Measurement of the Unpolarized SIDIS Cross Section from a ^{3}He Target with SoLID

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On behalf of the spokespersons
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E12-10-006 collaboration, E12-11-007 collaboration, and the SoLID Collaboration

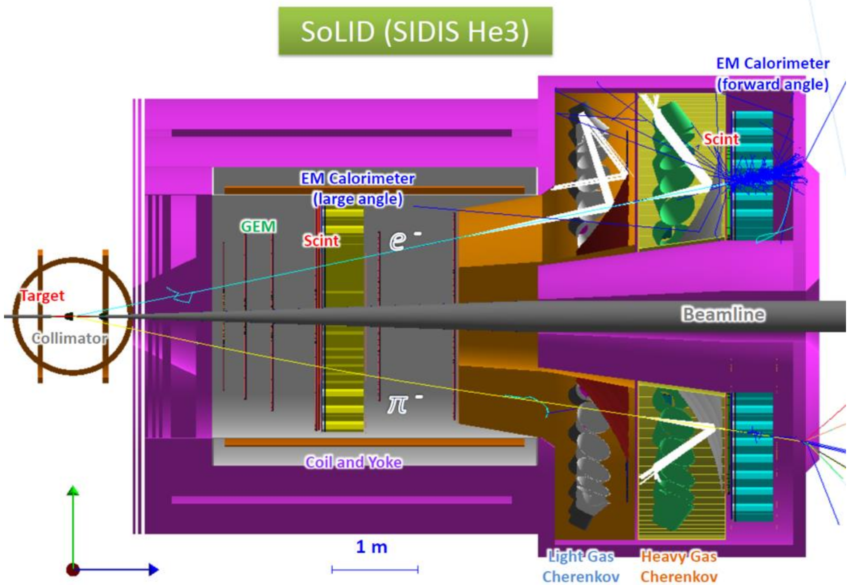
➢ **This run group experiment parasitic to SoLID SIDIS experiments of**

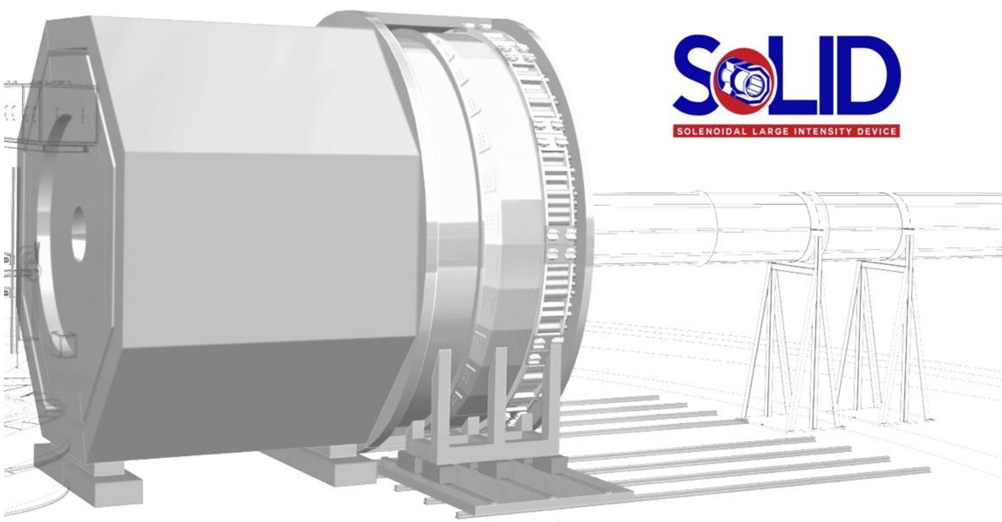
- **E12-10-006: Single Spin Asymmetries on Transversely Polarized ^{3}He (neutron):** Rating A
  Approved number of days: *48 days* (*11 GeV*) & *21 day* (*8.8 GeV*)

- **E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He (neutron):** Rating A
  Approved number of days: *22.5 days* (*11 GeV*) & *9.5 day* (*8.8 GeV*)

Outline

- Introduction
  - Reviews of this proposal
  - SIDIS process and differential cross section
- Motivation for the proposed SIDIS cross section measurement
- Estimated systematic uncertainties for this experiment
- Projected results and physics impact





SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

Review Comments from the SoLID Committee and PAC Reader

1. The importance of the cross-section measurement should be sharpened. For example, **why would an absolute cross section measurement of SIDIS be more valuable than the (traditional) multiplicity study?**

2. How well do we know (or expect to know) **the coincidence pion production cross sections and what are the uncertainties due to the coincidence acceptance?** This should be finalized.

3. What are the **ϕ -dependent effects and uncertainties from the electromagnetic radiative corrections**? Can you possibly quantify the uncertainty in the ϕ -dependence due to the radiative corrections and compare them with your best estimate of a physics signal expectation, especially the Boer-Mulder effect?

4. How does the **nuclear corrections affect** the significance of the physics impact on the neutron? For example, would **Fermi motion affect extracted $k_\perp$ or $p_\perp$ width**? Can PWIA be used to estimate the effect of the nuclear corrections?

5. On the importance of ^{3}He data: while **^{3}He and deuteron data are complementary, it is still useful to have a quantitative comparison of the impact with the Hall B deuteron data**.

6. Please make a **self sufficient/standalone plot** with legends, caption and axis labels which captures the physics quantity of interest and its impact from this run group proposal such that it that could be advertised by the SoLID collaboration.

9. Sec. 6.3 / Fig. 41: The quoted uncertainty on $\langle k_\perp^2 \rangle$ in Eq. (58) (±0.0002 GeV²) appears inconsistent with the 68% contour in Fig. 41 (~0.584–0.590 GeV²); suggest clarifying. Also, replace $p_\perp$ with $P_\perp$ in Eq. (58).

10. Figs. 43 & 44 (Eqs. 64 & 62): If factorization holds, the plotted quantities should be flat in z, but oscillations are observed. Are these due to deuteron structure effects, or do they indicate a breakdown of factorization?

11. Fermi Motion & Systematics (Secs. 6.1–6.5, 7.1): Unclear whether Fermi motion effects are included in results of Secs. 6.1–6.3. Fig. 35/36 uncertainties may need revision. Also, possible inconsistency between Sec. 7.1 and item (iii) on p. 68 regarding whether systematic uncertainties are included in azimuthal modulation analysis.

SIDIS Process

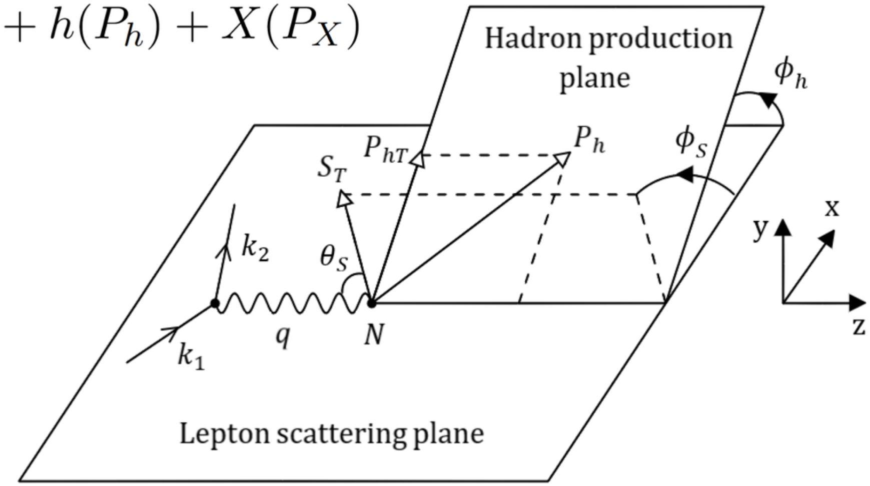
- The SIDIS process represented as (four-momenta given in parentheses)

$$l(k_1) + N(P) \rightarrow l'(k_2) + h(P_h) + X(P_X)$$

- l - lepton beam
- N - nucleon target
- h - produced hadron
- X - undetected hadron
- q – virtual photon momentum

$q \equiv l - l'$

$Q^2 \equiv -q^2$



Azimuthal angle between hadron production and lepton scattering planes designated as ϕ_h

Kinematics of the SIDIS process:
assume one-photon exchange approximation

$$x_{bj} = \frac{Q^2}{2P\cdot q}, \qquad y = \frac{P\cdot q}{P\cdot k_1}, \qquad z_h = \frac{P\cdot P_h}{P\cdot q}, \qquad \gamma = \frac{2M_N x_{bj}}{Q}$$

- Project unpolarized cross-section pseudo-data in **5-D binning**

$$x_{bj},\ P_{hT}, z_h, Q^2, \phi_h$$

Why Measure SIDIS Unpolarized Cross Section

Multiplicities (HERMES/COMPASS) constrain TMDs, but cross-section measurements are essential to test both the shape and magnitude, providing a critical test of TMD factorization beyond leading order.

$$\frac{d\sigma}{dx_{bj}\,dz_h\,dQ\,dP_{hT}^2\,d\phi_h} = \frac{4\pi\alpha^2}{x_{bj}\,Q^3}\left(1+\frac{\gamma^2}{2x_{bj}}\right) \times \left[c_1\, F_{UU} + c_2\cos(\phi_h)\, F_{UU}^{\cos(\phi_h)} + c_3\cos(2\phi_h)\, F_{UU}^{\cos(2\phi_h)}\right]$$

SoLID impact study on F_{UU} is performed using the MAPTMD24 framework with TMD evolution up to NNNLL accuracy.

test of TMD factorization theorems

There are no ϕ_h-dependent terms computed within TMD factorization (obtained within LO parton model)

Access to angular modulations and higher-twist physics

NNNLL means next-to-next-to-next-to-leading-log

SIDIS Unpolarized Cross Section

In LO factorization scheme

$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h} = 2\pi\,\frac{\alpha^2}{x_{bj}\,yQ^2}\left(1+\frac{\gamma^2}{2x_{bj}}\right)\times$$
$$\times\left[c_1\,F_{UU} + c_2\cos(\phi_h)\,F_{UU}^{\cos(\phi_h)} + c_3\cos(2\phi_h)\,F_{UU}^{\cos(2\phi_h)}\right],$$

- Use Gaussian parameterizations for the TMD PDF and TMD FF

Twist 3 effect: cos ϕ_h dependence

$$F_{UU}^{\cos(\phi_h)} = F_{UU}^{\cos(\phi_h)}\Big|_{\mathrm{Cahn}} + F_{UU}^{\cos(\phi_h)}\Big|_{\mathrm{BM}}$$

- Cahn effect $\propto f_1 \otimes D_1$
  - Non-zero Cahn effect solely requires **non-zero quark transverse momentum**
  - Related to quarks' **intrinsic transverse momentum distribution**

Twist-4 Cahn & twist-2 Boer-Mulders: cos($2\phi_h$) dependence

$$F_{UU}^{\cos(2\phi_h)} \approx F_{UU}^{\cos(2\phi_h)}\Big|_{\mathrm{Cahn}} + F_{UU}^{\cos(2\phi_h)}\Big|_{\mathrm{BM}}$$

- Boer-Mulders effect $\propto h^{\perp}_1 \otimes H^{\perp}_1$
- Twist-4 Cahn effect could have similar size of contribution to cos($2\phi_h$) as Boer- Mulders [Phys. Rev. D. 81:114026 (2010) based on HERMES/COMPASS results]

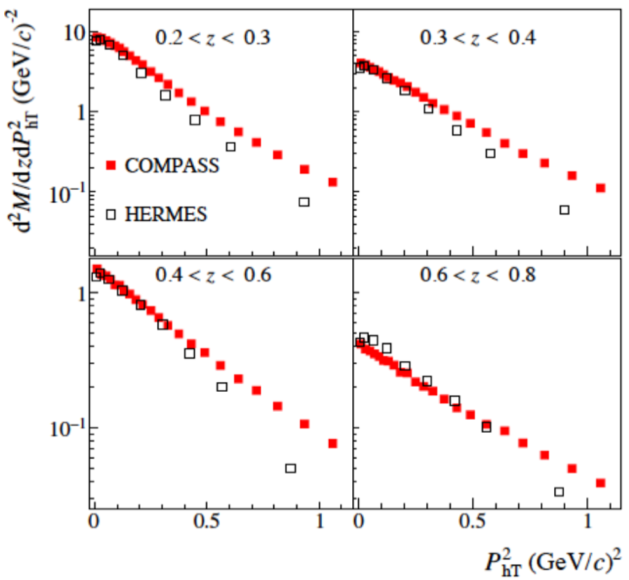
Why Measure Absolute Cross Sections in SIDIS?

