Measurement of the Unpolarized SIDIS Cross Section from a ^{3}He Target with SoLID (E12-11-007B/E12-10-006F)

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Shuo Jia — Duke University
Vlad Khachatryan — Duke University & Indiana University
Ye Tian — Syracuse University
E12-10-006 collaboration, E12-11-007 collaboration, and the SoLID Collaboration

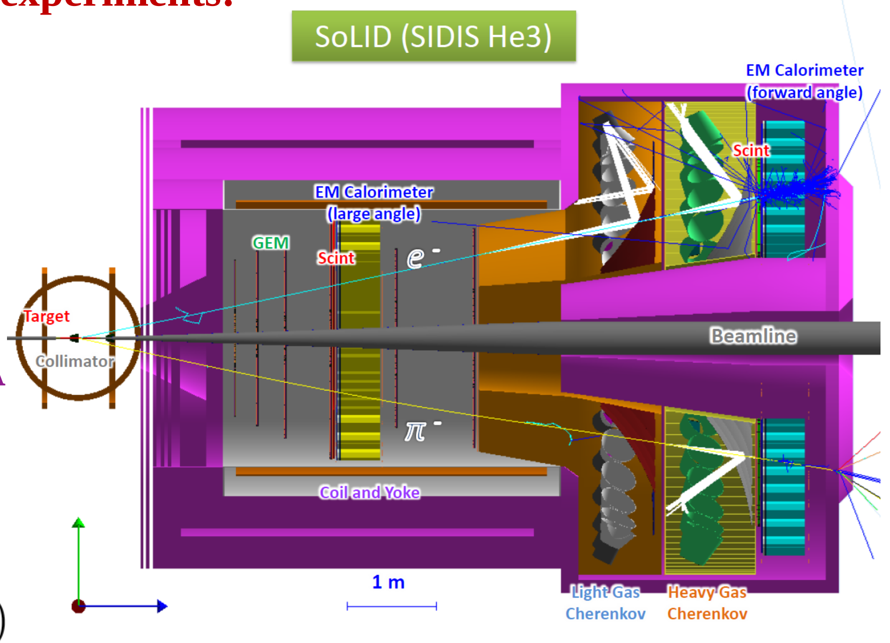
➢ **This run group experiment parasitic to SoLID SIDIS experiments:**

- **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*)

The SIDIS process represented as

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



Why Measure SIDIS Unpolarized Cross Section

Multiplicities from HERMES and COMPASS help constrain TMDs, but absolute cross-section measurements provide significantly more information. They offer 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

SoLID Review Committee Comments

The SoLID ad-hoc committee:

Jian-ping Chen, Mark Jones, Zein-Eddine Meziani, Chao Peng, Arun Tadepalli, Xiaochao Zheng (Chair)

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 $\boldsymbol{k_\perp}$ or $\boldsymbol{p_\perp}$ 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.

All the comments are addressed in the submitted proposal

The SoLID ad-hoc committee concludes that the proposal is in a reasonable state and recommends its approval.

PAC Review Report and Comments

PAC52 Feedback:

The proponents should work with theorists in this field to construct a more sophisticated framework on which their analysis could be based.

- This has been addressed by including the impact of SoLID pseudodata on the unpolarized TMDs extracted in the latest analysis by the MAP Collaboration.

PAC53 Theory Report summary:

Overall, **the proposal is well-motivated, methodologically sound, and has the potential to make a significant impact on the hadron physics community** by delivering results of broad relevance to the field.

PAC53 Reader's (Marco Radici's) comments and suggestions:

Comments 1–8 have been addressed, improving consistency in equations and formulations, and providing clarifications where needed.

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

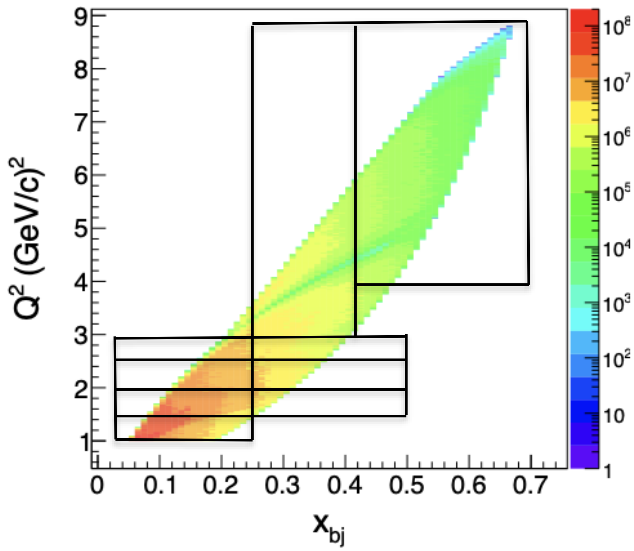
10. Figs. 43 & 44 (Eqs. 64 & 62): If factorization holds, the plotted quantities should be flat in z, but oscillations are observed. Are these due to deuteron structure effects, or do they indicate a breakdown of factorization?

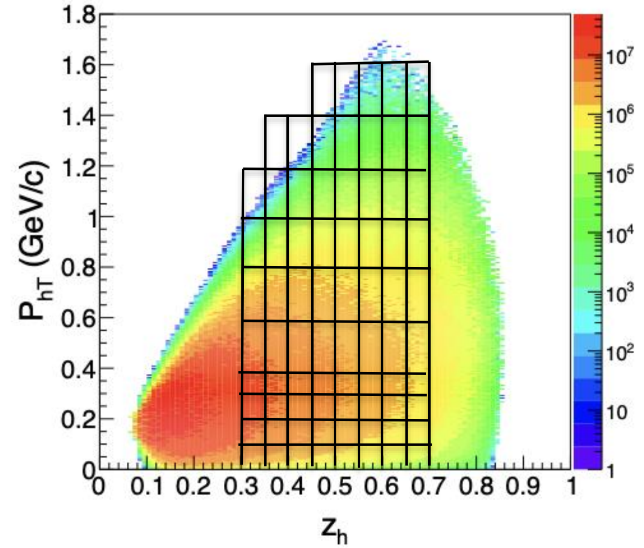
11. Fermi Motion & Systematics (Secs. 6.1–6.5, 7.1): Unclear whether Fermi motion effects are included in results of Secs. 6.1–6.3. Fig. 35/36 uncertainties may need revision. Also, possible inconsistency between Sec. 7.1 and item (iii) on p. 68 regarding whether systematic uncertainties are included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

The response to the comments has been sent to reviewer Marco Radici.

