Probing nucleon spin structure

Recent advances in spin-physics measurements

Caroline Riedl
15th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei (EINN2023)
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Probing nucleon spin structure

- How does QCD generate the spectrum and structure of conventional and exotic hadrons?
- How do the mass and spin of the nucleon emerge from the quarks and gluons inside and their dynamics?
- How are the pressure and shear forces distributed inside the nucleon?
- How does the quark–gluon structure of the nucleon change when bound in a nucleus?
- How are hadrons formed from quarks and gluons produced in high-energy collisions?

Disclaimer: the references and results in this talk are not exhaustive. Sorry if I overlooked your recent result, represented it wrongly, or did not cite you. Please reach out, criedl AT illinois DOT edu
Lessons from the first DIS experiments (SLAC-MIT late 1960's)

- There are two structure functions ($F_1$, $F_2$) parameterizing the “QCD non-perturbative structure” of the unpolarized spin-1/2 nucleon.

\[
\frac{d^2\sigma}{d\Omega dE'} = \frac{Z^2\alpha^2}{4E'^2\sin^4\left(\frac{\theta}{2}\right)} \cdot \cos^2\left(\frac{\theta}{2}\right) \left[ \frac{1}{y} F_2(v, Q^2) + \frac{2}{M} \tan^2\left(\frac{\theta}{2}\right) F_1(v, Q^2) \right]
\]

- The structure functions can be expressed in terms of quark longitudinal-momentum probability distributions $q(x)$. ⇒ parton distribution functions (PDFs)

- $F_2(x, Q^2)$ is in first order independent of $Q^2$ (scaling) ⇒ nucleons have a substructure of point-like constituents.
- The point-like constituents of the proton have spin-1/2 (quarks).
Experiments with nuclear and/or lepton polarization

- HERMES at DESY (1995-2007)
  - Self-polarized 27.6 GeV electrons and positrons in HERA storage ring
  - Pure L- and T-polarized gas targets

- COMPASS at CERN (2002-2022)
  - Secondary and tertiary beams (M2 SPS beam line).
  - 160 /200 GeV muons polarized via pion decay
  - Solid-state L- and T-polarized targets (ammonia and deuterated lithium)

  - Collisions of L- and T-polarized proton beams (pp & pA)
  - $\sqrt{s} = 200, 500/510$ GeV
  - Optically pumped ion source (OPPIS)

And many more: the polarized electron beams at JLab-CEBAF, the polarized targets at JLab, Fermilab, LHC-spin at CERN...
Quark spin contribution to the nucleon spin

- Measurements with longitudinal nucleon polarization at DESY, CERN and SLAC
- Need additional structure functions if targets and/or beams are polarized. Measurement of a spin asymmetry allows accessing information about the spin-dependent structure function.

\[
A_{\parallel} = \frac{1}{\langle P_B P_z \rangle} \left( g_1(x, Q^2) \right) \left( \frac{F_1(x, Q^2)}{P_z} \right)
\]

- From measurements related to the spin structure function \( g_1(x, Q^2) \) at fixed-target experiments at DESY, CERN and SLAC, and a full QCD analysis, the quark spin contribution to the spin of the proton was determined to be \( \Delta \Sigma \approx 1/4 \ldots 1/3 \).
Gluon spin contribution to the nucleon spin

- Measurements with longitudinal polarization at RHIC - pp accesses directly gluonic subprocesses at leading order.
- Last LL RHIC data collected 2013 & 2015.

Possible production channels:
- Charged and neutral pions
- Isolated direct photon
- Inclusive jet
- Dijets

- From global analysis of longitudinal double-spin asymmetries: \( \Delta g \approx 20\% \) (& indication there is more at lower x)

\[
\int_{0.05}^{1} dx \Delta g = 0.22 \pm 0.03
\]

DSSV (2019), PRD 100, 114027
White paper of the RHIC cold QCD program

STAR jets

PHENIX direct photon

DSSV14
NNPDFpol1.1

\( p + \bar{p} \rightarrow \gamma_{\text{iso}} + X, |s| = 510 \text{ GeV}, |\eta| < 0.25 \)

\[ A_L \]

PHENIX Data
DSSV14 with DSSVuncertainty
JAM22 \( \Delta g > 0 \) with JAMuncertainty
JAM22 \( \Delta g < 0 \) with JAMuncertainty

STAR endcap dijets preliminary
[STAR, DIS 2023]

STAR \( \pi^\pm \) tagged jet preliminary
[STAR, 2023]

gluon momentum range: 0.015 < x < 0.25 agree with NLO global analyses & input for better constraint on \( \Delta g \) shape

[STAR PRD 105, 092011 (2022)]

[PHENIX PRL 130 (2023) 25, 251901]

gluon momentum range: 0.02 < x < 0.08 favors positive gluon-spin contributions

C. Riedl (UIUC), nucleon spin structure
Proton spin puzzle & nucleon tomography

• Spin decomposition of the proton: $\frac{1}{2} = \frac{1}{2}\Delta \Sigma + \Delta G + \mathcal{L}$

• Experimental results from DIS and pp experiments & global QCD analysis:
  ‣ The quark spins contribute 1/4 to 1/3 to the spin of the proton.
  ‣ The gluon spins contribute some positive amount in the currently covered experimental range.

• Where is the remaining proton spin coming from? Parton orbital angular momentum?

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C. Riedl (UIUC), nucleon spin structure from https://arxiv.org/abs/2303.02579
see talk by A. Metz, Thu am
Introduction

- Longitudinal DIS, structure functions, & PDFs
- Spin-polarized experiments
- Proton spin puzzle & hadron tomography

TMDs

- Nucleon TMD structure and spin-orbit correlations
- TMD universal description
- Sivers TMD PDF in SIDIS and modified universality
- Gluon correlators & Sivers TMD PDF
- Sivers effect in di-jet production
- Collins FF in ee and Collins asymmetry in pp & SIDIS
- Di-hadron fragmentation function in pp and SIDIS
- Other spin-dependent fragmentation functions in SIDIS

GPDs

- Hard exclusive reactions
- Chiral-even GPDs & DVCS asymmetries
- Exploring Compton form factors
- Parton orbital angular momentum & gluon GPDs
- Chiral-odd GPDs & vector mesons
- Transition DAs & transition GPDs

Outlook & Summary
Taking into account parton intrinsic transverse momentum, 8 TMD PDFs are needed for a full description of nucleon structure (at leading order), some of which encode spin-orbit correlations.

\[
\vec{s}_T \cdot (\hat{P} \times \vec{k}_T)
\]

- Sivers TMD PDF
- Boer-Mulders TMD PDF
- transversity PDF ⊗ Collins TMD FF

C. Riedl (UIUC), nucleon spin structure
Observables to probe TMD universality

Parton distribution function (PDF)

Fragmentation function (FF)

SIDIS
- lepton
- proton
- hadron
- HERMES, COMPASS, JLab

Drell-Yan and W, Z
- hadron
- proton
- lepton
- COMPASS, STAR, SpinQuest

$e^+e^-$ annihilation
- electron
- positron
- hadron
- Belle, BaBar, BESIII

pp collisions
- hadron
- proton
- STAR, PHENIX, BRAHMS

Transverse spin asymmetries have **common origin** - simultaneous description across different collision species possible.

