

# First Observation of Near- and Sub-Threshold $J/\psi$ Photoproduction off Nuclei

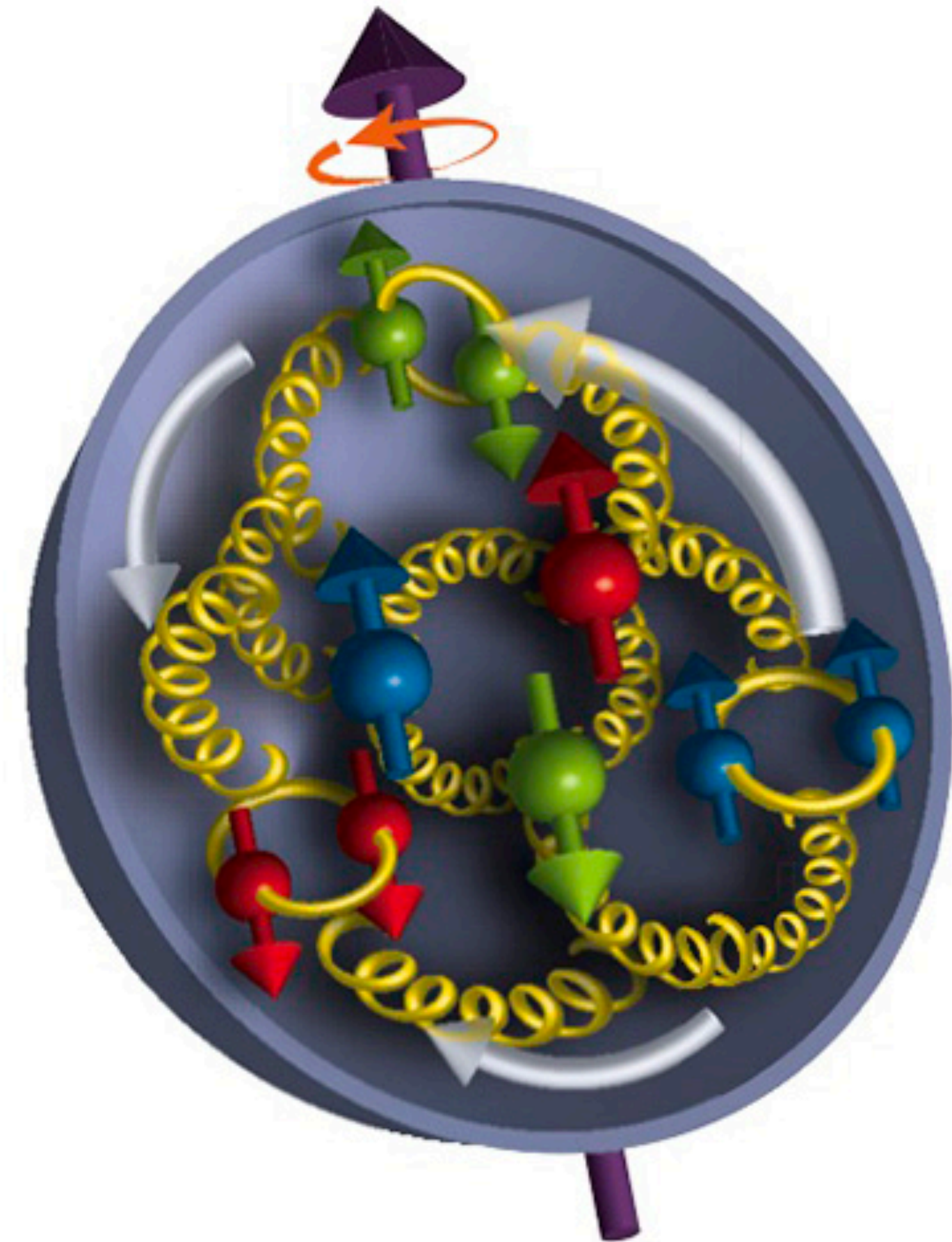
Jackson Pybus

June 26, 2025

2025 JLUO Annual Meeting

# Proton structure emerges from QCD dynamics

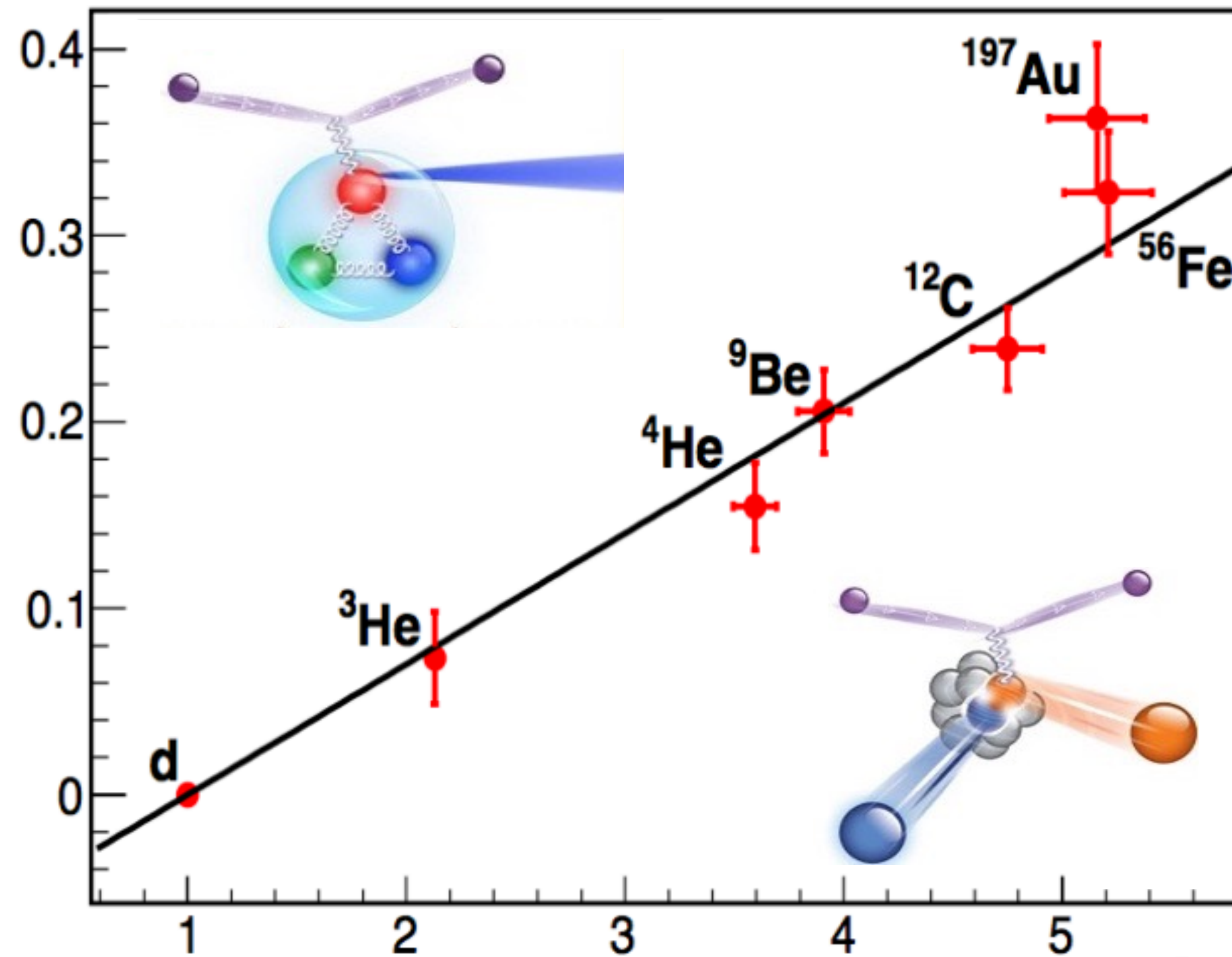
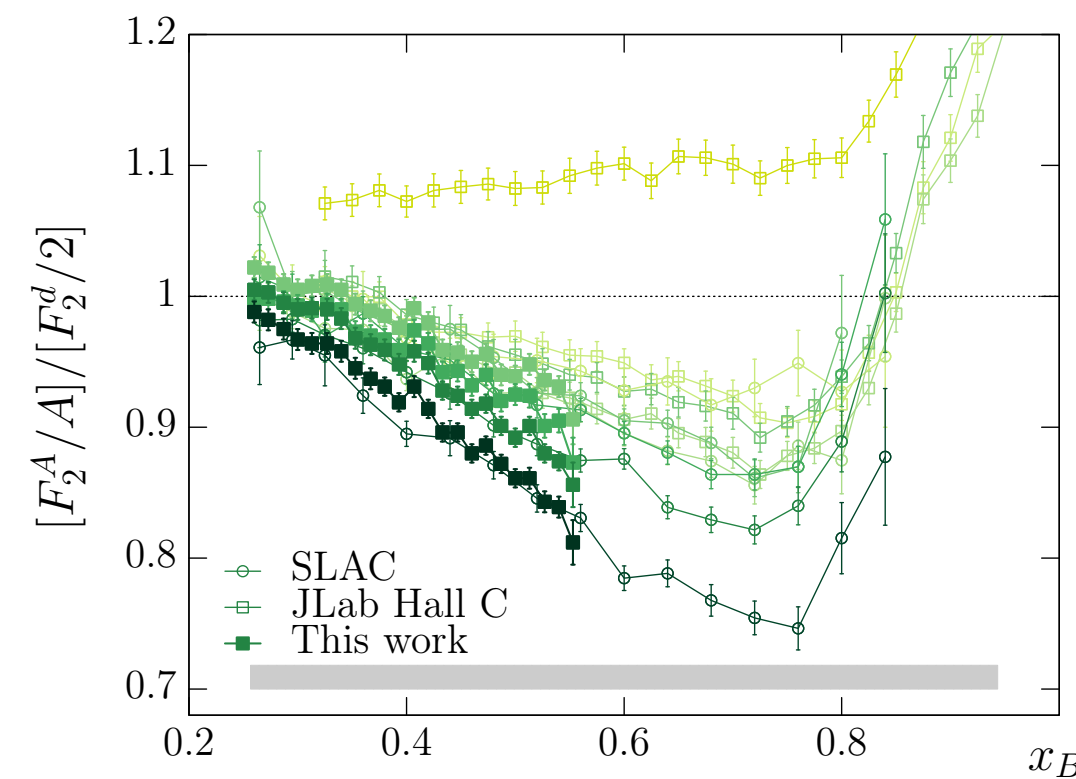
- Proton mass: **938 MeV**
- Higgs contribution to proton mass: **~10 MeV**
- Details of QCD dynamics drive proton structure
- Large fraction of proton mass and spin carried by massless gluons
- How does this manifest in nuclei?



# Strong indications SRC nucleons are modified

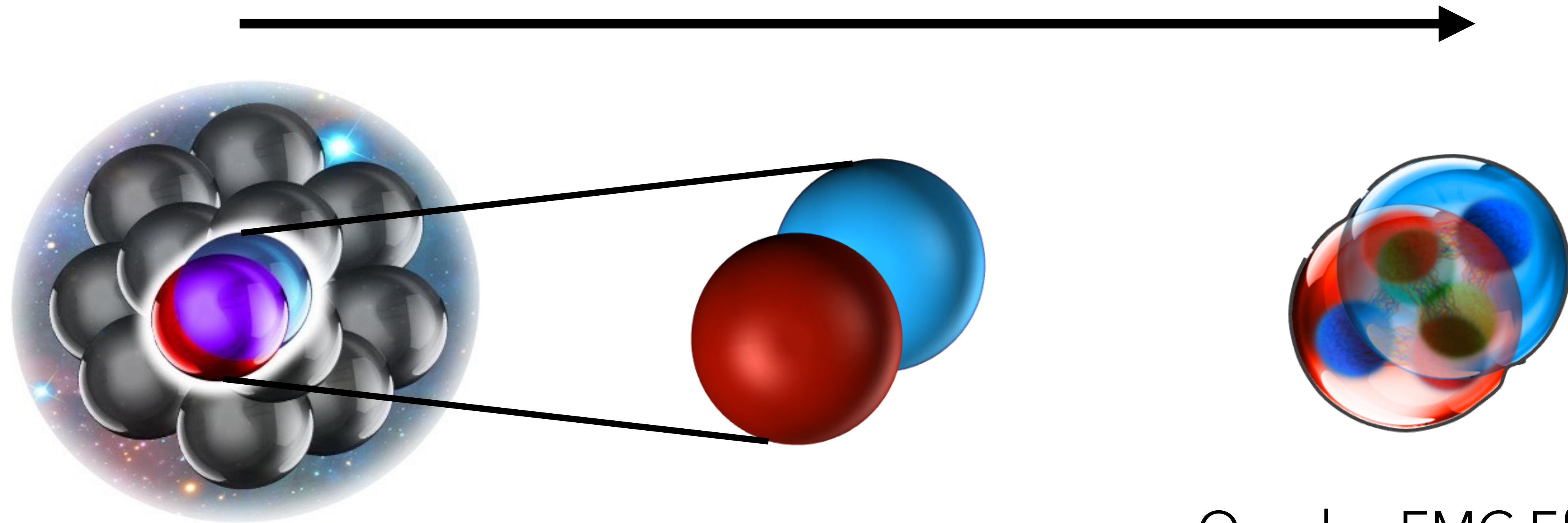
## EMC Effect

$A/d$



**SRC Abundance  $A/d$**

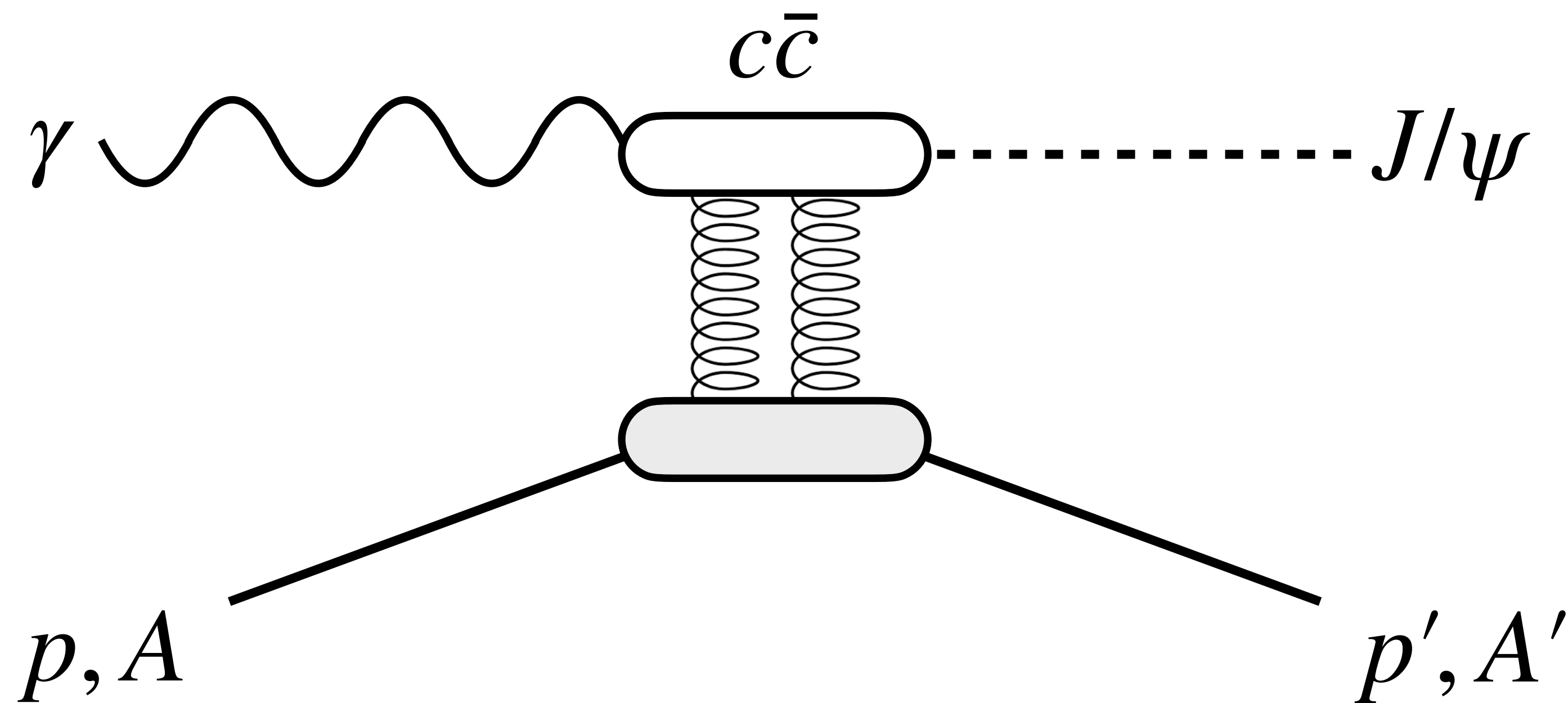
# How do nuclear systems impact gluon dynamics?



Quarks: EMC Effect

Gluons: ?

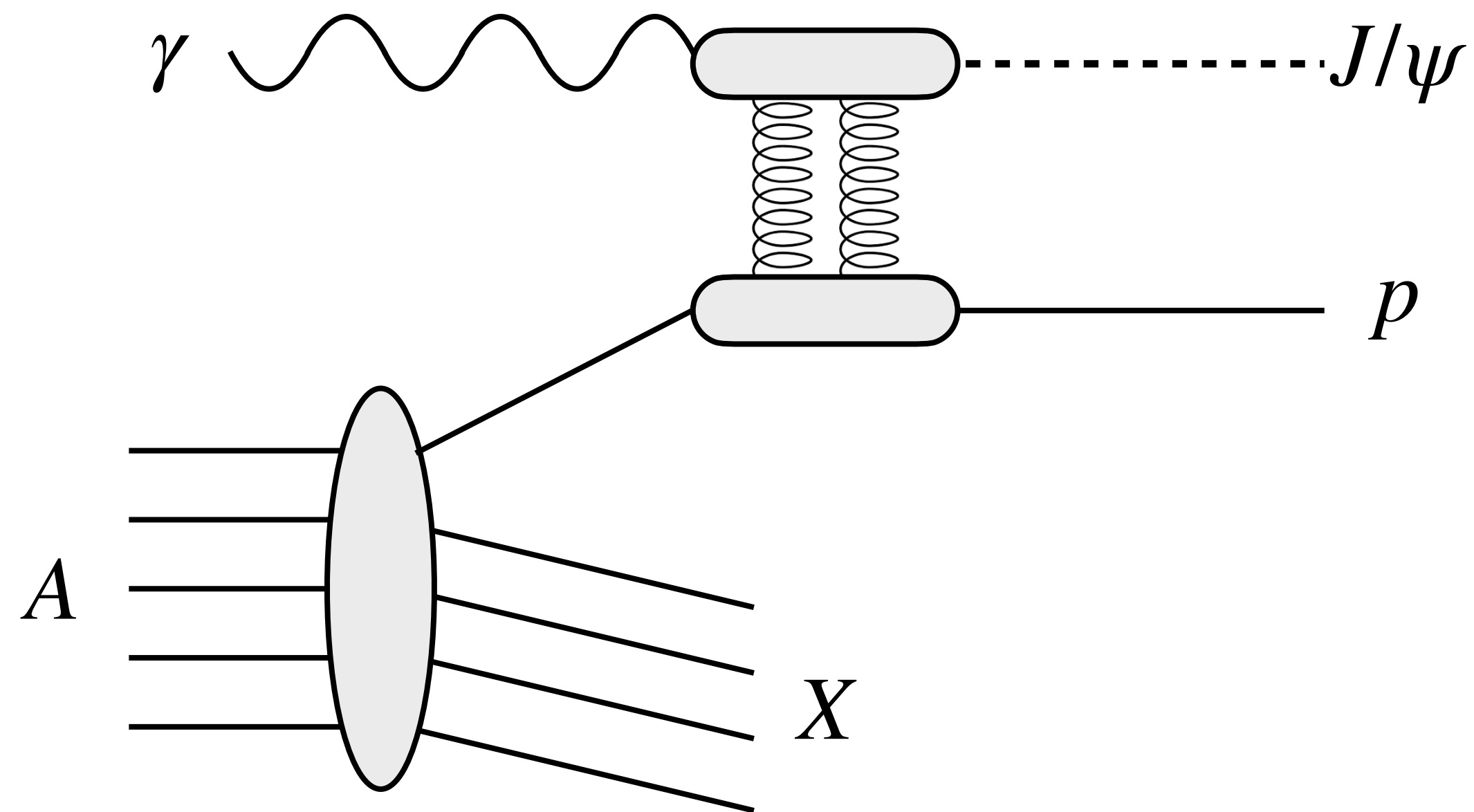
# $J/\psi$ is key probe of gluon physics



$J/\psi$  is "color dipole", interacts by exchanging gluons

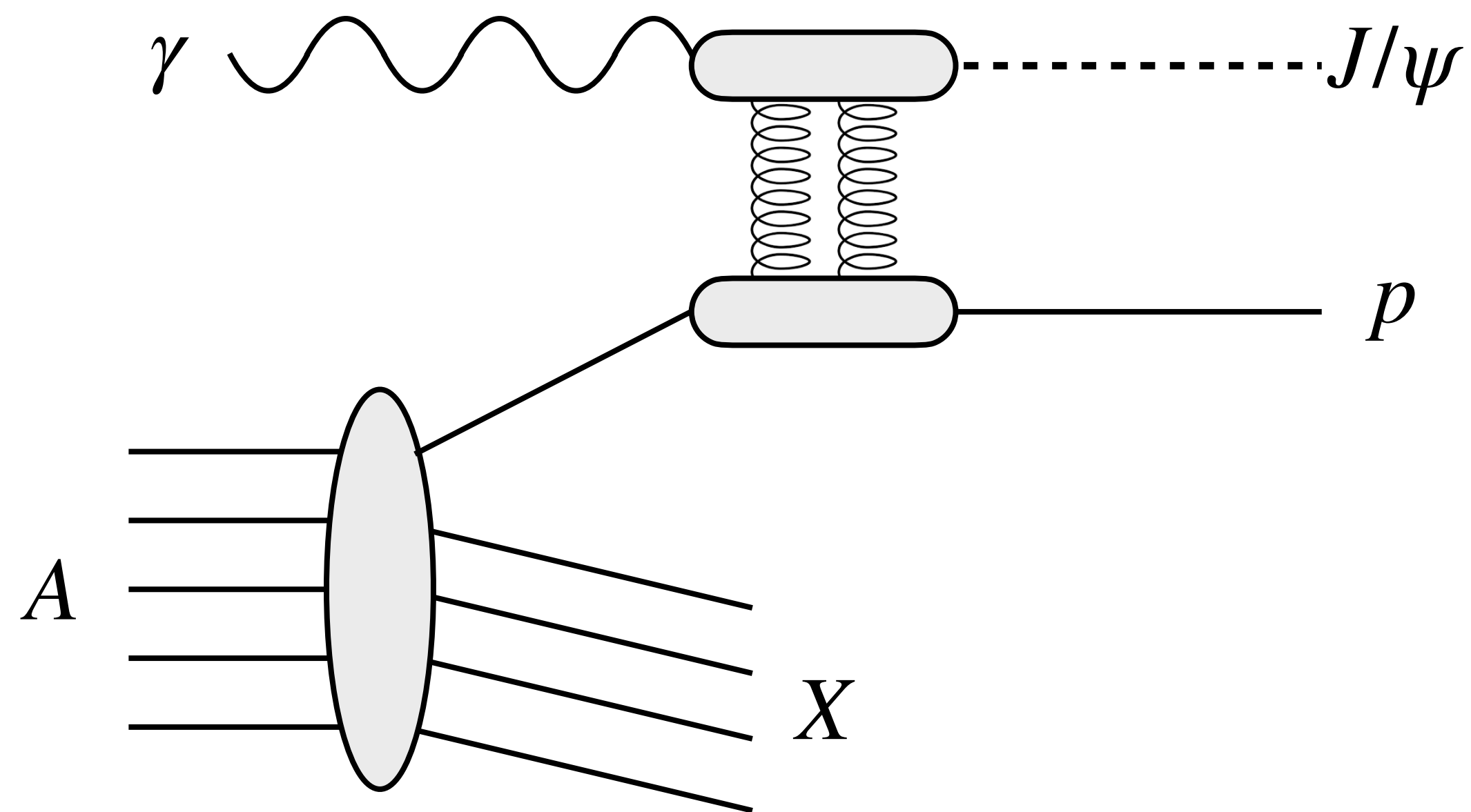
Sensitive to gluon densities and spatial distributions within the target

