Progress in the exploration of nucleon’s spin structures

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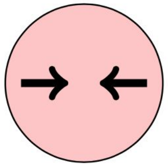
CIPANP
Aug 31 2022

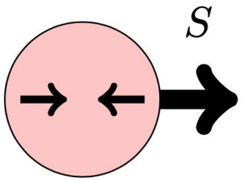
Jefferson Lab

Collinear Spin structures



$$f = f_{\rightarrow} + f_{\leftarrow}$$

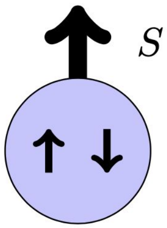
$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T}){\color{red}\gamma^+}\psi_i(0)|N\rangle$$



$$\Delta f = f_{\rightarrow} - f_{\leftarrow}$$

Helicity distribution

$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T}){\color{red}\gamma^+\gamma_5}\psi_i(0)|N\rangle$$



$$\delta_\mathrm{T} f = f_{\uparrow} - f_{\downarrow}$$

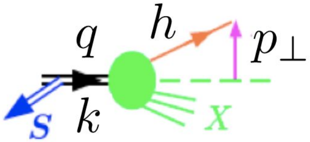
Transversity

$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T}){\color{red}\gamma^+\gamma_\perp\gamma_5}\psi_i(0)|N\rangle$$

TMD Spin structures

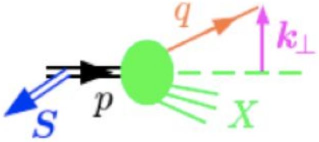
Sivers `89

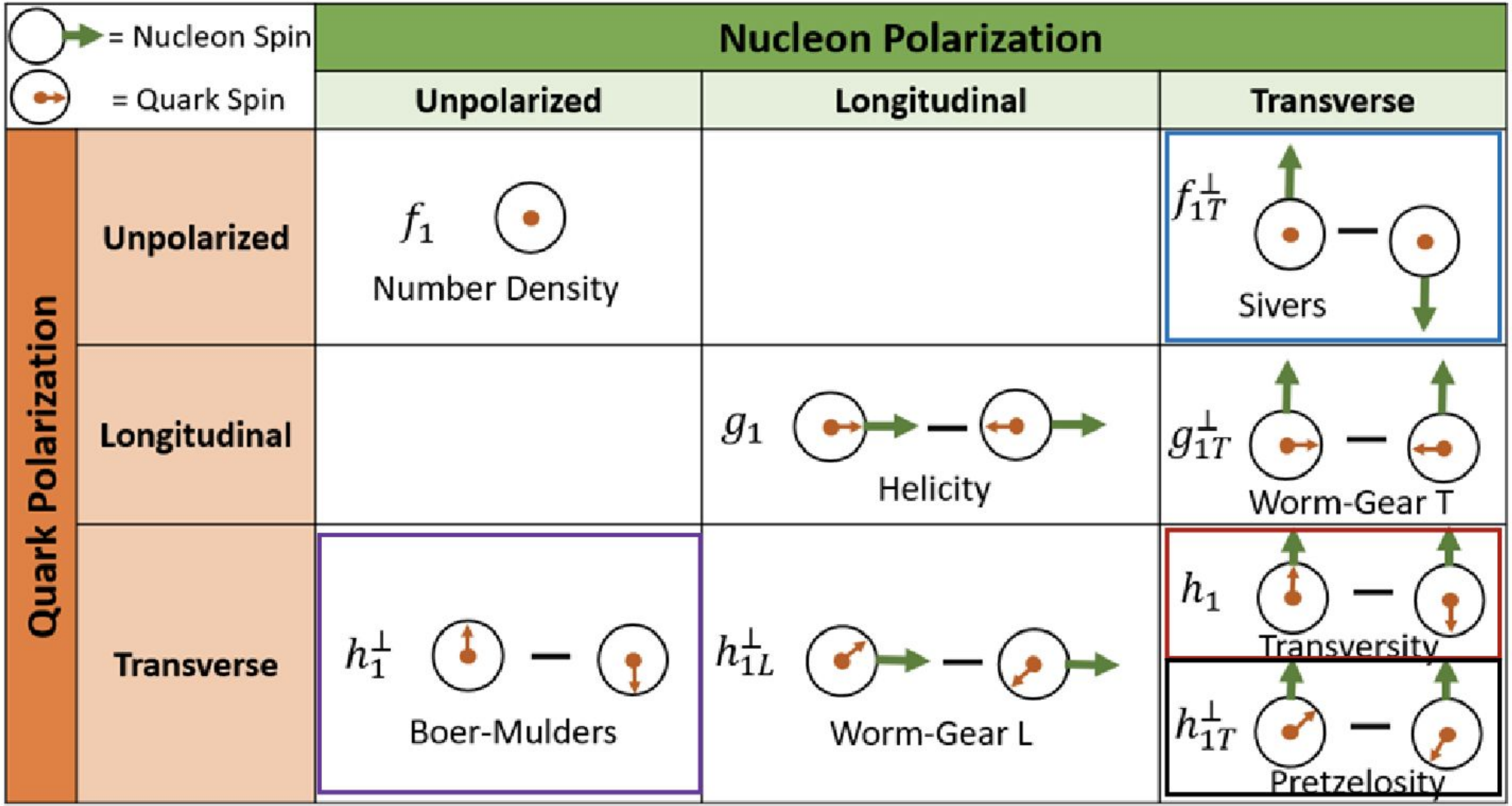
$$f_{q/h^\uparrow}(x,\vec{k}_\perp,\vec{S}) = f_{q/h}(x,k_\perp^2) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp^2)\vec{S}\cdot(\hat{P}\times\vec{k}_\perp)$$



Collins `92

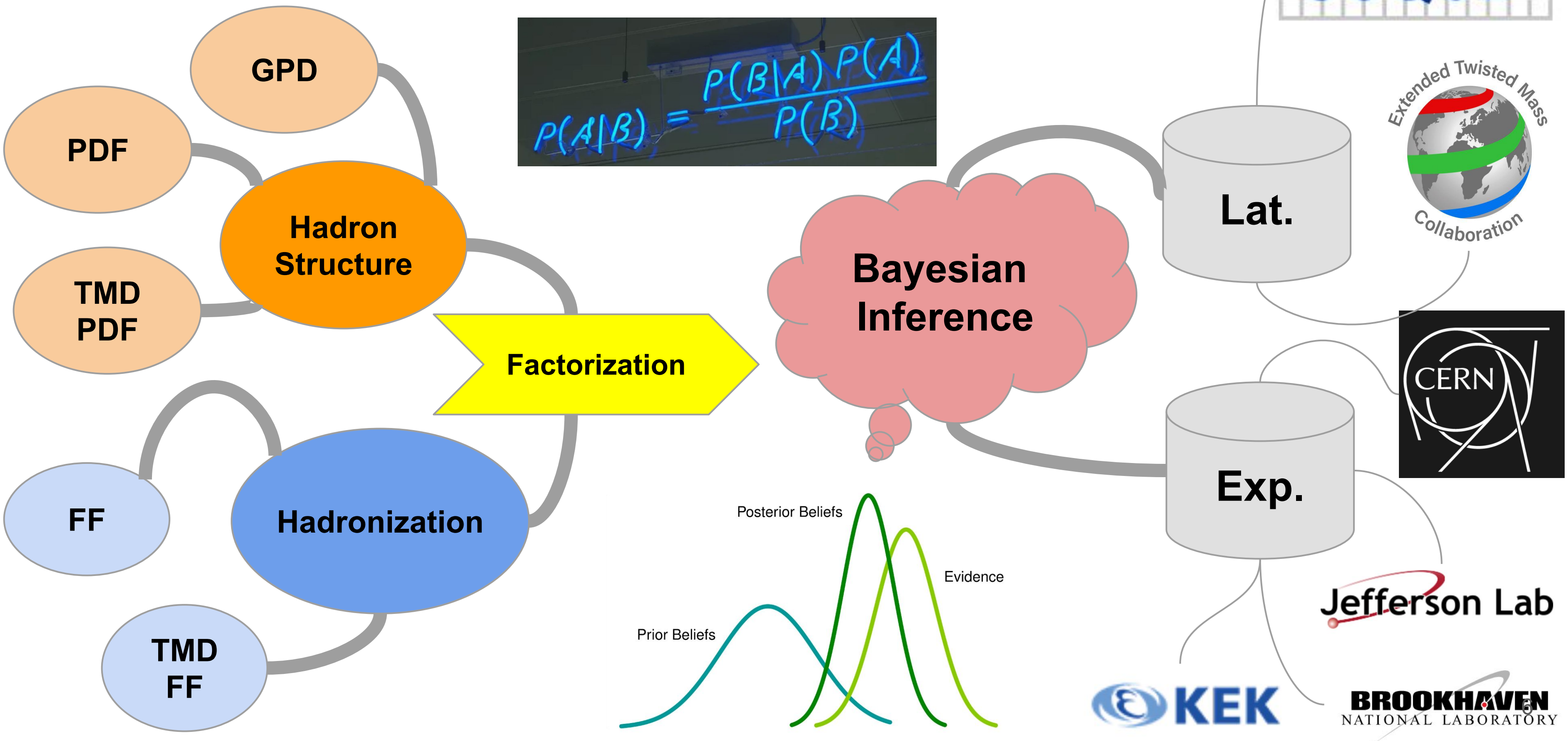
$$D_{q/h}(z,\vec{p}_\perp,\vec{s}_q) = D_{q/h}(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\vec{s}_q\cdot(\hat{k}\times\vec{p}_\perp)$$




