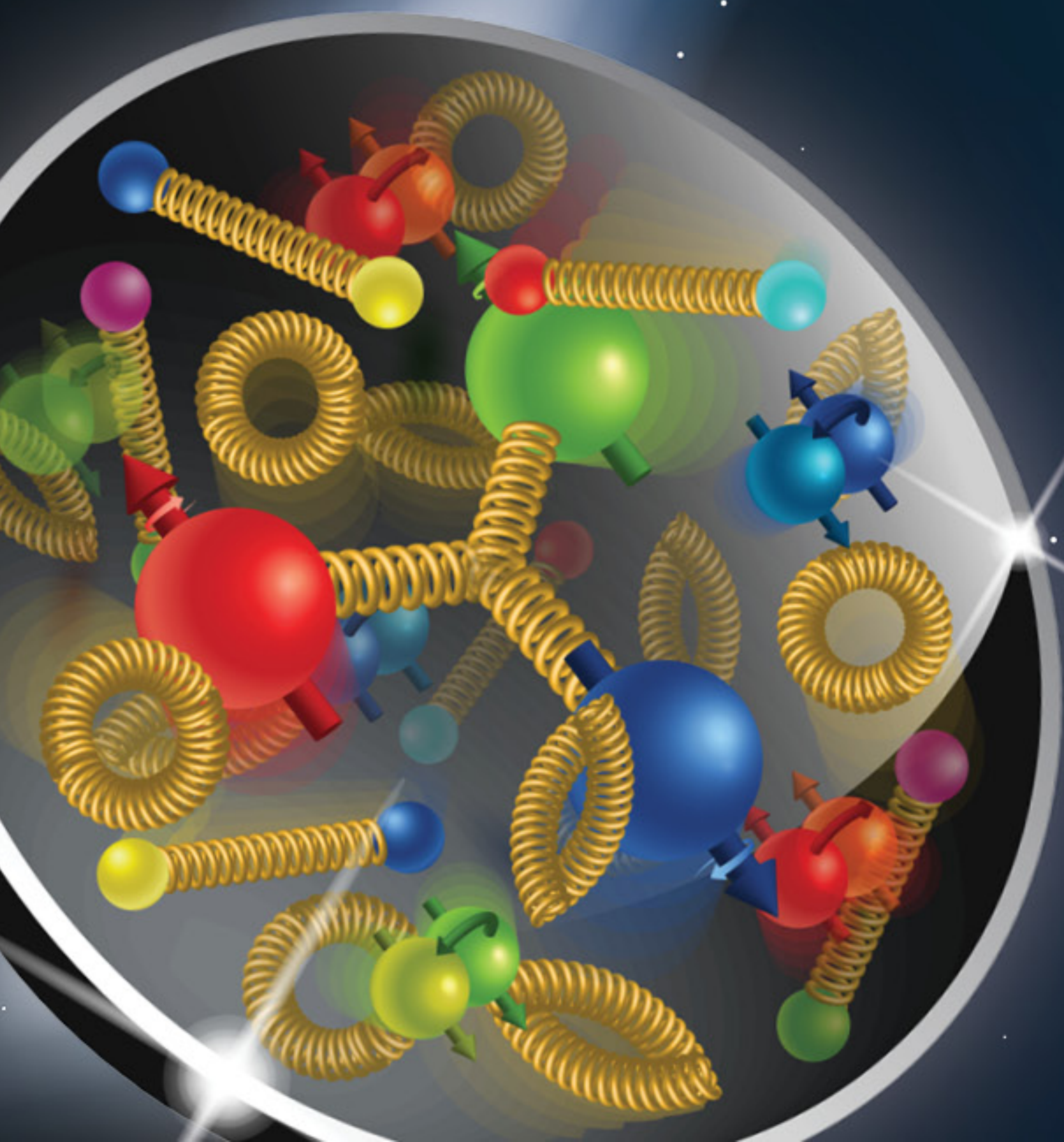
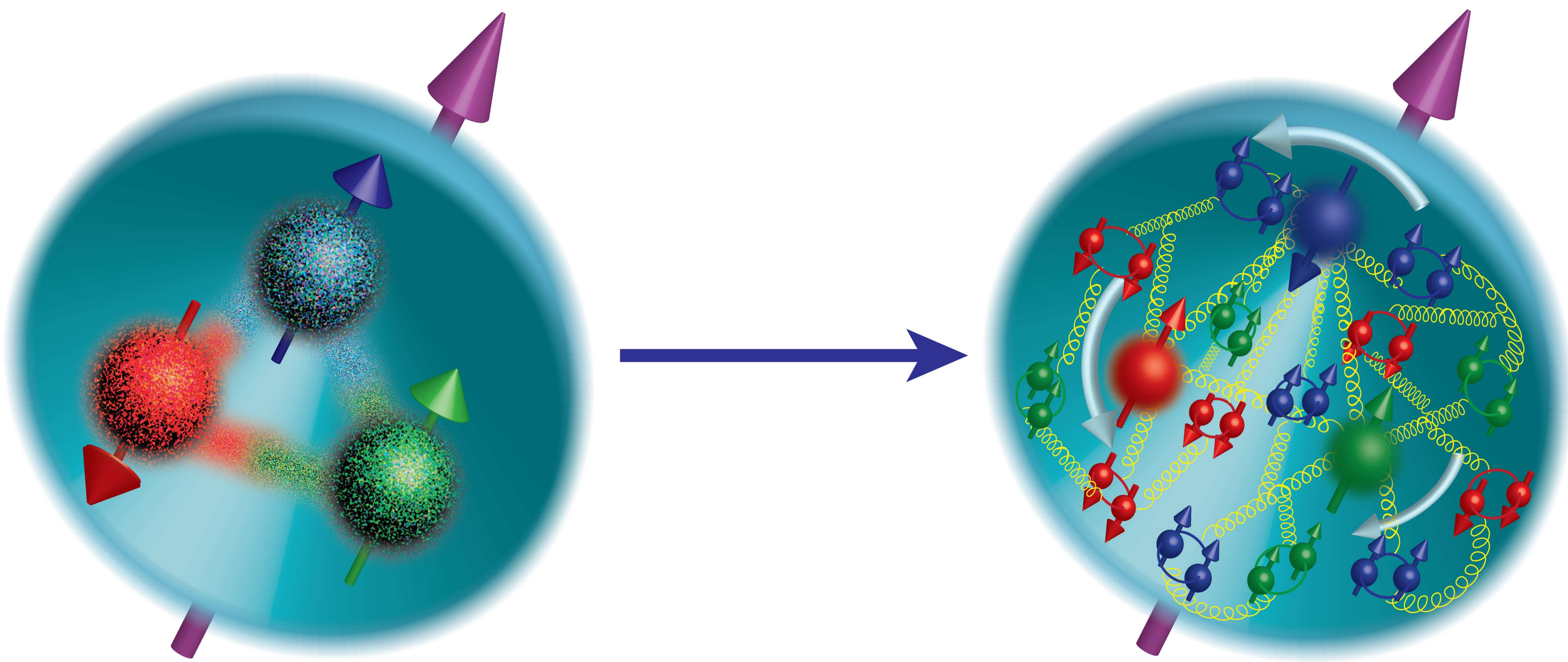
- JAM20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, Phys.Rev.D 102 (2020) 5, 054002
- JAM22, in preparation

Global analysis of SSAs and the role of lattice QCD and the Soffer bound



Alexei Prokudin

EVOLUTION OF OUR UNDERSTANDING OF THE SPIN STRUCTURE

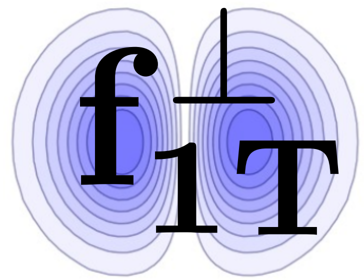


1980’ - the spin of the nucleon is due to the valence quarks

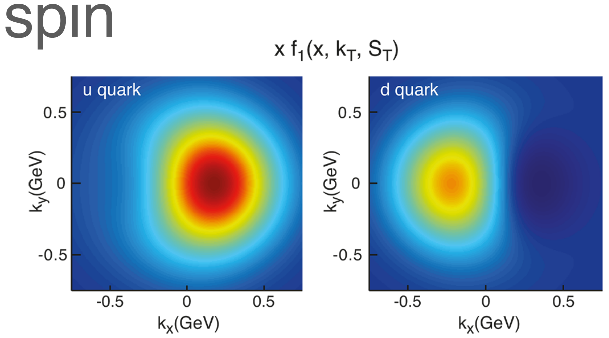
Modern concept: valence quarks, sea quarks, and gluons together with orbital angular momentum are contributing

POLARIZED TMD FUNCTIONS

Sivers function

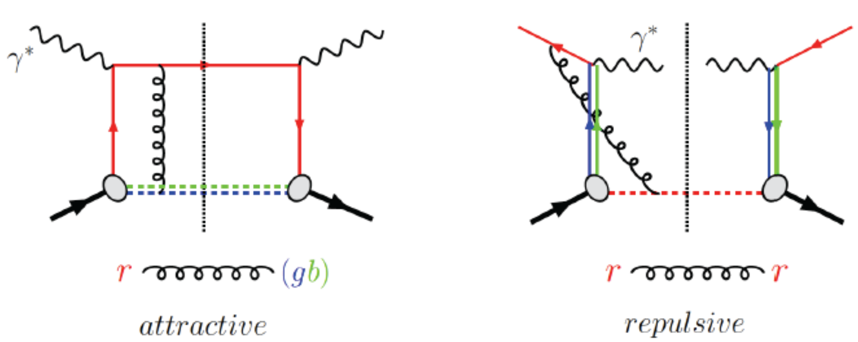


- Describes unpolarized quarks inside of transversely polarized nucleon
- Encodes the correlation of orbital motion with the spin



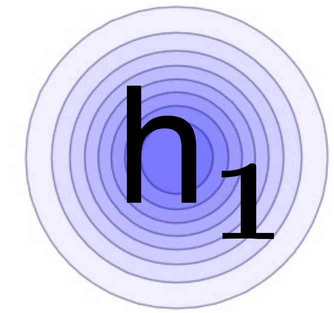
- Sign change of Sivers function is fundamental consequence of QCD

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



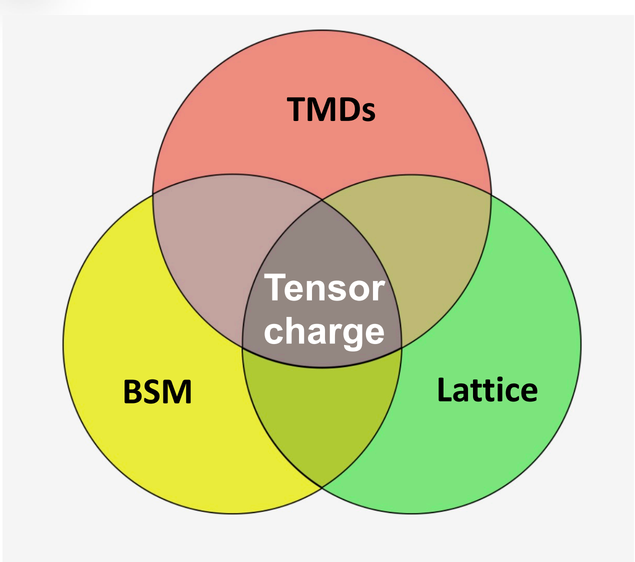
$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

