# First global analysis of SSAs in SIDIS, Drell-Yan, $e^+e^-$ annihilation, and proton-proton collisions

Daniel Pitonyak

*Lebanon Valley College, Annville, PA, USA*

Division of Nuclear Physics Fall Meeting

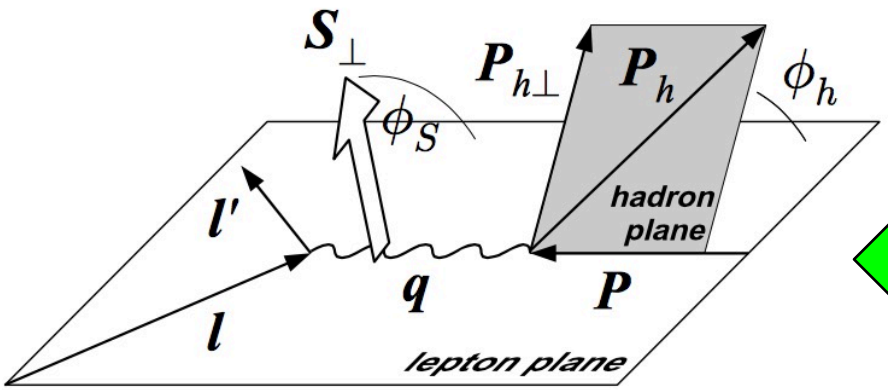
November 1, 2020

# Outline

- SSAs within TMD and collinear twist-3 (CT3) factorization
- Global analysis – methodology and results
- Tensor charge of the nucleon
- EIC impact study on transversity and tensor charge
- Summary and outlook

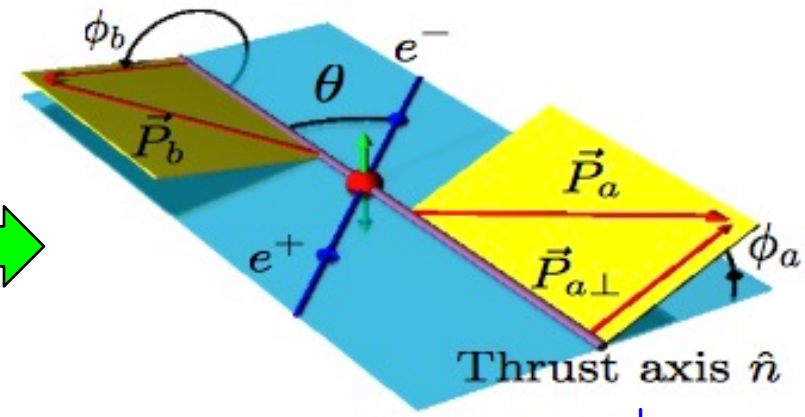
# Single Transverse-Spin Asymmetries (SSAs) within TMD and Collinear Twist-3 (CT3) Factorization

SIDIS (Sivers and Collins effects)

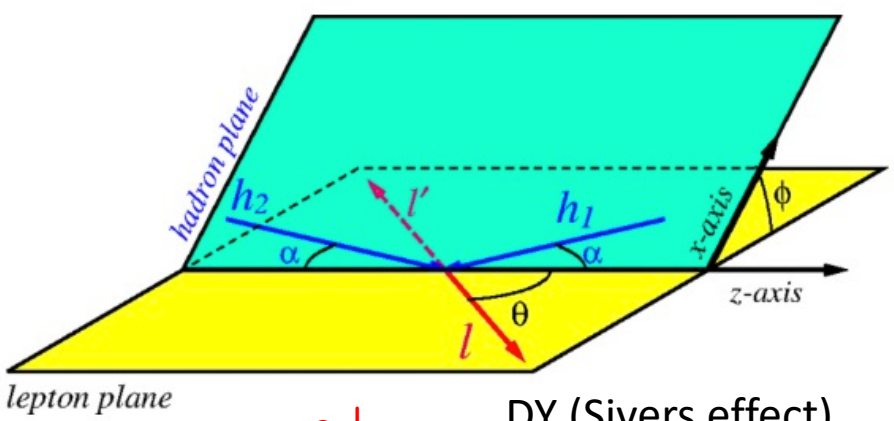



$h_1$, $f_{1T}^\perp$, $H_1^\perp$

SIA (Collins effect)



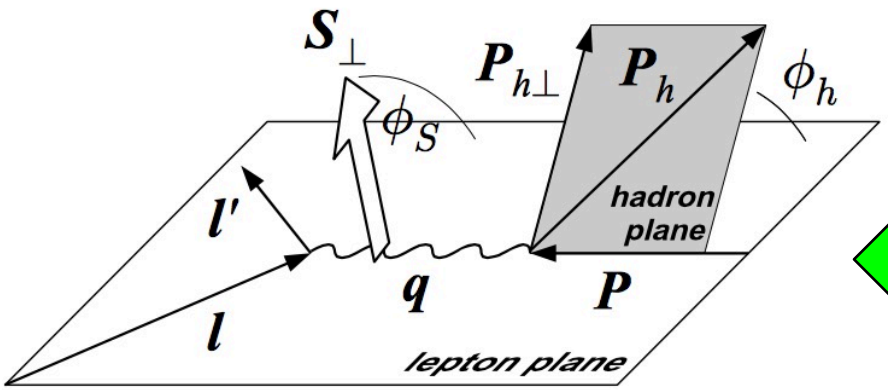

$H_1^\perp$




$f_{1T}^\perp$

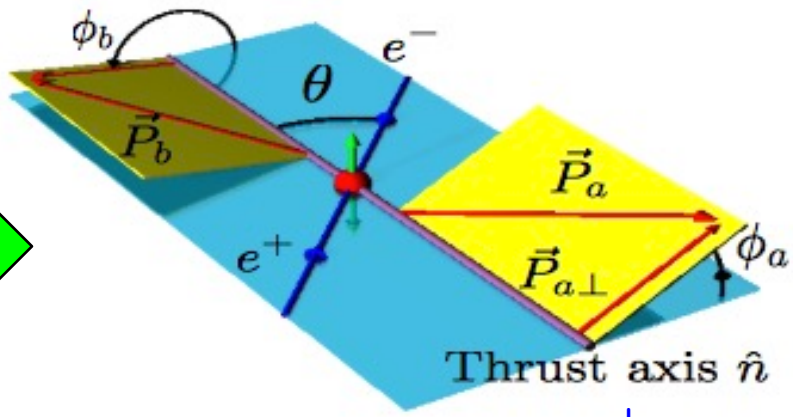
DY (Sivers effect)

SIDIS (Sivers and Collins effects)

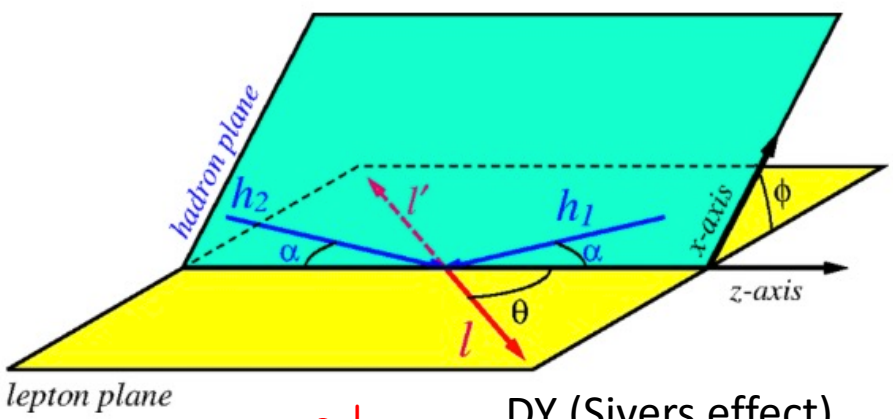



$h_1$, $f_{1T}^\perp$, $H_1^\perp$

SIA (Collins effect)

