Extracting the Proton's Tensor Charge from QCD Phenomenology

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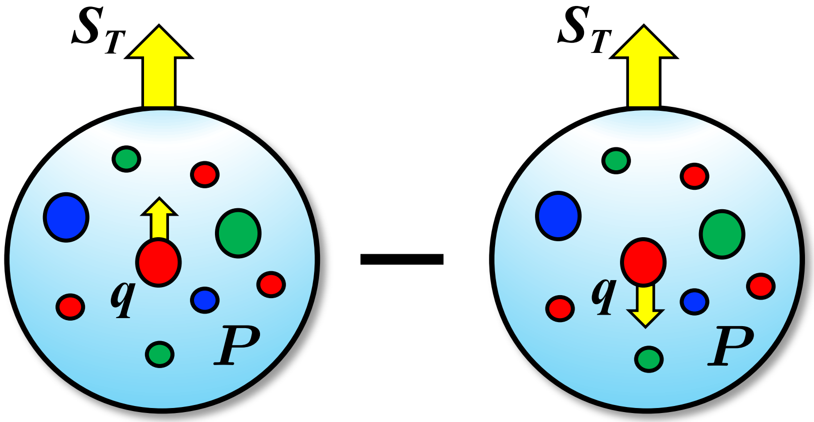
Outline

- Background and motivation
- Overview of two phenomenological approaches
- Previous results and impact studies for future experiments
- Recent analyses and current status
- Summary and outlook

Background and Motivation

$$S_T^i\, \boldsymbol{h_1^q(x)} = \frac{1}{2}\int \frac{d\xi^-}{2\pi} e^{ixP^+\xi^-}\,\mathrm{Tr}[\langle P,S|\bar{\psi}_q(0)\mathcal{W}(0,\xi^-)\psi_q(\xi^-)i\sigma^{i+}\gamma_5|P,S\rangle]$$

transversity PDF - universal parton density encoding the difference between the number of quarks with their spin aligned versus anti-aligned to the proton's spin when it's in a transverse direction



$$S_T^i\, h_1^q(x) = \frac{1}{2}\int \frac{d\xi^-}{2\pi} e^{ixP^+\xi^-}\,\mathrm{Tr}[\langle P,S|\bar{\psi}_q(0)\mathcal{W}(0,\xi^-)\psi_q(\xi^-)i\sigma^{i+}\gamma_5|P,S\rangle]$$

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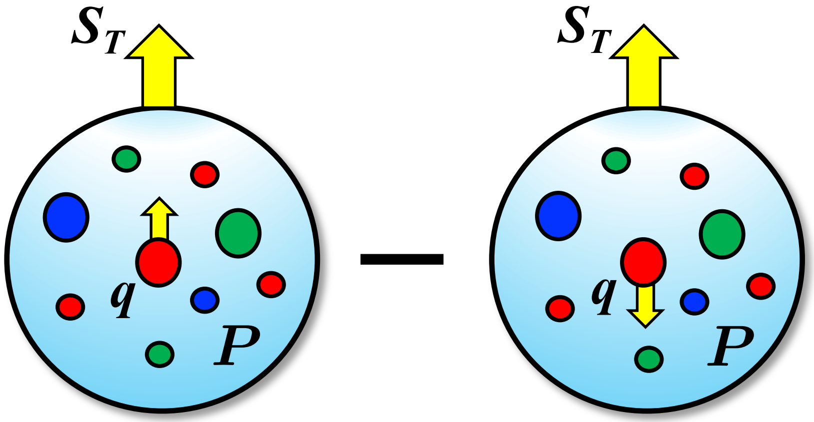


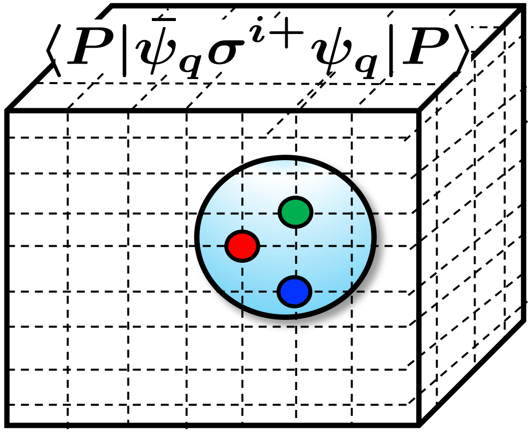
$$\delta q \equiv \int_0^1 dx\,[h_1^q(x) - h_1^{\bar{q}}(x)] \qquad g_T \equiv \delta u - \delta d$$

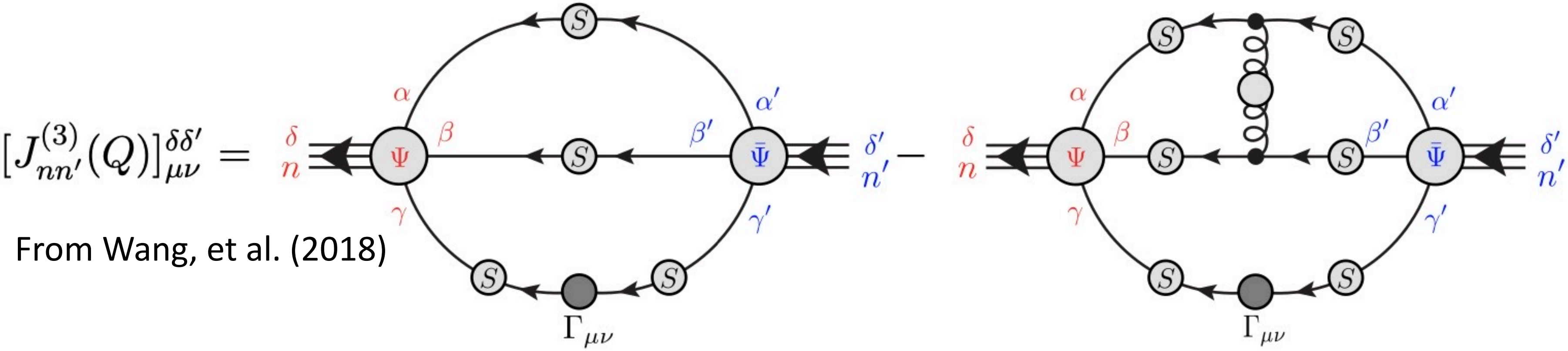
tensor charge for an individual flavor

isovector combination

$$\underbrace{\langle P|\bar{\psi}_q\sigma^{i+}\psi_q|P\rangle} = \boldsymbol{\delta q}\,[\bar{u}_P\sigma^{i+}u_P]$$

local matrix element - can be computed in lattice QCD as well as other approaches like Dyson-Schwinger equations





From Wang, et al. (2018)

- Importance of the nucleon tensor charge:
  - Like the scalar, vector, and axial charges, it is a fundamental charge of the nucleon (although scale dependent)
  - Since helicity PDF ≠ transversity PDF in relativistic quantum mechanics, it can be considered a measure of relativistic effects in the nucleon
  - Key point of comparison between QCD phenomenology/experiment and *ab initio* approaches like lattice QCD and DSE
  - Needed in certain beyond the Standard Model studies (e.g., beta decay, EDM)

$$\mathcal{L}_{n\to pe\bar{\nu}_e} \sim \ldots + 4\sqrt{2}G_F V_{ud}\, \boldsymbol{g_T}\, \epsilon_T\, \bar{p}\, \sigma^{\mu\nu} n\, \bar{e}\, \sigma_{\mu\nu} \nu_e + \ldots$$

Lagrangian for neutron beta decay

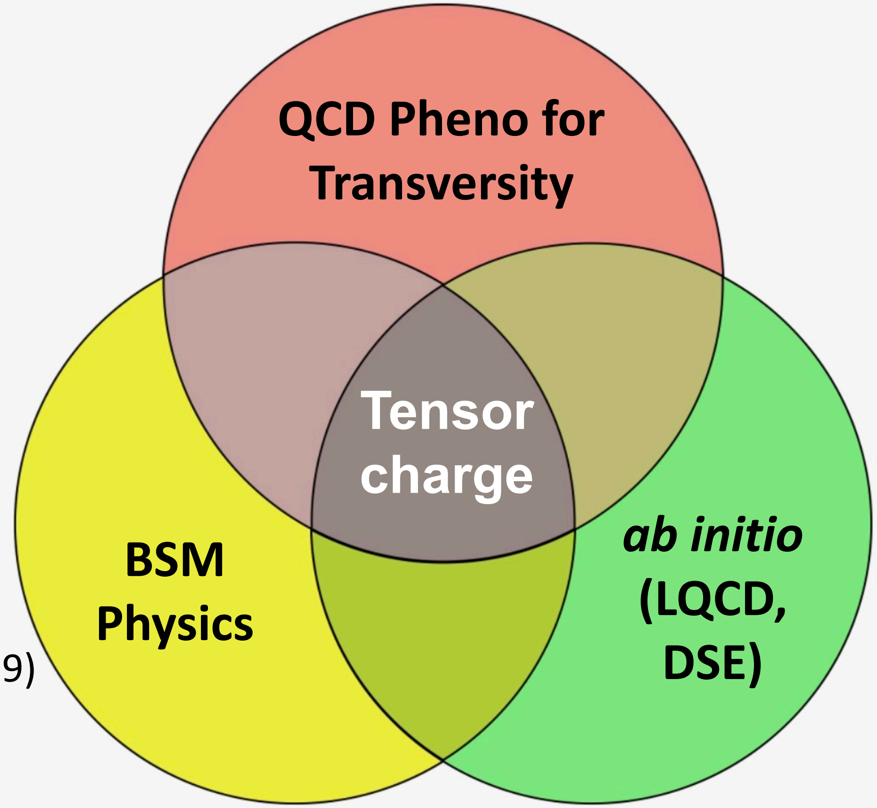
BSM coupling

$$\tilde{d}_p = \tilde{d}_u\, \boldsymbol{\delta u} + \tilde{d}_d\, \boldsymbol{\delta d}$$

proton EDM

quark EDMs

Anselmino, et al. (2007, 2009, 2013, 2015);
Goldstein, et al. (2014); Kang, et al. (2016); Radici, et al. (2013, 2015, 2018);
Benel, et al. (2020); D'Alesio, et al. (2020); Cammarota, et al. (2020);
Gamberg, et al. (2022); Cocuzza, et al. (in preparation)



