XXX INTERNATIONAL WORKSHOP ON DEEP-INELASTIC SCATTERING AND RELATED SUBJECTS

Recent Experimental Results on Spin and 3D Structure

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MARCH 27 - 31, 2023

U.S. DEPARTMENT OF ENERGY
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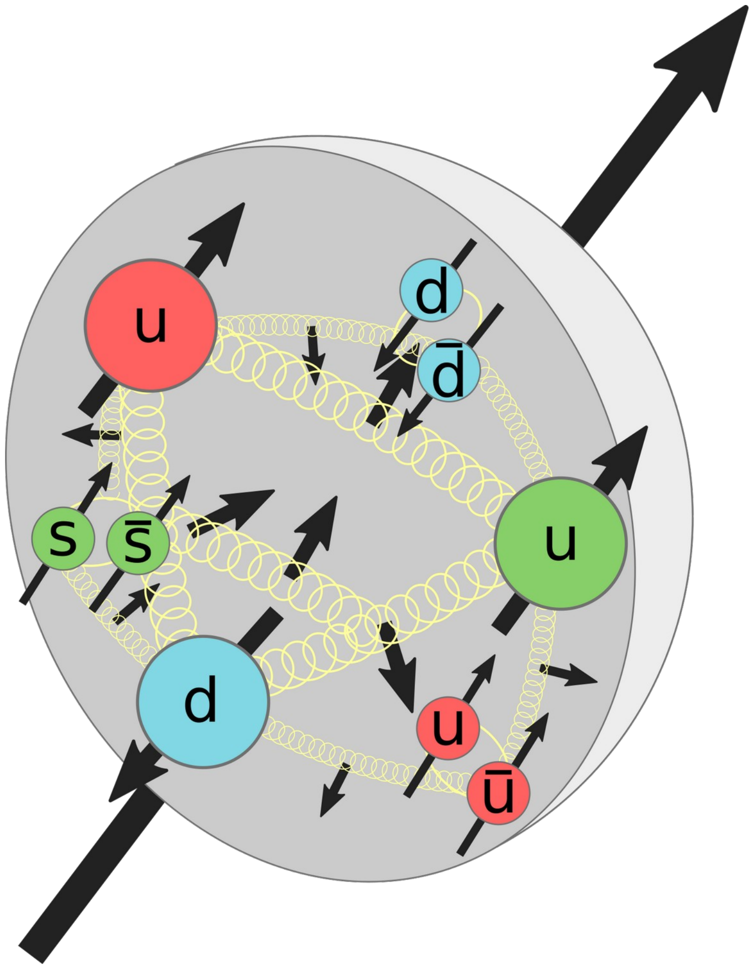
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PHYSICS QUESTIONS - OUTLOOK

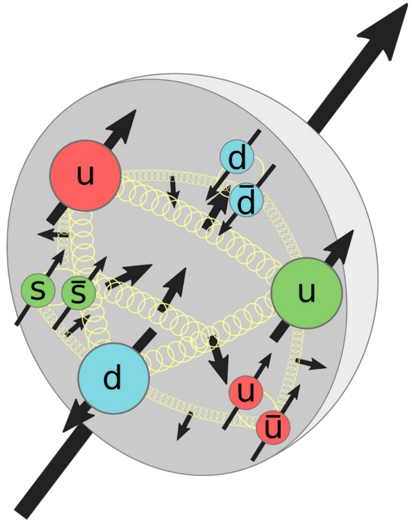
Questions

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. Large **Forward Transverse Single Spin Asymmetries**
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:

$$\Delta\Sigma/2 + L_q + J_g = \hbar/2$$

- $\Delta\Sigma/2$: Quark helicity
- L_q: Quark orbital angular momentum
- J_g: Gluon helicity and orbital angular momentum

Jaffe-Manohar sum rule:

$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

- $\Delta\Sigma/2$: Quark helicity
- ΔG: Gluon helicity
- ℓ_q: Quark canonical orbital angular momentum
- ℓ_g: Gluon canonical orbital angular momentum

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

Nucleon tomography

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

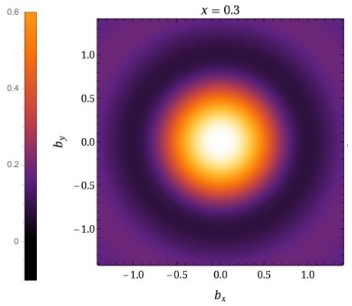
Transverse momentum dependent
parton distribution functions (TMDs) $f(x,k_T)$

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

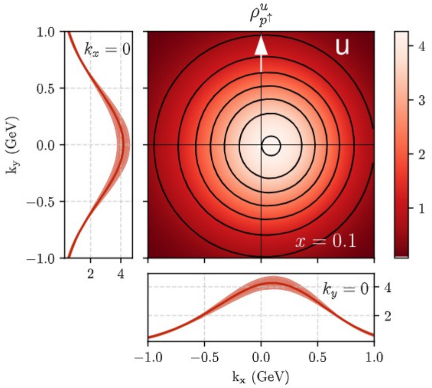
- Extrapolation to zero skewness $\xi \rightarrow 0$
- Fourier Transformation $t \leftrightarrow b_T$

Position space

Momentum space



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

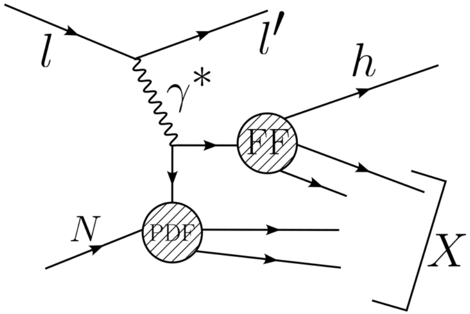


A. Bacchetta, F. Delcarro, C. Pisano, M. Radici,
PLB 827 (2022) 136961, from SIDIS and DY/W data

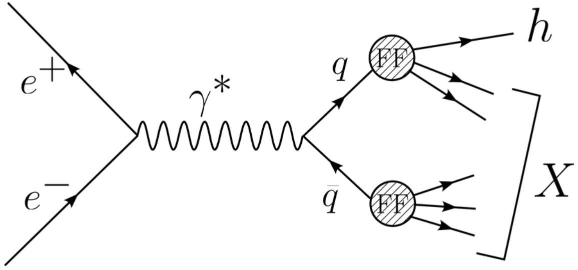
EXPERIMENTAL PROBES

How to access nucleon spin structure?

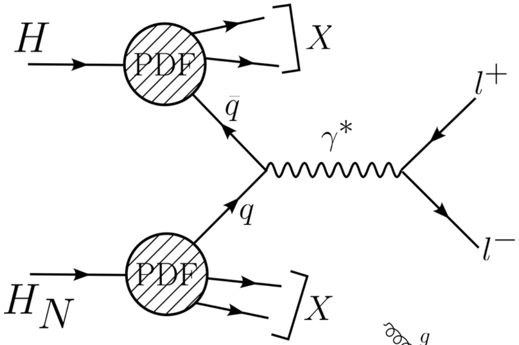
(Semi-Inclusive) Deep Inelastic Scattering

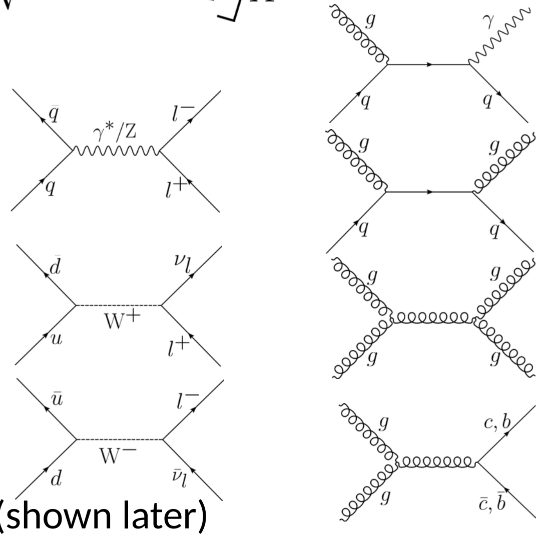


e+e- annihilation (access to FF)



