Global Analysis of Single Transverse-Spin Asymmetries

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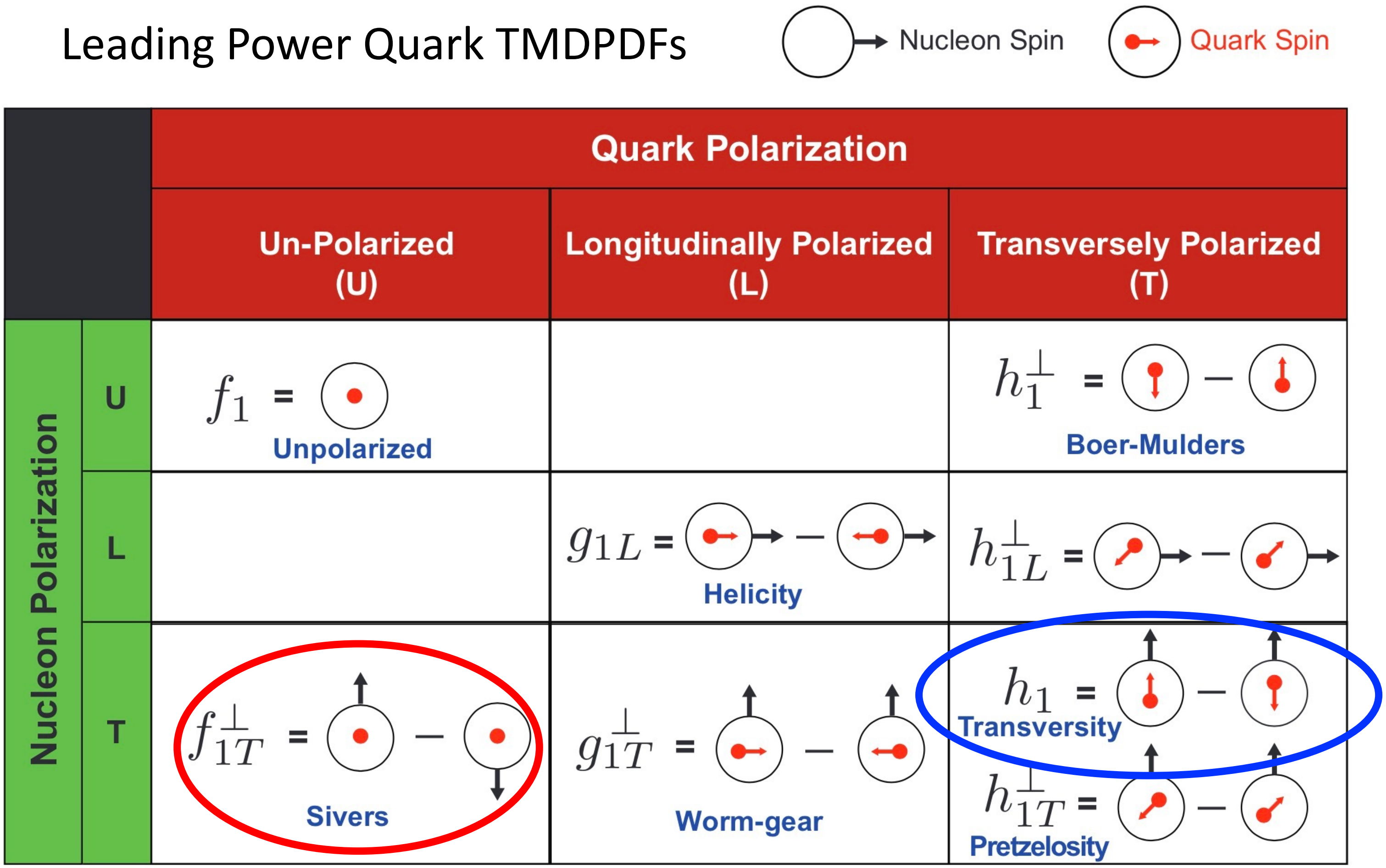
Background

Lebanon Valley College

D. Pitonyak

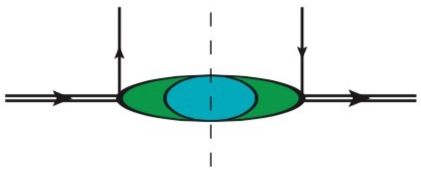
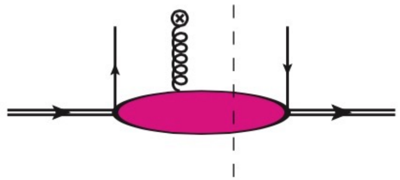
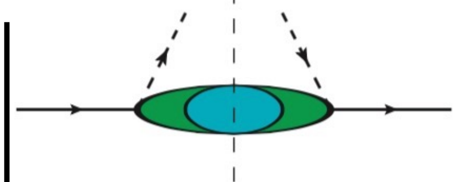
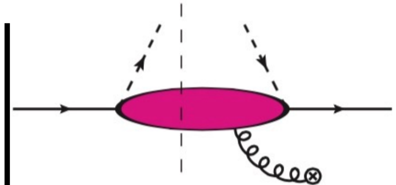
Leading Power Quark TMDPDFs

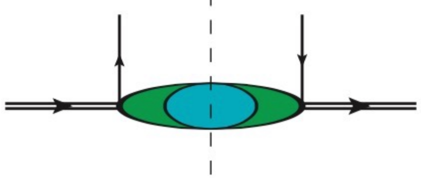


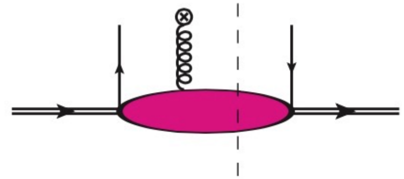
Leading Power Quark TMDFFs

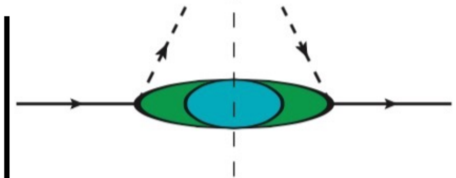
Hadron Spin   Quark Spin

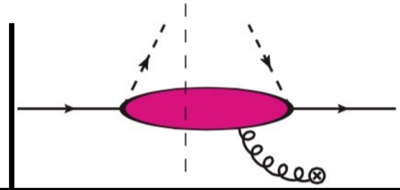
		Quark Polarization		
		Un-Polarized (U)	**Longitudinally Polarized (L)**	**Transversely Polarized (T)**
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^\perp$ = − Collins
Polarized Hadrons	**L**		G_{1L} = − Helicity	$H_{1L}^\perp$ = −
	T	$D_{1T}^\perp$ = − Polarizing FF	$G_{1T}^\perp$ = −	H_1 = − Transversity $H_{1T}^\perp$ = −

Hadron Pol.	CT3 PDF (x)		CT3 PDF (x, x_1)	CT3 FF (z)		CT3 FF (z, z_1)
						
	intrinsic	kinematical	dynamical	intrinsic	kinematical	dynamical
U	e	$h_1^{\perp(1)}$	H_{FU}	E, H	$H_1^{\perp(1)}$	$\hat{H}_{FU}^{\mathfrak{R},\mathfrak{I}}$
L	h_L	$h_{1L}^{\perp(1)}$	H_{FL}	H_L, E_L	$H_{1L}^{\perp(1)}$	$\hat{H}_{FL}^{\mathfrak{R},\mathfrak{I}}$
T	g_T	$f_{1T}^{\perp(1)}$, $g_{1T}^{\perp(1)}$	F_{FT}, G_{FT}	D_T, G_T	$D_{1T}^{\perp(1)}$, $G_{1T}^{\perp(1)}$	$\hat{D}_{FT}^{\mathfrak{R},\mathfrak{I}}, \hat{G}_{FT}^{\mathfrak{R},\mathfrak{I}}$





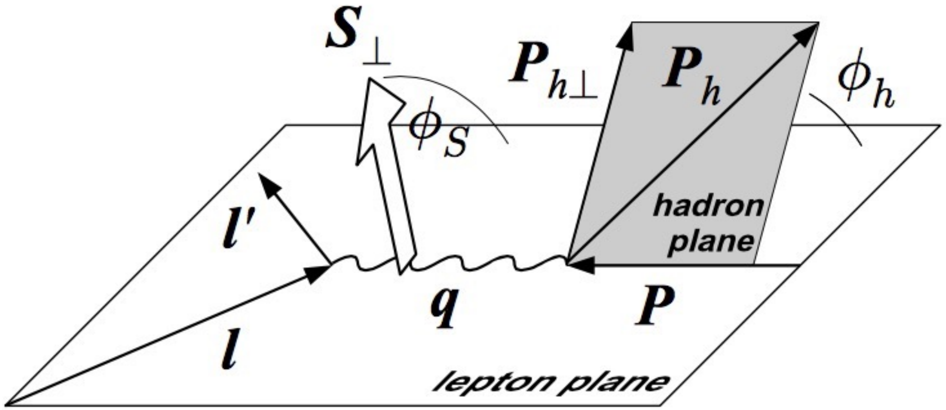




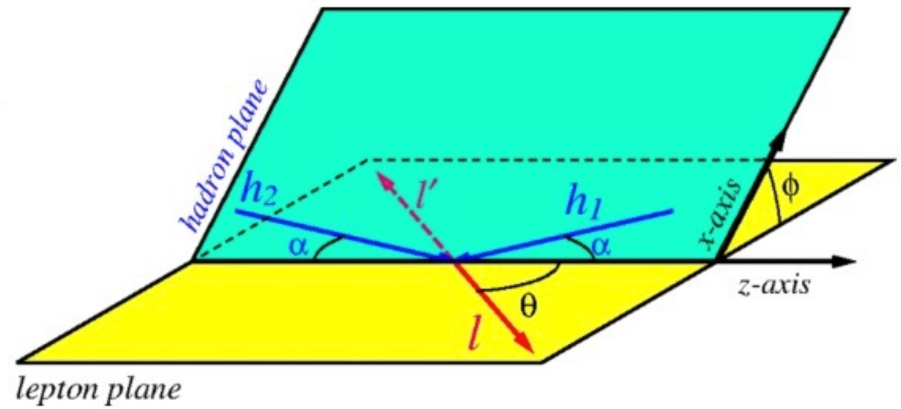
Hadron Pol.	CT3 PDF (x): intrinsic	CT3 PDF (x): kinematical	CT3 PDF (x, x_1): dynamical	CT3 FF (z): intrinsic	CT3 FF (z): kinematical	CT3 FF (z, z_1): dynamical
U	$\cancel{e}$	$\cancel{h_1^{\perp(1)}}$	H_{FU}	$\cancel{E}, \cancel{H}$	$\cancel{H_1^{\perp(1)}}$	$\hat{H}_{FU}^{\Re,\Im}$
L	$\cancel{h_L}$	$\cancel{h_{1L}^{\perp(1)}}$	H_{FL}	$\cancel{H_L}, \cancel{E_L}$	$\cancel{H_{1L}^{\perp(1)}}$	$\hat{H}_{FL}^{\Re,\Im}$
T	$\cancel{g_T}$	$\cancel{f_{1T}^{\perp(1)}}$, $\cancel{g_{1T}^{\perp(1)}}$	F_{FT}, G_{FT}	$\cancel{D_T}, \cancel{G_T}$	$\cancel{D_{1T}^{\perp(1)}}$, $\cancel{G_{1T}^{\perp(1)}}$	$\hat{D}_{FT}^{\Re,\Im}, \hat{G}_{FT}^{\Re,\Im}$

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

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



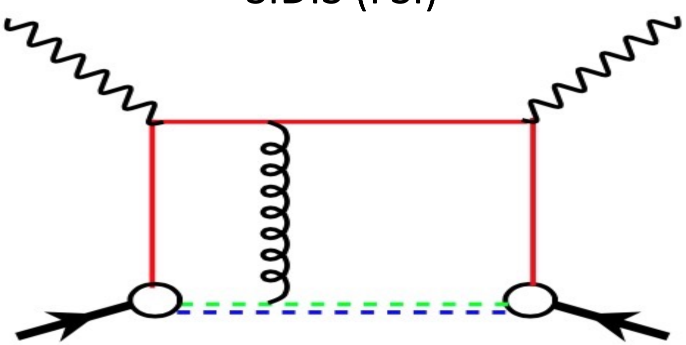
$$\{\pi, p\} p^\uparrow \to \{\ell^+\ell^-, W^\pm, Z\} X$$



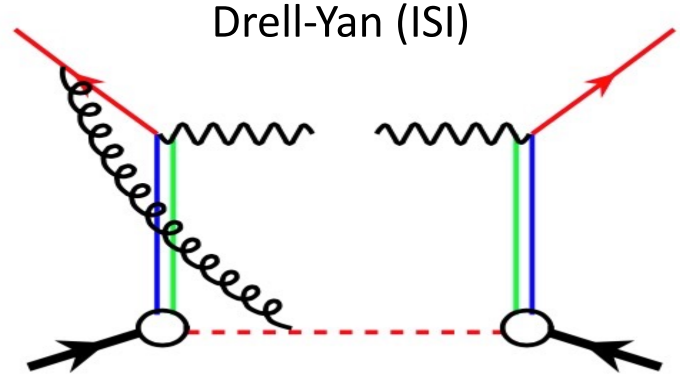
$$F_{UT}^{\sin(\phi_h - \phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M} \boldsymbol{f_{1T}^{\perp}} D_1\right]$$

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

SIDIS (FSI)



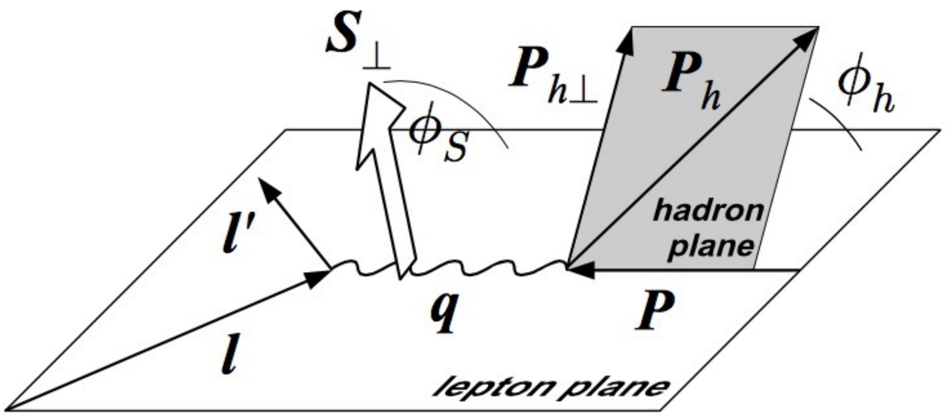
Drell-Yan (ISI)



