

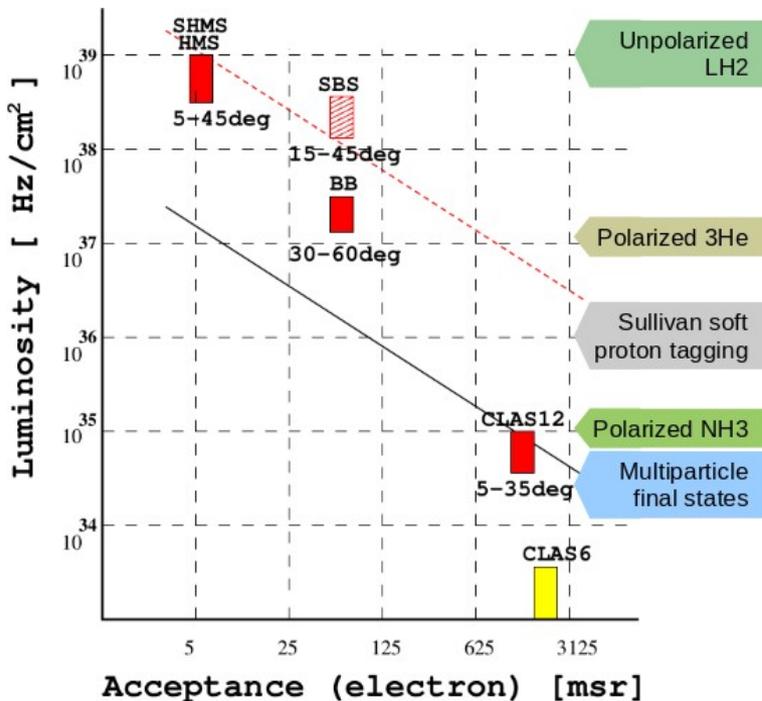
SBS SIDIS (E12-09-018)

Semi-Inclusive Deep Inelastic Scattering on a Transversely Polarized He-3 Target using the BigBite and Super BigBite Spectrometers in Hall A

*G. Cates (UVa), E. Cisbani (INFN),
A.J.R. Puckett (UConn), B. Quinn (CMU),
B. Wojtsekhowski (JLab)*

SBS/BB program (~2007 →)

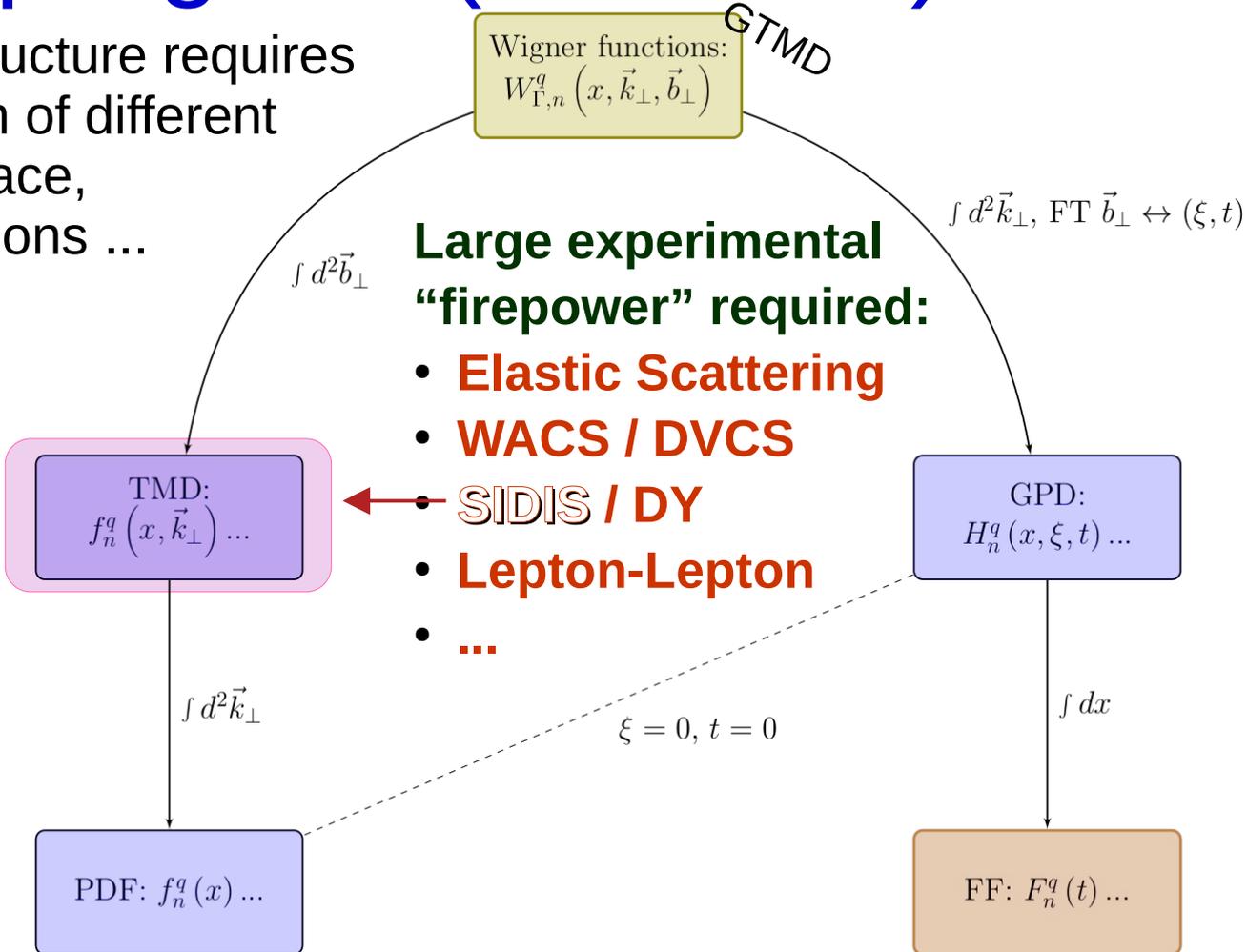
Study the complex hadron structure requires the experimental investigation of different processes on large phase space, with specific kinematic conditions ...



Wigner functions: $W_{T,n}^q(x, \vec{k}_\perp, \vec{b}_\perp)$ ^{GTMD}

Large experimental “firepower” required:

- Elastic Scattering
- WACS / DVCS
- SIDIS / DY
- Lepton-Lepton
- ...



SIDIS and Transverse Momentum Distributions

Kinematical conditions for SIDIS/TMDs

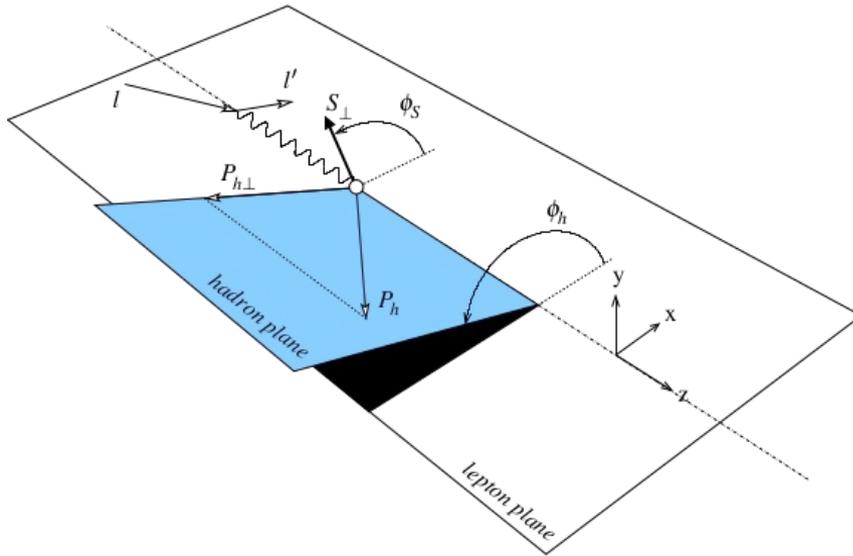
DIS region: $Q^2 > M_N^2$ and $\nu > M_N$

Large (but not too large) z :

- “current quark” fragmentation > “target remnant” fragmentation
- avoid dominance of exclusive/resonance region contributions

Small (but not too small) $P_{h\perp}$:

- sensitivity to quark transverse motion/spin
- applicability of PDF/TMD formalism; i.e., dominance of TMD effects over collinear pQCD effects (gluon radiation, etc.)



