QNP2022 - THE 9TH INTERNATIONAL CONFERENCE ON QUARKS AND NUCLEAR PHYSICS

Recent Spin Experimental Results and Future Opportunities

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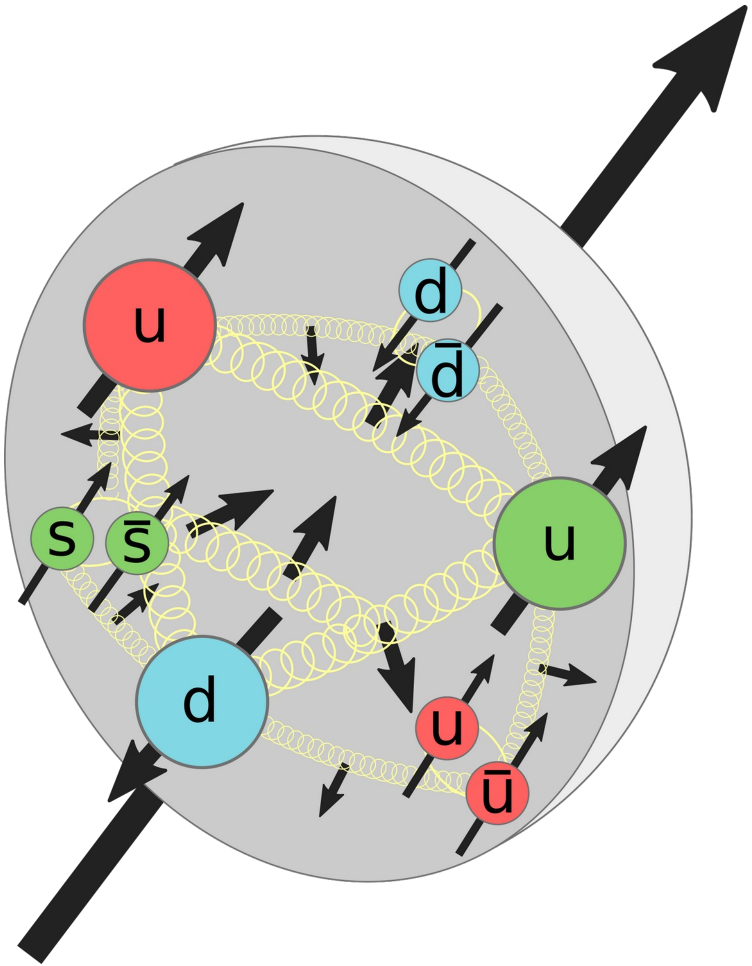
SEPTEMBER 5 - 9, 2022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PHYSICS QUESTIONS - OUTLOOK

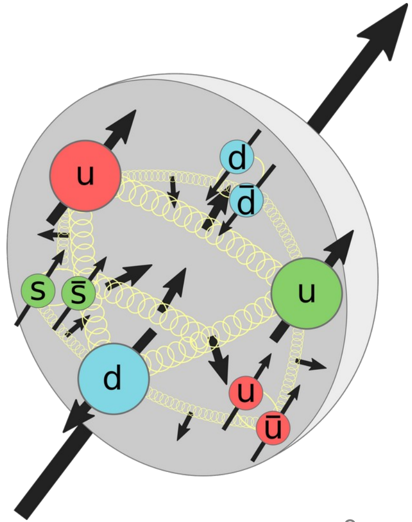
Questions

How does the **spin of the nucleon originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?

1. How do **gluons** contribute to the proton spin?
2. What is the **landscape of the polarized quark-sea** in the nucleon?
3. What is the **spin structure of nucleon at high-x**?

What can **transverse-spin phenomena** teach us about the structure of the nucleon and properties of QCD?
How is the **nucleon spin correlated with the motion** of partons?
How is the **nucleon spin correlated with the spatial distribution** of partons?

4. **GPD**-sensitive measurements
5. Quark and Gluon **Sivers' function**
6. Quark **Collins effect** (transversity + Collins Fragmentation Function)
7. **Higher Twist** Parton Distribution Functions
8. Unpolarized **Boer-Mulders** function



PHYSICS QUESTIONS

How does the **spin of the nucleon originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?

Two established approaches to look at the compositions of the proton spin:

Ji sum rule:

$$\underbrace{\boxed{\Delta\Sigma/2}}_{\text{Quark helicity}}+\underbrace{\boxed{L_q}}_{\text{Quark orbital angular momentum}}+\underbrace{\boxed{J_g}}_{\text{Gluon helicity and orbital angular momentum}}=\hbar/2$$

Jaffe-Manohar sum rule:

$$\underbrace{\boxed{\Delta\Sigma/2}}_{\text{Quark helicity}}+\underbrace{\boxed{\Delta G}}_{\text{Gluon helicity}}+\underbrace{\boxed{\ell_q}}_{\text{Quark canonical orbital angular momentum}}+\underbrace{\boxed{\ell_g}}_{\text{Gluon canonical orbital angular momentum}}=\hbar/2$$

- **Frame independent** spin sum rule
- **Quark and gluon Jq** (sum of ΔΣ/2 and Lq) **and Jg** can be obtained form Generalized Parton Distributions **(GPDs) moments**
- Phys. Rev. Lett. 78, 610–613 (1997)

- All terms have **partonic interpretation**
- In infinite-momentum frame
- **ℓq and ℓg** (Twist-3 quantities) can be extracted **from GPDs**
- Nucl. Phys. B 337, 509–546 (1990)

PHYSICS QUESTIONS

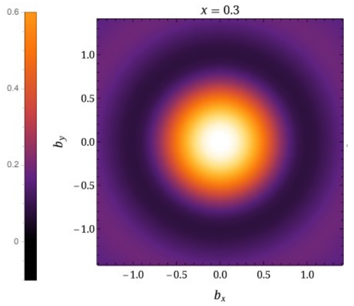
How is the **nucleon spin correlated with the motion** of partons?
How is the **nucleon spin correlated with the spatial distribution** of partons?

Nucleon tomography

Impact parameter dependent
parton distribution functions $f(x,b_T)$

Can be accessed from **GPDs:** $H(x, \xi, t) \rightarrow f(x,b_T)$

- Extrapolation to zero skewness $\xi \rightarrow 0$
- Fourier Transformation $t \leftrightarrow b_T$

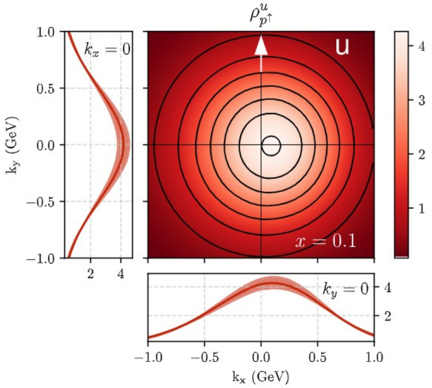


Huey-Wen Lin, PRL 127 (2021) 18, 182001, from Lattice

Position space

Momentum space

Transverse momentum dependent
parton distribution functions (TMDs) $f(x,k_T)$



A. Bacchetta, F. Delcarro, C. Pisano, M. Radici,
PLB 827 (2022) 136961, from SIDIS and DY/W data

PHYSICS QUESTIONS

See also plenary talks by M. Boglione, B. Badelek, C. Keppel, H. Gao

How is the **nucleon spin correlated with the motion** of quarks and gluons?
How is the **nucleon spin correlated with the spatial distribution** of partons?

