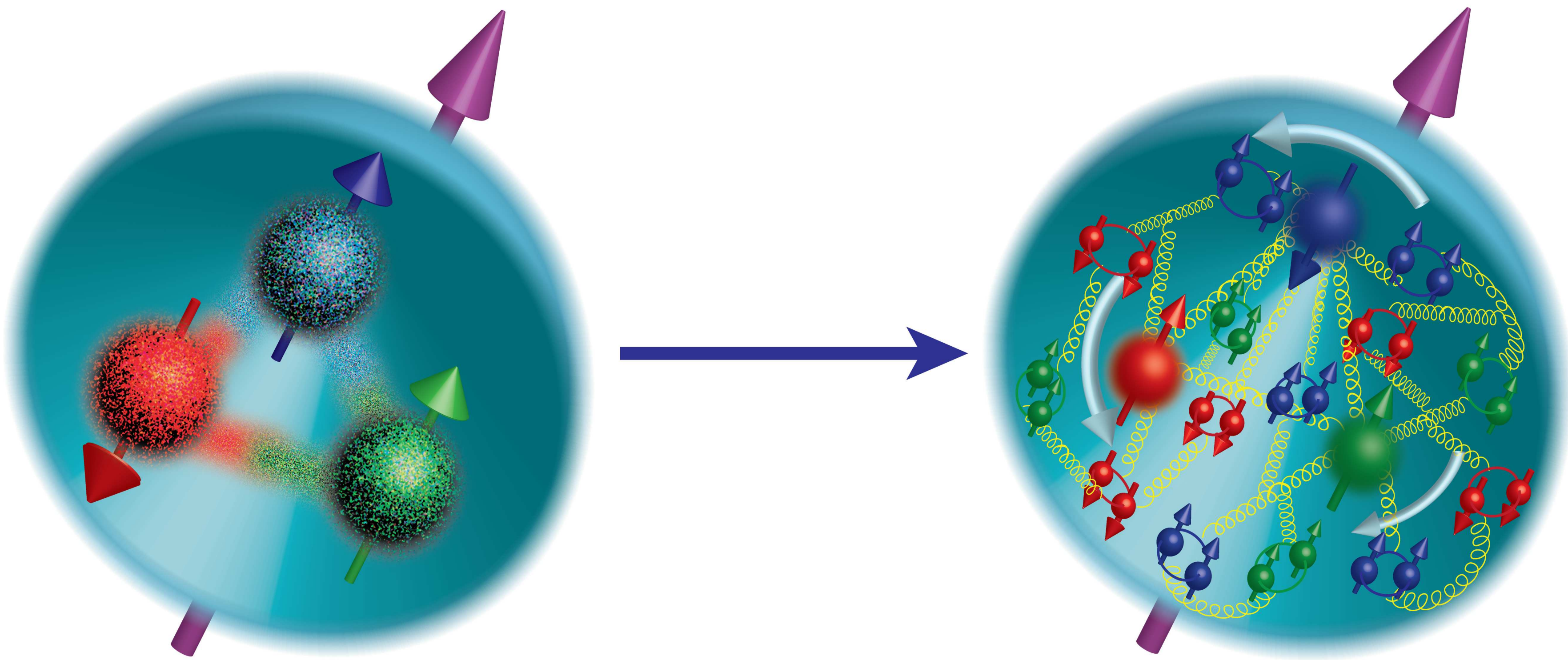
- Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, Phys.Rev.D 102 (2020) 5, 054002
- Gamberg, Kang, Pitonyak, Prokudin, Sato, Seidl, Phys.Lett.B 816 (2021) 136255

Global analysis of SSAs and the EIC impact on the tensor charge

Alexei Prokudin

EVOLUTION OF OUR UNDERSTANDING OF THE SPIN STRUCTURE

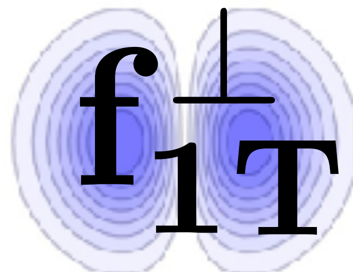


1980’ - the spin of the nucleon is due to the valence quarks

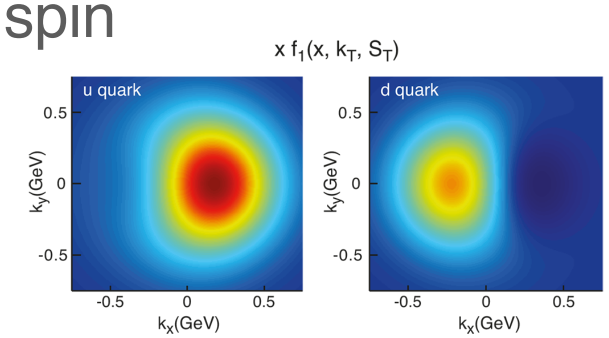
Modern concept: valence quarks, sea quarks, and gluons together with orbital angular momentum are contributing

POLARIZED TMD FUNCTIONS

Sivers function

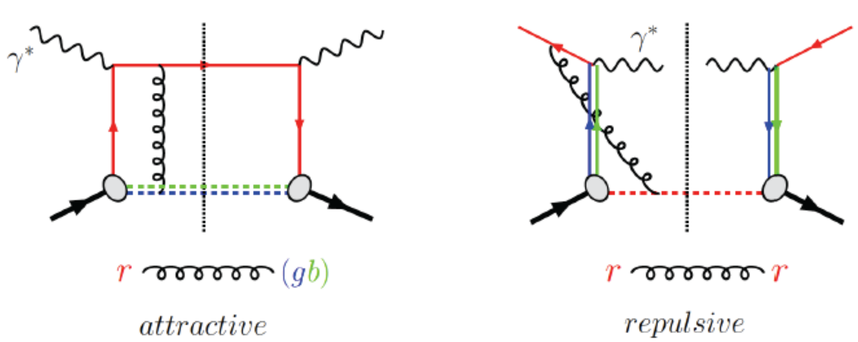


- Describes unpolarized quarks inside of transversely polarized nucleon
- Encodes the correlation of orbital motion with the spin



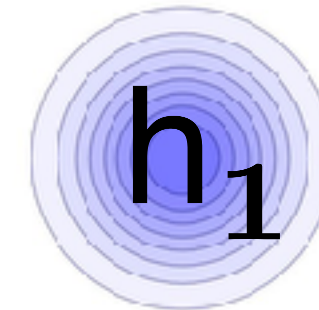
- Sign change of Sivers function is fundamental consequence of QCD

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



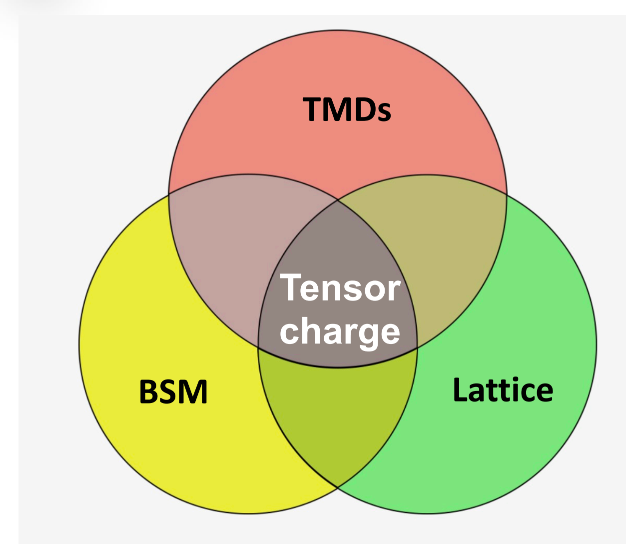
$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

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

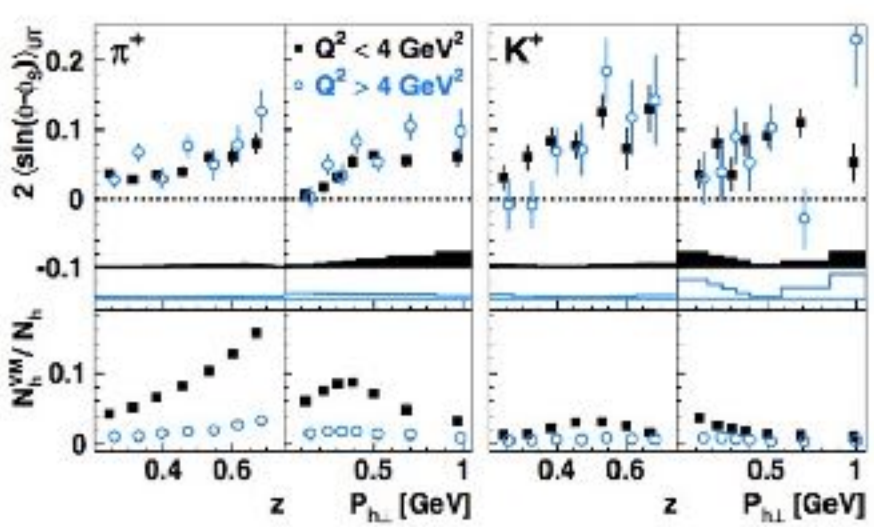
$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$



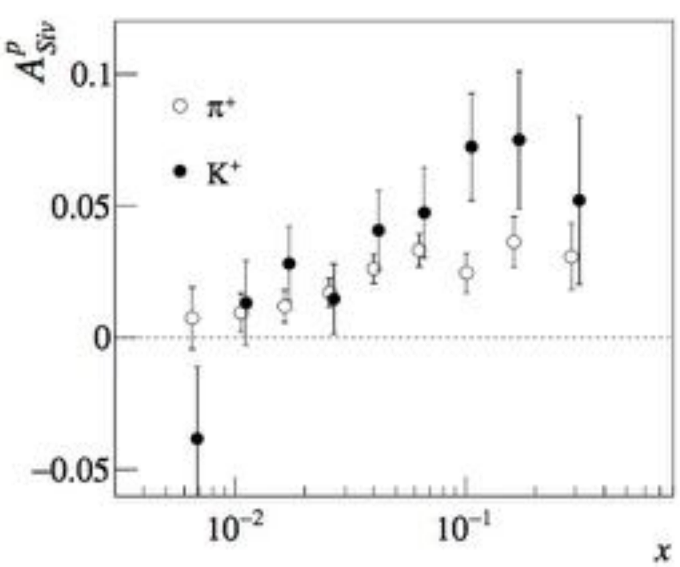
TRANSVERSE SPIN ASYMMETRIES

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

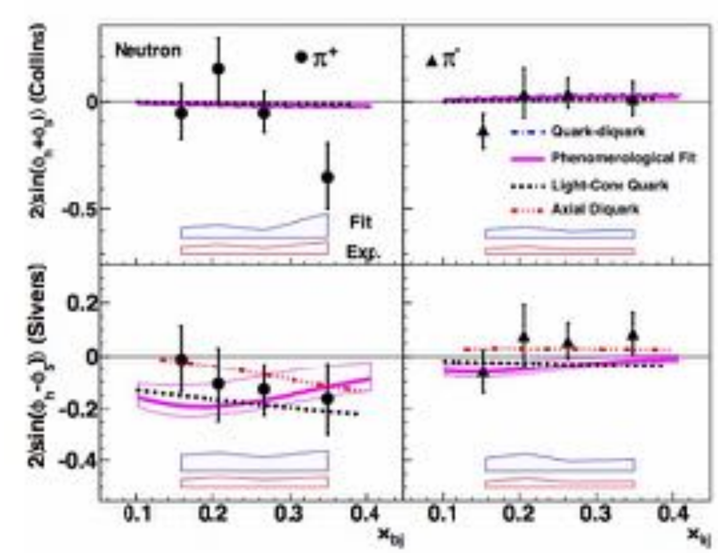
Sivers asymmetry in SIDIS



HERMES (09)



