Semi-Inclusive Deep Inelastic Scattering on Transversely Polarized Neutrons using the BigBite and Super BigBite Spectrometers in Jefferson Lab's Hall A (C?) (E12-09-018)

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University of Connecticut

SBS Collaboration Meeting

9/13/2024

UCONN

Major Research Questions in QCD: Nucleon "Tomography" and low-x physics (gluon saturation, etc)

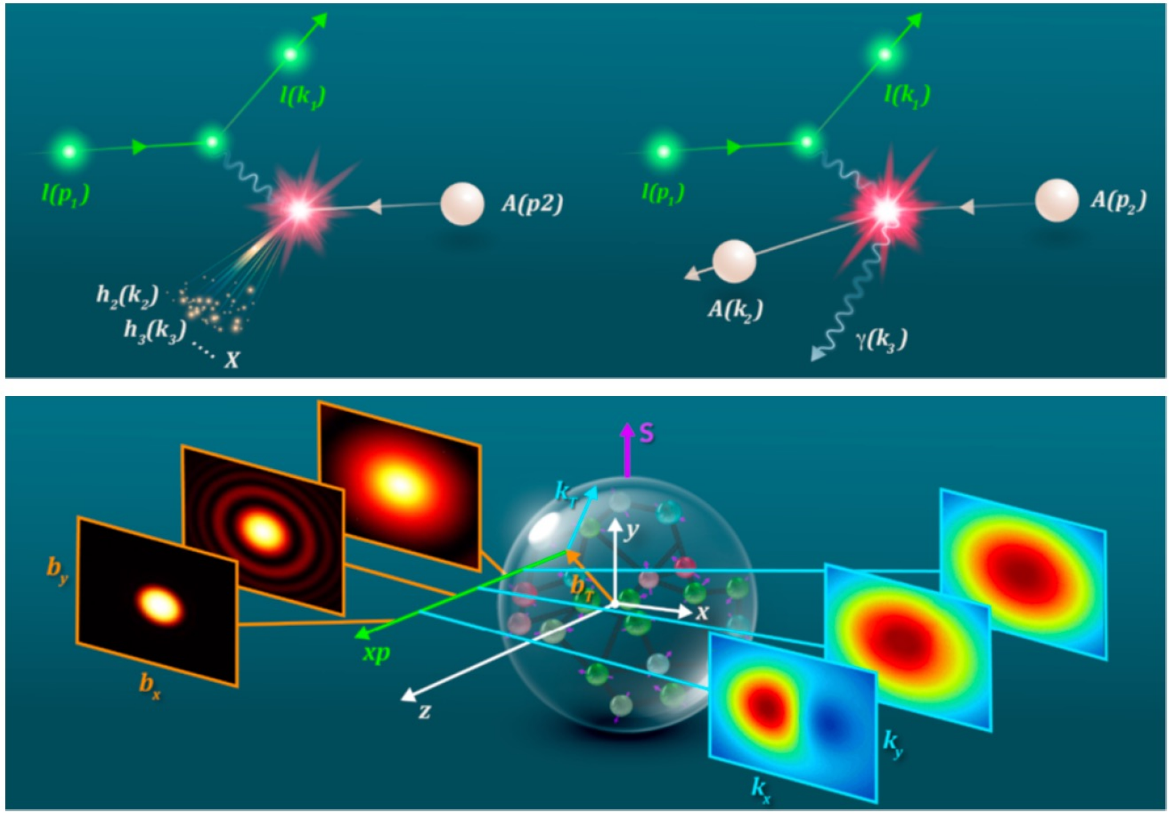


Figure 48: *Upper panel:* Illustration of the two types of processes that occur in lepton-nucleus collisions: a semi-inclusive process where a hadron, hadron pair, jet or dijet is measured and the remnant nucleus is destroyed (left) and an exclusive process where the nucleus remains intact (right). *Lower panel:* Tomographic images in slices of x for the quarks and gluons in a nucleus: (transverse) spatial tomography in $\mathbf{b}_T$-space provided by exclusive processes (left); (transverse) momentum tomography in $\mathbf{k}_T$-space provided by semi-inclusive processes (right). Figure from [1346].

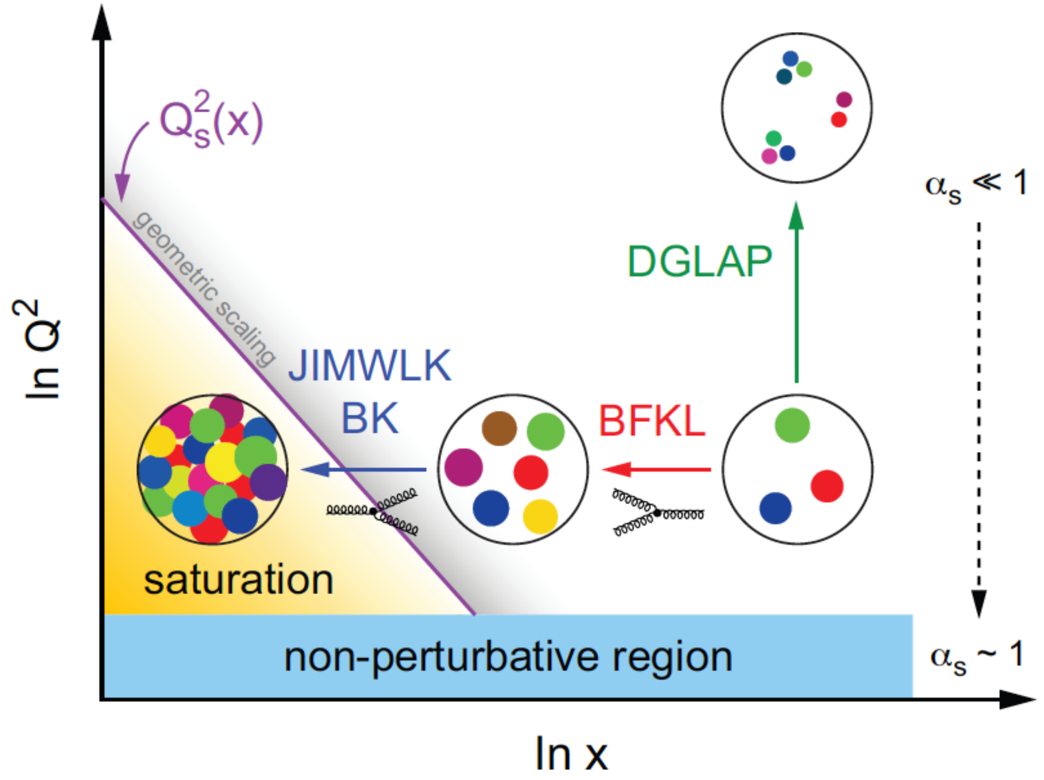
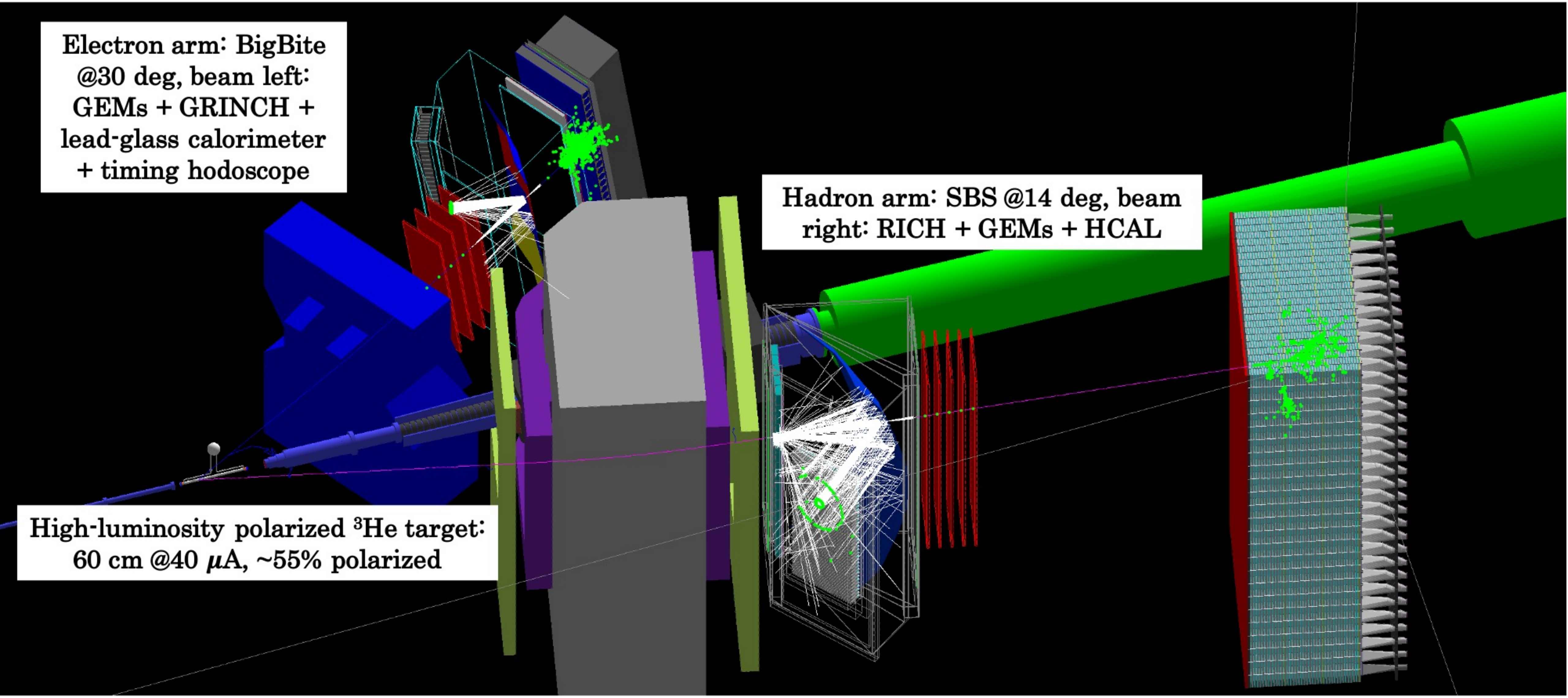


Figure 2.8: Schematic illustration of the probe resolution, Q^2, versus x, indicating regions of non-perturbative (band at the bottom) and perturbative QCD (everything above the non-perturbative region), including in the latter, low to high saturated parton density, and the transition region between them [6]. The perturbative (low-parton density) region is described by the standard DGLAP evolution [55–57] and the linear small-x BFKL evolution [58,59], denoted by the vertical and horizontal arrows correspondingly. The BFKL equation evolves the gluon distribution towards small x, where the parton density becomes large and parton saturation sets in. The transition to saturation is described by the non-linear BK [68–71] and JIMWLK [72–77] evolution equations. The saturation region is shown in yellow.

The SBS SIDIS Experiment (E12-09-018)



SBS SIDIS Collaboration

E12-09-018 is an SBS Collaboration experiment

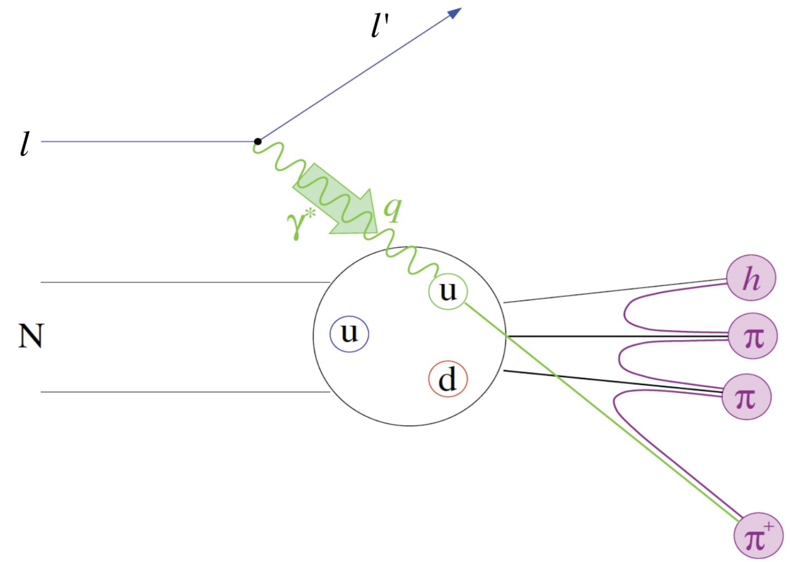
Spokespeople:

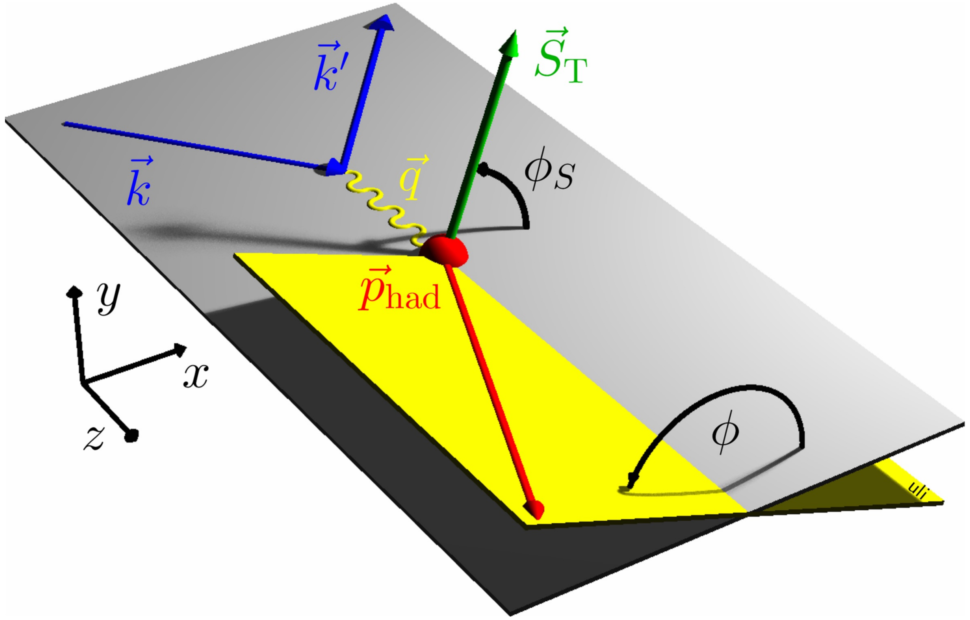
- Gordon Cates, UVA
- Evaristo Cisbani, INFN
- Brian Quinn, CMU
- Andrew Puckett, UConn
- Bogdan Wojtsekhowski, JLab

E12-09-018 History

- First proposed to PAC34 (2009), conditionally approved
- Proposed again to PAC37 (Jan. 2011), again conditionally approved
- Fully approved PAC38 (Aug. 2011), 64 days (40 days 11 GeV, 20 days 8.8 GeV, 4 days "calibration and configuration changes"). A- rating
- Re-approved at jeopardy evaluation at PAC49 (2021), no change in beam time/rating
- Similar physics goals as SOLID SIDIS (and EIC for that matter)
- Complementary kinematic coverage with SOLID (higher x, Q^2)
- Most approved beam time of any SBS experiment
- Almost no new data on this subject (transverse target SSA in SIDIS) for well over a decade (***high-luminosity with transverse polarization is hard***)!
- All detectors required by SIDIS (except RICH) were already used successfully in beam in Hall A, and under more demanding conditions than SIDIS proposal
- No costly spectrometer moves! Just sit and take data!

