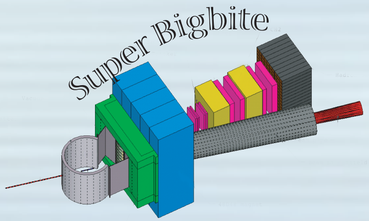
Diquarks in high Q^2 SBS SIDIS

Measurements of single-spin asymmetries in semi-inclusive deep inelastic scattering from a transversely polarized ^{3}He target (JLab E12-09-018). Spokespeople G. Cates (UVa), E. Cisbani (INFN), A. Puckett (UConn), N. Liyanage (UVa) and B. Wojtsekhowski (JLab)

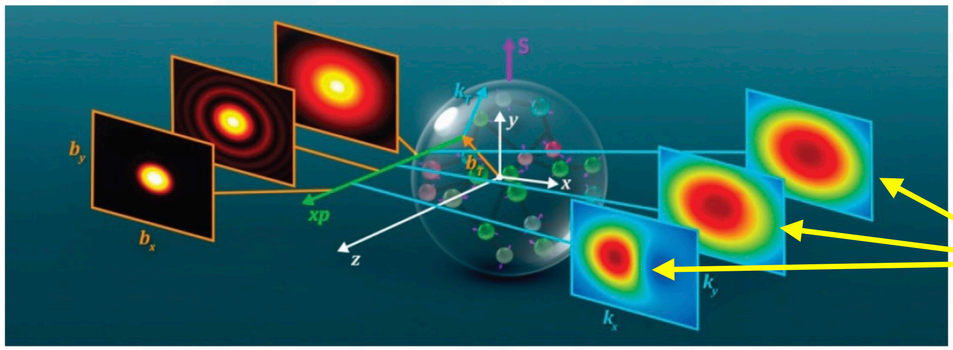
Gordon Cates

Theoretical Motivations and Experimental Evidence
for Diquark Correlations in Hadrons
October 22, 2026



3D imaging of quarks is a major emphasis of the 2023 Long Range Plan for Nuclear Science



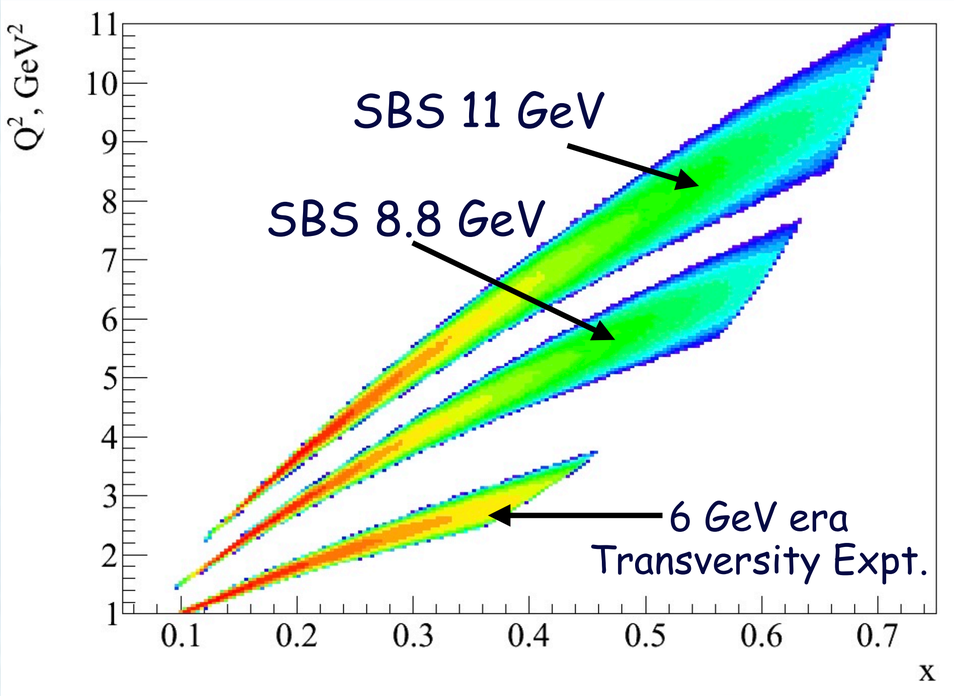


Imaging in momentum space using TMD's

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].*

- SBS SIDIS physics is among the central motivations for the EIC
- SBS SISIS will increase the overall statistics in the measurement of single-spin asymmetries by a factor of over ten, and considerably more in the high x region.
- SBS SIDIS is currently the only fully approved experiment that will measure single-spin asymmetries with a transversely polarized target.

Okay … so why did I choose the title: Diquarks in high Q^2 SBS SIDIS ?



- As emphasized by Bogdan on Monday, flavor separated form factors at high Q^2 (> 2 GeV^2) have a significant enhancement of diquark effects.
- It is reasonable to ask, given that diquarks are non-pointlike and non-static, whether there will be signatures of diquarks in TMDs at high Q^2.
- SBS SIDIS will provide the highest-Q^2 data at JLab on the study of single-spin asymmetries in TMDs.

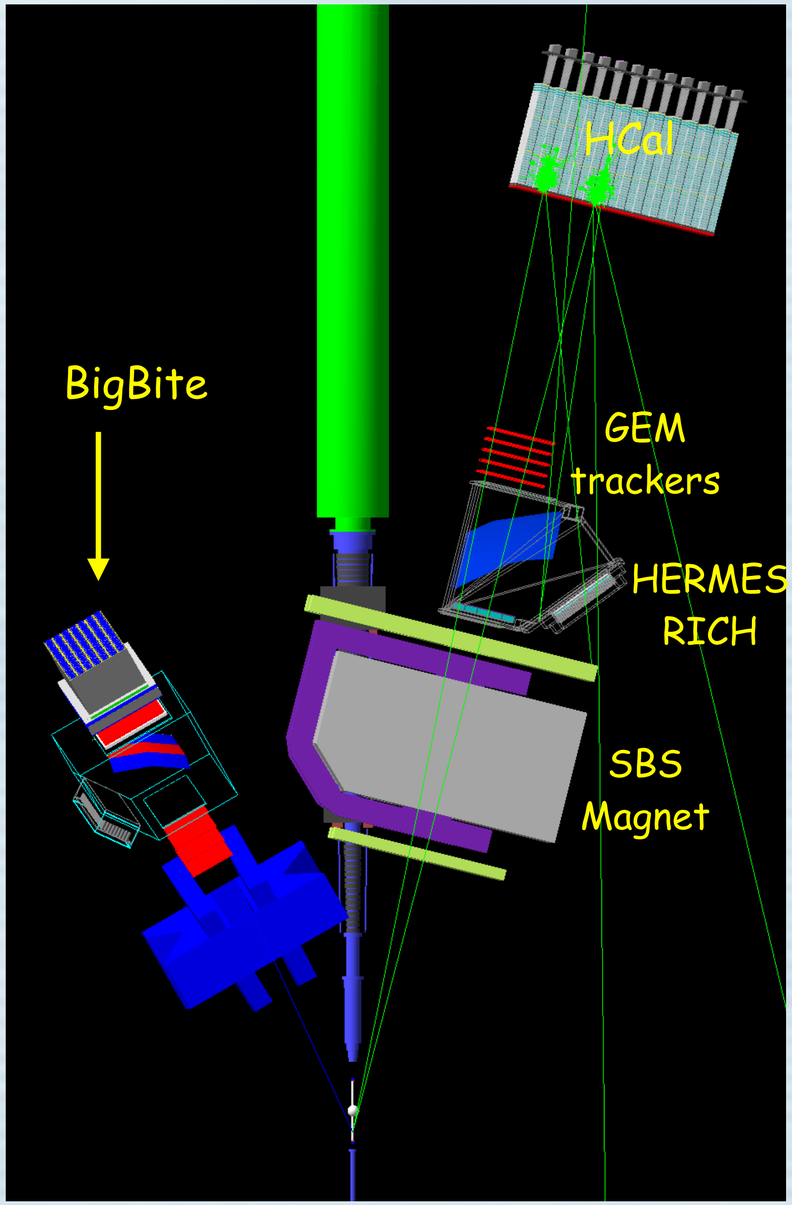
So … an important goal of this talk is bring the upcoming SBS SIDIS experiment to people's attention.

This is definitely the right crowd to consider this question!

The SBS SIDIS Experiment
(JLab E12-09-018)

- Will measure single-spin asymmetries in semi-inclusive pion and kaon electro-production in the DIS regime
- Will utilize a high-luminosity (~5×10^{36} $cm^{-2}s^{-1}$) transversely polarized ^3He target.
- Most of the experimental apparatus has already been successfully used in Phase I of the SBS program.
- Will utilize one of the HERMES RICH Detectors for particle ID
- Currently shown on a tentative schedule for installation beginning in 2031 and running in 2032.
- Will increase the overall statistics coming from SSA SIDIS experiments by a factor of >10, and even more in the high x region.

The SBS SIDIS Experiment



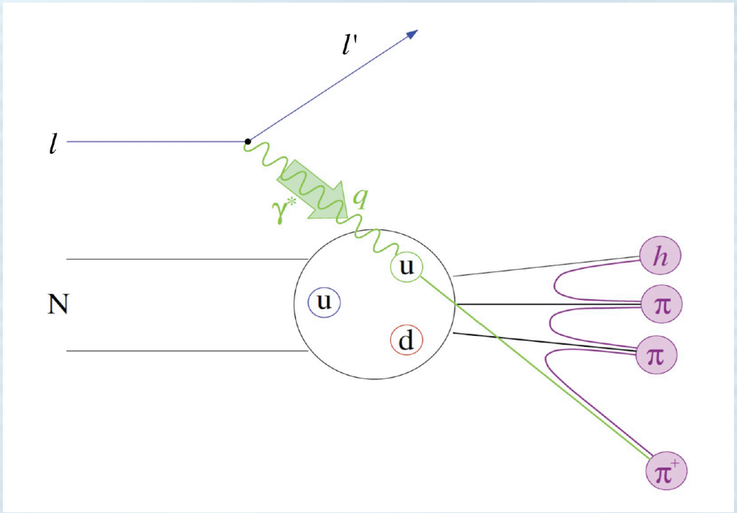
$$e + {}^3\mathrm{He}^{\uparrow} \rightarrow e' + \pi^0 + X$$

$$e + {}^3\mathrm{He}^{\uparrow} \rightarrow e' + \pi^{\pm} + X$$

$$e + {}^3\mathrm{He}^{\uparrow} \rightarrow e' + \mathrm{K}^{\pm} + X$$

- Both the electron and hadron arms will use large open-geometry dipoles with large momentum acceptance and ~1% resolution.
- Electron arm, at 30 degrees, will use the BigBite spectrometer with ~45 msr acceptance.
- The hadron arm, at 14 degrees, will use the SBS magnet, the HERMES RICH for particle ID and HCal, a hadron calorimeter.
- Very-high luminosity (~5x10^{36} cm^{-2}s^{-1}) polarized ^{3}He target, capable of rapid spin-flips in either the vertical or horizontal directions.
- ALL data collected with a single setting at each of two energies, 8.8 and 11 GeV.