# Photoproduction of $J/\psi$ from bound protons

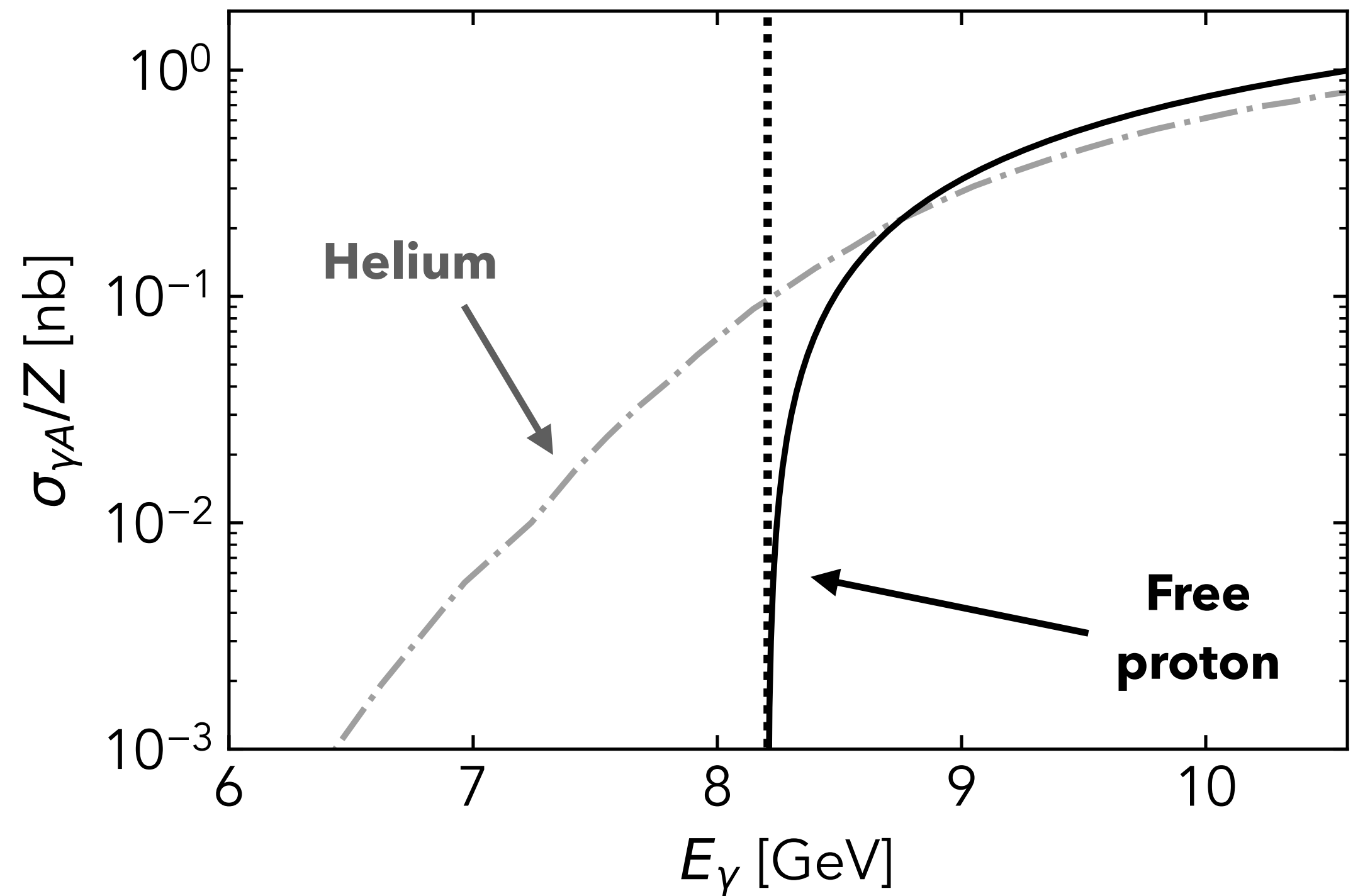


Incoherent  $J/\psi$  photoproduction near threshold sensitive to both nuclear and partonic effects

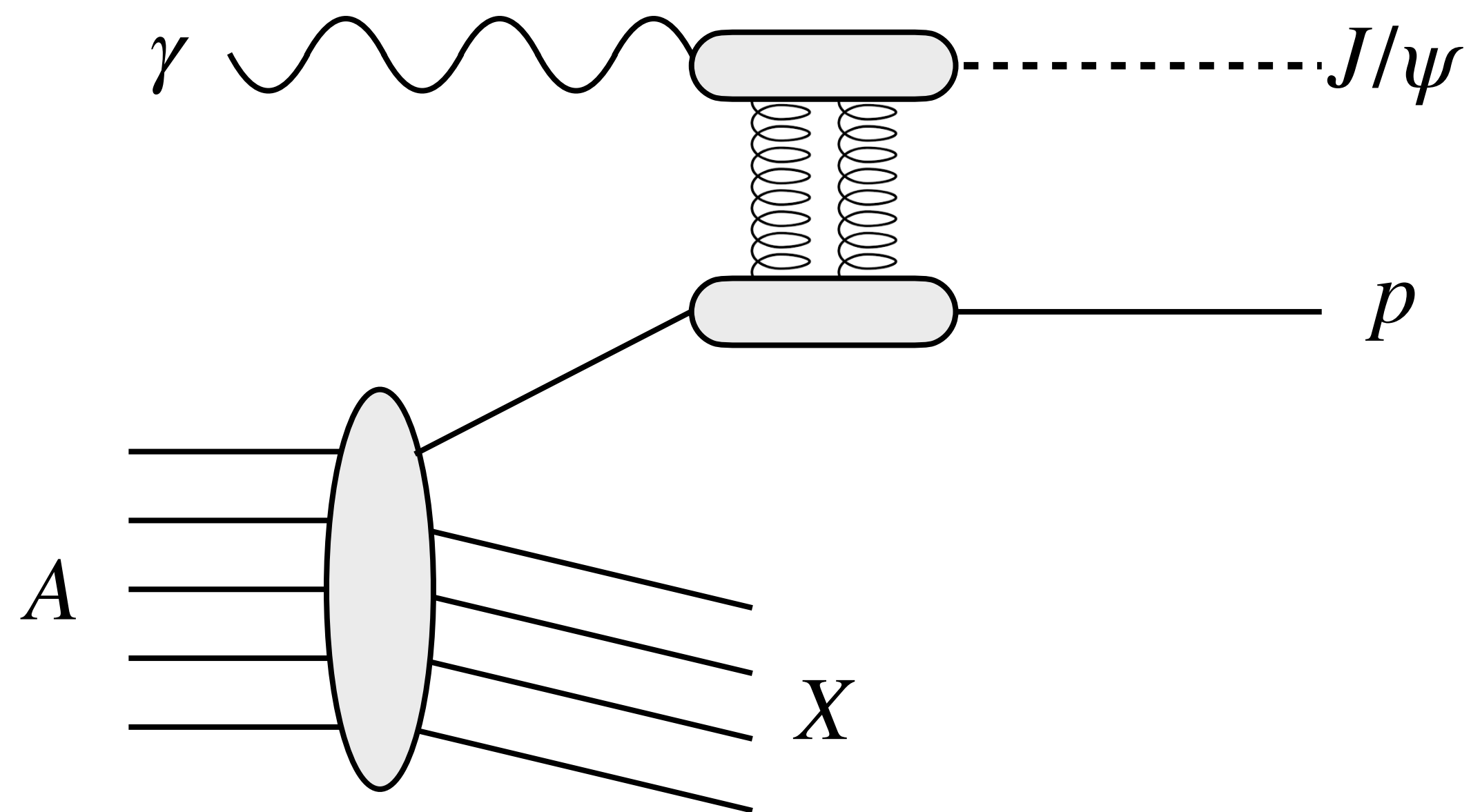
# Photoproduction of $J/\psi$ from bound protons



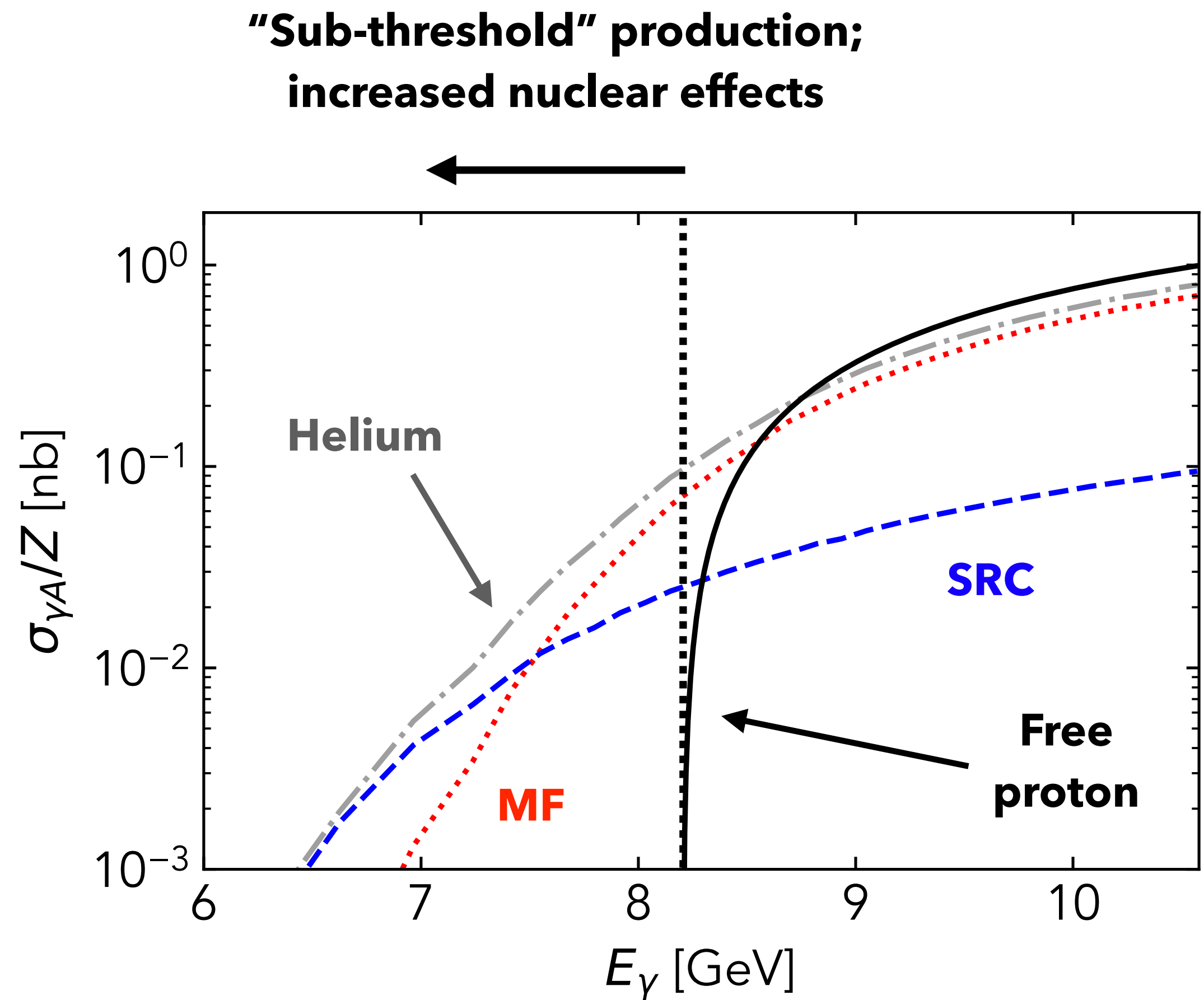
Incoherent  $J/\psi$  photoproduction near threshold sensitive to both nuclear and partonic effects



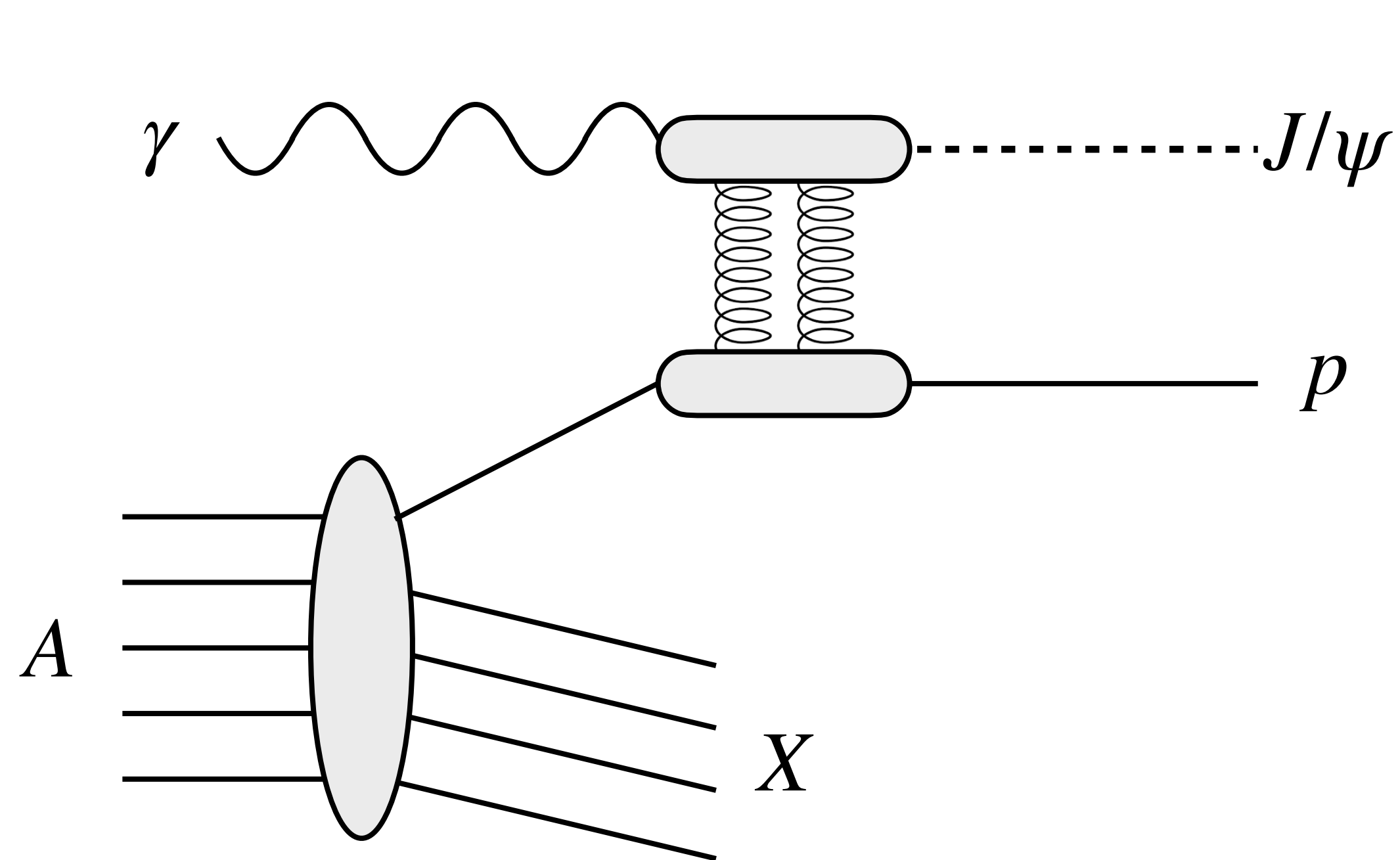
# Photoproduction of $J/\psi$ from bound protons



Incoherent  $J/\psi$  photoproduction near threshold sensitive to both nuclear and partonic effects

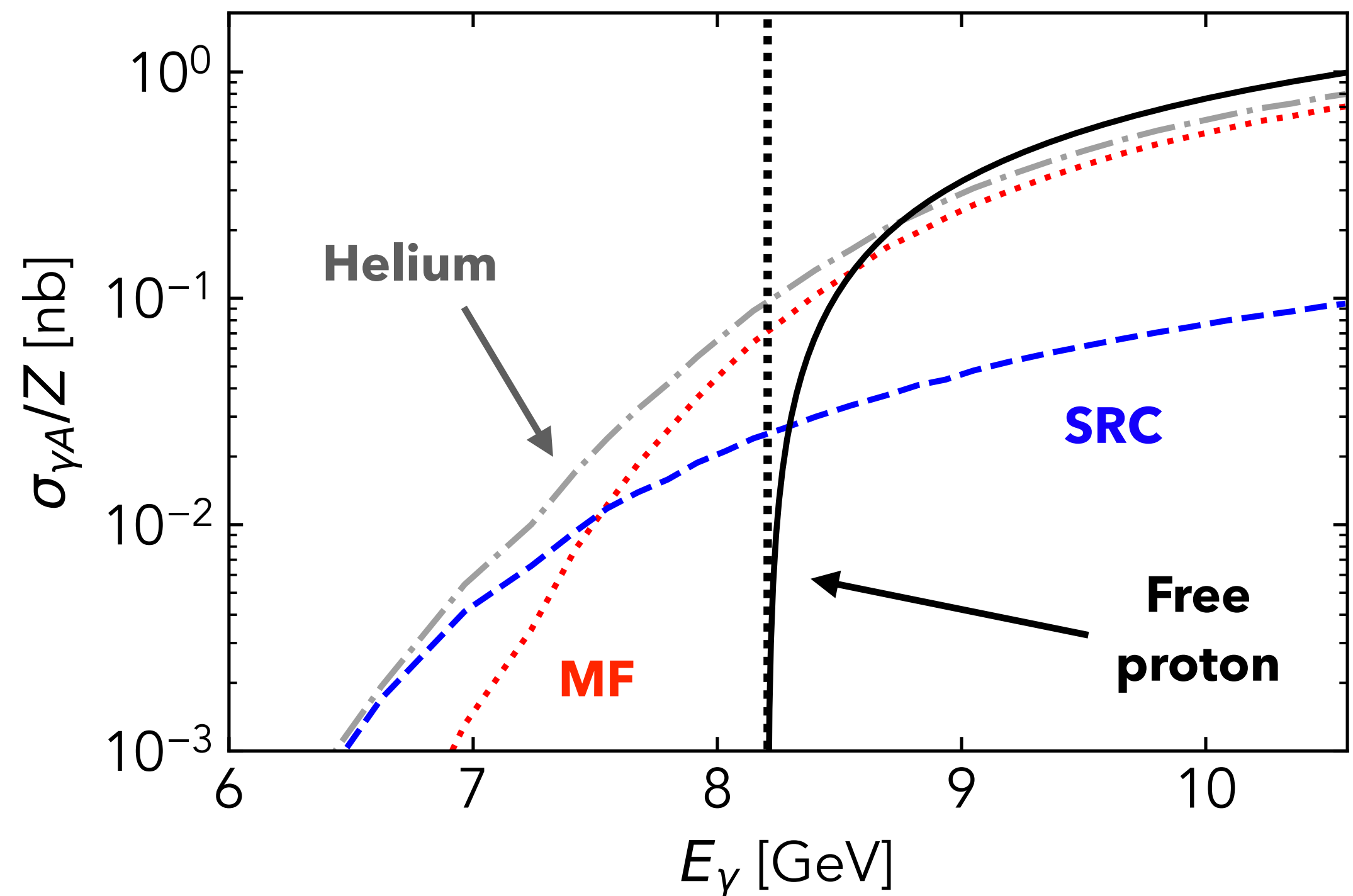


# Photoproduction of $J/\psi$ from bound protons

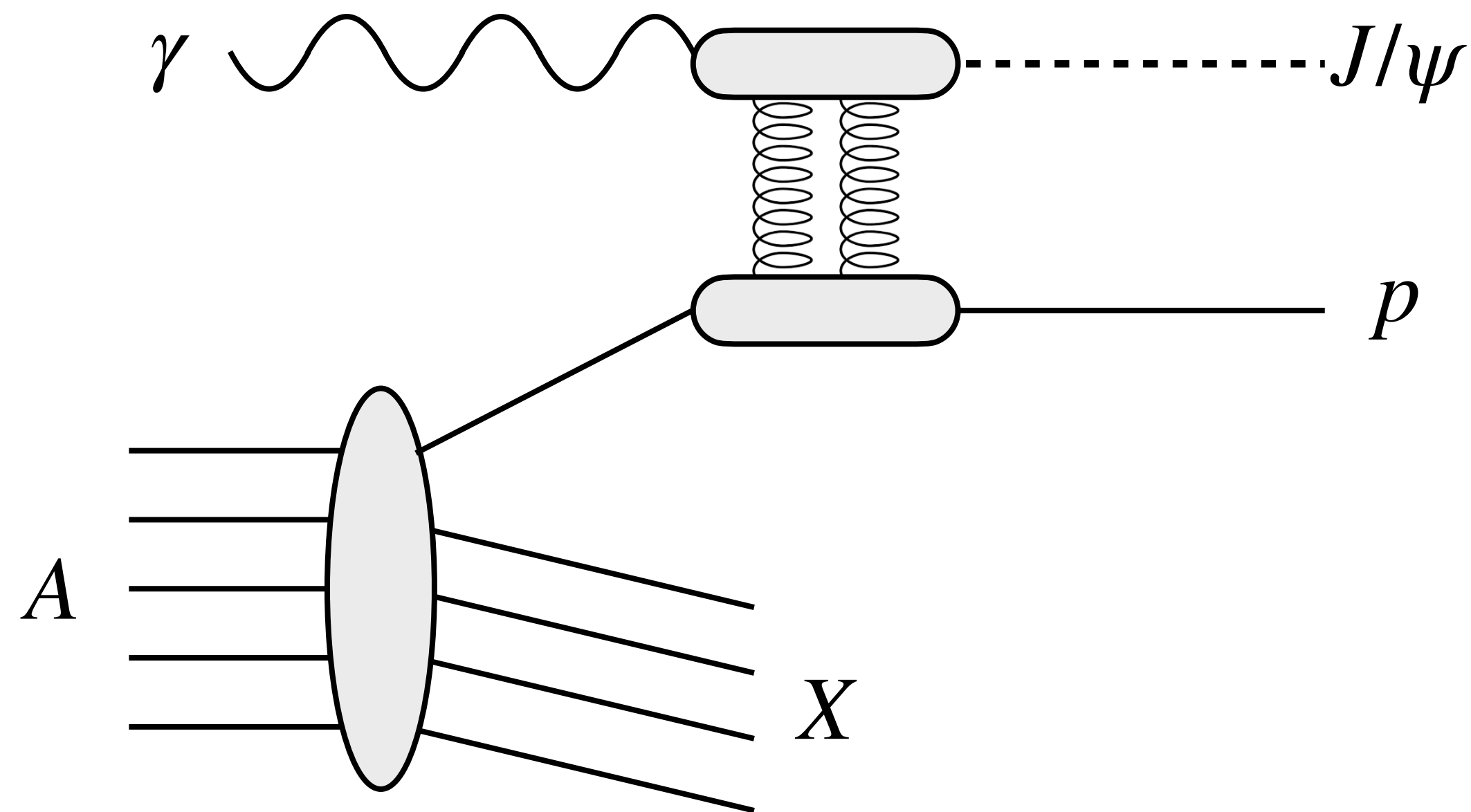


Incoherent  $J/\psi$  photoproduction near threshold sensitive to both nuclear and partonic effects