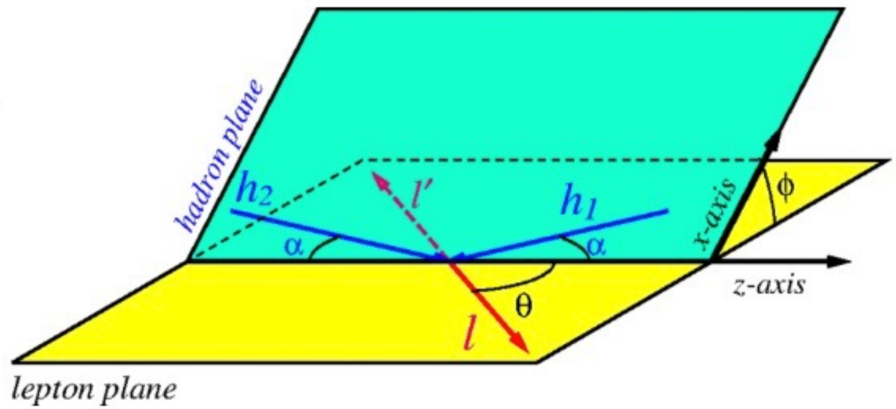
$$f_{1T}^{\perp}(x, \vec{k}_T^2)\big|_{SIDIS} = -f_{1T}^{\perp}(x, \vec{k}_T^2)\big|_{DY}$$

(Brodsky, Hwang, Schmidt (2002), Collins (2002))

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



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



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

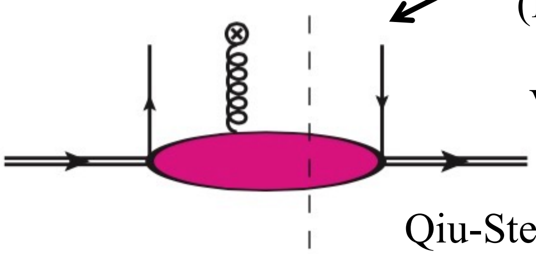
$$F_{TU}^1 = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_{aT}}{M_a} \boldsymbol{f_{1T}^\perp}\, \bar{f}_1\right]$$

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

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))



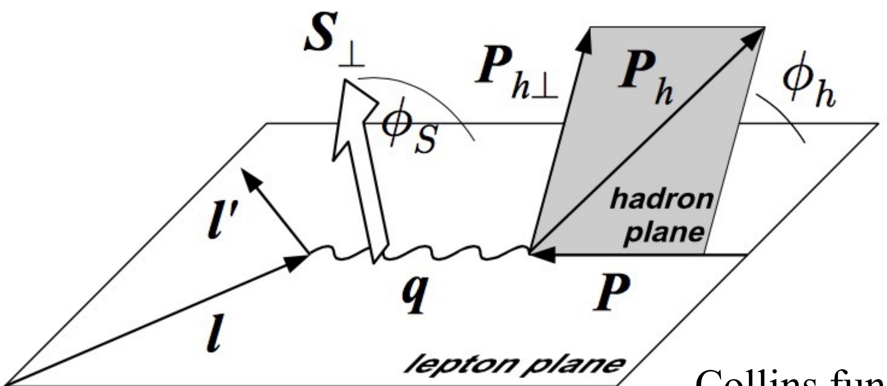
Qiu-Sterman function

<u>Parton model</u>

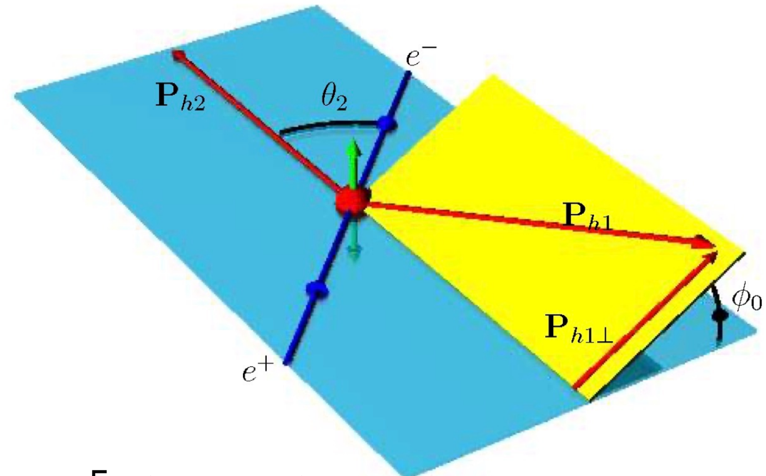
$$\pi F_{FT}(x, x) = \int d^2\vec{k}_T \, \frac{k_T^2}{2M^2} f_{1T}^\perp(x, k_T^2) \equiv f_{1T}^{\perp(1)}(x)$$

(Boer, Mulders, Pijlman (2003))

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



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



Collins function

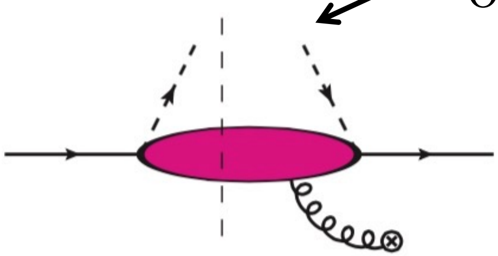
$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{p}_\perp}{M_h}\boldsymbol{h_1}\boldsymbol{H_1^\perp}\right] \qquad F_{UU}^{\cos(2\phi_0)} = \mathcal{C}\left[\frac{2\hat{h}\cdot\vec{p}_{a\perp}\,\hat{h}\cdot\vec{p}_{b\perp} - \vec{p}_{a\perp}\cdot\vec{p}_{b\perp}}{M_a M_b}\boldsymbol{H_1^\perp}\,\boldsymbol{\bar{H}_1^\perp}\right]$$

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

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

OPE

(Kang, et al. (2016))



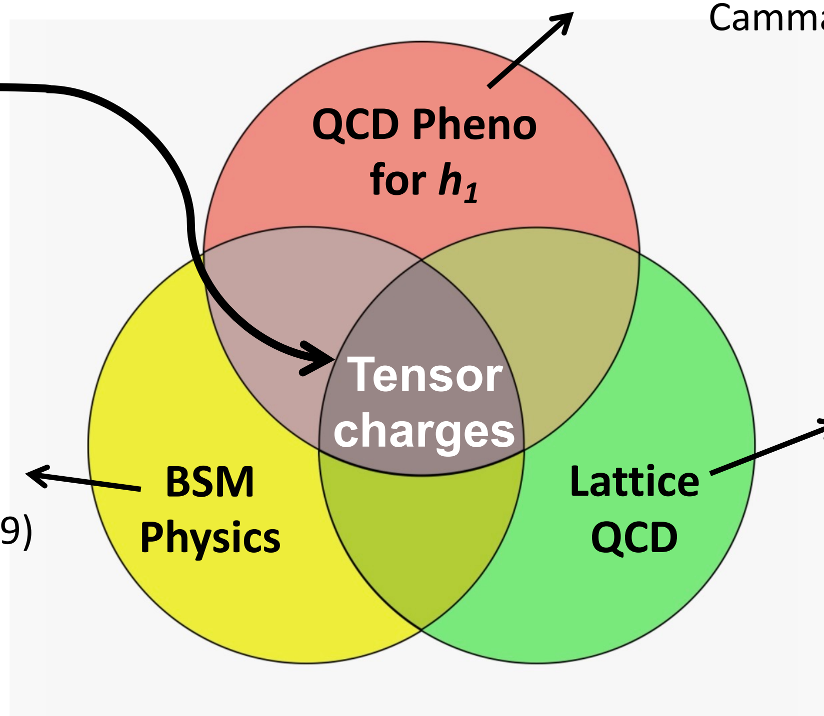
qgq fragmentation function

Parton model

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

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

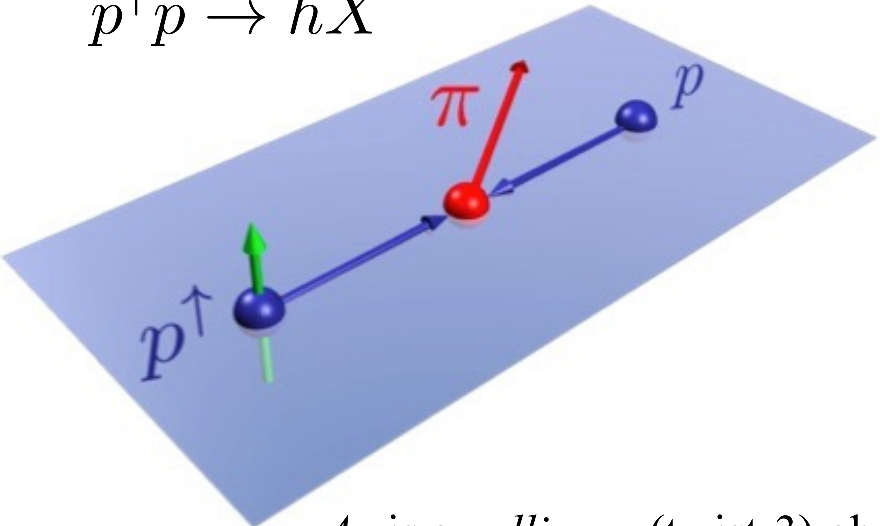
Anselmino, et al. (2013, 2015); Goldstein, et al. (2014);
Radici, et al. (2013, 2018); Kang, et al. (2016);
Benel, et al. (2019); D'Alesio, et al. (2020);
Cammarota, et al. (2020)



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)

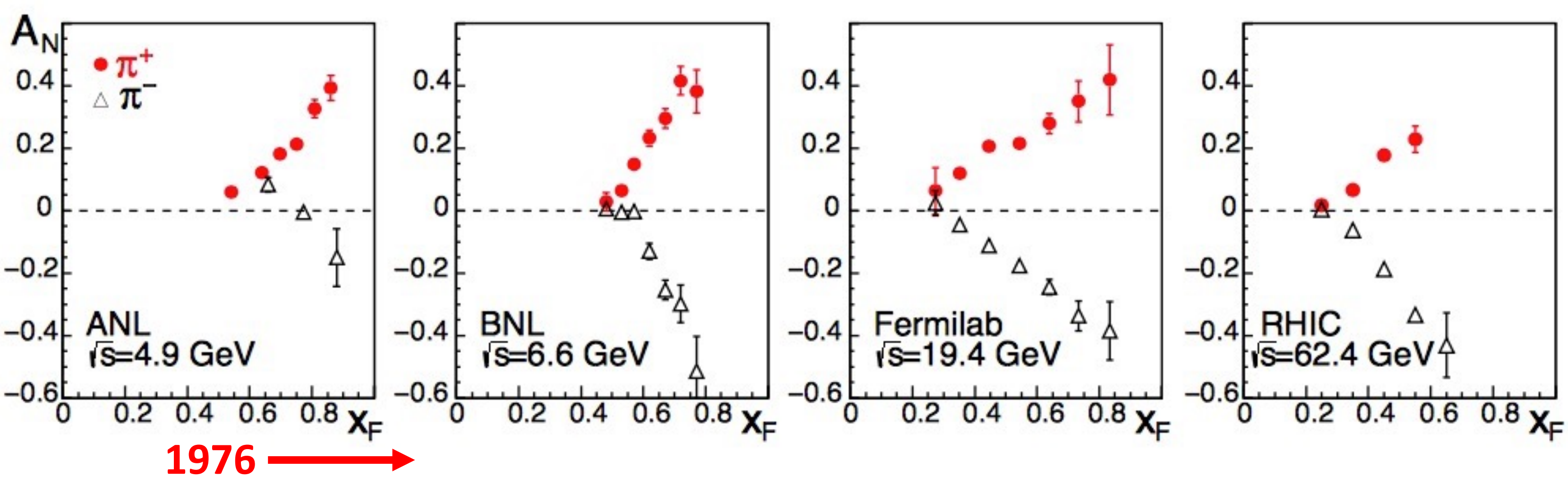
$$p^{\uparrow}p \to hX$$



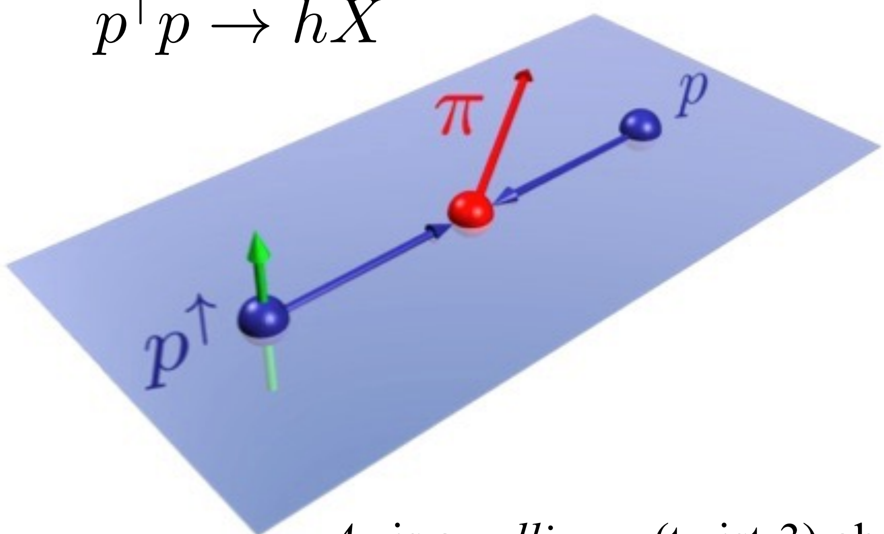
$$d\Delta\sigma(S_T) \sim \underbrace{H_{QS} \otimes f_1 \otimes \boldsymbol{F_{FT}} \otimes D_1}_{\text{Qiu-Sterman term}}$$