COMPASS (15)



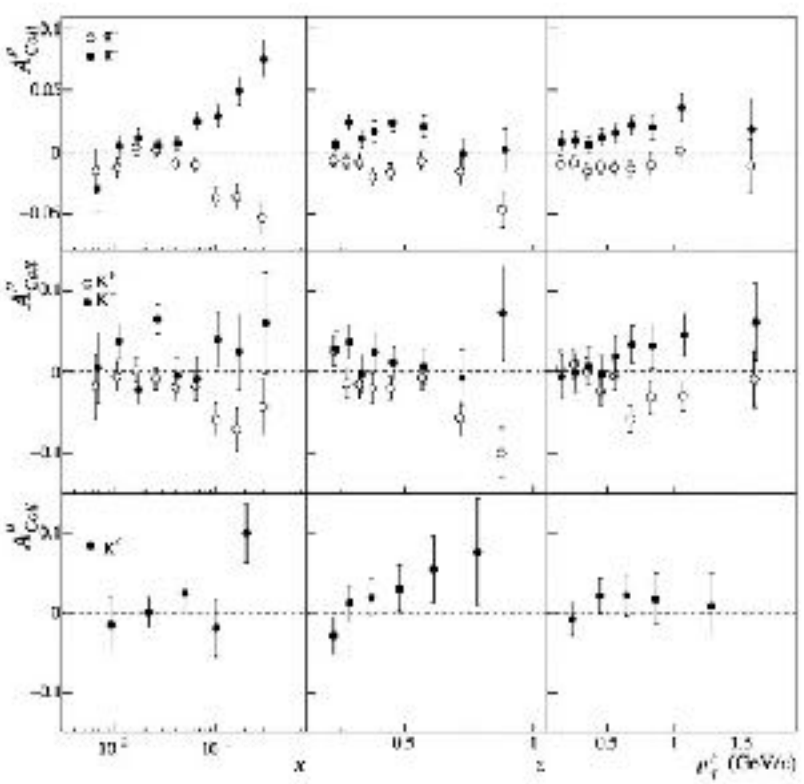
JLAB (11)

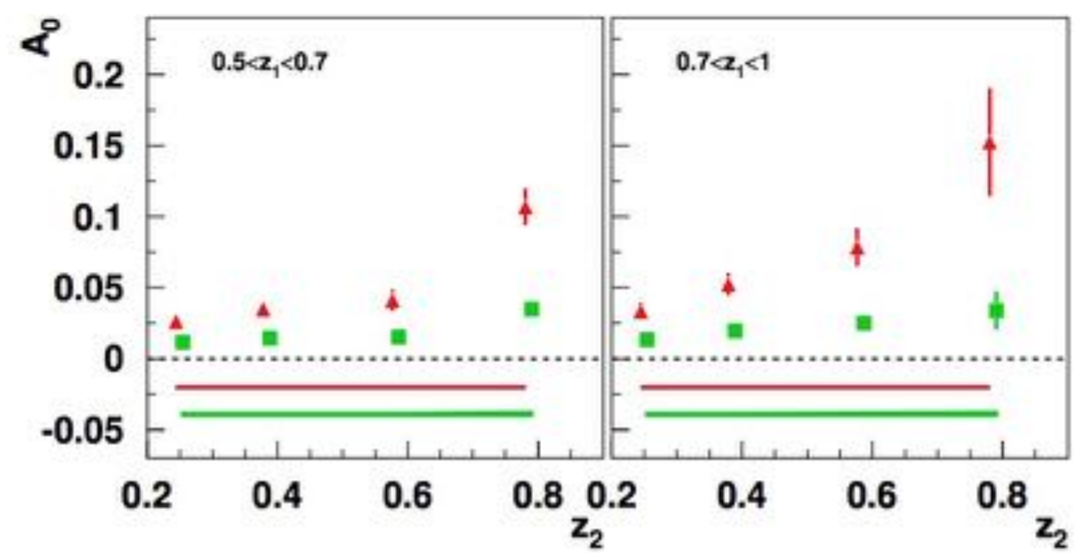
$$F_{UT}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M}\, \boldsymbol{f_{1T}^{\perp}} D_1\right]$$

TRANSVERSE SPIN ASYMMETRIES

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

Collins asymmetry in SIDIS and e^+e^-





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

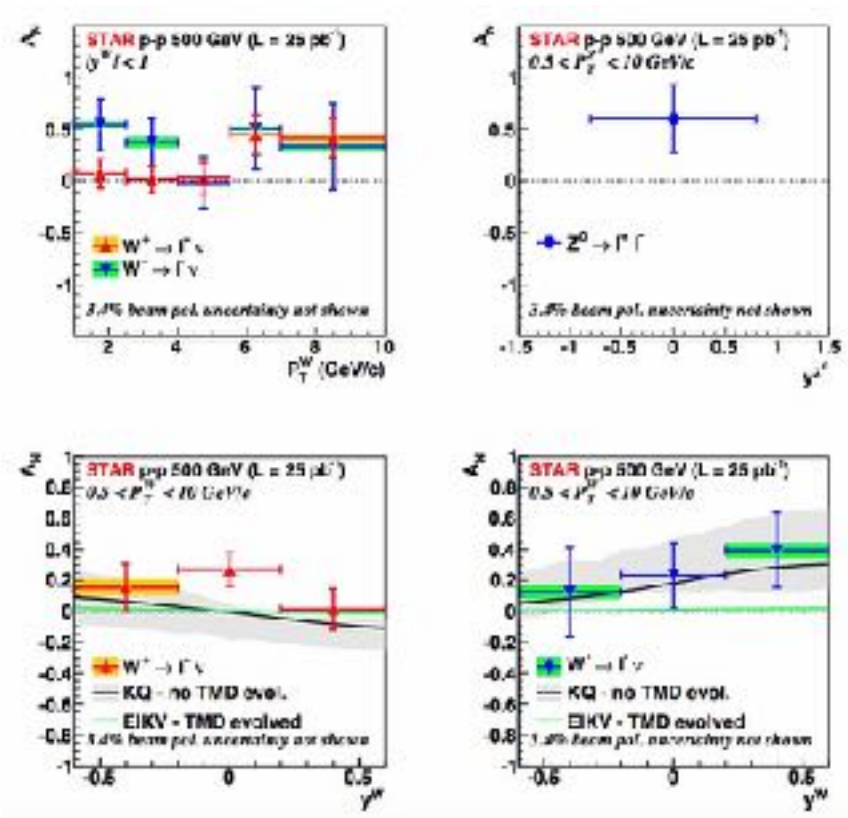
COMPASS (15),
also HERMES (05,10, 20), JLab (11,14)

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

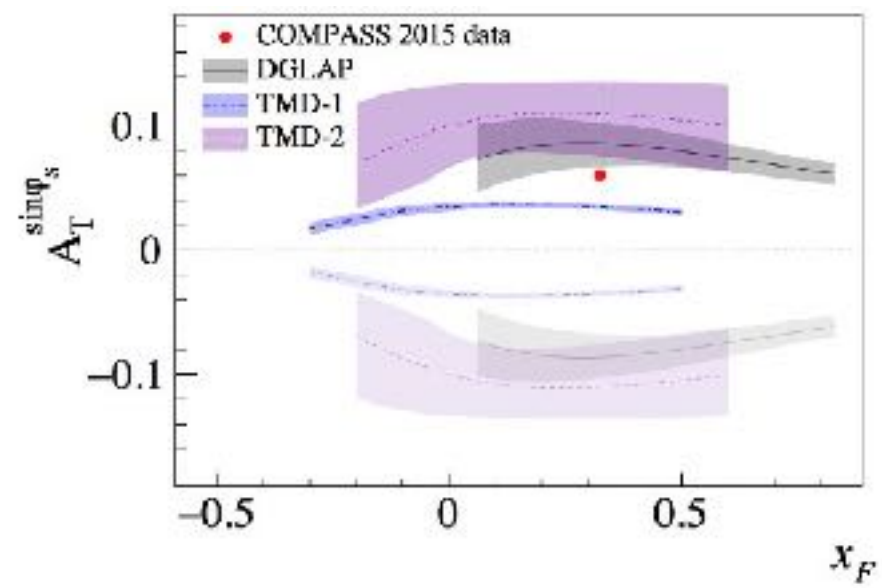
TRANSVERSE SPIN ASYMMETRIES

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

Sivers effect in Drell-Yan



STAR (15)



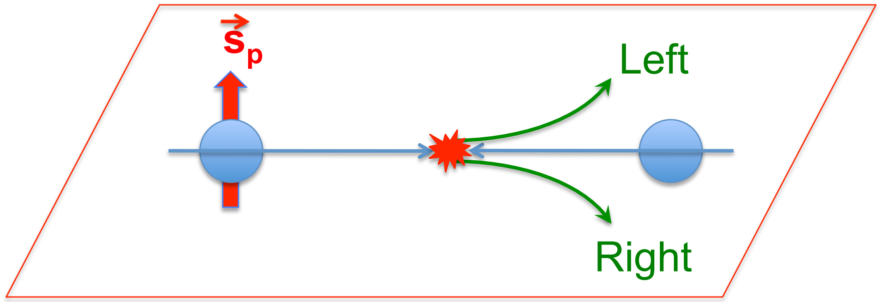
COMPASS (17)

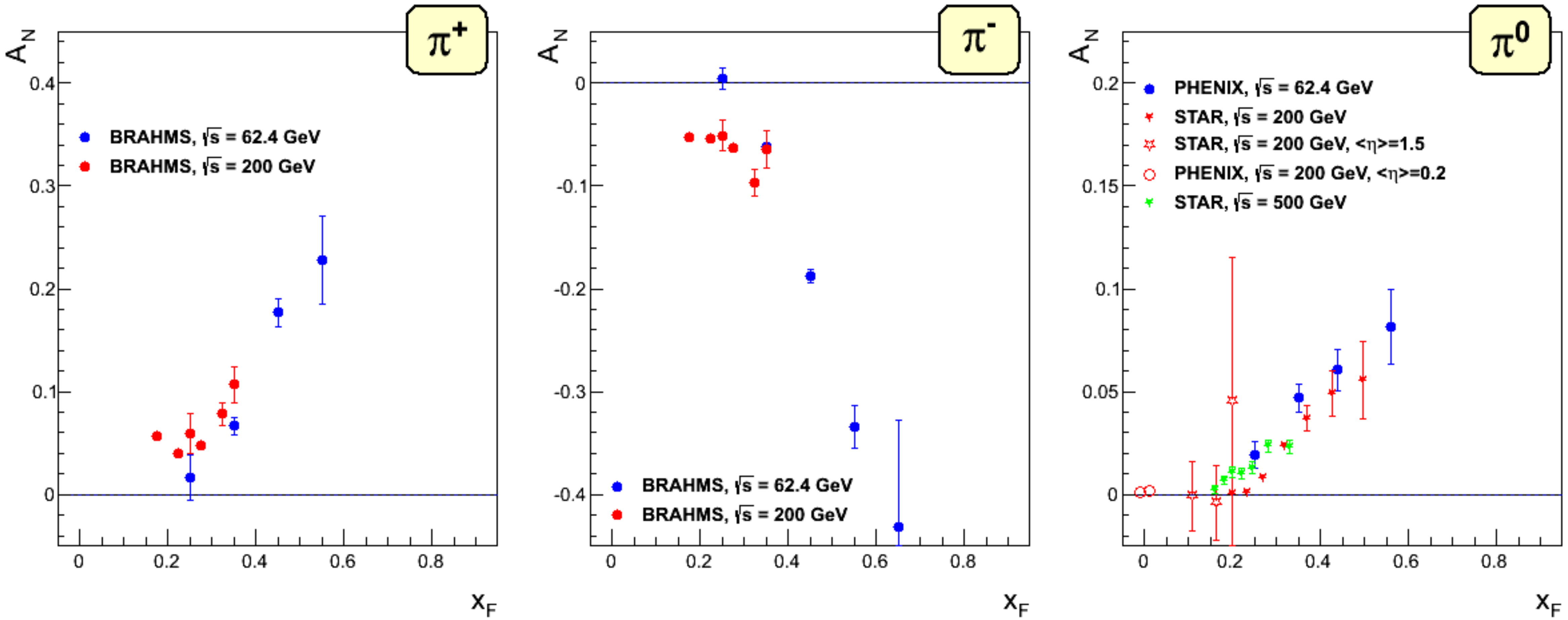
$$F_{TU}^{1} = \mathcal{C}\left[-\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a}\, \boldsymbol{f_{1T}^{\perp}}\, \bar{f}_1\right]$$

