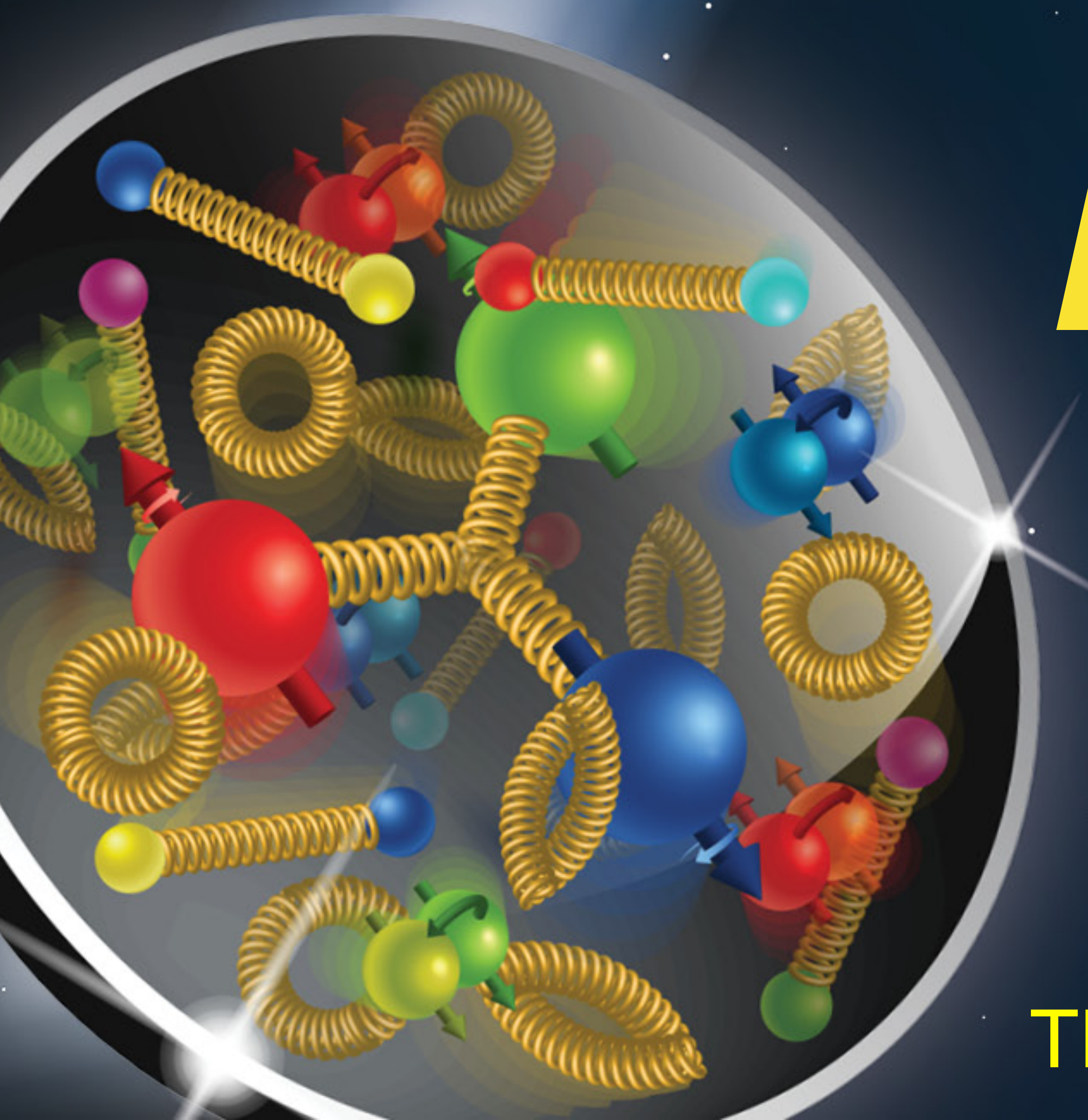


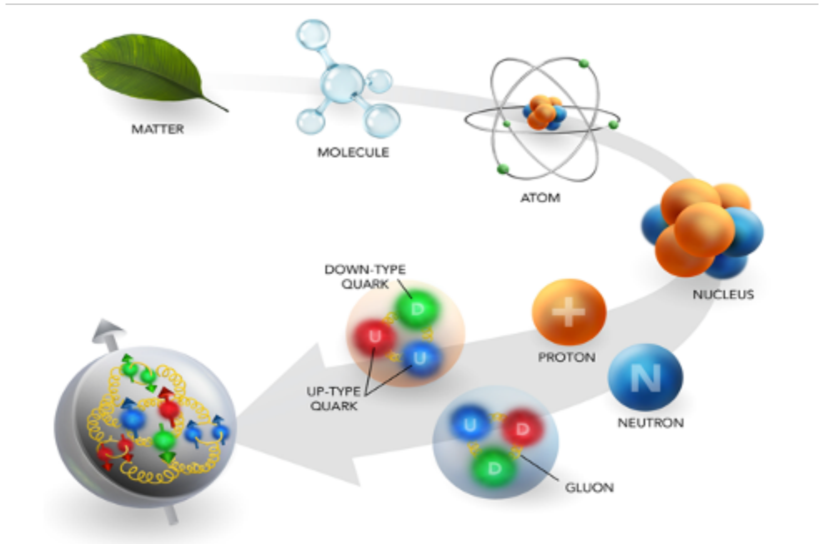
TMD phenomenology and Single Spin Asymmetries

Alexei Prokudin

PSU Berks and JLab

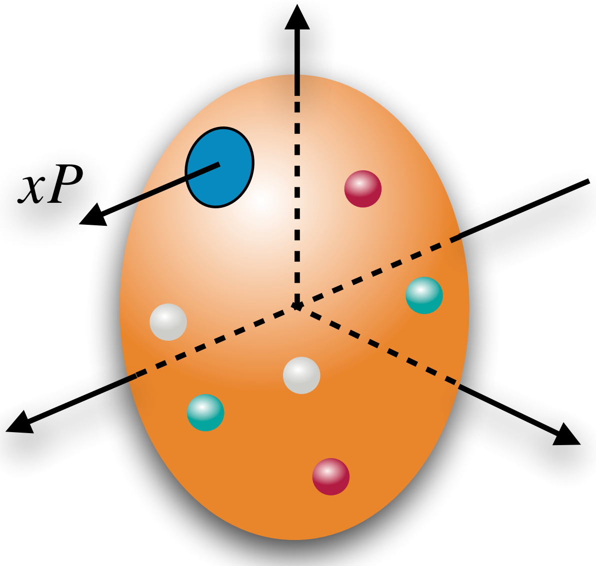
TMD = Transverse Momentum Dependent

UNRAVELLING THE MYSTERIES OF RELATIVISTIC HADRONIC BOUND STATES



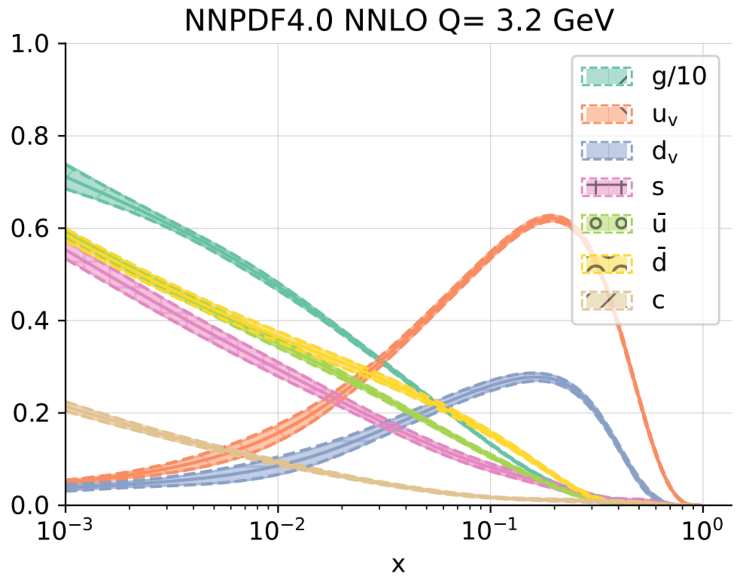
- Nucleons provide 98% of the mass of the visible universe
- One of the goals of the modern nuclear physics is to study details of the structure of the nucleon

Parton Distribution Functions provide fundamental description



$f_{q/P}(x)$

longitudinal

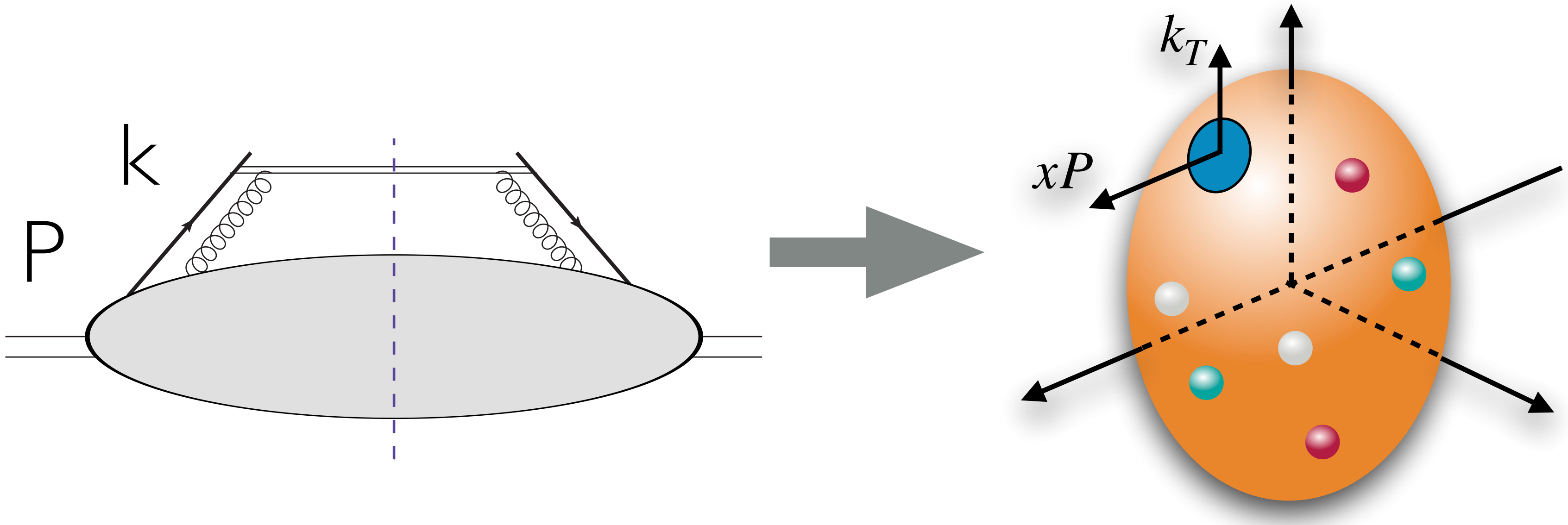


- Probability density to find a quark with a momentum fraction x
- 1D snapshop of fundamental constituents
- Study of confined quarks and gluons

HADRON'S PARTONIC STRUCTURE

To study the physics of *confined motion of quarks and gluons* inside of the proton one needs a new type "hard probe" with two scales.

Transverse Momentum Dependent functions (TMDs)



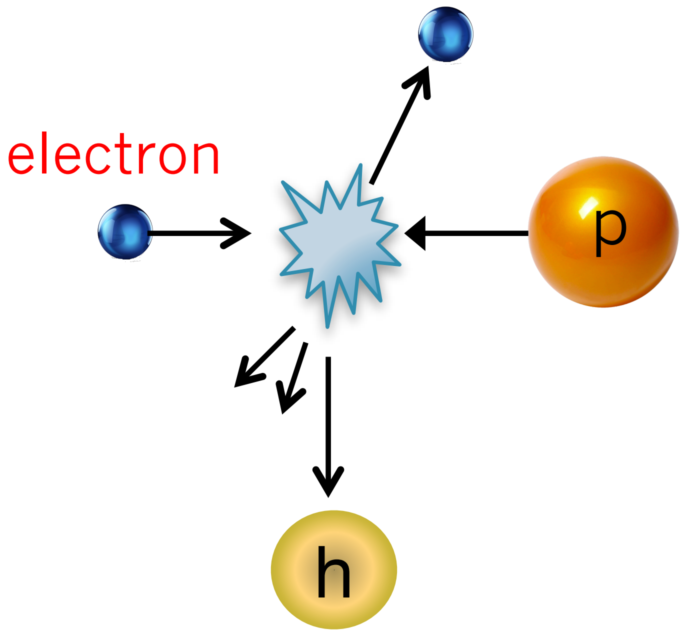
$$f_{q/P}(x, k_T)$$

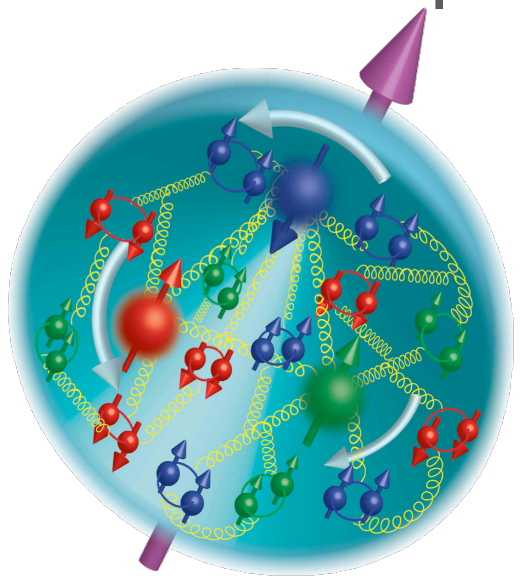
longitudinal & transverse

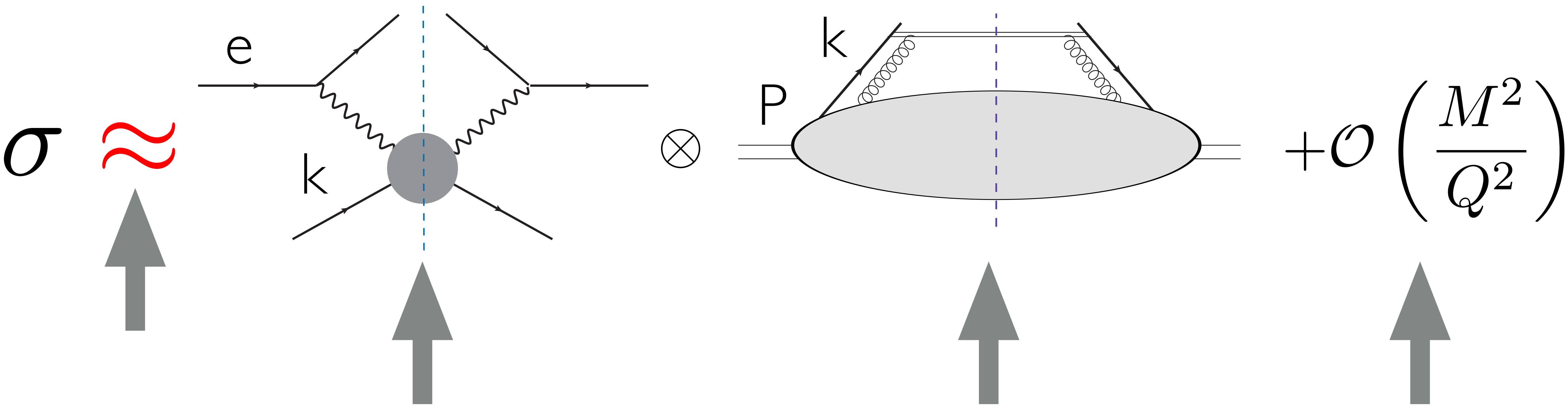
- One large scale (Q) sensitive to particle nature of quark and gluons
- One small scale (k_T) *sensitive to how QCD bounds partons* and to the detailed structure at ~fm distances.
- TMDs provide detailed information on the spin structure
- TMDs contain new probes, e.g. qgq operators rather that just qq or gg and thus include correlations
- TMDs encode 3D structure in the momentum space (complementary to GPDs)

QCD FACTORIZATION IS THE KEY!

