A 3D OVERVIEW OF THE LAST 20 YEARS

Alessandro Bacchetta

STRONG 2020

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

MY PERSONAL PARTICIPATION TO IWHSS WORKSHOPS

- IWHSS 2010 (Venice)
  The TMD frontier
- IWHSS 2011 (Paris)
  Transverse momentum distributions - theory overview
- IWHSS 2012 (Lisbon)
  Overview of transversity
- IWHSS 2015 (Suzdal)
  Progress in understanding the transverse structure of the nucleon
- IWHSS 2020 (Trieste, remote)
  The 3D nucleon structure
- IWHSS 2022 (here)
  A 3D overview of the last 20 years

In 2002, almost no data about the 3D structure of the proton (in momentum space) was available.

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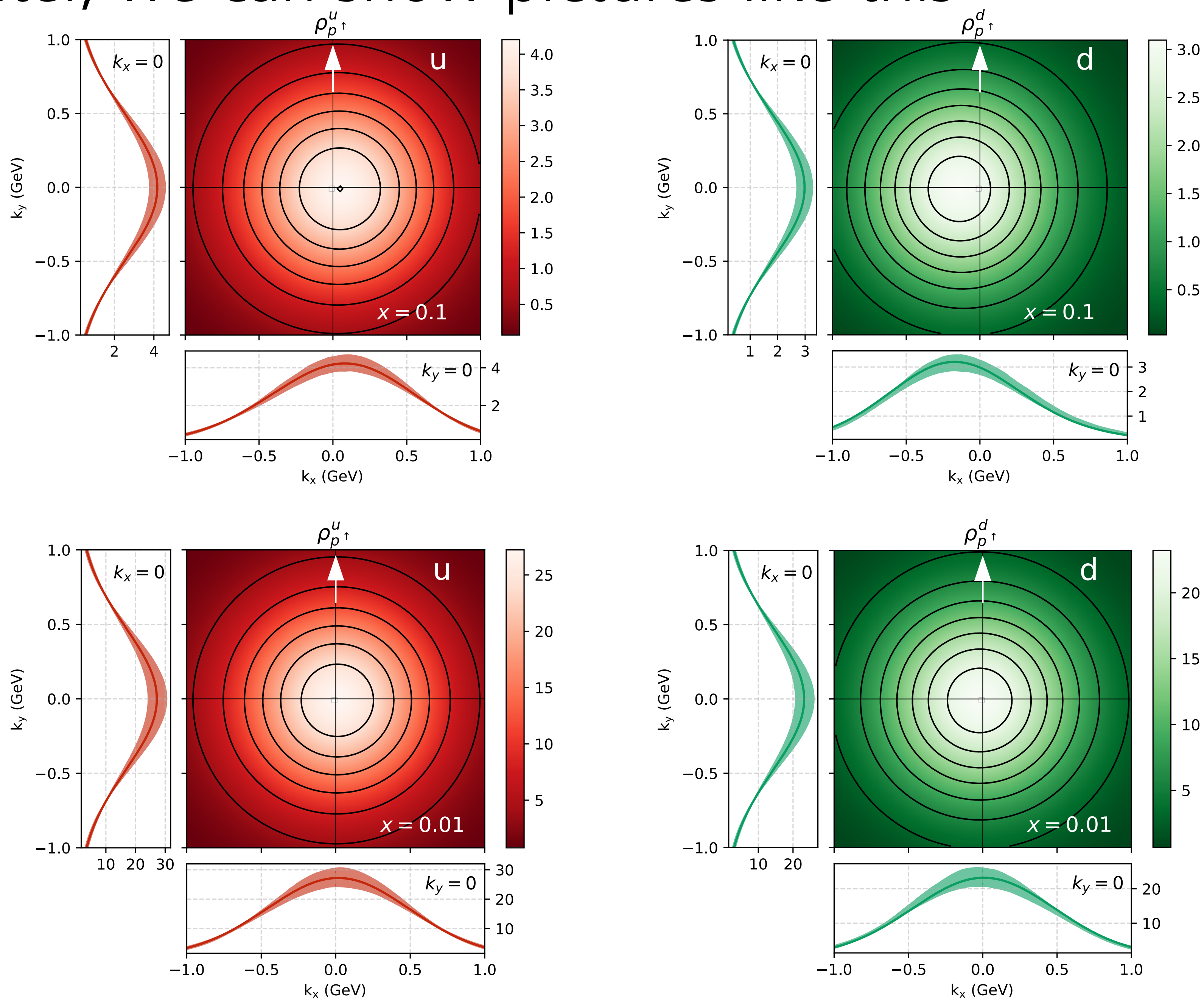
20 years later, we can show pictures like this



Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278

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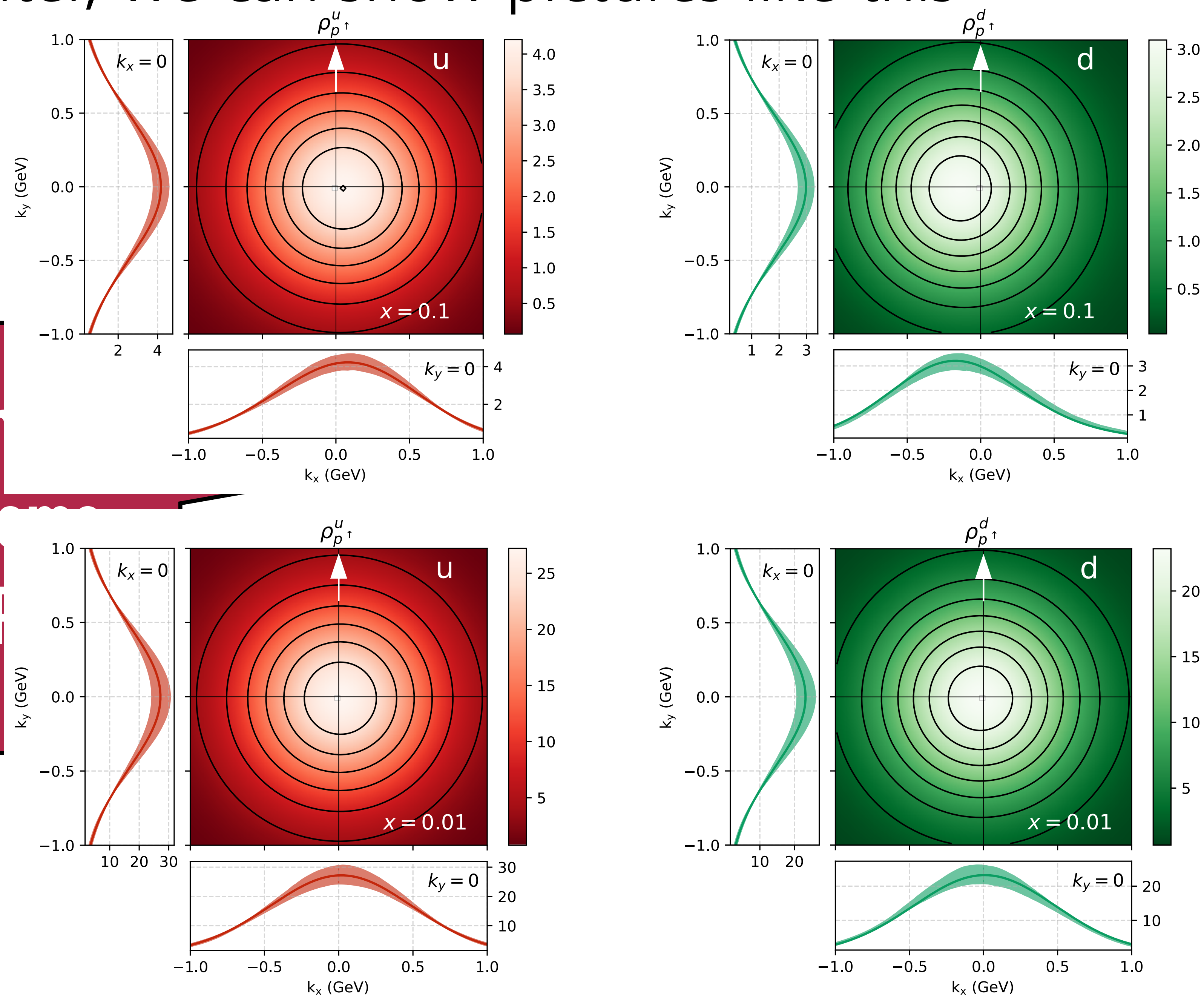
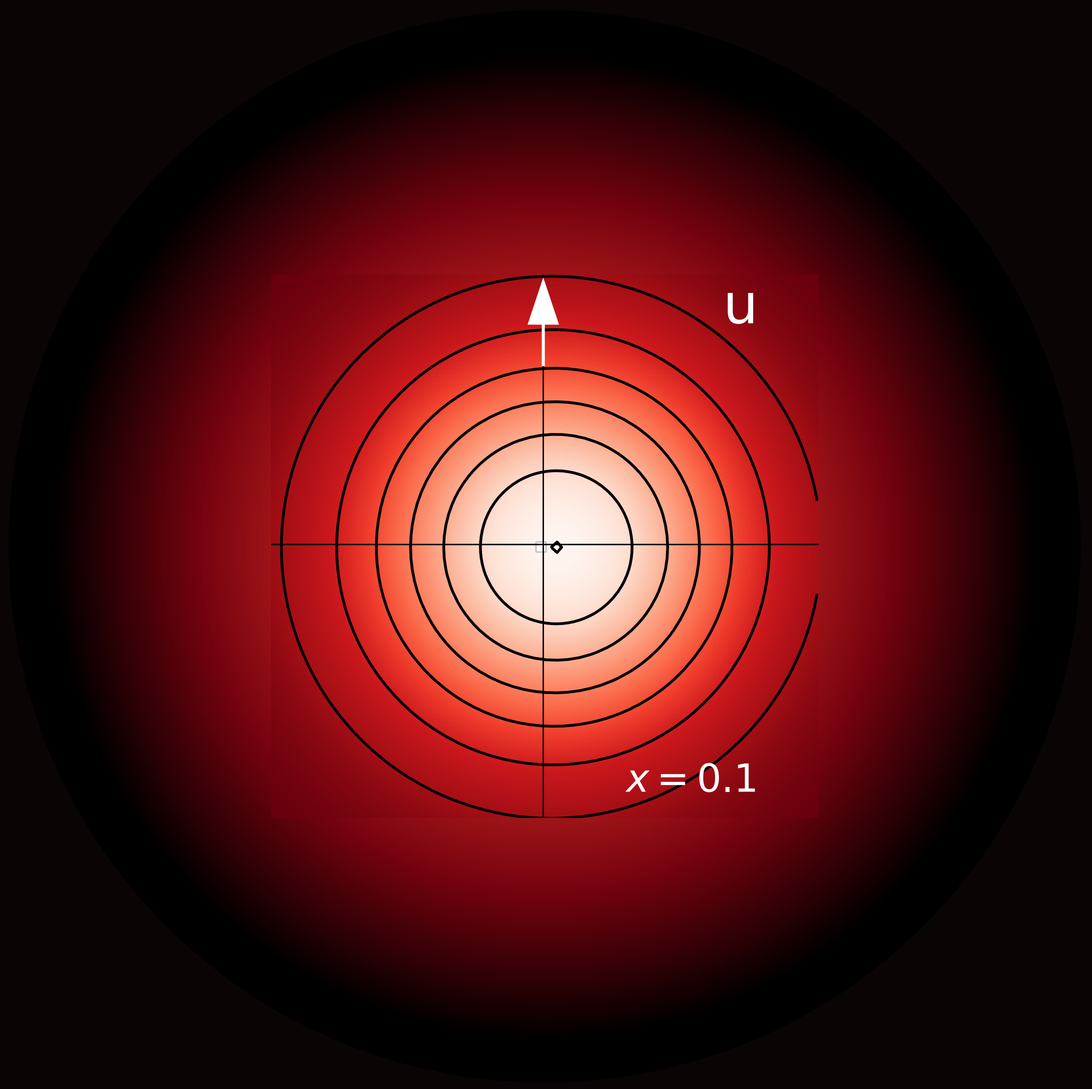


Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278

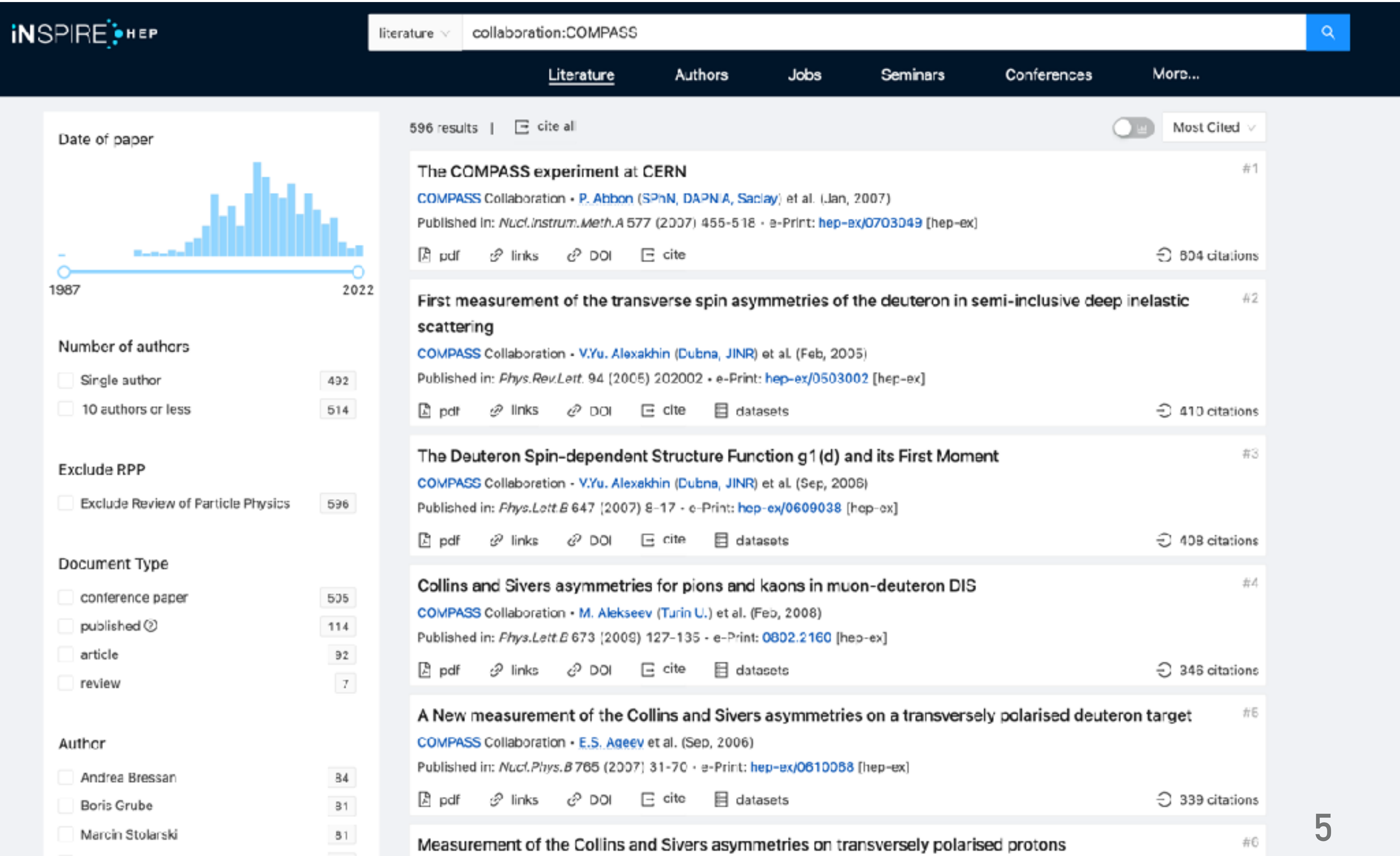
A picture of a black hole (2019)

A picture of a black hole (2019)

A picture of a proton (2020)



TOP FIVE HIGHLY CITED COMPASS PUBLICATIONS



TOP FIVE HIGHLY CITED COMPASS PUBLICATIONS

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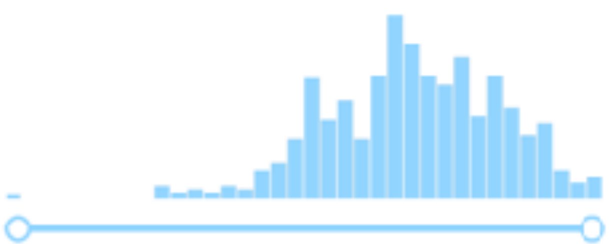

Number of authors

- Single author 432
- 10 authors or less 514

Exclude RPP

- Exclude Review of Particle Physics 596

Document Type

- conference paper 505
- published 114
- article 92
- review 7

Author

- Andrea Bressan 84
- Boris Grube 81
- Marcin Stolarski 81

596 results | cite all — Most Cited

The COMPASS experiment at CERN #1
COMPASS Collaboration • P. Abbon (SPhN, DAPNIA, Saclay) et al. (Jan, 2007)
Published in: *Nucl.Instrum.Meth.A* 577 (2007) 455-518 • e-Print: hep-ex/0703049 [hep-ex]
pdf | links | DOI | cite — 804 citations

First measurement of the transverse spin asymmetries of the deuteron in semi-inclusive deep inelastic scattering #2
COMPASS Collaboration • V.Yu. Alexakhin (Dubna, JINR) et al. (Feb, 2005)
Published in: *Phys.Rev.Lett.* 94 (2005) 202002 • e-Print: hep-ex/0503002 [hep-ex]
pdf | links | DOI | cite | datasets — 410 citations

The Deuteron Spin-dependent Structure Function g1 (d) and its First Moment #3
COMPASS Collaboration • V.Yu. Alexakhin (Dubna, JINR) et al. (Sep, 2006)
Published in: *Phys.Lett.B* 647 (2007) 8-17 • e-Print: hep-ex/0609038 [hep-ex]
pdf | links | DOI | cite | datasets — 408 citations

1D

Collins and Sivers asymmetries for pions and kaons in muon-deuteron DIS #4
COMPASS Collaboration • M. Alekseev (Turin U.) et al. (Feb, 2008)
Published in: *Phys.Lett.B* 673 (2009) 127-135 • e-Print: 0802.2160 [hep-ex]
pdf | links | DOI | cite | datasets — 346 citations

A New measurement of the Collins and Sivers asymmetries on a transversely polarised deuteron target #5
COMPASS Collaboration • E.S. Ageev et al. (Sep, 2006)
Published in: *Nucl.Phys.B* 765 (2007) 31-70 • e-Print: hep-ex/0610068 [hep-ex]
pdf | links | DOI | cite | datasets — 339 citations

Measurement of the Collins and Sivers asymmetries on transversely polarised protons #6

from IWHSS 2011

Old Chinese compass

Exploration

from IWHSS 2011

Hand-held compass

Consolidation

from IWHSS 2011

GPS compass

Precision

from IWHSS 2011

- **Exploration**

from IWHSS 2011

- **Exploration**

- **Consolidation**

from IWHSS 2011

- **Exploration**

- **Consolidation**

- **Precision**

from IWHSS 2011

- **Exploration**
    - parton-model theory
    - first measurements
- **Consolidation**
- **Precision**

from IWHSS 2011

- **Exploration**
  - parton-model theory
  - first measurements
- **Consolidation**
  - TMD factorization
  - many consistent measurements
- **Precision**

from IWHSS 2011

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  - full-fledged global analysis
  - precision measurements

from IWHSS 2011

2002

- **Exploration**
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  - TMD factorization
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from IWHSS 2011

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    - many consistent measurements
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    - full-fledged global analysis
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2002

2012

from IWHSS 2011

- **Exploration** 2002
  - parton-model theory
  - first measurements

2012

- **Consolidation**
  - TMD factorization
  - many consistent measurements

2022

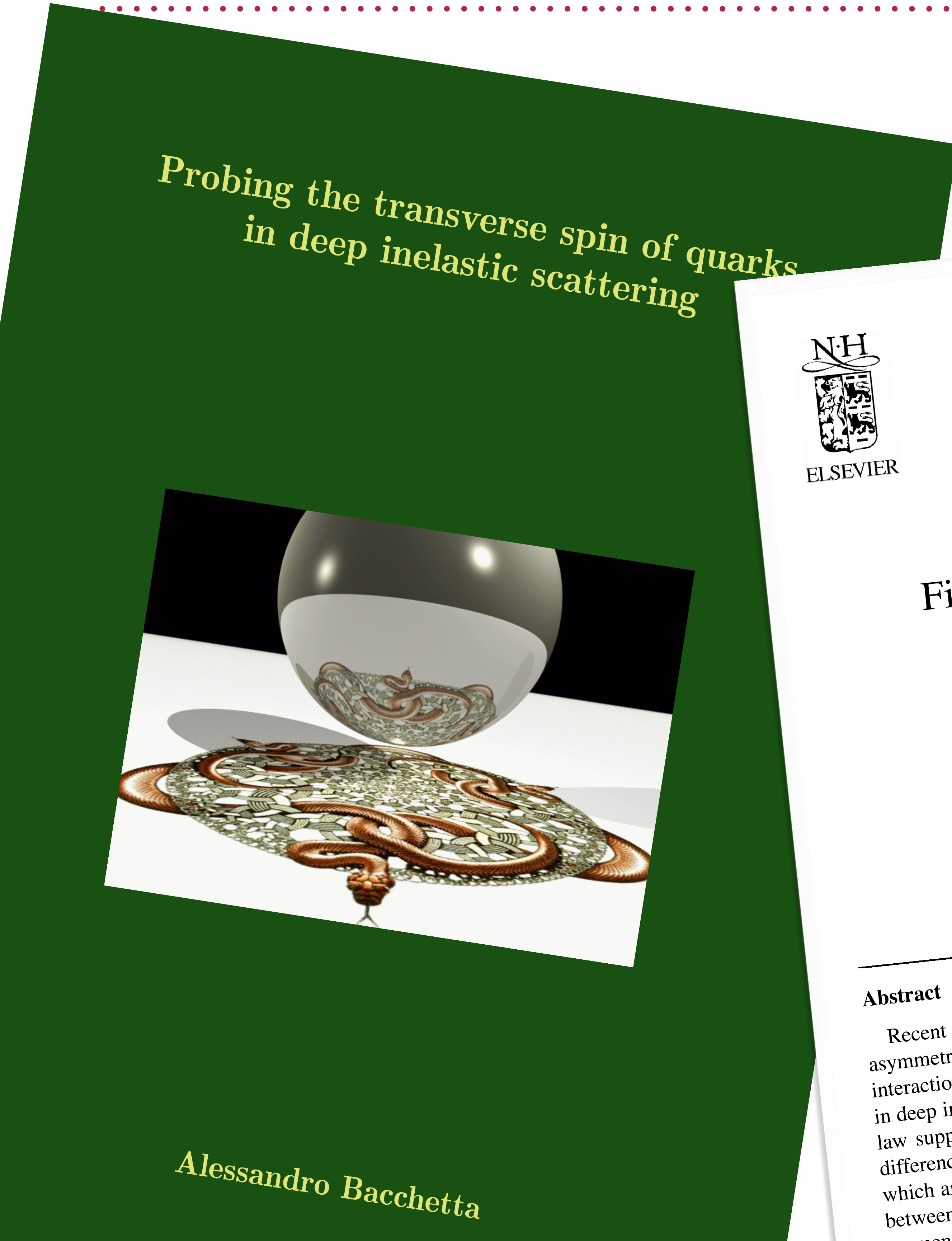
- **Precision**
  - full-fledged global analysis
  - precision measurements

from IWHSS 2011

Old Chinese compass

Exploration

2002: TRANSVERSITY AND SIVERS FUNCTION



PHYSICS LETTERS B

www.elsevier.com/locate/npe

Physics Letters B 530 (2002) 99–107

ELSEVIER

Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering ☆

Stanley J. Brodsky [a], Dae Sung Hwang [a,b], Ivan Schmidt [c]

[a] *Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA*

[b] *Department of Physics, Sejong University, Seoul 143-747, South Korea*

[c] *Departamento de Física, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile*

Received 2 February 2002; accepted 2 February 2002

Editor: H. Georgi

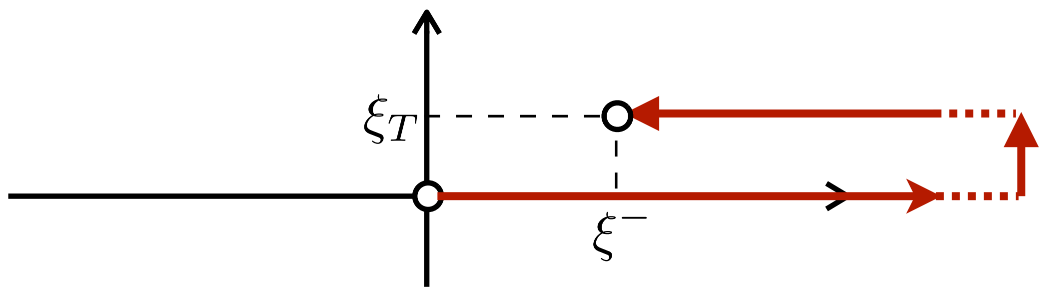
Abstract

Recent measurements from the HERMES and SMC Collaborations show a remarkably large azimuthal single-spin asymmetries A_{UL} and A_{UT} of the proton in semi-inclusive pion leptoproduction $\gamma^*(q)p \to \pi X$. We show that final-state interactions from gluon exchange between the outgoing quark and the target spectator system lead to single-spin asymmetries in deep inelastic lepton–proton scattering at leading twist in perturbative QCD; i.e., the rescattering corrections are not power-law suppressed at large photon virtuality Q^2 at fixed x_{bj}. The existence of such single-spin asymmetries requires a phase difference between two amplitudes coupling the proton target with $J_p^z = \pm 1/2$ to the same final-state, the same amplitudes which are necessary to produce a nonzero proton anomalous magnetic moment. We show that the exchange of gauge particles between the outgoing quark and the proton spectators produces a Coulomb-like complex phase which depends on the angula momentum J^z of the proton's constituents and is thus distinct for different proton spin amplitudes. The single-spin asymmetr ... interactions does not factorize into a product of distribution function and fragmentatio ... which correlates transversely polarized quarks with th

