SIDIS/Exclusive Processes with SBS

E. Cisbani
with contributions from the SBS collaboration members

- Hadron structure vs SBS program
- SIDIS + SBS details
- WACS & SBS

29/June/2023 – HallA/C summer collaboration meeting

Toward a unified picture of the hadron/nucleon structure and internal dynamics

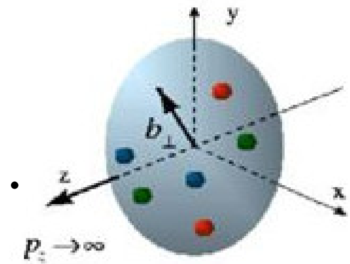
Large experimental "firepower" required:

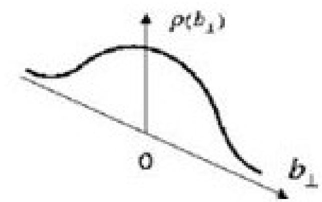
- **Elastic Scattering**
- **WACS / DVCS**
- **SI-DIS / DY**
- **TDIS**
- **Lepton-Lepton**
- **...**

SBS

PDFs: $\mathrm{f}_n^q(x)\ldots$

FFs: $\mathrm{F}_n^q(t)\ldots$



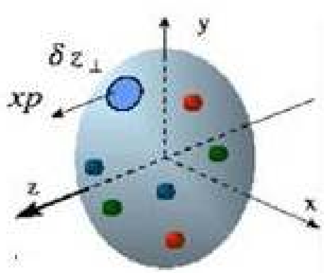


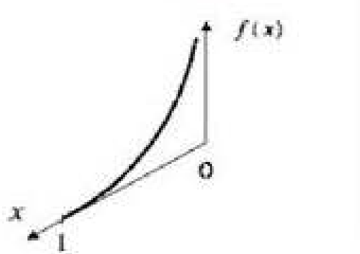
$\int d^2\vec{k}_\perp$

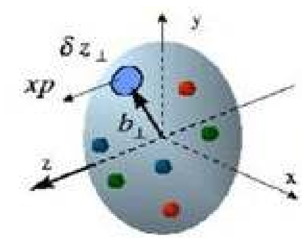
$\int dx$

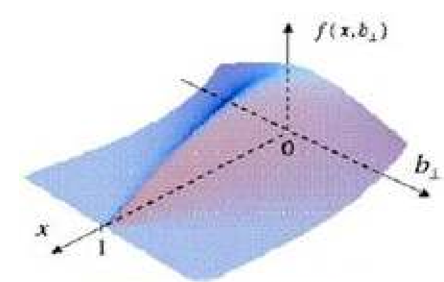
TMDs: $\mathrm{f}_n^q(x, \vec{k}_\perp)\ldots$

GPDs: $\mathrm{H}_n^q(x, \xi, t)\ldots$









$\int d^2\vec{b}_\perp$

$\int d^2\vec{k}_\perp$, FT $\vec{b}_\perp \leftrightarrow (\xi, t)$

Wigner Functions:

