Advances and Challenges in the Experimental Studies of Nucleon Transversity

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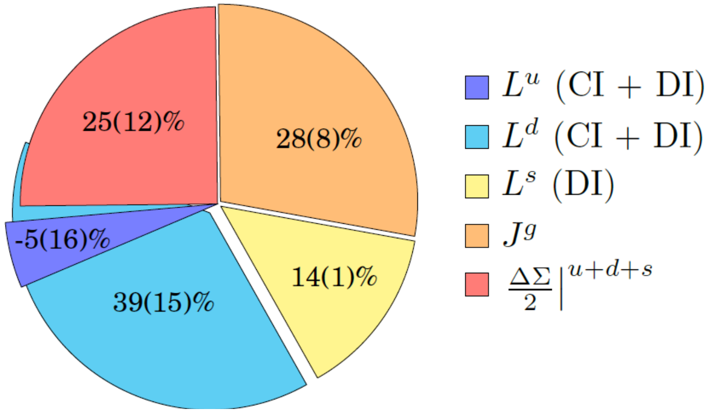
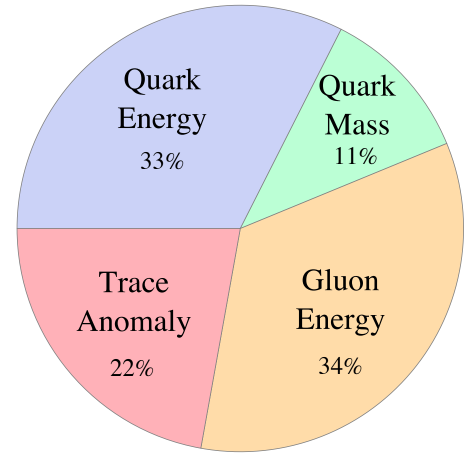
The Proton remains puzzling: spin mass and charge radius





$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$< N \,|\, \frac{\beta(g)}{2g} G^{\alpha\beta\gamma} G^{\gamma}_{\alpha\beta} + \sum_{u,d,s,} m_q \bar{q} q \,|\, N >= M_N$$

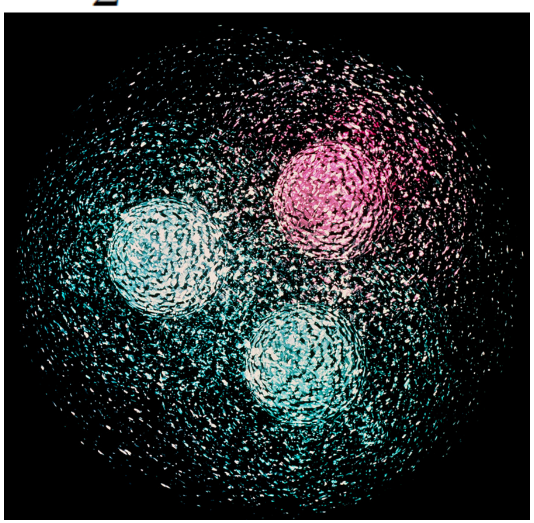
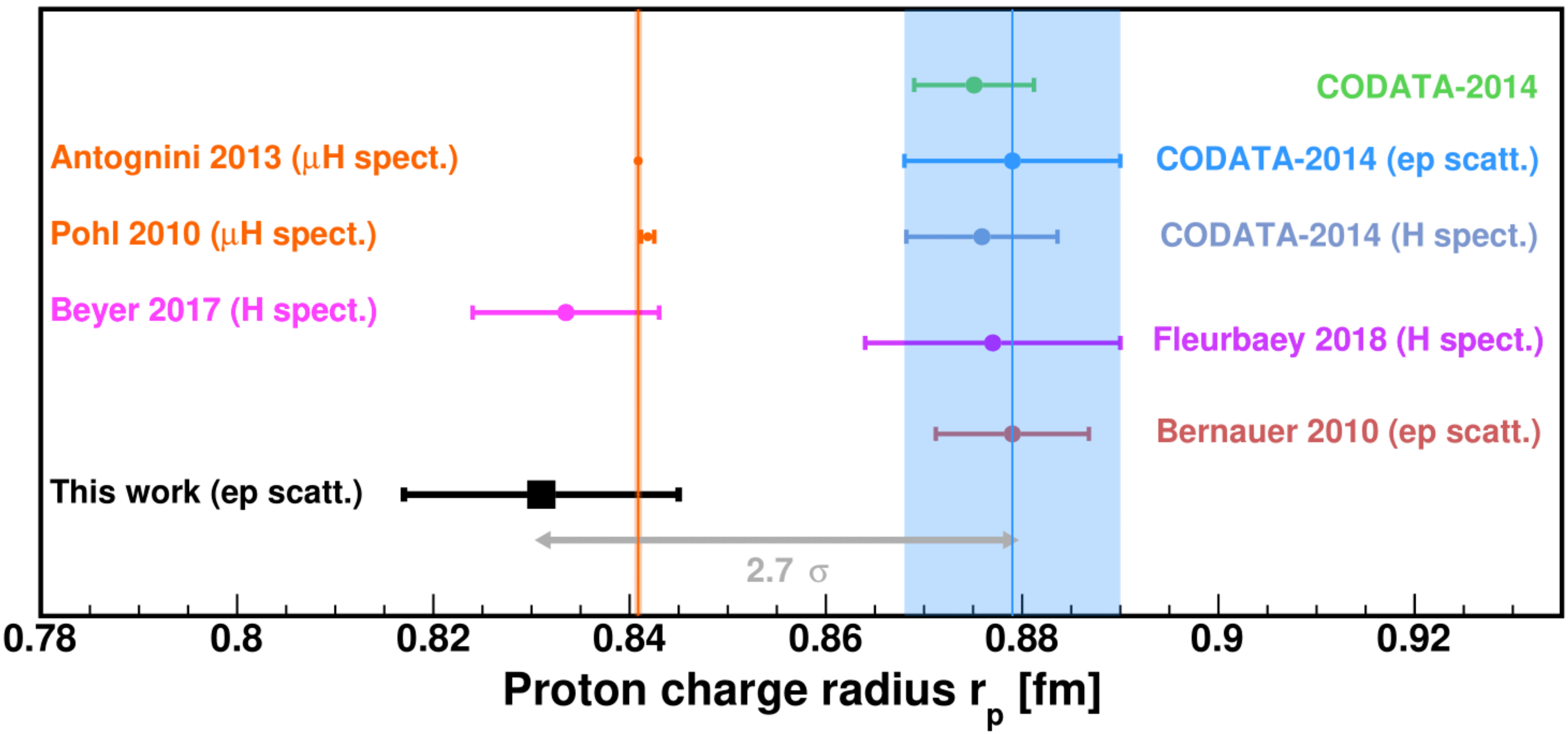


Image credit: fineartamerica.com

PRad result on the radius

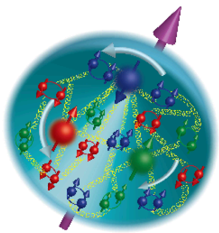
- PRad result: 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm



Xiong *et al.*, Nature 575, 147–150 (2019)

DOI:10.1038/s41586-019-1721-2

Nucleon Spin Decomposition



Proton spin puzzle

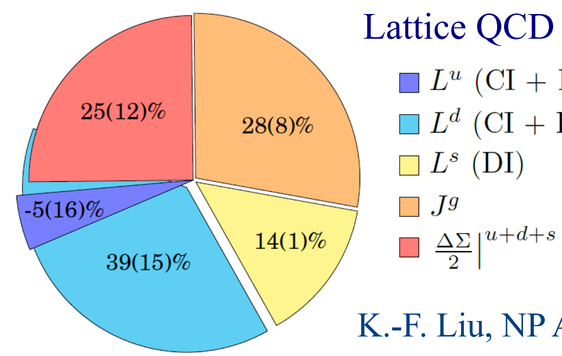
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

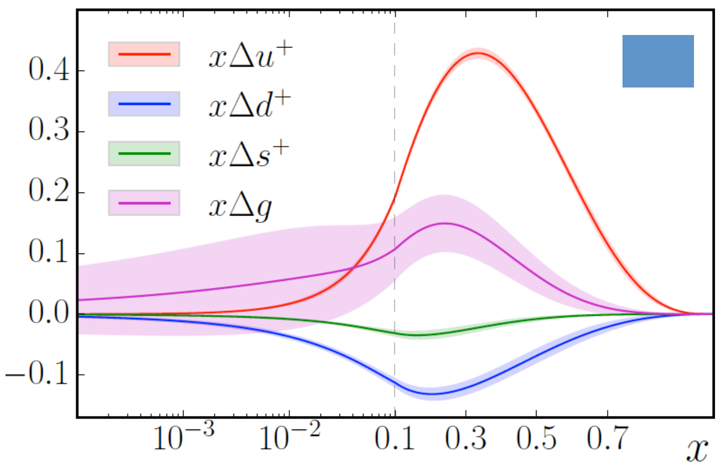
J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



K.-F. Liu, NP A928, 99 (2014).



JAM Collaboration, PRD (2016).

Gluon spin: STAR and PHENIX (pp collisions)
Lattice: Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017)

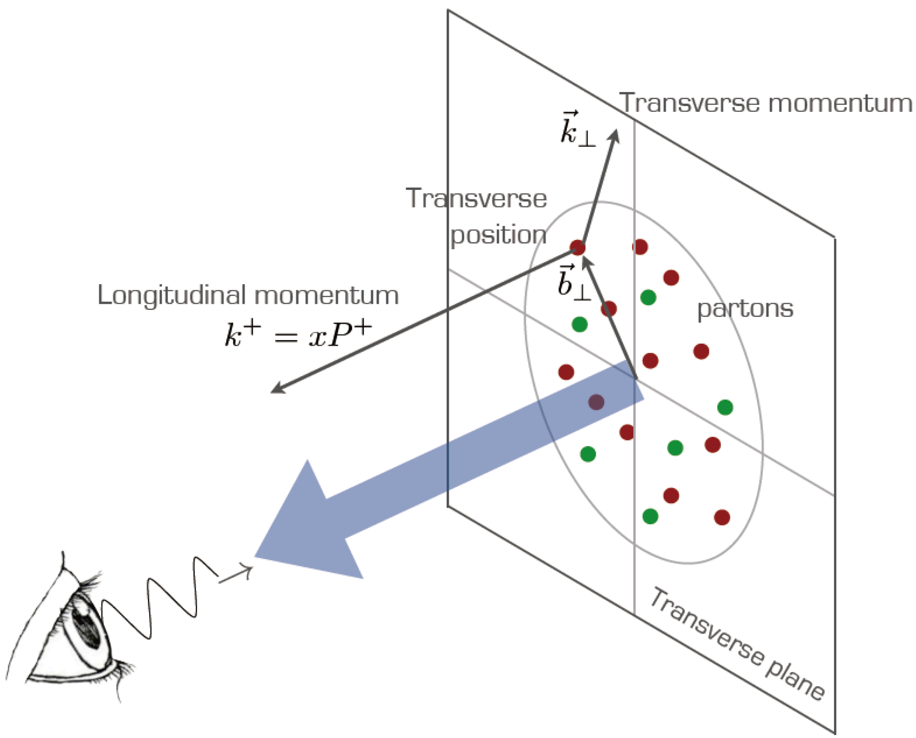
Access to $L_{q/g}$

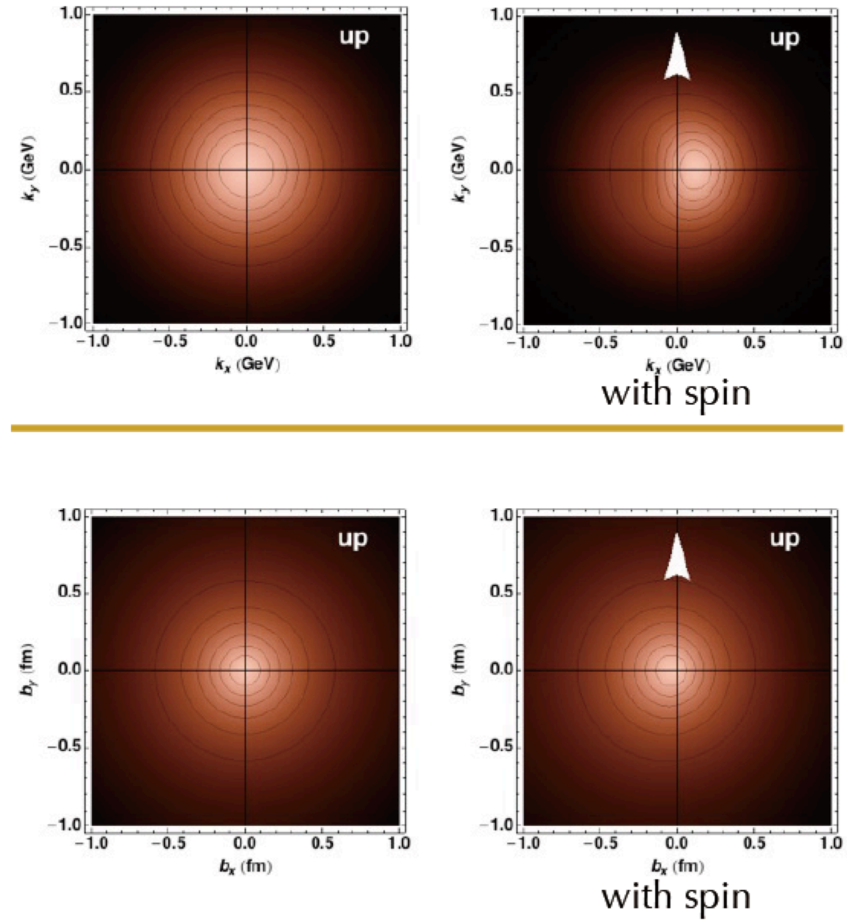
It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

Orbital motion - Nucleon Structure from 1D to 3D





Generalized parton distribution (GPD) (covered by others)
Transverse momentum dependent parton distribution (TMD)

[Bacchetta’s talk (2016)]

