Recent highlights in Spin and 3D Nucleon Structure

Sanghwa Park

Center for Frontiers in Nuclear Science

XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects

Santiago de Compostela, 2-6 May 2022

Outline

Spin and 3D Nucleon Structure

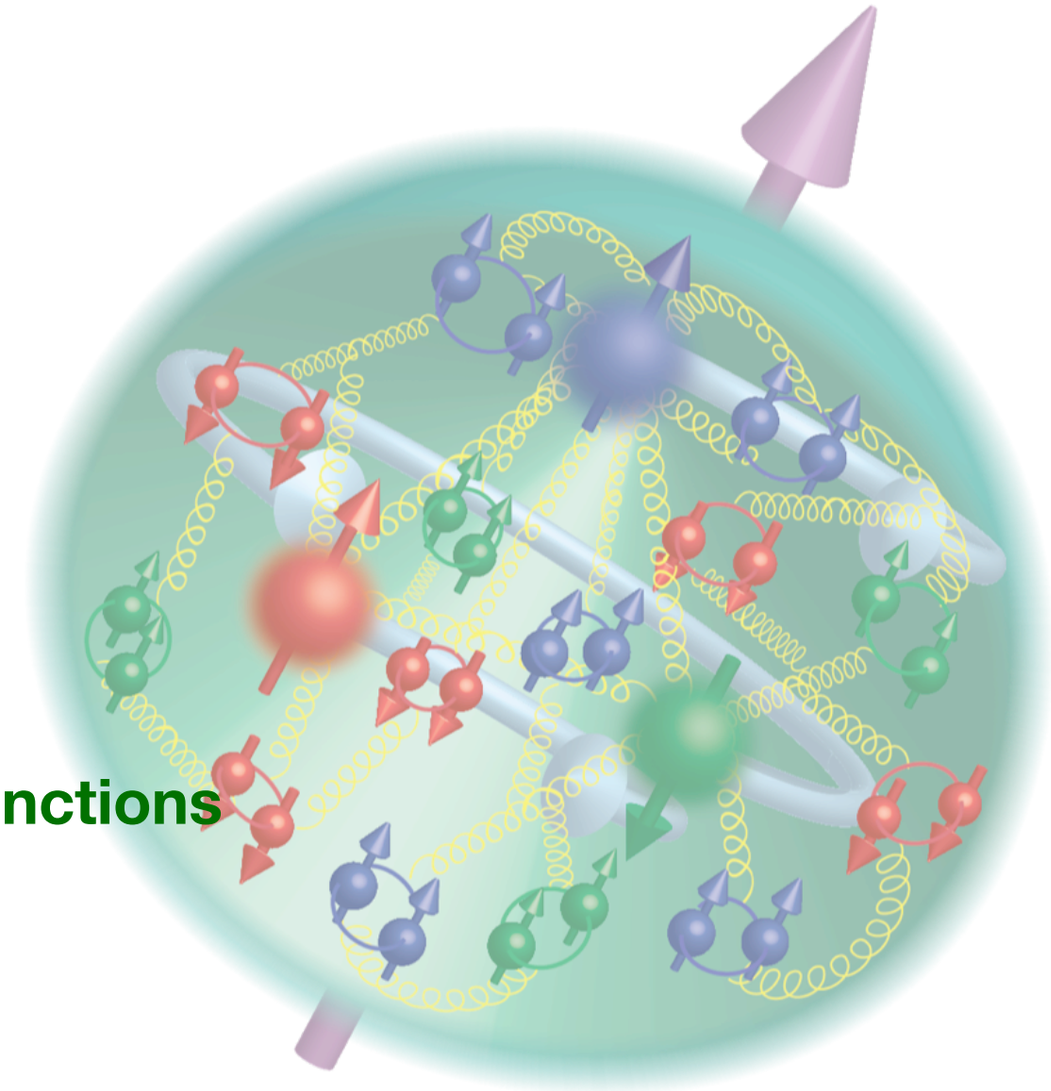
Helicity structure:

- **Polarized structure functions**
- **Structure function at large-x**
- **News from RHIC**

3D Imaging of the nucleon:

- **Generalized Parton Distributions**
  - **DVCS, TCS, HEMP**
- **Transverse Momentum Dependent Functions**
  - **Sivers and Collins asymmetries**
  - **Spin transfer of Lambda hyperons**
  - **Unpolarized TMDs**
  - **Twist-3 trigluon correlations**

Future prospect and Summary



- *Disclaimer: The selection is not complete and based on personal biases. Apologies for missing out many important results. For details, please refer to the parallel session talks!*

Spin and 3D Nucleon Structure

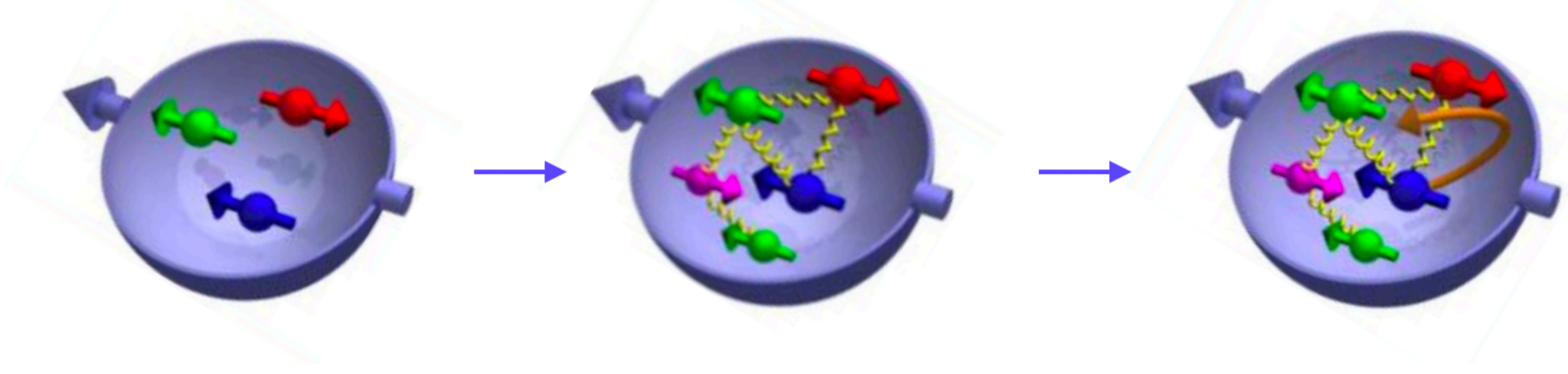
- **What's the origin of the proton spin?**
  How the constituents of the proton contribute and make up for the proton spin?

- **3D structure of the nucleon**
  How are quarks and gluons distributed in the polarized proton?

- **Spin as a tool for fundamental tests of QCD**
  Interplay between intrinsic properties and interactions of quarks and gluons

Origin of the Proton Spin

- **Proton spin can be studied via spin decomposition**



- **Sum Rules**

Ji sum rule

[Phys. Rev. Lett. 78, 610–613 (1997)]

$$\frac{\hbar}{2} = \frac{1}{2}\Delta\Sigma + L_q^{kin} + J_g$$

Frame-independent.
Jq and Jg can be obtained from the moments of GPDs.

Jaffe-Manohar sum rule

[Nucl. Phys. B 337, 509–546 (1990)]

$$\frac{\hbar}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q^{can} + L_g^{can}$$

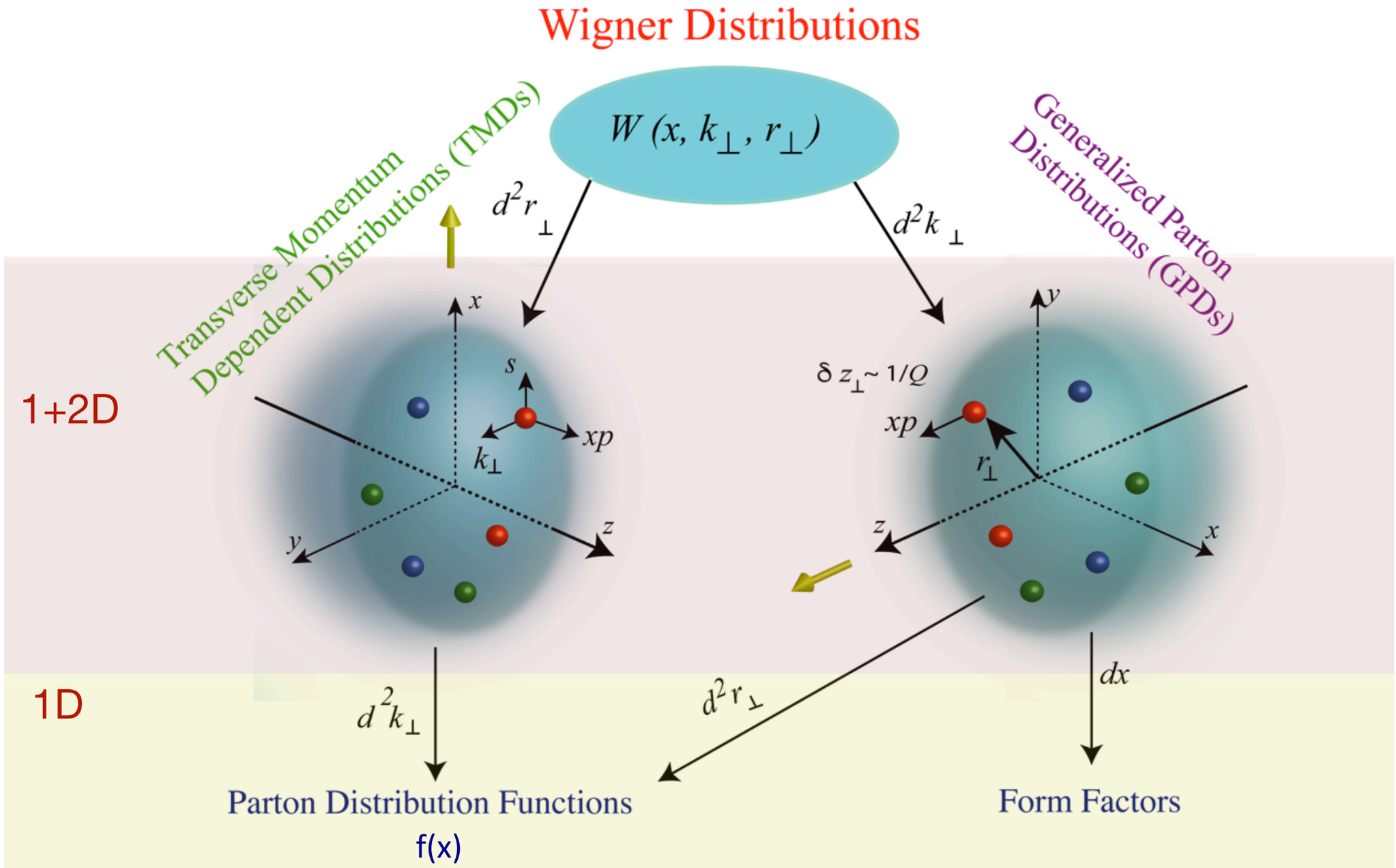
All terms have partonic interpretations;
Lq and Lg are twist-3 quantities, and can be extracted from twist-3 GPDs

- **Lattice QCD calculation of Jq and Jg** [C. Alexandrou, et al, Phys. Rev. D 101, 094513 (2020)]

1+2D Structure of the Nucleon

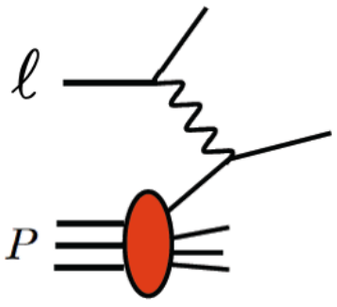
[Hatta, Xiao, Yuan, Phys. Rev. Lett. 116, (2016) 202301]
[Hagiwara, Hatta, et. al., Phys.Rev.D 96 (2017) 3, 03400]

2+3D

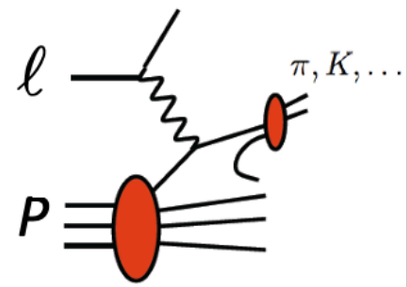


Helicity PDFs

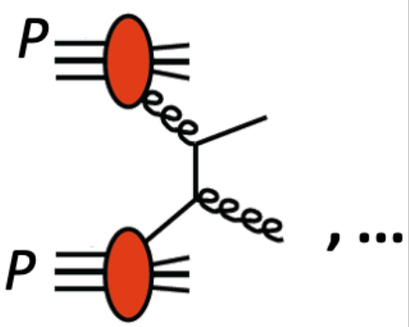
Decades of nucleon structure…



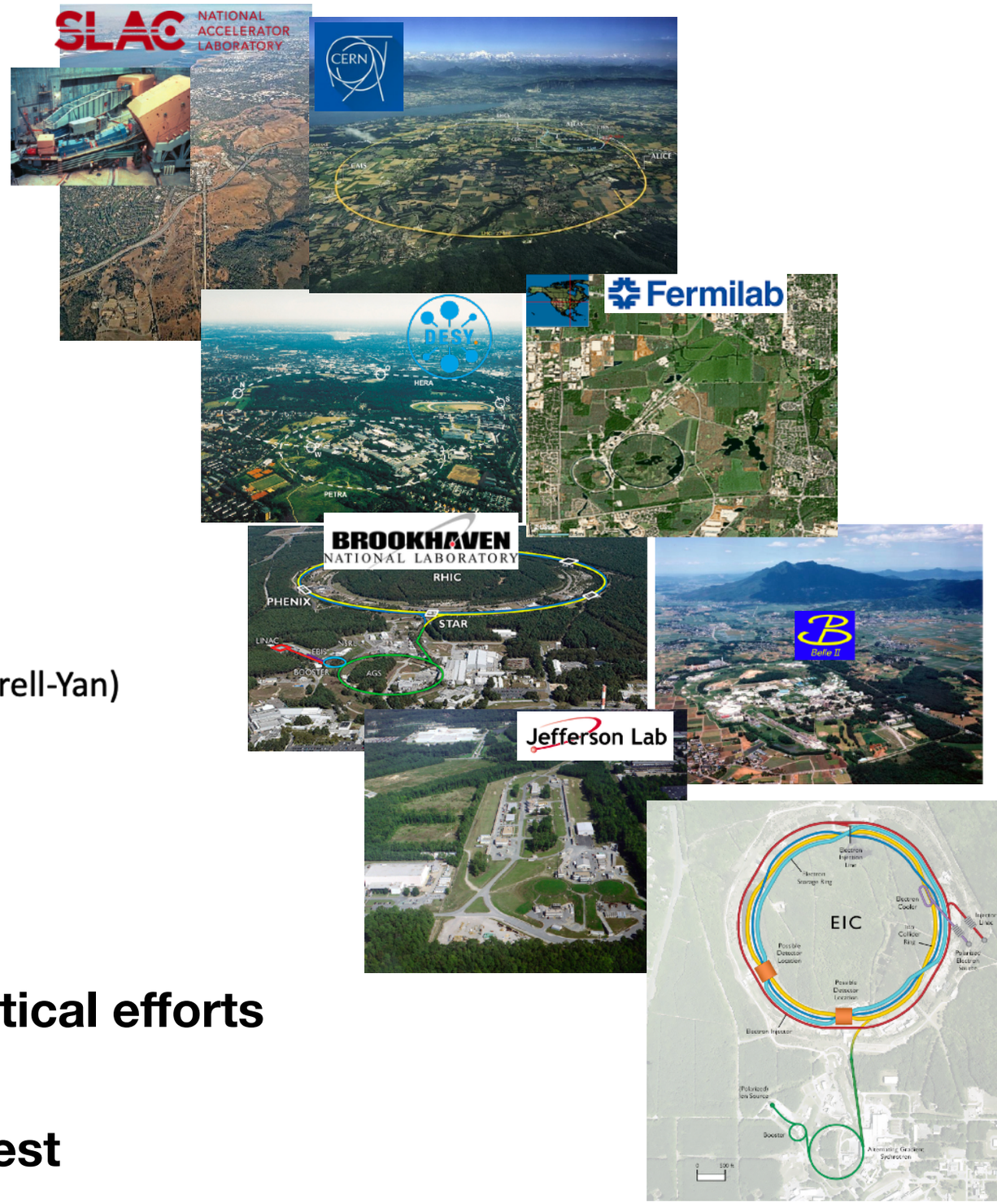
Inclusive spin-dependent DIS:
CERN, SLAC, DESY, Jlab
$\Delta q + \Delta \bar{q}$, Δg