❖ Addressing Reviewer **Comment #1** (SoLID Committee)

- Studies on Multiplicities of hadrons in SIDIS are available

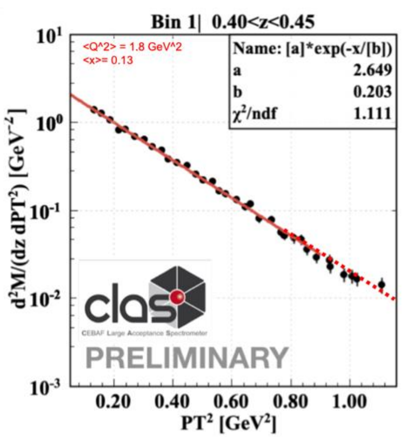
$$\frac{d^2M^h(x_{bj}, Q^2, z_h, P_{hT}^2)}{dz dP_{hT}^2} = \left(\frac{d^4\sigma^h}{dx dQ^2 dz dP_{hT}^2}\right) / \left(\frac{d^2\sigma^{DIS}}{dx dQ^2}\right)$$

- Systematic uncertainties largely cancel
- Ideal for global fits of fragmentation functions
- Denominator: inclusive DIS (collinear),
- Numerator: SIDIS (TMD) → mixed schemes; sensitive to kinematic cuts
- Not suitable for nuclear effect studies



❑ Lack of data on SIDIS unpolarized absolute cross sections

- Study both the shape and the magnitude of the SIDIS cross sections
- Ascertain the validity of the factorization theorems
- higher-twist effects on azimuthal angular modulations
- TMD flavor dependence
- Nuclear corrections: EMC effect, nuclear binding, Fermi motion, and off-shell effects
- Challenges:
  - Larger systematics
  - Requires high luminosity and large acceptance



Data Status: Published and Collected

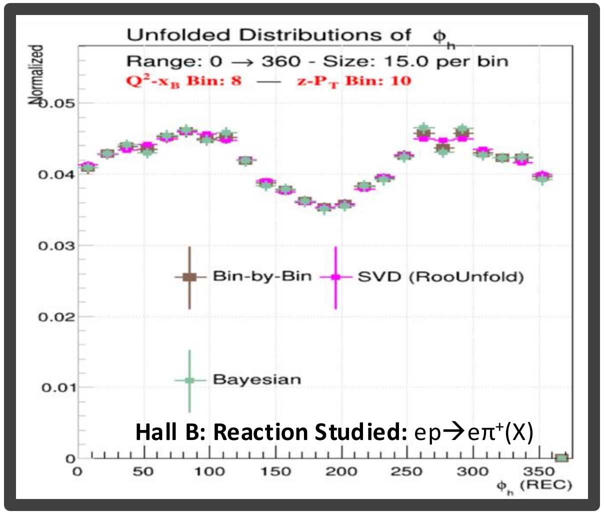
➢ Hall A data:

- **E06-010: SIDIS $\pi^{\pm}$ productions from a transversely polarized ^{3}He target with 5.9 GeV beam** ($0.12 < x_{bj} < 0.45$, $1 < Q^2 < 4$ GeV^2, $0.45 < z_h < 0.65$, $0.05 < P_{hT} < 0.55$ GeV)

X. Yan, et al., Phys. Rev. C 95, no.3, 035209 (2017)

➢ Hall B data:

- **RG-A/RG-B: Measurements of the $\cos\phi_h$ and $\cos 2\phi_h$ Moments of the Unpolarized SIDIS π^+ Cross-section with 10.6 GeV beam and hydrogen target**



R. Capobianco

➢ Hall C data:

- **E00-108: SIDIS $\pi^{\pm}$ productions from hydrogen and deuterium targets with 5.5 GeV beam** ($0.2 < x_{bj} < 0.6$, $2 < Q^2 < 4$ GeV^2, $0.3 < z_h < 1$, and $P_{hT}^2 < 0.2$ GeV^2)

R. Asaturyan and et.al Phys. Rev. C 85, 015202 (2012)

- **E12-09-017: Transverse momentum (P_{hT}) dependence of SIDIS $\pi^{\pm}$ and $K^{\pm}$ productions from hydrogen and deuterium targets with 8.8 GeV and 11 GeV beam** ($0.2 < x_{bj} < 0.5$, $2 < Q^2 < 5$ GeV^2, $0.3 < z_h < 0.5$, and PhT < 0.5 GeV)

This SoLID proposal: SIDIS $\pi^{\pm}$ and $K^{\pm}$

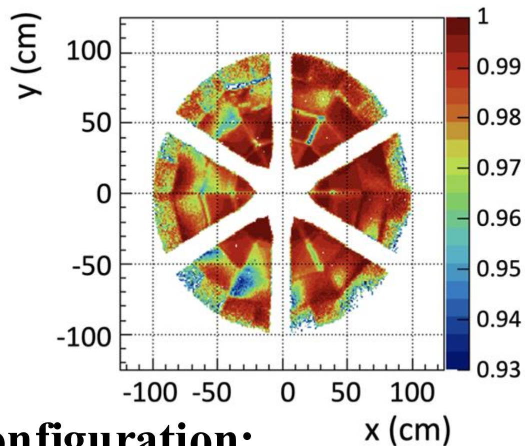
$0 < x_{bj} < 0.7$, $1 < Q^2 < 10$ GeV^2, $0.3 < z_h < 0.7$, $0 < P_{hT} < 1.6$ GeV, $-\pi < \phi_h < \pi$

SoLID's Advantage in Unpolarized SIDIS

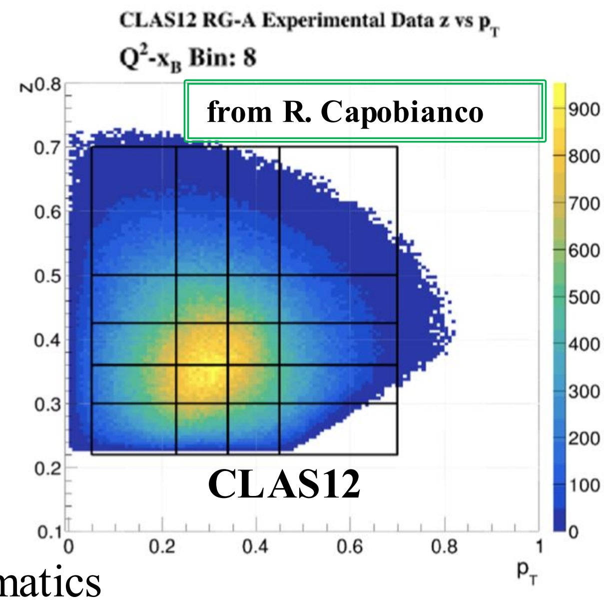
❖ Addressing Reviewer **Comment #5** (SoLID Committee)

➢ Hall B data: RG-A: Measurements of the $\cos\phi_h$ and $\cos 2\phi_h$ Moments of the Unpolarized SIDIS $\boldsymbol{\pi^+}$ Cross-section with **10.6 GeV** beam and hydrogen target

CLAS12



arXiv:2501.14996

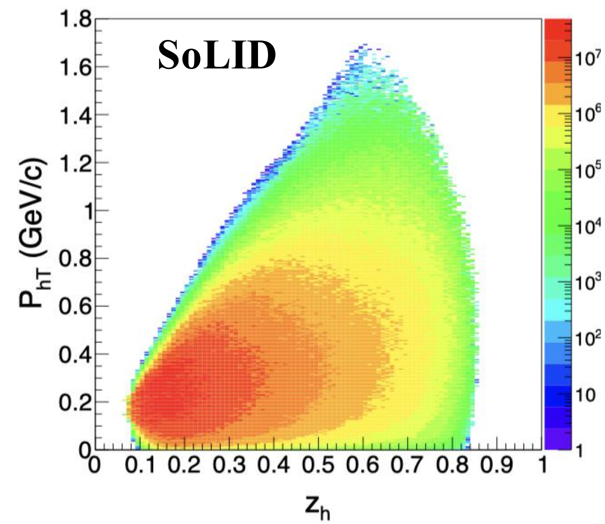


SoLID SIDIS configuration:

✓ Continuous azimuthal coverage → avoids sector-based systematics 4.4% from RG-A.

✓ Statistically rich dataset: ~100× CLAS12 deuteron (RG-B) data

✓ Enables fine binning in P_{hT}



Critical for TMD studies:

- Fine P_{hT} bins essential to probe TMD factorization region
- SoLID accesses **$1.0 < P_{hT} < 1.6$ GeV/c**
- Statistical uncertainty in high-P_{hT} region: **~0.9%**

Coincidence Acceptance Uncertainty

❖ Addressing Reviewer **Comment #2** (SoLID Committee)

10days of 11 GeV unpolarized hydrogen and deuterium runs (SIDIS transversely polarized ^{3}He experiment **E12-10-006**) above the resonance region $d\sigma/dt(x_{bj}, Q^2)$, $d^2\sigma/dtd\phi$

✦ $e' + \pi^+$

Proton target data

- **Hall C**

➢ **Q^2= 0.6-2.45 GeV^2, W=1.9 and 2.0 GeV, 0.026 GeV$^2 \leq$ -t $\leq$ 0.365 GeV^2**

H. P. Blok and et.al., Phys. Rev. C 78, 045202 (2008)

➢ **Q^2= 2.4 GeV^2, W=2.0 GeV, 0.272 GeV^2< -t < 2.127 GeV^2**

S. Basnet and et. al , Phys. Rev. C 100 (2019) 6, 065204

➢ **Hall C 12 GeV experiments E12-06-101 and E12-07-105**

Q^2 (GeV^2)	W (GeV)	t_{min} (GeV^2)	Beam energy (GeV)
0.6	1.95	0.03	3.548
0.75	1.95	0.044	3.548

uncertainty <4.3%

- **Hall B**

➢ **0.16 < x_{bj} < 0.58, 1.6 GeV^2 < Q^2 < 4.5 GeV^2 and 0.1 GeV^2 < −t < 5.3 GeV^2**

