SIDIS E12-09-018—Overview and prospect of running after GEN

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SBS Summer Collaboration Meeting 2019

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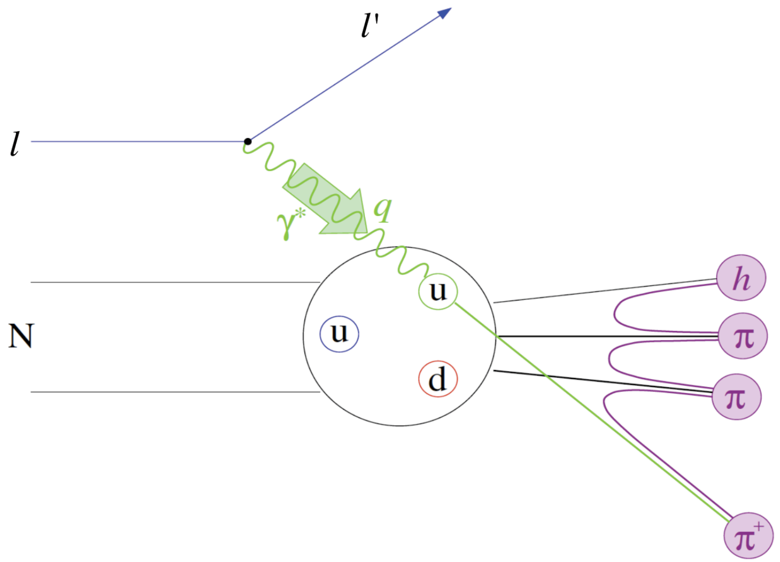
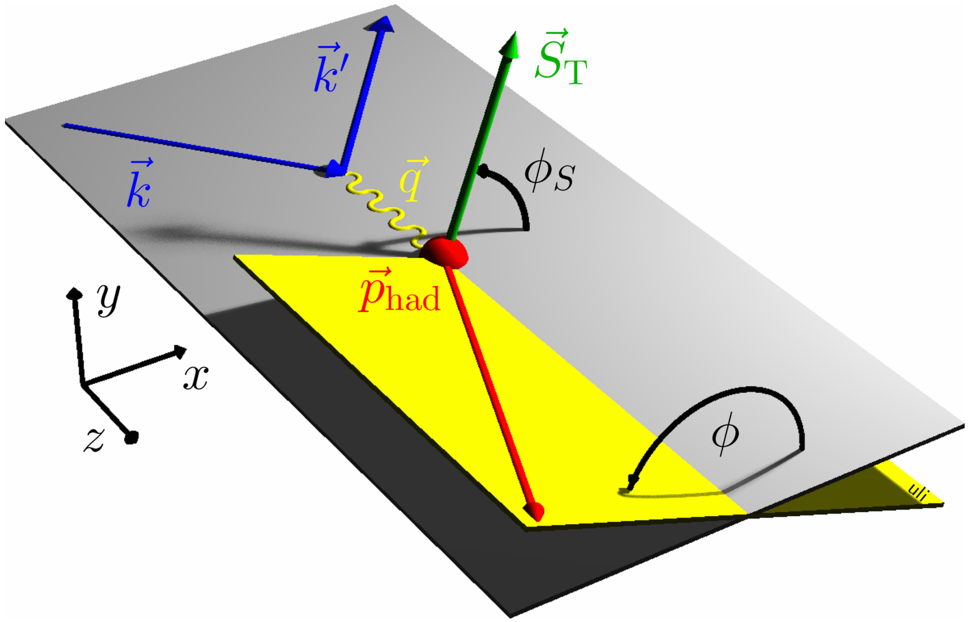
Semi-Inclusive Deep Inelastic Scattering





Kinematic Variables for SIDIS	Description
$z \equiv \frac{p_h \cdot p}{q \cdot p} \overset{lab}{\Longrightarrow} \frac{E_h}{\nu}$	Fraction of virtual photon energy carried by observed hadron
$p_T \equiv \boldsymbol{p}_h - \frac{\boldsymbol{p}_h \cdot \boldsymbol{q}}{\lvert\boldsymbol{q}\rvert^2}\boldsymbol{q}$	Transverse momentum of observed hadron relative to momentum transfer direction
ϕ_h	Azimuthal angle between lepton scattering and hadron production planes
ϕ_S	Azimuthal angle between (transverse component of) target spin and lepton scattering plane
$M_X^2 \equiv (p + q - p_h)^2$	Missing mass of unobserved final state particles

- The single-hadron SIDIS process N(e,e'h)X, in which leading (high-energy) hadrons are detected at "small" finite transverse momentum in DIS collisions provides access to additional aspects of nucleon structure that are inaccessible in DIS:
    - quark flavor
    - quark transverse motion
    - quark transverse spin
- ***Goal of SIDIS studies is (spin-correlated) 3D imaging of quarks in momentum space.***
- Transverse Momentum Dependent (TMD) PDF approach: ***Bacchetta et al. JHEP 02 (2007) 093, Boer and Mulders, PRD 57, 5780 (1998), etc.***

General Expression for SIDIS Cross Section at twist 3: *Bacchetta et al., JHEP 02, 093 (2007)*

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,d\phi_S\,dp_T^2} = {} & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{\boxed{F_{UU,T}} + \epsilon F_{UU,L} + \\
& \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \boxed{\epsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}} + \\
& \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} + \\
& S_\parallel\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \boxed{\epsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}}\right] + \\
& S_\parallel\lambda_e\left[\boxed{\sqrt{1-\epsilon^2}F_{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right] + \\
& S_\perp\Bigg[\boxed{\sin(\phi_h-\phi_S)F_{UT}^{\sin(\phi_h-\phi_S)}} \\
& \boxed{\epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}} + \\
& \boxed{\epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}} \\
& \sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\right)\Bigg] + \\
& S_\perp\lambda_e\Bigg[\boxed{\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}} + \\
& \sqrt{2\epsilon(1-\epsilon)}\left(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\right)\Bigg]\Bigg\}
\end{aligned}
$$