Semi-inclusive DIS:
SMC, COMPASS, HERMES, Jlab
$\Delta q + \Delta \bar{q}$, Δg



Polarized pp:
RHIC: PHENIX & STAR, FNAL (pol Drell-Yan)
$\Delta q + \Delta \bar{q}$, Δg (RHIC)

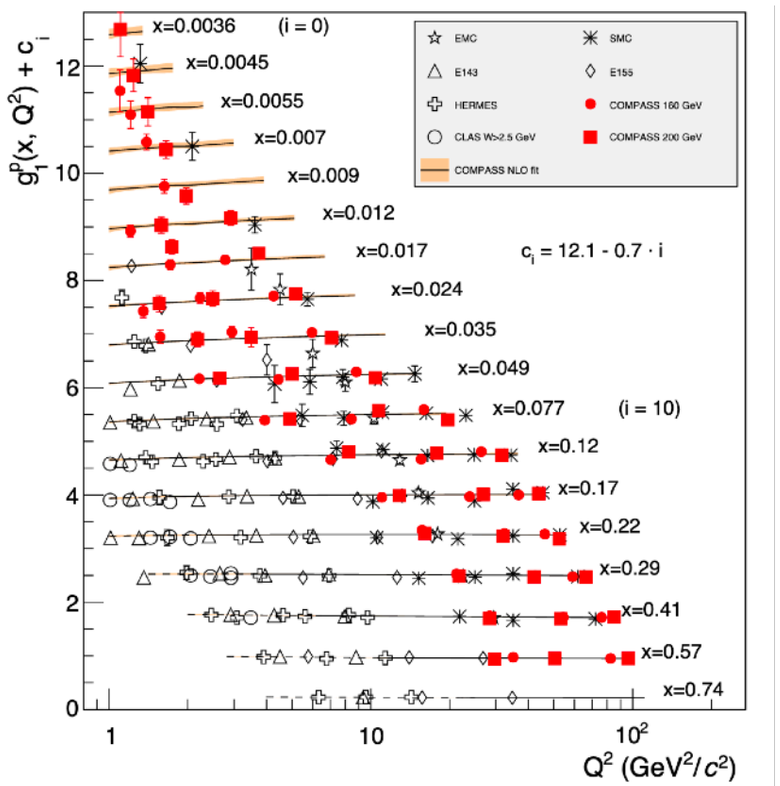


- **Decades of experimental and theoretical efforts**
- **Complementary datasets**
- **QCD factorization and Universality test**

Deep Inelastic Scattering

- DIS experiments have been successful mapping out the momentum distributions of quarks and gluons
- Polarized Structure Functions: $g_1(x, Q^2)$, $g_2(x, Q^2)$ arXiv:2007.08300

  In Quark parton model, $g_1(x,Q^2) \sim \sum_q e_q^2 \Delta q(x,Q^2)$ quark spin distribution
- Limited (x,Q^2) level arm compared to the unpolarized case
  - EIC will improve it significantly



Deep Inelastic Scattering

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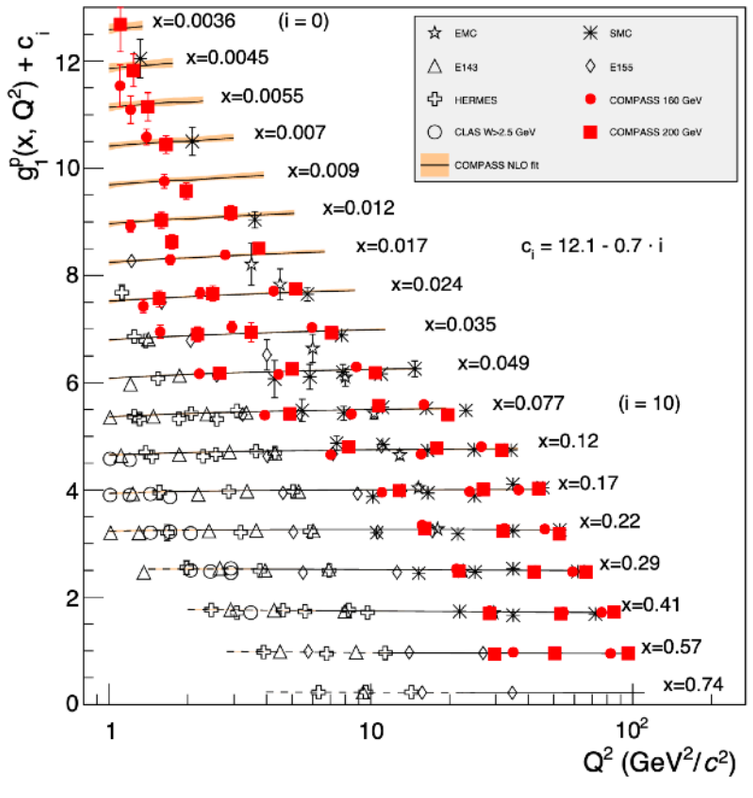
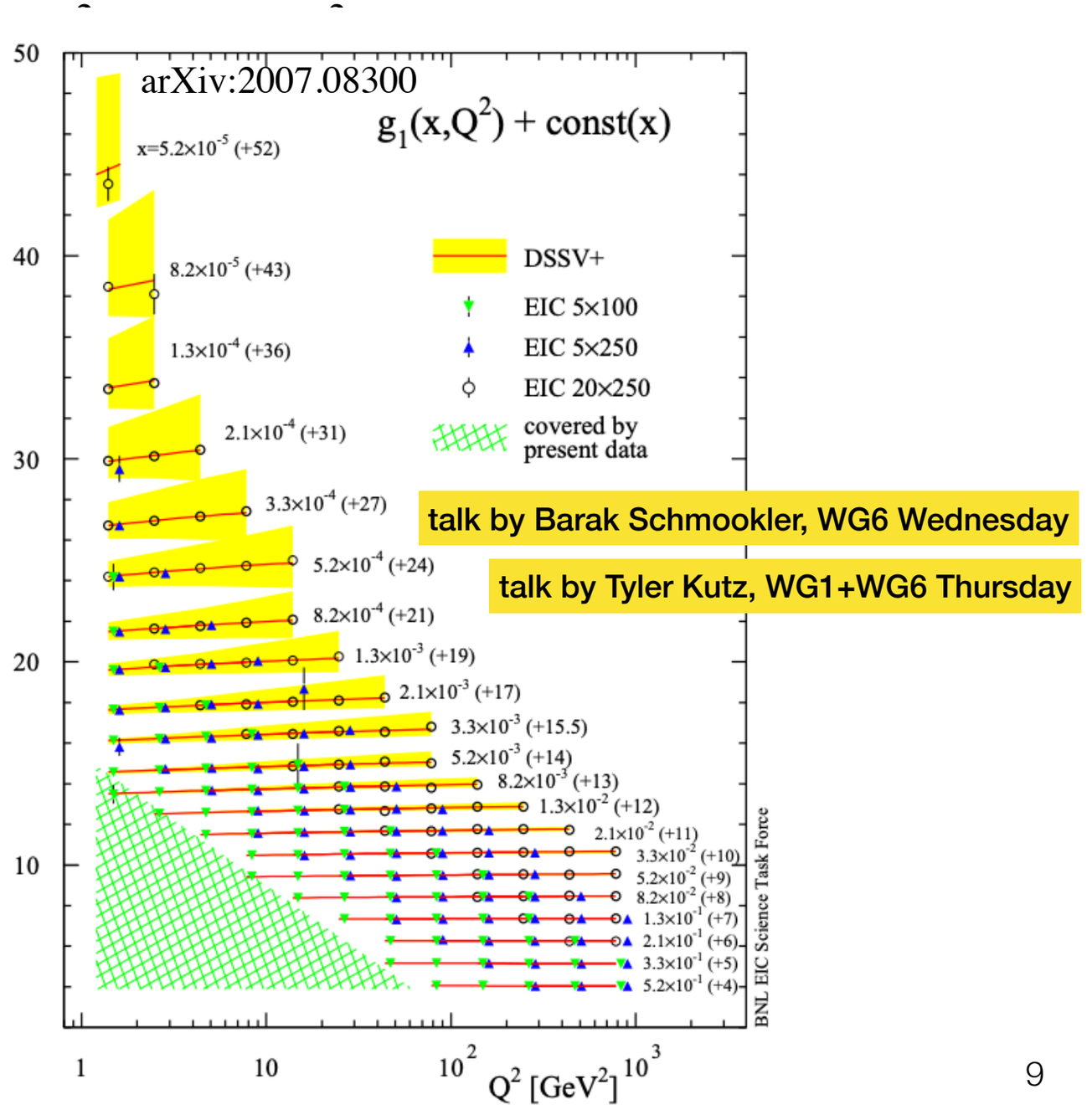
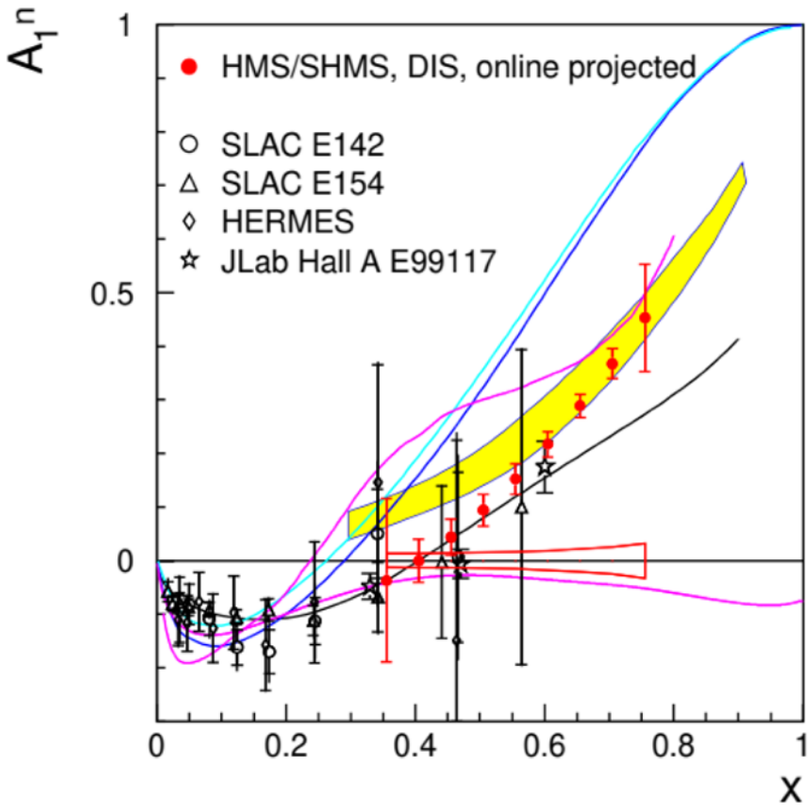




talk by Barak Schmookler, WG6 Wednesday

talk by Tyler Kutz, WG1+WG6 Thursday

Structure functions at large-x



- **JLab HallC A1n, d2n and g2n**
  - polarized 3He target
  - Took data in 2020

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1} \quad \text{at large } Q^2$$

Talk by Mingyu Chen, WG5 Tuesday

Model	F_2^n/F_2^p	d/u	Δ u/u	Δ d/d	A_1^n	A_1^p
SU(6) = SU3 flavor + SU2 spin	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark + Hyperfine	1/4	0	1	-1/3	1	1
pQCD + HHC	3/7	1/5	1	1	1	1
DSE-1 (realistic)	0.49	0.28	0.65	-0.26	0.17	0.59
DSE-2 (contact)	0.41	0.18	0.88	-0.33	0.34	0.88

Also expect new results on A1p from CLAS12

- **g_2 structure function and moments**
  - No simple interpretation
  - Provides information on the quark-gluon correlations through higher twist effects

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2)$$

x^2 weighted moment, d2: $d_2(Q^2) = \int_0^1 x^2 [g_2(x, Q^2) - g_2^{WW}(x, Q^2)] dx$

Twist-3 matrix element, related to color polarizabilities. Calculable in lattice QCD

  - **GDH sum rule and higher moments:** benchmark for theory, lattice calculation and chiral perturbative theory at low Q^2

[E97-110, Nature Phys. 17 (2021) 6, 687-692]

Gluon helicity distribution

- **Accessed indirectly in pDIS**
- **Polarized p+p at RHIC**

  Positive gluon contribution to the proton spin x > 0.05

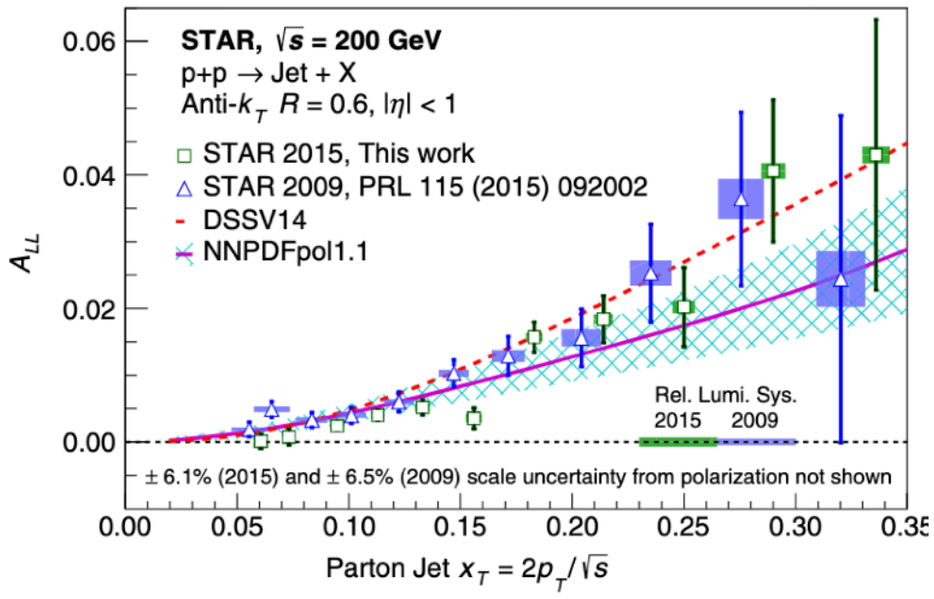
[PHENIX, Phys.Rev. D93 (2016) 011501]
[STAR, Phys.Rev. D100 (2019) 052005]
[DSSV14, Phys. Rev. Lett. 113 (2014) 012001]

