Recent Highlights from Spin-Physics Experiments

April 12, 2021

Chapter 1
Overview: Science, Machine and Deliverables of the EIC

1.1 Scientific Highlights
1.1.1 Nucleon Spin and its 3D Structure and Tomography

Several decades of experiments on deep inelastic scattering (DIS) of electron or muon beams on nucleons have taught us about how quarks and gluons (collectively called partons) share the momentum of a fast-moving nucleon. They have not, however, resolved the question of how partons share the nucleon's spin and build up other nucleon intrinsic properties, such as its mass and magnetic moment. The earlier studies were limited to providing the longitudinal momentum distribution of quarks and gluons, a one-dimensional view of nucleon structure. The EIC is designed to yield much greater insight into the nucleon structure by facilitating multi-dimensional maps of the distributions of partons in space, momentum (including momentum components transverse to the nucleon momentum), spin, and flavor.

Figure 1.1: Evolution of our understanding of nucleon spin structure. Left: In the 1980s, a nucleon's spin was naively explained by the alignment of the spins of its constituent quarks. Right: In the current picture, valence quarks, sea quarks and gluons, and their possible orbital motion are expected to contribute to overall nucleon spin.
# Overview: Science, Machine and Deliverables of the EIC

## 1.1 Scientific Highlights

### 1.1.1 Nucleon Spin and its 3D Structure and Tomography

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**Figure 1.1:** Evolution of our understanding of nucleon spin structure.

Left: In the 1980s, a nucleon's spin was naively explained by the alignment of the spins of its constituent quarks. Right: In the current picture, valence quarks, sea quarks and gluons, and their possible orbital motion are expected to contribute to overall nucleon spin.

For details, refer to parallel sessions.
The physics questions

- How do quarks & gluons, and their dynamics, make up proton spin?
- How is the proton spin correlated with the motion of quarks/gluons?
- How does the proton spin influence the spatial distribution of partons?

Spin puzzle

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g
\]

* so-called Ji decomposition. There is also the Jaffe & Manohar decomposition, \( \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + L_g \), but translations are not straightforward - see e.g. Matthias Burkardt arXiv:1011.2466

Nucleon tomography

Deformation of parton’s confined motion when hadron is polarized

Transverse Momentum Dependent PDFs

Generalized Parton Distributions

Deformation of parton’s spatial distribution when hadron is polarized


see next talk by B. Pasquini for a theory overview
Deep Inelastic Scattering: $\ell N \rightarrow \ell (h)X$

The DIS cross section contains non-perturbative, non-calcuable objects: **Parton Distribution Functions (PDFs)** encoding information about the momentum-dependent distribution of quarks inside the proton.

- **inclusive** $x, Q^2$
- **semi-inclusive DIS**

- **lepton**
- **photon virtuality** (~ resolution)
- **proton**
- **longitudinal momentum fraction of parton** ($x$-Bjorken)
- **z**
- **P_T** hadron transverse momentum
- **intrinsic transverse quark momentum**
- **longitudinal direction**

add spin... for example, inclusive DIS:
- "spin structure" or "helicity" function of the proton

\[ g_1(x, Q^2) \]

spin-independent from DESY (H1, ZEUS)
spin-dependent from SLAC, CERN, DESY (HERMES), JLab

---

C. Riedl (UIUC) - Spin-polarized experiments - DIS2021
SIDIS cross section parameterized by structure functions

\[ \sim \text{harmonic}(\phi, \phi_s) \cdot \text{PDF} \otimes \text{FF} \]

- Fragmentation function FF
  - Hard scattering cross section \( \sigma \)
  - Distribution function PDF

**Cahn-effect + BM \( \otimes \) Collins**

\[
\begin{align*}
F_{UU,T}^\phi &+ (1+\ell) \cos(2\phi) F_{UU,T}^{\cos(2\phi)} + \lambda_e \left[ \sqrt{2(1-\ell)} \sin(2\phi) F_{UU,T}^{\sin(2\phi)} \right] \\
+|S_T| \sin(\phi-\phi_S) &\left( F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)} \right) + \epsilon \sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon \sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \\
+ \lambda_e \left[ \sqrt{1-2(1-\ell)} F_{LT}^{\cos(2\phi-\phi_S)} + \sqrt{2(1-\ell)} \cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)} \right]
\end{align*}
\]

