Nuclear Charm Production and Short-Range Correlations in Hall D

Proposal PR12-23-009

Spokespersons:

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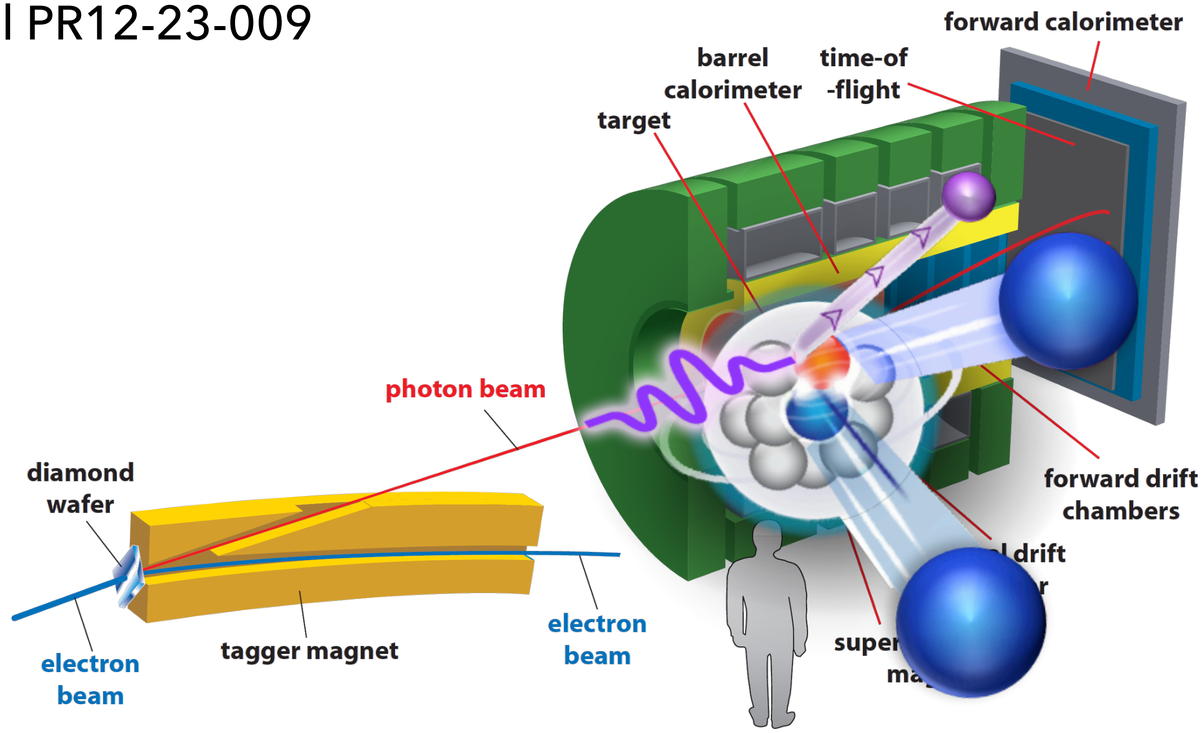
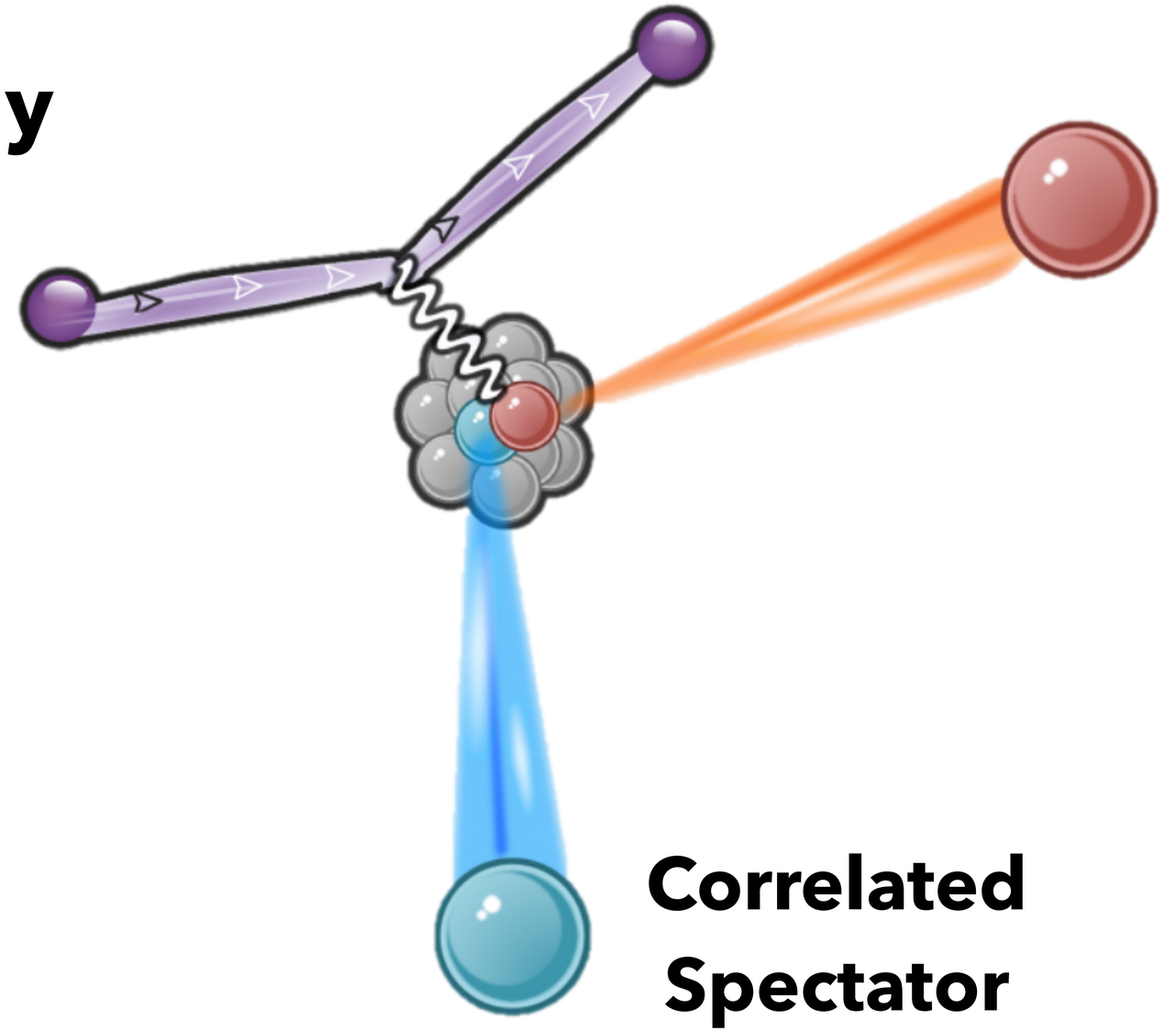
H. Szumila-Vance (JLab)



SRCs studied with hard breakup reactions

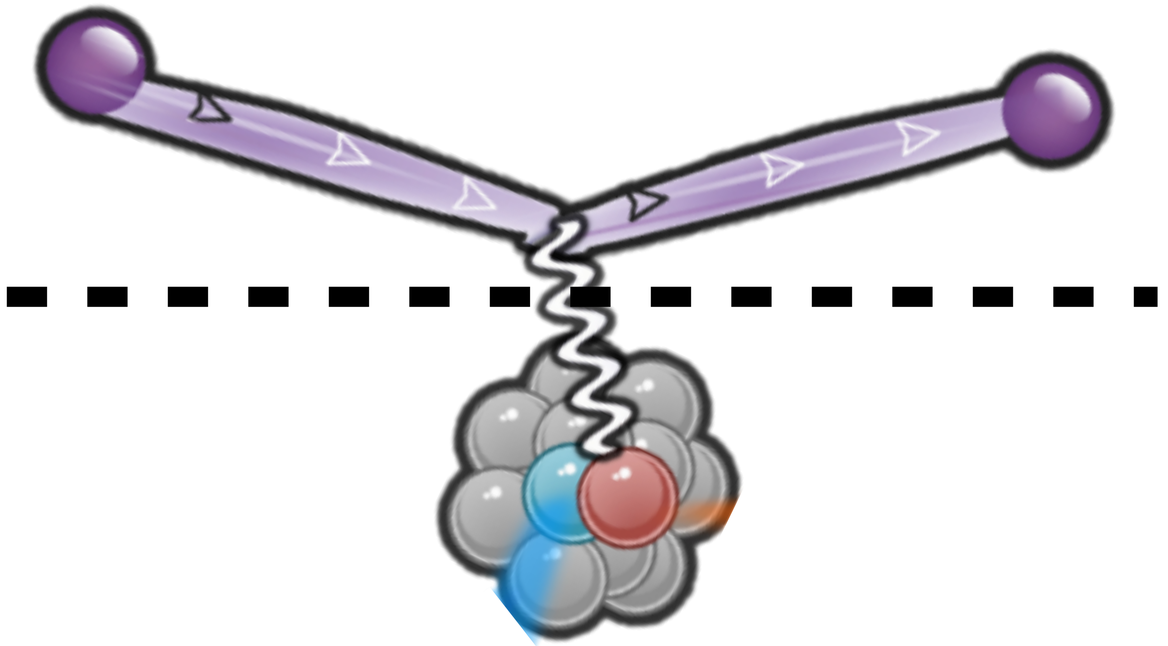
High-Energy Probe



Struck Nucleon

Correlated Spectator

Ground-state interpretation requires establishing factorization!

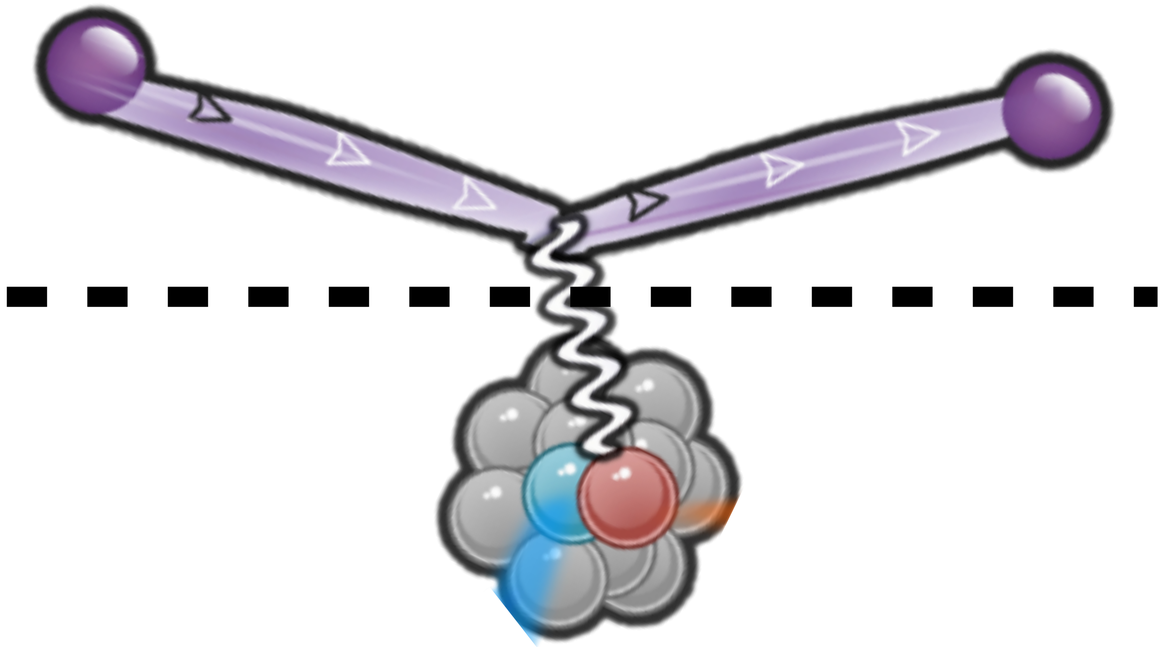


Reaction

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

Ground-State

Ground-state interpretation requires establishing factorization!



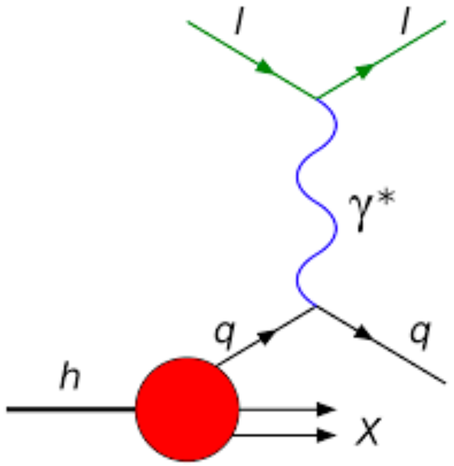
Reaction

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

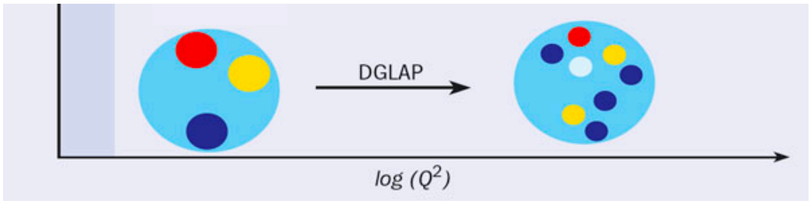
Ground-State

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

Example: PDF Universality

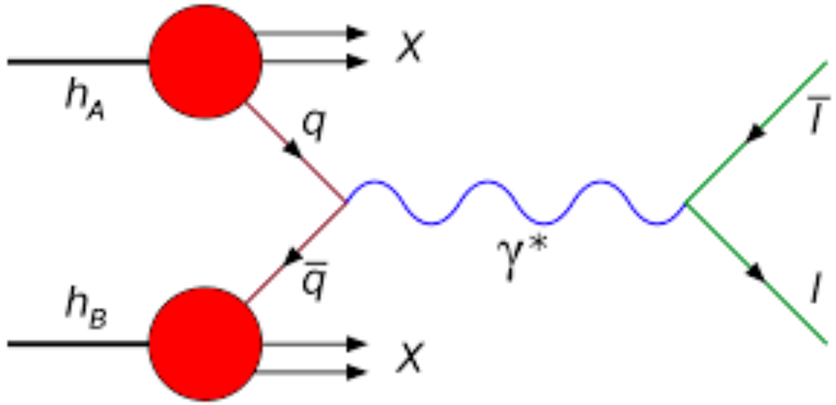


Deep-Inelastic Scattering



+ Q^2-evolution from DGLAP

VS



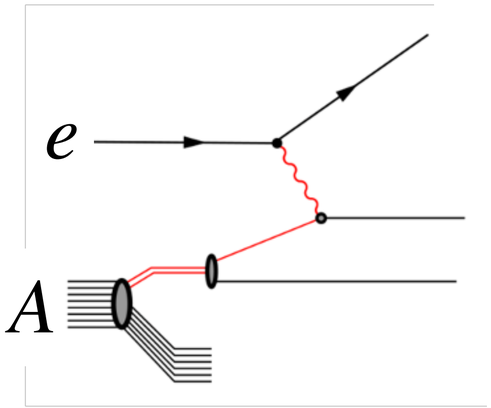
Drell-Yan

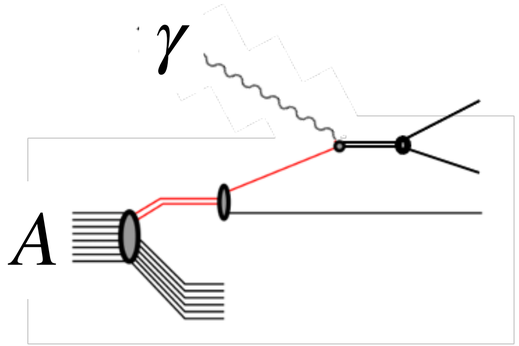
= Universal framework for measuring parton structure of the proton

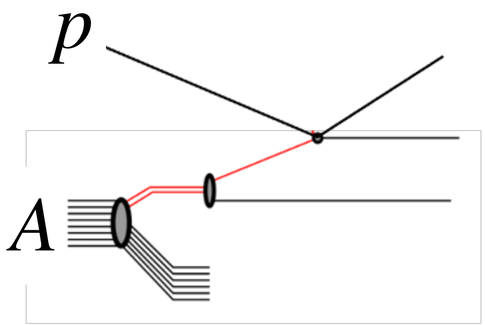
We need to examine two things:

Probe

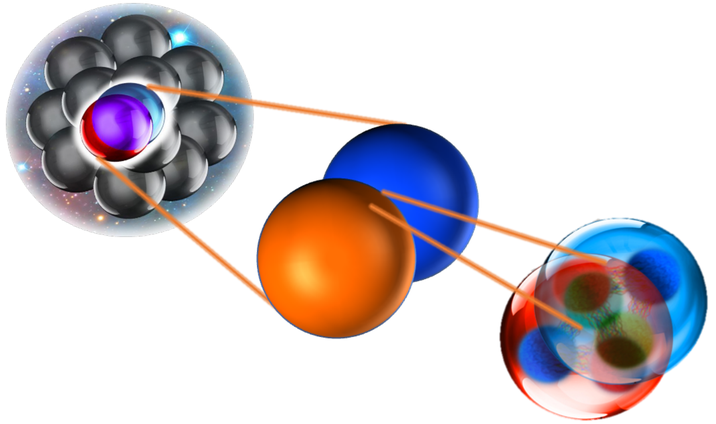
Compare different reactions using different **probes**





