

Semi-Inclusive Deep Inelastic Scattering on a
Transversely Polarized ^3He Target Using the BigBite
and Super BigBite Spectrometers in Hall A: PAC54
Jeopardy Update to E12-09-018

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PAC54
7/8/2026

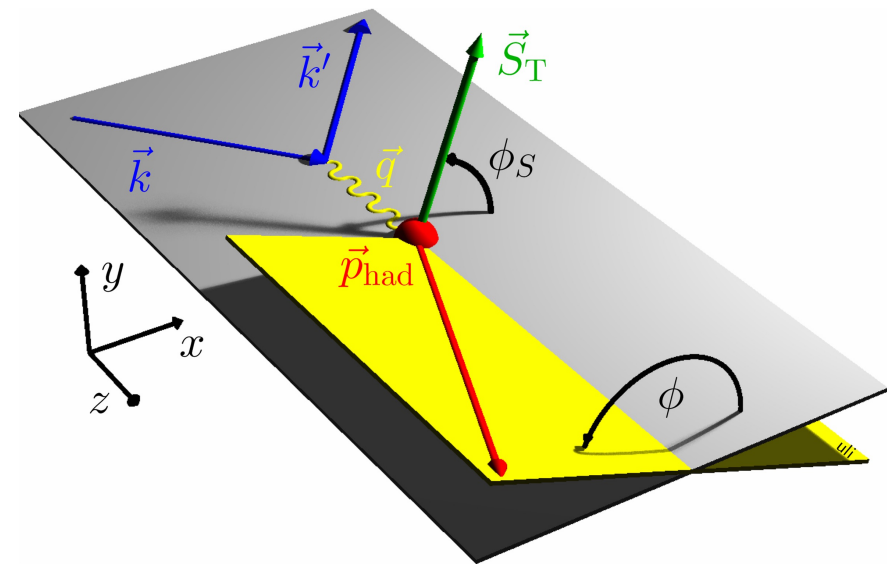
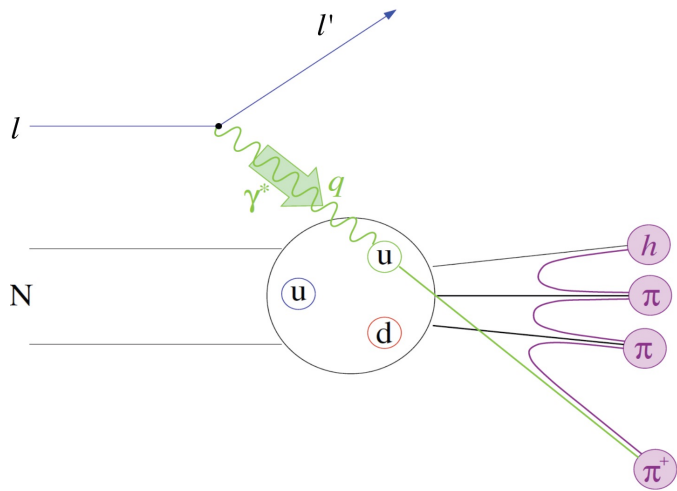
Outline

- E12-09-018 history, scientific motivation
- SBS Overview and Collaboration
- E12-09-018 details
- Projected Results/Impacts
- The *increasing* scientific merit of E12-09-018
- Summary/Conclusions

E12-09-018/J12-26-001 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/EIC TMD/CLAS12 RGH
 - Unique combination of kinematic coverage (high x/Q^2) and statistical figure-of-merit among approved JLab 12 GeV SIDIS proposals with transverse polarized target
- Little new data on this subject (transverse target SSA in SIDIS) since PAC38, other than 2022 COMPASS deuteron data
- Successful deployment of high-luminosity polarized ^3He target during GEN-II
 - ✓ **Achieved polarized target figure-of-merit (FOM) very close to SIDIS goal**
- All detectors required by SIDIS (except RICH) already used successfully under the more demanding conditions of the form factor program
- ✓ **Technical feasibility conclusively established**

Motivation: SIDIS and 3D "Imaging" of Quark Motion in the Nucleon



Kinematic Variables for SIDIS	Description
$z \equiv \frac{p_h \cdot p}{q \cdot p} \xrightarrow{lab} \frac{E_h}{\nu}$	Fraction of virtual photon energy carried by observed hadron
$p_T \equiv \mathbf{p}_h - \frac{\mathbf{p}_h \cdot \mathbf{q}}{ \mathbf{q} ^2} \mathbf{q}$	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)*

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

• 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 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 $eq \rightarrow eq$

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

Effects of Transverse Target Polarization 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 SIDIS cross section (at leading twist 2):

- **Collins effect**—probe transverse polarization of quarks
- **Sivers effect**—probes correlations between quark transverse momentum and nucleon transverse spin (“OAM”).
- “Transversal helicity” or Kotzinian-Mulders function 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

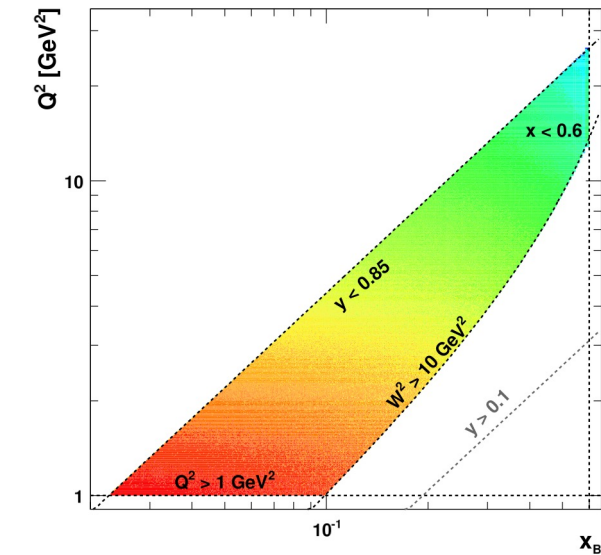
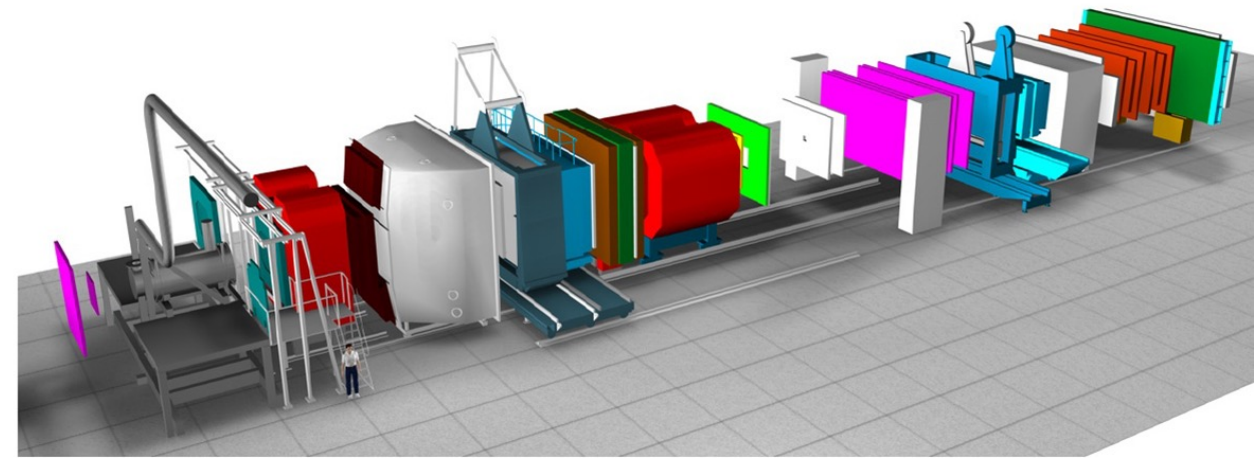
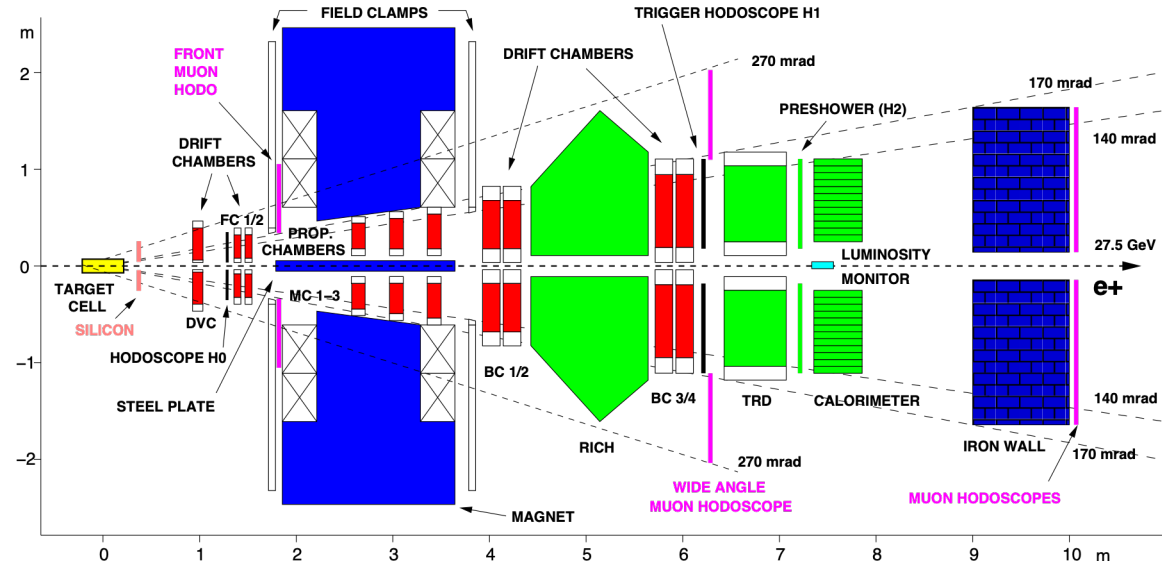
$$\begin{aligned}
 A_{UT}(\phi, \phi_S) &= \frac{1}{P_T} \frac{d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi)}{d\sigma(\phi, \phi_S) + d\sigma(\phi, \phi_S + \pi)} \\
 &= A_{UT}^{Collins} \sin(\phi + \phi_S) + \\
 &\quad A_{UT}^{Sivers} \sin(\phi - \phi_S) + \\
 &\quad A_{UT}^{Pretz} \sin(3\phi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

$$\begin{aligned}
 D_1 = \text{unpolarized} & & A_{UT}^{Collins} &\propto h_1 \otimes H_1^\perp \\
 \text{fragmentation function} & & A_{UT}^{Sivers} &\propto f_{1T}^\perp \otimes D_1 \\
 H_1^\perp = \text{Collins} & & A_{UT}^{Pretz} &\propto h_{1T}^\perp \otimes H_1^\perp \\
 \text{fragmentation function} & & &
 \end{aligned}$$

(note h_1 above $\equiv \delta q$ in the chart at left)

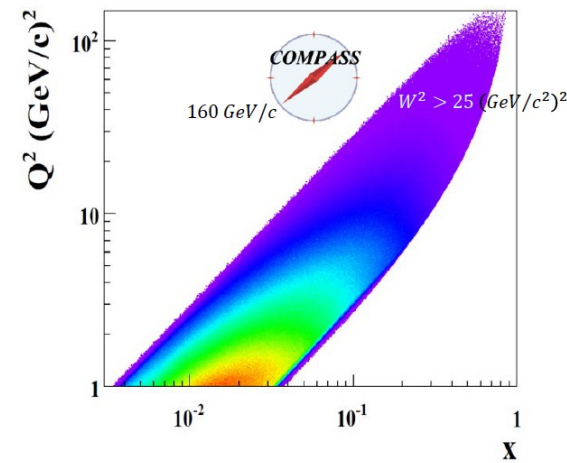
$$\begin{aligned}
 A_{LT}(\phi, \phi_S) &= \frac{1}{P_e P_T} \frac{Y_+(\phi, \phi_S) - Y_-(\phi, \phi_S)}{Y_+(\phi, \phi_S) + Y_-(\phi, \phi_S)} \\
 &\sim A_{LT}^{\cos(\phi - \phi_S)} \cos(\phi - \phi_S) \\
 &\sim g_{1T} \otimes D_1
 \end{aligned}$$

HERMES@DESY and COMPASS@CERN Experiments



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):
 $\sim 10^{31} - 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Data collection in various iterations from 1995-2007



COMPASS@CERN

- SIDIS program: 160 GeV polarized muon beam produced using CERN SPS on polarized ^6LiD and NH_3 targets (and also unpolarized LH_2 , LD_2 , etc.)
- Average luminosity (lepton-nucleon):
 $\approx 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- SIDIS running 2002-2007, 2010-2011, 2016-2017 (parasitic with dedicated DVCS run)
- Pion-induced Drell Yan 2015, 2018+
- Deuteron SIDIS 2022

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

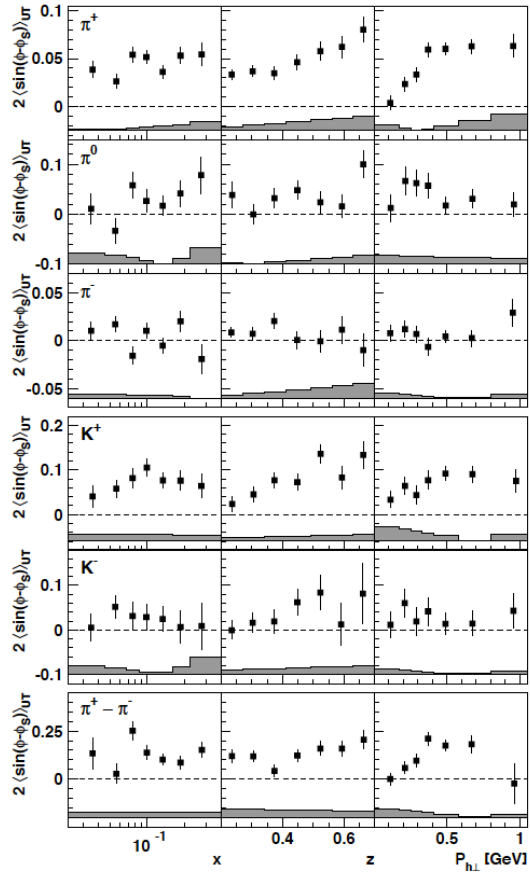


FIG. 1: Sivers amplitudes for pions, charged kaons, and the pion-difference asymmetry (as denoted in the panels) as functions of x , z , or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the target-polarization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

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

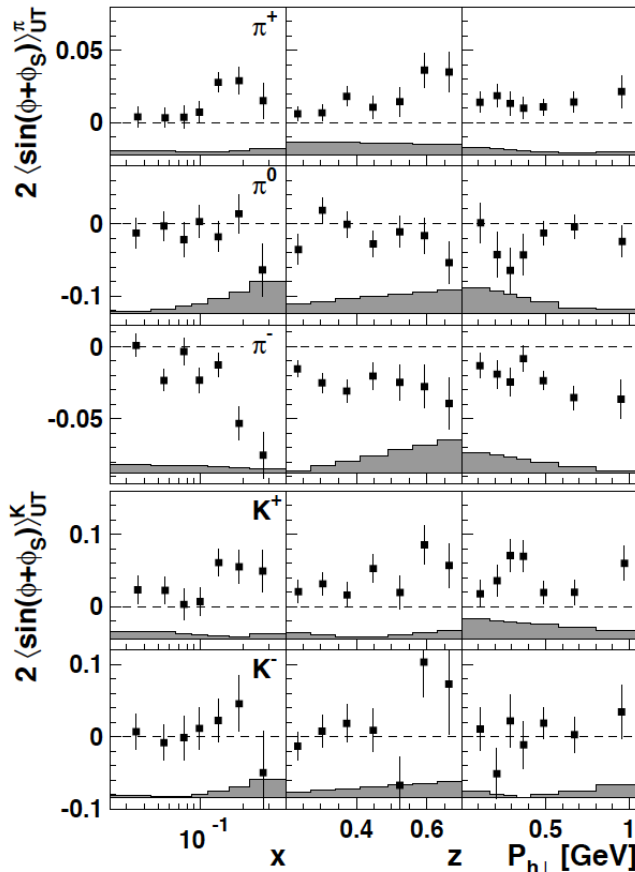


Fig. 2. Collins amplitudes for pions and charged kaons as a function of x , z , or $P_{h\perp}$. The systematic uncertainty is given at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the accuracy in the measurement of the target polarization.

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: latest COMPASS deuteron target data for C+S asymmetries (PRL 2024): <https://doi.org/10.1103/PhysRevLett.133.101903>

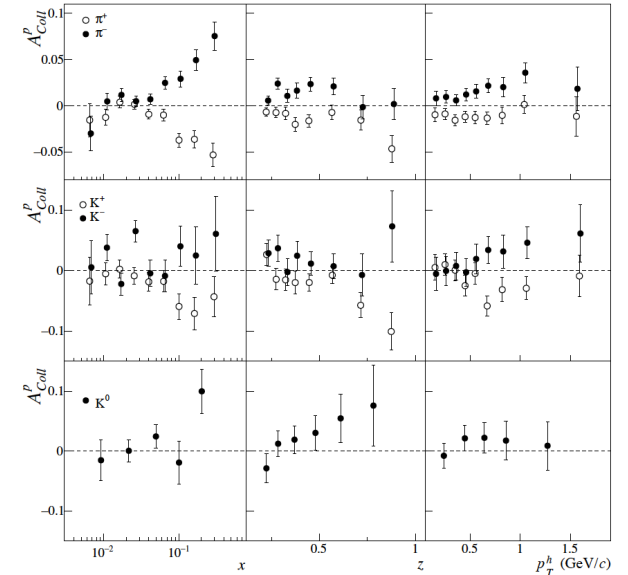


Fig. 6: The Collins asymmetries for charged pions (top), charged kaons (middle) and neutral kaons (bottom) on proton as a function of x , z and p_T^h .

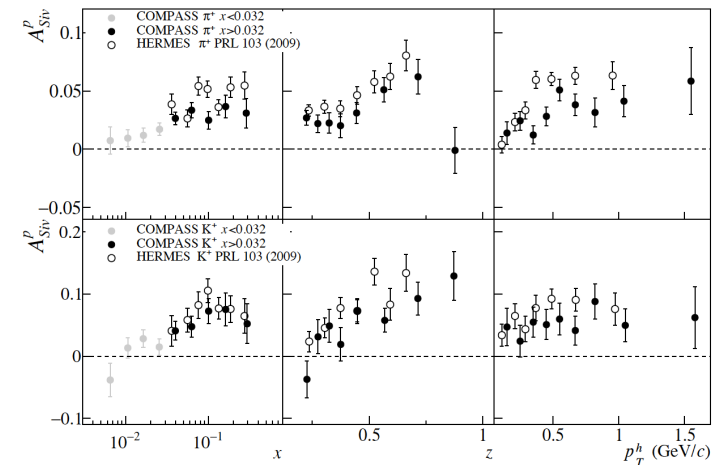


Fig. 11: The Sivers asymmetries for positive pions (top) and kaons (bottom) on proton as a function of x , z and p_T^h , requiring $x > 0.032$. The asymmetries are compared to HERMES results.

NSAC LRP 2023 Highlights—3D Imaging of Nucleon's Quark Structure

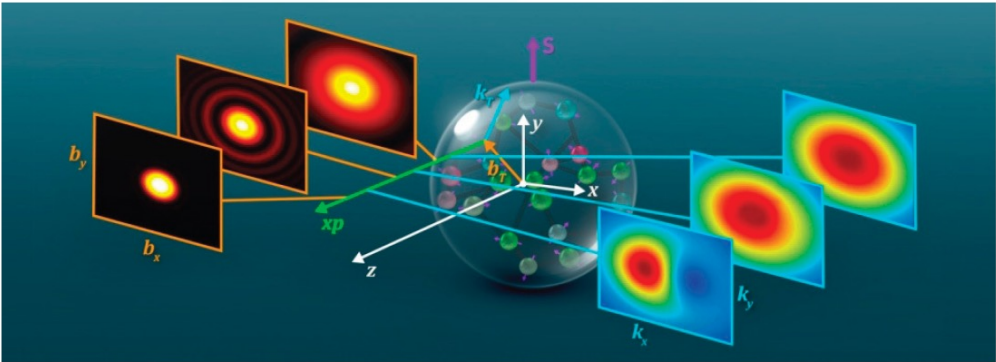


Figure 3.3. Parton images for a spin-up proton (magenta arrow) in slices of parton fractional momentum, x , for the quarks and gluons in a colliding hadron. The images on the left give a spatial distribution in transverse location, while the images on the right picture the transverse momentum distribution [3].

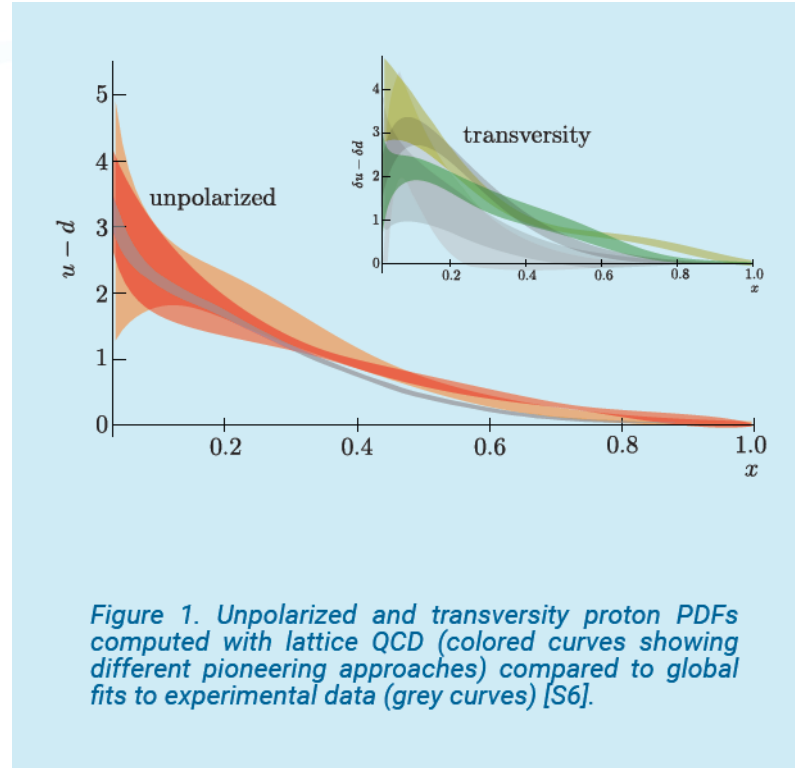


Figure 1. Unpolarized and transversity proton PDFs computed with lattice QCD (colored curves showing different pioneering approaches) compared to global fits to experimental data (grey curves) [S6].