- Sivers
- Collins
- "Pretzelosity"

- SIDIS structure functions depend on x, Q^2, z, p_T
- U, L, T subscripts indicate unpolarized, longitudinally and transversely polarized beam, target, respectively
- S = nucleon spin
- λ = lepton helicity
- **Eight terms survive at leading twist; the rest are twist-3 (M/Q suppressed)**
- Azimuthal angle dependence caused by spin-orbit effects.
- All leading-twist TMDs can be separately extracted from the azimuthal modulations of SIDIS cross section with polarized beam (longitudinal) and polarized target (longitudinal and transverse)

$$
\boxed{\begin{aligned}
\gamma &= \frac{2Mx}{Q} \\
\epsilon &= \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}
\end{aligned}}
$$

Parton Model Interpretation of SIDIS: Transverse Momentum Dependent PDFs (TMDs)

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ -
	L		$g_1 =$ -	$h_{1L}^\perp =$ -
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

- Only f_1, g_1, h_1 survive integration over quark k_T
- Physical observables are convolutions over two (unobserved) transverse momenta:
  - Initial quark k_T
  - Hadron p_T relative to recoiling quark, generated during fragmentation
- Unambiguous extraction of TMD PDFs from SIDIS data also requires input from e^+/e^- annihilation experiments to constrain quark → hadron fragmentation functions!

$$
\begin{aligned}
F_{UU,T} &\sim f_1 \otimes D_1 \\
F_{UU}^{\cos 2\phi_h} &\sim h_1^\perp \otimes H_1^\perp \\
F_{UL}^{\sin 2\phi_h} &\sim h_{1L}^\perp \otimes H_1^\perp \\
F_{LL} &\sim g_1 \otimes D_1 \\
F_{UT}^{\sin(\phi_h - \phi_S)} &\sim f_{1T}^\perp \otimes D_1 \\
F_{UT}^{\sin(\phi_h + \phi_S)} &\sim h_1 \otimes H_1^\perp \\
F_{UT}^{\sin(3\phi_h - \phi_S)} &\sim h_{1T}^\perp \otimes H_1^\perp \\
F_{LT}^{\cos(\phi_h - \phi_S)} &\sim g_{1T} \otimes D_1
\end{aligned}
$$

$$
\begin{aligned}
D_1(z, Q^2, p_\perp^2) &= \text{Unpolarized TMD FF} \\
H_1^\perp(z, Q^2, p_\perp^2) &= \text{Collins TMD FF}
\end{aligned}
$$

Kinematic Conditions for applicability of TMD formalism

- Requires large Q[2] ($Q^2 > 1\ GeV^2$), large W ($W > 2\ GeV$), as in DIS
- Requires large (but not too large) z:
  - High enough for dominance of "current quark" fragmentation over "target remnant" fragmentation
  - Low enough to avoid dominance of exclusive/resonance region contributions
- Requires small (but not too small) p_T:
  - Large enough for meaningful sensitivity to effects of quark transverse motion/spin: $k_\perp \approx \Lambda_{QCD} \approx 200\ MeV$
  - Small enough for applicability of TMD formalism; i.e., dominance of TMD effects over pQCD effects (gluon radiation, etc.)

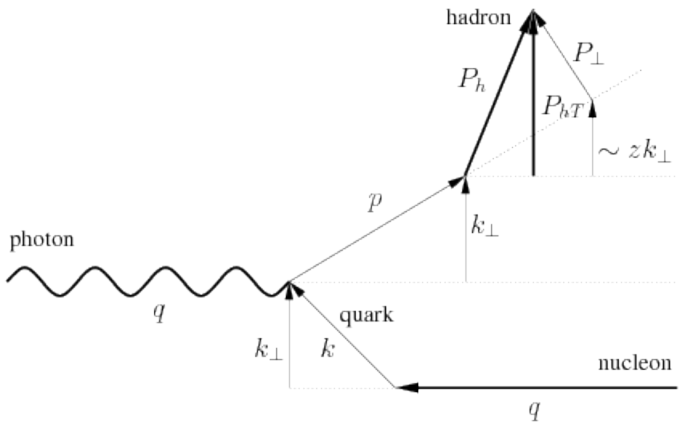


Figure credit: Bacchetta *et al.*, JHEP 1706 (2017) 081

At leading order in $k_\perp/Q$, we have:

$$\mathbf{P}_{hT} \approx z\mathbf{k}_\perp + \mathbf{P}_\perp$$

- Experimentalist's/phenomenologist's rule of thumb: $$\frac{|\mathbf{P}_{hT}|}{z} \ll Q$$
- For JLab-12 GeV: $0.3 \leq z \leq 0.7$ for pions; more restricted range for charged kaons, due to hadron mass/target fragmentation.

General Challenges of Measuring TMD-sensitive Observables

Statistics Requirements

Cross sections:

$$\sigma \propto N$$

$$\frac{\Delta\sigma}{\sigma} = \frac{1}{\sqrt{N}}$$

To measure a scattering cross section with a relative statistical precision of 1%, you need 10,000 events.