- **Worm-gear (Kotzian-Mulders) \( \otimes \)**

- **BM \( \otimes \) Collins**

**Sivers \( \otimes \) D1**

**Transversity \( \otimes \) Collins**

**Pretzelosity \( \otimes \) Collins**

\( \mathbf{P}_h \perp \mathbf{q} \)

- Type of experimental observable:

\[
A_{UT}(\phi) = \frac{1}{f_{ST}} \frac{N^U(\phi) - N^T(\phi)}{N^U(\phi) + N^T(\phi)}
\]

(more complicated in reality)

- \( F_{XY[Z]} \) = structure function. \( X=\text{beam}, Y=\text{target polarization}, \) \( Z=\text{virtual-photon polarization} \), \( X, Y \in \{U, L, T\} \)
- \( \ell \) = helicity of the lepton beam
- \( S_L \) and \( S_T \) = longitudinal and transverse target polarization
- \( \epsilon \) = ratio of longitudinal and transverse photon fluxes

C. Riedi (UIUC) - Spin-polarized experiments - DIS2021
Transverse momentum dependent (TMD) PDFs

<table>
<thead>
<tr>
<th>N</th>
<th>Q</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>$f_1$ number density</td>
<td>$g_1$ helicity</td>
<td>$h_{1T}$ Sivers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\bar{S}_T$ quark transverse momentum</td>
<td>$\hat{k}_T$ nucleon spin</td>
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- 8 TMD (PDFs) needed at leading-twist description.
- Analog table for fragmentation functions (capital letters except for UU=D_1)
- Flavor indices and kinematic dependences skipped for simplicity

TMDs surviving integration over $k_T$. “Collinear analysis”

Naive time-reversal odd TMDs describing strength of spin-orbit correlations.

Chiral odd TMDs Exist because of chiral symmetry breaking of the QCD nucleon wave function.
TMD effects in unpolarized SIDIS

Modern multi-dimensional binnings in $p_T$, $Q^2$, $x$, $z$, $W$ allow for TMD evolution studies & comparison between experiments.

New data will help to clarify the double-Gauss structures in $p_T$
- Real $<k_T^2>$ underestimated
- Importance of vector-meson decays (CLAS12)

Towards a more complete mapping of the SIDIS landscape - current vs. target fragmentation
Phenomenological approximation for $q_T$ works well for new COMPASS data.

$q_T = P_T/z$ to validate region of TMD formalism

[Boglione et al., JHEP10 (2019) 122]
Flavor composition of the sea

More anti-down than anti-up quarks in the proton from Drell-Yan with 120 GeV proton beam on liquid hydrogen and deuterium targets. The finding is in agreement with meson-cloud and statistical models.

Cross section ratio $W^+/W^-$ (dubar-u / ubar-d fusion) in proton-proton collisions at $\sqrt{s}=500$ GeV

Complementary to the SeaQuest result, at large momentum scale $Q^2 = M_W^2$ & complementary (@higher $x$) also to LHC results

New SeaQuest Drell-Yan dbar / ubar

New STAR weak boson dbar / ubar

Flavor asymmetric sea dbar(x) > ubar(x)
Quark helicities from longitudinally polarized protons

Final HERMES SIDIS valence quark helicities

- Hadron charge-difference double-spin asymmetry $A_{ALL}$ provides direct extraction of valence-quark helicities under isospin symmetry assumptions of fragmentation functions.

$P_T$ dependence found to be weak and consistent with findings by COMPASS & CLAS (not shown here)

STAR & PHENIX $W^+/W^-$ sea quark helicities

- Longitudinal spin asymmetry in weak-boson production

- Recent data allow improvement of NNPDF fits.

Strong evidence for flavor-symmetry breaking in the polarized sector

Opposite to unpolarized sector!

$\Delta u(x, Q^2) > \Delta d(x, Q^2)$

See talk by D. Veretennikov, Thursday, 12:15

[HERMES PRD 99, 112001 (2019)]

[STAR PRD 99 (2019) 051102]

with [PHENIX PRD 98 (2018) 032007]

Gluon helicity from longitudinally polarized protons

**RHIC longitudinal double-spin asymmetries**

- **PHENIX charged-pion $A_{LL}$**
  
  ![PHENIX charged-pion $A_{LL}$](image1)

  Recent high-precision mid-rapidity data consistent with global QCD fits that indicate non-zero positive and large (60%) gluon-spin contribution to the proton spin in the region $0.05 < x < 0.2$.