QCD Pheno for Transversity

Tensor charge

BSM Physics

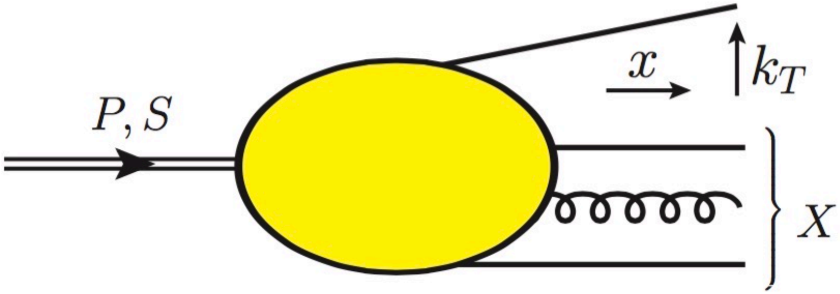
***ab initio* (LQCD, DSE)**

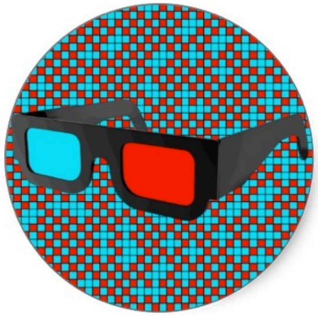
Courtoy, et al. (2015);
Yamanaka, et al. (2017);
Liu, et al. (2018);
Gonzalez-Alonso, et al. (2019)

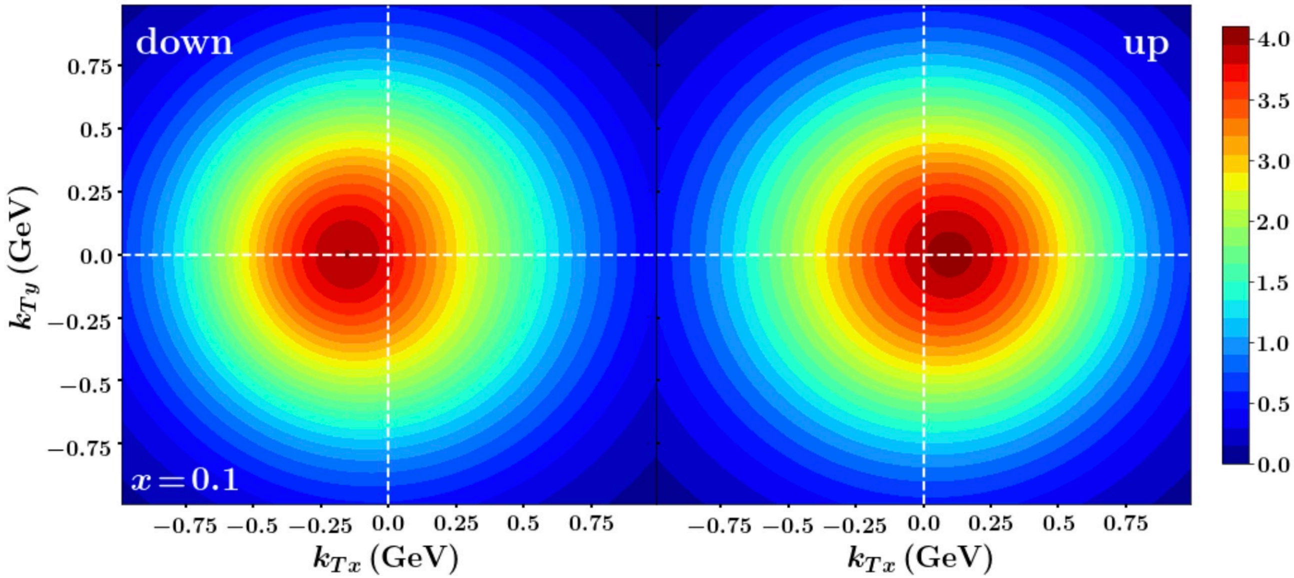
Gupta, et al. (2018);
Yamanaka, et al. (2018);
Hasan, et al. (2019);
Alexandrou, et al. (2019, 2023);
Yamanaka, et al. (2013);
Pitschmann, et al. (2015);
Xu, et al. (2015);
Wang, et al. (2018)

Overview of Two Phenomenological Approaches

Transverse Momentum Dependent/Collinear Twist-3 Approach







Transverse Momentum Dependent/Collinear Twist-3 Approach

intrinsic parton transverse momentum

TMD PDFs (x, k_T)

q pol. H pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T} $h_{1T}^\perp$

transversity
TMD PDF

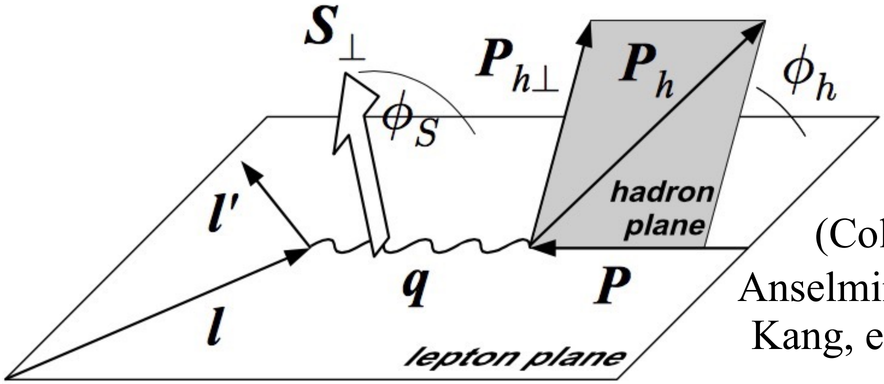
TMD FFs (z, $p_\perp$)

q pol. H pol.	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_{1T} $H_{1T}^\perp$

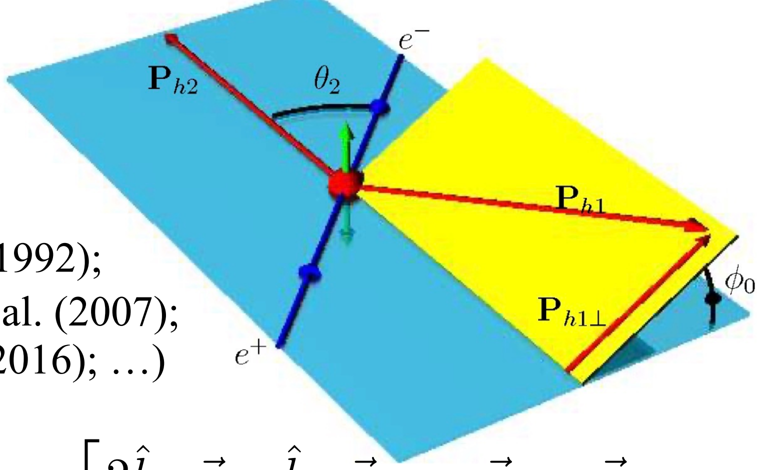
Collins
TMD FF

$\ell\, N^{\uparrow} \to \ell\, h\, X$

$e^+ e^- \to h_1 h_2 X$



(Collins (1992);
Anselmino, et al. (2007);
Kang, et al. (2016); …)



$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{p}_\perp}{M_h}\boldsymbol{h_1 H_1^\perp}\right] \qquad F_{UU}^{\cos(2\phi_0)} = \mathcal{C}\left[\frac{2\hat{h}\cdot\vec{p}_{a\perp}\,\hat{h}\cdot\vec{p}_{b\perp} - \vec{p}_{a\perp}\cdot\vec{p}_{b\perp}}{M_a M_b}\boldsymbol{H_1^\perp\,\bar{H}_1^\perp}\right]$$

TMD/Collins-Soper-Sterman (CSS) Evolution

OPE

Sudakov exponentials (gluon radiation)

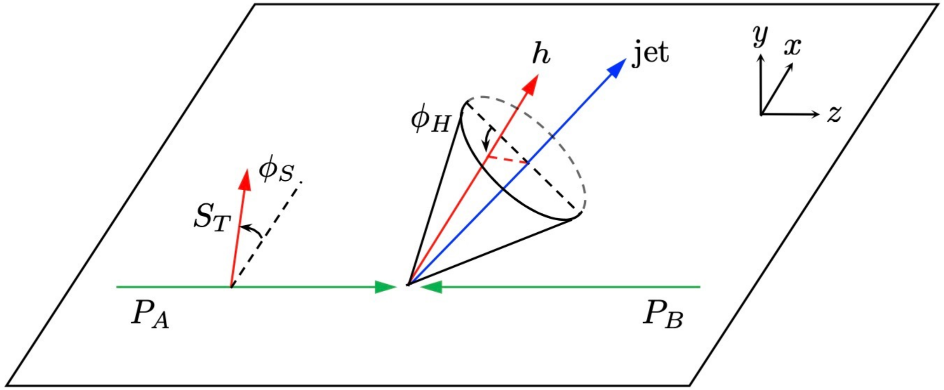
$$\boldsymbol{\tilde{h}_1(x, b_T; Q^2, \mu_Q)} \quad \sim \quad \boldsymbol{h_1(x; \mu_{b_*})}\exp\left[-S_{pert}(b_*(b_T); \mu_{b_*}, Q, \mu_Q) - S_{NP}^{h_1}(b_T, Q)\right]$$

$$\boldsymbol{\tilde{H}_1^{\perp(1)}(z, b_T; Q^2, \mu_Q)} \quad \sim \quad \boldsymbol{H_1^{\perp(1)}(z; \mu_{b_*})}\exp\left[-S_{pert}(b_*(b_T); \mu_{b_*}, Q, \mu_Q) - S_{NP}^{H_1^\perp}(b_T, Q)\right]$$

Parton model

$$h_1(x) = \int d^2\vec{k}_T\, h_1(x, \vec{k}_T^2) \qquad H_1^{\perp(1)}(z) = z^2\int d^2\vec{p}_\perp \frac{p_\perp^2}{2M_h^2} H_1^\perp(z, z^2 p_\perp^2)$$

