Status of TMD Studies (Transverse Polarization)

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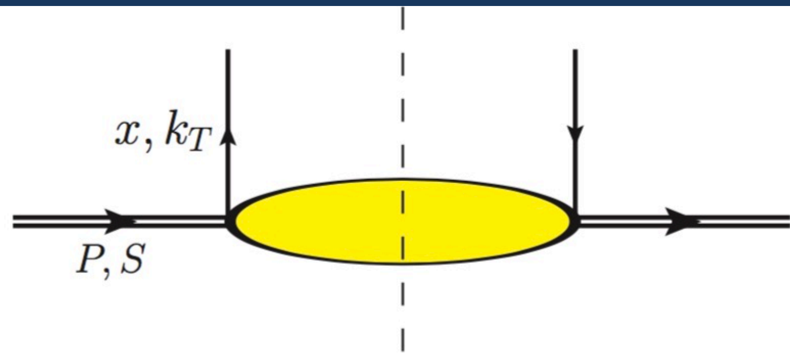
Snowmass EF06/EF07 TMD Meeting

October 28, 2020

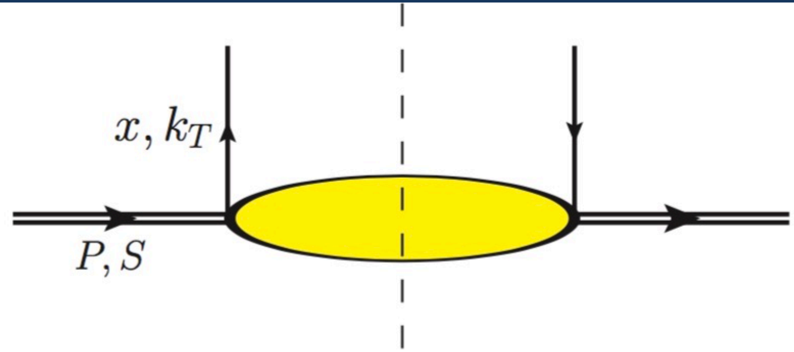


$$\mathcal{F}.\,\mathcal{T}.\left[\langle P,S|\bar{\psi}(0^-,0_T)\mathcal{W}(0;\xi)\,\Gamma\,\psi(\xi^-,\xi_T)|P,S\rangle\right]$$

Leading Twist TMDs

Nucleon Spin   Quark Spin

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



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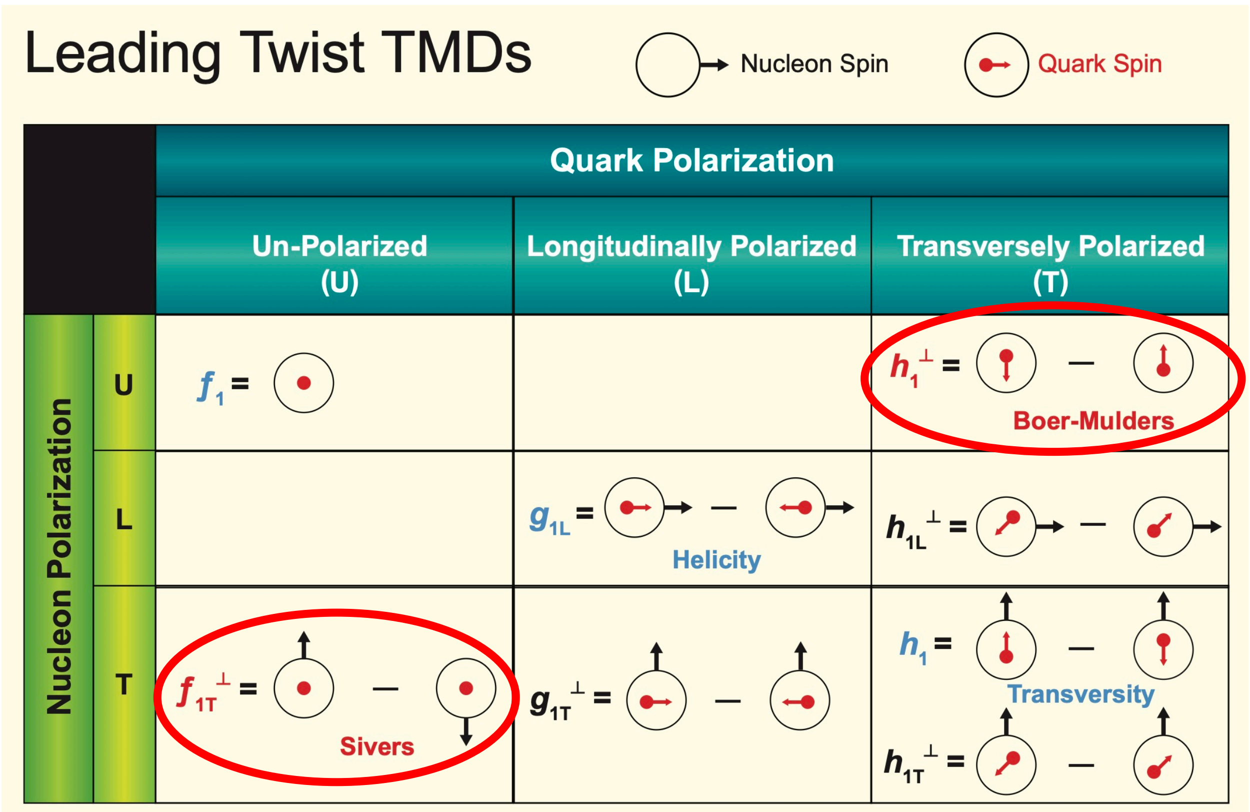
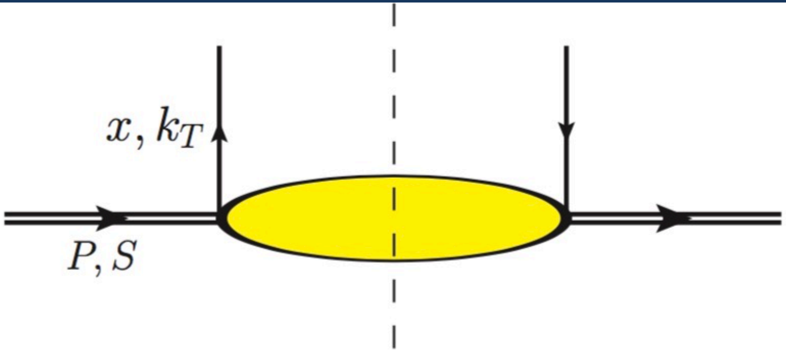


Naïve time-reversal odd (T-odd)



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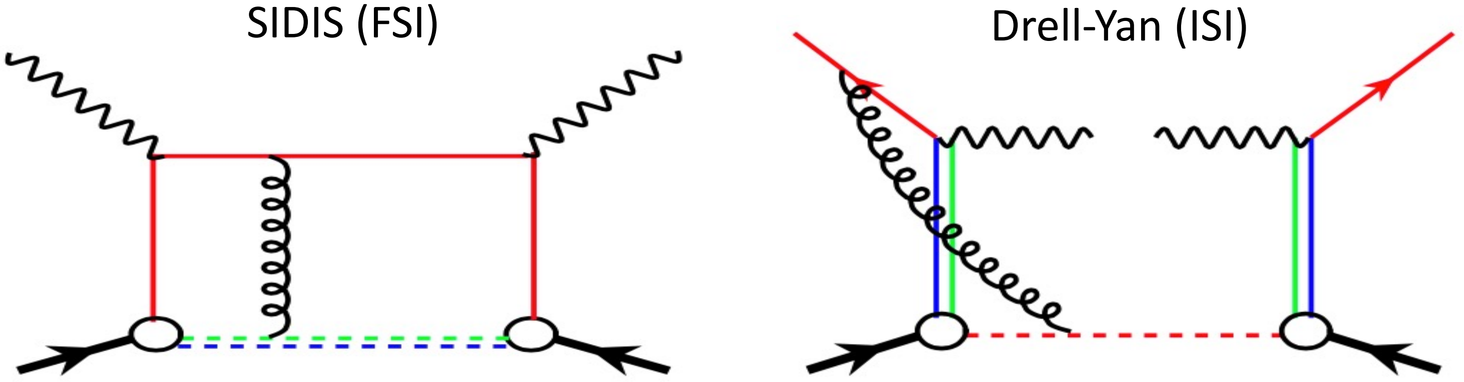
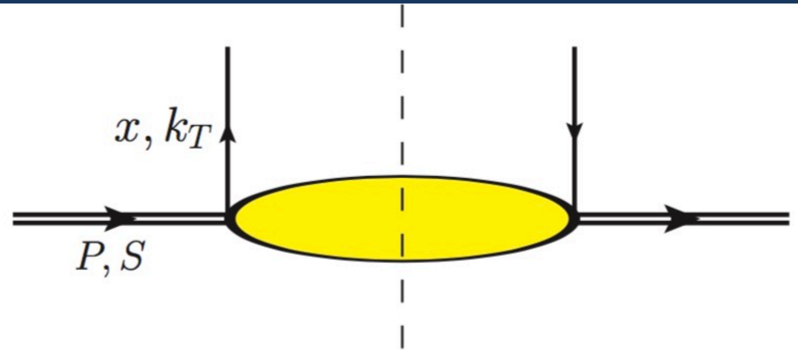
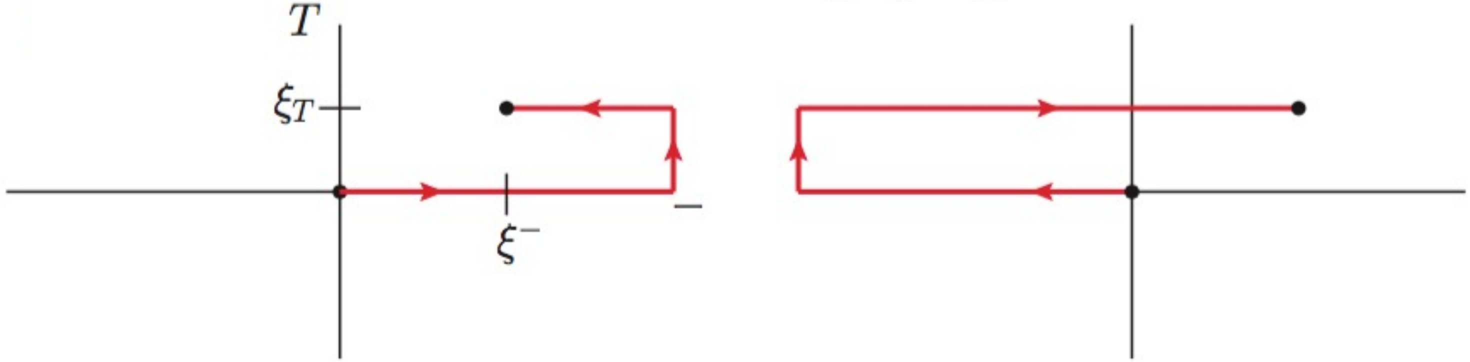




$$\mathcal{F.\,T.}\big[\langle P,S|\bar{\psi}(0^-,0_T)\mathcal{W}(0;\xi)\,\Gamma\,\psi(\xi^-,\xi_T)|P,S\rangle\big]$$