$\mathrm{W}_{\Gamma,n}^q(x, \vec{k}_\perp, \vec{b}_\perp)$

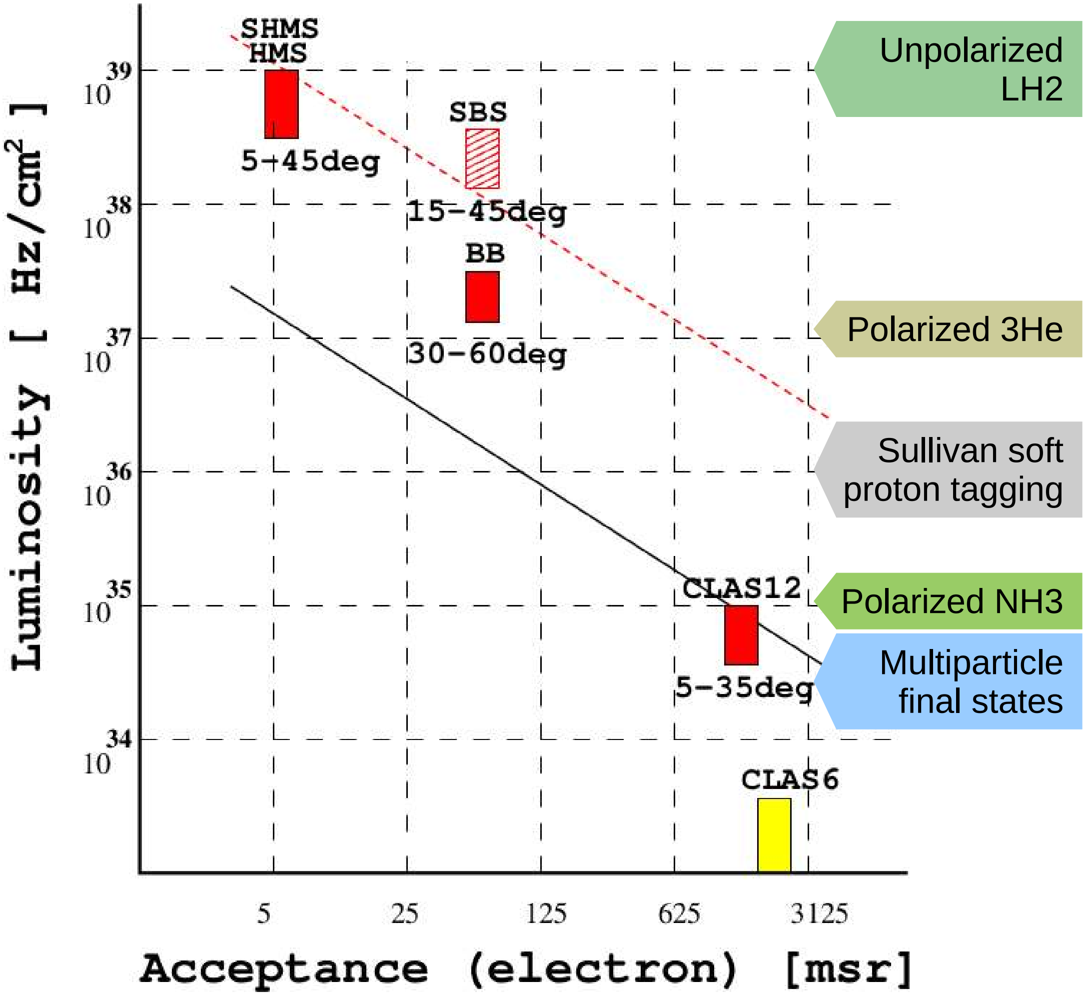
SBS/BB Experimental Program

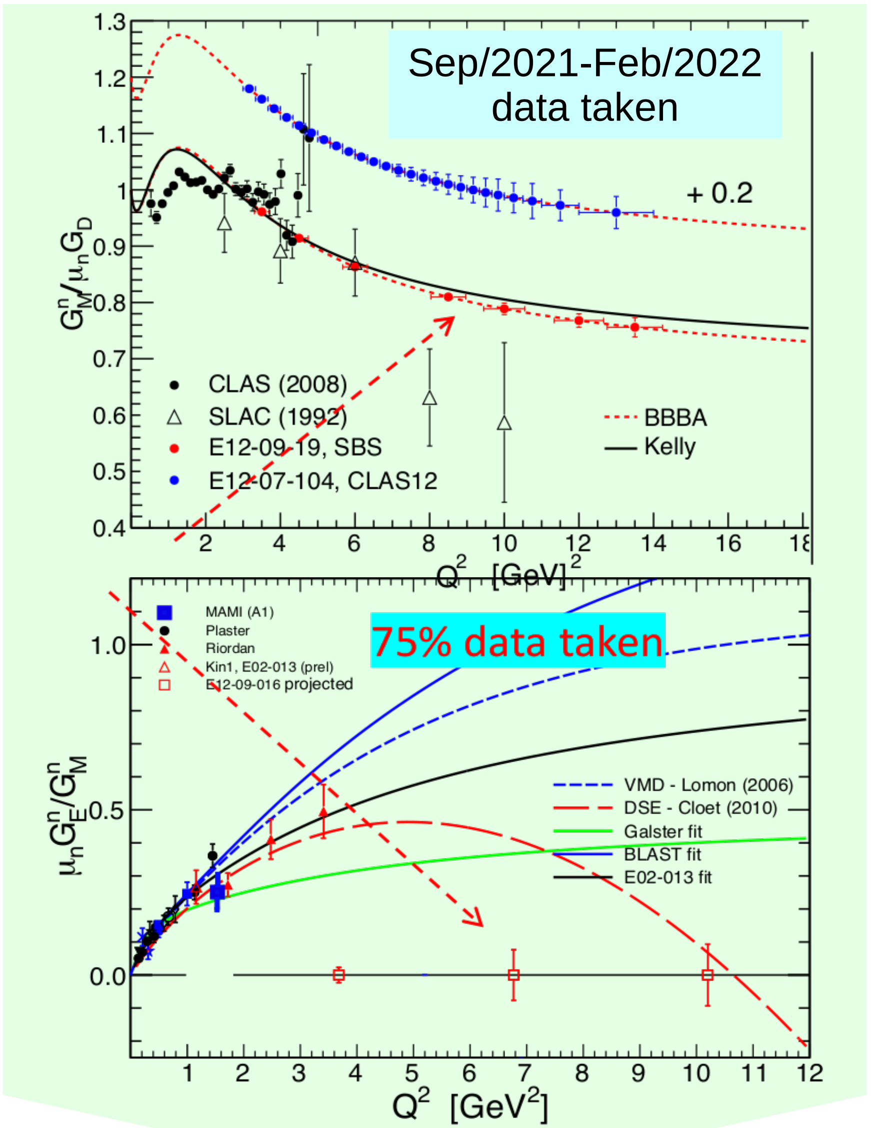
FF	GMN *done* (E12-09-019)	GMn/GMD up to 13.5 GeV2 (perspective to 18 GeV2)	Ratio Method D/H
	GEN-II *ongoing* (E12-09-016)	GEn/GMn up to 10 GeV2	Beam-target double spin asymmetry on 3He
	GEP-V **2024-25** (E12-07-109)	GEp/GMp to 12 GeV2 (perspective to 15 GeV2)	Polarization Transfer (the most demanding experiment)
	GEN-RP **2024** (E12-17-004)	GEn/GMn at 4.5 GeV2	Charge-exchange recoil polarimetry (first time!), on deuterium
	nTPE *done* (E12-20-010)	Rosenbluth slope in e+n scattering at Q2=4.5 GeV2, with high accuracy	Same apparatus of GMN; measure $\sigma(e,n)/\sigma(e,p)$ on deuterium
GPD	WAPP **2023-24** (E12-20-008, E12-21-005)	A_{LL} / K_{LL} from $\vec{\gamma} n \rightarrow \pi^- \vec{p}$	Pioneering measurements; Same apparatus of GEN(-RP), on 3He and LD2 target; Cu radiator for gamma production;
	(p)WACS (E12-17-008) HallC	$A_{LL,LS}$ / $K_{LL,LS}$ in $\vec{\gamma} \vec{p} \rightarrow \gamma p$	NPS + BB/SBS + GEM Tracker + HCal
TMD	SIDIS (E12-09-018) HallC?	Extract Sivers, Collins and Pretzelosity neutron asymmetries on π and K with high statistics in high x valence region	Transversely Polarized ^{3}He Target 3D binning on the relevant variables: x, P_{perp} and z, for both hadrons; 2 Q^2 values
PDF	TDIS (C12-15-006A)	Measure p/K F2 in valence regime **Rachel Talk**	Exploit Sullivan process e+N→e'(γm)N'→e'XN' tagging the spectator N'

New idea: DVCS, g2p/d2p, γDVCS; under evaluation: TCS, sFF

Adapted from B. Woijtsekhowski
SBS presentation 2023

SBS+BB @ JLab 12 GeV



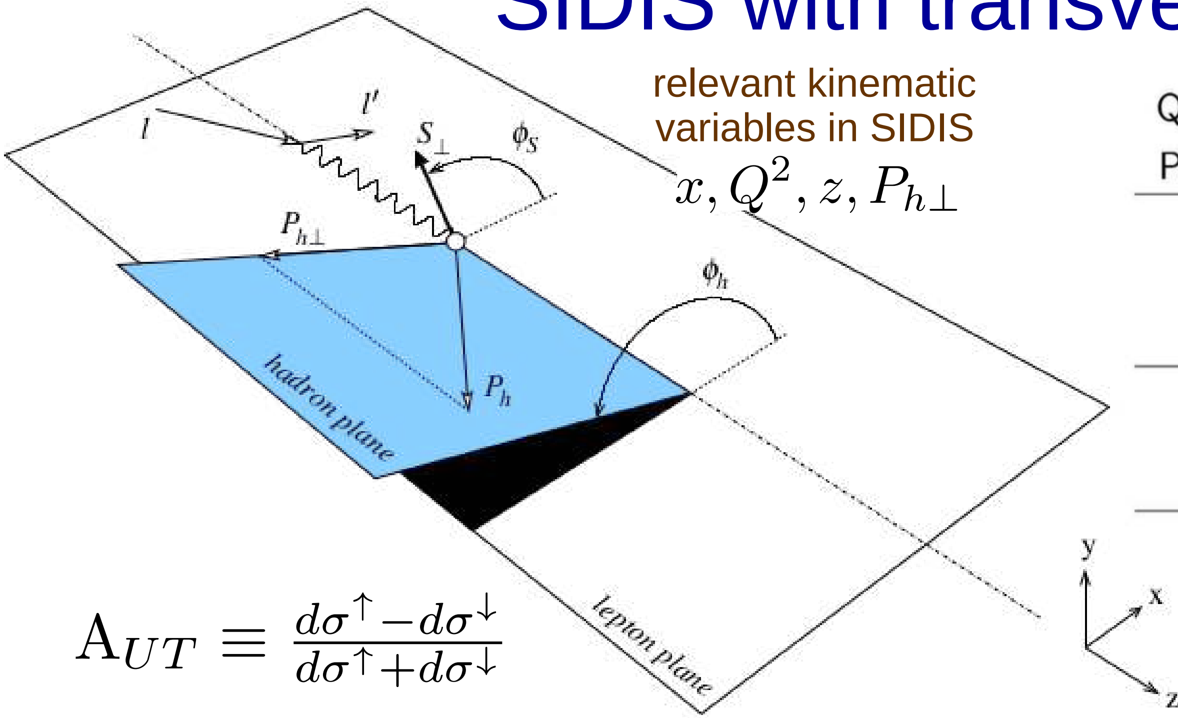


Moderately large acceptance (angular and momentum) combined to **high luminosity**

Unique configuration opportunities for **experiment specific optimization**

>2 years of data taking → toward **consolidated understanding** of new and refurbished components (pol. 3He, GEM trackers, calorimeters, Cherenkov …)

SIDIS with transversely polarized target



relevant kinematic variables in SIDIS

$x, Q^2, z, P_{h\perp}$

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

Quark Polar.	Nucleon Polarization 0	L	T	
0	$q(x)$			$f_{1T}^{\perp}(x, k_\perp)$ Sivers
L		$\Delta q(x)$		$g_{1T}(x, k_\perp)$
T	$h_1^{\perp}(x, k_\perp)$	$h_{1L}^{\perp}(x, k_\perp)$	$\delta q(x)$	$h_{1T}^{\perp}(x, k_\perp)$

Transversity (or h_1^q)

(at leading twist-2)

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

"Clean" probe of relativistic effects; chiral-odd Distribution and Fragmentation Functions

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

Link to quark Orbital Angular Momentum and QCD FSI mechanism; used to test DF universality

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

Transverse spin and momentum (~0)

Theoretical work ongoing for SIDIS description (and interpretation) at subleading powers
arXiv: 2109.09771, 2112.07680, 2306.09495 ...