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

Two complementary but related **theoretical descriptions**, depending on **what is reconstructed experimentally**

- **TMD framework** - measure 2 scales with $p_T \ll Q$: SIDIS, DY, W/Z, dijets, hadrons in jets

- **Collinear higher-twist (HT) framework** - measure 1 scale with $p_T \approx Q$: single inclusive particle production in pp (particle or jet $p_T$); spin asymmetries from quantum mechanical interference of multi-parton states ($\rightarrow$ qqq and ggg correlators)
**The Sivers sign switch - modified TMD universality**

**HERMES vs. COMPASS Sivers amplitude in SIDIS**

- **COMPASS** $\pi^0 p \rightarrow p^+ \mu^+ \mu^- X$
- **COMPASS** $p^0 p \rightarrow p^+ p^-$
- **HERMES** $p^0 p \rightarrow p^+ p^-$

**COMPASS Sivers amplitude in $\pi^- p^+ \rightarrow \mu^- \mu^+ X$**

- **COMPASS** preliminary
- **Drell-Yan, NH** 2015-2018 data
- **JHEP 02(2021)166**
- **LFCQM**
- **SPM**
- **JAM20**
- **Torino**

**Final publication in preparation**

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

**Important test of TMD-QCD framework, predicted due to the gauge invariance of QCD.**

**STAR: $A_N$ in $p^\uparrow p \rightarrow W^\pm \rightarrow e^{\pm} + \nu$**

- **STAR $p^\uparrow p$ 500 GeV (L = 25 pb$^{-1}$)**
  - $0.5 < P_T^W < 10$ GeV/c
  - $W^\rightarrow \nu \nu$
  - $W^\rightarrow f \nu$
  - EIKV - no TMD evol.
  - EIKV - TMD evolved

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**STAR new 2017 data**

- **STAR, AUM2021**

Curves with sign-switch assumption.

**With N3LO theory prediction [PRL 126 (2021) 112002]**

**C. Riedl (UIUC), nucleon spin structure**

**EINN2023, November 1, 2023**
Tri-gluon HT correlations at RHIC midrapidity

**PHENIX isolated direct-photon**
[PHENIX PRL 127, 162001 (2021)]

**PHENIX pion**
[PHENIX PRD 103 (2021) 5, 052009]

**PHENIX eta & nuclear**

RHIC midrapidity measurements sensitive to tri-gluon higher-twist correlation functions ↔
gluon Sivers TMD
no signals, at high precision

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**PHENIX open heavy flavor**

![Graph showing the correlation between p^+p → e^+e^- + X, √s = 200 GeV, |η| < 0.35](image)

- Open Heavy Flavor e^+
- Open Heavy Flavor e^-

PRD78, 114013

(λ_t, λ_0) = (-0.01 ± 0.03, 0.11 ± 0.09) GeV

PRD84, 014026

K_G = (6.0^{+14}_{-17}) × 10^{-4}
K_G' = (2.5^{+2.2}_{-2.2}) × 10^{-4}

3.4% polarization scale uncertainty not included

Consistent with expectation from Burkardt sum rule over parton transverse momenta, which leaves little room for gluon k_T

[PHENIX PRD 107 (2023), 5, 052012]

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C. Riedl (UIUC), nucleon spin structure

First observation of the Sivers effect in di-jet production

Di-jet production in pp$^\uparrow$ directly probes average intrinsic quark and gluon transverse momenta, $<k_T>$, via the asymmetry of the spin-dependent tilt of di-jet opening angle, closely tied to transv. mom. imbalance.

Jet charge tagging to create u- and d-quark enhanced categories

$\langle \hat{S}_T \cdot (\hat{P} \times \hat{k}_T) \rangle \neq 0$

$\Delta \langle \zeta \rangle = \frac{\langle \zeta \rangle^+ - \langle \zeta \rangle^-}{P}$

$\langle k^u_T \rangle \sim +19.3 \pm 7.6 \text{ (stat.)} \pm 2.6 \text{ (syst.) MeV}/c$

$\langle k^d_T \rangle \sim -40.2 \pm 23.0 \pm 9.3 \text{ MeV}/c$

Sivers partonic $<k_T>$ values for u- and d-quarks of opposite sign & similar magnitude, for sea quarks and gluons (combined) $\sim$ zero. $\leftrightarrow$ SIDIS

$Q = \sum_{|p^{\text{track}}| > 0.8 \text{ GeV}/c} \frac{|p^{\text{track}}|}{|p^{\text{jet}}|} \cdot q^{\text{track}}$

More data being analyzed incl. forward upgrade

C. Riedl (UIUC), nucleon spin structure

[STAR arXiv:2305.10359 (sub PRL)]
Collins fragmentation function in $e^+e^-$ & Collins asymmetry in pp

- **Collins effect:** spin-dependent fragmentation of a transversely polarized parton into a final-state hadron $\rightarrow$ **azimuthal modulations** of hadron yields (thrust or jet axis)
- In pp & SIDIS generated by the coupling of the Collins FF to the transversity PDF

**new STAR pp$^\uparrow$→jet h$^\pm$X (500 GeV midrapidity)**

**Tests of TMD universality, factorization breaking** (expected for hadronic interactions) and evolution

Model curves based on SIDIS & $e^+e^-$ data assuming Collins factorization & universality

[Belle (H. Li, A. Vossen et al.) PRD 100, 092008 (2019)]

Also kaons and protons

Belle $e^+e^-\rightarrow h_1h_2|_{\text{back-to-back}}X$

$e^+e^-$ annihilation provides cleanest environment to access to Collins FF

see talk by R. Seidl, Thu am

C. Riedl (UIUC), nucleon spin structure
Collins asymmetry and transversity TMD PDF in SIDIS

HERMES & COMPASS Collins asymmetries in $\ell N^{\uparrow} \to \ell h^{\pm} X$

- **$d$-quark transversity PDF less constrained**
  given the $u$-quark dominance of many of the processes used in the global fits.

  - Recent COMPASS 2022 transversity run on the **deuteron** will improve the experimental precision on the proton’s tensor charge, $g_1 = \delta_u - \delta_d$, by a factor of ~2.

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

- **Alternative method to access transversity: measure hyperon transverse polarization**, which may have been transferred from struck quark

  - COMPASS and STAR. Hyperon polarization also measured in unpolarized and longitudinally polarized settings at LHCb and CLAS12, resp.

