SIDIS/TMD Program with SBS+BigBite in Hall A (E12-09-018, +…?)

Andrew Puckett
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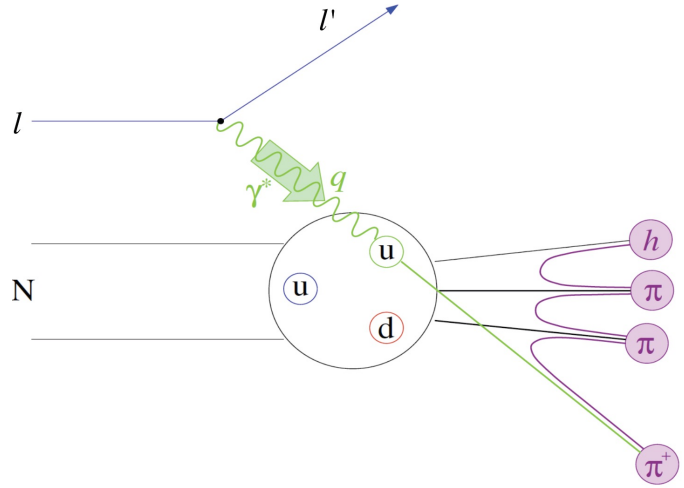
Workshop on Physics with High-Luminosity Facilities
Jefferson Lab
10/7/2026

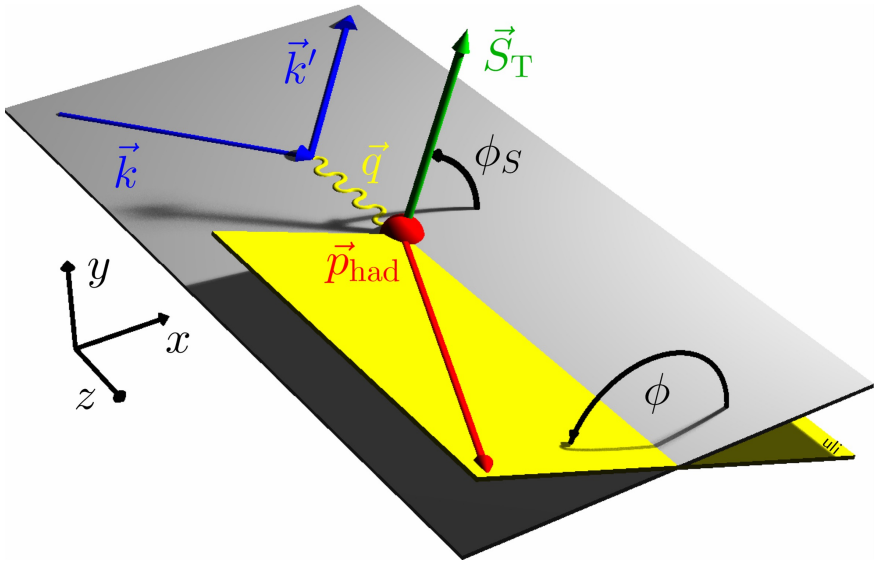
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Outline

- Science Motivation
- SBS Overview and Collaboration
- E12-09-018 overview/history
- E12-09-018 projected results/impacts
- E12-09-018 uniqueness/complementarity
- "DOSBS" concept and added physics potential
- Summary/Conclusions

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

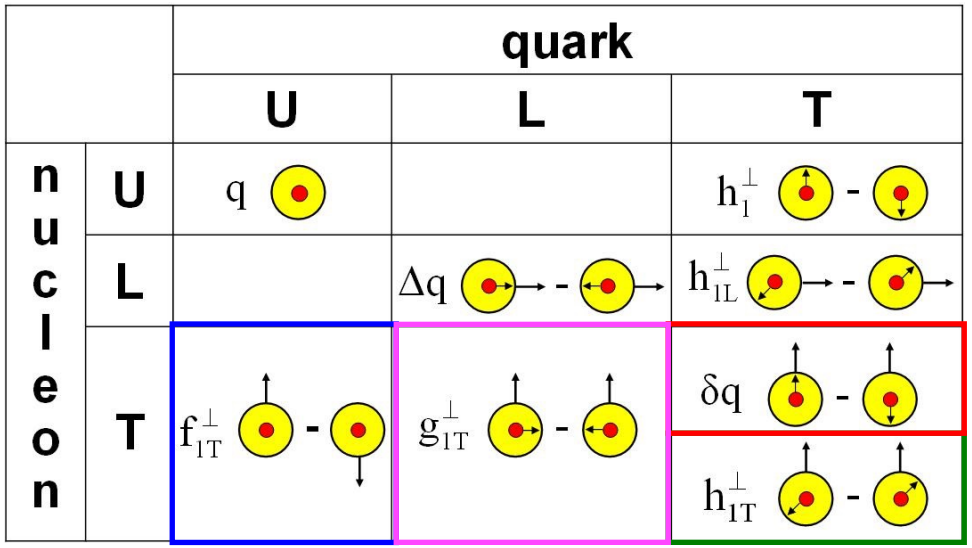




Kinematic Variables for SIDIS	Description
$z \equiv \frac{p_h \cdot p}{q \cdot p} \overset{lab}{\Longrightarrow} \frac{E_h}{\nu}$	Fraction of virtual photon energy carried by observed hadron
$p_T \equiv \boldsymbol{p}_h - \frac{\boldsymbol{p}_h \cdot \boldsymbol{q}}{\lvert\boldsymbol{q}\rvert^2}\boldsymbol{q}$	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.***

Effects of Transverse Target Polarization in SIDIS



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

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

D_1 = unpolarized fragmentation function
$H_1^\perp$ = Collins fragmentation function

$$A_{UT}^{Collins} \propto h_1 \otimes H_1^\perp$$
$$A_{UT}^{Sivers} \propto f_{1T}^\perp \otimes D_1$$
$$A_{UT}^{Pretz} \propto h_{1T}^\perp \otimes H_1^\perp$$

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

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

Kinematic Conditions for applicability of TMD formalism

- Requires large Q^2 ($Q^2 > 1\ GeV^2$), large W ($W > 2\ GeV$), as in DIS
- Requires large (but not too large) z:
  - High enough for dominance of "current quark" fragmentation over "target remnant" fragmentation
  - Low enough to avoid dominance of exclusive/resonance region contributions (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.)

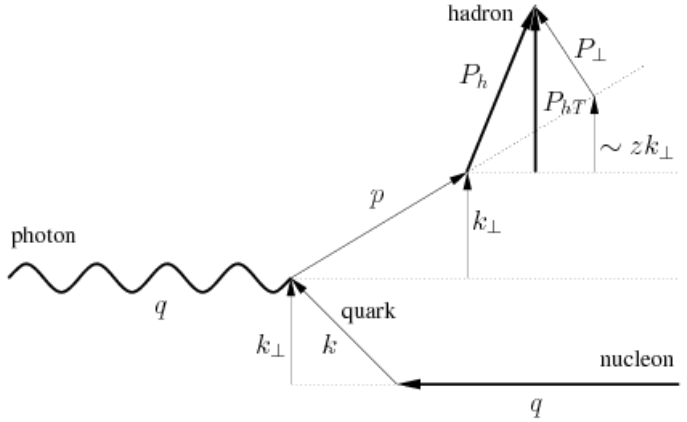


Figure: Bacchetta *et al.,* JHEP 1706 (2017) 081

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

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

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

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

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

General Challenges of Measuring TMD-sensitive Observables

Statistics Requirements

Cross sections:

$$\sigma \propto N$$

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

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

Asymmetries:

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

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

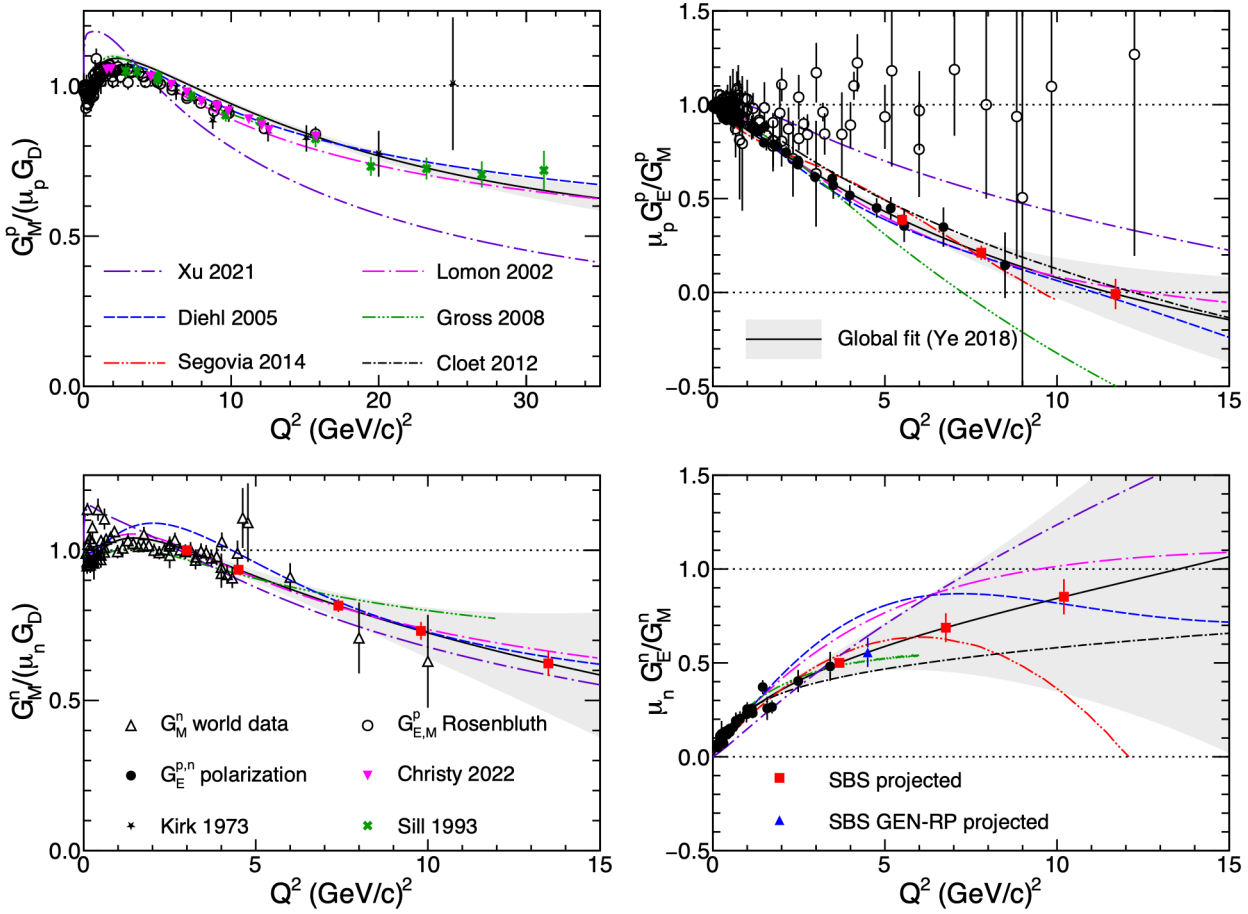
On the other hand, to measure an asymmetry A with a relative precision of 1%, you need $N = 10{,}000 \times \frac{1-A^2}{A^2}$.

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

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-performance particle-ID
- High beam and target ***polarization*** is required for spin-dependent observables: FOM is proportional to ***luminosity*** × ***polarization²***
- **Interpretability requires large Q^2**
  - Large Q^2 implies high x in both fixed-target and collider experiments
  - DIS event rate falls ~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 ^{3}He SEOP technology)**

SBS Collaboration and High-Q^2 Elastic FF Program (Hall A 2021-2025)



Above: Status of SBS FF Program ca. 2023—from 50 Years of QCD: https://inspirehep.net/literature/2617065 (Eur.Phys.J.C 83 (2023) 1125)

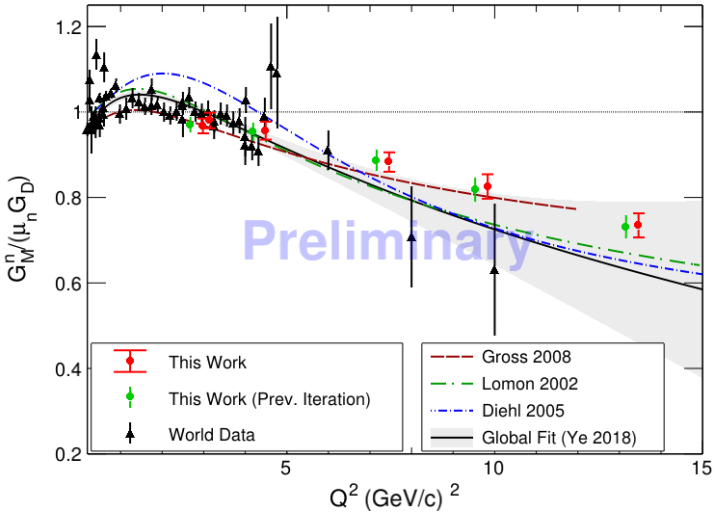


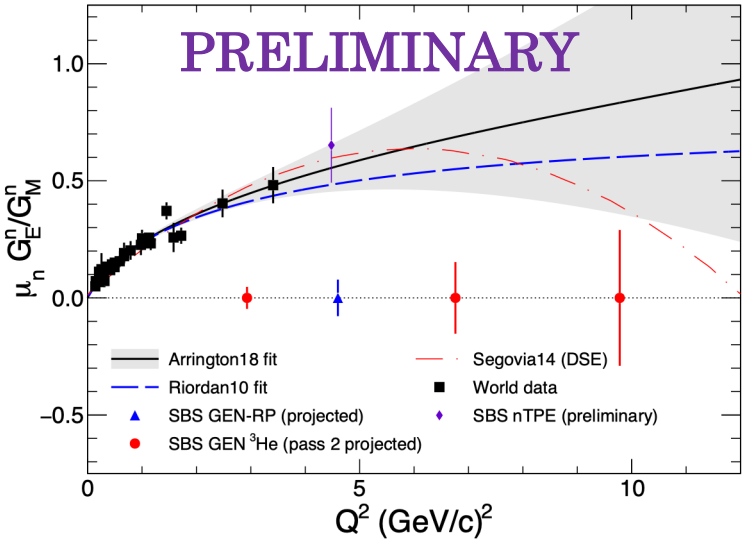
SBS Collaboration Mtg. March 2026

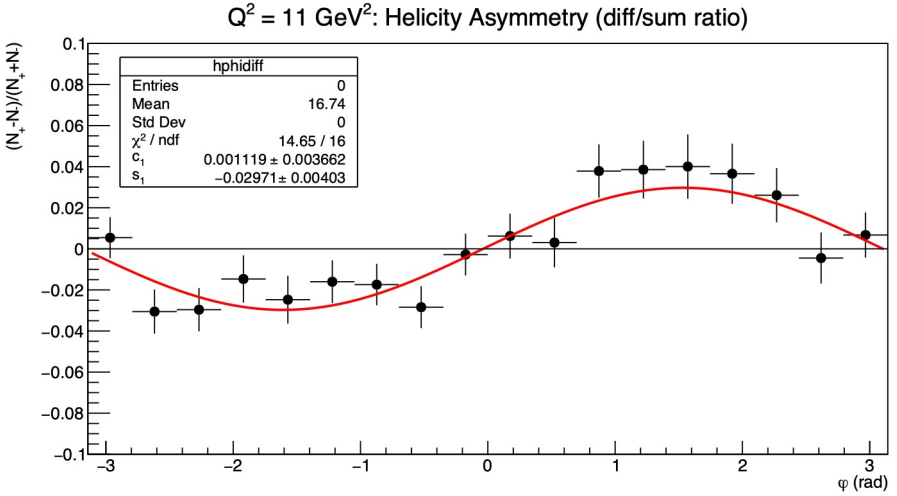
Completed Experiments 2021-2025

- 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 $Q^2 \geq 10$ GeV^2
- Data under analysis, publications forthcoming

Selected Highlights SBS FF Program (so far)



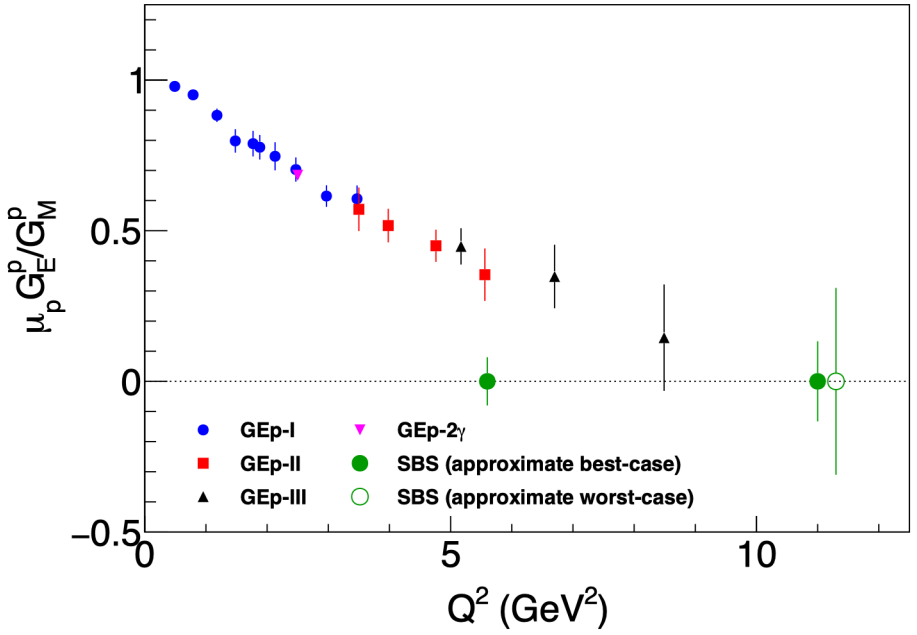




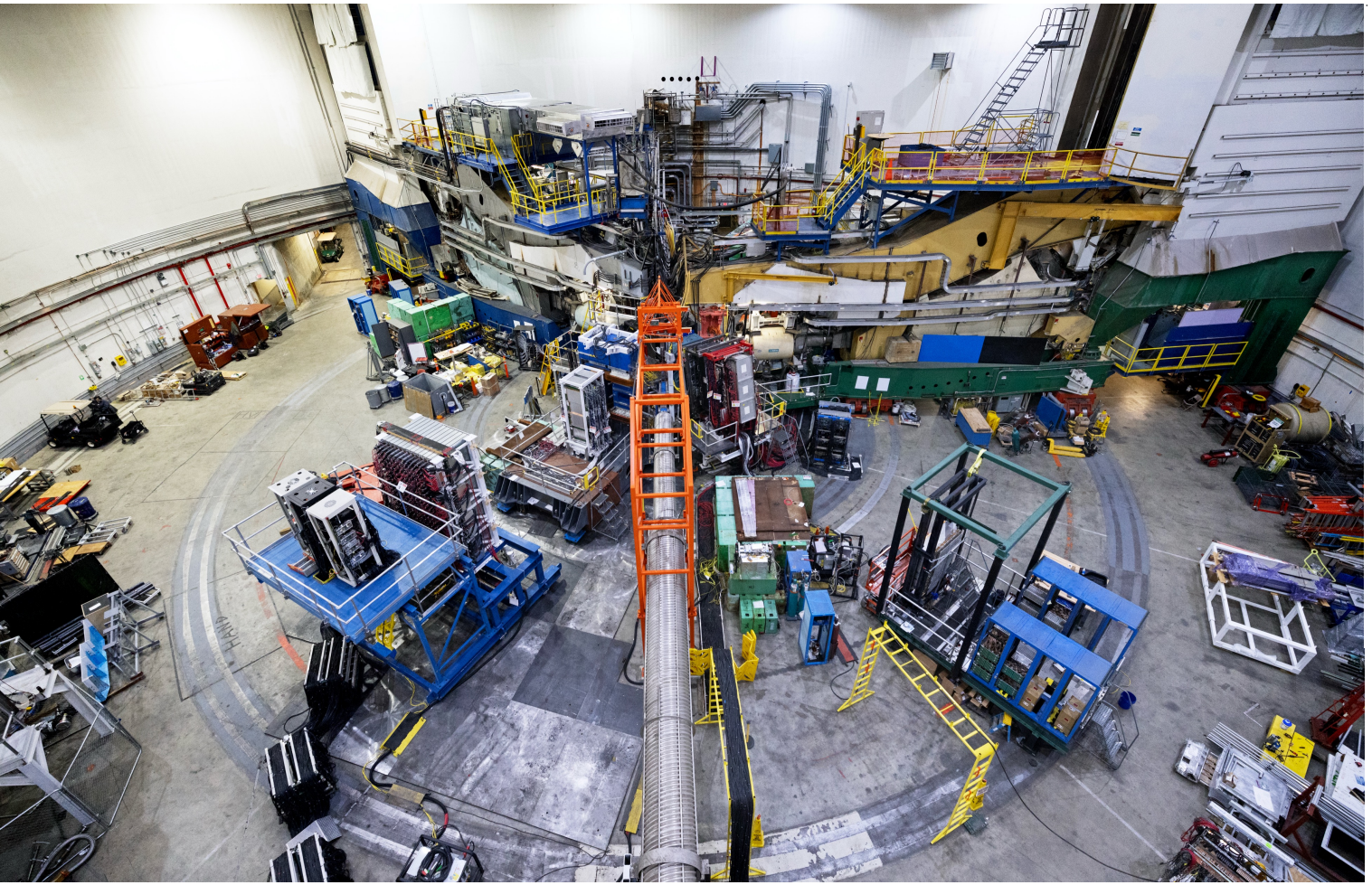


[The JSA/Jlab Thesis Prize 2025]

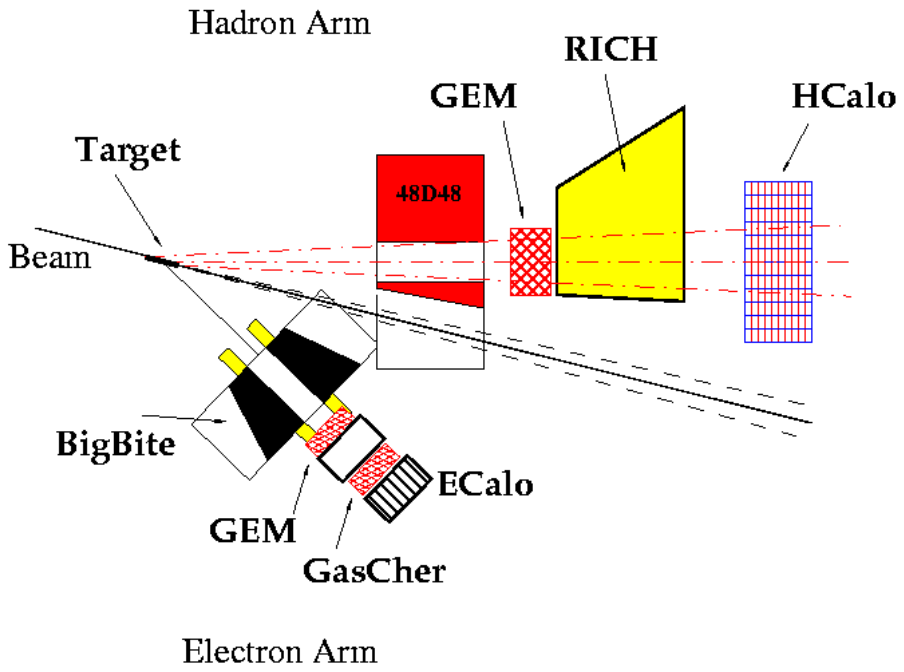
- Above, left: GMN preliminary results (pass 2/pass 3 analysis)
- Bottom, left: P. Datta Jlab thesis prize 2025
- Above, center: nTPE preliminary and projected GEN
- Above, right: proton polarimeter asymmetry from GEP @11 GeV²
- Below, right: Projected GEP uncertainties (stat. only)