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

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



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

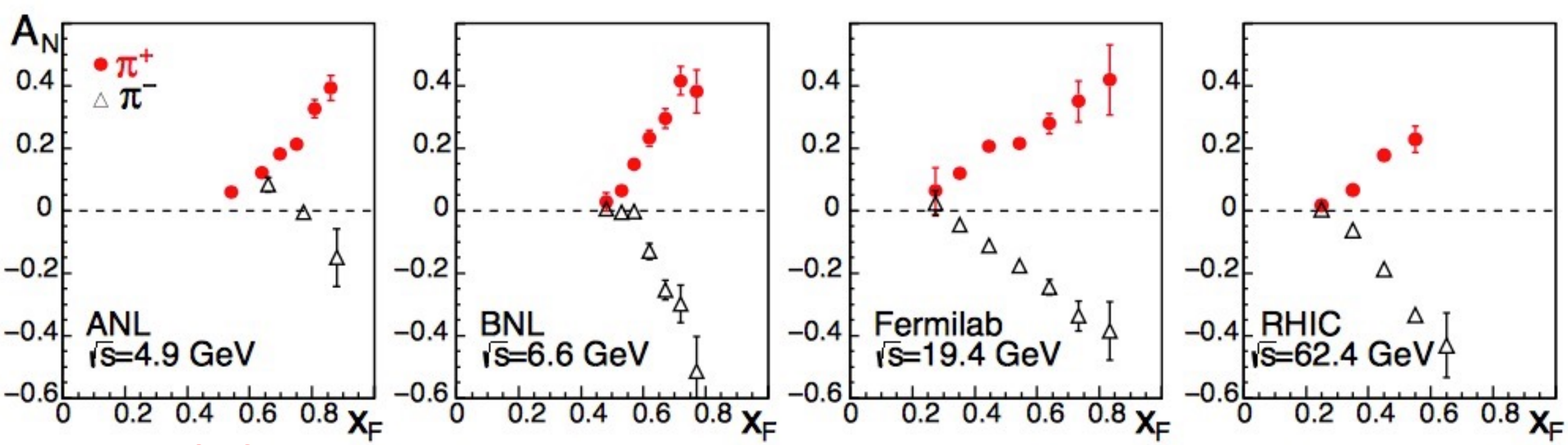


$$d\Delta\sigma(S_T) \sim \underbrace{H_{QS} \otimes f_1 \otimes \boldsymbol{F_{FT}} \otimes D_1}_{\text{Qiu-Sterman term}}$$

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

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

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



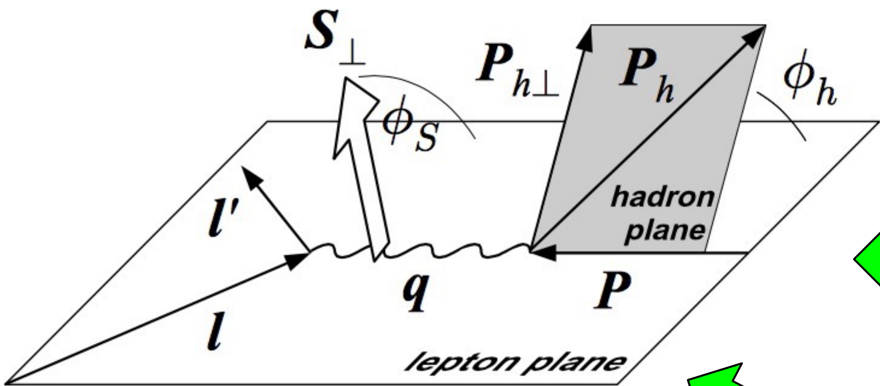
1976 →

Milestone 6:

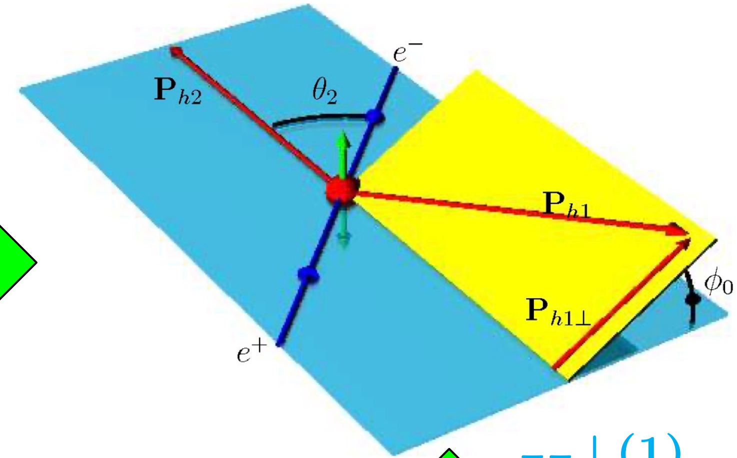
…perform global analysis of all existing data on SIDIS, Drell-Yan lepton pair production and di-hadron production in e+e- to extract a universal set of TMDs…

Simultaneous QCD Global Analysis of SSAs

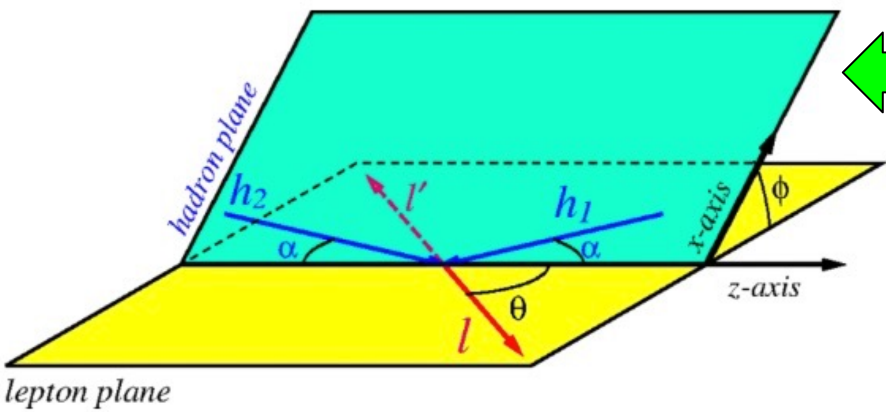
Cammarota, Gamberg, Kang, Miller, DP, Prokudin, Rogers, Sato, PRD **102** (2020)



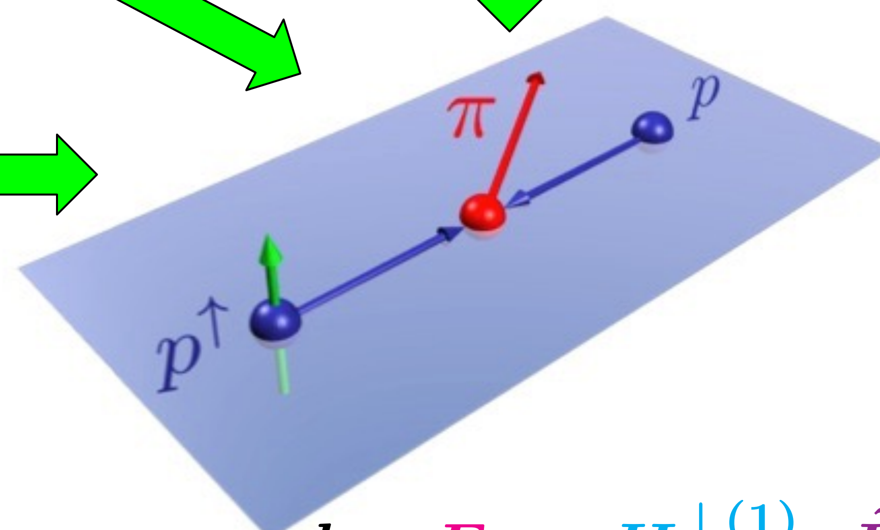
h_1, F_{FT}, $H_1^{\perp(1)}$



$H_1^{\perp(1)}$



F_{FT}



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

- In 2020 we 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: $\langle k_T^2\rangle_{f_{1T}^\perp}, \langle k_T^2\rangle_{h_1}, \langle p_\perp^2\rangle_{H_1^\perp}^{fav}, \langle p_\perp^2\rangle_{H_1^\perp}^{unf}$

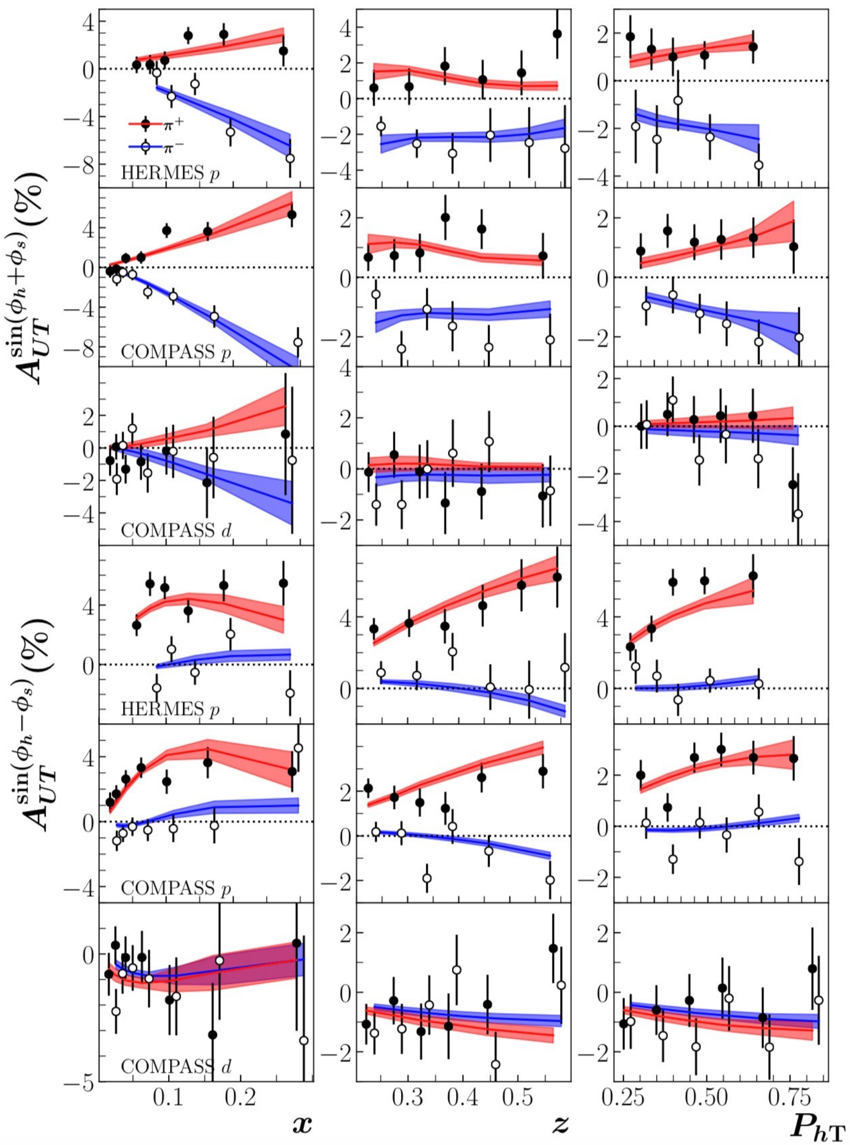
- We use a Gaussian ansatz: $F(x,k_T^2) \sim F(x)e^{-k_T^2/\langle k_T^2\rangle}$ where

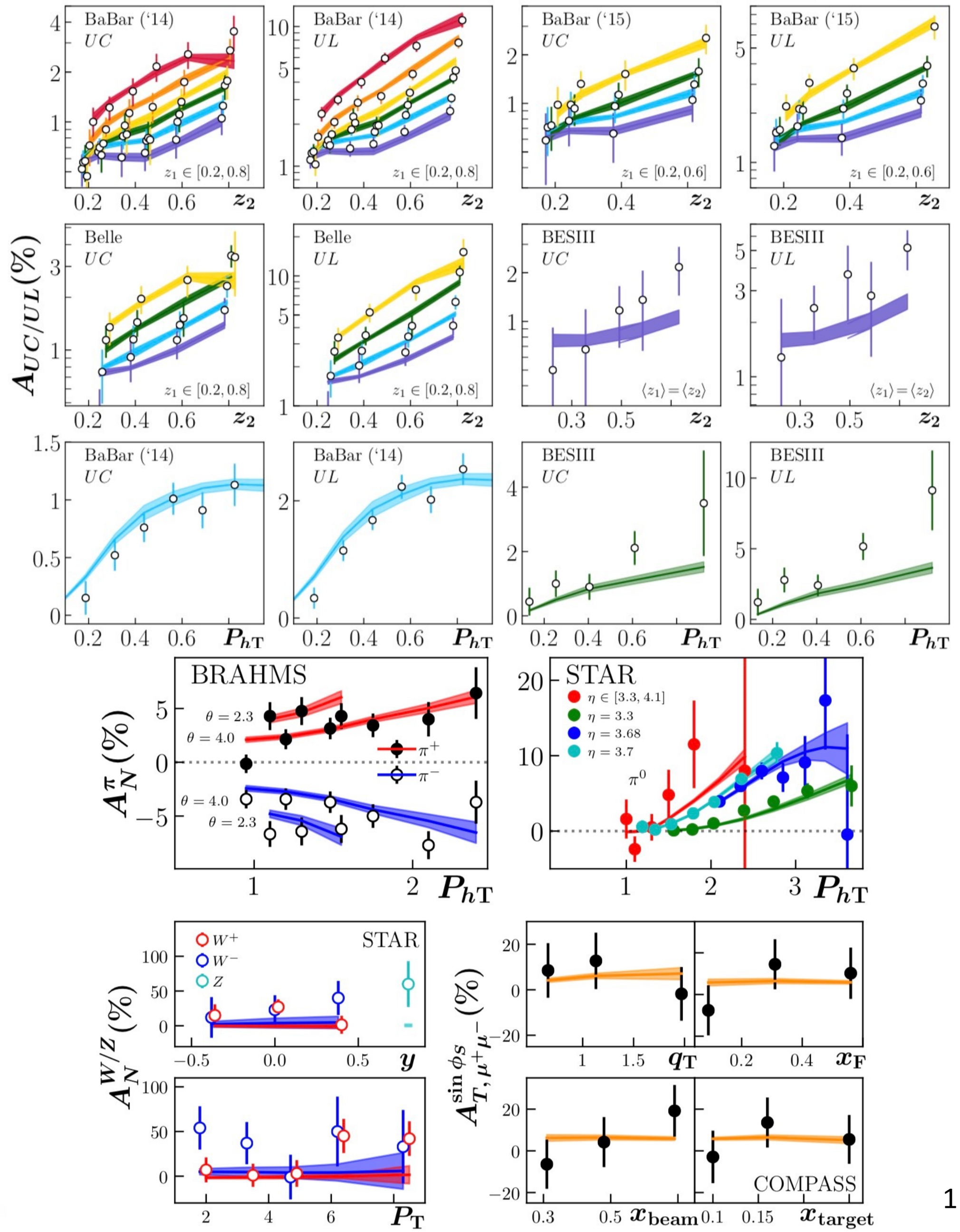
$$F^q(x) = \frac{N_q\, x^{a_q}(1-x)^{b_q}(1+\gamma_q\, x^{\alpha_q}(1-x)^{\beta_q})}{\mathrm{B}[a_q+2, b_q+1] + \gamma_q \mathrm{B}[a_q+\alpha_q+2, b_q+\beta_q+1]}$$