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



# Photoproduction of $J/\psi$ from bound protons



Incoherent  $J/\psi$  photoproduction near threshold sensitive to both nuclear and partonic effects

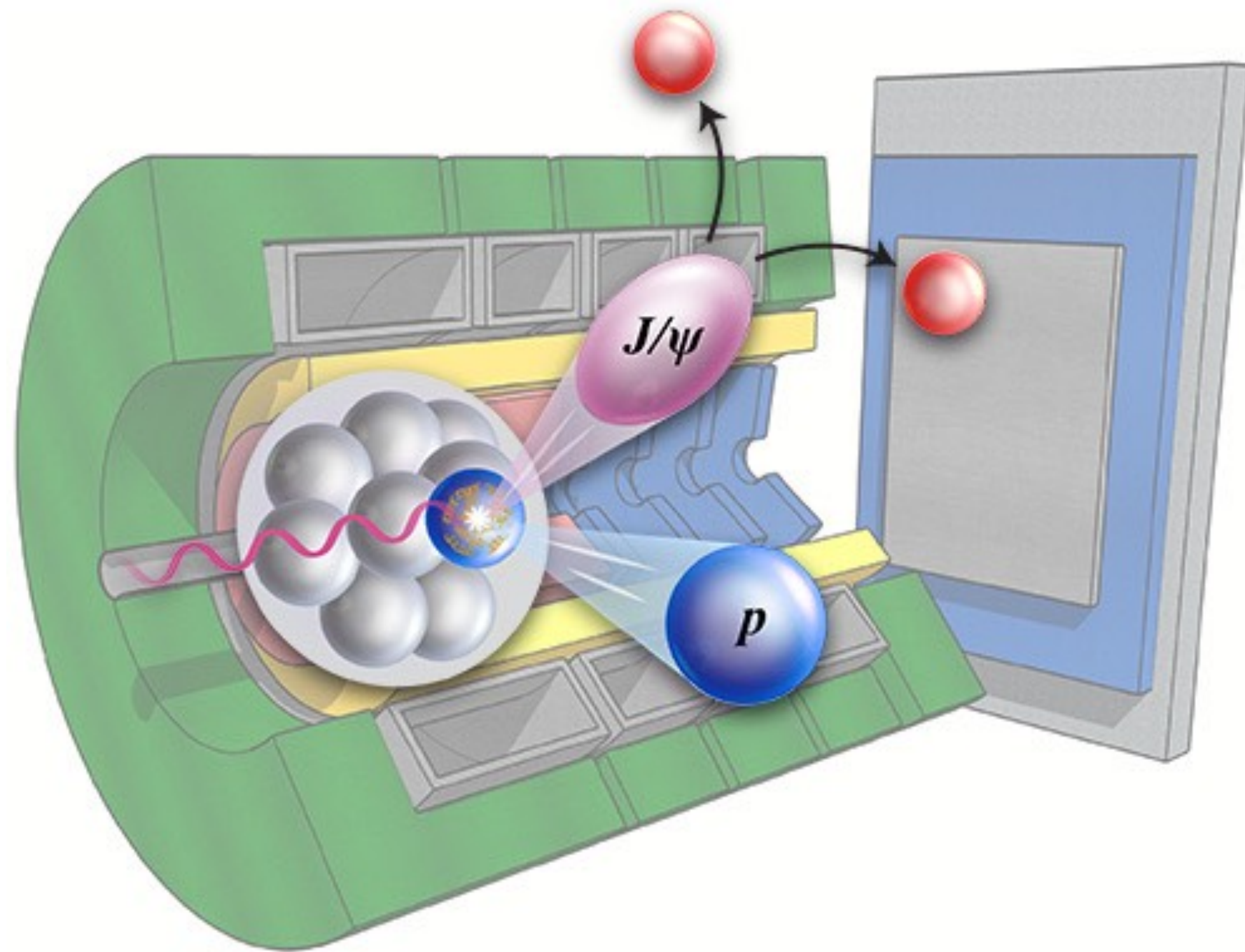
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$$\frac{d\sigma}{dt}(\gamma p \rightarrow J/\psi p) \approx \left. \frac{d\sigma}{dt} \right|_{t=0} (s_{\gamma p}) \times F^2(t)$$

**Forward cross section**

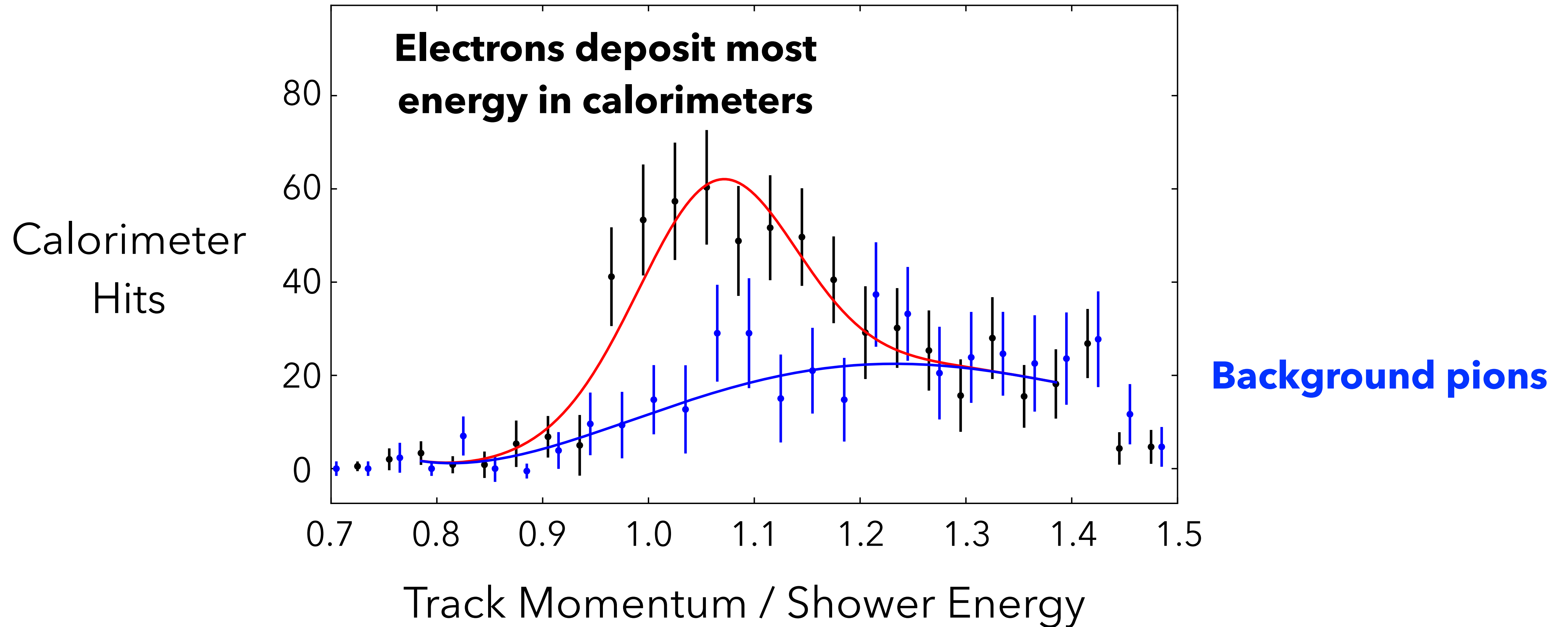
**Gravitational form factor**

# Hall D SRC-CT Experiment



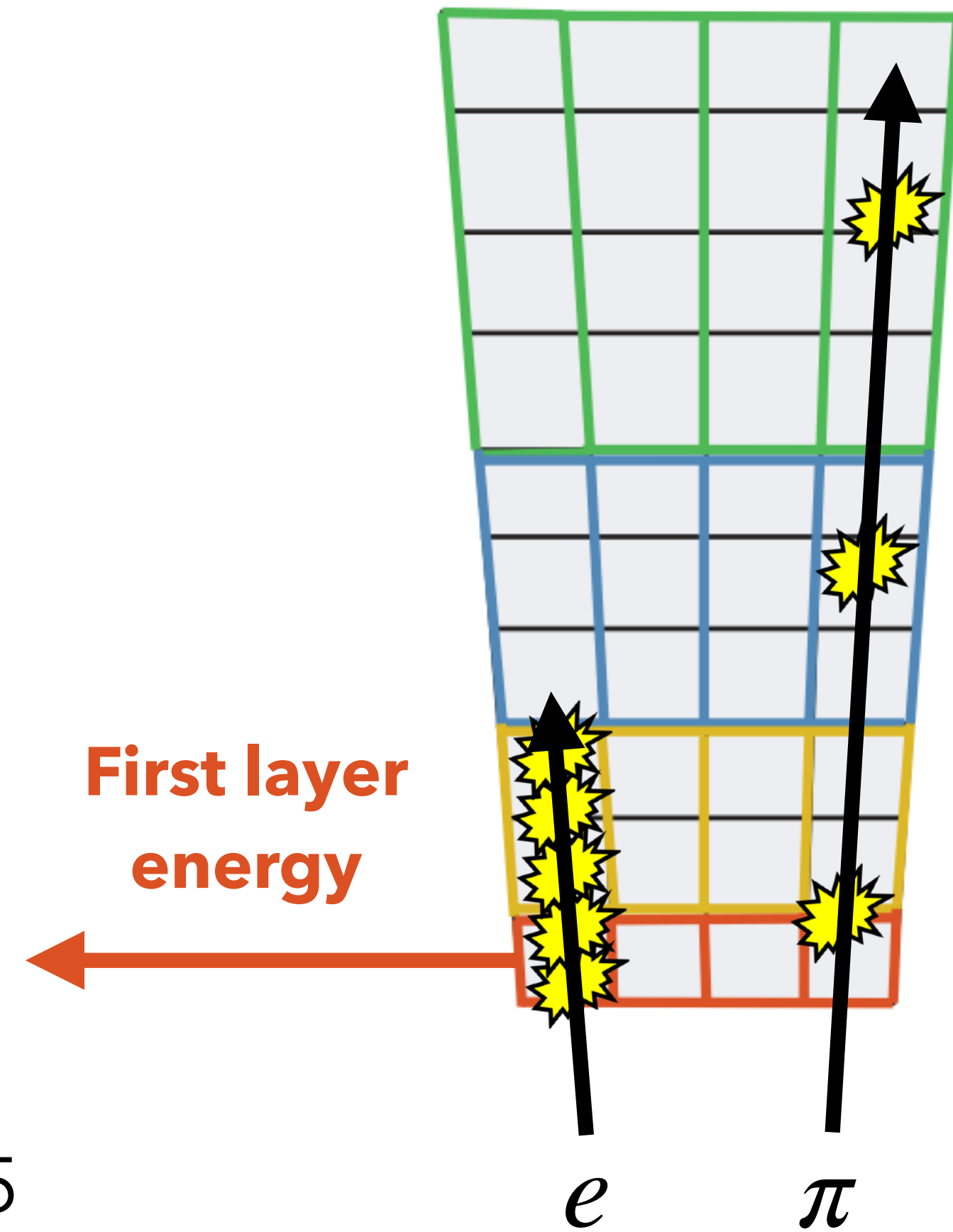
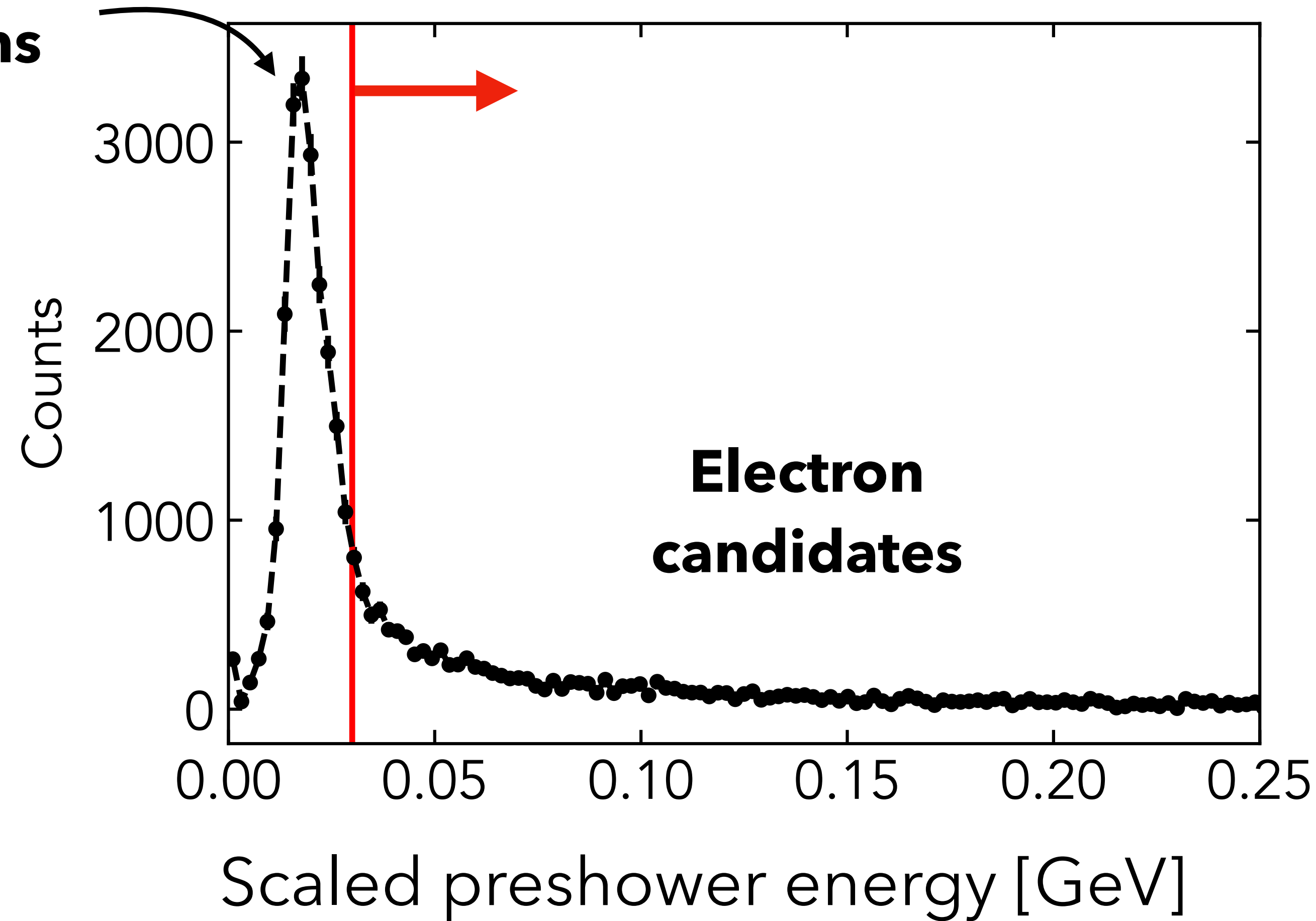
- Dedicated high-energy photonuclear measurement
- ~40-day measurement of targets  $^2\text{H}$ ,  $^4\text{He}$ ,  $^{12}\text{C}$
- 10.8-GeV electron beam – tagged coherent bremsstrahlung
- Final-state particles detected in large-acceptance GlueX spectrometer