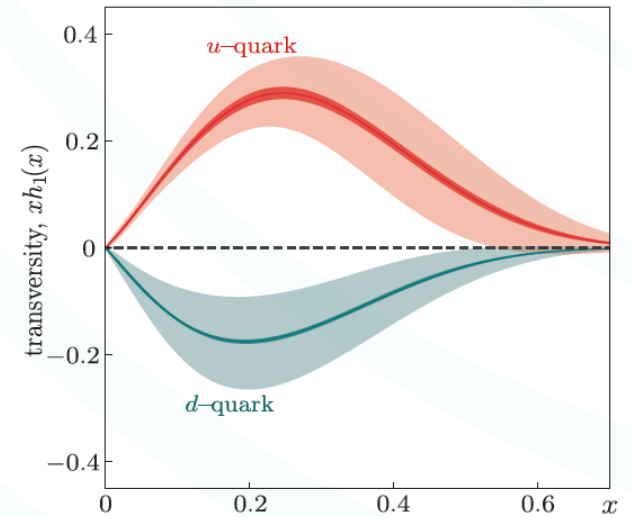
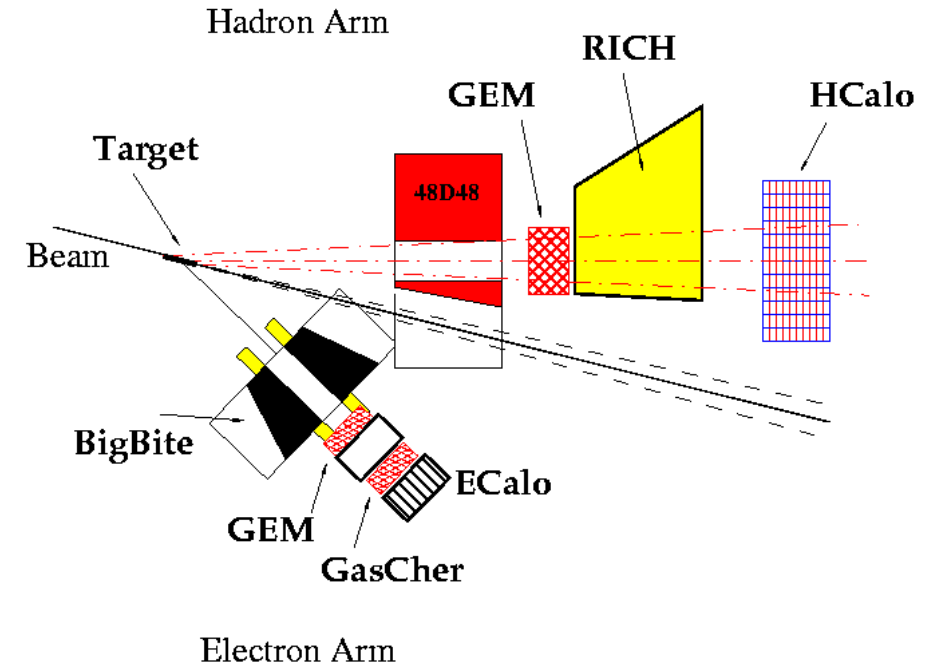
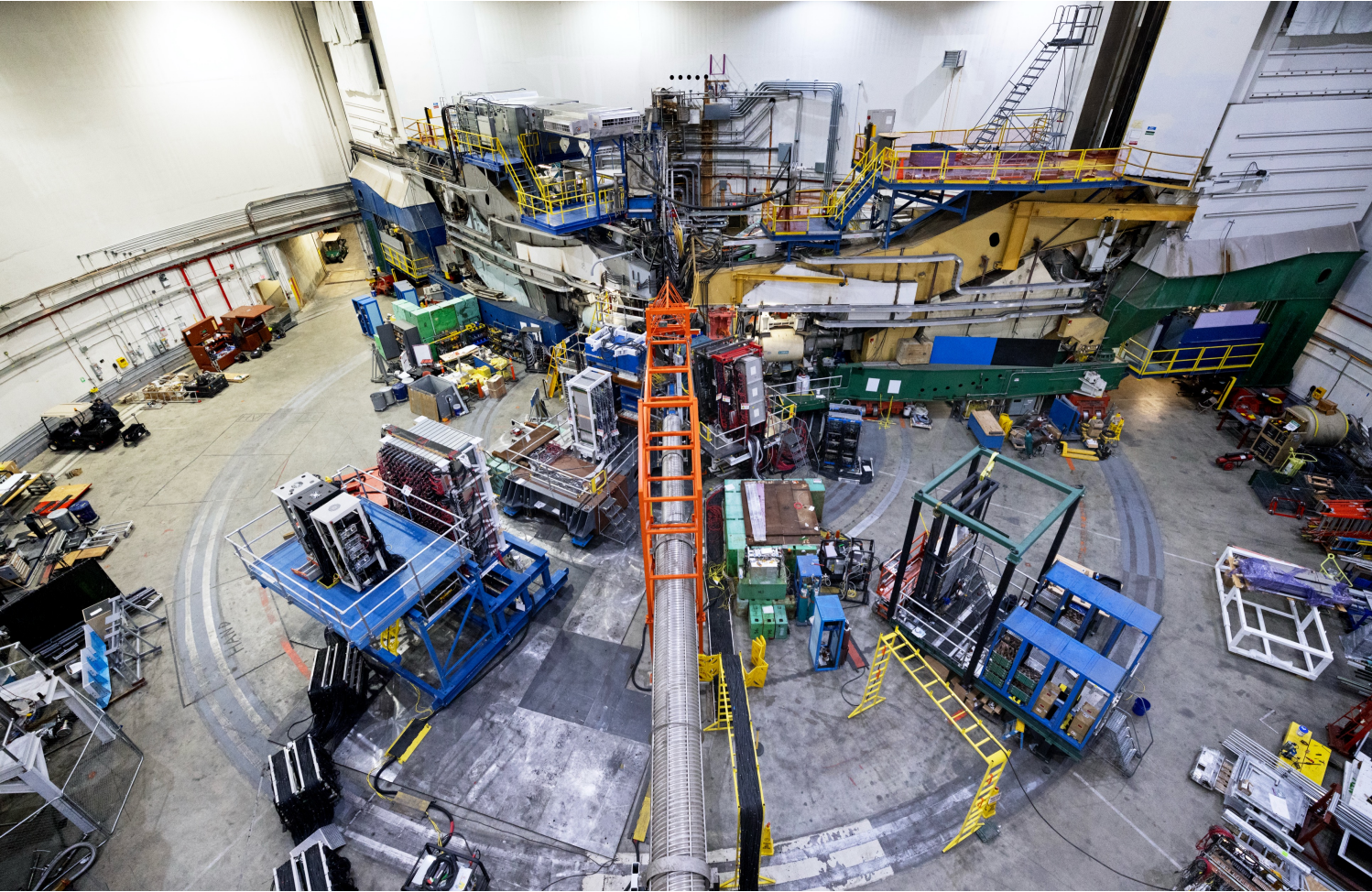


Figure 3.4. The up (red) and down (blue) quark transversity spin-spin correlation in the proton. The wide uncertainty bands show the latest results based on a global fit to world data while the narrower, darker bands show the expected improvement by the SoLID detector [4].

- <https://nuclearsciencefuture.org/>
- [LRP PDF download link](#)
- Left: illustration of nucleon 3D imaging in coordinate space (GPDs) and momentum space (TMDs)
- Middle: Transformative progress in lattice QCD calculations of PDFs, unpolarized and transversity
- Right: Projected impact of SoLID SIDIS program on quark transversity distributions wrt current world data
- **E12-09-018 physics is among the central motivations for EIC construction!**

The BigBite and Super BigBite Spectrometers in Hall A



Original schematic of SBS SIDIS

- Two-arm experiments: combines moderately large solid angle and large momentum bite at forward angles with high luminosity capability
- Optimized for two-particle coincidence (exclusive and semi-inclusive) reactions in "hard" (high- Q^2) collisions

Aerial View of SBS+BB in Hall A, late 2023/early 2024 during GEn-II→GEn-RP changeover

E12-09-018 is an SBS Collaboration experiment

Current Spokespeople:

- Prof. Gordon Cates, UVA
 - Polarized ^3He Target, Program Scientist
- Dr. Evaristo Cisbani, INFN
 - HERMES RICH/SIDIS/GEM expert
- Prof. Andrew Puckett, UConn
 - SBS software lead, HERMES RICH refurb
- Dr. Bogdan Wojtsekhowski, JLab (contact)
 - SBS Spectrometer, Principal Program Scientist



SBS Collaboration

Other key contributions/acknowledgements

- Dr. Provakar Datta, LBNL: expertise in SBS MC simulations, data analysis, calorimeter operations
- Prof. Todd Averett, W&M: BigBite GRINCH design/construction/operation, polarized ^3He target development, DIS/SIDIS expertise
- Prof. Nilanga Liyanage/Dr. Huong Nguyen, UVA: BigBite/SBS GEM design/construction/operational support:

“The UVA group (Liyanage, Nguyen) who designed, built, and operated the SBS GEMs during the form factor program, are active participants in the E12-09-018 collaboration. If E12-09-018 remains approved, then the UVA group is committed to supporting the operation of the BigBite and SBS GEMs during the run”



Completed Experiments 2021-2025

- E12-09-019/E12-20-010: GMn/nTPE (2021-2022)
- E12-09-016: GEn-II (2022-2023)
- E12-17-004/E12-20-008: GEn-RP/Pion- K_{LL} (2024)
- E12-07-109: GEp (2025)
- Proton and neutron Elastic form factors G_E^n, G_E^p, G_M^n now all measured to $Q^2 \geq 10 \text{ GeV}^2$
- Data under analysis, publications forthcoming

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

Experiment Design Challenges/Considerations

- High number and dimensionality of SIDIS structure functions: 4D phase space (x, Q^2, z, p_T) plus azimuthal modulations (ϕ_h, ϕ_S)
- 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 good statistical precision, especially for polarization observables and 4-D analysis
- High beam and target **polarization** is required for spin-dependent observables: FOM is proportional to **luminosity** $\times$ **polarization**²
- **Interpretability requires large Q^2**
 - Large Q^2 implies high x in fixed-target experiments (even in collider kinematics Q^2, x are correlated).
 - DIS event rate falls $\sim$ exponentially with x in the valence region
- **The kinematic focusing of high- z , low- p_T hadrons along $\vec{q}$ makes a medium-acceptance, high-luminosity experiment the most productive for certain kinds of observables, including, especially, transverse target SSA (Collins, Sivers, etc.) for the neutron (mature ^3He SEOP technology)**

Kinematic Conditions for applicability of TMD formalism

- Requires large Q^2 ($Q^2 > 1 \text{ GeV}^2$), large W ($W > 2 \text{ GeV}$), 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: $k_\perp \approx \Lambda_{QCD} \approx 200 \text{ MeV}$
 - Small enough for applicability of TMD formalism; i.e., dominance of TMD effects over collinear pQCD effects (gluon radiation, etc.)

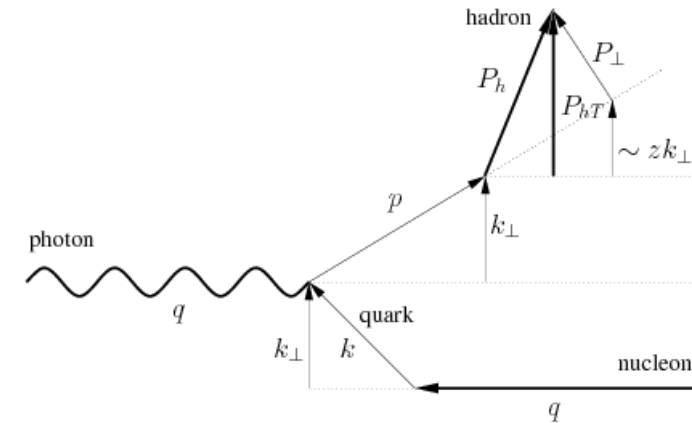


Figure: Bacchetta *et al.*, JHEP 1706 (2017) 081
At leading order in $k_\perp/Q$, we have:

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

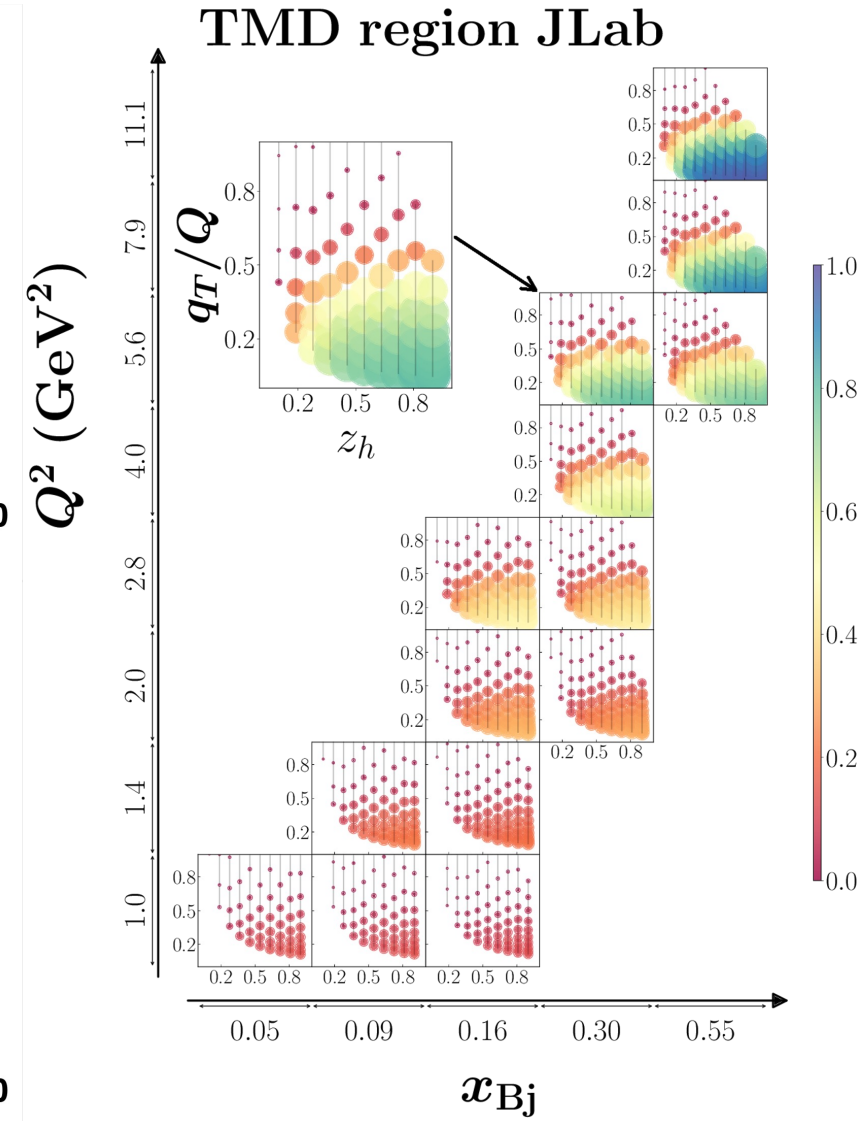
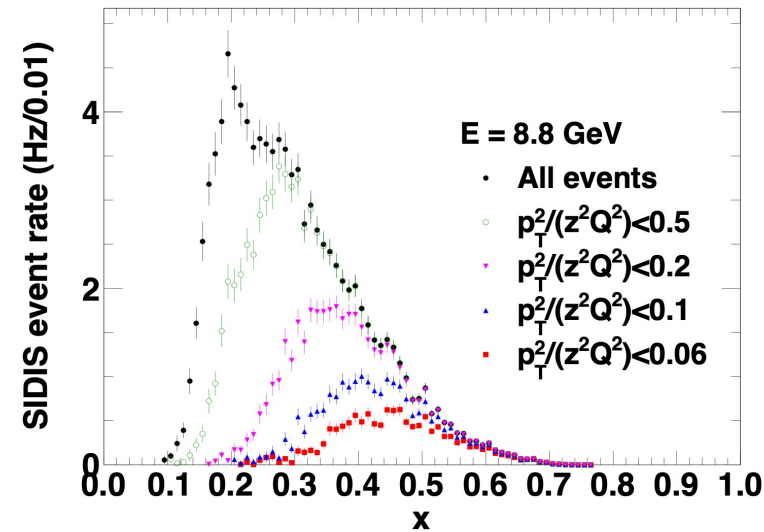
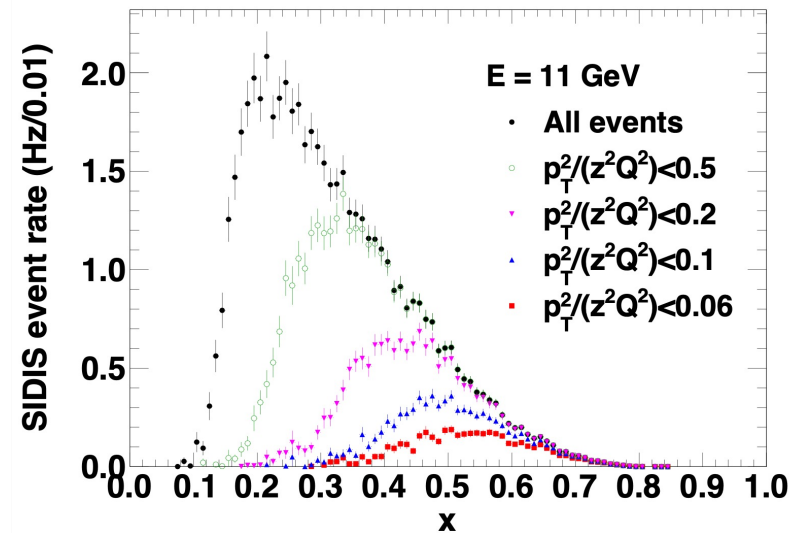
- Experimentalist's/phenomenologist's rule of thumb:

$$\frac{|\mathbf{P}_{hT}|}{z} \ll Q$$

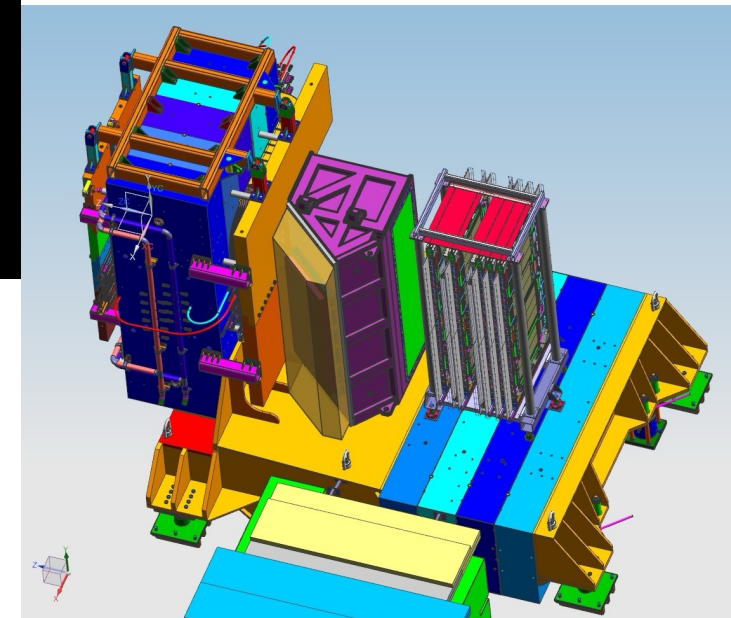
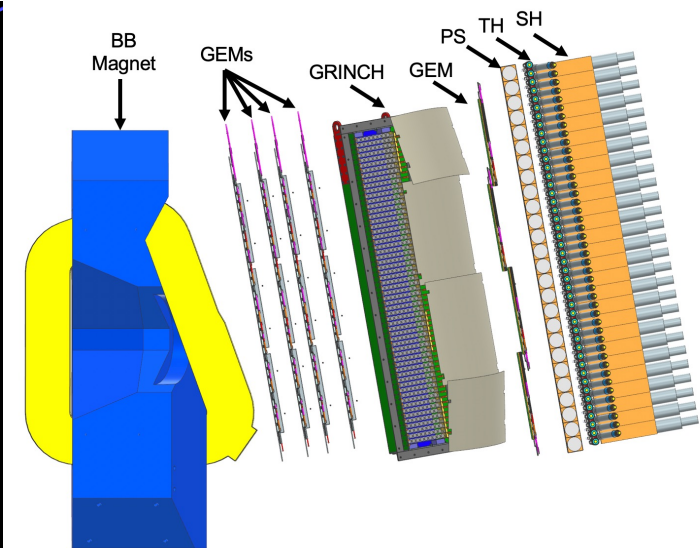
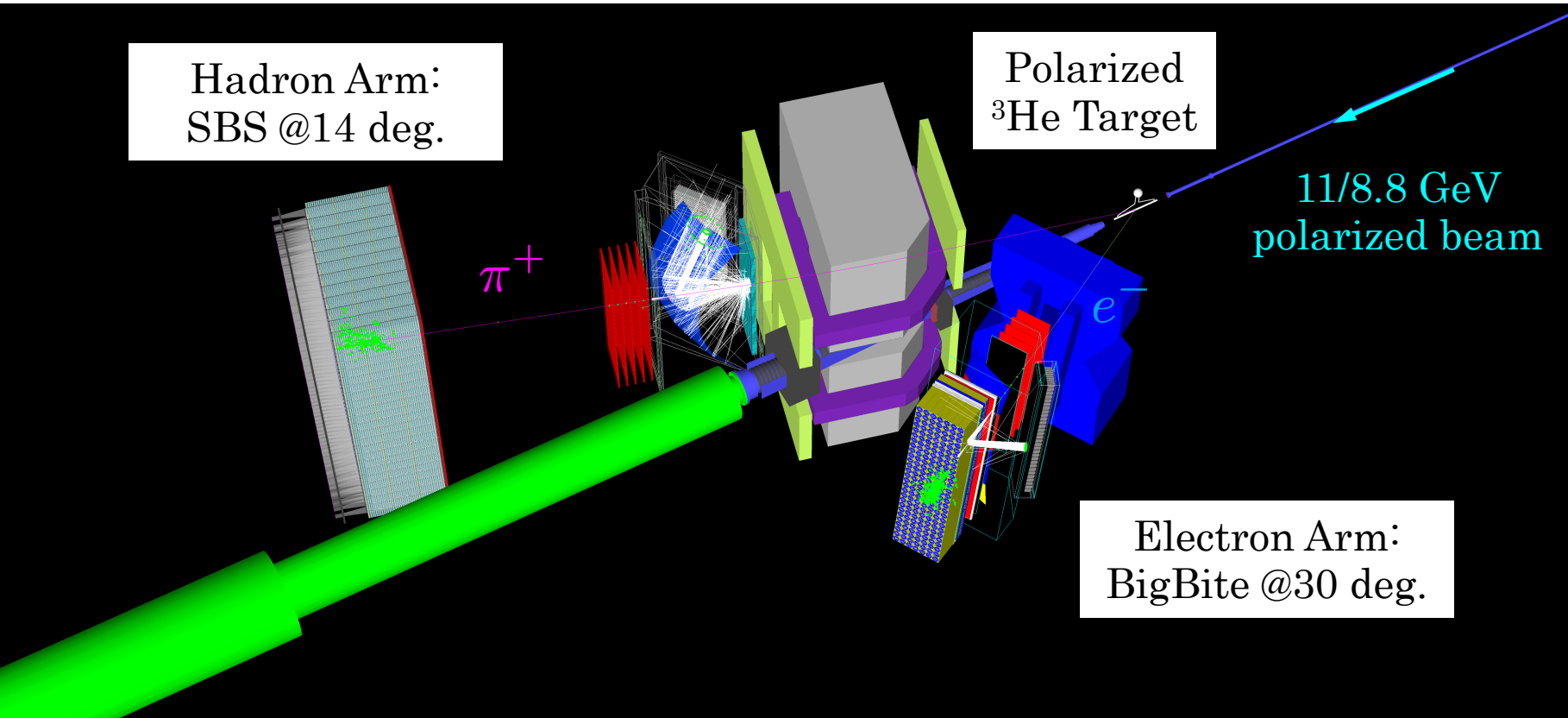
- For JLab-12 GeV: $0.3 \leq z \leq 0.7$ for pions; more restricted range for charged kaons, due to hadron mass/target fragmentation.