  - first shown at SPIN 2023 (talk A. Martin for COMPASS)

Mirror symmetry for $\pi^+$ & $\pi^-$: $u$- and $d$-quark transversity have ~ equal magnitude & opposite signs.
Di-hadron fragmentation function (h⁺h⁻) in pp and SIDIS

Transversity PDF coupled to interference, or di-hadron, fragmentation function (collinear) in SIDIS & pp as complementary probe of transversity PDF & independent measurement to e⁺e⁻

COMPASS di-hadron asymmetry in SIDIS

Collins h⁻

Interference $FF \approx \frac{1}{2}(\text{Collins}[h⁺] - (-1) \cdot \text{Collins}[h⁻])$ hints to common physical origin for Collins & IFF

Collins h⁺

STAR di-hadron asymmetry in pp

- Large signal increasing linearly with pT in the forward, small in the backward
- Enhancement of signal around δ mass
- Crucial role in constraining transversity in global fits
- More data on tape & to be taken; kaons → strange quark transversity

200 GeV: B. Pohkrel DIS 2023

EINN2023, November 1, 2023

C. Riedl (UIUC), nucleon spin structure
Other spin-dependent fragmentation functions in SIDIS

**COMPASS Collins asym. in $\rho^0$ production on $p^+$**

**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).

First empirical evidence of a nonzero **parton helicity-dependent di-pion fragmentation function** $G_{1}^{\perp}$: equivalent to the Collins FF for two pions. Coupled to sub-leading twist PDF $e(x)$.

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**CLAS & CLAS12 higher-twist di-hadron BSA**

[COMPASS PLB 843, 137950 (2023)]

[CLAS12 / T. Hayward PRL 126, 152501 (2021)]

also: [CLAS / M. Mirazita PRL 126, 062002 (2021)]

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**CLAS12 spin transfer to $\Lambda$ hyperons**

**Helicity fragmentation function of the $\Lambda$**

$$G_{1}^{\Lambda} \propto \left( s_{\Lambda} \quad -s_{\Lambda} \quad s_{\Lambda} \quad -s_{\Lambda} \right)$$

One analysis example with (planned) application of graph neural networks [M. McEnaney, A. Vossen 2023 JINST 18 P06002]

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**CLAS(12), HERMES and COMPASS HT single-hadron SIDIS beam-spin asymmetries - sizeable recent asymmetries from unpolarized target and longitudinally polarized lepton beam [backup].**

**Fracture functions $\leftrightarrow$ target fragmentation region:** final-state hadrons also form from the left-over target remnant, the partonic structure of which is defined by fracture functions. Complementary approach to understand SIDIS production [T. Hayward, H. Avakian at SPIN 2023].
Outline - Probing nucleon spin structure

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☐ Hard exclusive reactions
☐ Chiral-even GPDs & DVCS asymmetries
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☐ Outlook & summary
Hard exclusive reactions

From HERMES & JLab-6 & HERA to COMPASS & JLab12 & RHIC to the EIC

\[ \ell p \rightarrow \ell p\gamma \quad \ell p \rightarrow \ell pM \]

Deeply Virtual Compton Scattering (DVCS)

Deeply Virtual Meson Production (DVMP)

Standard channels to access generalized parton distributions

Different exclusive final-state particles allow probing different GPDs

4 chiral-even (conserve quark helicity)

4 chiral-odd GPDs (flip quark helicity)

→ connection with chiral-odd TMDs

x, \( \xi \): longitudinal momentum fractions of probed quark
- skewness \( \xi = x_B / (2-x_B) \) in Bjorken limit
  (\( Q^2 \) large & \( x_B \), \( t \) fixed)
- average mom. \( x \): mute variable, not accessible in DVCS & DVMP (is not \( x \)-Bjorken)

\( t \): squared 4-momentum transfer to target

C. Riedl (UIUC), nucleon spin structure

GPD    | flips nucleon helicity | conserves nucleon helicity
---|---|---
E     | \( F_1(x) \) forward limit \( \xi \rightarrow 0, t \rightarrow 0 \) | \( J^P=1^- \) vector mesons
\( \tilde{E} \) | depends on quark helicity | \( J^P=1^- \) pseudoscalar mesons
\( \tilde{H} \) | | \( J^p=1^- \) photon (DVCS)
Chiral-even GPDs from deeply virtual Compton scattering (DVCS)

How it started…
First beam spin asymmetries in 2001 at HERMES and CLAS

…how it evolved…
Azimuthal asymmetry amplitudes with respect to beam spin or beam charge or target spin, and cross sections

… and how it is going nowadays
Hall A high-precision extraction of Compton form factors from cross sections

CLAS 12 beam-spin asymmetry in the extended valence region

CLAS12 new longitudinal target spin asymmetry

GPDs at JLab - E. Voutier, Thu am
DVCS at CLAS12 - A. Hobart, Wed pm

CLAS12 (G. Christiaens et al.), PRL 130, 211902 (2023)

COMPASS t-differential cross section & t-slope to probe transverse extension of partons

This Analysis

Hall A Collaboration (F. Georges et al.), PRL 128, 252002 (2022)

EINN2023, November 1, 2023
In DVCS, the experimentally accessed quantity is a complex Compton Form Factor:

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

**Im(τDVCS)**

$$x = \xi$$

**Re(τDVCS)**

integral over x

**Im(τDVCS)**

$$|x| < \xi$$

**DVCS**

time-like Compton scattering, TCS = time-reversal symmetric process of DVCS.

CLAS12 (P. Chatagnon et al.),
PRL 127, 262501 (2021)

**COMPASS DVCS asymmetries**

$$d\sigma^\pm - d\sigma^\rightarrow$$

$$d\sigma^\pm + d\sigma^\rightarrow$$

(analysis in progress)

**CLAS12 TCS 1st ever measurement**

forward-backward asymmetry

photon circular polarization asymmetry
Exploring Compton FFs & gravitational FFs

- **Unmuting x (x≠±ξ line)** via Single Diffractive Hard Exclusive Processes (SDHEP), e.g.,
  - double DVCS. Small x-section & requires muon ID. LOIs: CLAS12 upgrade, SOLID@ Hall A
  - exclusive photoproduction - possibility @Hall D

\[ \text{D-term } D(t): \text{ related to shear forces and radial distribution of pressure inside the nucleon} \]

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

gravitational form factors (GFFs) of the proton
- matrix elements of QCD energy-momentum tensor (EMT)
- related to mass; angular momentum; shear force & pressure
- Linked to GPDs via x-moment

[Pedrak, Pire, Szymanowski, Wagner, PRD 96 (2017) 7, 074008]