- **New high precision jet data from STAR**

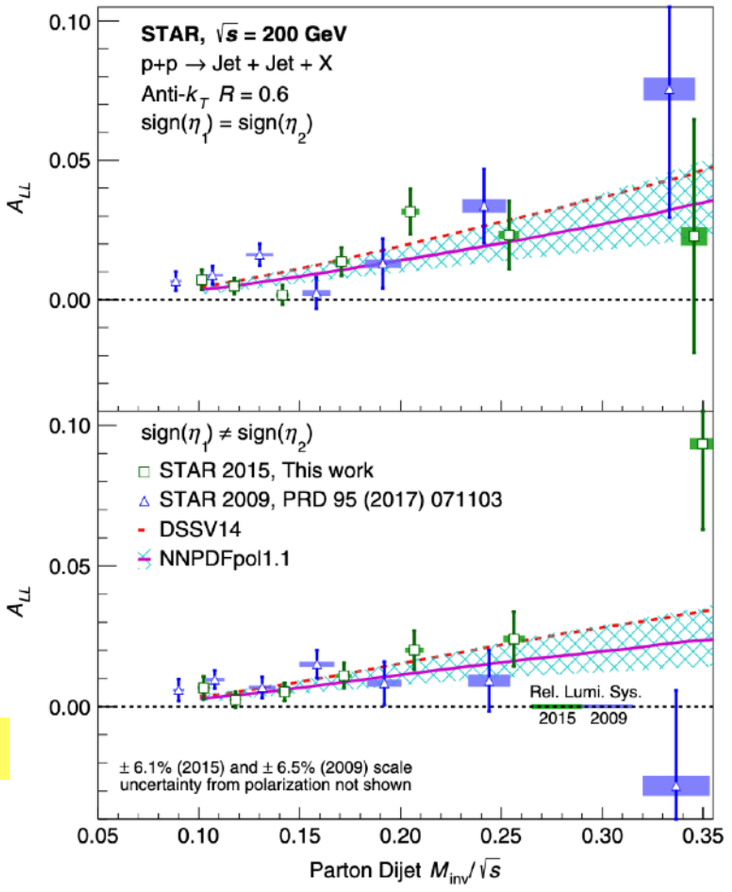
  Further constraint gluon helicity

  Access parton kinematics via di-jet measurements

[STAR, Phys. Rev. D 103, L091103 (2021)]



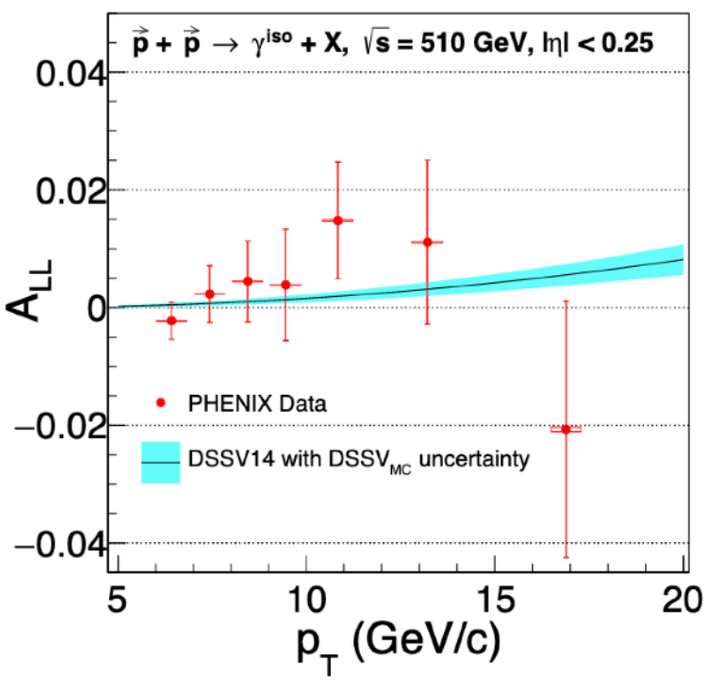
Talk by Scott Wissink, WG5 Tuesday



Talk by Y. Zhou, WG5 Tuesday
JAM helicity PDF analysis update

- **First published direct photon A_{LL}**

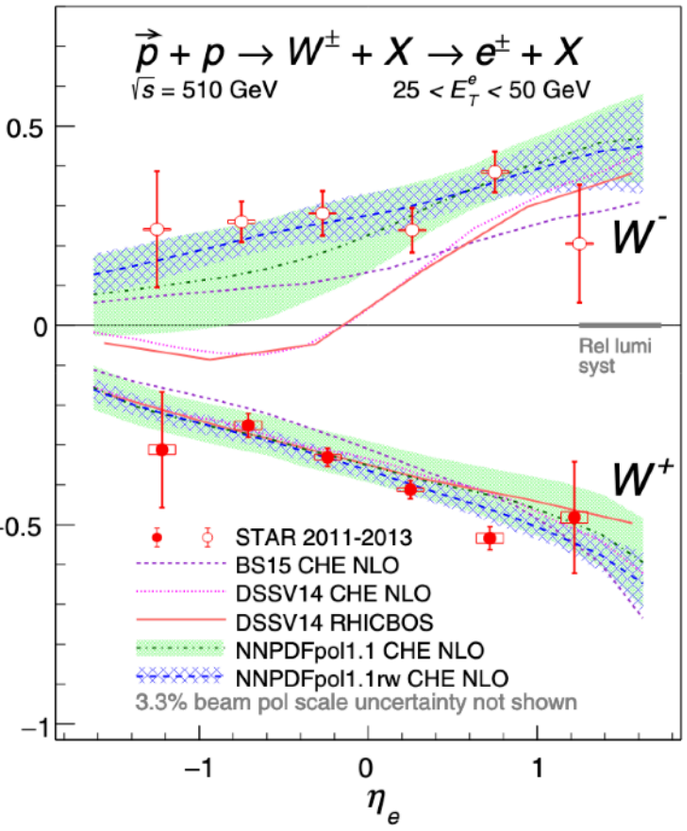
[PHENIX arXiv:2202.08158]



Talk by Zhongling Ji, WG5 Tuesday

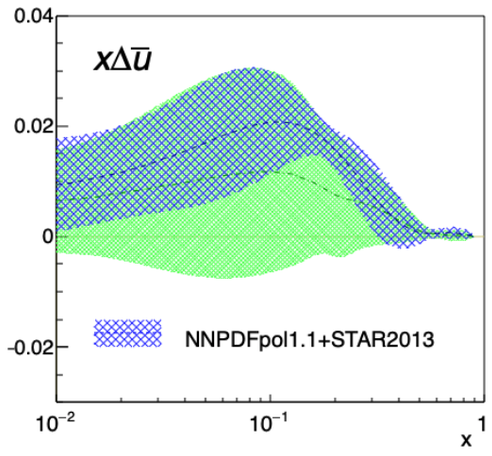
Light sea quarks $\Delta\bar{u}$, $\Delta\bar{d}$

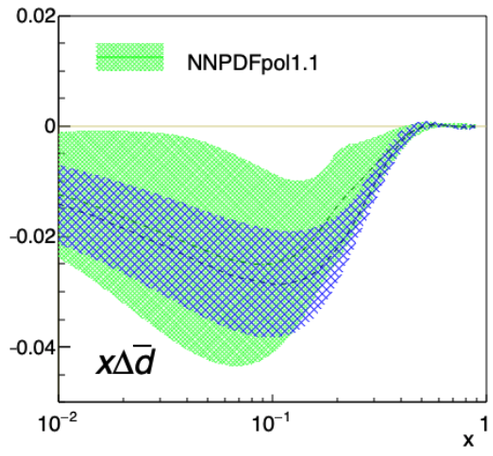
- **W single spin asymmetry**



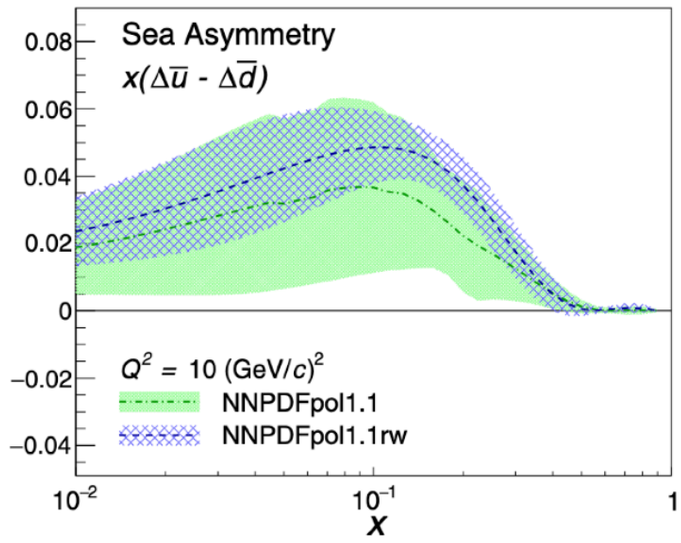
- constraints to light sea quark helicity PDFs at intermediate x region

  [STAR, Phys. Rev. D 99, 051102(R) (2019)]





Polarized light sea quark asymmetry



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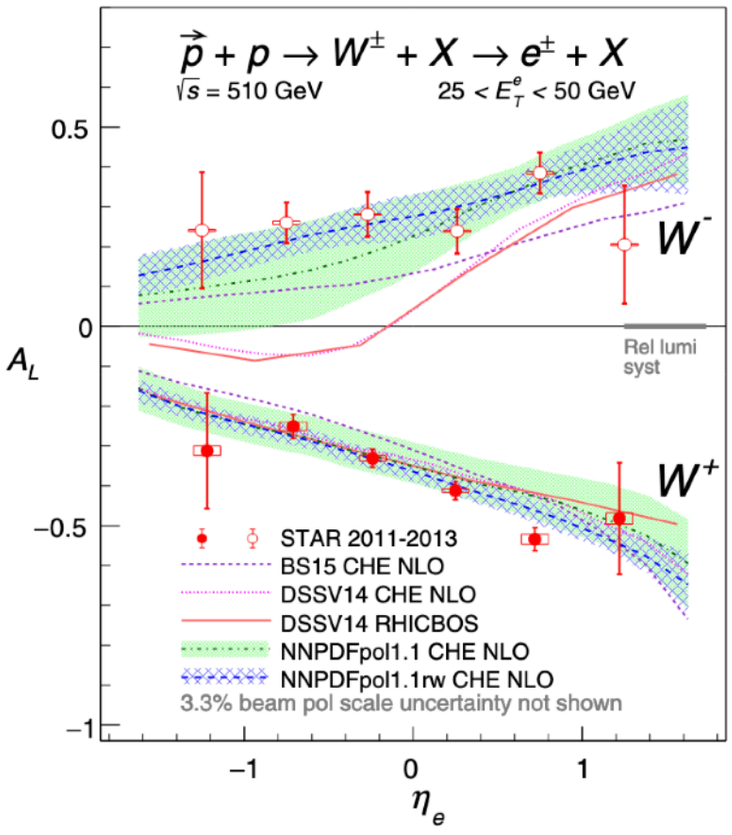
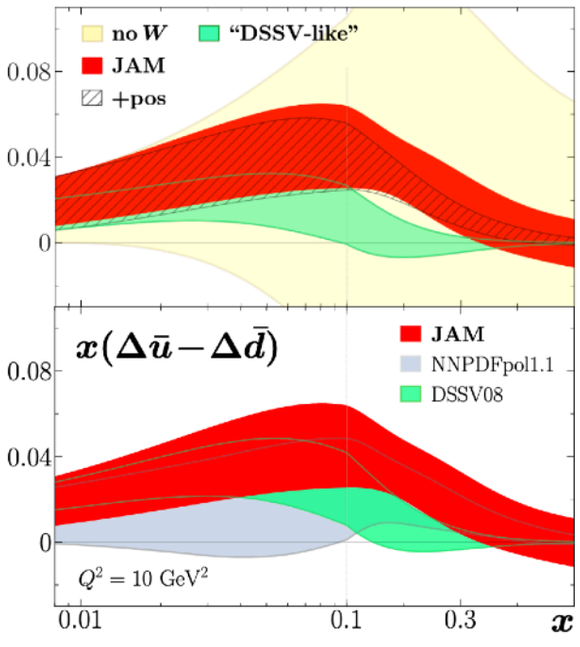


[JAM, arXiv:2202.03372]



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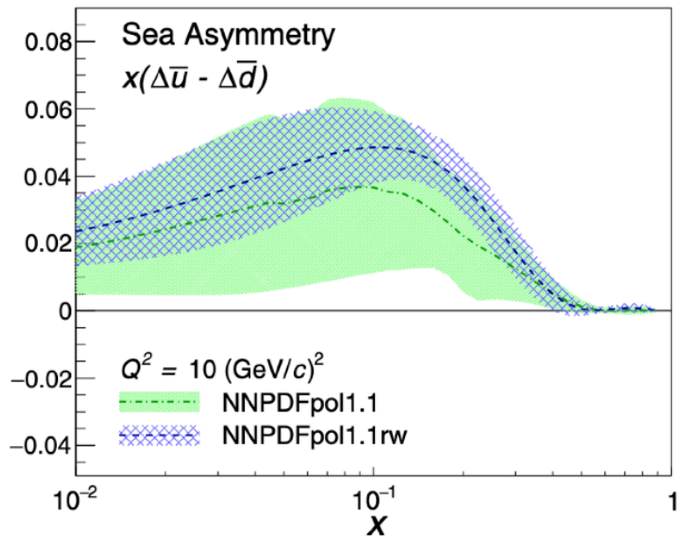