Motivation: 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 plane
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 formalism: ***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)*

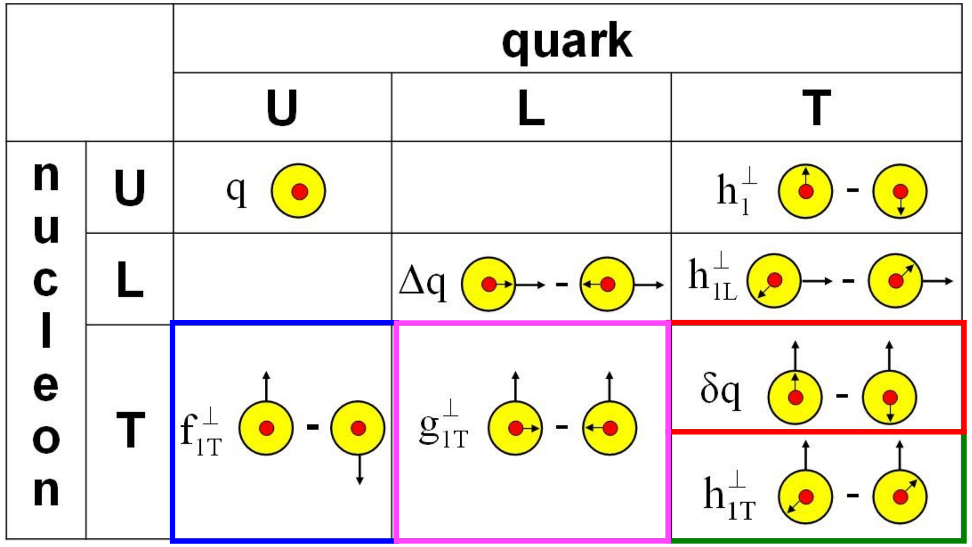
$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,d\phi_S\,dp_T^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \epsilon F_{UU,L} +$$
$$\sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h} +$$
$$\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h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

- 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 modulations allow separation of structure functions
- Partonic interpretation: SIDIS structure functions factorize as convolution of universal TMD PDF, universal TMD FF, and perturbatively calculable "hard" subprocess $eq \rightarrow eq$

$$\gamma = \frac{2Mx}{Q}$$
$$\epsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

Effects of Transverse Target Polarization in SIDIS



Transverse target spin-dependent cross section for SIDIS

- Collins effect—probe transverse polarization of quarks
- Sivers effect—probes correlations between quark transverse momentum and nucleon transverse spin.
- "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

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

D_1 = unpolarized fragmentation function

$H_1^\perp$ = Collins fragmentation function

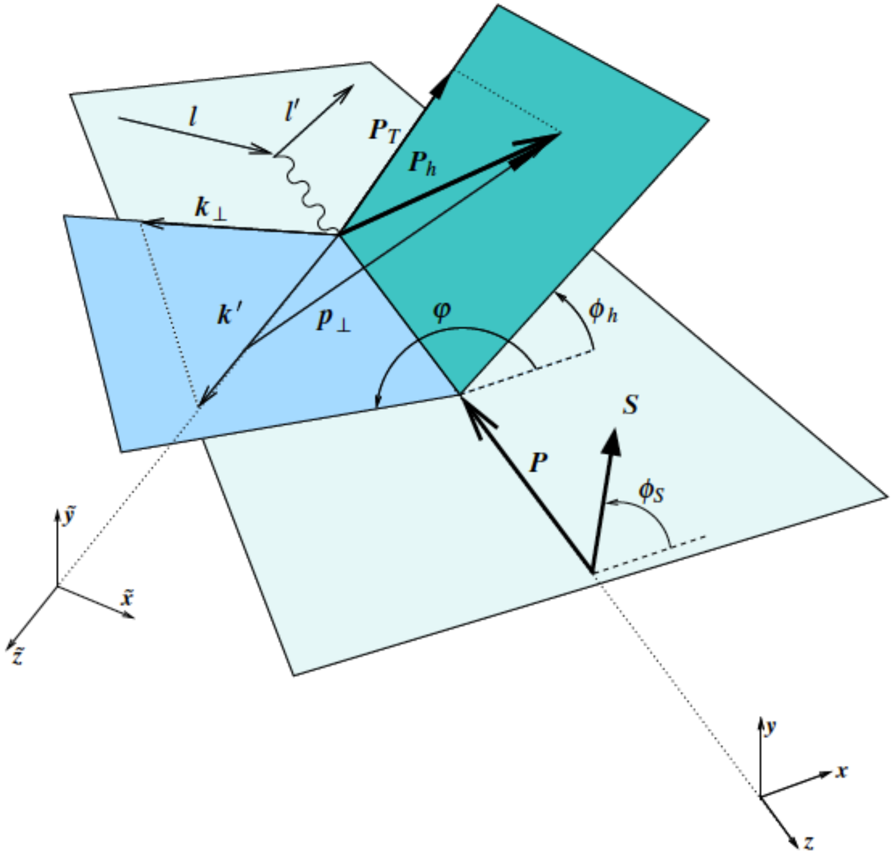
$$
\begin{aligned}
A_{UT}^{Collins} &\propto \delta q \otimes H_1^\perp \\
A_{UT}^{Sivers} &\propto f_{1T}^\perp \otimes D_1 \\
A_{UT}^{Pretz} &\propto h_{1T}^\perp \otimes H_1^\perp
\end{aligned}
$$

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

Where do the azimuthal dependences come from for transverse target SSAs?

• The Sivers effect is a correlation between unpolarized quark k_T and the nucleon's transverse polarization:

$$\begin{aligned} \mathbf{S}_T \cdot (\mathbf{P} \times \mathbf{k}_\perp) &\approx (\cos\phi_S \hat{x} + \sin\phi_S \hat{y}) \cdot \\ &\quad (-\hat{z} \times (\cos\phi_h \hat{x} + \sin\phi_h \hat{y})) \\ &= \sin\phi_h \cos\phi_S - \cos\phi_h \sin\phi_S \\ &= \sin(\phi_h - \phi_S) \end{aligned}$$

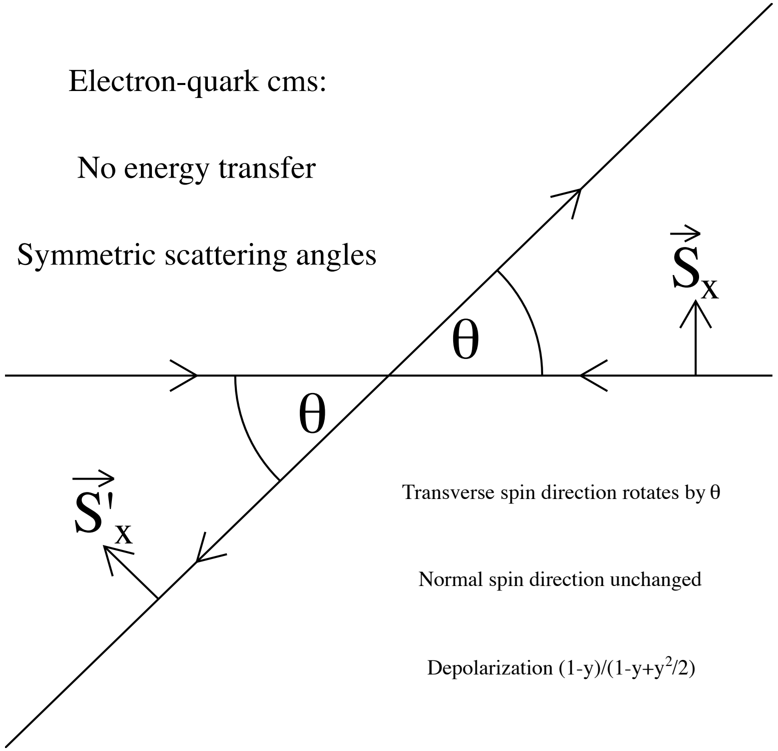


• The Collins effect is due to the left-right asymmetry in the fragmentation of a transversely polarized quark.
• The observable asymmetry results from the convolution of the transversity distribution and the Collins (spin-dependent) fragmentation function:

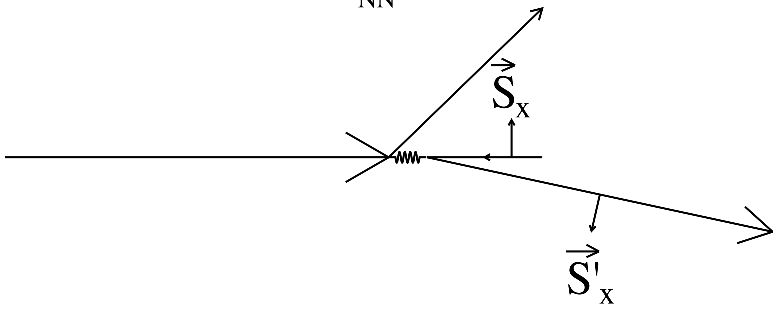
$$\begin{aligned} \mathbf{s}_q \cdot (\mathbf{k'}_q \times \mathbf{p}_\perp) &\approx (-\cos\phi_S \hat{x} + \sin\phi_S \hat{y}) \cdot \\ &\quad (\hat{z} \times (\cos\phi_h \hat{x} + \sin\phi_h \hat{y})) \\ &= \sin\phi_h \cos\phi_S + \cos\phi_h \sin\phi_S \\ &= \sin(\phi_h + \phi_S) \end{aligned}$$

• The in-plane component of quark transverse polarization must flip in order to absorb the transversely polarized virtual photon (angular momentum conservation) → Sign of ϕ_S is reversed in observable asymmetry

Transverse spin dynamics in eq→eq

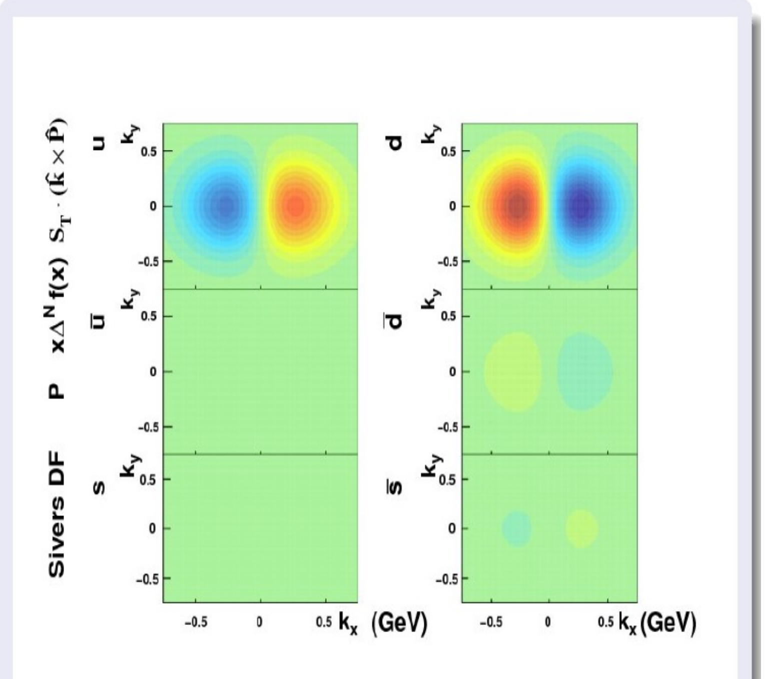


Target rest frame:
Large energy transfer
$\nu^2, Q^2 >> x^2M^2$
Flip of transverse spin direction
Normal polarization direction unchanged
Depolarization $D_{NN} = (1-y)/(1-y+y^2/2)$



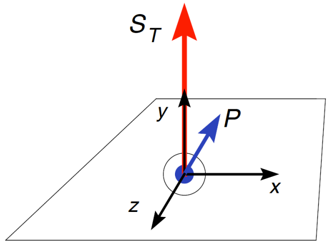
- Magnitude of quark normal and in-plane transverse polarization components is reduced by a factor of
    - $D_{nn} = (1-y)/(1-y+y^2/2)$, where $y = (1 - \cos\theta_{CM})/2$ is invariant ($y=(\nu/E)_{LAB}$).
- Direction of normal polarization is unchanged
- The in-plane transverse polarization component in the cms rotates with quark momentum vector—corresponds to a spin flip in target rest frame (P, q collinear)
- ***Ang. mom. conservation requires spin flip for quark to absorb transverse virtual photon***
- ***Depolarization factor D_{NN}, an inherent feature of the hard partonic subprocess, suppresses the observable SSA corresponding to Collins effect, esp. at large y!***

The Sivers effect as a probe of quark OAM

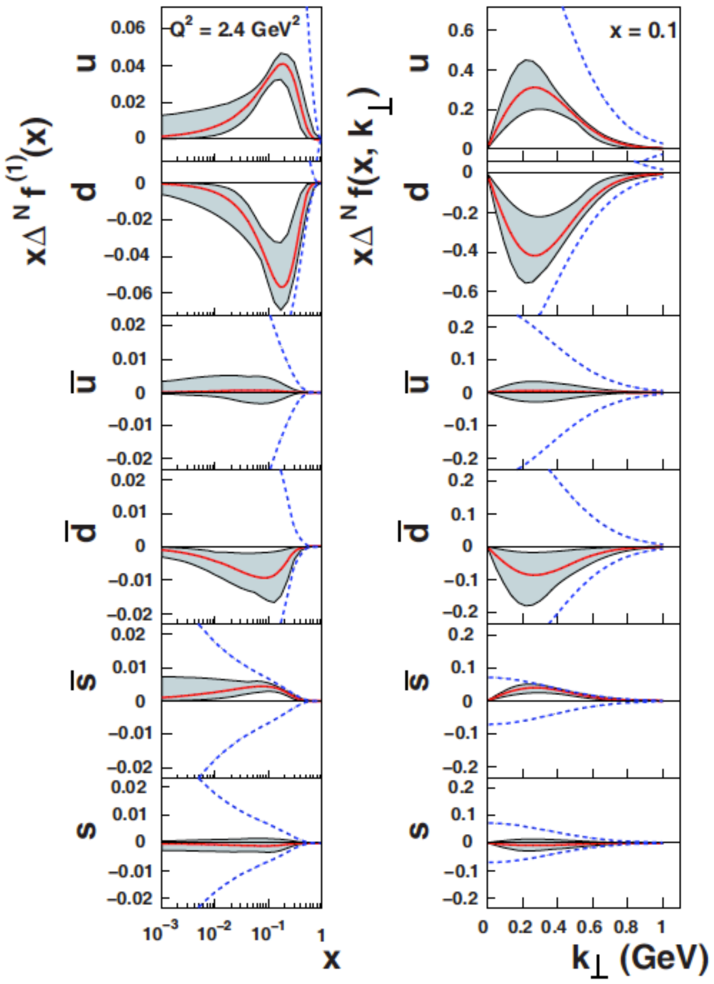


x = 0.2

Plots by A. Prokudin



- Proton spin is along +y axis (up)
- Proton momentum into screen
- Regions of higher/lower quark density in transverse momentum space



- Sivers effect: a left-right asymmetry in the transverse momentum distribution of unpolarized quarks in a transversely polarized nucleon

Kinematic Conditions for applicability of TMD formalism

- Requires large Q² ($Q^2 > 1\ GeV^2$), 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 (high Q^2 also helps here)
- 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 collinear pQCD effects (gluon radiation, etc.)

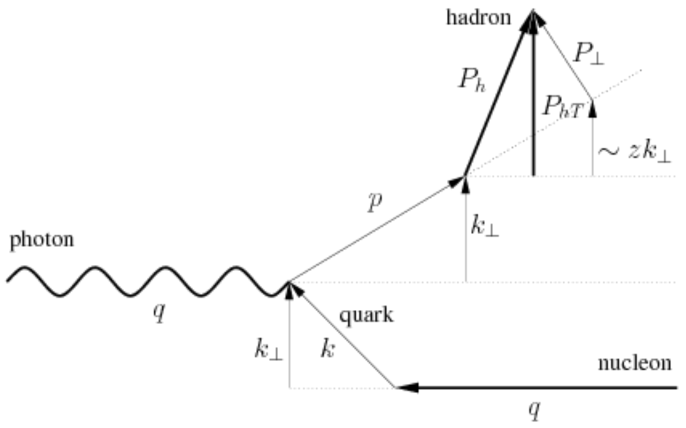


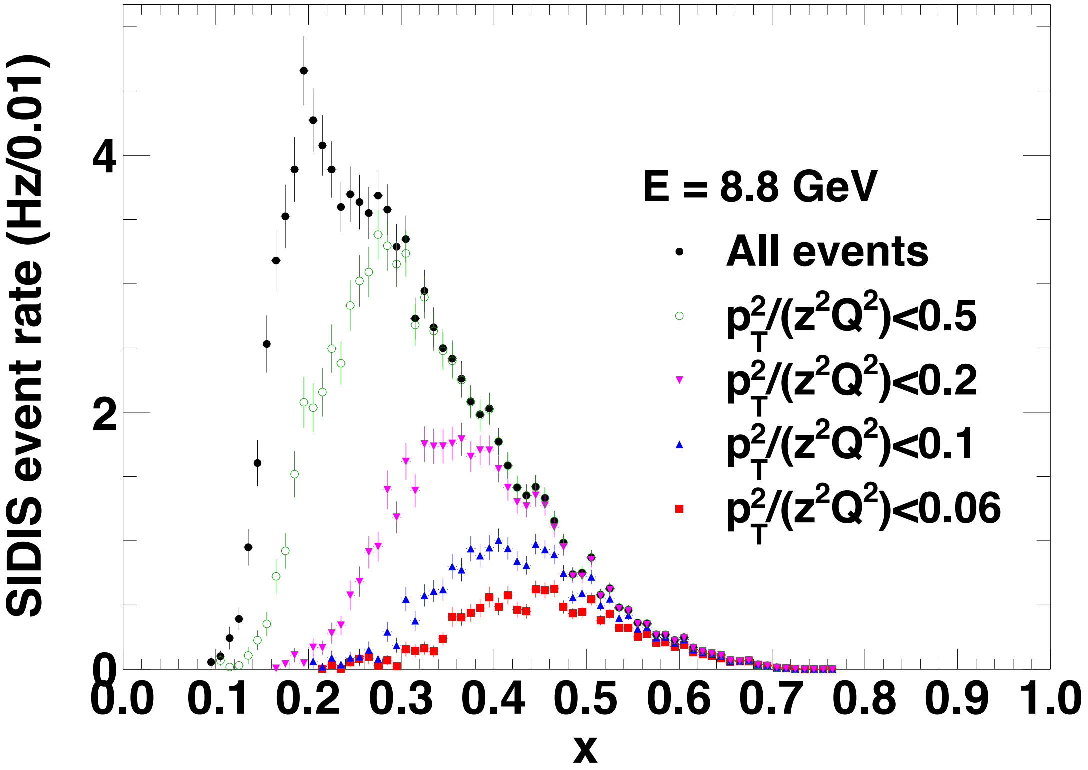
Figure credit: Bacchetta *et al.*, JHEP 1706 (2017) 081