Q^2, ν

x, k_\perp

K_\perp

$z, P_{h\perp} \equiv p_T$

ϕ_h

ϕ_S

γ 4-momentum and energy

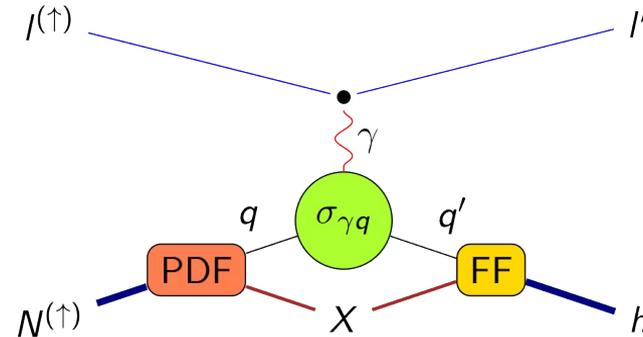
q long. mom. fraction, trans. mom.

q' trans. momentum

h energy fraction, trans. mom.

h azimuthal angle

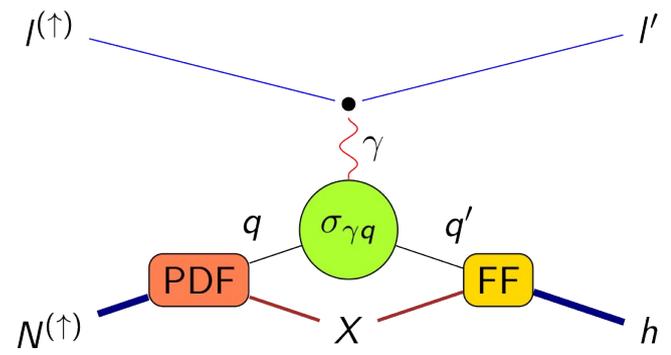
N spin azimuthal angle



$$\sigma^{SIDIS}(lN \rightarrow lhX) \sim$$

$$\sum_q e_q^2 \cdot PDF^q(x, k_\perp) \otimes \sigma_{\gamma q} \otimes FF_{q' \rightarrow h}(z, K_\perp)$$

Transverse-Target Spin Asymmetries (TTSA)



$$PDF^q(x, k_\perp) \equiv TMD$$

N \ q	U	L	T
U	f_1		h_1^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}	h_1, h_{1T}^\perp

(polarized target)

$$A_{UT} \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

$$A_{LT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow} + d\sigma^{\downarrow\uparrow} - d\sigma^{\downarrow\downarrow}}{\sum_{b,T} d\sigma^{b,T}}$$

(polarized beam and target)

Structure functions (out of 8) at leading order in M_N/Q can be extracted by proper azimuthal modulation

$$A_{UT}^{Collins} \sin(\phi_h + \phi_S) \sim \sum_q e_q^2 [h_1^q \otimes H_{1q}^\perp]$$

“Clean” probe of relativistic effects chiral-odd PDF and FF
 h_1 : correlation between N transverse spin \leftrightarrow q transverse polarization

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

Link to quark Orbital Angular Momentum and QCD FSI mechanism;
 “probe” of PDF universality
 f_{1T} : correlations between N transverse spin \leftrightarrow (unpolarized) q transverse momentum (naive-T-odd, opposite sign SIDIS/DY)

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

h_{1T} : chiral-odd, correlation between N transverse spin \leftrightarrow momentum of transversely polarized q; sensitive to q orbital motion in the N

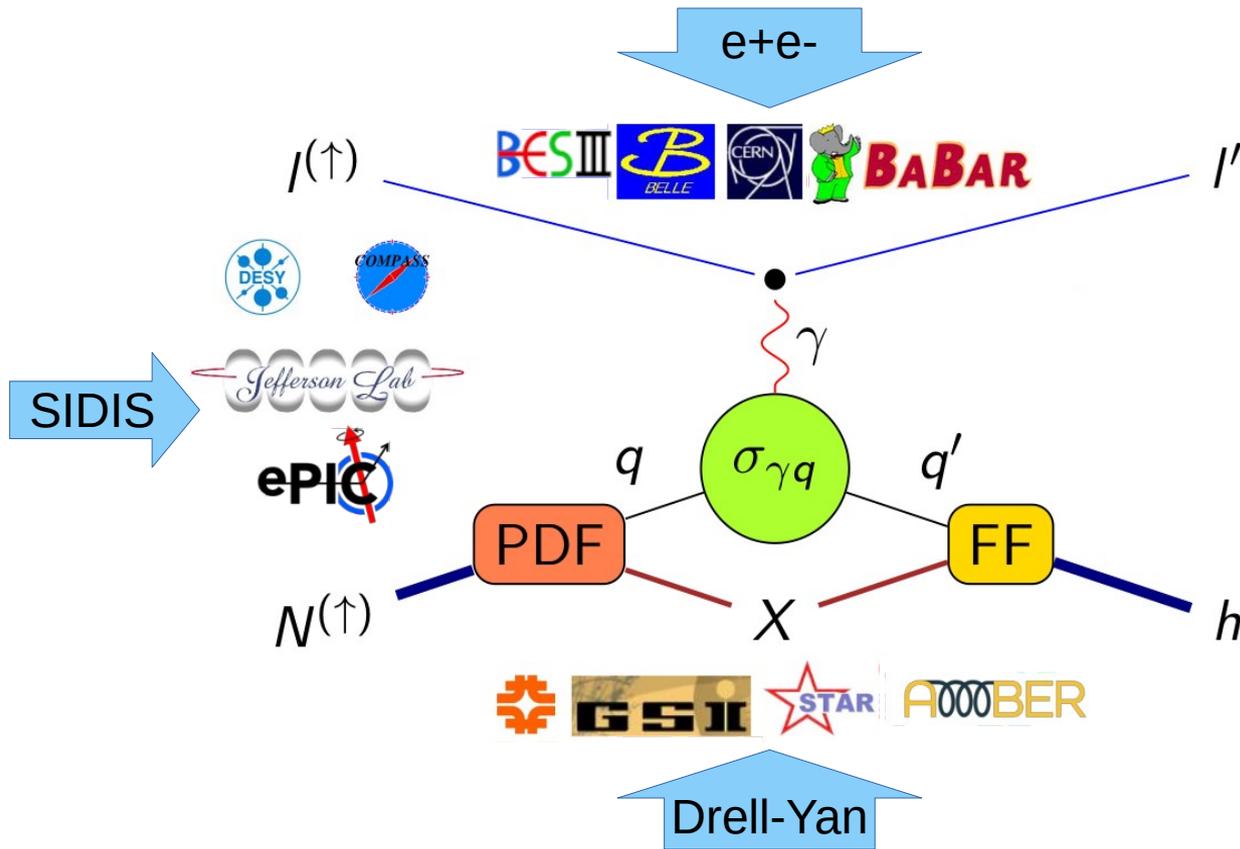
$$A_{LT}^{wg} \cos(\phi_h - \phi_S) \sim \sum_q e_q^2 [g_{1T}^q \otimes D_{1q}]$$