Transversity



- The only source of information on tensor charge of the nucleon
- Couples to Collins fragmentation function or di-hadron interference fragmentation functions in SIDIS

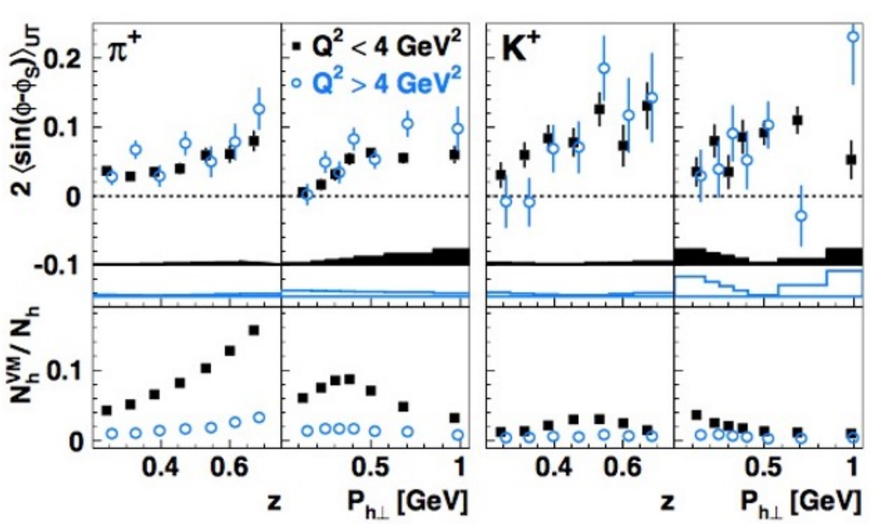
$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)\right]$$



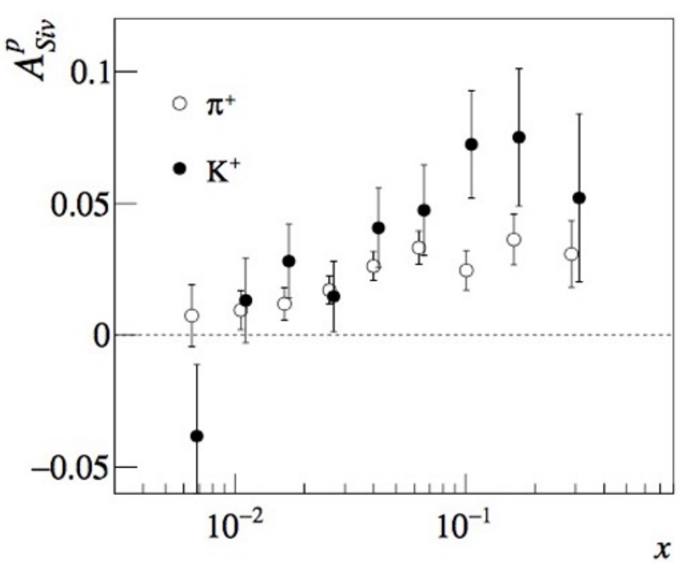
TRANSVERSE SPIN ASYMMETRIES

Transverse Single Spin Asymmetries (SSAs) have been observed in a variety of processes

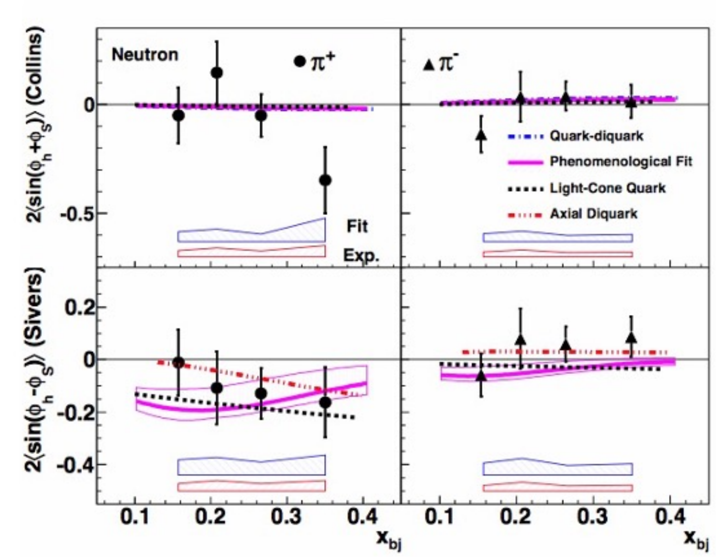
Sivers asymmetry in SIDIS



HERMES (09)



COMPASS (15)



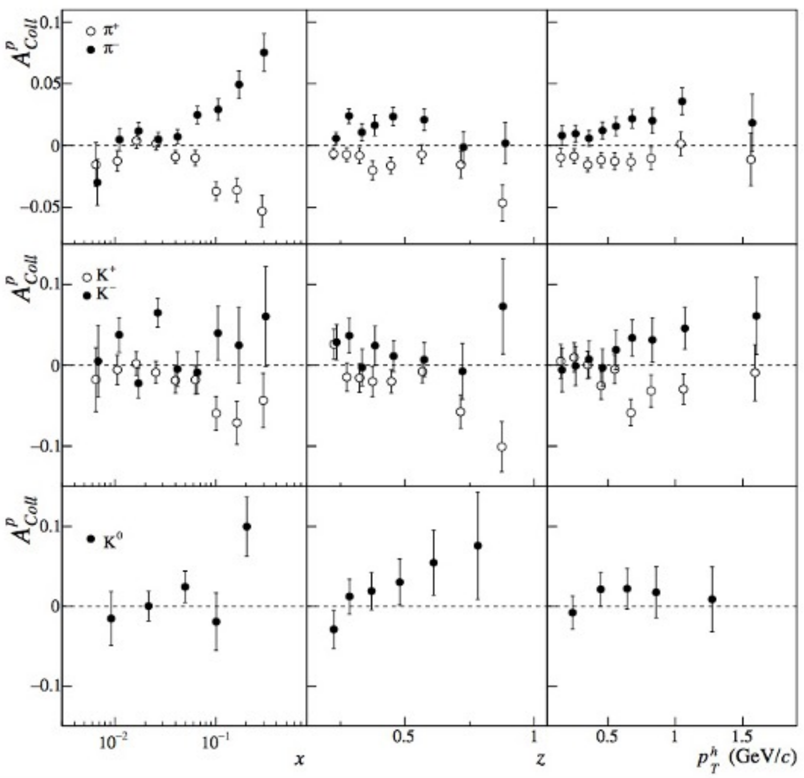
JLAB (11)

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

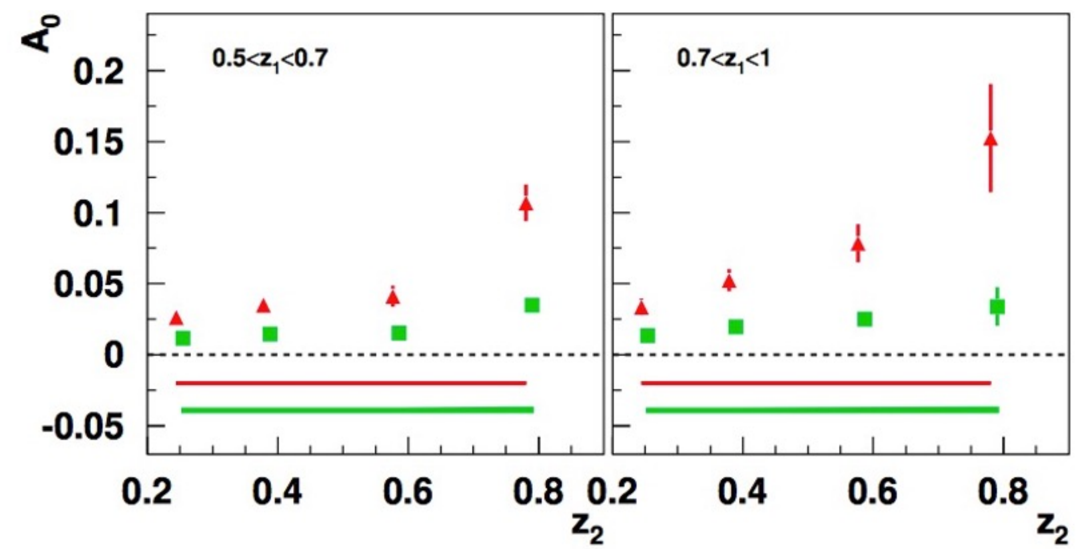
TRANSVERSE SPIN ASYMMETRIES

Transverse Single Spin Asymmetries (SSAs) have been observed in a variety of processes

Collins asymmetry in SIDIS and e^+e^-



COMPASS (15),
also HERMES (05,10, 20), JLab (11,14)



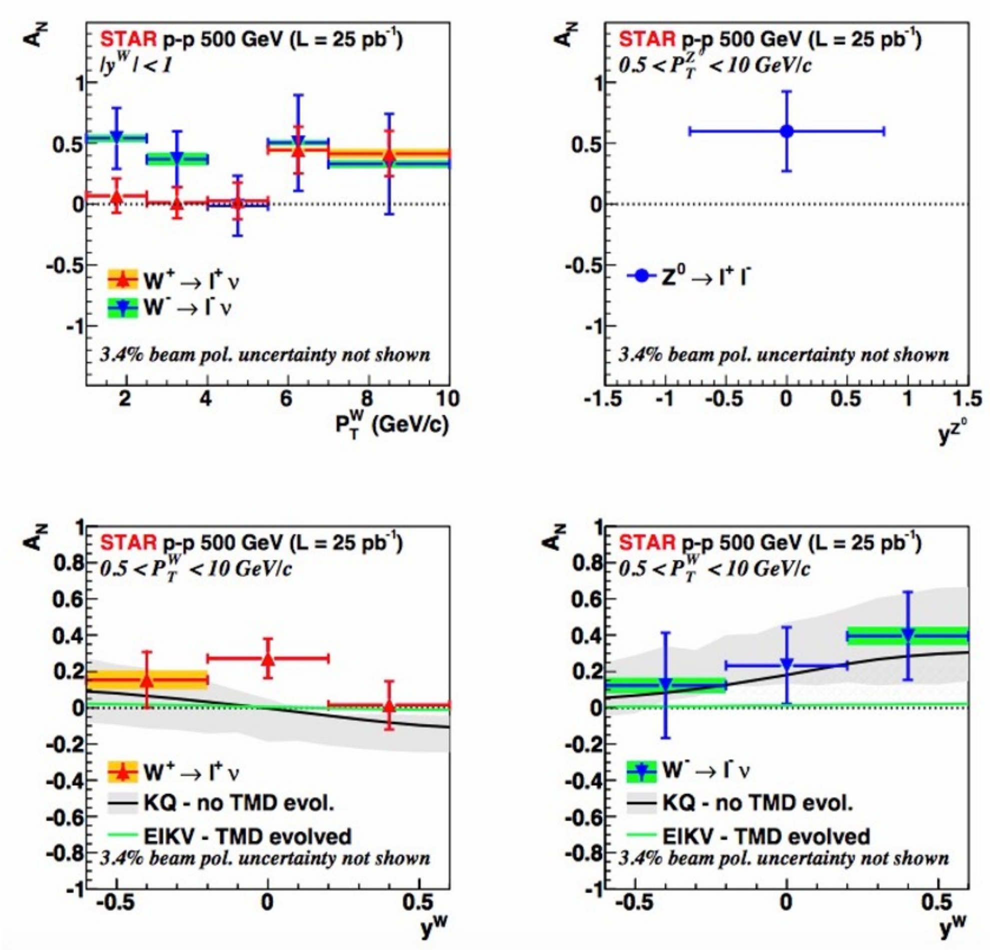
BELLE (08),
also BaBar (14), BESIII (16)