= Nucleon Spin
= Quark Spin
Nucleon Polarization
Unpolarized
Longitudinal
Transverse
Quark Polarization
Unpolarized
Longitudinal
Transverse
f_1
Number Density
$f_{1T}^{\perp}$
Sivers
g_1
Helicity
$g_{1T}^{\perp}$
Worm-Gear T
$h_1^{\perp}$
Boer-Mulders
$h_{1L}^{\perp}$
Worm-Gear L
h_1
Transversity
$h_{1T}^{\perp}$
Pretzelosity

- How do we measure these structures?
    - We cannot measure them but we can infer them from data
- Key elements for inference
    - Factorization/evolution
    - Input scale modeling
    - Likelihood function
    - Test of universality

QCD global analysis paradigm



Recent spin pheno studies

Updated QCD global analysis of single transverse-spin asymmetries: Extracting H˜, and the role of the Soffer bound and lattice QCD #5

Jefferson Lab Angular Momentum (JAM) and Jefferson Lab Angular Momentum Collaborations • Leonard Gamberg (Penn State U., Berks-Lehigh Valley) et al. (May 2, 2022)

Published in: *Phys.Rev.D* 106 (2022) 3, 034014 • e-Print: 2205.00999 [hep-ph]

First global QCD analysis of the TMD g1T from semi-inclusive DIS data #7

Shohini Bhattacharya (Brookhaven and Temple U.), Zhong-Bo Kang (UCLA and Stony Brook U.), Andreas Metz (Temple U.), Gregory Penn (Temple U. and Yale U.), Daniel Pitonyak (Lebanon Valley Coll.) (Oct 19, 2021)

Published in: *Phys.Rev.D* 105 (2022) 3, 034007 • e-Print: 2110.10253 [hep-ph]

Extraction of the Sivers function from SIDIS, Drell-Yan, and $W^{\pm}/Z$ boson production data with TMD evolution #13

Marcin Bury (Regensburg U.), Alexei Prokudin (Penn State U., Berks-Lehigh Valley and Jefferson Lab), Alexey Vladimirov (Regensburg U.) (Mar 4, 2021)

Published in: *JHEP* 05 (2021) 151 • e-Print: 2103.03270 [hep-ph]

Global analysis of the Sivers functions at NLO+NNLL in QCD #18

Miguel G. Echevarria (Alcala de Henares U.), Zhong-Bo Kang (UCLA and Stony Brook U.), John Terry (UCLA) (Sep 22, 2020)

Published in: *JHEP* 01 (2021) 126 • e-Print: 2009.10710 [hep-ph]

Origin of single transverse-spin asymmetries in high-energy collisions #34

Jefferson Lab Angular Momentum Collaboration • Justin Cammarota (Coll. William and Mary and Lebanon Valley Coll.) et al. (Feb 19, 2020)

Published in: *Phys.Rev.D* 102 (2020) 5, 054002 • e-Print: 2002.08384 [hep-ph]

The 3-dimensional distribution of quarks in momentum space #14

Alessandro Bacchetta (Pavia U. and INFN, Pavia), Filippo Delcarro (Jefferson Lab), Cristian Pisano (Cagliari U. and INFN, Cagliari), Marco Radici (INFN, Pavia) (Apr 29, 2020)

Published in: *Phys.Lett.B* 827 (2022) 136961 • e-Print: 2004.14278 [hep-ph]

Origin of single transverse-spin asymmetries in high-energy collisions

Justin Cammarota, Leonard Gamberg, Zhong-Bo Kang, Joshua A. Miller, Daniel Pitonyak, Alexei Prokudin, Ted C. Rogers, and Nobuo Sato (Jefferson Lab Angular Momentum (JAM) Collaboration)

Phys. Rev. D **102**, 054002 – Published 8 September 2020

First simultaneous extraction of spin structure from “all” SSAs by JAM

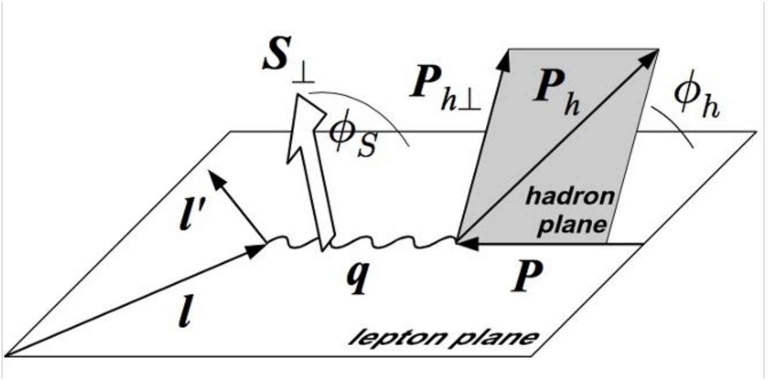
Cammarota, et al (‘20)

Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\text{pts.}}$	Refs.
$A_{\text{SIDIS}}^{\text{Siv}}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$150.0/126 = 1.19$	[65, 66, 68]
$A_{\text{SIDIS}}^{\text{Col}}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2), H_1^{\perp}(z,z^2p_\perp^2)$	$111.3/126 = 0.88$	[66, 68, 71]
$A_{\text{SIA}}^{\text{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^{\perp}(z,z^2p_\perp^2)$	$154.5/176 = 0.88$	[74–77]
$A_{\text{DY}}^{\text{Siv}}$	$\pi^- + p^{\uparrow} \to \mu^+\mu^- + X$	$f_{1T}^{\perp}(x,k_T^2)$	$5.96/12 = 0.50$	[73]
$A_{\text{DY}}^{\text{Siv}}$	$p^{\uparrow}+p \to (W^+,W^-,Z)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$31.8/17 = 1.87$	[72]
A_N^h	$p^{\uparrow}+p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi} f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$	[7, 9, 10, 13]

TABLE I. Summary of the SSAs analyzed in our global fit. There are a total of 18 different reactions. (UC and UL stand for “unlike-charged” and “unlike-like” pion combinations.) There are also a total of 6 non-perturbative functions when one takes into account flavor separation.