Asymmetries:

$$\Delta A = \sqrt{\frac{1 - A^2}{N}}$$

$$\frac{\Delta A}{A} = \sqrt{\frac{1 - A^2}{NA^2}}$$

On the other hand, to measure an asymmetry A with a relative precision of 1%, you need $N = 10{,}000 \times \frac{1-A^2}{A^2}$.

For example, if $A = 5\%, N = 4 \times 10^6$!

- SIDIS structure functions, *before* considering azimuthal angle dependence, are functions on a 4-D phase space (x, Q^2, z, p_T)
- Sufficiently high ***energy*** is needed to access this phase space
- Large ***acceptance*** is required to cover this phase space and unambiguously separate azimuthal modulations
- High ***luminosity*** is required to achieve reasonable statistical precision, especially for 4-D analysis
- High beam and/or target ***polarization*** is required for spin-dependent observables: FOM is ***luminosity*** × ***polarization***^{2}
- **Interpretability requires large Q^2**
  - Large Q^2 implies high *x* in fixed-target experiments (even in collider kinematics, Q^2 and *x* acceptances are correlated). DIS event rate typically falls ~exponentially with *x* in the valence region
- TMDs and nucleon spin structure are among the major goals of the future Electron-Ion-Collider (EIC).

Transverse target spin effects in SIDIS

		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$ -
	L		Δq -	$h_{1L}^\perp$ -
	T	$f_{1T}^\perp$ -	$g_{1T}^\perp$ -	δq -
				$h_{1T}^\perp$ -

Transverse target spin-dependent cross section for SIDIS

- Collins effect—chiral-odd quark transversity DF; chiral-odd Collins FF
- Sivers effect—access to quark OAM and QCD FSI mechanism
- "Transversal helicity" g_{1T}—real part of S wave-P wave interference (Sivers = imaginary part) (requires polarized beam)
- "Pretzelosity" or Mulders-Tangerman function—interference of wavefunction components differing by 2 units of OAM

$$
\begin{aligned}
A_{UT}(\phi,\phi_S) &= \frac{1}{P_T}\frac{d\sigma(\phi,\phi_S)-d\sigma(\phi,\phi_S+\pi)}{d\sigma(\phi,\phi_S)+d\sigma(\phi,\phi_S+\pi)} \\
&= A_{UT}^{Collins}\sin(\phi+\phi_S)+ \\
&\quad A_{UT}^{Sivers}\sin(\phi-\phi_S)+ \\
&\quad A_{UT}^{Pretz}\sin(3\phi-\phi_S)
\end{aligned}
$$

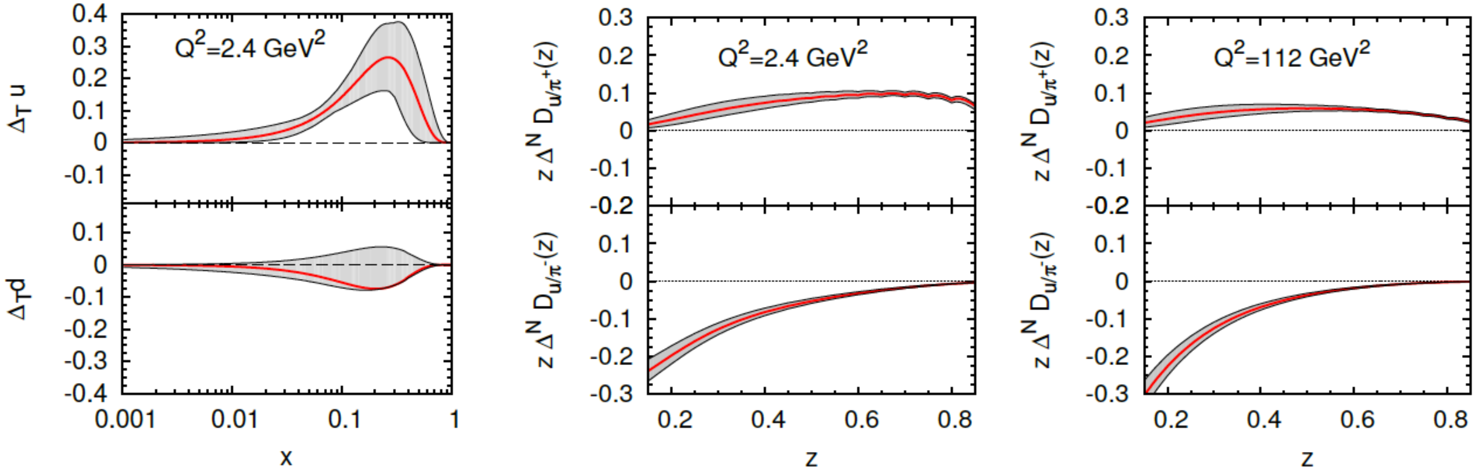
$$
\begin{aligned}
A_{UT}^{Collins} &\propto \delta q\otimes H_1^\perp \\
A_{UT}^{Sivers} &\propto f_{1T}^\perp\otimes D_1 \\
A_{UT}^{Pretz} &\propto h_{1T}^\perp\otimes H_1^\perp
\end{aligned}
$$