Kinematic Coverage

- 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 P_{hT} and z_h (top-right)*

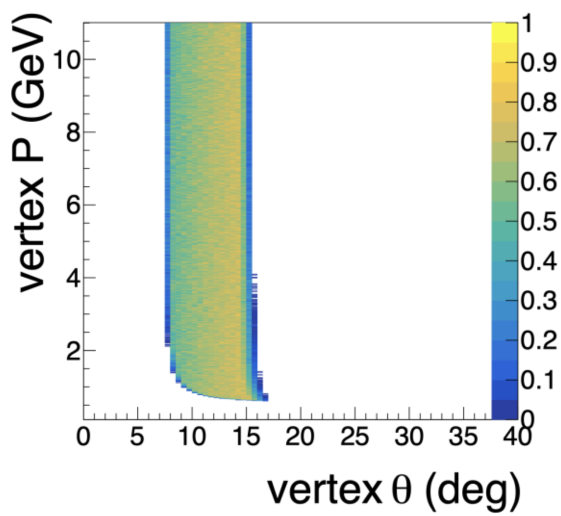


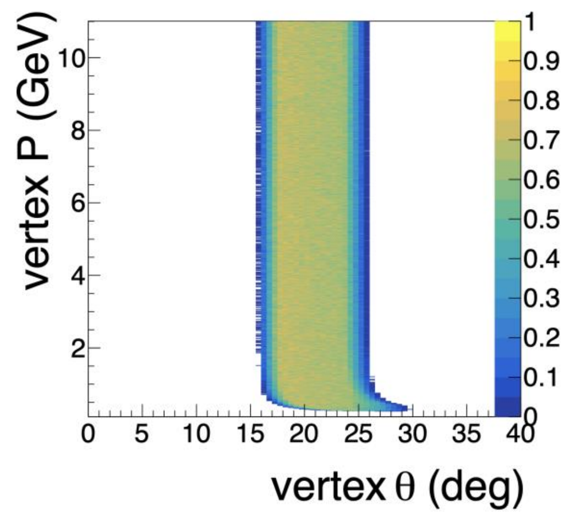


- **Electron acceptance**

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

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





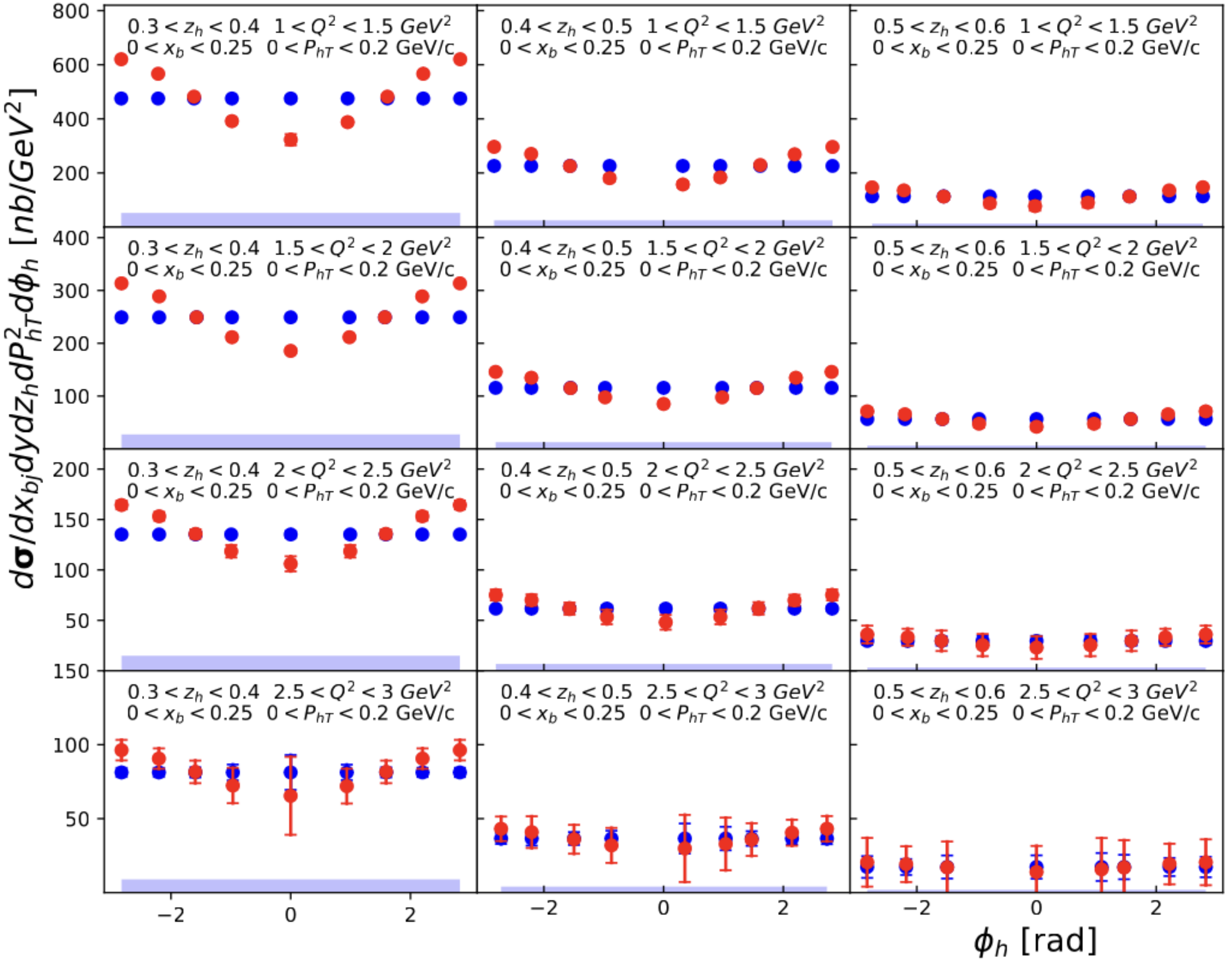
This SoLID proposal: SIDIS $\pi^{\pm}$ and $K^{\pm}$

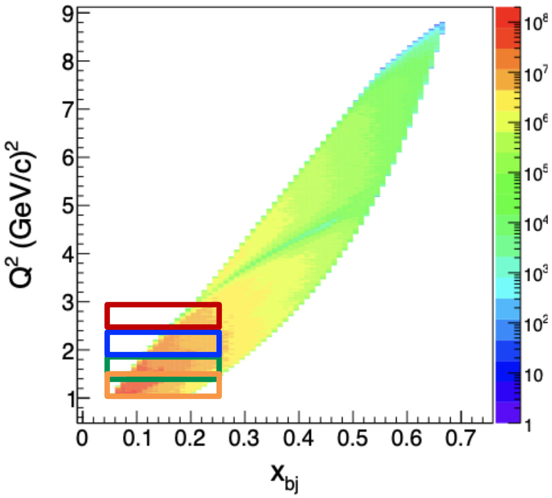
$$0 < x_{bj} < 0.7,\ 1 < Q^2 < 10\ \mathrm{GeV}^2,\ 0.3 < z_h < 0.7,\ 0 < P_{hT} < 1.6\ \mathrm{GeV},\ -\pi < \phi_h < \pi$$