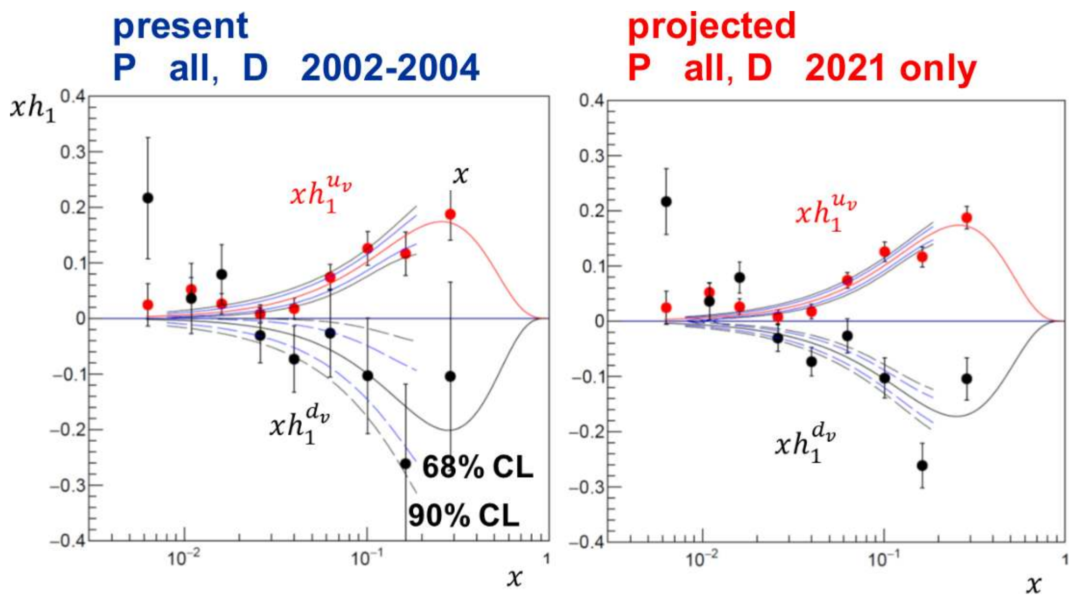
$$\otimes \equiv \int \cdot \, d^2 p_\perp \; d^2 k_\perp$$

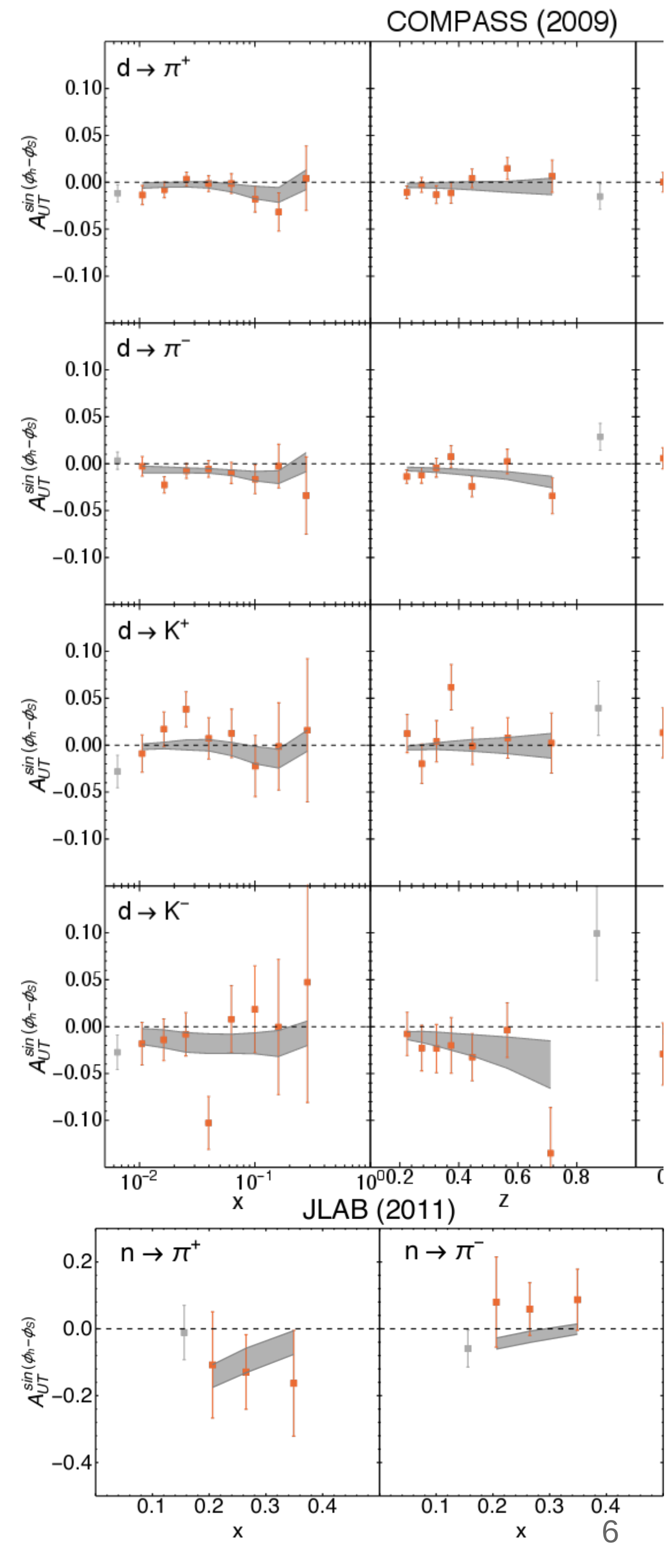
Convolution over unobserved transverse momenta

Why TMDs on neutron ?