TRANSVERSE SPIN ASYMMETRIES

A_N in pp scattering

RHIC: STAR, BRAHMS, PHENIX

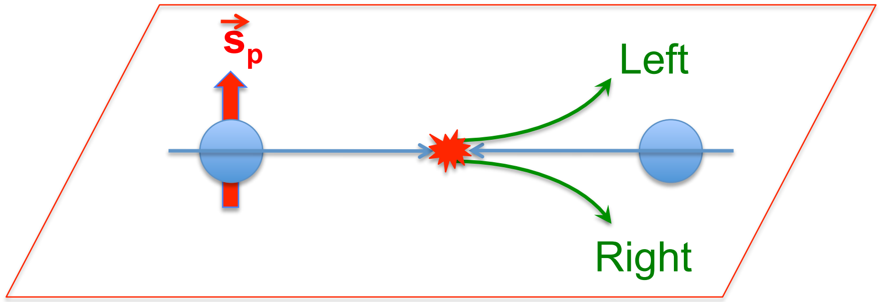




"The RHIC SPIN Program: Achievements and Future Opportunities", Aschenauer et al (15)

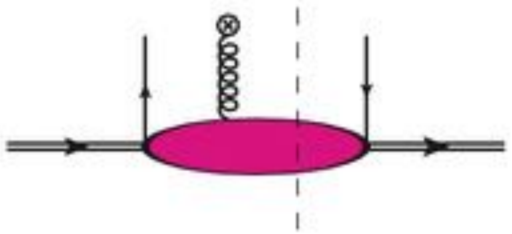
TRANSVERSE SPIN ASYMMETRIES

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

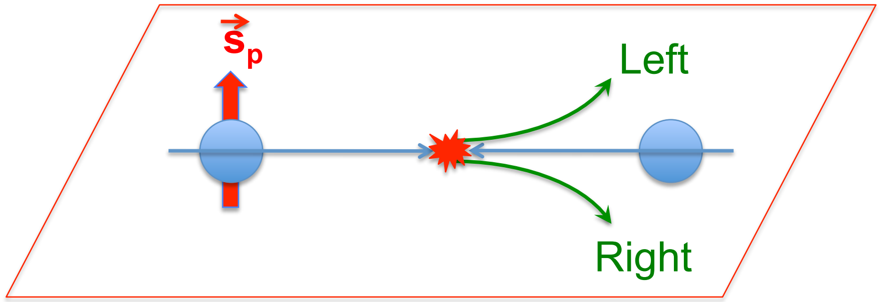
Boer, et al (03)

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



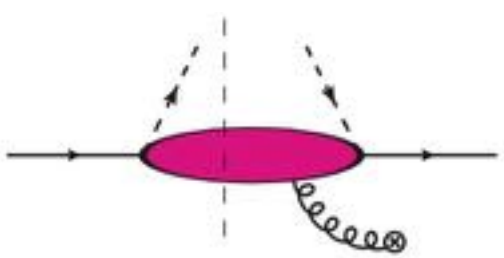
$$d\Delta\sigma(S_T) \sim H_{QS} \otimes f_1 \otimes F_{FT} \otimes D_1 + H_F \otimes f_1 \otimes h_1 \otimes \left(H_1^{\perp(1)}, \tilde{H}\right)$$

Fragmentation term

h_1 collinear transversity

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

$H_1^{\perp(1)}$ $\tilde{H}$ $\sim$



quark-gluon-quark fragmentation functions

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

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

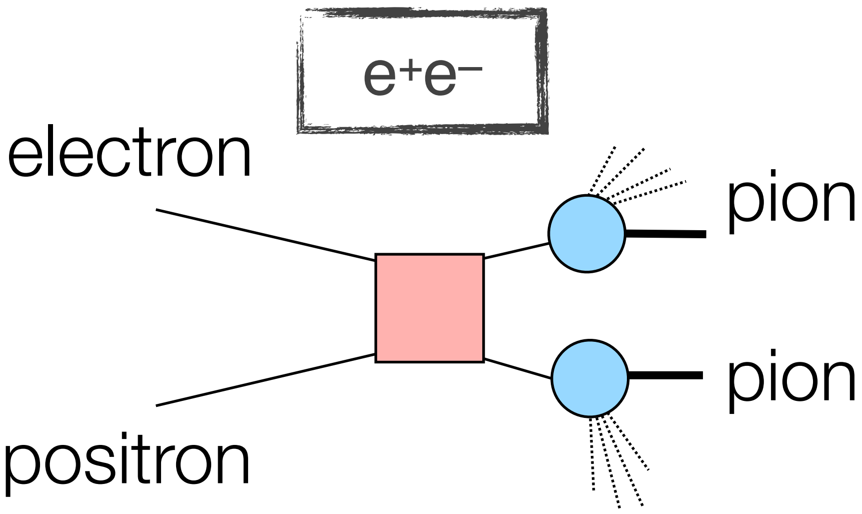
Mulders, Tangerman (96); Bacchetta, et al (07)

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

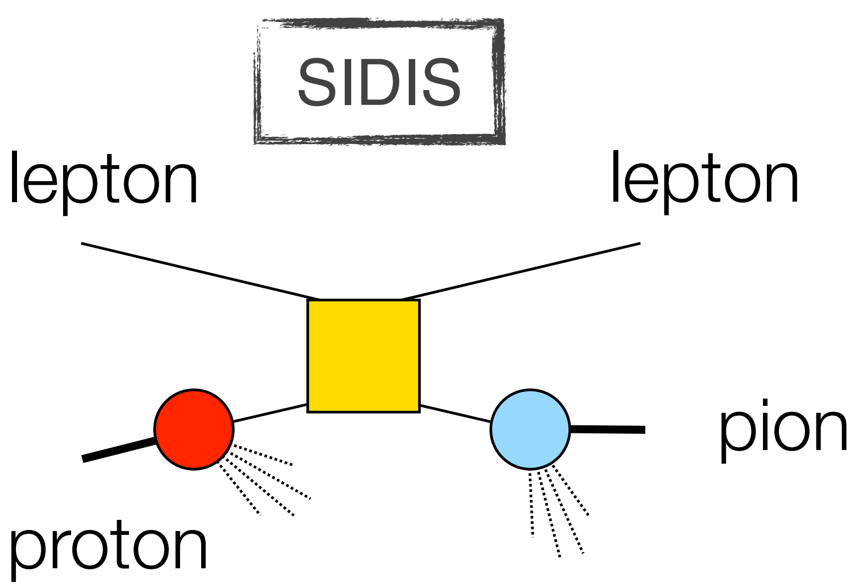
JAM20 ANALYSIS

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

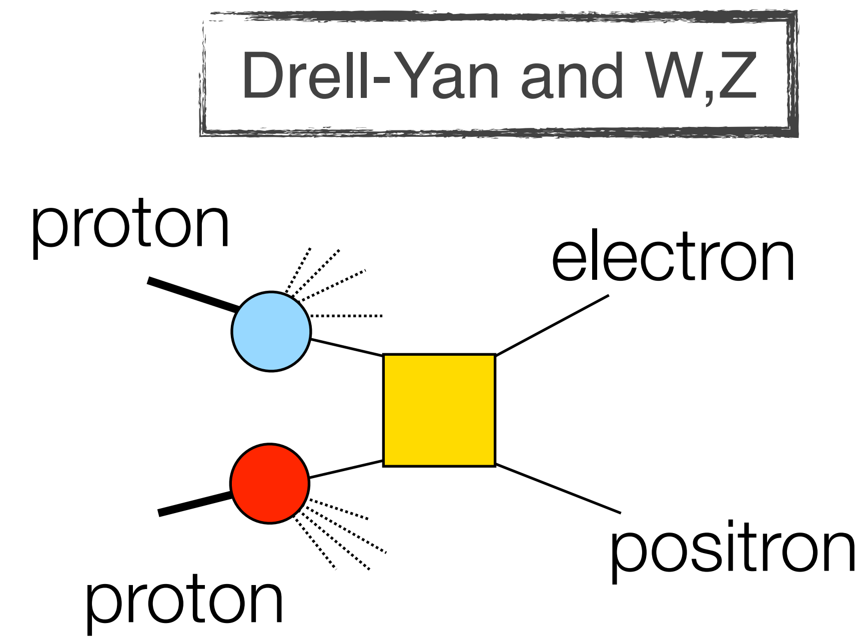


Collins asymmetries
BELLE, BaBar, BESIII data

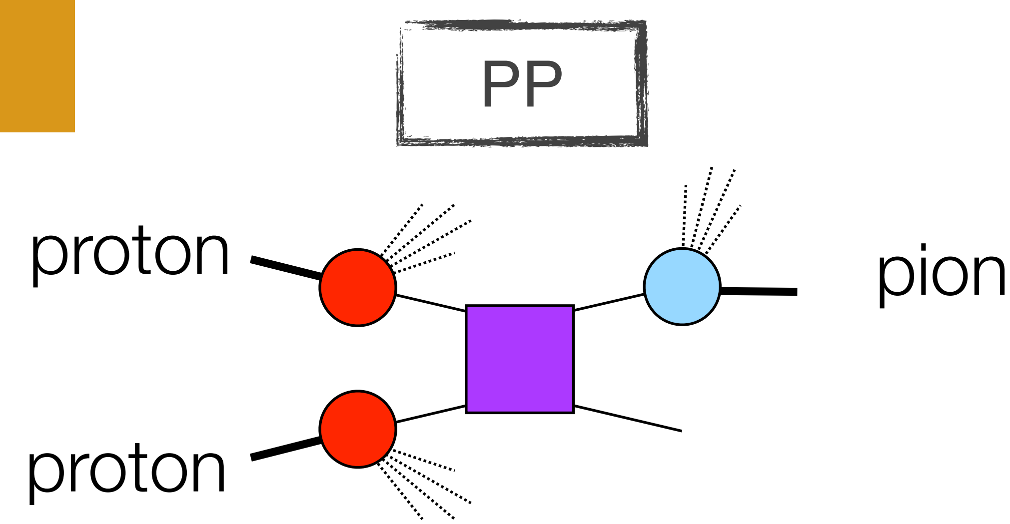


Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

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

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Jefferson Lab Angular Momentum Collaboration