We need a probe to “see” quarks and gluons







Factorization Probe Structure Power corrections

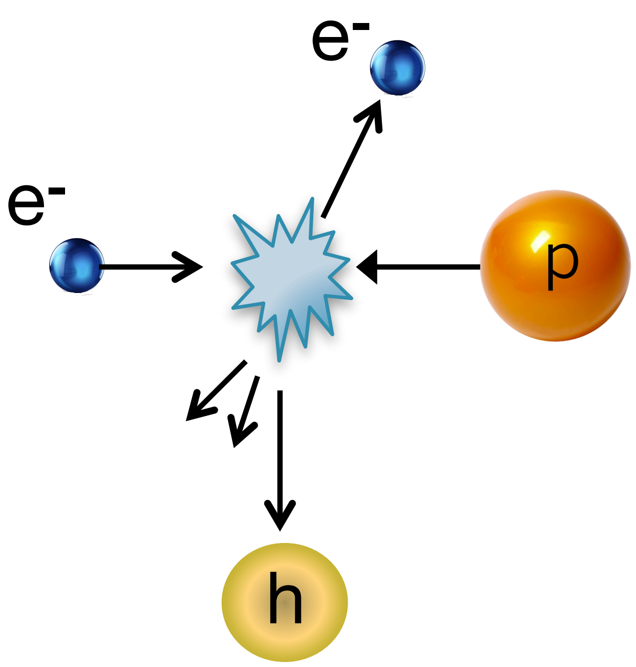
TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

Small scale → $q_T \ll Q$ ← Large scale

The confined motion (k_T dependence) is encoded in TMDs

Semi-Inclusive DIS

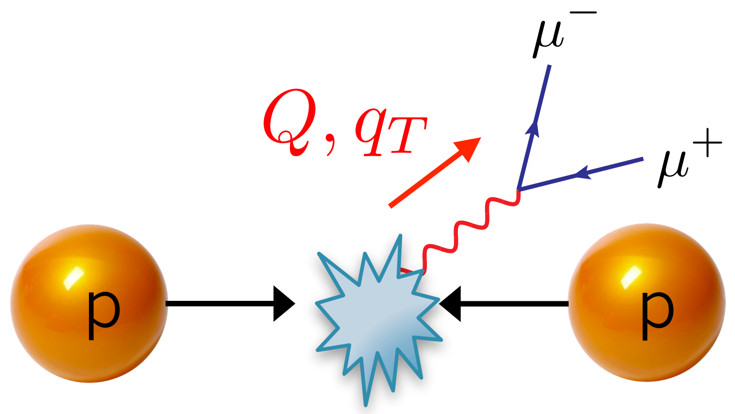
$$\sigma \sim f_{q/P}(x,k_T)D_{h/q}(z,k_T)$$



Meng, Olness, Soper (1992)
Ji, Ma, Yuan (2005)
Idilbi, Ji, Ma, Yuan (2004)
Collins (2011)

Drell-Yan

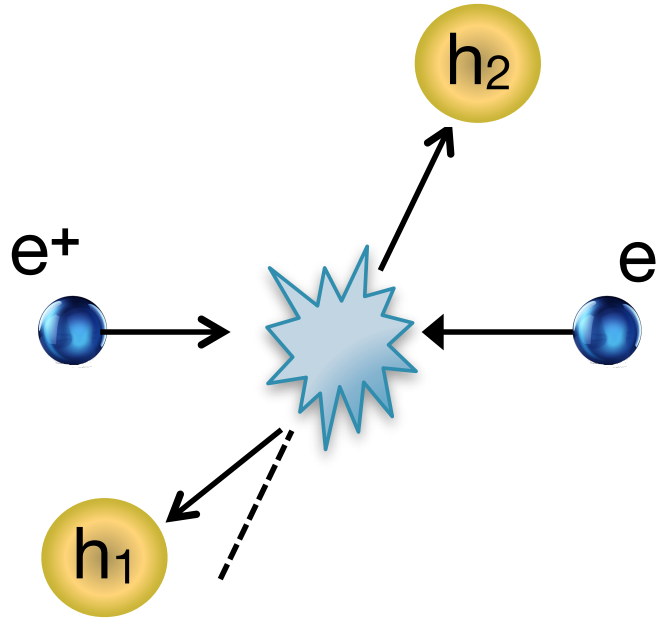
$$\sigma \sim f_{q/P}(x,k_T)f_{q/P}(x,k_T)$$



Collins, Soper, Sterman (1985)
Ji, Ma, Yuan (2004)
Collins (2011)

Dihadron in e^+e^-

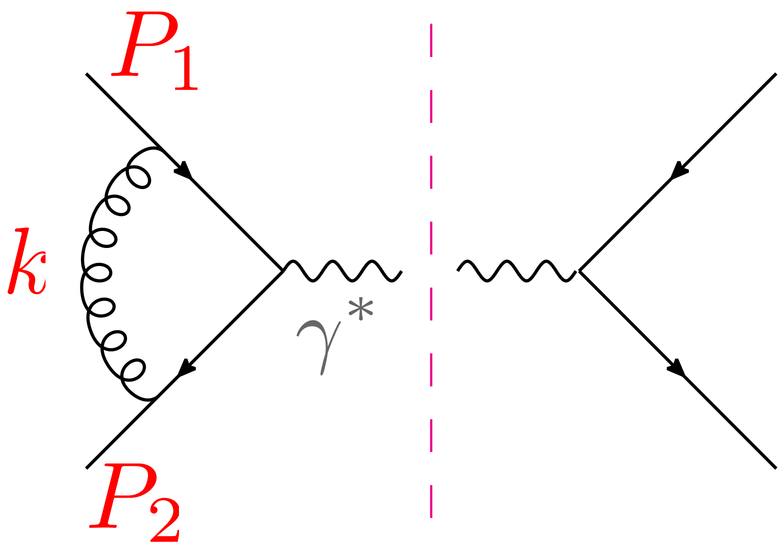
$$\sigma \sim D_{h_1/P}(z,k_T)D_{h_2/q}(z,k_T)$$



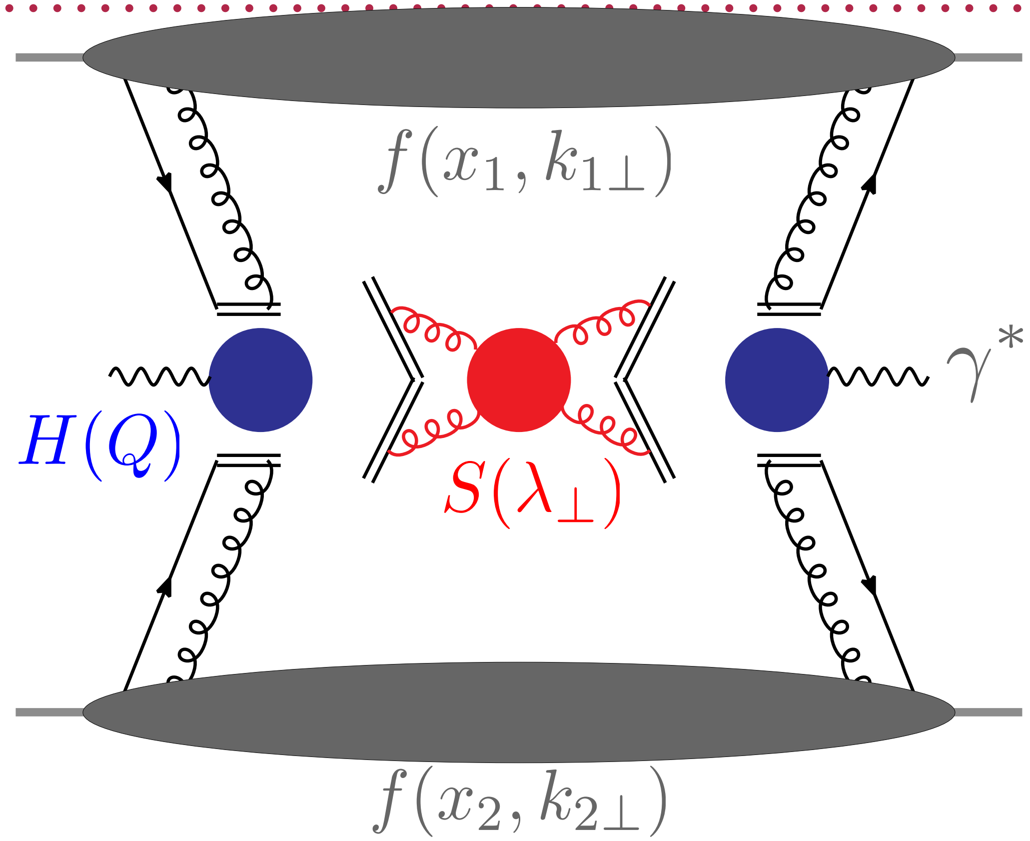
Collins, Soper (1983)
Collins (2011)

FIELD THEORY

$p+p \to [\gamma^* \to \ell^+\ell^-] + X$



Factorization of regions:
(1) k//P$_1$, (2) k//P$_2$, (3) k soft, (4) k hard



$$F(x,b) = f(x,b)\sqrt{S(b)}$$

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} = \int \frac{d^2 b}{(2\pi)^2} e^{i q_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)$$

$$\frac{d \ln \tilde{F}(x, b_T, \mu, \zeta)}{d \ln \mu} = \gamma_F(\mu)$$

$$\frac{\partial \ln \tilde{F}(x, b_T, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_T, \mu)$$

Collins-Soper Equations

μ = renormalization scale

ζ = Collins-Soper parameter

FIELD THEORY

Collins, Soper, Sterman (85), Collins (11), Rogers, Collins (15)

$$F(x,k_\perp;Q) = \frac{1}{(2\pi)^2}\int d^2b\, e^{ik_\perp\cdot b} F(x,b;Q) = \frac{1}{2\pi}\int_0^\infty db\, b J_0(k_\perp b) F(x,b;Q)$$

$$F(x,b;Q) \approx C\otimes F(x,c/b^*) \times \exp\left\{-\int_{c/b^*}^{Q}\frac{d\mu}{\mu}\left(A\ln\frac{Q^2}{\mu^2}+B\right)\right\} \times \exp\left(-S_{\text{non-pert}}(b,Q)\right)$$

OPE/collinear part

transverse part, Sudakov FF

- The evolution is complicated as one evolves in 2 dimensions
- The presence of a non-perturbative evolution kernel makes calculations more involved
- Theoretical constraints exist on both non-perturbative shape of TMD and the non-perturbative kernel of evolution
- Perturbative ingredients are known up to N4LL - precision science (LL = leading log)

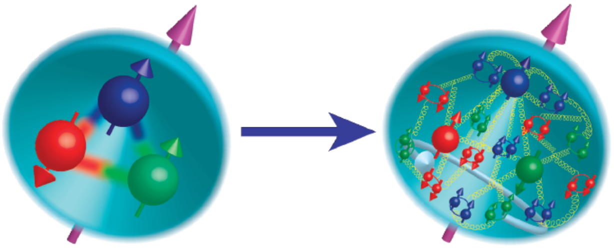
✓ **Non-perturbative: fitted from data**

✓ The key ingredient – ln(Q) piece is spin-independent

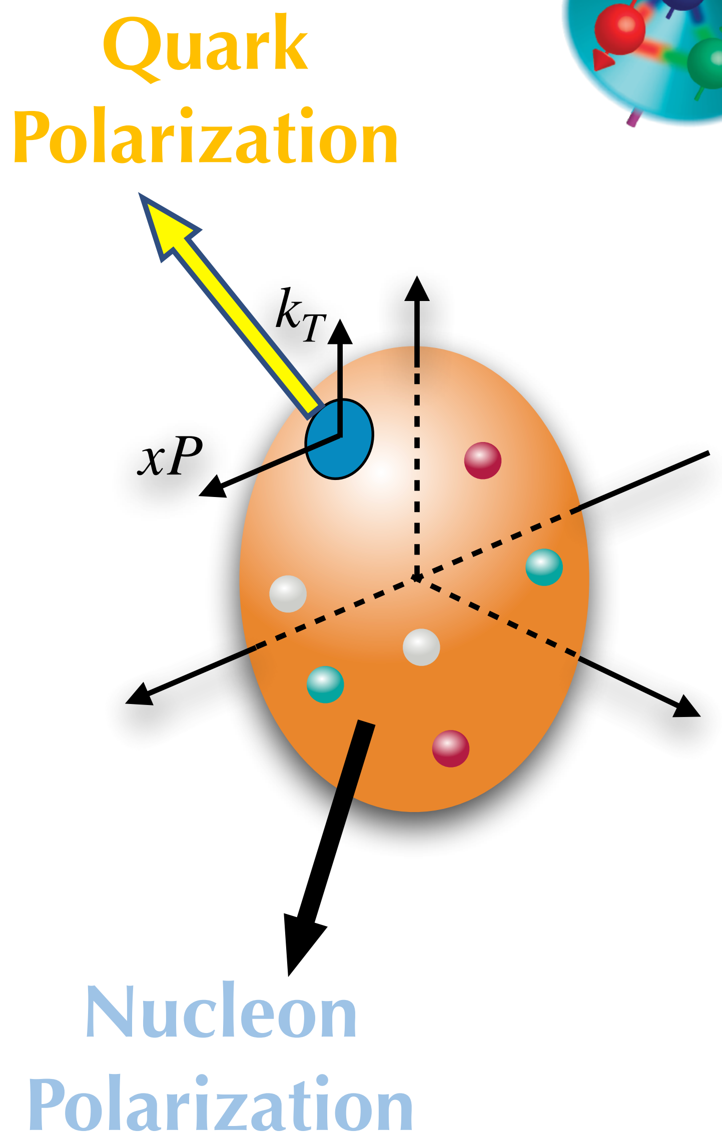
✓ Non-perturbative shape of TMDs is to be extracted from data

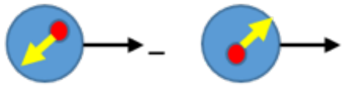
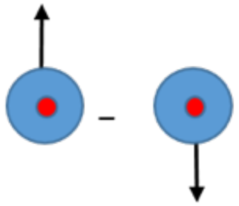
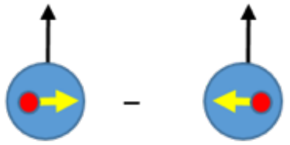
✓ One can use information from models or ab-initio calculations, such as lattice QCD: shape of TMDs, non-perturbative kernel.