Hadron-hadron interactions

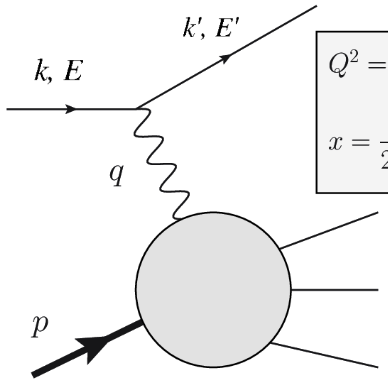




+ Hard exclusive processes for GPDs (shown later)

QUARK AND GLUON HELICITIES

LONGITUDINAL SPIN STRUCTURE



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

- 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)

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

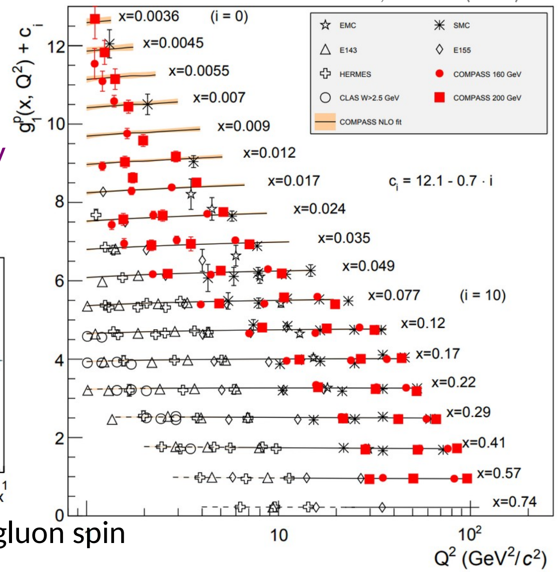
$$\nu = E - E'$$
$$y = \nu/E,\ \gamma^2 = Q^2/\nu^2$$

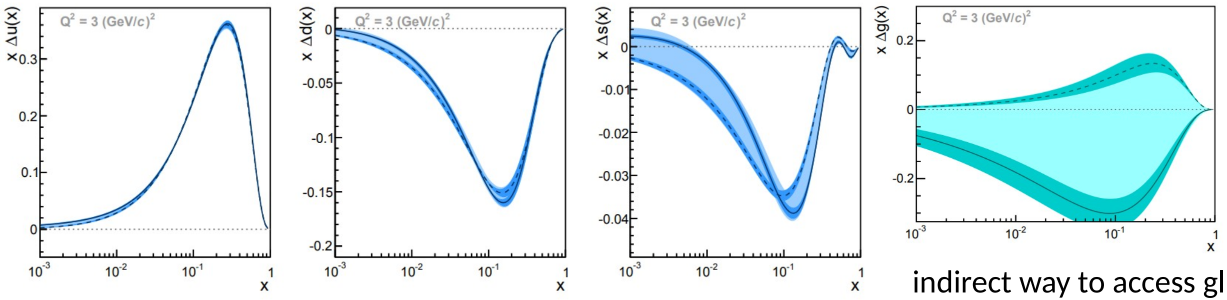
$$g_1(x) = \frac{1}{2}\sum_q e_q^2\ \Delta q(x)$$

In (LO QCD) Quark Parton Model

Quark helicity distribution

COMPASS, PLB 753 (2016) 18





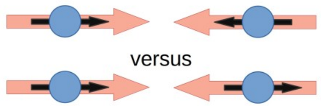
indirect way to access gluon spin

GLUON HELICITY

LO for illustration

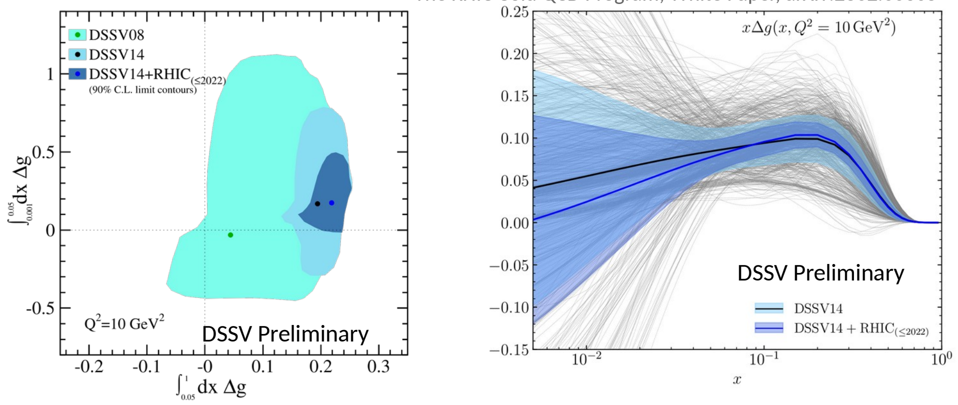
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a}_{LL} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

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



- 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
- Data included in global pQCD analysis provided evidence for **positive gluon polarization for x > 0.05 at Q^2 = 10 GeV^2**

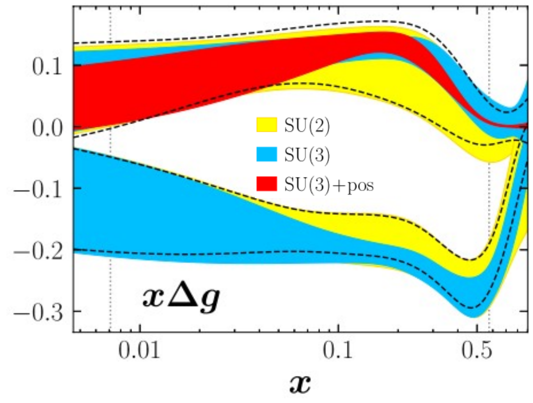
The RHIC Cold QCD Program, White Paper, arXiv:2302.00605



ΔG = 0.218(27), x > 0.05, Q^2 = 10 GeV^2 (68% C.L.)

DSSV14+RHIC≤2022: newest RHIC data included (STAR jets and dijets, PHENIX π)

JAM, PRD 105, 074022 (2022)



ΔG = 0.25(3), x > 0.05, Q^2 = 10 GeV^2 (SU(3) + pos)

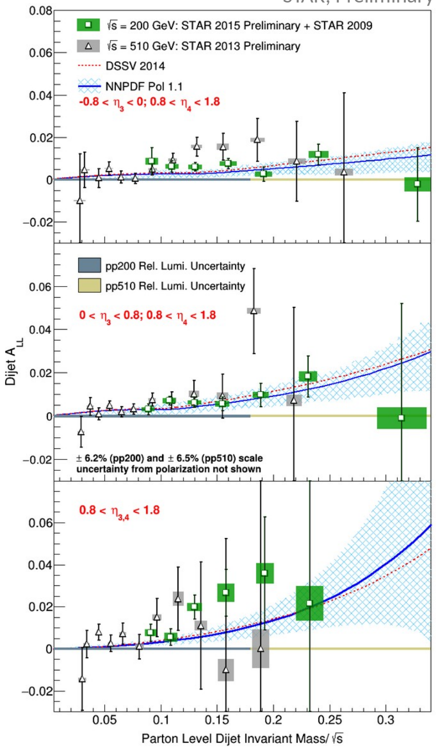
Inclusive jet data (also STAR 2015) from unpol. and pol. hadron collisions (+ DIS and DY) included