  [PHENIX PRD 102 (2020) 3, 032001]

- **PHENIX $A_{LL}$ in isolated direct-photon cleanest probe, hard interaction ~ $qg$**
  
  ![PHENIX $A_{LL}$ in isolated direct-photon](image2)

- **STAR: $A_{LL}$ in di-jet and inclusive jet production**
  
  ![STAR: $A_{LL}$ in di-jet and inclusive jet production](image3)

  [STAR arXiv:2103.05571]

  [STAR, $s = 200$ GeV
  *p+p* → Jet + Jet + X
  Anti-$k_T$, $R = 0.8$
  sign$(x_L) = $sign$(x_R)$]

  see talk by Z. Ji, Wednesday, 12:51

  see talk by M. Zurek, Wednesday, 12:33
Spin-orbit correlations in the proton

If TMDs describing strength of spin-orbit correlations are non-zero: indicates parton orbital angular momentum (OAM).

No quantitative relation between TMDs & OAM identified yet.

The Sivers function was originally thought to vanish (*).

A nonzero Sivers function was then shown to be allowed due to QCD final state interactions (soft gluon exchange) in SIDIS between the outgoing quark and the target remnant (**).

Sivers TMD in SIDIS

**Final HERMES Sivers asymmetries**

- Final compendium of HERMES TMD results. Refined analysis, multi-dimensional binnings, first (anti-)proton measurements. [HERMES JHEP 12 (2020) 010]

- Kaon amplitudes larger than pion. Unexpected if u-quark scattering dominates. Role of sea quarks?

- Kaon amplitudes: direct measurement of TMD $k_T^2$ moments that avoids assumptions on shape of $k_T$. Products instead of convolutions of TMDs.

- Sivers signal smaller at COMPASS than at HERMES. TMD evolution...?

- Higher lepton-beam energy than at HERMES (160 GeV vs. 27.6 GeV)

**COMPASS Sivers asymmetries**

- $\vec{S}_T \cdot (\vec{P} \times \vec{k}_T)$

- $\pi^+$ and $K^+$ Sivers functions have different signs

- COMPASS Sivers asymmetries see talk by L. Pappalardo, Tuesday, 12:00

- COMPASS PLB 744 (2015) 250
- HERMES PRL 103 (2009) 152002
- COMPASS NPB 940 (2019) 34

- $\rho_T$-weighted asymmetries: direct measurement of TMD $k_T^2$ moments that avoids assumptions on shape of $k_T$. Products instead of convolutions of TMDs

- Sivers signal smaller at COMPASS than at HERMES. TMD evolution...?
Measuring TMD observables in different scattering processes allows to probe TMD universality.

The naive time-reversal odd TMD PDFs - Sivers and the Boer-Mulders - are expected to switch sign when measured in SIDIS vs. Drell Yan. The experimental test of this prediction is an important test of TMD-QCD framework.
The Sivers sign switch

**COMPASS Drell-Yan Sivers**

- COMPASS measurement of Sivers SIDIS & DY asymmetries with ~same apparatus & in overlapping kinematics.

- Also other TMDs measured in DY, including Boer-Mulders and Lam-Tung relation on tungsten. [see talk by Y-S. Lien Tuesday, 12:20]

**Drell-Yan (DY) 2015 data**

**SIDIS in the DY kinematic range**

**STAR W±/Z A_N**

- STAR: A_N in p⁺p→W±→e±+ν Curves with sign-change assumption.

- Both collaborations currently working on the analysis of more data for the same channels.