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

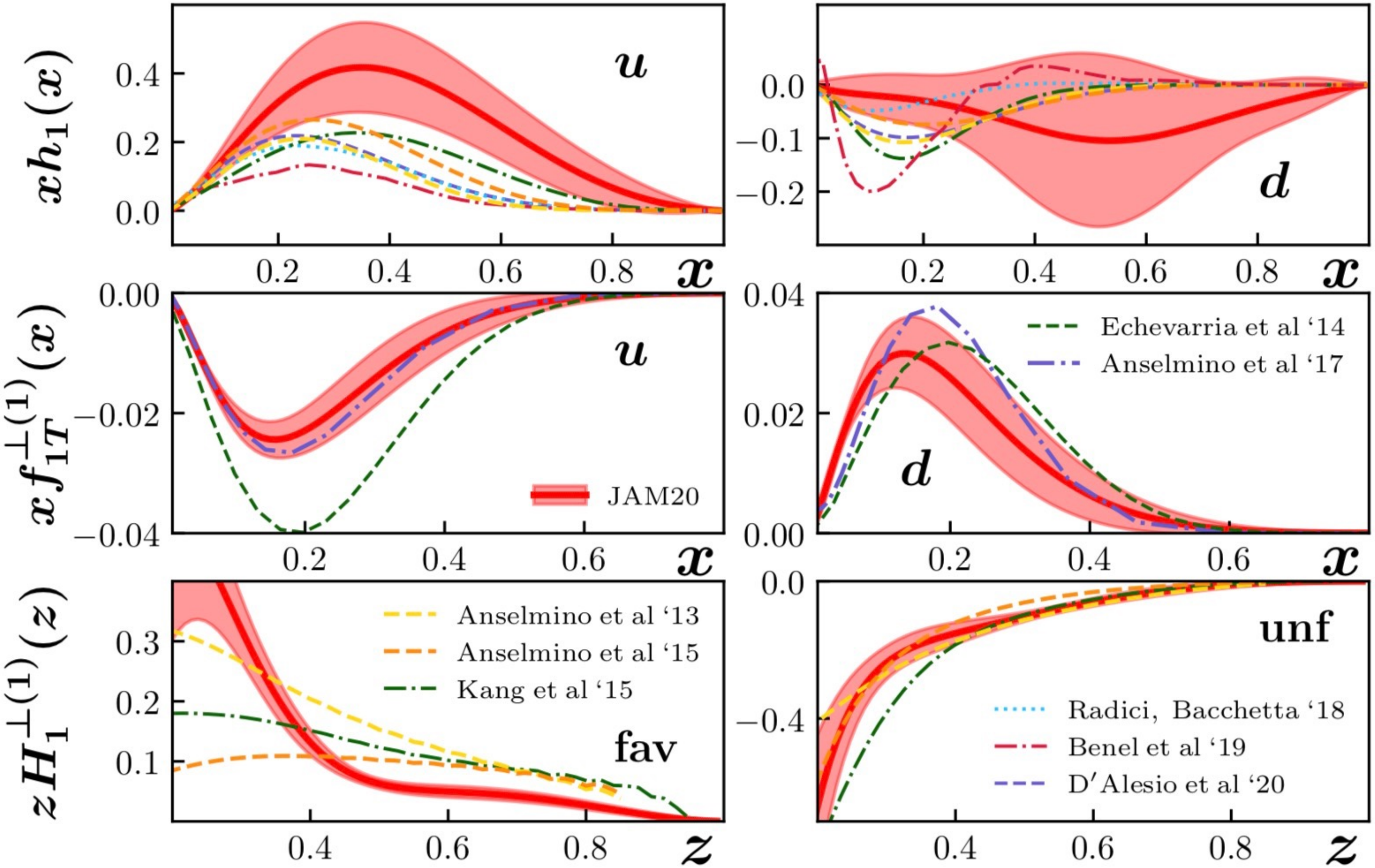
- DGLAP-type evolution for the collinear functions analogous to Duke & Owens (1984): double-log Q^2-dependent term explicitly added to the parameters

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





JAM3D-20

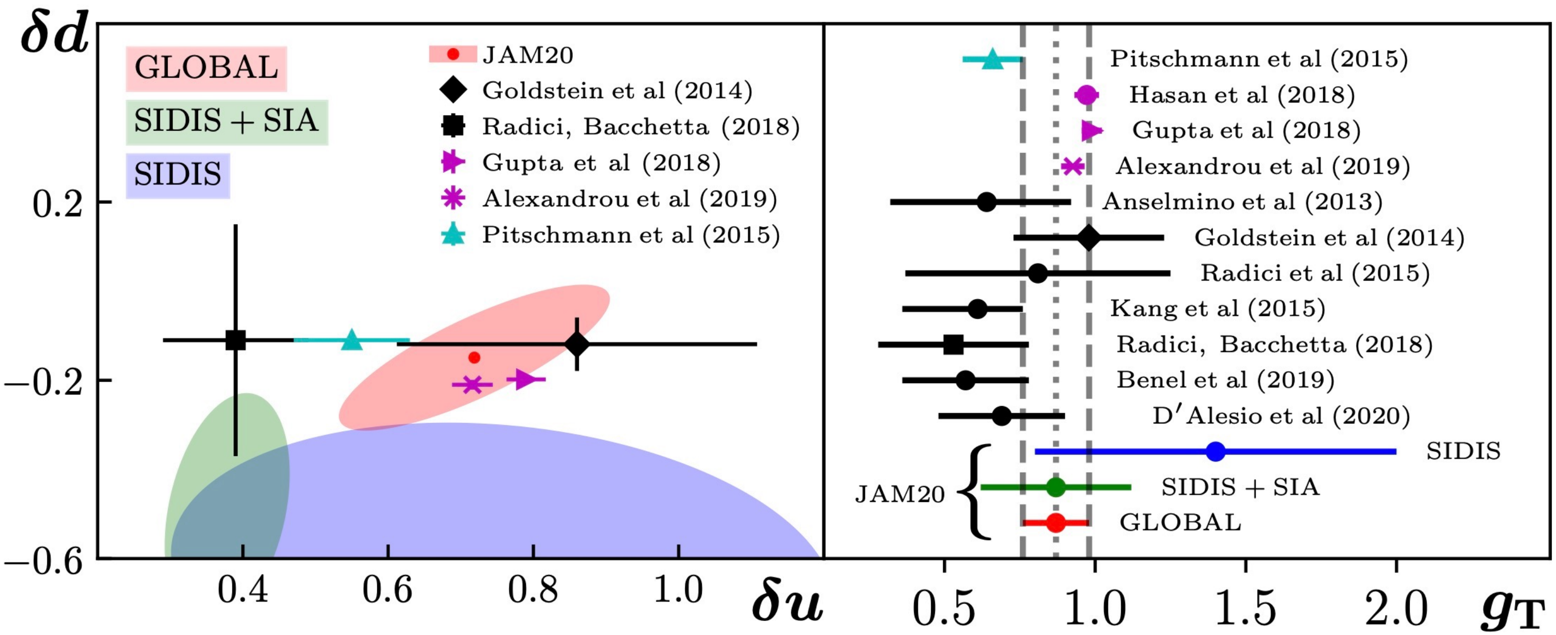


Transversity

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)

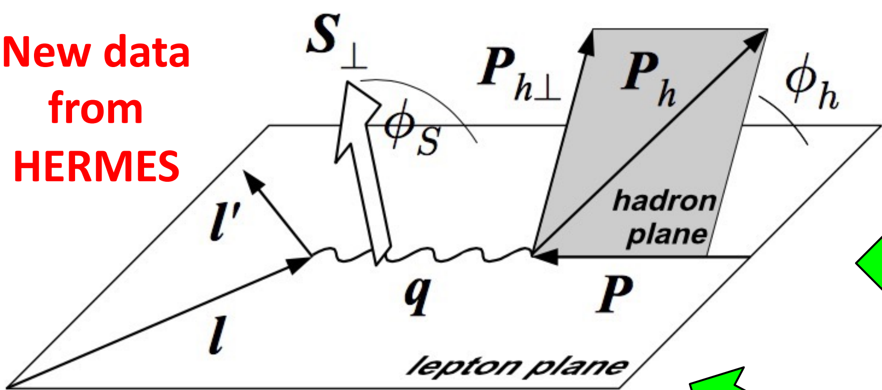
Only after a *simultaneous* QCD global analysis of SSAs does the phenomenological extraction of the tensor charges agree with lattice.

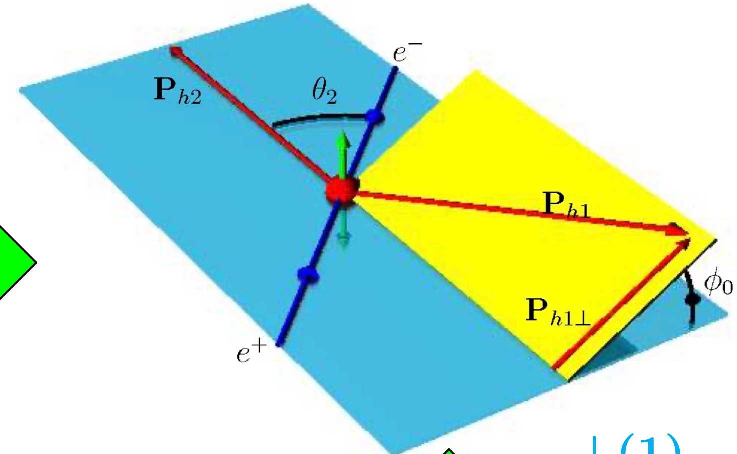
Updated QCD Global Analysis of SSAs

Gamberg, Malda, Miller, DP, Prokudin, Sato, arXiv:2205.00999 [hep-ph], submitted to PRD

User-friendly jupyter notebook to calculate functions and asymmetries:
https://colab.research.google.com/github/pitonyak25/jam3d_dev_lib/blob/main/JAM3D_Library.ipynb

New data from HERMES

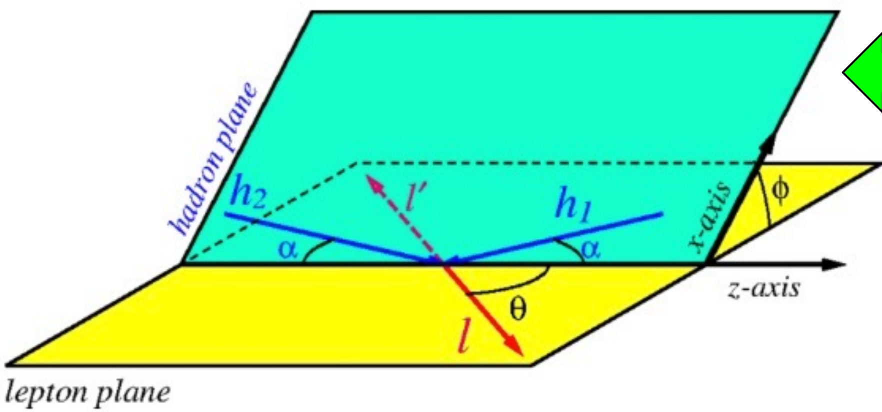


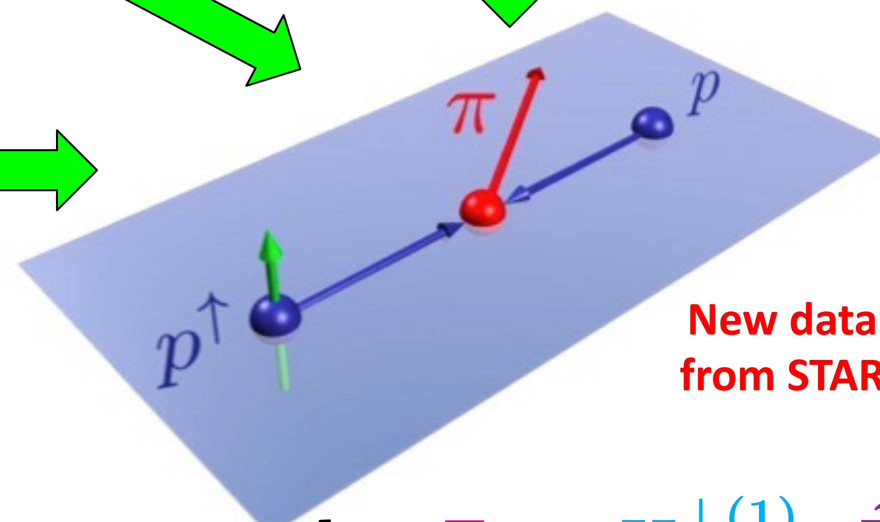


$h_1,\ F_{FT},\ H_1^{\perp(1)},\ \tilde{H}$

$A_{UT}^{\sin\phi_S}$ now available

$H_1^{\perp(1)}$





New data from STAR

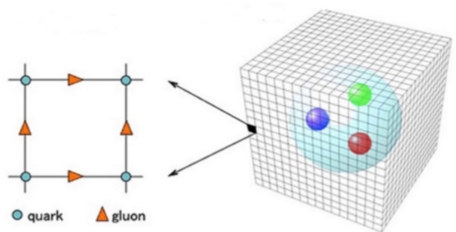
F_{FT}

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

- Additional data/constraints included in the fit:
  - Collins and Sivers effects (3D-binned) SIDIS data from HERMES (2020)
  - $A_{UT}^{\sin\phi_S}$ data (x and z projections only) from HERMES (2020)

$$\int d^2\vec{P}_{hT}\, F_{UT}^{\sin\phi_S} = -\frac{x}{z}\sum_q e_q^2\,\frac{2M_h}{Q}\,h_1^{q/N}(x)\,\tilde{H}^{h/q}(z)$$

