Impact Study of Future Data on the Tensor Charge from a QCD Global Analysis

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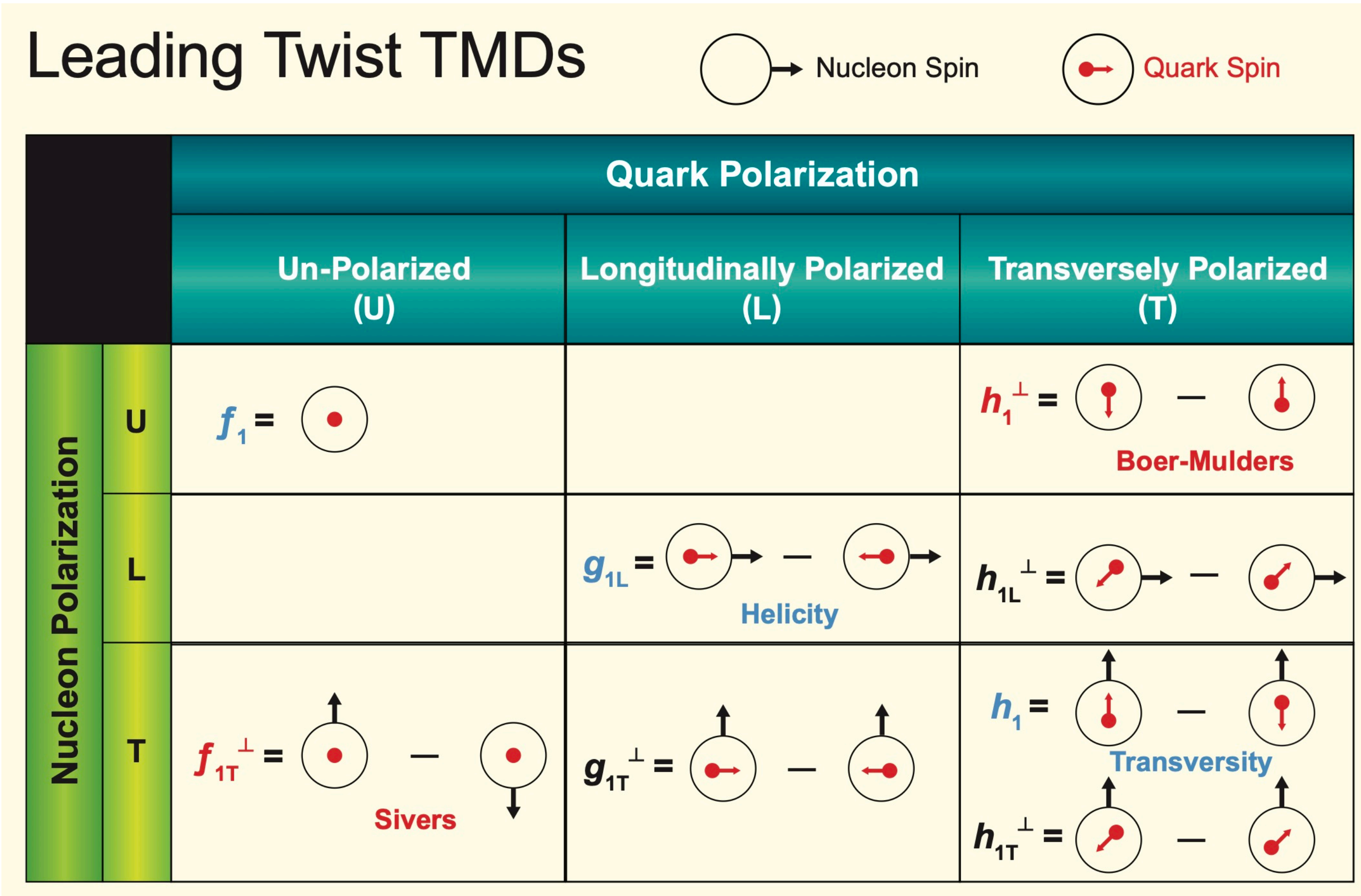
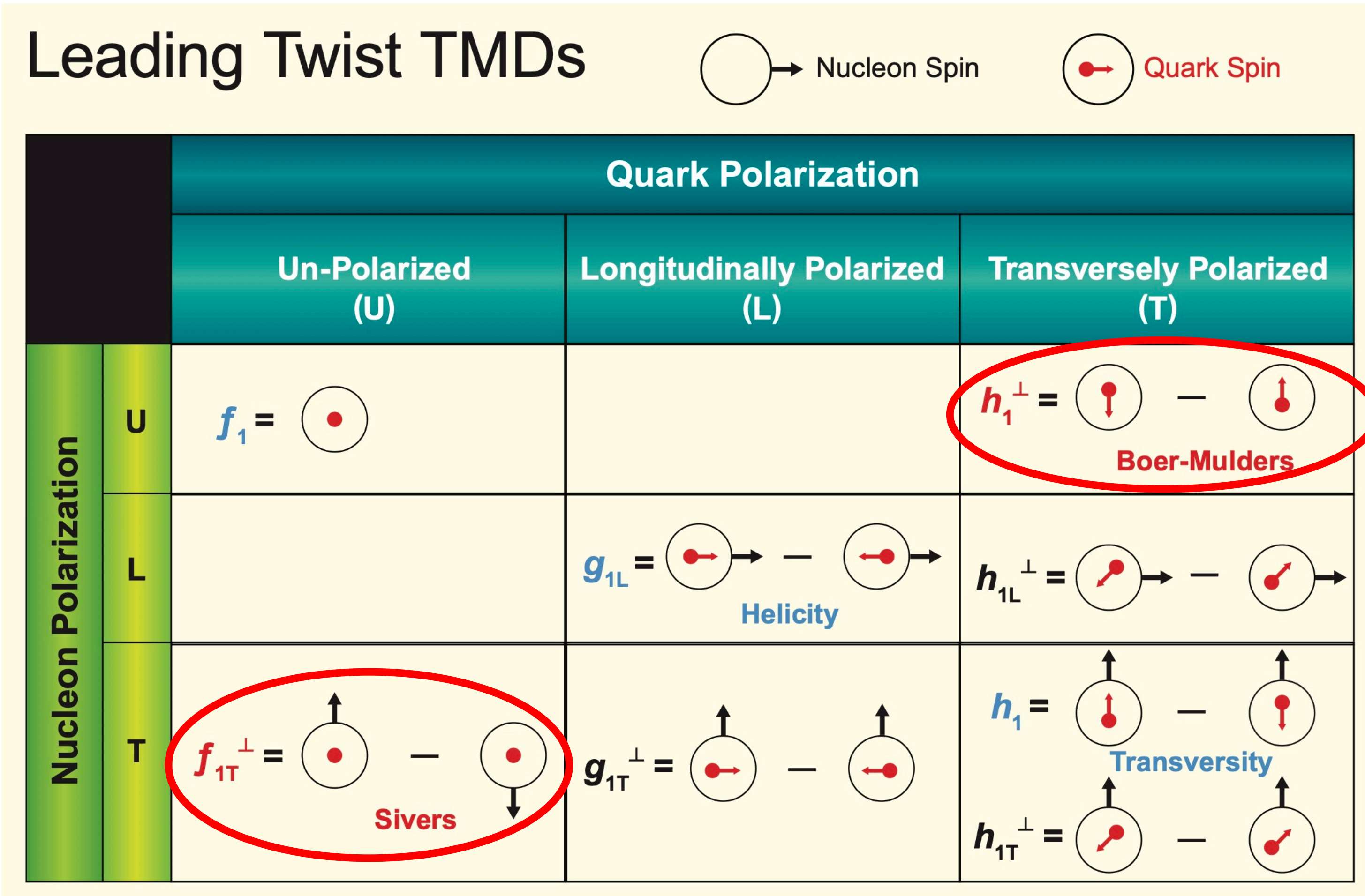
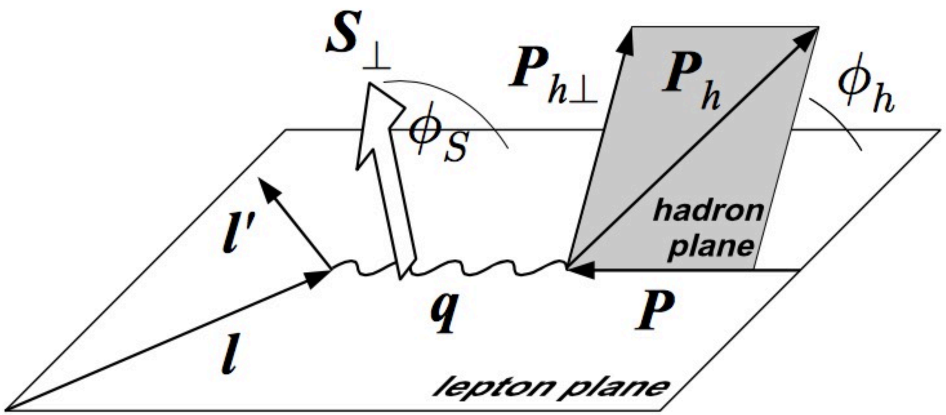
Background


Leading Twist TMDs
Nucleon Spin
Quark Spin
Quark Polarization
Un-Polarized (U)
Longitudinally Polarized (L)
Transversely Polarized (T)
Nucleon Polarization
U
L
T
$f_1 =$
$h_1^\perp =$
Boer-Mulders
$g_{1L} =$
Helicity
$h_{1L}^\perp =$
$f_{1T}^\perp =$
Sivers
$g_{1T}^\perp =$
$h_1 =$
Transversity
$h_{1T}^\perp =$

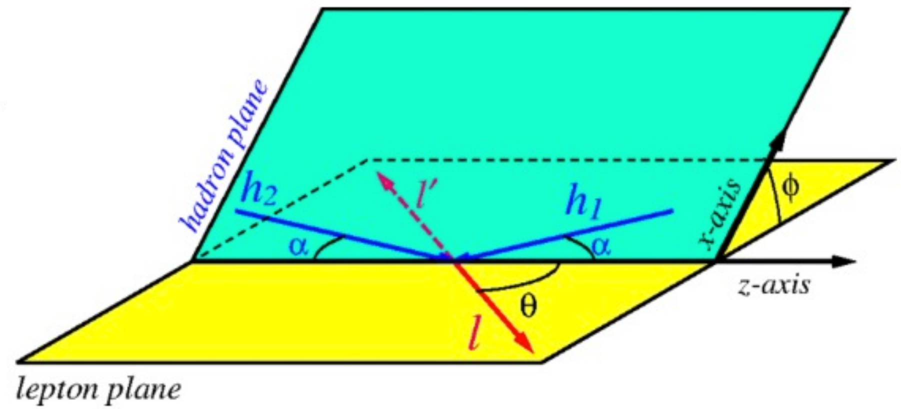


Naïve time-reversal odd (T-odd)

$$\ell p^{\uparrow} \to \ell h X$$



$$\{\pi, p\} p^{\uparrow} \to \{\ell^+\ell^-, W^{\pm}, Z\} X$$



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

$$F_{TU}^{\sin\phi} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_{aT}}{M_a} \boldsymbol{f_{1T}^{\perp}}\, \bar{f}_1\right]$$