Our understanding of hadron evolves: TMDs with Polarization



Nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons



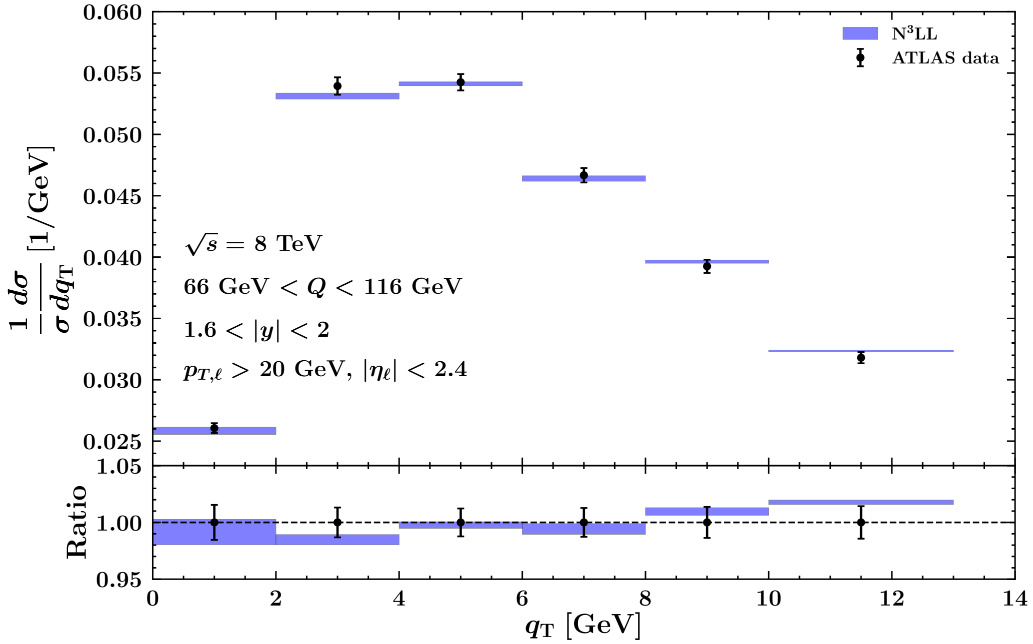
		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$  **Unpolarized**		$h_1^\perp(x,k_T^2)$  **Boer-Mulders**
	L		$g_1(x,k_T^2)$  **Helicity**	$h_{1L}^\perp(x,k_T^2)$  **Kozinian-Mulders, "worm" gear**
	T	$f_{1T}^\perp(x,k_T^2)$  **Sivers**	$g_{1T}(x,k_T^2)$  **Kozinian-Mulders, "worm" gear**	$h_1(x,k_T^2)$  **Transversity** $h_{1T}^\perp(x,k_T^2)$  **Pretzelosity**

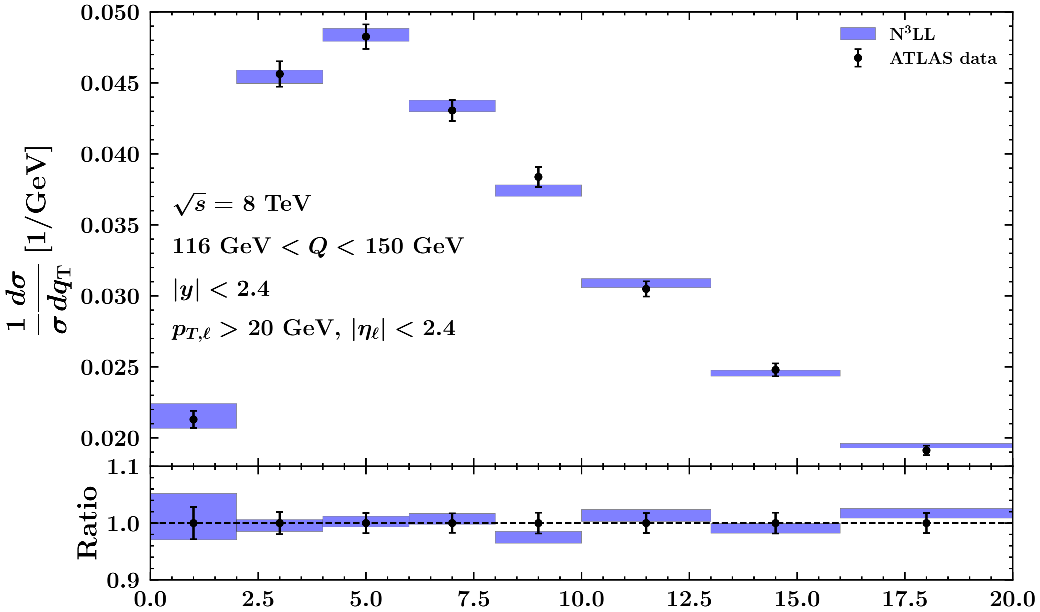
Analogous tables for:

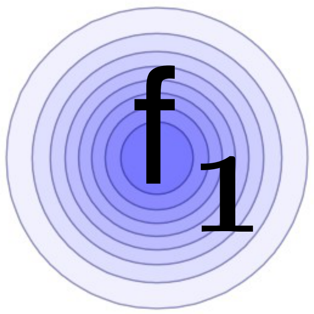
- Gluons $f_1 \to f_1^g$ etc
- Fragmentation functions
- Nuclear targets $S \neq \frac{1}{2}$

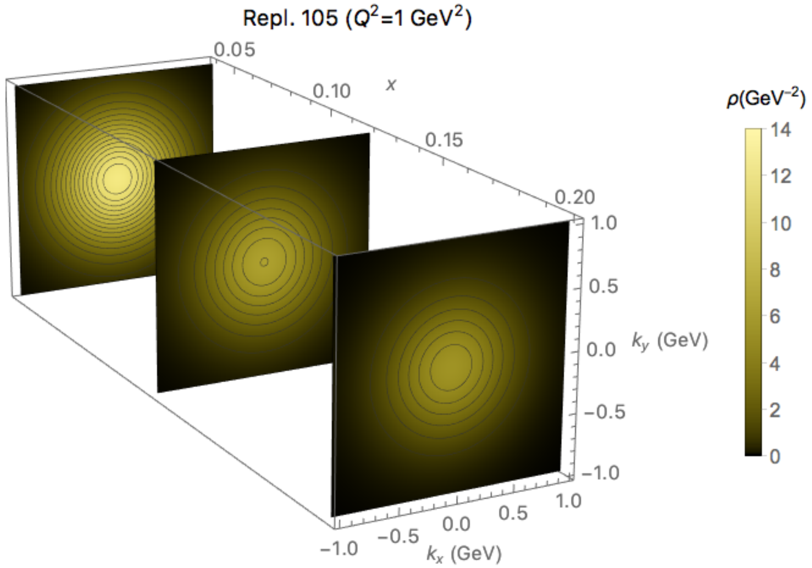
UNPOLARIZED TMD MEASUREMENTS

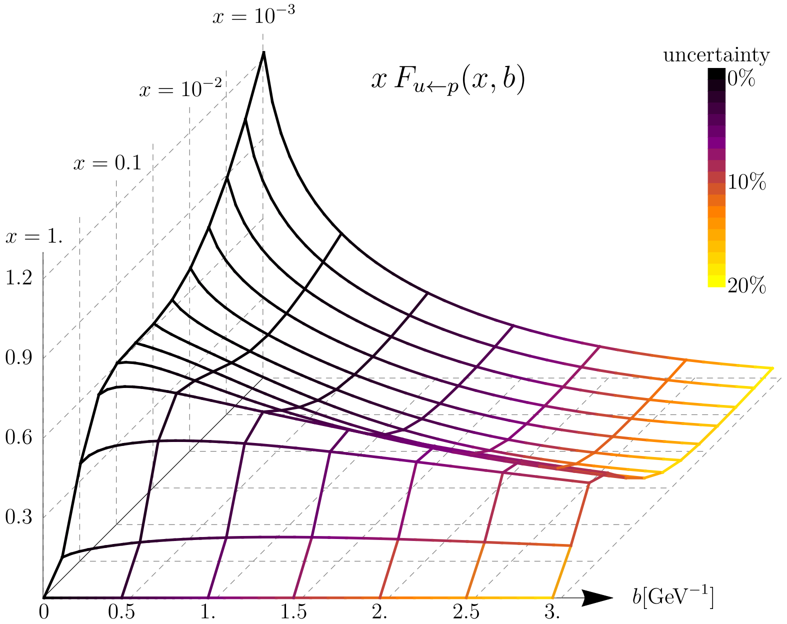
Unpolarized Drell-Yan cross section at N3LL accuracy in the region of validity of TMD factorization











- ➤ Addresses the question of partonic confined motion
- ➤ Evolution with x and Q^2
- ➤ LHC provides precise data

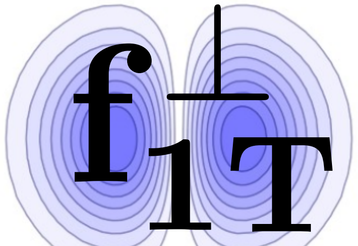
Bacchetta, Delcarro, Pisano, Radici, Signori, JHEP 07 (2020) 117

Bertone, Scimemi, Vladimirov, JHEP 06 (2019) 028

SPIN STRUCTURE OF THE NUCLEON

POLARIZED TMD FUNCTIONS

Sivers function

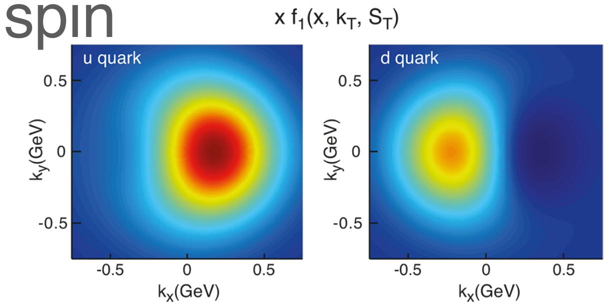


$f_{1T}^{\perp}$

- Describes unpolarized quarks inside of transversely polarized nucleon

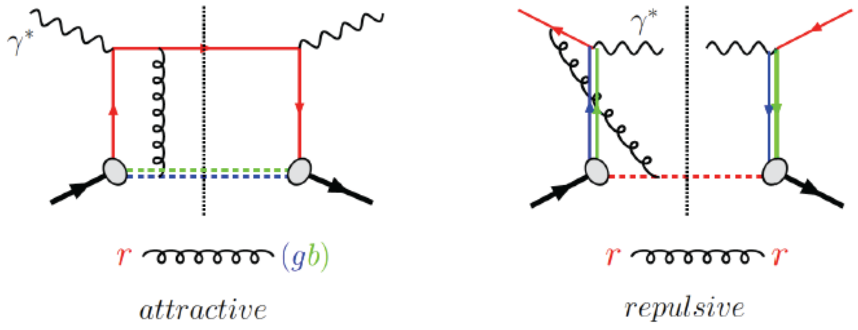
$$\rho_{1;q\leftarrow h^{\uparrow}}(x,\boldsymbol{k}_T,\boldsymbol{S}_T,\mu)=f_{1;q\leftarrow h}(x,k_T;\mu,\mu^2)-\frac{k_{Tx}}{M}f^{\perp}_{1T;q\leftarrow h}(x,k_T;\mu,\mu^2)$$

- Encodes the correlation of orbital motion with the spin



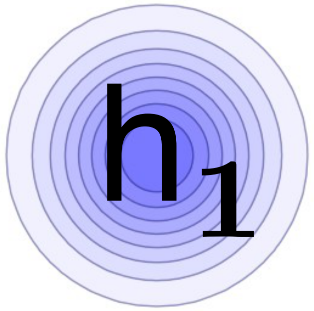
- Sign change of Sivers function is fundamental consequence of QCD

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



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

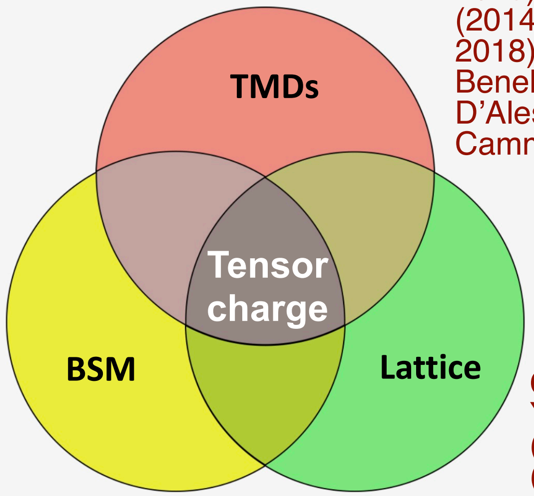
Transversity



h_1

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

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



TMDs

Tensor charge

BSM

Lattice

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)

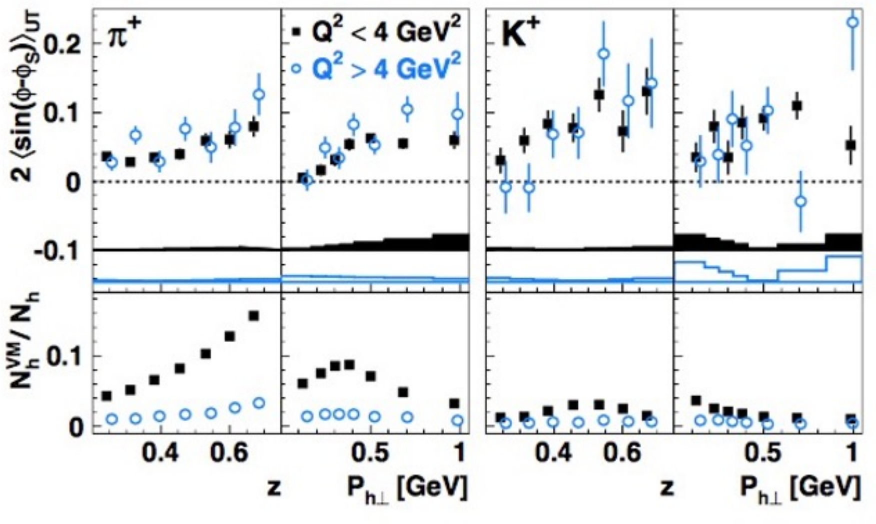
Courtoy, et al. (2015); Yamanaka, et al. (2017); Liu, et al. (2018); Gonzalez-Alonso, et al. (2019)

Gupta, et al. (2018); Yamanaka, et al. (2018); Hasan, et al. (2019); Alexandrou, et al. (2019)

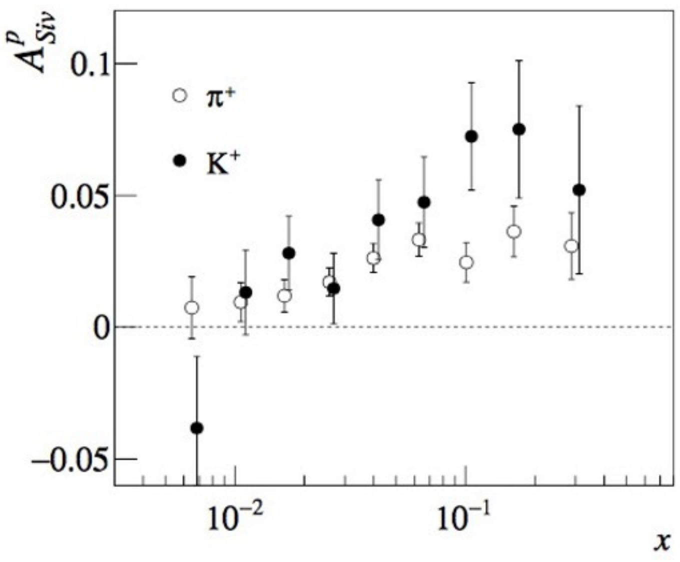
TRANSVERSE SPIN ASYMMETRIES

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

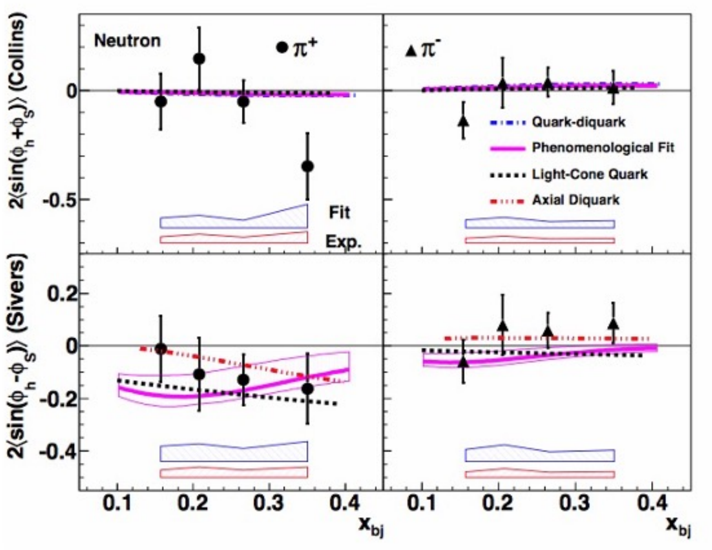
Sivers asymmetry in SIDIS



HERMES (09)



COMPASS (15)