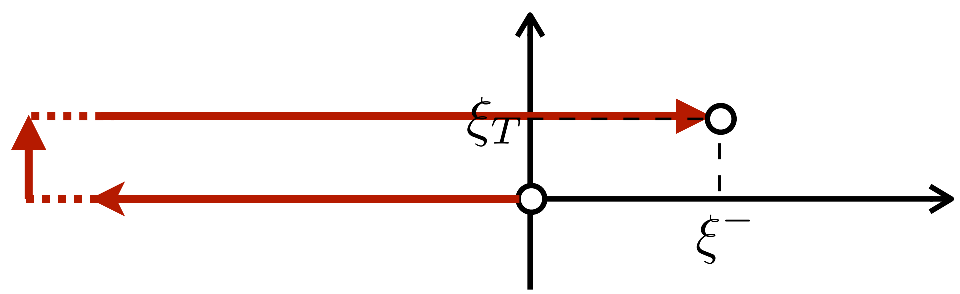
2002: TMD UNIVERSALITY

Nontrivial gauge link structure induces surprising behaviors

SIDIS



Drell-Yan



2002: TMD UNIVERSALITY

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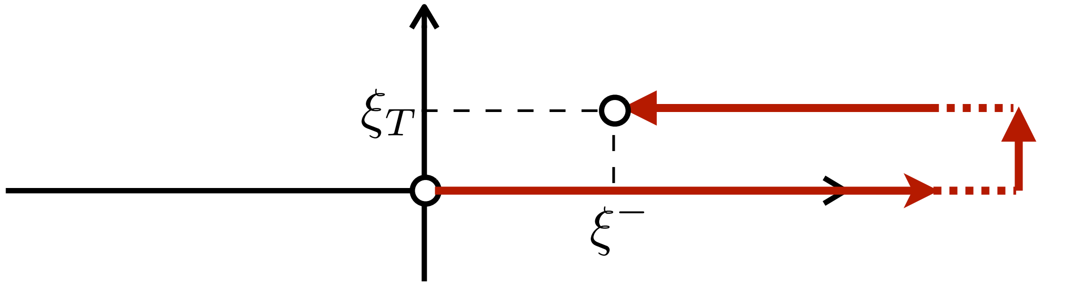
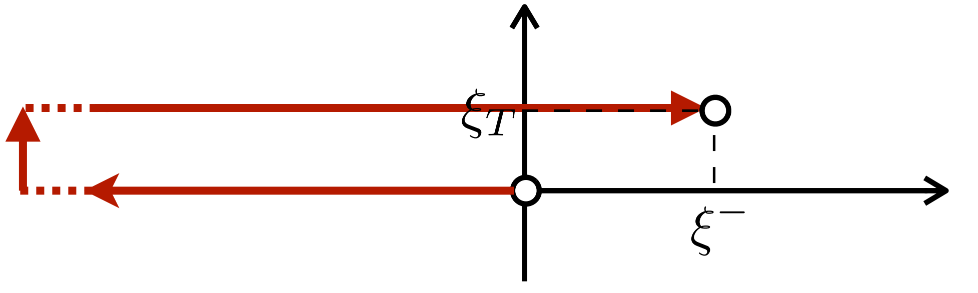


Drell-Yan



Sivers function $_{\text{SIDIS}}$ = – Sivers function $_{\text{Drell-Yan}}$

Collins, PLB 536 (02)

from IWHSS 2011

“[The experimental check of the change of sign] would **crucially test the factorization approach** to the description of processes sensitive to transverse parton momenta.”

from IWHSS 2011

“[The experimental check of the change of sign] would **crucially test the factorization approach** to the description of processes sensitive to transverse parton momenta.”

Efremov, Goeke, Menzel, Metz, Schweitzer, PLB 612 (05)

from IWHSS 2011

“It is a remarkable and fundamental QCD prediction that really tests all concepts we know of for analyzing hard-scattering reactions in strong interactions, and it awaits experimental verification.”

from IWHSS 2011

“It is a remarkable and fundamental QCD prediction that really tests all concepts we know of for analyzing hard-scattering reactions in strong interactions, and it awaits experimental verification.”

Bomhof, Mulders, Vogelsang, Yuan, PRD 75 (07)

from IWHSS 2011

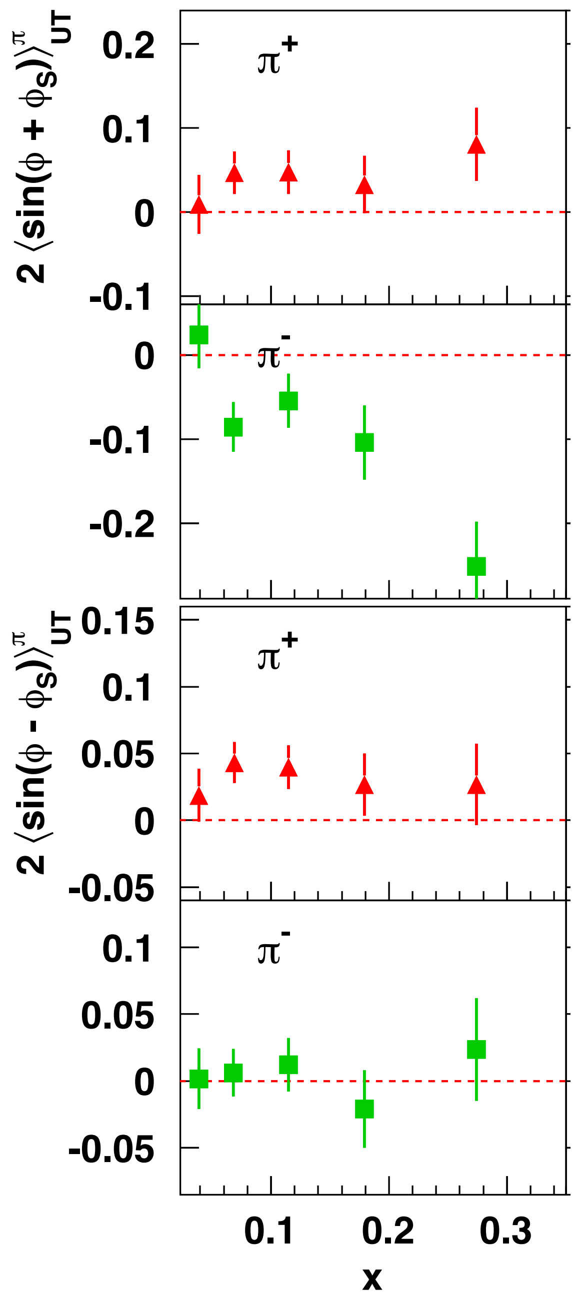
"Its experimental verification would be **crucial to confirm the validity of our present conceptual framework** for analyzing hard hadronic reactions."

from IWHSS 2011

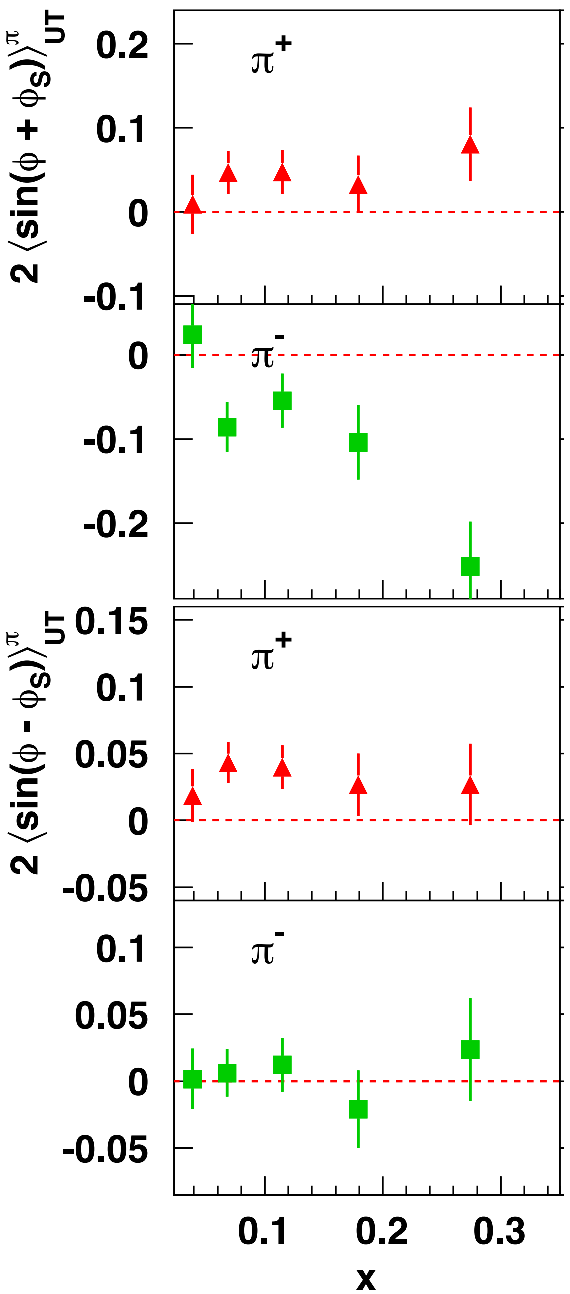
“Its experimental verification would be **crucial to confirm the validity of our present conceptual framework** for analyzing hard hadronic reactions.”

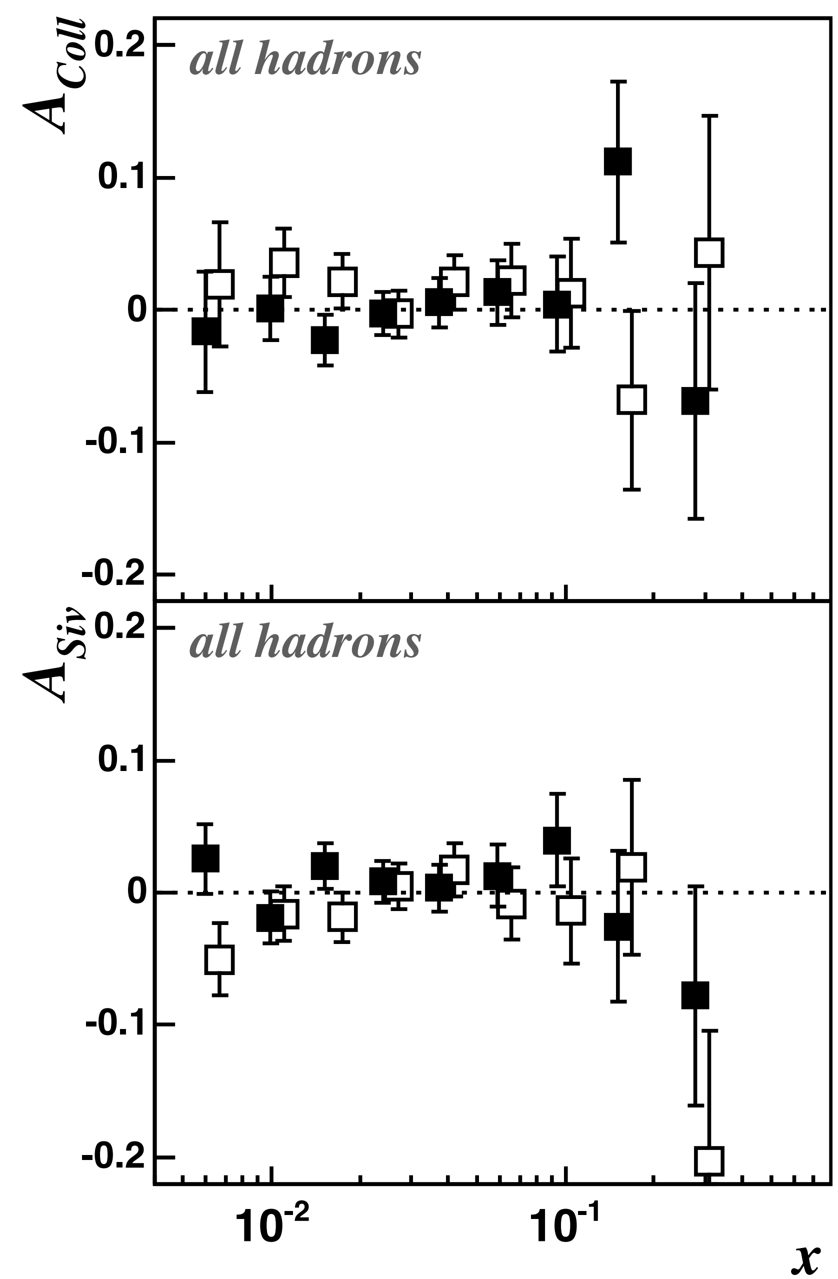
A.B., Bomhof, D’Alesio, Mulders, Murgia, PRL 99 (07)

2005: PIONEERING MEASUREMENTS

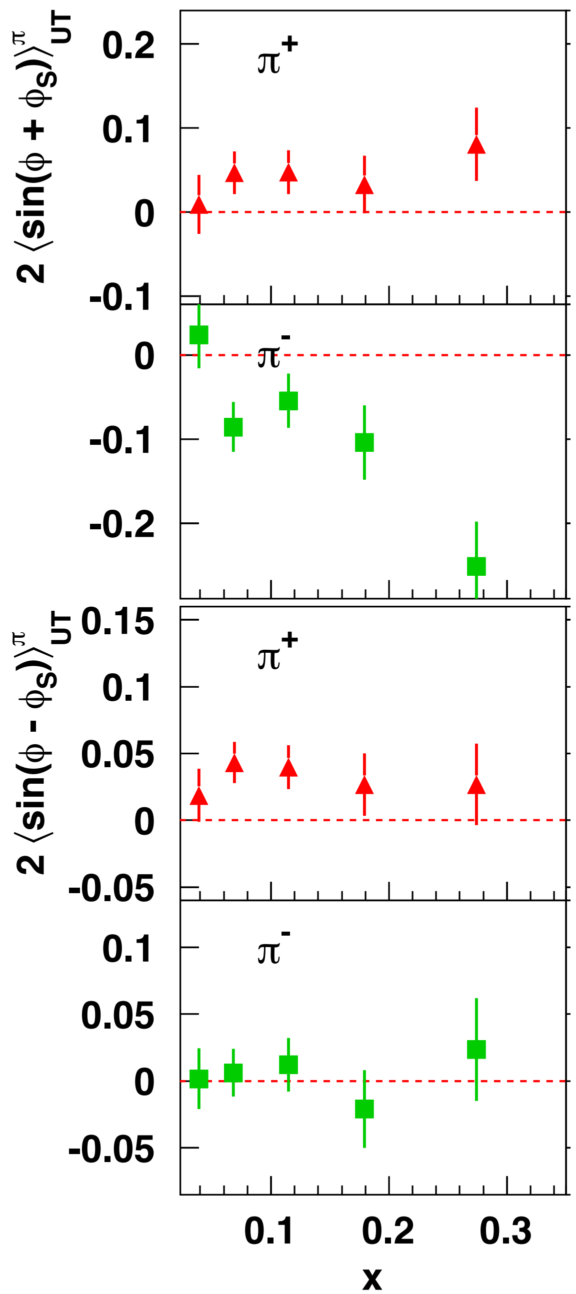


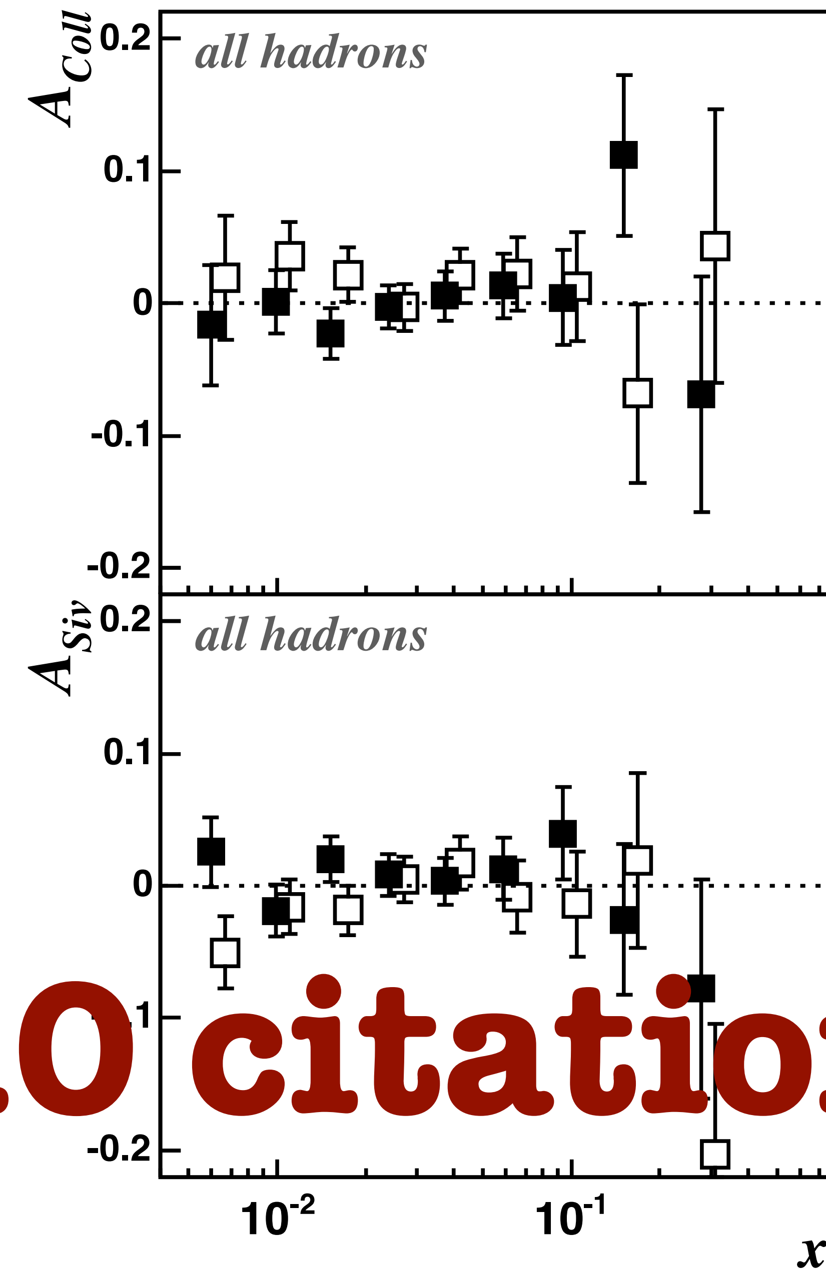
2005: PIONEERING MEASUREMENTS





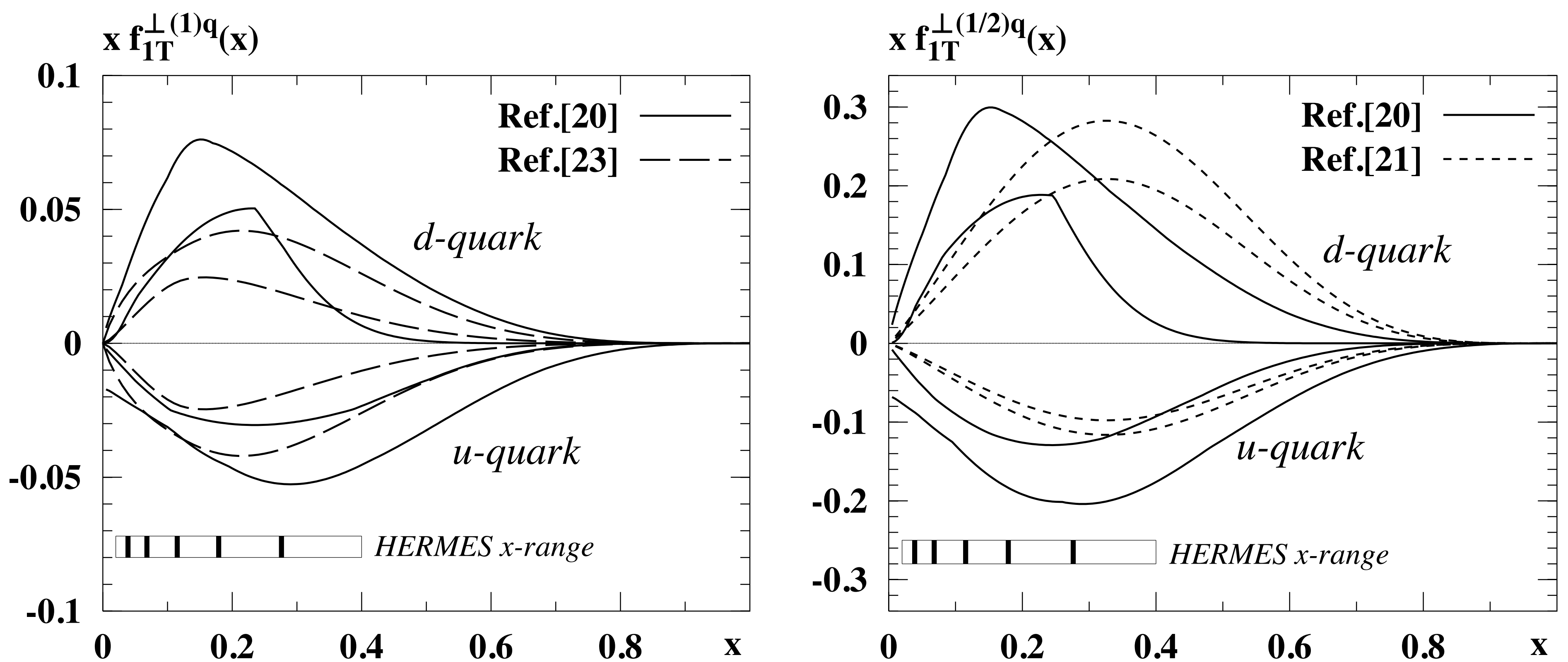
2005: PIONEERING MEASUREMENTS





410 citations

2005: PIONEERING EXTRACTIONS OF THE SIVERS FUNCTION

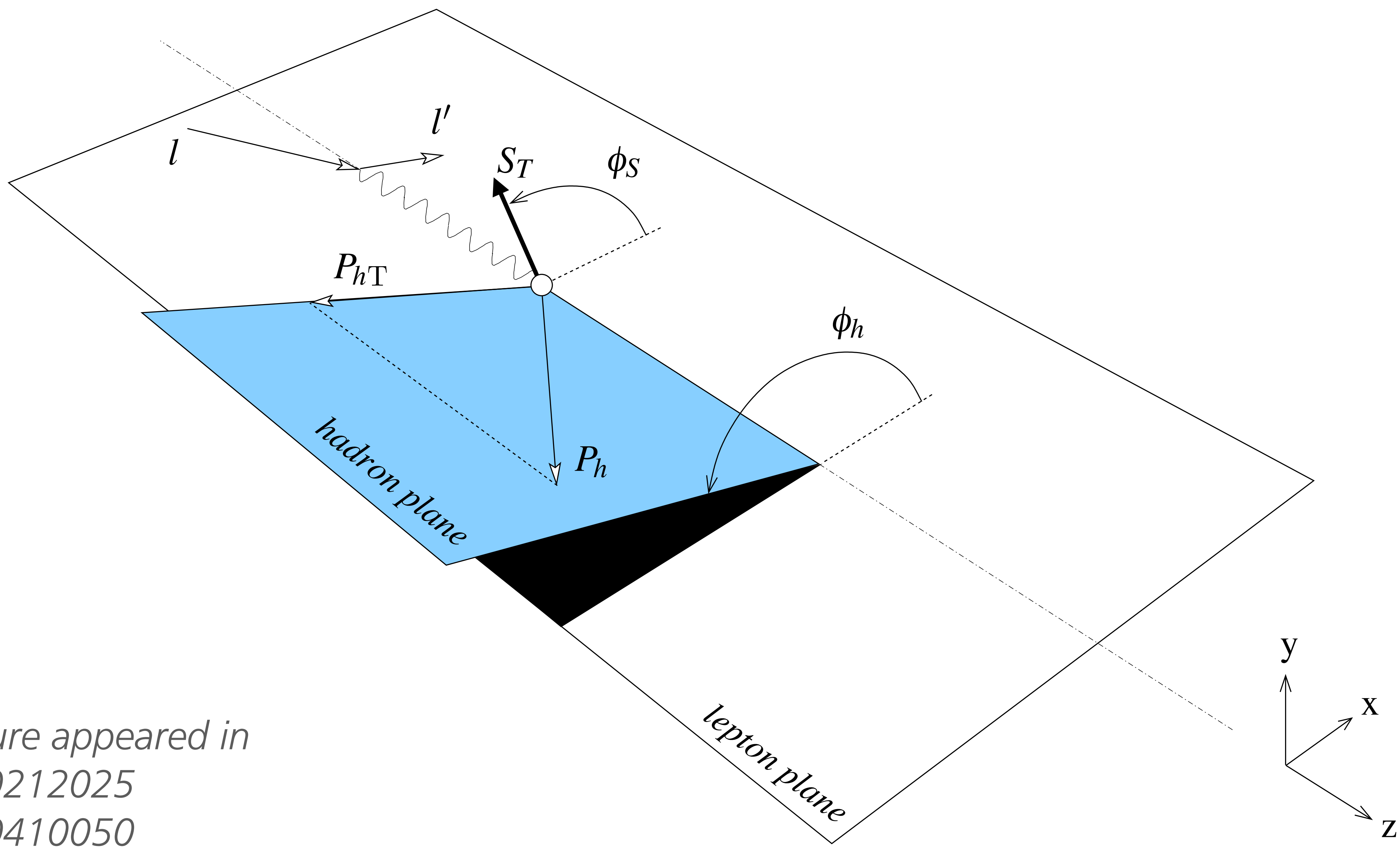


Anselmino, Boglione, Collins, D'Alesio, Efremov, Goeke, Kotzinian, Menzel, Metz, Murgia, Prokudin, Schweitzer, Vogelsang, Yuan, hep-ph/0511017