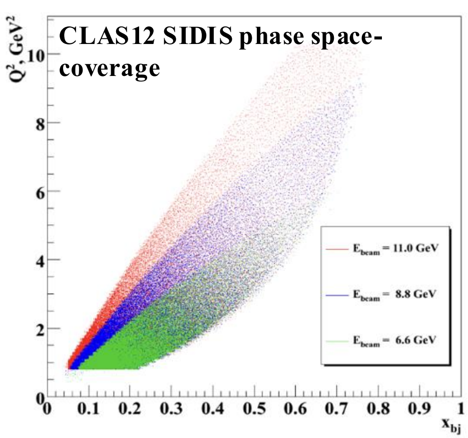
K. Park and et al., Phys. J. A 49, 16 (2013)

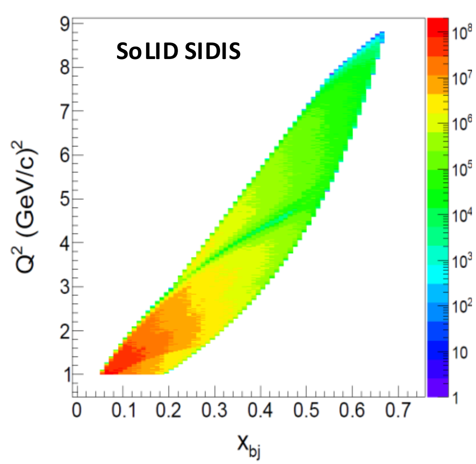
➢ **Hall B 12 GeV experiment PR12-10-010**

https://www.jlab.org/exp_prog/proposals/10/PR12-10-010.pdf

Calibration Approach:

- Exclusive channels will be calibrated in overlapping regions using existing or forthcoming data.
- Calibration will be extended into broader kinematic regions via **SIDIS reactions**.





Coincidence Acceptance Uncertainty

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10days of 11 GeV unpolarized hydrogen and deuterium runs (SIDIS transversely polarized ^{3}He experiment **E12-10-006**) above the resonance region $d\sigma/dt(x_{bj}, Q^2)$, $d^2\sigma/dtd\phi$

✦ $e' + \pi^-$

Deuterium target data

- **Hall C**
  - **Q^2= 0.6-1.6 GeV^2, W=1.95, Q^2= 2.45 GeV^2, W=2.2**

    G. M. Huber and et al., Phys. Rev. C 91, 015202 (2015)

- **Hall B**
  - **Hall B 12 GeV experiment PR12-10-010**

    https://www.jlab.org/exp_prog/proposals/10/PR12-10-010.pdf

Use of CLAS12 Data:

- CLAS12 SIDIS data from unpolarized proton & deuteron targets will be used
→ Targeting **7.2% uncertainty** for SIDIS pion cross sections
- **High-P_{hT}>1 GeV** region lacks CLAS12 coverage
→ will rely on **simulations,** additional 4% from tracking-related uncertainty. ~**8% total uncertainty** for high-P_{hT} pion measurements.

COMPASS and HERMES data provide cross-checks (10–15% stat. uncertainty)

- **HERMES**
  - **$0.02 < x_{bj} < 0.55$, 1 GeV$^2 < Q^2 <$ 11 GeV^2 and $-t <$ 2 GeV^2**

    A. Airapetian and et al., Phys. Lett. B. 659, 486 (2008).

- **COMPASS**
  - **1 < Q^2 < 16 GeV^2, 0.003 < x < 0.13,0.2 < y < 0.9, W > 5.0GeV/c^2, 0.01 < $P_\perp^2$< 3.0 (GeV/c)2, and 0.2 < z < 0.8**

    JPS Conf. Proc. 37, 020105 (2022)

✦ $e' + K^\pm$

- Hall C data: 7.9% total uncertainty

  Phys. Rev. C 97, no.2, 025204 (2018)

- Hall B CLAS12 $e'K^\pm$ data (in progress)

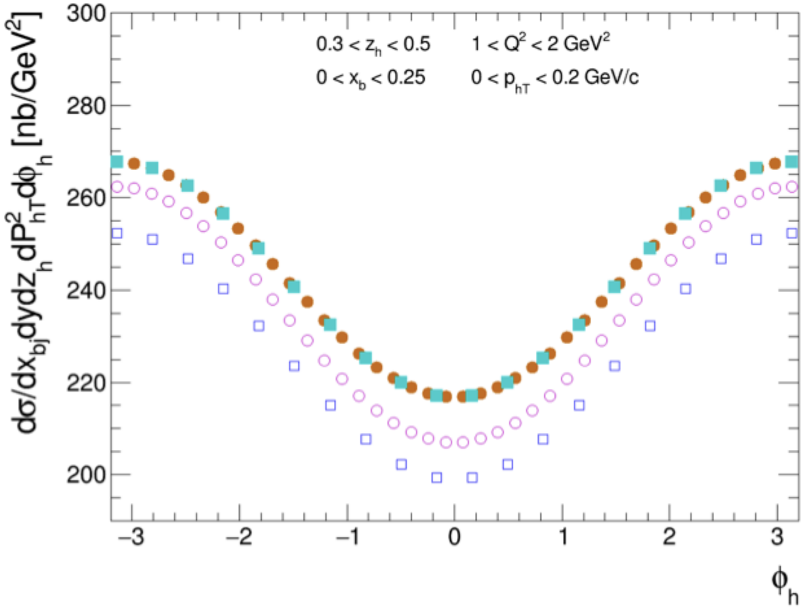
  https://indico.jlab.org/event/928/contributions/16228/attachments/12264/19427/Kripko_kaon_sidis_cos.pdf

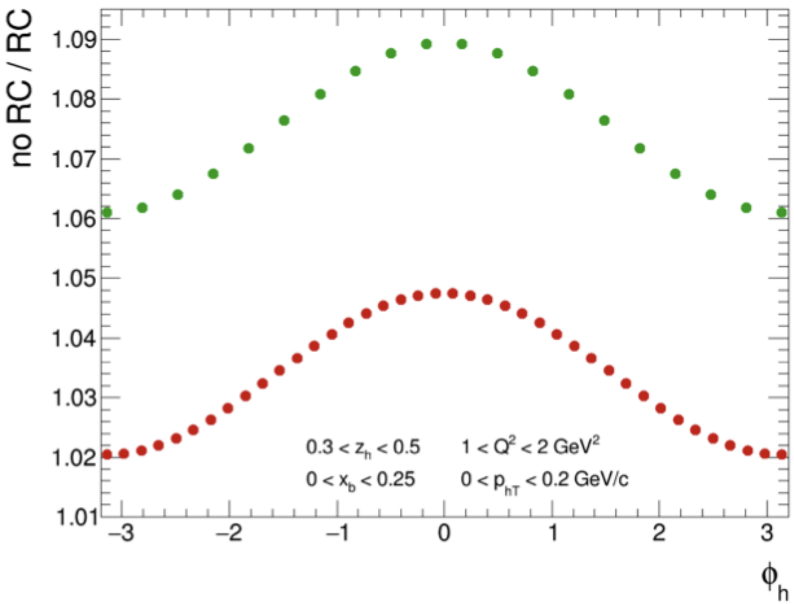
ϕ_h-dependent Effects and Uncertainties from Radiative corrections

❖ Addressing Reviewer **Comment #3** (SoLID Committee)

Traditional method: Orange curve -- σ_B, Cyan curve -- $\sigma_B + \sigma_{RC}$
Factorized method: Magenta curve -- σ_B, Blue curve -- $\sigma_B + \sigma_{RC}$

Traditional method: Red curve – ratio of σ_B and $\sigma_B + \sigma_{RC}$
Factorized method: Green curve – ratio of σ_B and $\sigma_B + \sigma_{RC}$





$$\sigma_{\rm RC}(\text{shape}) \times \phi_h \ \Rightarrow \ \delta(\sigma_{\rm RC}(\text{shape})) \times \delta(\phi_h) \approx 4\% \times 0.5 = 2\%.$$

The 4% amplitude uncertainty between the two approaches translates into a ϕ_h-angle dependent uncertainty at the 2% level.

Physics Implications (Boer-Mulders Effect):

- Effect size ≥ 10% ⟶ Measurable with good precision
- Effect size < 5% ⟶ Challenging to extract cleanly; Interpretation limited by theoretical RC uncertainties; Help guide future theoretical/phenomenological studies in the right direction

Systematic Uncertainty Budget for Unpolarized Cross Section

Charged pions

Sources	Uncertainty
Coincidence acceptance correction	8.2%
Experimental resolution	3.5%
Pion detection efficiency	4%
Electron detection efficiency	$< 2\%$
Radiative corrections	2.1%
Vector meson production	1%
Luminosity determination	$\lesssim 3\%$
Total	$\lesssim 11\%$

Charged kaons

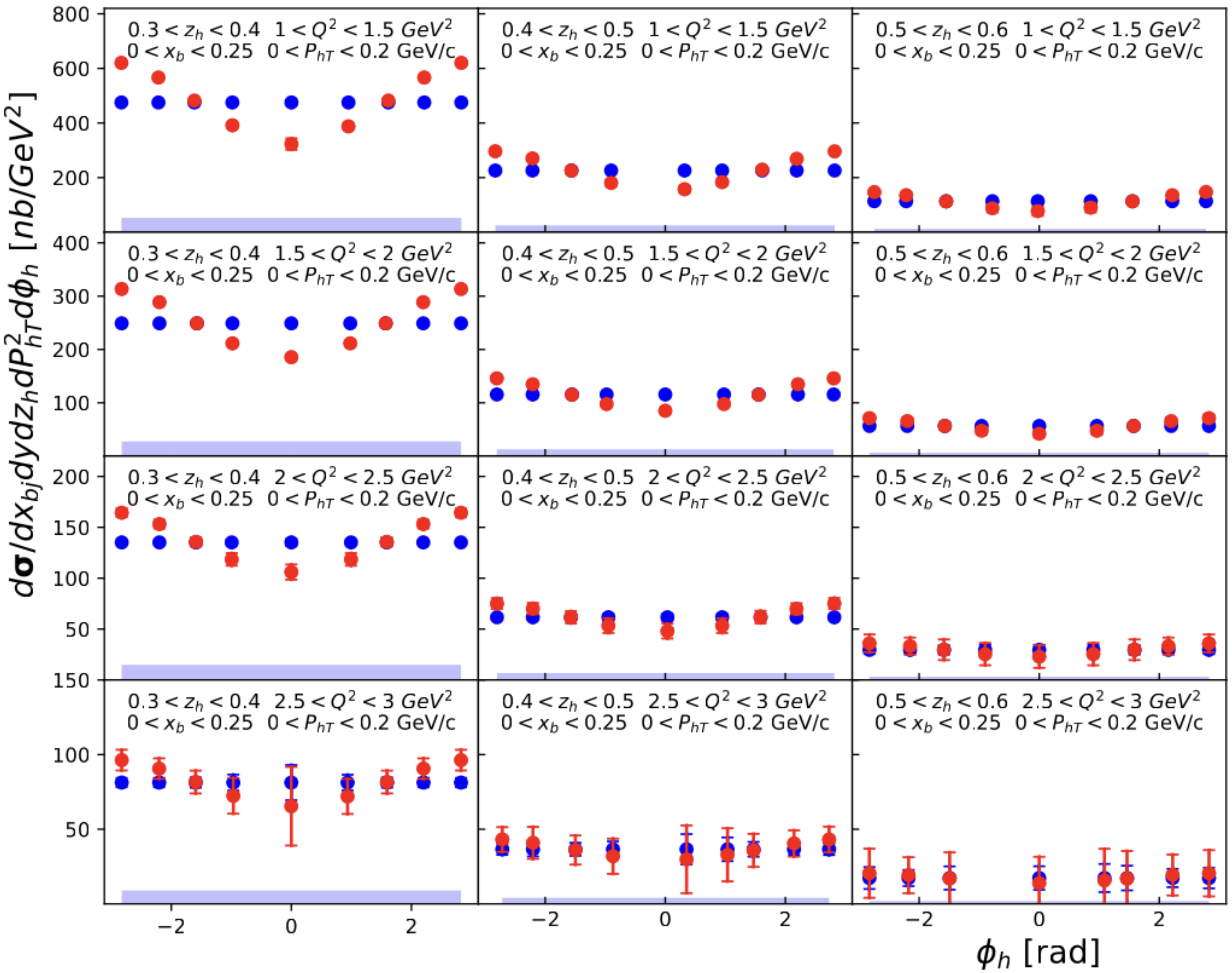
Sources	Uncertainty
Coincidence acceptance correction	$\sim 13\%$
Experimental resolution	3.5%
Kaon detection efficiency	11%
Electron detection efficiency	$< 2\%$
Radiative corrections	2.1%
Vector meson production	1%
Luminosity determination	$\lesssim 3\%$
Total	$\lesssim 18\%$