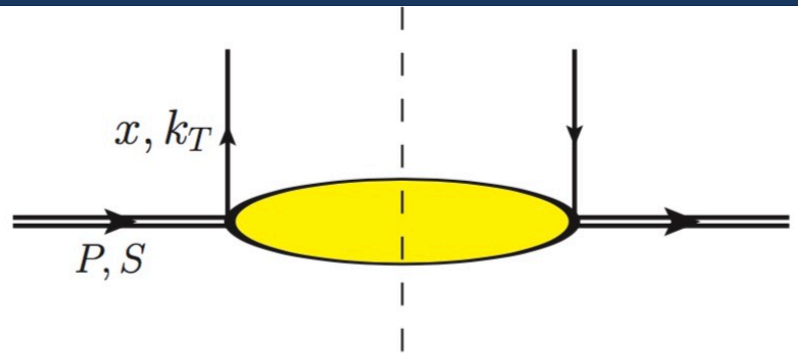
SIDIS (FSI) Drell-Yan (ISI)



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

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

(Collins (2002))



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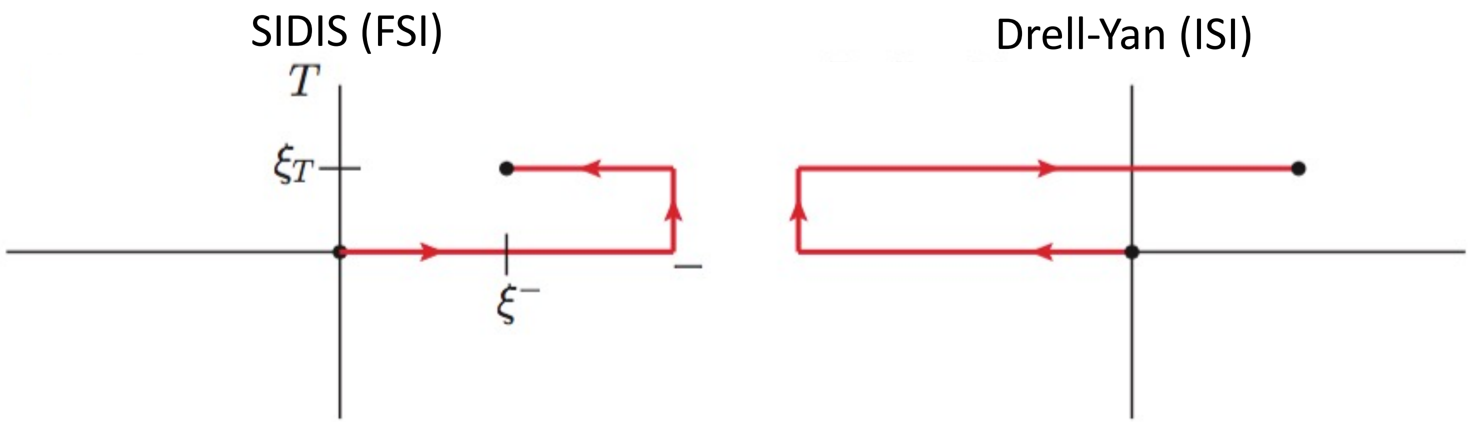

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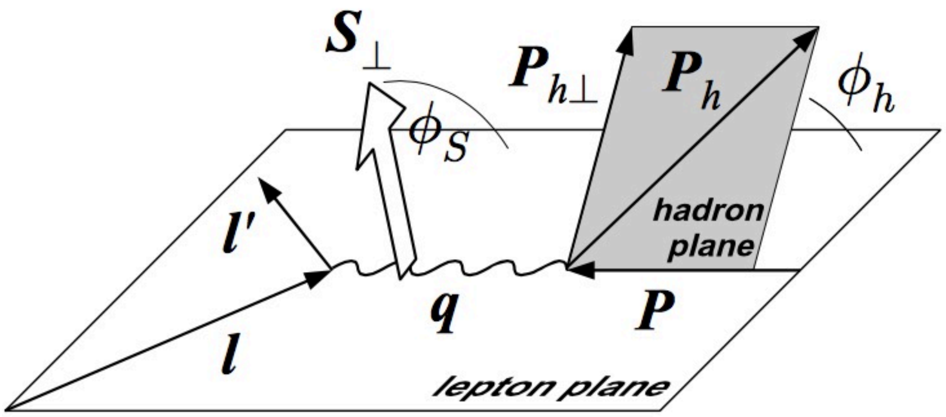
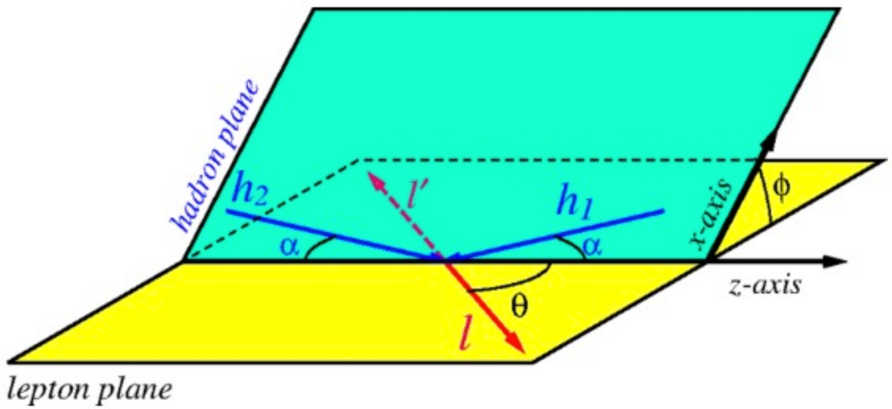
(Collins (2002))

The "sign change" of these functions is an important *prediction* from our current understanding of QCD and TMD factorization

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

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

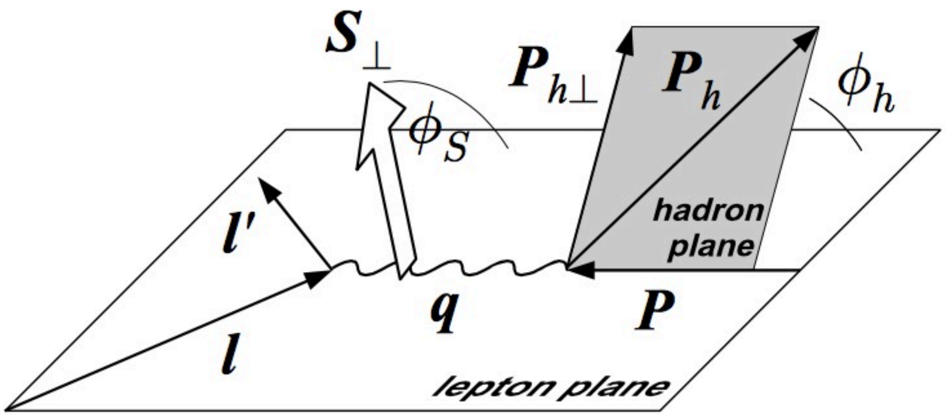




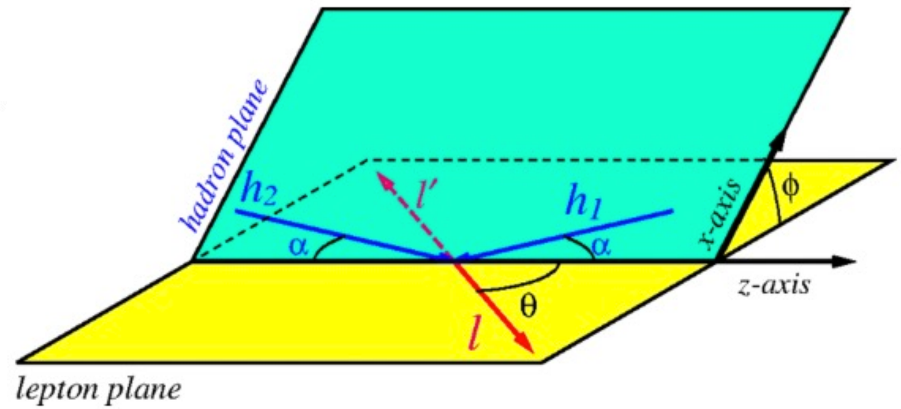
$$F_{UT}^{\sin(\phi_h - \phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M} f_{1T}^{\perp} D_1\right]$$

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

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



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



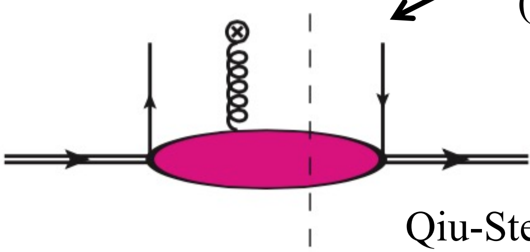
$$F_{UT}^{\sin(\phi_h - \phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M} \boldsymbol{f_{1T}^{\perp}} D_1\right] \qquad F_{TU}^{\sin\phi} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_{aT}}{M_a} \boldsymbol{f_{1T}^{\perp}}\, \bar{f}_1\right]$$

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

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

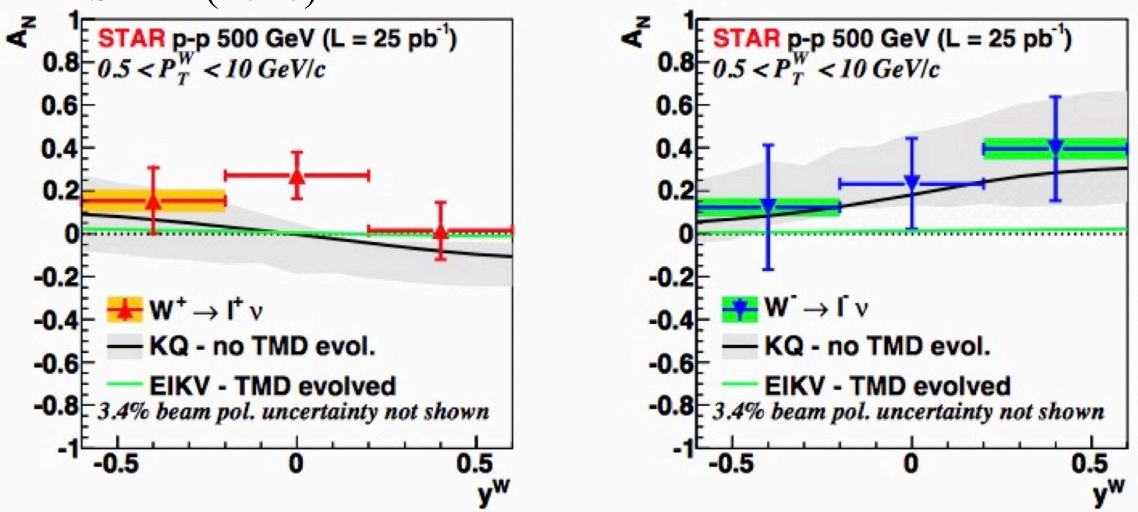
$g_{f_{1T}^{\perp}}(x, b_T) + g_K(b_T)\ln(Q/Q_0)$