g_{1T} : longitudinally polarized q on transversely polarized N; one of the least know TMDs

$$\otimes \equiv \int \cdot d^2 K_\perp d^2 k_\perp$$

\rightarrow 3D description of the nucleon structure in momentum space

Factorization and Universality

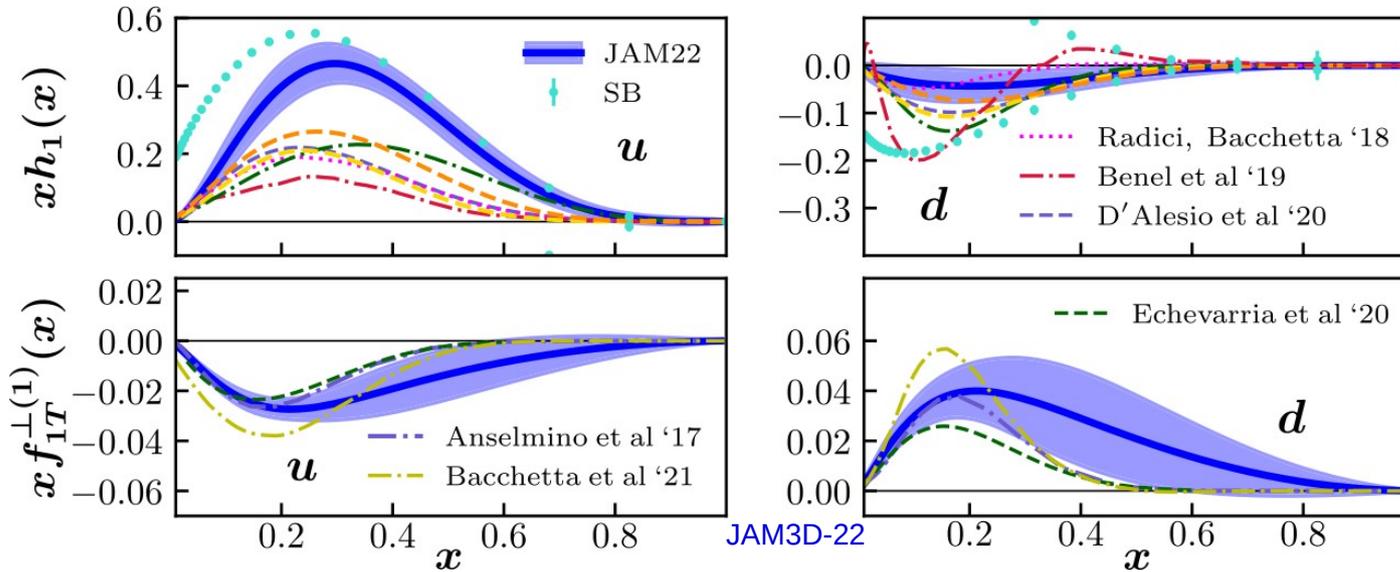


PDF/TMD and Fragmentation Functions (FF) describe SIDIS, Drell-Yan and e^+e^- annihilation into hadrons pairs; optimal exploitation of the data collected in these processes requires global analyses (combined to theoretical models) \rightarrow becoming the standard approach of investigation

Global Analysis – Single Transverse-spin asymmetries

Simultaneous fits of SIDIS, Drell-Yan and e^+e^- data

TMD evolution frameworks now standard in fits



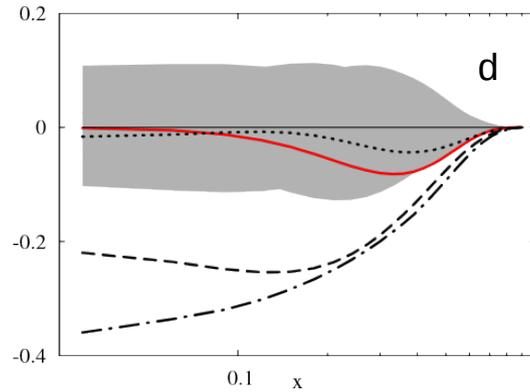
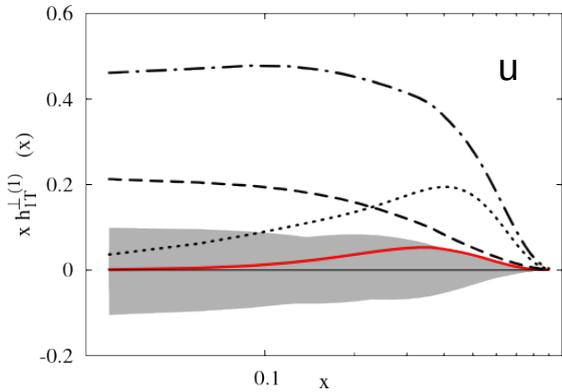
L. Gamberg et al. Phys. Rev. D 106, 034014 (2022)
JLab Angular Momentum Collaboration

SIDIS:
HERMES+COMPASS
 e^+e^- :
Belle+BABAR+BESIII
Drell-Yan:
STAR+COMPASS

Sivers d-quark (in particular) is still poorly constrained by existing data in the valence region (proton data dominated by u-quarks)

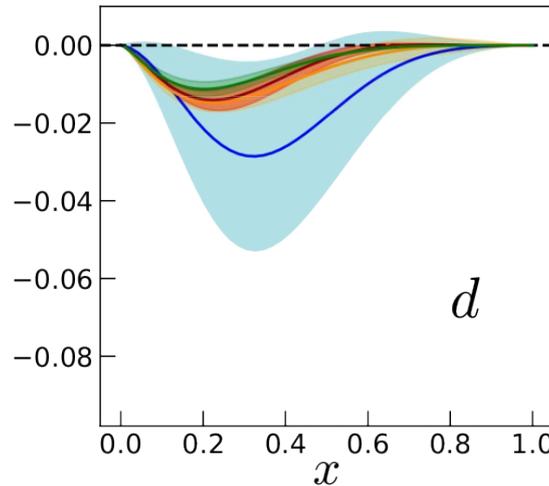
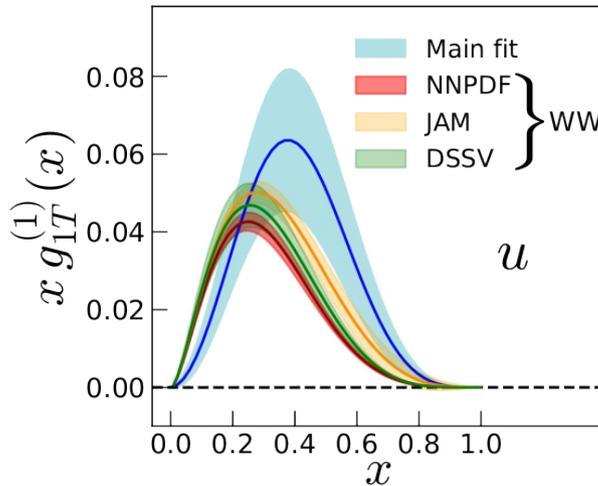
Significant margin to improve flavor decomposition by new data

Pretzelosity and worm-gear analyses (data fits)