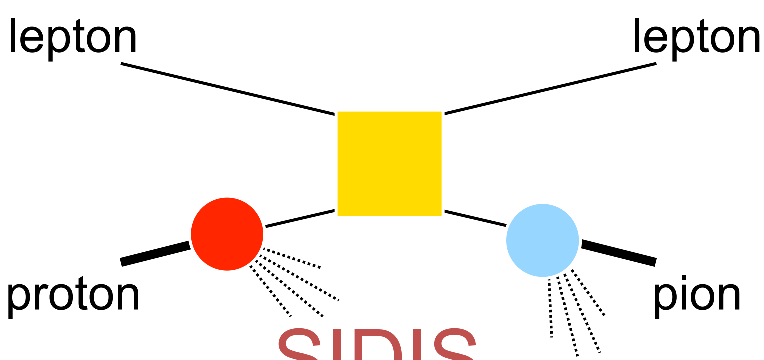
Marc Vanderhaeghen’s talk

Leading Twist TMDS

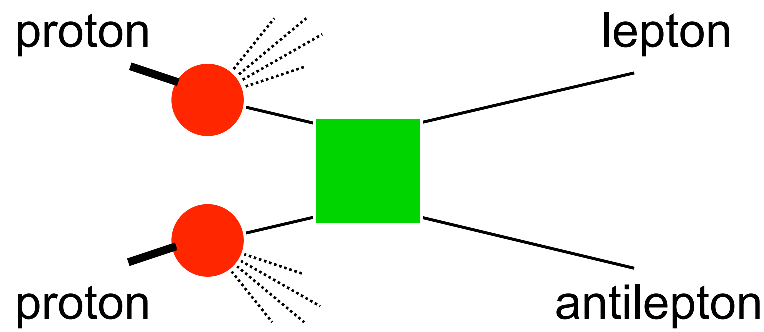
→ Nucleon Spin
→ Quark Spin

Nucleon Polarization		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
	U	$f_1 =$		$h_1^{\perp} =$ − Boer-Mulder
	L		$g_1 =$ − Helicity	$h_{1L}^{\perp} =$ −
	T	$f_{1T}^{\perp} =$ − Sivers	$g_{1T}^{\perp} =$ −	$h_{1T} =$ − Transversity $h_{1T}^{\perp} =$ − Pretzelosity

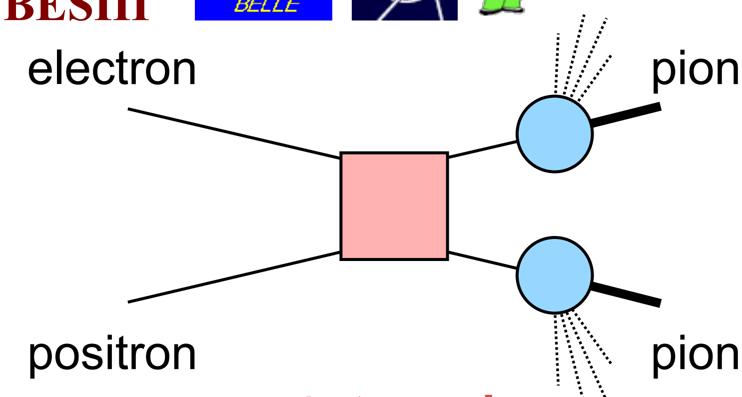
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

- Partonic scattering amplitude (yellow square)
- Fragmentation amplitude (light blue circle)
- Distribution amplitude (red circle)

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

Fragmentation Functions

quark pol.

hadron pol.

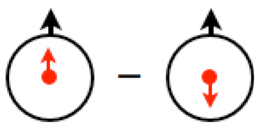
Ordinary FF → D_1

Collins FF → $H_1^{\perp}$

	U	L	T
U	D_1		$H_1^{\perp}$
L		G_1	$H_{1L}^{\perp}$
T	$D_{1T}^{\perp}$	$G_{1T}^{\perp}$	H_1 $H_{1T}^{\perp}$

Transverse Spin Structure

Transversity (TMD)

h_1  (Collinear & TMD)

A transverse counter part to the longitudinal spin structure: helicity g_{1L}

They are NOT the same due to relativity.

Chiral-odd

Unique for the quarks.
No mixing with gluons.
Simpler evolution effect.

NOT accessible via inclusive DIS process.
Must couple to another chiral-odd function.
(*e.g.* Collins function $H_1^{\perp}$)

Measured via SIDIS, Di-hadron, Drell-Yan

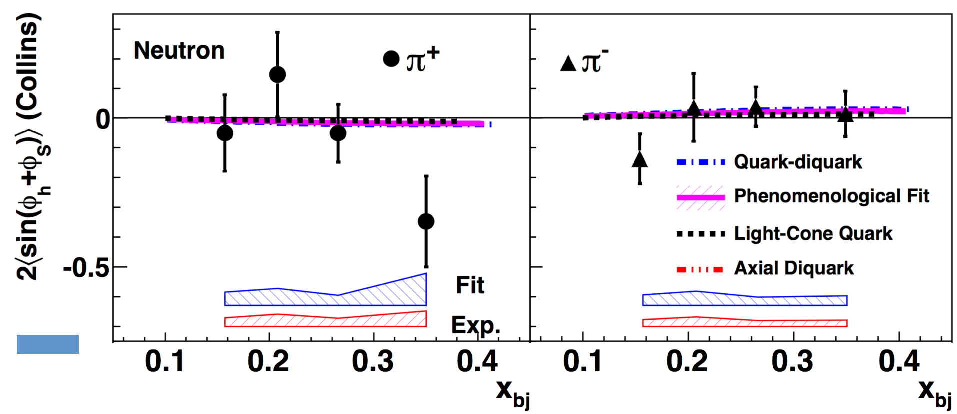
Measurement in SIDIS

Single spin asymmetry
(Collins asymmetry)

$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1(x, k_\perp) \bigotimes H_1^{\perp}(z, p_\perp)$$

$H_1^{\perp}(z, p_\perp)$ Collins fragmentation function

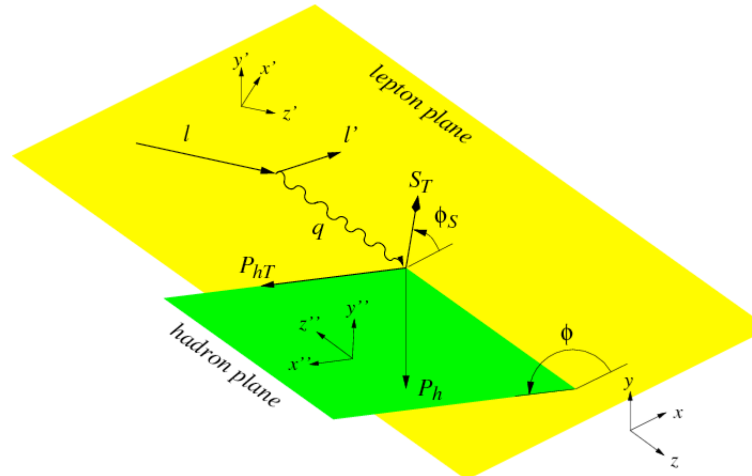
pioneered by HERMES
and COMPASS



6 GeV JLab E06-010, X. Qian et al., PRL 107, 072003 (2011).

Transversity GPD: A Kim (next talk)

SIDIS and Structure Functions



[Diehl&Sapeta EPJC2005]

SIDIS differential cross section

18 structure functions $F(x, z, Q^2, P_T)$, model independent. (one photon exchange approximation)

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

SoLID:
4D bins in (x, z, Q^2, P_T)

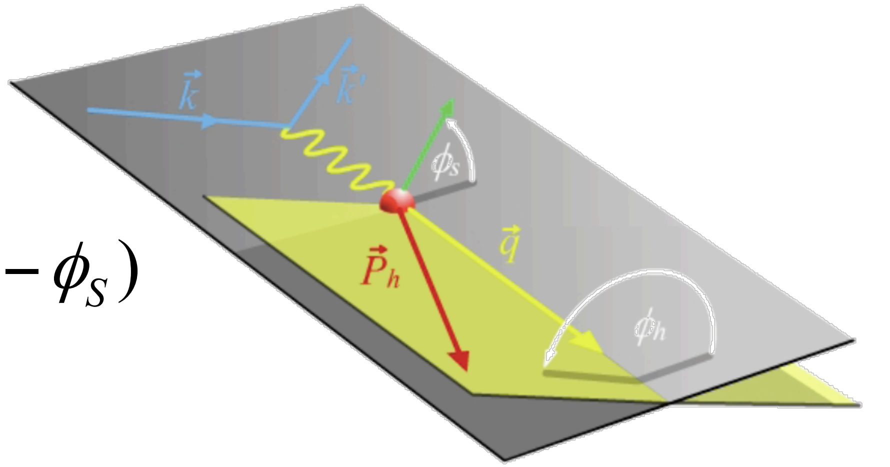
In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMD PDFs and FFs.

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l,\varphi_S^l)=\frac{1}{P}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$$

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

$$+A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S)$$



$$A_{UT}^{Collins}\propto\left\langle\sin(\phi_h+\phi_S)\right\rangle_{UT}\propto h_1\otimes H_1^{\perp}$$

$$A_{UT}^{Sivers}\propto\left\langle\sin(\phi_h-\phi_S)\right\rangle_{UT}\propto f_{1T}^{\perp}\otimes D_1$$

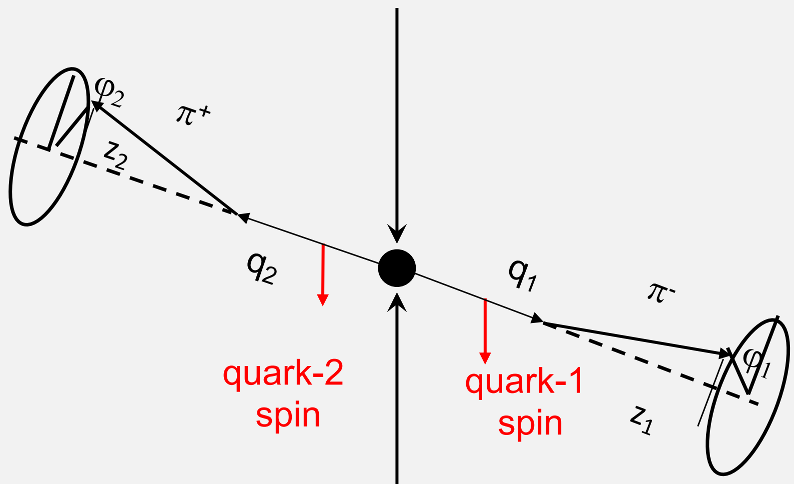
$$A_{UT}^{Pretzelosity}\propto\left\langle\sin(3\phi_h-\phi_S)\right\rangle_{UT}\propto h_{1T}^{\perp}\otimes H_1^{\perp}$$

Collins frag. Func. from e^+e^- collisions

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

COLLINS FFs IN e^+e^-

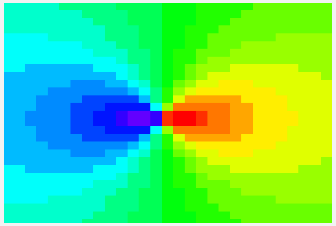


•First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ √s ~ 10.6 GeV (PRL 111,062002(2008), PRD 88,032011(2013)) leads to first extraction of transversity (Phys.Rev. D75 (2007) 054032) from SIDIS and e+e-

- Confirmed by BaBar @ √s ~ 10.6 GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for KK and Kπ)
- Measured at BESIII @ √s = 3.65 GeV (PRL 116,42001(2016))

Cross-section $e^+e^- \to (h_1 h_2)(\overline{h_1}\,\overline{h_2}) + X$

$$\propto D_1^\perp \overline{D_1^\perp} + H_1^\perp \overline{H_1^\perp}\cos(\phi_1 + \phi_2)$$



- Access spin dependence and p_T dependence (convolution or in jet) without PDF complication
- Made possible by B-factory luminosities

Workshop on Novel Probes of the Nucleon Structure in SIDIS, e+e- and pp (FF2019), chaired by Anselm Vossen and Harut Avagyan ***https://www.jlab.org/indico/event/308/***

SSA and transversity in di-hadron production

$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q) = \frac{1}{|\boldsymbol{S}_T|}\frac{\frac{8}{\pi}\int d\phi_R\, d\cos\theta\,\sin(\phi_R+\phi_S)\,(d\sigma^{\uparrow}-d\sigma^{\downarrow})}{\int d\phi_R\, d\cos\theta\,(d\sigma^{\uparrow}+d\sigma^{\downarrow})}$$

$$= \frac{\frac{4}{\pi}\,\varepsilon\int d\cos\theta\, F_{UT}^{\sin(\phi_R+\phi_S)}}{\int d\cos\theta\,(F_{UU,T}+\varepsilon\, F_{UU,L})} \quad .$$

Where

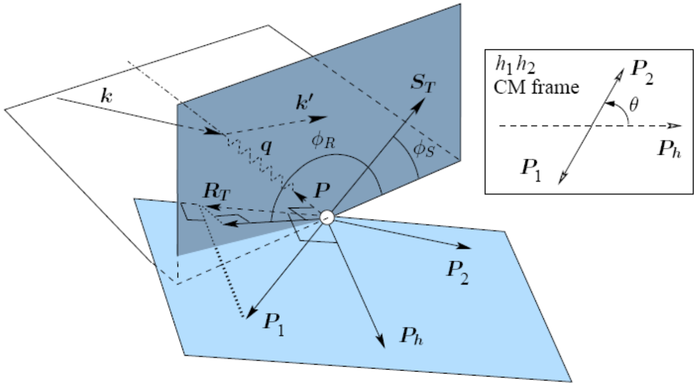
$$F_{UU,T} = x\, f_1(x)\, D_1\big(z,\cos\theta,M_h\big) \quad ,$$

$$F_{UU}^{\cos\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\,\frac{1}{z}\, f_1(x)\,\widetilde{D}^{\sphericalangle}\big(z,\cos\theta,M_h\big)$$

$$F_{UT}^{\sin(\phi_R+\phi_S)} = x\frac{|\boldsymbol{R}|\sin\theta}{M_h}\, h_1(x)\, H_1^{\sphericalangle}\big(z,\cos\theta,M_h^2\big) \quad ,$$

$$|\boldsymbol{R}| = \frac{1}{2}\sqrt{M_h^2 - 2(M_1^2+M_2^2) + (M_1^2-M_2^2)^2}$$