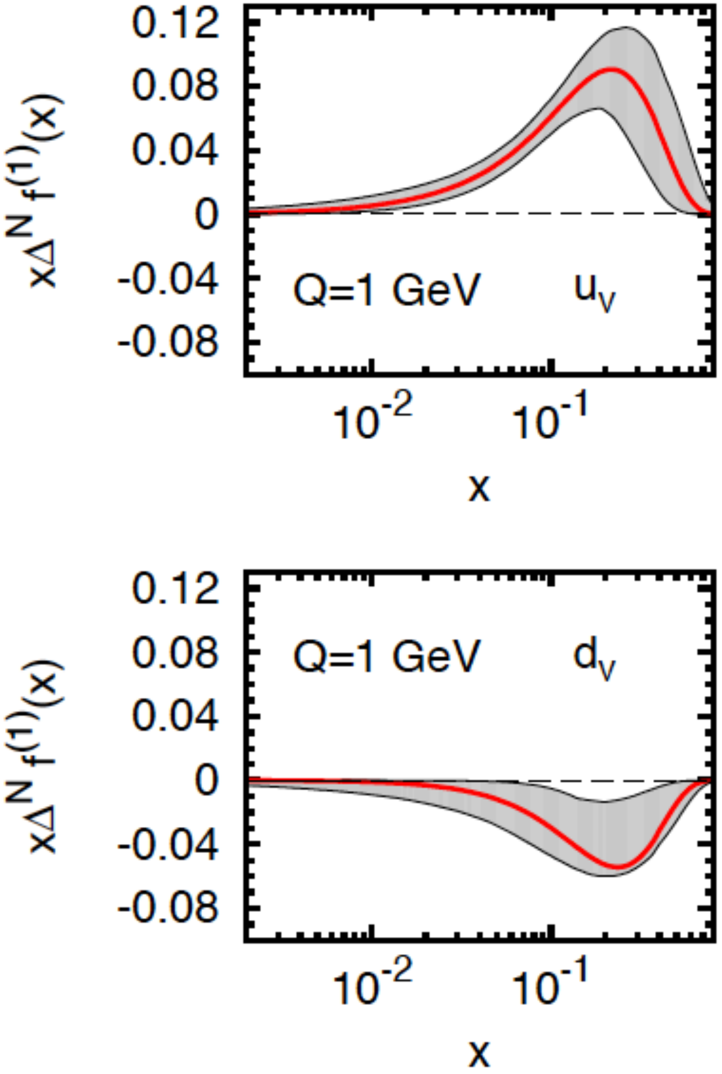
$D_1 =$ unpolarized fragmentation function

$H_1^\perp =$ Collins fragmentation function

$$
\begin{aligned}
A_{LT}(\phi,\phi_S) &= \frac{1}{P_eP_T}\frac{Y_+(\phi,\phi_S)-Y_-(\phi,\phi_S)}{Y_+(\phi,\phi_S)+Y_-(\phi,\phi_S)} \\
&\sim A_{LT}^{\cos(\phi-\phi_S)}\cos(\phi-\phi_S) \\
&\sim g_{1T}\otimes D_1
\end{aligned}
$$

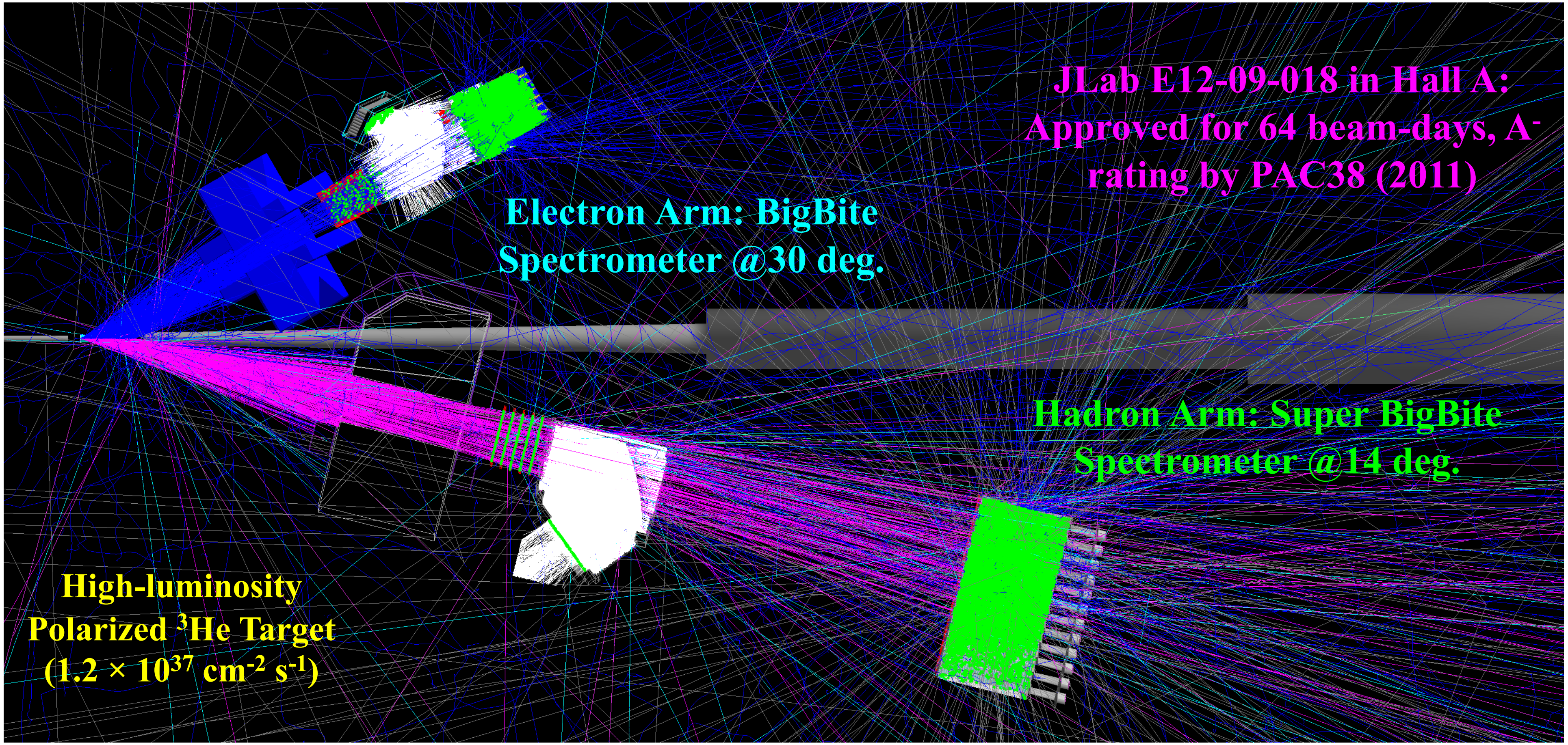
Transversity, Collins, and Sivers: Existing Knowledge