- [Lorcé, Metz, Pasquini, Rodini, JHEP 2021, 121 (2021)]
- [Burkert, Elouadrhiri, Girod, Nature 557, 396–399 (2018)]

**Related:** gluonic gravitational form factor of the nucleon from threshold J/\(\psi\) photoproduction

[see talk by S. Joosten, Tue am Hall C J/\(\psi\)-007]

[Duran, Meziani, Joosten, et al., Nature 615, 813–816 (2023)]
**GPD E and parton orbital angular momentum**

- **Ji sum rule** links GPD E to parton orbital angular momentum (see next slide - connection with Sivers TMD PDF & spin-orbit correlations)

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

[Ji, PRL 78 (1997) 610]

- CLAS12: DVCS on the neutron (LD$_2$ target with detection of active neutron), preliminary results (A. Hobart)
- CLAS12: on the transversely polarized proton, data to be taken (so far available data are from HERMES)

- All so-far discussed GPDs were **quark** GPDs

- STAR: exclusive J/Psi production in ultra-peripheral collisions (UPC) → **gluon** GPD E. Future new data with forward upgrade

C. Riedl (UIUC), nucleon spin structure
Deeply virtual meson production allows access to higher-twist **chiral-odd GPDs**, which are related to TMD PDFs (e.g., tranversity). Mesons act as quark **flavor filter** & provide different sensitivity to **gluon GPDs**.

**CLAS12 exclusive vector meson beam-spin asymmetries**
preliminary results for $\rho$, $\omega$ (N. Trotta) and $\phi$ (B. Clary), gluon GPDs

**COMPASS exclusive vector meson transverse target-spin asymmetries**

\[
E^\phi = -\frac{1}{3} E^s + \frac{1}{8} \frac{E^g}{x}
\]

[C. Riedl (UIUC), nucleon spin structure]

[COMPASS PLB B731 (2014) 19]  Different contributions from pion pole

[COMPASS NPB 915 (2017) 454]  EINN2023, November 1, 2023
Spin density matrix elements describe how the spin components of the virtual photon are transferred to the created vector meson, and provide sensitivity to the chiral-odd GPDs $H_T$ and $E_T$.

- Provide further constraints on GPD parameterizations beyond cross-section and spin-asymmetry measurements.
- Test of s-channel helicity conservation (SCHC), $\lambda_{T^*} = \lambda_{VM}$, only SDMEs of classes A&B are not restricted to $=0$ if SCHC. Observed: considerable SCHC in $\gamma^*_T \rightarrow \omega_0$ (class C).

[$^\rho^0$ COMPASS EPJC (2023) 83, 924]
[$^\rho^0$ HERMES EPJC (2009) 62, 659]
[$^\omega$ COMPASS EPJC (2021) 81, 126] (not shown)
Exclusive pion leptoproduction

\[
\frac{d^2 \sigma_{\gamma^* p}}{dt d\phi} = \frac{1}{2\pi} \left[ \frac{d\sigma_T}{dt} + \frac{d\sigma_L}{dt} + \epsilon \cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon (1 + \epsilon)} \cos(\phi) \frac{d\sigma_{LT}}{dt} \right]
\]

L, T indices indicate polarization of virtual photon. Double index = interference

\[
[(1 - \xi^2)|\langle \hat{H}_T \rangle|^2 - \frac{t'}{4M^2} |\langle \hat{E}_T \rangle|^2]
\]

\[
(1 - \xi^2)|\langle \hat{H} \rangle|^2 - 2\xi^2 \text{Re} \left[ \langle \hat{H} \rangle^* \langle \hat{E} \rangle \right] - \frac{t'}{4M^2} \xi^2 |\langle \hat{E} \rangle|^2
\]

\[
\xi \sqrt{1 - \xi^2} \sqrt{-t'} \text{Re} \left[ \langle \hat{H}_T \rangle^* \langle \hat{E} \rangle \right]
\]

\[
\xi \sqrt{1 - \xi^2} \sqrt{-t'} \text{Im} \left[ \langle \hat{E}_T \rangle^* \langle \hat{H} \rangle \right] + \langle \hat{H}_T \rangle^* \langle \hat{E} \rangle
\]

Effects of chiral-odd GPDs \( \hat{E}_T, H_T \) in exclusive \( \pi^0, \pi^+ \) production

COMPASS \( \pi^0 \) x-section

CLAS12 \( \pi^0, \pi^+ \) beam-spin asymmetry

JLab12 Hall A \( \pi^0 \) x-section

[Hall A collaboration (M. Diamini et al.), PRL 127, 152301 (2021)]

Large TT contribution \( \rightarrow \) significant role of transversely polarized photons in excl. \( \pi^0 \) production

[\( \pi^0 \) CLAS12 (A. Kim et al), arXiv:2307.07874, submitted to PLB]

[\( \pi^0 \) CLAS (S. Diehl et al), PLB 839, 137761 (2023)]

Dip at small \( |t| \) indicative of large effect by chiral-odd GPD \( \hat{E}_T \)

C. Riedl (UIUC), nucleon spin structure
**Transition DAs and transition GPDs**

**CLAS excl. $\pi^+$ beam-spin asymmetries in the backward**

**CLAS12 excl. $\pi^-\Delta^{++}$ beam-spin asymmetries, first ever data**

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

How does nucleon resonant excitation affect its 3D structure? Information encoded in transition GPDs (8 chiral-even and 8 chiral-odd).

[CASL (S. Diehl et al., PRL125, 182001)]

C. Riedl (UIUC), nucleon spin structure

[CLAS12 (S. Diehl et al.), PRL131, 021901 (2023)]

very forward kinematics ($-t/Q^2\approx1$)
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**Outlook & summary**
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.

- **SpinQuest / E1039 at FNAL (2024++):**
  - Transversely polarized NH3/ND3 target with E906 spectrometer
  - First polarized DY experiment with proton beam
  - Sivers & transversity TMDs of sea quarks

- **LHCspin at CERN,** fixed trans.polarized H2 & D2 targets with LHCb as forward spectrometer, >2025, https://inspirehep.net/literature/1821190

- **STAR cold QCD with forward upgrade at RHIC:**
  - Tracking system of silicon & small TGC
  - Forward electromagnetic & hadronic calorimetry, 2.5<\(\eta<4\)
  - midrapiditiy: improve statistics of Sivers via dijet & W/Z, Collins via hadrons in jets, GDP E via J/Psi UPC
  - forward rapidity: TMDs at high-x & GDP E

- **sPHENIX cold QCD at RHIC:**
  - Optimized for jets, heavy-flavor measurements and displaced vertices with MAPS-based vertex tracker
  - Gluon Sivers TMD PDF via \(A_N\) in single-photon & heavy flavor
  - Di-hadron IFF / Collins asymmetry & transversity PDF via hadron-charge tagging & hadron-in-jet