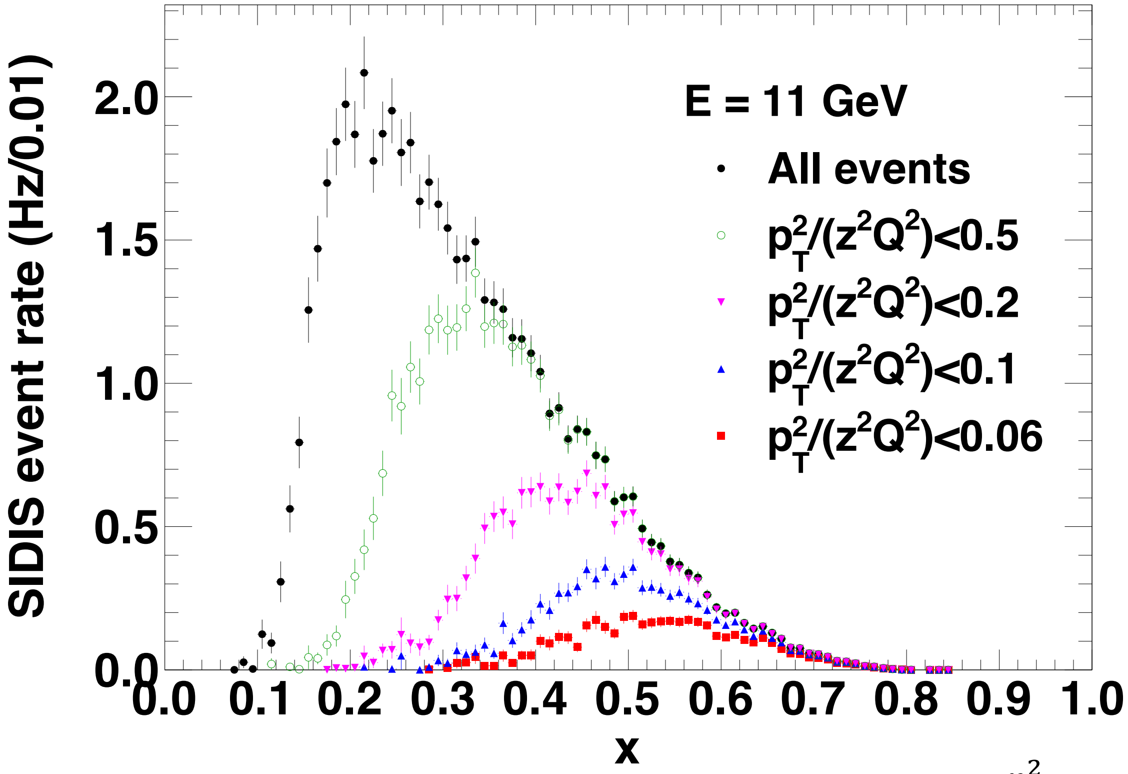
At leading order in $k_\perp/Q$, we have:

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

- 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.

To what extent is $\frac{p_T}{zQ} \ll 1$ satisfied by E12-09-018 (and in JLab kinematics generally)?





- A recent global analysis of unpolarized TMD data by Scimemi and Vladimirov (arxiv:1912.06532) suggested a limit of $\frac{p_T^2}{z^2Q^2} < 0.06$ for applicability of TMD interpretation of SIDIS data
- Other widely cited analyses, such as Bacchetta *et al.* (arxiv:1703.10157) have achieved self-consistent descriptions of world data with far less stringent criteria.
- Domain of applicability of TMD formalism remains very much an open question
- E12-09-018 kinematic coverage is focused in the highest practically accessible Q^2 regime with 11 GeV fixed-target SIDIS→well suited to investigate this issue empirically.

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.

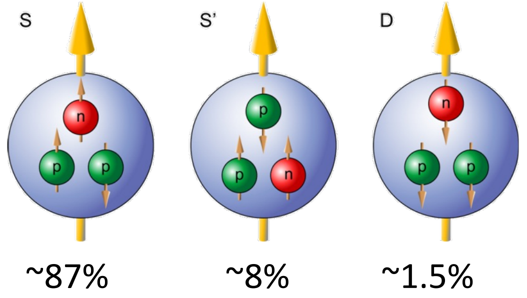
Asymmetries:

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

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

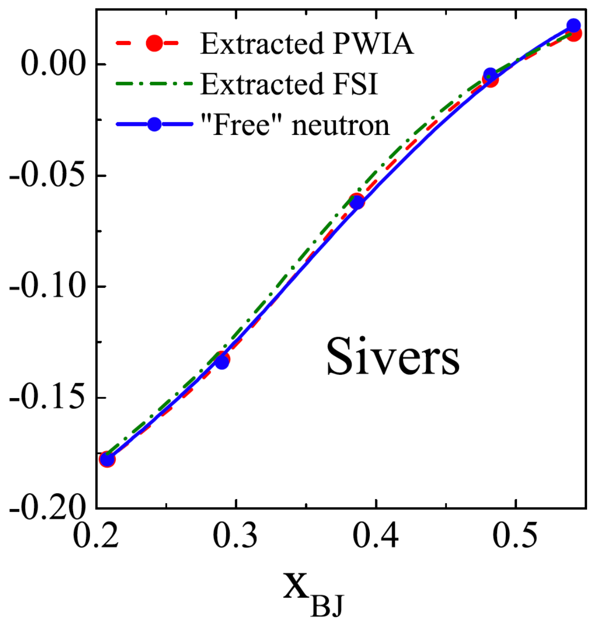
- SIDIS structure functions, *before* considering azimuthal angle dependence, are functions on a 4-D phase space (x, Q^2, z, p_T) (and a purely kinematic dependence on y for some observables due to helicity structure of hard partonic subprocess $eq \rightarrow eq$)
- Sufficiently high ***energy*** is 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 polarization observables and for 4-D analysis
- High beam and/or target ***polarization*** is required for spin-dependent observables: FOM is proportional to ***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).

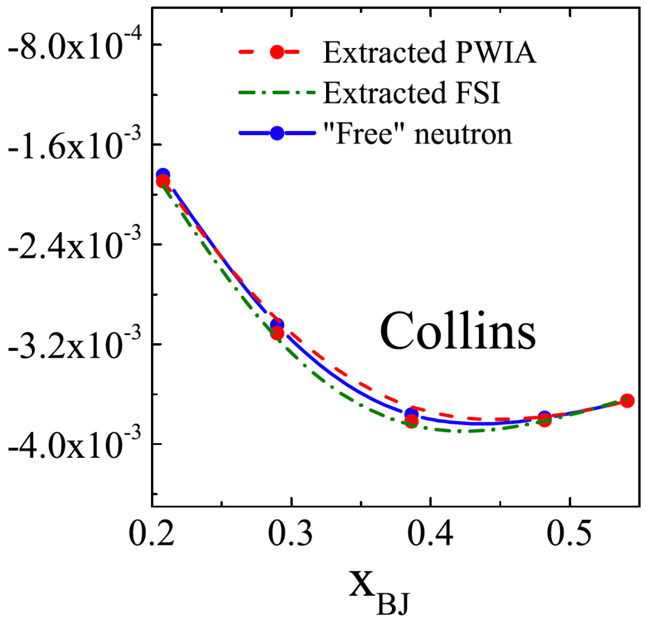
Reminder: Helium-3 as Effective Polarized Neutron Target



$$A_{^3\text{He}} = P_n(1-f_p)A_n + P_p f_p A_p$$
$$P_n = 0.86^{+0.036}_{-0.02}$$
$$P_p = -0.028^{+0.009}_{-0.004}$$
$$f_p = \frac{2\sigma_p}{\sigma_{^3\text{He}}}$$

Effective nucleon polarization approximation:
Scopetta, Phys. Rev. D 75, 054005 (2007)



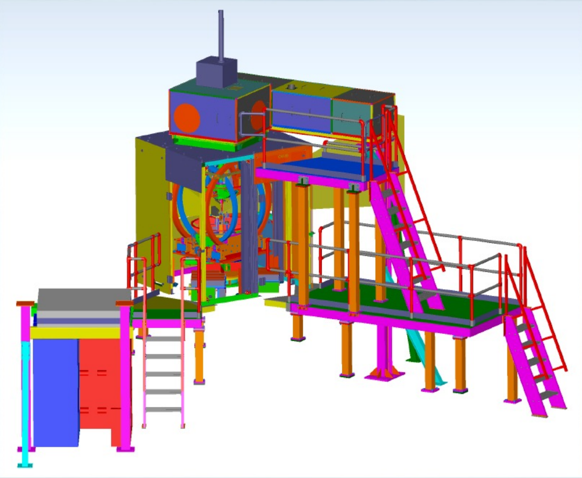


Del Dotto *et al.,* Phys. Rev. C 96, 065203 (2017)

- Effect of nuclear FSI on extraction of neutron Collins and Sivers effects from SIDIS on ^{3}He under good theoretical control
- Advantages of Helium-3 for study of polarized neutron:
  - Protons almost unpolarized
  - High luminosity capability (up to several 10^{37} cm^{-2} s^{-1})
  - Small holding field → small systematics of target spin flips

The SBS GEN/SIDIS polarized Helium-3 Target

The SBS SIDIS Polarized ^{3}He Target



- Essentially the SBS G_E^n polarized ^{3}He target with small modifications
  - Will add capability for vertical polarization
- Magnetic shielding protects target from SBS and BigBite magnet fringe fields.
- For both SIDIS and G_E^n, the quantity of ^{3}He is twice what was used for recent Hall C experiments.
- Double the luminosity follows from twice the ^{3}He and twice the laser power.
- Note: Hall C A_1^n experiment, (with twice the luminosity of previous experiments) ran with performance essentially identical to expectations from simulated beam tests.

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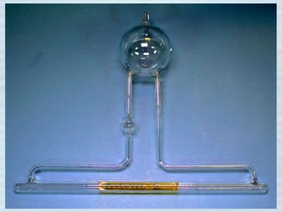
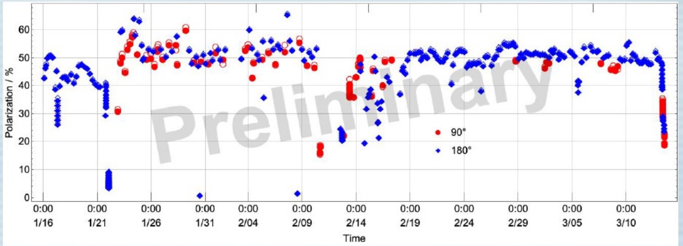
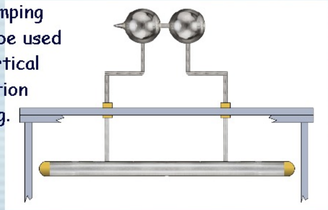
The SBS SIDIS Polarized ^{3}He Target

Shown is Mike Souza, our Princeton glassblower, holding a G_E^n prototype target cell.





Double pumping chamber to be used during vertical polarization running.



- The Hall C polarized ^{3}He target was the first used at JLab with the so-called "convection design", permitting full control of the movement of gas between the pumping and target chambers.
- The figure-of-merit of the Hall C A_1^n target was over twice that achieved with a polarized ^{3}He target anywhere.
- As noted earlier, it ran with performance essentially identical to expectations from simulated beam tests.

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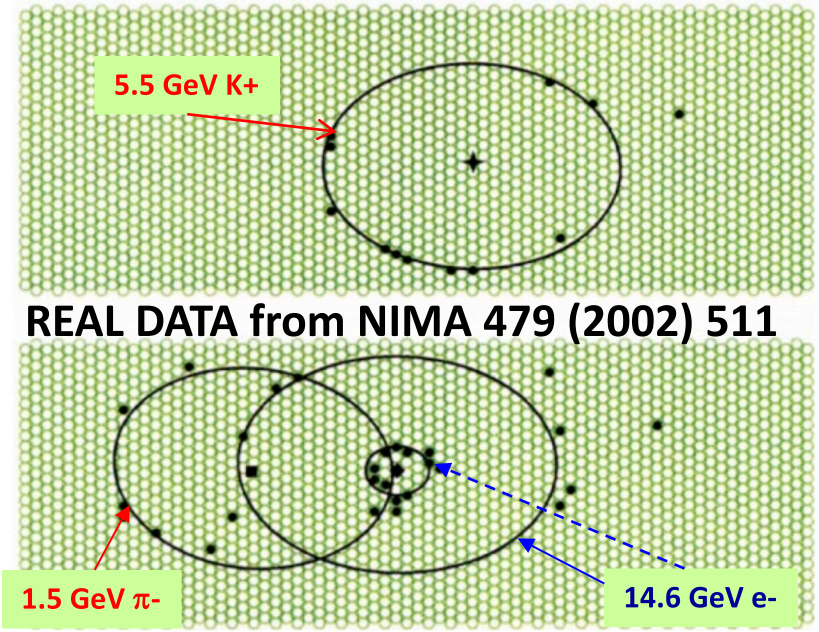
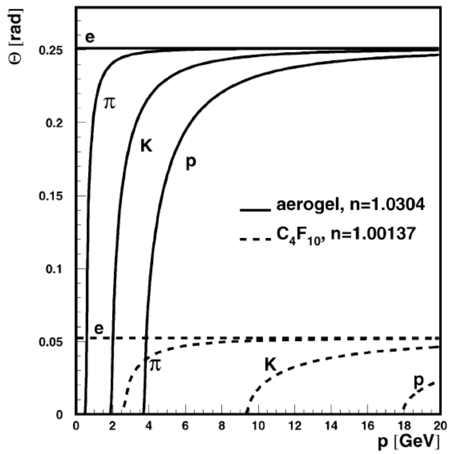
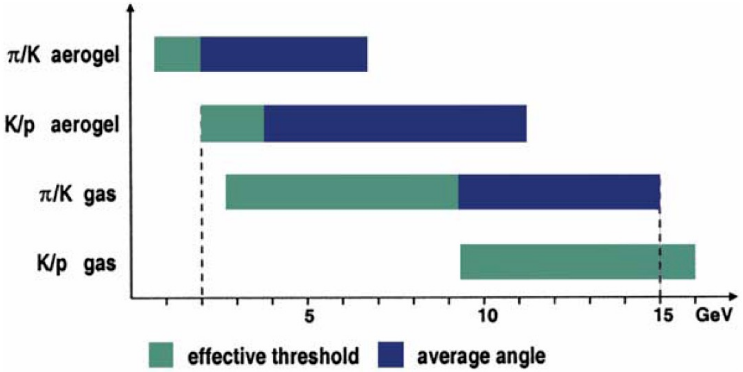
- These slides are from Gordon's Jeopardy presentation at PAC49 (2021, before GMN started)
- See also Gordon's target talk

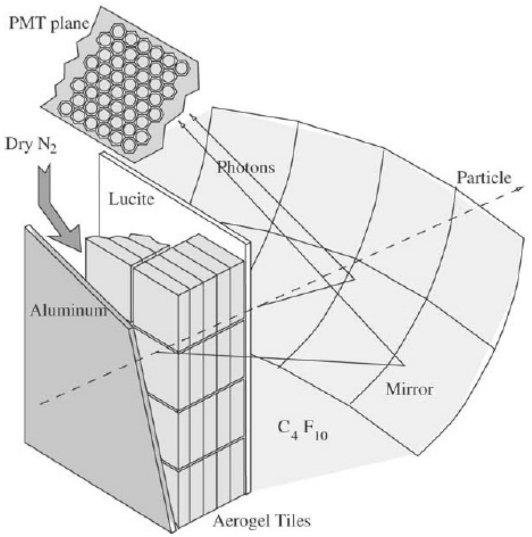
The HERMES/SBS RICH detector, I

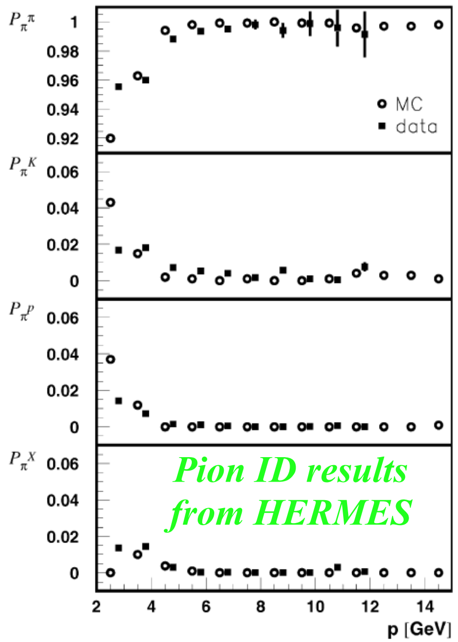


- ***HERMES RICH geometry, performance characteristics well matched to SBS needs.***
- π/K/p separation for p from 2-15 GeV based on dual-radiator design.
- Re-use one half of detector, both aerogels

