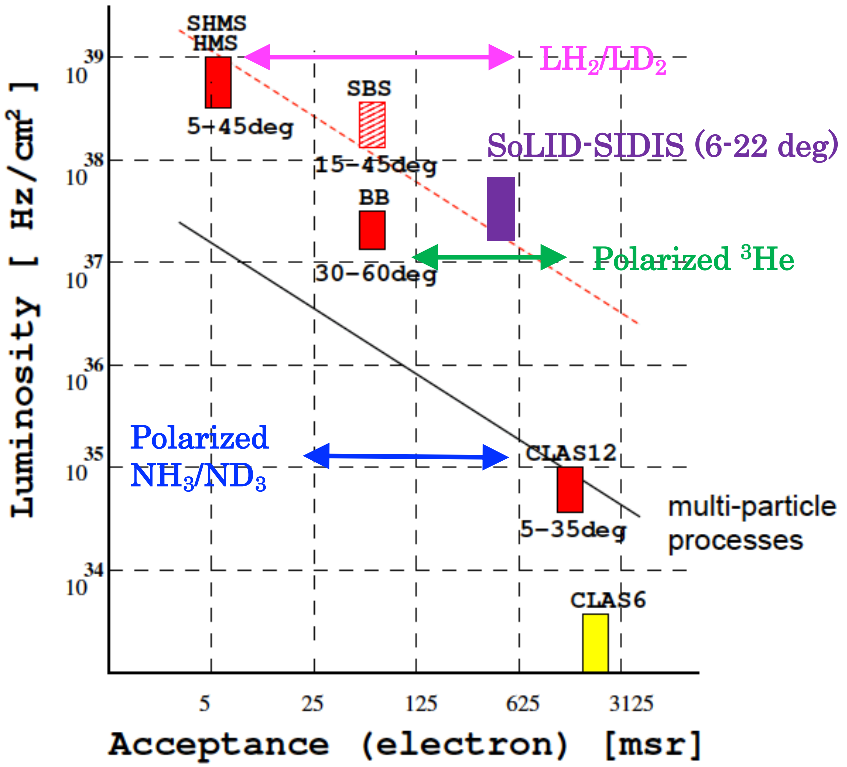
Future SBS Experiments

Andrew Puckett
University of Connecticut
Hall A Collaboration Winter Meeting 2026

UCONN

JLab detector landscape



A range of 10^4 in luminosity.

A big range in solid angle:
from 5 msr (SHMS)
to about 1000 msr (CLAS12).

========================

The SBS is in the middle:
for solid angle (up to 70 msr)
and high luminosity capability.

In several A-rated experiments
SBS was found to be the best
match to the physics.

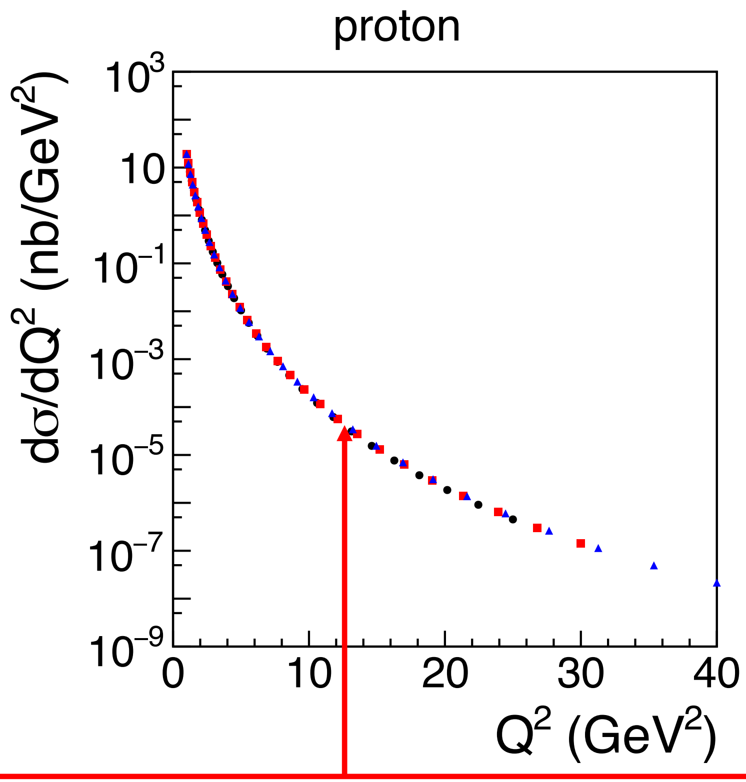
GEM allows a spectrometer
with open geometry (->large
acceptance) at high L.

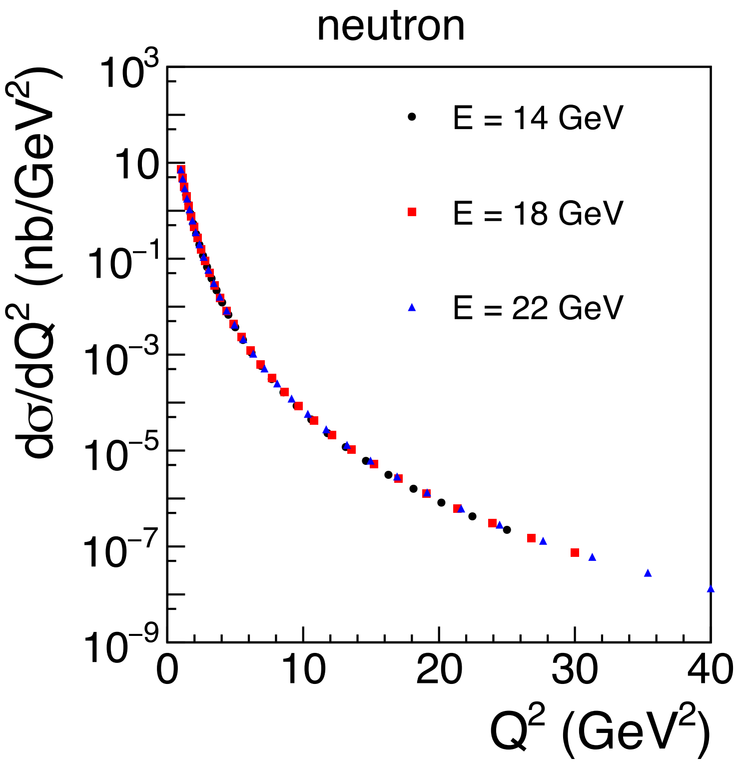
11/16/15 Super Bigbite Spectrometer Review slide 9

- Complementary equipment/capabilities of Halls A, B, C allow optimal matching of (Luminosity x Acceptance) of the detectors to the luminosity capabilities of the targets, including state-of-the-art polarized target technology.

Challenges with high-Q^2 measurements of exclusive processes

- In a high-Q^2 Form Factor measurement we are playing the game of "how hard can we hit a proton without breaking it?"





17.91 mm, cross sectional area = 2.5 cm^2

Compared to a US dime, the elastic *ep* scattering cross section at $Q^2 = 12\ GeV^2$ is about the same as the size of said dime compared to a circle with a diameter of 13.4 light-years! Neutron cross sections are about 3x smaller!

Elastic ep cross section at 12 GeV^2 is ~50 *femtobarn*/GeV^2 $= 5\times10^{-38}\ cm^2$

- This cross section is equivalent to hitting a bull's eye 1 million times smaller than the diameter of the proton itself with an electron!
- But if you get enough protons together in a small enough volume and you shoot enough electrons at them, this can (and does) happen!

Statistical requirements: asymmetries vs. cross section measurements

Cross sections:

$$\sigma \propto N$$

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

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

Asymmetries:

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

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

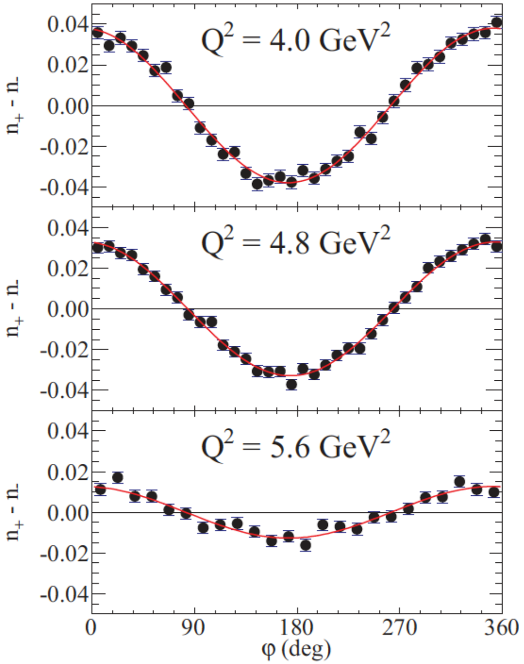


FIG. 6. (Color online) Focal-plane helicity-difference asymmetry $n_+ - n_- \equiv (N_{\text{bins}}/2)[N^+(\varphi)/N_0^+ - N^-(\varphi)/N_0^-]$, where N_{bins} is the number of φ bins and $N^{\pm}(\varphi)$, $N_0^{\pm}$ are defined as in Eq. (4), for the three highest Q^2 points from GEp-II. Curves are fits to the data. See text for details.

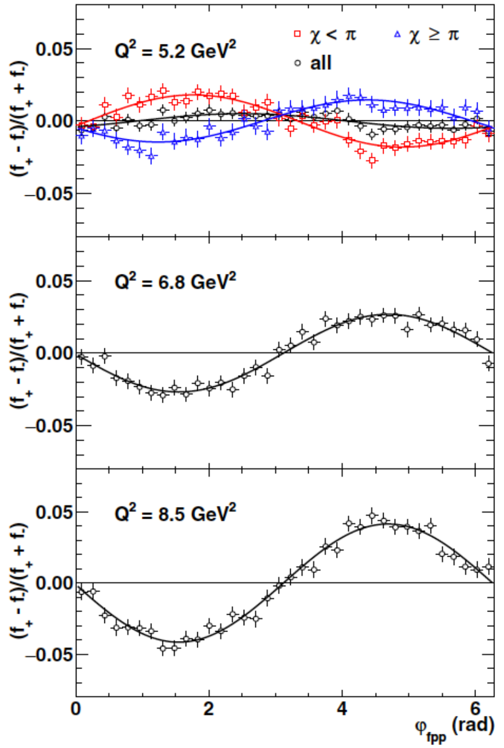
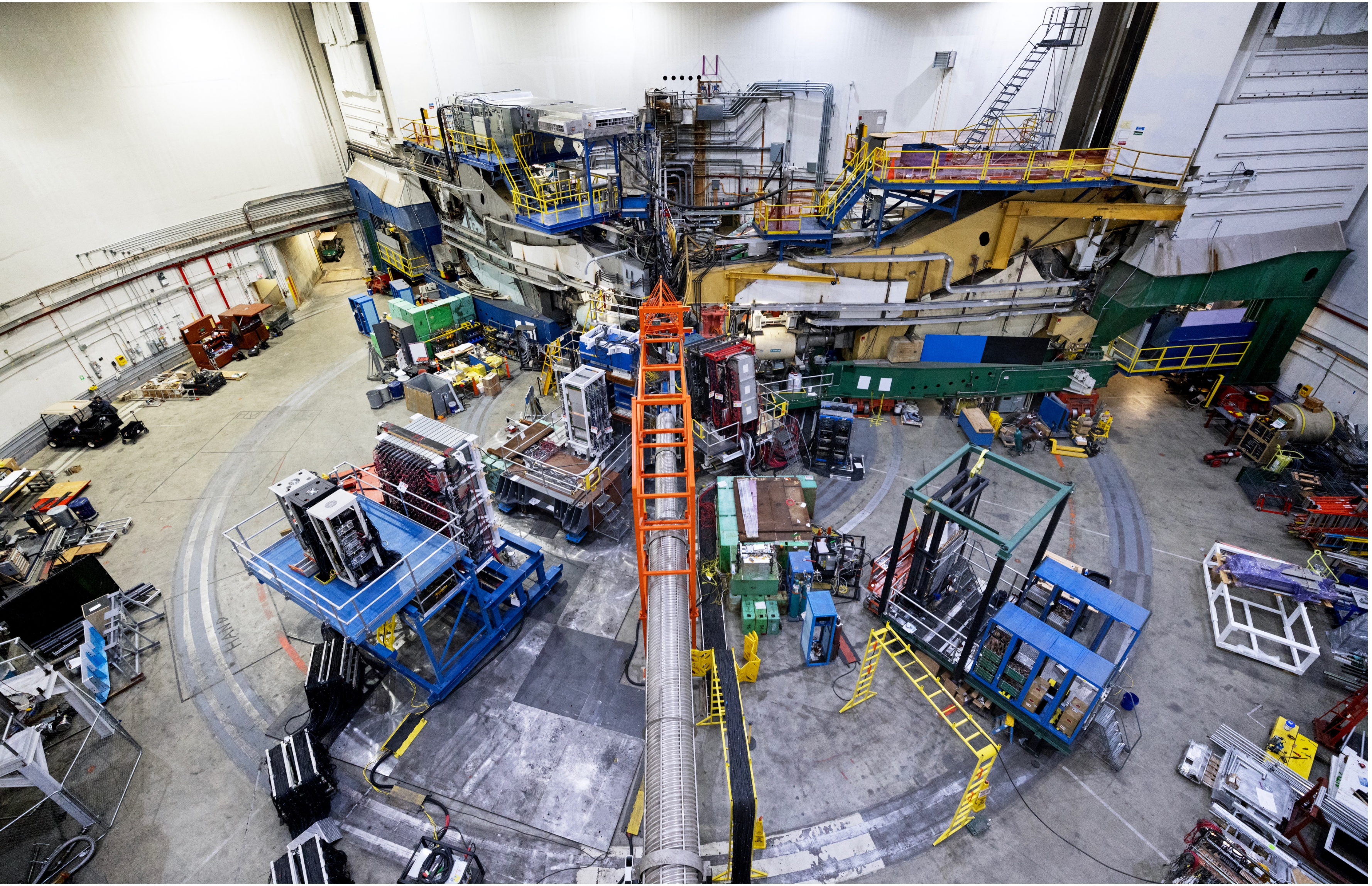


FIG. 10. Focal plane helicity difference/sum ratio asymmetry $(f_+ - f_-)/(f_+ + f_-)$, defined as in Eq. (20), for the GEp-III kinematics, for FPP1 and FPP2 data combined, for single-track events selected according to the criteria discussed in Sec. III B 2. Asymmetry fit results are shown in Table V. The asymmetry at $Q^2 = 5.2$ GeV^2 is also shown separately for events with precession angles $\chi < \pi$ and $\chi \geqslant \pi$, illustrating the expected sign change of the sin(φ) term.

- Example: Typical asymmetry magnitude in a recoil proton polarimeter at "high" momentum is ~few percent.
- To measure a 5% asymmetry with a relative precision of 1%, one needs $N = 10{,}000 \times \frac{1-A^2}{A^2} \approx 4\times10^6$ events!

→ Asymmetry measurement must maximize beam and/or target polarization, and luminosity × acceptance!