BigBite and Super BigBite Spectrometers in Hall A



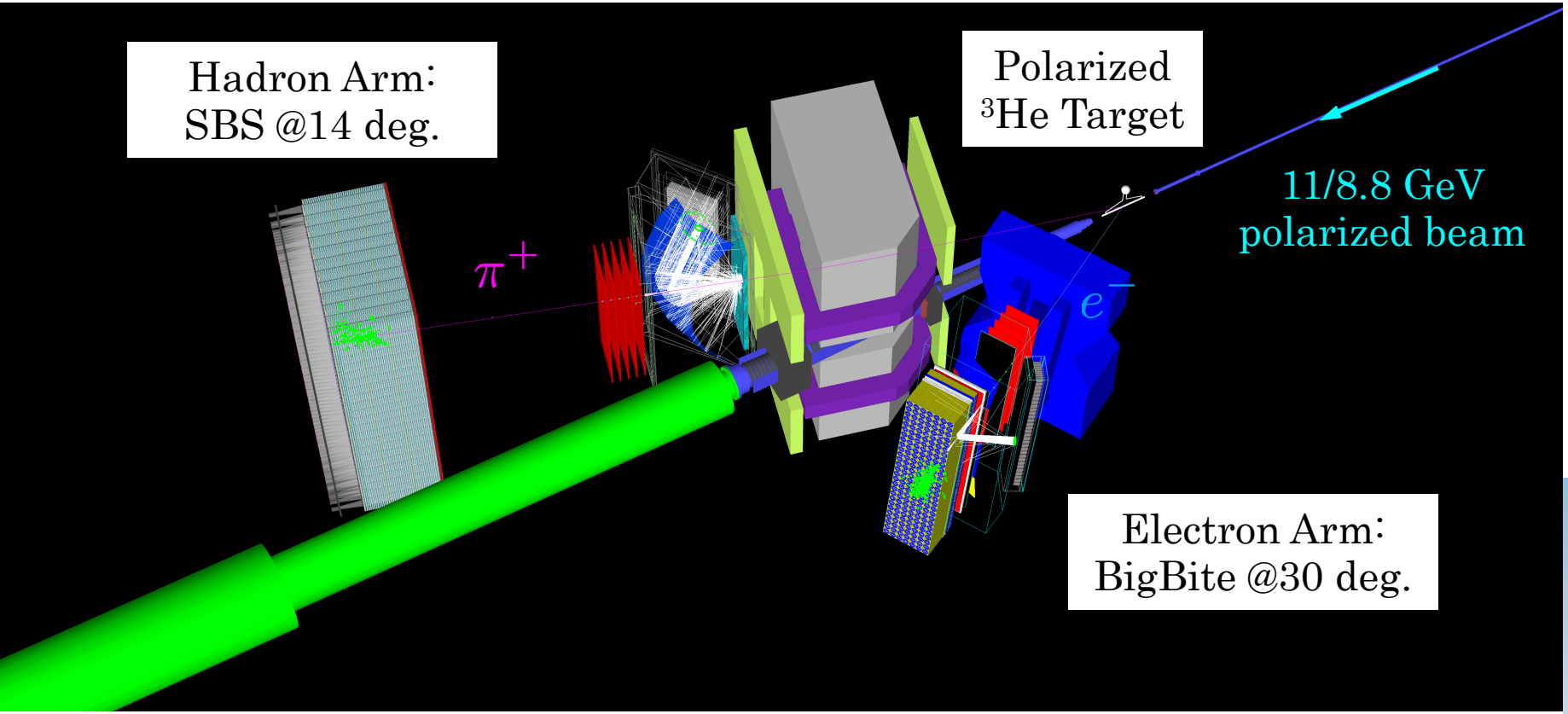
Aerial View of SBS+BB in Hall A, late 2023/early 2024 during GEn-II→GEn-RP changeover

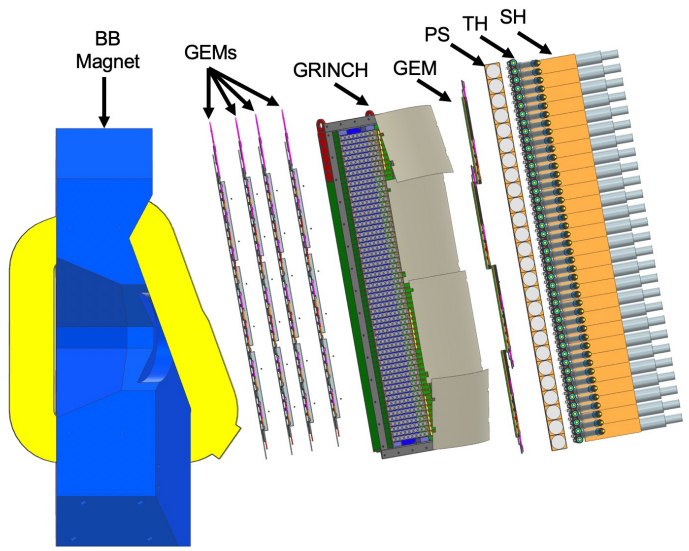


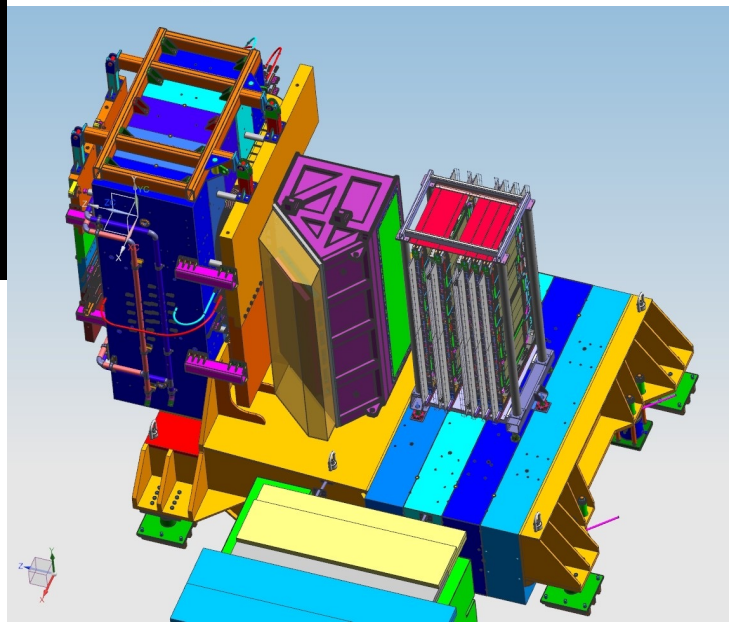
Original schematic of SBS SIDIS

- 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

The SBS SIDIS Experiment (E12-09-018)







- Above, left: screenshot of a single $^3He(e,e'\pi^+)X$ 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

E12-09-018 is an SBS Collaboration experiment

Current Spokespeople:

- **Prof. Gordon Cates, UVA**
  - Polarized ^{3}He 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

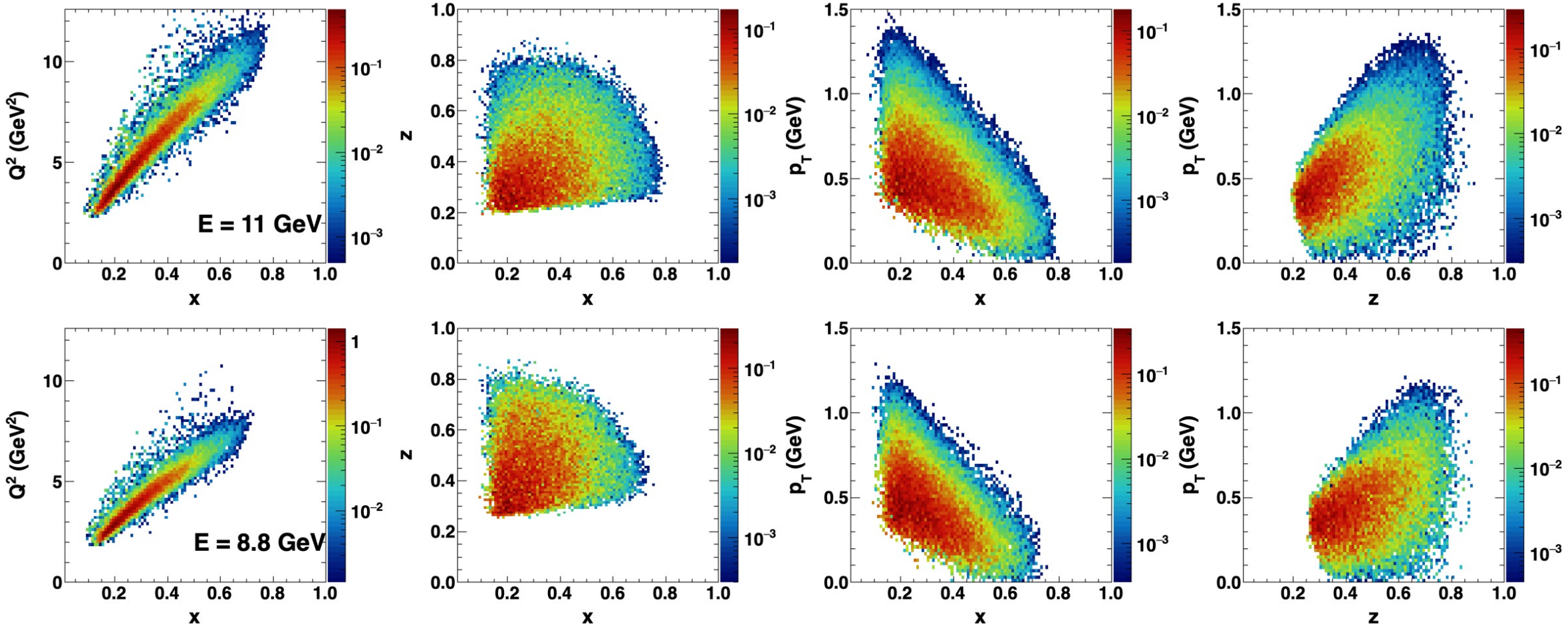
E12-09-018/J12-26-001 History

- 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 ^{3}He 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

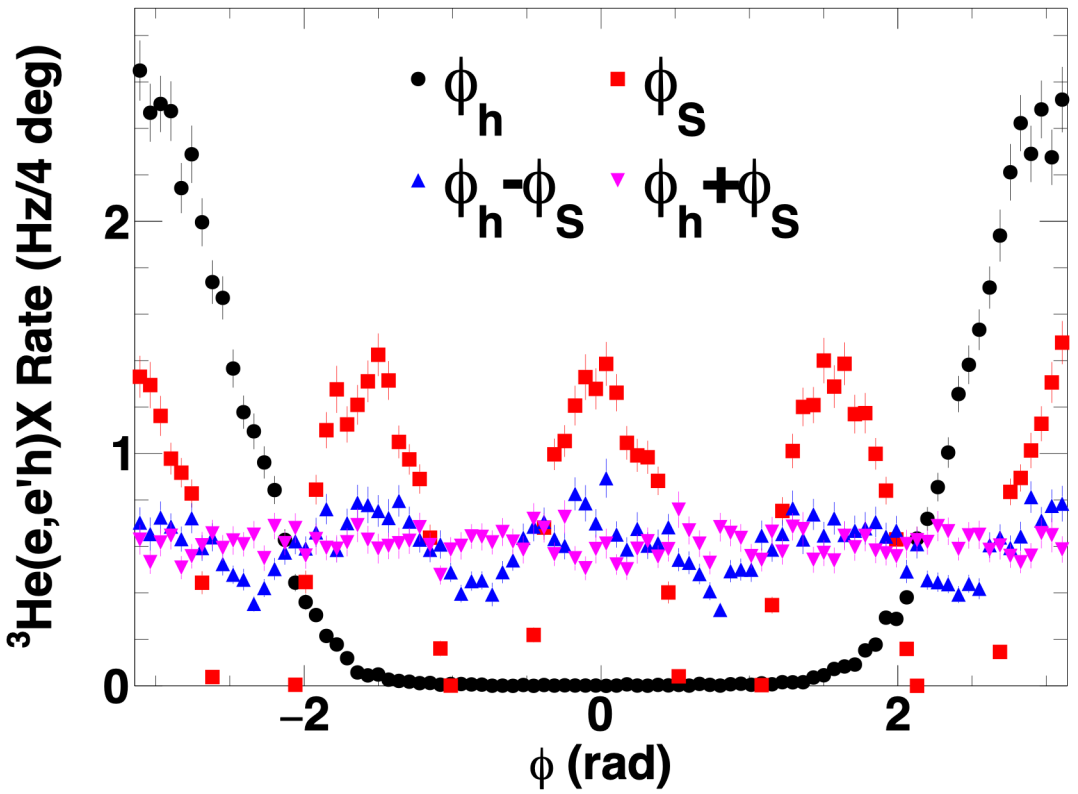
✓ Second jeopardy evaluation PAC54 (July '26), experiment re-approved and upgraded to "A" rating

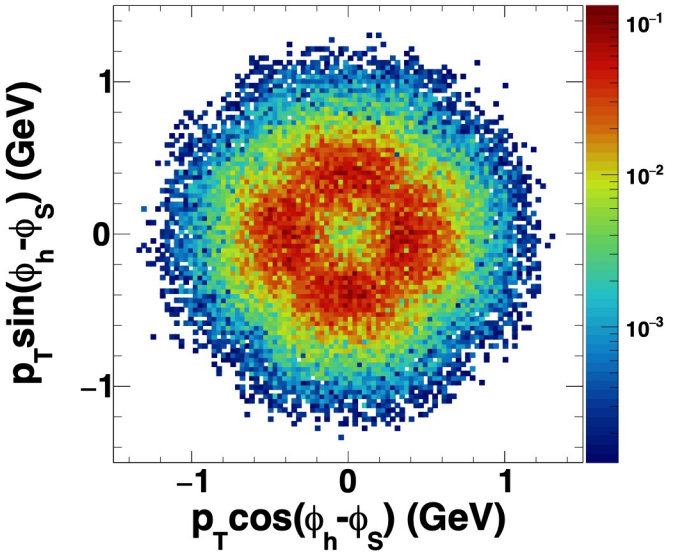
SBS SIDIS Kinematic Coverage

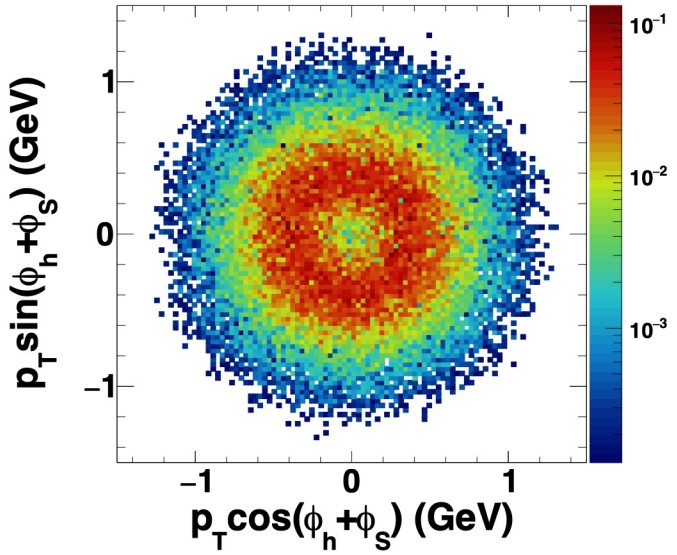


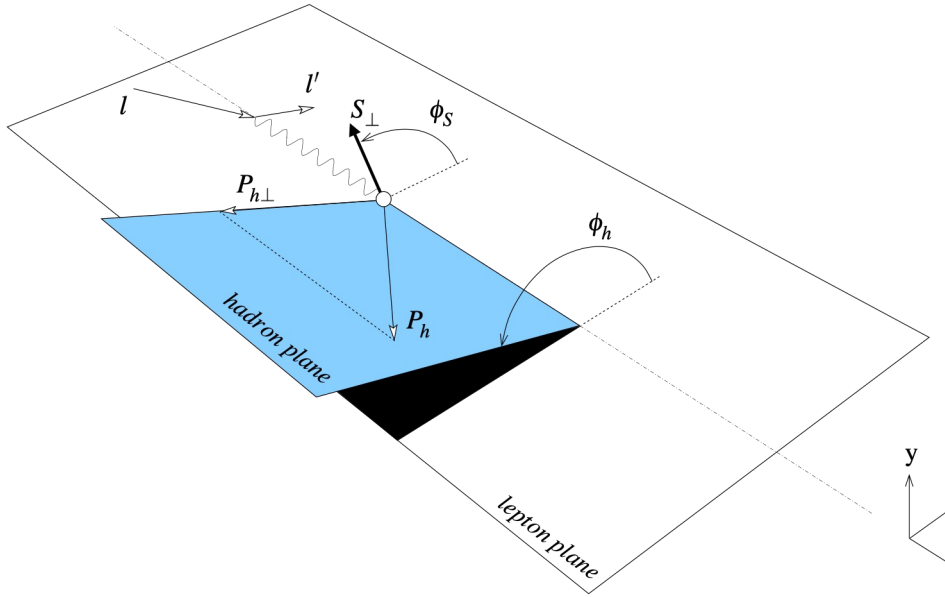
- Above, left to right: SBS SIDIS kinematic coverage in $(Q^2, x), (z, x), (p_T, x), (p_T, z)$, for E = 11 GeV (top row) and 8.8 GeV (bottom row), from *g4sbs*
- Cuts applied are: $Q^2 \geq 1\ GeV^2, W^2 \geq 4\ GeV^2, M_X^2 \geq 2.3\ GeV^2, E_e' \geq 1\ GeV$ (roughly equivalent to $y \leq 0.9$), $p_h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

SBS SIDIS Azimuthal Angle Coverage



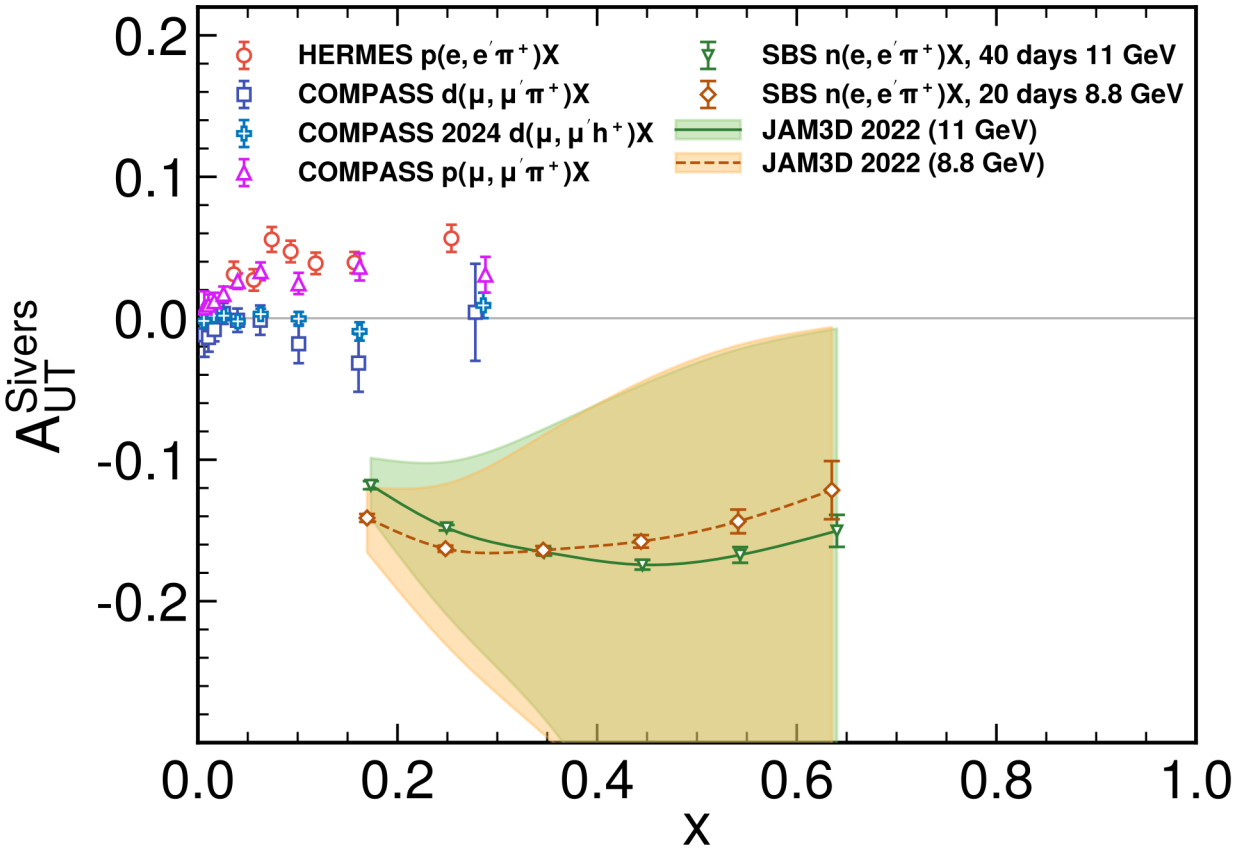




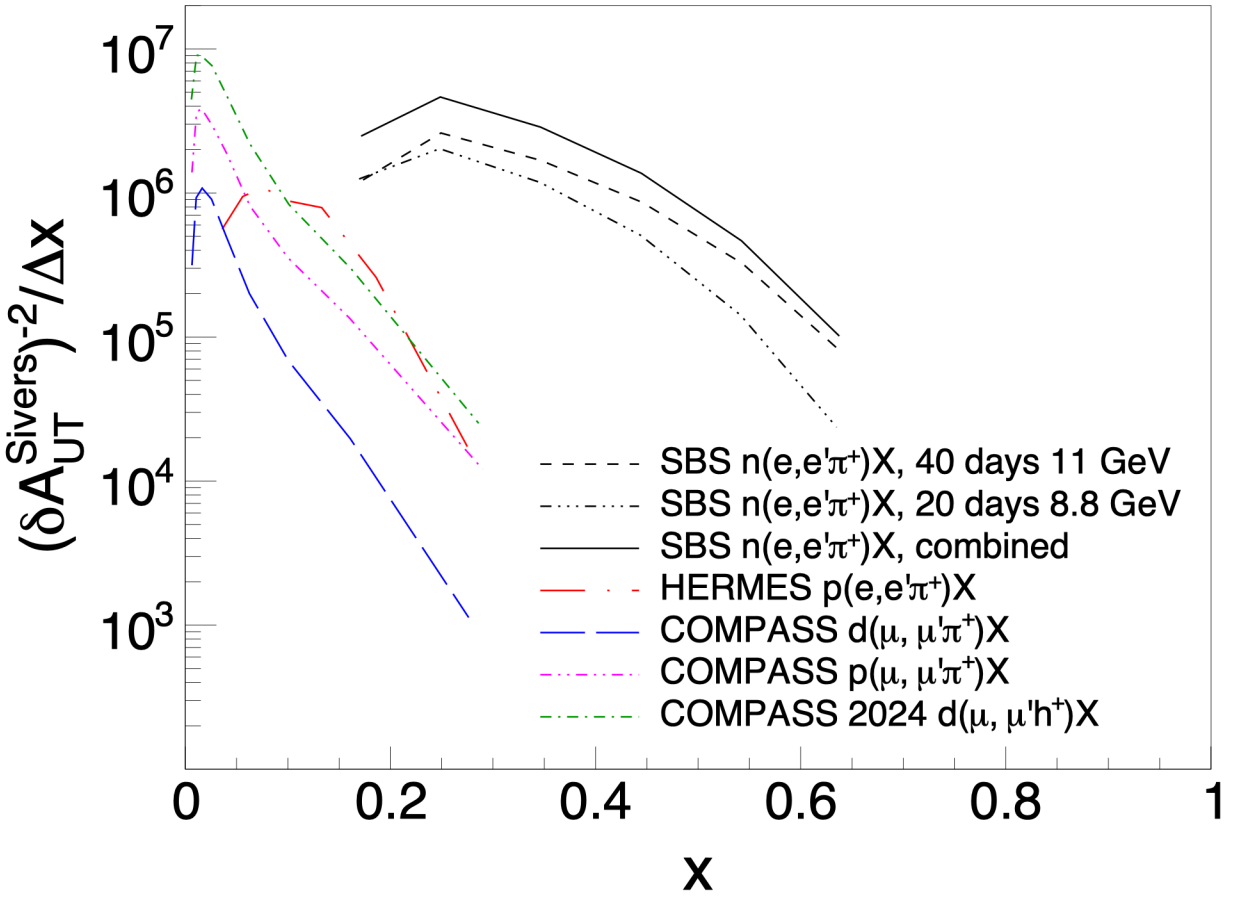


- Original proposal envisioned 8 target spin directions
- Simulations show full and (sufficiently) uniform coverage of $\phi_h \pm \phi_S$, no reduction of physics impact with 4 target directions
- Dramatically simplifies target design & operation

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



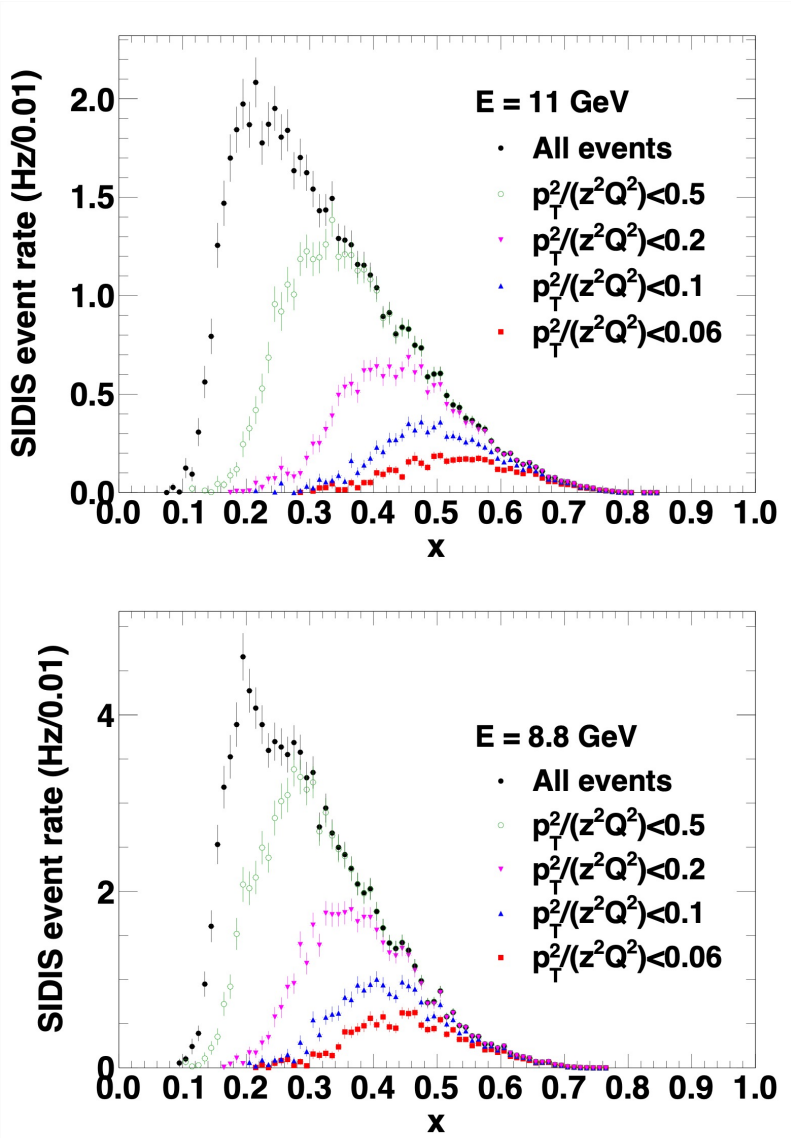
Example comparison of E12-09-018 projected neutron Sivers asymmetry to HERMES and COMPASS published data (including COMPASS 2022 deuteron data for unidentified charged hadrons)