Nucleon tomography

Impact parameter dependent
parton distribution functions $f(x,b_T)$

Three-dimensional structure of the nucleon: challenges and prospects	*Harut Avagyan*	*online*	11:30 - 11:55
GPDs of light nuclei	*Sara Fucini*	*online*	11:55 - 12:20
A novel approach to calculate GPDs from lattice QCD	*Shohini Bhattacharya*	*online*	12:20 - 12:45
Revisting GPD evolution	*Valerio Bertone*	*online*	12:45 - 13:10
Deeply virtual Compton Scattering on the proton and the neutron at Jefferson Lab	*Silvia Niccolai*	*online*	13:10 - 13:35

Theory overview of GPDs - fits and modelization	*Kresimir Kumericki*	*online*	11:30 - 11:55
Virtual Compton Scattering and the Generalized Polarizabilities of the proton	*Nikos Sparveris*	*online*	11:55 - 12:20
Timelike Compton Scattering with CLAS12 at Jefferson Lab	*Pierre Chatagnon*	*online*	12:20 - 12:45
Compton scattering on liquid deuterium target at HIγS: Measuring nucleon polarizabilities	*Danula Godagama*	*online*	12:45 - 13:10
Multichannel approach for new GPD-sensitive experimental measurements	*Marie BOER*	*online*	13:10 - 13:30

pace

Transverse momentum dependent
parton distribution functions (TMDs) $f(x,k_T)$

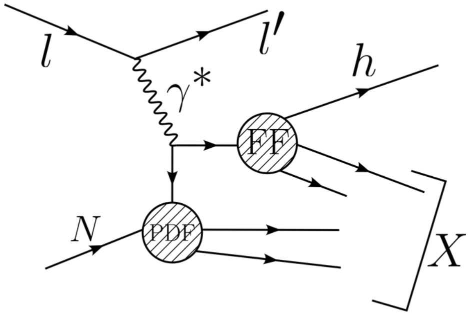
Momentum space

MAPTMD22: a new global fit of unpolarized TMDs	*Matteo Cerutti*	*online*	14:00 - 14:25
TMD distributions at the next-to-leading power.	*Simone Rodini*	*online*	14:25 - 14:50
Exploring the potential role of diquarks in hadronization using SIDIS on nuclear targets	*Will Brooks*	*online*	14:50 - 15:15
New insights on the factorization of single-inclusive e^+e^- annihilation	*Andrea Simonelli*	*online*	15:15 - 15:40
TMD measurements at JLab and future EIC.	*Marco Contalbrigo*	*online*	15:40 - 16:05

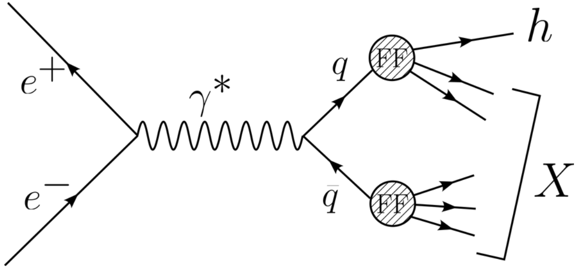
EXPERIMENTAL PROBES

How to access nucleon spin structure?

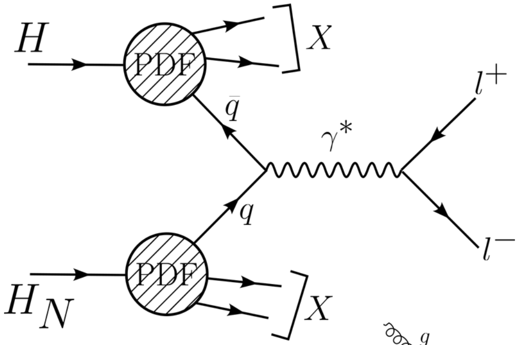
(Semi-Inclusive) Deep Inelastic Scattering

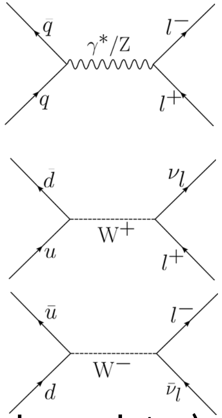


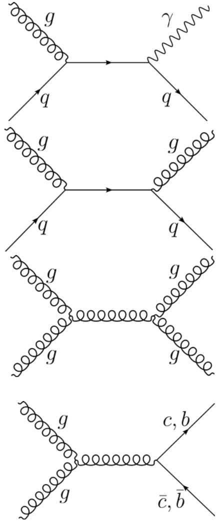
e+e- annihilation (access to FF)



Hadron-hadron interactions





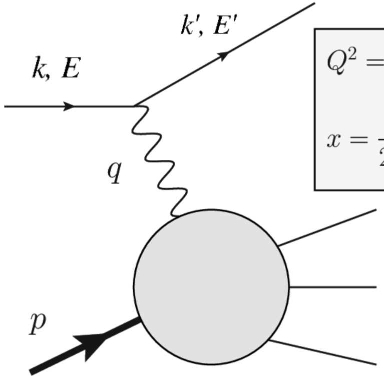


+ Hard exclusive processes for GPDs (shown later)

QUARK AND GLUON HELICITIES

LONGITUDINAL SPIN STRUCTURE

- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering** and **proton-proton** collisions
- **Polarized DIS cross section** studied at SLAC, CERN, DESY (HERMES), JLab encodes information about **helicity structure of quarks** inside the proton (double spin asymmetries)



$$Q^2 = -q^2$$
$$x = \frac{Q^2}{2\,p \cdot q}$$

$$\frac{\mathrm{d}^2\sigma_{\mathrm{LL}}\left(x, Q^2\right)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{8\pi\alpha^2 y}{Q^4}\left[\left(1 - \frac{y}{2} - \frac{y^2}{4}\gamma^2\right)\boxed{g_1\left(x, Q^2\right)} - \frac{y}{2}\gamma^2 g_2\left(x, Q^2\right)\right]$$

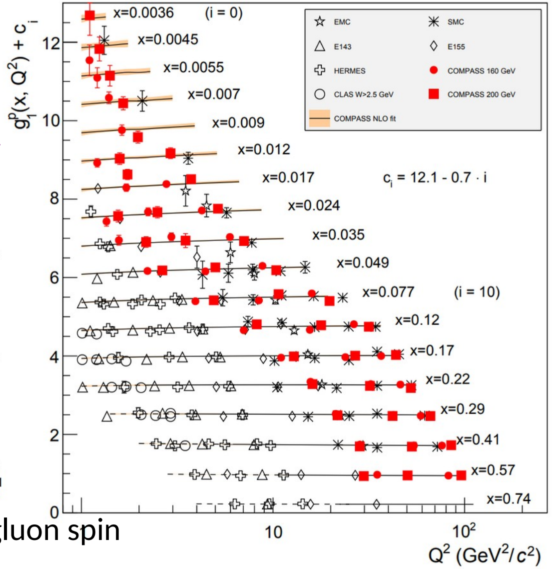
$$\nu = E - E'$$
$$y = \nu/E,\ \gamma^2 = Q^2/\nu^2$$

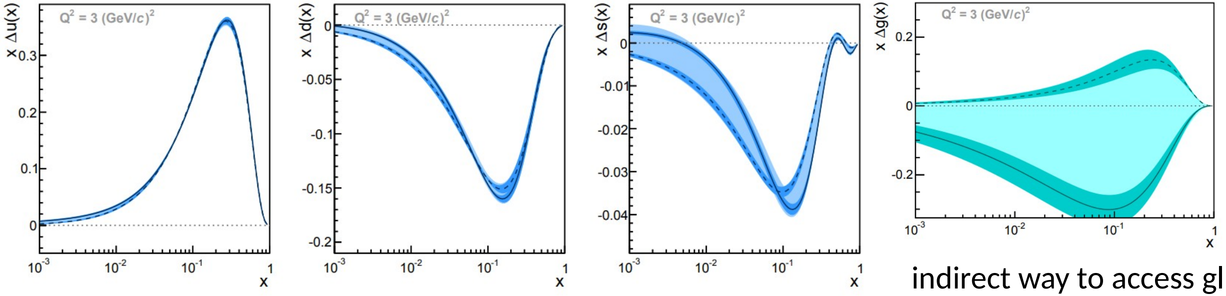
$$g_1(x) = \frac{1}{2}\sum_q e_q^2\ \Delta q(x)$$

In (LO QCD) Quark Parton Model

Quark helicity distribution

COMPASS, PLB 753 (2016) 18





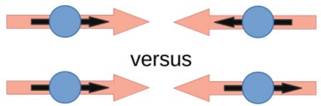
indirect way to access gluon spin

GLUON HELICITY

LO for illustration

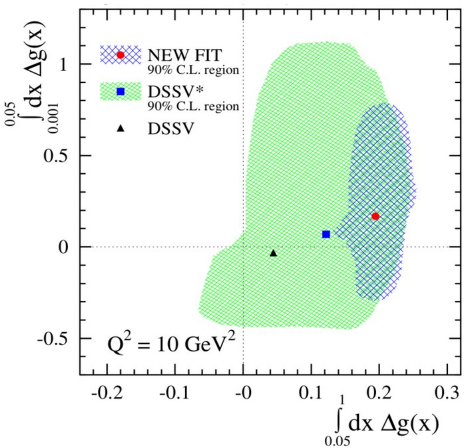
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a_{LL}} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