GLUON HELICITY

WG5 Session 3 (Wed): Zilong Chang, Bernd Surrow and Devon Loomis

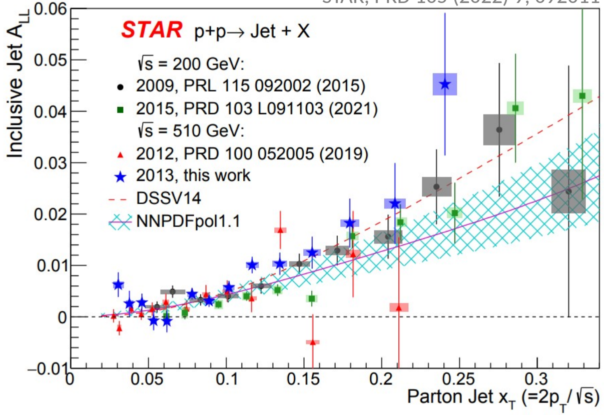
Di-jets

STAR, Preliminary



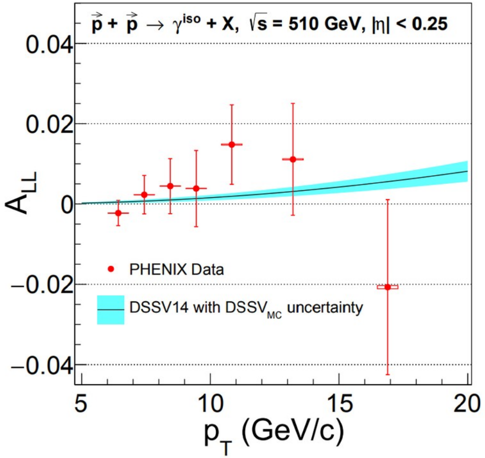
Inclusive Jets

STAR, PRD 105 (2022) 9, 092011



Direct Photon

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
- **Dijets** provide stricter constraints to underlying partonic kinematics
- **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

QUARK SEA HELICITY

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

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

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

LO for illustration

Separation of quark flavor

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

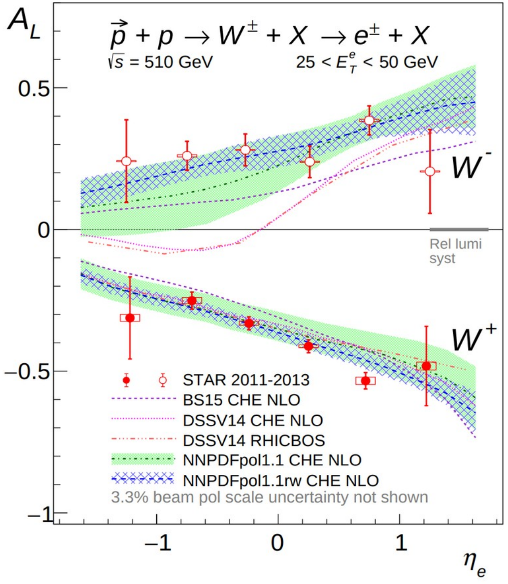
Maximal parity violation

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

The decay process is calculable

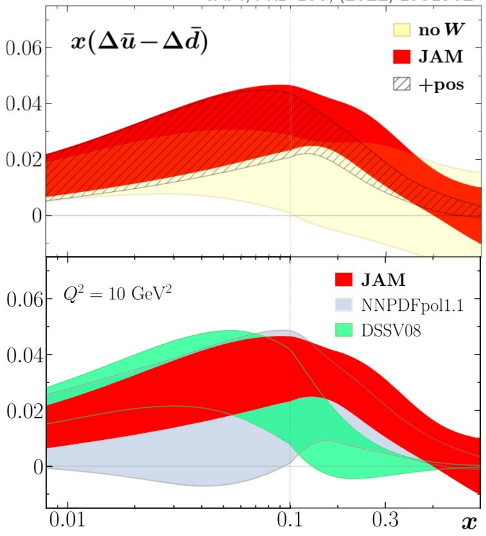
- Free from fragmentation function

STAR, PRD RC 99 (2019), 051102



Covered lepton η: $0.05 < x_1 < 0.25$

JAM, PRD 106, (2022) L031502



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

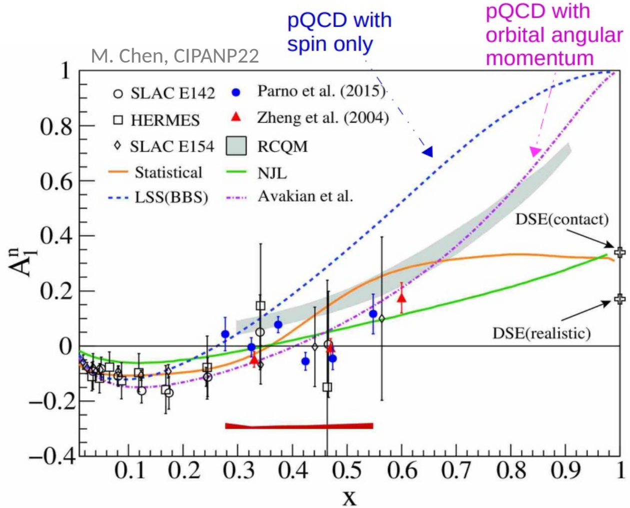
- **Significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$** → Opposite of the spin-averaged quark-sea distributions
- Evaluations from DSSV and NNPDF agree with data in sea and valence quark region

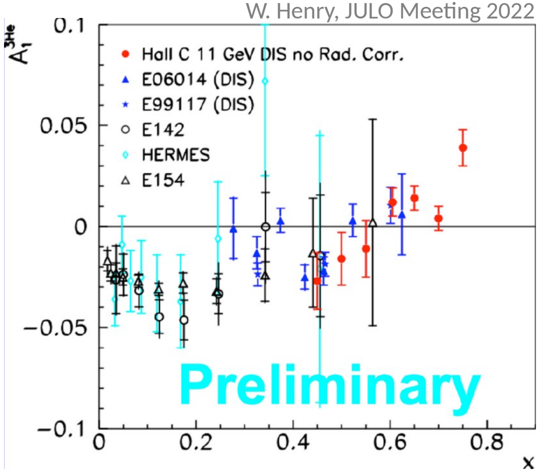
NEUTRON SPIN STRUCTURE AT HIGH-X

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

Observable: 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





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

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

- 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**:

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

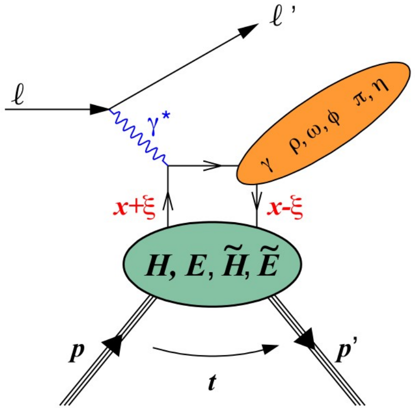
Accessed via hard exclusive processes: cross section and asymmetries

- 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

DVCS and access to GPDs

- Experimental access to GPDs via Compton Form Factors
- Different configurations: target and beam polarization, beam charge → different CFFs
- proton + neutron DVCS → flavor separation of GPDs