Uniqueness of E12-09-018 kinematics and “TMD Affinity”

- The JAM Collaboration published “New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering”: [JHEP 04, 084 \(2022\)](#)
- Authors define quantitative “affinity” criteria for TMD, collinear, and intermediate regions
- Results underscore the importance of high x, Q^2 , which E12-09-018 is uniquely suited to address
- Note that very aggressive cuts on $\frac{q_T}{Q}$ tend to exclude most existing (HERMES/COMPASS) data on transverse target SSA!
- The SBS+BB combination is uniquely well suited to investigate the question empirically for Collins/Sivers effects!

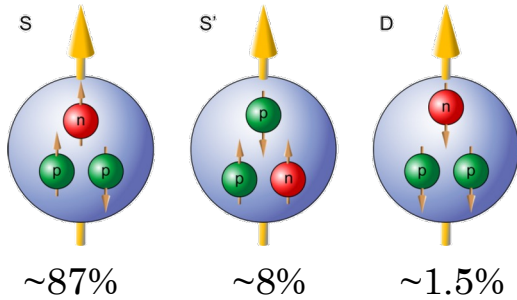


The SBS SIDIS Experiment



- Above, left: screenshot of a single $^3\text{He}(e, e'\pi^+)X$ event in the SBS GEANT4 MC (note: green dots represent “hits” in sensitive volumes)
- Above, right: Side view of SBS-era BigBite detector package
- Below, right: Hadron arm detector package in SBS CAD model

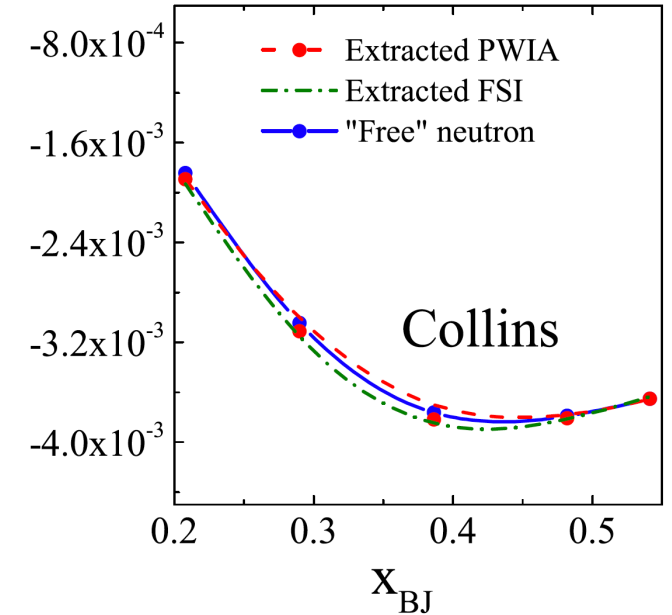
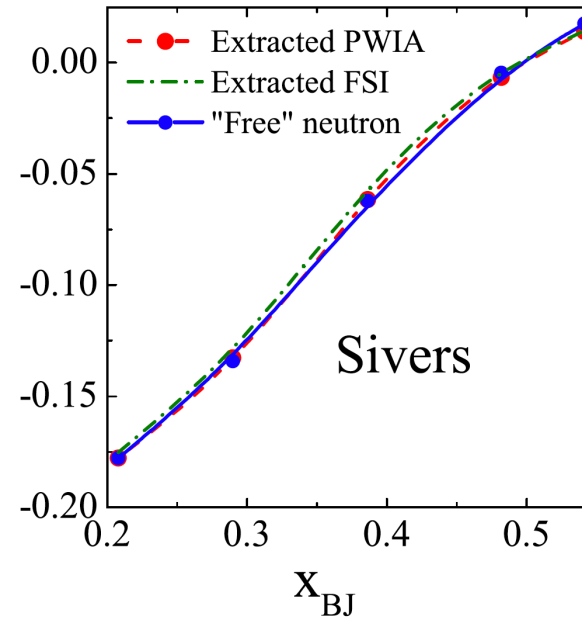
Helium-3 as Effective Polarized Neutron Target



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

Effective polarization approximation for
DIS/SIDIS on ^3He :

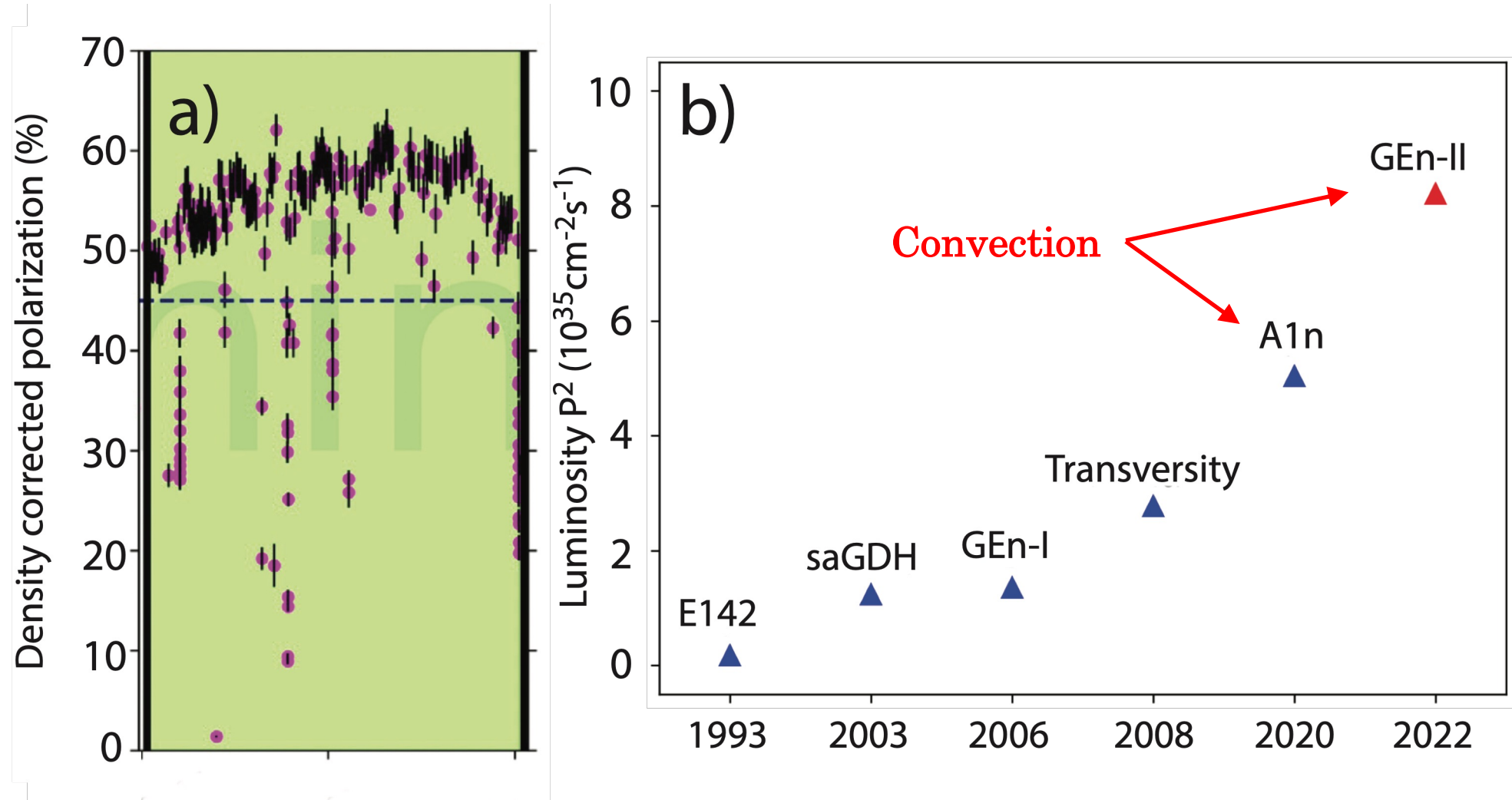
Scopetta, Phys. Rev. D 75, 054005 (2007)



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

- Effects of nuclear FSI on extraction of neutron Collins and Sivers effects from SIDIS on ^3He under good theoretical control
- Advantages of Helium-3 for study of polarized neutron:
 - Protons almost unpolarized—asymmetry dominated by neutron!
 - High luminosity capability (up to several $10^{37} \text{ cm}^{-2} \text{ s}^{-1}$)
 - Small holding field $\rightarrow$ negligible effect of target spin flips on acceptance/efficiency for SSA extraction

Polarized Helium-3 Target Performance During GEn-II



Best-performing target cell “Fringe” achieved $\sim 95\%$ of SIDIS FOM ($P_{tgt}^2 I_{beam}$) goal

Raw asymmetry at $Q^2 = 3 \text{ GeV}^2$ (plot credit: Vimukthi Gamage thesis (UVA))

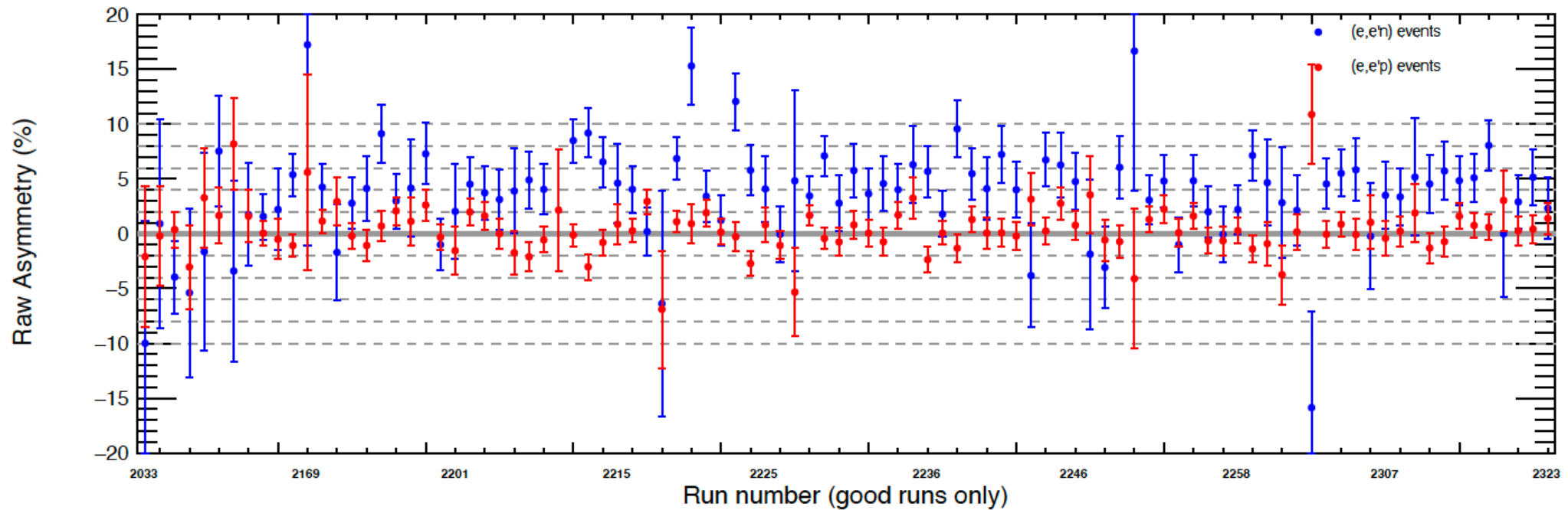


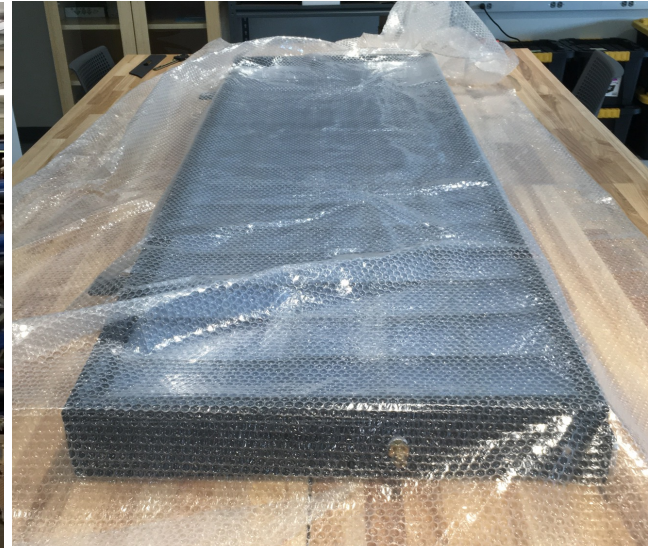
Figure 5.14: Run by run asymmetry for Kin2 after accounting for the half-wave plate and accelerator settings. Certain runs are excluded from the analysis due to various quality issues including helicity measurement malfunctions.

- Neutron (proton) quasi-elastic asymmetry “large” (“small”) as expected for ^3He target

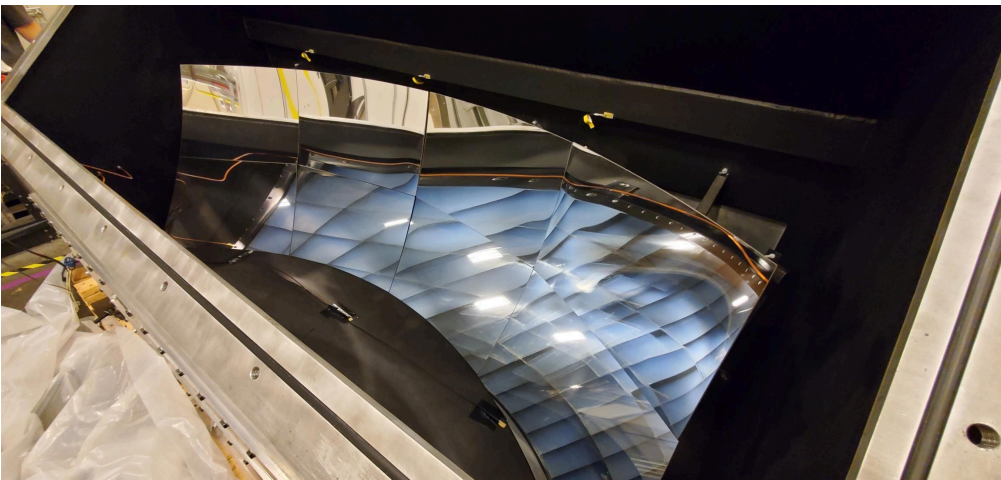
HERMES→SBS RICH: Hardware Status



RICH detector at Jlab



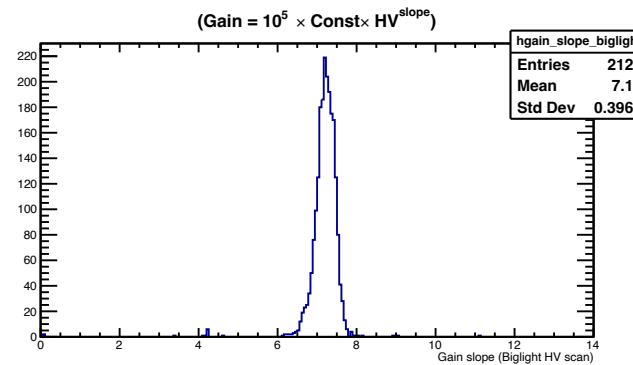
"Spare" aerogel wall
@UConn



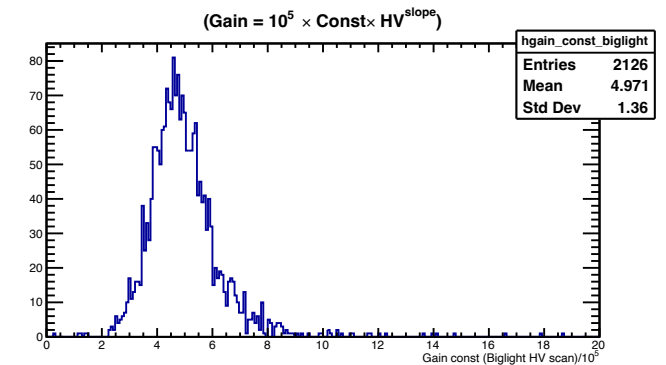
Inspecting RICH mirrors

RICH PMT testing summary

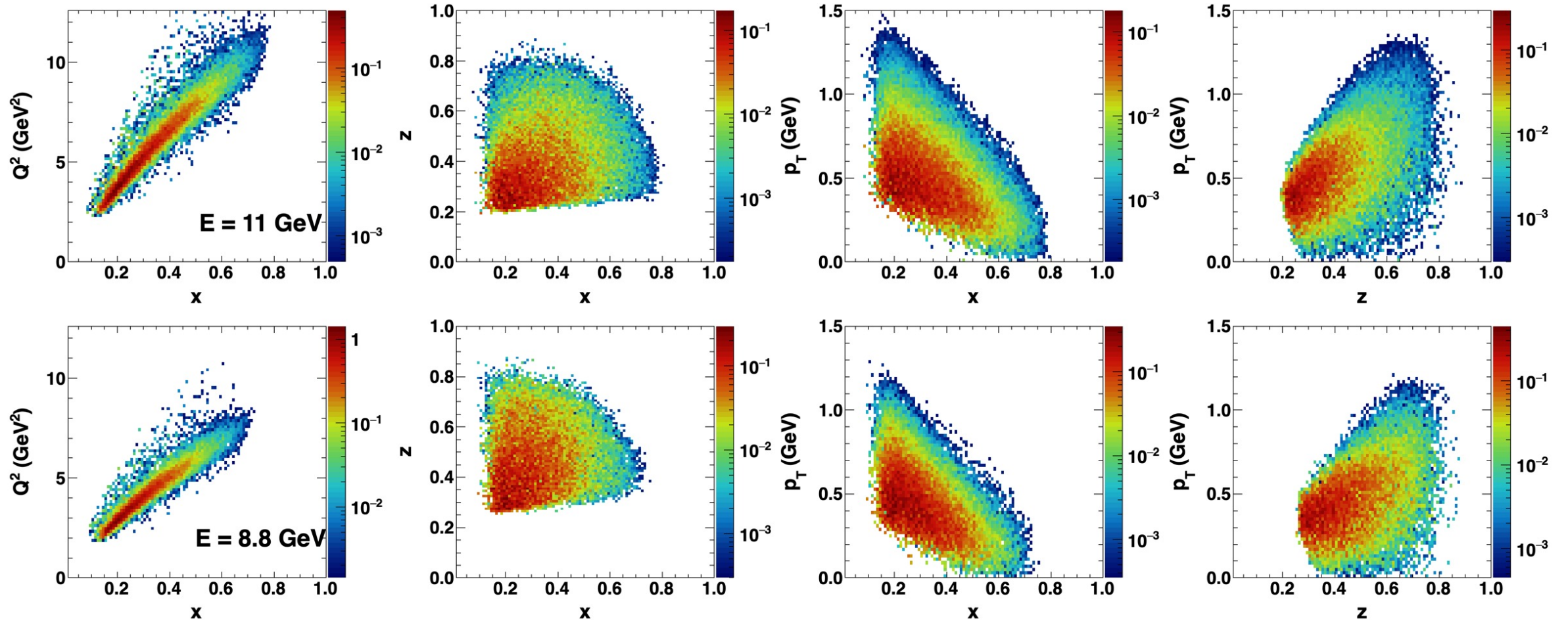
- All RICH PMTs and 224 "spare" PMTs tested
- 2,126 "good" (1,934 needed, 192 spares)
- All front-end and readout electronics available and used during FF program
- Mirrors inspected, in good shape
- Absolute quantum efficiency measured for ~215 tubes, found consistent with spec
- See [here](#) for more details



RICH PMT gain slope and "constant" = (gain at 1 kV)/ 10^5

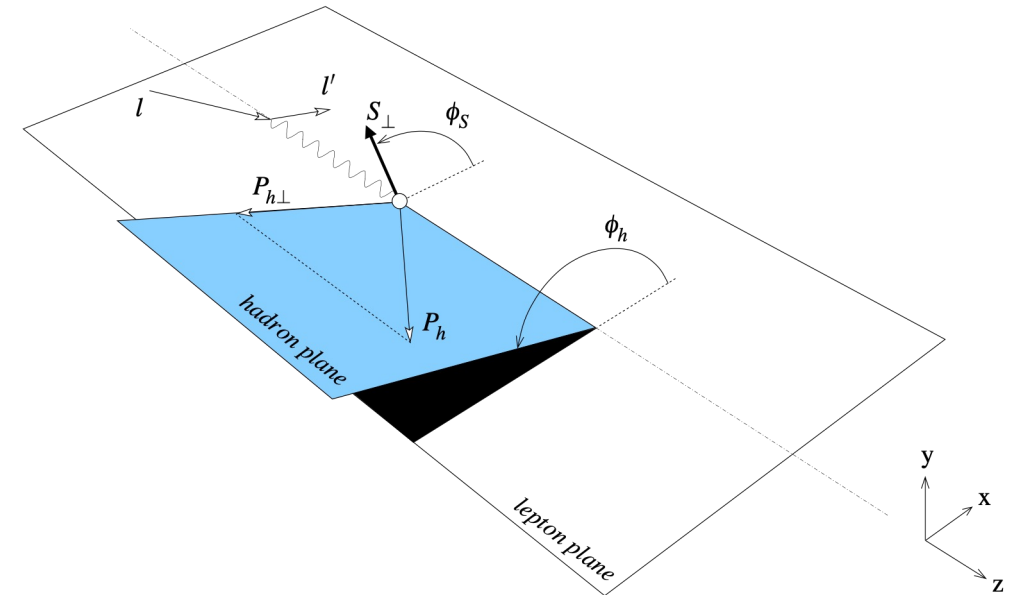
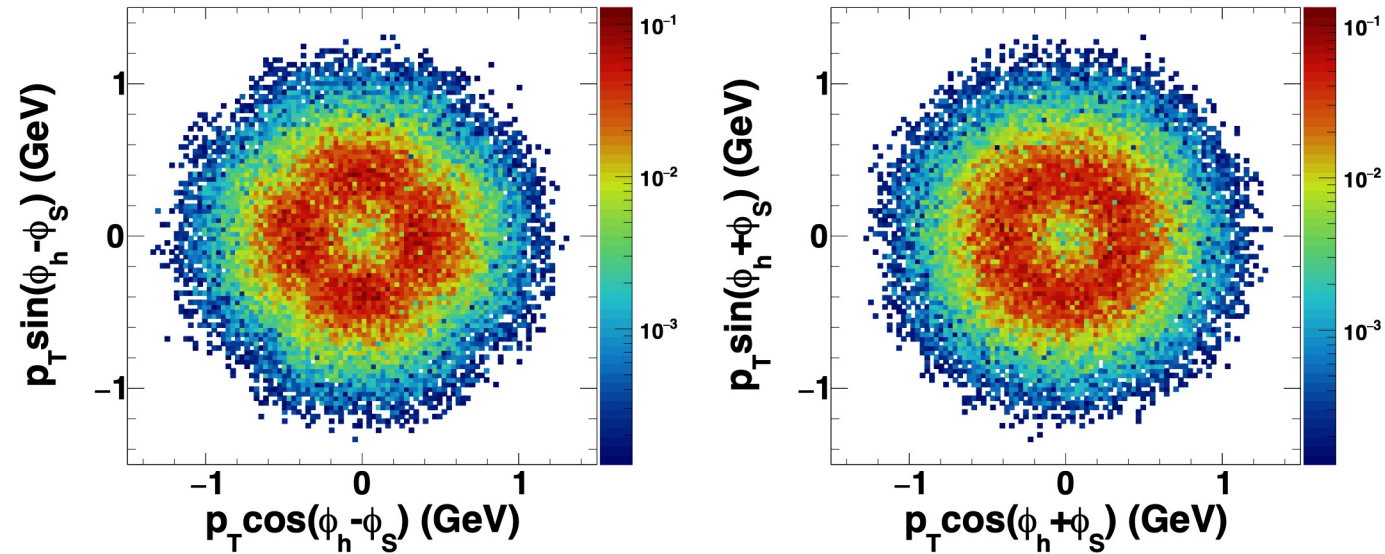
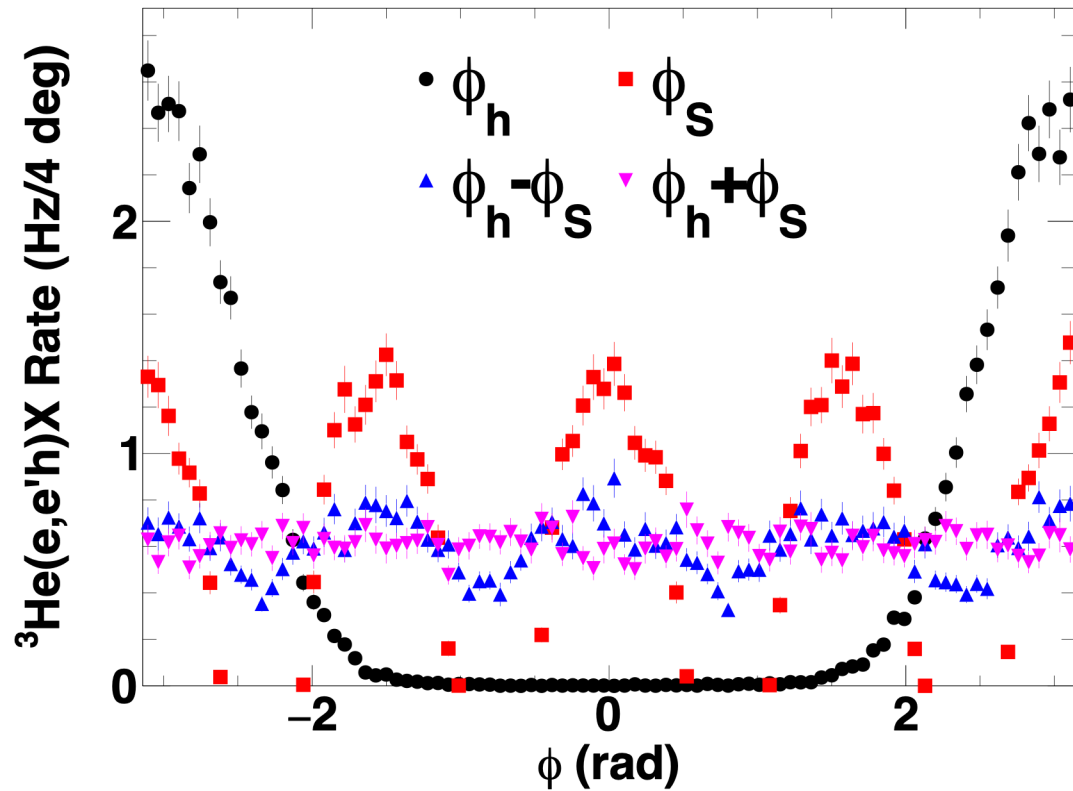