$\vec{p} + \vec{p} \to \text{jet/dijet/hadrons} + X$

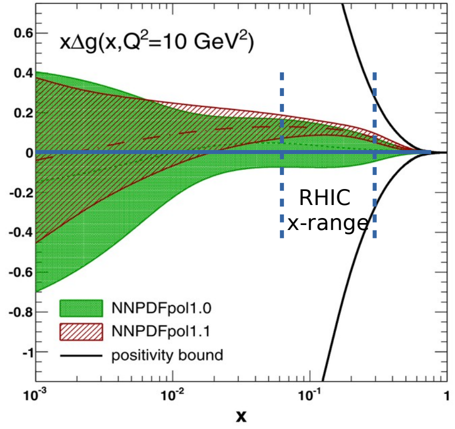


- At RHIC energies: sensitivity to qg and gg – Access to **Δg(x)/g(x)**
- Cross-section measurement to support the NLO pQCD interpretation of asymmetries
- STAR inclusive jet A_{LL} from 2009 data at √s = 200 GeV PRL 115 (2015) 9, 092002
  - Included in global pQCD analysis provided evidence for **positive gluon polarization for x > 0.05 at Q² = 10 GeV**

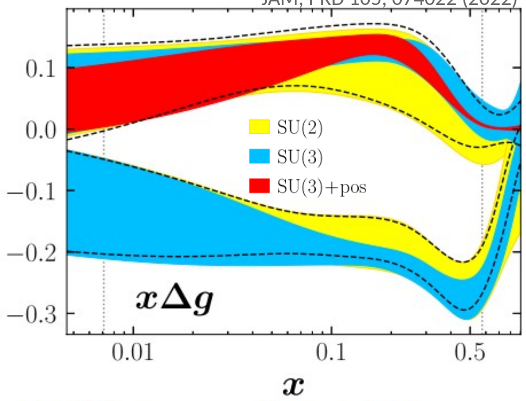
DSSV, PRL 113 (2014) 1, 012001



NNPDF, Nucl. Phys. B 887 (2014) 276



JAM, PRD 105, 074022 (2022)



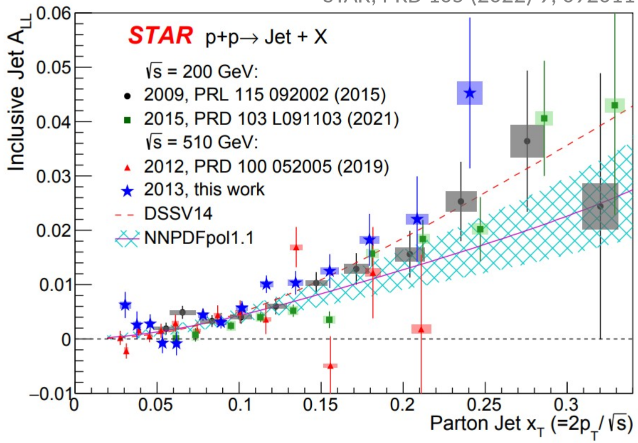
$\mathbf{SU(3) + pos:}\ 0.25 \pm 0.03\ ,\ x > 0.05$

NNPDFpol1.0, DSSV*: STAR 2009 jet data not included
NNPDFpol1.1, DSSV new fit: STAR 2009 jet data included

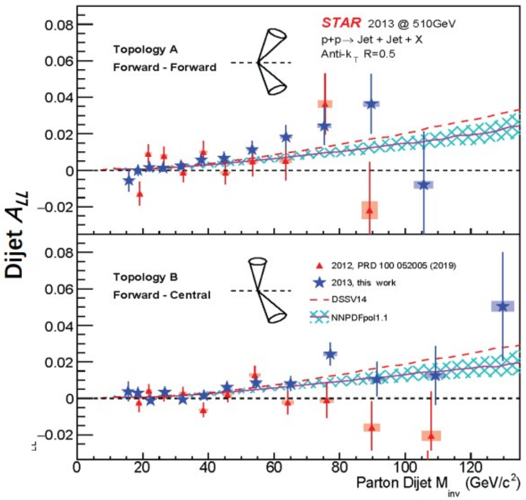
Global fit including single jet data (also STAR 2015) from unpol. and pol. hadron collisions (+ DIS and DY)

GLUON HELICITY

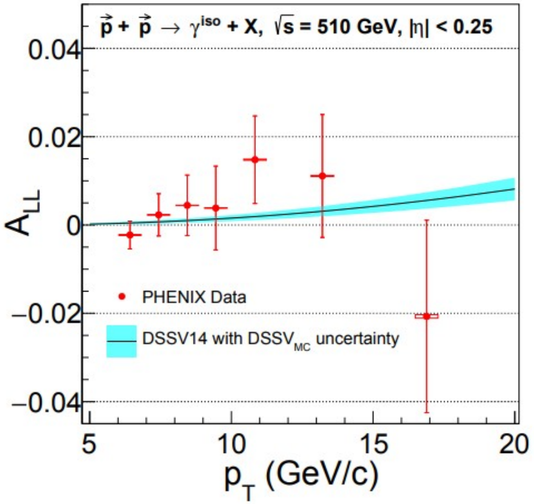
STAR, PRD 105 (2022) 9, 092011



STAR, PRD 105 (2022) 9, 092011



PHENIX, arXiv:2202.08158



Higher √s and more forward rapidity push sensitivity to lower x

- Down to ~0.004 with STAR Endcap (η < 1.8) dijets at 510 GeV (analysis being finalized)
- **Dijets** provide stricter constraints to underlying partonic kinematics - **better constraints on functional form of ΔG(x)**
- **Direct photon** sensitive to gq → γq LO process; **clean access to Δg(x)** (no hadronization)
- **Consistent results from both energies and both experiments**

RHIC concluded the data taking with longitudinally polarized protons in 2015

The data are anticipated to provide the most precise insights in Δg(x) well into the future

POLARIZED QUARK SEA

$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

$$A_\mathrm{L} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

LO for illustration

Separation of quark flavor

- $W^+(W^-)$: predominantly u(d) and $\bar{d}(\bar{u})$

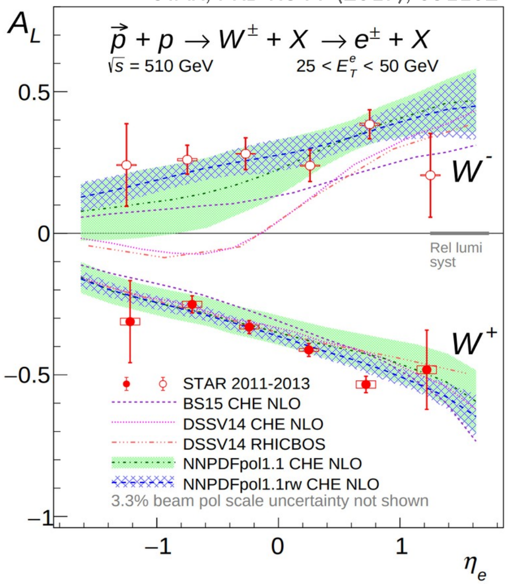
Maximal parity violation

- W couples to left-handed particles or right-handed antiparticles

The decay process is calculable

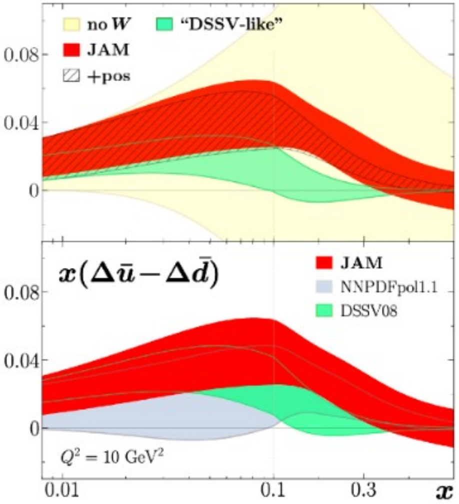
- Free from fragmentation function

STAR, PRD RC 99 (2019), 051102



Covered lepton η: 0.05 < x_1 < 0.25

JAM, arXiv:2202.03372



Full available data set analized from STAR (shown) and PHENIX (PHENIX, PRD 98 (2018), 032007)