Will use the Trento conventions for relevant variables



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

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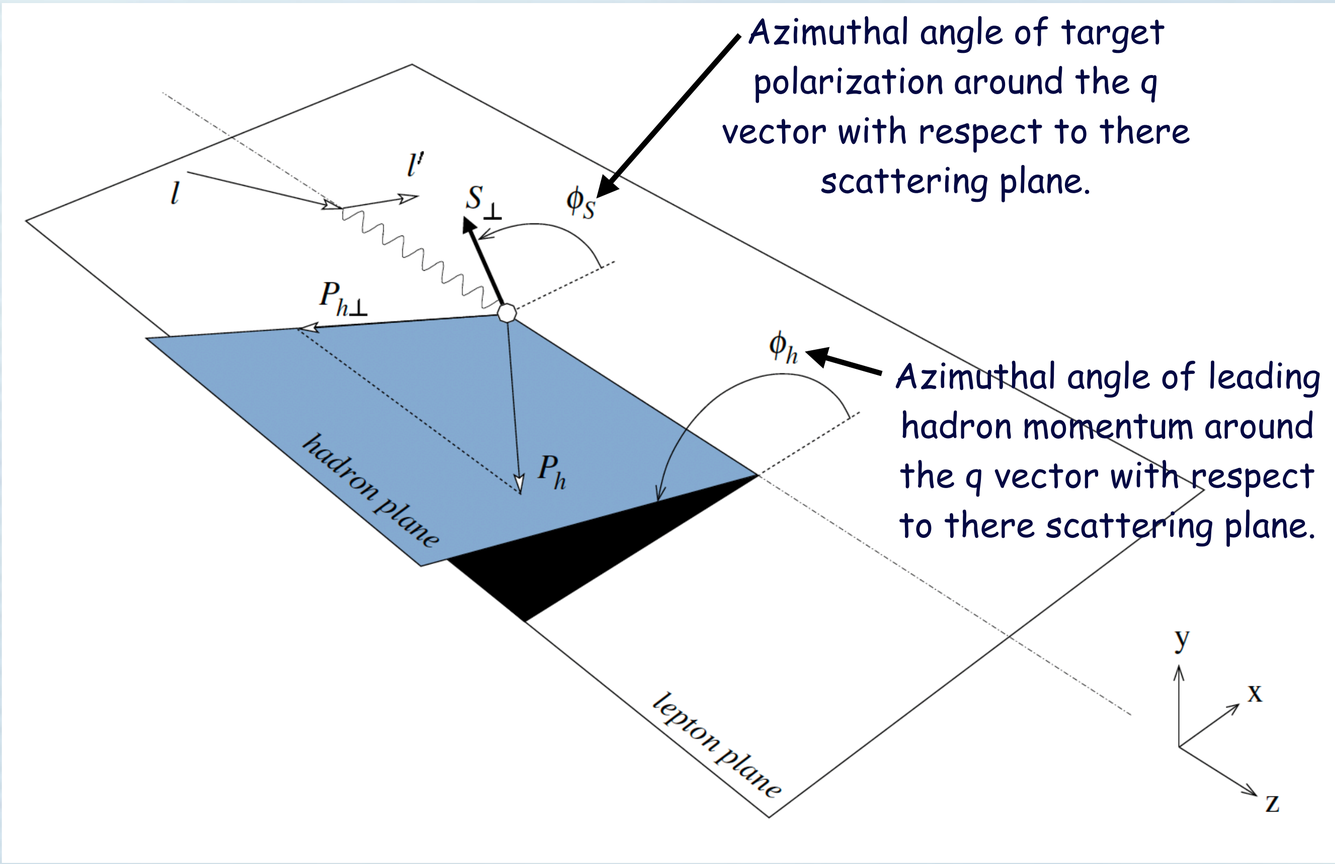
Single-spin asymmetries: The Trento conventions



SBS SIDIS will measure single-spin asymmetries using a transversely polarized ^{3}He target

$$A_{UT}(\phi,\phi_S) = \frac{1}{P_T}\frac{d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi)}{d\sigma(\phi,\phi_S) + d\sigma(\phi,\phi_S+\pi)}$$

$$= A_{UT}^{Collins}\sin(\phi+\phi_S) + A_{UT}^{Sivers}\sin(\phi-\phi_S) + A_{UT}^{Pretz}\sin(3\phi-\phi_S)$$

$$A_{UT}^{Collins}\ \sin(\phi_h+\phi_S) \sim \sum_q e_q^2[\delta q^q \otimes H_{1q}^{\perp}]$$

$H_1^{\perp}$ = Collins fragmentation function

Collins effect - probes transverse polarization of quarks

$$A_{UT}^{Sivers}\ \sin(\phi_h-\phi_S) \sim \sum_q e_q^2[f_{1T}^{\perp q} \otimes D_{1q}]$$

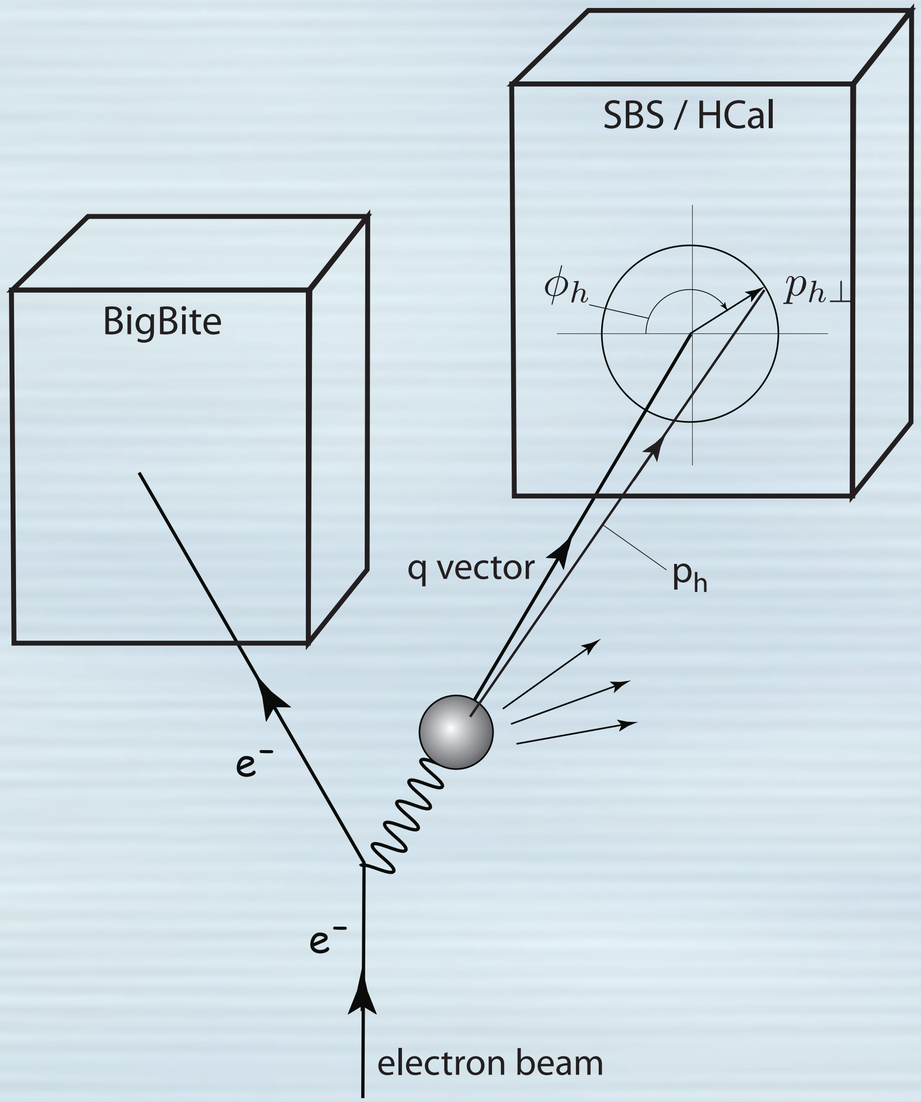
D_1 = unpolarized fragmentation function

Sivers effect - probes correlations between quark transverse momentum and nucleon transverse spin

$$A_{UT}^{Pretz}\ \sin(3\phi_h-\phi_S) \sim \sum_q e_q^2[h_{1T}^{\perp q} \otimes H_{1q}^{\perp}]$$

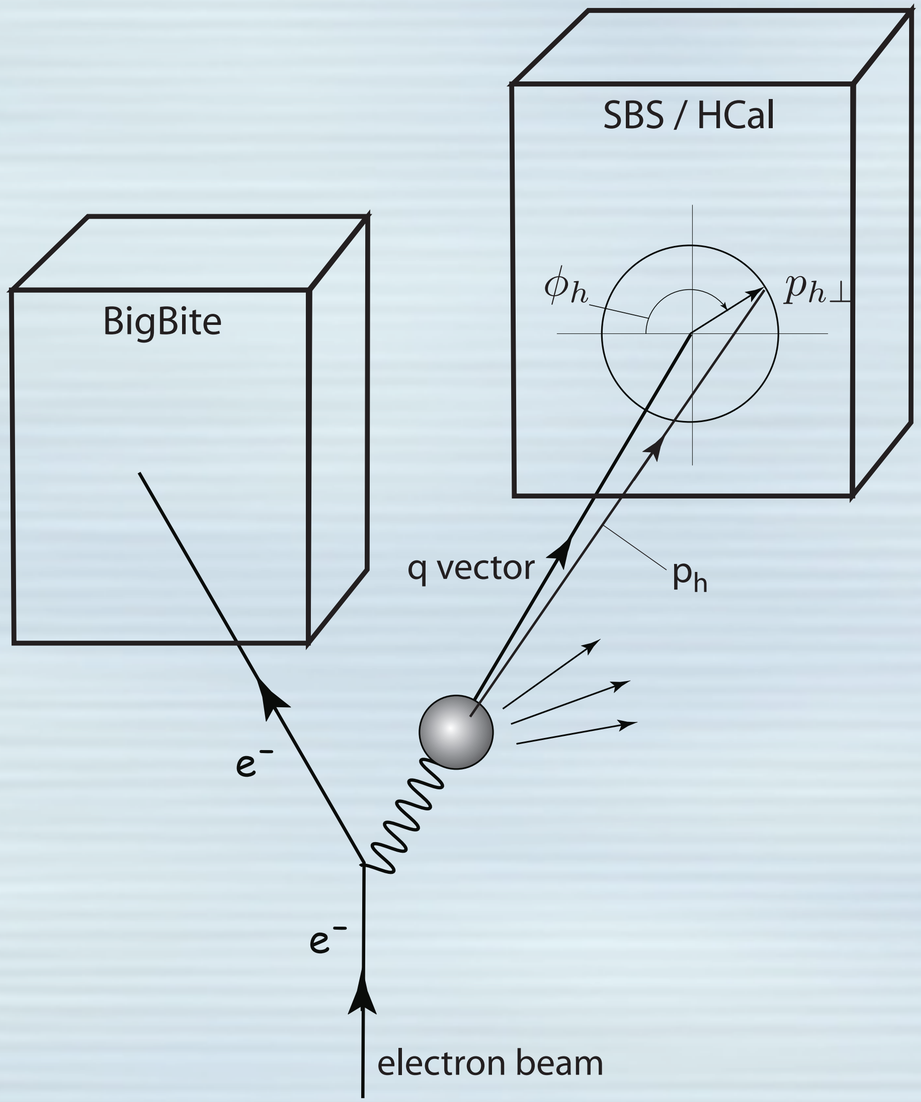
Pretzelosity or Mulders-Tangerman function - interference of wave function components differing by two units of OAM

Why SBS SIDIS provides such an excellent opportunity despite moderate acceptance



- Being a two-arm experiment, the SBS and BigBite can be placed to achieve relatively high Q^2.
- This is particularly true because of SBS's unique ability to run at small angles.
- By centering the hadron arm on q, kinematic focussing ensures that a large fraction of the events of interest will be detected.
- The high luminosity polarized ^3He target ensures a high count rate, and flexibility orienting the polarization.

Kinematic conditions for applicability of TMD formalism

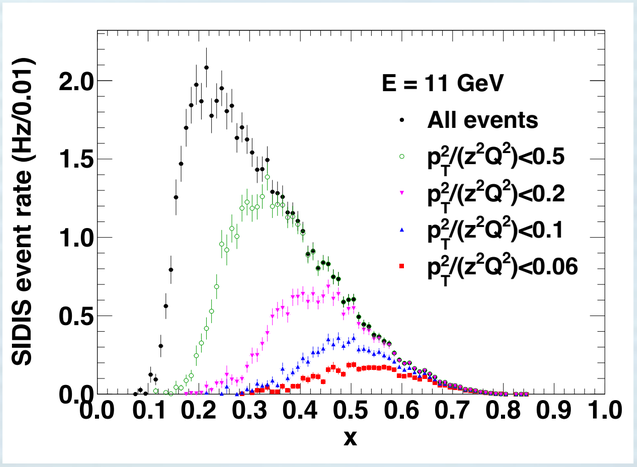


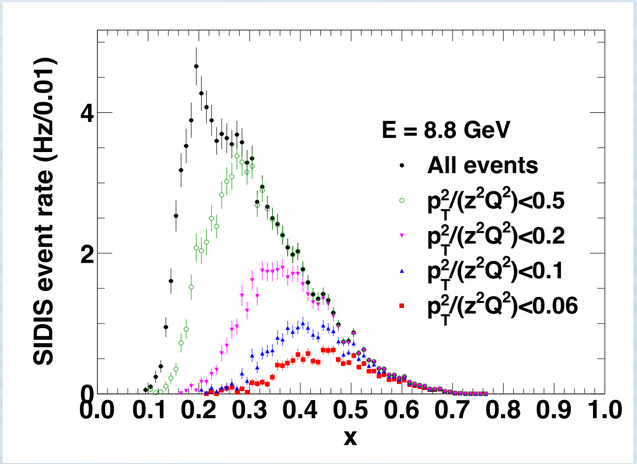
- Requires large $Q^2 > 1$ GeV^2 and large $W > 2$ GeV for DIS
- Requires large (but not too large) z
  - high enough for current quark fragmentation over target remnant fragmentation.
  - low enough to avoid dominance of exclusive/resonance contributions (high Q^2 helps here too).
- Requires small (but not too small) p_T
  - large enough for reasonable sensitivity to effects of quark transverse motion/spin $k_\perp \sim \Lambda_{QCD} \sim 200$ MeV
  - Small enough for dominance of TMD effects over collinear perturbative QCD effects (gluon radiation, etc.).