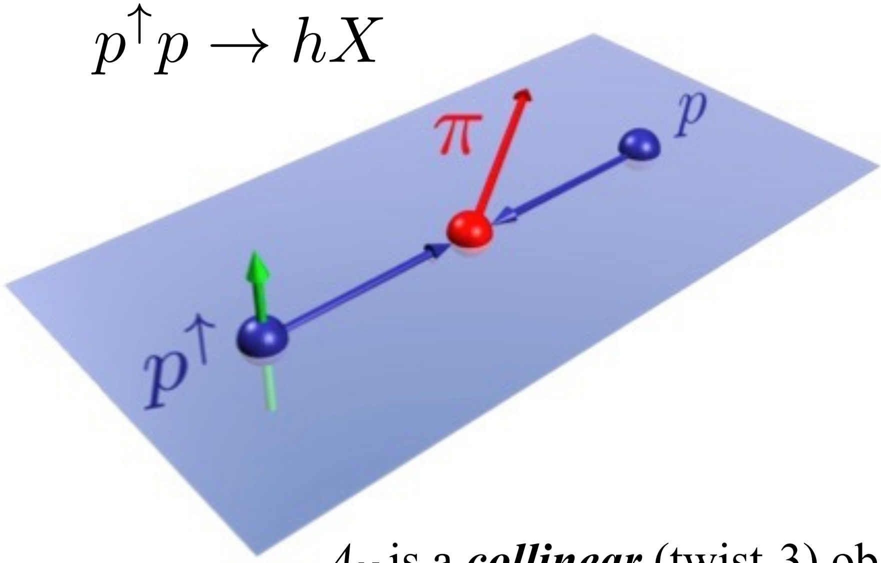
$$p^{\uparrow}p \to (h\,jet)\,X$$



(Yuan (2008); D'Alesio, Murgia, Pisano (2017); Kang, Prokudin, Ringer, Yuan (2017), …)

$$F_{UT}^{\sin(\phi_S-\phi_H)} \sim H_{ab\to c}^{\text{Collins}}(\hat{s},\hat{t},\hat{u}) \otimes \boldsymbol{h_1^a(x_1)} \otimes f_1^b(x_2) \otimes (j_\perp/(z_h M_h))\boldsymbol{H_1^{\perp h/c}(z_h, j_\perp^2)}$$

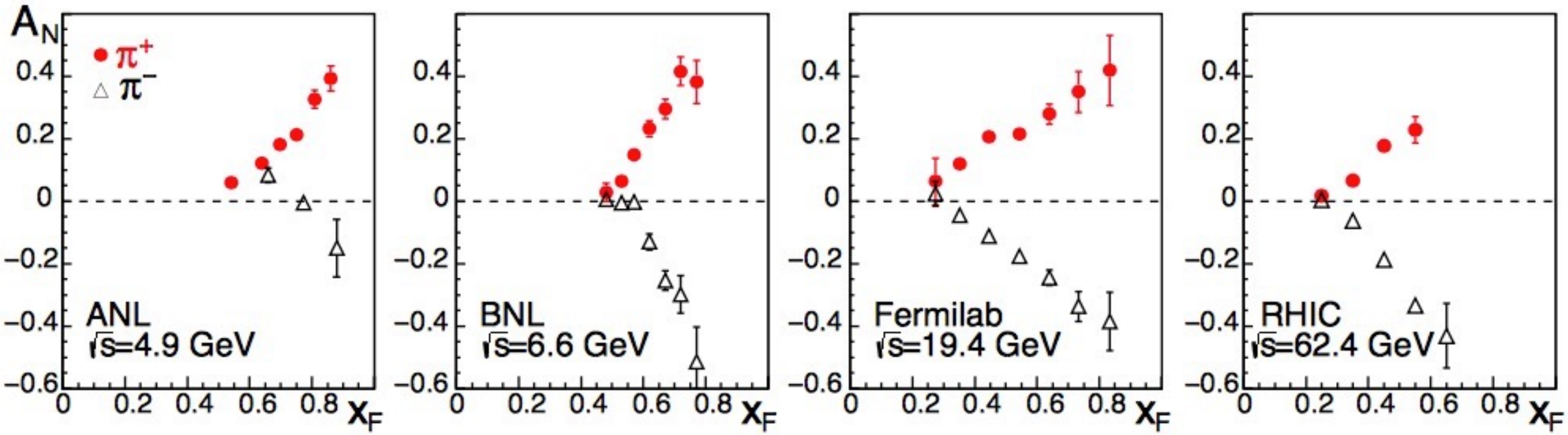
$p^{\uparrow}p \to hX$



$$d\Delta\sigma(S_T) \sim \underbrace{H_{QS} \otimes f_1 \otimes \boldsymbol{F_{FT}} \otimes D_1}_{\text{Qiu-Sterman term}}$$

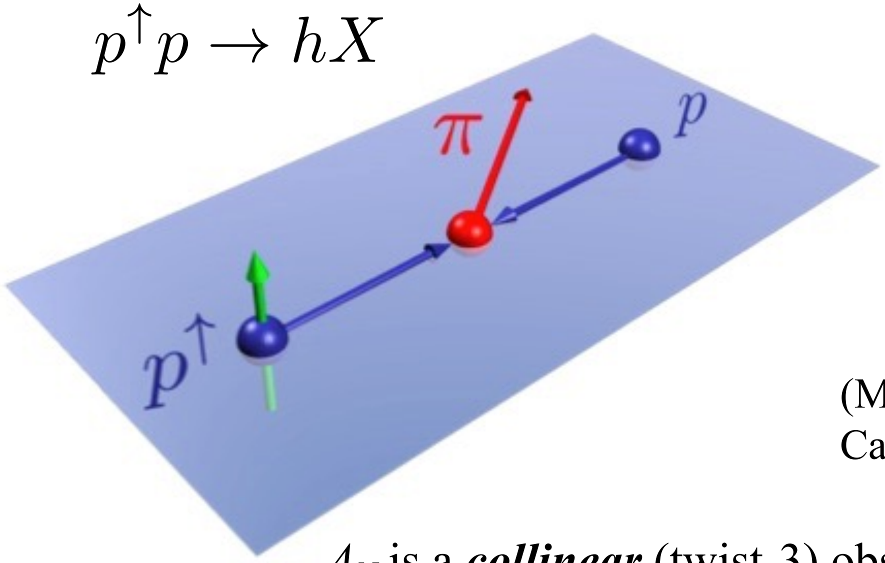
$$+\ \underbrace{H_F \otimes f_1 \otimes \boldsymbol{h_1} \otimes \left(\boldsymbol{H_1^{\perp(1)}}, \boldsymbol{\tilde{H}}\right)}_{\text{Fragmentation term}}$$

A_N is a ***collinear*** (twist-3) observable



1976 →

$$p^{\uparrow}p \to hX$$



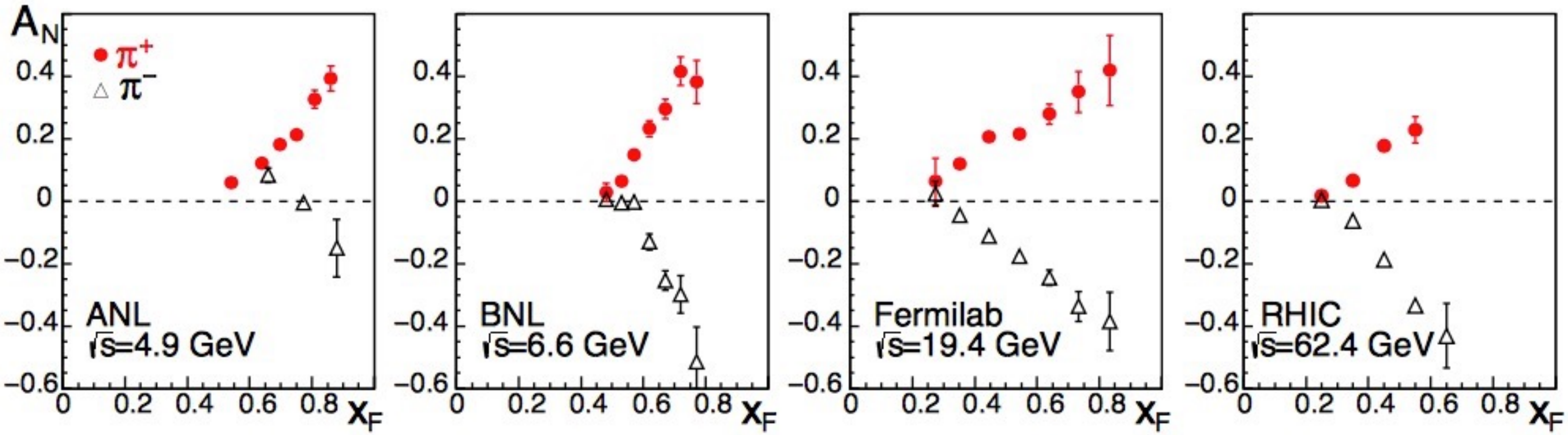
$$d\Delta\sigma(S_T) \sim \underbrace{H_{QS}\otimes f_1\otimes \boldsymbol{F_{FT}}\otimes D_1}_{\text{Qiu-Sterman term}}$$

$$+\boxed{\underbrace{H_F\otimes f_1\otimes \boldsymbol{h_1}\otimes\left(\boldsymbol{H_1^{\perp(1)}},\boldsymbol{\tilde{H}}\right)}_{}}$$

Fragmentation term

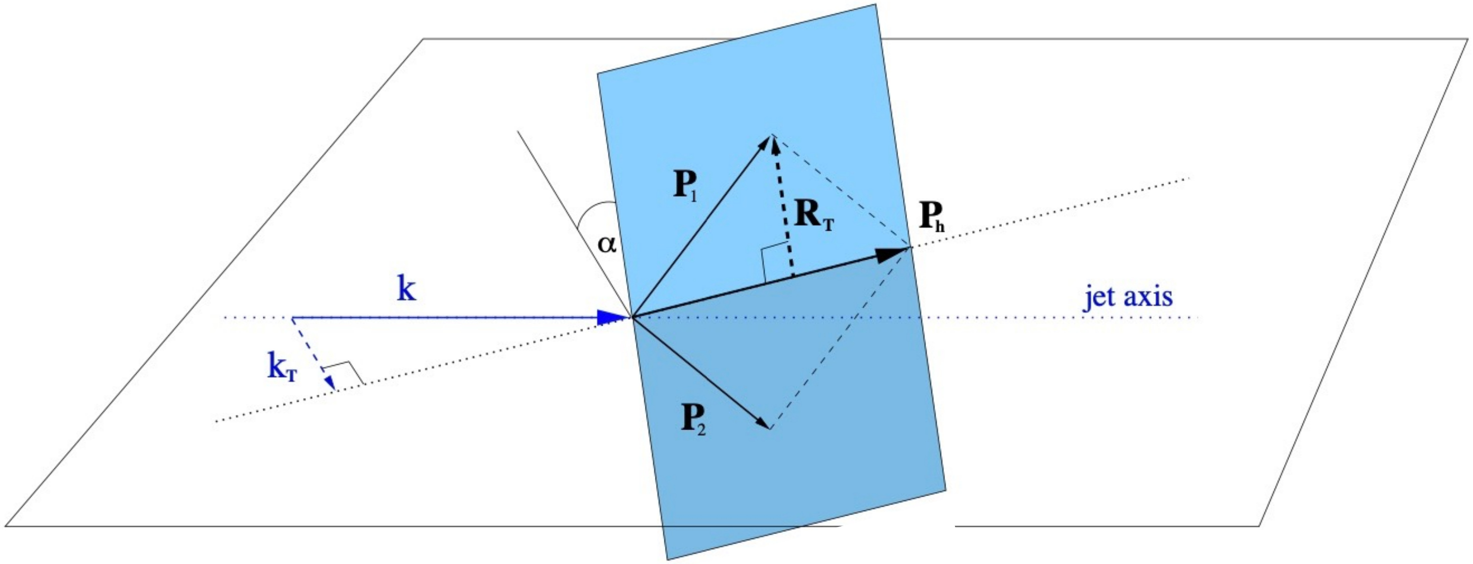
(Metz, DP (2012); Kanazawa, et al. (2014);
Cammarota, et al. (2020); Gamberg, et al. (2017, 2022))