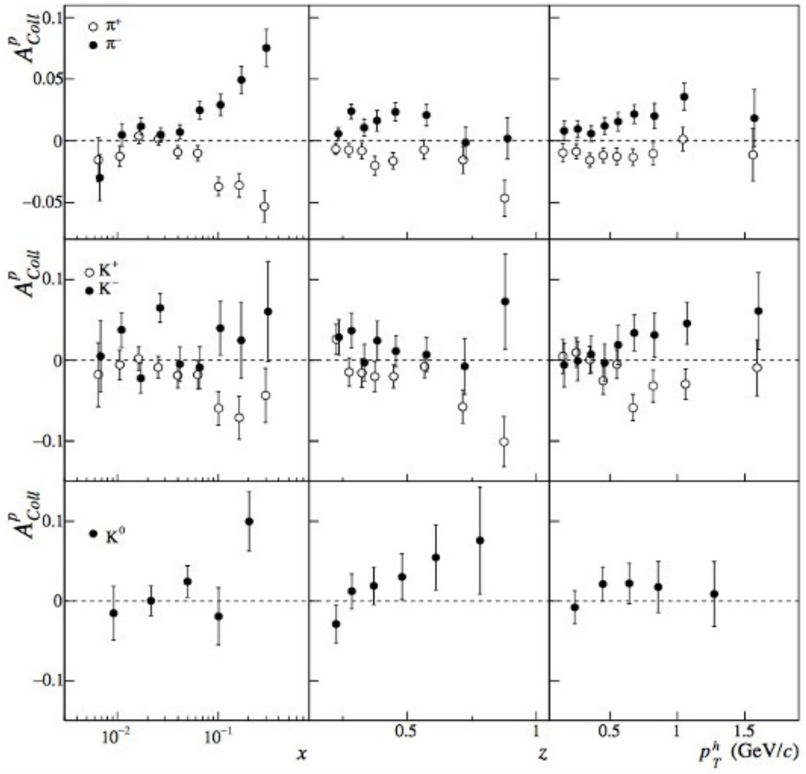
JLAB (11)

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

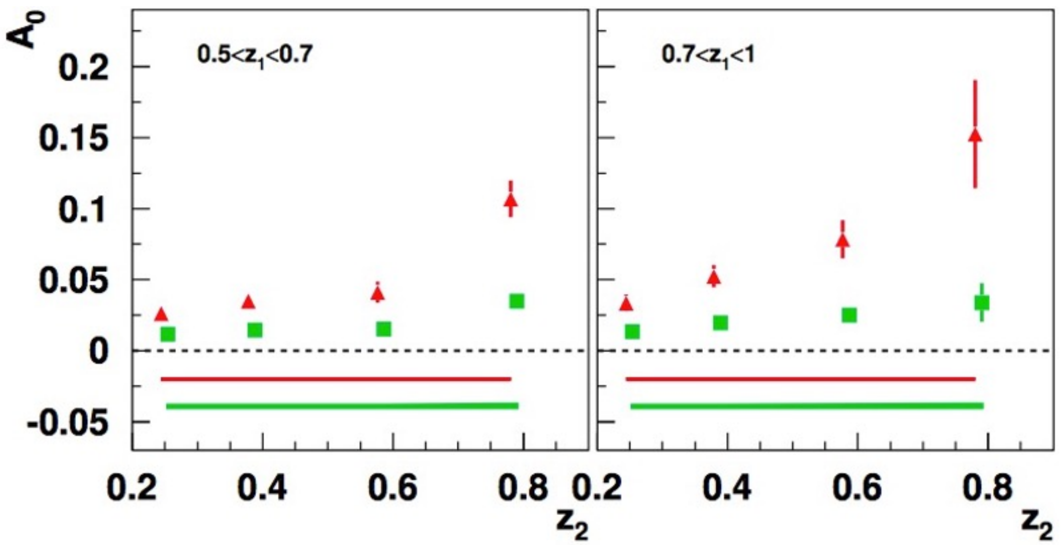
TRANSVERSE SPIN ASYMMETRIES

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)

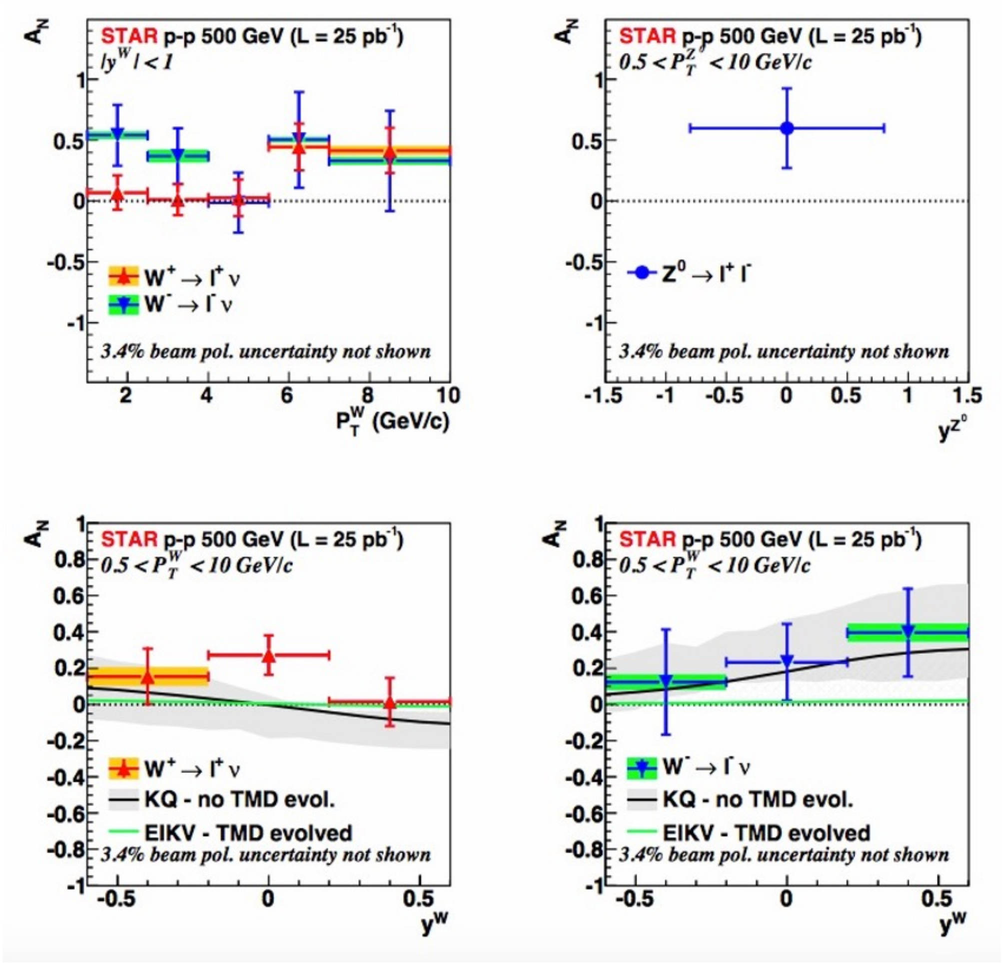
$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{p}_\perp}{M_h}\boldsymbol{h_1}\boldsymbol{H_1^\perp}\right]$$

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

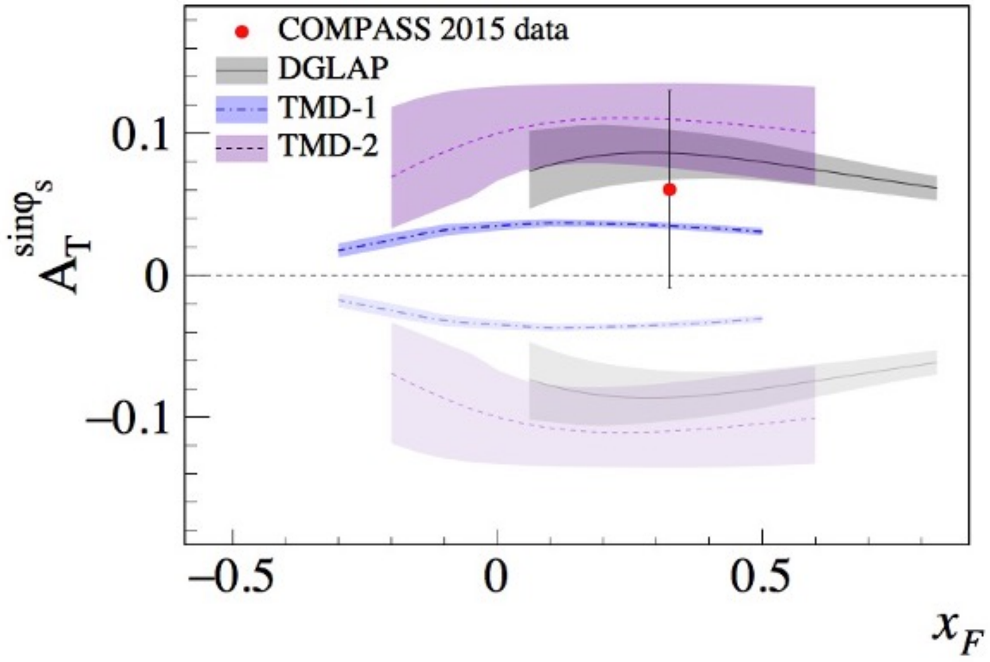
TRANSVERSE SPIN ASYMMETRIES

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

Sivers effect in Drell-Yan



STAR (15)



COMPASS (17)

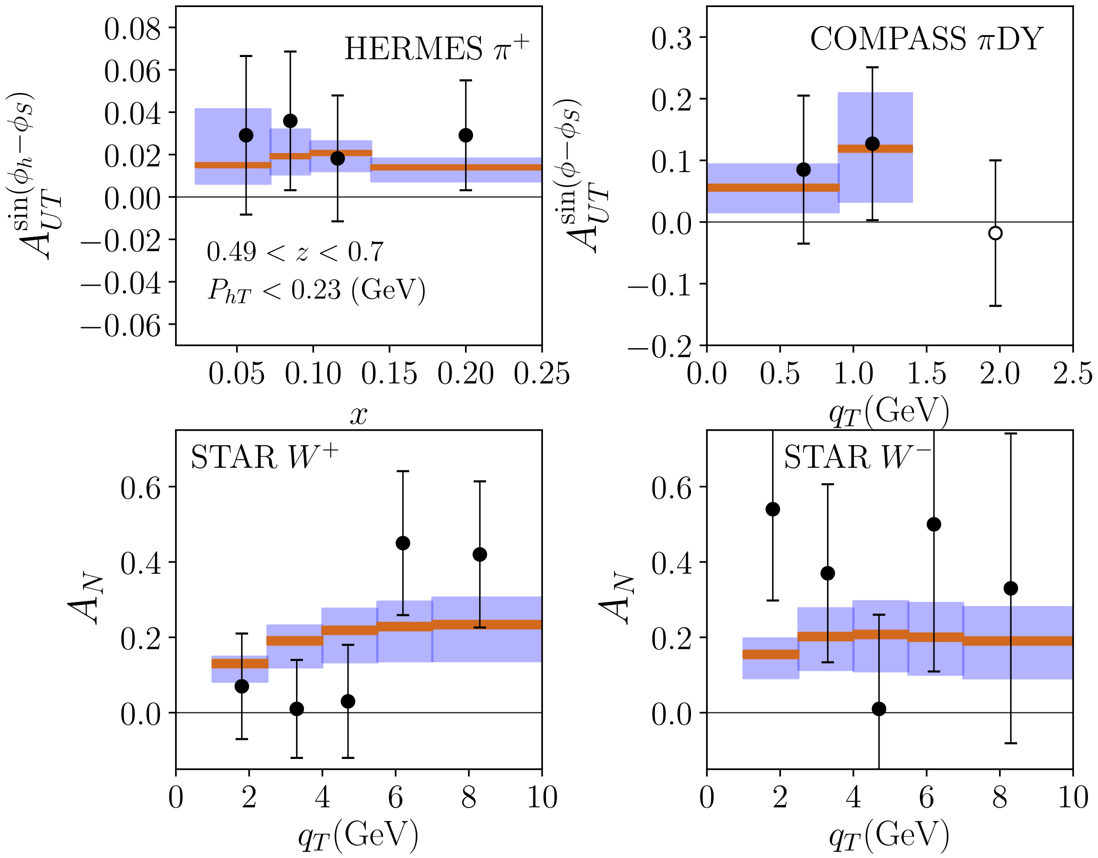
$$F_{TU}^{1} = \mathcal{C}\left[-\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a}\, \boldsymbol{f_{1T}^{\perp}}\, \bar{f}_1\right]$$

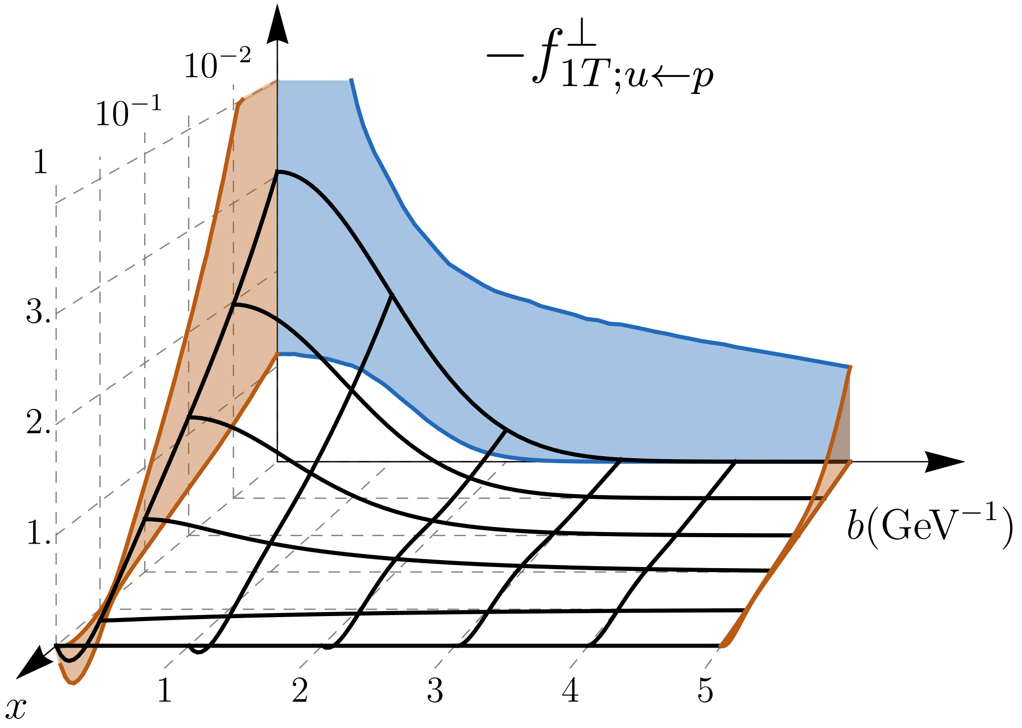
Bury, Prokudin, Vladimirov Phys.Rev.Lett. 126 (2021) 11, 11200
Bury, Prokudin, Vladimirov JHEP 05 (2021) 151

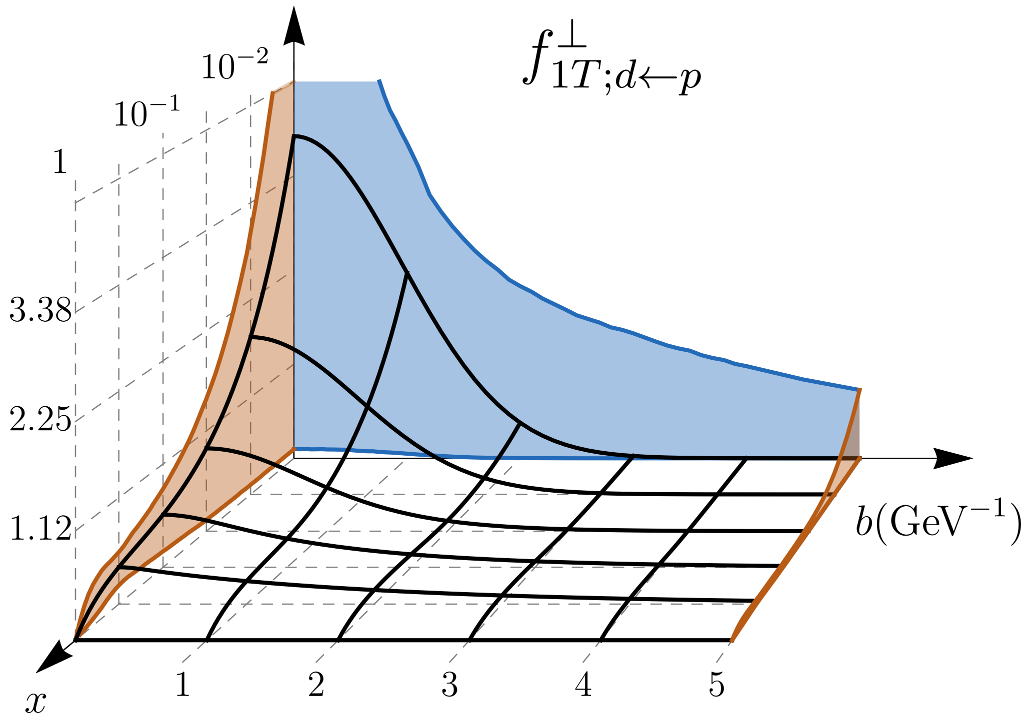
EXTRACTION OF THE SIVERS FUNCTIONS

N3LO EXTRACTION OF THE SIVERS FUNCTION

Bury, Prokudin, Vladimirov Phys.Rev.Lett. 126 (2021) 11, 11200
Bury, Prokudin, Vladimirov JHEP 05 (2021) 151