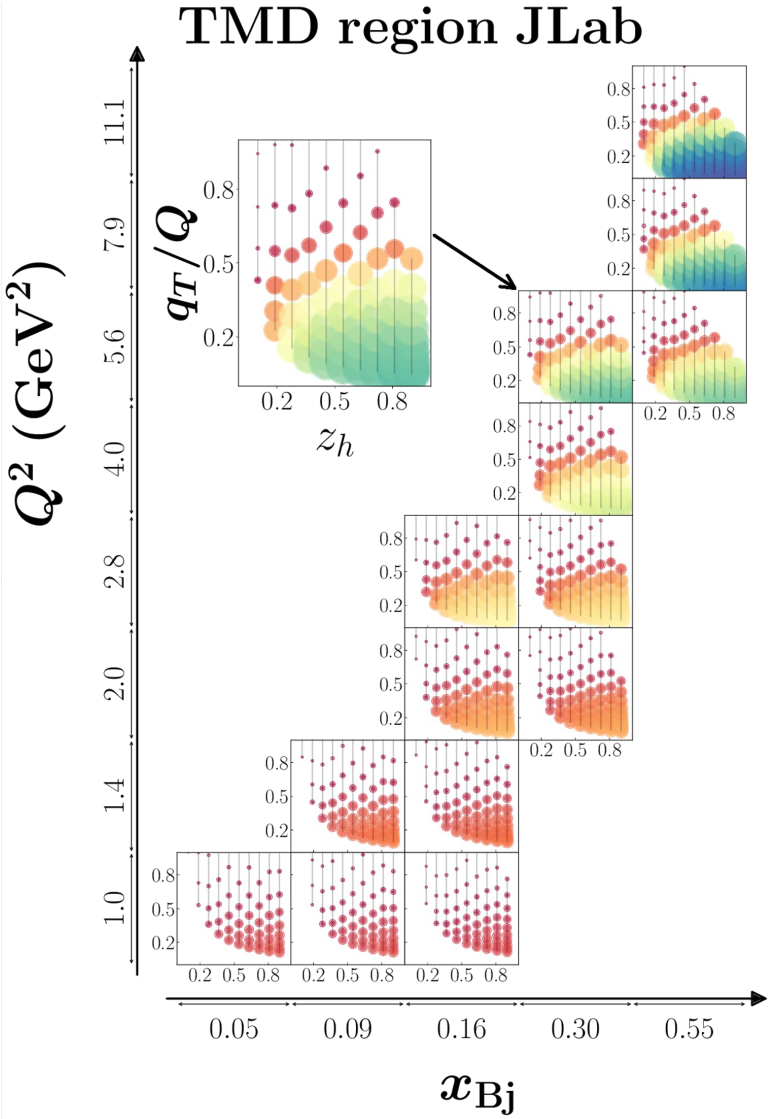


Same as left, plotted as statistical Figure-of-Merit (FOM) per x interval.

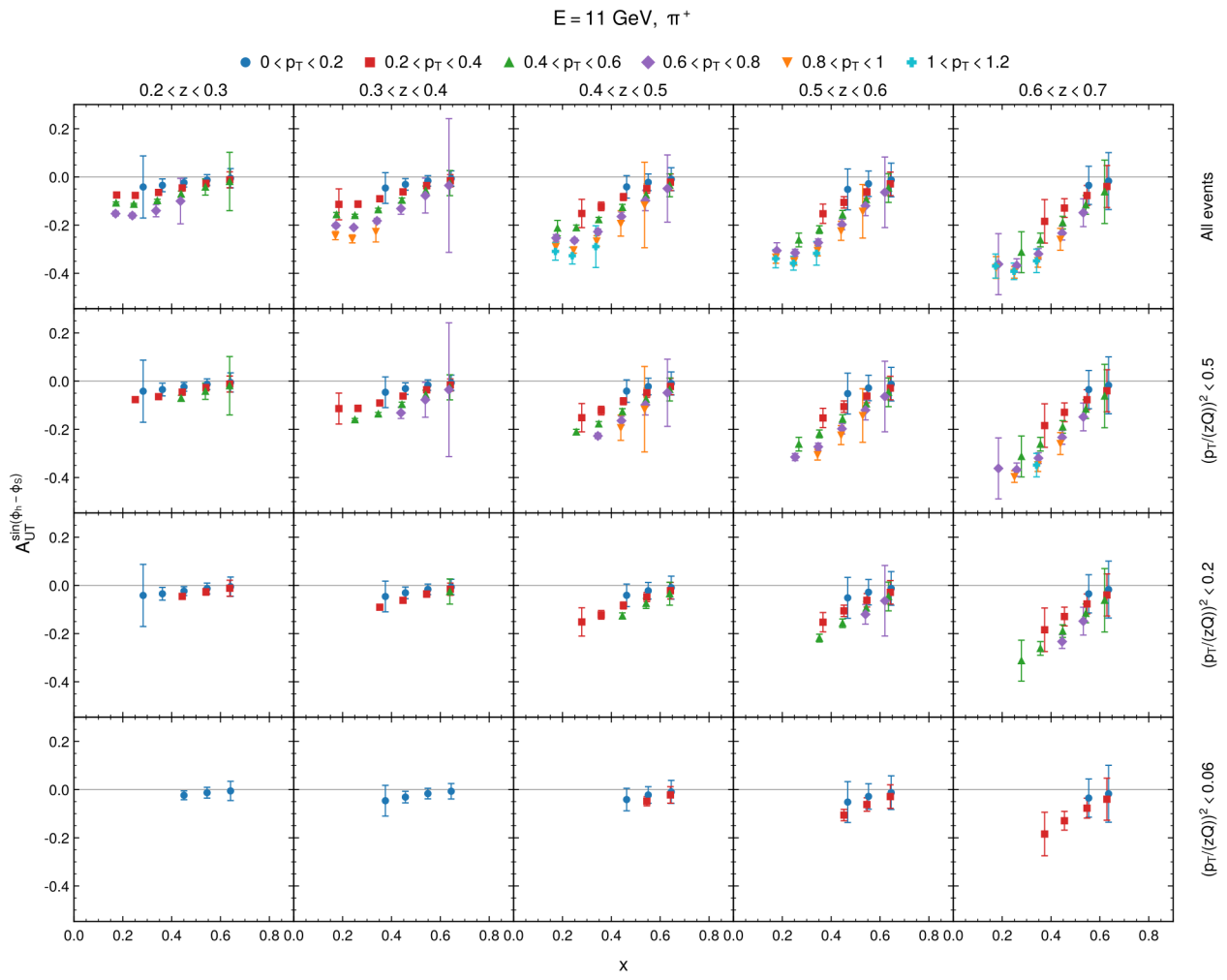
Uniqueness of E12-09-018 kinematics and "TMD Affinity"

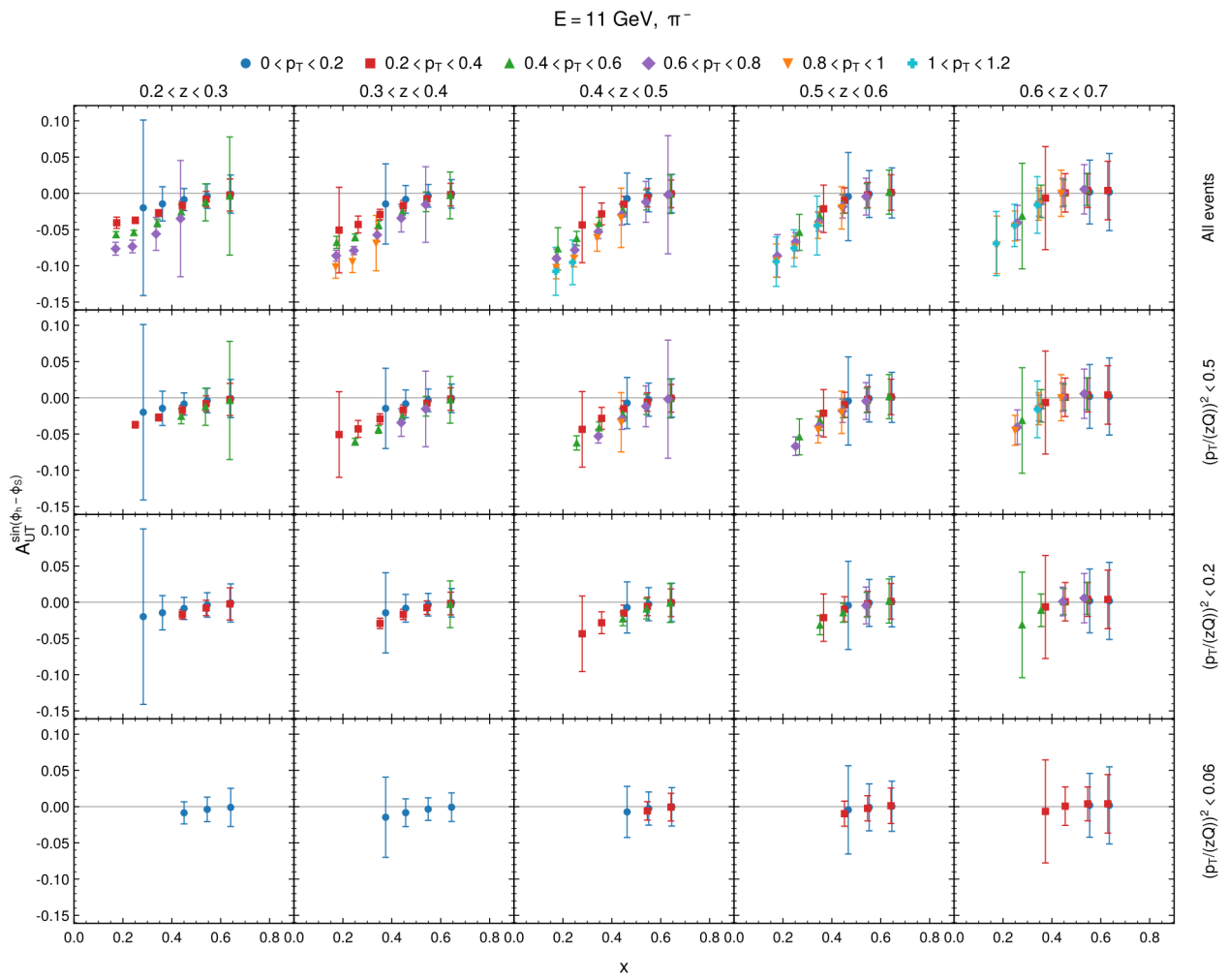
- The JAM Collaboration published "New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering": JHEP 04, 084 (2022)
- Authors define quantitative "affinity" criteria for TMD, collinear, and intermediate regions
- Results underscore the importance of high x, Q^2, which E12-09-018 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!





Fully Differential Analysis, Effects of $\frac{p_T}{zQ}$ Cuts (P. Datta)





Advantages of SBS+BB for SIDIS/TMD Physics

- Uniquely optimized for high-x/Q^2→Azimuthal coverage is *more* complete/uniform at high x, even compared to e.g., SoLID
- Independent electron and hadron arms→magnetic field and/or polarity of one arm can be changed without affecting the other
- Straight-line tracking in field-free regions; simple, reliable data analysis/well understood acceptance/resolution
- Small target holding field ~25 G → Negligible systematics of target spin flips

- High luminosity capability (up to 10^{38} $cm^{-2}s^{-1}$) of SBS+BB detectors, well matched to polarized SEOP ^{3}He targets.
- Why is neutron target SSA the only approved SBS SIDIS proposal so far?
  - For unpolarized and/or longitudinally polarized SIDIS and/or for polarized proton target SIDIS, the advantages of the BB+SBS setup over CLAS12 still exist, but are less clear/strong
  - Longitudinally polarized nSIDIS was also proposed (PR12-14-008, 30 days), but deferred due to FOM advantage over CLAS12 and/or SoLID being less clear with longitudinal polarization
- SEOP ^{3}He still provides superior neutron sensitivity compared to the deuteron

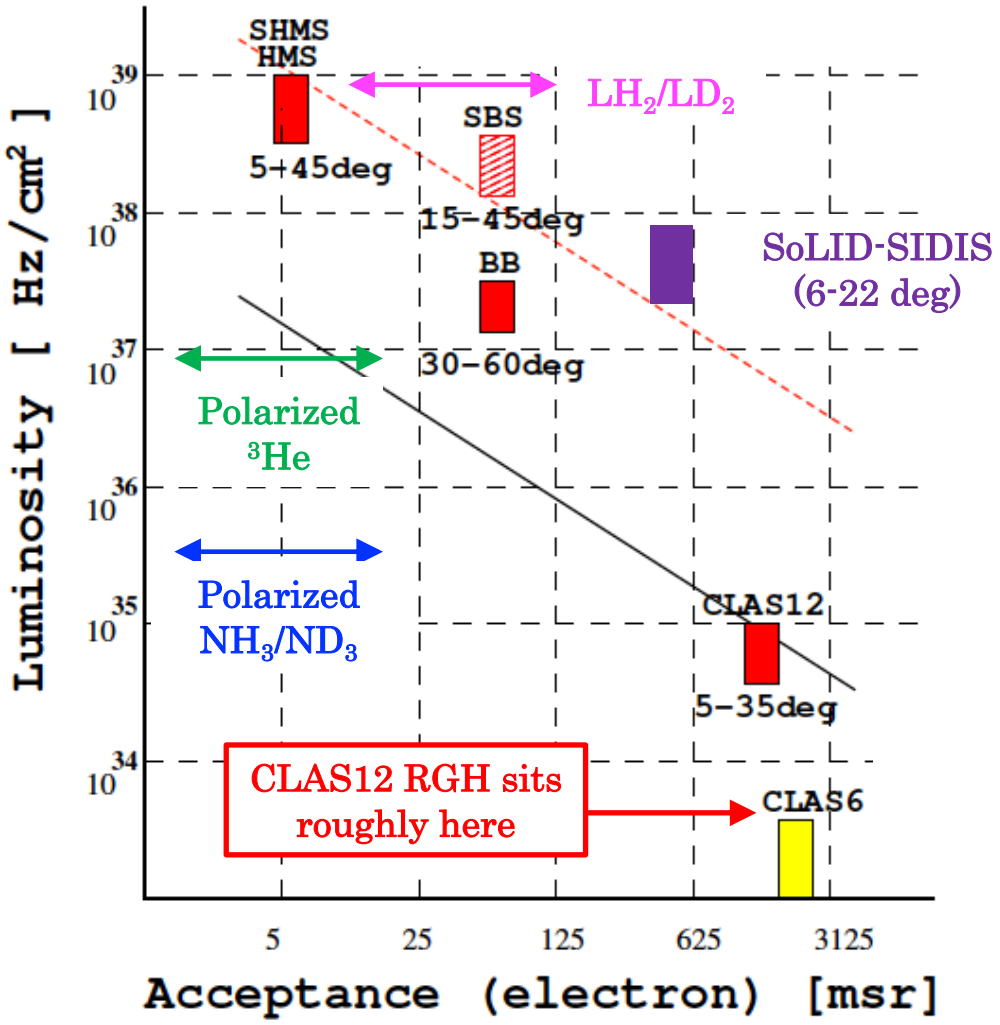
Summary of Projected Statistics and Status

TABLE I. Total projected $^3\mathrm{He}(e,e'h)X$ 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 $Q^2 > 1$ 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. 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].

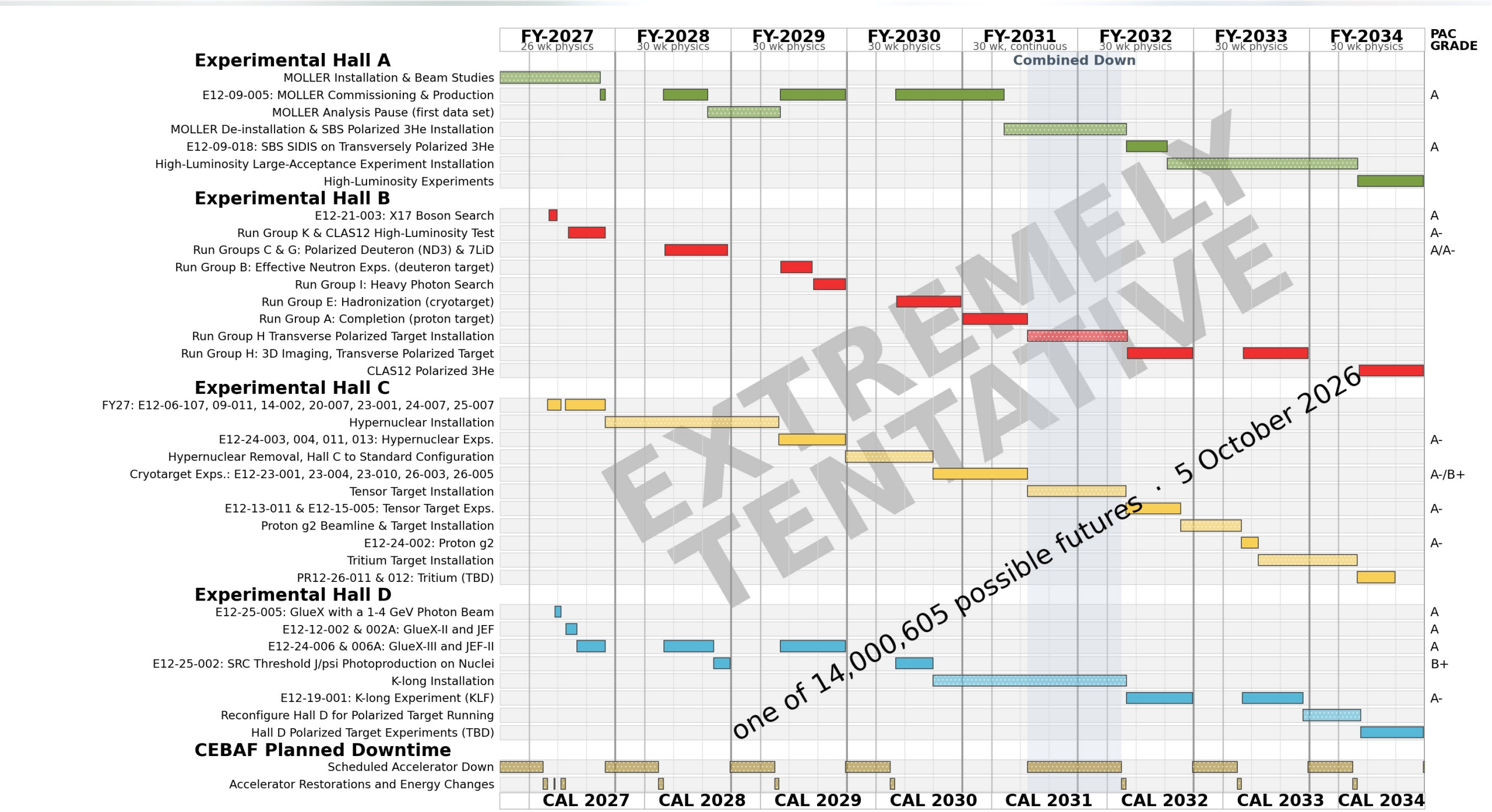
E_e (GeV)	Days	$^3\mathrm{He}(e,e'\pi^+)X$ Events/10^6	$^3\mathrm{He}(e,e'\pi^-)X$ Events/10^6	$^3\mathrm{He}(e,e'K^+)X$ Events/10^6	$^3\mathrm{He}(e,e'K^-)X$ Events/10^6	$^3\mathrm{He}(e,e'\pi^0)X$ Events/10^6
11	40	104	69	14	2.4	17
8.8	20	101	57	14	2.1	15

- Full statistical uncertainty projections by hadron (1D, 2D, 3D) and beam energy
- PAC54 Jeopardy Proposal
- 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.
- Polarized ^{3}He target efforts for SIDIS already resuming at both JLab and UVA
- Tentative Hall A schedule shows SBS returning to Hall A after MOLLER

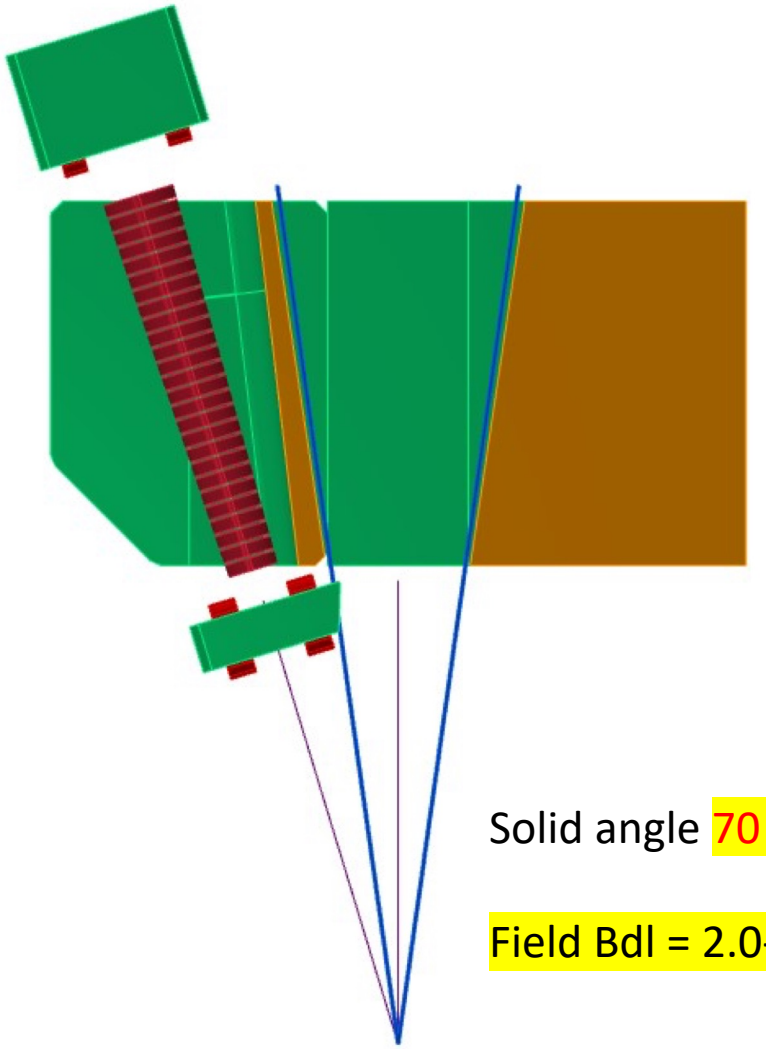
E12-09-018 uniqueness/complementarity in JLab SIDIS landscape



- Recent experimental developments:
  - EIC has progressed from CD-1 → CD-3b
  - COMPASS 2022 ^{6}LiD run: publication
  - SBS FF program completed, including GEn-II
  - CLAS12 RGH approval for proton (NH_3) target
- JLab 12 GeV has yet to weigh in on this important physics (transverse target SSA in SIDIS) despite a decade+ of running
- E12-09-018 kinematics fully complementary with SoLID-SIDIS on ^{3}He
- E12-09-018 luminosity ~2,500X CLAS12 RGH (~10-100X overall FOM in overlapping regions of x/Q^2)
  - Also neutron vs proton target
- Of all approved JLab SIDIS proposals with transversely polarized target, this experiment has (by far) the lowest cost/schedule/technical risk