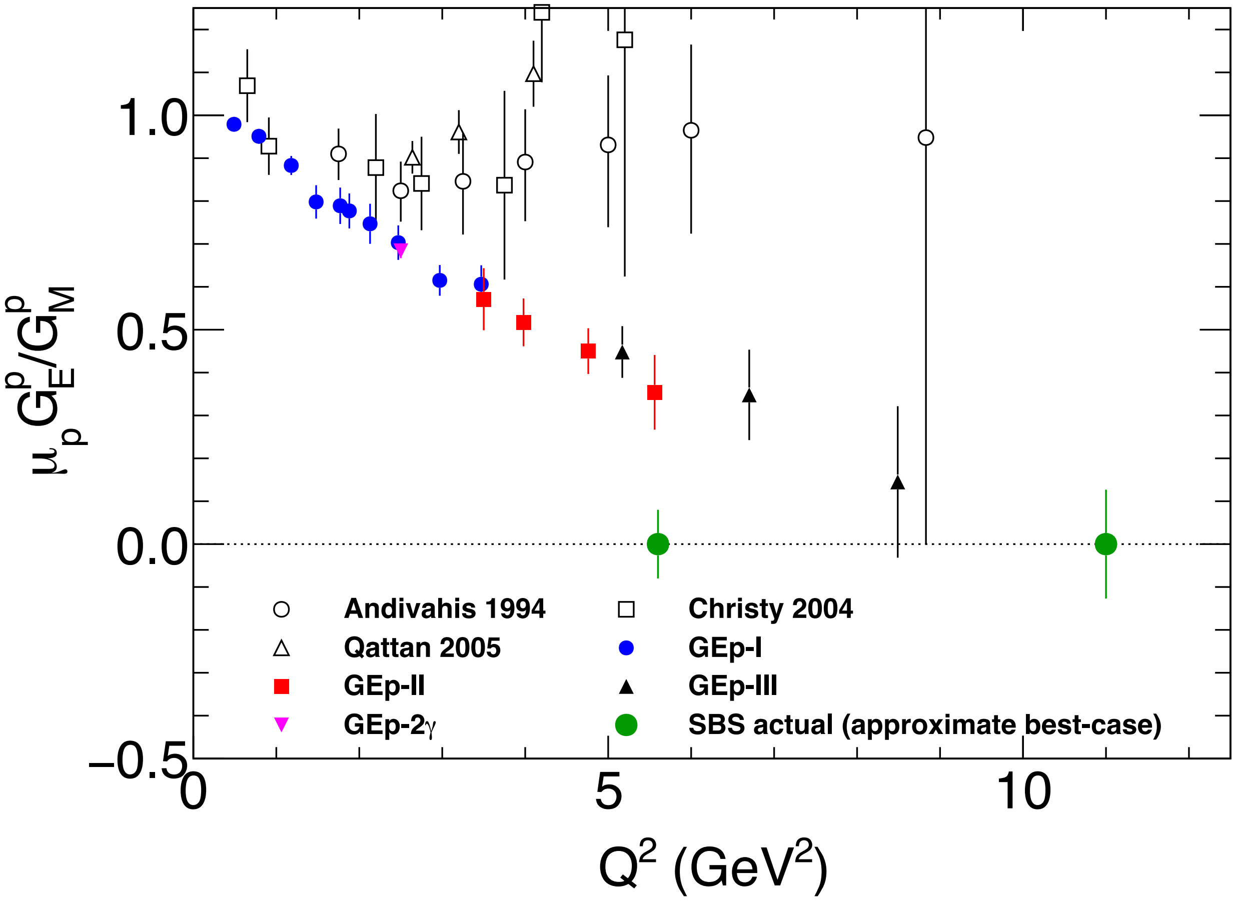
The Super BigBite Spectrometer in Hall A



- Designed to operate at high luminosity at forward scattering angles with large momentum bite, moderate solid angle acceptance
- Enables the study of large-momentum transfer exclusive and semi-inclusive reactions in electron-nucleus scattering
- ***Large solid-angle + high luminosity @ forward angles = most interesting physics!***

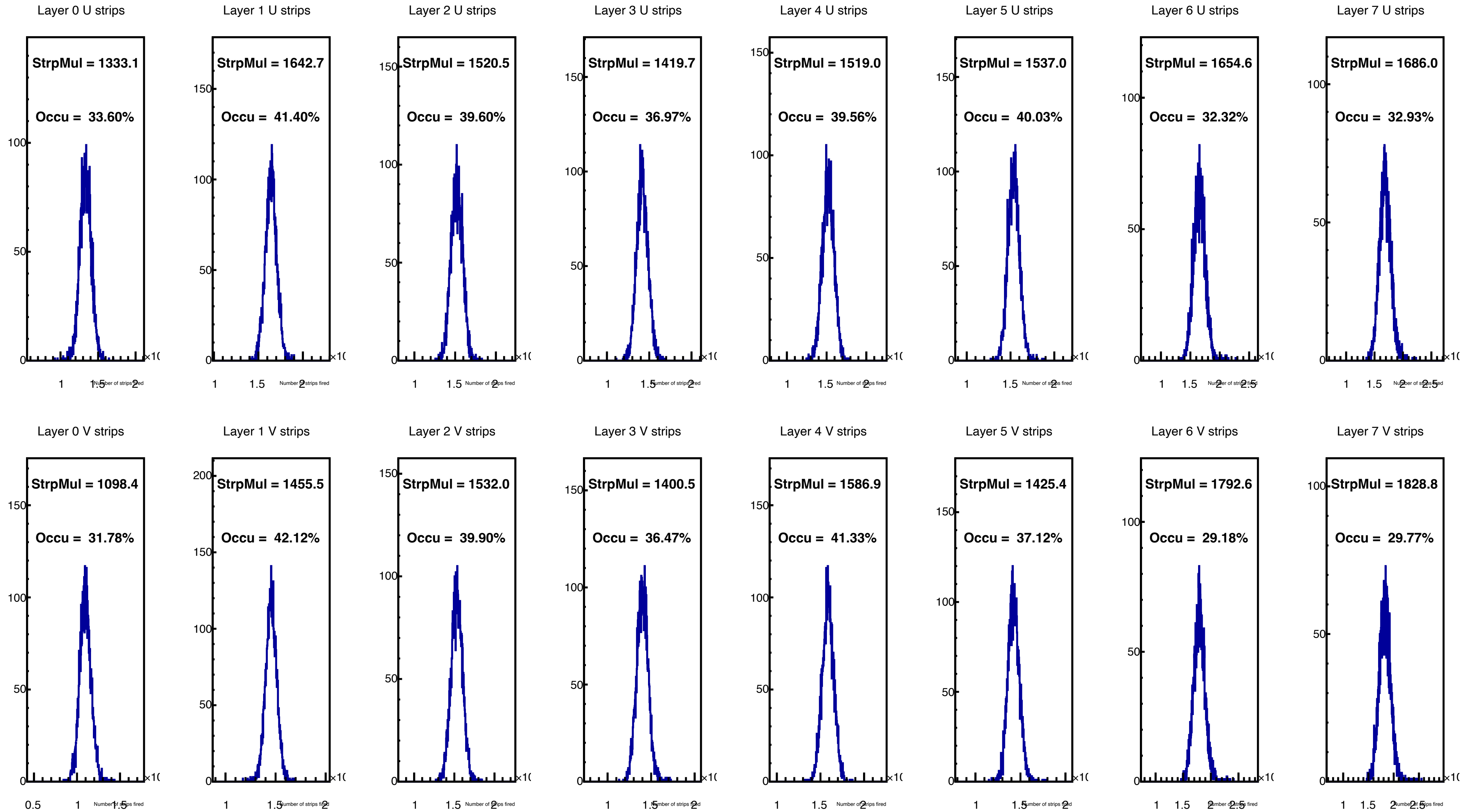
SBS Performance—Lessons from the FF program

- Right: approximate best-case scenario for physics output of SBS GEP 2025 run based on (livetime-corrected) charge
- Falls short of proposal in both the number of Q^2 points and their precision
- Planned measurement at $Q^2 = 8\ GeV^2$ and E12-24-010 measurement at $Q^2 = 3.7\ GeV^2$ had to be abandoned (for now)
- GEP luminosity limited to $\approx 2\times10^{38}$ by trigger and overall GEM system performance (high occupancy/low signal-noise ratio/APV25 baseline sagging/broadening)
- Tracking efficiency and speed need improvement → exploring the use of AI/ML for hit reconstruction and track-finding.



- Above: projected statistical uncertainties based on charge collected, *assuming* 70% overall detection/reconstruction efficiency
- *Demonstrated* efficiency currently well below 70%

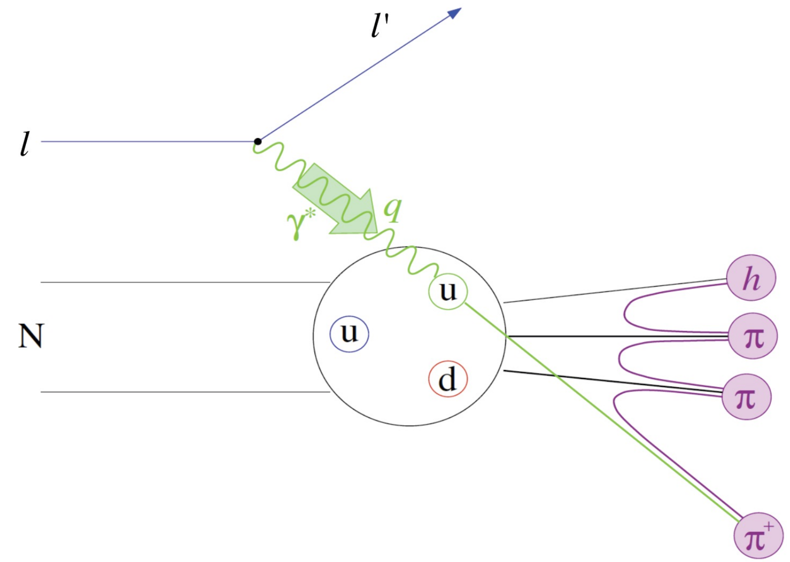
GEP GEM Front Tracker (raw) occupancy at 15 uA on 30-cm LH_2

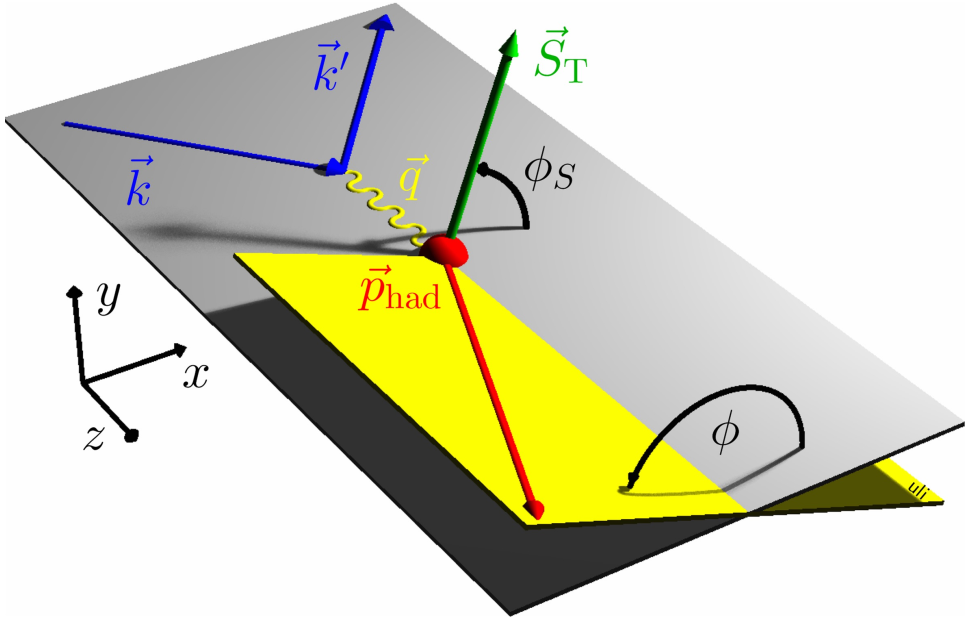


A few lessons from the SBS FF program for future intensity-frontier experiments (e.g., SOLID)

- More commissioning/calibration time with new/custom equipment operating in extreme high-rate/high-background regimes
- High-rate GEM tracking is more challenged for MIP-like particles (e.g., 7-GeV protons) than for ultra-relativistic electrons (signal/noise ratio!)
- APV25 front-end seems inadequate for the most extreme conditions (e.g., GEP)—need faster pulse shaping, better stability of baseline/gain/etc
- APV25 would have worked significantly better in SBS with 9 time samples instead of 6
- Pay VERY close attention to trigger threshold calibrations and efficiencies for both electron and hadron calorimeters—need clear plans to validate trigger efficiencies and TIME to collect the data—even (especially) for asymmetry measurements

Semi-Inclusive Deep Inelastic Scattering and TMDs





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

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

Transverse target spin-dependent cross section for SIDIS

- Collins effect—probe transverse polarization of quarks
- Sivers effect—probes correlations between quark transverse momentum and nucleon transverse spin.
- “Transversal helicity” g_{1T}—real part of S wave-P wave interference (Sivers = imaginary part) (requires polarized beam)
- “Pretzelosity” or Mulders-Tangerman function—interference of wavefunction components differing by 2 units of OAM

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

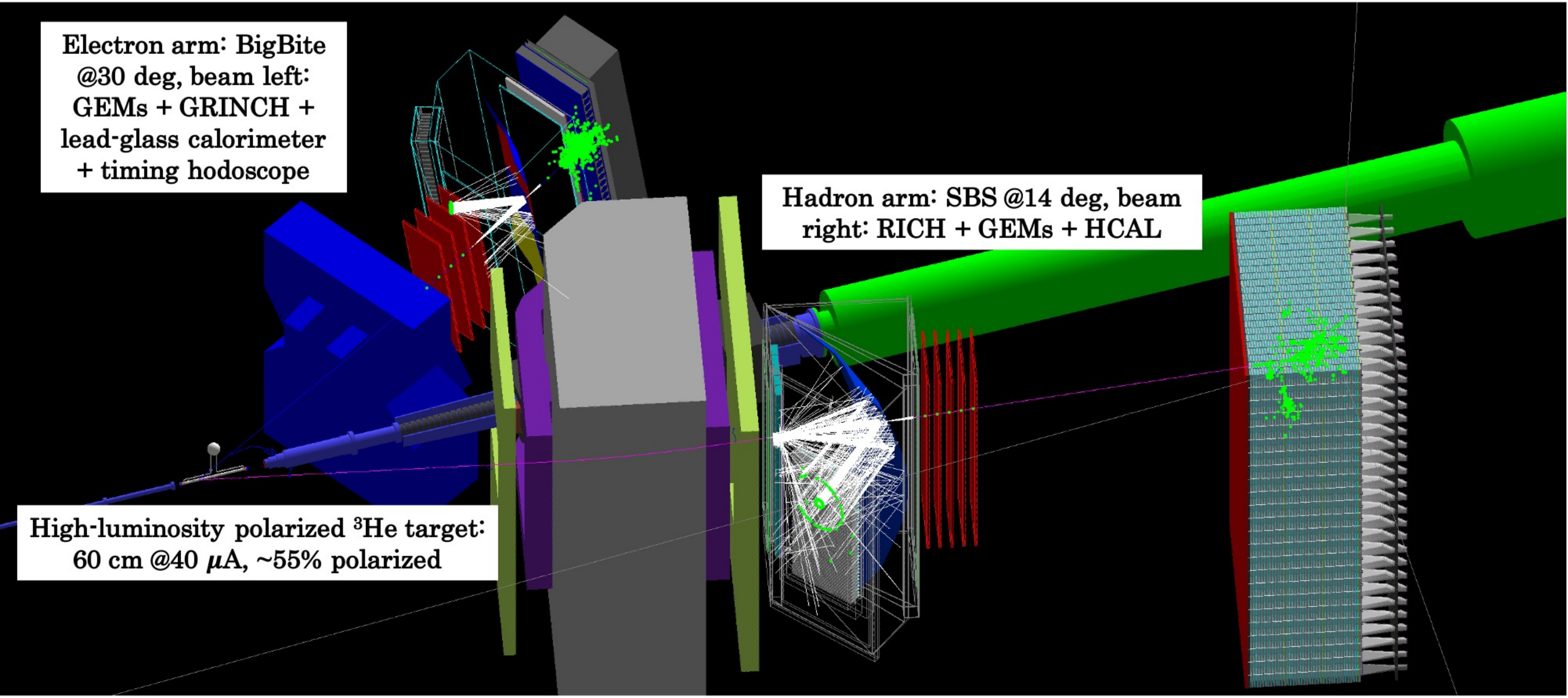
$D_1 =$ unpolarized fragmentation function

$H_1^\perp =$ Collins fragmentation function

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

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

The SBS SIDIS Experiment (E12-09-018)



SBS SIDIS Collaboration

E12-09-018 is an SBS Collaboration experiment

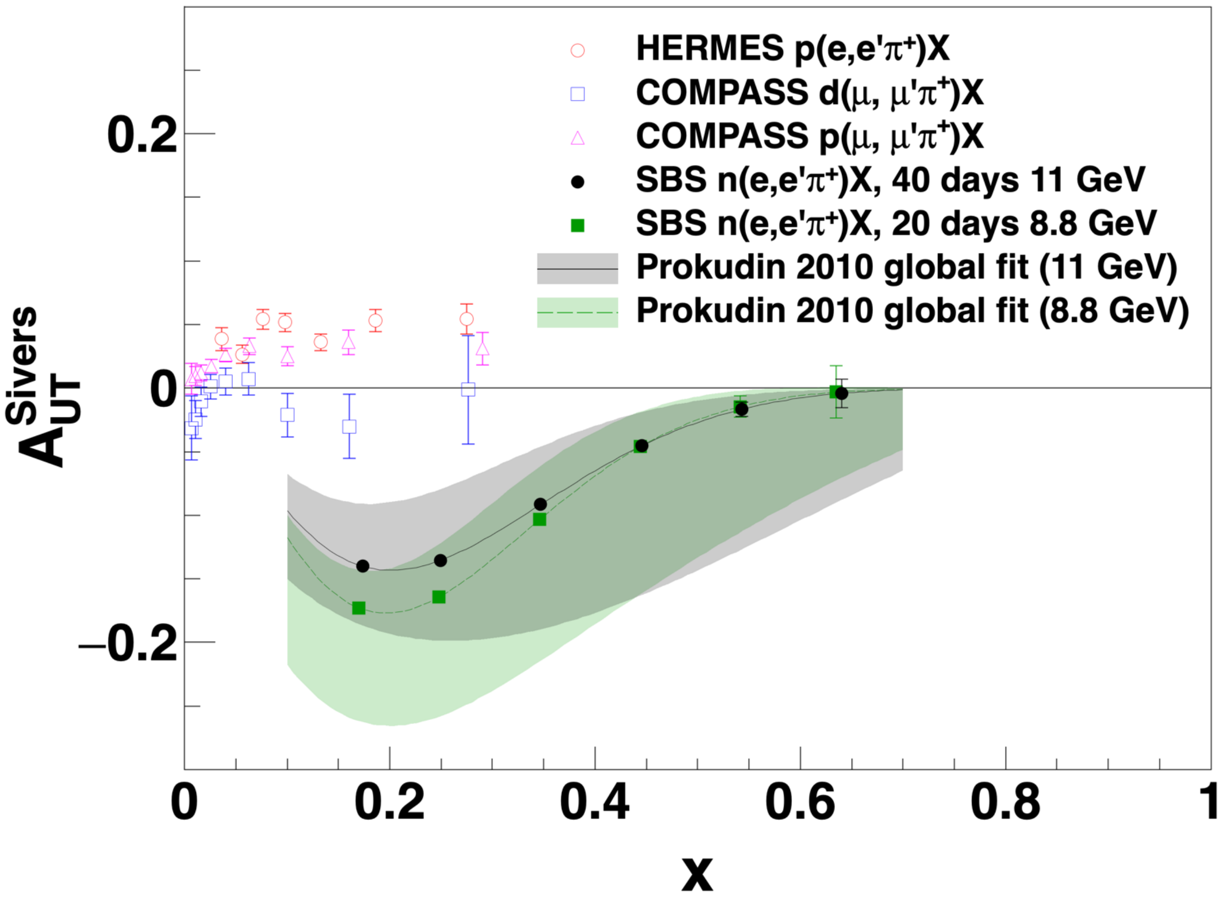
Spokespeople:

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

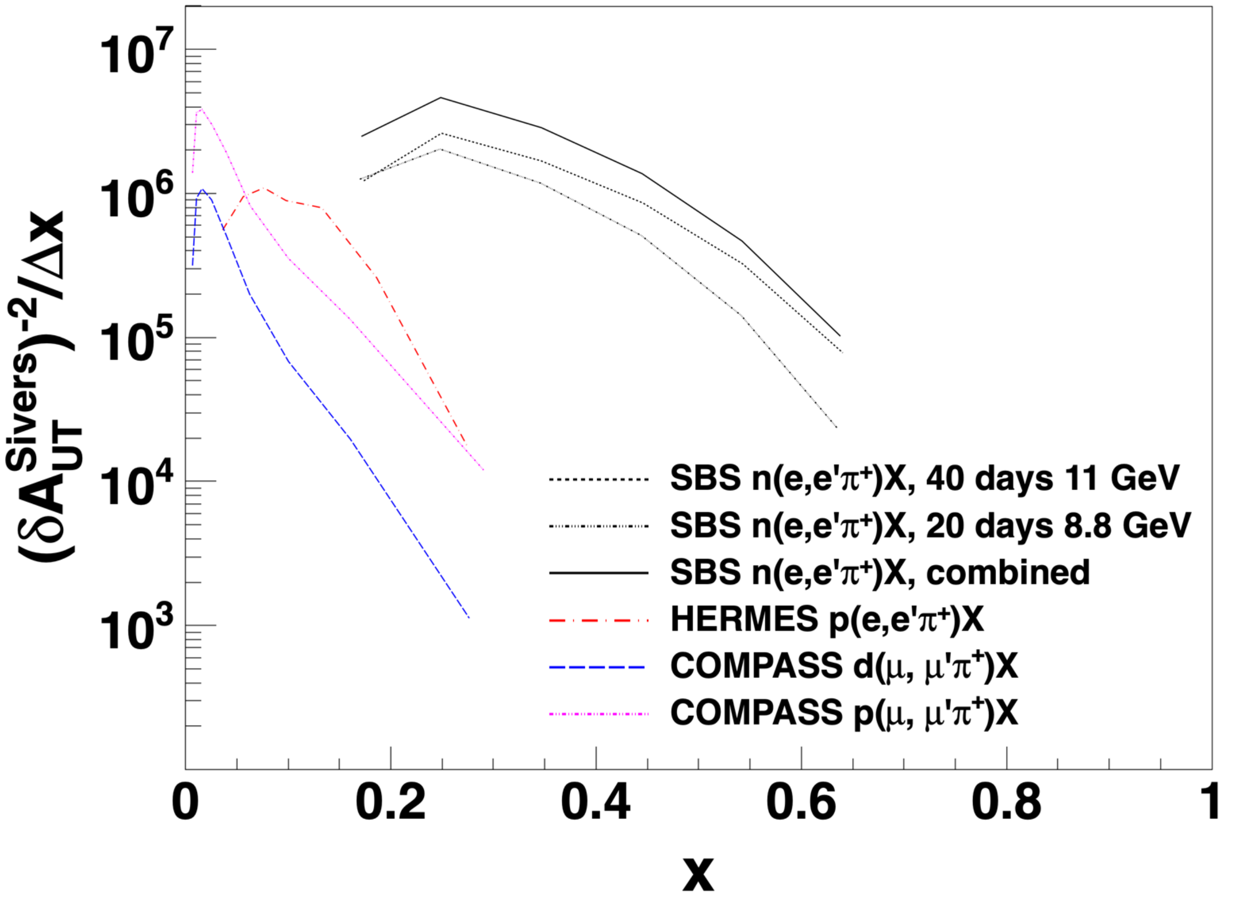
E12-09-018 History

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

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



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



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

E12-09-018 Summary (as shown in PAC49 Jeopardy Proposal)

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

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

E_e (GeV)	Days	$^3\mathrm{He}(e,e'\pi^+)X$ 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

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

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

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

Tagged DIS program

Slide credits: Dipangkar Dutta (MSU) and Rachel Montgomery (Glasgow U)

C12-15-006

The Tagged Deep Inelastic Scattering (TDIS) Experiment

Goal:

A direct measurement of the mesonic content of the nucleon and a unique extraction of the **pion's F_2 structure functions**, by scattering from a **virtual pion target**, accessed via **spectator tagging**.

Spokespersons: D. Dutta, N. Liyanage, C. Keppel, P. King, R, Montgomery, H. Nguyen, B. Wojtsekhowski

C1 conditionally approved with A- rating for **27 PAC days**

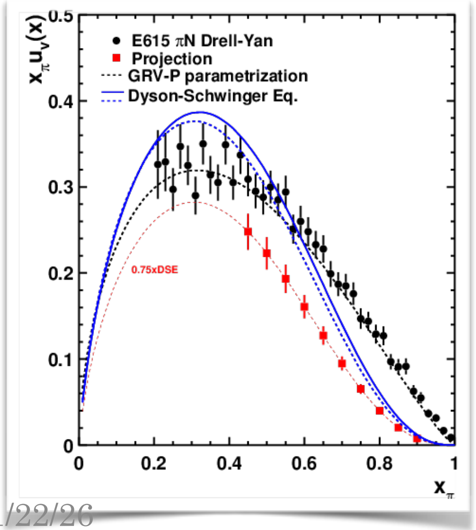
Motivations:

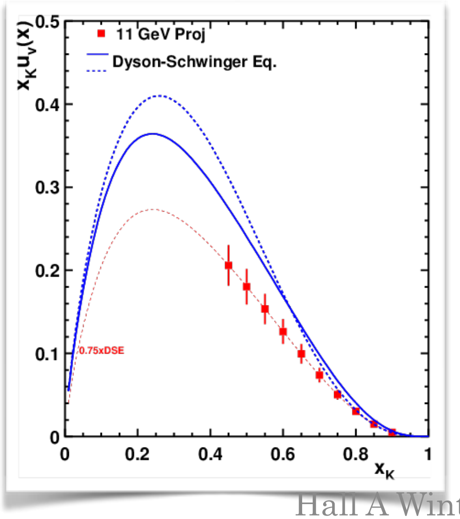
There is ample evidence that nucleons have pionic content in them, but no direct measurements.

Pions and kaons are the simplest bound states of QCD and its Nambu-Goldstone bosons- knowledge of meson structure is critical to a complete understanding of the emergence of hadron mass.
But, very little data due to the lack of "meson targets".

TDIS will use spectator tagging - a well established technique- to tag the "meson cloud" of the nucleon.

TDIS is a pioneering experiment but the proposed technique to extract meson structure function is an essential proof-of-principle for future experiments at the EIC & 22 GeV JLab.





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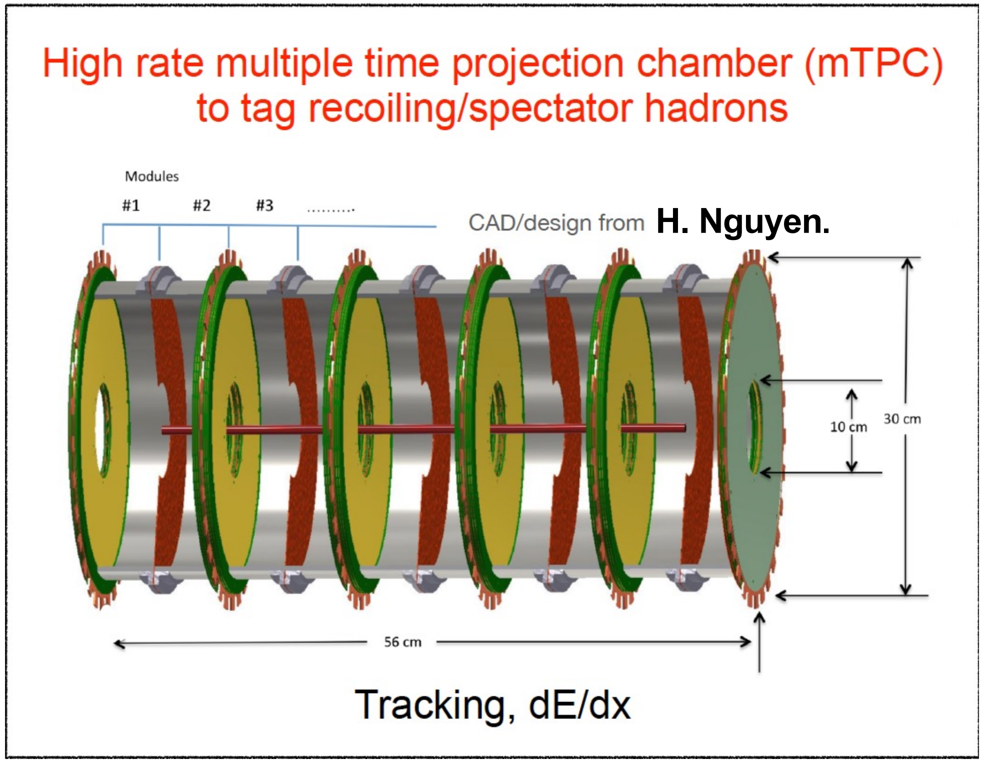
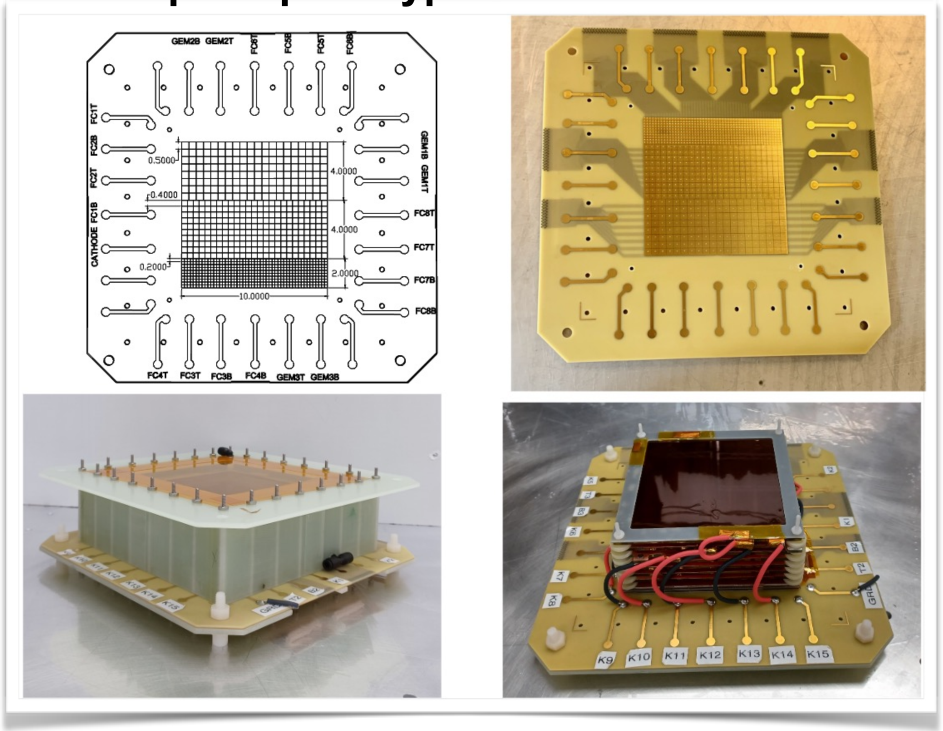
We have converged on a design for the recoil detector- a multi-Time Projection Chamber (mTPC)



A square prototype has been constructed



Images from H. Nguyen

- Each TPC unit of the composite mTPC will be exposed to a fraction of the background rate.
- The drift field is parallel to the magnetic field, leading to reduced drift times and significantly simplified track reconstruction.

Target: 40 cm long, 25 um wall thickness Kapton straw at room temperature and 3 atm. pressure.

Testing is currently underway at JLab to validate the time projection field cage and the readout configuration.

A cylindrical prototype will be built after validation.

Our strategy going forward?

1. Focus on answering the bulk of the review committee's questions

a) Get basic device parameters from the square prototype and move forward with a cylindrical prototype.

b) Make progress with including the toy algorithm within an already developed framework such as ACTS + adopt ML/AI.

c) Establish if new magnet design should be included in technical review.

Aim for passing technical review by July 2026.

Positrons @JLab and the Proton Form Factor Ratio Puzzle

- https://inspirehep.net/literature/1809448

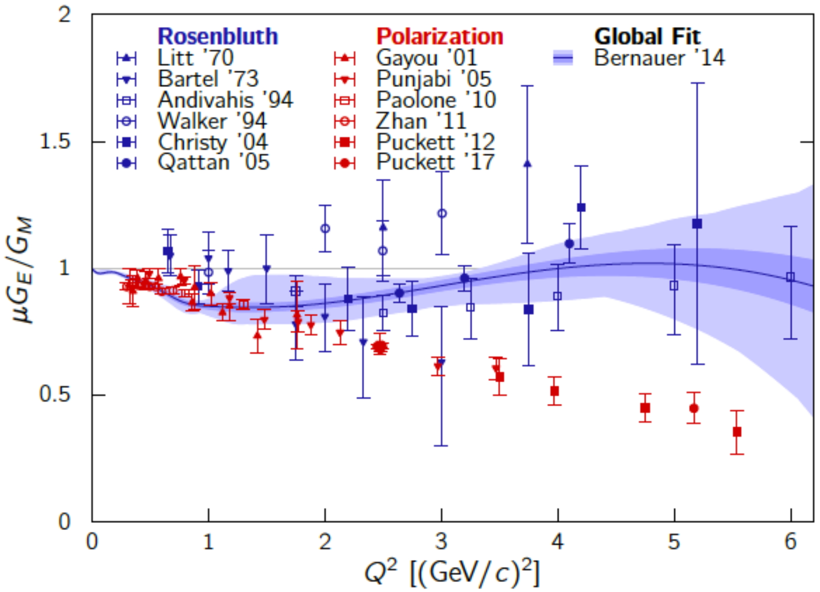


Fig. 1 A representative sample of the world data on the proton's form factor ratio, $\mu_p G_E/G_M$ shown as a function of squared four-momentum transfer, Q^2. Rosenbluth separations of unpolarized cross sections are shown in blue [48, 49, 50, 51, 52, 53]. Polarized measurements are shown in red [35, 36, 37, 38, 39, 40]. A global fit to unpolarized cross sections [59] is shown, along with statistical and systematic uncertainties, by a blue curve with light blue bands.

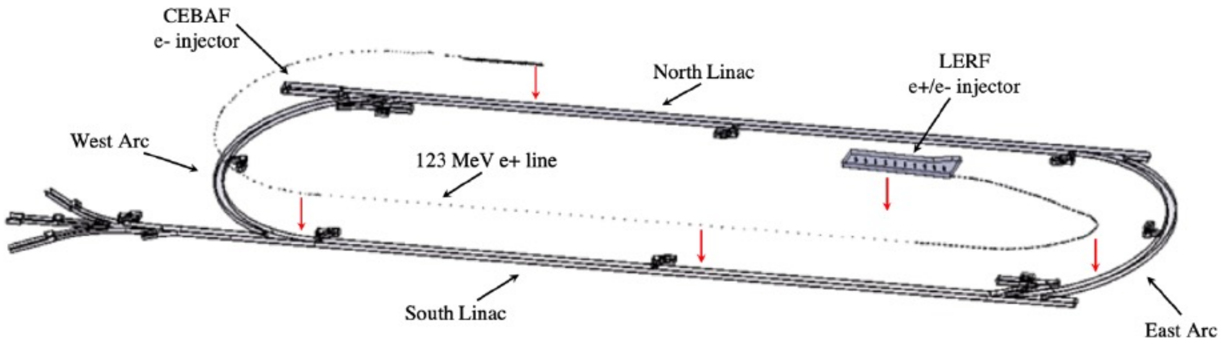


Figure 44: A new tunnel and beam line (shown raised) connects the LERF to CEBAF and transports the 123 MeV e^+ beam for injection and acceleration into CEBAF 12 GeV.