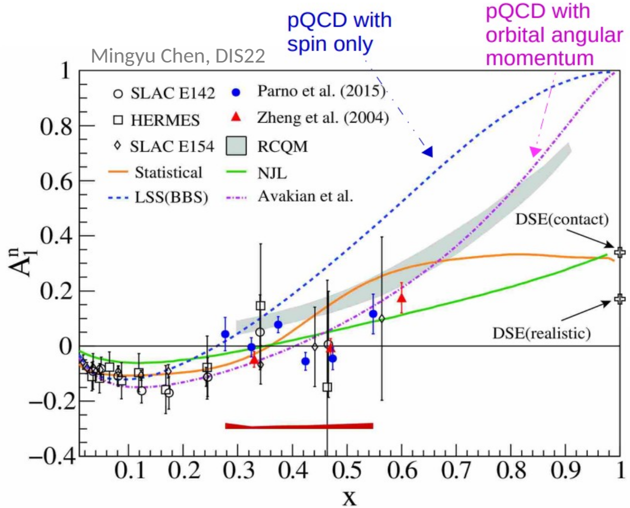
- **Significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$** → Opposite to the spin-averaged quark-sea distributions
- Evaluations from DSSV and NNPDF agree with data in sea and valence quark region

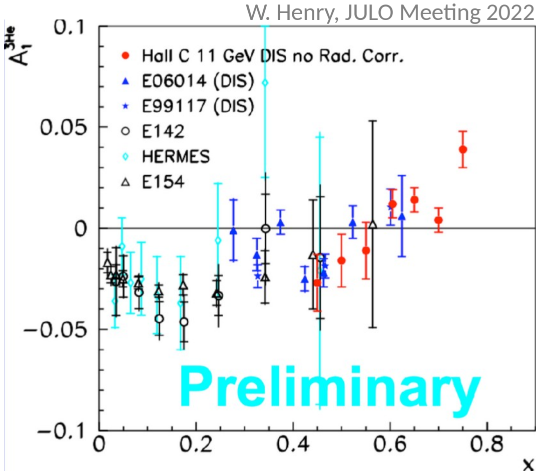
NEUTRON SPIN STRUCTURE AT HIGH-X

Observable: The Virtual photon-nucleon asymmetry $A_1 = (\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2})$

$A_1(x, Q^2) = \left[g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)\right]/F_1(x, Q^2) \approx g_1(x)/F_1(x)$ for large Q^2

Hall C A1n experiment with polarized ^{3}He target (E12-06-110)





- Without radiative corrections
- Statistical uncertainties only
- Nuclear corrections to be applied

$$A_1^n = \frac{F_2^{^3\mathrm{He}}\left[A_1^{^3\mathrm{He}} - 2\frac{F_2^p}{F_2^{^3\mathrm{He}}}P_p A_1^p\left(1 - \frac{0.014}{2P_p}\right)\right]}{P_n F_2^n\left(1 + \frac{0.056}{P_n}\right)}$$

- Explore the **Q^2 dependence of A1n** with large x value **0.61 < x < 0.77**
- After combining with proton data (CLAS12), extract **polarized to unpolarized parton distribution function** ratios **Δu/u** and **Δd/d** for large x region

GENERALIZED PARTON DISTRIBUTIONS

ACCESS TO GPDs

N / q	U	L	T
U	H		E_T
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	H_T $\tilde{H}_T$

4 chiral-even and 4 chiral-odd quark **GPDs at leading twist** for a spin-½ hadron

Connection to the **proton spin**:

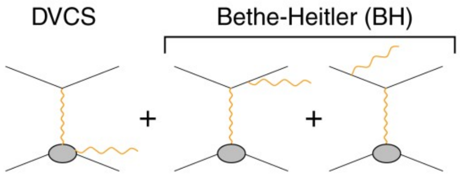
$$J_\mathrm{q} = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} \mathrm{d}x\, x\,[H^\mathrm{q}(x,\xi,t) + E^\mathrm{q}(x,\xi,t)] \qquad J_q = \frac{1}{2}\Delta\Sigma + L_q$$

Accessed via hard exclusive processes: cross section and asymmetries

- Deep virtual Compton scattering (**DVCS**) and hard exclusive meson production (**HEMP**)
- H, E accessed in vector meson production, $\widetilde{H}, \widetilde{E}$ in pseudoscalar meson production
- All 4 chiral-even GPDs accessed in DVCS

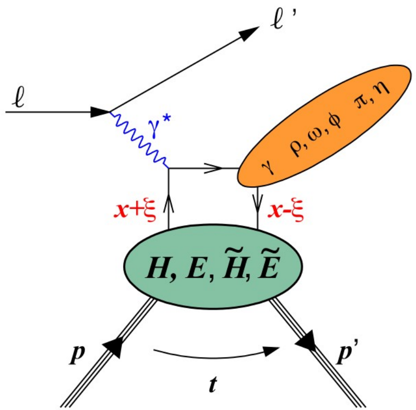
Interference between DVCS and Bethe-Heitler amplitude plays key role

- Allows to determine both magnitude and phase of the DVCS amplitude
- σ_{int} ~ electromagnetic form factor × Compton form factor



$$\sigma(ep \to ep\gamma) = |DVCS|^2 + |BH|^2 + Interference$$

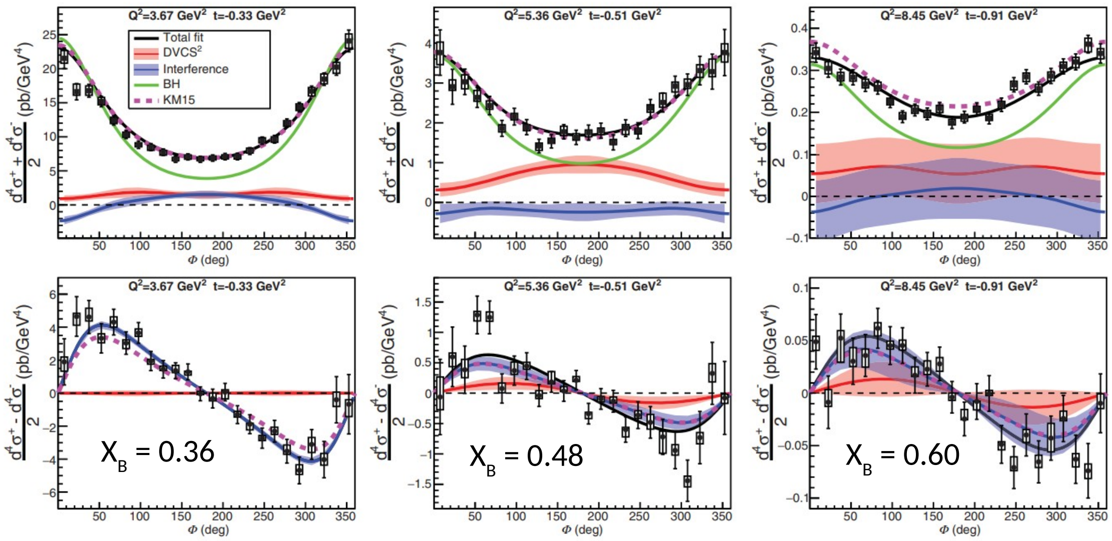
$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{1} dx\, H^q(x,\xi,t)\left(\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon}\right)$$