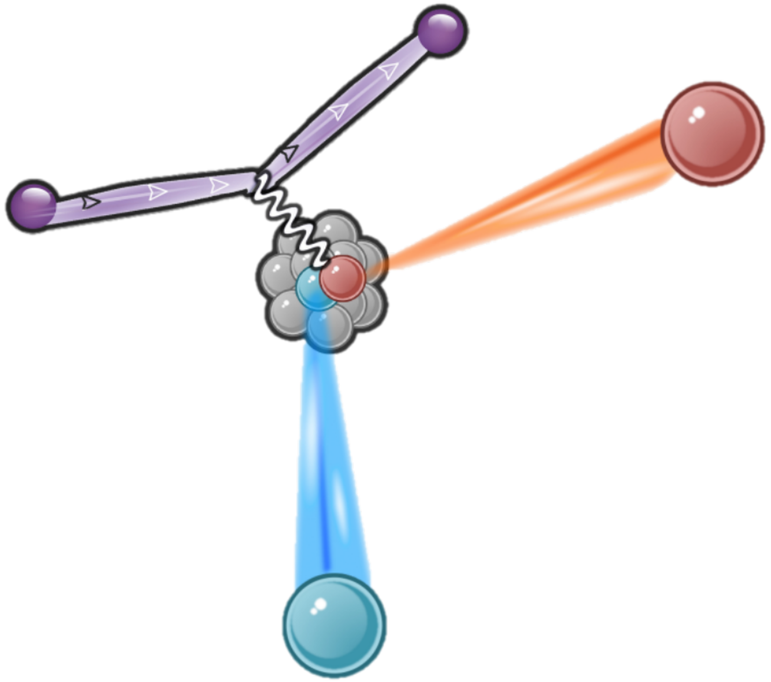


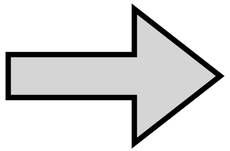
Scale

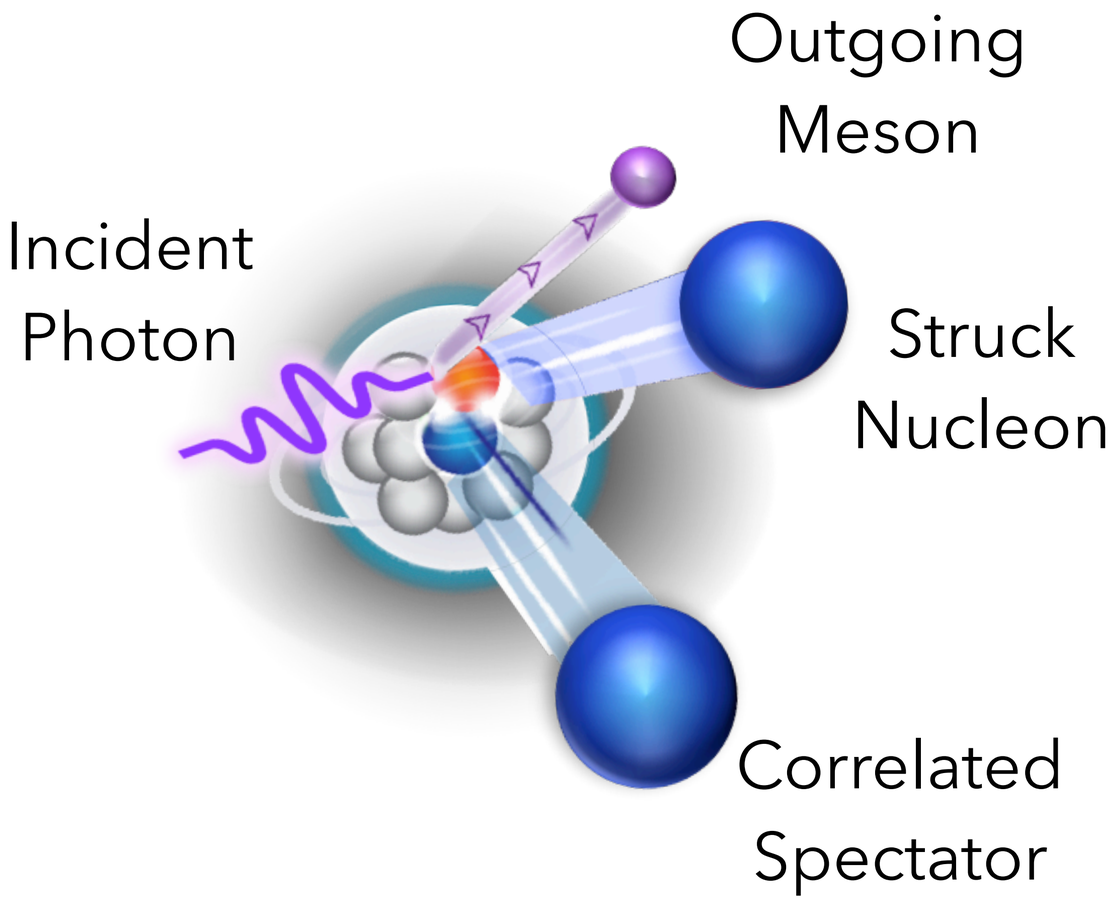


Change the resolution **scale** of the reaction Q^2, $|t|$

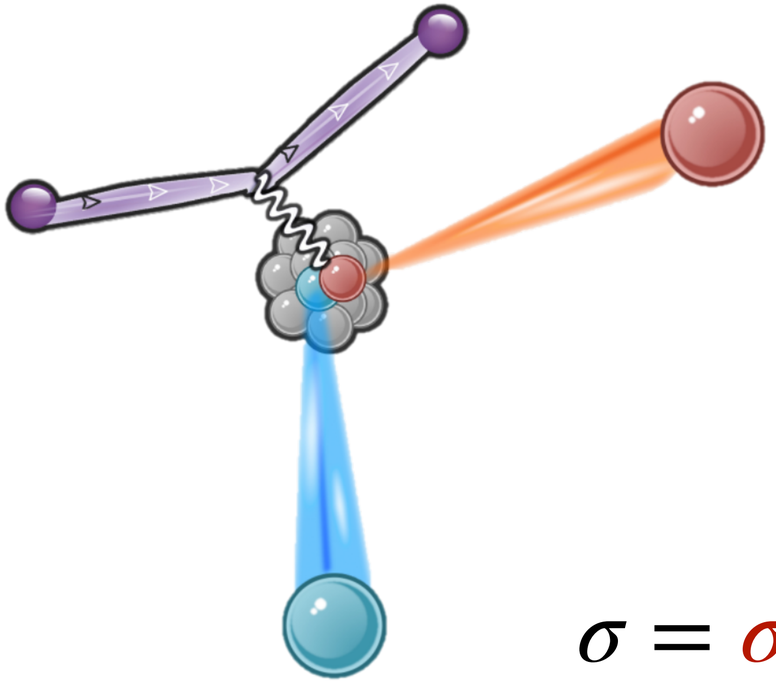
From electrons to photons

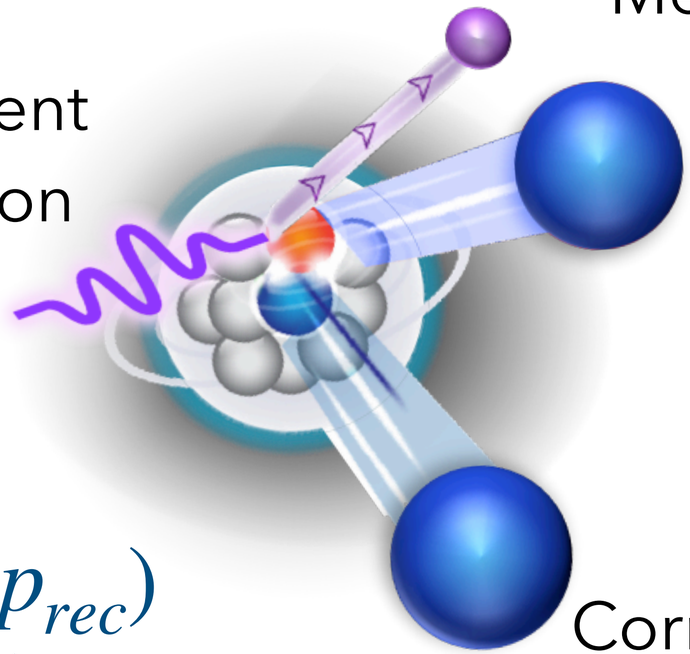






From electrons to photons





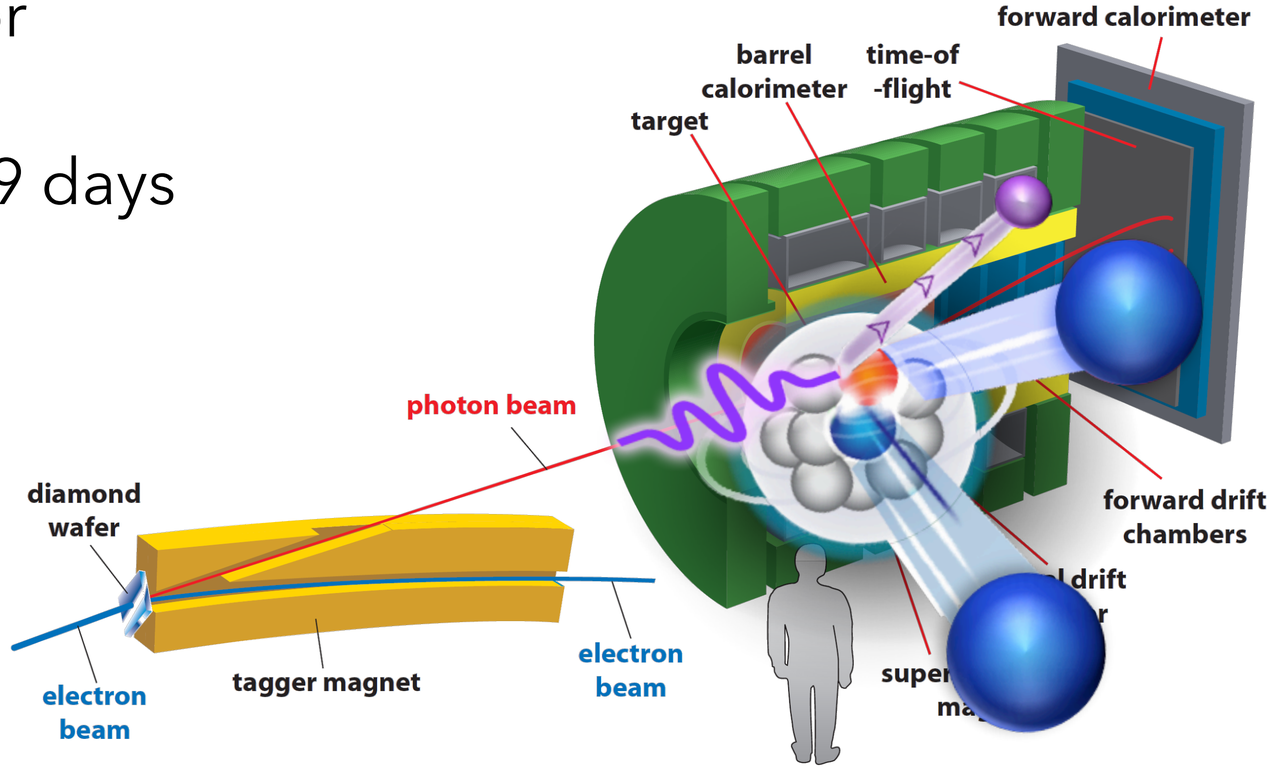
$$\sigma = \sigma_N(q) \times S(p_i, p_{rec})$$

Different reactions!

Same ground-state?

2021 SRC-CT Experiment

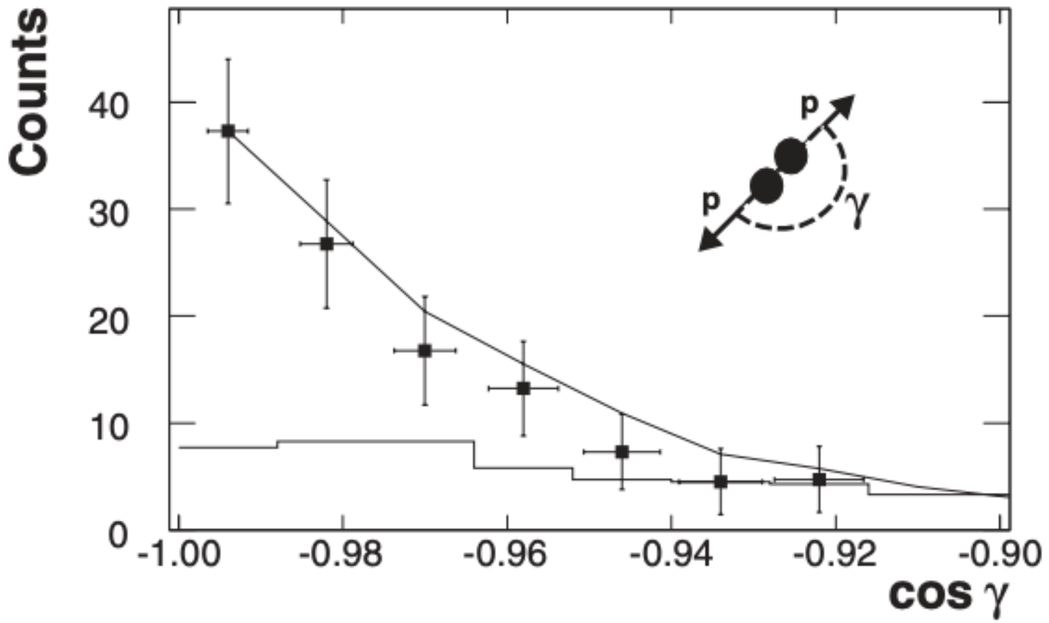
- 10.8 GeV + diamond radiator
- ^{2}H, ^{4}He, ^{12}C targets: total ~19 days
- Standard Hall D setup



Success of 2021 SRC Hall D Run

What have we found?	What do we *want* to learn?
First observation in photoproduction	Resolution/$\lvert t \rvert$-dependence and reaction mechanisms
Probe-Independence and contact with ab-initio calculations	Precision constraints of NN interaction at short distance
A-dependence and scaling	3N-SRC
Evolution of isospin structure	Gluonic probes/structure of SRC

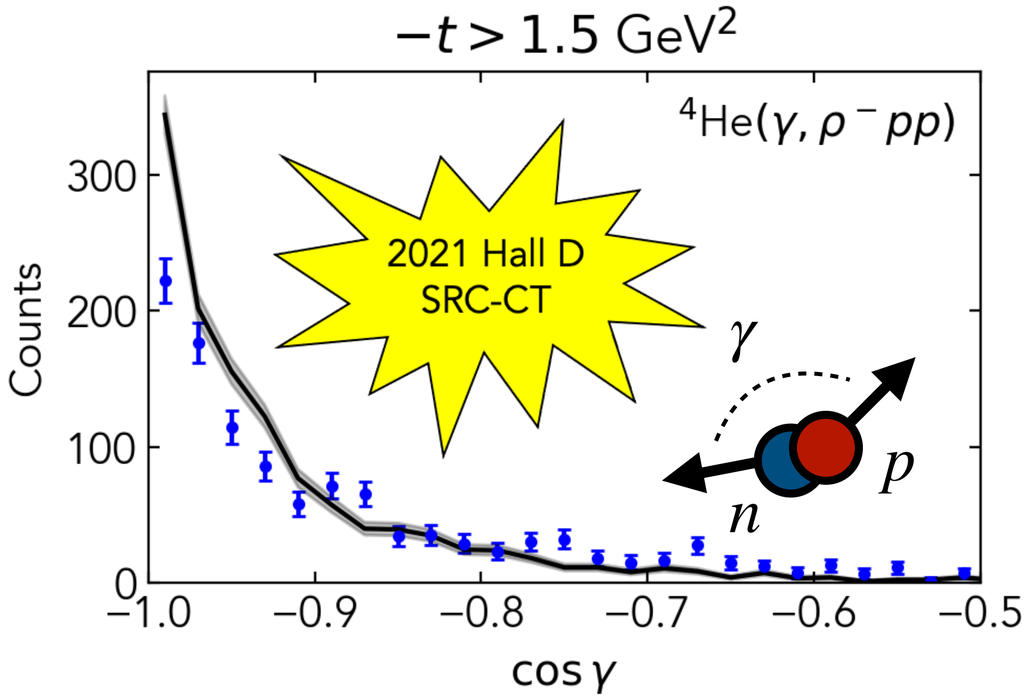
First observation of SRCs in photoproduction!

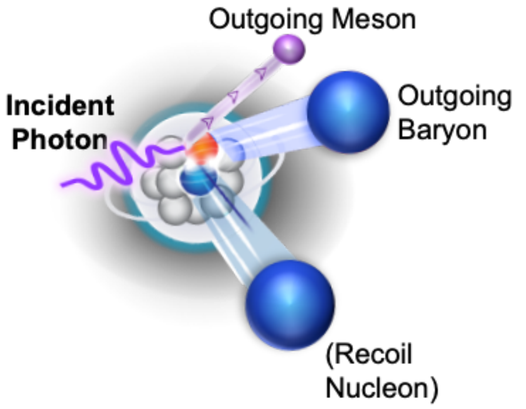


PRL 2007

Back-to-back correlation in

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

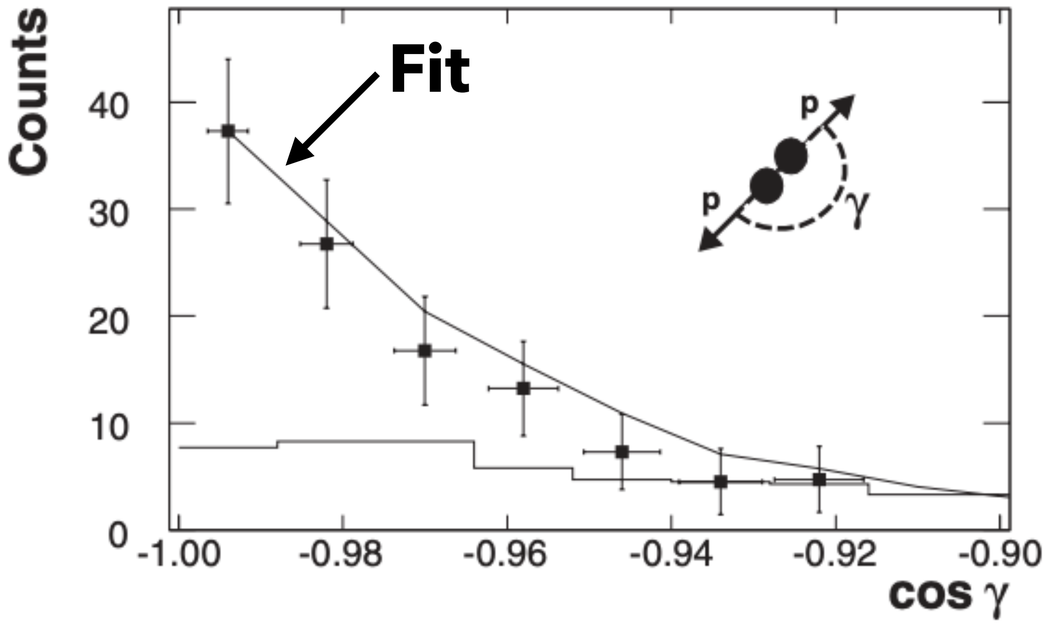




$\gamma np \rightarrow \rho^- pp$

@ Hall D

First observation of SRCs in photoproduction!