- **Above: Anselmino *et al.*, Phys. Rev. D 92, 114023 (2015) arXiv:1510.05389v1:** latest extractions of valence u and d quark transversities and favored/unfavored Collins FFs
- **Right: Anselmino *et al.*, Phys.Rev. D86 (2012) 014028, arXiv:1204.1239v1:** Fits to most recent HERMES and COMPASS SIDIS Sivers data with TMD/DGLAP evolution
- d-quark Sivers/Transversity are poorly constrained by existing data
  - Proton data dominated by u-quarks
  - Limited precision/sensitivity to d quark from COMPASS deuteron/JLab Hall A ^{3}He data

E12-09-018—Transversely Polarized SIDIS on ^{3}He (“neutron”)

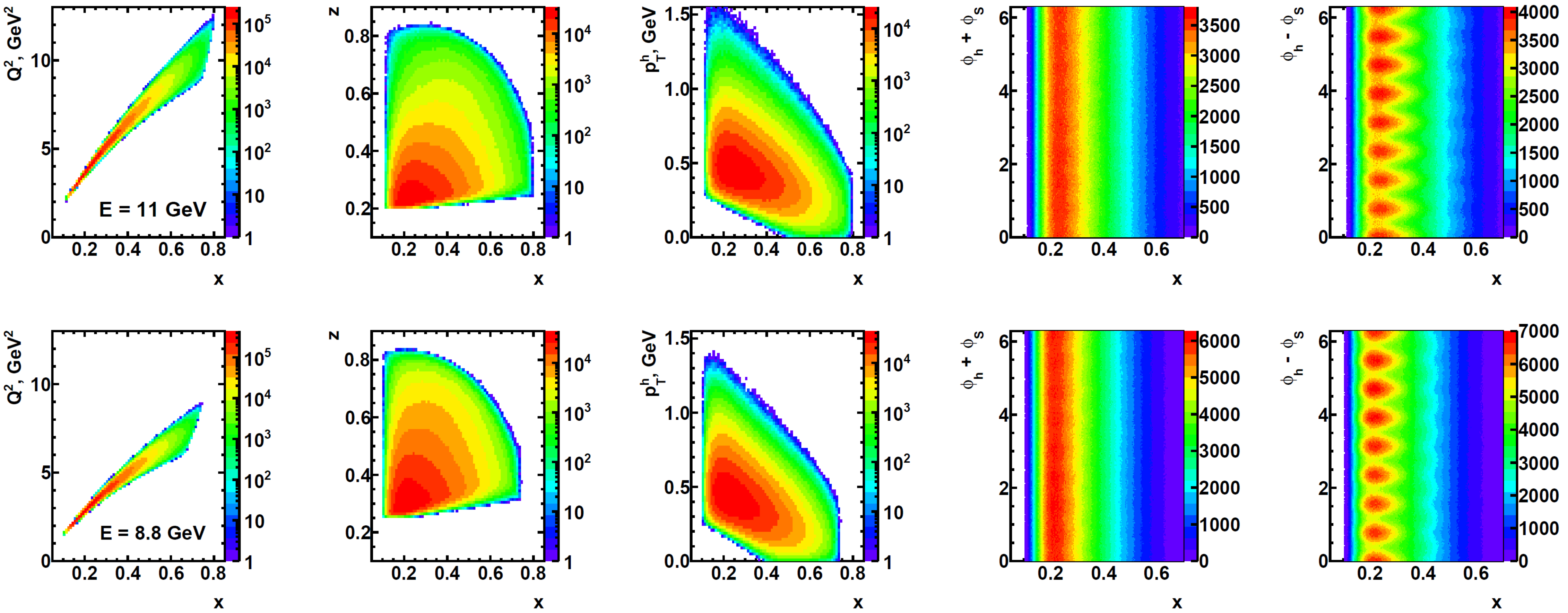


- **E12-09-018** in Hall A: transverse spin physics with high-luminosity polarized ^{3}He as effective polarized *n*.
- 40 (20) days production at E = 11 (8.8) GeV—significant Q^2 range at fixed x
- Collins, Sivers, Pretzelosity, A_{LT} for $\mathbf{n}(e, e'h)X, h = \pi^+, \pi^-, K^+, K^-, \pi^0$, etc.
- Re-use of HERMES RICH detector for charged hadron PID
- Reach high x (up to ~0.7) and high statistical FOM (~1,000X Hall A E06-010 @6 GeV)