SBS SIDIS Kinematic Coverage



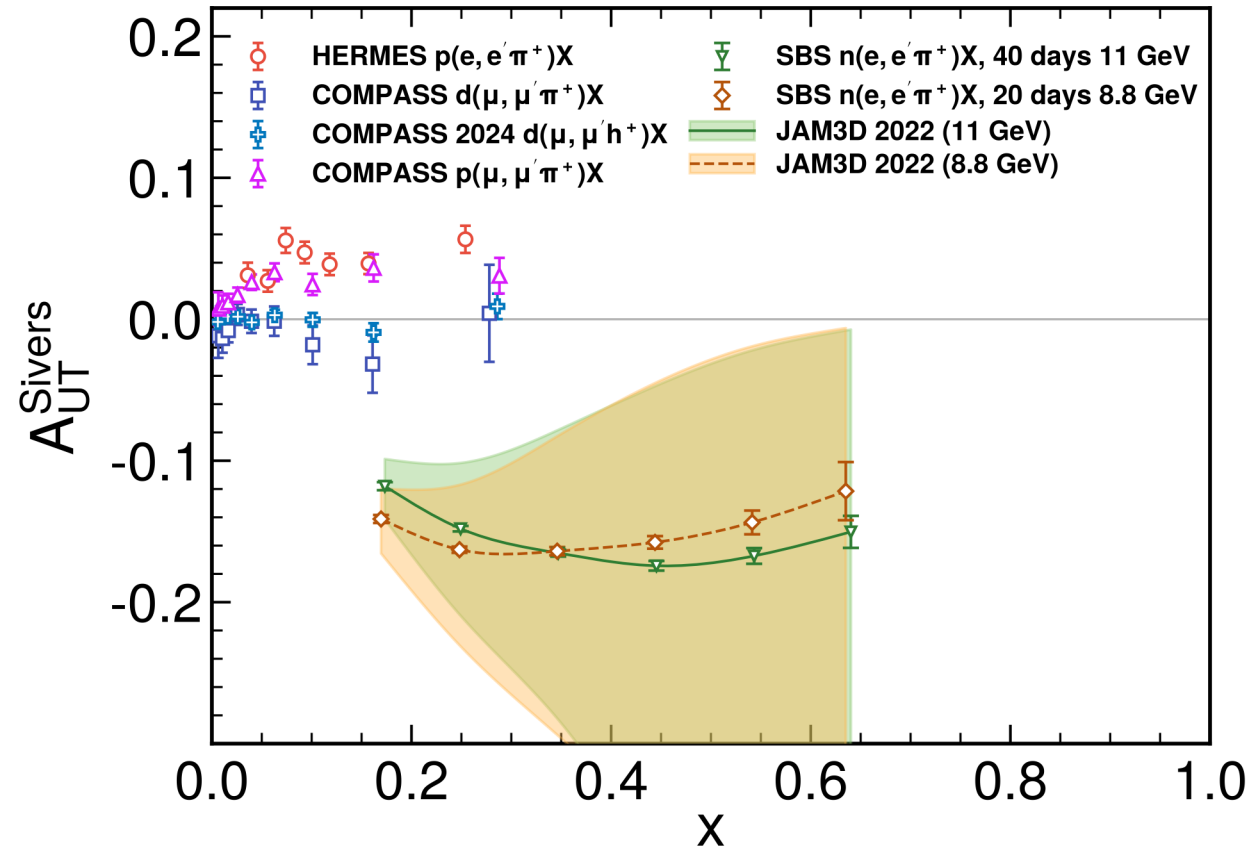
- Above, left to right: SBS SIDIS kinematic coverage in (Q^2, x) , (z, x) , (p_T, x) , (p_T, z) , for $E = 11$ GeV (top row) and 8.8 GeV (bottom row), from *g4sbs*
- Cuts applied are: $Q^2 \geq 1 \text{ GeV}^2$, $W^2 \geq 4 \text{ GeV}^2$, $M_X^2 \geq 2.3 \text{ GeV}^2$, $E'_e \geq 1 \text{ GeV}$ (roughly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

SBS SIDIS Azimuthal Angle Coverage

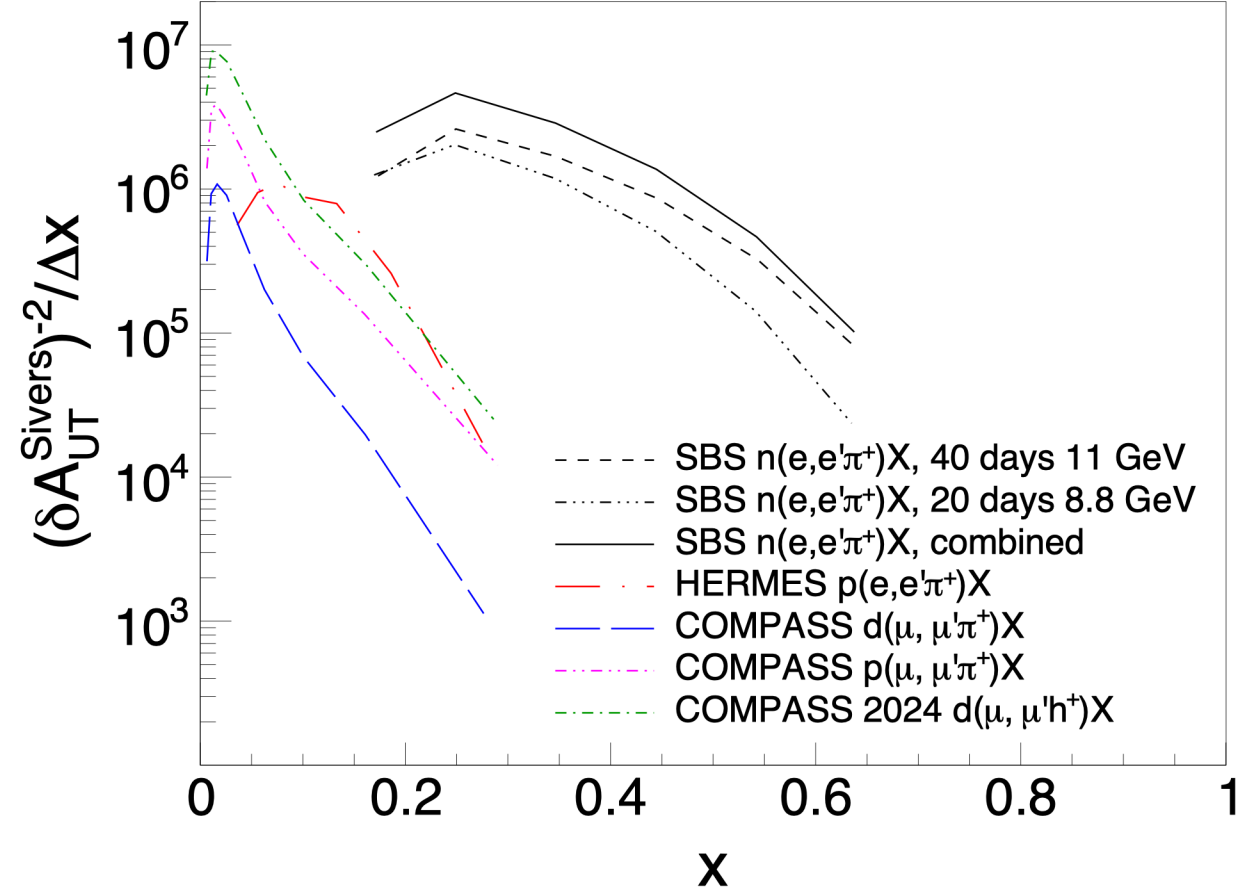


- Original proposal envisioned 8 target spin directions
- Simulations show full and (sufficiently) uniform coverage of $\phi_h \pm \phi_s$, no reduction of physics impact with 4 target directions
- Dramatically simplifies target design & operation

Example of projected results (1D): A_{UT}^{Sivers} for $\vec{n}(e, e' \pi^+) X$

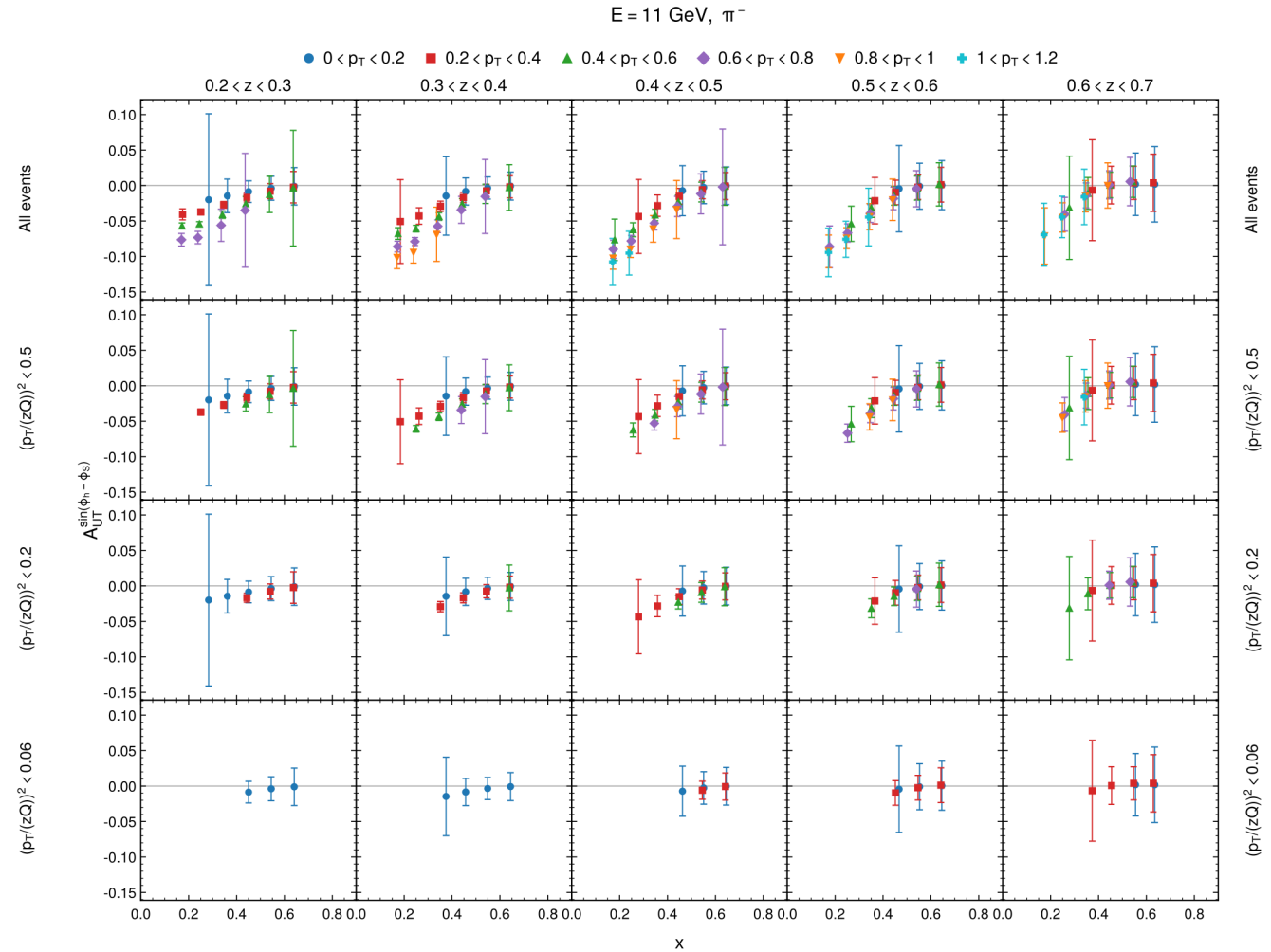
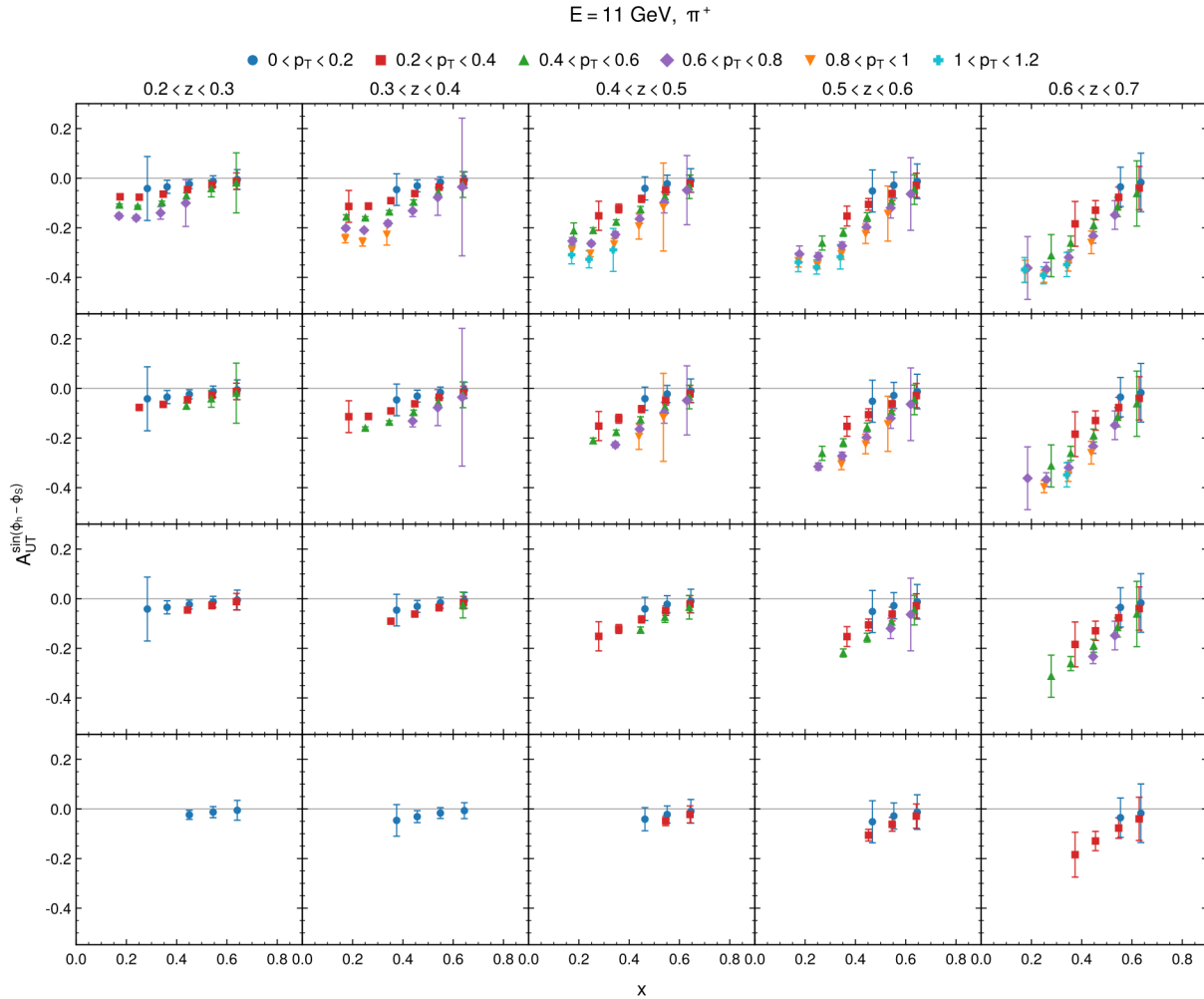


Example comparison of E12-09-018 projected neutron Sivers asymmetry to HERMES and COMPASS published data (including COMPASS 2022 deuteron data for unidentified charged hadrons)

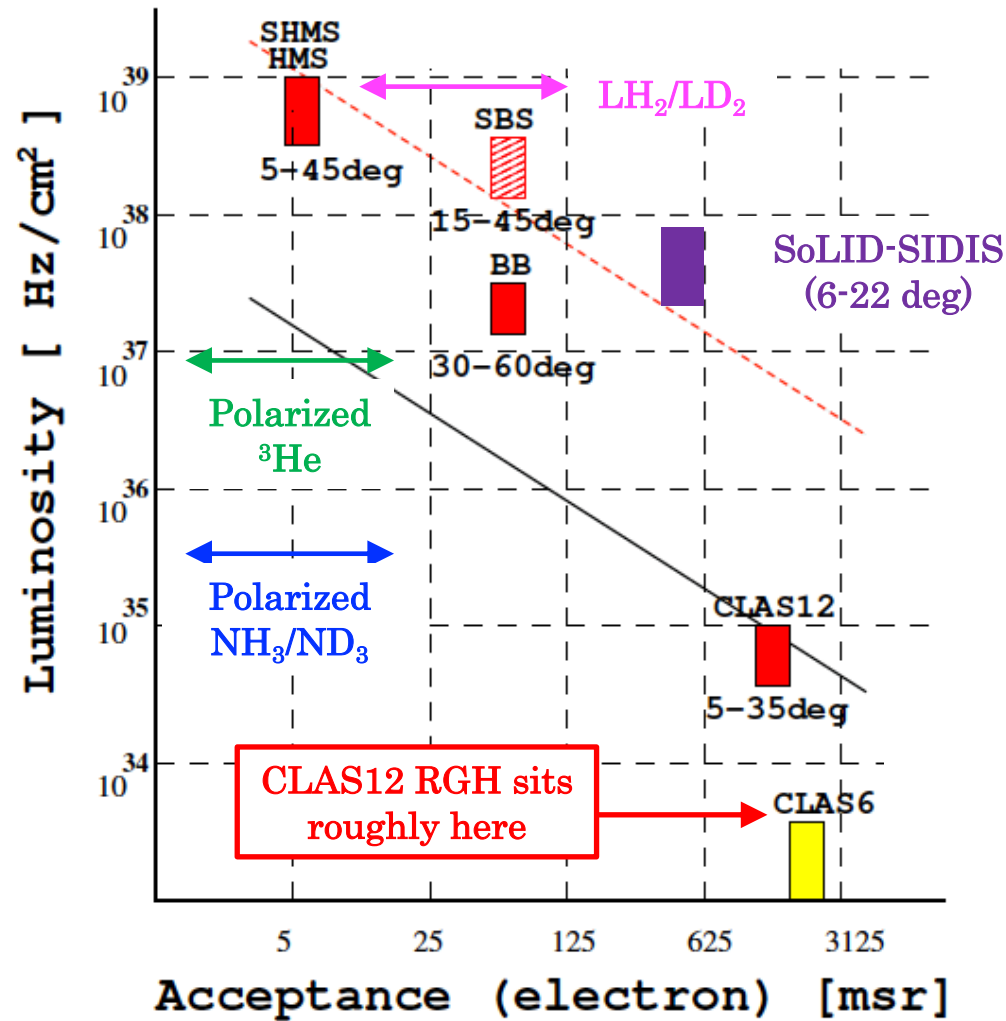


Same as left, plotted as statistical Figure-of-Merit (FOM) per x interval.

Fully Differential Analysis, Effects of $\frac{p_T}{zQ}$ Cuts



The *Increasing* Scientific Merit of E12-09-018



- Major experimental developments since PAC49:
 - EIC has progressed from CD-1 → CD-3b
 - COMPASS 2022 ^6LiD run: [publication](#)
 - SBS FF program completed, including GEn-II
 - CLAS12 RGH approval for proton (NH_3) target
- Urgent* need to keep the theory community engaged with new data
- JLab 12 GeV has yet to weigh in on this important physics despite a decade+ of running
- Of all approved JLab SIDIS proposals with transverse target, this experiment has (by far) the lowest cost/schedule/technical risk
- In light of these considerations, we ask the PAC to reconsider the scientific rating of E12-09-018 → an upgraded rating will help with scheduling/support/resources

Summary of Beamtime Request, More Information

TABLE I. Total projected $^3\text{He}(e, e'h)X$ statistics in the PAC38/49-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 $Q^2 > 1 \text{ GeV}^2$, $W^2 > 4 \text{ GeV}^2$, $M_X^2 > 2.3 \text{ GeV}^2$, $p_T \geq 0.05 \text{ GeV}$, $E'_e \geq 1 \text{ GeV}$ and $p_h \geq 2 \text{ GeV}$. 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. [55].