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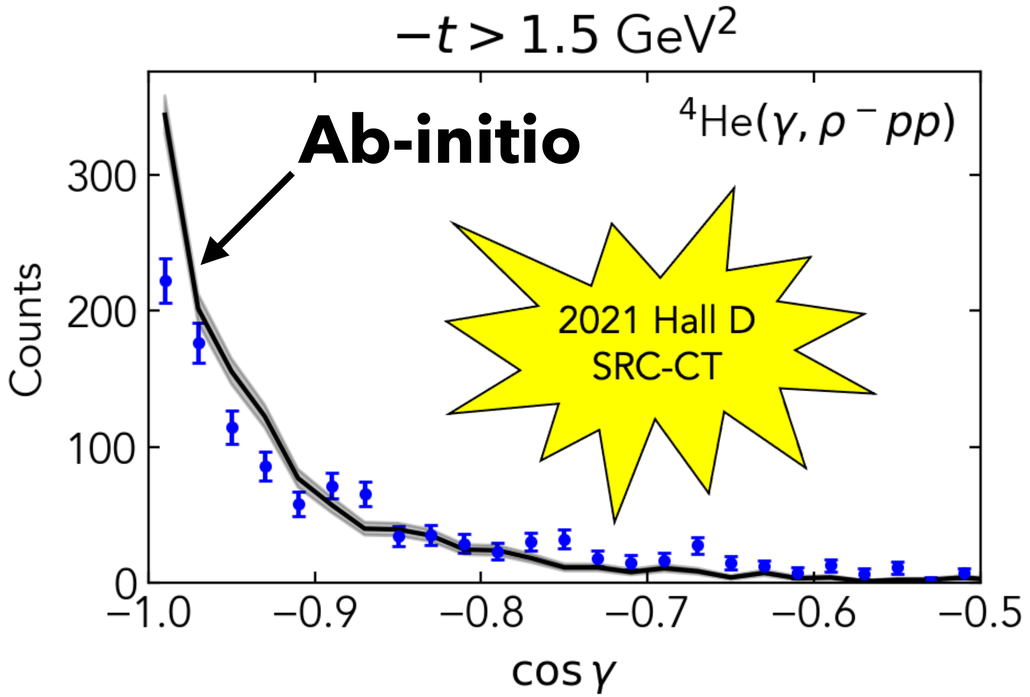
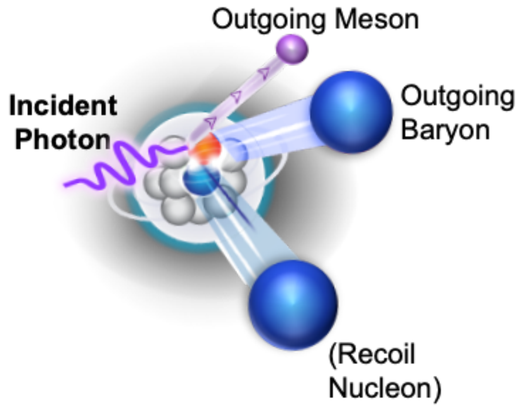


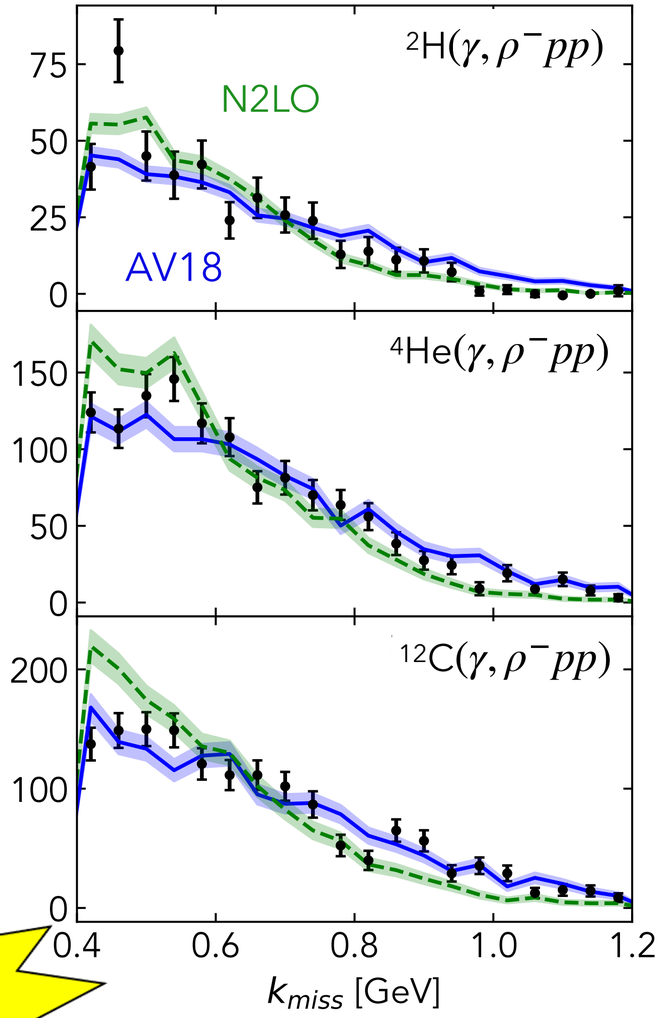


$\gamma np \rightarrow \rho^- pp$

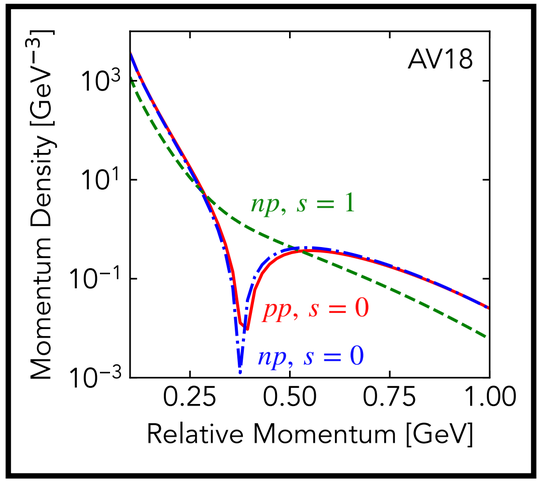
@ Hall D

Data can constrain ab-initio theory at high momentum

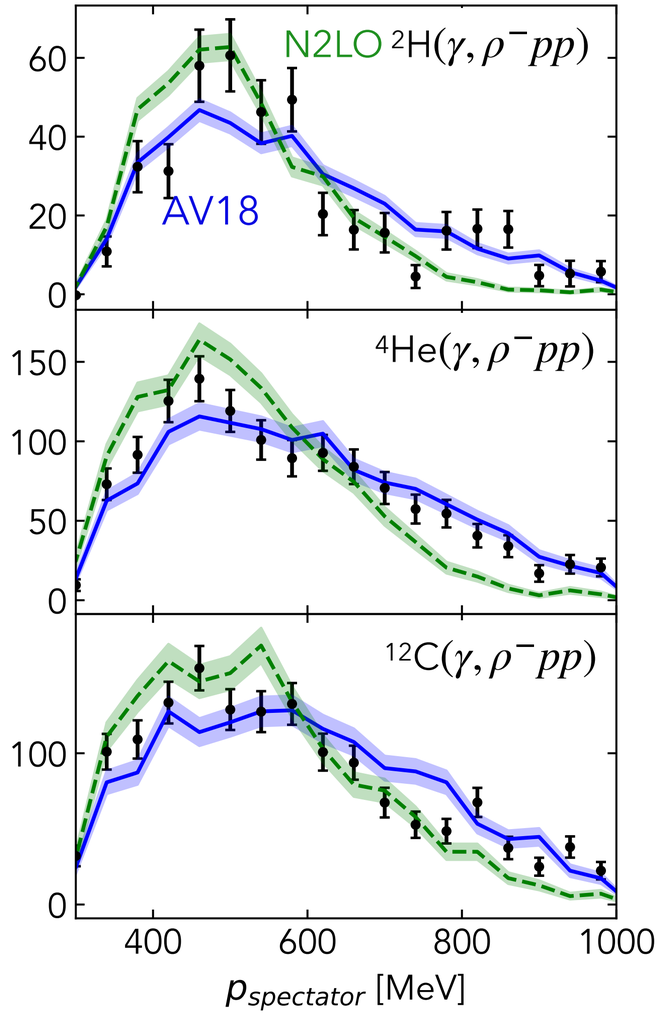
Initial Neutron Momentum



NN Interaction



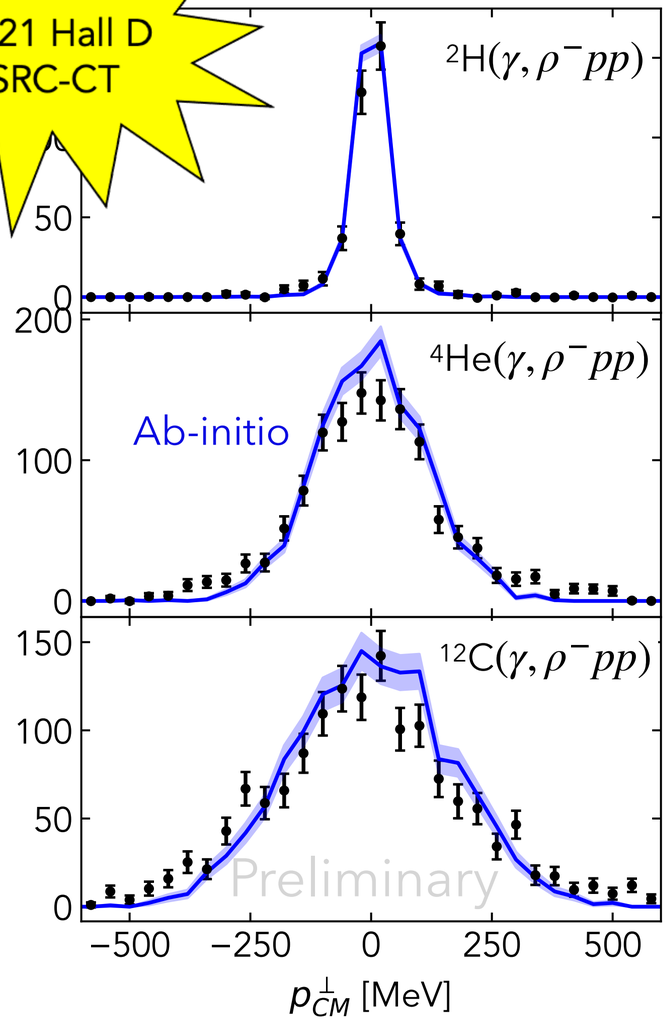
Recoil Proton Momentum



2021 Hall D SRC-CT

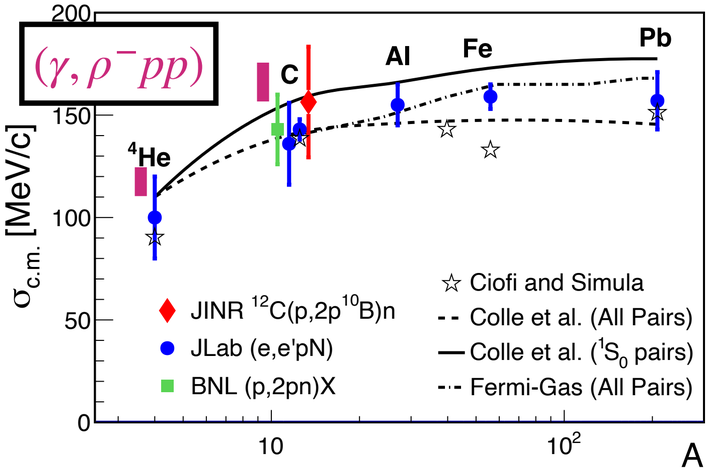
A-dependent properties of SRCs also established

2021 Hall D
SRC-CT

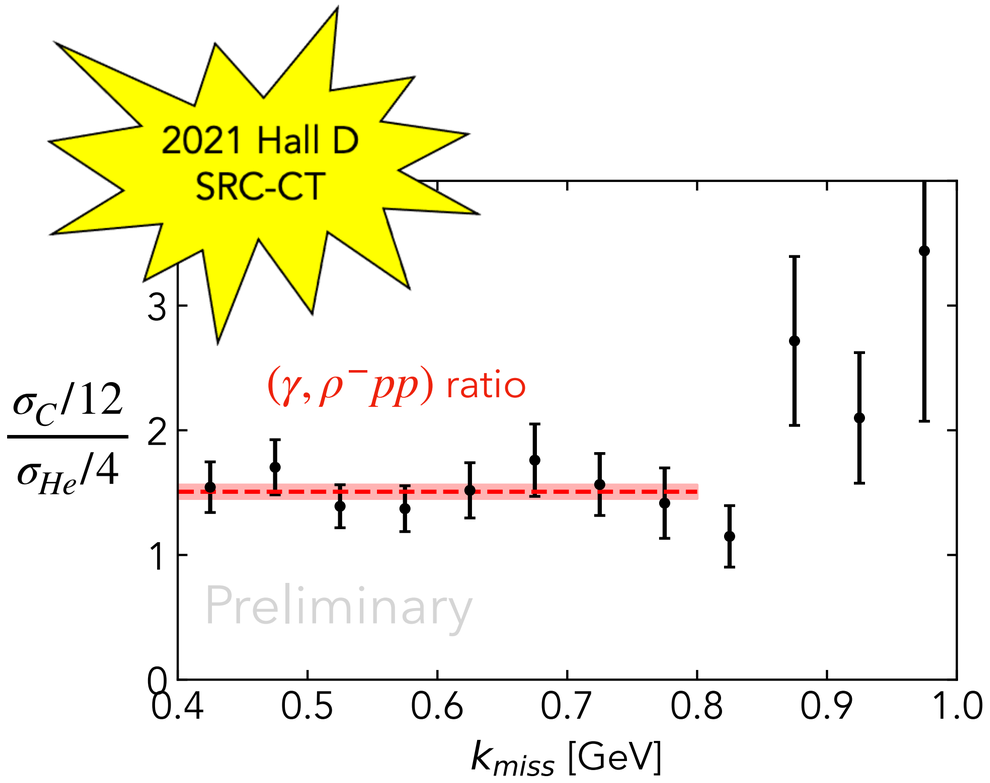


- Center-of-mass behavior of pairs

PRL (2018)
Nature Physics (2021)

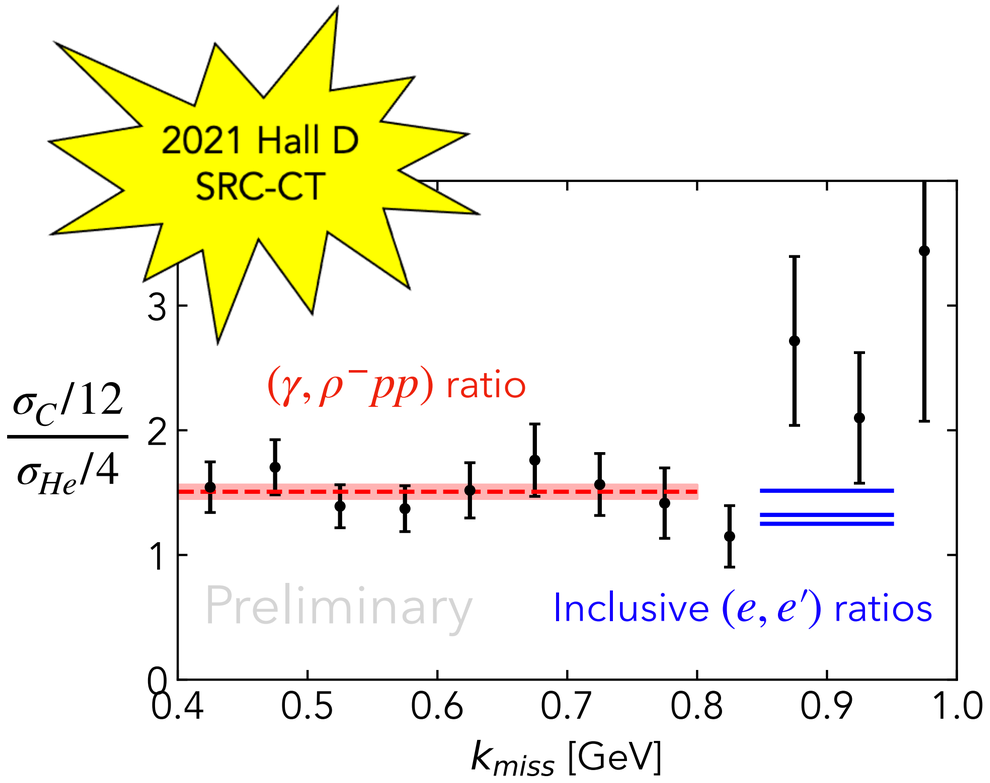


A-dependent properties of SRCs also established



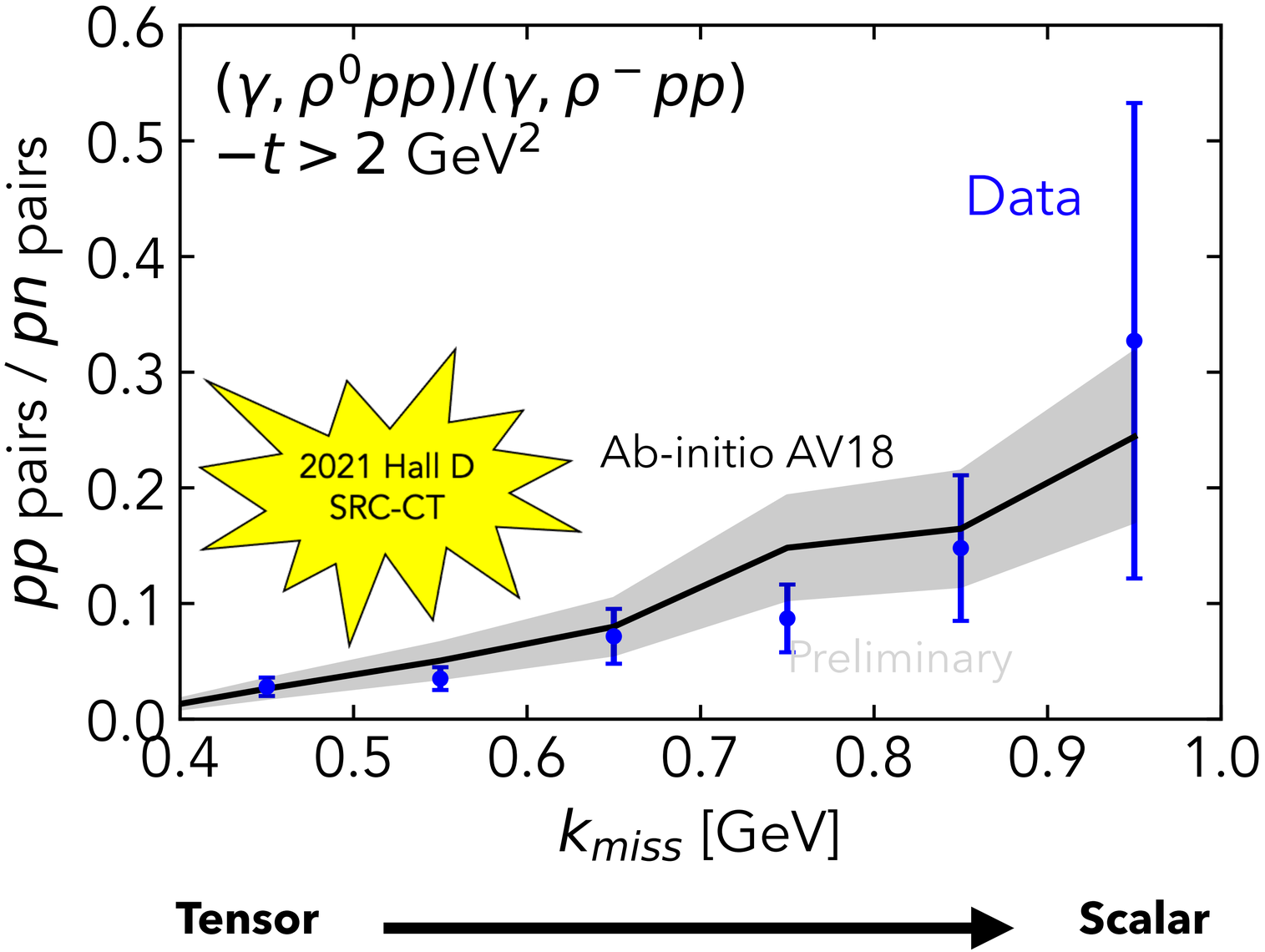
- Center-of-mass behavior of pairs
- Cross-section scaling → universal high-momentum tail

A-dependent properties of SRCs also established



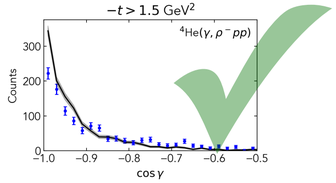
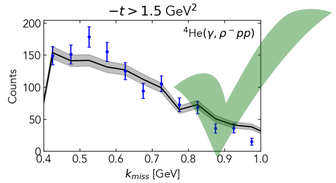
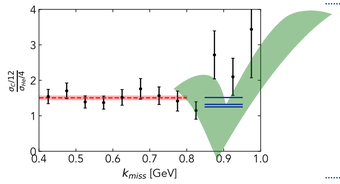
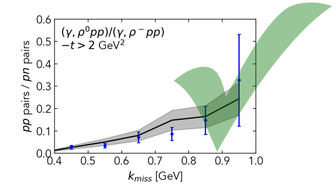
- Center-of-mass behavior of pairs
- Cross-section scaling → universal high-momentum tail
- SRC abundances match electron-scattering

First indications of universal isospin evolution!