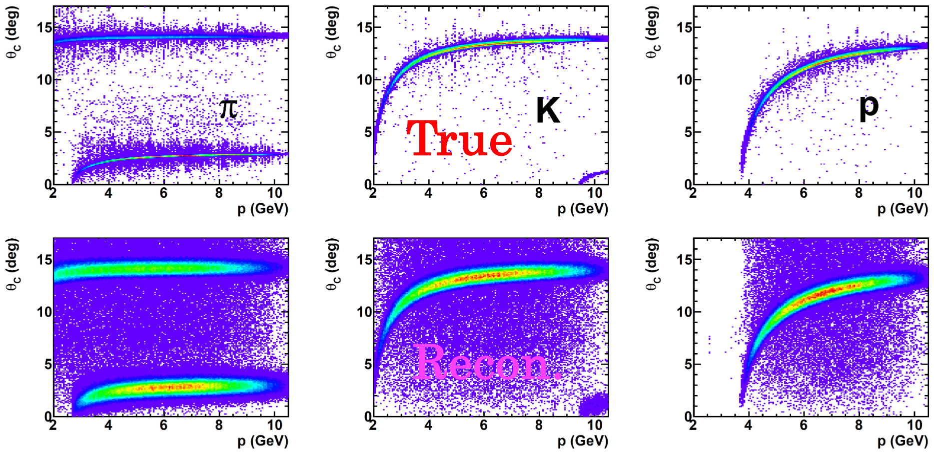






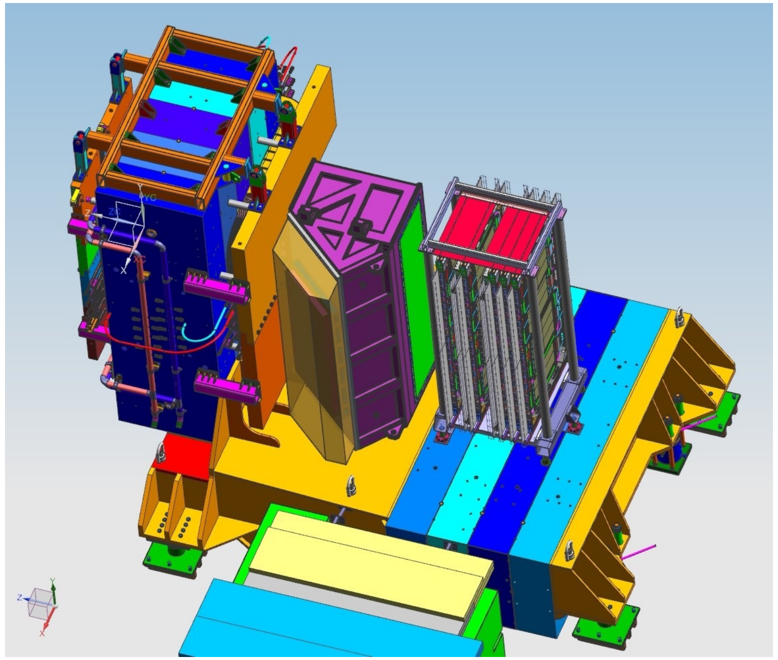


The HERMES/SBS RICH detector, II

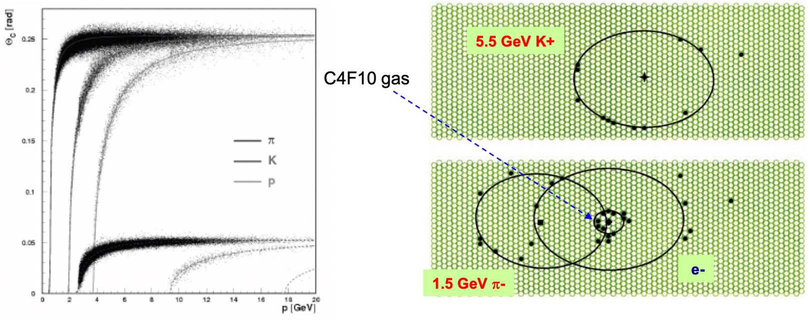


Simulated RICH reconstruction in SBS

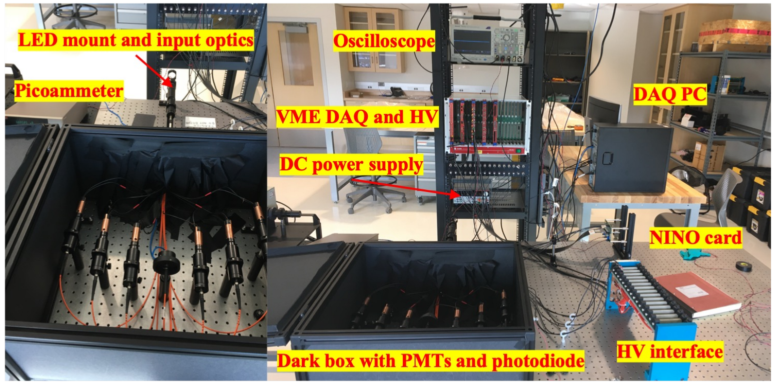
RICH detector at JLab



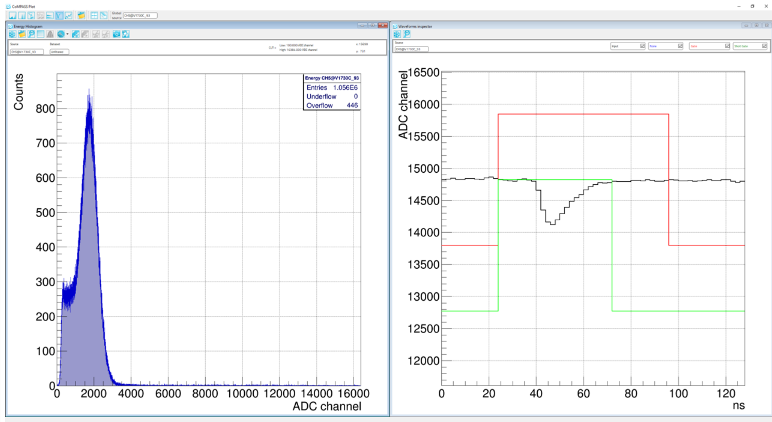
RICH in SBS CAD model



RICH performance in HERMES

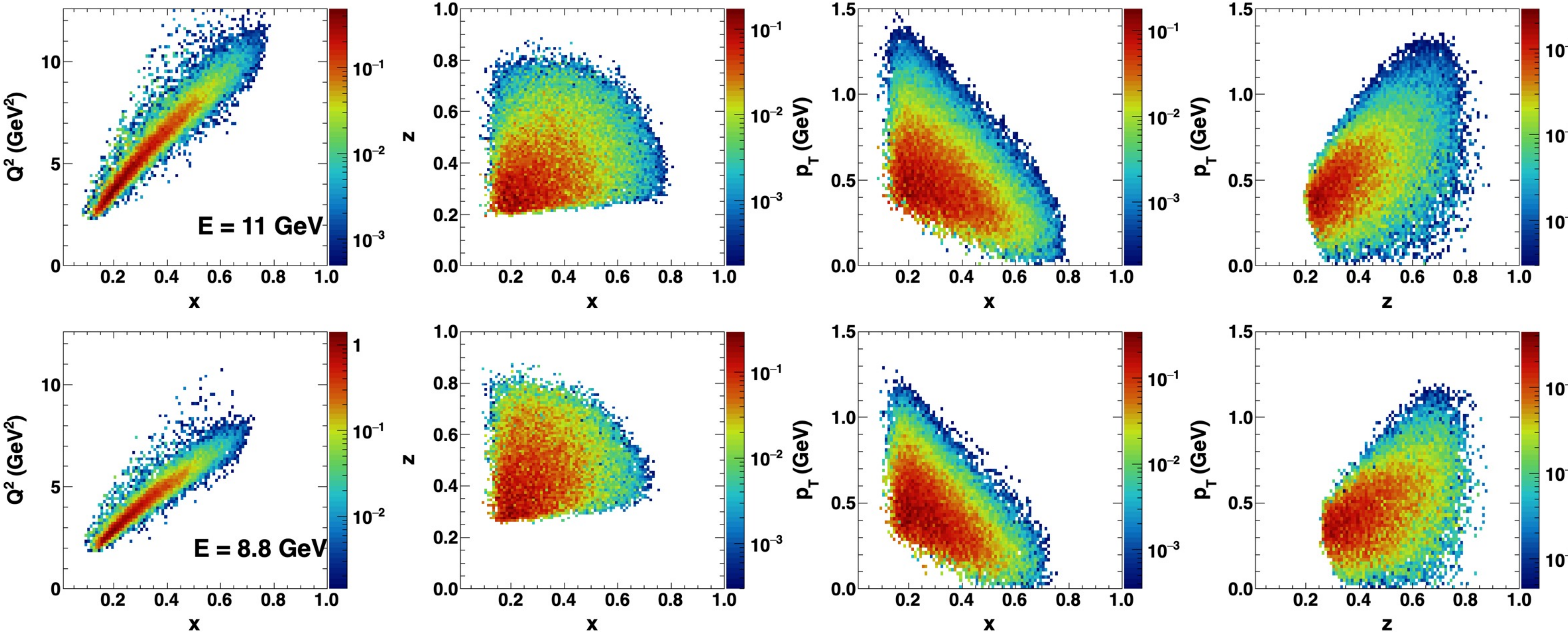


RICH PMT test stand at UConn



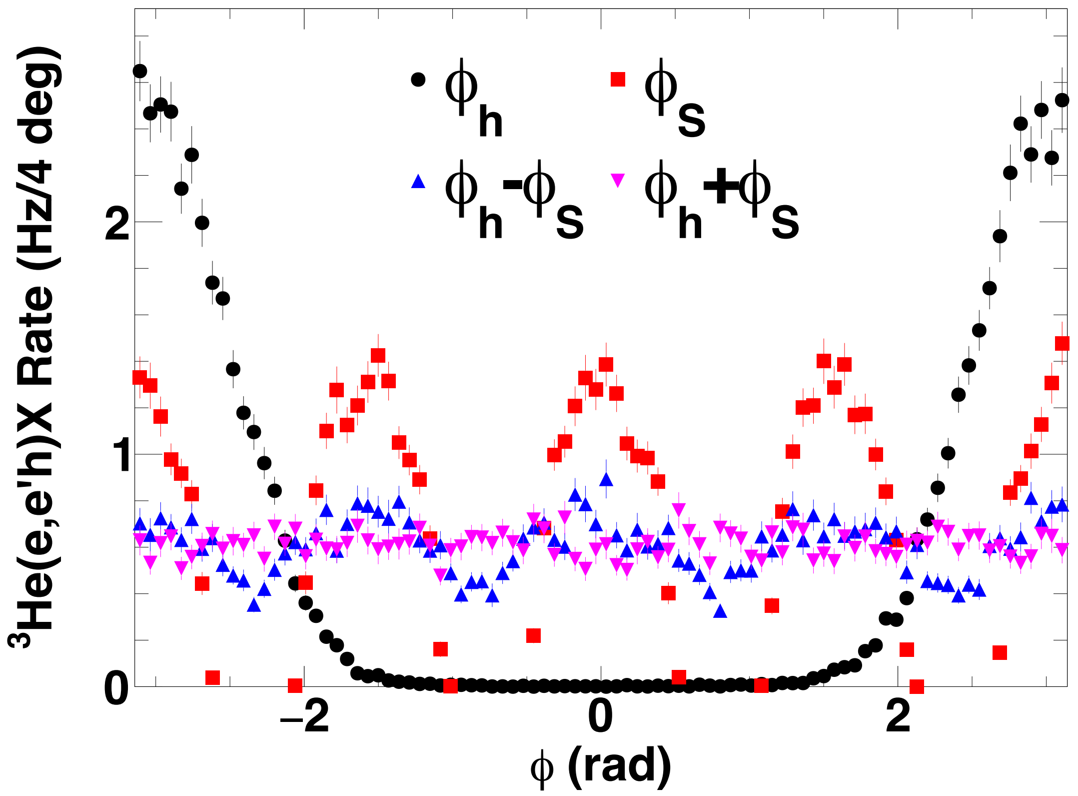
RICH PMT single-photoelectron pulse and charge spectrum

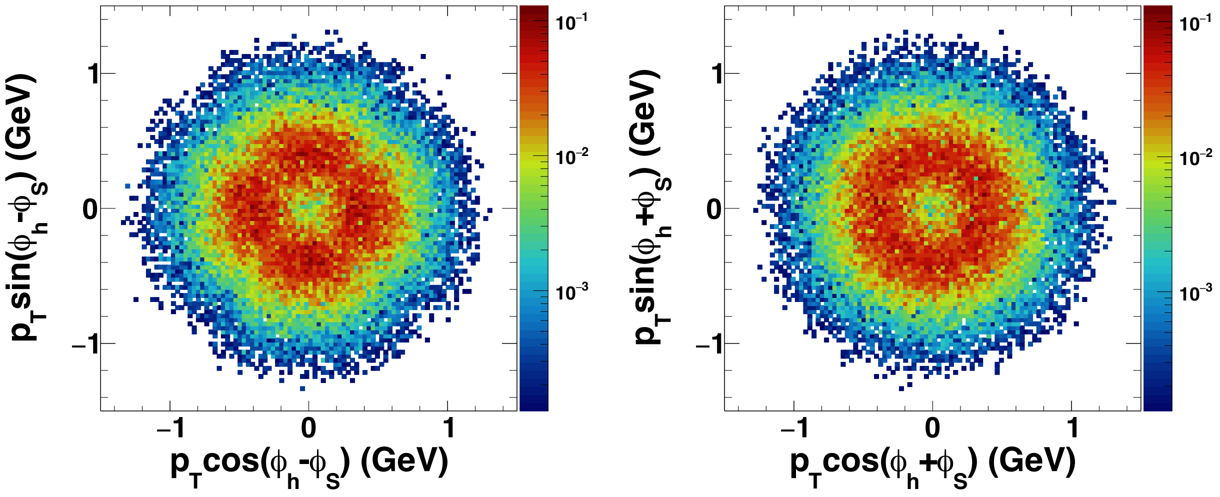
SBS SIDIS Kinematic Coverage

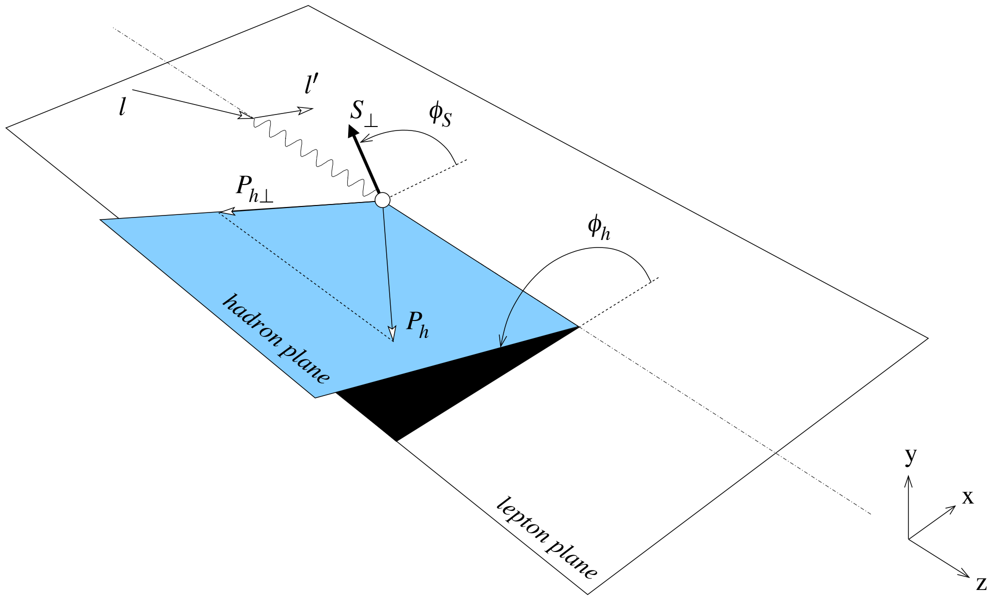


- Above, left to right: SBS SIDIS kinematic coverage in $(Q^2, x), (z, x), (p_T, x), (p_T, z)$, for E = 11 GeV (top row) and 8.8 GeV (bottom row), from *g4sbs*
- Cuts applied are: $Q^2 \geq 1\ GeV^2, W^2 \geq 4\ GeV^2, M_X^2 \geq 2.3\ GeV^2, E_e' \geq 1\ GeV$ (roughly equivalent to $y \leq 0.9$), $p_h \geq 2\ GeV$, and good tracks/signals required in all relevant SBS+BB detectors