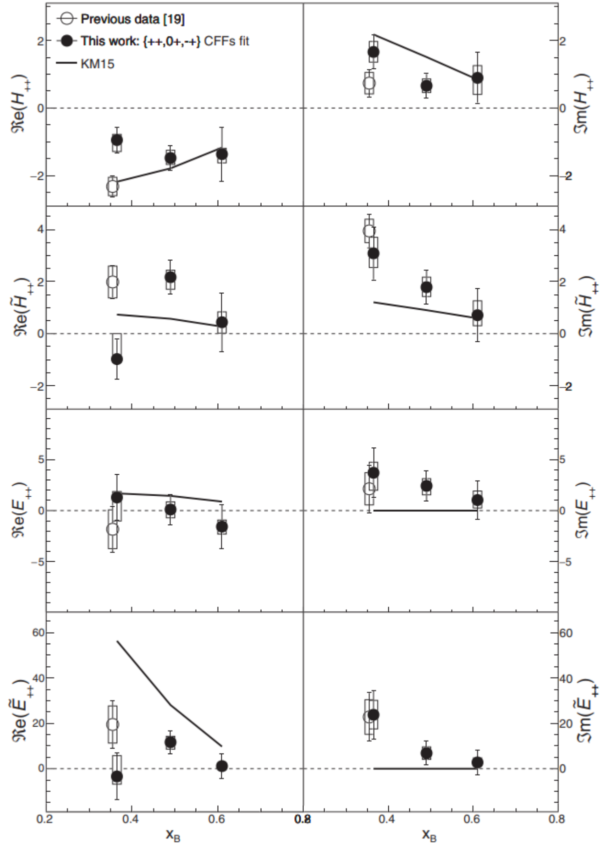


DVCS AT HALL A

→ See talk by S. Niccolai and M. Boer

F. Georges et al., Phys. Rev. Lett. 128, 252002 (2022)

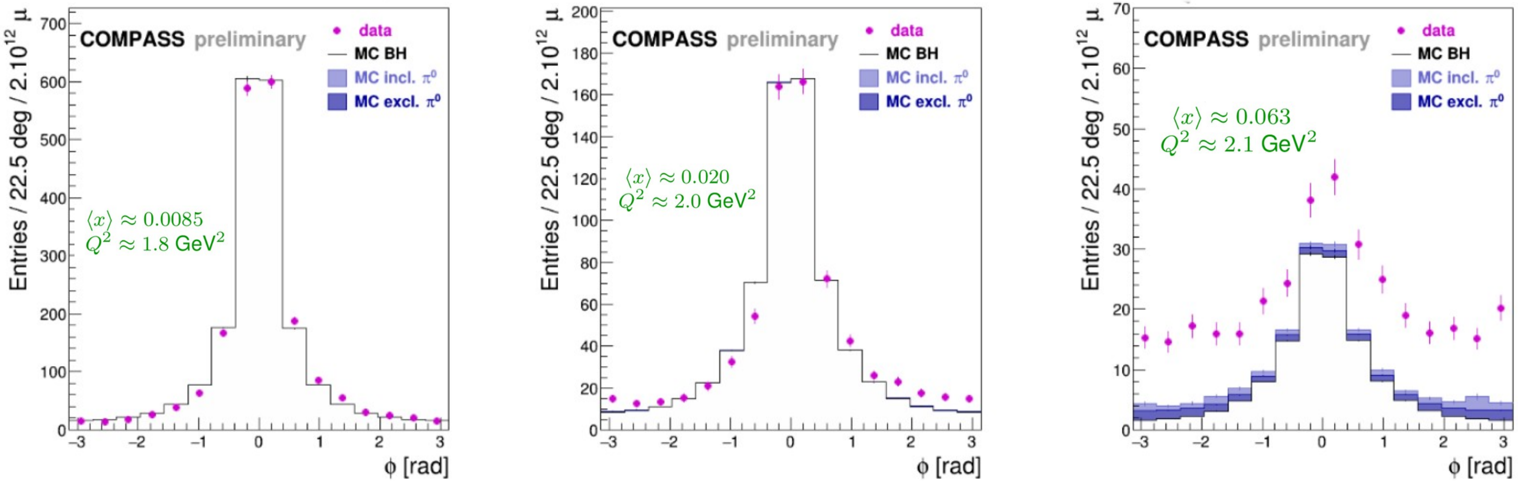




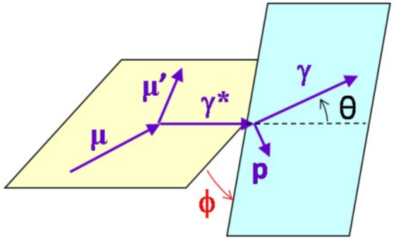
- Helicity independent and dependent cross-section at high values of the Bjorken x_B
- 2014 and 2016 data analyzed
- Extraction of 4 helicity-conserving CFF of the nucleon as a function of x_B
- See also the Preliminary DVCS Beam Spin Asymmetries from CLAS12 in S. Niccolai talk

DVCS AT COMPASS

→ See talk by B. Badelek



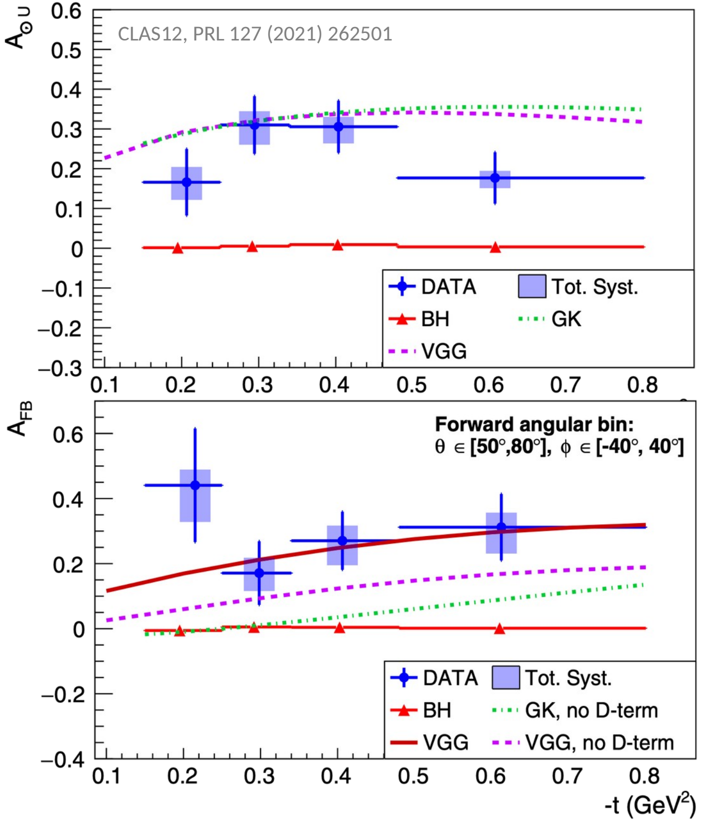
$$S_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(\mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + e_\mu P_\mu \mathrm{Im} I\right)$$



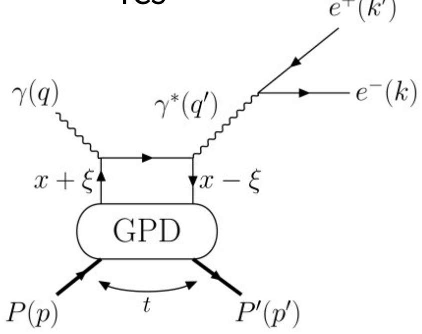
- Helicity dependent cross-section (unpolarized target)
- 2012 data (PLB 793 (2019) 188) + part of 2016 data
- Full 2016 dataset to be analized (~ x5 statistics)
- Determination of transverse extension of partons (from t-slope of cs)

$$\frac{\mathrm{d}\sigma^{\mathrm{DVCS}}}{\mathrm{d}t} \propto e^{-b|t|}$$

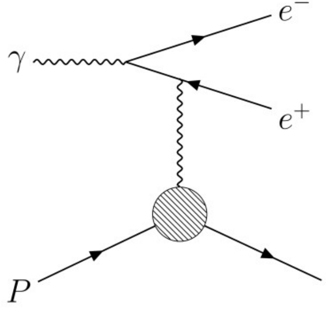
TIMELIKE COMPTON SCATTERING AT CLAS12



TCS



Bethe-Heitler



Timelike Compton Scattering: time reversal process of DVCS

Photon polarization asymmetry

- Sensitive to Im(CFF)
- Comparison to DVCS allows to test the universality of GPDs - especially the imaginary part of H