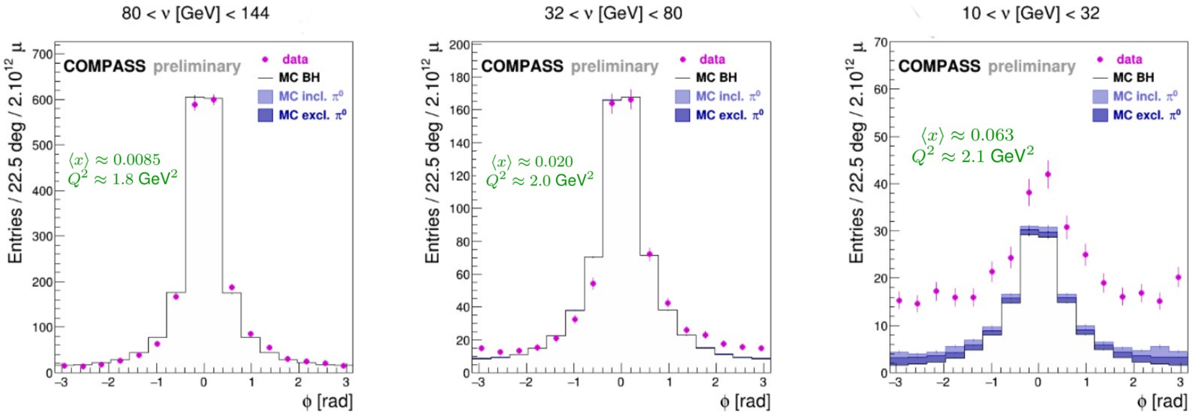
$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{1} dx\, H^q(x,\xi,t)\left(\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon}\right)$$



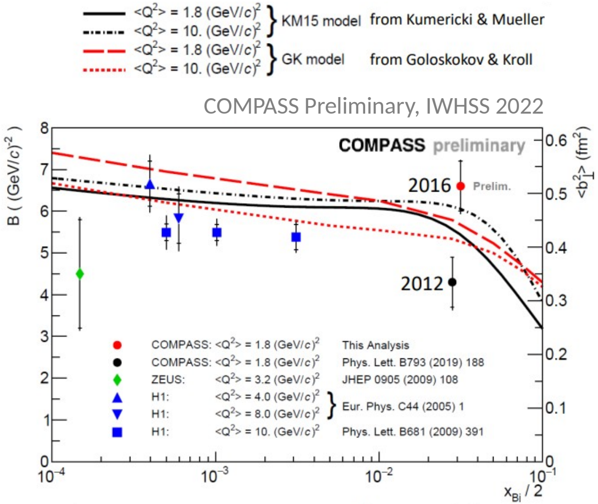
WG5 Session 2 (Tue): Marie Boer

DVCS AND TRANSVERSE IMAGING

COMPASS Preliminary, IWHSS 2022



COMPASS Preliminary, IWHSS 2022

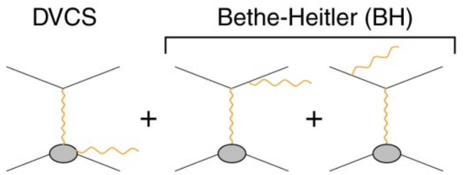


Interference between DVCS and Bethe-Heitler amplitude plays key role

- Allows to determine both magnitude and phase of the DVCS amplitude

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

Slope of DVCS dσ/dt - determination of **transverse extension of partons**



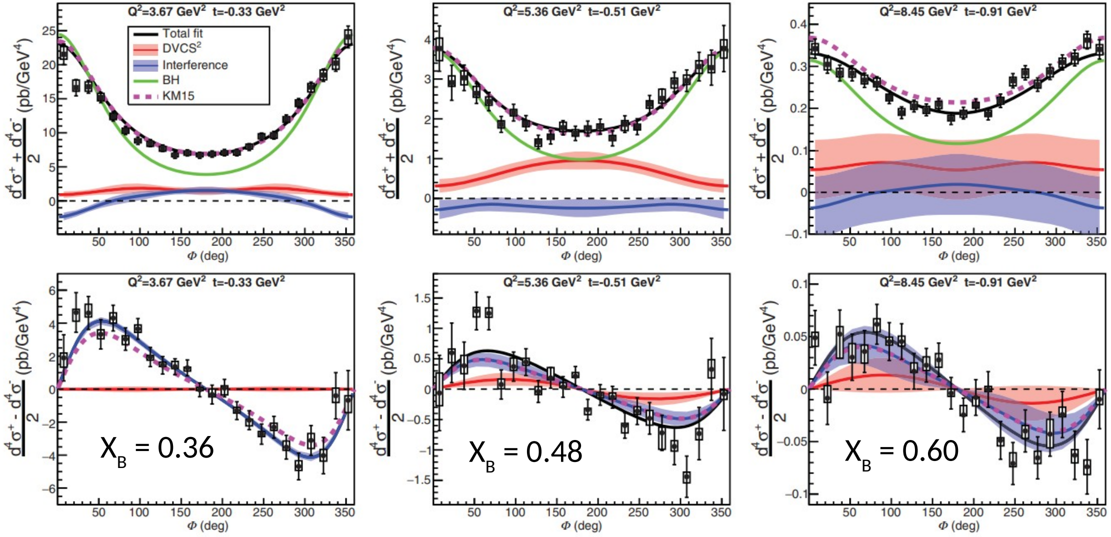
- Sum of the cross sections for μ^+ and μ^- (polarized beams + unpolarized target)
- 2012 data (PLB 793 (2019) 188) + part of 2016 data
- Full 2016 dataset to be analized (~ x5 statistics)

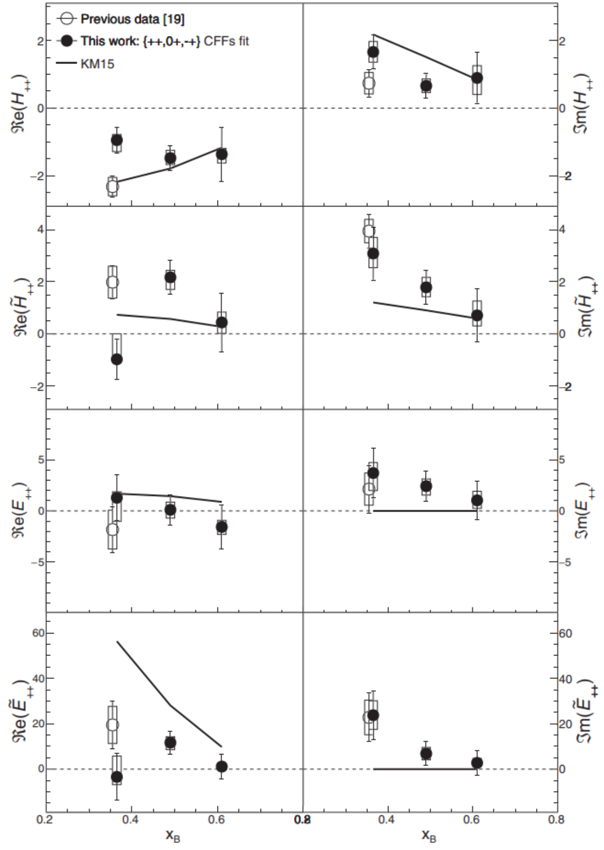
$$\frac{d\sigma^{DVCS}}{dt} \propto e^{-b|t|}$$