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

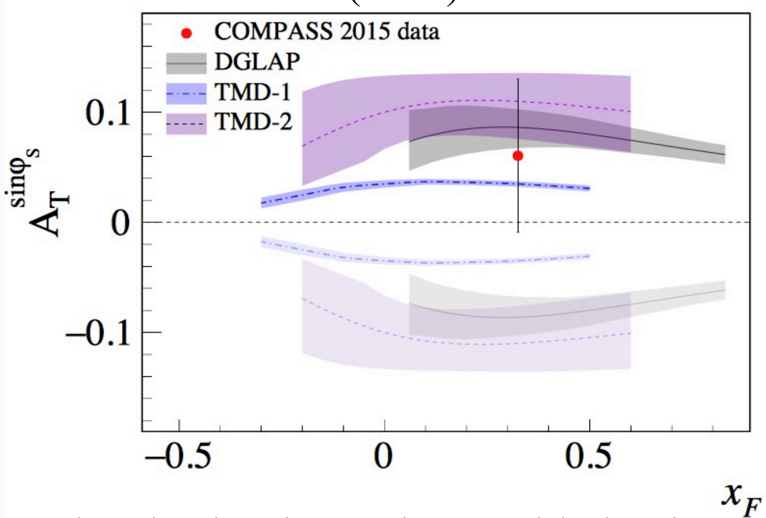


Qiu-Sterman function

STAR (2016)



COMPASS (2017)



Recent analyses of the Sivers effect in SIDIS and Drell-Yan show that the data is consistent with the sign change.

Anselmino, Boglione, D'Alesio, Murgia, Prokudin (2017) – DGLAP+Gaussian ansatz

Cammarota, Gamberg, Kang, Miller, DP, Prokudin, Rogers, Sato (2020) – DGLAP-type+Gaussian ansatz

Bacchetta, Delcarro, Pisano, Radici (2020) – TMD evo w/ DGLAP+NLL(S_{pert}) (only SIDIS data)

Echevarria, Kang, Terry (2020) – TMD evolution at NLO(modified OPE)+NNLL(S_{pert})

Vladimirov, Prokudin, Bury (in preparation) – TMD evolution at N^3LO ("ζ- prescription")

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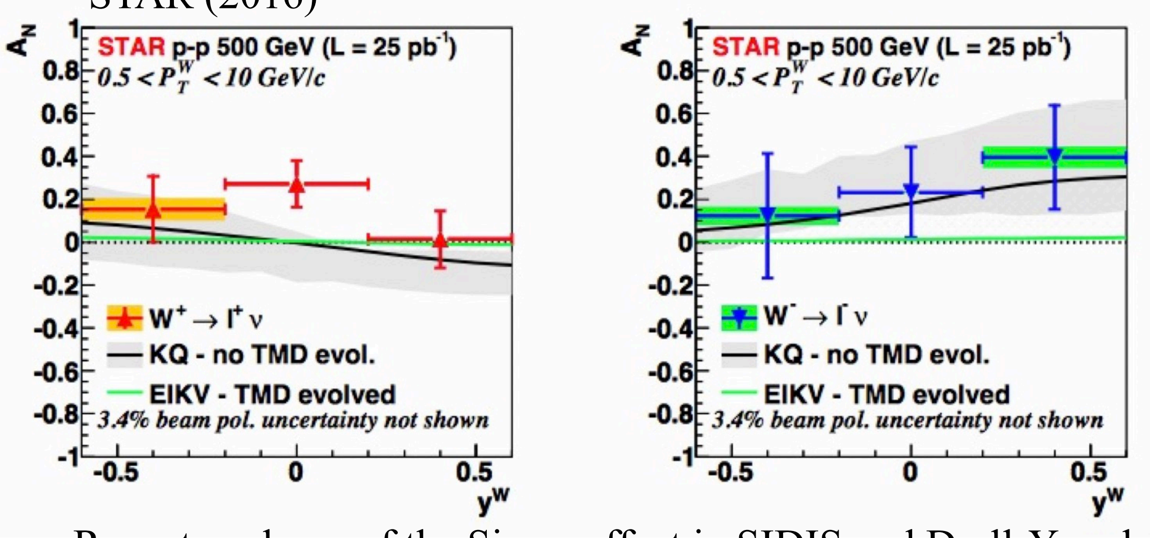

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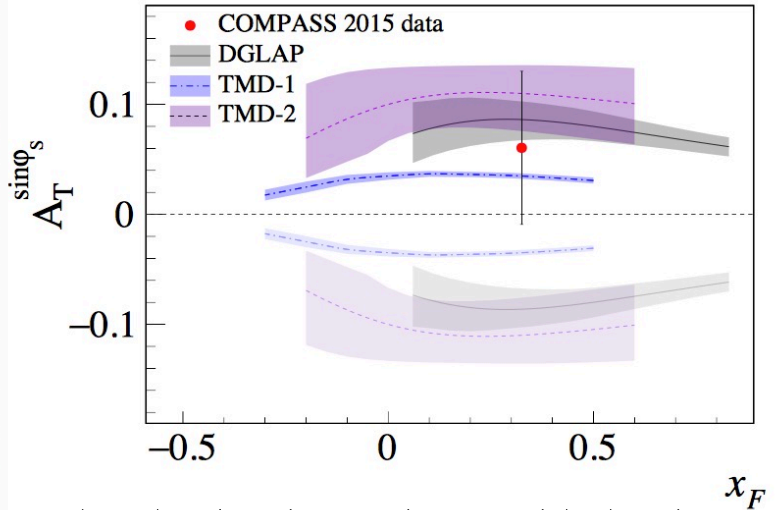

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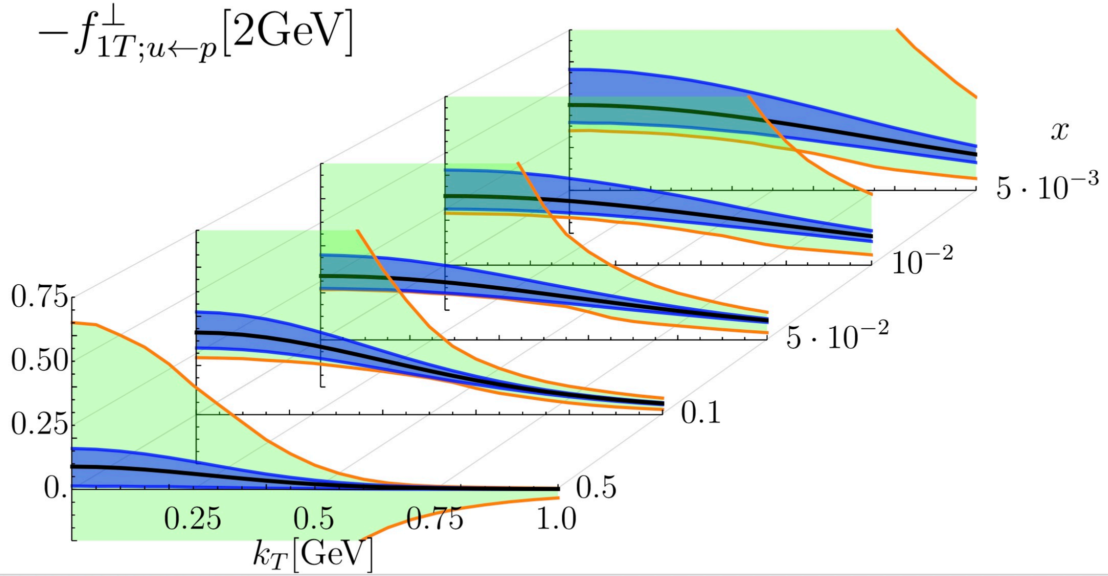
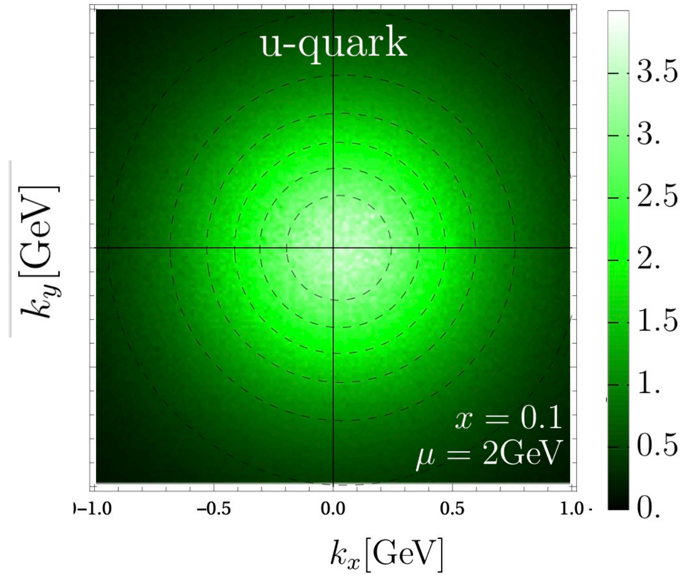
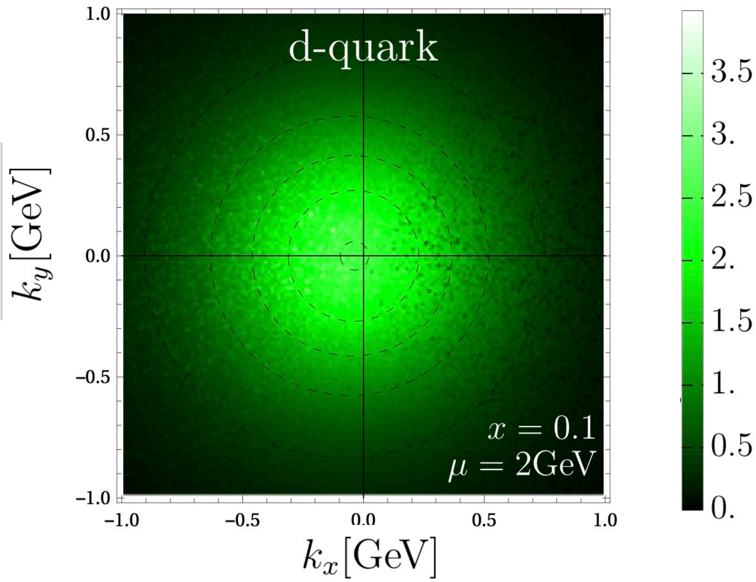
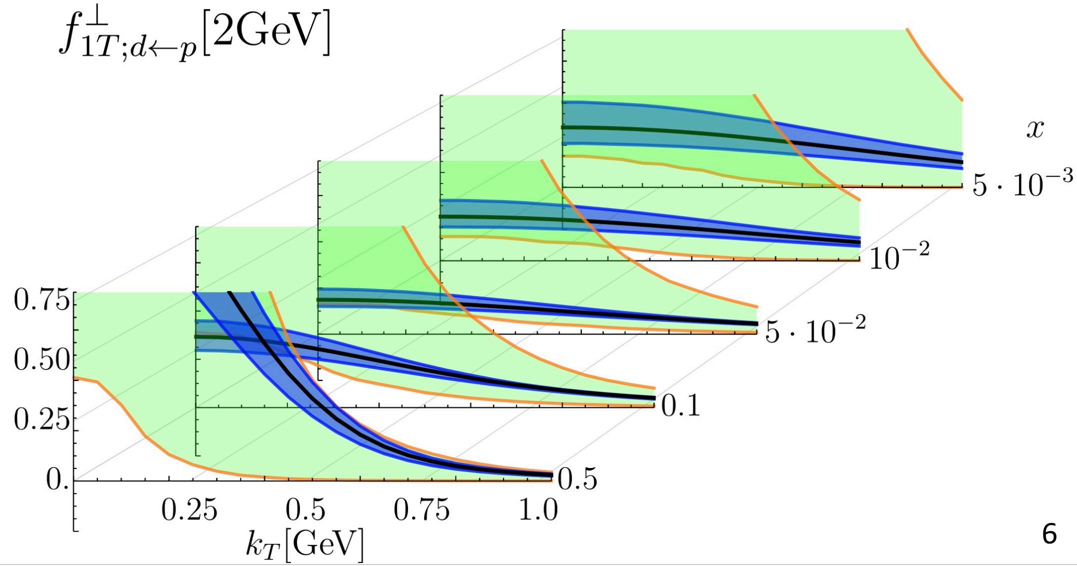
More precise SIDIS and DY data and a better understanding of TMD evolution for the Sivers function are needed to fully test the sign change. The precision and x-Q^2 coverage of the EIC will be crucial and also bring increased sensitivity to the sea quark Sivers functions.