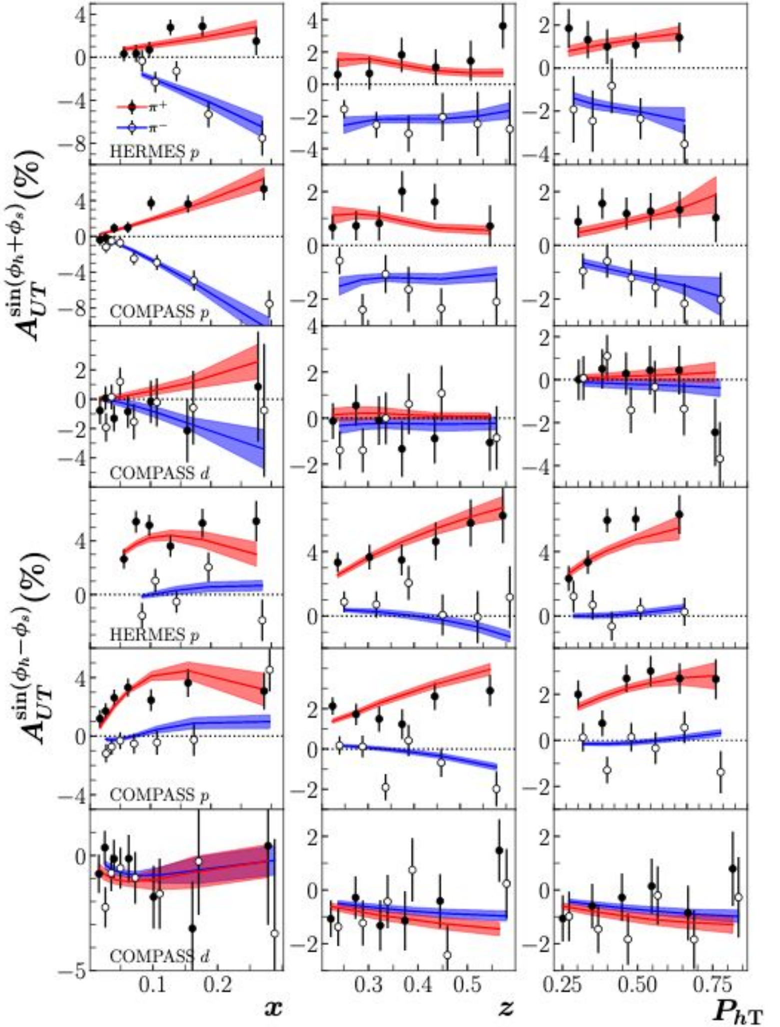
$$\chi^2/N_{\text{pts.}} = 520/517 = 1.01$$

SSAs in SIDIS

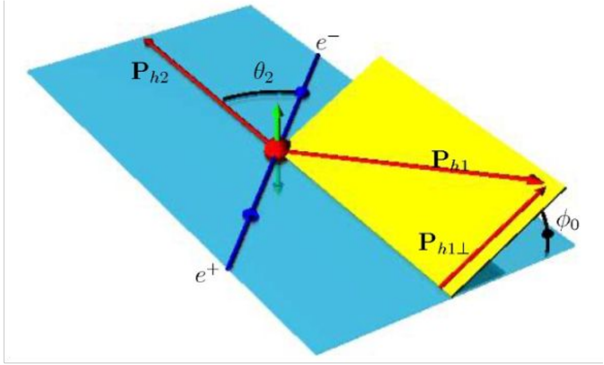


$$F_{UT}^{\sin(\phi_h-\phi_s)} = -\mathcal{C}_{\text{SIDIS}}\left[\frac{\hat{h}\cdot\vec{k}_T}{M} f_{1T}^{\perp} D_1\right]$$

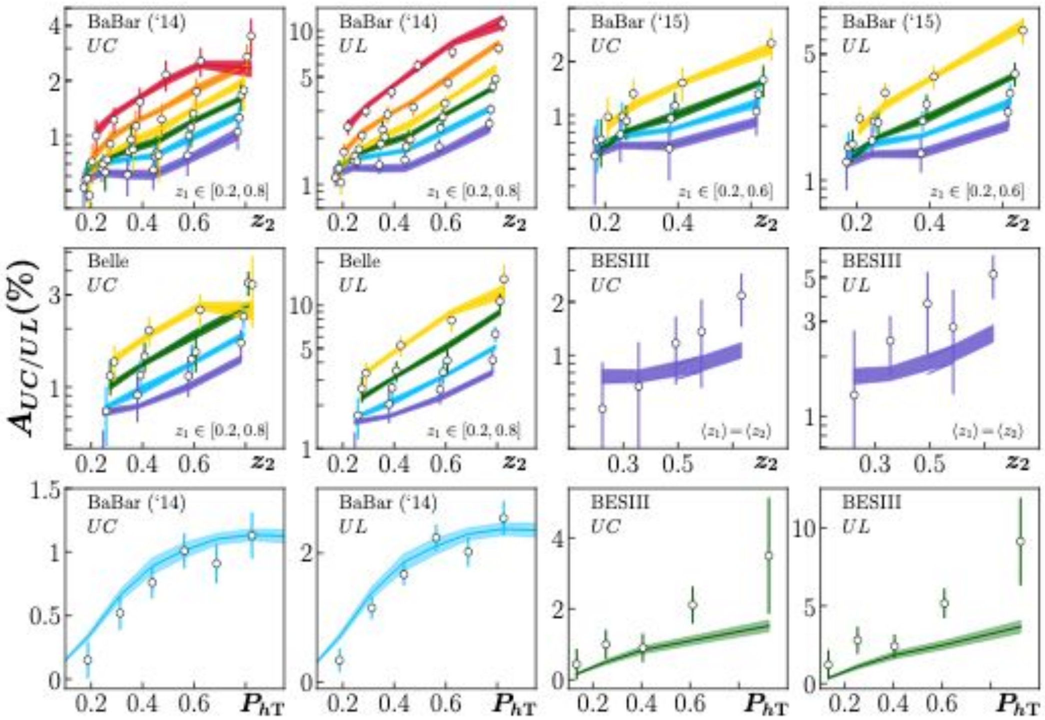
$$F_{UT}^{\sin(\phi_h+\phi_s)} = -\mathcal{C}_{\text{SIDIS}}\left[\frac{\hat{h}\cdot\vec{p}_T}{M_h} h_1 H_1^{\perp}\right]$$



SSAs in e+ e-

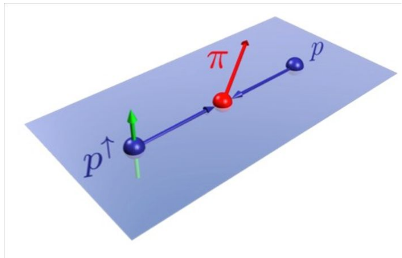


$$F^{h_1 h_2}_{\cos 2\phi_0} = \mathcal{C}_{\text{SIA}} \left[\frac{2(\hat{h} \cdot \vec{p}_{1T})(\hat{h} \cdot \vec{p}_{2T}) - \vec{p}_{1T} \cdot \vec{p}_{2T}}{M_{h_1} M_{h_2}} H_1^{\perp} \bar{H}_1^{\perp} \right],$$