WG5 Session 1 (Tue): Anatolii Koval

DVCS AT HALL A

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

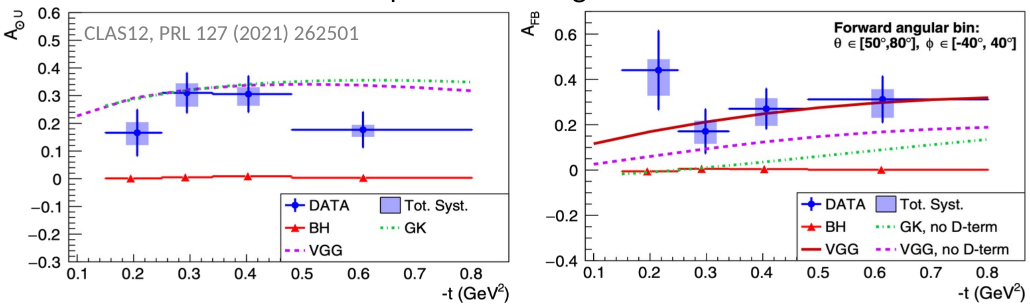




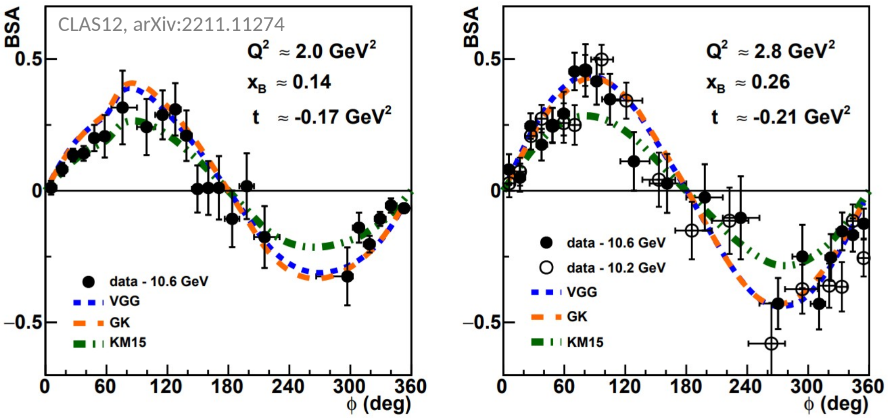
- Helicity independent and dependent cross-section at high values of the Bjorken x_B
- 2014 and 2016 data analyzed
- Extraction of 4 helicity-conserving CFF of the nucleon as a function of x_B

DVCS AND TCS AT CLAS12

Timelike Compton Scattering: time reversal to DVCS



Beam spin asymmetry for DVCS on the proton



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)

beam-spin asymmetries in the extended valence region

- Many kinematics never covered before
- In previously measured kinematics, the new data are shown to be in good agreement with existing data and improve the precision of GPD fits

- Sensitivity to Im $\mathcal{H}$, the imaginary part of the CFF corresponding to the GPD H

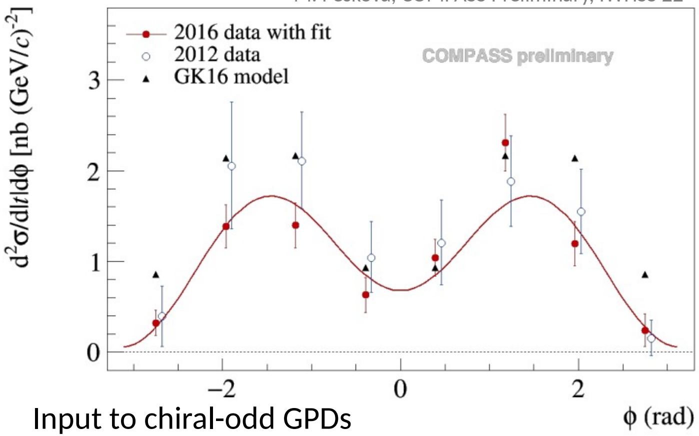
See also WG6 Session 5 (Thu): Igor Korover

HARD EXCLUSIVE MESON PRODUCTION

$$\frac{d^2\sigma_{\gamma^* p}^{\leftrightarrows}}{dt d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{\epsilon(1+\epsilon)}\cos\phi\frac{d\sigma_{LT}}{dt} \mp |P_l|\sqrt{\epsilon(1-\epsilon)}\sin\phi\frac{d\sigma'_{LT}}{dt}\right]$$

π^0 spin-averaged cross-section on unpolarized proton

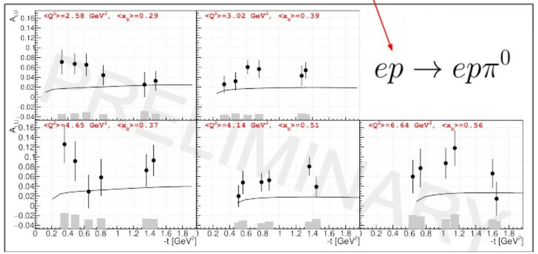
M. Peskova, COMPASS Preliminary, IWHSS 22

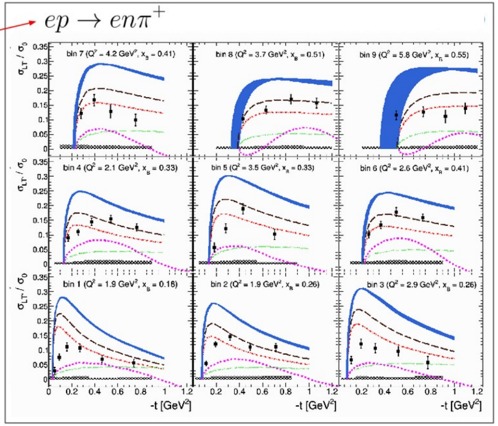


π^+/π^0 beam spin asymmetries

CLAS12, PLB 839, 137761 (2023)

$$\sigma_{LT'} = \xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m} \times \text{Im}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle + \langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle\right]$$





A. Kim, CLAS12 Preliminary, APCTP 22

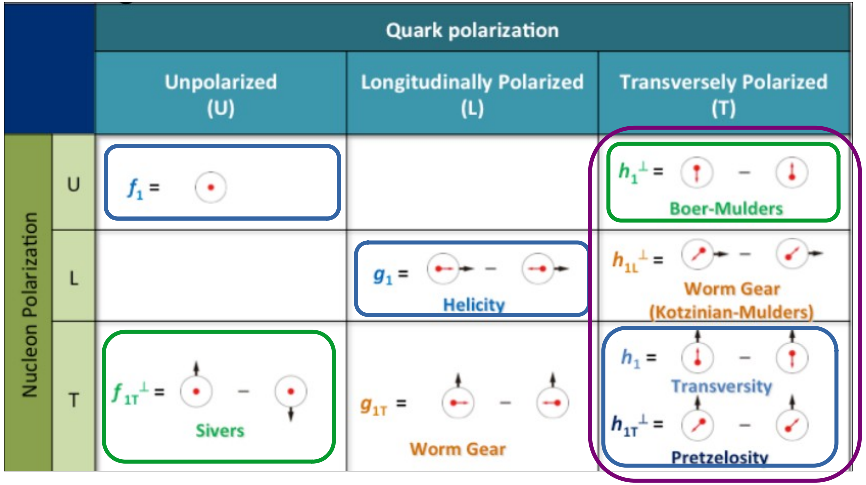
- Input to chiral-odd GPDs
- PLB 805 (2020) 135454 - Large σ_{TT} → impact of $\bar{E}_T$
- Statistics shown about 2.3 x larger than the published data
- WG5 Session 1 (Tue): Anatolii Koval

Spin density matrix elements in exclusive ω and ρ0 meson muoproduction arXiv:2210.16932, Eur. Phys. J. C 81, 126 (2021)

- Important input for modeling Generalized Parton Distributions
- Input for the model dependent evaluation of the role of parton helicity-flip GPDs in exclusive VM production
- WG5 Session 1 (Tue): Vincent Andrieux