- STAR measured first flavor-tagged di-jet Sivers asymmetries in polarized pp that flip with charge sign. Connection between di-jet opening angle and k_T. [see DNP2019]

- Modified universality concept of Sivers & Boer-Mulders TMDs. The experimental data tend to support the Sivers sign switch, albeit still within large experimental uncertainties.
Left-right asymmetries

- The simultaneous description of left-right asymmetries $A_N$ across multiple collision species indicates that all $A_N$ have a common origin that is related to multi-parton correlations.

  e.g. [Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (JAM Collaboration), PRD 102, 054002 (2020)]

- TMD factorization vs. collinear twist-3 factorization
  Example: the $k_T$ moment of the Sivers TMD is related to the twist-3 Efremov-Teryaev-Qiu-Sterman (ETQS) function.

\[ A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \]

The 2-factorization schemes are related and equivalent in the overlapping kinematics.

\[ A_N \text{ from TMD mechanism.} \]

\[ A_N \text{ from spin-momentum correlations (qqg or ggg)} \]

Collinear twist-3 factorization 1-scale problem

\[ f(x; Q^2) \]

single inclusive particle production in pp (particle or jet $p_T$)

[Continuation of measurements is important to further the understanding of the physical origin of $A_N$]

[The RHIC spin program - achievements and future opportunities, E. Aschenauer et al. arXiv:1304.0079]
Twist-3 tri-gluon correlations & gluon Sivers

New PHENIX isolated direct-photon $A_N$

✦ Direct photons as clean probe
  - first measurement in ~30 years, with higher $p_T$ reach and ~50x better uncertainty

[PHENIX arXiv:2102.13585]

New PHENIX pion and eta $A_N$

✦ How do these results relate to the non-zero SIDIS results from COMPASS?
  - Photon-gluon fusion with signature of 2 high-$p_T$ hadrons, $p+d$: $A_{Siv} = -0.23 \pm 0.08$(stat) $\pm 0.05$(sys), PLB 772 (2017) 854
  - Exclusive J/Psi production in SIDIS on $p$: $A_{Siv} = -0.28 \pm 0.18$, preliminary

✦ Yet another gluon probe: PHENIX heavy-flavor $A_N$ to be released at DIS 21

heavy flavor $A_N$: see talk by D. Fitzgerald, Tuesday, 10:01

[J/Psi production in pion-proton collisions at COMPASS. Analysis in progress.

Subprocess fractions at RHIC energies for $gg$, $qg$, $qq+qqbar$
**A_N in the very forward**

**PHENIX**

- Detection of very forward neutrons using a zero-degree calorimeter (ZDC) ~20m from PHENIX IP

**STAR**

- π⁰ and electromagnetic jets using Forward Meson Spectrometer

**RHICf**

- RHICf(owrd) calorimeter 18m from STAR IP
- π⁰ in elmag jet, 2.8 < \( \eta \) < 4.0

\[ \text{p}_T = m \rightarrow \pi^0 X \]

- \( A_N \) increases with \( p_T \) & forwardness & π⁰ isolation (STAR) & γ multiplicity (STAR)

- \( A_N \) from soft processes such as diffractive scattering?

[PHENIX PRD 103 (2021) 3, 032007]


see talk by M. Kim, Wednesday, 10:00

see talk by Z. Zhu, Tuesday, 9:25

Collins asymmetries small…
Collins asymmetries

Collins asymmetry Calculations based on SIDIS & e+e- data assuming Collins factorization & universality [PLB 773 (2017) 300]

Coupling of Collins to transversity TMD leads to azimuthal modulations of charged-hadron yields around the jet axis

Two hard scales allow for TMD interpretation: \( p_T \) of jet \( j \) and \( p_T \) of hadron in jet

RHIC results enable tests of TMD universality and factorization breaking (expected for hadronic interactions)

Collins-dihadron-interference-fragmentation asymmetry vs. di-pion invariant mass in highest \( p_T \) bin.

Not shown today: FFs measured in e+e- at Belle, Barber, BESIII

More STAR data analyzed in multi-dimensional binning & kaons / protons: see talk by B. Pokhrel, Wednesday, 8:18

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Collins effect: spin-dependent fragmentation of a transversely polarized parton into a final-state hadron — “quark polarimeter”

STAR hadrons in jets (midrapidity) [STAR PRD 97 (2018) 032004]

First experimental constraint on Collins-like asymmetry, sensitive to linear gluon polarization (gluon analog to quark FF)

STAR hadrons in jets (midrapidity)

Calculations based on Collins factorization & universality [PLB 773 (2017) 300]
Collins asymmetries in SIDIS $\ell N^\uparrow \rightarrow \ell h(h)X$

HERMES & COMPASS Collins asymmetries

**Mirror symmetry for $\pi^+$ & $\pi^-$:**
- $u$- ($\delta_u$) and $d$-quark transversity ($\delta_d$) have ~
equal magnitude &
 oppo sites for fav & unfav Collins FFs.