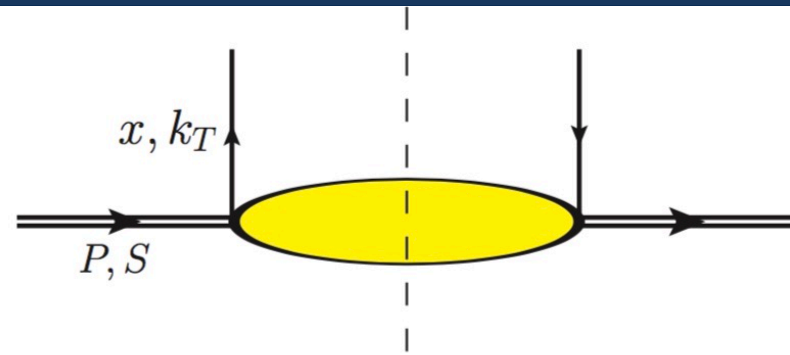
Courtesy of A. Vladimirov (for EIC YR, based on work in preparation with A. Prokudin, M. Bury)











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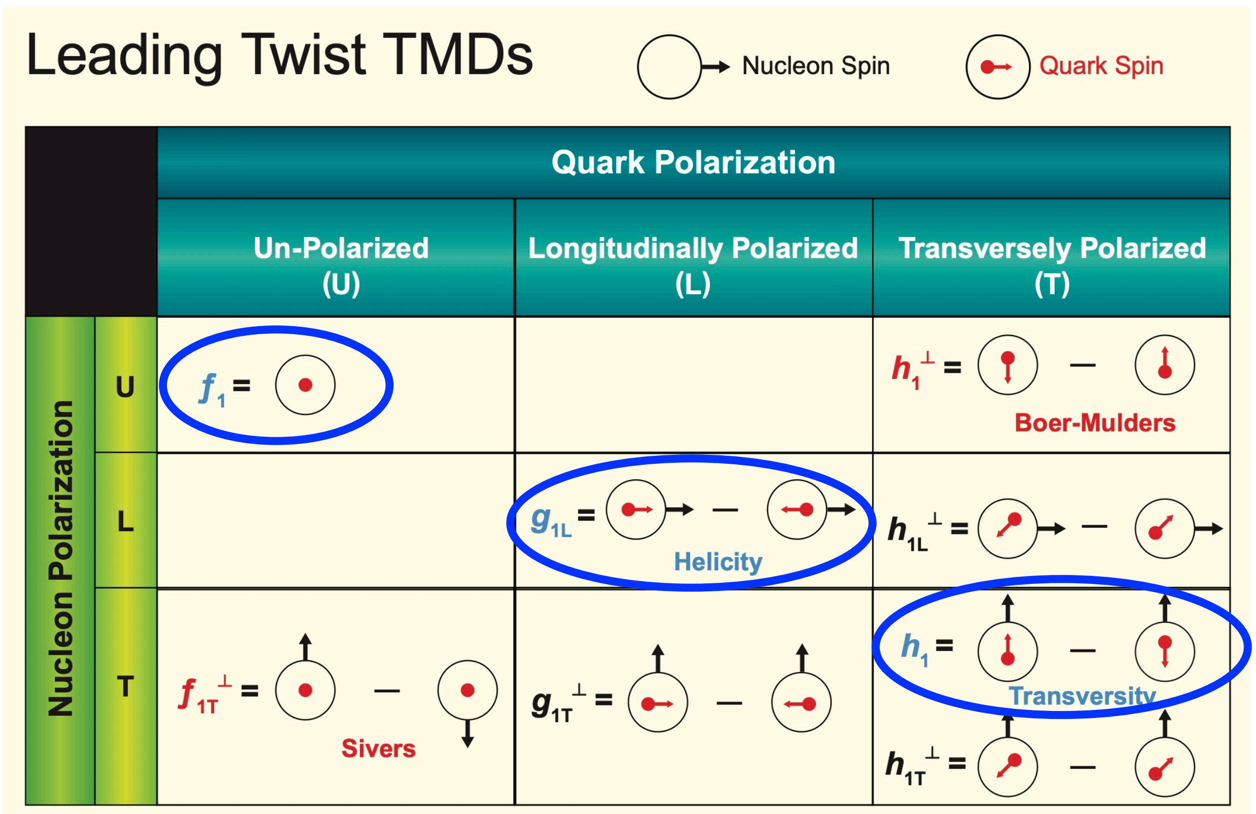
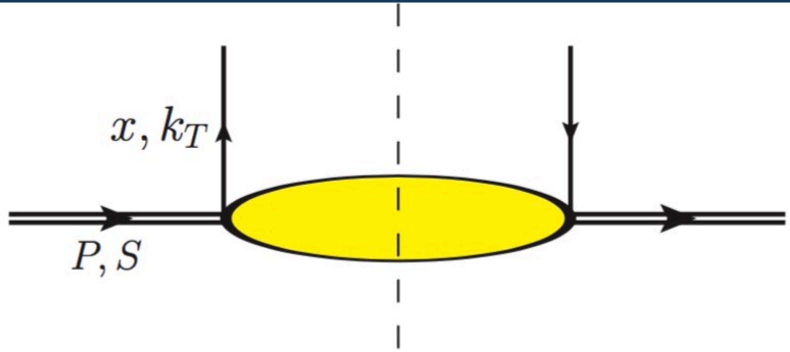


Survive integration over k_T



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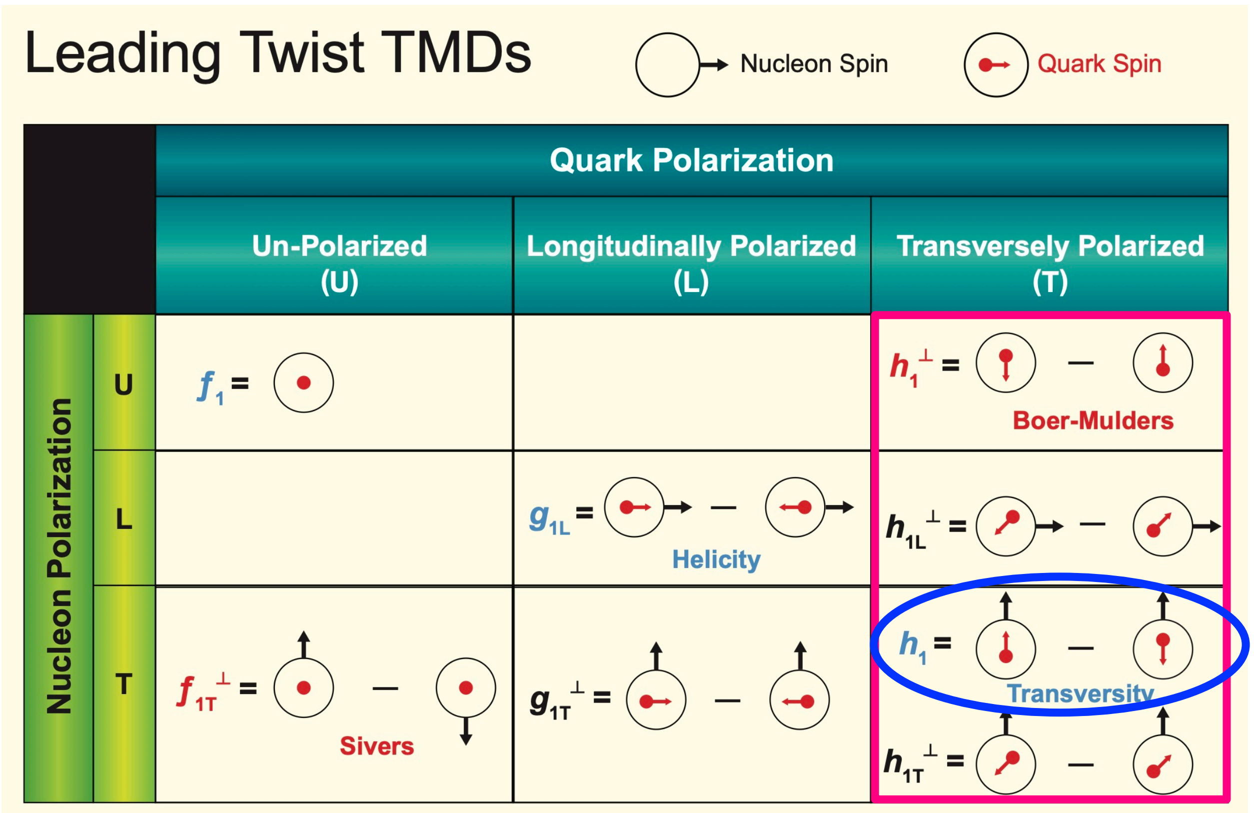
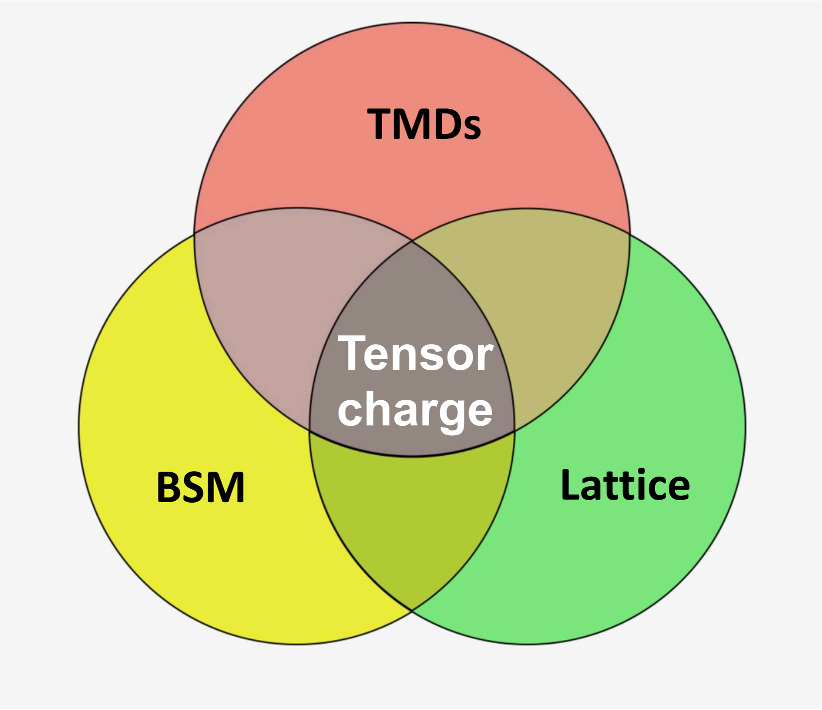