# Calorimetry allows for $e/\pi$ separation

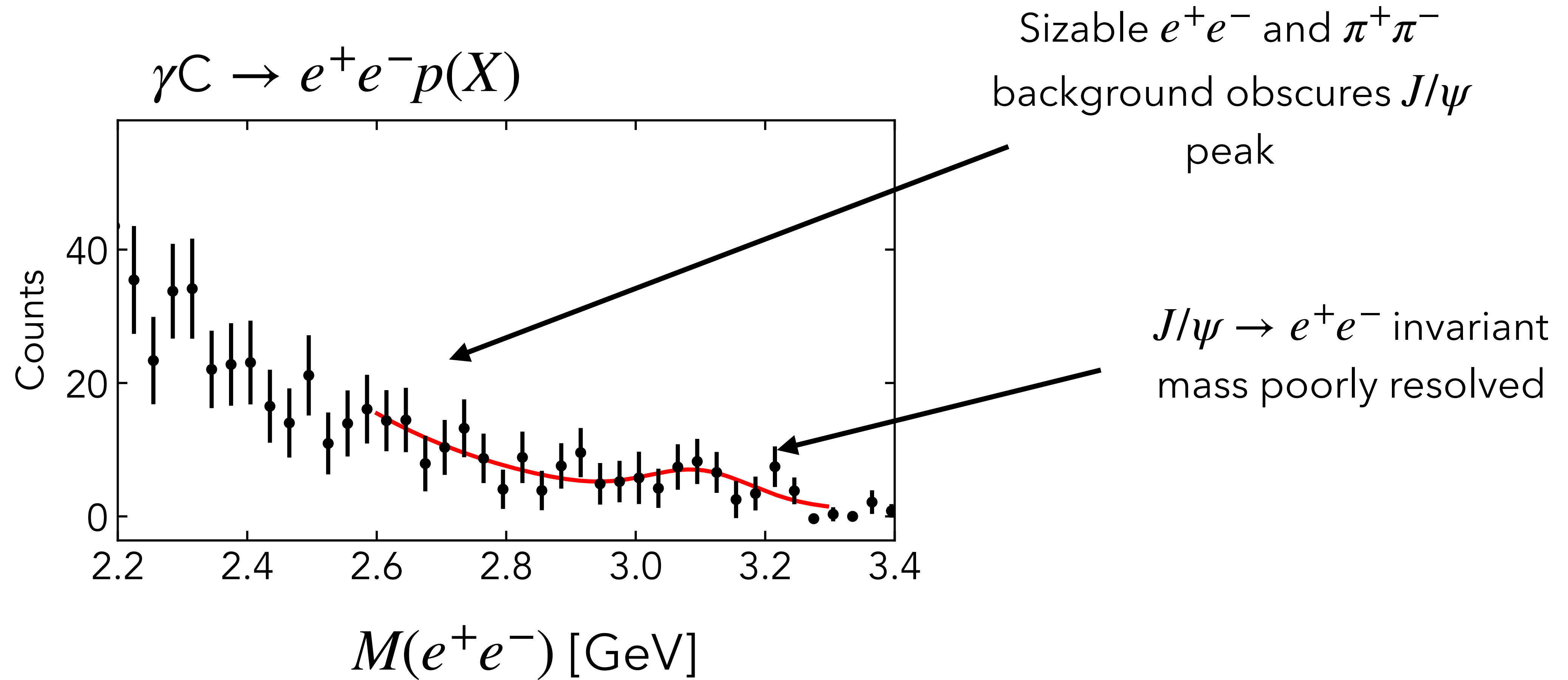


# Barrel calorimeter can measure shower evolution

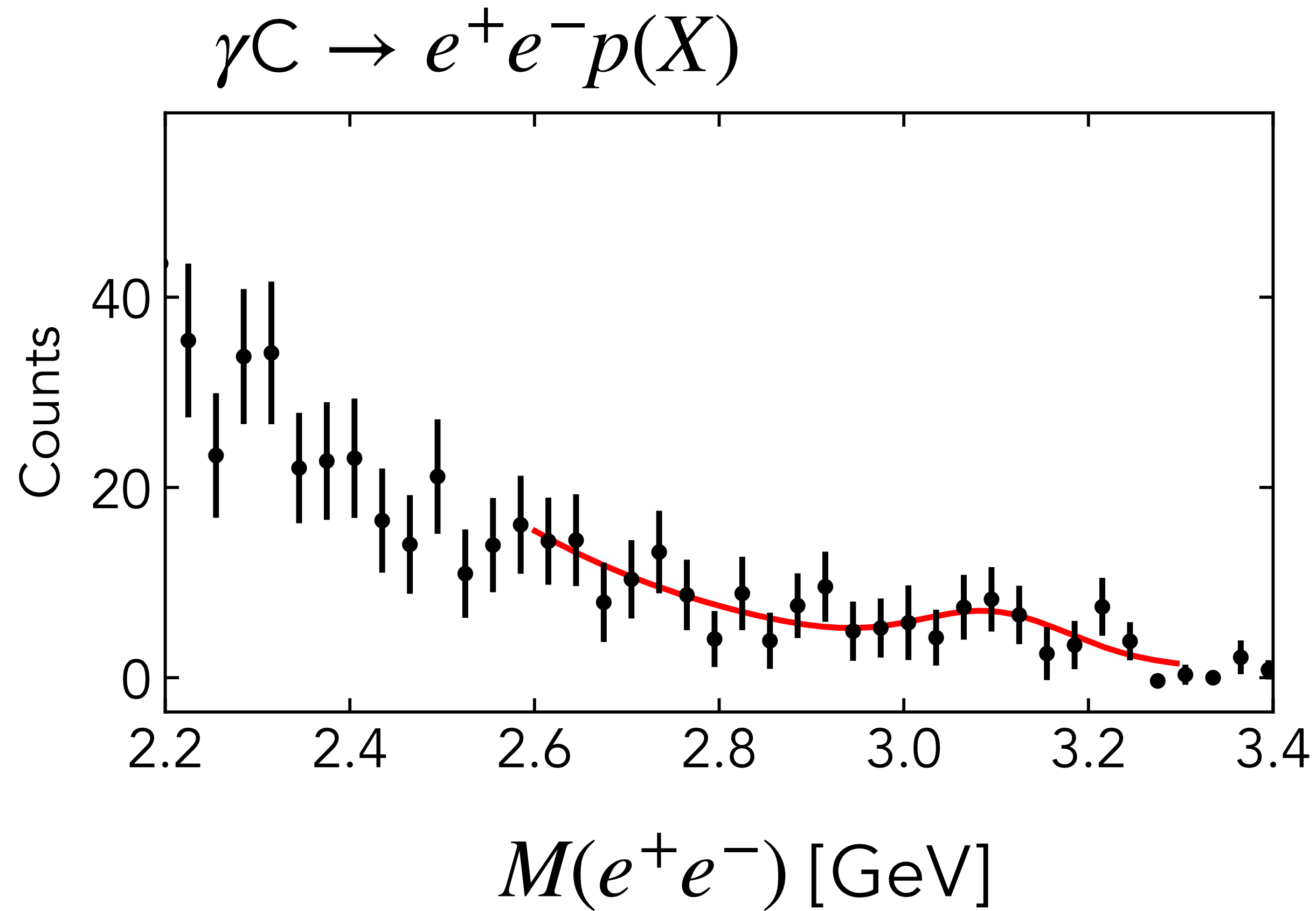
**Background  
pions**



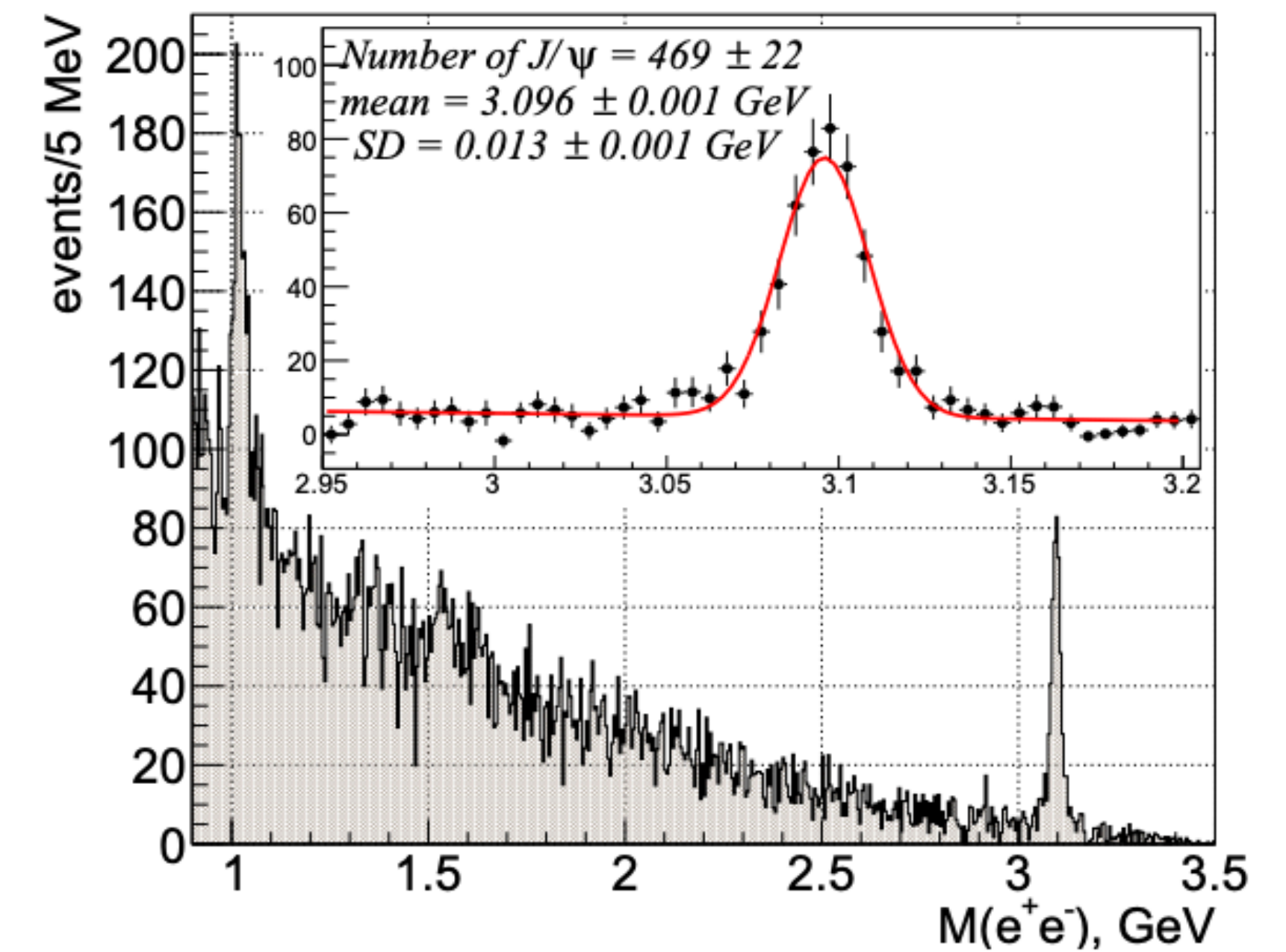
# Still hard to resolve $J/\psi$ !



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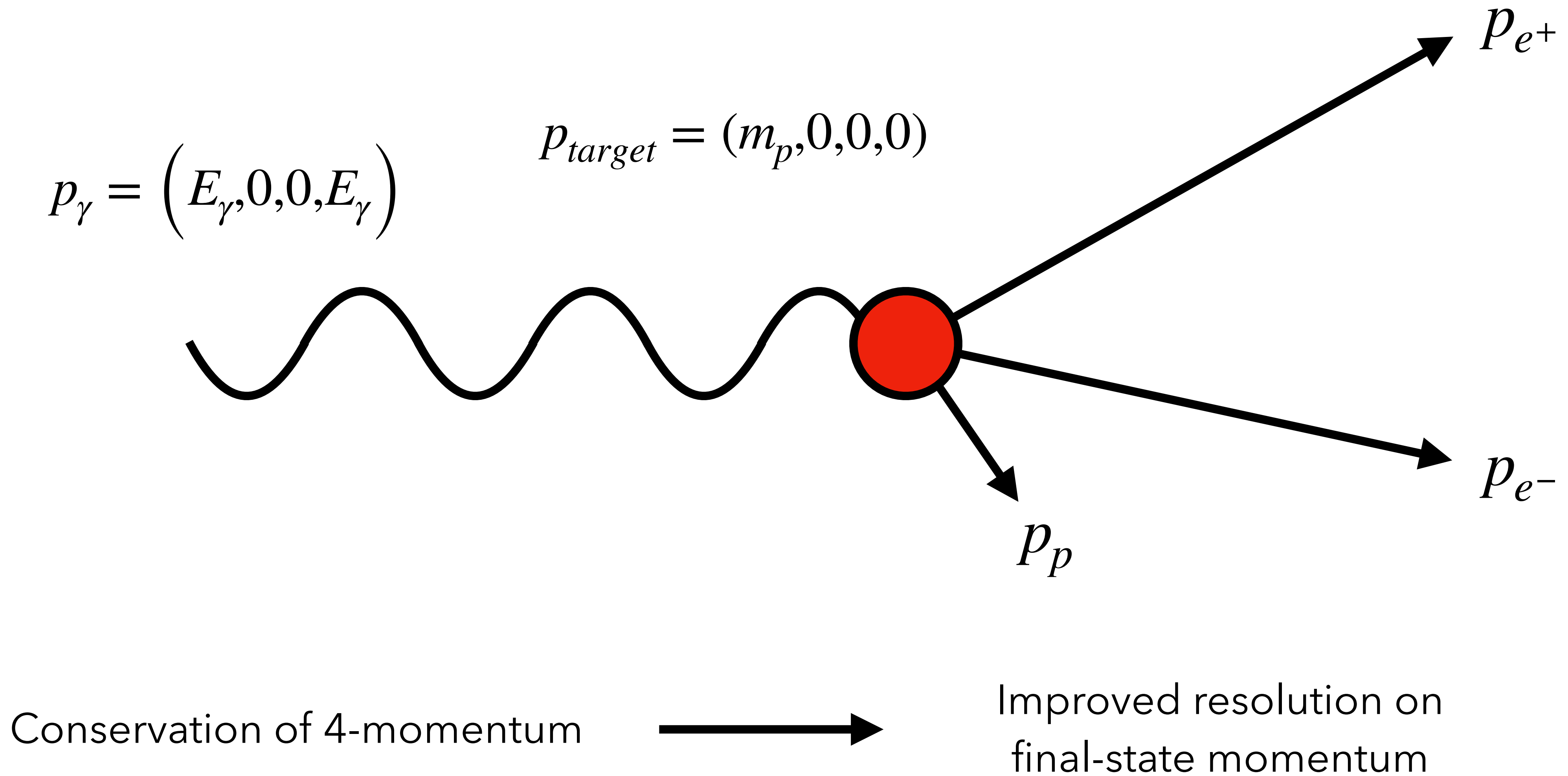


**Compare with GlueX  
result for  $\gamma p \rightarrow J/\psi p$**

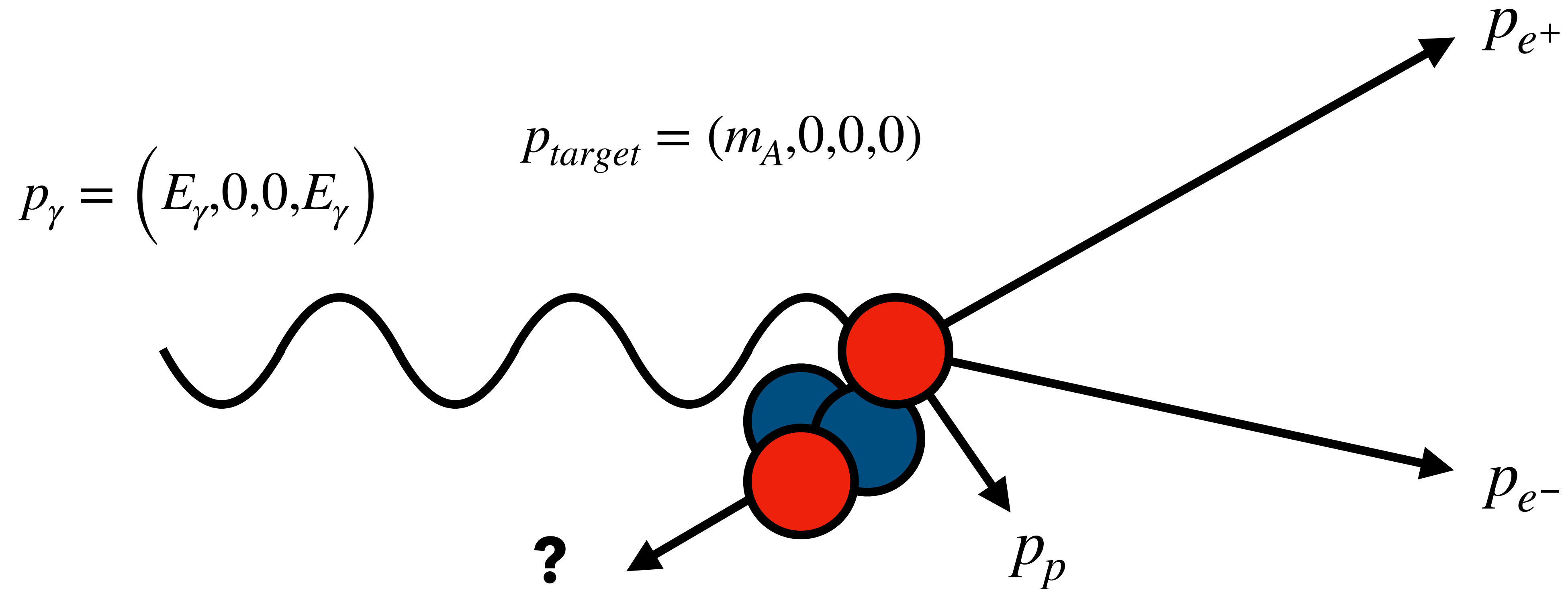


**Ali et al. PRL (2019)**

# Standard GlueX hydrogen running uses kinematic fitting



# Standard GlueX hydrogen running uses kinematic fitting

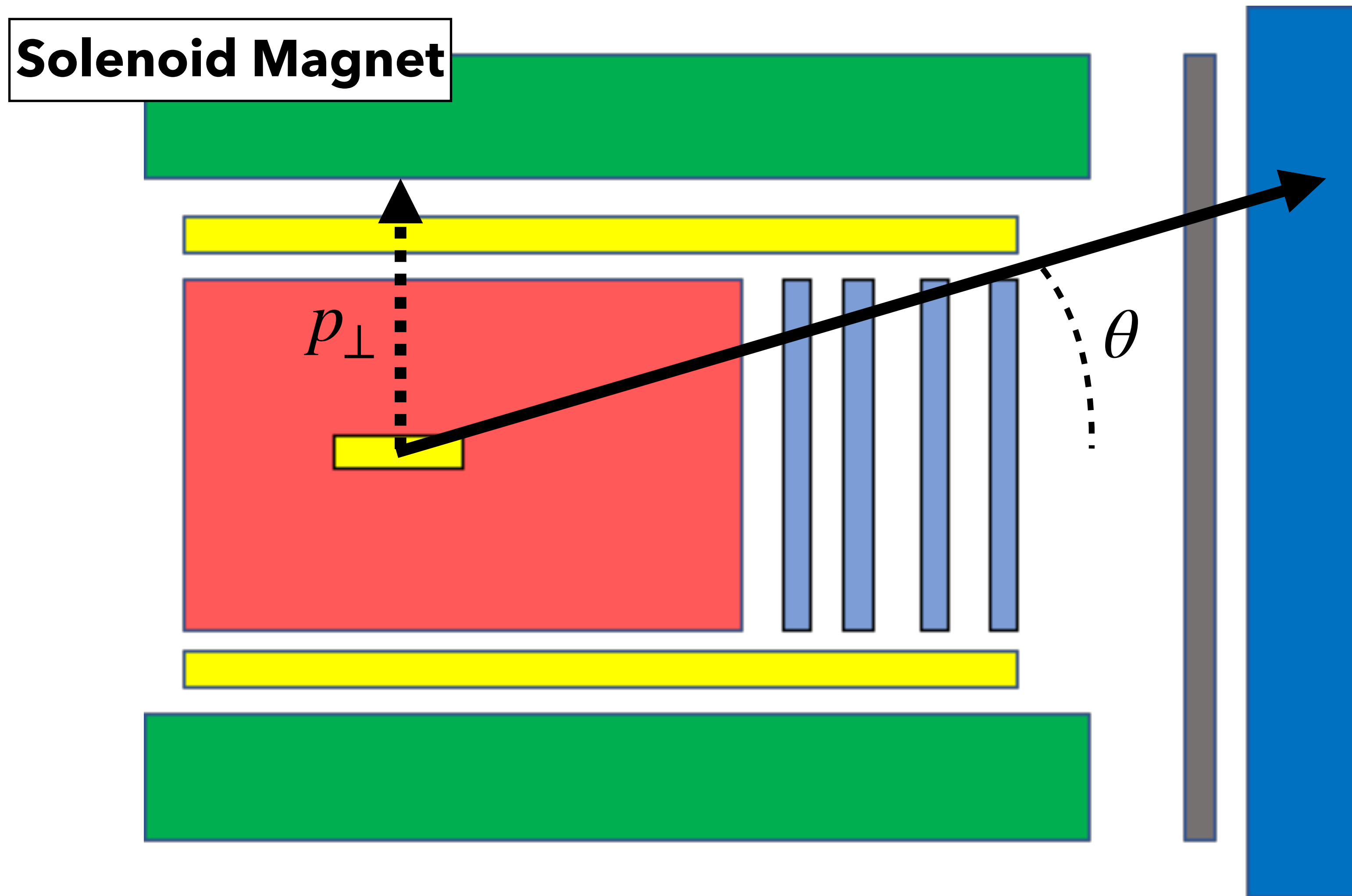


~~Conservation of 4-momentum~~



**Poor resolution!**

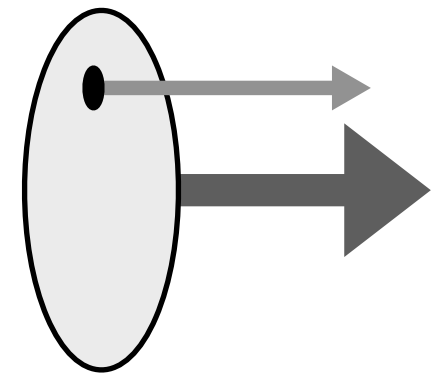
# Momentum measurement in GlueX



- Solenoid magnet – measure  $p_{\perp}$  and  $\theta$
- **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

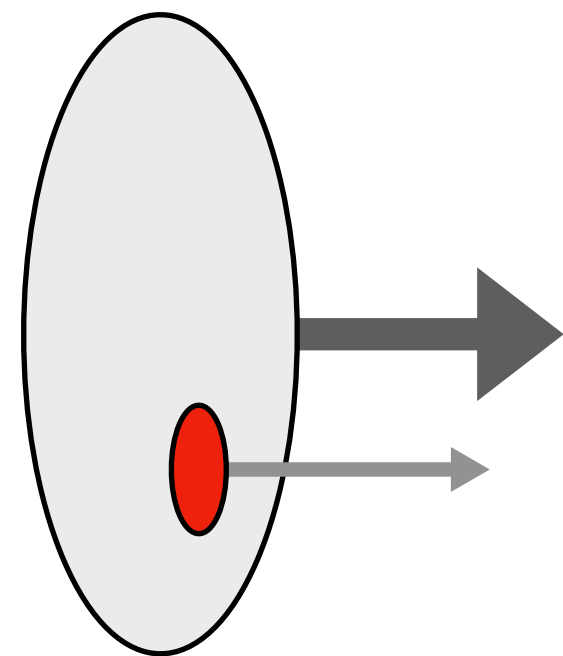
## Parton in Hadron



Parton momentum fraction

$$x_B$$

## Nucleon in Nucleus

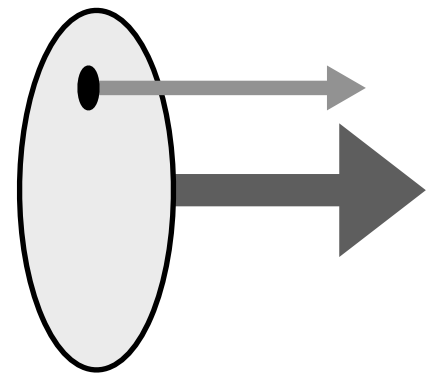


Nucleon momentum fraction

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

# Analysis on the light-front

## Parton in Hadron

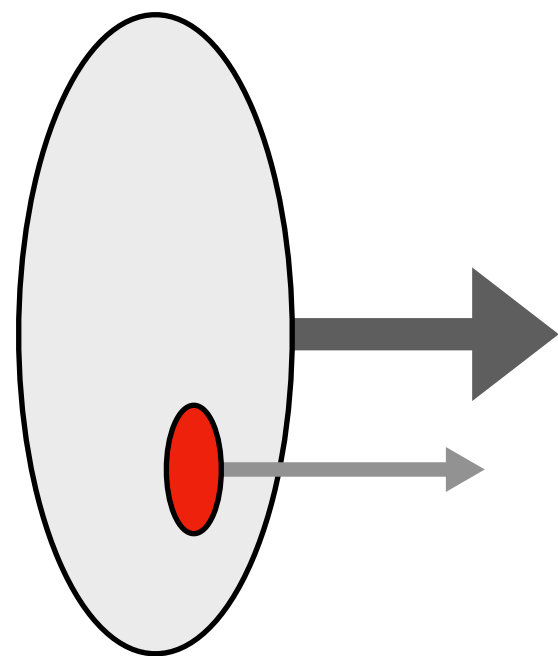


Parton momentum fraction

$$x_B$$

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:

$$\text{Large } |\alpha_N - 1|$$

# Reformulate invariant mass using light-front variables

$$M_{e^+e^-}^2 = (p_{e^+}^- + p_{e^-}^-) (p_{e^+}^+ + p_{e^-}^+) - (\vec{p}_{e^+}^\perp + \vec{p}_{e^-}^\perp)^2 \quad p^\pm = E \pm p_z$$

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

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

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

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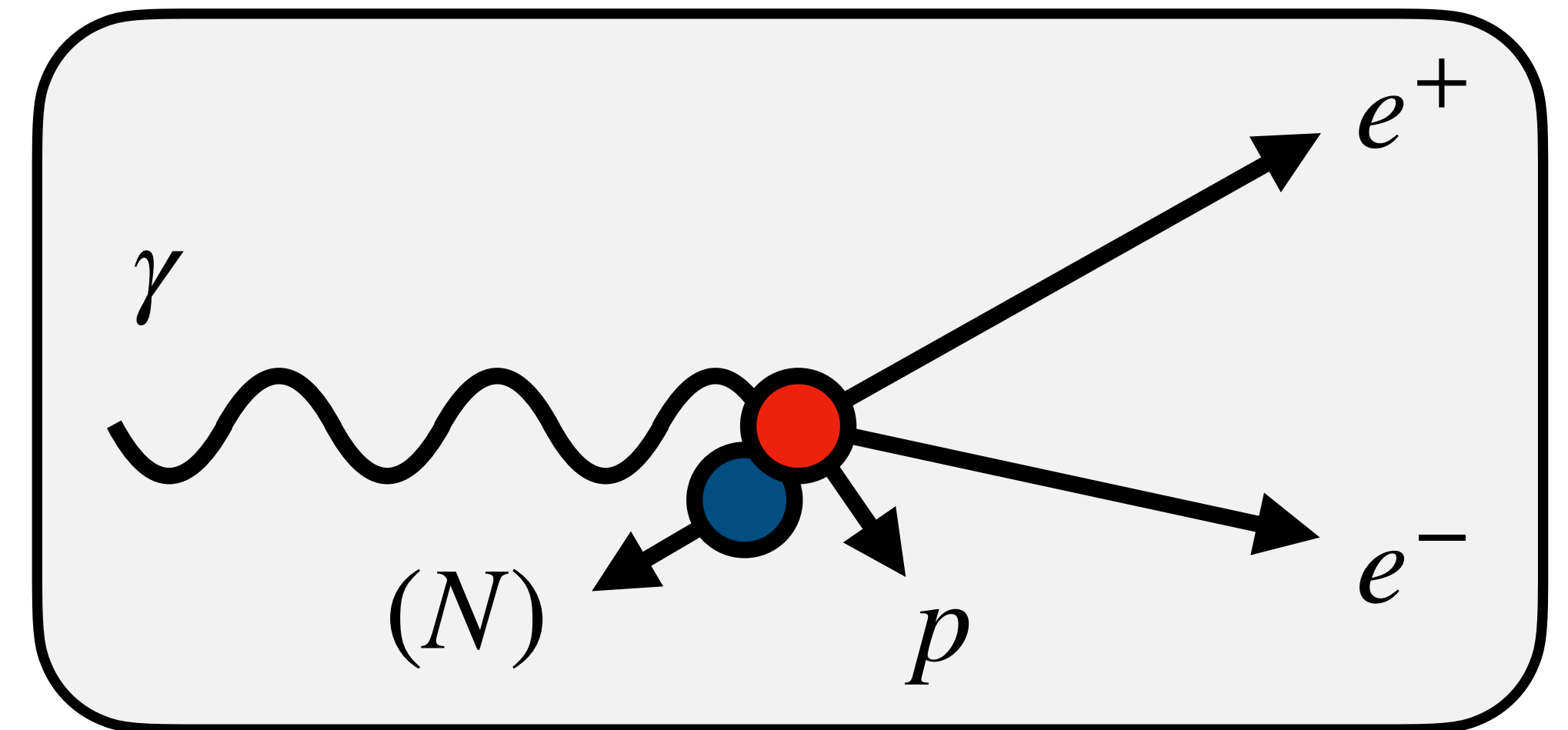
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$$p_\gamma + p_{2N} = p_{e^+} + p_{e^-} + p_p + p_N$$