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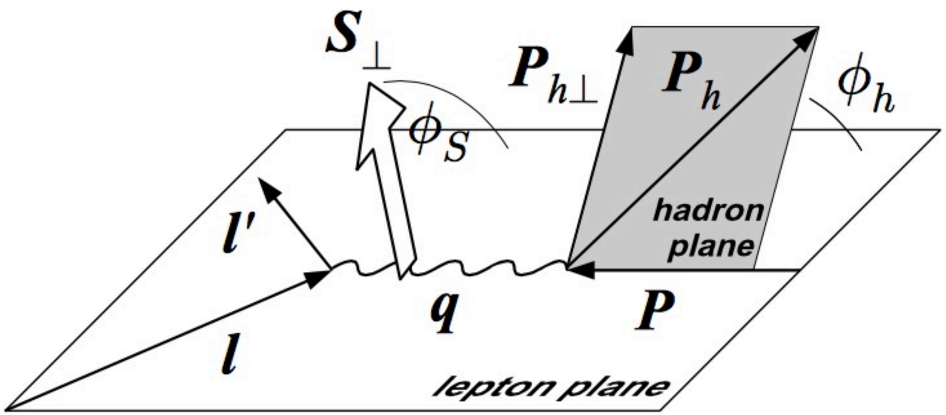

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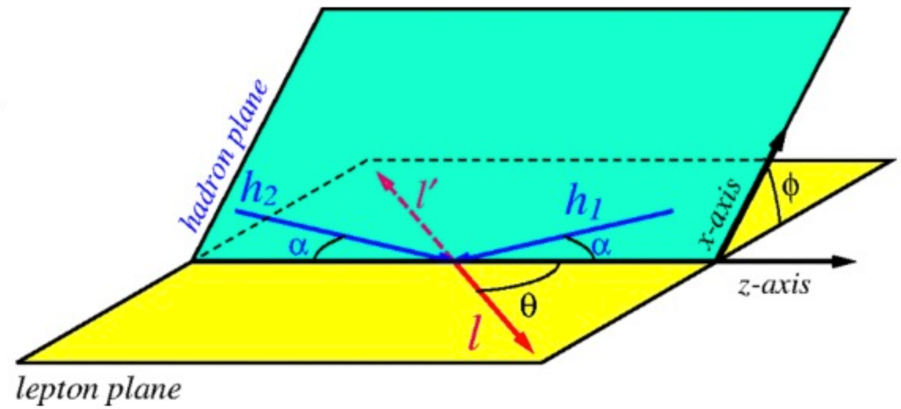

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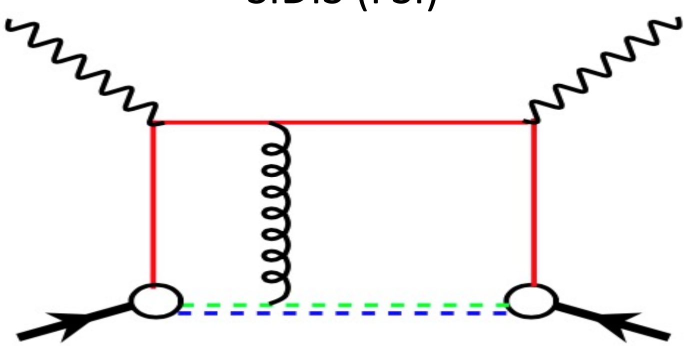
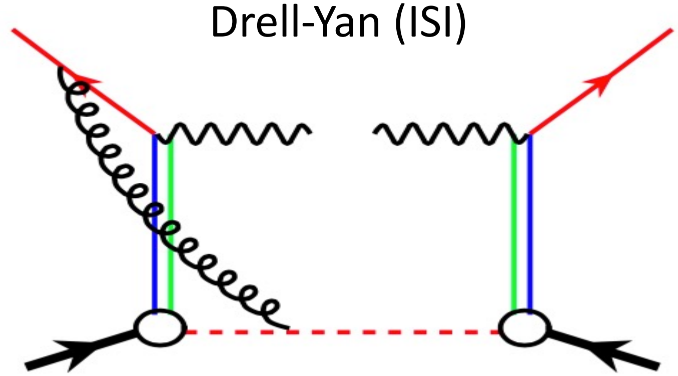
$$F_{TU}^{\sin\phi} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_{aT}}{M_a} \boldsymbol{f_{1T}^{\perp}}\, \bar{f}_1\right]$$

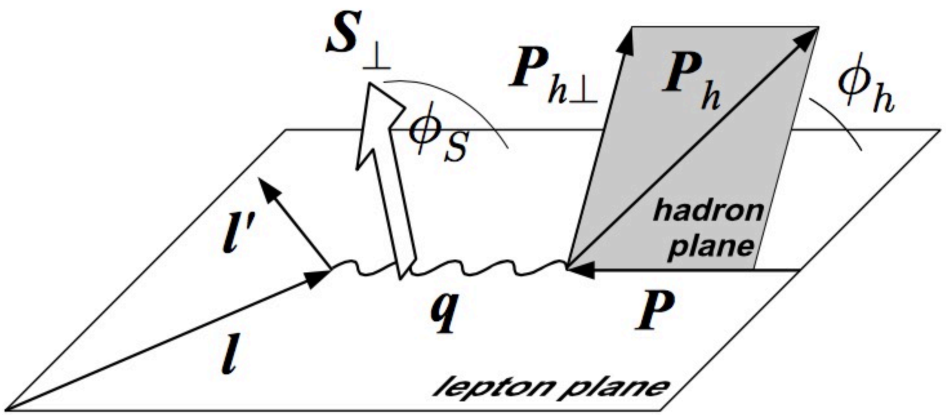
SIDIS (FSI)



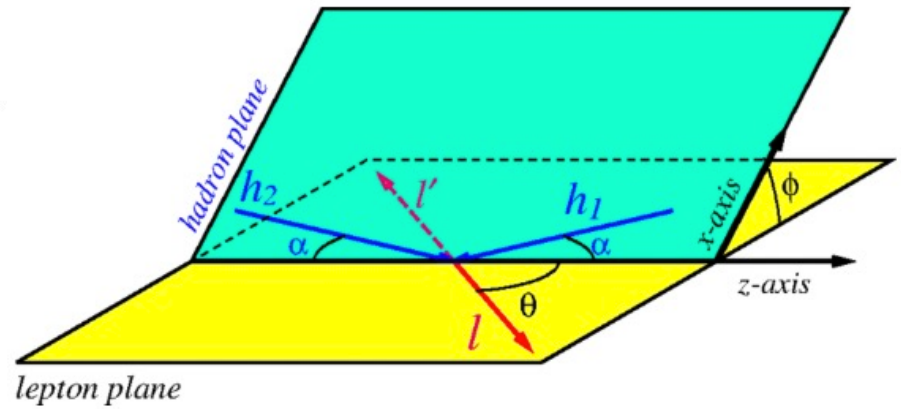
Drell-Yan (ISI)



$$\ell p^{\uparrow} \to \ell h X$$

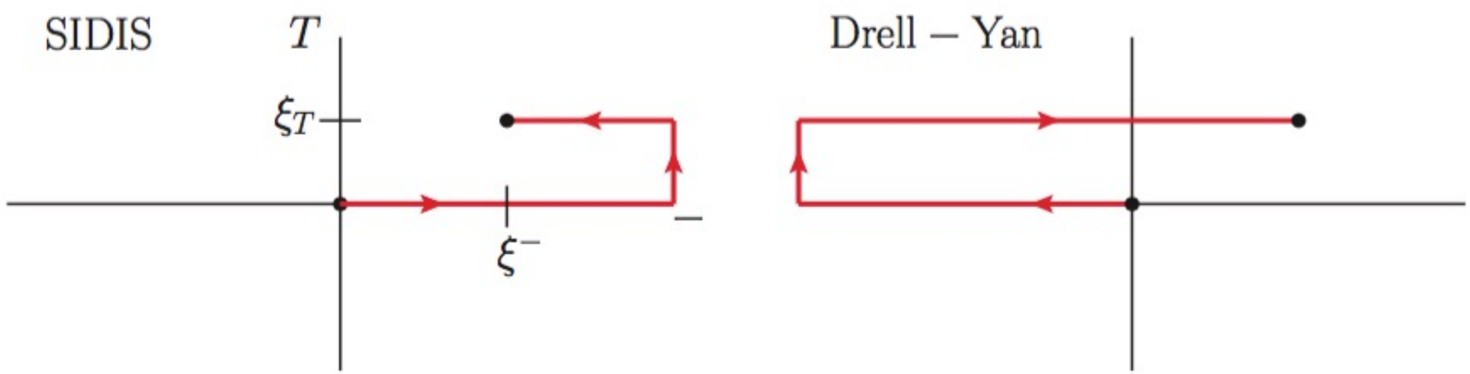


$$\{\pi, p\} p^{\uparrow} \to \{\ell^+\ell^-, W^{\pm}, Z\} X$$



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

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

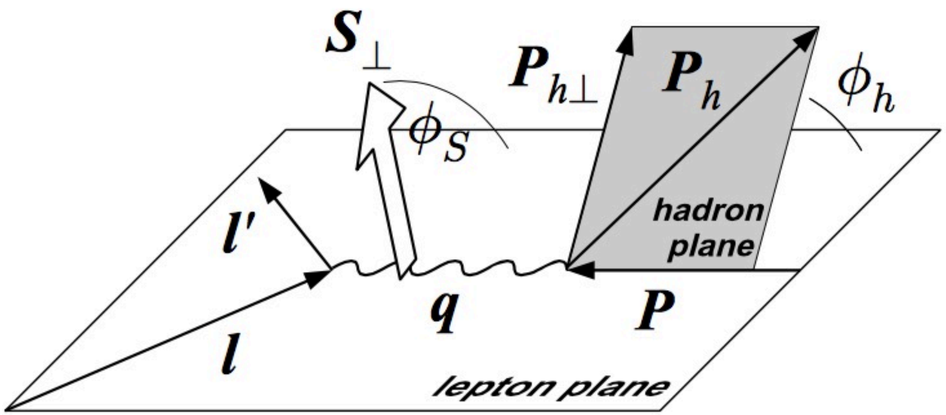


$$f_{1T}^{\perp}(x, \vec{k}_T^2)\big|_{SIDIS} = -f_{1T}^{\perp}(x, \vec{k}_T^2)\big|_{DY}$$

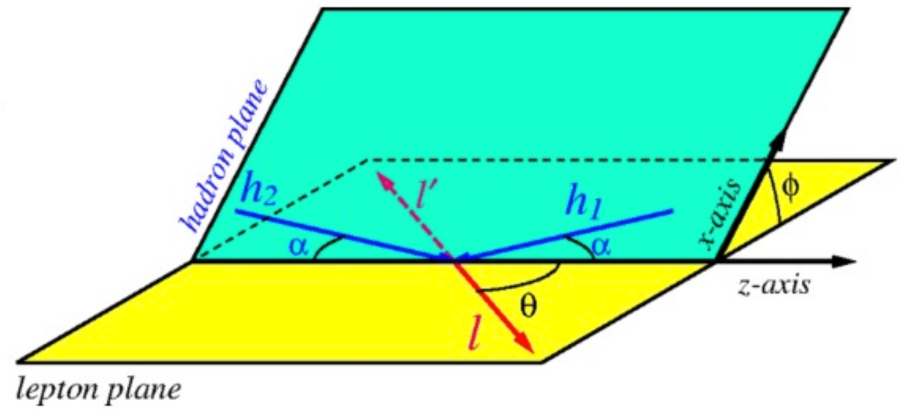
$$h_1^{\perp}(x, \vec{k}_T^2)\big|_{SIDIS} = -h_1^{\perp}(x, \vec{k}_T^2)\big|_{DY}$$