Key Features

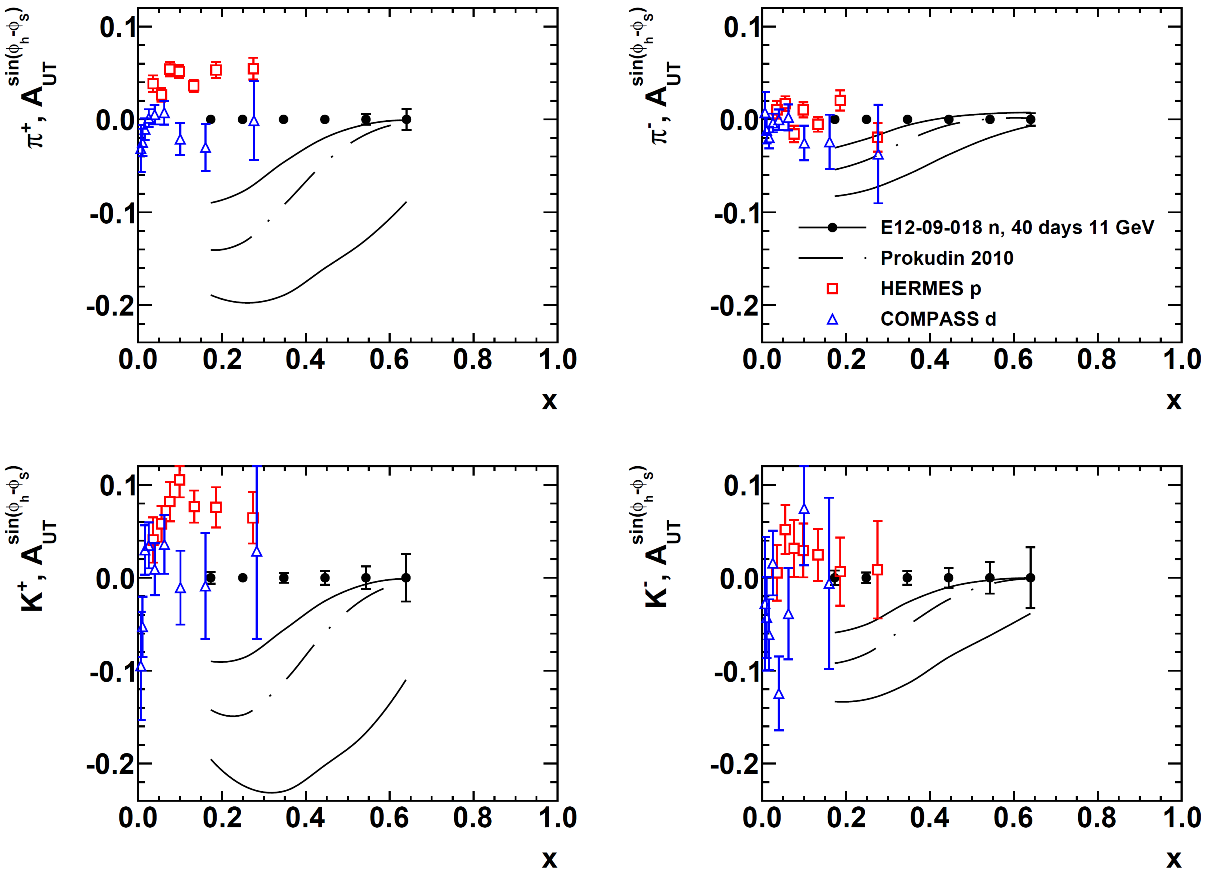
- Cost-effective solution to enable high-impact transverse SSA measurements *soon*: re-use existing BigBite w/partially upgraded detector package
- Reuse other SBS components already being built for form factor program
- Reuse HERMES RICH
- Exploit high-luminosity ^{3}He target upgrade developed for G_E^n.
- Cover full SIDIS phase space in a single spectrometer configuration with moderate solid angle, large momentum bite
- http://hallaweb.jlab.org/collab/PAC/PAC38/SBS-SIDIS.pdf