**Assume recoil 4-momentum  
carried by single nucleon**



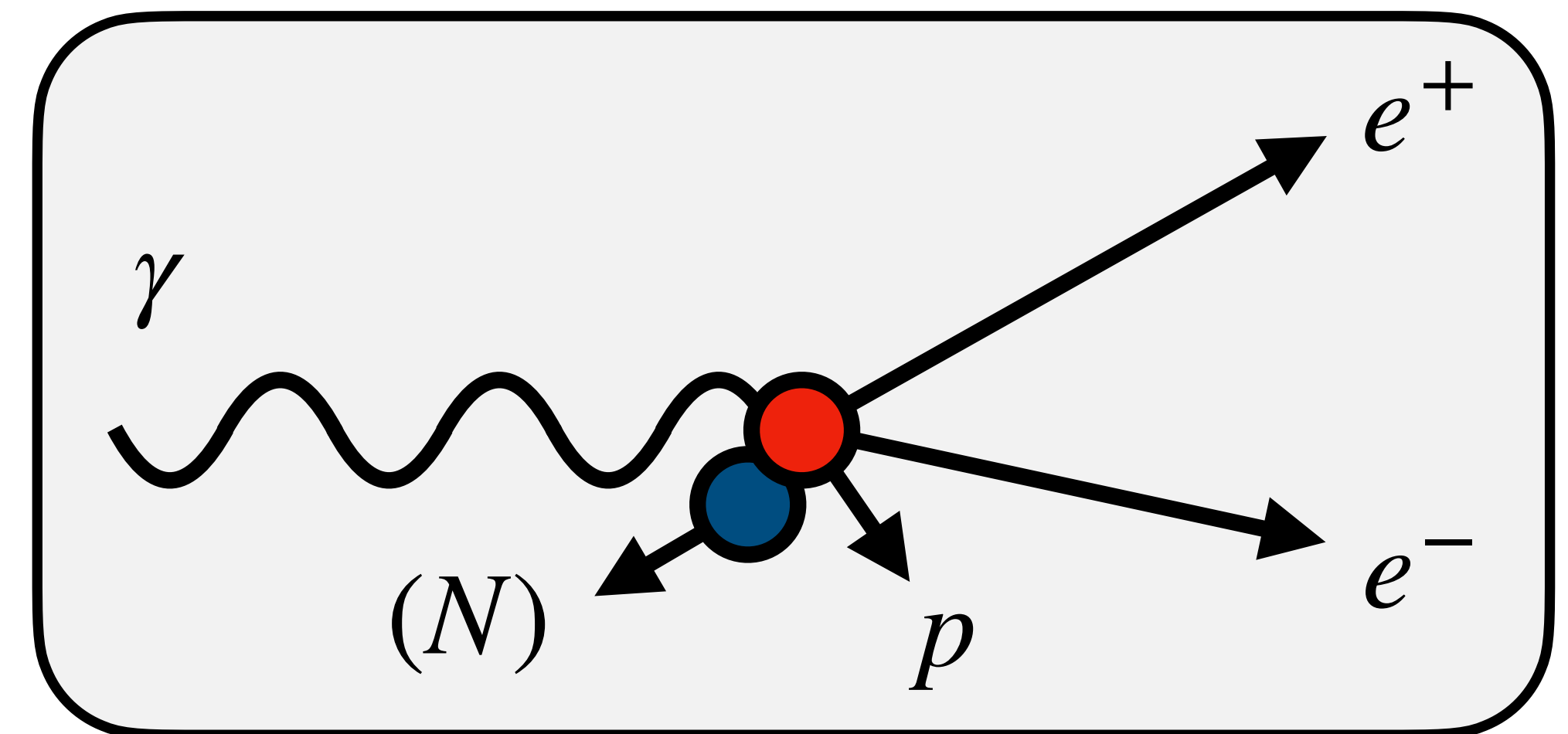
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$$p_N^{-,\perp} = p_\gamma^{-,\perp} + p_{2N}^{-,\perp} - p_{e^+}^{-,\perp} - p_{e^-}^{-,\perp} - p_p^{-,\perp}$$

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# Reformulate invariant mass using light-front variables

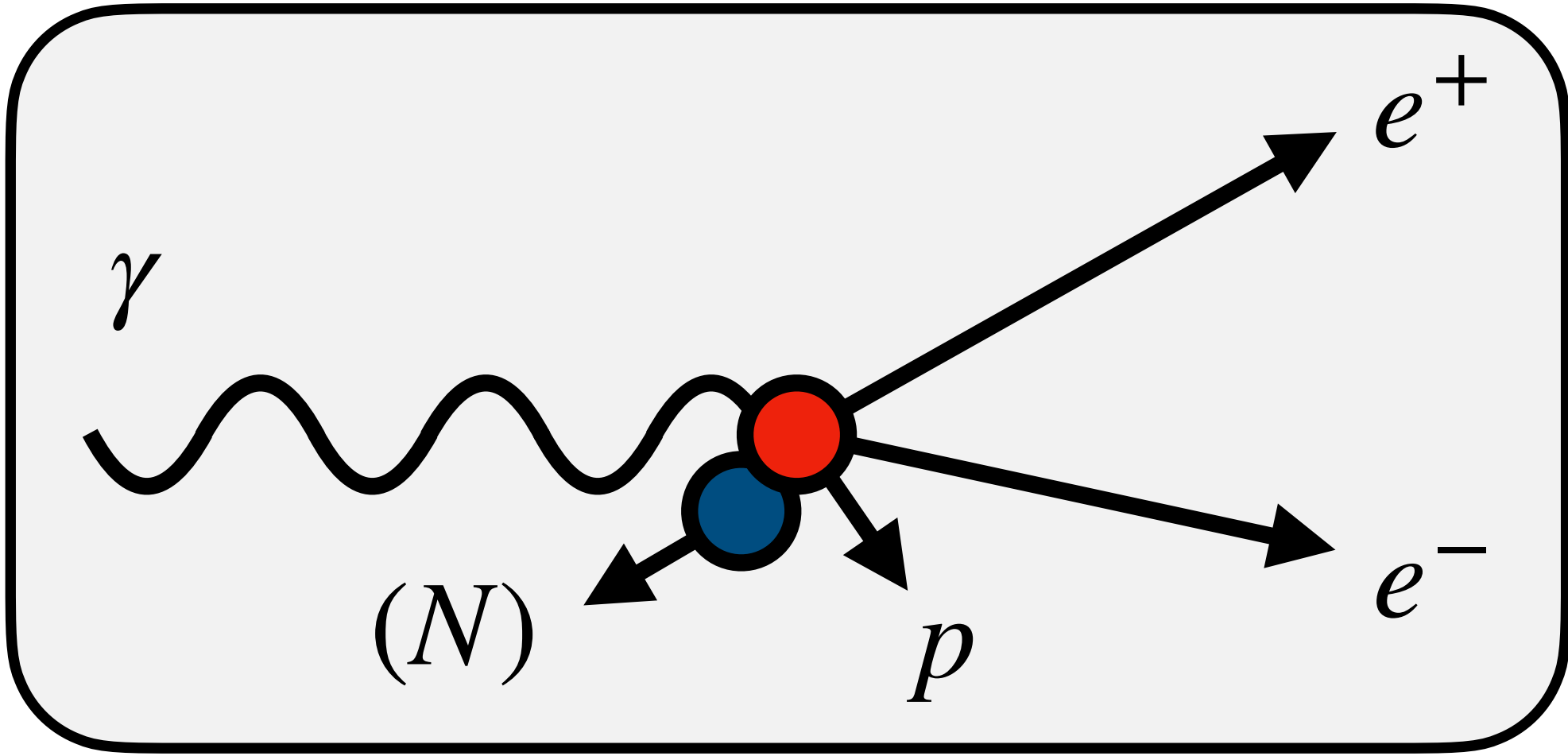
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$$p_N^{-,\perp} = p_\gamma^{-,\perp} + p_{2N}^{-,\perp} - p_{e^+}^{-,\perp} - p_{e^-}^{-,\perp} - p_p^{-,\perp}$$

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

**Assume recoil 4-momentum carried by single nucleon**



# Reformulate invariant mass using light-front variables

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

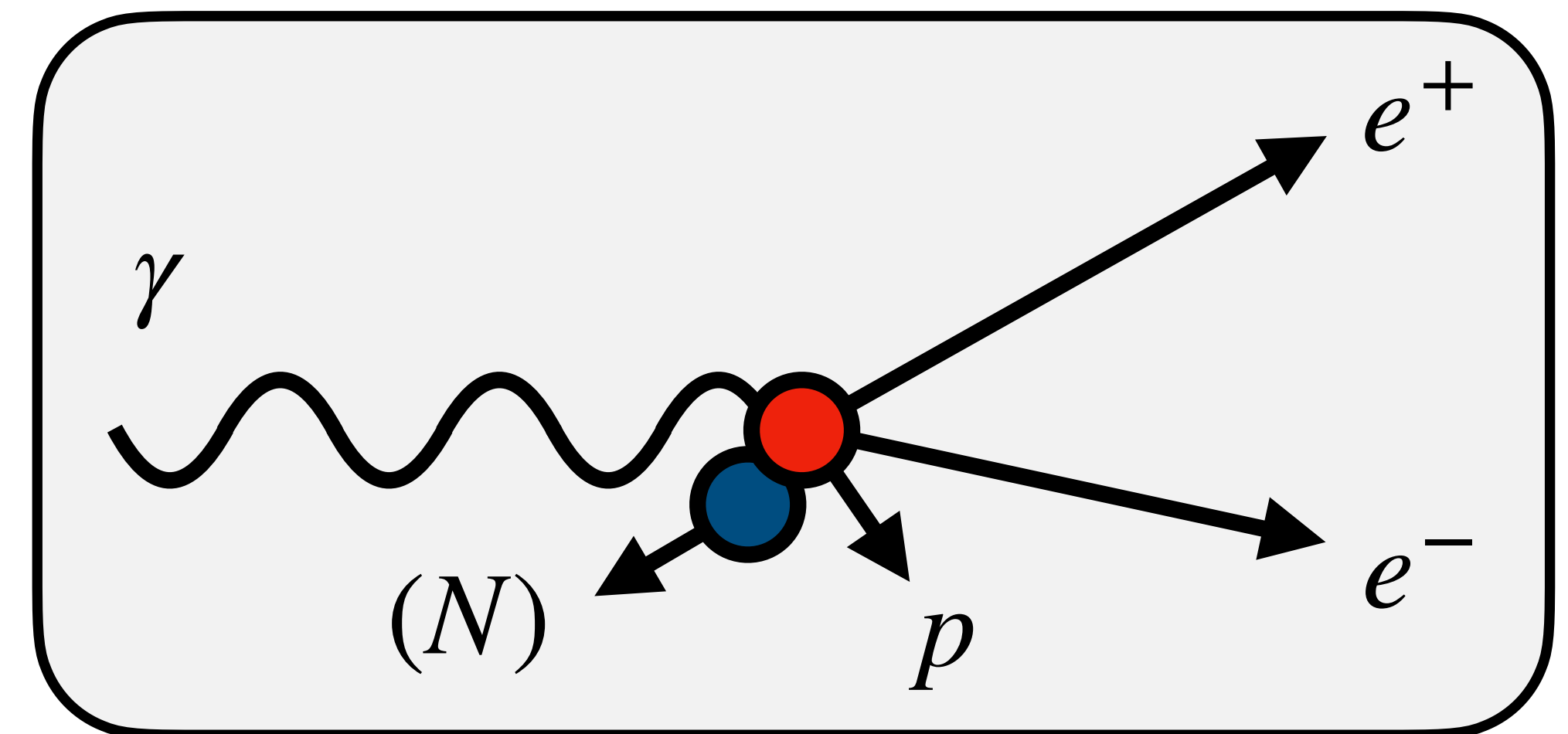
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$$p_N^+ = \frac{p_{N,\perp}^2 + m_N^2}{p_N^-}$$

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

**Assume recoil 4-momentum  
carried by single nucleon**

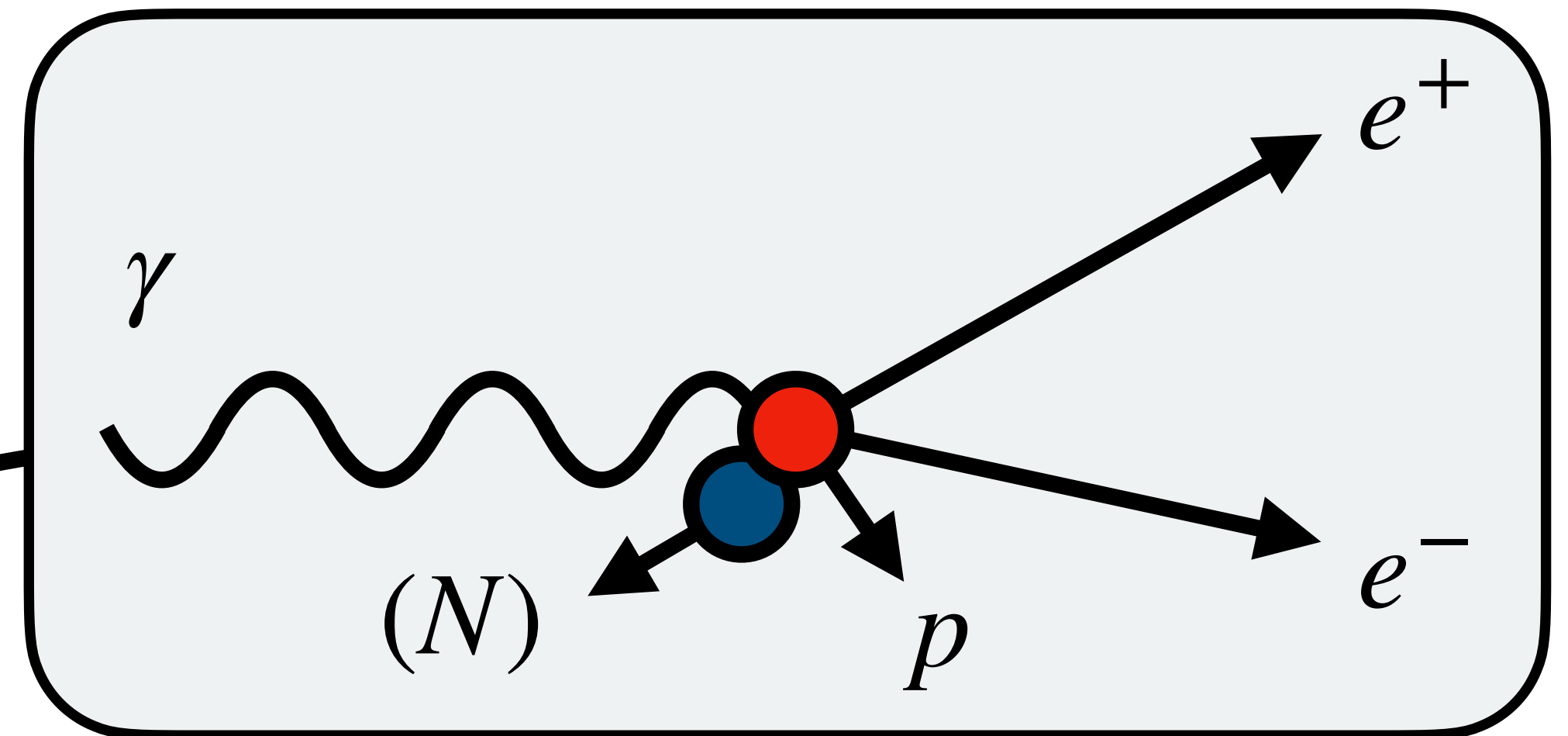


# Reformulate invariant mass using light-front variables

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

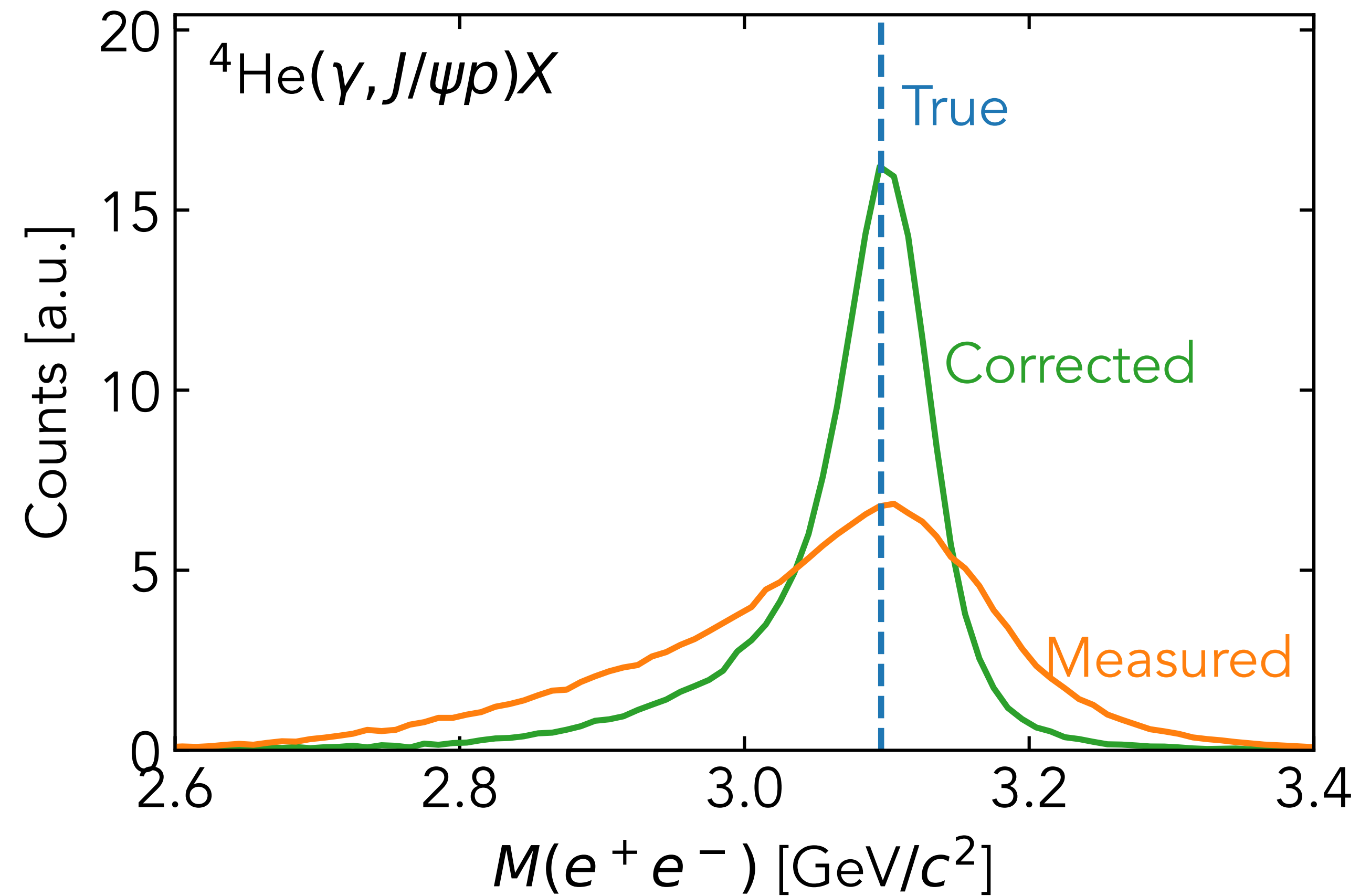
**Assume recoil 4-momentum  
carried by single nucleon**

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



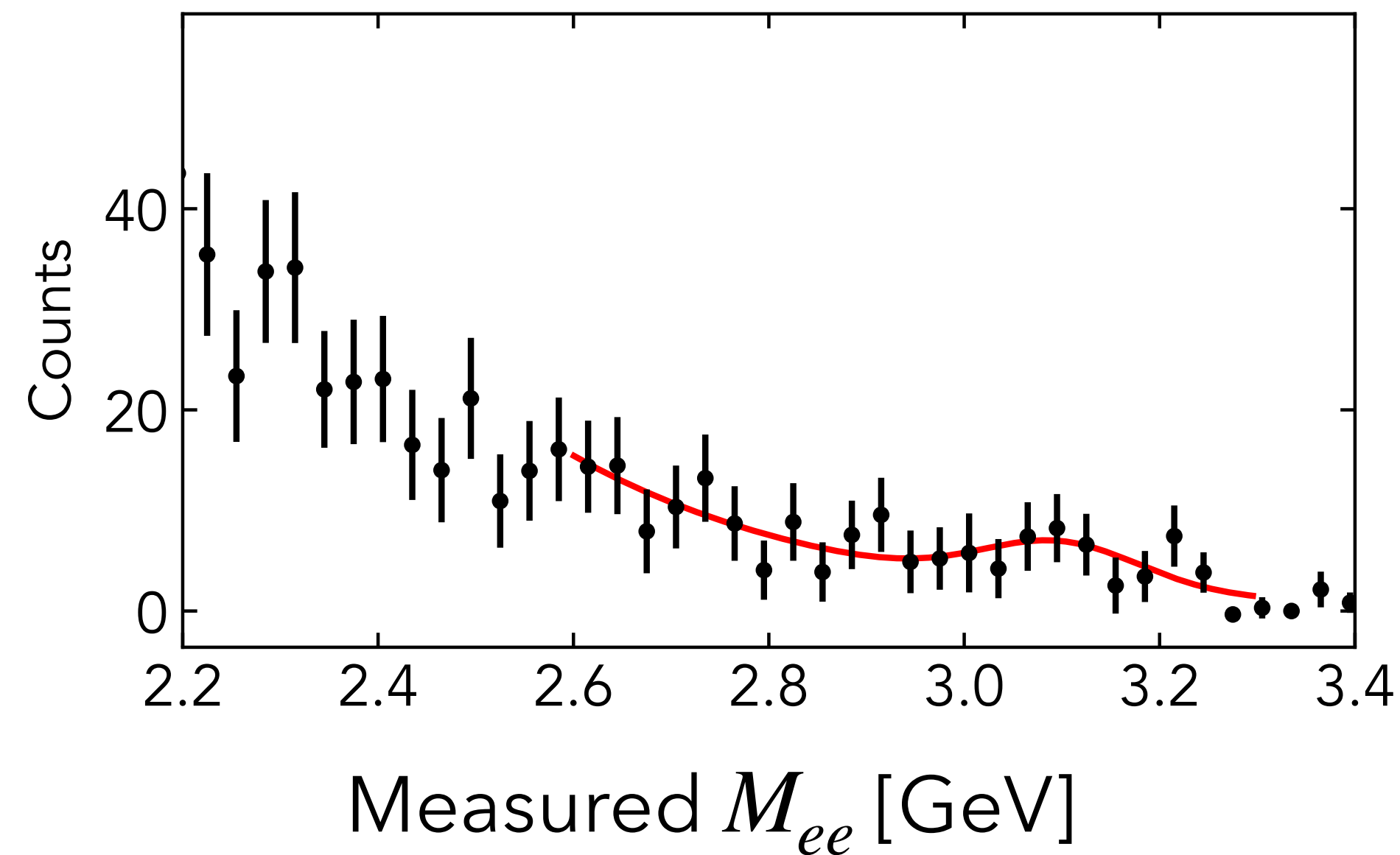
$$M_{e^+e^-}^2 \approx (p_{e^+}^- + p_{e^-}^-) \left( 2E_\gamma + 2m_N - p_p^+ - \frac{m_N^2 + p_{tot}^2}{2m_N - p_{tot}^-} \right) - (\vec{p}_{e^+}^\perp + \vec{p}_{e^-}^\perp)^2$$