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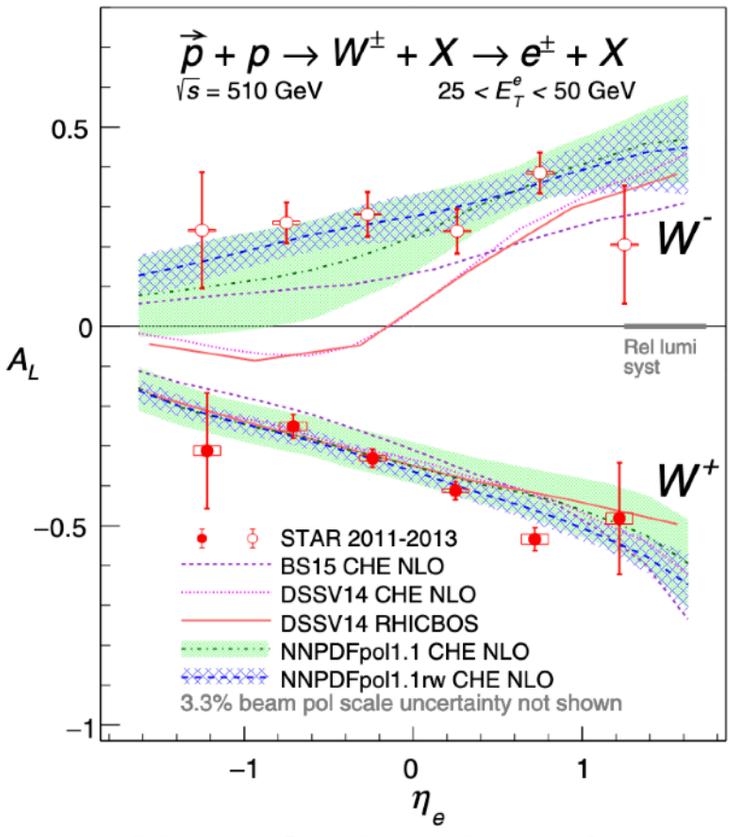
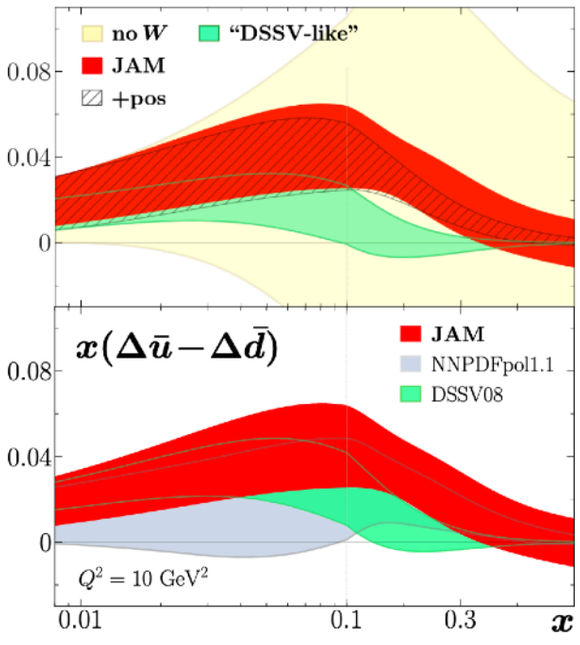
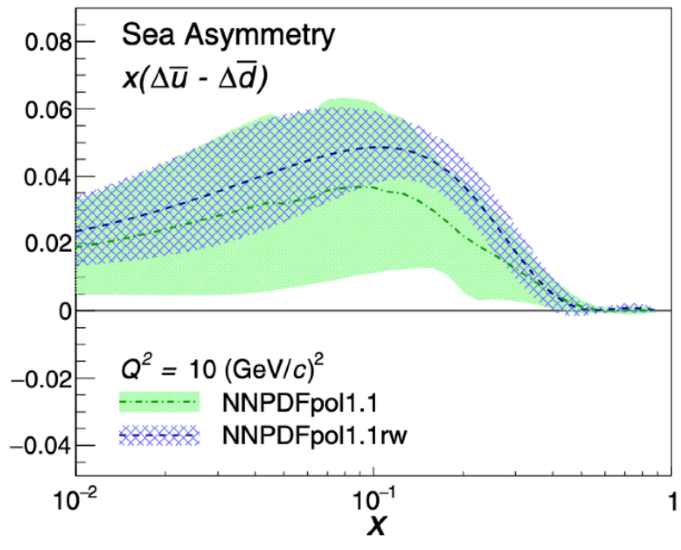


[JAM, arXiv:2202.03372]

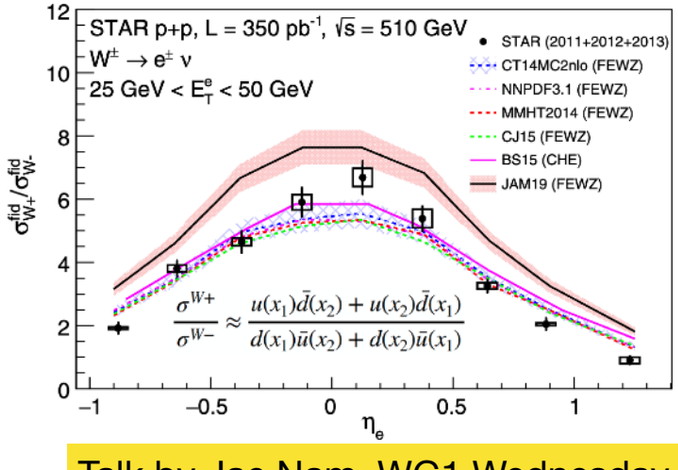


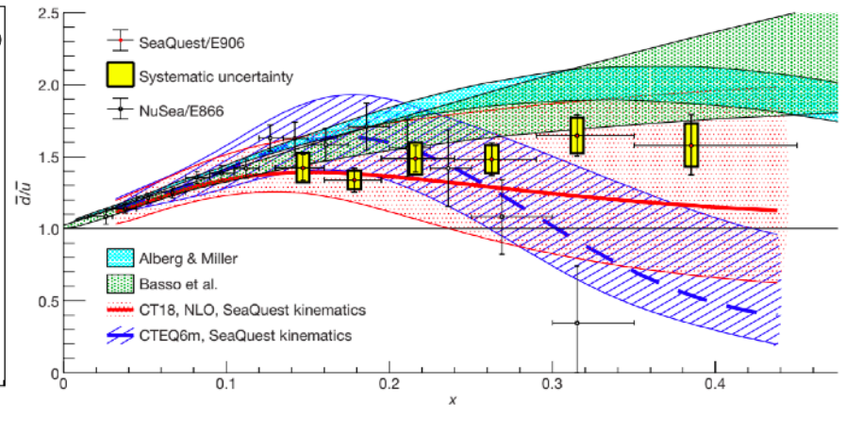
Polarized light sea quark asymmetry



- **Unpolarized antiquark sea asymmetry**

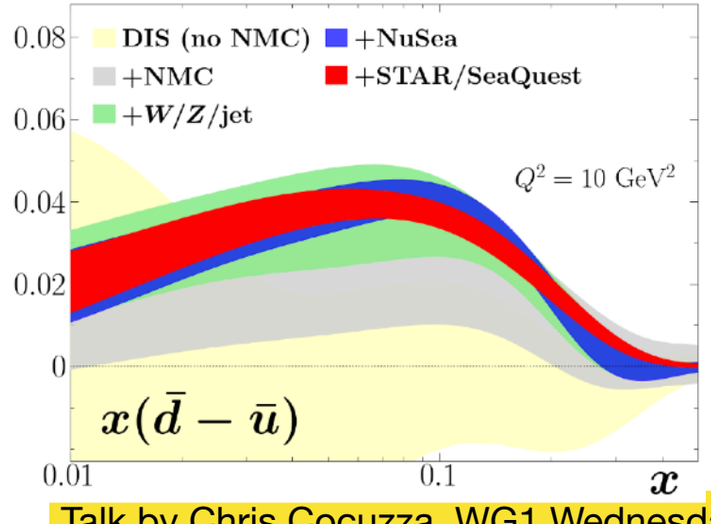
[STAR, Phys. Rev. D 103, 012001 (2020)] [SeaQuest, Nature 590, 561-565 (2021)]





- **Included in the Global QCD analyses**

[C. Cocuzza, et al (JAM), Phys. Rev. D 104, 074031 (2021)]



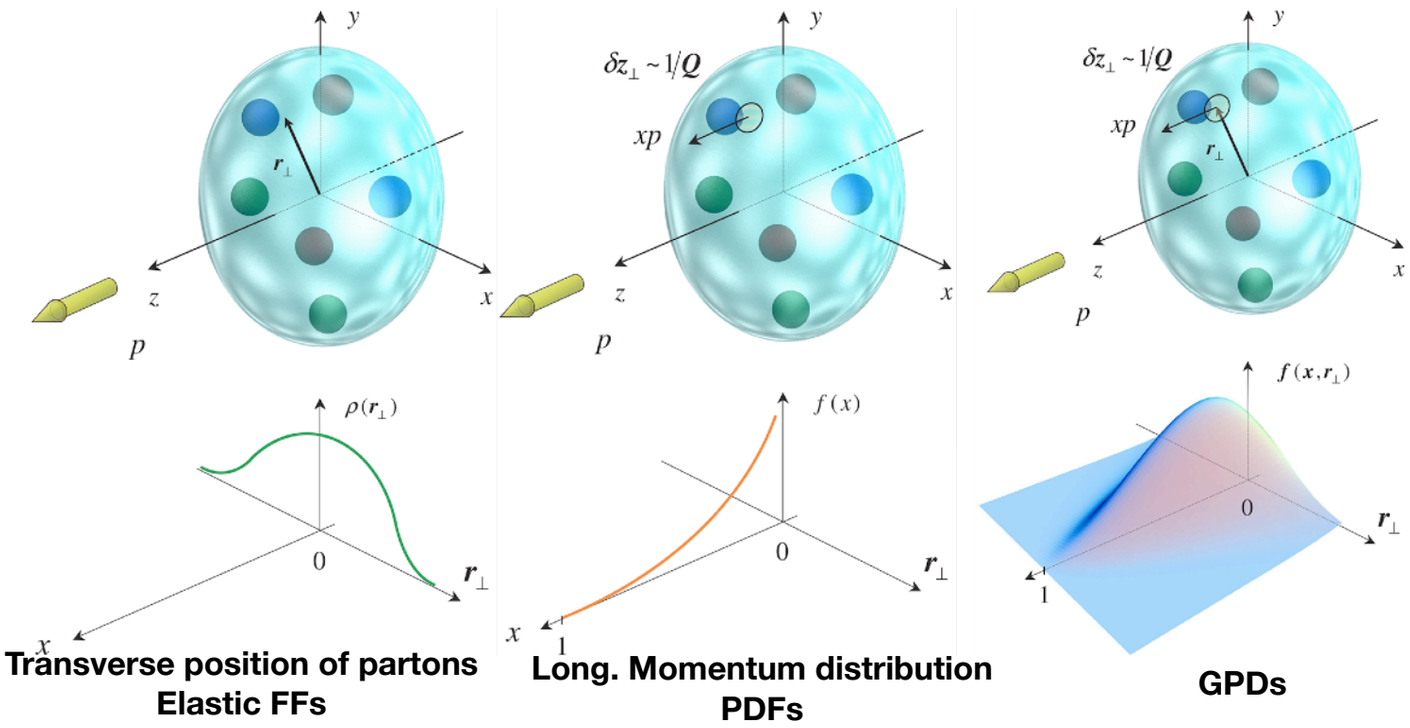
Spin Talk by Jae Nam, WG1 Wednesday

Talk by Chris Cocuzza, WG1 Wednesday

3D Nucleon Structure

Generalized Parton Distributions

- **Nucleon Tomography**



Transverse position of partons
Elastic FFs

Long. Momentum distribution
PDFs

GPDs

GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$

Leading-twist GPDs:

4 chiral-even GPDs $H, \tilde{H}, E, \tilde{E}$

- DVCS, DVMP, Pseudoscala mesons

4 chiral-odd GPDs $H_T, \tilde{H}_T, E_T, \tilde{E}_T$

- ρ production, ..

Talk by S. Nabeebaccus, WG2 Wednesday

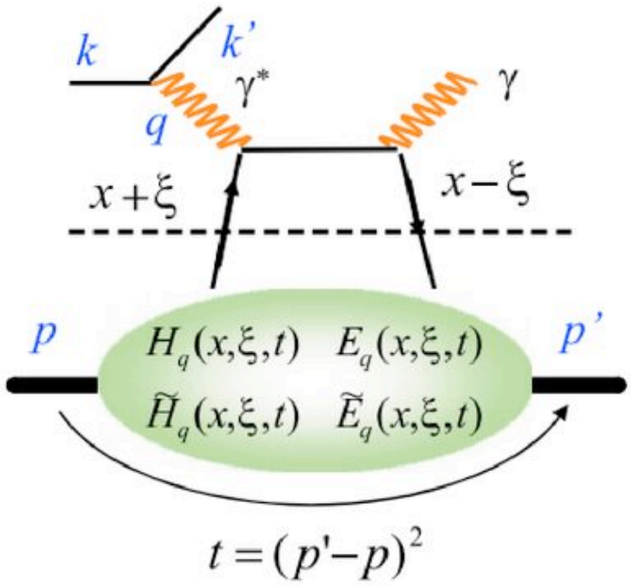
- **Quark OAM contribution to the proton spin**

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

[X. Ji PRL 78, 610 (1997)]

- **Accessed via exclusive processes; cross section and asymmetries**

Deeply Virtual Compton scattering



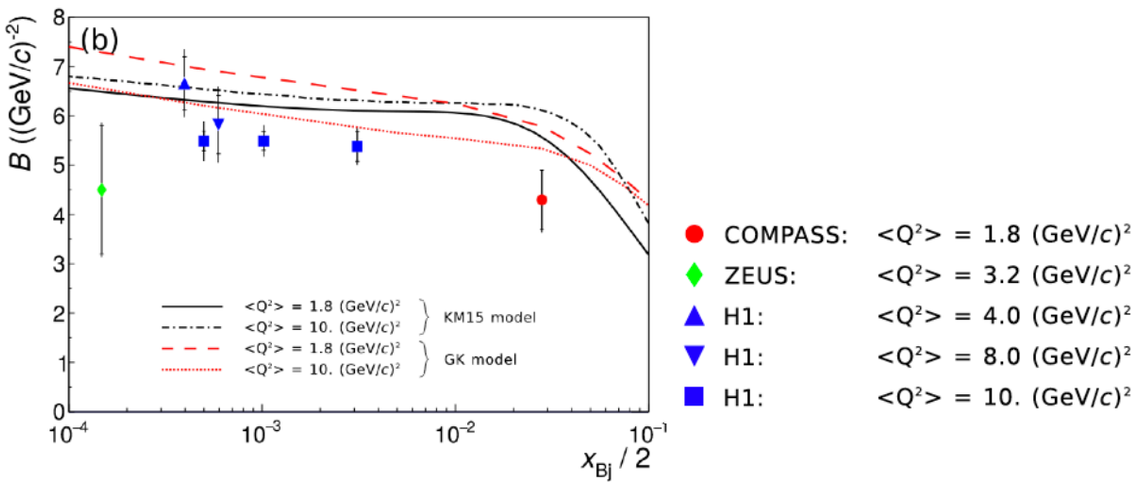
- **Sensitive to H and E**
- **GPDs appear in the DVCS amplitude through CFFs**

$$\mathcal{H}_{++}(\xi,t) = \int_{-1}^{1} H(x,\xi,t)\left(\frac{1}{\xi-x-i\epsilon}-\frac{1}{\xi+x-i\epsilon}\right)dx$$

$$\sigma_{(ep\to ep\gamma)} = |DVCS|^2 + |BH|^2 + Interference$$

- **COMPASS** Talk by J. V. Giarra, WG5 Tuesday

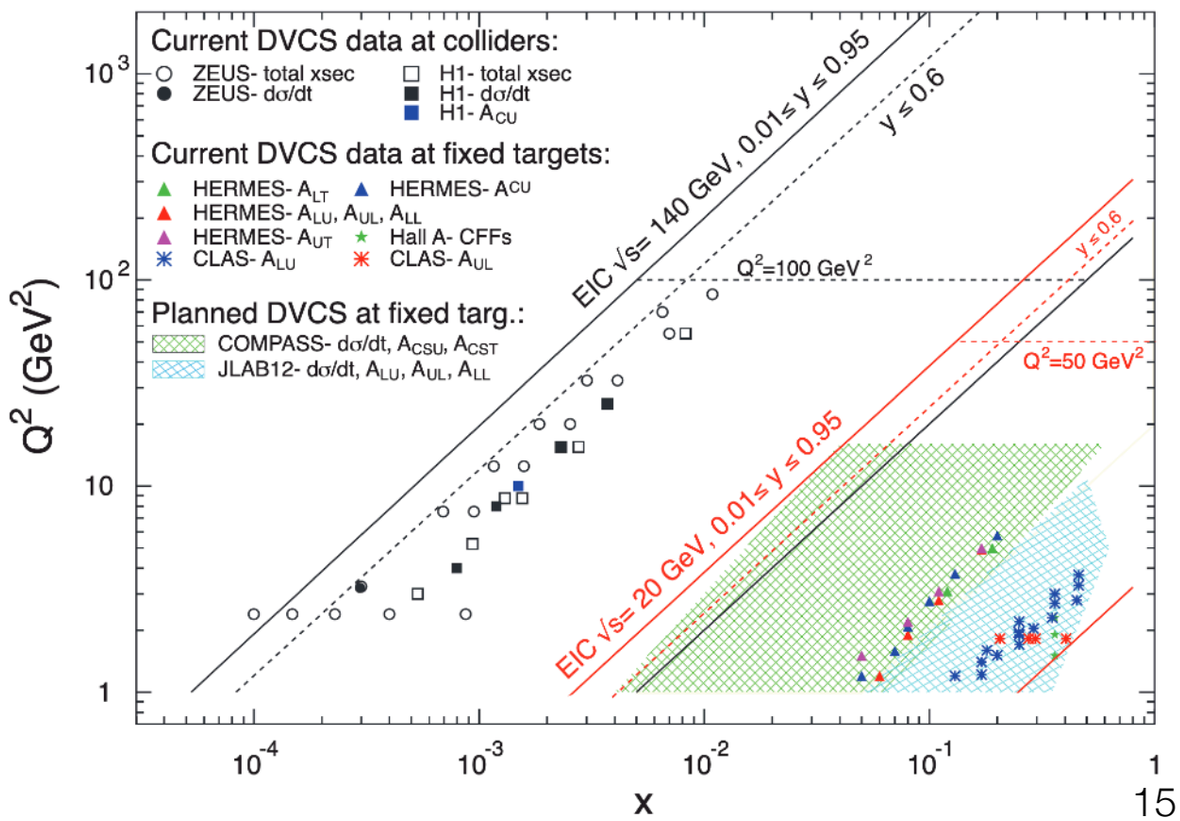
[COMPASS, PLB 793 (2019) 188]



t-slope of DVCS cross section related to distance between struck quark and spectator c.m. $\langle r^2_{perp}\rangle$