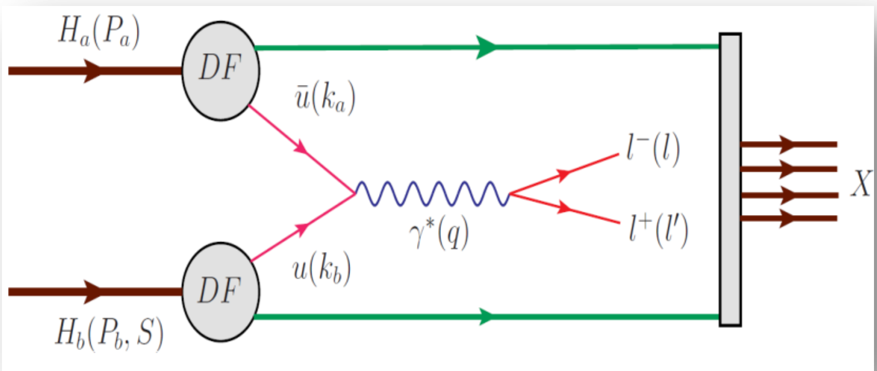
dihadron fragmentation function (DiFF). Fitting from $e^+ e^-$ annihilation data of Belle



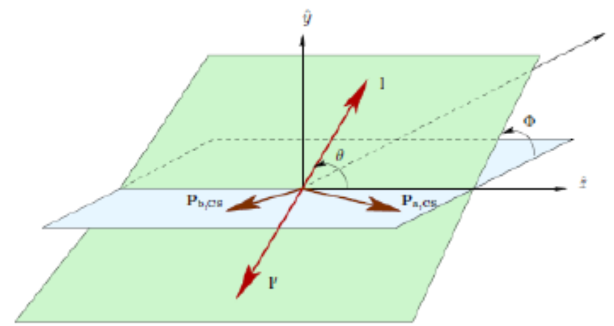
$P_h = (P_1 + P_2)$
$R = (P_1 - P_2) / 2$

Collinear factorization

Single-spin polarized DY cross sections

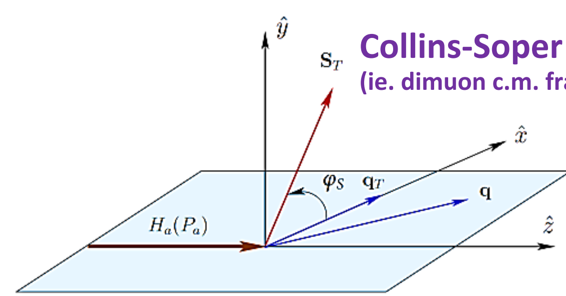


$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1+\cos^2\theta + \sin^2\theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}} + S_T \left[\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S} + \sin^2\theta \left(\begin{array}{l} \sin\left(2\varphi_{CS}+\varphi_S\right) A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ +\sin\left(2\varphi_{CS}-\varphi_S\right) A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array} \right) \right] \right\}$$



Cleanest probe to study hadron structure:

- no QCD final state effects
- no fragmentation process
- production of two TMD parton distribution functions
- ability to select sea quark distribution



target rest frame

credit: M. Chiosso & B. Parsamyan

LO SIDIS and single polarized DY cross sections

SIDIS

$$\frac{d\sigma^{LO}_{SIDIS}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) + S_T\begin{bmatrix}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{bmatrix}\right.$$

DY

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\left\{ 1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}} + S_T\left[\begin{matrix}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\ +\sin^2\theta\left(\begin{matrix}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ +\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{matrix}\right)\end{matrix}\right]\right\}$$

			PDF $\otimes$ FF		beam / target: PDF $\otimes$ PDF			
$A_{UU}^{\cos 2\phi_h}$	$\propto$	$h_1^{\perp q}\otimes H_{1q}^{\perp h}$	BM $\otimes$ CF		BM $\otimes$ BM	$A_T^{\cos 2\varphi_{cs}}$	$\propto$	$h_1^{\perp q}\otimes h_1^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_s)}$	$\propto$	$f_{1T}^{\perp q}\otimes D_{1q}^{h}$	Sivers $\otimes$ FF		f_1 $\otimes$ Sivers	$A_T^{\sin\varphi_s}$	$\propto$	$f_1^{q}\otimes f_{1T}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_s)}$	$\propto$	$h_1^{q}\otimes H_{1q}^{\perp h}$	Transv $\otimes$ CF		BM $\otimes$ Transv	$A_T^{\sin(2\varphi_{cs}-\varphi_s)}$	$\propto$	$h_1^{\perp q}\otimes h_{1T}^{\perp q}$
$A_{UT}^{\sin(3\phi_h-\phi_s)}$	$\propto$	$h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$	Pretz $\otimes$ CF		BM $\otimes$ Pretz	$A_T^{\sin(2\varphi_{cs}+\varphi_s)}$	$\propto$	$h_1^{\perp q}\otimes h_1^{q}$

within QCD TMD framework:

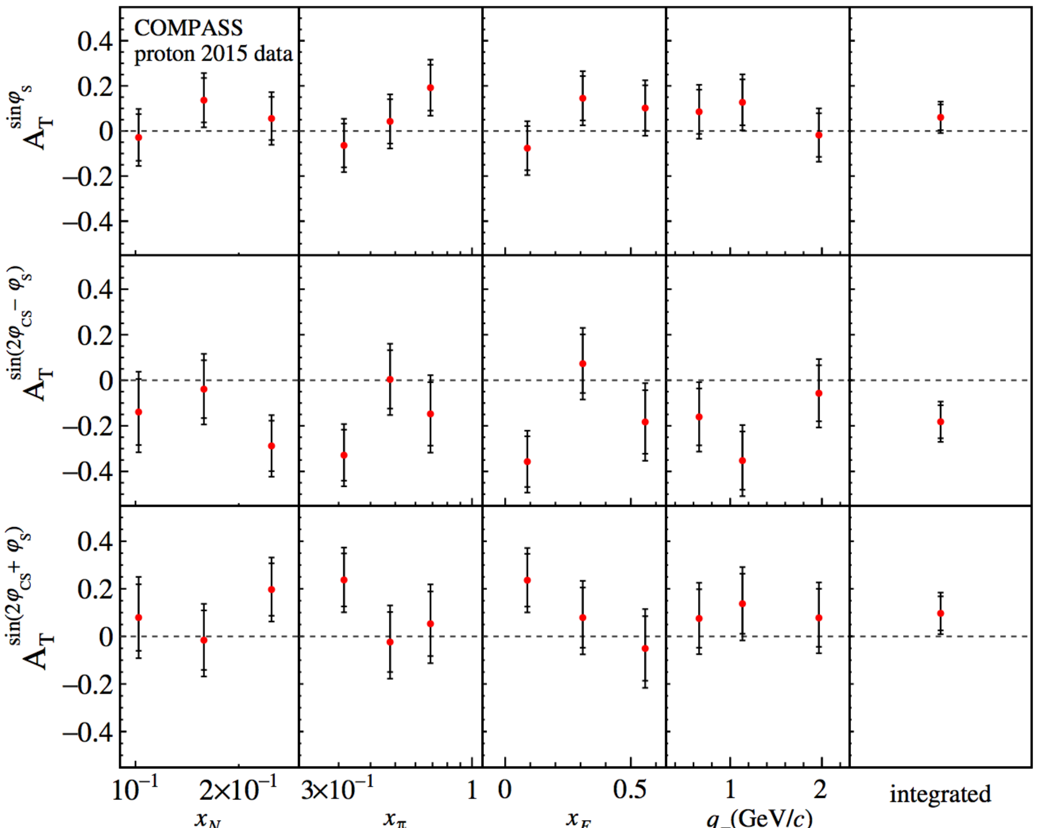
$$h_1^{\perp q}\Big|_{SIDIS} = -\,h_1^{\perp q}\Big|_{DY} \qquad f_{1T}^{\perp q}\Big|_{SIDIS} = -\,f_{1T}^{\perp q}\Big|_{DY}$$

$$h_1^{q}\Big|_{SIDIS} = h_1^{q}\Big|_{DY} \qquad h_{1T}^{\perp q}\Big|_{SIDIS} = h_{1T}^{\perp q}\Big|_{DY}$$

Transverse Spin Asymmetry in Drell-Yan

First measurement of transverse spin dependent azimuthal asymmetry in DY

190 GeV/c π^- beam, transversely polarized NH_3 target



Sivers

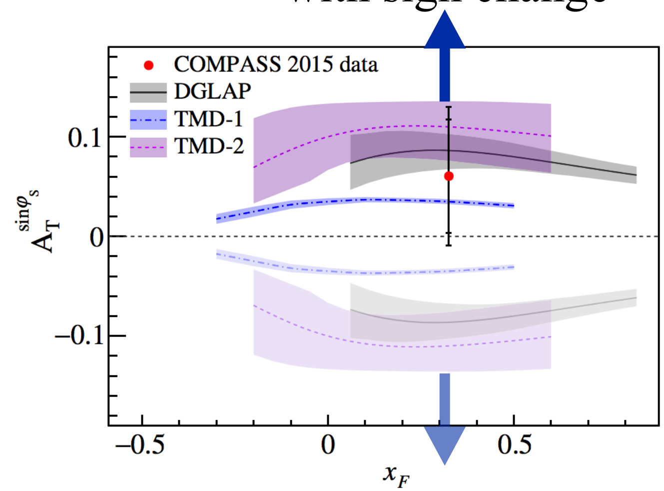
Transversity

Pretzelosity

Sign change test

$$f_{1T,\mathrm{DY}}^{\perp} = -f_{1T,\mathrm{SIDIS}}^{\perp}$$

with sign change



without sign change

M. Aghasyan *et al.* (COMPASS Collaboration), Phys. Rev. Lett. 119, 112002 (2017).

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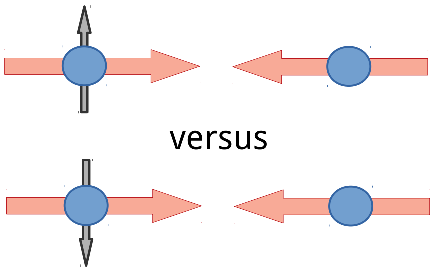
For a complete picture of nucleon spin structure at leading twist: **transversity**

Methods to access it at RHIC

Single spin asymmetries of the azimuthal distributions $\mathbf{A_{UT}}$



Spin-dependent modulation of hadrons in jets
Collins function (TMD FF)

Correlation of transverse spin of fragmenting quark and transverse momentum kick given to fragmentation hadron

Di-hadron correlation measurements
“interference FF” (collinear framework)

Correlation of transverse spin of fragmenting quark and and momentum cross-product of di-hadron pair

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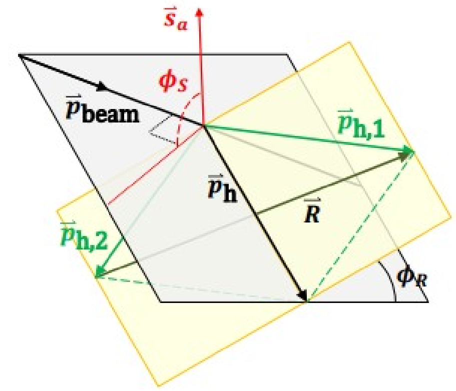
Interference Fragmentation Function (IFF)

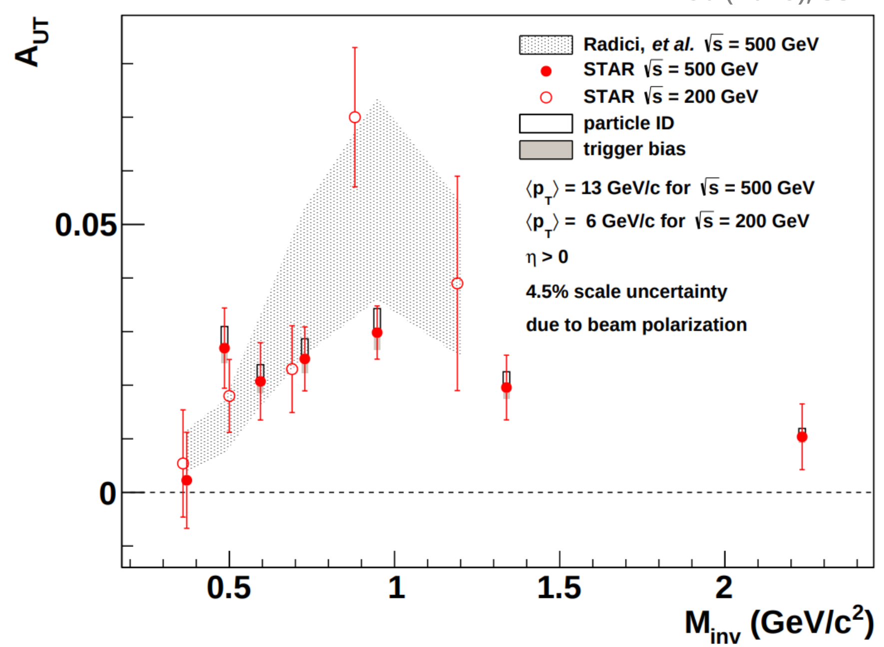
- The angle $\varphi_{RS} = \varphi_R - \varphi_S$ modulates the asymmetry due to the product of transversity and the IFF by $\sin(\varphi_{RS})$

- First **significant transversity signal** measured in the central detector in pp collisions
- Well described by **recent IFF asymmetry calculations** incorporating SIDIS and Belle e^+e^- data

- **Gobal analysis** including the IFF results from 200 GeV pp collisions
  M. Radici and A. Bacchetta, PRL 120, (2018) 192001
  - Reduction of the uncertainty for h_1^u
  - uncertainty for h_1^d: dominated by $g \rightarrow \pi^+\pi^-$ FF