Chiral odd

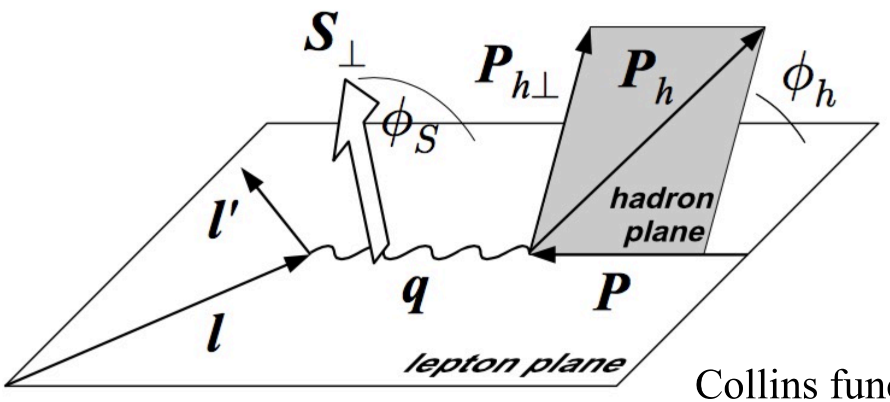
Survive integration over k_T

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

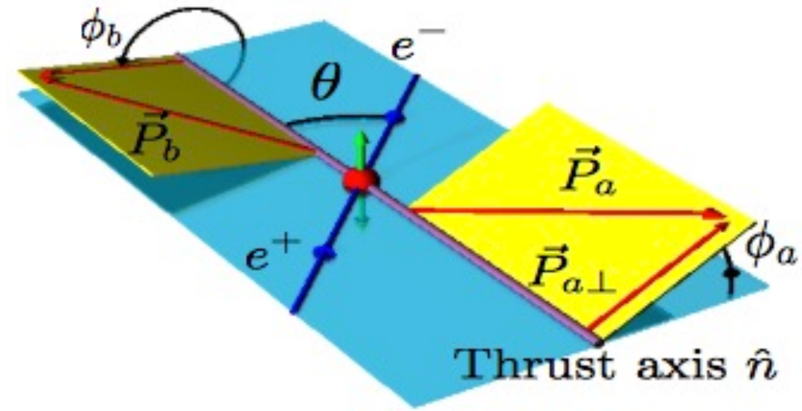
The tensor charge of the nucleon is one of its fundamental charges and is important for BSM studies (beta decay, EDM). Processes sensitive to TMDs can play an important role in these efforts (Courtoy, et al. (2015); Liu, et al. (2018),…). Lattice QCD has also calculated the tensor charges with great precision (Gupta, et al. (2018); Hasan, et al. (2019), Alexandrou, et. (2019),…).



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



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



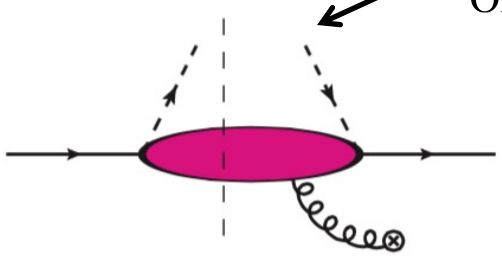
Collins function

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

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

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

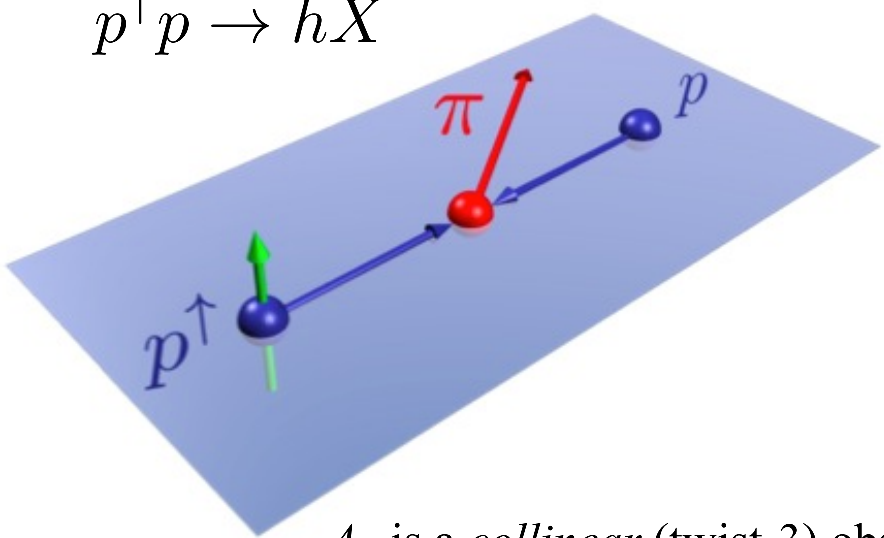
OPE



qgq
fragmentation
function

(Kang, et al. (2016))

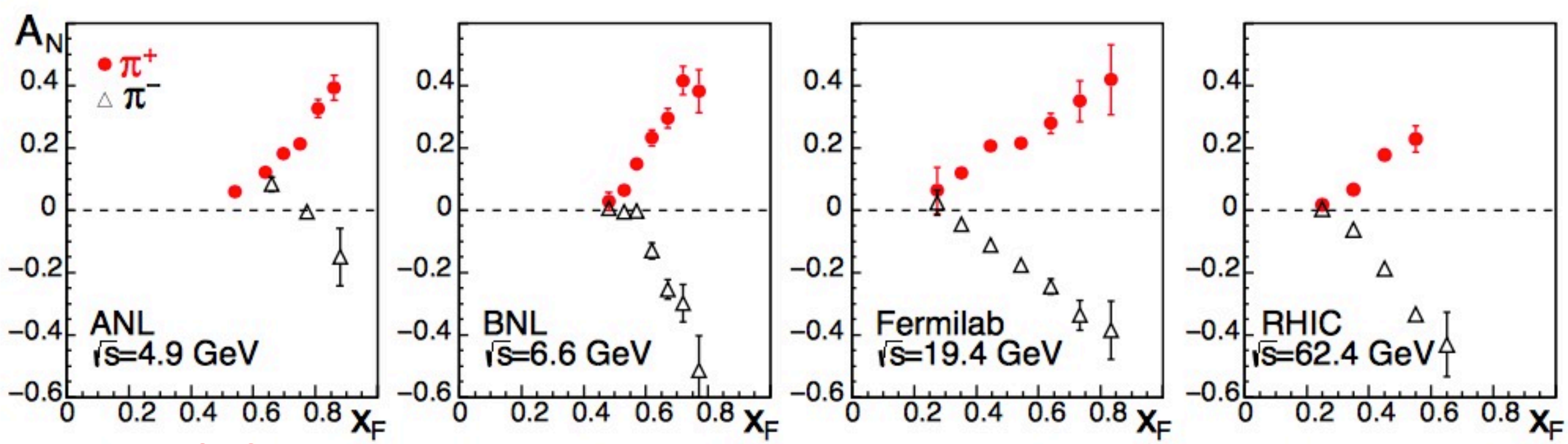
$$p^{\uparrow}p \to hX$$



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

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

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



1976 →

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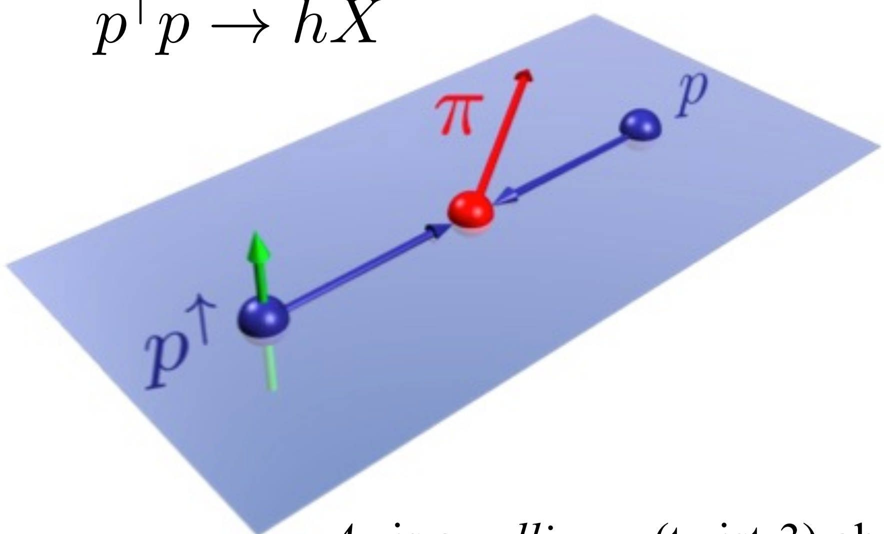