Talk by G. Penman, WG2 Wednesday

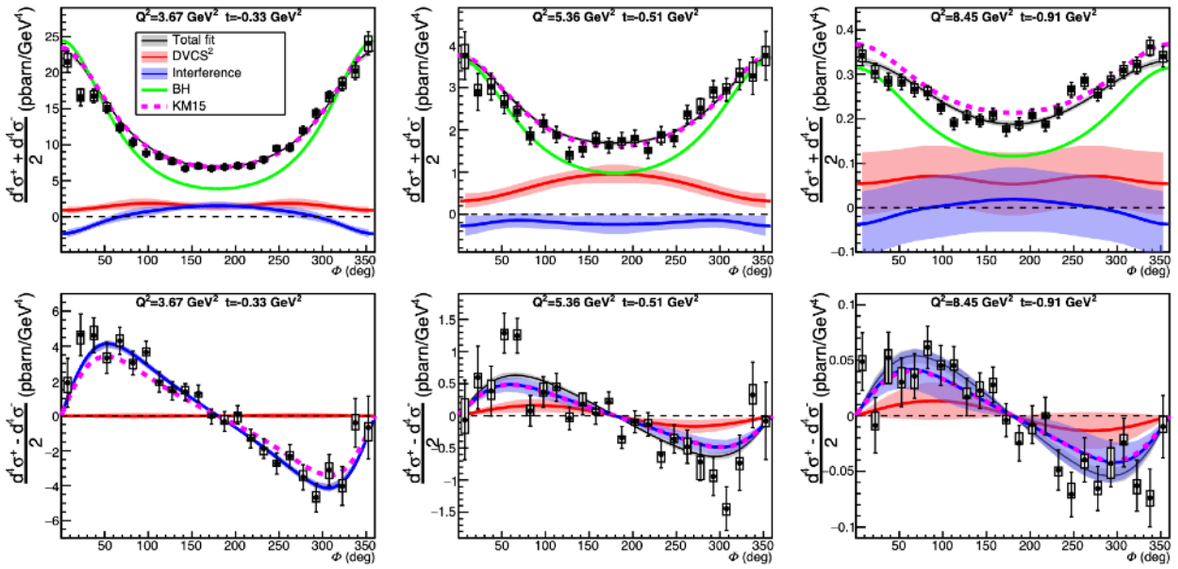
[EIC Yellow Report, arXiv:2103.05419]

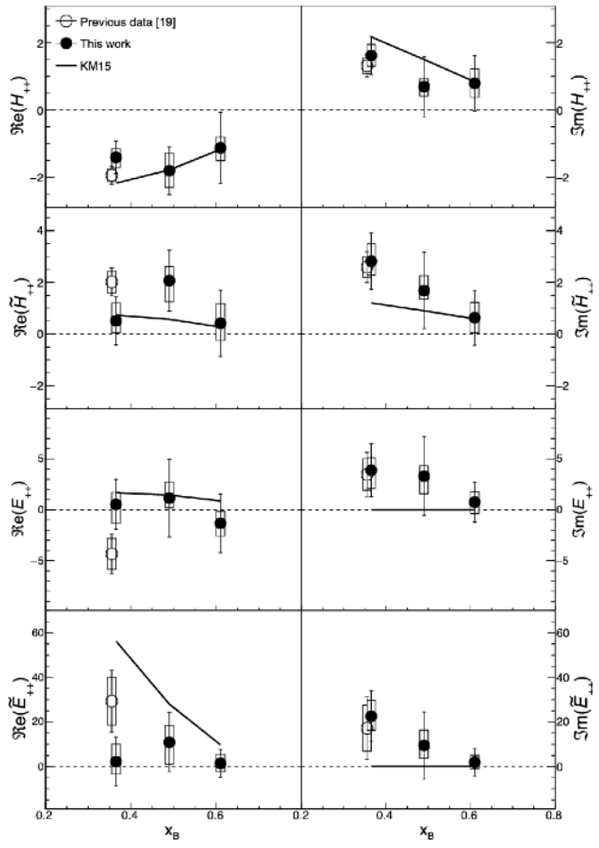


DVCS at high-x

Talk by C. Hyde, WG5 Wednesday

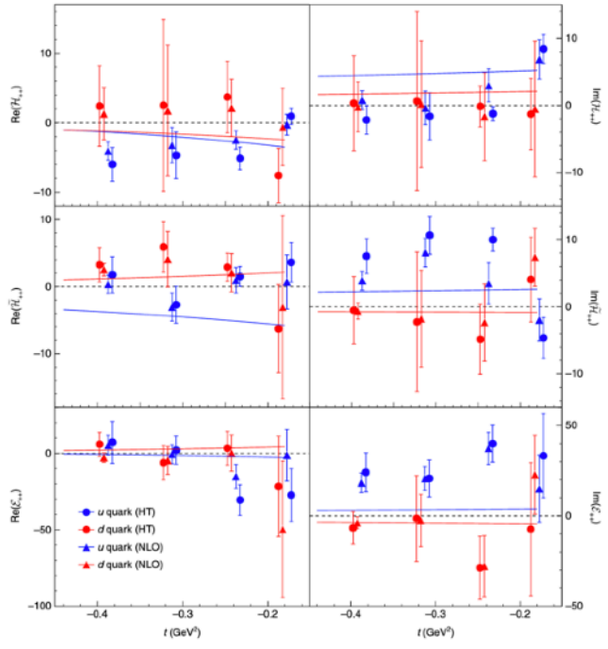
- **JLab HallA** arXiv:2201.03714 [hep-ph]
  - First experimental extraction of all four helicity-conserving CFFs





- **DVCS off neutron**
  - Flavor separation of CFFs (combined with proton data)
  - Sensitive to GPD E

[Benali, *et al.*, Nature Physics 16, 191–198 (2020)]
6 GeV data from HallA, NLO and HT analyses



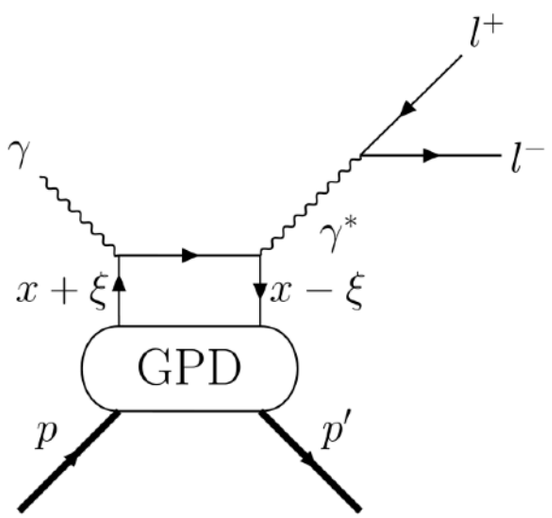
- **New CLAS12 DVCS results with high statistics**

Talk by M. Defurne, WG5 Wednesday

- **DVCS with positron beam at JLab**

Talk by S. Niccolai Tuesday, WG6

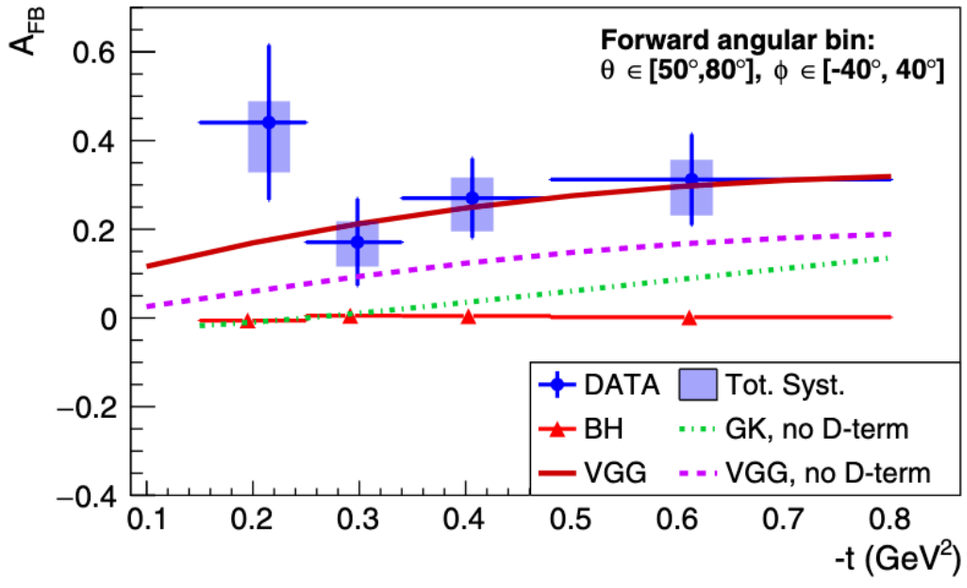
Timelike Compton Scattering

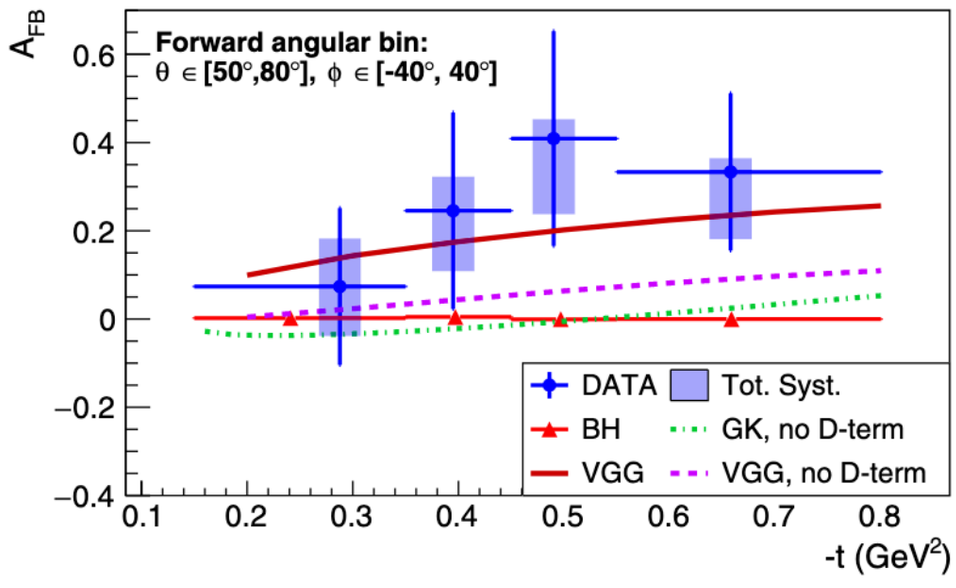


- Time-reversal conjugate process of DVCS
- Both Im($\mathcal{H}$) and Re($\mathcal{H}$) can be accessed
- Comparison with DVCS: Universality test of GPDs
- Real part of the CFF and nucleon D-term:

  pressure distribution in the nucleon [Burkert et al., Nature 557, 396-399 (2018)]

- **First measurement by CLAS12** [CLAS, Phys. Rev. Lett. 127, 262501 (2021)]





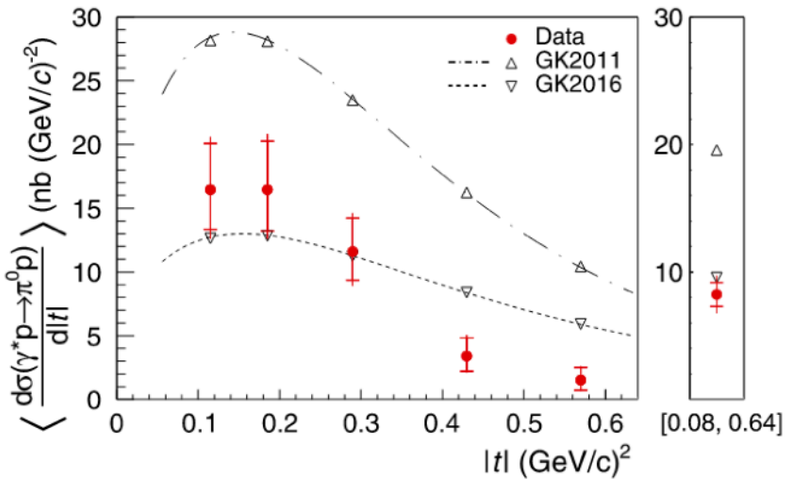
- **TCS at EIC** Talk by Daria Sokhan, WG5 Wednesday