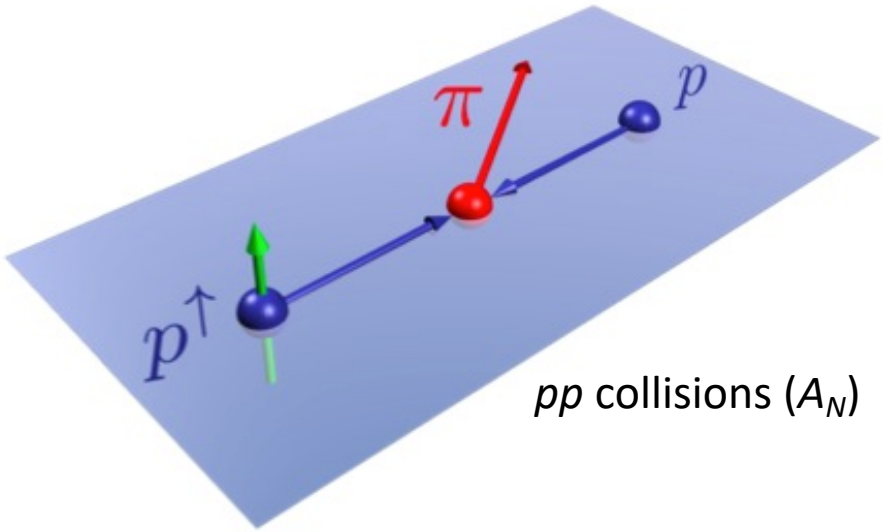



$H_1^\perp$




$f_{1T}^\perp$

DY (Sivers effect)

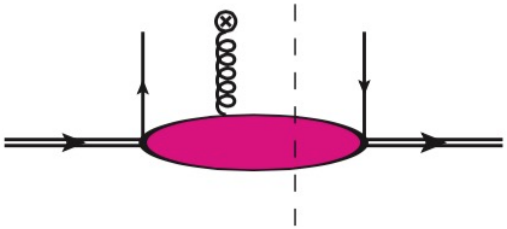



*pp* collisions ($A_N$)

$$d\Delta\sigma(S_T) \sim \underbrace{H_{QS} \otimes f_1 \otimes \boldsymbol{F_{FT}} \otimes D_1}_{\text{Qiu-Sterman term}} + \underbrace{H_F \otimes f_1 \otimes \boldsymbol{h_1} \otimes \left(\boldsymbol{H_1^{\perp(1)}}, \boldsymbol{\tilde{H}}\right)}_{\text{Fragmentation term}}$$

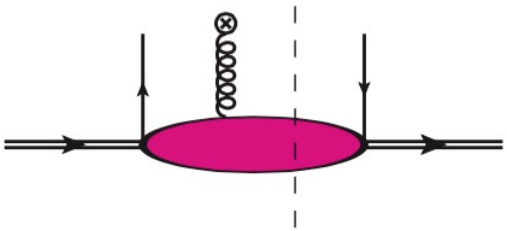
$$H_{QS} \otimes f_1 \otimes \boldsymbol{F_{FT}} \otimes D_1$$

(Qiu and Sterman (1999), Kouvaris, et al. (2006))

$\boldsymbol{F_{FT}} \sim$  quark-gluon-quark correlator (soft-gluon pole)

$$H_{QS} \otimes f_1 \otimes \boldsymbol{F_{FT}} \otimes D_1$$

(Qiu and Sterman (1999), Kouvaris, et al. (2006))

$\boldsymbol{F_{FT}} \sim$  quark-gluon-quark correlator (soft-gluon pole)

***Connection to Sivers function***

$$\tilde{f}_{1T}^{\perp(1)}(x, b_T; Q^2, \mu_Q) \sim F_{FT}(x, x; \mu_{b_*}) \exp\left[-S_{pert}(b_*(b_T); \mu_{b_*}, Q, \mu_Q) - S_{NP}^{f_{1T}^{\perp}}(b_T, Q)\right]$$

$$g_{f_{1T}^{\perp}}(x, b_T) + g_K(b_T) \ln(Q/Q_0)$$

(Aybat, et al. (2012); Echevarria, et al. (2014))

$$\pi F_{FT}(x, x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2) \equiv f_{1T}^{\perp(1)}(x)$$ (Boer, et al. (2003))

***NB:*** TMD ($\Lambda_{QCD} \sim q_T << Q$) and CT3 factorization ($\Lambda_{QCD} << q_T \sim Q$) agree in their overlapping region of applicability ($\Lambda_{QCD} << q_T << Q$)

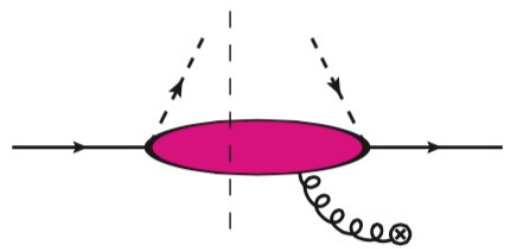
(Ji, et al. (2006); Koike, et al. (2008); Zhou, et al. (2008, 2010); Yuan and Zhou (2009))

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

(Metz & DP - PLB **723** (2013); Gamberg, Kang, DP, Prokudin, PLB **770** (2017))

$\boldsymbol{h_1}$ – twist-2 ***collinear*** transversity PDF

$$\left.\begin{matrix} \boldsymbol{H_1^{\perp(1)}} \\ \boldsymbol{\tilde{H}} \end{matrix}\right\} \sim \int dz_1 \, \boldsymbol{\hat{H}_{FU}^{\Im}} \sim$$



quark-gluon-quark fragmentation function

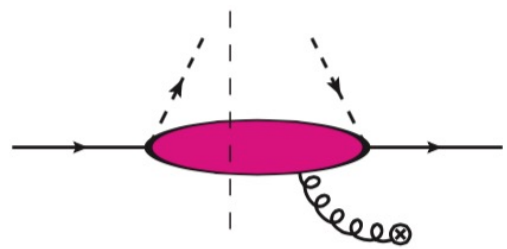
(Kanazawa, Koike, Metz, DP, Schlegel, PRD **93** (2016))

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

(Metz & DP - PLB **723** (2013); Gamberg, Kang, DP, Prokudin, PLB **770** (2017))

$\boldsymbol{h_1}$ – twist-2 ***collinear*** transversity PDF

$$\left.\begin{matrix} \boldsymbol{H_1^{\perp(1)}} \\ \boldsymbol{\tilde{H}} \end{matrix}\right\} \sim \int dz_1 \, \boldsymbol{\hat{H}_{FU}^{\Im}} \sim$$



quark-gluon-quark fragmentation function

(Kanazawa, Koike, Metz, DP, Schlegel, PRD **93** (2016))

***Connection to Collins function***

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

$$g_{H_1^\perp}(z, b_T) + g_K(b_T) \ln(Q/Q_0)$$

(Kang, et al. (2016))

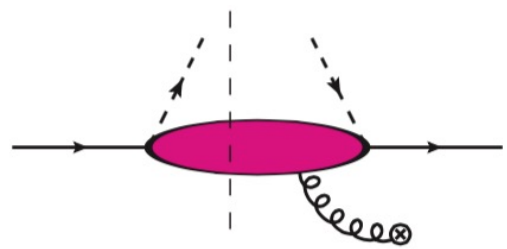
$$\boldsymbol{H_1^{\perp(1)}(z)} \equiv z^2 \int d^2\vec{p}_\perp \frac{p_\perp^2}{2M_h^2} \boldsymbol{H_1^\perp(z, z^2 p_\perp^2)}$$

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

(Metz & DP - PLB **723** (2013), Gamberg, Kang, DP, Prokudin, PLB **770** (2017))

$\boldsymbol{h_1}$ – twist-2 ***collinear*** transversity PDF

$$\left.\begin{matrix} \boldsymbol{H_1^{\perp(1)}} \\ \boldsymbol{\tilde{H}} \end{matrix}\right\} \sim \int dz_1 \, \boldsymbol{\hat{H}_{FU}^{\Im}} \sim$$



quark-gluon-quark fragmentation function

(Kanazawa, Koike, Metz, DP, Schlegel, PRD **93** (2016))