# Simulation shows resolution improvement

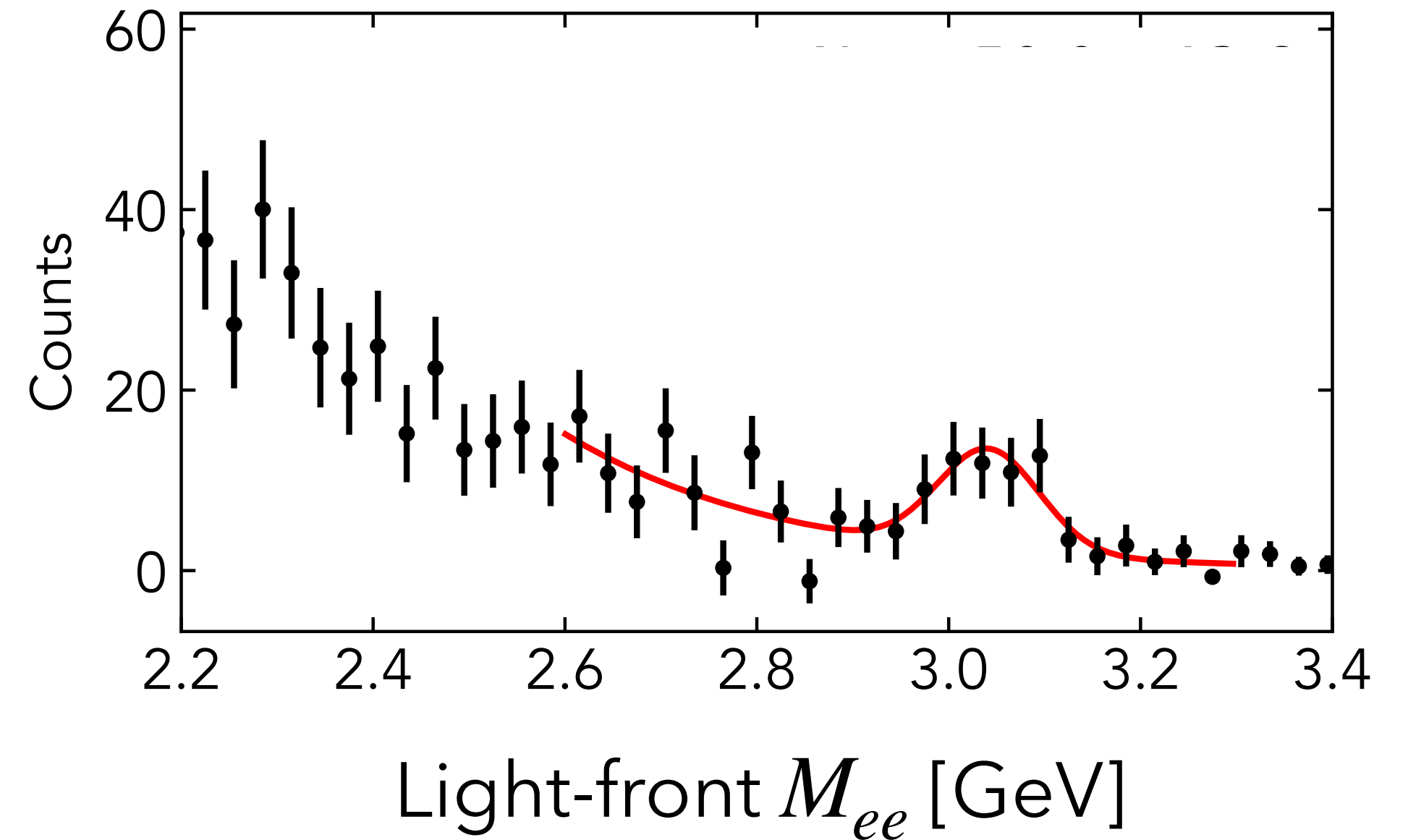


# Careful selection of observables improves signal resolution

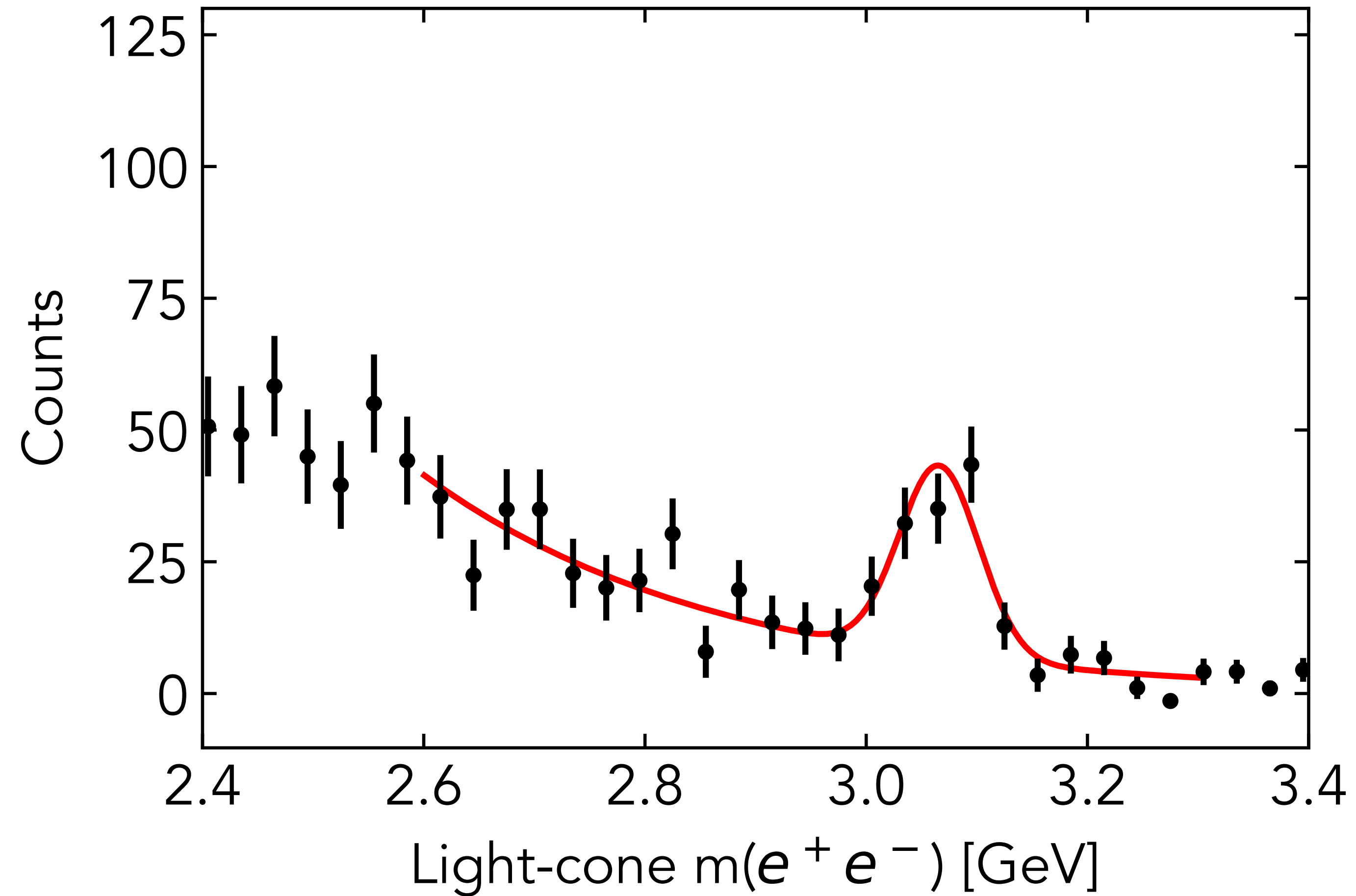
$$\gamma C \rightarrow e^+ e^- p(X)$$



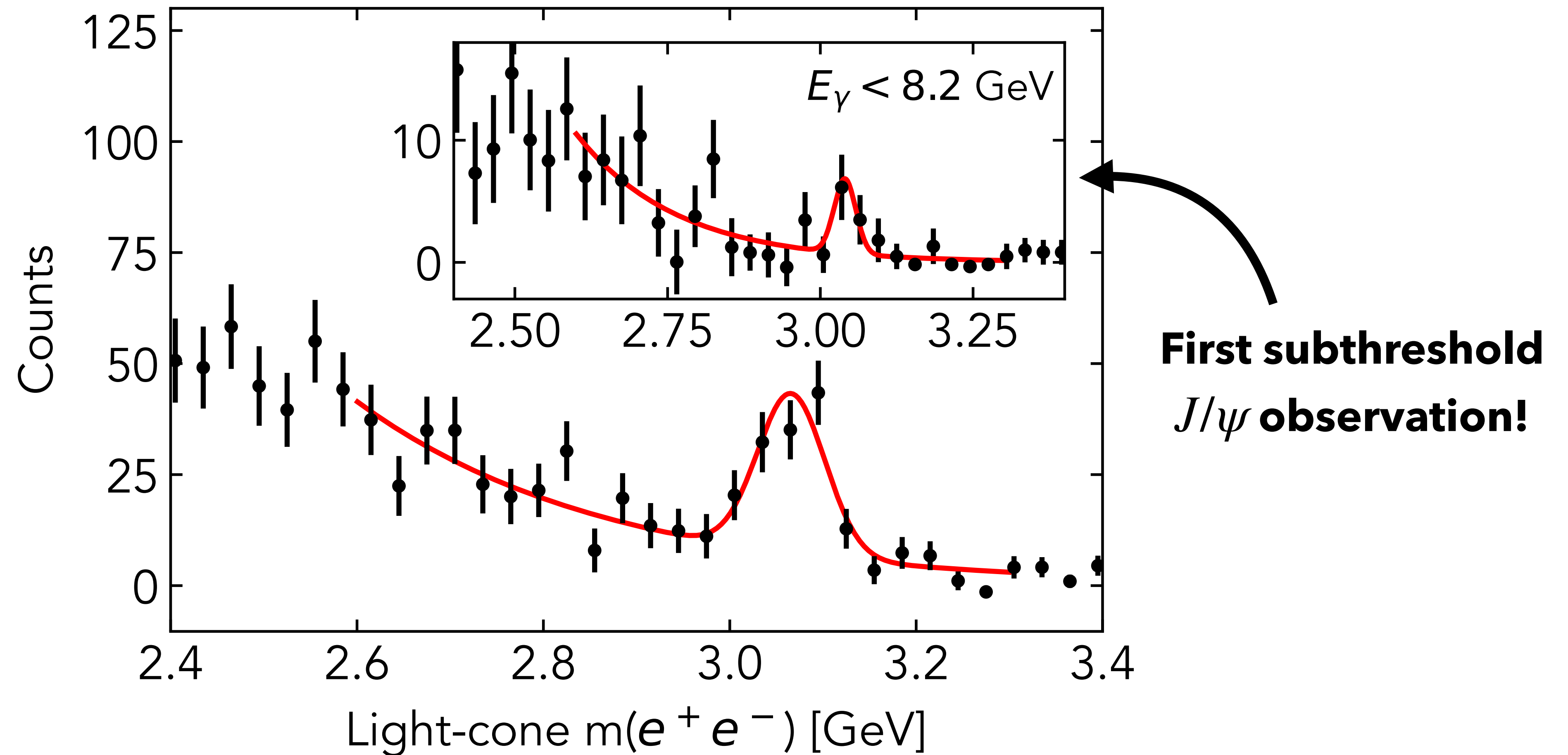
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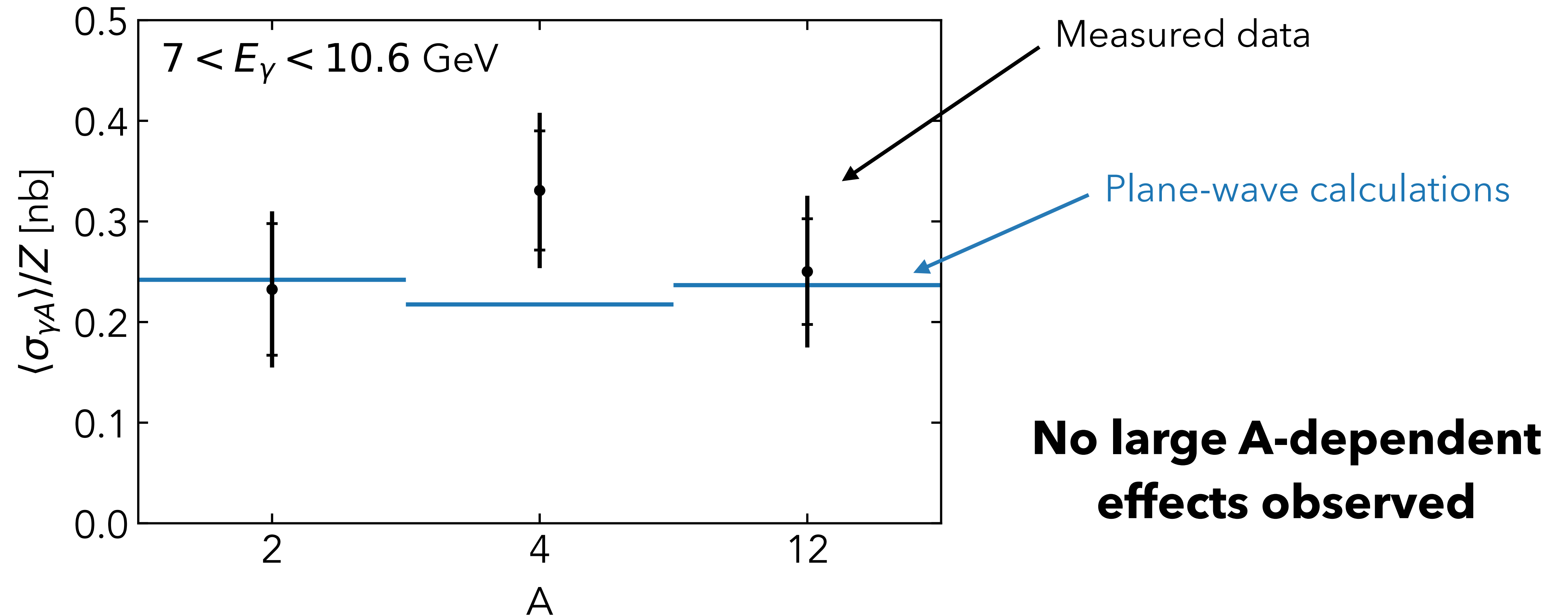
# Invariant mass shows $J/\psi \rightarrow e^+e^-$ decay



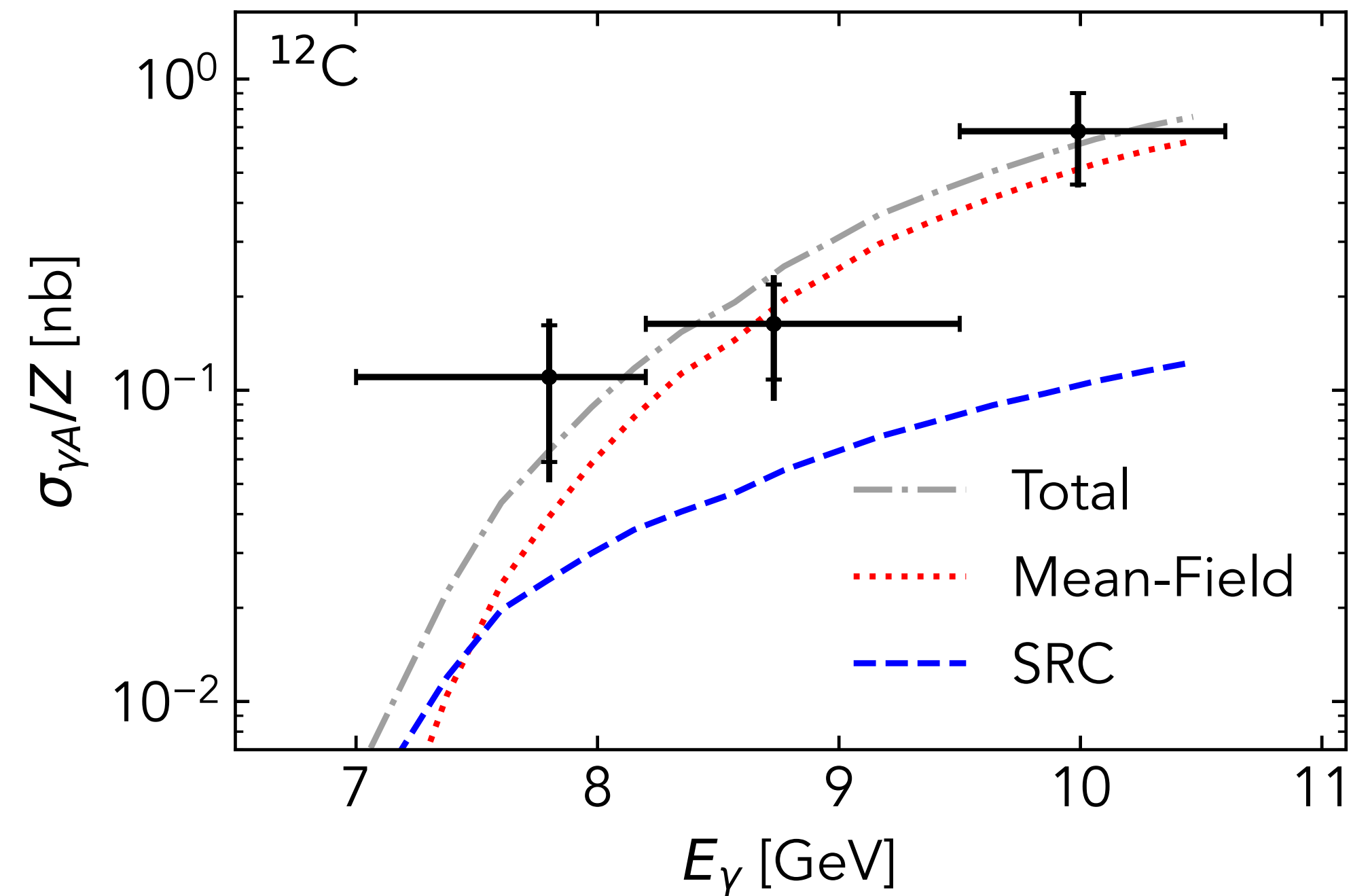
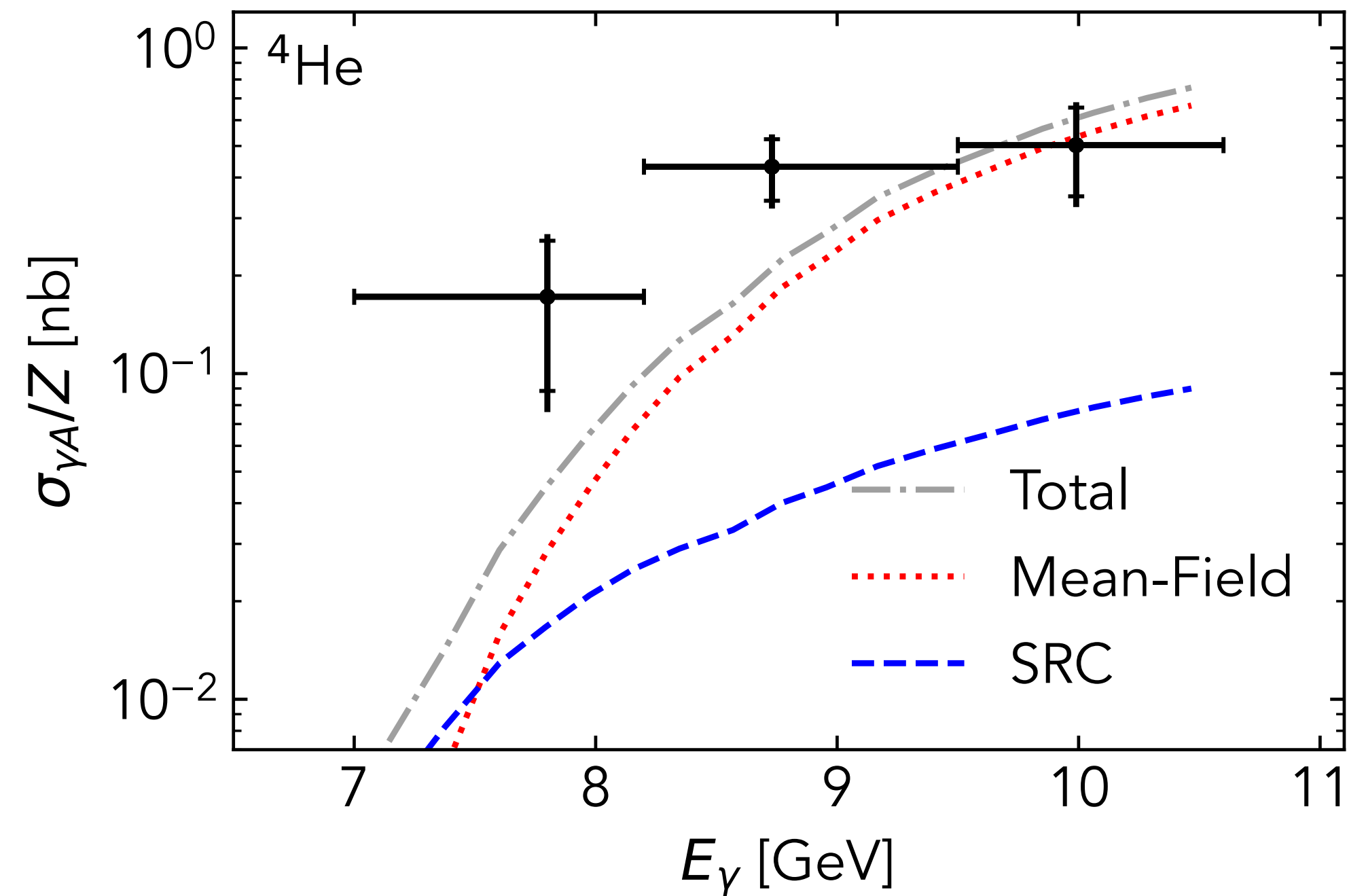
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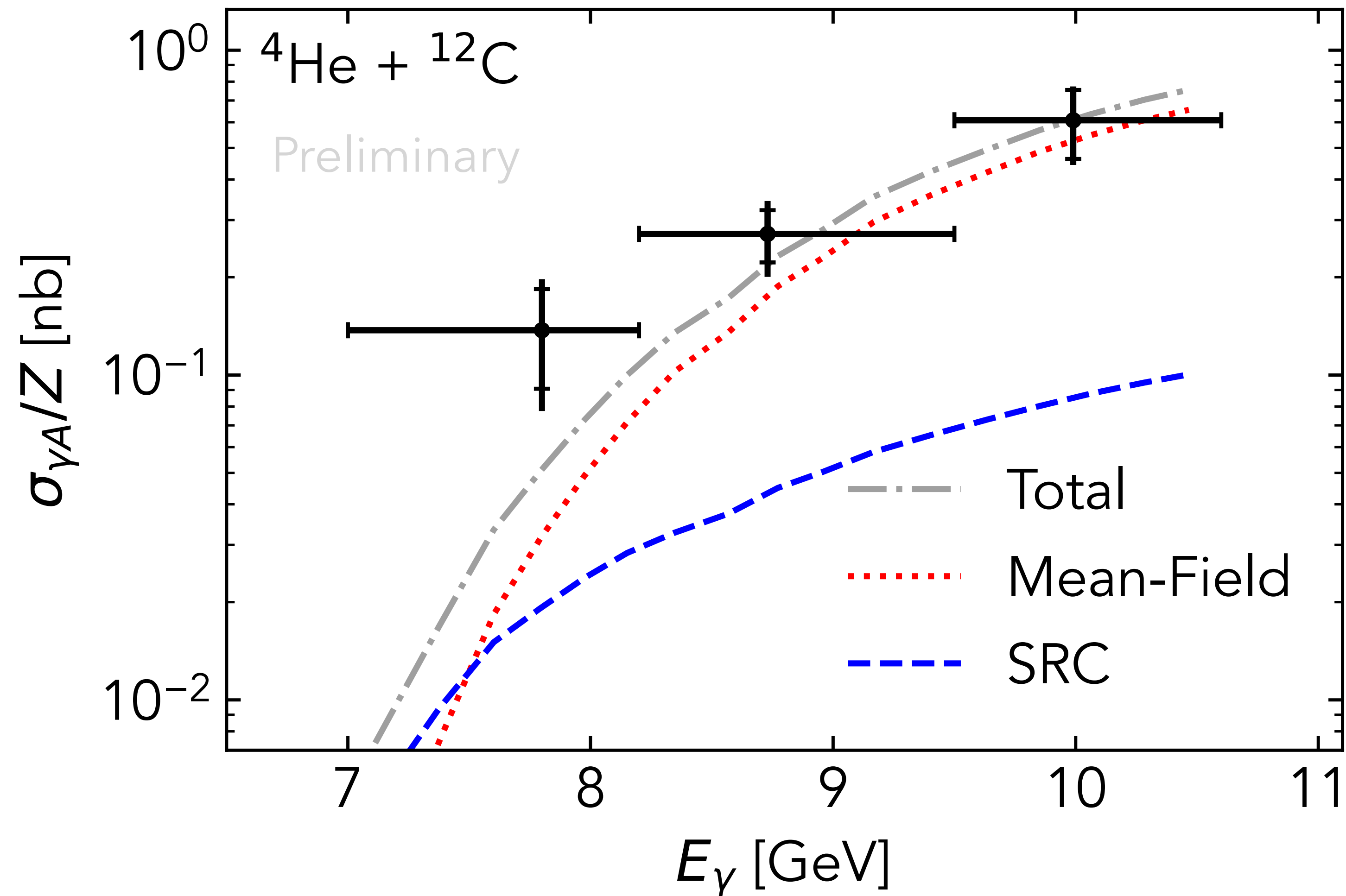
# Energy-averaged cross section across nuclei