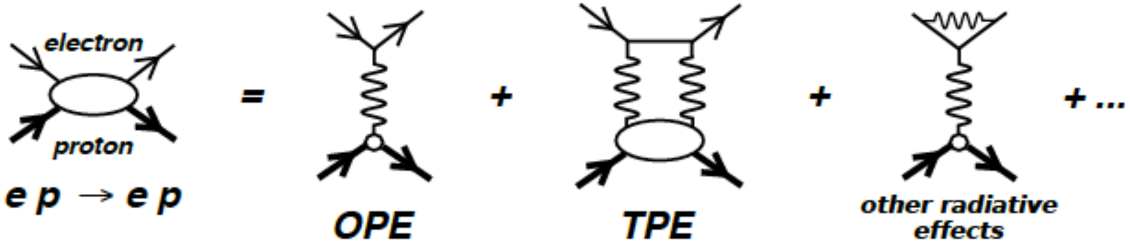


Fig. 2 Feynman diagram series for elastic electron-proton scattering. The two-photon exchange amplitude contributes at the same order as several other radiative processes.

- Differences between e^+p and e^-p scattering are considered "direct" signatures of hard TPE, as the $1\gamma - 2\gamma$ interference changes sign with the lepton charge

Prospects for polarization transfer using positrons

Regular Article - Experimental Physics | Published: 09 June 2021

Polarization transfer in $e^+p \to e^+p$ scattering using the Super BigBite Spectrometer

A. J. R. Puckett, J. C. Bernauer & A. Schmidt

The European Physical Journal A **57**, Article number: 188 (2021) | Cite this article

142 Accesses | **3** Citations | **1** Altmetric | Metrics

Abstract

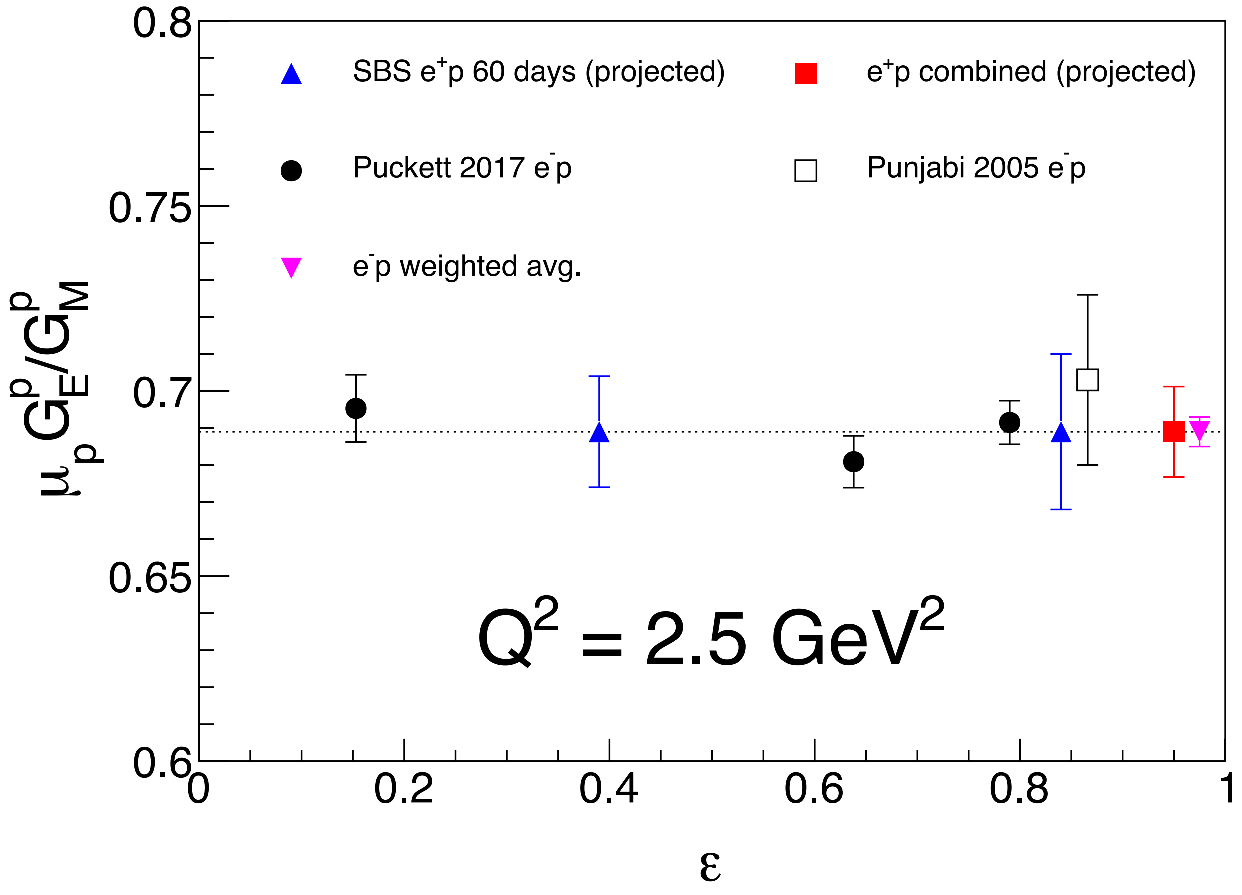
The effects of multi-photon-exchange and other higher-order QED corrections on elastic electron-proton scattering have been a subject of high experimental and theoretical interest since the polarization transfer measurements of the proton electromagnetic form factor ratio G_E^p/G_M^p at large momentum transfer Q^2 conclusively established the strong decrease of this ratio with Q^2 for $Q^2 > 1$ GeV^2. This result is incompatible with previous extractions of this

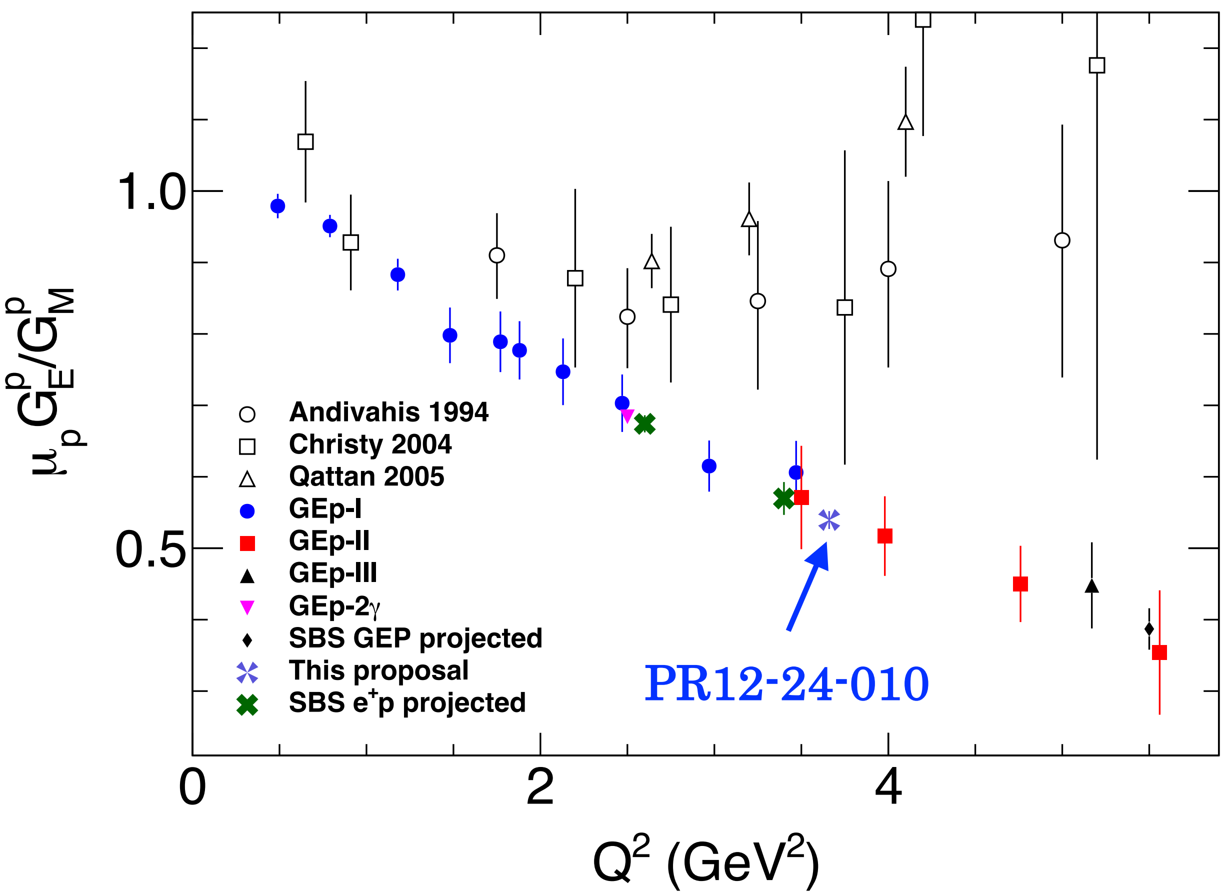
A. J. R. Puckett *et al.*, Eur.Phys.J.A 57 (2021) 6, 188

- Kinematics and projections for an exploratory program of PT measurements in $e^+p \to e^+p$ were laid out in LOI12-23-008 (and EPJA paper)

- PEPPO experiment demonstrated concept of polarized positron source driven by high-intensity polarized electron beams.
- *PT has never been measured in positron scattering at any Q^2 (to my knowledge)*
- PT/LT discrepancy is still by far the most significant (albeit indirect) evidence for the importance of hard TPE effects in elastic *ep*.
- Cross section ratios and L/T separations with positrons will be pursued in the Q^2 regime where the discrepancy is most significant
- Comparison of PT between e^+/e^- and comparison of LT/PT results for e^+p scattering (independent of electron scattering data) will be extremely interesting, and essential in the eventual conclusive resolution of the discrepancy
- **SBS GEP apparatus enables competitive precision in a reasonable amount of beam time!**

A program of polarized positron-proton scattering using SBS (LOI12-23-008)





- Left: ϵ dependence at $Q^2 = 2.5\ GeV^2$ (compare to GEp-2γ)
- Right: Q^2 dependence in the region where the discrepancy is largest and most statistically significant. **Improved precision of e^-p data is needed at the higher Q^2 (PR12-24-010)**

E12-24-010 Summary (as presented to PAC 52 in 2024)

TABLE III. Kinematics, projected accuracy and beam time allocations for "GEP+". The projected statistical uncertainties in the form factor ratio include the assumption of 70% overall event reconstruction efficiency due to the combined efficiencies of the individual detectors, including DAQ dead-time.

Status	E_{beam}, GeV	Q^2 range, GeV^2	$\langle Q^2 \rangle$ GeV^2	θ_{ECAL} degrees	$\langle E'_e \rangle$, GeV	θ_{SBS} degrees	$\langle P_p \rangle$ GeV	$\langle \sin \chi \rangle$	Event rate Hz	Days (PAC)	$\Delta\,(\mu G_E/G_M)$ (statistical)
Proposed	4.3	3.1-4.4	3.7	35.0	2.35	28.5	2.73	0.55	882	2	0.011
Approved/scheduled	6.4	4.5-7.0	5.5	29.8	3.66	25.7	3.77	0.72	291	2	0.029
Approved/scheduled	8.5	6.5-10.0	7.8	27.5	4.64	22.1	5.01	0.84	72	11	0.038
Approved/scheduled	10.6	10.0-14.5	11.7	30.0	4.79	16.9	7.08	0.99	13	32	0.081

- We postponed a full proposal for the positron measurements to a future PAC, in order to optimize the experiment design and obtain the latest theoretical predictions/perform impact studies (and incorporate lessons learned from SBS GEP run)
- Achievable kinematics and precision goals for a positron PT program are already well-defined, science motivation endorsed by PAC51
- **The upcoming SBS GEP run presents a one-time opportunity to obtain the needed electron beam measurement at the higher Q^2 (~3.7 GeV^2) at a low cost in beam time—measurement will be done before PAC53 if PAC52 approves the requested two PAC days (at 50 uA, 2nd-pass, 85% polarized beam)**
- **Ancillary benefit: addition of a fourth, high-precision Q^2 point will provide improved control of systematics for SBS GEP, and aid rapid commissioning of the apparatus**
- **STATUS: approved 2 PAC days; sadly did not run during GEP 2025—will be re-proposed with positron measurements to a future PAC**

Positron nTPE+ (E. Fuchey *et al.*)

- Slide credit—Eric Fuchey, PAC53 presentation
- Status: conditionally approved (C2)

PR12+25-006

Scientific Rating: N/A

Recommendation: Conditionally approved (C2) in Hall C

Title: Measurement of the Two-Photon Exchange Contribution in Electron-Neutron and Positron-Neutron Elastic Scattering

Spokespersons: S. Alsalmi, P. Blunden, P. Datta, E. Fuchey (contact), E. Wertz

Motivation: This experiment proposes to measure the two-photon exchange (TPE) contribution in elastic e^+-neutron and e^--neutron scattering. Such measurements are interesting because a significant two-photon exchange current would lead to a measurable difference in the respective Rosenbluth slopes between the positron and electron scattering results. The measurement program is focused on the neutron where there has not been as extensive a measurement campaign as for the proton and targets a Q^2 region where larger two-photon exchange contributions are expected.

Measurement and Feasibility: The experiment plans to use the same experimental setup as the GMn/TPE experiments in Hall A, but with equipment that the laboratory plans to move to Hall C. Their simulation/analysis efforts are benefitting from experience gained from E12-20-010. Their plans are to measure G^n_E/G^n_M, S^n, and $R^n_{2\gamma}$, the later providing the first such measurements for the neutron. The data will be taken at 6 kinematic settings which includes 3 momentum transfers (Q^2=3.0, 4.5, 5.5 GeV^2) and 3 beam energies (E_{beam}=3.3, 4.4, 6.6 GeV). Since their LOI, the proponents have added H_2 data-taking to aid in reducing systematics (following a PAC52 recommendation) as well as a higher Q^2 point, both of which have further strengthened their measurement program. The requested 38.5 PAC days (30 cm target) as presented in their presentation to PAC53, includes both physics running and time for configuration changes. Assumptions have been made about how long beam changes will take. When a better understanding of the change times are available, it may be necessary to reexamine the requested PAC days.

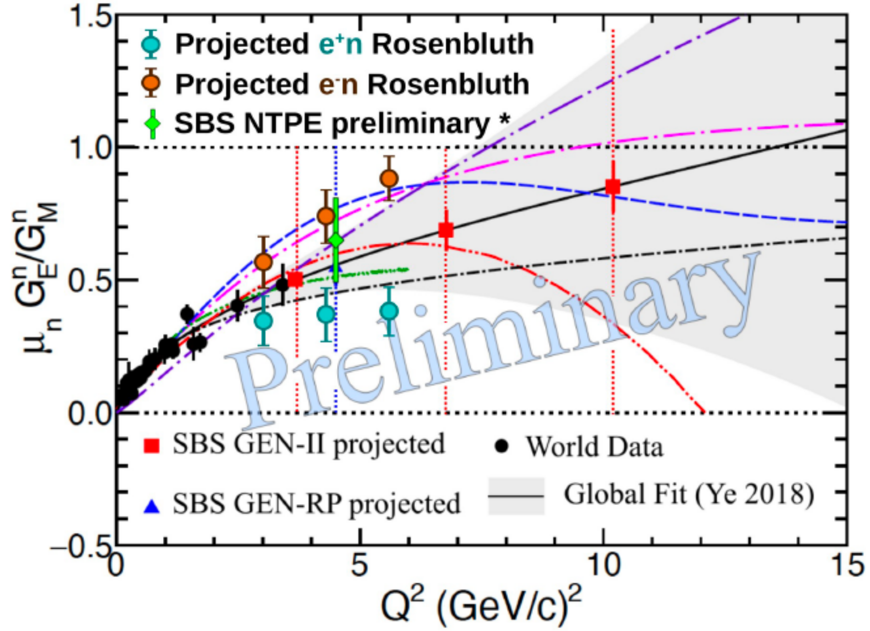
Issues: In their measurement projections, the proponents assume that a factor of three improvement in radiative correction uncertainties will be realized, which if not achieved, would significantly change the precision of the results. The PAC would like to see further justification that this error reduction is a reasonable assumption. Following a suggestion from the TAC, the possibility of running with a longer 30 cm target was also presented. The PAC would like to see a more detailed analysis of how systematic uncertainties are impacted for the 30 cm target.