(Collins (2002))

$$\ell p^\uparrow \to \ell h X$$



$$\{\pi, p\} p^\uparrow \to \{\ell^+\ell^-, W^\pm, Z\} X$$

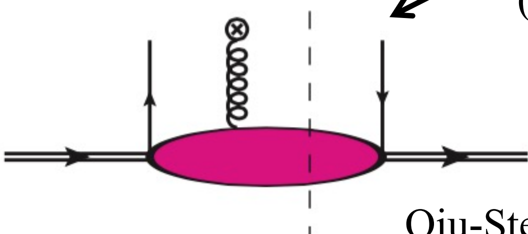


$$F_{UT}^{\sin(\phi_h - \phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M} f_{1T}^\perp D_1\right]$$

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

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

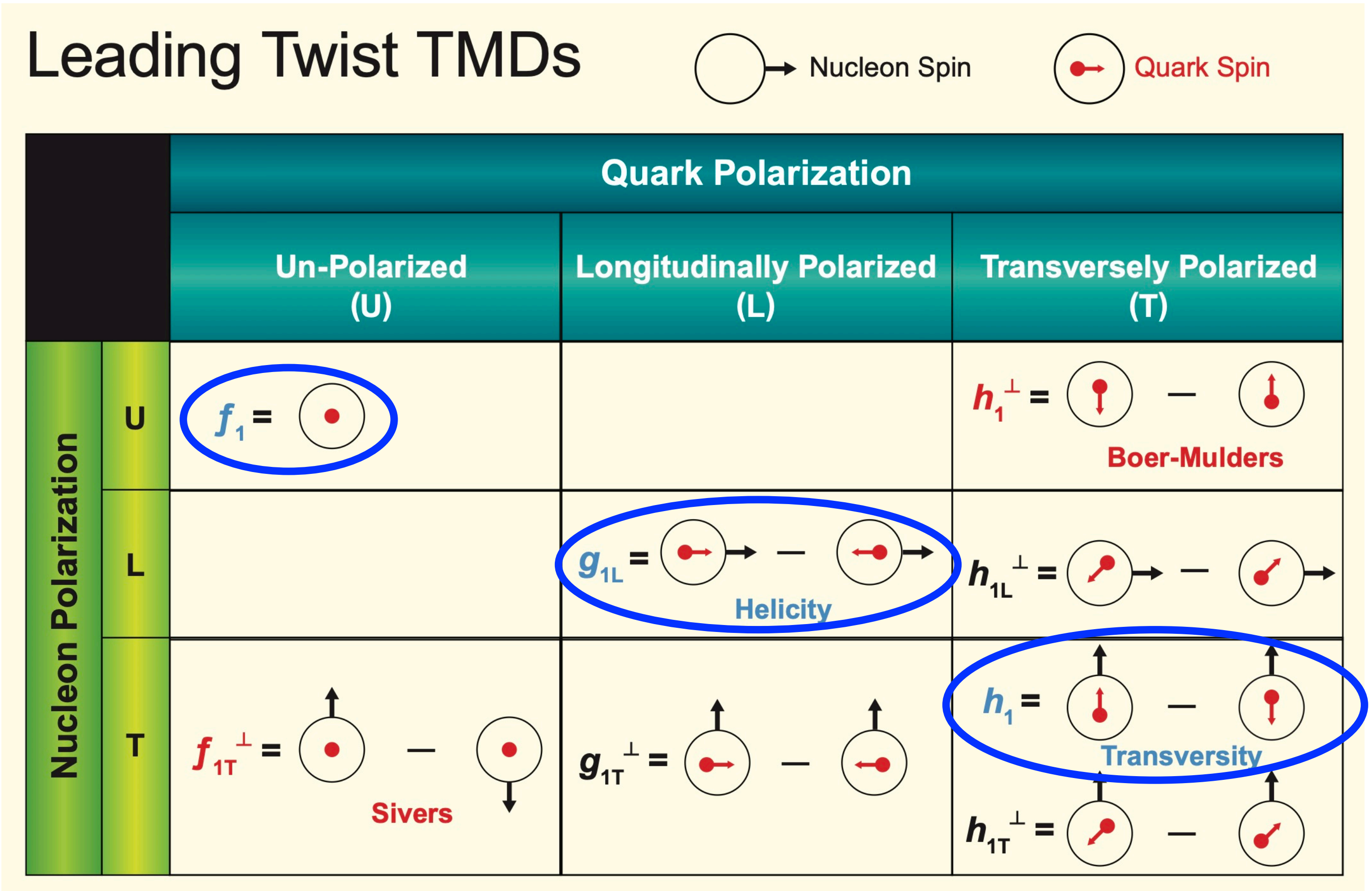
OPE
(NLO available from Scimemi, Tarasov, Vladimirov (2019))



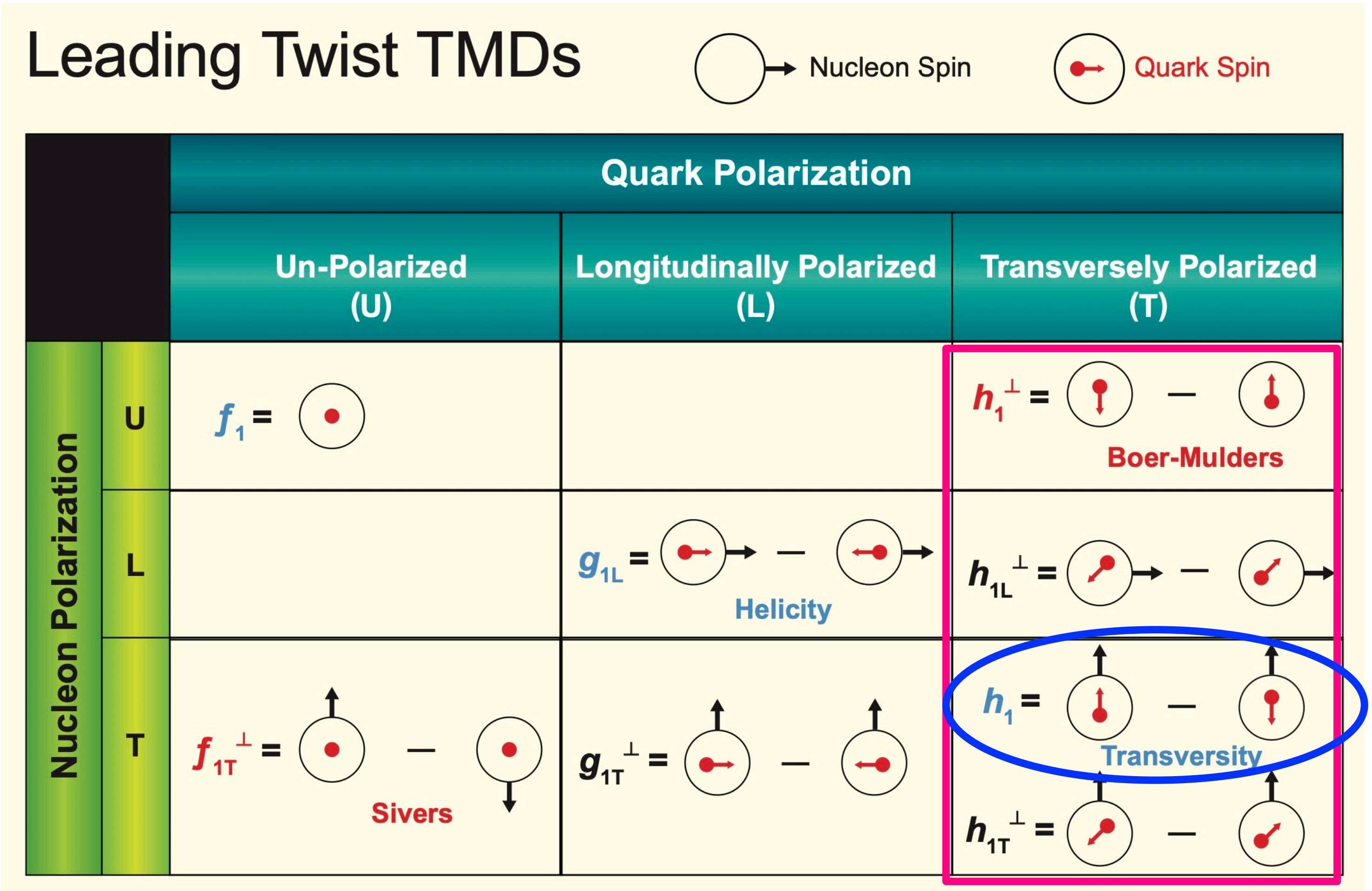
Qiu-Sterman function

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

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



Survive integration over k_T



Chiral odd

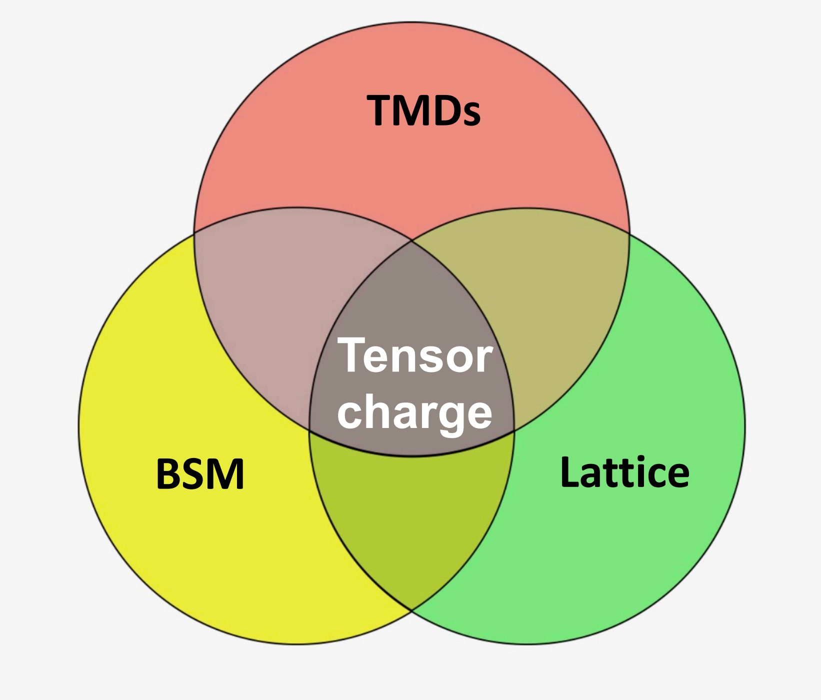
Survive integration over k_T

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

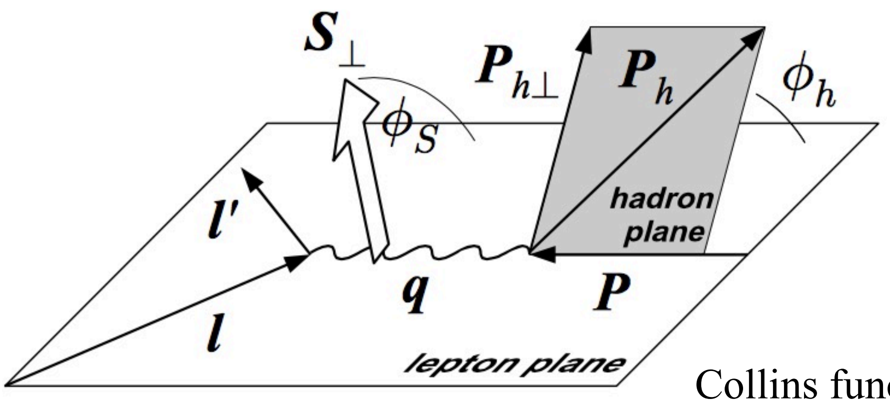
The tensor charge of the nucleon is one of its fundamental charges and is important for BSM studies in, e.g., beta decays (Gonzalez-Alonso, et al. (2018),…)