Transversity = valence-quark effect (increase with $x$).

**$d$-quark transversity** less constrained given the $u$-quark dominance of many of the processes used in the global fits. **COMPASS 2021 transversity run** on the deuteron will **double** the experimental precision on the proton’s tensor charge $g_T = \delta_u - \delta_d$ [CERN–SPSC–2017–034]

- Further prior-to-EIC measurements of Collins asymmetries: STAR with forward upgrade, sPHENIX, JLab12/SoLID, SpinQuest

**Check of TMD universality:** COMPASS Collins asymmetries SIDIS vs. Drell-Yan.

**Global extractions - Collins function:**

- **unf**
- **fav**

**Alternative methods to access transversity:** measure hyperon transverse polarization, which may have been transferred from struck quark
- **COMPASS:** SIDIS on trans.pol protons, to be submitted to PLB
- **STAR:** see talk by Y. Xu, Thursday, 10:00
Novel spin-dependent fragmentation functions

New COMPASS Collins asymmetry in $\rho^0$ production

- **Fragmentation function $H_{1LL}$** describing fragmentation of quarks in vector mesons.
- Investigate the different Collins mechanisms of spin-1 vector mesons vs. pseudoscalar mesons (ordinary Collins FF). Czyzewski model, Artru, string+3P0 model
- Collins (and also Sivers) asymmetry for $\rho^0$ production on transversely polarized proton target will be shown

see talk by A. Kerbizi, Thursday, 12:51

New CLAS12 higher-twist di-hadron beam-spin asymmetry

- First empirical evidence of a nonzero parton helicity-dependent di-pion fragmentation function $G_{\perp1}$
  - Encodes spin-momentum correlations in hadronization
  - Equivalent to the Collins FF for two pions
- In the $p$-mass region, can be used to test predictions by the Artru model about the relative size of Collins asymmetries of vector and scalar mesons
- Data also allow for a point-by-point extraction of the collinear-twist-3 PDF $e(x)$

\[
d\sigma_{LU} \propto W \lambda e \sin(\phi_{R_{\perp}}) \left( x e(x) H_{1}^{\perp}(z, M_h) + \frac{1}{z} f(x) \tilde{G}_{\perp}^{\perp}(z, M_h) \right) \]

$G_{1}^{\perp}$

New CLAS higher-twist di-hadron beam-spin asymmetry

- First measurement of that BSA; sensitive to $e(x)$


[CLAS12 / T. Hayward arxiv:2101.04842]

see talk by C. Dilks, Thursday, 13:27
More higher twist in single-hadron SIDIS

- Sizeable recent asymmetries from unpolarized target and longitudinally polarized lepton beam. Expected to be suppressed by $O(M/Q)$

- Provides access to so-far poorly known subleading twist-3 TMD PDFs & fragmentation functions containing information about quark-gluon correlations in the proton and in the hadronization process

\[
A_{LU}^{\sin \phi} = \frac{\sqrt{2\varepsilon(1-\varepsilon)}}{F_{UU,T} + \varepsilon F_{UU,L}} F_{LU}^{\sin \phi}
\]
Hard exclusive processes

\[\ell p \rightarrow \ell p \gamma\]

Deeply Virtual Compton Scattering (DVCS)

\[\ell p \rightarrow \ell p M\]

Deeply Virtual Meson Production (DVMP)

- **Standard channels to access generalized parton distributions are DVCS & DVMP**

\[4 \text{ chiral-even & } 4 \text{ chiral-odd GPDs}\]

\[x, \xi: \text{longitudinal momentum fractions of probed quark}\]

- skewness \(\xi = x_B / (2-x_B)\)
  in Bjorken limit \((Q^2 \text{ large & } x_B, t \text{ fixed})\)

- average mom. \(x: \text{mute variable, not accessible in DVCS & DVMP}\)

\[t: \text{squared 4-momentum transfer to target}\]