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

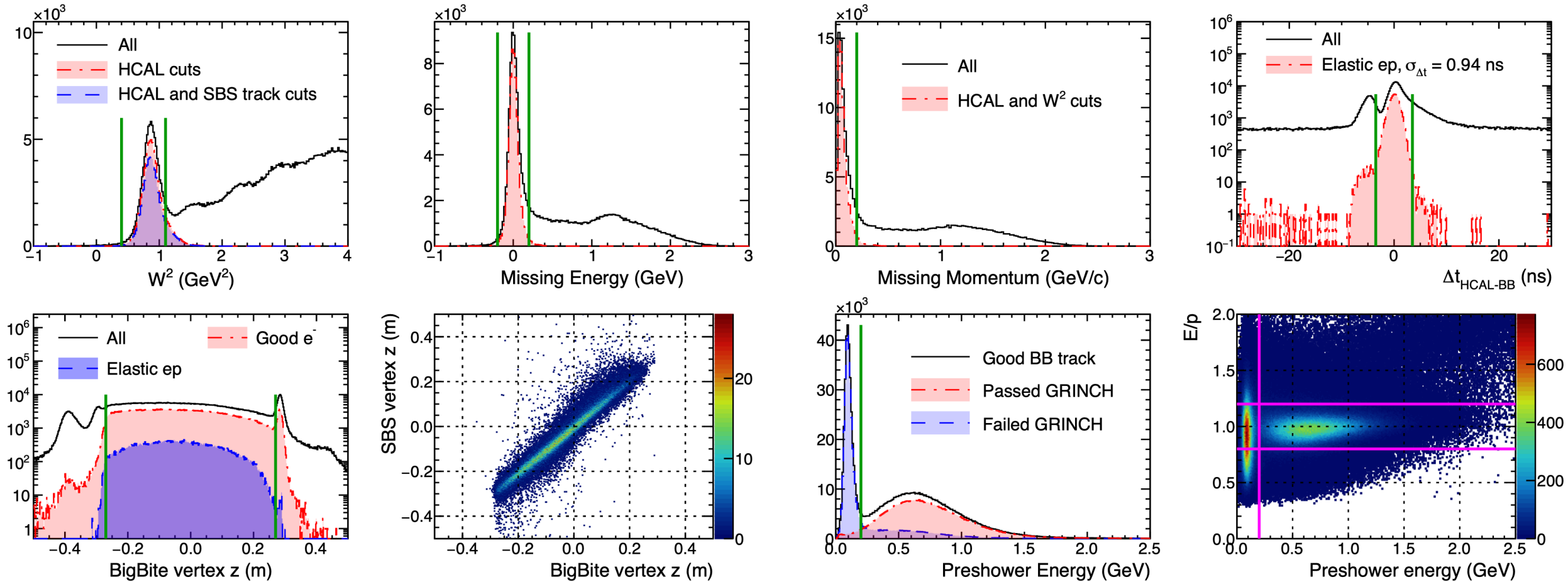
TABLE II. E12-09-018 beam-time requests, unchanged from PAC38 and PAC49.

Beam Energy (GeV)	Beam Current (μA)	Beam Requirements	Target Material	Material Thickness (mg/cm^2)	Purpose	Beamtime (days)
8.8	40	Polarized	^3He	80 ^a	Production	20
11.0	40	Polarized	^3He	80	Production	40
8.8	≤ 45		Various	Various ^b	Calibrations	2
11.0	≤ 45		Various	Various	Calibrations	2
Total Time						64

- Full statistical uncertainty [projections](#) by hadron (1D, 2D, 3D) and beam energy
- [Replies](#) to PAC reader comments
- [Plots](#) of 1D projections by hadron, compared to JAM3D 22 and existing data
- Approved [PAC38 proposal](#)
- [Plots](#) showing effect of cuts on $\frac{p_T}{zQ}$ and W^2 on our kinematic coverage and precision.
- [TAC comments](#): we agree with all $\rightarrow$ no show-stoppers, need ERR, etc.

Backups

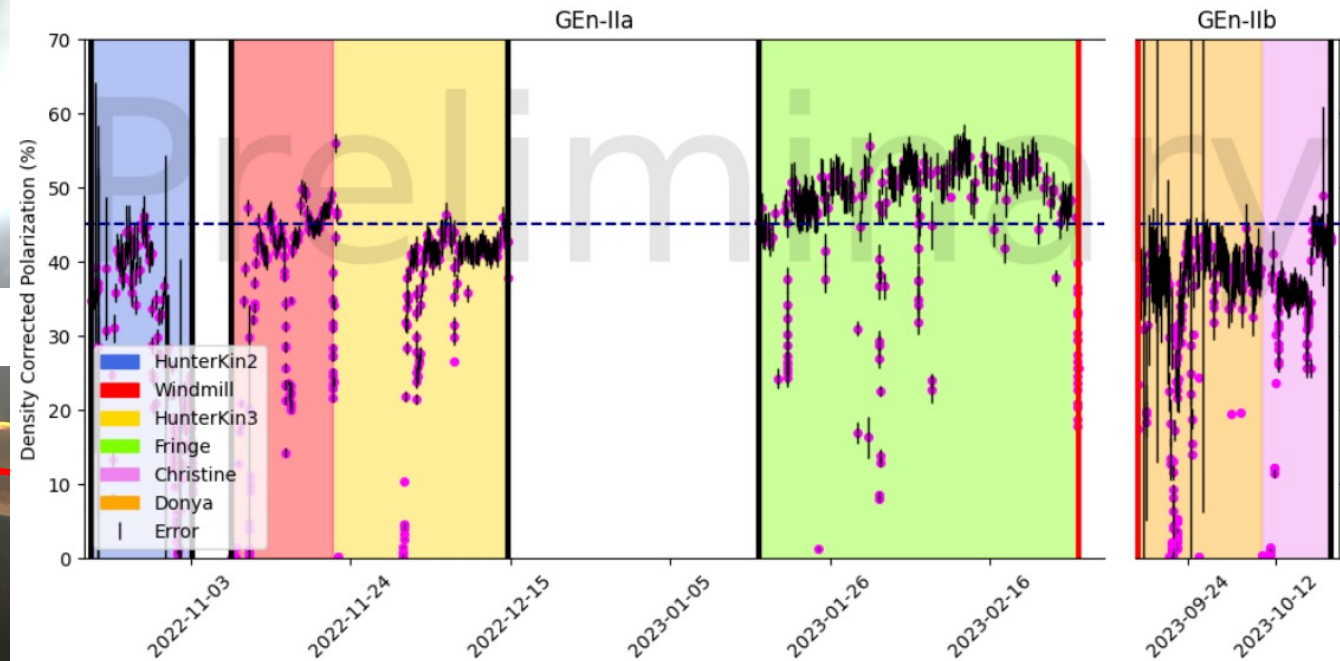
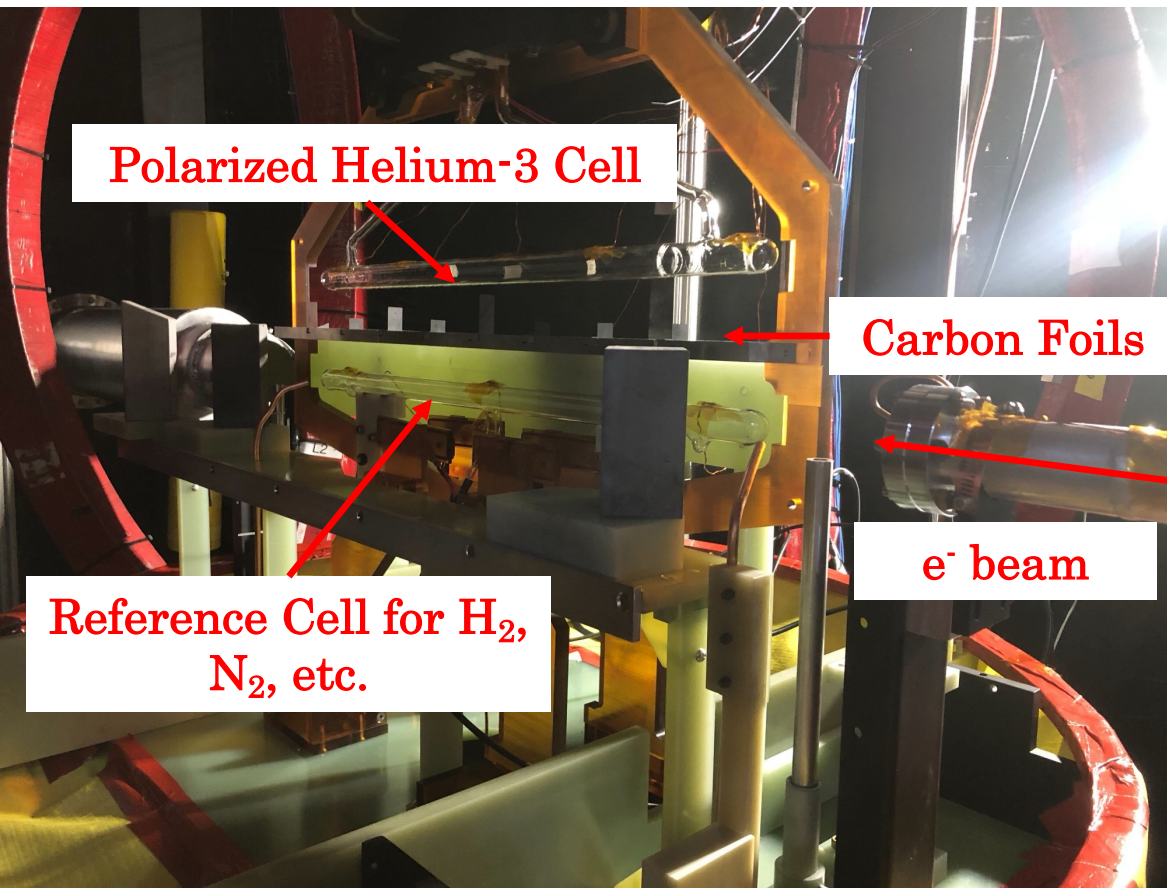
SBS and BigBite Detector Performance during GEn-II



Elastic ep scattering at $Q^2 = 3.0 \text{ GeV}^2$ w/ H_2 “reference cell” during GEn-II

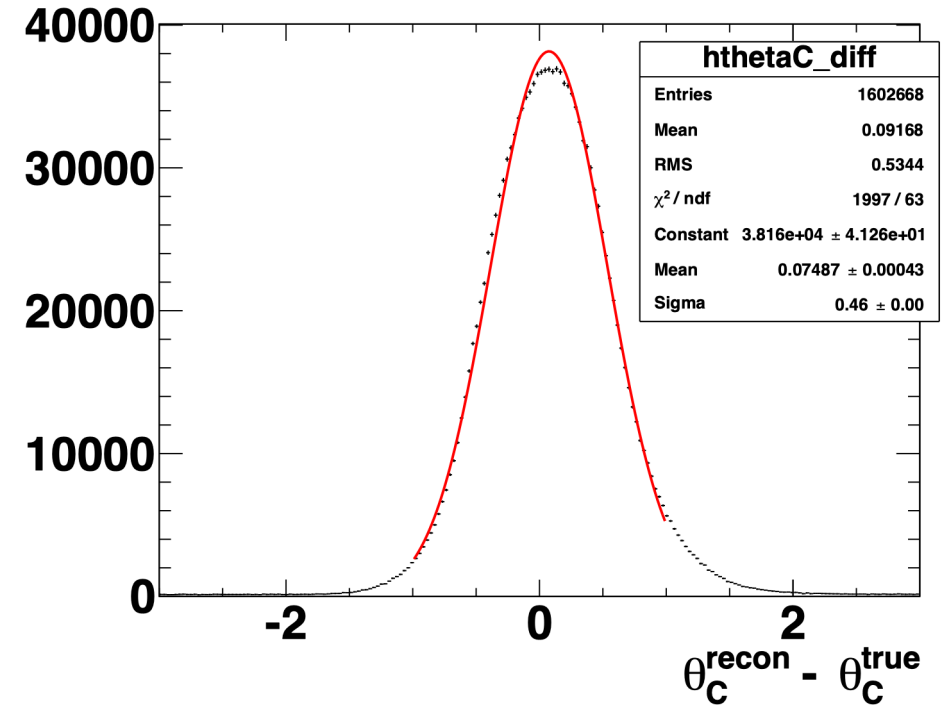
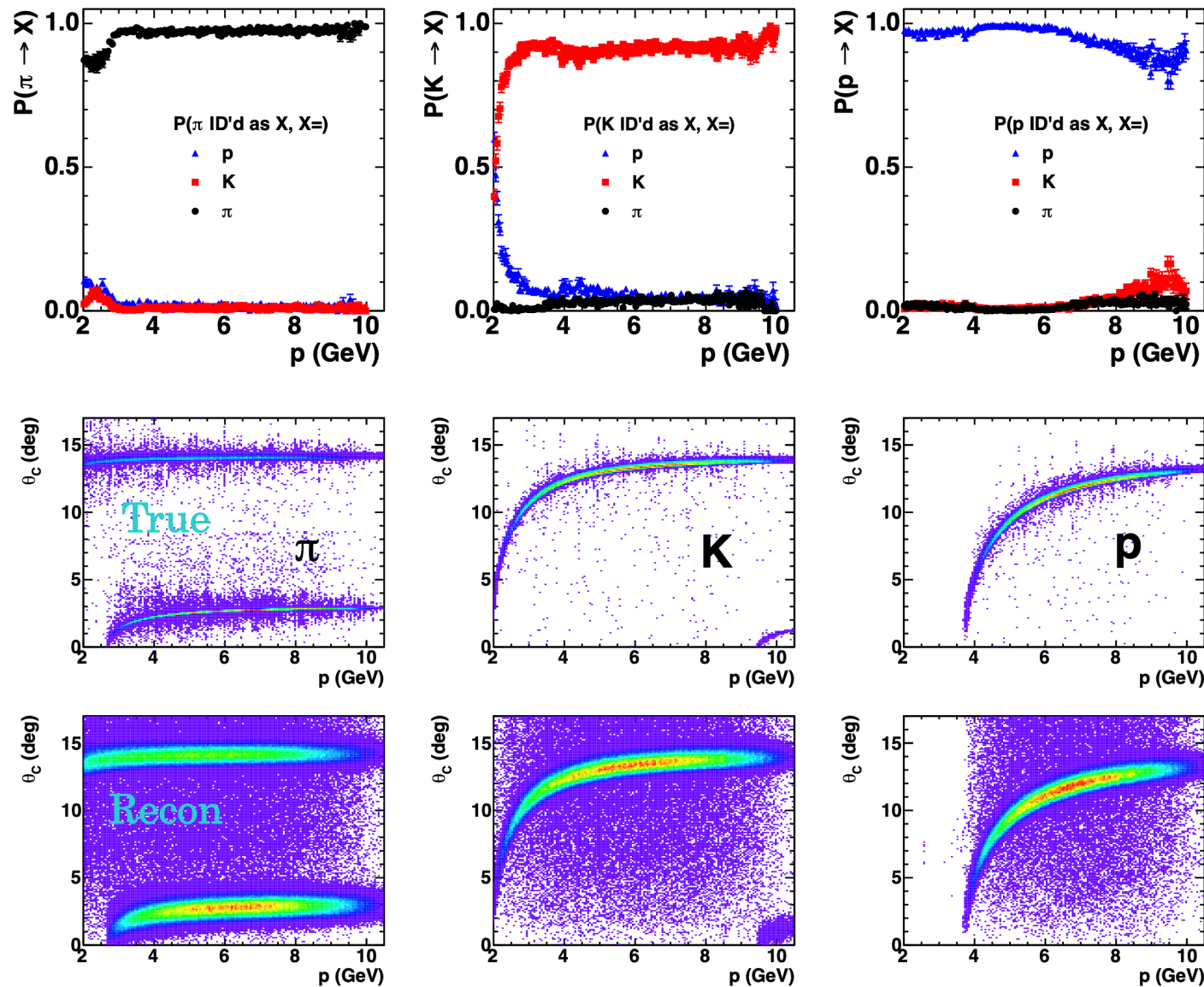
- GEMs in SBS were commissioned parasitically during GEn-II, demonstrating good tracking and PID performance for the “two-arm” system required by E12-09-018

The SBS GEn-II polarized Helium-3 target



- Above, left: Inside the target enclosure
- Above, right: preliminary target polarization results
- Below, right: estimated FOM compared to previous experiments

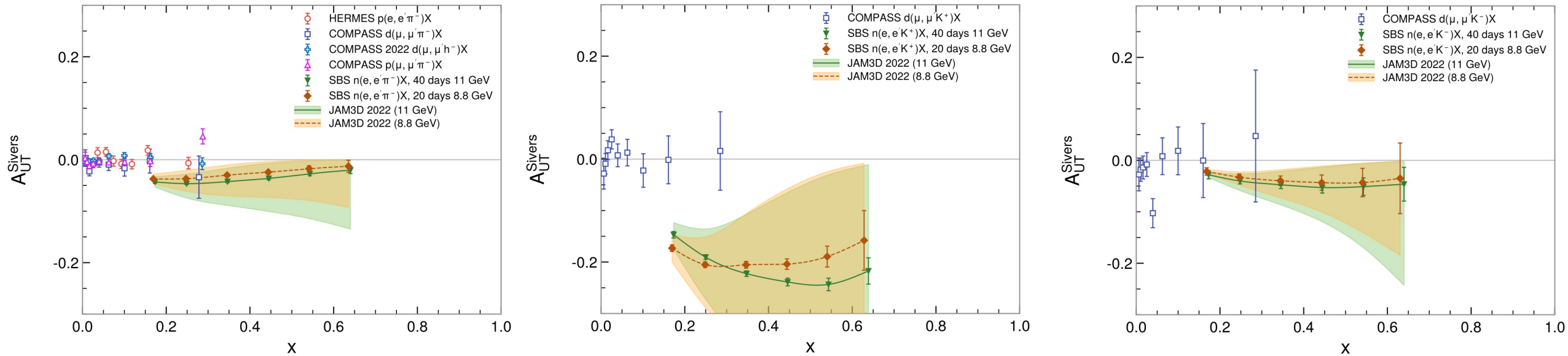
Simulated RICH performance in SBS



More details of RICH simulations [here](#)

- Above, left: simulated SBS PID probabilities vs. particle momentum
- Below, left: simulated SBS Cherenkov angle reconstruction
- Above, right: simulated SBS Cherenkov angle resolution (consistent with HERMES performance)

1D neutron Siverson projections: other hadrons



- Projected Siverson asymmetry precision for $n(e, e'h)X$, for $h = \pi^-, K^+, K^-$ (from left to right)
- **Analysis credit: Provakar Datta (LBNL)**
- NOTES: JAM3D 2022 projections and uncertainty bands interpolated for our kinematics, binnings, and cuts from public Jupyter notebook:
 - https://colab.research.google.com/github/pitonyak25/jam3d_dev_lib/blob/main/JAM3D_Library.ipynb
 - Based on this paper: <https://doi.org/10.1103/PhysRevD.106.034014>
- SBS projections are those from the PAC38 proposal, full tables can be found here in a (hopefully) self-explanatory format: <https://userweb.jlab.org/~puckett/PR1209018/KineTables/>
- Collins projections (not shown) available on request (with sufficient advance notice!). Projected (absolute) uncertainties for Collins asymmetries are generally similar to Siversons.

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

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

- 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 $\rightarrow$ hadron fragmentation functions!

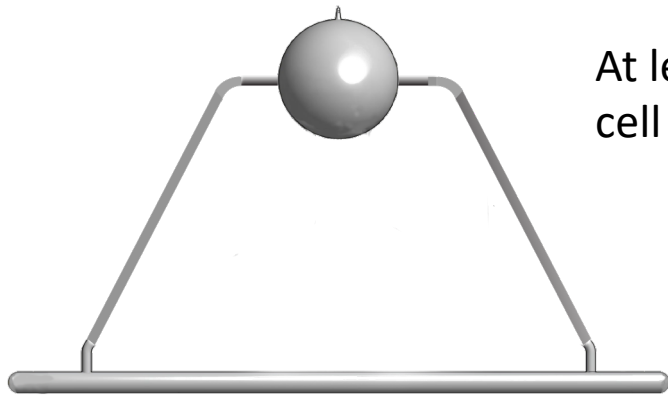
$F_{UU,T} \sim f_1 \otimes D_1$
 $F_{UU}^{\cos 2\phi_h} \sim h_1^\perp \otimes H_1^\perp$
 $F_{UL}^{\sin 2\phi_h} \sim h_{1L}^\perp \otimes H_1^\perp$
 $F_{LL} \sim g_1 \otimes D_1$
 $F_{UT}^{\sin(\phi_h - \phi_S)} \sim f_{1T}^\perp \otimes D_1$
 $F_{UT}^{\sin(\phi_h + \phi_S)} \sim h_1 \otimes H_1^\perp$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

$D_1(z, Q^2, p_\perp^2) =$ Unpolarized TMD FF
 $H_1^\perp(z, Q^2, p_\perp^2) =$ Collins TMD FF

Polarized ^3He target for SBS SIDIS

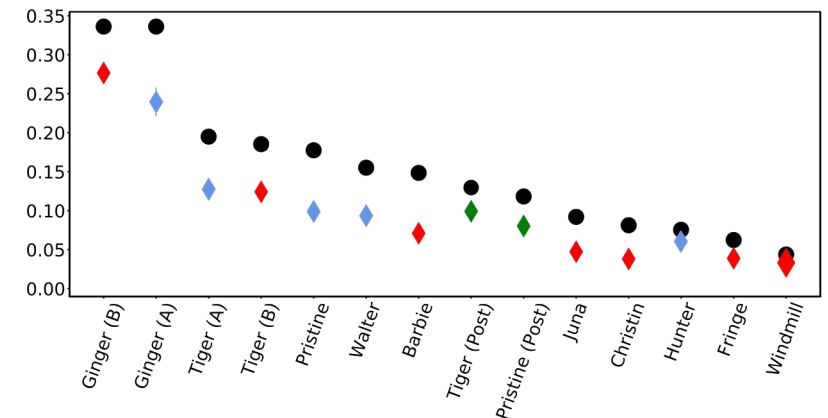
As shown earlier, there have been substantial gains in the figure-of-merit for successive ^3He experiments, and there is good reason to expect that trend to continue for SBS SIDIS

- The easiest part: the GEn-II target was limited by the laser system.
 - Moving to a simpler laser-light transport system will bring some gains.
- The largest limiting factor for GEn-II was stress-induced micro-fractures that caused both orientation-dependent (so called “hysteresis effect”) and orientation-independent wall-induced spin relaxation.
 - New cell geometry will significantly reduce stress in glass.
 - Use ultra-low iron content glass (as was done at Mainz)