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

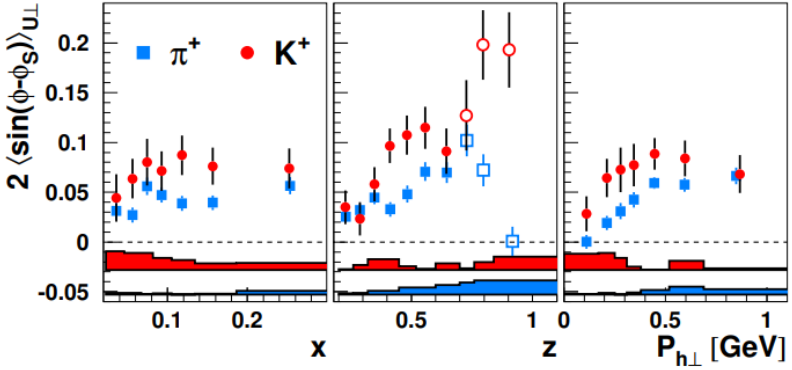
TMD IN SIDIS MEASUREMENTS

See also WG6 Session 4 (Thu): Caroline Riedl

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

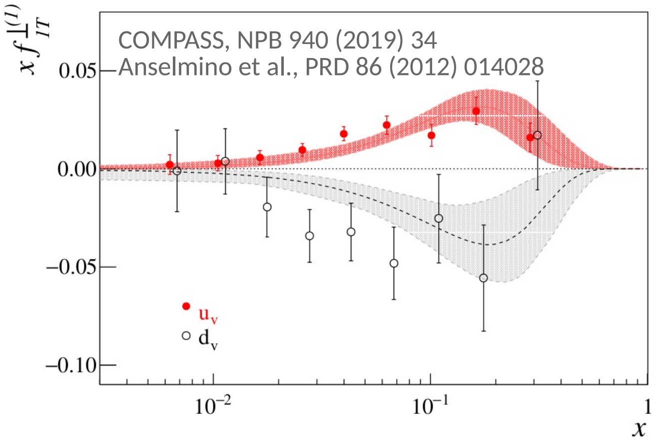


Kaon ($u\bar{s}$) amplitudes larger than pion ($u\bar{d}$)

- Unexpected if u-quark scattering dominates
- May point to 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

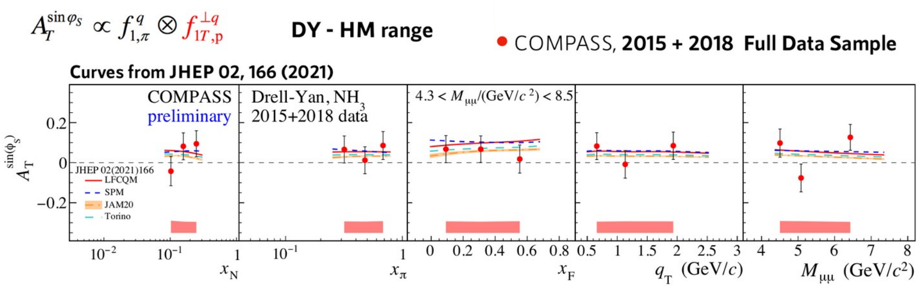


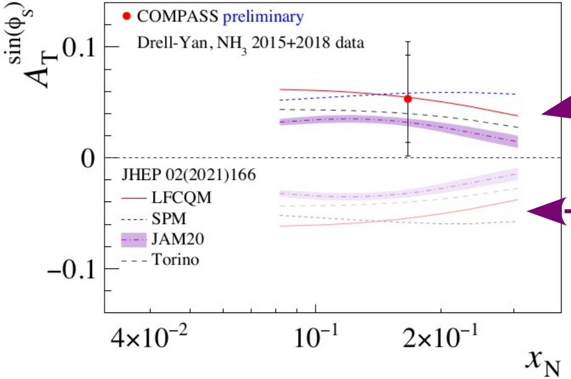
SIVERS FUNCTION SIGN CHANGE

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

COMPASS Drell-Yan

COMPASS Preliminary, CPHI22

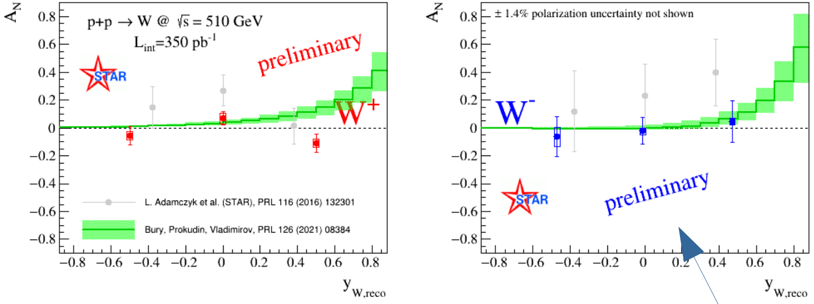




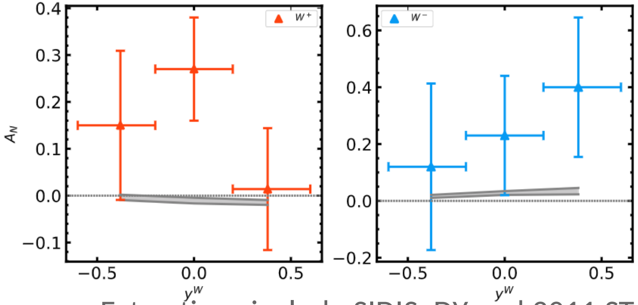
COMPASS data favor the sign change of Sivers TMD

STAR W Production

STAR Preliminary, RAUM 2021



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



2 x more data to come from 2022

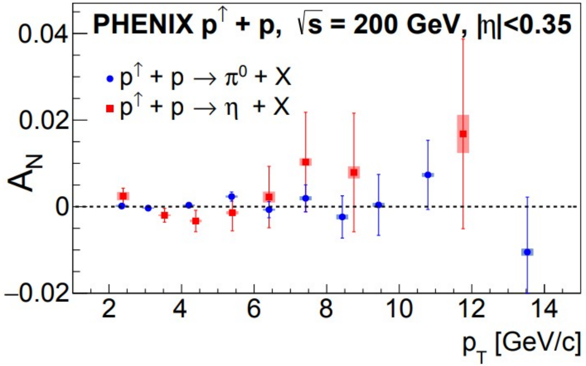
Extractions include SIDIS, DY and 2011 STAR data assuming sign change

TWIST-3 CORRELATORS

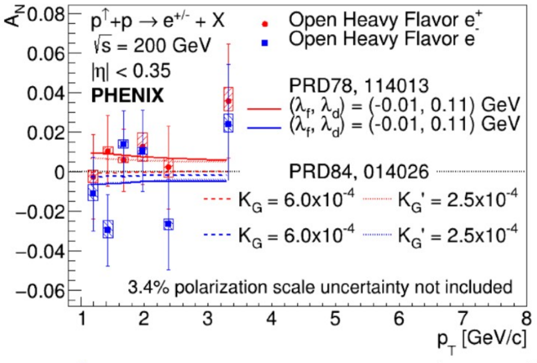
WG6 Session 4 (Thu): Dillon Scott Fitzgerald

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

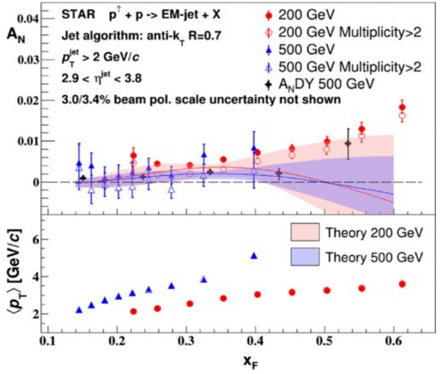
PHENIX, PRD 103, 052009 (2021)