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

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

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

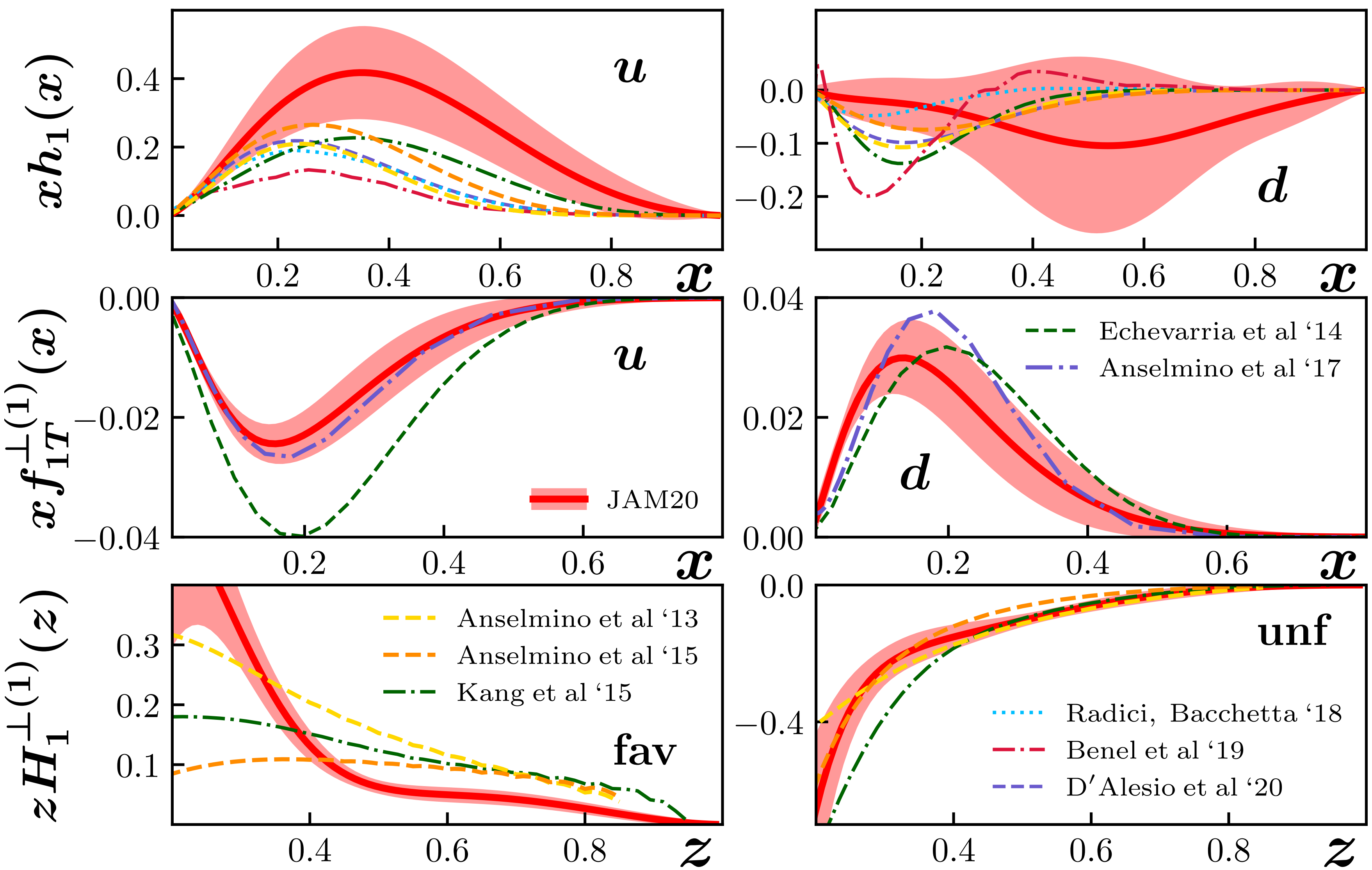
- 18 observables and 6 non-perturbative functions (Sivers up/down; transversity up/down; Collins favored/unfavored)

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

- 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 FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



Transversity

$h_1(x)$

Sivers

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

Collins FF

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

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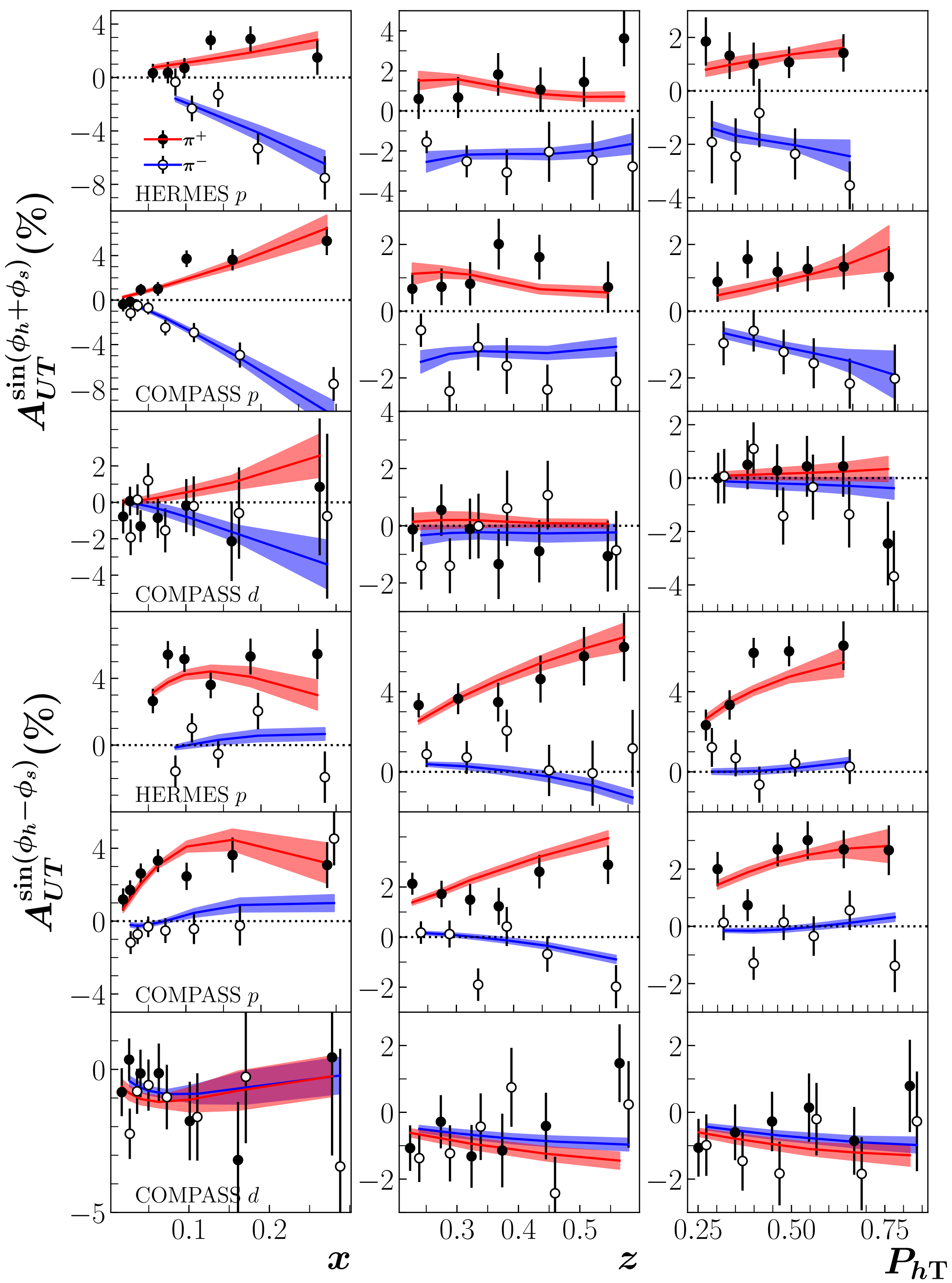
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

SIDIS



Collins asymmetry

$$\frac{\chi^2}{npoints} = \frac{107.1}{126} = 0.85$$

Sivers asymmetry

$$\frac{\chi^2}{npoints} = \frac{85.4}{88} = 0.97$$

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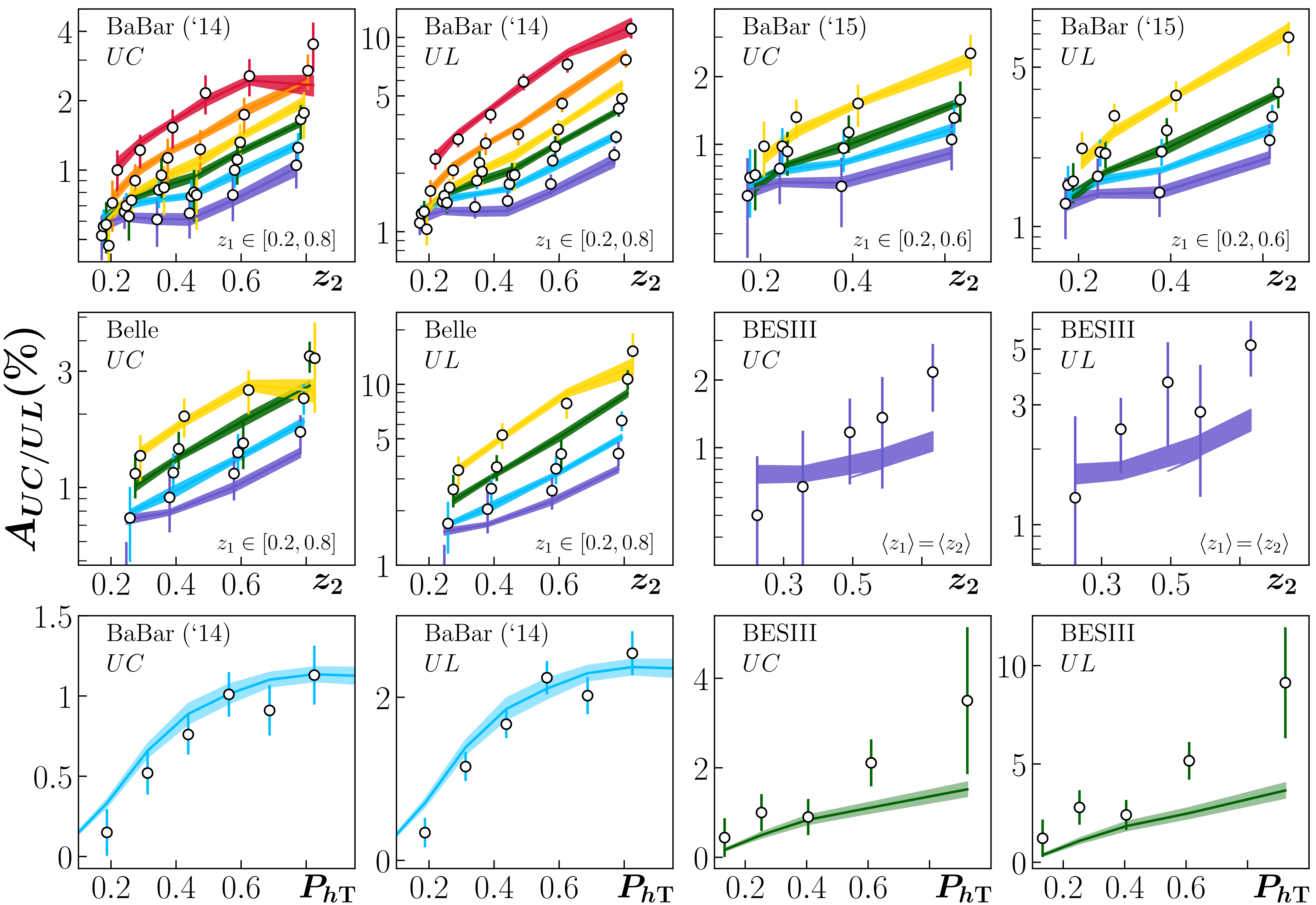
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