- **AMBER:**
  - Emergence of hadron mass, pion and kaon PDFs, proton and meson radius

[Aschenauer, Barish, Bazilevsky, et al.,arXiv:2302.00605]
sPHENIX - preparing for transversely polarized pp in 2024

- Commissioning 2023 with brand new experiment at RHIC IP 8
- Optimized for jets, heavy-flavor measurements & displaced vertices with MAPS-based vertex tracker
- Gluon Sivers TMD PDF via $A_N$ in single-photon & heavy flavor production
- Di-hadron IFF / Collins asymmetry & transversity PDF via hadron-charge tagging & hadrons-in-jets

**Expected stat uncertainties for isolated photon & heavy-flavor production**

- **sPHENIX BUP 2022, Years 1-3**
  - 62 pb$^{-1}$ samp. $p^+p \rightarrow \gamma + X$, $P=0.57$

- **$A_N$**
  - sPHENIX BUP 2022, $p^+p \rightarrow D^0\bar{D}^0 + X$, $P=0.57$
  - 6.2 pb$^{-1}$ str. $p+p$, Years 1-3
  - Kang, PRD78, $\lambda_i = \gamma_d = 0$
  - Kang, PRD78, $\lambda_i = \gamma_d = 70$ MeV

**First pi0s in the EMCal**

- sPHENIX internal
  - Au-Au $\langle$NN$\rangle = 200$ GeV Run 9457
  - $\Sigma$ ADC$_{emcal} < 275,000$

C. Riedl (UIUC), nucleon spin structure

Expect factor of ~2 less stat in 2024 than shown here
Summary - Probing nucleon spin structure

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

Probes for TMD factorization, evolution & universality

GPDs beyond chiral even; nucleon ground state; away from the $x=±\xi$ line; extremely high precision in the valence region & bridging the region between gluons and valence

OAM as prerequisite for Sivers effect... and linked to GPDs

Experiments at BNL, JLab, CERN, DESY, RIKEN, Fermilab, et al. unravel proton and nucleus structure

Experimental (and in some cases lattice) data serve as input to global fits

The 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 $x_{\text{Bjorken}}$.

Skipped probably many results - e.g., unpolarized Boer-Mulders TMD

- Some of it covered in backup

- The RHIC Cold QCD Program (White Paper) - Contribution to the NSAC Long-Range Planning process, E.C. Aschenauer et al. (RHIC SPIN collaboration), [arXiv:2302.00605](https://arxiv.org/abs/2302.00605)

C. Riedl (UIUC), nucleon spin structure
Going polarized at fixed-targets experiments

- HERMES at DESY (1995-2007)
  - Self-polarized 27.6 GeV electrons and positrons in HERA storage ring
  - Pure L- and T-polarized gas targets

- COMPASS at CERN (2002-2022)
  - Secondary and tertiary beams (M2 SPS beam line)
    - Muons polarized via pion decay
  - Solid-state L- and T-polarized targets

And many more: the polarized electron beams at JLab-CEBAF, the polarized targets at JLab, Fermilab, LHC-spin…

Polarization achieved by Dynamic Nuclear Polarization (DNP)
- dilution refrigerator: ~60mK
- dipole magnet (transverse): 0.5T
- solenoid (longitudinal): 2.5T
- microwave system
Polarization determined with Nuclear Magnetic Resonance (NMR)

NH₃ ammonia beads, ⁴LiD: deuterated lithium dilution factor ~ 0.22 (NH₃), 0.5 (LiD)
The 2022 data-taking campaign was the last run of the COMPASS experiment, and the last of the exploratory study of the nucleon structure. COMPASS changed from “data taking” to “data analysis” and will continue for several years. The spectrometer will stay in the experimental hall and is being upgraded and run by the AMBER Collaboration.

- Polarization achieved by Dynamic Nuclear Polarization (DNP):
  - dilution refrigerator: ~60mK
  - dipole magnet (transverse): 0.5T
  - solenoid (longitudinal): 2.5T
  - microwave system
- Polarization determined with Nuclear Magnetic Resonance (NMR)

COMPASS polarized solid-state target

- He-3 precooler
- Microwave cavity
- Target cells
- Target holder
- Magnets
- Pulse tube cryocooler
- 80 K Thermal radiation shields
- 4.2 K Thermal radiation shields
- Dilution refrigerator
- He-4 gas-liquid separator
- 1 m
- 180 mrad

NH₃, ammonia beads, ⁶LiD: deuterated lithium
dilution factor ~ 0.22 (NH₃), 0.5 (LiD)

C. Riedl (UIUC), nucleon spin structure
Collisions with polarized protons at RHIC

- Relativistic heavy ion collider - RHIC
- Collisions of L- and T-polarized protons, $\sqrt{s} = 200, 500/510$ GeV
- Optically pumped ion source (OPPIS) that transfers electron polarization to protons. Siberian Snakes to overcome the effects of depolarizing resonances.
Accessing intrinsic transverse parton momenta in SIDIS

Semi-inclusive DIS

detect in addition to scattered lepton also hadron with energy $z$ and transverse momentum $P_T$

$k_T$ intrinsic transverse quark momentum

transverse momenta:
- $P_T$ final-state hadron (GNS)
- $k_T$ quark intrinsic
- $p_\perp$ hadron wrt struck quark
TMD backup
TMD measurements - a huge experimental effort

Current data for Collins and Sivers asymmetry:

- COMPASS $h^n$: $P_{T} < 1.6$ GeV/c
- HERMES $\pi^{0,\pm}$, $K^\pm$: $P_{T} < 1$ GeV/c
- JLab Hall-A $\pi^n$: $P_{T} < 0.45$ GeV/c
- JLab 12
- STAR 500 GeV $-1 < \eta < 1$ Collins
- STAR 500 GeV $1 < \eta < 4$ Collins
- STAR W bosons

EIC $\sqrt{s} = 140$ GeV, $0.01 < y < 0.95$
EIC $\sqrt{s} = 20$ GeV, $0.01 < y < 0.95$

[EIC yellow report, arXiv:2103.05419]
Transverse spin asymmetries have **common origin** - simultaneous description across different collision species possible.

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

Two complementary but related **theoretical descriptions**, depending on **what is measured** (reconstructed experimentally)

- **TMD framework** when transverse momentum is probed
  - measure 2 scales with $p_T \ll Q$: SIDIS, DY, W/Z, dijets, hadrons in jets
- **Collinear higher-twist (HT) framework**
  - Measure 1-scale with $p_T \approx Q$: single inclusive particle production in pp (particle or jet $p_T$)
  - spin asymmetries from quantum mechanical interference of multiparton states ($\rightarrow$ qgq and ggg correlators)

**Probing with two scales** (not only here) - hard resolves particle nature of partons, soft reveals emergent phenomena
Spin-orbit correlations in the proton

• If TMDs describing strength of spin-orbit correlations are non-zero: may in certain models be connected to parton orbital angular momentum (OAM).
  
