

QCD with Electron-Ion Collider (QEIC)

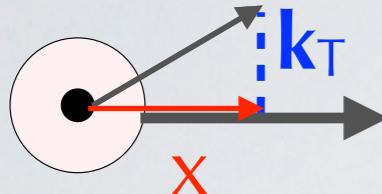
4-7 Jan. 2020, IIT Bombay

Extraction of polarized TMDs and the Nucleon Spin Structure

Marco Radici
INFN - Pavia



Transv.-Mom. Dependent Parton Distributions

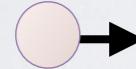


TMD PDFs ($x, k_T^2; Q$) at leading twist

quark



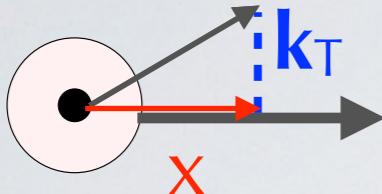
nucleon



		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		
	L			
	T			

previous talk

Transv.-Mom. Dependent Parton Distributions

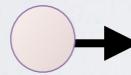


TMD PDFs ($x, k_T^2; Q$) at leading twist

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nucleon

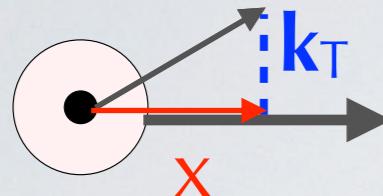


		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$	*	$h_1^\perp = \odot \downarrow - \odot \uparrow$
	L	*	$g_1 = \odot \rightarrow - \odot \rightarrow$	$h_{1L}^\perp = \odot \rightarrow \downarrow - \odot \rightarrow \uparrow$
	T	$f_{1T}^\perp = \odot \uparrow - \odot \downarrow$	$g_{1T} = \odot \uparrow - \odot \downarrow$	$h_1 = \odot \uparrow \downarrow - \odot \downarrow \uparrow$ $h_{1T}^\perp = \odot \uparrow \downarrow - \odot \downarrow \uparrow$

* forbidden by parity invariance

Mulders & Tangerman,
N.P. **B461** (96)
Boer & Mulders,
P.R. **D57** (98)
Bacchetta et al.,
JHEP **02** (07) 093

Transv.-Mom. Dependent Parton Distributions

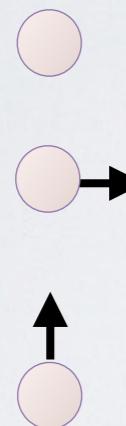


TMD PDFs ($x, k_T^2; Q$) at leading twist

quark •



nucleon



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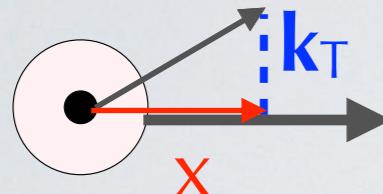
* forbidden by parity invariance

3D maps of

- partonic quantum correlations: spin-spin, spin-momentum (orbit)
- quantum correlations between partonic motion and macroscopic nucleon properties (spin)
- partonic orbital motion (most TMDs vanish with no L^q)

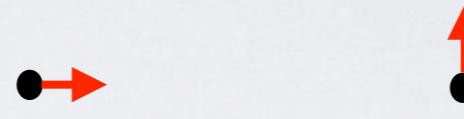
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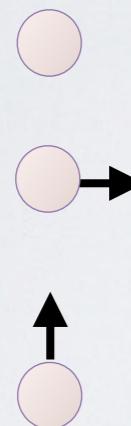


TMD PDFs ($x, k_T^2; Q$) at leading twist

quark •



nucleon



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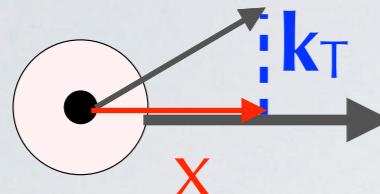
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3D maps of

- partonic quantum correlations: spin-spin, spin-momentum (orbit)
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- partonic orbital motion (most TMDs vanish with no L^q)
- color (gauge-inv.) residual interactions and (no) T-reversal symmetry

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Transv.-Mom. Dependent Parton Distributions

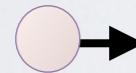


TMD PDFs ($x, k_T^2; Q$) at leading twist

quark



nucleon



3D maps of

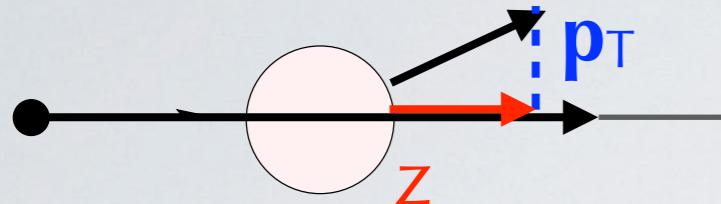
- partonic quantum correlations: spin-spin, spin-momentum (orbit)
- quantum correlations between partonic motion and macroscopic nucleon properties (spin)
- partonic orbital motion (most TMDs vanish with no L^q)
- color (gauge-inv.) residual interactions and T-reversal odd symmetry
- helicity-flipping (chiral-odd) structures; need a chiral-odd partner in the cross section

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$	*	$h_1^\perp = \odot - \odot$
	L	*	$g_1 = \odot \rightarrow - \odot \rightarrow$	$h_{1L}^\perp = \odot \rightarrow - \odot \rightarrow$
	T	$f_{1T}^\perp = \odot - \odot$	$g_{1T} = \odot - \odot$	$h_1 = \odot - \odot$ $h_{1T}^\perp = \odot - \odot$

* forbidden by parity invariance

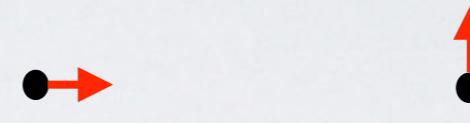
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Transv.-Mom. Dependent Fragmentations

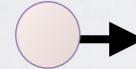


TMD FFs ($z, \mathbf{p}_T^2; Q$) at leading twist
and $S_h \leq 1/2$

quark

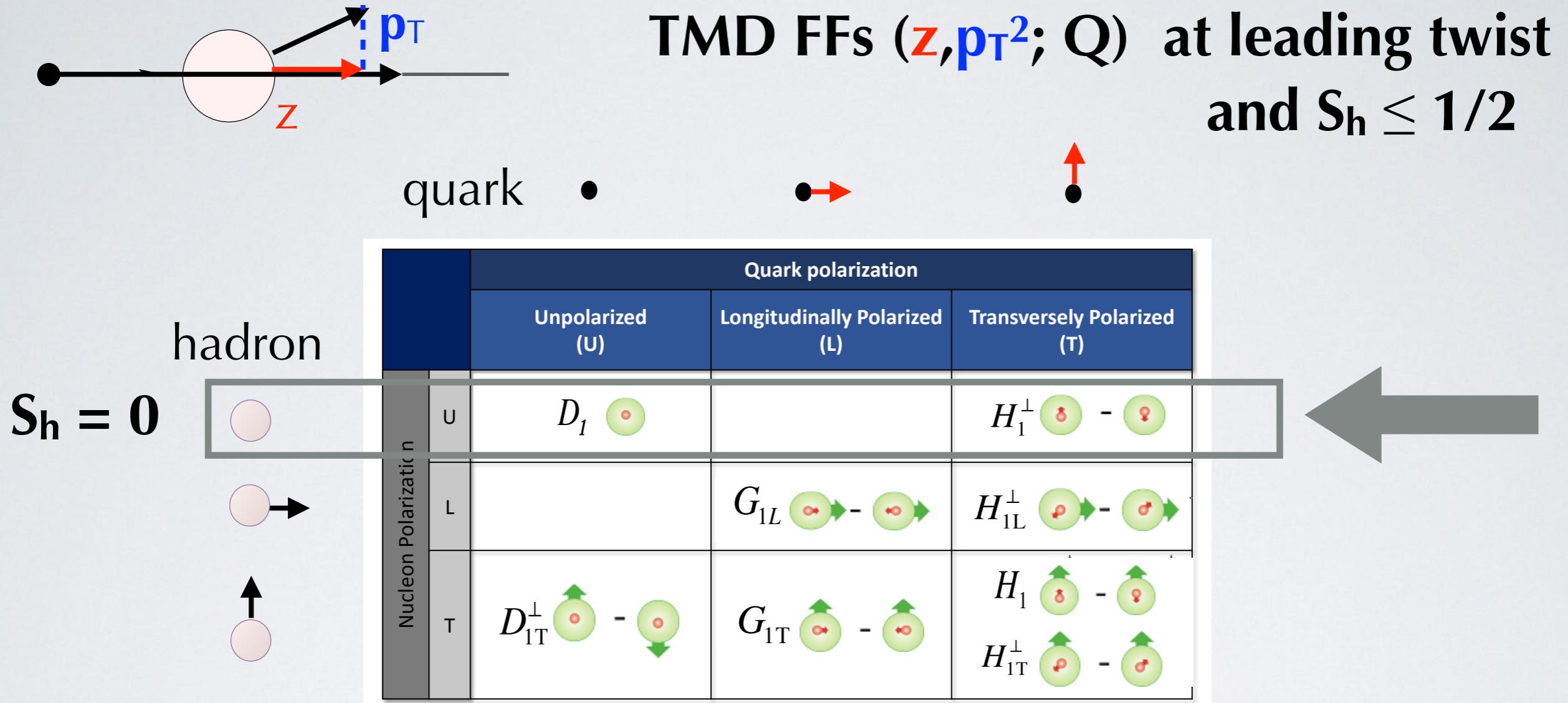


hadron



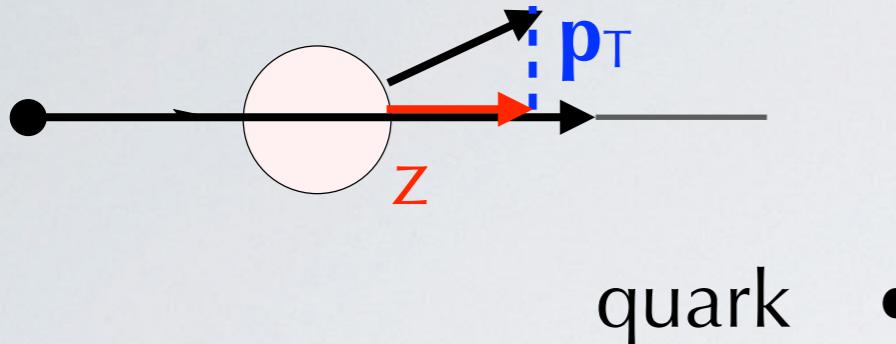
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	D_1		H_1^\perp
	L		G_{1L}	H_{1L}^\perp
	T	D_{1T}^\perp	G_{1T}	H_1 H_{1T}^\perp

Transv.-Mom. Dependent Fragmentations



most of the time, detection of final unpolarized mesons ($\pi, K..$)
 \Rightarrow use only first row of table

Transv.-Mom. Dependent Fragmentations



TMD FFs ($z, p_T^2; Q$) at leading twist
and $S_h \leq 1/2$

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
hadron	U	D_1		H_1^\perp
	L		G_{1L}	H_{1L}^\perp
$S_h = 1/2$	T	D_{1T}^\perp	G_{1T}	H_1 H_{1T}^\perp



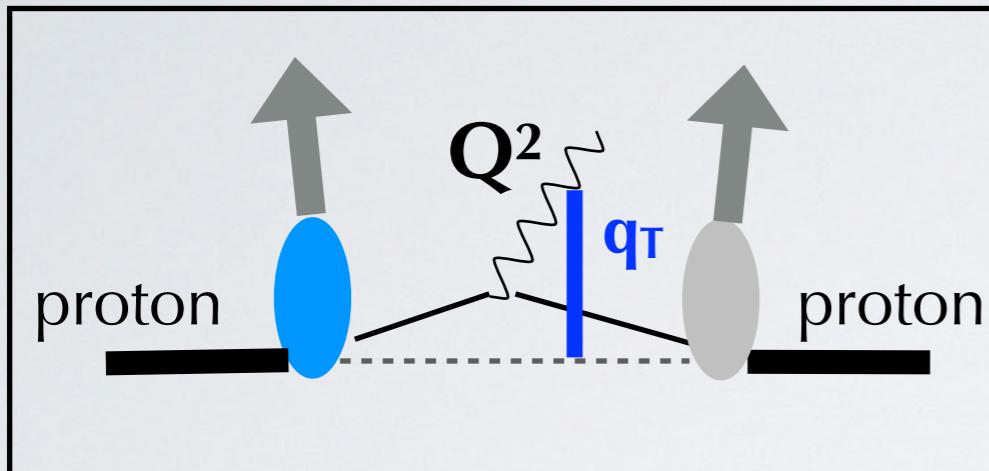
recent data on Λ^\dagger production \rightarrow access to D_{1T}^\perp ?

from BELLE *Abdesselam et al. (BELLE), arXiv:1611.06648*

(see also old data from FermiLab, Hera-B and CERN-NA48/OPAL
+ new data from CERN-ATLAS)

Factorization theorems for TMDs

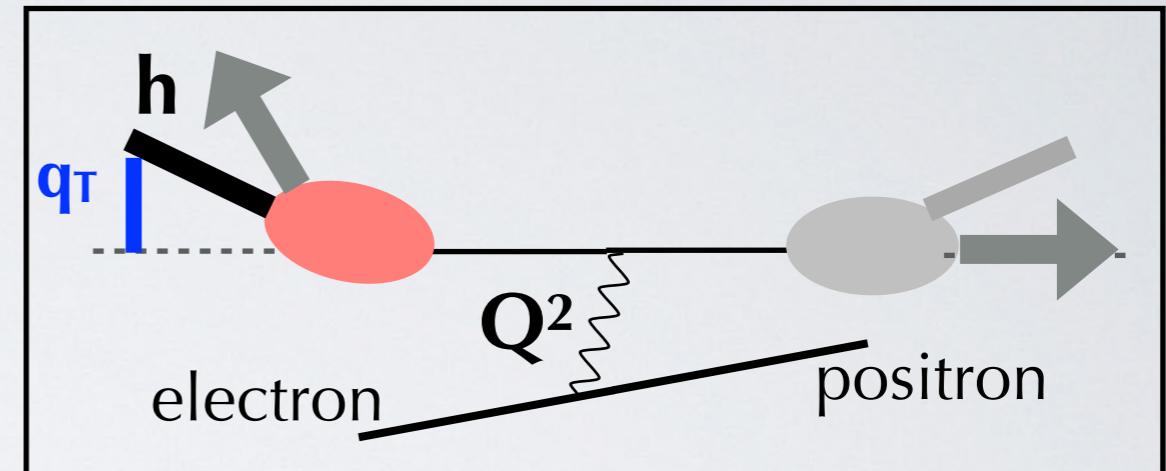
Factorization theorems well understood for $q_T \ll Q$



Drell-Yan



TMD PDFs



e^+e^- annihilation

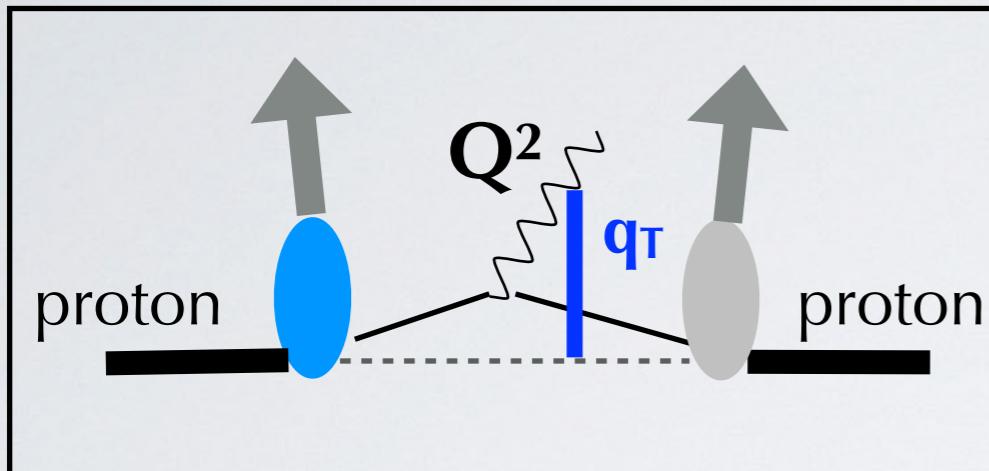


TMD FFs

Rogers & Aybat, P.R. D83 (11)
Collins, "Foundations of Perturbative QCD" (11)
Echevarria, Idilbi, Scimemi, JHEP 1207 (12)

Factorization theorems for TMDs

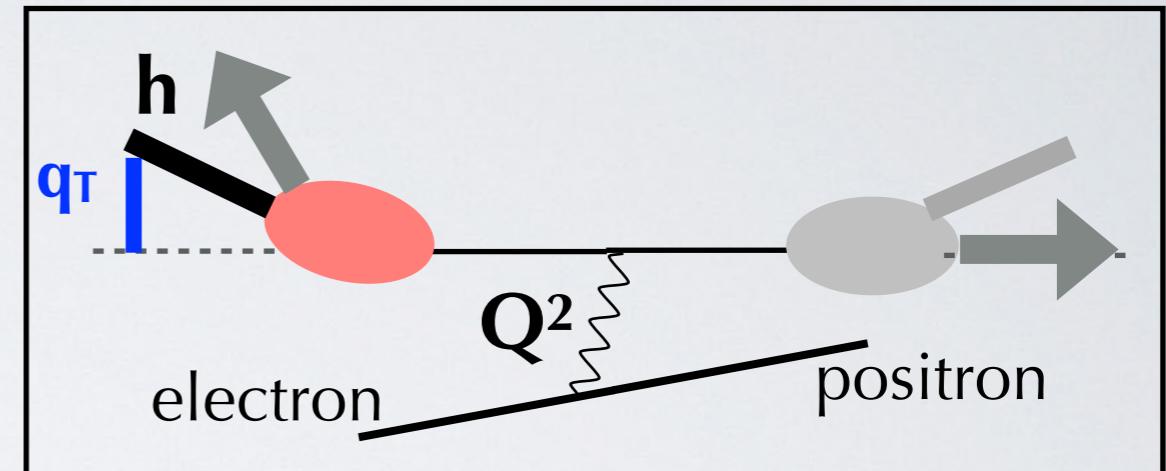
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TMD PDFs



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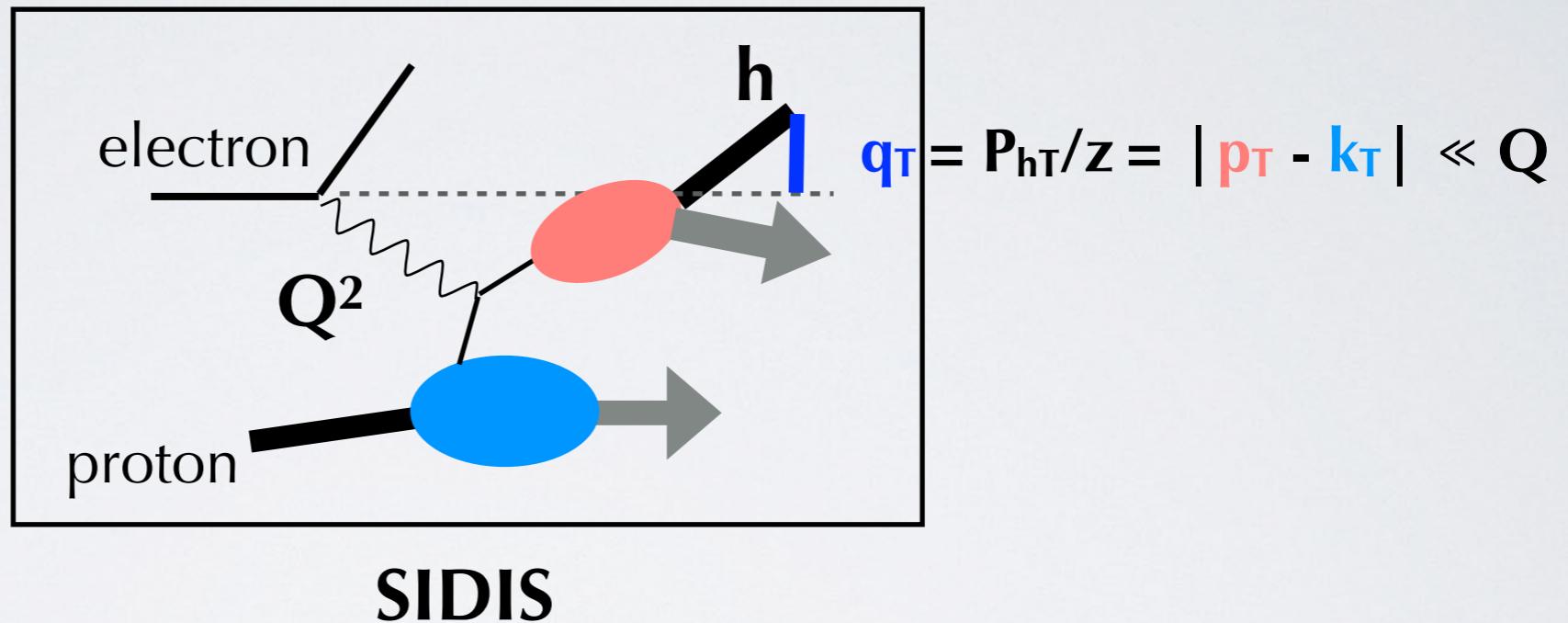
TMD FFs

but only very few (recent) data with polarization

Rogers & Aybat, P.R. D83 (11)
Collins, "Foundations of Perturbative QCD" (11)
Echevarria, Idilbi, Scimemi, JHEP 1207 (12)

TMDs depend on two scales

most data from polarized Semi-Inclusive DIS (SIDIS)
under the form of spin asymmetries



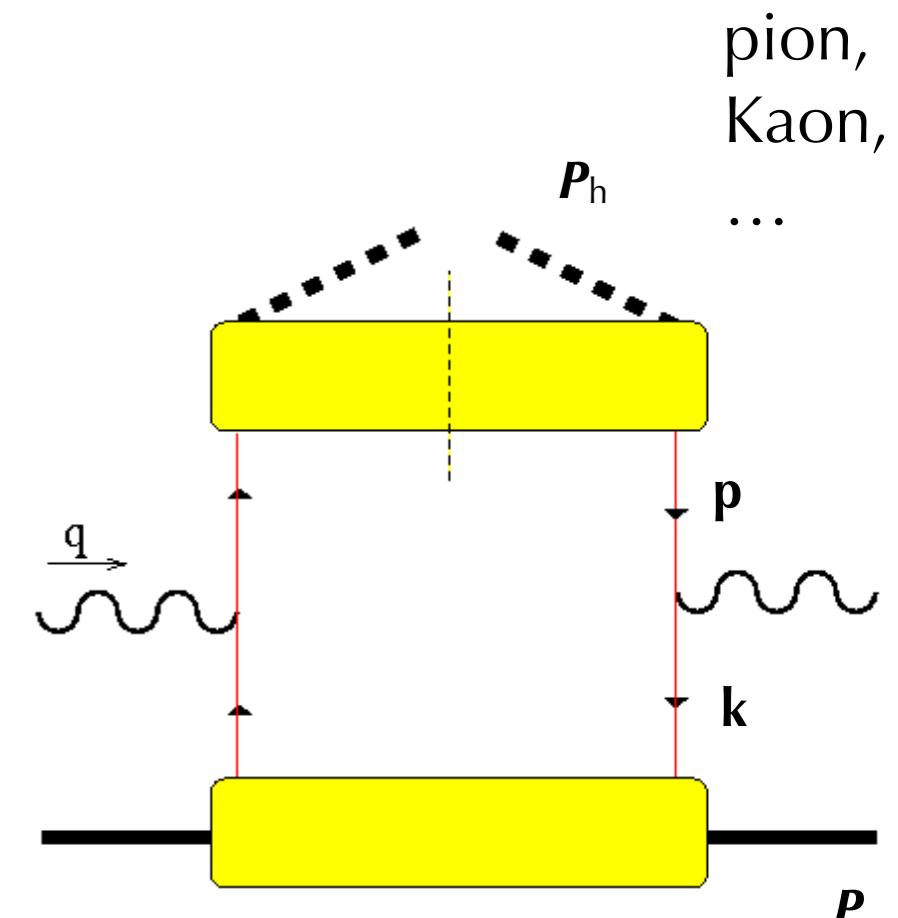
Factorization theorem valid for $q_T \ll Q$

Ji, Yuan, Ma, P.R. D71 (05)
Rogers & Aybat, P.R. D83 (11)
Collins, "Foundations of Perturbative QCD" (11)
Echevarria, Idilbi, Scimemi, JHEP 1207 (12)

two scales:

- hard Q to “see” partons
- soft $q_T \ll Q$ to be sensitive to k_T motion of confined partons

polarized Semi-Inclusive DIS

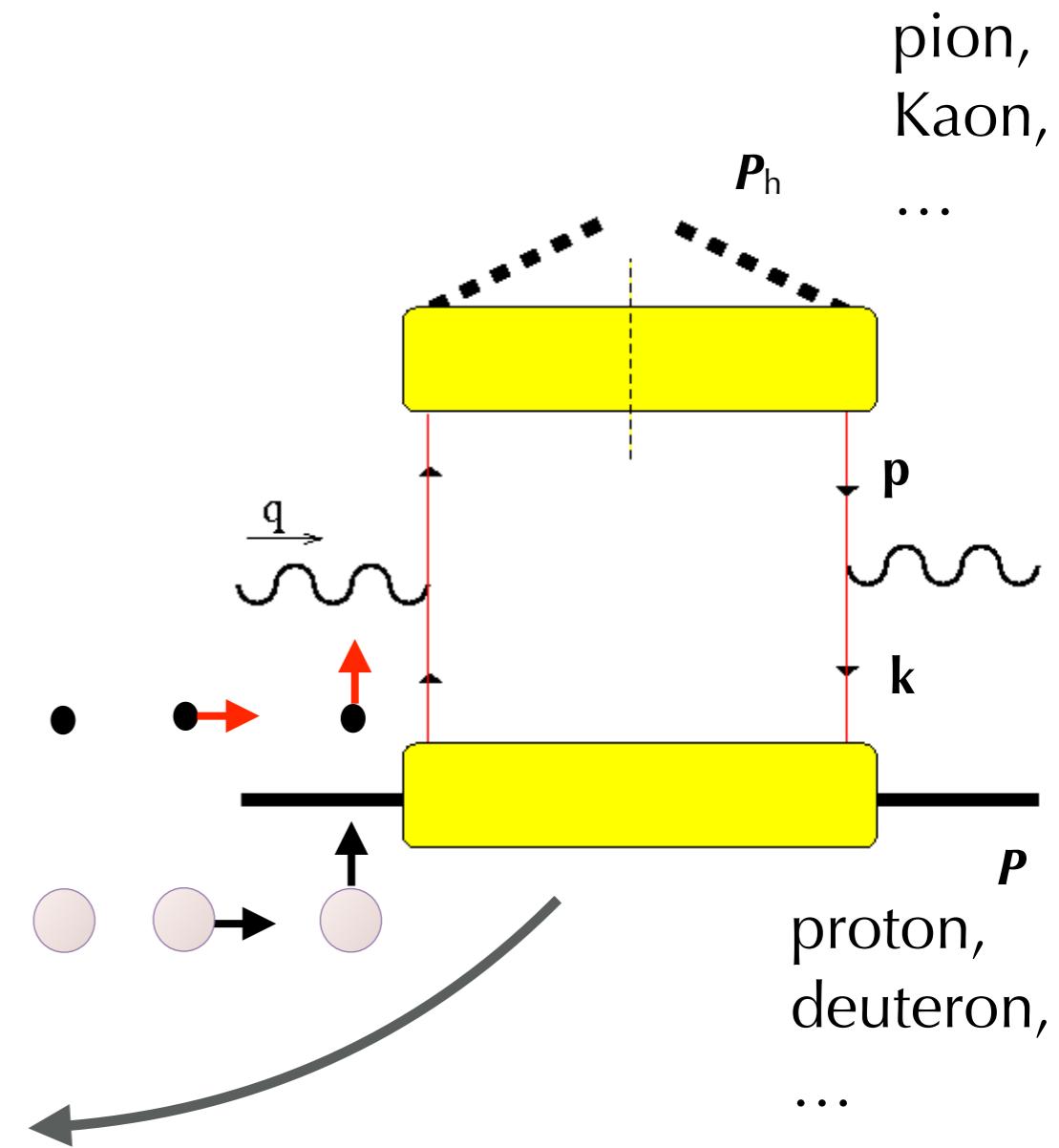


pion,
Kaon,
...
 P_h
 p
 k
 P
proton,
deuteron,
...
 P

dominant diagram
(from diagrammatic
approach to OPE)

polarized Semi-Inclusive DIS

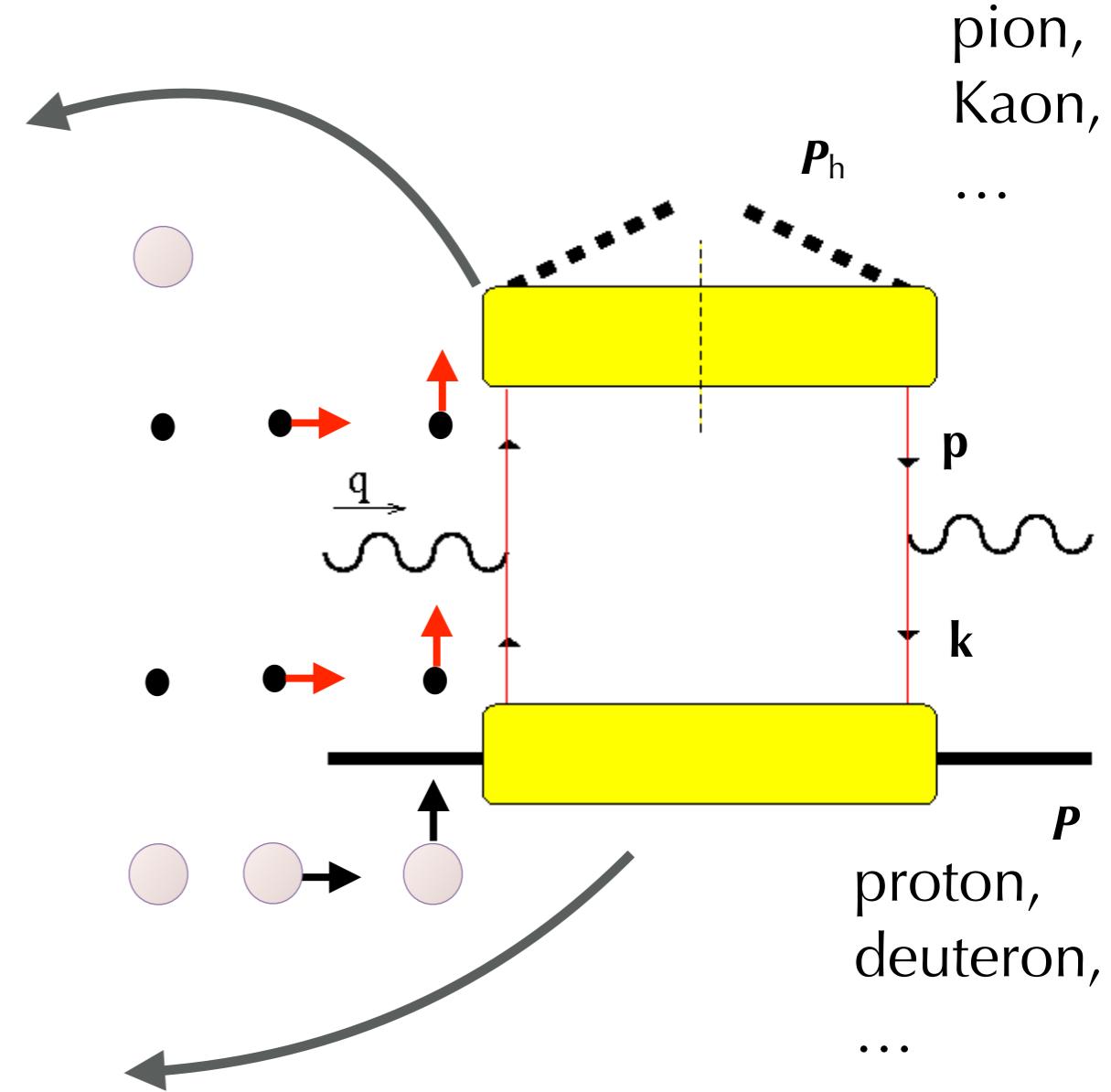
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dominant diagram
(from diagrammatic approach to OPE)

polarized Semi-Inclusive DIS

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$$\begin{aligned}
\frac{d\sigma}{dx dy dz d\phi_h dP_{hT}^2} \sim & A(y) F_U + B(y) \cos 2\phi_h F_U^{\cos 2\phi_h} \\
& + C(y) F_{LL} + B(y) \sin 2\phi_h F_L^{\sin 2\phi_h} \\
& + A(y) \sin(\phi_h - \phi_S) F_T^{\sin(\phi_h - \phi_S)} \\
& + B(y) \sin(\phi_h + \phi_S) F_T^{\sin(\phi_h + \phi_S)} \\
& + B(y) \sin(3\phi_h - \phi_S) F_T^{\sin(3\phi_h - \phi_S)} \\
& + C(y) \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)}
\end{aligned}$$

8 structures at leading twist
(more at subleading twist...)

polarized Semi-Inclusive DIS

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
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Nucleon Polarization	u	$f_1 = \odot$		$h_1^\perp = \odot - \odot$
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$$\begin{aligned}
\frac{d\sigma}{dx dy dz d\phi_h dP_{hT}^2} \sim & \\
& A(y) F_U + B(y) \cos 2\phi_h F_U^{\cos 2\phi_h} \\
& + C(y) F_{LL} + B(y) \sin 2\phi_h F_L^{\sin 2\phi_h} \\
& + A(y) \sin(\phi_h - \phi_S) F_T^{\sin(\phi_h - \phi_S)} \\
& + B(y) \sin(\phi_h + \phi_S) F_T^{\sin(\phi_h + \phi_S)} \\
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\end{aligned}$$

each structure is a convolution in $\mathbf{k}_T, \mathbf{p}_T$: $F \sim [\text{TMDPDF}(x, \mathbf{k}_T) \otimes \text{TMDFF}(z, \mathbf{p}_T)]$

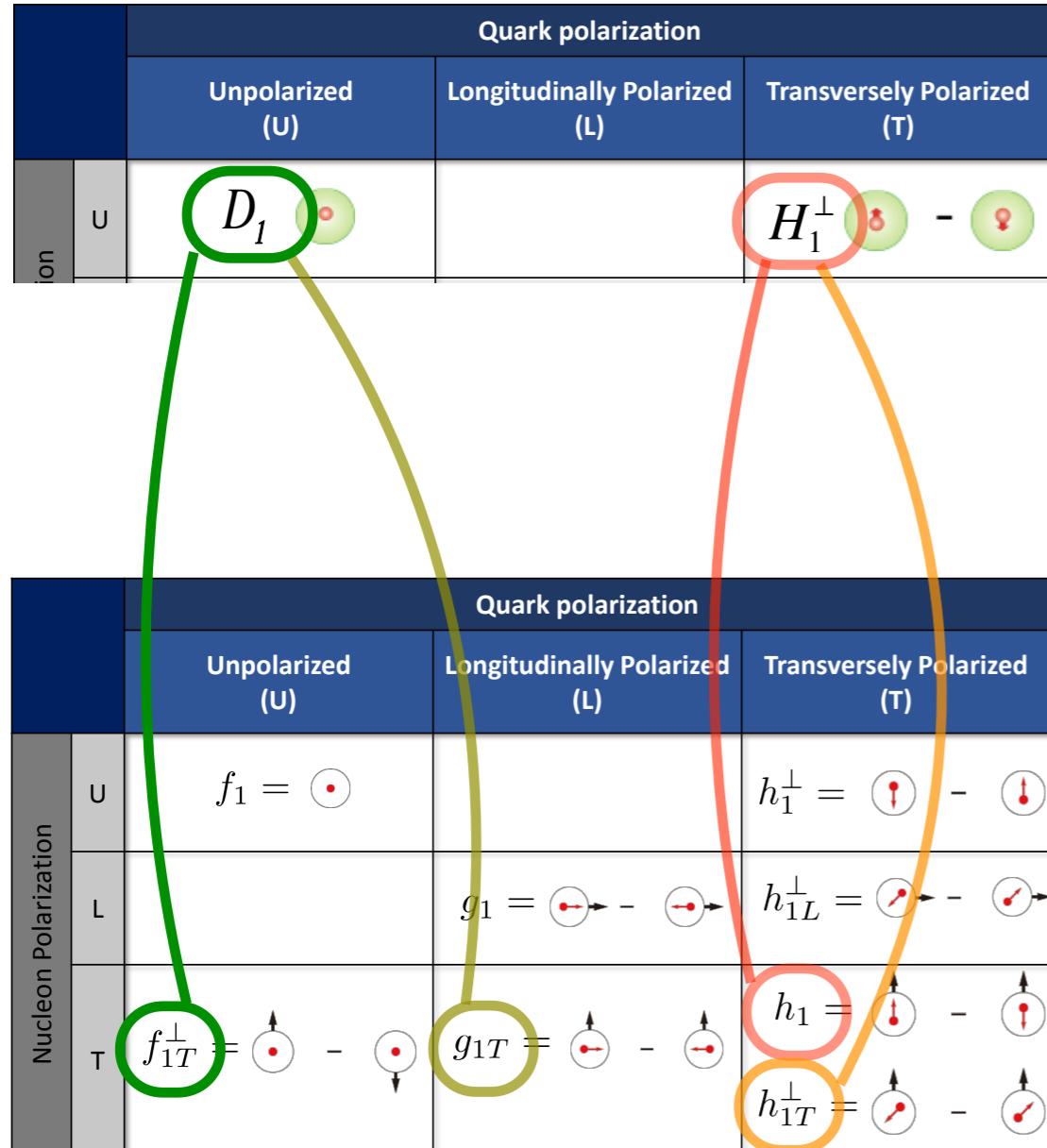
polarized Semi-Inclusive DIS

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$$\begin{aligned}
& \frac{d\sigma}{dx dy dz d\phi_h dP_{hT}^2} \sim \\
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& + C(y) F_{LL} + B(y) \sin 2\phi_h F_L^{\sin 2\phi_h} \\
& \quad \uparrow \\
& \text{requires polarized electron} \\
& + A(y) \sin(\phi_h - \phi_S) F_T^{\sin(\phi_h - \phi_S)} \\
& + B(y) \sin(\phi_h + \phi_S) F_T^{\sin(\phi_h + \phi_S)} \\
& + B(y) \sin(3\phi_h - \phi_S) F_T^{\sin(3\phi_h - \phi_S)} \\
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\end{aligned}$$

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polarized Semi-Inclusive DIS

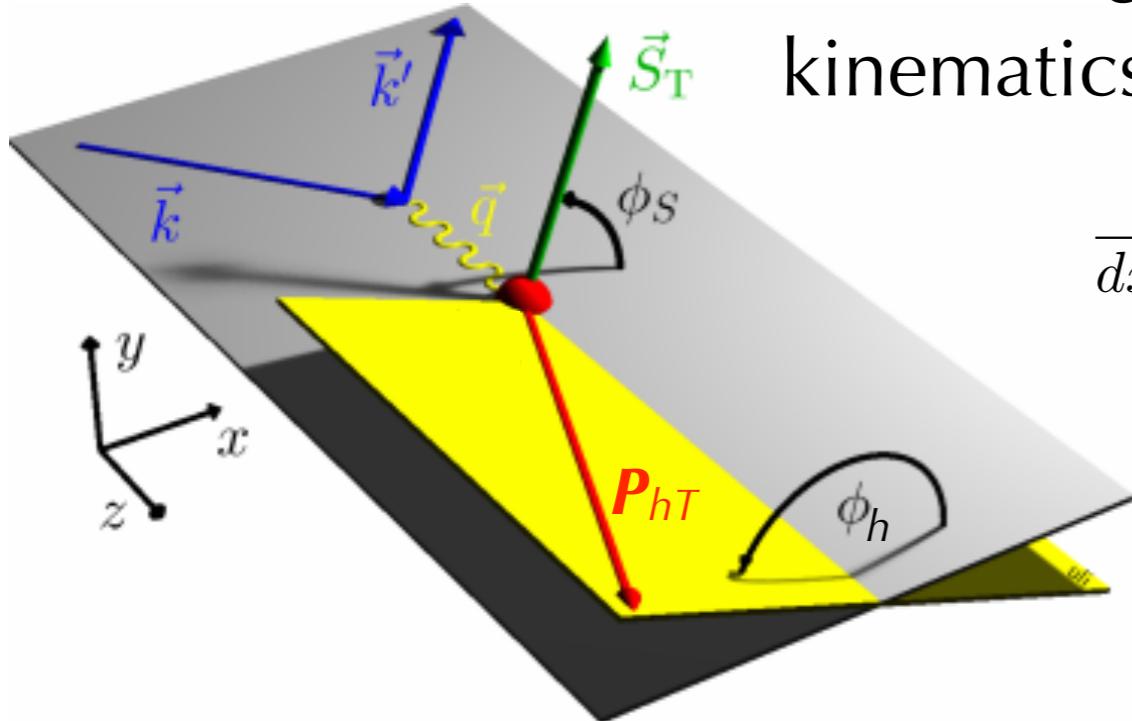


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\end{aligned}$$

each structure is a convolution in $\mathbf{k}_T, \mathbf{p}_T$: $F \sim [\text{TMDPDF}(x, \mathbf{k}_T) \otimes \text{TMDFF}(z, \mathbf{p}_T)]$

Azimuthal Spin Asymmetries

SIDIS
kinematics & cross section



$$\frac{d\sigma}{dx dy dz d\phi_h dP_{hT}^2} \sim \begin{aligned} & A(y) F_U + B(y) \cos 2\phi_h F_U^{\cos 2\phi_h} \\ & + C(y) F_{LL} + B(y) \sin 2\phi_h F_L^{\sin 2\phi_h} \\ & + A(y) \sin(\phi_h - \phi_S) F_T^{\sin(\phi_h - \phi_S)} \\ & + B(y) \sin(\phi_h + \phi_S) F_T^{\sin(\phi_h + \phi_S)} \\ & + B(y) \sin(3\phi_h - \phi_S) F_T^{\sin(3\phi_h - \phi_S)} \\ & + C(y) \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} \end{aligned}$$

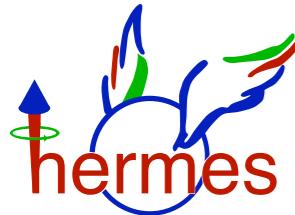
- build $\frac{d\sigma^\uparrow(\phi_h, \phi_S) - d\sigma^\downarrow(\phi_h, \phi_S + \pi)}{d\sigma^\uparrow(\phi_h, \phi_S) + d\sigma^\downarrow(\phi_h, \phi_S + \pi)}$ (or similar when electron is polarized)

- isolate specific azimuthal component, coefficient $\sim \frac{F_X^{xxx}(x, z, P_{hT}^2; Q^2)}{F_U(x, z, P_{hT}^2; Q^2)}$

Azimuthal Spin Asymmetry $\equiv A_X^{xxx}(x, z, P_{hT}^2; Q^2)$

Experimental data

All 8 asymmetries have been measured (plus more at subleading twist..)



$A_U^{\cos 2\phi_h}$ on p & D targets [arXiv:1204.4161](#)

$A_L^{\sin 2\phi_h}$ on p^\uparrow [hep-ph/0608048](#)

$A_T^{\sin(\phi_h - \phi_S)}$ on p^\uparrow [arXiv:0906.3918](#)

$A_T^{\sin(\phi_h + \phi_S)}$ on p^\uparrow [arXiv:1006.4221](#)



Hall A $A_T^{\sin(\phi_h \pm \phi_S)}$ on ${}^3\text{He}^\uparrow$ with π [arXiv:1106.0363](#) with K [arXiv:1404.7204](#)

$A_T^{\sin(\phi_h - \phi_S)}$ on ${}^3\text{He}^\uparrow$ with π [arXiv:1311.1866](#)

Hall B A_{LL} & $A_L^{\sin 2\phi_h}$ on p^\uparrow [arXiv:1003.4549](#)



$A_U^{\cos 2\phi_h}$ on D targets [arXiv:1401.6284](#)

A_{LL} on p^\uparrow [arXiv:1509.03526](#)

A_{LL} & $A_L^{\sin 2\phi_h}$ on p^\uparrow [arXiv:1509.03526](#) on D^\uparrow [arXiv:1609.06062](#)

$A_T^{\sin(\phi_h - \phi_S)}$ on p^\uparrow [arXiv:1205.5122](#)
 $A_T^{\sin(\phi_h + \phi_S)}$ on p^\uparrow [arXiv:1205.5121](#) } [arXiv:1005.5609](#)
 $A_T^{\sin(\phi_h \pm \phi_S)}$ on D^\uparrow [arXiv:1408.4405](#) [arXiv:1609.07374](#)

$A_T^{\sin(\phi_h \pm \phi_S)}$ & $A_{LT}^{\cos(\phi_h - \phi_S)}$ & $A_T^{\sin(3\phi_h - \phi_S)}$ on p^\uparrow [arXiv:0802.2160](#)
 $A_T^{\sin(3\phi_h - \phi_S)}$ on ${}^3\text{He}^\uparrow$ [arXiv:1512.06590](#)

Two Most Relevant Cases

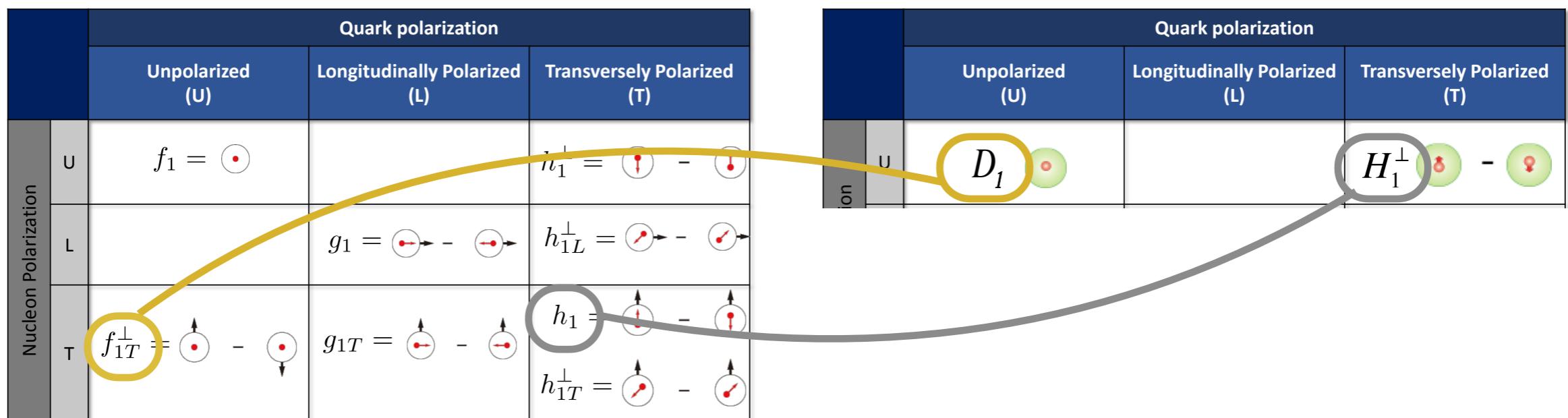
The EIC White Paper

Accardi et al., E.P.J. A52 (16) 268, arXiv:1212.1701 , see also Boer et al., arXiv:1108.1713



Deliverables	Observables	What we learn
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations 3D Imaging of quark's motion: valence + sea 3D Imaging of gluon's motion QCD dynamics in a unprecedented Q^2 (P_{hT}) range
Chiral-odd functions: Transversity; Boer-Mulders	SIDIS with Transverse polarization	3 rd basic quark PDF: valence + sea, tensor charge Novel spin-dependent hadronization effect QCD dynamics in a chiral-odd sector with a wide Q^2 (P_{hT}) coverage

Table 2.2: Science Matrix for TMD: 3D structure in transverse momentum space: (upper) the golden measurements; (lower) the silver measurements.

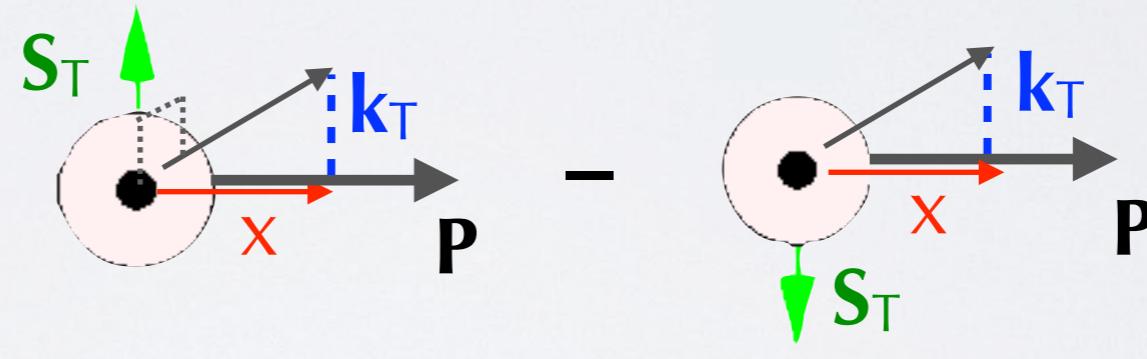


The Sivers effect



		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		$h_1^\perp = \odot - \odot$
	L		$g_1 = \odot \rightarrow - \odot \rightarrow$	$h_{1L}^\perp = \odot \rightarrow - \odot \rightarrow$
	T	$f_{1T}^\perp = \odot \uparrow - \odot \downarrow$	$g_{1T} = \odot \uparrow - \odot \uparrow$	$h_1 = \odot \uparrow - \odot \uparrow$ $h_{1T}^\perp = \odot \uparrow - \odot \uparrow$

the Sivers function



$$\mathbf{S}_T \cdot (\mathbf{P} \times \mathbf{k}_T)$$

(spin-orbit) correlation between \mathbf{k}_T of parton and \mathbf{S}_T of proton
distortion of quark distribution in transv. polarized proton P^\uparrow

The Sivers effect

Bacchetta & Contalbrigo,
Il Nuovo Saggiatore **28** (12) n. 1,2

no polarization

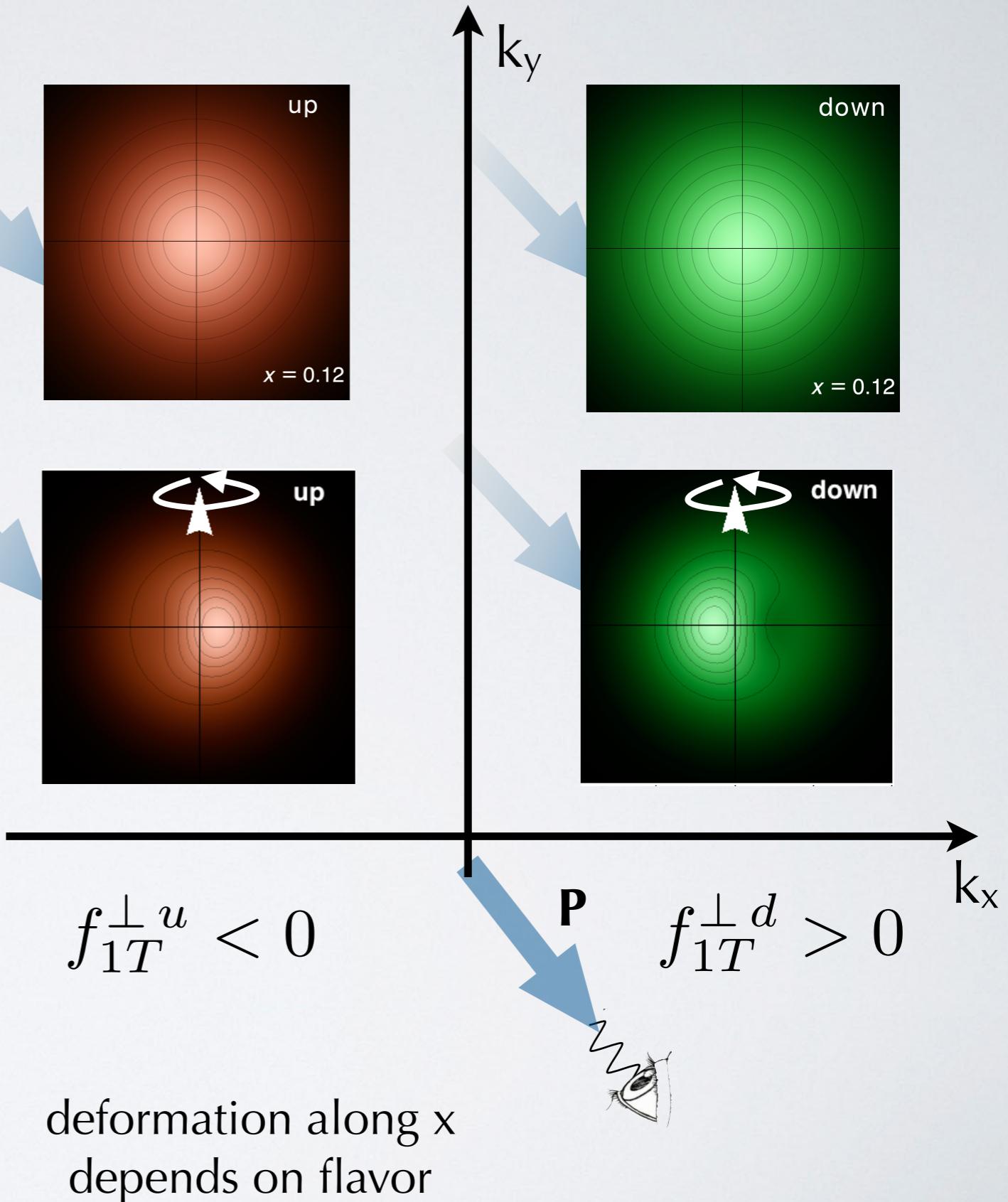
polarization S_y

distortion of quark distribution
in transversely polarized proton P^\uparrow

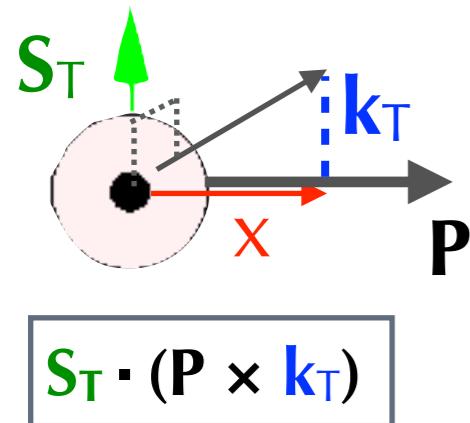
$$f_{q/p^\uparrow}(x, \mathbf{k}_T) = f_1^q(x, \mathbf{k}_T^2) - f_{1T}^{\perp q}(x, \mathbf{k}_T^2) \mathbf{S} \cdot \left(\frac{\hat{\mathbf{P}}}{M} \times \mathbf{k}_T \right)$$

density of q in (proton) $^\uparrow$

Sivers, P.R. D**41** (90) 83

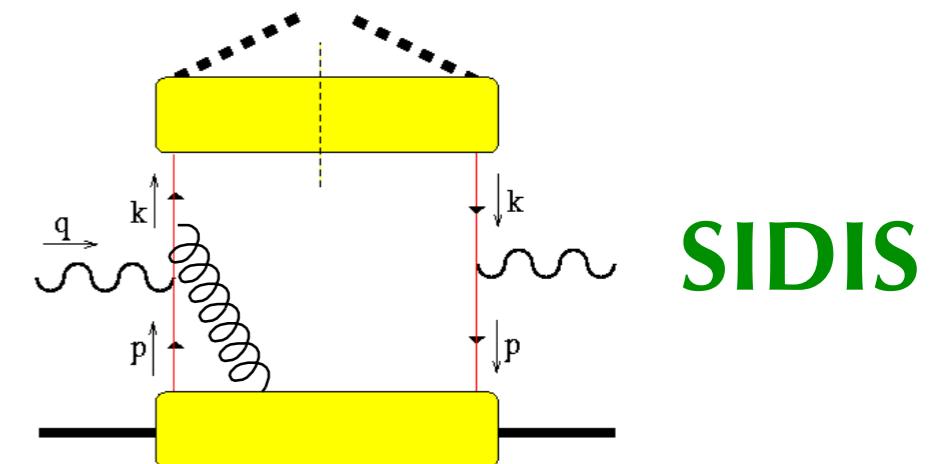


Non-universality of Sivers function

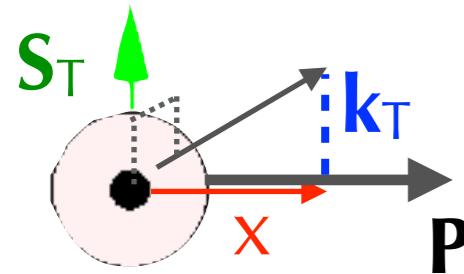


Sivers effect apparently forbidden by T-rev. invariance
but Sivers function entirely given by residual color
interactions, that restore
color-gauge invariance