PHENIX, arXiv:2204.12899



STAR, PRD 103 (2021) 92009



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

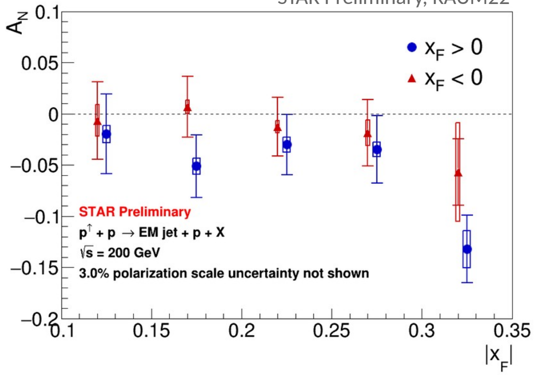
- RHIC midrapidity measurements for direct photon, pions, HF electrons and jets sensitive to tri-gluon twist-3 → gluon Sivers TMD
- **sPHENIX** capabilities in mid-rapidity: direct photons and D^0 meson asymmetries
- **STAR enhanced capabilities with forward upgrade**: jet, π^0, charged hadrons, photons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

FORWARD TRANSVERSE A_N

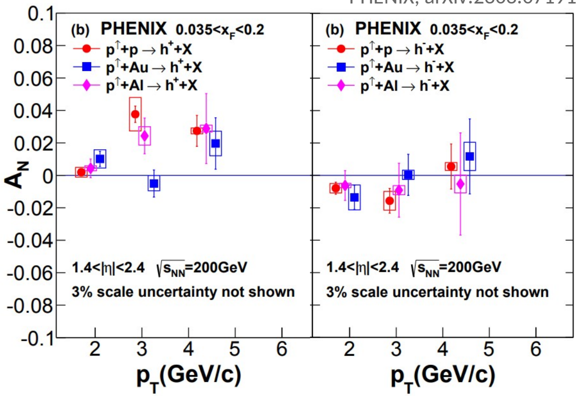
WG5 Session 2 (Tue): Xilin Liang, Jeongsu Bok and Minho Kim

Studying origin of large forward transverse single spin asymmetries and their nuclear dependence

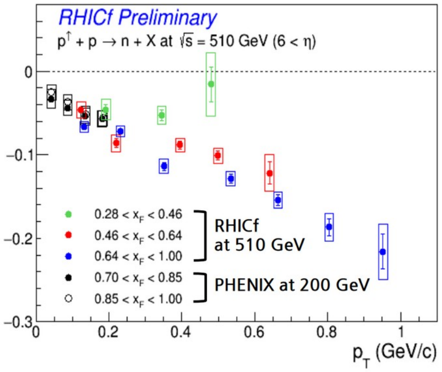
STAR Preliminary, RAUM22



PHENIX, arXiv:2303.07191



PHENIX, PRD105,032004(2022)
RHICf Preliminary, RAUM22



- Large A_N at forward region is observed in proton-proton collisions, e.g. $p^{\uparrow} + p \to \pi + X$
  - **Possible origin:** Sivers and Collins effects, Twist-3 correlators and FF, Diffractive Processes
  - STAR diffractive A_N negative - theoretical inputs are needed for interpretation

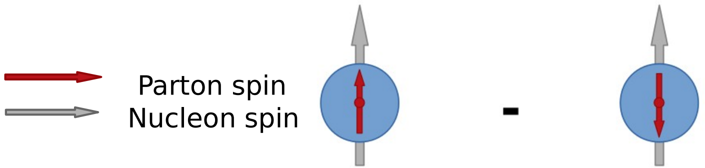
- **Nuclear dependence** for charged hadrons studied in PHENIX: In $x_F > 0$, h^- A_N: small to zero in pp and zero in pA. For h^+ noticeable A_N suppression in pA collisions. STAR π^0 A_N ($2.6 < \eta < 4.0$, $0.2 < xF < 0.7$, $1.5 < pT < 7$ GeV/c): No strong A dependence.

- **Neutron forward A_N from PHENIX and RHICf**: π and a_1 exchange model predicts that the A_N increases in magnitude with p_T without x_F dependence (B. Z .Kopeliovich et al., PRD 84,114012 (2011)).

WG5 Session 5 (Thu): Babu Pokhrel, Navagyan Ghimire

TRANSVERSITY

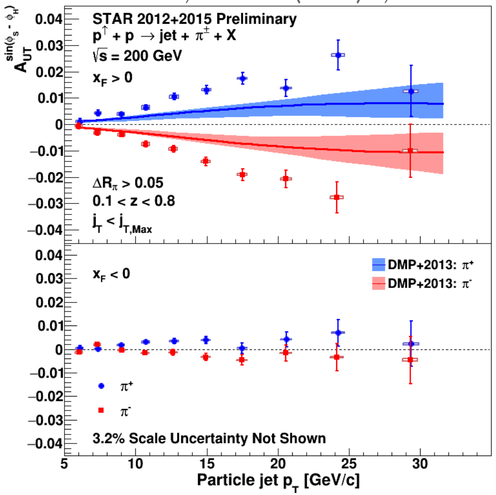
- Net density of quarks with spin aligned with the transversely polarized nucleon (leading twist)
- Two asymmetries A_{UT} provide sensitivity at RHIC



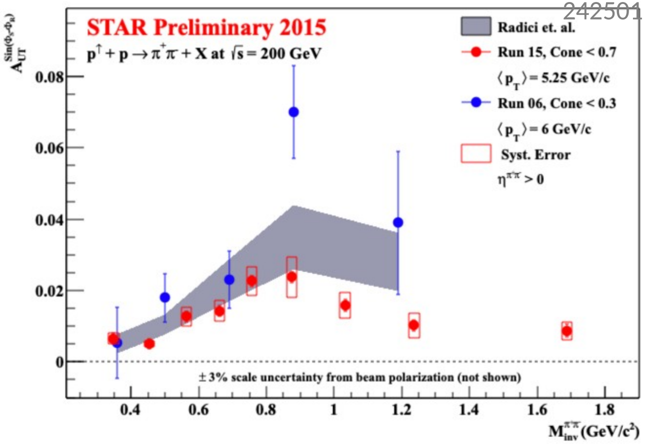
Spin-dependent modulation of hadrons in jets
Collins function (TMD FF)
Correlation of transverse spin of fragmenting quark and transverse momentum kick given to fragmentation hadron

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

STAR, PRD 106 (2022) 7, 072010



STAR Preliminary, DIS2021 and PRL 115 (2015) 242501



See also WG5 Session 5 (Thu):
Fragmentation Function Measurements at Belle, Katherine Parham
Transverse-Momentum-Dependent Fragmentation at LHCb, Sook Hyun Lee

