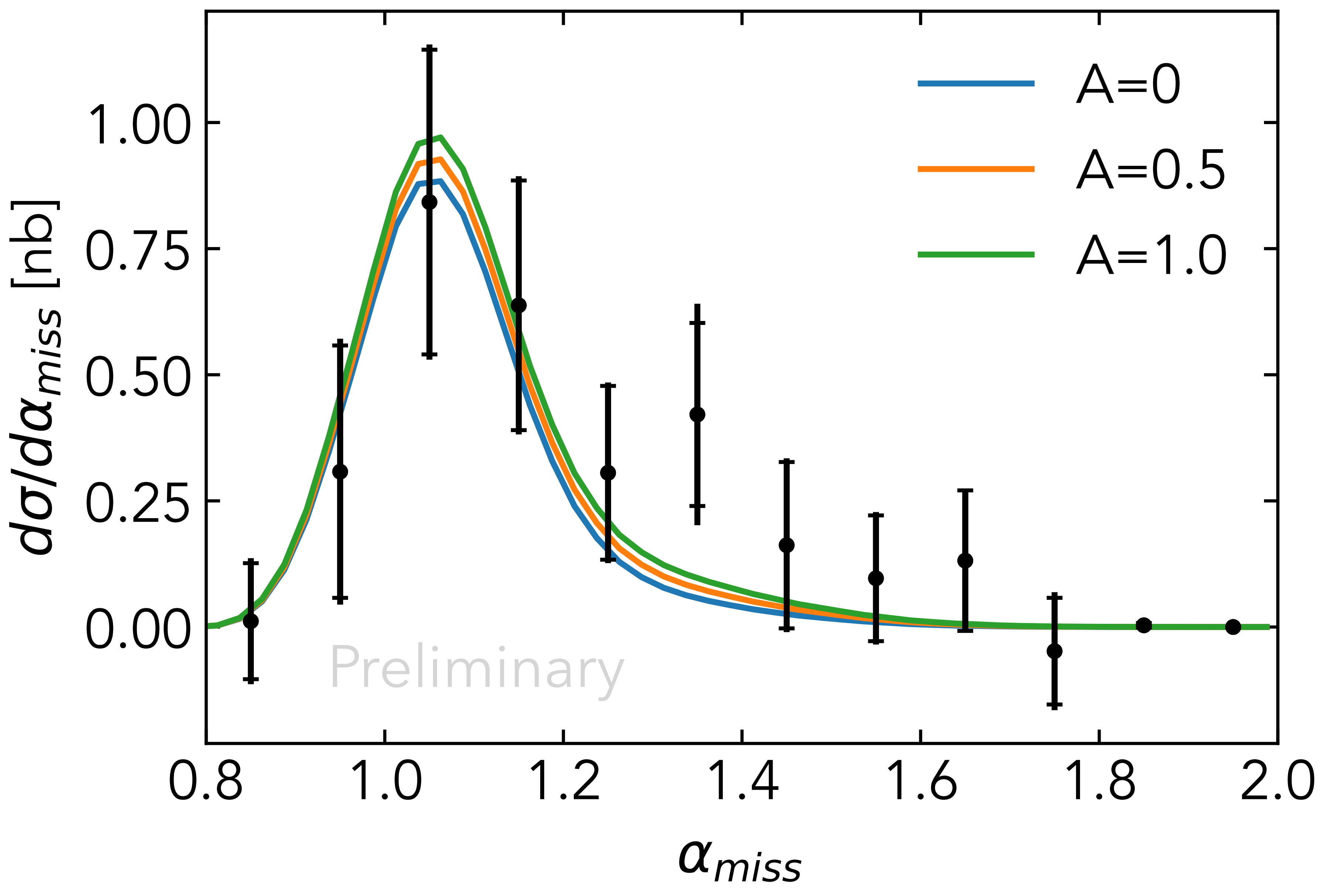
$$\langle r_m \rangle \to (1 + Bv)\langle r_m \rangle$$

$$\Lambda \to \frac{\Lambda}{(1 + Bv)}$$

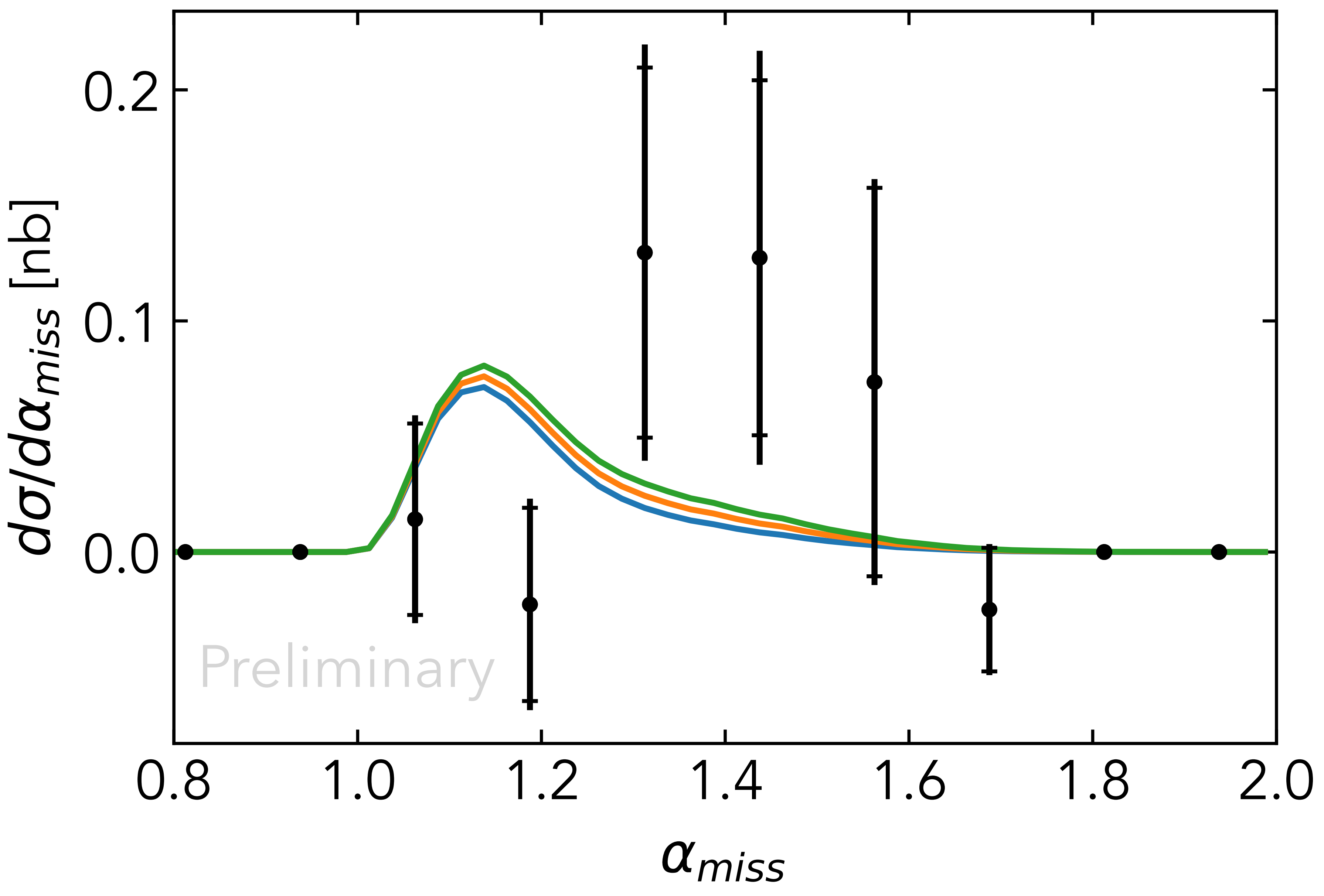


Larger cross section struggles to explain data

Above threshold: $E_\gamma > 8.2$ GeV



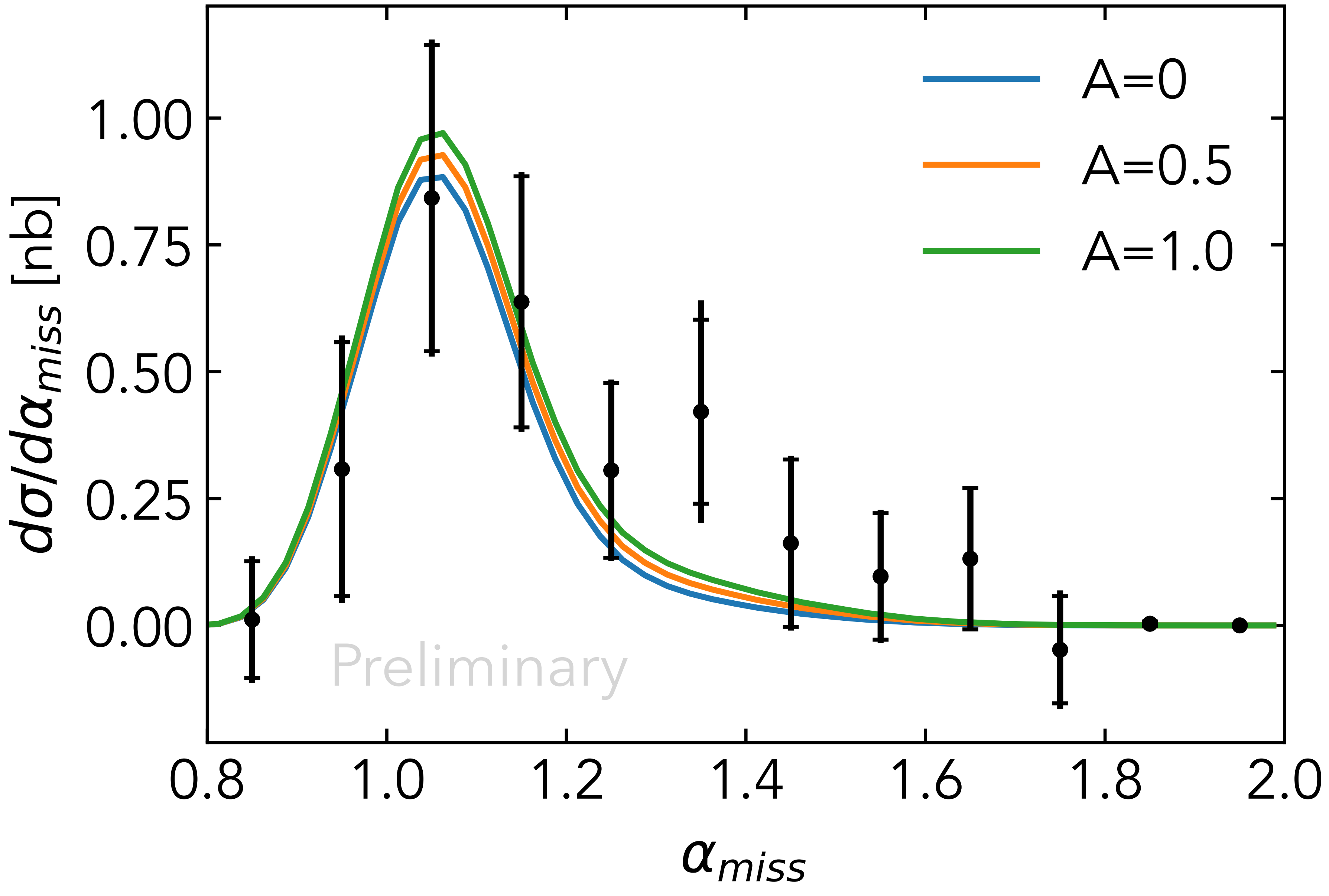
Below threshold: $E_\gamma < 8.2$ GeV



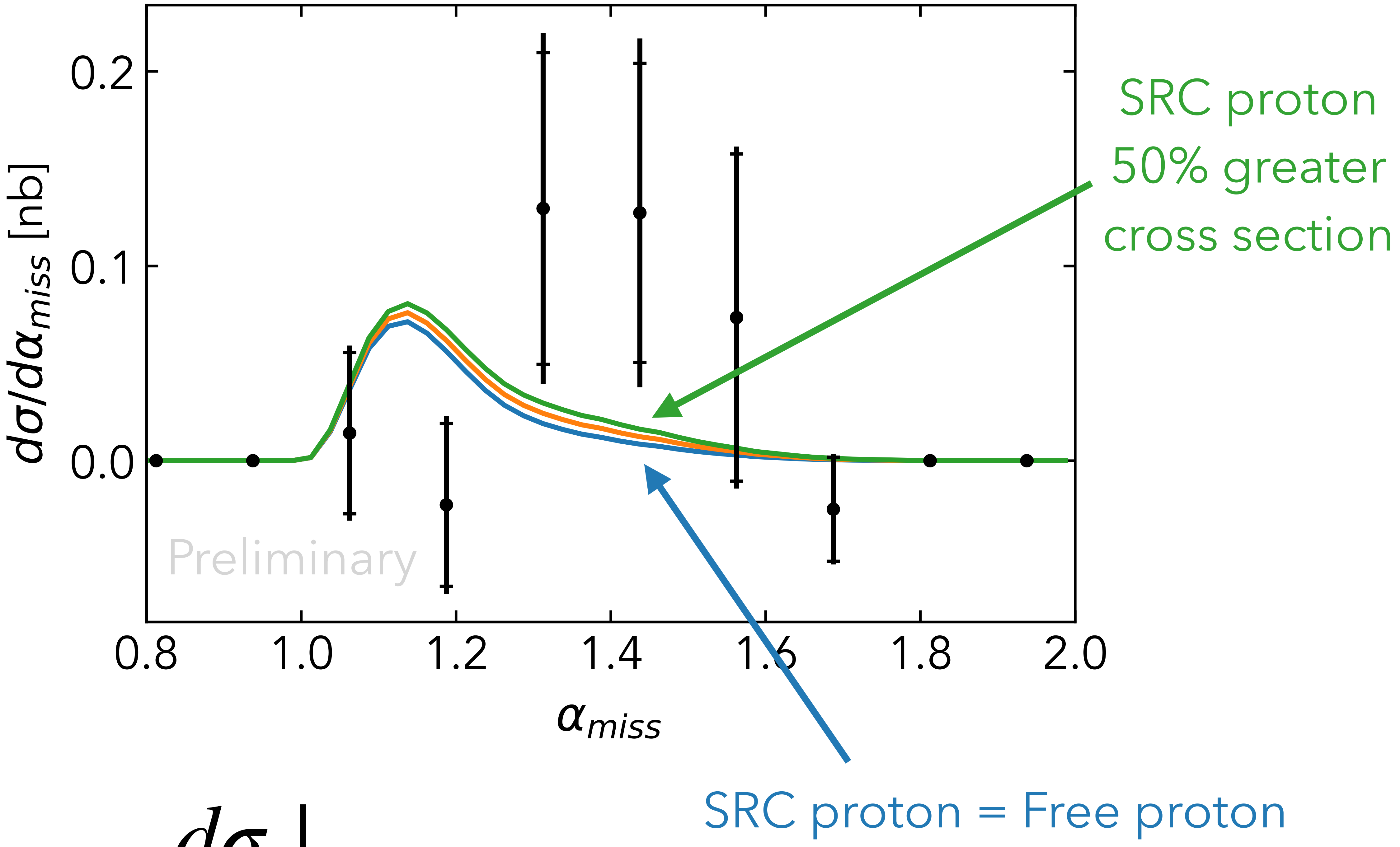
$$\left.\frac{d\sigma}{dt}\right|_{t=0} \rightarrow (1 - Av) \times \left.\frac{d\sigma}{dt}\right|_{t=0}$$