A_N is a ***collinear*** (twist-3) observable



1976 →

Dihadron Fragmentation Approach



From Bianconi, et al. (2000)

Dihadron Fragmentation Approach

Collinear **PDFs (*x*)**

q pol. / H pol.	U	L	T
U	f_1		
L		g_1	
T			h_1

transversity PDF

extDiFFs (z, M_h)

q pol. / H pol.	U	L	T
U	D_1		$H_1^{\sphericalangle}$

(Collins, et al. (1994); Bianconi, et al. (1999), …)

“interference” FF

Dihadron Fragmentation Approach

Collinear PDFs (x)

H pol. \ q pol.	U	L	T
U	f_1		
L		g_1	
T			h_1

extDiFFs (z, M_h)

H pol. \ q pol.	U	L	T
U	D_1		$H_1^{\sphericalangle}$

(Collins, et al. (1994); Bianconi, et al. (1999), …)

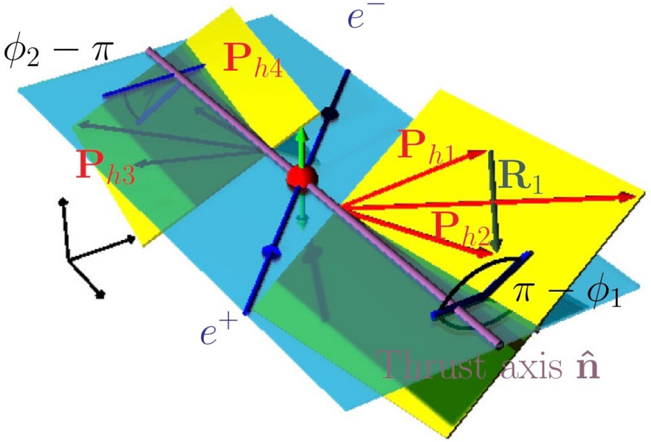
$z = z_1 + z_2$, M_h = invariant mass of dihadron

“extended” DiFFs (extDiFFs) depend on z and M_h (or equivalently R_T)

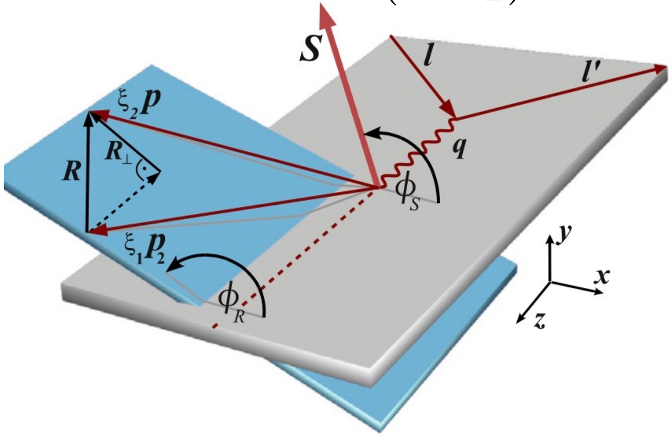
DiFFs at the fully unintegrated level depend on a few more variables

Correction needed to original correlator definition in order to have a number density interpretation (Cocuzza, Metz, DP, Prokudin, Sato, in preparation)

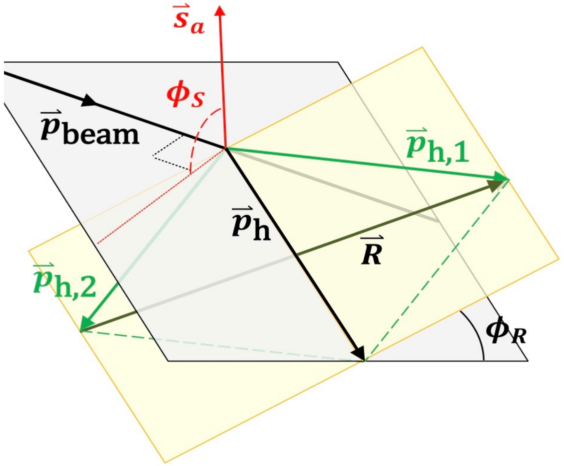
$$e^+e^- \to (h_1h_2)(\bar{h}_1\bar{h}_2)\,X$$



$$\ell\,N^\uparrow \to \ell\,(h_1h_2)\,X$$



$$p^\uparrow p \to (h_1h_2)\,X$$



(Collins, et al. (1994); Bianconi, et al. (1999); Bacchetta, Radici (2003, 2004); Courtoy, et al. (2012); Matevosyan, et al. (2018); Radici, et al. (2013, 2015, 2018); Benel, et al. (2020), …)

$$a_{12R} = \frac{\sin^2\theta \sum_q e_q^2\, H_1^{\sphericalangle,q}(z,M_h^2)\,H_1^{\sphericalangle,\bar{q}}(\bar{z},\overline{M}_h^2)}{(1+\cos^2\theta)\sum_q e_q^2\, D_1^q(z,M_h^2)\,D_1^{\bar{q}}(\bar{z},\overline{M}_h^2)}$$

Artru-Collins asymmetry

Note: D_1 can be constrained using measurements of $d\sigma/dzdM_h$ from BELLE (2017)

$$A_{UT}^{\sin(\phi_R+\phi_S)} = \frac{\sum_q e_q^2\, h_1^q(x)\, H_1^{\sphericalangle,q}(z,M_h^2)}{\sum_q e_q^2\, f_1^q(x)\, D_1^q(z,M_h^2)}$$

$$A_{UT}^{\sin(\phi_R-\phi_S)} \sim \frac{\frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}} \otimes f_1^a(x_a)\otimes h_1^b(x_b)\otimes H_1^{\sphericalangle,c}(z,M_h^2)}{\frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} \otimes f_1^a(x_a)\otimes f_1^b(x_b)\otimes D_1^c(z,M_h^2)}$$

Previous Results and Impact Studies for Future Experiments

Transverse Momentum Dependent/Collinear Twist-3 Approach

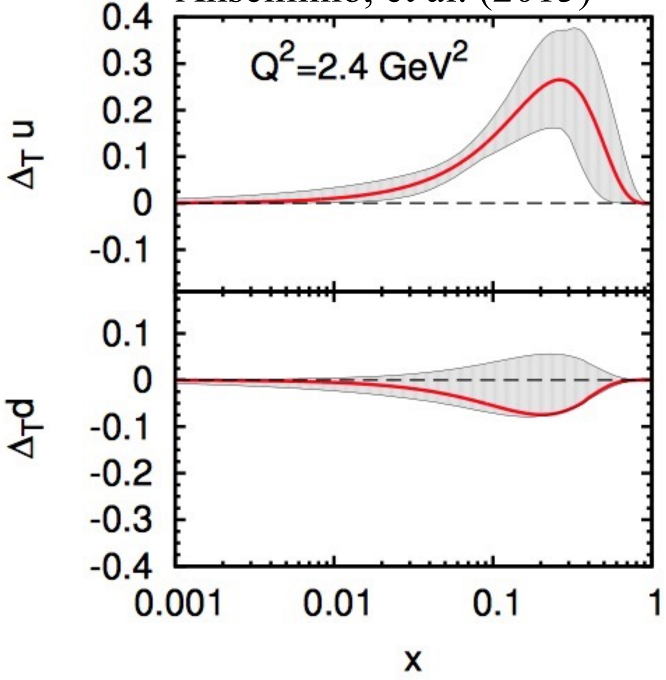
	e^+e^- Collins	SIDIS Collins	Hadron-in-jet Collins	Proton-proton A_N	Lattice tensor charge(s)	Soffer bound	Framework
Anselmino, et al. (2015)	✓	✓	X	X	X	✓	Parton model
Kang, et al. (2016)	✓	✓	X	X	X	✓	CSS/TMD evolution
Lin, et al. (2018)	X	✓	X	X	✓ g_T	X	Parton model
D'Alesio, et al. (2020)	✓	✓	X	X	X	X†	Parton model
Cammarota, et al. (2020) JAM3D-20*	✓	✓	X	✓	X	X	Parton model

*Also included Sivers effects in SIDIS and Drell-Yan

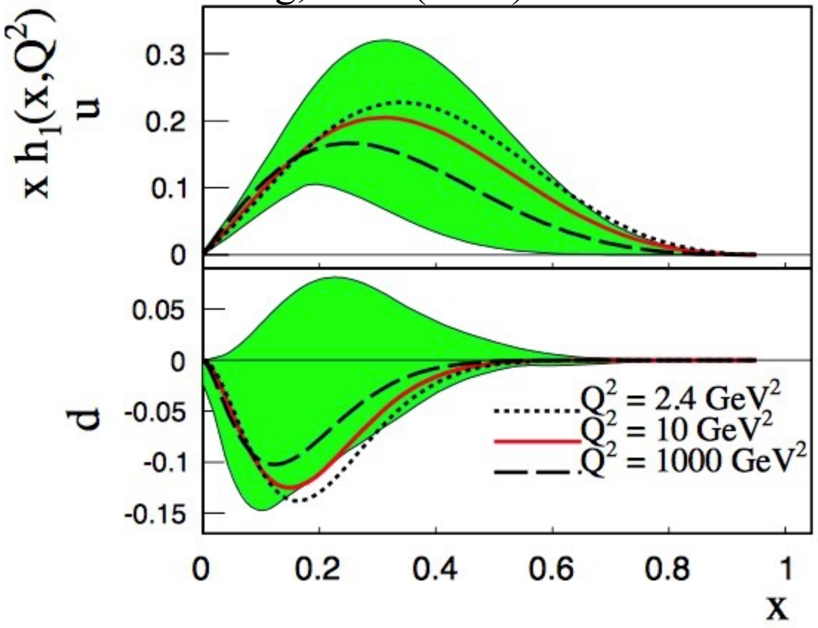
†Performed fit both with and without SB

Soffer bound (SB): $|h_1^q(x)| \leq \frac{1}{2}(f_1^q(x) + g_1^q(x))$

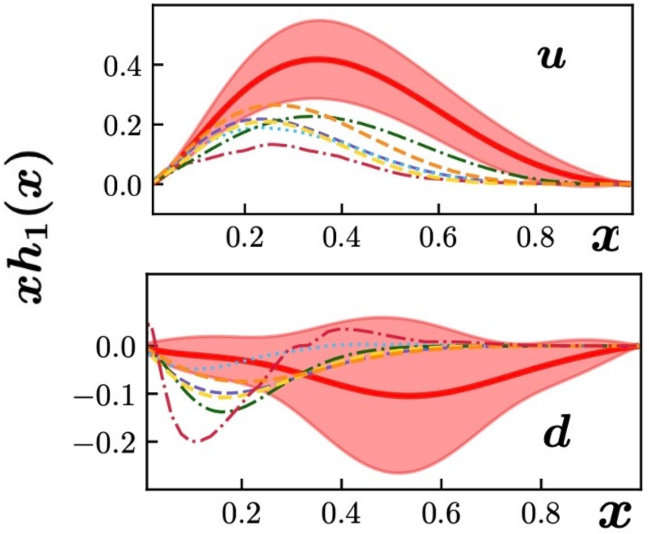
Note: Predictions exist for hadron-in-jet Collins effect (D'Alesio, et al. (2017); Kang, et al. (2017)) but no groups have included the STAR data in a fit. These are important measurements to use in future studies.