Summary: This experiment would provide new explorations of two photon exchange spanning a range of Q^2 from 3.0-5.5 GeV^2 in elastic e^+ and e^- neutron scattering. The PAC conditionally approves this proposal (C2) pending the resolution of the above issues at a future PAC and preparation of a revised run time request after a final decision is made on the target length.

nTPE+ Projections

- **Predictions from P. Blunden:** e^+n and e^-n Rosenbluth slopes for all settings
  - Superimposed on nTPE (E12-20-010) *preliminary analysis* by E. Wertz
  - $\mu_n\, G_E^n/G_M^n$ calculated from projected Rosenbluth slopes;
  - Other G_E^n measurements and projections are polarization data;

* *"A Measurement of the Neutron Electromagnetic Form Factor Ratio from a Rosenbluth Technique with Simultaneous Detection of Neutrons and Protons"*, Ph.D Thesis, William & Mary (July 2025).



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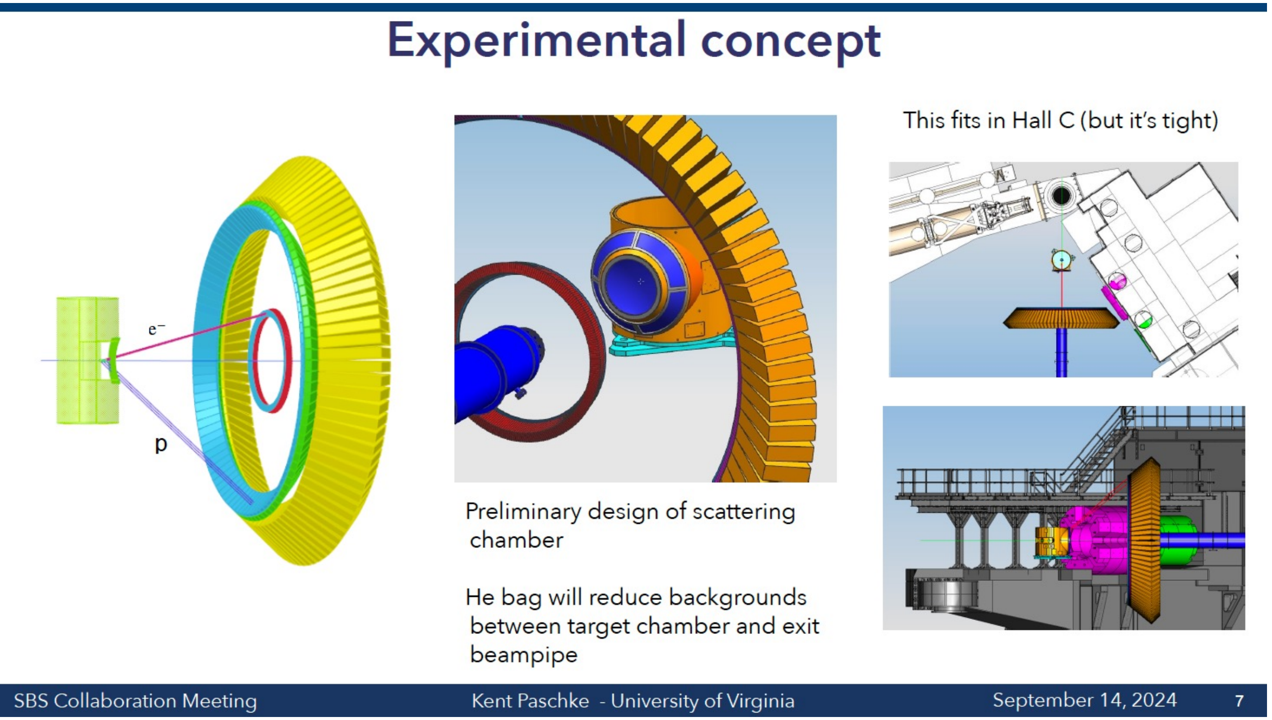
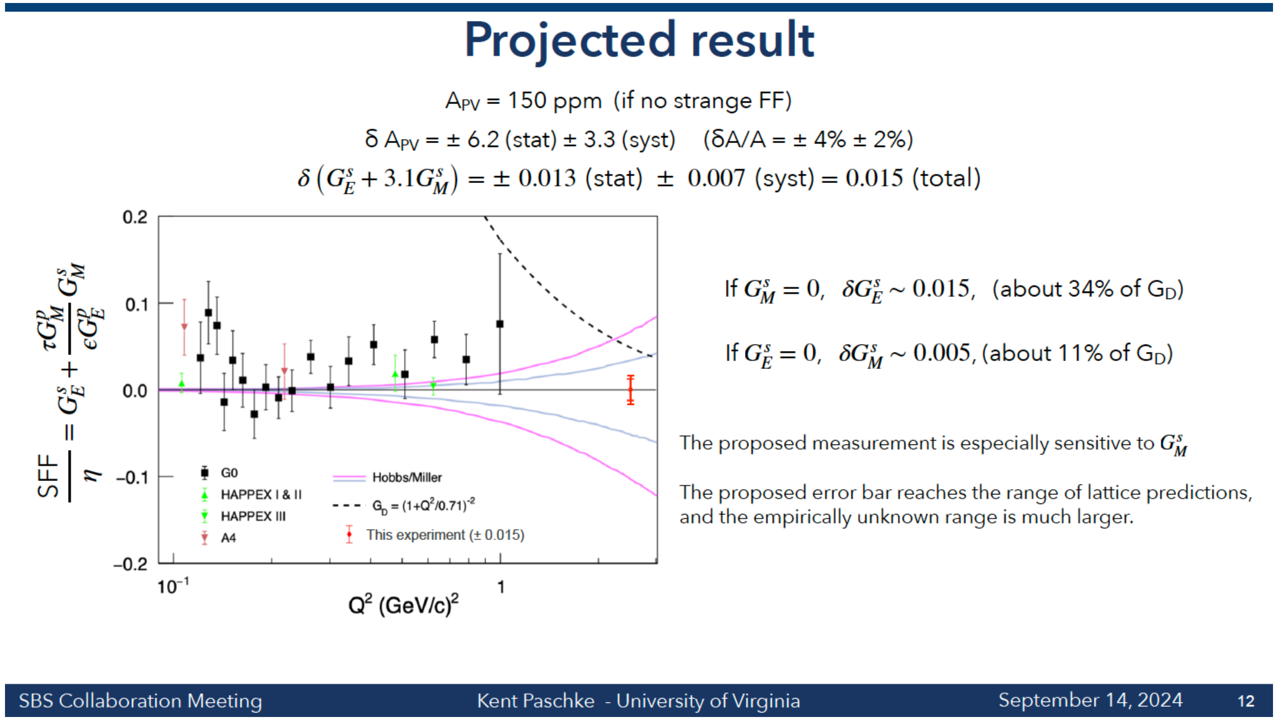
Strange FF of the proton at high Q^2--K. Paschke *et al.*





Expressing A_{PV} for e-p scattering, with proton and neutron EM form-factors plus strange form factors:

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \cdot [(1-4\sin^2\theta_W) - \frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} - \frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} + \epsilon'(1-4\sin^2\theta_W)\frac{G_M^p G_A^{Zp}}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}]$$

- Slides credit: Kent Paschke, SBS Collab. Meeting, 2024
- **Status: Approved PAC51, 45 days, A-rating (E12-23-004)**

Proton Axial Form Factor from the $ep \rightarrow n\nu_e$ reaction (PR12-25-009)

PR12-25-009

Scientific Rating: N/A

Recommendation: Deferred

Title: The Nucleon Axial-Vector Form Factor from the $H(\vec{e}, n)\nu_e$ Reaction (new)

Spokespersons: T. Averett, J. Napolitano, B. Wojtsekhowski (contact), W. Xiong

Motivation: This proposal seeks to determine the nucleon axial-vector form factor F_A, at $Q^2 = 1$ GeV^2 with 39% precision. Previous determinations used neutrino scattering and pion electroproduction, but this will be the first to use inverse neutron beta decay (INBD). The primary goal is to extract the axial mass M_A, with half the precision of the form factor, addressing a controversial issue in neutrino physics that limits cross-section predictions. The proposal also links this measurement to GPDs as an additional motivation.

Measurement and Feasibility: The measurement compares signal rates between left- and right-handed polarized electron beams, as the parity-violating nature of inverse beta decay requires a left-handed electron. Due to the small INBD cross-section, the expected beam helicity correlation is $R = (N_+ - N_-)/(N_+ + N_-) \approx 6.8 \times 10^{-4}$ with ~10,000 weak charge current (CC) events detected. Observing such a small signal requires a neutron arm with 100 ps TOF resolution to distinguish neutrons from photon backgrounds and track them to the proper beam bunch. A sweeper magnet reduces scattered proton and charged particle backgrounds, while a veto arm eliminates electron elastic scattering events. The experimental method is sound and has been extensively simulated.

Issues: Since the LOI, predicted uncertainty for the axial mass increased from 7-8% to 18-20% primarily due to the identification of a significant background arising from two-pion photoproduction. GEANT4 and FLUKA simulations show significant discrepancies in background predictions, varying by factors of 2 (on LH2) to 10 (on Al). The effort required to mount the experiment is quite significant. Beyond the relatively high estimated M&S costs for the neutron arm, TAC reviewers also pointed out the installation is "huge, much larger than SBS", and the work to reconfigure the hall to place the target 7.2 m downstream from the pivot would mean the target scattering chamber must be moved along with all the infrastructure needed to operate cryotargets and motion of the target ladder. An 18-20% axial mass estimate, while useful to the neutrino community, lacks the precision to resolve similar level differences arising from assuming a dipole ansatz versus taking a z-pole expansion, and is unlikely to clarify complexities from nuclear effects and non-monochromatic beams in neutrino scattering determinations of M_A.

Summary: The proponents are to be commended for the excellent work they have done in both developing the theoretical framework, the clever experimental design based on using the neutron time-of-flight techniques, and the extensive simulations performed to understand and suppress potential sources of background in the experiment. The experiment is well-motivated. However, the physics merit of an 18-20% extraction of the axial mass does not justify the scale of the cost and effort.

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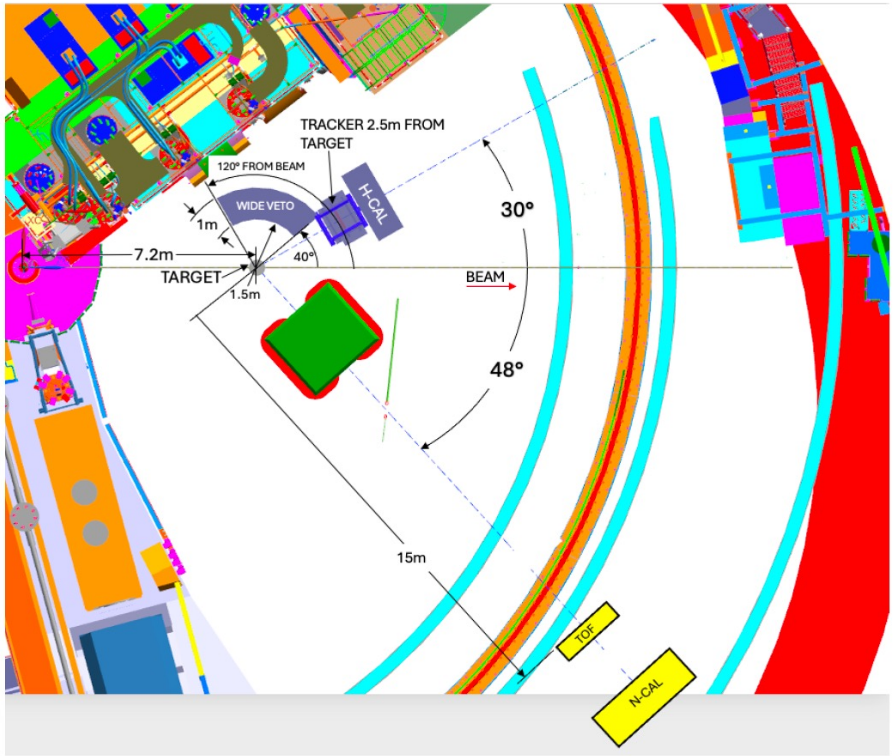


FIG. 14. Hall C design for the AVFF experiment.

- Nucleon Axial FF poorly known; high interest and relevance to both hadronic and neutrino physics
- Never before measured using inverse beta decay
- "Proof-of-concept" measurement at 1 GeV^2 proposed to PAC53
- Status: Deferred by PAC53 due to cost-benefit analysis
- More good physics can be done with high-resolution neutron detector (GEn, etc)

- Relies on neutron detection with ~mrad angular resolution, high-resolution TOF measurement (100-ps), "veto" arm and the 100% physics asymmetry for CC weak interaction to achieve a signal:background ratio of ~1:500 for ~10k signal events in a 50-day run, for a ~39% measurement of F_A

Some other SBS possibilities I won't have time to discuss—a laundry list

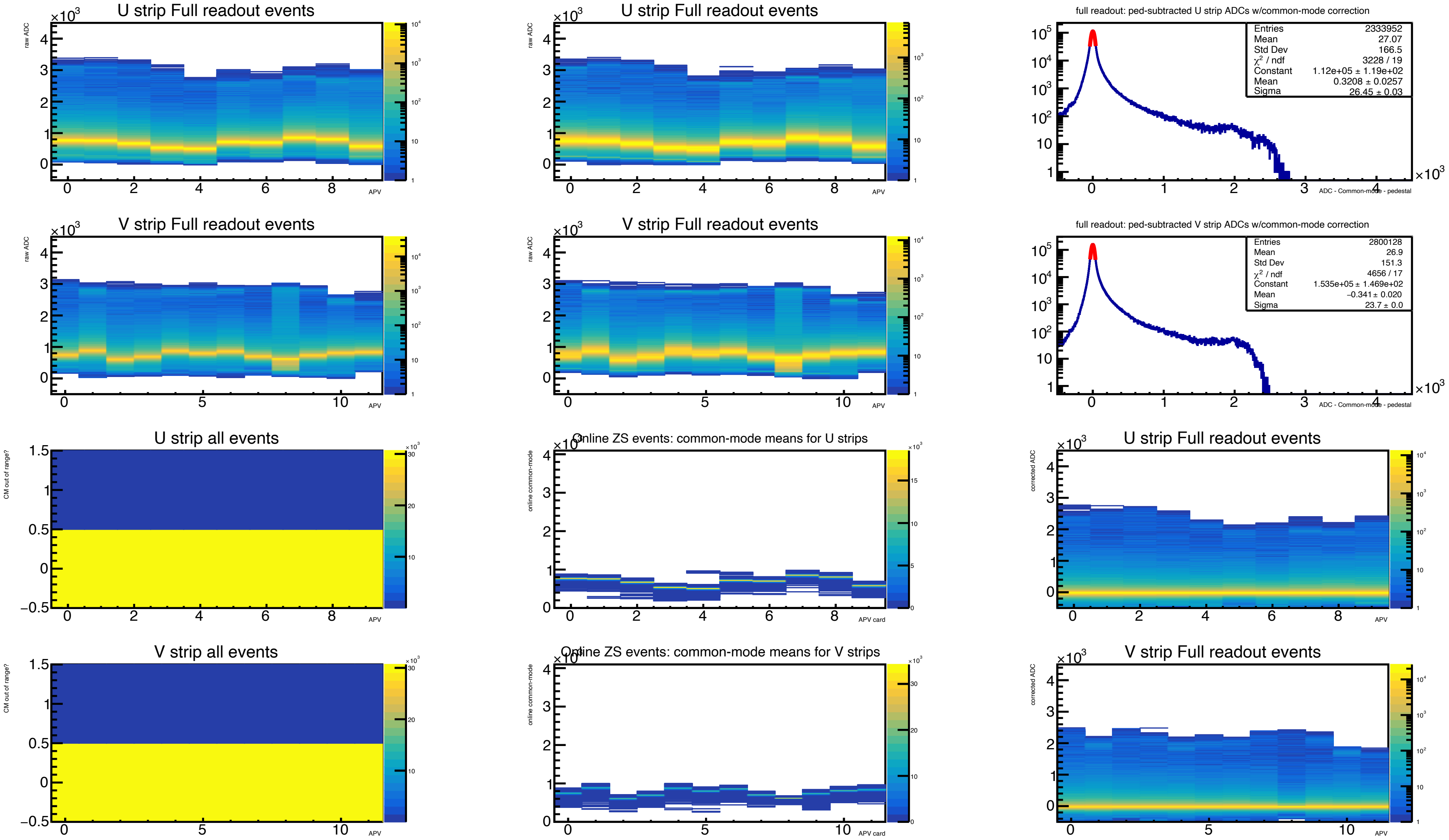
- GMn to 18 GeV^2—success of E12-09-019 clearly demonstrates feasibility, proposal already written since ~2009
- Higher-Q^2 GEn with Helium-3 → need neutron detector with better TOF/missing momentum resolution
- GEp to 15 GeV^2—need upgraded tracker and/or tracker electronics at minimum and higher-performing electron calorimeter
- A1/A2 neutron with Helium-3
  - BigBite/SBS can clearly improve on Hall C (at least statistics-wise)
- A1/A2 proton with NH_3
- Neutron DVCS—medium acceptance and medium resolution of SBS well-suited for DVCS from nuclear targets
- Other SIDIS—e.g., longitudinal spin structure with Helium-3 and/or NH3/ND3
- Exclusive phi and other VM production—BigBite + SBS w/HERMES RICH
- nDVCS
- Tensor polarized ND3 and T_{20}