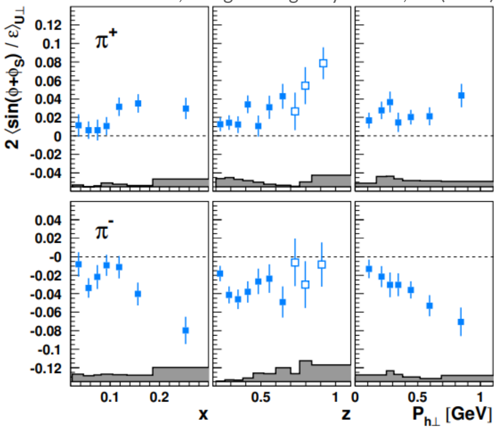
WG6 Session 4 (Thu): Caroline Riedl

TRANSVERSITY

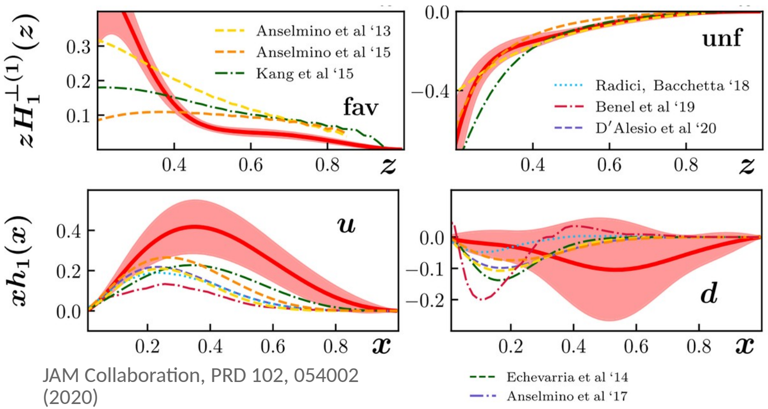
- Net density of quarks with spin aligned with the transversely polarized nucleon (leading twist)
- **HERMES & COMPASS** Collins asymmetries

- COMPASS, NPB 765 (2007) 31, PLB 736 (2014) 124, PLB 744 (2015) 250, PLB 717 (2012) 376
- F. Bradamante, IWHSS 2022

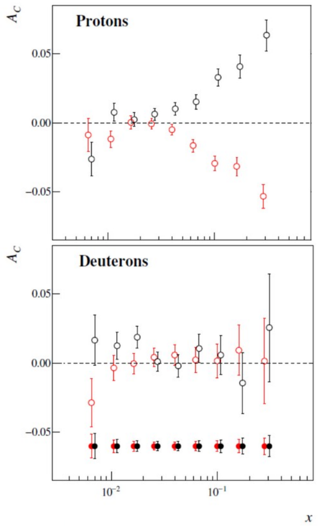
HERMES, J. High Energ. Phys. 2020, 10 (2020)



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 2022 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

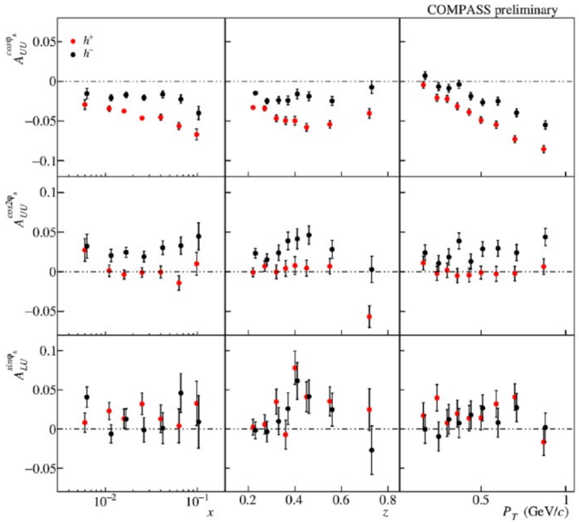
Cahn effect *Boer-Mulders term*

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

$$F_{UU}^{\cos 2\varphi_h} = \mathcal{C}\left[-\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_\perp) - \vec{k}_T\cdot\vec{p}_\perp}{zMM_h} h_1^\perp H_1^\perp\right]$$

Boer-Mulders term

A. Moretti, CPHI22



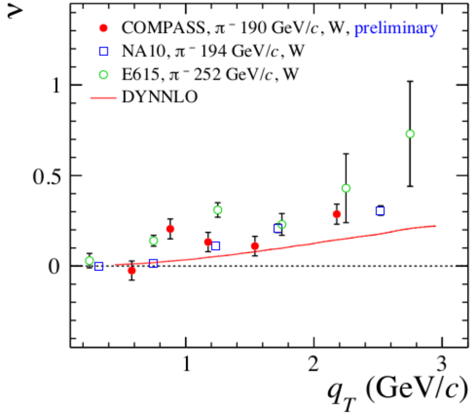
Rich kinematic dependences, difference between positive and negative hadrons

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

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

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

R. Longo, CPHI22

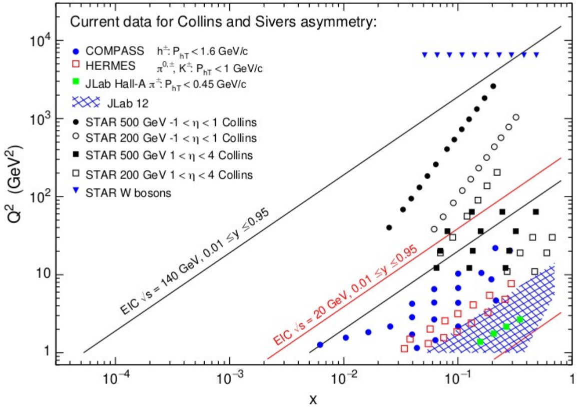


DYNNLO pQCD calculation not enough to well describe the ν -dependence

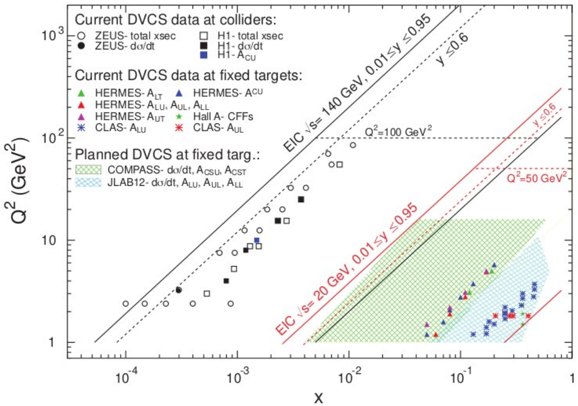
- Room for a non-zero **TMD Boer-Mulders effect**

OVERLAP WITH KINEMATIC REACH OF EIC

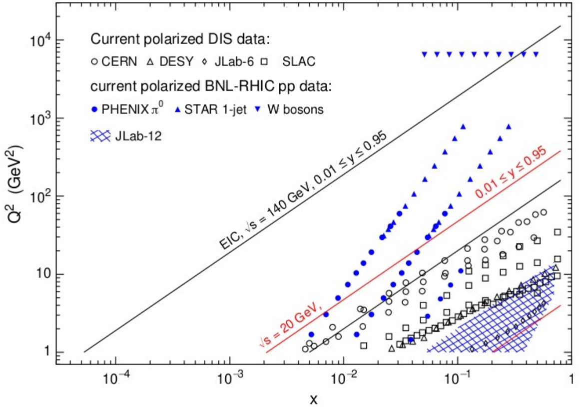
Collins and Sivers



DVCS



Polarized DIS (Proton Spin)



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

→ 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

→ Extensive kinematic reach of EIC opens new possibilities → precision era

Fri Plenary: The electron-ion collider -- A world wide unique collider to unravel the mysteries of visible matter, Elke-Caroline Aschenauer + WG6 session talks

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

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

COMPASS:
- transversely polarized ^{6}LiD target (2022 run)
  - d-quark transversity (and more)

JLab 12 GeV:
- Precision data for valence quarks from CLAS12, HallA/C, SoLID, …
- **Upgrade perspectives**: positron beam, higher luminosity and energy (JLab 20+ GeV)

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+

SPD at JINR: polarized proton and deuteron beams, 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 **complementary scattering experiments**
- The **Electron Ion Collider will bring precision** in spin structure of nucleons from low to high x
- Exciting times for the Spin and 3D Structure community

Thanks to all speakers and collaboration conveners for providing me with plots, suggestions and comments!