2006: FULL SIDIS ANALYSIS

$$\ell(l) + N(P) \rightarrow \ell(l') + h(P_h) + X,$$

Bacchetta et al., hep-ph/0611265



**this figure appeared in*
hep-ph/0212025
hep-ph/0410050

THE 18 SIDIS STRUCTURE FUNCTIONS

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\,\Bigg\{ F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad + S_T\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

THE 18 SIDIS STRUCTURE FUNCTIONS

Unpolarized structure function

$f_1 \otimes D_1$

$$
\begin{aligned}
&\frac{d\sigma}{dx\, dy\, d\phi_S\, dz\, d\phi_h\, dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\, y\, Q^2}\, \frac{y^2}{2\,(1-\varepsilon)} \Bigg\{ F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\, \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} + S_L \left[\sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} \right] \\
&\quad + S_L\, \lambda_e \left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_h\, F_{LL}^{\cos\phi_h} \right] \\
&\quad + S_T \Bigg[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) + \varepsilon\, \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\, \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Bigg] + S_T \lambda_e \Bigg[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Bigg] \Bigg\}
\end{aligned}
$$

THE 18 SIDIS STRUCTURE FUNCTIONS

Unpolarized structure function

$f_1 \otimes D_1$

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&+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right] \\
&+ S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\, F_{LL}^{\cos\phi_h}\right] \\
&+ S_T\left[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)}\right. \\
&+ \varepsilon\,\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} \\
&\left.+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\right] + S_T\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)}\right. \\
&\left.+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Bigg\}
\end{aligned}
$$

Sivers structure function

$f_{1T}^{\perp} \otimes D_1$

THE 18 SIDIS STRUCTURE FUNCTIONS

Unpolarized structure function

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\end{aligned}
$$

Sivers structure function

$f_{1T}^{\perp} \otimes D_1$

Collins structure function

$h_1 \otimes H_1^{\perp}$

TMD TABLE

quark pol. / nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Twist-2 TMDs

TMDs in black survive integration over transverse momentum
TMDs in red are time-reversal odd

Mulders-Tangerman, NPB 461 (96)
Boer-Mulders, PRD 57 (98)

TMD TABLE

helicity

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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Twist-2 TMDs

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Sivers

Twist-2 TMDs

transversity

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Boer-Mulders

Sivers

Twist-2 TMDs

transversity

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Mulders-Tangerman, NPB 461 (96)
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TMD TABLE

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
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T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Twist-2 TMDs

helicity

Boer-Mulders

Sivers

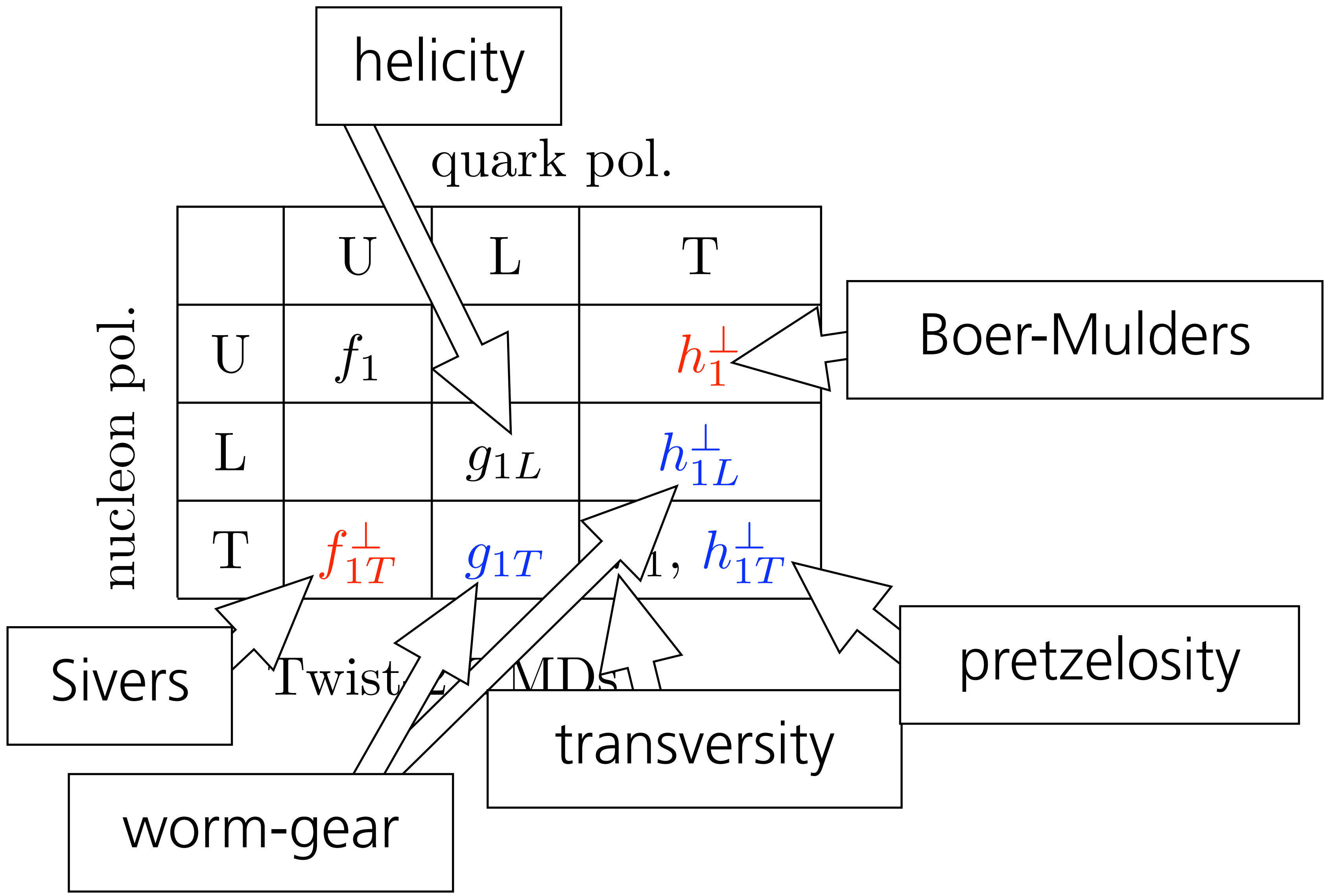
transversity

pretzelosity

TMDs in black survive integration over transverse momentum
TMDs in red are time-reversal odd

Mulders-Tangerman, NPB 461 (96)
Boer-Mulders, PRD 57 (98)

TMD TABLE



TMDs in black survive integration over transverse momentum
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Mulders-Tangerman, NPB 461 (96)
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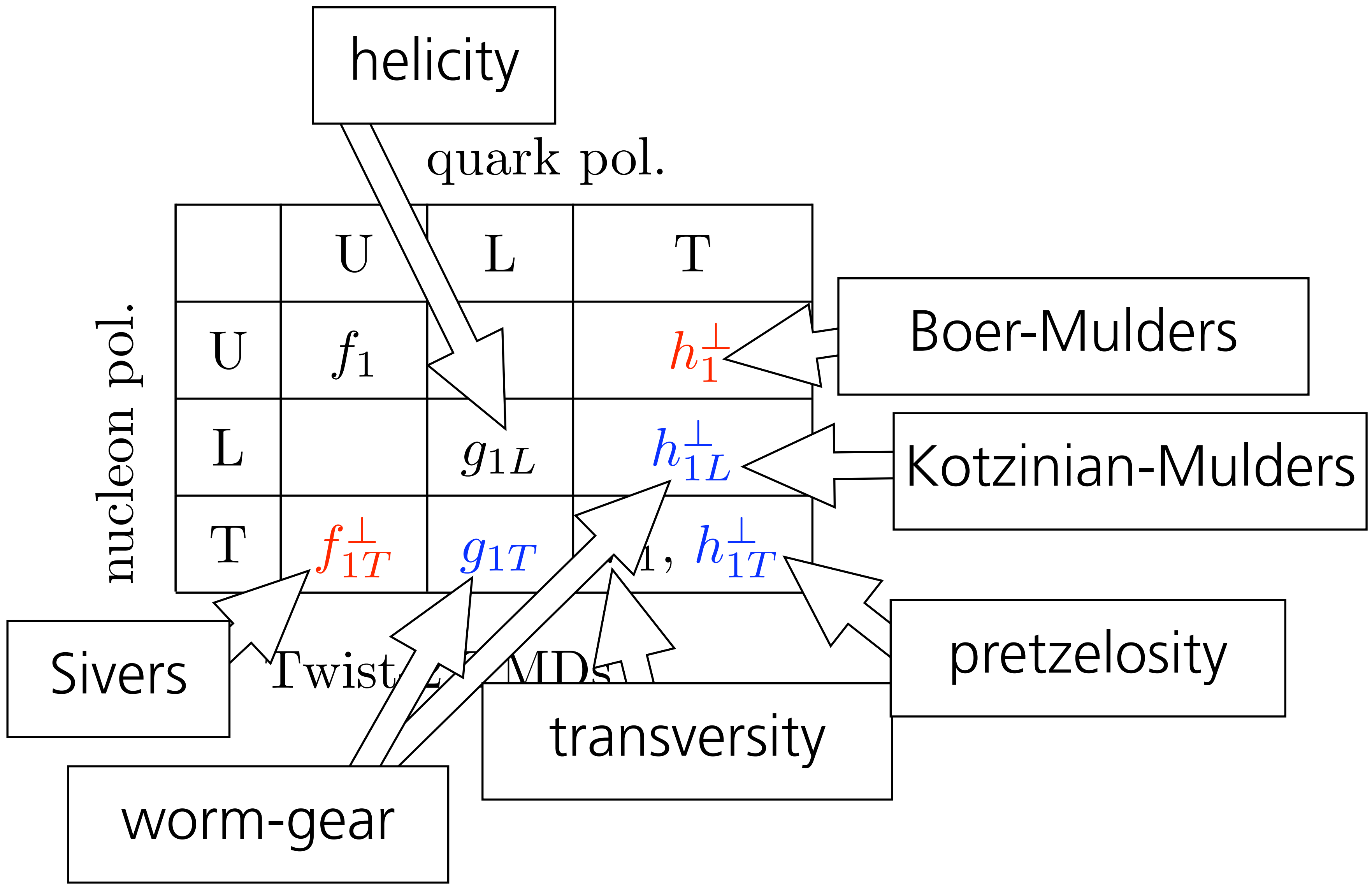
TMD TABLE



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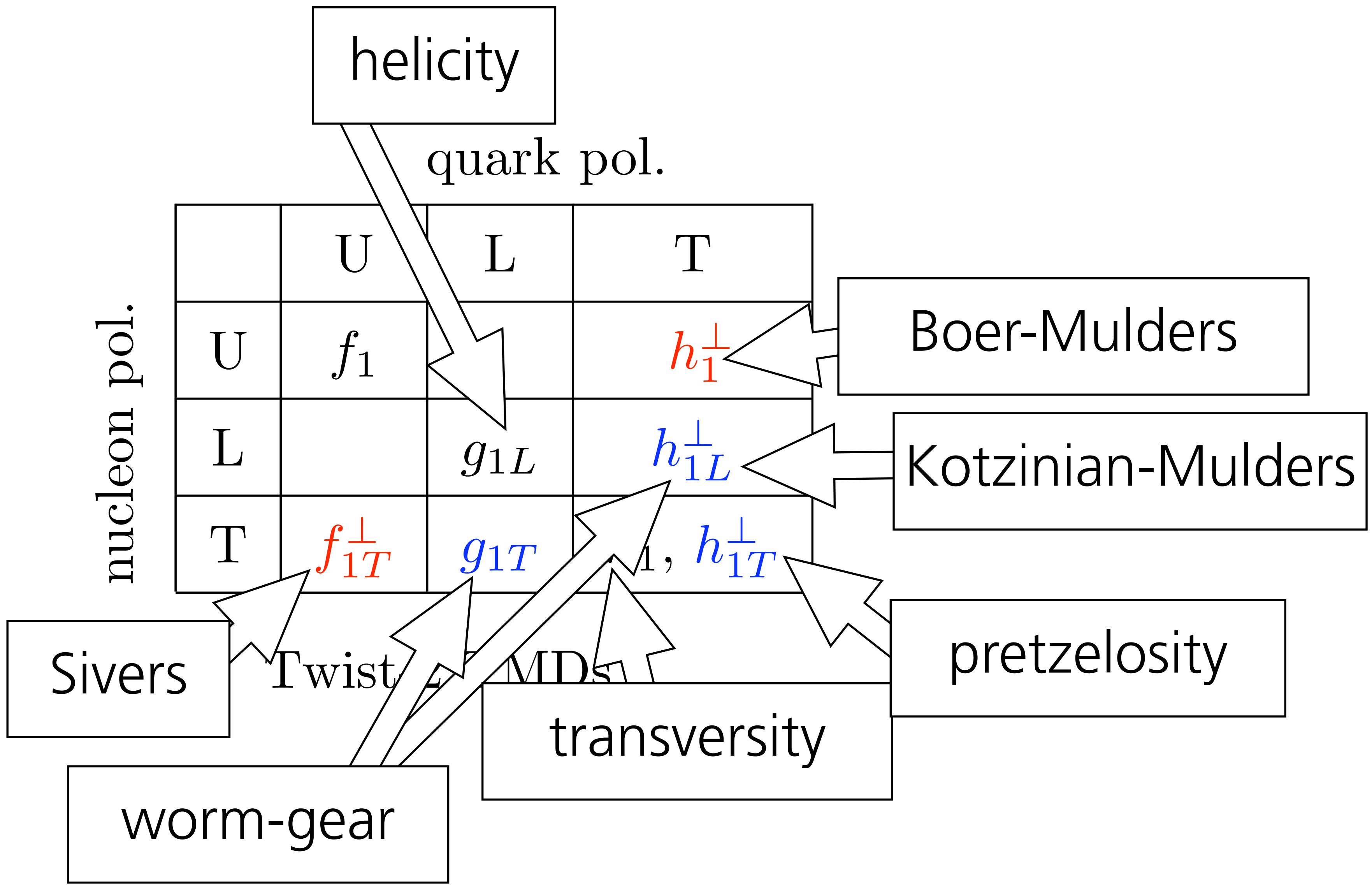
Mulders-Tangerman, NPB 461 (96)

Boer-Mulders, PRD 57 (98)

TMD TABLE

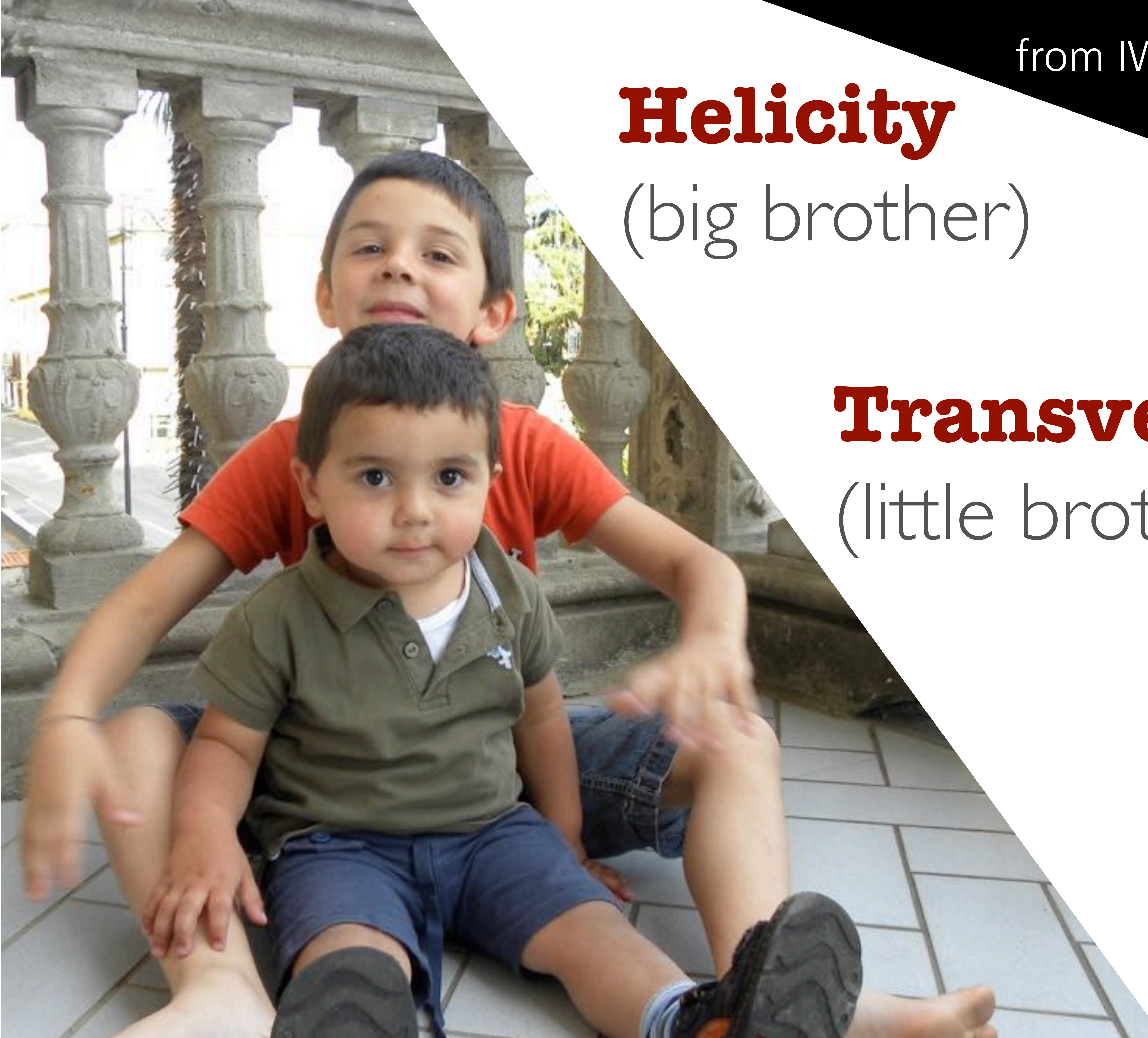


TMDs in black survive integration over transverse momentum
TMDs in red are time-reversal odd

Mulders-Tangerman, NPB 461 (96)
Boer-Mulders, PRD 57 (98)

On top of these, there are twist-3 functions

from IWHSS 2012



Helicity

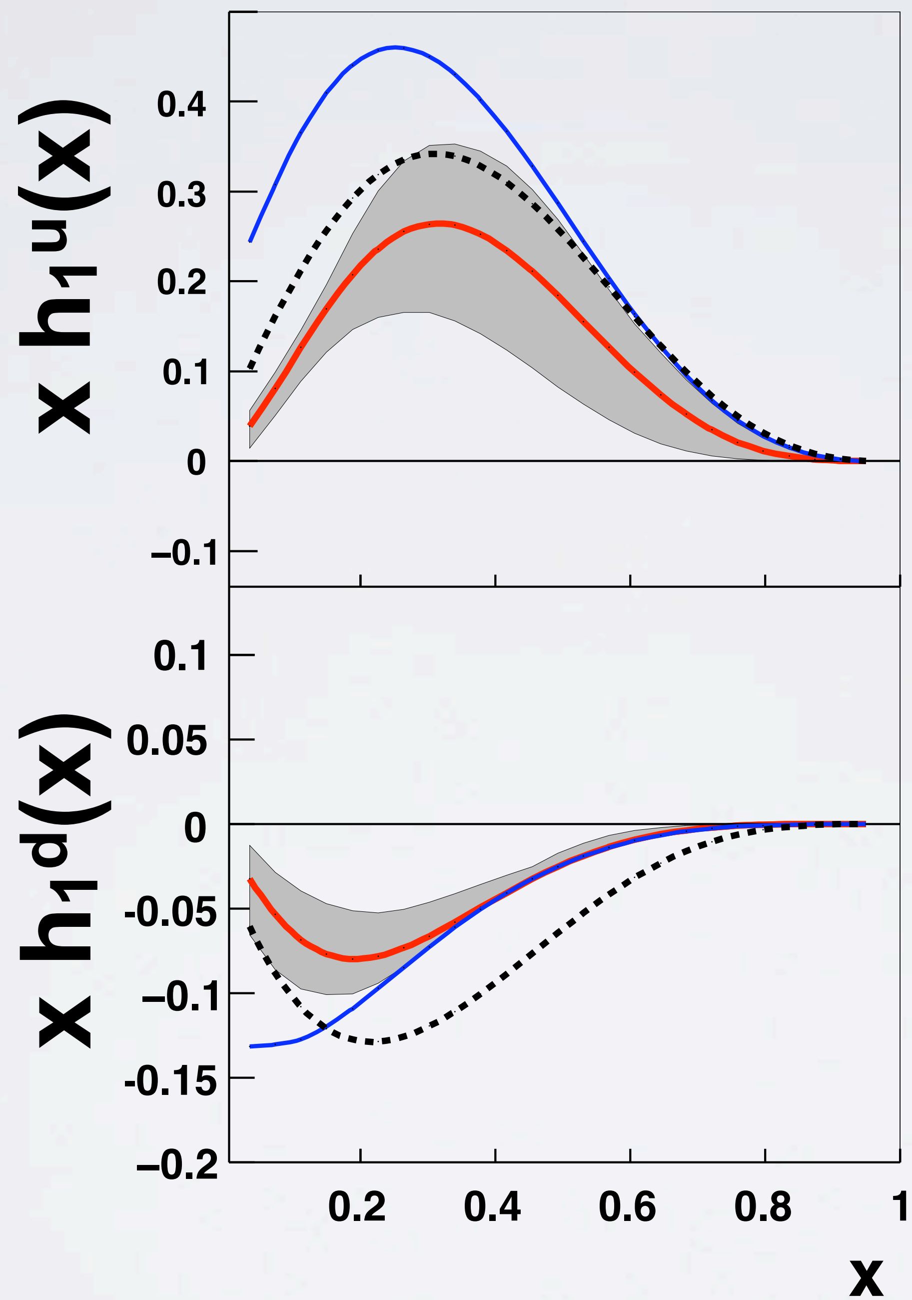
(big brother)

Transversity

(little brother)