C. Lefky & A. Prokudin (2015)
doi: 10.1103/PhysRevD.91.034010

red line: best fit, shadowed region: error
data are mainly from JLab/HallA



SIDIS data from
HERMES
COMPASS
JLAB

S. Bhattacharya et al., (2022) arXiv:2110.10253

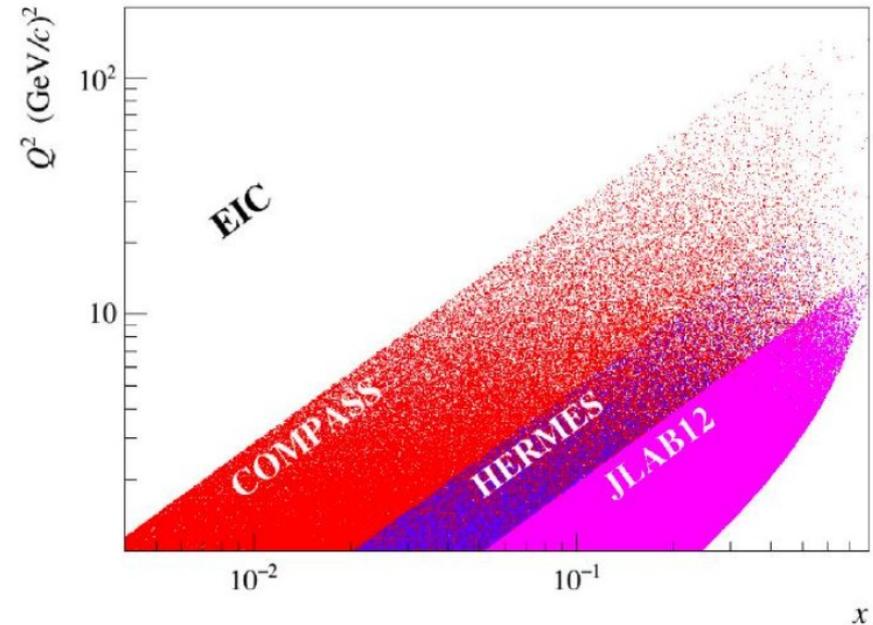
First global extraction of the
worm-gear TMD g_{1T}

- large error at $x > 0.2$

Both demand for more (precise) data

SIDIS – Exp. Status

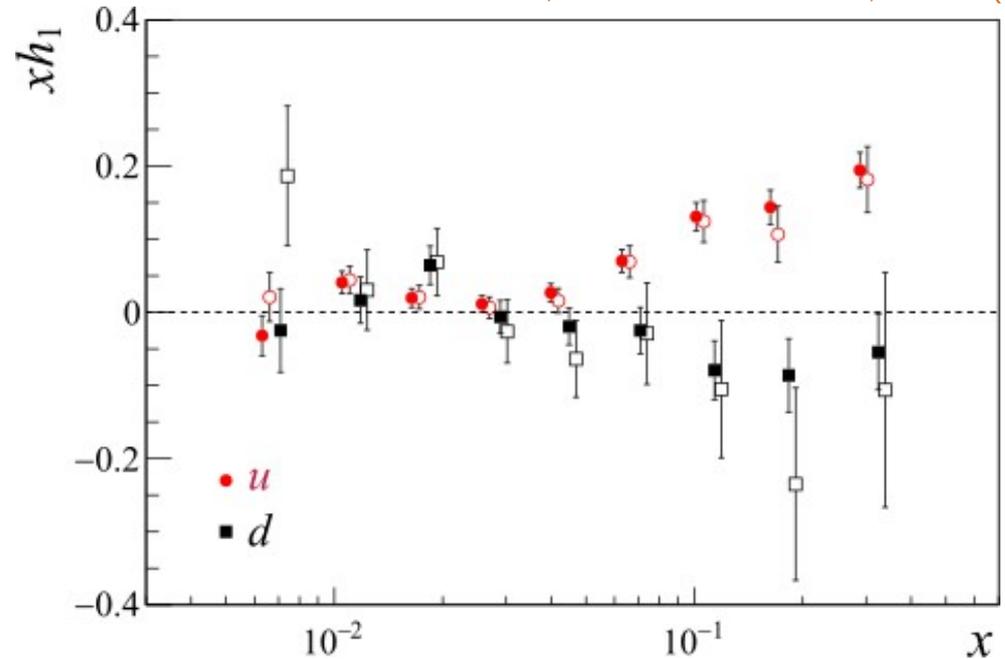
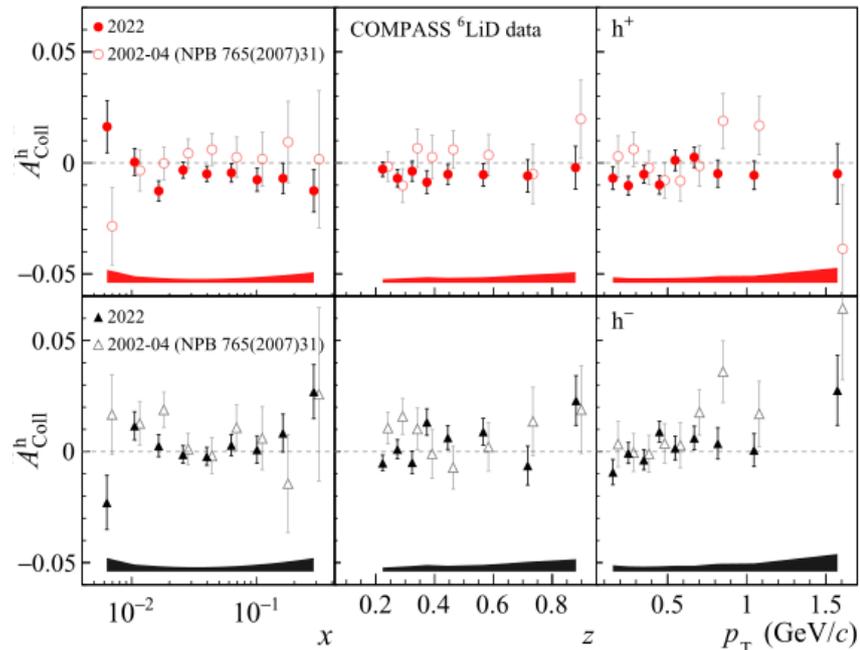
- HERMES: refined/extended analysis of pre 2000 data
- COMPASS: completed major high-statistics measurements of Collins and Sivers by 160 GeV/c muons on ${}^6\text{LiD}$ target in 2022
- JLAB: past, ongoing and future (extended) measurement with high accuracy
- EIC: future exploration in particular at very low x



COMPASS / 2022 - transversity

- Transversity flavor decomposition
- latest measurement improved statistical accuracy up to a factor of ~ 3