“final-state” color interactions



Non-universality of Sivers function



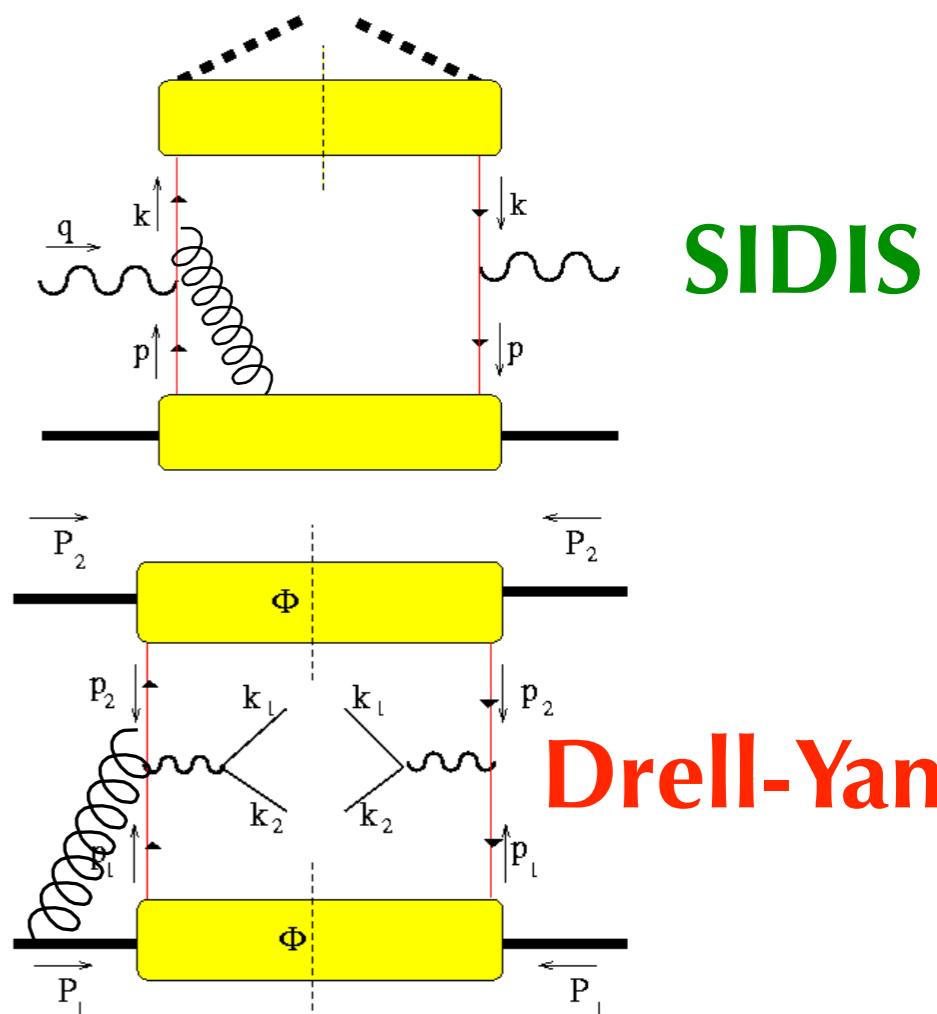
$$S_T \cdot (P \times k_T)$$

Sivers effect apparently forbidden by T-rev. invariance
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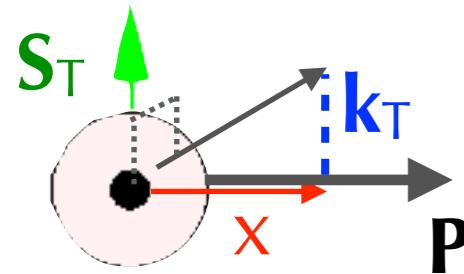
“final-state” color interactions

the Sivers function can be extracted also from
transv. polarized Drell-Yan $p^\uparrow + p \rightarrow \ell^+ + \ell^- + X$

“initial-state” color interactions



Non-universality of Sivers function



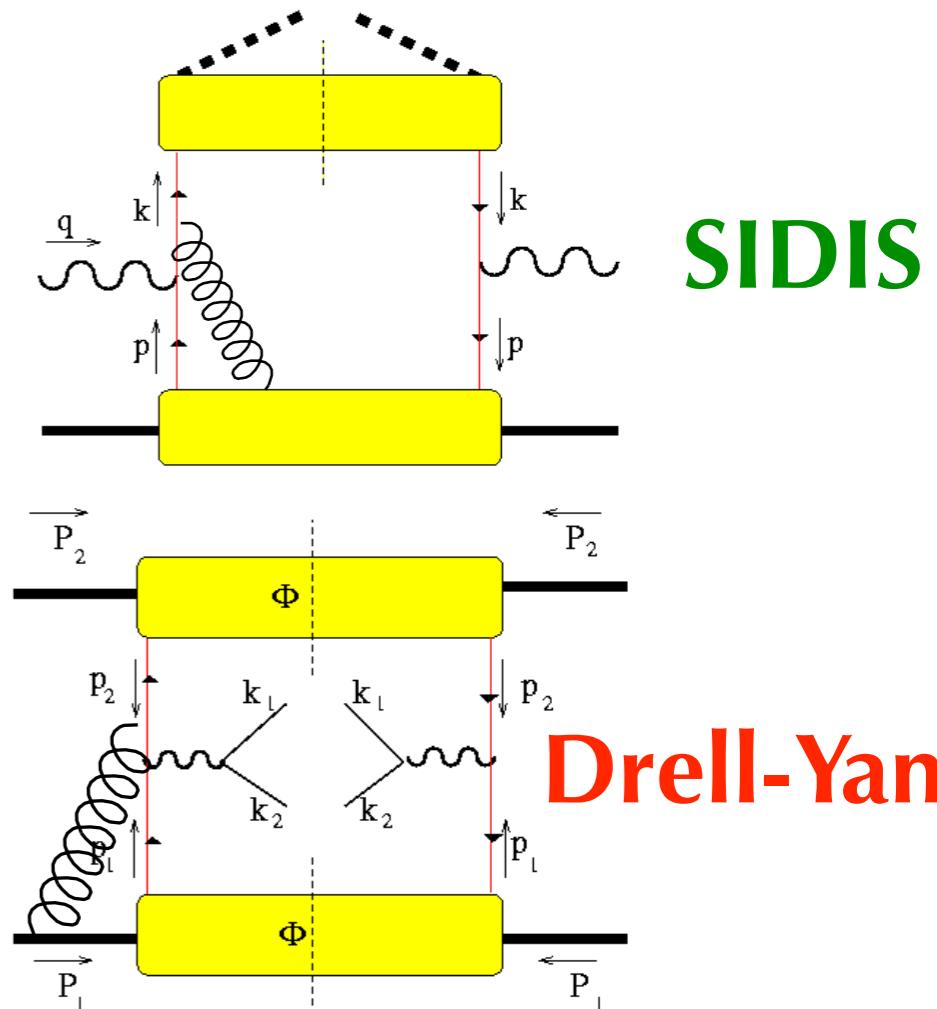
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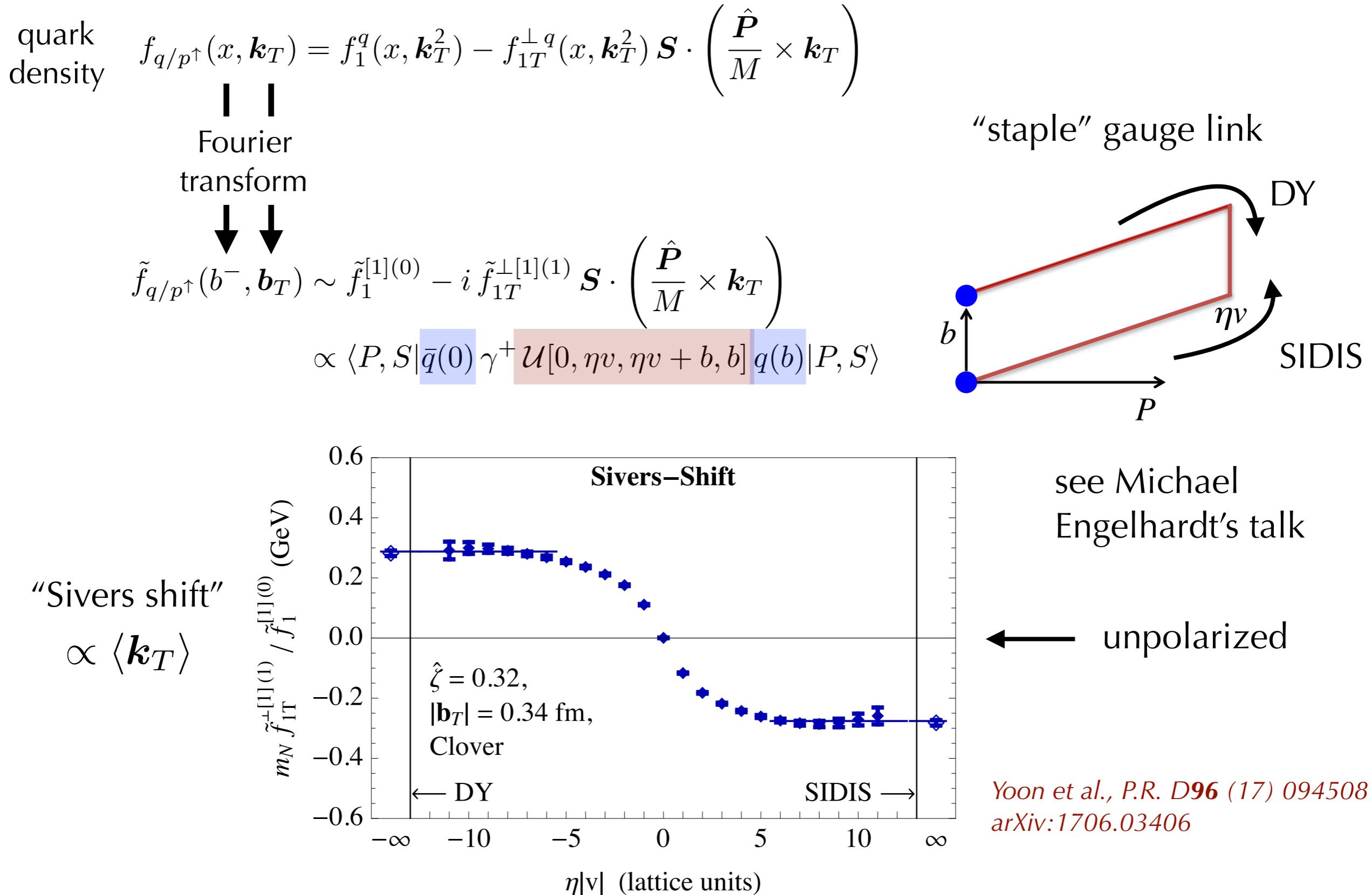
“initial-state” color interactions



QCD prediction to be tested:

$$\text{Sivers}\Big|_{\text{SIDIS}} = -\text{Sivers}\Big|_{\text{D-Y}}$$

Non-universality of Sivers on lattice



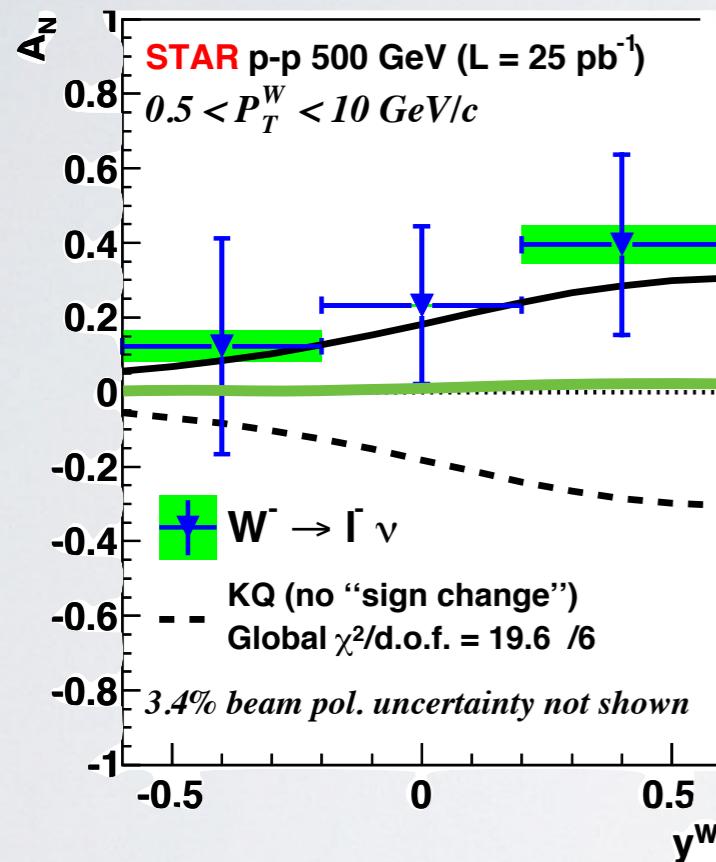
Exp. test of Sivers sign change

first data on transversely polarized Drell-Yan

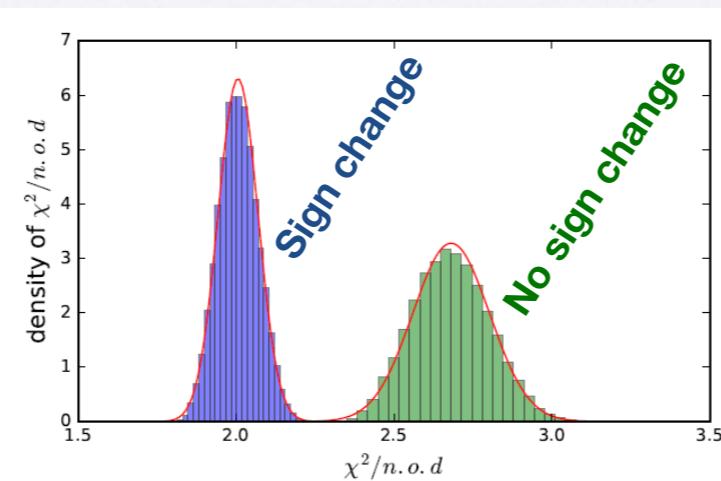


*Adamczyk et al., PRL 116 (16) 132301
arXiv:1511.06003*

$$p^\uparrow + p \rightarrow W^\pm/Z^0 + X$$



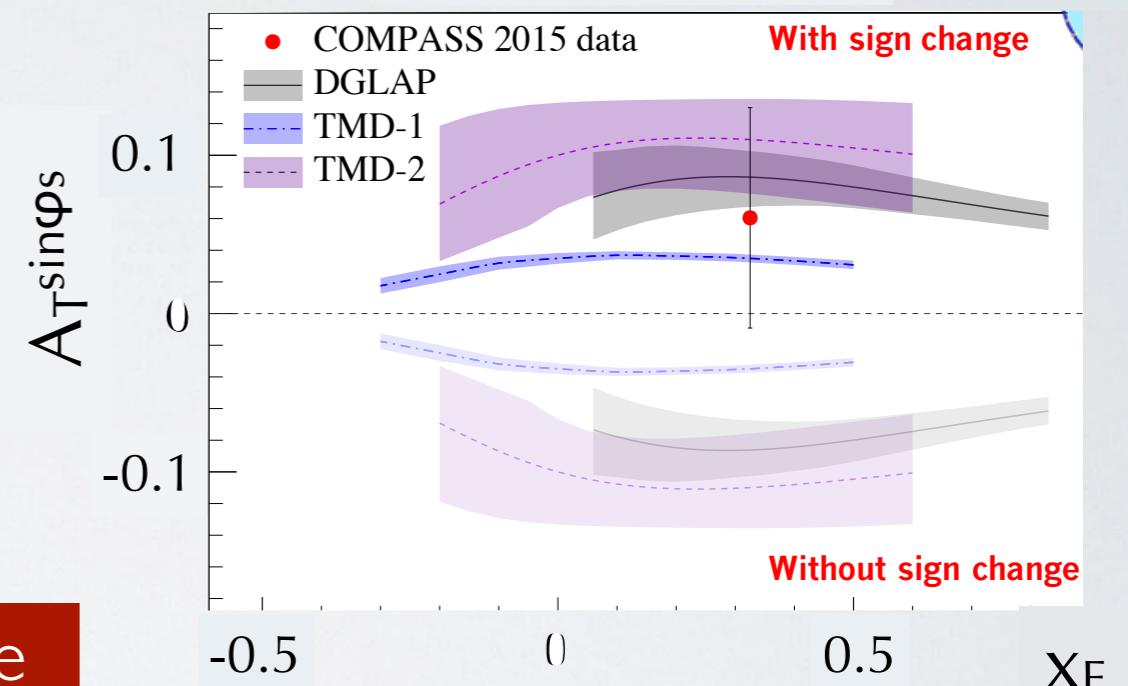
Kang & Qiu,
PRL 103 (09) 172001



*Aghasyan et al., PRL 119 (17) 112002
arXiv:1704.00488*



$$\pi^- + p^\uparrow \rightarrow \ell^+ \ell^- X$$



TMD-1 *Echevarria et al., PR D89 (14) 074013
arXiv:1401.5078*

TMD-2 *Sun & Yuan, PR D88 (13) 114012
arXiv:1308.5003*

DGLAP *Anselmino et al., JHEP 1704 (17) 046
arXiv:1612.06413*

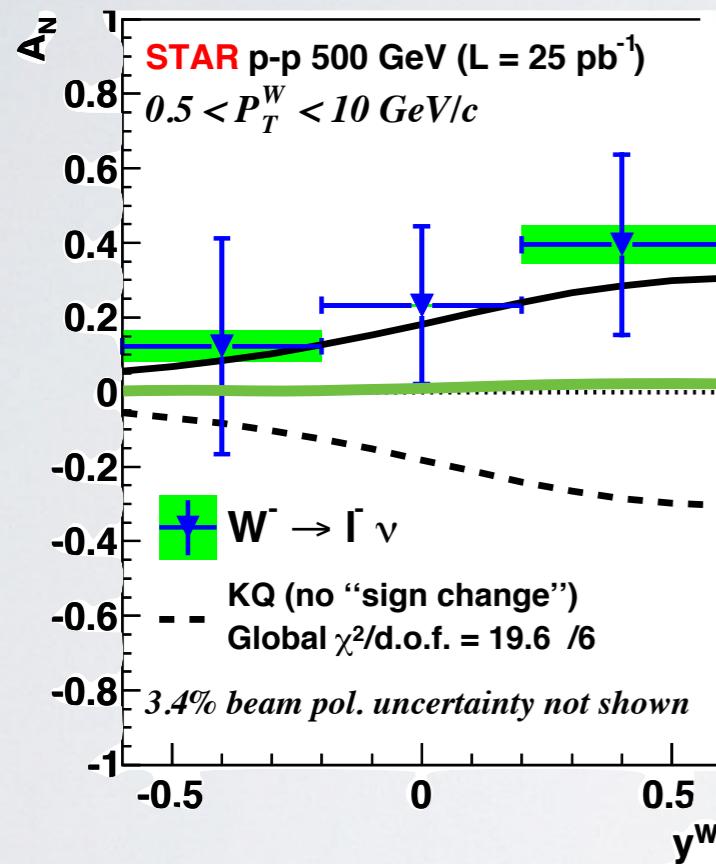
Exp. test of Sivers sign change

first data on transversely polarized Drell-Yan



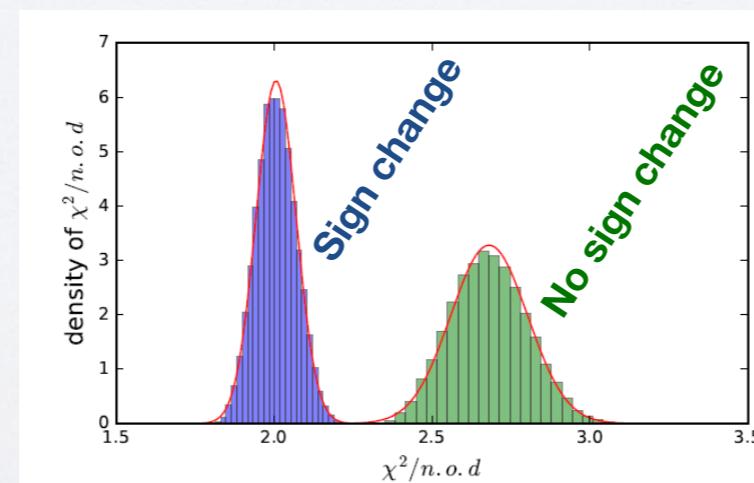
*Adamczyk et al., PRL 116 (16) 132301
arXiv:1511.06003*

$$p^\uparrow + p \rightarrow W^\pm/Z^0 + X$$



prediction with TMD evolution (??)

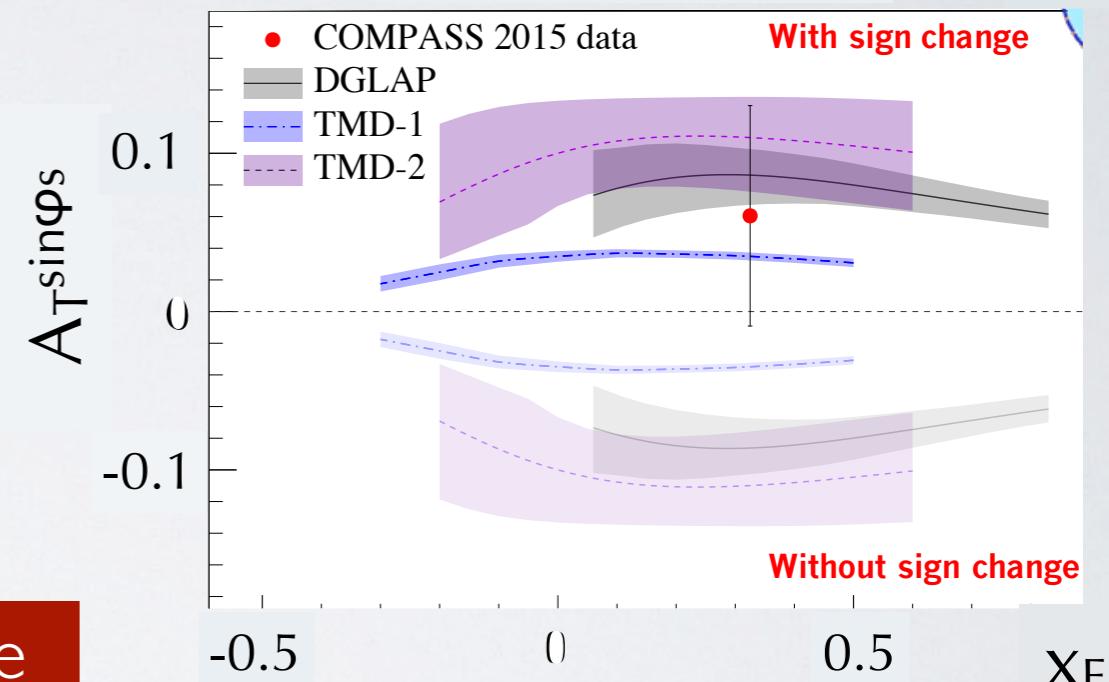
hints of sign change statistically favored



*Aghasyan et al., PRL 119 (17) 112002
arXiv:1704.00488*



$$\pi^- + p^\uparrow \rightarrow \ell^+ \ell^- + X$$



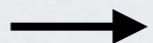
TMD-1 *Echevarria et al., PR D89 (14) 074013
arXiv:1401.5078*

TMD-2 *Sun & Yuan, PR D88 (13) 114012
arXiv:1308.5003*

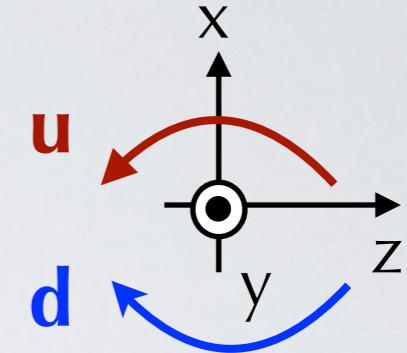
DGLAP *Anselmino et al., JHEP 1704 (17) 046
arXiv:1612.06413*

Sivers \leftrightarrow Nucleon spin ?

N^\uparrow polarized along y
(~ spin-orbit effect)



charge distribution
distorted along x:
up mostly at $x>0$
down at $x<0$

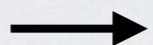


see Hatta's talk

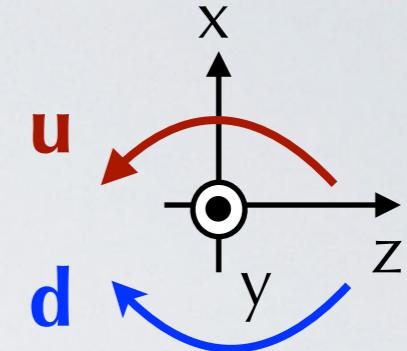
distortion described
by function E^q (GPD)

Sivers \leftrightarrow Nucleon spin ?

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charge distribution
distorted along x:
up mostly at $x > 0$
down at $x < 0$



see Hatta's talk

distortion described
by function E^q (GPD)

$$1/2 = \sum_q J_y^q (Q^2)$$

$J^q (Q^2)$ = total angular momentum from parton q

The Ji's sum rule

Ji, P.R.L. 78 (97) 610

$$= \frac{1}{2} \int_0^1 dx x [f_1^q(x, Q^2) + E^q(x, Q^2)]$$

forward limit of E^q

distortion in
position space

E^q

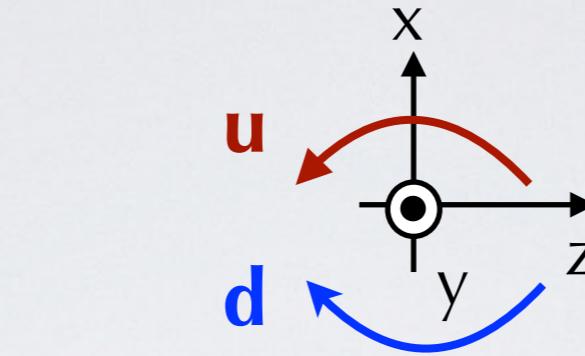
?