e⁺e⁻



$$\frac{\chi^2}{npoints} = \frac{149.6}{176} = 0.85$$

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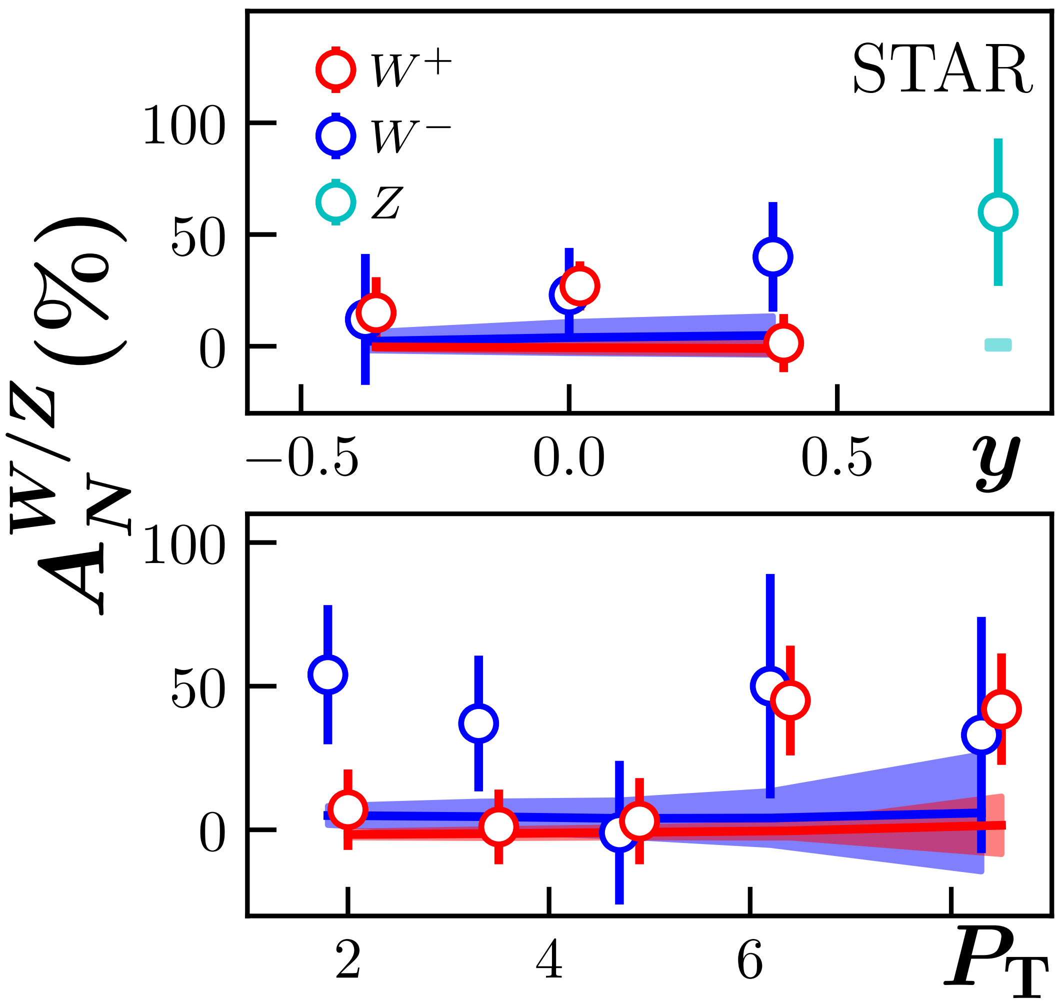
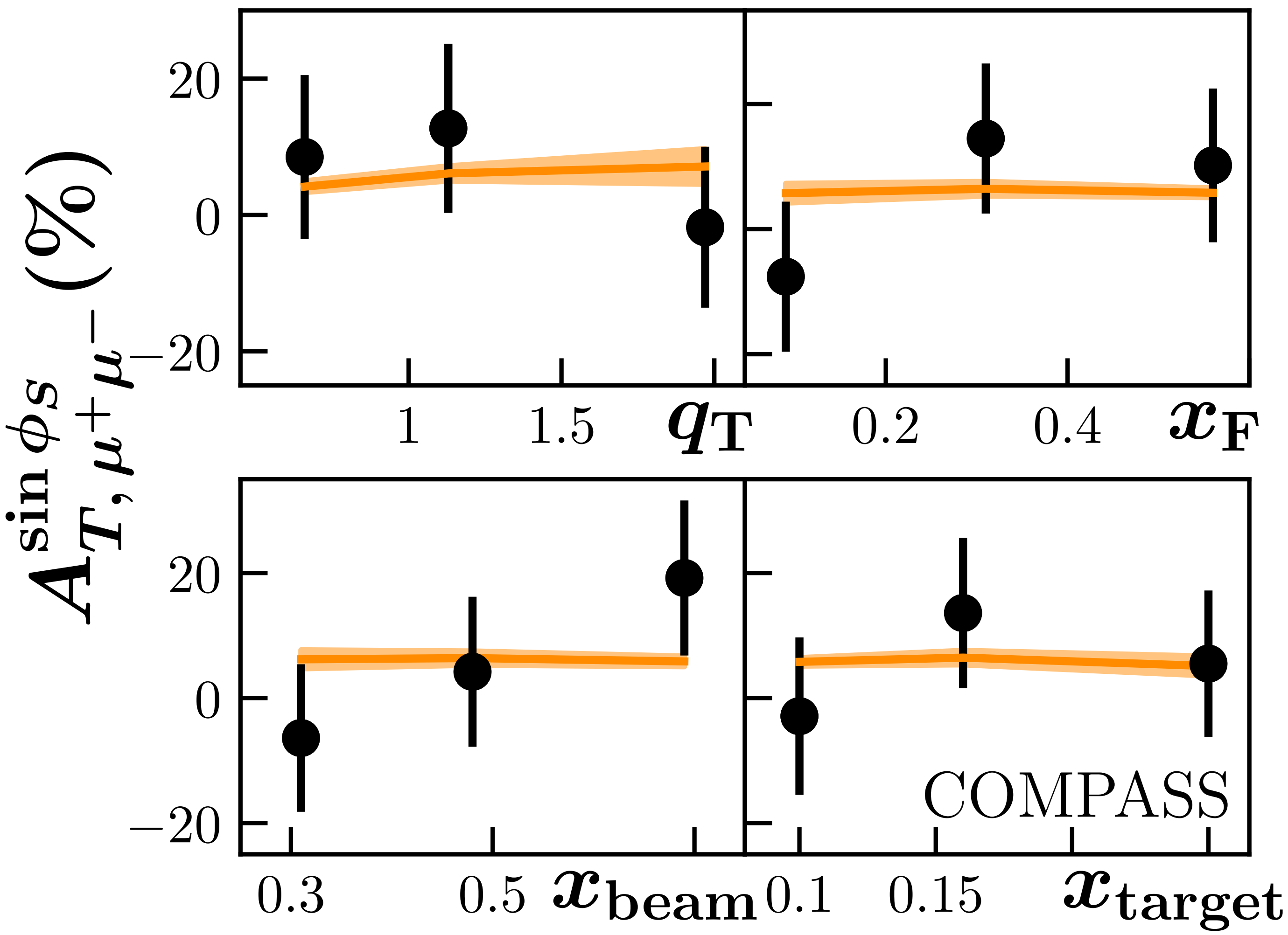
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

Drell-Yan



$$\frac{\chi^2}{npoints} = \frac{29.8}{17} = 1.75$$

STAR



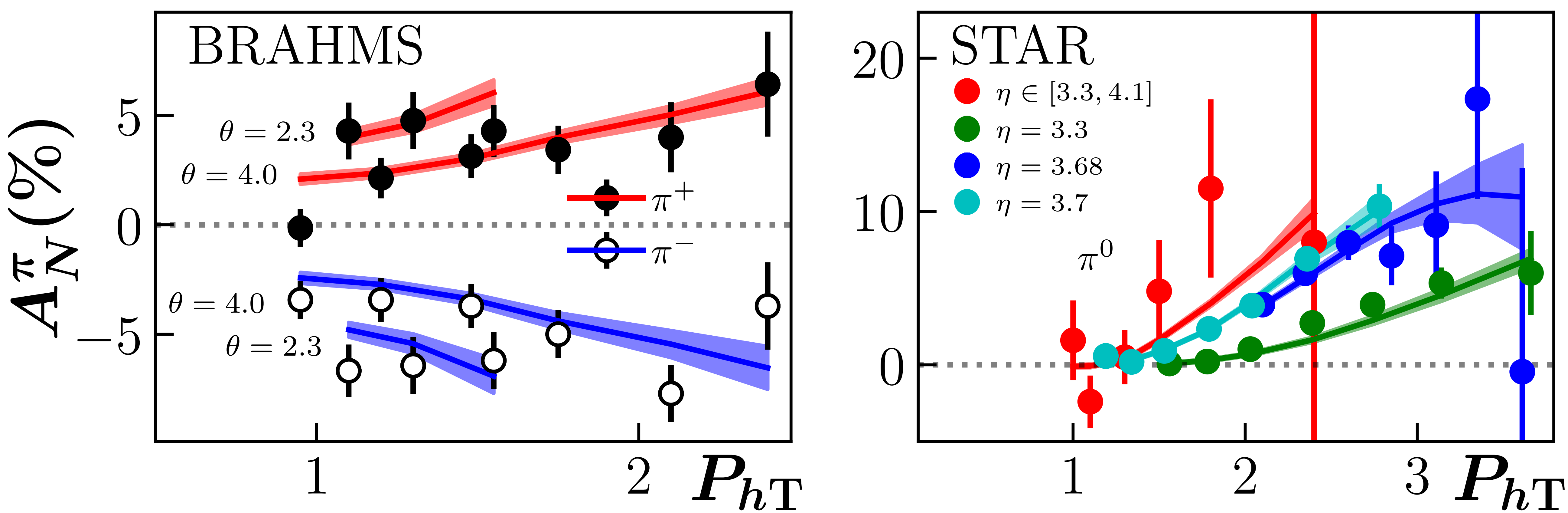
$$\frac{\chi^2}{npoints} = \frac{7.6}{12} = 0.63$$