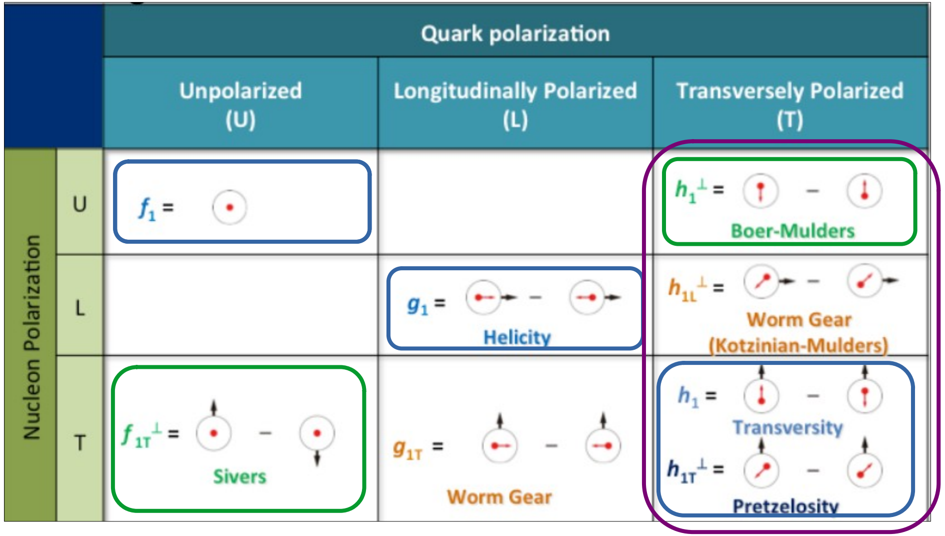
Forward-backward asymmetry

- Real part of the CFF and nucleon D-term
- Relates to mechanical properties of the nucleon (quark pressure distribution)

→ See talk by P. Chatagnon

TRANSVERSE MOMENTUM DEPENDENT PDFs

LEADING TWIST TMDs



TMDs surviving integration over k_T

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

Chiral odd TMDs

- **8 TMD** (PDFs) at leading-twist description (analog table for **fragmentation functions**)
- Off-diagonal part vanishes without parton's transverse motion

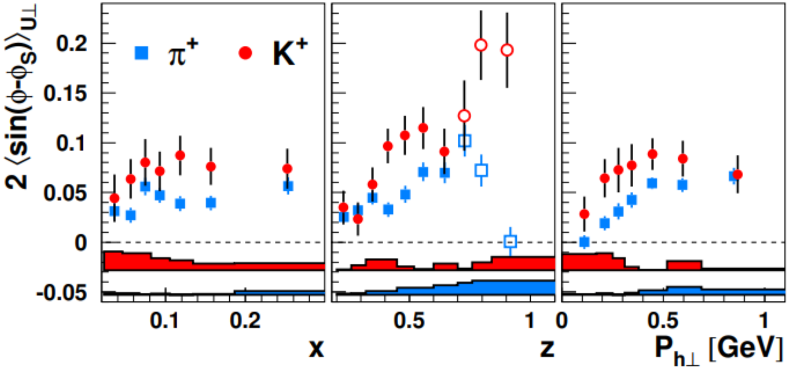
- **Sivers effect:** correlations between the nucleon transverse spin direction and parton transverse momentum in the polarized nucleon
- **Collins effect:** fragmentation of a transversely polarized parton into a final-state hadron
- **Boer-Mulders effect:** correlations between the parton transverse spin direction and parton transverse momentum in the polarized nucleon

TMD IN SIDIS MEASUREMENTS

Compendium of **HERMES** TMD results
HERMES, J. High Energ. Phys. 2020, 10 (2020)

- TMD results with transversely polarized H target
- Refined analysis with 3D binning (x, z, P_T)
- (Anti-)proton measurements

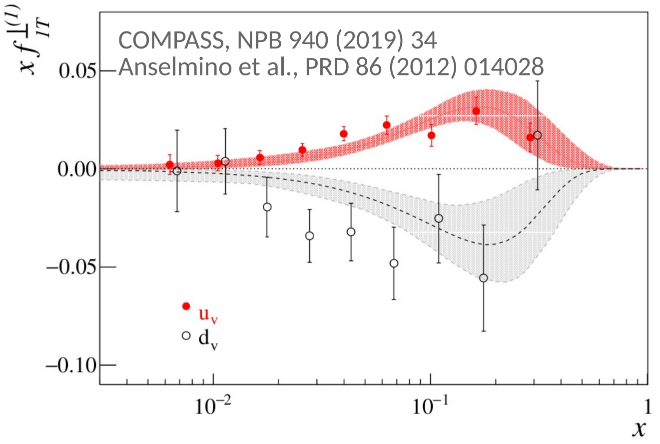
Sivers $\sin(\varphi - \varphi_S)$ asymmetry amplitudes



Kaon ($u\bar{s}$) amplitudes larger than pion ($u\bar{d}$)
- Unexpected if u-quark scattering dominates
- May point to a role of sea quarks

Sivers at **COMPASS**
COMPASS, PLB 744 (2015) 250
COMPASS, NPB 940 (2019) 34

- Sivers signal smaller at COMPASS (27.6 GeV) than at HERMES (160 GeV) – TMD evolution?
- P_T -weighted asymmetry amplitudes
  - Measurement of TMD k_T moments that avoids assumptions on shape of k_T

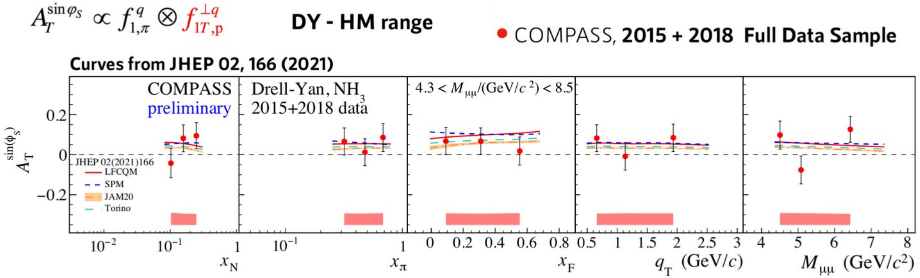


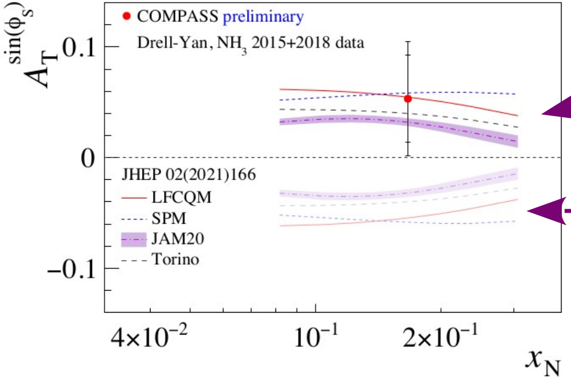
SIVERS FUNCTION SIGN CHANGE

Test of nonuniversality of Sivers function: $\text{Sivers}_{DIS} = -\,\text{Sivers}_{DY/W/Z}$ and TMD evolution effects

R. Longo, CPHI22

COMPASS Drell-Yan





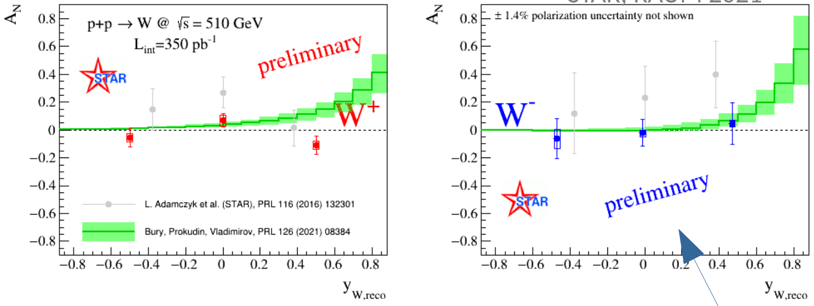
Sign change

No sign change

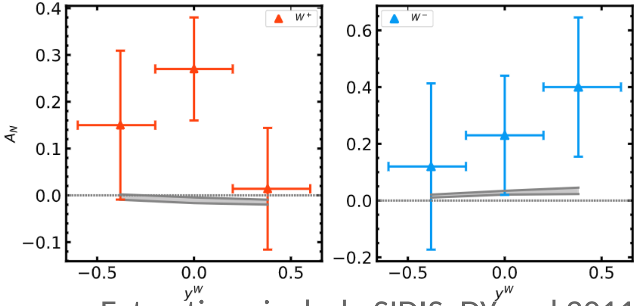
COMPASS data favors the sign-change of Sivers TMD