Sivers
 $f_{1T} \perp q$

distortion in
momentum space

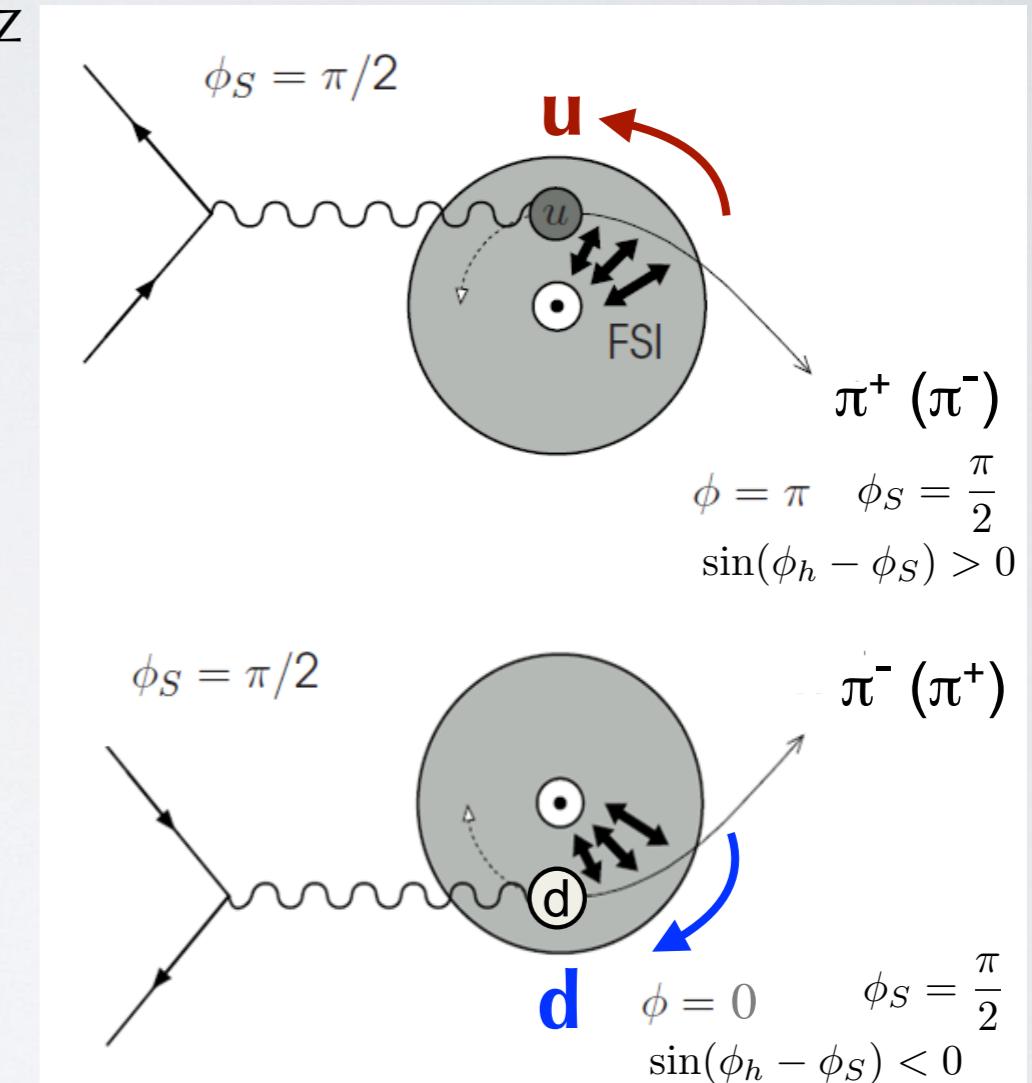
The color lensing effect

N^\uparrow polarized along y
 ↓
 distortion along x :
up mostly at $x > 0$
down at $x < 0$
 ↓
 quarks hit by virtual photon
 try to escape color FSI
 ↓
up bended to $x < 0$
down bended to $x > 0$



described by E

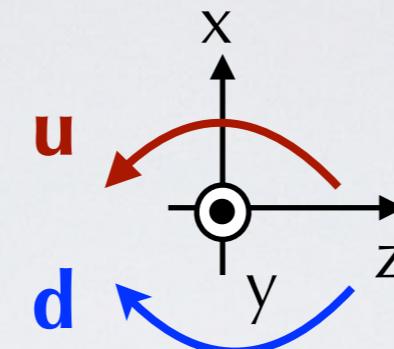
Burkardt, P.R. D66 (02) 114005



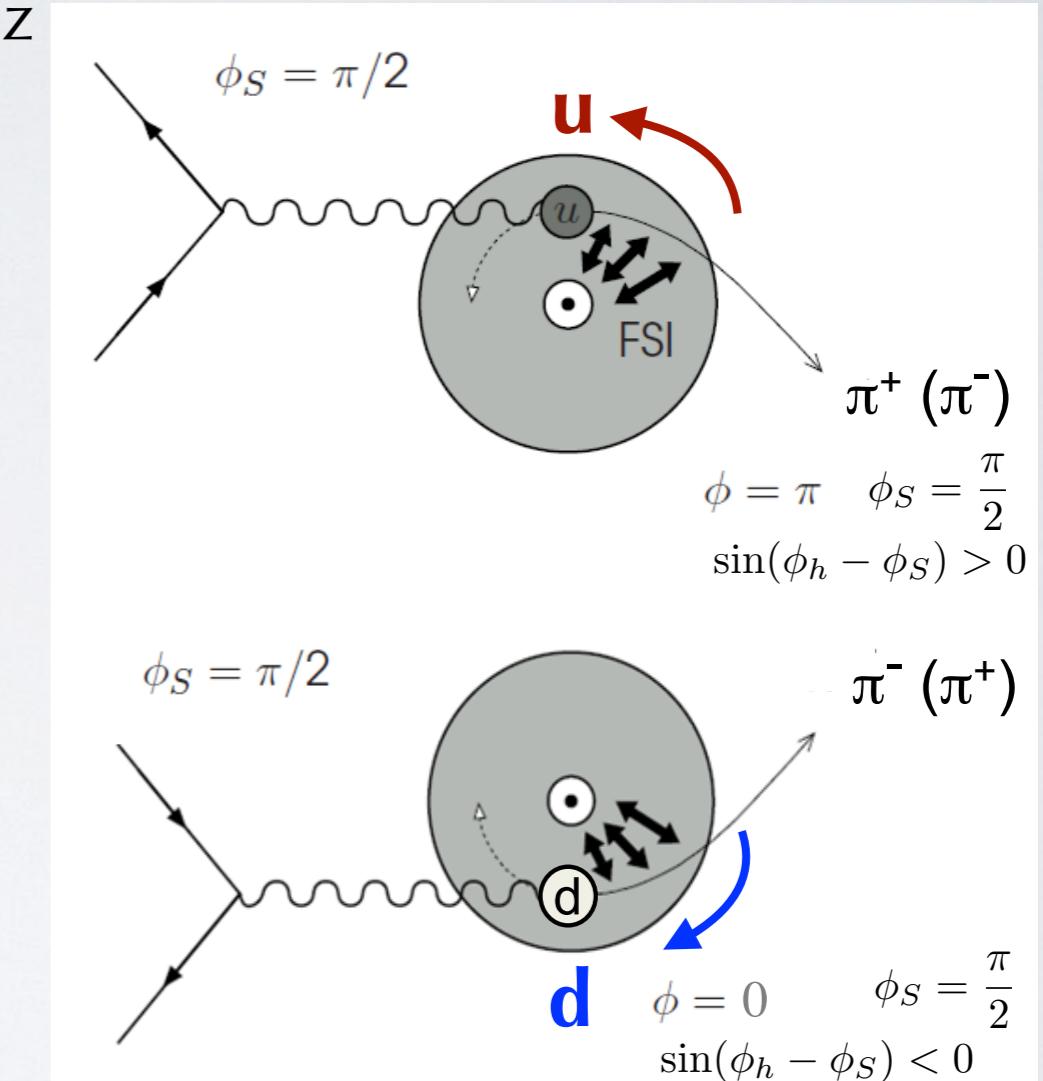
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color lensing
 $L(x)$
 described by
 Sivers $-f_{1T}^\perp$



Burkardt, P.R. D66 (02) 114005



color lensing:
 at some scale Q_L^2

$$\int d\mathbf{k}_T f_{1T}^{\perp q}(x, \mathbf{k}_T; Q_L^2) = -L(x) E^q(x, 0, 0; Q_L^2)$$

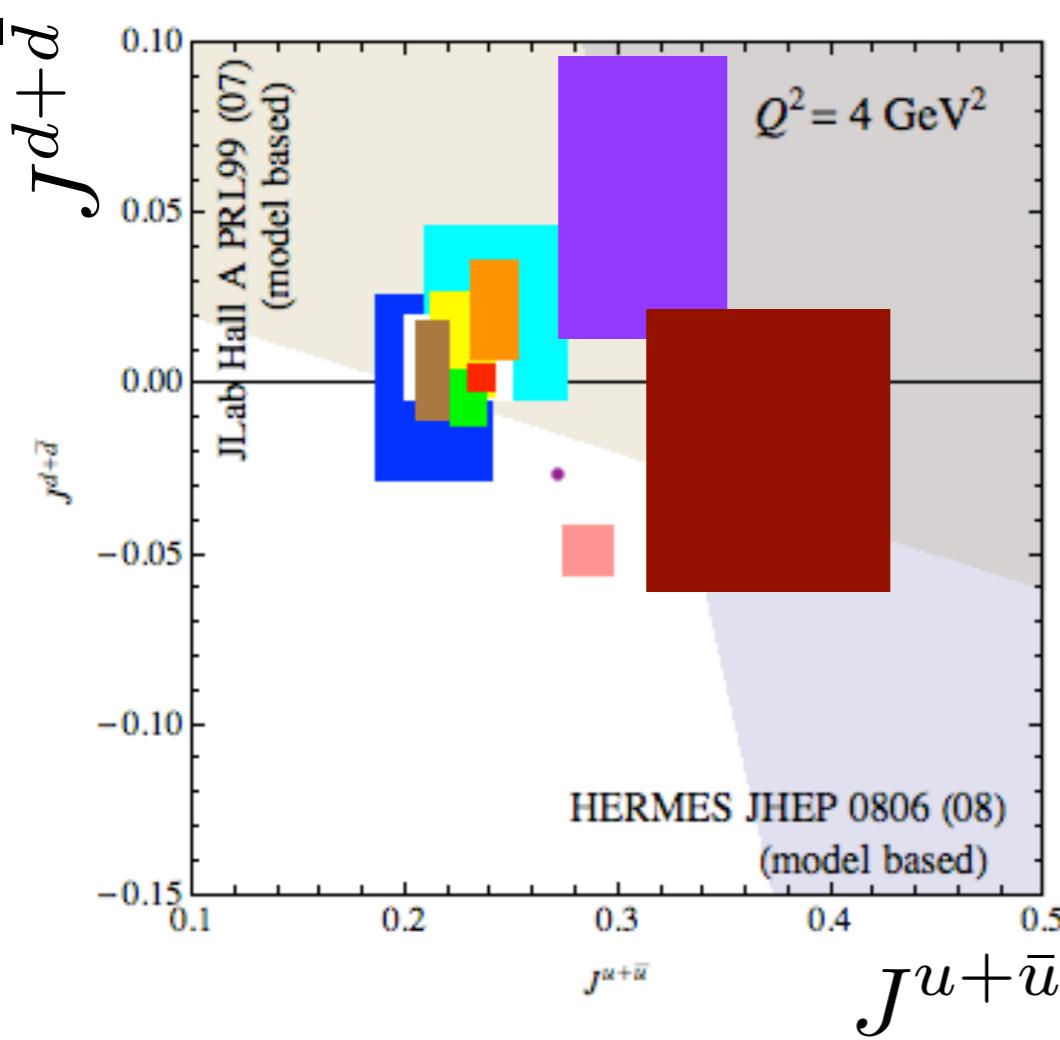
Bacchetta & Radici, P.R.L. 107 (11) 212001

Sivers function \leftrightarrow quark total J

- extract Sivers f_{1T^\perp} from data +
- model lensing function $L(x)$ +
- Ji's sum rule

(applicable only to 2-body systems)

*Pasquini, Rodini, Bacchetta, PR D100 (19) 054039,
arXiv:1907.06960*



- Goloskokov & Kroll, EPJ C59 (09) 809
- Diehl & Kroll, E.P.J. C73 (13) 2397
- Diehl et al., EPJ C39 (05) 1
- Guidal et al., PR D72 (05) 054013
- Liuti at al., PRD 84 (11) 034007
- Bacchetta & Radici, PRL 107 (11) 212001**
- LHPC-1, PR D77 (08) 094502
- LHPC-2, PR D82 (10) 094502
- QCDSF, arXiv:0710.1534
- Wakamatsu, EPJ A44 (10) 297
- Alexandrou et al., arXiv:1706.02973
- Deka et al., arXiv:1312.4816

models
of
GPD E

color lensing

lattice

the Sivers Spin Asymmetry in SIDIS

several extractions of Sivers f_{1T}^\perp :

Vogelsang & Yuan, P.R. **D72** (05) 054028
Collins et al., P.R. **D73** (06) 014021
Bacchetta & Radici, P.R.L. **107** (11) 212001
Anselmino, Boglione, Melis, P.R. **D86** (12) 014028
Aybat, Prokudin, Rogers, P.R.L. **108** (12) 242003
Sun & Yuan, P.R. **D88** (13) 034016
Boer, N.P. **B874** (13) 217
.....

$$A_T^{\sin(\phi_h - \phi_S)} \propto \frac{f_{1T}^\perp \otimes D_1}{f_1 \otimes D_1} \longleftarrow$$

from global fit PV17 of data on
SIDIS, DY and Z-boson

Bacchetta et al., JHEP **1706** (17) 081; E **1906** (19) 051
arXiv:1703.10157 (see previous talk)

First extraction of Sivers function using in denominator
unpolarized TMDs from global fit
consistently in the same TMD framework

Bacchetta, Delcarro, Pisano, Radici, *in preparation*

The PV19 fit of Sivers f_{1T}^\perp (preliminary)

Bacchetta, Delcarro, Pisano, Radici,
in preparation

data coverage



proton [H]
95
data points



neutron [^3He]
6
data points

*Qian et al.,
P.R.L. **107** (11) 072003*



deuteron [^6LiD]
88
data points



Proton [NH_3]
111
data points

Same [kinematic cuts](#) applied to unpolarized

x, z, P_{hT} data projections

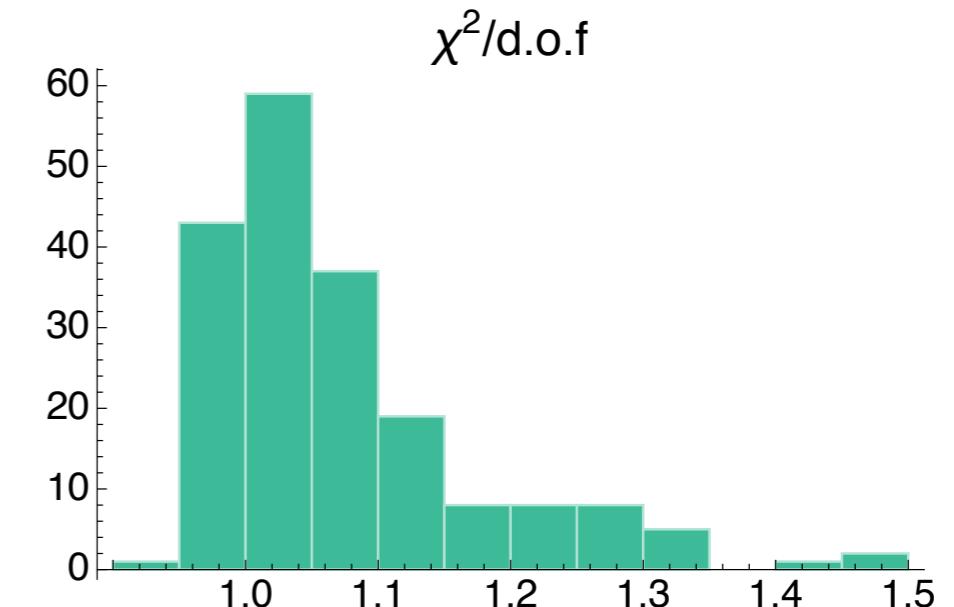
$$\begin{aligned} Q^2 &\geq 1.4 \text{ GeV}^2 & 0.2 \leq z \leq 0.7 \\ P_{hT} &< \min[0.2 Q, 0.7 Qz] + 0.5 \text{ GeV} \end{aligned}$$

data points
117

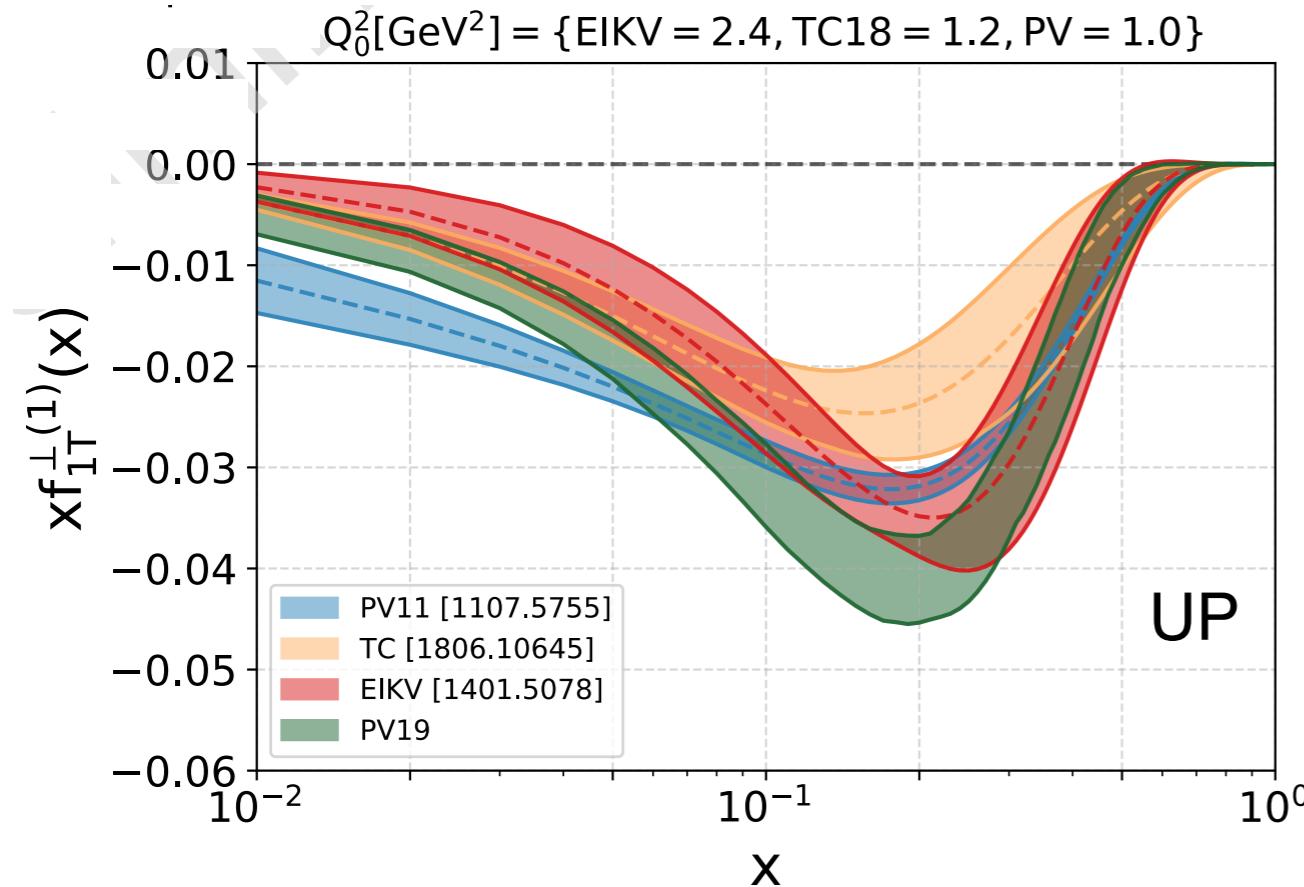
fit parameters
14

global $\chi^2/\text{d.o.f.}$
 1.06 ± 0.10

statistical error with
replica method (200)

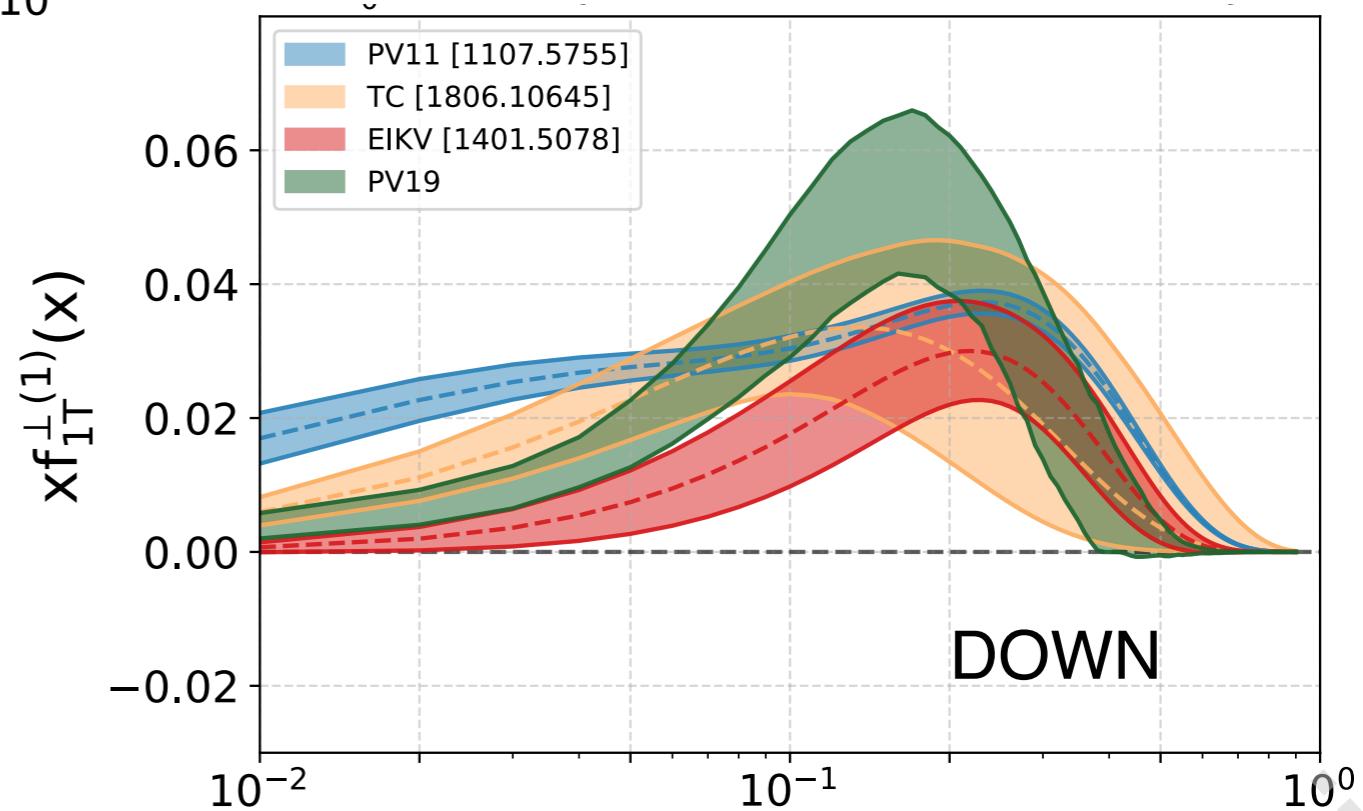


The PV19 fit of Sivers f_{1T}^\perp (preliminary)

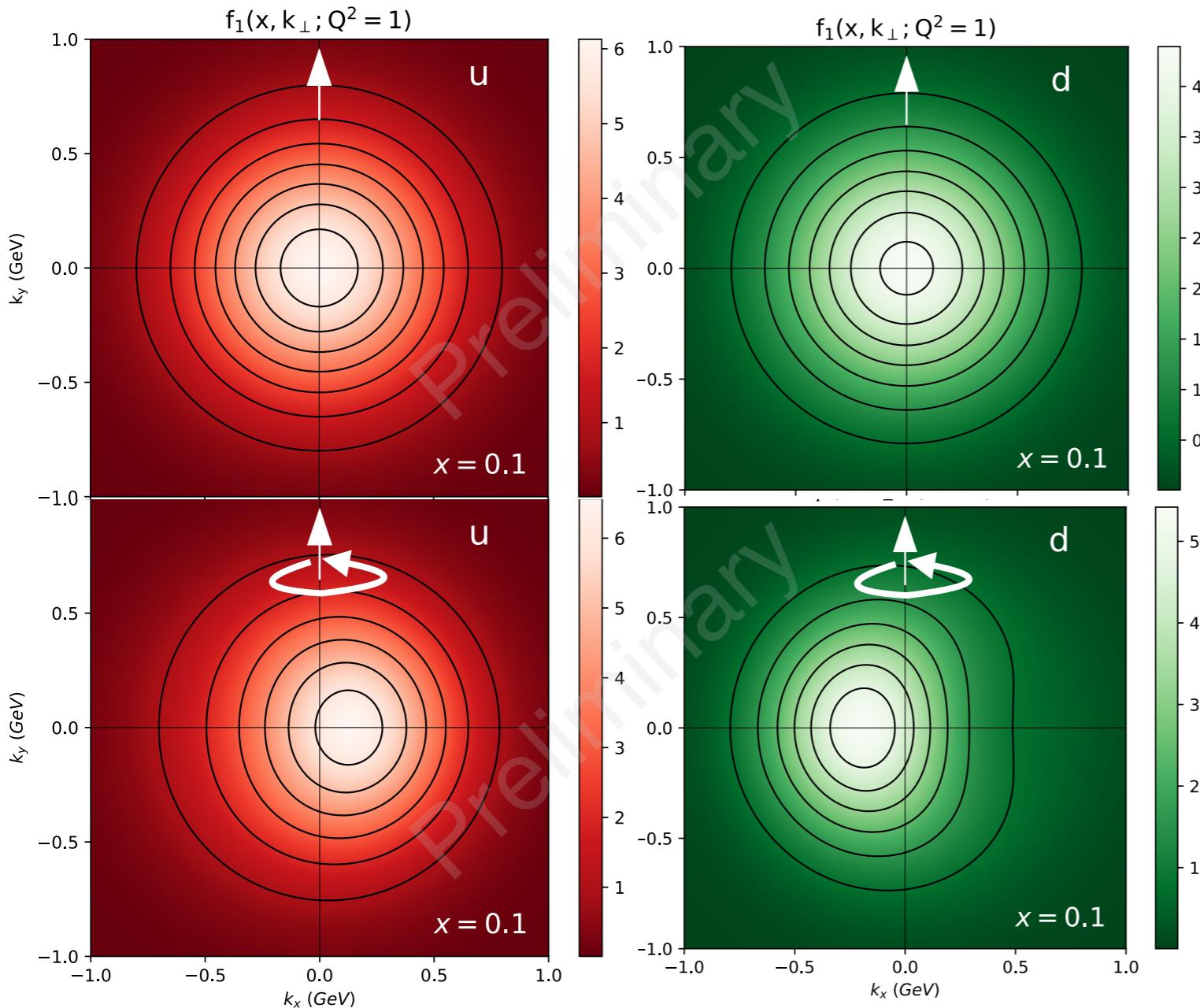


$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \frac{\mathbf{k}_T^2}{2M^2} f_{1T}^\perp(x, \mathbf{k}_T)$$