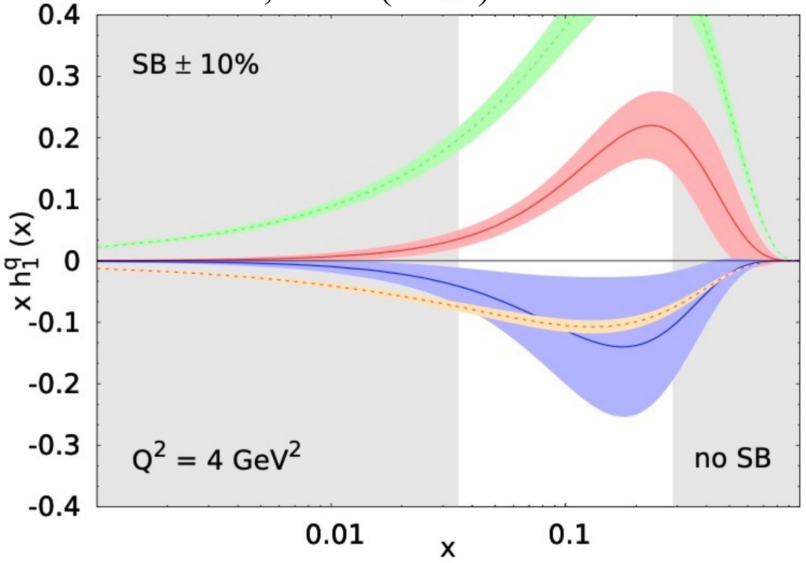
Anselmino, et al. (2015)



Kang, et al. (2016)

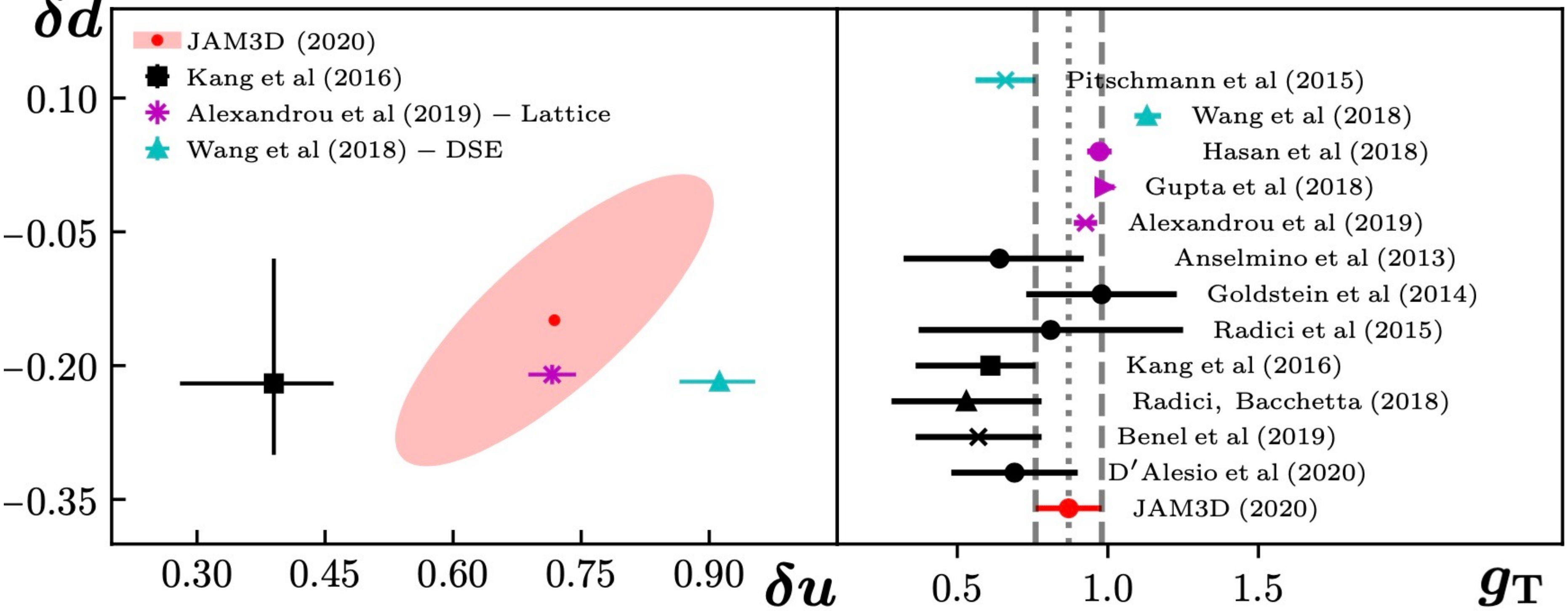


Cammarota, et al. (2020) - JAM3D-20



D’Alesio, et al. (2020)

Figure modified from Cammarota, et al. (2020)



- Analyses that only include e^+e^- and SIDIS Collins effect data (e.g., Kang, et al. (2016)) are generally below the lattice values for g_T and δu
- JAM3D-20 also includes A_N data, which causes a larger $h_1^u(x)$ and brought g_T and δu in agreement with lattice for the first time

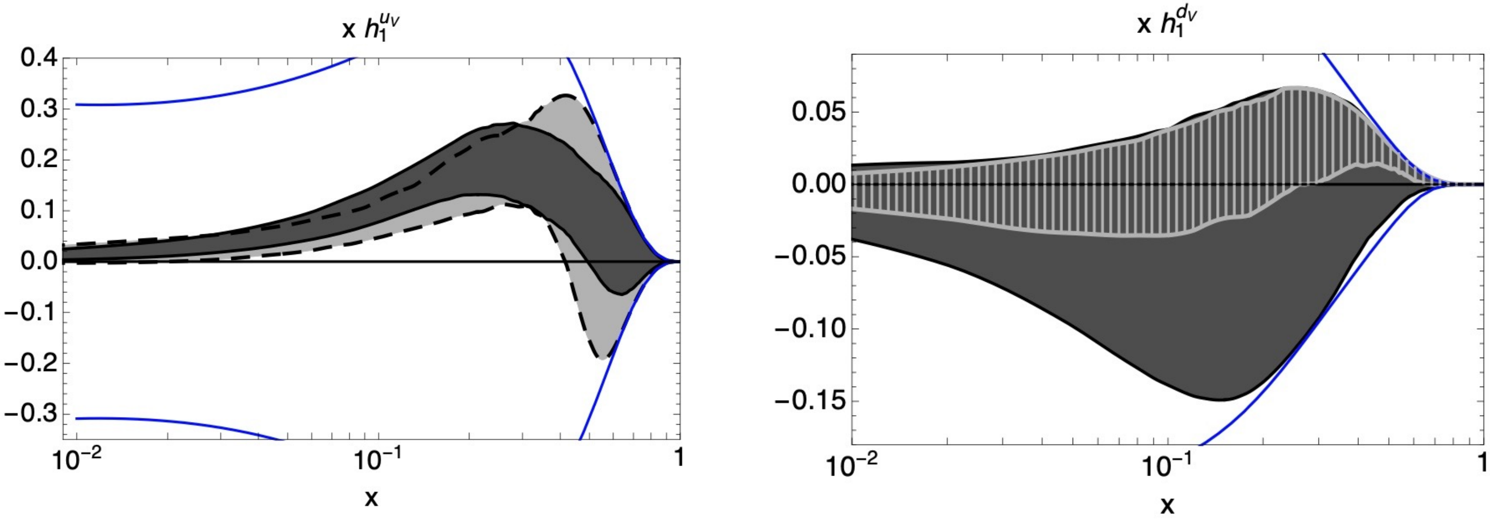
Dihadron Fragmentation Approach

	e^+e^- $d\sigma/dzdM_h$	e^+e^- Artru-Collins	SIDIS $\sin(\varphi_R+\varphi_S)$	Proton-proton $\sin(\varphi_R-\varphi_S)$	Lattice tensor charge(s)	Soffer bound
Radici, Bacchetta (2018)	✓* PYTHIA	✓*	✓	✓	X	✓
Benel, et al. (2020)	✓* PYTHIA	✓*	✓	X	X	✓^

* $D_1(z,M_h)$ and $H_1^{\sphericalangle}(z,M_h)$ were fit in a separate analysis and then fixed when extracting $h_1(x)$

^ Imposed the SB but allowed for violations given the uncertainties in $f_1(x)$ and $g_1(x)$

Radici, Bacchetta (2018)



Benel, et al. (2020)