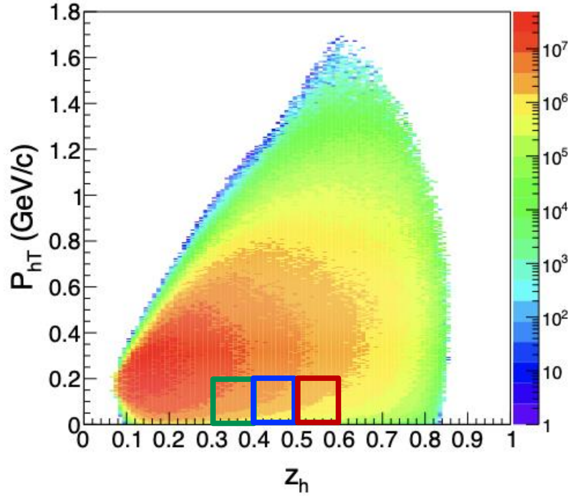
Physics Projections @ Low-Q^2

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

SoLID low-Q^2 region







Central points from simple TMD model

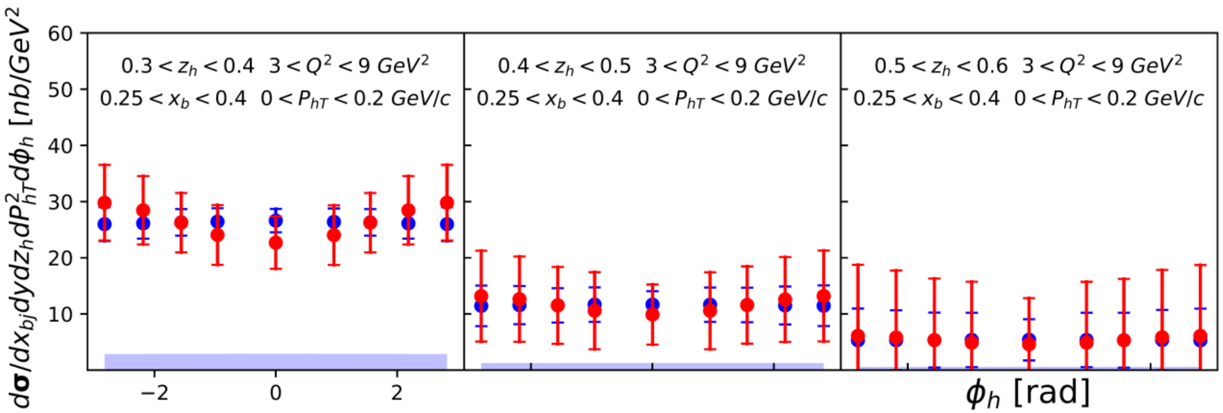
Blue points: Flat distribution

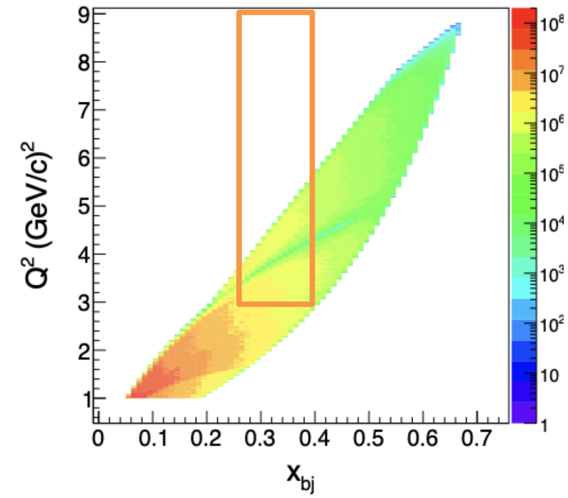
Red points: Cross section including azimuthal modulations

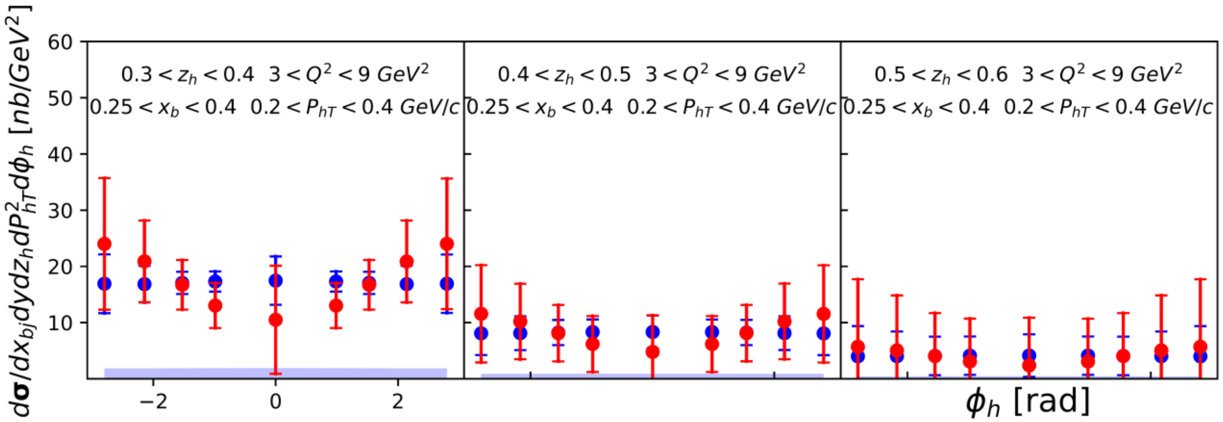
Physics Projections @ High-Q^2

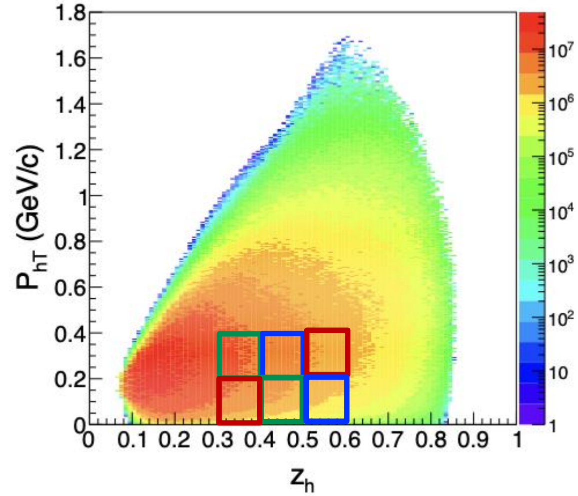
- Produced **π^+** unpolarized cross section at **11 GeV** beam energy