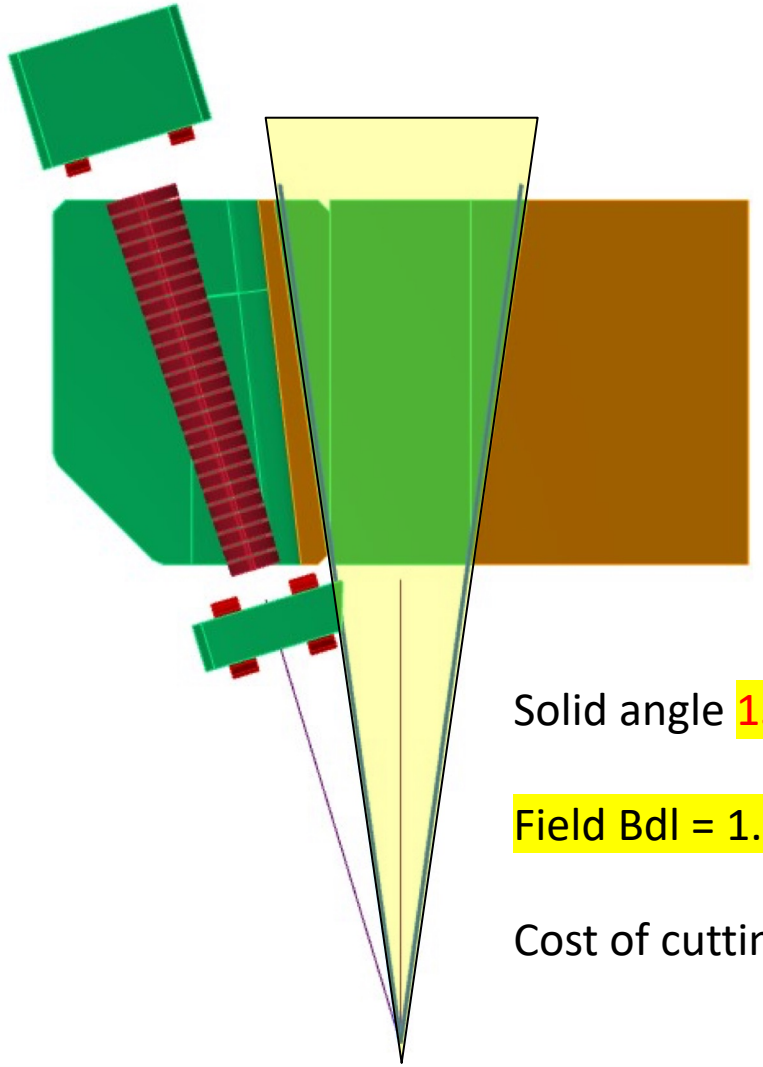

FY-2027
26 wk physics
FY-2028
30 wk physics
FY-2029
30 wk physics
FY-2030
30 wk physics
FY-2031
30 wk, continuous
FY-2032
30 wk physics
FY-2033
30 wk physics
FY-2034
30 wk physics
PAC GRADE
Combined Down
Experimental Hall A
MOLLER Installation & Beam Studies
E12-09-005: MOLLER Commissioning & Production
A
MOLLER Analysis Pause (first data set)
MOLLER De-installation & SBS Polarized 3He Installation
E12-09-018: SBS SIDIS on Transversely Polarized 3He
A
High-Luminosity Large-Acceptance Experiment Installation
High-Luminosity Experiments
Experimental Hall B
E12-21-003: X17 Boson Search
A
Run Group K & CLAS12 High-Luminosity Test
A-
Run Groups C & G: Polarized Deuteron (ND3) & 7LiD
A/A-
Run Group B: Effective Neutron Exps. (deuteron target)
Run Group I: Heavy Photon Search
Run Group E: Hadronization (cryotarget)
Run Group A: Completion (proton target)
Run Group H Transverse Polarized Target Installation
Run Group H: 3D Imaging, Transverse Polarized Target
CLAS12 Polarized 3He
Experimental Hall C
FY27: E12-06-107, 09-011, 14-002, 20-007, 23-001, 24-007, 25-007
Hypernuclear Installation
E12-24-003, 004, 011, 013: Hypernuclear Exps.
A-
Hypernuclear Removal, Hall C to Standard Configuration
Cryotarget Exps.: E12-23-001, 23-004, 23-010, 26-003, 26-005
A-/B+
Tensor Target Installation
E12-13-011 & E12-15-005: Tensor Target Exps.
A-
Proton g2 Beamline & Target Installation
E12-24-002: Proton g2
A-
Tritium Target Installation
PR12-26-011 & 012: Tritium (TBD)
Experimental Hall D
E12-25-005: GlueX with a 1-4 GeV Photon Beam
A
E12-12-002 & 002A: GlueX-II and JEF
A
E12-24-006 & 006A: GlueX-III and JEF-II
A
E12-25-002: SRC Threshold J/psi Photoproduction on Nuclei
B+
K-long Installation
E12-19-001: K-long Experiment (KLF)
A-
Reconfigure Hall D for Polarized Target Running
Hall D Polarized Target Experiments (TBD)
CEBAF Planned Downtime
Scheduled Accelerator Down
Accelerator Restorations and Energy Changes
CAL 2027
CAL 2028
CAL 2029
CAL 2030
CAL 2031
CAL 2032
CAL 2033
CAL 2034
EXTREMELY TENTATIVE
one of 14,000,605 possible futures · 5 October 2026

“DOSBS” Concept → Increase SBS solid angle and productivity



Solid angle 70 msr

Field Bdl = 2.0-2.5 T-m



Solid angle 130 msr

Field Bdl = 1.6 T-m

Cost of cutting ~ $50k

- Low-cost option to effectively double SBS solid angle
- 1.6 T-m BdL is more than adequate for SIDIS physics
- Still need detectors to actually cover larger acceptance → not currently under serious consideration for E12-09-018

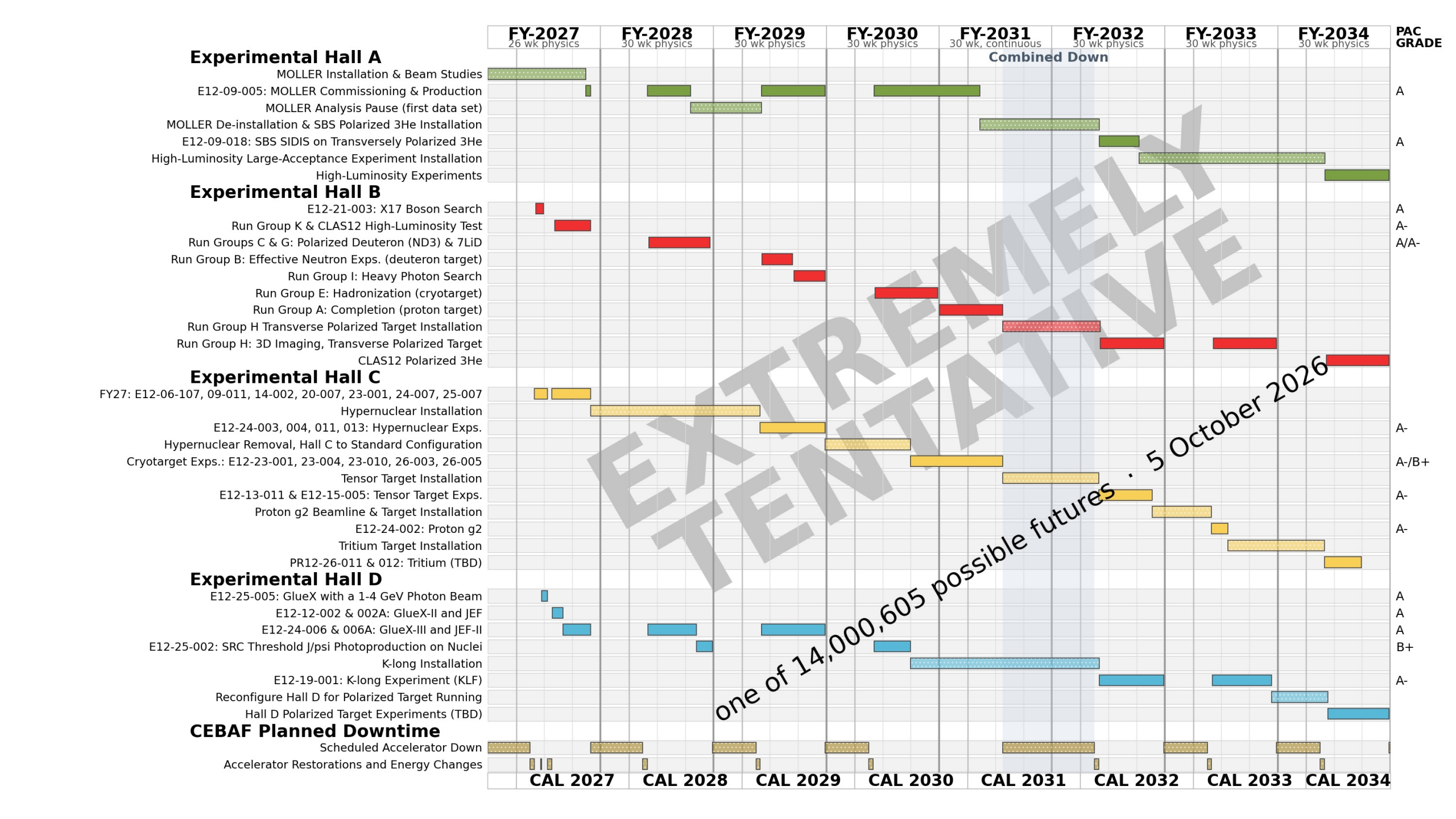
Summary and Conclusions

- After DOE approval of the SBS+BB construction for the FF program, it was quickly recognized that this apparatus would be well suited to SIDIS/TMD physics, *especially* transverse *neutron* target SSA
  - E12-09-018 first proposed to PAC34, fully approved PAC38
  - PAC49 jeopardy re-approval
  - PAC54 second jeopardy re-approval and upgrade to "A" rating
- Successful completion of the form factor program, with detectors operated under *more* difficult conditions than E12-09-018, and GEn-II, the polarized ^{3}He target for which achieved ~95% of SIDIS FOM goal, conclusively demonstrates technical feasibility

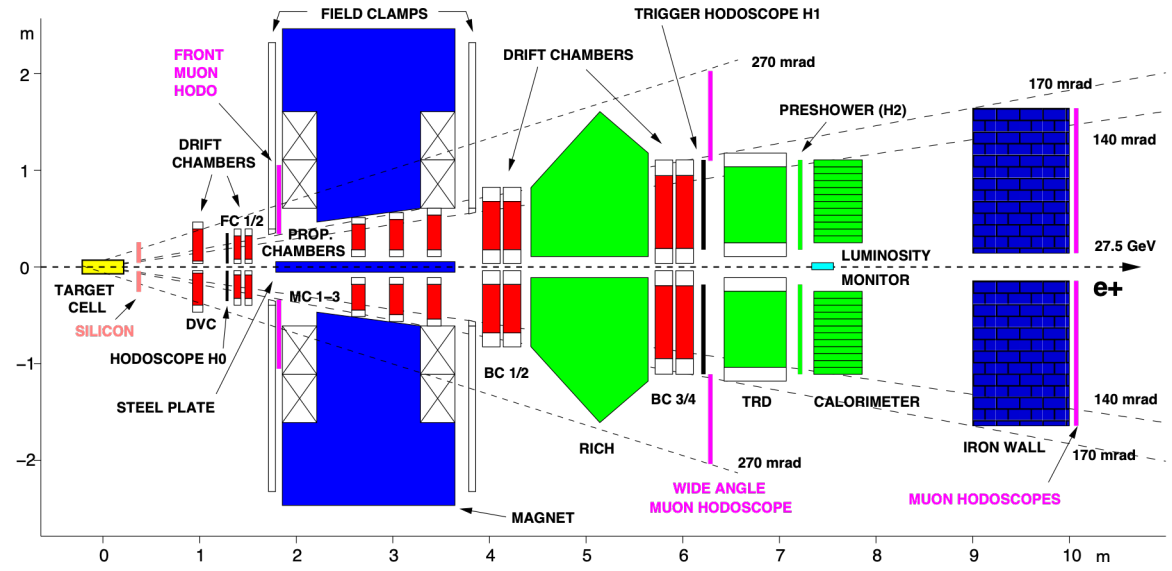
PAC54 Final Report

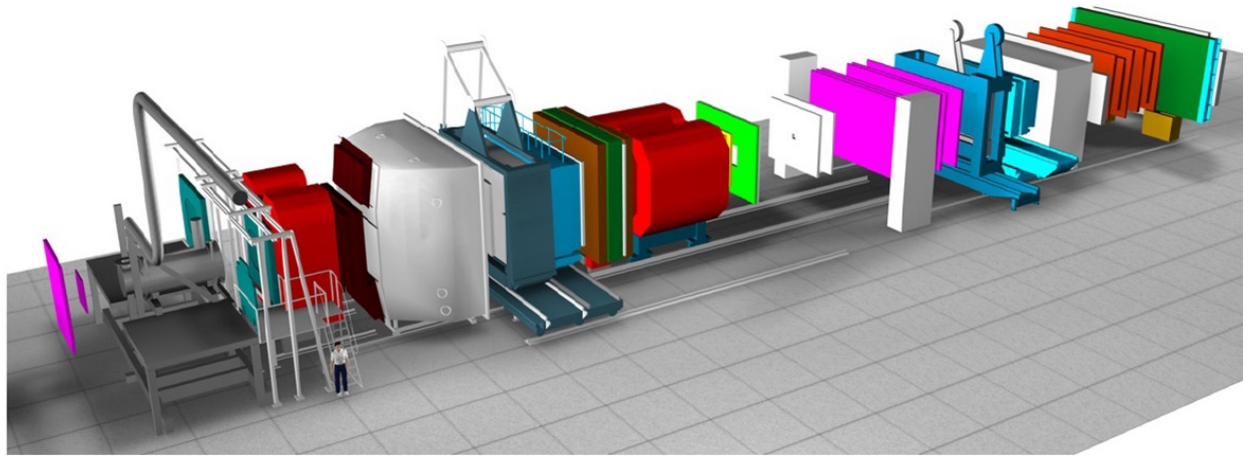
Summary: *E12-09-018 remains scientifically well motivated and technically mature. Its neutron sensitivity, high luminosity, and high-x/high-Q2 coverage continue to justify the experiment as an important component of the JLab SIDIS/TMD program. PAC recommends maintaining the approved beam time and increases the scientific rating to A.*

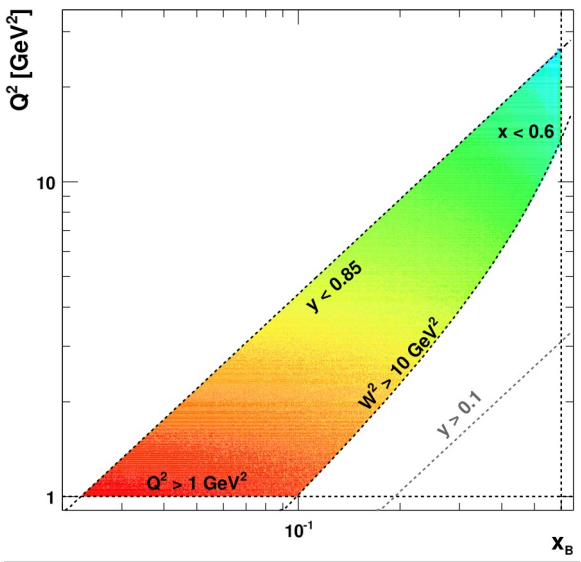
Backups


FY-2027
26 wk physics
FY-2028
30 wk physics
FY-2029
30 wk physics
FY-2030
30 wk physics
FY-2031
30 wk, continuous
FY-2032
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A
High-Luminosity Large-Acceptance Experiment Installation
High-Luminosity Experiments
Experimental Hall B
E12-21-003: X17 Boson Search
A
Run Group K & CLAS12 High-Luminosity Test
A-
Run Groups C & G: Polarized Deuteron (ND3) & 7LiD
A/A-
Run Group B: Effective Neutron Exps. (deuteron target)
Run Group I: Heavy Photon Search
Run Group E: Hadronization (cryotarget)
Run Group A: Completion (proton target)
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A-
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A-/B+
Tensor Target Installation
E12-13-011 & E12-15-005: Tensor Target Exps.
A-
Proton g2 Beamline & Target Installation
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A-
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Experimental Hall D
E12-25-005: GlueX with a 1-4 GeV Photon Beam
A
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A
E12-24-006 & 006A: GlueX-III and JEF-II
A
E12-25-002: SRC Threshold J/psi Photoproduction on Nuclei
B+
K-long Installation
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EXTREMELY TENTATIVE
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HERMES@DESY and COMPASS@CERN Experiments

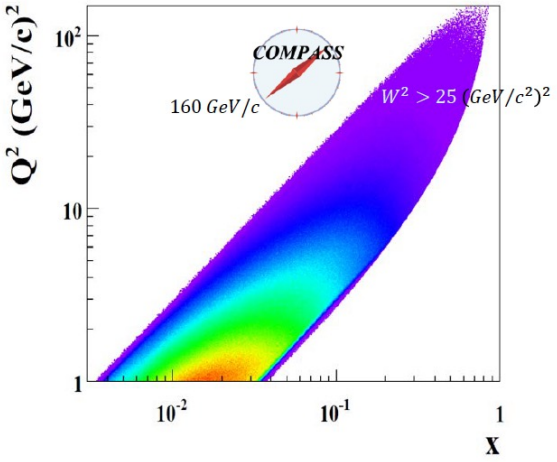






HERMES@DESY

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



COMPASS@CERN

- SIDIS program: 160 GeV polarized muon beam produced using CERN SPS on polarized ^{6}LiD and NH_3 targets (and also unpolarized LH_2, LD_2, etc.)
- Average luminosity (lepton-nucleon):
  $\approx 2\times10^{32}\ cm^{-2}s^{-1}$
- 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

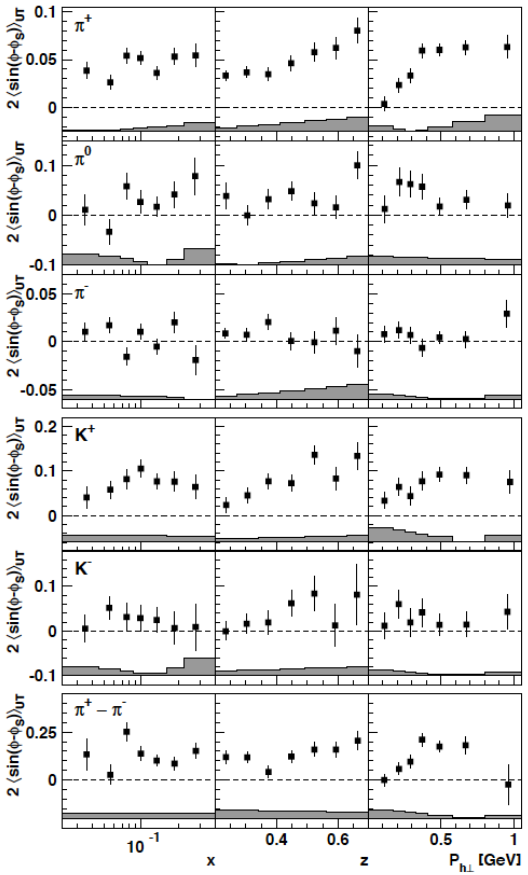


FIG. 1: Sivers amplitudes for pions, charged kaons, and the pion-difference asymmetry (as denoted in the panels) as functions of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the target-polarization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

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

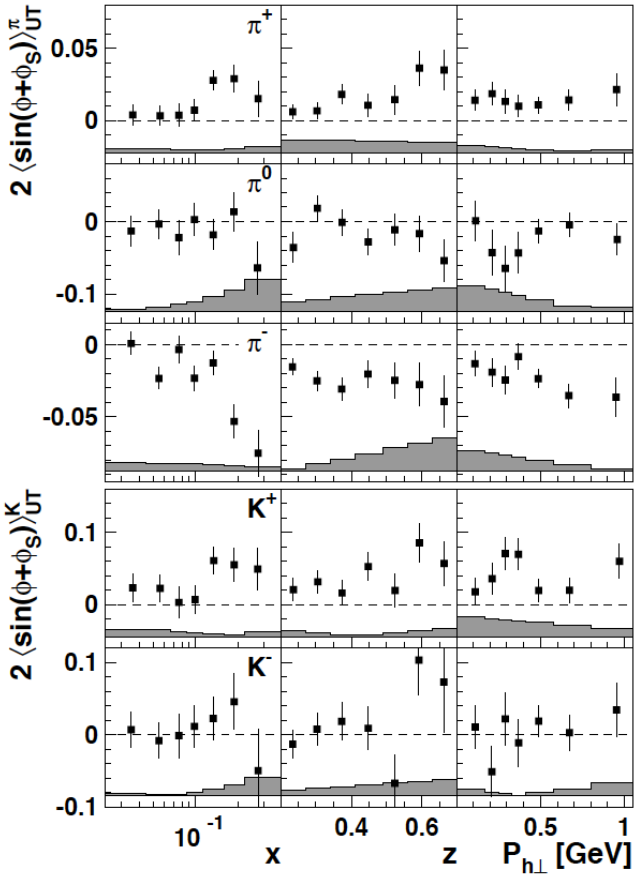


Fig. 2. Collins amplitudes for pions and charged kaons as a function of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the accuracy in the measurement of the target polarization.

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

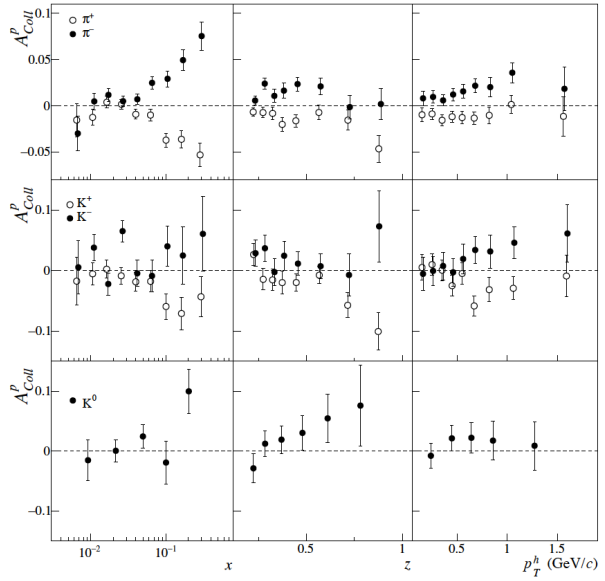


Fig. 6: The Collins asymmetries for charged pions (top), charged kaons (middle) and neutral kaons (bottom) on proton as a function of x, z and p_T^h.

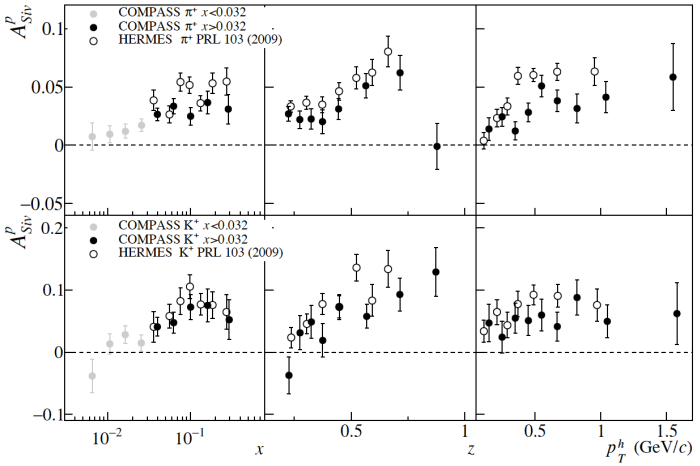


Fig. 11: The Sivers asymmetries for positive pions (top) and kaons (bottom) on proton as a function of x, z and p_T^h, requiring $x > 0.032$. The asymmetries are compared to HERMES results.

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

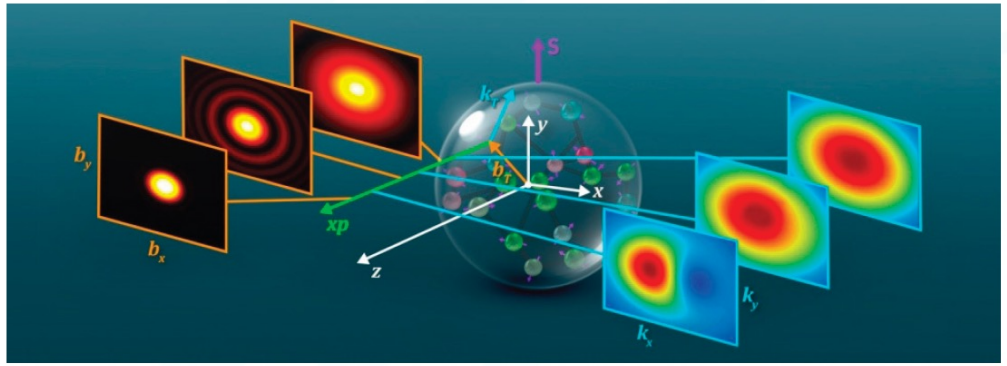


Figure 3.3. Parton images for a spin-up proton (magenta arrow) in slices of parton fractional momentum, x, for the quarks and gluons in a colliding hadron. *The images on the left give a spatial distribution in transverse location, while the images on the right picture the transverse momentum distribution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

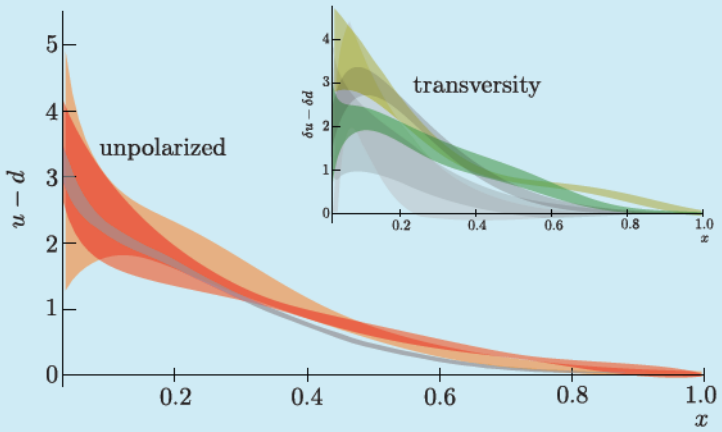


Figure 1. Unpolarized and transversity proton PDFs computed with lattice QCD (colored curves showing different pioneering approaches) compared to global fits to experimental data (grey curves) [S6].