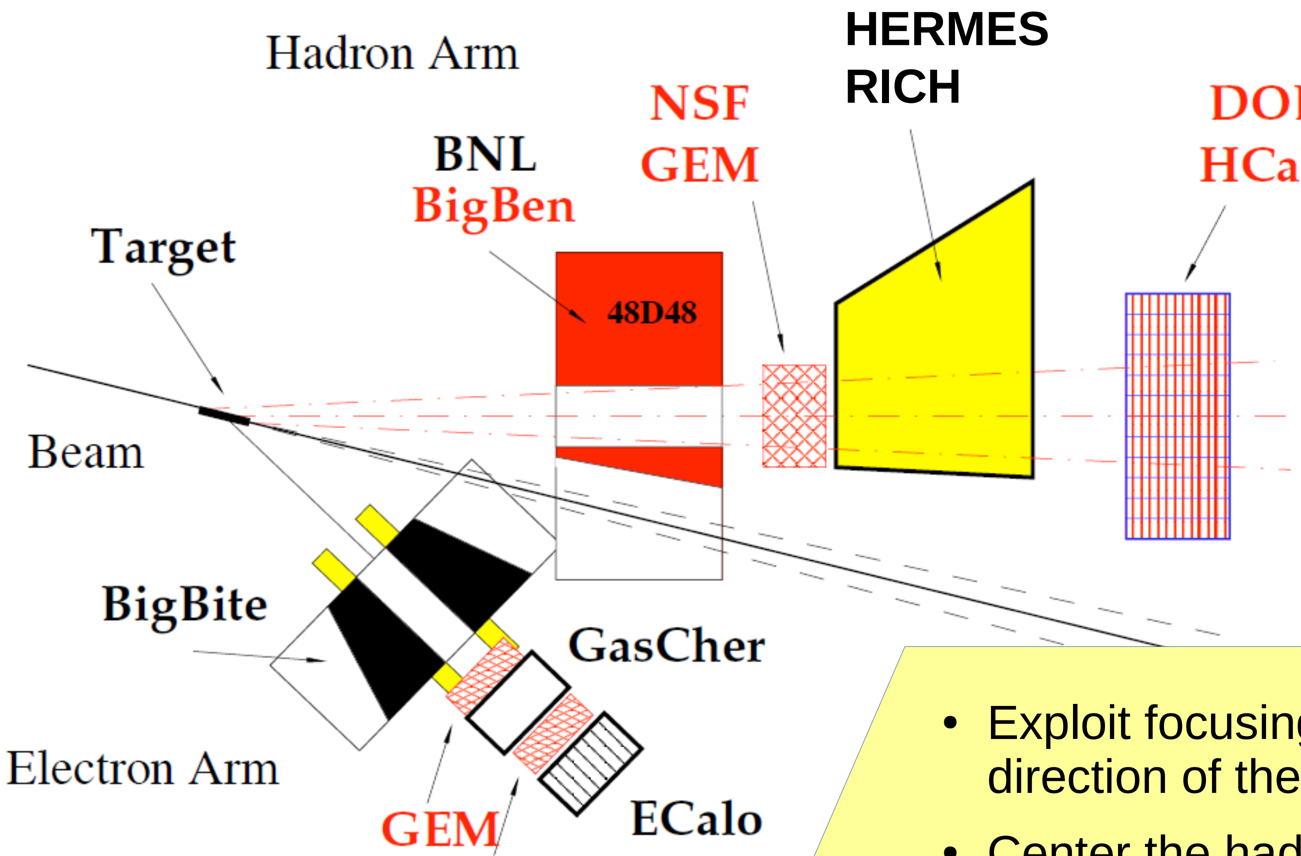
d-quark Sivers/Transversity are poorly constrained by existing data

- Proton data dominated by u-quarks
- d-quarks TMD limited precision
- Scarsity of deuteron (COMPASS) and neutron (^{3}He/Hall A) data to constraint d-quark TMDs
  → in 2022/23 expected new polarized deuteron data from COMPASS
- u and d quark transversity have opposite sign





SBS-SIDIS Experiment Concept



$$e + {}^3He^{\uparrow} \rightarrow e' + \pi^{\pm,0}(K^{\pm}) + X$$

Lumi > 10^{37} Hz/cm^2

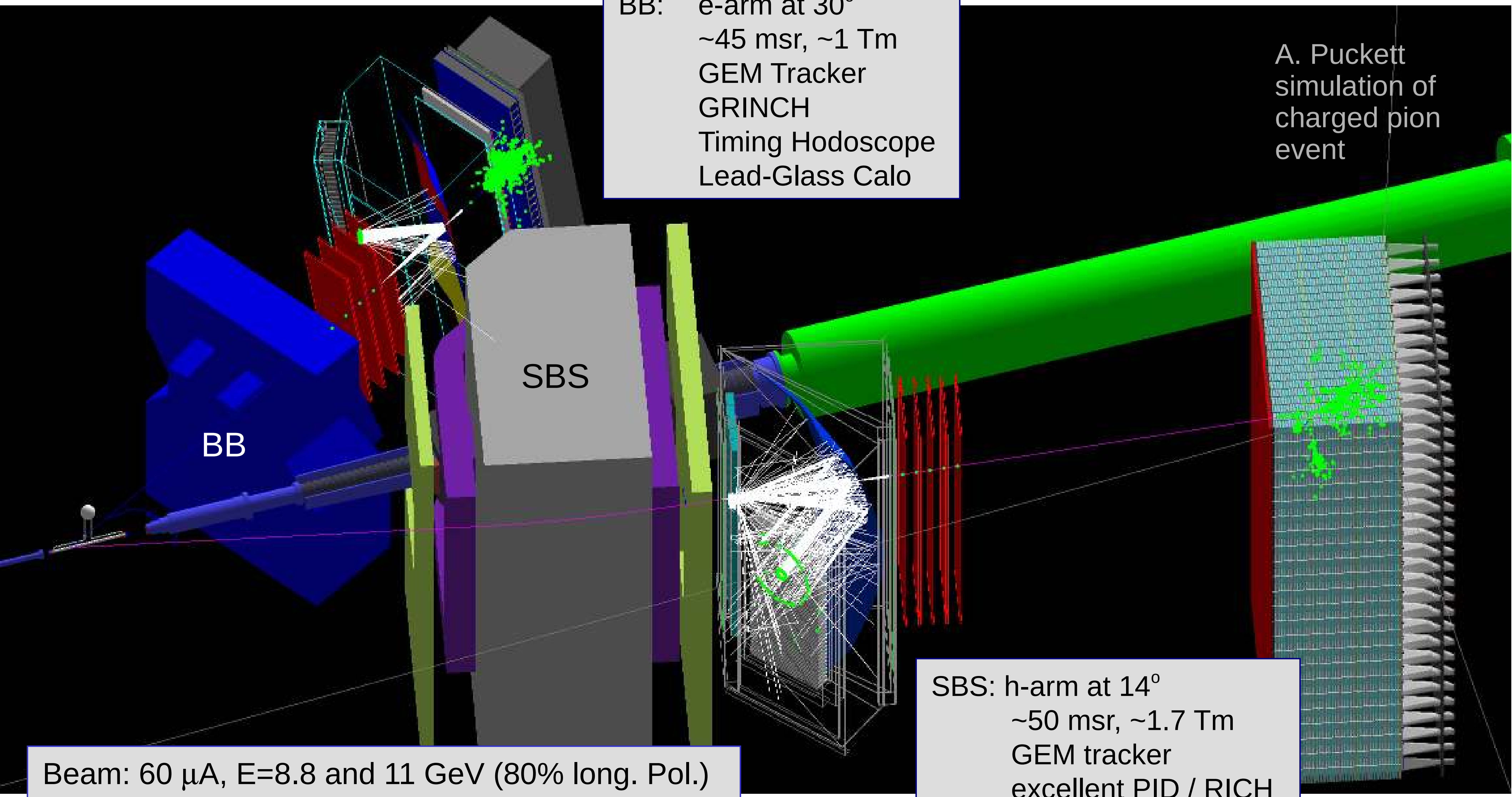
(**HERMES unp. ≤$2.5 \cdot 10^{33}$ Hz/cm^2**)
Th. Benisch et al. NIMA 471 (2001) 314

- Exploit focusing of scattered hadrons along the direction of the momentum transfer **q**
- Center the hadron arm along **q**
- Use two relatively large open-geometry dipoles (40-50 msr)
- Flexible orientation of the target polarization within the plane perpendicular to **q** thanks to the modest field (tens of Gauss) in the target region
- Dipoles sweep out low energy background

SBS-SIDIS Experiment Configuration

(E12-09-018) Semi-Inclusive Deep Inelastic Scattering on a Transversely Polarized 3He Target using the BigBite and Super BigBite Spectrometers in Hall A

BB: e-arm at 30°
~45 msr, ~1 Tm
GEM Tracker
GRINCH
Timing Hodoscope
Lead-Glass Calo



SBS: h-arm at 14°
~50 msr, ~1.7 Tm
GEM tracker
excellent PID / RICH
HCAL

Beam: 60 μA, E=8.8 and 11 GeV (80% long. Pol.)
^{3}He Target: 40 cm, ~55% transversely polarized

^{3}He (SBS) polarized target

Evolution of the 3He polarized target HallA/C in latest years ending up to SIDIS:

Convection design → Hall C (A1n and d2n) (30 uA, 50% pol)