2008 Torino's transversity

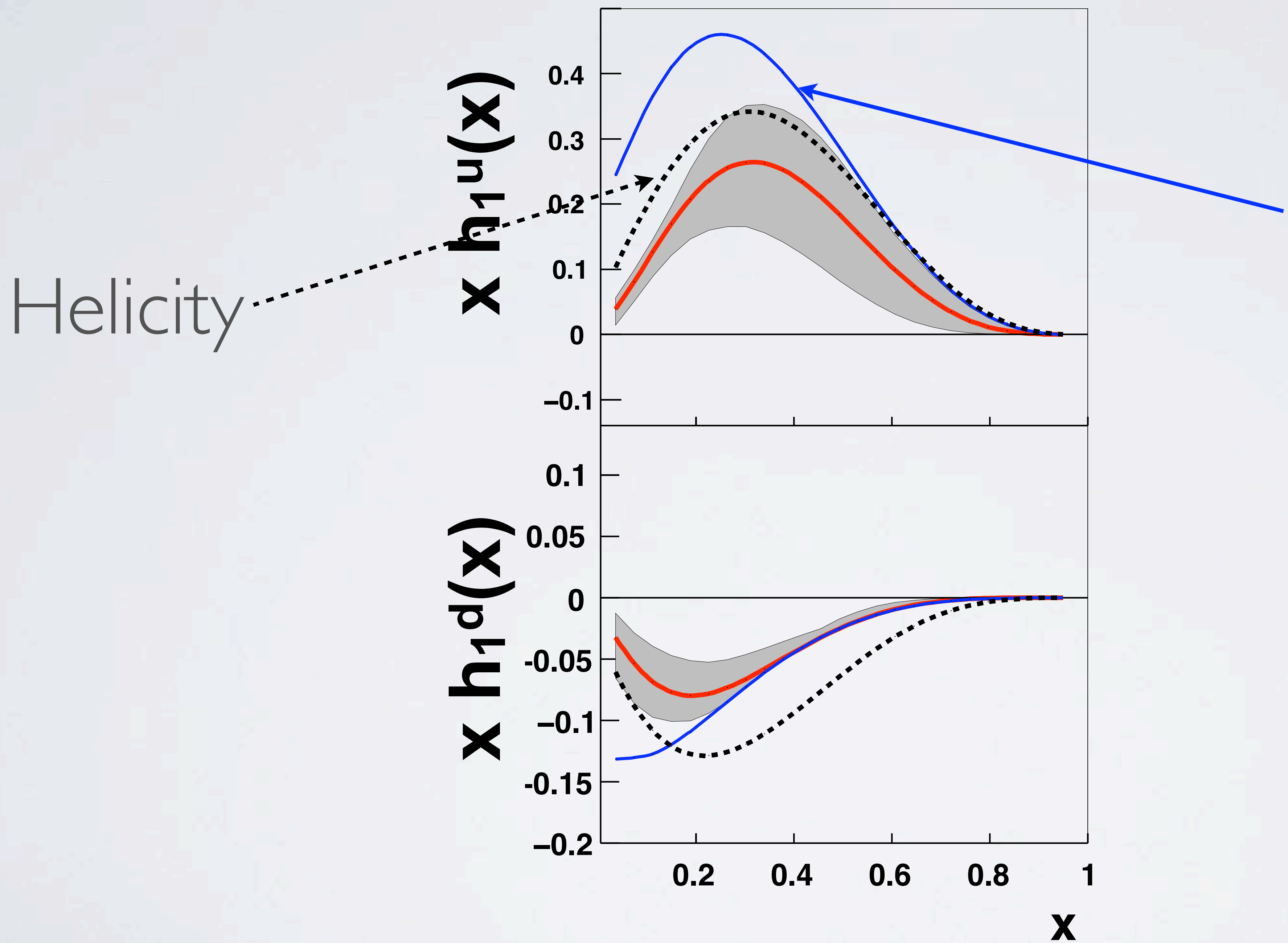
from IWHSS 2012



Anselmino et al. , arXiv:0812.4366

from IWHSS 2012

2008 Torino's transversity



Anselmino et al. , arXiv:0812.4366

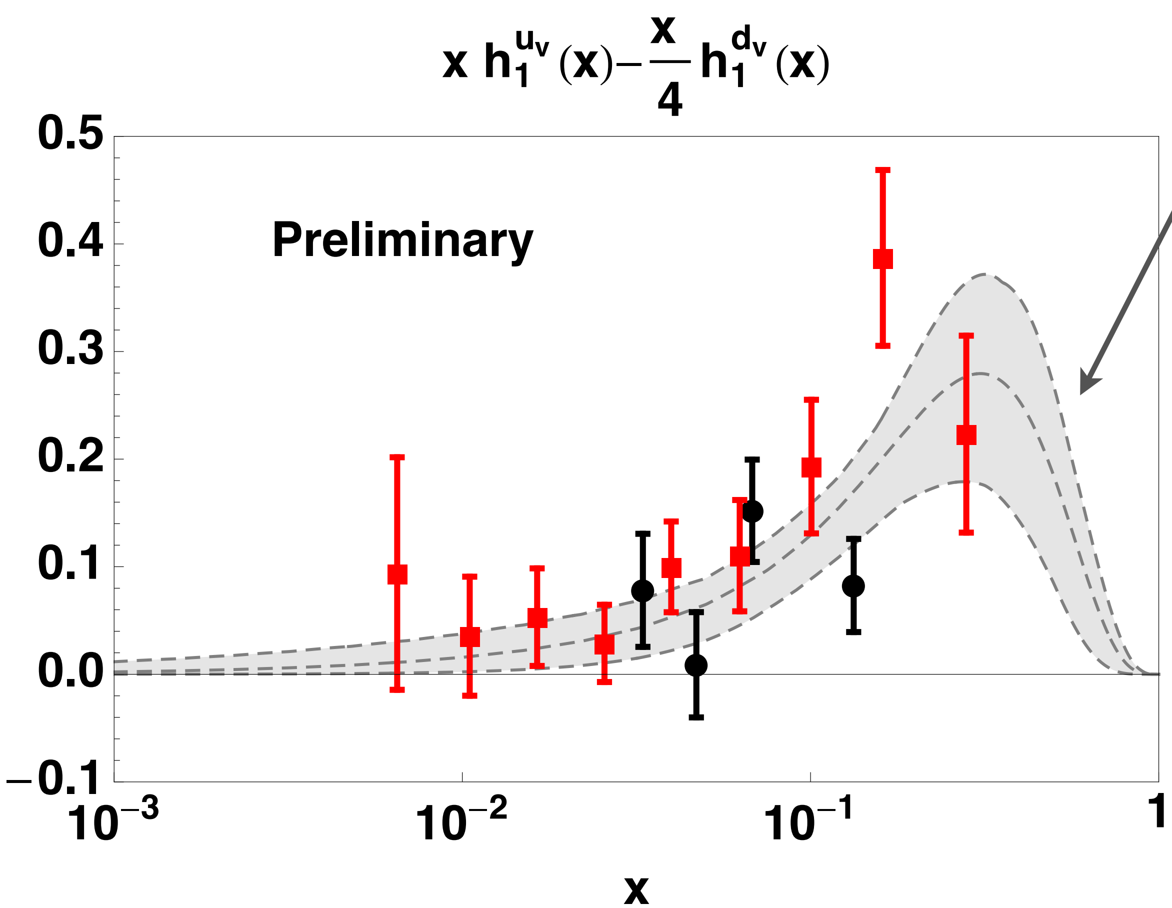

from IWHSS 2012
The
dihadron way
to transversity has opened

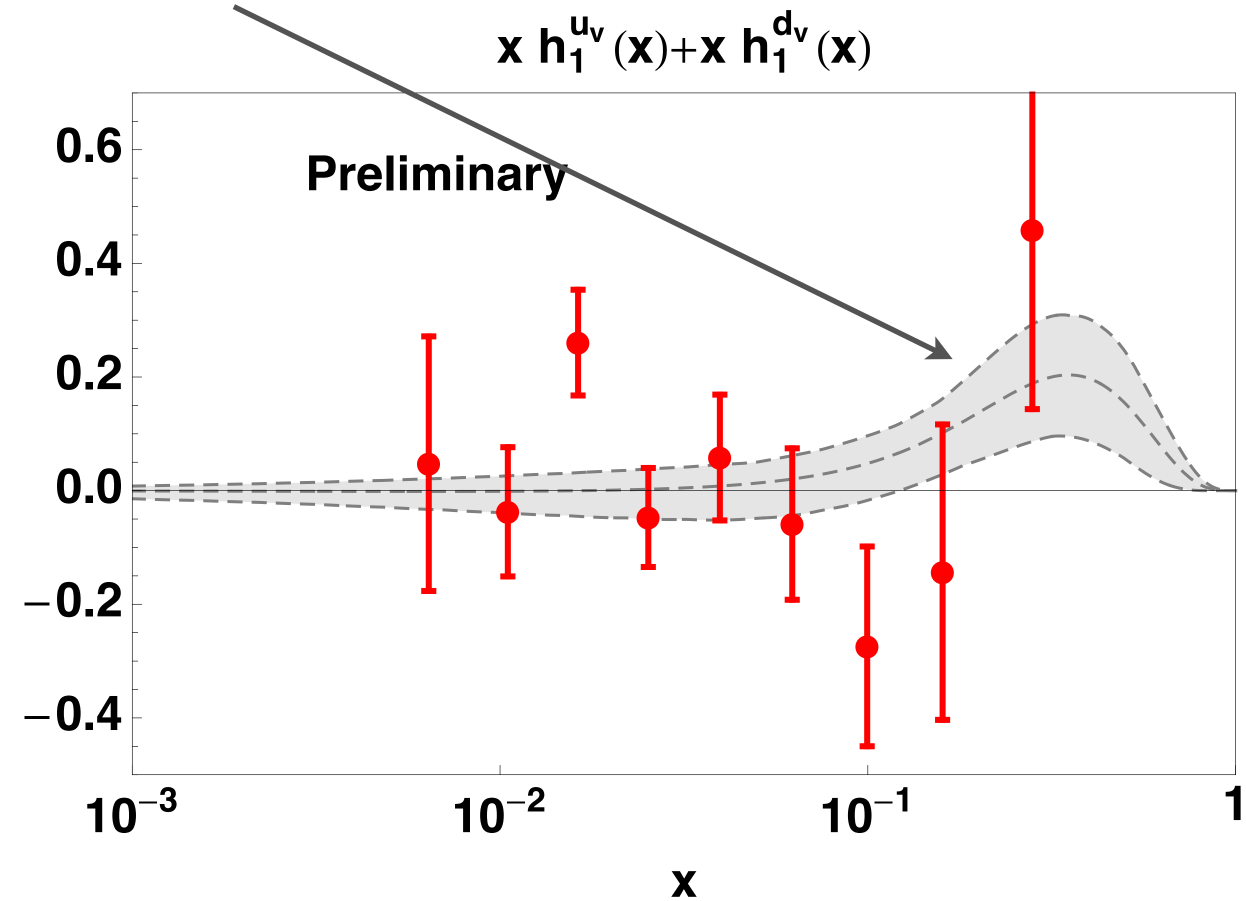
2011

from IWHSS 2012

NEW extraction

Torino's fit





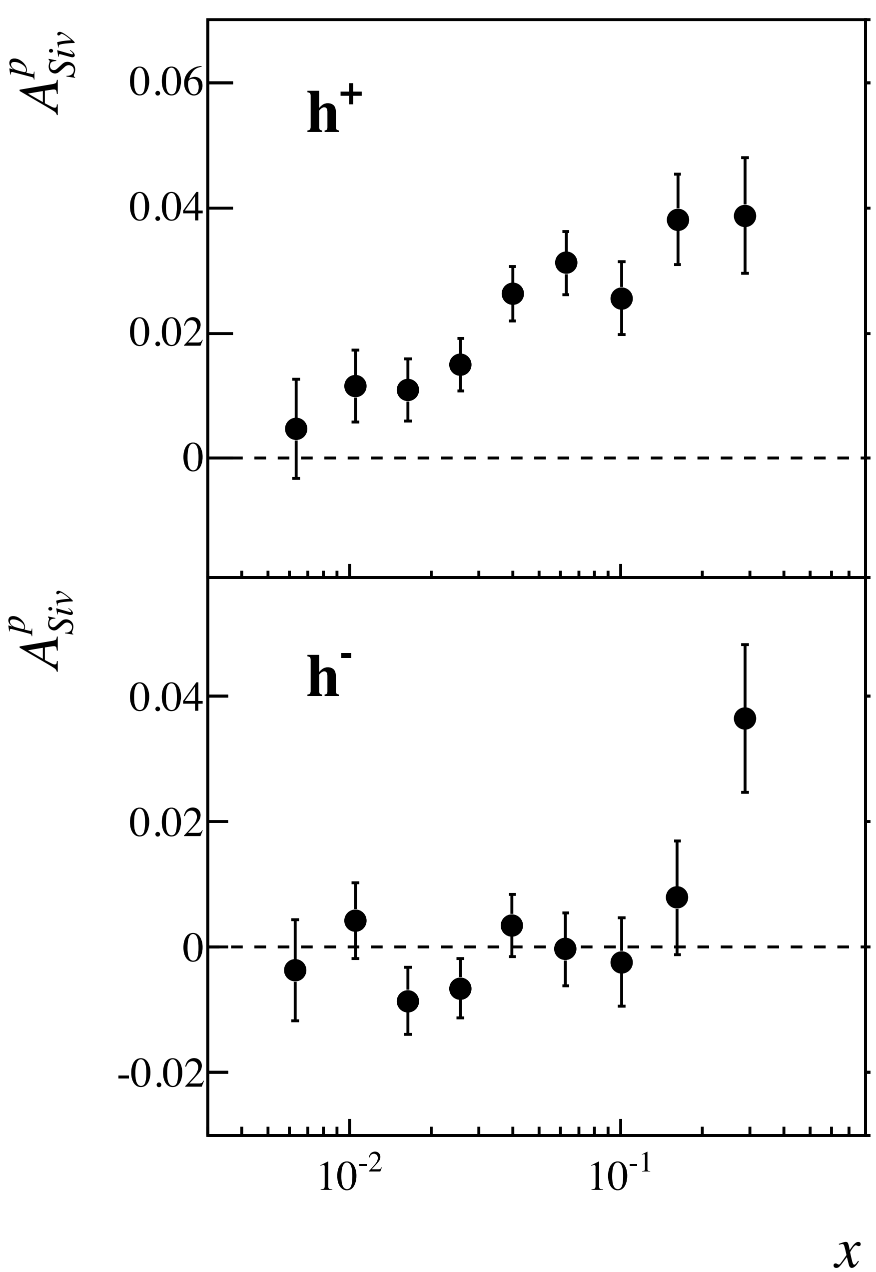
Bacchetta, Courtoy, Radici, PRL 107 (2011)

Hand-held compass

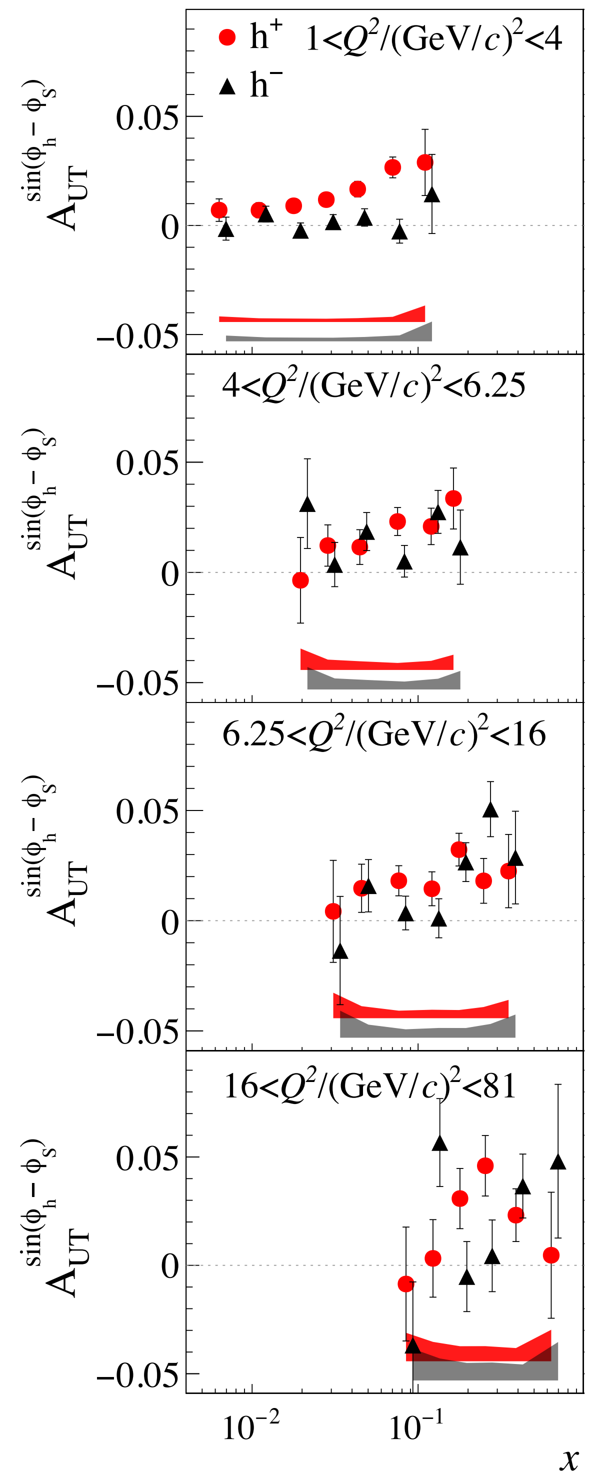
Consolidation

NEW COLLINS AND SIVERS DATA

arXiv:1205.5122

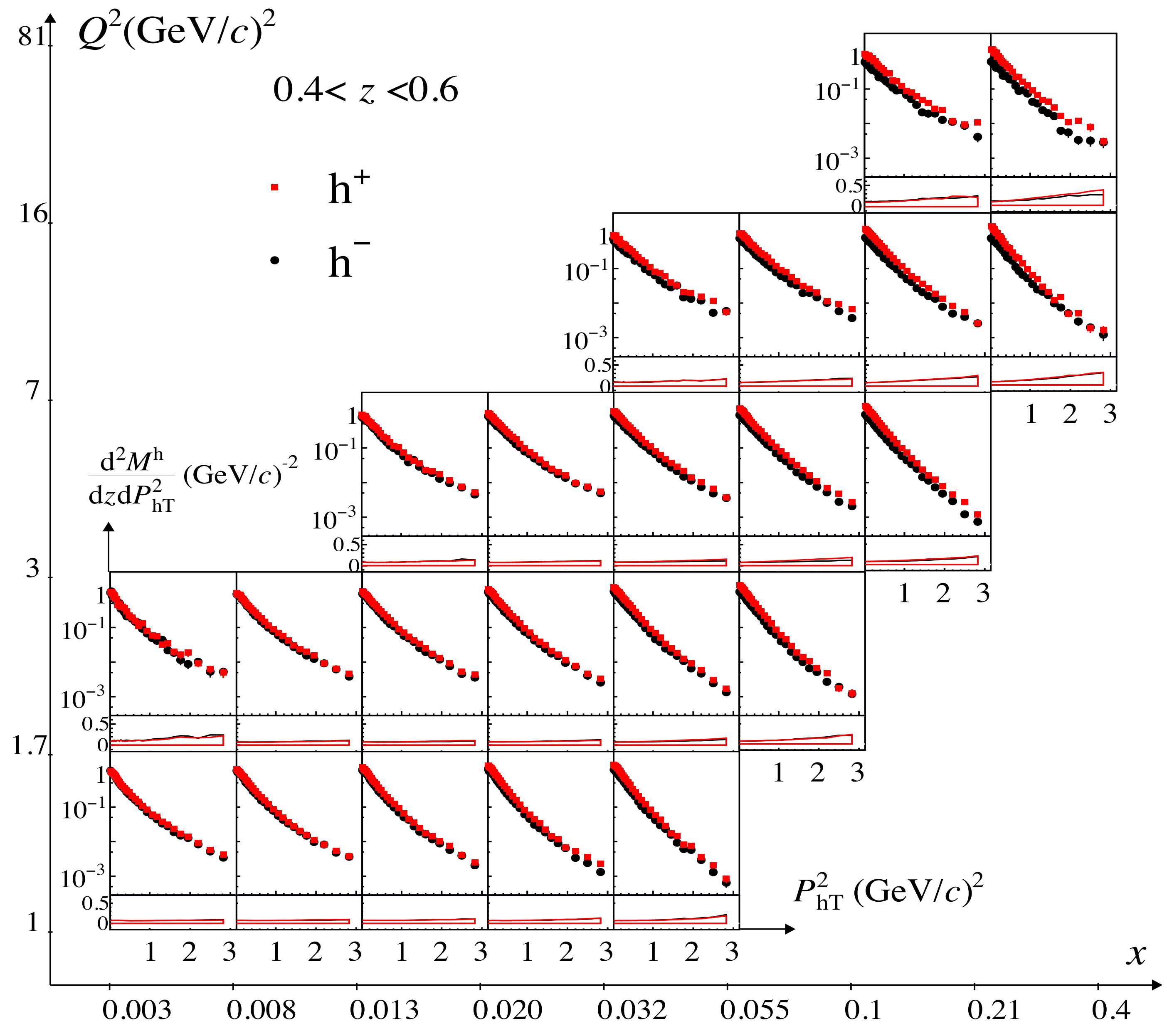


arXiv:1609.07374



NEW MULTIPLICITIES DATA

arXiv:1709.07374



MANY MORE MEASUREMENTS

see, e.g., arXiv:1401.6284, arXiv:1609.06062

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}$$

$$= \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$

$$+ \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+ S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+ S_T\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}$$

$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}$$

$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}$$

MANY MORE MEASUREMENTS

see, e.g., arXiv:1401.6284, arXiv:1609.06062

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad + S_T\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

MANY MORE MEASUREMENTS

see, e.g., arXiv:1401.6284, arXiv:1609.06062

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{ F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad + S_T\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

MANY MORE MEASUREMENTS

see, e.g., arXiv:1401.6284, arXiv:1609.06062

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}$$

$$= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$

$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Bigg[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Bigg]$$

$$+ S_L\,\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Bigg]$$

$$+ S_T\Bigg[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}$$

$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}$$

$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}$$

MANY MORE MEASUREMENTS

see, e.g., arXiv:1401.6284, arXiv:1609.06062

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
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&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&\quad + S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&\quad + S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\quad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}
$$

MANY MORE MEASUREMENTS

see, e.g., arXiv:1401.6284, arXiv:1609.06062

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
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&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
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&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

MANY MORE MEASUREMENTS

see, e.g., arXiv:1401.6284, arXiv:1609.06062

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&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
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&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right. \\
&\quad + S_T\left[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \right. \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad \left. + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\right] + S_T\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\right. \\
&\qquad \left. + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Bigg\}
\end{aligned}
$$

Not all have been published yet

Much more “fun” with TMDs...

from IWHSS 2010

Much more “fun” with TMDs...

from IWHSS 2010

Generalized universality

gauge links

Soft factors

nondiagonal evolution

twist-3

factorization breaking

from IWHSS 2010

Much more “fun” with TMDs...