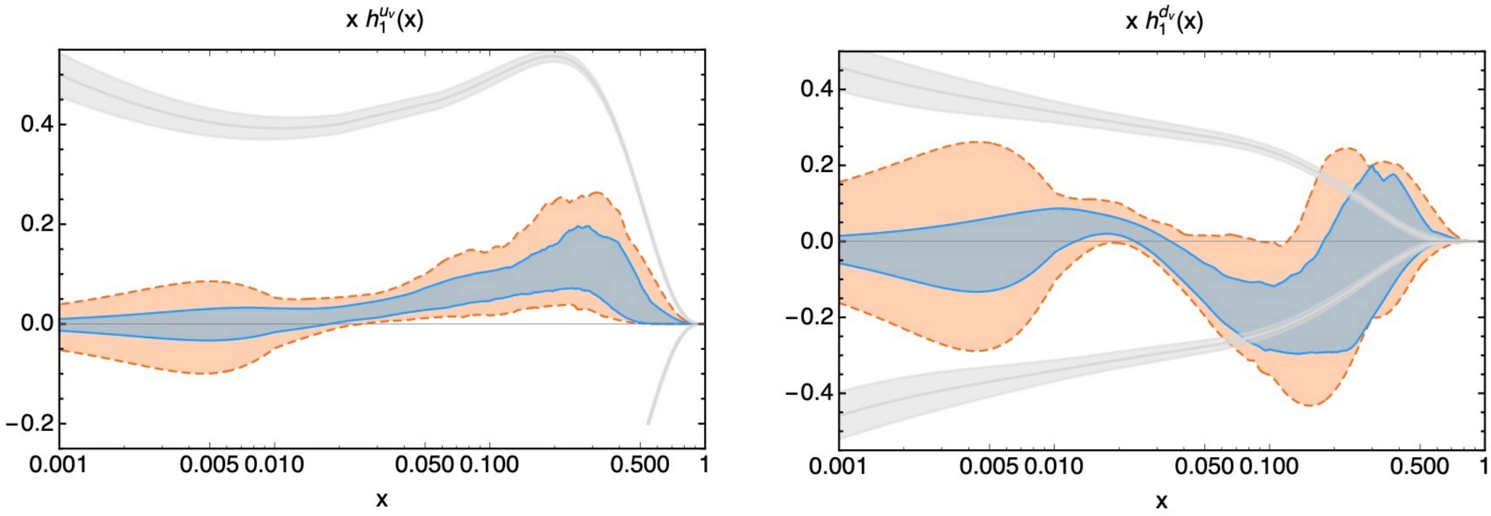
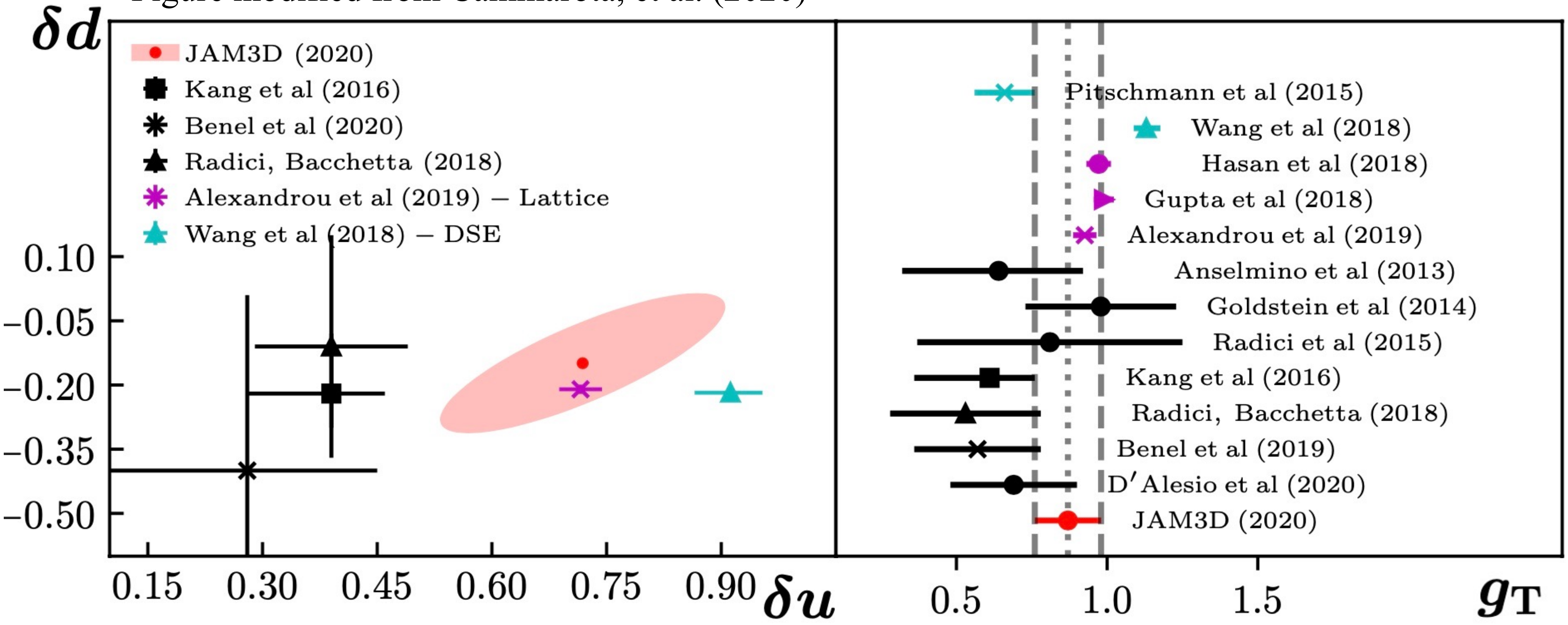


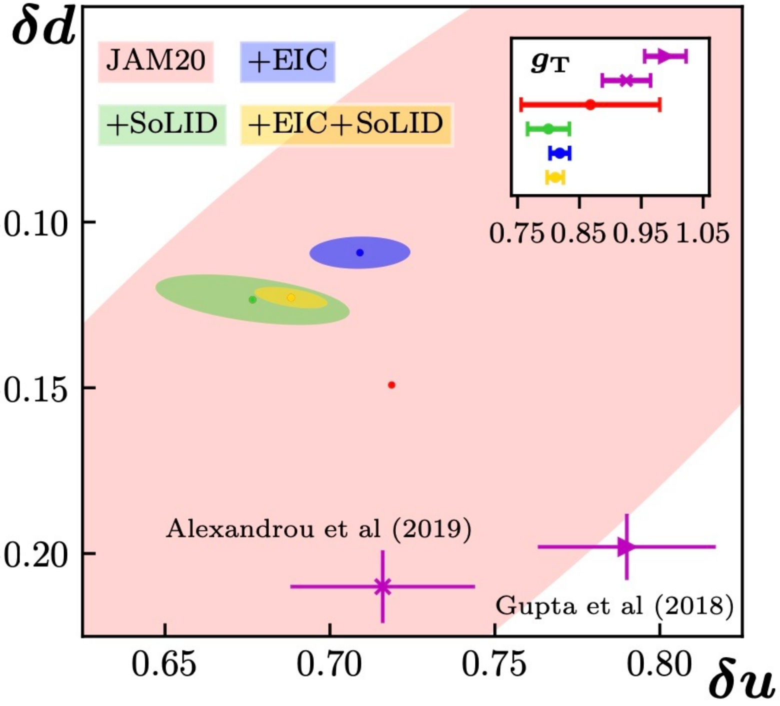
Figure modified from Cammarota, et al. (2020)



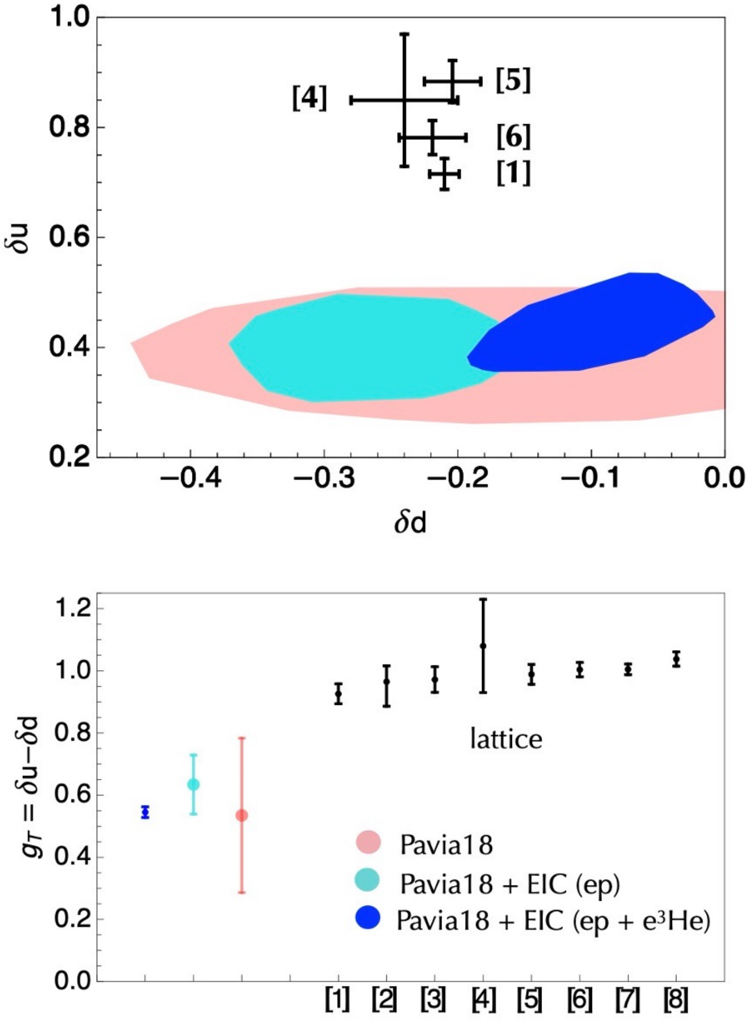
- Dihadron analyses (e.g., Benel, et al. (2020); Radici, Bacchetta (2018)), along with TMD fits that only include e^+e^- and SIDIS Collins effect data (e.g., Kang, et al. (2016)), are generally below the lattice values for g_T and $\boldsymbol{\delta}u$

"Transverse Spin Puzzle"

Gamberg, Kang, DP, Prokudin, Sato, Seidl (2021) – EIC and SoLID pseudodata on **SIDIS Collins effect**



Radici and Bacchetta from EIC Yellow Report (2021) – pseudodata on **dihadron SIDIS**



- With future EIC and SoLID data, phenomenological extractions of the tensor charge will become as (or more) precise as current lattice computations