SoLID high-Q^2 region







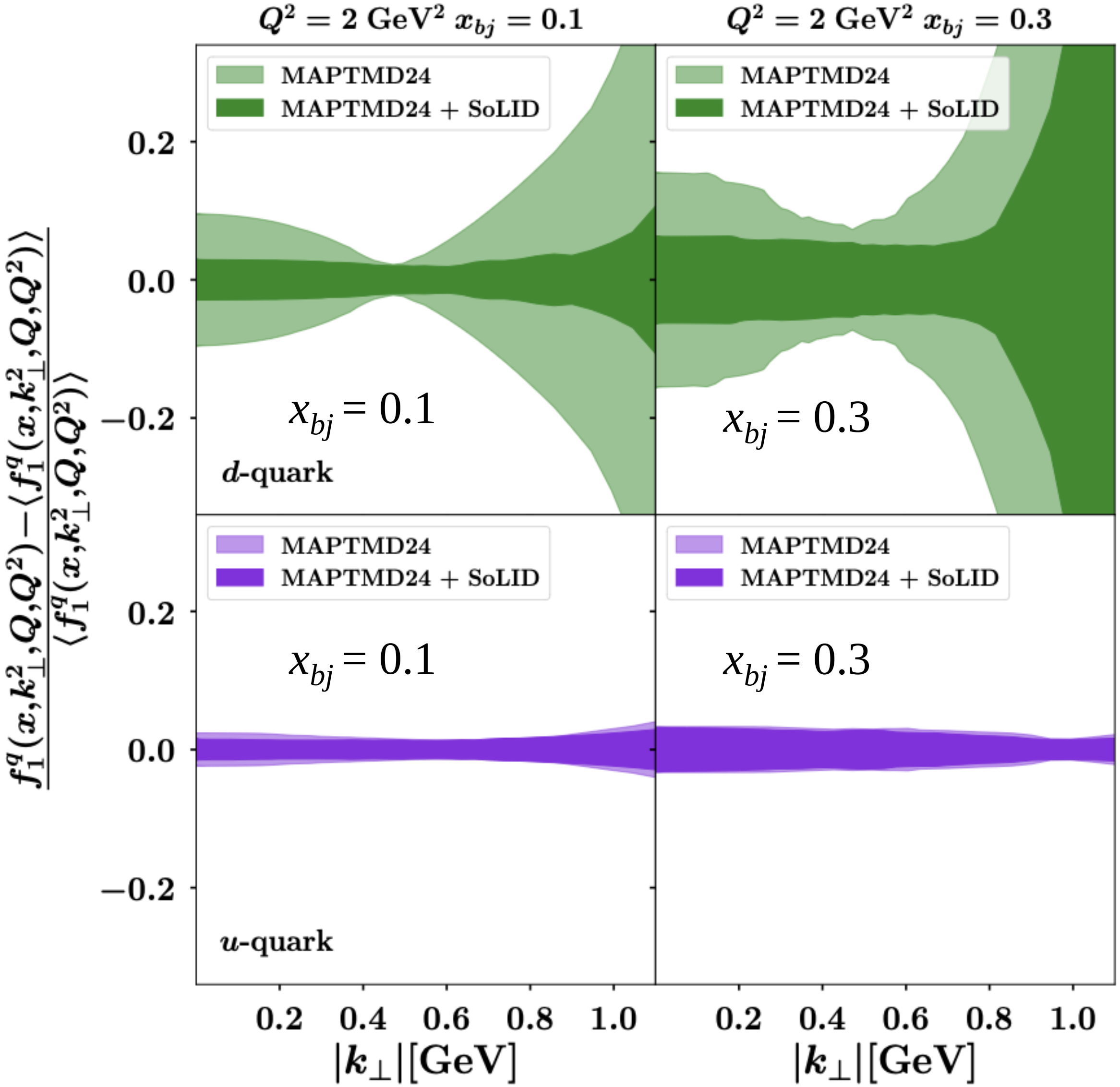


Central points from simple TMD model

Blue points: Flat distribution

Red points: Cross section including azimuthal modulations

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.

Transverse Momentum Widths from Azimuthal Modulations

- Transverse momentum widths

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

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

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

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

In model, we have (in GeV²)

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

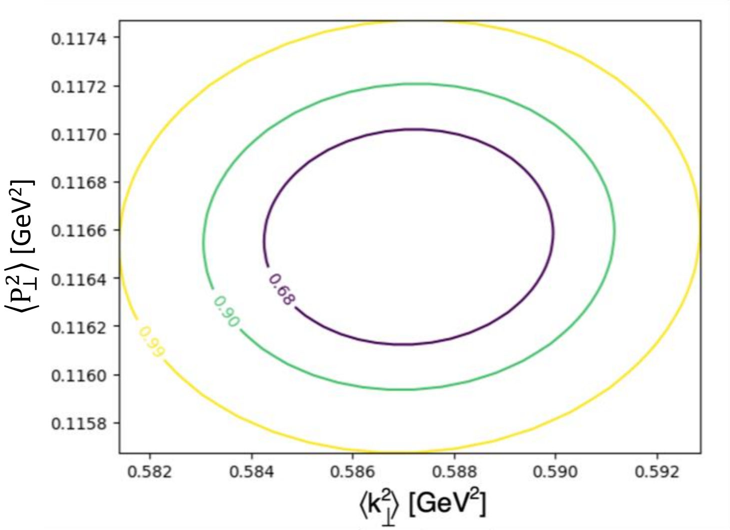
$$\text{Least\_Square} = \sum(pseudodata - Model)^2/(\sigma_{stat}^2 + \sigma_{sys}^2)$$

The fitting results shows (in GeV²):

$$\langle k_\perp^2\rangle = 0.5868 \pm 0.0015$$
$$\langle P_\perp^2\rangle = 0.1166 \pm 0.0002$$

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 ~2-3%

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 $\langle P_\perp^2\rangle$

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	$\lesssim 18\%$

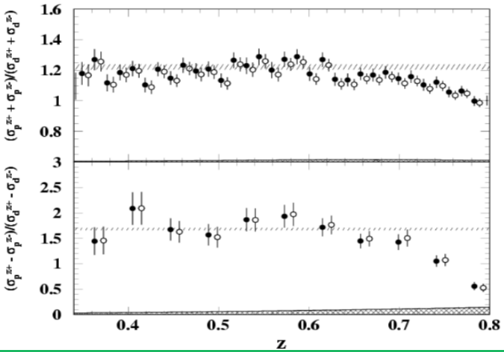
Total uncertainty calculated by rounding off the quadrature sum of separate contributions