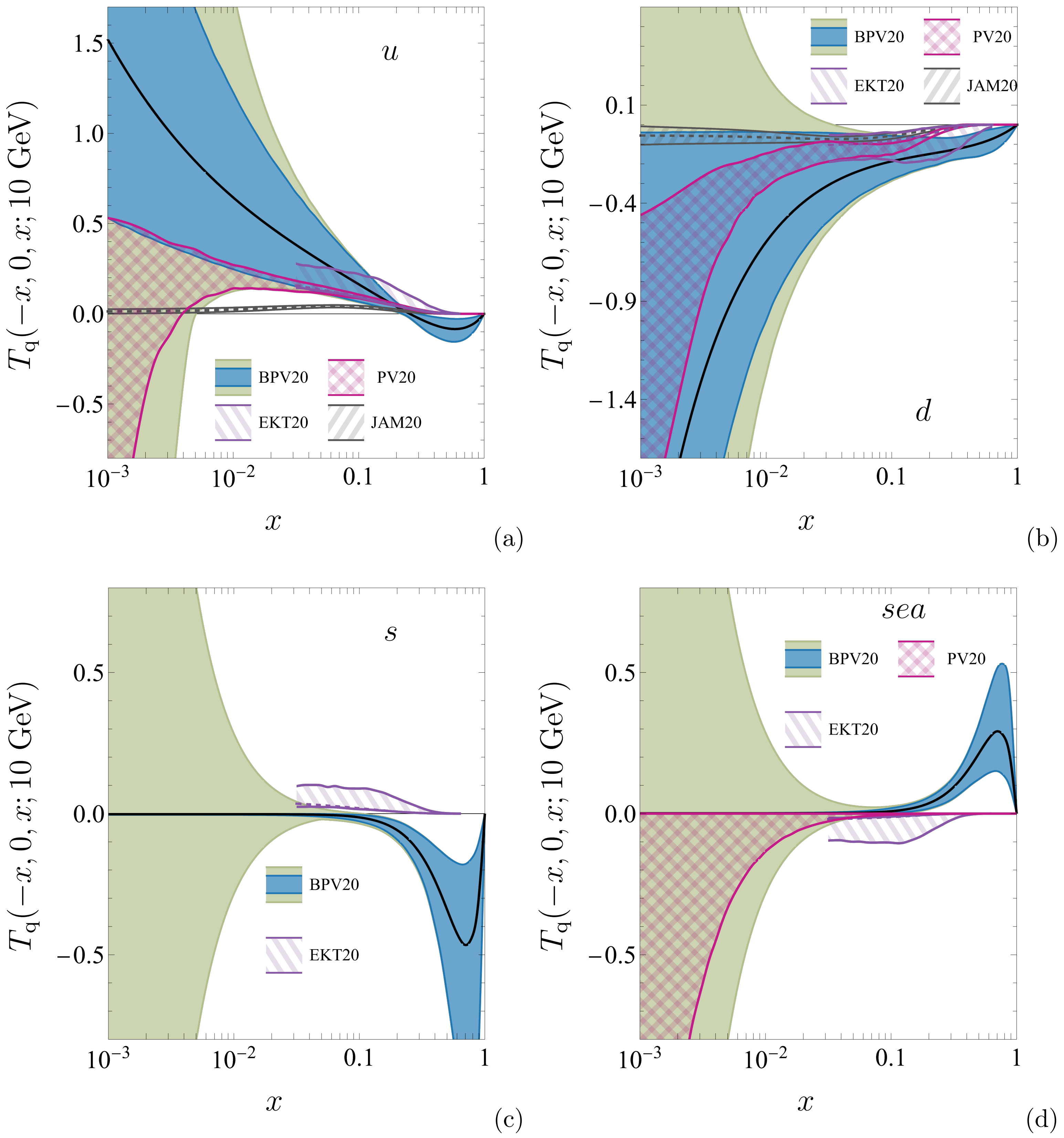




- The first next-to-next-to-next-to-leading order N^3LO global QCD analysis of SIDIS, Drell-Yan and $W^{\pm}$/Z production data.
- Uses the unpolarized functions extracted at the same N^3LO precision

Bury, Prokudin, Vladimirov Phys.Rev.Lett. 126 (2021) 11, 11200
Bury, Prokudin, Vladimirov JHEP 05 (2021) 151

THE QIU-STERMAN MATRIX ELEMENT



Compares well with JAM 20 (LO)

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

PV20 (NLL)

Bacchetta, Delcarro, Pisano, Radici (2020)

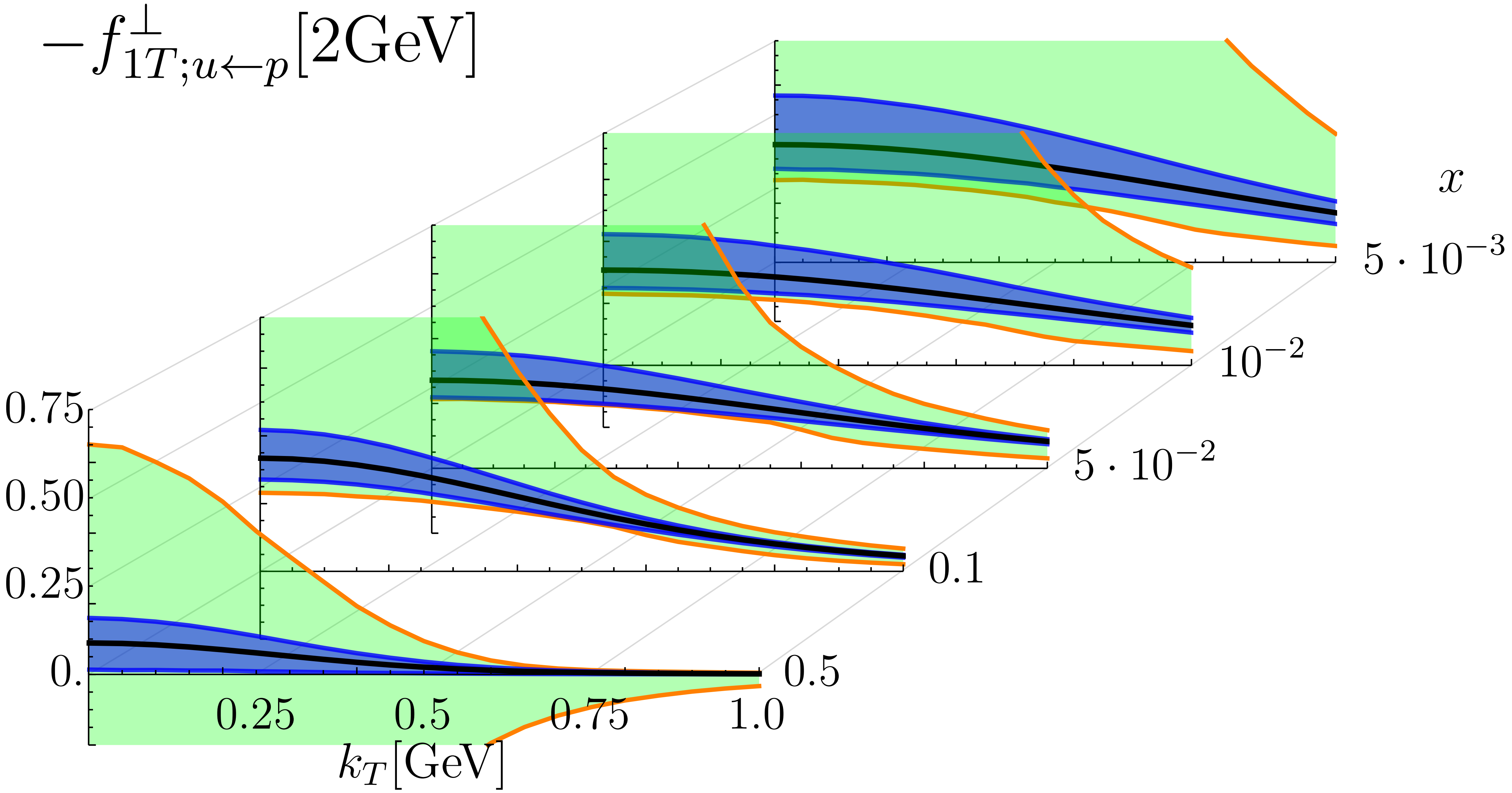
EKT20 (N2LL)

Echevarria, Kang, Terry (2020)

Sea quark functions is still a mystery to be explored at the EIC

EIC AND THE SIVERS FUNCTION

Vladimirov (2021)

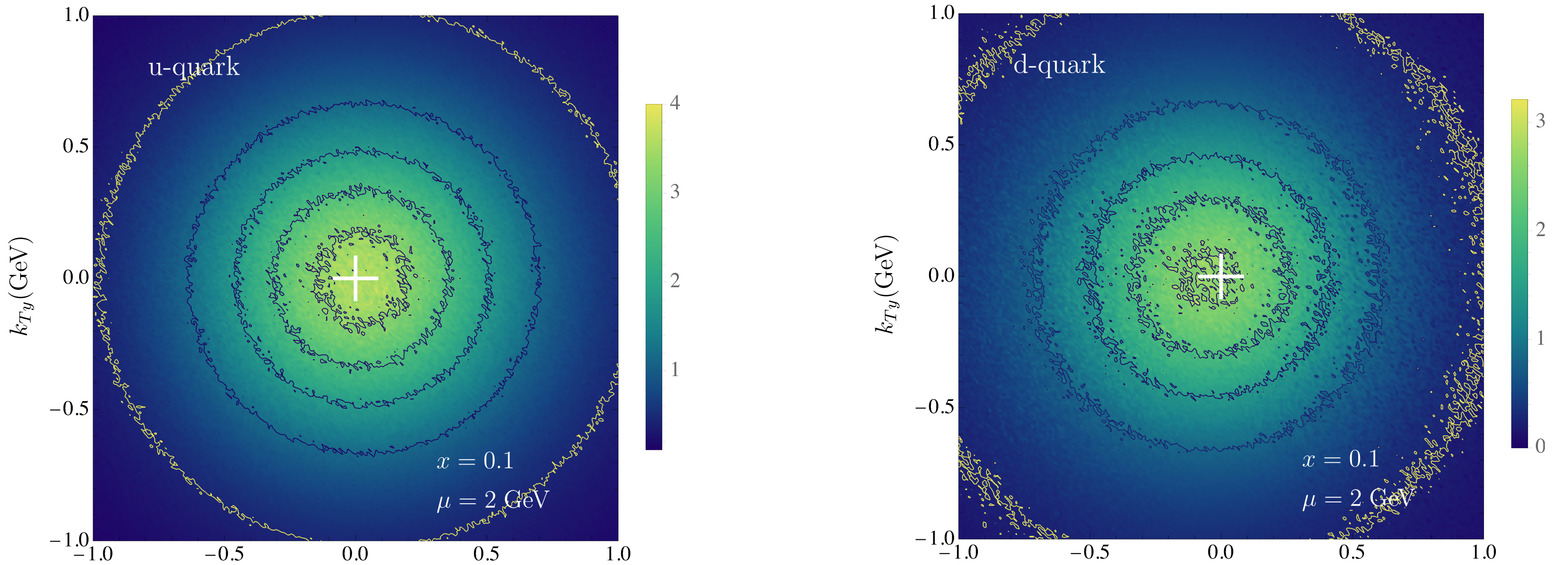


- The impact of the EIC is very substantial

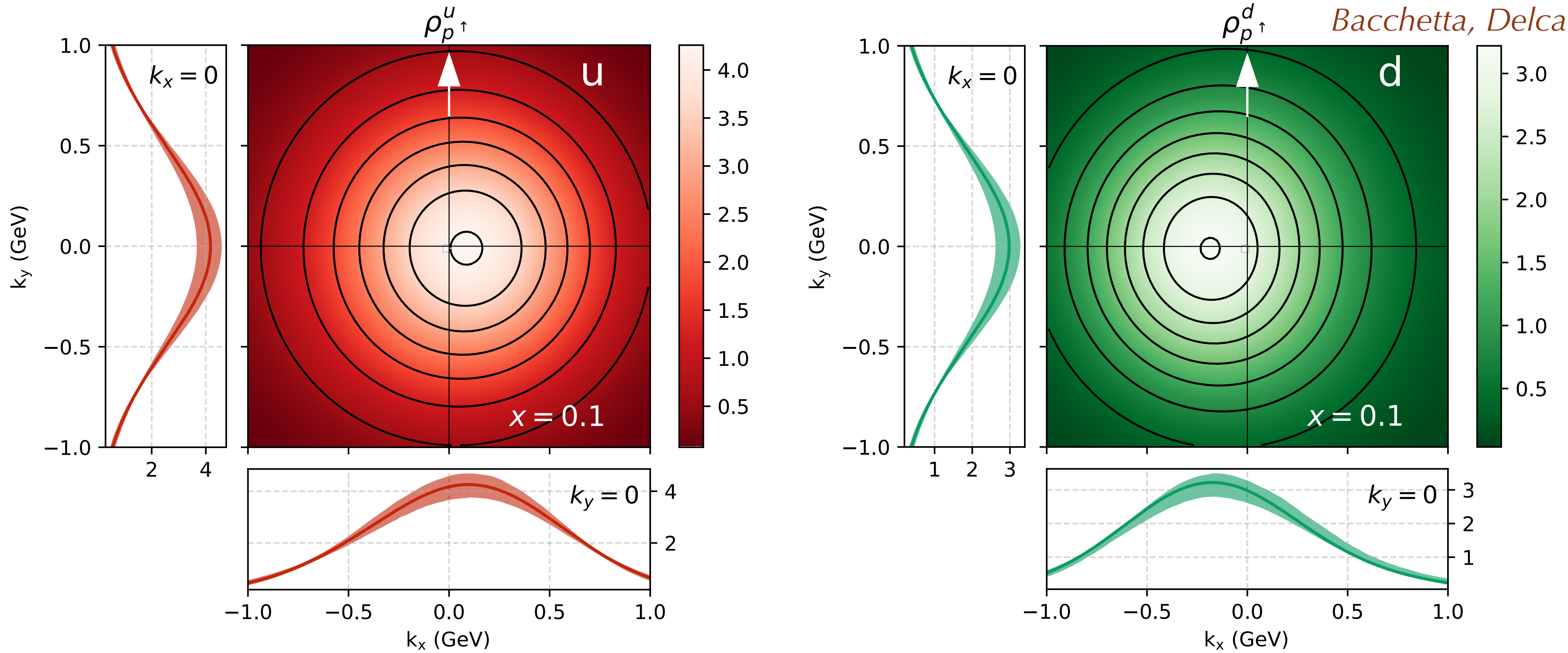
NUCLEON TOMOGRAPHY – THE FINAL GOAL

$$\rho_{1;q\leftarrow h^{\uparrow}}(x,\boldsymbol{k}_T,\boldsymbol{S}_T,\mu) = f_{1;q\leftarrow h}(x,k_T;\mu,\mu^2) - \frac{k_{Tx}}{M} f_{1T;q\leftarrow h}^{\perp}(x,k_T;\mu,\mu^2)$$

Bury, Prokudin, Vladimirov (2021)



Bacchetta, Delcarro, Pisano, Radici (2020)