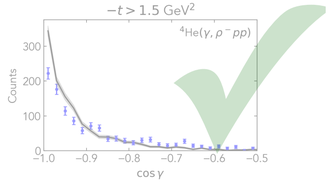
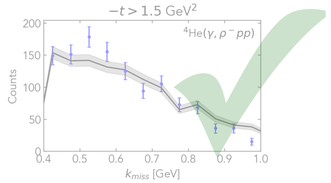
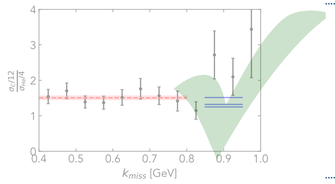
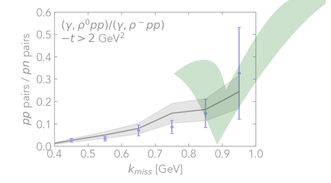


Tensor → **Scalar**

Photoproduction works!

	What have we found?	What do we *want* to learn?
	First observation in photoproduction	Resolution/$\lvert t \rvert$-dependence and reaction mechanisms
	Probe-Independence and contact with ab-initio calculations	Precision constraints of NN interaction at short distance
	A-dependence and scaling	3N-SRC
	Evolution of isospin structure	Gluonic probes/structure of SRC

Open avenues with photoproduction

What have we found?	What do we *want* to learn?
 First observation in photoproduction	Resolution/$\|t\|$-dependence and reaction mechanisms
 Probe-Independence and contact with ab-initio calculations	Precision constraints of NN interaction at short distance
 A-dependence and scaling	3N-SRC
 Evolution of isospin structure	Gluonic probes/structure of SRC

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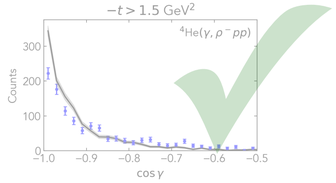
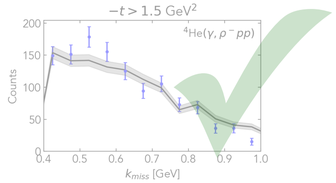
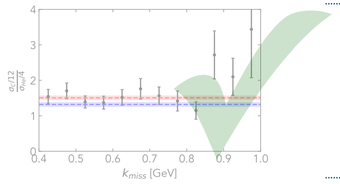
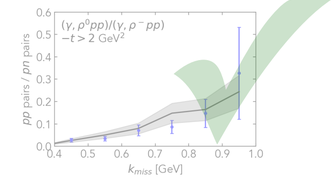
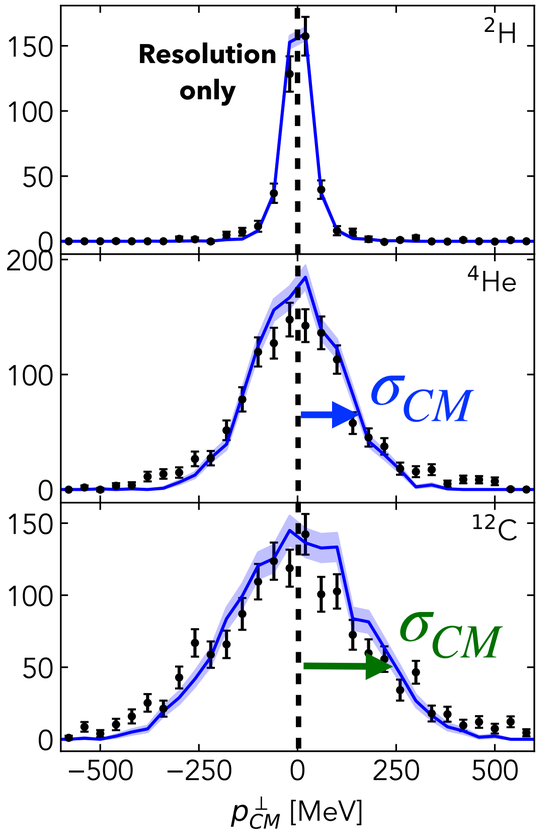
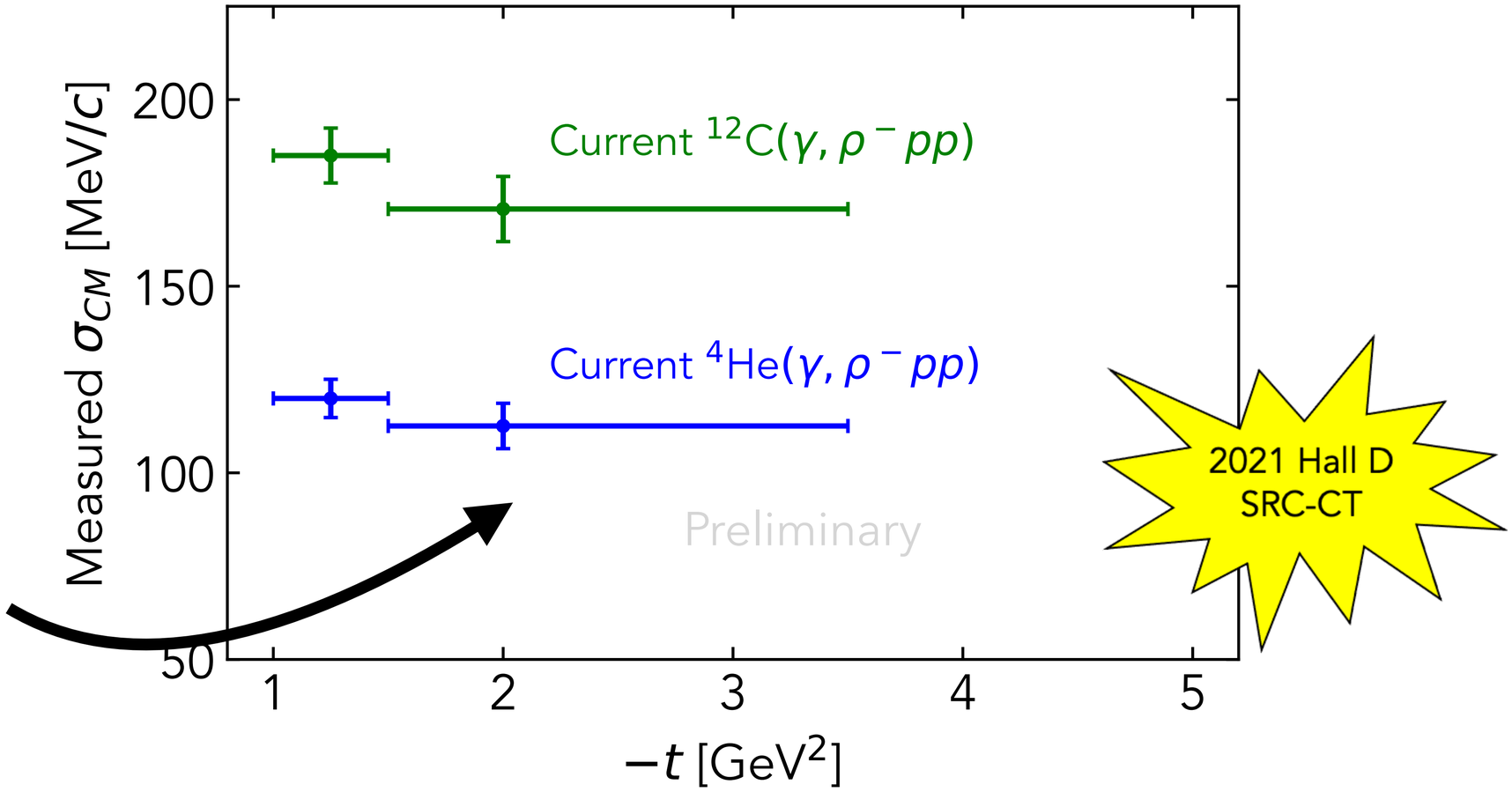
 First observation in	Resolution/|*t*|-dependence and reaction mechanisms
	Precision constraints of NN interaction at short distance
	3N-SRC
 Evolution of isospin structure	Gluonic probes/structure of SRC

PR12-23-009

2021 SRC-CT data used to make rate estimates for 95 PAC days on Helium-4

Resolution-dependence of SRC properties

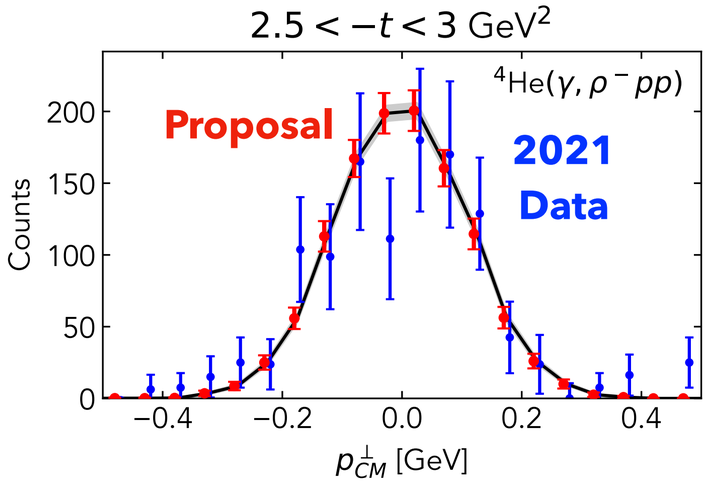


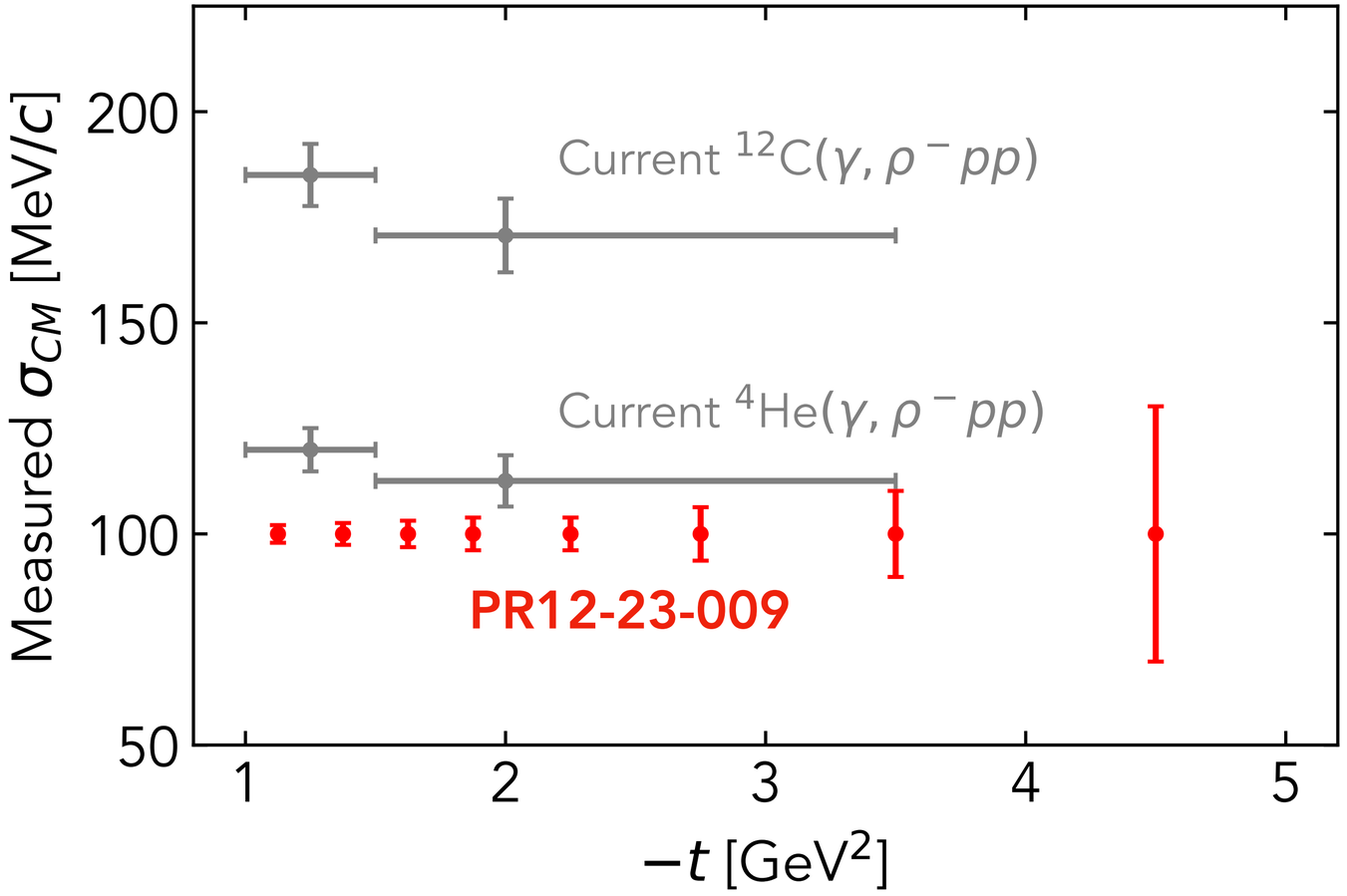


Current data are limited; reach extends to ~3.5 GeV², with limited number of bins

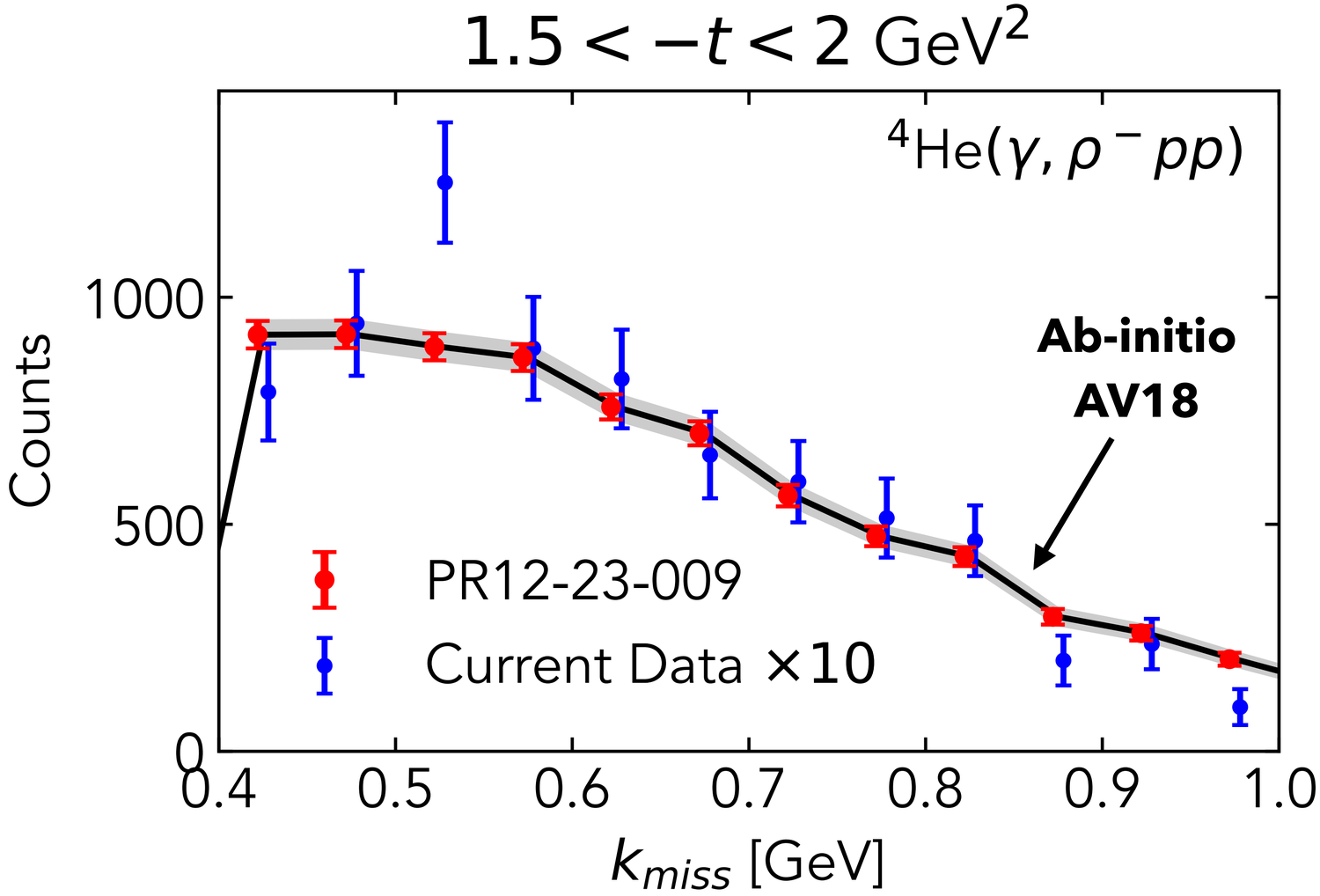
Detailed scan in $|t|$!