STAR W Production

STAR, RAUM 2021



Bacchetta et al., Phys. Lett. B 827 (2022) 136961



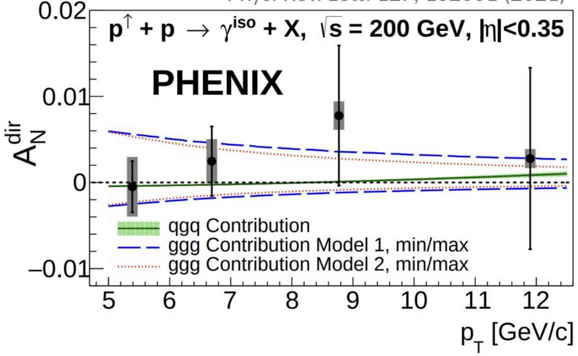
2 x more data to come from 2022

Extractions include SIDIS, DY and 2011 STAR data assuming sign-change

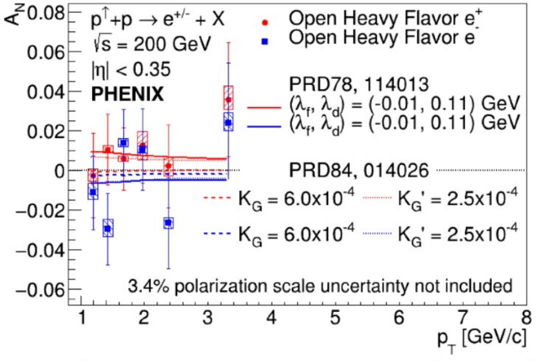
TWIST-3 CORRELATORS

Indirect constraint on the **Sivers function** via integral relationship with the **Twist-3 trigluon correlator**

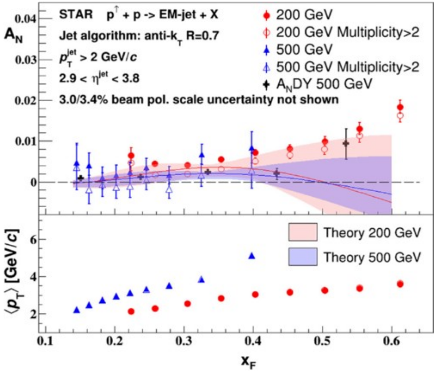
Phys. Rev. Lett. 127, 162001 (2021)



PHENIX, arXiv:2204.12899



STAR, PRD 103 (2021) 92009



Theory curves : L. Gamberg, Z. Kang, A. Prokudin, PRL 110 23, 232301 (2013)

- RHIC midrapidity measurements for direct photon and HF electrons sensitive to tri-gluon twist-3 → gluon Sivers TMD
- **sPHENIX** capabilities in mid-rapidity: direct photons and D^0 meson asymmetries
- **STAR enhanced capabilities with forward upgrade**: jet, π^0, charged hadrons, photons A_N:
  → constraint on the evolution and flavor dependence of the Twist-3 ETQS function

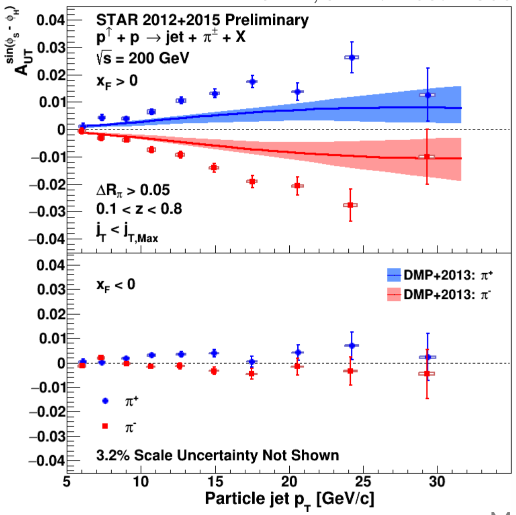
TRANSVERSITY

- Net density of quarks with spin aligned with the transversely polarized nucleon (leading twist)
- Two asymmetries A_{UT} provide sensitivity at RHIC

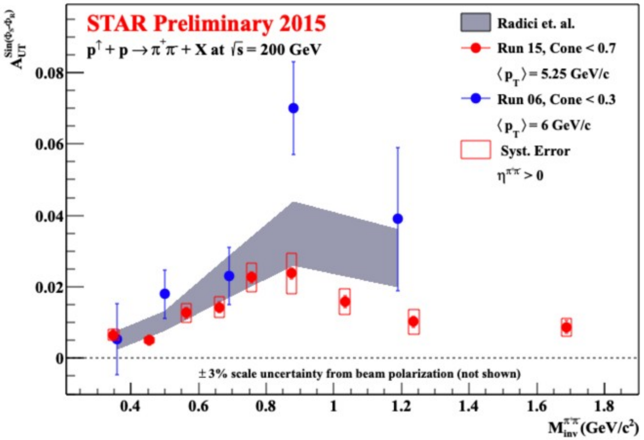
Spin-dependent modulation of hadrons in jets
Collins function (TMD FF)
Correlation of transverse spin of fragmenting quark and transverse momentum kick given to fragmentation hadron

Di-hadron correlation measurements
"interference FF" (collinear framework)
Correlation of transverse spin of fragmenting quark and momentum cross-product of di-hadron pair

STAR, arXiv:2205.11800



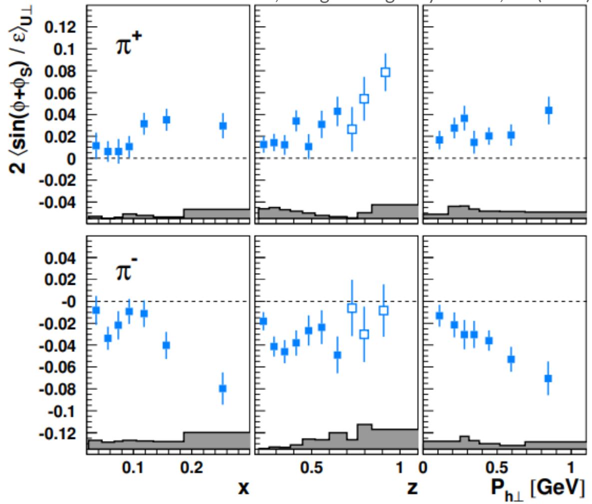
STAR, DIS2021 and PRL 115 (2015) 242501



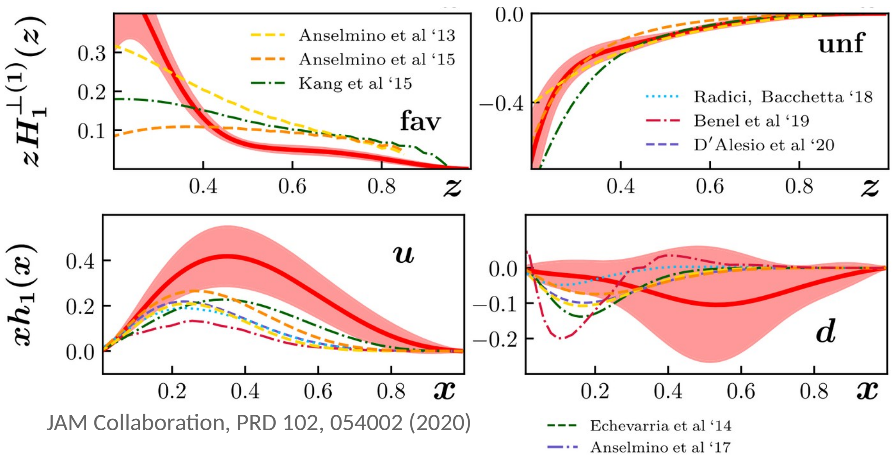
TRANSVERSITY

- Net density of quarks with spin aligned with the transversely polarized nucleon (leading twist)
- **HERMES & COMPASS** Collins asymmetries

HERMES, J. High Energ. Phys. 2020, 10 (2020)



Global extractions - Collins function and transversity



JAM Collaboration, PRD 102, 054002 (2020)

- u and d-quark transversity have ~equal magnitude and opposite size for favored and unfavored Collins FFs