Total uncertainty calculated by rounding off the quadrature sum of separate contributions

Physics Projections @ Low-Q^2

- Produced π^+ unpolarized cross section at **11 GeV** beam energy

SoLID low-Q^2 region

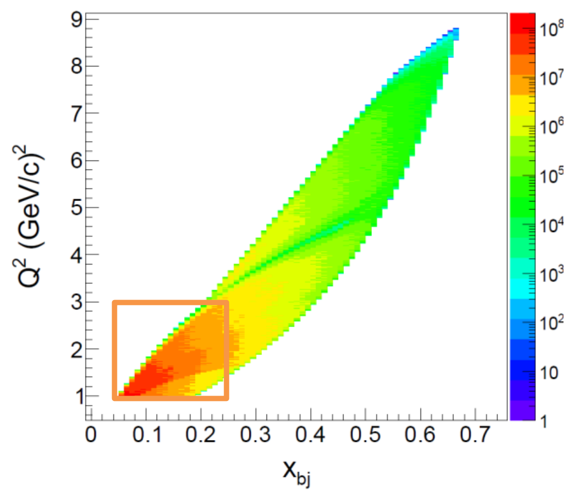


SoLID pseudo-data

Central points from simple TMD model

Blue points: Flat distribution

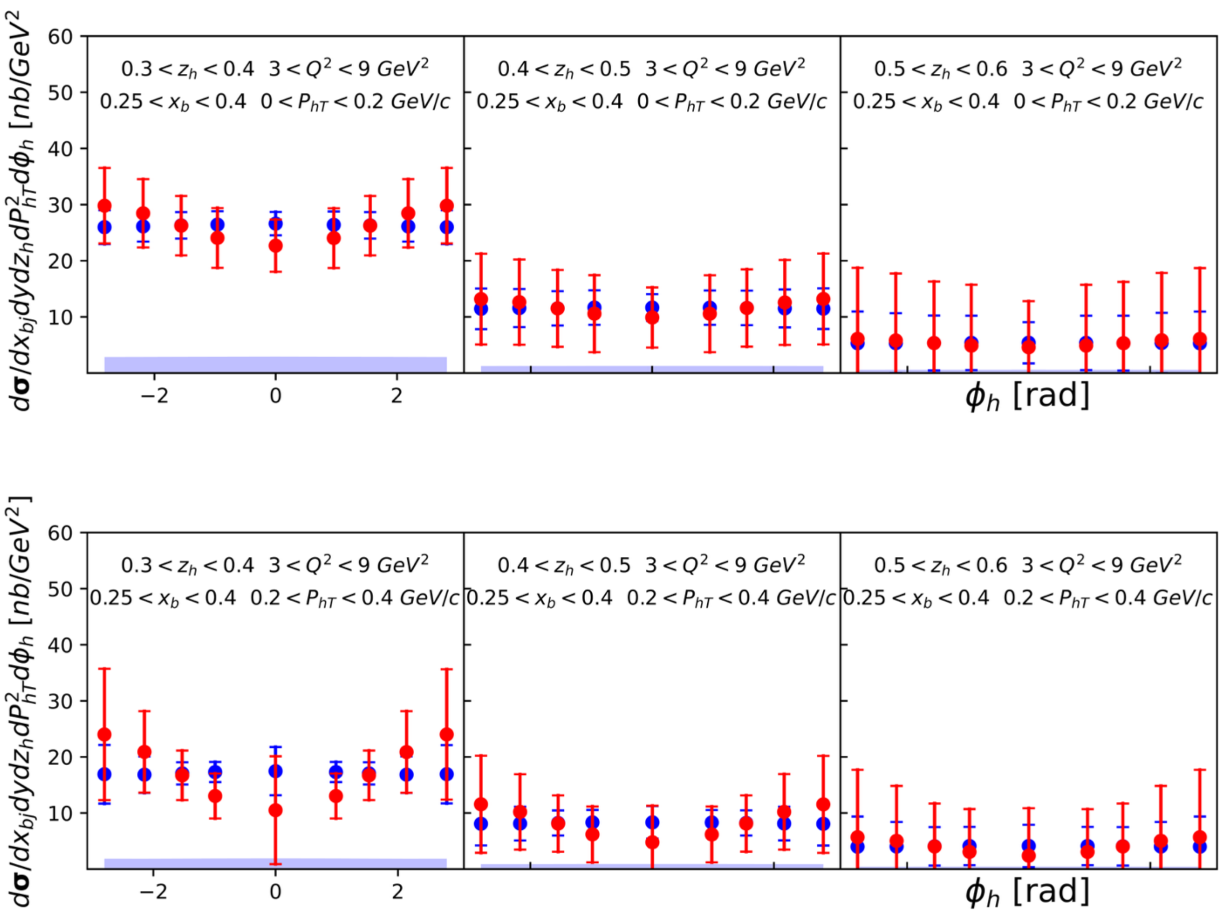
Red points: Cross section including azimuthal modulations



Physics Projections @ High-Q^2

- Produced **π^+** unpolarized cross section at **11 GeV** beam energy

SoLID high-Q^2 region

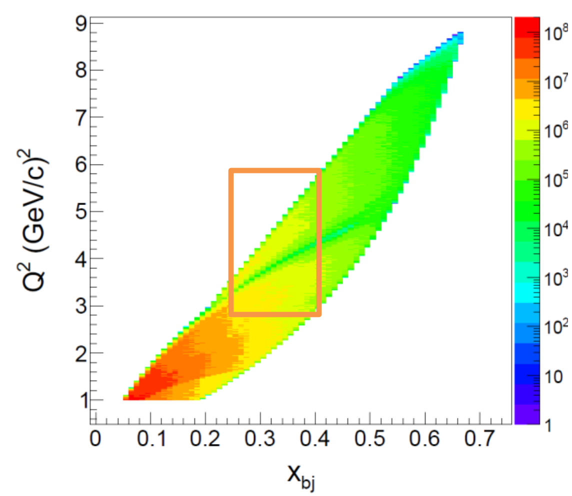


SoLID pseudo-data

Central points from simple TMD model

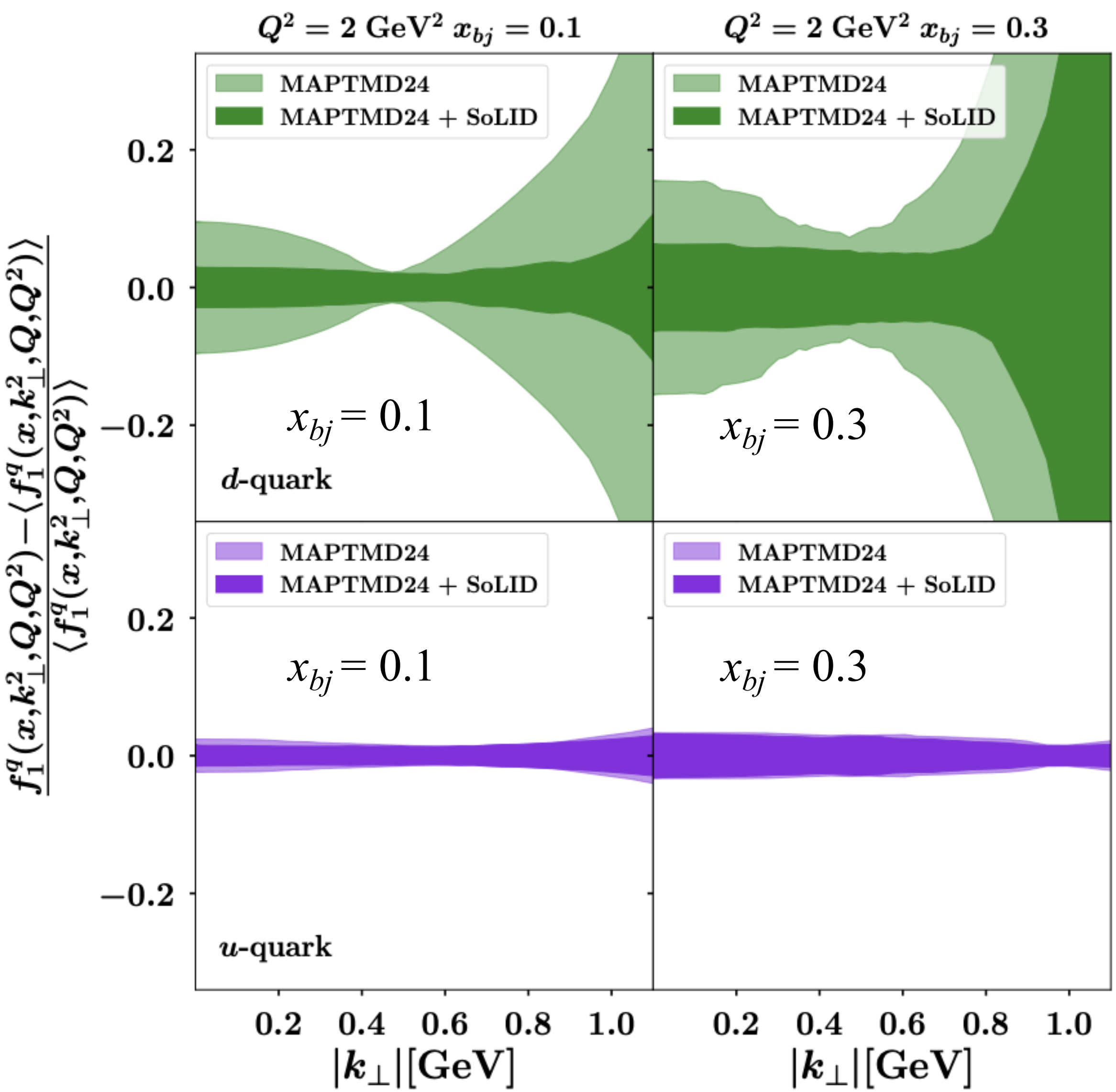
Blue points: Flat distribution

Red points: Cross section including azimuthal modulations



Impact Study of SoLID Pseudo Data

❖ Addressing Reviewer **Comment #6** (SoLID Committee)



