Nuclear Charm Production and Short-Range Correlations in Hall D

Proposal C12-23-009

Spokespersons:

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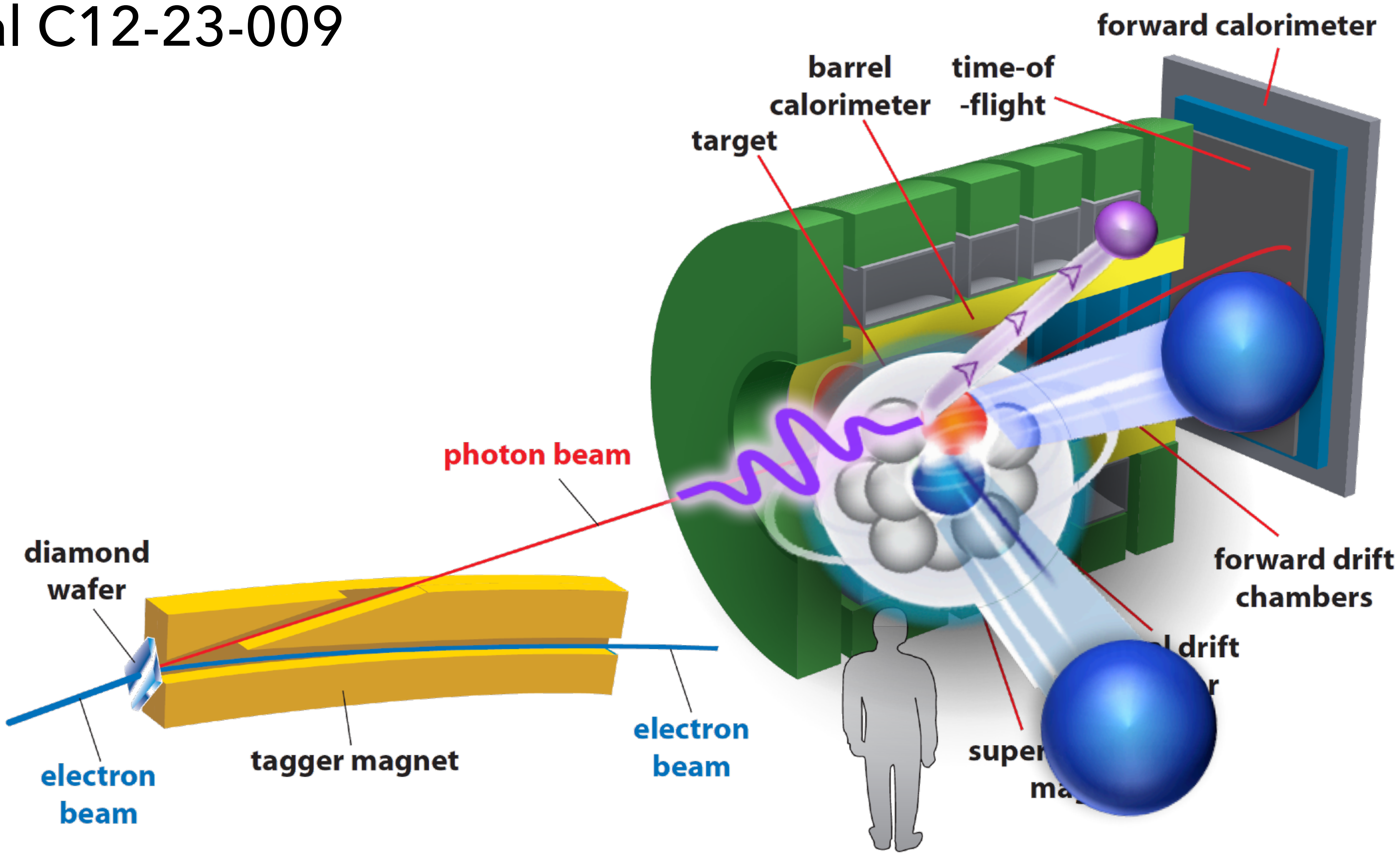
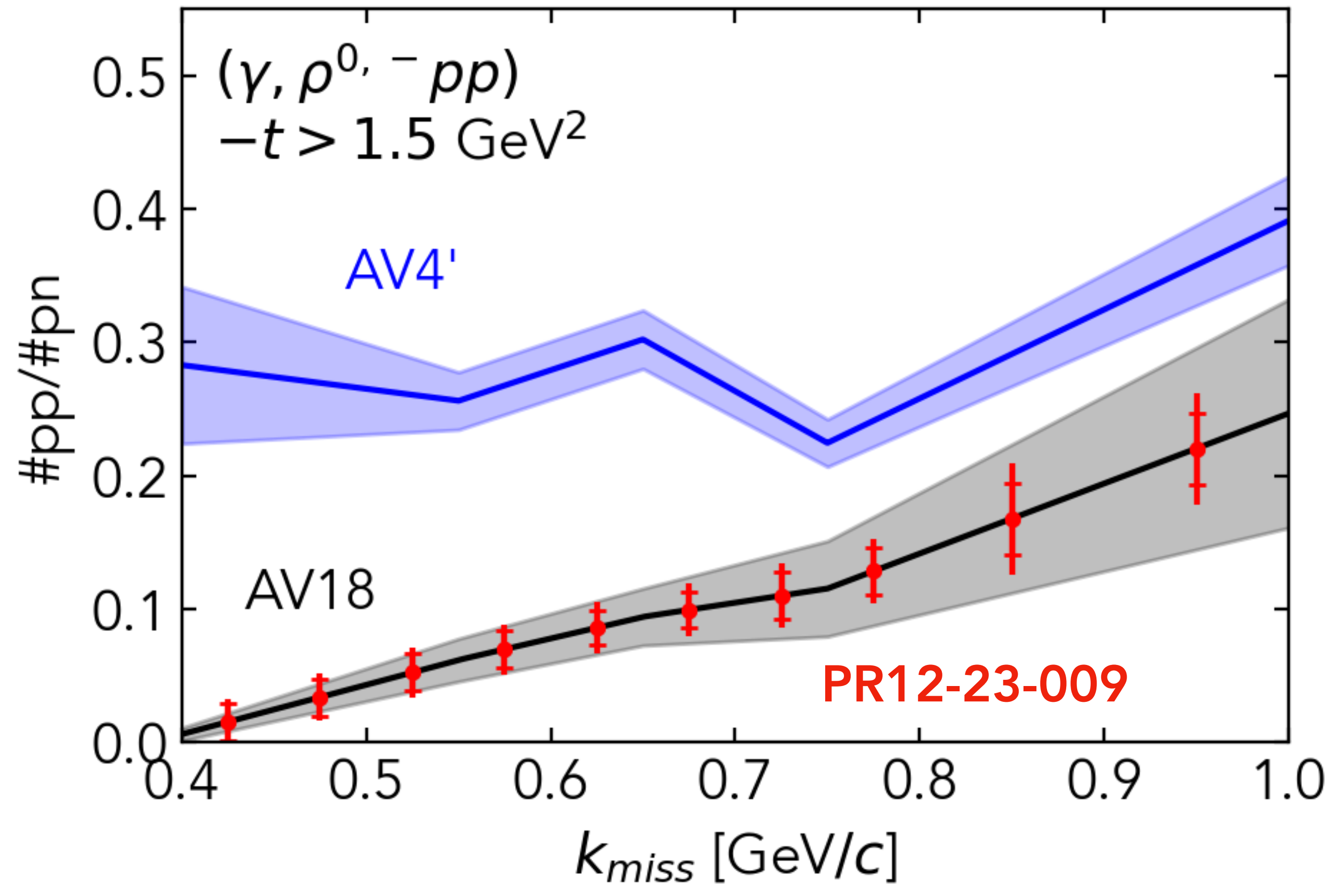


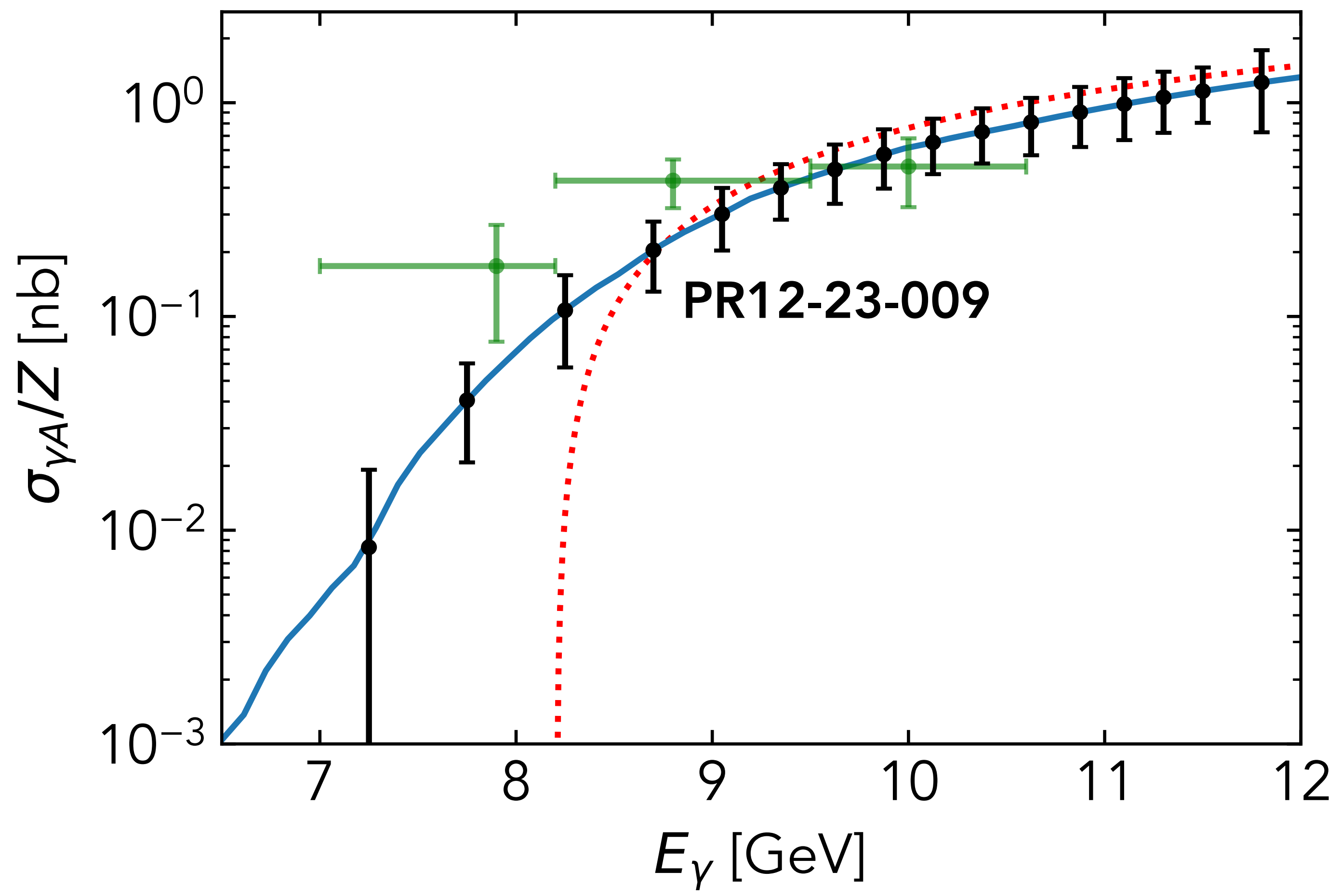
Background on C12-23-009

- PAC51 C2: 100 days, ^{4}He, Hall D/GlueX
- Goals:
  - Precision SRC physics
  - Nuclear J/ψ photoproduction near and below threshold
- Conditionally approved:

  ✓ Understanding systematics

  ✓ Publication of current results





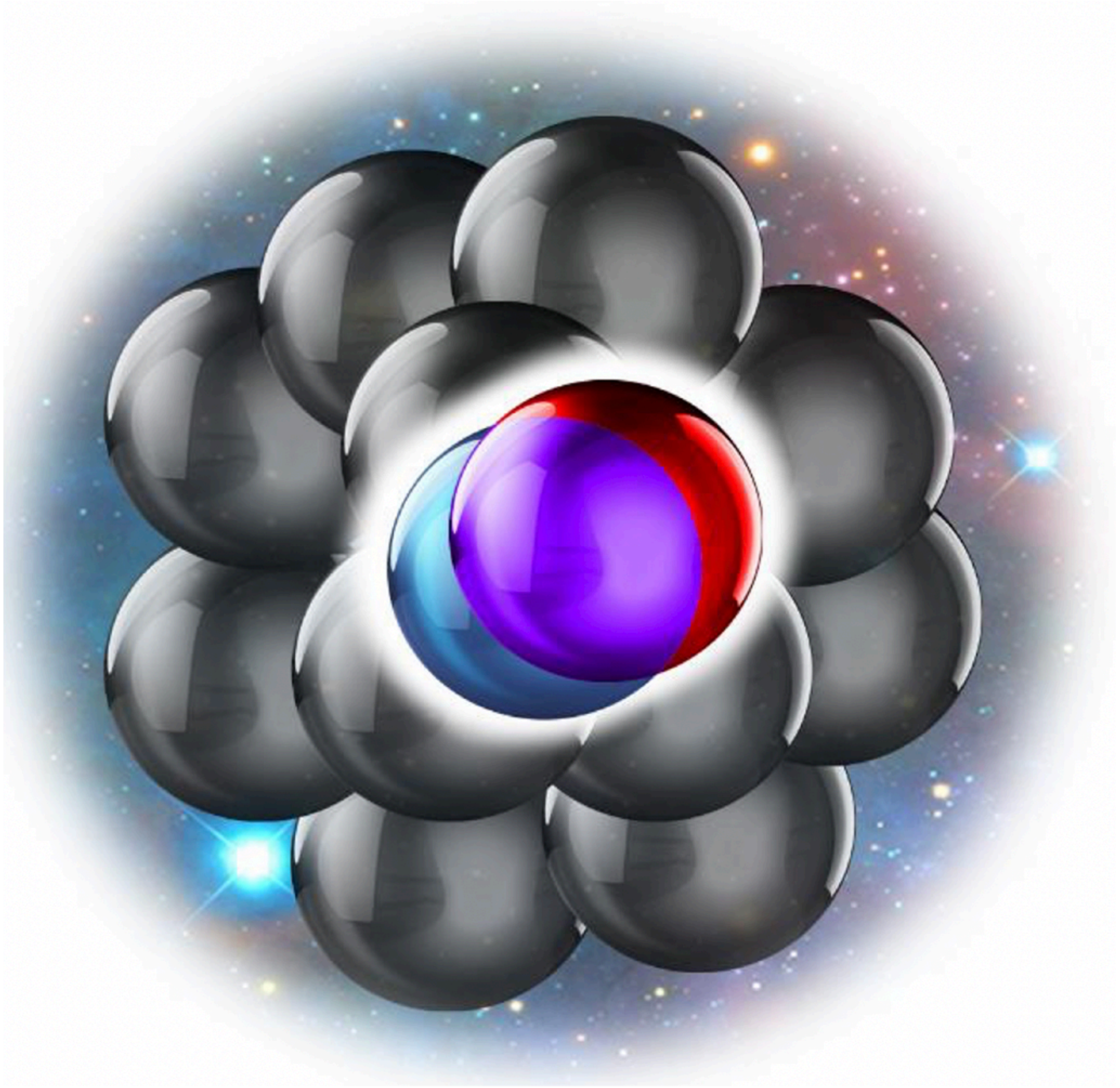
Outline of this talk

1. Physics intro: SRC + J/ψ from current data

2. Meeting approval conditions: systematics & publications

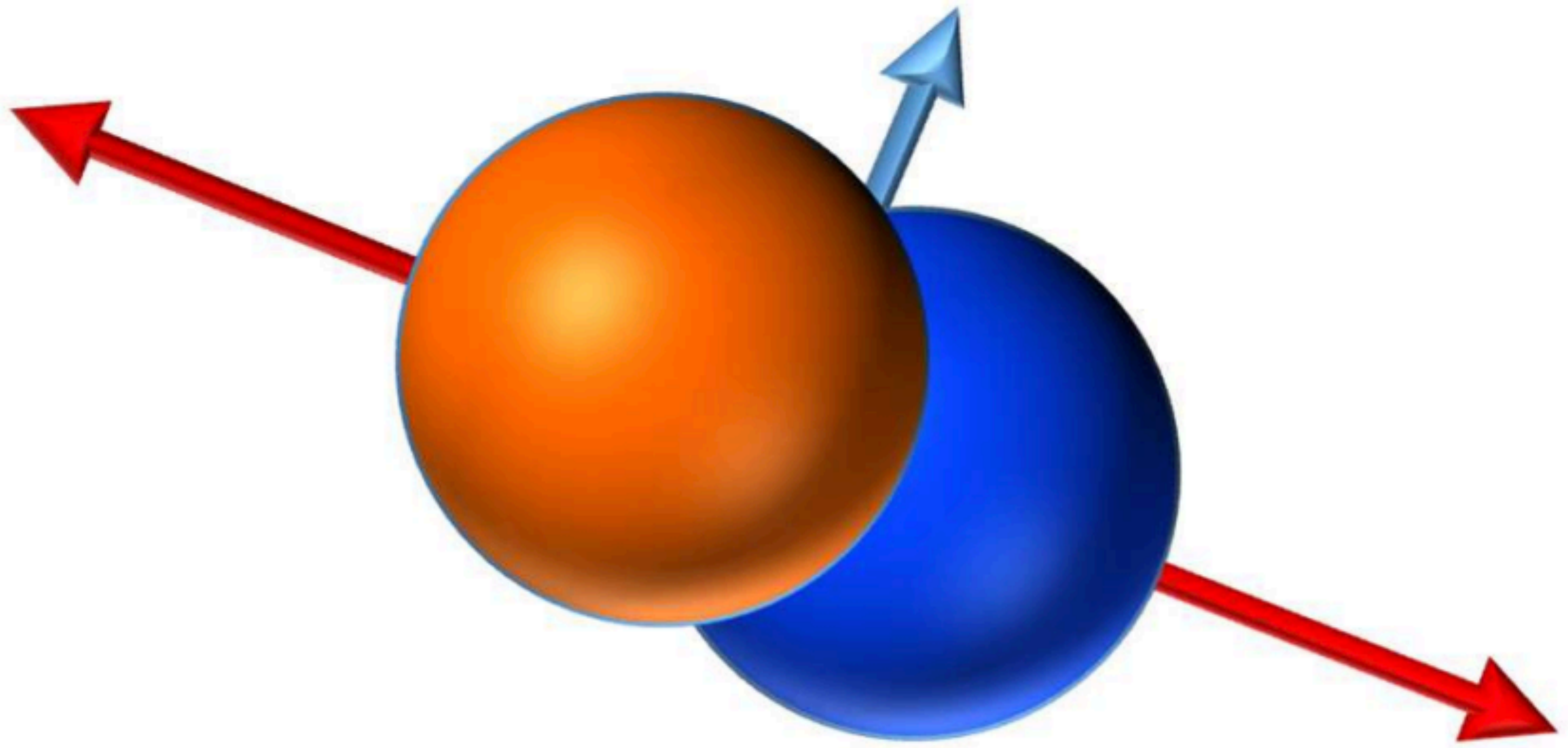
What are SRCs?

Short-ranged, short-lived, highly correlated pairs of nucleons



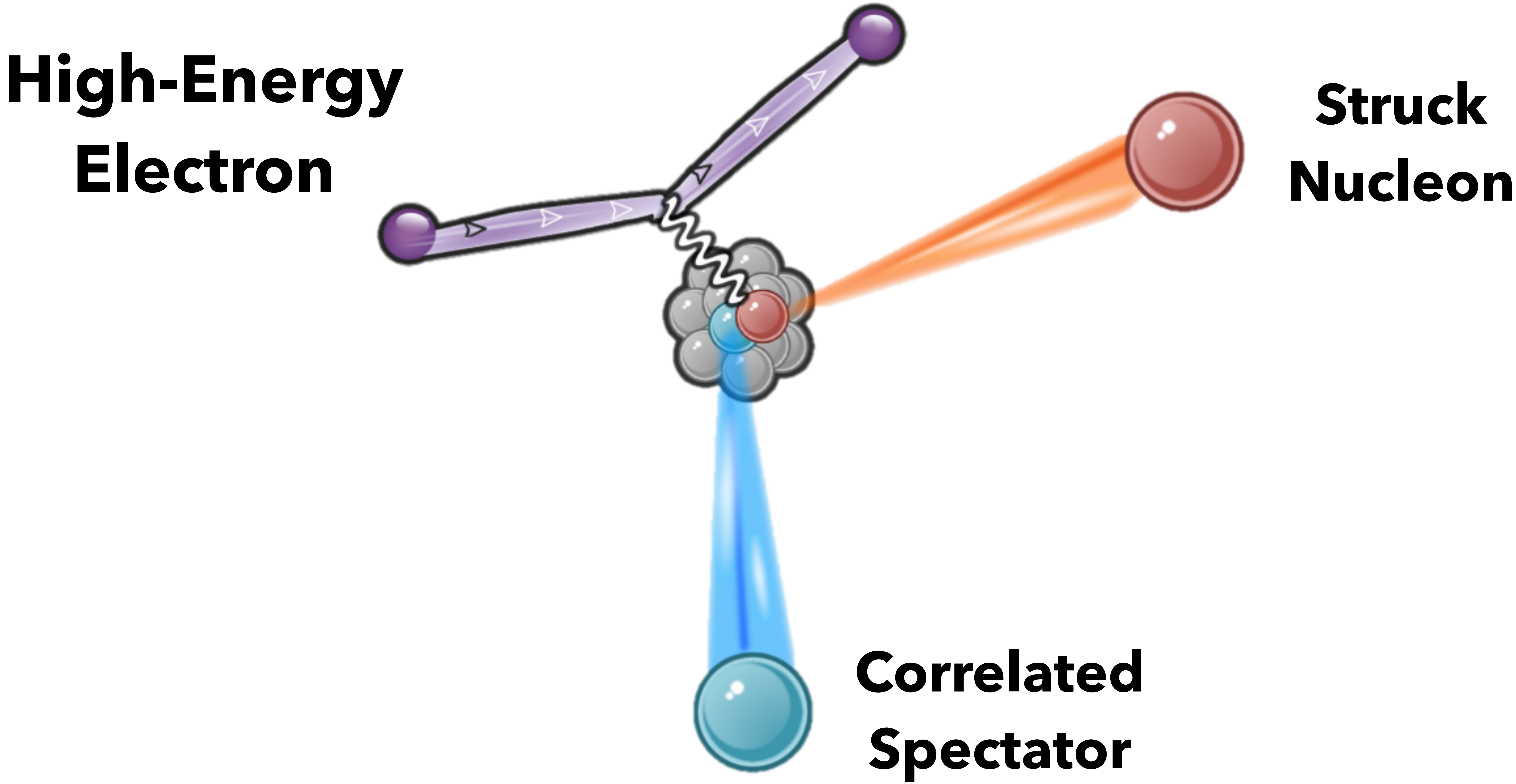
Position-space

High relative and lower center-of-mass momentum



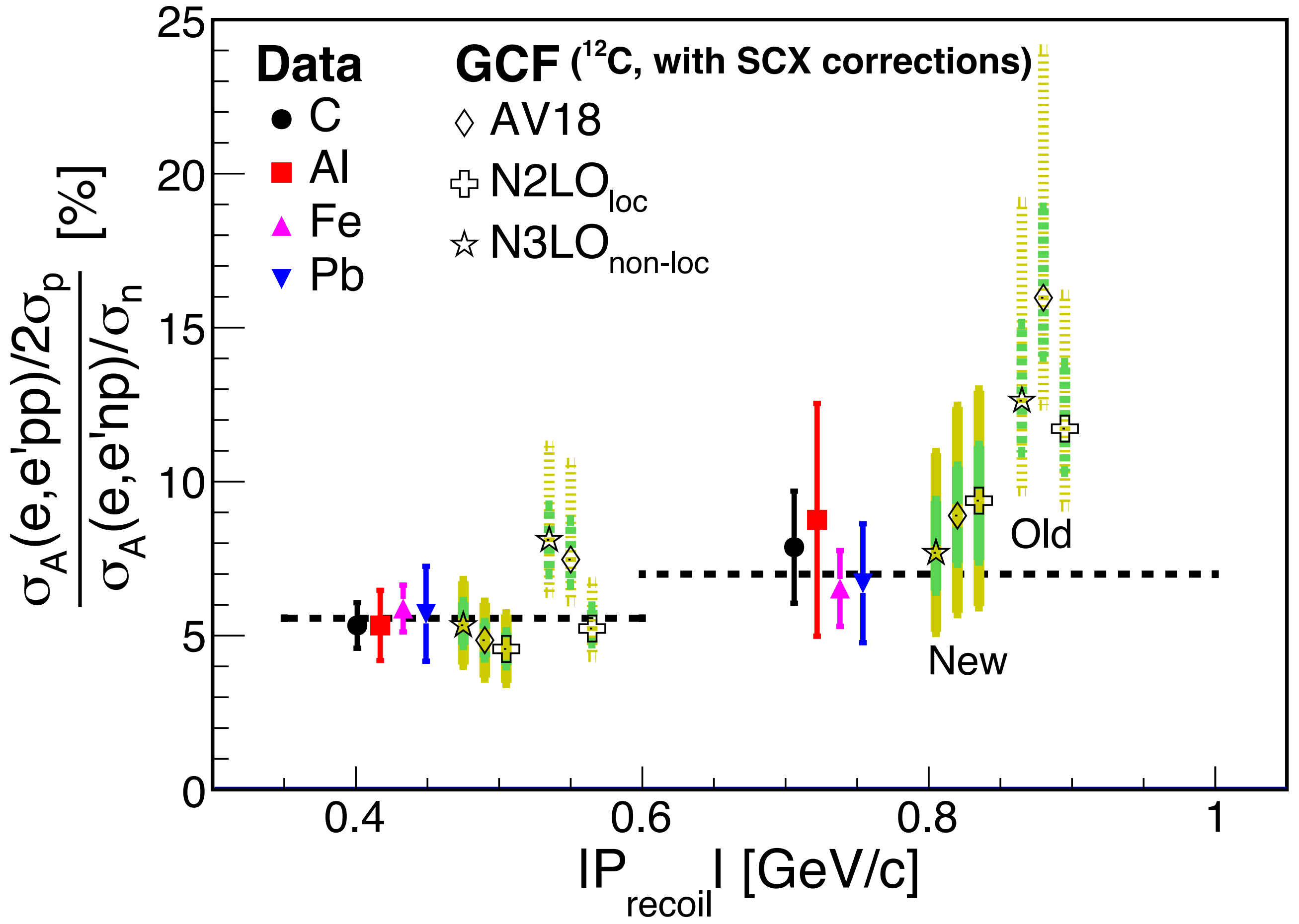
Momentum-space

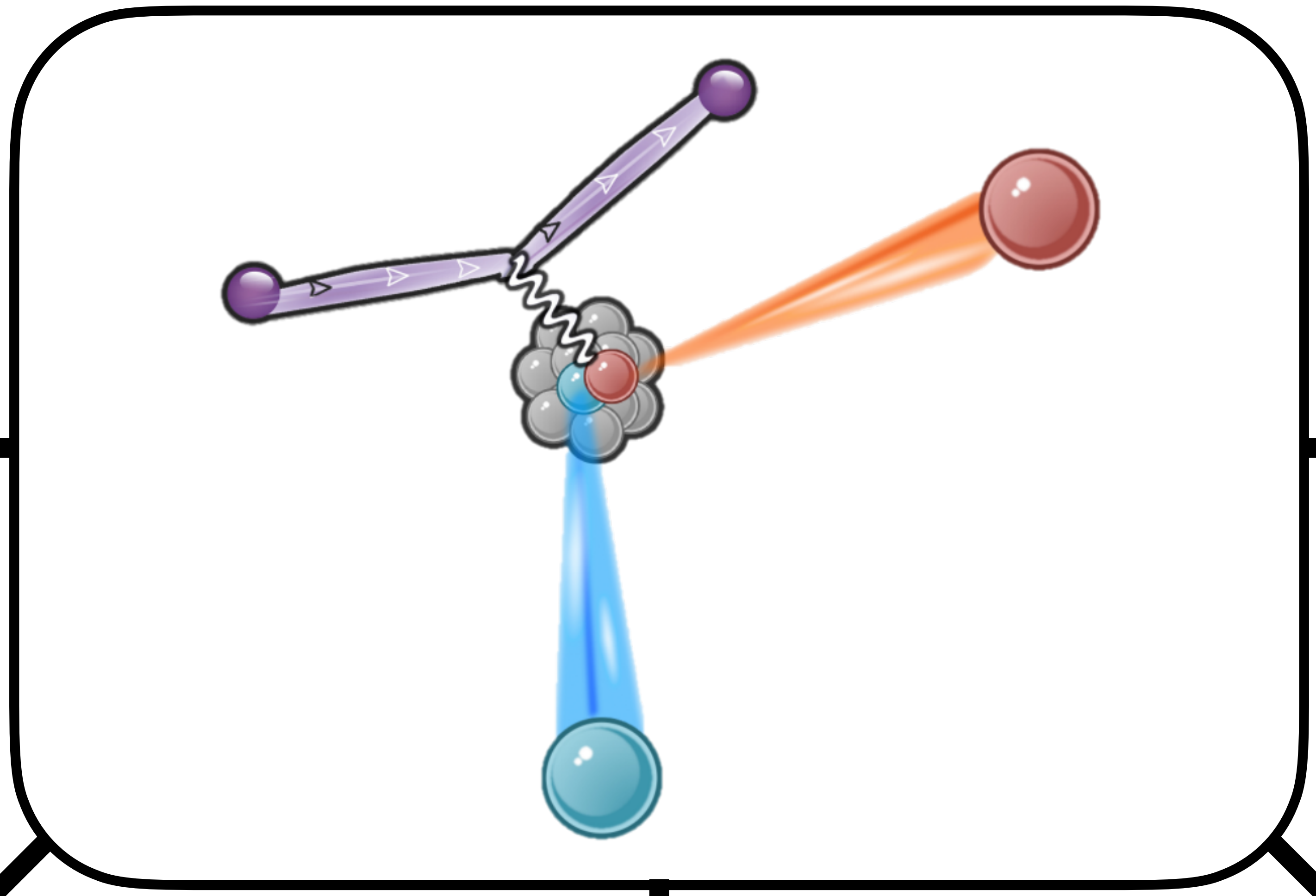
SRCs studied with hard breakup reactions



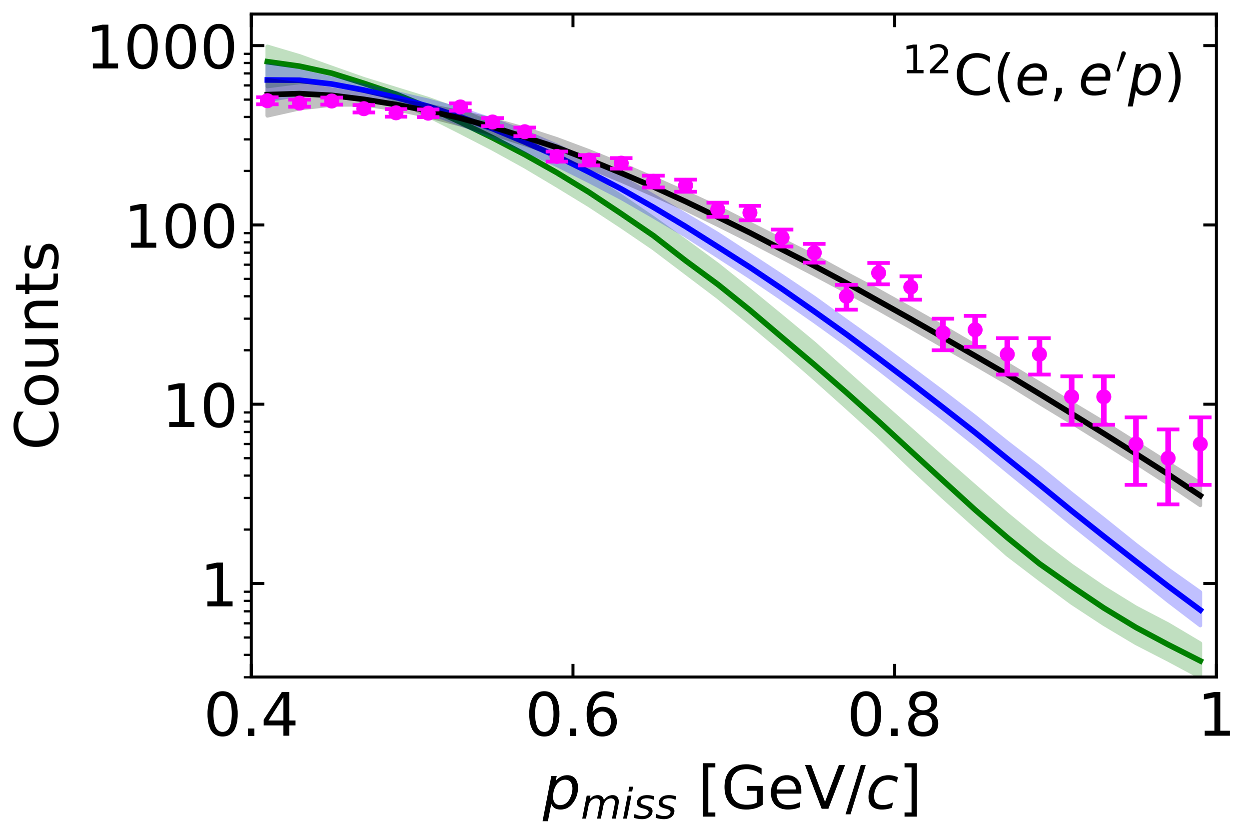
Results from on electron-scattering

PRL 122, 172502 (2019)

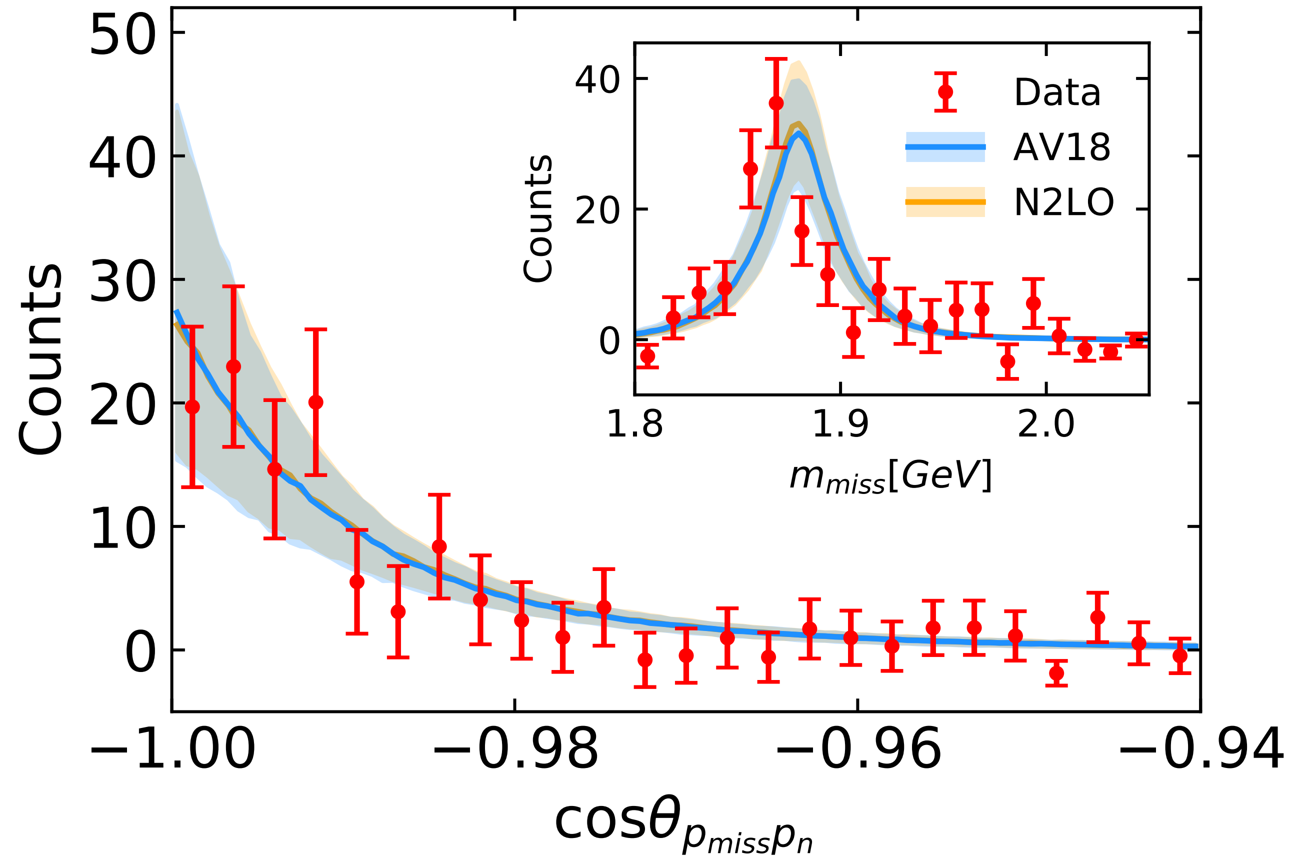




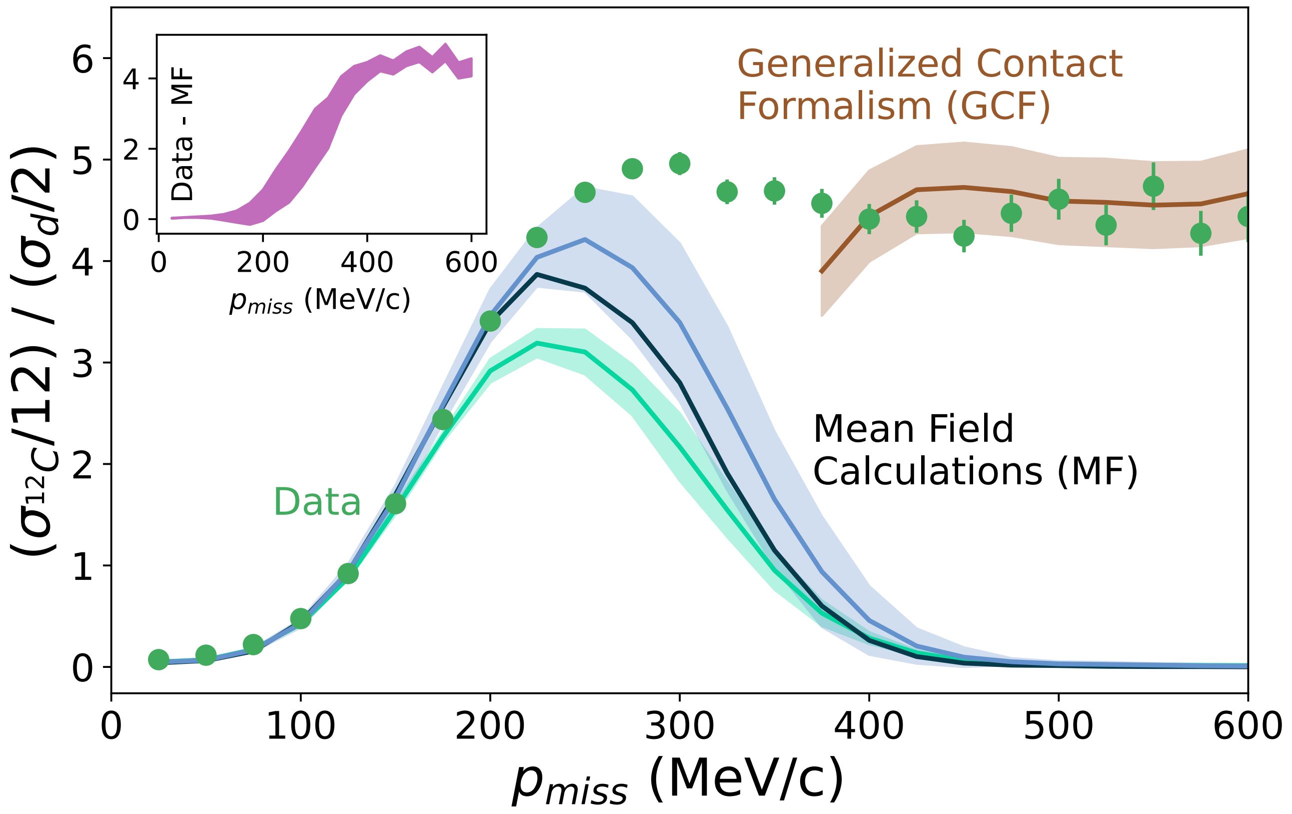
Nature 578, 540 (2020)