PLB 780 (2018), 332



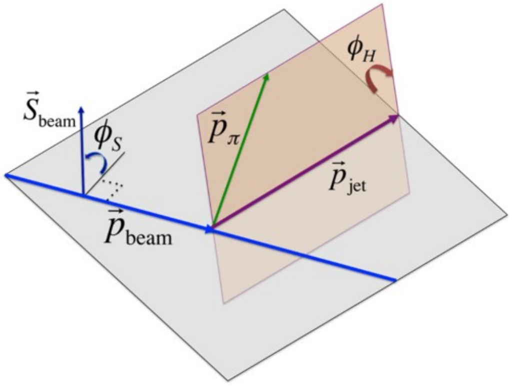
TRANSVERSITY

Collins asymmetry

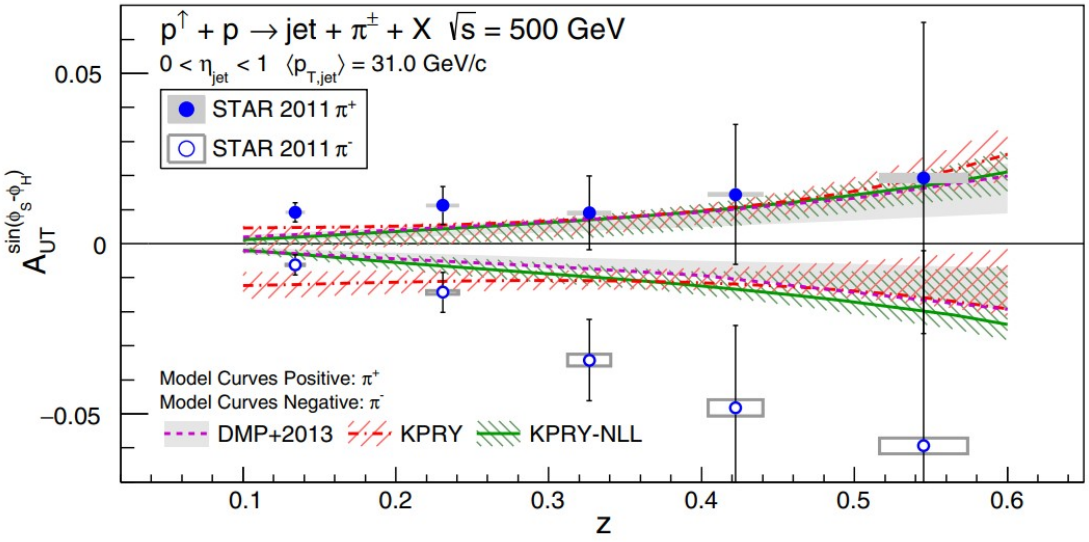
Transversity x Collins

$$d\sigma_{UT} \sim d\sigma_{UU}[1 + A'_{UT}\sin(\phi_s - \phi_h) + A''_{UT}\sin(\phi_s - 2\phi_h)]$$

The angle $\varphi_{SH} = \varphi_S - \varphi_H$ modulates the asymmetry due to the product of transversity and the Collins function by $\sin(\varphi_{RS})$



PRD 97 (2018), 032004

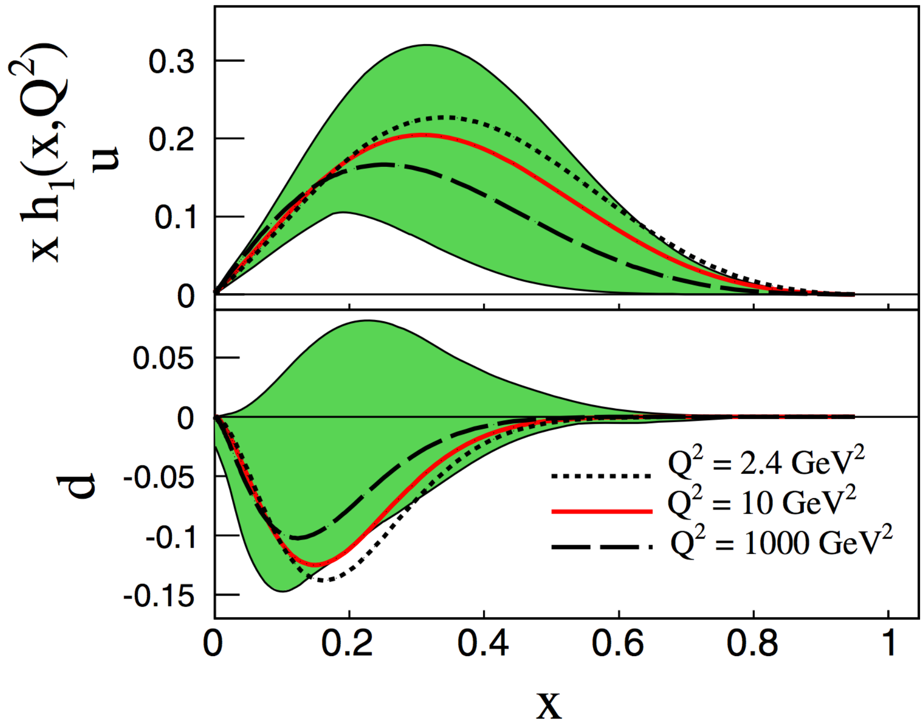


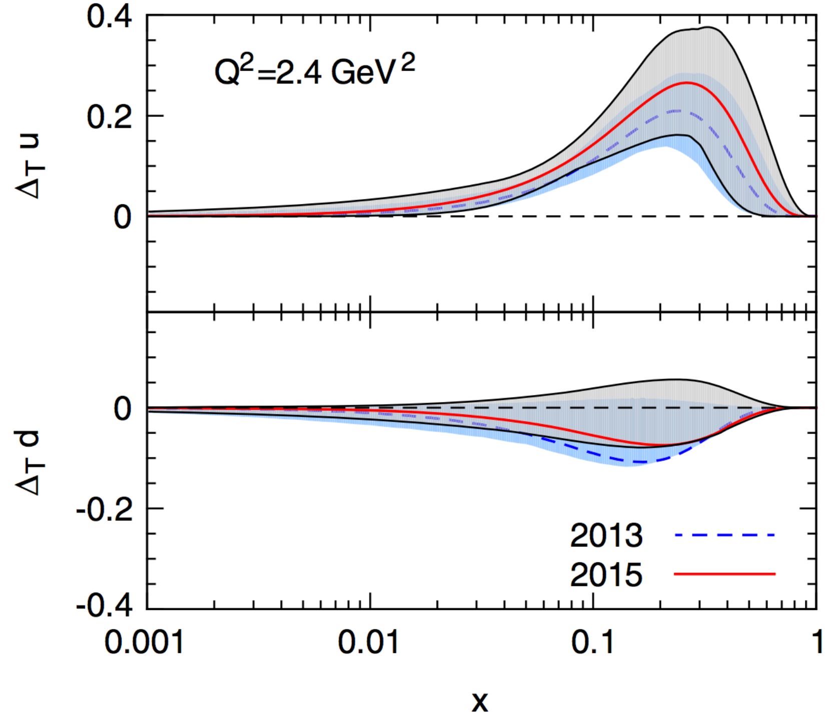
D'Alesio, Murgia & Pisano
PLB 773 (2017), 300

Kang, Prokudin, Ringer & Yuan,
PLB 774 (2017), 635
without and with evolution

- Theory predistions using transversity and Collins FF extracted from SIDIS and e^+e^-
- TMD Evolution effects appear to be small

Global Analysis: Transversity





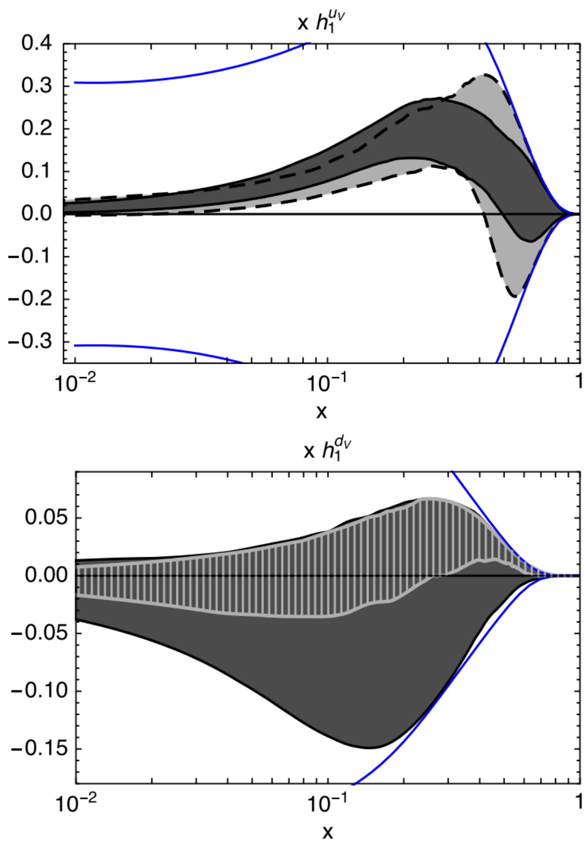
Z.-B. Kang et al., Phys. Rev. D 93, 014009 (2016).

M. Anselmino et al., Phys. Rev. D 92, 114023 (2015).

Latest from Phenomenological Extractions

Extraction in collinear factorization

First global fit of ep and pp data (pion pairs)

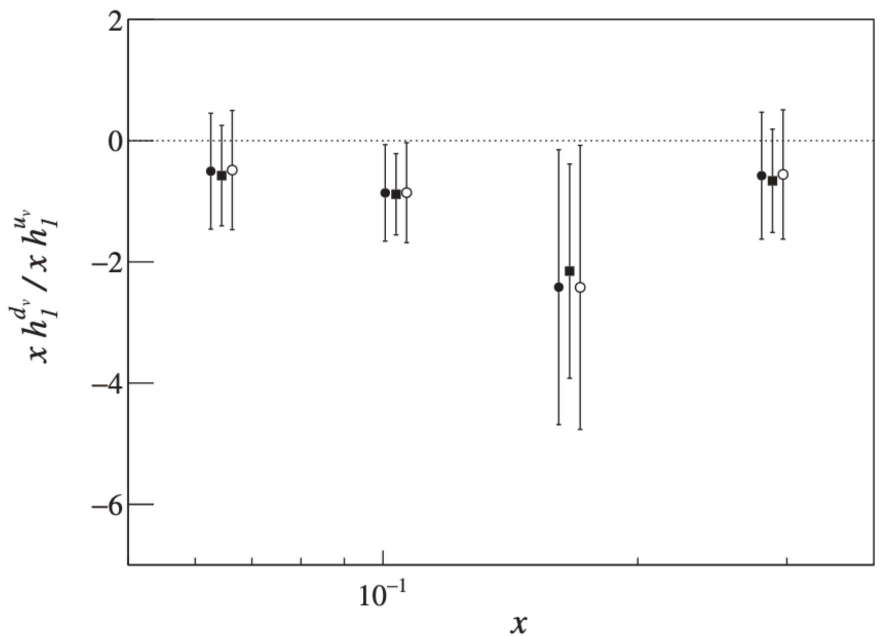


M. Radici and A. Bacchetta, Phys. Rev. Lett. 120, 192001 (2018).

M. Radici's talk yesterday

Extraction in TMD factorization

Extract d/u transversity ratio from SIDIS data only, without knowledge of Collins FFs.

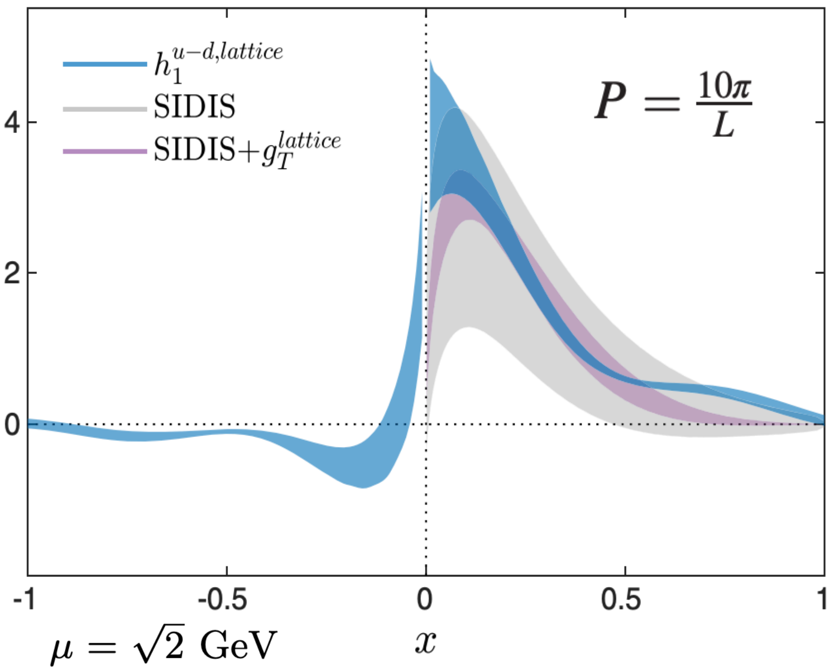


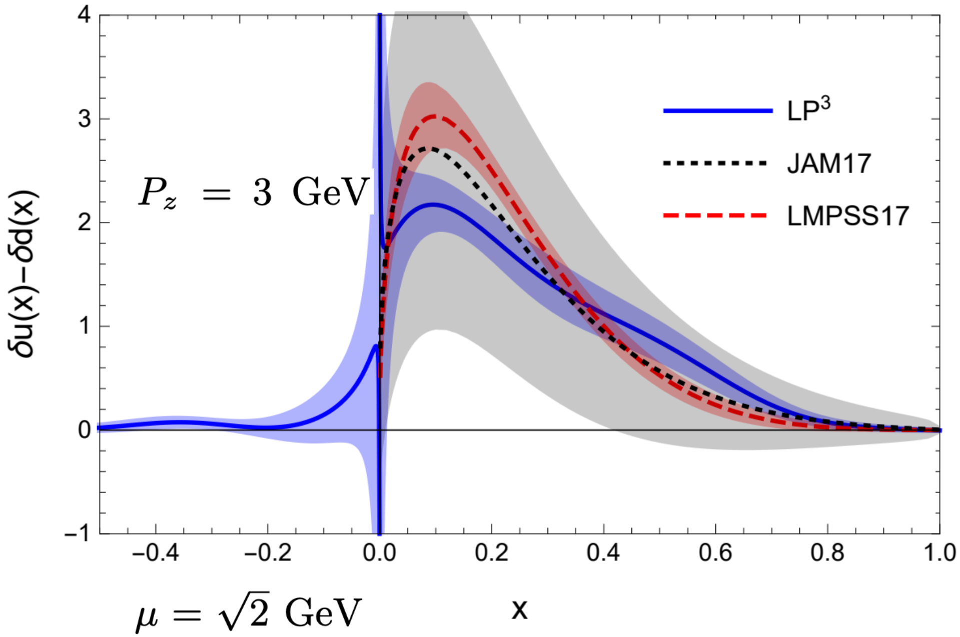
V. Barone *et al.*, Phys. Rev. D 99, 114004 (2019)

Lattice QCD Calculations

Progress on lattice QCD calculations of the transversity distribution

Physical quark mass; nonperturbative renormalization; one-loop matching.