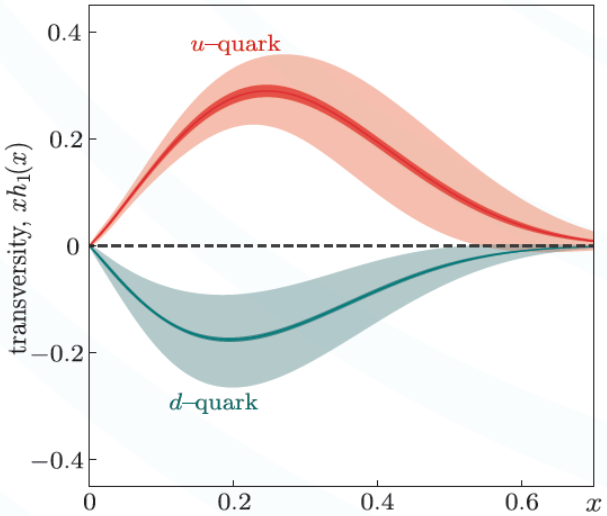
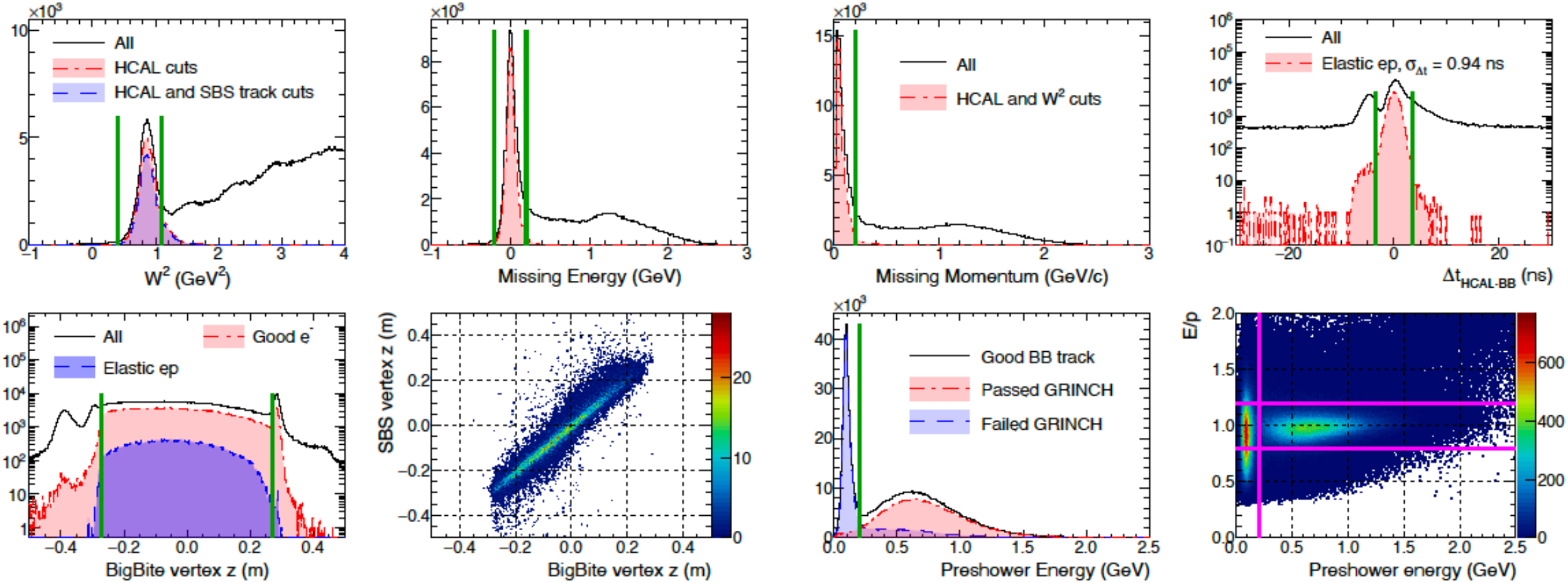


Figure 3.4. The up (red) and down (blue) quark transversity spin-spin correlation in the proton. *The wide uncertainty bands show the latest results based on a global fit to world data while the narrower, darker bands show the expected improvement by the SoLID detector [4].*

- 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!

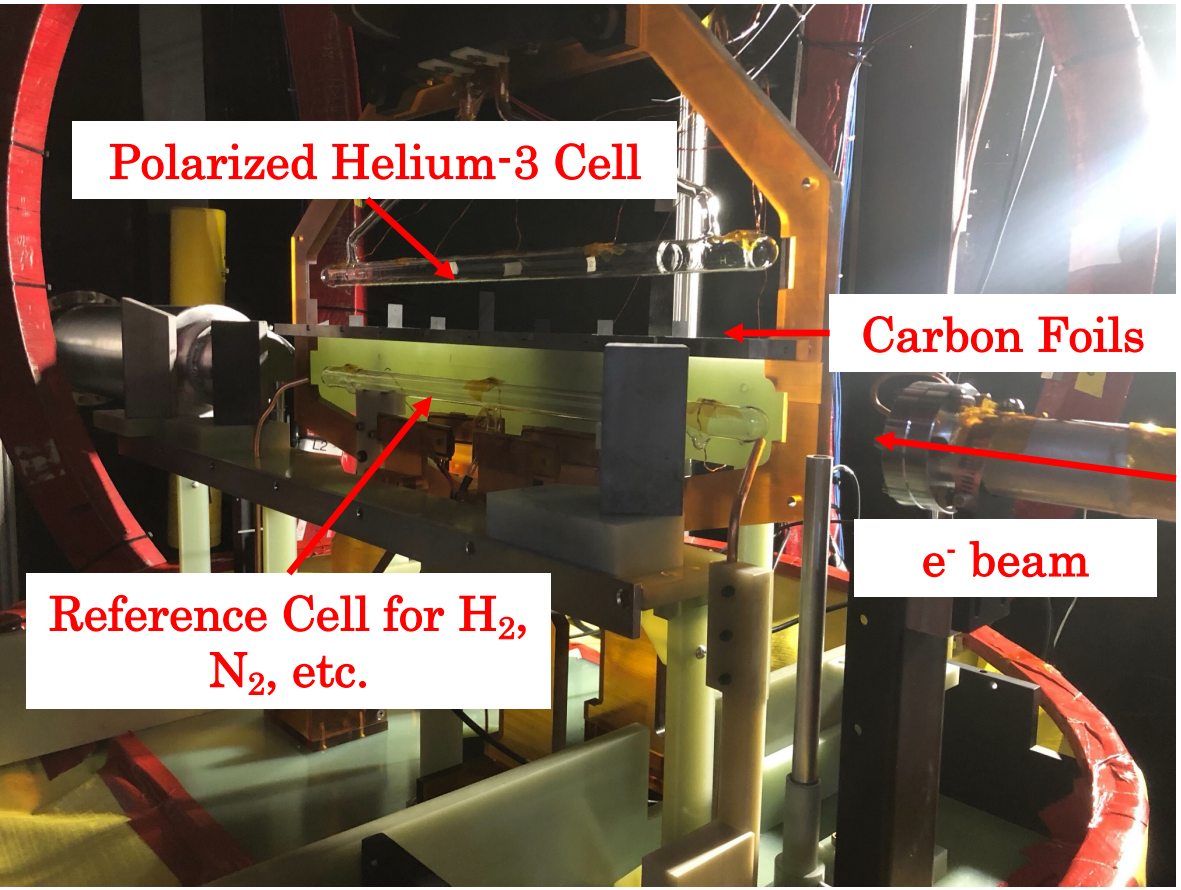
SBS and BigBite Detector Performance during GEn-II

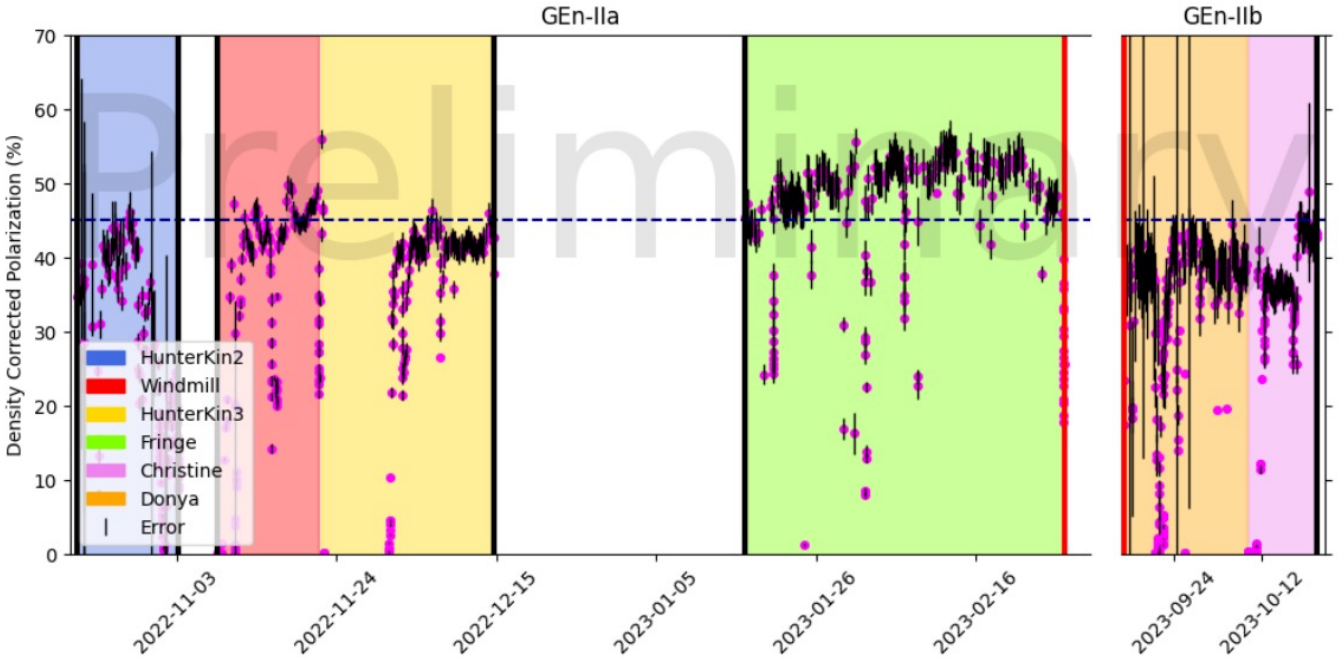


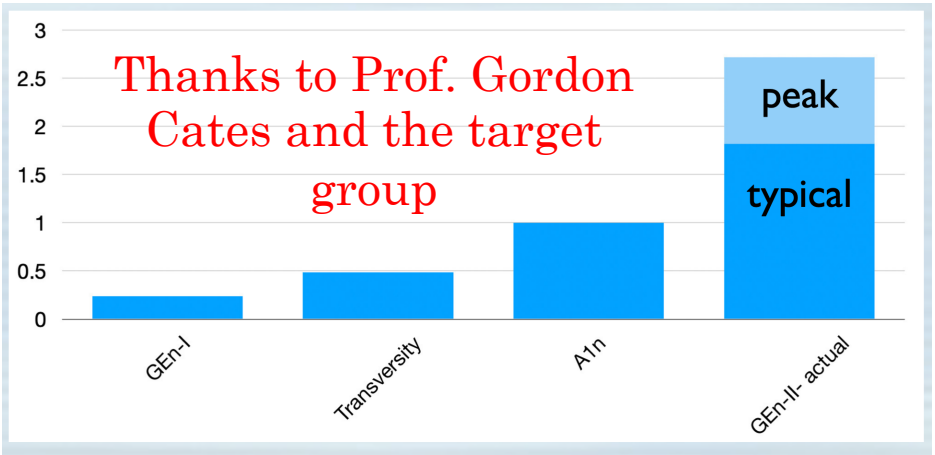
Elastic ep scattering at $Q^2 = 3.0\ \mathrm{GeV}^2$ w/H_2 "reference cell" during GEn-II

- 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

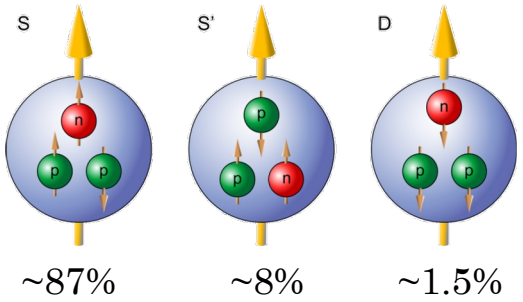






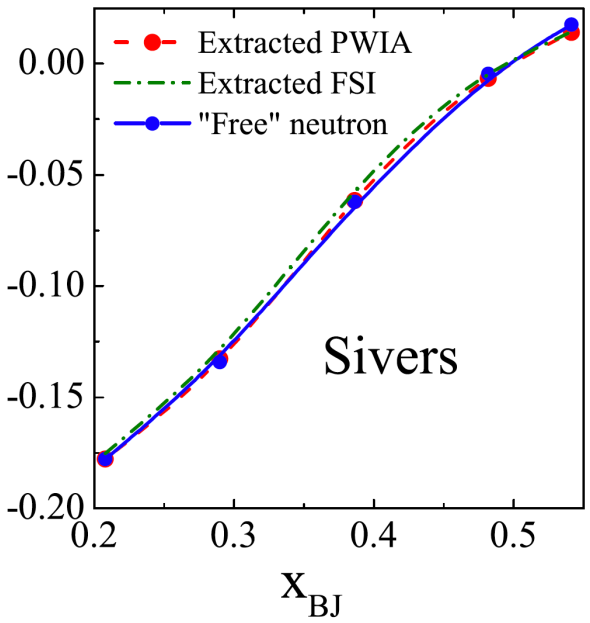
- Above, left: Inside the target enclosure
- Above, right: preliminary target polarization results
- Below, right: estimated FOM compared to previous experiments

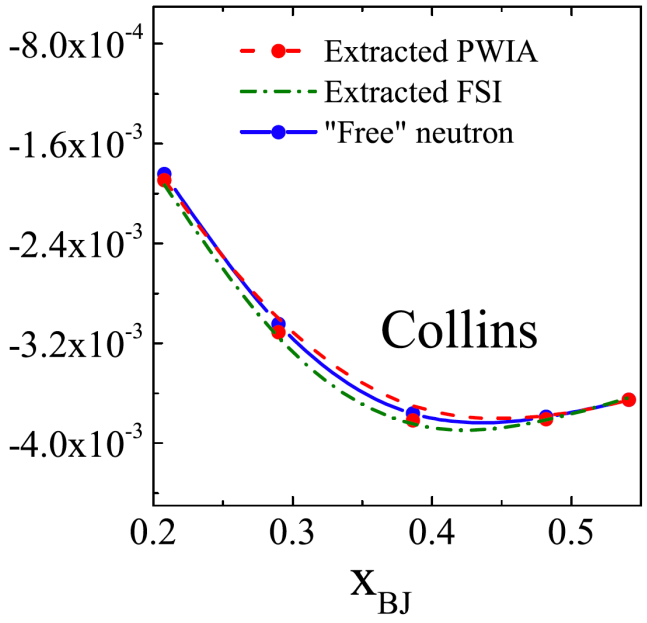
Helium-3 as Effective Polarized Neutron Target



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

Effective polarization approximation for DIS/SIDIS on ^{3}He:
Scopetta, Phys. Rev. D 75, 054005 (2007)

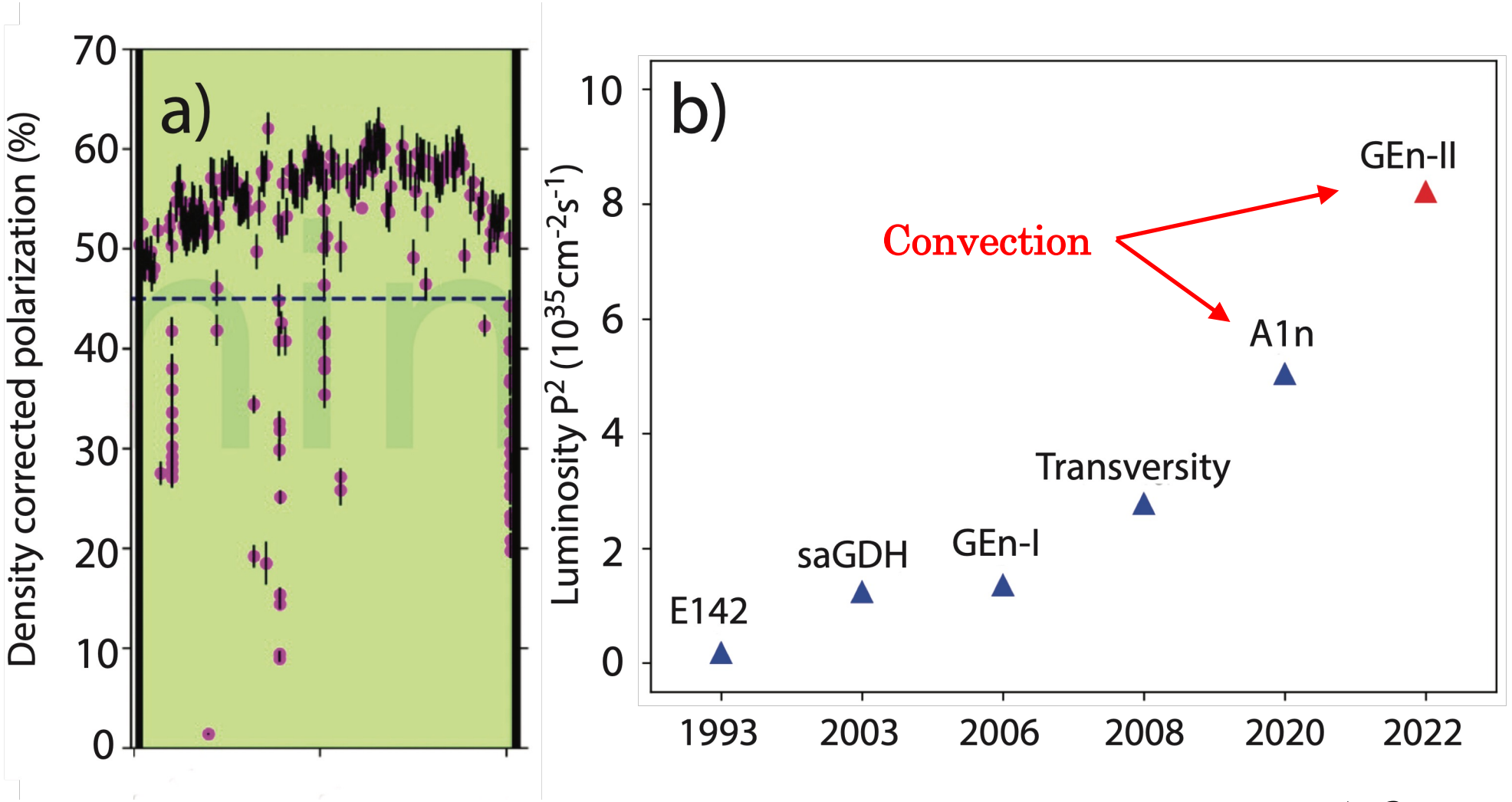




Del Dotto *et al.*, Phys. Rev. C 96, 065203 (2017)

- Effects of nuclear FSI on extraction of neutron Collins and Sivers effects from SIDIS on ^{3}He 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} cm^{-2} s^{-1})
  - Small holding field → negligible effect of target spin flips on acceptance/efficiency for SSA extraction

Polarized Helium-3 Target Performance During GEn-II

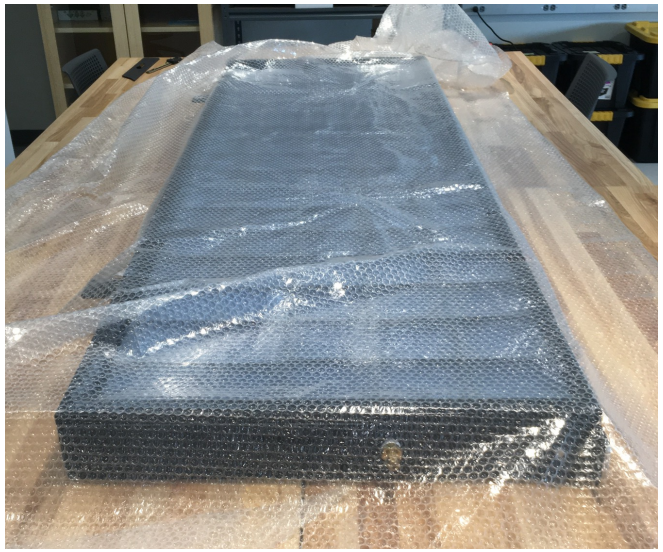


Best-performing target cell "Fringe" achieved ~95% of SIDIS FOM ($P_{tgt}^2 I_{beam}$) goal