- Final-state hadrons

$$\pi^+ \ \pi^-$$
$$K^+ \ K^-$$

- Plotted quantity

$$\frac{f_1^q(x,k_\perp^2,Q,Q^2)-\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}{\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}$$

- Uncertainty bans account for 68% CL

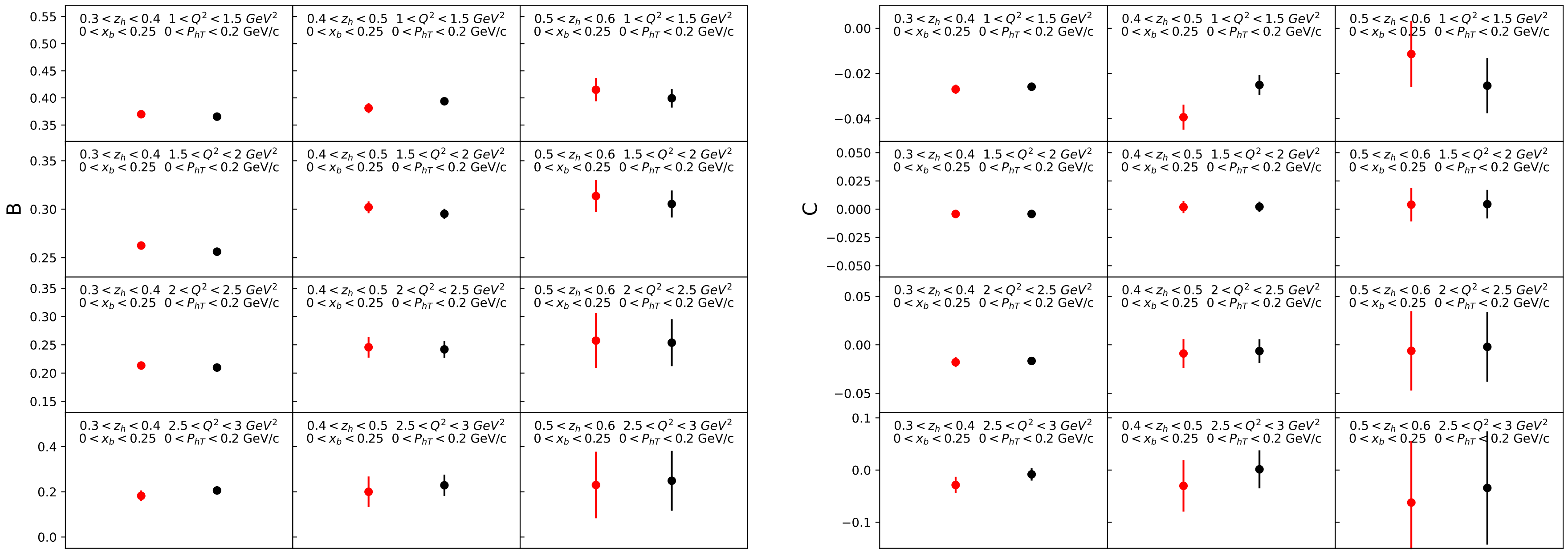
- SoLID greatly reduces the uncertainty on $k_\perp$-dependence for the d-quark.

More Physics Projections

- Azimuthal modulation effect

$$\frac{d\sigma}{dx_{bj}dydz_h dP_{hT}^2 d\phi_h} \equiv \mathcal{F}_{UU} = \mathcal{F}_{UU,\mathcal{A}}\cos 0 + \mathcal{F}_{UU,\mathcal{B}}\cos(\phi_h) + \mathcal{F}_{UU,\mathcal{C}}\cos(2\phi_h)$$

Fitting ϕ_h distribution with a simple function: $A(1 - B \cdot \cos(\phi_h) - C \cdot \cos(2\phi_h))$



Red points for π^+, black points for π^-

Transverse Momentum Widths from Azimuthal Modulations

❖ Addressing Reviewer **Comment #9** (PAC Reader)

➢ Transverse momentum widths

$$F_{UU} = \sum_q e_q^2 x_{bj} f_q(x_{bj}) D_q(z_h) \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle}$$

where $\langle P_{hT}^2\rangle = \langle P_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$

$$F_{UU}^{\cos(\phi_h)} = F_{UU}^{\cos(\phi_h)}\big|_{\mathrm{Cahn}} + F_{UU}^{\cos(\phi_h)}\big|_{\mathrm{BM}}$$

$$F_{UU}^{\cos(2\phi_h)} \approx F_{UU}^{\cos(2\phi_h)}\big|_{\mathrm{Cahn}} + F_{UU}^{\cos(2\phi_h)}\big|_{\mathrm{BM}}$$

In model, we have (in GeV²)

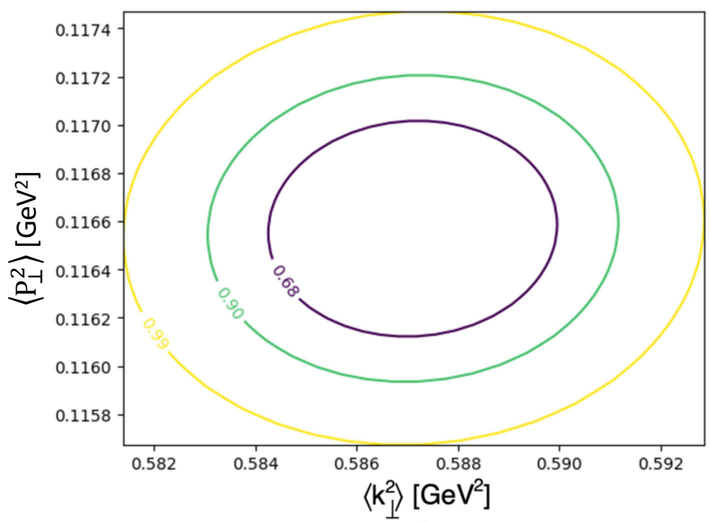
$\langle k_\perp^2\rangle = 0.604$, $\langle P_\perp^2\rangle = 0.114$

$$\mathrm{Least\_Square} = \sum(pseudodata - Model)^2/(\sigma_{stat}^2 + \sigma_{sys}^2)$$

The fitting results shows (in GeV²):

$\langle k_\perp^2\rangle = 0.5871 \pm 0.0002$

$\langle P_\perp^2\rangle = 0.1165 \pm 0.0003$



Three contours corresponding to confidence levels of 68%, 90% and 99%

Both Cahn and Boer-Mulders contributions included

The fitting results differs from the model by 4%

By measuring the unpolarized cross section with and without azimuthal modulations, we will be able to extract the Gaussian width parameters $\langle k_\perp^2\rangle$ and $\langle P_\perp^2\rangle$

More Physics Projections

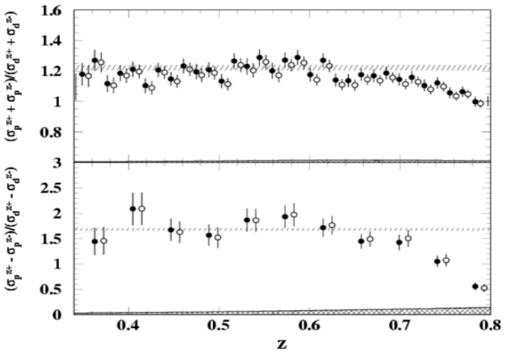
❖ Addressing Reviewer **Comment #10** (PAC Reader)

➢ Test of factorization

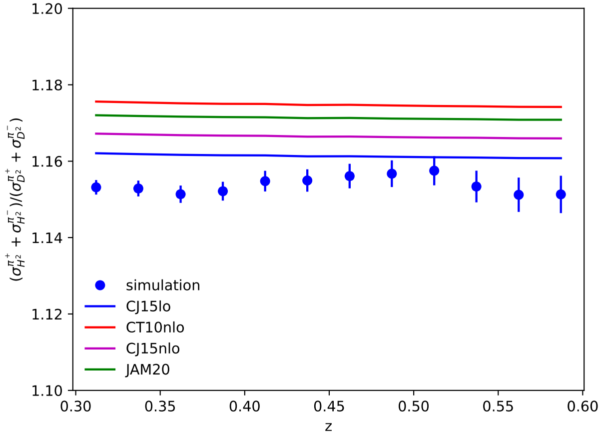
Assume no P_{hT} dependence and ignore heavy quark contributions

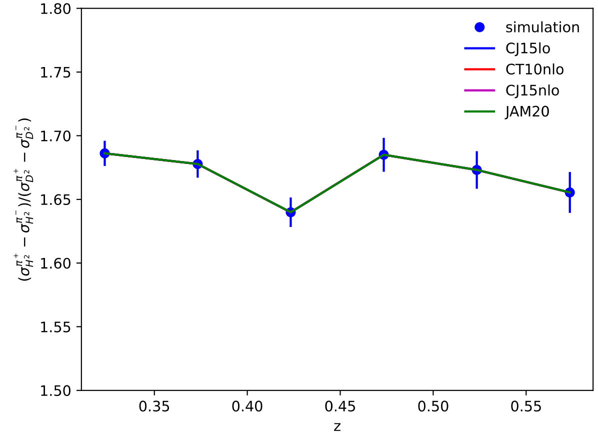
$$\frac{Y_p^{\pi^+} + Y_p^{\pi^-}}{Y_d^{\pi^+} + Y_d^{\pi^-}} = \frac{4u + 4\bar{u} + d + \bar{d}}{5(u + \bar{u} + d + \bar{d})}$$

$$\frac{Y_p^{\pi^+} - Y_p^{\pi^-}}{Y_d^{\pi^+} - Y_d^{\pi^-}} = \frac{4u_v - d_v}{3(u_v + d_v)}$$



T. Navasardyan and et al. Phys. Rev. Lett.98, 022001 (2007)

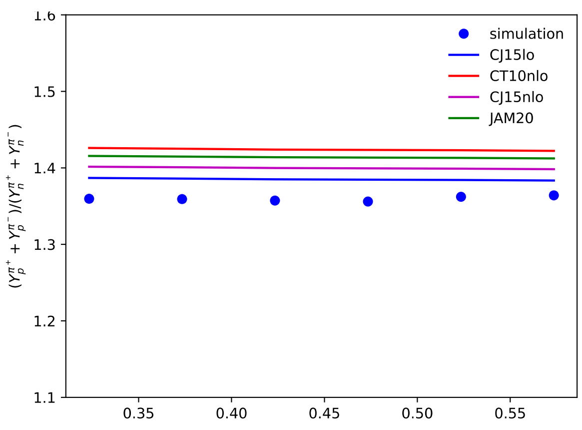


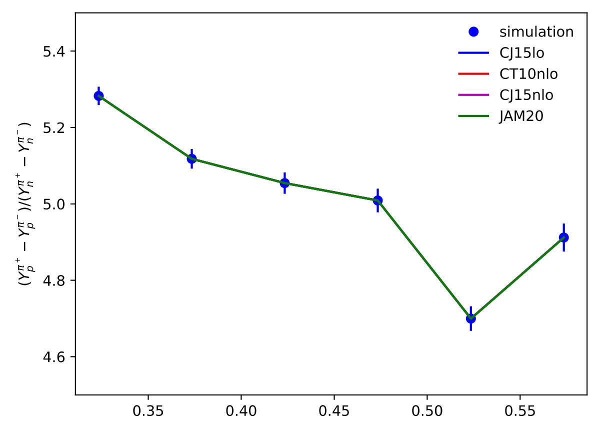


$$\frac{Y_p^{\pi^+} + Y_p^{\pi^-}}{Y_n^{\pi^+} + Y_n^{\pi^-}} = \frac{4u + 4\bar{u} + d + \bar{d}}{u + \bar{u} + 4d + 4\bar{d}}$$

$$\frac{Y_p^{\pi^+} - Y_p^{\pi^-}}{Y_n^{\pi^+} - Y_n^{\pi^-}} = \frac{4u_v - d_v}{4d_v - uv}$$