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

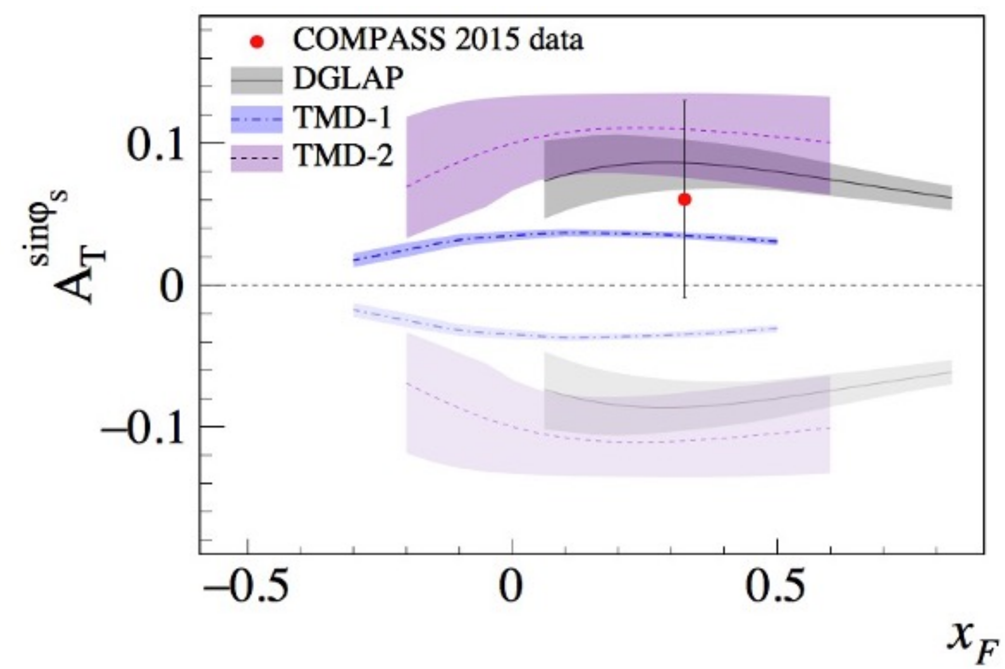
TRANSVERSE SPIN ASYMMETRIES

Transverse Single Spin Asymmetries (SSAs) have been observed in a variety of processes

Sivers effect in Drell-Yan



STAR (15)



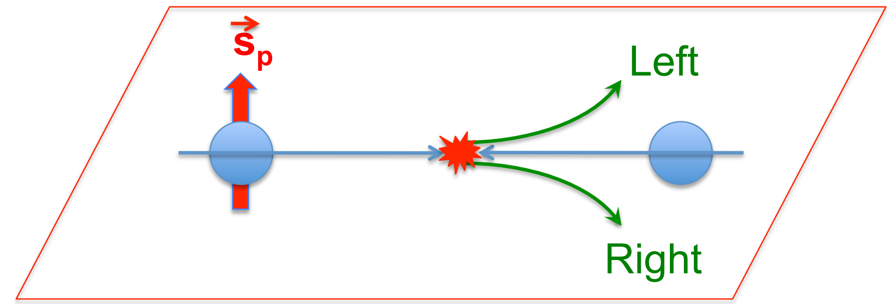
COMPASS (17)

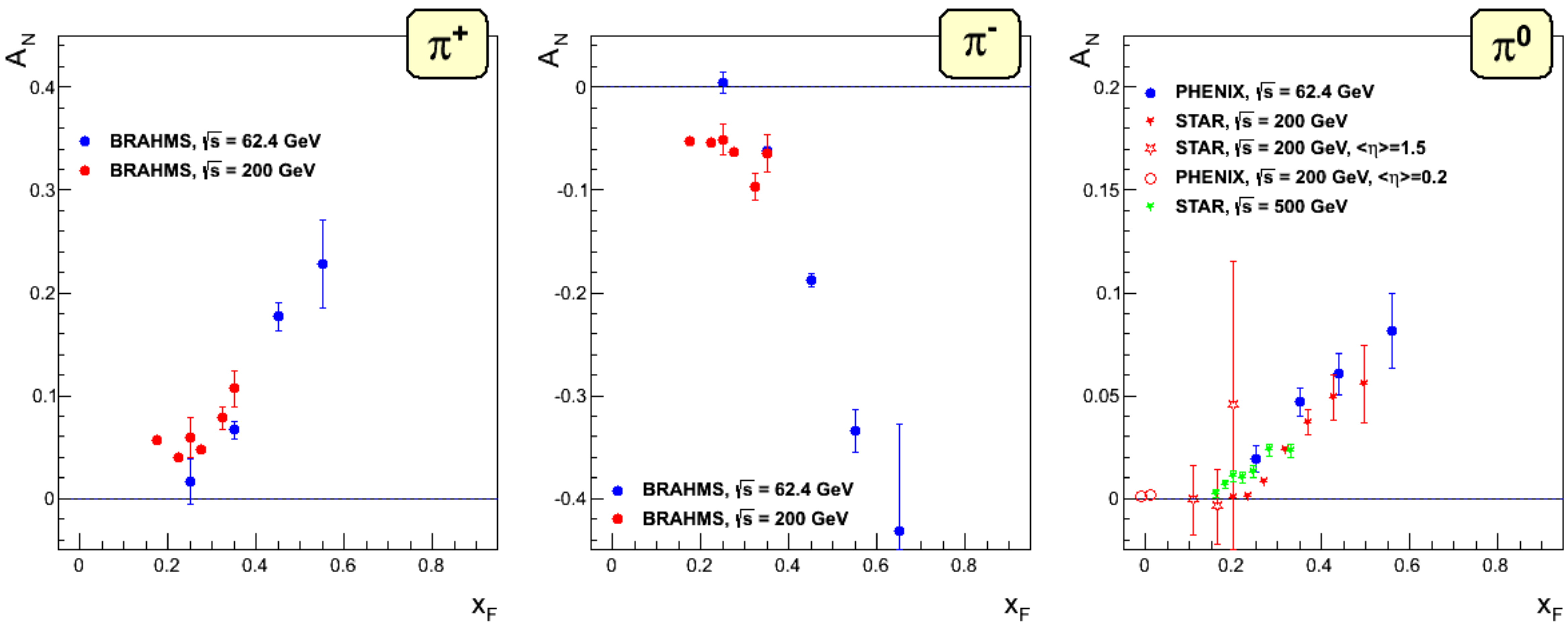
$$F_{TU}^1 = \mathcal{C}\left[-\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} \boldsymbol{f_{1T}^{\perp}}\, \bar{f}_1\right]$$

TRANSVERSE SPIN ASYMMETRIES

A_N in proton proton scattering

RHIC: STAR, BRAHMS, PHENIX

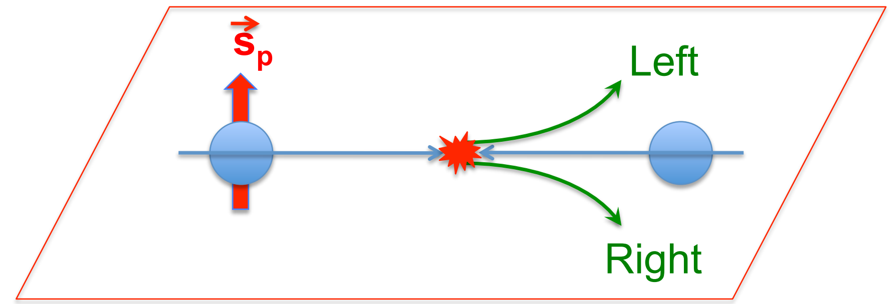




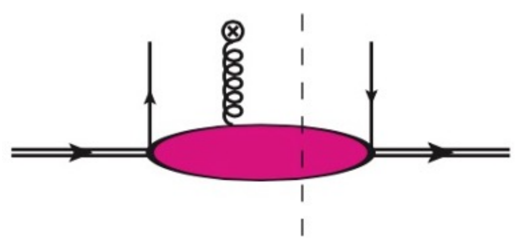
"The RHIC SPIN Program: Achievements and Future Opportunities", Aschenauer et al (15)

TRANSVERSE SPIN ASYMMETRIES

A_N in pp scattering is related to collinear twist-3 (CT3) factorization



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

$\boldsymbol{F_{FT}} \sim$  quark-gluon-quark correlator

Qiu, Sterman (99), Kouvaris, et al (06)

$$\pi \boldsymbol{F_{FT}(x,x)} = \int d^2\vec{k}_T \, \frac{k_T^2}{2M^2} \boldsymbol{f_{1T}^{\perp}(x, k_T^2)} \equiv f_{1T}^{\perp(1)}(x)$$ the first moment of Sivers function

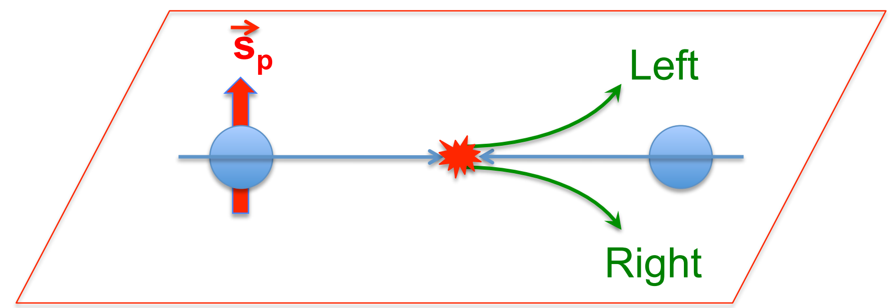
Boer, et al (03)

TMD and CT3 factorization agree in their overlapping region of applicability

Ji, et al (06); Koike, et a. (08); Zhou, et al (08, 10); Yuan and Zhou (09)