HERMES→SBS RICH: Hardware Status



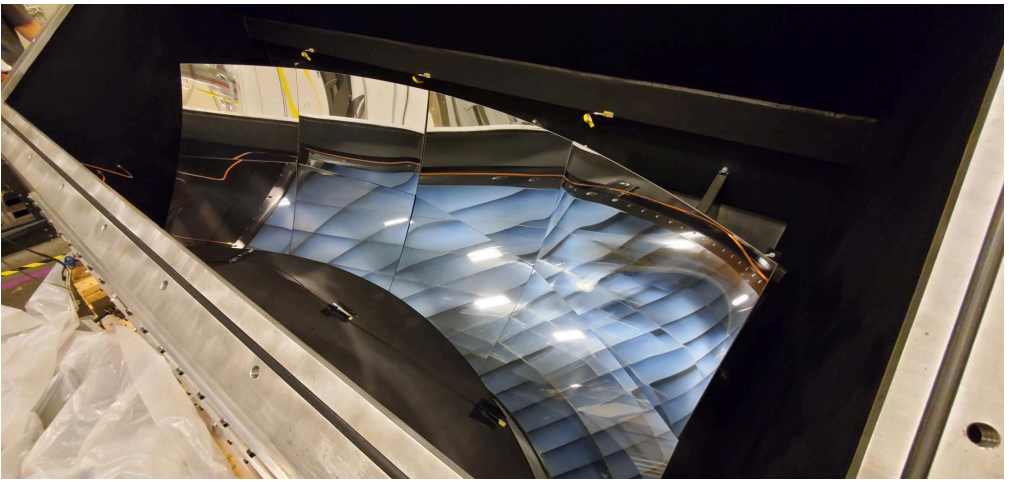
RICH detector at Jlab



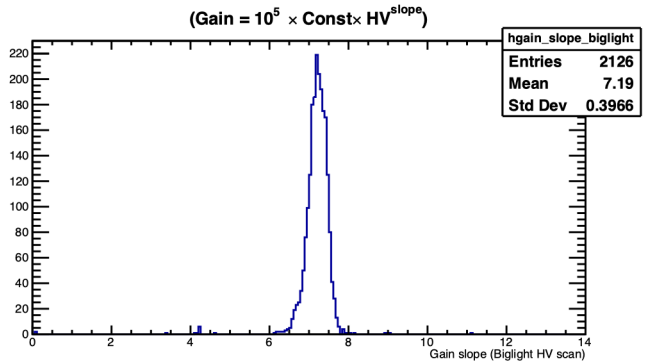
”Spare” aerogel wall @UConn

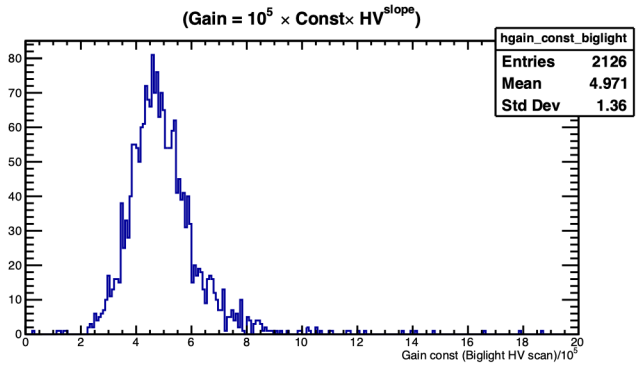
RICH PMT testing summary

- 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



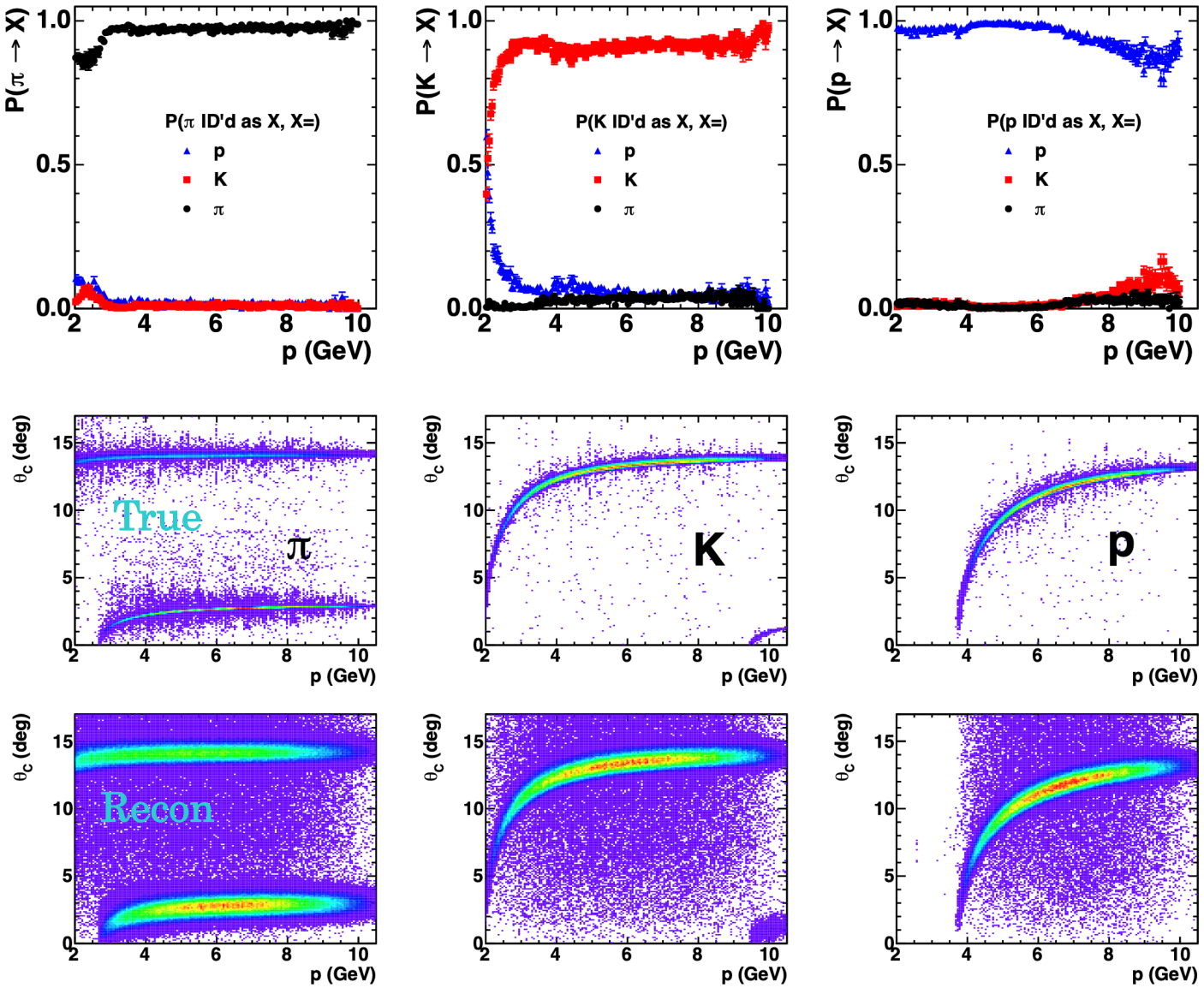
Inspecting RICH mirrors

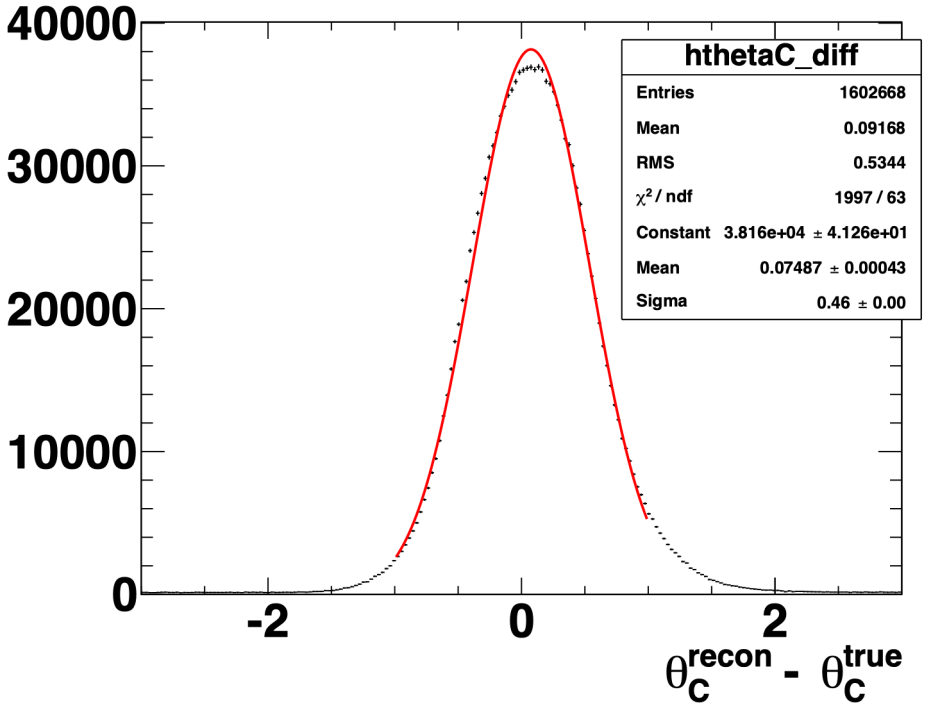




RICH PMT gain slope and “constant” = (gain at 1 kV)/10^5

Simulated RICH performance in SBS

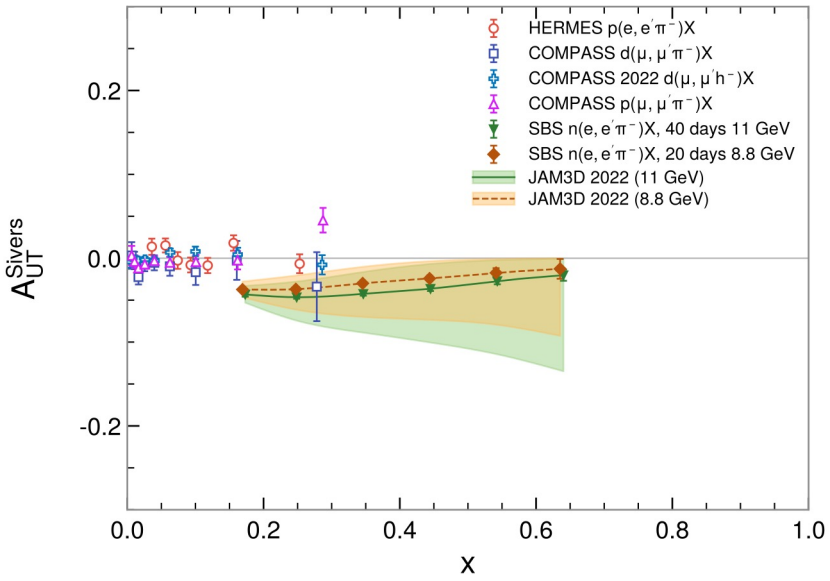


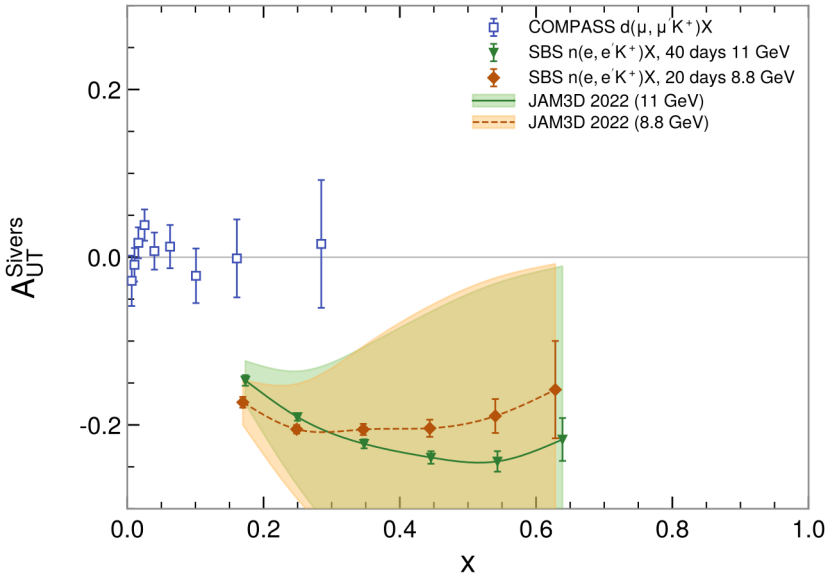


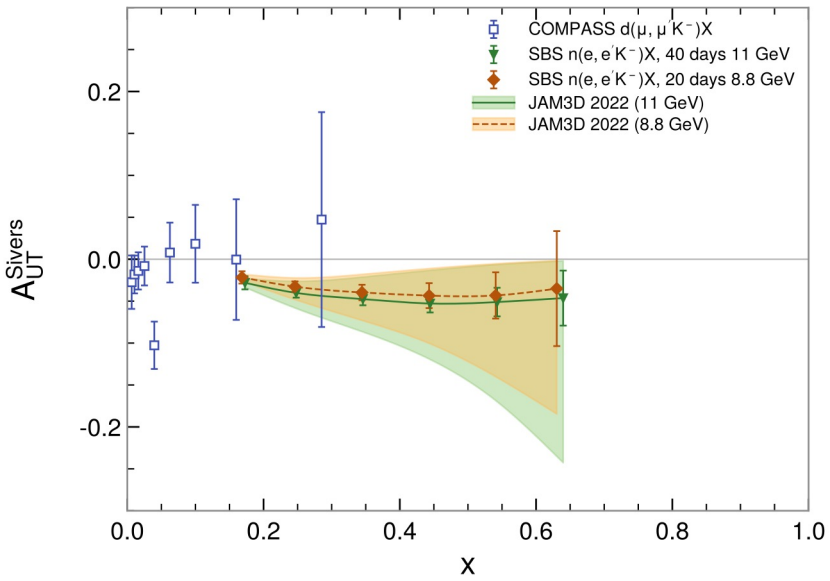
More details of RICH simulations here

- 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 Sivers projections: other hadrons







- Projected Sivers 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 Sivers.

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

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

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

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

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

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

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

- 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 $eq \to eq$

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

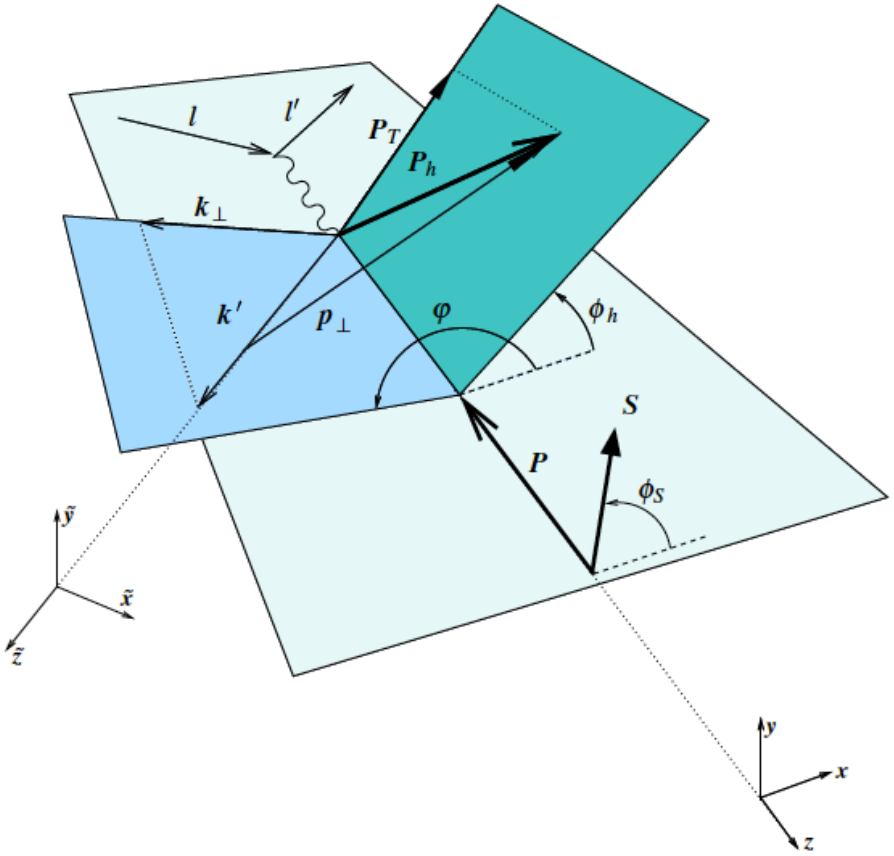
Where do the azimuthal dependences come from for transverse target SSAs?

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

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

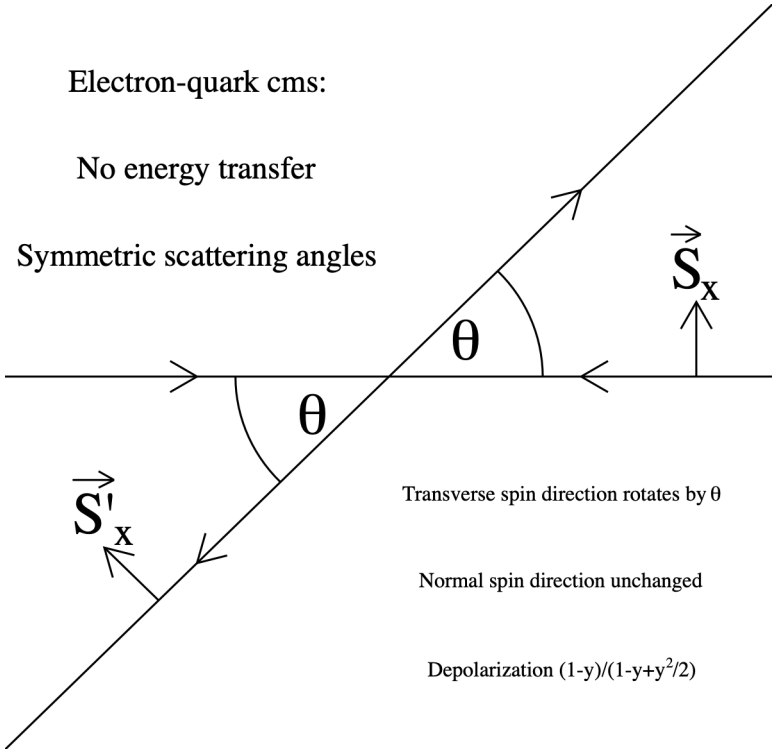
• The Collins effect is due to the left-right asymmetry in the fragmentation of a transversely polarized quark.
• The observable asymmetry results from the convolution of the transversity distribution and the Collins (spin-dependent) fragmentation function:

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

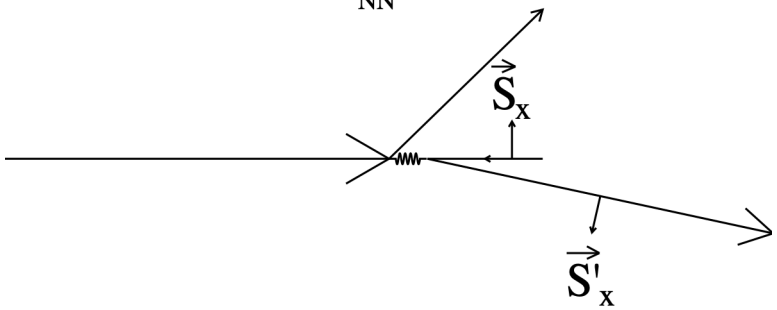


• The in-plane component of quark transverse polarization must flip in order to absorb the transversely polarized virtual photon (angular momentum conservation) → Sign of ϕ_S is reversed in observable asymmetry

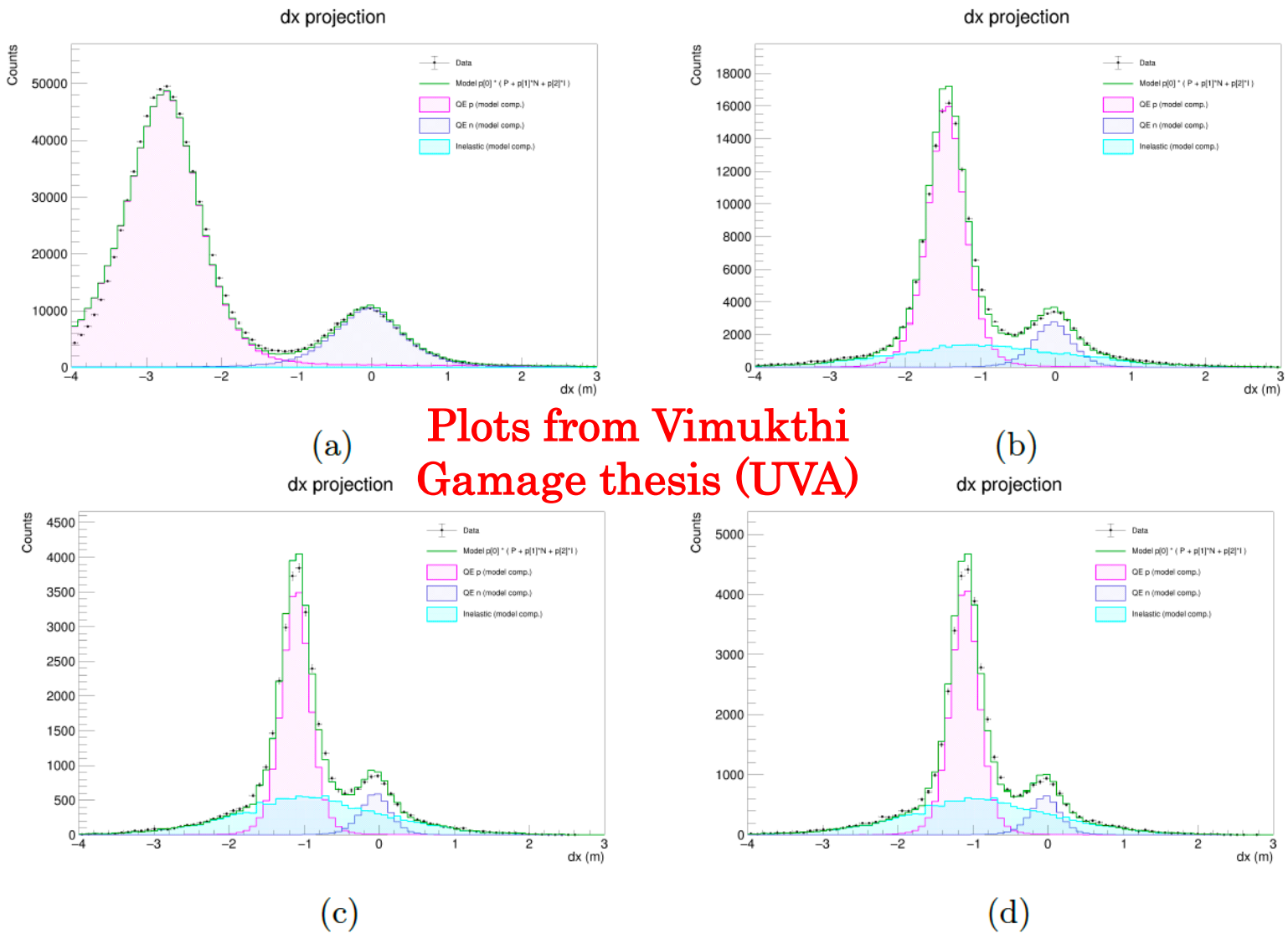
Transverse spin dynamics in eq→eq



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!***



Plots from Vimukthi Gamage thesis (UVA)

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

- Quasi-elastic event selection and inelastic background contamination estimates
- Kin. 2 → $Q^2 = 3.0$ GeV^2
- Kin. 3 → $Q^2 = 6.8$ GeV^2
- Kin. 4a → $Q^2 = 9.8$ GeV^2 (spring 2023 running)
- Kin. 4b → $Q^2 = 9.8$ 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

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

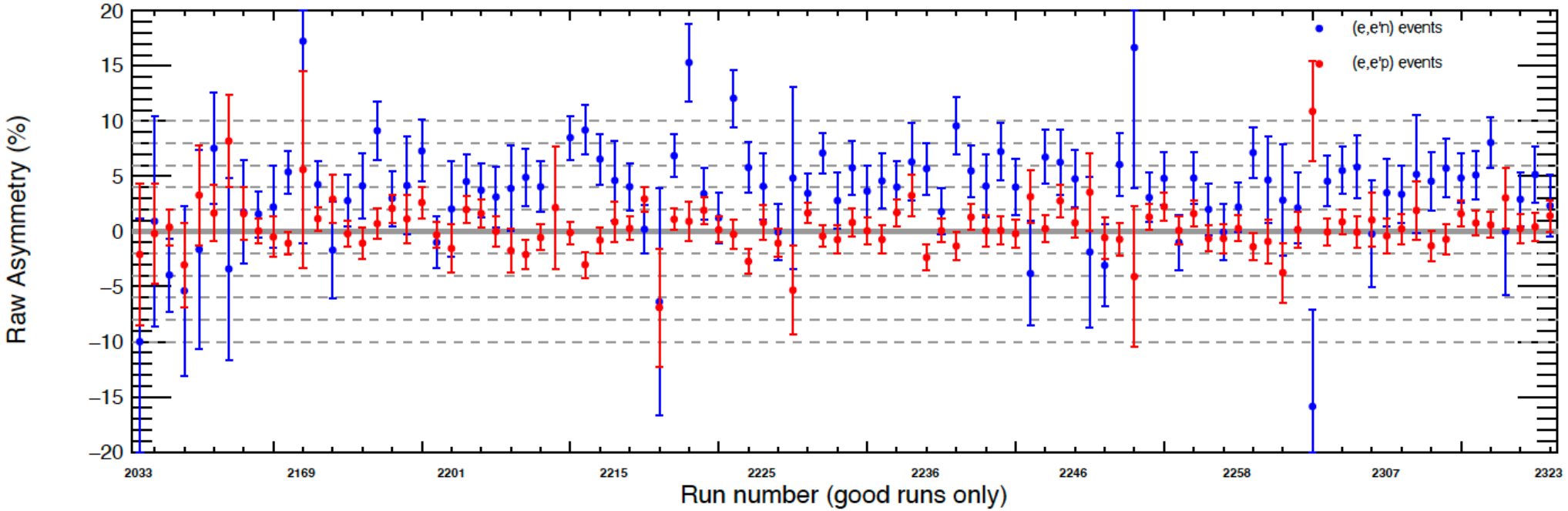
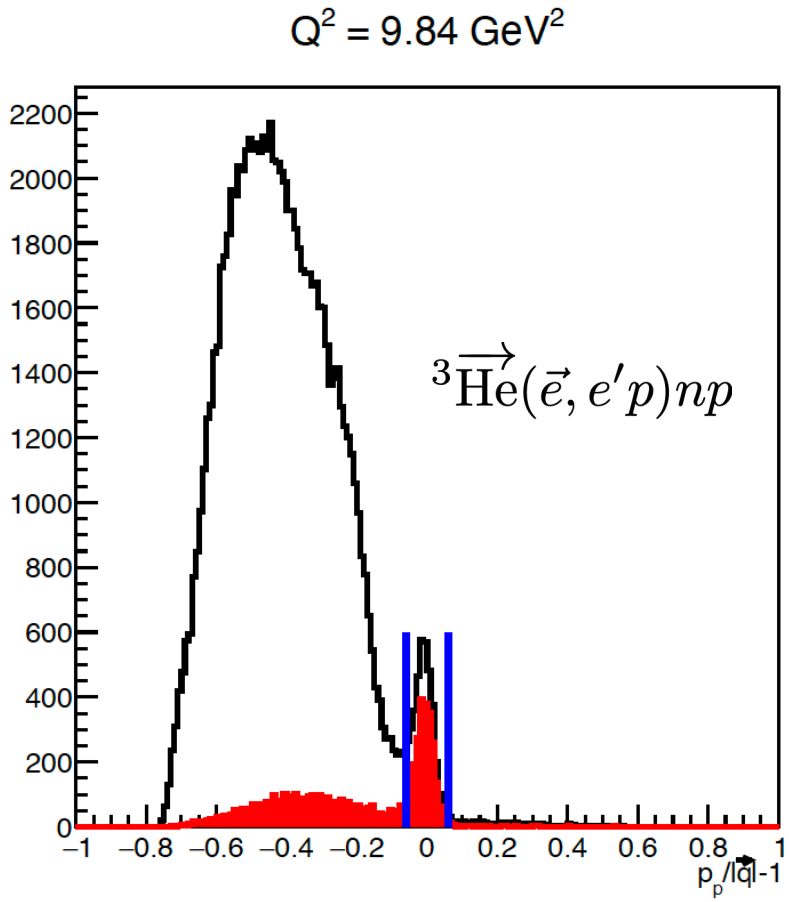
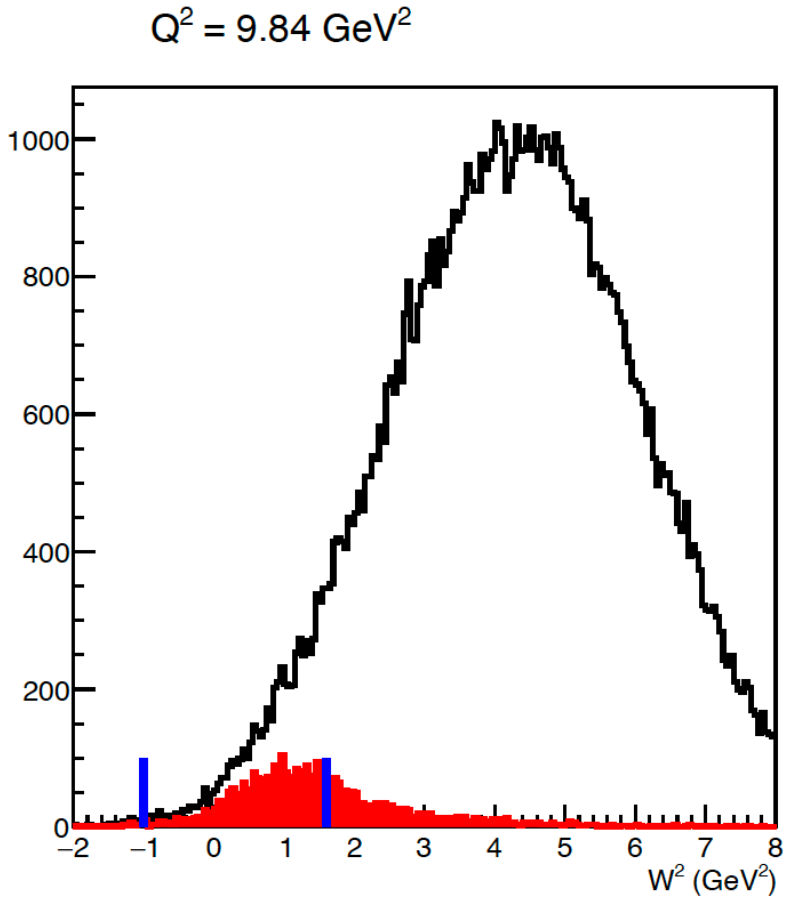


Figure 5.14: Run by run asymmetry for Kin2 after accounting for the half-wave plate and accelerator settings. Certain runs are excluded from the analysis due to various quality issues including helicity measurement malfunctions.