Summary and Conclusions

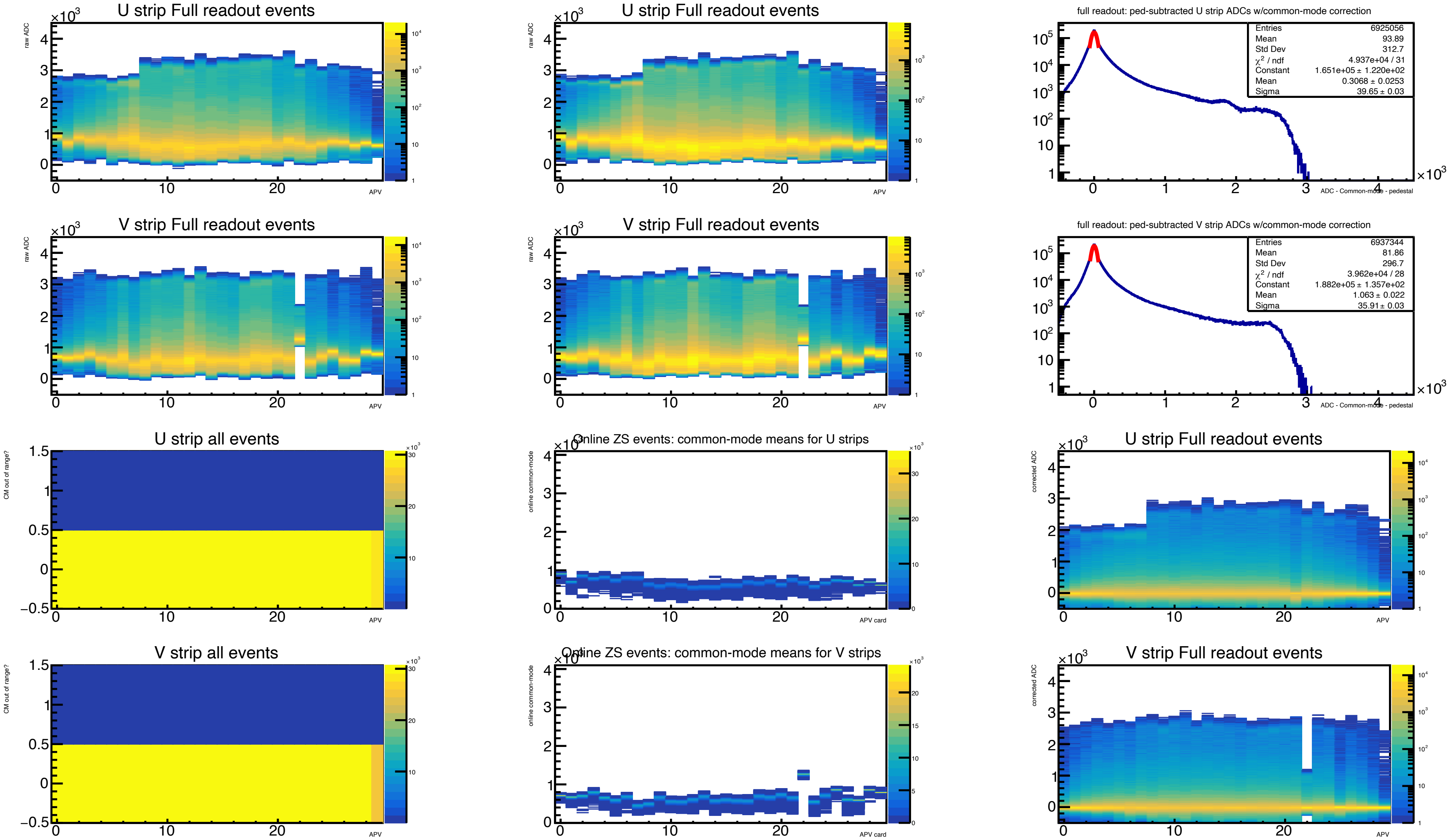
- As you have seen from the previous talks, the SBS FF program was a major success despite some setbacks and disappointments; reaching unprecedented Q^2 and precision for all four nucleon EMFFs
- SBS equipment adds a powerful capability to Halls A/C for one-and-two-arm experiments studying "hard" exclusive and semi-inclusive reactions at high intensity
- E12-09-018 (SIDIS SSA) is the largest remaining fully-approved SBS experiment on the books"
  - Needed detector capabilities already demonstrated
  - Needs Helium-3 target with transverse horizontal and VERTICAL polarization
  - Huge physics impact prior to SOLID/EIC
- Tagged DIS program making steady progress toward technical review for full approval
- Lessons learned from SBS 2021-2025 "era" help to plan for SOLID and other future intensity-frontier experiments
- Many compelling physics opportunities remain using SBS equipment!
- Thank you for your attention

Backups

APV25 baseline sagging/broadening—FPP module 6 @20 uA



APV25 baseline sagging/broadening—FT layer 5 @20 μA



Kinematic Conditions for applicability of TMD formalism

- Requires large Q² ($Q^2 > 1\ GeV^2$), large W ($W > 2\ GeV$), as in DIS
- Requires large (but not too large) z:
  - High enough for dominance of "current quark" fragmentation over "target remnant" fragmentation
  - Low enough to avoid dominance of exclusive/resonance region contributions (high Q^2 also helps here)
- Requires small (but not too small) p_T:
  - Large enough for meaningful sensitivity to effects of quark transverse motion/spin: $k_\perp \approx \Lambda_{QCD} \approx 200\ MeV$
  - Small enough for applicability of TMD formalism; i.e., dominance of TMD effects over collinear pQCD effects (gluon radiation, etc.)

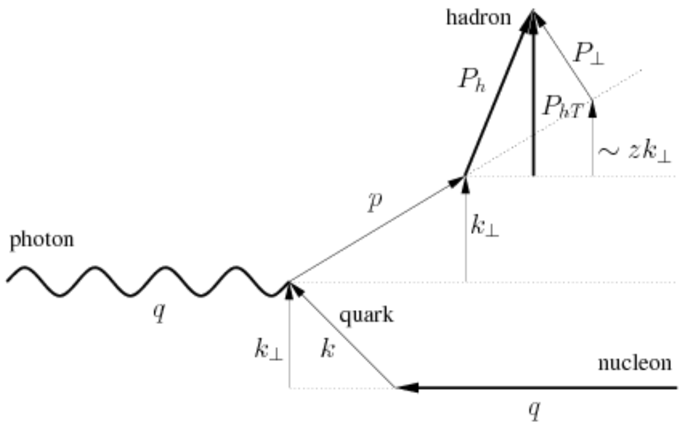


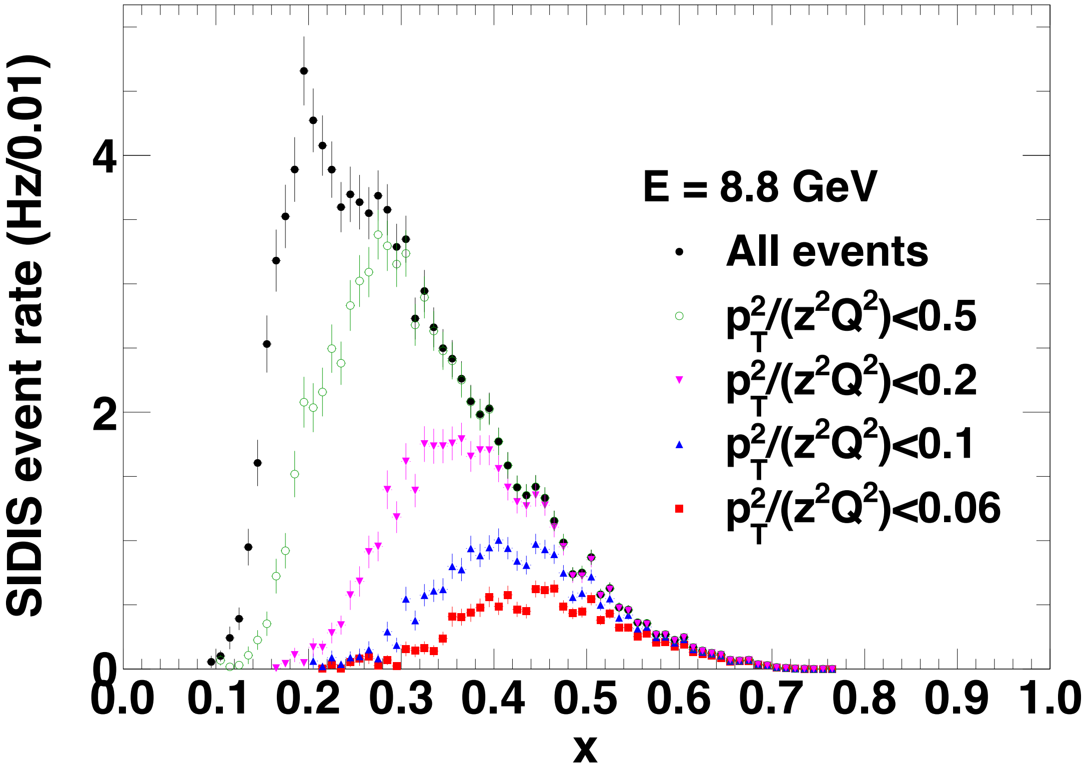
Figure credit: Bacchetta *et al.,* JHEP 1706 (2017) 081

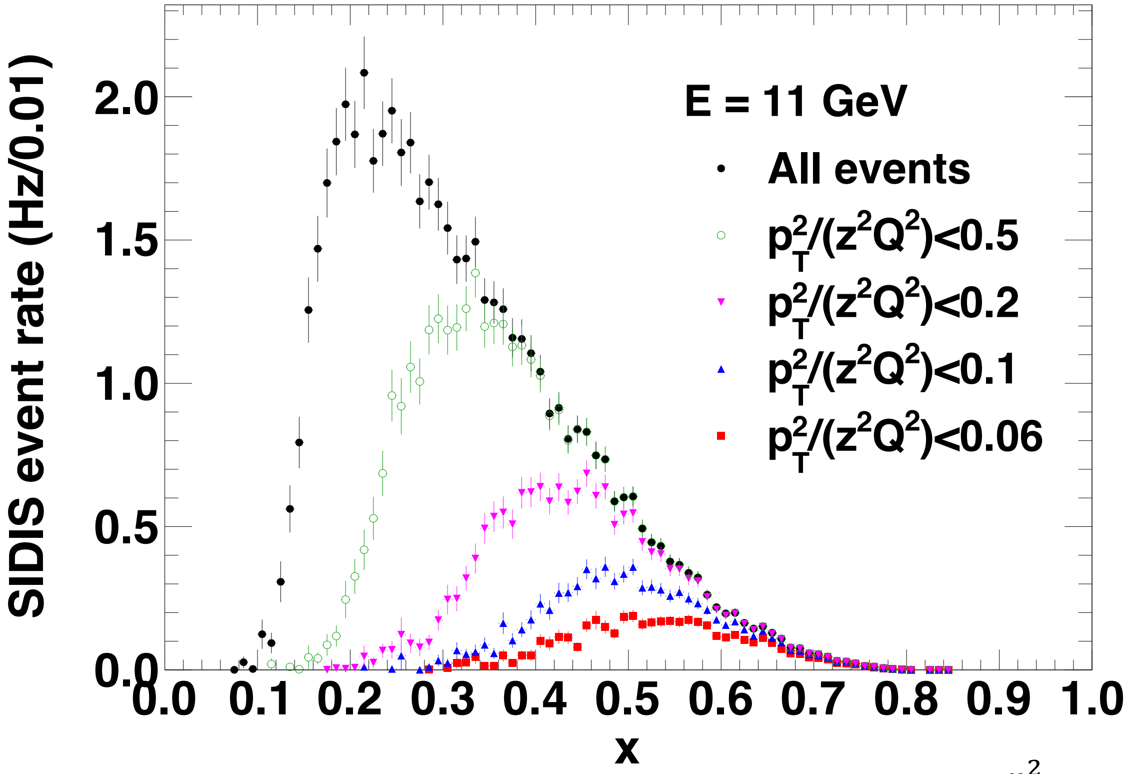
At leading order in $k_\perp/Q$, we have:

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

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

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





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

General Challenges of Measuring TMD-sensitive Observables

Statistics Requirements

Cross sections:

$$\sigma \propto N$$

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

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

Asymmetries:

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

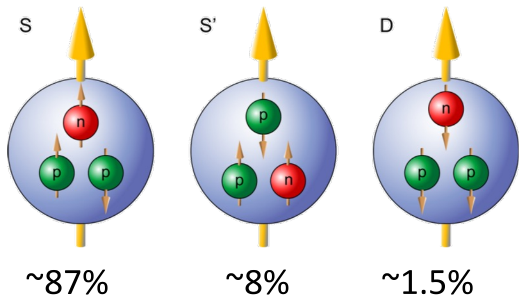
$$\frac{\Delta A}{A} = \sqrt{\frac{1 - A^2}{NA^2}}$$

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

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

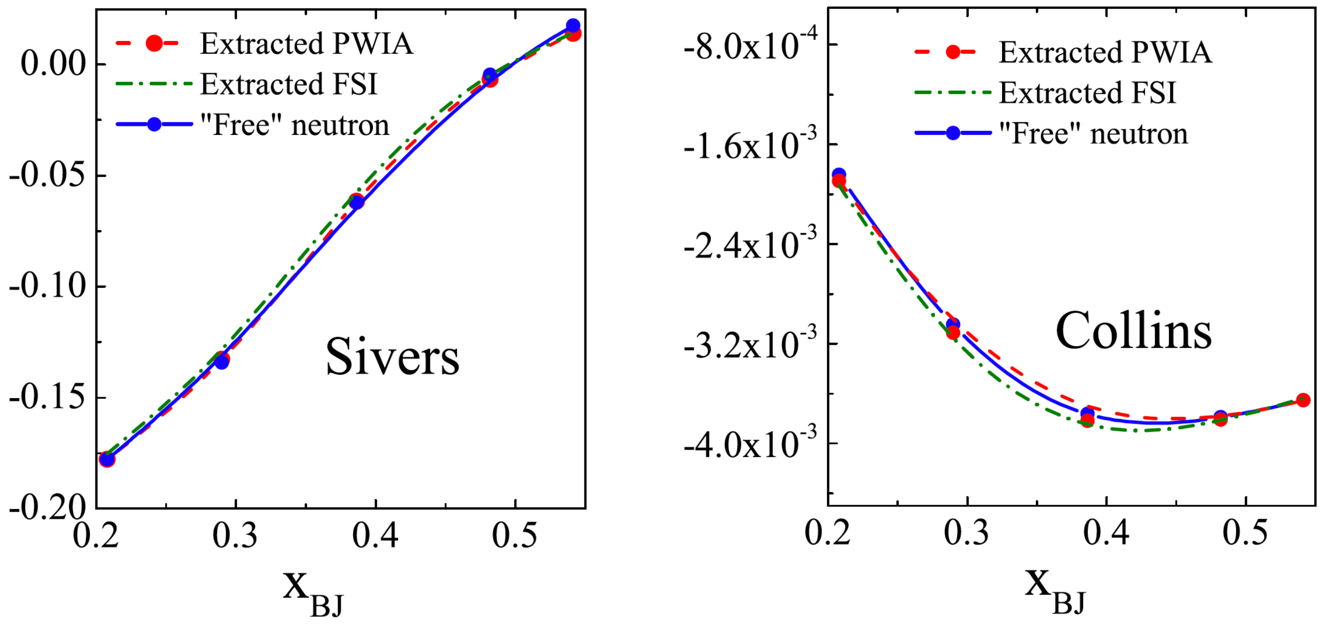
- SIDIS structure functions, *before* considering azimuthal angle dependence, are functions on a 4-D phase space (x, Q^2, z, p_T) (and a purely kinematic dependence on y for some observables due to helicity structure of hard partonic subprocess $eq \to eq$)
- Sufficiently high ***energy*** is needed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

Reminder: Helium-3 as Effective Polarized Neutron Target



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

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

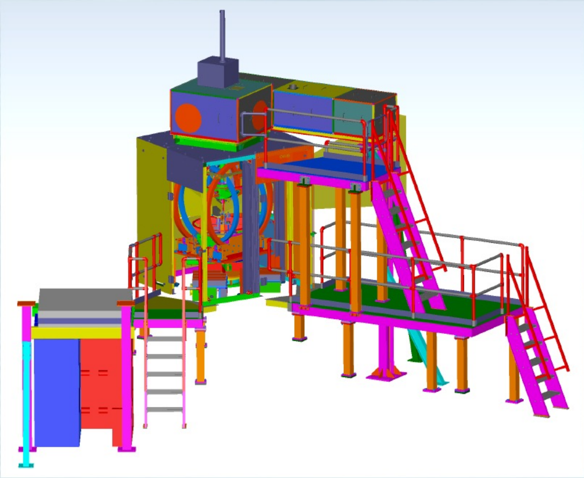


Del Dotto *et al.,* Phys. Rev. C 96, 065203 (2017)

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

The SBS GEN/SIDIS polarized Helium-3 Target

The SBS SIDIS
Polarized ^{3}He Target

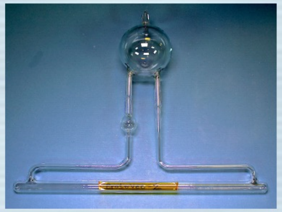


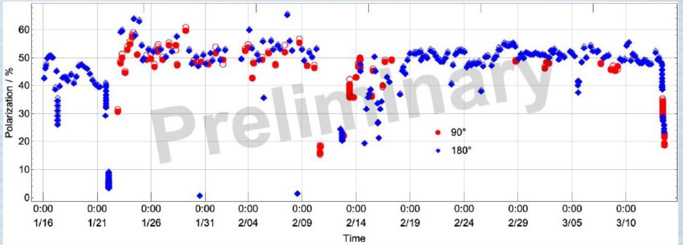
- Essentially the SBS G_E^n polarized ^{3}He target with small modifications
  - Will add capability for vertical polarization
- Magnetic shielding protects target from SBS and BigBite magnet fringe fields.
- For both SIDIS and G_E^n, the quantity of ^{3}He is twice what was used for recent Hall C experiments.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

6

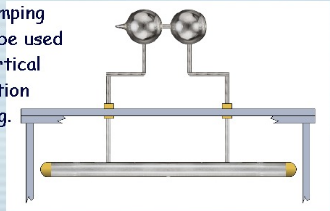
The SBS SIDIS
Polarized ^{3}He Target

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





Double pumping chamber to be used during vertical polarization running.