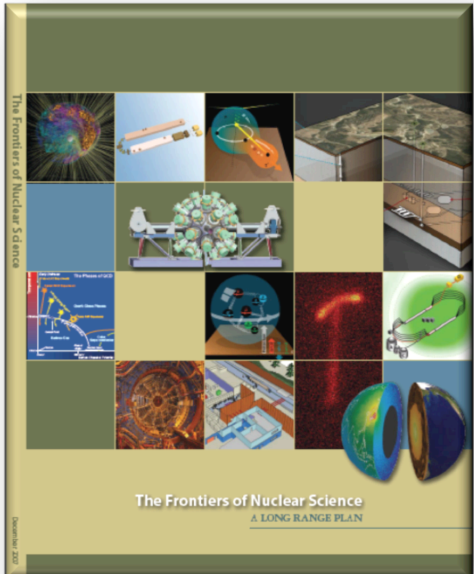


C. Alexandrou *et al.*, Phys. Rev. D 98, 091503(R) (2018).

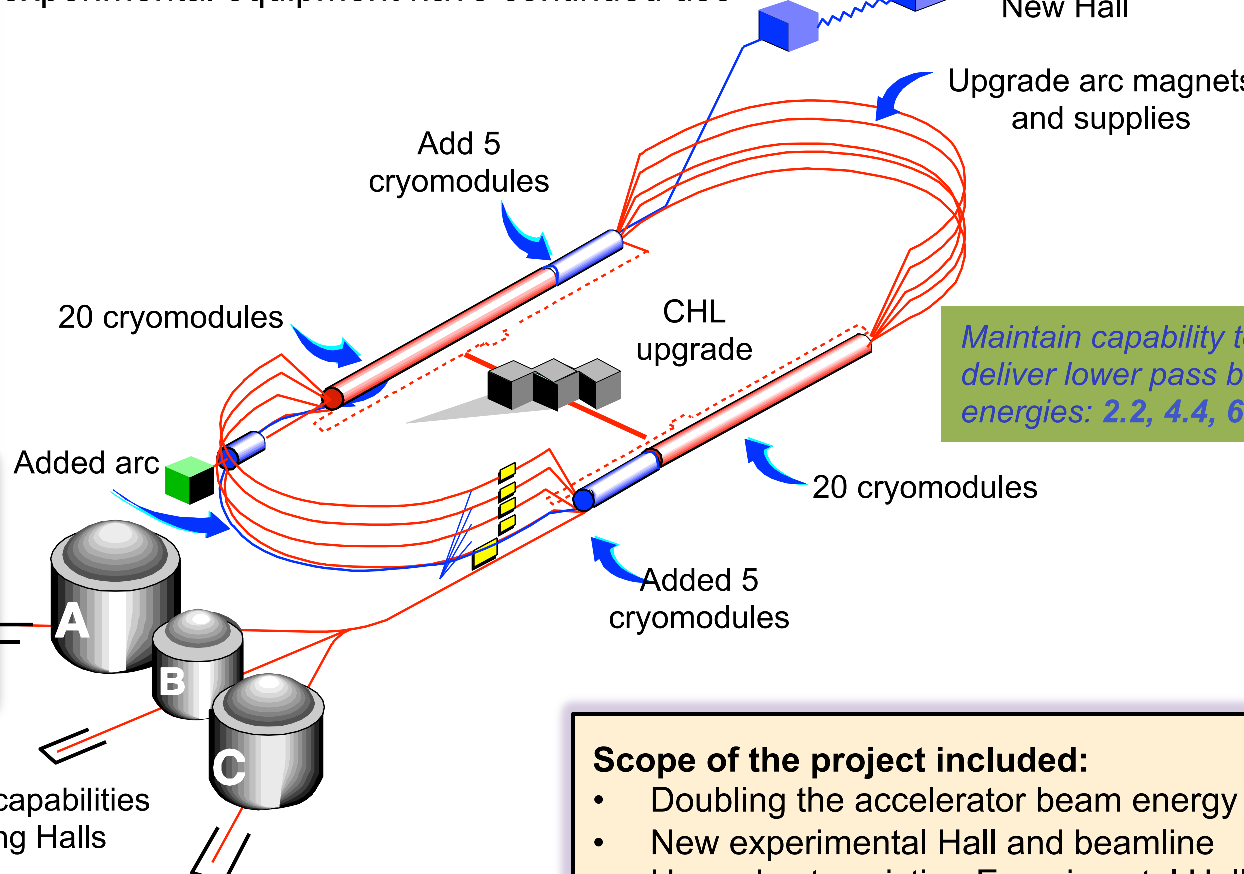
Y.-S. Liu *et al.*, arXiv:1810.05043.

H.W-Lin's talk

12 GeV Upgrade at JLab



Upgrade was designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

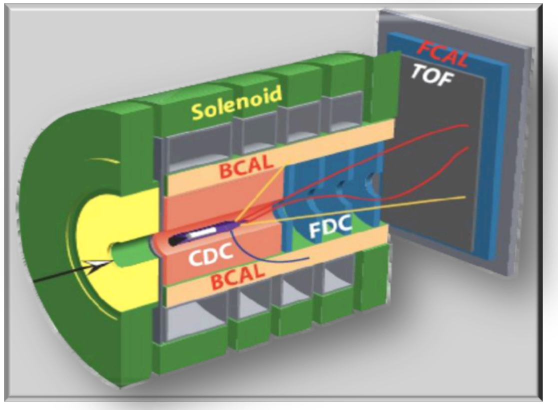
Scope of the project included:

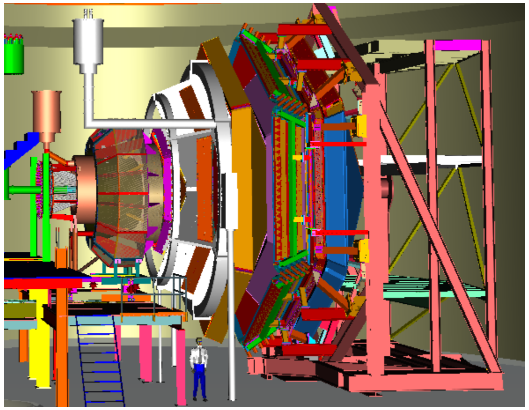
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

Solenoidal Large Intensity Device (SoLID) proposed for Hall A

12 GeV Upgrade Physics Instrumentation

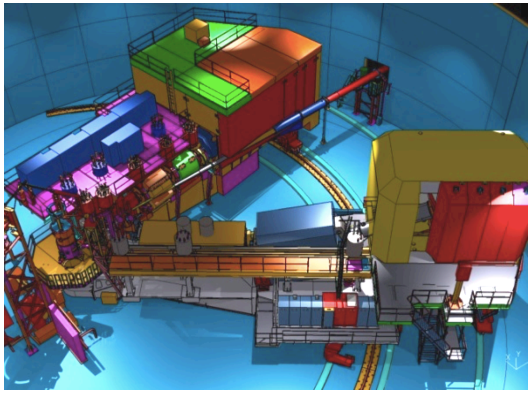
GLUEx (Hall D): exploring origin of confinement by studying hybrid mesons

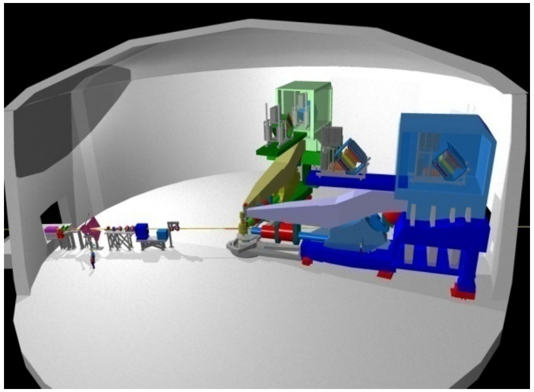




CLAS12 (Hall B): understanding nucleon structure via generalized parton distributions

SHMS (Hall C): precision determination of valence quark properties in nucleons and nuclei

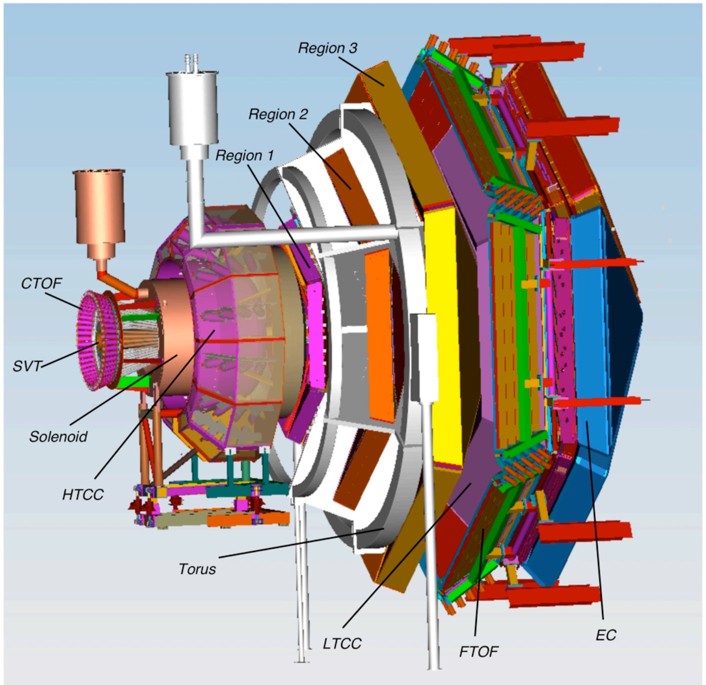


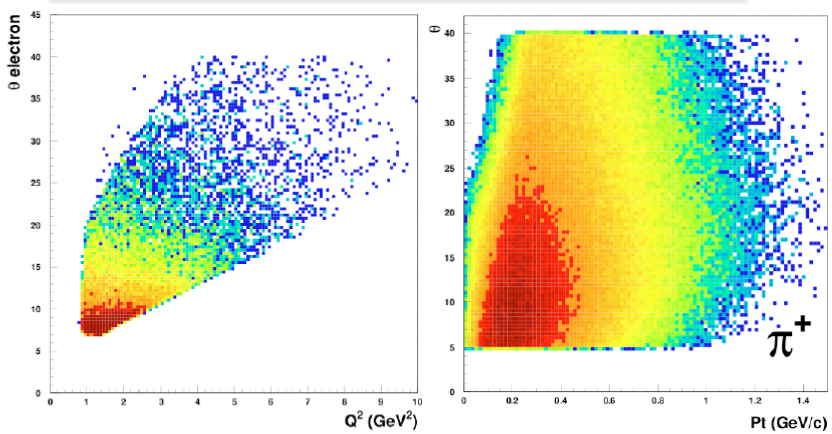


Hall A: nucleon form factors,

& future new experiments using new devices

CLAS 12

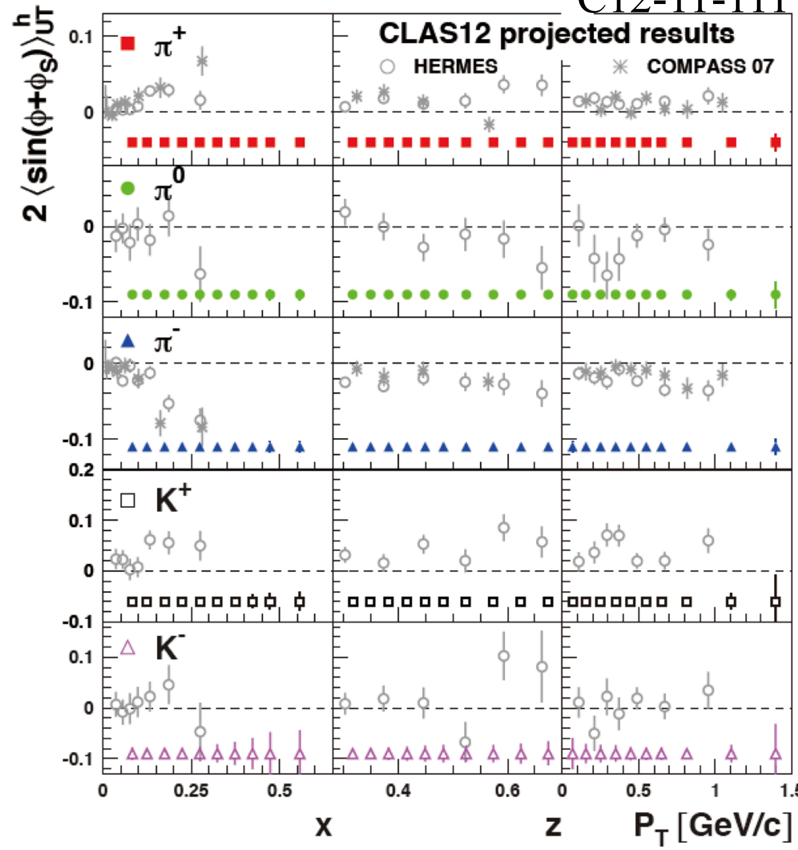




E12-09-007, E12-09-008
E12-09-009, E12-07-107

NH_3 and ND_3 targets

C12-11-111



Hall C SIDIS Program (typ. x/Q^2 ~ constant)