Generalized universality

gauge links

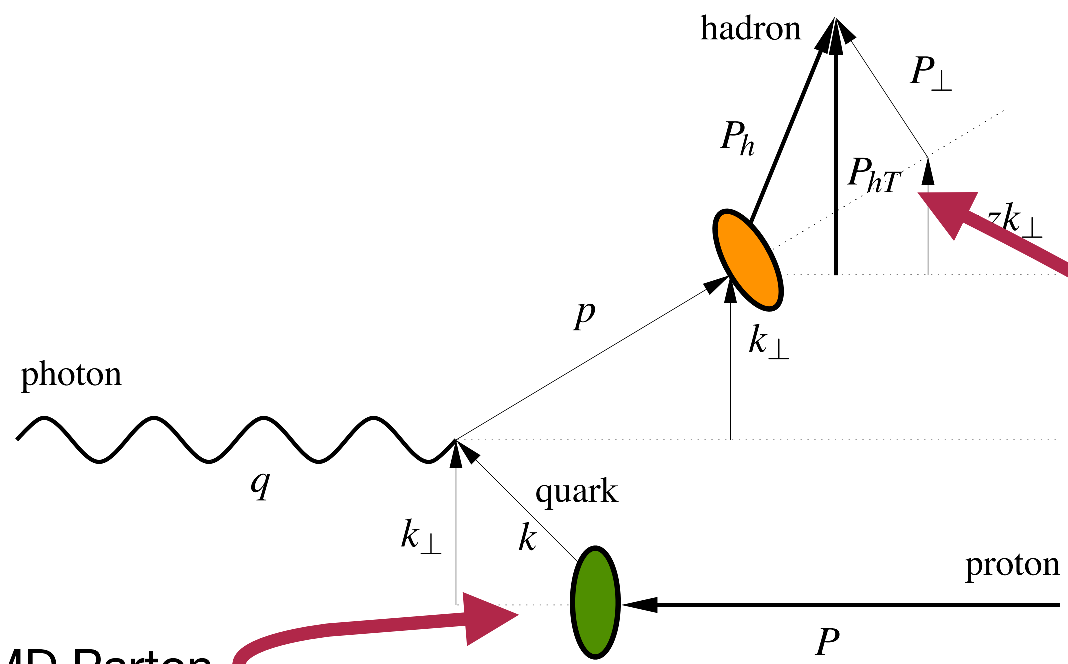
Soft factors

nondiagonal evolution

twist-3

factorization breaking

TMDS IN SEMI-INCLUSIVE DIS

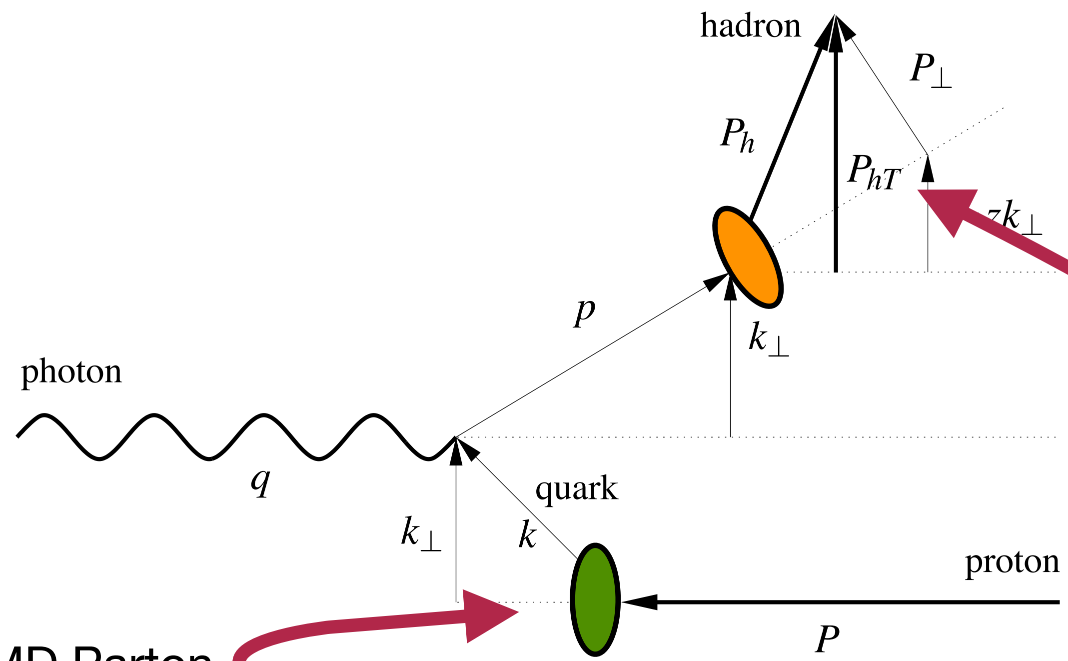


TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$
\begin{aligned}
&F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) \\
&= x \sum_q \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int d^2\boldsymbol{k}_\perp \, d^2\boldsymbol{P}_\perp \, f_1^a\big(x, \boldsymbol{k}_\perp^2; \mu^2\big) \, D_1^{a\to h}\big(z, \boldsymbol{P}_\perp^2; \mu^2\big) \, \delta\big(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp\big) \\
&= x \sum_a \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|) \hat{f}_1^q\big(x, z^2 b_\perp^2; \mu^2\big) \, \hat{D}_1^{a\to h}\big(z, b_\perp^2; \mu^2\big)
\end{aligned}
$$

TMDS IN SEMI-INCLUSIVE DIS



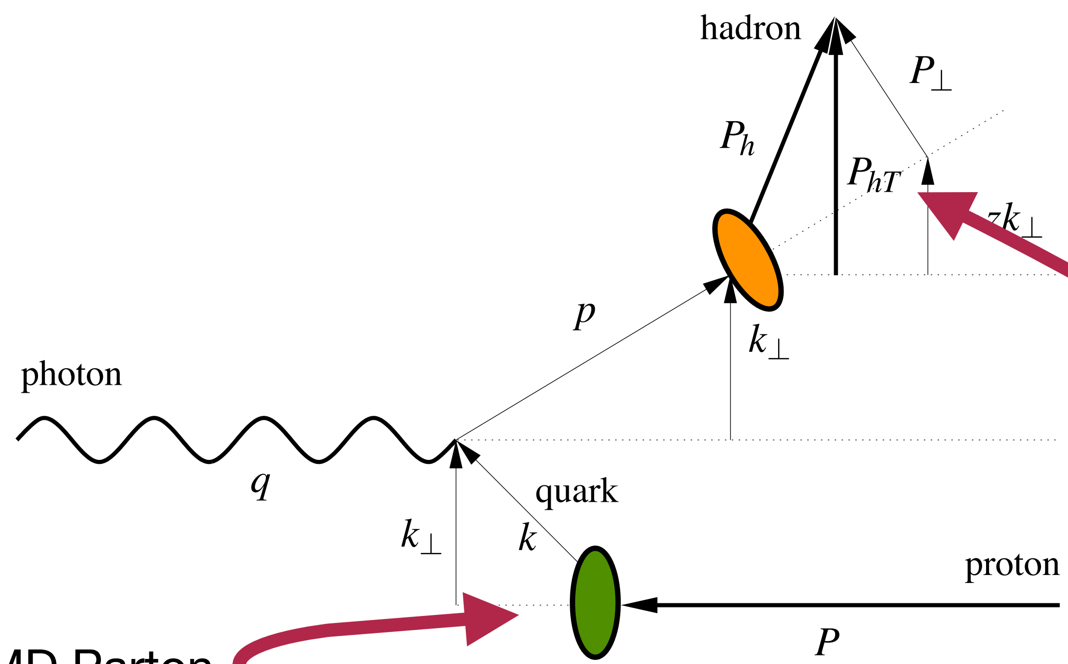
TMD Parton
Distribution Functions

TMD Parton
Fragmentation Functions

$$
\begin{aligned}
&F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)\\
&\quad = x\sum_q \mathcal{H}^q_{UU,T}(Q^2,\mu^2)\int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a\big(x,\boldsymbol{k}_\perp^2;\mu^2\big)\, D_1^{a\to h}\big(z,\boldsymbol{P}_\perp^2;\mu^2\big)\,\delta\big(z\boldsymbol{k}_\perp-\boldsymbol{P}_{hT}+\boldsymbol{P}_\perp\big)\\
&\quad = x\sum_a \mathcal{H}^q_{UU,T}(Q^2,\mu^2)\int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|)\hat{f}_1^q\big(x,z^2b_\perp^2;\mu^2\big)\,\hat{D}_1^{a\to h}\big(z,b_\perp^2;\mu^2\big)
\end{aligned}
$$

At small transverse momentum, the dominant part is given by TMDs.

TMDS IN SEMI-INCLUSIVE DIS



TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$$

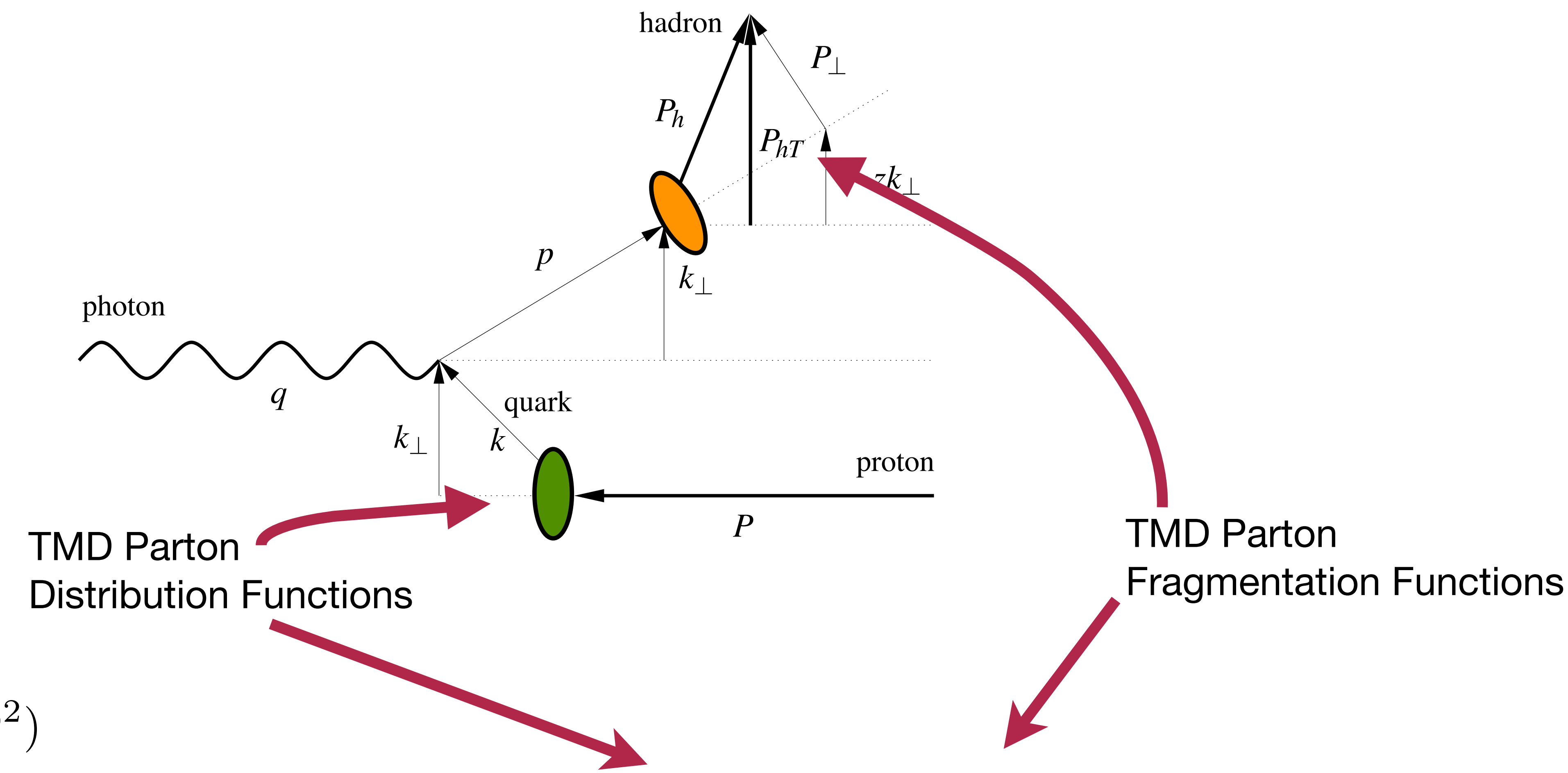
$$= x \sum_q \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int d^2\boldsymbol{k}_\perp \, d^2\boldsymbol{P}_\perp \, f_1^a\left(x, \boldsymbol{k}_\perp^2; \mu^2\right) D_1^{a\to h}\left(z, \boldsymbol{P}_\perp^2; \mu^2\right) \delta\left(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp\right)$$

$$= x \sum_a \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|) \hat{f}_1^q\left(x, z^2 b_\perp^2; \mu^2\right) \hat{D}_1^{a\to h}\left(z, b_\perp^2; \mu^2\right)$$

At small transverse momentum, the dominant part is given by TMDs.

The analysis is usually done in Fourier-transformed space

TMDS IN SEMI-INCLUSIVE DIS



$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$$
$$= x \sum_q \mathcal{H}_{UU,T}^q(Q^2, \mu^2) \int d^2\boldsymbol{k}_\perp \, d^2\boldsymbol{P}_\perp \, f_1^a\big(x, \boldsymbol{k}_\perp^2; \mu^2\big) \, D_1^{a\to h}\big(z, \boldsymbol{P}_\perp^2; \mu^2\big) \, \delta\big(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp\big)$$
$$= x \sum_a \mathcal{H}_{UU,T}^q(Q^2, \mu^2) \int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|) \hat{f}_1^q\big(x, z^2 b_\perp^2; \mu^2\big) \, \hat{D}_1^{a\to h}\big(z, b_\perp^2; \mu^2\big)$$

At small transverse momentum, the dominant part is given by TMDs.

The analysis is usually done in Fourier-transformed space

TMDs formally depend on two scales, but for convenience I set them equal.

TMD STRUCTURE

$$\hat{f}_1^a\big(x,|\boldsymbol{b}_T|;\mu,\zeta\big) = \int d^2\boldsymbol{k}_\perp\, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp}\, f_1^a\big(x,\boldsymbol{k}_\perp^2;\mu,\zeta\big)$$

$$\hat{f}_1^a(x,b_T^2;\mu_f,\zeta_f) = [C\,\otimes\,f_1](x,\mu_{b_*})\; e^{\int_{\mu_{b_*}}^{\mu_f}\frac{d\mu}{\mu}\left(\gamma_F-\gamma_K\,\ln\frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\rm resum}+g_K} f_{1\,NP}(x,b_T^2;\zeta_f,Q_0)$$

see, e.g., Ji, Ma, Yuan, PRD 71 (05)
Collins, "Foundations of Perturbative QCD" (11)
Rogers, Aybat, PRD 83 (11)
Echevarria, Idilbi, Scimemi JHEP 1207 (12)

TMD STRUCTURE

$$\hat{f}_1^a\big(x,|\boldsymbol{b}_T|;\mu,\zeta\big)=\int d^2\boldsymbol{k}_\perp\, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp}\, f_1^a\big(x,\boldsymbol{k}_\perp^2;\mu,\zeta\big)$$

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$$\mu_b=\frac{2e^{-\gamma_E}}{b_*}$$

see, e.g., Ji, Ma, Yuan, PRD 71 (05)
Collins, "Foundations of Perturbative QCD" (11)
Rogers, Aybat, PRD 83 (11)
Echevarria, Idilbi, Scimemi JHEP 1207 (12)

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T \cdot \boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \, e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\text{resum}} + g_K} f_{1\,NP}(x, b_T^2; \zeta_f, Q_0)$$

$$\mu_b = \frac{2e^{-\gamma_E}}{b_*}$$

collinear PDF

matching coefficients (perturbative)

Collins-Soper kernel (perturbative and nonperturbative)

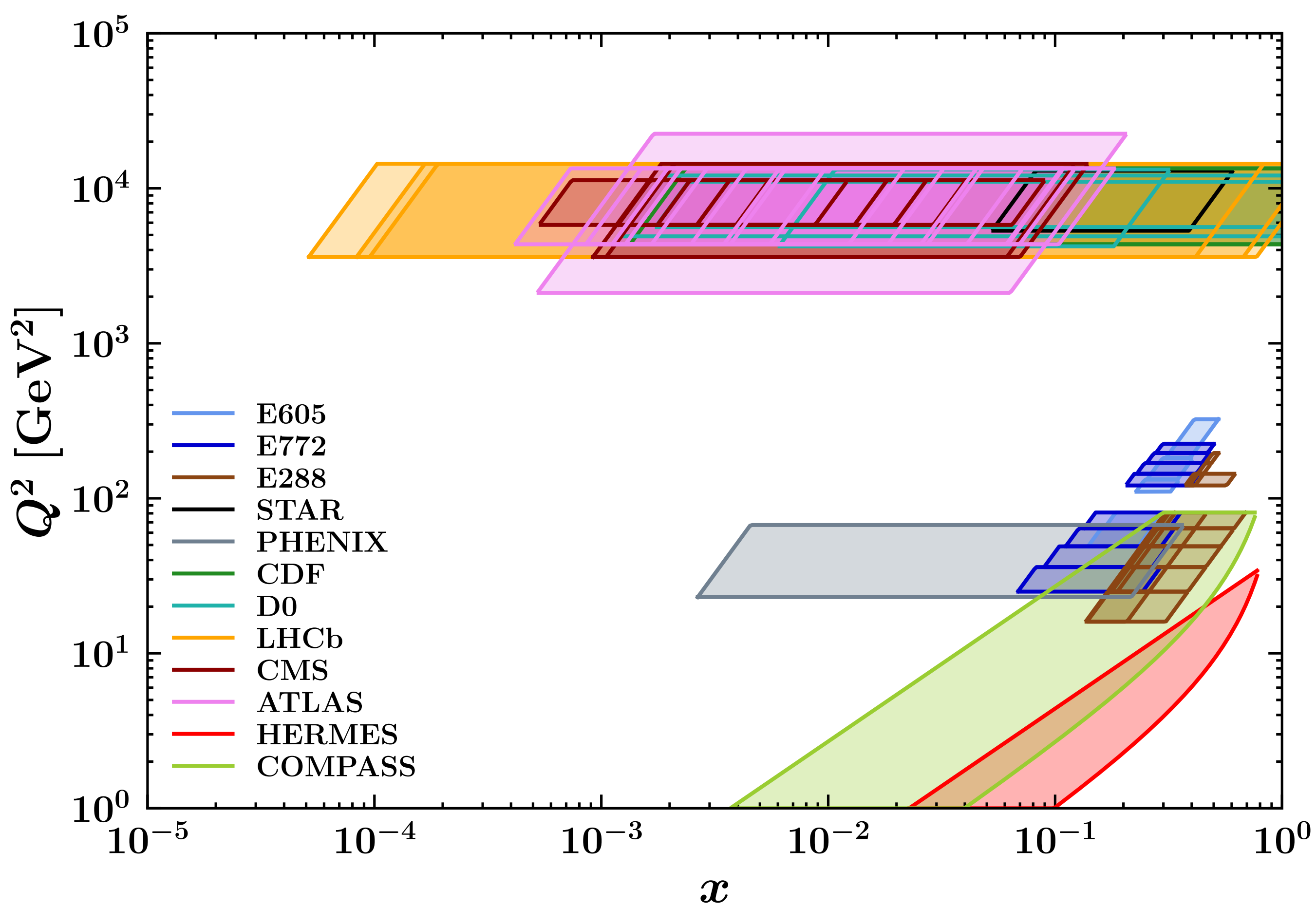
nonperturbative part of TMD

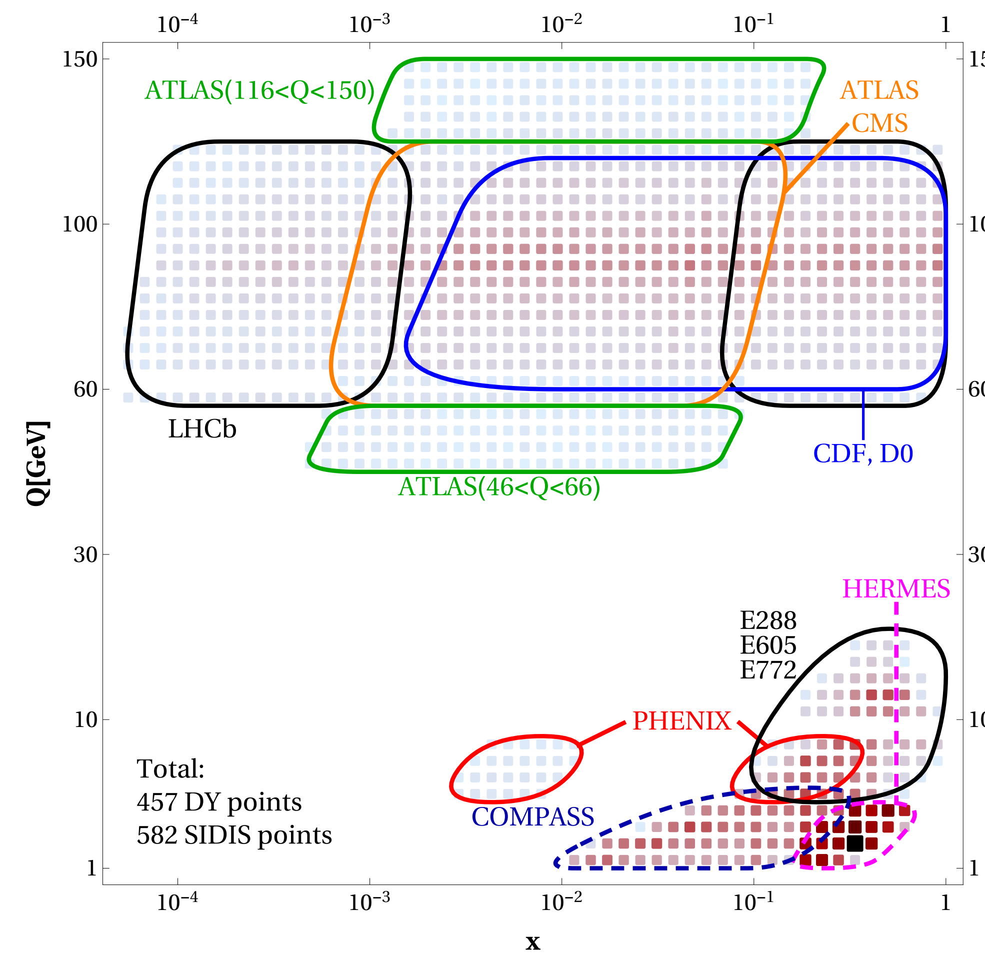
see, e.g., Ji, Ma, Yuan, PRD 71 (05)
Collins, "Foundations of Perturbative QCD" (11)
Rogers, Aybat, PRD 83 (11)
Echevarria, Idilbi, Scimemi JHEP 1207 (12)

TMD FITS OF UNPOLARIZED DATA

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia 2013 arXiv:1309.3507	parton model	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	parton model	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLL′	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457
SV 2019 arXiv:1912.06532	N^3LL^-	✔	✔	✔	✔	1039
Pavia 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353
MAP22 arXiv:2206.07598	N^3LL^-	✔	✔	✔	✔	2031

x–Q² COVERAGE

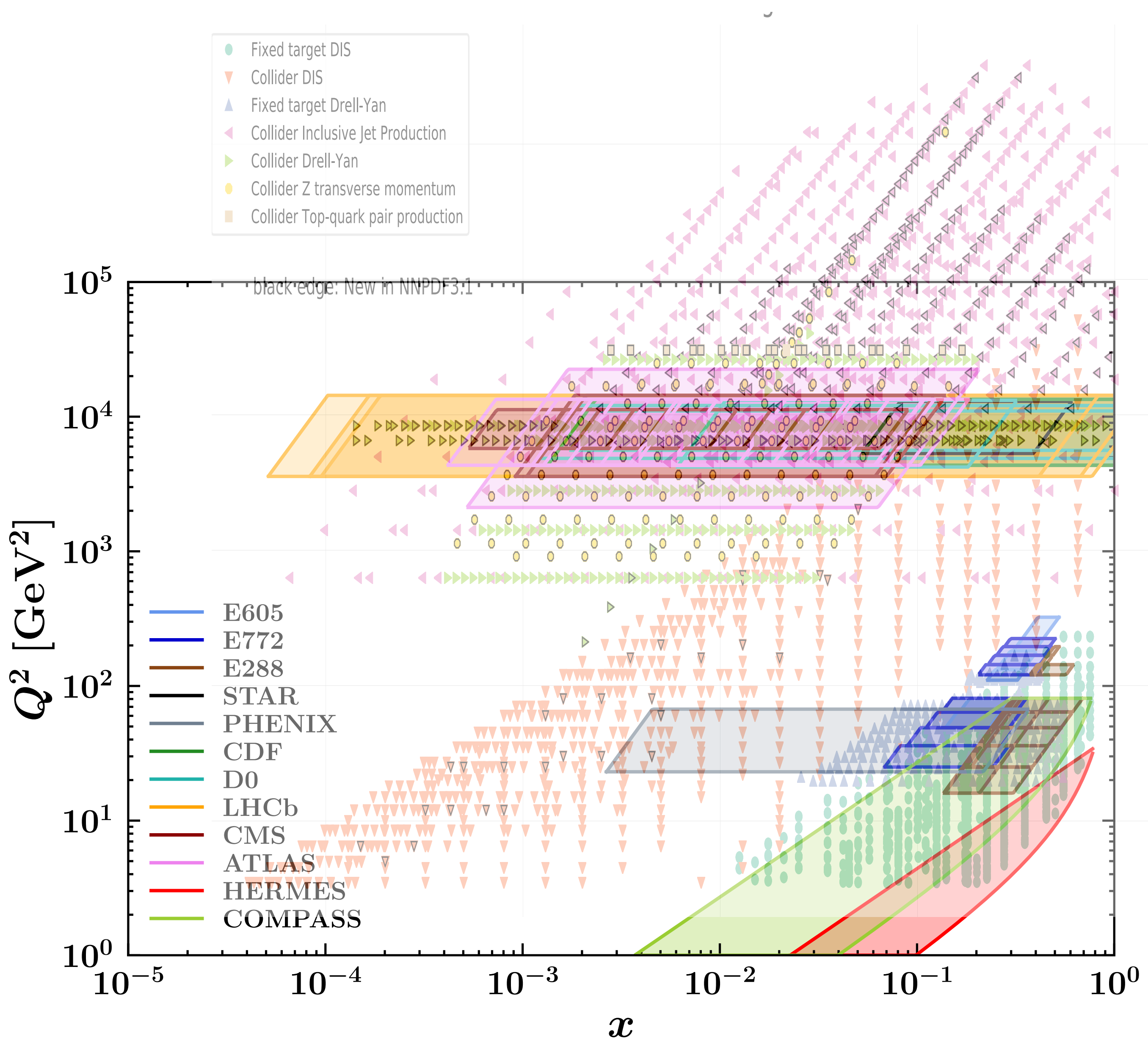


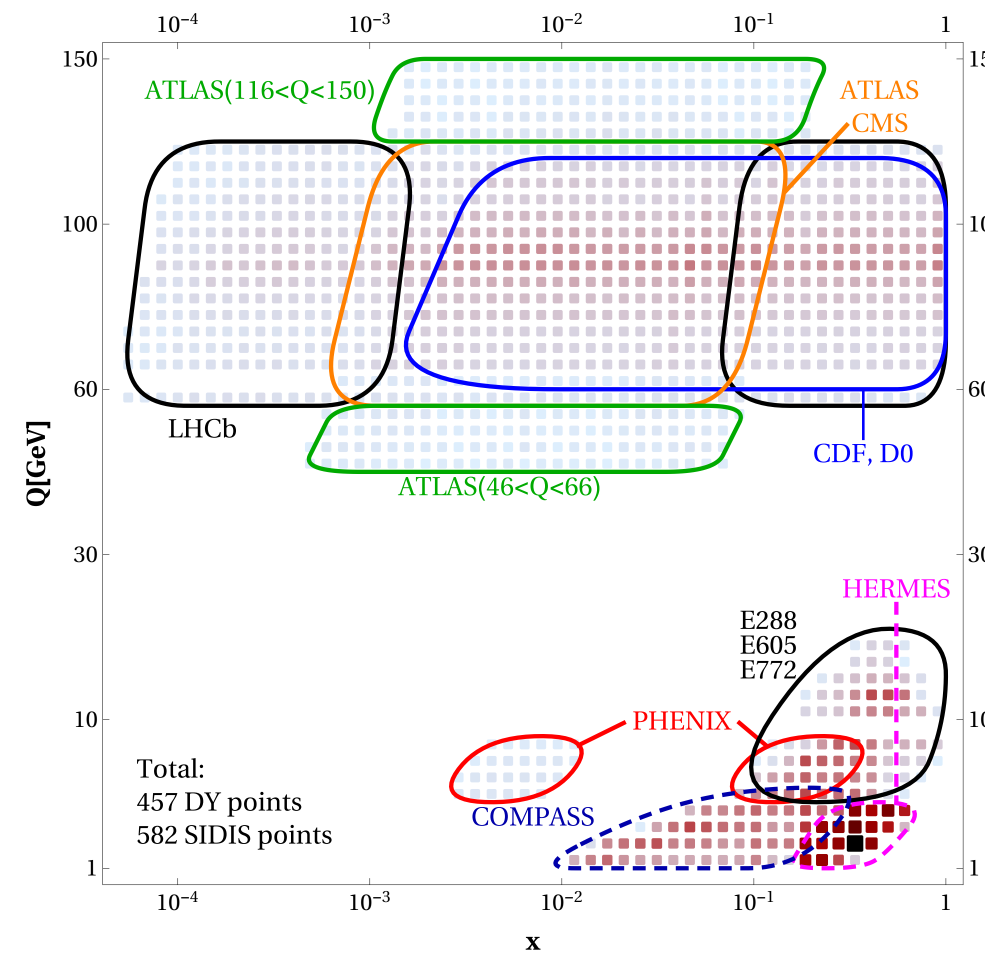


MAP Collaboration
Bacchetta, Bertone, Bissolotti, Bozzi, Cerutti, Piacenza, Radici, Signori, arXiv:2206.07598