Larger cross section struggles to explain data

Above threshold: $E_\gamma > 8.2$ GeV



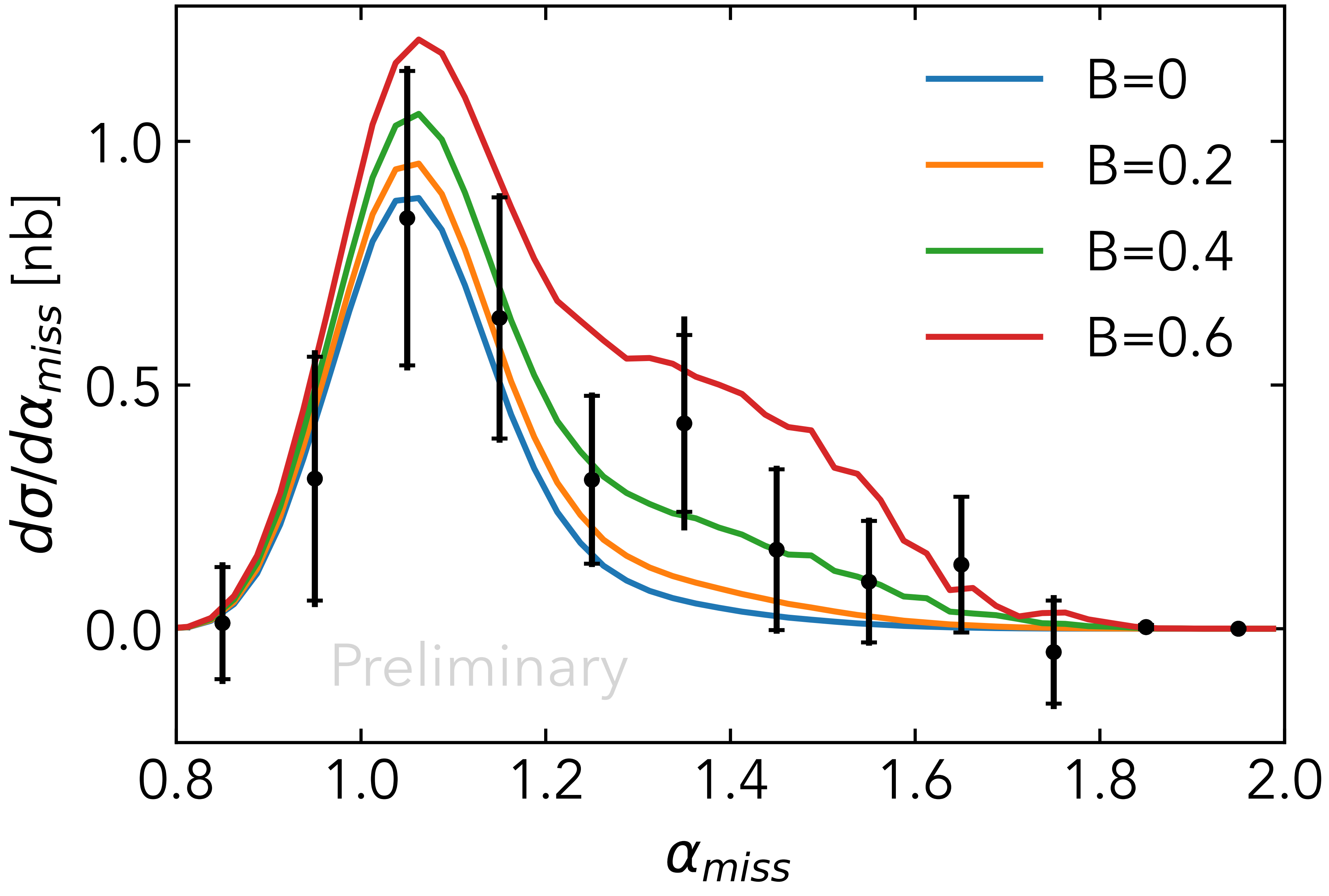
Below threshold: $E_\gamma < 8.2$ GeV



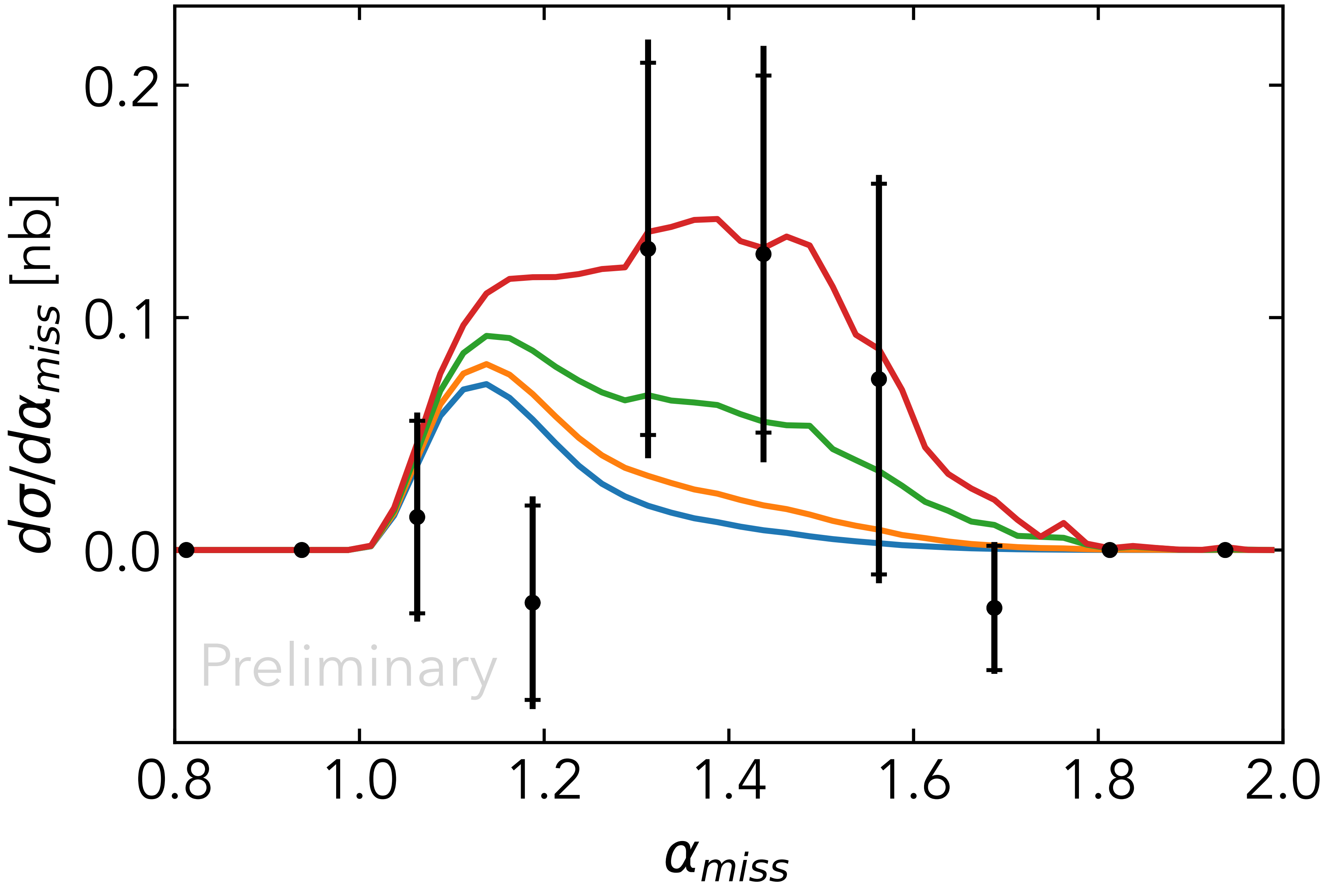
$$\left.\frac{d\sigma}{dt}\right|_{t=0} \to (1 - Av) \times \left.\frac{d\sigma}{dt}\right|_{t=0}$$