# Cross section extracted as function of beam energy

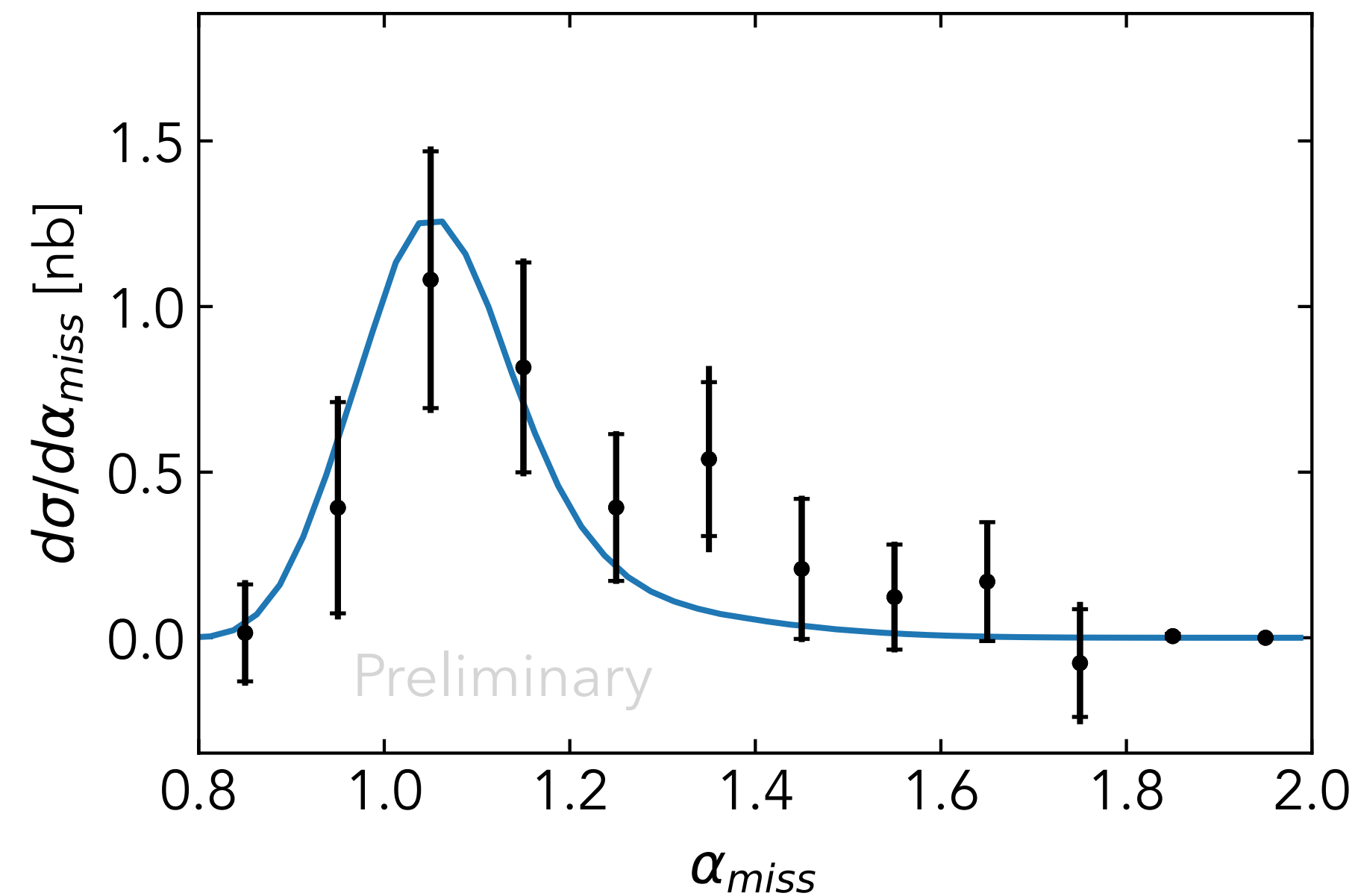


# Combining nuclei improves precision

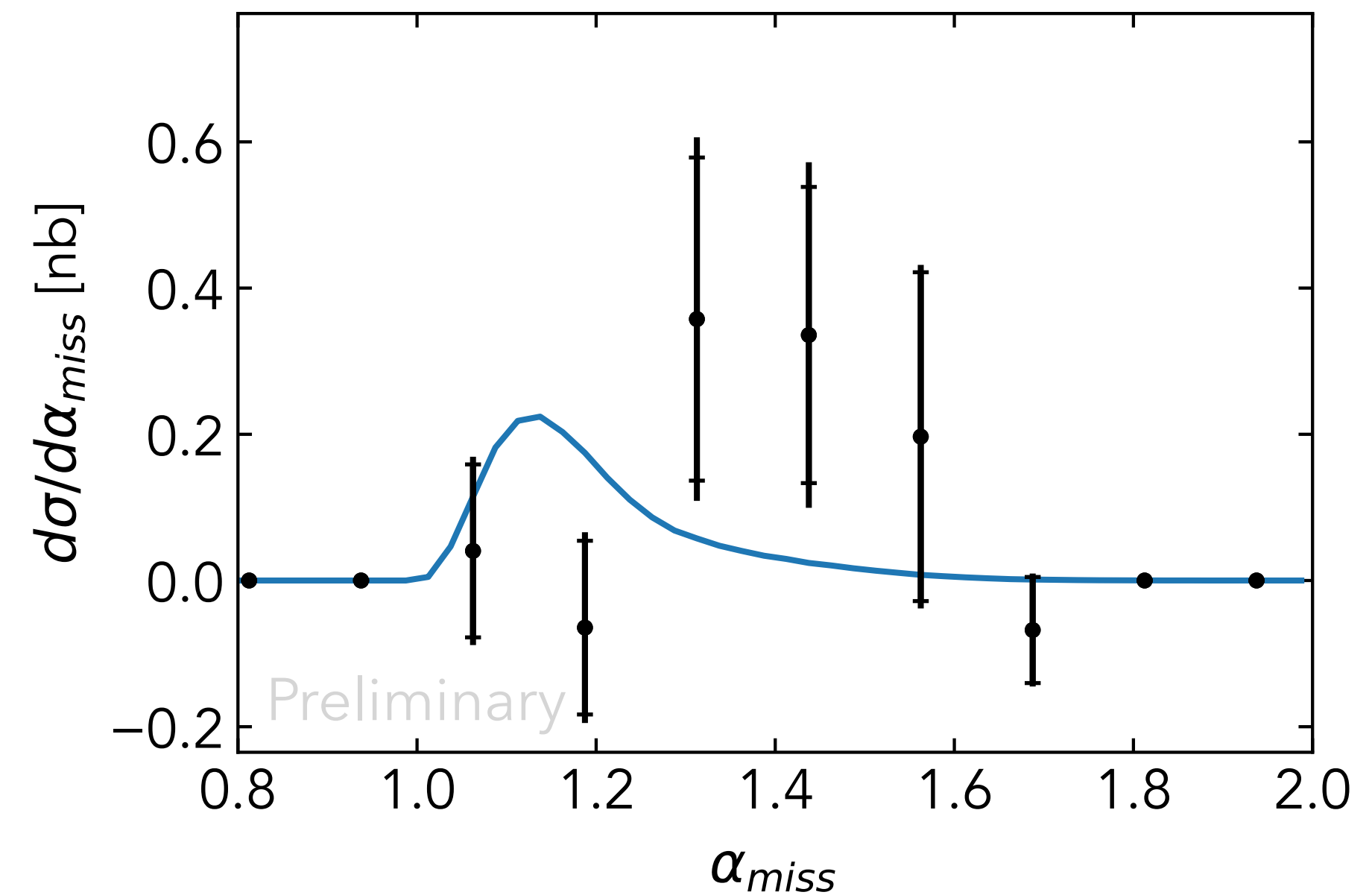


# Kinematics give insight into reaction mechanisms

**Above threshold:  $E_\gamma > 8.2$  GeV**

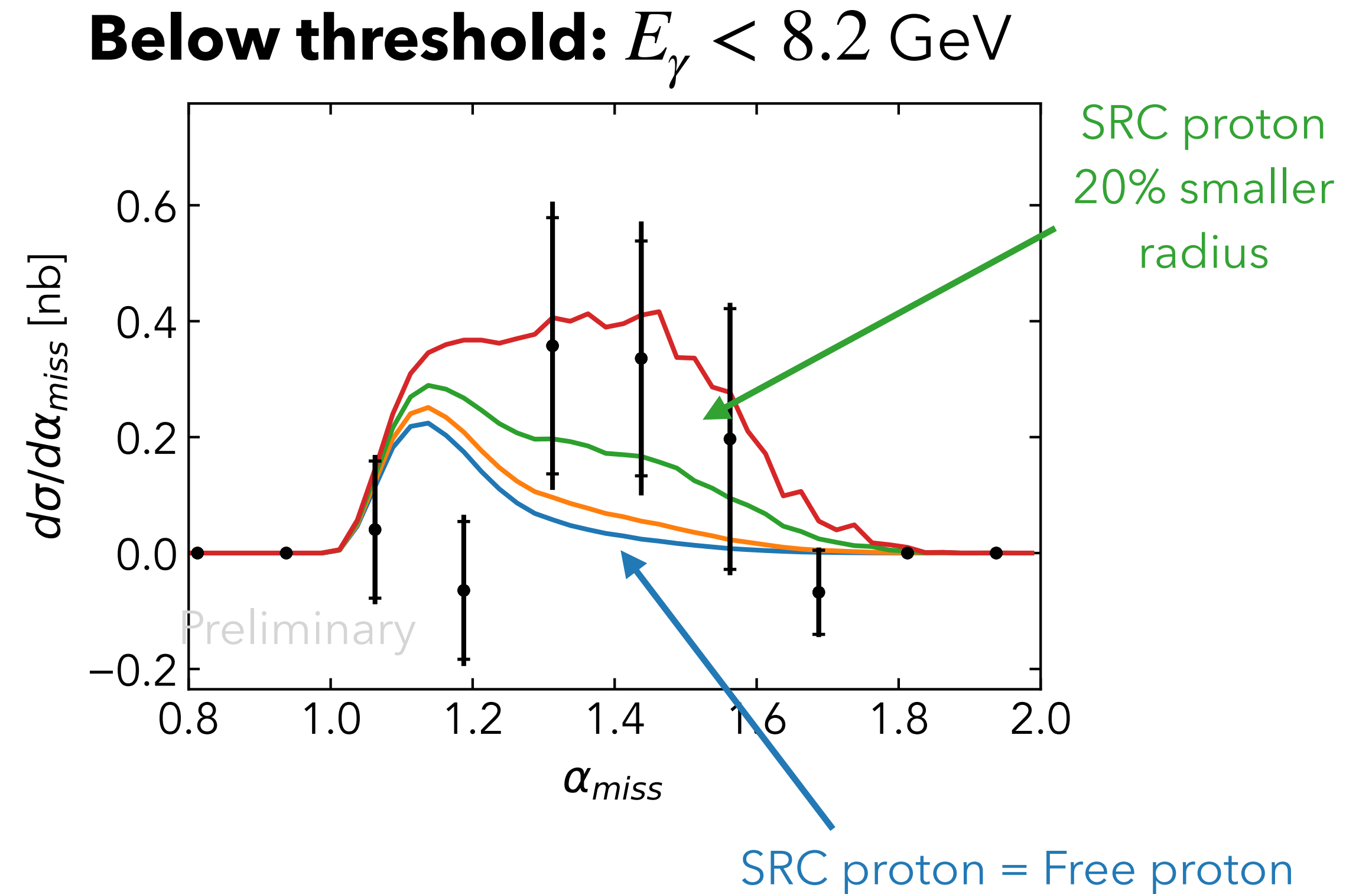
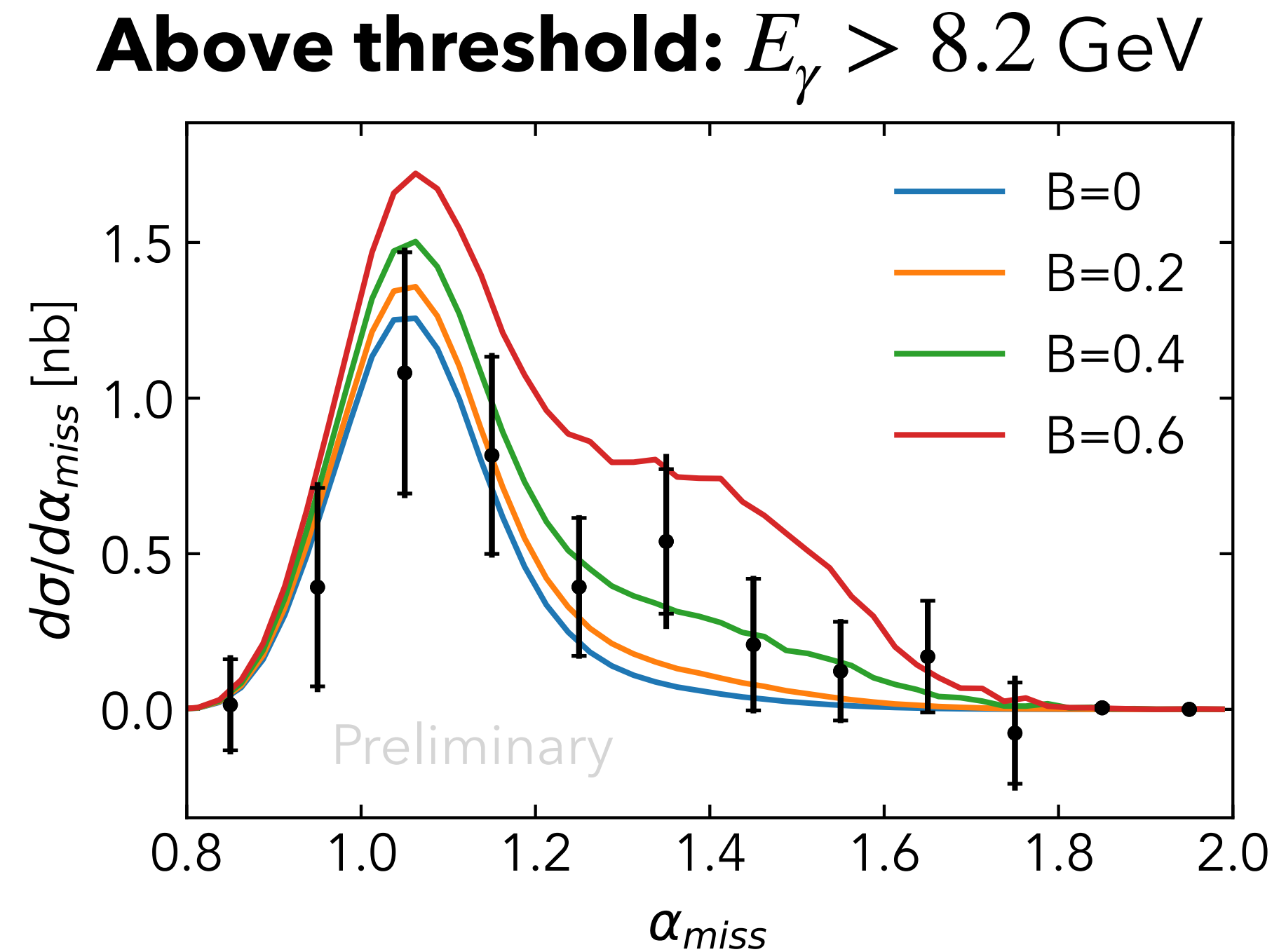


**Below threshold:  $E_\gamma < 8.2$  GeV**



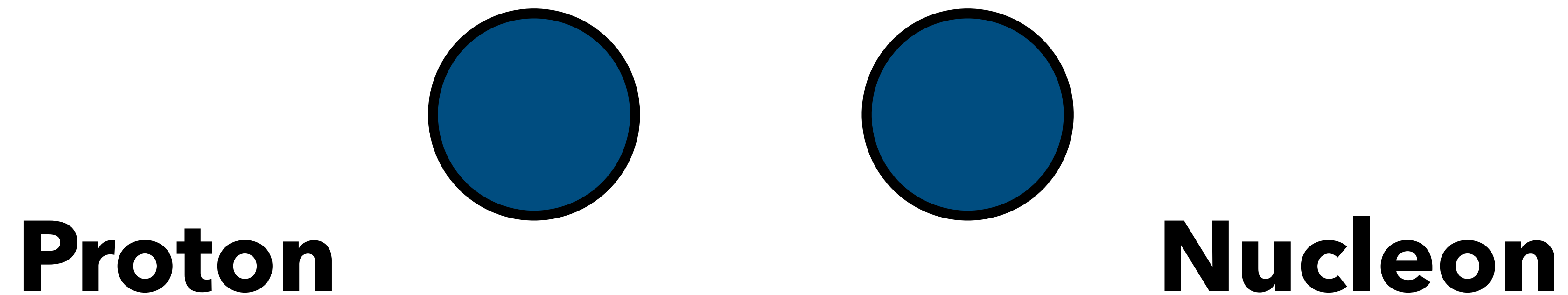
Lightcone momentum fraction  $\alpha_{miss} = \frac{E_{miss} - p_{z,miss}}{m_A/A}$

# Smaller-size proton could enhance large- $\alpha$ cross section

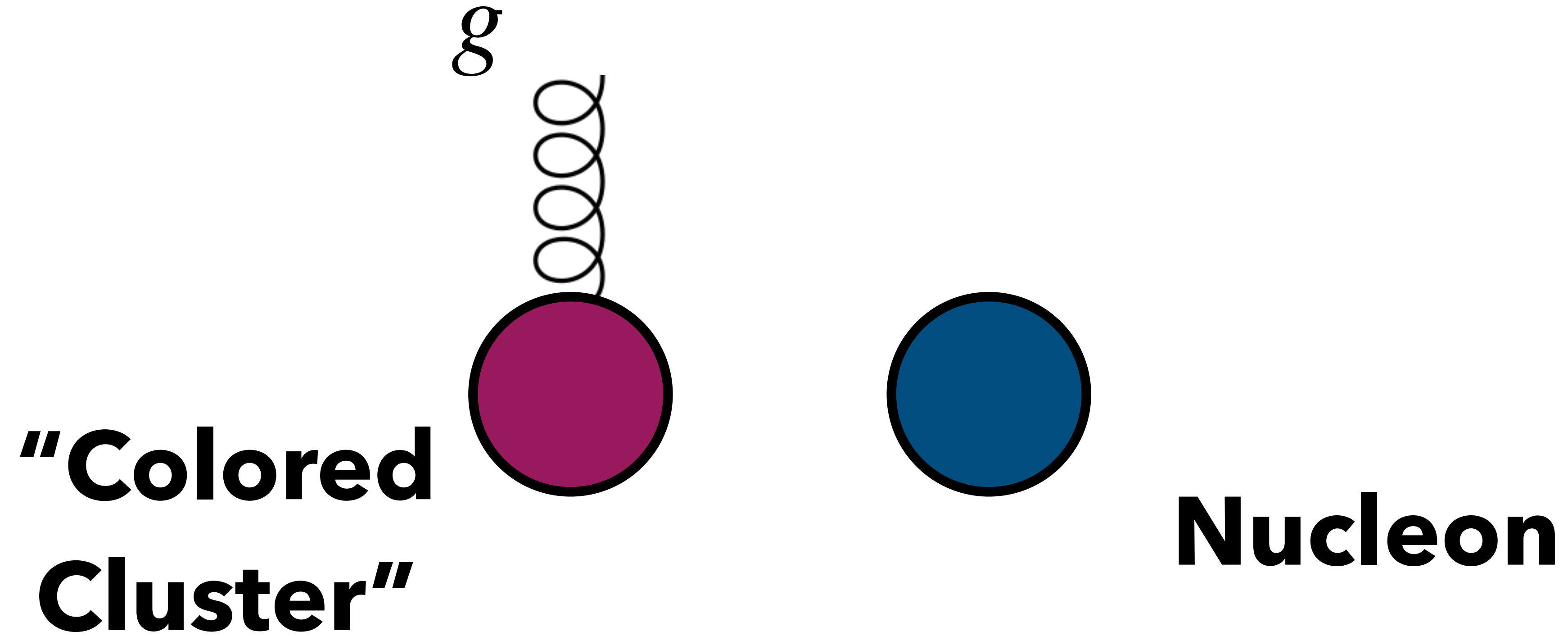


Modified gluon radius:  $\langle r \rangle_g \rightarrow (1 + Bv)\langle r \rangle_g$