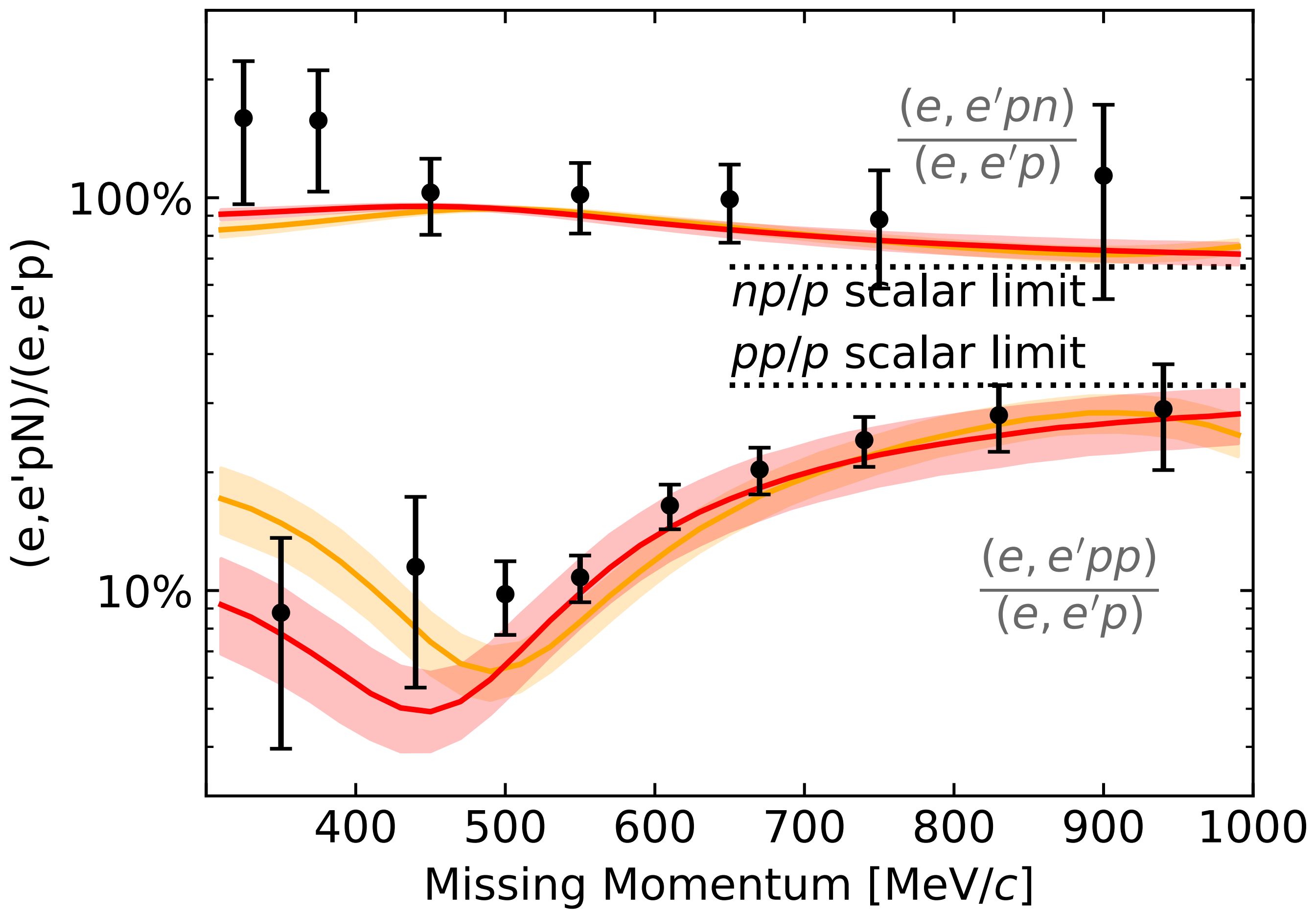
PLB 805, 135429 (2020)



PRC Lett. 107, L061301 (2022)

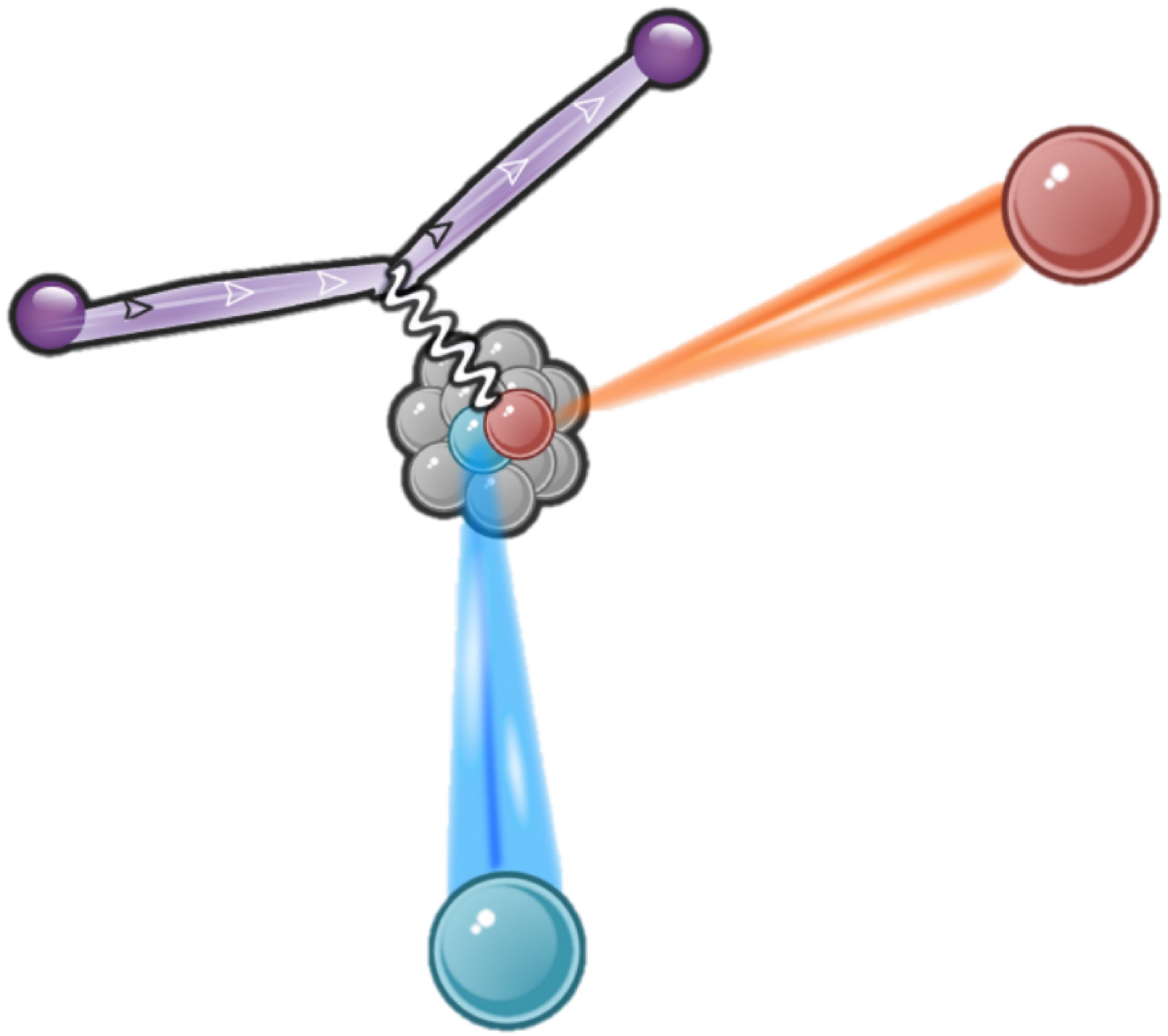


PLB 820, 136523 (2021)

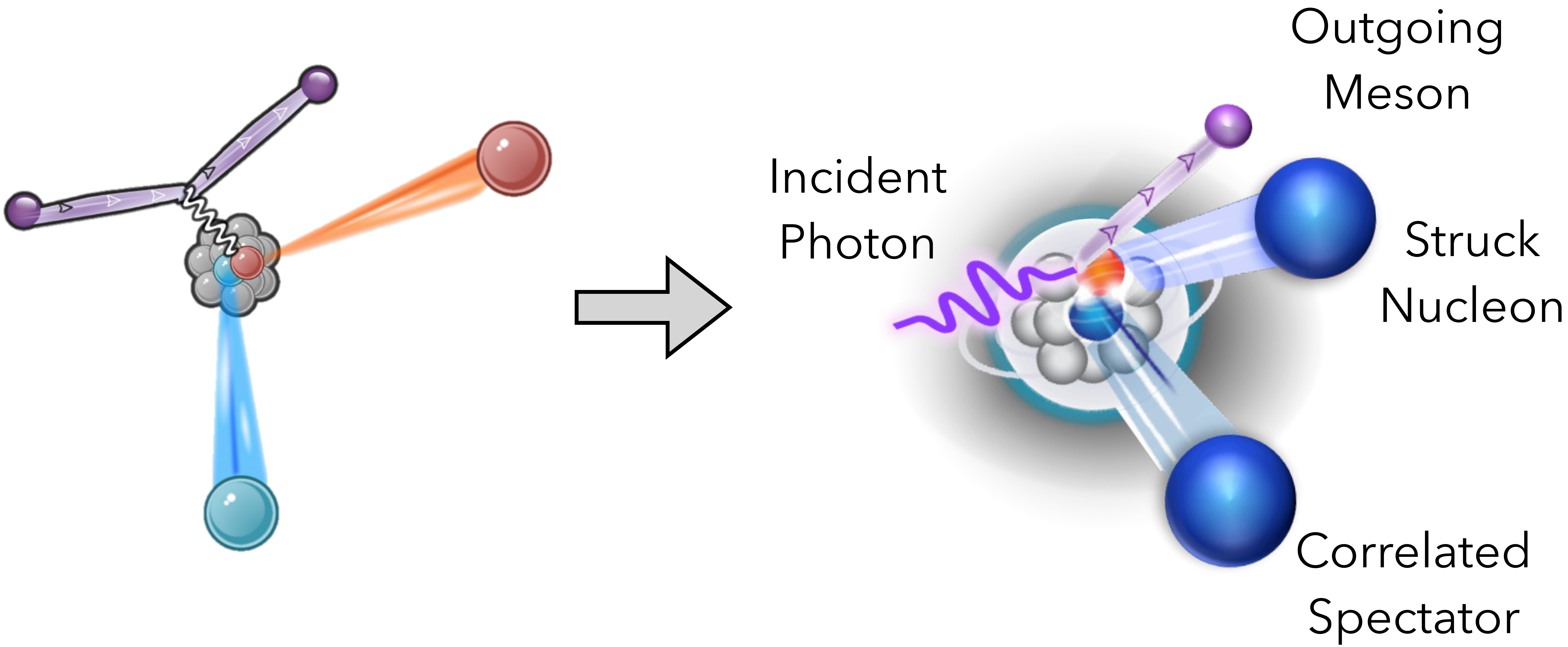


PRL (2007), PRL (2014), Science (2014), PRL (2018)…

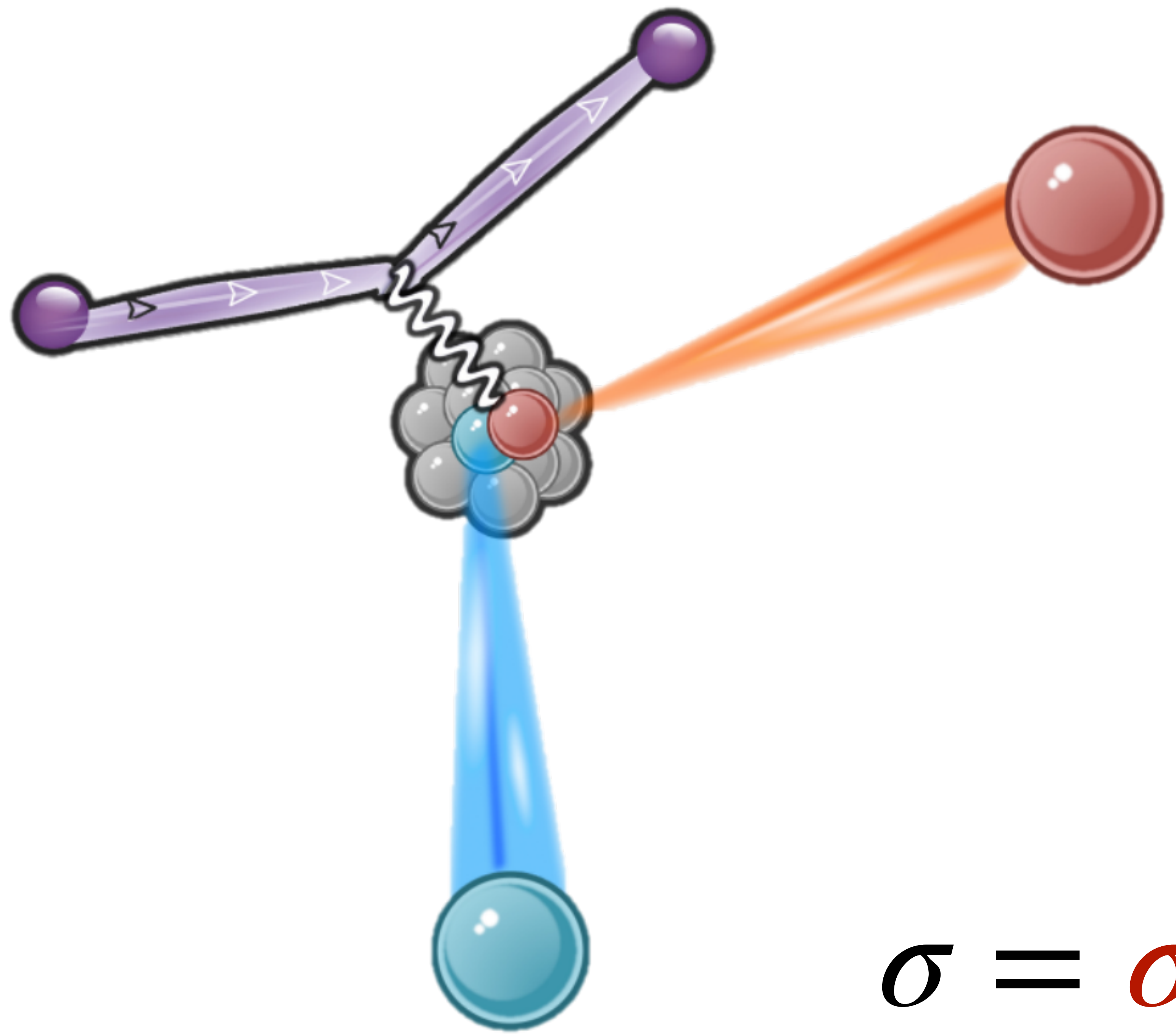
From electrons to photons

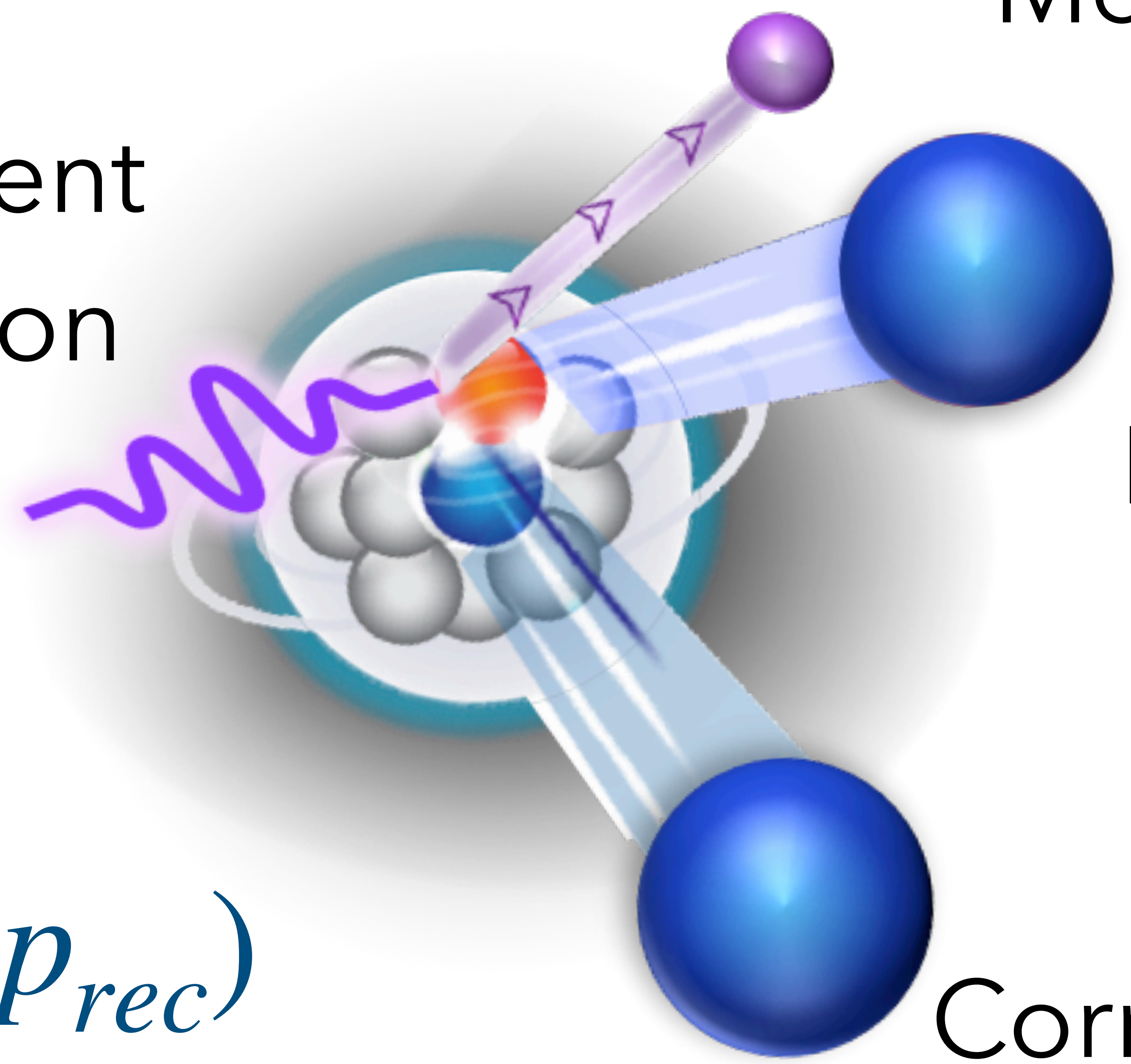


From electrons to photons



From electrons to photons





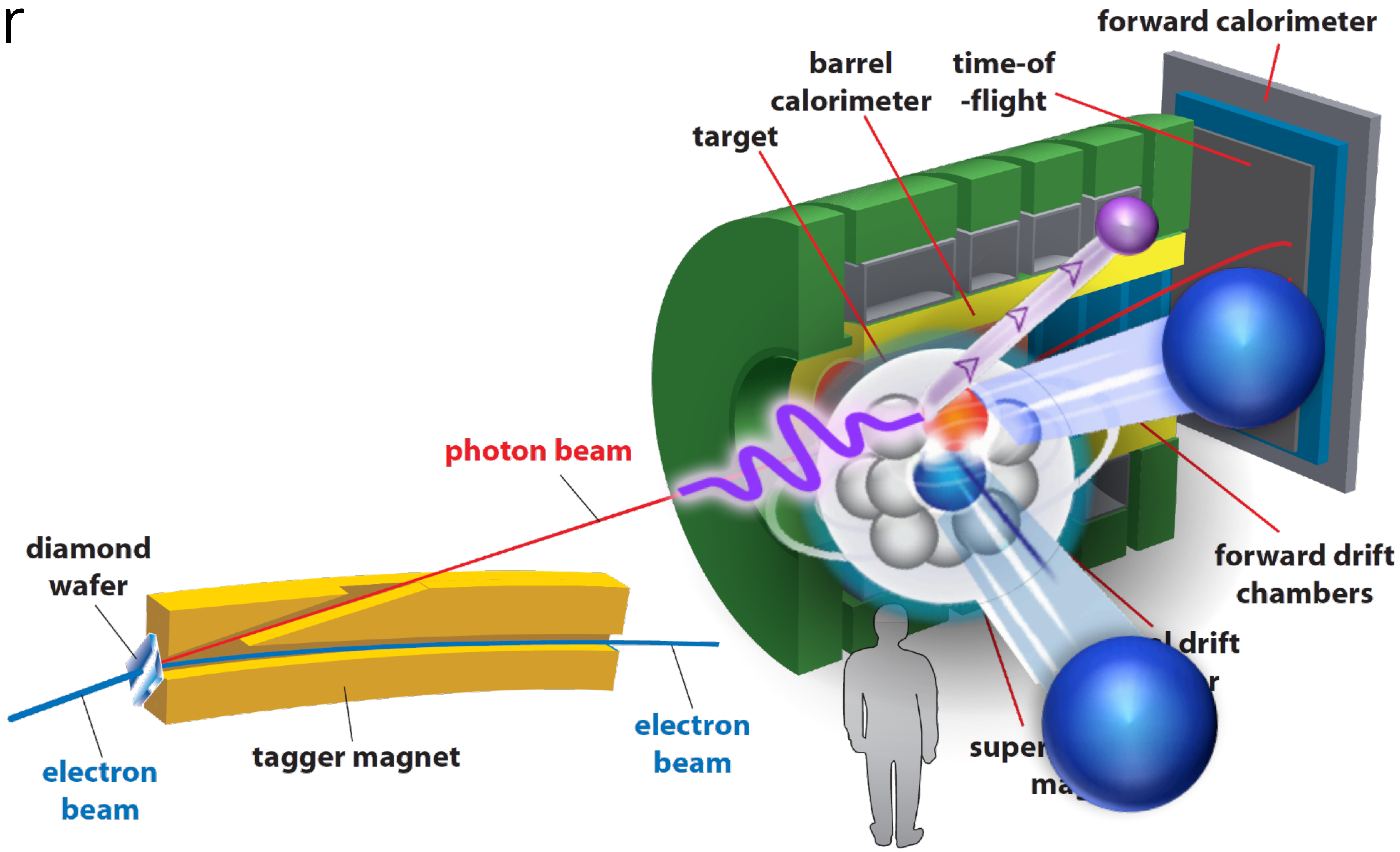
$$\sigma = \sigma_N(q) \times S(p_i, p_{rec})$$

Different reactions!

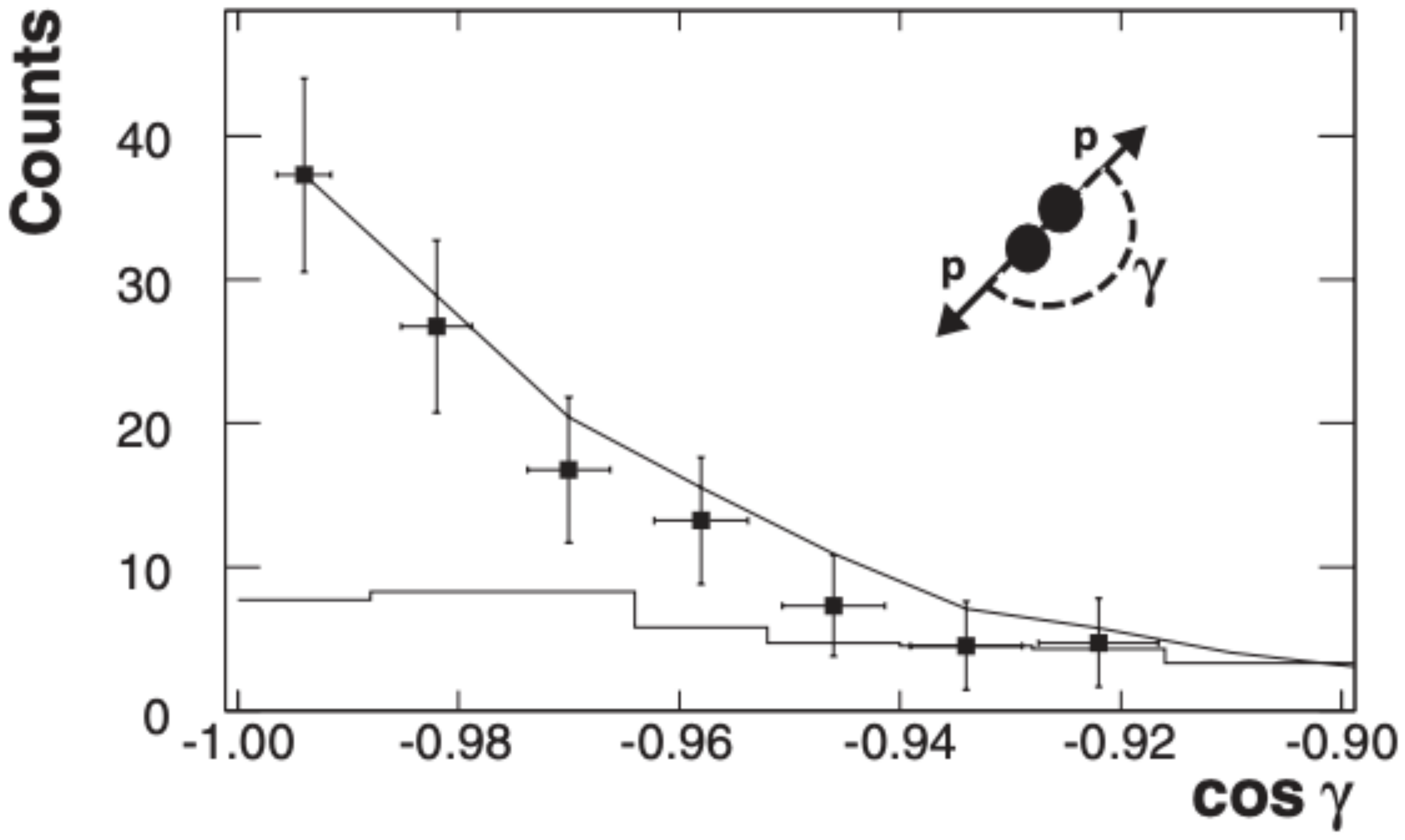
Same ground-state?

2021 SRC-CT Experiment

- 10.8 GeV + diamond radiator
- 19 days: ^{2}H, ^{4}He, ^{12}C
- Standard Hall D setup



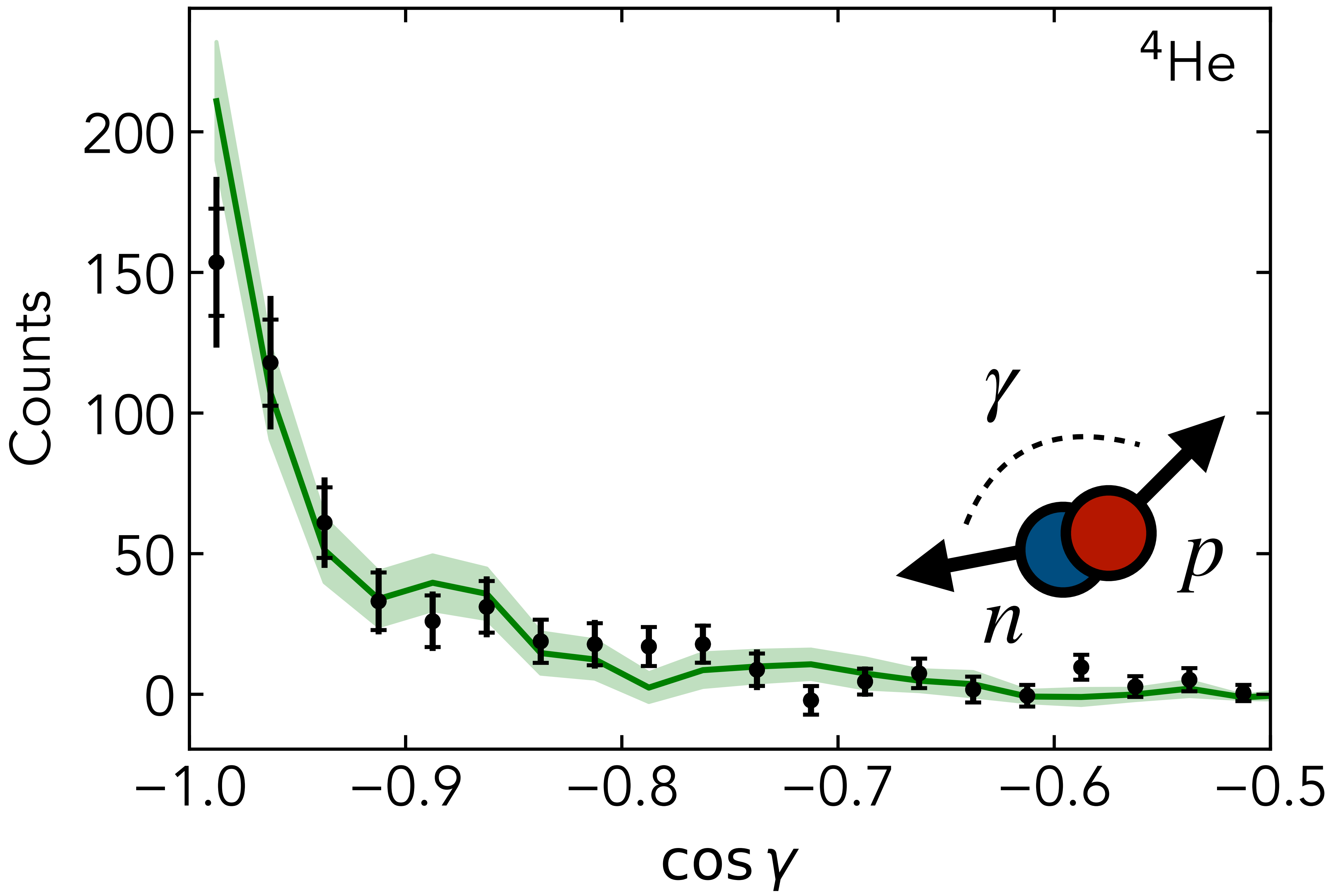
First observation of SRCs in photoproduction

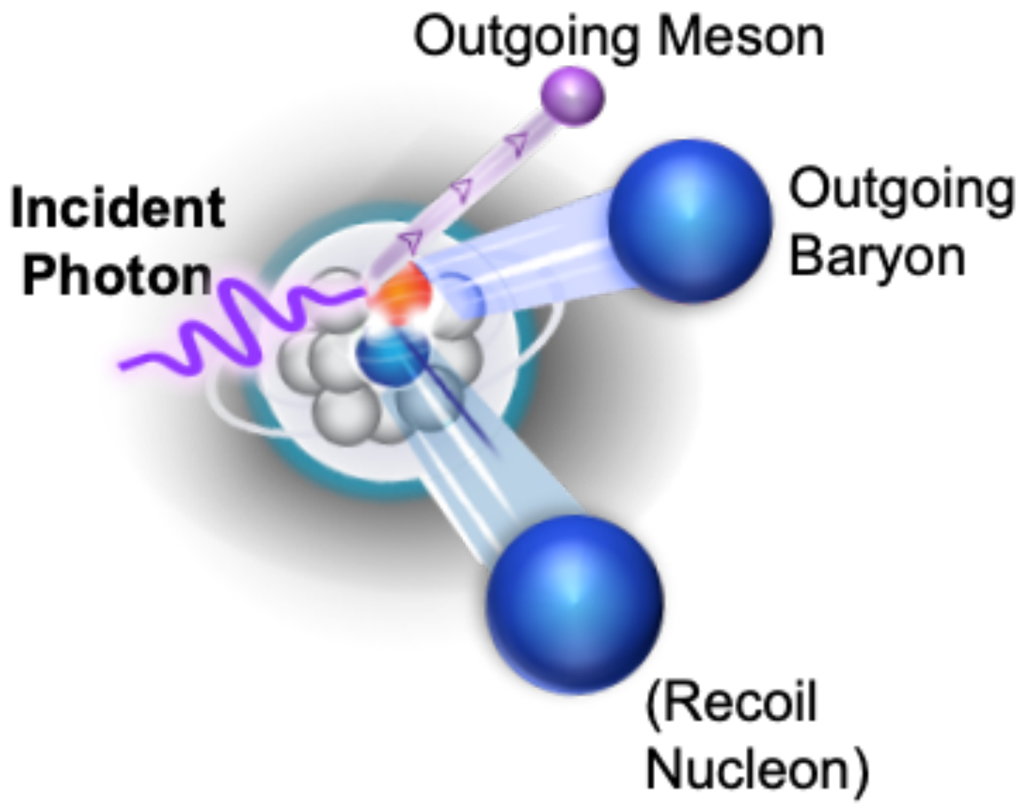


PRL 2007

Back-to-back correlation in

$(e, e'pp)$ @ Hall A



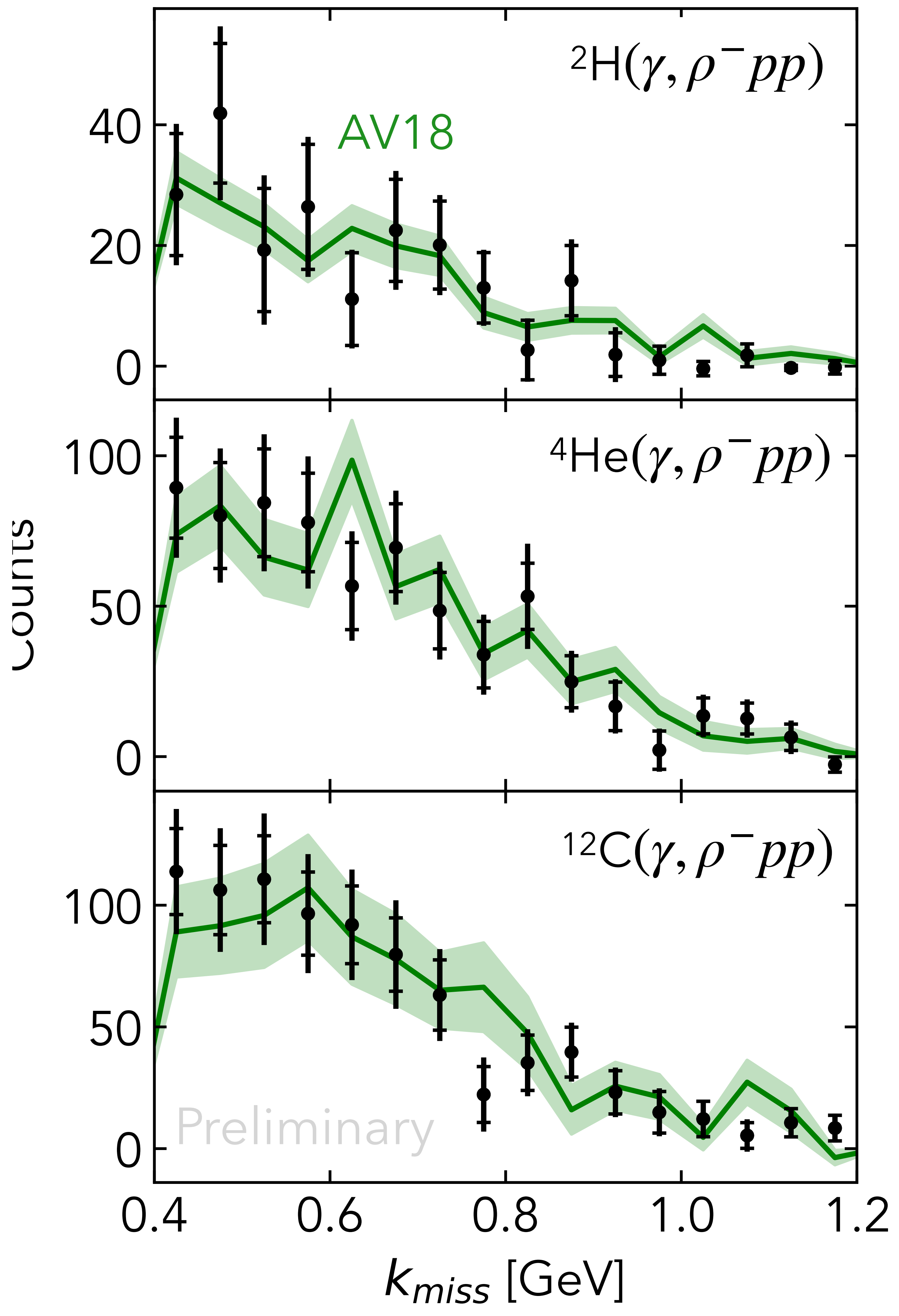


$\gamma np \to \rho^- pp$

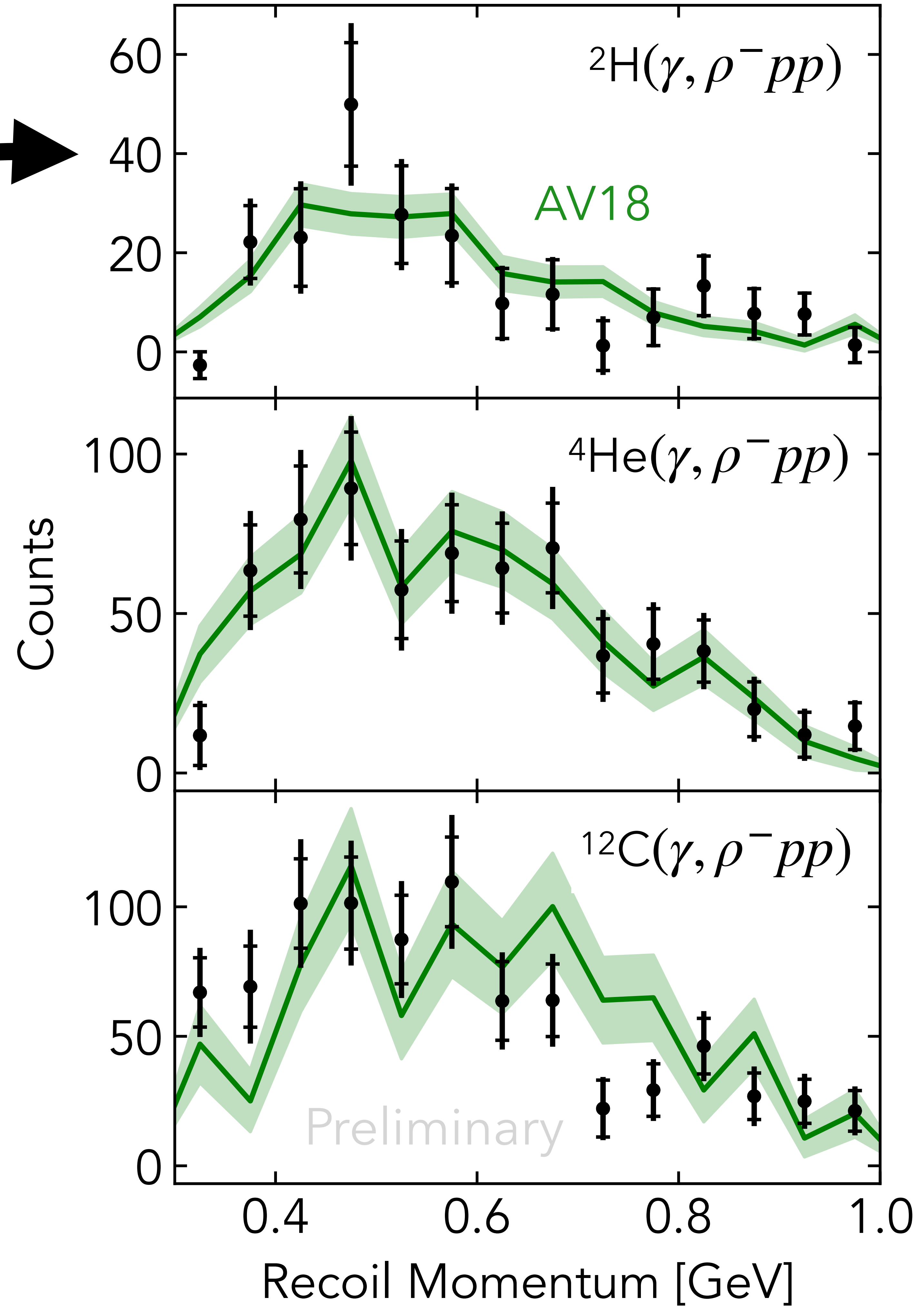
@ Hall D

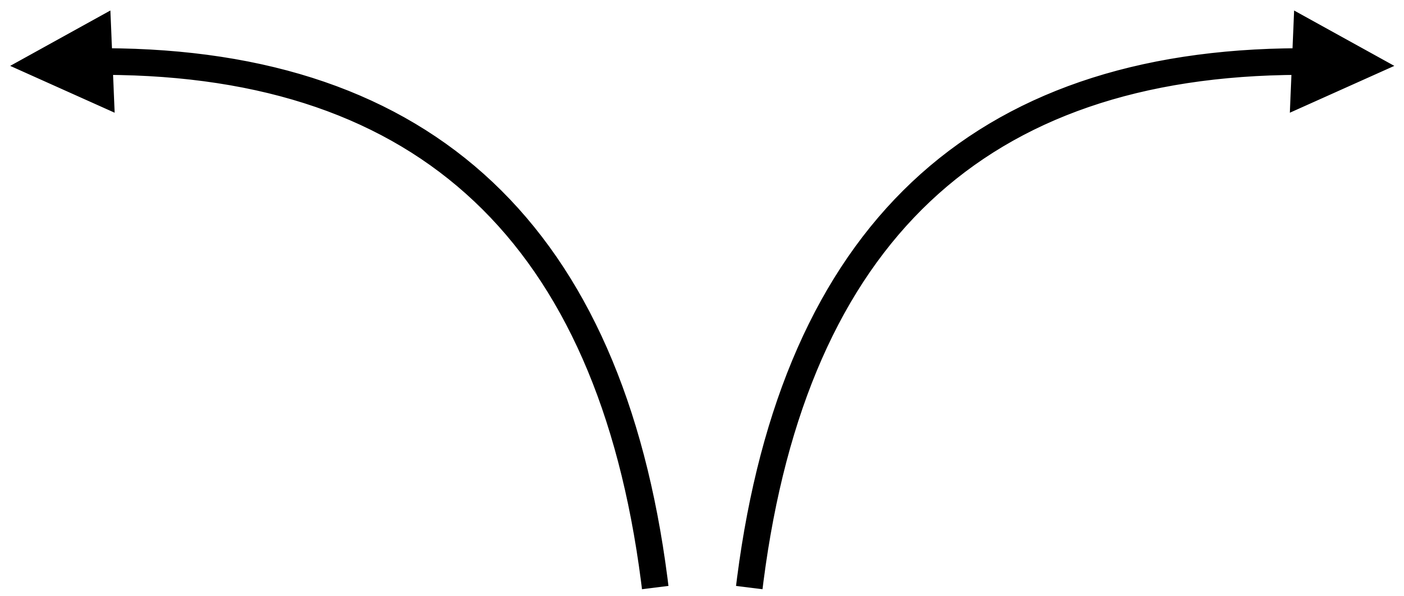
Data can constrain ab-initio theory at high momentum