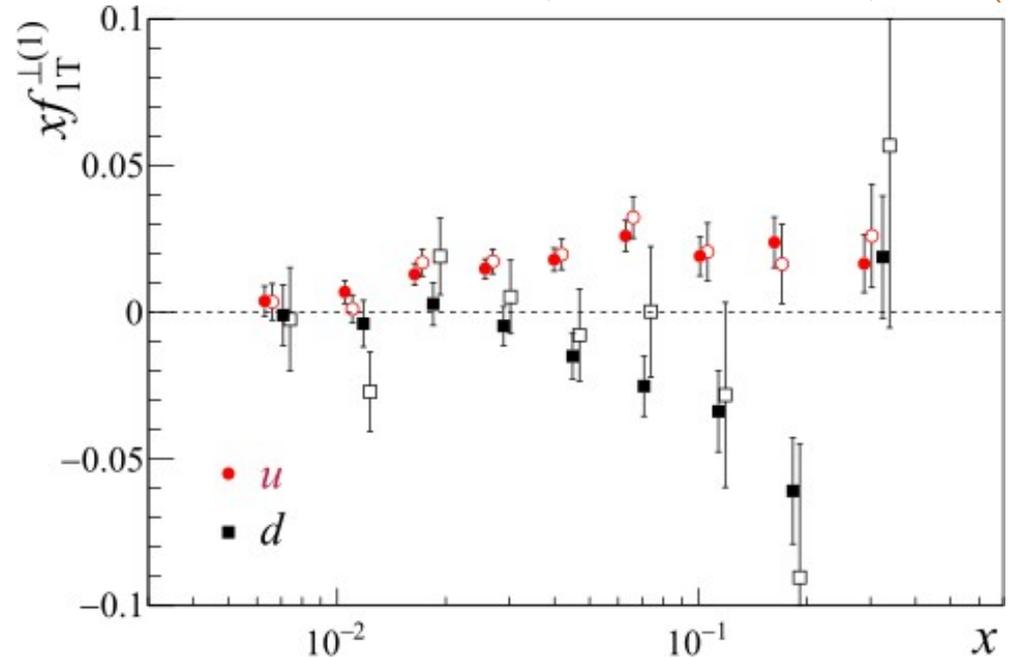
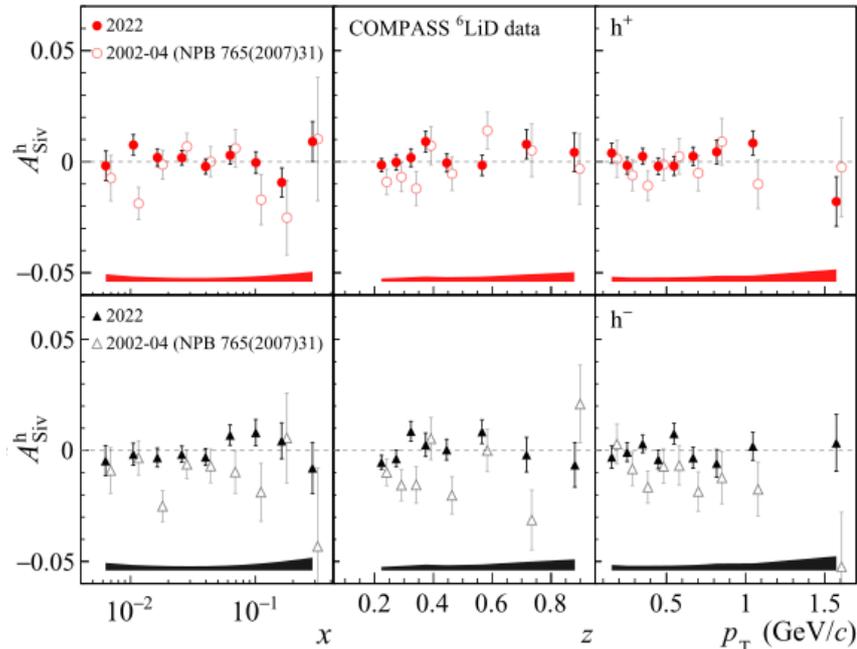
G.D. Alexeev et al, PHYS. REV. LETT. 133, 101903 (2024)



COMPASS / 2022 - Sivers

- Sivers TMD flavor decomposition
- latest measurement improved statistical accuracy up to a factor of ~ 3

G.D. Alexeev et al, PHYS. REV. LETT. 133, 101903 (2024)



SIDIS/TTSA program @ JLab12

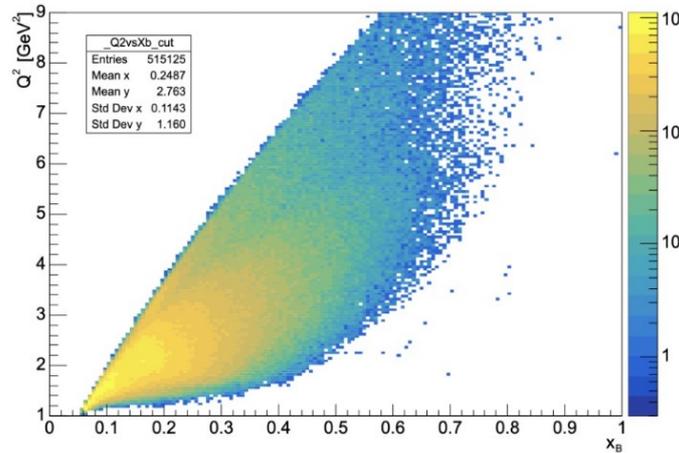
	SBS-SIDIS	CLAS12 RGH	SoLID
Acceptance	Small–medium	Very large	Large
Luminosity (1/cm²/s)	10 ³⁷	5 x 10 ³³	10 ³⁷
Pol. Target	Mature ³ He	NH ₃ (No HDice) + beam chicane	Mature ³ He & protons
Kinematic coverage	Focused region	Broad (x,Q ² ,z,P _{hT})	Broad + fine binning
Systematic control	"Straightforward" tracking setup	Challenging large acceptance	Requires extensive modeling
Flavor separation	Good (neutron focus)	Excellent (multi targeting)	Excellent (neutron + proton)

CLAS12 - RGH

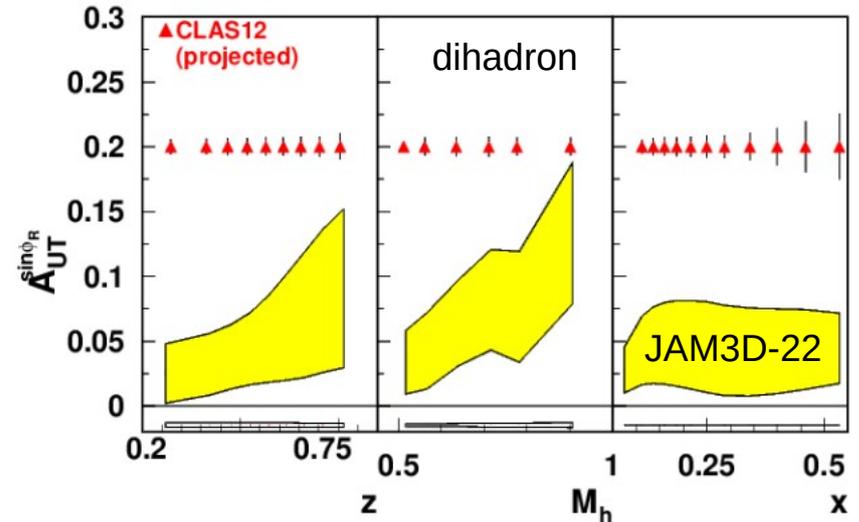
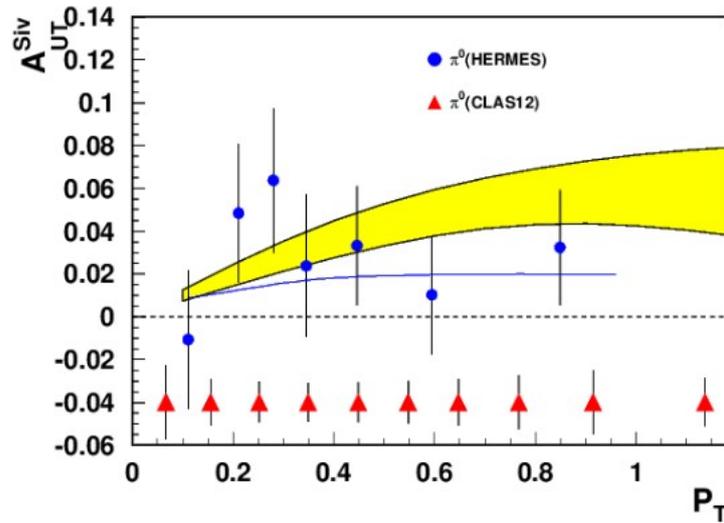
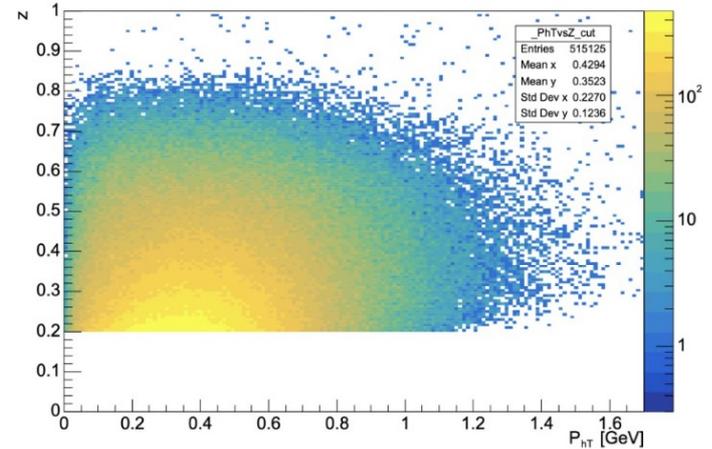
PAC53 – 2025 A rating