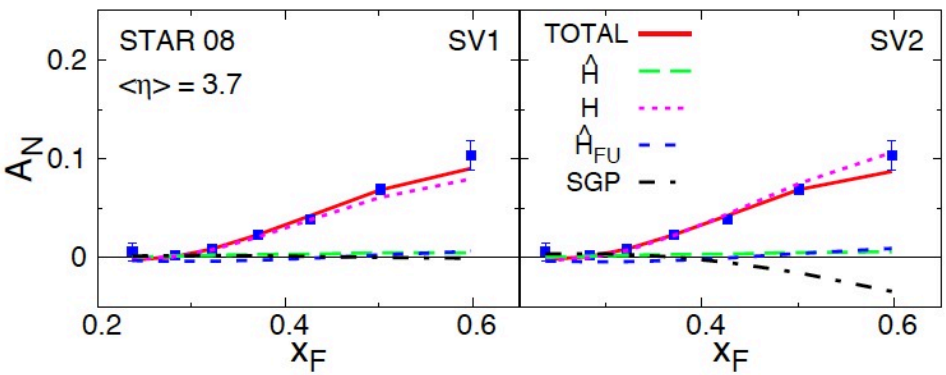
***NB:*** $A_{UT}^{\sin\phi_S}$ in SIDIS integrated over $P_T$ (Mulders, Tangerman (1996); Bacchetta, et al. (2007))

$$F_{UT}^{\sin\phi_S} \sim \sum_a e_a^2 \frac{2M_h}{Q} \boldsymbol{h_1^a}(x) \frac{\boldsymbol{\tilde{H}}(z)}{z}$$

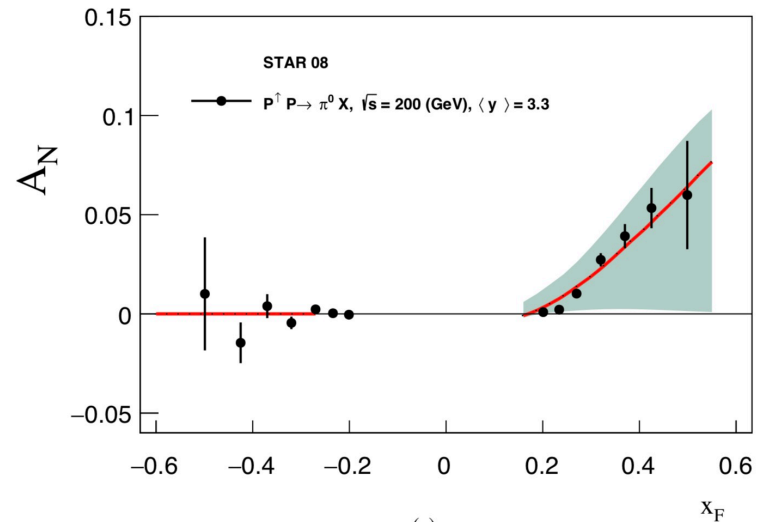
$$H_F \otimes f_1 \otimes \boldsymbol{h_1} \otimes \left( \boldsymbol{H_1^{\perp(1)}}, \boldsymbol{\tilde{H}} \right)$$

(Metz & DP - PLB **723** (2013), Gamberg, Kang, DP, Prokudin, PLB **770** (2017))

***SSAs in $p^{\uparrow}p \to \pi X$ are due to this fragmentation term!***



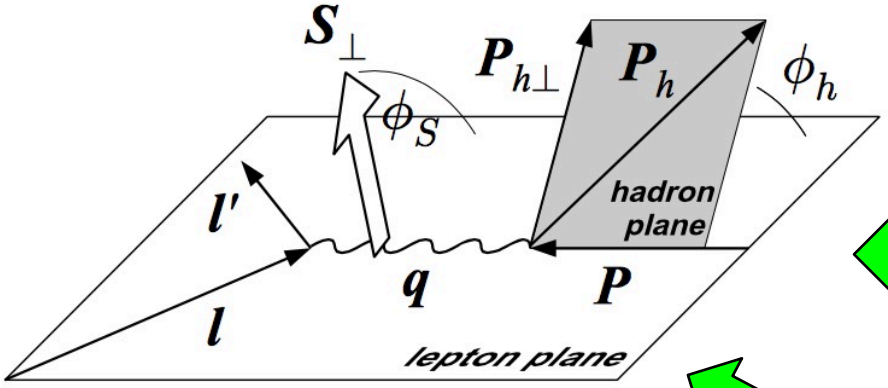

(Kanazawa, Koike, Metz, DP, PRD **89**(RC) (2014))




(Gamberg, Kang, DP, Prokudin, PLB **770** (2017))

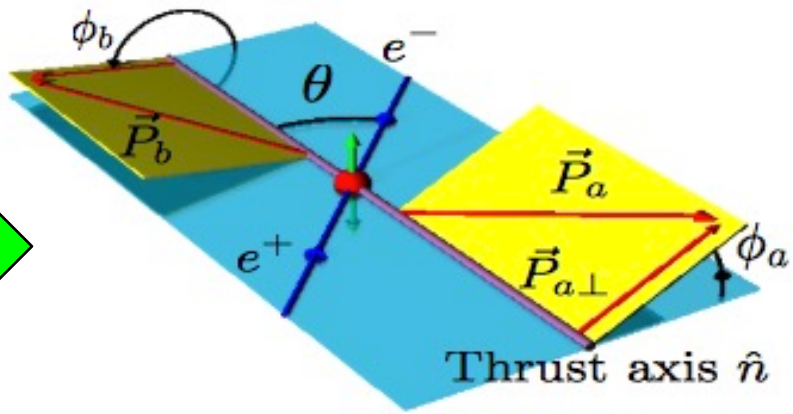
***This is a direct probe of transversity in collinear factorization!***

SIDIS (Sivers and Collins effects)

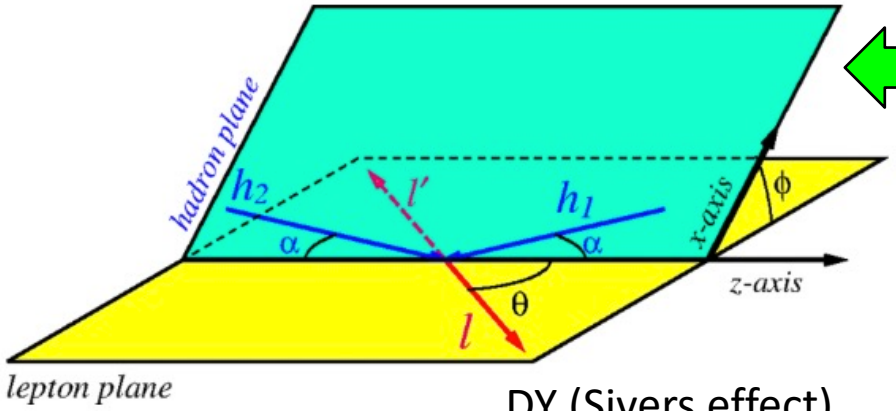



$h_1$, $F_{FT}$, $H_1^{\perp(1)}$

SIA (Collins effect)

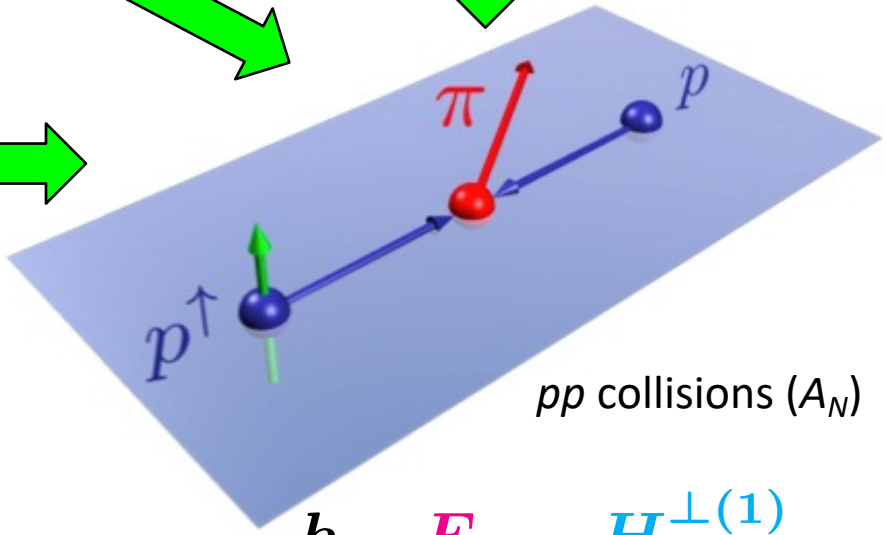



$H_1^{\perp(1)}$




DY (Sivers effect)