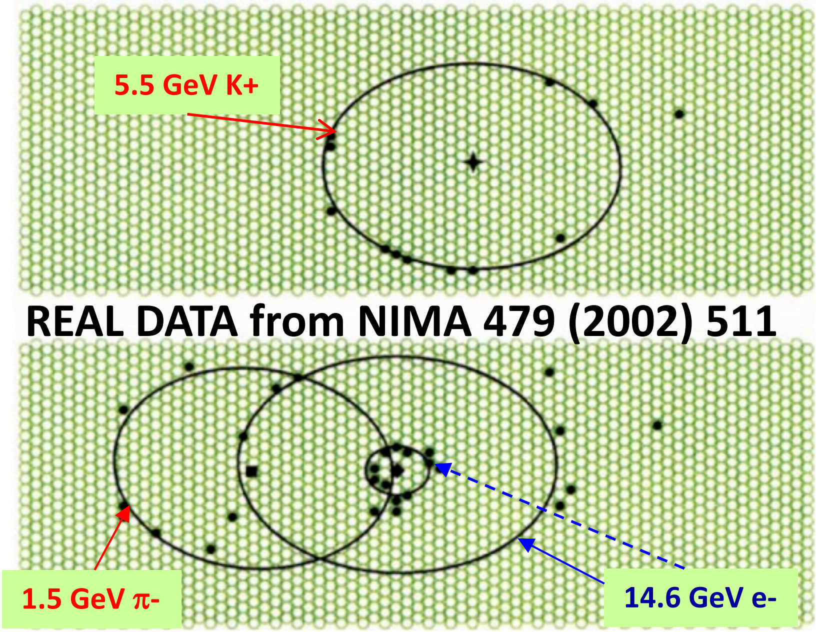


- The Hall C polarized ^{3}He target was the first used at JLab with the so-called "convection design", permitting full control of the movement of gas between the pumping and target chambers.
- The figure-of-merit of the Hall C A_1^n target was over twice that achieved with a polarized ^{3}He target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

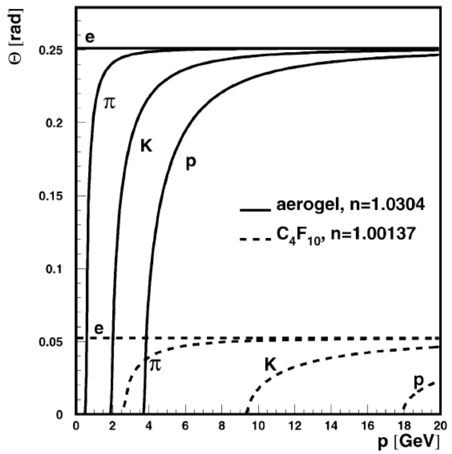
7

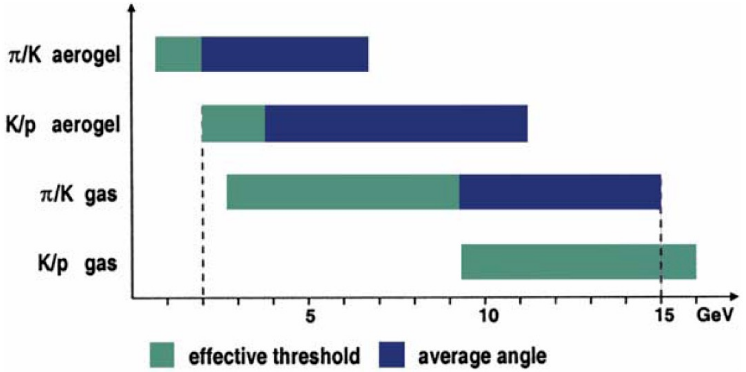
- These slides are from Gordon's Jeopardy presentation at PAC49 (2021, before GMN started)
- See also Gordon's target talk

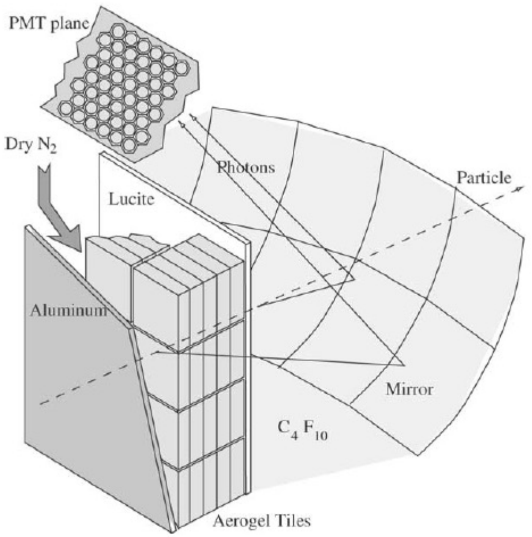
The HERMES/SBS RICH detector, I

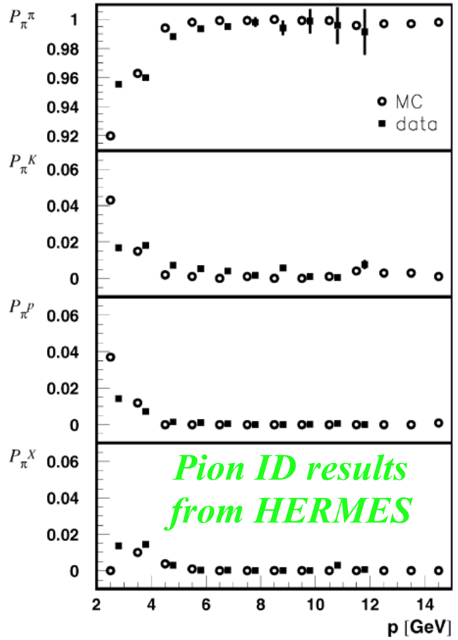


- ***HERMES RICH geometry, performance characteristics well matched to SBS needs.***
- π/K/p separation for p from 2-15 GeV based on dual-radiator design.
- Re-use one half of detector, both aerogels

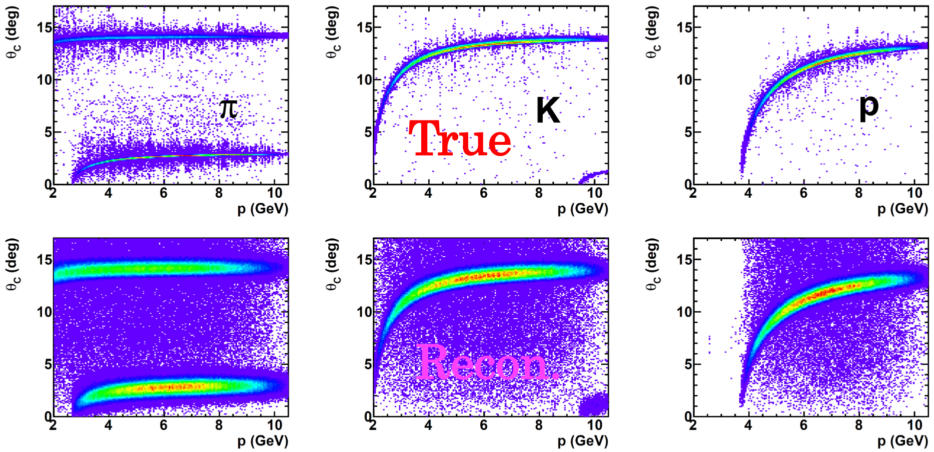




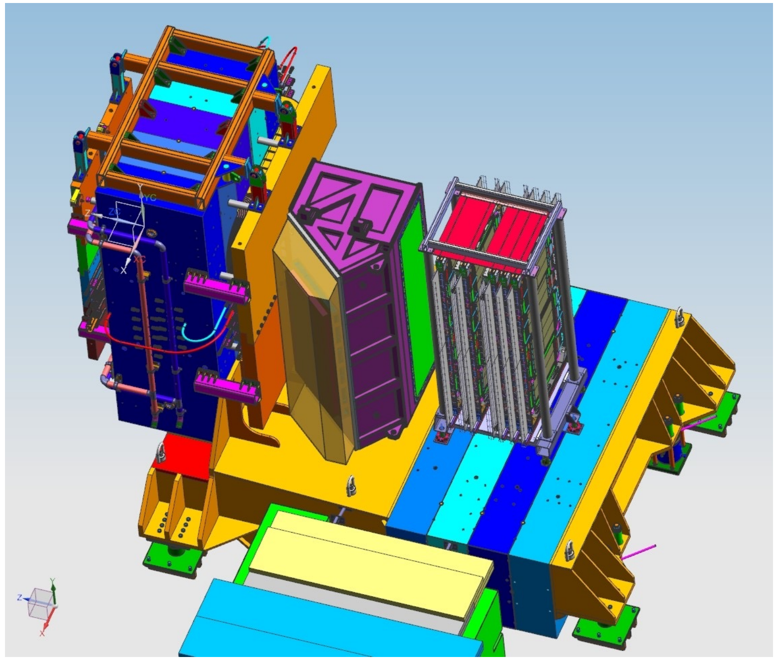




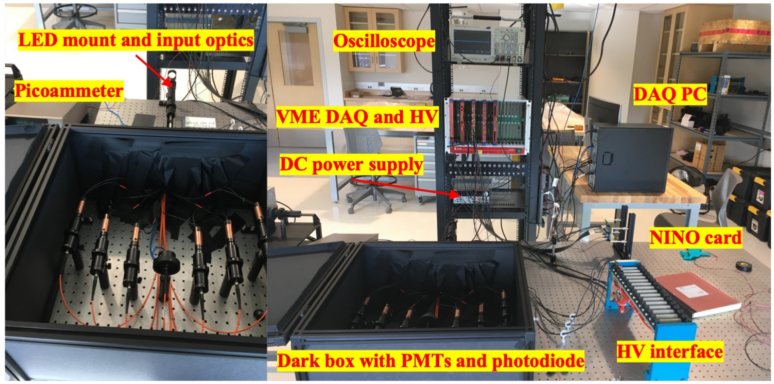
The HERMES/SBS RICH detector, II



Simulated RICH reconstruction in SBS

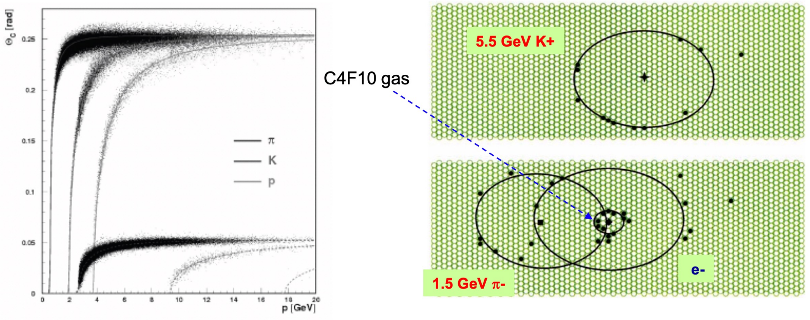


RICH in SBS CAD model

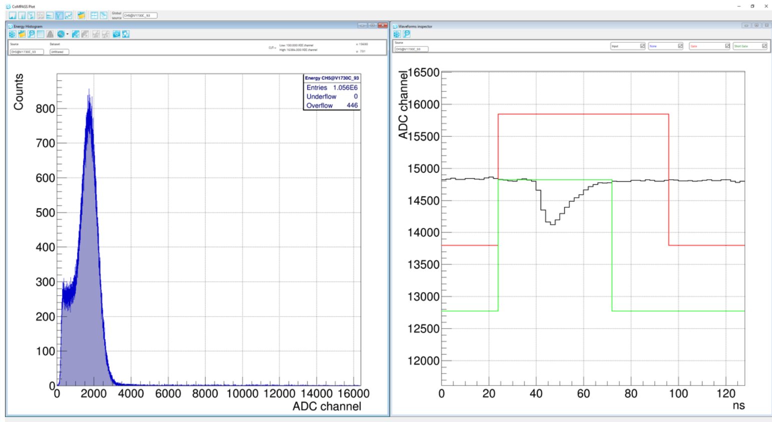


RICH PMT test stand at UConn

RICH detector at JLab



RICH performance in HERMES



RICH PMT single-photoelectron pulse and charge spectrum

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

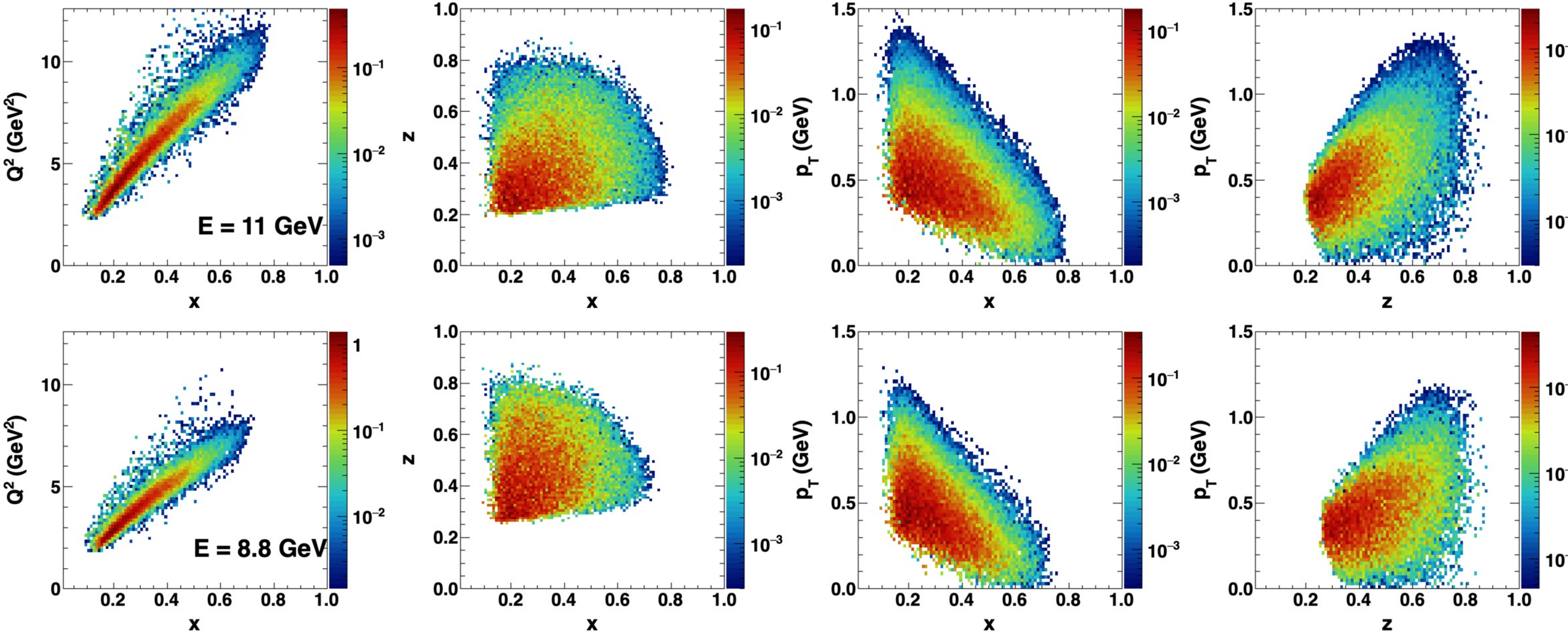
$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,d\phi_S\,dp_T^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \epsilon F_{UU,L} +$$
$$\sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h} +$$
$$\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h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