Initial Neutron Momentum

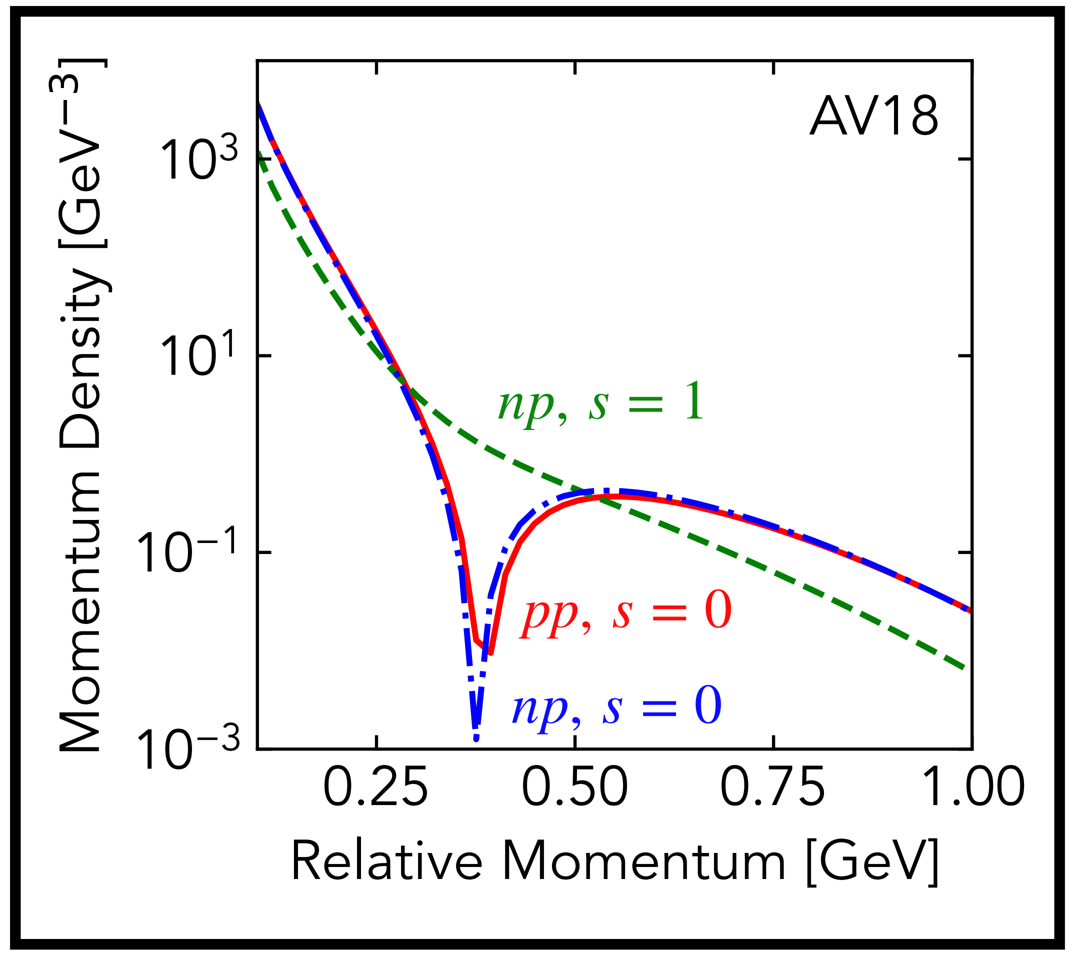


Recoil Proton Momentum

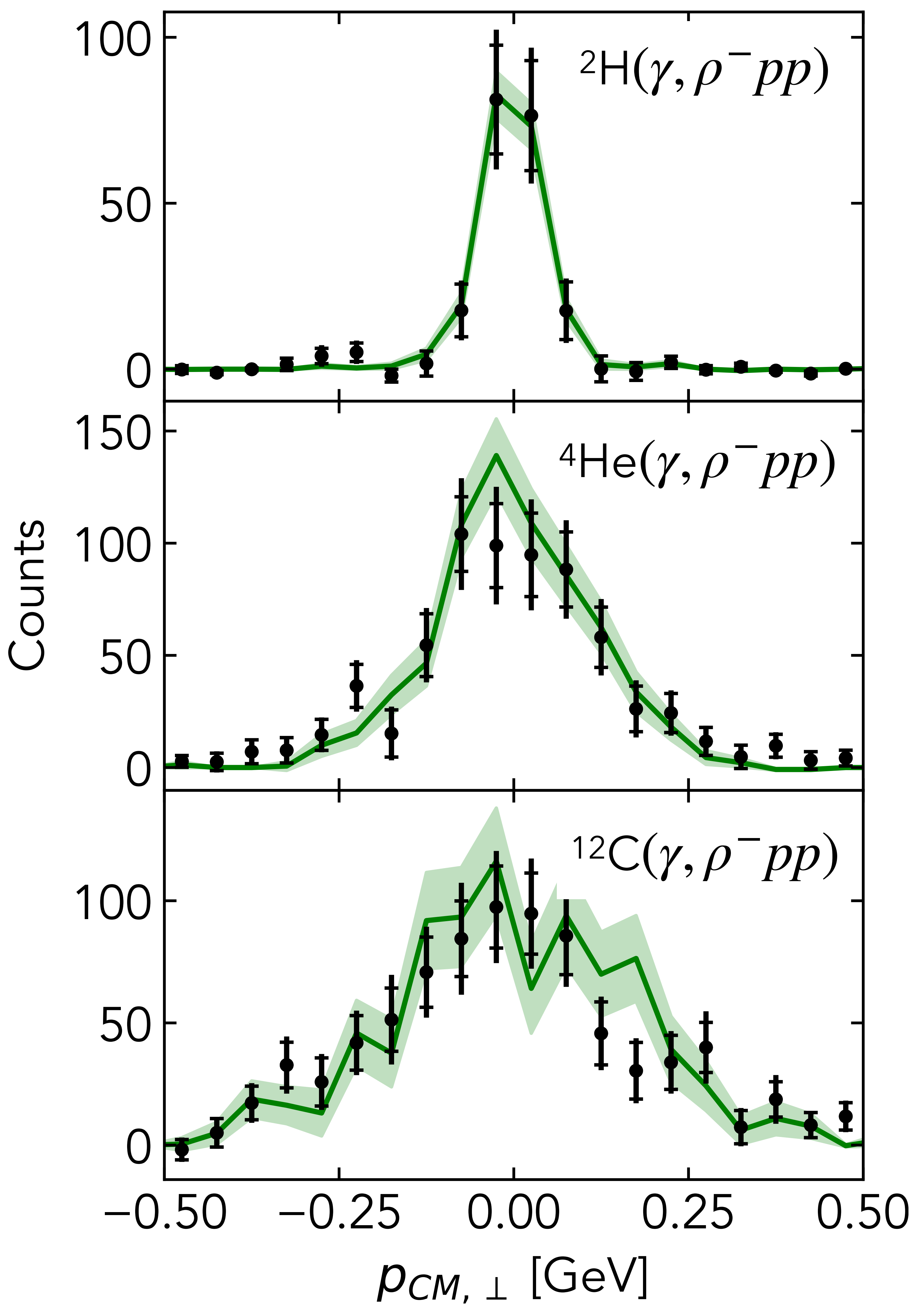




NN Interaction



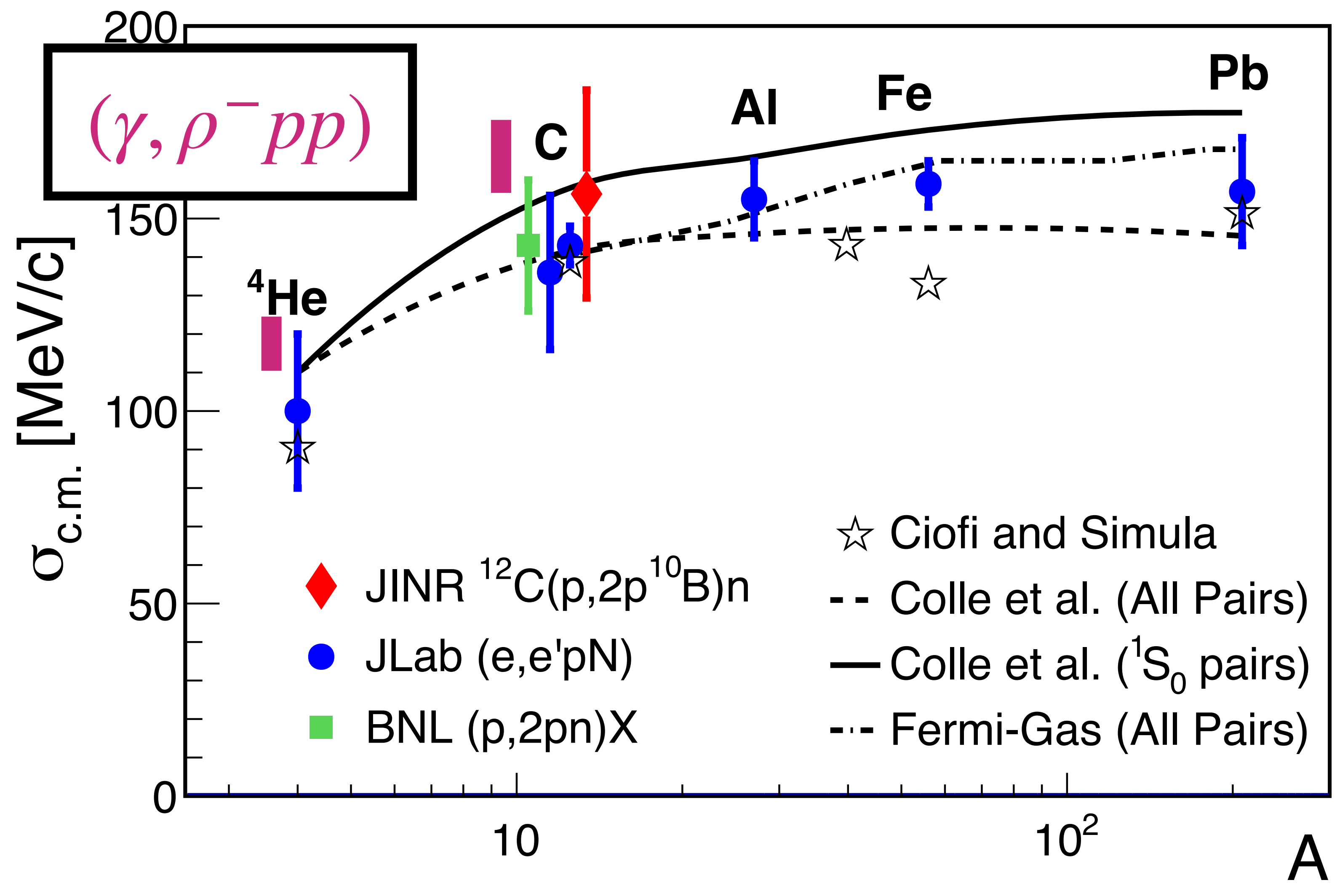
A-dependent properties of SRCs also measured



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

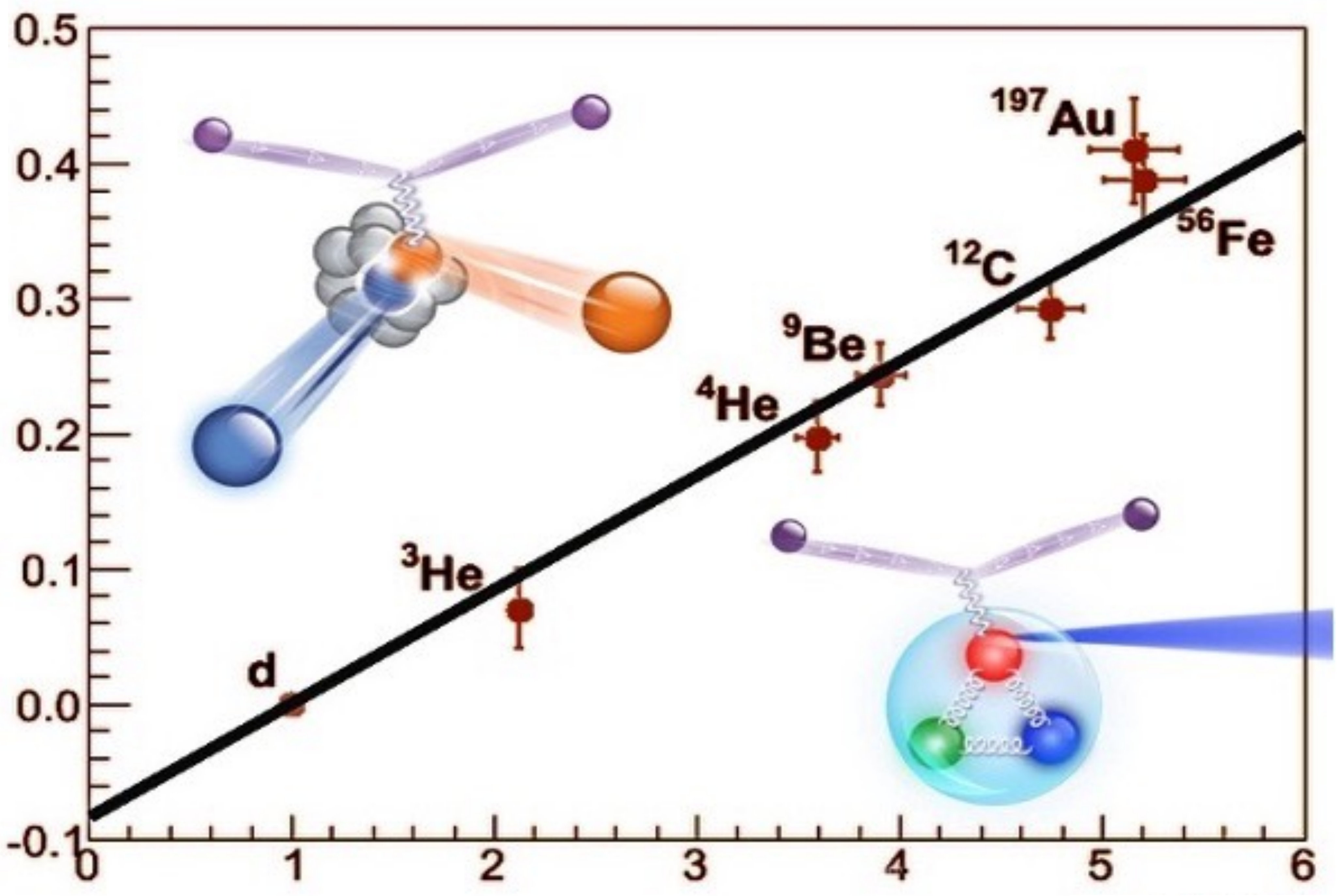
p: **Nature Physics (2021)**

γ: **SRC-CT (2024)**



SRCs are also related to medium-modification

EMC Strength dR/dx

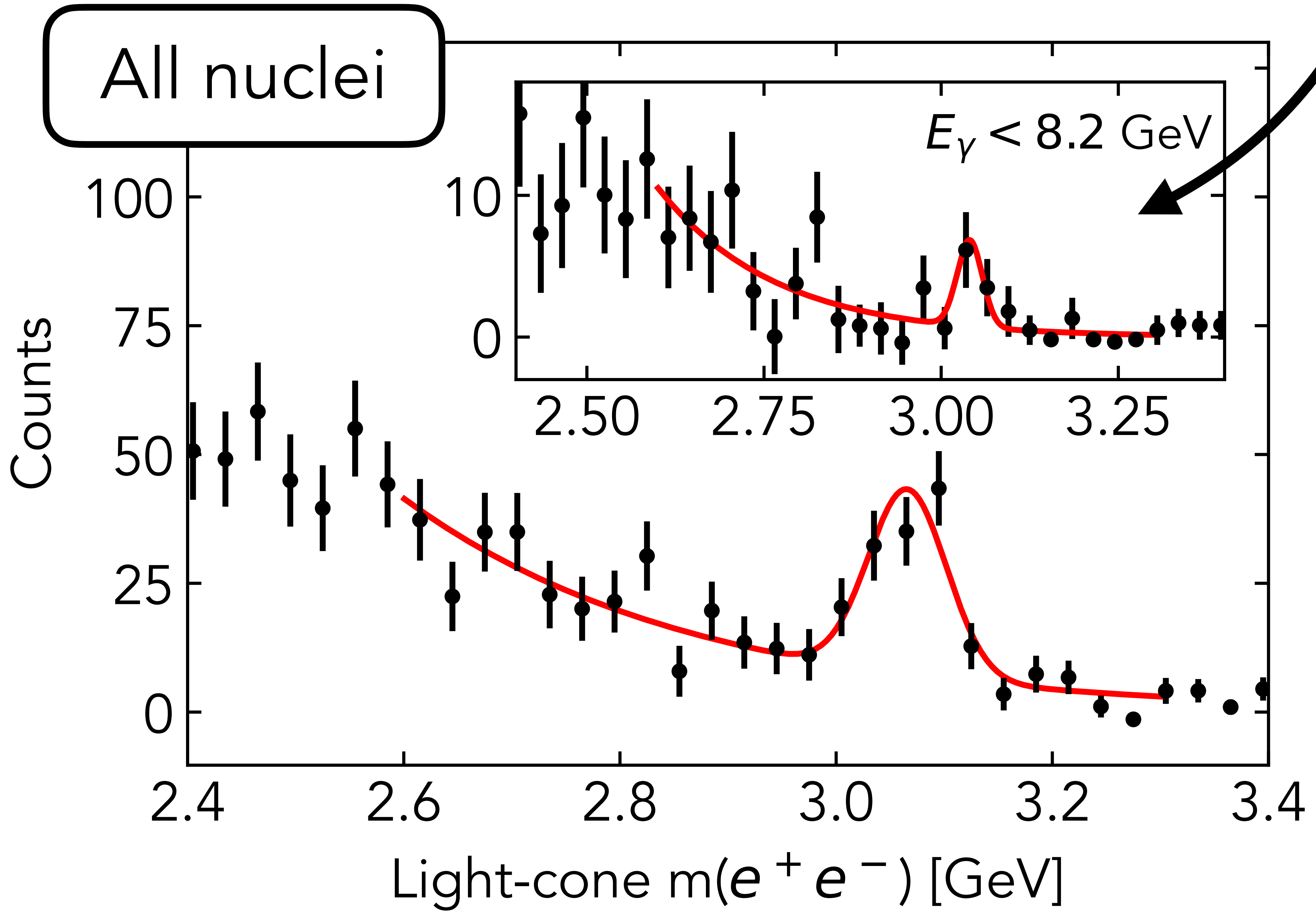


SRC Abundance a_2

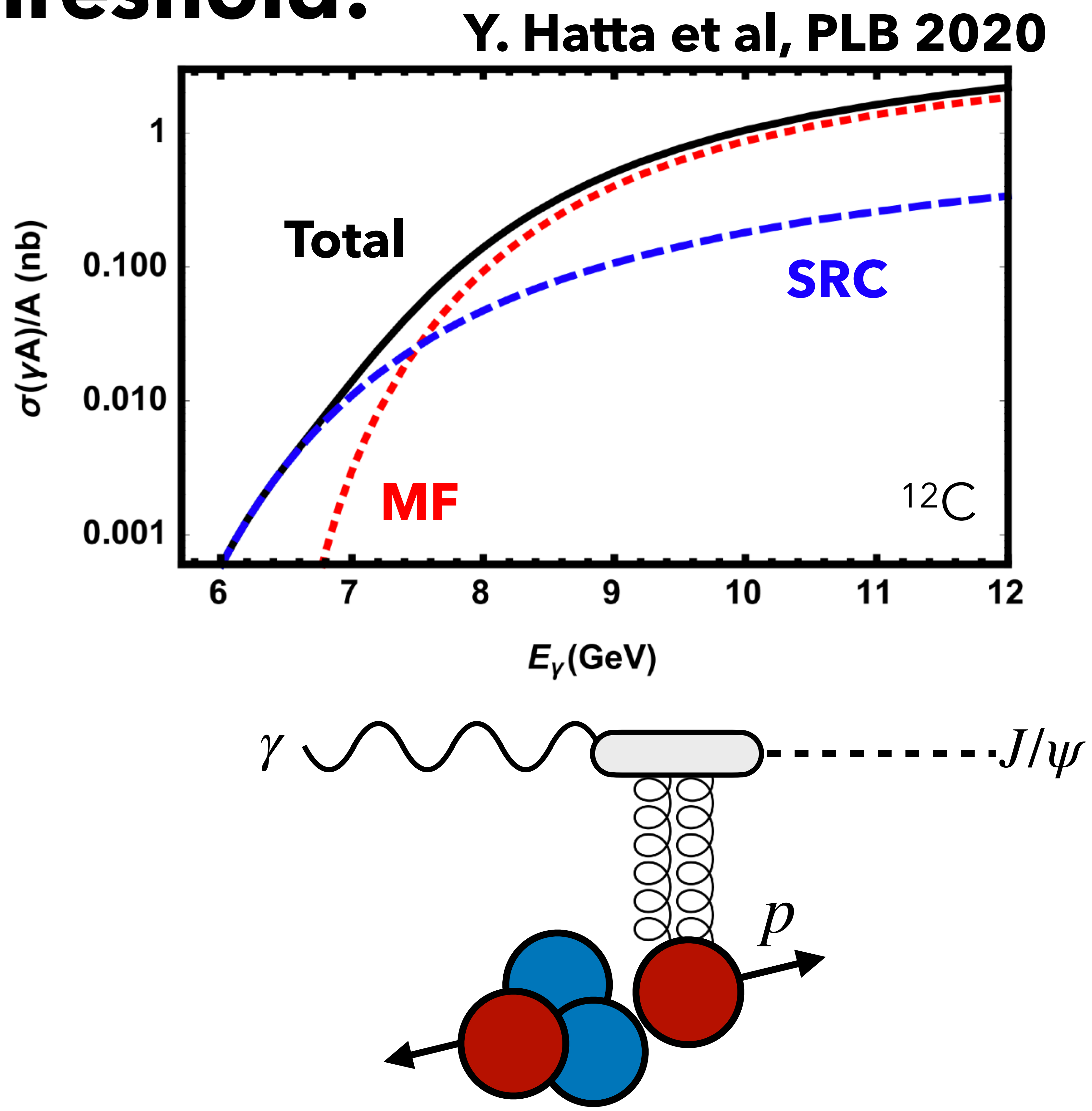
- Structure functions potentially modified in SRCs
- Photon beams are sensitive to SRC **gluons**

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

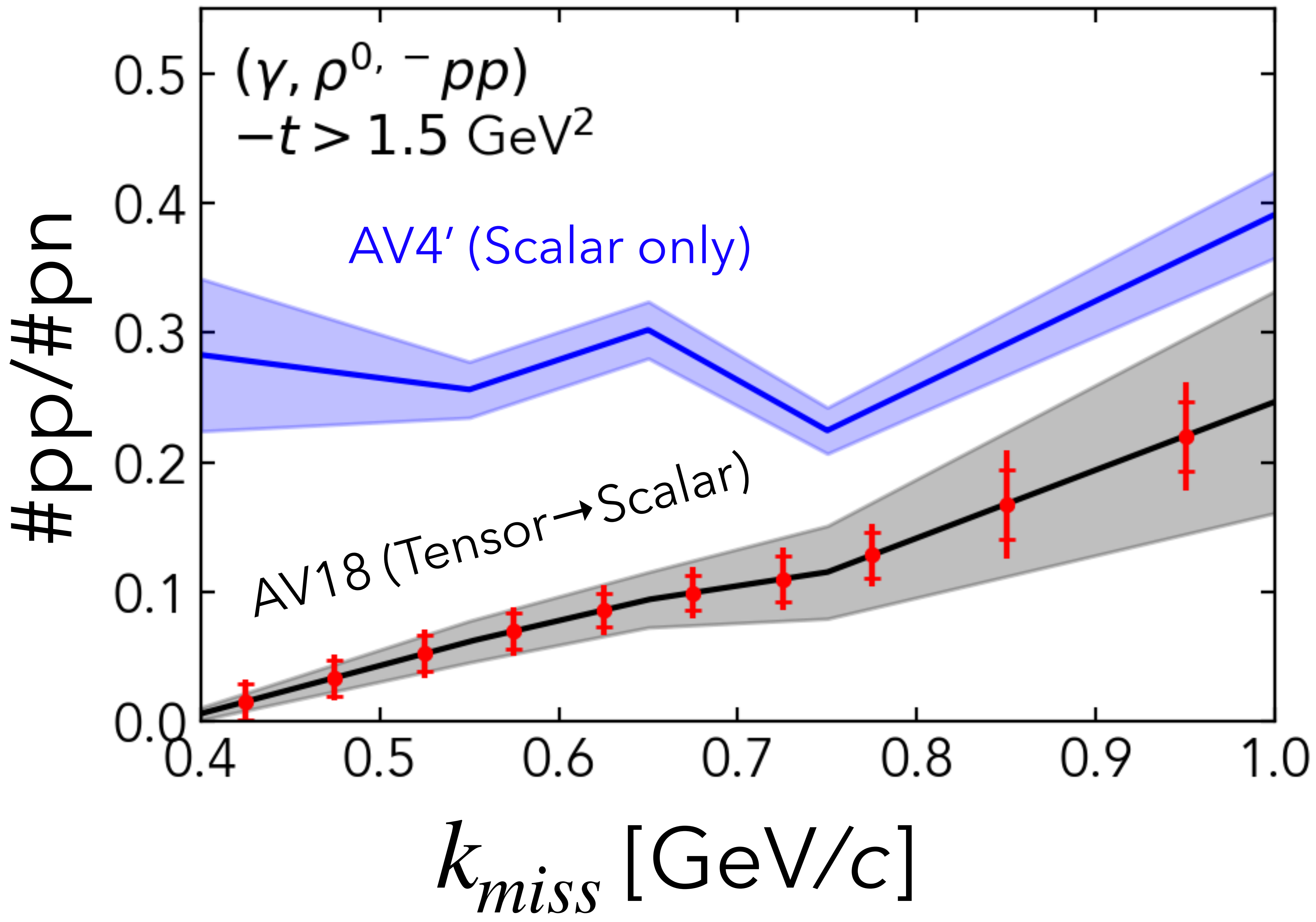
J/ψ photoproduction probe nuclear gluons; Successfully observed in current data



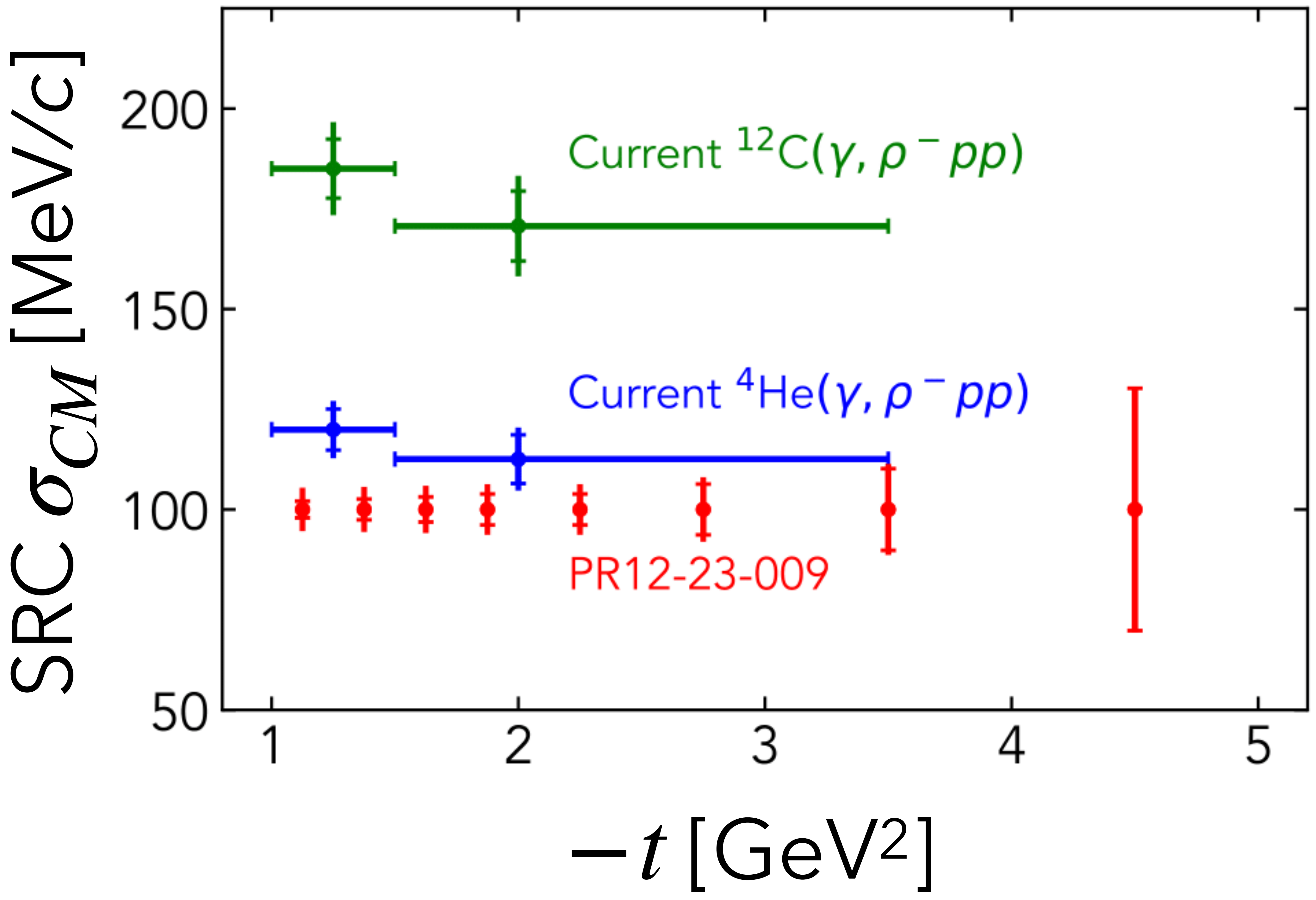
Subthreshold!



Proposed data: Precision measurement of SRCs

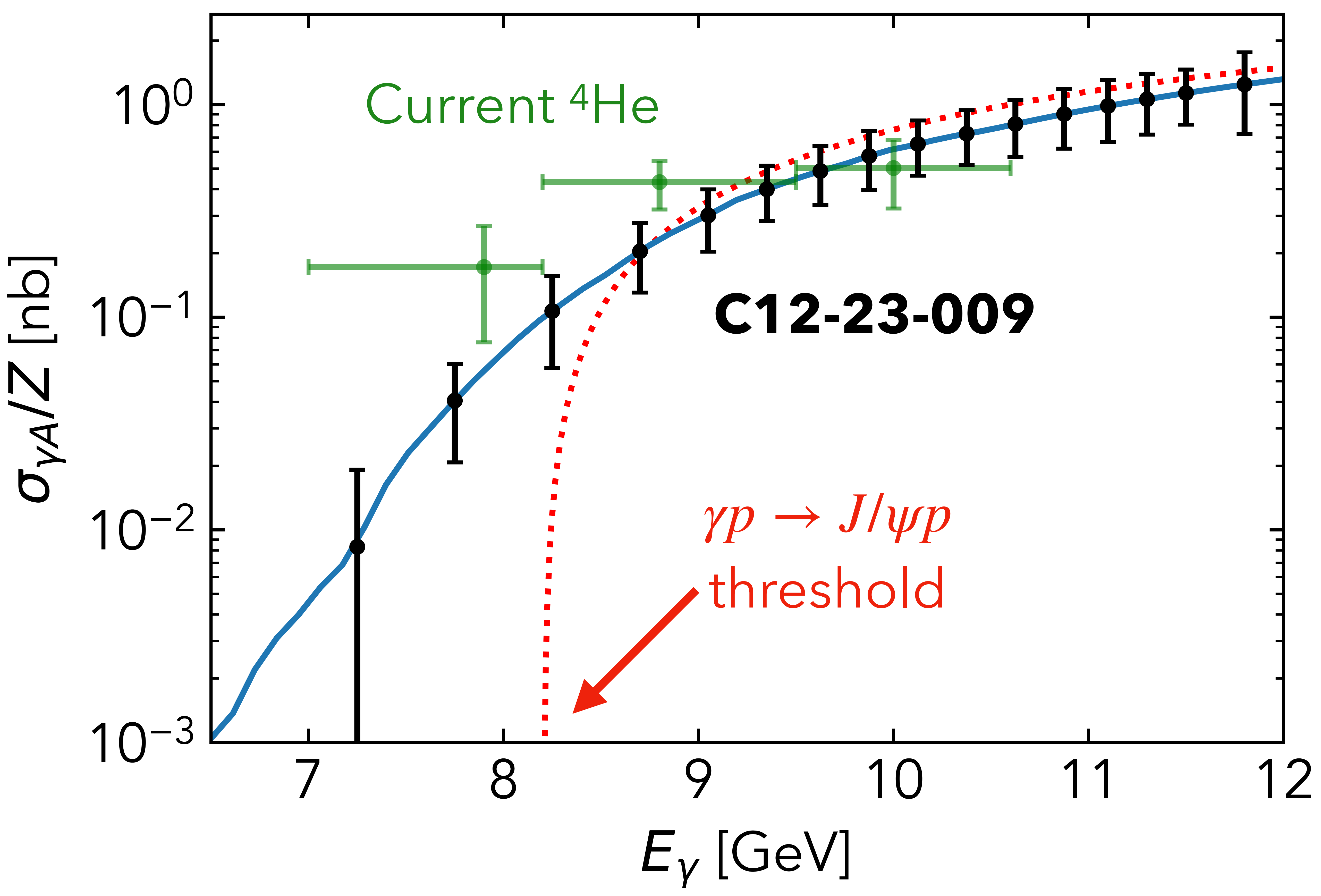


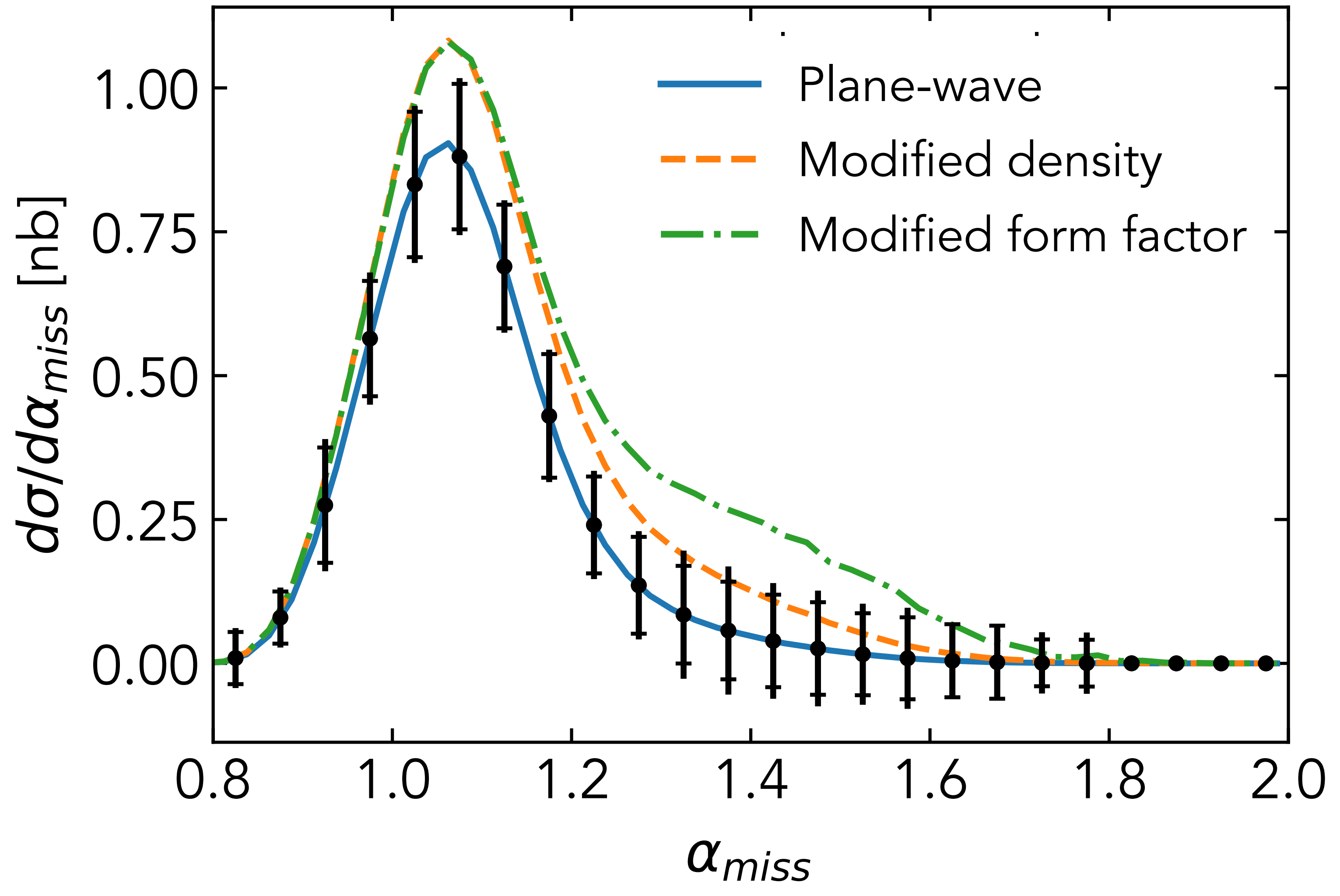
Precision constraints of NN interaction at short distance

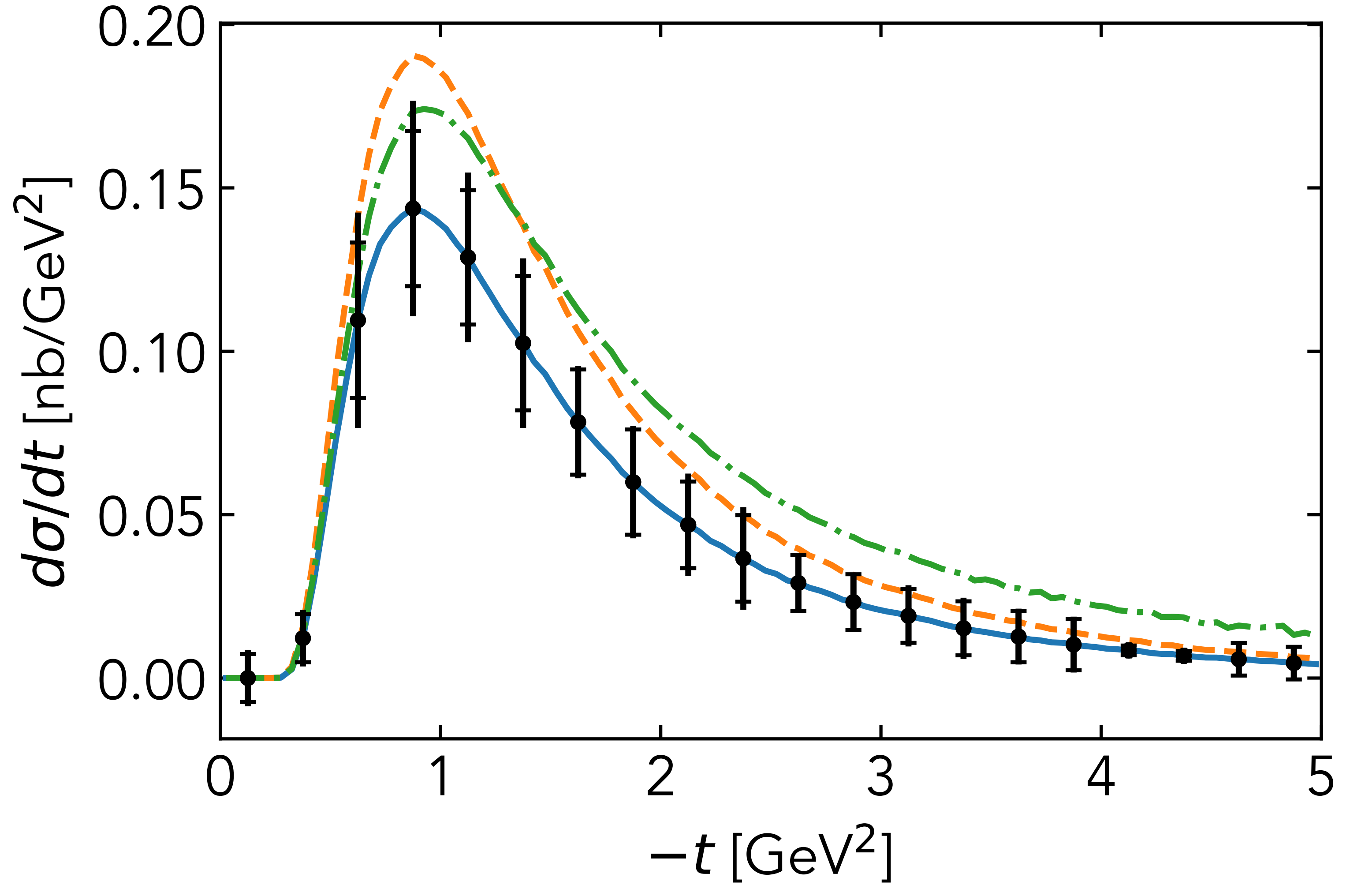


Resolution-dependence of SRC properties

Proposed data: Detailed measurement of nuclear J/ψ







PAC51 Report

"(The first) observation of J/ψ photoproduction from ^{4}He."