Smaller-size proton enhances large-α cross section

Above threshold: $E_\gamma > 8.2$ GeV

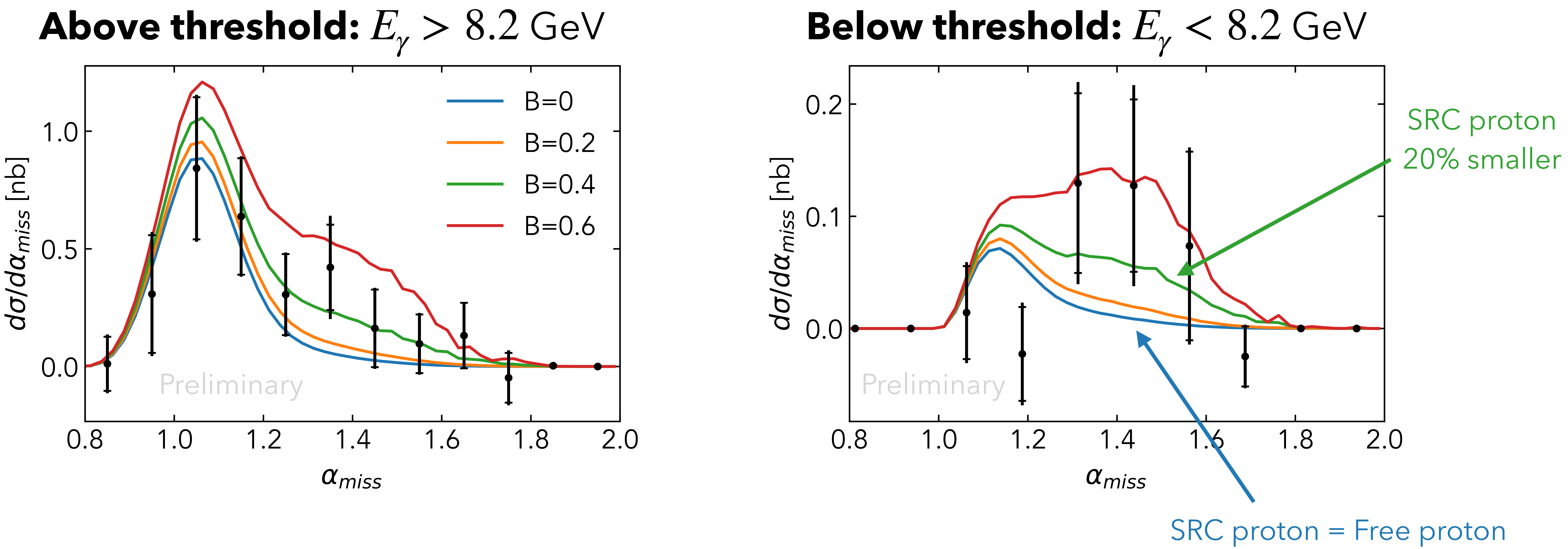


Below threshold: $E_\gamma < 8.2$ GeV



$$\langle r \rangle \rightarrow (1 + Bv)\langle r \rangle$$

Smaller-size proton enhances large-α cross section

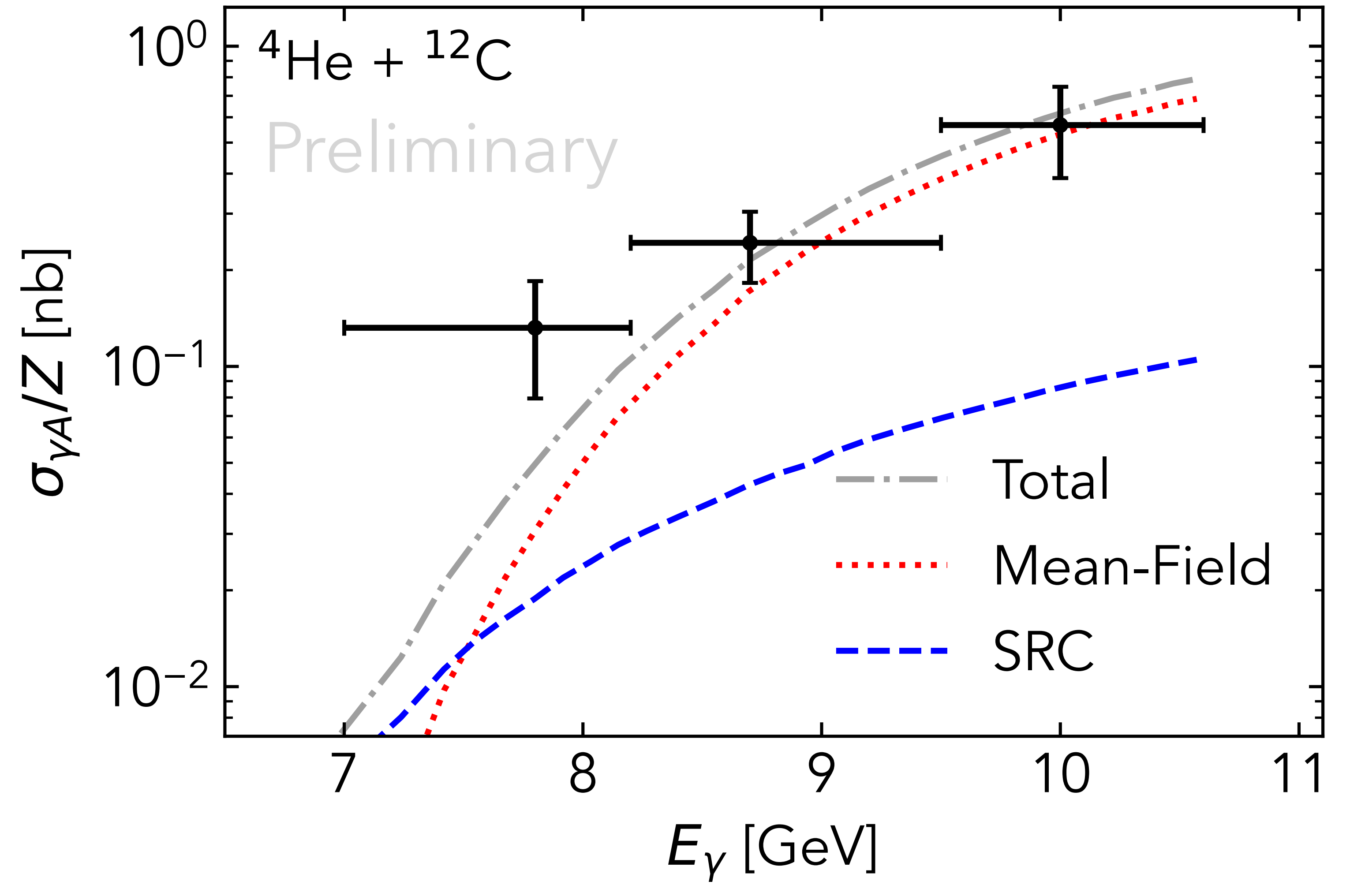


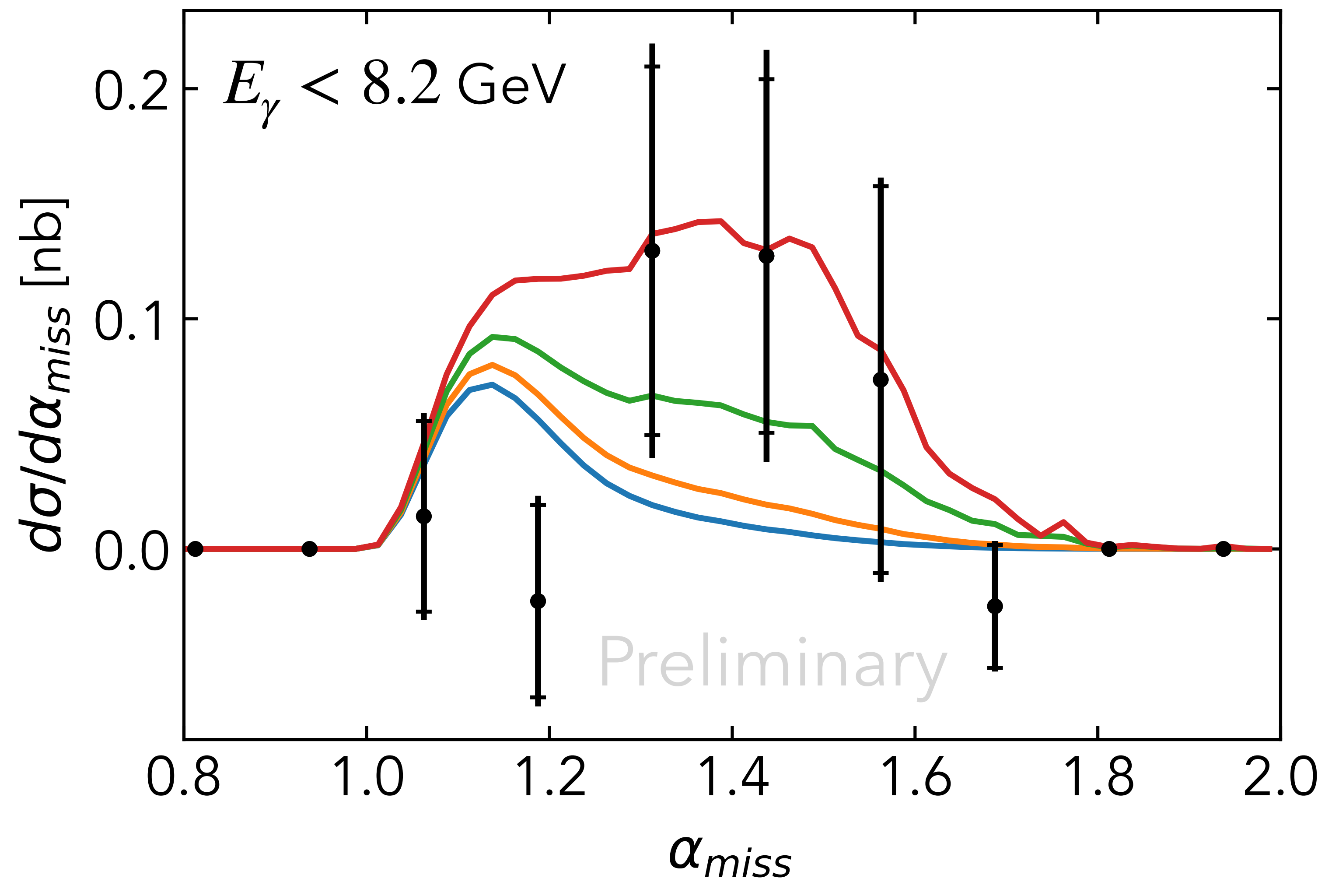
$$\langle r \rangle \rightarrow (1 + Bv)\langle r \rangle$$

Conclusions

- New photonuclear measurement gives first measurement of incoherent J/ψ production at and below threshold energy

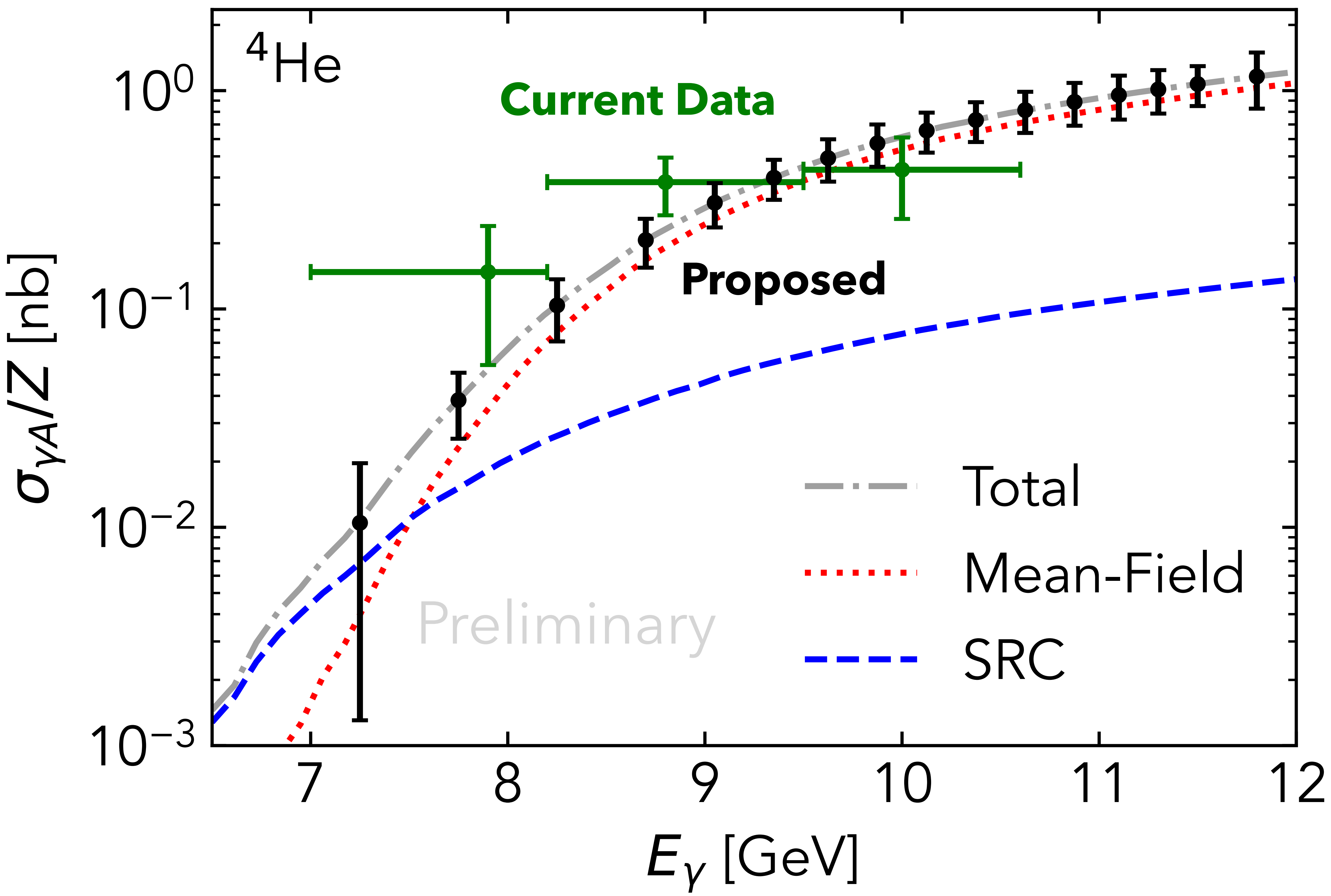
- Kinematic distributions suggest possible modification of gluons in bound proton





Backup

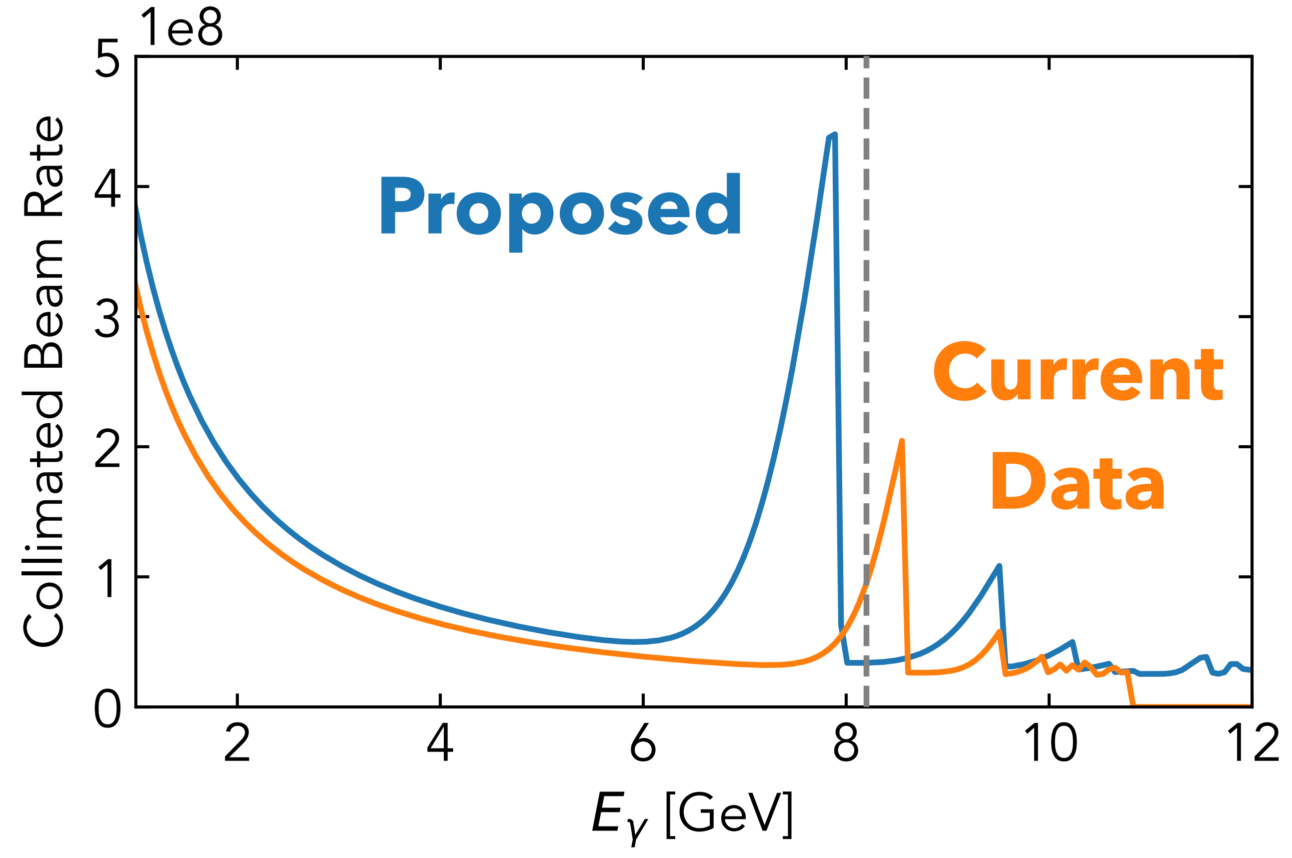
High-statistics photonuclear measurement on ^{4}He conditionally approved