COMPASS DY

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

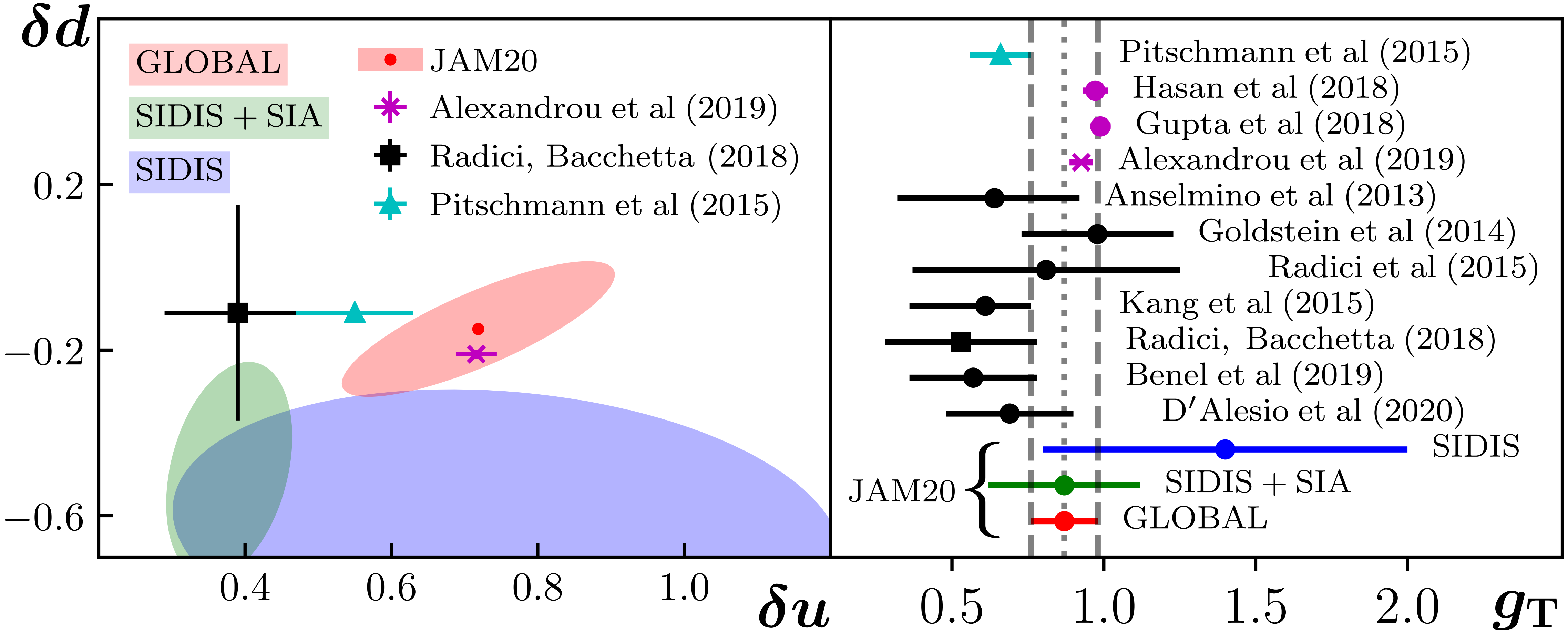
proton-proton A_N



$$\frac{\chi^2}{npoints} = \frac{72.0}{60} = 1.2$$

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



- **Tensor charge** from up and down quarks is constrained and compatible with lattice results
- Isovector tensor charge $g_T = \delta u - \delta d$
  $g_T = 0.89 \pm 0.12$ compatible with lattice results

δu and δd Q^2=4 GeV^2

δu= 0.65 $\pm$ 0.22

δd= -0.24 $\pm$ 0.2

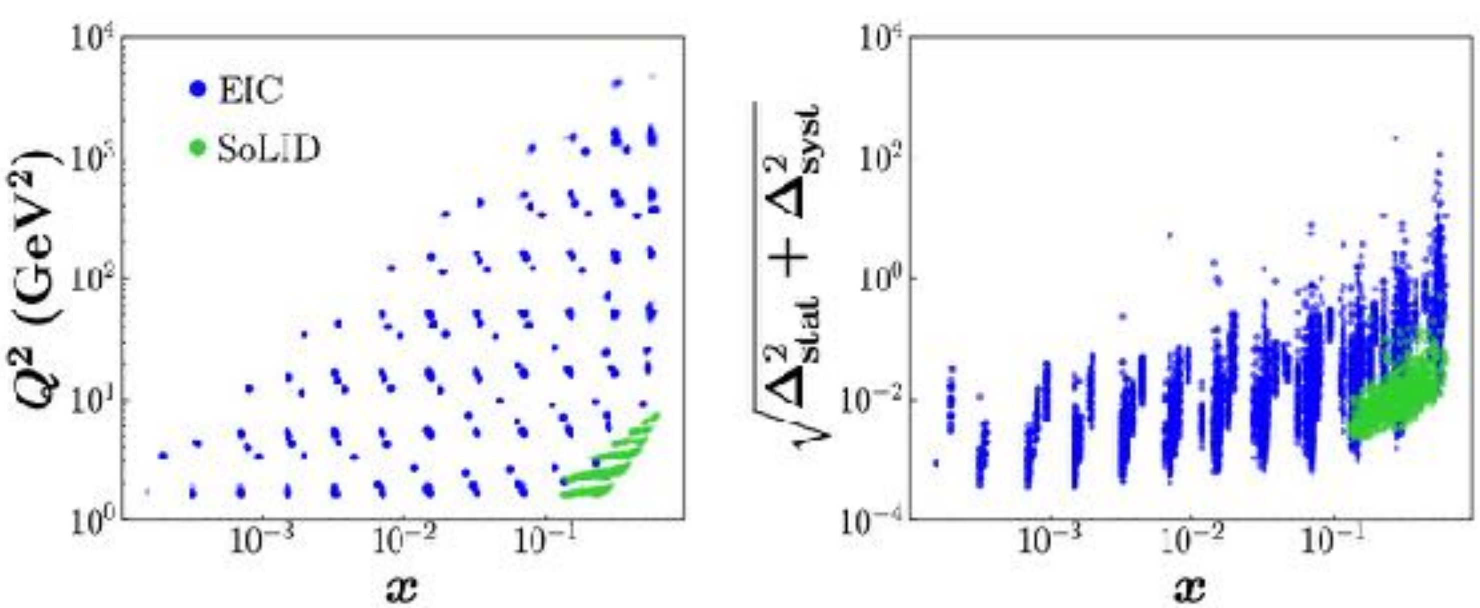
EIC IMPACT STUDY

TENSOR CHARGE AND FUTURE FACILITIES

Gamberg, Kang, Pitonyak, Prokudin, Sato, Seidl (21)

EIC Pseudo-data			
Observable	**Reactions**	**CM Energy ($\sqrt{S}$)**	**$N_{pts.}$**
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 $N_{pts.}$	**8223**

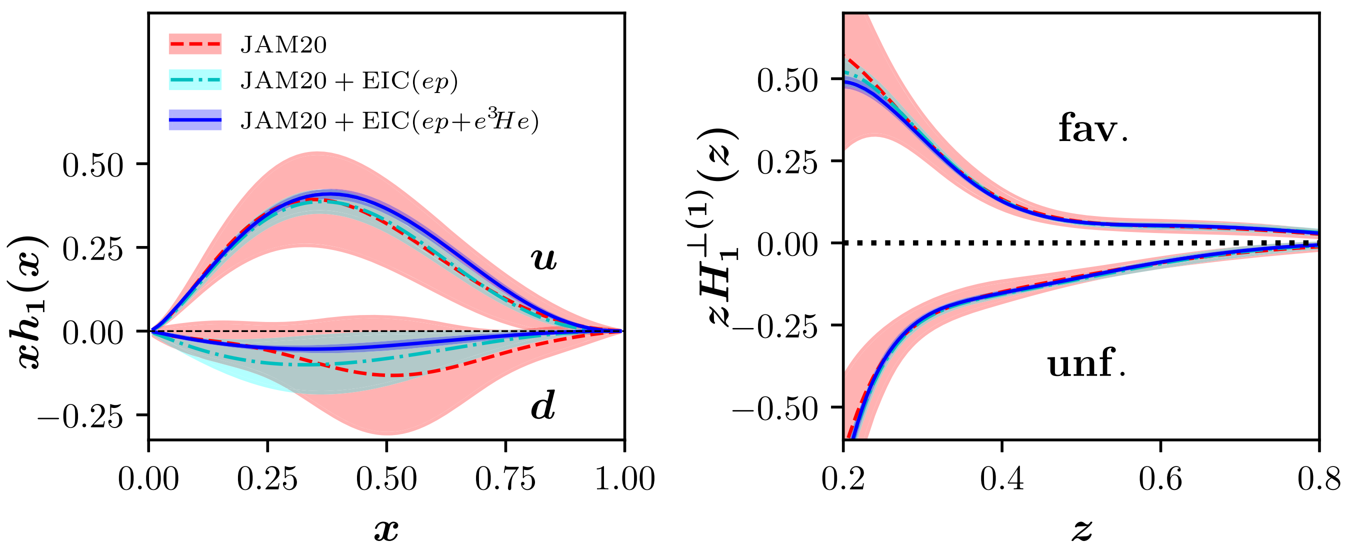
Assumed accumulated luminosities of 10 fb^{-1}, 70% polarization, conservatively accounted for detector smearing and acceptance effects

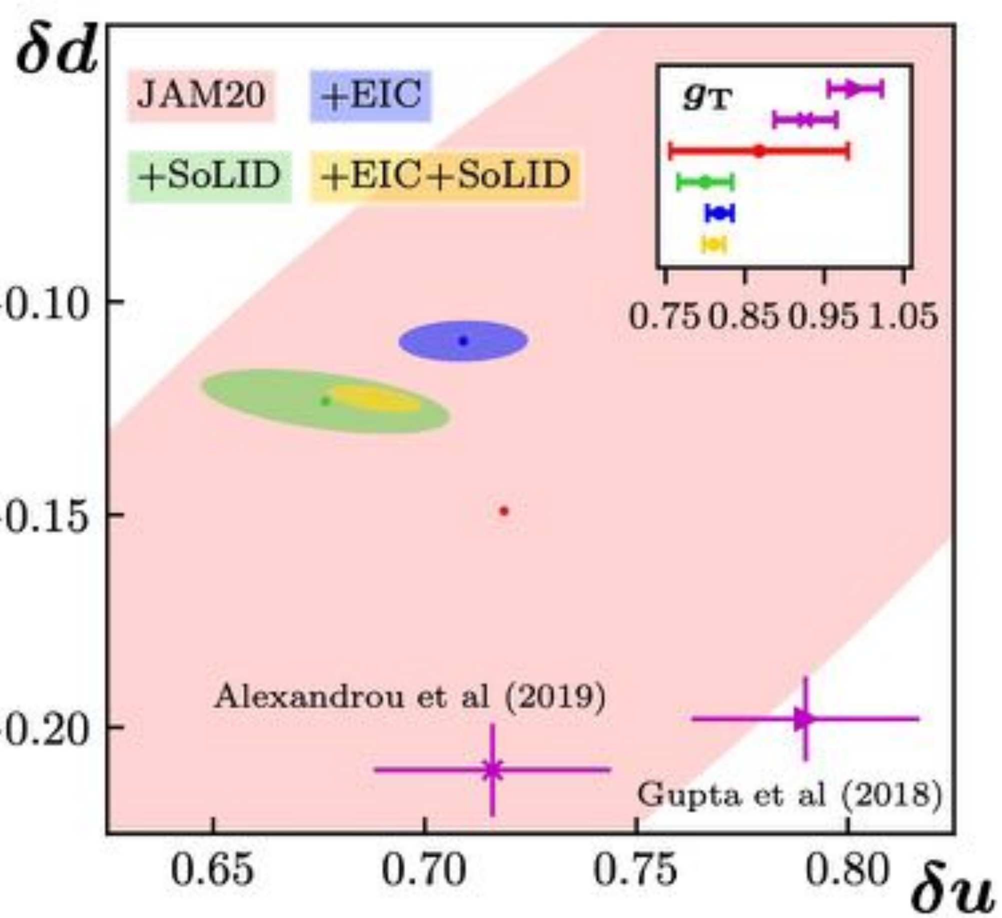


SoLID at JLab covers a complimentary region at higher x and lower Q^2 with much greater luminosity – important to explore the effect of multiple measurements in different kinematic regions