- 3 experiments with transversely polarized proton target
- single and dihadron detection
- SIDIS and DVCS investigation on proton

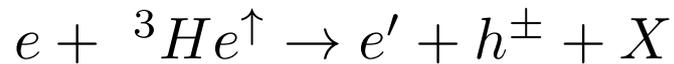
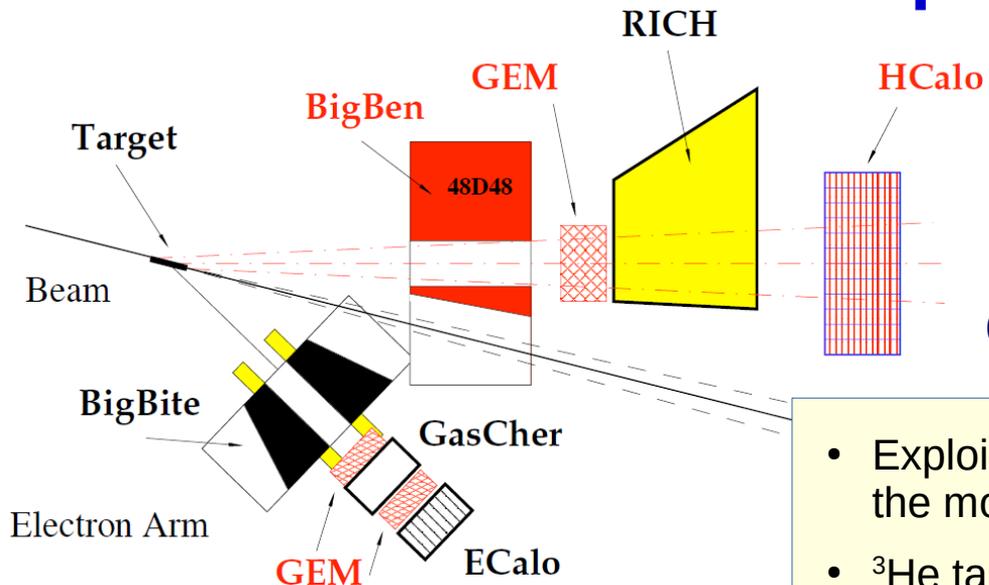
Correlation Q^2 vs x_B | Pion | $z > 0.2, M_x > 1.6$ GeV



Correlation P_{hT} vs Z | Pion | $M_x > 1.6$ GeV



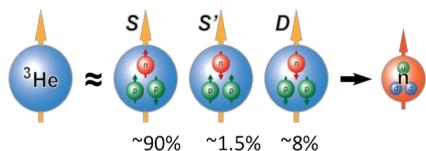
SBS-SIDIS Experimental Concept



$h = \pi \text{ or } K$

$$A_{UT} = \frac{1}{P_t f} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \quad \text{FOM} \sim P_t^2 \cdot f^2 \cdot L$$

0.3 < z < 0.7 for π 's; more restricted range for charged K's



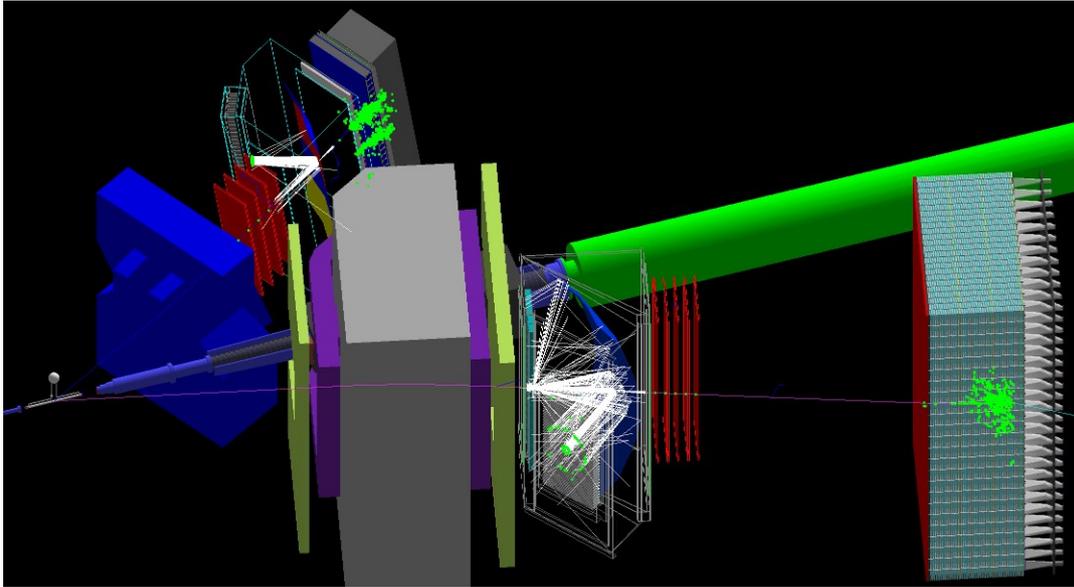
Lumi > 10^{37} Hz/cm²

(HERMES unp. $\leq 2.5 \cdot 10^{33}$ Hz/cm²)

Th. Benisch et al. NIMA 471 (2001) 314

- Exploit focusing of scattered hadrons along the direction of the momentum transfer \mathbf{q}
- ${}^3\text{He}$ target as effective polarized neutron target
- Flexible orientation of the target polarization within the plane perpendicular to \mathbf{q} thanks to the modest field (tens of Gauss) in the target region
- Use two moderately large open-geometry dipoles (40-50 msr)
- Dipoles sweep out low energy background
- GEM tracking, RICH PID, e/h Calorimeters

SBS-SIDIS Experiment Configuration Details



Two beam energy settings: 8.8 and 11 GeV
(x 2 target orientations)

^3He transversely polarized target

→ Gordon talk on Wed

Electron Arm: BigBite

- GRINCH: pion rejection (and photon rejection in trigger)
- Lead-glass calo: trigger and additional pion rejection