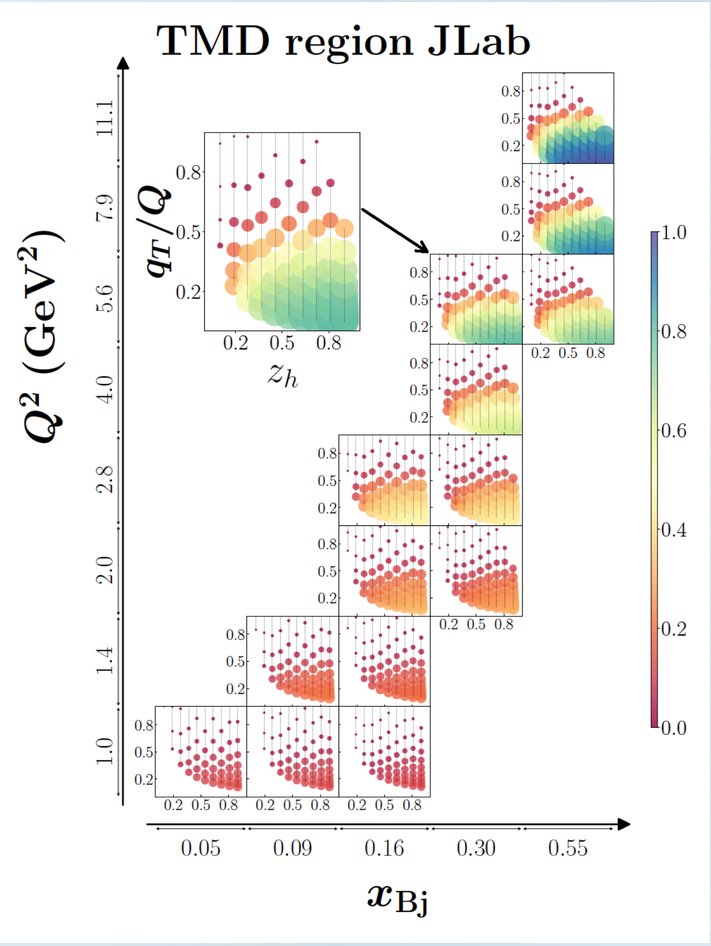
Want: $|P_{hT}|/z \ll Q$

Uniqueness at JLab for SBS SIDIS regarding "TMD affinity"

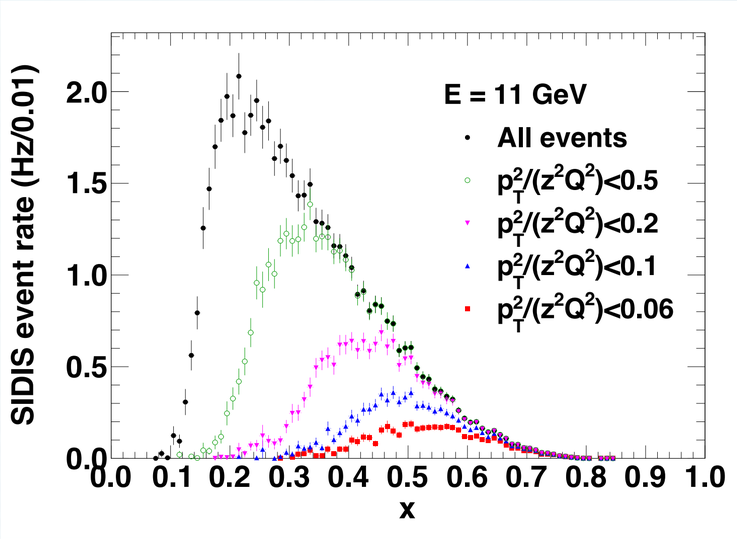
- The Jefferson Lab Angular Momentum (JAM) collaboration published a "New tool for kinematic regime estimation in semi-inclusive deep inelastic scattering": JHEP 04, 084 (2022)
- Authors define quantitative "affinity" criteria for TMD, collinear, and intermediate regions
- Results underscore the importance of high x and Q^2, which SBS SIDIS is uniquely suited to address.
- Note that aggressive cuts on q_T/Q tend to exclude much of the existing (HERMES/ COMPASS) data on transverse target SSAs !

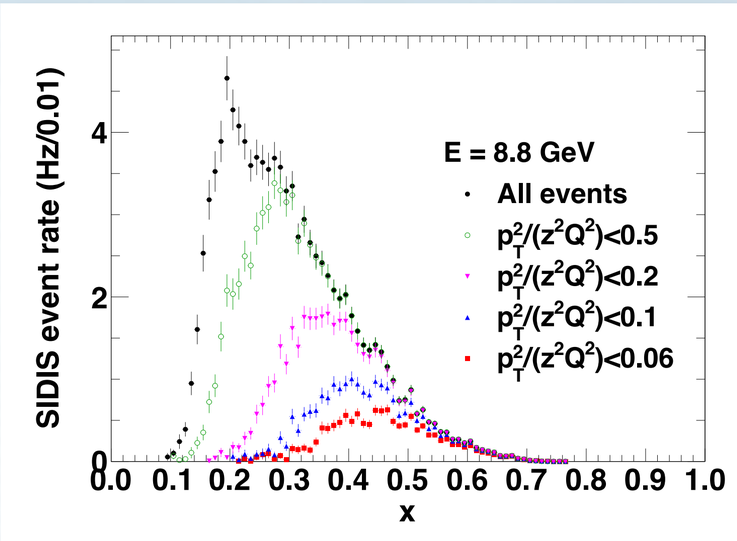


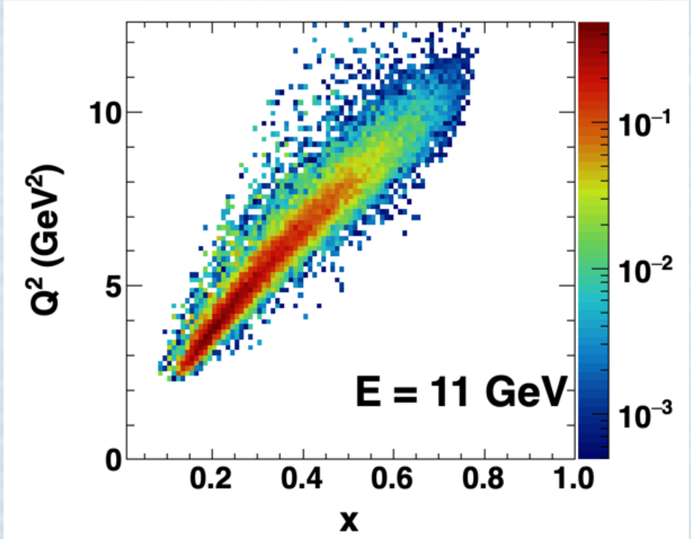


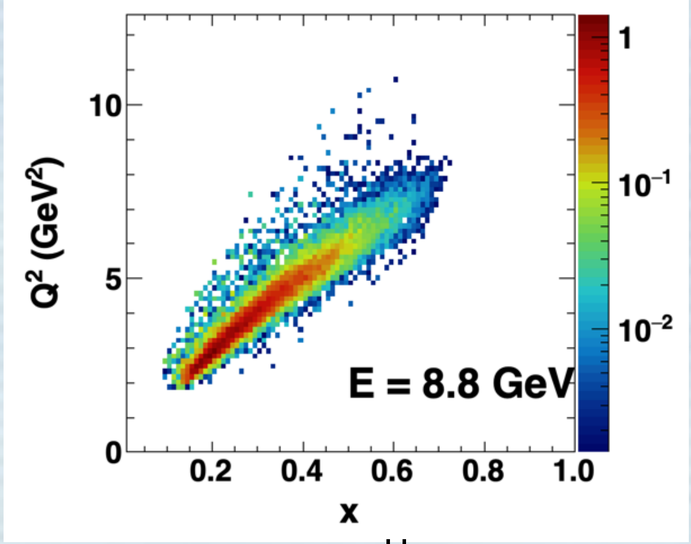


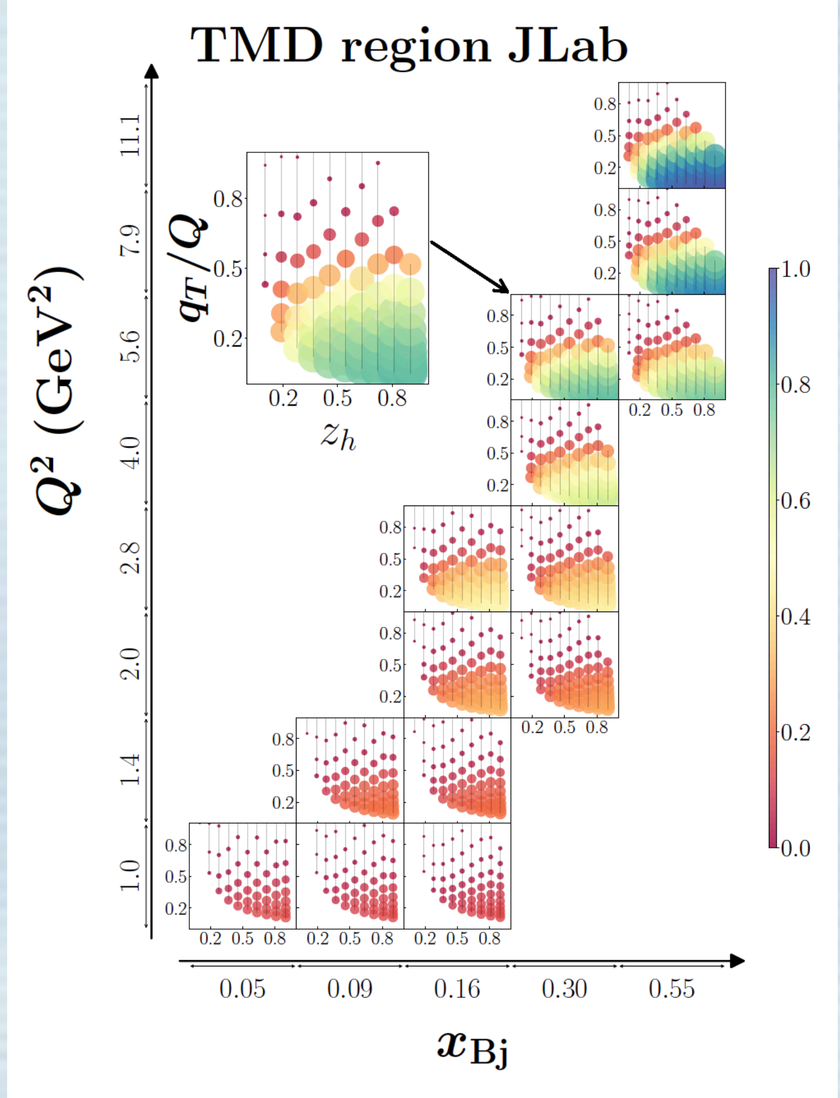
Uniqueness at JLab for SBS SIDIS regarding "TMD affinity"