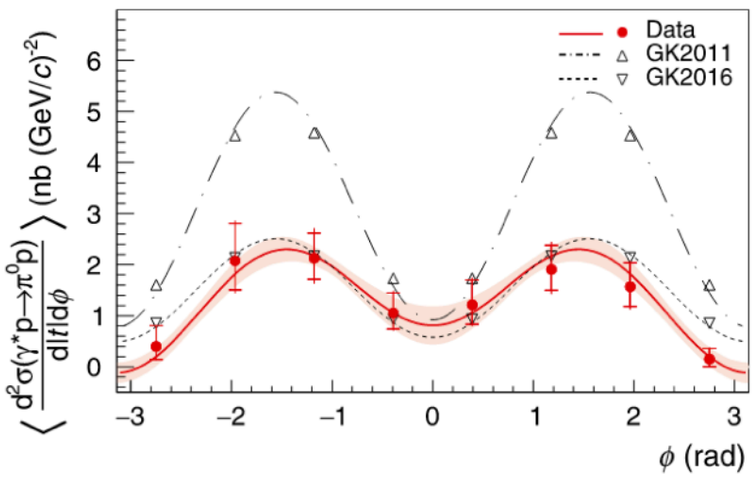
Hard Exclusive Meson Production

- **COMPASS exclusive π^0 cross section**
  - Input to Chiral-odd GPDs

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

[COMPASS, PLB 805 (2020) 135454]





$$\frac{d\sigma_T}{dt} \propto \left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle \bar{E}_T\rangle|^2\right],$$

$$\frac{d\sigma_L}{dt} \propto \left[(1-\xi^2)|\langle \tilde{H}\rangle|^2 - 2\xi^2 Re\left[\langle \tilde{H}\rangle^*\langle \tilde{E}\rangle\right] - \frac{t'}{4M^2}\xi^2|\langle \tilde{E}\rangle|^2\right],$$

$$\boxed{\frac{d\sigma_{TT}}{dt} \propto t'|\langle \bar{E}_T\rangle|^2,}$$

$$\frac{d\sigma_{LT}}{dt} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\,Re\left[\langle H_T\rangle^*\langle \tilde{E}\rangle\right].$$

- Large negative contribution by σ_{TT}

$$\left\langle \frac{d\sigma_{TT}}{d|t|} \right\rangle = (-6.1 \pm 1.3_{\text{stat}}{}^{+\,0.7}_{-\,0.7}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

- Significant role of transversely polarized photons in the process
- Evidence for the existence of chiral-odd GPD $\bar{E}_T$

- **CLAS12**

  π^0, π^+ beam-spin asymmetry measurements

  [CLAS, Phys. Rev. Lett. 125, 182001 (2020)]

  - New result of π^- beam-spin asymmetry

  Talk by S. Diehl, WG5 Wednesday

- **Spin Density Matrix Elements for exclusive ω meson production from COMPASS**

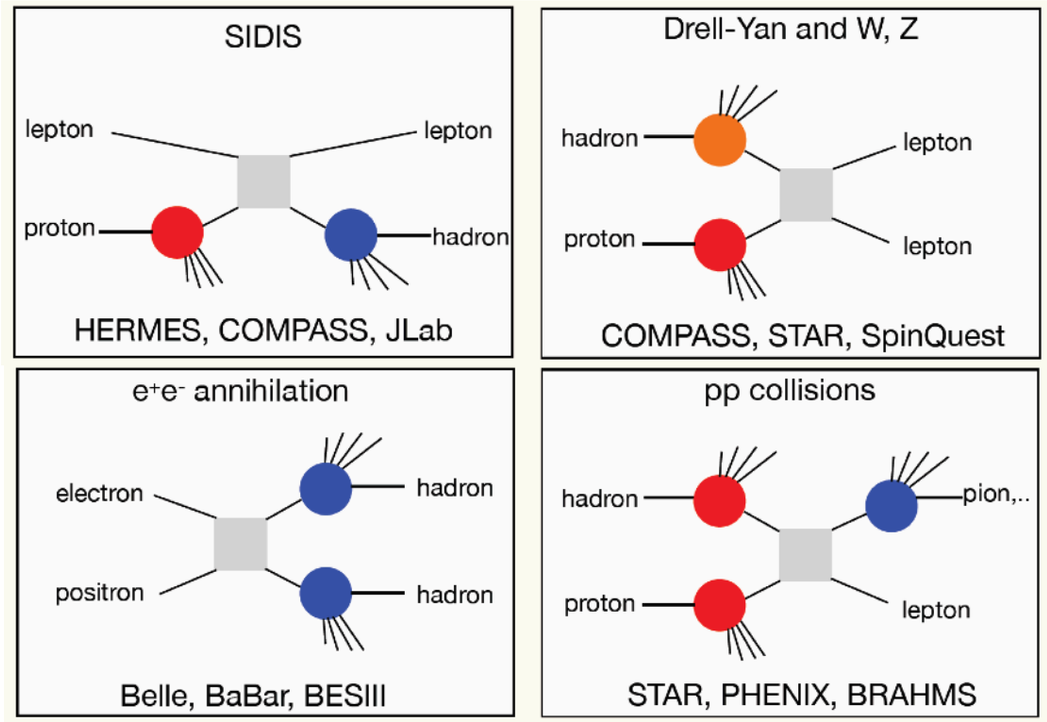
  [COMPASS Eur. Phys. J. C (2021) 81:126]

Transverse Momentum Dependent Functions

Leading twist TMDs

Nucleon Polarization	Quark polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 =		$h_1^\perp$ = − **Boer-Mulders**
L		g_1 = − **Helicity**	$h_{1L}^\perp$ = − **Worm Gear (Kotzinian-Mulders)**
T	$f_{1T}^\perp$ = − **Sivers**	g_{1T} = − **Worm Gear**	h_1 = − **Transversity** $h_{1T}^\perp$ = − **Pretzelosity**

and FFs: $D_1, G_1, H_1^\perp$

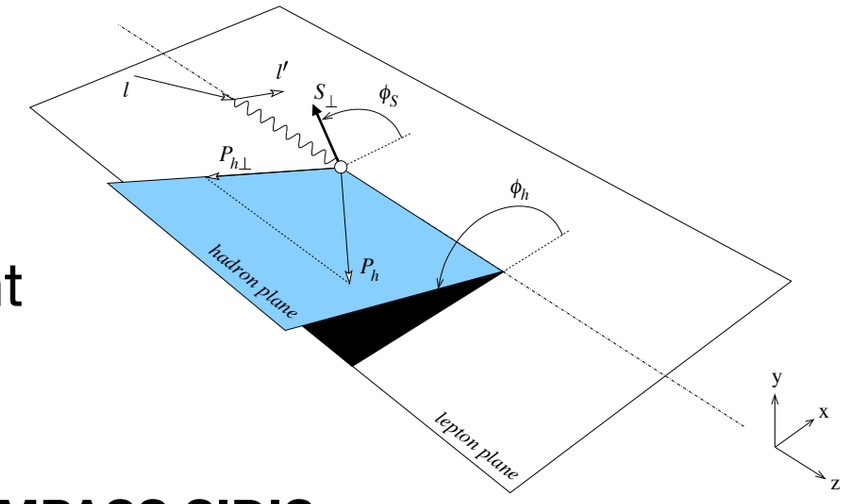


C. Reidl (DIS2021)

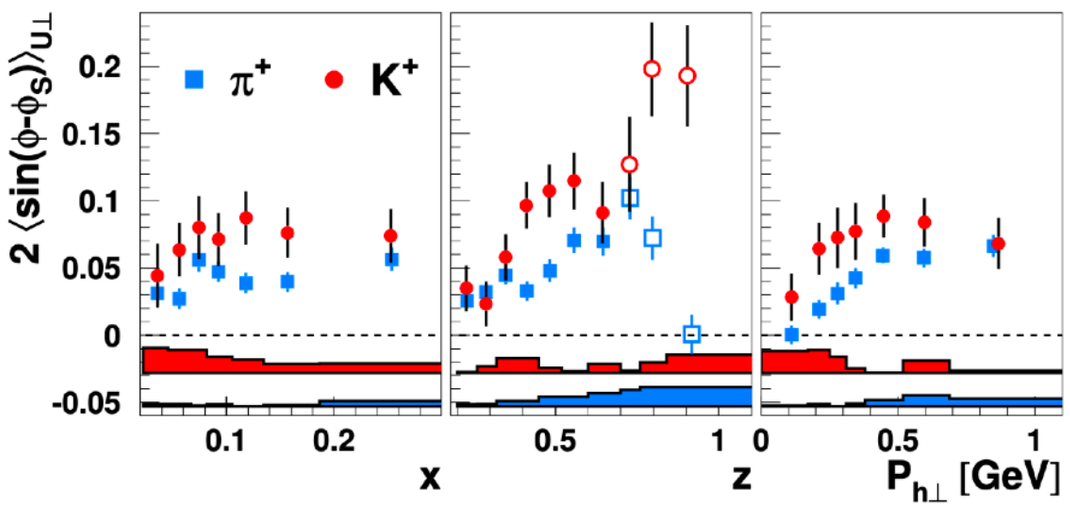
- Sensitive to confined motion of quarks and gluons inside the nucleon
- Connection to OAM: Off-diagonal part vanishes without parton's transverse motion
  - Pretzelosity: Link to quark OAM (model-dependent)
- Accessed via various processes (SIDIS, DY, e+e-, p+p)
  - TMD factorization and universality test

TMDs in SIDIS

- Semi-Inclusive process is ideal to study TMDs
  Naturally have two scales: $Q^2 >> p_T^2, \Lambda_{QCD}^2$
- Access all 8 leading twist TMDs via spin (in)dependent azimuthal modulations

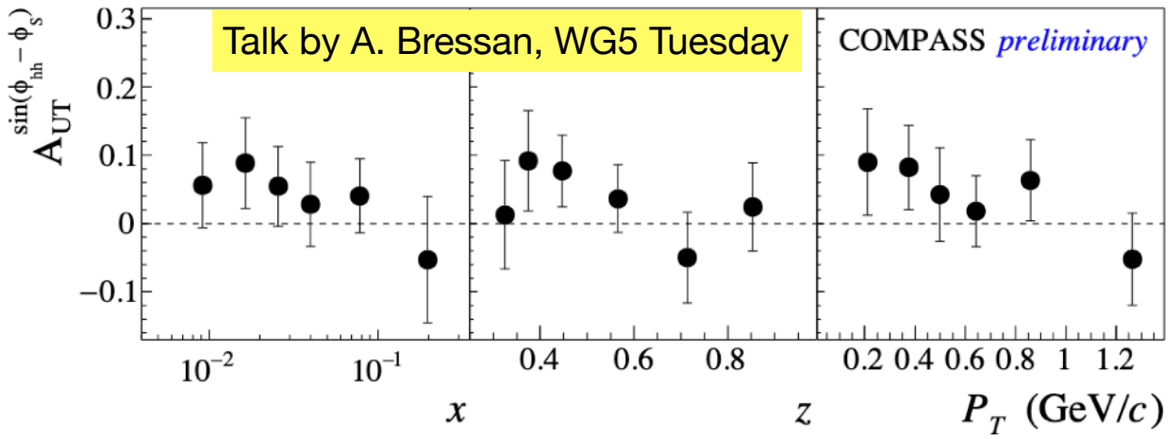


- **HERMES "TMDs bible"**
  [HERMES, J. High Energ. Phys. 2020, 10 (2020)]



  - TMD results with transversely polarized H target
  - Several new updates to the previous published results including 3D binning (x, z, pT) analysis and proton asymmetries
  - Included in the new JAM fits

- **COMPASS SIDIS**
  - **pT weighted Sivers asymmetries**
    [COMPASS, Nucl. Phys. B 940 (2019) 34-53]
  - **First ρ^0 meson measurement**



  - **New data taking in 2022 with polarized proton and neutron targets**
    d-quark transversity and other TMDs

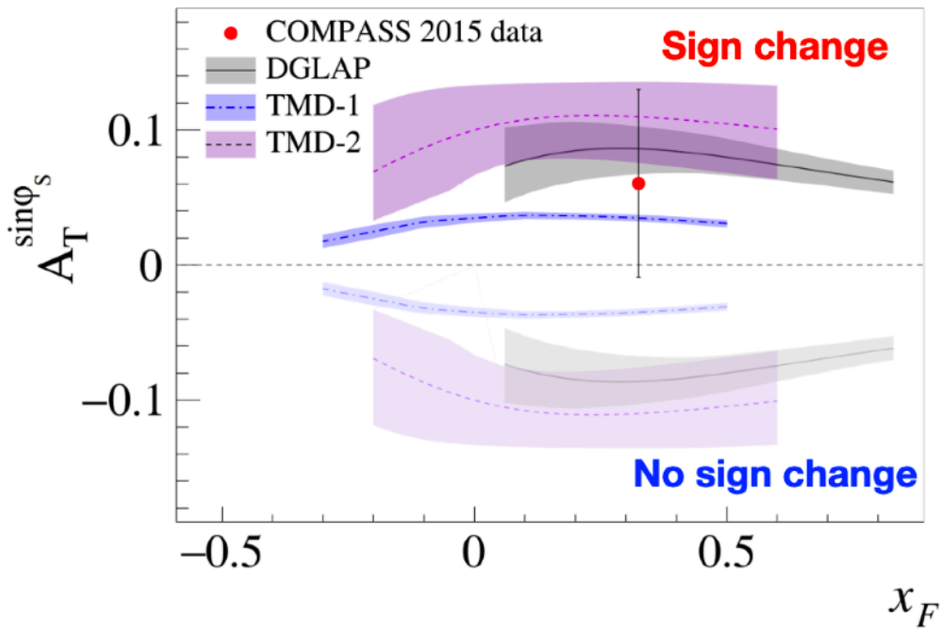
Talk by B. Parsamyan, WG5 Tuesday

Sivers Sign Change

$$f_{q/h^{\uparrow}}^{SIDIS}(x, k_T, Q^2) = -f_{q/h^{\uparrow}}^{DY/W^{\pm}/Z}(x, k_T, Q^2)$$ [Collins, PLB 536 (02)]

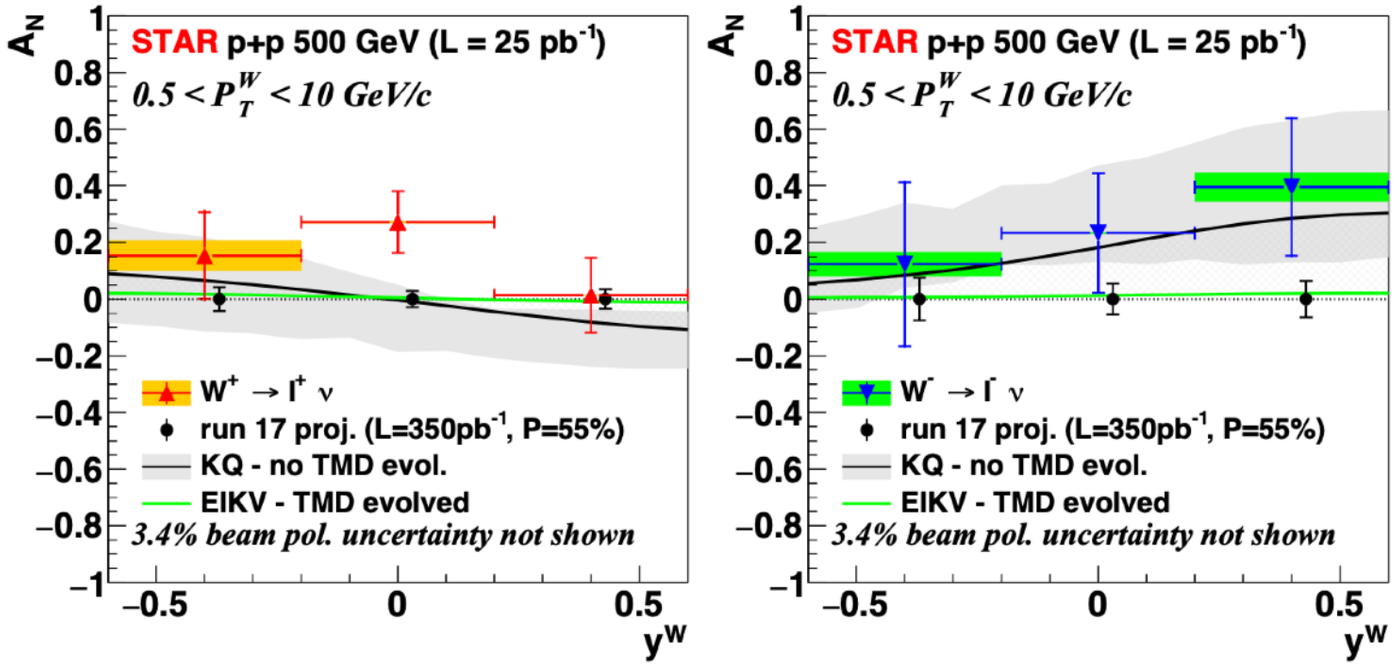
- Nonuniversality of Sivers function and sign change: fundamental prediction from the gauge invariance of QCD, direct verification of QCD factorization