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(Metz, DP (2012); Kanazawa, et al. (2014); Gamberg, et al. (2017); Cammarota, et al. (2020))

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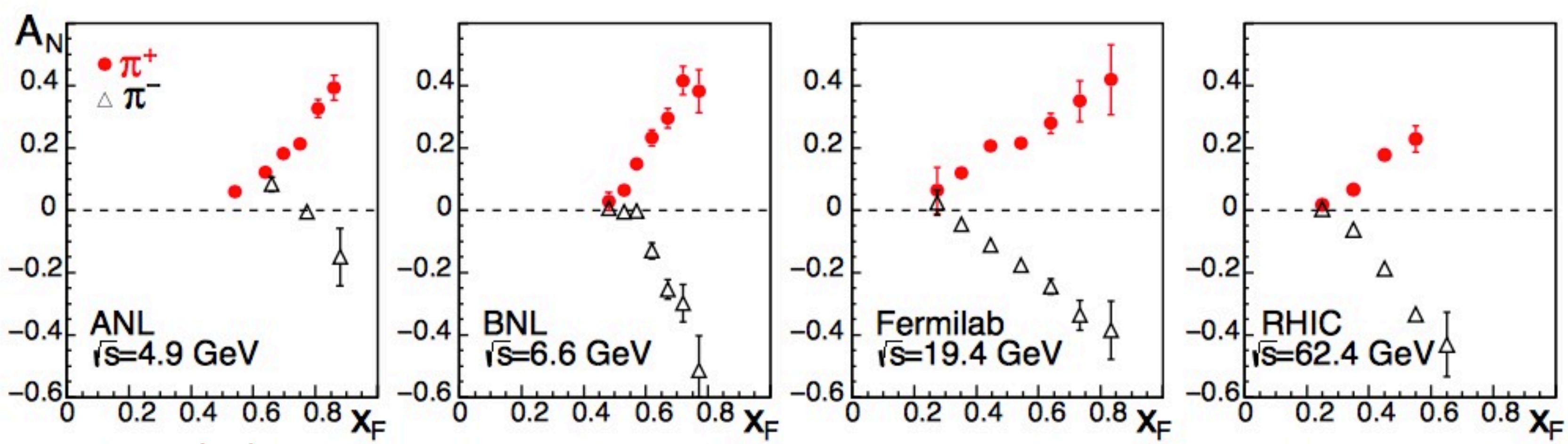
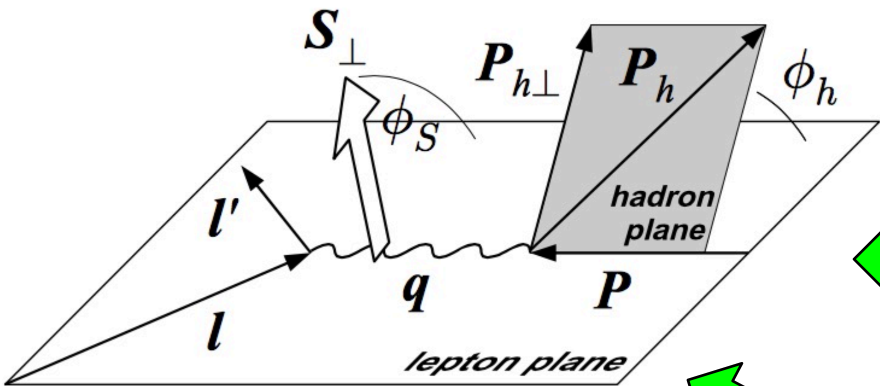
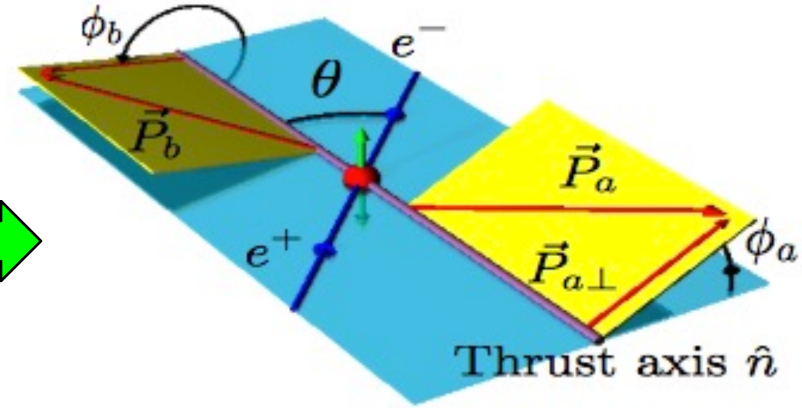