[R. Ent, DIS2016]

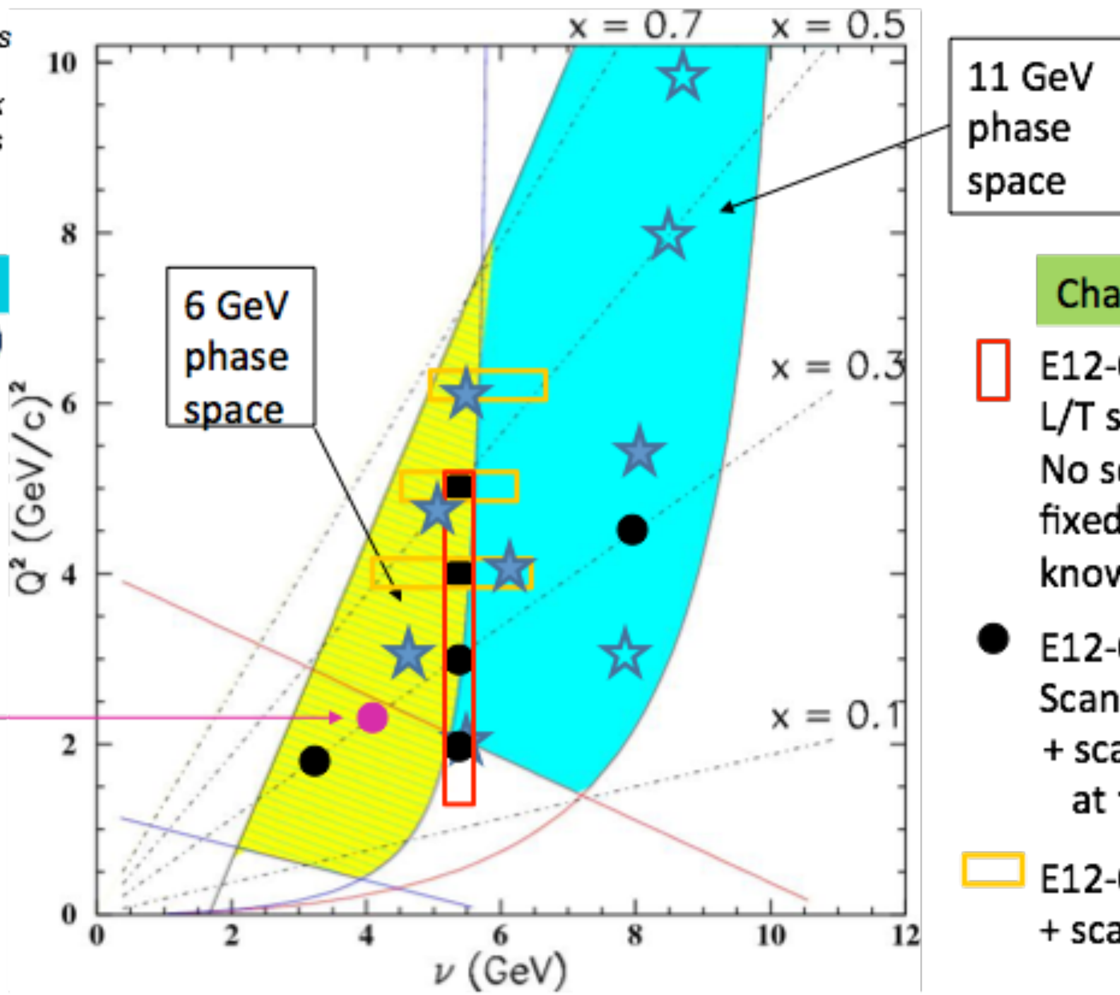
HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007
★ Neutral pions:
Scan in (x,z,P_T)
Overlap with E12-09-017 & E12-09-002

☆ Parasitic with E12-13-010

E00-108 (6 GeV)



Charged pions:

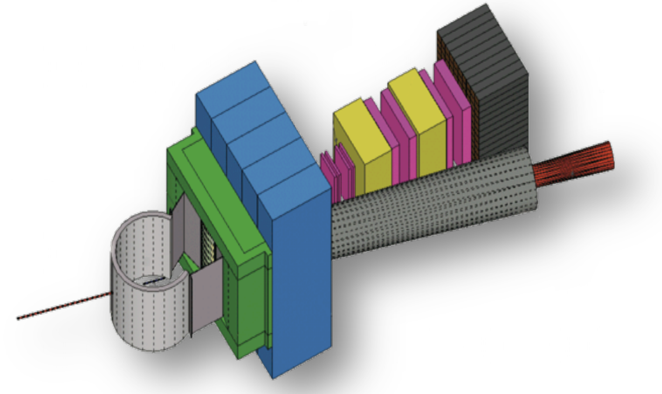
E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

● E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

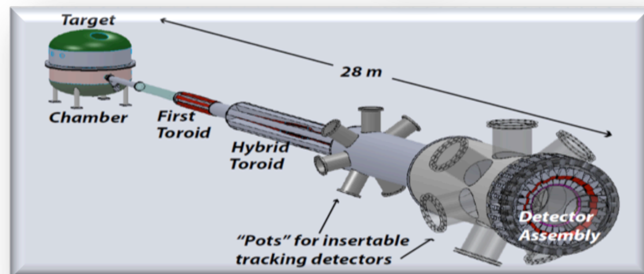
E12-09-002
+ scans in z

Beyond Baseline 12 GeV Upgrade

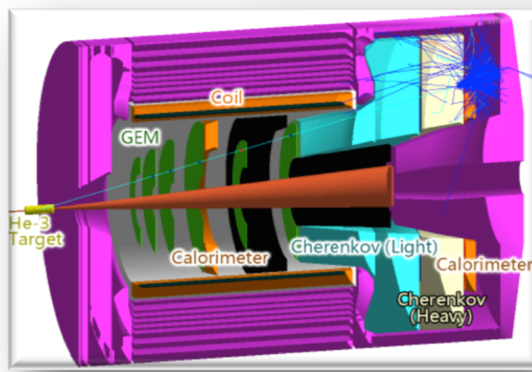
- **Super BigBite Spectrometer under construction**
  - **high Q^2 form factors**
  - **SIDIS**



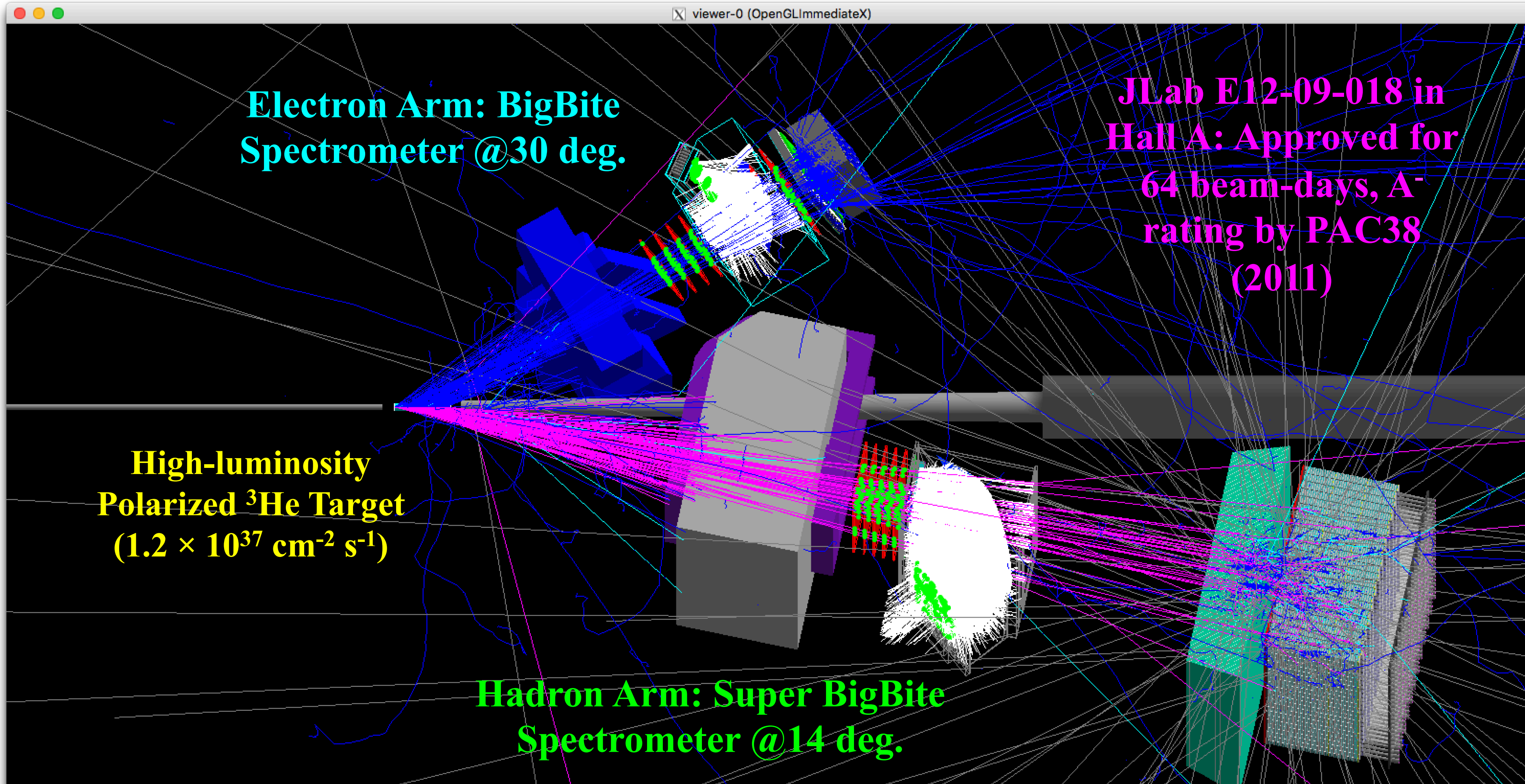
- **MOLLER experiment (MIE – FY20-24, CD0→CD1)**
  - **Standard Model Test**



- **SoLID program Proton mass, spin and Standard Model Test**

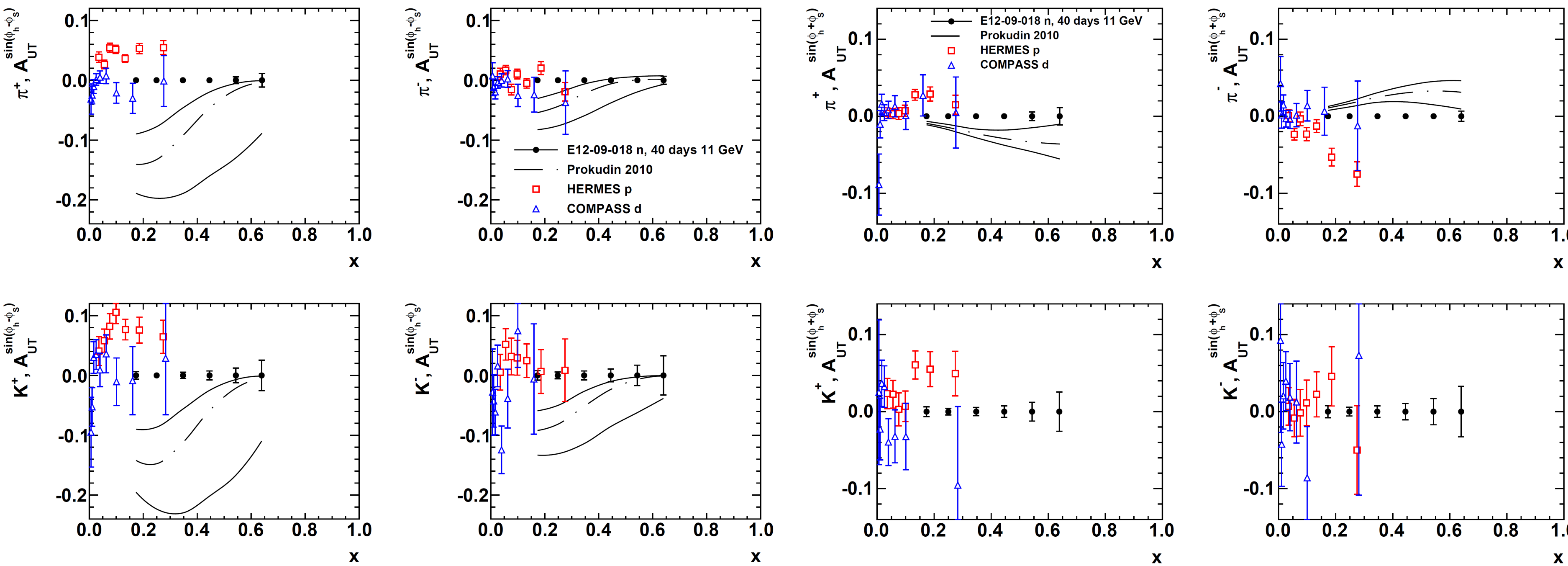


E12-09-018—Transversely Polarized



- **E12-09-018** in Hall A: transverse spin physics with high-luminosity polarized ^{3}He.
- 40 (20) days production at E = 11 (8.8) GeV—significant Q^2 range at fixed x
- Collins, Sivers, Pretzelosity, A_{LT} for n(e,e'h)X, h = $\pi^+/\pi^-/\pi^0/K^+/K^-$
- Re-use HERMES RICH detector for charged hadron PID
- Reach high x (up to ~0.7) and high statistical FOM (~1,000X Hall A E06-010 @6 GeV)

SBS+BB Projected Results: Collins and Sivers SSAs



Projected A_{UT}^{Sivers} vs. x (11 GeV data only)

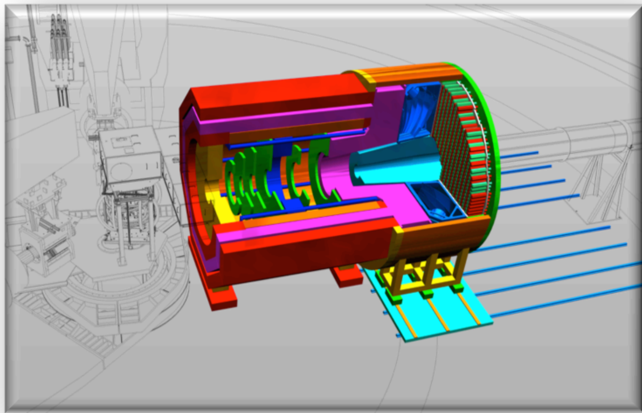
Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)

- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than E06-010 neutron data.
- Kaon and neutral pion data will aid flavor decomposition, and understanding of reaction-mechanism effects.