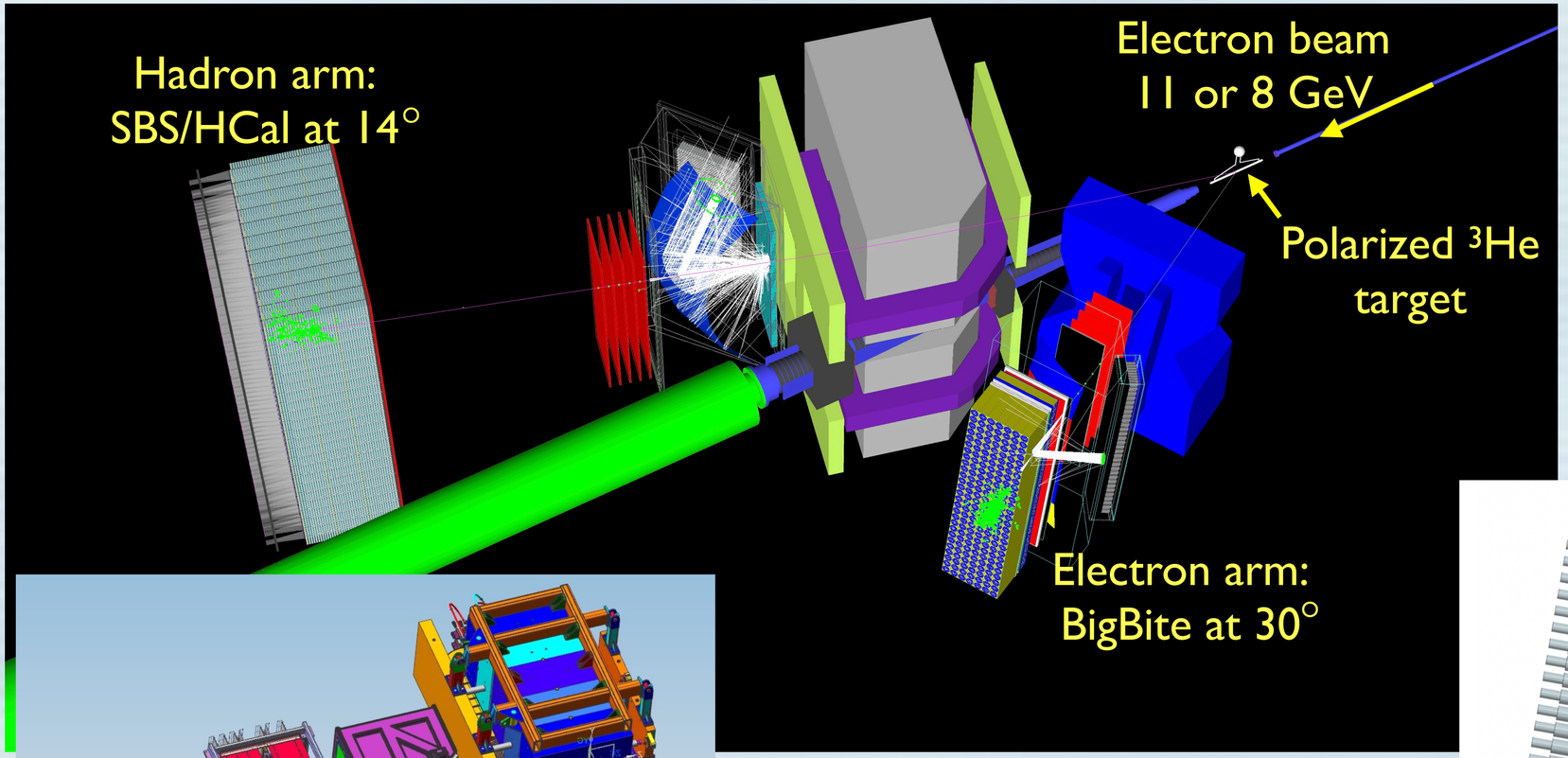




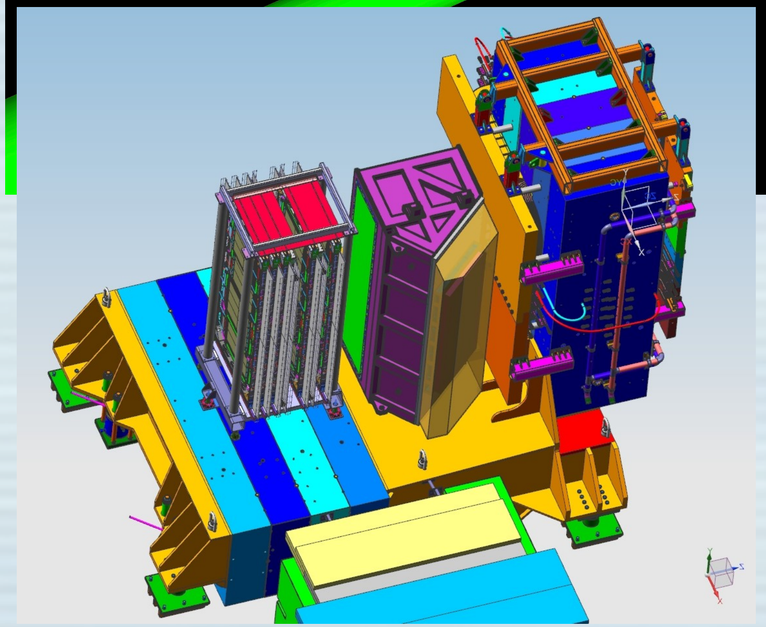




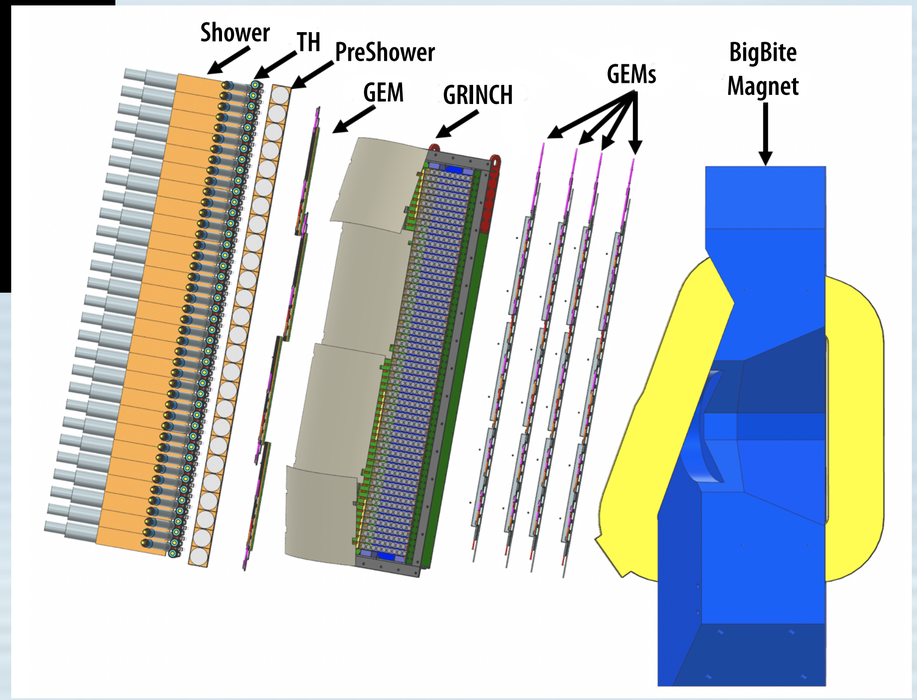
The SBS SIDIS Experiment



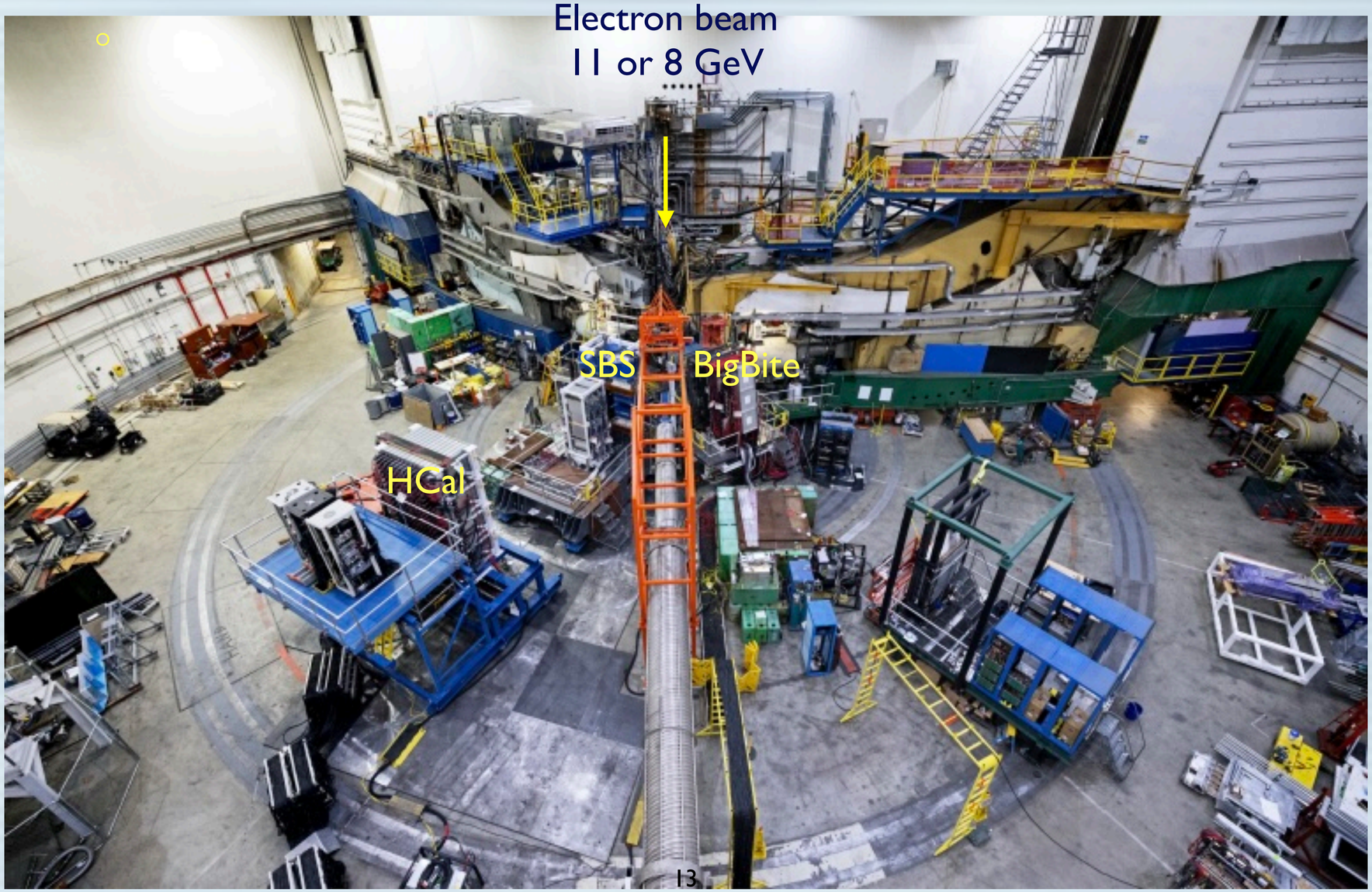
Shown below, the BigBite spectrometer and detector package for the SBS SIDIS experiment.