  ▶ No quantitative relation between TMDs & OAM identified yet.

• Sivers effect: correlation between the nucleon transverse spin & parton transverse momentum in the transversely polarized nucleon

• 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 (**).

“Chromodynamic lensing”


C. Riedl (UIUC), nucleon spin structure
The strength of distortion in transverse-momentum space is proportional to

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

and is called the Sivers amplitude

$$f_{1T}^{\perp q}$$

$$f_{q/p^+}(x, \vec{k}_T) = f_1^q(x, \vec{k}_T) - f_{1T}^{\perp q}(x, \vec{k}_T^2) \cdot \left( \hat{P} \cdot \vec{k}_T \right)$$

PV19 fit using SIDIS data from HERMES, COMPASS and Hall A

[Bacchetta, Deleer, Pisano, Radici, PLB 827, 136961 (2022)]
Semi-inclusive deep-inelastic scattering cross section

\[ A_{UT}(\phi) = \frac{1}{fS_T} \frac{N^\uparrow(\phi) - N^\downarrow(\phi)}{N^\uparrow(\phi) + N^\downarrow(\phi)} \]

\[
\sigma(\phi, \phi_S) = \int \frac{d^6\sigma}{dx dy dz d\phi d\phi_S dP_T^2} \frac{\alpha^2 \gamma^2}{x y Q^2 2(1-\epsilon)} \left( 1 + \frac{\gamma^2}{2x} \right)
\]

\[
\begin{aligned}
&\lambda_c \left[ 2\epsilon(1+\epsilon) \cos\phi F_{UU}^{cos}\phi + \epsilon \cos(2\phi) F_{UU}^{cos(2\phi)} \right] \\
&+ S_L \left[ \sqrt{2\epsilon(1+\epsilon)} \sin\phi F_{UL}^{sin}\phi + \epsilon \sin(2\phi) F_{UL}^{sin(2\phi)} \right] \\
&+ S_L \lambda_c \left[ \sqrt{1 - \epsilon^2} F_{LL}^{cos}\phi + 2\epsilon(1-\epsilon) \cos\phi F_{LL}^{cos(2\phi)} \right]
\end{aligned}
\]

\[
\begin{aligned}
&\lambda_c \left[ \sqrt{2\epsilon(1+\epsilon)} \sin\phi_S F_{UT}^{sin}\phi_S + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi - \phi_S) F_{UT}^{sin(2\phi - \phi_S)} \right] \\
&+ S_T \lambda_c \left[ 1 - \epsilon^2 \cos(\phi - \phi_S) F_{LT}^{cos(\phi - \phi_S)} + 2\epsilon(1-\epsilon) \cos(2\phi - \phi_S) F_{LT}^{cos(2\phi - \phi_S)} \right]
\end{aligned}
\]

\[
\begin{aligned}
&\lambda_c \left[ \sqrt{2\epsilon(1+\epsilon)} \sin\phi_F F_{UT}^{sin}\phi_F + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi - \phi_F) F_{UT}^{sin(2\phi - \phi_F)} \right] \\
&+ S_T \lambda_c \left[ 1 - \epsilon^2 \cos(\phi - \phi_F) F_{LT}^{cos(\phi - \phi_F)} + 2\epsilon(1-\epsilon) \cos(2\phi - \phi_F) F_{LT}^{cos(2\phi - \phi_F)} \right]
\end{aligned}
\]
Sivers TMD PDF from SIDIS

HERMES vs. COMPASS Sivers asymmetries

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

Sivers function from COMPASS asym.

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

Sivers TMD PDF

HERMES TMD final compendium

- u- and d-quark Sivers functions have opposite signs

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

Kaon amplitudes larger than pion

- Unexpected if u-quark scattering dominates. Role of sea quarks?

C. Riedl (UIUC), nucleon spin structure
The experimental test of the Sivers TMD PDF (and other naive time-reversal odd TMDs) sign-switch prediction is an important test of TMD-QCD framework.
Global TMD analysis - Collins FF, di-hadron FF, transversity TMD PDF

- *d*-quark transversity less constrained* given the *u*-quark dominance of many of the processes used in the global fits.
  - JAM-22 reduced uncertainties wrt JAM20 due to inclusion of lattice QCD data and Soffer bound.
  - COMPASS 22 transversity run on the deuteron will improve the experimental precision on the proton’s tensor charge, $g_1 = \delta_u - \delta_d$, by a factor of $\sim 2$.
  - Further prior-to-EIC measurements of Collins asymmetries include STAR with forward upgrade, sPHENIX, JLab12/SoLID, SpinQuest.

- Transversity TMD PDF coupled to interference, or di-hadron, fragmentation function
  - 2 collinear observables (DGLAP evolution, not TMD) - *complementary probe of transversity TMD*
  - interference of different channels of the fragmentation process into the two-hadron system (interference of S and P states)

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Global extraction of transversity from di-hadron data:

- pion-pair multiplicities in pp needed

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C. Riedl (UIUC), nucleon spin structure

[Radici, Bacchetta, PRL 120, 192001 (2018)]

[Jam Collaboration - JAM3D-22, PRDD 106, 034014 (2022)]
The 2022 COMPASS run: $μd^{↑}→hX$

- June - November 2022 with transversely polarized deuteron ($^6$LiD) target with almost the same conditions as 2010 proton run.
- Impact on the deuteron SIDIS Collins asymmetry - the 2022 uncertainties are expected to be a factor 2 to 5 smaller.
- Impact on transversity TMD PDF and on tensor charge

<table>
<thead>
<tr>
<th>$Ω_+: 0.008 \pm 0.210$</th>
<th>$δ_u = \int_{Ω_x} dx h_1^{u^p}(x)$</th>
<th>$δ_d = \int_{Ω_x} dx h_1^{d^p}(x)$</th>
<th>$g_T = δ_u - δ_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>present</strong></td>
<td>$0.201 \pm 0.032$</td>
<td>$-0.189 \pm 0.108$</td>
<td>$0.390 \pm 0.087$</td>
</tr>
<tr>
<td><strong>projected</strong></td>
<td>$0.201 \pm 0.019$</td>
<td>$-0.189 \pm 0.040$</td>
<td>$0.390 \pm 0.044$</td>
</tr>
</tbody>
</table>

The work will not be over with the COMPASS measurements - precise measurements are needed $Q^2_{\text{GeV}^2}$ asap, in particular at larger $x$.

The complementary measurements at Jlab 12 and 20+ will allow for a more precise measurement of the tensor charge and, in the farther future, the EIC.