- | | |
|--|--|
| PV11
EIKV
TC
PV19 | <i>Bacchetta & Radici, P.R.L. 107 (11)</i>
<i>Echevarria et al., P.R. D89 (14)</i>
<i>Boglione et al., JHEP 1807 (18)</i>
<i>Bacchetta, Delcarro, Pisano, Radici, in preparation</i> |
|--|--|



The PV19 fit of Sivers f_{1T^\perp} (preliminary)



*Bacchetta, Delcarro, Pisano, Radici,
in preparation*

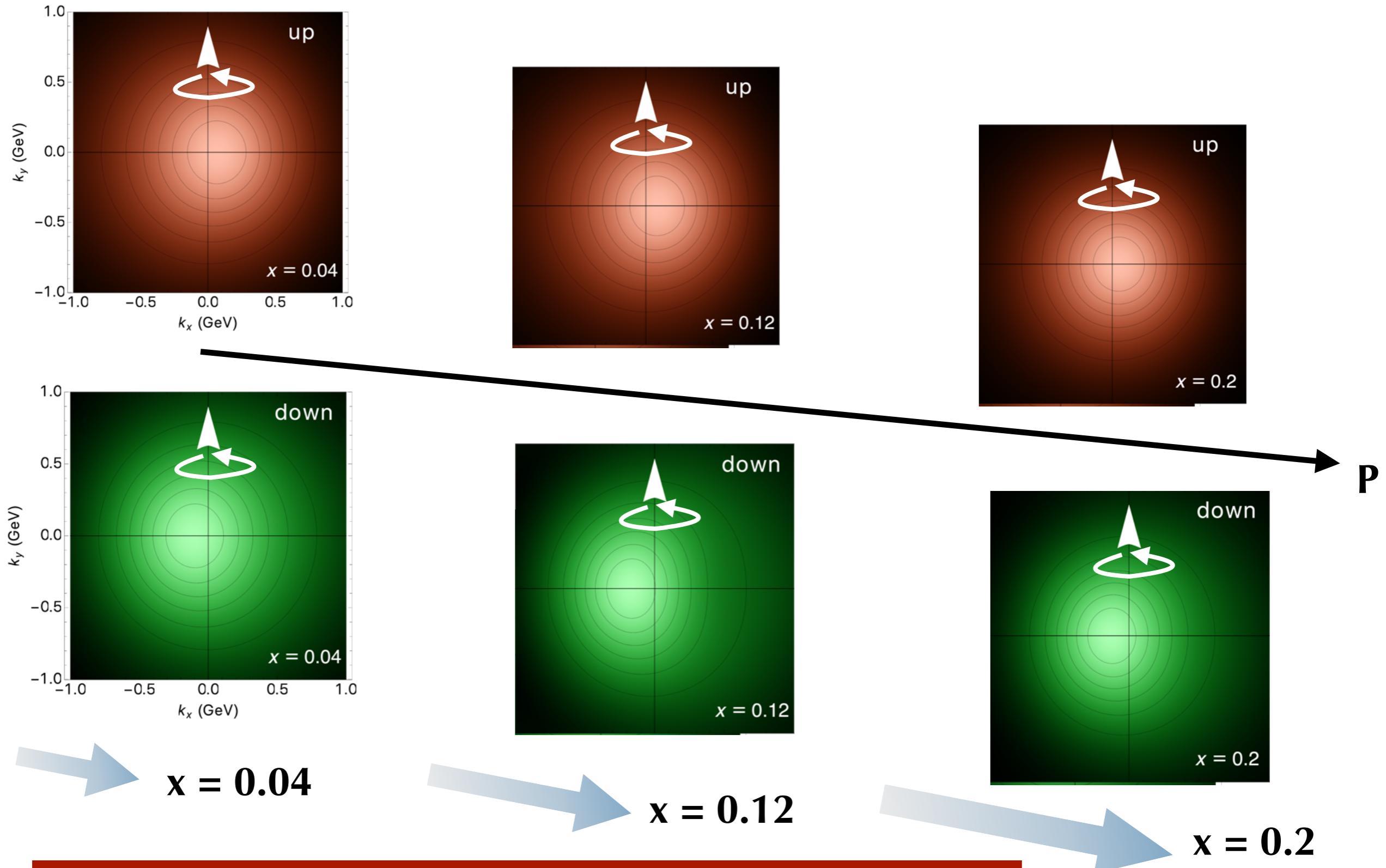
$$f_{q/p^\uparrow}(x, \mathbf{k}_T) = f_1^q(x, \mathbf{k}_T^2)$$

$$f_{q/p^\uparrow}(x, \mathbf{k}_T) = f_1^q(x, \mathbf{k}_T^2)$$

$$- f_{1T}^{\perp q}(x, \mathbf{k}_T^2) \mathbf{S} \cdot \left(\frac{\hat{\mathbf{P}}}{M} \times \mathbf{k}_T \right)$$

(distorted) plots entirely based on real data !

tomography of transversely polarized proton

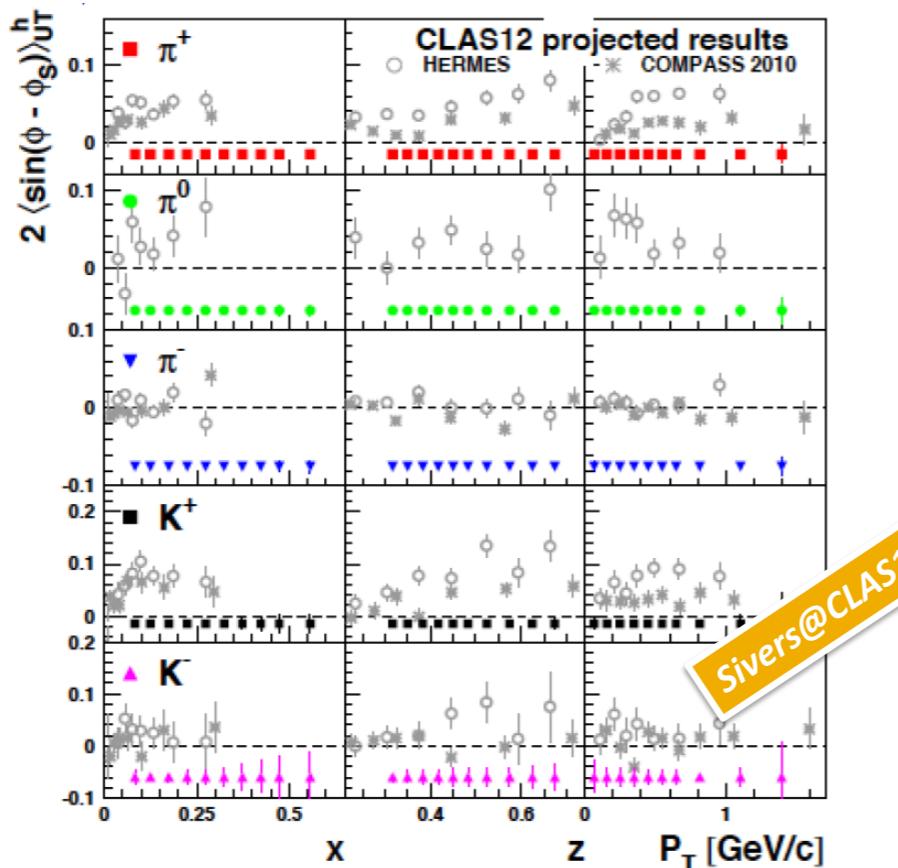


(distorted) plots entirely based on real data !

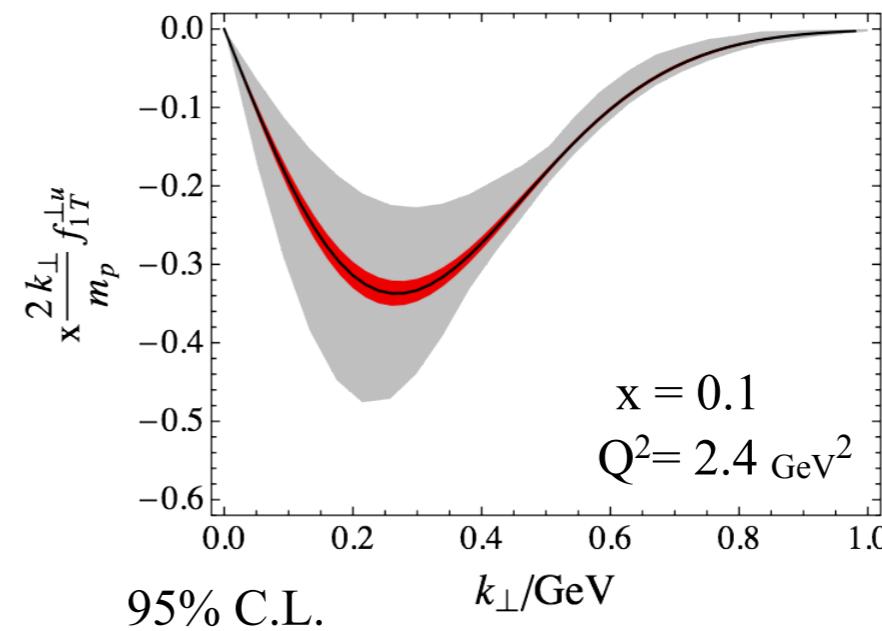
The Future

Mid-Term
JLab12

Hall B clas



Hall A SoLID

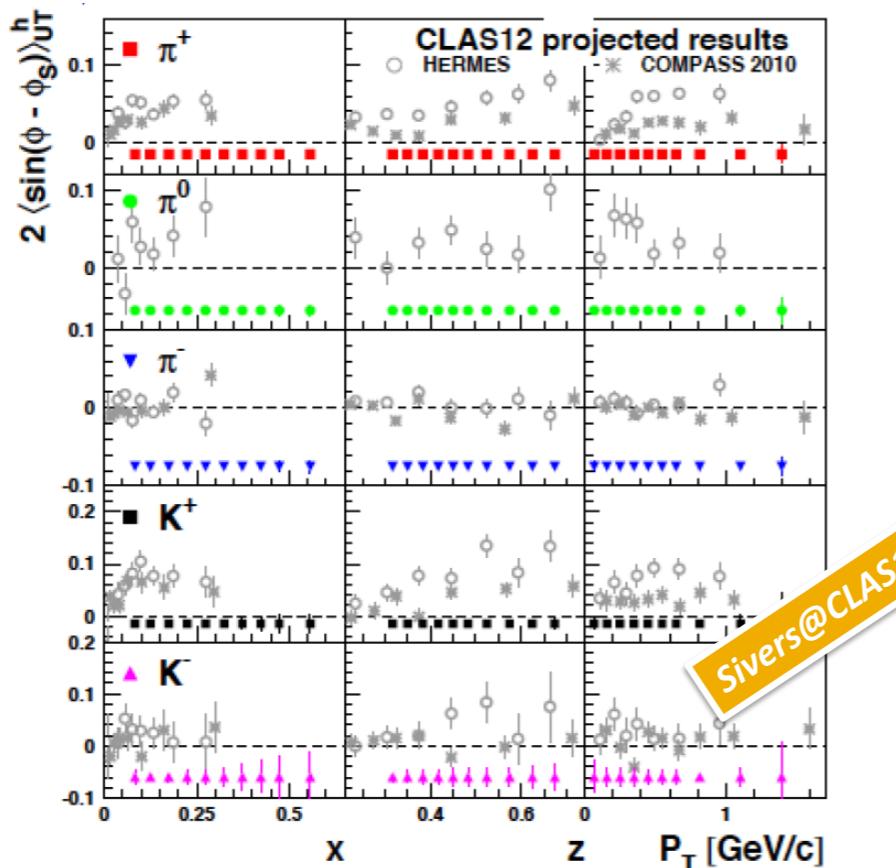


projection with ${}^3\text{He}^\uparrow$ and p^\uparrow data
Anselmino et al., E.P.J. A39 (09)

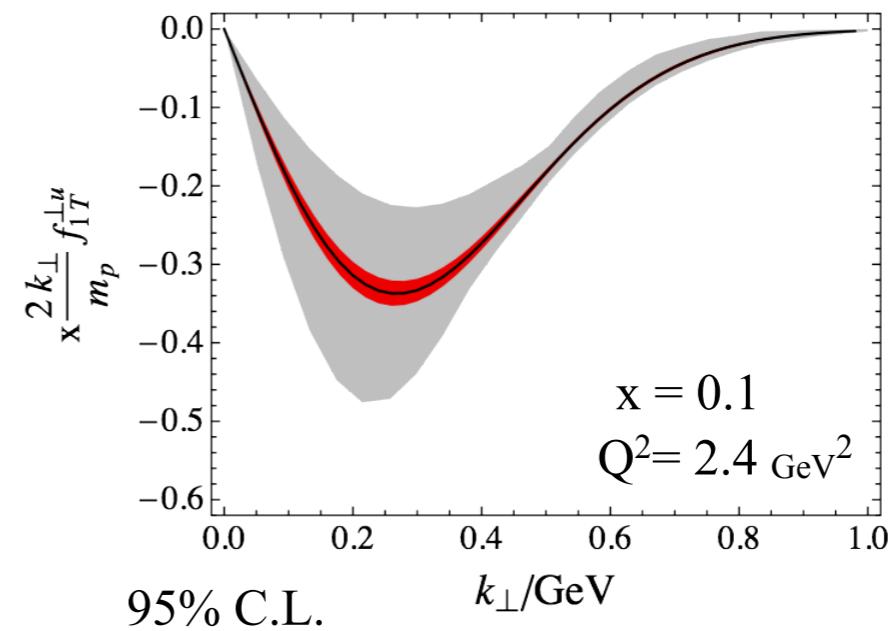
The Future

Mid-Term
JLab12

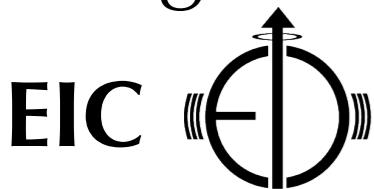
Hall B clas



Hall A SoLID

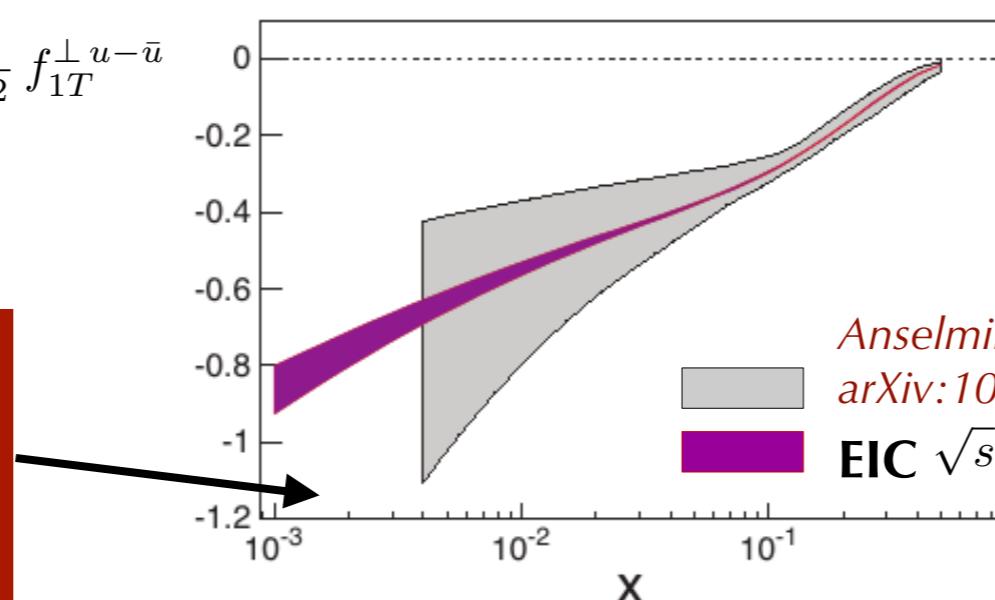


Long-Term



extend range in x
explore Sivers effect
for sea quarks

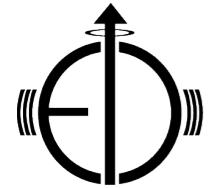
$$\int dk_\perp^2 \frac{k_\perp^2}{2M^2} f_{1T}^{\perp u-\bar{u}}$$



Accardi et al.,
E.P.J. A52 (16) 268
arXiv:1212.1701

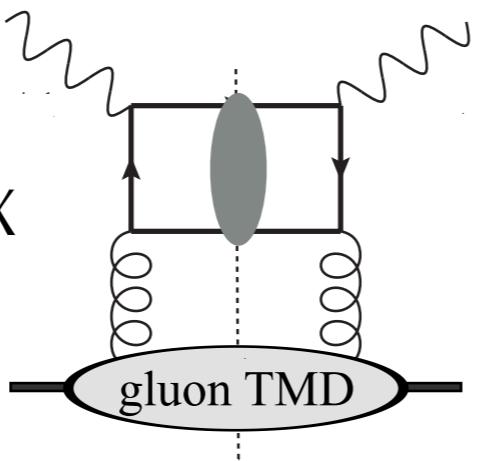
The Future

gluon Sivers function basically unknown!



explore:

$$e \ p^\uparrow \rightarrow e + J/\psi + X$$



Godbole et al.,
arXiv:1201.1066

Mukherjee & Rajesh,
arXiv:1609.05596

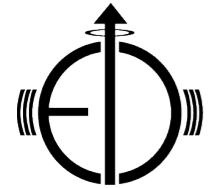
Bacchetta et al.,
arXiv:1809.02056

Boer et al.,
arXiv:1605.07934

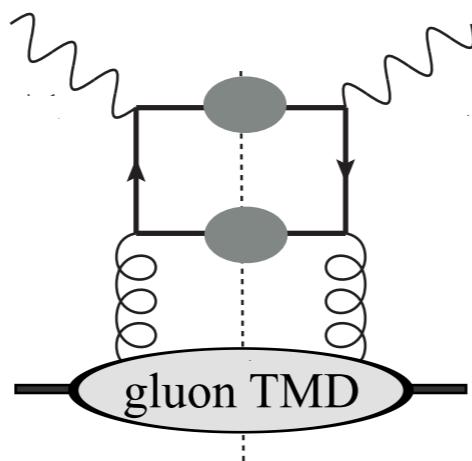
Rajesh et al.,
arXiv:1802.10359

The Future

gluon Sivers function basically unknown!



explore:



$$e p^\uparrow \rightarrow e + h_1 + h_2 + X$$

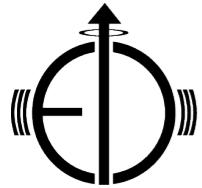
$$e p^\uparrow \rightarrow e + \text{jet} + \text{jet} + X$$

*Zheng et al.,
arXiv:1805.05290*

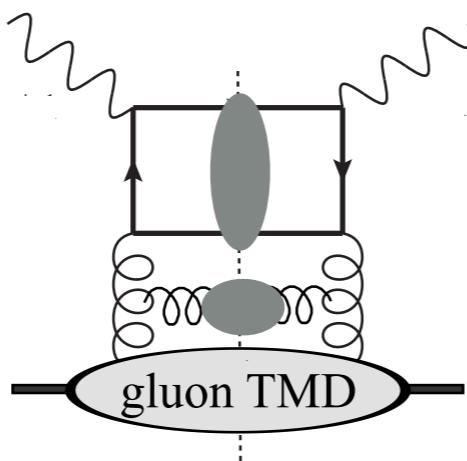
*Boer et al.,
arXiv:1605.07934*

The Future

gluon Sivers function basically unknown!



explore:



$$e p^\uparrow \rightarrow e + J/\psi + \text{jet} + X$$

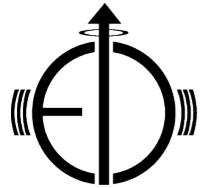
*D'Alesio et al.,
arXiv:1908.00446*

.....

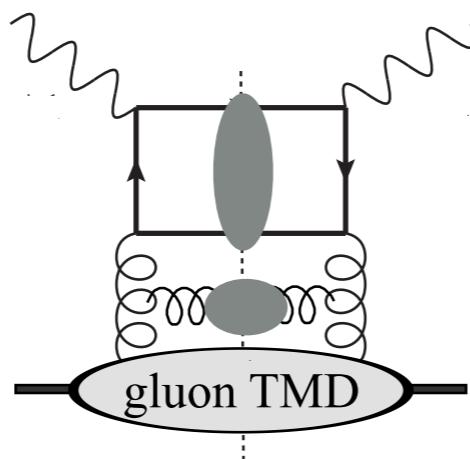
see also
next talk

The Future

gluon Sivers function basically unknown!



explore:



$$e p^\uparrow \rightarrow e + J/\psi + \text{jet} + X$$

D'Alesio et al.,
arXiv:1908.00446

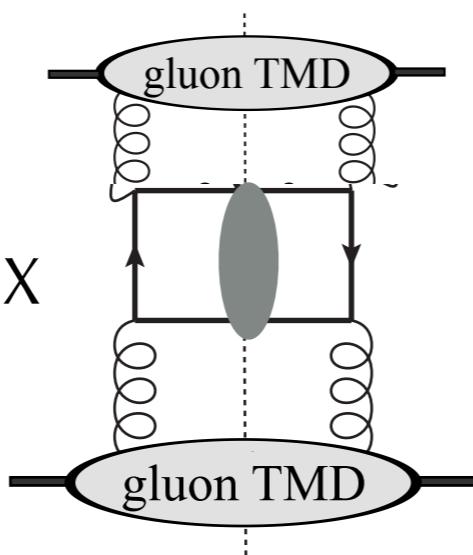
.....

see also
next talk

RHIC & LHC

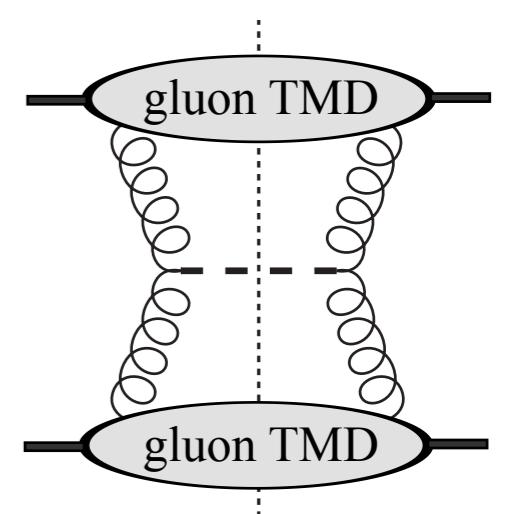
see also:

$$p^\uparrow p \rightarrow J/\psi + X$$



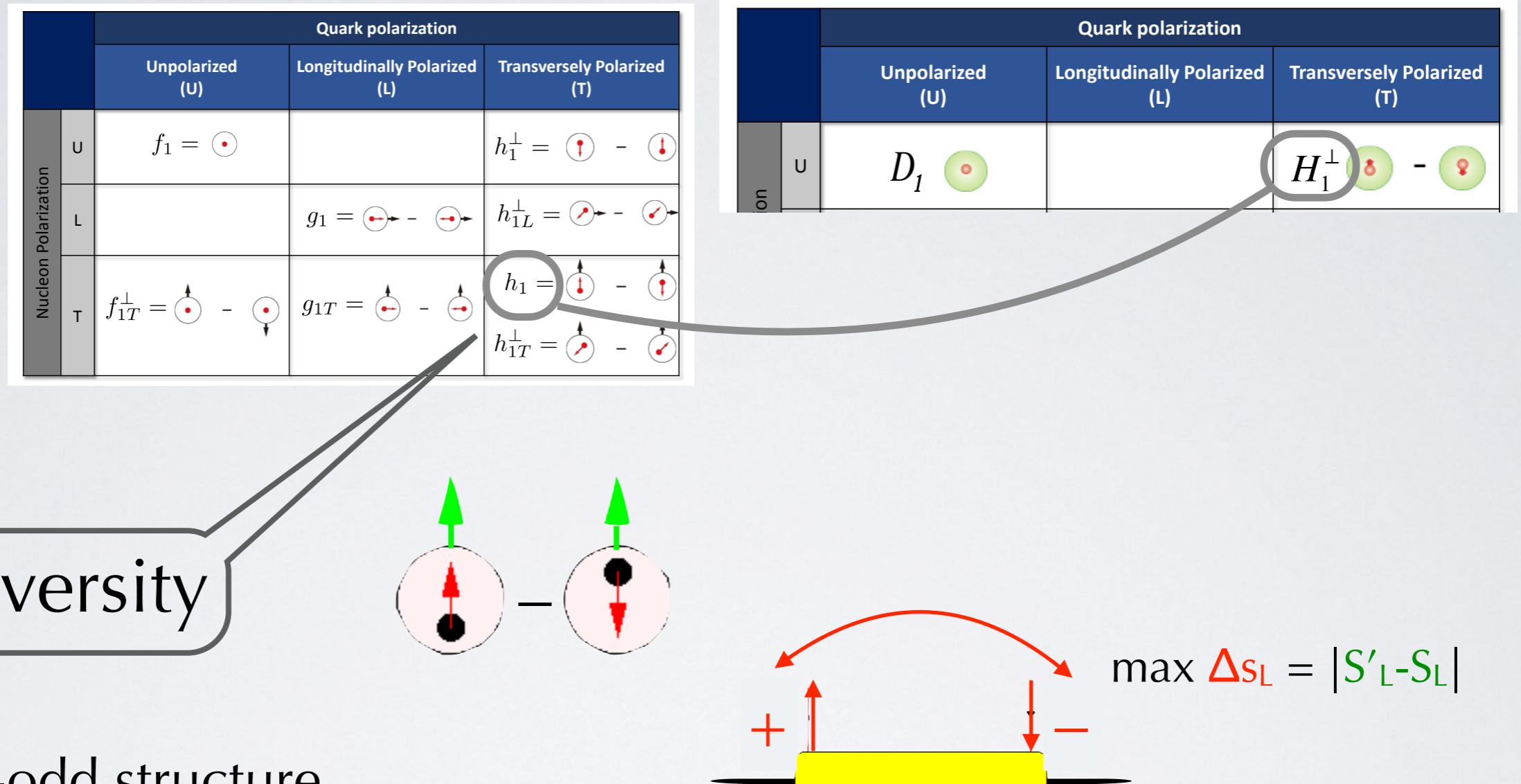
Godbole et al.,
arXiv:1703.01991

$$p^\uparrow p \rightarrow D + X$$



D'Alesio et al.,
arXiv:1705.04169
arXiv:1910.09640

Transversity and the Collins effect



- chiral-odd structure in spin-1/2 hadron no gluon transversity → h_1 is a non-singlet object
- related to tensor operator $\bar{q} \sigma^{\mu\nu} q$ not included in \mathcal{L}_{SM} (at tree level)
→ low-energy footprint of BSM physics at higher scale ?