- **d-quark transversity** less constrained given the u-quark dominance of many of the processes used in the global fits
- **COMPASS 2021 run on the deuteron** will double the experimental precision on the proton's tensor charge $g_T = \delta u - \delta d$
- **Further prior-to-EIC measurements** of Collins asymmetries: STAR with forward upgrade, sPHENIX, JLab12/SoLID, SpinQuest

BOER MULDERS

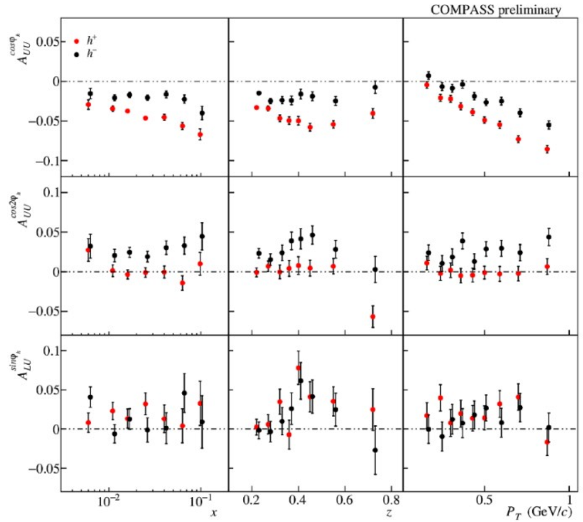
Unpolarized **SIDIS on proton** at **COMPASS**

- Transverse momentum distributions and azimuthal symmetries

$$F_{UU}^{\cos\varphi_h} = \frac{2M}{Q}\mathcal{C}\left[-\overbrace{\frac{(\hat{h}\cdot\vec{k}_T)}{M} f_1 D_1}^{\text{Cahn effect}} - \overbrace{\frac{(\hat{h}\cdot\vec{p}_\perp)k_T^2}{zM^2M_h} h_1^\perp H_1^\perp}^{\text{Boer-Mulders term}} + \cdots\right]$$

$$F_{UU}^{\cos 2\varphi_h} = \mathcal{C}\left[-\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_\perp) - \vec{k}_T\cdot\vec{p}_\perp}{zM\,M_h}\underbrace{\boxed{h_1^\perp} H_1^\perp}_{\text{Boer-Mulders term}}\right]$$

A. Moretti, CPHI22



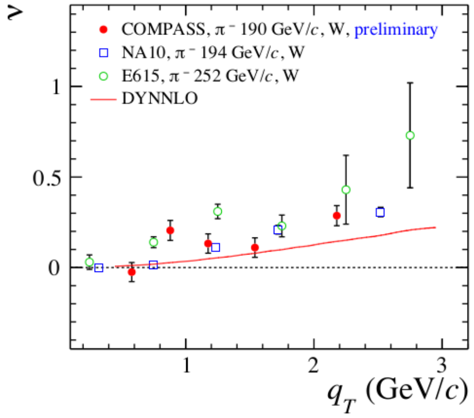
Rich kinematic dependences,difference between positive and negative hadrons

Unpolarized **DY** angular distribution at **COMPASS**

$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1 + \lambda\, cos^2\theta_{CS} + \mu\, sin2\theta_{CS}\, cos\phi_{CS} + \frac{\nu}{2} sin^2\theta_{CS}\, cos2\phi_{CS}\right]$$

R. Longo, CPHI22

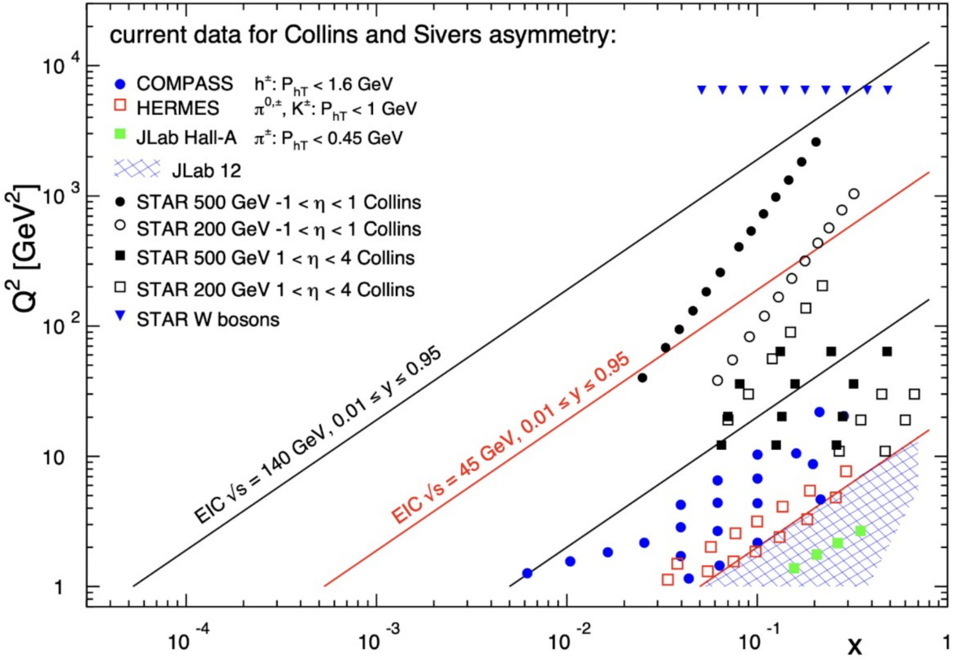
$$A_{UU}^{\cos 2\phi} = \frac{\nu}{2} \propto \boxed{h_1^{\perp q}(p)} \otimes h_1^{\perp \bar{q}}(\pi^-)$$



DYNNLO pQCD calculation not enough to well describe the ν -dependence

- Room for a non-zero **TMD Boer-Mulders effect**

OVERLAP WITH KINEMATIC REACH OF EIC



→ Study factorization breaking effects for TMD observables in hadronic collisions

→ Important input to study evolution of TMDs and essential kinematic overlap in x-Q^2 with future EIC

Fixed-target DIS, RHIC-spin, and EIC are truly complementary

SELECTED FUTURE OPPORTUNITIES

STAR Forward Upgrade:
- $p^\uparrow p^\uparrow$, $p^\uparrow$Au at 200 GeV 2024, $p^\uparrow p^\uparrow$ at 510 GeV 2022
- Forward jet capability and charge-sign discrimination
- **Fwd rapidities: TMD measurements at high x**
  - Sivers, Transversity at high x + Collins/IFF
- **Midrapidity:** improve statistics of Sivers via dijet & W/Z, Collins via hadrons in jets
- → See talk by J. Brandenburg

sPHENIX:
- $p^\uparrow p^\uparrow$, $p^\uparrow$Au at 200 GeV 2024
- Utilizing the **jet, heavy flavor** (MAPS-based vertex tracker) and **direct photon** strengths of the sPHENIX barrel to probe:
  - Sivers and Collins effect
  - Nuclear PDFs and FF in midrapidity

→ See talk by D. Perepelitsa, H. Gao

JLab 12 GeV:
- Precision data for valence quarks from CLAS12, HallA/C, SoLID, ...
- **Upgrade perspectives**: positron beam, higher luminosity and energy (JLab 20+ GeV)
  → See talk by M. Battaglieri, H. Avakian, S. Niccolai, M. Contalbrigo, M. Boer

COMPASS:
- transversely polarized ^{6}LiD target (2021 run)
  - d-quark transversity (and more)

  → See talk by B. Badelek

AMBER at the M2 beam line of CERN SPS
- Approved for phase 1 (Pion PDFs, proton radius and more)

→ See talk by A. Dzyuba

SpinQuest at Fermilab:
- Transversely polarized NH_3 /ND_3 target
- Polarized DY experiment with proton beam
  - Sivers & transversity TMDs of sea quarks

LHCspin at CERN
- Transversely polarized H_2 & D_2 targets with LHCb, 2025+

AFTER at LHC
- Fix target program at LHC, 2025+

SPD at JINR: polarized proton and deuteron beams, 2025+
→ See talk by I. Denisenko

EicC (China), PANDA, … 2025+

SUMMARY

- Experiments utilizing both lepton scattering processes and hadron-hadron interactions unravel **complex nucleon spin structure**
- The **3D structure of nucleon** in transverse-momentum and position space is studied using data from various types of **complimentary scattering experiments**
- The **Electron Ion Collider** precision in spin structure of nucleons from low to high x