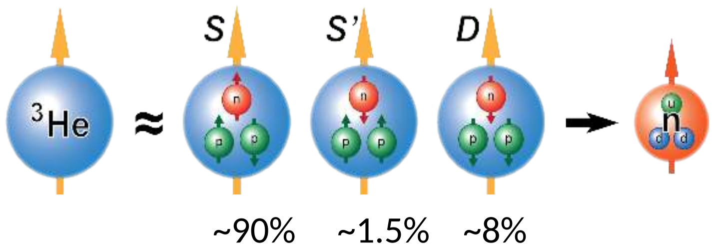
⇓

Twice target thickness → GEn (60 uA)

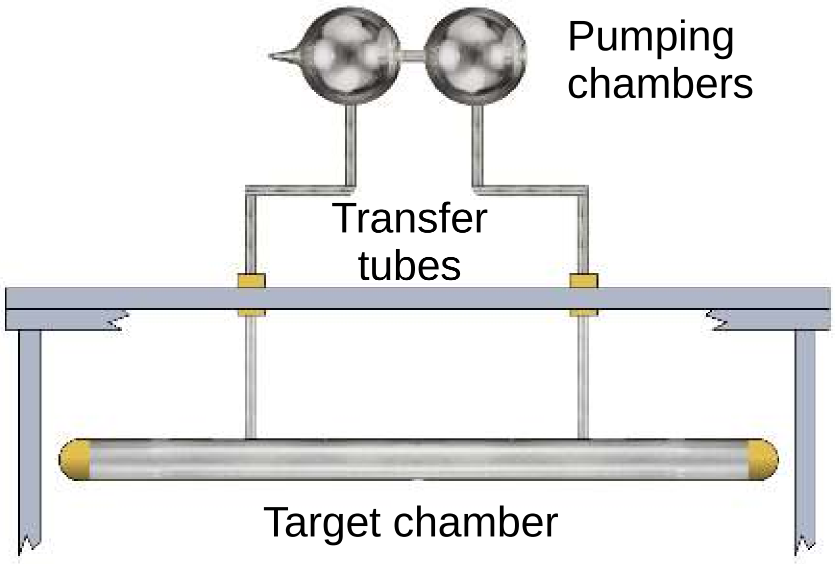
⇓

SIDIS can reuse most of the GEn target hardware including soft iron magnetic shield and to get different orientations will:

- rotate the magnetic-field coils (~ 1 week) for hor./ver. holding field
- use two pumping chambers, each served by one optics module pointing directly to it;
- install new forced-hot-air oven (for the 2 pumping chambers)



Effective polarized n target



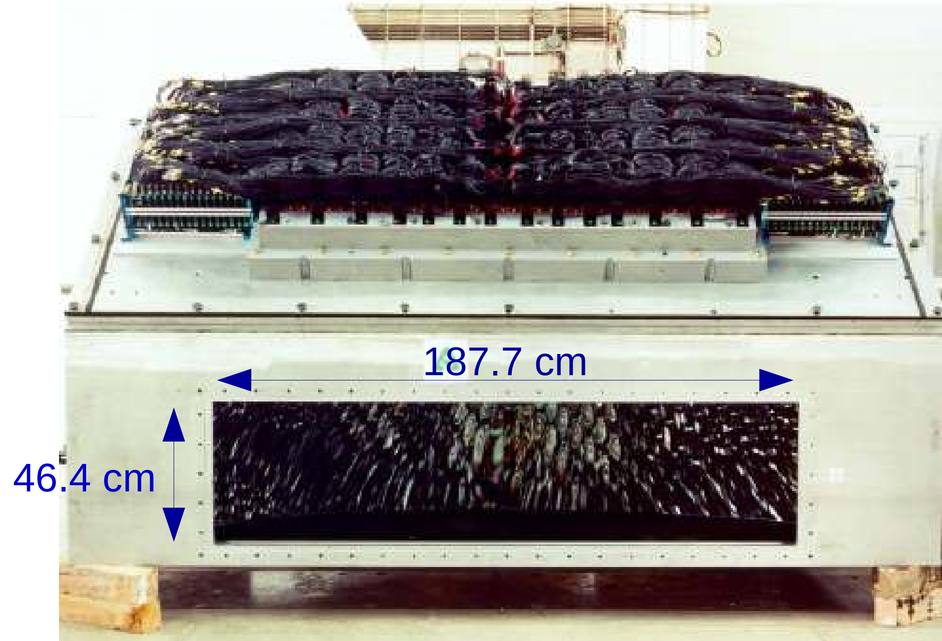
Only 4 spin directions (+/- hor. and +/- ver.) instead of original 8 (approach already validated in E06-010)

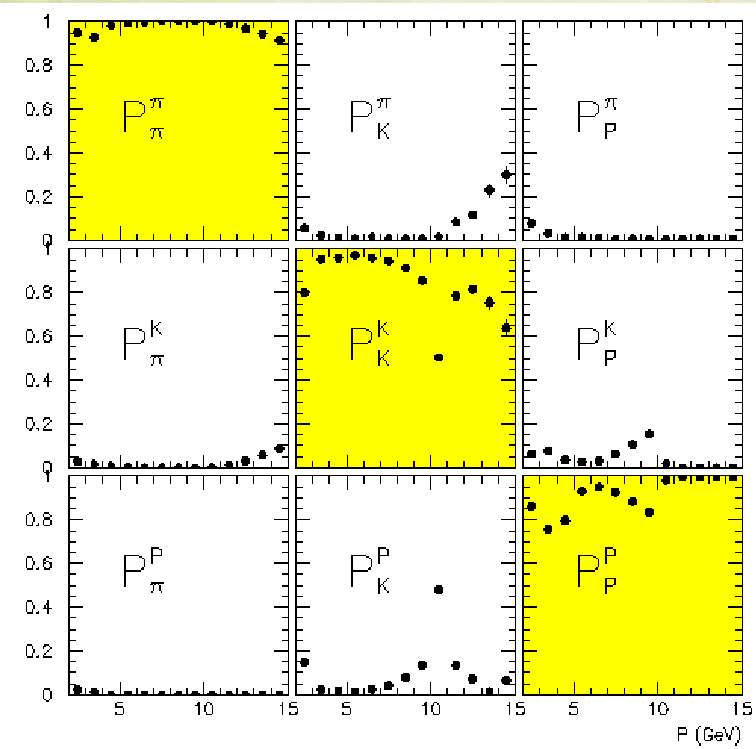
→ simplification in design, minimal changer relative to SBS-GEn)