Processes sensitive to TMDs can play an important role in these efforts (Courtoy, et al. (2015); Yamanaka, et al. (2017), Liu, et al. (2018),…)

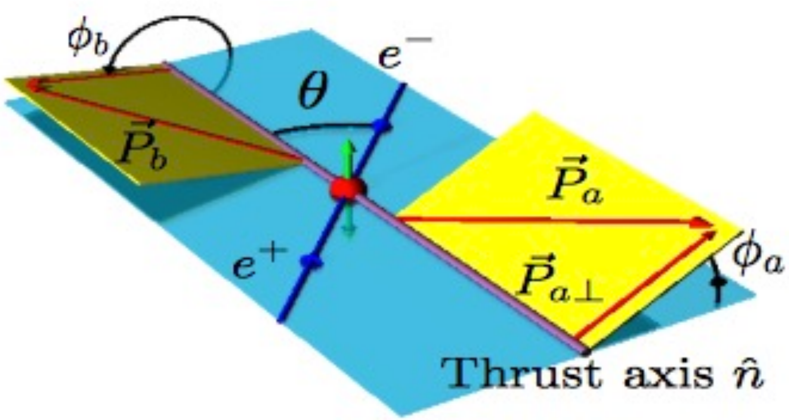
Lattice QCD has also calculated the tensor charges with great precision (Gupta, et al. (2018); Hasan, et al. (2019), Alexandrou, et. (2019),…)



$\ell p^{\uparrow} \to \ell h X$



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



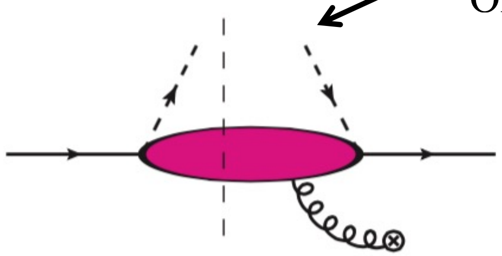
Collins function

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

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

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

OPE



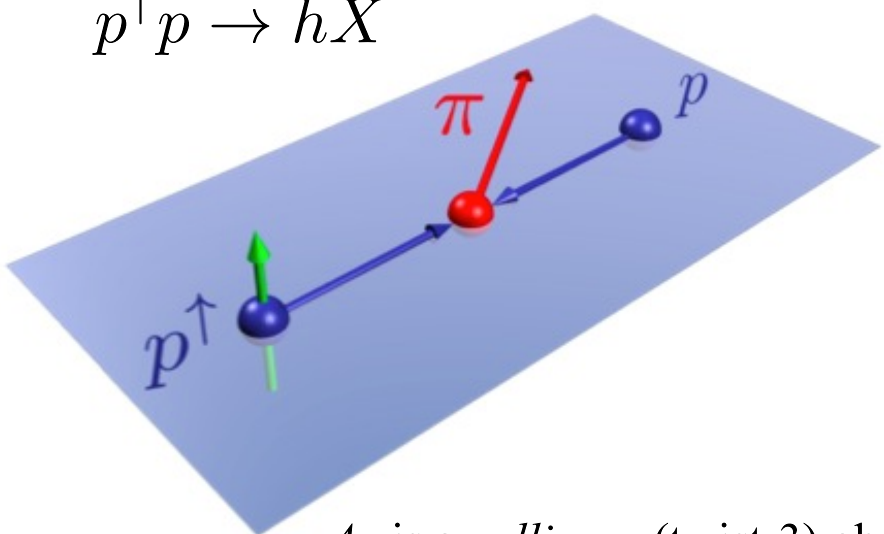
qgq
fragmentation
function

(Kang, et al. (2016))

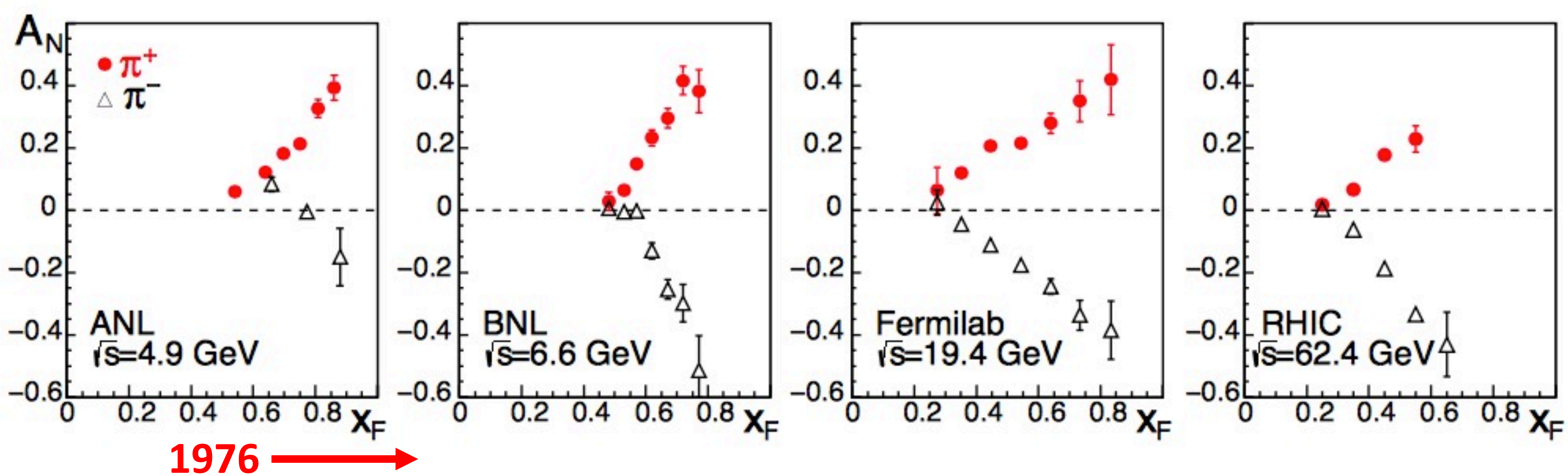
$$d\Delta\sigma(S_T) \sim \underbrace{H_{QS} \otimes f_1 \otimes \boldsymbol{F_{FT}} \otimes D_1}_{\text{Qiu-Sterman term}}$$

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

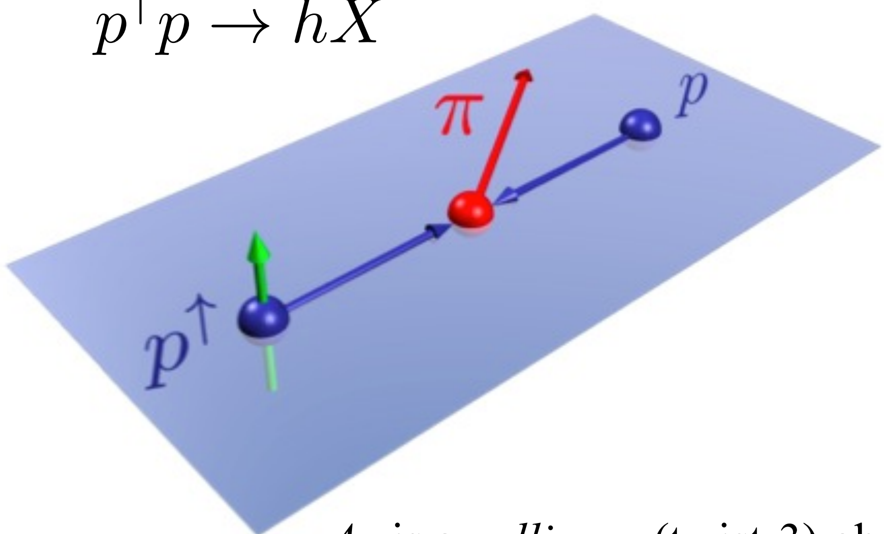
$p^\uparrow p \to hX$



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



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

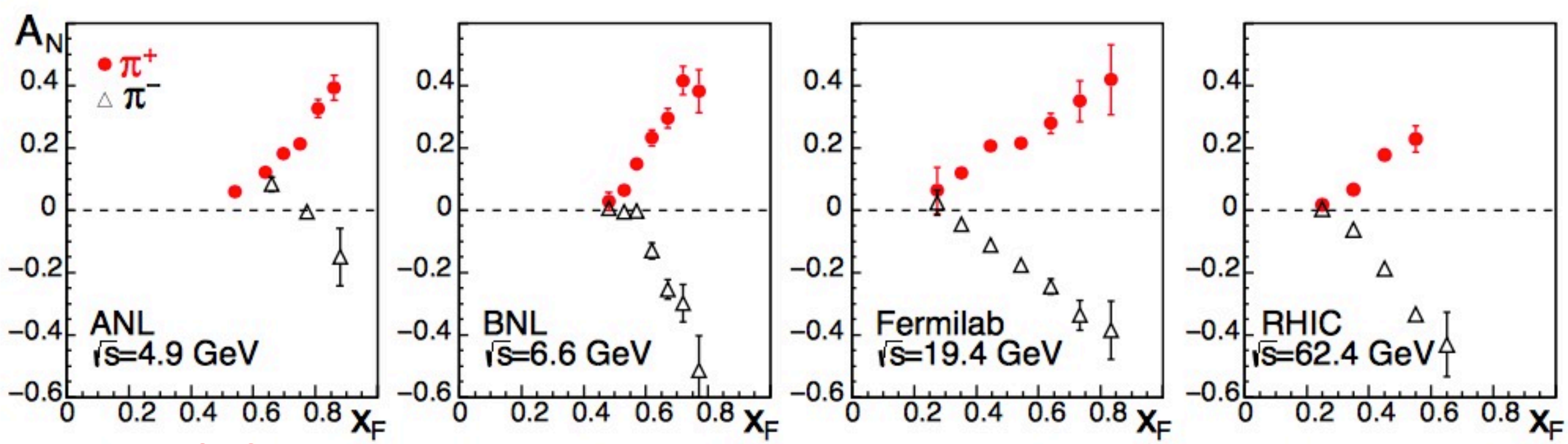


$$d\Delta\sigma(S_T) \sim \underbrace{H_{QS} \otimes f_1 \otimes \boldsymbol{F_{FT}} \otimes D_1}_{\text{Qiu-Sterman term}}$$

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

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

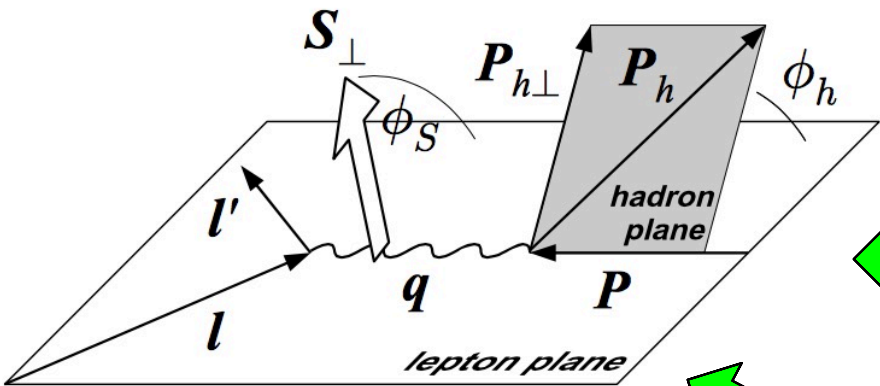
A_N is a *collinear* (twist-3) observable