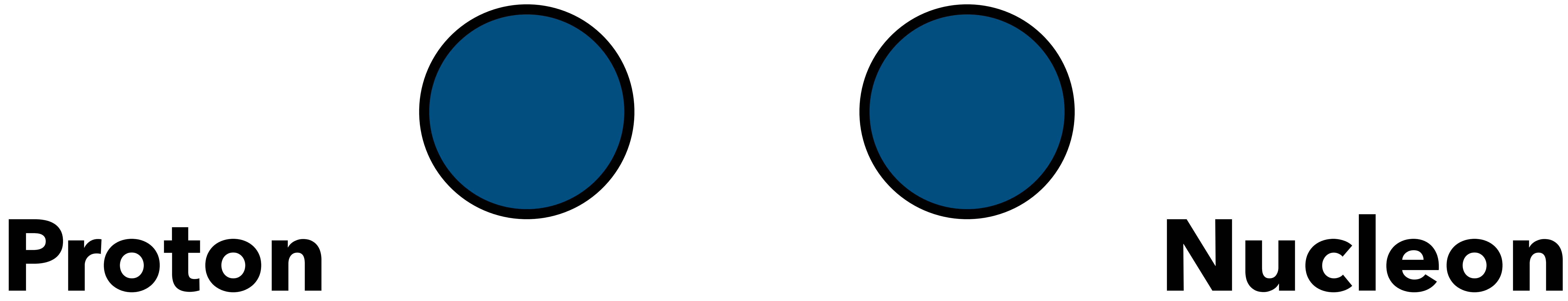
190-day measurement of a single nucleus; ~1000 J/ψ production events

Measure cross section across full energy range and kinematics

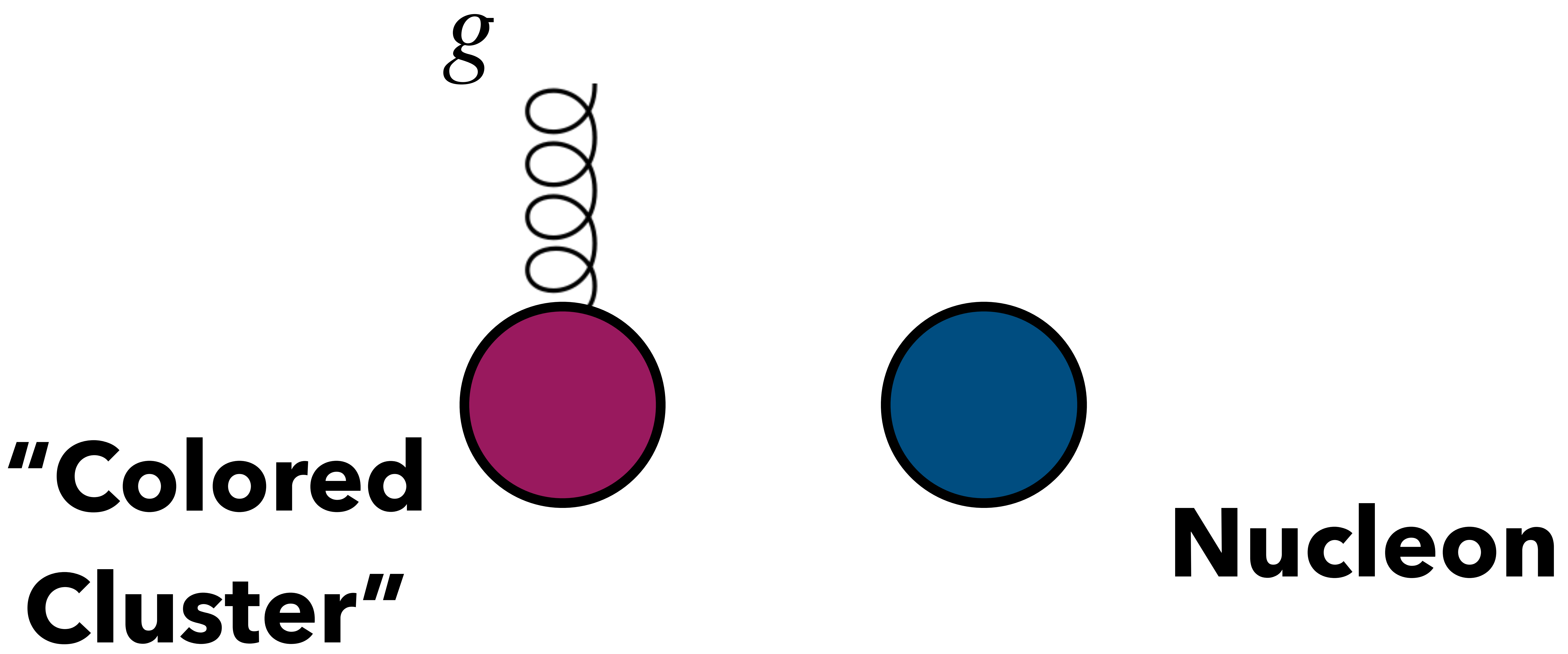
Optimized radiator geometry maximizes measurement of sub-threshold production