Requested Data:
95 beam days on ^{4}He

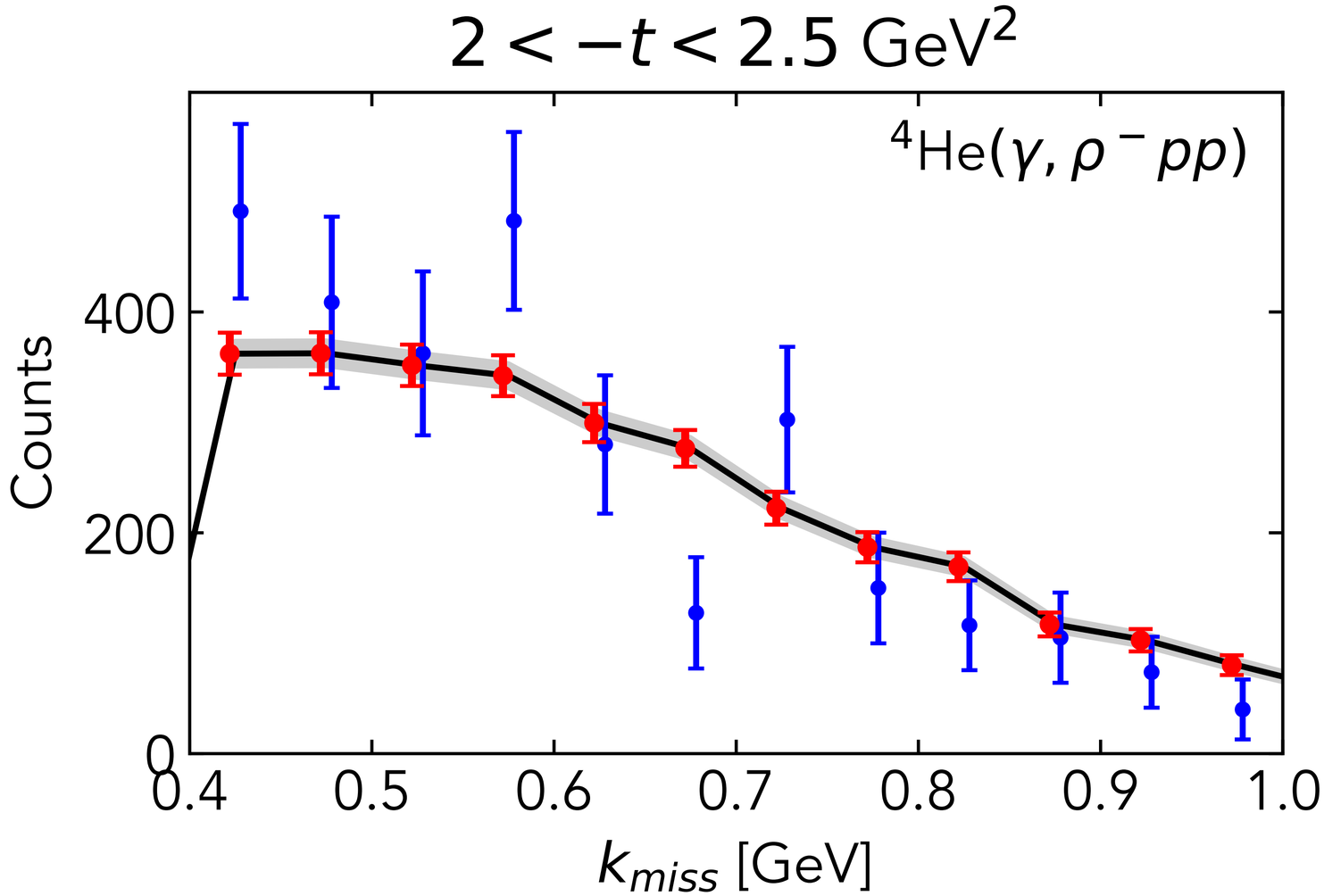




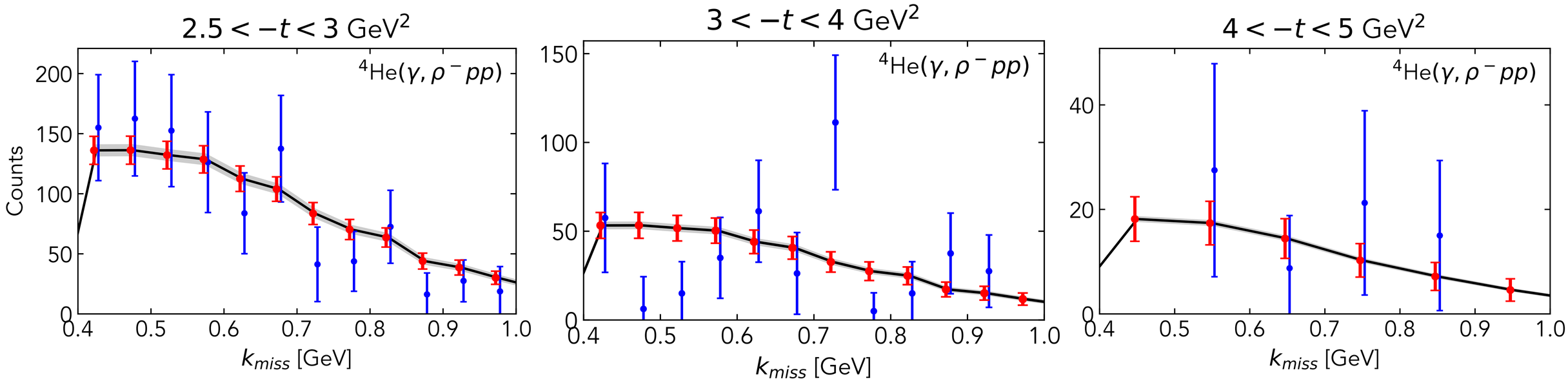
Current data dominated by low $|t|$



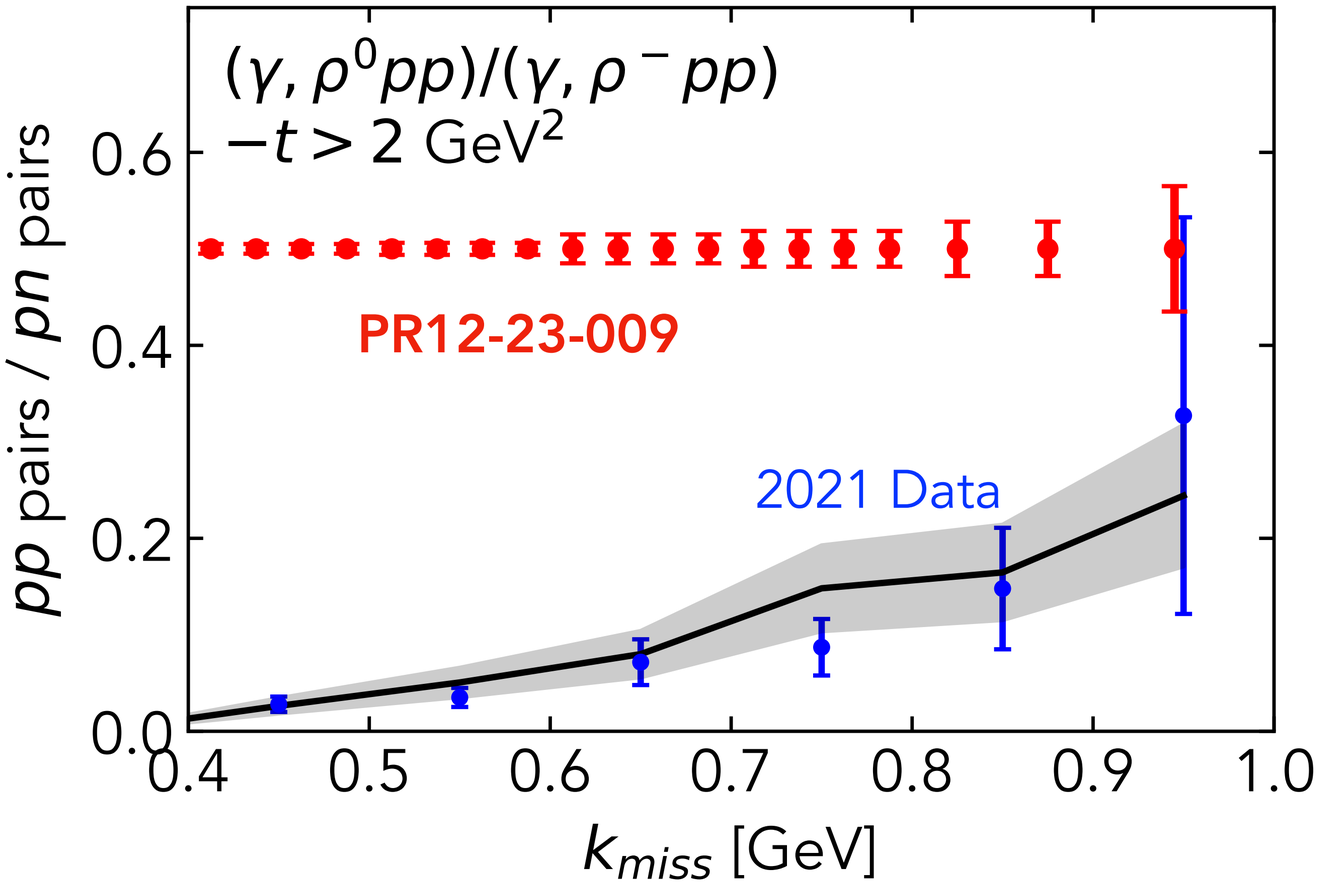
Marginal Reach to $|t| \sim 2.5$ GeV^2



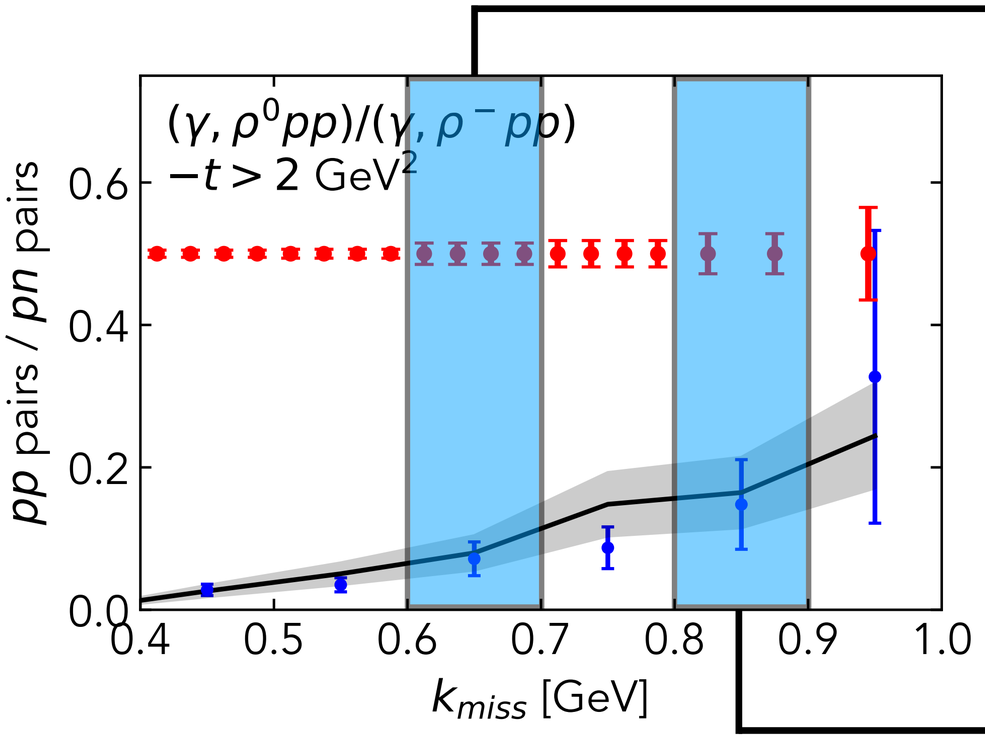
Only new data reach high-$|t|$!

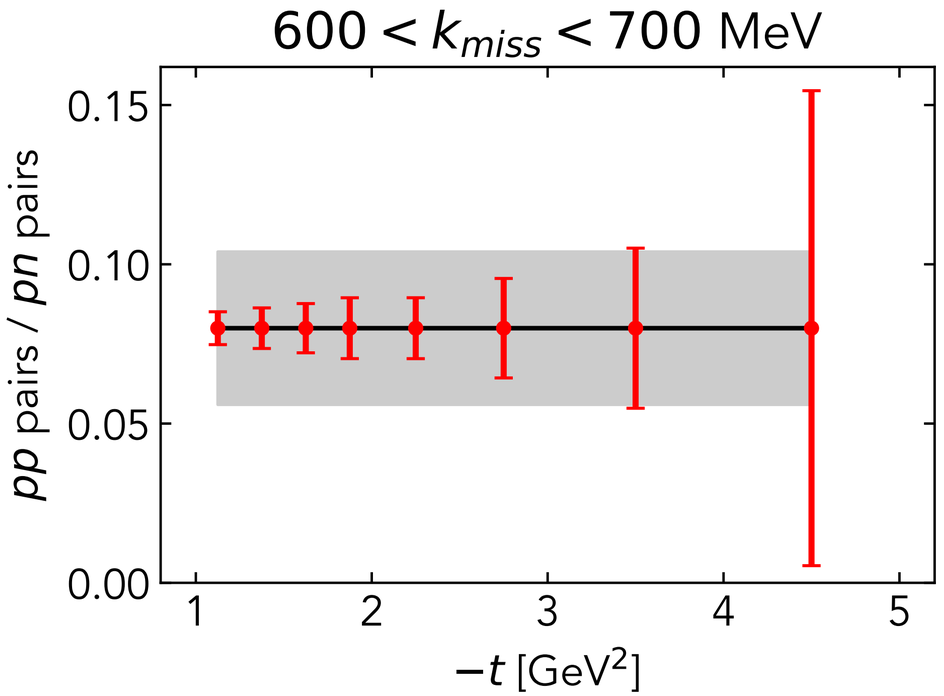


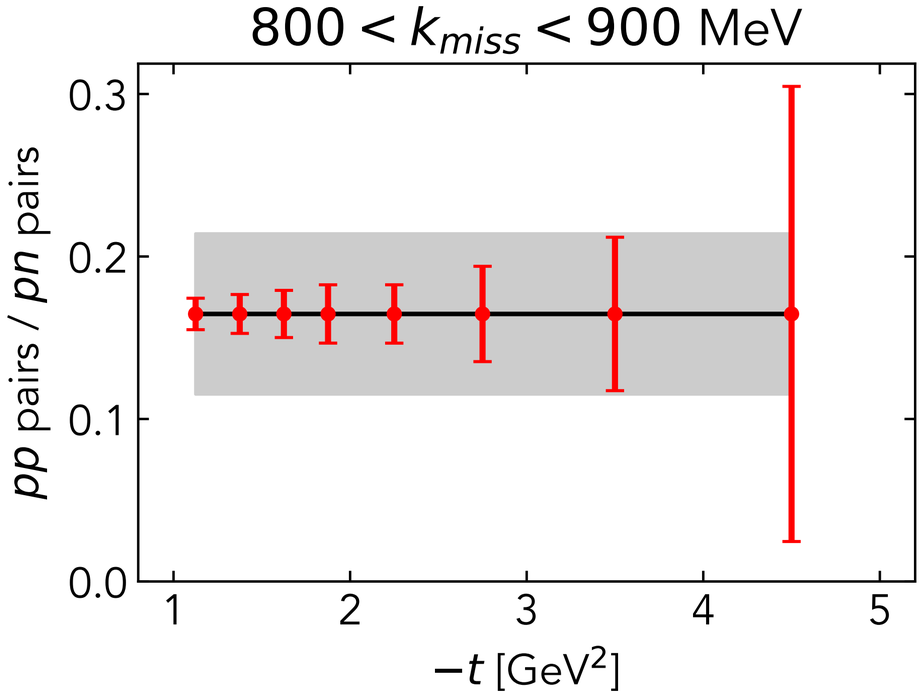
Constrain parameter-free ab-initio theory



Will confirm short-distance universality







Search for 3N-SRCs

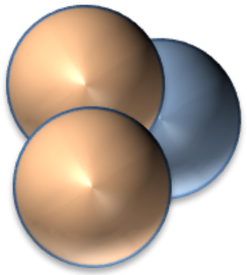
- Significant ongoing theory effort to understand and model 3N-SRCs

- Parallel experimental effort:

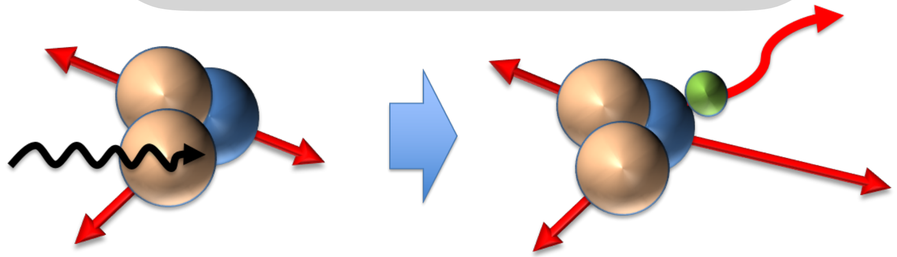
arXiv 2023,
PRC 2017,
PRC 2012

Exclusive electron scattering
(CLAS12)

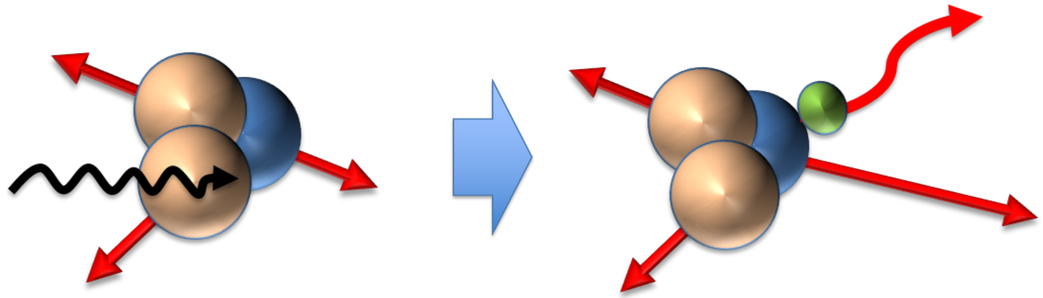
Inclusive high-x_B electron scattering
(Hall C)



Photoproduction
(This proposal)

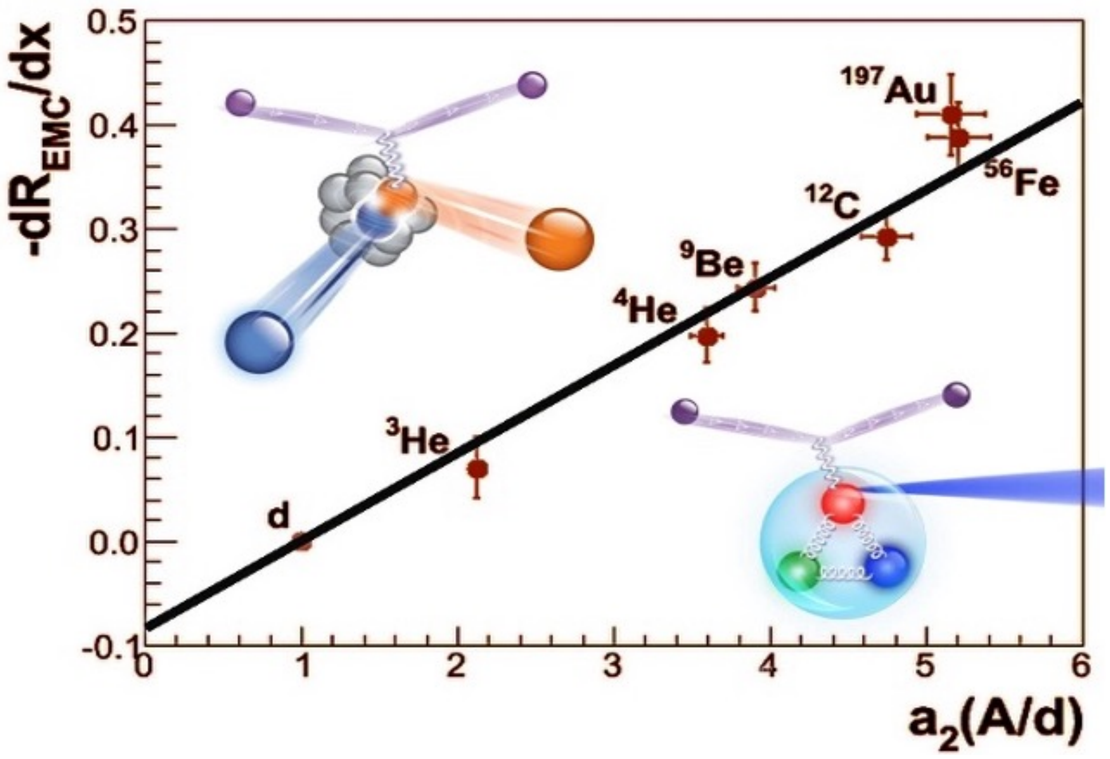


Photoproduction addresses many challenges!