SIDIS Kinematic Coverage in E12-09-018: As Proposed

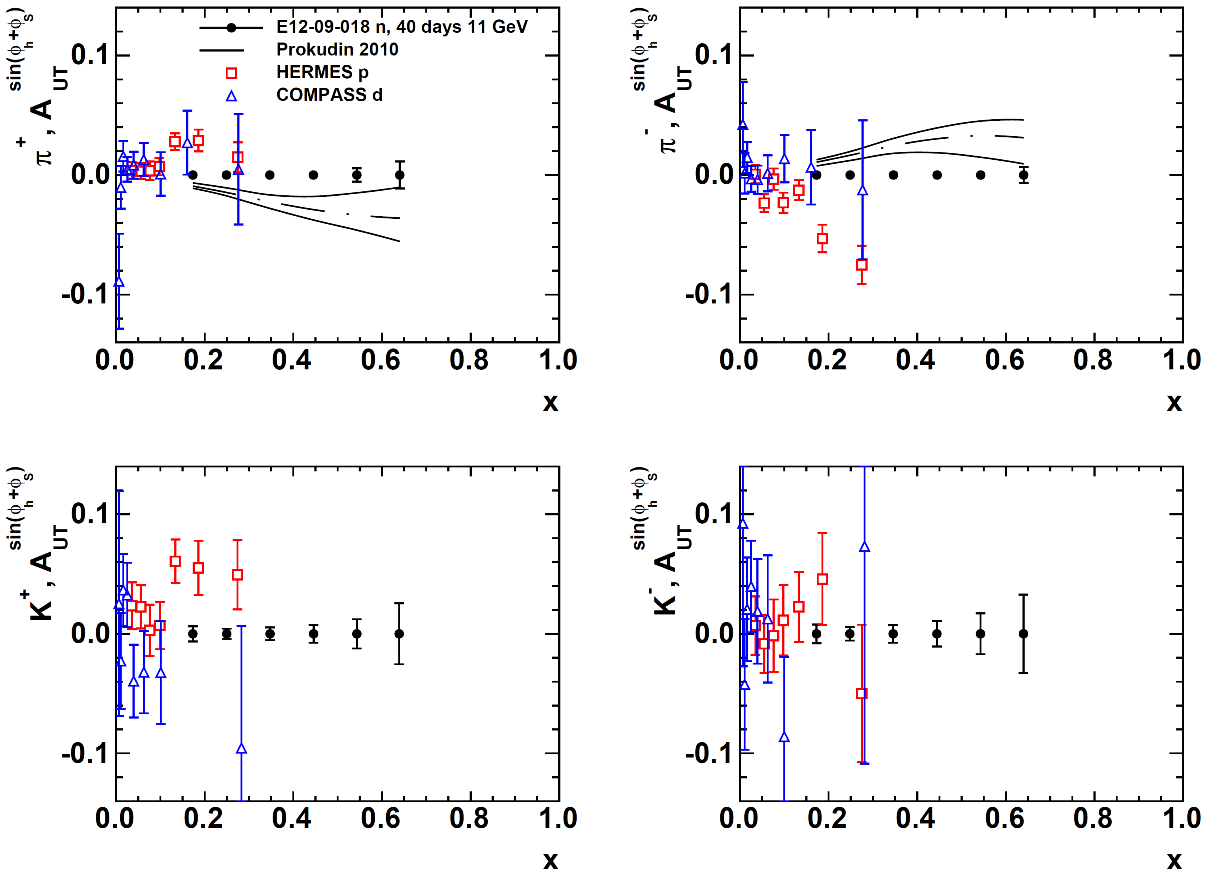


- Cuts applied are: $Q^2 > 1\ GeV^2, W > 2\ GeV, P_h \geq 2\ GeV, M_X \geq 1.5\ GeV, y \leq 0.9$
- E12-09-018 emphasizes precision neutron measurements at high Q^2 and large x: complementary kinematic coverage to aid eventual interpretation of future, higher-precision data at (mostly) lower Q^2 from SOLID

SBS+BB Projected Results: Collins and Sivers SSAs



Projected A_{UT}^{Sivers} vs. x (11 GeV data only)



Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)

- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than Hall A E06-010 neutron data. *Near-future more precise COMPASS deuteron data will sharpen expected impacts, urgency of E12-09-018*
- SBS installation starts 2020. E12-09-018 could run as early as 2022; 2023 more likely.

3D and "4D" extraction of neutron SIDIS SSAs with SBS

Example results for 2D/3D binning (x,z,p_T)

- E = 11 GeV, 40 days

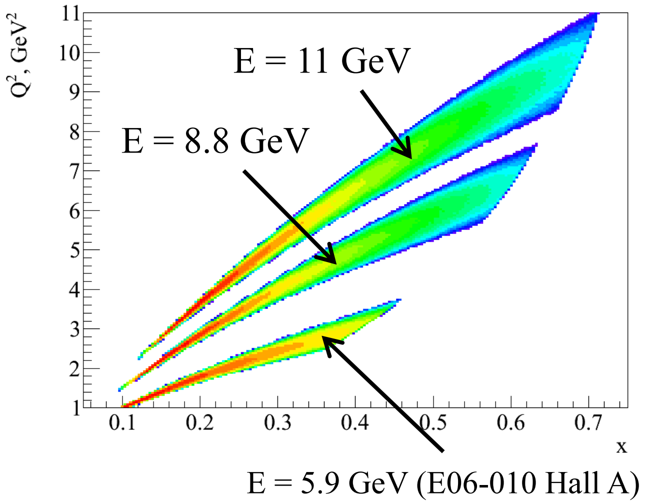
$$A_{UT}^{\sin(\phi_h-\phi_S)} \text{ for } \mathbf{n}(e,e'\pi^+)X:$$