→ no meaningful impact in physics

The HERMES RICH becomes the SBS RICH

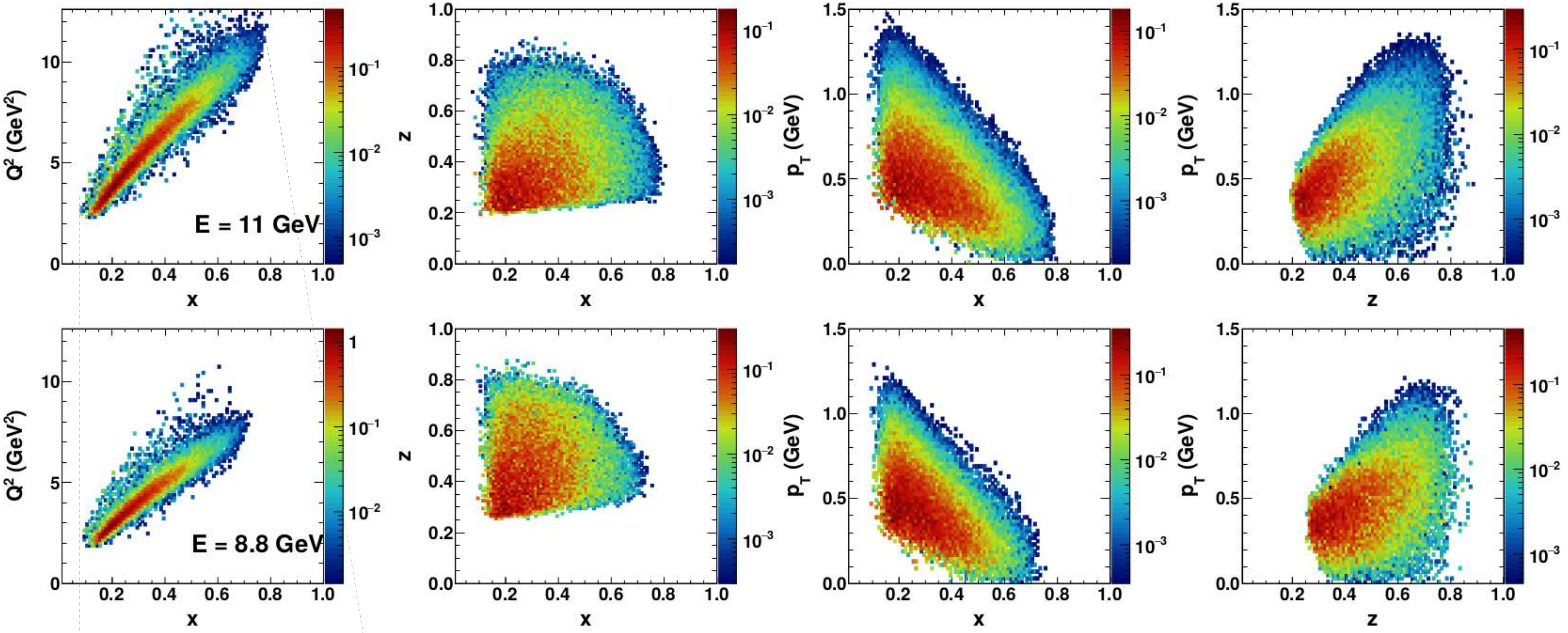
- The dual radiator HERMES RICH operated very well and stable from 2 GeV/c to more that 10 GeV/c
- We had chance to preserve one of the two HERMES RICH (and spare PMTs and aerogel tiles)
- HERMES RICH (rotated) fits reasonably well in SBS acceptance
- High segmentation (~2000 PMTs) with new NINO-chip based front-end electronics read out by VETROC back-end modules → estimated <0.1% PMT occupancy.
- Expected to provide excellent p-K-π separation

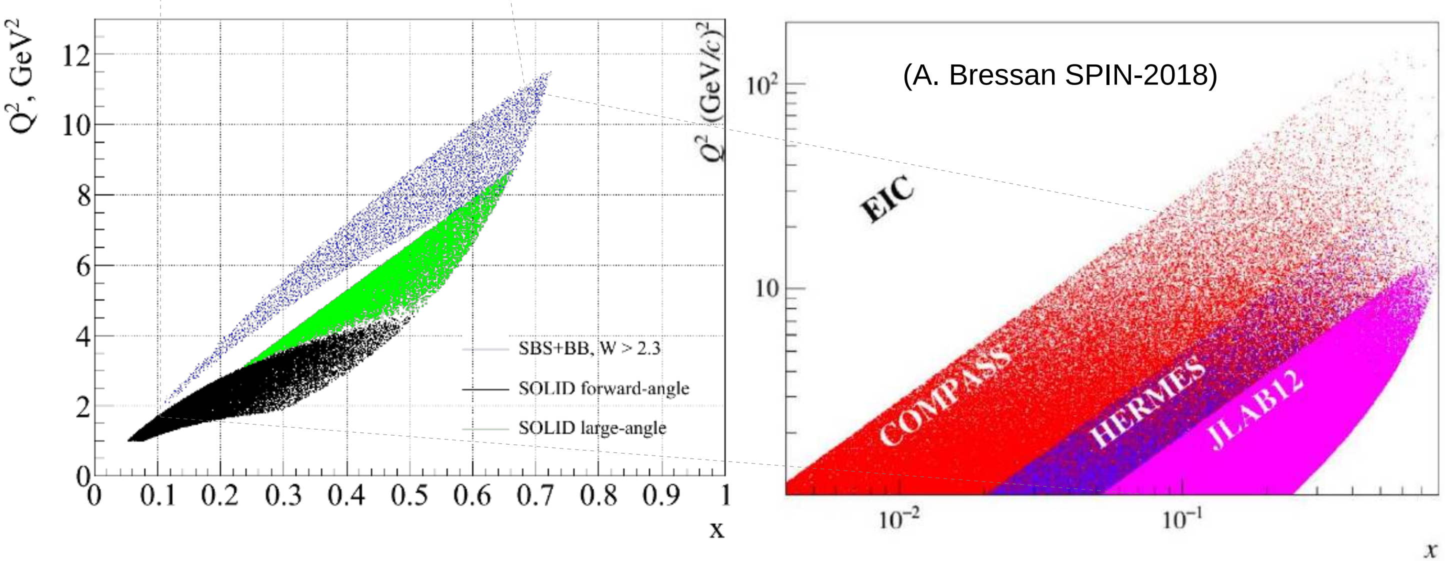




SBS SIDIS Kinematic Coverage

A.J.R. Puckett g4sbs



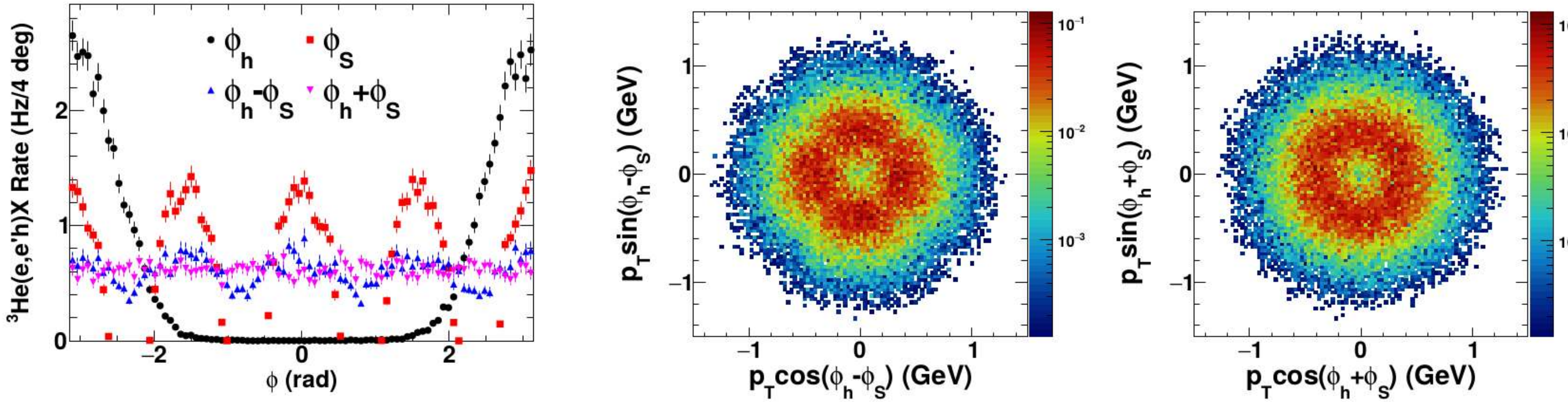


Cuts applied:
$Q^2 \geq 1$ GeV^2 ,
$W^2 \geq 4$ GeV,
$M^2_X \geq 2.3$ GeV^2,
$E'e \geq 1$ GeV,
$p_h \geq 2$ GeV,
and good tracks/signals required in all relevant SBS+BB detectors