At left – new lower-stress cell design for SBS SIDIS

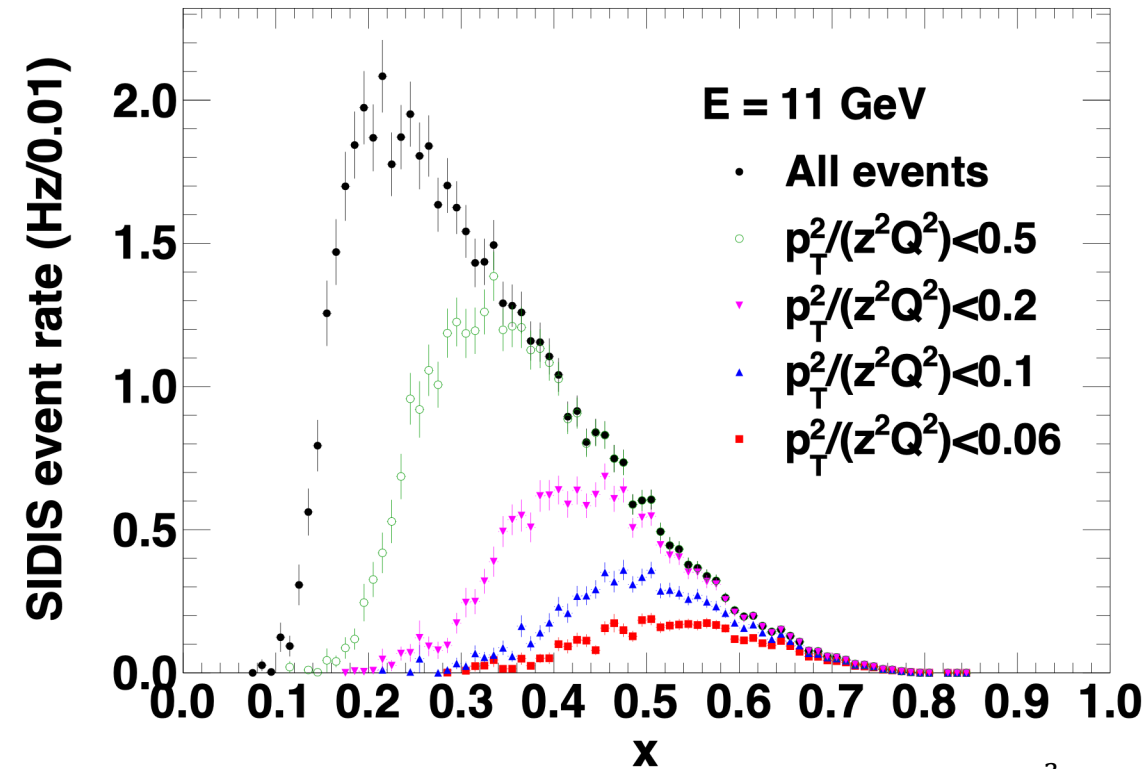
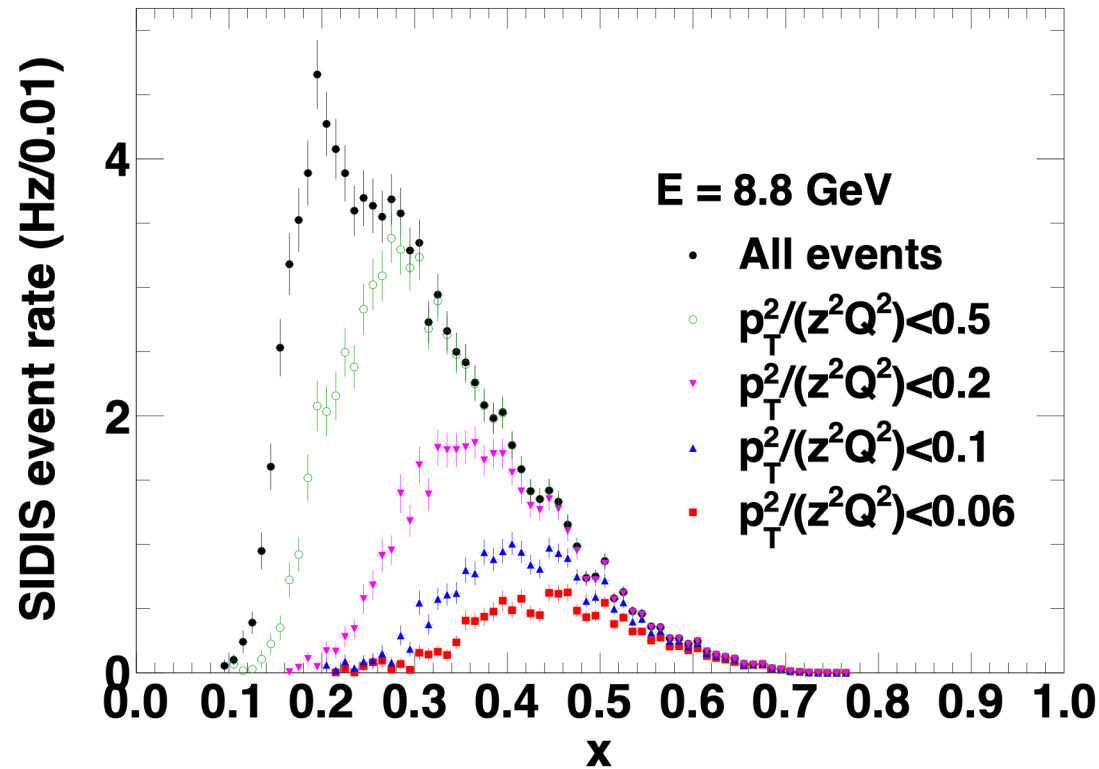
At right – study of GEn-II target cells showing hysteresis effect in every target cell.



Increased scientific merit

- Since we last went up on jeopardy, the EIC has been approved, and recently reached CD 3b
- It is important to keep the theory community engaged in the area of TMDs and single-spin asymmetries.
 - Given the time scales for the construction and commissioning of the EIC, this will be difficult without new data.
- SBS SIDIS is the only fully approved experiment that will measure single-spin asymmetries with sufficient statistics for multidimensional fully-differential binning
- With the new COMPASS data, as well as earlier data from HERMES, it would be quite valuable to obtain complimentary data at higher x_{BJ} .

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](https://arxiv.org/abs/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](https://arxiv.org/abs/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.

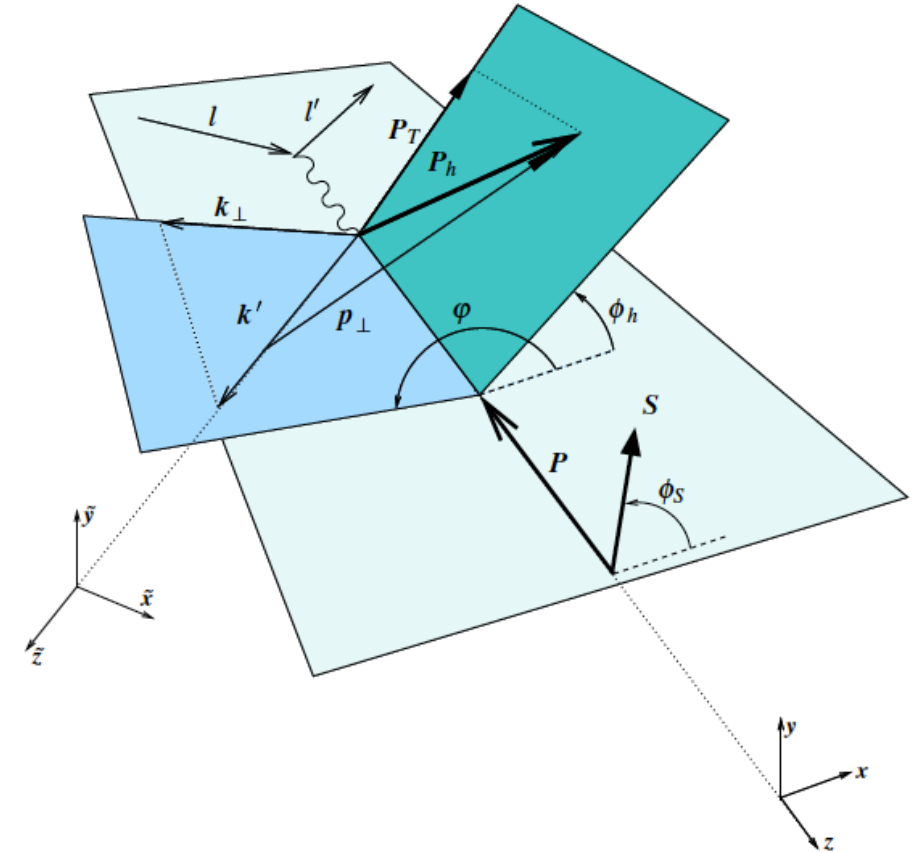
Where do the azimuthal dependences come from for transverse target SSAs?

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

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

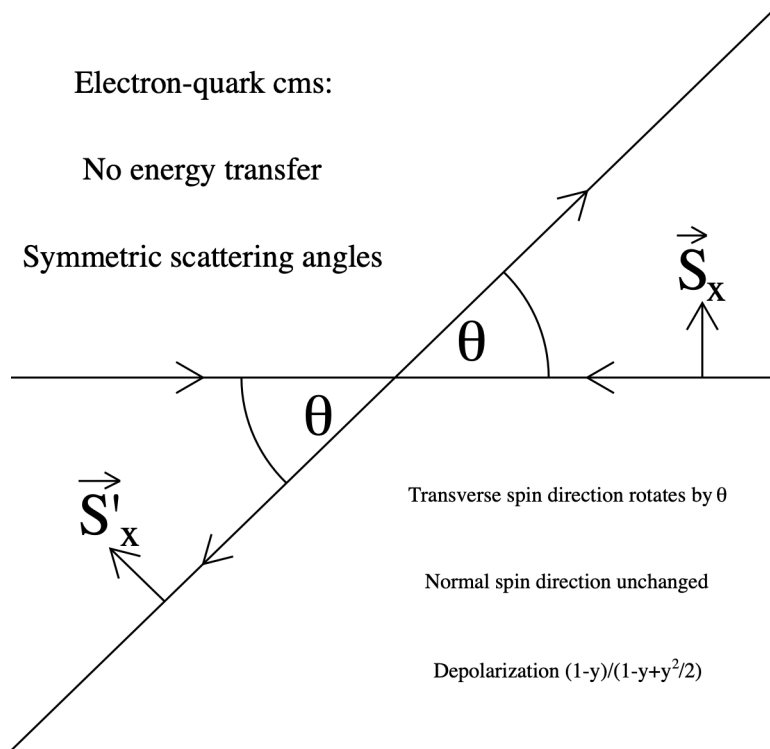
- The Collins effect is due to the left-right asymmetry in the fragmentation of a transversely polarized quark.
- The observable asymmetry results from the convolution of the transversity distribution and the Collins (spin-dependent) fragmentation function:

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

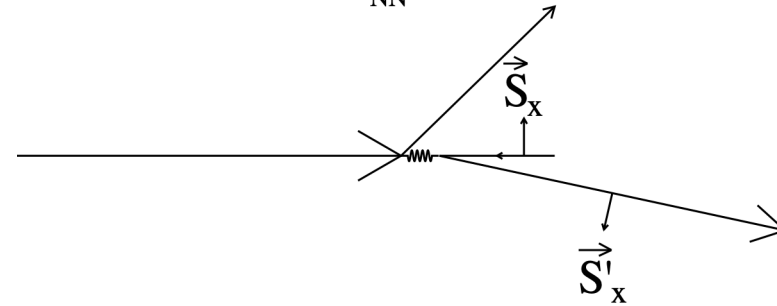


- *The in-plane component of quark transverse polarization must flip in order to absorb the transversely polarized virtual photon (angular momentum conservation) → Sign of ϕ_S is reversed in observable asymmetry*

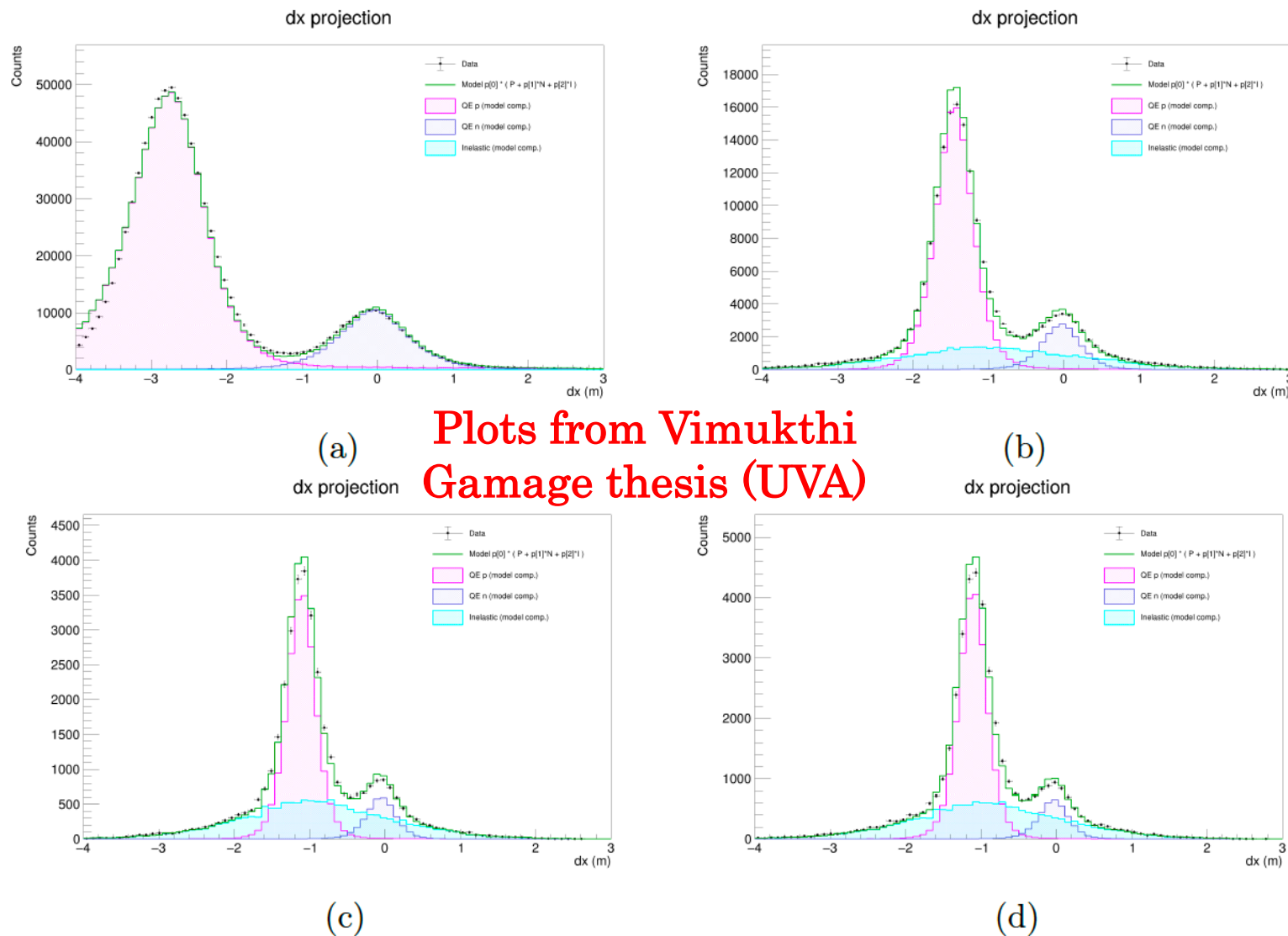
Transverse spin dynamics in eq→eq



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



- Magnitude of quark normal and in-plane transverse polarization components is reduced by a factor of
 - $D_{nn} = (1-y)/(1-y^2/2)$, where $y = (1 - \cos\theta_{CM})/2$ is invariant ($y=(v/E)_{LAB}$).
- 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!*



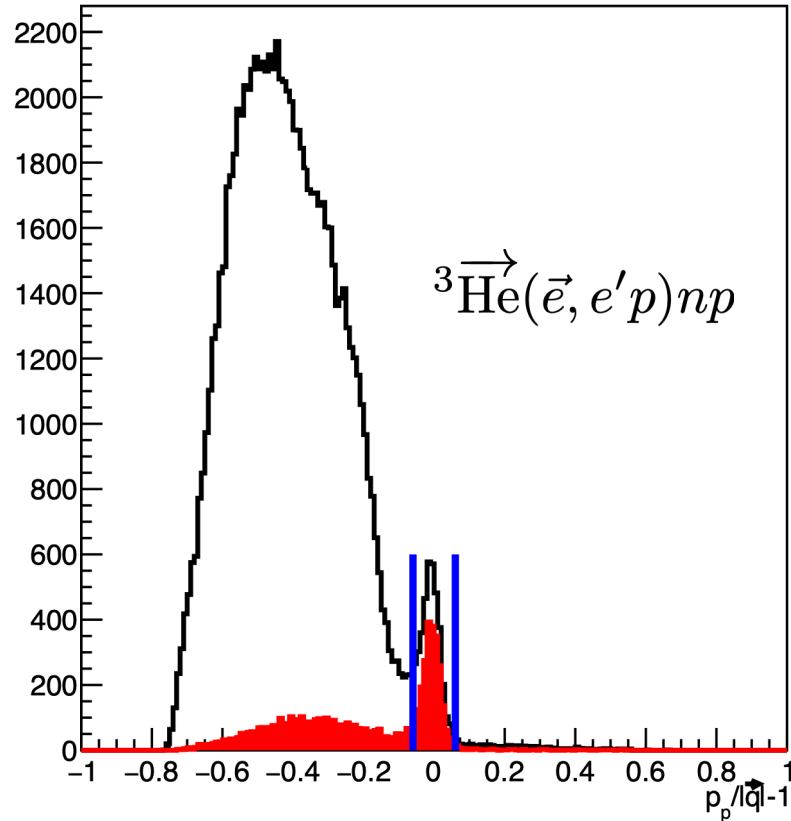
Plots from Vimukthi
Gamage thesis (UVA)

- Quasi-elastic event selection and inelastic background contamination estimates
- Kin. 2 $\rightarrow Q^2 = 3.0 \text{ GeV}^2$
- Kin. 3 $\rightarrow Q^2 = 6.8 \text{ GeV}^2$
- Kin. 4a $\rightarrow Q^2 = 9.8 \text{ GeV}^2$ (spring 2023 running)
- Kin. 4b $\rightarrow Q^2 = 9.8 \text{ GeV}^2$ (fall 2023 running)
- Inelastic contamination limits both statistical precision and accuracy of the result at highest Q^2
- Data with SBS GEMs help understand the signal and (charged) background shapes

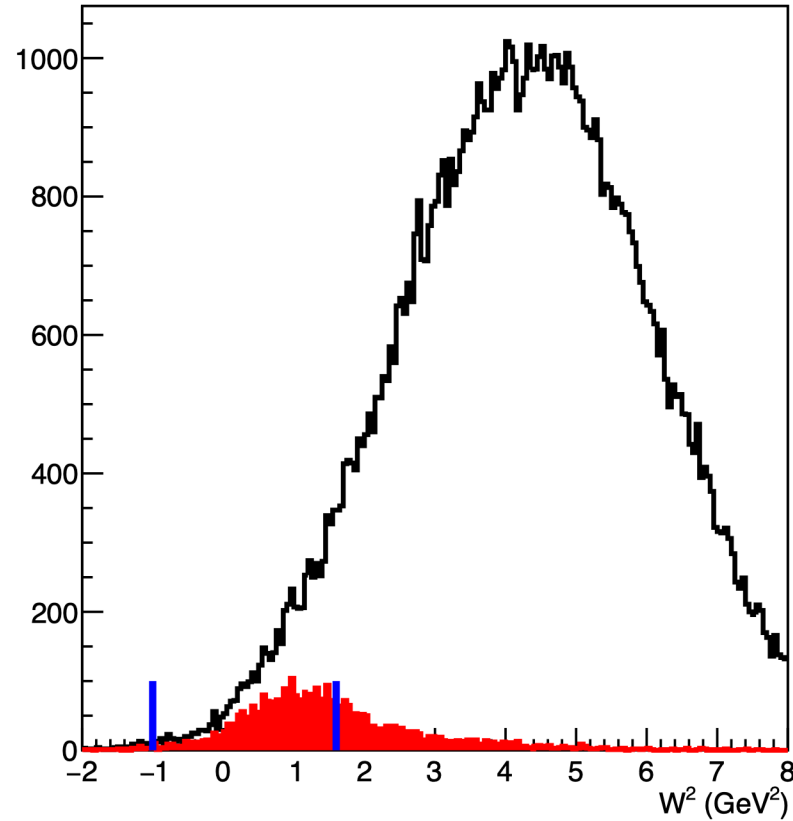
Figure 6.6: Δx projection distributions showing inelastic and proton contamination for each kinematic point. (a) Kin2 (b) Kin3 (c) Kin4a (d) Kin4b

Understanding GEn-II detector performance with SBS GEMs, II—High- Q^2 data

$Q^2 = 9.84 \text{ GeV}^2$



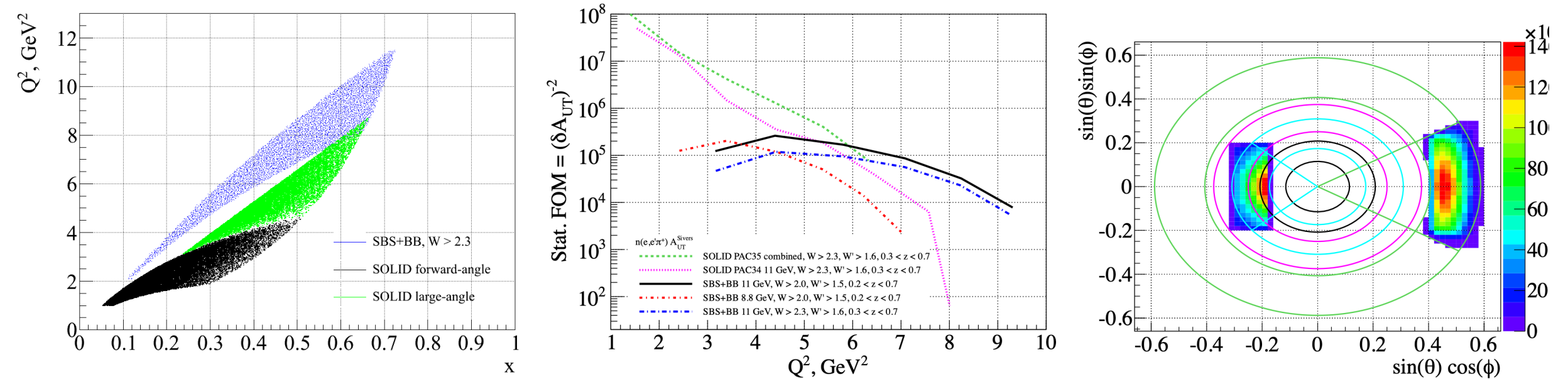
$Q^2 = 9.84 \text{ GeV}^2$



- This is Helium-3 data with a positively charged track in SBS, at the highest Q^2
- (Surprisingly?) clean (quasi-)elastic $^3\text{He}(e, e'p)np$ event selection with full kinematic reconstruction in both arms (missing energy, missing momentum, etc) $\rightarrow$ Too bad we can't do this for neutron events!
- Helps understand signal and background shape with large Fermi smearing and inelastic background, and validate MC generators
- QE W^2 distribution matches MC shape

- Left: fractional deviation of proton momentum from magnitude of $\vec{q}$ -(three) vector from BigBite, without and with W^2 cut
- Right: W^2 , without and with cut on $\frac{p_p}{|\vec{q}|-1}$

SBS-SOLID Comparison—Kinematic Coverage and FOM



- Left: SBS+BB vs SoLID coverage of (x, Q^2) plane (for 11 GeV beam energy)
- Middle: SBS-SoLID FOM comparison vs. Q^2 (note: SoLID FOM was converted to Bjorken x bins of equivalent width)
- Right: Comparison of SBS+BB vs SoLID polar and azimuthal angle coverage (around beamline)
 - **SOLID forward-angle:** θ range $\sim 6.6\text{-}12^\circ$
 - **SOLID large-angle:** θ range $\sim 14.5\text{-}22^\circ$
 - **SBS:** θ range $\sim 10\text{-}18^\circ$, $\phi \pm 40^\circ$
 - **BigBite:** θ range $\sim 24\text{-}36^\circ$, $\phi \pm 30^\circ$