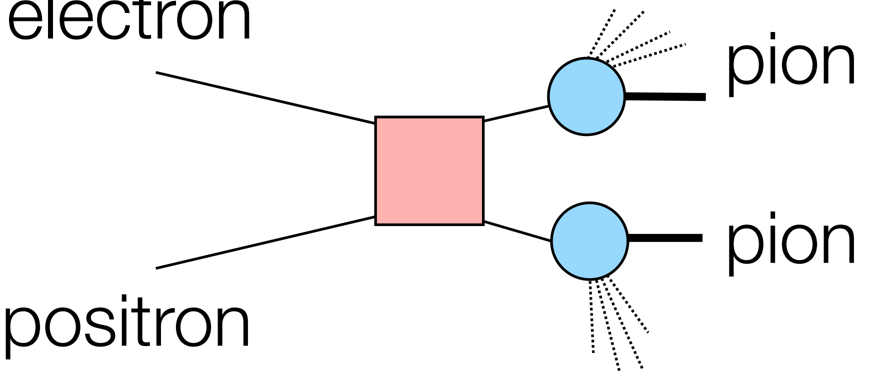
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

JAM20/JAM22 ANALYSIS

UNIVERSAL GLOBAL ANALYSIS 2020 AND 2022

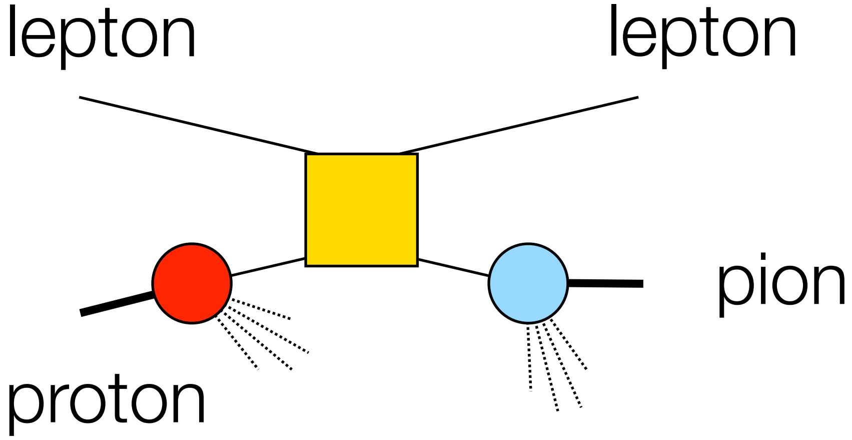
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

e+e−



Collins asymmetries
BELLE, BaBar, BESIII data

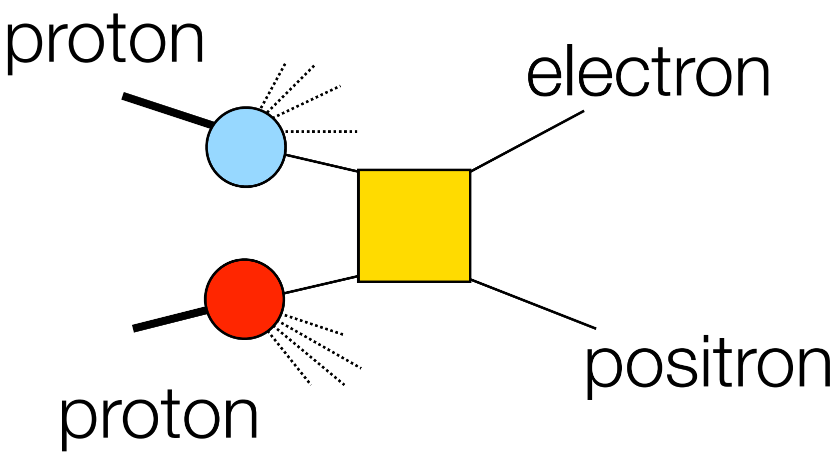
SIDIS



Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

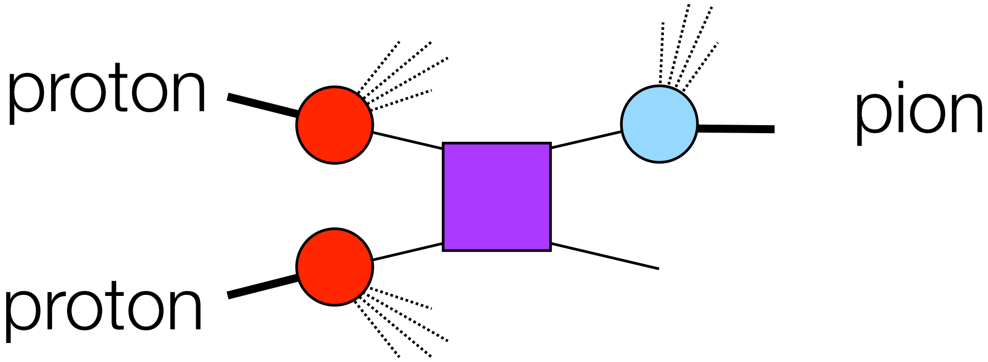
To demonstrate the common origin of SSAs in various processes, we combined all available data and extracted a universal set of non perturbative functions that describes all of them

Drell-Yan and W,Z



Sivers asymmetries
COMPASS, STAR data

PP



A_N asymmetry
STAR, PHENIX, BRAHMS data

JAM22: SET UP

JAM22: Gamberg, Malda, Miller, Pitonyak, Prokudin,
Sato, Phys.Rev.D 106 (2022) 3, 034014

- 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 (COMPASS, BELLE, RHIC), 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, $\widetilde{H}$ 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)

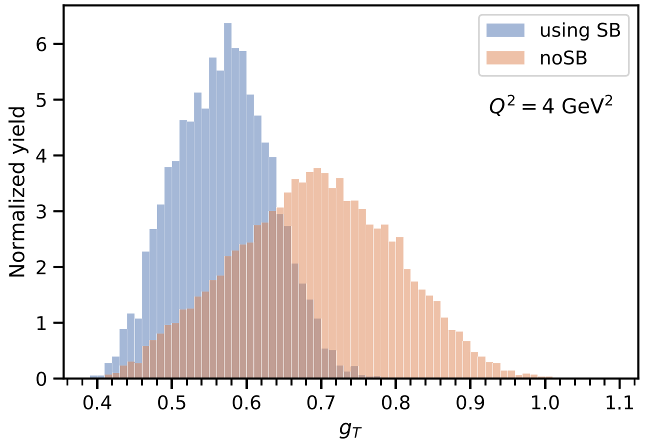
  C. Alexandrou et al, Phys.Rev.D 102 (2020)

- 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)

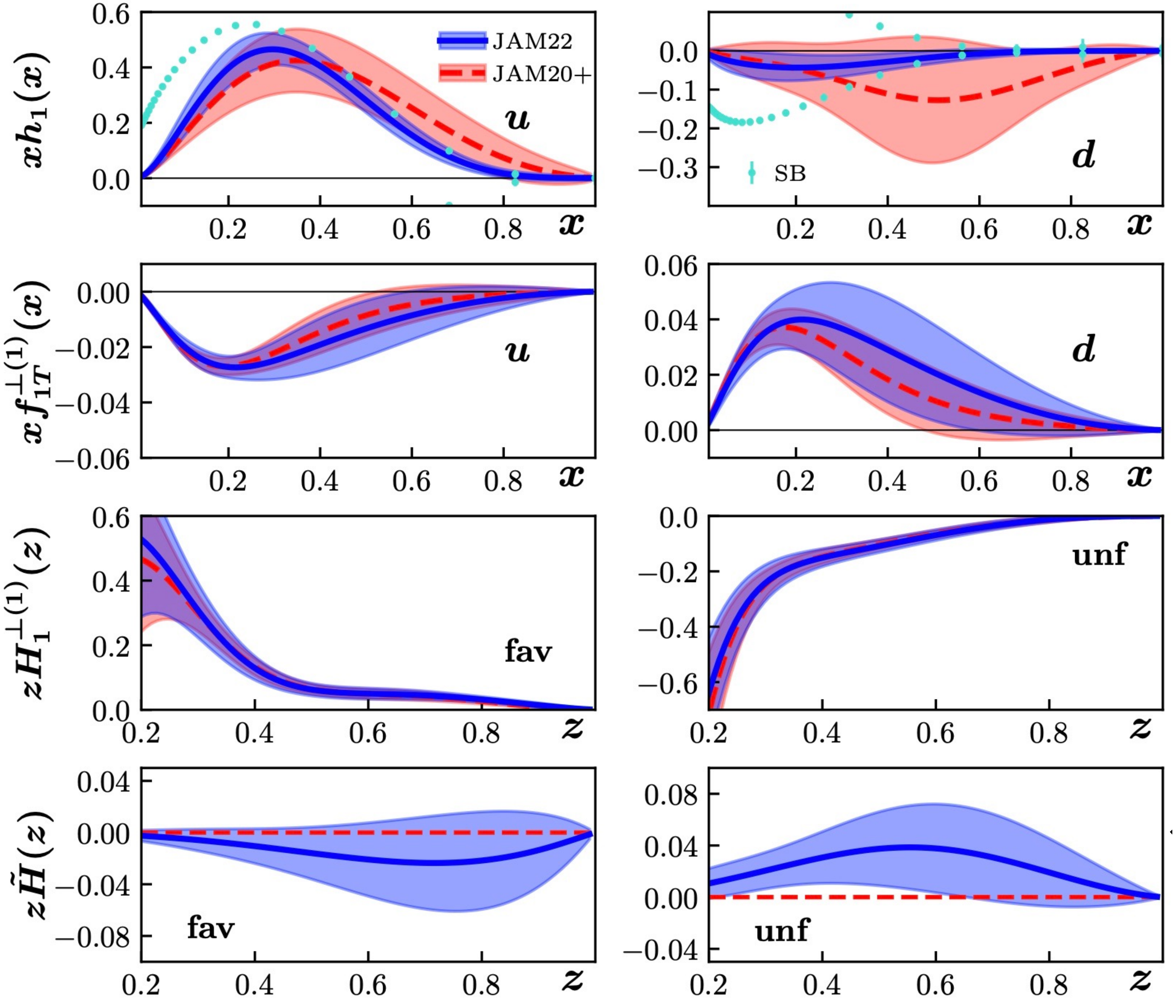
Recent phenomenology indicates substantial influence of imposing the Soffer bounds

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



UNIVERSAL GLOBAL ANALYSIS 2022

JAM22: Gamberg, Malda, Miller, Pitonyak, Prokudin, Sato, Phys.Rev.D 106 (2022) 3, 034014



Transversity

$h_1(x)$

Sivers

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

Collins FF

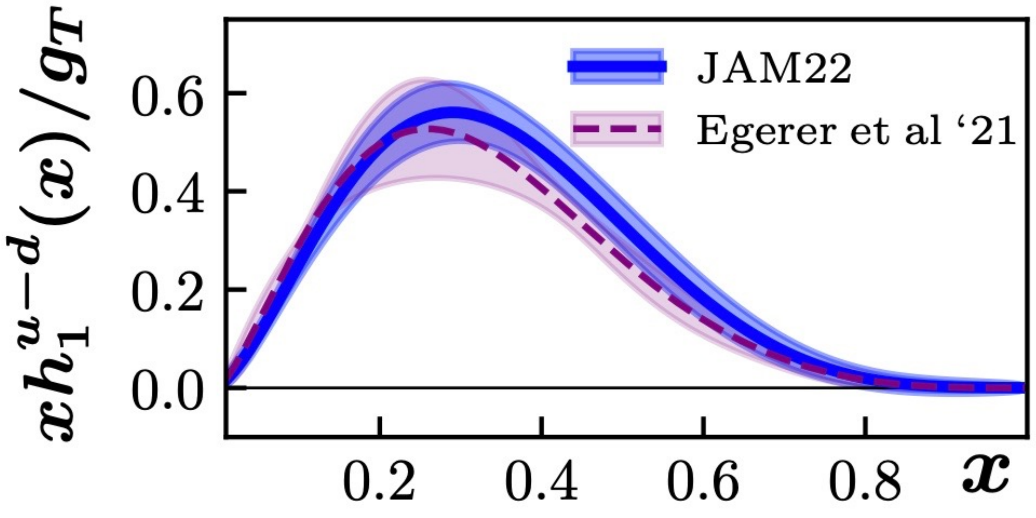
$H_1^{\perp(1)}(z)$

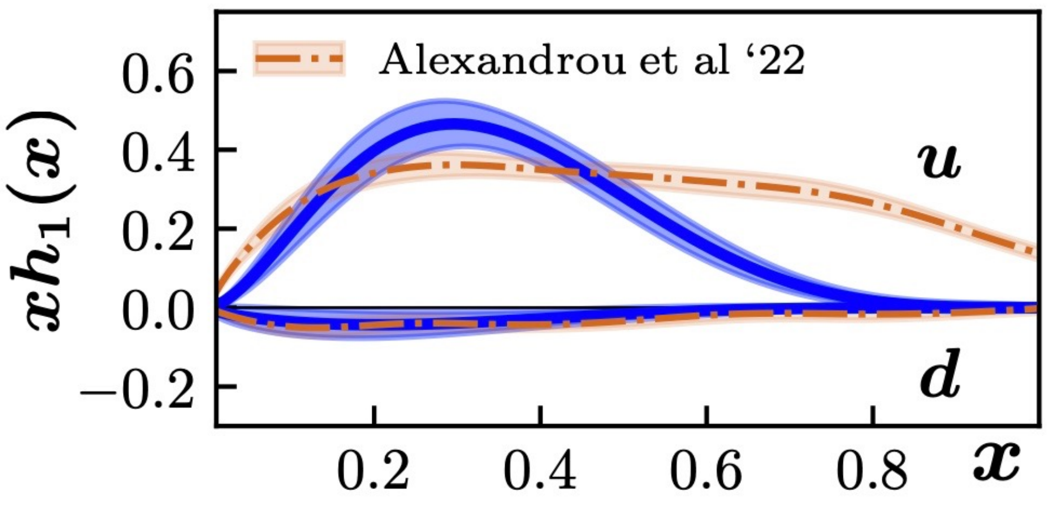
Twist-3 FF

$\tilde{H}(z)$

JAM22: TRANSVERSITY AND LATTICE

JAM22: Gamberg, Malda, Miller, Pitonyak, Prokudin, Sato, Phys.Rev.D 106 (2022) 3, 034014





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

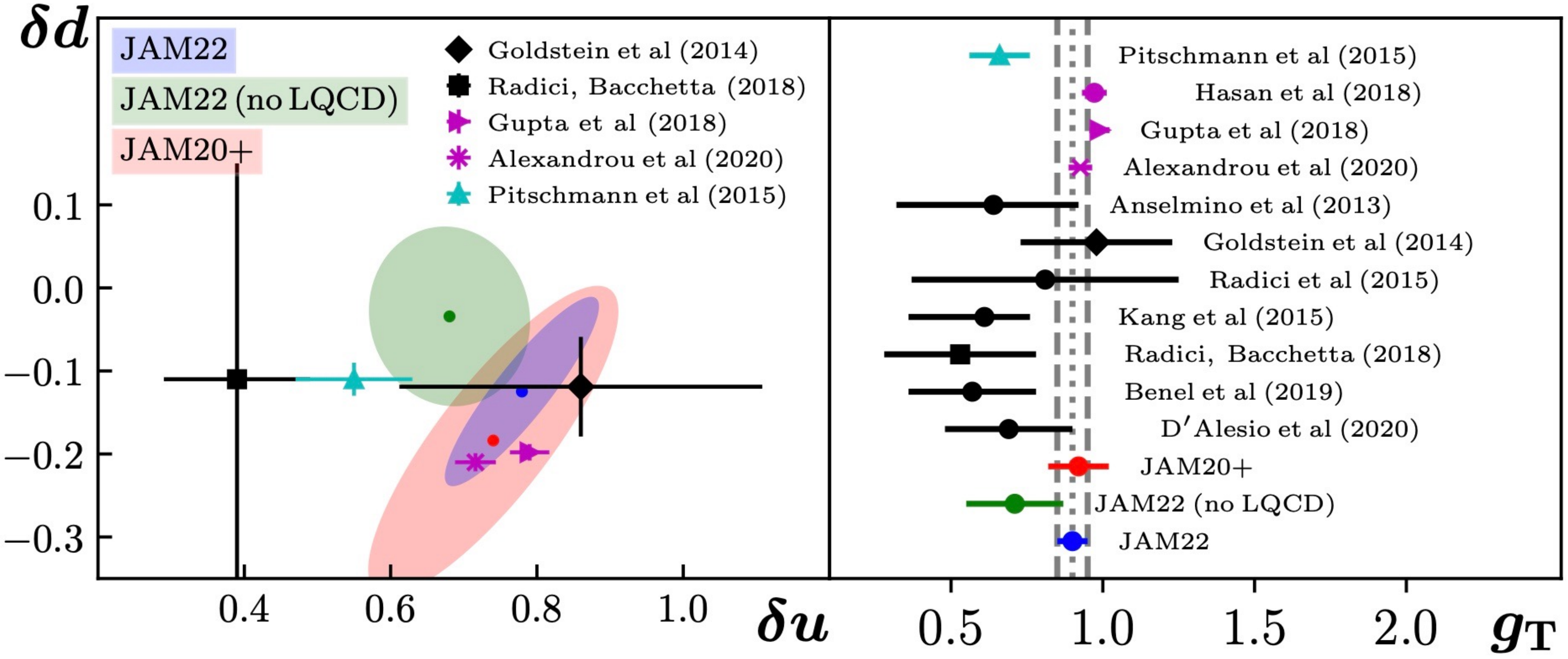
The behavior at large x for the up quark in Alexandrou, et al. is due to systematics in the reconstruction of the x dependence in the quasi-PDF approach