[COMPASS, PRL 118 (2017) 112002]



- Measures SIDIS and DY with the same detector
- COMPASS DY results favor the sign change hypothesis

[STAR, Phys. Rev. Lett. 116, 132301 (2016)]



Fully reconstructed W kinematics via its recoil compared to curves with sign-change scenario

Expect new results with higher precision to be published

New results 2015+2018 data Talk by B. Parsamyan, WG5 Wednesday

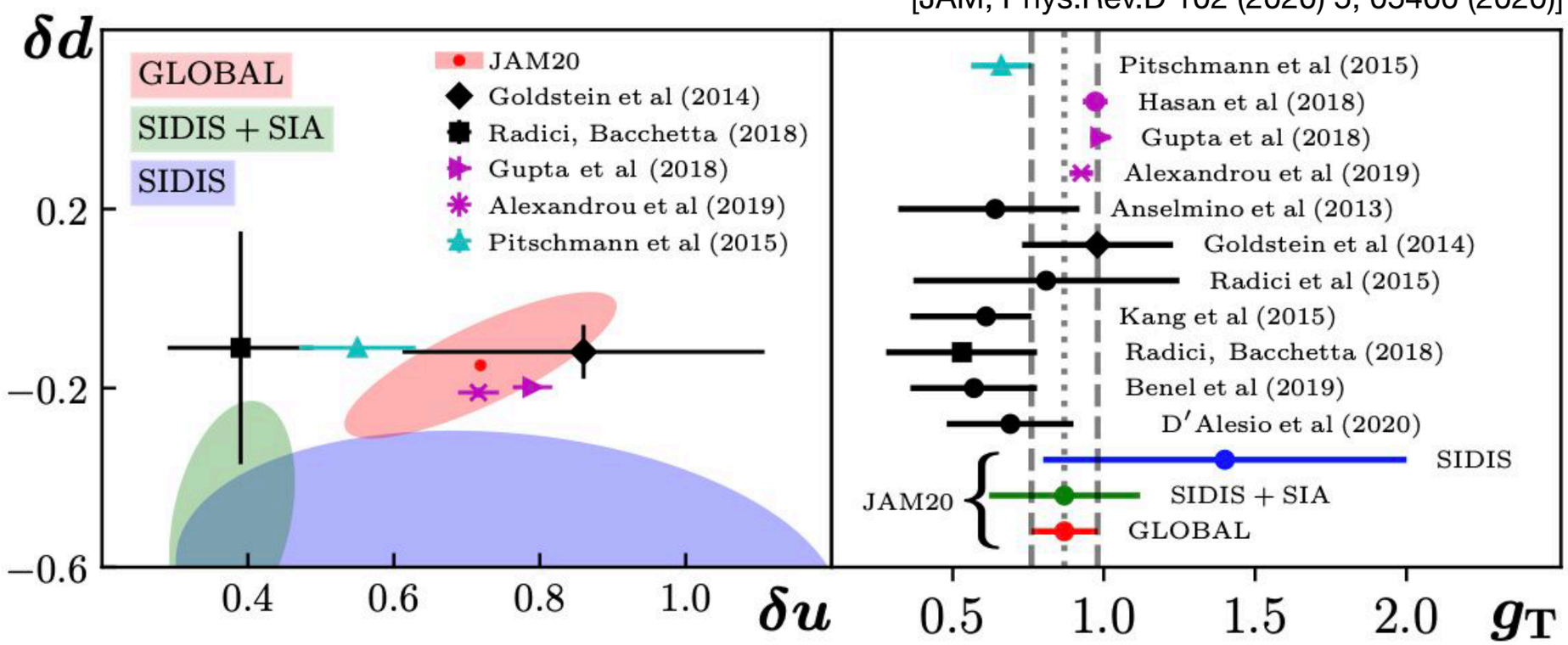
Transversity

- One of three standard PDFs, however least known
- Can be observed in combination with additional spin dependent final state effects (e.g Collins FF or interference FF)

- Tensor charge
  - lowest moment of transversity
  - Fundamental quantity of nucleon. Can be compared with Lattice QCD calculation.

$$\delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x) \right] \mathrm{d}x$$

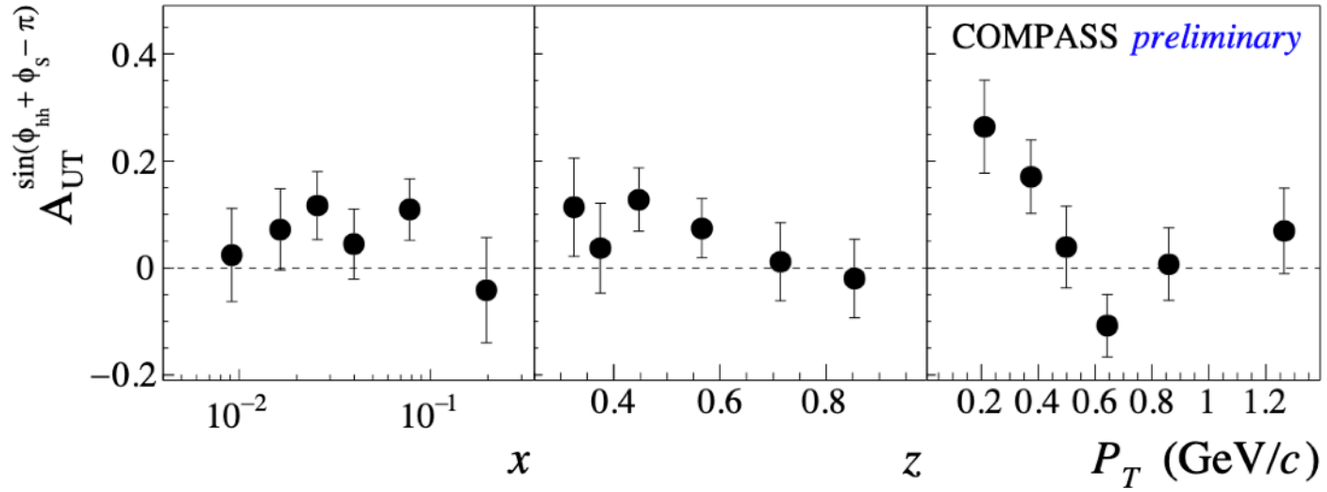
[JAM, Phys.Rev.D 102 (2020) 5, 05400 (2020)]



Collins asymmetries

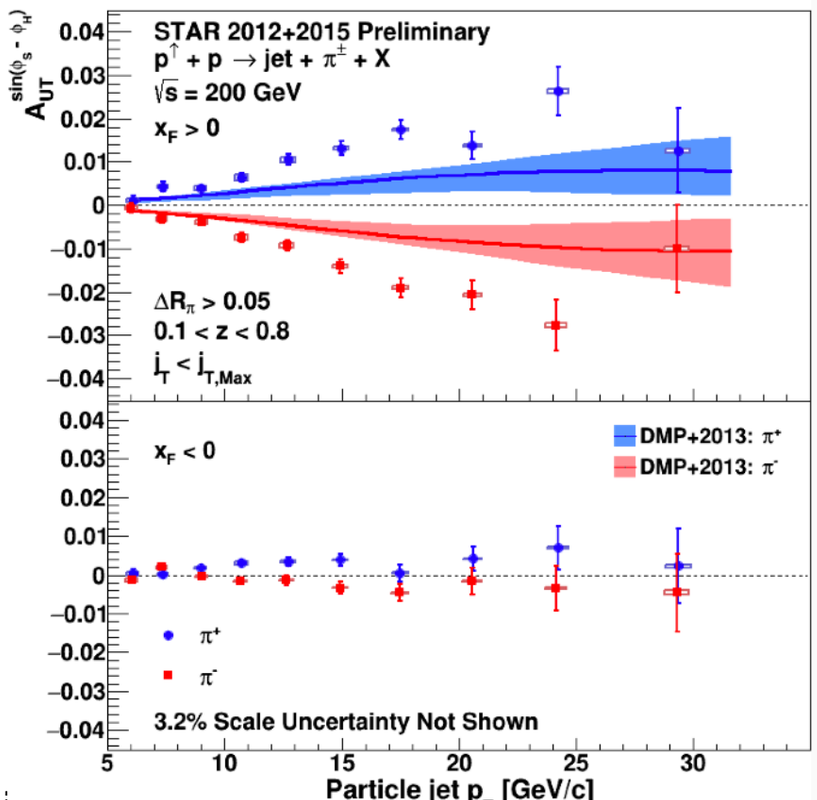
- **COMPASS: SIDIS ρ^0**
  - First SIDIS ρ^0 meson measurement

    Talk by A. Bressan, WG5 Tuesday

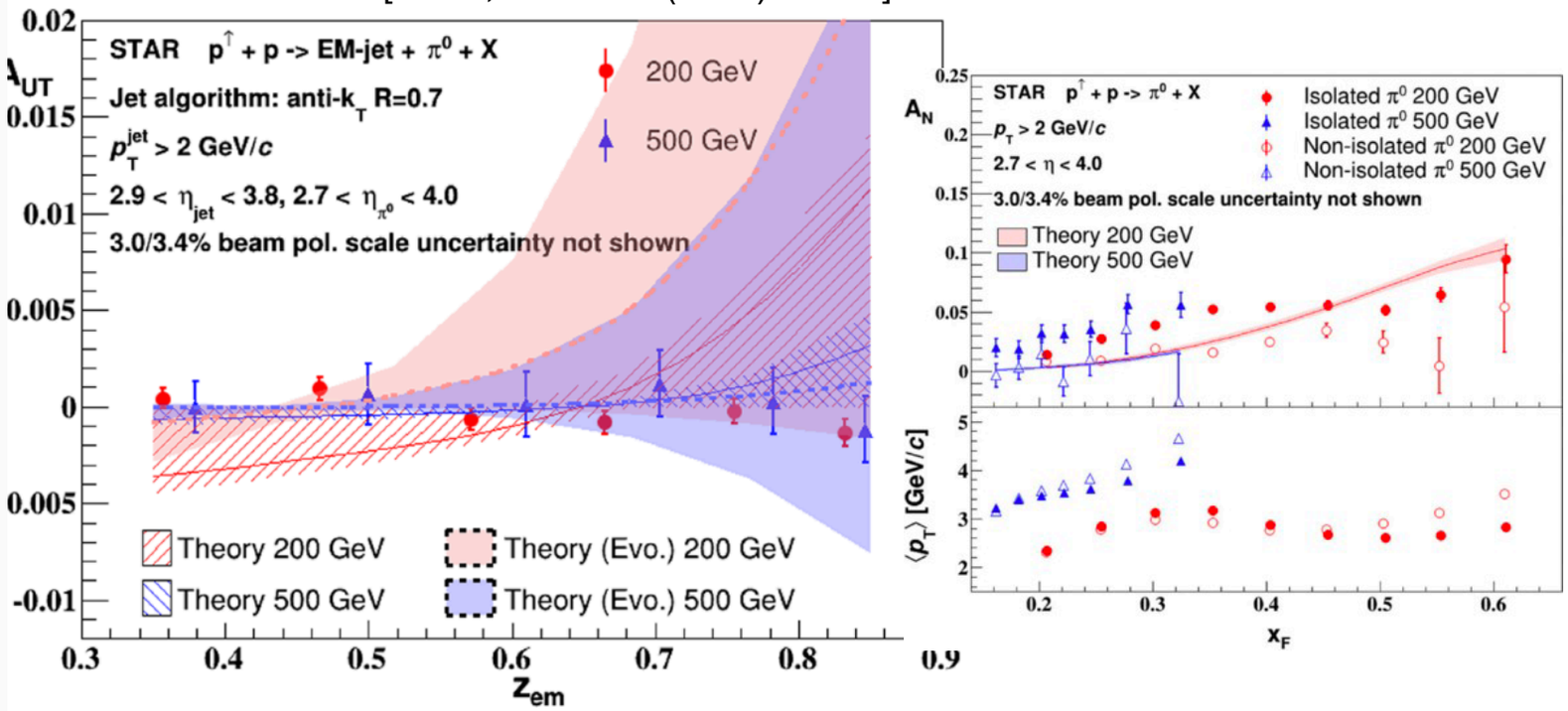


- **STAR: Identified hardons within jets**

  Talk by T. Lin, WG5 Thursday



[STAR, PRD 103 (2021) 92009]



Transversity via dihadron IFF: Talk by N. Ghimire, WG5 Tuesday

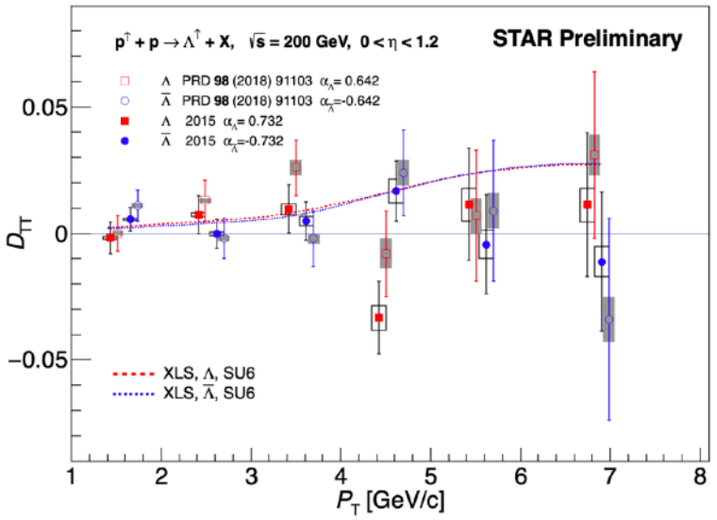
Transverse spin transfer Λ, $\bar{\Lambda}$

- **Longitudinal and transverse spin transfer of Λ, $\bar{\Lambda}$ hyperons**

  Shed light on the helicity and transversity distributions of the strange in the proton

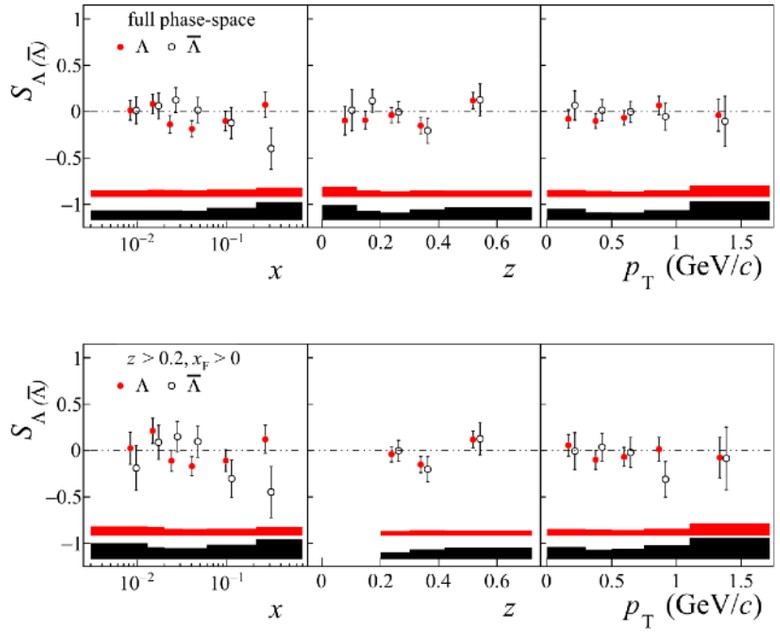
  - **Longitudinal spin transfer of Λ and $\bar{\Lambda}$** Talk by Y. Yu, WG5 Thursday
    - Sensitive to strange helicity PDF

  - **Transverse spin transfer of Λ and $\bar{\Lambda}$**
    - **STAR (p+p)** Talk by T. Gao, WG5 Thursday



    - **e+e- Belle**
      - Large transverse Λ polarization observed
      - Nonzero contribution from Polarizing Fragmentation Function

    - **COMPASS (SIDIS)** [Physics Letters B 824 (2022) 136834]



    - **Lambda polarization and spin transfer at EIC**
      - Recent studies via SIDIS as well as back-to-back lepton-jet production and impact on the TMD PFF and transversely TMD FF.