Backup

More Physics Projections

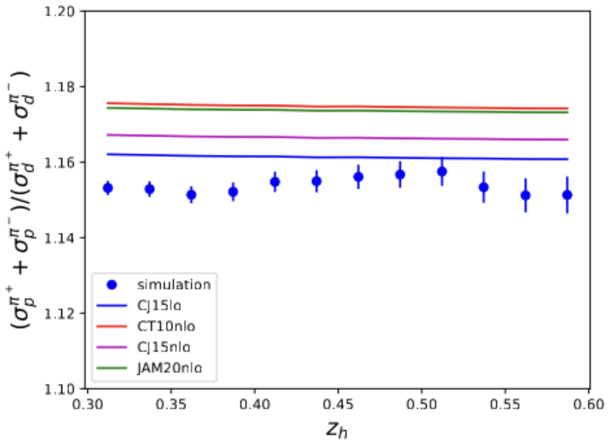
- Test of factorization

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

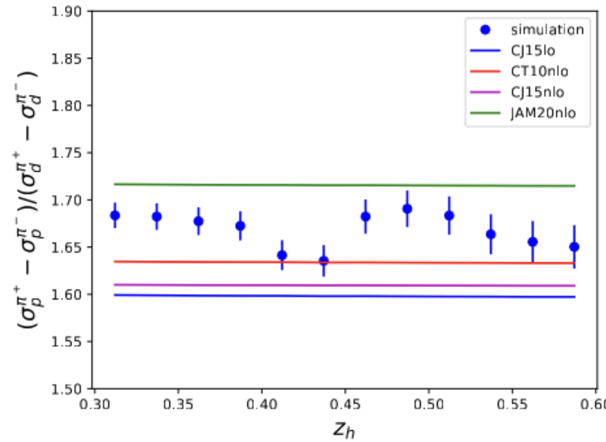


T. Navasardyan and et al. Phys. Rev. Lett.98, 022001 (2007)

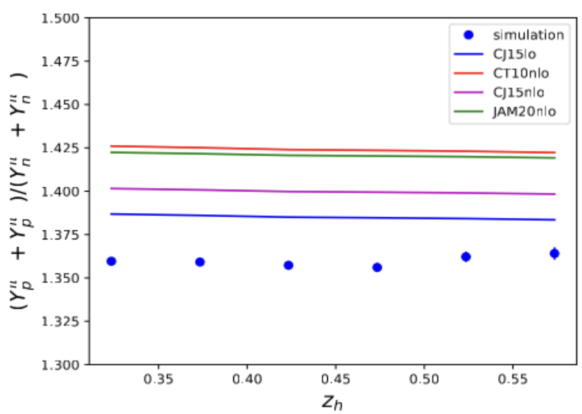
$$\frac{Y_p^{\pi^+}+Y_p^{\pi^-}}{Y_d^{\pi^+}+Y_d^{\pi^-}}=\frac{4u+4\bar{u}+d+\bar{d}}{5(u+\bar{u}+d+\bar{d})}$$



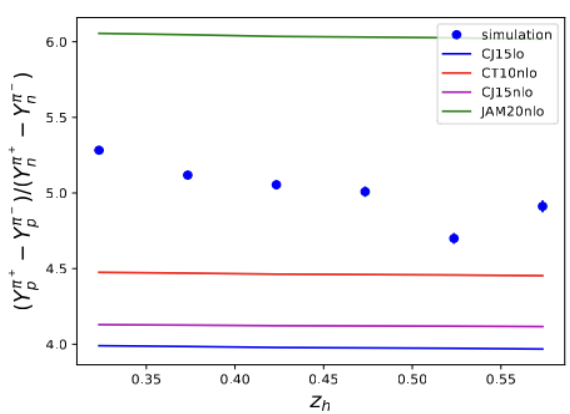
$$\frac{Y_p^{\pi^+}-Y_p^{\pi^-}}{Y_d^{\pi^+}-Y_d^{\pi^-}}=\frac{4u_v-d_v}{3(u_v+d_v)}$$



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

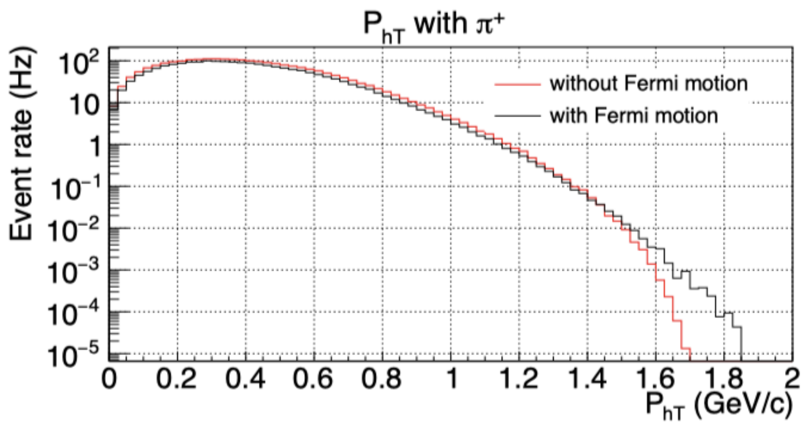


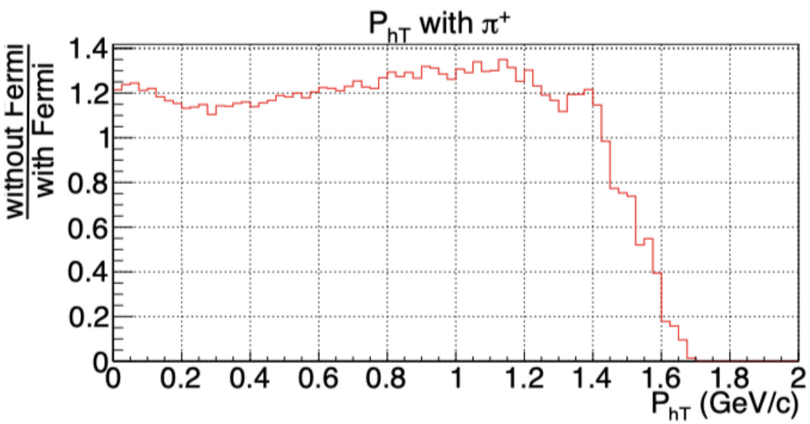
$$\frac{Y_p^{\pi^+}-Y_p^{\pi^-}}{Y_n^{\pi^+}-Y_n^{\pi^-}}=\frac{4u_v-d_v}{4d_v-uv}$$

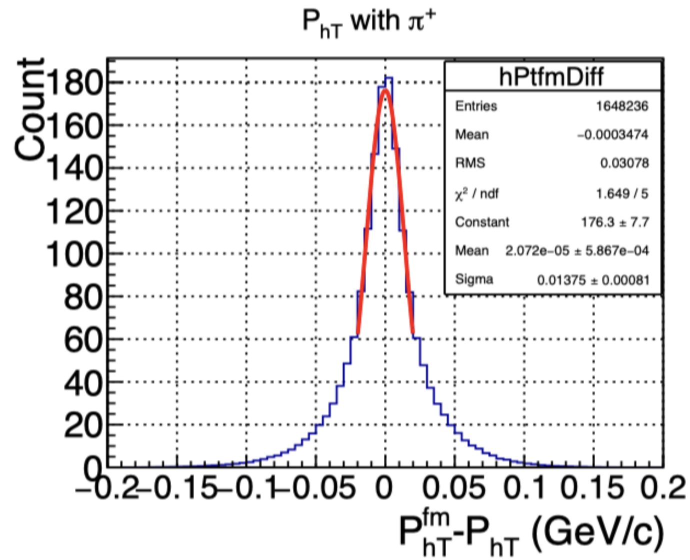


- The curves are ratios of collinear PDFs from global fits.
- The simulation points generated using the LHAPDF CJ15lo (PDFs) and the DSSFFlo (collinear FFs).

Nuclear Effects







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

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.

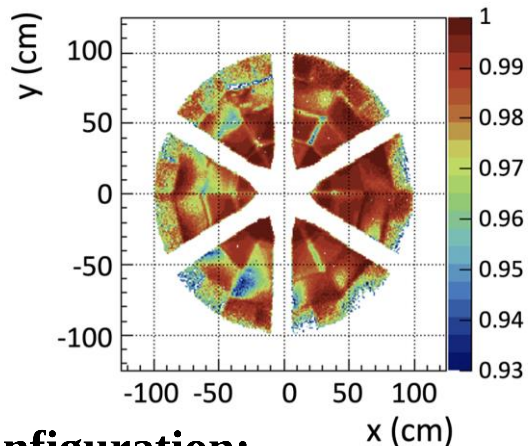
❖ Aid in investigating the EMC effect with ^{3}He SIDIS data.