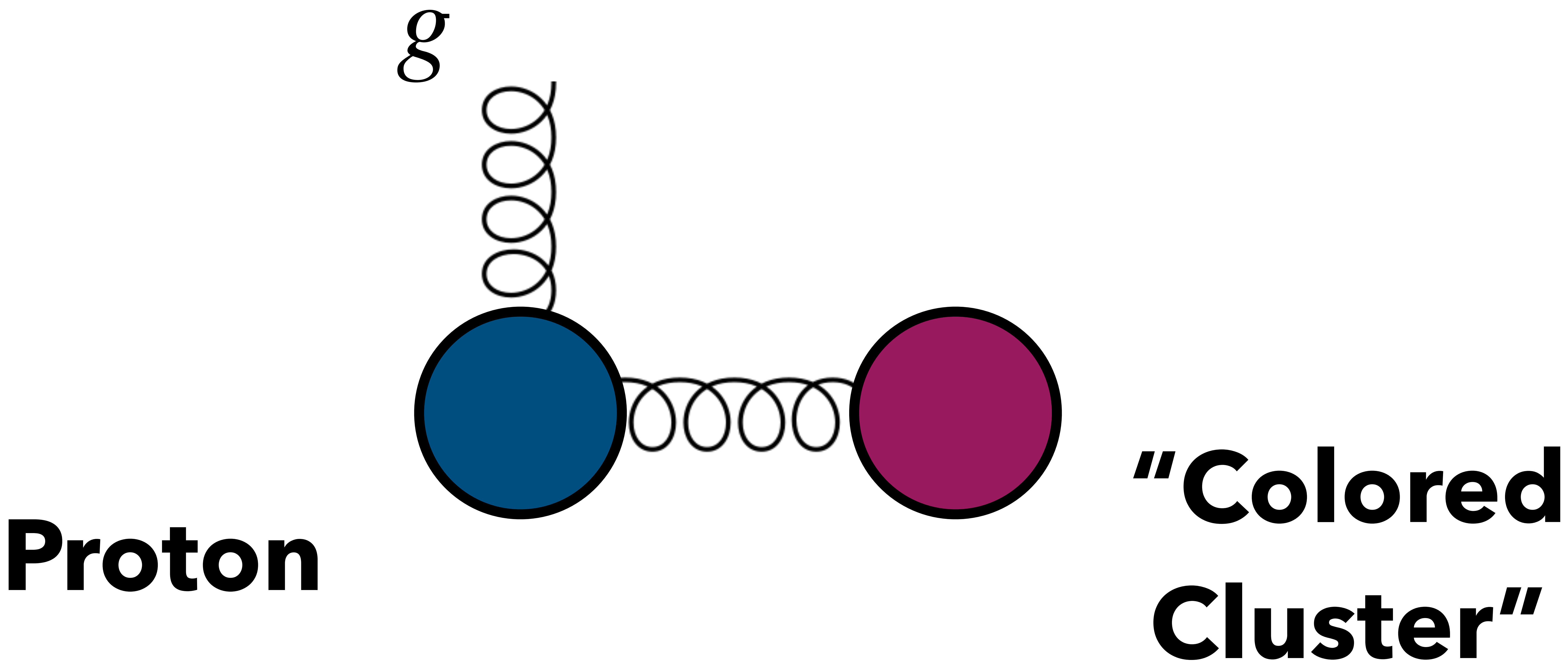
Third Hypothesis: Two-body currents



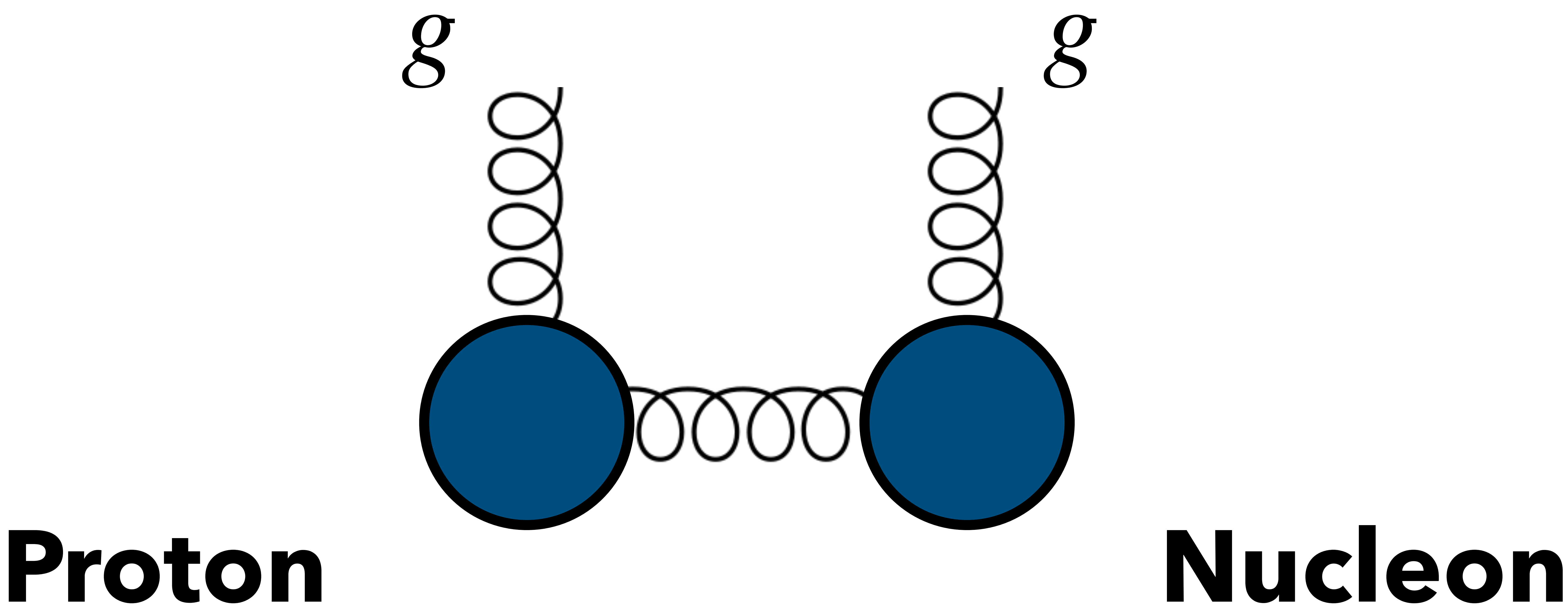
Two-body currents



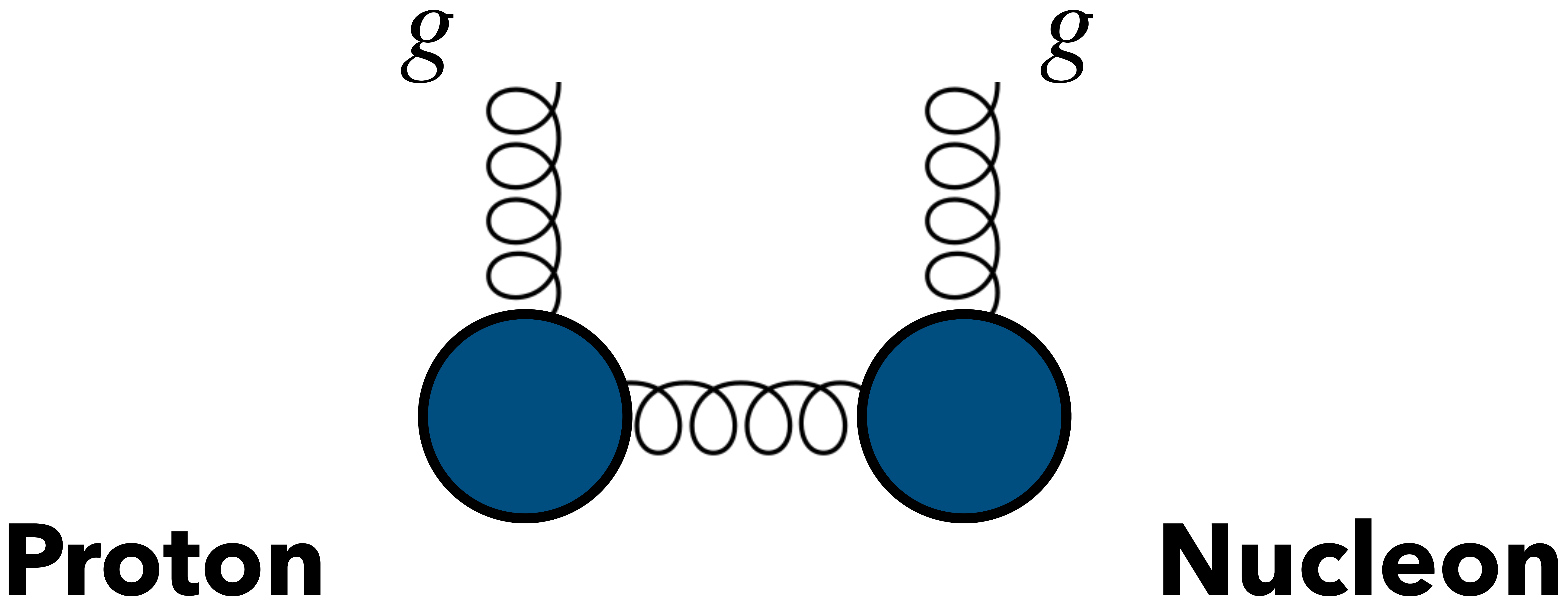
Two-body currents



Two-body currents

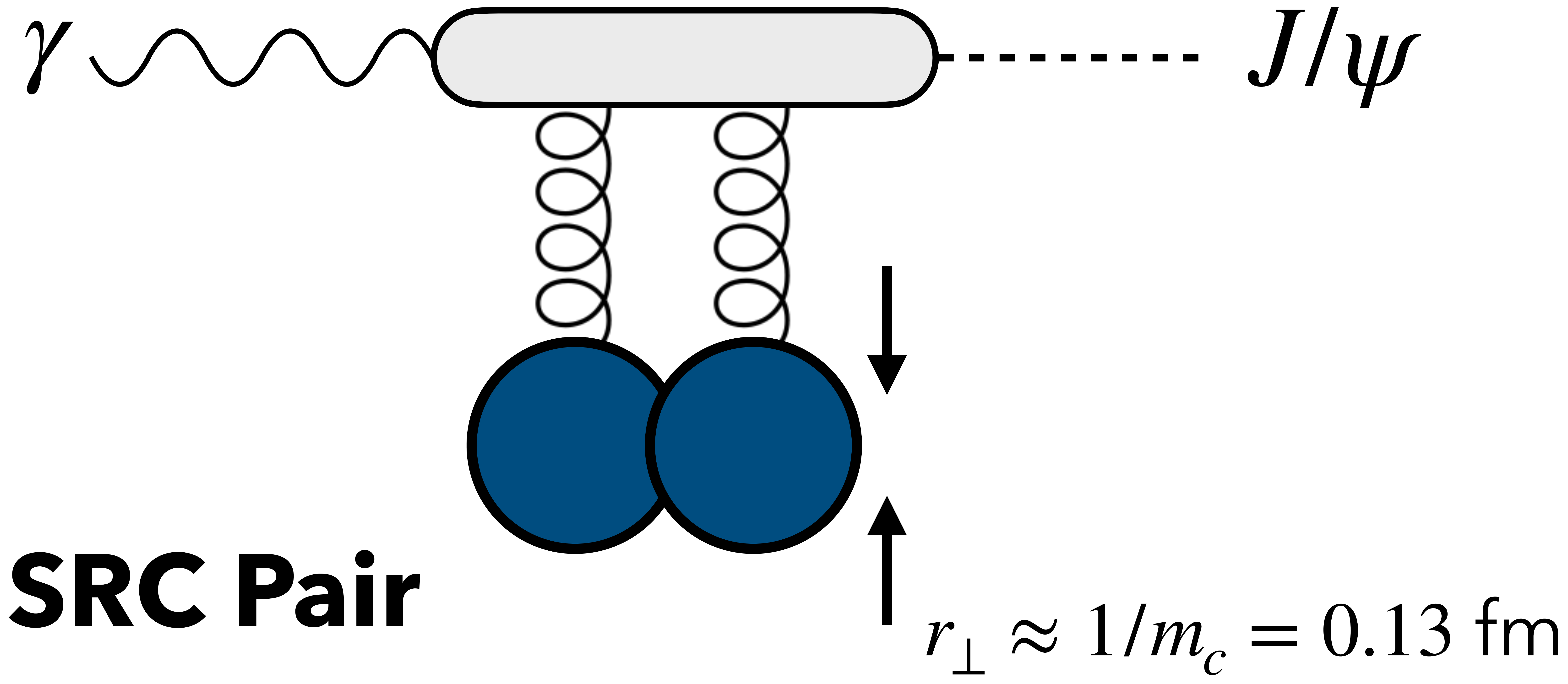


Two-body currents



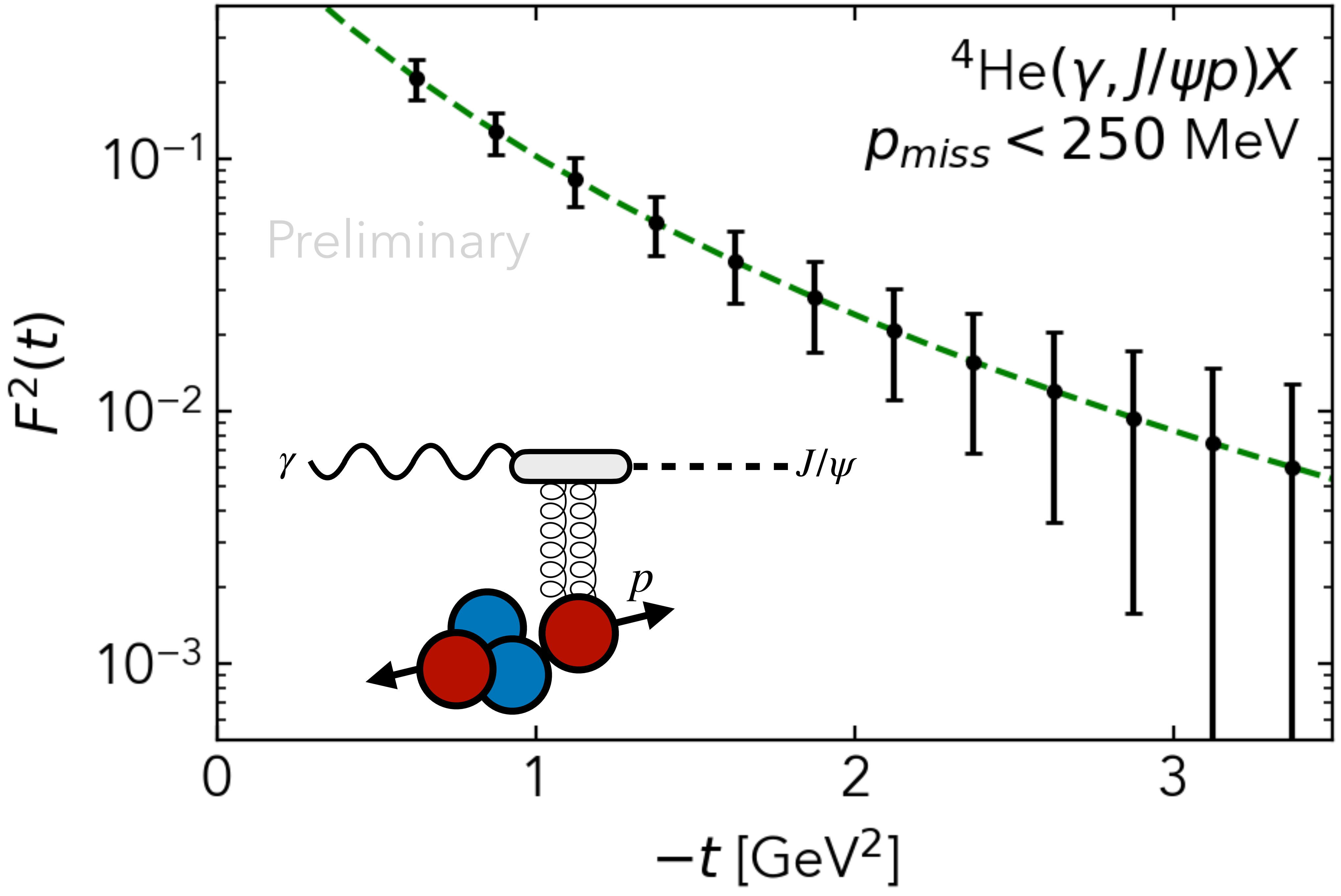
Possible "color correlations" between nucleons?

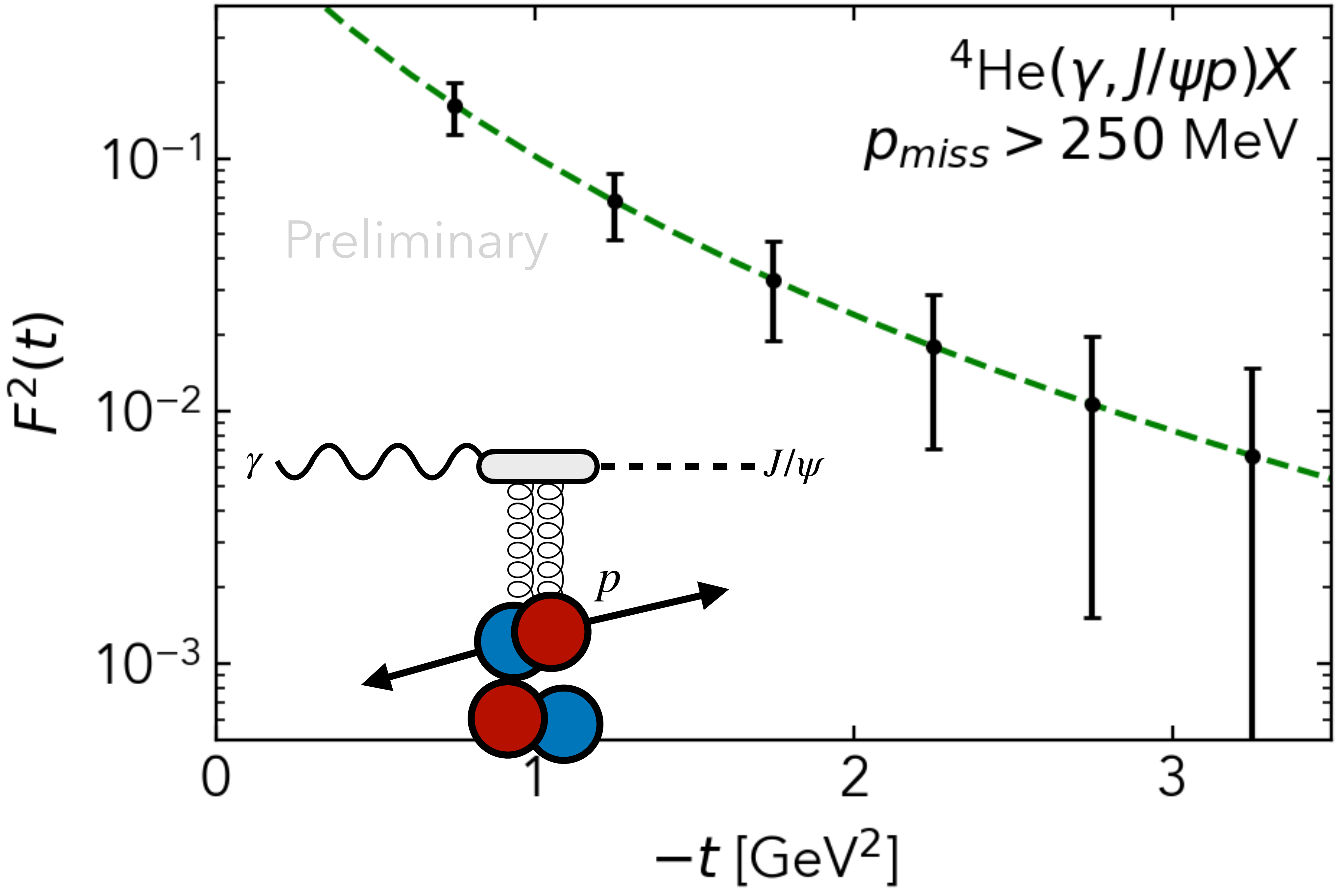
Two-body currents



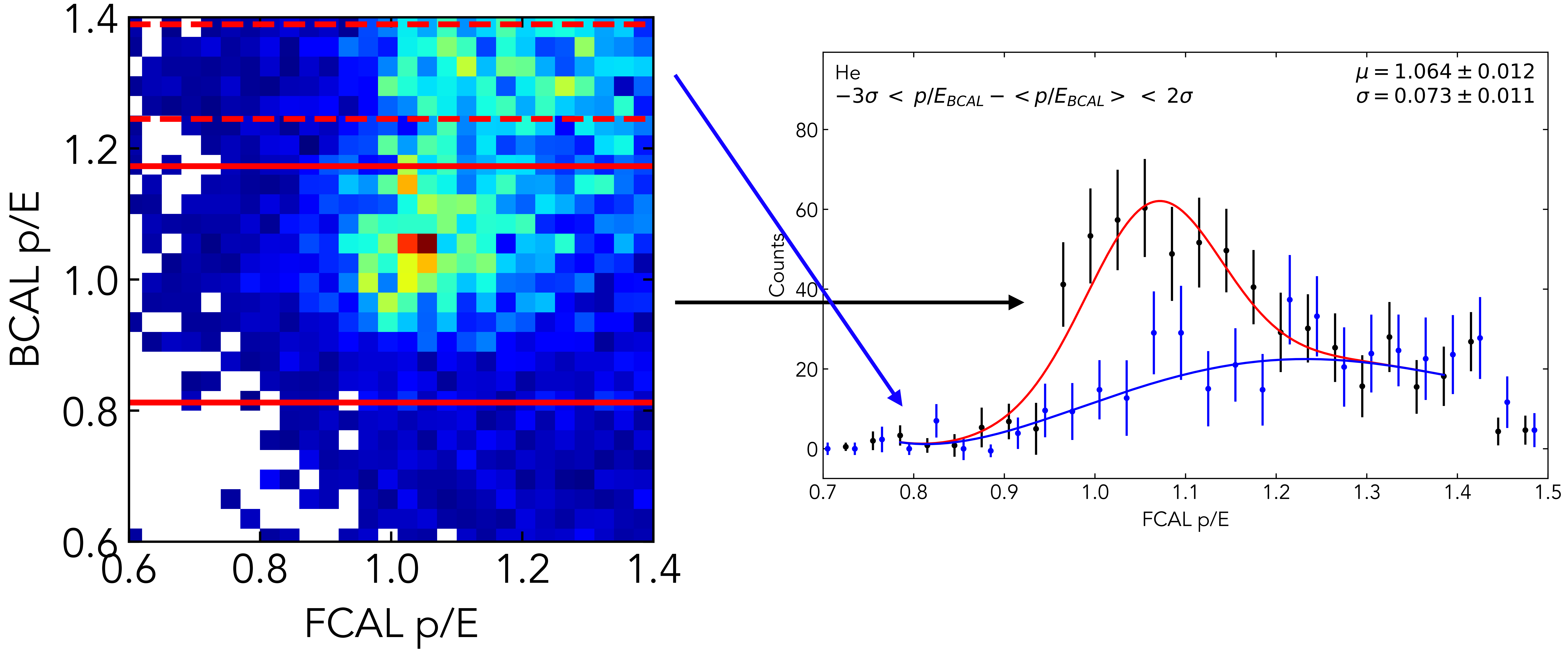
Particularly sensitive to short-distance configurations!