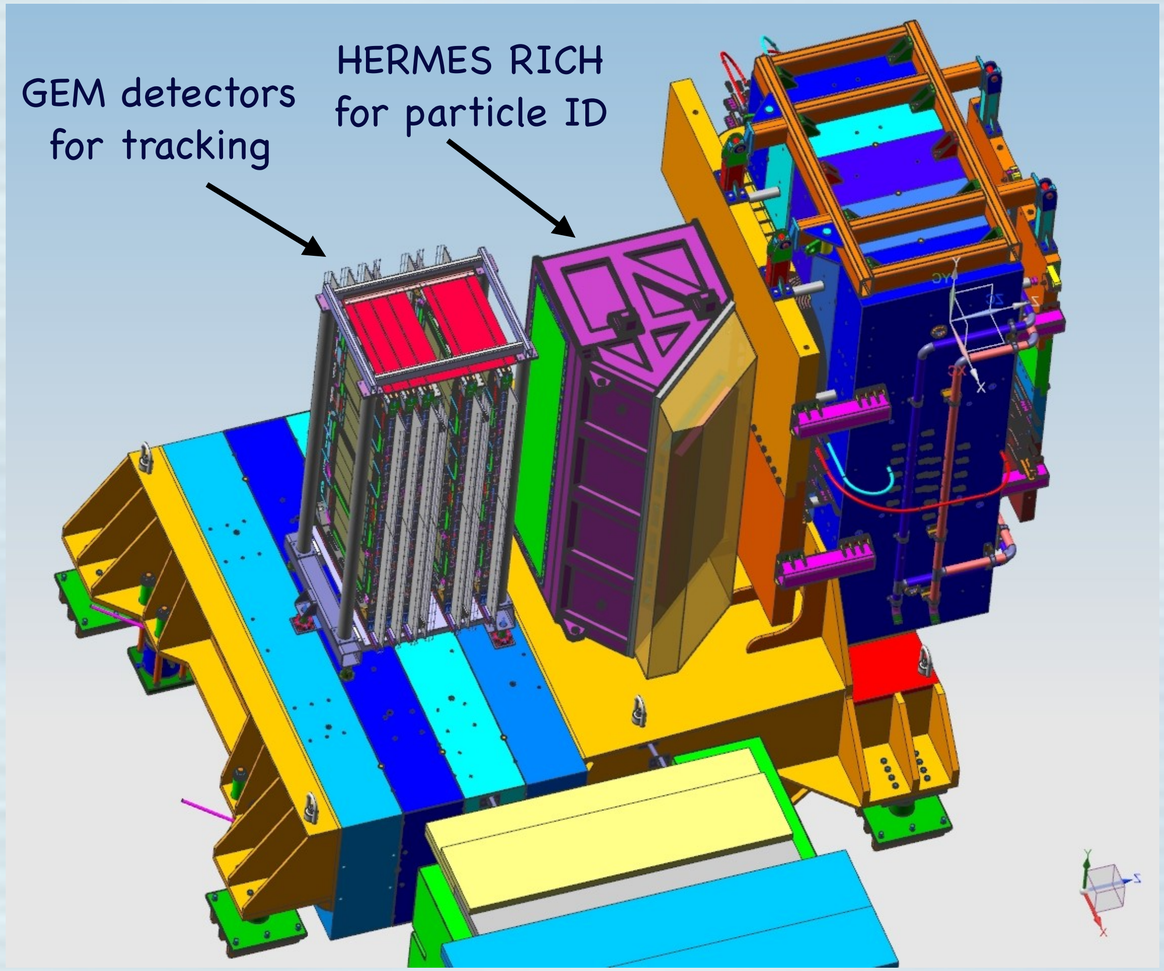
Shown at left, the configuration of SBS for the SIDIS experiment.

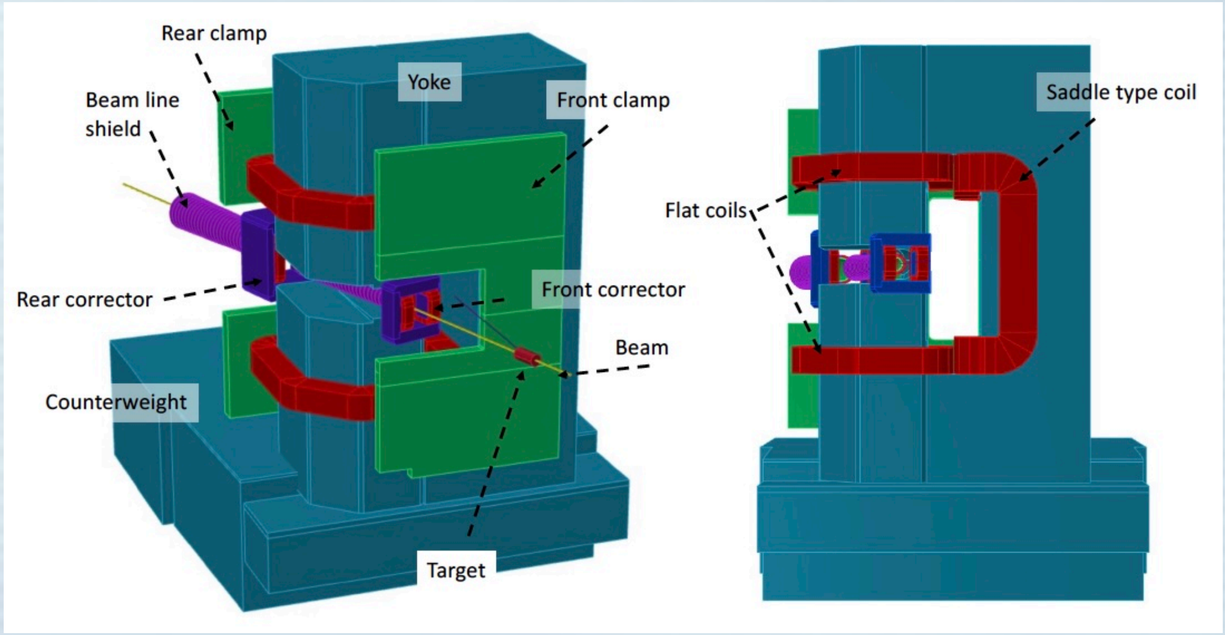


SBS SIDIS will use apparatus that has been, almost entirely, run successfully for previous SBS experiments



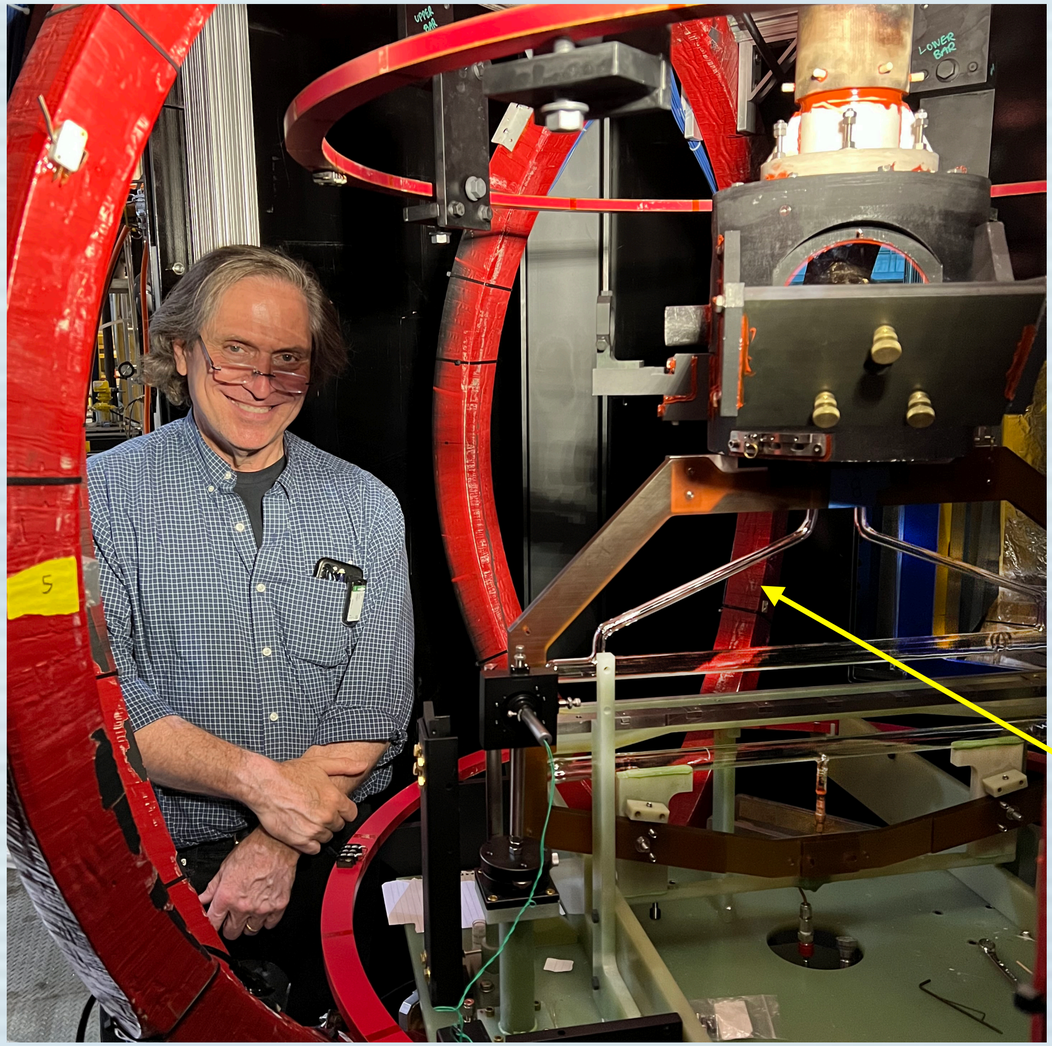
The SBS configuration for SIDIS



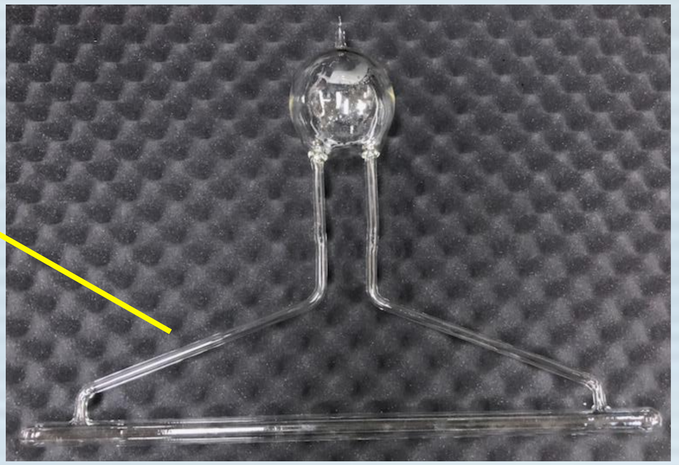


The SBS magnet, with a cut through the Yoke to permit significantly smaller detection angles without sacrificing acceptance.

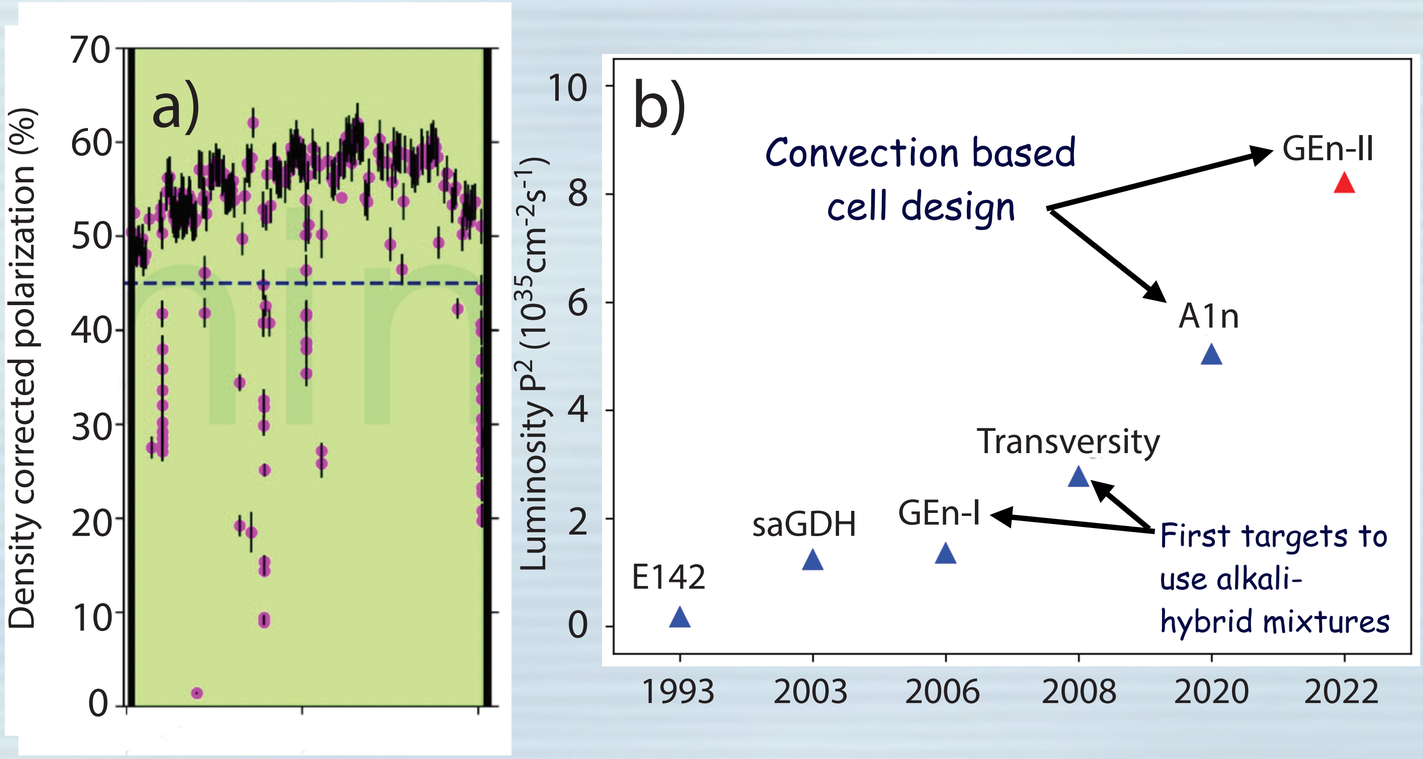
Polarized ^{3}He target based on spin-exchange optical pumping