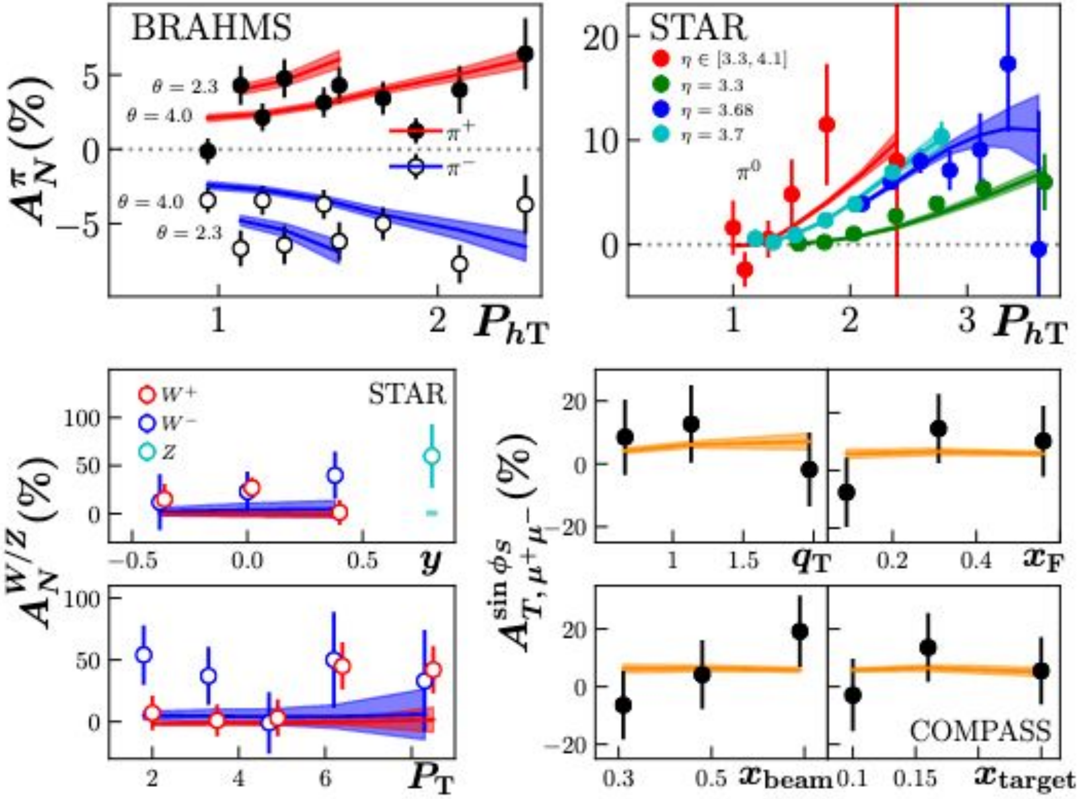
SSAs in pp

$$p(P, S_T) + p(P') \to h(P_h) + X$$

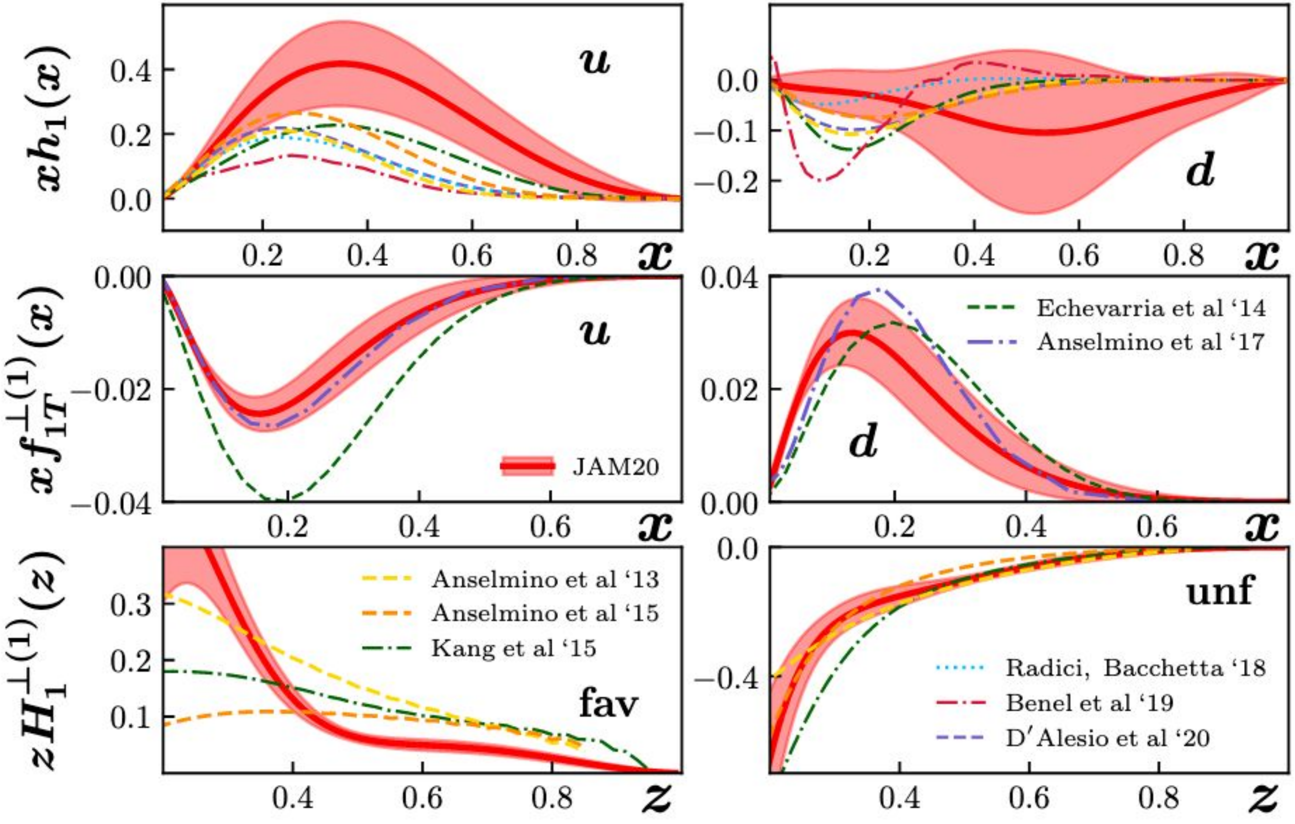


$$p(P, S_T) + p(P') \to \{W^+, W^-, \text{or } Z\} + X\,,$$

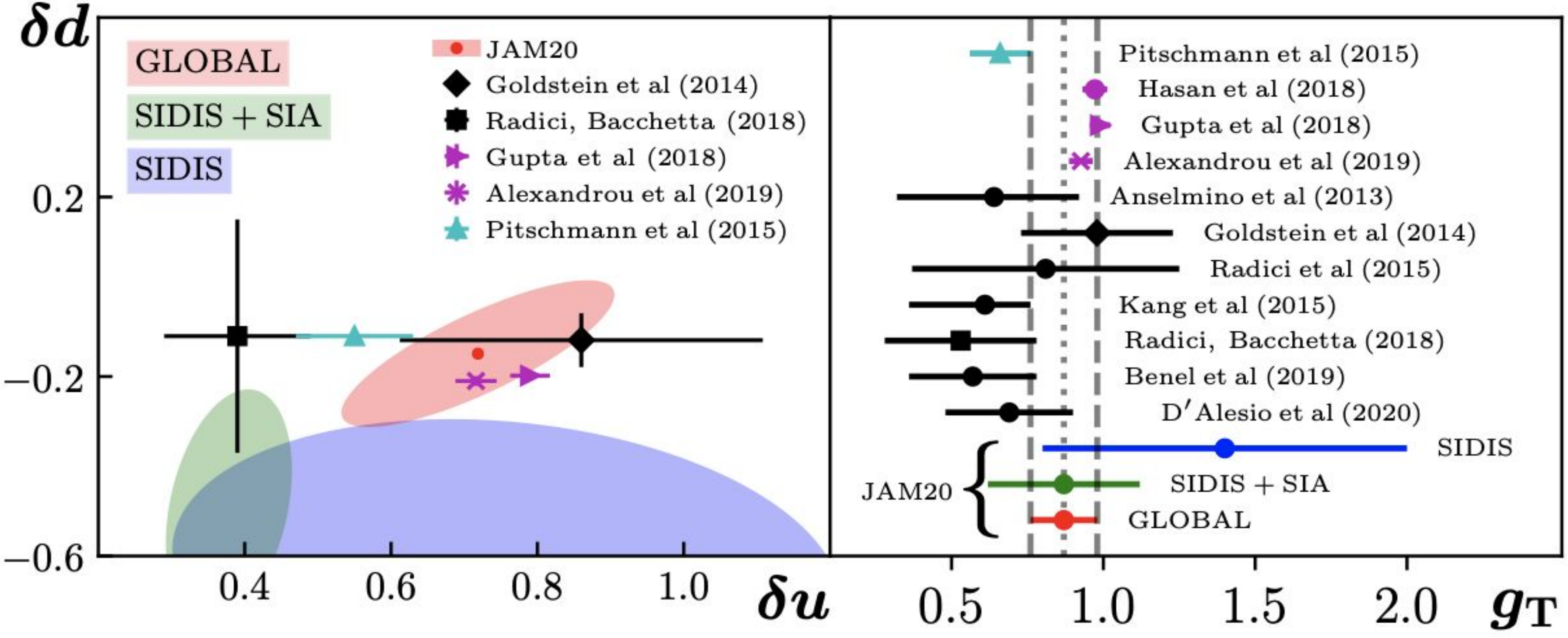
$$F_{TU}^1 = -\mathcal{C}_{\text{ew}}\left[\frac{\hat{h}\cdot\vec{k}_{1T}}{M} f_{1T}^{\perp}\bar{f}_1\right]$$