Examples of BSM connections

- **neutron EDM:** estimate CPV induced by quark chromo-EDM d_q

$$\mathcal{L}_{\text{CPV}} \supset ie \sum_{f=u,d,s,e} d_f \bar{f} \sigma_{\mu\nu} \gamma_5 f F^{\mu\nu} \quad F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

$$d_n = \delta u d_u + \delta d d_d + \delta s d_s$$

exp. bounds

+ **tensor charge**

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

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constraints on CPV q EDM

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- **nuclear β -decay:** effective field theory including, e.g., tensor operator

hadron level : $n \rightarrow p e^- \bar{\nu}_e$

$$C_T \bar{p} \sigma^{\mu\nu} n \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_e$$

exp. data

C_T

$$g_T = \delta u - \delta d$$

quark level : $d \rightarrow u e^- \nu_e$

$$\langle p | \bar{u} \sigma^{\mu\nu} d | n \rangle \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_e$$

$\leftrightarrow g_T \epsilon_T$

exp. bounds

+ isovector tensor
charge

Examples of BSM connections

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exp. bounds

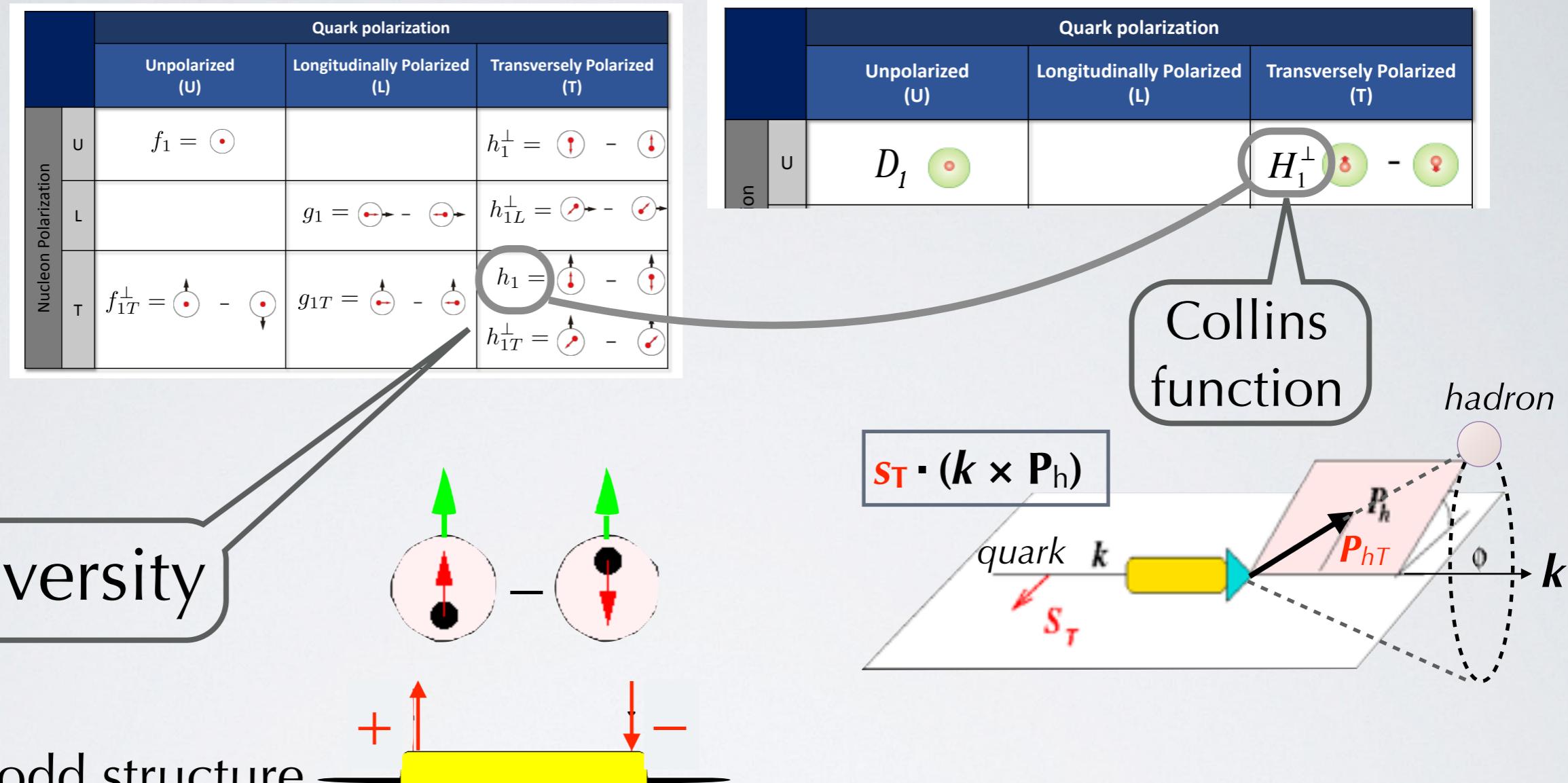
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charge

quark level : $d \rightarrow u e^- \nu_e$

$$\langle p | \bar{u} \sigma^{\mu\nu} d | n \rangle \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_e$$

constraints on unknown ϵ_T

Transversity and the Collins effect



- related to tensor operator $\bar{q} \sigma^{\mu\nu} q$ not included in \mathcal{L}_{SM} (at tree level)
 → low-energy footprint of BSM physics at higher scale ?

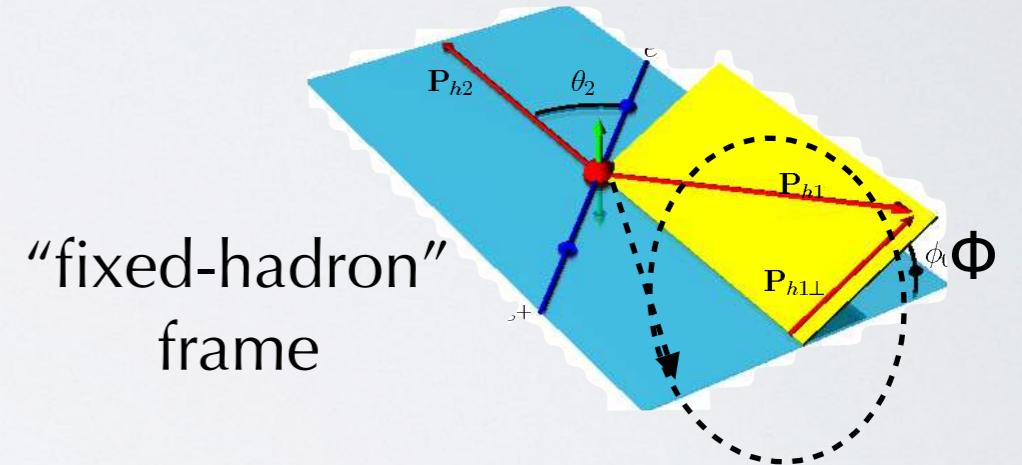
Transversity and the Collins effect

combined fit of azimuthal asymmetries in
SIDIS

$$A_T^{\sin(\phi_h + \phi_S)} \propto \frac{h_1 \otimes H_1^\perp}{f_1 \otimes D_1}$$
$$A_0^{\cos 2\phi} \propto \frac{H_1^\perp \otimes \bar{H}_1^\perp}{D_1 \otimes \bar{D}_1}$$

e⁺e⁻





alternative requires defining thrust axis, which poses problems with TMD factorization th.

Transversity and the Collins effect

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e⁺e⁻ exp. data (for ππ pairs)



*Abe et al., P.R.L. **96** (06) 232002*
*Seidl et al., P.R. **D78** (08) 032011*
***D86** (12) 039905(E)*

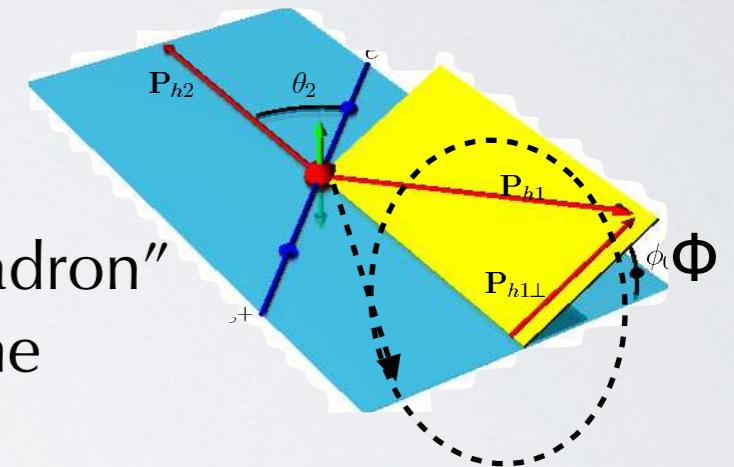
$\sqrt{s} = 10.58$ GeV



*Lees et al., P.R. **D90** (14) 052003*
*Lees et al., P.R. **D92** (15) 111101*

includes also \mathbf{P}_{hT1} & \mathbf{P}_{hT2} dependence and Kaons

“fixed-hadron”
frame



alternative requires defining thrust axis, which poses problems with TMD factorization th.

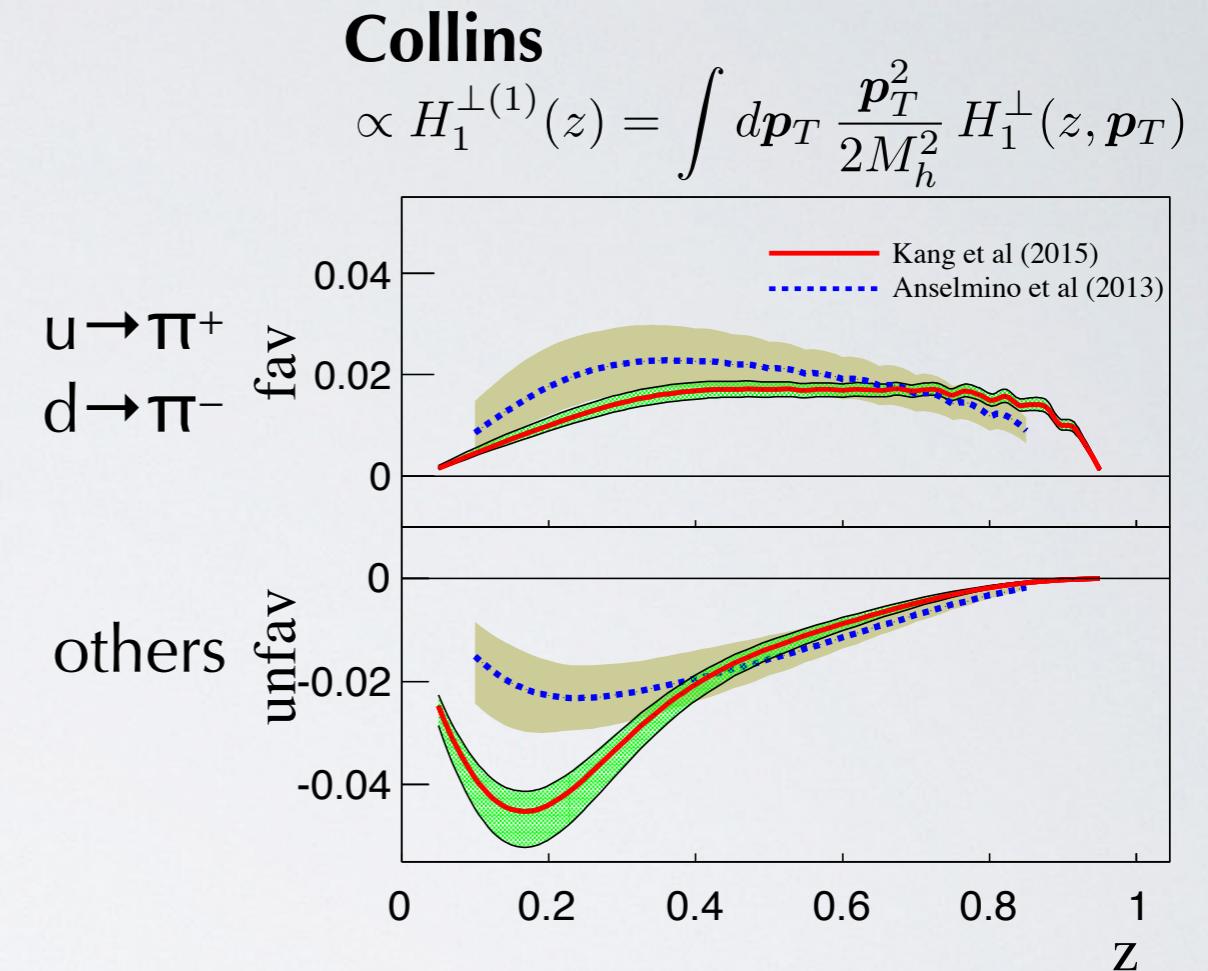
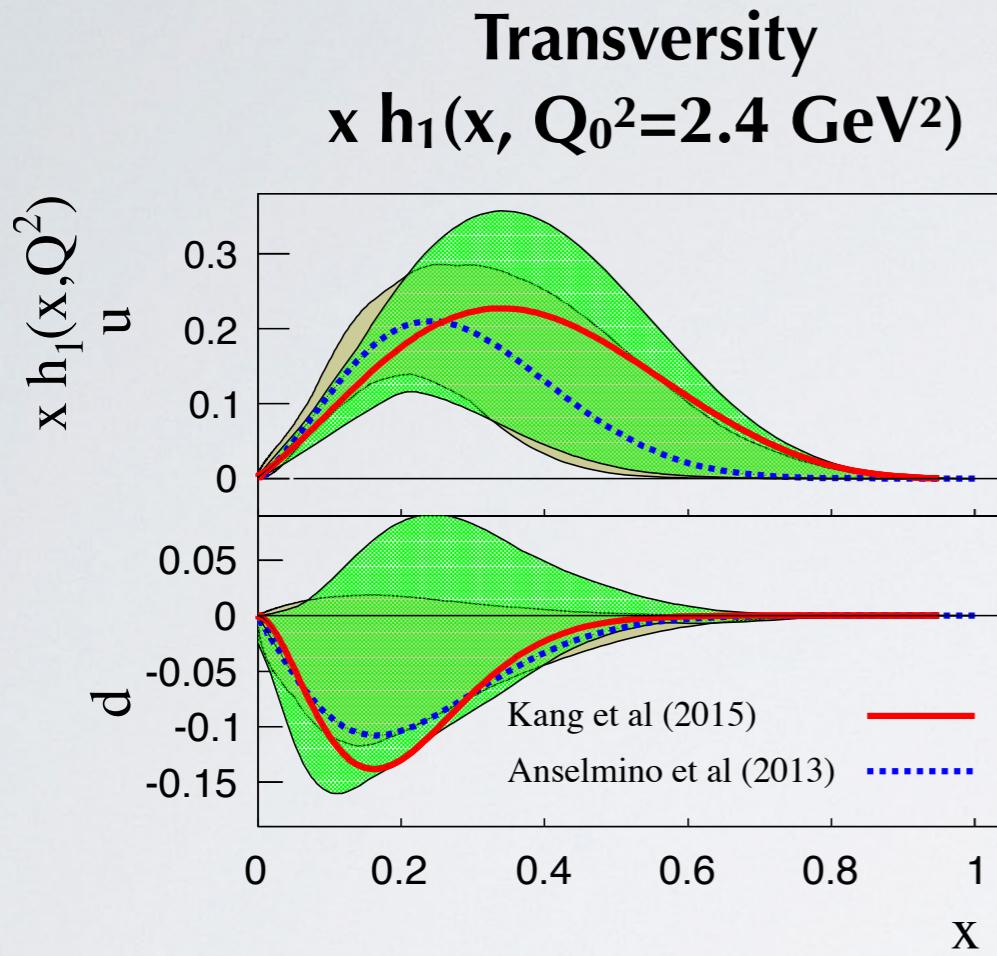


$\sqrt{s} = 3.60$ GeV *Ablikim et al., P.R.L. **116** (16) 042001*



predicted, not fitted

Transversity and the Collins function



Kang et al., P.R. D93 (16) 014009

Anselmino et al., P.R. D87 (13) 094019

Anselmino et al., P.R. D92 (15) 114023

TMD framework with proper evolution equations

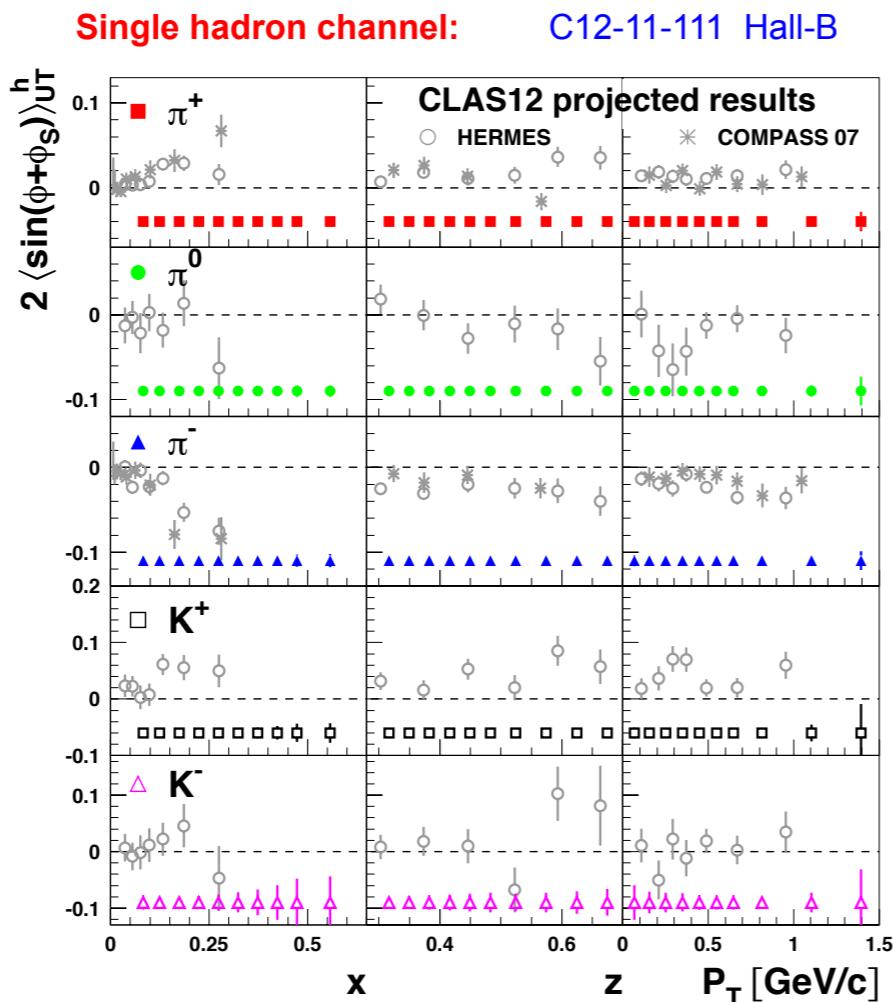
Generalized Parton Model (GPM) with no evolution for k_T dependence

update that smoothes differences in Collins funct.

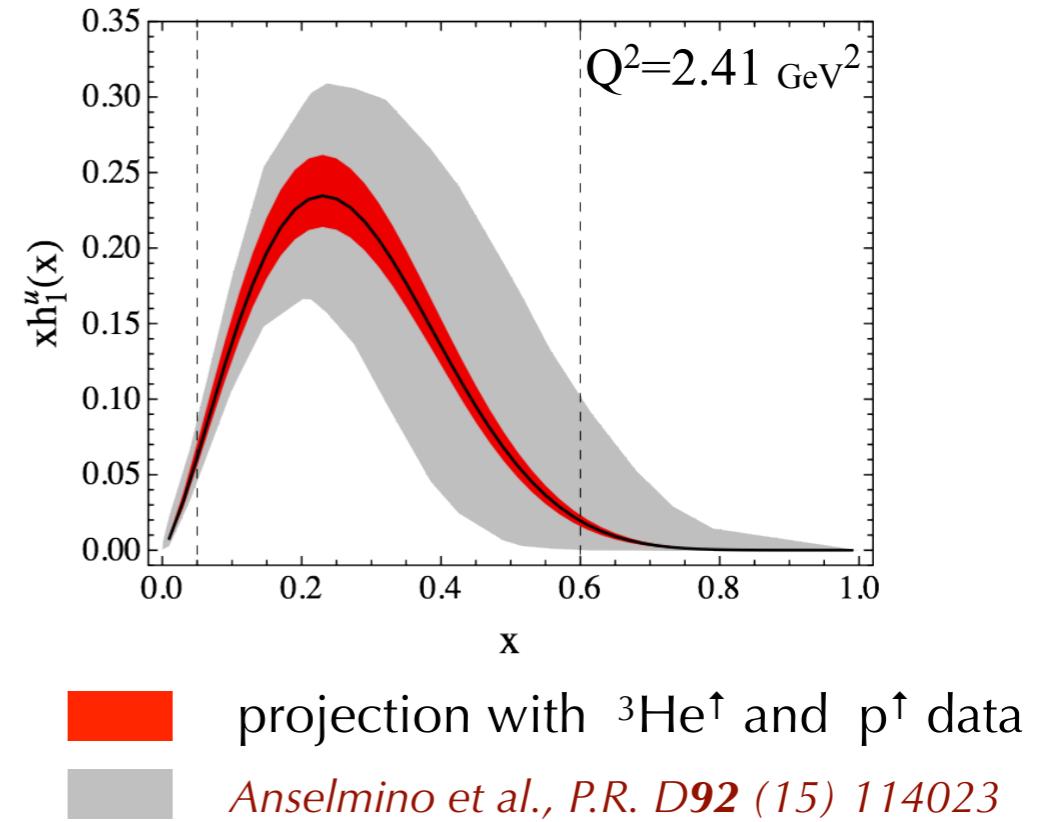
The Future

Mid-Term
JLab12

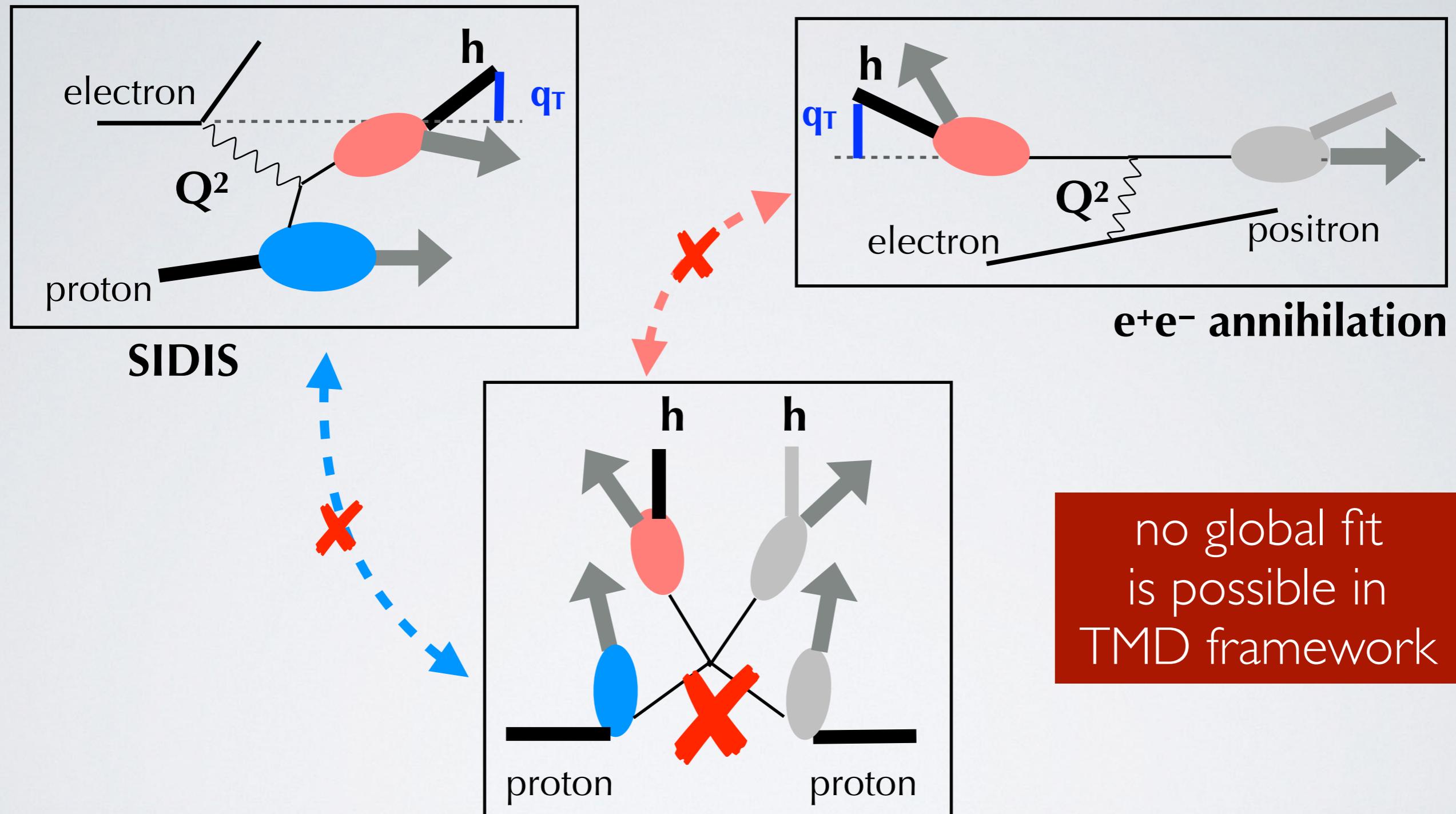
Hall B clas



Hall A SoLID



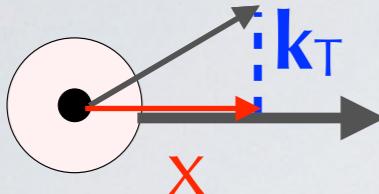
TMD factorization breaking



Factorization breaking in
 $p+p \rightarrow \text{hadrons}$; is it large?