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**GPDs**

<table>
<thead>
<tr>
<th>GPDs</th>
<th>flips nucleon helicity</th>
<th>conserves nucleon helicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>does not depend on quark helicity</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~E</td>
<td>depends on quark helicity</td>
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</tbody>
</table>

**4 chiral-even quark GPDs**

@leading twist for a spin-\(\frac{1}{2}\) target

- \(q(x)\)
- \(\Delta q(x)\)

**4 chiral-odd GPDs:**

- \(H_t \leftrightarrow \text{transversity TMD; } (2H_t + E_t) \leftrightarrow \text{Boer-Mulders; } E_T\)

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From HERMES & JLab-6 & HERA to COMPASS & JLab12 & RHIC to the EIC
Transverse imaging of the nucleon

\[ \frac{d\sigma^{DVCS}}{dt} \propto e^{-b|t|} \]

\( b = \text{"t-slope"} = \text{average impact parameter} \)

Impact-parameter representation:

\[ q^f(x, b) = \int \frac{d^2\Delta_1}{(2\pi)^2} e^{-i\Delta_1 \cdot b} H^f(x, 0, -\Delta_1^2) \]


Determination of transverse extension of partons
- in the Bjorken-\( x \) domain of COMPASS between valence quarks and gluon
- 2012 DVCS data on LH\(_2\) target (10% of 2016/17) with recoil-proton detector CAMERA

\[ \sqrt{\langle \Delta_1^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.04_{\text{model}}) \text{ fm} \]

at \( <Q^2> = 1.8\text{GeV}^2 \) & \( <x_{Bj}> = 0.056 \)

COMPASS DVCS t-slope

\[ \sigma_{\gamma \gamma N} \sim \frac{1}{2} \left( T_{BH}^2 + |T_{DVCS}|^2 \right) \]

BH reference yield

DVCS amplitude:
\( \phi \)-modulations in cross section

Transverse imaging:
\( \phi \)-integrated cross section

BH + measured & simulated \( n^\pi \) subtracted

new: 2016/17 DVCS data (~25% of available data, 2 times more than 2012 data) on LH\(_2\) target with recoil-proton detector CAMERA

see talk by B. Ventura (N. D’Hose), Thursday, 8:54

exclusivity ensured by recoil-proton detector
Exploring Compton Form Factors

**Experimental access to GPDs** via CFFs. Access to different (parts of) CFFs via different experimental configurations: (target polarization, beam polarization, beam charge, and their combinations.

\[
\mathcal{H}(\xi, t) = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i\pi H(\xi, \xi, t)
\]

**Dispersion relation with D-term** \(D(t)\): related to shear forces and radial distribution of pressure inside the nucleon

\[
\text{Re}(\tau_{\text{DVCS}}) = \mathcal{P} \int_{-1}^{+1} dx \frac{\text{Im}(H(x, \xi, t))}{x - \xi} + D(t)
\]

Hall A neutron DVCS

- **Flavor separation of CFFs:** u-quark, d-quark

- **Dispersion relation with D-term** \(D(t)\): related to shear forces and radial distribution of pressure inside the nucleon

- **Flavor separation of CFFs:** u-quark, d-quark with reggeized diquark model (Goldstein, Liuti, et al.)

- **Dispersion relation with D-term** \(D(t)\): related to shear forces and radial distribution of pressure inside the nucleon

- **Flavor separation of CFFs:** u-quark, d-quark with reggeized diquark model (Goldstein, Liuti, et al.)

**CLAS12 TCS**

- Data before CLAS
- CLAS
- CLAS12 proj.

- Impact on radial pressure distribution by CLAS and expected impact by CLAS12

- **Compass DVCS asymmetries** (results to come)

- **CLAS12 proton DVCS** analysis in progress, GPD \(H\)


GPD $E$ linked to orbital angular momentum

**Ji sum rule for the nucleon:** [Ji, PRL 78 (1997) 610]

\[
J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \; x \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right]
\]

- CLAS12: DVCS on the neutron (LD$_2$ target with neutron detector), analysis in progress
- CLAS12: on the transversely polarized proton, data to be taken
- All so-far discussed GPDs were quark GPDs

- STAR: exclusive J/Psi production in ultra-peripheral collisions (UPC) $\rightarrow$ gluon GPD $E$
  Significant improvement of precision expected with the upgrades (ITPC & forward), more data will be taken

- RHIC with UPC and COMPASS with high-energy muon beams at CERN will provide first results of sea quarks and gluons at small $x_B$.  