  - Lattice data on g_T at the physical pion mass from Alexandrou, et al. (2019)



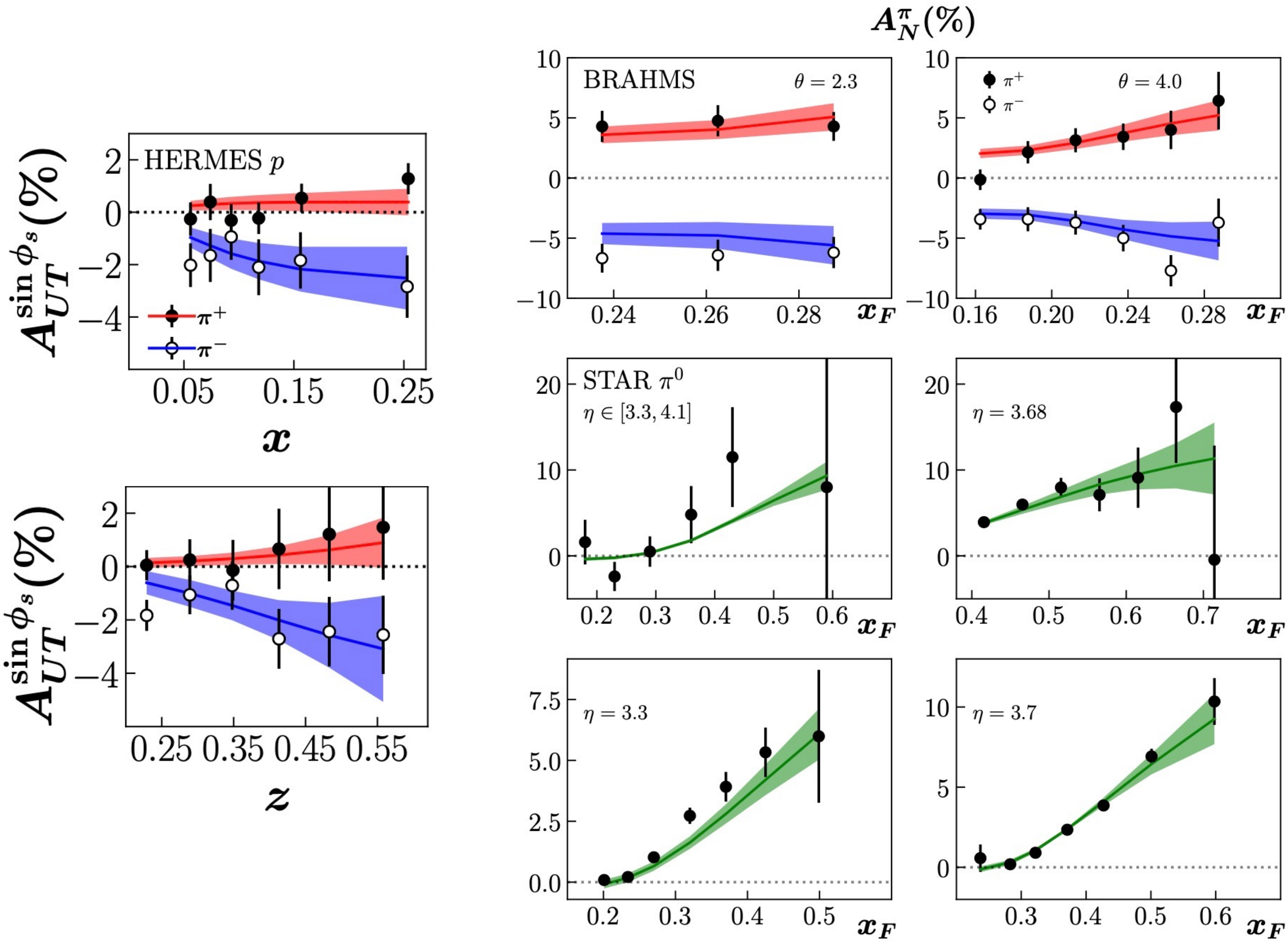
  - Imposing the Soffer bound on transversity: $|h_1^q(x)| \leq \frac{1}{2}(f_1^q(x) + g_1^q(x))$

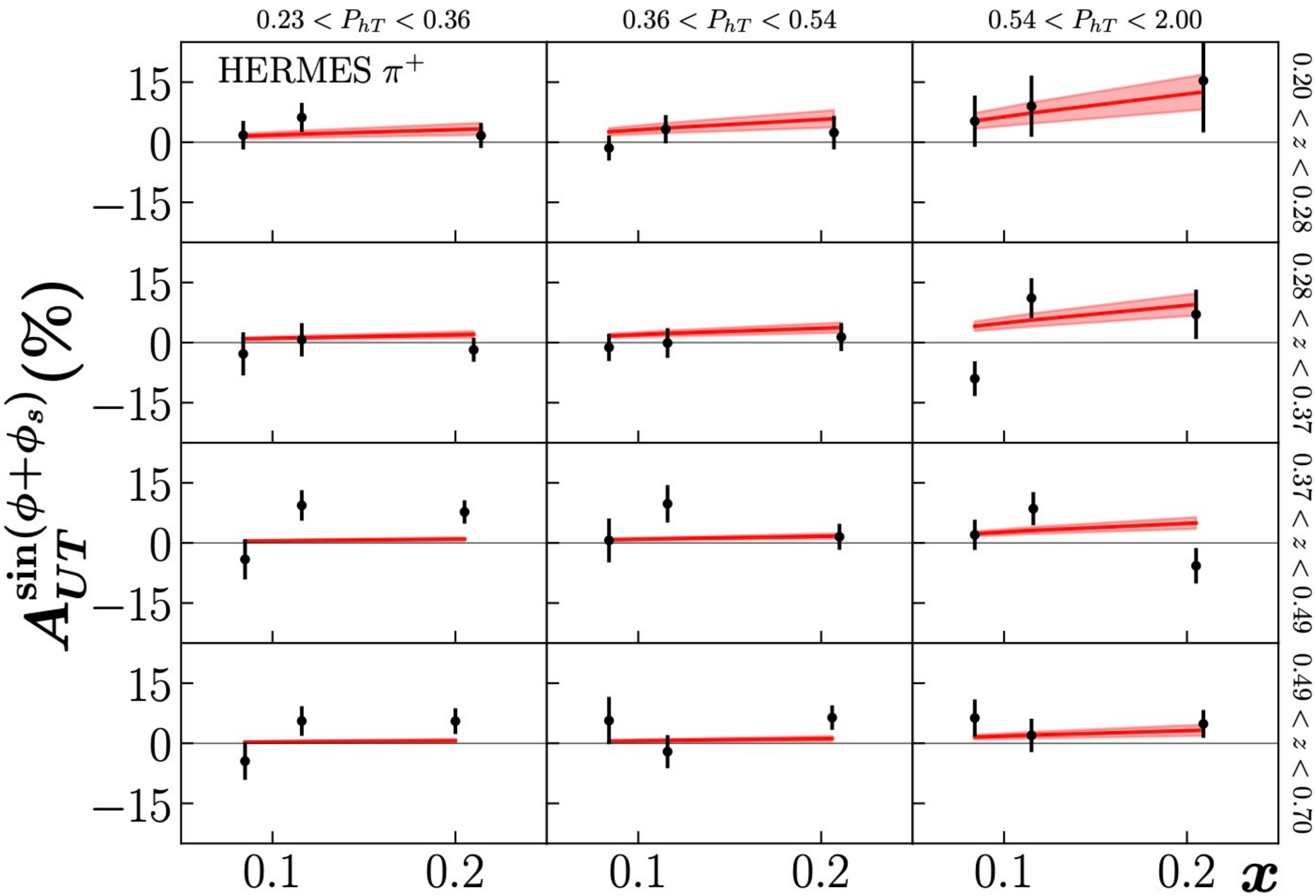
Generate "data" (central value and 1-σ uncertainty) using recent simultaneous fit of f_1 and g_1 from Cocuzza, et al. (2022) and add to the χ^2 if SB is violated by more than the uncertainty in the data

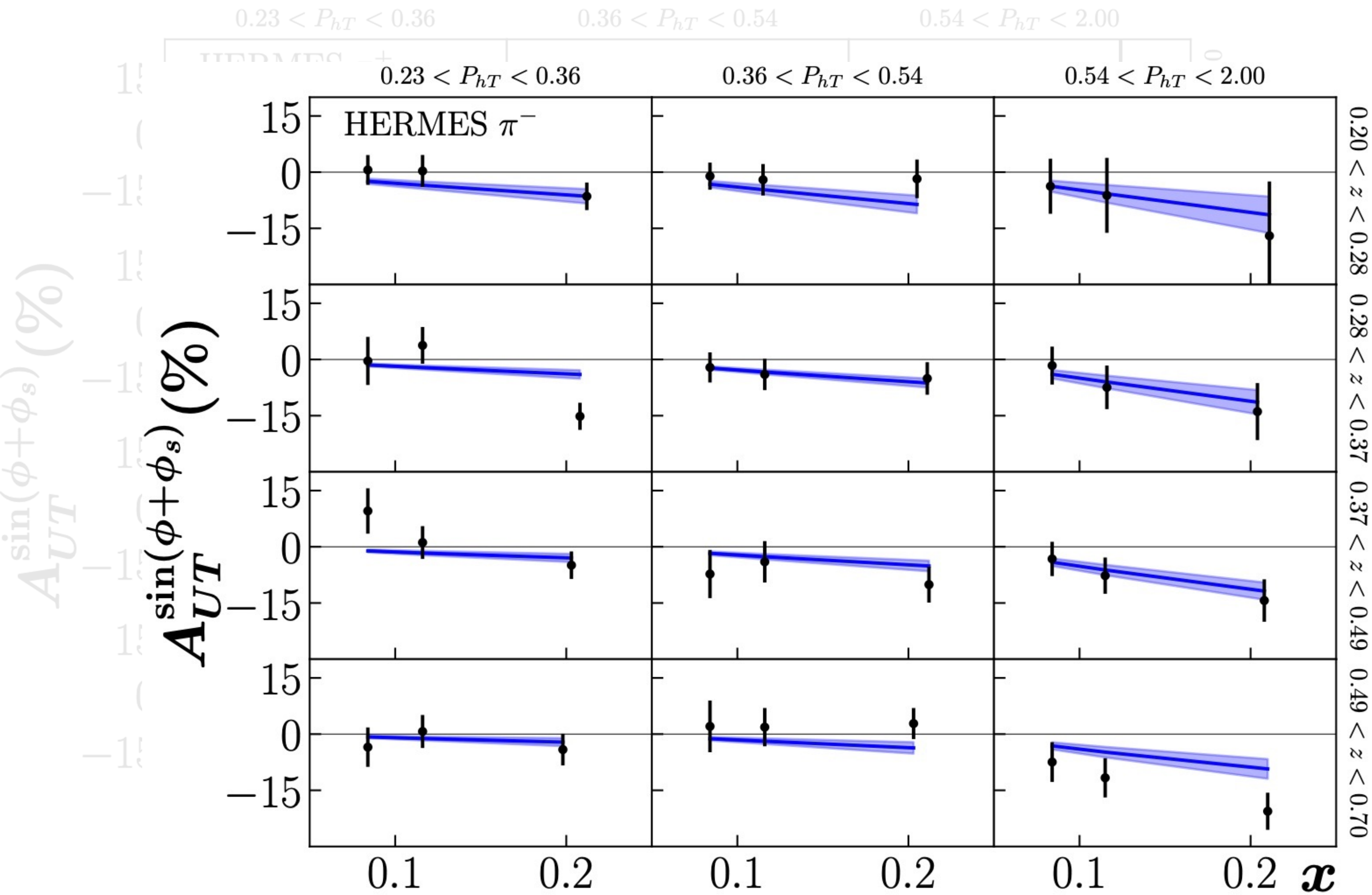
$$\chi^2/N_{\text{pts.}} = 647/634 = 1.02$$