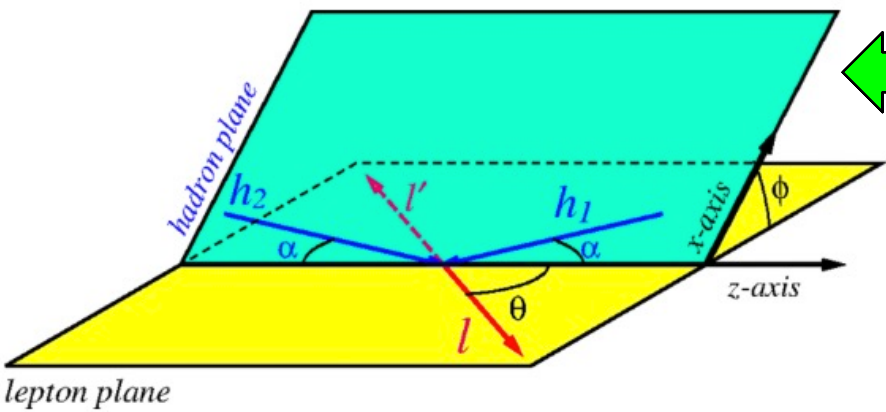
1976 →



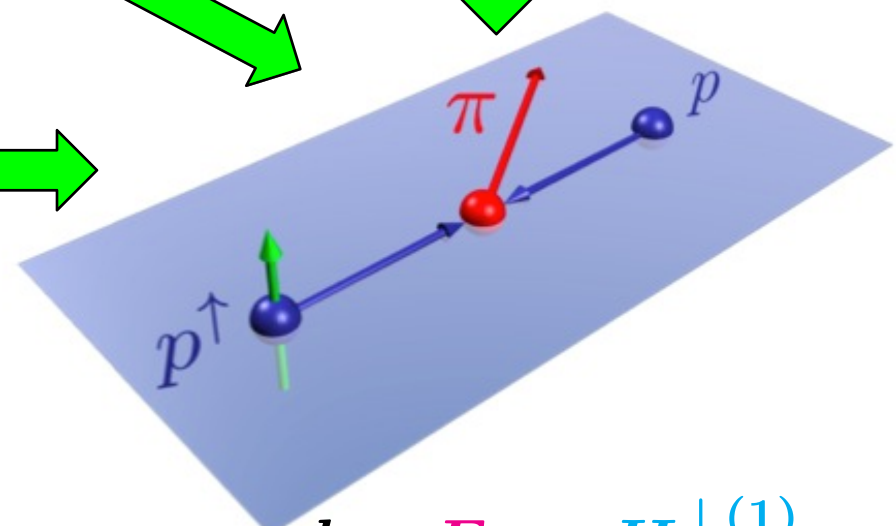
$h_1, F_{FT}, H_1^{\perp(1)}$



$H_1^{\perp(1)}$

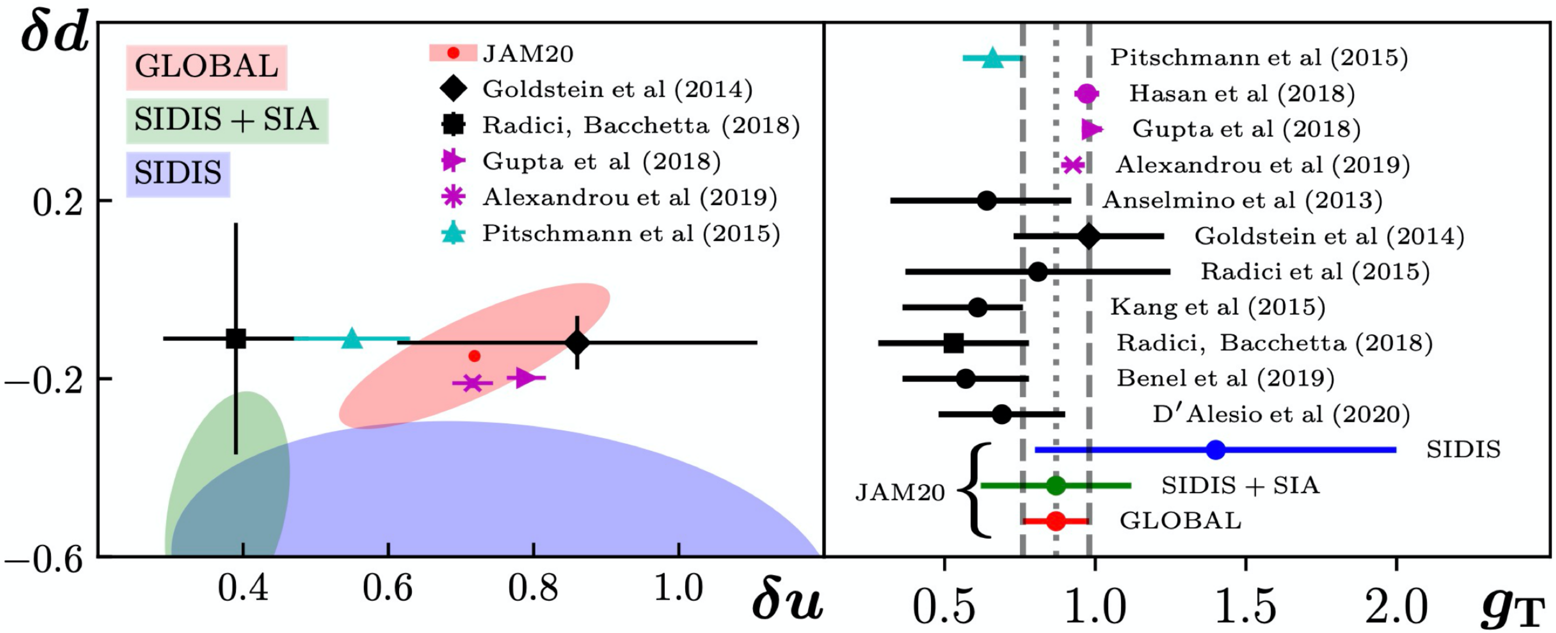


F_{FT}



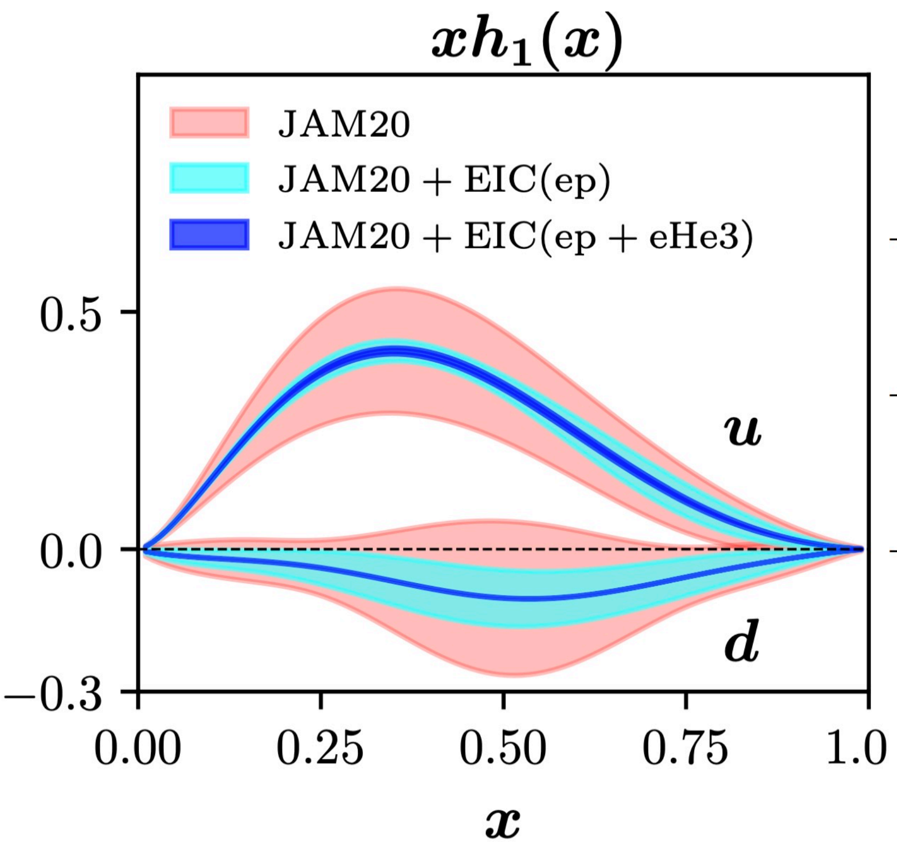
$h_1, F_{FT}, H_1^{\perp(1)}$

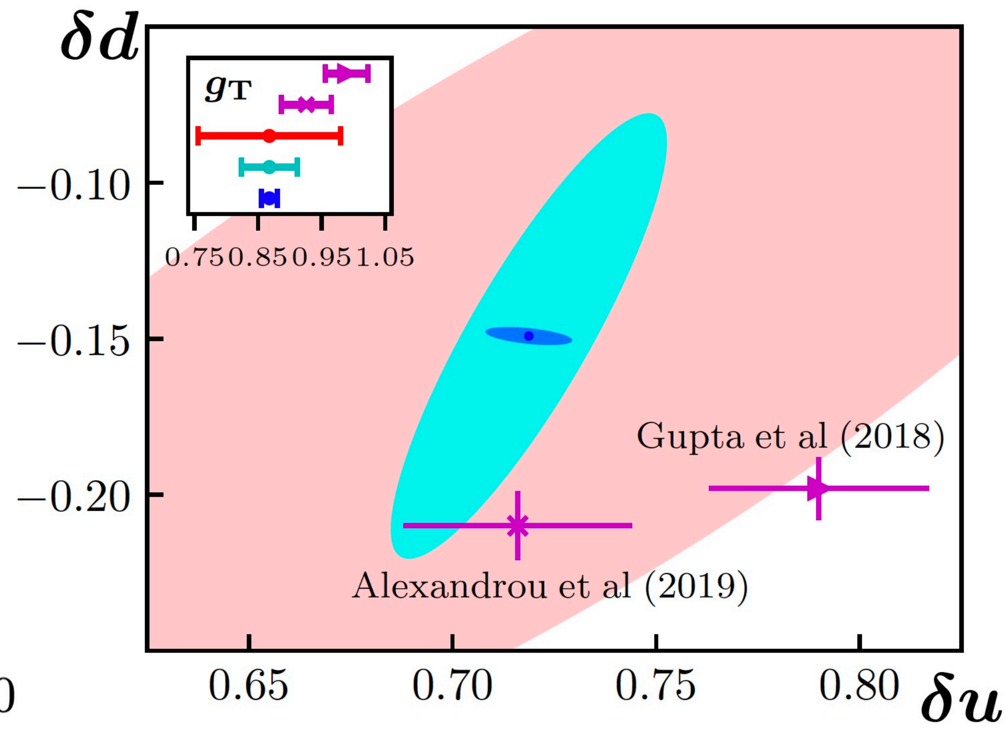
Cammarota, Gamberg, Kang, Miller, DP, Prokudin, Rogers, Sato (2020) – simultaneous fit of SSAs in SIDIS, Drell-Yan, e^+e^- annihilation, and proton-proton collisions (JAM20) using a Gaussian ansatz for the TMDs



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*

Seidl, DP, Gamberg, Kang, Prokudin, Rogers, Sato (EIC YR and in preparation)

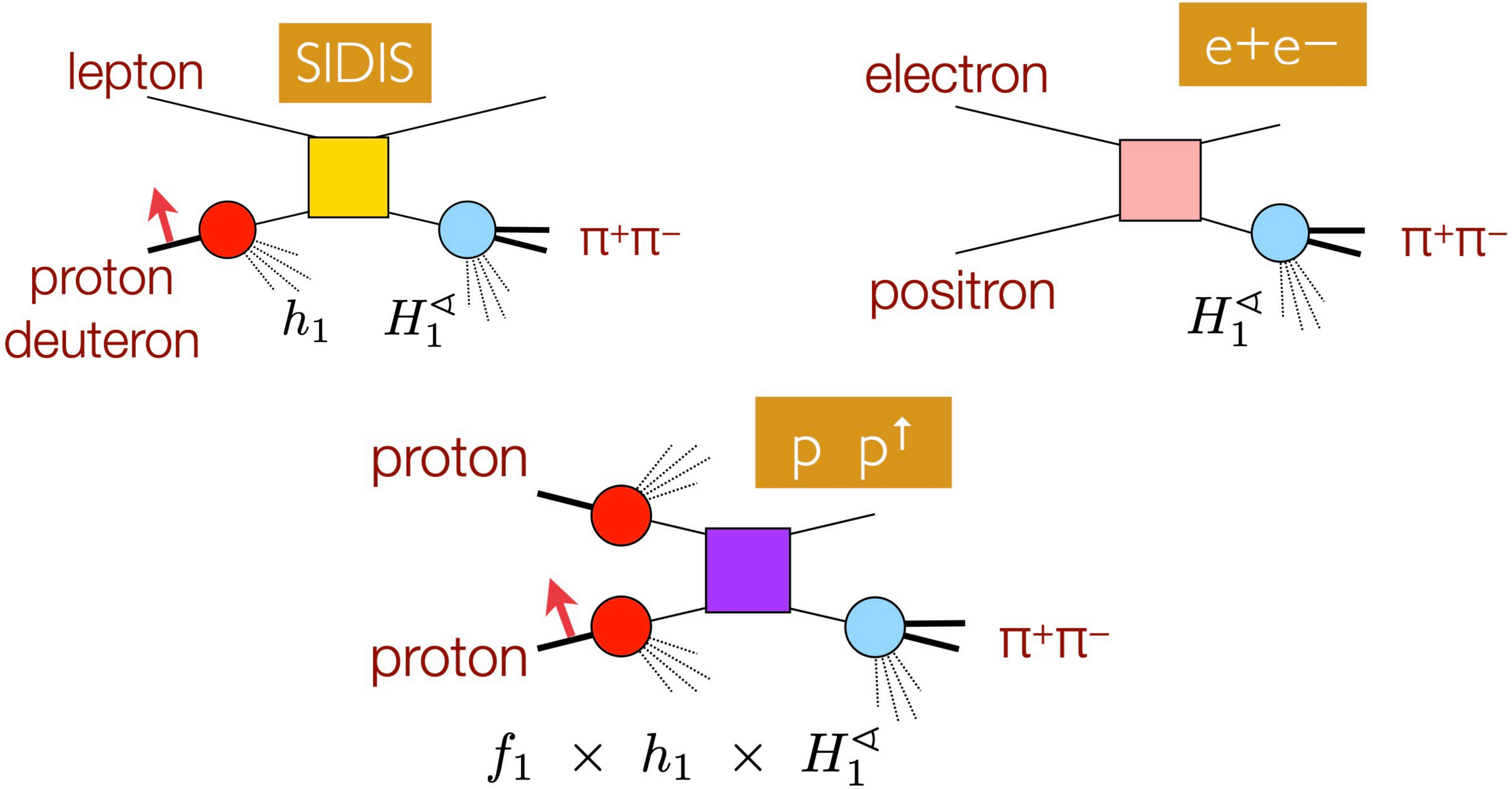




NB: JAM20+EIC includes all energy configurations (18x275, 10x100, 5x100, 5x41 for ep and 18x100, 5x100, 5x41 for eHe3) = 8223 points after data cuts