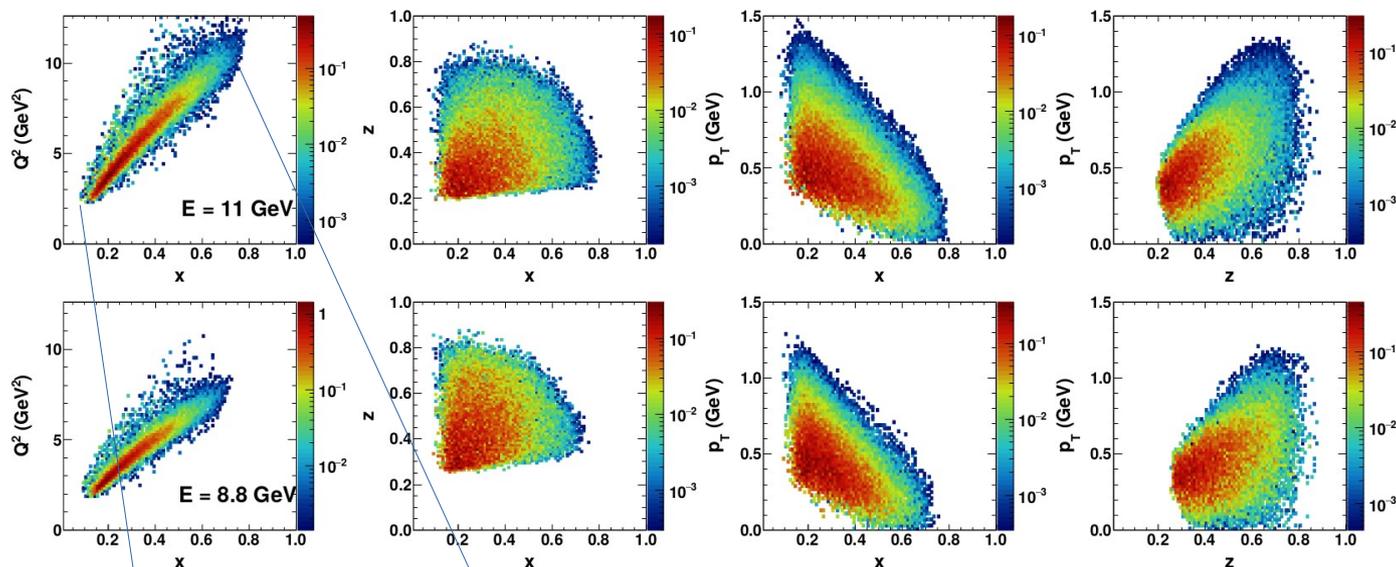
Hadron Arm:

- HERMES RICH: h-PID
→ Andrew talk on Tue
- HCAL (as far away from target as possible without compromising acceptance)
 - trigger, coarse spatial constraint for RICH and GEM
 - ToF for low momenta charged hadrons
 - neutral pion reconstruction

GEM trackers in both arms

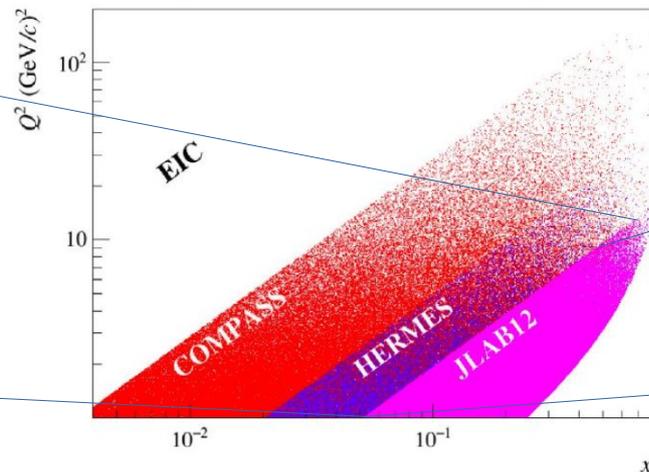
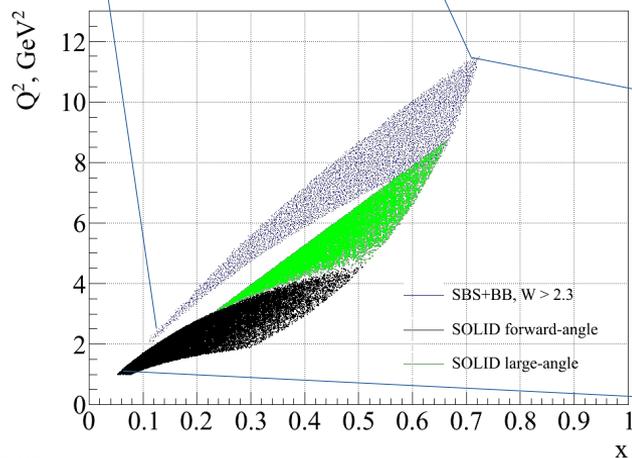
SBS SIDIS Kinematic Coverage

adapted from
A.J.R. Puckett g4sbs
in 2021 jeopardy proposal

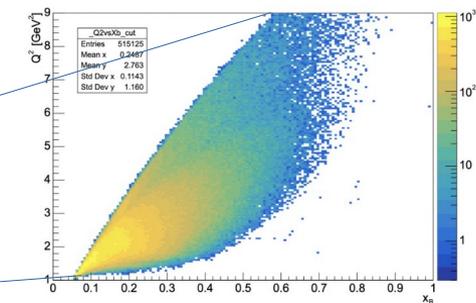


Cuts applied:
 $Q^2 \geq 1 \text{ GeV}^2$,
 $W^2 \geq 4 \text{ GeV}$,
 $M_x^2 \geq 2.3 \text{ GeV}^2$,
 $E'_e \geq 1 \text{ GeV}$,
 $p_h \geq 2 \text{ GeV}$,
 and good tracks/signals
 required in all relevant
 SBS+BB detectors

SBS/SOLID complementary
kinematic coverage

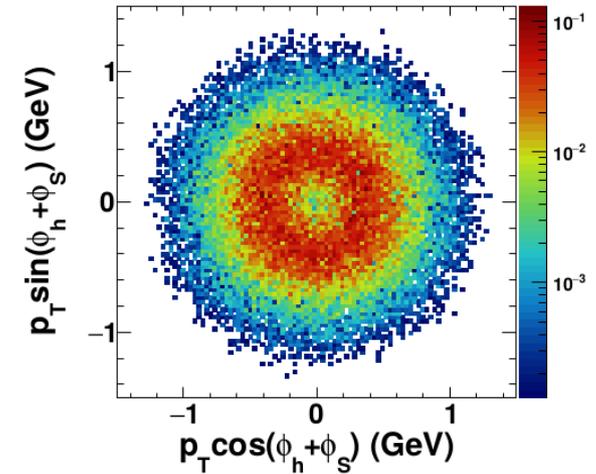
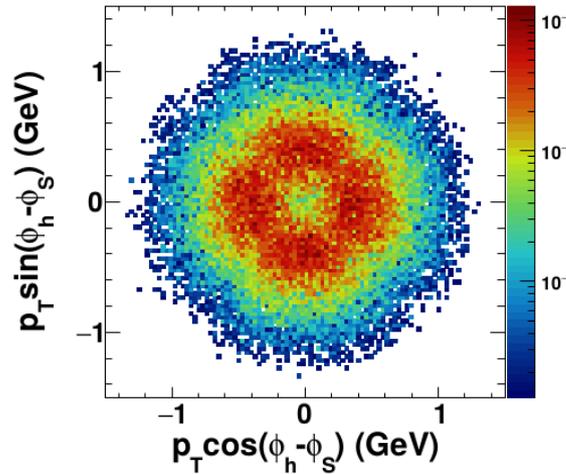
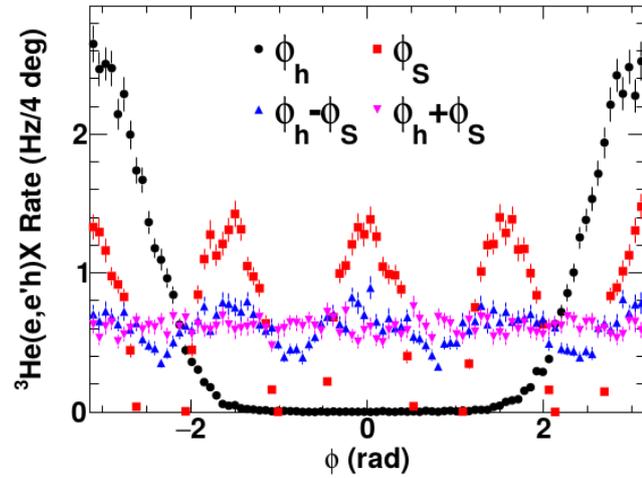