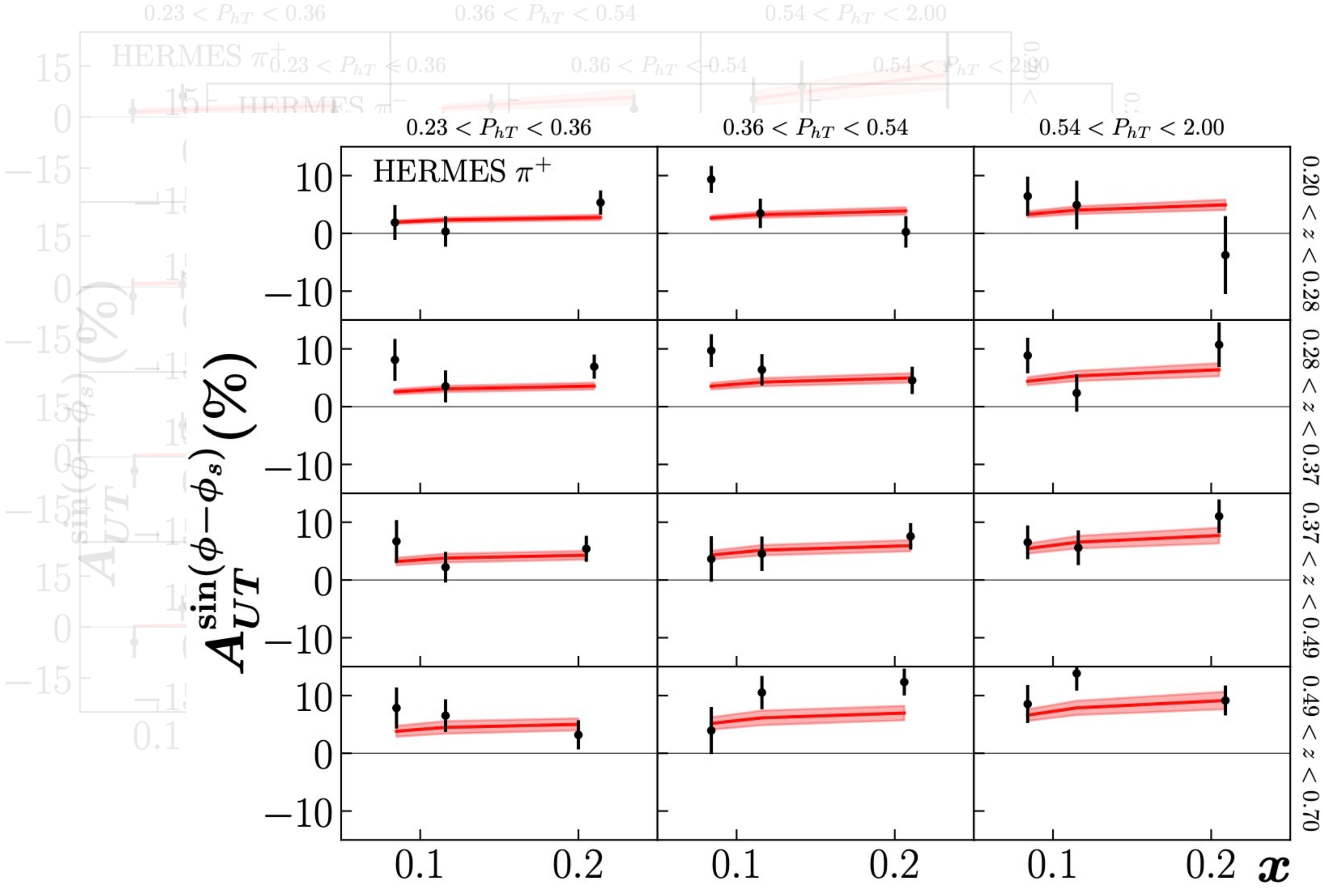
Observable	Reactions	Non-Perturbative Function(s)	χ^2/npts
$A_{UT}^{\sin(\phi_h-\phi_S)}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^{\perp}(x,\vec{k}_T^2)$	$182.9/166 = 1.10$
$A_{UT}^{\sin(\phi_h+\phi_S)}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,\vec{k}_T^2), H_1^{\perp}(z,z^2\vec{p}_T^2)$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

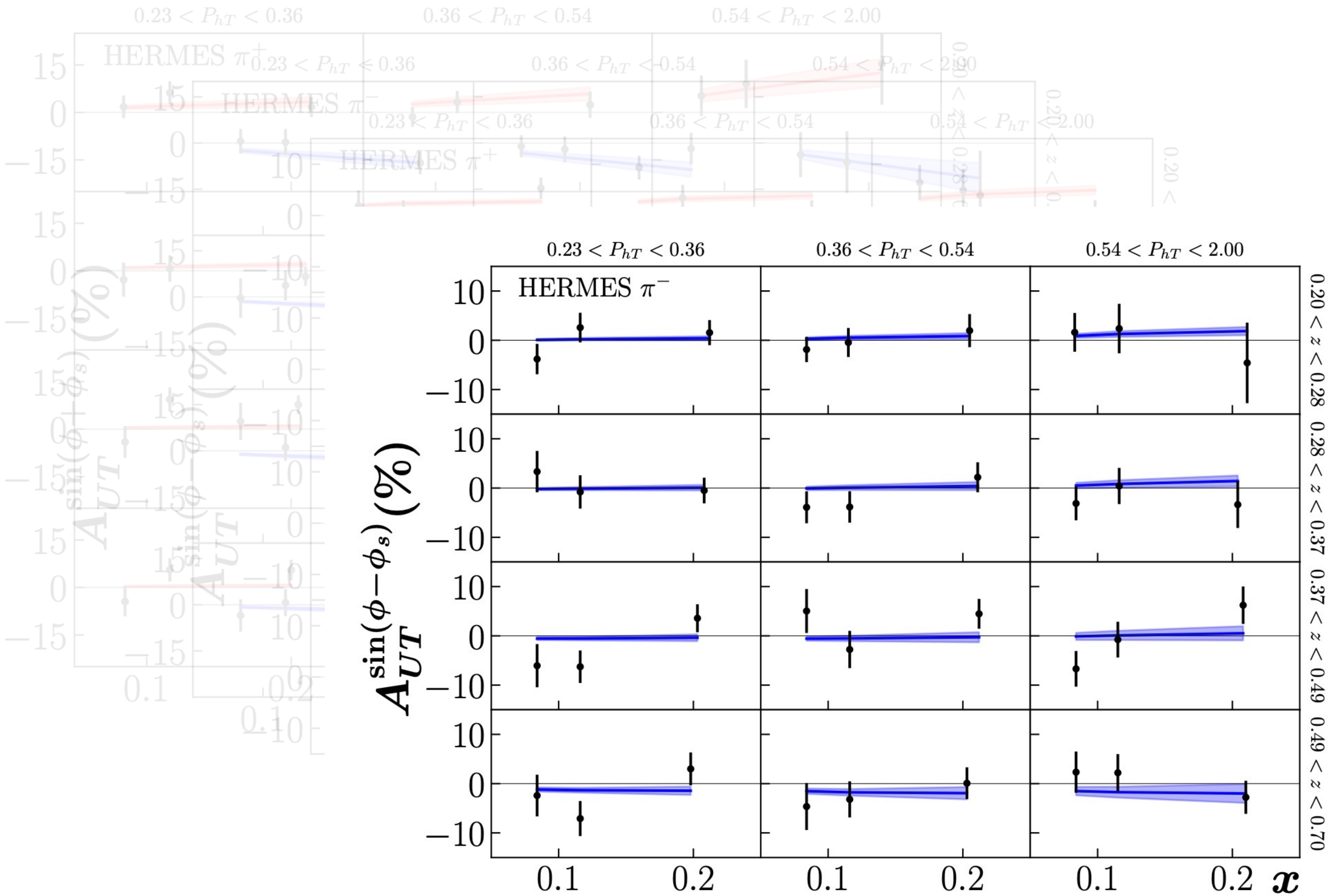
TABLE I: Summary of the observables analyzed in JAM3D-22 . There are a total of 21 different reactions. There are also a total of 8 non-perturbative functions when one takes into account flavor separation. The χ^2 is computed based on calculating for each point the theory expectation value from the replicas.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

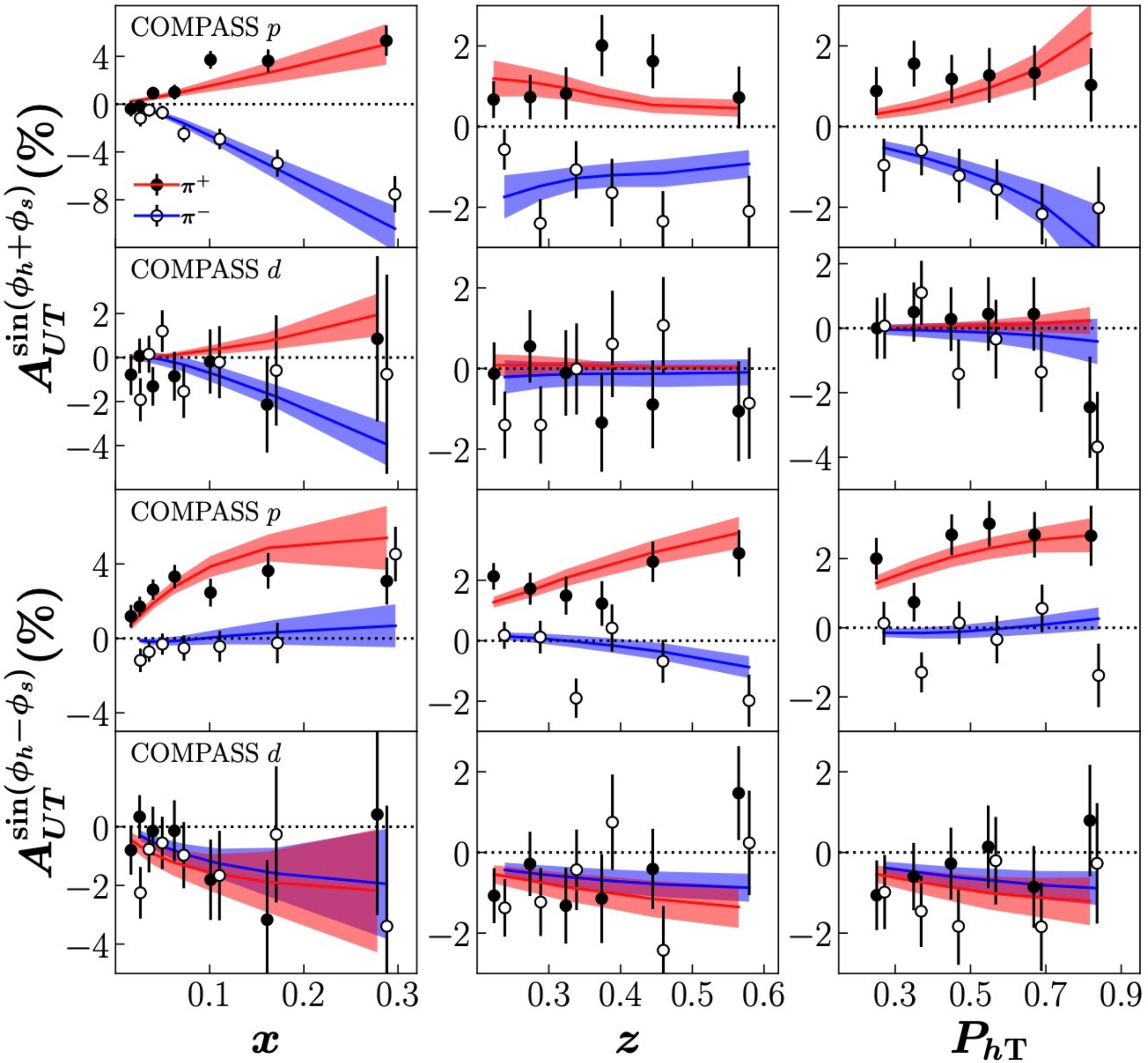

HERMES p
$A_{UT}^{\sin\phi_s}(\%)$
π^+
π^-
x
z
$A_N^{\pi}(\%)$
BRAHMS
$\theta = 2.3$
$\theta = 4.0$
STAR π^0
$\eta \in [3.3, 4.1]$
$\eta = 3.68$
$\eta = 3.3$
$\eta = 3.7$
x_F

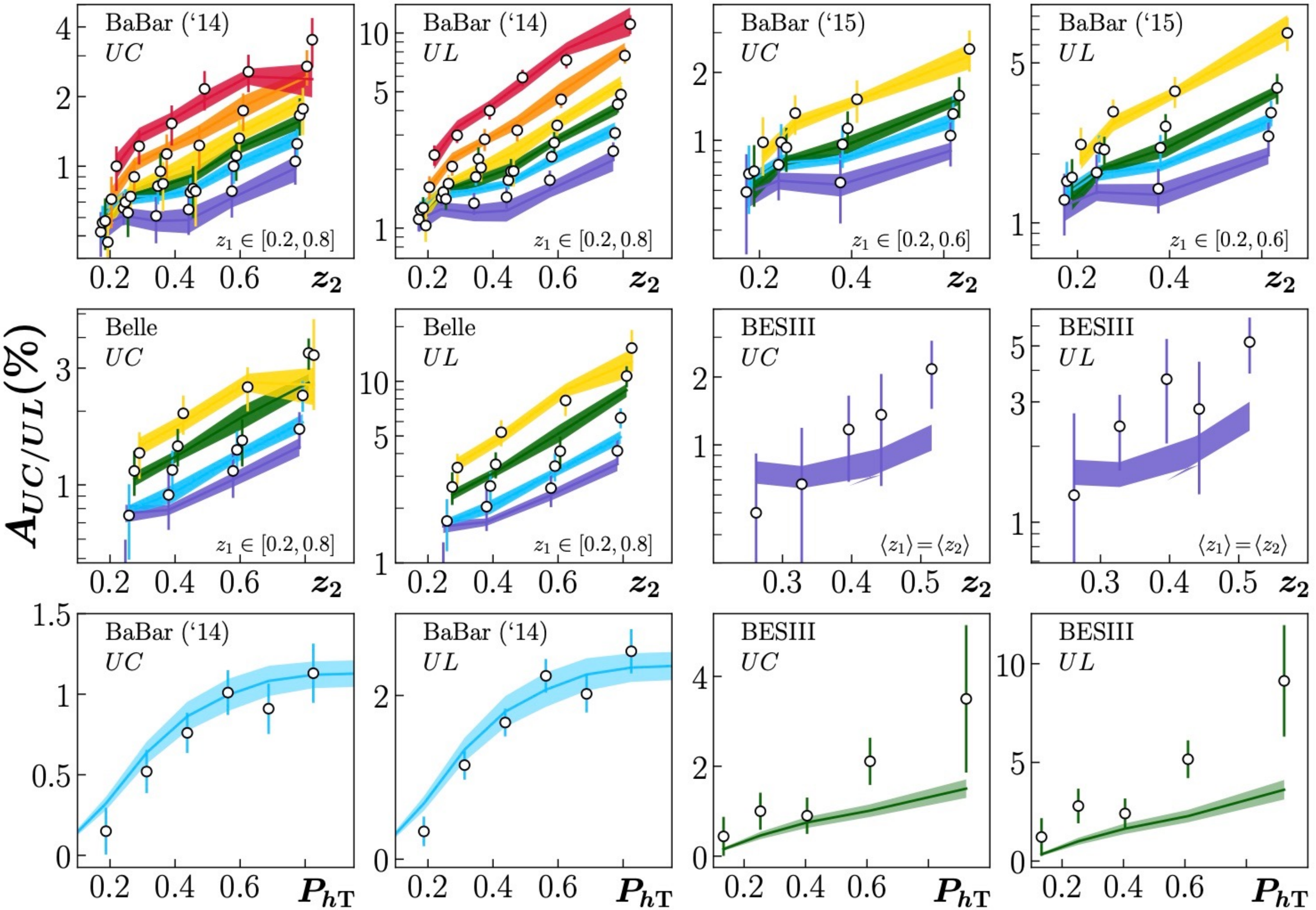

$0.23 < P_{hT} < 0.36$
$0.36 < P_{hT} < 0.54$
$0.54 < P_{hT} < 2.00$
HERMES π^+
$A_{UT}^{\sin(\phi+\phi_s)}$ (%)
15
0
−15
0.1
0.2
x
$0.20 < z < 0.28$
$0.28 < z < 0.37$
$0.37 < z < 0.49$
$0.49 < z < 0.70$