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 compatible with lattice

UNIVERSAL GLOBAL ANALYSIS 2022

JAM22: Gamberg, Malda, Miller, Pitonyak, Prokudin, Sato, Phys.Rev.D 106 (2022) 3, 034014



- 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

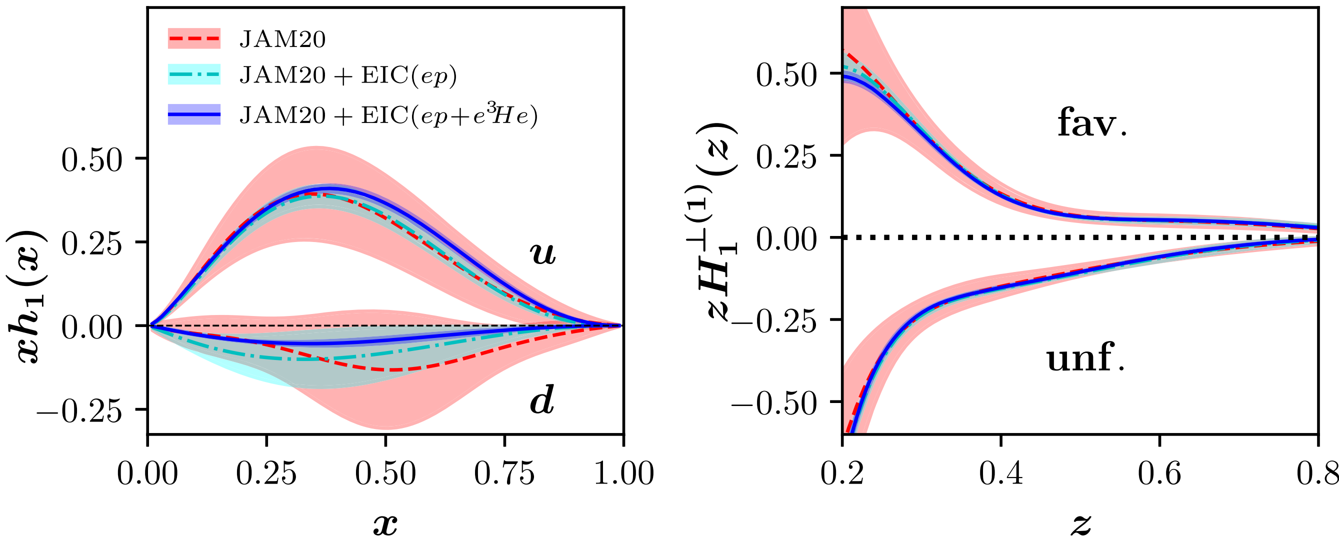
δd= -0.15 ± 0.12

g_T= 0.89 ± 0.06

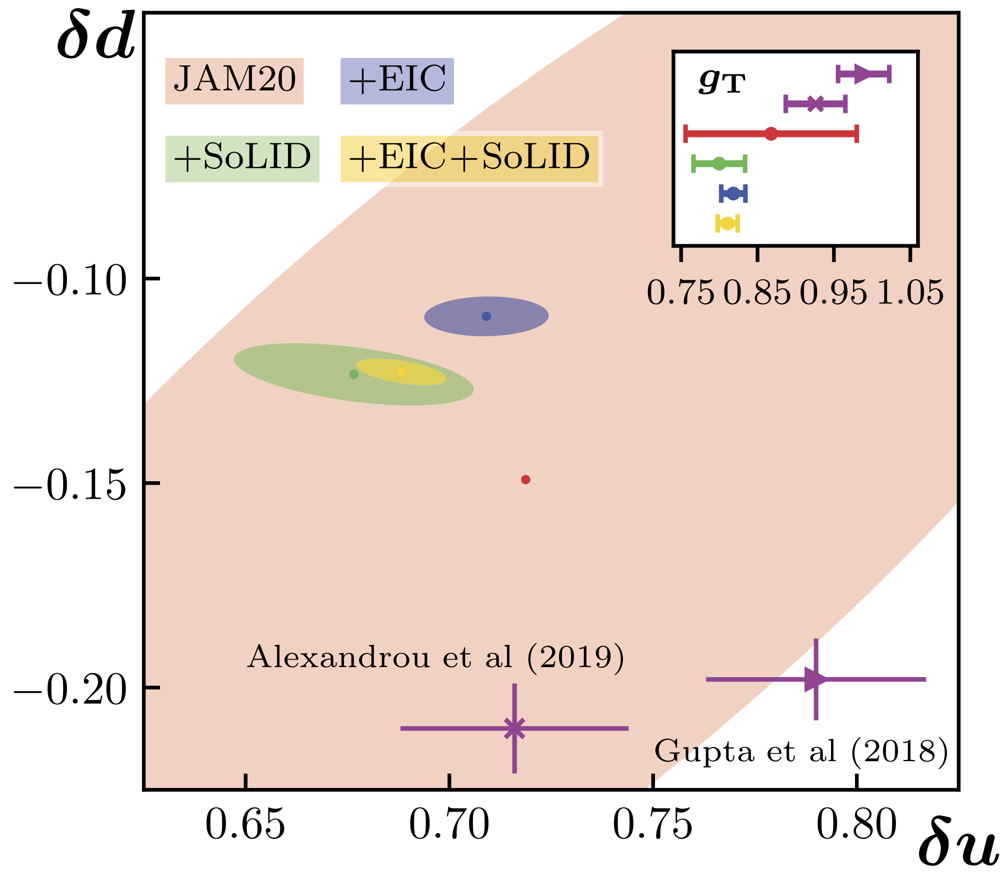
- The tension with diFF method, Radici, Bacchetta (2018) becomes more pronounced: is it due to the data, theory, methodology? Both methods should be scrutinized.

TENSOR CHARGE AT THE EIC AND JLAB

L. Gamberg, Z. Kang, D. Pitonyak, A. Prokudin, N. Sato Phys.Lett.B 816 (2021)



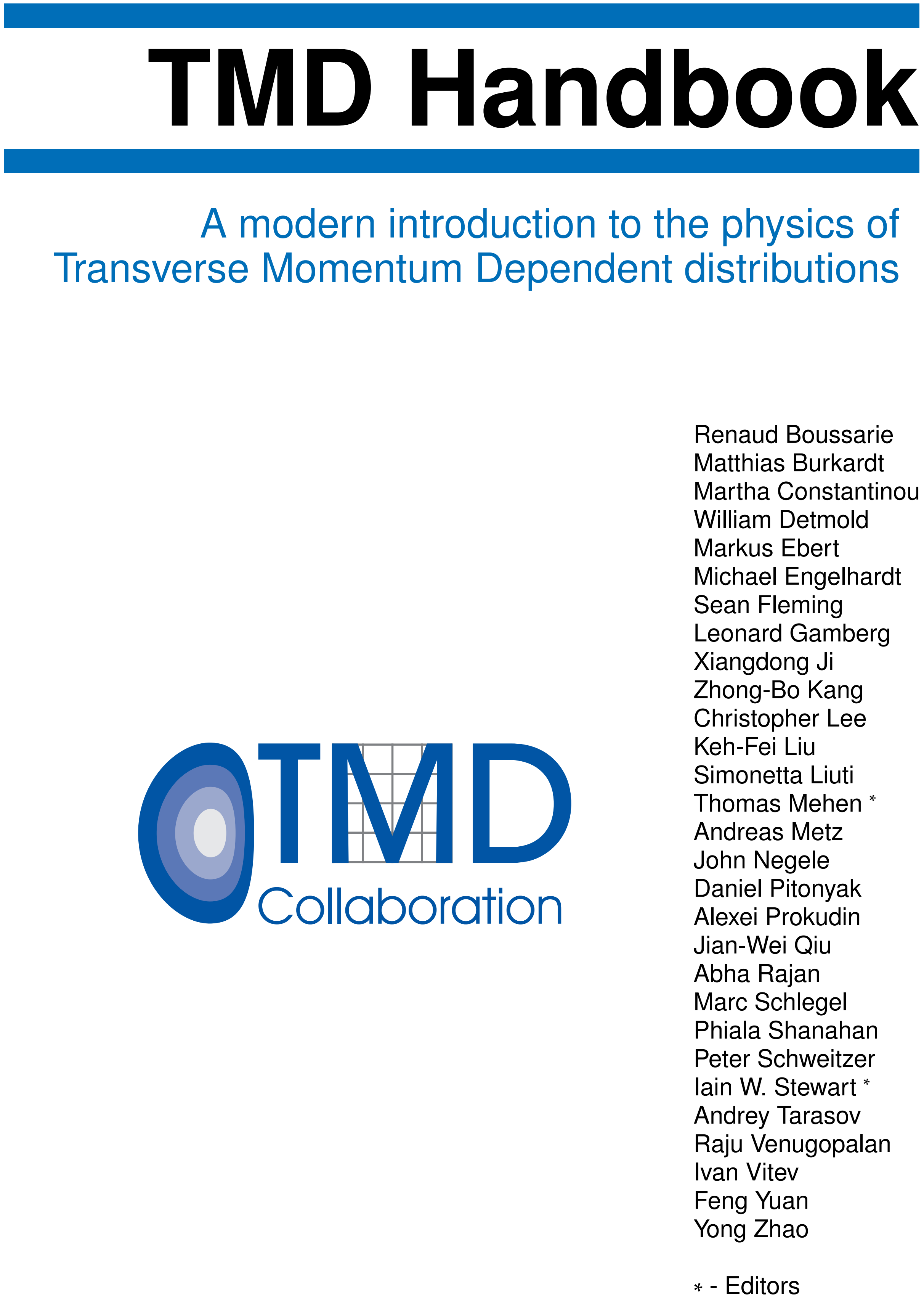
JAM20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, Phys.Rev.D 102 (2020)



- EIC data will allow to have g_T extraction at the precision at the level of lattice QCD calculations
- JLab 12 data will allow to have complementary information on tensor charge to test the consistency of the extraction and expand the kinematical region

TMD BOOK

- TMD Topical Collaboration
- 12 chapters
- 470 pages
- To be released soon



TMD Handbook

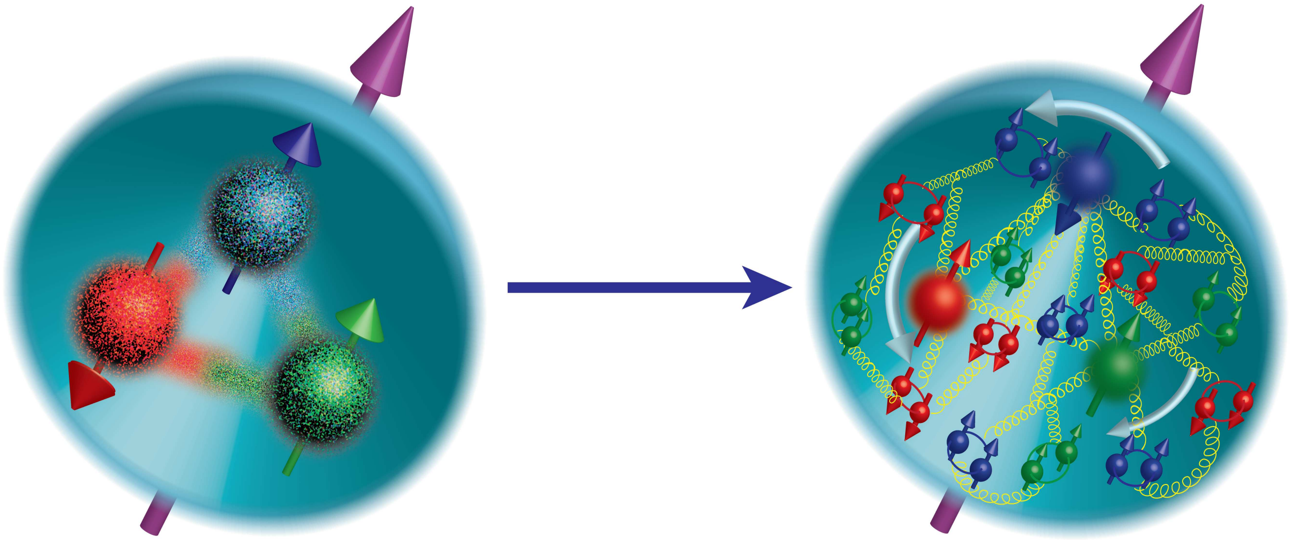
A modern introduction to the physics of
Transverse Momentum Dependent distributions

Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

* - Editors

CONCLUSIONS

- TMD studies have made great progress, they are synergistic with many other areas: lattice QCD, SCET, small-x, jets, etc
- Current: HERMES, COMPASS, JLab 12, BELLE, RHIC spin, and LHC provide great experimental measurements for TMD physics
- Future: EIC, together with other experiments such as SoLID and BELLE II, will make significant contributions to TMD physics