CLAS12 RGH



Azimuthal coverage

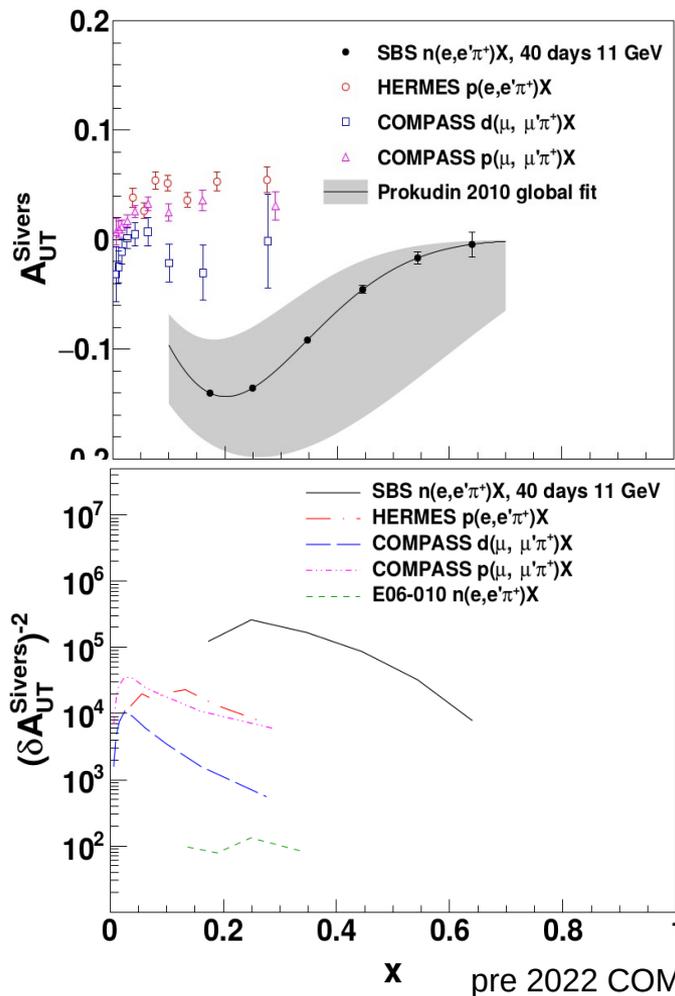
${}^3\text{He}(e, e'h)X$ @ 11 GeV
 $h = \pi^+, \pi^-, K^+, K^-$



- Rate-weighted coverage with 4 target spin directions (instead of the 8 originally considered in the proposal) → no reduction of physics sensitivity
- Azimuthal coverage independent from the charged hadron species, slightly better in 8.8 GeV
- π_0 coverage slightly worse than charged hadrons due to reduced acceptance

from 2021 jeopardy proposal

Expected Physics Impact (on Sivers)



Projected statistics

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

	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

+ Target pol. change (no beam) 1 week (additional request)

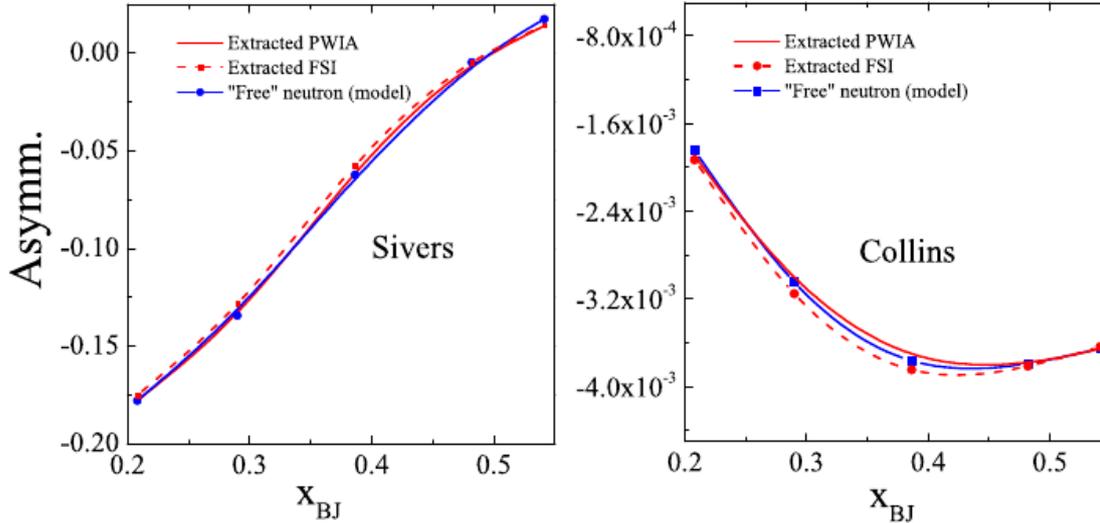
Figure of Merit (reciprocal square of asymmetry uncertainty)

not corrected for different x bin widths of published data, significantly understates SBS advantage for $x \geq 0.1$

from 2021 jeopardy proposal

FSI in ^3He distorted spectral function

L. Kaptari et al. PRC 89 (2014), A. Del Dotto et al. PRC95 (2017)



1) PWIA: $\langle p_n \rangle = 0.876$, $\langle p_p \rangle = -0.0237$, $\theta_e = 30^\circ$, $\theta_\pi = 14^\circ$

E_{beam} , GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x, z)$	$\langle p_n \rangle f_n$	$f_p(x, z)$	$\langle p_p \rangle f_p$
8.8	0.21	7.55	3.40	0.304	0.266	0.348	-8.410^{-3}
8.8	0.29	7.15	3.19	0.286	0.251	0.357	-8.510^{-3}
8.8	0.48	6.36	2.77	0.257	0.225	0.372	-8.910^{-3}
11	0.21	9.68	4.29	0.302	0.265	0.349	-8.310^{-3}
11	0.29	9.28	4.11	0.285	0.25	0.357	-8.510^{-3}

2) FSI: $\langle p_n \rangle = 0.756$, $\langle p_p \rangle = -0.0265$, $\langle N_n \rangle = 0.85$, $\langle N_p \rangle = 0.87$, $\langle \sigma_{eff} \rangle = 71 \text{ mb}$

E_{beam} , GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x, z)$	$\langle p_n \rangle f_n$	$f_p(x, z)$	$\langle p_p \rangle f_p$
8.8	0.21	7.55	3.40	0.353	0.267	0.405	-1.110^{-2}
8.8	0.29	7.15	3.19	0.332	0.251	0.415	-1.110^{-2}
8.8	0.48	6.36	2.77	0.298	0.225	0.432	-1.210^{-2}
11	0.21	9.68	4.29	0.351	0.266	0.405	-1.10^{-2}
11	0.29	9.28	4.11	0.331	0.250	0.415	-1.110^{-2}

$$A_n \simeq \frac{1}{p_n^{\text{FSI}} f_n^{\text{FSI}}} (A_3^{\text{exp}} - 2p_p^{\text{FSI}} f_p^{\text{FSI}} A_p^{\text{exp}}) \simeq \frac{1}{p_n f_n} (A_3^{\text{exp}} - 2p_p f_p A_p^{\text{exp}})$$

- The effective polarizations $p_{p(n)}$ differs by 15-20%, but they have to be considered in combination with the dilution factor \rightarrow the products in the asymmetries extraction change very little
- The extraction procedure seems to be safe and can be carefully tested in MC simulating the phase space of the JLab ^3He target dedicated experiments

Where we are

- First Proposal in 2009 (PAC34) conditionally approved
- Fully approved in 2011 (PAC38) with A- rating
- Re-approved at jeopardy in 2021 (PAC49) with no change in rating and requested timing
- **New jeopardy required this year**
- **Technical feasibility stronger than in 2021 thanks also to the gained experience on SBS equipment from the last years data taking**
- **Physics case basically unchanged (likely strengthened): demand for TTSA data (especially on neutron)!**