Spin structures



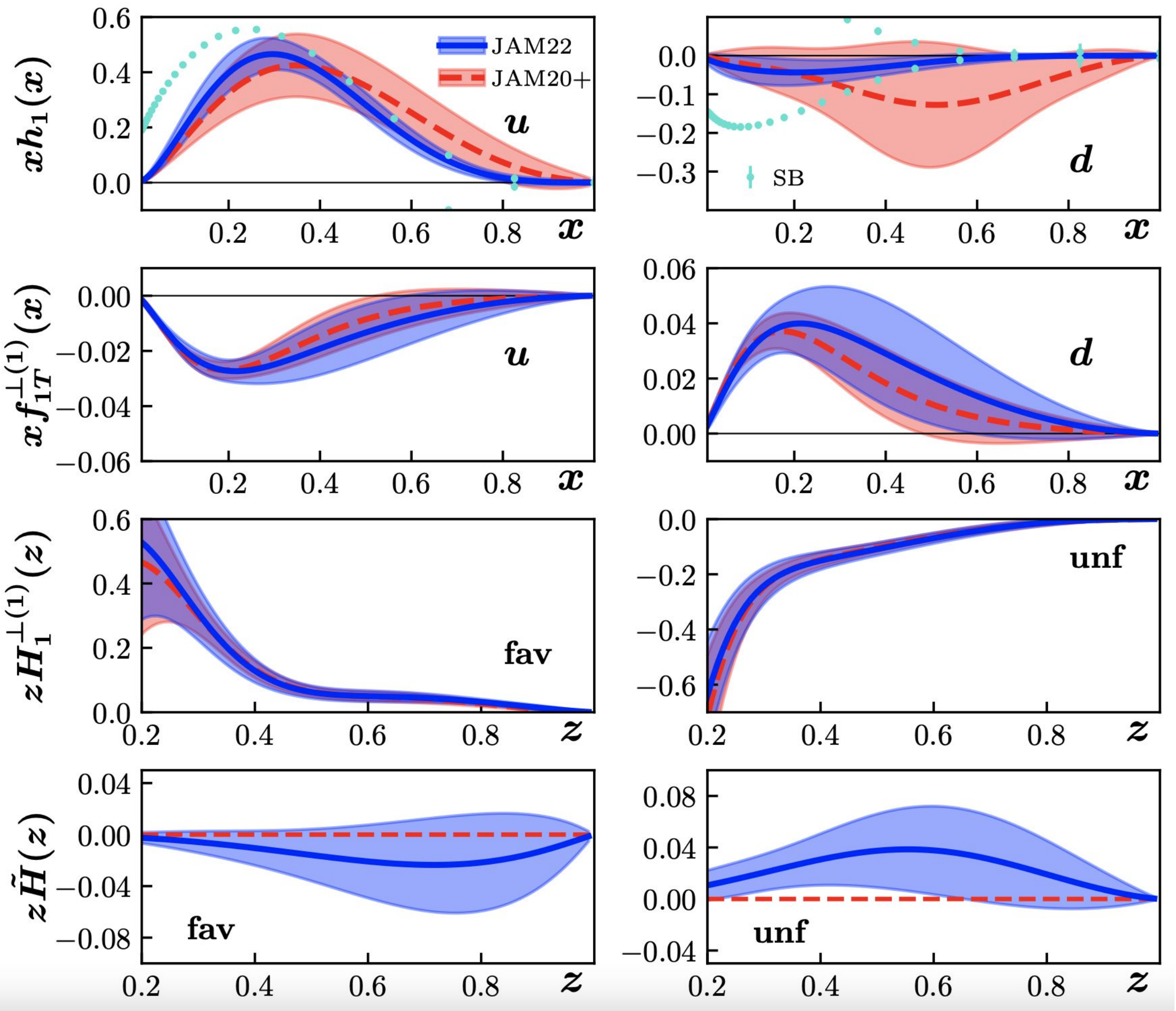
Tensorcharges



Updated version JAM 22

Observable	Reactions	Non-Perturbative Function(s)	χ^2/npts	Exp. Refs.
$A_{UT}^{\sin(\phi_h-\phi_S)}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$182.9/166=1.10$	[22, 24, 27]
$A_{UT}^{\sin(\phi_h+\phi_S)}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,\vec{k}_T^2), H_1^\perp(z,z^2\vec{p}_T^2)$	$181.0/166=1.09$	[22, 24, 27]
$^*A_{UT}^{\sin\phi_S}$	$e+p^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x), \tilde{H}(z)$	$18.6/36=0.52$	[22, 24, 27]
$A_{UC/UL}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^\perp(z,z^2\vec{p}_T^2)$	$154.9/176=0.88$	[29–32]
$A_{T,\mu^+\mu^-}^{\sin\phi_S}$	$\pi^- + p^\uparrow \to \mu^+\mu^- + X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$6.92/12=0.58$	[34]
$A_N^{W/Z}$	$p^\uparrow + p \to (W^+,W^-,Z)+X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$30.8/17=1.81$	[35]
A_N^π	$p^\uparrow + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x)=\frac{1}{\pi}f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z), \tilde{H}(z)$	$70.4/60=1.17$	[7, 9, 10, 13]
Lattice g_T	——	$h_1(x)$	$1.82/1=1.82$	[89]

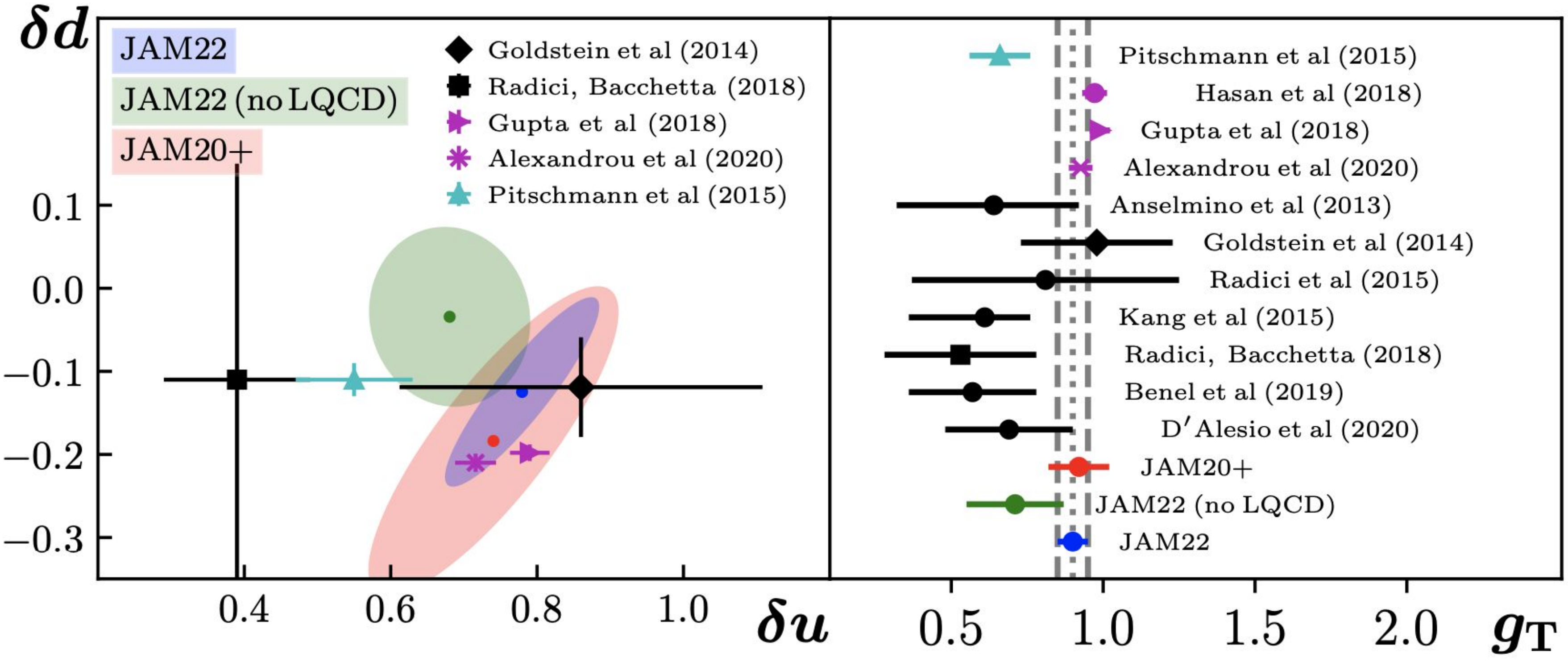
TABLE I: Summary of the observables analyzed in JAM3D-22 . There are a total of 21 different reactions. There are also a total of 8 non-perturbative functions when one takes into account flavor separation. The χ^2 is computed based on calculating for each point the theory expectation value from the replicas. *For the $A_{UT}^{\sin\phi_S}$ data we only use the x- and z-projections.