TRANSVERSE SPIN ASYMMETRIES

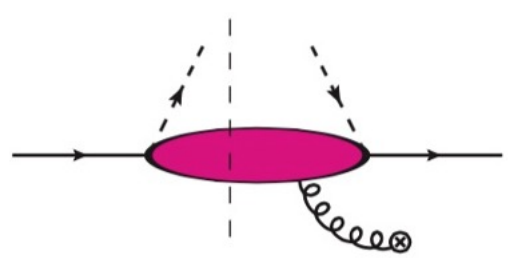
A_N in pp scattering is related to collinear twist-3 (CT3) factorization



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

$\boldsymbol{h_1}$ collinear transversity

Kanazawa, Koike, Metz, Pitonyak, Schlegel, (16)

$\boldsymbol{H_1^{\perp(1)}}$ $\boldsymbol{\tilde{H}}$ $\sim$  quark-gluon-quark fragmentation functions

$$\boldsymbol{H_1^{\perp(1)}(z)} \equiv z^2 \int d^2\vec{p}_\perp \frac{p_\perp^2}{2M_h^2} \boldsymbol{H_1^\perp(z, z^2 p_\perp^2)}$$ the first moment of Collins FF

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

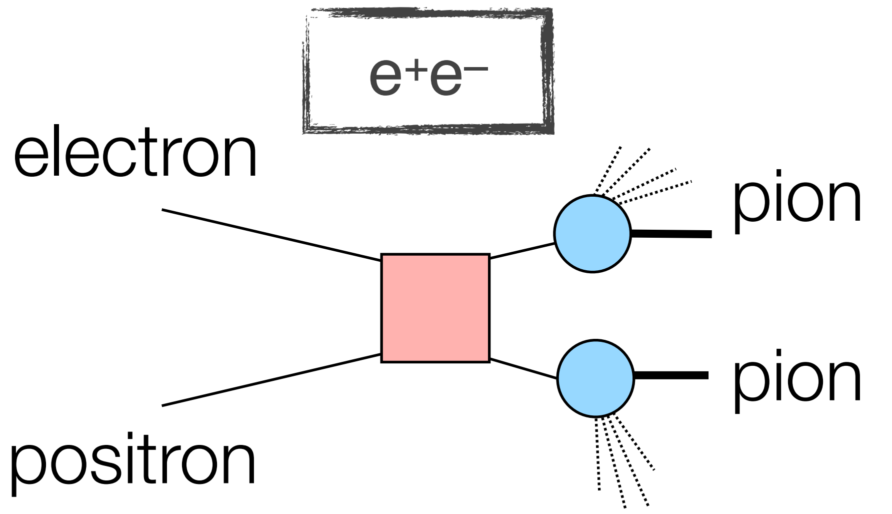
Mulders, Tangerman (96); Bacchetta, et al (07)

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

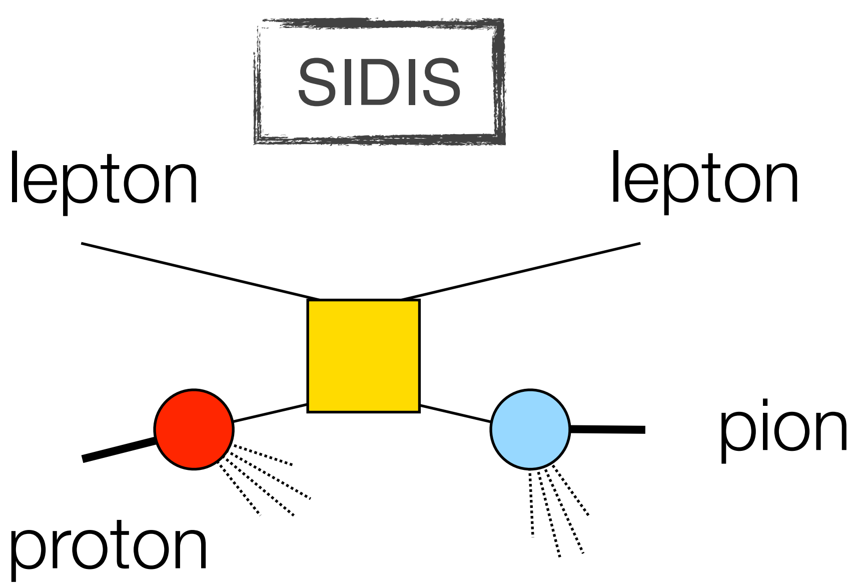
JAM20 ANALYSIS

UNIVERSAL GLOBAL ANALYSIS 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

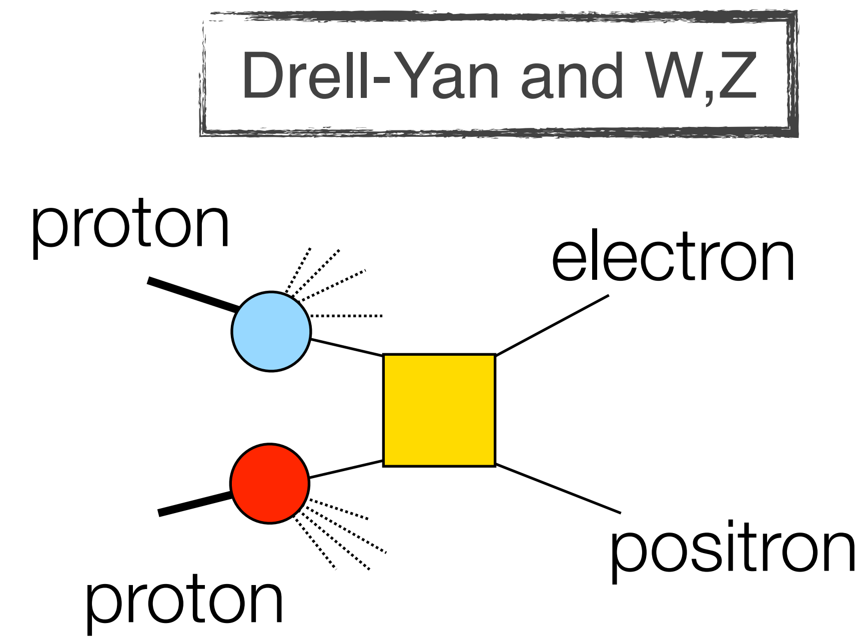


Collins asymmetries
BELLE, BaBar, BESIII data

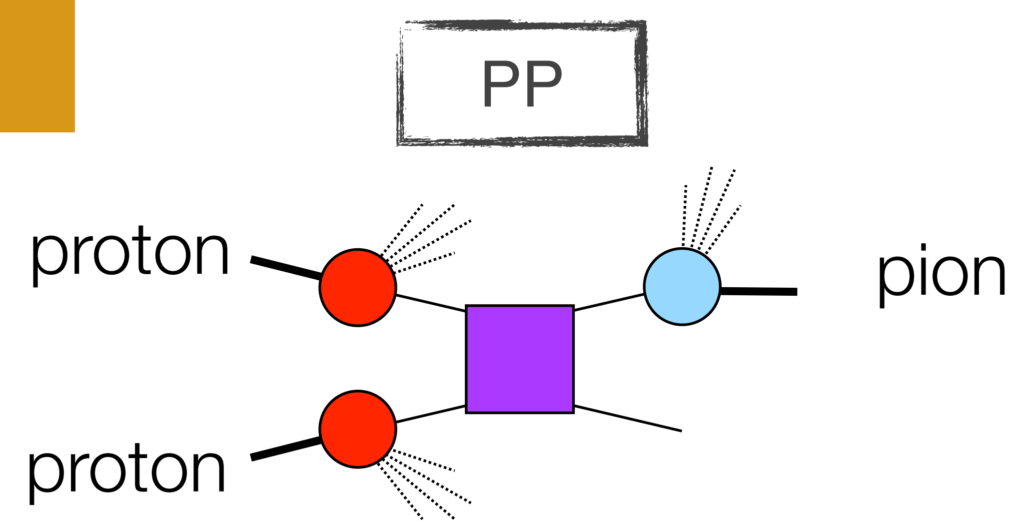


Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

To demonstrate the common origin of SSAs in various processes, we combined all available data and extracted a universal set of non perturbative functions that describes all of them



Sivers asymmetries
COMPASS, STAR data



A_N asymmetry
STAR, PHENIX, BRAHMS data

UNIVERSAL GLOBAL ANALYSIS 2020

Jefferson Lab Angular Momentum Collaboration

https://www.jlab.org/theory/jam

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	$p^{\uparrow} + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi} f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

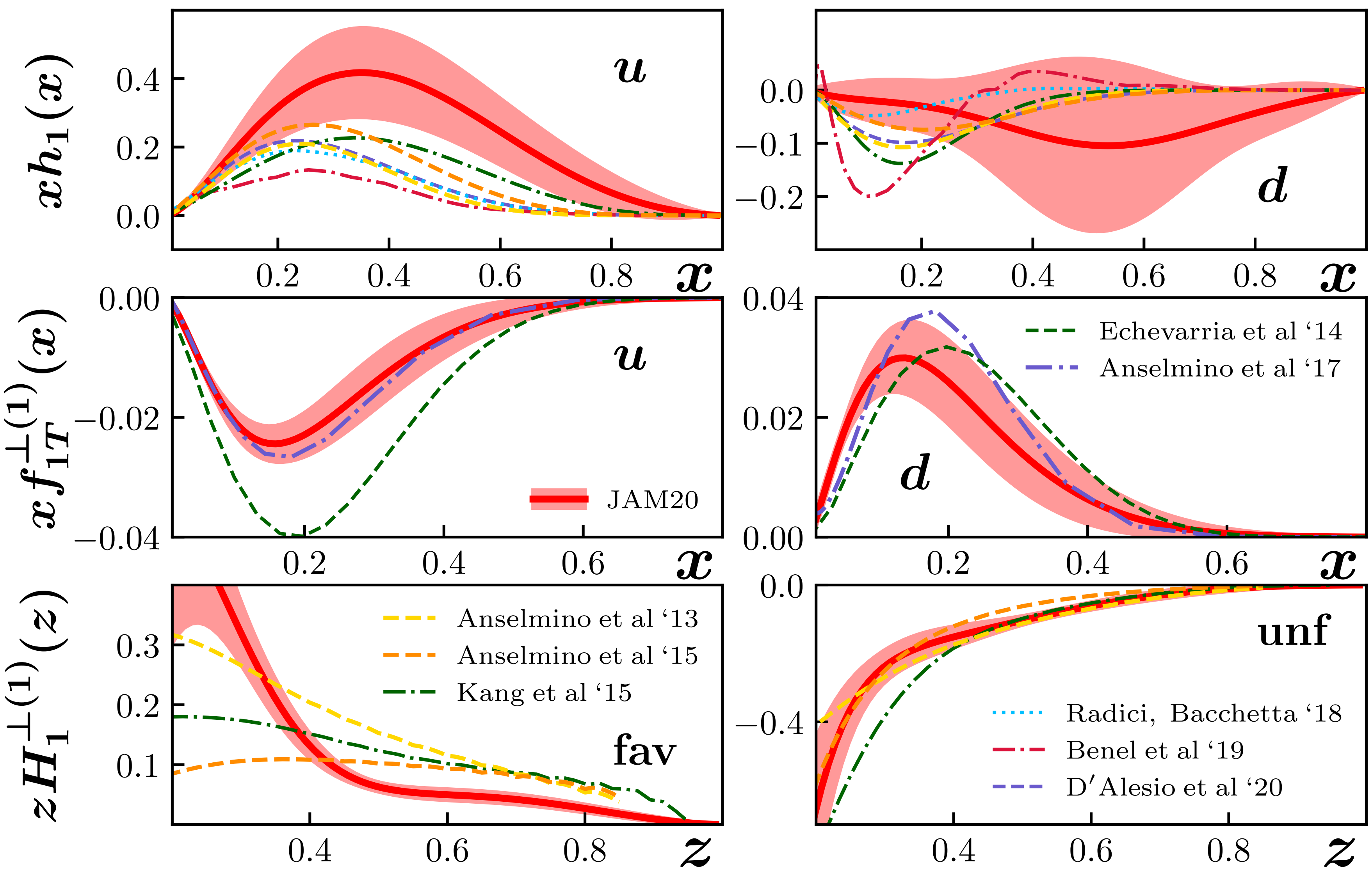
- 18 observables and 6 non-perturbative functions (Sivers up/down; transversity up/down; Collins favored/unfavored)