C. Riedl (UIUC), nucleon spin structure
Subprocess fractions at RHIC energies
for $gg$, $qg$, $qq+q\bar{q}bar$
(leading order hard QCD processes)

A. Mukherjee et al., PRD86,094009

courtesy Z. Chang
$A_N$ in the very forward

**PHENIX charged hadrons**

\[ p^+ + p, p^+ + A, p^+ + Au \rightarrow h^+ + X \]

- Smaller $A_N$ for h+ at $0.1 < x_F < 0.2$ in pA
  - $A_N(h^-)$ small to zero at $x_F > 0$: opposite sign of $A_N$ for h- canceled partially

**RHICf very forward neutrons ($\eta < 6$)**

- Publication with improved background estimation in preparation.
  - Increase in $p_T$: interference between spin flip and spin non-flip amplitudes ($\pi / a_1$ exchange model [PRD 84 (2011) 114012])

- Analysis for 510 GeV ongoing.
  - (p0 not shown) also - [STAR PRD 103, 092009 (2021)]

**STAR electromagnetic jets**

- $A_N$ increases with $p_T$ (for $x_F > 0.46$ - RHICf) & forwardness & $\pi^0$ isolation (STAR) & lower $\gamma$ multiplicity (STAR)

- $A_N$ from soft processes such as diffractive scattering?

[PHENIX arXiv:2303.07191]

C. Riedl (UIUC), nucleon spin structure
TMD fragmentation function (Collins) from $pp \rightarrow \text{jet } h^+X$ - kaons and protons

STAR hadrons in jets (midrapidity)

[STAR PRD 106, 072010 (2022)]
More higher twist in single-hadron SIDIS

CLAS(12), HERMES and COMPASS SIDIS beam-spin asymmetries

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

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

[HERMES PLB 797 (2019) 134886]
COMPASS collected a large amount of L-SIDIS data with unprecedented precision for some amplitudes

\[ A_{UL}^{\sin\phi_h} \]
- Q-suppression, higher-twist subleading effects
- Sizable TSA-mixing
- Significant h+ asymmetry, clear z-dependence
- h− compatible with zero

\[ A_{UL}^{\sin2\phi_h} \]
- Only “twist-2” ingredients
- Additional P_{T}-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

\[ A_{LL}^{\cos\phi_h} \]
- Q-suppression, higher-twist subleading effects
- Compatible with zero, in agreement with models

- Di-hadron asymmetries (not shown)
Accessing intrinsic transverse parton momenta in SIDIS

Azimuthal modulation of hadron yield

- **Cahn effect** - $\cos \phi_h$ modulation purely due to the presence of intrinsic transverse momenta of unpolarized quarks in the unpolarized nucleon.
  - No such modulation in the collinear case. Next-to-leading-order effect.

$$\langle k_T^2 \rangle_{eff} = -\frac{Q\langle P_T^2 \rangle A_{UUU}^{\cos \phi_h}}{2zP_T}$$

- Double-Gauss structure in $P_T$ spectrum separated at $\sim 1$ GeV/c

Transverse-momentum dependent hadron multiplicities

$$d^2N^h(x, Q^2, z, P_T^2) dz \frac{dP_T^2}{dP_T^2} \propto \exp\left(-\frac{P_T^2}{\langle P_T^2 \rangle}\right)$$

$$\langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_{\perp}^2 \rangle$$

transverse momenta:
- $P_T$ final-state hadron (GNS)
- $k_T$ quark intrinsic
- $p_{\perp}$ hadron wrt struck quark

C. Riedl (UIUC), nucleon spin structure
courtesy A. Moretti
Transverse-momentum distributions

- Allow to gain information about intrinsic quark momentum $k_T$ by measuring transverse momentum $P_T$ of the produced hadron.
- Important for TMD evolution studies & comparison between experiments. Intense theoretical work ongoing to reproduce the experimental distributions over a wide energy range.
- In Gaussian approximation, at small values of $P_T$, the number of hadrons is expected to follow:

$$\frac{d^2N^h(x, Q^2; z, P_T^2)}{dz\, dP_T^2} \propto \exp\left(-\frac{P_T^2}{\langle P_T^2 \rangle}\right)$$

$$\langle P_T^2 \rangle = z^2\langle k_T^2 \rangle + \langle p_T^2 \rangle$$

- Double Gauss structure in $P_T$ spectrum separated at 1 GeV/c $\rightarrow$ 2 different slopes
  - Perturbative effects expected to contribute more at high $P_T$
  - Likely not sufficient to explain the high-$P_T$ trend
- Hadron multiplicities (not shown)
  - $p$-/$p+$ and $K^{-}/K^{+}$ at high $z$ PLB 807 (2020) 135600, $K^{-}/K^{+}$ at high $z$ PLB 786 (2018) 390
  - $h$ PRD 97 (2018) 032006, $K$ isoscalar PLB 767 (2017) 133, $\pi^\pm$ and $h^\pm$ PLB 764 (2017) 001

C. Riedl (UIUC), nucleon spin structure
Boer-Mulders function and Cahn effect in SIDIS

- The **Boer-Mulders function** describes the strength of the spin-orbit correlation between quark spin $s_T$ and intrinsic transverse momentum $k_T$:

  \[ \vec{s}_T \cdot (\vec{P} \times \vec{k}_T) \]

  - Contributes to $\cos \phi_h$ and $\cos(2\phi_h)$
  - Strong kinematic dependences & interesting differences between positive and negative hadrons, as observed in previous measurements by COMPASS on deuteron and by HERMES (u-quark dominance, opposite signs of Collins FF into h+ and h-)

- **Cahn effect**
  - Contributes to $\cos \phi_h$ only → next slide

  - Higher-twist beam-spin asymmetry $A_{LU}^{\sin \phi_h} = \frac{F_{LU}^{\sin \phi_h}}{F_{UU,T}^{\sin \phi_h}}$ (backup)

  - Azimuthal asymmetries for **hadron pairs** on the unpolarized proton (backup)
    - Collins FF for 2 hadrons & interference fragmentation function

Azimuthal asymmetries defined as the ratios

COMPASS preliminary

Proton 2016 data

The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim \sigma_{stat}$ (1D)
Cahn effect and quark intrinsic momentum from SIDIS

- **Cahn effect** - additional (to BM) \( \cos \phi_h \) modulation purely due to the presence of intrinsic transverse momenta of unpolarized quarks in the unpolarized nucleon. No such modulation in the collinear case. Next-to-leading-order effect.
  - Clear signal, strong dependence on \( P_T \).
    - Compatible with zero at high \( z \). In agreement with COMPASS deuteron results.