Recent Analyses and Current Status

Transverse Momentum Dependent/Collinear Twist-3 Approach

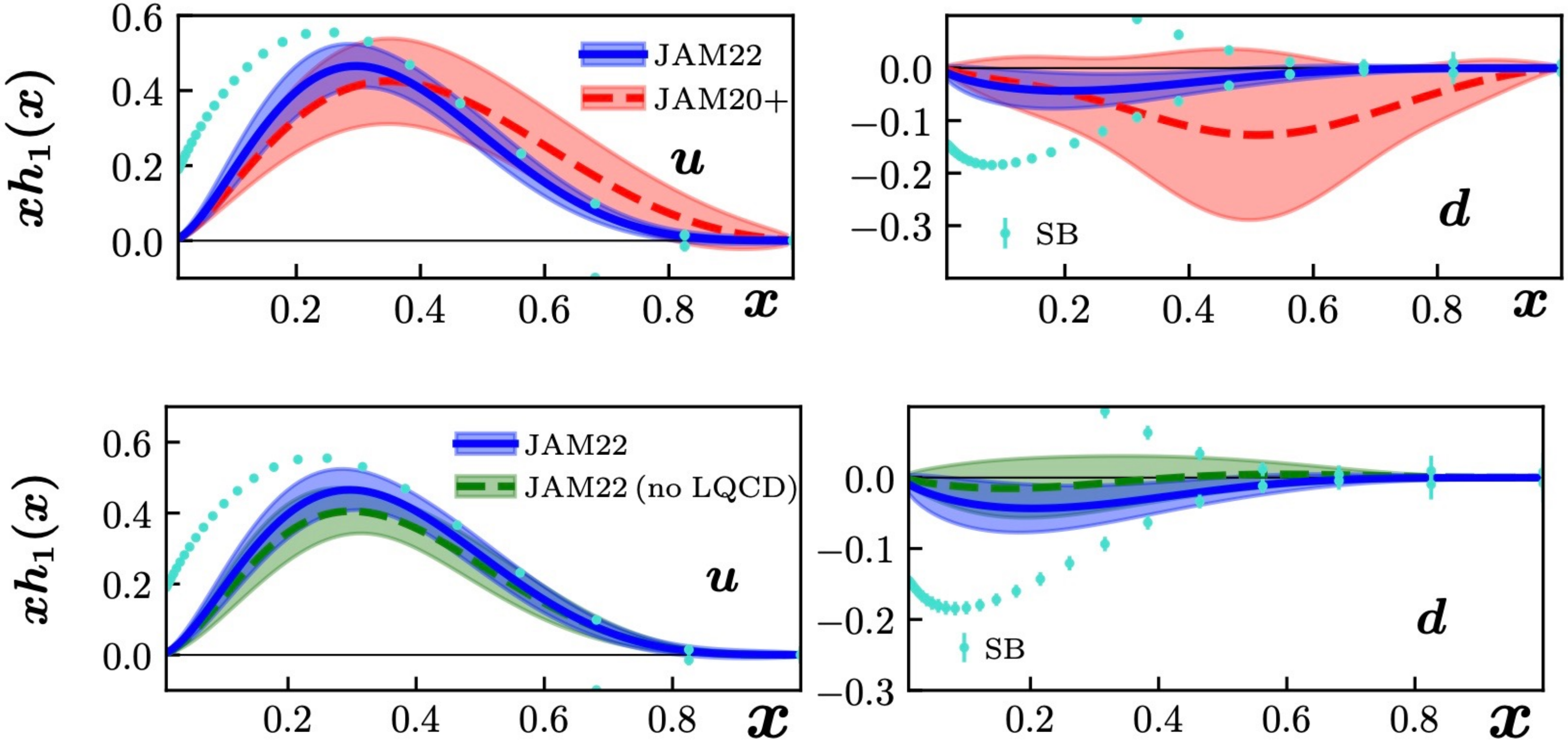
	e^+e^- Collins	SIDIS Collins	Hadron-in-jet Collins	Proton-proton A_N	Lattice tensor charge(s)	Soffer bound	Framework
Anselmino, et al. (2015)	✓	✓	X	X	X	✓	Parton model
Kang, et al. (2016)	✓	✓	X	X	X	✓	CSS/TMD evolution
Lin, et al. (2018)	X	✓	X	X	✓ g_T	X	Parton model
D'Alesio, et al. (2020)	✓	✓	X	X	X	X[†]	Parton model
Cammarota, et al. (2020) JAM3D-20*	✓	✓	X	✓	X	X	Parton model
Gamberg, et al. (2022) JAM3D-22*	✓	✓	X	✓	✓ g_T	✓^	Parton model

*Also included Sivers effects in SIDIS and Drell-Yan

[†] Performed fit both with and without SB

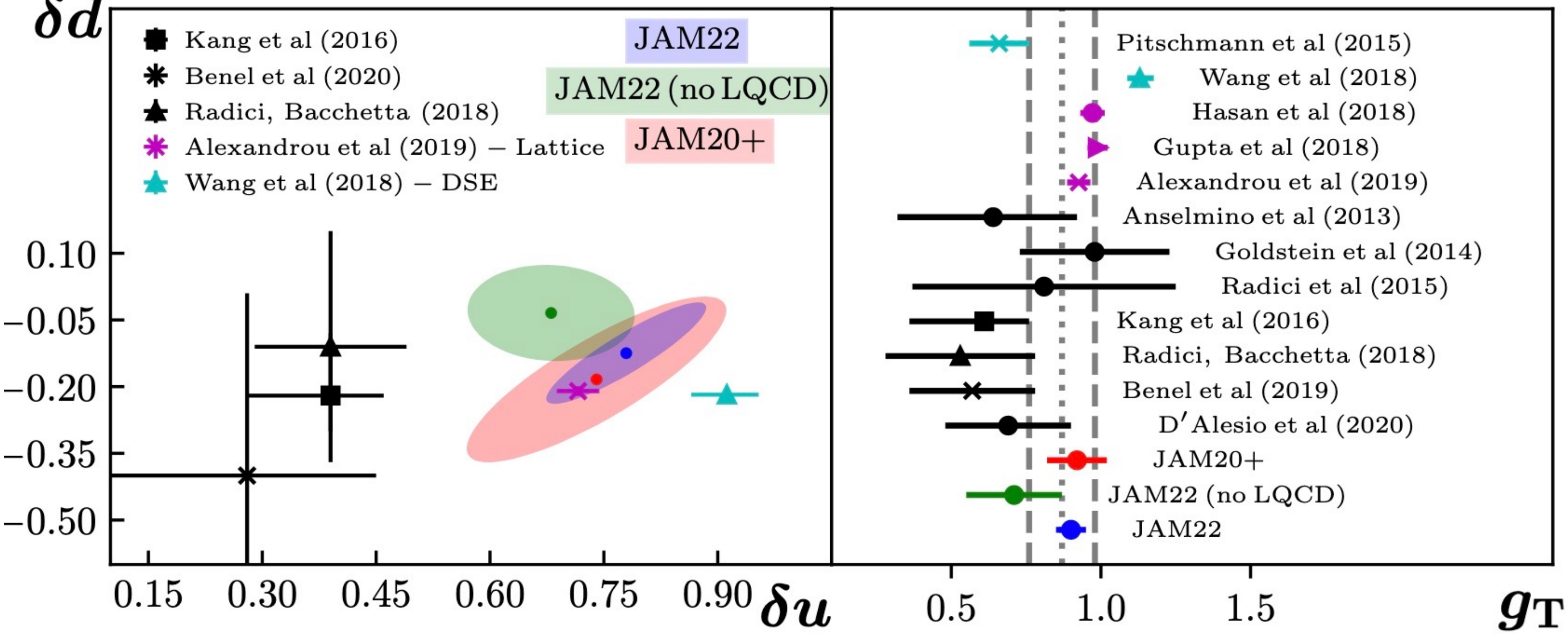
^ Imposed the SB but allowed for violations given the uncertainties in $f_1(x)$ and $g_1(x)$

Gamberg, Malda, Miller, DP, Prokudin, Sato (2022) - JAM3D-22



- Transversity becomes much more tightly constrained by imposing the SB and including the lattice g_T data point, in particular the latter

Figure modified from Gamberg, Malda, Miller, DP, Prokudin, Sato (2022)



- The JAM3D-22 tensor charges are more precise because of including the lattice g_T data point
- Note that because of the SB, one initially finds more tension between JAM3D-22 and lattice, but this does *not* imply phenomenology and lattice are incompatible – *one can only fully answer this by including lattice data in the analysis*
- Once the lattice g_T data point is included, the JAM3D-22 non-perturbative functions can accommodate it **and still describe the experimental data very well**

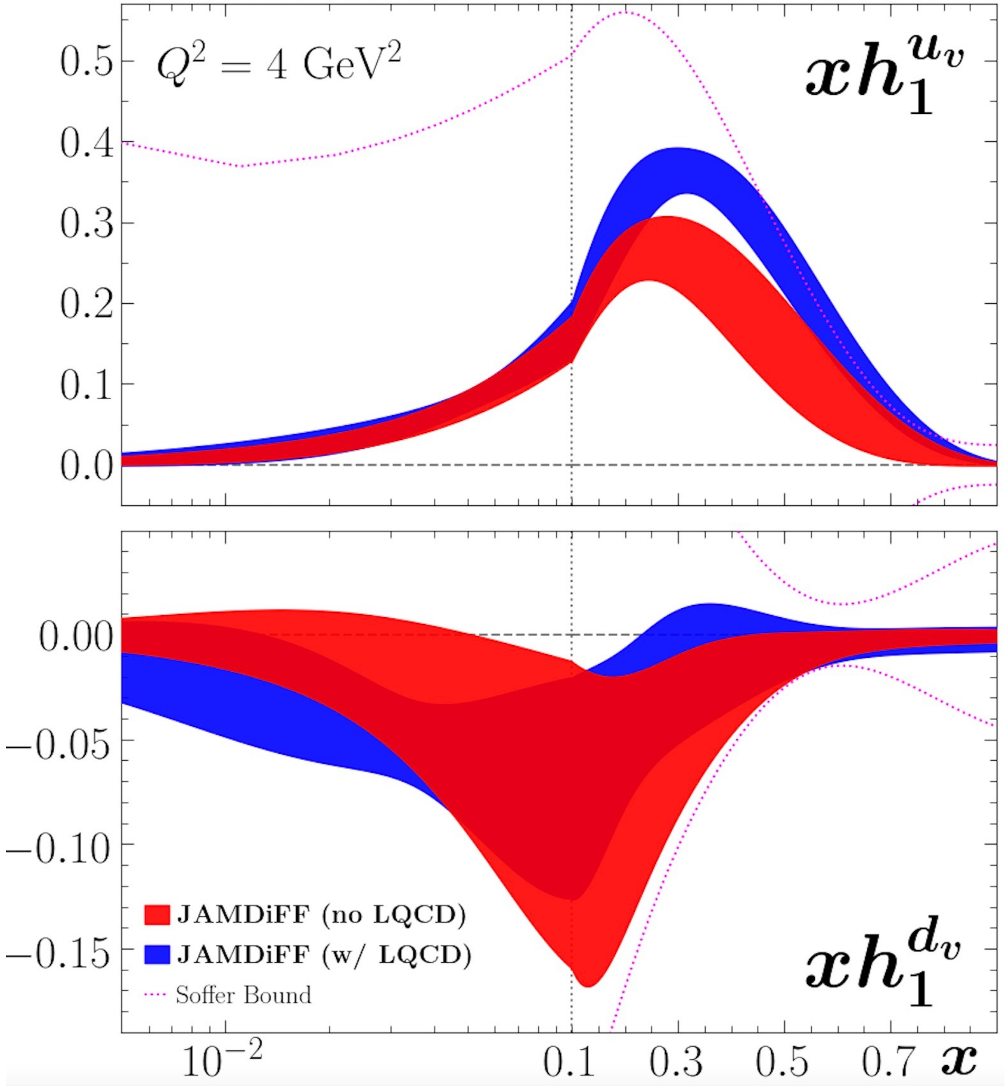
Dihadron Fragmentation Approach

	e^+e^- $d\sigma/dzdM_h$	e^+e^- Artru-Collins	SIDIS $\sin(\varphi_R+\varphi_S)$	Proton-proton $\sin(\varphi_R-\varphi_S)$	Lattice tensor charge(s)	Soffer bound
Radici, Bacchetta (2018)	✓* PYTHIA	✓*	✓	✓	X	✓
Benel, et al. (2020)	✓* PYTHIA	✓*	✓	X	X	✓^
Cocuzza, et al. (in prep) JAMDiFF-23	✓	✓	✓	✓	✓ $\delta u, \delta d$	✓^