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

- Broad kinematical coverage to test universality
- The analysis is performed at parton level leading order, gaussian model is used for TMDs, and DGLAP-type evolution is implemented

UNIVERSAL GLOBAL ANALYSIS 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)



Transversity

$h_1(x)$

Sivers

$f_{1T}^{\perp(1)}(x)$

Collins FF

$H_1^{\perp(1)}(z)$

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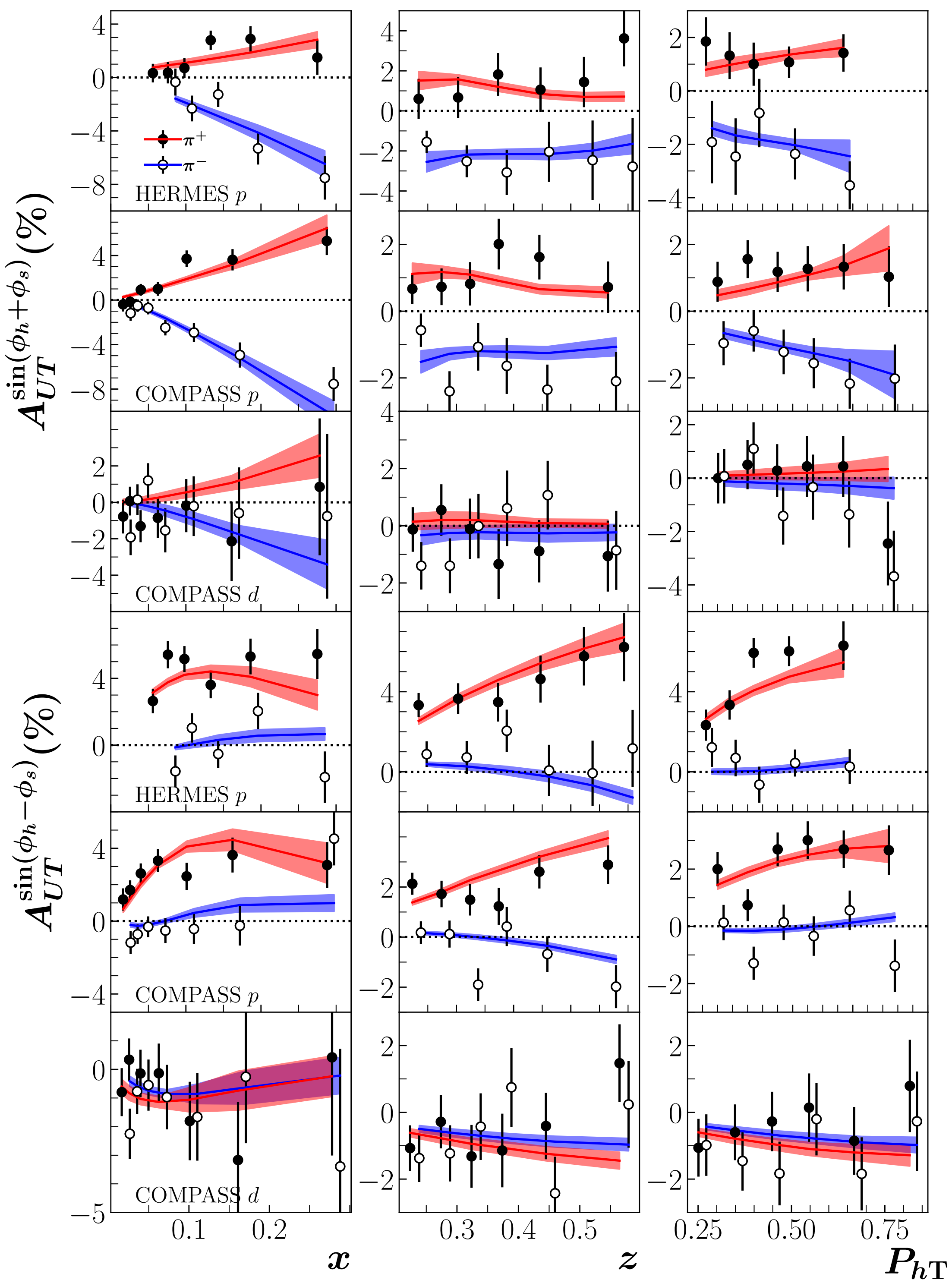
SIDIS



Collins asymmetry

$$\frac{\chi^2}{npoints} = \frac{111.3}{126} = 0.88$$

Sivers asymmetry

$$\frac{\chi^2}{npoints} = \frac{150.0}{126} = 1.19$$

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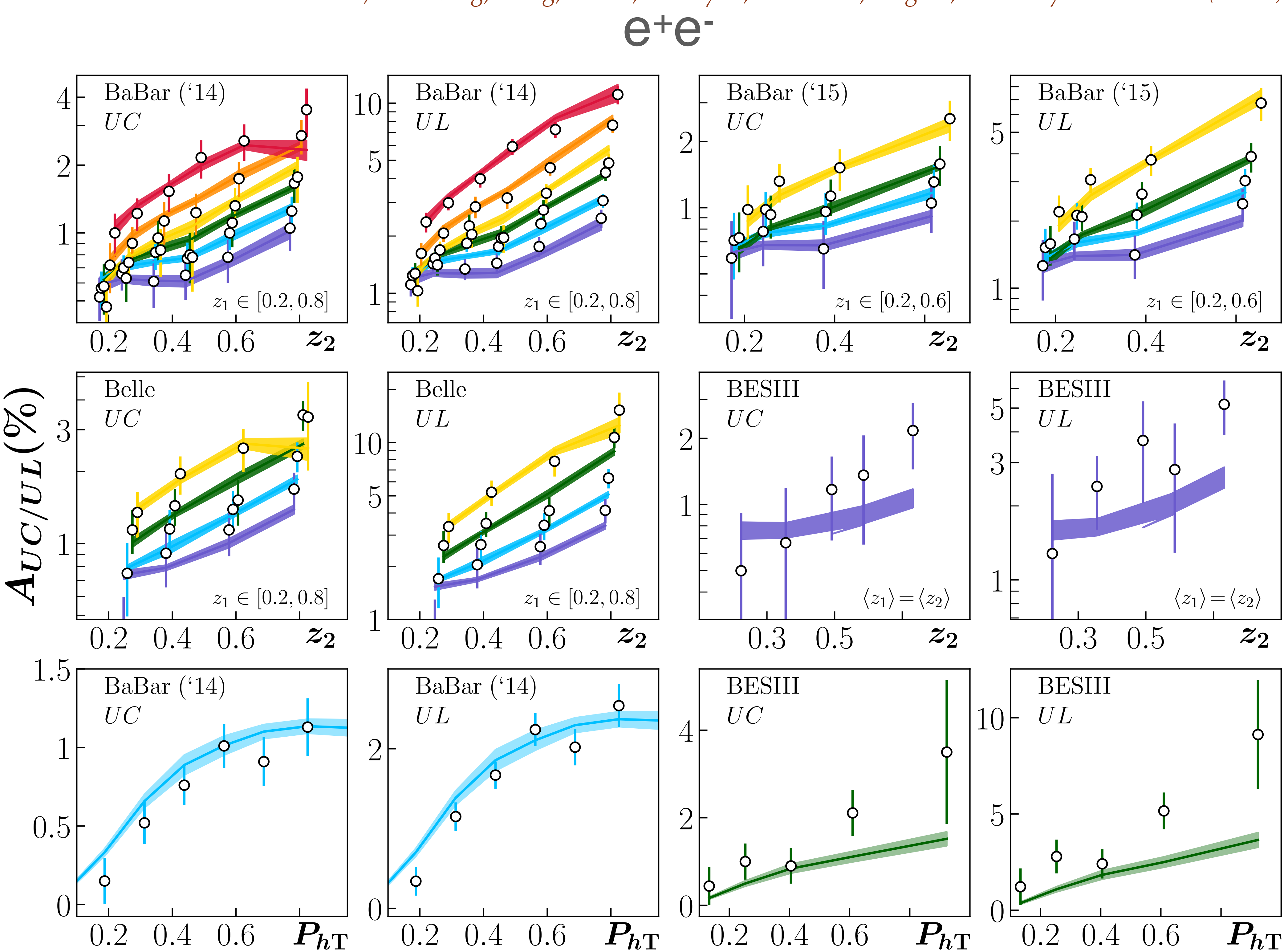