Unpolarized TMD global fitting—Pavia 2017

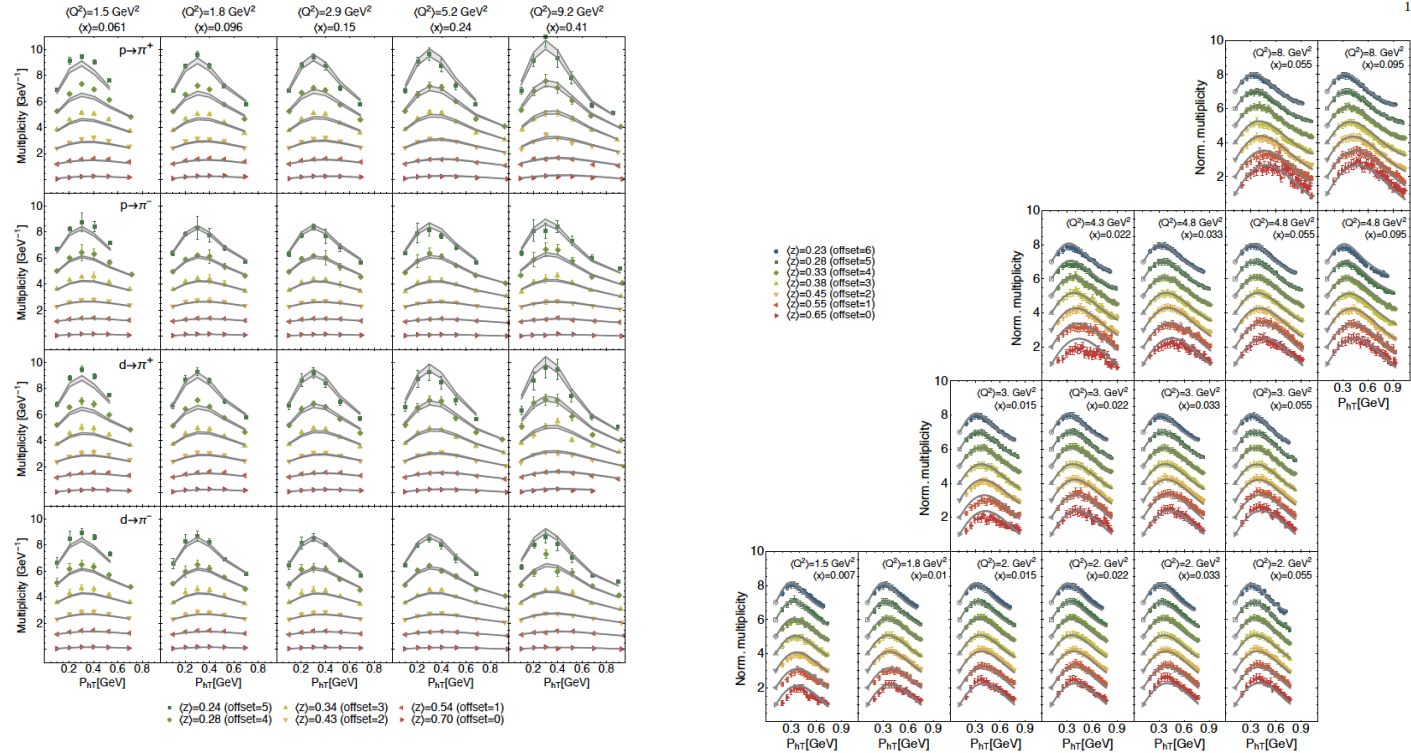


FIG. 3: HERMES multiplicities for production of pions off a proton and a deuteron for different (x) , (z) , and (Q^2) bins as a function of the transverse momentum of the detected hadron P_{hT} . For clarity, each (z) bin has been shifted by an offset indicated in the legend.

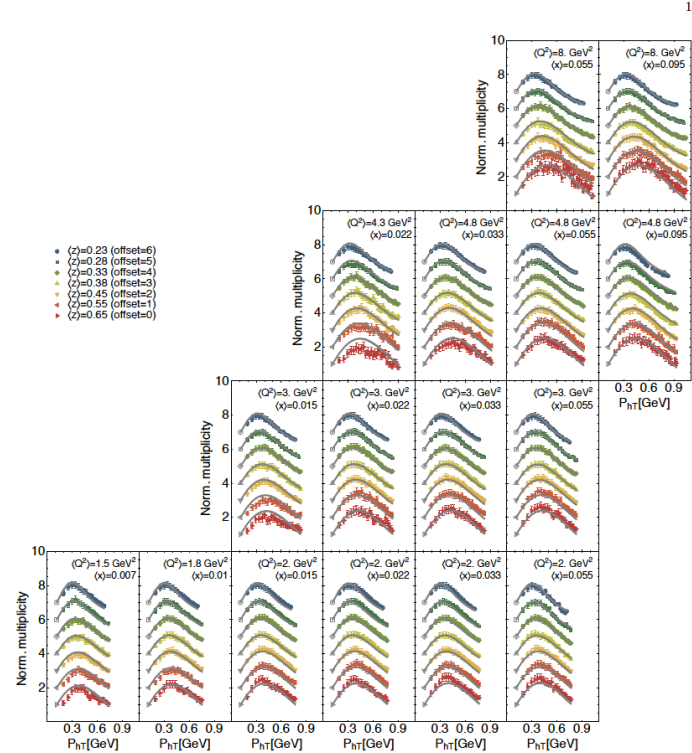


FIG. 6: COMPASS multiplicities for production of positive hadrons (π^+) off a deuteron for different (x) , (z) , and (Q^2) bins as a function of the transverse momentum of the detected hadron P_{hT} . Multiplicities are normalized to the first bin in P_{hT} for each (z) value (see (41)). For clarity,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

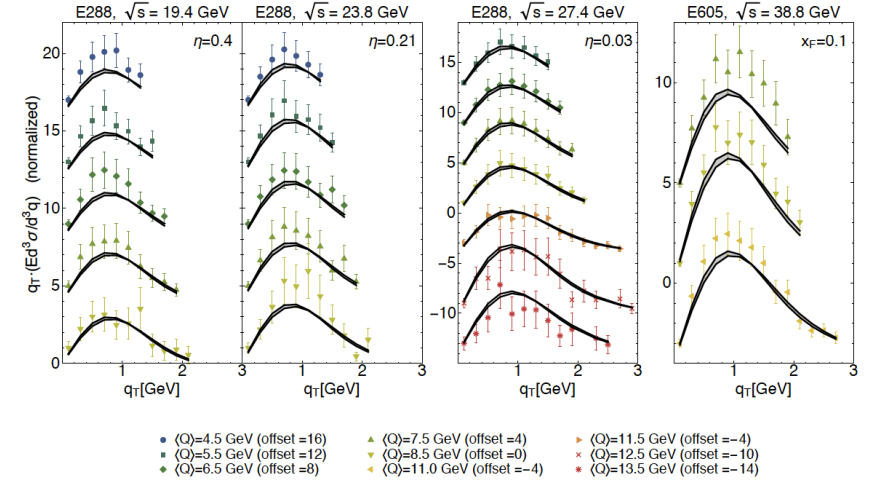


FIG. 7: Drell-Yan differential cross section for different experiments and different values of $\sqrt{s}$ and for different $\langle Q \rangle$ bins. For clarity, each $\langle Q \rangle$ bin has been normalized (the first data point has been set always equal to 1) and then shifted by an offset indicated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

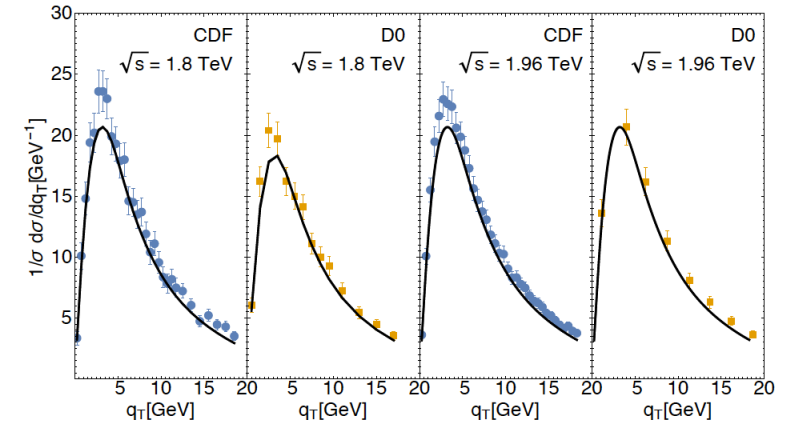
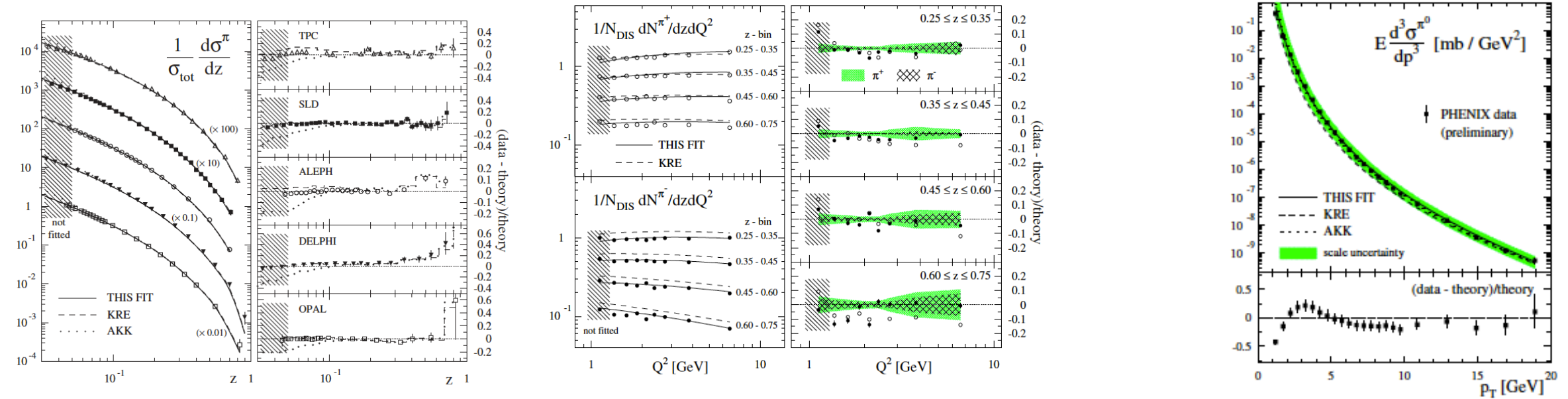


FIG. 8: Cross section differential with respect to the transverse momentum q_T of a Z boson produced from $p\bar{p}$ collisions at Tevatron. The four panels refer to different experiments (CDF and D0) with two different values for the center-of-mass energy ($\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 1.96$ 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 $\sim 8,000$ data points with 11 adjustable parameters

Factorization and universality for Fragmentation Functions



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

- TMD PDFs aren't directly observable, but convoluted with universal quark $\rightarrow$ 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

3D and “4D” extraction of SIDIS SSAs with SBS

Example result for 3D binning

(x, z, p_T)

- E = 11 GeV, 40 days

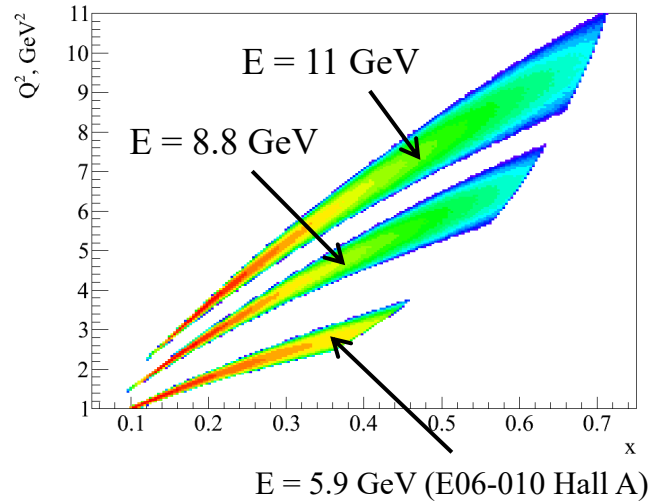
$A_{UT}^{\sin(\phi_h - \phi_S)}$ for $n(e, e' \pi^+) X$:

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

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

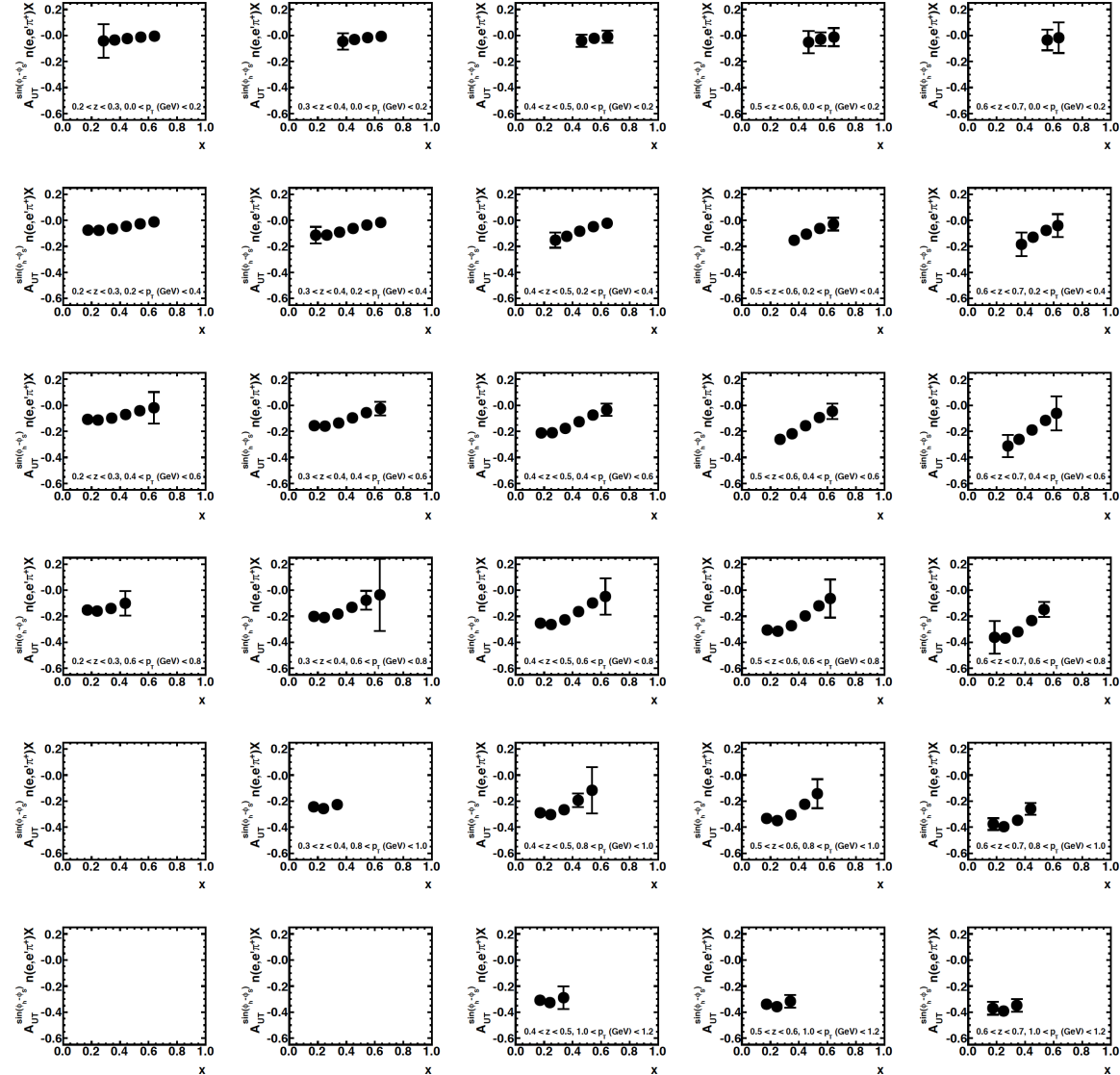
$0 \leq p_T(\text{GeV}) \leq 1.2, \Delta p_T = 0.2 \text{ GeV}$

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

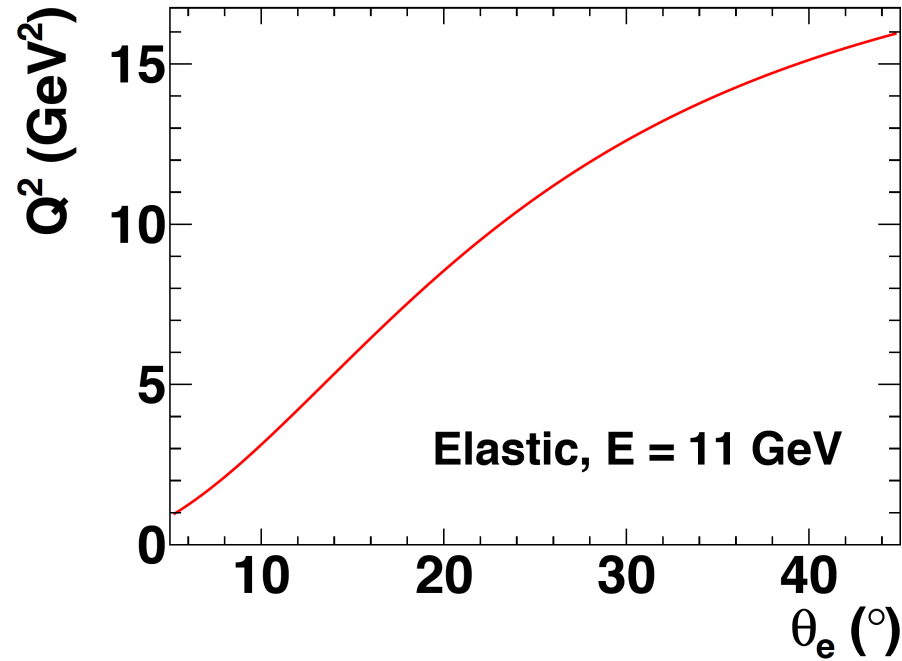


← Increasing p_T

Increasing $z \rightarrow$



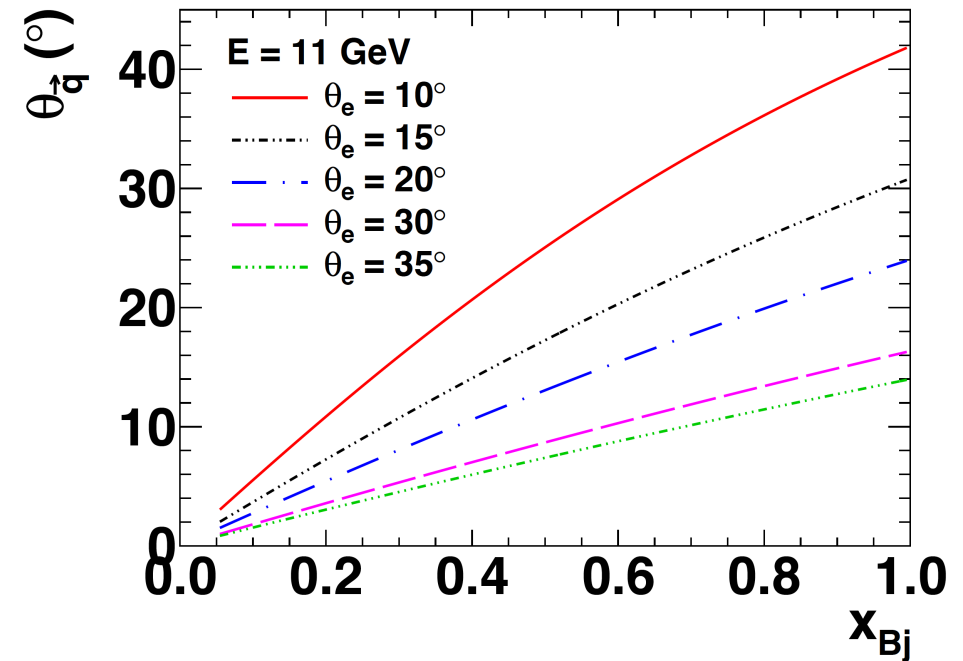
Toward high- Q^2 : Fixed-target Electron Scattering Kinematics @11 GeV



- Particles associated with the partonic (or other) degree of freedom that absorbed the virtual photon are found predominantly near the direction of the momentum transfer $\mathbf{q}$
- *Partonic interpretation of electron scattering data is accessible at large $Q^2 \rightarrow$ particles of interest are located at forward angles and high momentum*

- Measurements of high- Q^2 elastic FFs, SIDIS, DVCS, etc involve coincidence $N(e,e'X)$ (electroproduction) reactions, where $X =$
 - N' (elastic or quasi-elastic)
 - h (SIDIS or DVMP)
 - γ (DVCS)
- Virtual photon angle decreases as “inelasticity” and Q^2 increase:

$$Q^2 = 2M\nu x_{Bj}$$



JLab E06-010: ${}^3\text{He}/n(e, e'\pi^\pm)X$ TSSA/TDSA

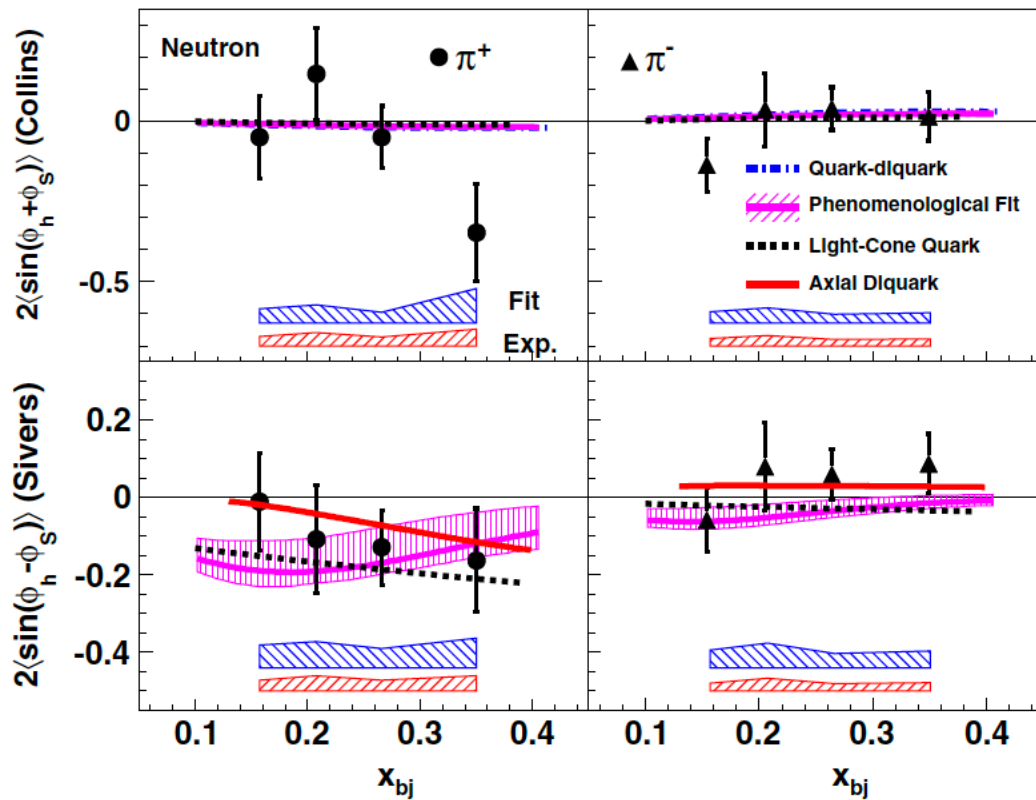


FIG. 2 (color online). The extracted neutron Collins and Sivers moments with uncertainty bands for both π^+ and π^- electro-production. See text for details.