SoLID's Advantage in Unpolarized SIDIS

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

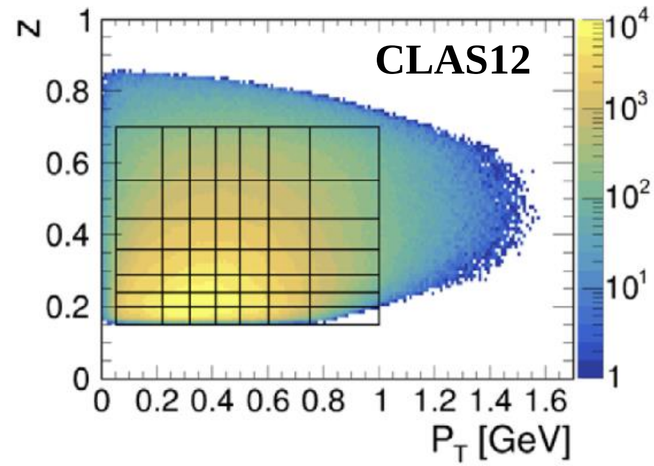
➢ Hall B data: RG-A: Measurements of the $\cos\phi_h$ and $\cos 2\phi_h$ Moments of the Unpolarized SIDIS π^+ Cross-section with **10.6 GeV** beam and hydrogen target

CLAS12



arXiv:2501.14996

Phys. Rev. Lett.,128, 062005, (2022)

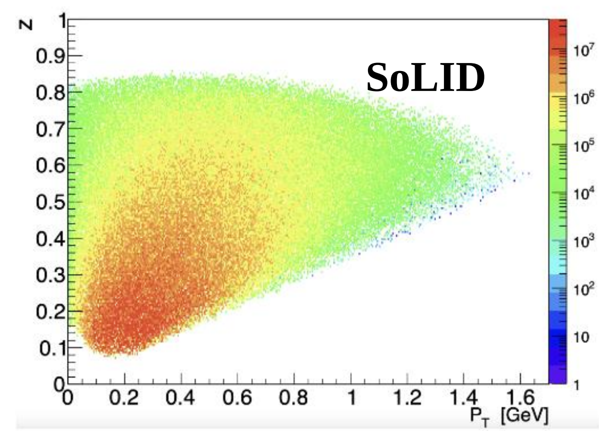


SoLID SIDIS configuration:

✓ 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%

Calibration Approach:

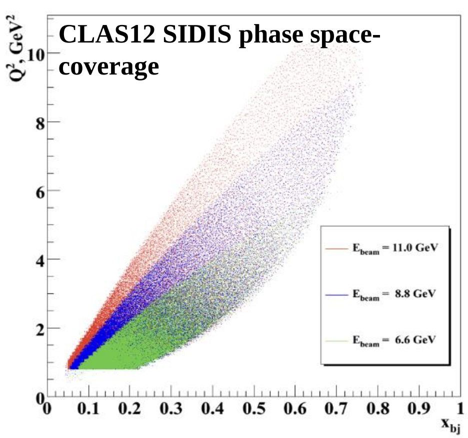
- Exclusive channels will be calibrated in overlapping regions using existing or forthcoming data.
- Calibration will be extended into broader kinematic regions via **SIDIS reactions**.

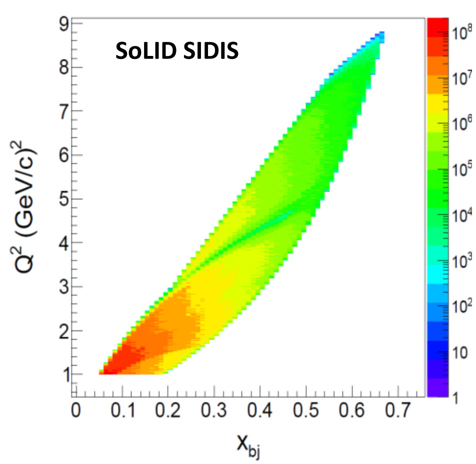
- **Hall B**

➢ **$0.16 < x_{bj} < 0.58$, 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





Coincidence Acceptance Uncertainty

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

10days of 11 GeV unpolarized hydrogen and deuterium runs (SIDIS transversely polarized ^3He 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)

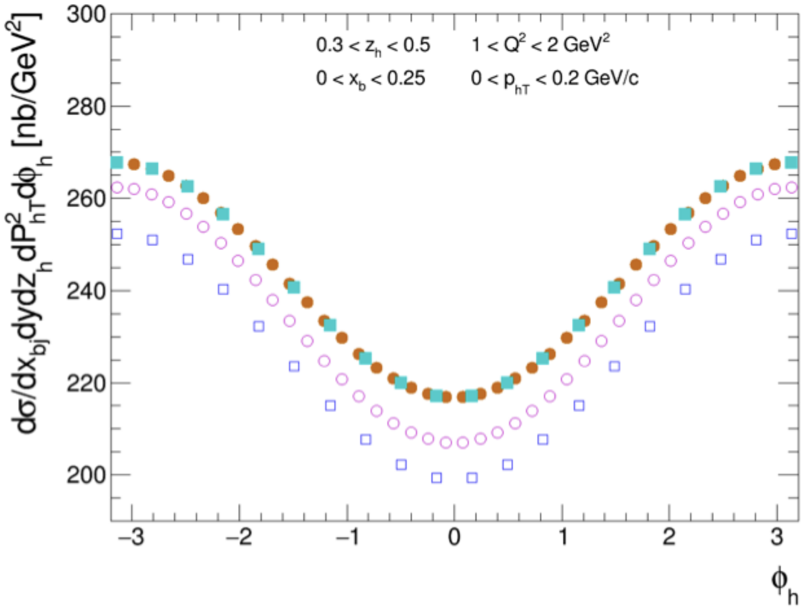
  https://indico.jlab.org/event/928/contributions/16228/attachments/12264/19427/Kripko_kaon_sidis_cos.pdf

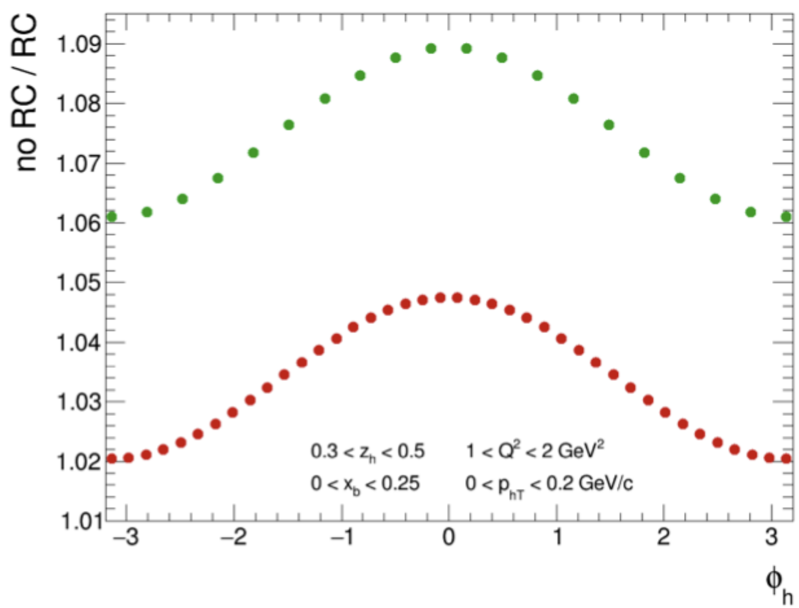
ϕ_h-dependent Effects and Uncertainties from Radiative corrections