SBS SIDIS Azimuthal Angle Coverage

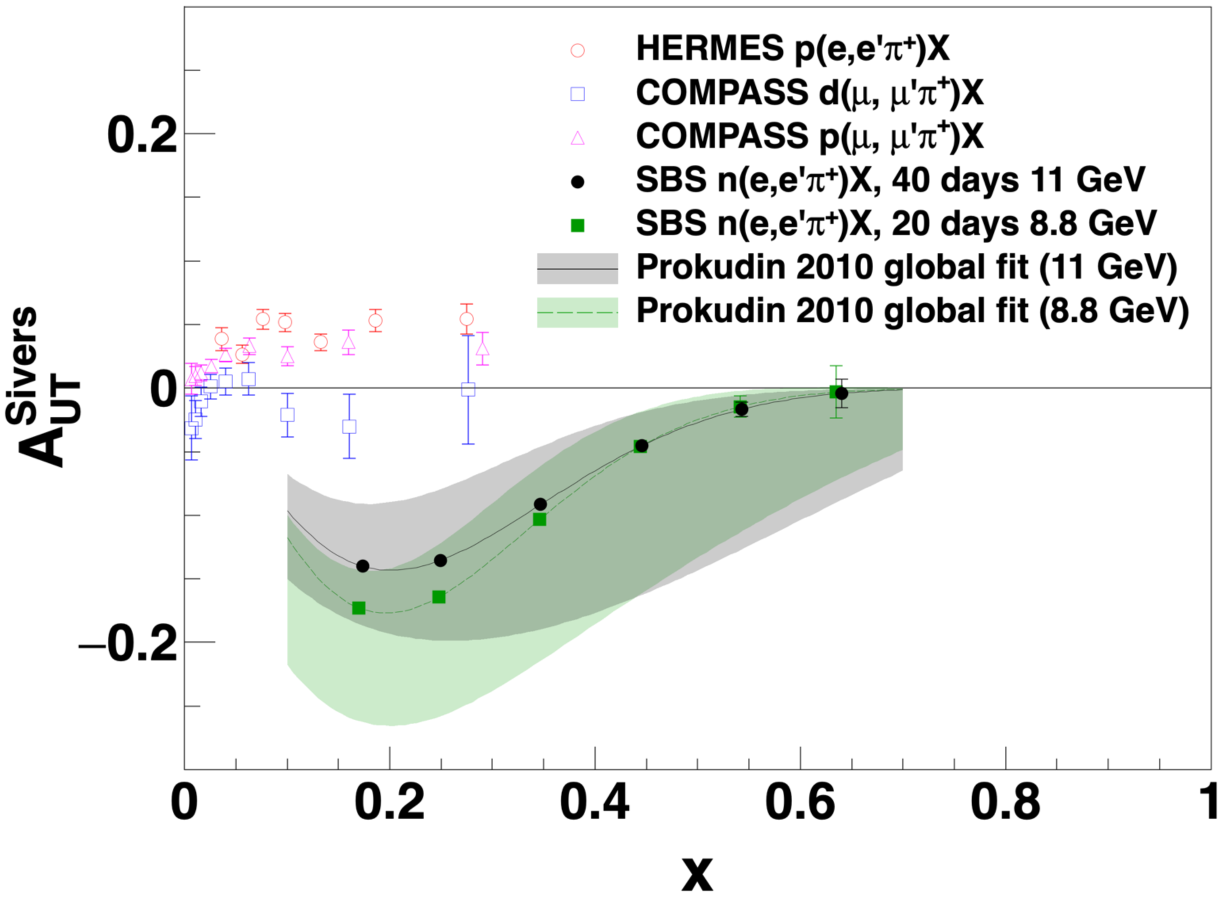




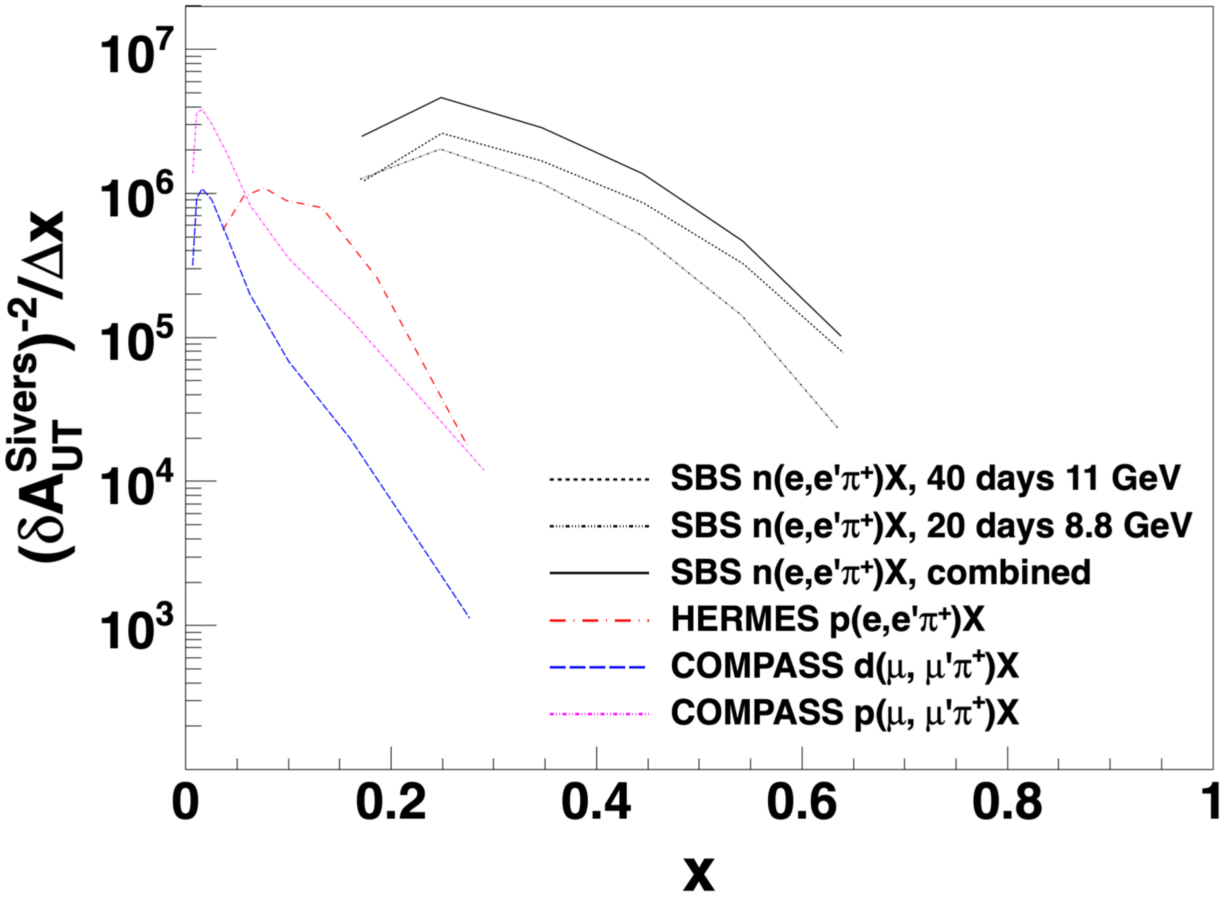


- Original proposal envisioned 8 target spin directions
- Simulations show full and (sufficiently) uniform coverage of $\phi_h \pm \phi_S$, no reduction of physics impact with 4 target directions
- Dramatically simplifies target design & operation

SBS SIDIS projected results: A_{UT}^{Sivers} for $\vec{n}(e,e'\pi^+)X$

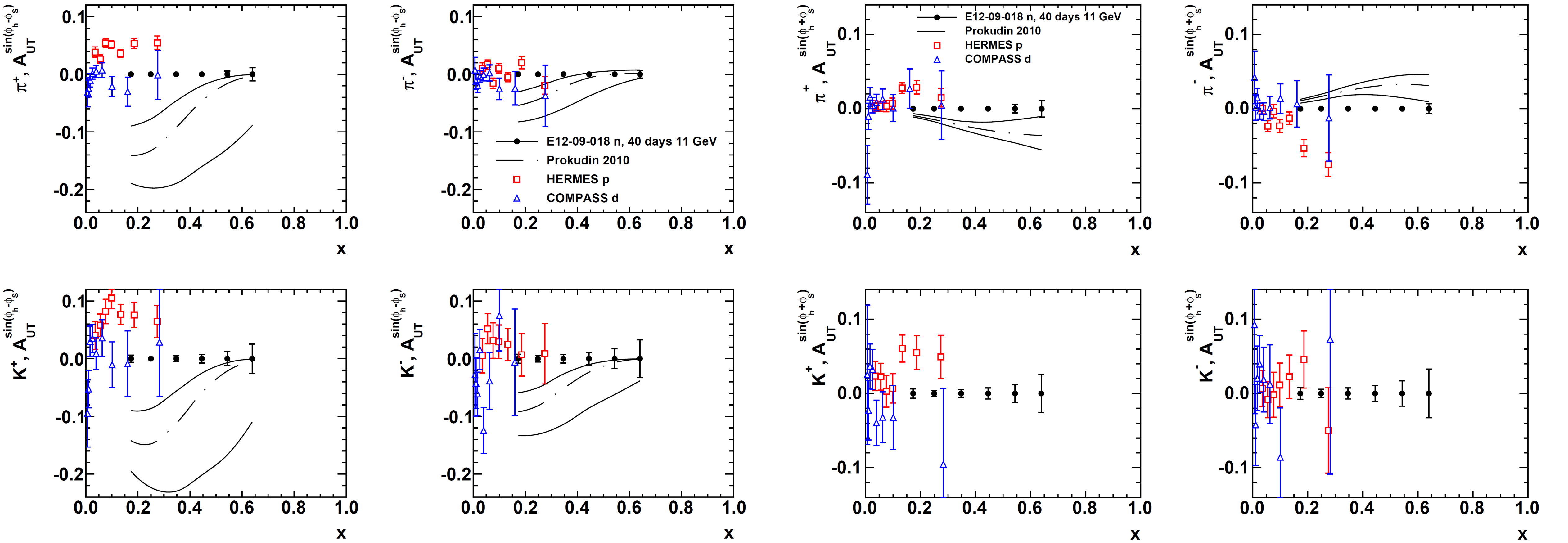


Example comparison of E12-09-018 projected statistics to HERMES and COMPASS published data



Same as left, plotted as statistical Figure-of-Merit (FOM) per x interval.

SBS+BB Projected Results: Collins and Sivers for π^+, π^-, K^+, K^-



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.

E12-09-018 Summary (as shown at PAC49 jeopardy review)

Semi-Inclusive Deep Inelastic Scattering on a Transversely Polarized He-3 Target Using the BigBite and Super BigBite Spectrometers in Hall A: PAC49 update to E12-09-018

G. Cates (UVa), E. Cisbani (INFN), A. J. R. Puckett (UConn), B. Quinn (CMU), B. Wojtsekhowski (JLab), E12-09-018 collaboration, and the SBS collaboration

E_e (GeV)	Days	$^3He(e,e'\pi^+)X$ Events/10^6	$^3He(e,e'\pi^-)X$ Events/10^6	$^3He(e,e'K^+)X$ Events/10^6	$^3He(e,e'K^-)X$ Events/10^6	$^3He(e,e'\pi^0)X$ Events/10^6
11	40	104	69	14	2.4	17
8.8	20	101	57	14	2.1	15

TABLE I. Total projected $^3He(e,e'h)X$ statistics in the PAC38-approved E12-09-018 beam time at 11 and 8.8 GeV by hadron, after applying all relevant calorimeter, track, and Cherenkov cuts in both spectrometers. Kinematic cuts applied are $Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2, $M_X^2 > 2.3$ GeV^2, $p_T \geq 0.05$ GeV, $E_e' \geq 1$ GeV and $p_h \geq 2$ GeV. In addition, adequate signals in the BigBite and SBS detectors were required as described in the text. Full statistical projections for Collins and Sivers asymmetries $\vec{n}(e,e'h)X$, as evaluated for the original PAC38 proposal, are tabulated in Ref. [39].

	Time (day)
Production run at $E = 11$ GeV	40
Production run at $E = 8.8$ GeV	20
Calibration Runs	2
Target maintenance and configuration changes	2
Total	64

- **Jeopardy proposal re-approved by PAC49 (2021) with no change in beam time or scientific rating.**
- E12-09-018 has progressed to an advanced stage of readiness. Science case has not changed (if anything it has strengthened) since PAC38.
- Truly dramatic increase in statistical precision: ~10-100X increase in FOM over any existing or projected proton or neutron TSSA data available before SOLID/EIC → E12-09-018 data will dominate the empirical study of transverse-spin-dependent TMD phenomena for years to come
- Can run either in Hall C (~late 2020s?) or in Hall A after MOLLER/before SOLID

Backups

Unpolarized TMD global fitting—Pavia 2017

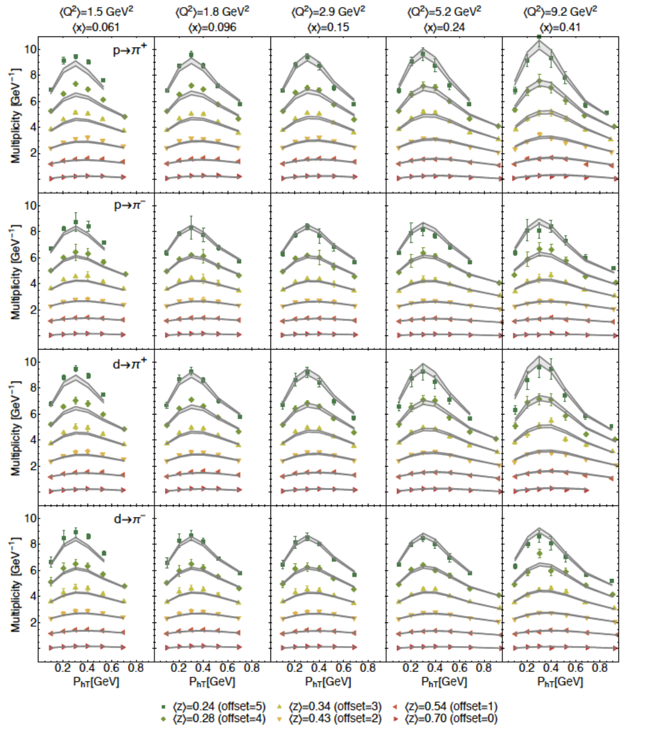


FIG. 3: HERMES multiplicities for production of pions off a proton and a deuteron for different $\langle x\rangle$, $\langle z\rangle$, and $\langle Q^2\rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. For clarity, each $\langle z\rangle$ bin has been shifted by an offset indicated in the legend.

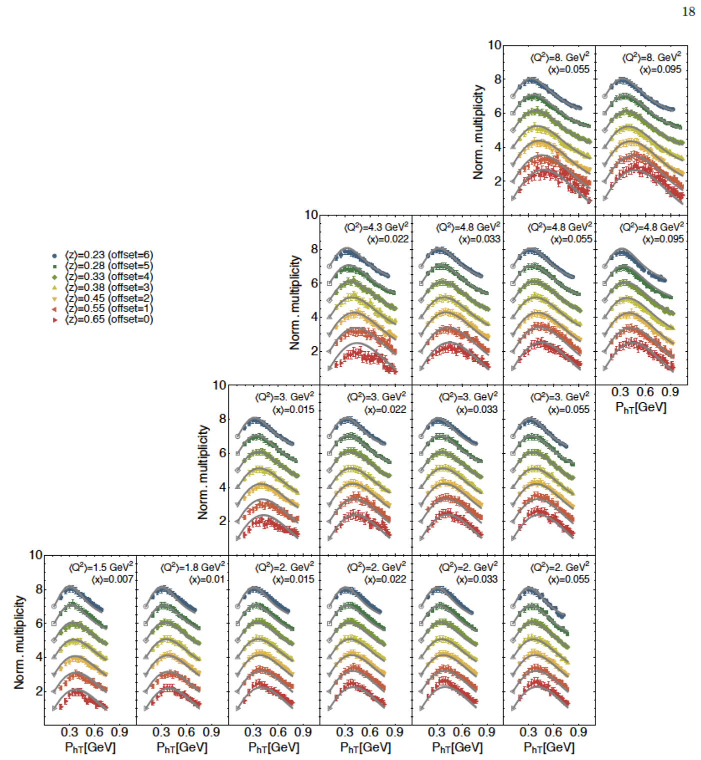


FIG. 6: COMPASS multiplicities for production of positive hadrons (π^+) off a deuteron for different $\langle x\rangle$, $\langle z\rangle$, and $\langle Q^2\rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. Multiplicities are normalized to the first bin in P_{hT} for each $\langle z\rangle$ value (see (41)). For clarity, each $\langle z\rangle$ bin has been shifted by an offset indicated in the legend.