"High-precision and high-statistics… provide constraints on SRCs in ^{4}He."

"Direct test of the differences between photoproduction on mean-field and SRC nucleons."

PAC51 Report

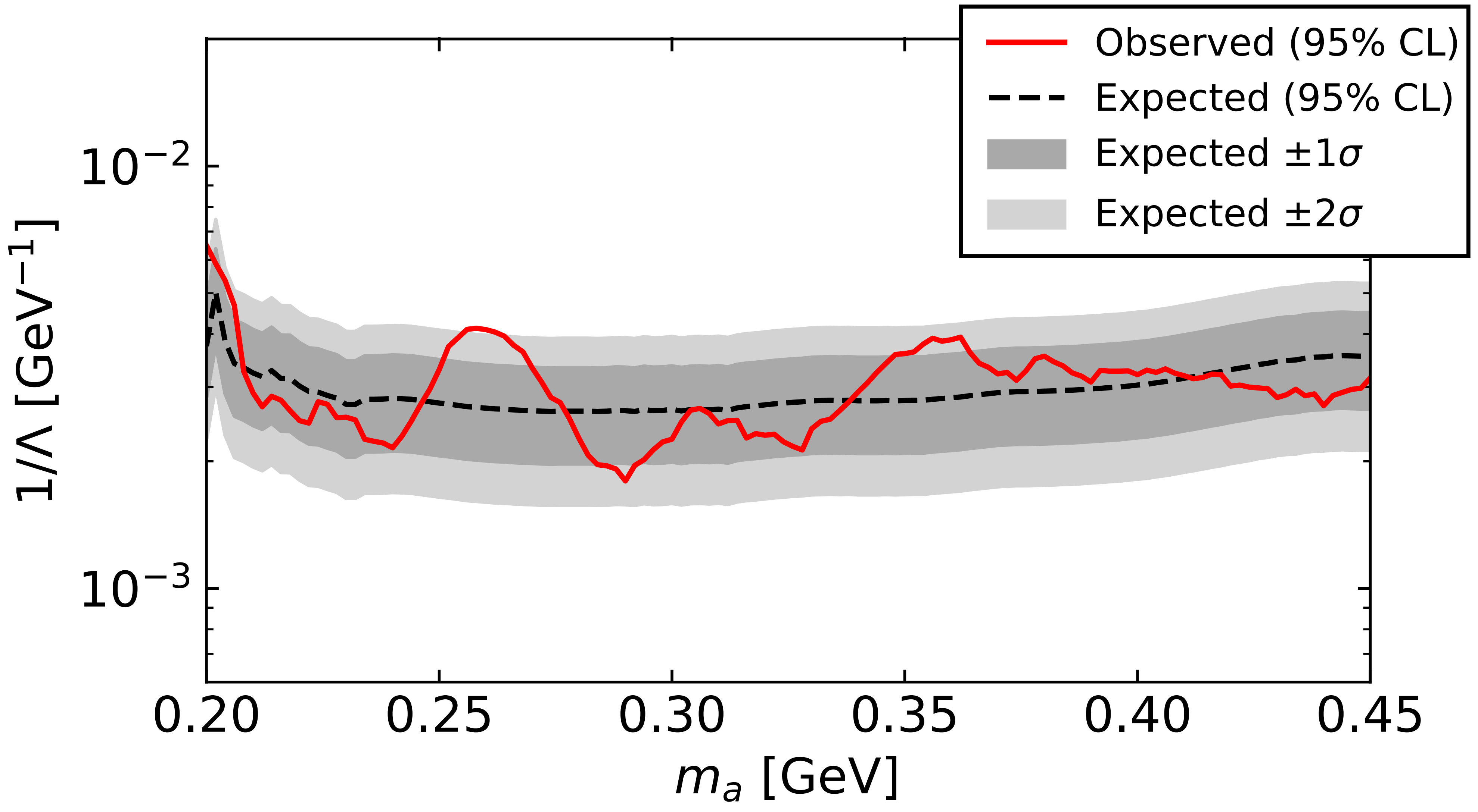
"(The first) observation of J/ψ photoproduction from ^{4}He."

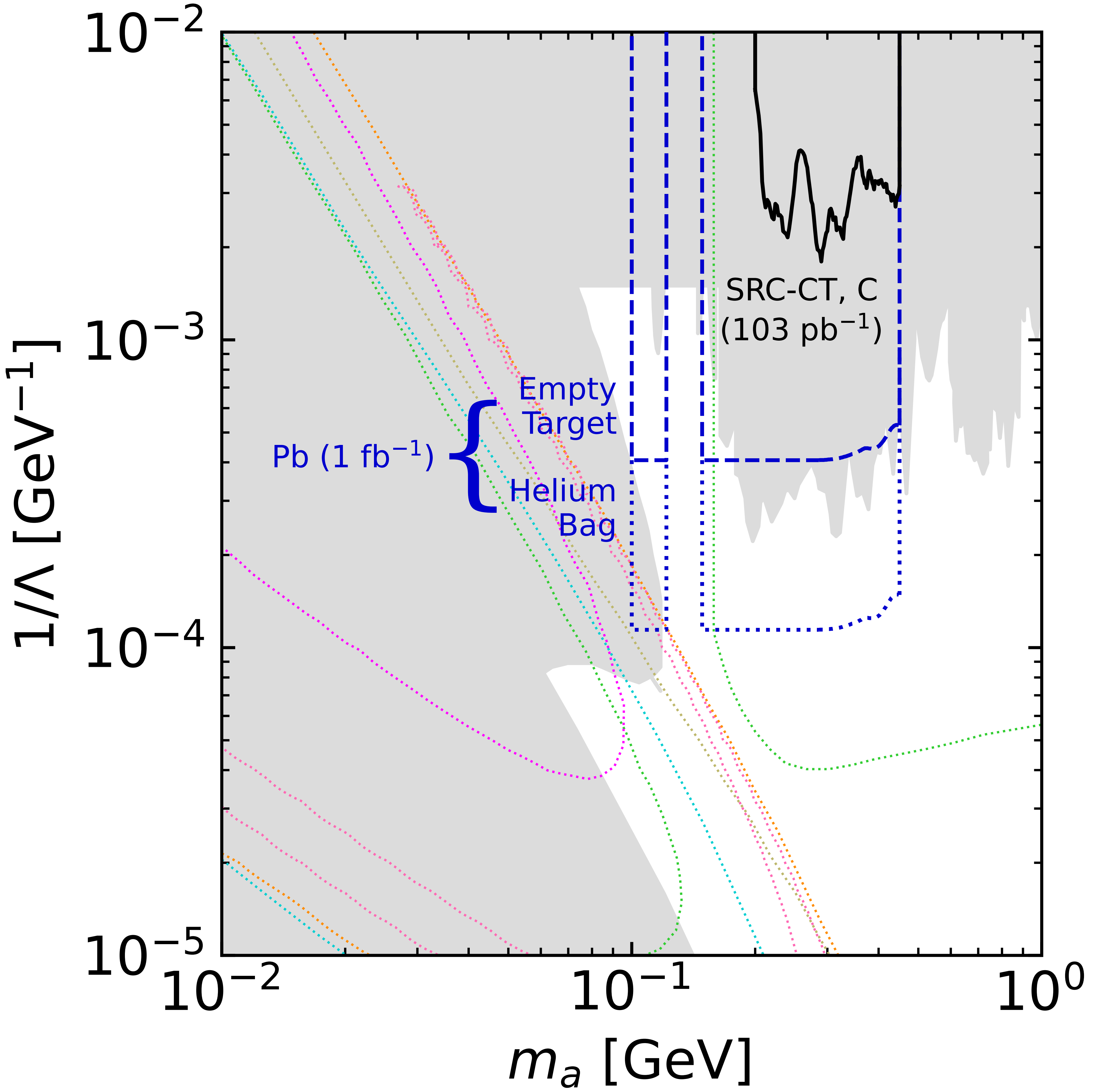
"High-precision and high-statistics… provide constraints on SRCs in ^{4}He."

"Direct test of the differences between photoproduction on mean-field and SRC nucleons."

"The proposed SRC experiment will be limited by **systematic** errors. The committee feels that **publication** of the results of E12-19-003 is needed to allow for more accurate estimates of the systematic uncertainties and of the beam time request for the high-precision measurement."

Published Results: SRC-CT Search for Axion-Like Particles

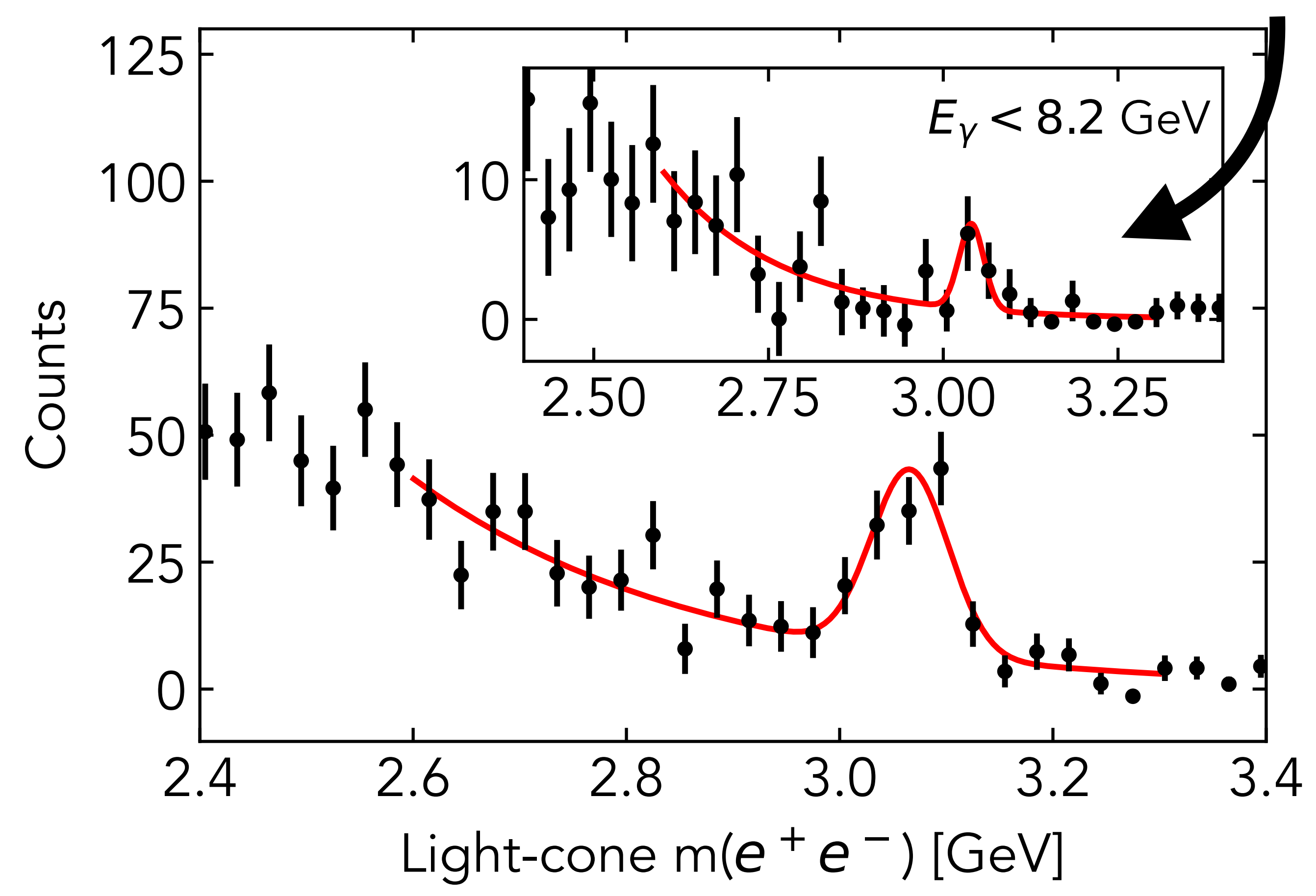


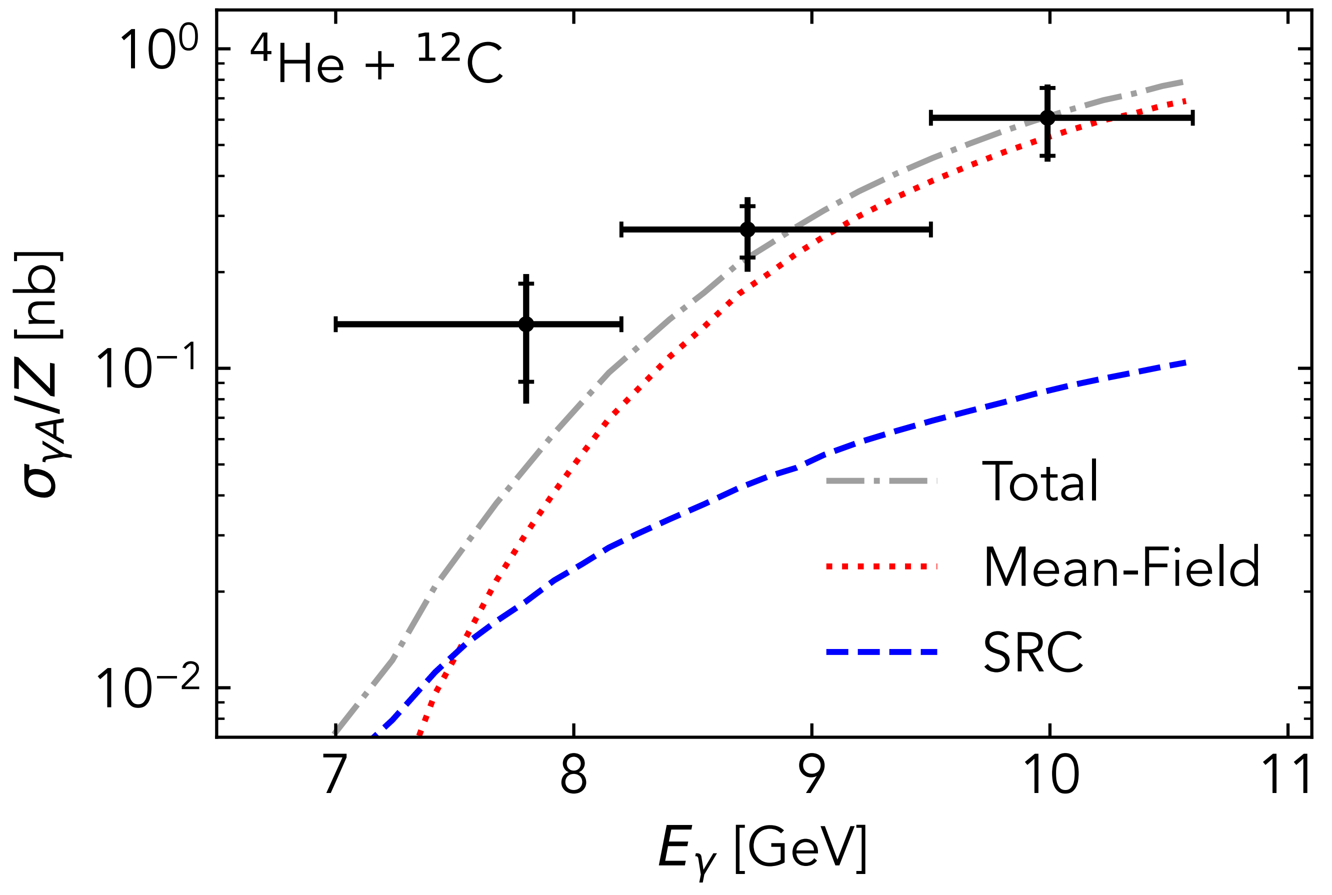


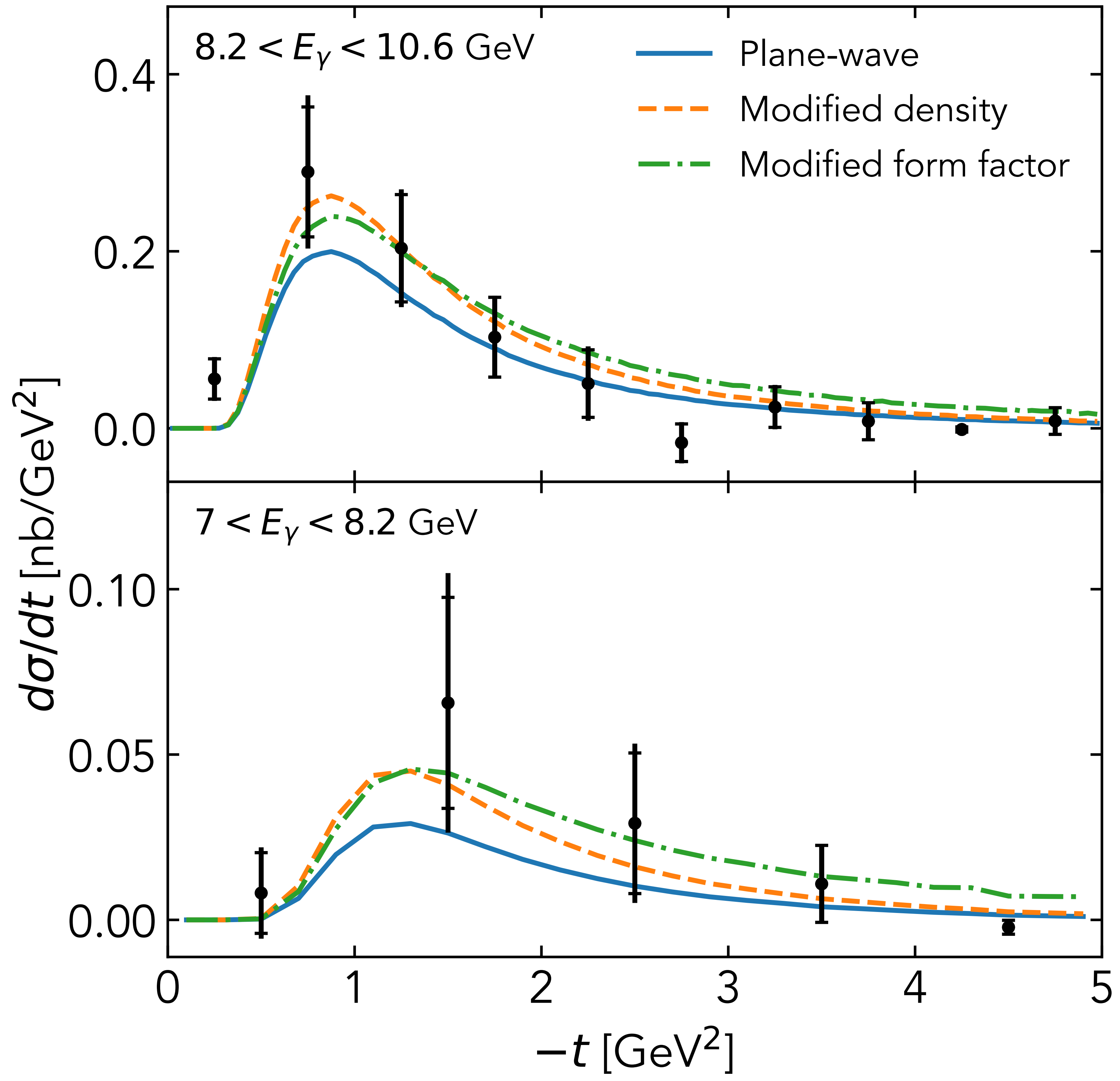
- First Primakoff-based search for Axion-Like Particles
- Demonstrated feasibility of method and potential for dedicated ALP search using high-Z nuclei
- Results published in Physics Letters B:
  - DOI: 10.1016/j.physletb.2024.138790
  - arXiv: 2308.06339

Final Results: Nuclear Photoproduction of J/ψ

Subthreshold!







- First measurement of semi-inclusive $A(\gamma, J/\psi p)$ in threshold region
- First observation of several **sub-threshold** $A(\gamma, J/\psi p)$ events (>3σ)!

Note **Paper** **Supplement**

Significant study of systematic uncertainties on extracted J/ψ cross section

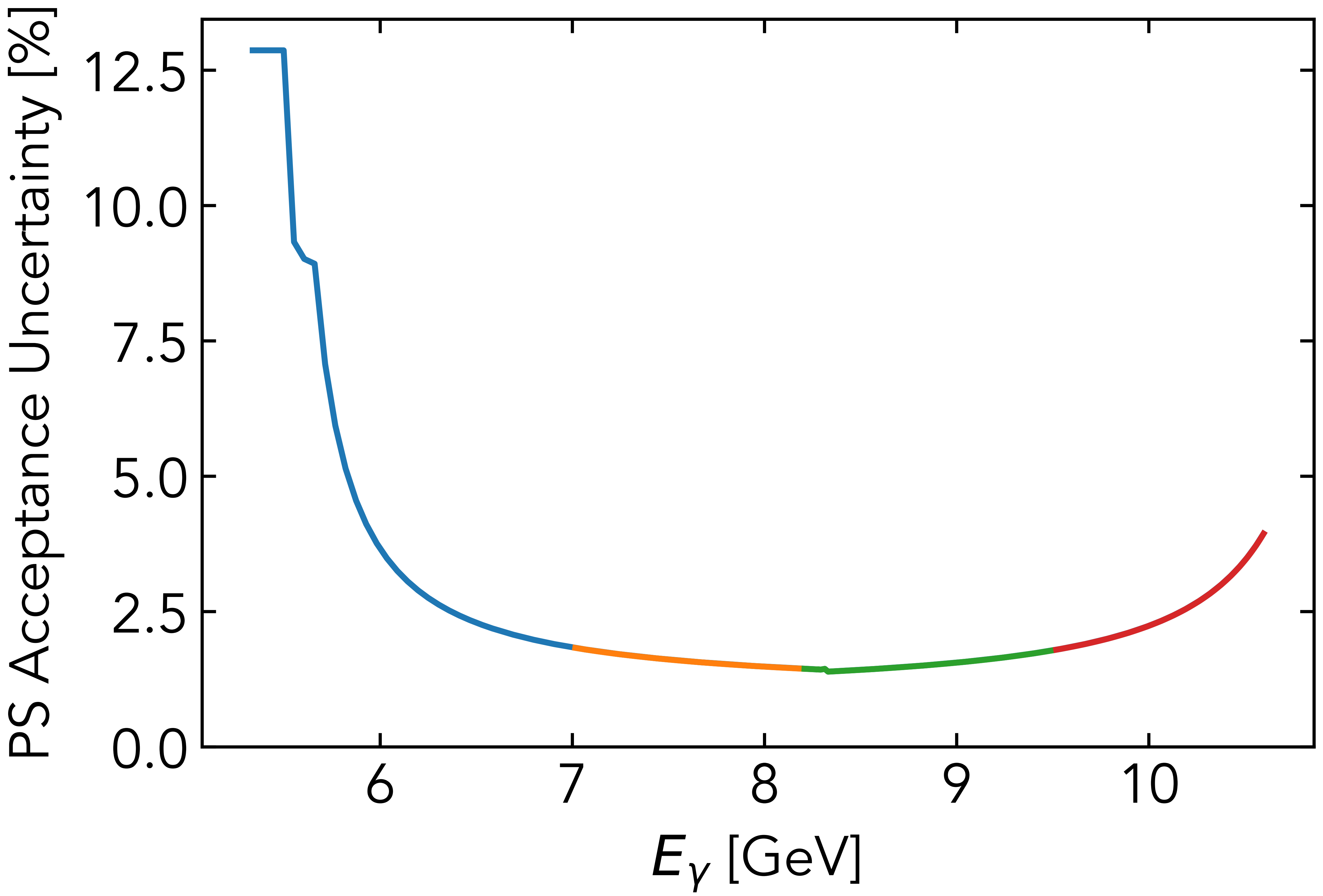
	7-8.2 GeV			8.2-9.5 GeV			9.5-10.6 GeV		
Source of Uncertainty	**D**	**He**	**C**	**D**	**He**	**C**	**D**	**He**	**C**
Event Yield	-	7.2	6.0	7.7	27.1	15.1	16.1	15.8	31.6
Stat.	-	49%	47%	42%	21%	34%	29%	30%	33%
Sys: Lumi	1.6%			1.4%			2.1%		
Sys: Efficiency	0.6%	1.3%	1.0%	1.8%	1.7%	1.7%	2.7%	2.2%	2.1%
* Sys: Fitting	-	16%	11%	29%	7%	8%	17%	10%	5%
* Sys: Cuts	-	22%	25%	18%	12%	26%	21%	15%	8%
Sys: Bin-Centering	0.5%			1.1%			0.2%		
Total Sys.	-	28%	27%	34%	14%	27%	27%	18%	9.5%
Total	-	68%	70%	62%	33%	52%	46%	44%	43%

Table 3: Point-to-point uncertainties for the extracted total cross section in bins of beam photon energy E_γ, compared to the event yields.

***Data-driven systematics: improve with statistics**

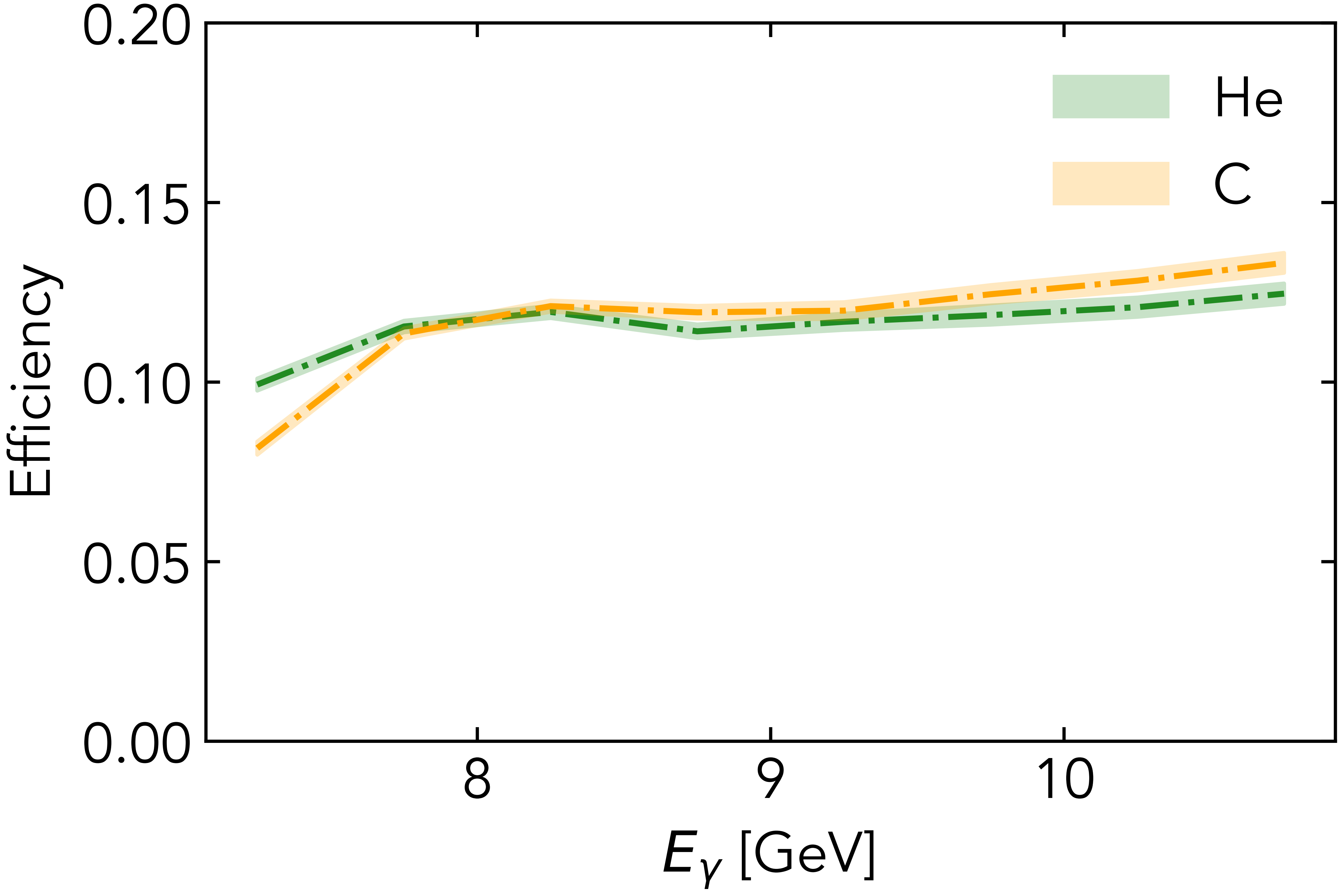
Uncertainty treated from several sources

- Luminosity



Uncertainty treated from several sources

- Luminosity
- Detector acceptance + efficiency



Uncertainty treated from several sources

- Luminosity
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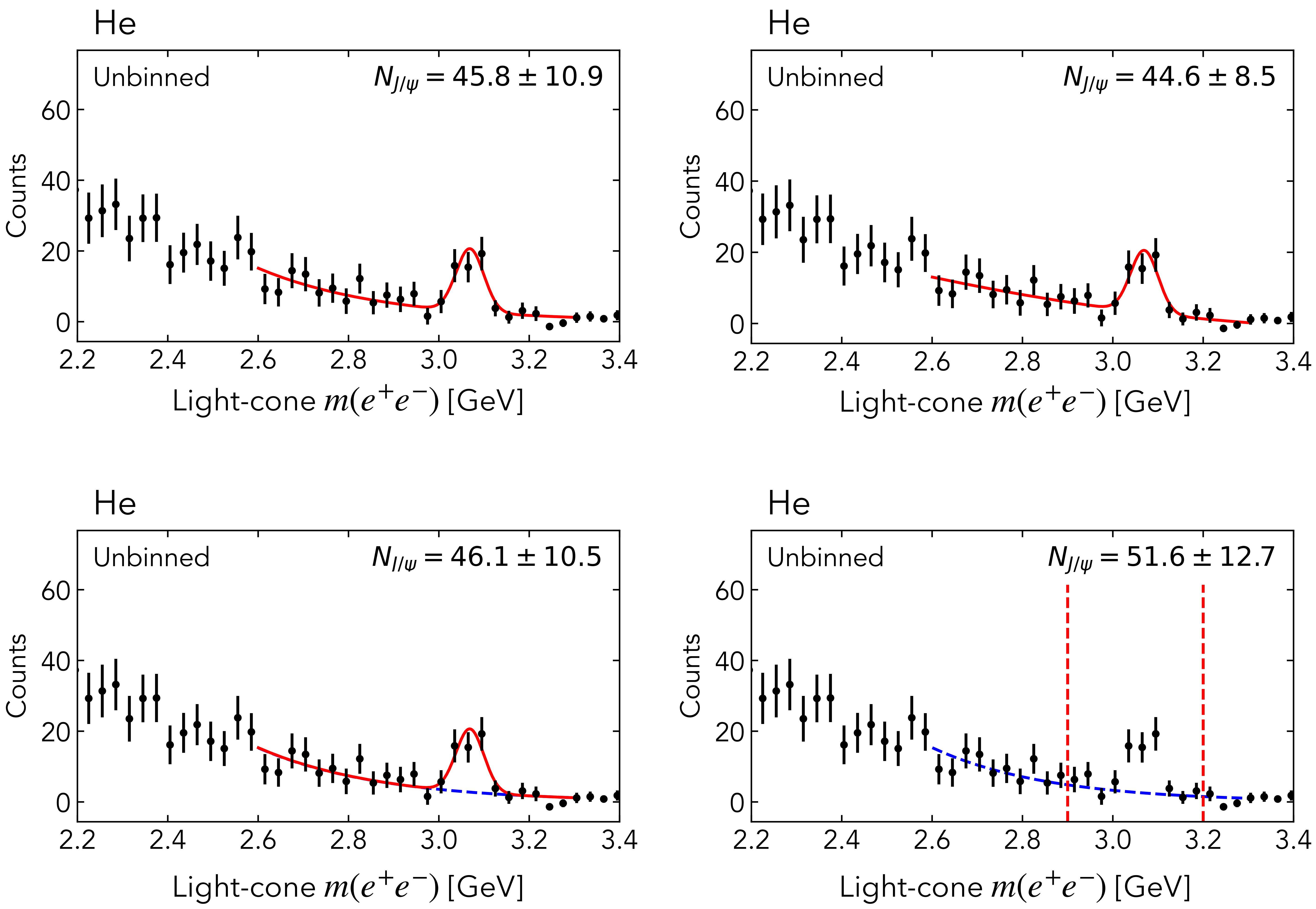
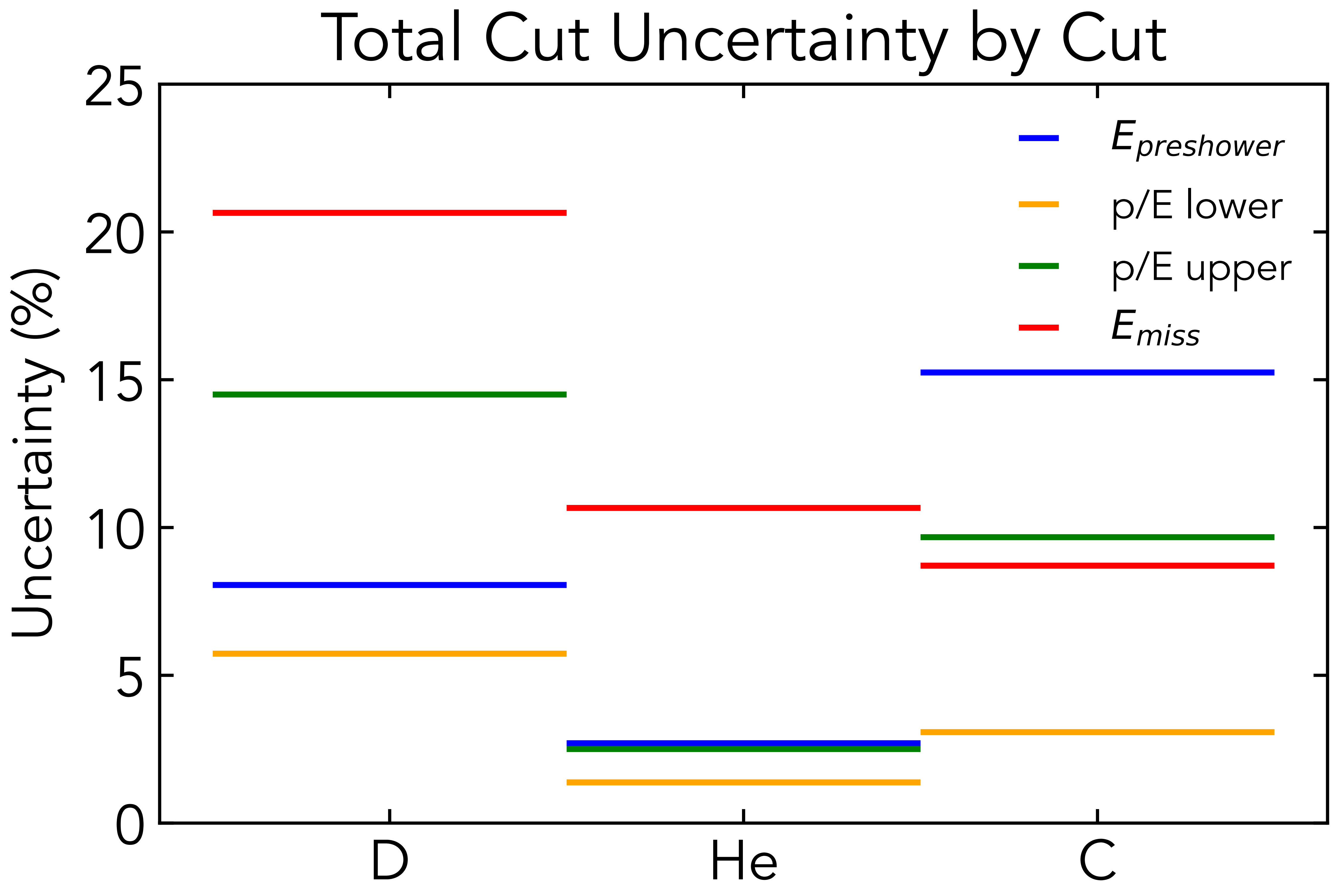
- Yield extraction*