Inclusion of Soffer bounds + lattice moments

qgq FF

Tensorcharges ('22)

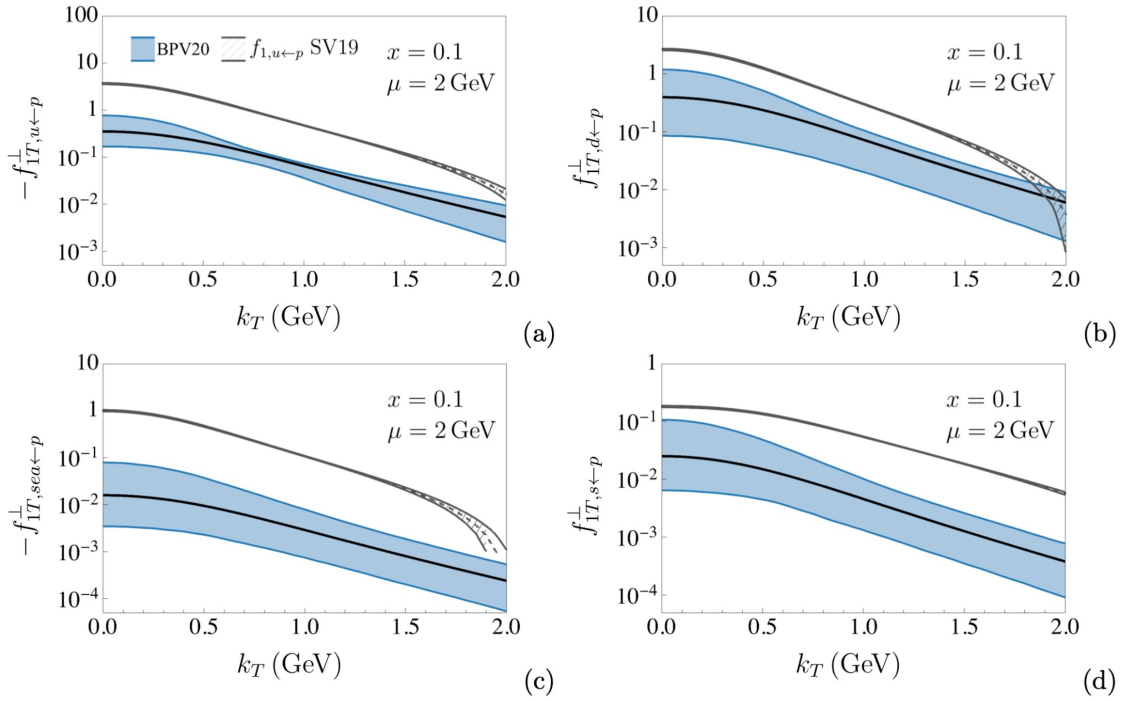


Extraction of the Sivers function from SIDIS, Drell-Yan, and $W^{\pm}/Z$ boson production data with TMD evolution

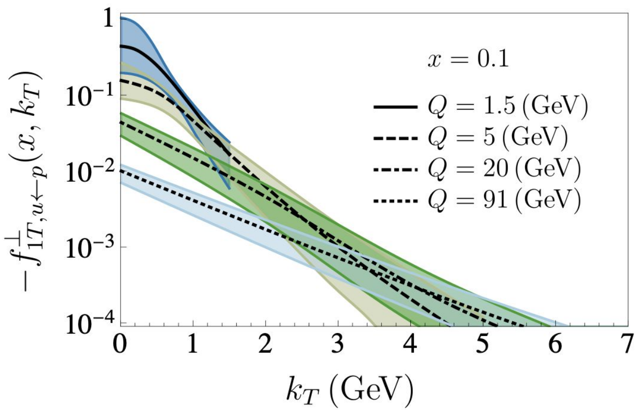
Marcin Bury[a] **Alexei Prokudin**[b,c] **Alexey Vladimirov**[a]

SIDIS	N_{pt}	χ^2/N_{pt}	DY	N_{pt}	χ^2/N_{pt}
Compass08	4	$0.29^{+0.30}_{-0.01}$	CompassDY	2	$0.19^{+0.49}_{-0.15}$
Compass16	10	$0.34^{+0.36}_{+0.01}$	STAR.W+	5	$0.72^{+0.69}_{+0.40}$
Hermes π^+	11	$0.79^{+0.16}_{-0.05}$	STAR.W-	5	$0.92^{+0.31}_{-0.14}$
Hermes π^-	11	$0.49^{+0.08}_{+0.01}$	STAR.Z	1	$2.04^{+0.10}_{-1.15}$
Hermes K^+	12	$1.36^{+0.15}_{-0.11}$			
Hermes K^-	12	$1.62^{+0.12}_{-0.01}$			
Jlab	3	$0.26^{+1.13}_{-0.04}$			
SIDIS total	63	$0.88^{+0.15}_{+0.05}$	DY total	13	$0.90^{+0.31}_{+0.00}$
Total SIDIS and DY				76	$0.88^{+0.15}_{+0.05}$