$$\frac{\chi^2}{npoints} = \frac{154.5}{176} = 0.88$$

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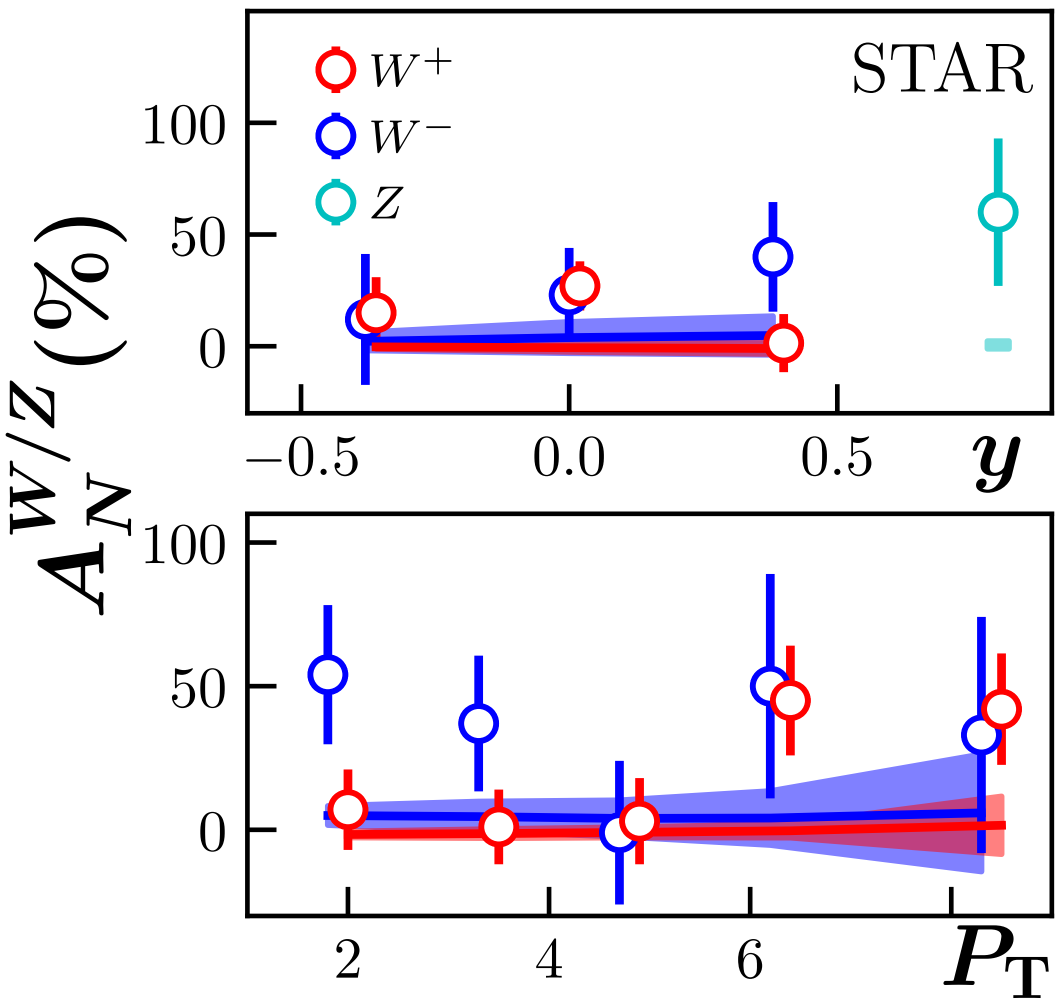
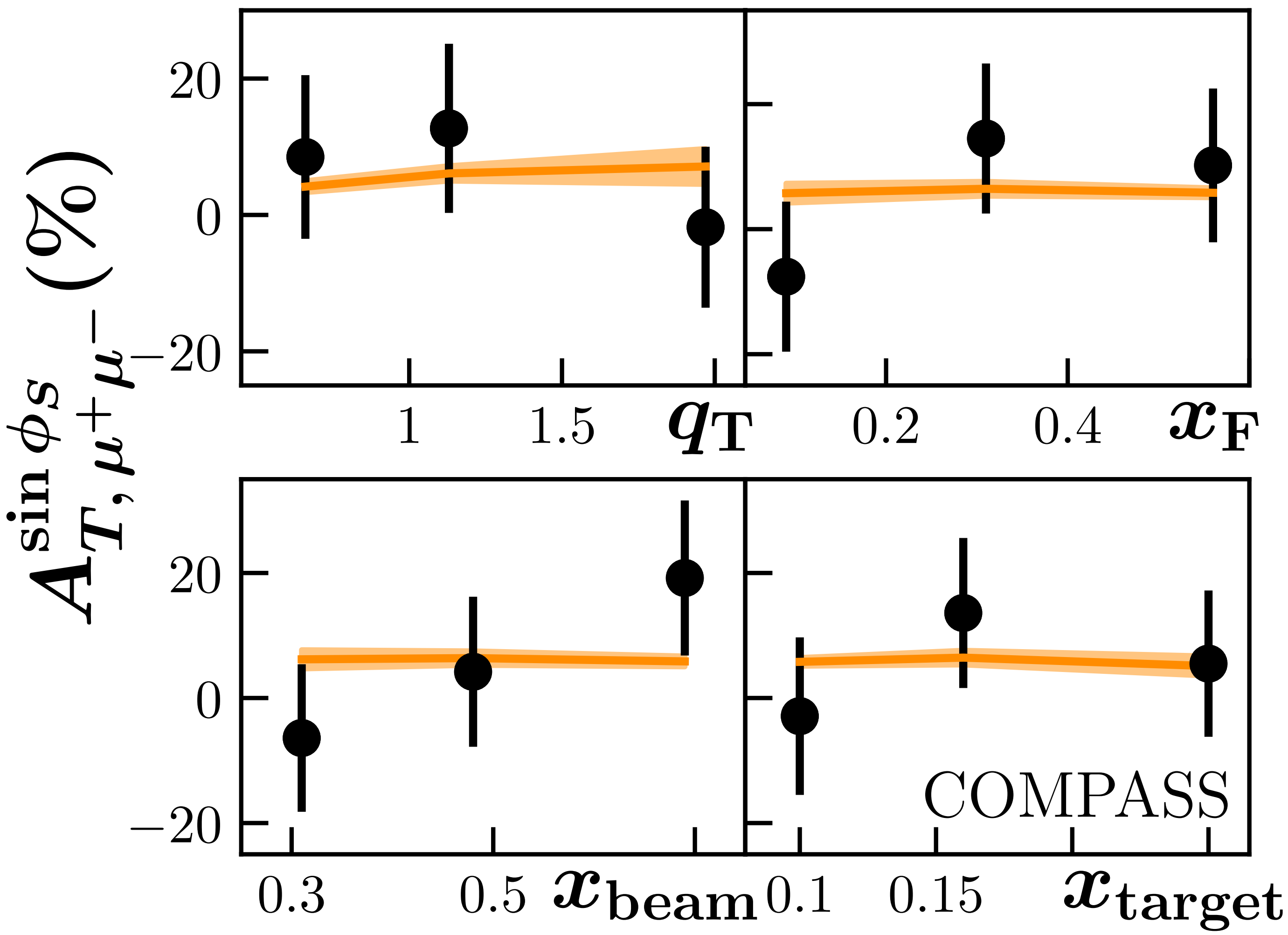
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

Drell-Yan



$$\frac{\chi^2}{npoints} = \frac{31.8}{17} = 1.87$$

STAR



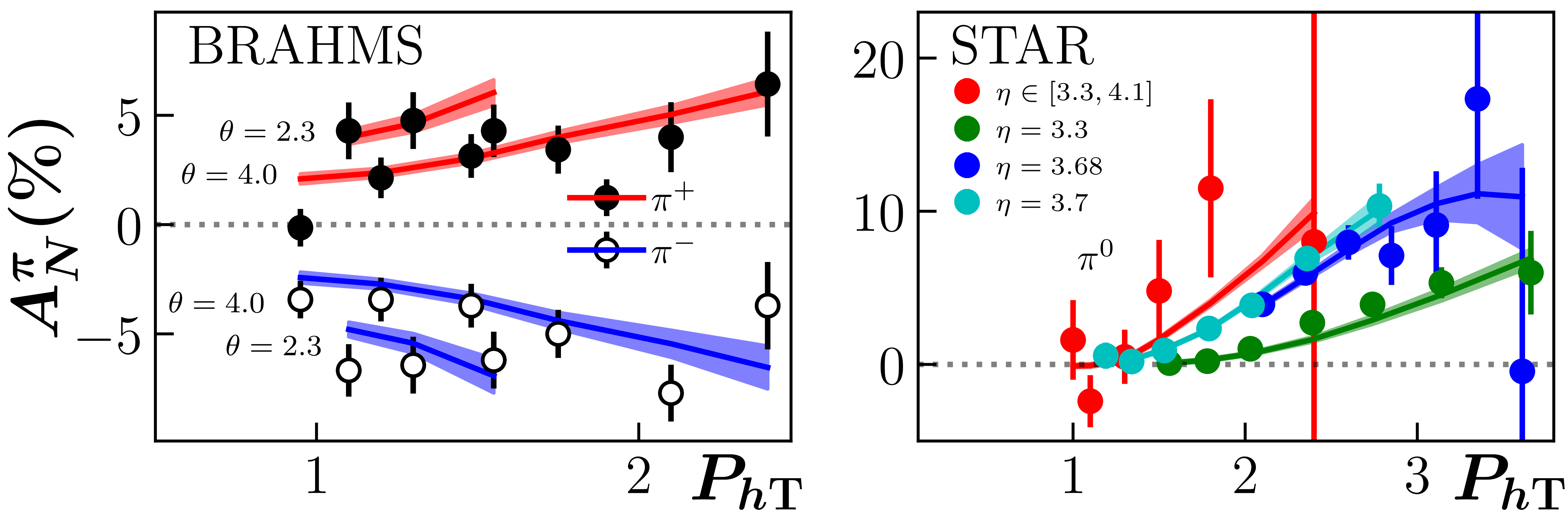
$$\frac{\chi^2}{npoints} = \frac{5.96}{12} = 0.5$$

COMPASS DY

UNIVERSAL GLOBAL ANALYSIS 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

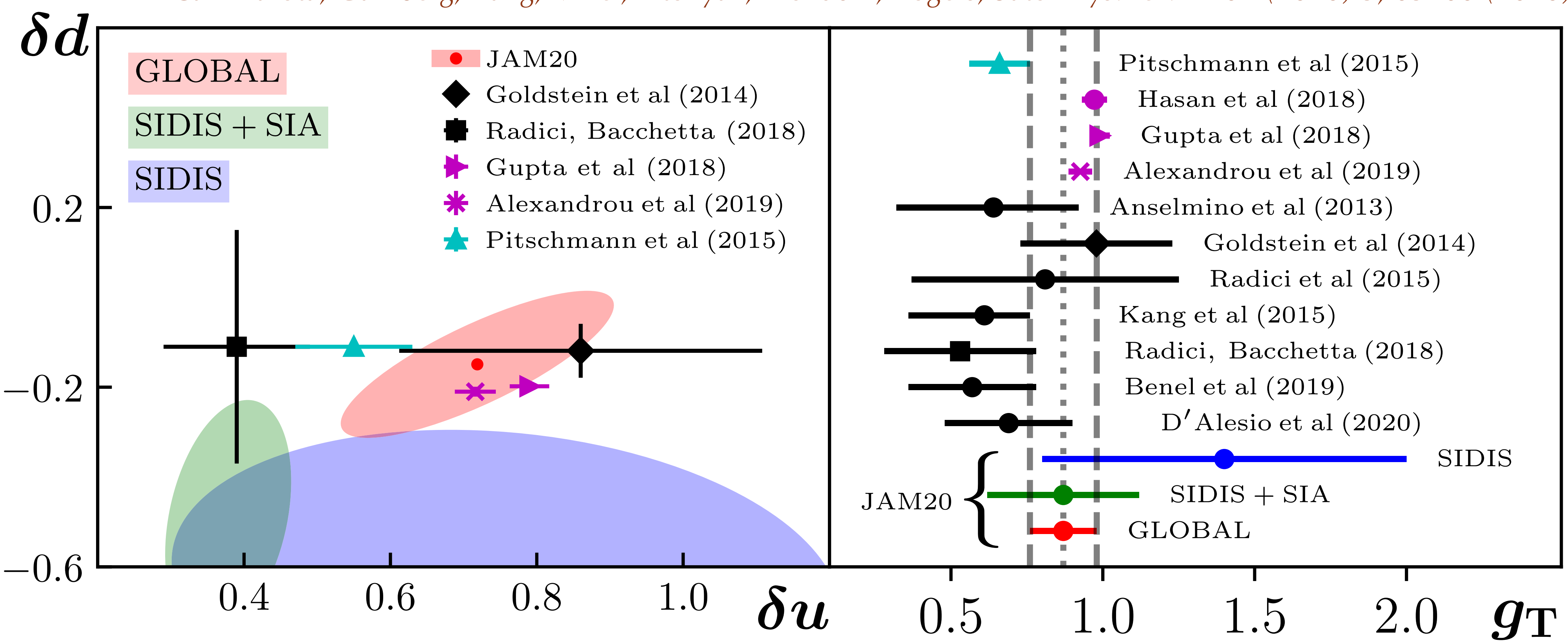
proton-proton A_N



$$\frac{\chi^2}{npoints} = \frac{66.5}{60} = 1.11$$

UNIVERSAL GLOBAL ANALYSIS 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)