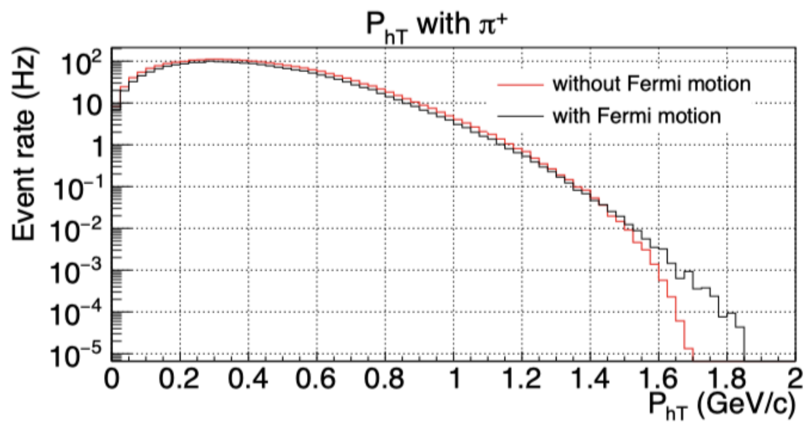
Write two types of simple ratios

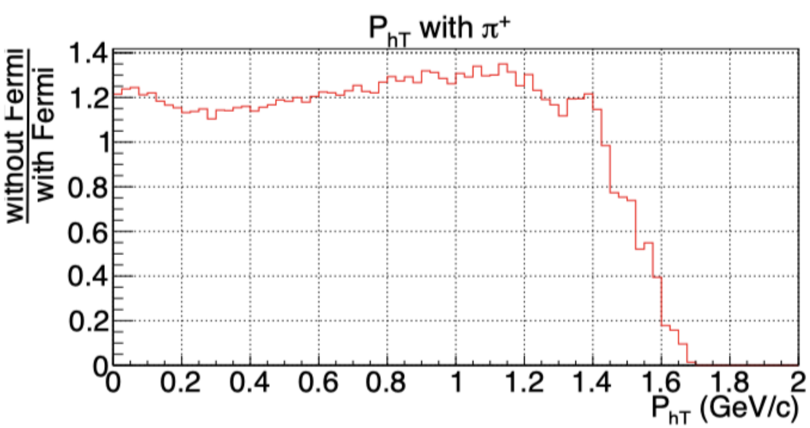


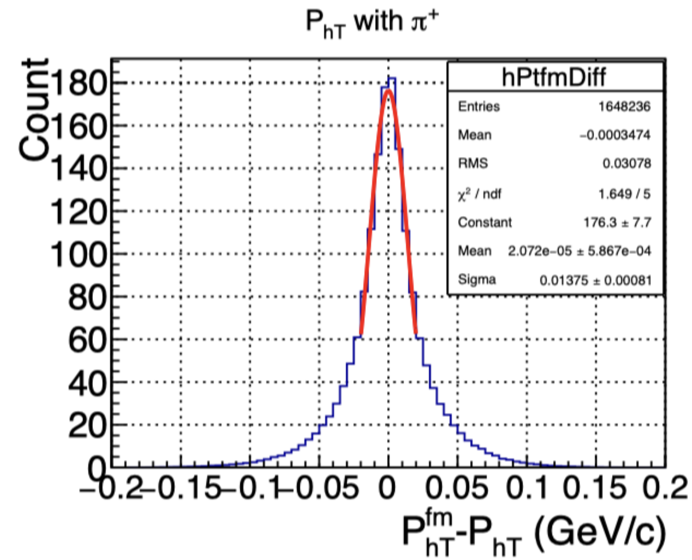


Nuclear Corrections

❖ Addressing Reviewer **Comment #4** (SoLID Committee) **and Comment #10** (PAC Reader)







$$P_{hT} = zk_{\perp} + P_{\perp}$$

Induced uncertainties:

$\langle k_{\perp}^2 \rangle$: $\pm 0.0006\,(GeV/c)^2$

$\langle P_{\perp}^2 \rangle$: $\pm 0.0001(GeV/c)^2$

changes ~**20%** in the kinematic range of interest

❖ Stimulate further theoretical studies on nuclear effects.

✓ Scopetta: Effects can be corrected using **nucleon effective polarizations** from precise few-body calculations.

Phys. Rev. D 104, 054005, (2007)

✓ Liu et al.:Found **few-percent-level effects** on structure functions, even **smaller** for azimuthal asymmetries.

❖ Aid in investigating the EMC effect with ^{3}He SIDIS data.

Summary and Outlook

- With high luminosity and large acceptance, SoLID could provide **high-precision** SIDIS unpolarized cross-section data with **full azimuthal angular coverage**

- The updated run-group proposal includes (Since Jan. 2025)
  - Sharpened motivation for absolute SIDIS cross-section measurements
  - Detailed coincident systematic uncertainty studies and calibration plan
  - Quantified uncertainty on azimuthal modulation from radiative corrections
  - Nuclear corrections addressed: Fermi motion effects on kinematic variables and P_{hT}, $\langle k_\perp^2 \rangle$, and $\langle P_\perp^2 \rangle$
  - Quantitative comparison with Hall B deuteron data added to highlight SoLID's impact
  - "Money plot" added: physics impact on unpolarized TMDs using state-of-the-art MAP framework

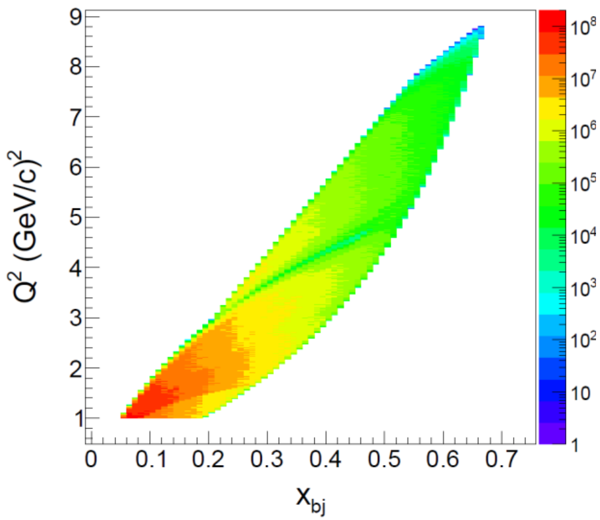
Thank You !

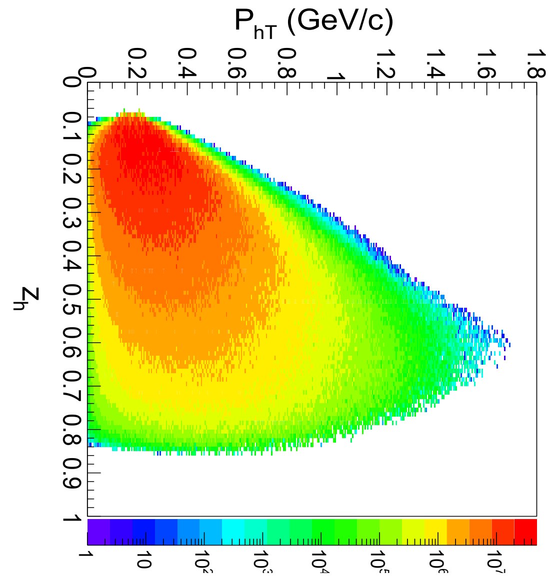
Acknowledgements: the entire SoLID collaboration
Supported in part by U.S. Department of Energy under contract numbers:
DE-FG02-03ER41231 and DE-FG02-84ER40146

Backup

Systematic Uncertainties

- Kinematic coverage examples of produced π^+ particles
  - *11 GeV and 8.8 GeV combined*
- *Phase-space correlation between* Q^2 and x_{bj} (*top-left*)
- *Phase-space correlation between* x_{bj} and z_h (*top-right*)

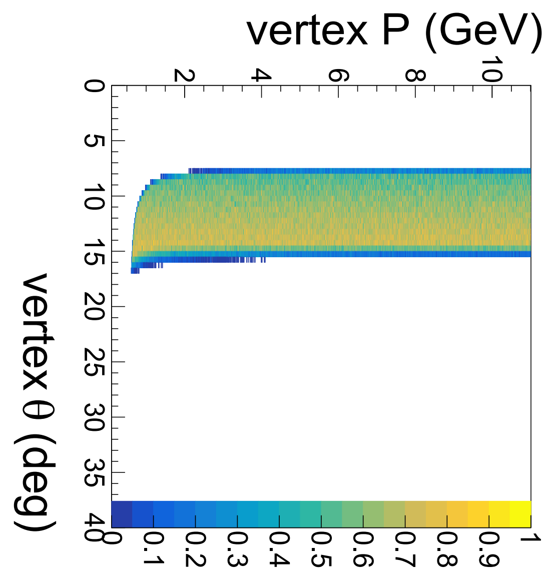


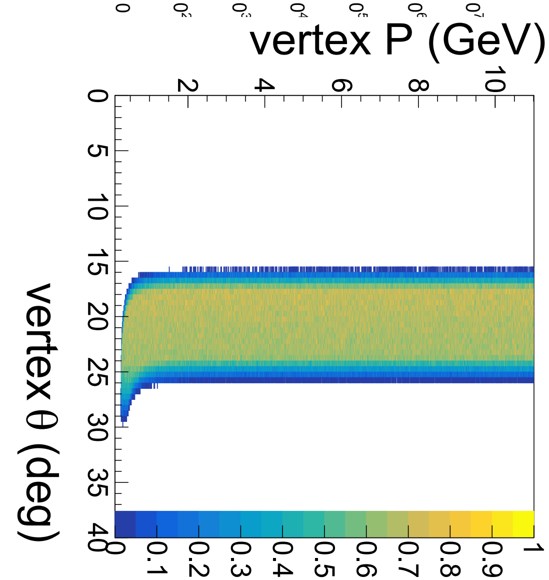


- **Electron acceptance**

as a function of polar angle and momentum forward angle (bottom left)