- Large energy transfer: sensitive to high virtuality 3N-SRC states!
- Favors parallel kinematics (hard to reach with electrons)
- Neutron probed through charge-exchange reactions (π^-, ρ^-)
- Large acceptance detection in Hall D setup

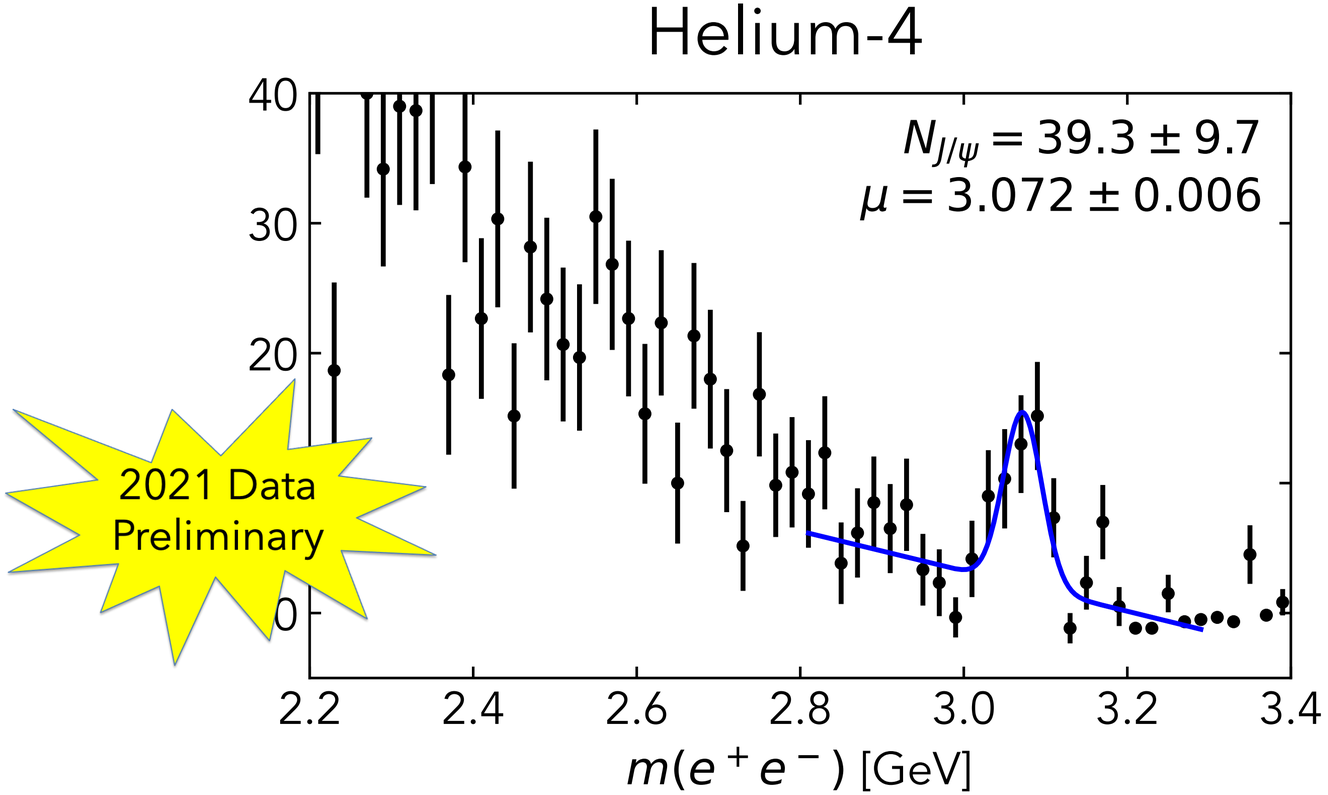
SRCs are related to medium-modification

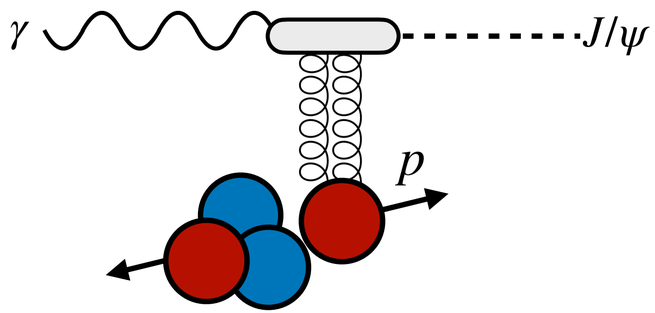


- Structure functions potentially modified by short-distance interaction
- Photon beams do not access nuclear structure function
- Photon beams are sensitive to nuclear **gluons!**

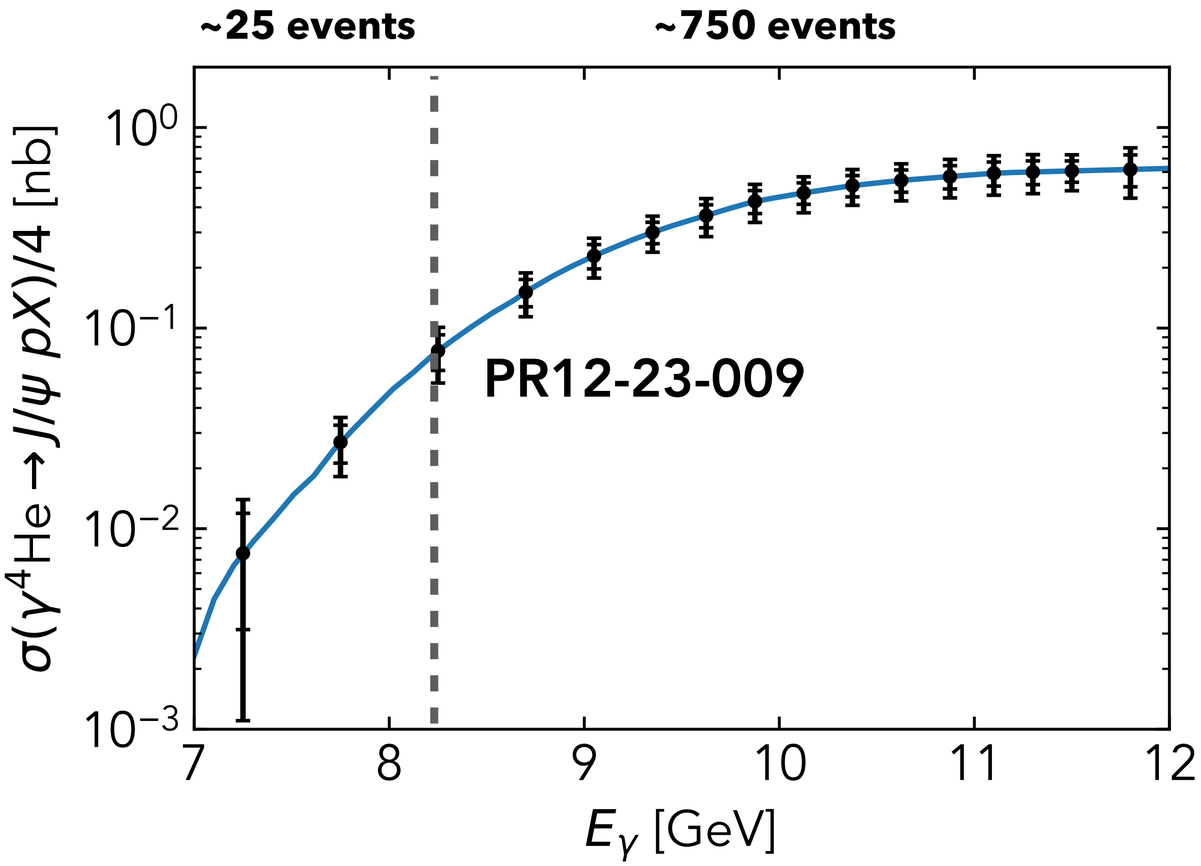
Nature (2019); RMP (2017); IJMPE (2013); PRC (2012); PRL (2011)

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





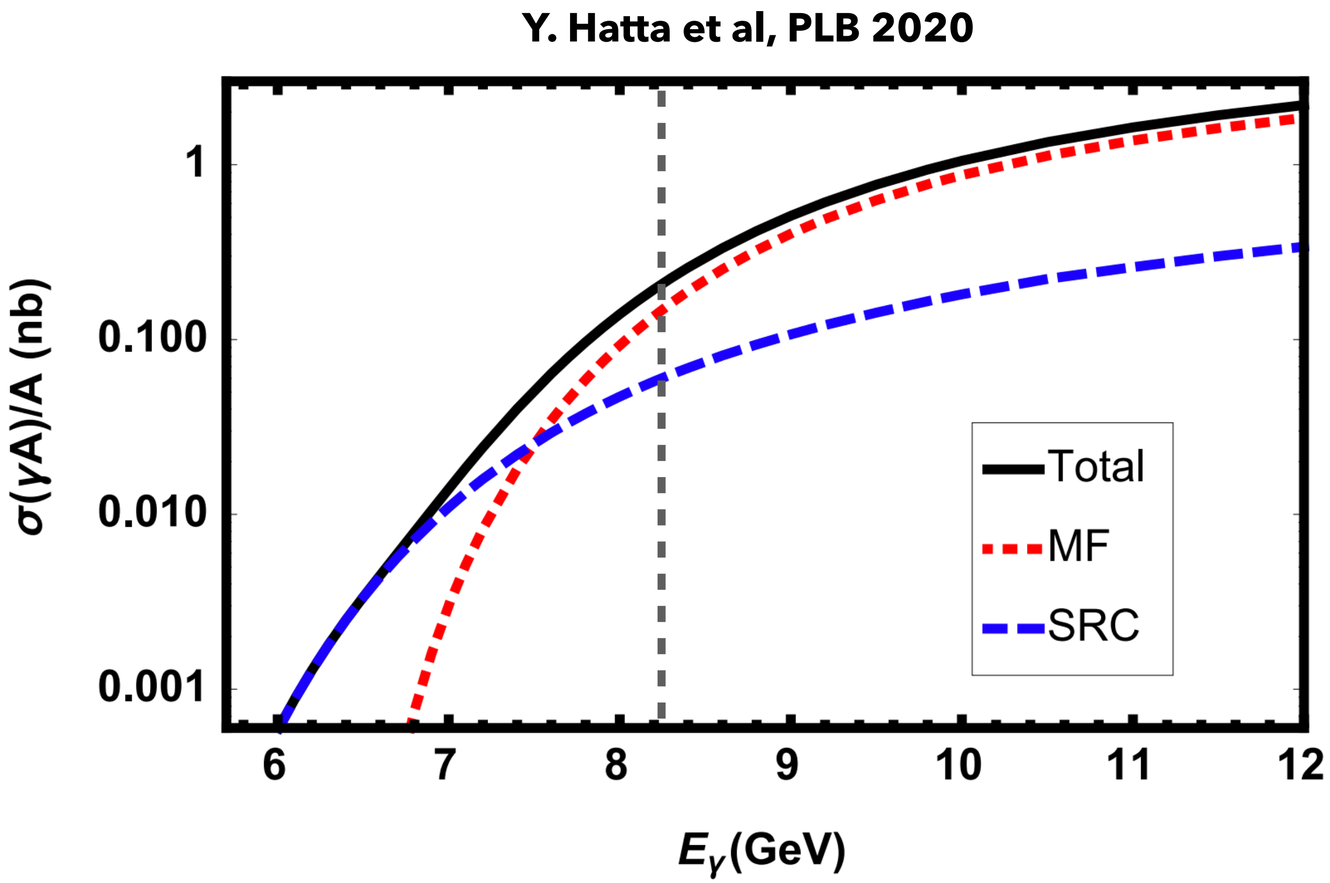
95 days on ^{4}He provide energy-dependent measurement at and below J/ψ threshold



Add threshold
Add hydrogen

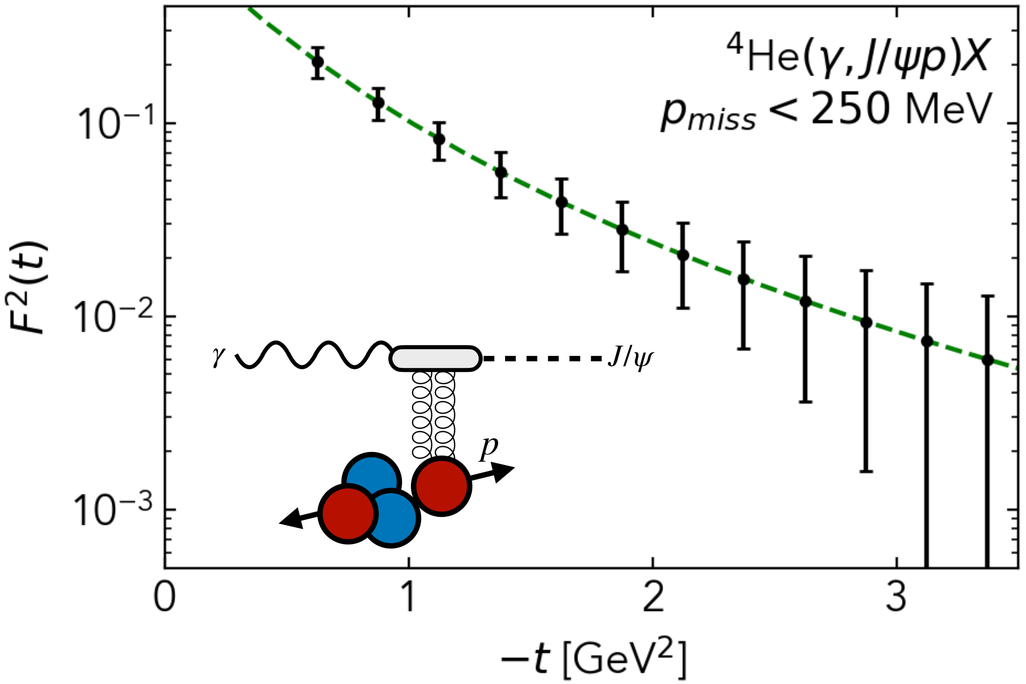
Subthreshold production has increased sensitivity to SRC

Subthreshold cross section provides a unique measure of nuclear structure, including SRCs

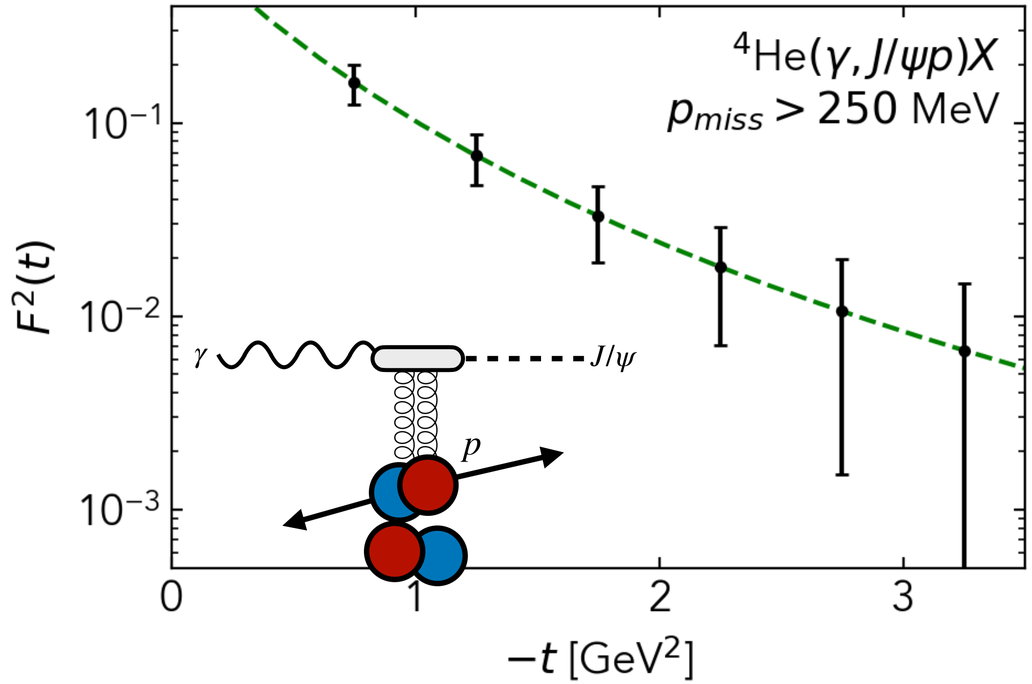


Semi-inclusive measurement allows separating mean-field and SRC gluon structure!

~700 events



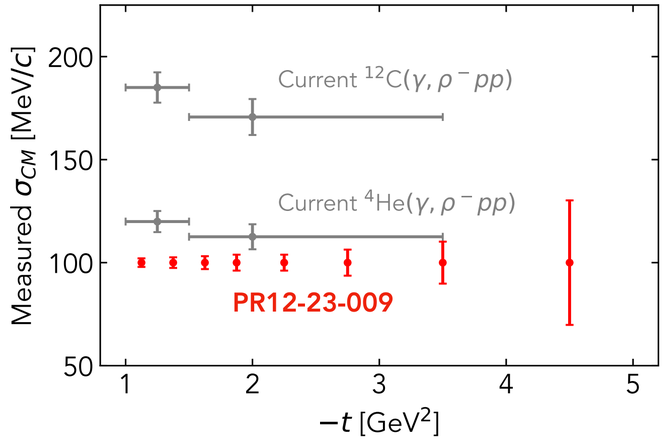
~100 events

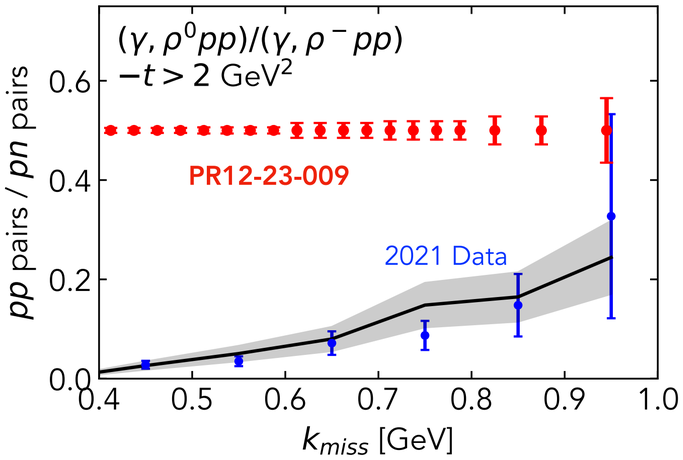


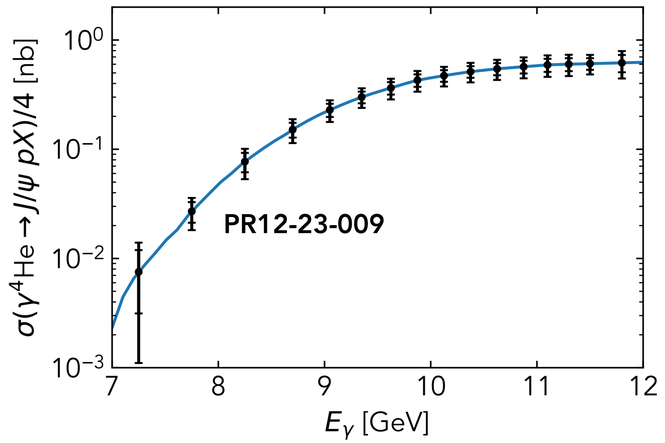
Can expose exotic behaviors of high-x gluons in nuclei — gluonic EMC, hidden color, etc.