- Tensor charge from up and down quarks is constrained and compatible with lattice results
- Isovector tensor charge $g_T = \delta u - \delta d$
  $g_T = 0.87 \pm 0.11$ compatible with lattice results

δu and δd Q^2=4 GeV^2

$\delta u = 0.72 \pm 0.19$

$\delta d = -0.15 \pm 0.16$

JAM22 ANALYSIS

JAM22: SET UP

JAM22, in preparation

- Collins and Sivers (3D binned) SIDIS data from HERMES (2020)

  HERMES Collaboration, A. Airapetian et al. JHEP 12 (2020) 010

- $A_{UT}^{\sin\phi_S}$ (x and z projections only) from HERMES (2020)

- All other data sets are the same as in JAM20, except for the new HERMES data that supersedes previous sets
- 19 observables and 8 non-perturbative functions (Sivers up/down; transversity up/down; Collins fav/unf, $\tilde{H}$ fav/unf)

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

- Lattice data on g_T at the physical pion mass from Alexandrou, et al. (2020)

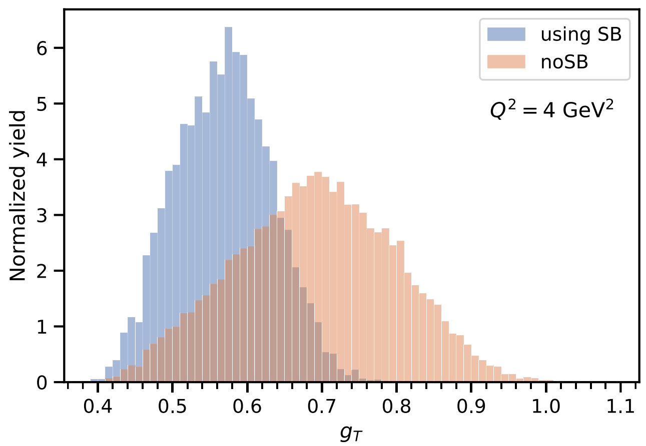
  C. Alexandrou et al, Phys.Rev.D 102 (2020)

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

  J. Soffer, Phys.Rev.Lett. 74 (1995)

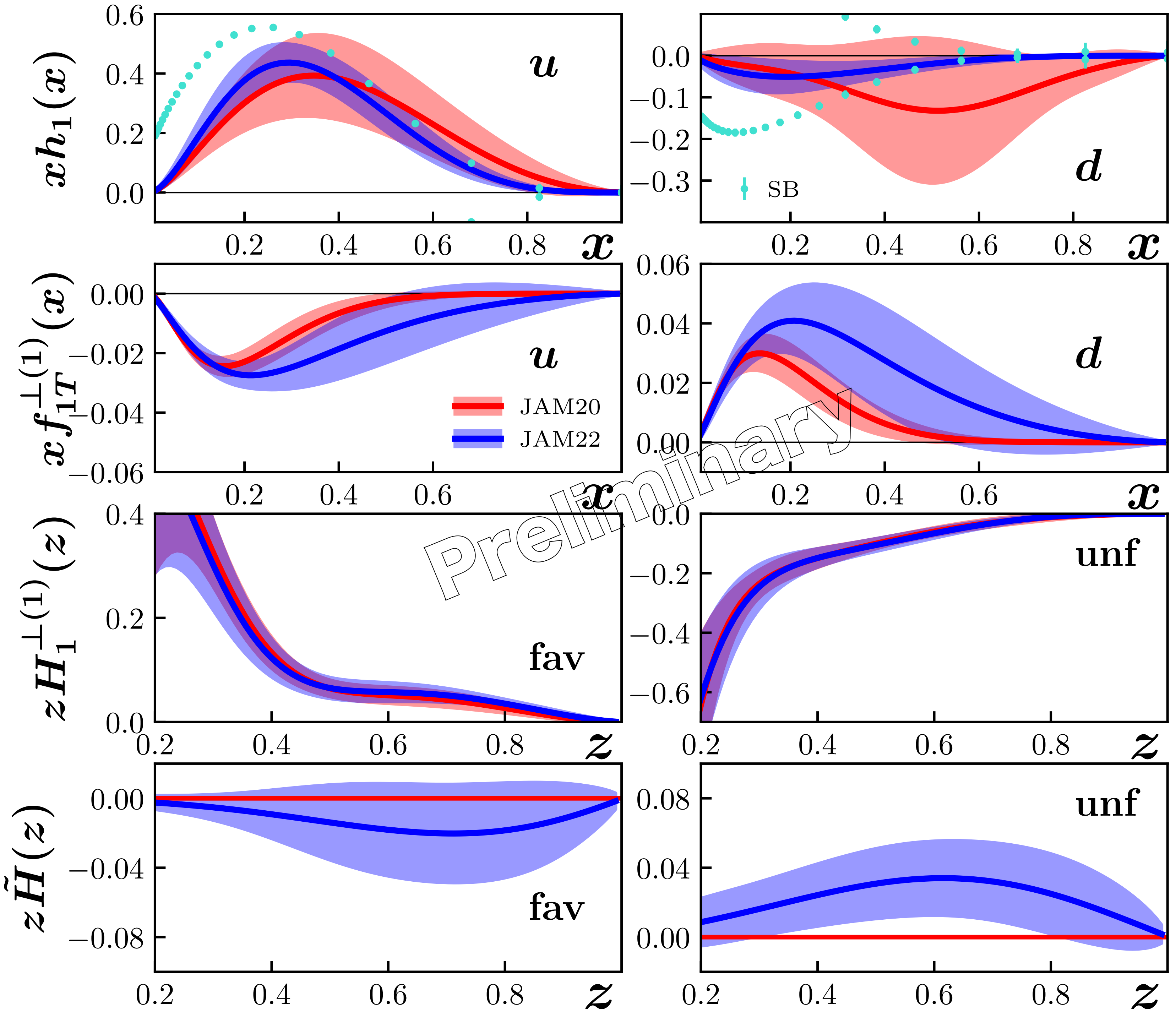
Recent phenomenology indicates substantial influence of imposing the Soffer bounds

U. D'Alesio, C. Flore, A. Prokudin
Phys.Lett.B 803 (2020) 135347



UNIVERSAL GLOBAL ANALYSIS 2022

JAM22, in preparation



Transversity

$h_1(x)$

Sivers

$f_{1T}^{\perp(1)}(x)$

Collins FF

$H_1^{\perp(1)}(z)$

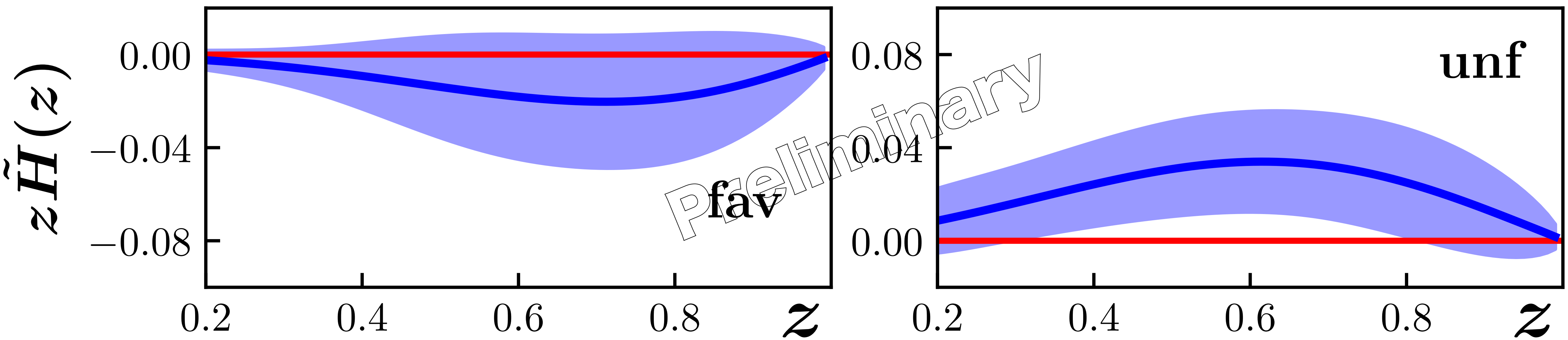
Twist-3 FF

$\tilde{H}(z)$

JAM22: TWIST-3 FF $\tilde{H}$

JAM22, in preparation

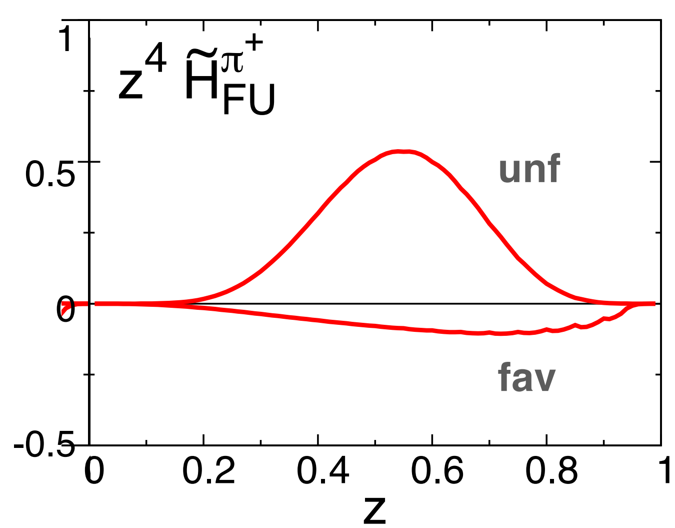
The first insight to the twist-3 fragmentation function $\tilde{H}$