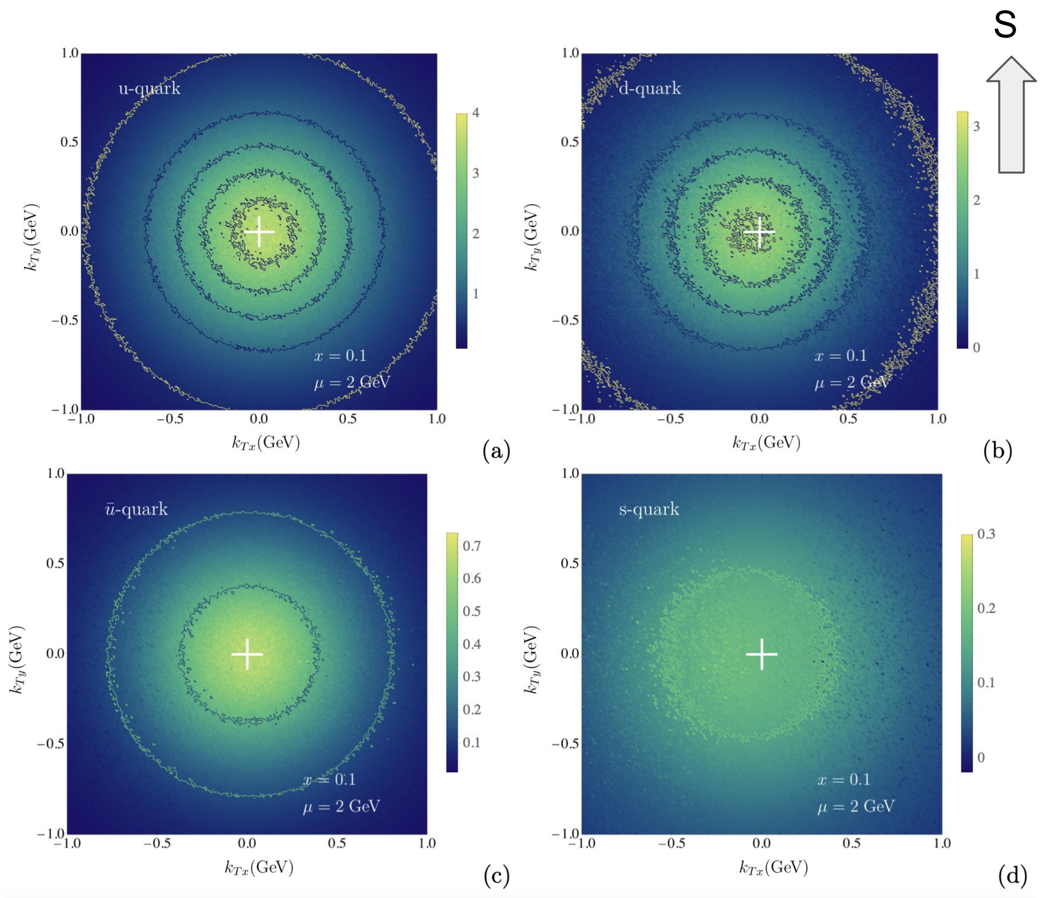
Sivers function

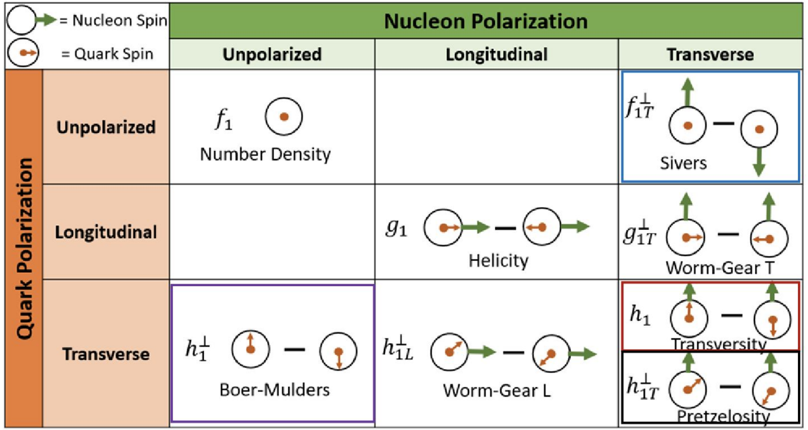


Evolution effects

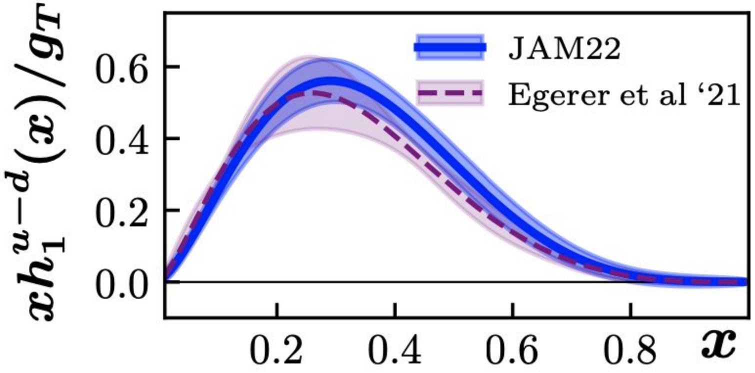


Momentum space tomography





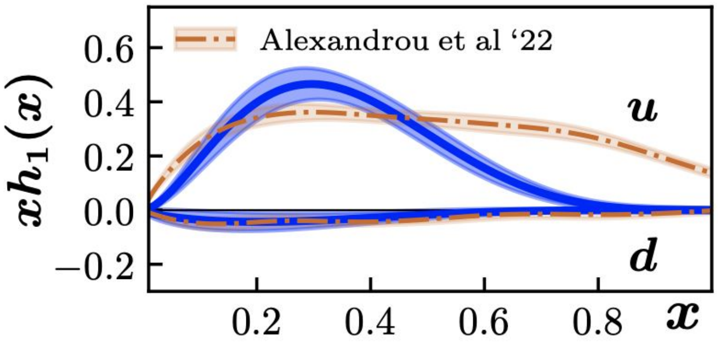
Synergies with LQCD



Ioffe-time distributions

$$h(x,\mu) = \int_{-\infty}^{\infty} \frac{d\nu}{2\pi} e^{-ix\nu} \mathcal{I}(\nu,\mu) \qquad \text{with} \qquad ,$$

$$2P^+ S^{\rho_\perp} \mathcal{I}(P^+ z^-, \mu) = \langle P, S^{\rho_\perp} | \bar{\psi}(z^-) \gamma^+ \gamma^{\rho_\perp} \gamma_5 W_+(z^-, 0) \psi(0) | P, S^{\rho_\perp} \rangle$$



quasi distributions

$$\tilde{q}(x, P_3) = \int_{-z_{\max}}^{+z_{\max}} \frac{dz}{4\pi} e^{-ixP_3 z} \langle N | \overline{\psi}(0,z) \, \Gamma W(z,0) \, \psi(0,0) | N \rangle \, ,$$

Hybrid QED/QCD factorization

Liu, Melnitchouk, Qiu, NS ('21)

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sum_i w_i F_i(x,Q^2,z,\mathbf{P}_{h\perp})$$

⬇

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \int_{\zeta_{\min}}^{1} d\zeta \int_{\xi_{\min}(\zeta)}^{1} d\xi\, \underline{f_{k/l}(\xi) D_{k'/l'}(\zeta)}$$
$$\times \frac{\hat{x}}{x\xi\zeta}\left[\frac{\alpha^2}{\hat{x}\hat{y}\widehat{Q}^2}\frac{\hat{y}}{2(1-\hat{\varepsilon})}\left(1+\frac{\hat{\gamma}^2}{2\hat{x}}\right)\sum_i \hat{w}_i F_i(\hat{x},\widehat{Q}^2,\hat{z},\hat{\mathbf{P}}_{h\perp})\right]$$

Collinear LDFs and LFFs

Angular projections

$$\left.\frac{\mathrm{d}^6\sigma_{\ell P(S_T)\to\ell' P_h X}}{\mathrm{d}x_B\mathrm{d}y\,\mathrm{d}\psi\,\mathrm{d}z_h\,\mathrm{d}P_{hT}^2}\right|_{UT,T}^{\sin(\phi_h-\phi_S)} = \int \mathrm{d}\phi_h\,\mathrm{d}\phi_S\,\sin(\phi_h-\phi_S)\,\frac{\mathrm{d}^6\sigma_{\ell P(S_T)\to\ell' P_h X}}{\mathrm{d}x_B\mathrm{d}y\,\mathrm{d}\psi\,\mathrm{d}z_h\,\mathrm{d}\phi_h\mathrm{d}P_{hT}^2},$$

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} \overset{\text{no QED}}{=} \int \mathrm{d}\phi_h\,\mathrm{d}\phi_S\,\sin(\phi_h-\phi_S)\Big[\sin(\phi_h-\phi_S)F_{UT,T}^{\sin(\phi_h-\phi_S)} + \sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}\Big].$$

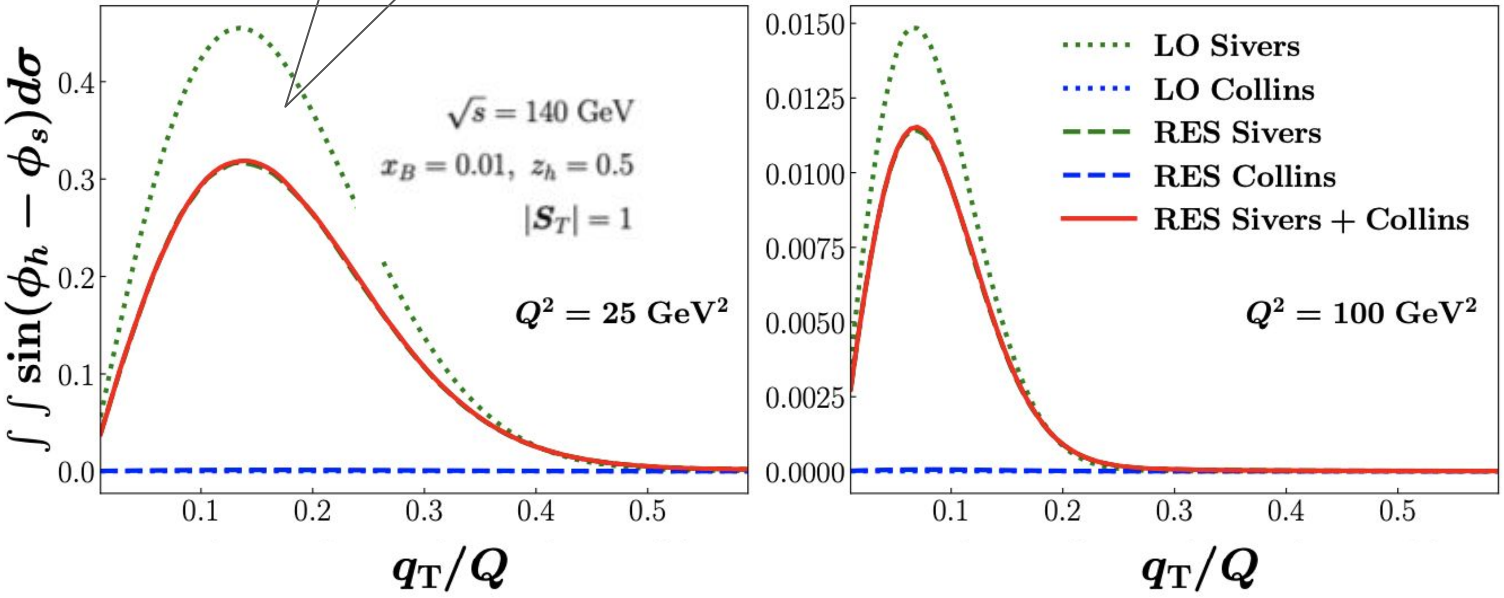
$$\int d\phi_h d\phi_S\ \sin(\phi_h-\phi_S)\ \sin(\phi_h+\phi_S) = 0$$

BUT with QED this does not hold!