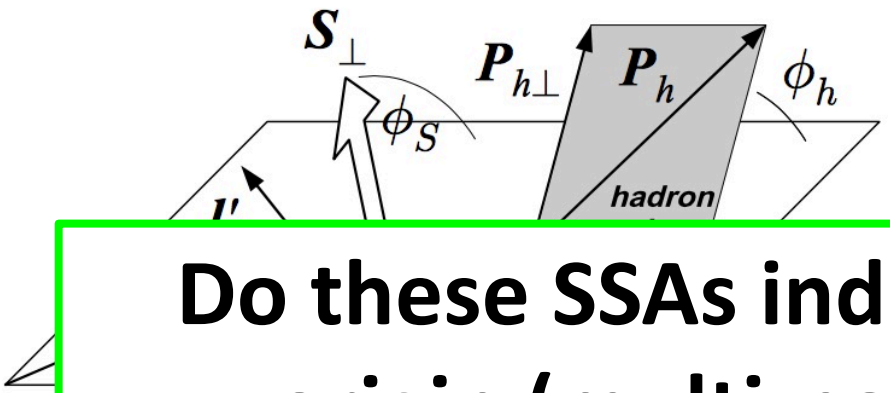
$F_{FT}$



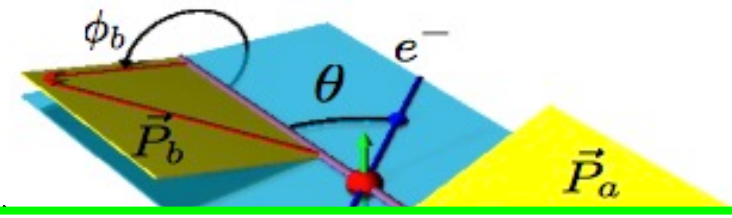

*pp* collisions ($A_N$)

$h_1$, $F_{FT}$, $H_1^{\perp(1)}$

SIDIS (Sivers and Collins effects)

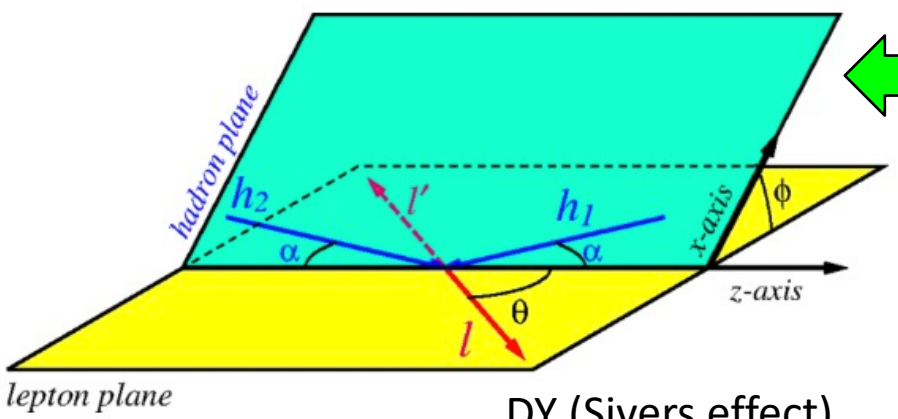



SIA (Collins effect)



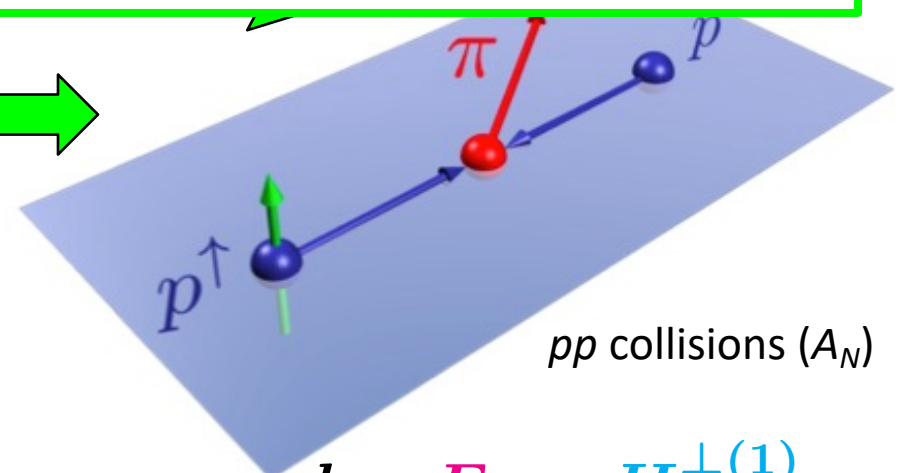

**Do these SSAs indeed have a common origin (multi-parton correlators)?**

**Need a GLOBAL ANALYSIS of SSAs!**




DY (Sivers effect)

$F_{FT}$




*pp* collisions ($A_N$)

$h_1,\ F_{FT},\ H_1^{\perp(1)}$

# Global Analysis – Methodology and Results

(Cammarota, Gamberg, Kang, Miller, DP, Prokudin, Rogers, Sato, PRD **102** (2020))

- We have performed the first QCD global analysis of SSAs in SIDIS, Drell-Yan, $e^+e^-$ annihilation, and proton-proton collisions and extracted a universal set of non-perturbative functions

$$h_1(x),\ F_{FT}(x,x),\ H_1^{\perp(1)}(z),\ \tilde{H}(z)$$

along with the relevant transverse momentum widths for the Sivers, transversity, and Collins functions: $\langle k_T^2\rangle_{f_{1T}^\perp}, \langle k_T^2\rangle_{h_1}, \langle p_\perp^2\rangle_{H_1^\perp}^{fav}, \langle p_\perp^2\rangle_{H_1^\perp}^{unf}$

- We use a Gaussian ansatz: $F(x,k_T^2) \sim F(x)e^{-k_T^2/\langle k_T^2\rangle}$ where

$$F^q(x) = \frac{N_q\, x^{a_q}(1-x)^{b_q}(1+\gamma_q\, x^{\alpha_q}(1-x)^{\beta_q})}{\mathrm{B}[a_q+2, b_q+1] + \gamma_q \mathrm{B}[a_q+\alpha_q+2, b_q+\beta_q+1]}$$

*NB:* $\{\gamma,\alpha,\beta\}$ only used for Collins function

- DGLAP-type evolution for the collinear functions analogous to Duke & Owens (1984): double-log $Q^2$-dependent term explicitly added to the parameters

- We have performed the first QCD global analysis of SSAs in SIDIS, Drell-Yan, $e^+e^-$ annihilation, and proton-proton collisions and extracted a universal set of non-perturbative functions

$$h_1(x),\ F_{FT}(x,x),\ H_1^{\perp(1)}(z),\ \cancel{\tilde{H}(z)}$$

noise in the fit – need $A_{UT}^{\sin\phi_S}$

along with the relevant transverse momentum widths for the Sivers, transversity, and Collins functions: $\langle k_T^2\rangle_{f_{1T}^\perp}, \langle k_T^2\rangle_{h_1}, \langle p_\perp^2\rangle_{H_1^\perp}^{fav}, \langle p_\perp^2\rangle_{H_1^\perp}^{unf}$

- We use a Gaussian ansatz: $F(x,k_T^2) \sim F(x)e^{-k_T^2/\langle k_T^2\rangle}$ where

$$F^q(x) = \frac{N_q\, x^{a_q}(1-x)^{b_q}(1+\gamma_q\, x^{\alpha_q}(1-x)^{\beta_q})}{\mathrm{B}[a_q+2, b_q+1] + \gamma_q \mathrm{B}[a_q+\alpha_q+2, b_q+\beta_q+1]}$$