Azimuthal coverage

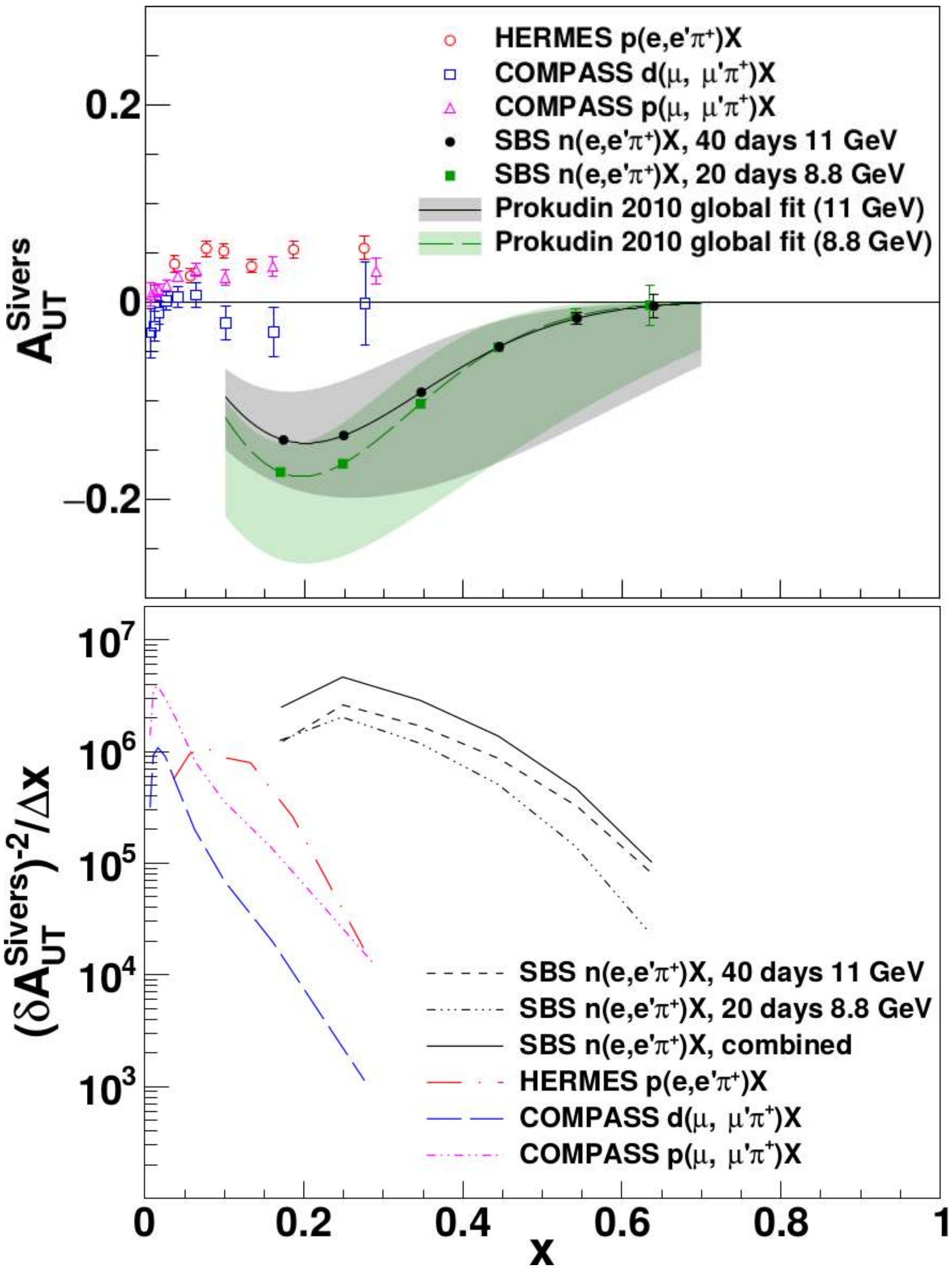
$h = \pi^+, \pi^-, K^+, K^-$

$^3\mathrm{He}(e, e'h)X$ @ 11 GeV



- 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

Expected Physics Impact (on Sivers)



Projected statistics (from A. Puckett)

(Δx=0.1, 0.1≤x≤0.7)

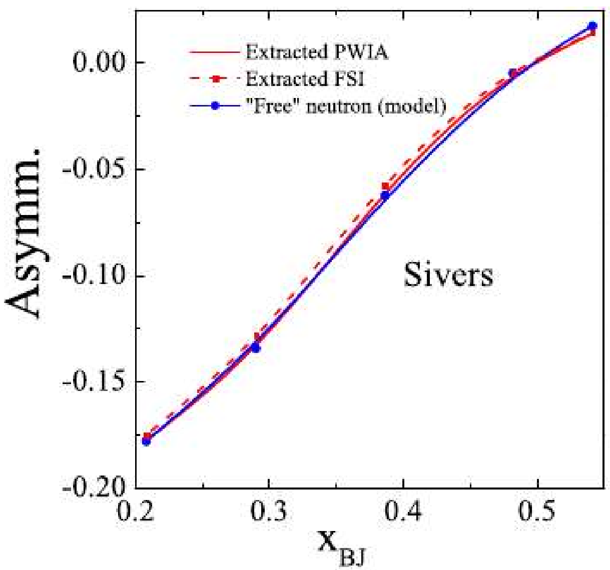
	Time (day)
Production run at $E = 11$ GeV	40
Production run at $E = 8.8$ GeV	20
Calibration Runs	2
Target maintenance and configuration changes	2
Total	64

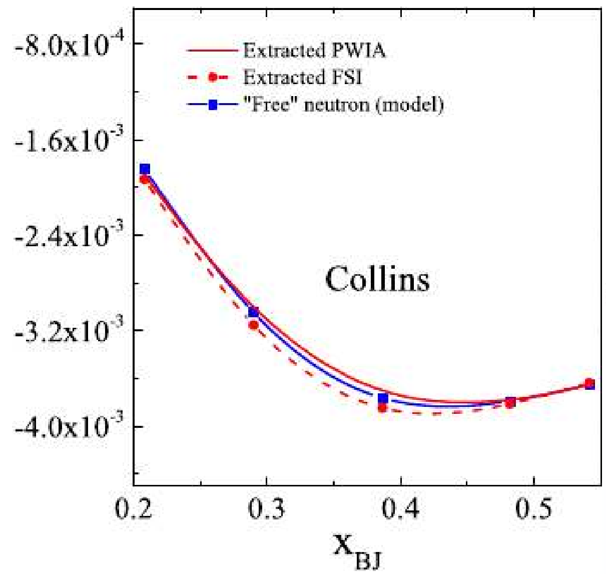
+ Target pol. change (no beam) 1 week (additional request)

Figure of Merit

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

FSI in ^{3}He distorted spectral function





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

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}

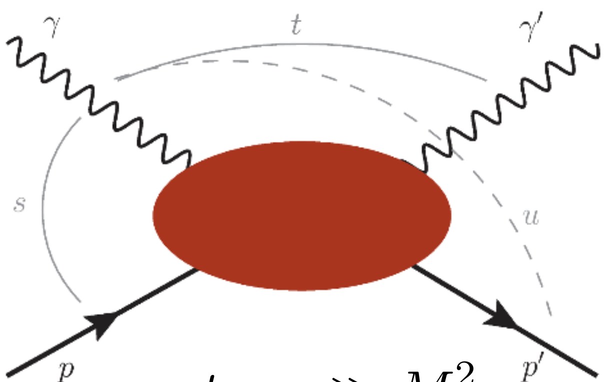
L. Kaptari et al. PRC 89 (2014)
A. DelDotto et al. PRC95 (2017)

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

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

Courtesy of Alessio Del Dotto

Wide Angle Compon Scattering (WACS)



$s, -t, -u \gg M_N^2$

Complementary to:
DVCS (large Q^2, small t)
ep elastic scattering at high Q^2
Deeply Virtual meson electroproduction

... one of the least investigated/understood hard regime process!