Summary

- 100 days: **helium-4** (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





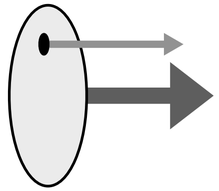


* Amorphous radiator also possible

Backup

Analysis on the light-front

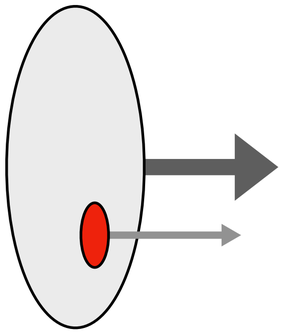
Parton in Hadron



Parton momentum fraction

$$x_B$$

Nucleon in Nucleus

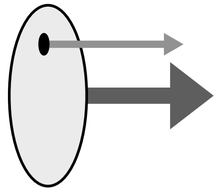


Nucleon momentum fraction

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

Analysis on the light-front

Parton in Hadron

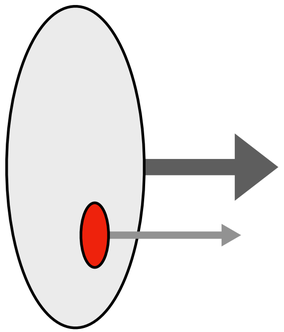


Parton momentum fraction

$$x_B$$

Light-front variables mitigate resolution effects

Nucleon in Nucleus



Nucleon momentum fraction

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

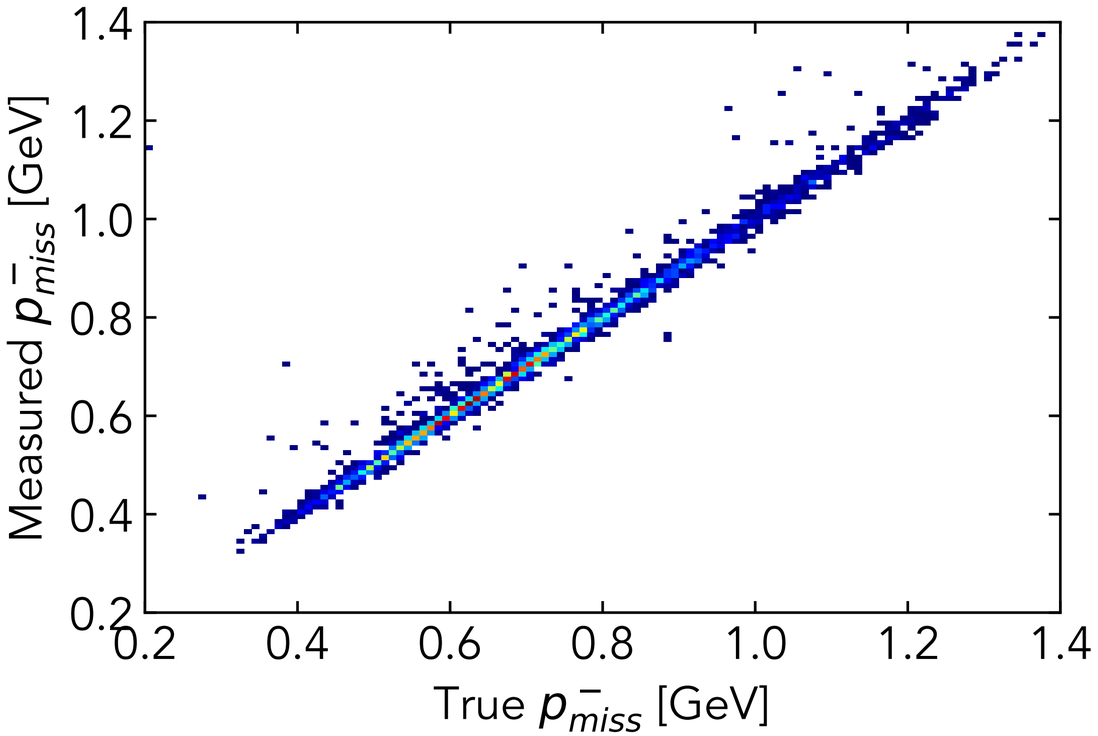
Low-momentum nucleon

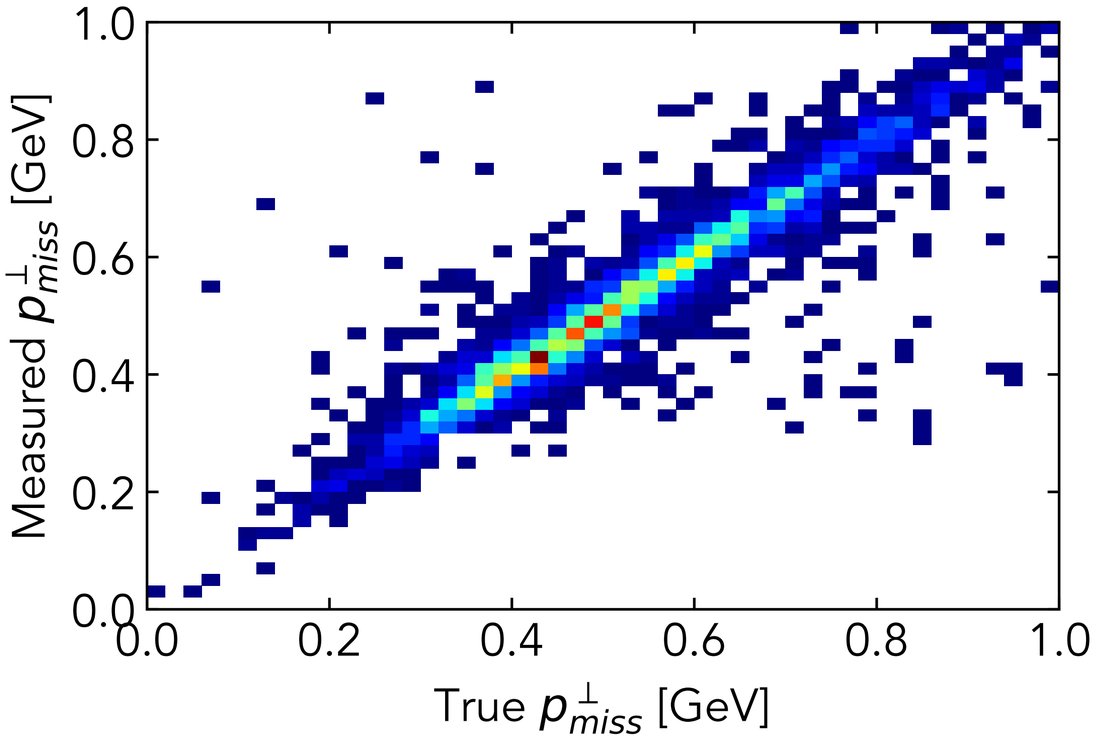
$$\alpha_N \sim 1$$

Standing nucleon pair

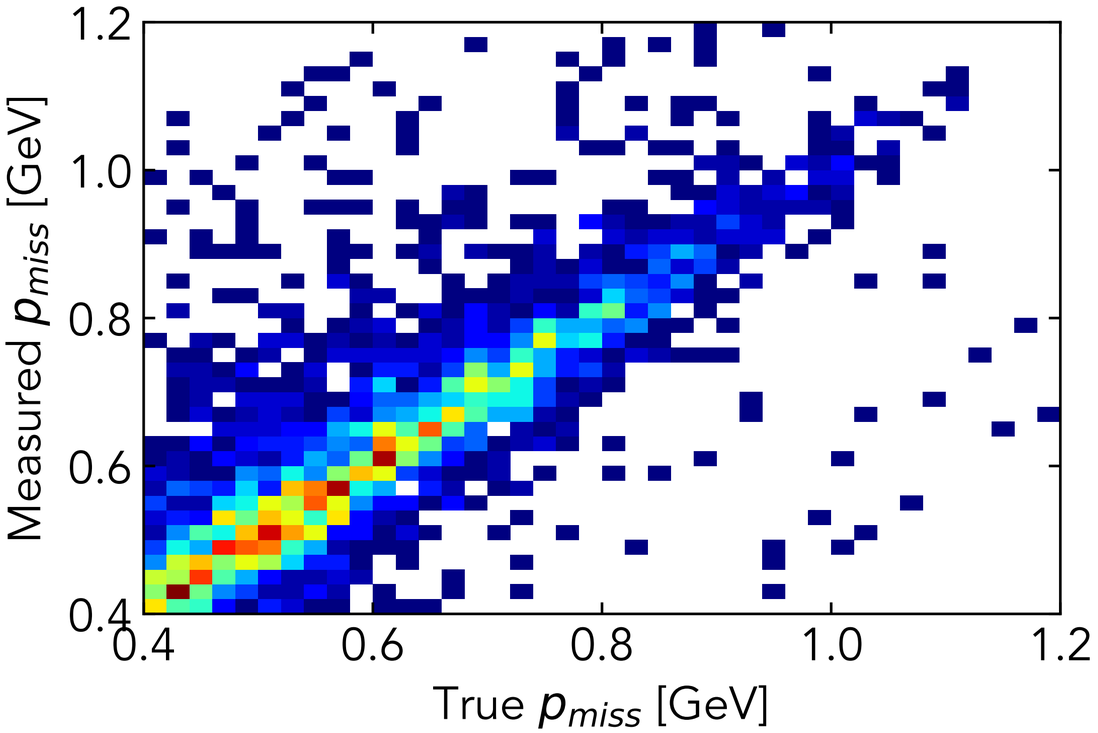
$$\alpha_1 + \alpha_2 \equiv \alpha_{CM} \sim 2$$

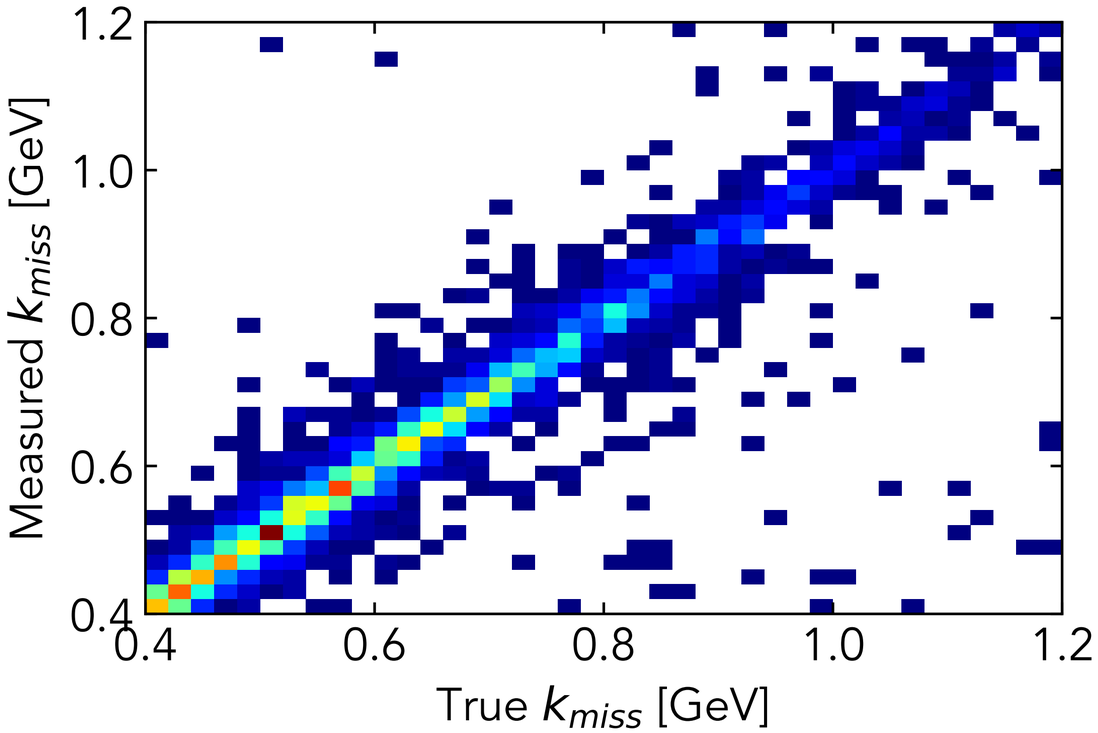
Resolution of Light-Cone Variables





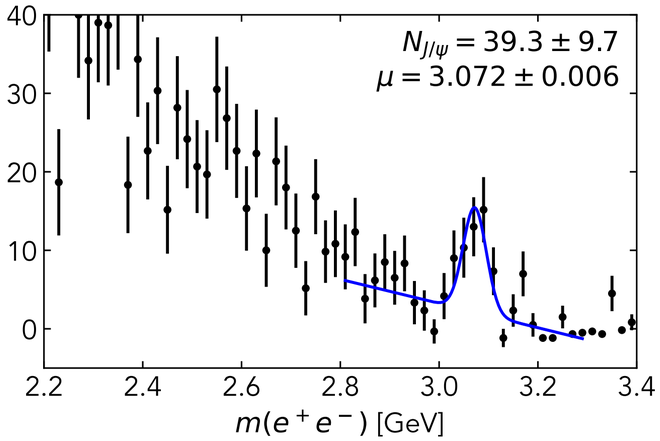
Resolution of Missing Momentum

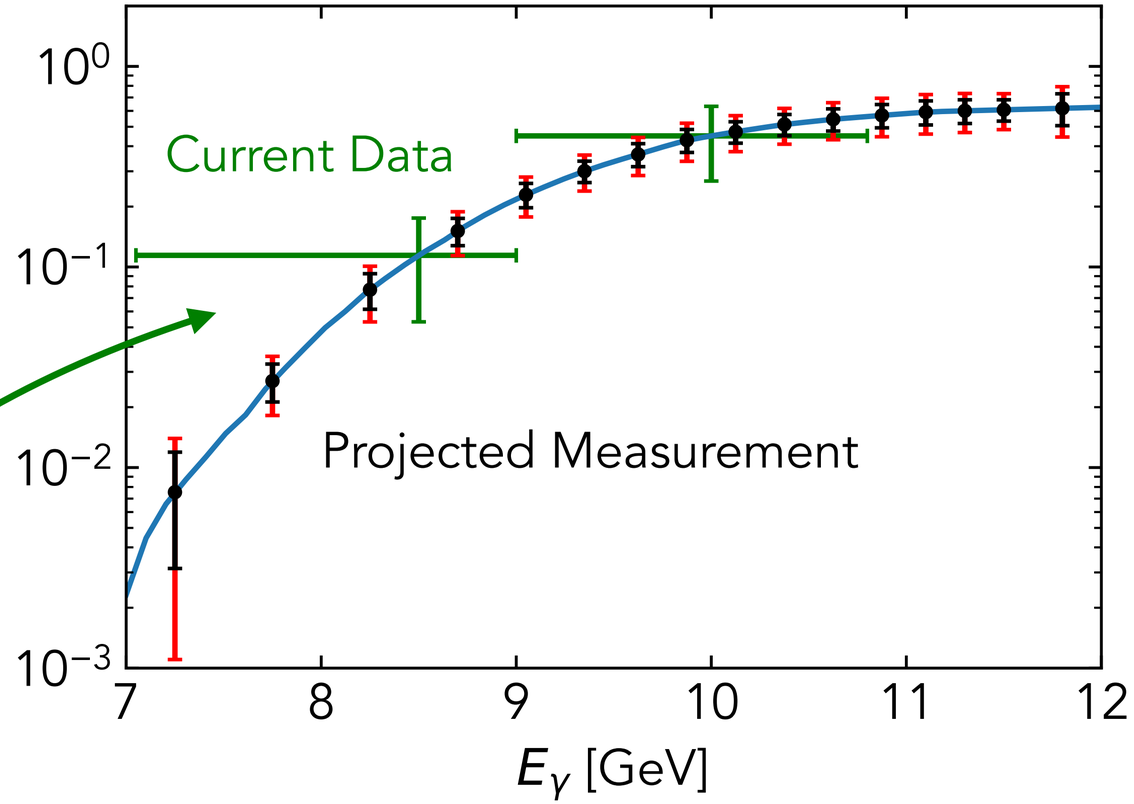




95 days of ^{4}He can allow energy-dependent J/ψ measurement at and below threshold