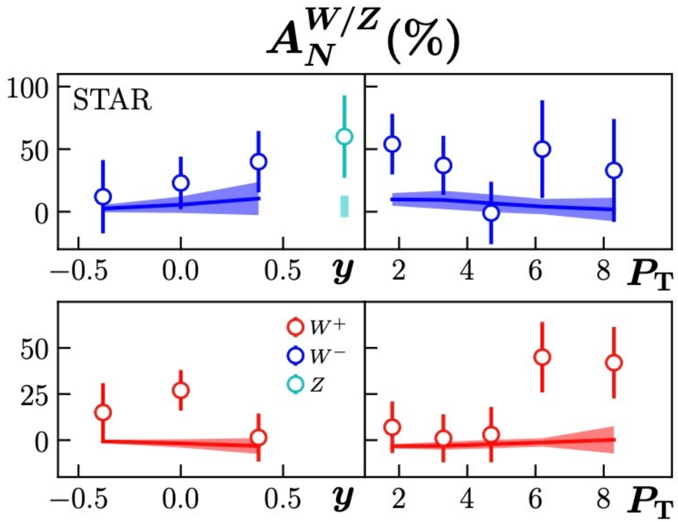

0.23 < P_{hT} < 0.36
0.36 < P_{hT} < 0.54
0.54 < P_{hT} < 2.00
HERMES π^-
15
0
−15
$A_{UT}^{\sin(\phi+\phi_s)}$ (%)
0.20 < z < 0.28
0.28 < z < 0.37
0.37 < z < 0.49
0.49 < z < 0.70
0.1
0.2
x

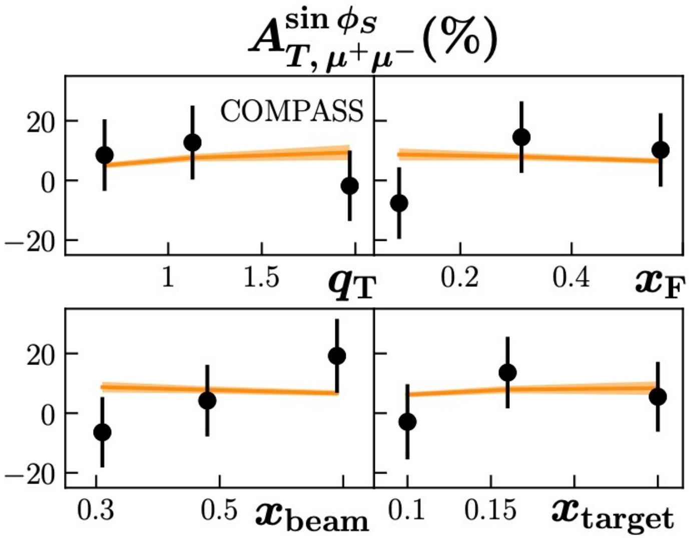

$0.23 < P_{hT} < 0.36$
$0.36 < P_{hT} < 0.54$
$0.54 < P_{hT} < 2.00$
HERMES π^+
$A_{UT}^{\sin(\phi-\phi_s)}$ (%)
$0.20 < z < 0.28$
$0.28 < z < 0.37$
$0.37 < z < 0.49$
$0.49 < z < 0.70$
x


0.23 < P_hT < 0.36
0.36 < P_hT < 0.54
0.54 < P_hT < 2.00
HERMES π−
0.20 < z < 0.28
0.28 < z < 0.37
0.37 < z < 0.49
0.49 < z < 0.70
A_UT^sin(φ−φs) (%)
10
0
−10
0.1
0.2
x


COMPASS p
COMPASS d
COMPASS p
COMPASS d
π^+
π^-
$A_{UT}^{\sin(\phi_h+\phi_s)}$ (%)
$A_{UT}^{\sin(\phi_h-\phi_s)}$ (%)
x
z
P_{hT}

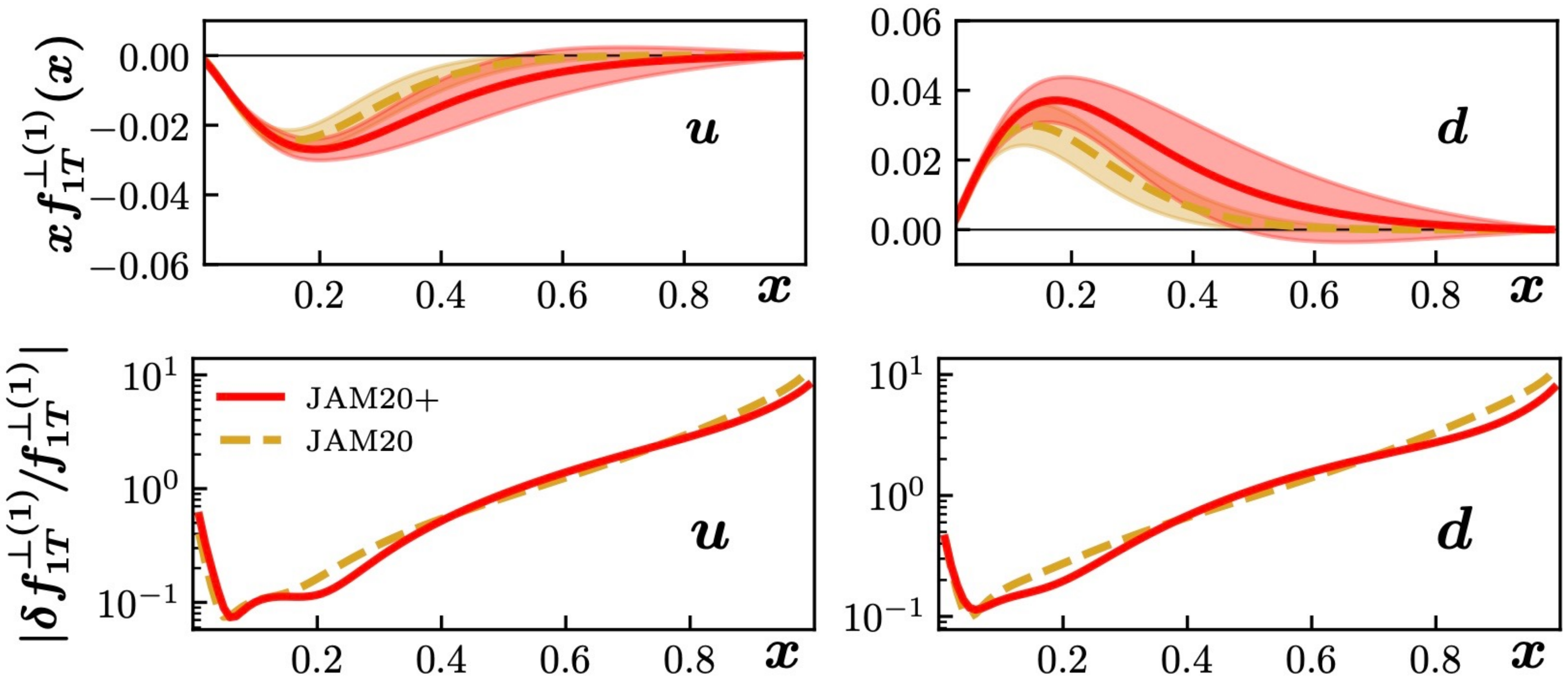

BaBar ('14) UC
BaBar ('14) UL
BaBar ('15) UC
BaBar ('15) UL
Belle UC
Belle UL
BESIII UC
BESIII UL
$z_1 \in [0.2, 0.8]$
$z_1 \in [0.2, 0.6]$
$\langle z_1 \rangle = \langle z_2 \rangle$
$A_{UC/UL}(\%)$
z_2
P_{hT}


$A_N^{W/Z}$ (%)
STAR
100
50
0
−0.5
0.0
0.5
y
2
4
6
8
P_T
W^+
W^-
Z
50
25
0


$A_{T,\mu^+\mu^-}^{\sin\phi_S}$ (%)
COMPASS
20
0
−20
1
1.5
q_T
0.2
0.4
x_F
0.3
0.5
x_{beam}
0.1
0.15
x_{target}

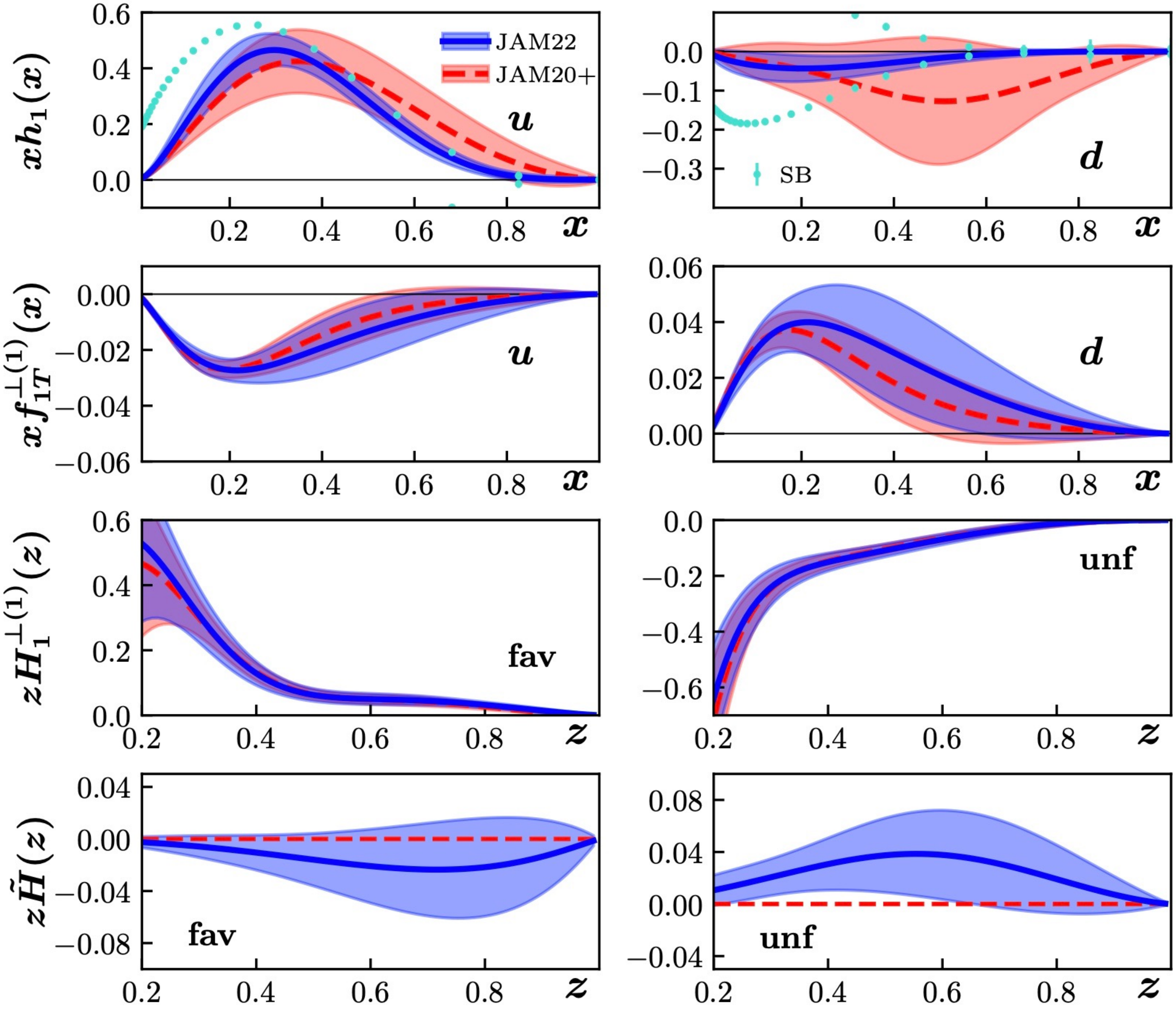
JAM3D-20+

Replace the Sivers effect and Collins effect HERMES data from JAM20 with their superseding 3D-binned version. No other constraints/data are added yet.