*NB:* $\{\gamma,\alpha,\beta\}$ only used for Collins function

- DGLAP-type evolution for the collinear functions analogous to Duke & Owens (1984): double-log $Q^2$-dependent term explicitly added to the parameters

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

- 18 observables and 6 non-perturbative functions (Sivers up/down; transversity up/down; Collins favored/unfavored)

- Broad kinematical coverage:

SIDIS: $x \lesssim 0.3 \qquad 0.2 \lesssim z \lesssim 0.6 \qquad 2 \lesssim Q^2 \lesssim 40\,\text{GeV}^2$

SIA: $0.2 \lesssim z \lesssim 0.8 \qquad Q^2 \approx 13\,\text{GeV}^2$ or $110\,\text{GeV}^2$

DY: $0.1 \lesssim x \lesssim 0.35 \qquad Q^2 \approx 30\,\text{GeV}^2$ or $(80\,\text{GeV})^2$

$A_N^h$: $0.2 \lesssim (x_{min}, z_{min}) \lesssim 0.7 \qquad 1 \lesssim Q^2 \lesssim 13\,\text{GeV}^2$

| Observable | Reactions | Non-Perturbative Function(s) | $\chi^2/N_{\rm pts.}$ |
|---|---|---|---|
| $A_{\rm SIDIS}^{\rm Siv}$ | $e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$ | $f_{1T}^\perp(x,k_T^2)$ | $150.0/126=1.19$ |
| $A_{\rm SIDIS}^{\rm Col}$ | $e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$ | $h_1(x,k_T^2), H_1^\perp(z,z^2p_\perp^2)$ | $111.3/126=0.88$ |
| $A_{\rm SIA}^{\rm Col}$ | $e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$ | $H_1^\perp(z,z^2p_\perp^2)$ | $154.5/176=0.88$ |
| $A_{\rm DY}^{\rm Siv}$ | $\pi^- + p^\uparrow \to \mu^+\mu^- + X$ | $f_{1T}^\perp(x,k_T^2)$ | $5.96/12=0.50$ |
| $A_{\rm DY}^{\rm Siv}$ | $p^\uparrow + p \to (W^+,W^-,Z)+X$ | $f_{1T}^\perp(x,k_T^2)$ | $31.8/17=1.87$ |
| $A_N^h$ | $p^\uparrow + p \to (\pi^+,\pi^-,\pi^0)+X$ | $h_1(x), F_{FT}(x,x)=\frac{1}{\pi}f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$ | $66.5/60=1.11$ |

- 18 observables and 6 non-perturbative functions (Sivers up/down; transversity up/down; Collins favored/unfavored)

**Test of universality!**

- Broad kinematical coverage:

SIDIS: $x \lesssim 0.3 \qquad 0.2 \lesssim z \lesssim 0.6 \qquad 2 \lesssim Q^2 \lesssim 40\,\mathrm{GeV}^2$

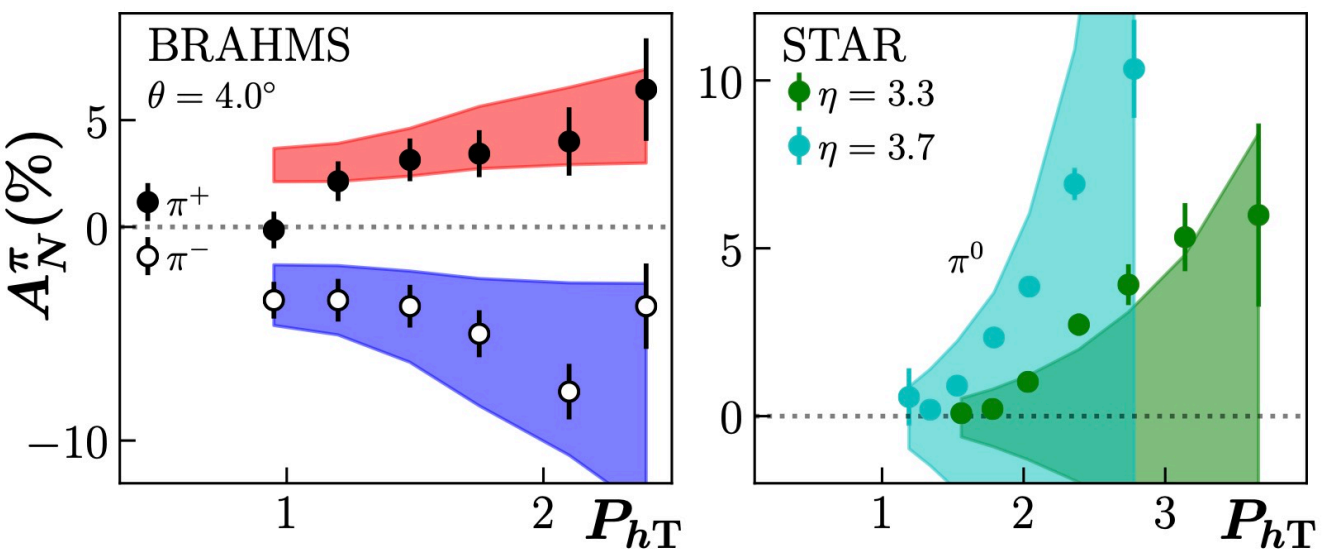
SIA: $0.2 \lesssim z \lesssim 0.8 \qquad Q^2 \approx 13\,\mathrm{GeV}^2$ or $110\,\mathrm{GeV}^2$

DY: $0.1 \lesssim x \lesssim 0.35 \qquad Q^2 \approx 30\,\mathrm{GeV}^2$ or $(80\,\mathrm{GeV})^2$

$A_N^h$: $0.2 \lesssim (x_{min}, z_{min}) \lesssim 0.7 \qquad 1 \lesssim Q^2 \lesssim 13\,\mathrm{GeV}^2$

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

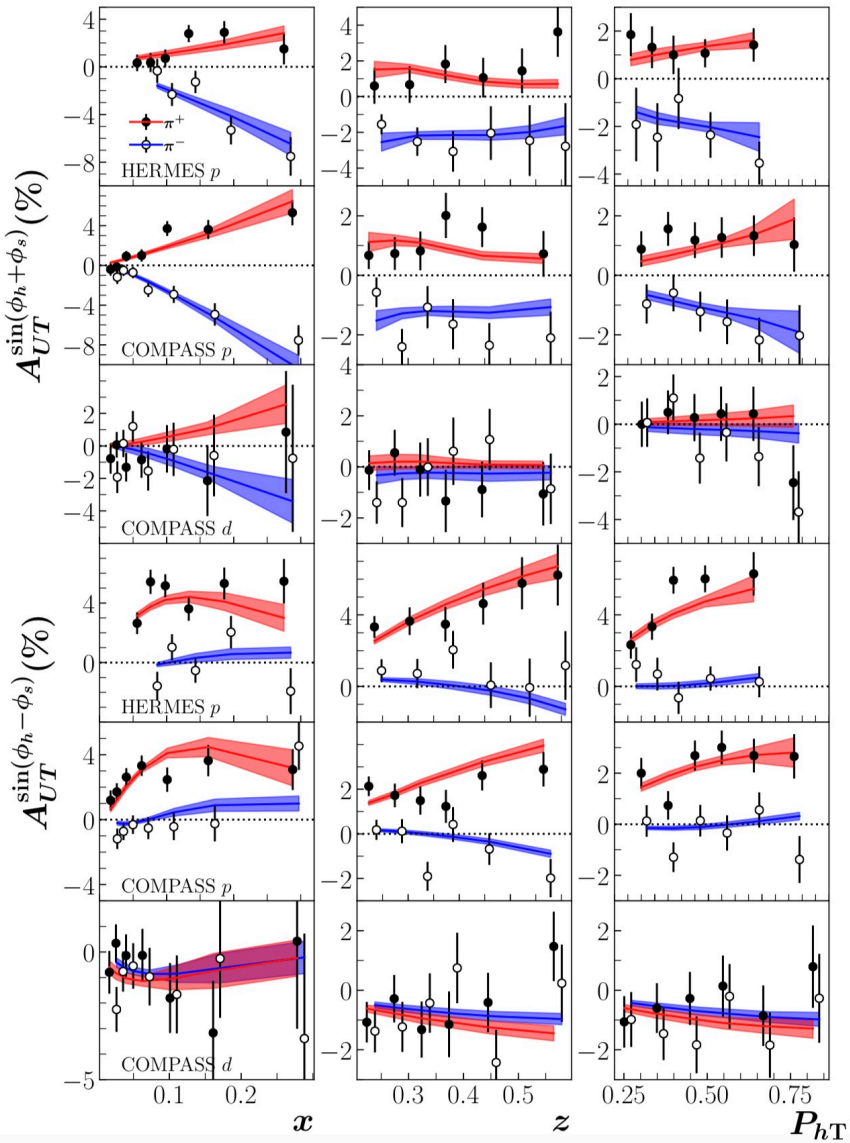
- *Predictions* of $A_N$ using a fit of only TMD observables