- Neutron (proton) quasi-elastic asymmetry "large" ("small") as expected for ^{3}He target

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

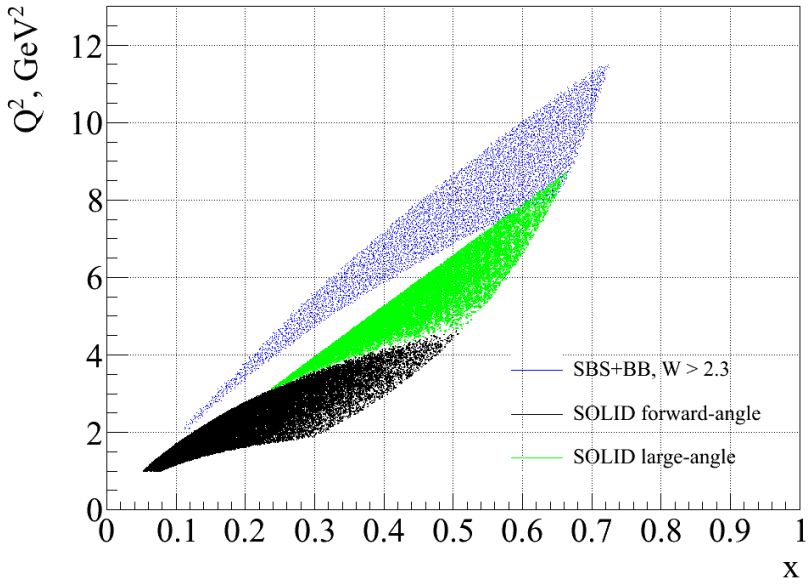


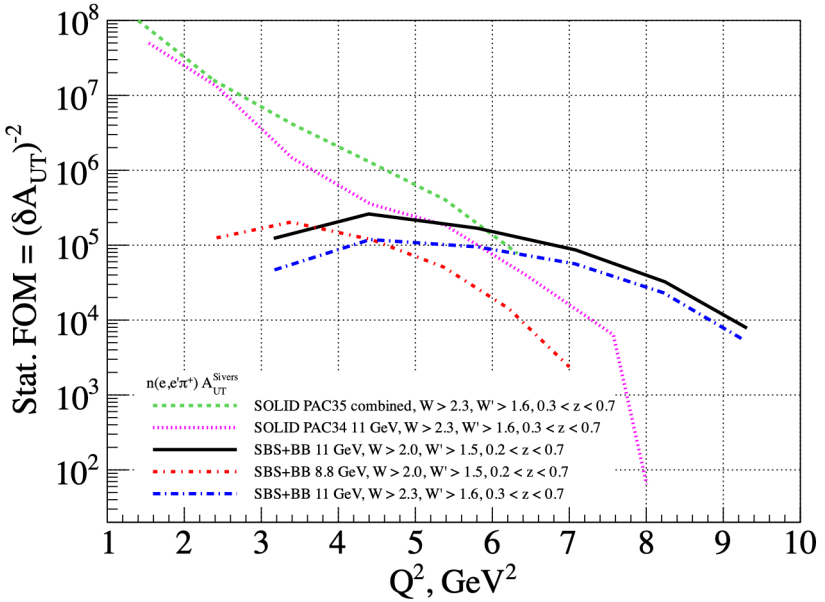


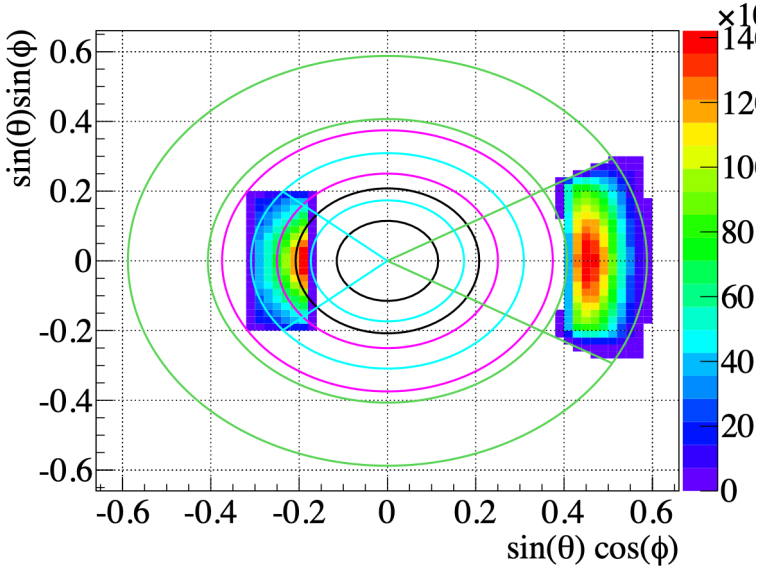
- Left: fractional deviation of proton momentum from magnitude of $\vec{q}$-(three) vector from BigBite, **without** and **with** W^2 **cut**
- Right: W^2, **without** and **with cut** on $\frac{p_p}{|\vec{q}|} - 1$

- **This is Helium-3 data with a positively charged track in SBS, at the highest Q^2**
- (Surprisingly?) clean (quasi-)elastic ^{3}He(e,e'p)np event selection with full kinematic reconstruction in both arms (missing energy, missing momentum, etc)→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

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 ~6.6-12°***
  - ***SOLID large-angle: θ range ~14.5-22°***
  - ***SBS: θ range ~10-18°, ϕ ±40°***
  - ***BigBite: θ range ~24-36°, ϕ ±30°***

Unpolarized TMD global fitting—Pavia 2017

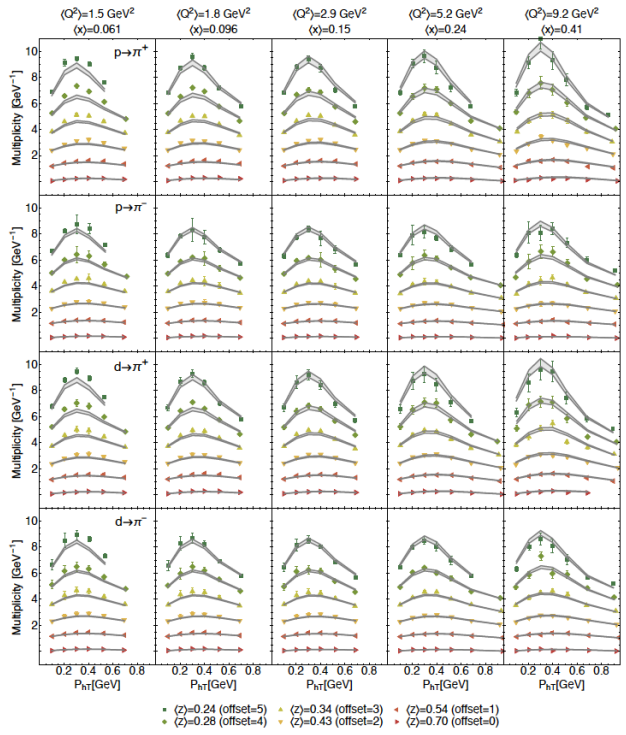


FIG. 3: HERMES multiplicities for production of pions off a proton and a deuteron for different $\langle x \rangle$, $\langle z \rangle$, and $\langle Q^2 \rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. For clarity, each $\langle z \rangle$ bin has been shifted by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

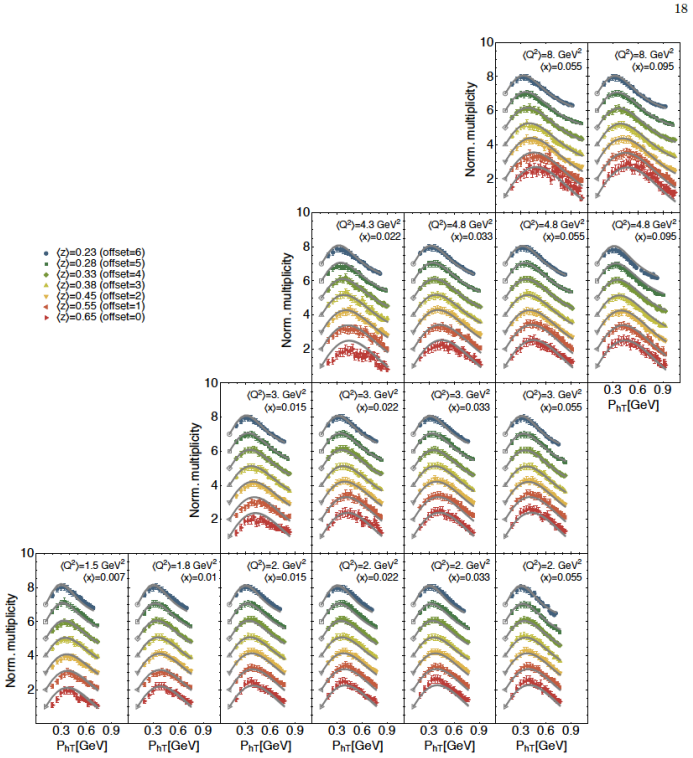


FIG. 6: COMPASS multiplicities for production of positive hadrons (π^+) off a deuteron for different $\langle x \rangle$, $\langle z \rangle$, and $\langle Q^2 \rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. Multiplicities are normalized to the first bin in P_{hT} 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.

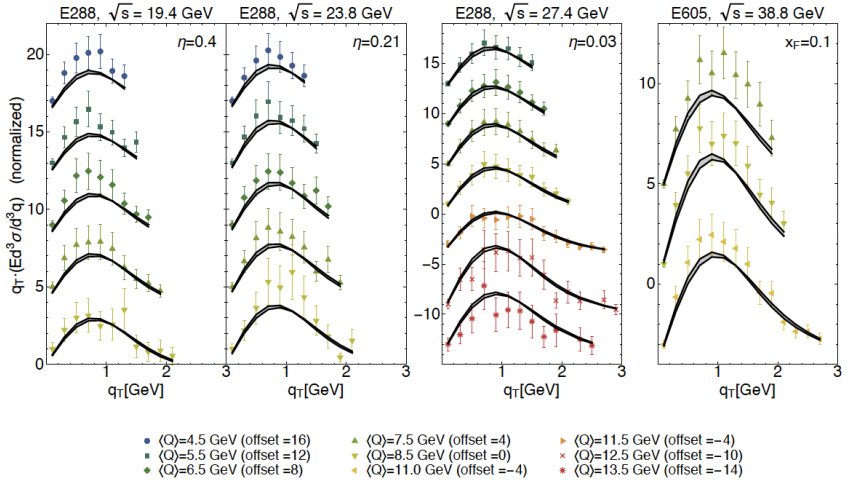


FIG. 7: Drell–Yan differential cross section for different experiments and different values of $\sqrt{s}$ and for different $\langle Q \rangle$ bins. For clarity, each $\langle Q \rangle$ bin has been normalized (the first data point has been set always equal to 1) and then shifted by an offset indicated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

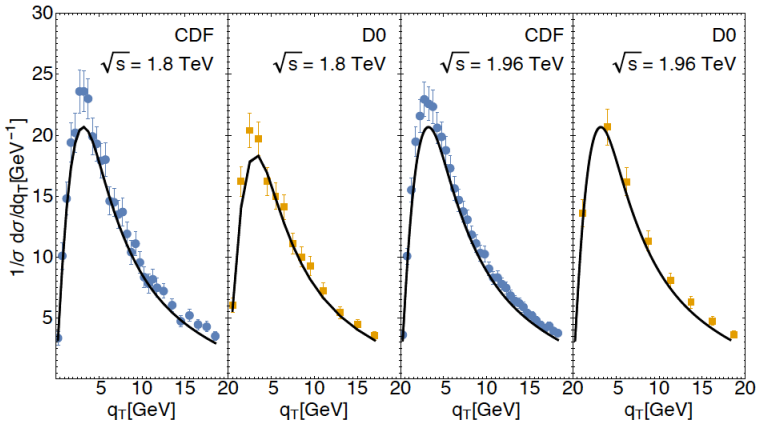
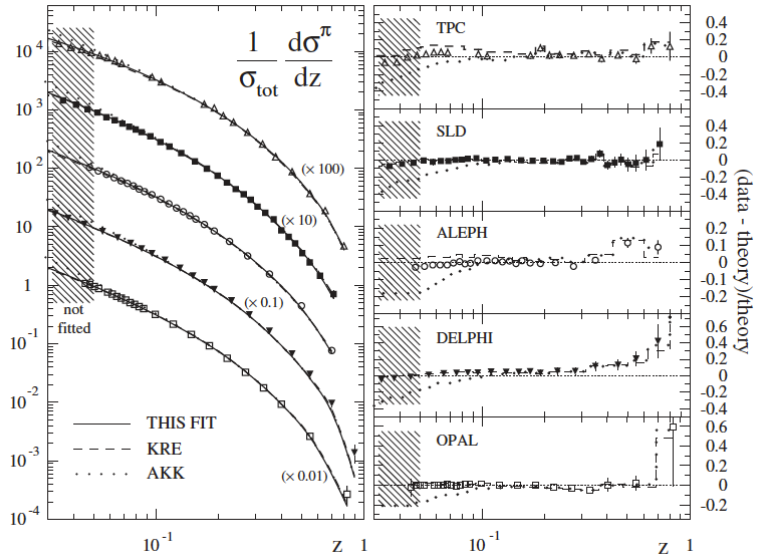
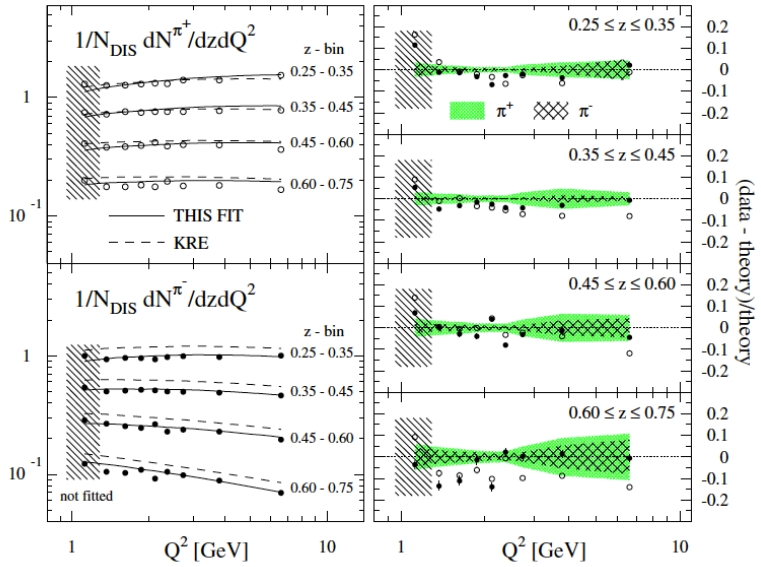


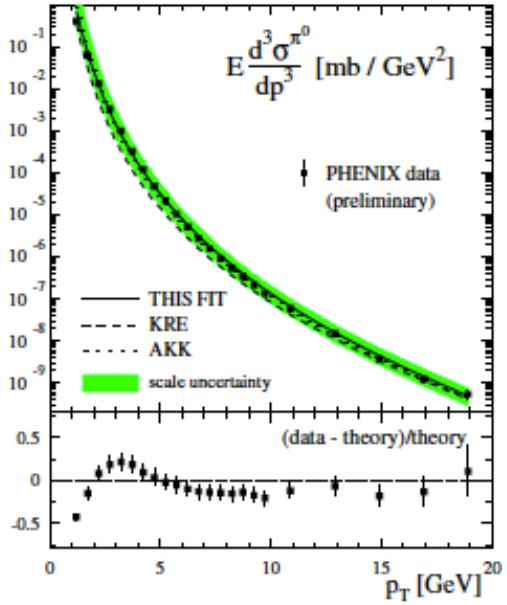
FIG. 8: Cross section differential with respect to the transverse momentum q_T of a Z boson produced from $p\bar{p}$ collisions at Tevatron. The four panels refer to different experiments (CDF and D0) with two different values for the center-of-mass energy ($\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 1.96$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

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

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

- E = 11 GeV, 40 days

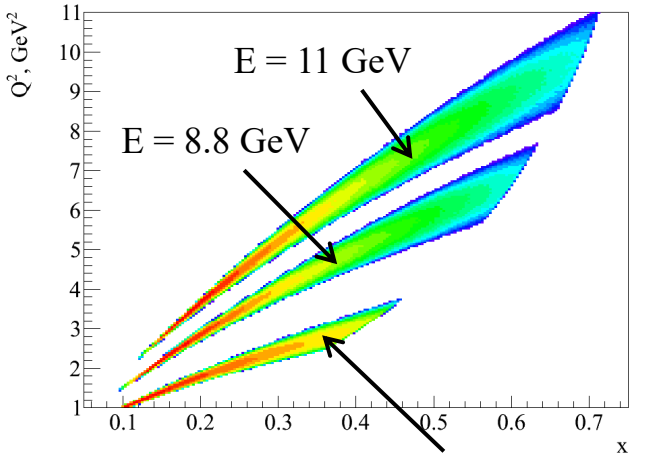
$$A_{UT}^{\sin(\phi_h-\phi_S)} \text{ for } \mathbf{n}(e,e'\pi^+)X:$$

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

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

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

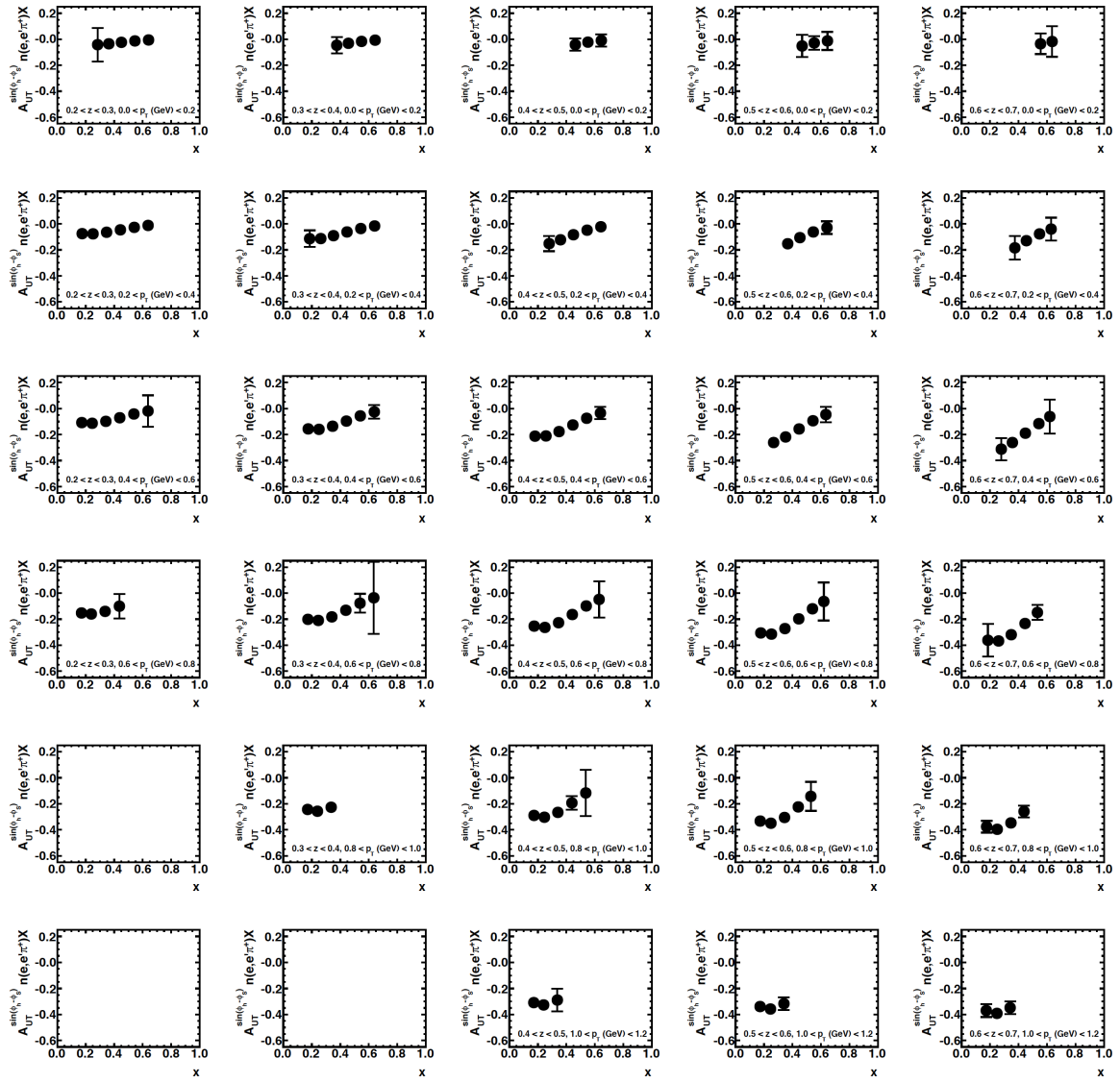
- "4D" with Q^2 dependence from 20 days at 8.8 GeV:



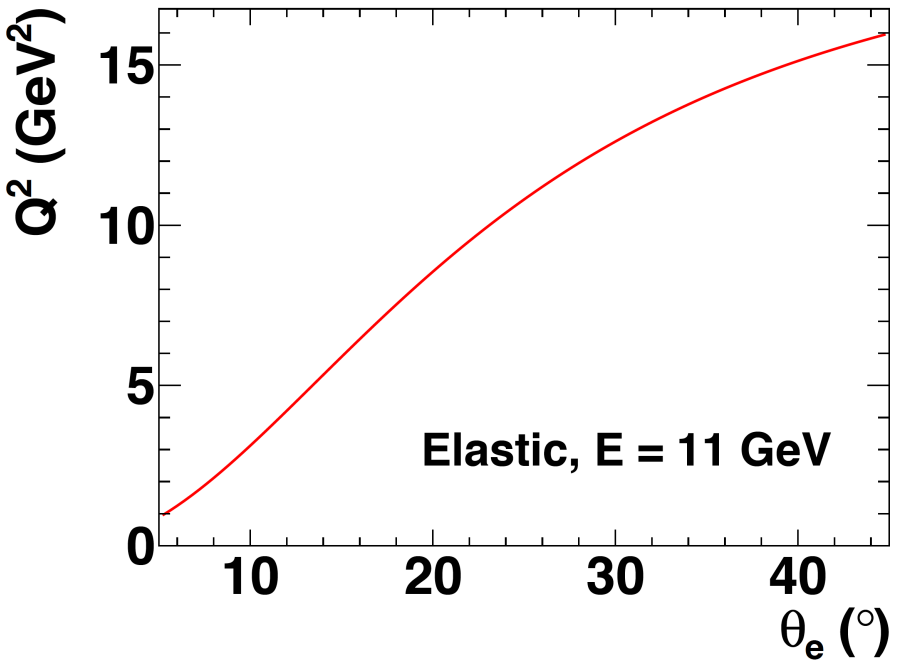
E = 5.9 GeV (E06-010 Hall A)