Different theoretical descriptions available: pQCD, Soft-Collinear Effective Theory, Relativistic Constituent Quark Model, Dyson-Schwinger Equation, Handbag/GPD, ...

$$\frac{d\sigma(\Uparrow_\gamma, \Uparrow_p; s,t,u)}{dt}$$

Cross section

$$A_{LL}\frac{d\sigma}{dt} \equiv \frac{d\sigma(\uparrow\uparrow)}{dt} - \frac{d\sigma(\downarrow\uparrow)}{dt}$$

Helicity correlation between **initial photon** and **initial nucleon**

$$A_{LS}\frac{d\sigma}{dt} \equiv \frac{d\sigma(\uparrow\rightarrow)}{dt} - \frac{d\sigma(\downarrow\rightarrow)}{dt}$$

Correlation between **initial photon helicity** and **initial nucleon sideway/transverse polarization**

...

$K_{i,j}$

Similarly for the **final nucleon** (polarization transfer)

assuming
no helicity-flip

$A_{LL} = K_{LL}$
$A_{LS} = - K_{LS}$

parity conservation

$K_{L,N}=0$

SBS/BB-pWACS - HallC

Ideal Apparatus:

- low cross section → high lumi (beam x target)
- two bodies constrains → high resolution detectors
- initial polarization and polarization trasfer

Re-use SBS-BB components:
BB, GEMs, 3He pol Target

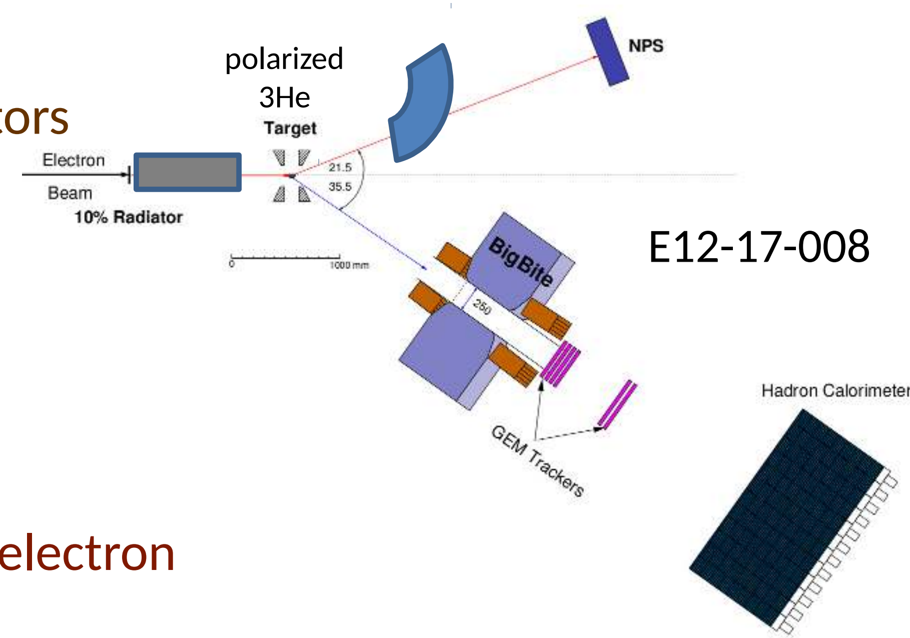
New equipments:

Neutral Particle Spectrometer:

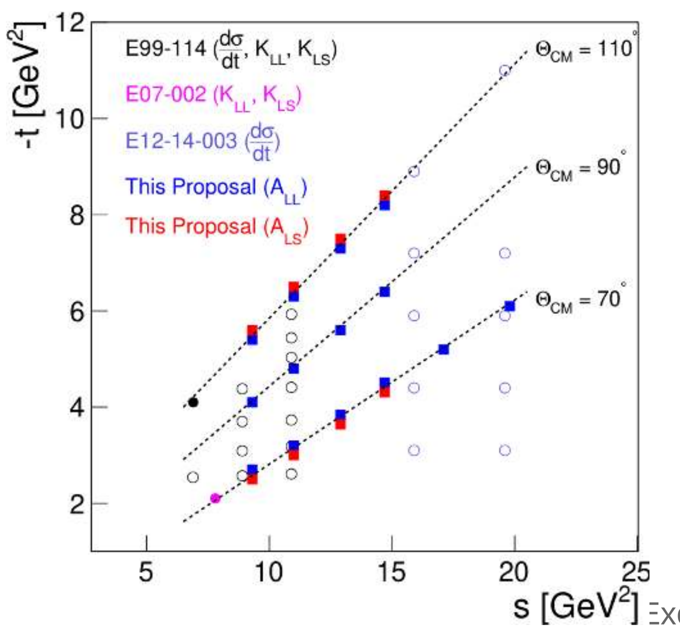
- vertical sweeping magnet (field integral ~0.6 Tm)
- highly segmented and energy resolution photon/electron calorimeter based on PbWO4 blocks

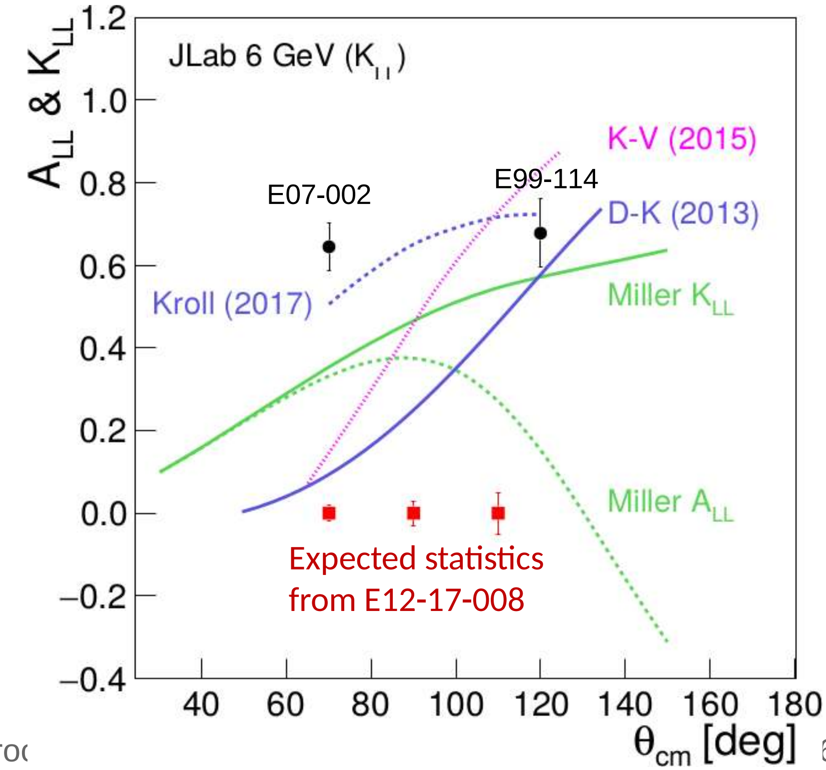
Compact Photon Source

- compact ~1m long magnet with 2.5T, 3 cm gap
- 10% radiator



E12-17-008





Final remarks

The SBS experimental program is dedicated to extended investigation of nucleon structure and related dynamics

Intensive effort is ongoing to take valuable physics data, get familiar with, and optimize the new SBS equipments designed for experiments with polarized beam / target at high luminosity

E12-09-18/SBS-SiDIS was originally approved by PAC38 and re-approved after jeopardy by PAC49;
its science case has not changed, but likely strengthened
Its technical feasibility improved and will largely benefit of the consolidated SBS operations

WACS exclusive process can be investigated using SBS equipment; it will provide new data to constrain theoretical prediction and likely clarifing the intriguing E07-002 result