Scimemi, Vladimirov, arXiv:1912.06532

x–Q² COVERAGE

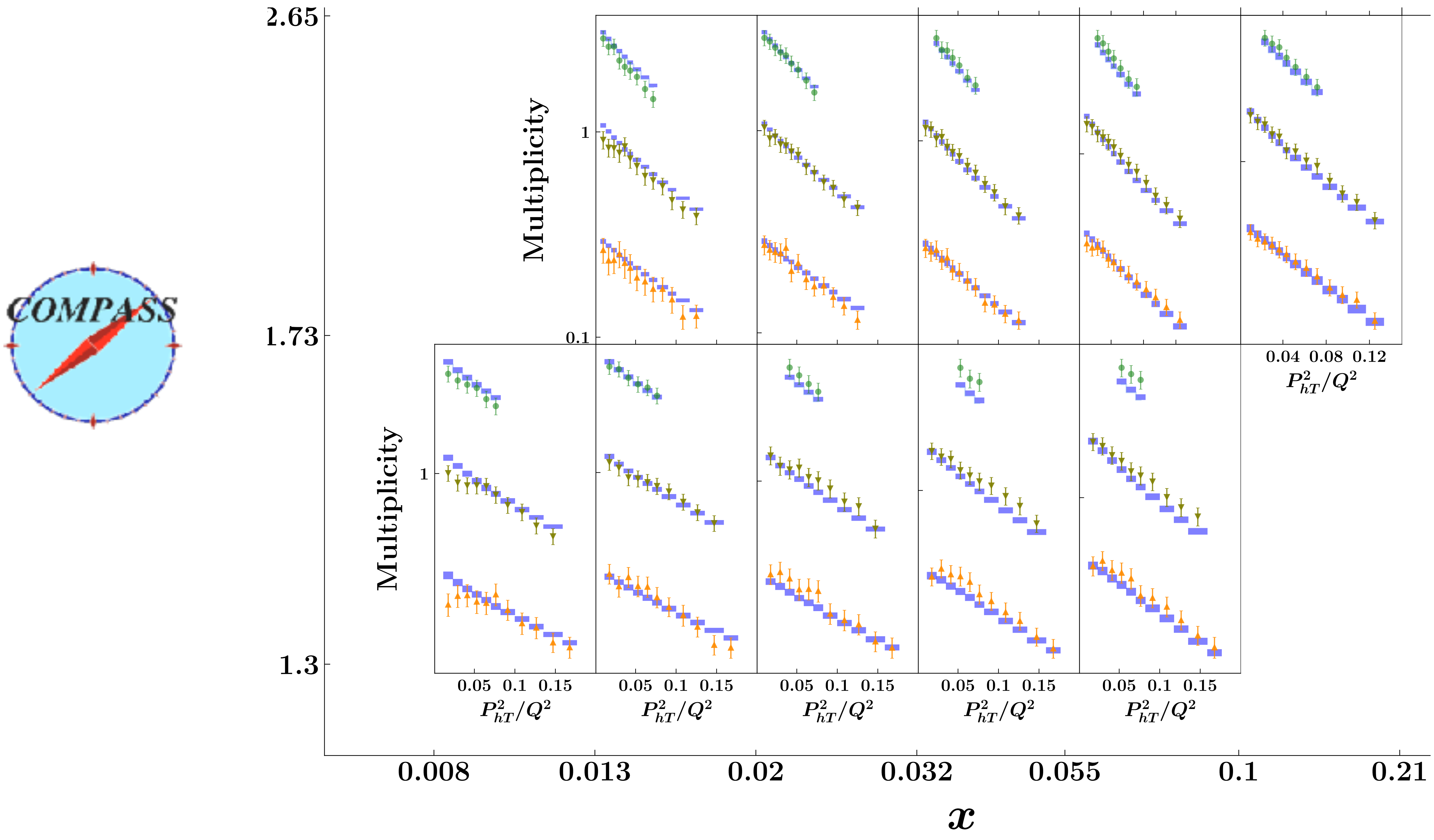




MAP Collaboration
Bacchetta, Bertone, Bissolotti, Bozzi, Cerutti, Piacenza, Radici, Signori, arXiv:2206.07598

Scimemi, Vladimirov, arXiv:1912.06532

EXAMPLE OF AGREEMENT WITH DATA



RESULTING TMDS

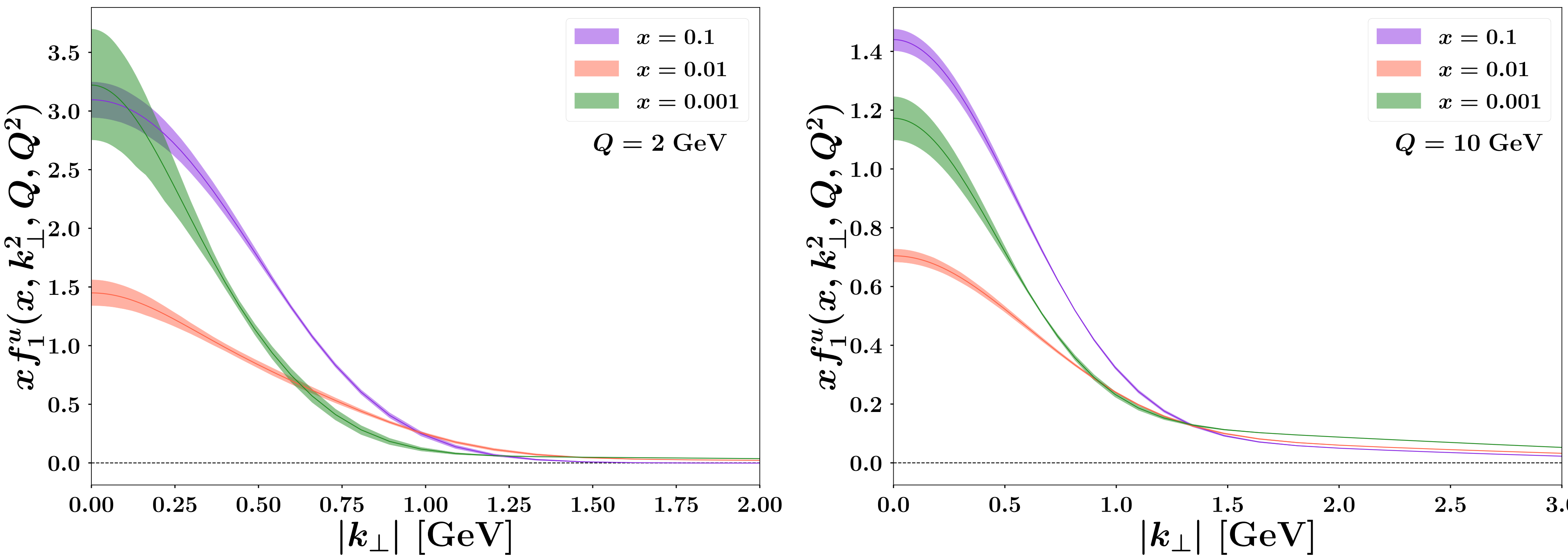
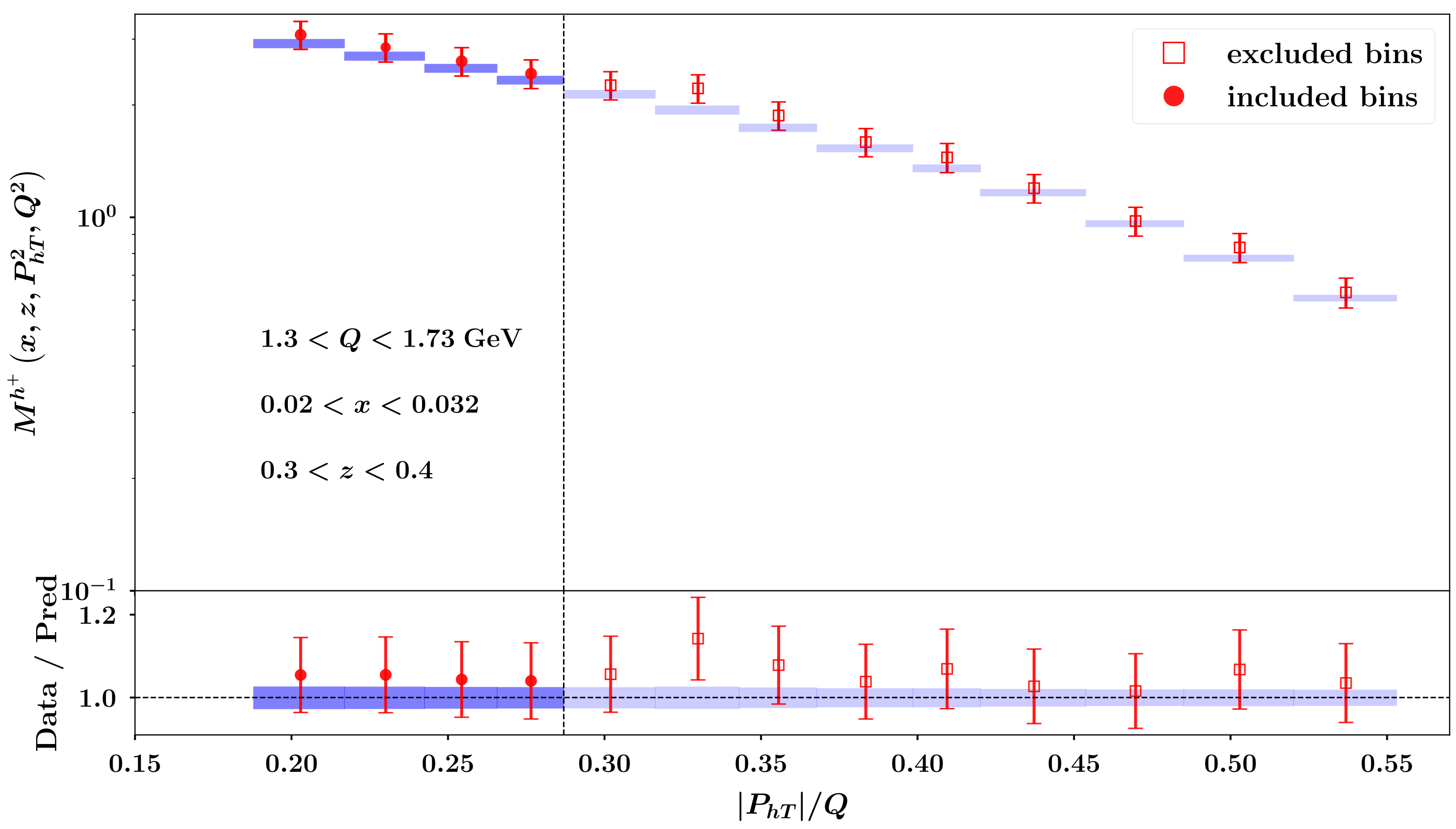
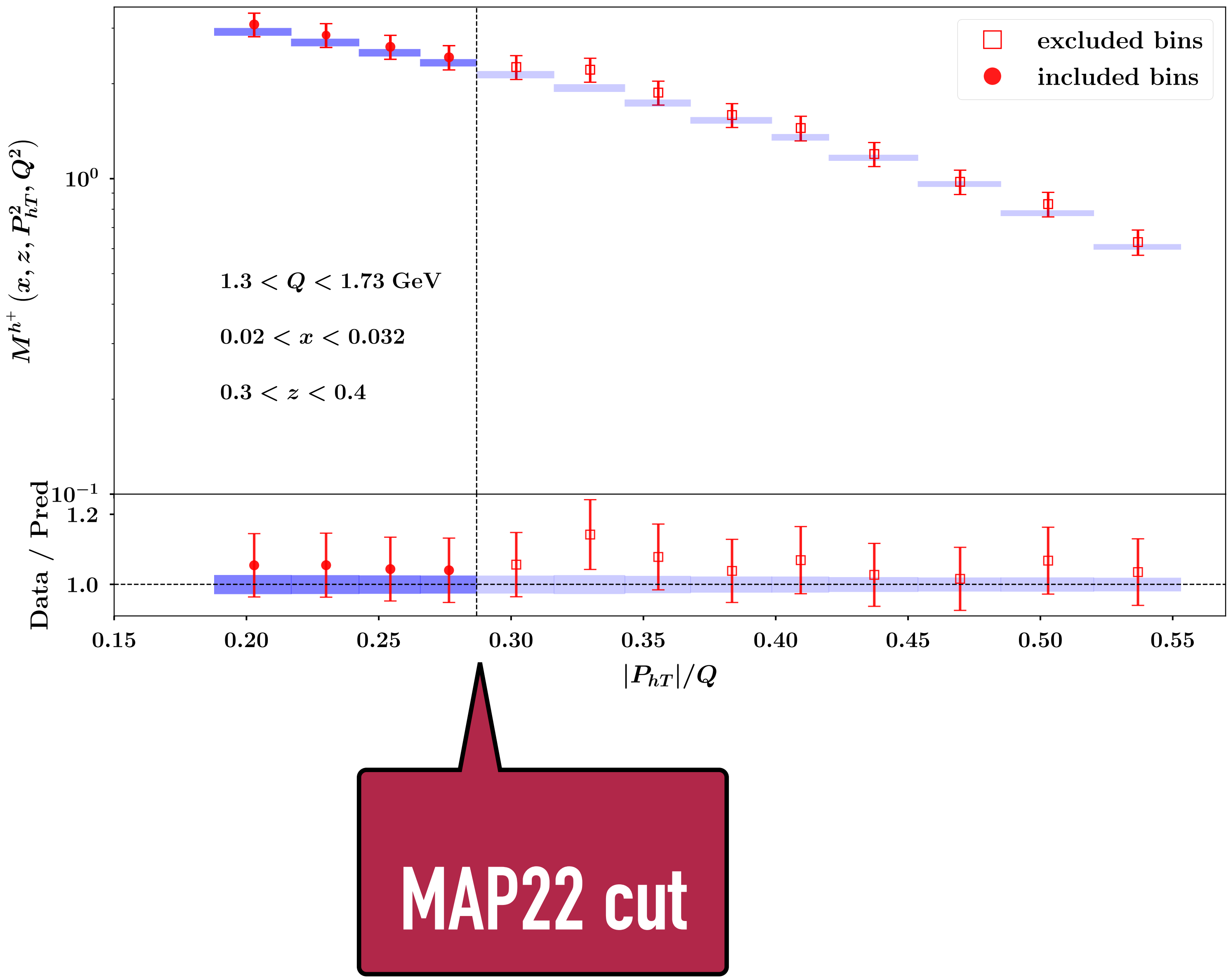


FIG. 13: The TMD PDF of the up quark in a proton at $\mu = \sqrt{\zeta} = Q = 2$ GeV (left panel) and 10 GeV (right panel) as a function of the partonic transverse momentum $|\boldsymbol{k}_\perp|$ for $x = 0.001$, 0.01 and 0.1. The uncertainty bands represent the 68% CL.

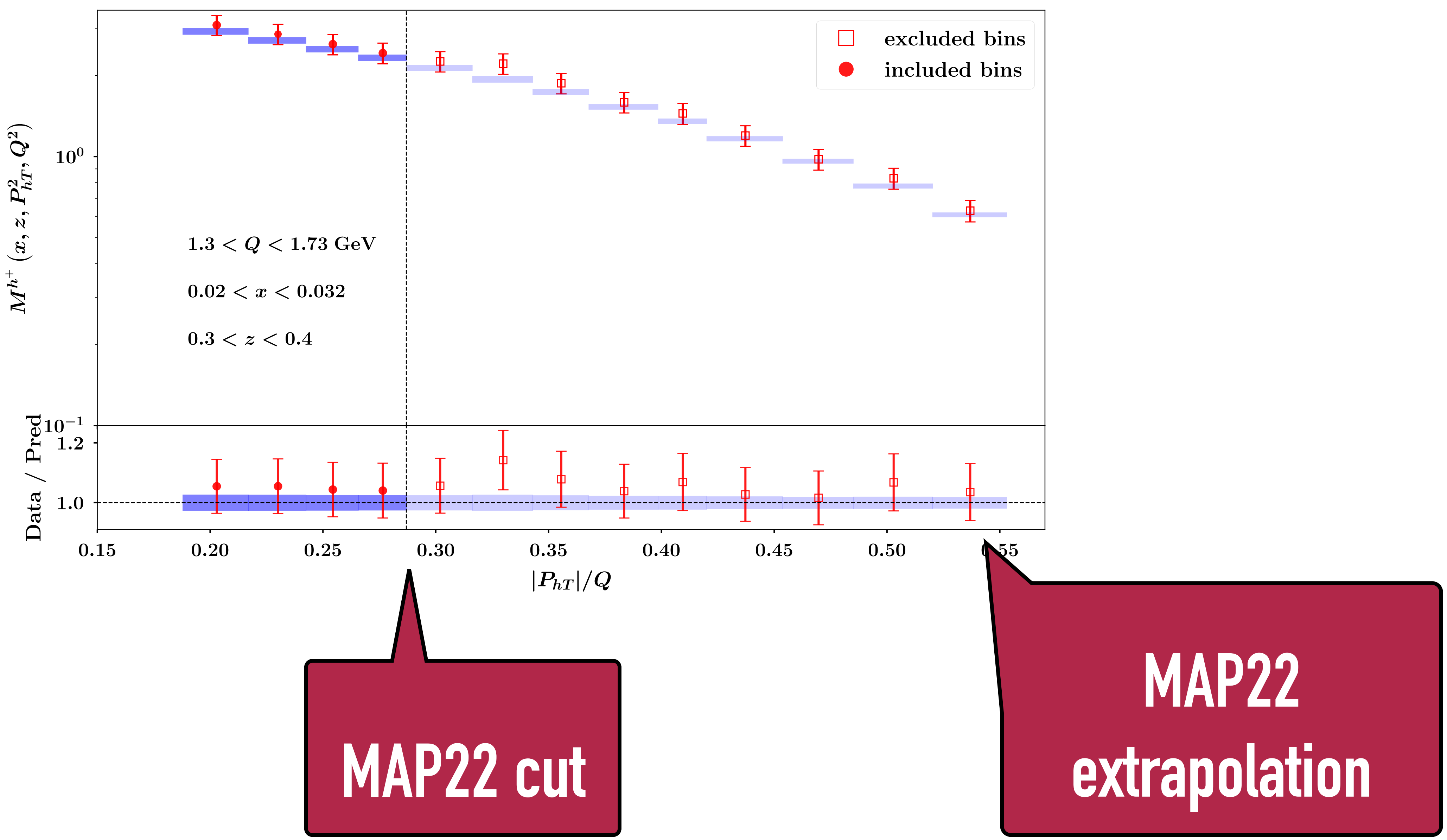
REGION OF VALIDITY OF TMD FORMALISM



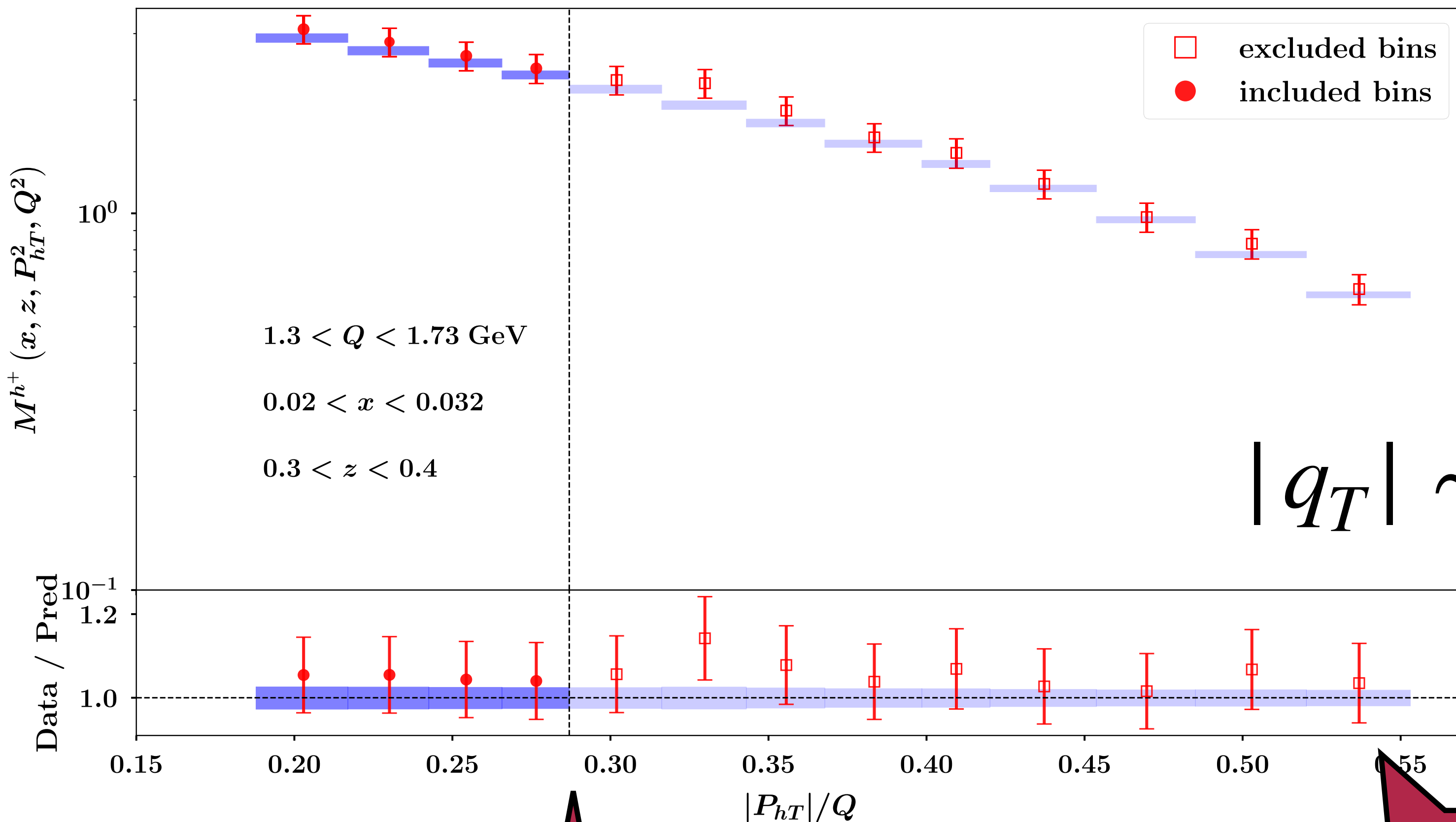
REGION OF VALIDITY OF TMD FORMALISM



REGION OF VALIDITY OF TMD FORMALISM



REGION OF VALIDITY OF TMD FORMALISM

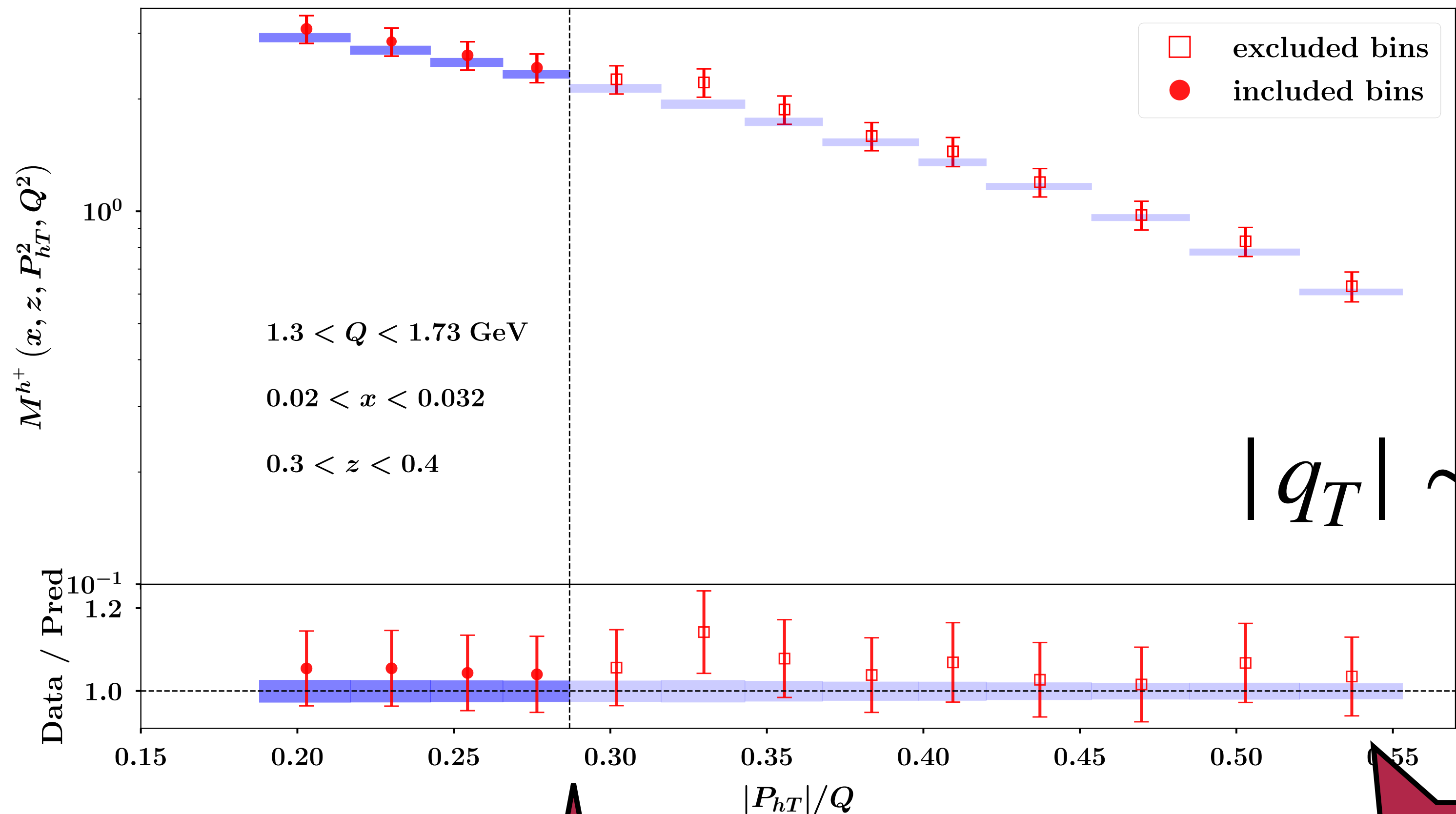


$|q_T| \sim 1.5\ Q$!