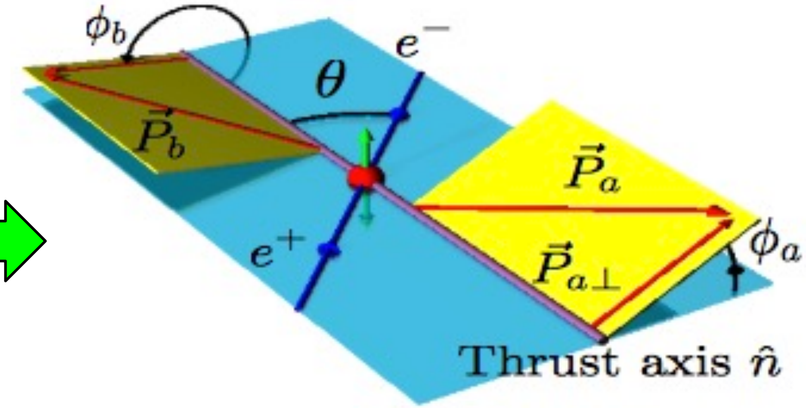
1976 →

Simultaneous QCD Global Analysis of SSAs

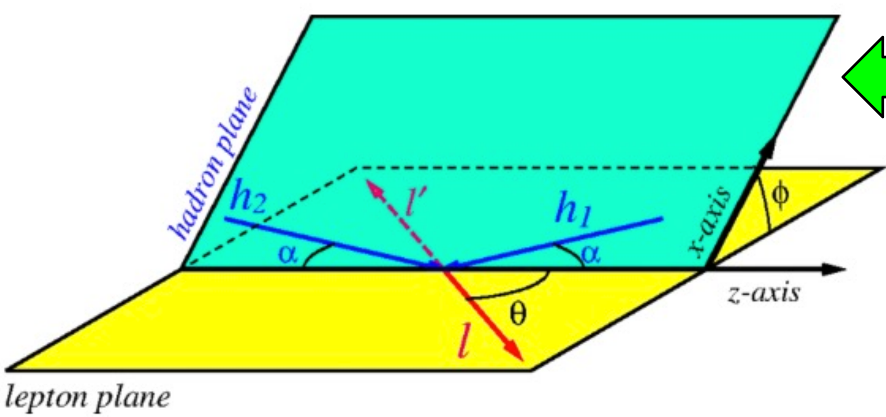
Cammarota, Gamberg, Kang, Miller, DP, Prokudin, Rogers, Sato, PRD **102** (2020)



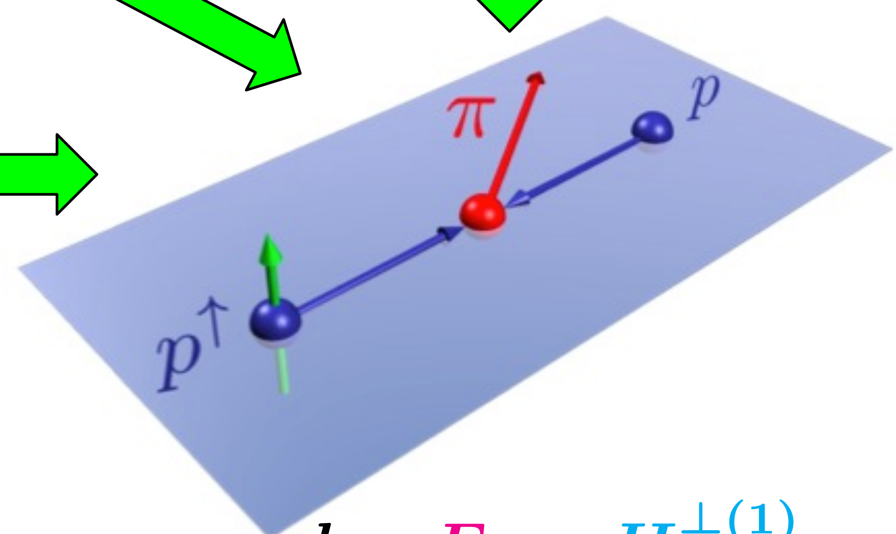
h_1, F_{FT}, $H_1^{\perp(1)}$



$H_1^{\perp(1)}$



F_{FT}



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

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

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

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)

Test of universality!

- Broad kinematical coverage:

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

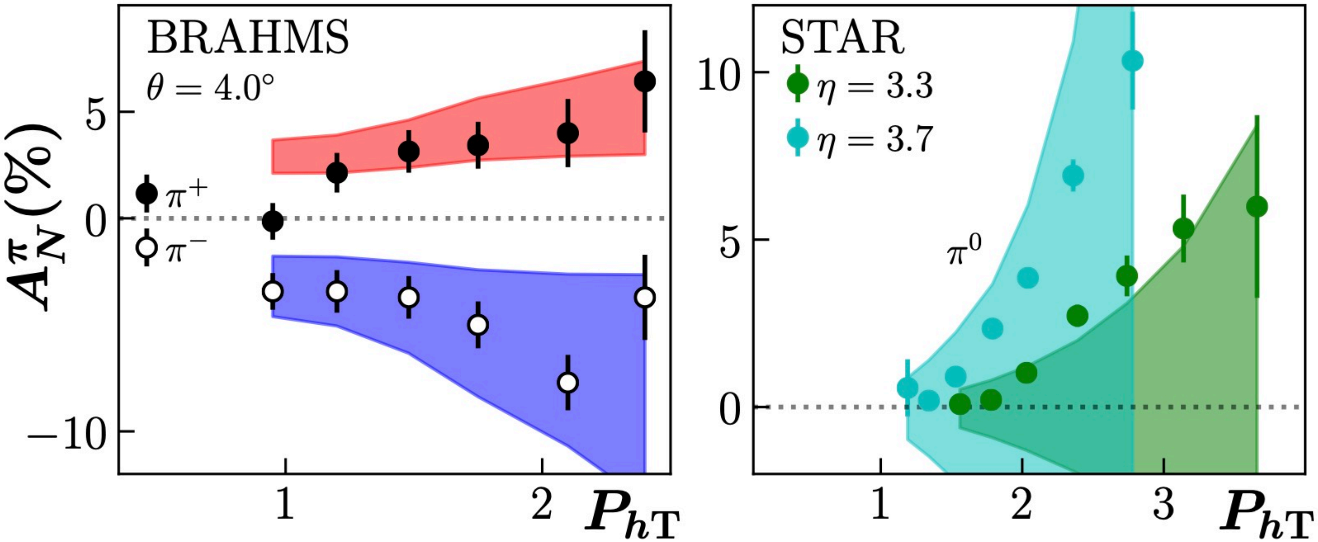
$$\text{SIA}: \quad 0.2\lesssim z\lesssim 0.8 \qquad Q^2\approx 13\,\text{GeV}^2 \text{ or } 110\,\text{GeV}^2$$

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

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

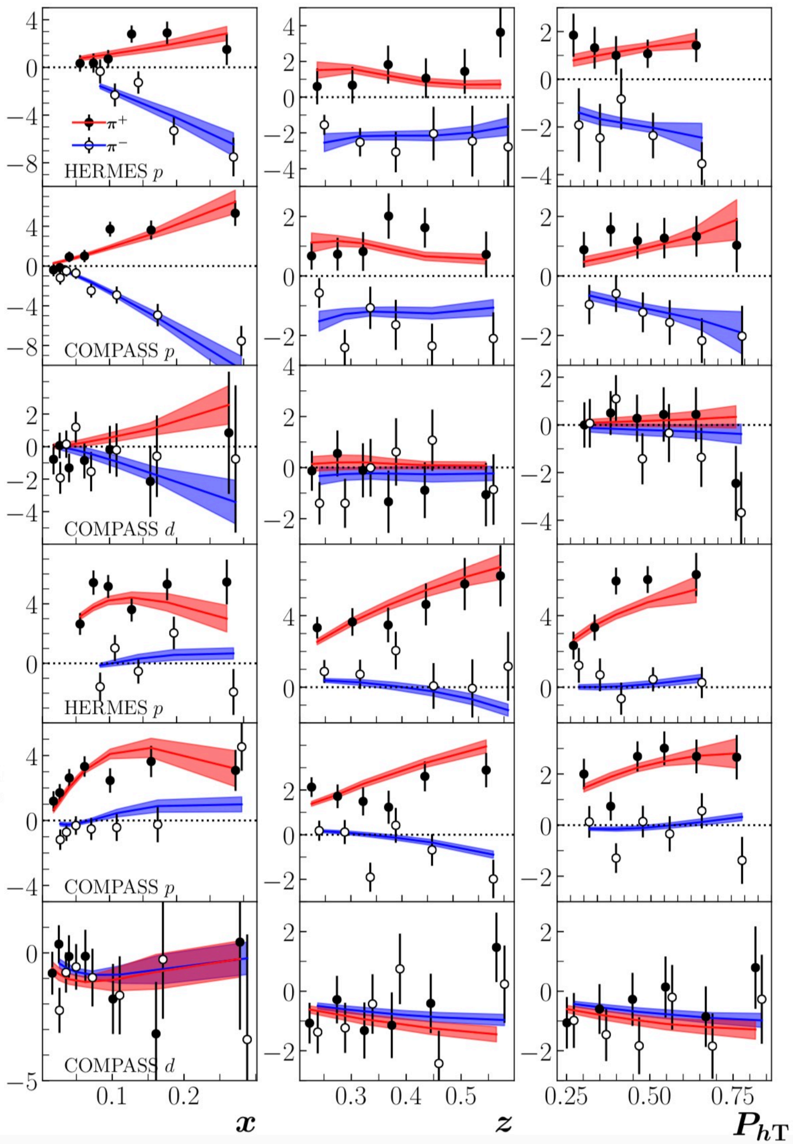
Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\rm pts.}$
$A_{\rm SIDIS}^{\rm Siv}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^\perp(x,k_T^2)$	$150.0/126=1.19$
$A_{\rm SIDIS}^{\rm Col}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2),\,H_1^\perp(z,z^2p_\perp^2)$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