Improved data will allow detailed test of bound proton structure



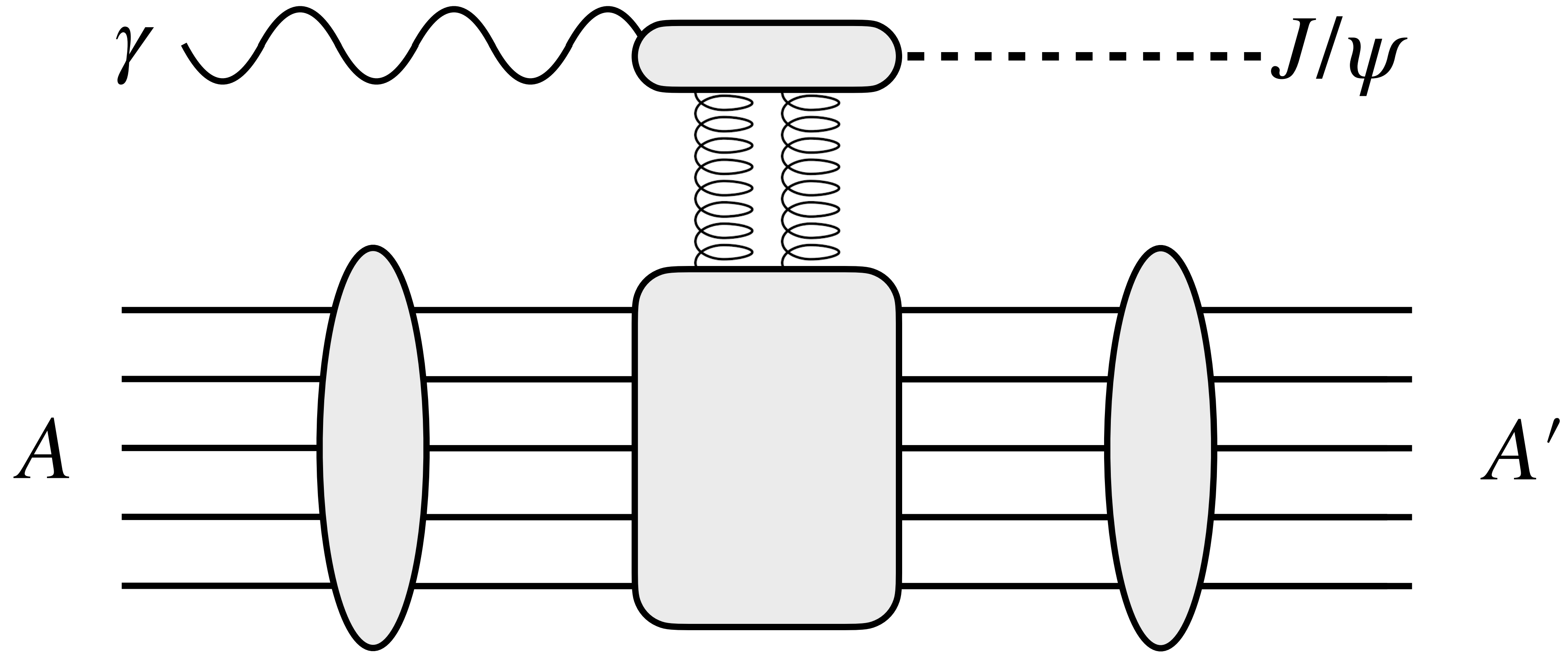


Lepton PID: p/E cuts



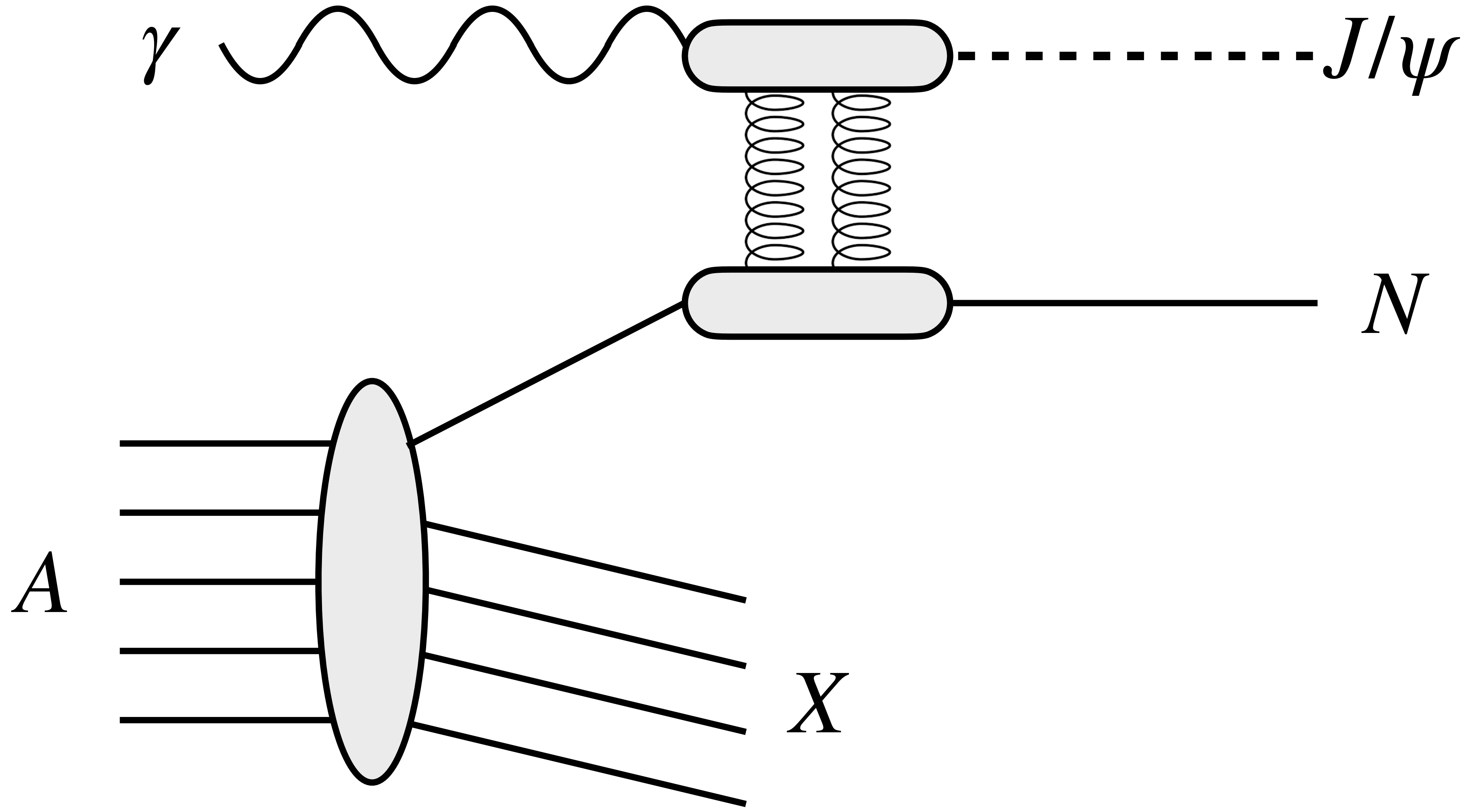
Photoproduction from the nucleus

Coherent Photoproduction



- Nucleus intact in the final-state
- Tells us about the ground-state of the nucleus
- Physics interpretations: Gluon radius of the nucleus, nuclear trace anomaly, nuclear gGPDs

Incoherent Photoproduction



- Nucleus broken-up in the final state
- Tells us about fluctuations in the nucleus + bound nucleons within the nucleus
- Physics interpretations: Gluon content of the bound proton, neutron

Light-front variables

- Both energy E and longitudinal momentum p_z have poor resolution, but what about combinations of these?
- We can define "plus" and "minus" components of momentum

$$p^{\pm} = E \pm p_z = \sqrt{p_\perp^2 + p_z^2 + m^2} \pm p_z$$

- Resolution for these variables can be

$$\sigma_{p^\pm}^2 = \left(\frac{p_\perp}{E}\right)^2 \sigma_{p_\perp}^2 + \left(\frac{p^\pm}{E}\right)^2 \sigma_{p_z}^2$$

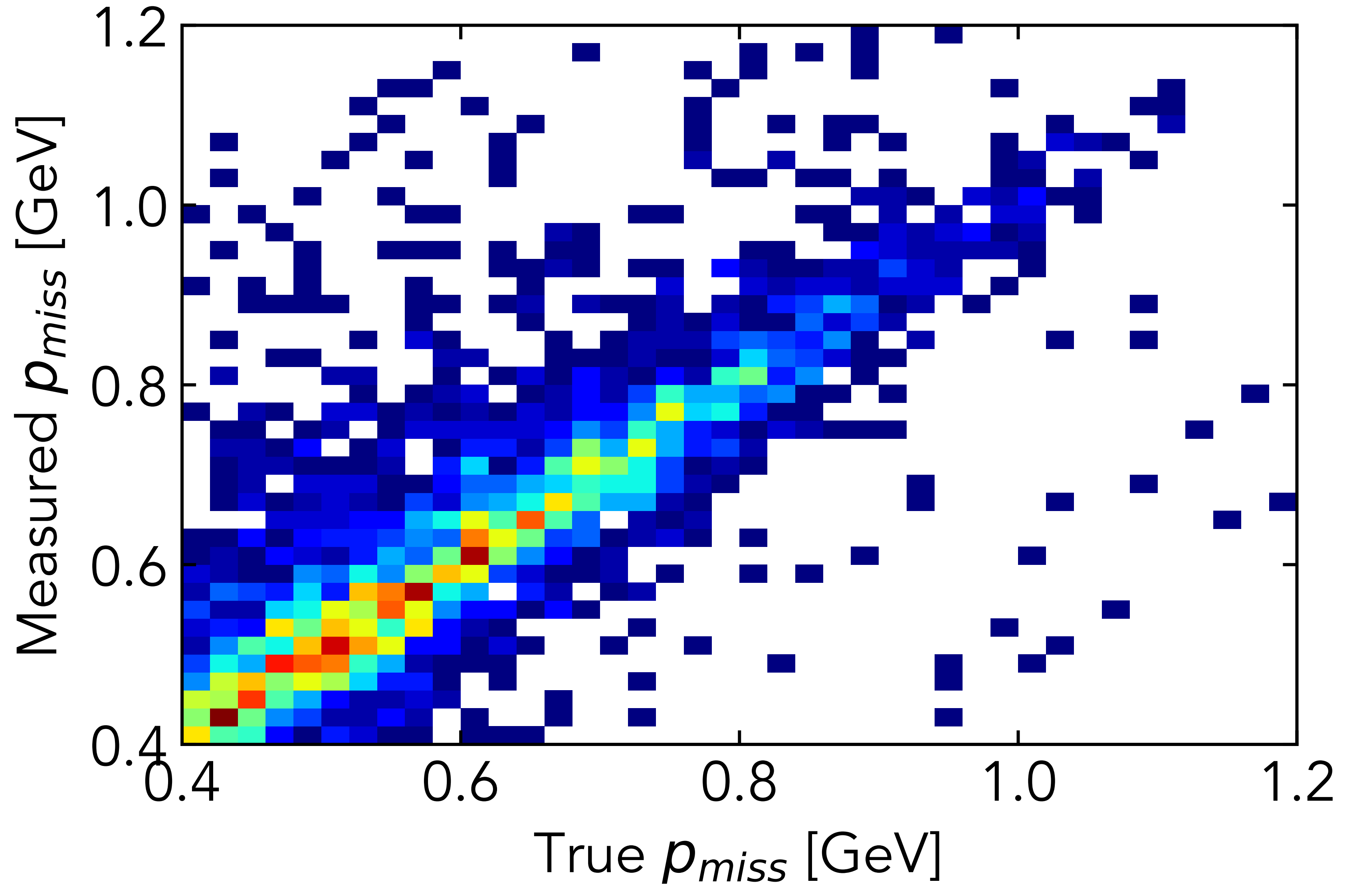
- For forward, high-momentum particles, momentum and resolution are dominated by p_z:

$$p^+ = 2p_z + \ldots \qquad\qquad p^- \approx \frac{p_\perp^2}{2p_z} + \ldots$$

$$\sigma_{p^+} \approx 2\sigma_{p_z} \qquad\qquad \sigma_{p^-} \approx \left(\frac{p_\perp}{2p_z}\right)\sigma_{p_z}$$