MAP22 cut

MAP22 extrapolation

REGION OF VALIDITY OF TMD FORMALISM



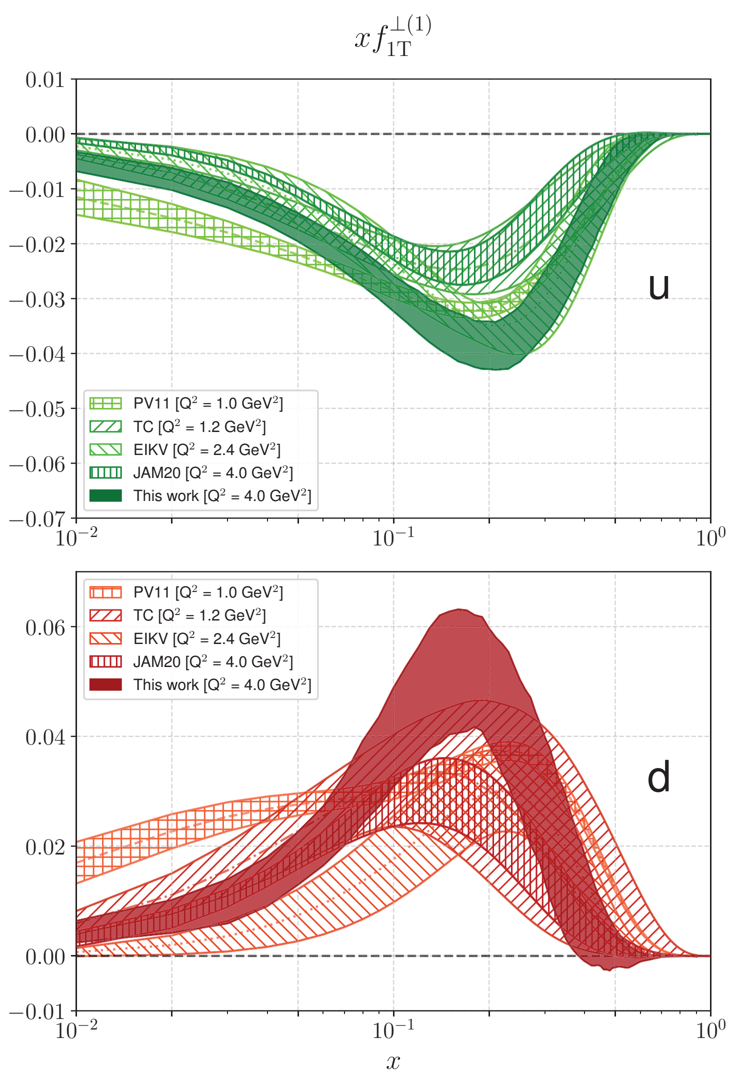
$|q_T| \sim 1.5\ Q$!

MAP22 cut

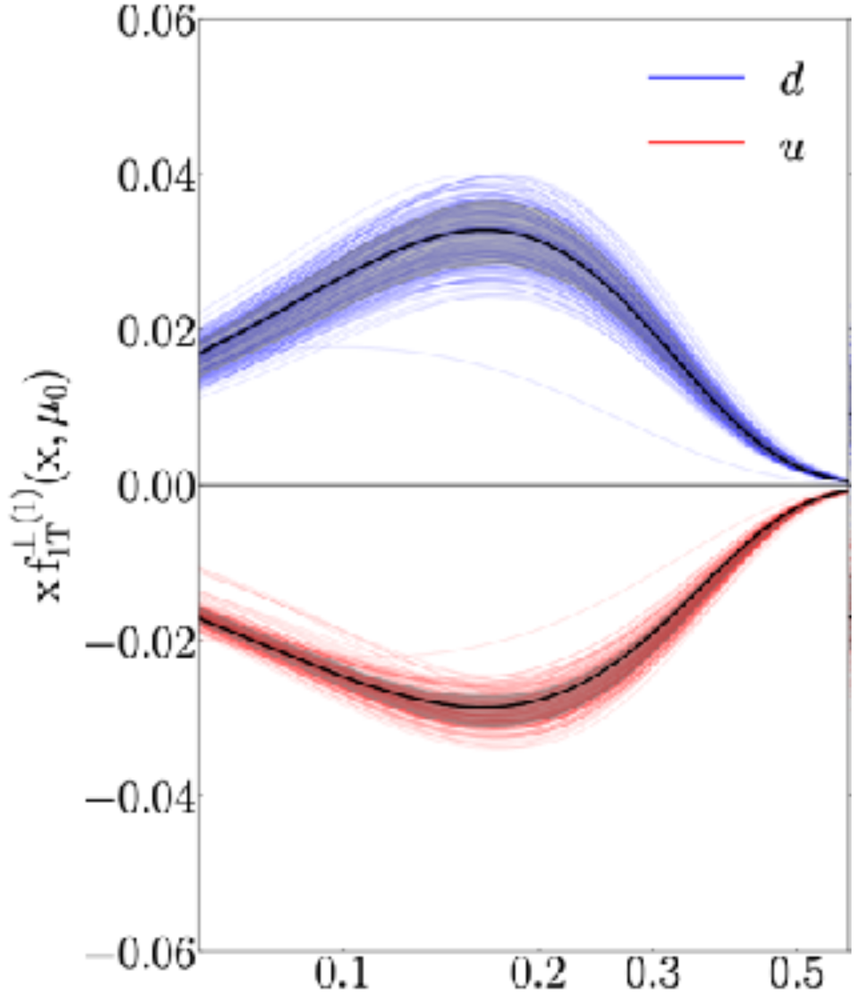
MAP22 extrapolation

The MAP22 cut is already considered to ge “generous”, but the physics seems to be the same for a much wider P_T

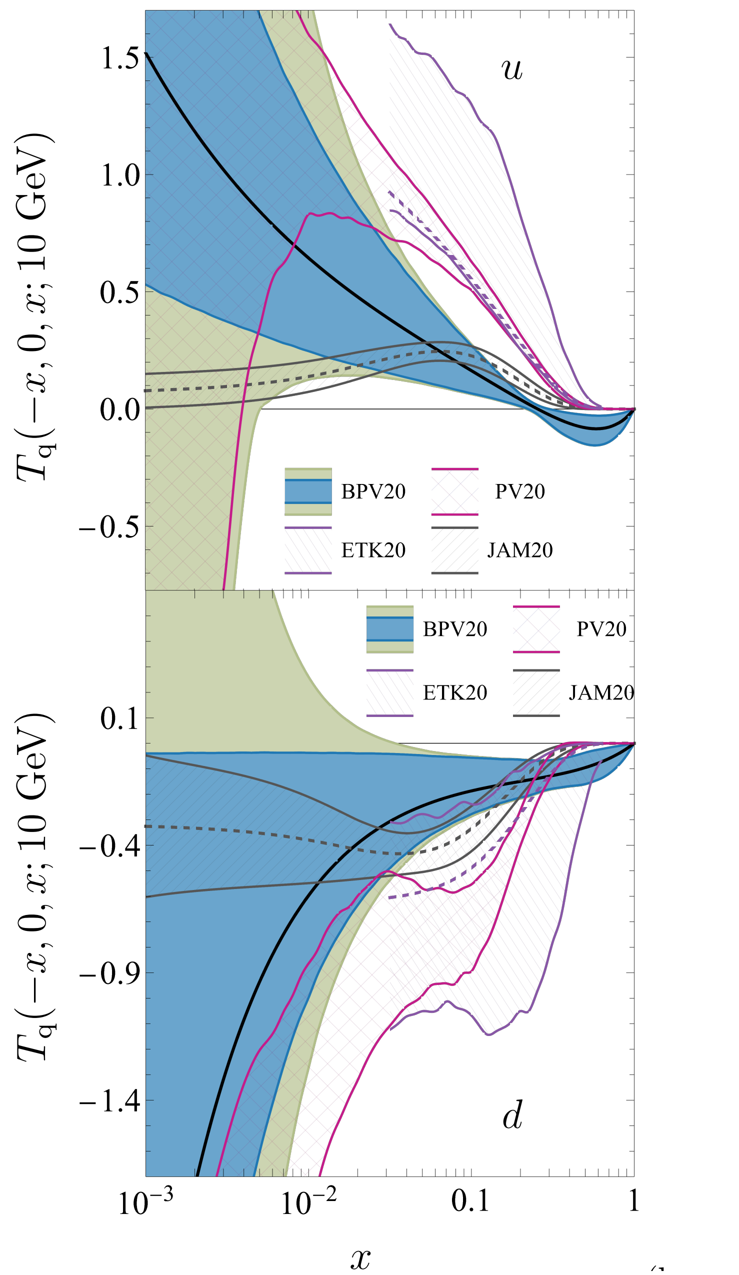
"CONSOLIDATED" SIVERS FUNCTION FITS



Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278



Echevarria, Kang, Terry, arXiv:2009.10710



Bury, Prokudin, Vladimirov, arXiv:2103.03270

SIVERS SIGN CHANGE

Sivers function SIDIS = – Sivers function Drell-Yan

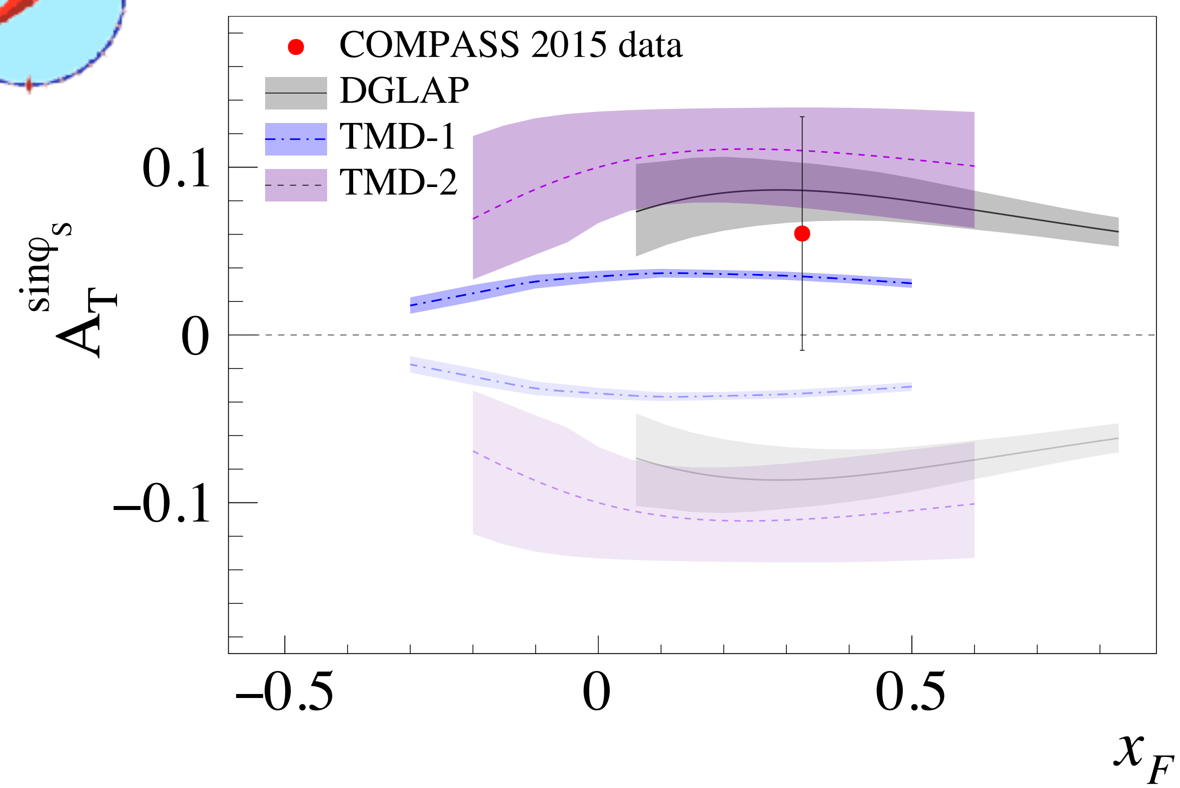
Collins, PLB 536 (02)

SIVERS SIGN CHANGE

Sivers function SIDIS = – Sivers function Drell-Yan

Collins, PLB 536 (02)

arXiv:1704.00488

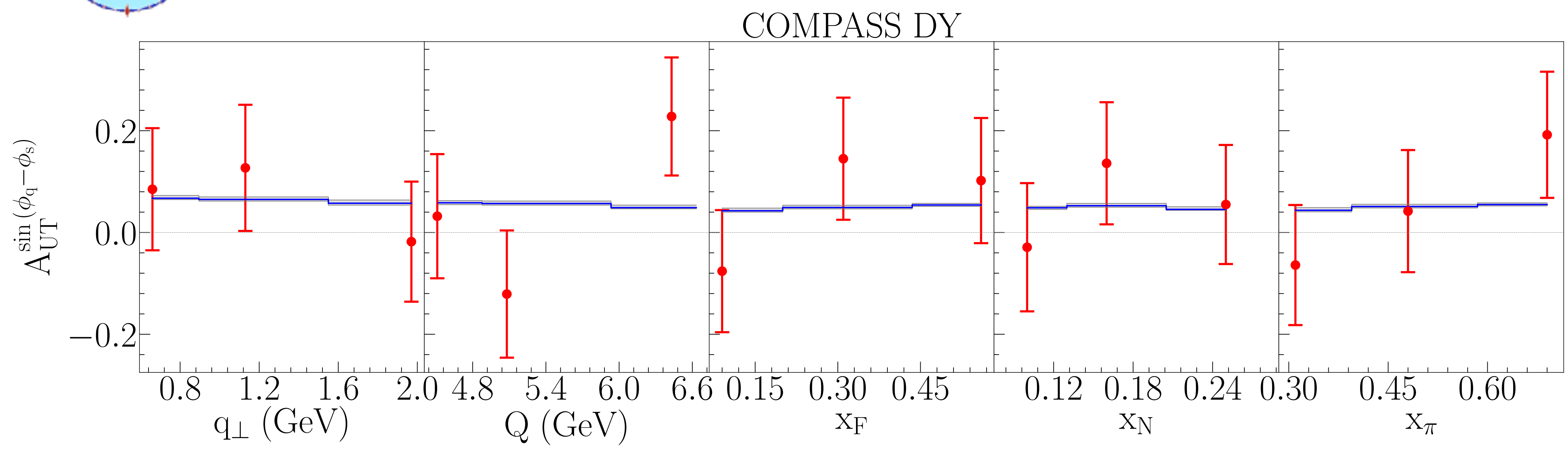


sign change

no sign change

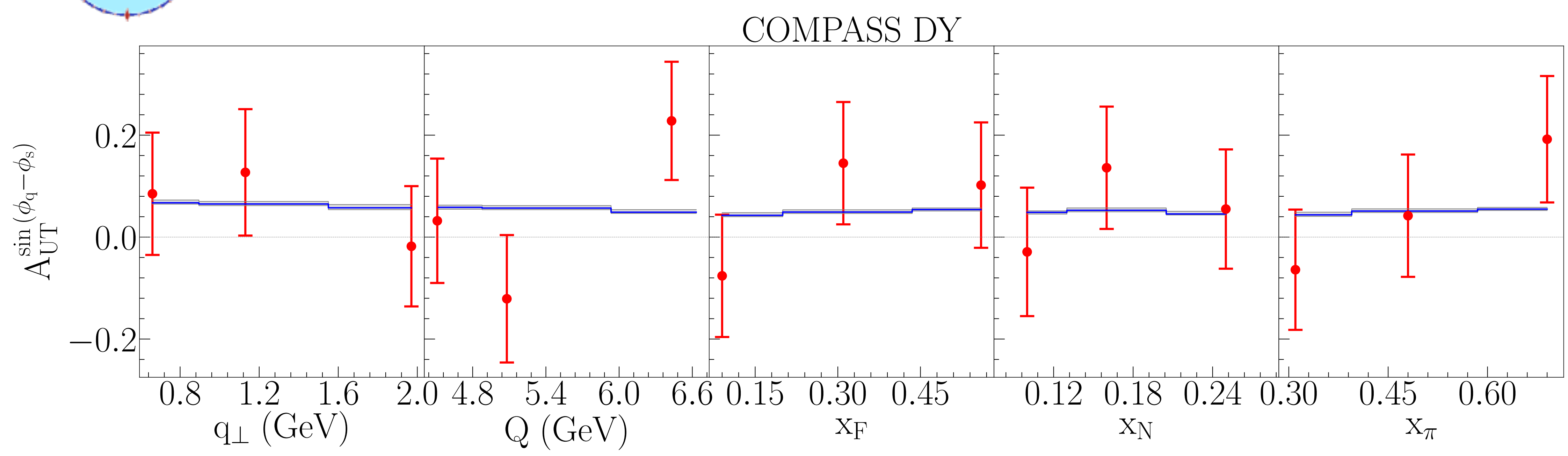
SIVERS SIGN CHANGE

Echevarria, Kang, Terry, arXiv:2009.10710



SIVERS SIGN CHANGE

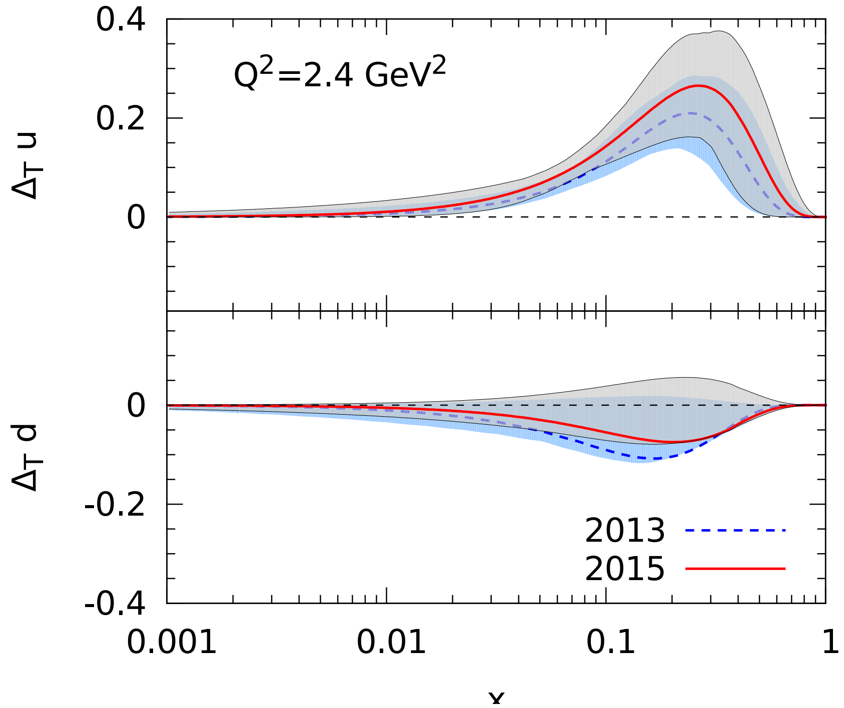
Echevarria, Kang, Terry, arXiv:2009.10710



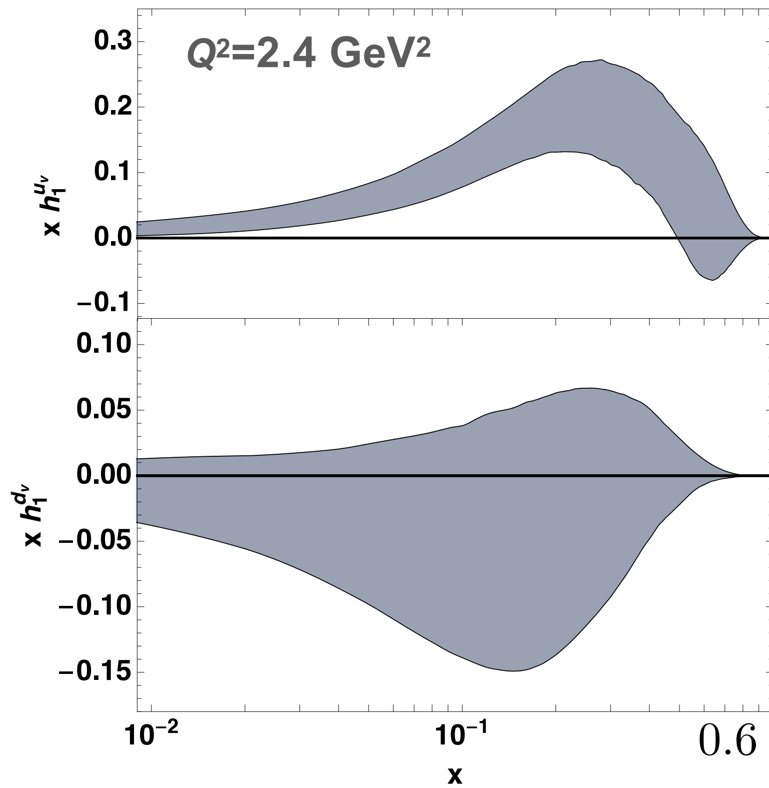
Agreement with sign change of Sivers function (but the significance is still low)