**CLAS12 DVCS beam-spin asymmetries** on the deuteron (neutron)

**CLAS12 DVCS target-spin asymmetries** on the transversely polarized proton

**STAR excl. J/Psi $A_N$ in UPC, GPD $E$ of the gluon**

**STAR preliminary**
Exclusive $\pi^0$ & $\pi^\pm$ production

COMPASS excl. $\pi^0$ cross section

$$\frac{d^2\sigma}{dt d\phi} = \frac{1}{2\pi} \left[ \left( \frac{d\sigma_T}{dt} - \frac{d\sigma_L}{dt} \right) + \epsilon \cos 2\phi \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi \frac{d\sigma_{LT}}{dt} \right]$$

$$\left|\langle H_T\rangle\right|^2 - \frac{t'}{4m^2} \left|\langle E_T\rangle\right|^2$$

$$\frac{\sigma_T}{\sigma_L} = \frac{(8.2 \pm 0.9_{stat} \pm 1.2_{syst})}{(GeV/c)^2}$$

$\sigma_T$ large (impact of $E_T$)

$\sigma_T$ smaller but significantly positive as at CLAS

[COMPASS PLB 805 (2020)]

CLAS12 excl. $\pi^0$ beam-spin asymmetry
Analysis in progress, to be released very soon.

CLAS12 excl. $\pi^+$ beam-spin asymmetry
to improve the extraction on $H_T$
Analysis in progress
Spin density matrix elements in $\ell p \rightarrow \ell p \nu \pi^0$

If SCHC ($\lambda^\gamma = \lambda_{\nu \pi}^0$)

- Considerable SCHC in $\gamma_T^* \rightarrow \omega_L$ (class C), with interesting kinematic dependence.
- Transitions sensitive to chiral-odd GPDs $H_T$ and $E_T$

Cross-section ratio $R$ of longitudinal to transverse vector mesons comparison to HERMES

<table>
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<tr>
<th>SDMEs</th>
<th>COMPASS 2012 $\omega$ SDMEs</th>
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<tr>
<td>$r_{10}^T$</td>
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</tbody>
</table>

Shaded: polarized elements

- Test of hierarchy of helicity amplitudes
- Test of hypothesis of s-channel helicity conservation (SCHC)
- Evaluation of unnatural-parity-exchange transitions
- Determination of phase differences between helicity amplitudes & longitudinal-to-transverse cross-section ratio.
- Constraints on GPD parameterizations beyond cross section and spin-asymmetry measurements.
More exclusive measurements

New CLAS coherent DVCS

- For the first time, DVCS beam-spin asymmetry in the coherent channel measured to be larger than in the incoherent proton channel, thanks to measuring the helium recoils using a radial TPC.

Recoil in nuclear DVCS at HERMES was not detected

More measurements planned at CLAS12

Coherent DVCS allows to study if the DVCS amplitude rises with $A$ and if there is a ‘generalized EMC effect’

Exclusive pion production in the backward allows to study nucleon-to-pion baryonic transition distribution amplitudes (TDAs), a further generalization of the GPD concept

[CLAS / S. Diehl PRL125, 182001]

see talk by S. Diehl, Wednesday, 10:18
Selected near future - before the EIC

**JLab 12 GeV** high-luminosity facility:
- Has started experimental program
- New generation of precision data for valence quarks to come from CLAS12, SoLID, et al.