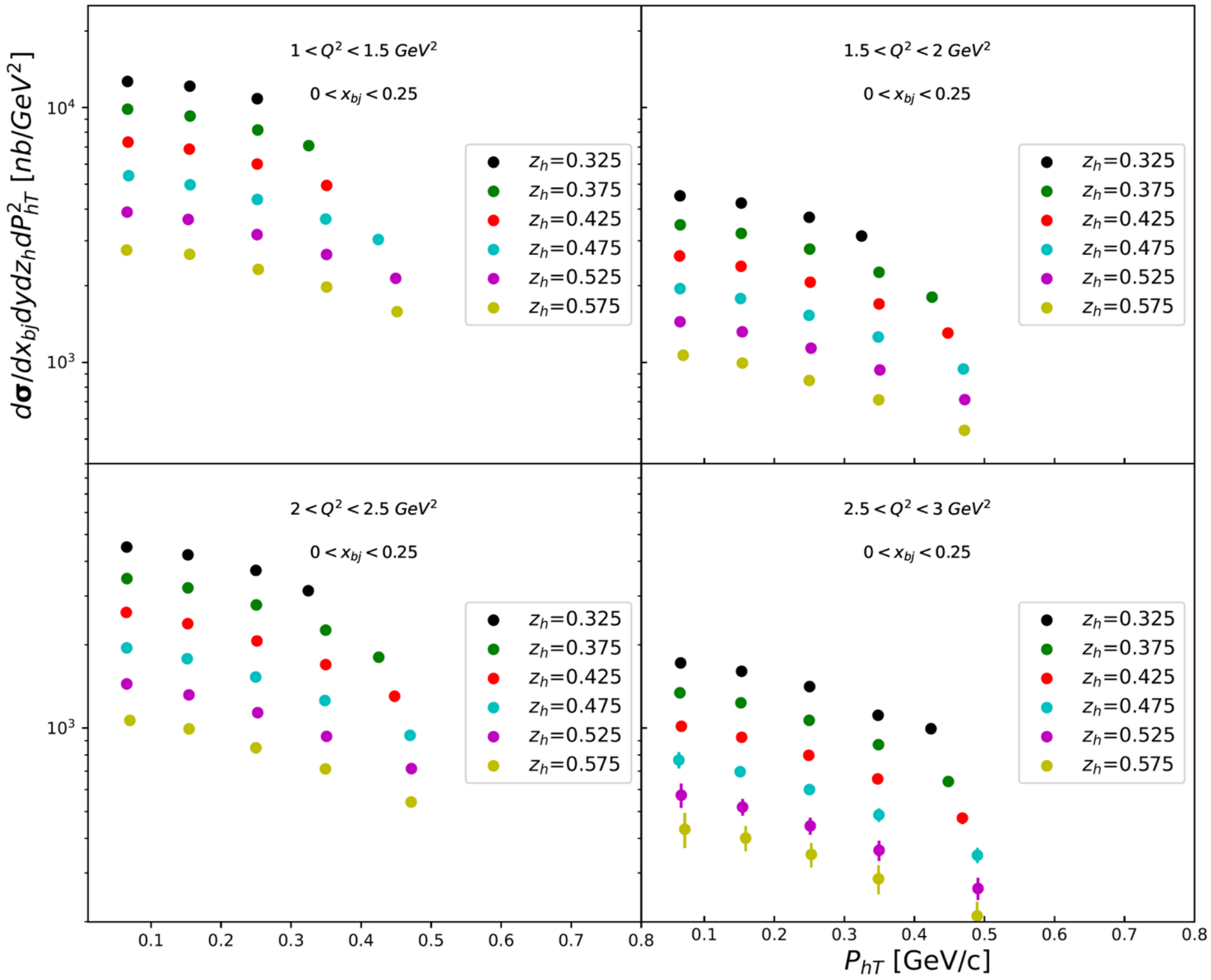
as a function of polar angle and momentum large angle (bottom right)



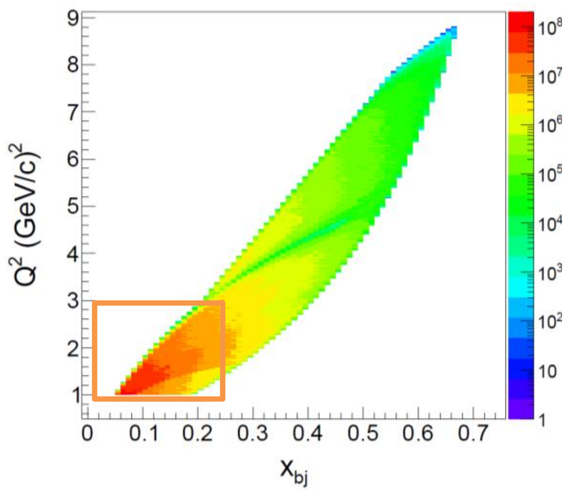


More Physics Projections

➢ Produced <u>**π⁺**</u> unpolarized cross section at **11 GeV** beam energy



SoLID low-Q^2 region

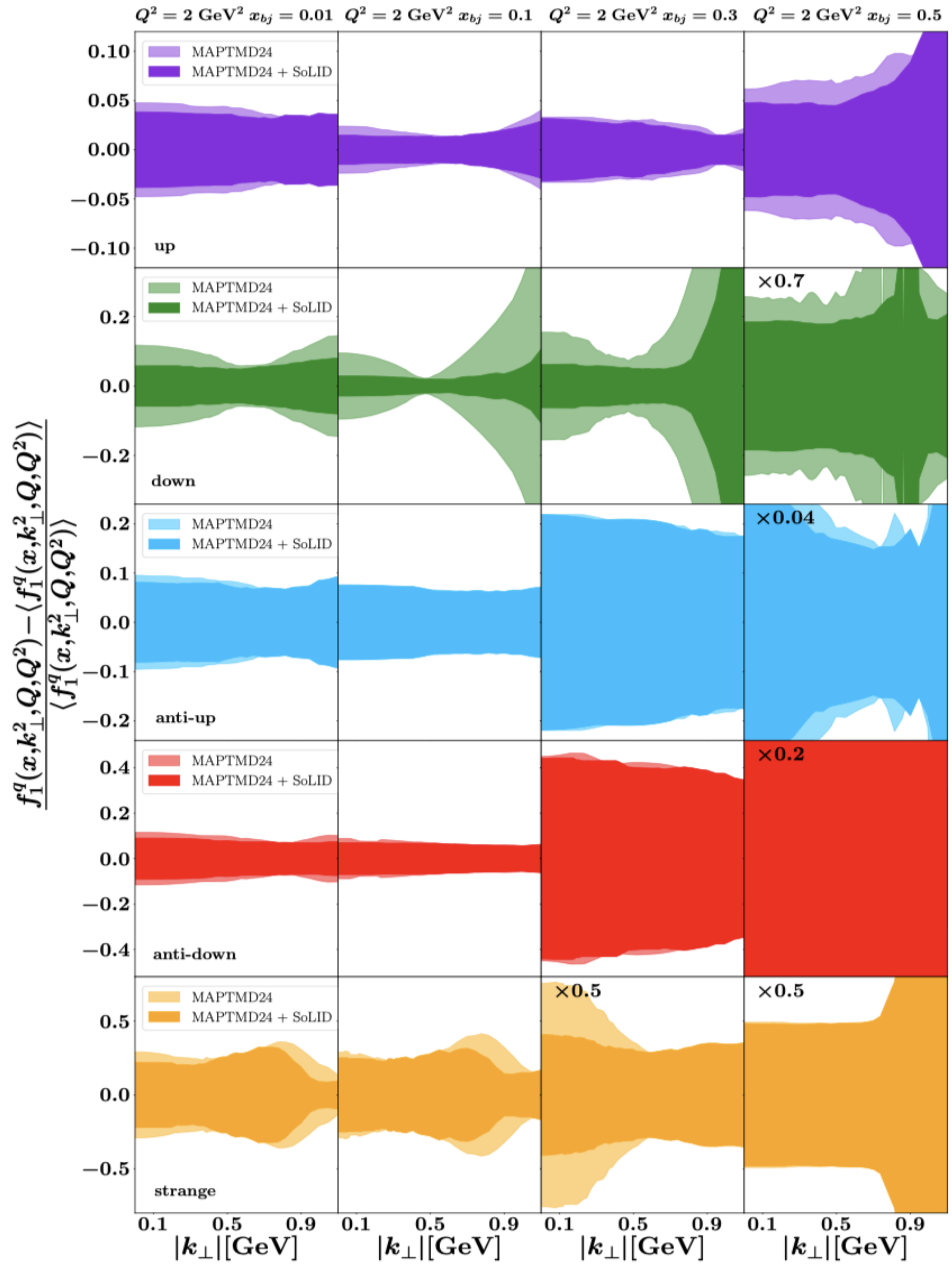


<u>SoLID pseudo-data</u>

Integrated cross section shown with
MAP central points

Errors are SoLID uncertainties

Impact Study of SoLID Pseudo Data



- Final-state hadrons

$$\pi^+ \ \pi^-$$
$$K^+ \ K^-$$

- Plotted quantity

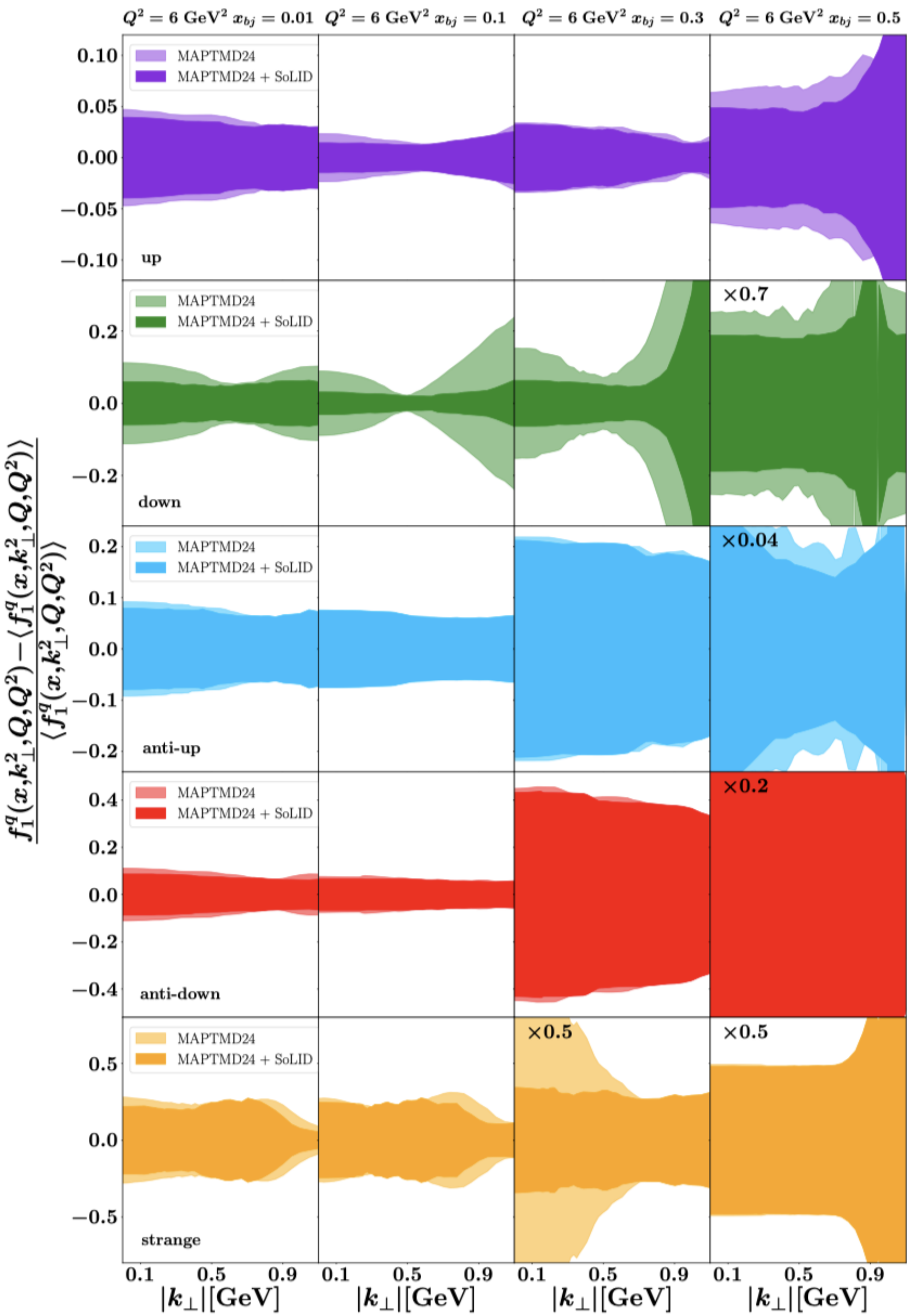
$$\frac{f_1^q(x,k_\perp^2,Q,Q^2)-\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}{\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}$$

- Uncertainty bans account for 68% CL

- SoLID greatly reduces the uncertainty on $k_\perp$-dependence for the d-quark.