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

Traditional method: Orange curve -- σ_B, Cyan curve -- $\sigma_B + \sigma_{RC}$ | Traditional method: Red curve – ratio of σ_B and $\sigma_B + \sigma_{RC}$

Factorized method: Magenta curve -- σ_B, Blue curve -- $\sigma_B + \sigma_{RC}$ | Factorized method: Green curve – ratio of σ_B and $\sigma_B + \sigma_{RC}$





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

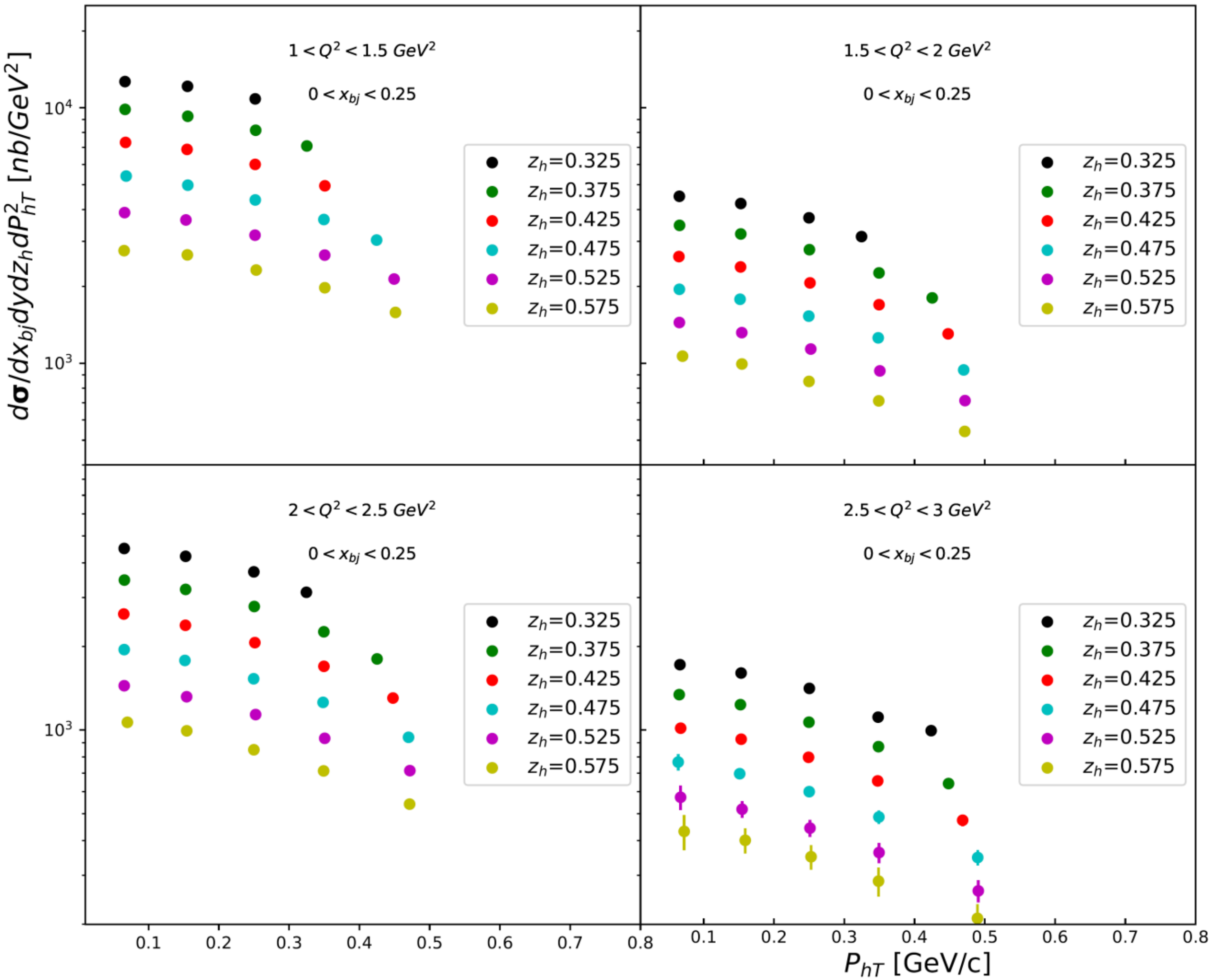
The 4% amplitude uncertainty between the two approaches translates into a ϕ_h-angle dependent uncertainty at the 2% level.

Physics Implications (Boer-Mulders Effect):

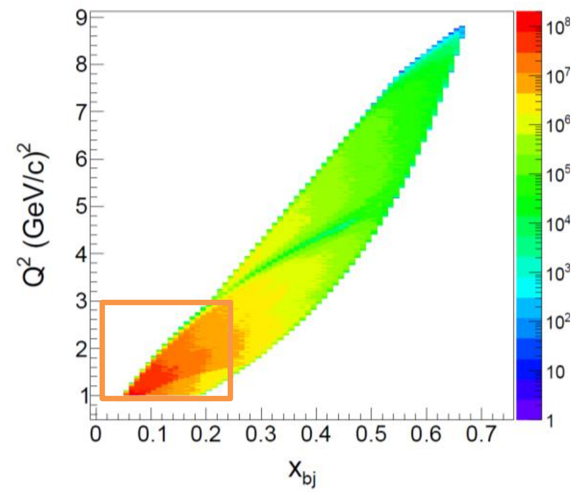
- Effect size ≥ 10% ⟶ Measurable with good precision
- Effect size < 5% ⟶ Challenging to extract cleanly; Interpretation limited by theoretical RC uncertainties; Help guide future theoretical/phenomenological studies in the right direction