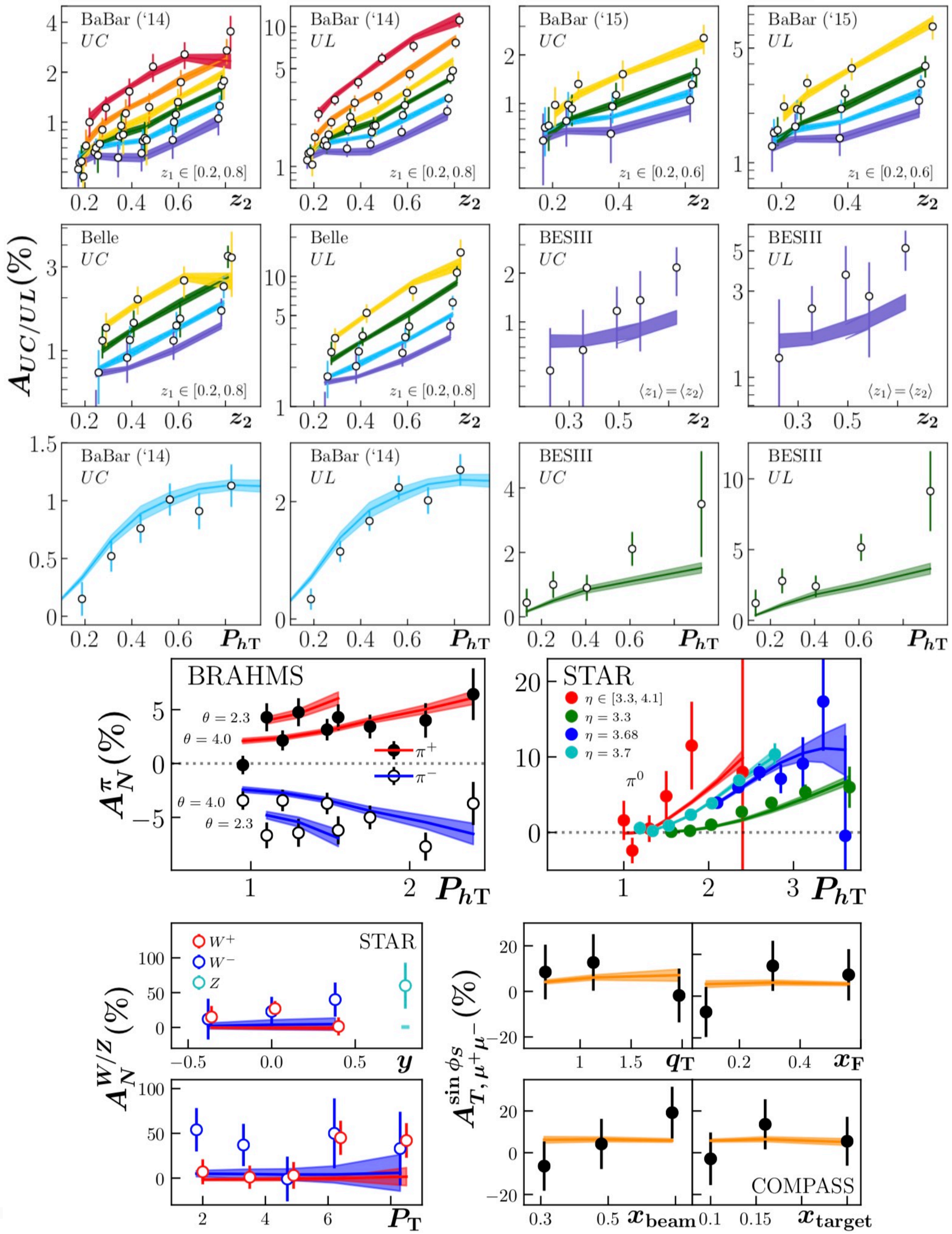
- *Predictions* of A_N using a fit of only TMD observables



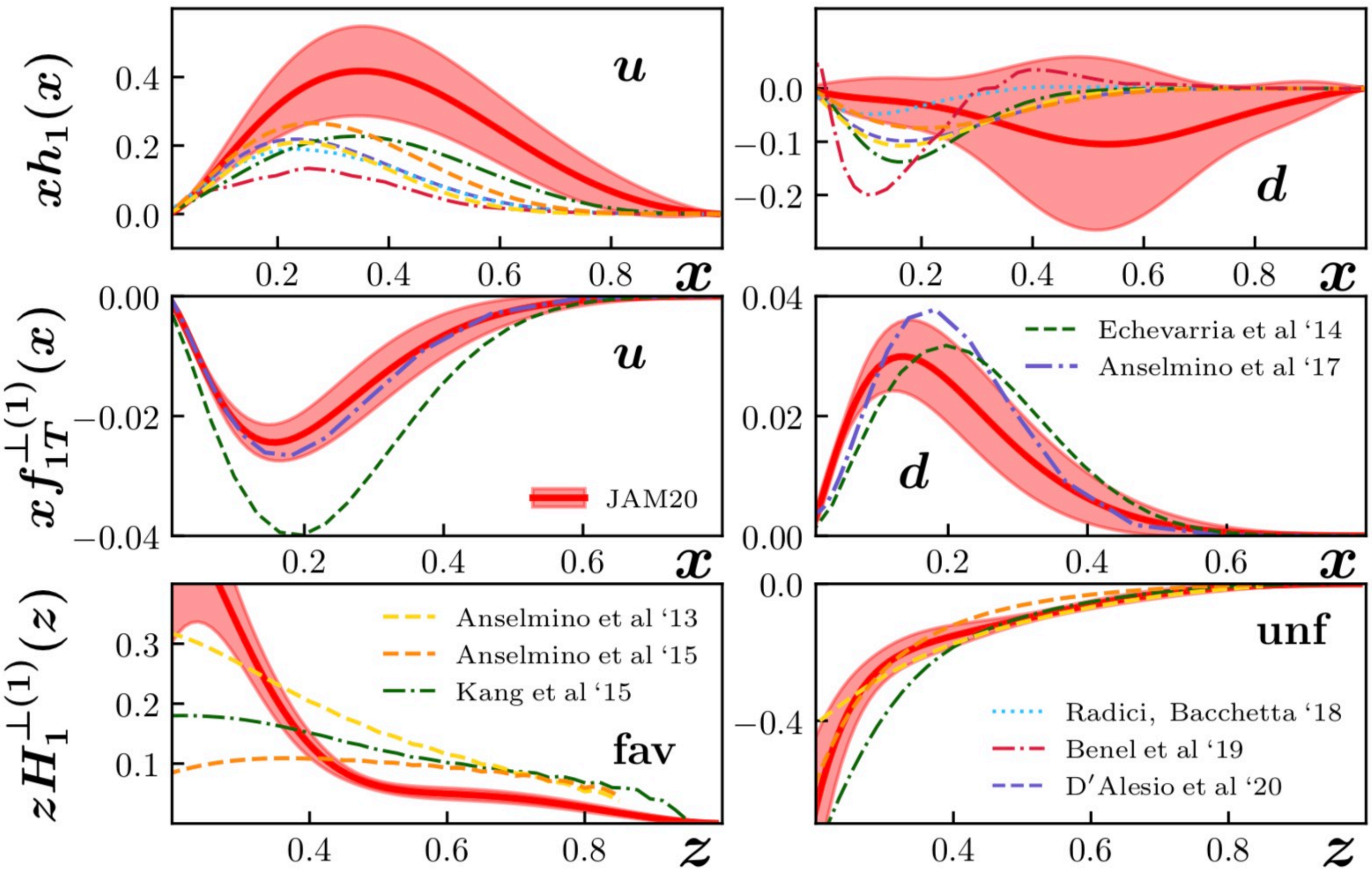
Test of universality!

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





JAM3D

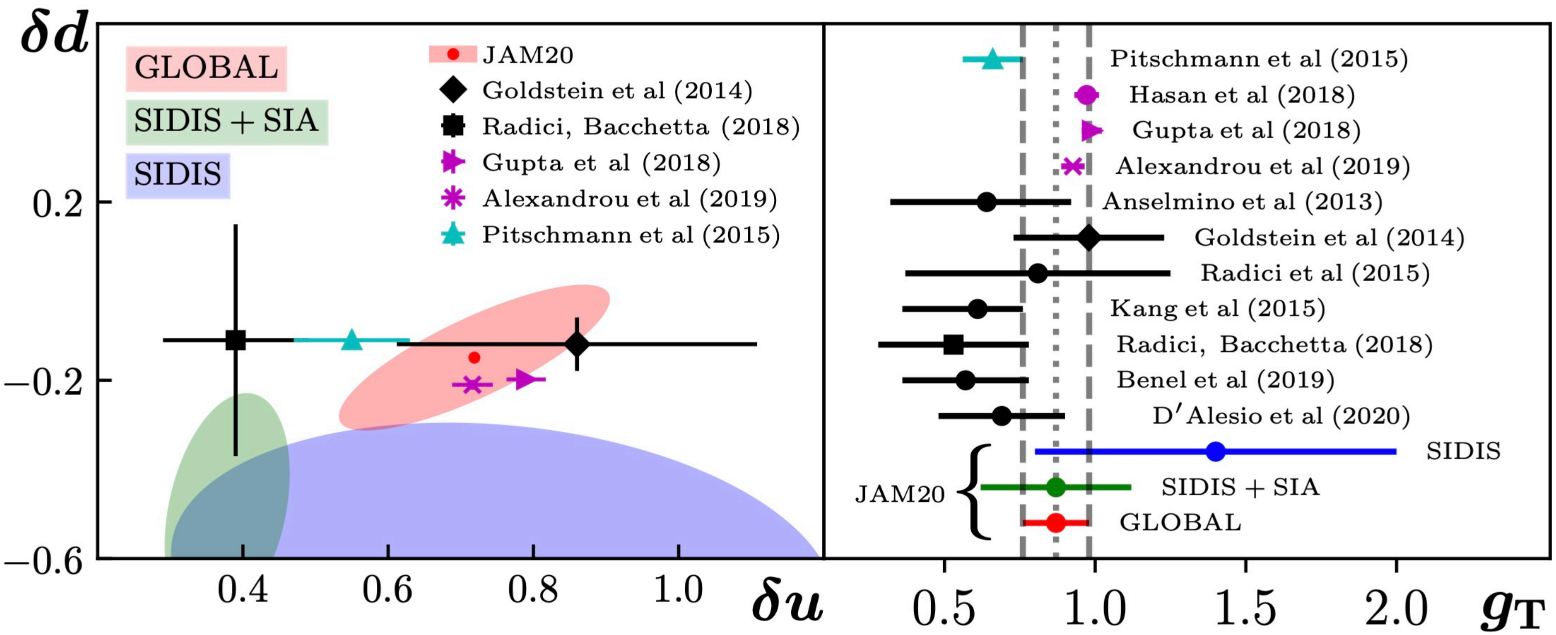


Transversity

Sivers first moment (QS function)

Collins first moment

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



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

Only after a *simultaneous* QCD global analysis of SSAs does the phenomenological extraction of the tensor charges agree with lattice, *but still with large uncertainties.*