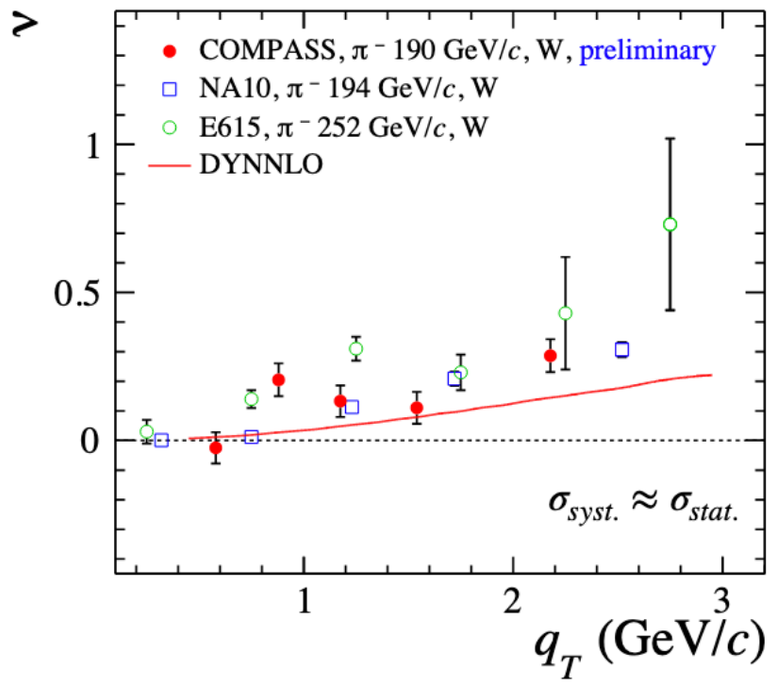
      [Z. Kang *et al.*, arXiv:2018.05383]

Talk by Y. Song, WG5 Thursday,
Systematic study of Lambda polarization in SIDIS and e+e-

Unpolarized TMDs: Boer-Mulder PDF

- **Unpolarized DY angular distribution**
  - **Pion-induced DY from COMPASS**

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

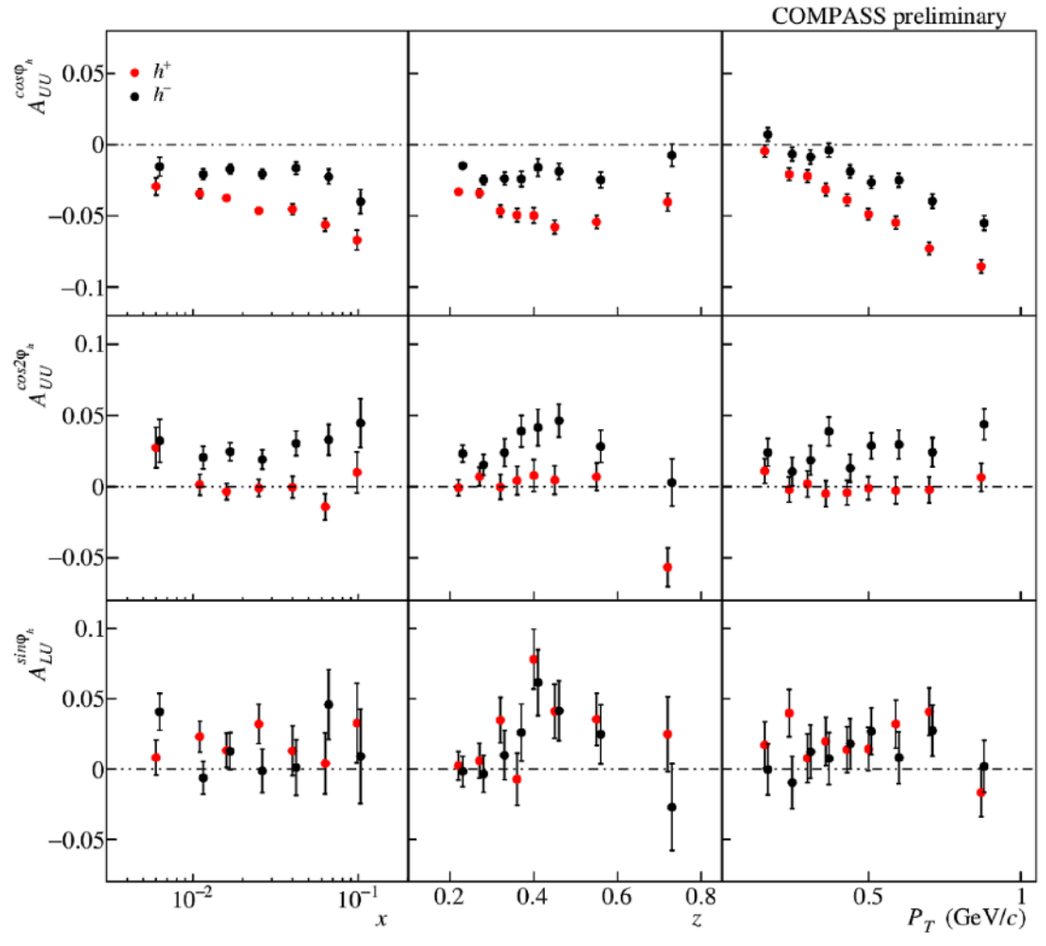


  - Tend to deviate from pQCD calculation, indicating nonzero BM effect

- **First photon-induced DY results at SeaQuest** Talk by K. Nagai, WG5 Wednesday

- **SIDIS measurements from COMPASS** Talk by J. Matousek, WG5 Wednesday
  - Transverse momentum distributions and azimuthal symmetries
  - Clear signal and kinematic dependence

$$A_{UU}^{\cos 2\phi_h} = \frac{F_{UU}^{\cos 2\phi_h}}{F_{UU,T}+\varepsilon F_{UU,L}}$$

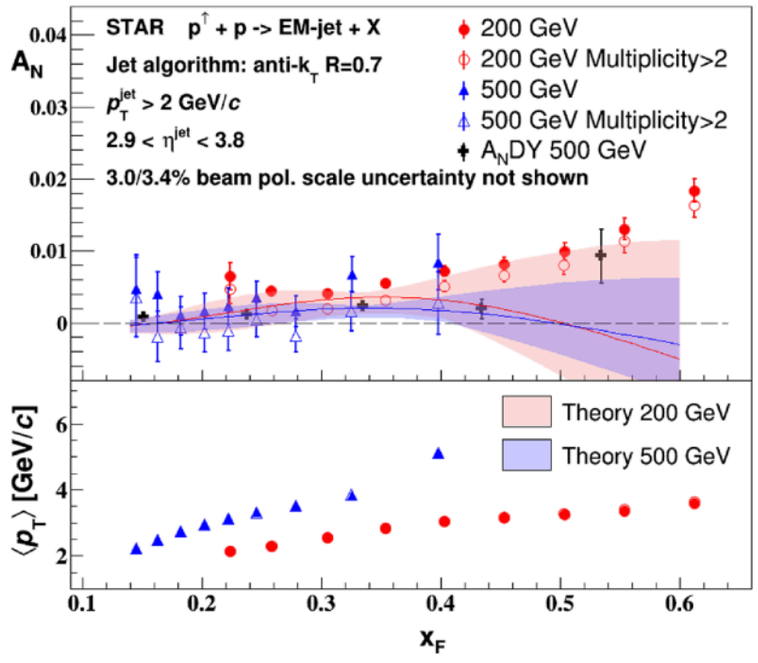


TSSA and Twist-3 multiparton correlators

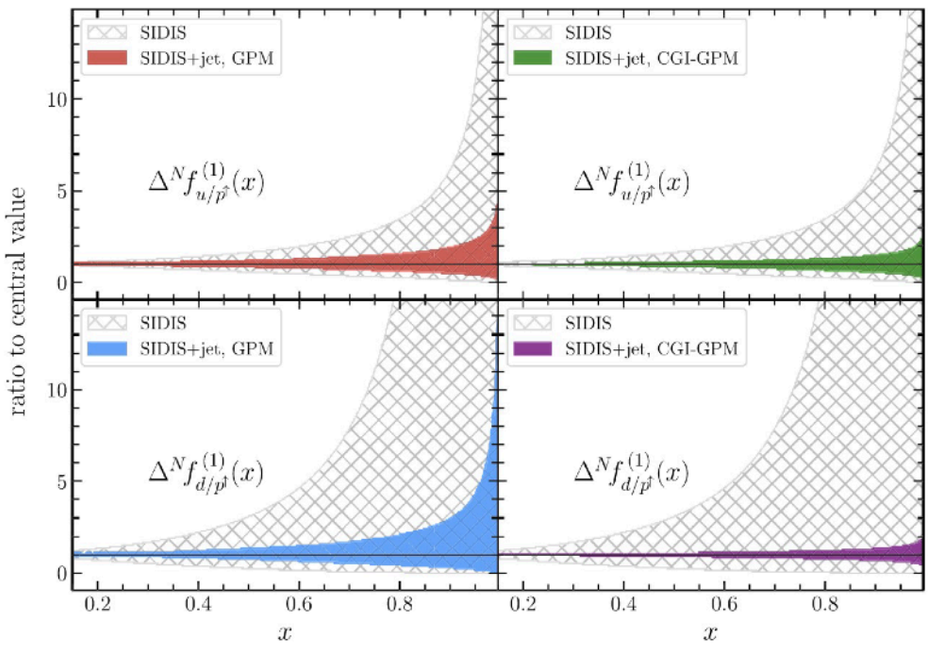
- Twist-3 trigluon correlation functions in collinear framework
  - Connected to TMDs [Ji, Qui, Vogelsan, Yuan Phys. Rev. Lett. 97, 082002 (2006)]

Talk by X. Liang, WG5 Thursday

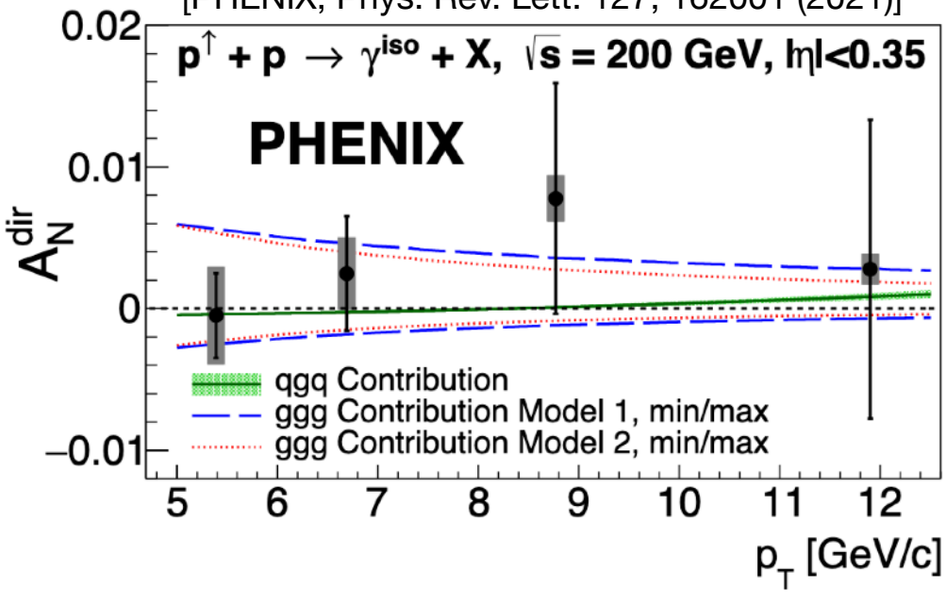
[STAR, PRD 103 (2021) 92009]



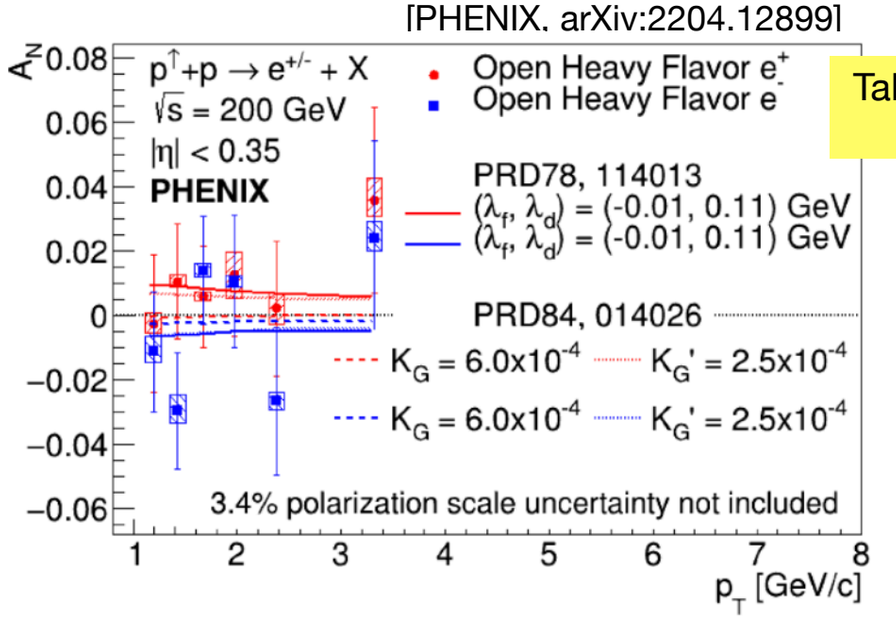
[M.Boglione, et al., Phys. Lett. B 815 (2021) 136135]



[PHENIX, Phys. Rev. Lett. 127, 162001 (2021)]



[PHENIX, arXiv:2204.12899]



Talk by Dillon Fitzgerald, WG5 Wednesday

Summary

- **The study of nucleon spin has revealed the complicated and rich nature of the QCD**
- **New experimental data and theoretical developments are leading us into the precision era of 3D nucleon structure**
- **Future programs: Toward the understanding 3D structure of the nucleon**