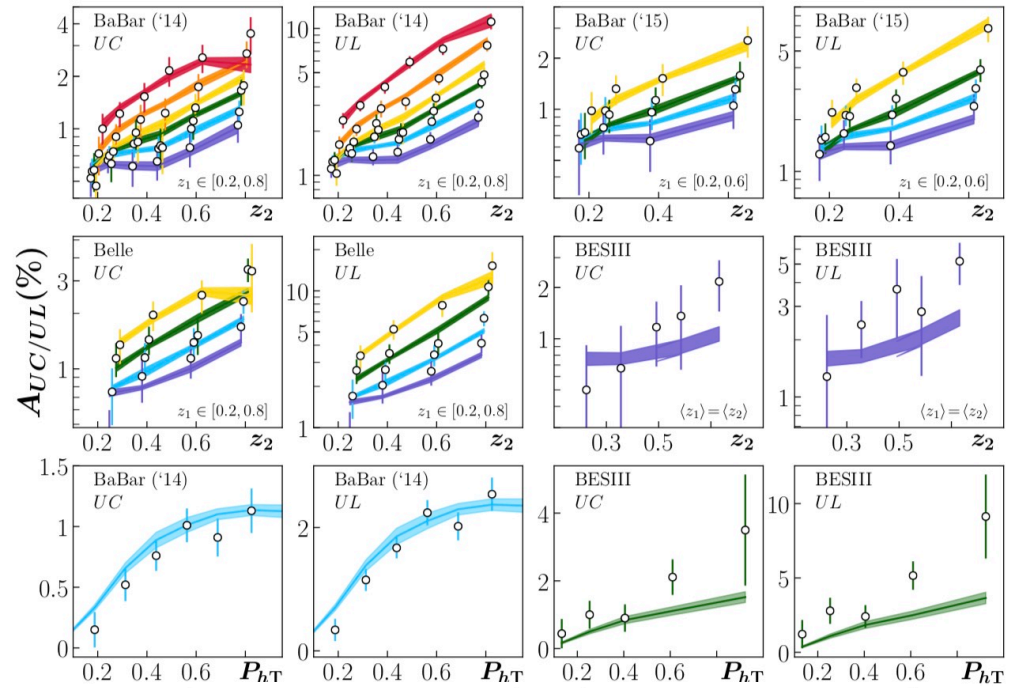


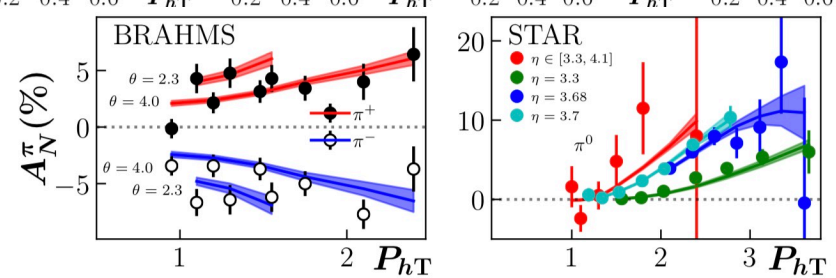

**Test of universality!**

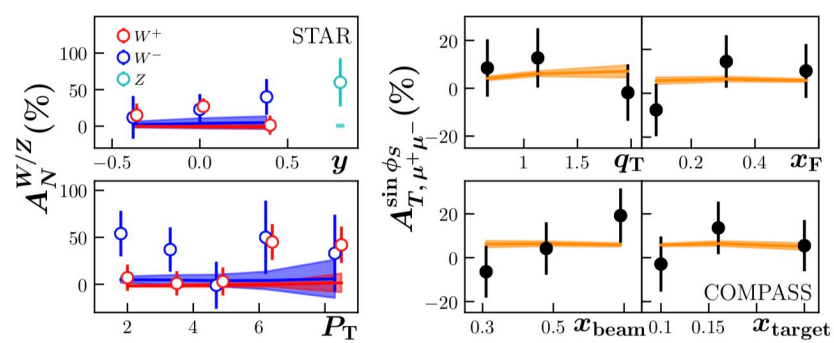
- We use Bayesian inference in order to sample the posterior distribution for all parameters
- Due to the large dimensionality of the parameter space we use a multi-step strategy to fit the data (Sato, et al. (2019))
- Our results are based off ~1000 Monte Carlo samples

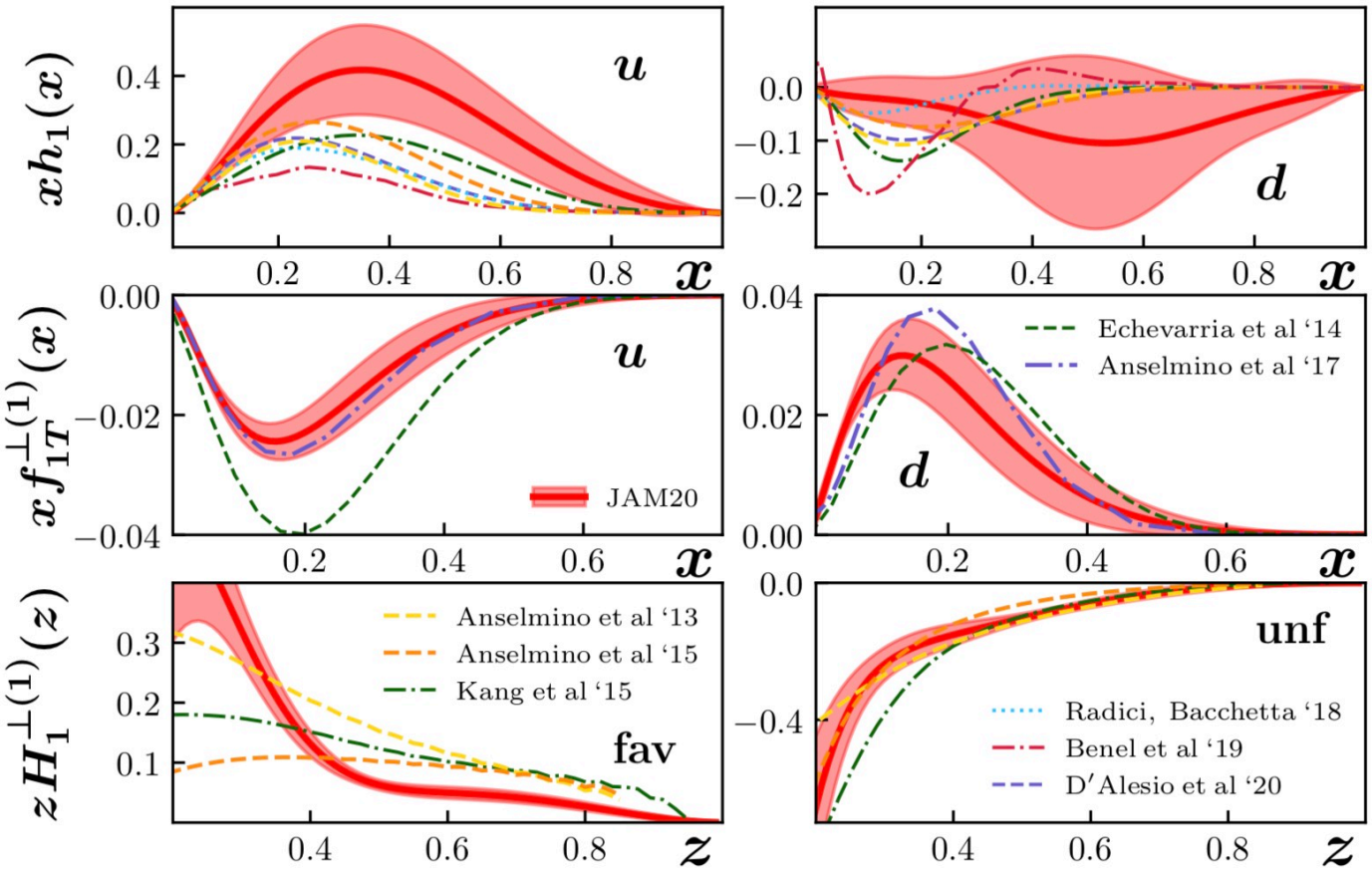
$$\chi^2/N_{\text{pts.}} = 520/517 = 1.01$$