Solenoidal Large Intensity Device (SoLID) Physics

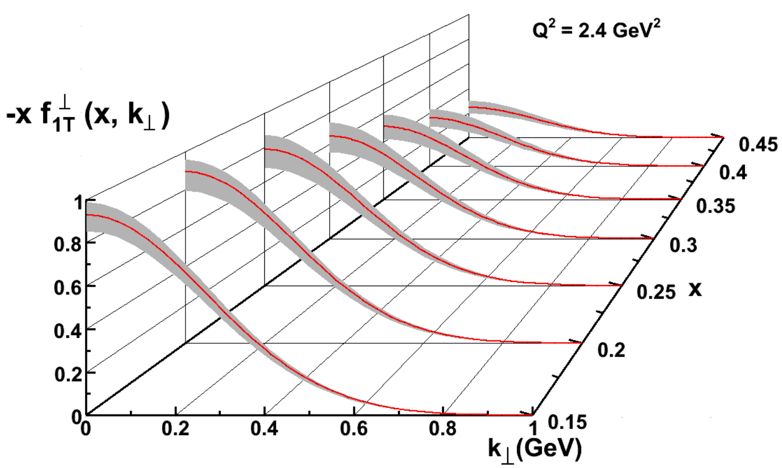
SoLID provides unique capability:

- ✓ high luminosity ($10^{37\text{-}39}$)
- ✓ large acceptance with full ϕ coverage

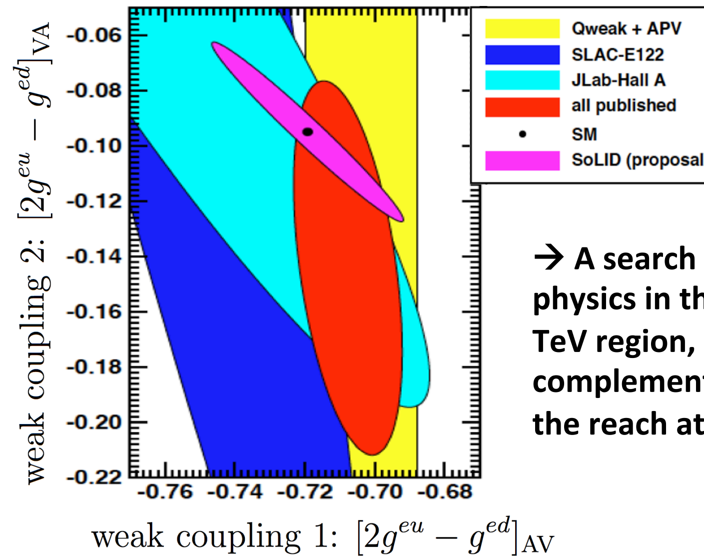


→ multi-purpose program to maximize the 12-GeV science potential

1) Precision in 3D momentum space imaging of the nucleon

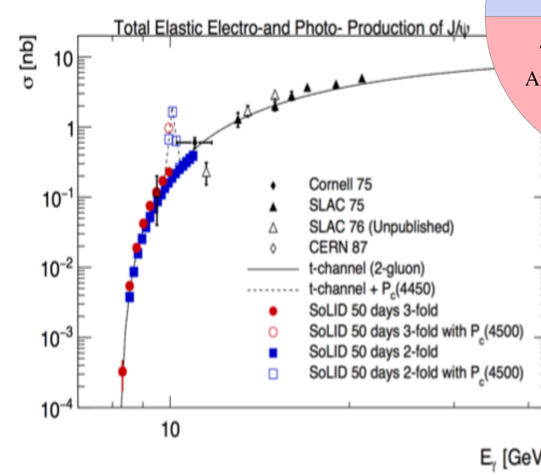


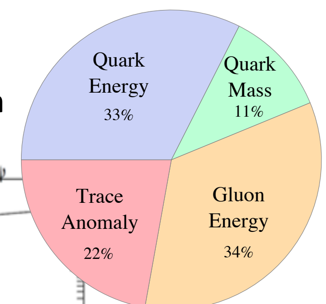
2) Precise determination of the electroweak couplings



→ **A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.**

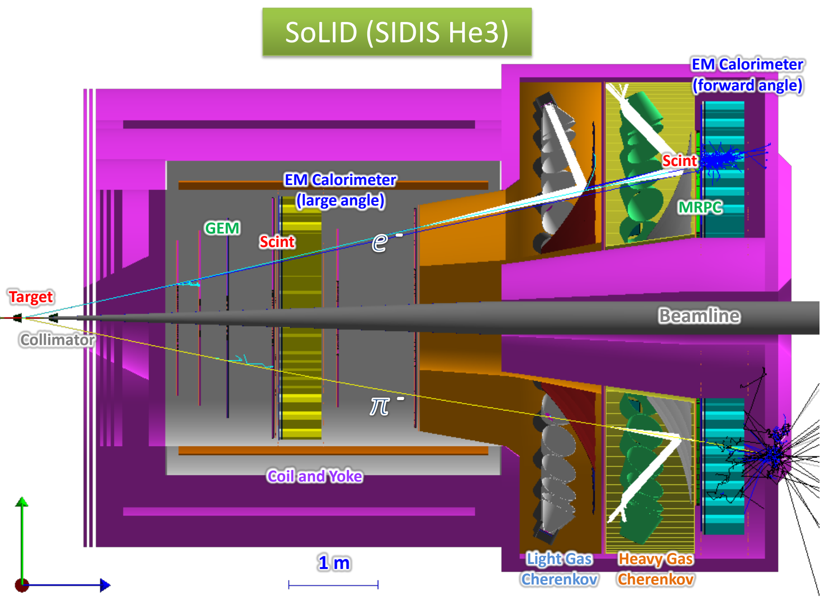
3) J/ψ production cross section

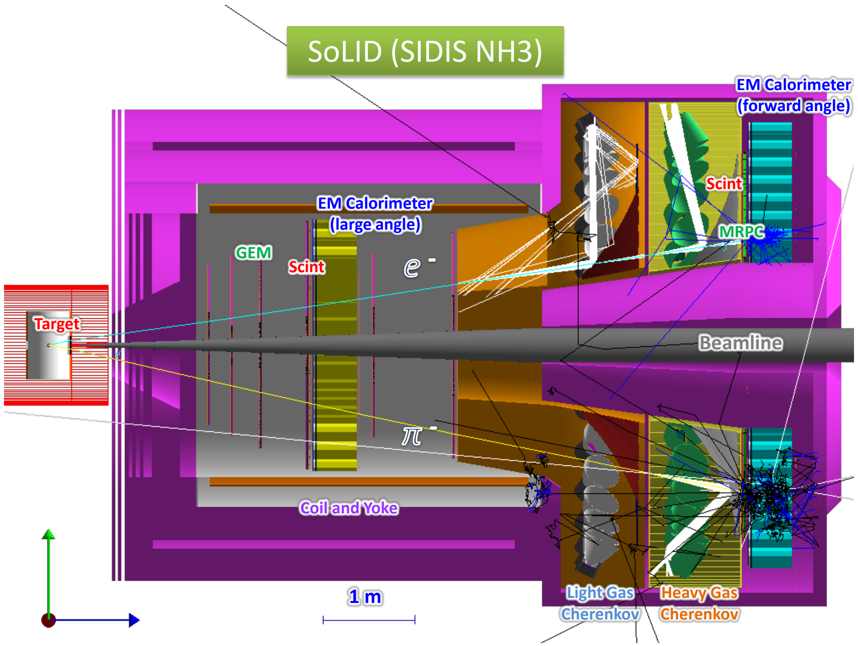




→ **Constrain the QCD trace anomaly, Proton mass , LHCb charmed pentaquark**

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV





E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

Several run group experiments approved: TMDs, GPDs, and much more

Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

SoLID SIDIS Projection

Compare SoLID with World Data

Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation

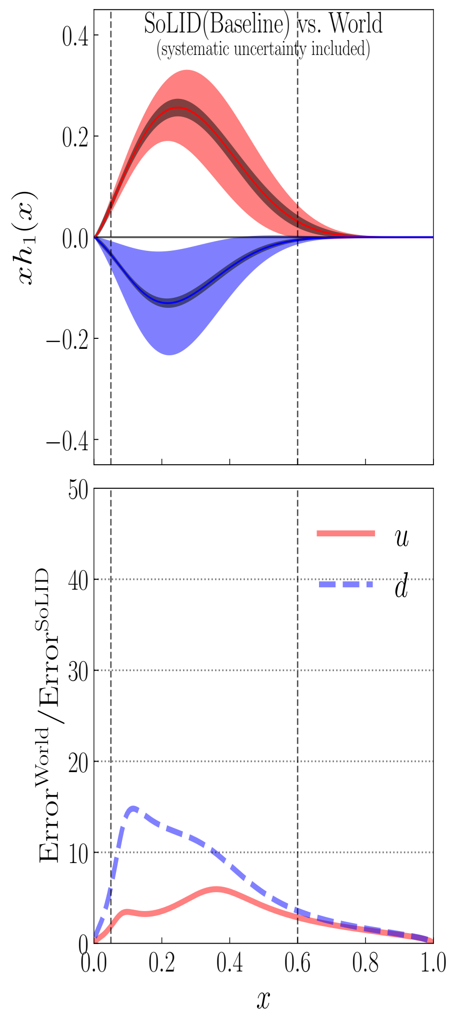
World data from HERMES, COMPASS and JLab-6 GeV

e^+e^- data from BELLE and BABAR

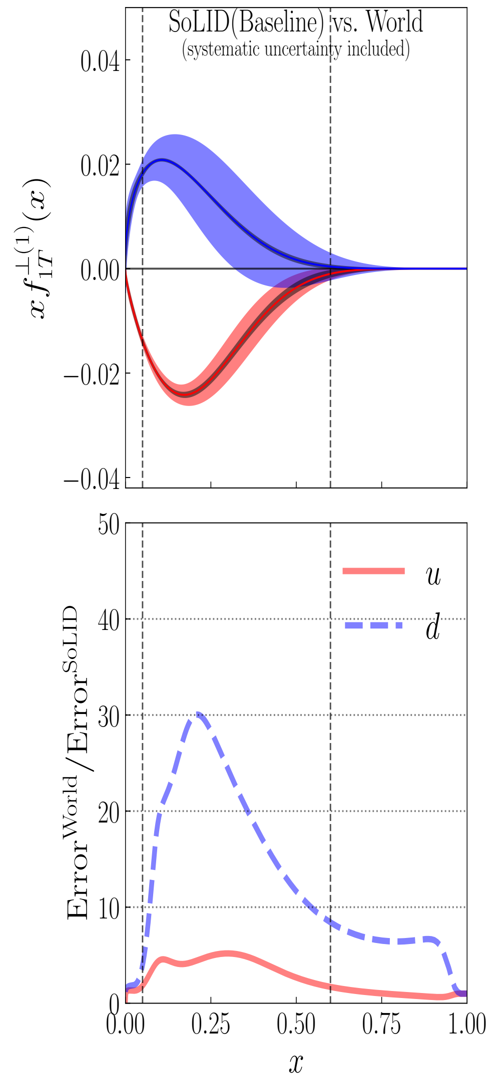
Monte Carlo method with nested sampling algorithm is applied

Including both systematic and statistical uncertainties

Transversity



Sivers

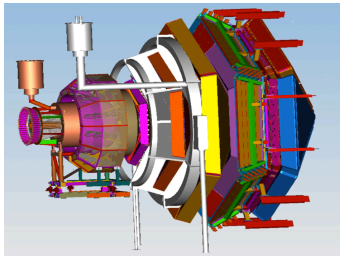


Ref: Z. Ye *et al*, Phys. Lett. B 767, 91 (2017)

SoLID baseline used

Accessing transversity in dihadron production at JLab

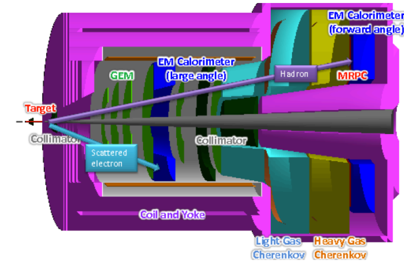
Measurements with polarized protons



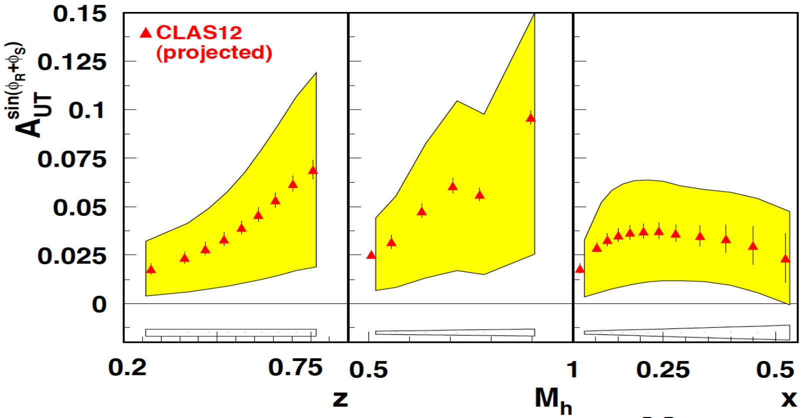
CLAS12

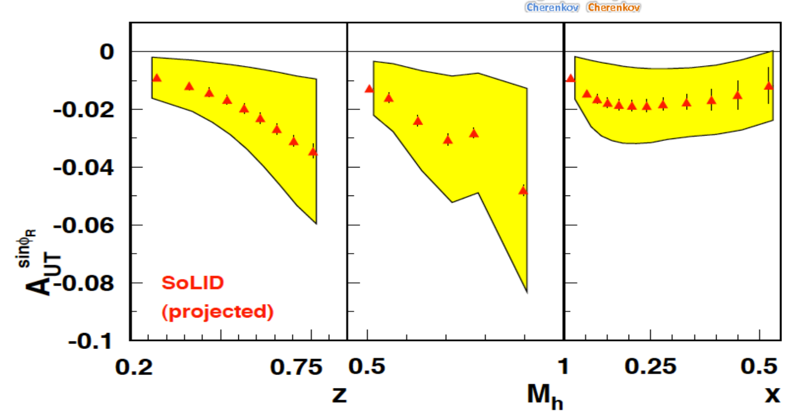
$$A_{UT}(\phi_R,\theta) = \frac{1}{fP_t}\frac{(N^+ - N^-)}{(N^+ + N^-)}$$