Increasing z →

← *Increasing p_T*



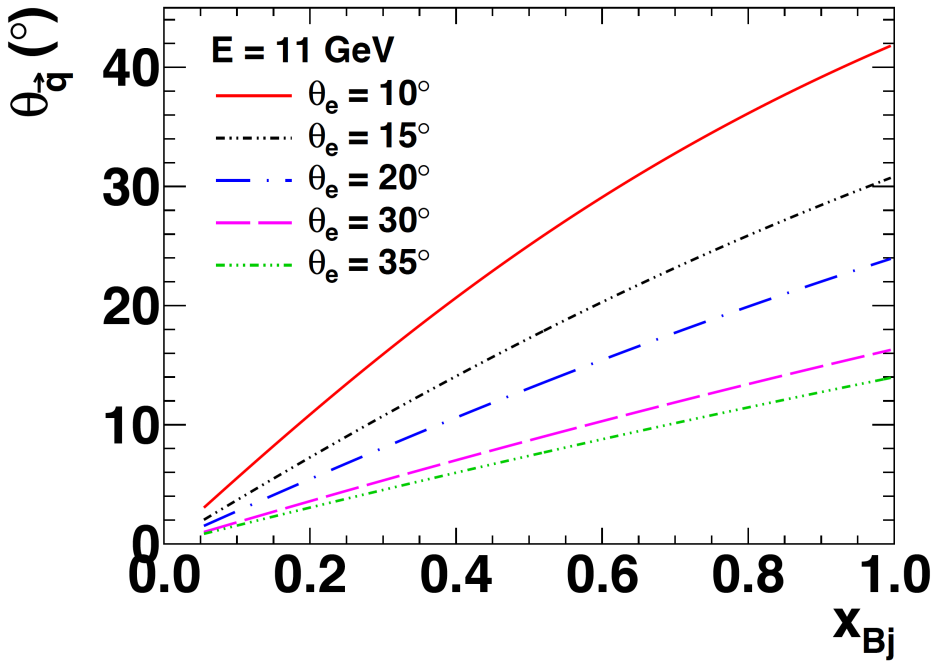
Toward high-Q^2: Fixed-target Electron Scattering Kinematics @11 GeV



- 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 **q**
- *Partonic interpretation of electron scattering data is accessible at large Q^2 → 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: $^3He/n(e,e'\pi^{\pm})X$ TSSA/TDSA

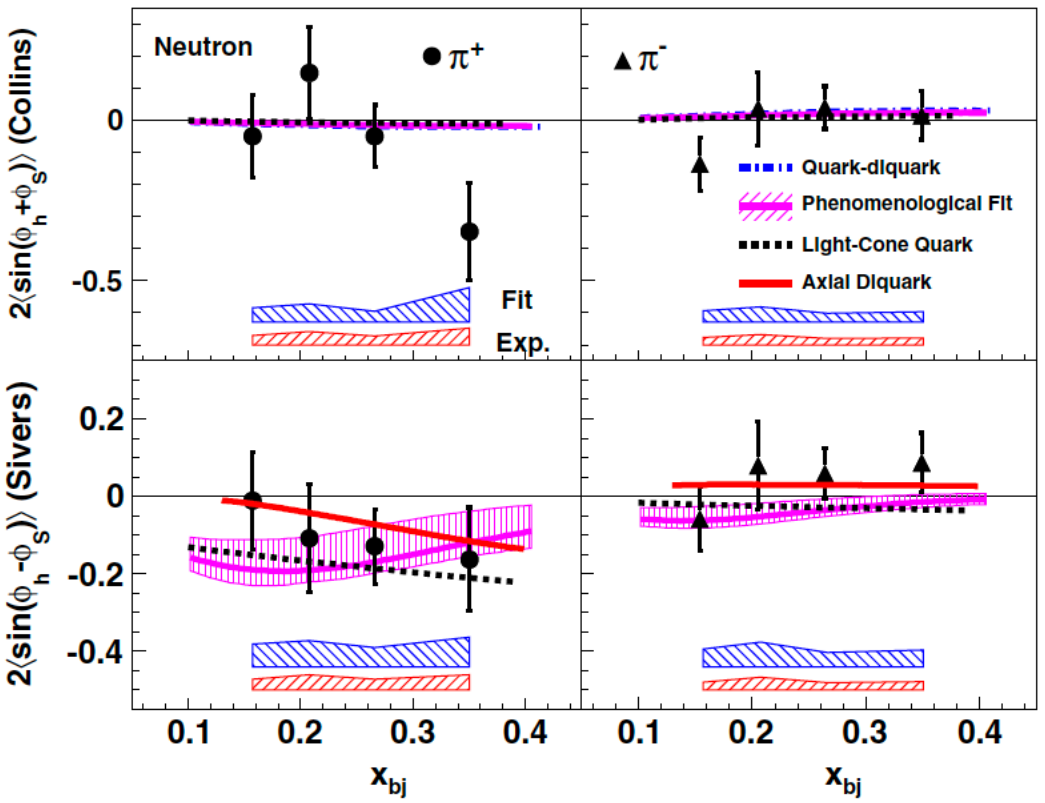


FIG. 2 (color online). The extracted neutron Collins and Sivers moments with uncertainty bands for both π^+ and π^- electroproduction. See text for details.

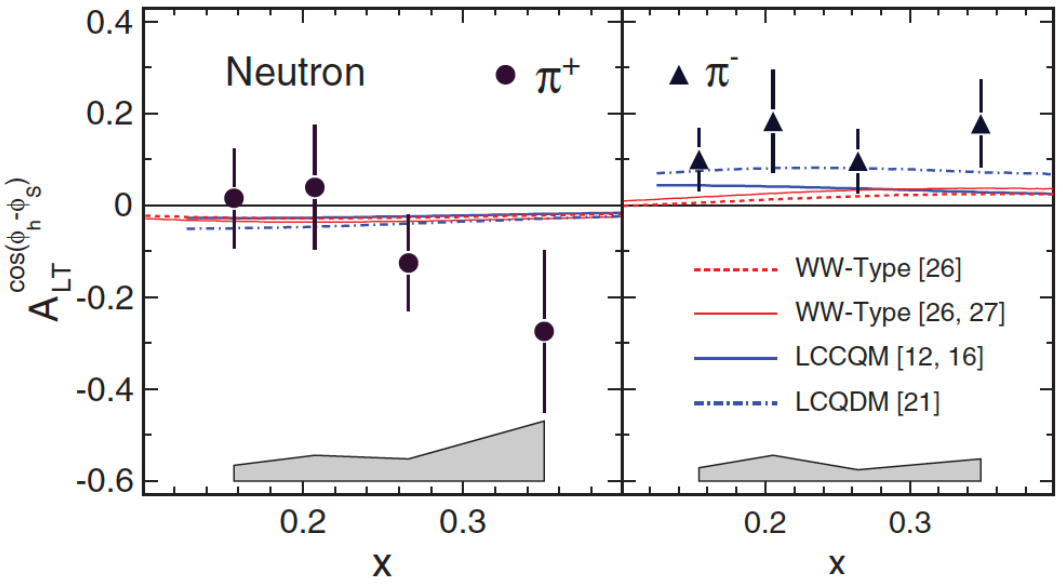


FIG. 2 (color). Neutron $A_{\mathrm{LT}}^{\cos(\phi_h-\phi_S)}$ azimuthal asymmetry for positive (left) and negative (right) charged pions vs x.

- 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 ^{3}He asymmetry)	0.1-0.2% absolute (*relative* 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)

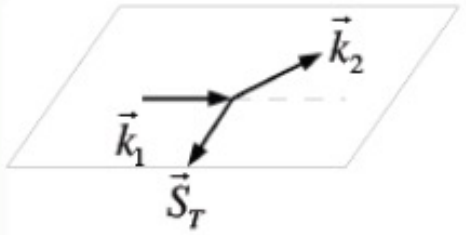
- SBS+BB w/polarized ^{3}He has significant advantages in control of experimental systematics, as discussed in our replies to PAC reader comments/questions
- Theoretical systematics (diffractive vector meson, exclusive contamination, nuclear effects, etc) qualitatively similar to all other JLab SIDIS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

SSA check: HRS single-arm ^{3}He SSA

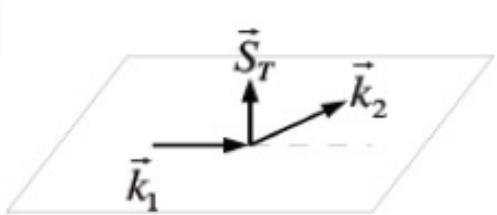
(Witness channels on ^{3}He, not corrected for target polarization and dilution)

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

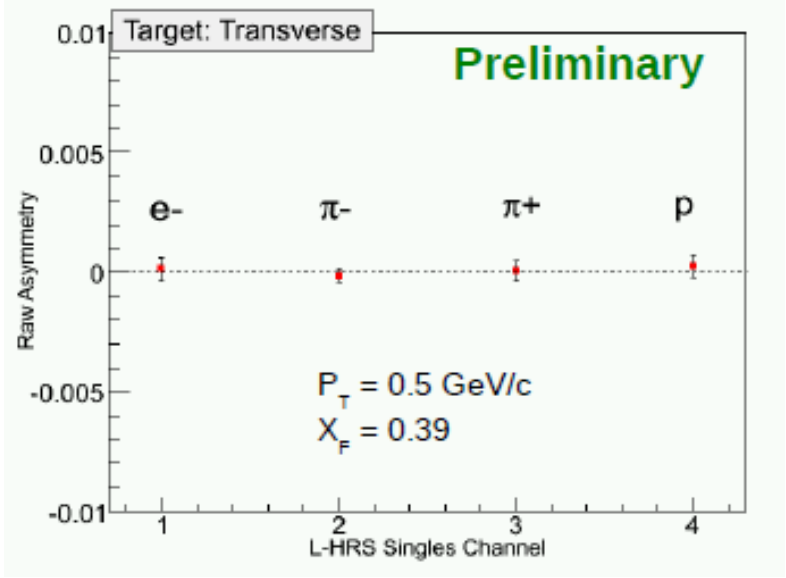
$A = e', \pi^{+/-}$ or p

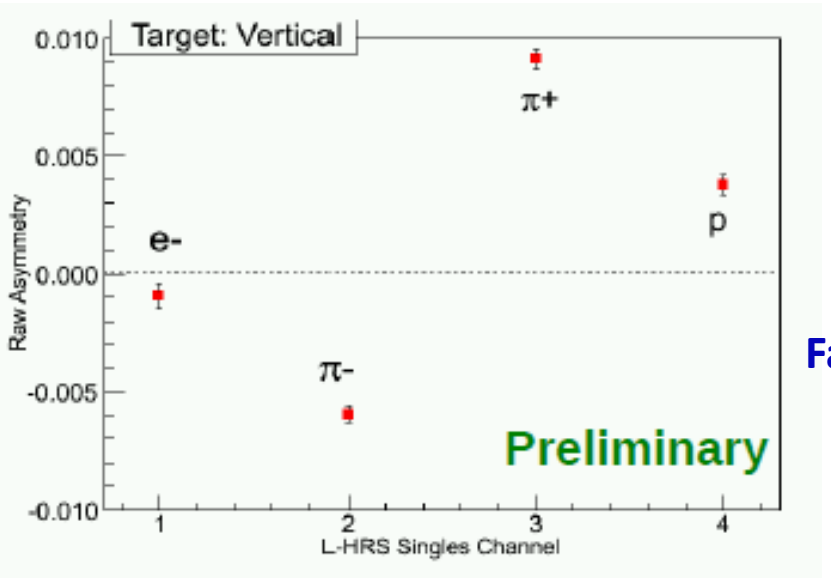


$(\vec{k}_1 \times \vec{k}_2) \cdot \vec{S}_T = 0$

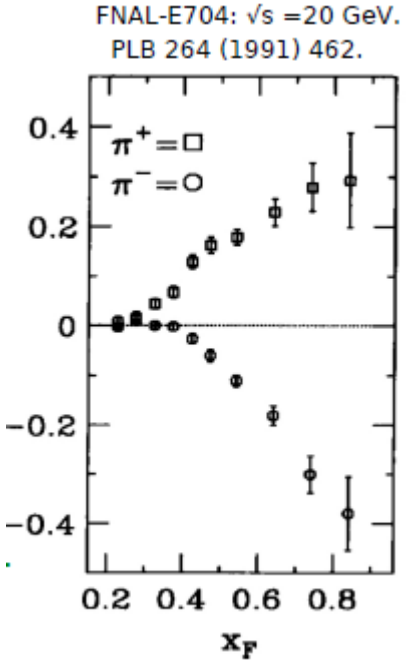


$(\vec{k}_1 \times \vec{k}_2) \cdot \vec{S}_T \neq 0$



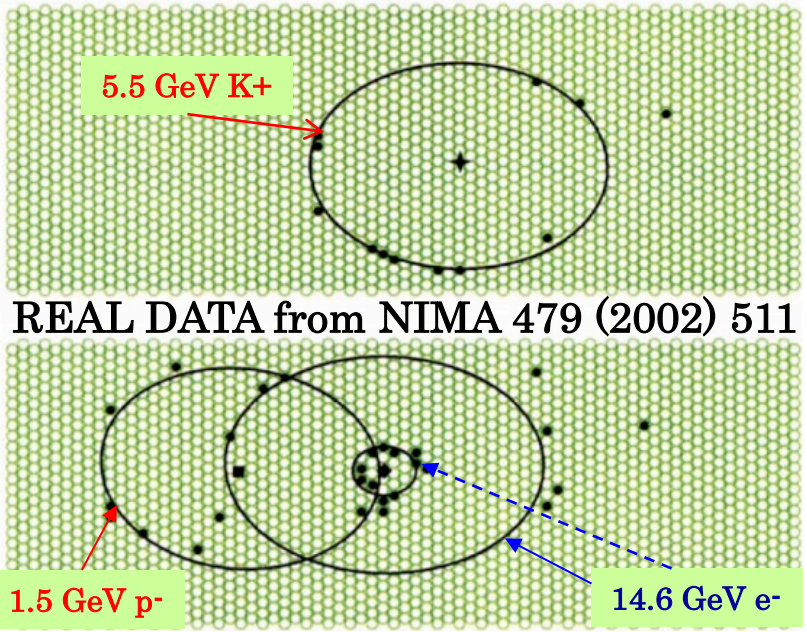


K. Allada
Univ. of Kentucky
2010.



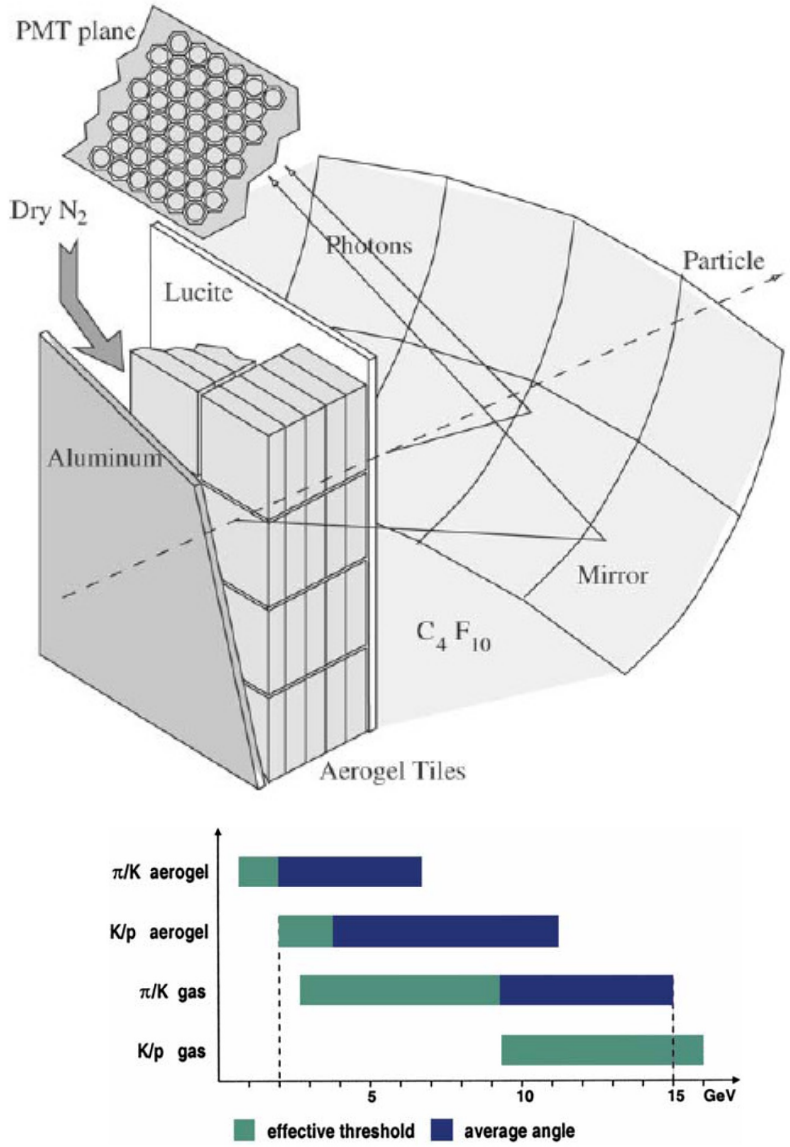
False asymmetry < 0.1%

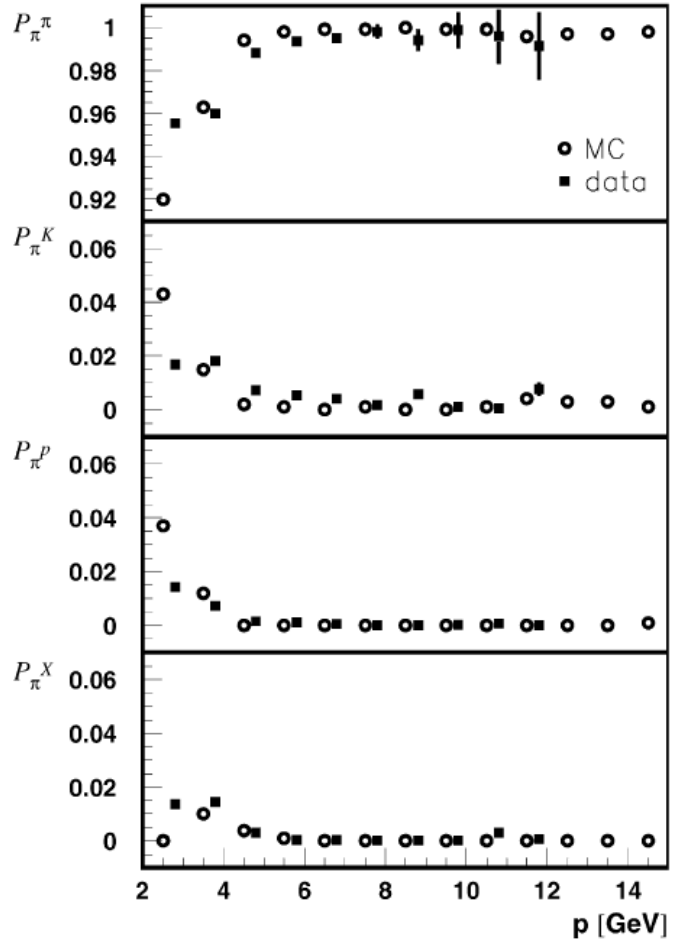
The HERMES→SBS RICH detector



REAL DATA from NIMA 479 (2002) 511

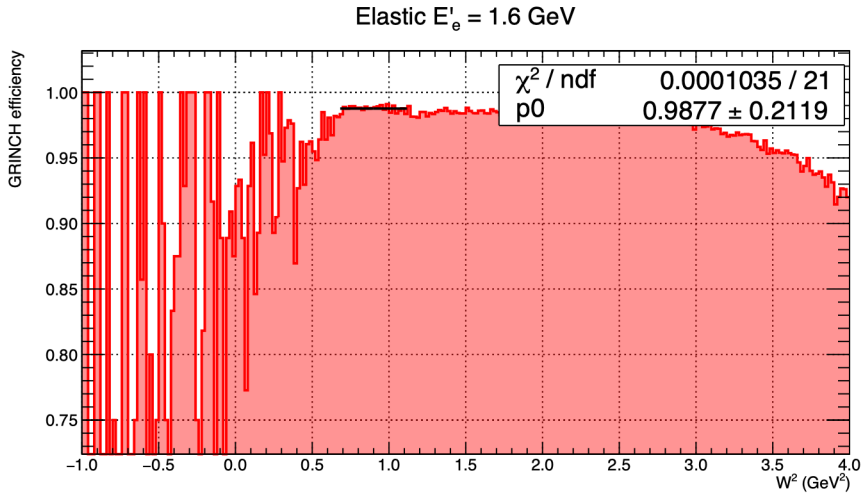
- ***HERMES RICH geometry, performance characteristics well matched to SBS needs.***
- π/K/p separation for p from 2-15 GeV based on dual-radiator design.
- Re-use one half of detector
- ~224 spare PMTs and "spare" aerogel wall from the other half

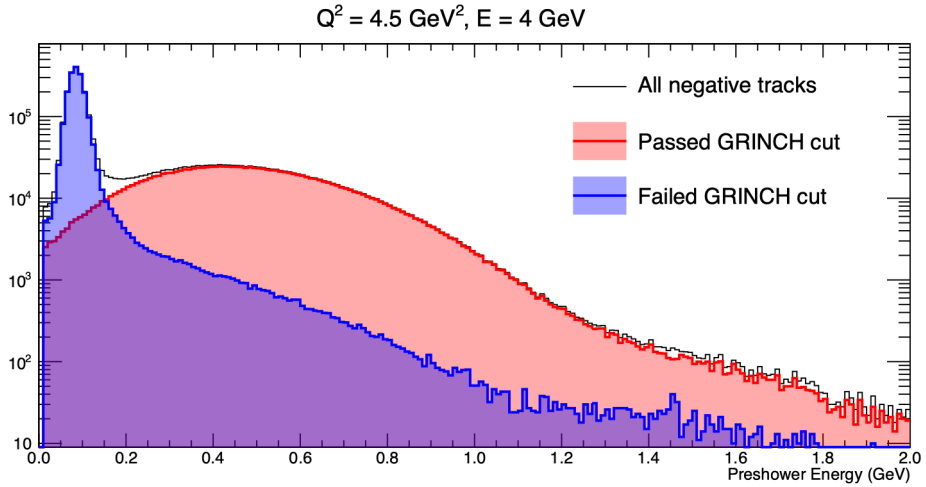


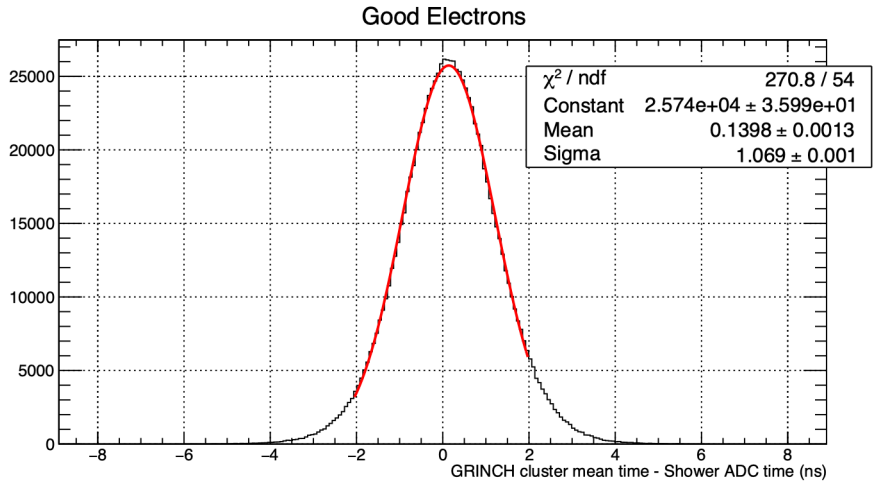


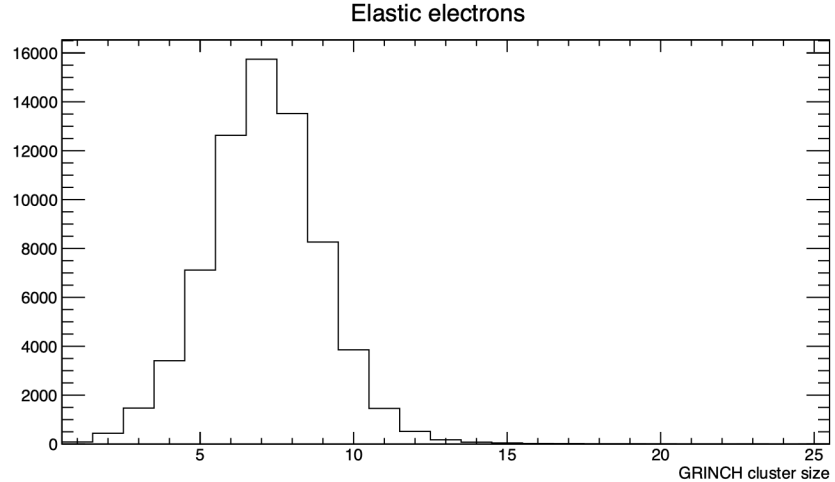
Pion PID results from HERMES

GRINCH Success Demonstrates RICH Feasibility









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