TENSOR CHARGE AND FUTURE FACILITIES

Gamberg, Kang, Pitonyak, Prokudin, Sato, Seidl (21)





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)

The combined fit that includes both EIC and SoLID pseudo-data provides the best constraint on transversity and the tensor charges, with the results more precise than current lattice calculations

TOWARDS JAM21

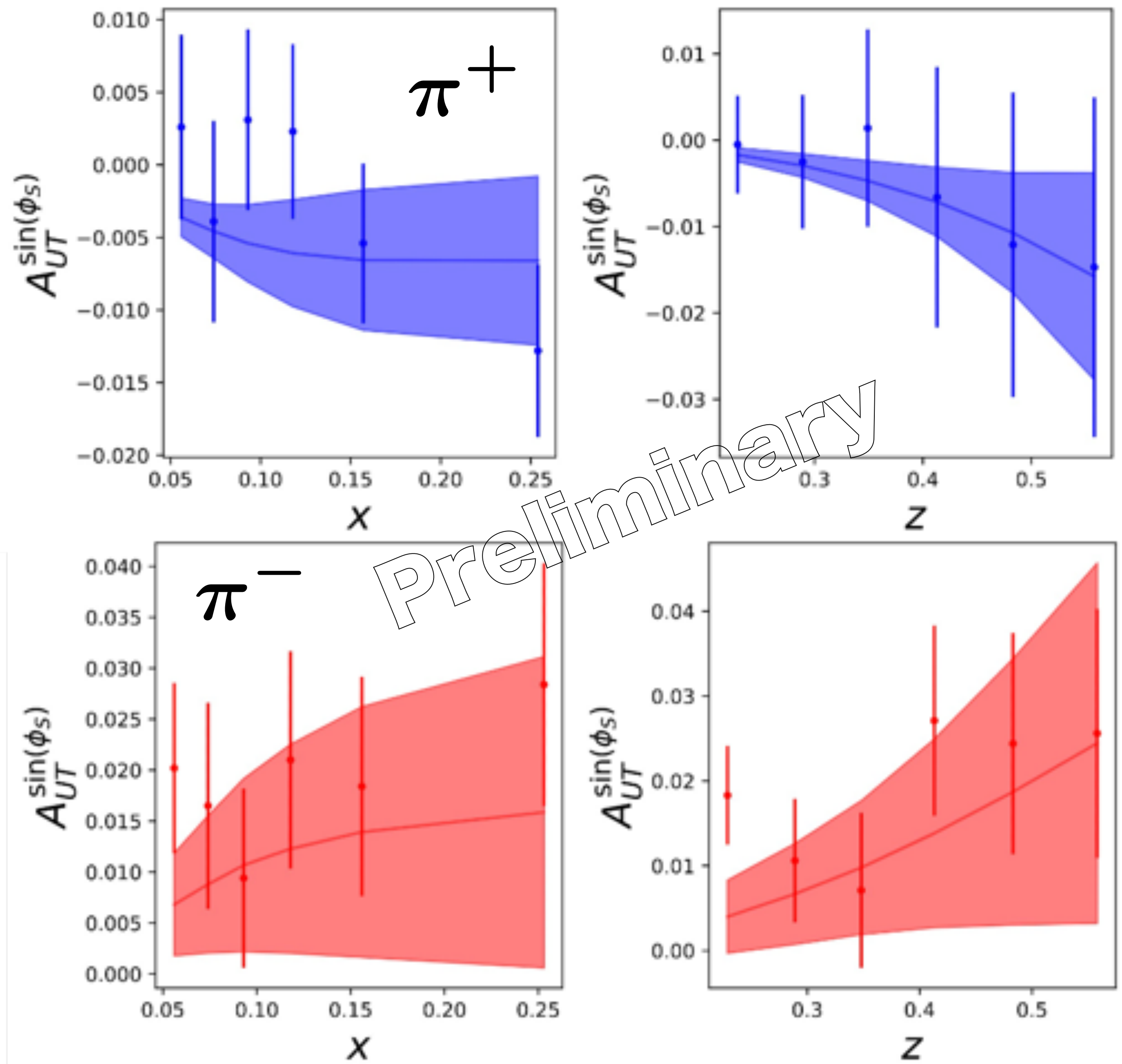
JAM21

- Collins and Sivers effects (3D binned) SIDIS data from HERMES (2020) data
- $A_{UT}^{\sin\phi_S}$ (x and z projections only) from HERMES (2020) $\tilde{H}$
- A_N (x_F and p_T dependent) data from STAR (2021)

- Lattice data on δu, δd, g_T at the physical pion mass from Alexandrou, et al. (2019)
- Imposing the Soffer bound on transversity $$|h_1^q(x)| \leq \frac{1}{2}(f_1^q(x) + g_1^q(x))$$