Rogers & Mulders, *P.R. D81* (10)
Buffing, Kang, Lee, Liu, arXiv:1812.07549

Transv.-Mom. Dependent Parton Distributions



TMD PDFs ($x, k_T^2; Q$) at leading twist

quark



nucleon

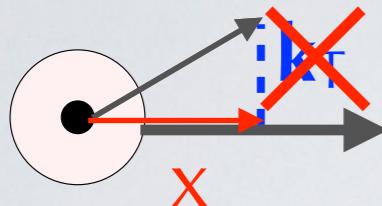


		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$	*	$h_1^\perp = \odot \downarrow - \odot \uparrow$
	L	*	$g_1 = \odot \rightarrow - \odot \rightarrow$	$h_{1L}^\perp = \odot \rightarrow \downarrow - \odot \rightarrow \uparrow$
	T	$f_{1T}^\perp = \odot \uparrow - \odot \downarrow$	$g_{1T} = \odot \uparrow - \odot \downarrow$	$h_1 = \odot \uparrow \downarrow - \odot \downarrow \uparrow$ $h_{1T}^\perp = \odot \uparrow \downarrow - \odot \downarrow \uparrow$

* forbidden by parity invariance

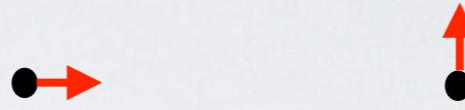
Mulders & Tangerman,
N.P. **B461** (96)
Boer & Mulders,
P.R. **D57** (98)
Bacchetta et al.,
JHEP **02** (07) 093

~~Transv.-Mom. Dependent~~ Parton Distributions

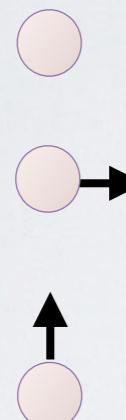


~~TMD~~ PDFs ($x, k_T^2; Q$) at leading twist

quark •

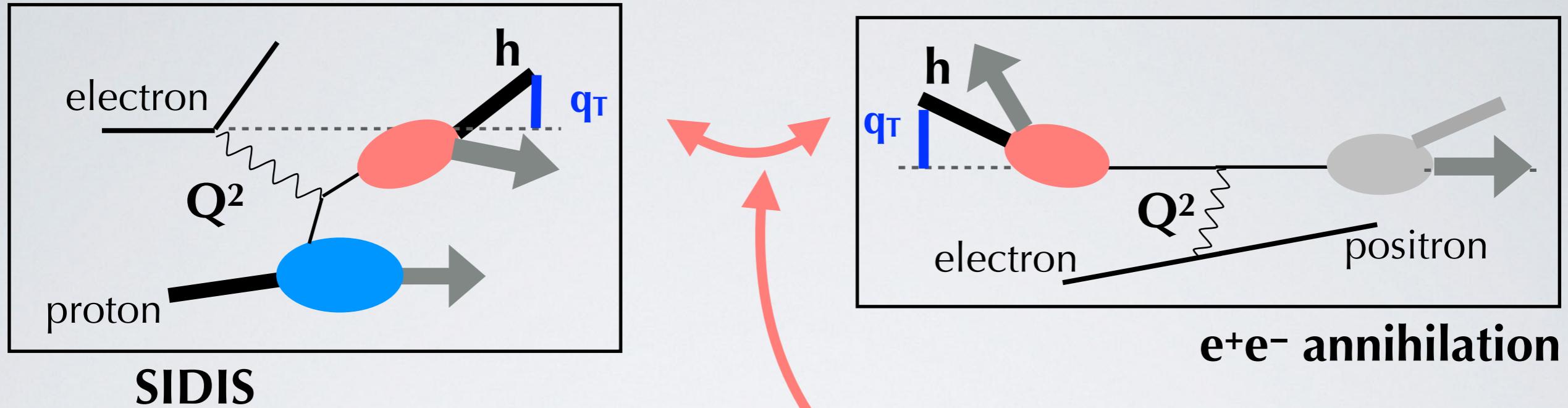


nucleon



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		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		
	L		$g_1 = \odot \rightarrow - \odot \rightarrow$	
	T			$h_1 = \odot \uparrow - \odot \uparrow$

Alternative : hadron-in-jet framework



hybrid scheme:

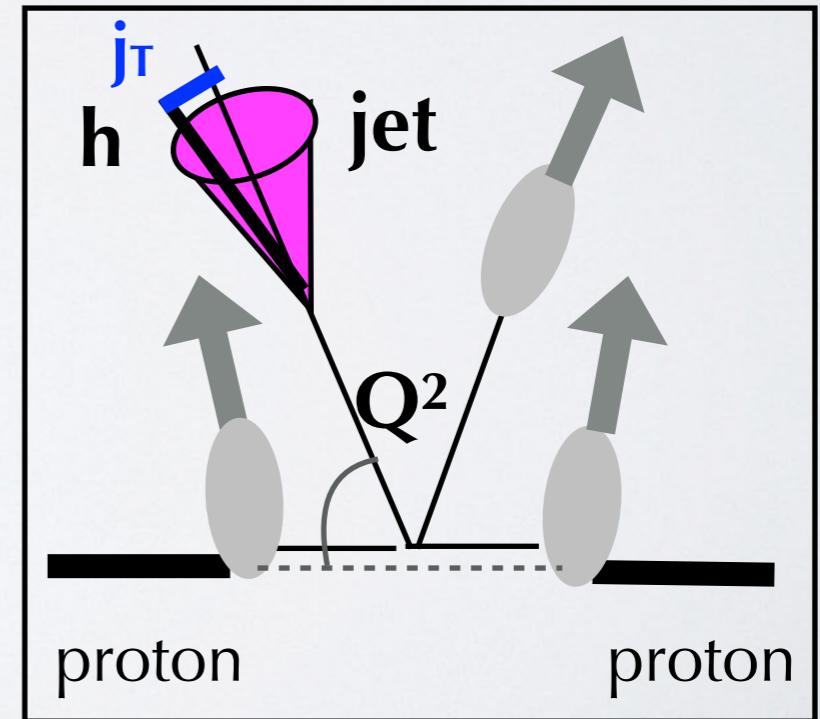
- TMD framework for TMD **fragmentation**
- collinear framework for PDF

Factorization theorem for $j_T \ll Q$
universality for TMD fragmentation

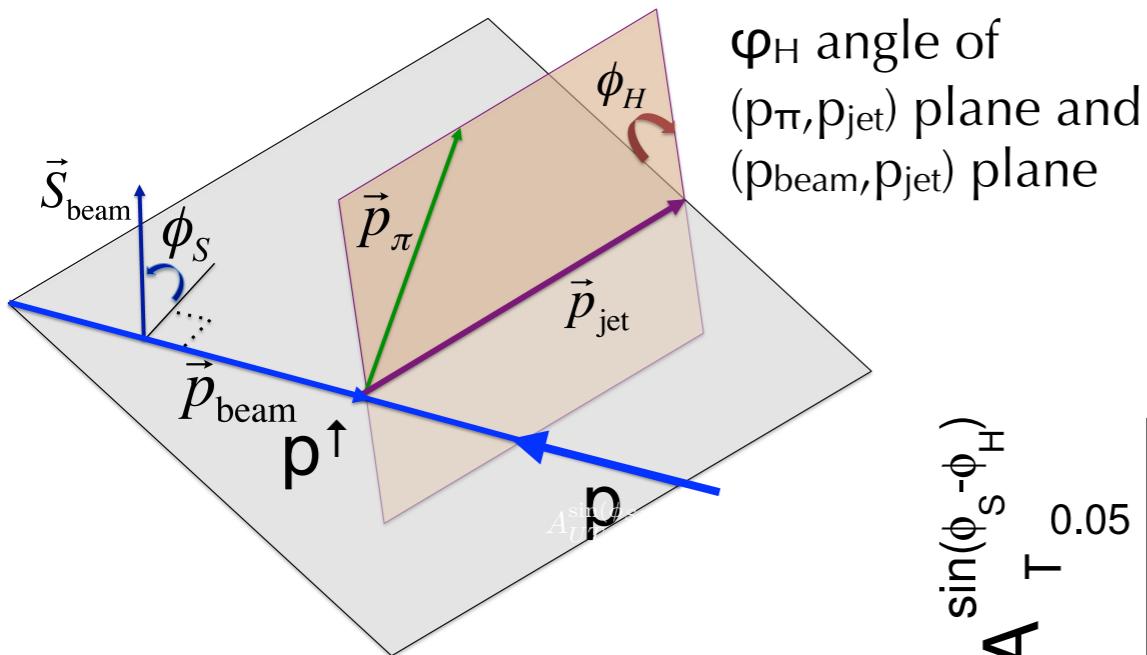
Kang, Liu, Ringer, Xing, *JHEP* **1711** (17), arXiv:1705.08443

Kang, Prokudin, Ringer, Yuan, *P.L.* **B774** (17), arXiv:1707.00913

see Felix Ringer's talks

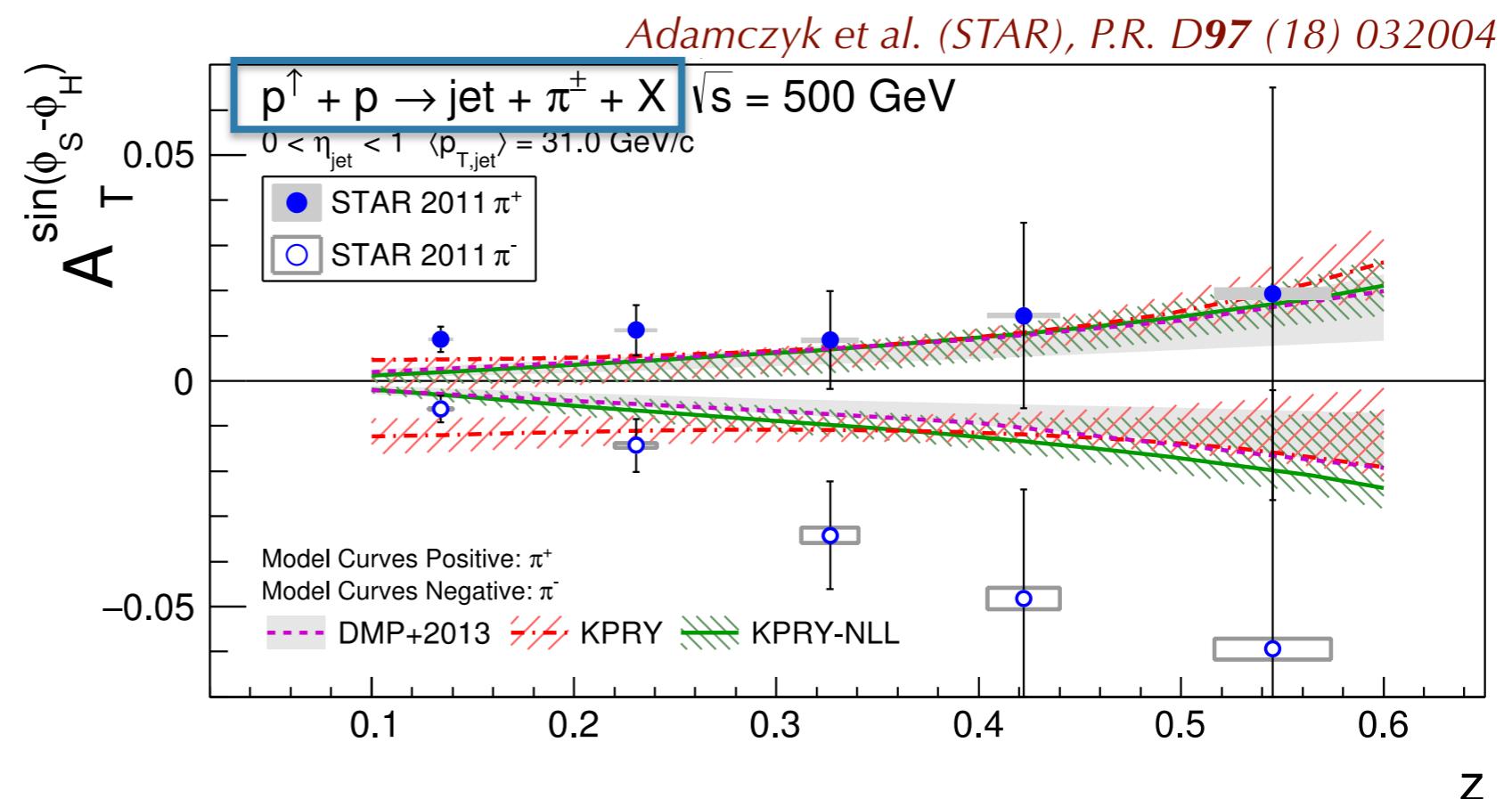


Collins effect for hadron-in-jet



PDF & TMDFF from SIDIS + e^+e^- analysis

$$A_T^{\sin(\phi_S - \phi_H)} \propto \frac{h_1^q \otimes f_1^{\bar{q}} \otimes H_1^{\perp q}}{f_1^q \otimes f_1^{\bar{q}} \otimes D_1^q}$$



--- DMP+2013 (no evolution)

Anselmino et al., P.R. D87 (13) 094019

D'Alesio et al., P.L. B773 (17) 300

// KPRY (no evolution)

// KPRY-NLL (TMD evolution)

Kang et al., P.L. B774 (17) 635

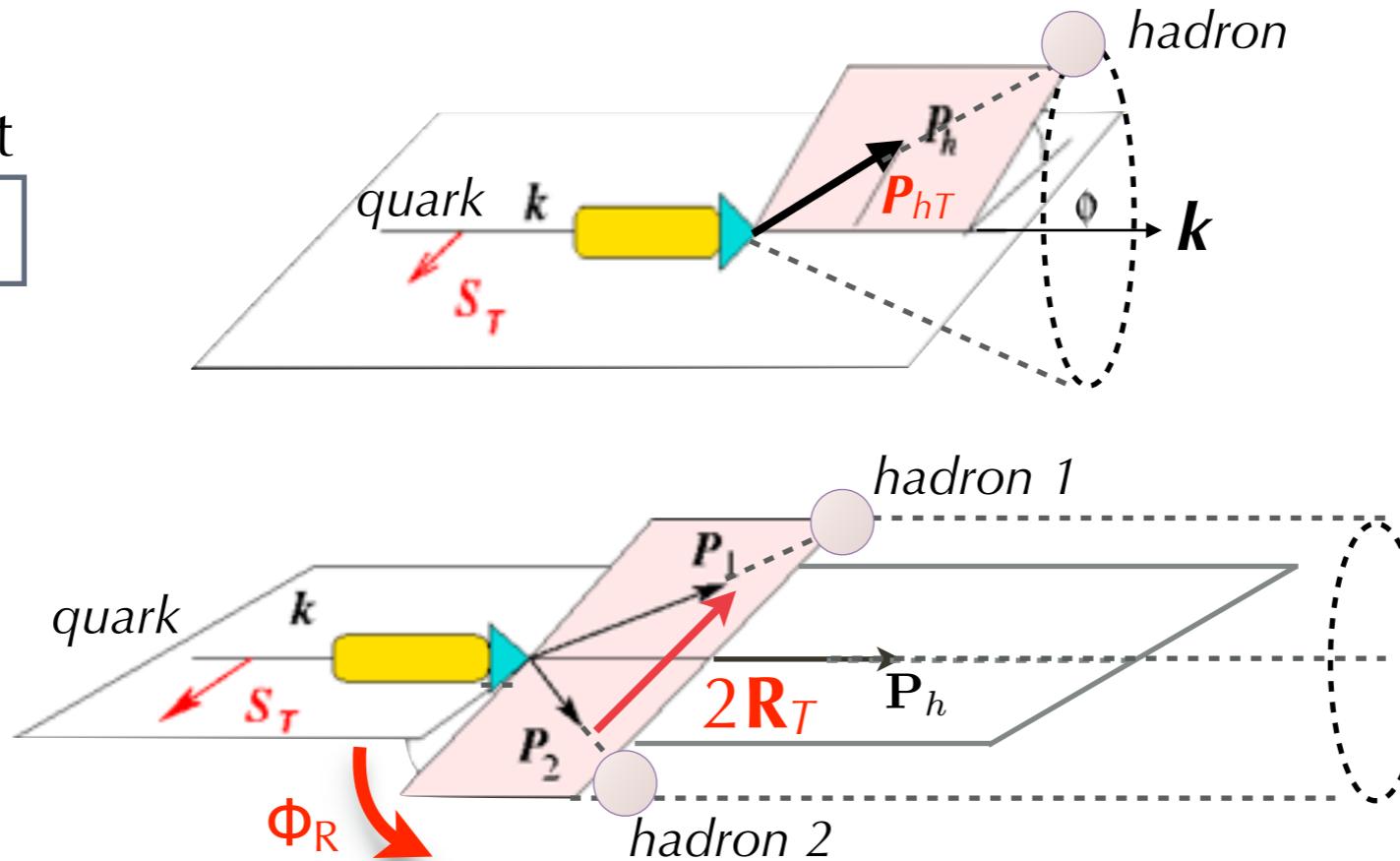
Alternative : the di-hadron mechanism

Collins effect

$$\mathbf{s}_T \cdot (\mathbf{k} \times \mathbf{P}_h)$$

di-hadron
mechanism

$$\mathbf{s}_T \cdot (\mathbf{P}_2 \times \mathbf{P}_1)$$



$$\begin{aligned} P_h &= P_1 + P_2 \\ 2R &= P_1 - P_2 \end{aligned}$$

correlation \mathbf{s}_T and $\mathbf{R}_T \rightarrow$ azimuthal asymmetry in Φ_R

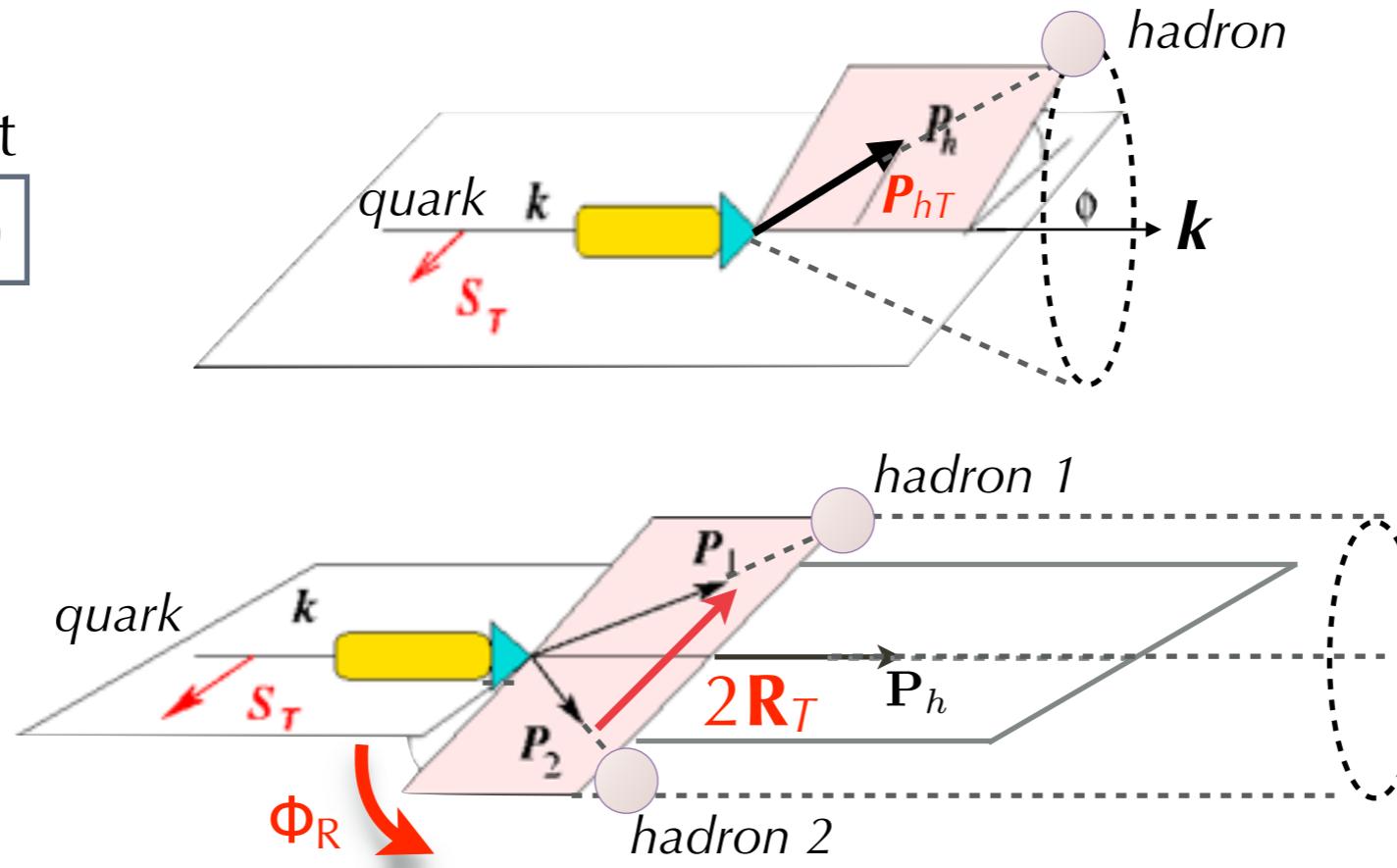
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correlation \mathbf{s}_T and $\mathbf{R}_T \rightarrow$ azimuthal asymmetry in Φ_R

survives to $\int d\mathbf{P}_{hT} \rightarrow \mathbf{P}_h \parallel \mathbf{k}$

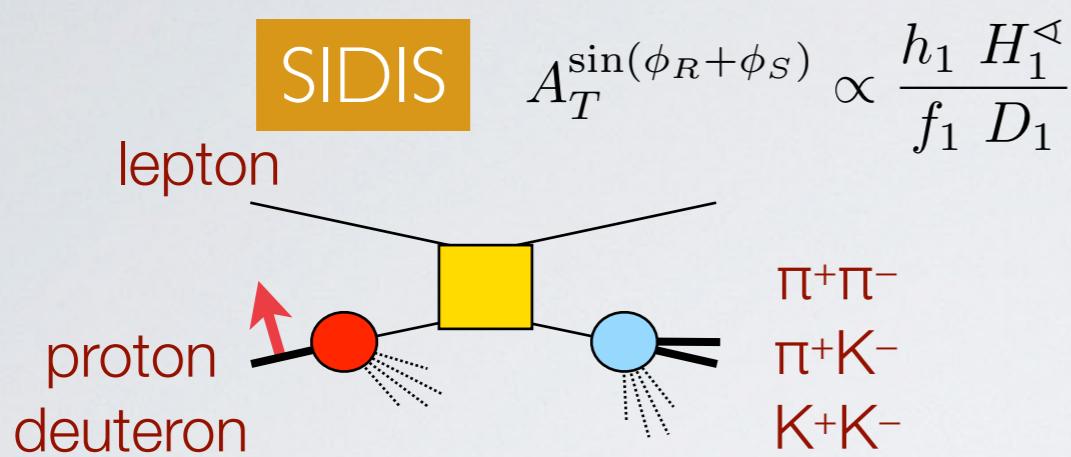
can be studied in collinear framework

if $R_T \ll Q$ correlation encoded in di-hadron FF (DiFF)

$$H_1^\leftarrow(z = z_1 + z_2, \mathbf{R}_T^2 \propto M_h^2; Q^2)$$

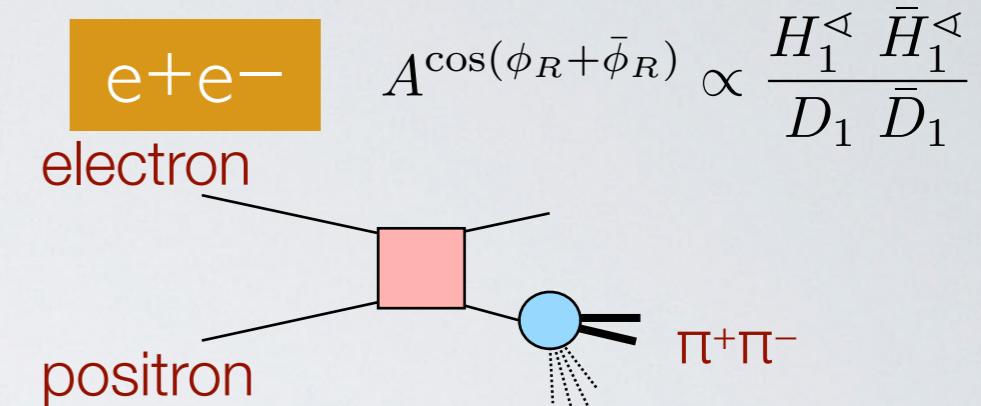
pair invariant mass

Global fit for di-hadron production

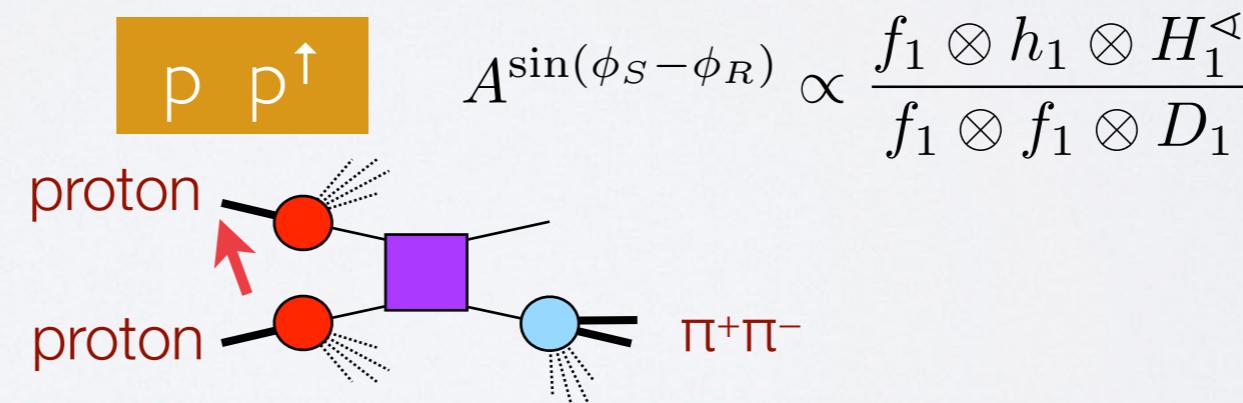


 *Airapetian et al., JHEP **0806** (08) 017*

 *Adolph et al., P.L. **B713** (12)*
*Braun et al., E.P.J. Web Conf. **85** (15) 02018*



*Vossen et al., P.R.L. **107** (11) 072004*
*Seidl et al., P.R. D**96** (17) 032005*



*Adamczyk et al. (STAR), P.R.L. **115** (2015) 242501*
*Adamczyk et al. (STAR), P.L. **B780** (18) 332*

Our global fit

*Radici and Bacchetta, P.R.L. **120** (18) 192001
arXiv:1802.05212*

SIDIS



18 data points



4 data points

pp collisions

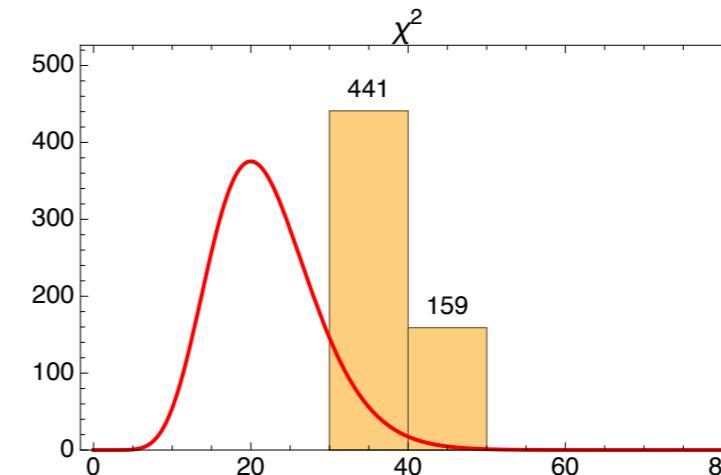


run 2006
($s=200 \text{ GeV}^2$)

10 independent data points

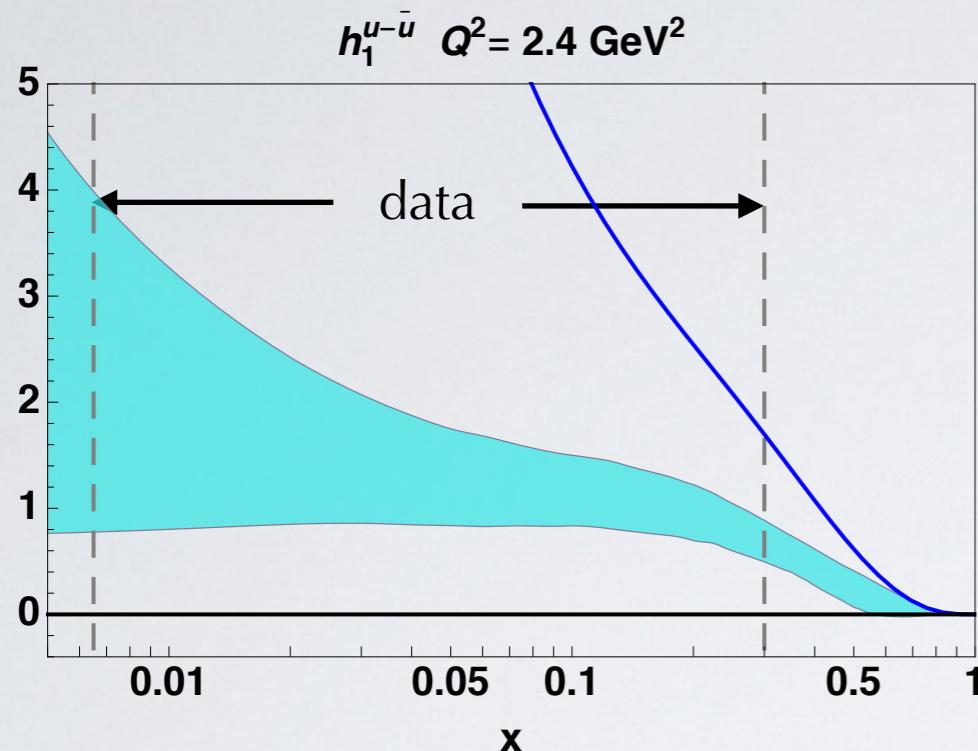
probability density function of
 χ^2 distribution for 22 d.o.f.