***Data-driven systematics: improve with statistics**

Uncertainty treated from several sources

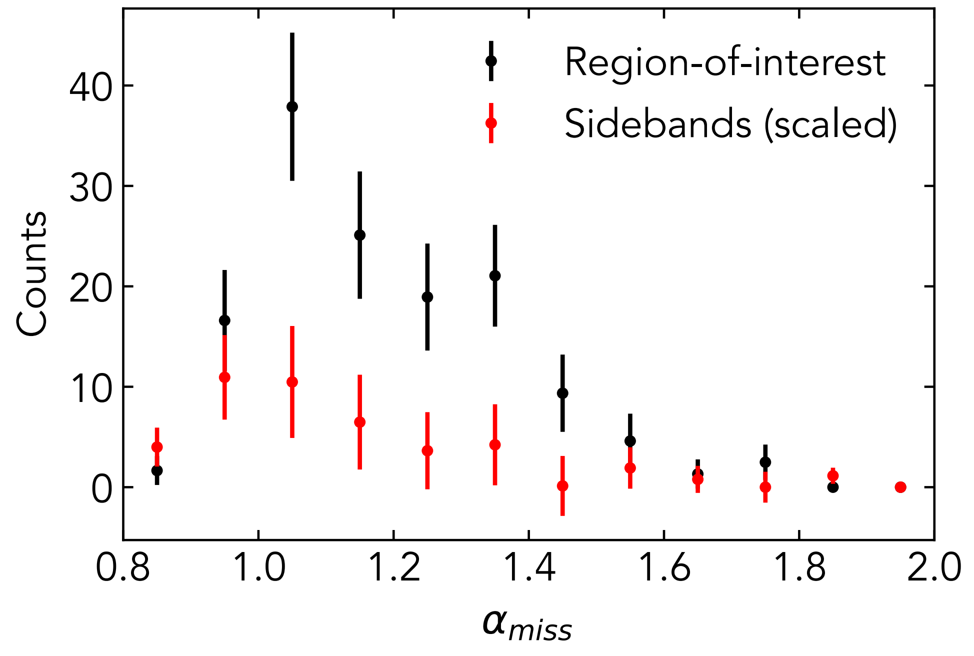
- Luminosity
- Detector acceptance + efficiency
- Yield extraction*
- Choice of selection criteria*



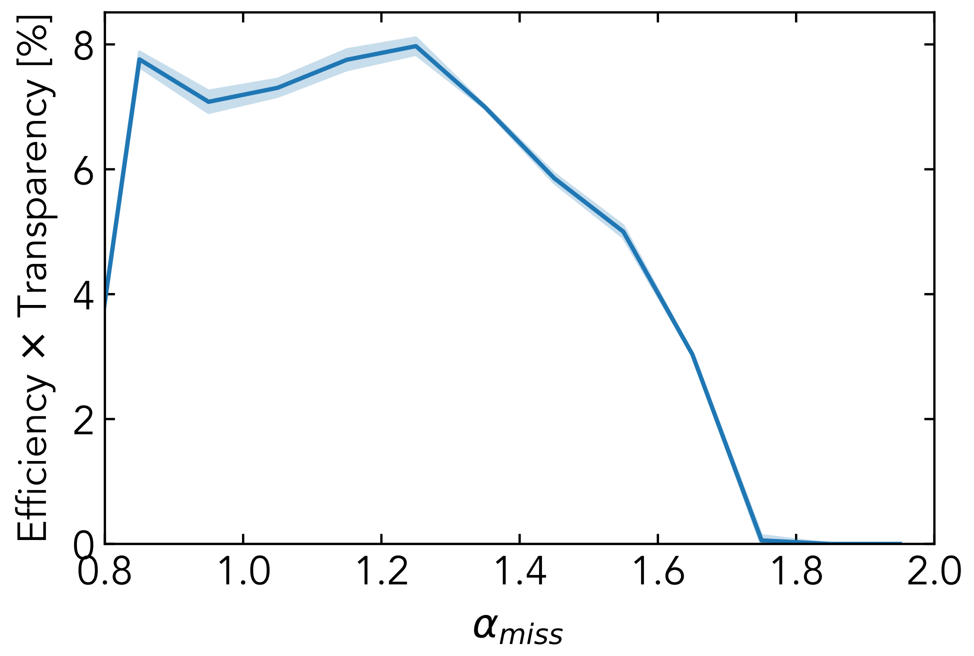
***Data-driven systematics: improve with statistics**

Differential cross sections also extracted from current combined-nuclei data

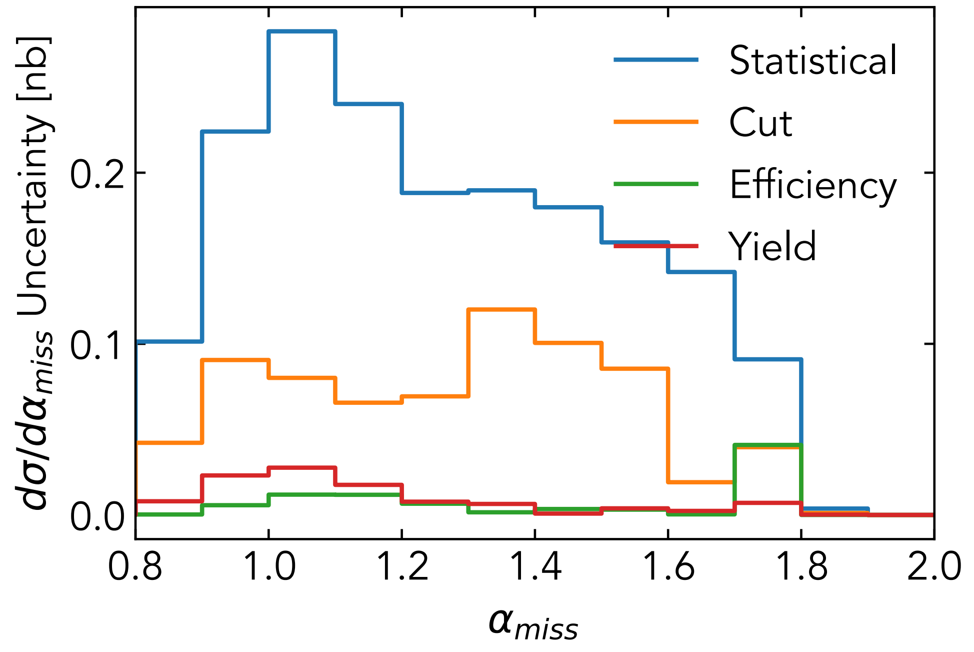
Background-subtracted J/ψ yields

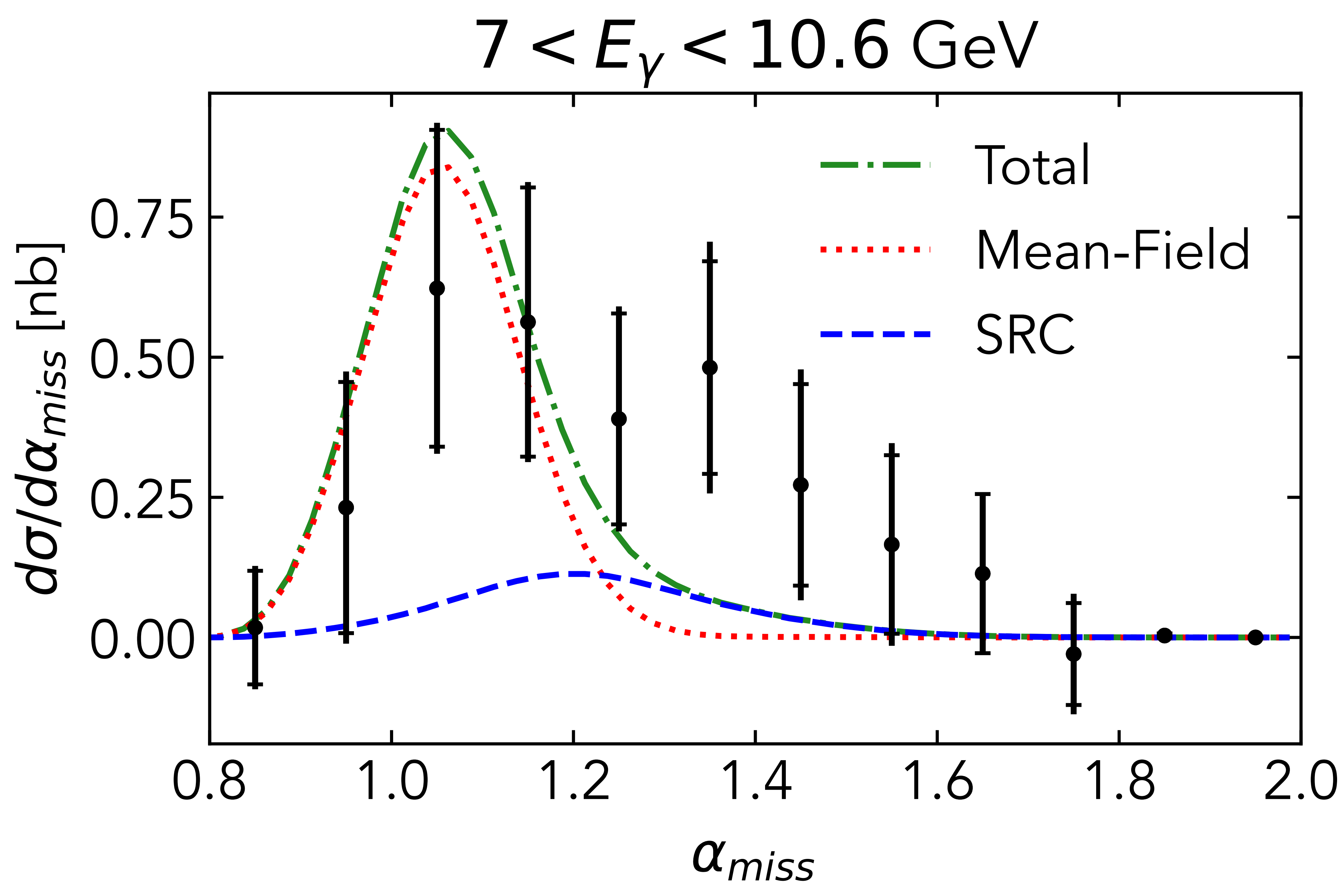


Efficiency + acceptance corrections

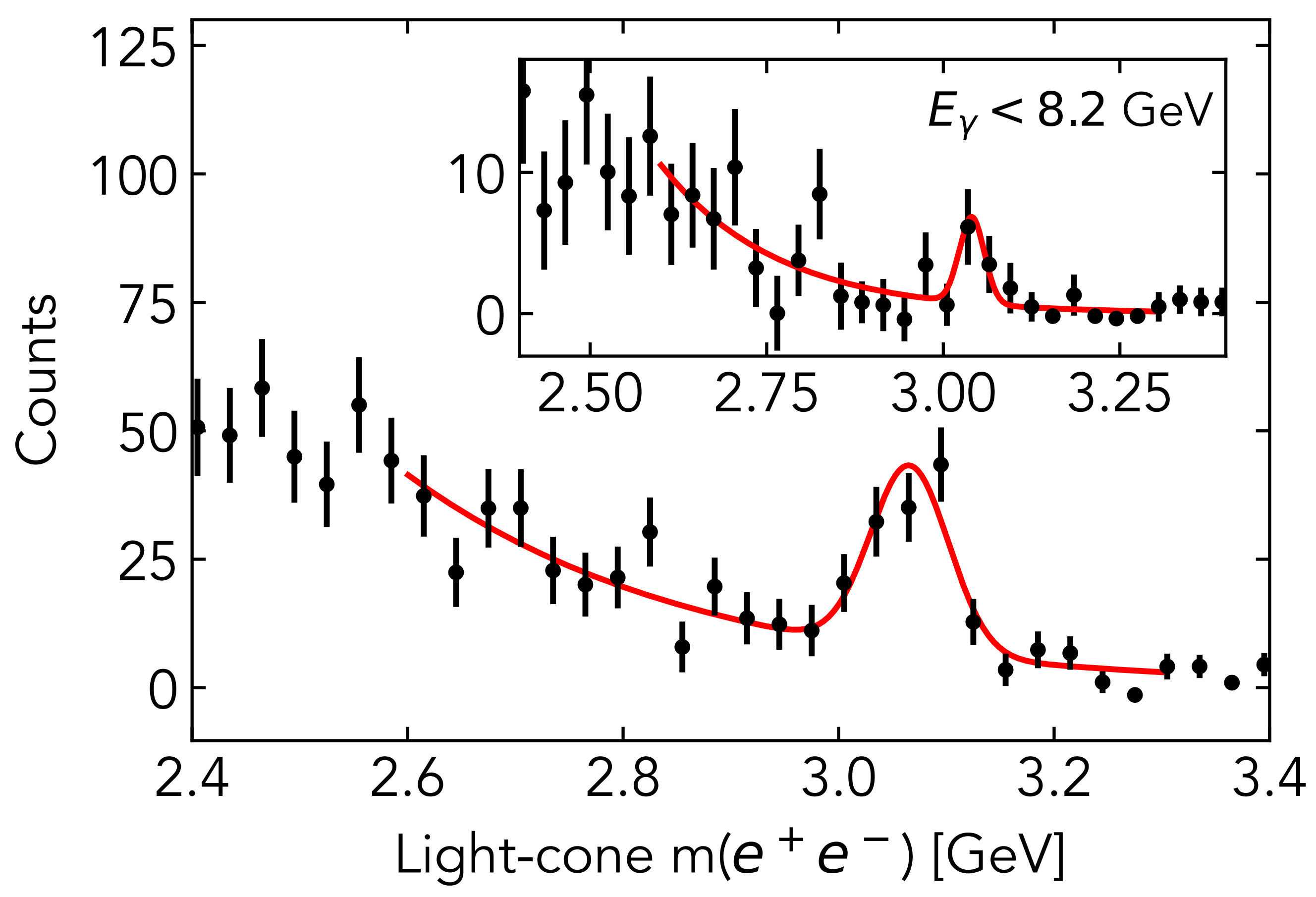


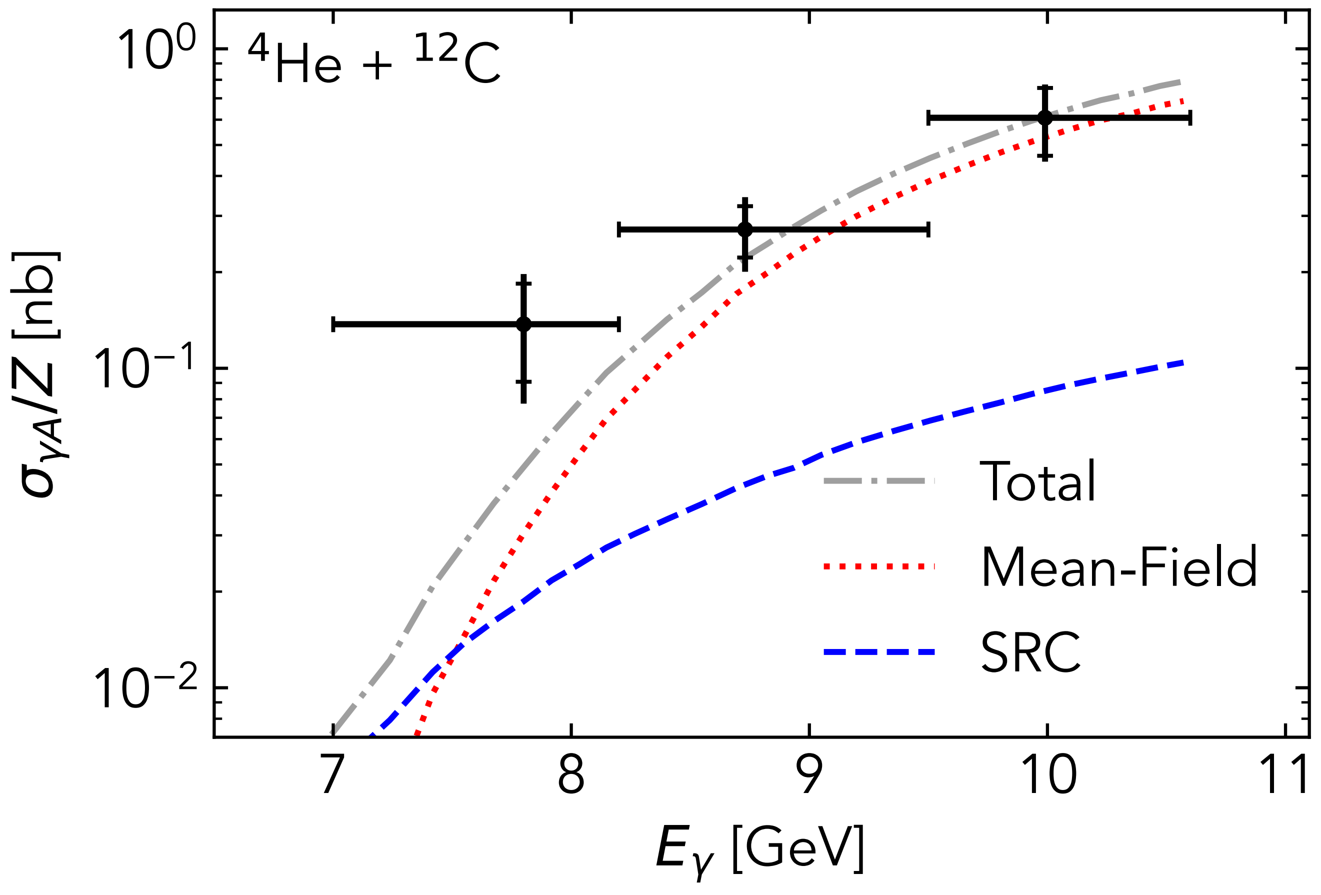
Systematic uncertainties

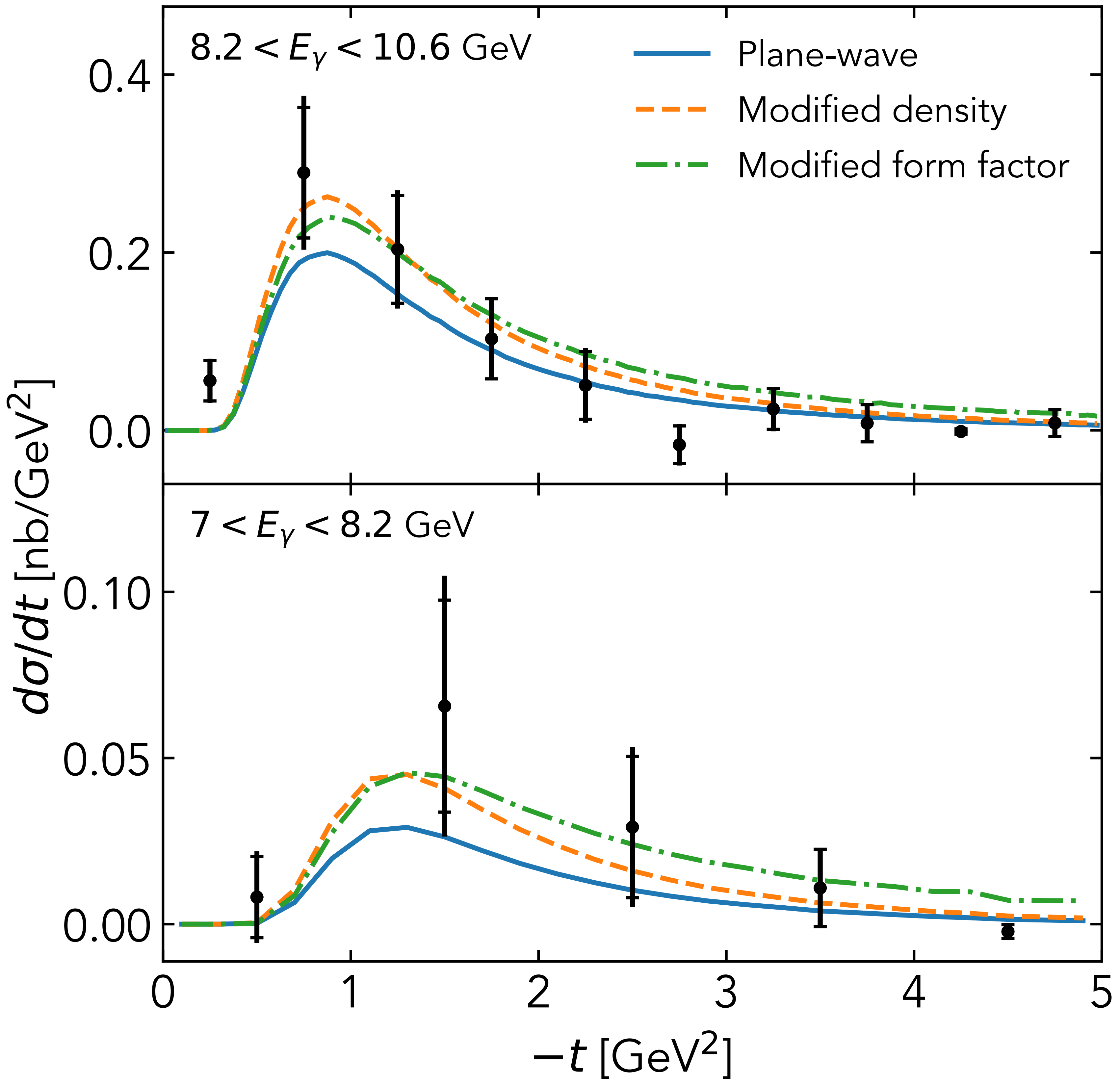




“First Measurement of Near- and Sub-Threshold J/ψ Photoproduction off Nuclei”



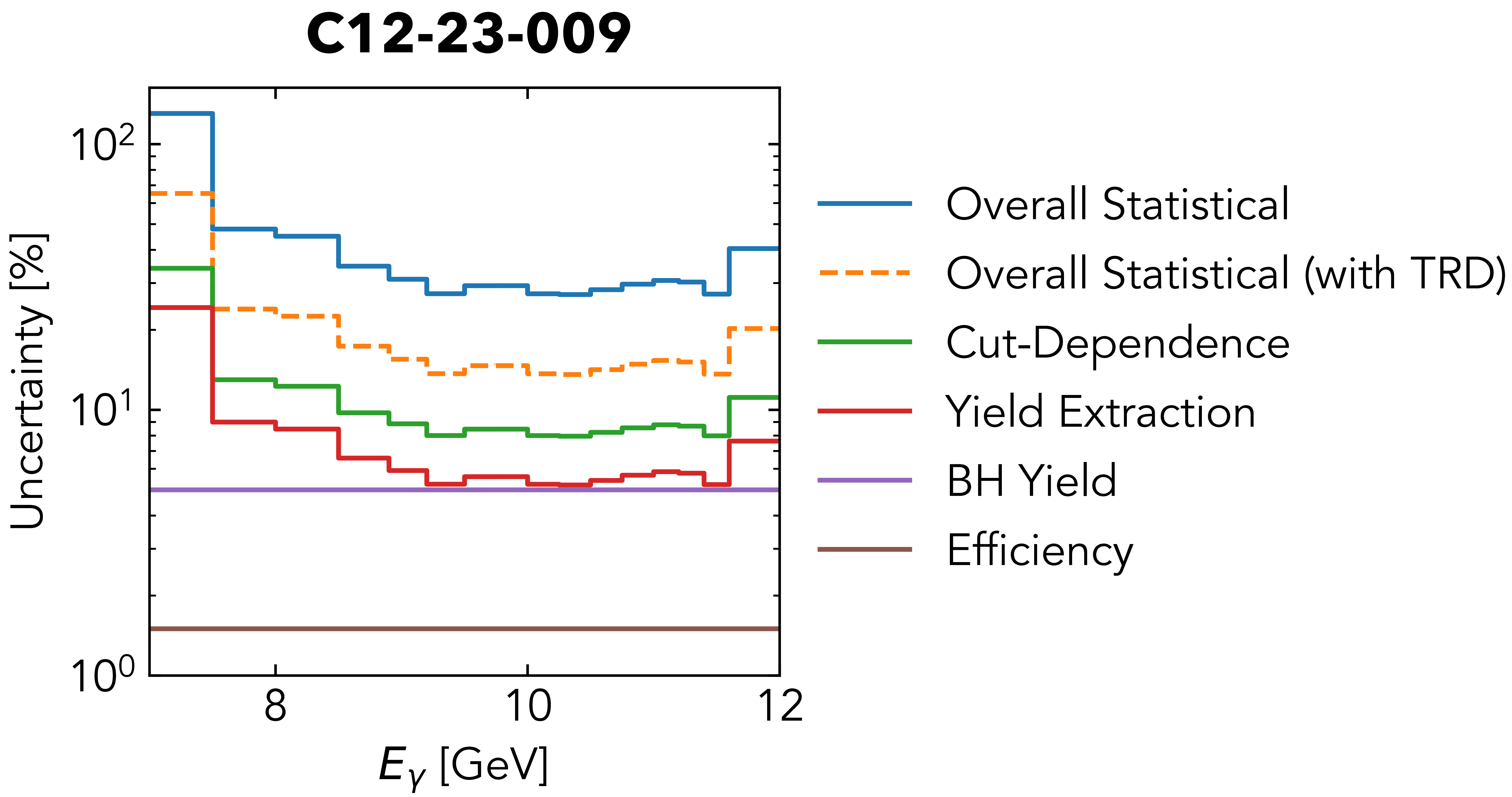




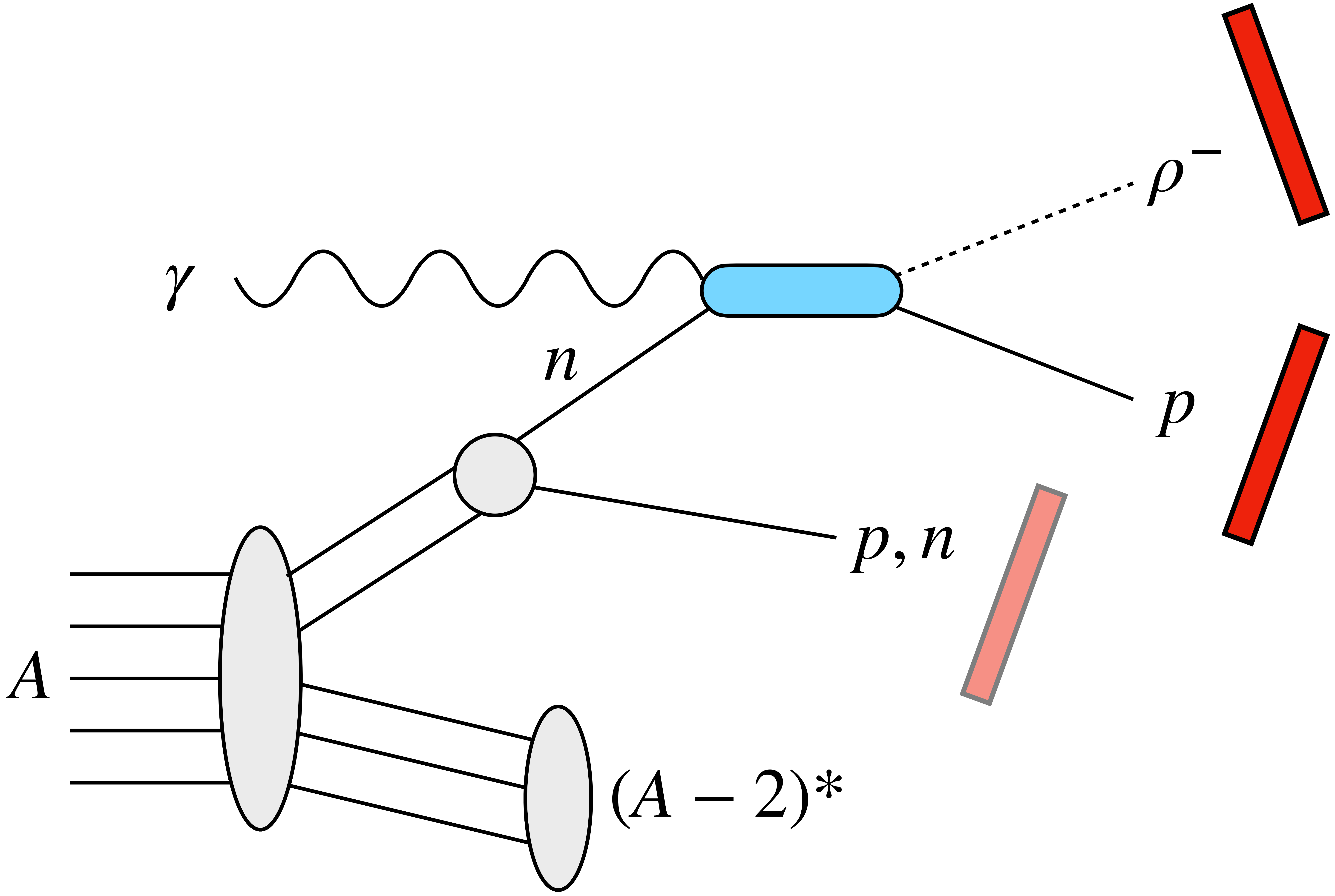
- First measurement of semi-inclusive $A(\gamma, J/\psi p)$ cross section near and below threshold
- Differential cross sections compared with models of nuclear modification
- Completed review; PRL submission next week

Note **Paper** **Supplement**

Detailed systematic study for J/ψ production



SRC photoproduction has been further studied



Key measurements:

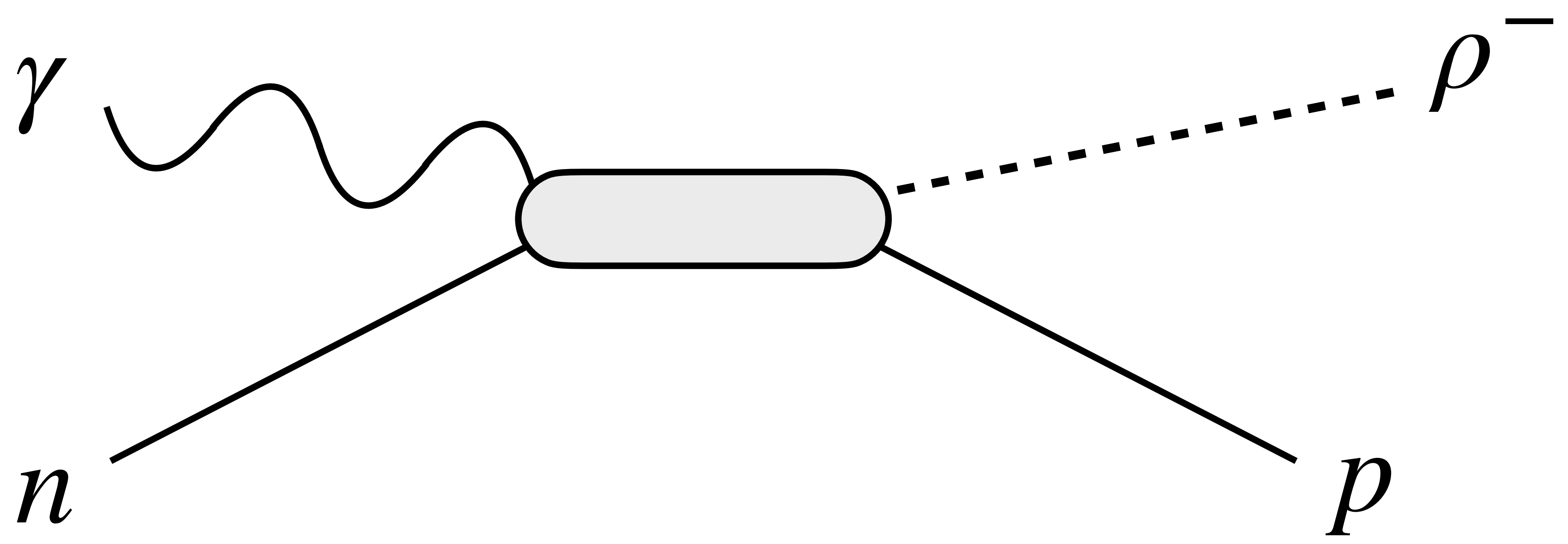
$(\gamma, \rho^- p)$

and

$(\gamma, \rho^- pp)$

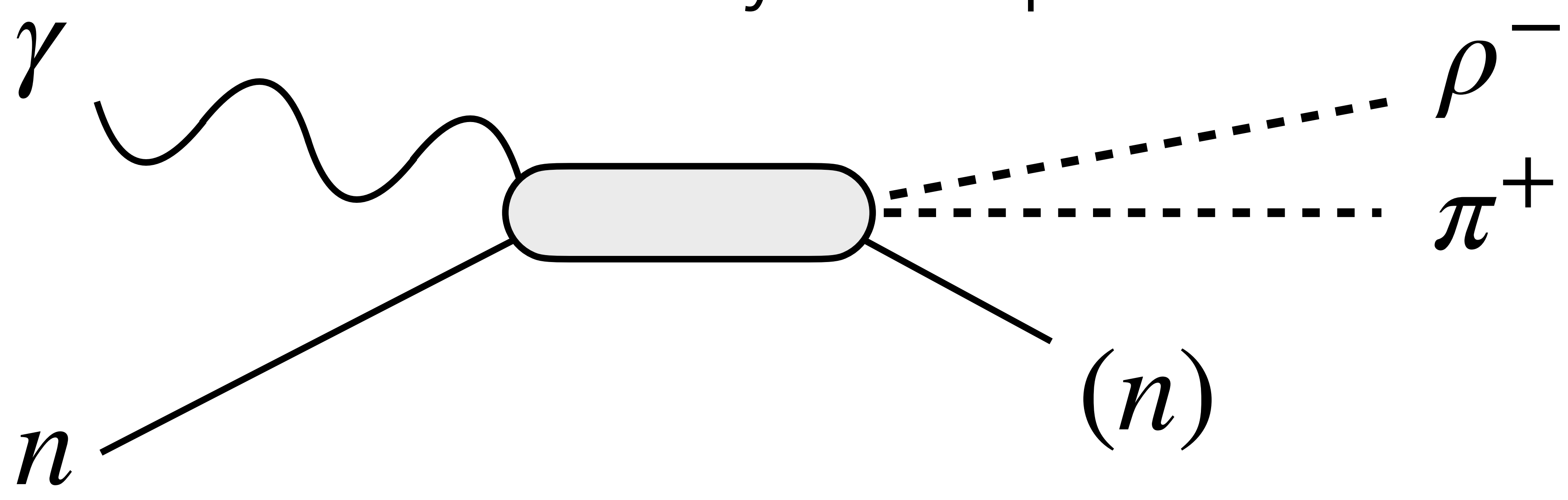
PID-related Backgrounds

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



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

Misidentify π^+ as proton



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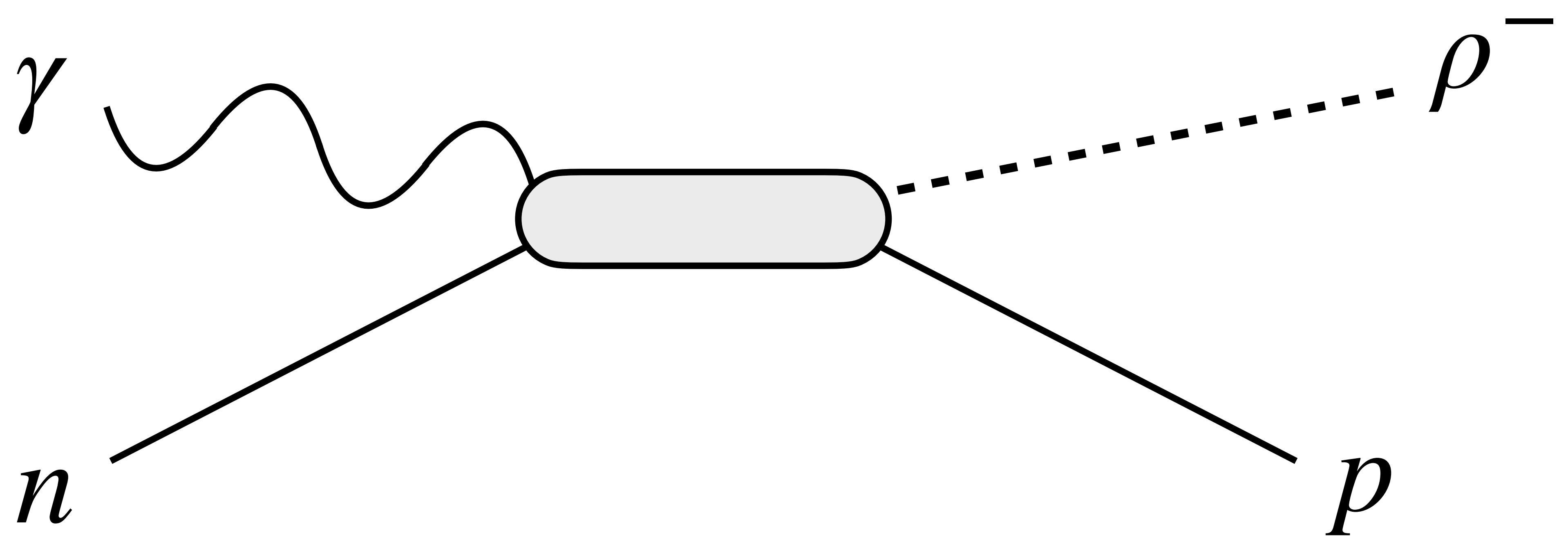