➢ Only the Sivers function changes size and shape but the relative uncertainty remains the same

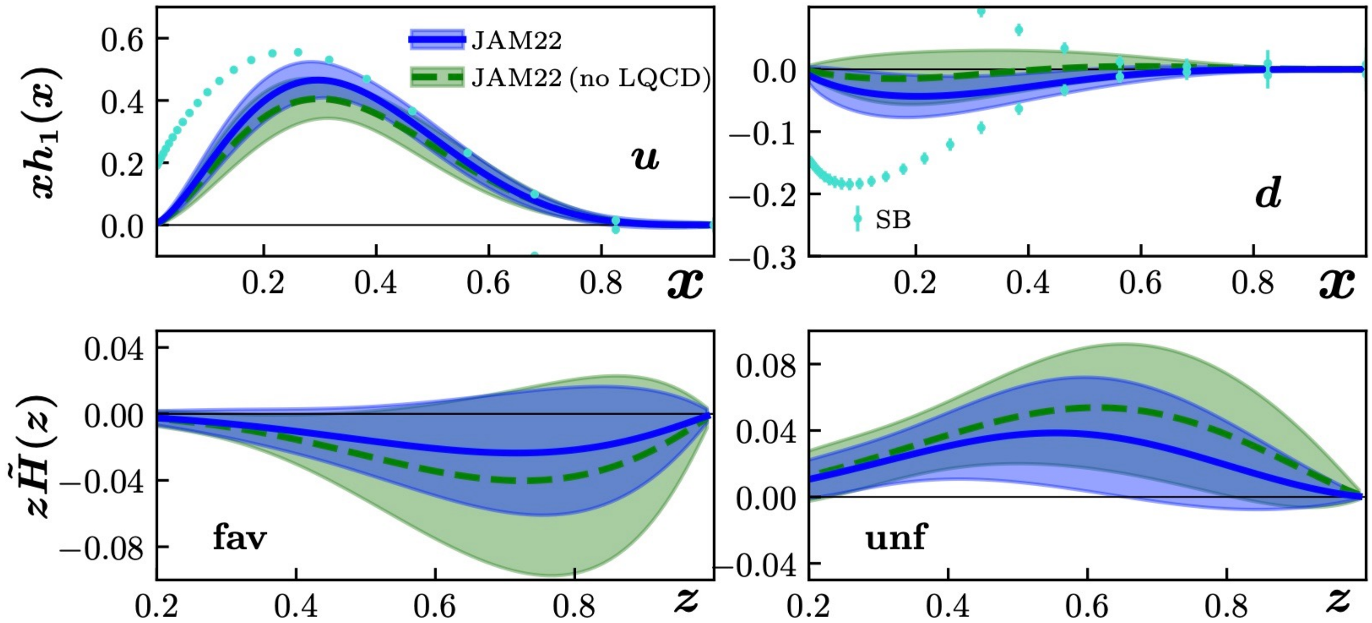
JAM3D-22



First direct information from experiment on $\tilde{H}(z)$

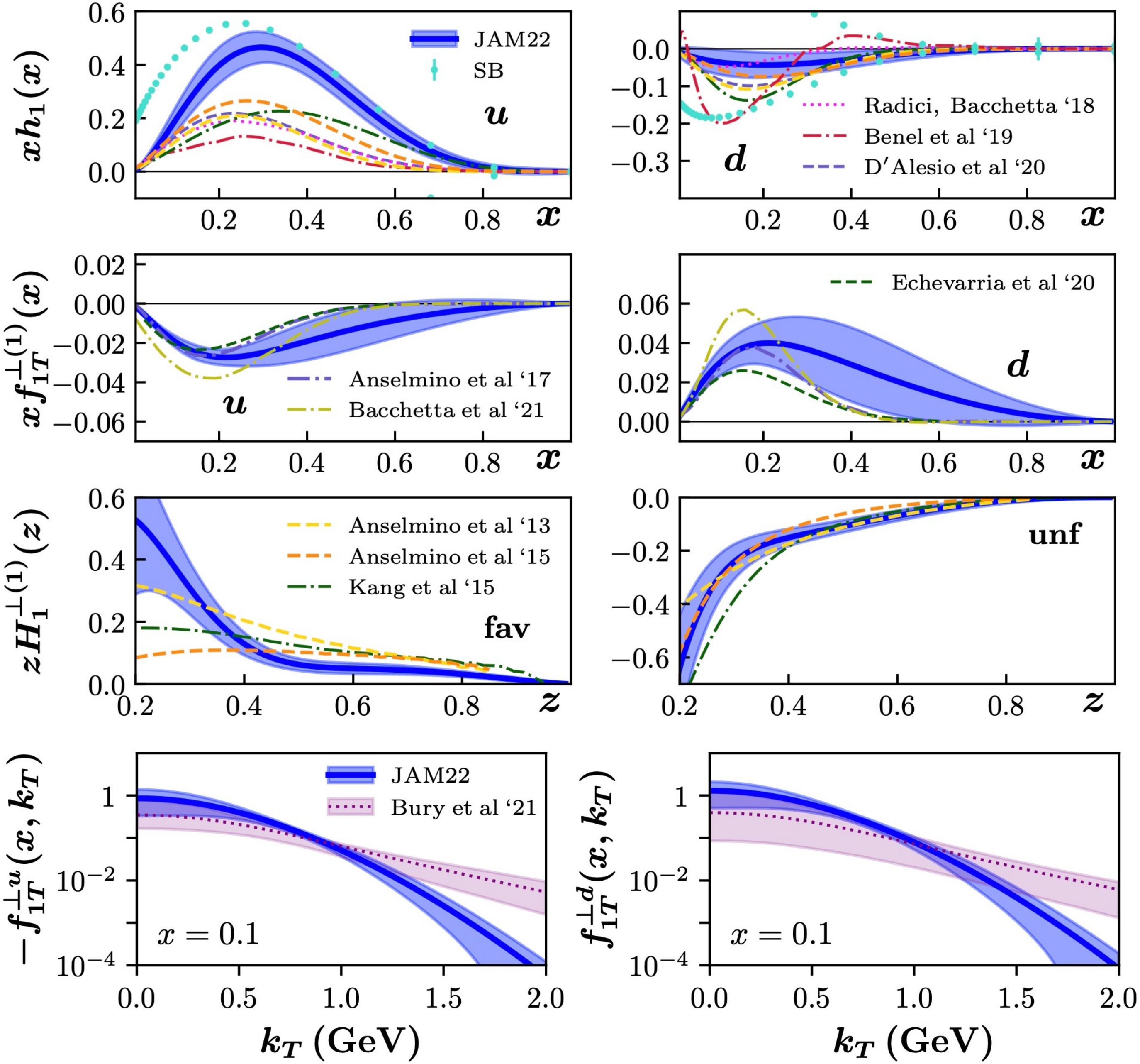
- Comments on the non-perturbative functions:

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



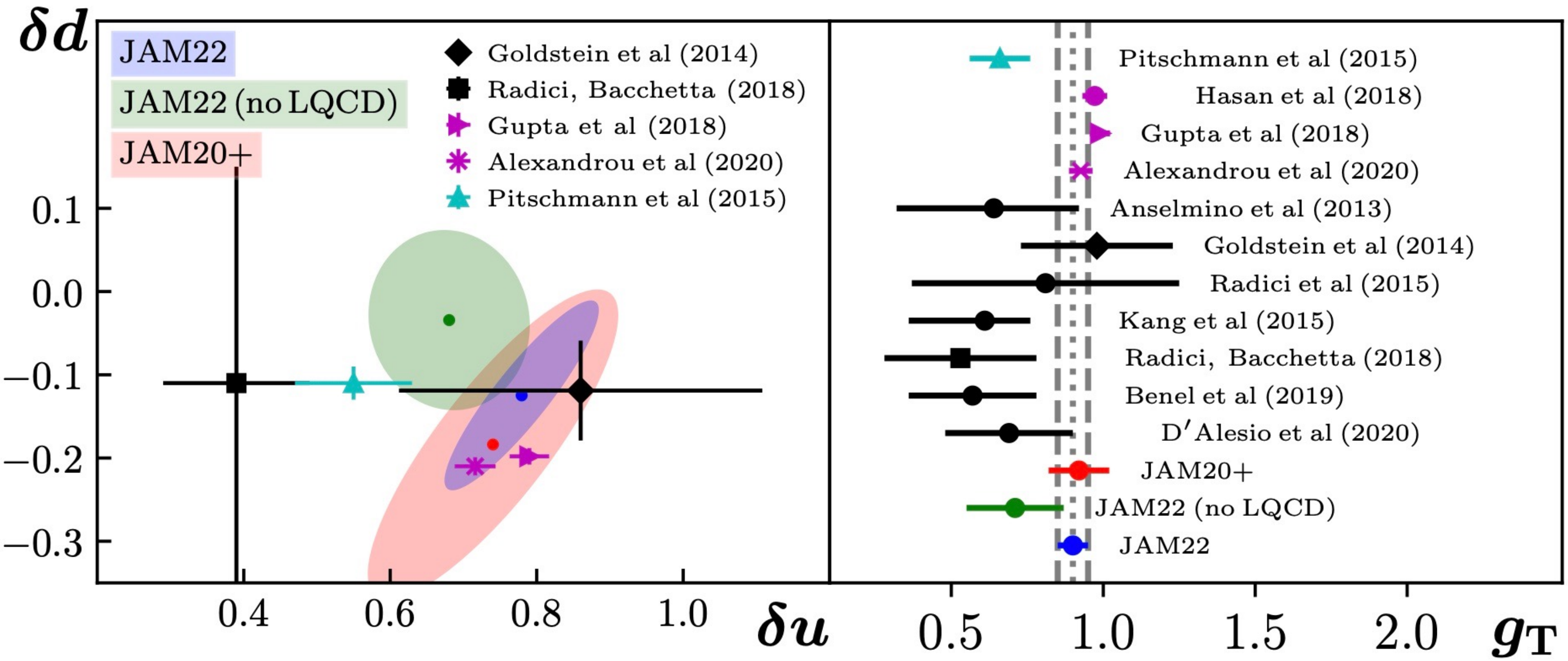
  - Collins and Sivers functions remain basically the same from JAM3D-20+

  - $\tilde{H}(z)$ behaves similar to the Collins function (favored and unfavored roughly equal in magnitude but opposite in sign) - expected since both are derived from the same underlying quark-gluon-quark FF (Kanazawa, et al. (2016))


JAM22
SB
Radici, Bacchetta '18
Benel et al '19
D'Alesio et al '20
Echevarria et al '20
Anselmino et al '17
Bacchetta et al '21
Anselmino et al '13
Anselmino et al '15
Kang et al '15
Bury et al '21
$xh_1(x)$
$xf_{1T}^{\perp(1)}(x)$
$zH_1^{\perp(1)}(z)$
$-f_{1T}^{\perp u}(x, k_T)$
$f_{1T}^{\perp d}(x, k_T)$
u
d
fav
unf
$x = 0.1$
x
z
k_T (GeV)

<u>Disclaimer</u>: only central curves of the 68% CL error band are shown

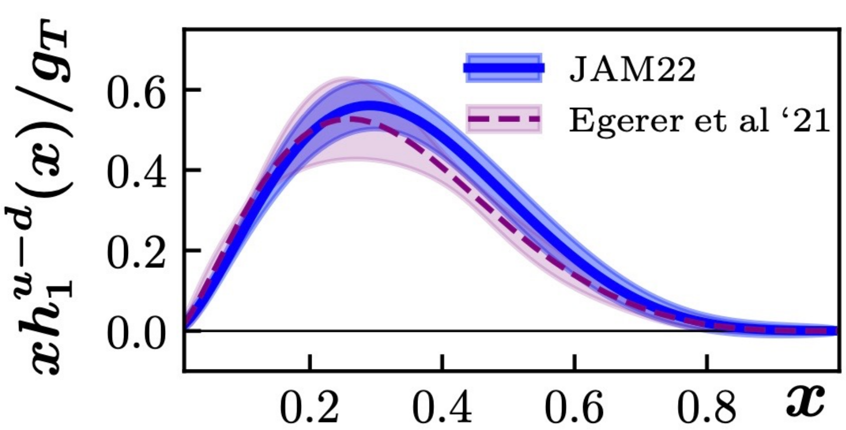
- Comments on comparison to other groups:
  - Now that we impose the Soffer bound, the down quark transversity is similar to other extractions
  - The *up quark transversity saturates the Soffer bound* due to the inclusion of proton-proton A_N data - analyses that only use TMD or dihadron data do *not* find this solution
  - The magnitude of the Sivers function first moment (function of x) is similar to recent extractions from Bacchetta, et al. and Echevarria, et al. but the fall off with x is slower in JAM3D-22 (due to using 3D-binned HERMES data)
  - Bury, et al. do *not* directly extract the Qiu-Sterman function but rather $\tilde{f}_{1T}^{\perp}(x, b_T)$
    - comparison with the F.T. agrees well at small k_T
    - at large k_T, effects from gluon radiation cause a deviation

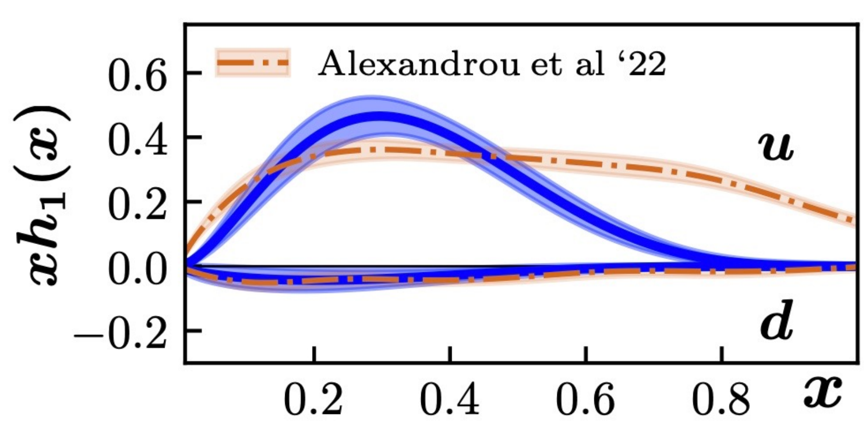


- The tensor charge extractions are more precise from including the lattice g_T data point

- Note that because of the SB, one initially finds more tension with 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 the lattice g_T data point is included, we find the non-perturbative functions can accommodate it along with the experimental data





- Comments on comparison to other lattice calculations of transversity:
  - The raw lattice data for Egerer, et al. and Alexandrou, et al. are compatible, but the former uses pseudo-PDFs and the latter quasi-PDFs
  - The behavior at large *x* for the up quark in Alexandrou, et al. is due to systematics in the reconstruction of the *x* dependence in the quasi-PDF approach
  - We find good agreement with lattice calculations of transversity
  - *Now that the lattice g_T data point is included in JAM3D-22, the uncertainties in the phenomenological extraction of transversity are comparable with lattice*

Conclusions

- In 2020 we 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. This helps to fulfill Milestone 6 of the TMD Collaboration.

- We have updated our analysis using new data from HERMES (3D-binned Collins and Sivers effects and $A_{UT}^{\sin\phi_S}$) as well as constraints from lattice QCD (tensor charge g_T) and the Soffer bound on transvesity.

- Our results show it is still possible to accommodate these data/constraints and describe all SSAs. The newly extracted transversity function and associated tensor charges are much more precise. We also have the first direct information from experiment on $\tilde{H}(z)$.

- Another update will include new STAR pion A_N data, jet A_N data (A_NDY, STAR) and hadron-in-jet Collins effect data (STAR).