“CONSOLIDATED” TRANSVERSITY FITS

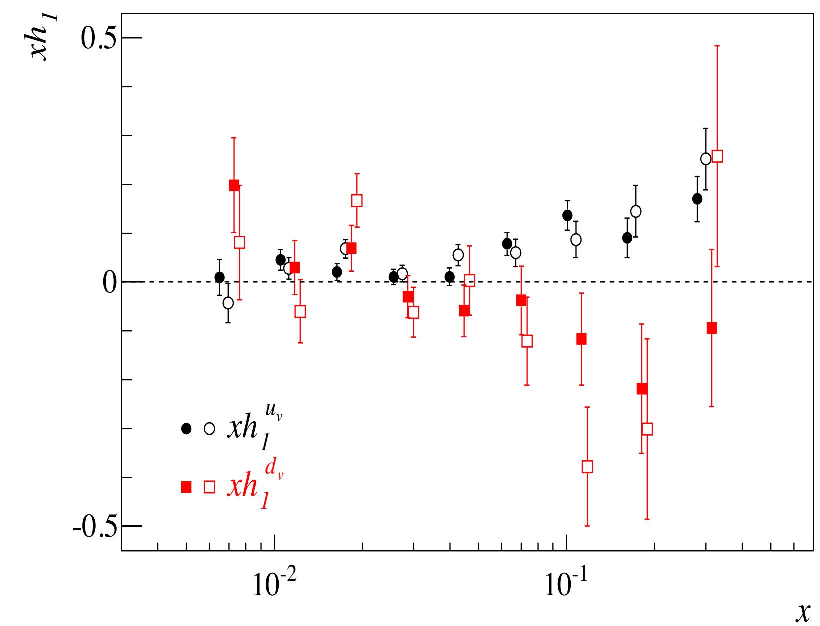
Anselmino et al., arXiv:1510.05389



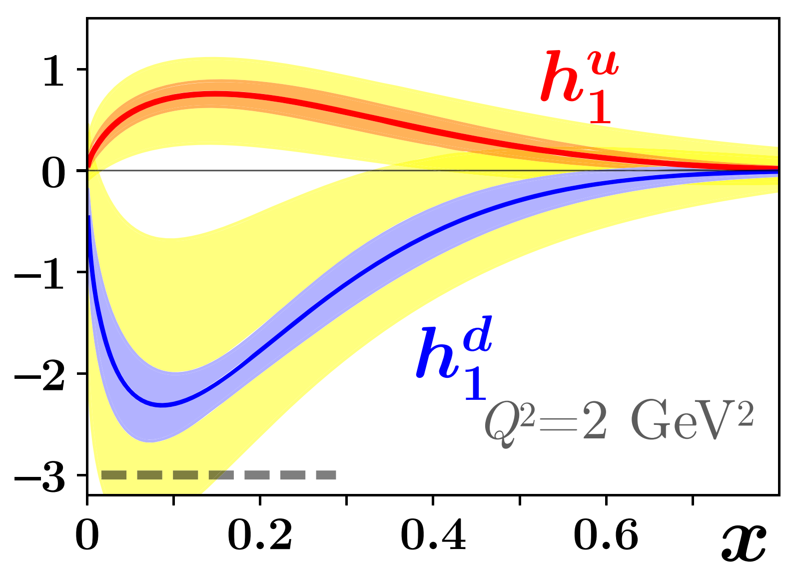
Radici, Bacchetta, arXiv:1802.05212



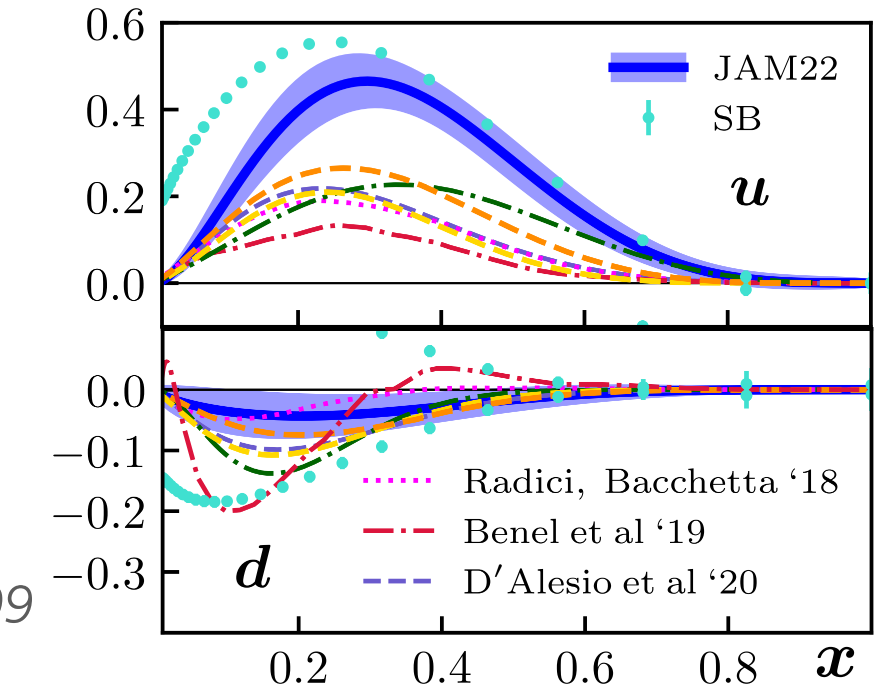
Martin, Bradamante, Barone, arXiv:1412.5946



Lin et al., arXiv:1710.09858

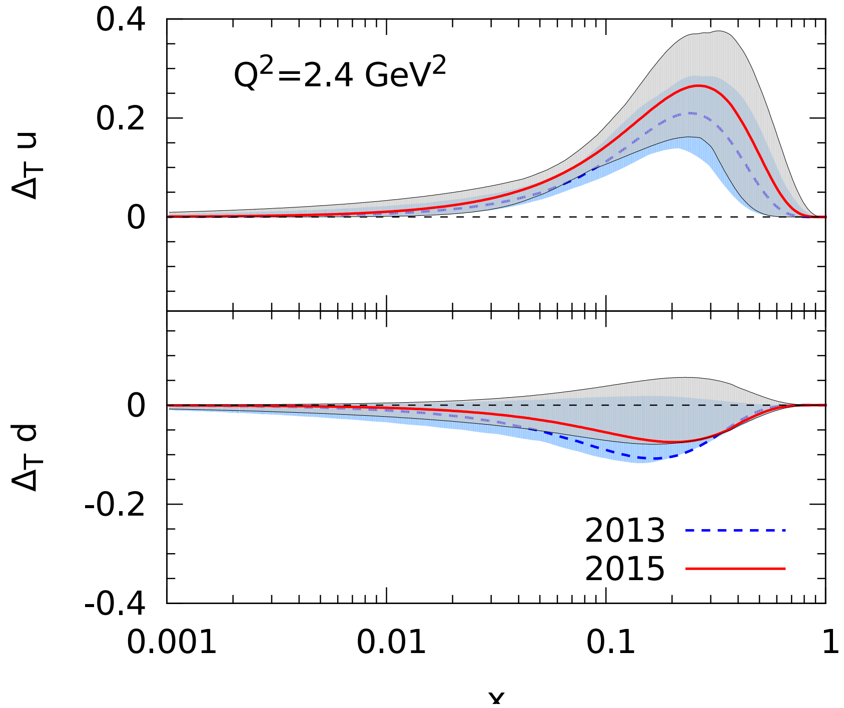


JAM Coll. arXiv:2205.00999

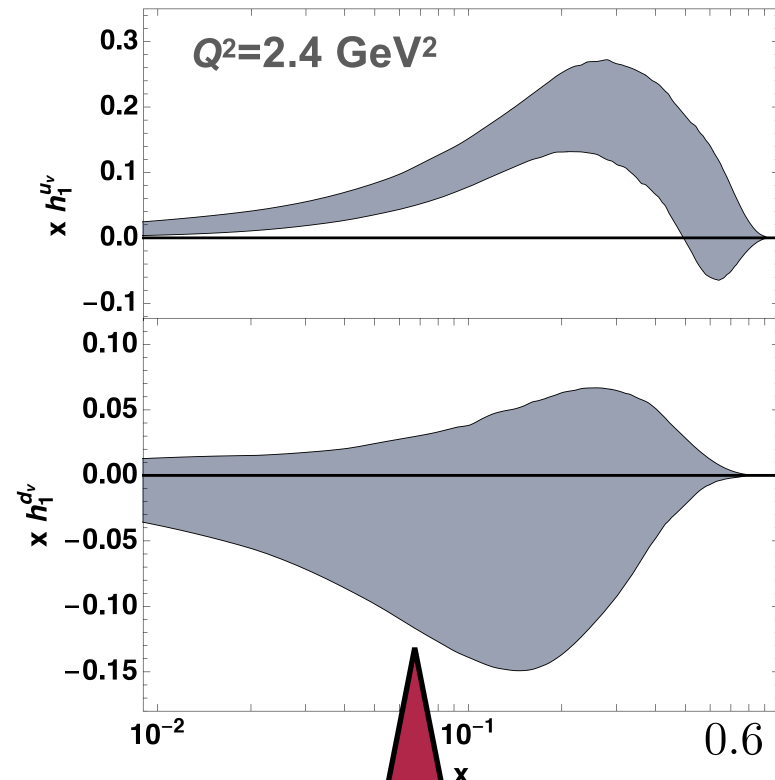


“CONSOLIDATED” TRANSVERSITY FITS

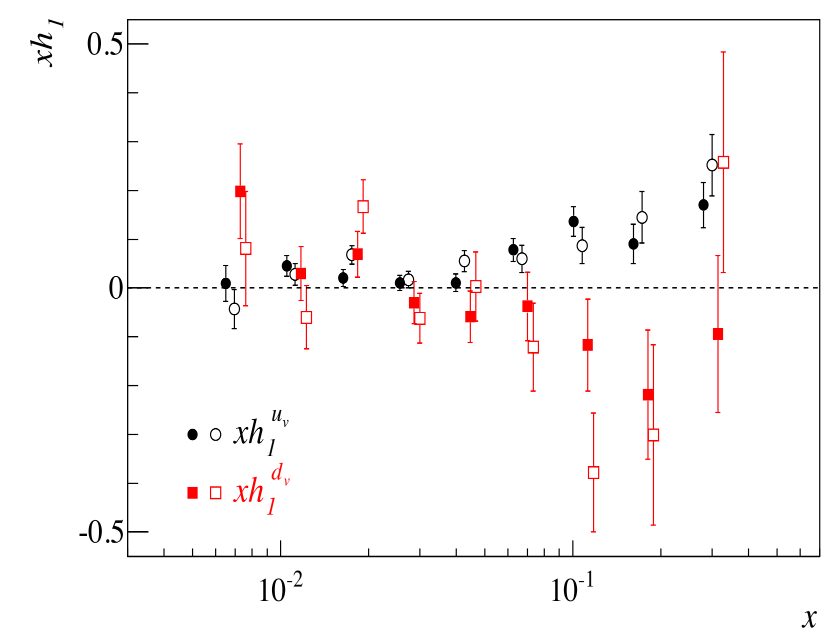
Anselmino et al., arXiv:1510.05389



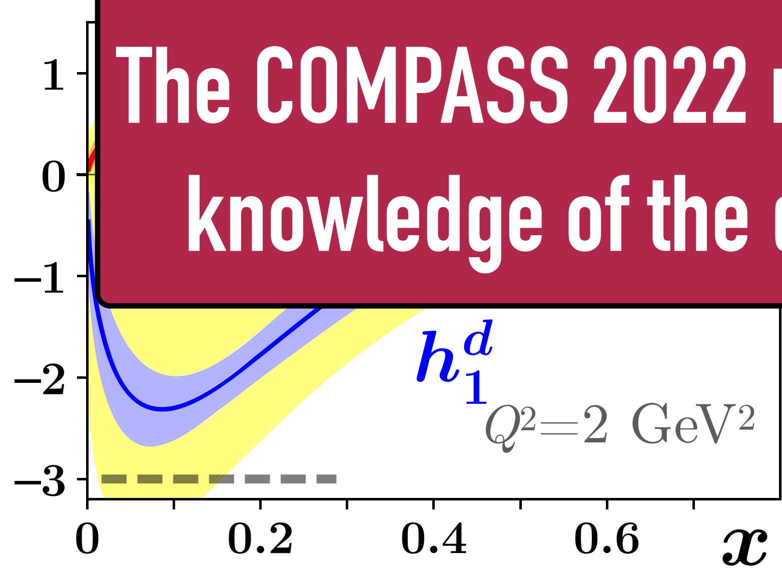
Radici, Bacchetta, arXiv:1802.05212



Martin, Bradamante, Barone, arXiv:1412.5946

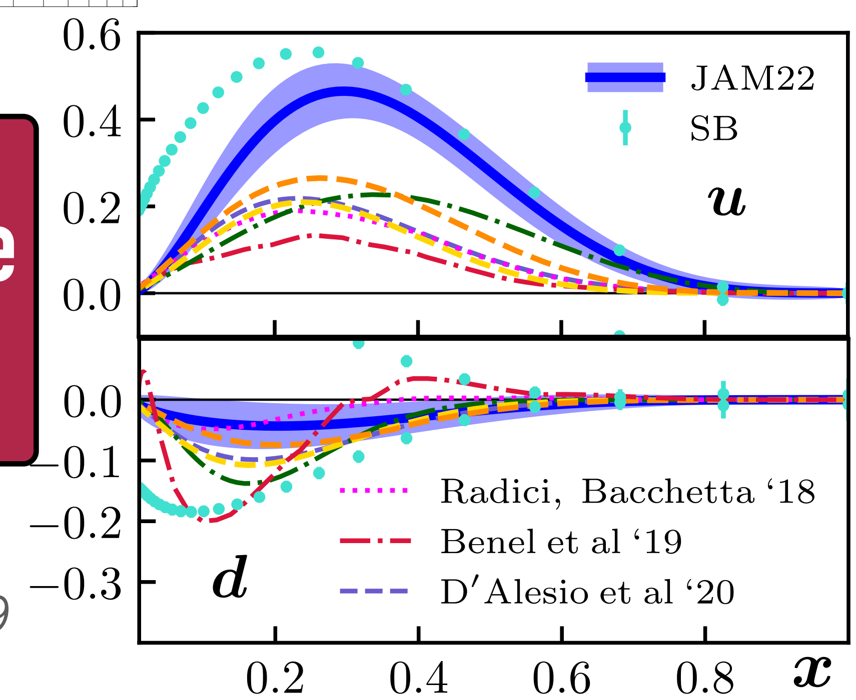


Lin et al.,



The COMPASS 2022 run will improve the knowledge of the down transversity

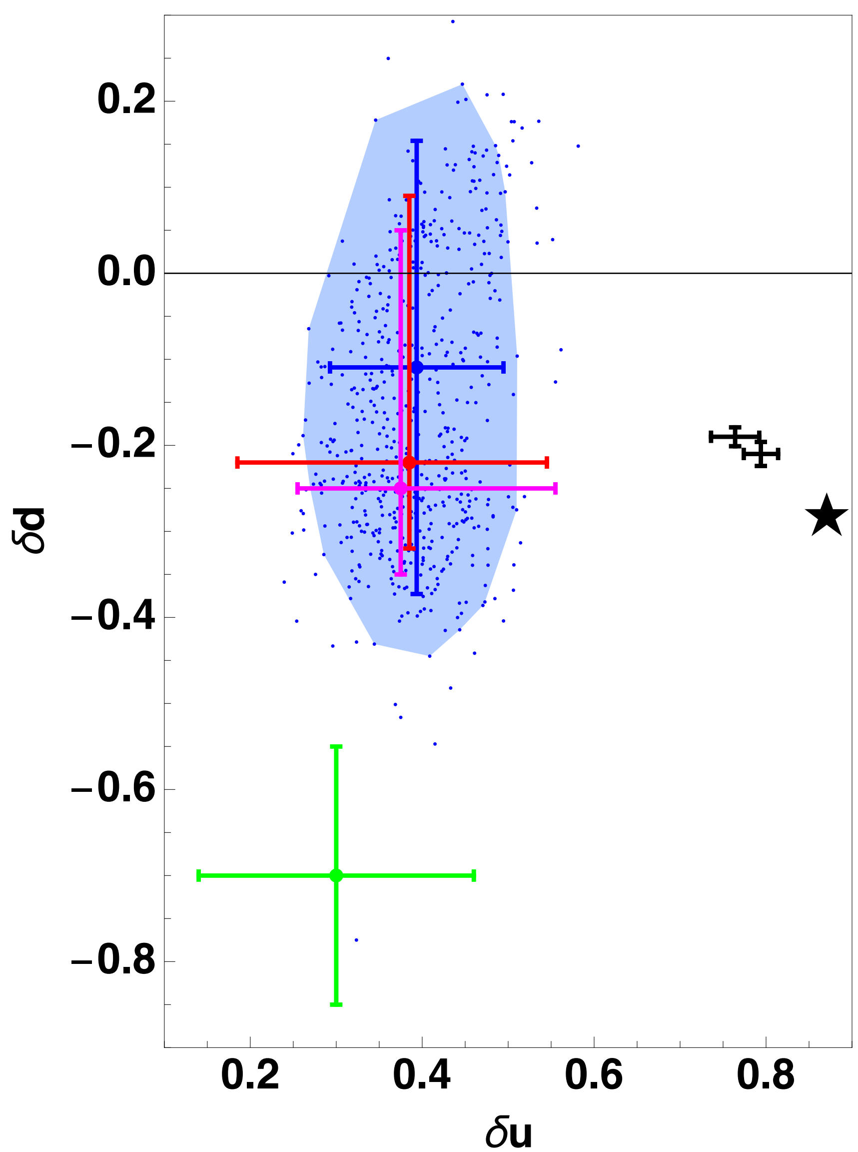
JAM Coll. arXiv:2205.00999



TENSOR CHARGE AND COMPARISON WITH LATTICE QCD

Tensor charge

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



★ Alexandrou et al., arXiv:1703.08788

● Gupta et al., arXiv:1806.09006

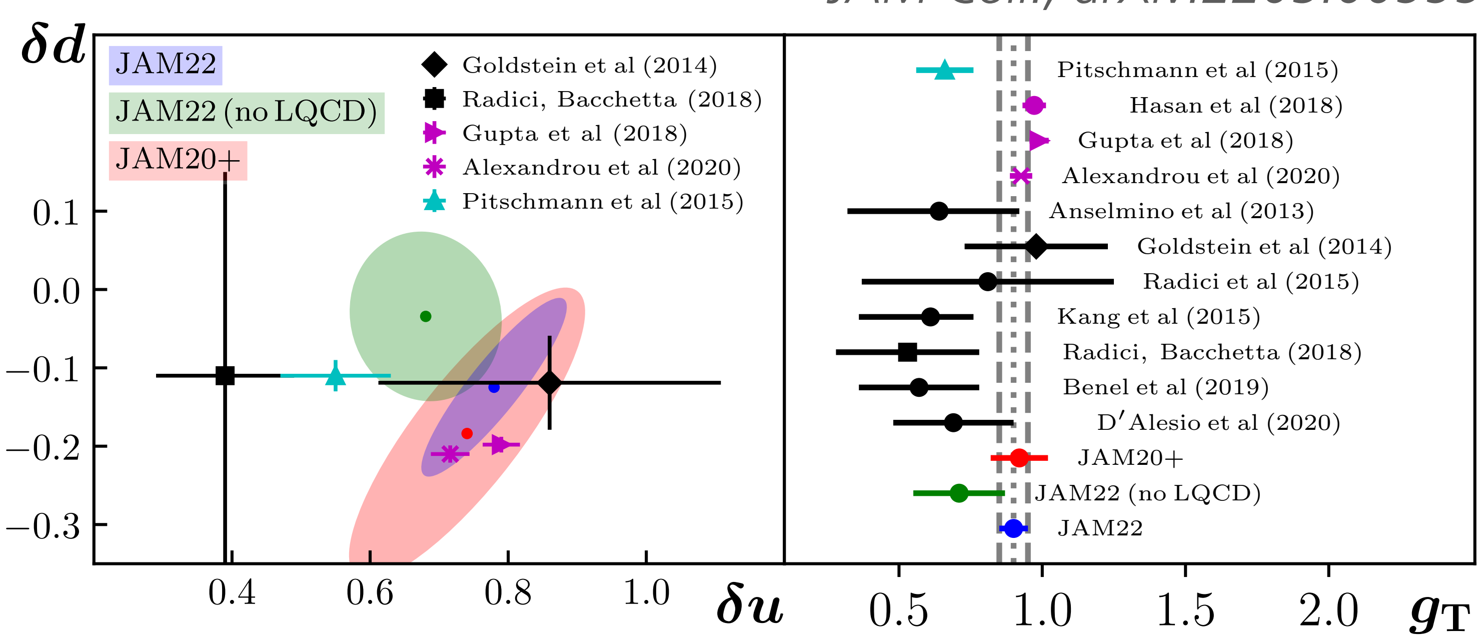
● Anselmino et al., arXiv:1303.3822

● Kang et al., arXiv:1505.05589

● Lin et al., arXiv:1710.09858

● Radici et al., arXiv:1802.05212

JAM Coll., arXiv:2205.00999



WHAT CAN STILL BE DONE BY COMPASS?

WHAT CAN STILL BE DONE BY COMPASS?

- Proton multiplicities

WHAT CAN STILL BE DONE BY COMPASS?

- Proton multiplicities
- Transversely polarized deuteron data

WHAT CAN STILL BE DONE BY COMPASS?

- Proton multiplicities
- Transversely polarized deuteron data
- Pion DY unpolarized cross section

WHAT CAN STILL BE DONE BY COMPASS?

- Proton multiplicities
- Transversely polarized deuteron data
- Pion DY unpolarized cross section
- All structure functions for proton and deuteron, with identified hadrons and multidimensional binning

WHAT ARE THE BIG OPEN ISSUES?

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- Are we sure about our interpretation of the measurements? (higher twist, normalization issues…)

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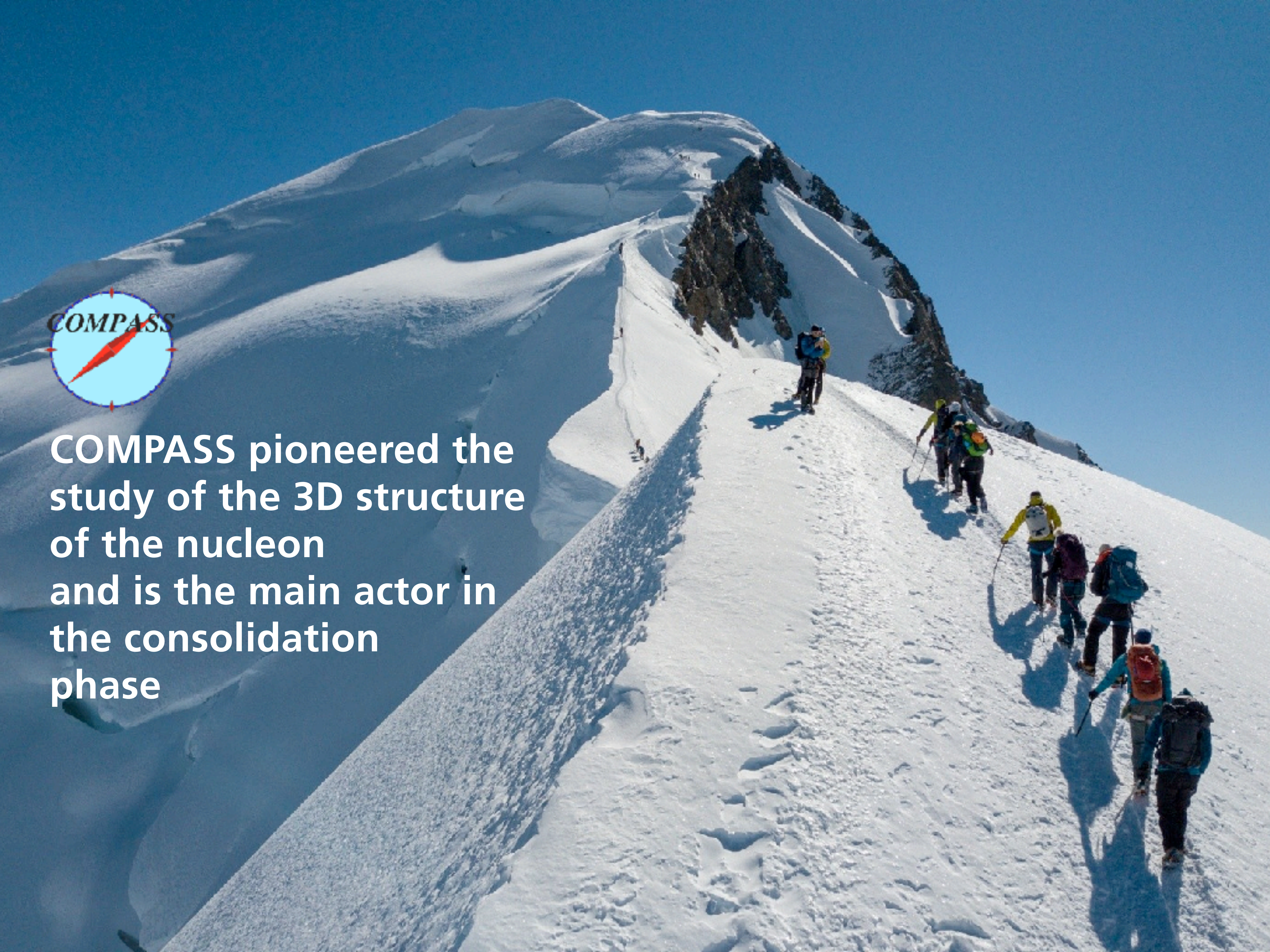
- Can we look for physics beyond the Standard Model?

WHAT ARE THE BIG OPEN ISSUES?

- Are we sure about our interpretation of the measurements? (higher twist, normalization issues…)
- Can we compare the phenomenology to lattice QCD?
- Can we look for physics beyond the Standard Model?
- How do we use the knowledge of the structure of the proton?


COMPASS
COMPASS pioneered the study of the 3D structure of the nucleon and is the main actor in the consolidation phase