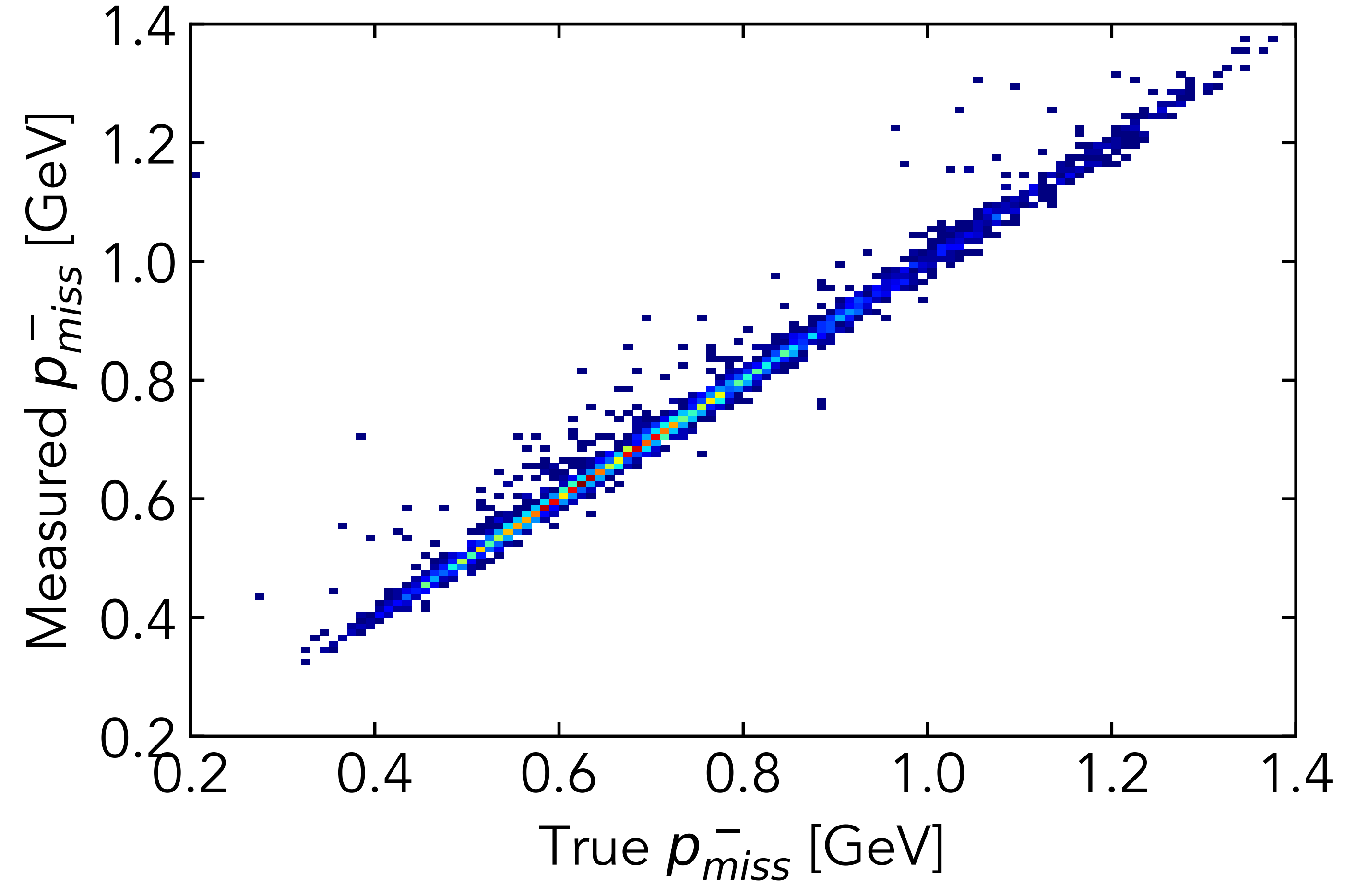
Light-front momentum gives good basis for analysis

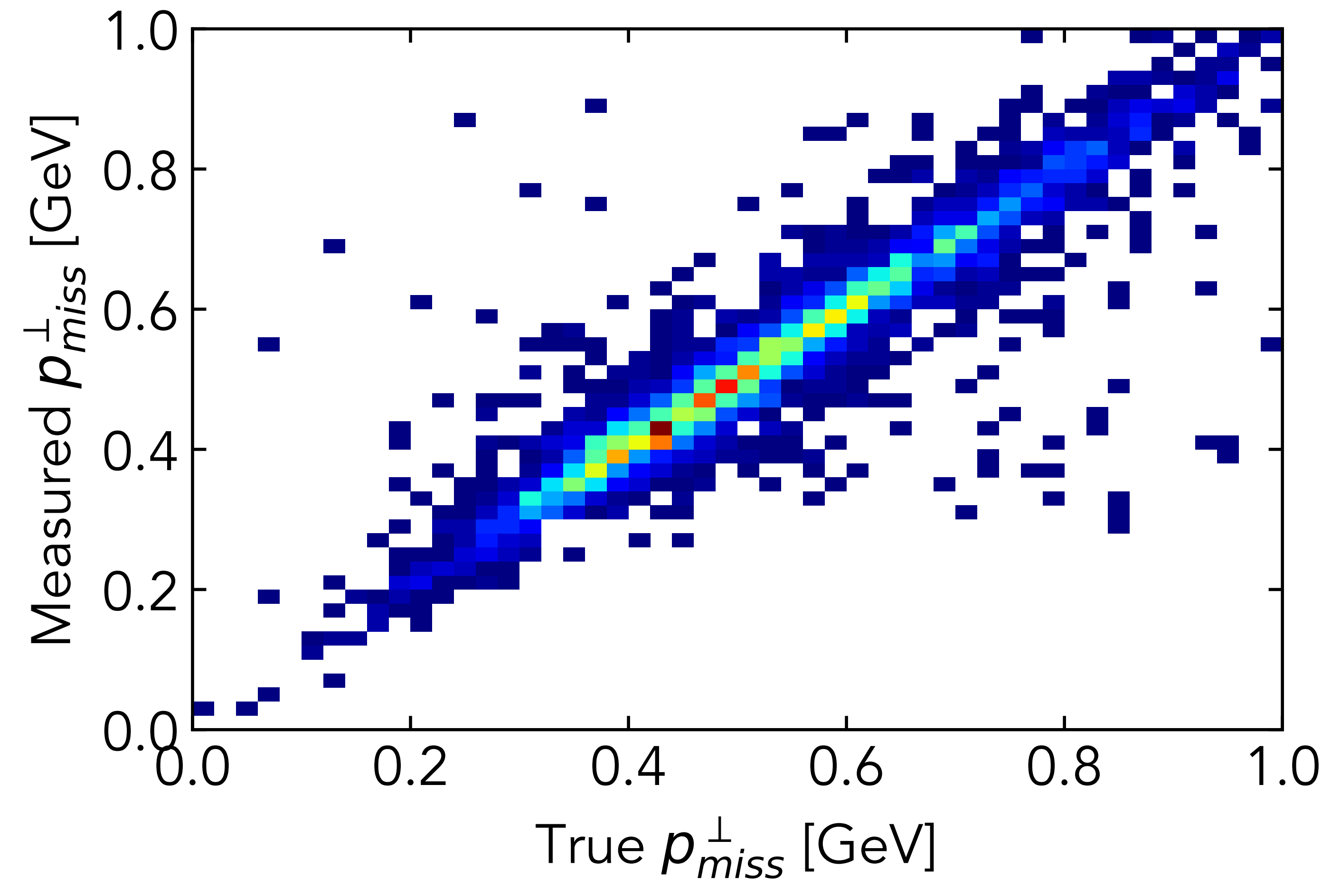
Monte-Carlo simulation shows bin migration of reconstructed variables



Missing 3-momentum hard to resolve:

$$p_{miss} = p_{meson} + p_p - p_\gamma$$





Dilepton Mass Reconstruction

- Invariant mass of dilepton can be expressed in light-front momentum:

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

- Resolution dominated by "plus" component of momentum

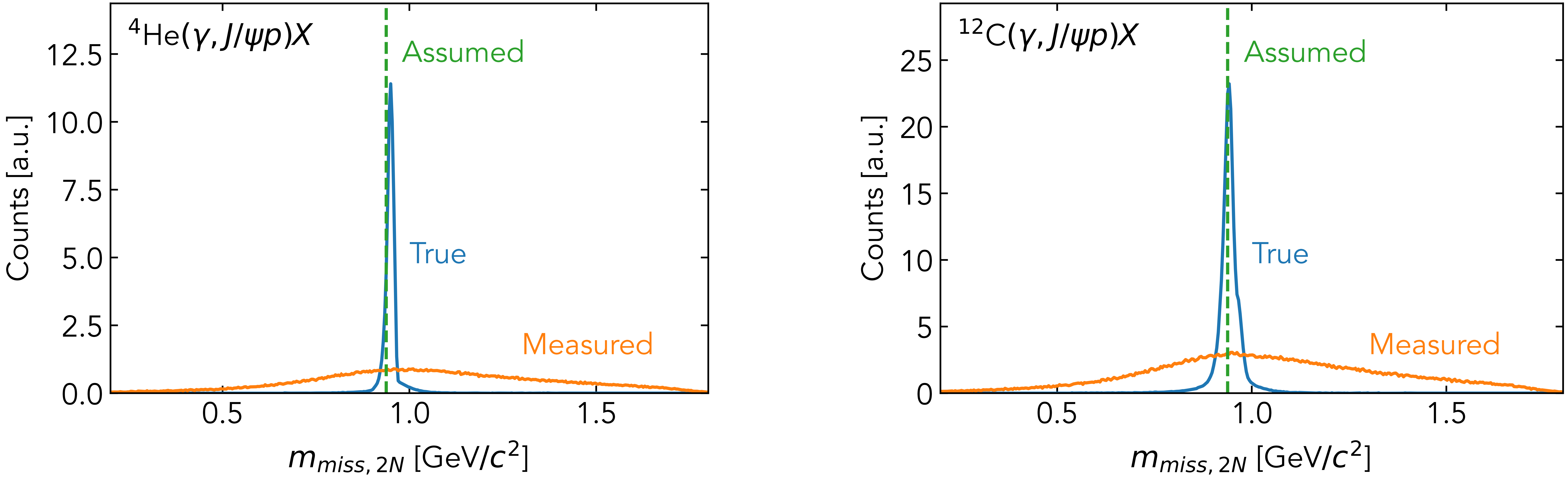
- In case of deuteron, we can define missing mass

$$m^2_{miss} = (p_\gamma + p_d - p_{e^+} - p_{e^-} - p_p)^2 \to m^2_n$$

- Dilepton mass can be reexpressed:

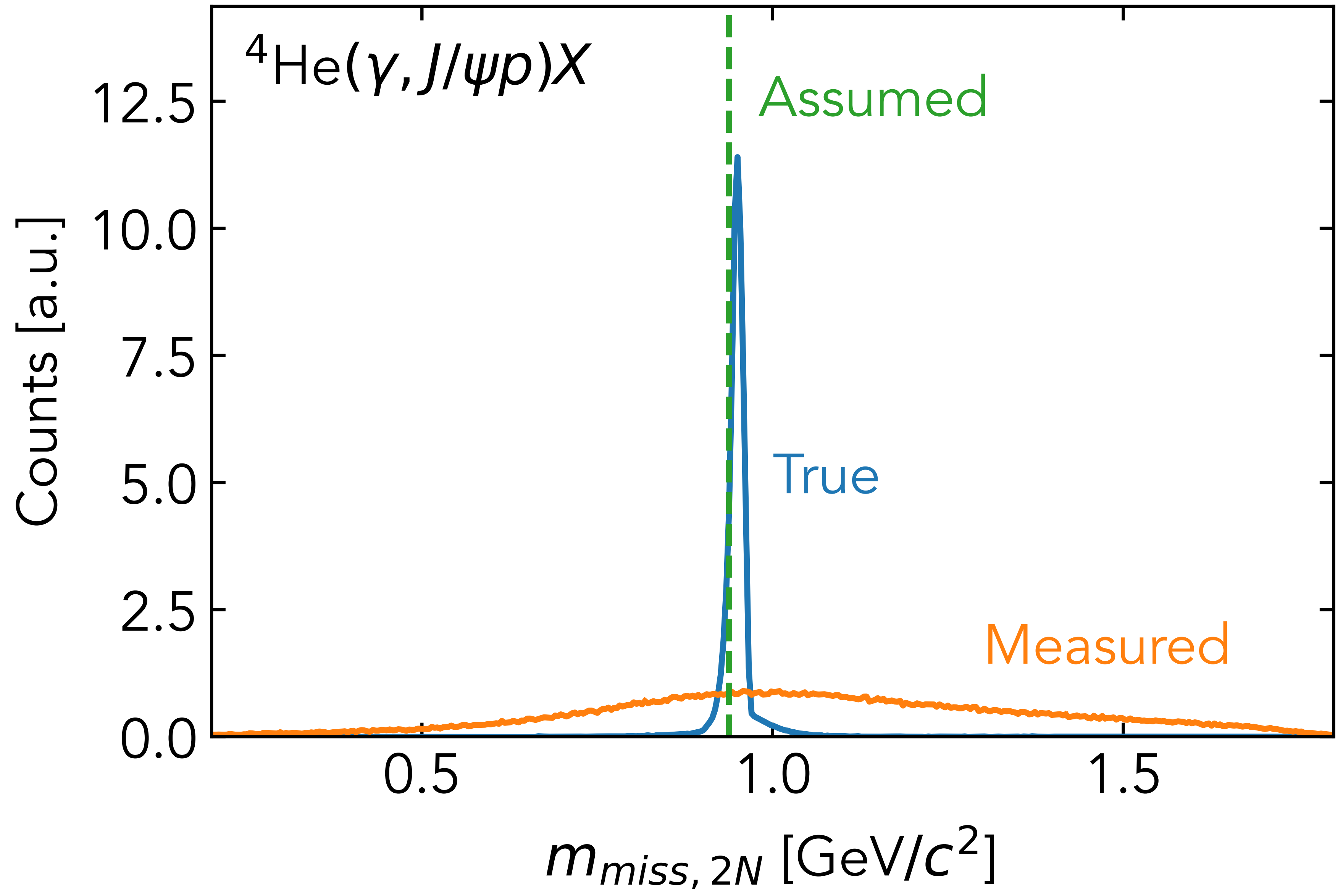
$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(2E_\gamma + m_d - p^+_p - \frac{m^2_{miss} + p^2_{tot,\perp}}{m_d - p^-_{tot}}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