More Physics Projections

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



SoLID low-Q^2 region

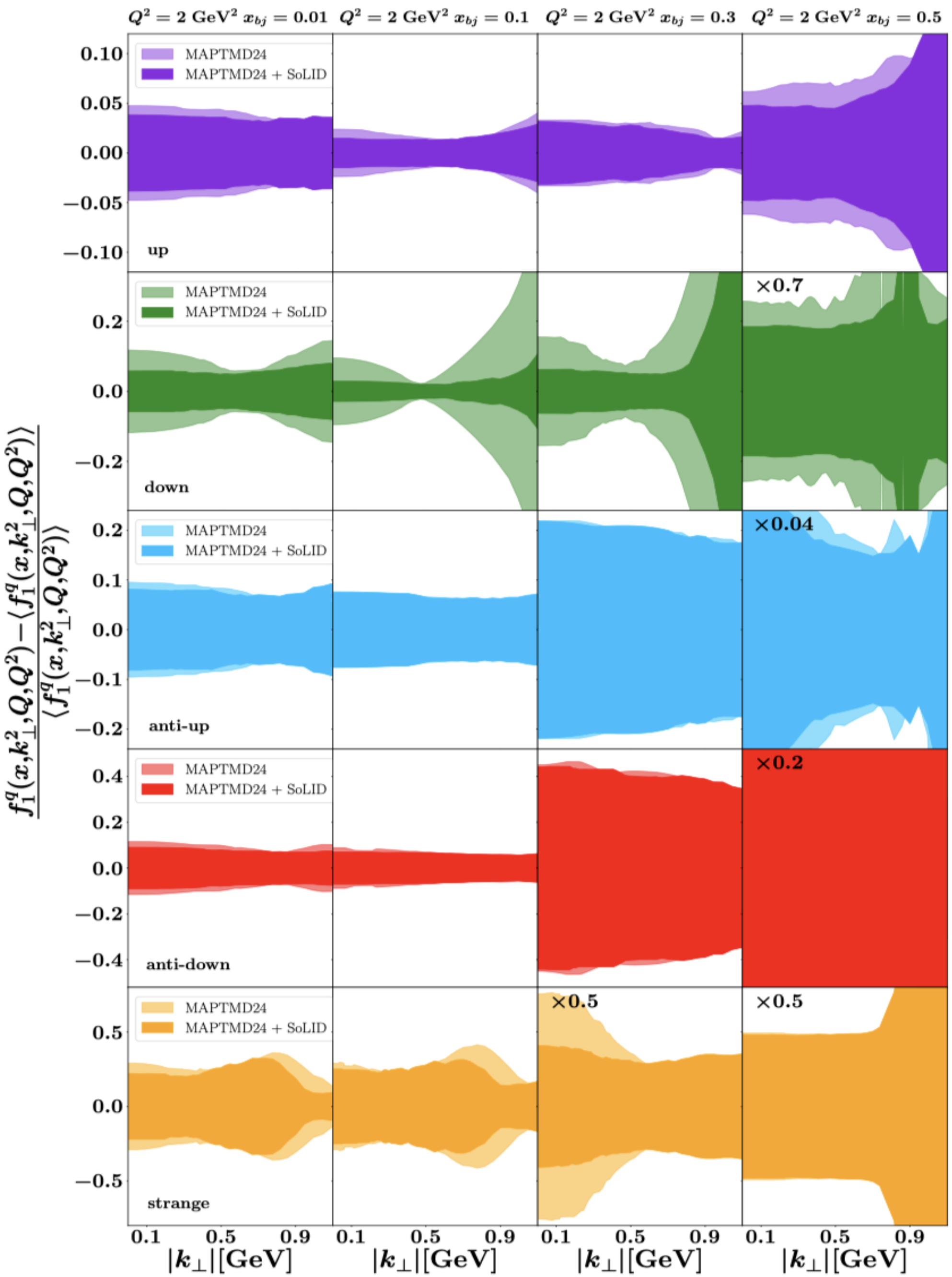


SoLID pseudo-data

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

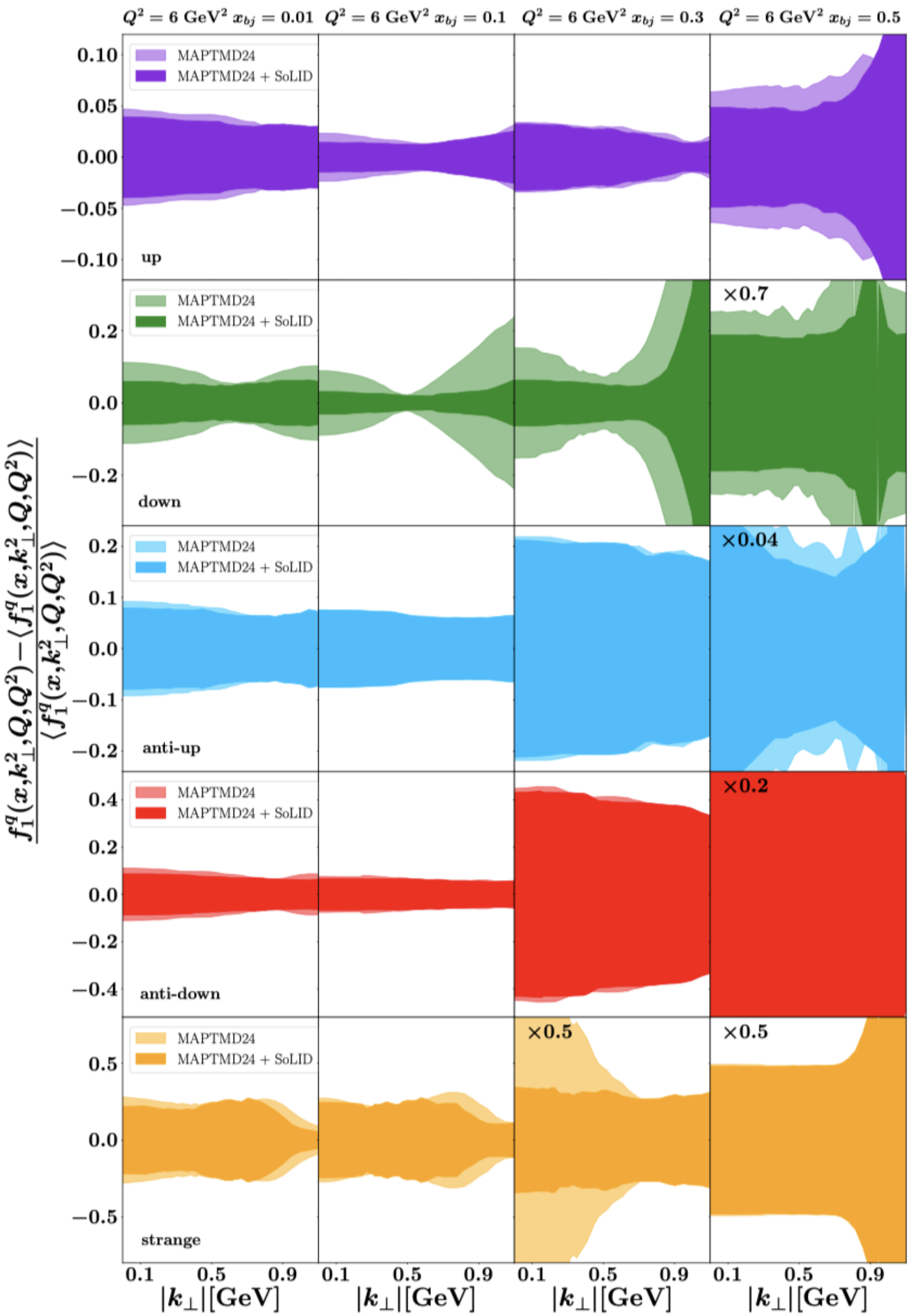
$$\frac{f_1^q(x,k_\perp^2,Q,Q^2)-\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}{\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}$$

- 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

  $\pi^+ \ \pi^-$

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

- Uncertainty bans account for 68% CL

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

Q^2 =6 GeV^2