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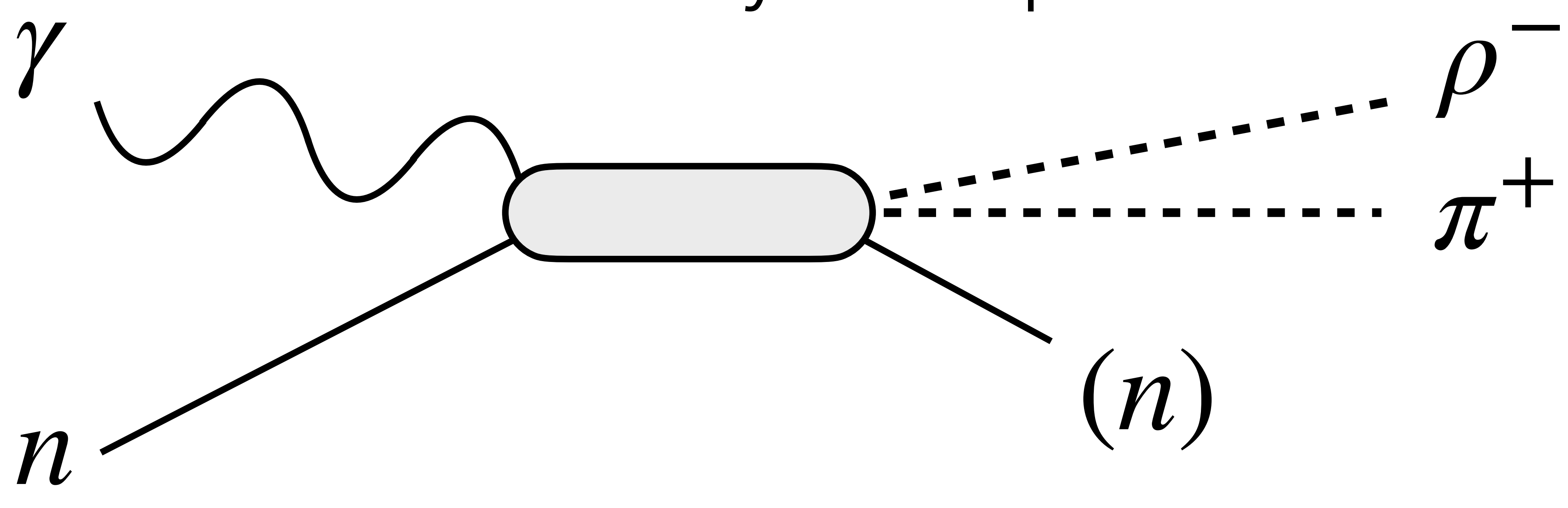
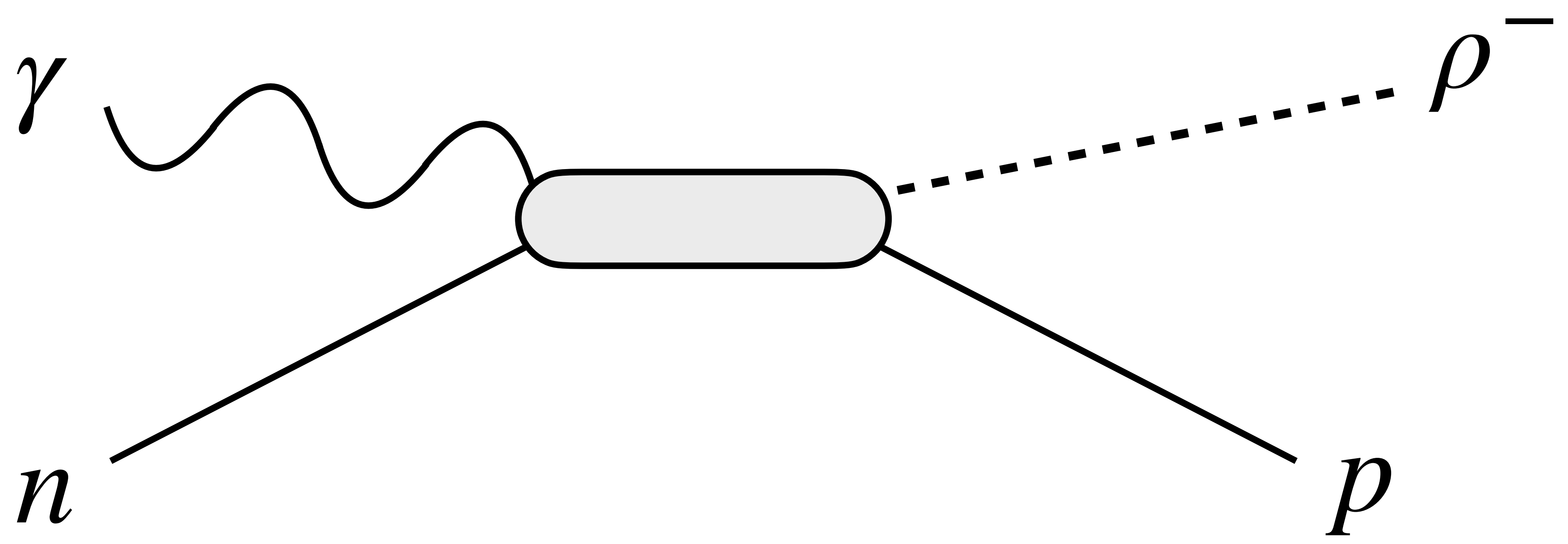


Inclusive variables:

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

PID-related Backgrounds

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



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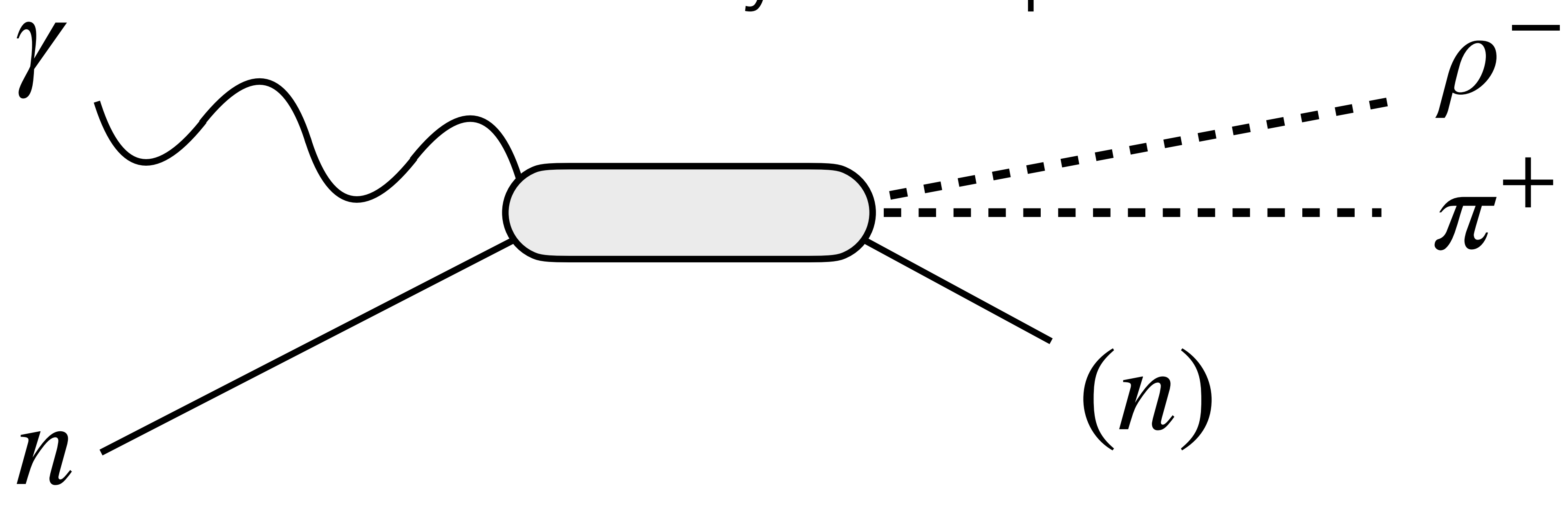


Inclusive variables:

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

We can assume:

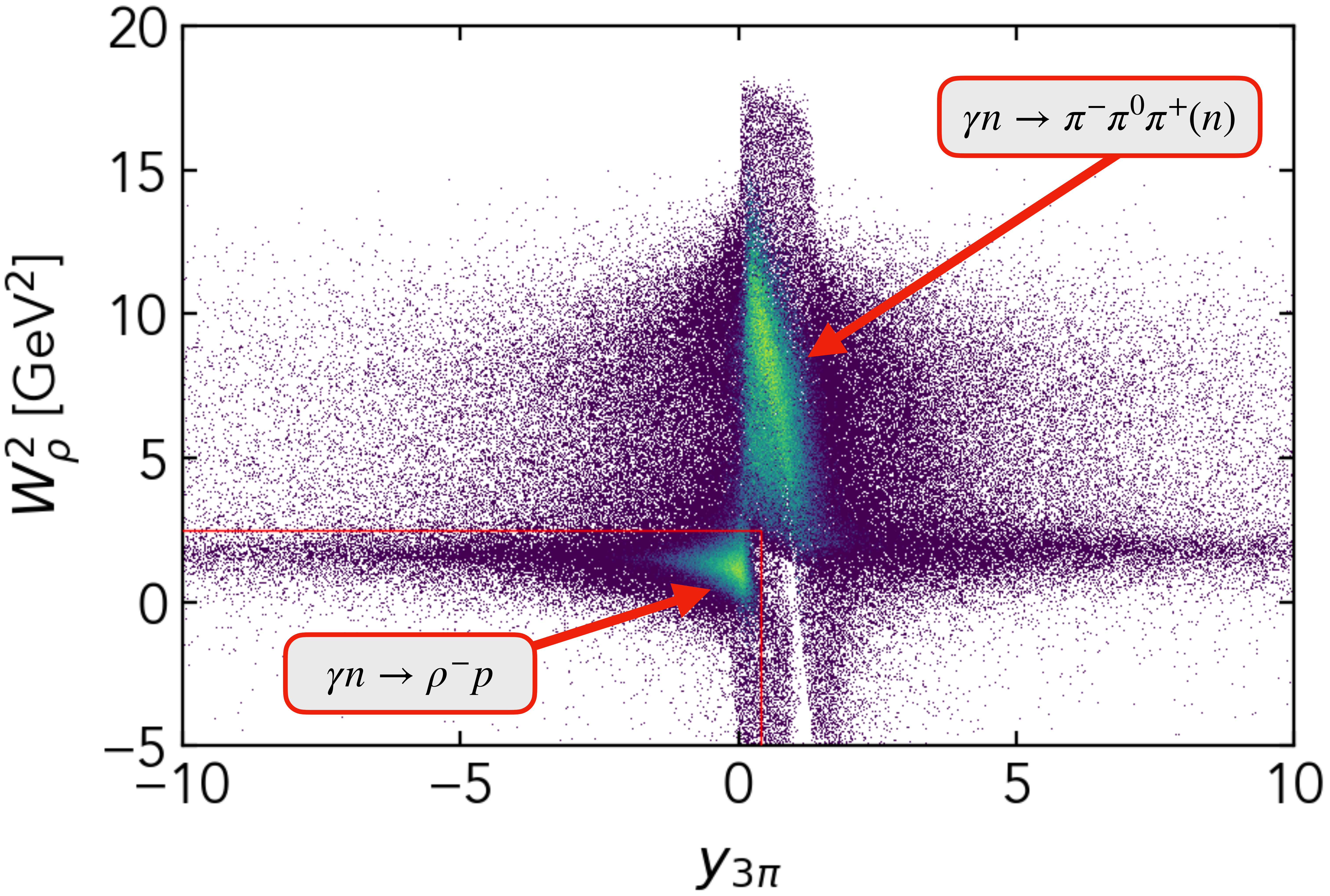
$$p_M = p_{\pi^0} + p_{\pi^-}$$

OR

$$p_M = p_{\pi^+} + p_{\pi^0} + p_{\pi^-}$$

Meson-inclusive observables separate signal and background

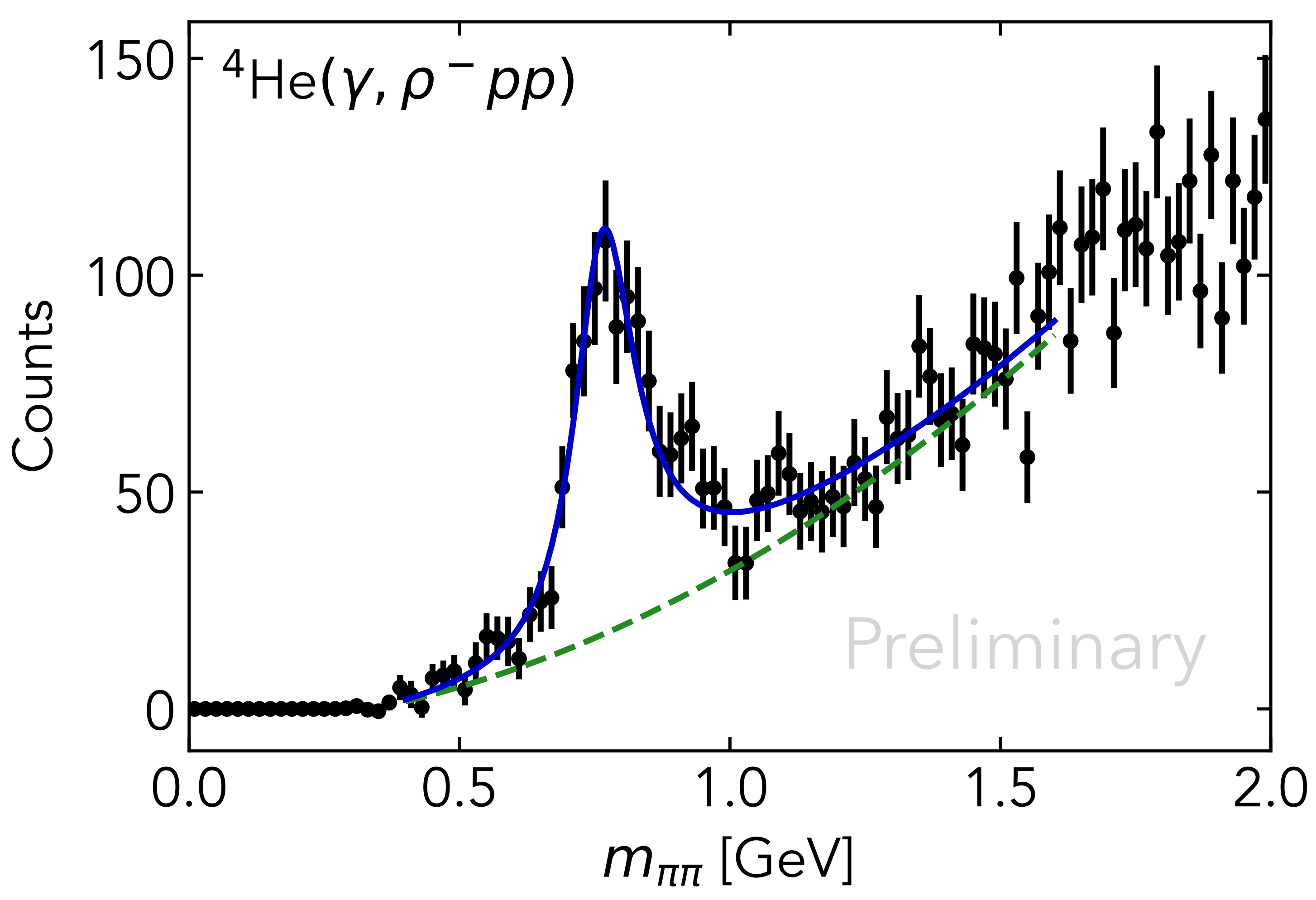
Invariant mass assuming ρ^- production

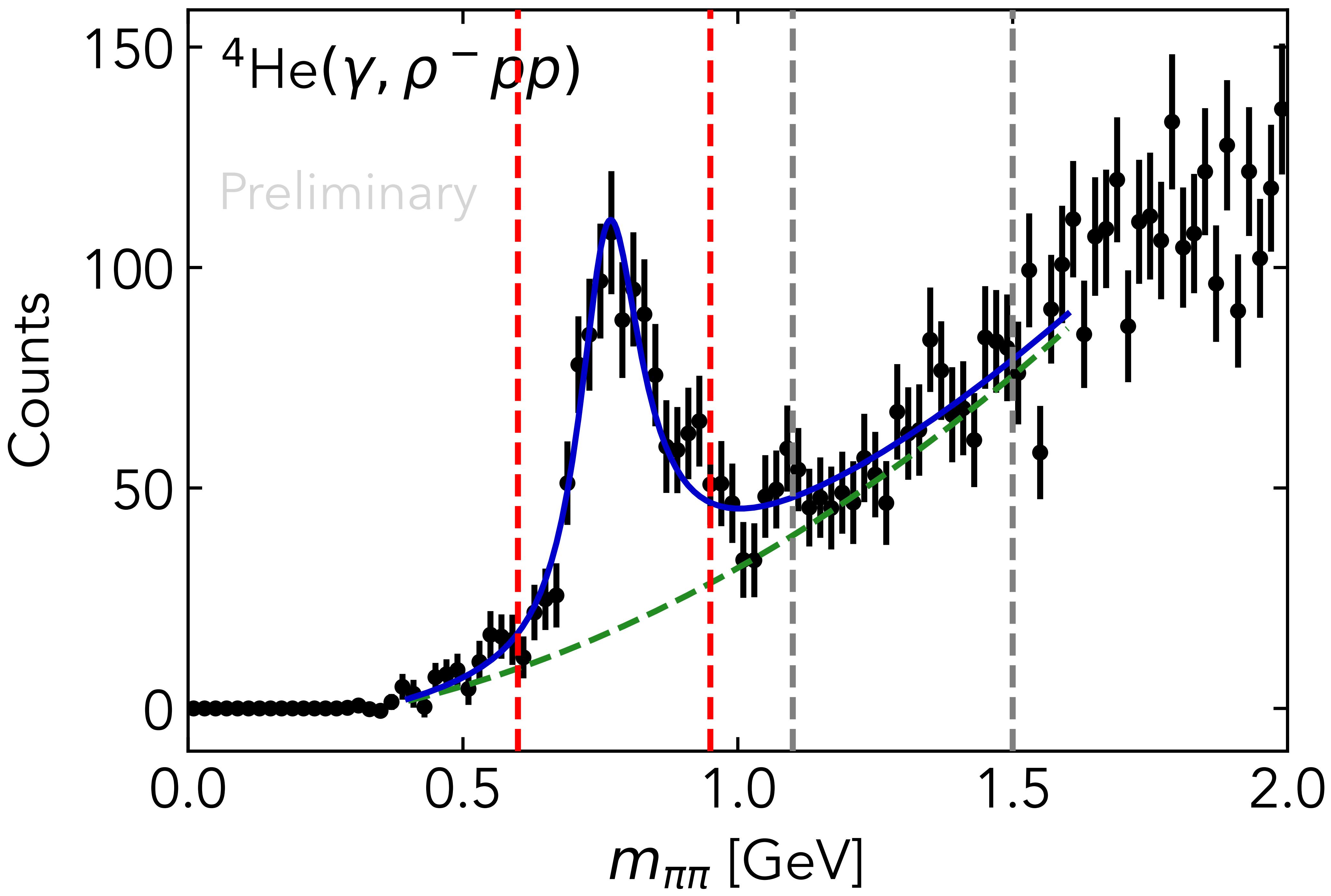


Scaling variable assuming 3π production

SRC Backgrounds: Non-resonant $\pi^0\pi^-$

Non-resonant $\pi^0\pi^-$ backgrounds

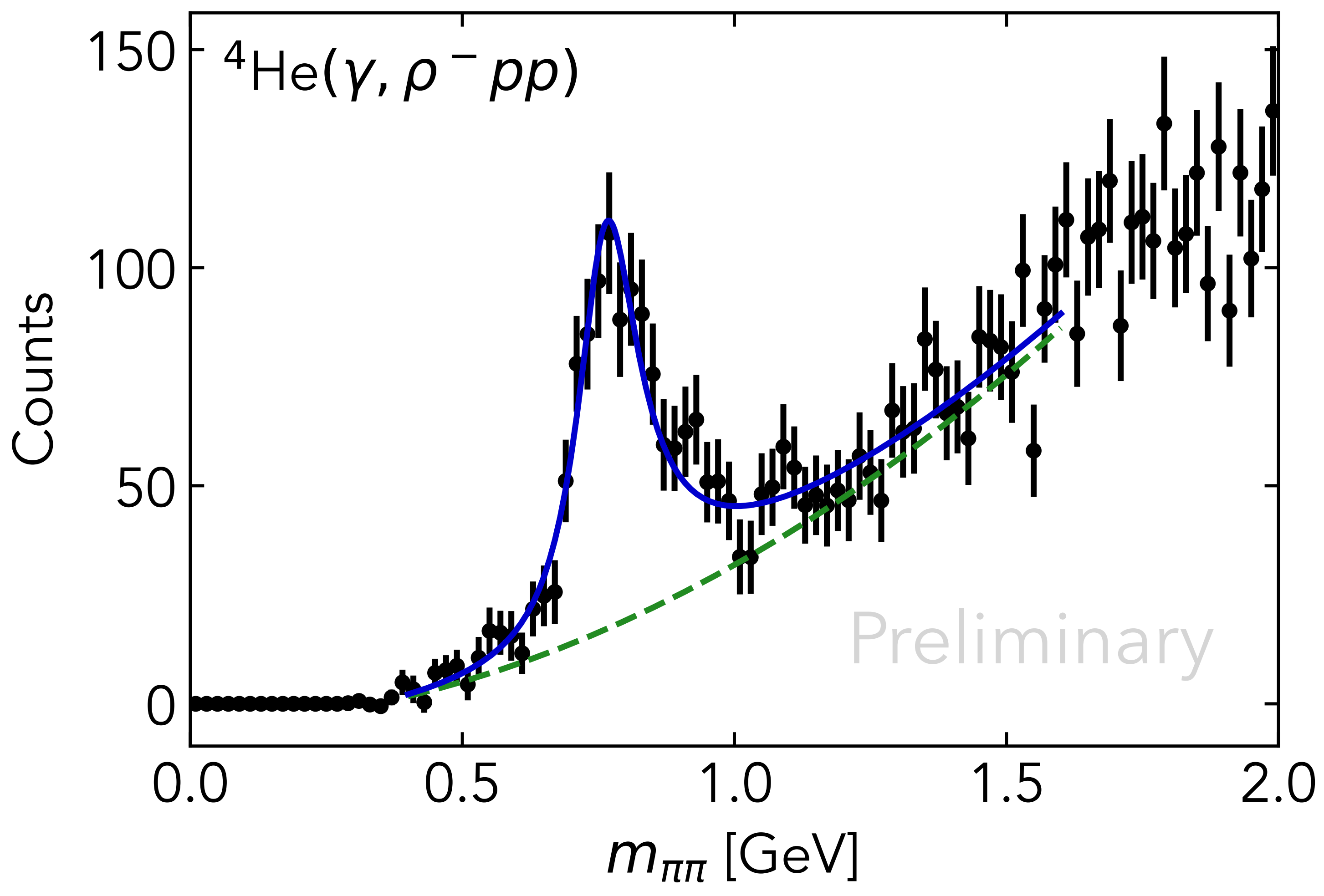


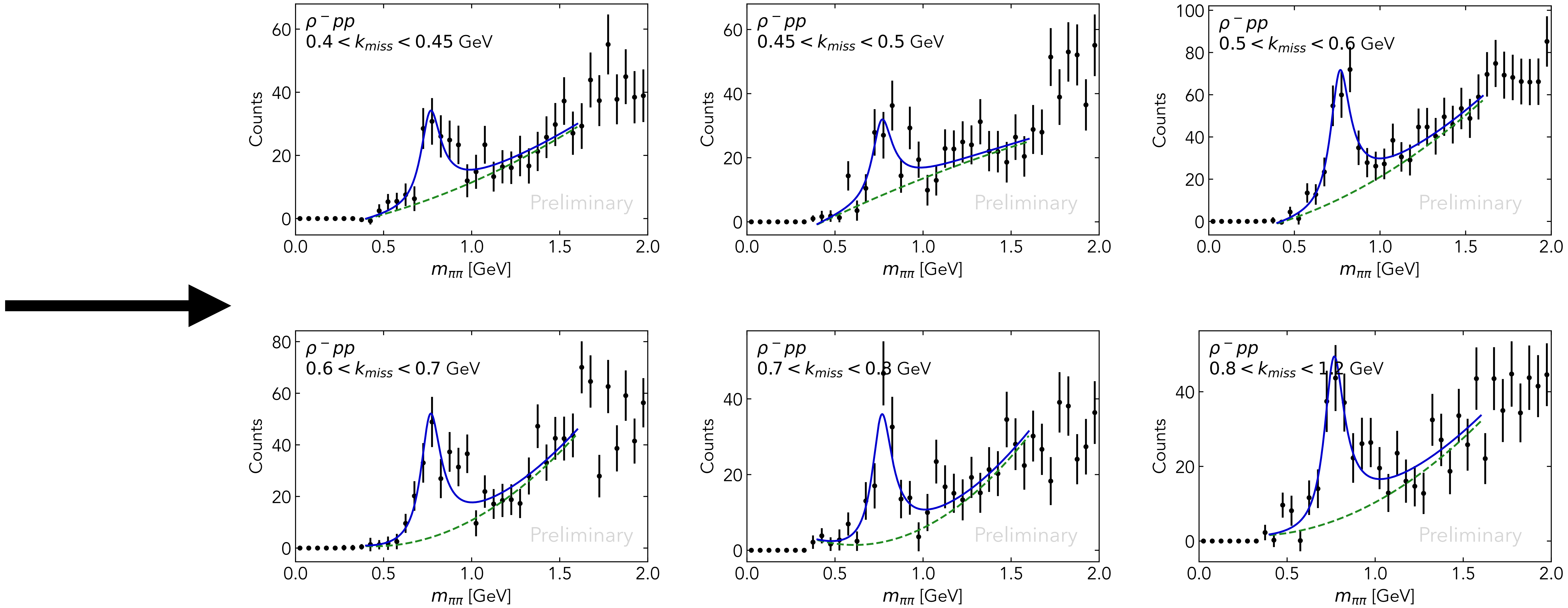


Approach 1: Side-band subtraction

SRC Backgrounds: Non-resonant $\pi^0\pi^-$

Non-resonant $\pi^0\pi^-$ backgrounds





Approach 2: Bin-by-bin fitting

Primary systematic uncertainties are selection cuts and yield extraction method

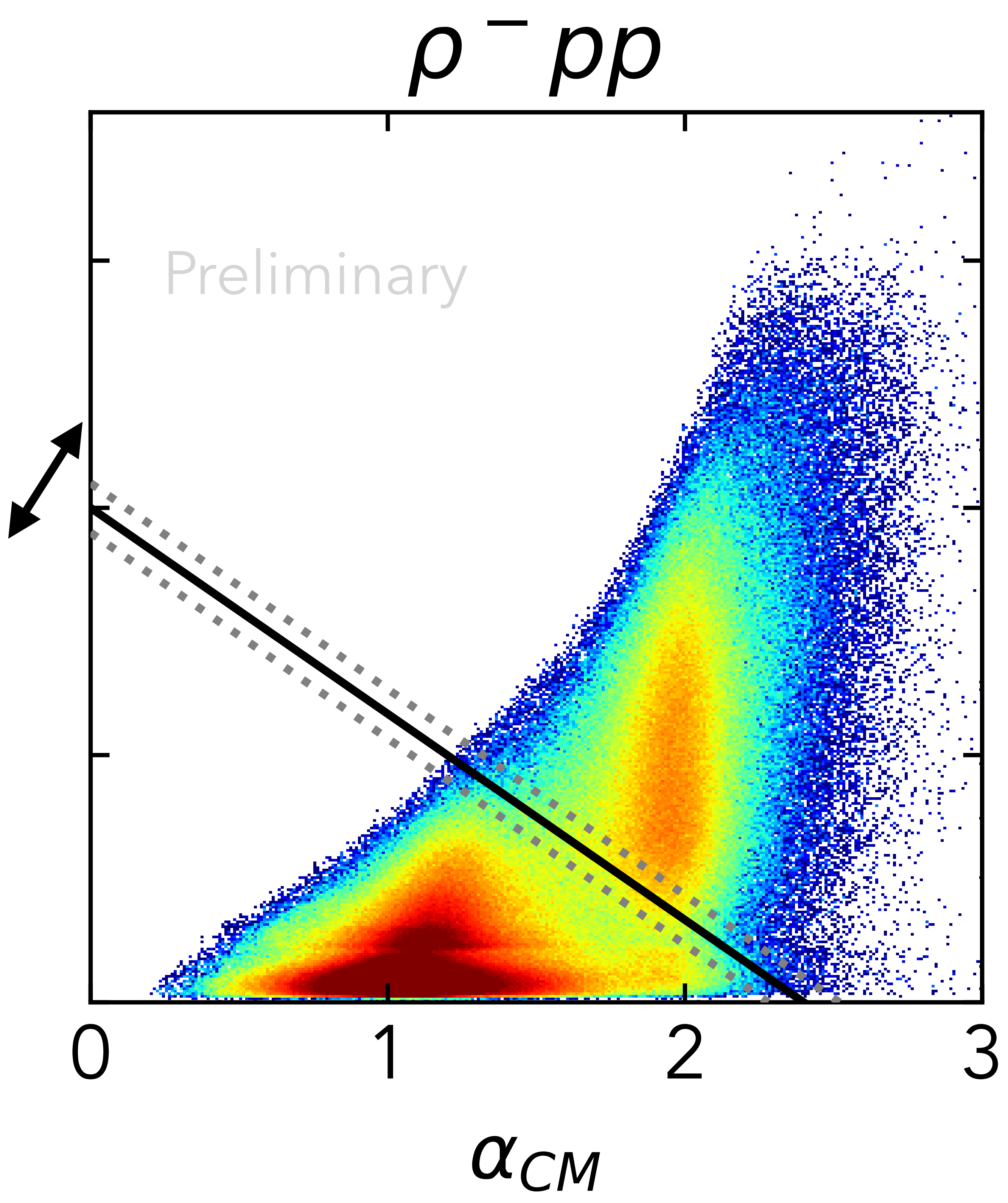
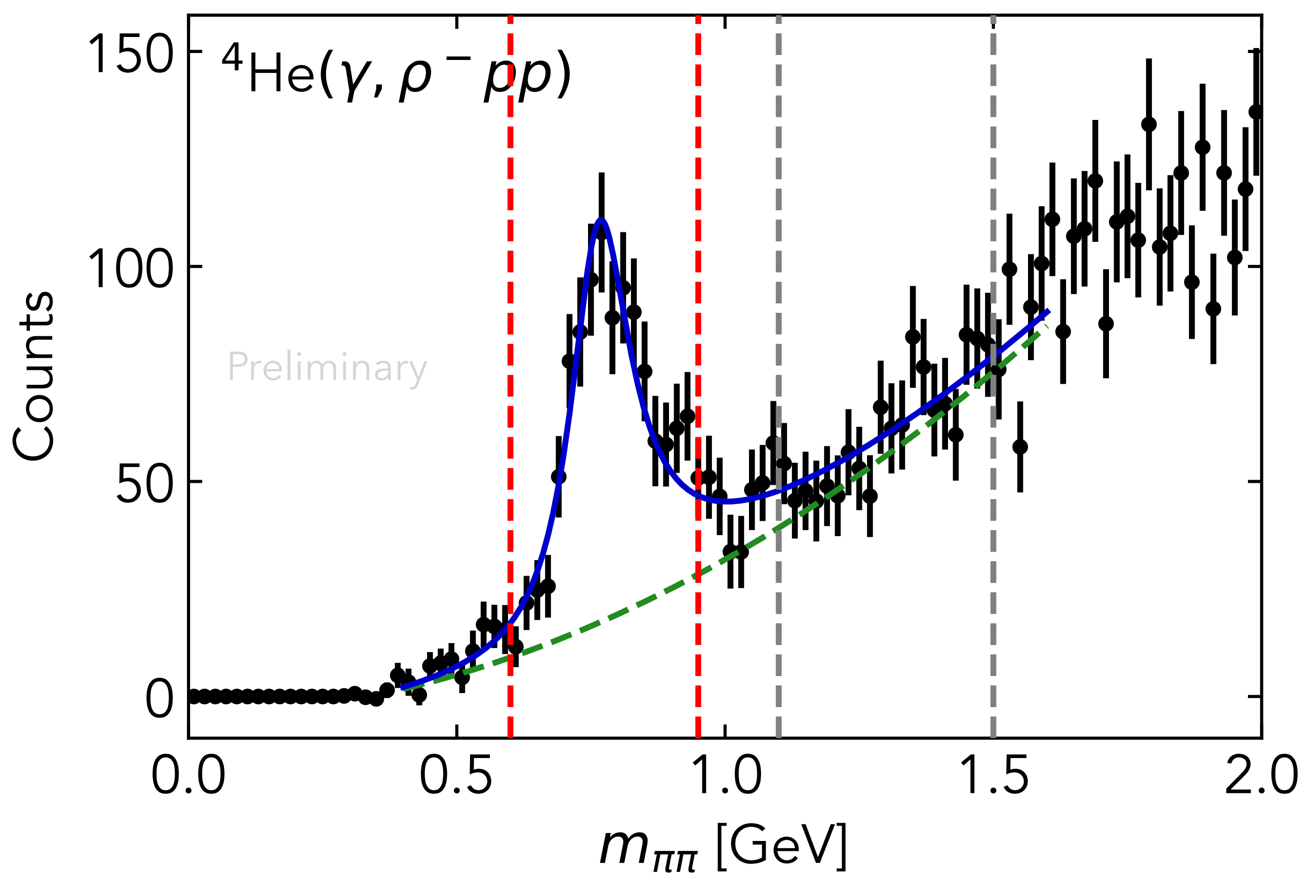


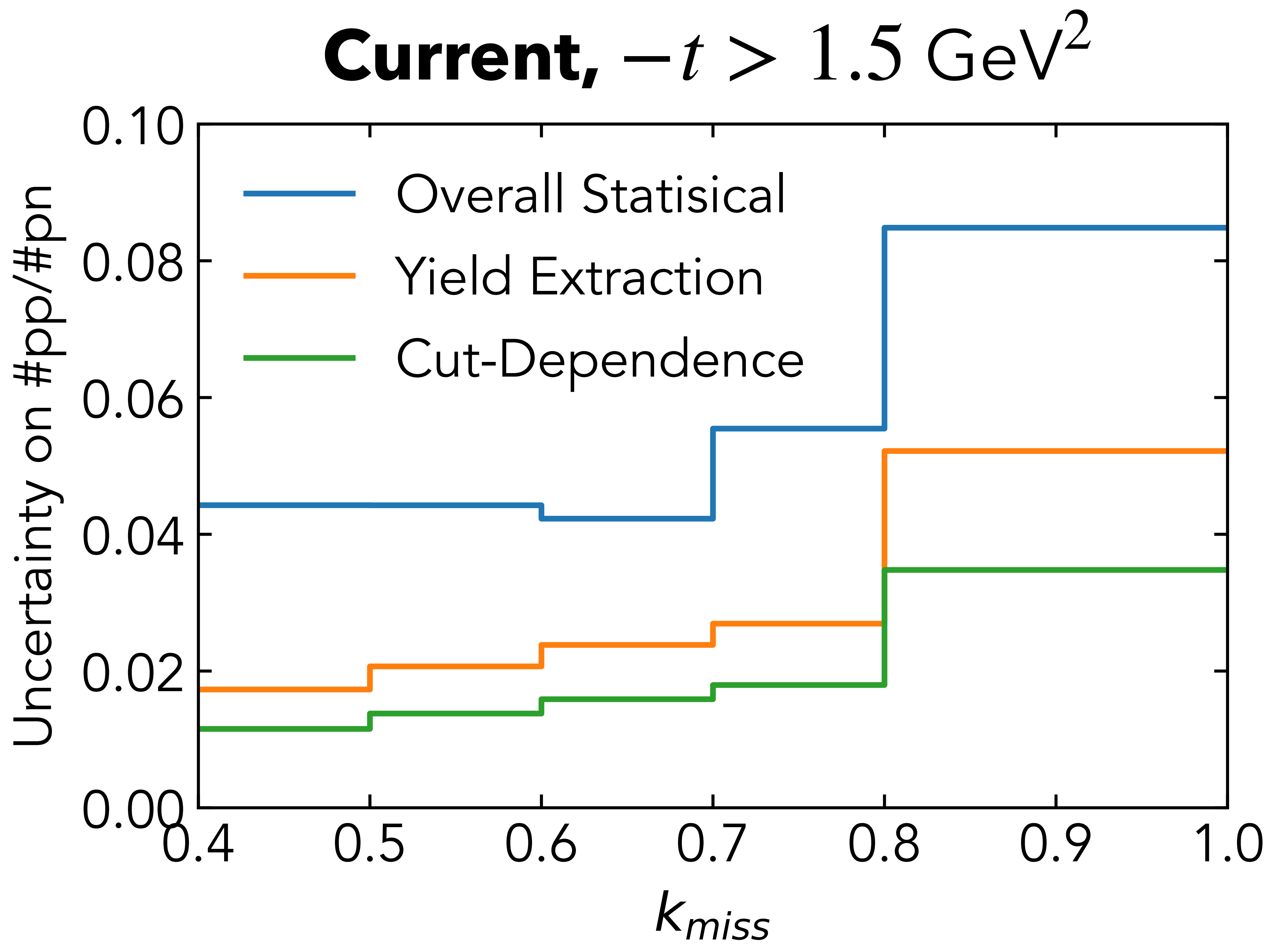
Table 1: Projected sources of point-to-point uncertainty on measured SRC breakup yields in a typical kinematic bin expecting a yield of 50 SRC breakup events.