Current ^{4}He data from E12-19-003 show feasibility of measurement



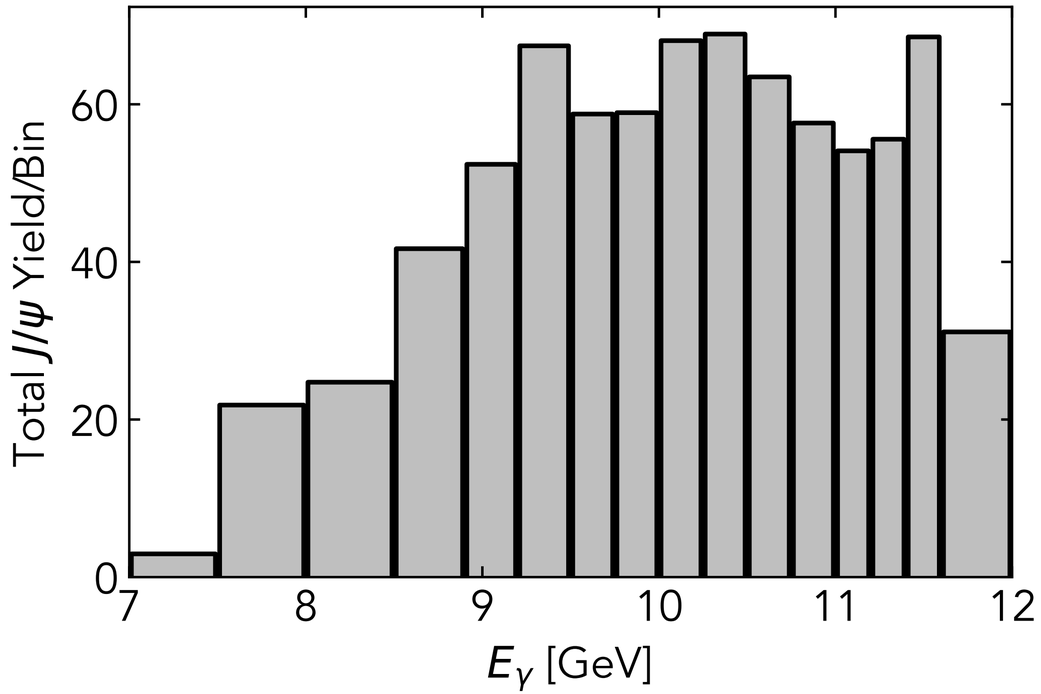


2021 SRC-CT Data

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

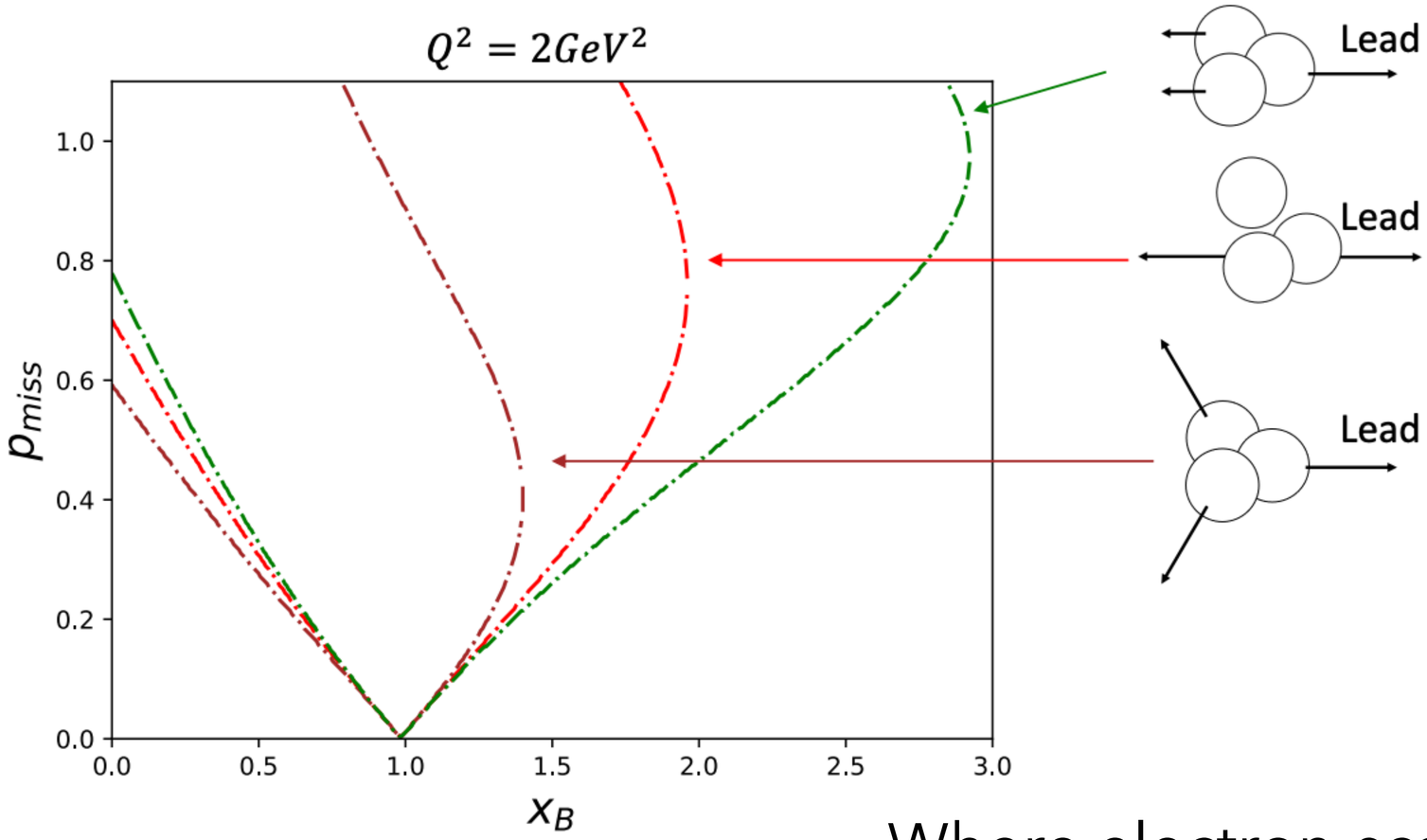
Estimated Rates

$\gamma\,^4\mathrm{He} \rightarrow J/\psi p(X)$



	MF	2N-SRC		3N-SRC	
Reaction	$(\gamma, \rho^0 p)$	$(\gamma, \rho^0 pp)$	$(\gamma, \rho^- pp)$	$(\gamma, \rho^0 ppp)$	$(\gamma, \rho^- ppp)$
# Events Projected ^{4}He ($\lvert t\rvert > 1.5$ GeV^2)	510k	10k	12k	100	120
# Events Projected ^{4}He ($\lvert t\rvert > 2$ GeV^2)	110k	2.5k	4.7k	30	50
# Events Projected ^{4}He ($\lvert t\rvert > 3$ GeV^2)	20k	500	480	5	5

Challenges in 3N-SRC detection with electrons



Limited by backgrounds!

Where electron-scattering wants to search for 3N

Open Questions and Worldwide SRC Program

Probe Independence

CLAS12/RGM
GSI/JINR
SRC@HallD

Pair Abundance

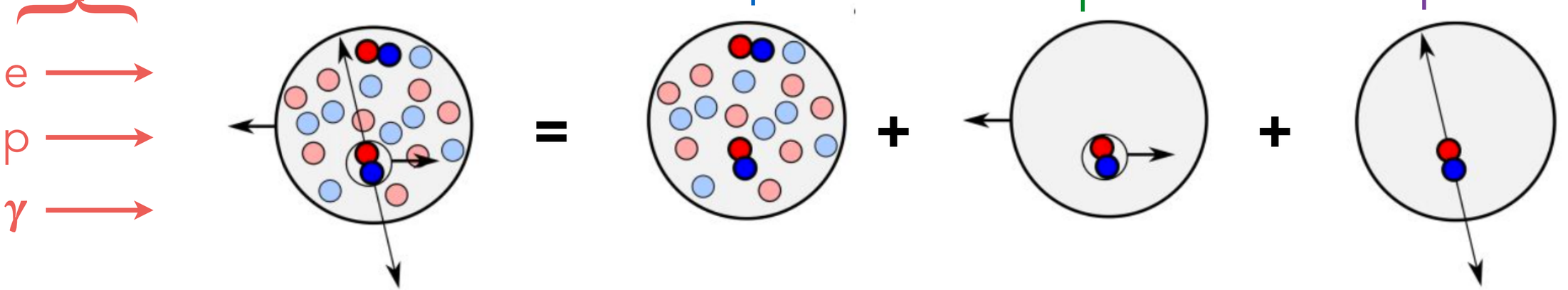
CLAS12/RGM
CaFe@HallC
Inclusive@HallC
GSI

Pair Properties

CLAS12/RGM
SRC@Hall D

NN Interaction

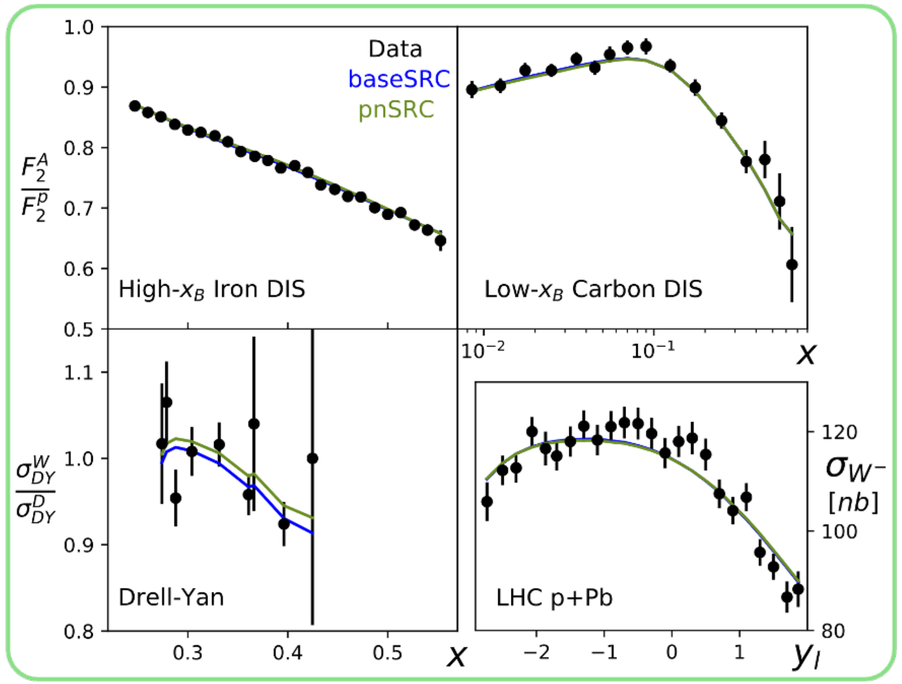
CLAS12/RGM
SRC@Hall D



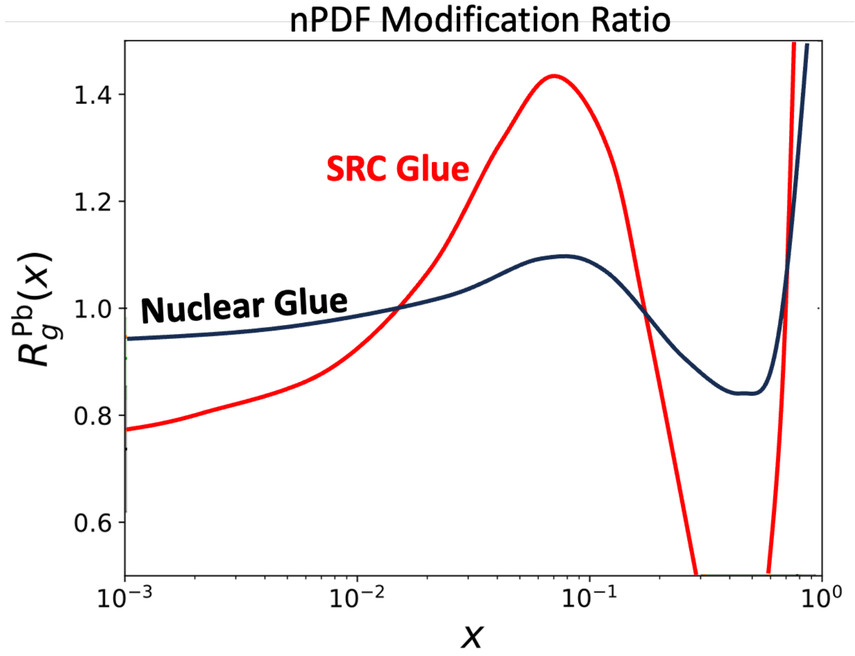
Gluon Modification in SRCs

SRC-nCTEQ: A New Global nPDF Analysis

$$q_i^A(x,Q) = \left(1 - \%_{SRC}^A\right) \times f_i^{free}(x,Q) + \%_{SRC}^A \times f_i^{SRC}(x,Q)$$



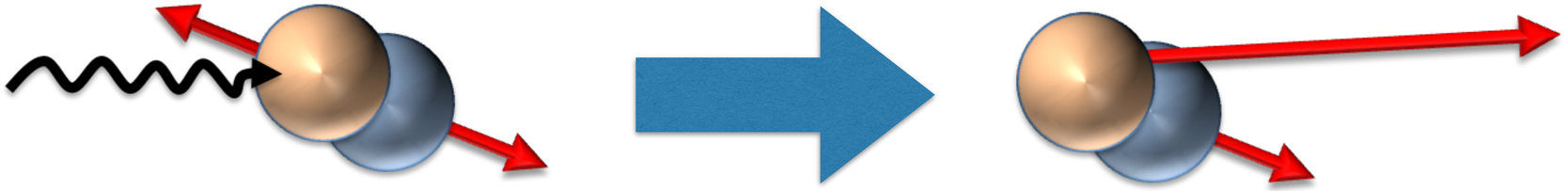
Predicts large SRC glue modification!



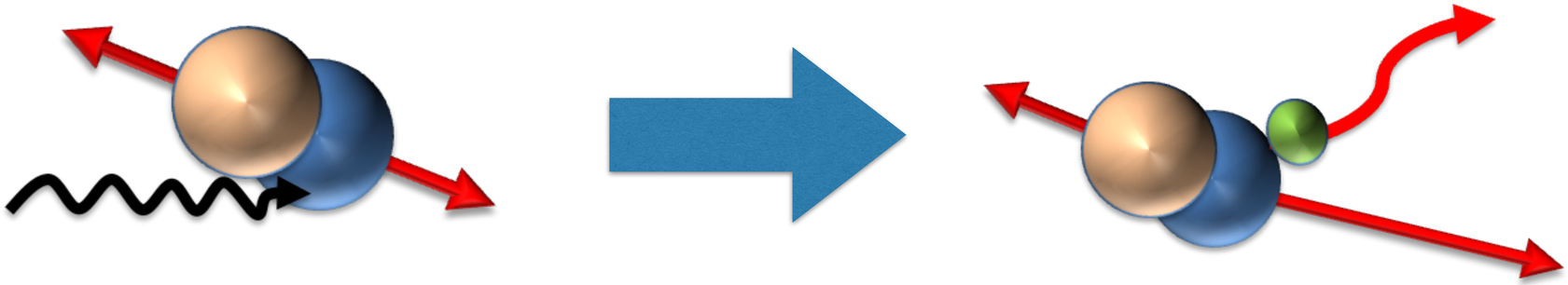
*Under peer review with Nature Physics

Electrons vs. Photons

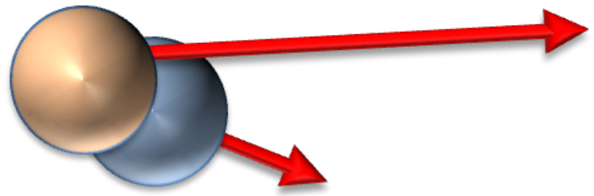
(e,e'NN) @ x > 1:



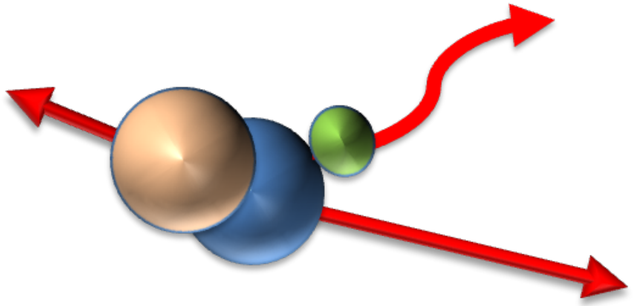
(γ,NNπ):



(e,e'NN) @ x > 1:



(γ,NNπ):



FSI:

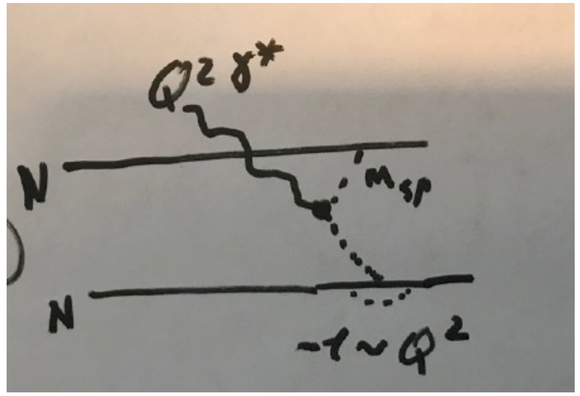
Similar to elastic NN scattering off a mean-field nucleon.

The (γ,NNπ) recoil nucleon goes backwards in the lab.

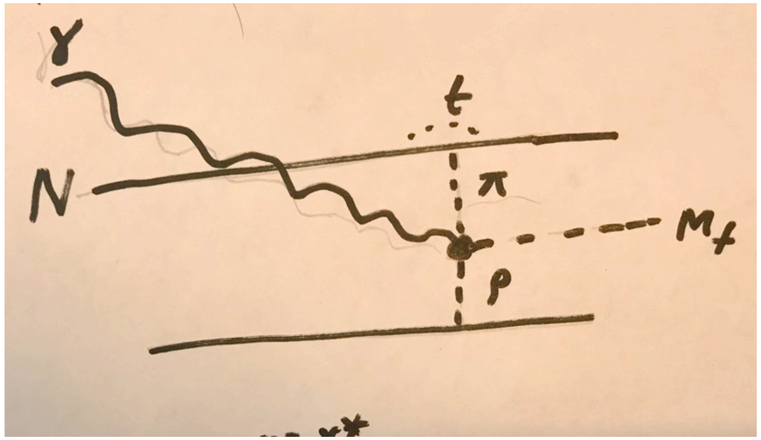
→ Cannot be produced by elastic FSI.

Also study using event generators w/ FSI and SRC

(e,e'NN) @ x > 1:



(γ,NNπ):



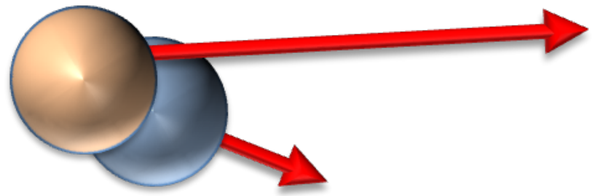
MEC:

Sensitive to different processes.

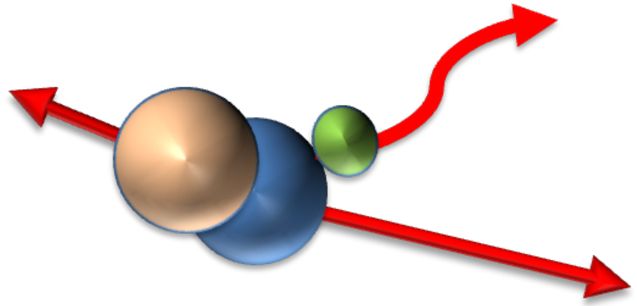
(γ,NNπ) requires much higher meson virtuality than (e,e'NN) which suppresses MEC contributions

* From Mark Strikman

(e,e'NN) @ x > 1:



(γ,NNπ):



Relativistic Effects:

The effective nucleon 'boost' is very different.

Forward α>1 boost for the electron case;
Backward α<1 boost for the γ case

Comparing reactions with light-cone fractions >1 (e) and <1 (γ) is a stringent test or relativistic treatment.

What about other reaction channels?

What about other reaction channels?

- Hall D setup capable of measuring many final states.
- Focus on the high cross-section ρ^0 and ρ^- channels, as planned
- **ρ results are mature, stable, and enough to establish what can be learned from existing data and why a deep-dive into photon measurements is needed**
- We are analyzing other channels as well. Less relevant for SRC physics

Proton Reactions	Neutron Reactions
$\gamma + p \rightarrow \pi^0 + p$	$\gamma + n \rightarrow \pi^- + p$
$\gamma + p \rightarrow \pi^- + \Delta^{++}$	$\gamma + n \rightarrow \pi^- + \Delta^+$
$\gamma + p \rightarrow \rho^0 + p$	**$\gamma + n \rightarrow \rho^- + p$**
$\gamma + p \rightarrow K^+ + \Lambda^0$	$\gamma + n \rightarrow K^0 + \Lambda^0$
$\gamma + p \rightarrow K^+ + \Sigma^0$	$\gamma + n \rightarrow K^0 + \Sigma^0$
$\gamma + p \rightarrow \omega + p$	x
$\gamma + p \rightarrow \phi + p$	x
...	...