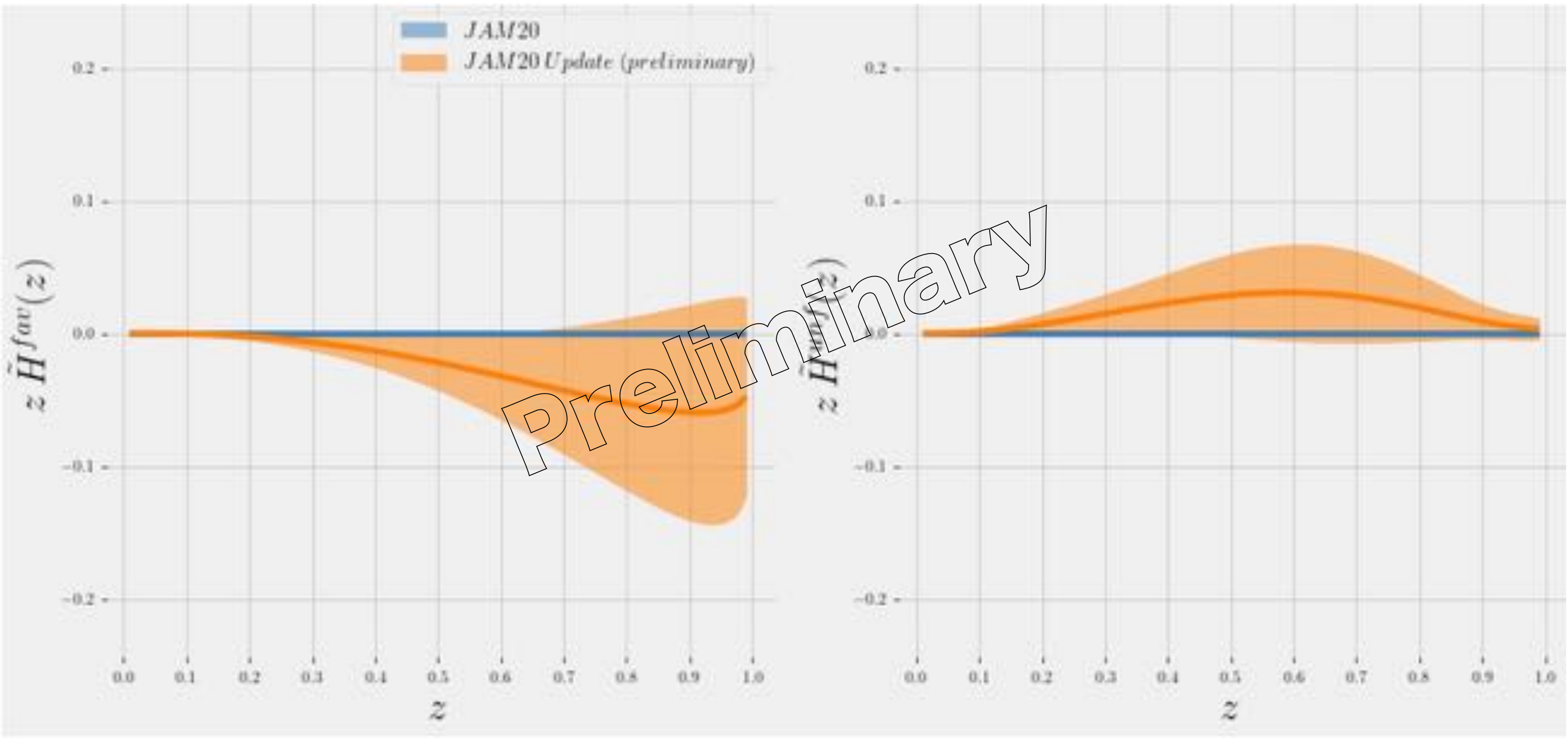
JAM21

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



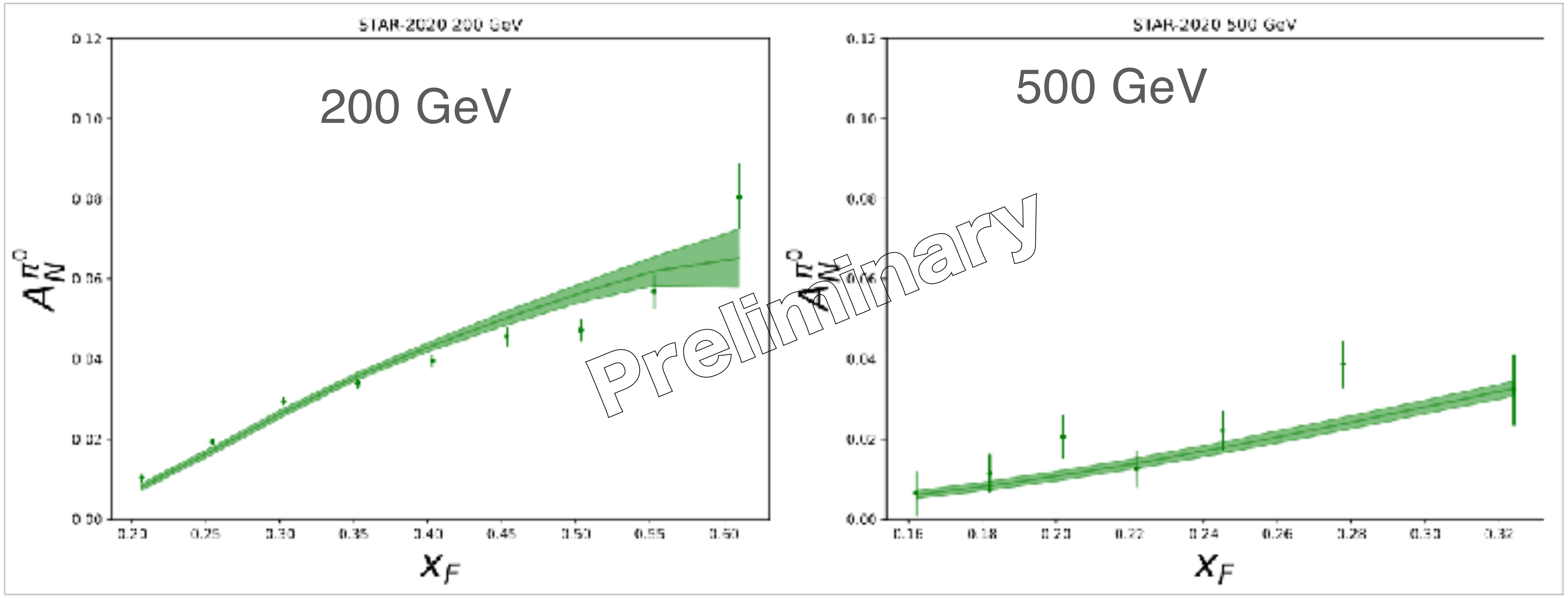
JAM21

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



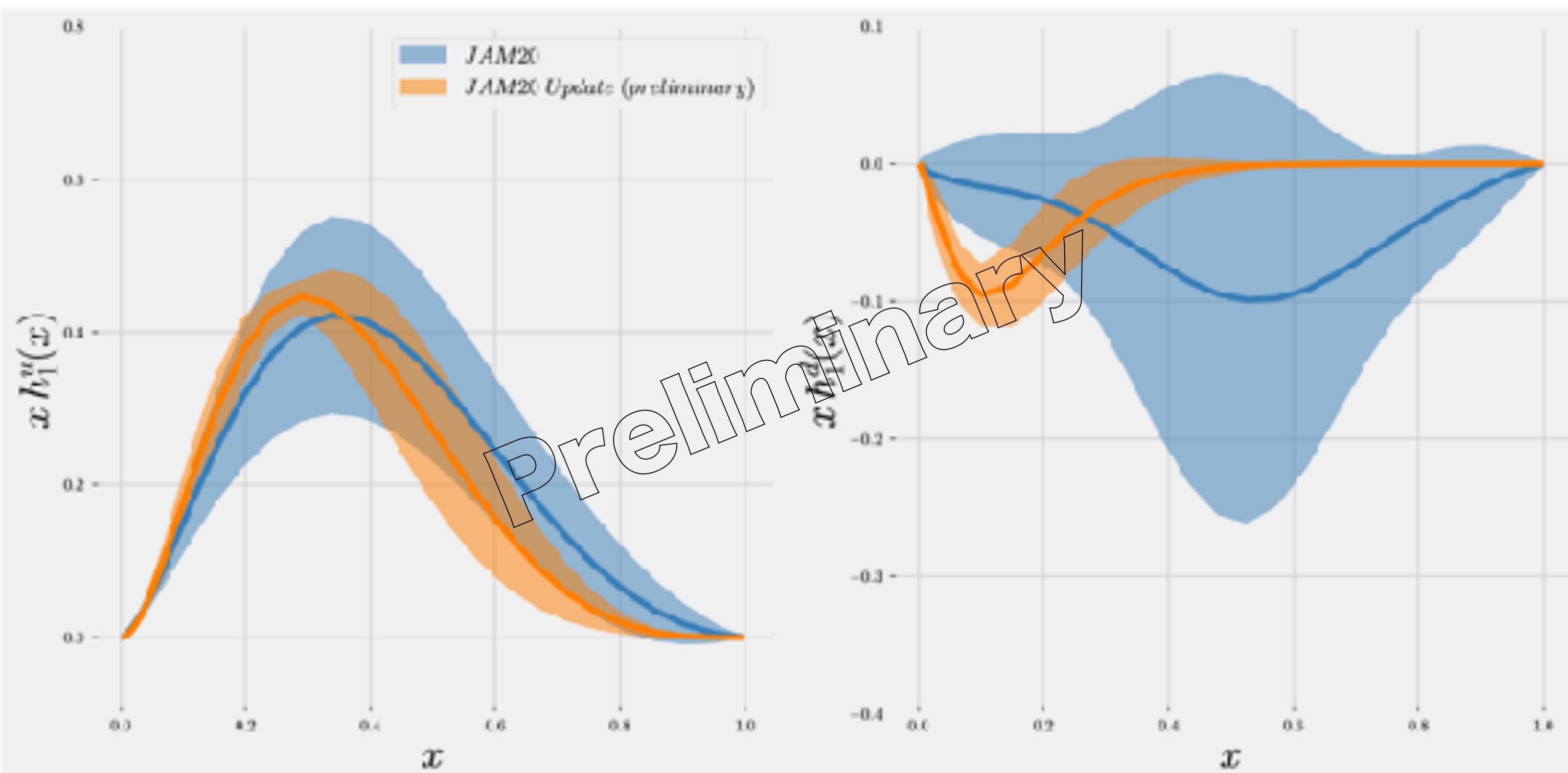
JAM21

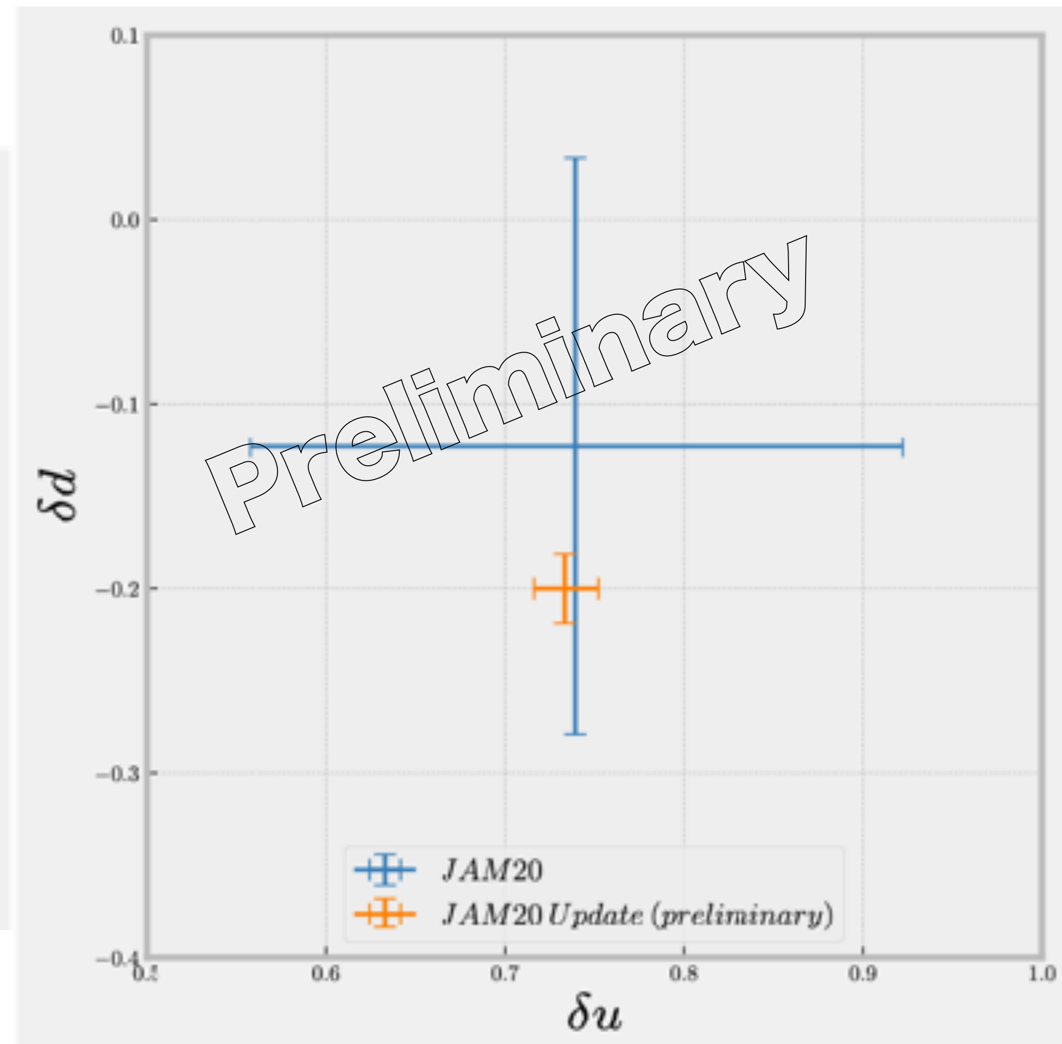
Description of the new A_N STAR data



JAM21

Improved extraction of transversity and the tensor charge.





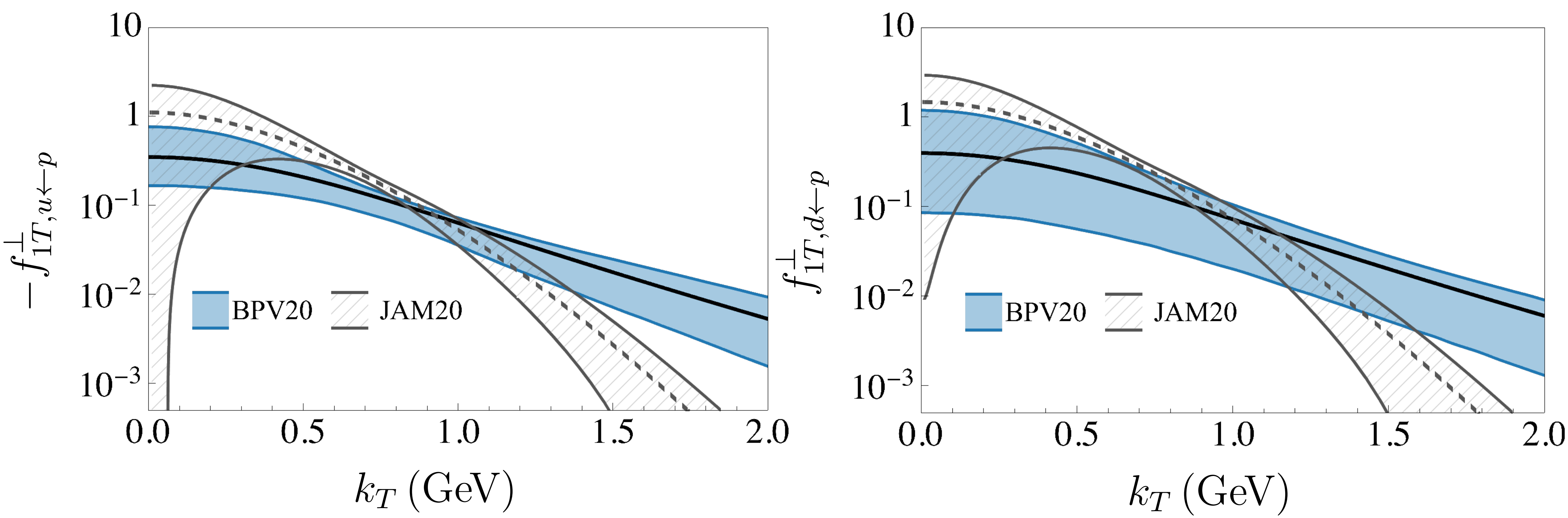
CONCLUSIONS

- 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
- Phenomenological results are consistent with lattice QCD in extraction of the isovector tensor charge g_T and individual contributions from up and down quarks
- The future EIC and JLab data will allow to have tensor charge extraction at the precision level of lattice QCD calculations

BACKUP SLIDES

SIVERS FUNCTION IN THE MOMENTUM SPACE

Bury, Prokudin, Vladimirov (2021)



- Comparison to Jam20 (LO) analysis

Jam20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)