Q^2 =2 GeV^2

Impact Study of SoLID Pseudo Data



- Final-state hadrons

  $\pi^+ \ \pi^-$

  $K^+ \ K^-$

- Plotted quantity

  $$\frac{f_1^q(x,k_\perp^2,Q,Q^2)-\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}{\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}$$

- Uncertainty bans account for 68% CL

- SoLID greatly reduces the uncertainty on $k_\perp$-dependence for the d-quark.

Q^2 =6 GeV^2

Naïve x-z factorization & Gaussian ansatz

➢ Analytical forms of the Cahn and Boer-Mulders azimuthal modulation given by

$$F_{UU} = \sum_q e_q^2 x_{bj} f_q(x_{bj}) D_q(z_h) \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle},$$

$$F_{UU}^{\cos(\phi_h)}\Big|_{\rm Cahn} = -2\frac{P_{hT}}{Q}\sum_q e_q^2 x_{bj} f_q(x_{bj}) D_q(z_h) \frac{z_h\langle k_\perp^2\rangle}{\langle P_{hT}^2\rangle}\frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle},$$

$$F_{UU}^{\cos(\phi_h)}\Big|_{\rm BM} = 2e\frac{P_{hT}}{Q}\sum_q e_q^2 x_{bj} \frac{\Delta f_{q^\uparrow/p}(x_{bj})}{M_{\rm BM}}\frac{\Delta D_{h/q^\uparrow}(z_h)}{M_{\rm C}}\frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle_{\rm BM}}}{\pi\langle P_{hT}^2\rangle_{\rm BM}^4}$$
$$\times\frac{\langle k_\perp^2\rangle_{\rm BM}^2\langle p_\perp^2\rangle_{\rm C}^2}{\langle k_\perp^2\rangle\langle p_\perp^2\rangle}\left[z_h^2\langle k_\perp^2\rangle_{\rm BM}\left(P_{hT}^2-\langle P_{hT}^2\rangle_{\rm BM}\right)+\langle p_\perp^2\rangle_{\rm C}\langle P_{hT}^2\rangle_{\rm BM}\right],$$

$$F_{UU}^{\cos(2\phi_h)}\Big|_{\rm Cahn} = 2\frac{P_{hT}^2}{Q^2}\sum_q e_q^2 x_{bj} f_q(x_{bj}) D_q(z_h) \frac{z_h^2\langle k_\perp^2\rangle^2}{\langle P_{hT}^2\rangle^2}\frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle},$$

$$F_{UU}^{\cos(2\phi_h)}\Big|_{\rm BM} = -eP_{hT}^2\sum_q e_q^2 x_{bj} \frac{\Delta f_{q^\uparrow/p}(x_{bj})}{M_{\rm BM}}\frac{\Delta D_{h/q^\uparrow}(z_h)}{M_{\rm C}}\frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle_{\rm BM}}}{\pi\langle P_{hT}^2\rangle_{\rm BM}^3}$$
$$\times\frac{z_h\langle k_\perp^2\rangle_{\rm BM}^2\langle p_\perp^2\rangle_{\rm C}^2}{\langle k_\perp^2\rangle\langle p_\perp^2\rangle},$$

where

$$\langle P_{hT}^2\rangle_{\rm BM} = \langle p_\perp^2\rangle_{\rm C} + z_h^2\langle k_\perp^2\rangle_{\rm BM}$$

$$\langle p_\perp^2\rangle_{\rm C} = \frac{\langle p_\perp^2\rangle M_{\rm C}^2}{\langle p_\perp^2\rangle + M_{\rm C}^2}$$

$$\langle k_\perp^2\rangle_{\rm BM} = \frac{\langle k_\perp^2\rangle M_{\rm BM}^2}{\langle k_\perp^2\rangle + M_{\rm BM}^2}$$

$M_{\rm C}^2$ and $M_{\rm BM}^2$ and all the other functional forms to be found in

JHEP 06, 007 (2019)

and

https://github.com/TianboLiu/LiuSIDIS

SIDIS Unpolarized Cross Section

In LO factorization scheme

$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h} = 2\pi\,\frac{\alpha^2}{x_{bj}\,y\,Q^2}\left(1+\frac{\gamma^2}{2x_{bj}}\right)\times$$
$$\times\left[c_1\,\boxed{F_{UU}} + c_2\cos(\phi_h)\,F_{UU}^{\cos(\phi_h)} + c_3\cos(2\phi_h)\,F_{UU}^{\cos(2\phi_h)}\right],$$

- Use the following Gaussian parameterizations for the TMD PDF and TMD FF

Twist 2 effect

$$F_{UU} = \sum_q e_q^2\,x_{bj}\,f_q(x_{bj})\,D_q(z_h)\,\frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle}$$

Gaussian widths
where $\langle P_{hT}^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$

SIDIS Unpolarized Cross Section

In LO factorization scheme

$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h} = 2\pi\frac{\alpha^2}{x_{bj}yQ^2}\left(1+\frac{\gamma^2}{2x_{bj}}\right)\times \times\left[c_1\,F_{UU} + c_2\cos(\phi_h)\,F_{UU}^{\cos(\phi_h)} + c_3\cos(2\phi_h)\boxed{F_{UU}^{\cos(2\phi_h)}}\right],$$

Twist-4 Cahn & twist-2 Boer-Mulders: $\cos(2\phi_{\mathrm{h}})$ dependence

$$F_{UU}^{\cos(2\phi_h)} \approx F_{UU}^{\cos(2\phi_h)}\big|_{\mathrm{Cahn}} + F_{UU}^{\cos(2\phi_h)}\big|_{\mathrm{BM}}$$

- Boer-Mulders effect $\propto h^{\perp}{}_1 \otimes H^{\perp}{}_1$
- Twist-4 Cahn effect could have similar size of contribution to $\cos(2\phi_{\mathrm{h}})$ as Boer- Mulders [Phys. Rev. D. 81:114026 (2010) based on HERMES/COMPASS results]

Coincidence Acceptance Uncertainty: Need to address the uncertainty from the coincidence acceptance study.

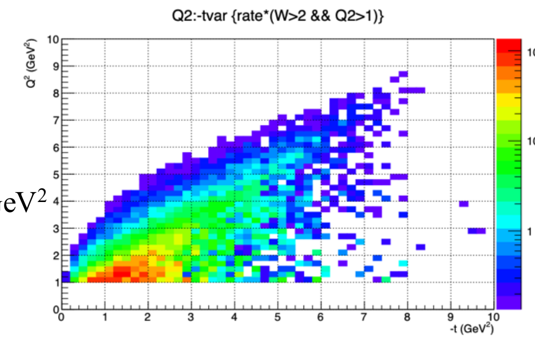
10days of 11 GeV unpolarized hydrogen and deuterium runs (SIDIS transversely polarized ^{3}He experiment **E12-10-006**)

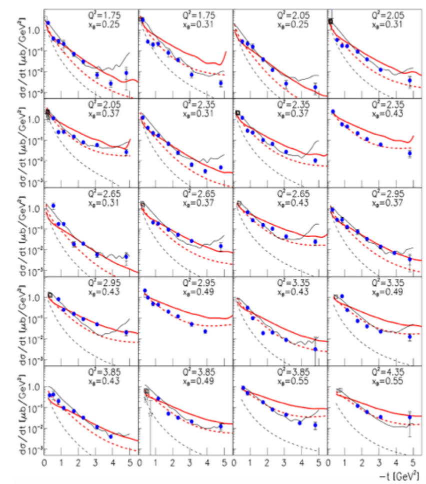
above the resonance region $d\sigma/dt\ (x_{bj}, Q^2)$

$e+p \rightarrow e'+\pi^+ + n$

Proton target data

- Hall C
  - Q^2= 0.6-2.45 GeV^2, W=1.9 and 2.0 GeV, 0.026 GeV$^2 \leq$ -t $\leq$ 0.365 GeV^2
    H. P. Blok and et.al., Phys. Rev. C 78, 045202 (2008)
  - Q^2= 2.4 GeV^2, W=2.0 GeV, 0.272 GeV^2< -t < 2.127 GeV^2
    S. Basnet and et. al , Phys. Rev. C 100 (2019) 6, 065204
- Hall B
  - $0.16 < x_{bj} < 0.58$, 1.6 GeV^2 < Q^2 < 4.5 GeV^2 and 0.1 GeV^2 < $-t$ < 5.3 GeV^2
    K. Park and et al., Phys. J. A 49, 16 (2013)
- HERMES
  - $0.02 < x_{bj} < 0.55$, 1 GeV^2 < Q^2 < 11 GeV^2 and $-t$ < 2 GeV^2
    A. Airapetian and et al., Phys. Lett. B. 659, 486 (2008).





$\lvert t\rvert$ (GeV^2)	$\overline{Q^2}$ (GeV^2)	$\overline{W}$ (GeV)	P_π (GeV/c)	θ_π (deg)	$\frac{d^2\sigma}{dt\,d\phi_\pi}\rvert_{\phi_\pi=\pi}$ (μb/GeV^2)
0.272	2.402	2.039	2.845	15.68	0.367 ± 0.030, 0.013
0.378	2.427	2.029	2.788	20.32	0.288 ± 0.051, 0.010
0.688	2.449	2.018	2.622	25.15	0.164 ± 0.034, 0.006
1.145	2.427	2.029	2.378	30.07	0.096 ± 0.006, 0.003
1.608	2.433	2.020	2.131	34.50	0.054 ± 0.002, 0.002
2.127	2.423	2.026	1.853	39.50	0.032 ± 0.002, 0.001

$e+n \rightarrow e'+\pi^- + p$

Deuterium target data

- Hall C
  - Q^2= 0.6-1.6 GeV^2, W=1.95, Q^2= 2.45 GeV^2, W=2.2
    G. M. Huber and et al., Phys. Rev. C 91, 015202 (2015)

Note that Hall B data has an uncertainty of 9-14%, while Hall C data shows an uncertainty of 6-20% (depends on kinematic bins).