2N missing mass exactly m_N for deuterium, but very close for other QE reactions

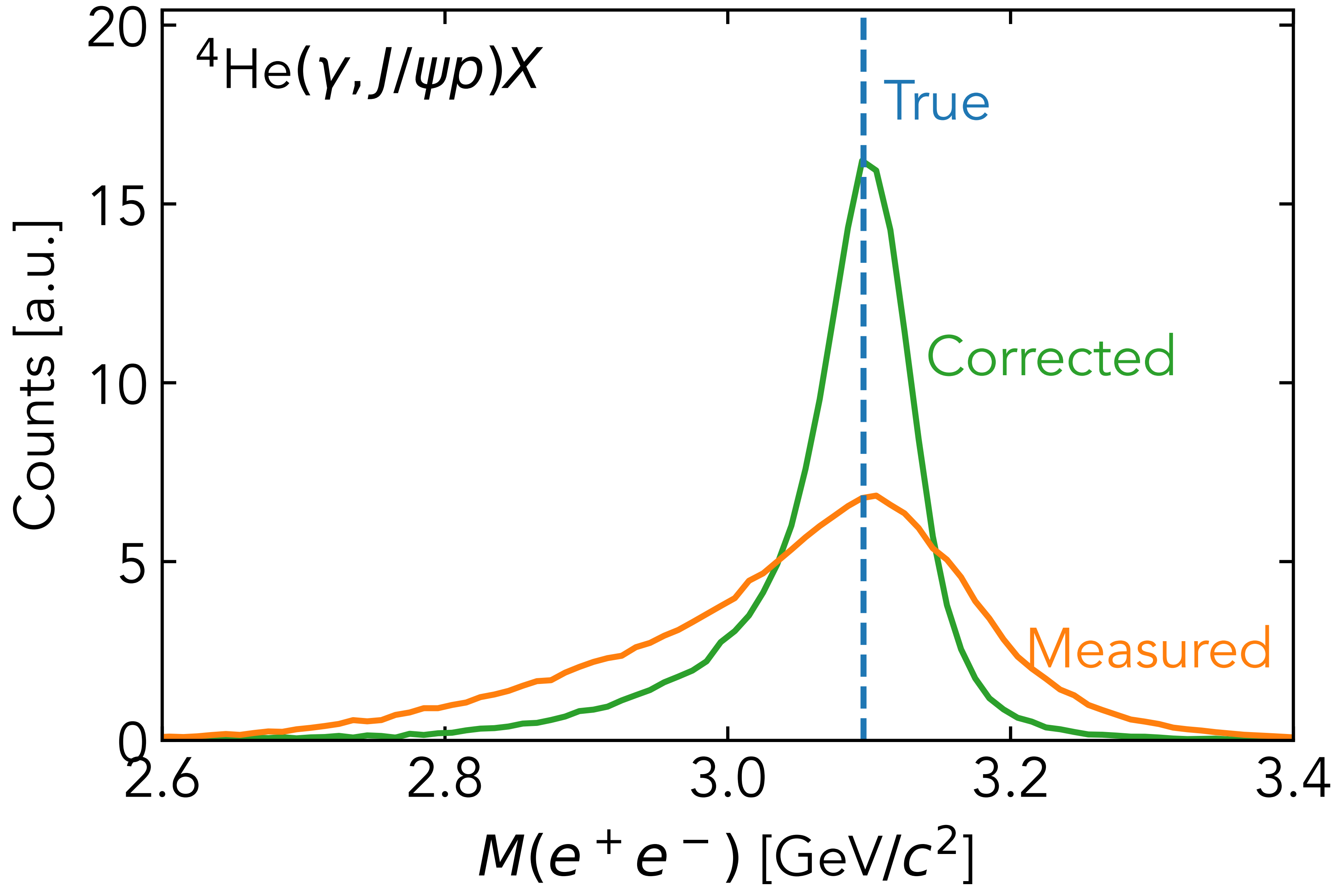


Fixing $m_{miss} = m_N$ for all nuclei allows substantial constraint on the reaction

Improved mass observable increases resolution on dilepton mass

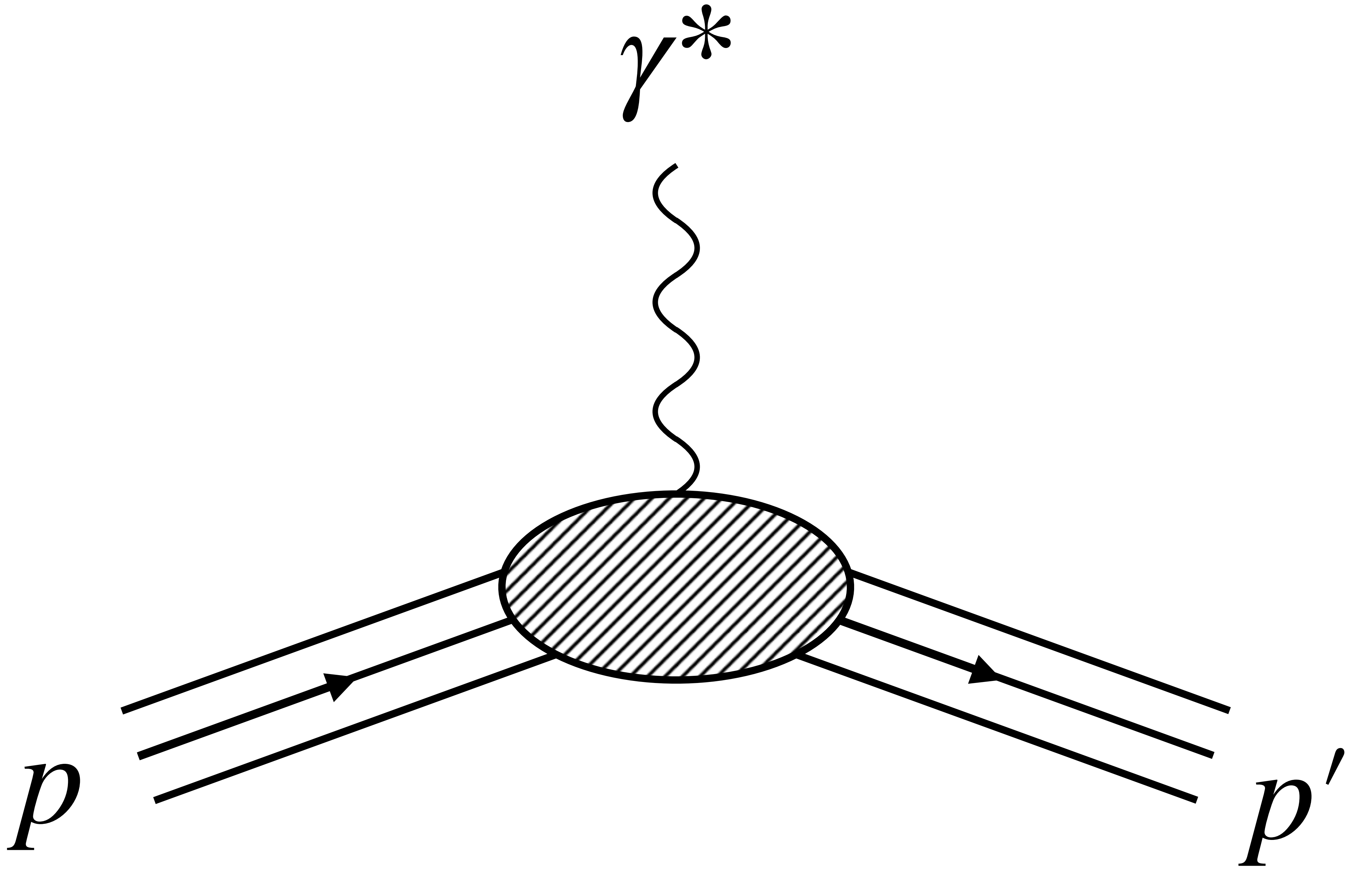


Improved mass observable more that doubles resolution



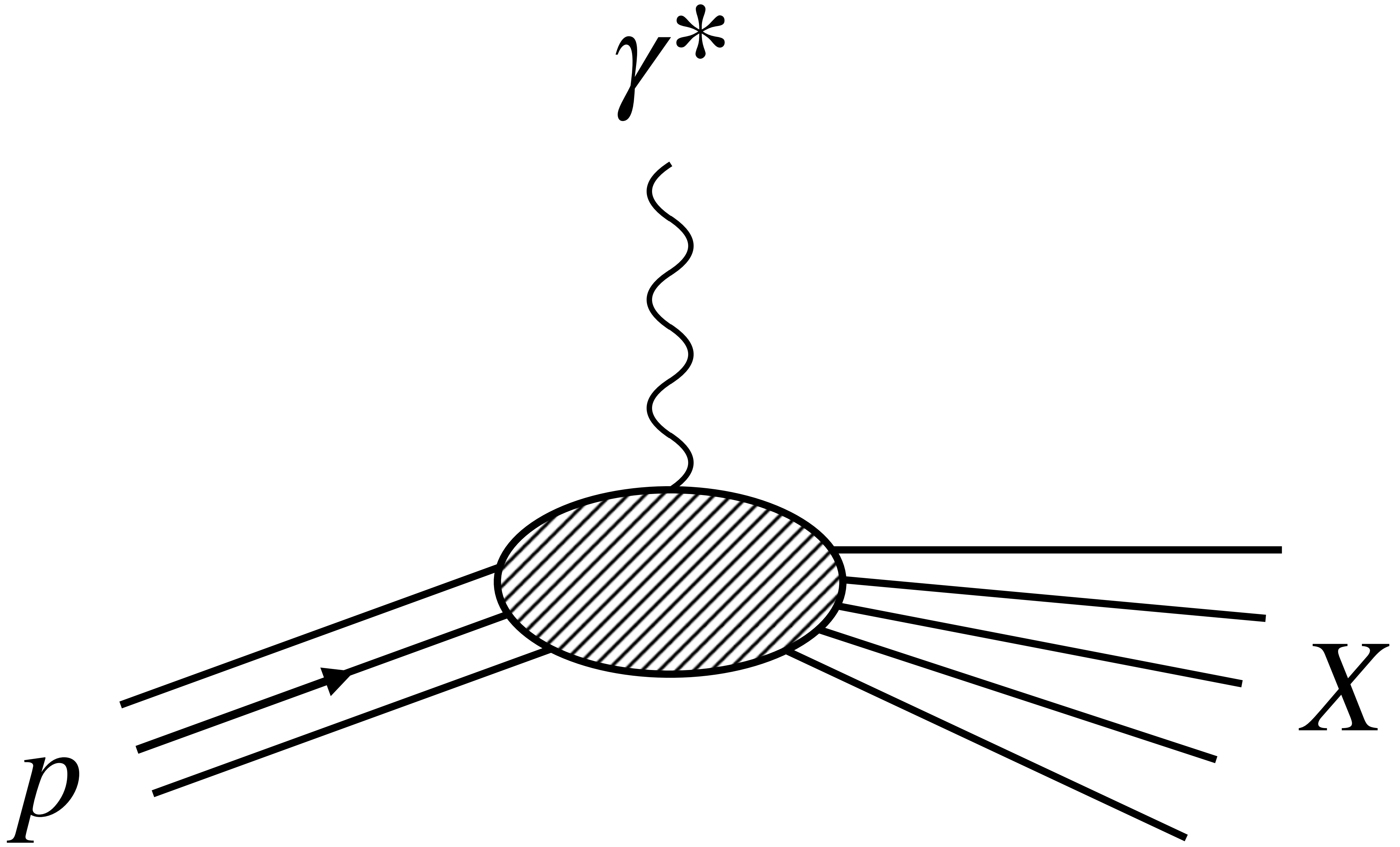
$$M^2_{e^+e^-} = \left(p^-_{e^+} + p^-_{e^-}\right)\left(2E_\gamma + 2m_N - p^+_p - \frac{m_N^2 + p^2_{tot,\perp}}{2m_N - p^-_{tot}}\right) - \left(\vec{p}^{\perp}_{e^+} + \vec{p}^{\perp}_{e^-}\right)^2$$

Electron-scattering couples to charge



Quasi-elastic scattering

Measure of proton charge distribution



Deep-inelastic scattering

Measure of quark PDFs

Motivation for high-statistics photonuclear data

- Currently ~1.5 months of nuclear data in Hall D (not including PrimeX)
- Sufficient to establish SRC breakup in high-statistics channels, but further data could be used
    - Study of $|t|$-dependence of SRC breakup data
    - **Low-rate channels could be the most interesting**

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