Measurements with polarized neutrons

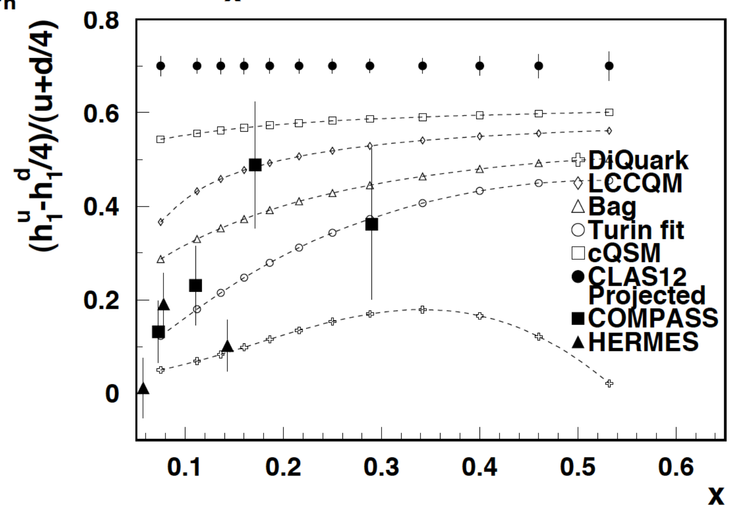


SoLID





$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_h)[4h_1^u - h_1^d(x)]}{D_1^u(4f_1^u + f_1^d)}$$



$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_{\pi\pi})\ (4h_1^d(x) - h_1^u(x))}{D_1^u(z,M_{\pi\pi})\ (4f_1^d(x) + f_1^u(x))}$$

SoLID Impact on Tensor Charge

Definition

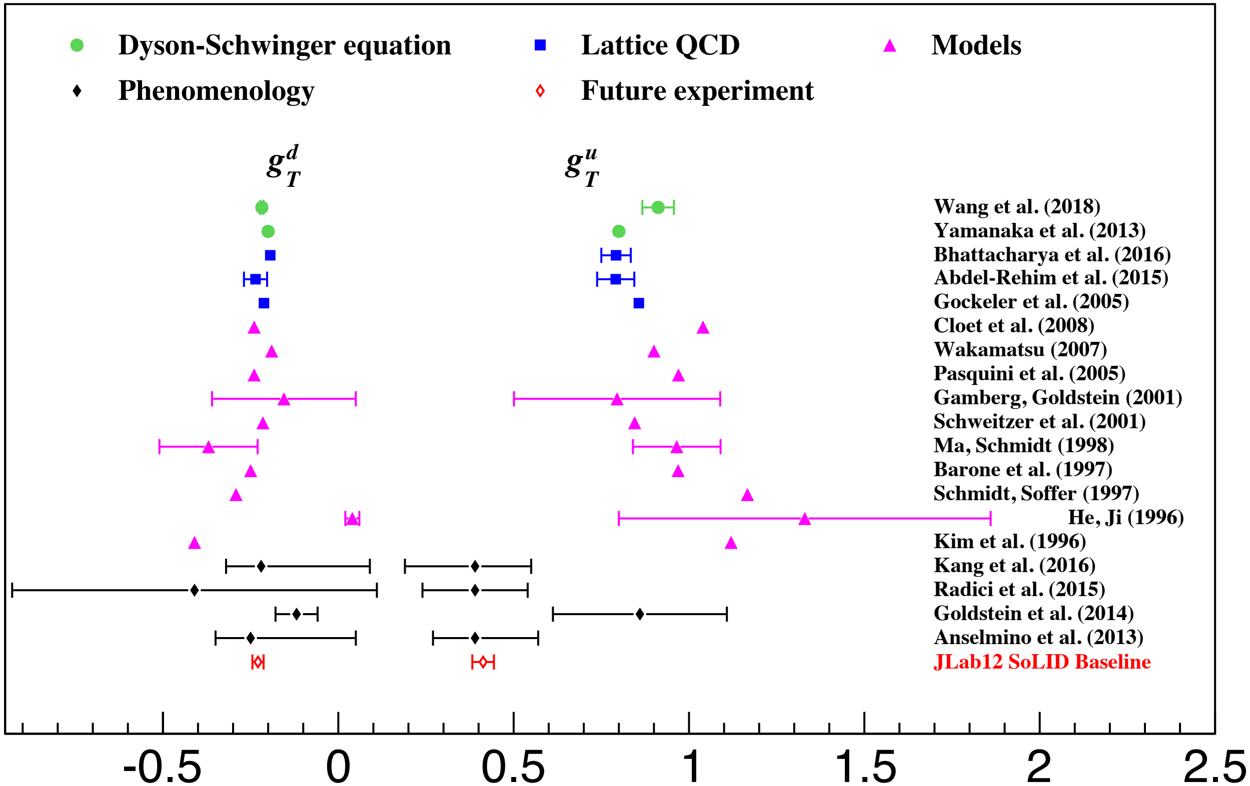
$$g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = g_T^q\,\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S)$$

- A fundamental QCD quantity: matrix element of local operators.
- Moment of the transversity distribution: valence quark dominant.
- Calculable in lattice QCD.

Including both systematic and statistical uncertainties

SoLID baseline used



H.-W. Lin *et al.*, Phys. Rev. Lett. 120, 152502: MC global analysis with lattice constraints

M. Radici's talk, Craig Roberts's talk

Constraint on Quark EDMs

$$d_n = g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s$$

Constraint on quark EDMs with combined proton and neutron EDMs

	d_u upper limit	d_d upper limit
Current g_T + current EDMs	$1.27\times10^{-24}\,e$ cm	$1.17\times10^{-24}\,e$ cm
SoLID g_T + current EDMs	$6.72\times10^{-25}\,e$ cm	$1.07\times10^{-24}\,e$ cm
SoLID g_T + future EDMs	$1.20\times10^{-27}\,e$ cm	$7.18\times10^{-28}\,e$ cm

Include 10% isospin symmetry breaking uncertainty

Sensitivity to new physics

$$d_q \sim \bar{e} m_q/(4\pi\Lambda^2)$$

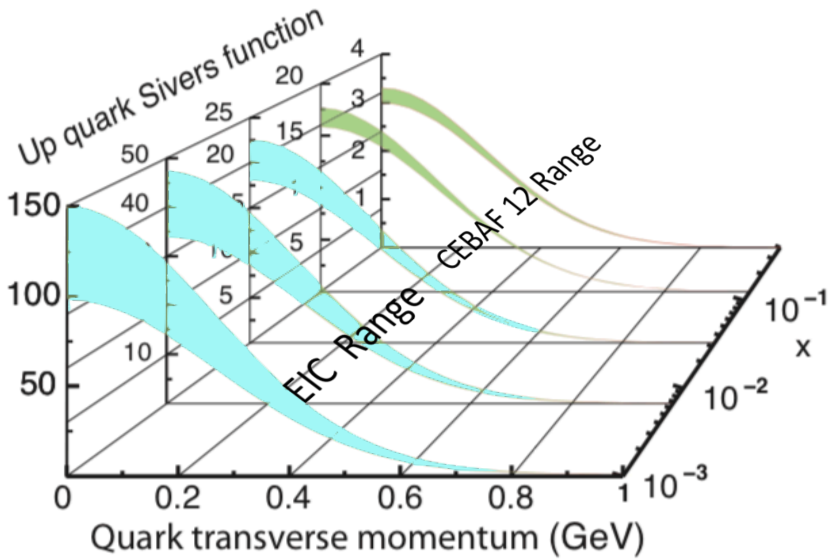
Three orders of magnitude improvement on quark EDM limit → Probe to 30 ~ 40 times higher scale

Current quark EDM limit: $10^{-24}e$ cm → ~ 1 TeV

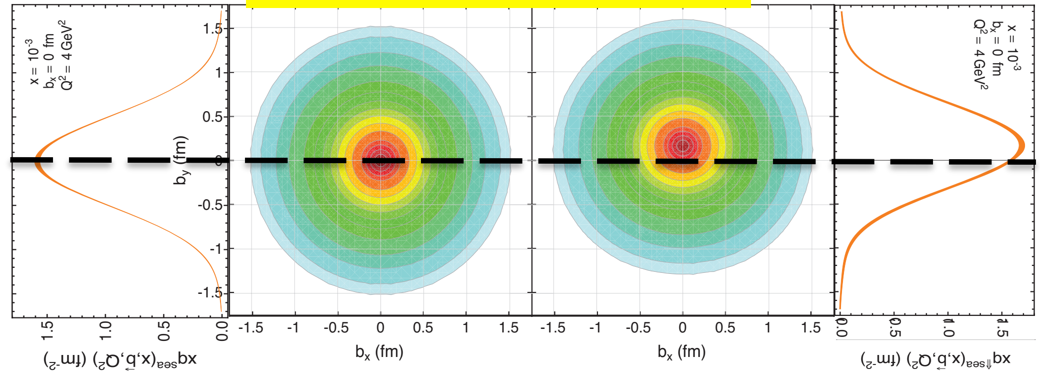
Future quark EDM limit: $10^{-27}e$ cm → 30 ~ 40 TeV

H. Gao, T. Liu, Z. Zhao, PRD 97, 074018 (2018)

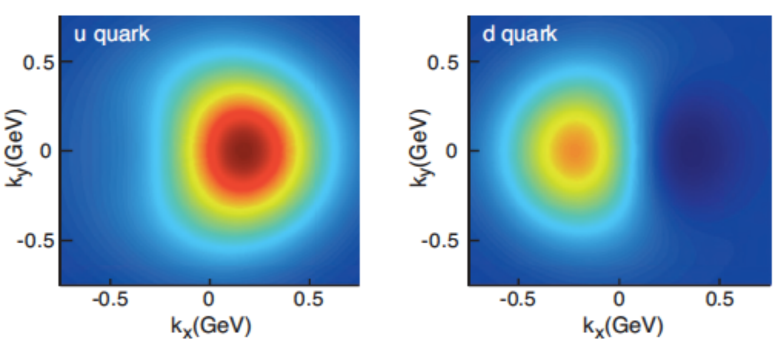
EIC Science: Imaging quarks and gluons in nucleons



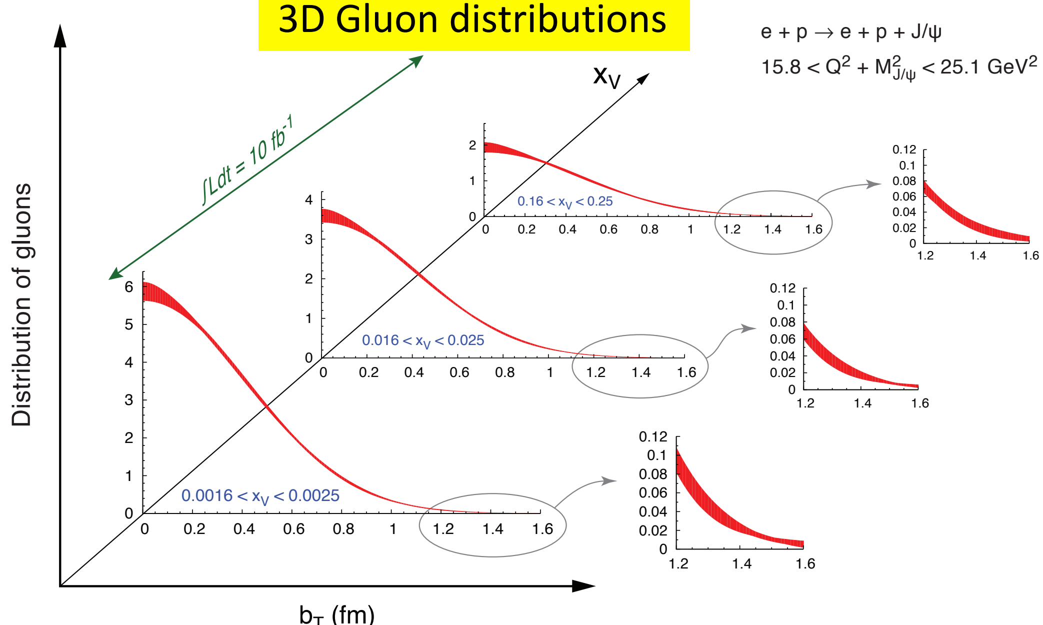
3D Sea Quark distributions unpolarized and polarized



Polarized Quark 3D Momentum distributions



3D Gluon distributions



Summary

- Three-dimensional imaging of nucleon helps solve the remaining puzzle to the proton spin, and uncovers the rich dynamics of QCD, TMDs also uncover the confined motion of quarks and gluons inside the nucleon
- Major progress made in experimental studies of TMDs and particularly concerning transversity
- More results will become available from experiments worldwide, especially from JLab 12 GeV
- TMDs at EIC: Sea quark region and the gluons, together with 12-GeV, provide full tomography of nucleons in momentum space

Thanks to H. Avakian, J.-P Chen, R. Ent, C. Keppel, T.-B. Liu, W. Lorenzon, Z.-E. Meziani, A. Prokudin, A. Puckett, N. Sato, P. Souder, A. Vossen, J.X. Zhang, Z. Zhao, and others

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