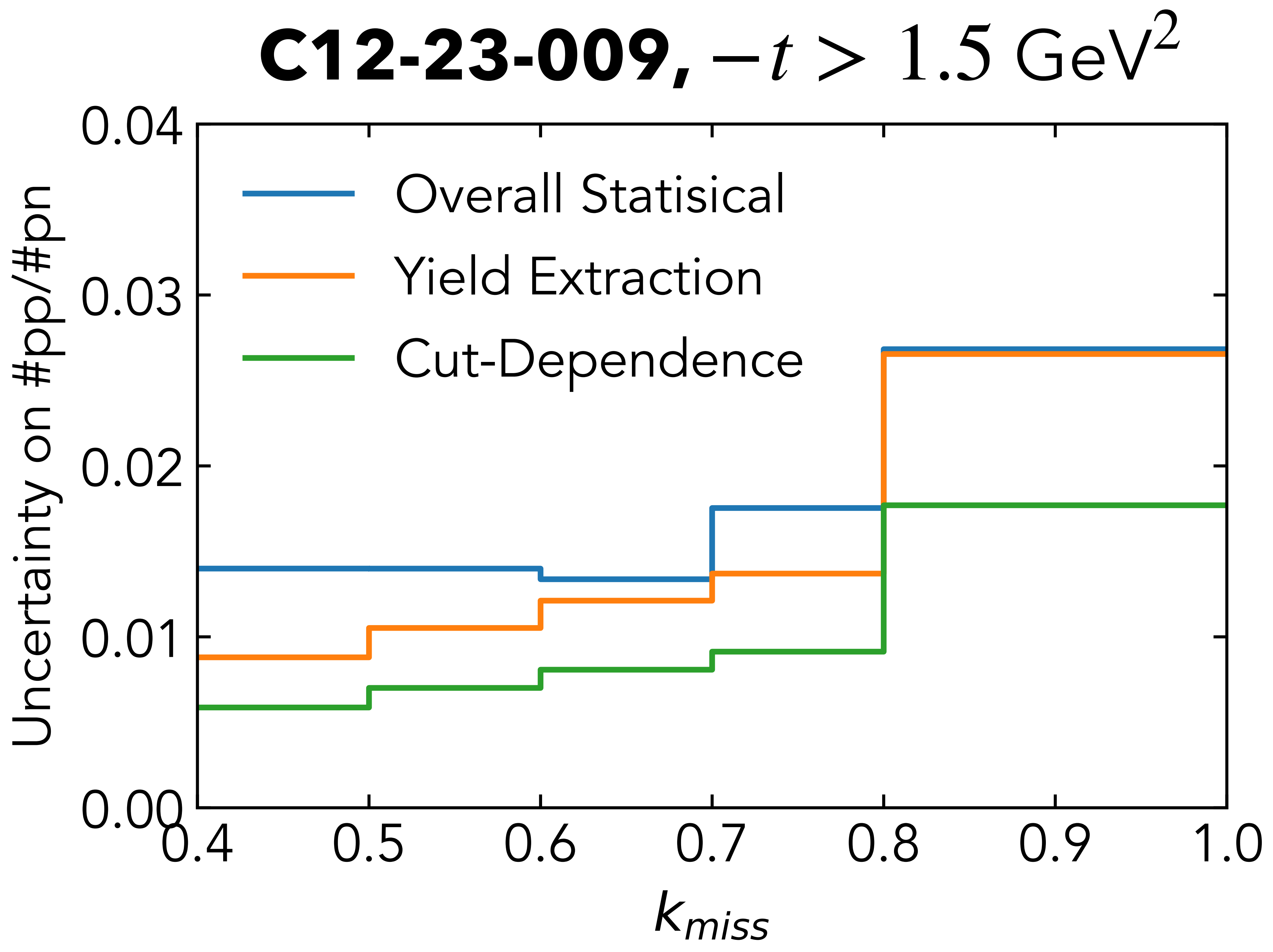
Source of Uncertainty	Contribution
Statistical	14%
Background	16%
Cut-dependence	10%
Yield extraction	15%
Total	28%



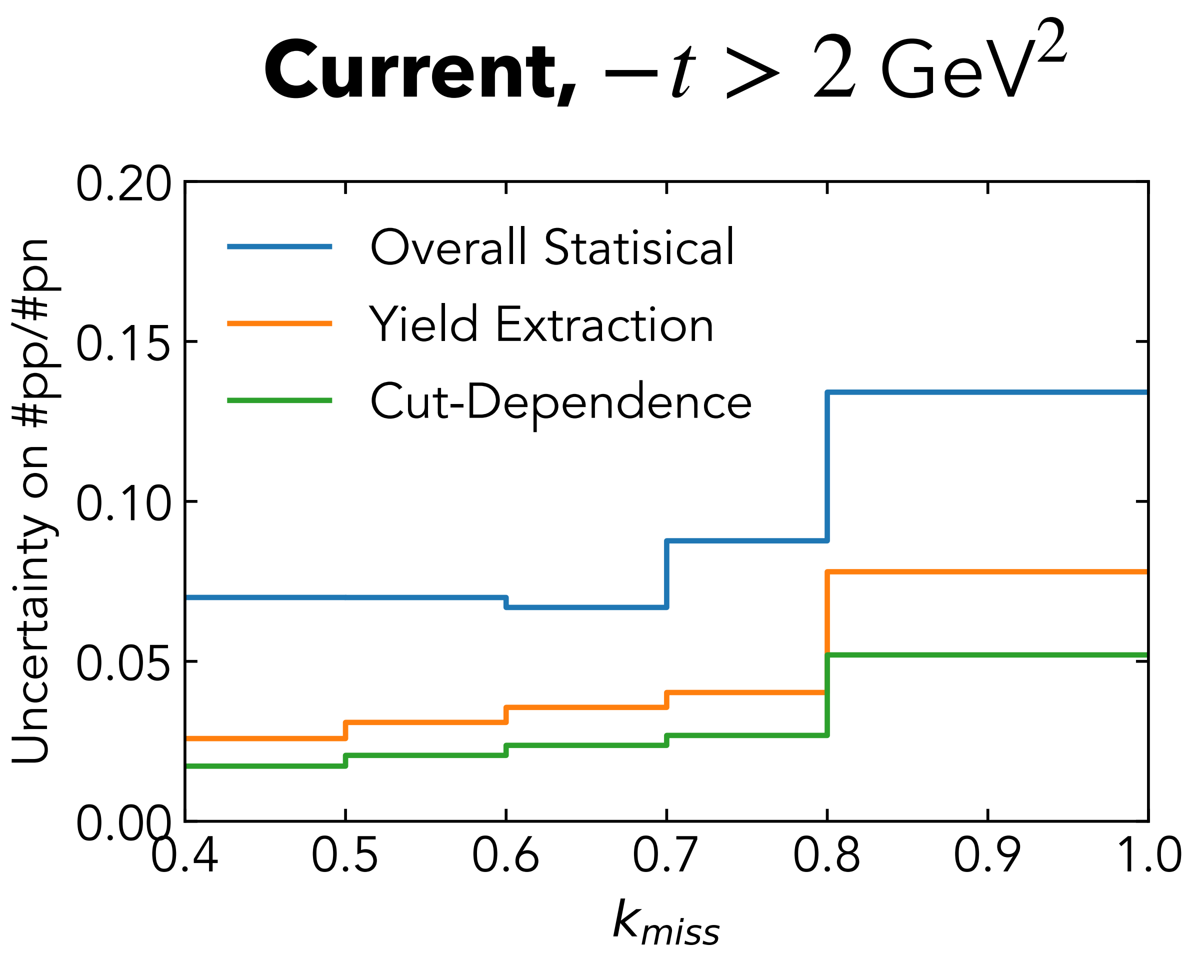
"Overall statistical": 21% – still statistically-dominated with larger dataset

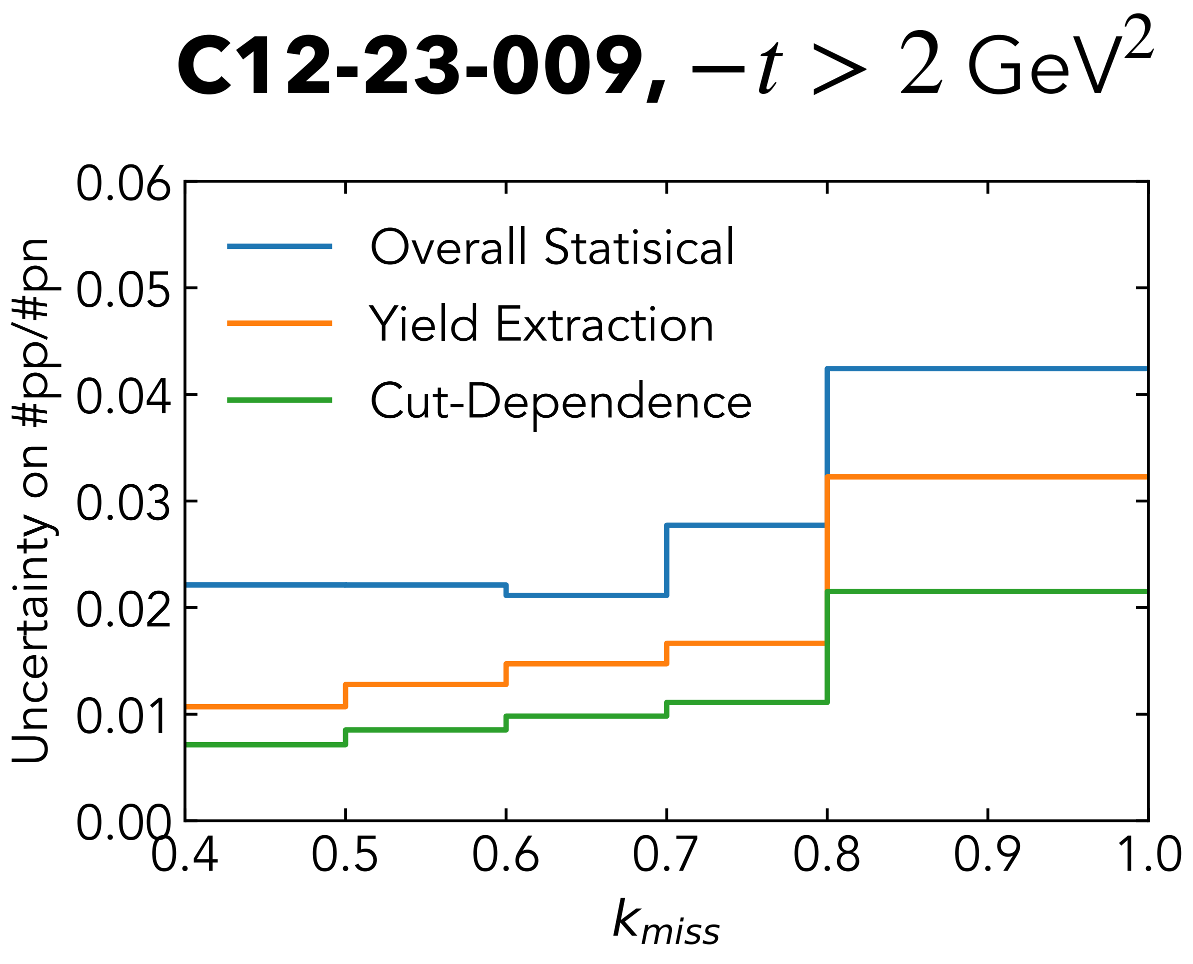
Statistical precision improved with projected data, but still dominates over systematic uncertainty

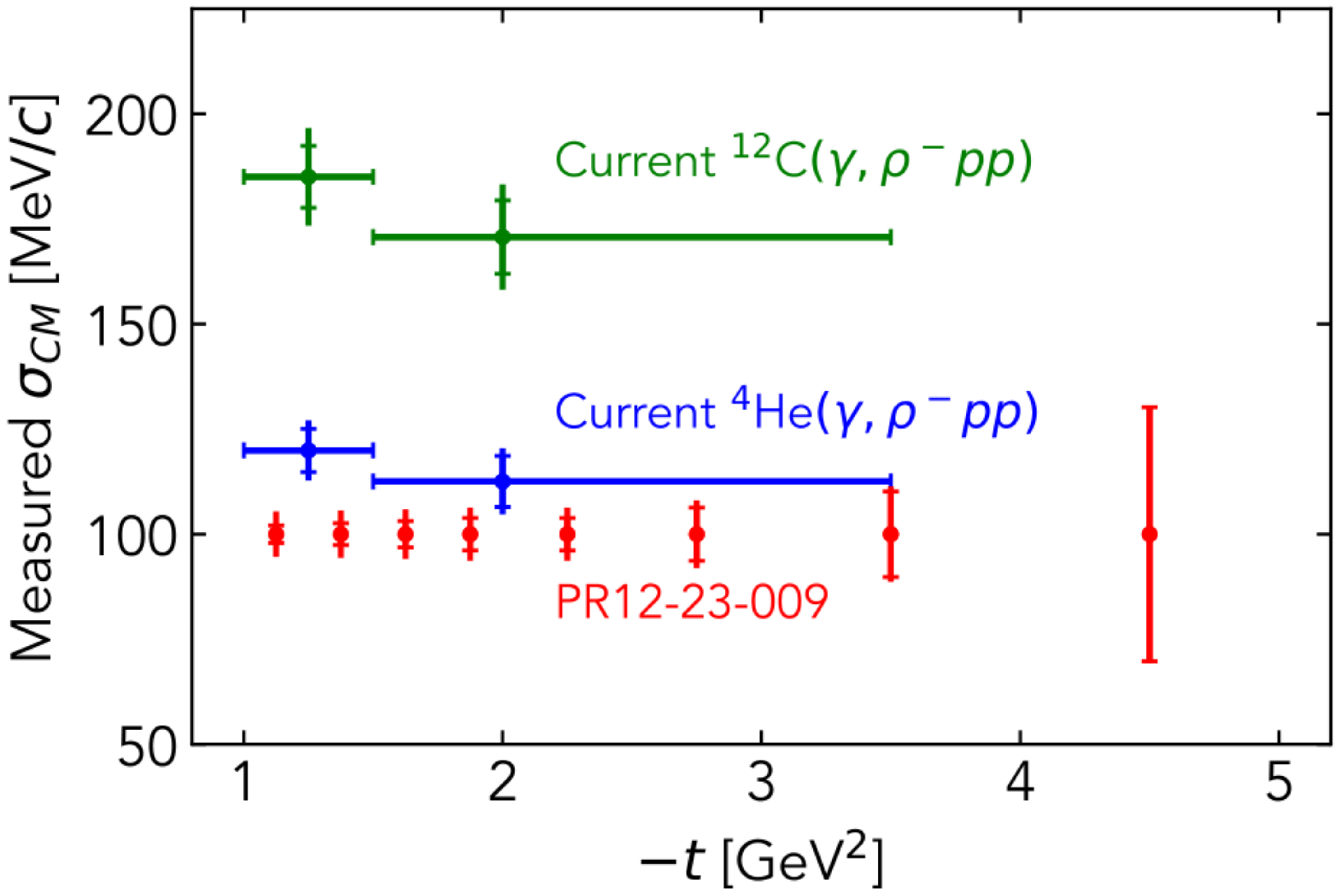




Pushing to high momentum-transfer

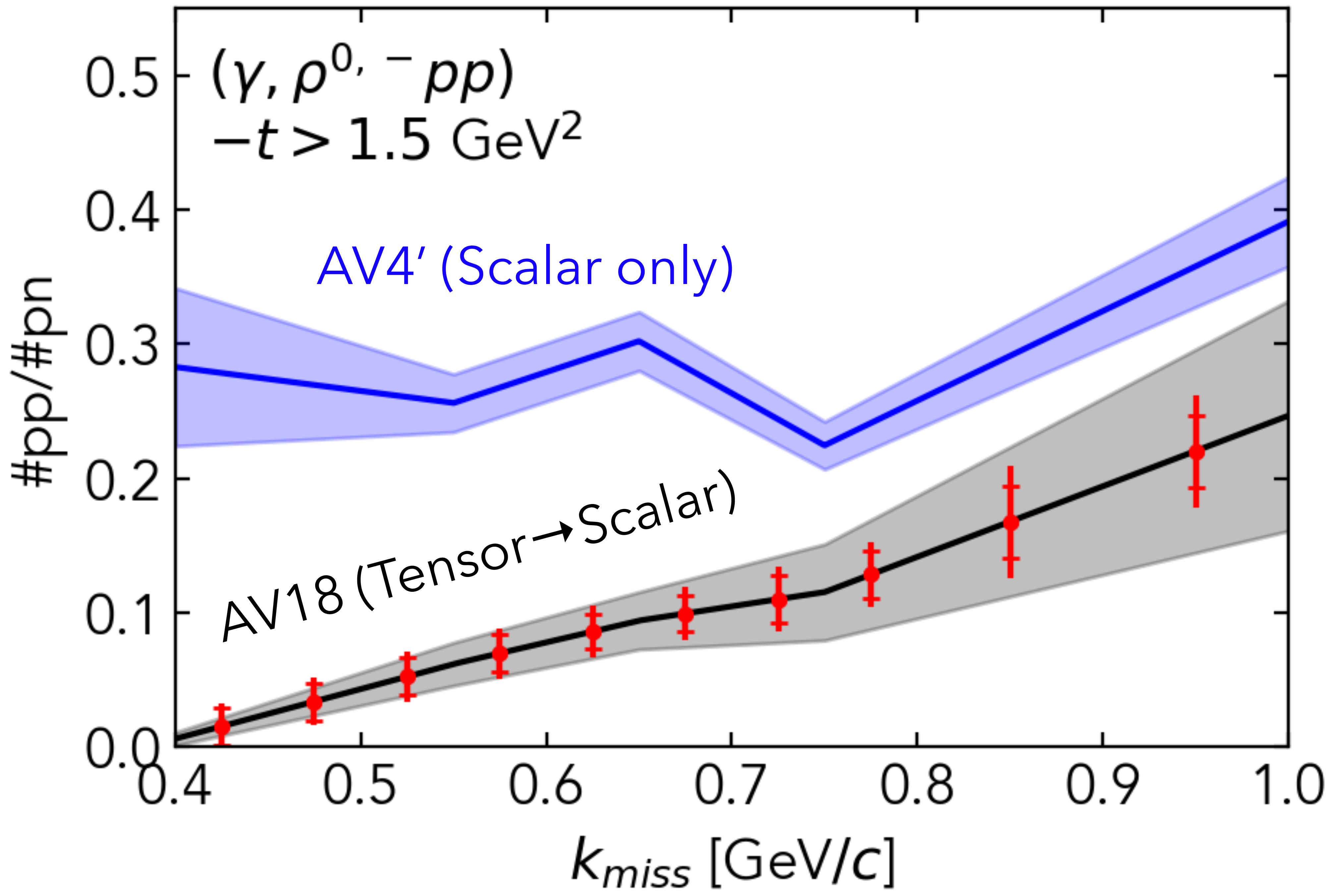


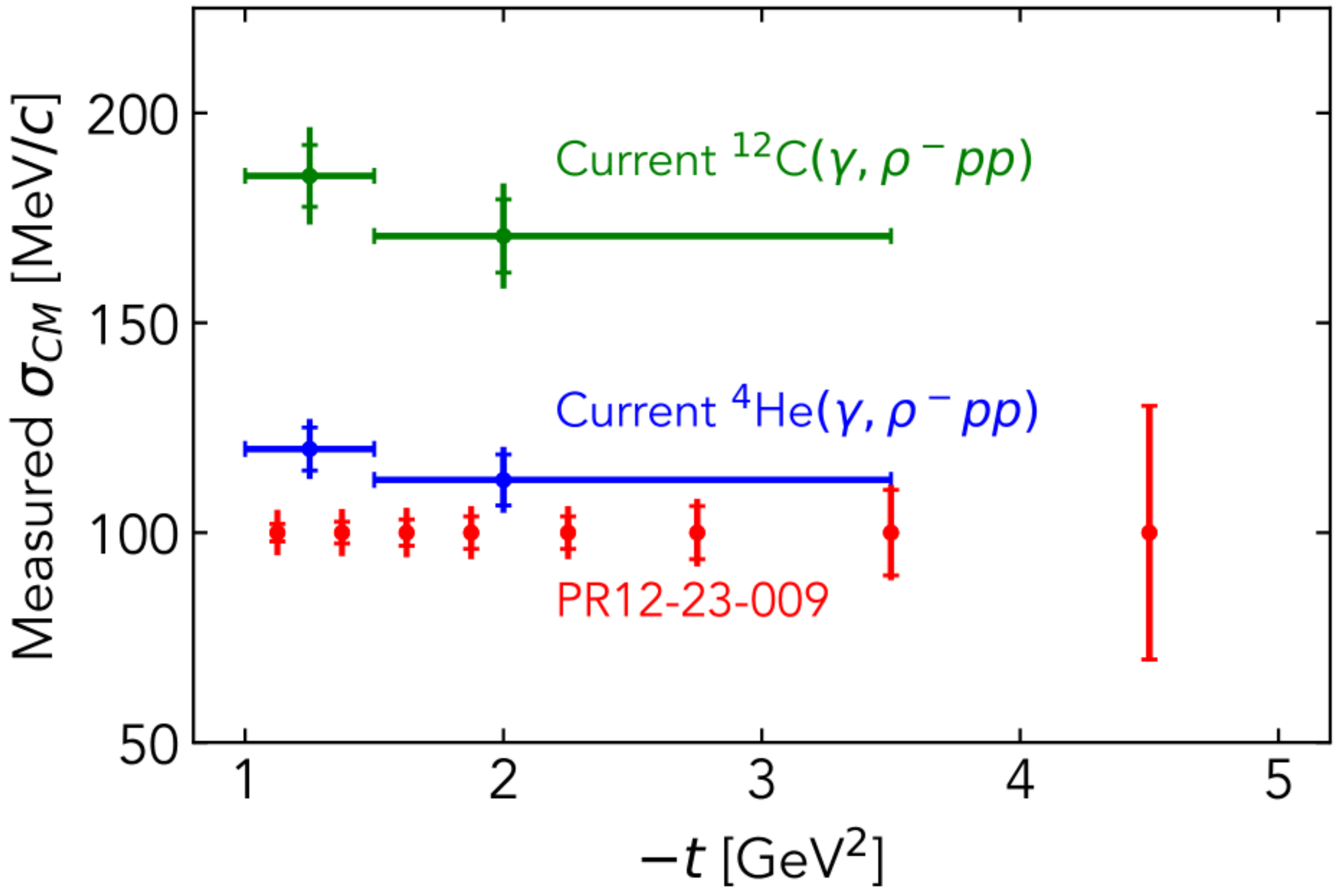




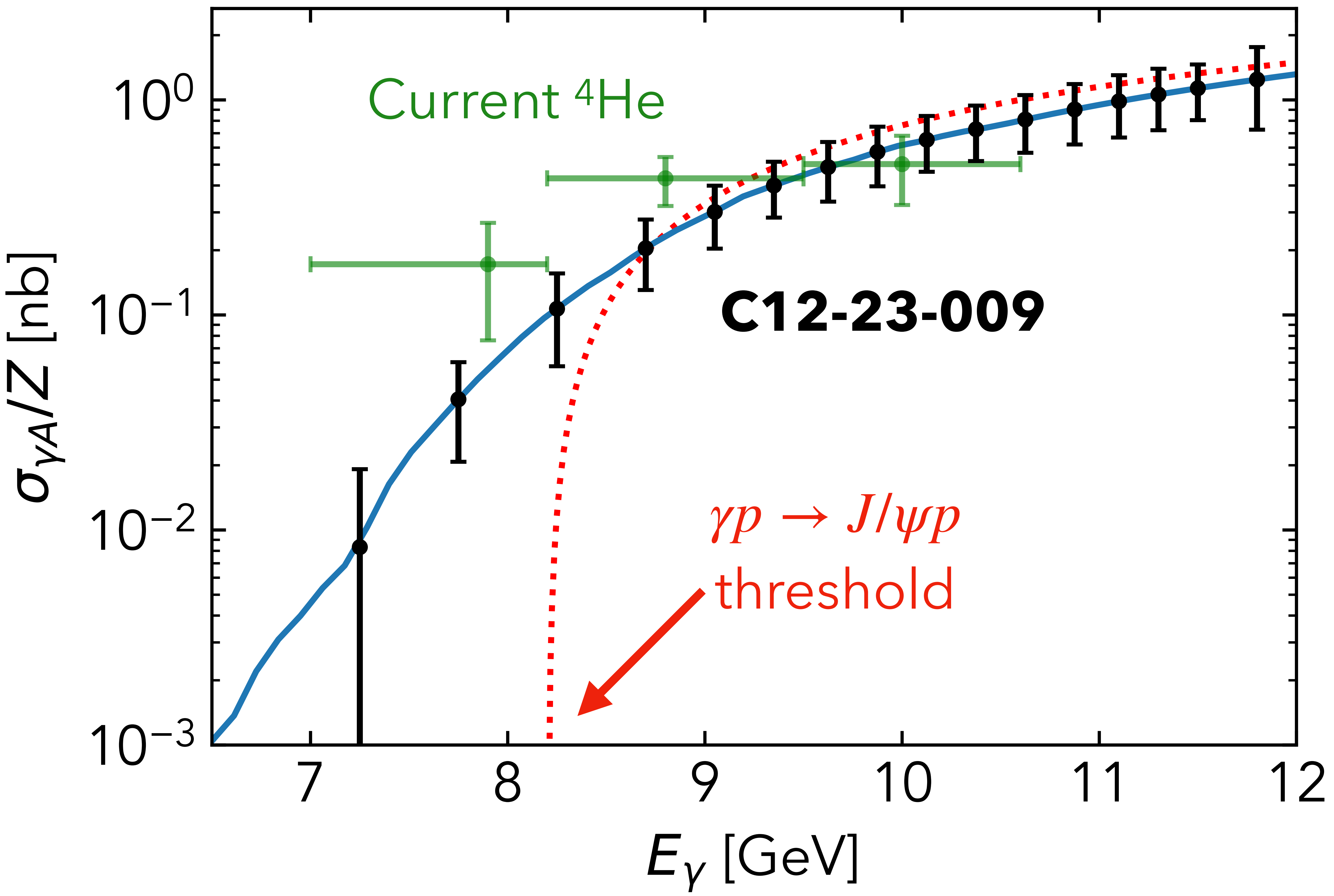
At large momentum-transfer, statistical uncertainties increasingly dominate

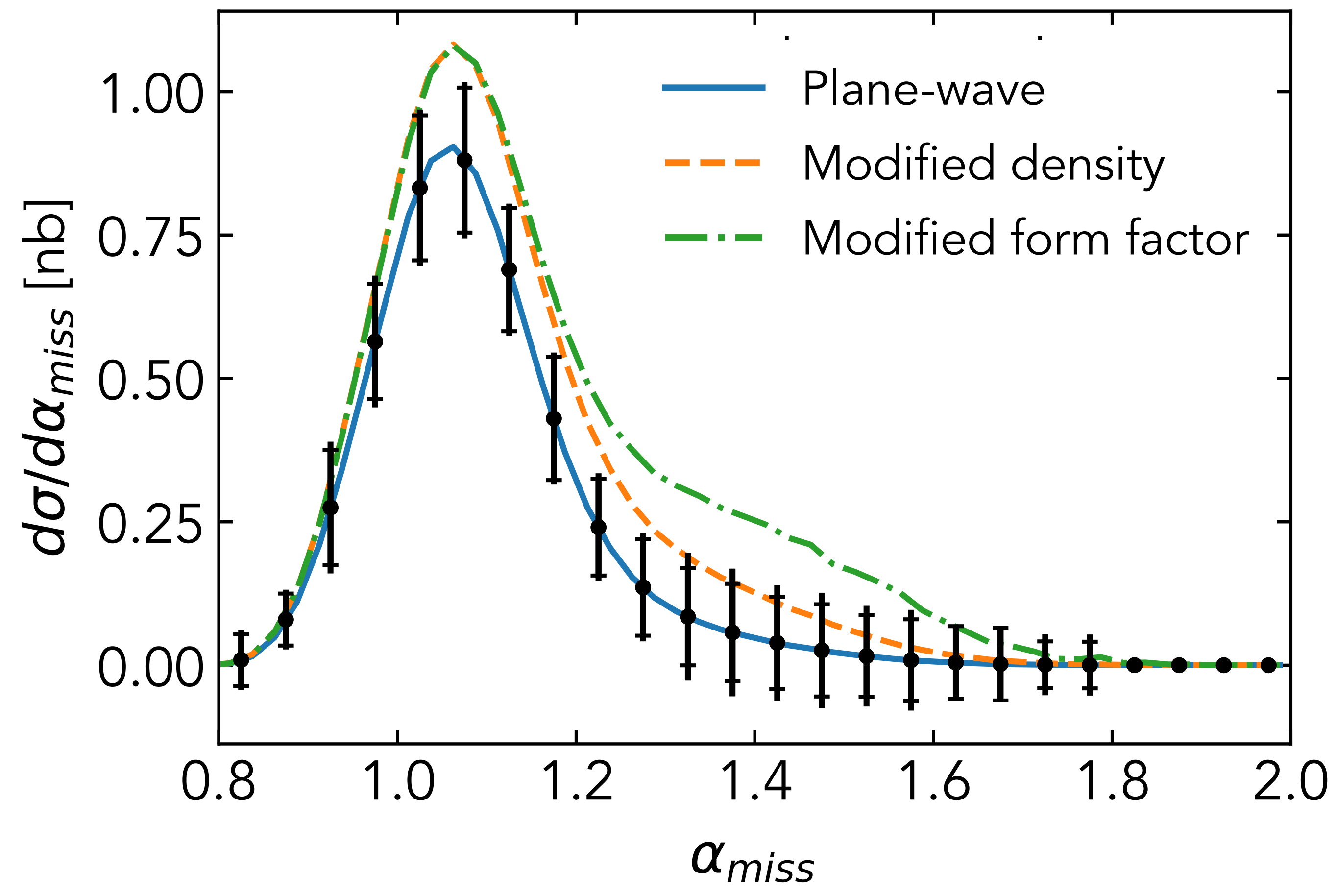
Proposed data will give precision measurement of SRCs and resolution-dependence

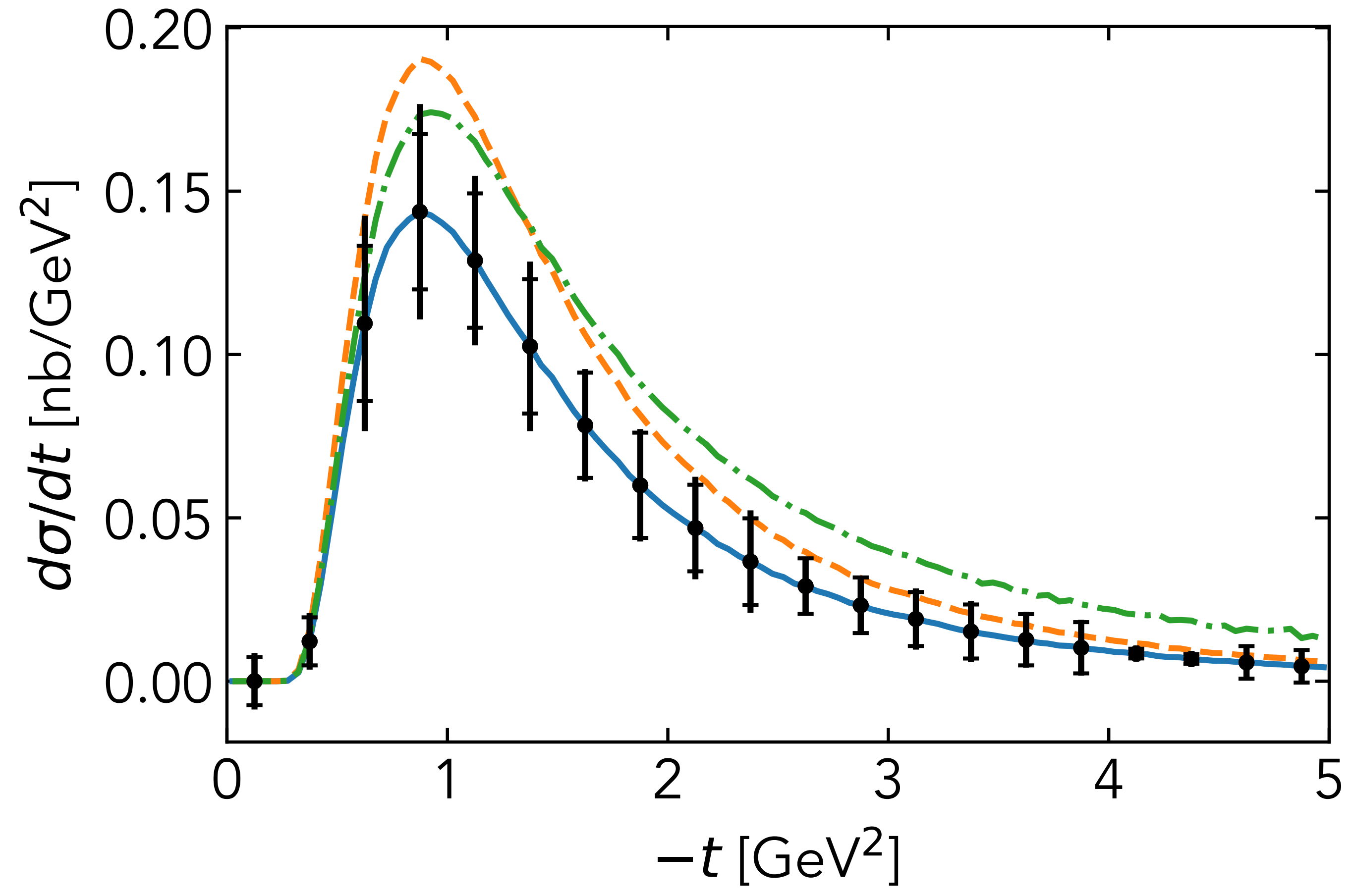




Proposed data will give constraints on gluon content of nuclei

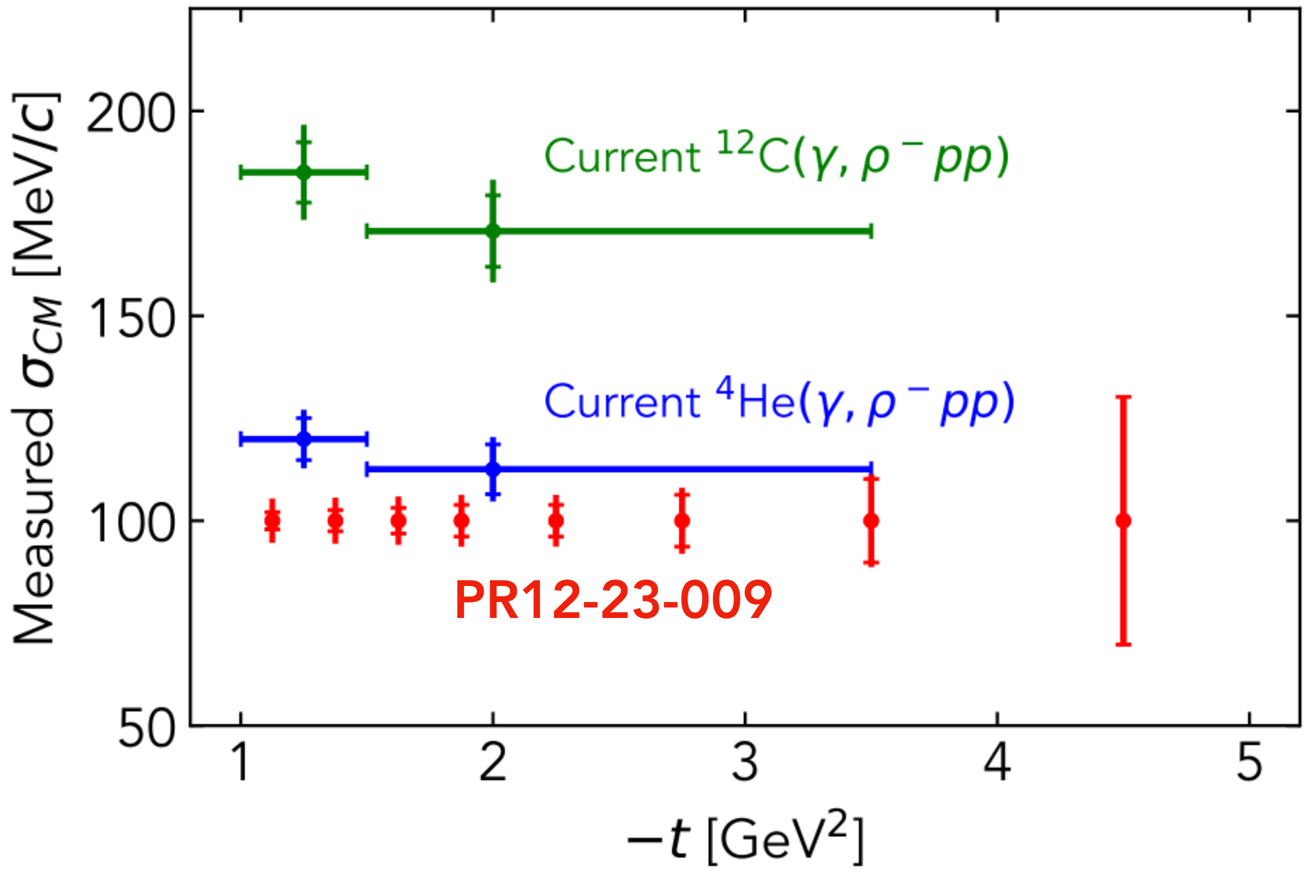


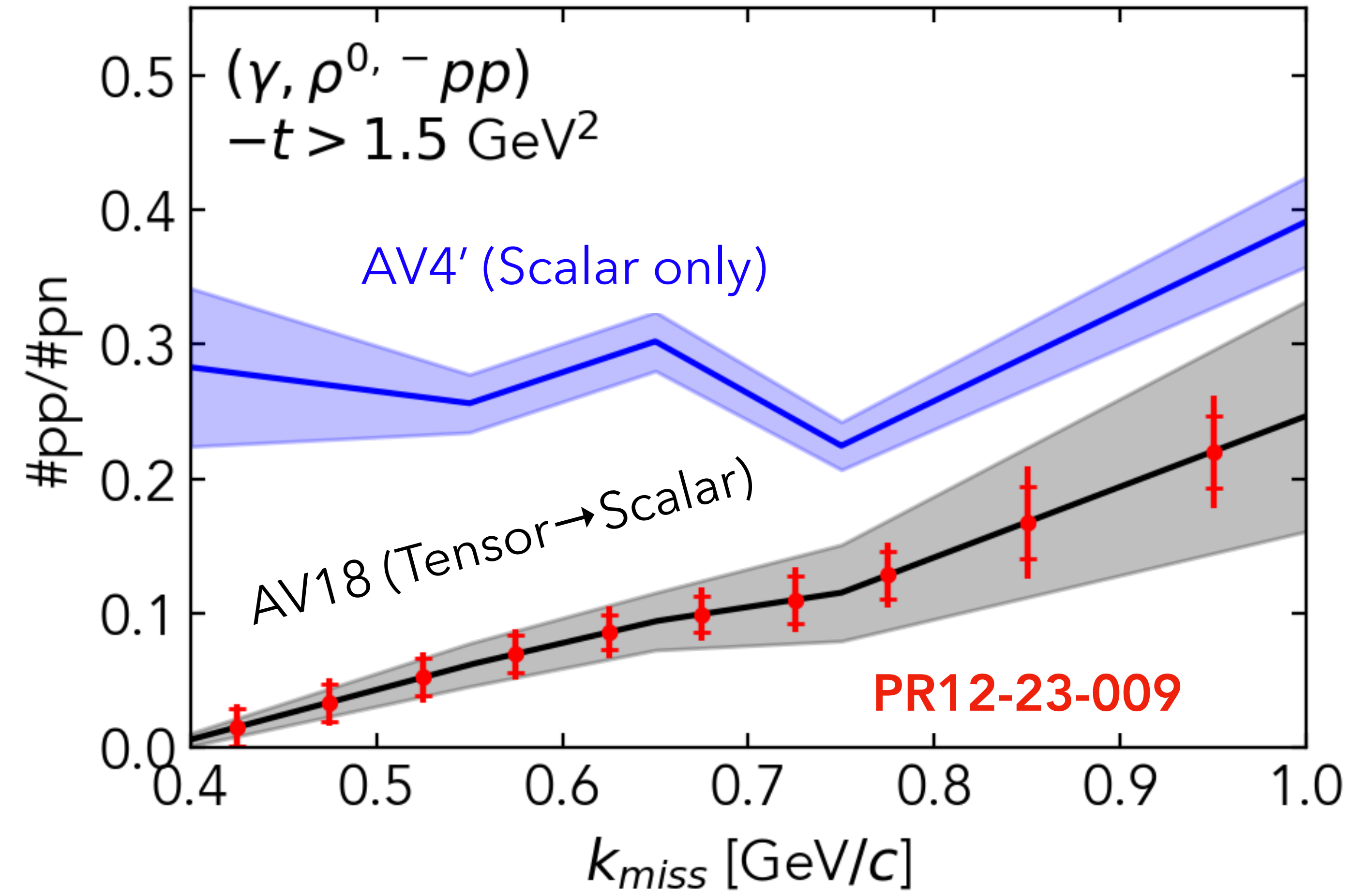


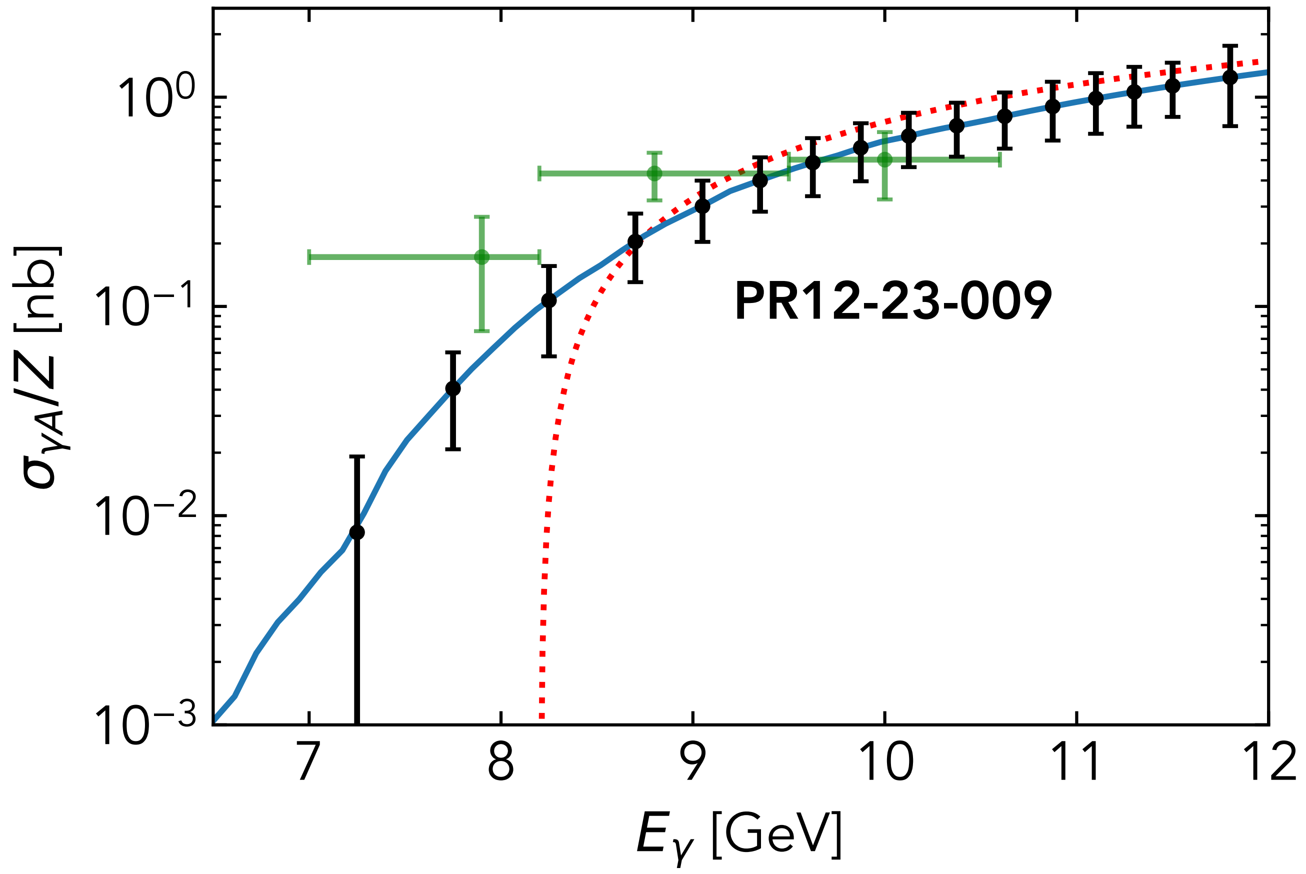


Summary

- 100 days: **<u>helium-4</u>** (95 days) and deuterium (5 days)
- Standard Hall D setup, equivalent to 2021 SRC-CT run
- Diamond radiator, 8 GeV coherent photopeak
- Semi-inclusive photoproduction measurement:
  - SRC breakup from (γ, mN) and (γ, mNN)
  - J/ψ photoproduction from (γ, e^+e^-p)
- Expands program of previous E12-19-003 experiment

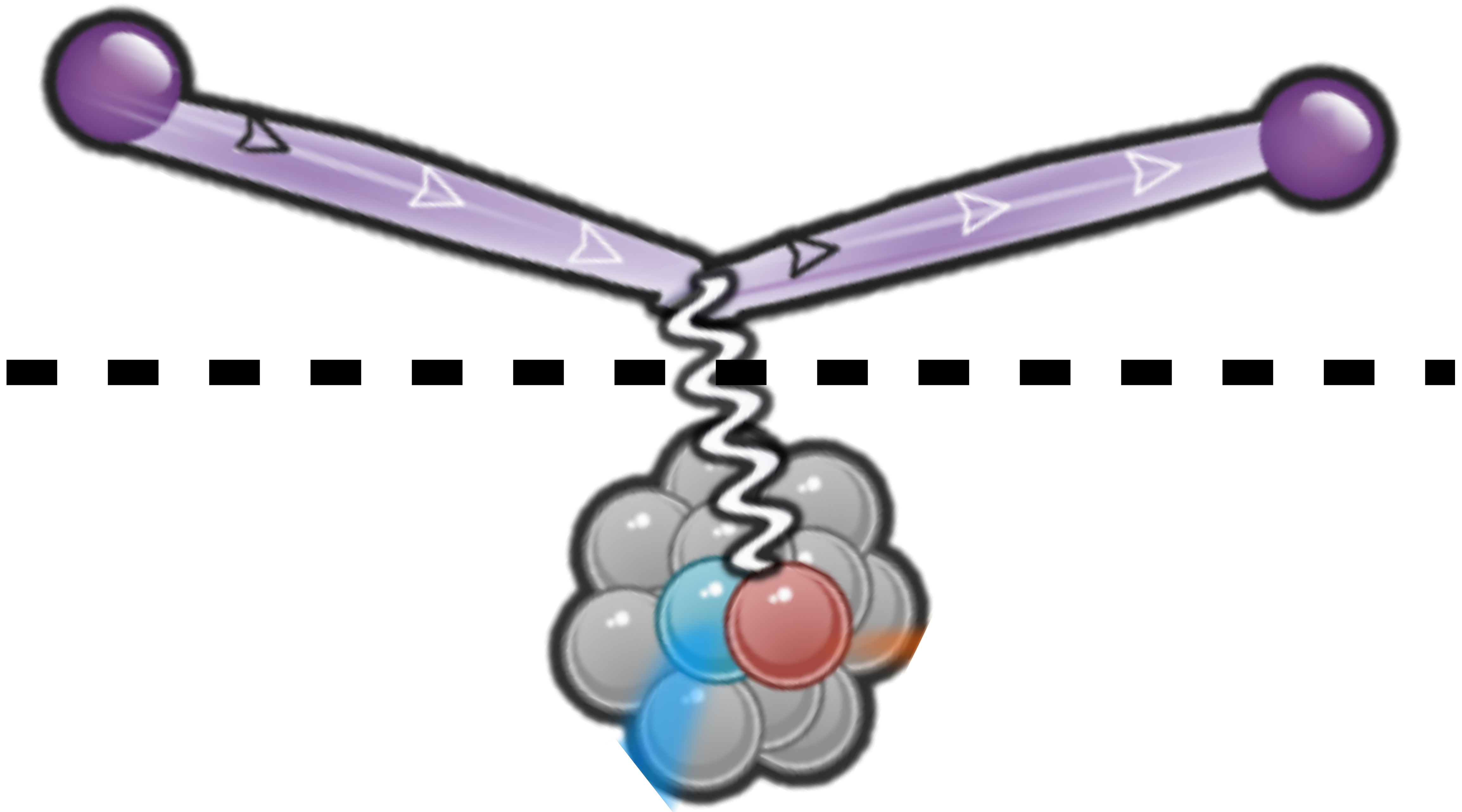






Extra Slides

Ground-state interpretation requires establishing factorization!