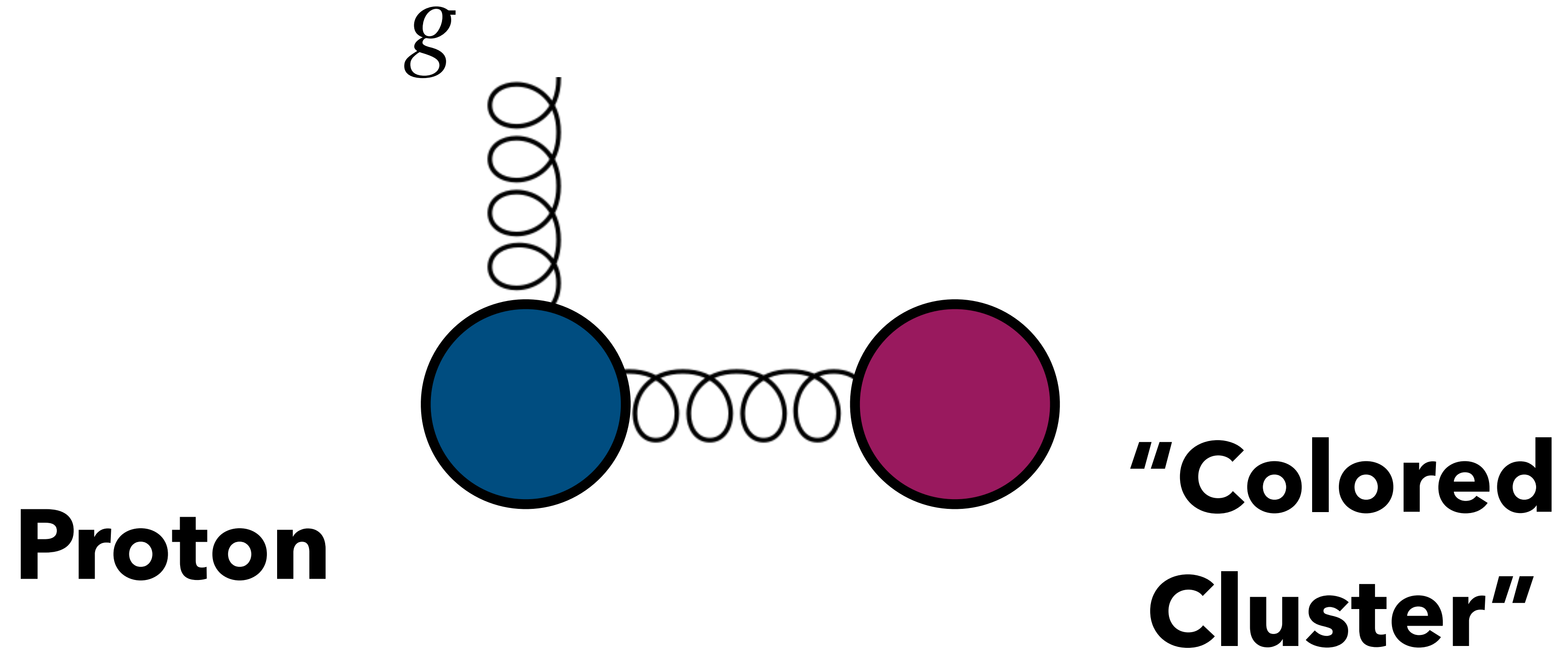
# Alternate Hypothesis: Two-body effects



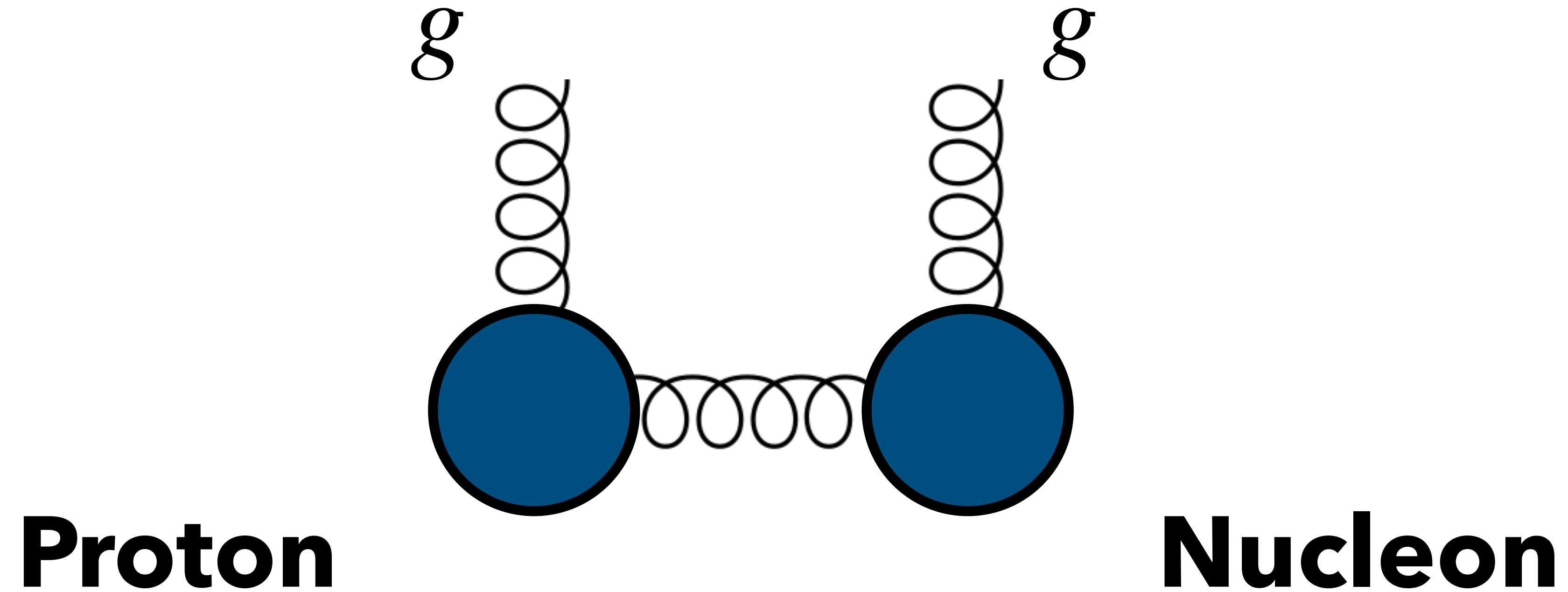
# Two-body effects



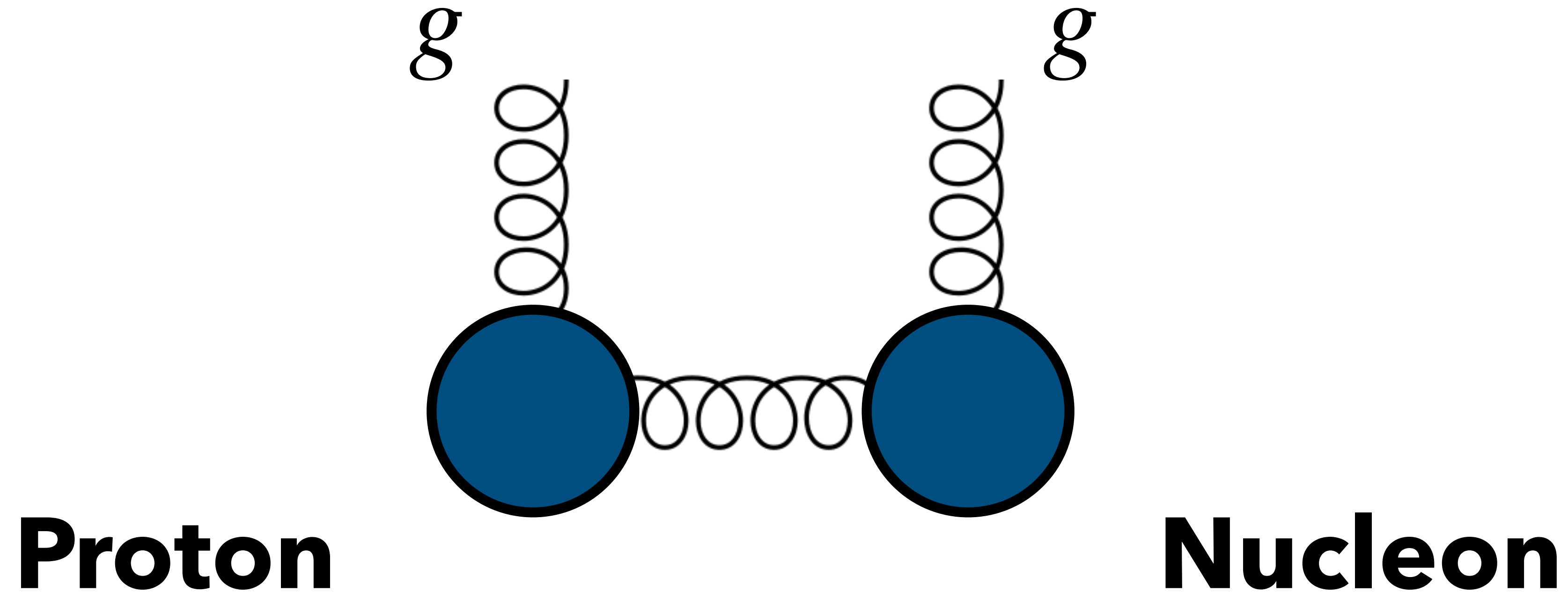
# Two-body effects



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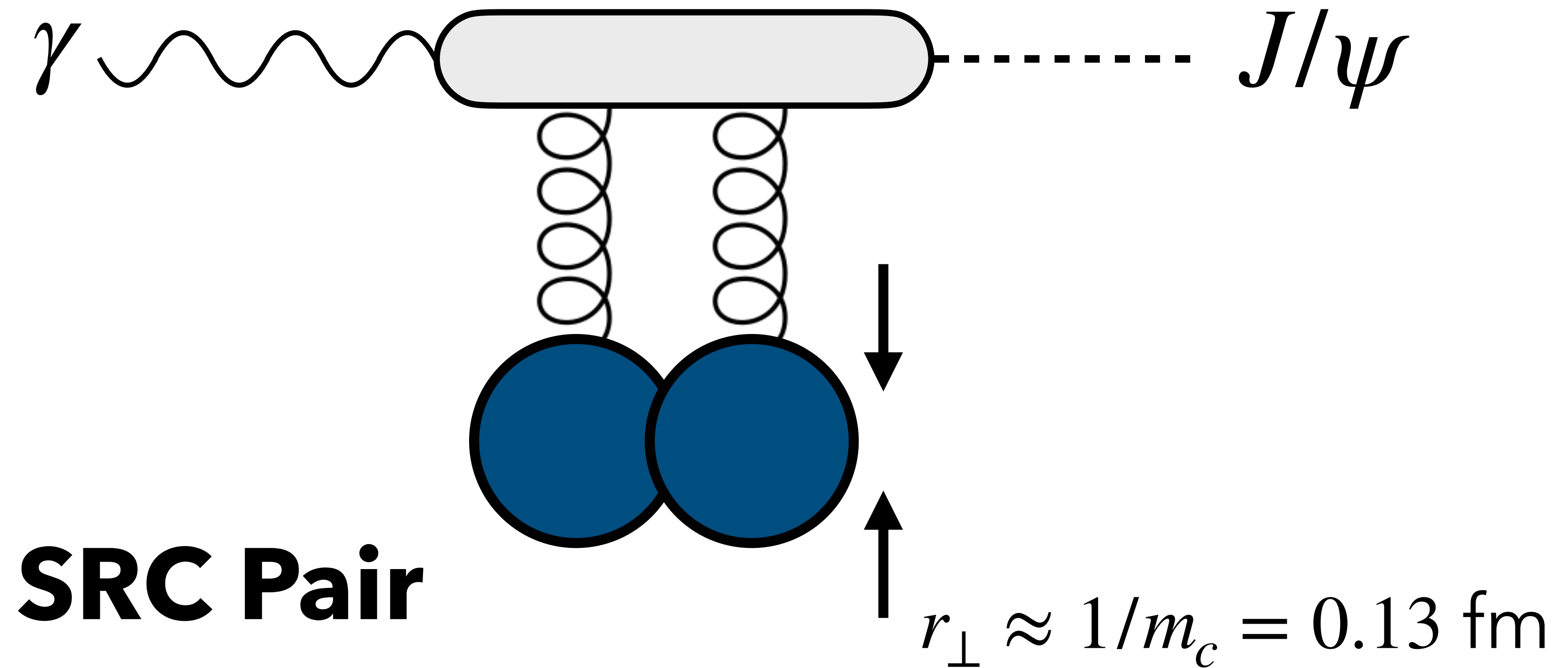


# Two-body effects



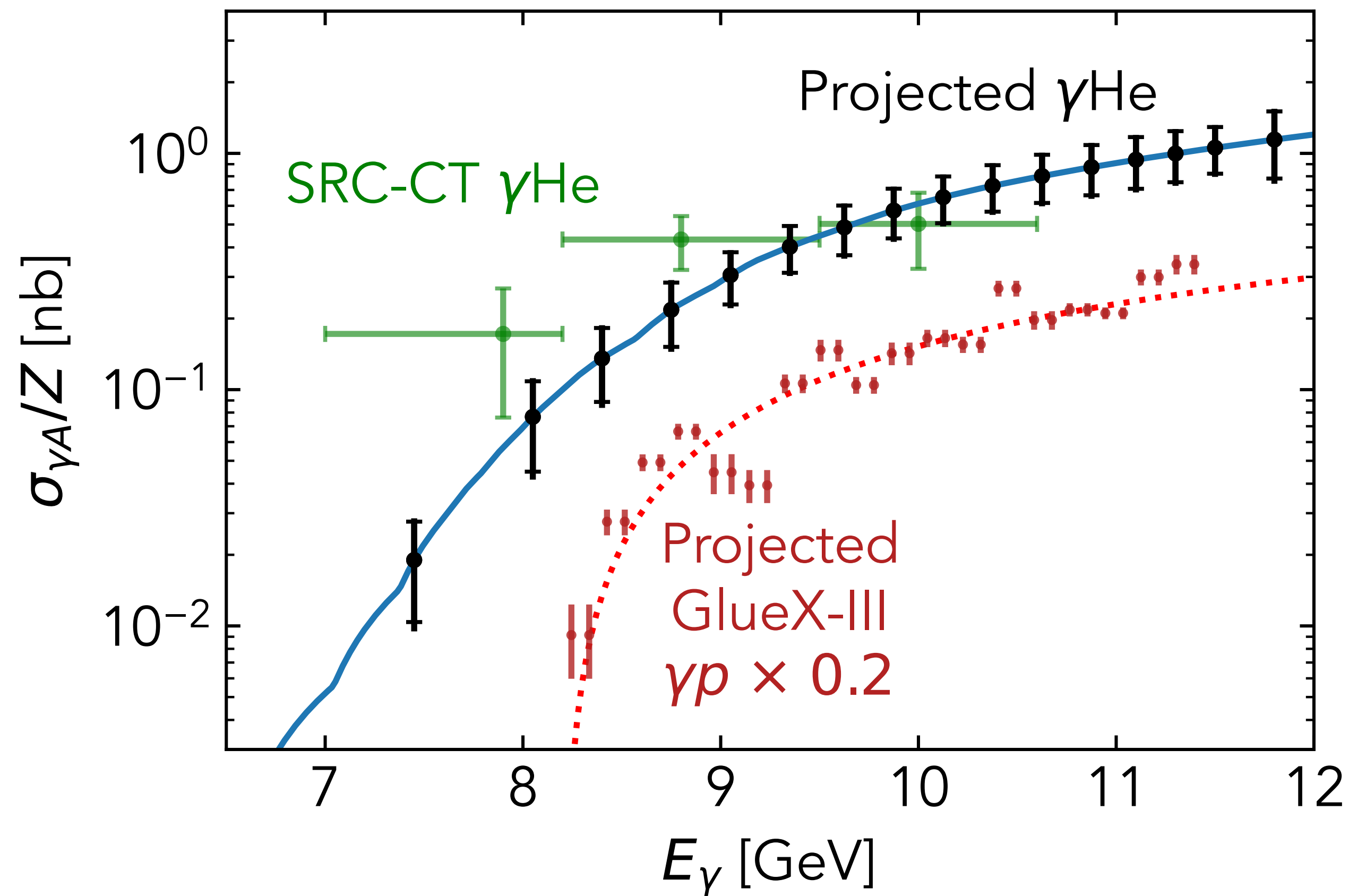
Possible "color correlations" between nucleons?  
Or pre-existing "hidden-color" states?

# Two-body effects



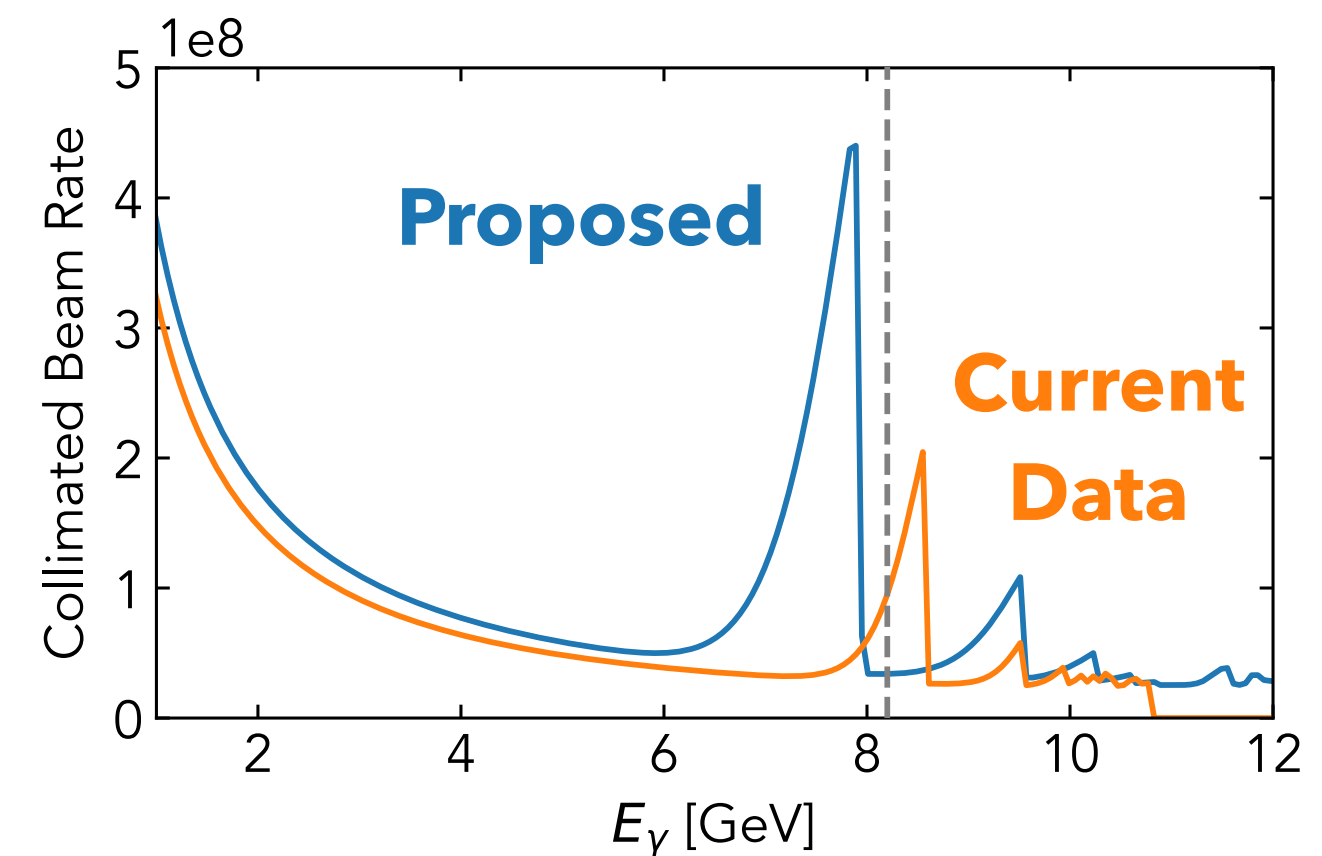
Particularly sensitive to short-distance configurations!

# Proposed measurement of $^4\text{He}$ can constrain mechanisms of $J/\psi$ production from nuclei at threshold

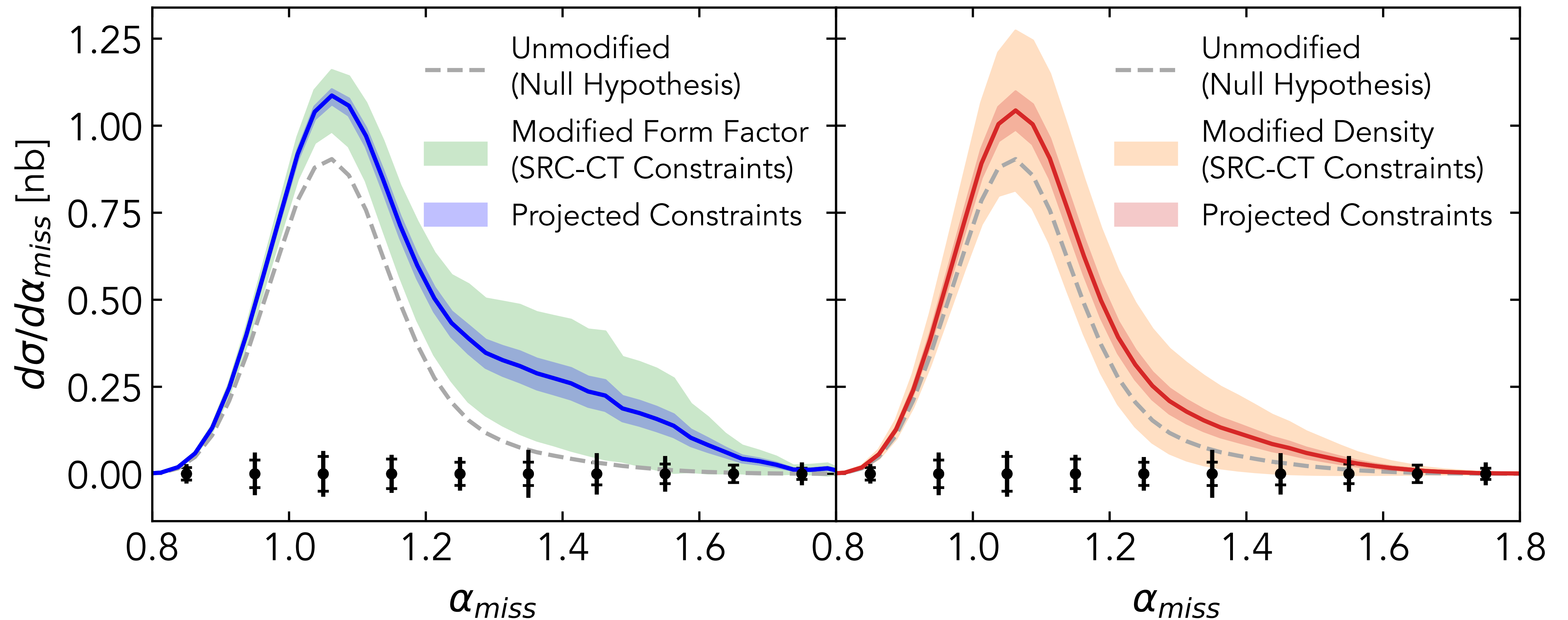


**160-day measurement of a single nucleus;**  
 **$\sim 800$   $J/\psi$  production events**  
**Measure cross section across full energy**  
**range and kinematics**

Optimized radiator geometry maximizes measurement of sub-threshold production



# Proposed measurement of $^4\text{He}$ can constrain mechanisms of $J/\psi$ production from nuclei at threshold



# Conclusions

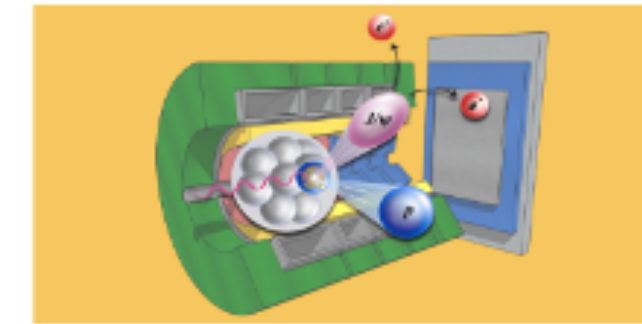
- New photonuclear measurement gives first measurement of incoherent  $J/\psi$  production at and below threshold energy
- Kinematic distributions indicate possible modification of gluons in bound proton
- Proposed data can identify mechanisms of  $J/\psi$  production off nuclei

Physics

SYNOPSIS

**Peering into Protons**

May 22, 2025



The internal structure of protons bound in nuclei has been probed by studying short-lived particles created when high-energy photons strike nuclei.