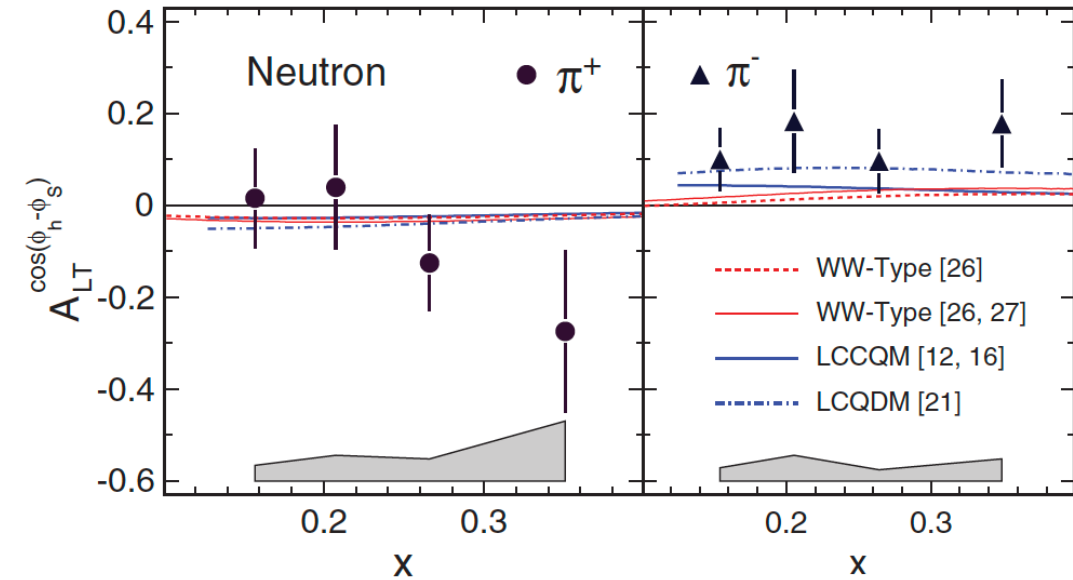


FIG. 2 (color). Neutron $A_{LT}^{\cos(\phi_h - \phi_s)}$ azimuthal asymmetry for positive (left) and negative (right) charged pions vs x .

- Collins/Sivers results (above): [X. Qian *et al.* PRL 107, 072003 \(2011\)](#)
- $A_{LT}^{\cos(\phi_h - \phi_s)}/g_{1T}$ results (right): [J. Huang *et al.* PRL 108, 052001 \(2012\)](#)
- Pioneering experiment, key instrumentation achievements:
 - BigBite as open-geometry electron arm
 - Rotation of target spin polarization for full coverage of Collins and Sivers angles
- C12-09-018 will provide >1000X more statistics for neutron asymmetries than E06-010

Statistical and (dominant, experimental) Systematic Errors for Target SSA

Statistical error (in fully-differential (x, z, p_T) bins for charged pion channels, for RAW ^3He asymmetry)	0.1-0.2% absolute (<i>relative</i> uncertainty ~few percent at best based on JAM3D 2022 prediction, usually bigger)
Raw (target single-spin) asymmetry systematics	$<10^{-4}$
Target polarimetry	3-4% relative
Beam polarimetry (for A_{LT})	$<2\%$ relative
“Unwanted” azimuthal modulations (higher-twist, longitudinal target contributions)	Negligible
Dilutions (N_2 , charge-symmetric background, protons, accidentals)	$<3\%$ relative
Radiative corrections	Up to 5-10% relative (worst-case)

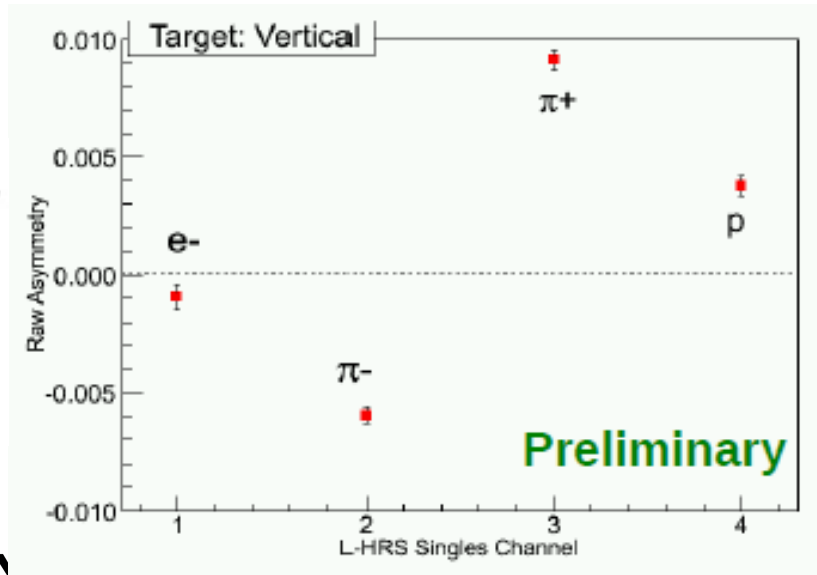
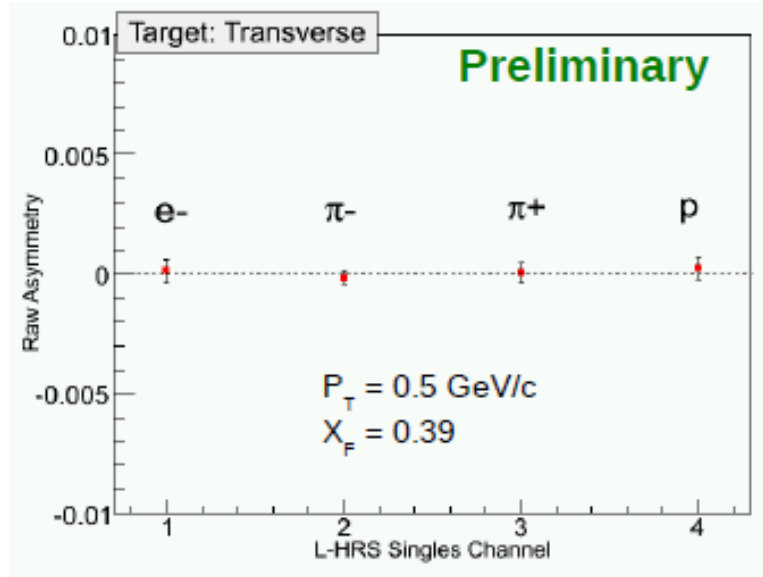
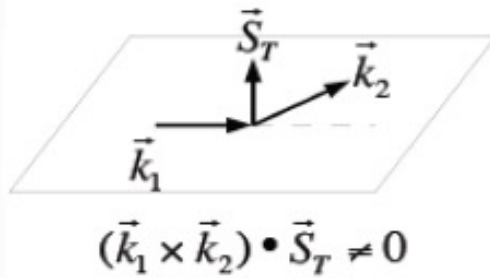
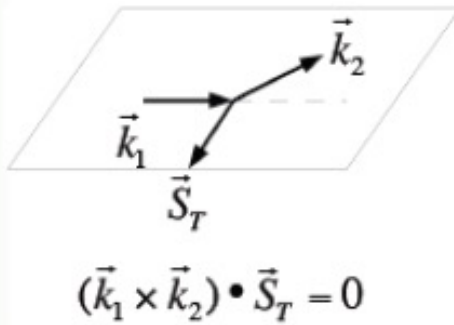
- SBS+BB w/polarized ^3He has significant advantages in control of experimental systematics, as discussed in our replies to PAC reader comments/questions
- Theoretical systematics (diffractive vector meson, exclusive contamination, nuclear effects, etc) qualitatively similar to all other JLab SIDIS SSA proposals—we will engage/work closely with theory community

SSA check: HRS single-arm ^3He SSA

(Witness channels on ^3He , not corrected for target polarization and dilution)

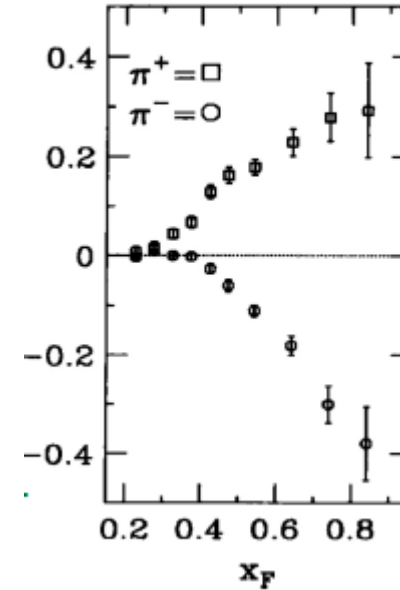
$$e + ^3\text{He} \rightarrow A + X$$

$$A = e', \pi^{+/-} \text{ or } p$$



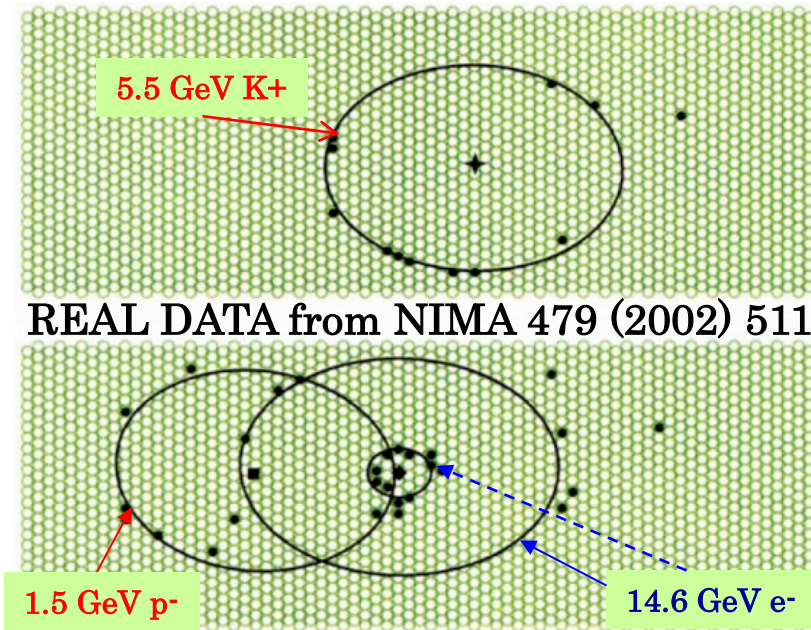
K. Allada
Univ. of Kentucky
2010.

FNAL-E704: $\sqrt{s} = 20 \text{ GeV}$.
PLB 264 (1991) 462.



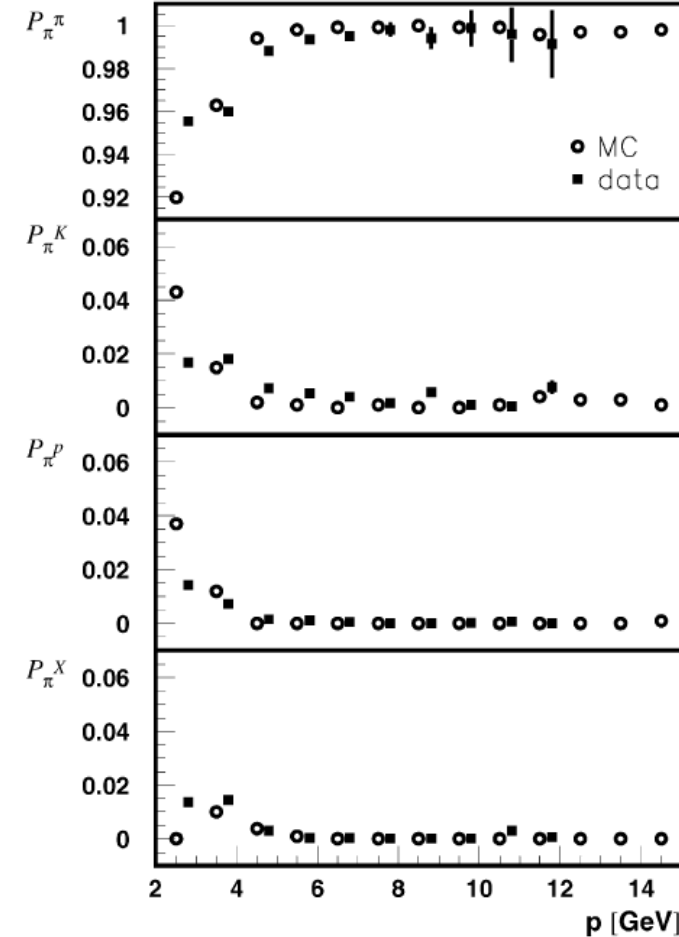
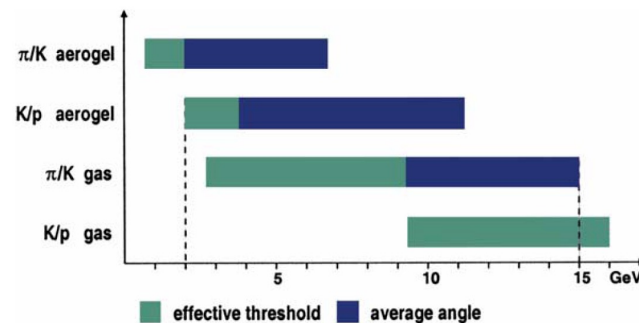
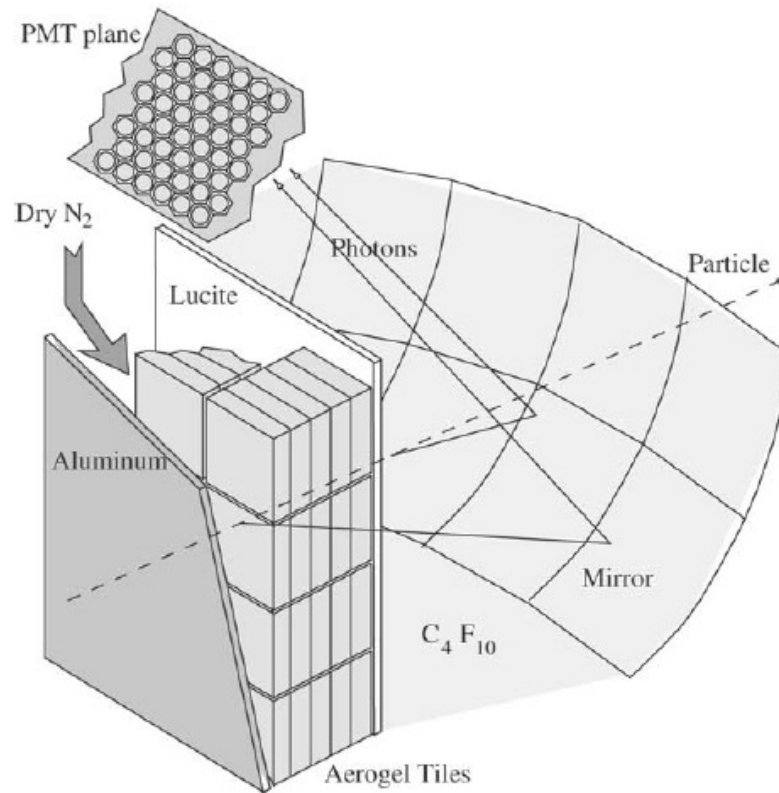
False asymmetry < 0.1%

The HERMES→SBS RICH detector



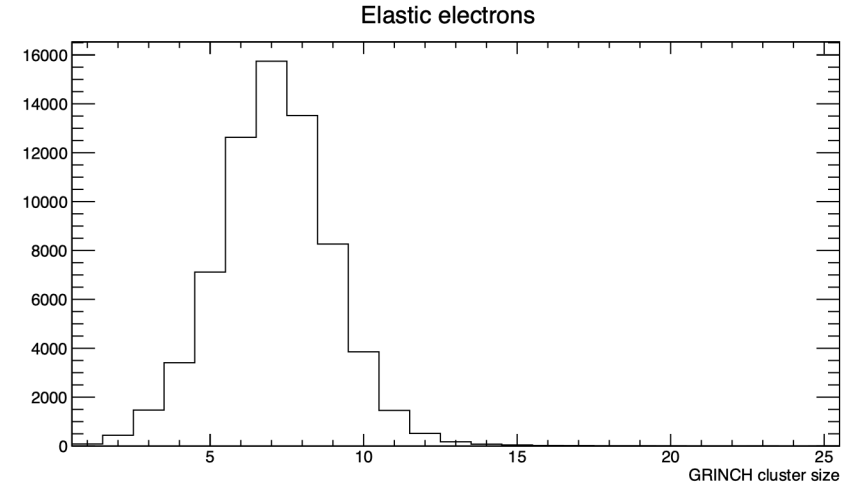
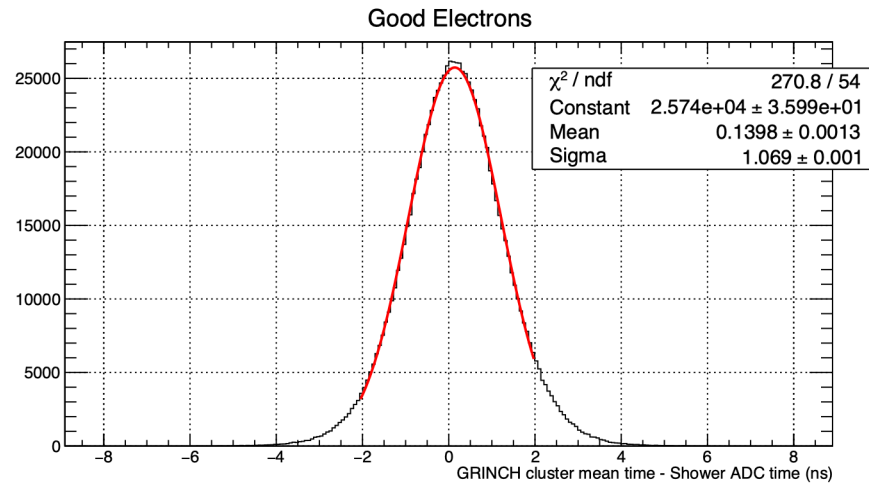
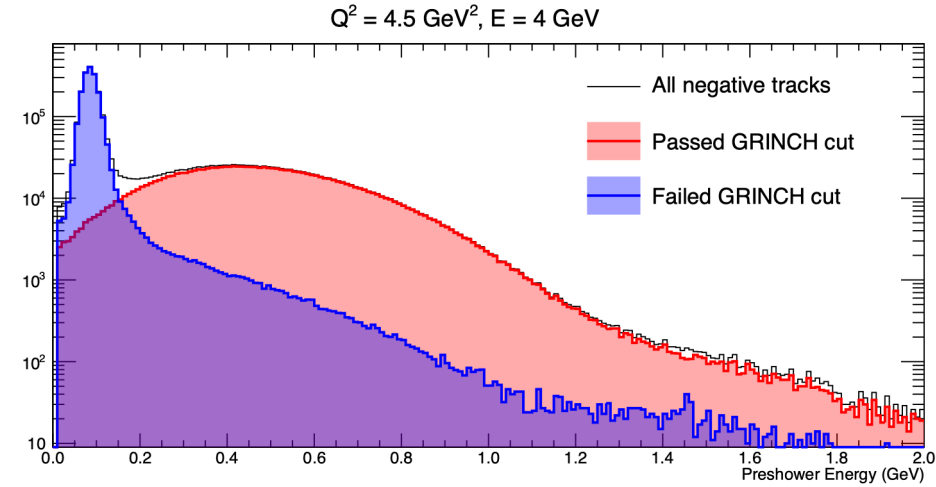
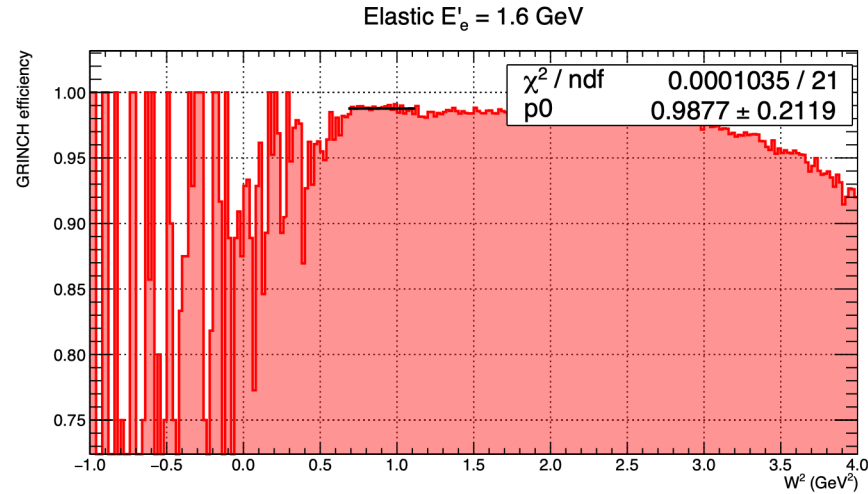
• *HERMES RICH geometry, performance characteristics well matched to SBS needs.*

- $\pi/K/p$ separation for p from 2-15 GeV based on dual-radiator design.
- Re-use one half of detector
- ~224 spare PMTs and “spare” aerogel wall from the other half



Pion PID results from HERMES

GRINCH Success Demonstrates RICH Feasibility

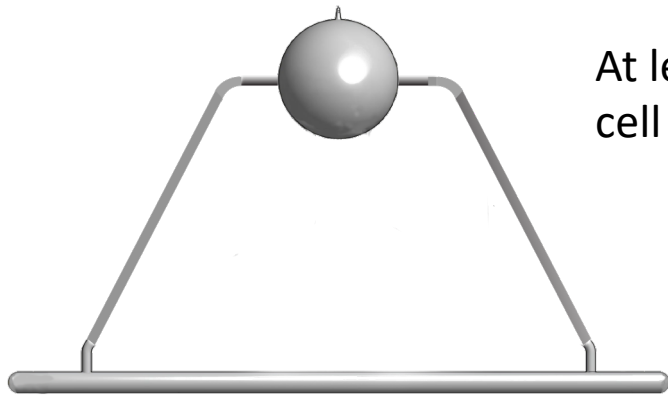


- GRINCH efficiency for 1.6 GeV electrons, track-matched cluster with >2 PMTs $\sim 99\%$
- Cluster mean time resolution ~ 1 ns
- Single PMT hit time resolution ~ 1.8 ns

Polarized ^3He target for SBS SIDIS

As shown earlier, there have been substantial gains in the figure-of-merit for successive ^3He experiments, and there is good reason to expect that trend to continue for SBS SIDIS

- The easiest part: the GEN-II target was limited by the laser system.
 - Moving to a simpler laser-light transport system will bring some gains.
- The largest limiting factor for GEN-II was stress-induced micro-fractures that caused both orientation-dependent (so called “hysteresis effect”) and orientation-independent wall-induced spin relaxation.
 - New cell geometry will significantly reduce stress in glass.
 - Use ultra-low iron content glass (as was done at Mainz)



At left – new lower-stress cell design for SBS SIDIS

At right – study of GEN-II target cells showing hysteresis effect in every target cell.