**Transversity**

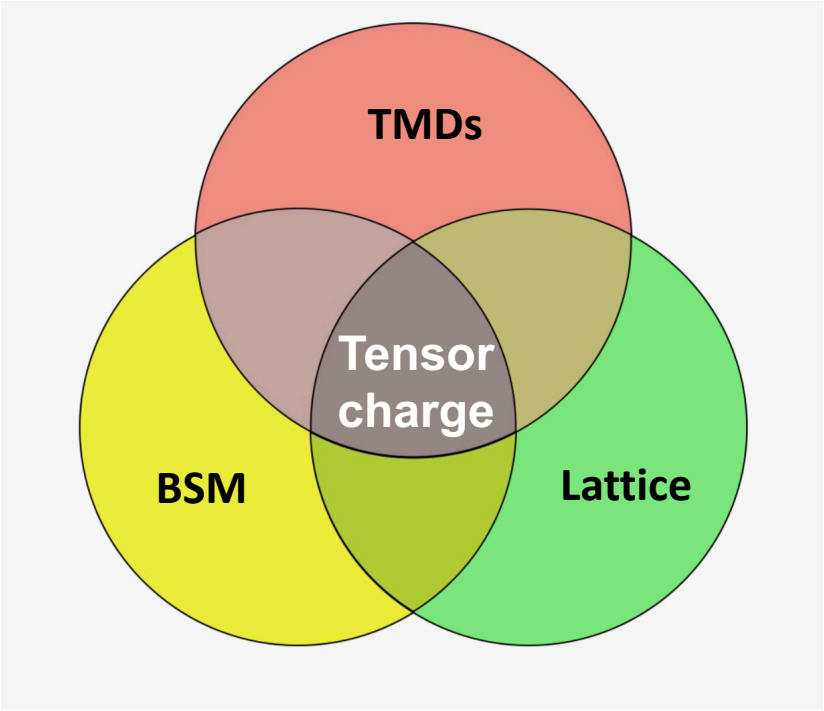
**Sivers first moment (QS function)**

**Collins first moment**

# Tensor Charge of the Nucleon from JAM20

(Cammarota, Gamberg, Kang, Miller, DP, Prokudin, Rogers, Sato, PRD **102** (2020))

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



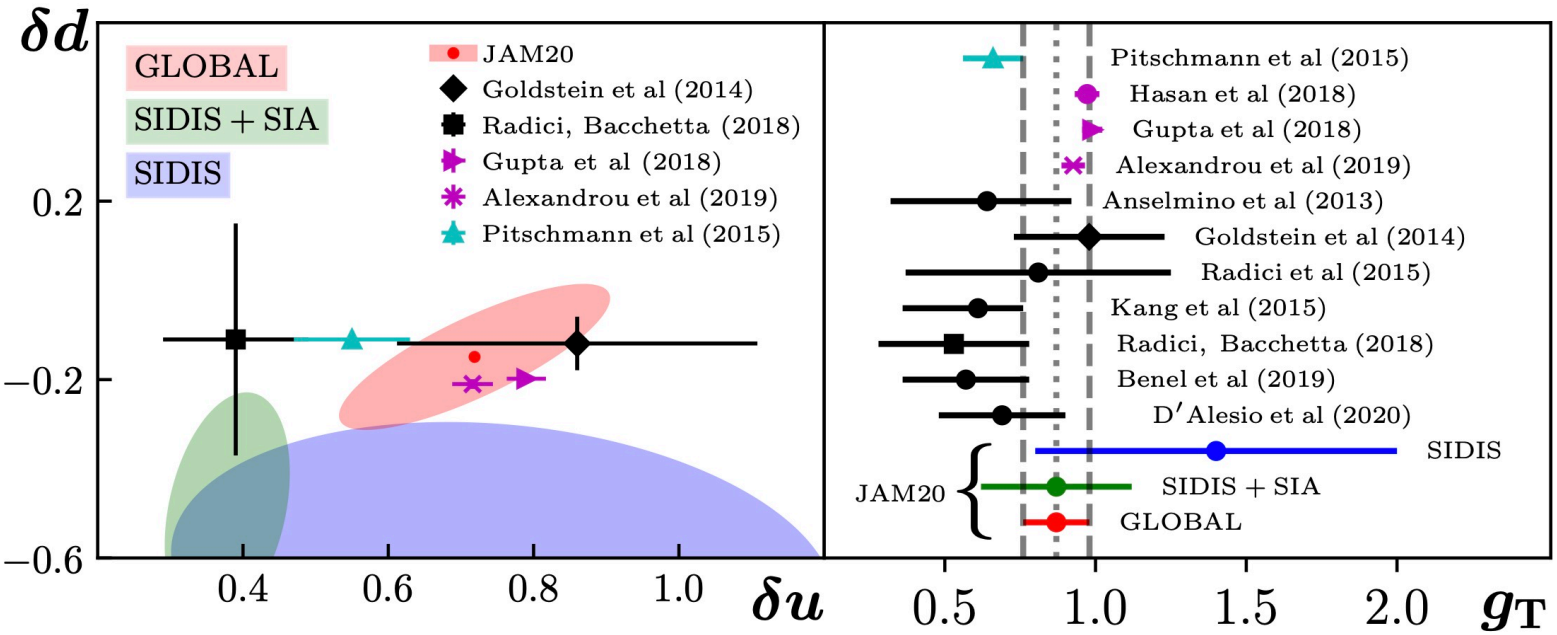
$$\delta q \equiv \int_0^1 dx\,[h_1^q(x) - h_1^{\bar{q}}(x)] \qquad g_T \equiv \delta u - \delta d$$

- The tensor charge of the nucleon is one of its fundamental charges and is important for BSM studies (beta decays, EDM)

- Lattice QCD has made very precise calculations at the physical point that are typically at odds with extractions from phenomenology – **the central value for *δu* from phenomenology tends to be smaller than lattice**, which also causes $g_T$ to fall below lattice as well ("transverse spin puzzle")

- Up until now, the phenomenological extractions of the tensor charges have been based on either fits of SIDIS+SIA data or dihadron fragmentation data

- **We have achieved the first phenomenological agreement with lattice** for ***all*** the tensor charges ($\delta u, \delta d, g_T$), which highlights the importance of carrying out a ***global analysis*** ***(i.e., including $A_N$ data along with SIDIS+SIA)***




$$\text{SIDIS} \to (\text{SIDIS} + \text{SIA}) \to \text{GLOBAL} : \boldsymbol{g_T} = 1.4(6) \to 0.87(25) \to \mathbf{0.87(11)}$$