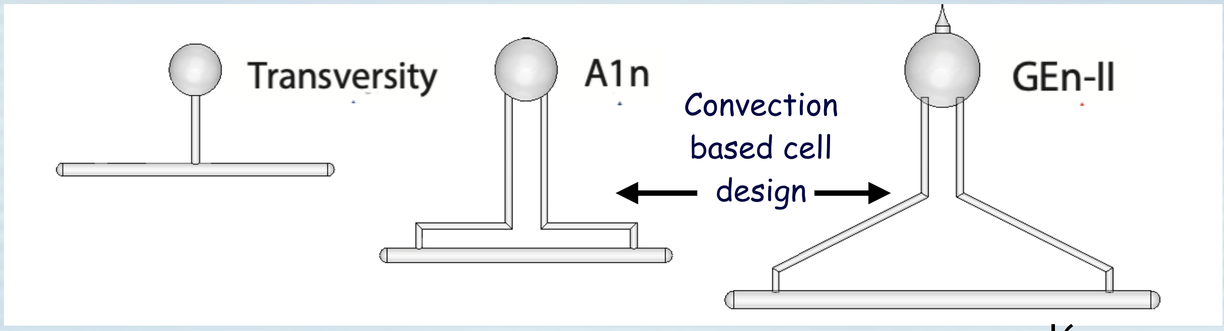


- Modified version of the Hall A polarized ^{3}He target.
- Important difference is the ability to orient in vertical direction.
- Another difference is request flipping of target polarization direction.
- These features were successively implemented for the Transversity experiments in the 6 GeV era.



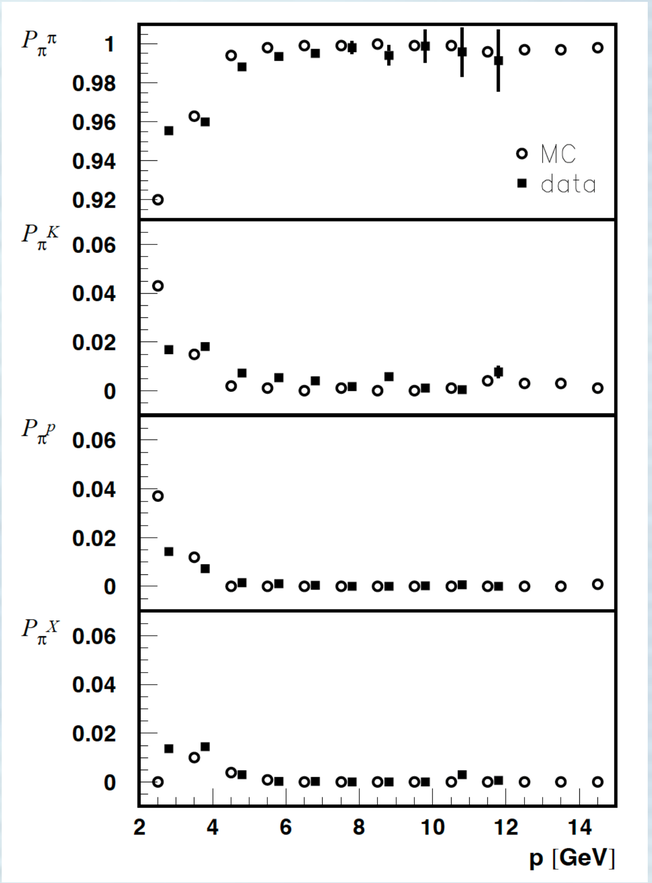
Polarized ^{3}He target performance during GEn-II

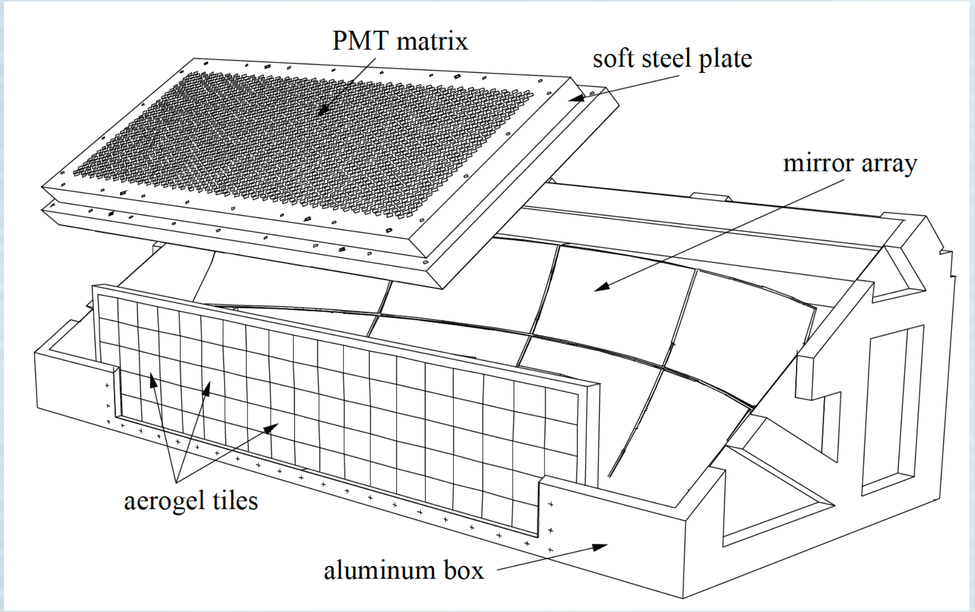


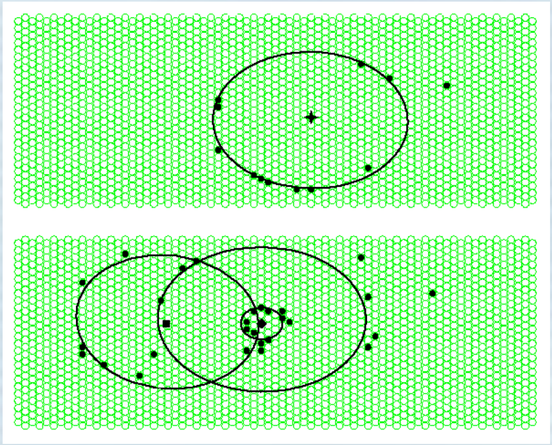


- Polarized ^{3}He target performance has steadily increased since early spin-structure studies at SLAC (E142 and E154) due to
  - better understanding of the underlying atomic physics,
  - advances in laser technolgy
  - and improved target-cell designs.
- The best performing target cell during GEn-II achieved ~95% of the SBS SIDIS target figure-of-merit.

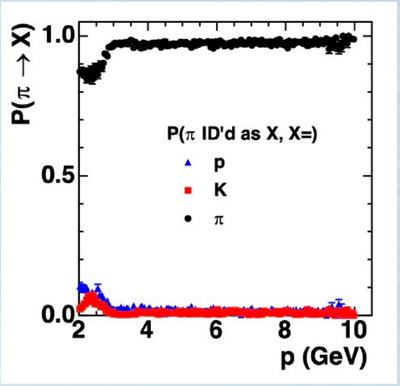
The Hermes (and now) SBS RICH Detector

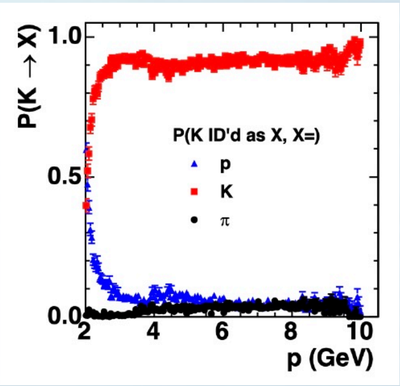




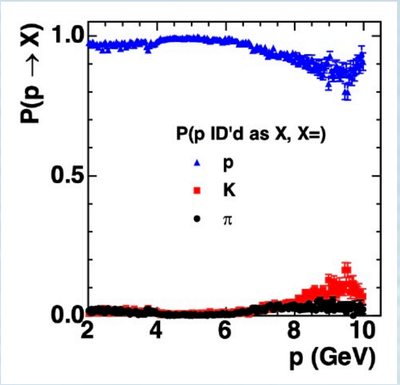


Simulations of SBS particle ID for pions (top) kaons (middle) and protons (bottom)



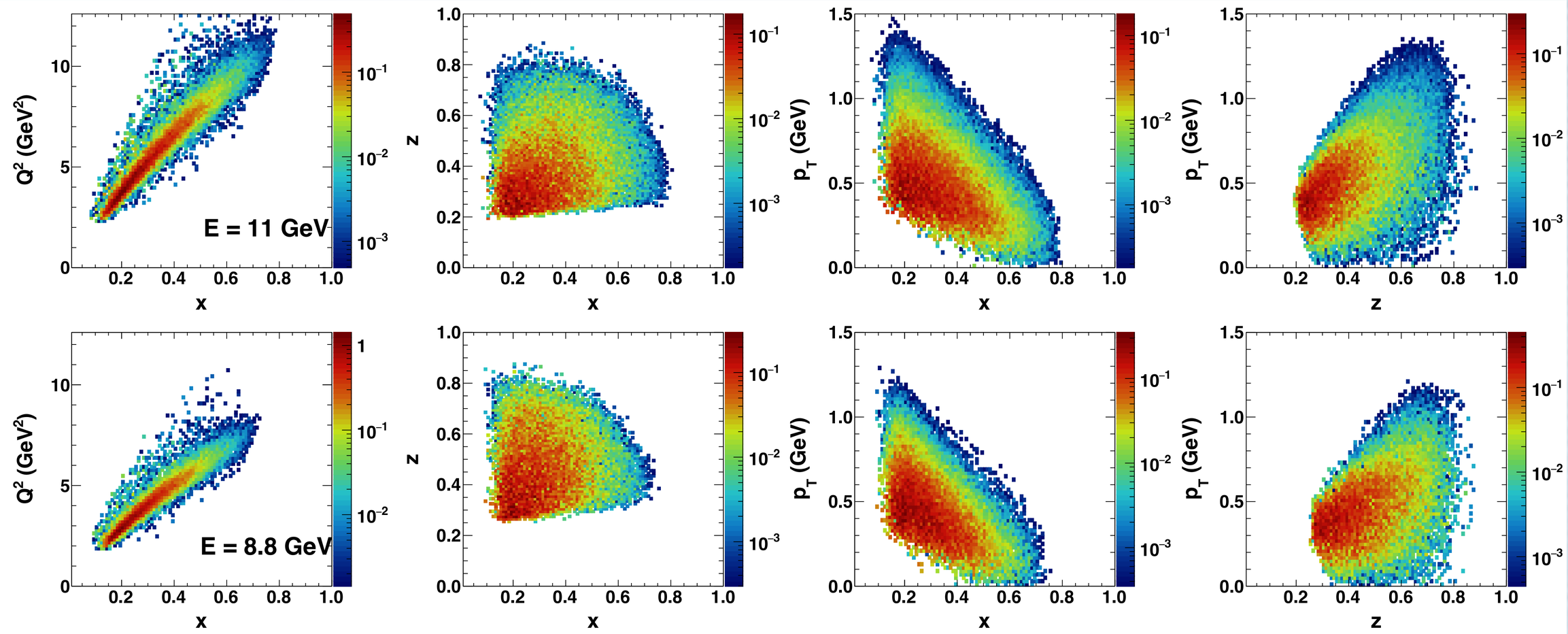


Refurbishing of HERMES RICH for SBS is ongoing. The PMT matrix is tested and looks good.