Compatible with signs to the model calculation and previous phenomenology

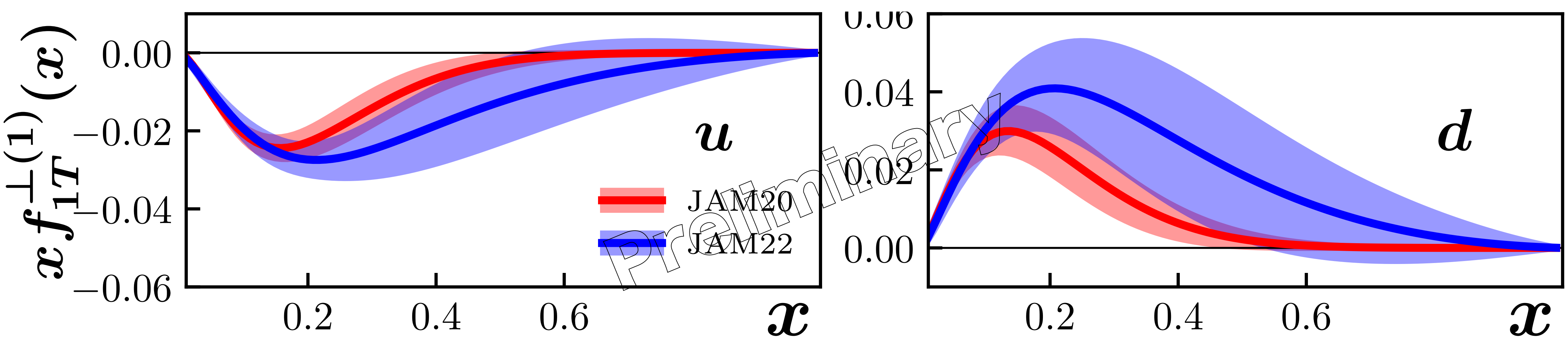
Z. Lu and I. Schmidt Phys.Lett.B 747 (2015)

K. Kanazawa, Y. Koike, A. Metz, D. Pitonyak, Phys.Rev.D 89 (2014) 11, 111501



JAM22: SIVERS FUNCTIONS, THE QIU-STERMAN MATRIX ELEMENT

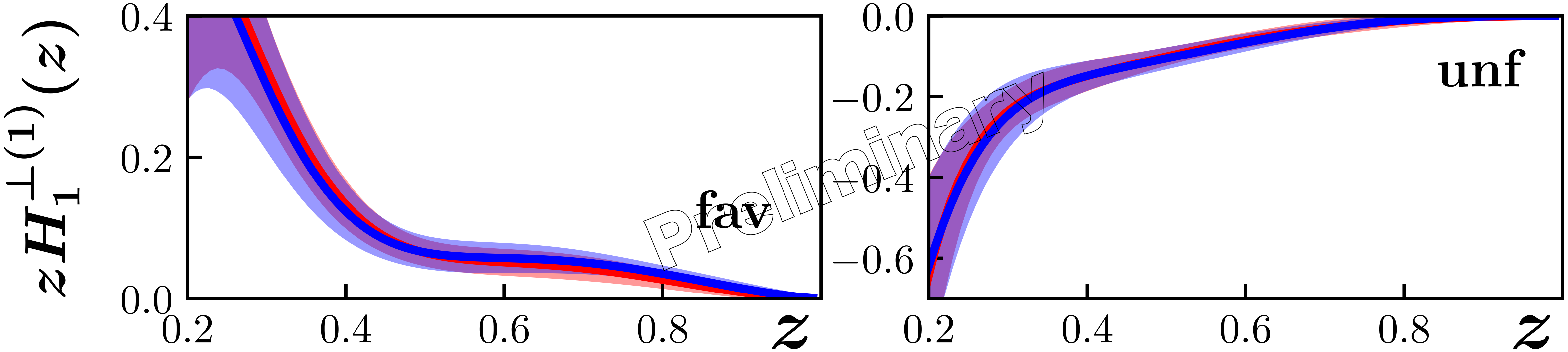
JAM22, in preparation



Extracted Sivers functions are compatible within the errors with JAM20, the increase in magnitude and the error is due to the new HERMES 3D data.

JAM22: COLLINS FRAGMENTATION FUNCTIONS

JAM22, in preparation

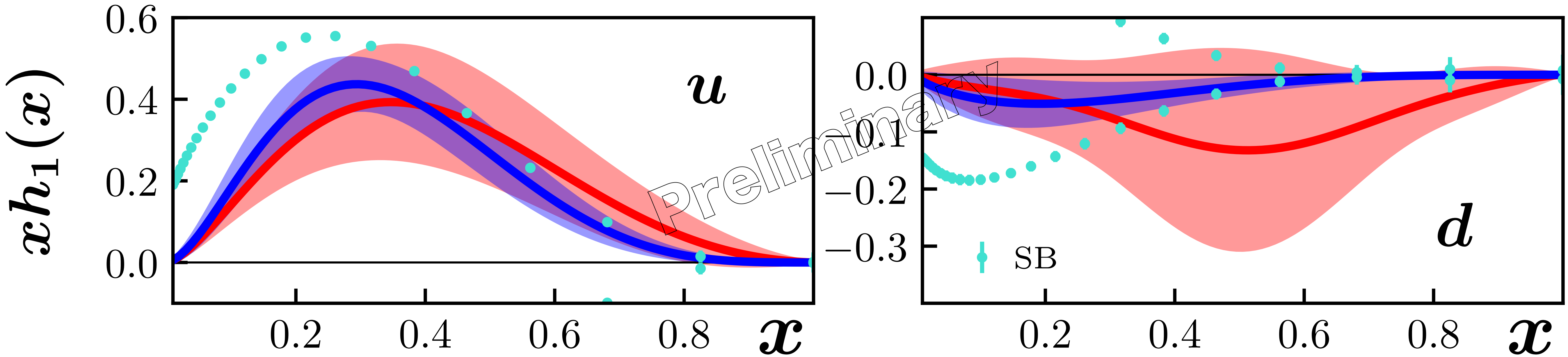


Extracted Collins FFs are compatible within the errors with JAM20, e+e- data constrains those functions well.

JAM22: TRANSVERSITY AND THE SOFFER BOUND

JAM22, in preparation

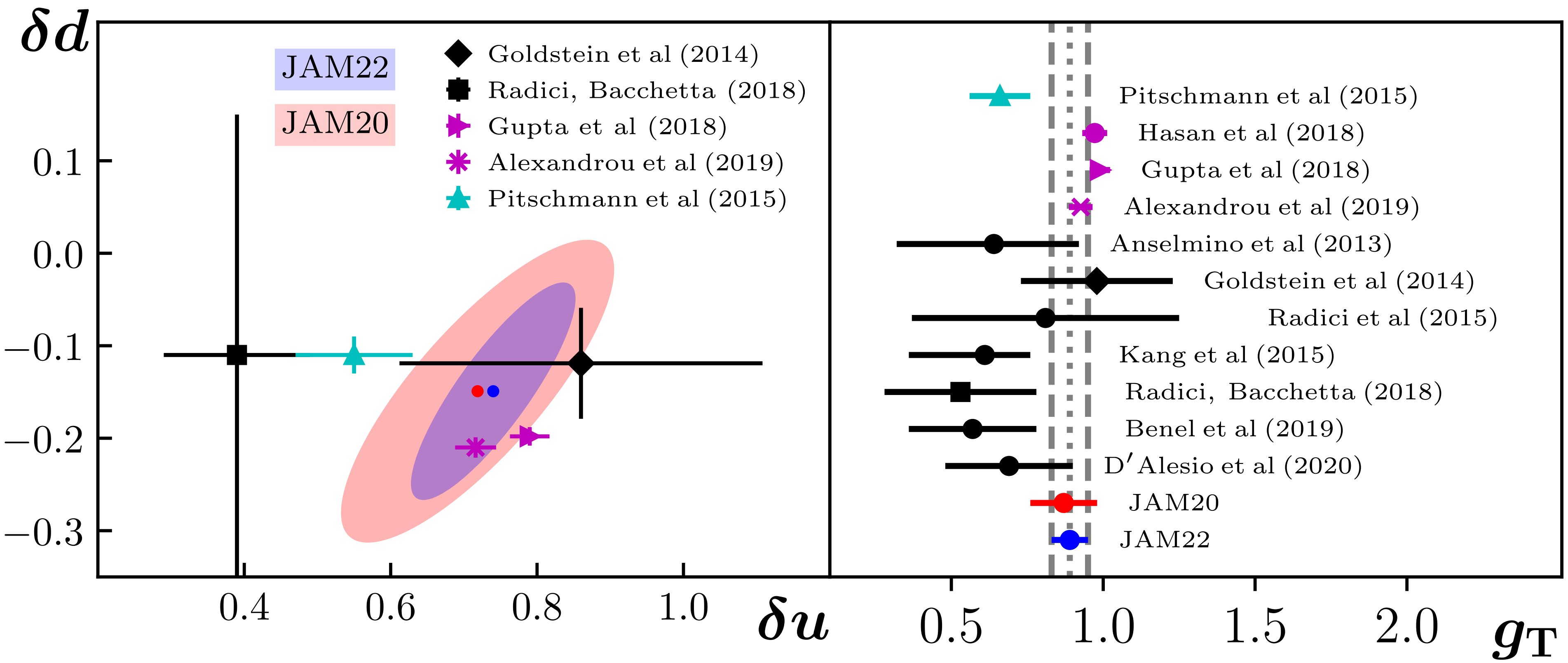
Extracted transversity is compared to the Soffer bound (the data generated by JAM extraction of unpolarized and helicity distributions)



Extracted transversity is compatible with the Soffer bound and within the errors with JAM20

UNIVERSAL GLOBAL ANALYSIS 2022

JAM22, in preparation



- Tensor charge from up and down quarks and $g_T = \delta u - \delta d$ are well constrained and compatible with both lattice results and the Soffer bound

δu and δd Q^2=4 GeV^2

δu= 0.74 ± 0.11

δd= -0.15 ± 0.12

g_T= 0.89 ± 0.06

- The tension with diFF method, Radici, Bacchetta (2018) becomes more pronounced: is it due to the data, theory, methodology? Both methods should be scrutinized.

CONCLUSIONS

- The transverse spin asymmetries in a variety of processes SIDIS, Drell-Yan, e^+e^-, and proton proton scattering have the same origin: (multi) parton correlation functions
- These effects have predominantly non perturbative origin and are universal
- New extraction is consistent with lattice QCD in extraction of the isovector tensor charge g_T and individual contributions from up and down quarks and with the Soffer bound.
- The new 3D HERMES data allows for extraction of $\tilde{H}$ which plays a key role in maintaining good description of A_N observed in proton-proton scattering.
- The future development will include analysis of the data sets with new observables, such as pion in jet asymmetries (STAR), jet asymmetries (STAR, AnDY), new A_N from STAR, sensitive to the transverse spin structure.