- Naive expectation

\[
A_{UU|\text{Cahn}}^{\cos \phi_h} = -\frac{2z P_T \langle k_T^2 \rangle}{Q \langle P_T^2 \rangle}
\]

- Observed trend is however opposite (increase with \( Q^2 \))

- Complementary access to **quark intrinsic transverse momentum** + other PDFs & FFs contributions

**Proton**

2016 data
GPD backup
2 most recent JLab DVCS publications - my cheat sheet

left: one of 64 bins accessible only with ~10 GeV beam. Tension in KM15. right: "weighted" and "unweighted" is PARTON ANN. Only part of data set taken is published, already now compatible with JLab 6-Gev

CLAS12 (G. Christiaens et al.),
PRL 130, 211902 (2023)

Selection of exclusive data sample

Hall-A DVCS: $e\gamma$ detection
- $6 \text{ GeV}$
- $M_X^2$ cut window
- After $x^*$ & accidental subtraction
- DVCS MC

HERMES DVCS:
- 27.6 GeV
- no Recoil: $e\gamma$

COMPASS DVCS:
- $\mu\gamma p$ detection
- 160 GeV

HERMES & COMPASS excl. $q$: $\ell\pi^-\pi^+$ detection

CLAS DVCS:
- no Inner Calo: $ep$ or $ep\gamma$

with Recoil: $e\gamma$

H1/ZEUS DVCS:
- $e\gamma$ + forward veto
- ZEUS subsample: $e\gamma$

C. Riedl (UIUC), nucleon spin structure
**Selection of exclusive event sample - COMPASS**

**DVMP** without recoil-proton detection: missing energy technique assuming proton mass

**DVCS** with recoil-proton detector (RPD): comparison of proton kinematics measured in RPD vs. expected in spectrometer (from $\mu \gamma$)

**Exclusive $\rho^0$ production**

$\mu p (^{1}) \rightarrow \mu p p^0$

with simulated exclusive signal & SIDIS background

In case of transverse target polarization: additional azimuthal angle $\phi_S$ defined by direction of transverse target-polarization vector

+ kinematically complete event reconstruction via kinematic event fitting

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C. Riedl (UIUC), nucleon spin structure
Access to CFFs at COMPASS

\[ \sigma_{\gamma^*pN} = |T_{BH}|^2 + (T_{DVCS}T_{BH}^* + T_{BH}^*T_{DVCS}) + |T_{DVCS}|^2 \]

The DVCS / Bethe-Heitler interference term allows to disentangle \( \text{Re}(T_{DVCS}) \) and \( \text{Im}(T_{DVCS}) \), magnitude and phase of DVCS amplitude \( T_{DVCS} \).

\[ S_{CS,U} \equiv d\sigma^\pm + d\sigma^- \]
\[ D_{CS,U} \equiv d\sigma^\pm - d\sigma^- \]

\[ A_{CS,U} \equiv \frac{d\sigma^\pm - d\sigma^-}{d\sigma^\pm + d\sigma^-} = \frac{D_{CS,U}}{S_{CS,U}} \]

Spin-independent DVCS cross section \( \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2} \mathcal{E}\mathcal{E}^* \)

Analysis of azimuthal modulations (HERMES- and JLab-type) on DVCS on the unpolarized proton in progress

dominant at small \( x_B \)
(remainder \( \sim 5\% \) from KM / GK model)

Sign & magnitude of \( \cos\varphi \) amplitude for beam-charge asymmetry? (changes sign between HERMES and HERA)

C. Riedl (UIUC), nucleon spin structure

Test of GPD universality: use DVMP data to constrain GPD parameters

Extraction of pure DVCS yield at COMPASS

$$|\mathcal{T}_{BH}|^2 + (\mathcal{T}_{DVCS} \mathcal{T}_{BH}^* + \mathcal{T}_{DVCS}^* \mathcal{T}_{BH}) + |\mathcal{T}_{DVCS}|^2$$

BH reference yield:
- at small $<x_B>=0.0085$

DVCS amplitude:
- $\phi$-modulations in cross section
- at medium $<x_B>=0.0200$

Transverse imaging:
- $\phi$-integrated cross section
- at medium $<x_B>=0.0630$

- $80 < \nu [\text{GeV}] < 144$
- $32 < \nu [\text{GeV}] < 80$
- $10 < \nu [\text{GeV}] < 32$

C. Riedl (UIUC), nucleon spin structure portion of the 2016 data = 2x 2012 data
Extraction of pure DVCS yield at COMPASS

$\pi^0$ production: $\mu p \rightarrow \mu p \pi^0 \rightarrow \mu p \gamma (\gamma) (X)$ exclusive or SIDIS

$\gamma \gamma$: “visible $\pi^0$”, $\gamma$: invisible $\pi^0$ background

Determine BH reference yield at low-$x_B$ $\leftrightarrow$ high-$v$: tune MC to data

Subtract BH yield in high-$x_B$ $\leftrightarrow$ low-$v$ bin

Subtract measured visible $\pi^0$ yield in high-$x_B$ $\leftrightarrow$ low-$v$ bin

Estimate $\pi^0$ invisible background from MC: SIDIS 40% (LEPTO) + exclusive 60% (HEPGEN with GK model) with 10% uncertainty each

Remove invisible $\pi^0$ yield (invisible normalized to visible yield)

Pure DVCS yield

portion of the 2016 data = 2x 2012 data
Transverse imaging of the nucleon

Impact-parameter representation of parton distribution function:

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


“spatial parton density = Fourier transform of GPD”

\( \mathbf{b}_\perp \) is the impact parameter,
\( \Delta_\perp \) is the difference of initial and final transverse momenta,
\( \Delta^2_\perp \) is related to the Mandelstam-\( t \)

The differential DVCS cross section allows to probe the **transverse extension of partons** in the nucleon:

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

\( b = \text{“} t \text{-slope”} = \text{average impact parameter} \)
Transverse imaging of the nucleon

PDF impact-parameter representation:

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


“spatial parton density = Fourier transform of GPD”

- \( b_\perp \) is the impact parameter,
- \( \Delta_\perp \) is the difference of initial and final transverse momenta,
- \( \Delta_\perp^2 \) is related to the Mandelstam-\( t \)

Differential DVCS cross section with “\( t \)-slope” = average impact parameter

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

COMPASS DVCS \( t \)-slope

- Sea-quark domain between gluons and valence-quarks
- Transverse extension of partons and \( t \)-slope \( B \):
  \[ \langle r_\perp^2(x_{Bj}) \rangle \approx 2 \langle B(x_{Bj}) \rangle \hbar^2 \]
  \[ \sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \pm 0.01_{\text{sys}} \pm 0.04_{\text{model}}) \text{fm} \]

C. Riedl (UIUC), nucleon spin structure
Flavor separation of CFFs

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


with reggeized diquark model
(Goldstein, Liu, et al.)

Hall A neutron DVCS

JLab 6&12
p & n DVCS

Preliminary global fits
of CFF using NN &
dispersion relation

[Marija Ćući et al, arxiv2007.00029]

C. Riedl (UIUC), nucleon spin structure

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