HERMES data from NIM A Vol. 479, pg. 511 (2002)

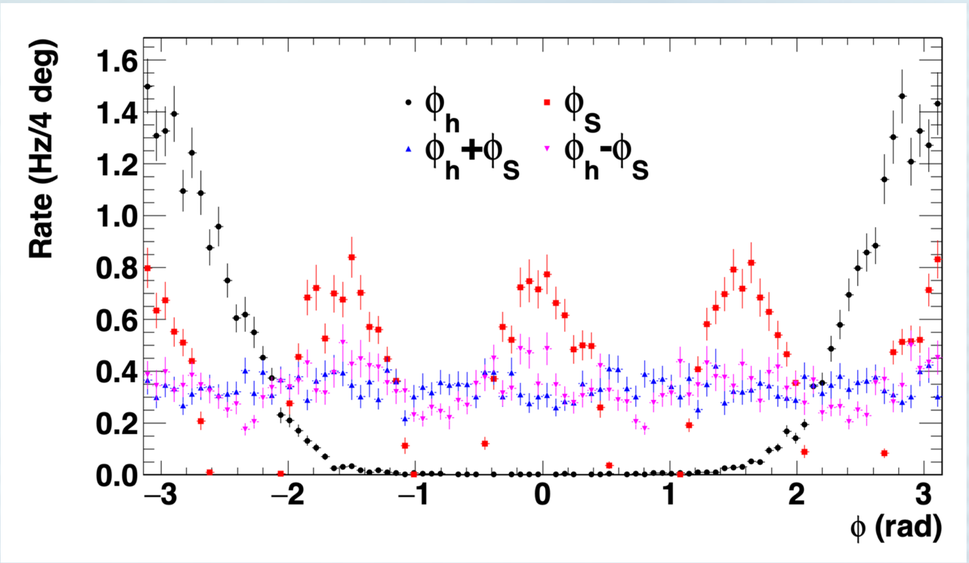
SBS SIDIS kinematic coverage

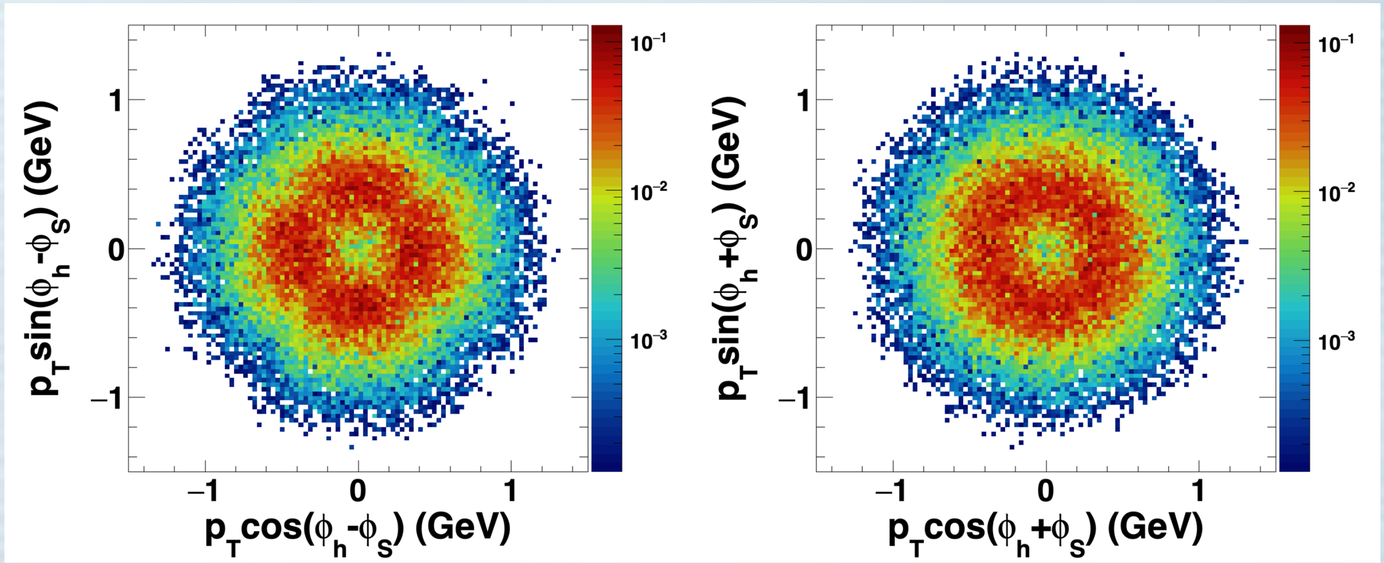


Q^2 vs. x | z vs. x | p_T vs. x | p_T vs. z

Generated using g4sbs. Cuts include $Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2, $M_X^2 > 2.3$ GeV^2, $E_e' > 1$ GeV (roughly equivalent to $y < 0.9$), $p_h > 2$ GeV and good tracks and signals required in all relevant SBS and BB detectors.

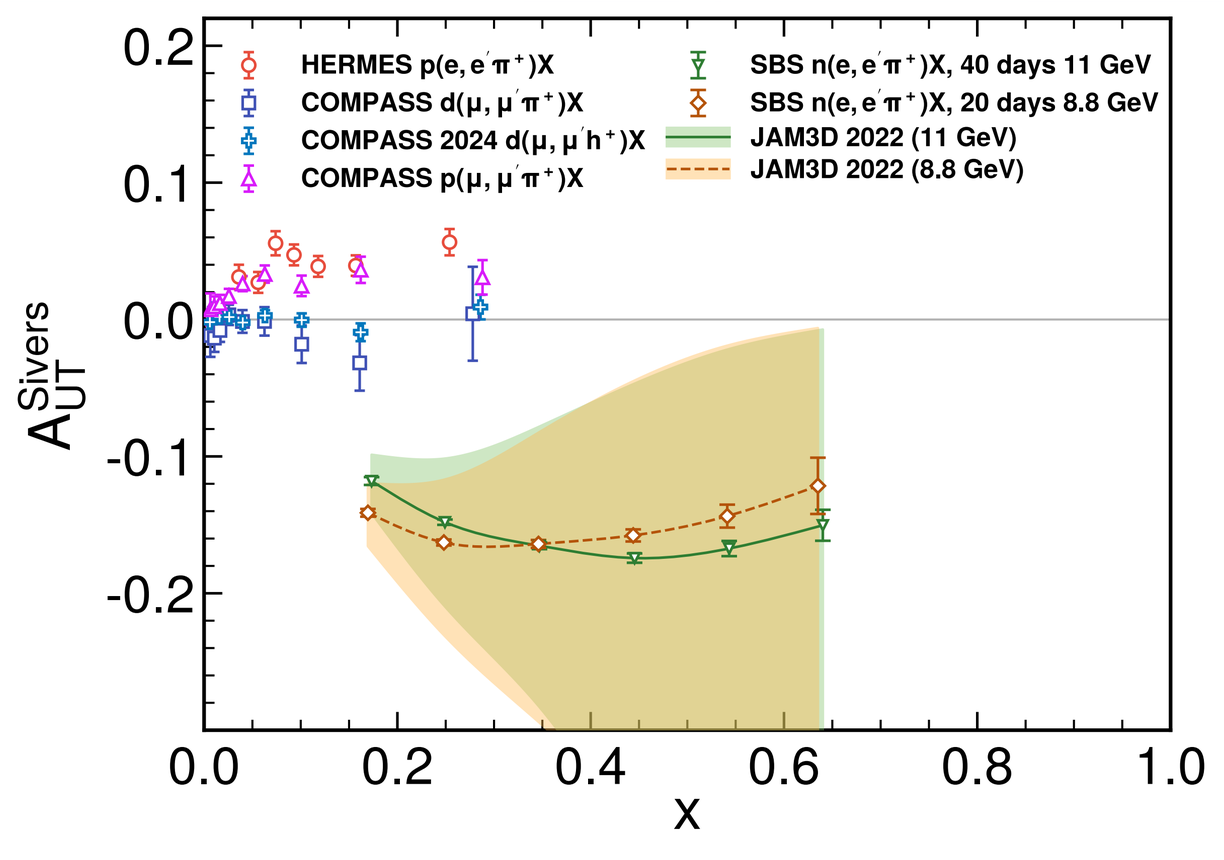
SBS SIDIS azimuthal angular coverage



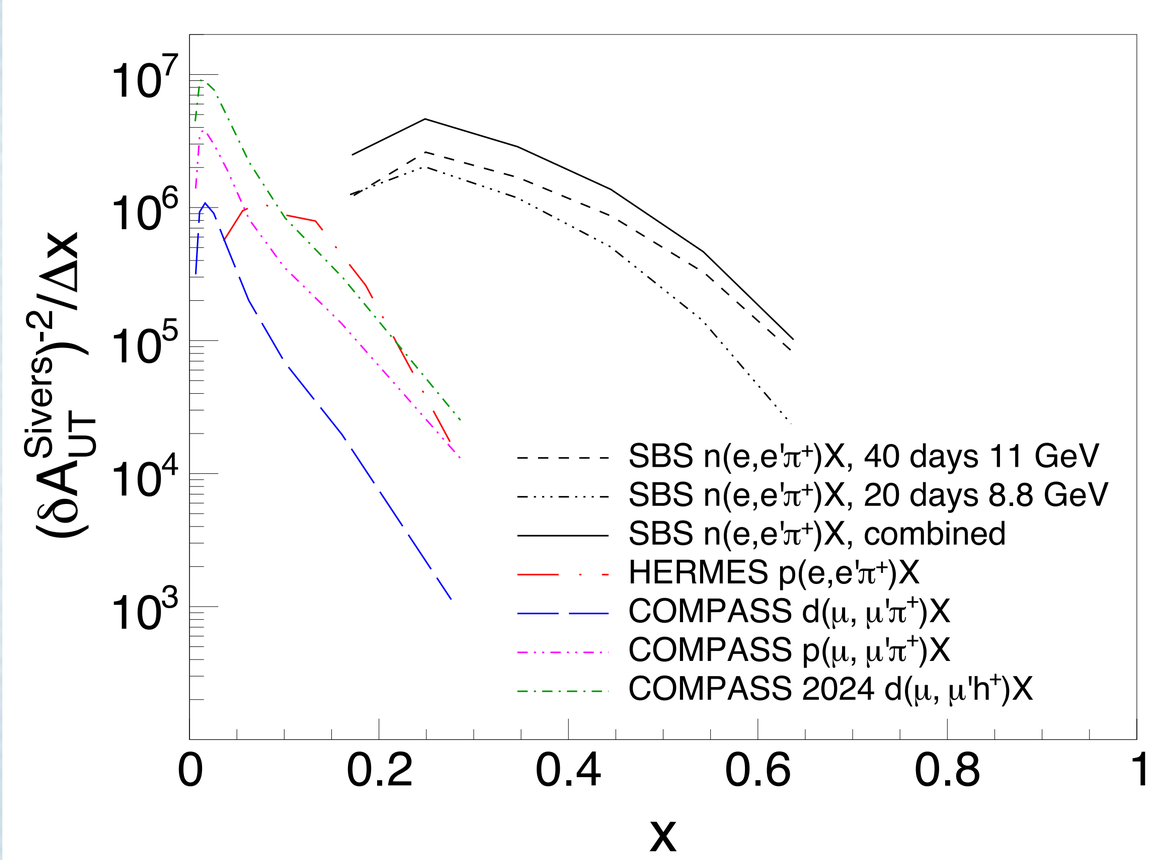


- Polarized ^{3}He target can be oriented either vertically or horizontally transverse to beam.
- Target can be flipped by 180 degrees multiple times per hour.
- Very uniform azimuthal coverage.