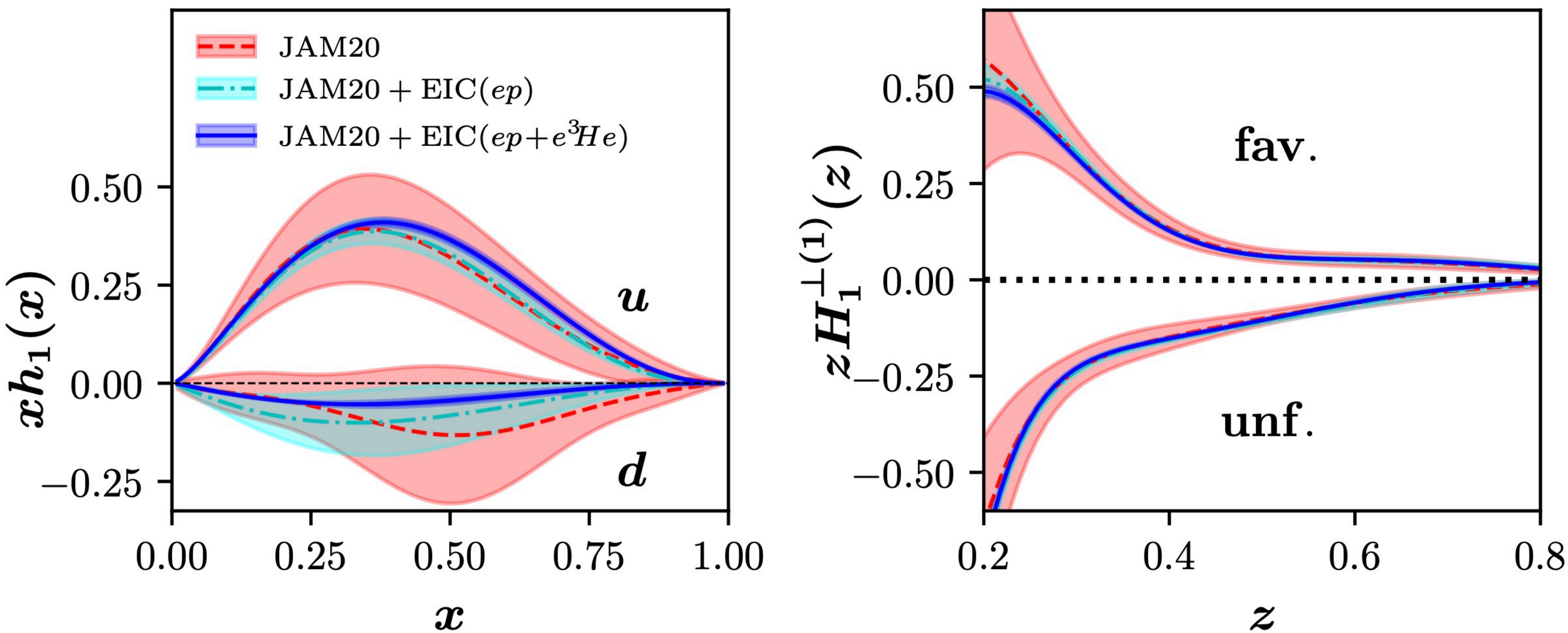
Impact Study on the Tensor Charge

Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)

EIC Pseudo-data			
Observable	**Reactions**	**CM Energy ($\sqrt{S}$)**	**$N_{\text{pts.}}$**
Collins (SIDIS)	$e + p^{\uparrow} \to e + \pi^{\pm} + X$	141 GeV	756 (π^+) 744 (π^-)
		63 GeV	634 (π^+) 619 (π^-)
		45 GeV	537 (π^+) 556 (π^-)
		29 GeV	464 (π^+) 453 (π^-)
	$e + {}^3He^{\uparrow} \to e + \pi^{\pm} + X$	85 GeV	647 (π^+) 650 (π^-)
		63 GeV	622 (π^+) 621 (π^-)
		29 GeV	461 (π^+) 459 (π^-)
		Total EIC $N_{\text{pts.}}$	**8223**

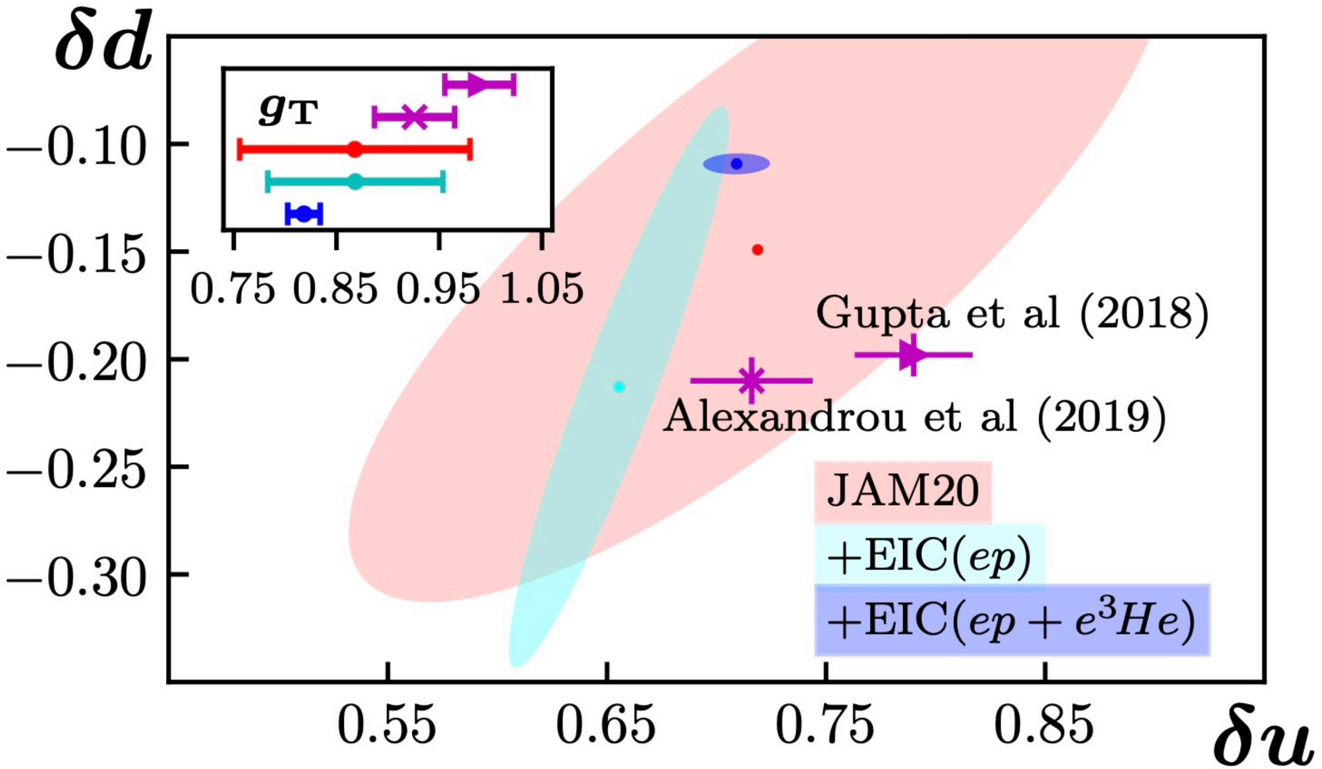
Assumed accumulated luminosities of 10 fb^{-1}, 70% polarization, conservatively accounted for detector smearing and acceptance effects

Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)



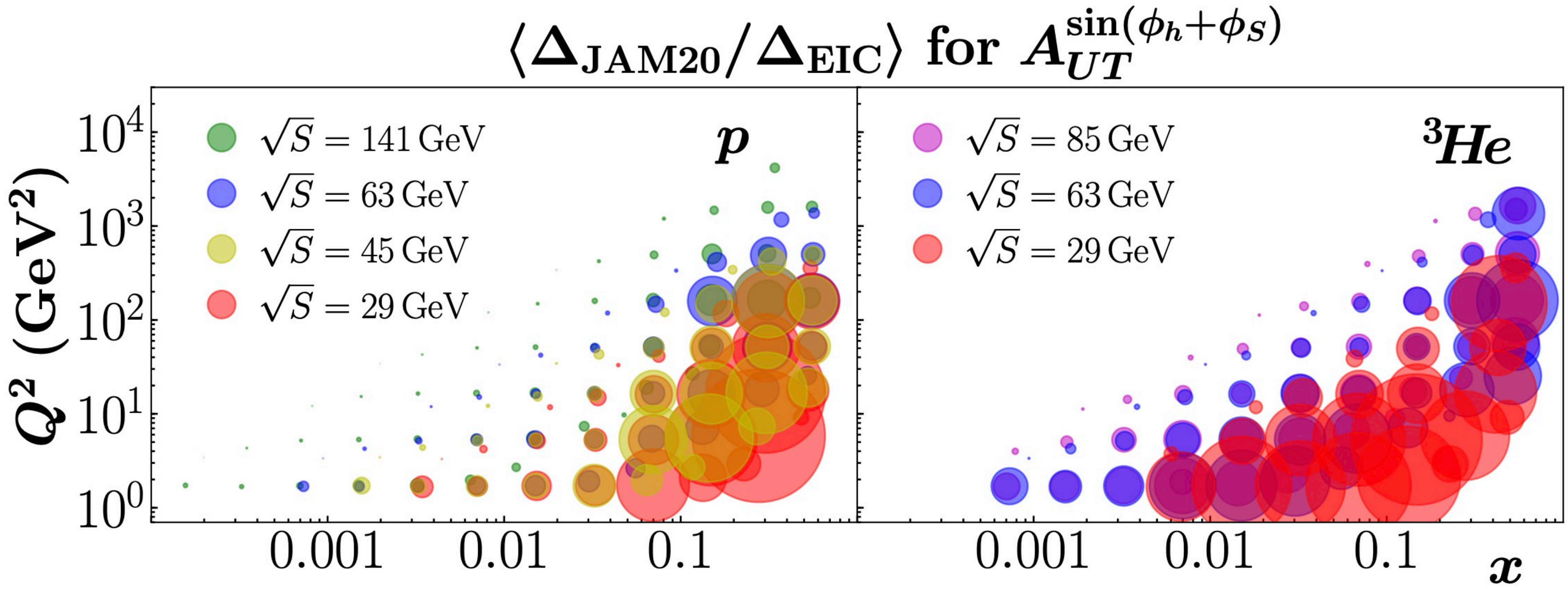
EIC data on the Collins effect will significantly reduce the uncertainties in extractions of the transversity PDF (as well as the Collins FF)

Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)



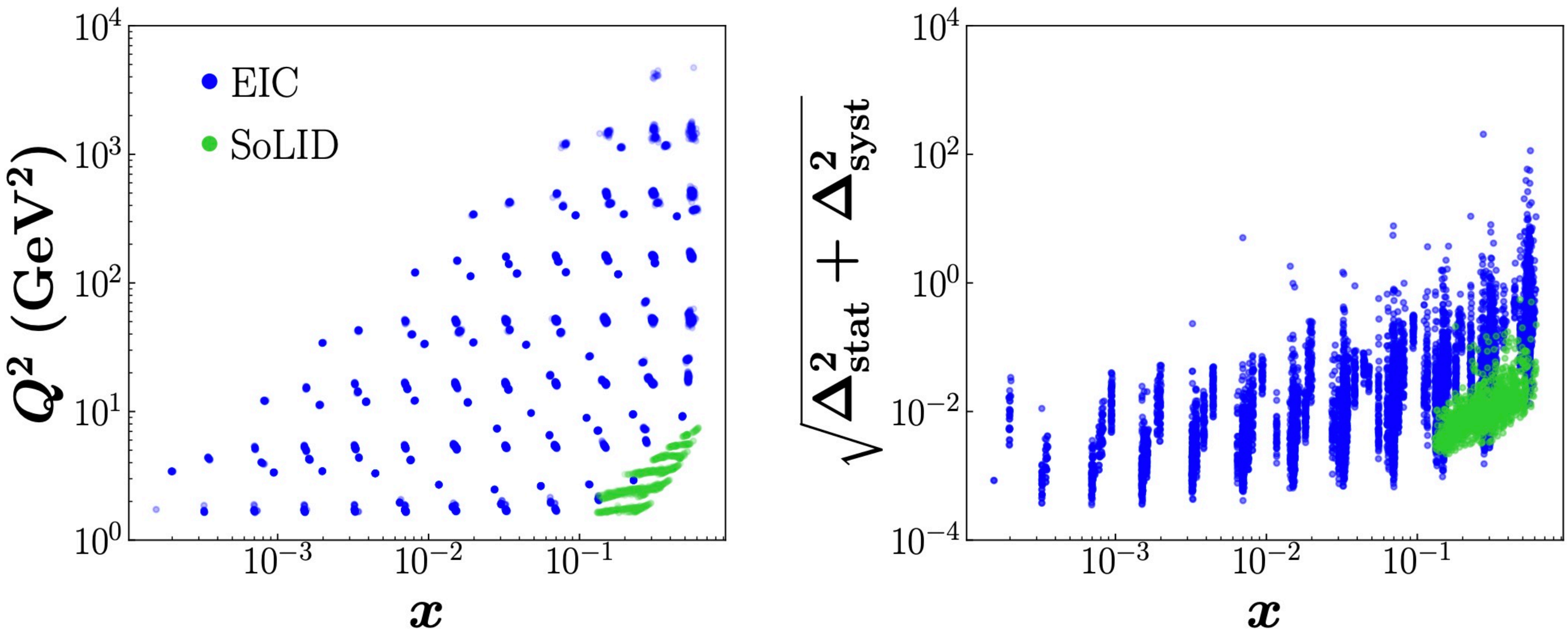
EIC data will allow phenomenological extractions of the tensor charge to become as precise as current lattice calculations. ^{3}He data is especially important to decorrelate the extraction of *δu* and *δd.*

Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)



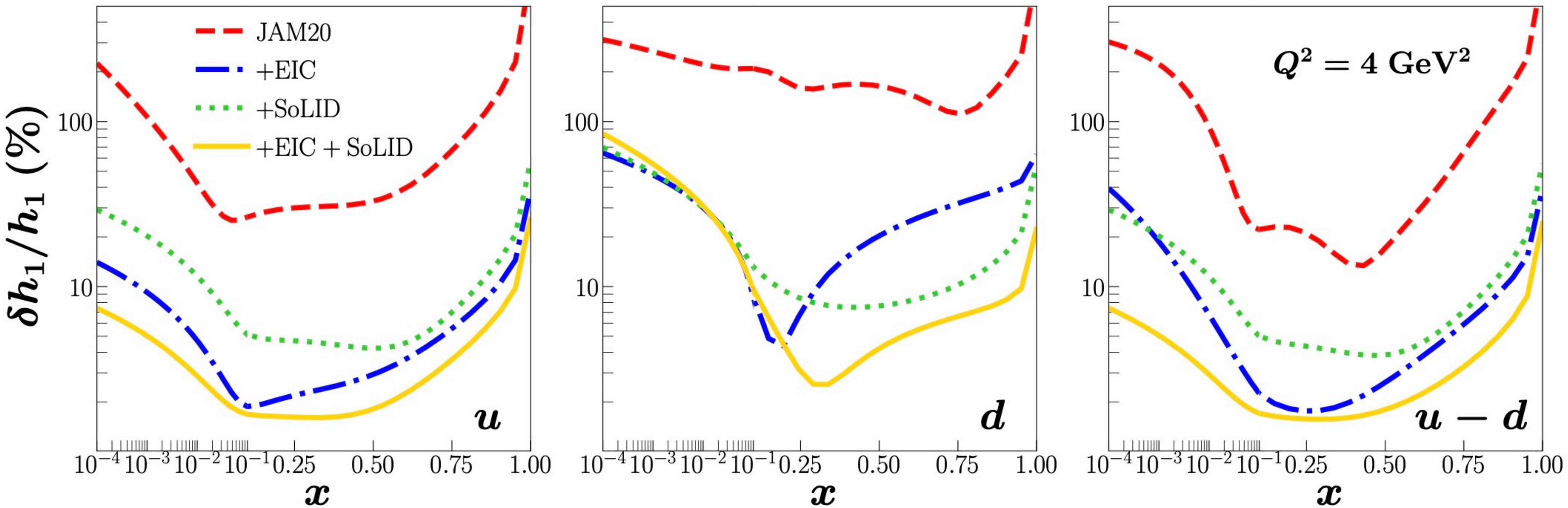
Most impact on JAM20 will be at moderate to higher x, across multiple decades in Q^2, and we again see the importance of the ^{3}He program

Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)



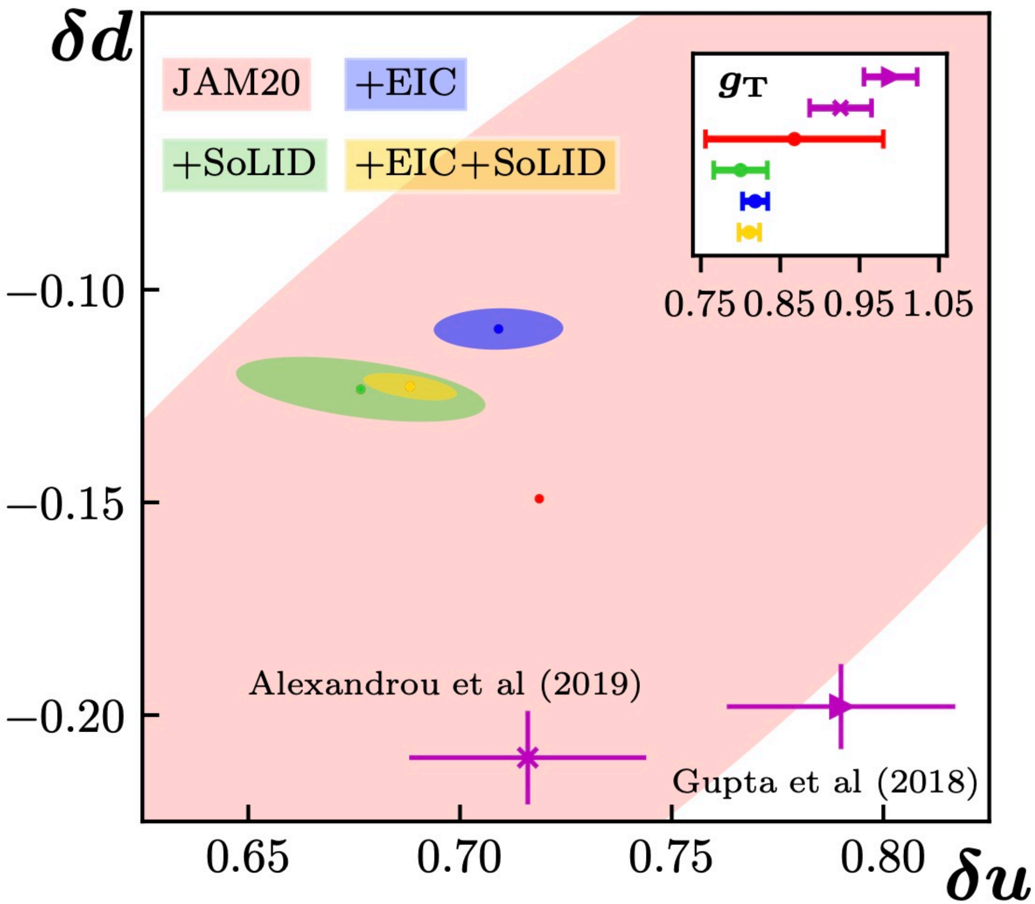
SoLID at JLab covers a complimentary region at higher x and lower Q^2 with much greater luminosity – important to explore the effect of multiple measurements in different kinematic regions

Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)



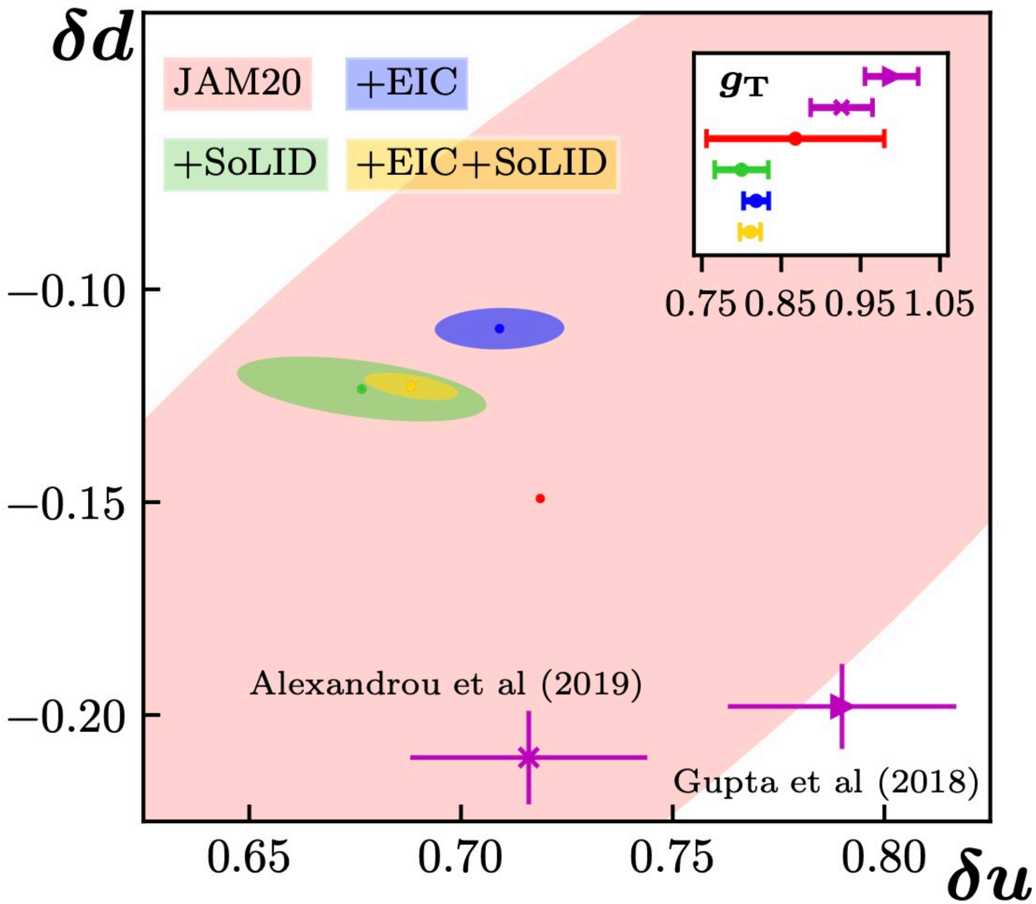
SoLID reduces the relative uncertainty in the down quark h_1 at higher x more than the EIC, and overall the relative uncertainties improve the most when data sets from both facilities are included

Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)



SoLID at JLab will also provide important constraints on the tensor charges. The combined analysis with EIC data gives the most precise phenomenological determination of them.

Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)



N.B.: accuracy vs. precision – a precise measurement cannot always guarantee a very accurate extraction of the distributions, and multiple experiments, such as EIC and SoLID, should be performed in a wide kinematical region in order to minimize bias and expose any potential tensions between data sets (also one reason to have IR2@EIC)

Conclusions

- 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, showing a common origin of SSAs.

- First agreement with lattice QCD on the tensor charges of the nucleon was obtained, but still with large uncertainties.

- EIC data on the Collins effect will allow for phenomenological extractions of the tensor charge to be as precise as current lattice calculations. SoLID at JLab will also provide important constraints.

- In order to reduce bias and obtain the most accurate extraction of the tensor charge, one must have data from multiple future facilities (e.g., EIC and SoLID) that give the most kinematic coverage possible in x and Q^2.