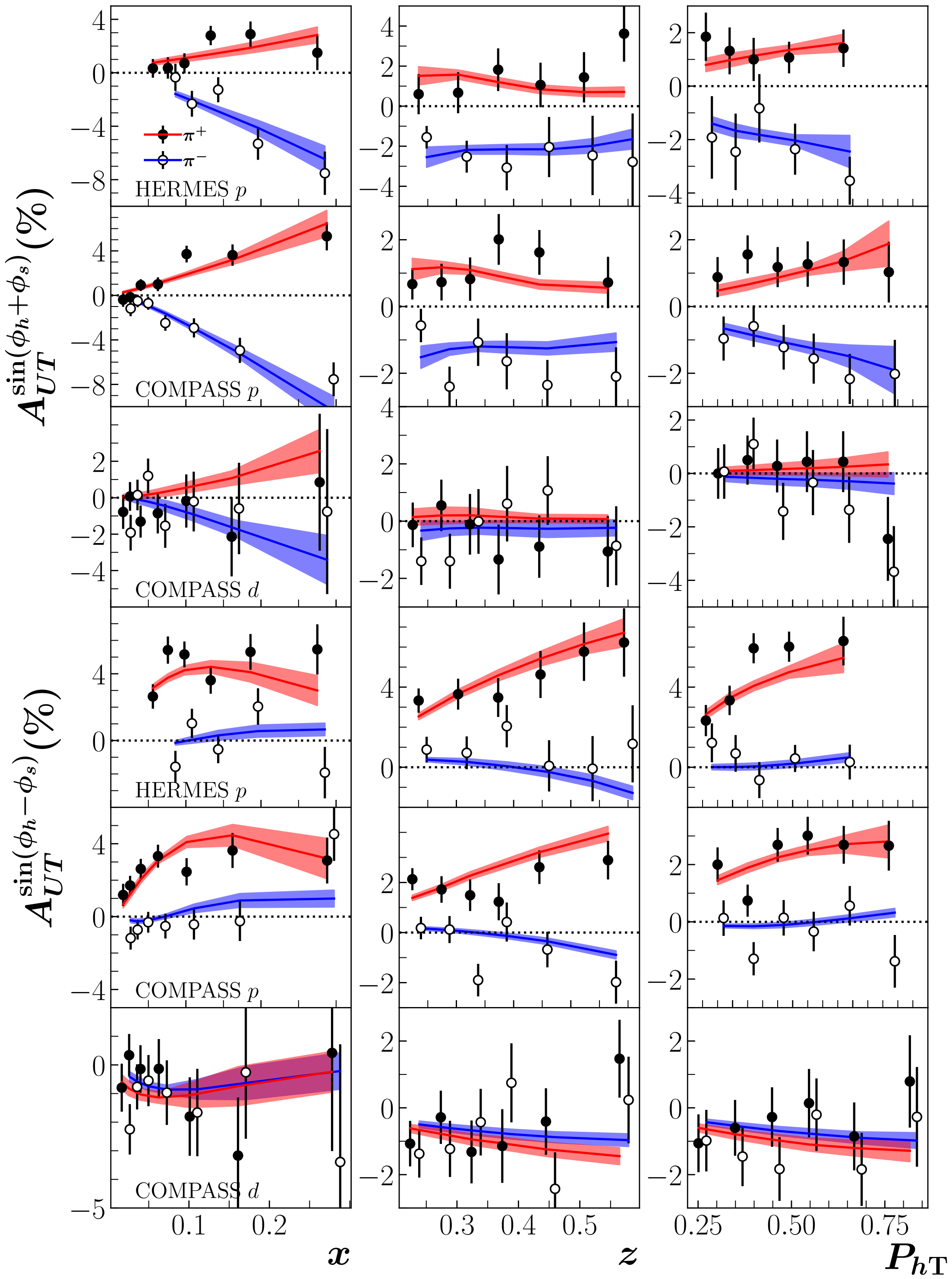


BACK UP SLIDES

UNIVERSAL GLOBAL ANALYSIS 2020

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

SIDIS



Collins asymmetry

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

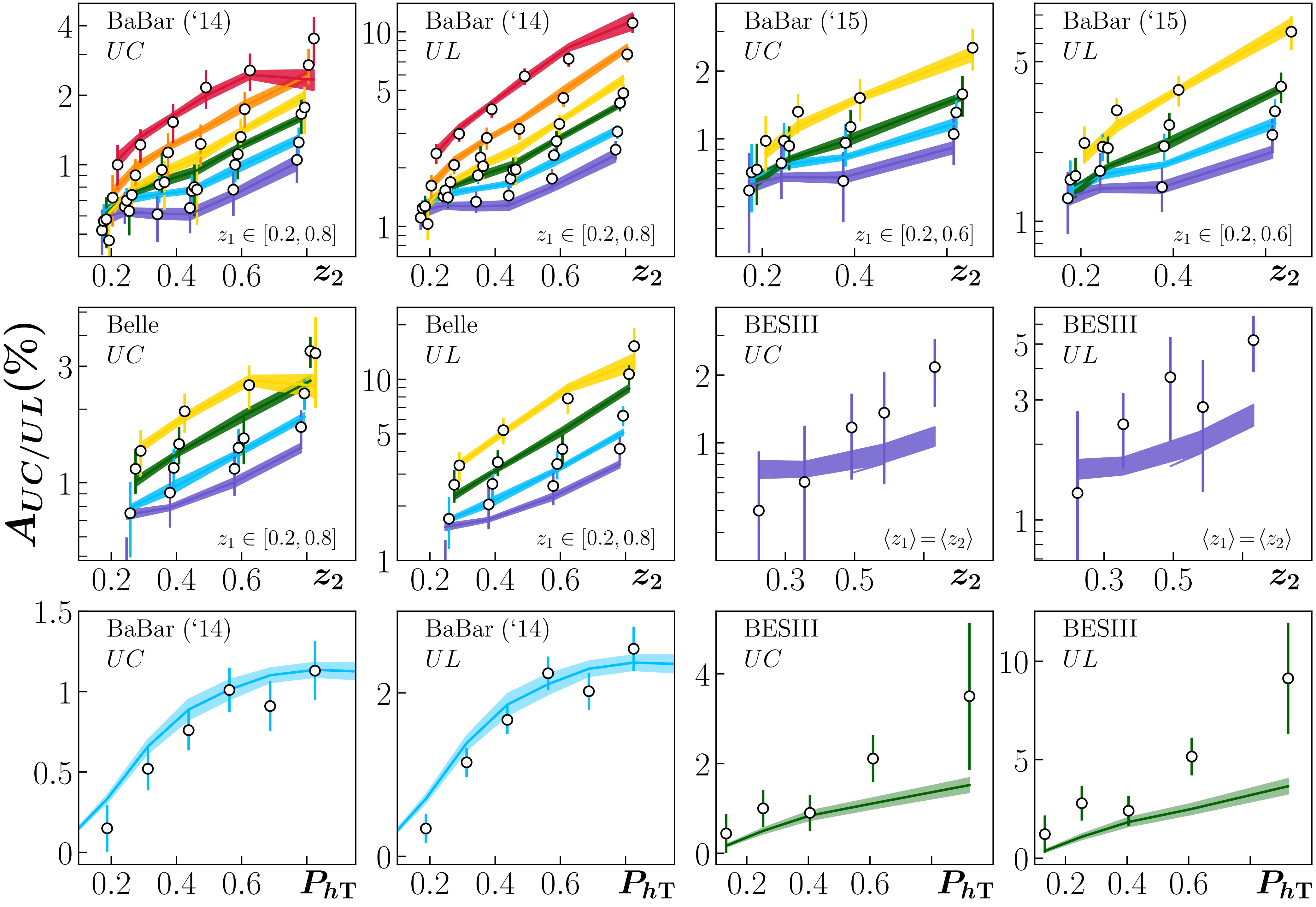
Sivers asymmetry

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

UNIVERSAL GLOBAL ANALYSIS 2020

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

e^+e^-

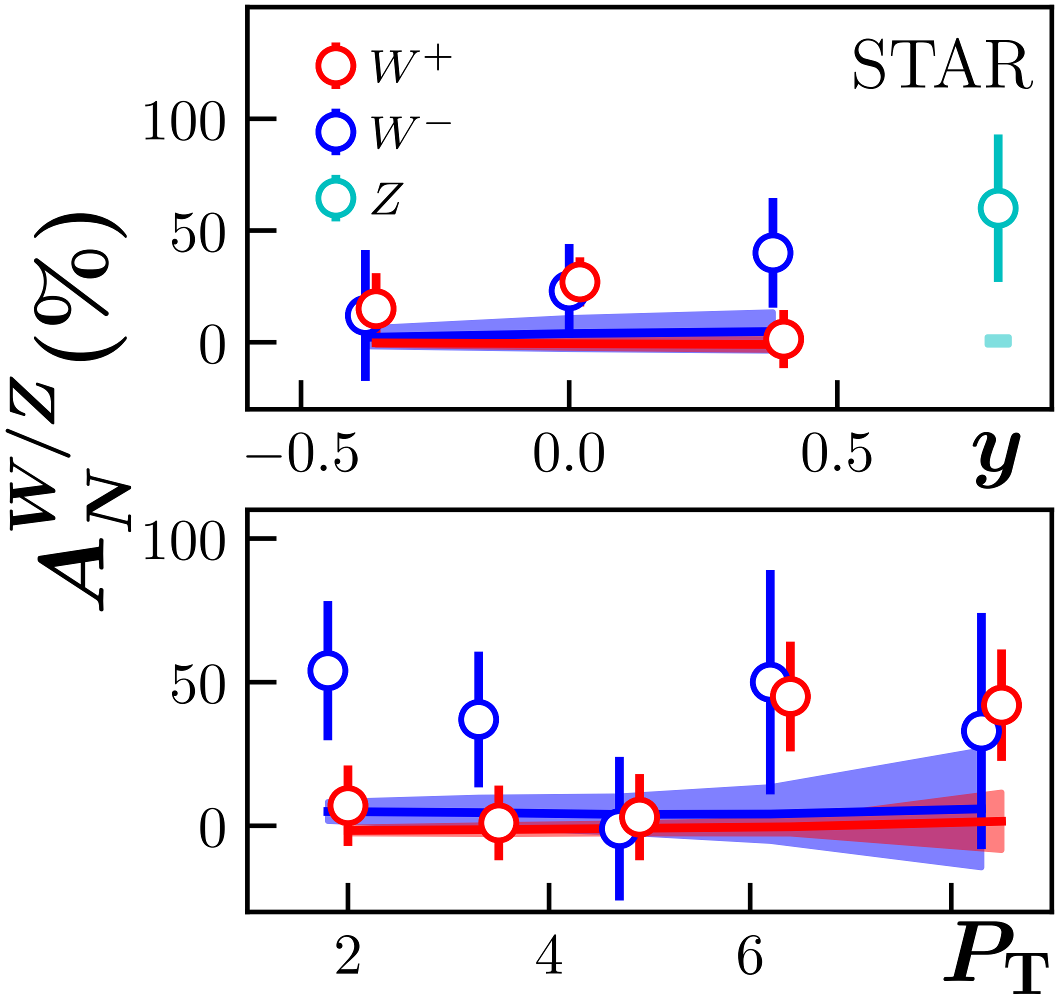


$$\frac{\chi^2}{npoints} = \frac{154.5}{176} = 0.88$$

UNIVERSAL GLOBAL ANALYSIS 2020

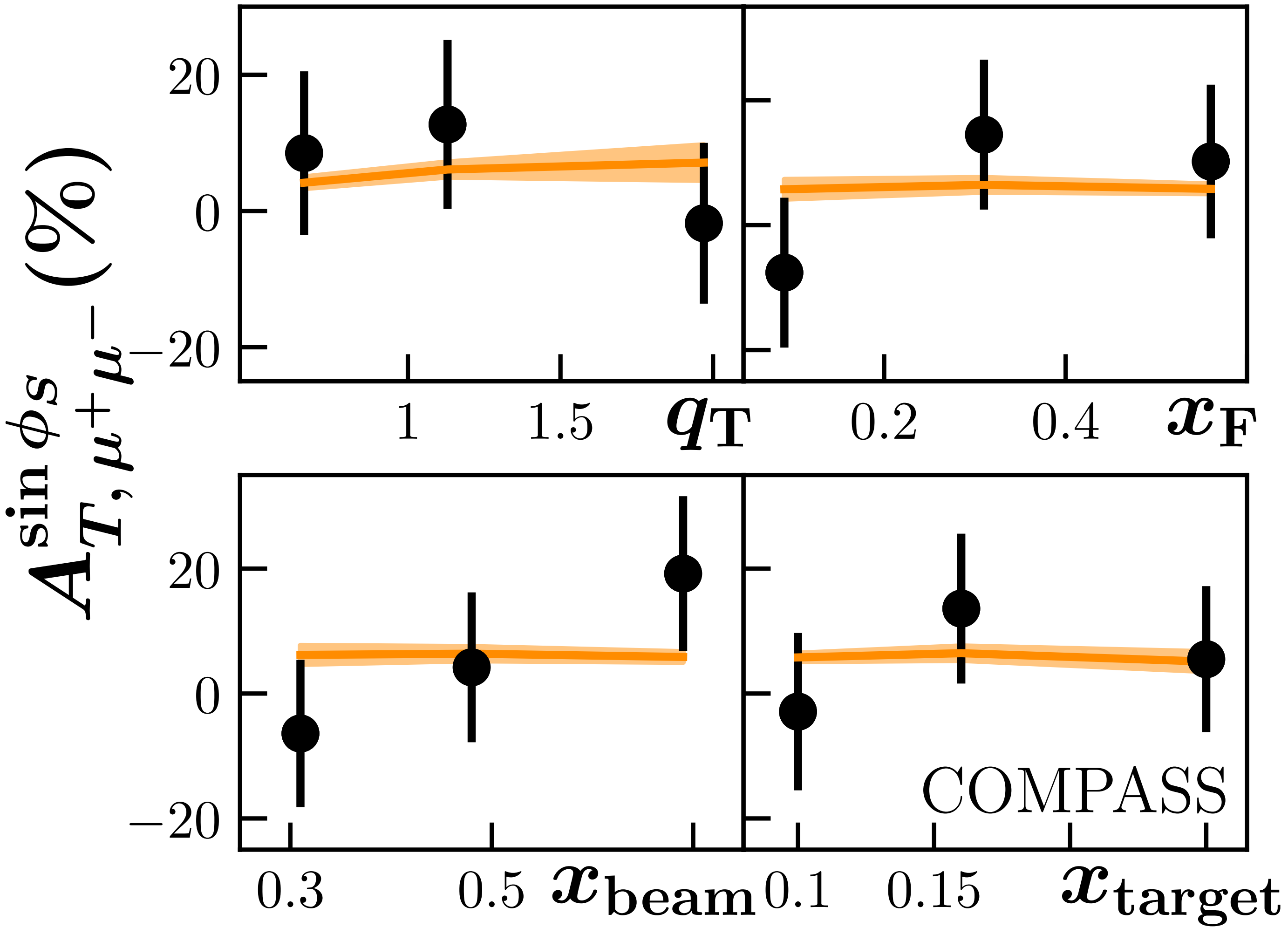
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

Drell-Yan



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

STAR



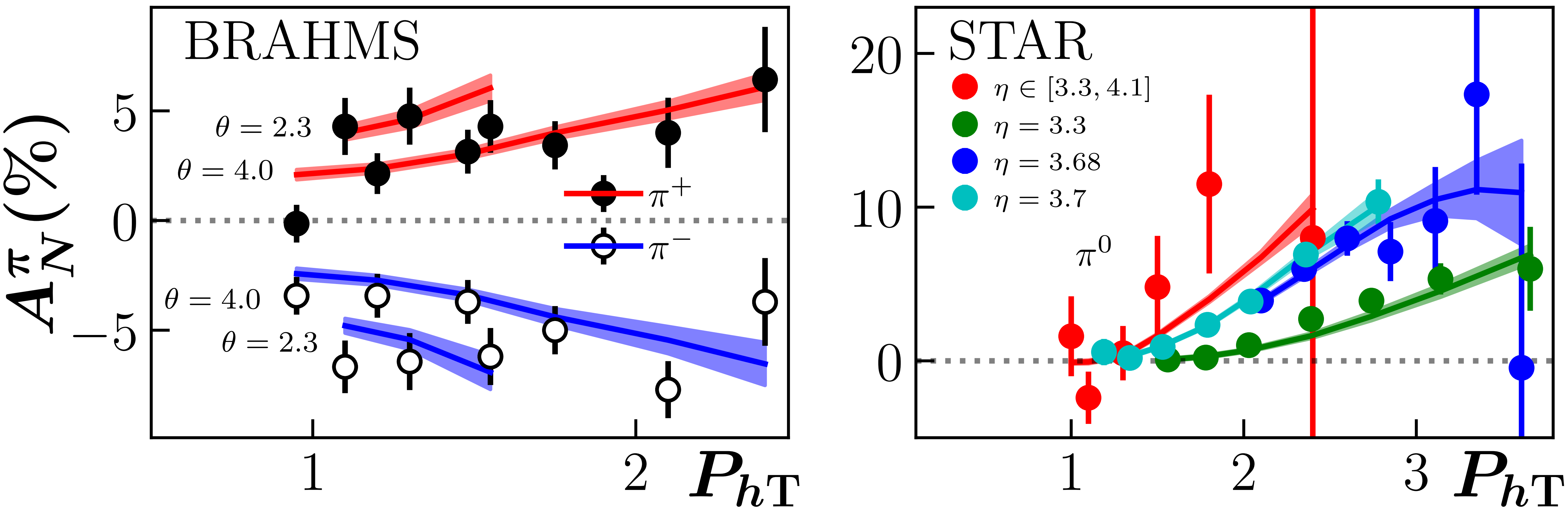
$$\frac{\chi^2}{npoints} = \frac{5.96}{12} = 0.5$$

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



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