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

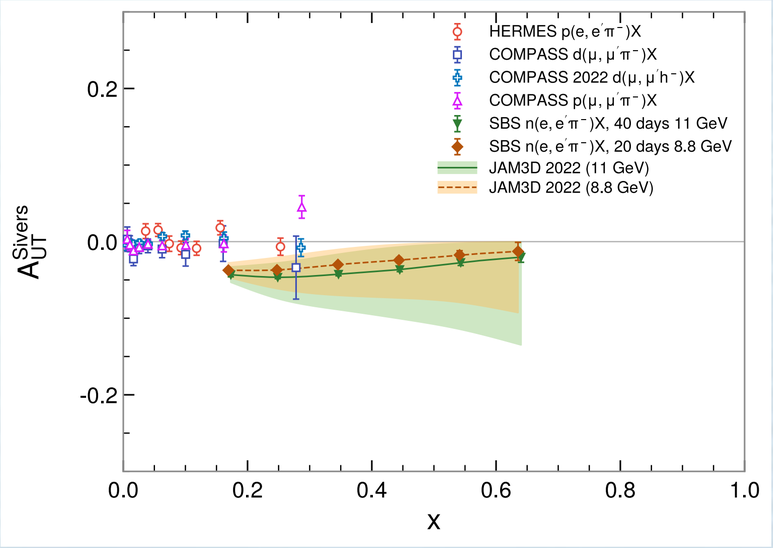


Sample comparison of SBS SIDIS projected neutron Sivers asymmetry with HERMES and COMPASS published data (including COMPASS 2022 deuteron data for unidentified charged hadrons)

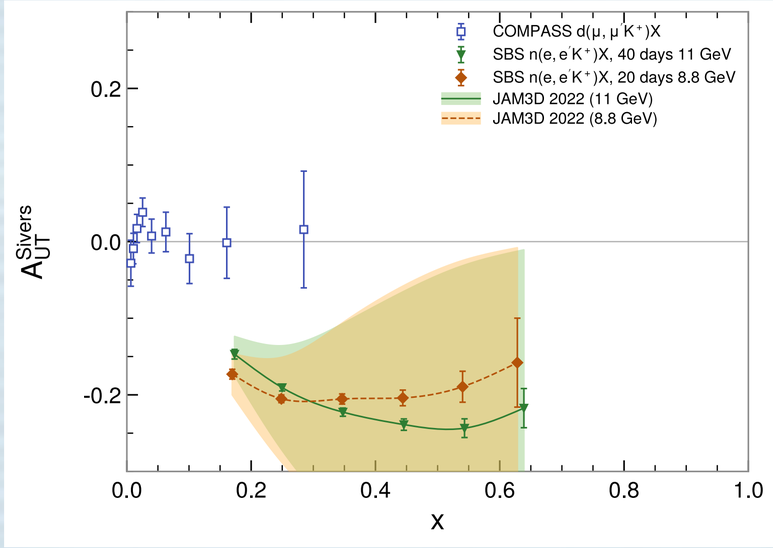


Same as at left, plotted as statistical Figure-of-Merit (FOM) per x interval.

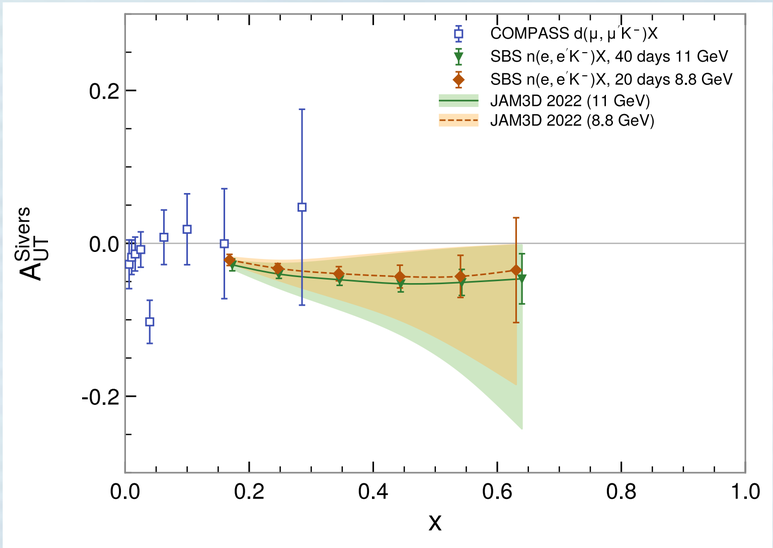
1D Neutron Sivers projections: other hadrons



A_{UT}^{Sivers} for $\vec{n}(e, e'\,\pi^-)\,X$



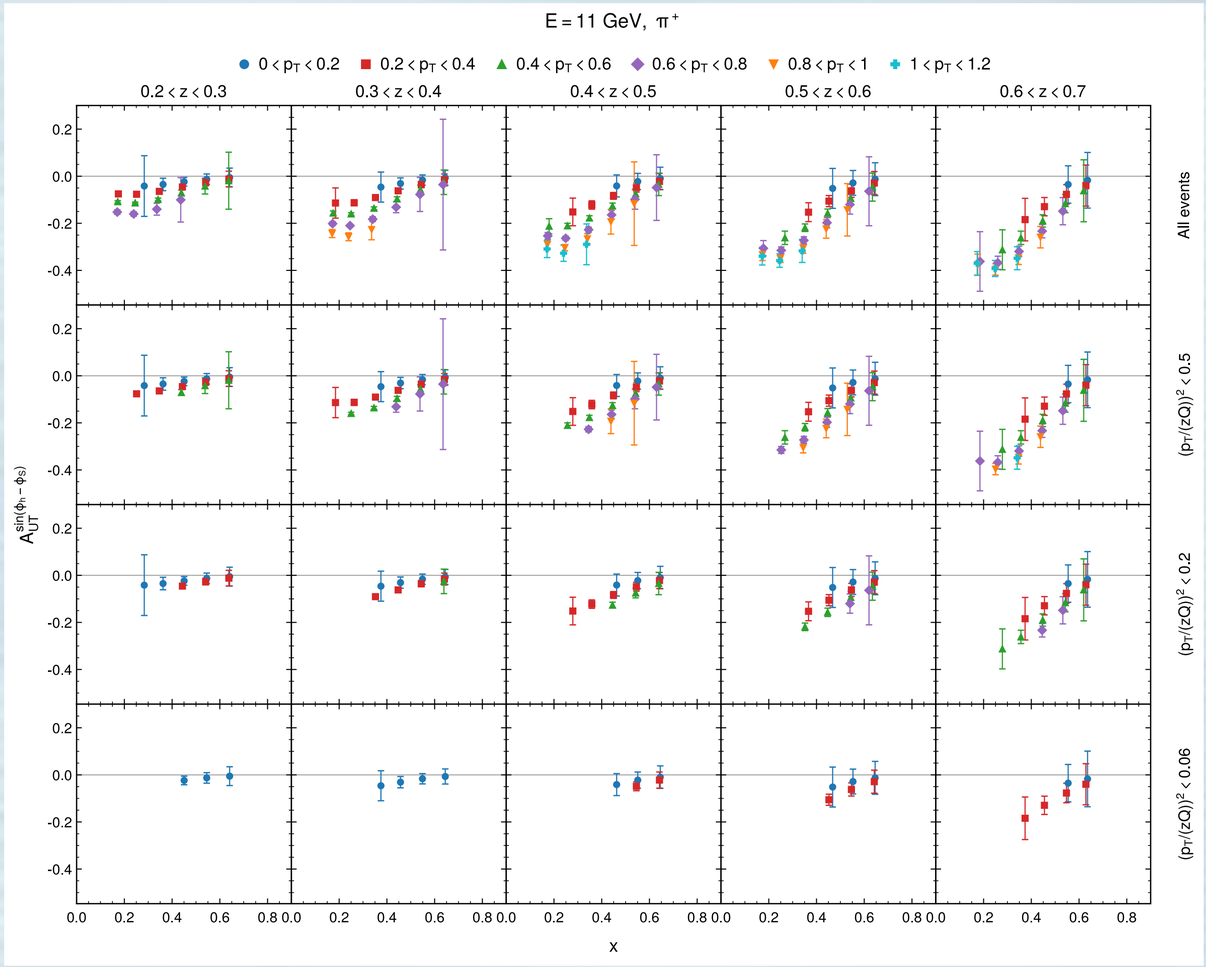
A_{UT}^{Sivers} for $\vec{n}(e, e'\,K^+)\,X$



A_{UT}^{Sivers} for $\vec{n}(e, e'\,K^-)\,X$

Analysis credit: Provakar Datta (LBNL). JAM3D 2022 projections and uncertainty bands interpolated for our kinematics, binnings, and cuts from public Jupyter notebook based on paper by L. Gamberg, M. Malda, J. Miller, D. Pitonyak, A. Prokudin and N. Sato (JAM Collaboration), PRD vol. 106, 034014 (2022).

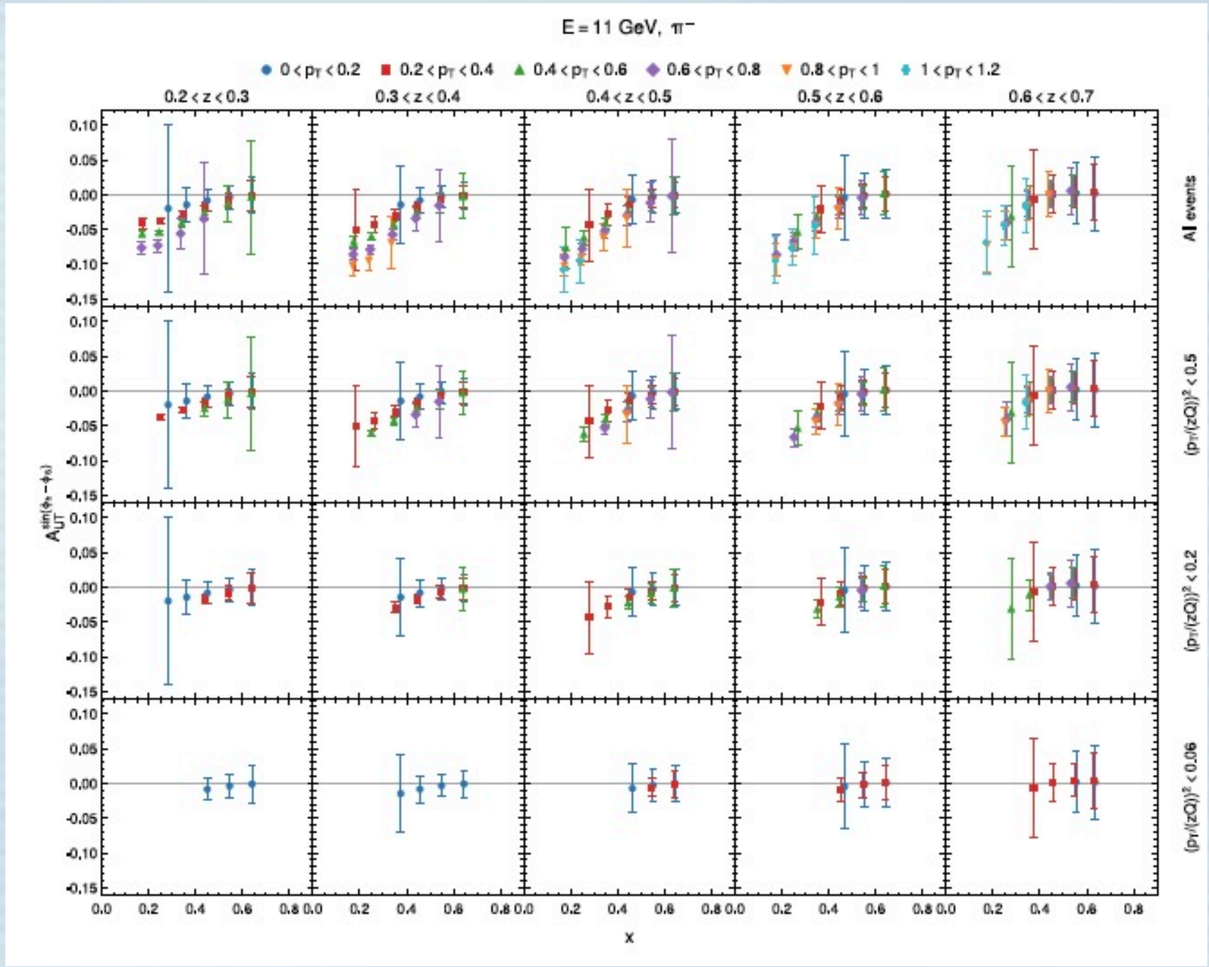
Full differential analysis (11 GeV), effect of P_T/zQ cuts



$0.3 < z < 0.4$ $0.2 < z < 0.3$ $0.4 < z < 0.5$ $0.5 < z < 0.6$ $0.6 < z < 0.7$

A_{UT}^{Sivers} for $\vec{n}(e, e'\,\pi^+)\,X$

← Increasingly restrictive cuts on $(P_T/(zQ))^2$



$0.3 < z < 0.4$ $0.2 < z < 0.3$ $0.4 < z < 0.5$ $0.5 < z < 0.6$ $0.6 < z < 0.7$

A_{UT}^{Sivers} for $\vec{n}(e, e'\,\pi^-)\,X$

Summary

- SBS SIDIS is currently the only fully approved experiment that will study single-spin asymmetries on a transversely polarized target.
- SBS SISIS will increase the overall statistics in the measurement of single-spin asymmetries by a factor of over ten, and considerably more in the high x region.
- SBS SIDIS is tentatively scheduled for installation in Hall A at JLab beginning in 2031 and running in 2032.