**STAR** cold QCD with forward upgrade at RHIC:
- 2022/24, p^+p & p^+A, \( \sqrt{s_{NN}}=200 & 500 \) GeV
- Tracking system of silicon & small TGC
- Forward electromagnetic & hadronic calorimetry, 2.5<ets<4
- midrapidity: improve statistics of Sivers via dijet & W/Z, Collins via hadrons in jets, GPD E via J/Psi UPC
- forward rapidity: TMDs at high-x & GPD E

**sPHENIX** cold QCD program at RHIC:
- 2024, p^+p & p^+A, \( \sqrt{s_{NN}}=200 \) GeV, \( \eta=\pm 1.1 \)
- Design optimized for heavy-flavor measurements with jets and displaced vertices with MAPS-based vertex tracker
- Gluon Sivers TMD via \( A_{N} \) in single-photon & heavy flavor
- Di-hadron IFF / Collins asymmetry & transversity TMD via hadron-charge tagging & hadron-in-jet
- and more, sPHENIX-note sPH-cQCD-2017-002

**SpinQuest / E1039** at FNAL (2021++):
- Transversely polarized NH\(_3\)/ND\(_3\) target with E906 spectrometer
- First polarized DY experiment with proton beam
- Sivers & transversity TMDs of sea quarks.

**COMPASS transversity run 2021**
- transversely polarized \( ^{6}\)LiD target for d-quark transversity et al.

**AMBER / NA66** at the CERN M2 beamline:
- Beam time approved for phase 1 after 2021 after the end of the COMPASS d-quark transversity run, no time window yet.
- Pion structure in phase I with pion beams
- Kaon structure in phase II with kaon beams
- TMDs with \( \pi, K \), anti-proton beams
- and more (e.g., proton radius in elastic \( \mu p \) scattering), https://ngf-m2.web.cern.ch
  see talk by D. Banerjee, Thursday, 12:40


**LHCspin at CERN**, fixed trans.polarized H\(_2\) & D\(_2\) targets with LHCb as forward spectrometer, >2025,
https://inspirehep.net/literature/1821190

**AFTER @LHC, CERN** fixed target, >2025,
https://doi.org/10.1016/j.physrep.2021.01.002

**SPD at NICA, JINR**: collider experiment with polarized proton and deuteron beams, >2025,
http://spd.jinr.ru/
see talk by A. Korzenev, Tuesday, 10:51

**PANDA at FAIR**, fixed target with anti-proton beams,
https://panda.gsi.de/article/panda-physics

**EicC (China) at HIAF**, > 2025, arXiv:2102.09222
Experiments at BNL, JLab, FNAL, CERN, DESY, RIKEN, JPARC, \textit{et al.} unravel proton and nucleus structure.

The \textbf{spins of quarks and gluons} contribute to the \textit{proton's spin} and there is indication they also possess \textbf{orbital angular momentum}. The nucleon is explored via \textbf{tomographic images} in transverse-momentum- and position-space using data from various types of scattering experiments.

\textbf{In transverse-momentum space ($k_x, k_y$):}

density distribution of unpolarized $u$-quark in transversely polarized proton at $x=0.1$ and $Q^2=4$ GeV$^2$.

\textbf{In impact-parameter space ($b, x$):}

position of up quarks in an unpolarized proton at $t=-0.3$ GeV$^2$ and $Q^2=2$ GeV$^2$.

\textbf{PARTONS} fits 2018-1 using world data of elastic form factors and DVCS proton data from HERMES, CLAS, Hall A and COMPASS.

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\textbf{1} The \textbf{Electron Ion Collider} will be the ultimate tool to precisely map the rich spin- and multi-dimensional structure of nucleons and nuclei from low- to high $x_{Bjorken}$. 

\textbf{Summary and outlook}

\textbf{1.1 Scientific Highlights}

\textbf{1.1.1 Nucleon Spin and its 3D Structure and Tomography}

Several decades of experiments on deep inelastic scattering (DIS) of electron or muon beams on nucleons have taught us about how quarks and gluons (collectively called partons) share the momentum of a fast-moving nucleon. They have not, however, resolved the question of how partons share the nucleon's spin and build up other nucleon intrinsic properties, such as its mass and magnetic moment. The earlier studies were limited to providing the longitudinal momentum distribution of quarks and gluons, a one-dimensional view of nucleon structure. The EIC is designed to yield much greater insight into the nucleon structure (Fig. 1.1, from left to right), by facilitating multi-dimensional maps of the distributions of partons in space, momentum (including momentum components transverse to the nucleon momentum), spin, and flavor.

\textbf{1} The \textbf{Electron Ion Collider} will be the ultimate tool to precisely map the rich spin- and multi-dimensional structure of nucleons and nuclei from low- to high $x_{Bjorken}$.