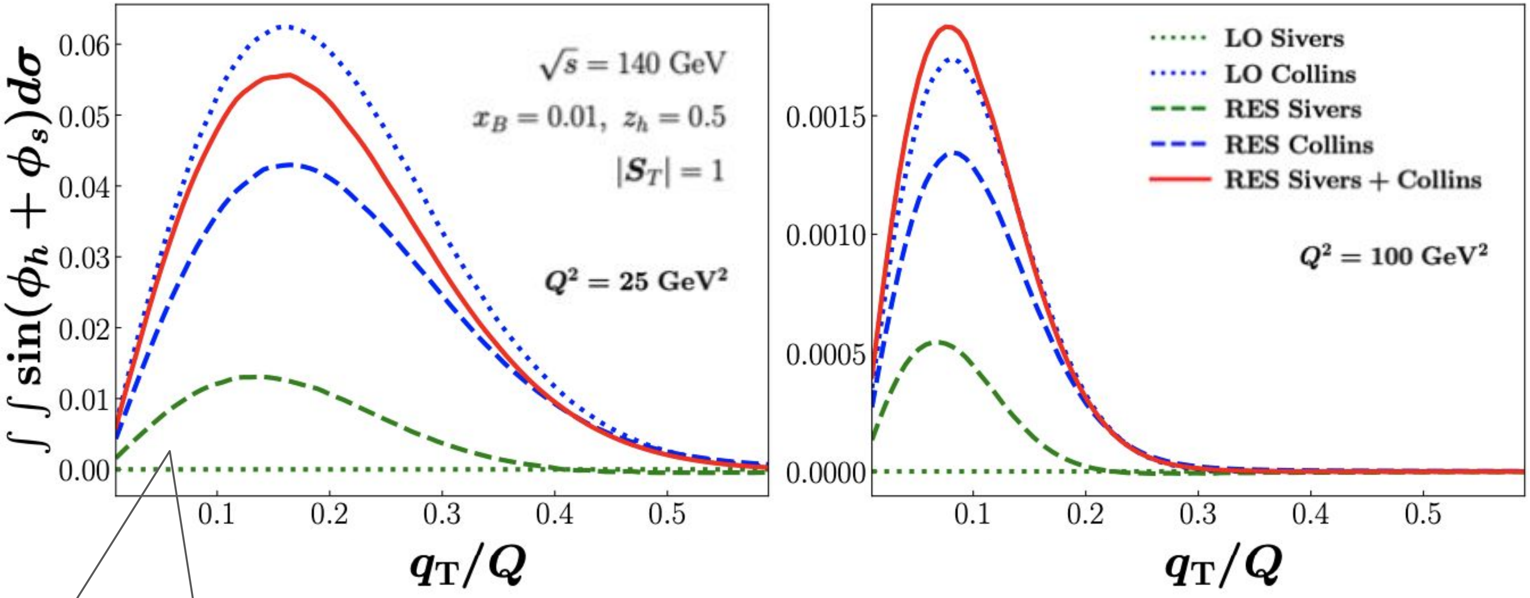
$$\int \mathrm{d}\phi_h\,\mathrm{d}\phi_S\,\sin(\phi_h-\phi_S)\sin(\hat{\phi}_h+\hat{\phi}_S) \neq 0$$

Sivers

Signal washes out



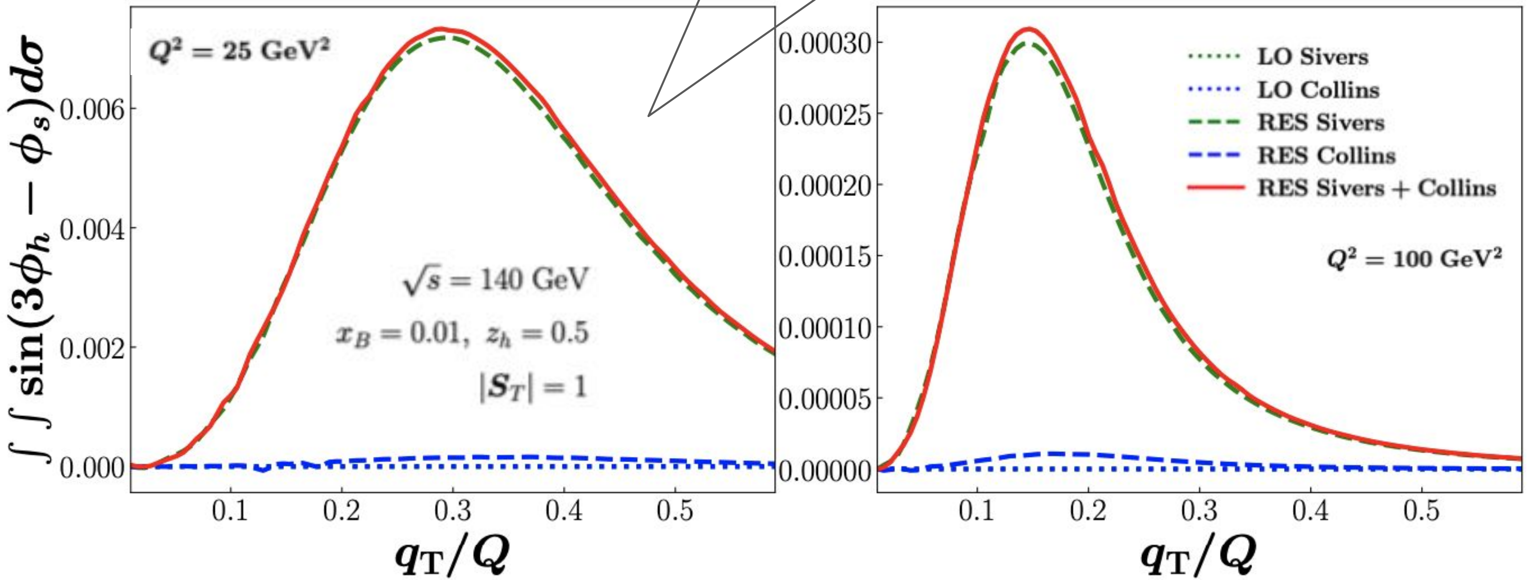
Collins



Leaking effects from Sivers

$3\phi_h - \phi_s$

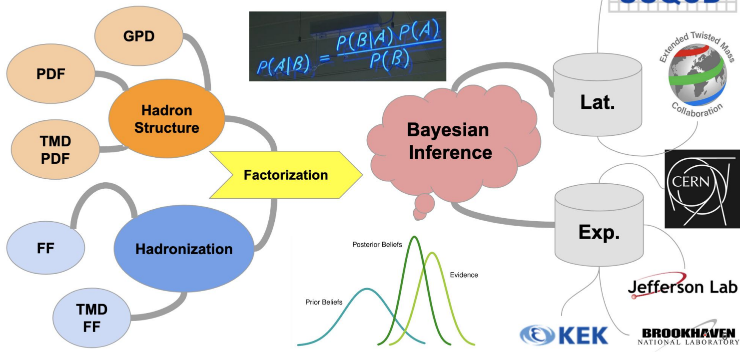
Fake signal is created



Summary/Outlook

- New era of QCD global analysis has started -> spin physics
- First generation of global analysis with uncertainty quantification are now available
- The community has build tools to embrace new data from JLab 12 GeV and prepare for EIC

QCD global analysis paradigm



$$\mathcal{L}_{QCD} = \sum_q \bar{\psi}_q (i\gamma_\mu D^\mu - m_q)\psi_q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$