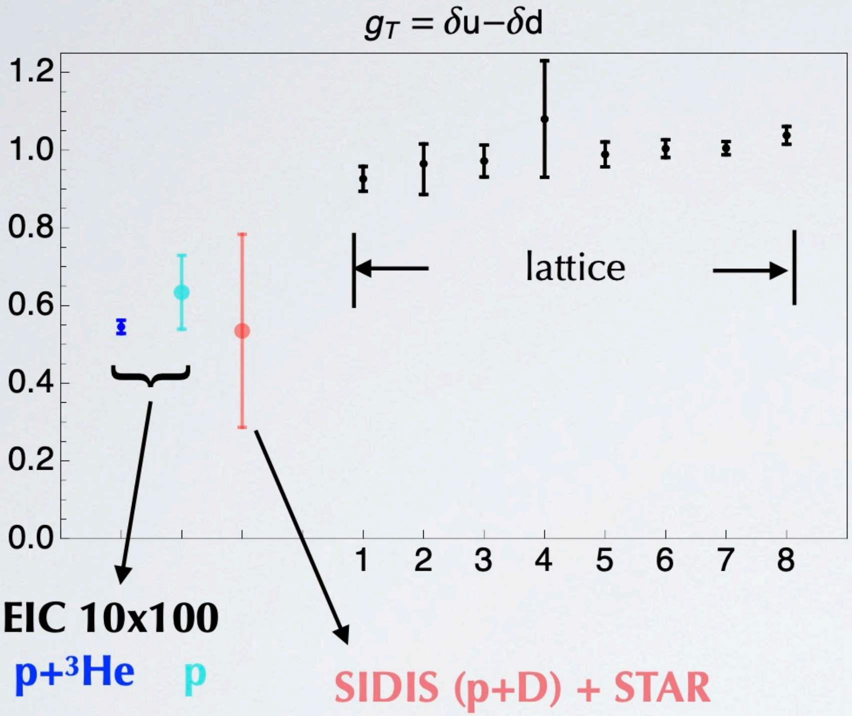
A complementary method to extract the tensor charge is through dihadron fragmentation (Bacchetta, Courtoy, Radici (2013); Radici, Courtoy, Bacchetta, Guagnelli (2015); Pisano, Radici (2016); Bacchetta and Radici (2017))

Courtesy of M. Radici



Courtesy of M. Radici (for EIC YR, based on Bacchetta and Radici (2017))

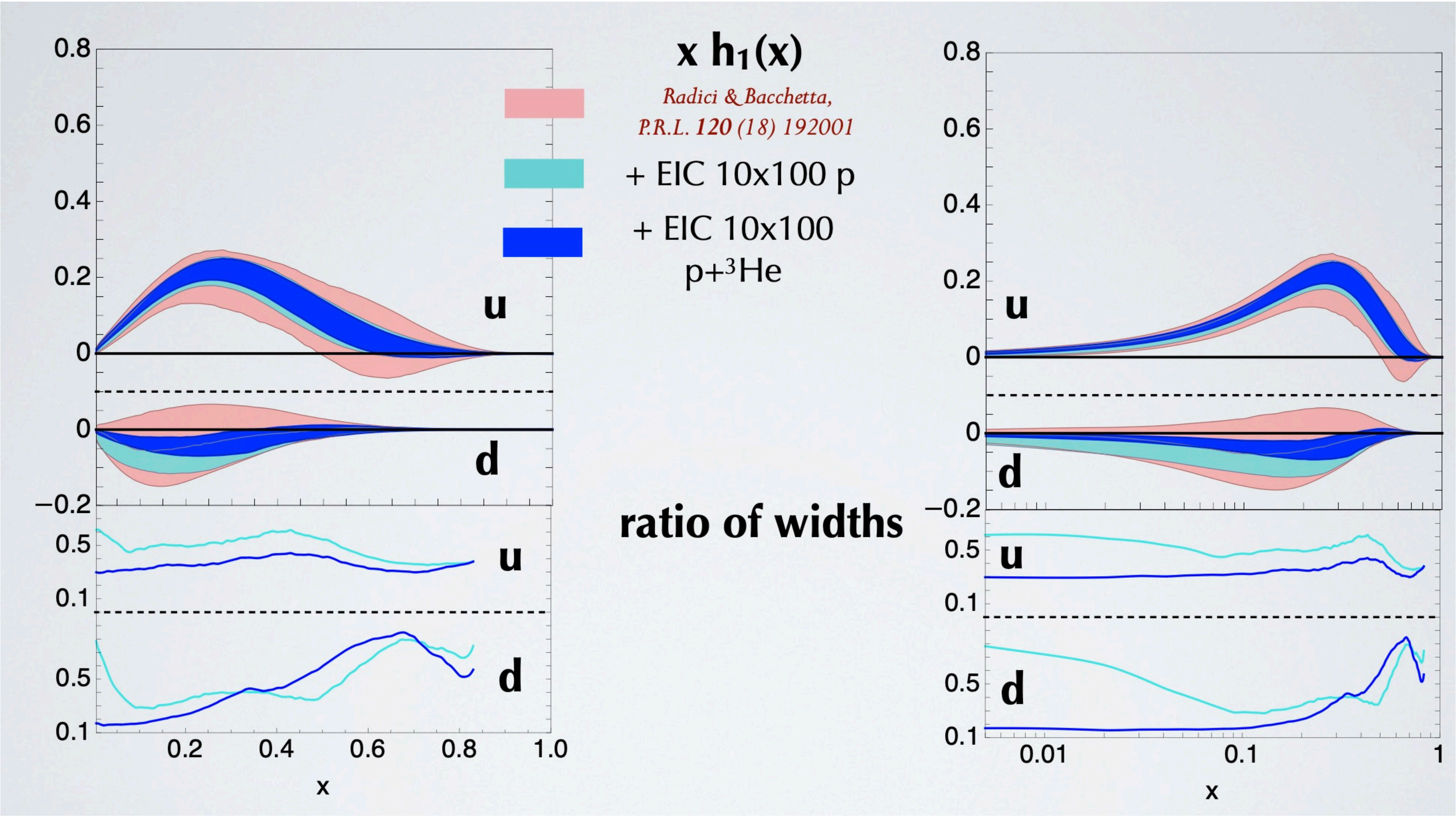
isovector tensor charge

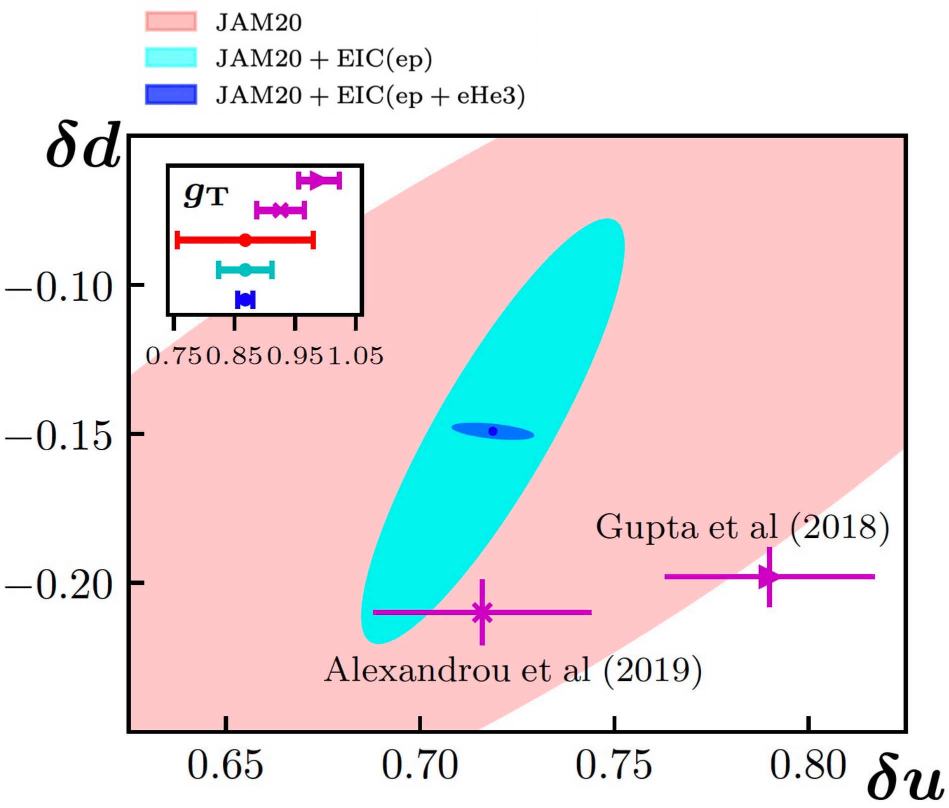


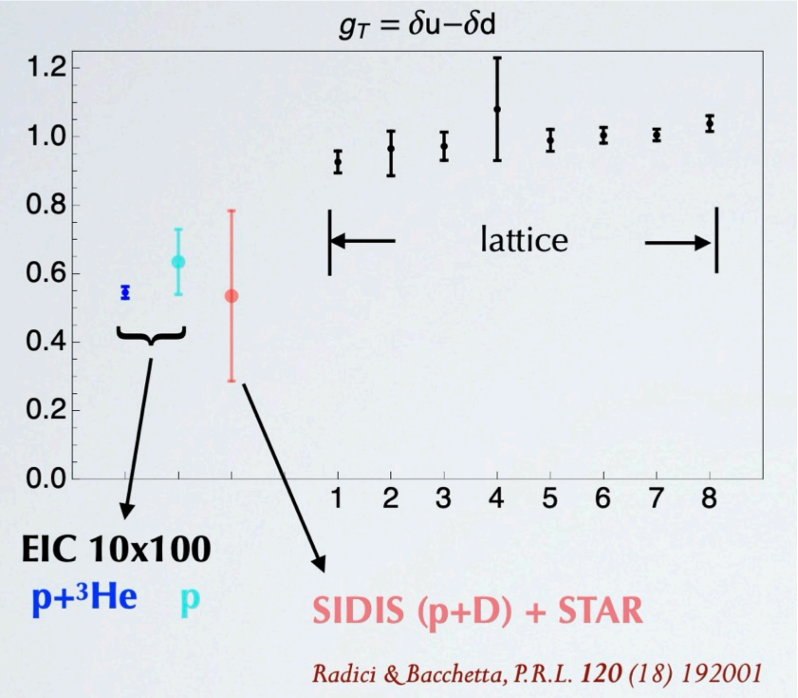
Radici & Bacchetta, P.R.L. ***120*** *(18) 192001*

1) **ETMC ’19** — *Alexandrou et al., arXiv:1909.00485*
2) **Mainz ’19** — *Harris et al., P.R. D**100** (19) 034513*
3) **LHPC ‘19** — *Hasan et al., P.R. D**99** (19) 114505*
4) **JLQCD ’18** — *Yamanaka et al., P.R. D**98** (18) 054516*
5) **PNDME ’18** — *Gupta et al., P.R. D**98** (18) 034503*
6) **ETMC ’17** — *Alexandrou et al., P.R. D**95** (17) 114514; E P.R. D**96** (17) 099906*
7) **RQCD ‘14** — *Bali et al., P.R. D**91** (15) 054501*
8) **LHPC ‘12** — *Green et al., P.R. D**86** (12) 114509*

Courtesy of M. Radici (for EIC YR, based on Bacchetta and Radici (2017))







With EIC data, phenomenological extractions of the tensor charge will become as (or more) precise as current lattice calculations. This will be an important test of whether first principles (non-perturbative) and perturbative QCD approaches agree.

Studies of TMDs involving transverse polarization will continue to play a crucial role in exploring aspects of factorization and evolution as well as making connections to BSM and lattice QCD