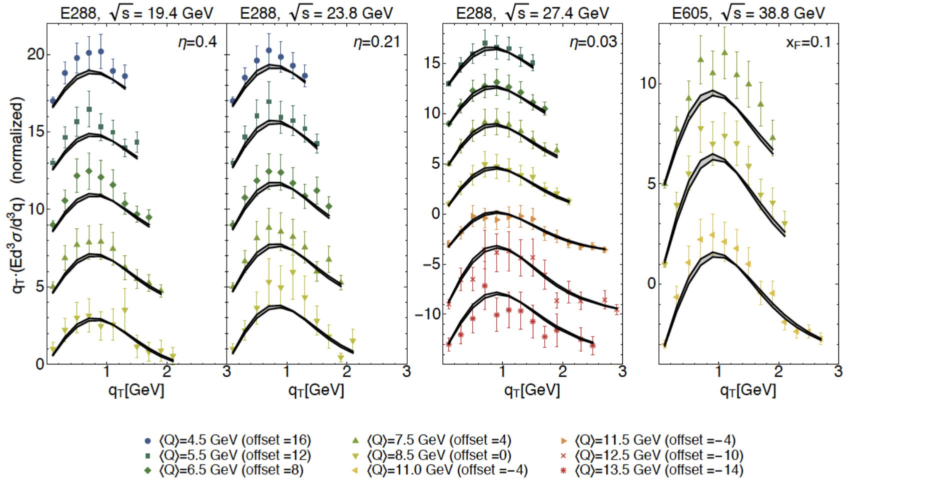


FIG. 7: Drell–Yan differential cross section for different experiments and different values of $\sqrt{s}$ and for different $\langle Q\rangle$ bins. For clarity, each $\langle Q\rangle$ bin has been normalized (the first data point has been set always equal to 1) and then shifted by an offset indicated in the legend.

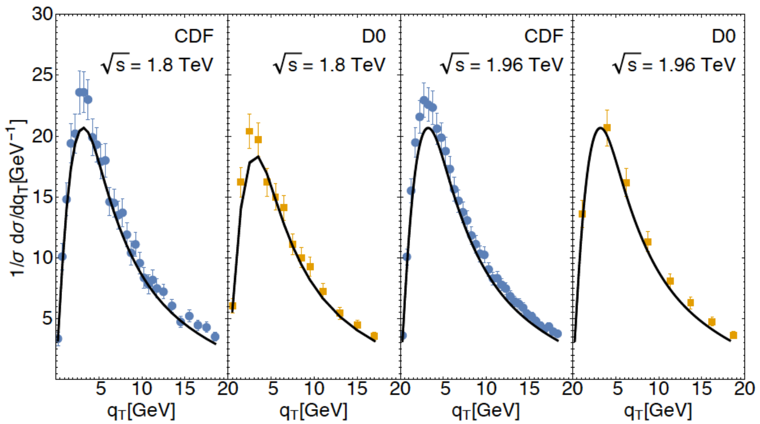
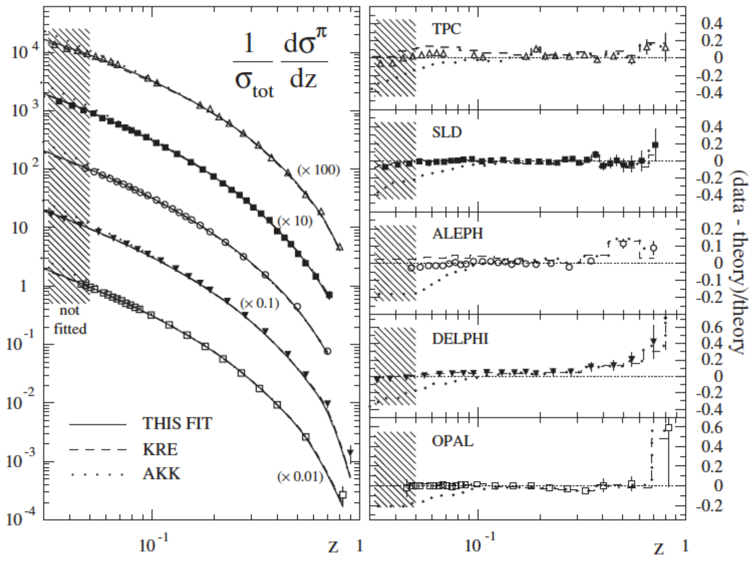
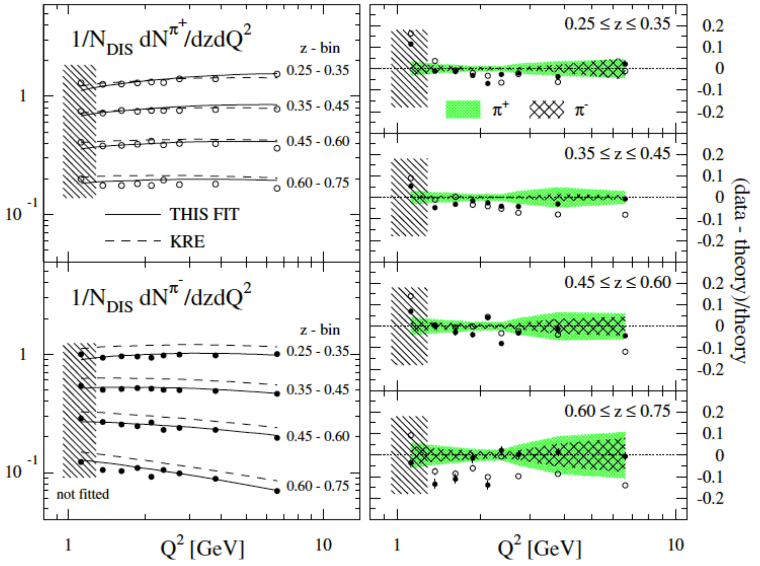


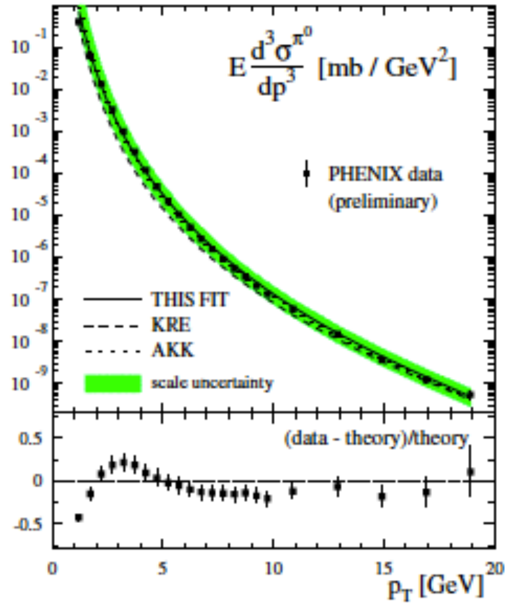
FIG. 8: Cross section differential with respect to the transverse momentum q_T of a Z boson produced from $p\bar{p}$ collisions at Tevatron. The four panels refer to different experiments (CDF and D0) with two different values for the center-of-mass energy ($\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 1.96$ TeV). In this case the band is narrow due to the narrow range for the best-fit values of g_2.

- **Bacchetta *et al.*, JHEP 1706 (2017) 081**
- Simultaneous global fit of HERMES and COMPASS SIDIS data, Drell-Yan, and Z boson production data, achieving $\frac{\chi^2}{d.o.f.} = 1.55$ for ~8,000 data points with 11 adjustable parameters

Factorization and universality for Fragmentation Functions





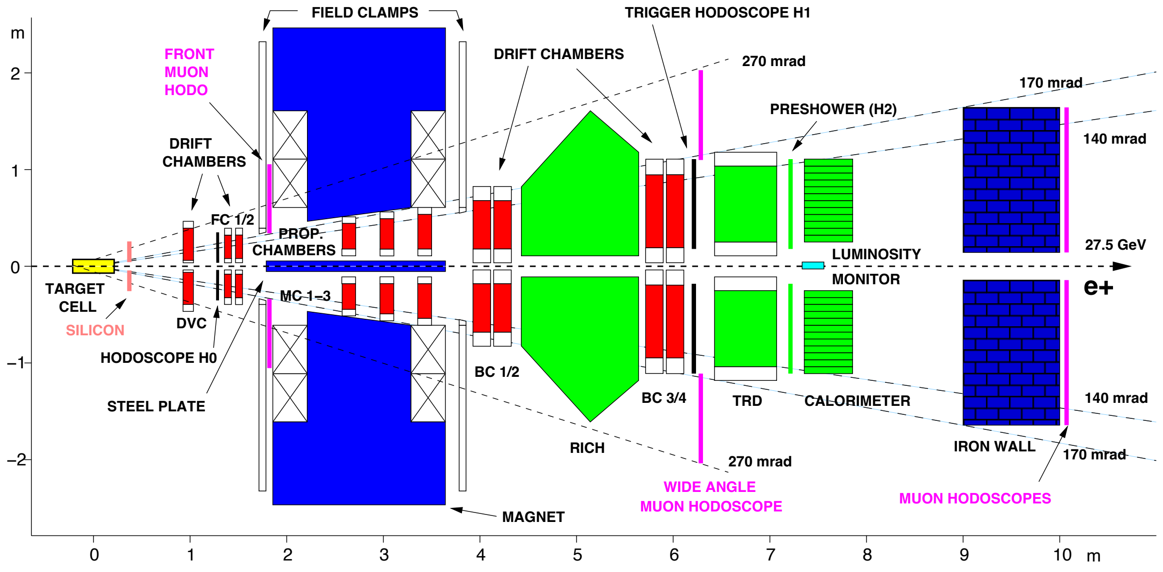


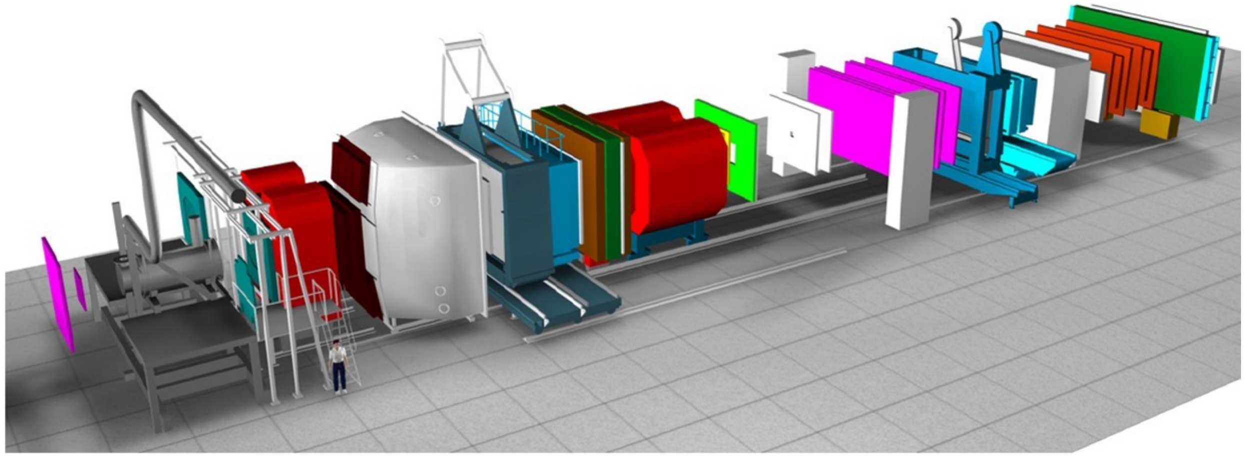
$$d\sigma^{\ell p\to\ell' hX} = \sum_q \hat{f}_{q/p}(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{\ell q\to\ell q} \otimes \hat{D}_{h/q}(z, \boldsymbol{p}_\perp; Q^2).$$

- TMD PDFs aren't directly observable, but convoluted with universal quark → hadron fragmentation functions in the SIDIS observables

- Above: comparisons of unpolarized cross section data to NLO global QCD FF fits (DSS 2007)
  - Left: single inclusive e+/e- annihilation to charged pions
  - Middle: charged pion multiplicities in SIDIS
  - Right: inclusive π^0 production in pp collisions
- FFs can be independently constrained by e^+/e^- annihilation (and other) experiments
- Partonic interpretations of SIDIS depends on factorization into TMD distribution, TMD FF, and "hard" subprocess calculable in QED/pQCD

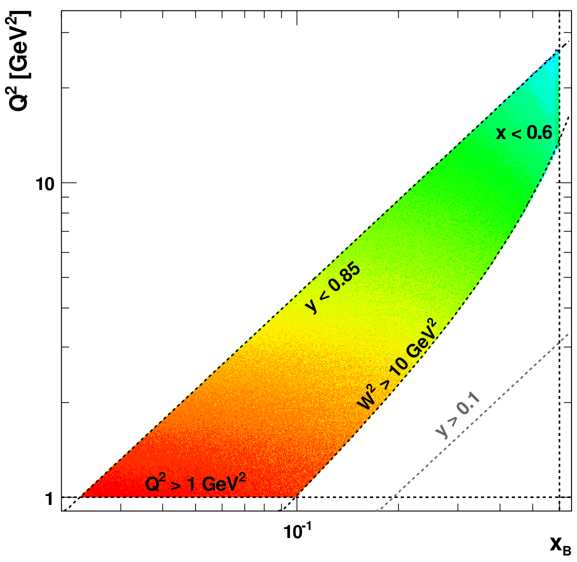
HERMES@DESY and COMPASS@CERN Experiments





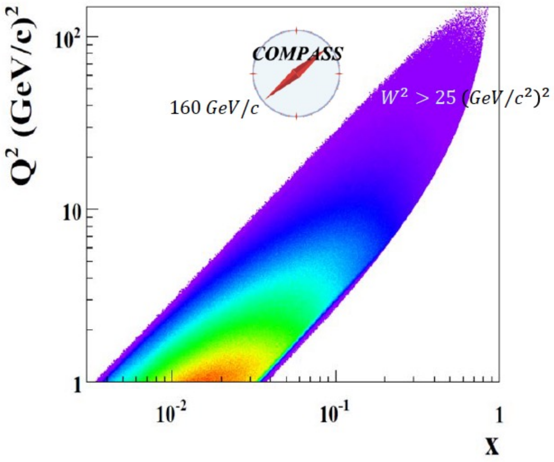
COMPASS@CERN

- SIDIS program: 160 GeV polarized muon beam produced using CERN SPS on polarized ^{6}LiD and NH_3 targets (and also unpolarized LH_2, LD_2, etc.)
- Average luminosity (lepton-nucleon): $\approx 2{\times}10^{32}\ cm^{-2}s^{-1}$
- SIDIS running 2002-2007, 2010-2011, 2016-2017 (parasitic with dedicated DVCS run)
- Pion-induced Drell Yan 2015, 2018+
- More deuteron SIDIS 2021



HERMES@DESY

- 27.5 GeV stored e^+ and e^- beams on polarized and unpolarized, isotopically pure internal gas H (and D) targets
- Luminosity (lepton-nucleon): $\sim 10^{31} - 10^{33}\ cm^{-2}\ s^{-1}$
- Data collection in various iterations from 1995-2007



Key Results of HERMES and COMPASS—Discovery of non-zero Collins and Sivers Effects

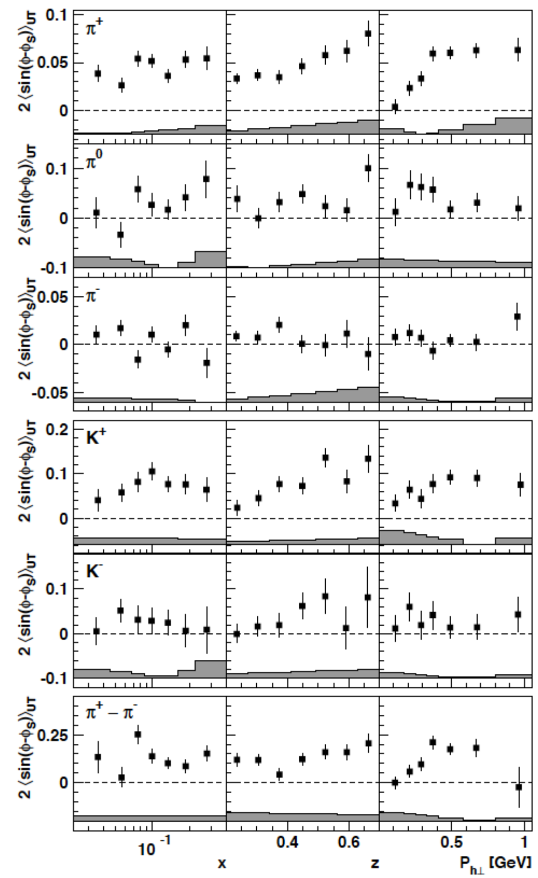


FIG. 1: Sivers amplitudes for pions, charged kaons, and the pion-difference asymmetry (as denoted in the panels) as functions of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the target-polarization measurement.