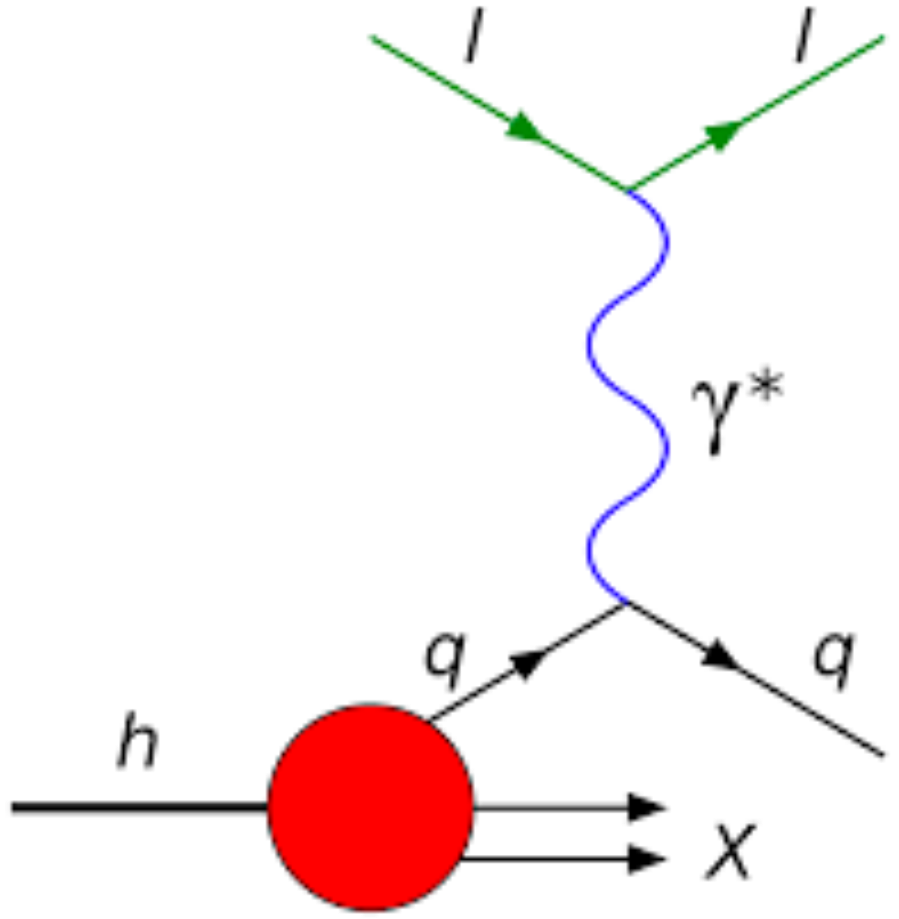
Reaction

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

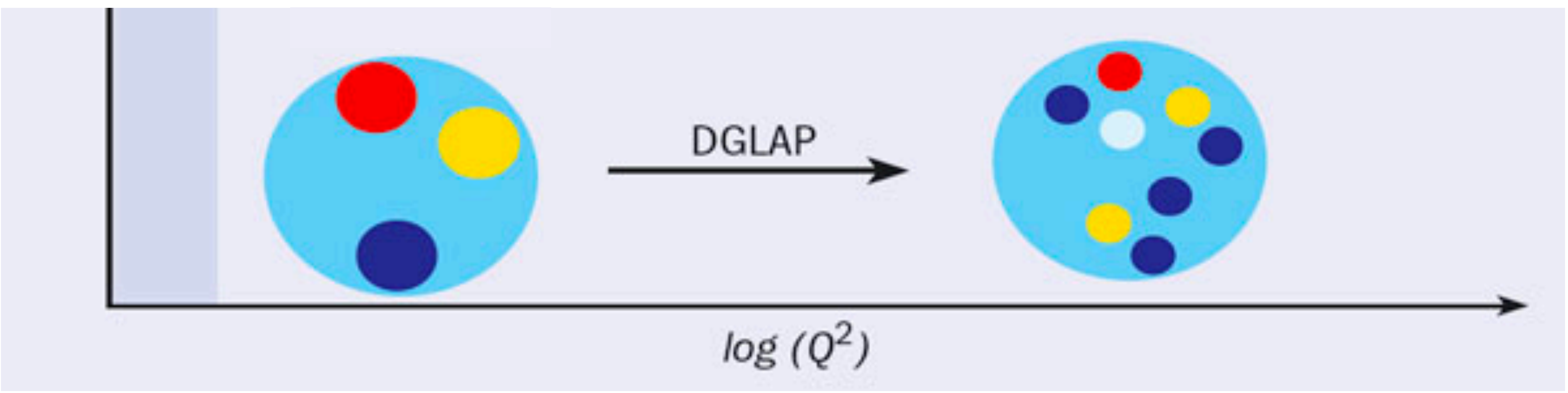
Ground-State

$$S(p_i, p_{rec}) = \sum_{\alpha} C_A^{\alpha} \cdot |\phi_{\alpha}(p_{rel})|^2 \cdot n(P_{CM})$$

Example: PDF Universality

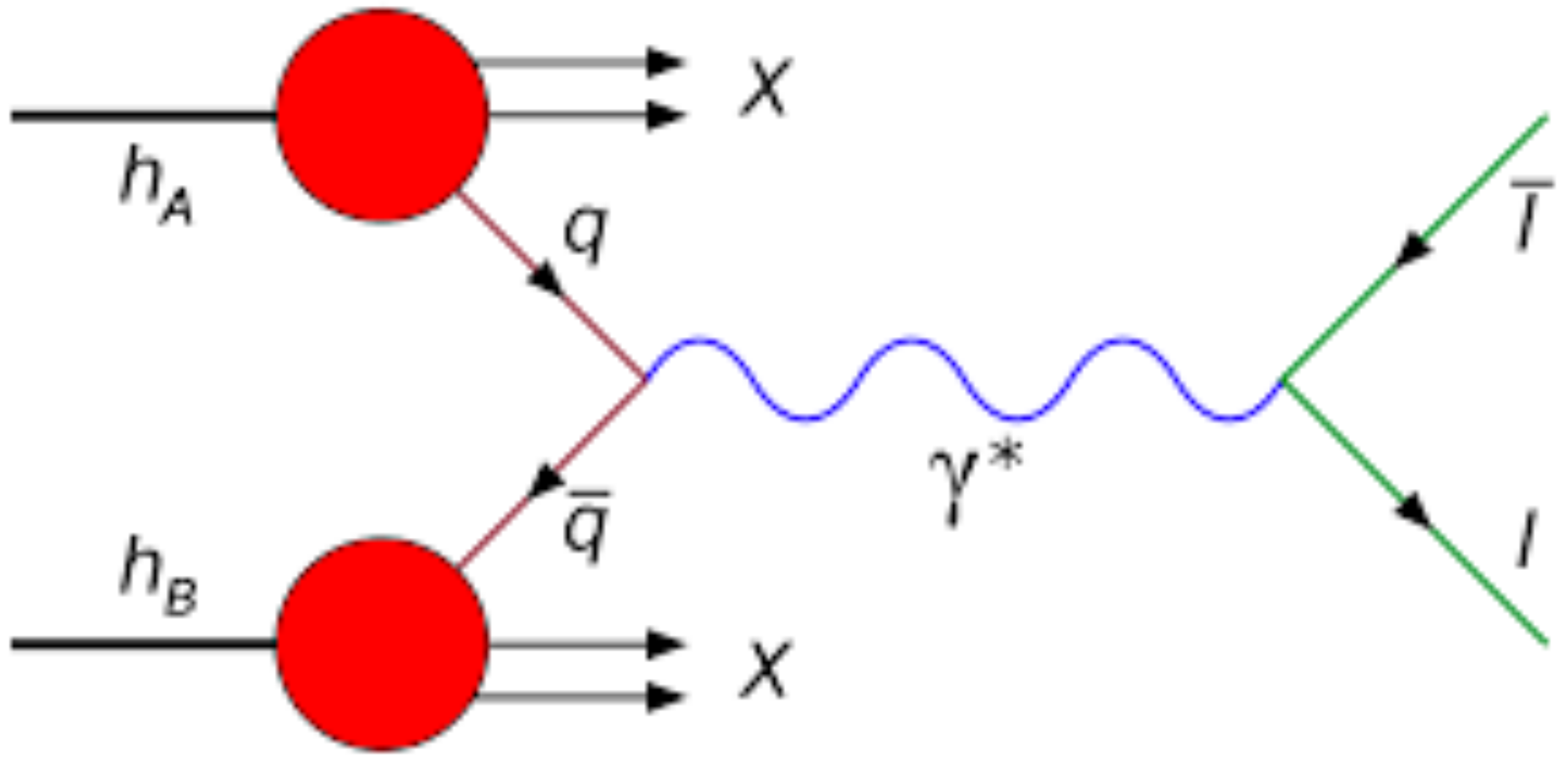


Deep-Inelastic Scattering



+ Q^2-evolution from DGLAP

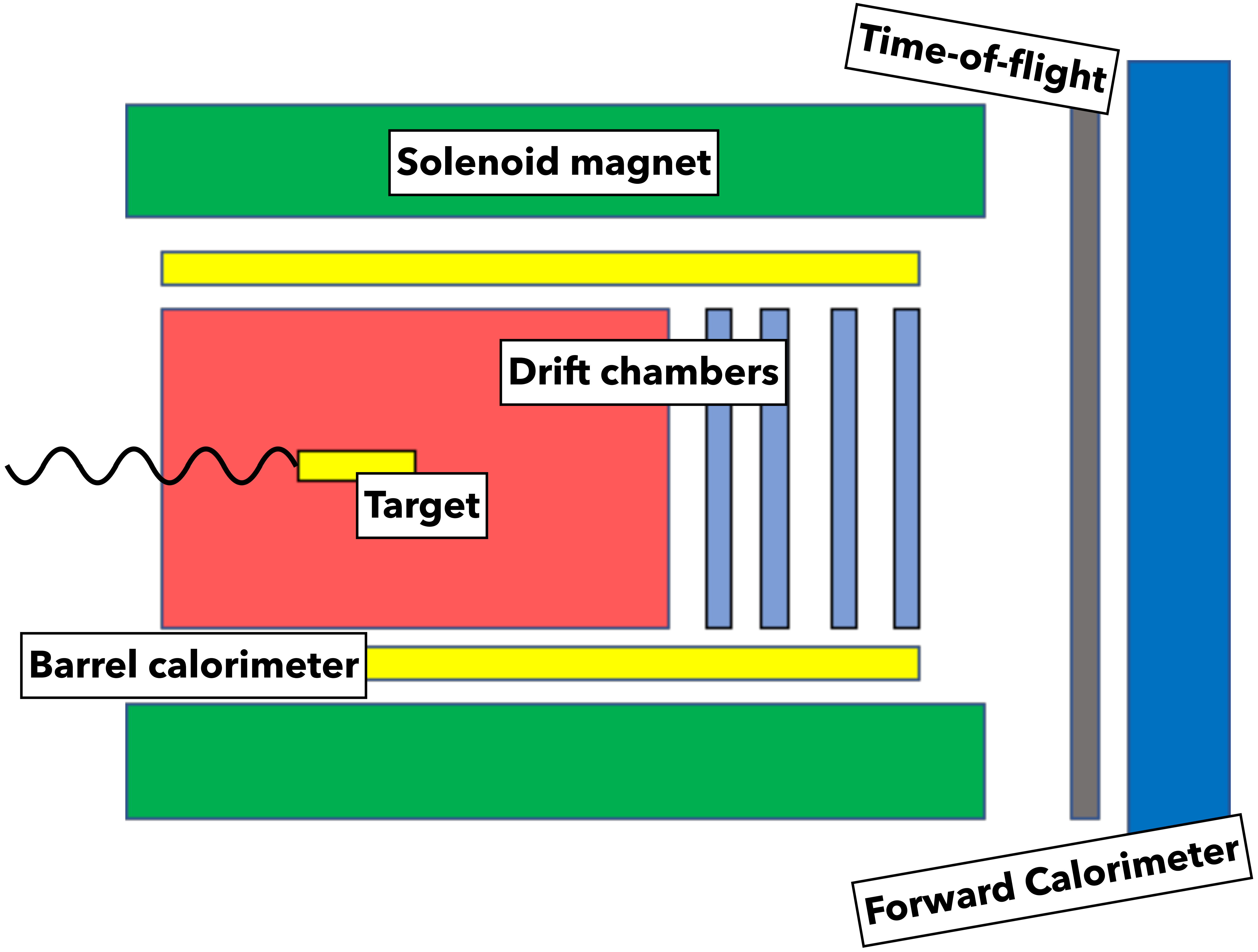
vs



Drell-Yan

= Universal framework for measuring parton structure of the proton

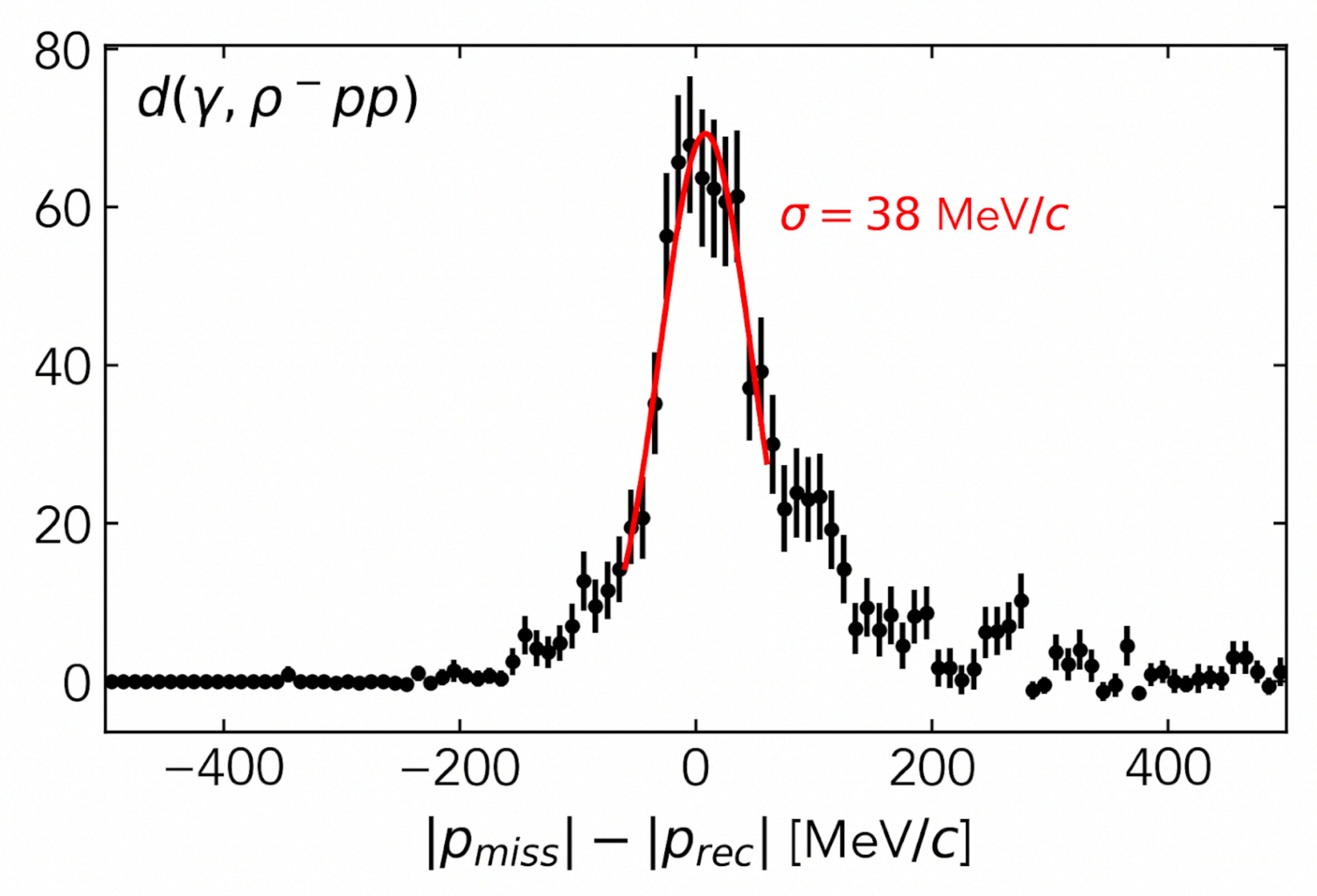
Hall D Experimental Setup



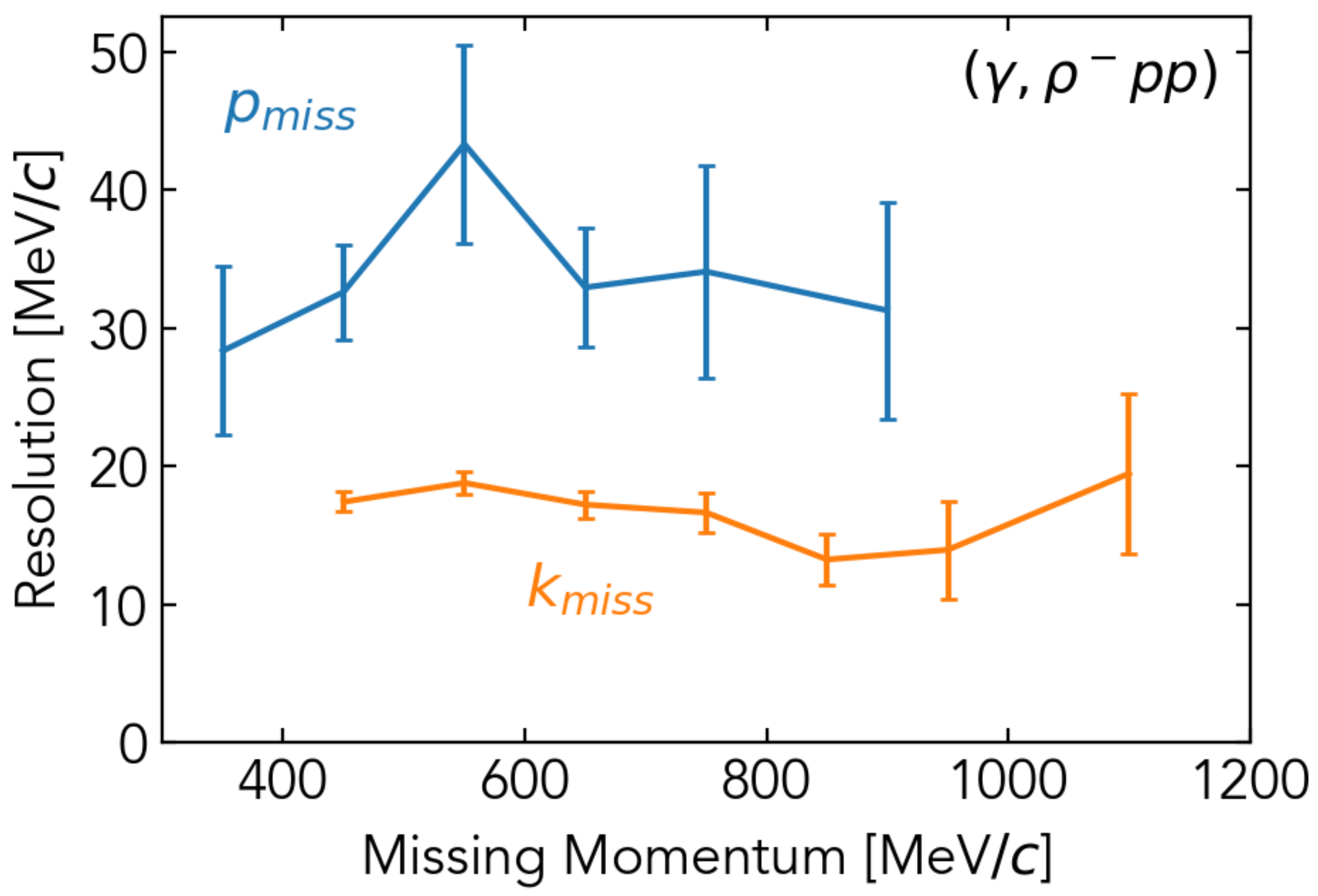
- Large-acceptance detector
- Solenoidal magnet:
  - Good p_T resolution
  - Poor p_z resolution
- Time-of-flight allows particle identification for forward-going charged particles
- Calorimeters allows good acceptance and reconstruction of final-state photons

Missing-momentum resolution in SRC kinematics is good!

Data-driven resolution

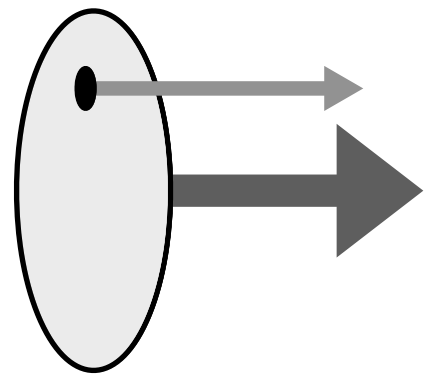


Simulated resolution



Analysis on the light-front

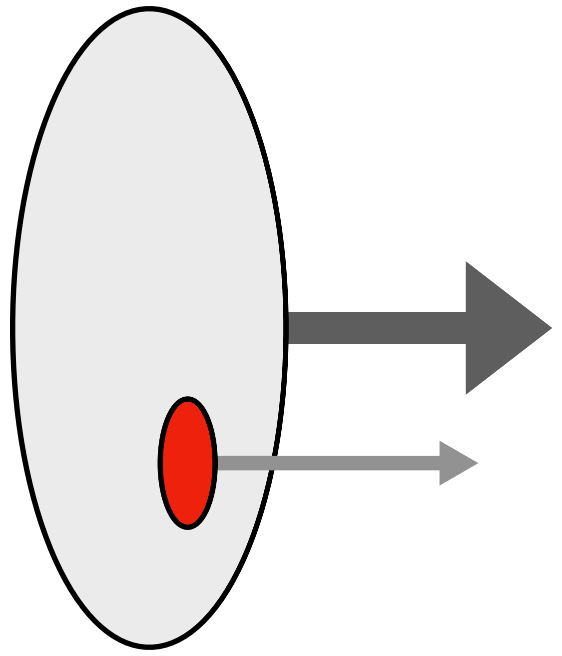
Parton in Hadron



Parton momentum fraction

$$x_B$$

Nucleon in Nucleus

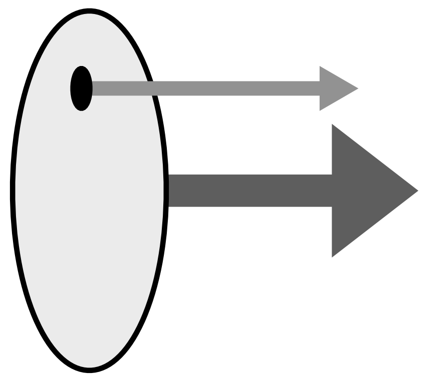


Nucleon momentum fraction

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

Analysis on the light-front

Parton in Hadron

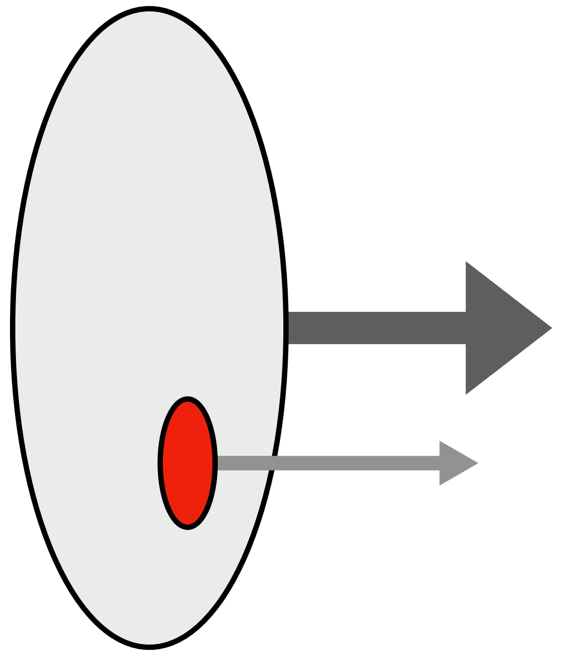


Parton momentum fraction

x_B

Light-front variables mitigate resolution effects

Nucleon in Nucleus



Nucleon momentum fraction

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

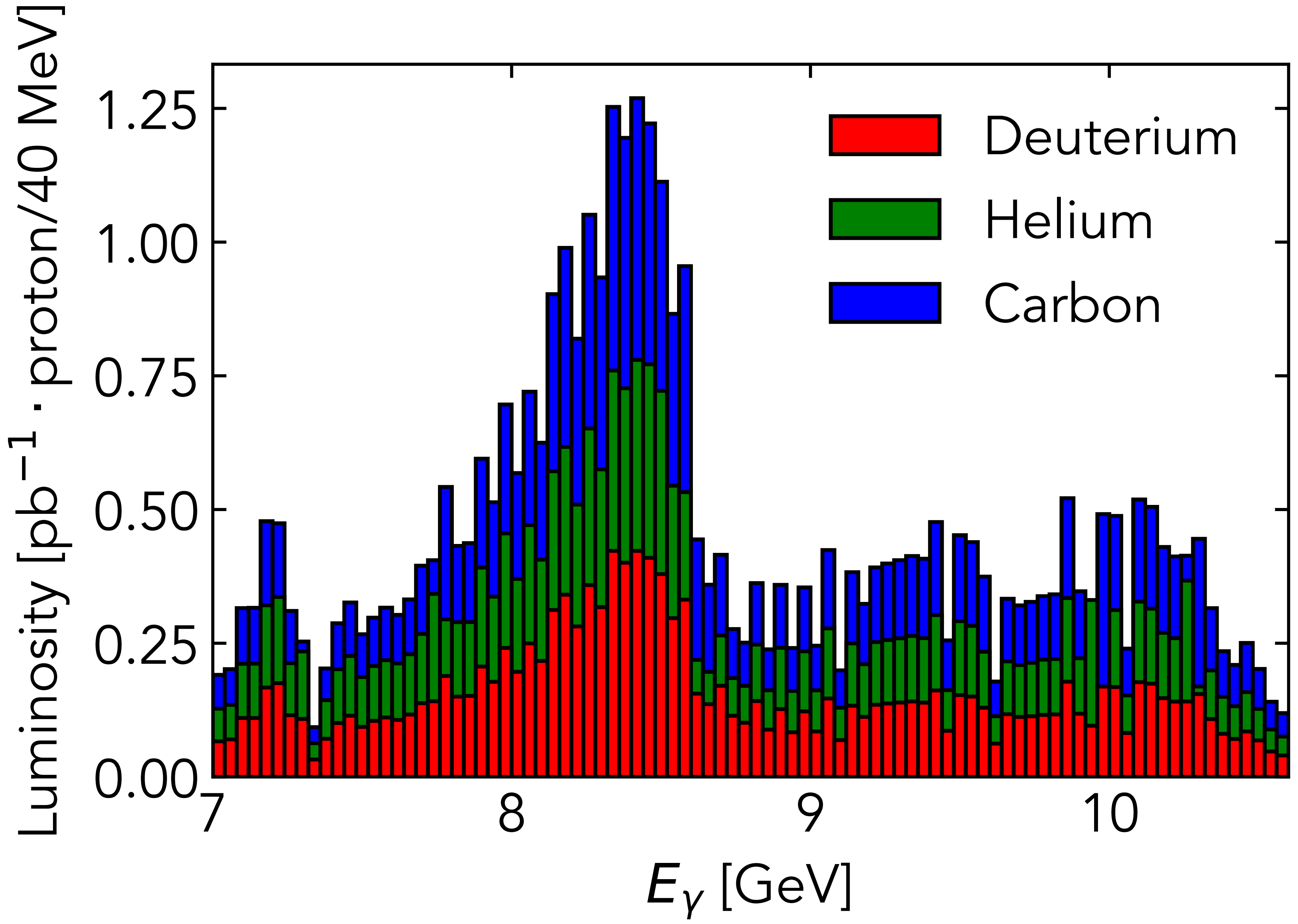
Low-momentum nucleon

$\alpha_N \sim 1$

Standing nucleon pair

$\alpha_1 + \alpha_2 \equiv \alpha_{CM} \sim 2$

Cross section extracted from binned J/ψ yield



Yield from dilepton invariant mass fit

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

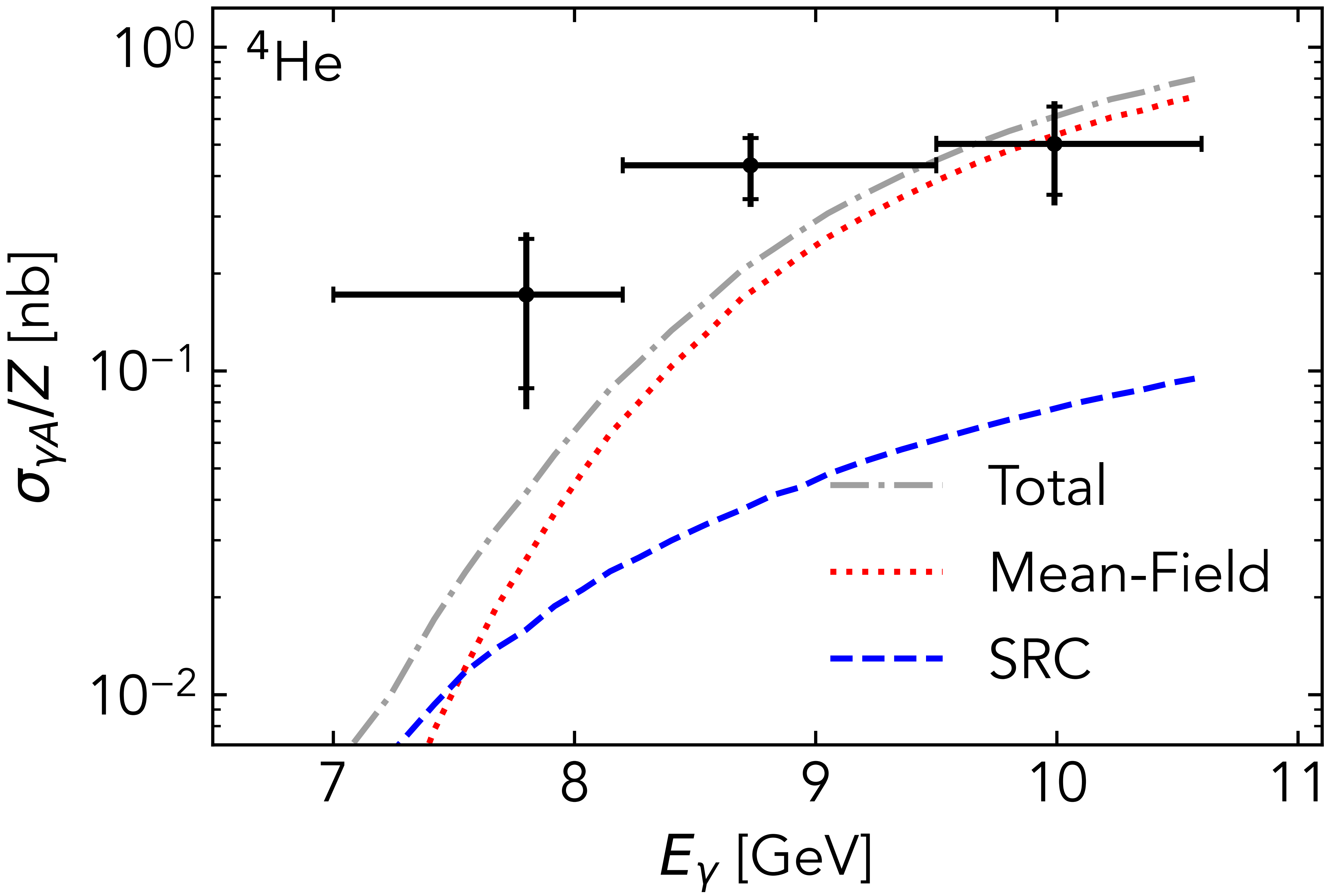
Luminosity from measured tagged photon flux

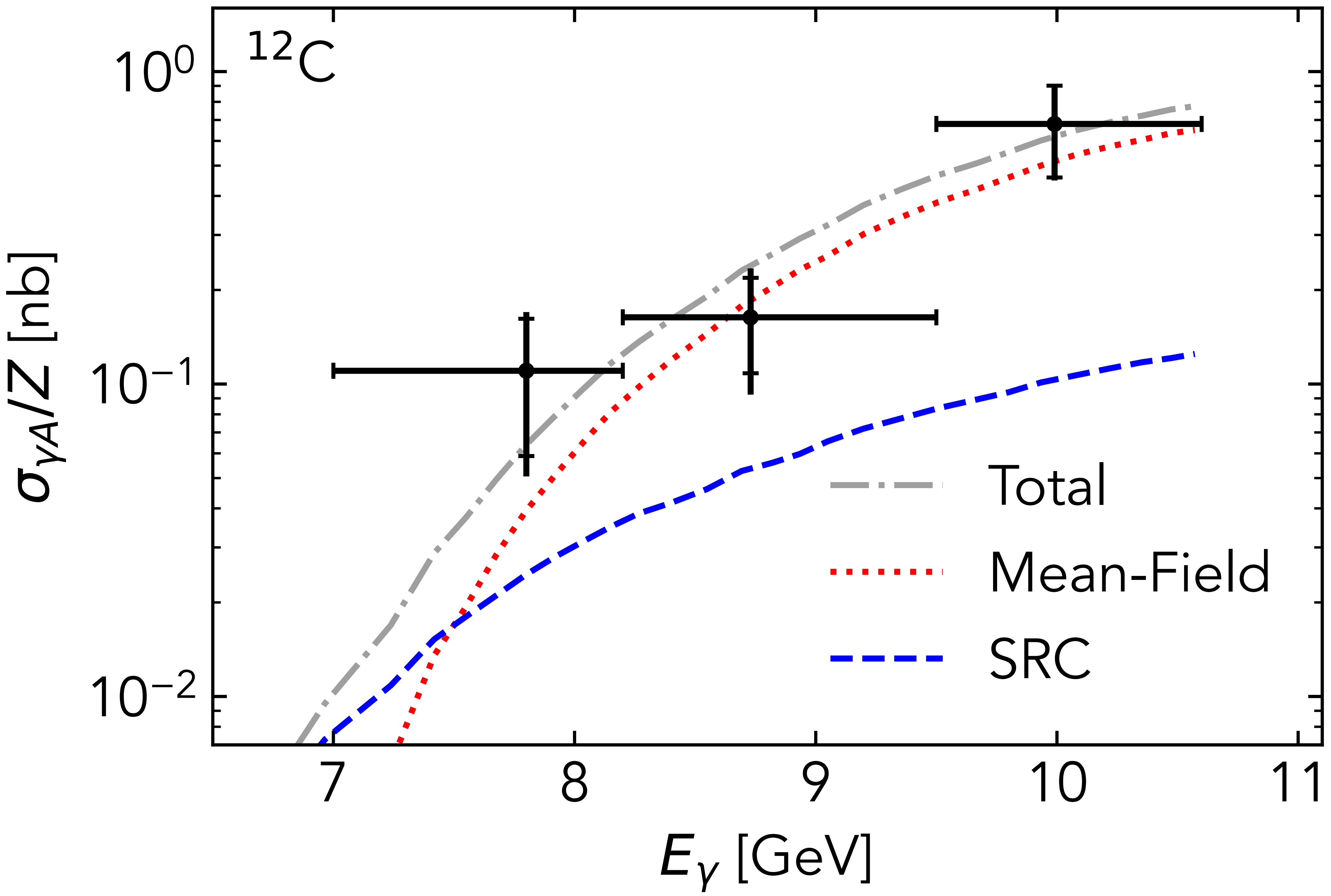
Efficiency from MC calculations

Proton nuclear transparency

Branching fraction

Total cross sections extracted as a function of energy





2021 SRC-CT Data

Target	Days of Beam	Luminosity (E_γ > 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

Comparison to PrimEx II Luminosity

- Increase in total beam time of 2.5:

$55 \times 0.7 \rightarrow 100$ PAC days

- Increase in photon flux by 3:

200 nA × 1E-4 X_0 → 150 nA × 4E-4 X_0

- Additional increase in photon energy <8 GeV by coherent diamond peak