- This is the most precise phenomenological determination of $g_T$ to date

- Our tensor charges, especially $\boldsymbol{\delta u}$, show excellent agreement with lattice: $\delta u = 0.72(19)$, $\delta d = -0.15(16)$

***The inclusion of $A_N$ data is crucial in order to achieve agreement between phenomenology and lattice for the tensor charges!***

# EIC Impact Study on Transversity and Tensor Charge

(Gamberg, Kang, DP, Prokudin, Sato, Seidl, in preparation)

- We generated SIDIS Collins EIC pseudo-data with PID+smearing systematics. The number of points listed is after the following cuts are made

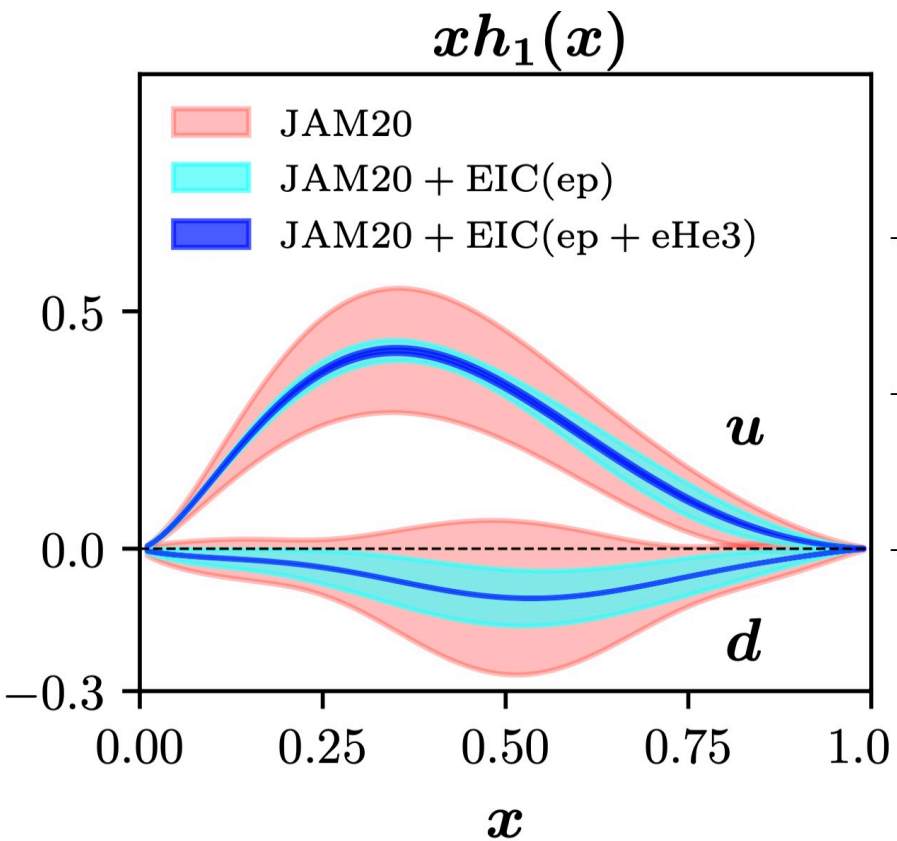
$$0.2 < z < 0.6, Q^2 > 1.63\,\mathrm{GeV}^2, 0.2 < P_{hT} < 0.9\,\mathrm{GeV}$$

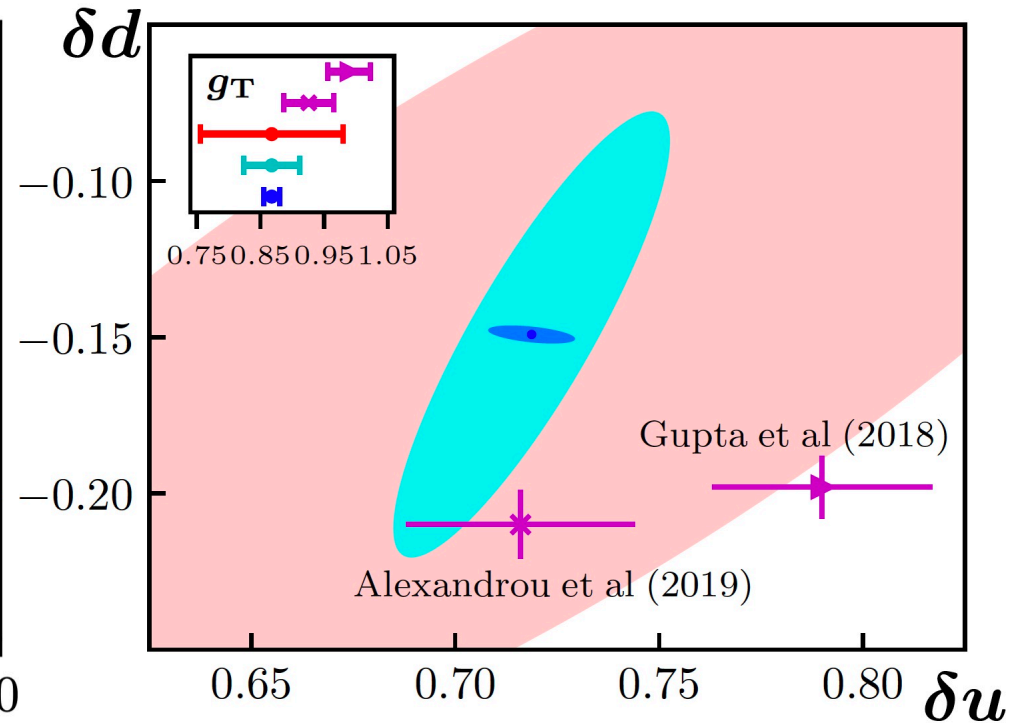
| $e\,p^{\uparrow} \to e\,\pi^+\,X$ | $e\,p^{\uparrow} \to e\,\pi^-\,X$ | $e\,n^{\uparrow} \to e\,\pi^+\,X$ | $e\,n^{\uparrow} \to e\,\pi^-\,X$ |
|---|---|---|---|
| 18x275 (756 pts.) | 18x275 (744 pts.) | 18x100 (647 pts.) | 18x100 (650 pts.) |
| 10x100 (634 pts.) | 10x100 (619 pts.) | 10x100 (622 pts.) | 10x100 (621 pts.) |
| 5x100 (537 pts.) | 5x100 (556 pts.) | 5x41 (461 pts.) | 5x41 (459 pts.) |
| 5x41 (464 pts.) | 5x41 (453 pts.) | | |

---

Total EIC points = 8223
JAM20 original fit (SSA points) = 517 (362 sensitive to Collins and/or transversity, i.e., SIDIS Collins, $e^+e^-$, and $A_N$)

- We re-fit the 8223 + 517 = 8740 data points with ~200 replicas using priors from the JAM20 global analysis




| JAM20 | JAM20+EIC(ep) | JAM20+EIC(ep+eHe3) |
|---|---|---|
| $\delta u = 0.72 \pm 0.19$ | $\delta u = 0.719 \pm 0.034$ | $\delta u = 0.719 \pm 0.011$ |
| $\delta d = -0.15 \pm 0.16$ | $\delta d = -0.149 \pm 0.071$ | $\delta d = -0.149 \pm 0.003$ |
| $g_T = 0.87 \pm 0.11$ | $g_T = 0.869 \pm 0.044$ | $g_T = 0.869 \pm 0.012$ |

# Summary and Outlook

- We have performed the first global analysis of SSAs in SIDIS, DY, $e^+e^-$ annihilation, and proton-proton collisions and extracted a universal set of non-perturbative functions
- We have achieved the first phenomenological agreement with lattice QCD for all the tensor charges of the nucleon, which highlights the importance of carrying out a global analysis
- The EIC impact on the tensor charge will be significant and make phenomenological extractions as precise as lattice calculations
- Future studies will implement the proper TMD and CT3 evolution and include $A_{UT}^{\sin\phi_S}$ data to constrain $\tilde{H}$, as well as eventually other data (like hadron in a jet, dihadron, …)

***Global analyses using data that cover a broad kinematical range are crucial if one is to claim we truly understand 3D hadronic structure!***