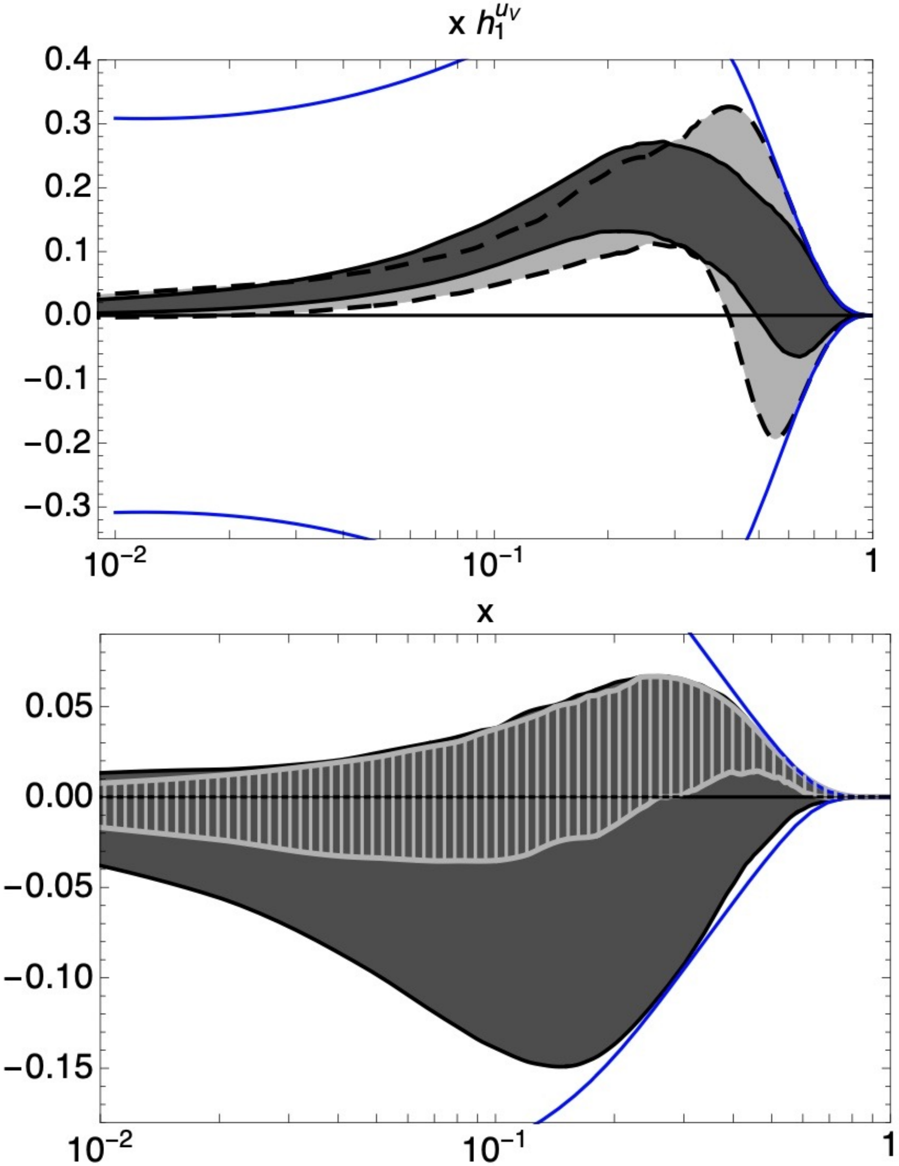
* $D_1(z,M_h)$ and $H_1^{\sphericalangle}(z,M_h)$ were fit in a separate analysis and then fixed when extracting $h_1(x)$

^ Imposed the SB but allowed for violations given the uncertainties in $f_1(x)$ and $g_1(x)$

Cocuzza, Melnitchouk, Metz, DP, Prokudin, Sato, Seidl (in preparation) - JAMDiFF-23



Radici, Bacchetta (2018)



Transverse Momentum Dependent/Collinear Twist-3 Approach

	e^+e^- Collins	SIDIS Collins	Hadron-in-jet Collins	Proton-proton A_N	Lattice tensor charge(s)	Soffer bound	Framework
Gamberg, et al. (2022) JAM3D-22*	✓	✓	X	✓	✓ $\delta u, \delta d$	✓^	Parton model

*Also included Sivers effects in SIDIS and Drell-Yan

Slight modification to published fit

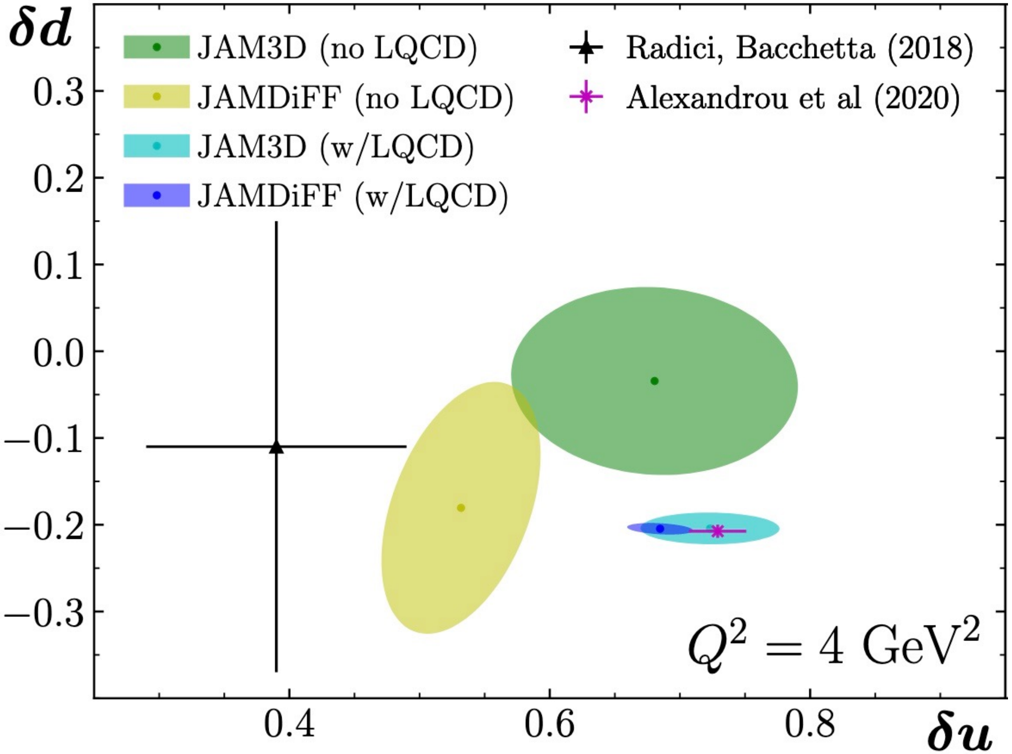
Dihadron Fragmentation Approach

	e^+e^- $d\sigma/dzdM_h$	e^+e^- Artru-Collins	SIDIS $\sin(\varphi_R+\varphi_S)$	Proton-proton $\sin(\varphi_R-\varphi_S)$	Lattice tensor charge(s)	Soffer bound
Radici, Bacchetta (2018)	✓* PYTHIA	✓*	✓	✓	X	✓
Cocuzza, et al. (in prep) JAMDiFF-23	✓	✓	✓	✓	✓ $\delta u, \delta d$	✓^

* $D_1(z,M_h)$ and $H_1^{\sphericalangle}(z,M_h)$ were fit in a separate analysis and then fixed when extracting $h_1(x)$

^ Imposed the SB but allowed for violations given the uncertainties in $f_1(x)$ and $g_1(x)$

Cocuzza, Melnitchouk, Metz, DP, Prokudin, Sato, Seidl (in preparation)



- Similar to the JAM3D analysis, JAMDiFF also finds compatibility with lattice once that data is included in the fit (**and the experimental data is still described very well** - only weakly sensitive to the nucleon tensor charges)

- This is not an unexpected outcome given the nature of the "inverse problem"

- *JAM3D, JAMDiFF, and lattice QCD now all overlap for* ***δ****u,* ***δ****d, and* g_T*, resolving the "transverse spin puzzle" from earlier studies*

Summary and Outlook

Summary

- The tensor charges are fundamental properties of the nucleon that have connections to QCD phenomenology, *ab initio* computations (e.g., lattice QCD, DSE), and beyond the Standard Model studies (e.g., beta decay, EDM)

- There are two approaches in QCD phenomenology to extract the transversity PDF in order to compute the tensor charges: one analyzing TMD/collinear twist-3 observables, and the other utilizing dihadron fragmentation measurements

- Historically there has always been an apparent tension between the tensor charges extracted from experimental data and those computed in lattice QCD, creating a so-called “transverse spin puzzle”

- Recent analyses by the JAM Collaboration (Gamberg, et al. (2022), Cocuzza, et al. (in preparation)) in both approaches show that lattice QCD tensor charge data can be accommodated within phenomenology

Outlook

- Further refinements/improvements:
  - TMD/collinear twist-3: include lattice tensor charge data and hadron-in-jet Collins effect measurements with CSS evolution in the analysis, …
  - Dihadron: other groups including lattice tensor charge data; unpolarized *pp* cross section measurements to better constrain $D_1^g(z, M_h)$, …
  - "Universal" analysis where TMD/collinear twist-3 ***<u>and</u>*** dihadron measurements are fit simultaneously
  - Incorporate small-*x* evolution for transversity (Kovchegov, Sievert (2019))

$$\delta q \equiv \int_{\boxed{0}}^{1} dx\,[h_1^q(x) - h_1^{\bar{q}}(x)]$$

  - Using pseudo-PDF or quasi-PDF approaches, lattice can now compute $h_1(x)$ - eventually can include data into phenomenology (more constraining than the tensor charge data)