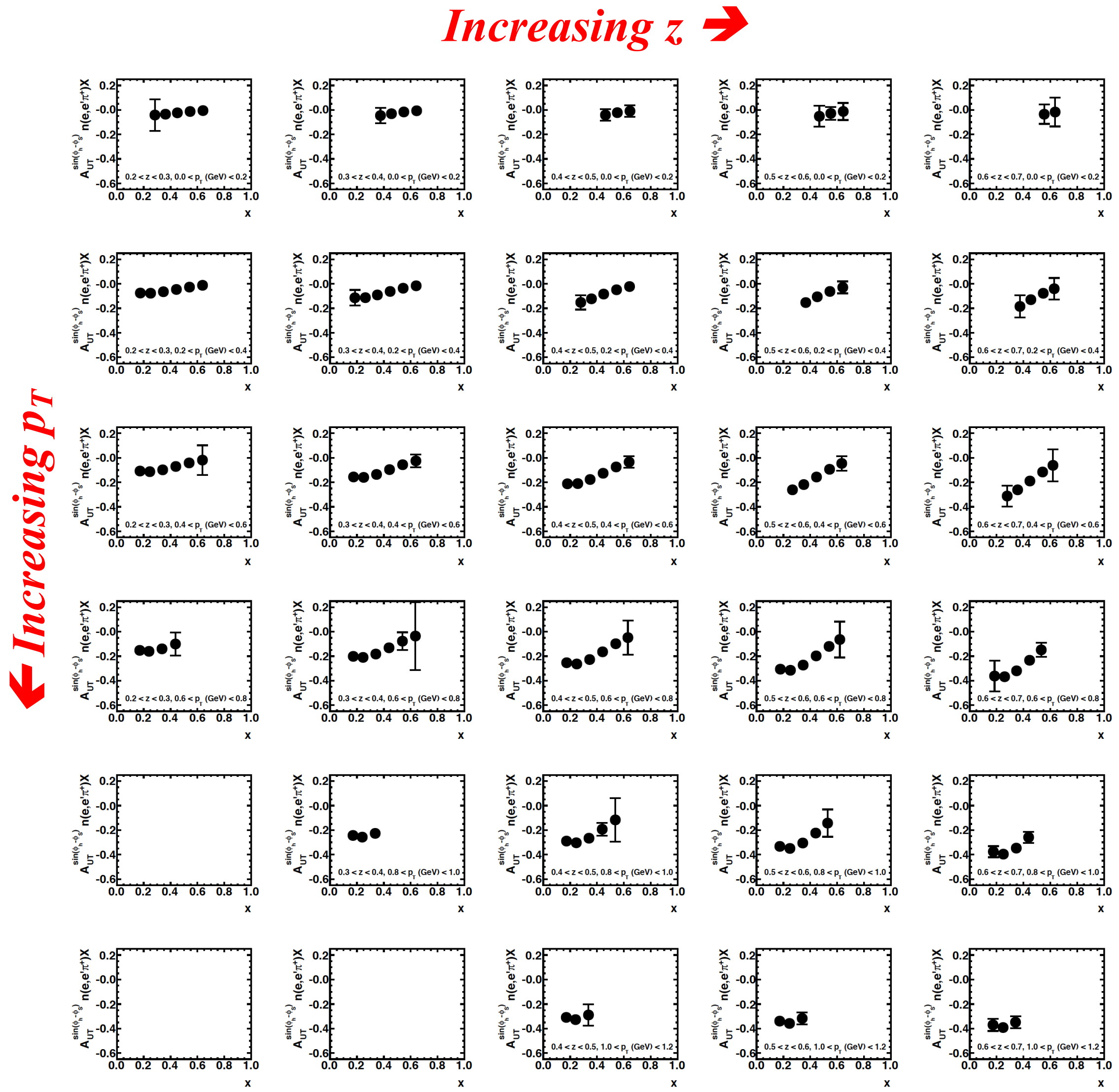
$$0.1 \leq x \leq 0.7, \Delta x = 0.1$$

$$0.2 \leq z \leq 0.7, \Delta z = 0.1$$

$$0 \leq p_T(\text{GeV}) \leq 1.2, \Delta p_T = 0.2 \text{ GeV}$$

- "4D" with Q^2 dependence from 20 days at 8.8 GeV:





SIDIS Kinematic Configurations

As Proposed:

$E_e\ (GeV)$	$\theta_{BB}\ (deg)$	$d_{BB}(m)$	$\theta_{48D48}\ (deg)$	$d_{48D48}\ (m)$	$d_{HCAL}\ (m)$	Beam Line Configuration #
11.0	30.0	1.55	14.0	**2.5**	8.5	2
8.8	30.0	1.55	14.0	**2.5**	8.5	2

Using GEN beamline unmodified:

$E_e\ (GeV)$	$\theta_{BB}\ (deg)$	$d_{BB}(m)$	$\theta_{48D48}\ (deg)$	$d_{48D48}\ (m)$	$d_{HCAL}\ (m)$	Beam Line Configuration #
11.0	30.0	1.55	14.0	**2.8**	8.5	2
8.8	30.0	1.55	14.0	**2.8**	8.5	2

Slight compromise in hadron arm solid angle: $\frac{2.5^2}{2.8^2} = 0.8$

Rationale for Running SIDIS After GEN

- SIDIS electron arm configuration is identical* to GEN:
  - BigBite spectrometer—only significant difference is desire to include GRINCH in BigBite trigger for SIDIS because the reaction is inclusive DIS and threshold is low (1 GeV). More gain from GRINCH in trigger for SIDIS than for GEN/GMN
- SIDIS can use identical beamline configuration as GEN (I'm reasonably confident)
- Hadron arm uses SBS magnet and HCAL.
- Main detector addition is charged particle tracking and PID on hadron side:
  - GEMs (UVA style) and RICH (next talk)
- Target is also polarized ^{3}He, albeit with highly non-trivial differences compared to GEN
- COMPASS will be taking more deuteron SIDIS data with transverse polarization in 2021.
  - **While COMPASS precision won't be competitive with SBS+BB even with more data, this increases the urgency for JLab to weigh in on this physics!**
  - **On the other hand, GEP has no competition, and moreover 30-cm LH_2 cryotarget with 75 μA *may* require ESR-II upgrade (not sure).**
- E06-010, a similar experiment with 1,000 times lower figure-of-merit, produced eight physics publications so far, and the main result already has over 200 citations in INSPIRE
- These measurements are (arguably) interesting to and anticipated by a significantly larger cross section of the hadronic physics community compared to the elastic FFs, and represent an (arguably) greater advance in knowledge compared to existing.

SIDIS after GEN—issues and To-Do List

- Would need to accelerate schedule for SBS RICH and SBS GEM readiness—needs design effort and probably some modest funding.
- Evaluate impact on physics output of a reduced number of available target spin orientations:
  - Proposal asked for eight spin orientations, equally spaced at 45-degree intervals perpendicular to beam direction
  - We can probably live with four: $\pm$horizontal and **$\pm$vertical.**
  - Based on discussions with Gordon, my understanding is that vertical polarization requires the most non-trivial modifications relative to the GEN design → target design could require more design, engineering, possibly R&D, and almost certainly $$.
- Worth taking a serious look at nonetheless, given the likely impact of E12-09-018 and the reduced installation time required due to re-use of GEN beamline and similarity of detector layout.