- Sivers
- Collins
- "Pretzelosity"

- SIDIS structure functions depend on *x*, Q^2, *z*, p_T
- U, L, T subscripts indicate unpolarized, longitudinally and transversely polarized beam, target, respectively
- S = nucleon spin
- λ = lepton helicity
- **Eight terms survive at leading twist; the rest are twist-3 (M/Q suppressed)**
- Azimuthal modulations allow separation of structure functions
- Partonic interpretation: SIDIS structure functions factorize as convolution of universal TMD PDF, universal TMD FF, and perturbatively calculable "hard" subprocess *eq* → *eq*

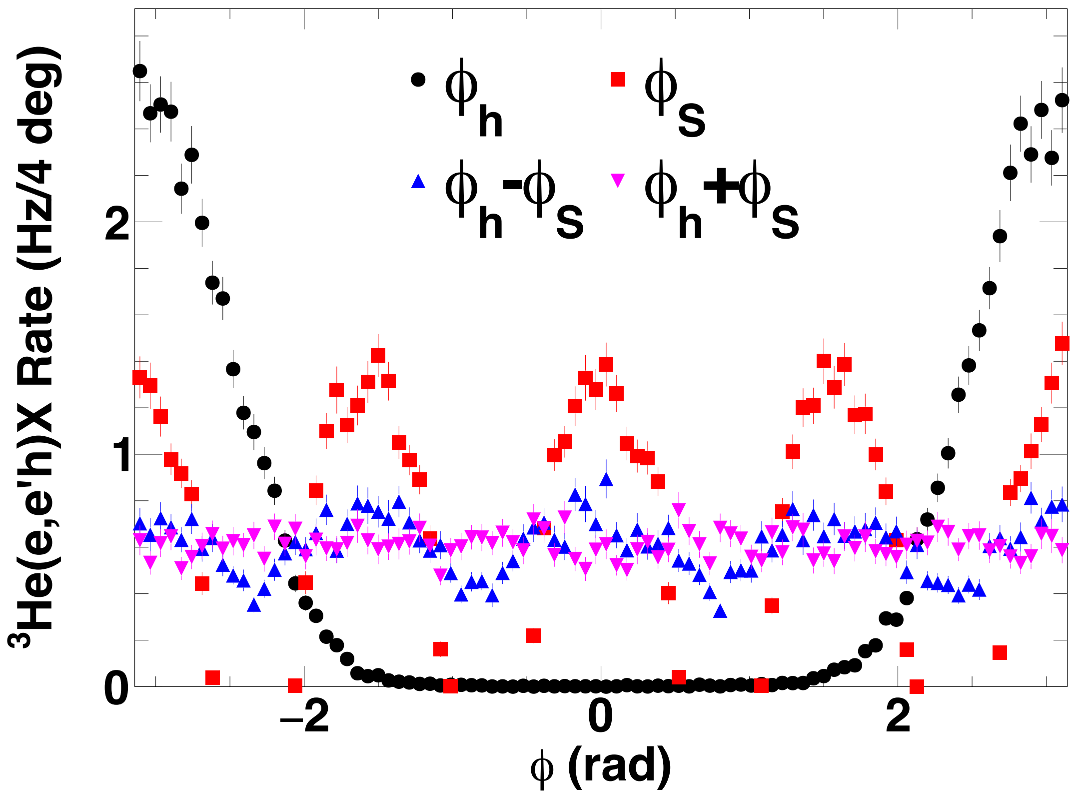
$$\gamma = \frac{2Mx}{Q}$$
$$\epsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

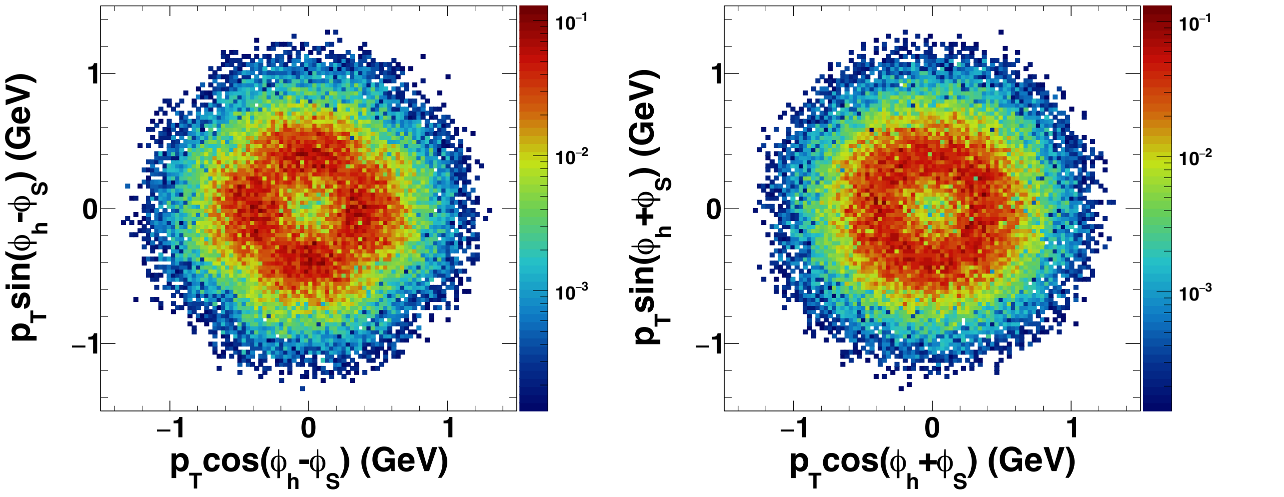
SBS SIDIS Kinematic Coverage

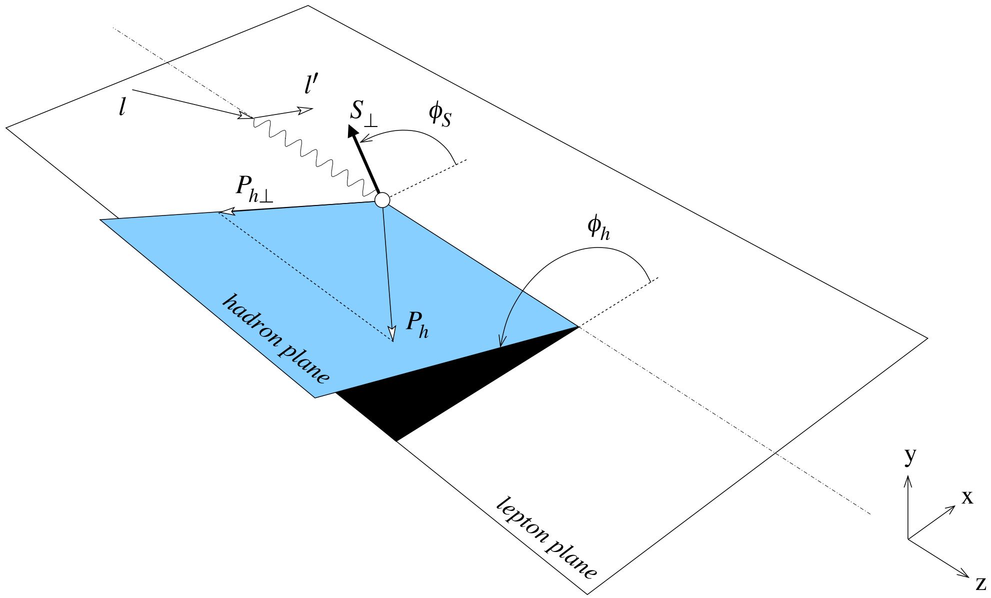


- Above, left to right: SBS SIDIS kinematic coverage in $(Q^2, x), (z, x), (p_T, x), (p_T, z)$, for E = 11 GeV (top row) and 8.8 GeV (bottom row), from *g4sbs*
- Cuts applied are: $Q^2 \geq 1\ GeV^2, W^2 \geq 4\ GeV^2, M_X^2 \geq 2.3\ GeV^2, E_e' \geq 1\ GeV$ (roughly equivalent to $y \leq 0.9$), $p_h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

SBS SIDIS Azimuthal Angle Coverage







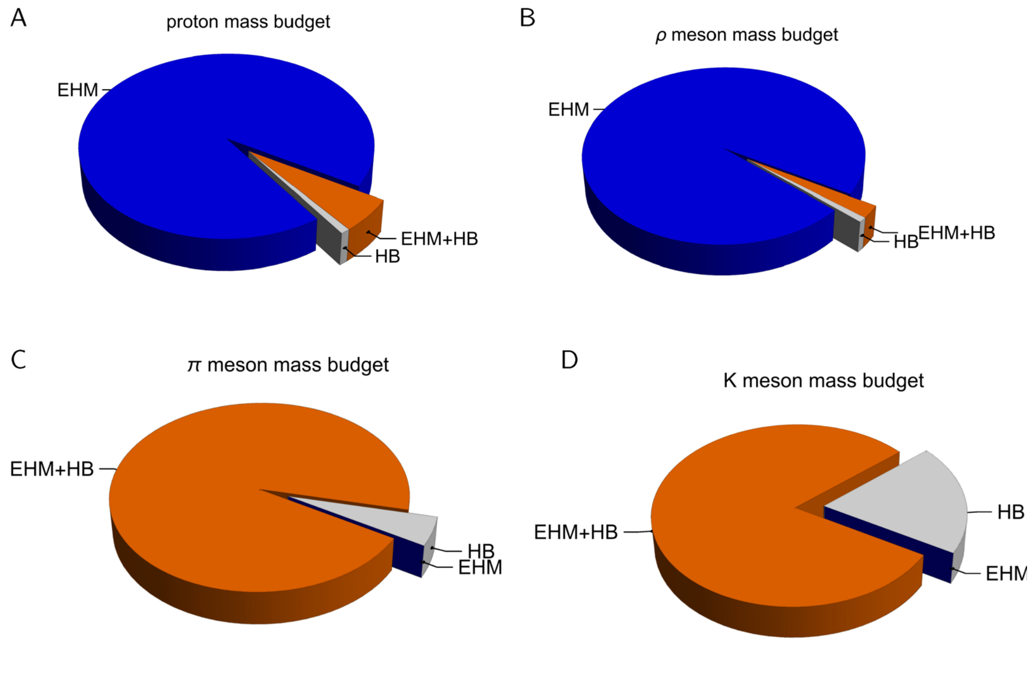
- Original proposal envisioned 8 target spin directions
- Simulations show full and (sufficiently) uniform coverage of $\phi_h \pm \phi_S$, no reduction of physics impact with 4 target directions
- Dramatically simplifies target design & operation

Since approval, there has been a surge of interest in both the technique and the science goal

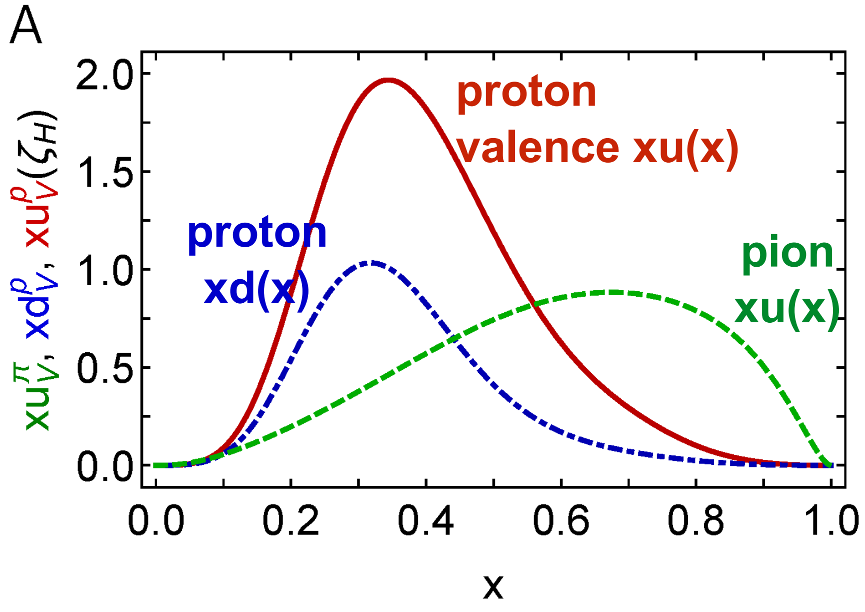
Significant progress in understanding meson structure through emergent hadron mass - over 50 publications with more than 1200 citations (including LRP white paper & EIC yellow report).

Mass budget for mesons and nucleons are vastly different

- Emergent hadron mass
- Interference of emergent hadron mass & Higgs mechanism
- Higgs mechanism



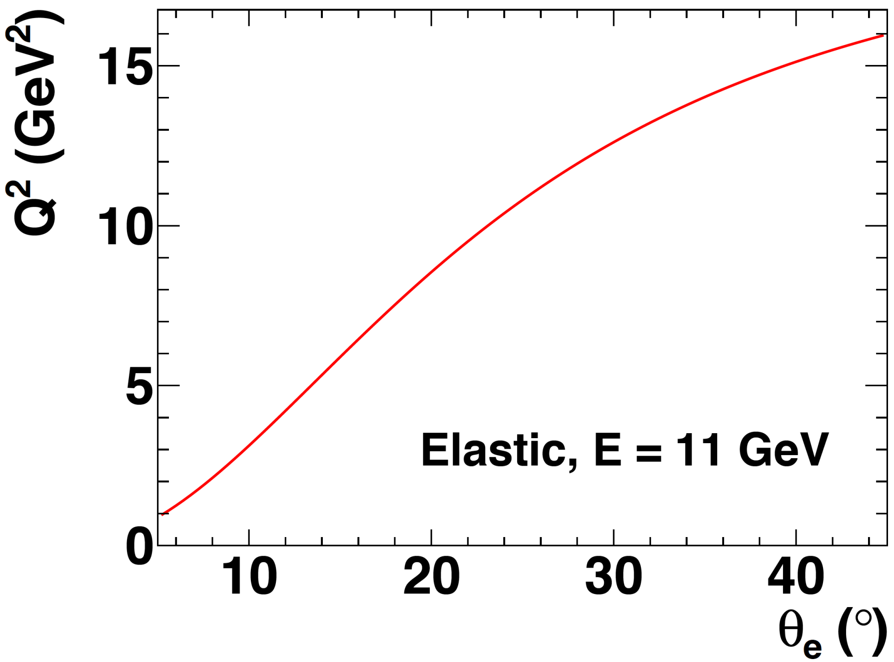
M. Ding, C.D. Roberts & S.M. Schmidt, *Particles* 6, 57 (2023)



pion/proton valence quark distributions are very different

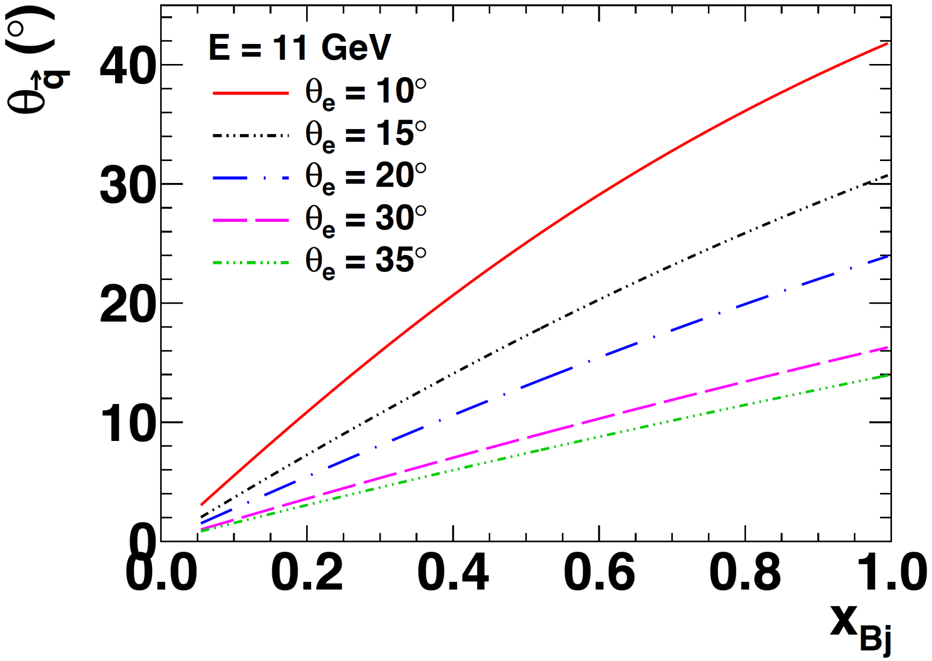
difference between meson PDFs: direct information on emergent hadron mass

Fixed-target Electron Scattering Kinematics @11 GeV



- 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:

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



- 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***