HERMES Sivers Results: Phys. Rev. Lett. 103 (2009) 152002

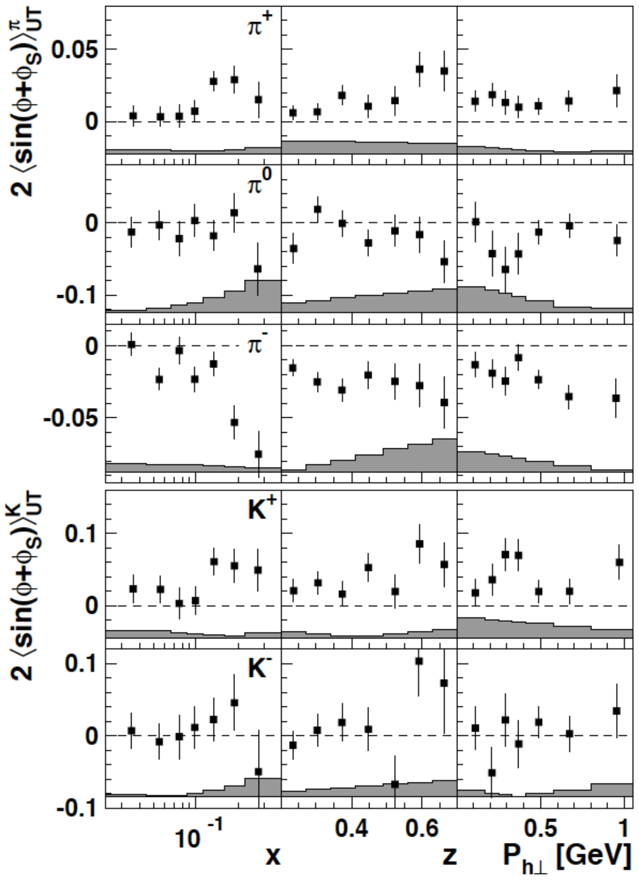


Fig. 2. Collins amplitudes for pions and charged kaons as a function of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the accuracy in the measurement of the target polarization.

HERMES Collins Results: Phys. Lett. B 693 (2010) 11-16

- Right: COMPASS proton Collins and Sivers asymmetries for identified hadrons: Phys.Lett. B744 (2015) 250-259
- See also: COMPASS deuteron target data for Collins and Sivers asymmetries

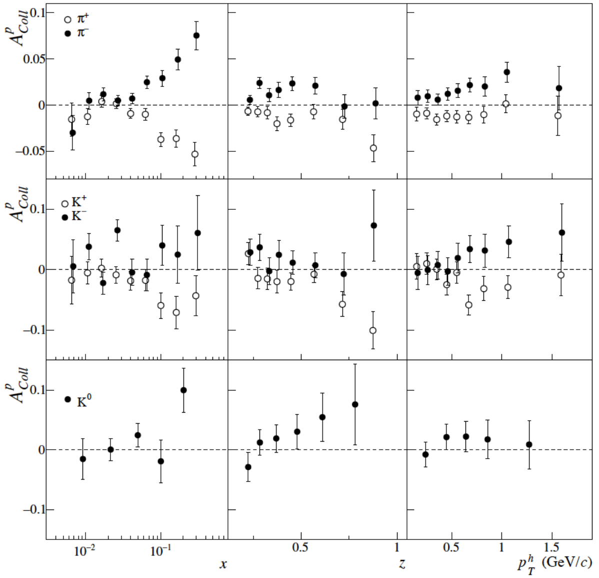


Fig. 6: The Collins asymmetries for charged pions (top), charged kaons (middle) and neutral kaons (bottom) on proton as a function of x, z and p^h_T.

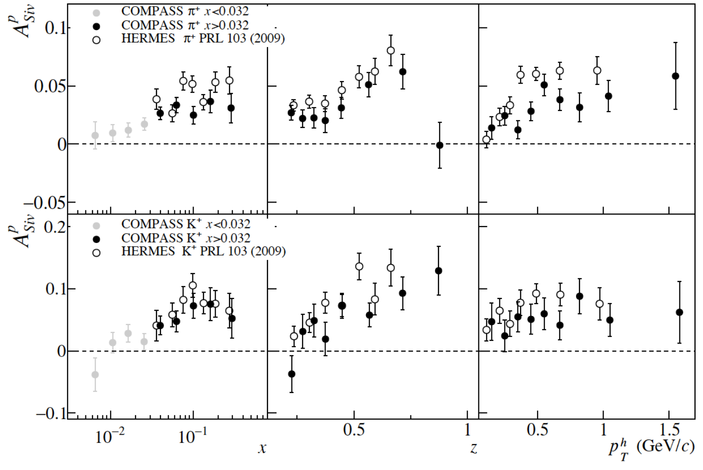


Fig. 11: The Sivers asymmetries for positive pions (top) and kaons (bottom) on proton as a function of x, z and p^h_T, requiring $x > 0.032$. The asymmetries are compared to HERMES results.

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	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

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

- 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!

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

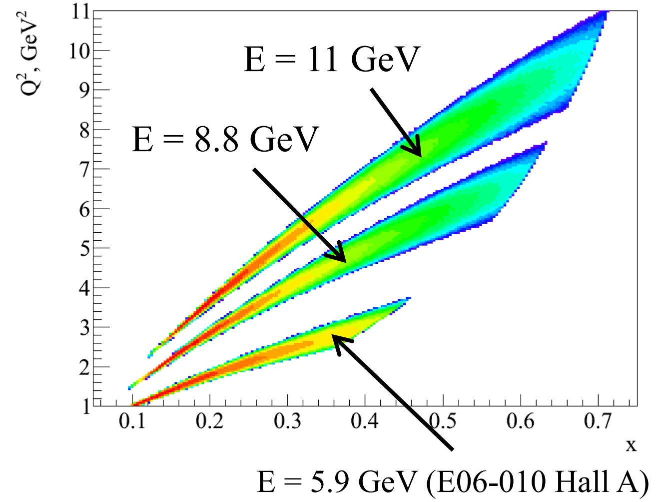
3D and "4D" extraction of SIDIS SSAs with SBS

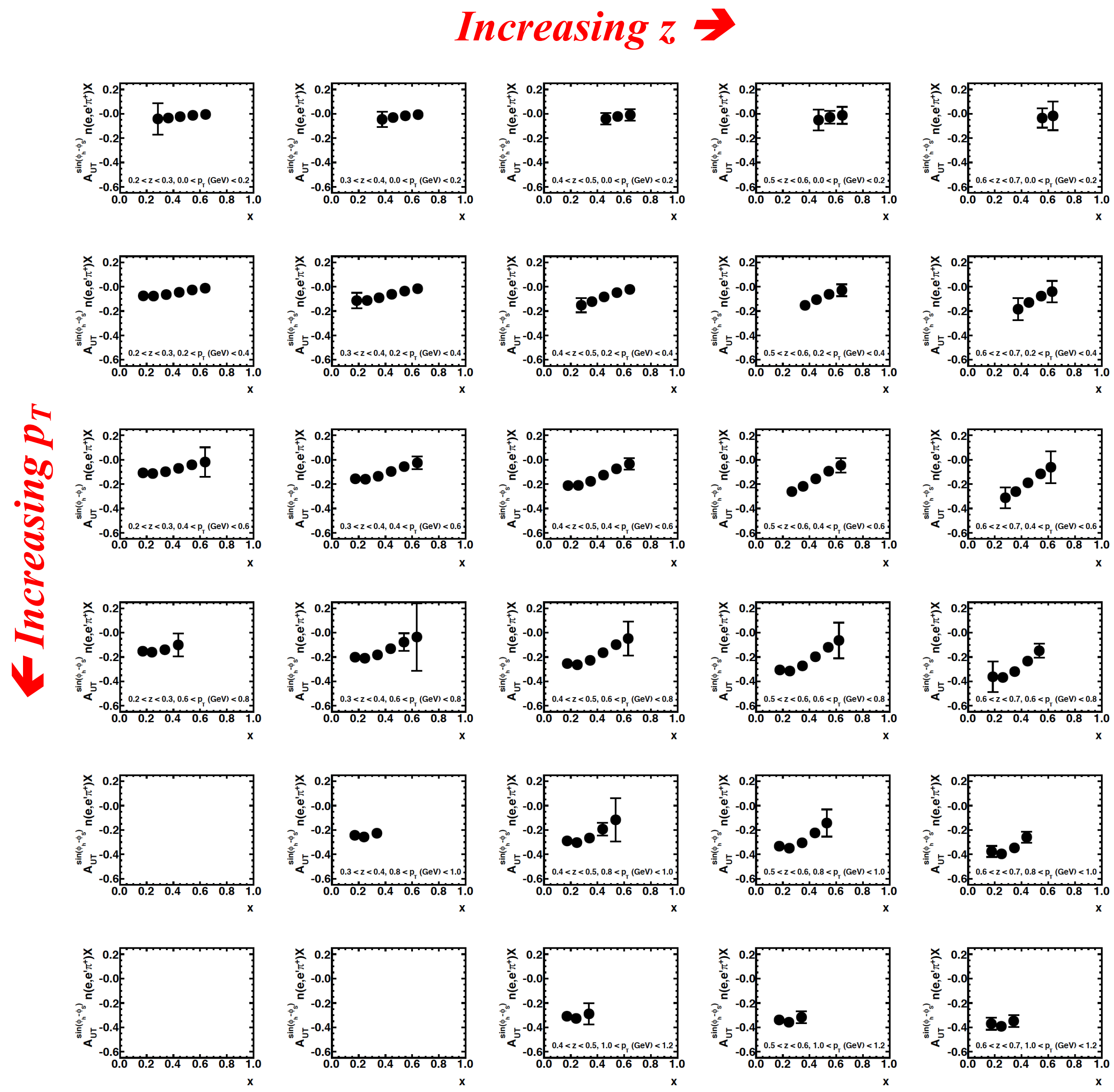
Example result for 3D binning (x,z,p_T)

- E = 11 GeV, 40 days

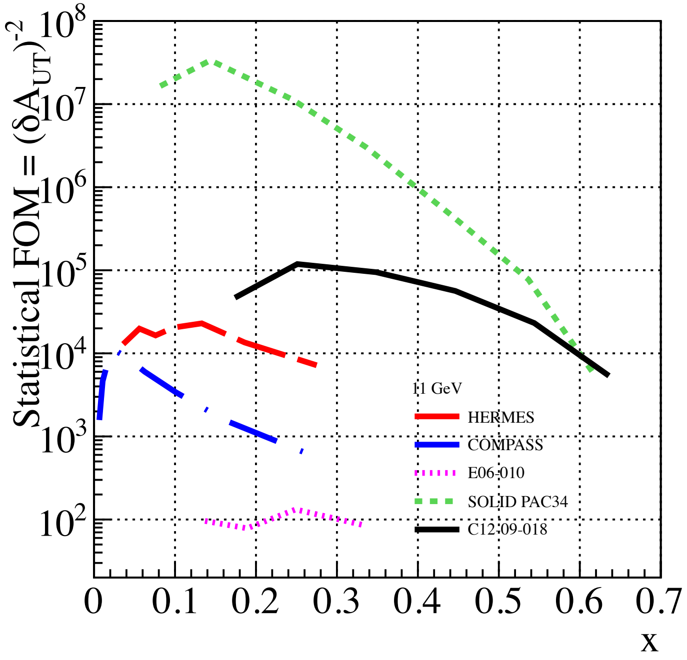
$$A_{UT}^{\sin(\phi_h - \phi_S)} \text{ for } \mathbf{n}(e, e'\pi^+)X:$$
$$0.1 \leq x \leq 0.7, \Delta x = 0.1$$
$$0.2 \leq z \leq 0.7, \Delta z = 0.1$$
$$0 \leq p_T(\text{GeV}) \leq 1.2, \Delta p_T = 0.2 \text{ GeV}$$

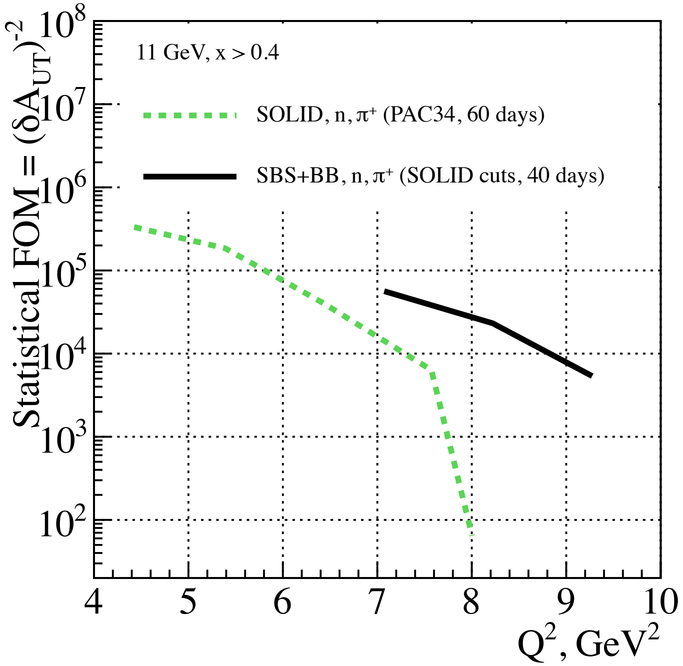
- "4D" with Q^2 dependence from 20 days at 8.8 GeV:

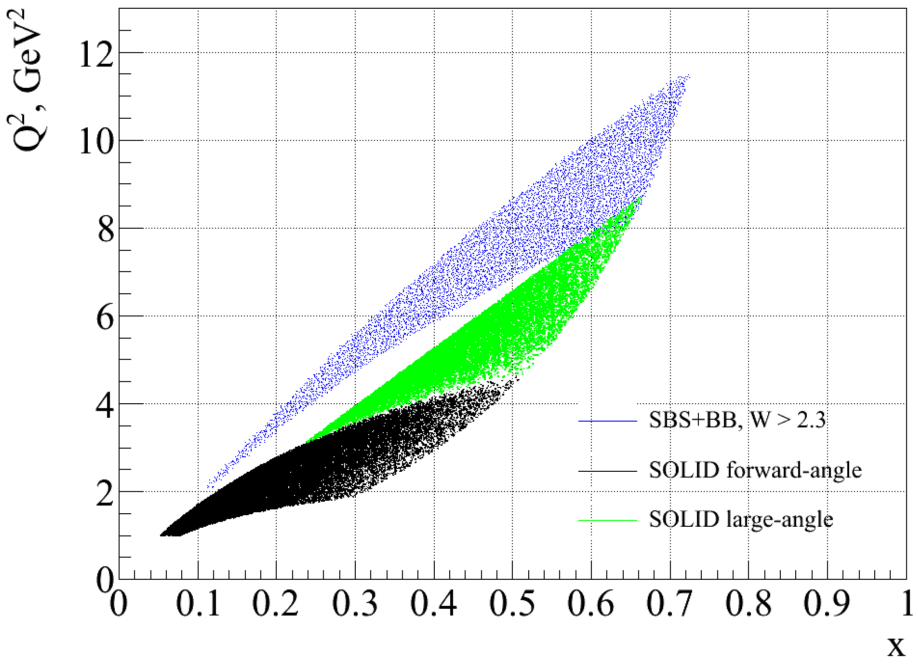




SBS SIDIS vs SOLID SIDIS

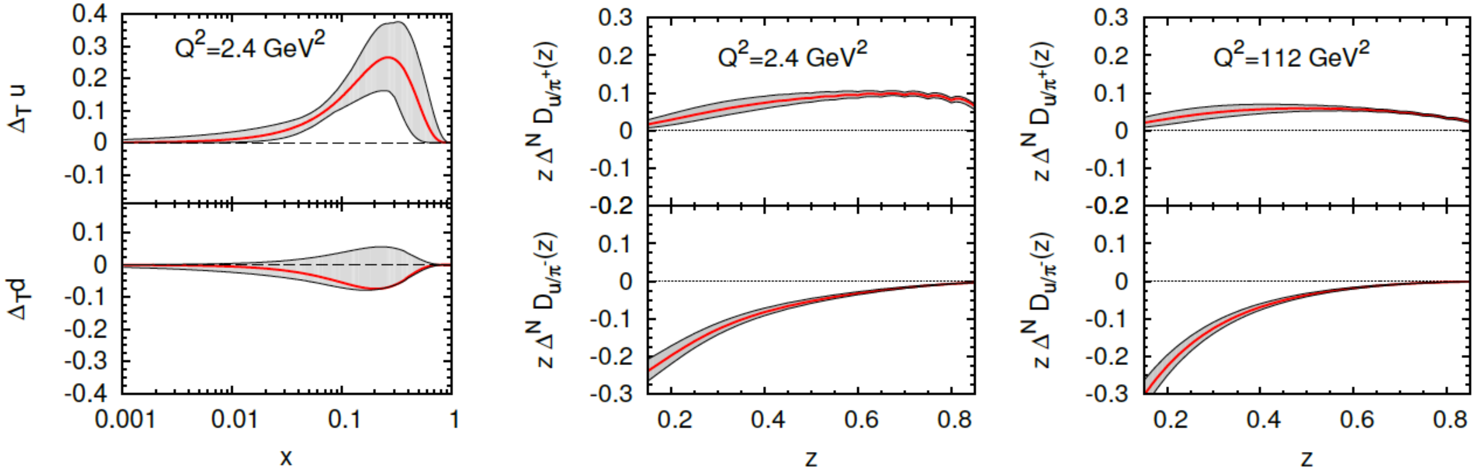


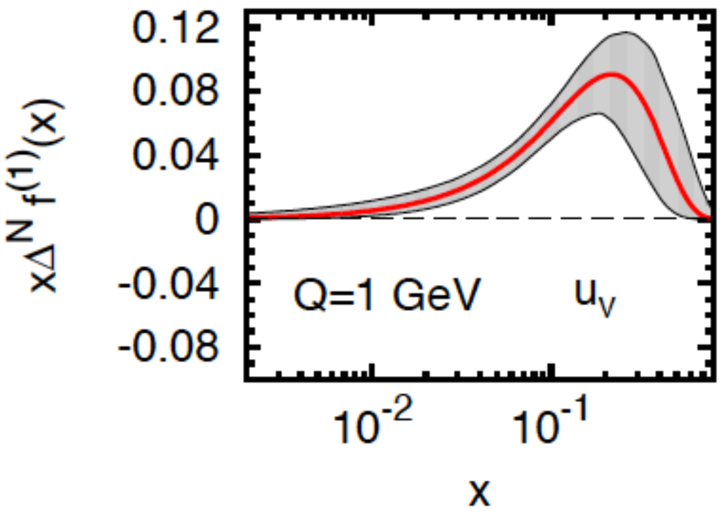


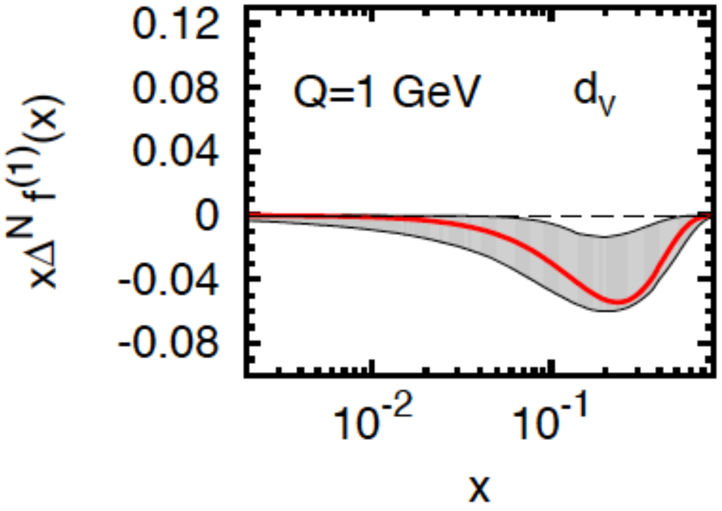


- SBS+BB and SOLID SIDIS kinematic coverages are entirely complementary (i.e., essentially zero overlap in (Q^2, x, y) phase space):
  - SOLID polar angle acceptance only reaches ~25 degrees
  - BB in E12-09-018 covers ~25-37 degrees for the electron
- The statistical advantage of SOLID-SIDIS over SBS SIDIS derives as much (if not more so) from lower Q^2 (higher cross section) than from acceptance
- For $x > 0.4 - 0.5$, SBS SIDIS has comparable statistical precision and significantly higher Q^2
- The kinematic regime accessed by E12-09-018 is unique and *not even in principle accessible by SOLID SIDIS*

Transversity, Collins, and Sivers Effects: Existing Knowledge







- **Above: Anselmino *et al.*, Phys. Rev. D 92, 114023 (2015) arXiv:1510.05389v1:** 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
  - Soffer bound nearly saturated in *d* quark transversity fits

The Sivers effect, time reversal and gauge invariance

- Sivers, PRD 41, 83 (1990):
  - Left-right asymmetry in the k_T distribution of unpolarized quarks in a transversely polarized nucleon could lead to observable single-spin asymmetry (SSA).
- Collins, NPB 396, 161 (1993):
  - Left-right asymmetry in the fragmentation of a transversely polarized quark leads to observable SSA.
  - Sivers effect forbidden due to time-reversal invariance of QCD
- Brodsky, Hwang and Schmidt, PLB 530, 99 (2002):
  - Sivers effect allowed in the presence of QCD final-state interaction phases
  - Corresponds to imaginary part of the interference between quark wavefunction components differing by one unit of orbital angular momentum, coupling to the same final state
- Collins, PLB 536, 43 (2002):
  - Attractive final-state interaction in SIDIS mirrored by repulsive initial-state interaction in Drell-Yan reaction $pp \rightarrow \mu^+\mu^- X$
  - Application of time-reversal and gauge invariance in QCD leads to a fundamental prediction (***needs experimental verification***):

$$f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY}$$

The Collins effect and transversity

General properties of transversity:

• $h_1 = g_1$ for non-relativistic quarks (boosts and rotations commute); → $h_1 \neq g_1$ signifies relativistic effects

• Helicity conservation → gluon transversity = 0. quark transversity is "valence-like", simpler Q^2 evolution.

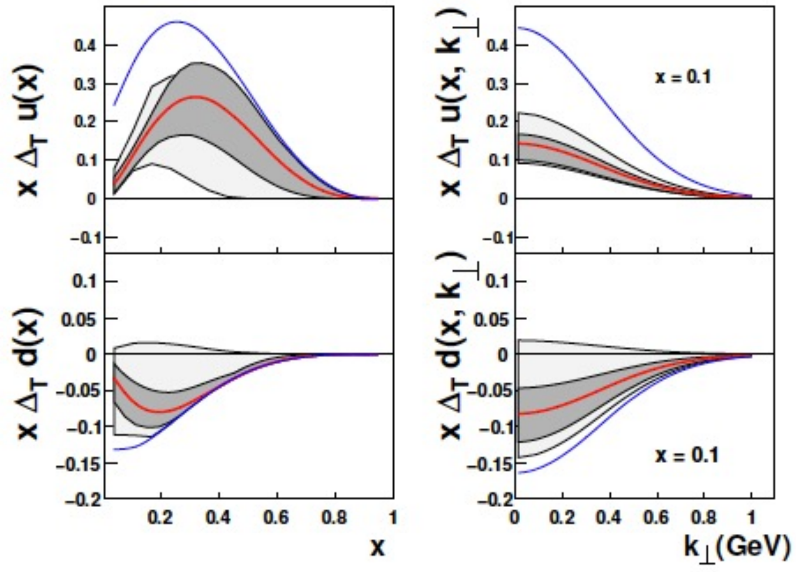
• h_1 is chiral-odd, inaccessible in DIS. Accessible in SIDIS when coupled to chiral-odd Collins fragmentation function.

• Soffer, PRL 74, 1292 (1995): Positivity, unitarity & parity conservation → Soffer bound: $|h_1| \leq ½(f_1 + g_1)$

- ***Doubt has been cast on validity of Soffer bound: Ralston, arxiv:0810.0871***
- ***Not experimentally verified in the valence region (x >~ 0.3)***

• First x moment of transversity = tensor charge, calculated on the lattice: QCDSF/UKQCD collaboration, PLB 627, 113 (2005)

What is known about transversity?

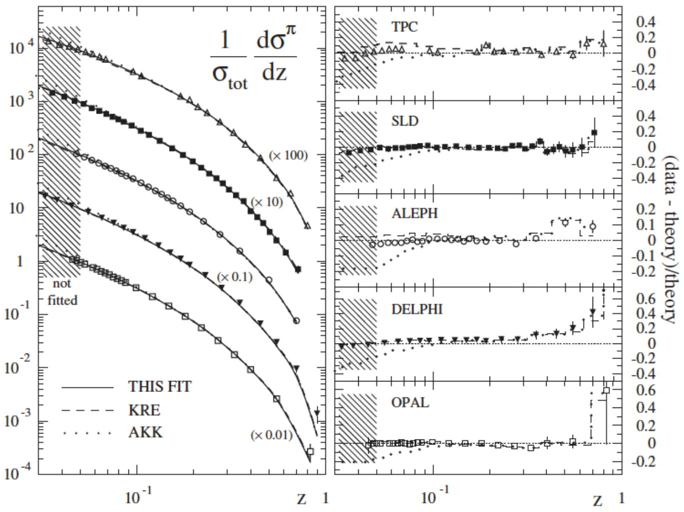


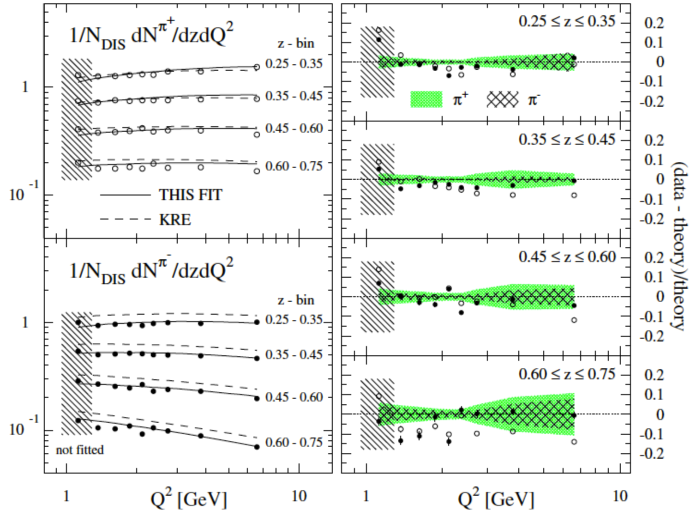
Anselmino et al., NPB 191, 98 (2009)

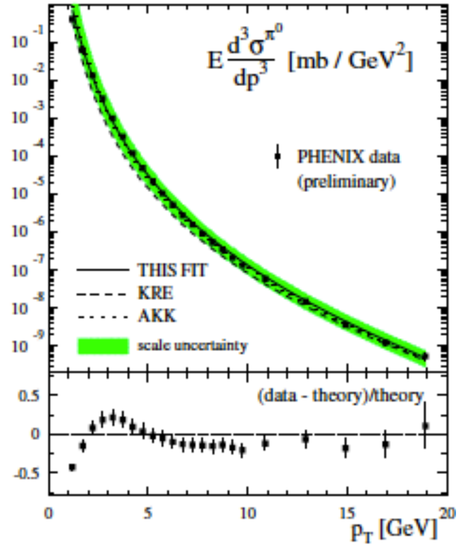
• Transversity and Collins functions from global fit to HERMES+COMPASS SIDIS and BELLE $e^+ e^- \rightarrow h_1 h_2$ X data.

• Notably, Soffer bound, enforced in the fit, is saturated at high x, particularly for d quark.

Factorization and universality for FFs



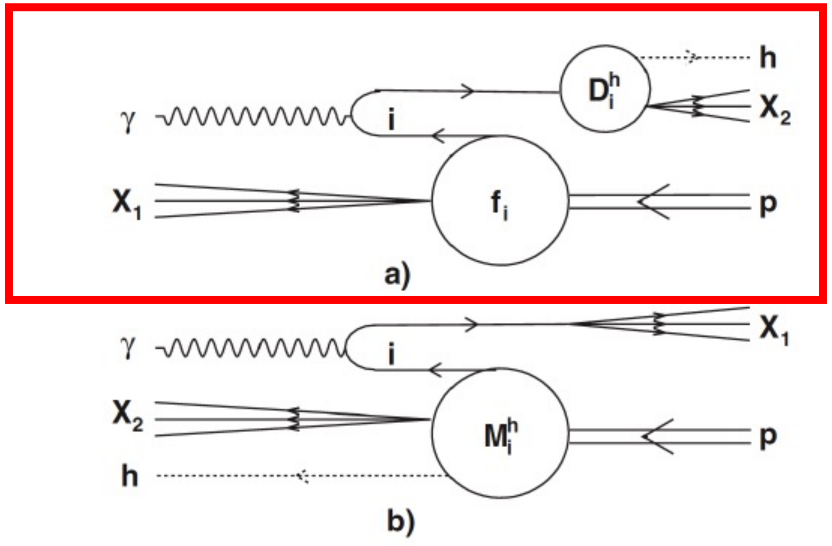


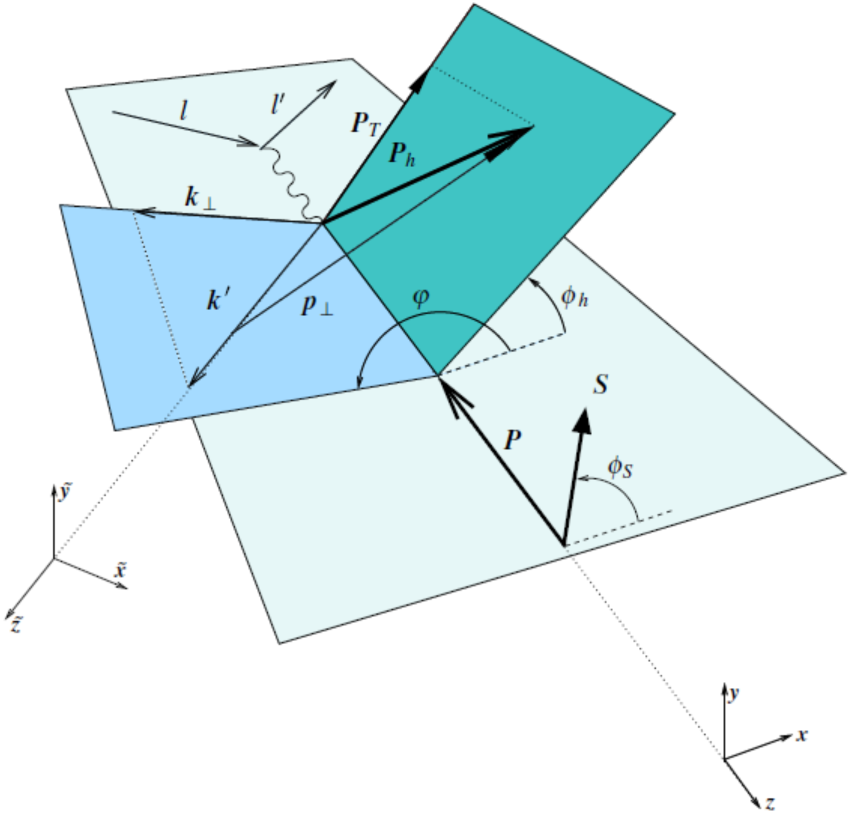


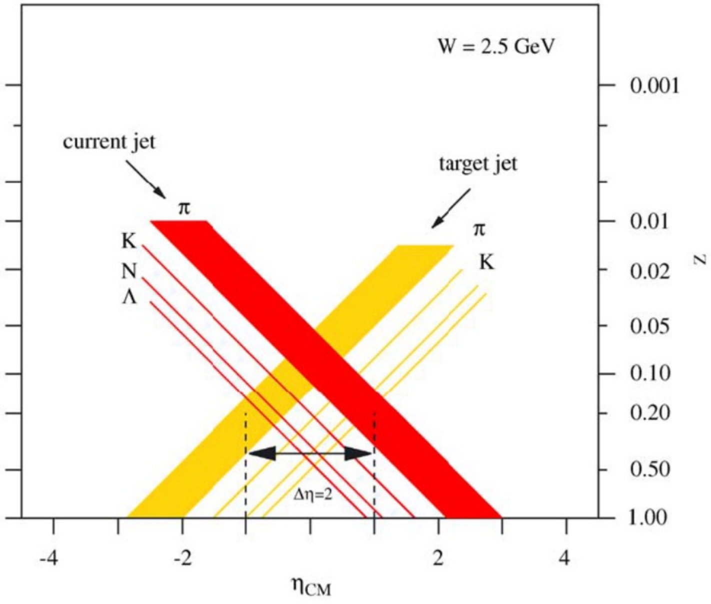
- Above: comparisons of unpolarized cross section data to NLO global QCD FF fits (DSS 2007)
  - Left: single inclusive e+/e- annihilation to charged pions
  - Middle: charged pion multiplicities in SIDIS
  - Right: inclusive π^0 production in pp collisions
- Below: factorization of SIDIS cross section at leading-order, including quark distribution q(x), hard scattering subprocess (eq→eq), and fragmentation function $D^h_q(z)$

$$d\sigma^{\ell p \to \ell' h X} = \sum_q \hat{f}_{q/p}(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{\ell q \to \ell q} \otimes \hat{D}_{h/q}(z, \boldsymbol{p}_\perp; Q^2).$$

How does SIDIS access 3D quark information?







- Recoiling quark is not directly observed (confinement)—but "fragments" into observable hadrons (e.g., pions, kaons) with probability described by ***fragmentation functions*** $D_h^q(z,Q^2)$
- At "high" energies, fragmentation is independent of the hard scattering→ "factorization"!