(for $\chi^2/\text{dof} = 1$ perfect overlap)

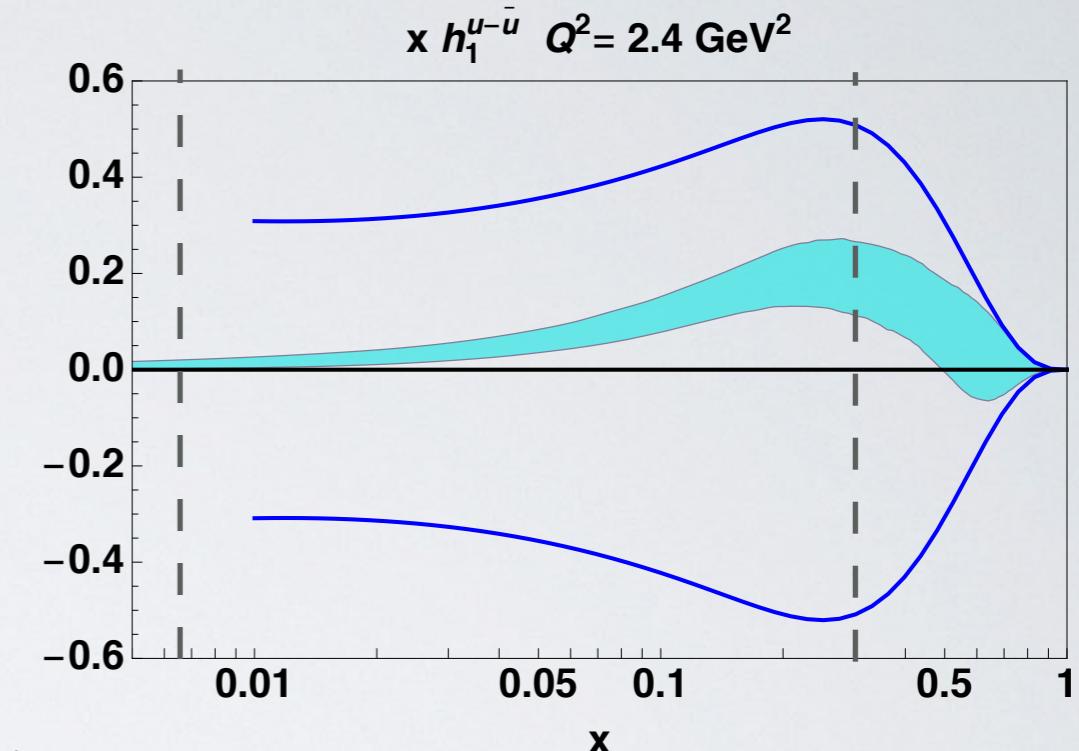


$$\chi^2/\text{dof} = 1.76 \pm 0.11$$

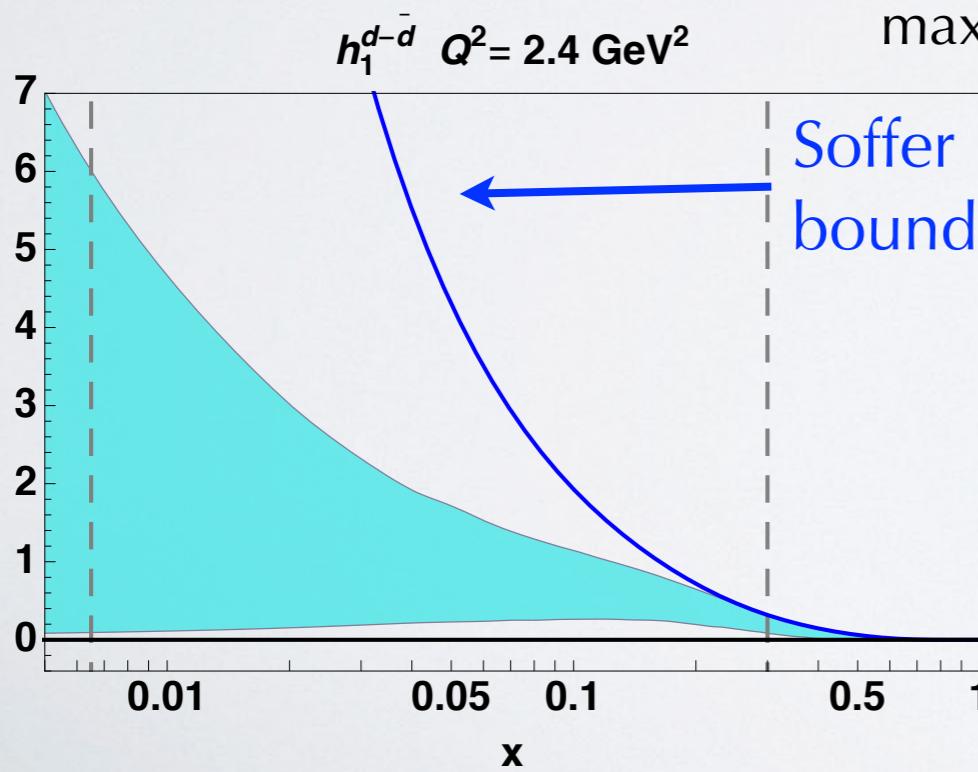
The transversity from first ever global fit



up

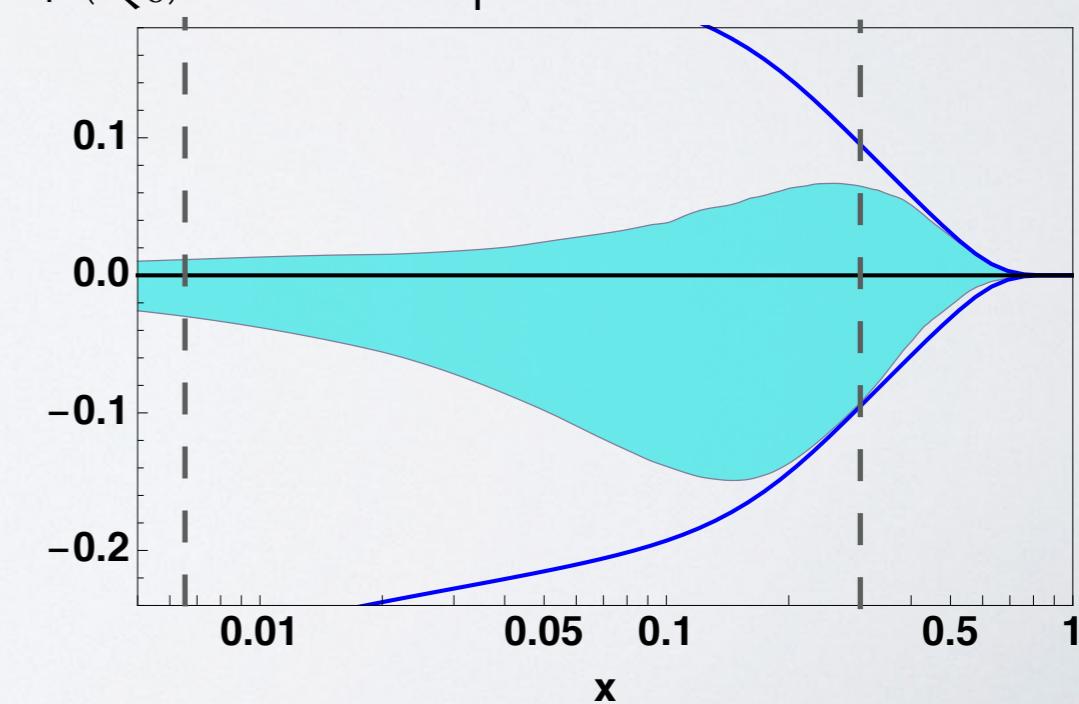


diverges less than $1/x$



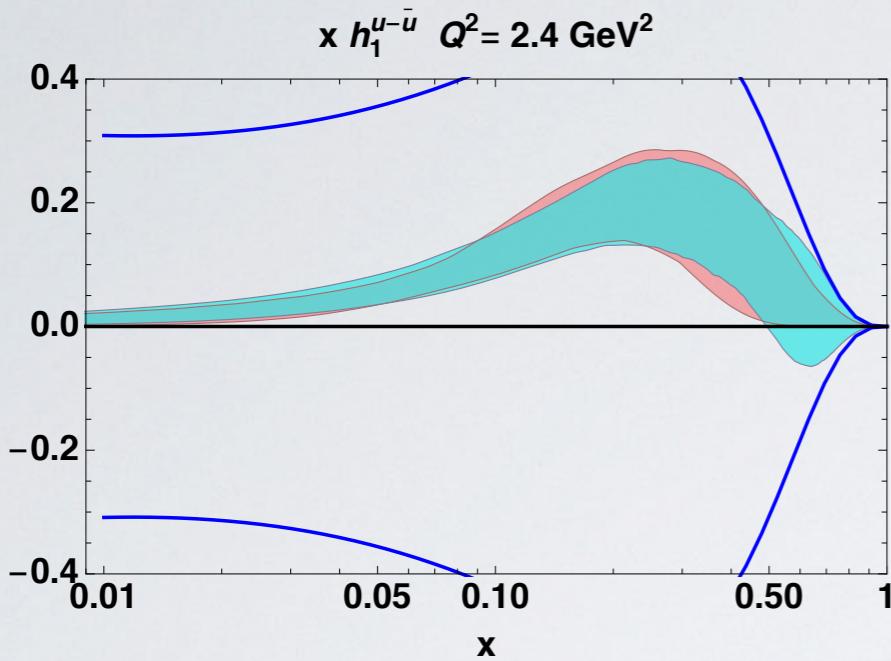
uncertainty band from
90% of 600 replicas =
max uncertainty on $D_{1g}(Q_0)$

down



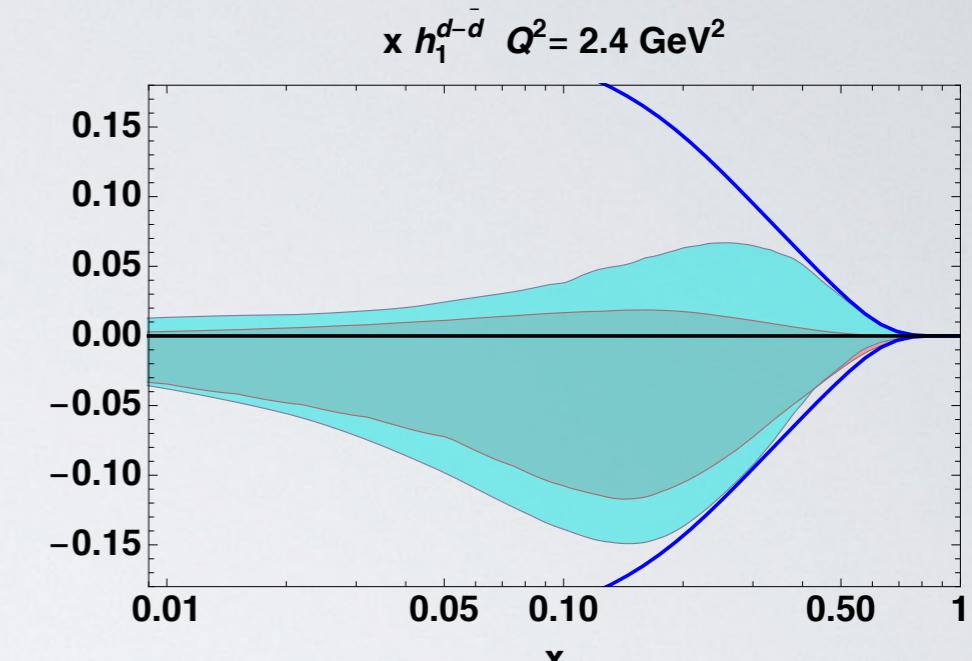
Comparison with other extractions

Collins effect,
only SIDIS data



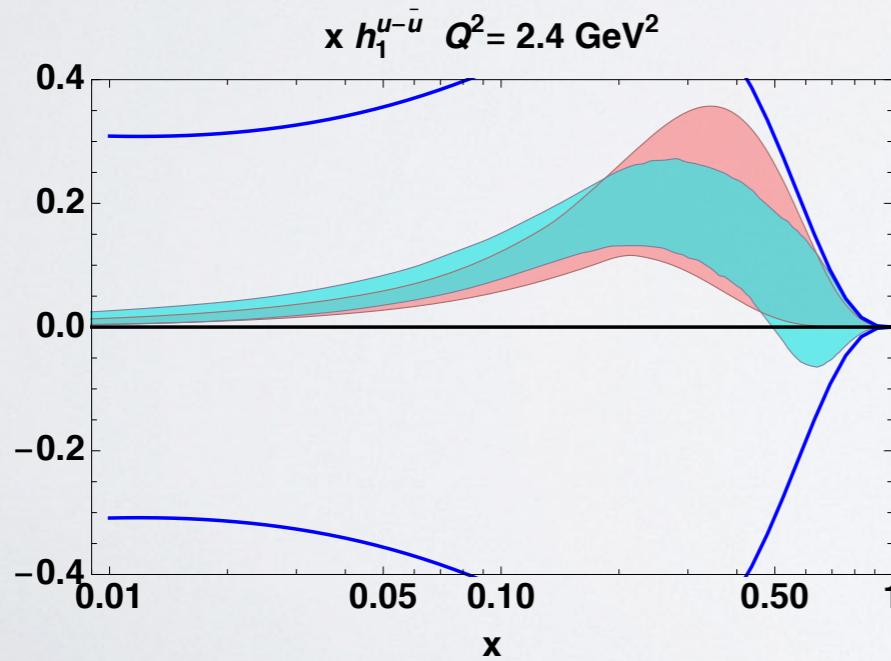
Anselmino et al.,
P.R. D87 (13) 094019

Torino

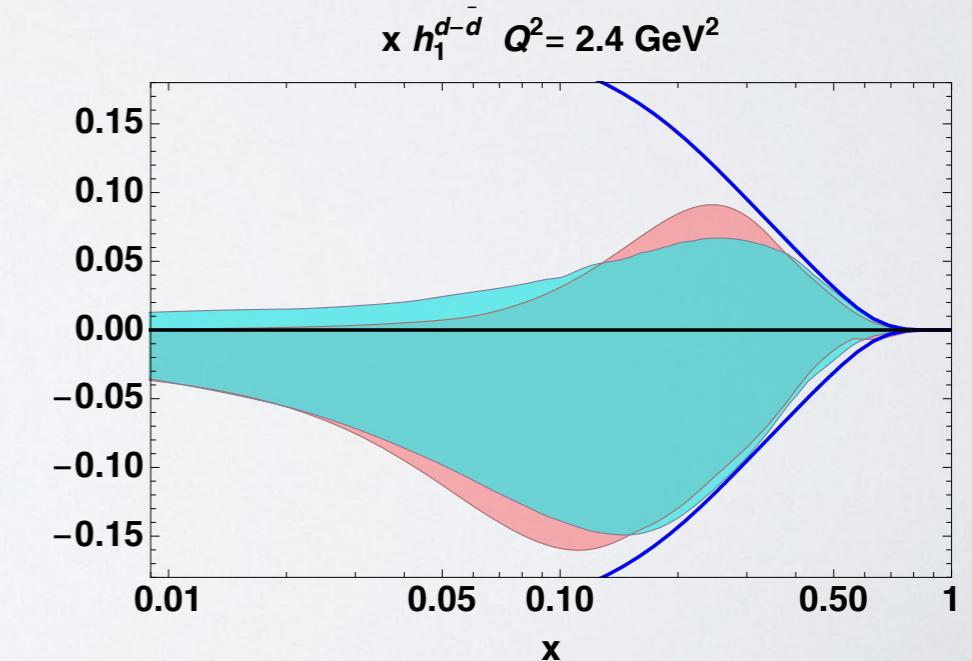


global fit

Radici and Bacchetta,
P.R.L. 120 (18) 192001

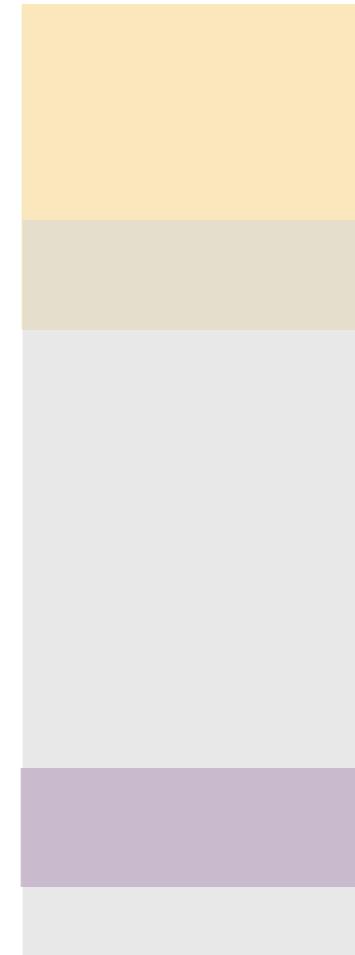
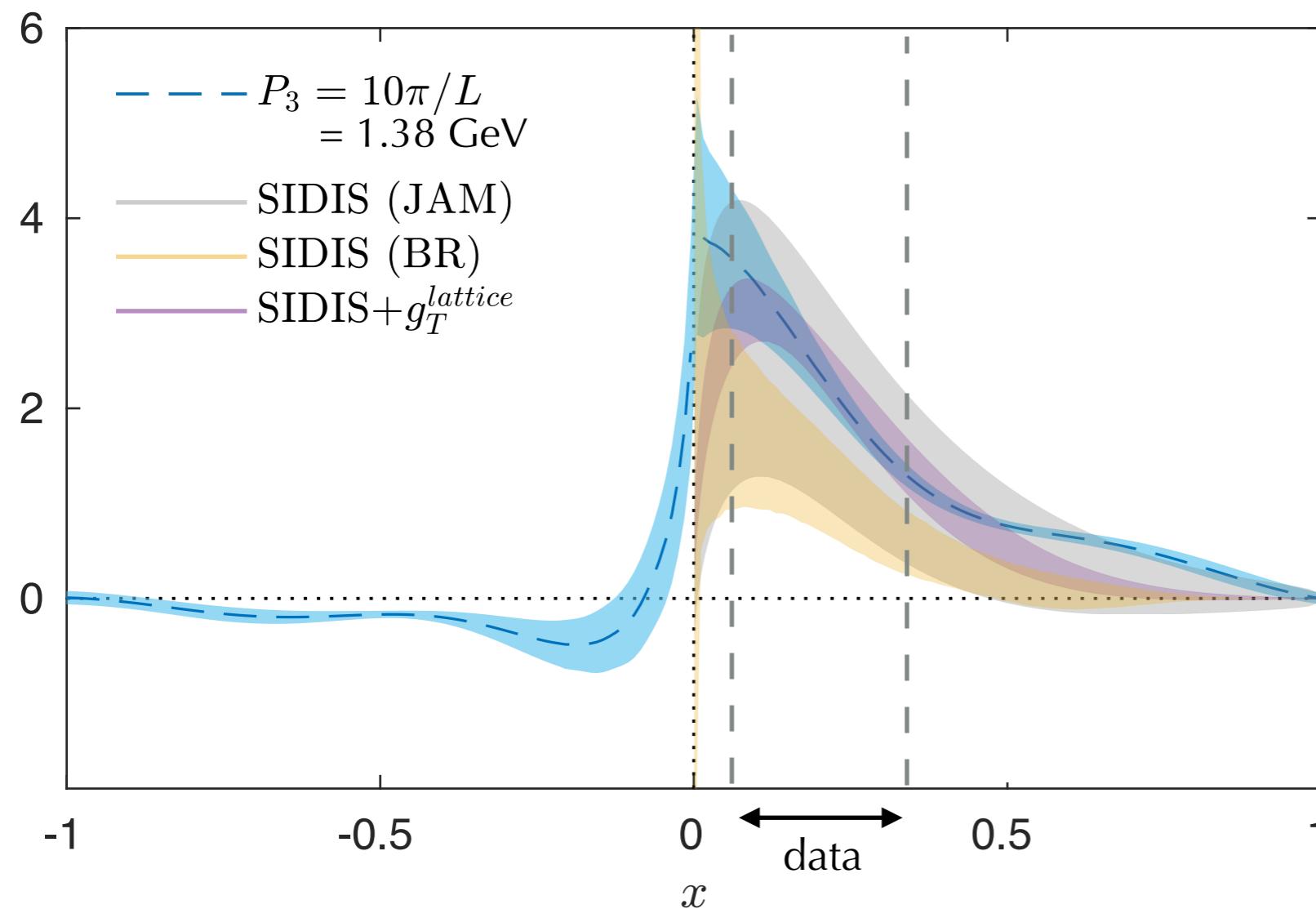


TMD
Kang et al.,
P.R. D93 (16) 014009



Comparison with lattice

$h_1^u - h_1^d \quad Q^2 = 4 \text{ GeV}^2$



courtesy of F. Steffens

our global fit

*Radici and Bacchetta,
P.R.L. **120** (18) 192001*

JAM Collab.

*Lin et al.,
P.R.L. **120** (18) 152502*

Collins effect
only SIDIS data

constrained to
 g_T^{u-d} from lattice

ETMC quasi- h_1

*Alexandrou et al.,
P.R. **D99** (19) 114504*

The tensor “charge” of the proton

1st Mellin moment of transversity PDF \Rightarrow tensor “charge”

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

tensor charge connected to tensor operator

$$\begin{aligned} \langle P, S_p | \bar{q} \sigma^{\mu\nu} q | P, S_p \rangle &= (P^\mu S_p^\nu - P^\nu S_p^\mu) \delta q \\ &= (P^\mu S_p^\nu - P^\nu S_p^\mu) \int dx h_1^{q-\bar{q}}(x, Q^2) \end{aligned}$$

compute on lattice

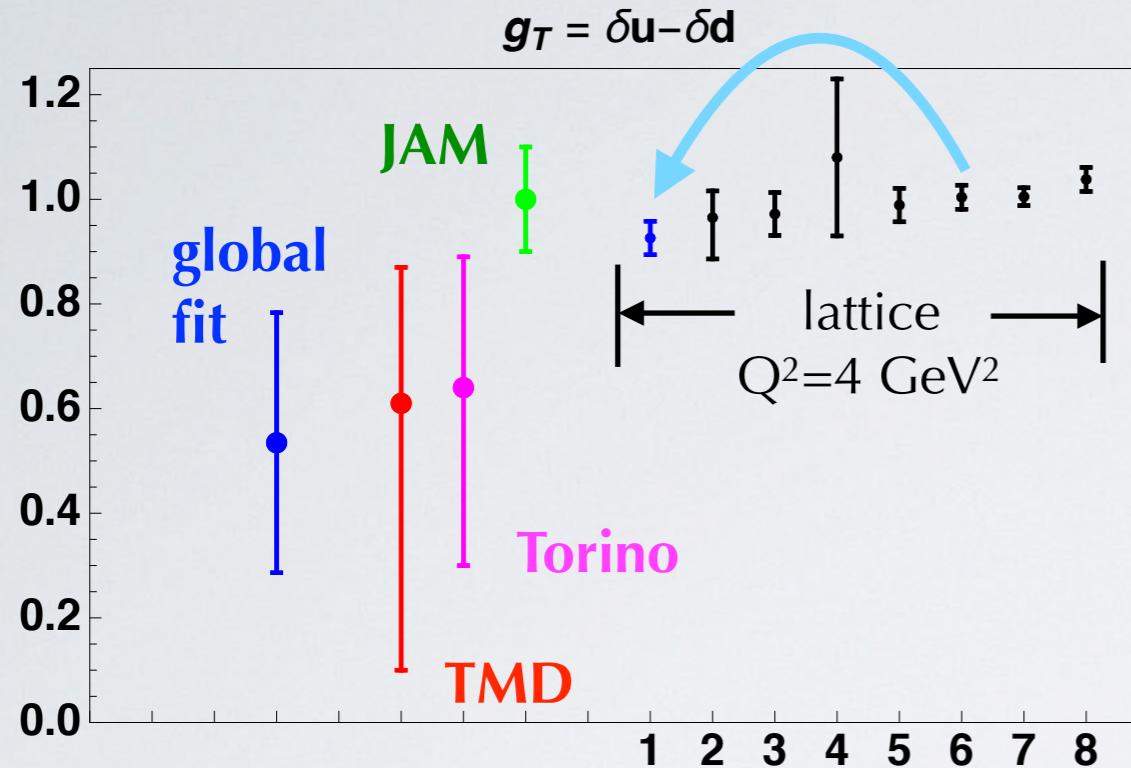
lattice δq

preferably the isovector $g_T = \delta u - \delta d$
(cancellation of “disconnected” diagrams)

extract transversity from data with
transversely polarized protons

pheno δq

Comparison on tensor charge



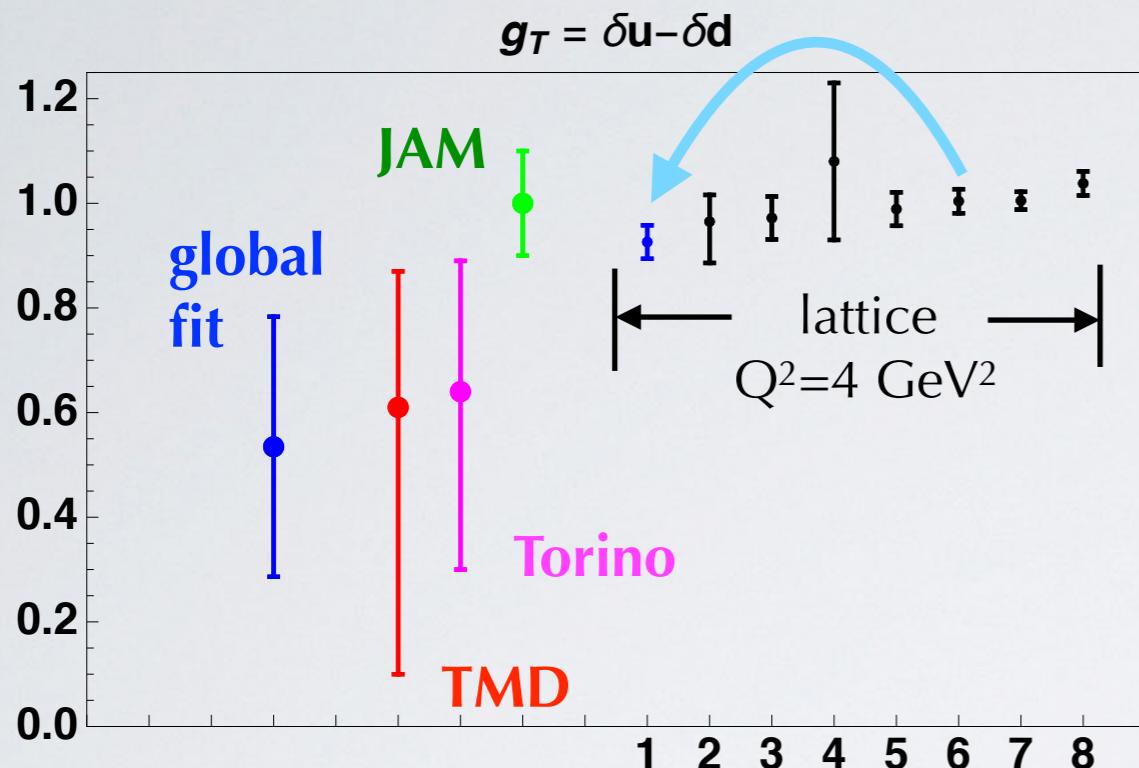
Collins effect
no p-p data

{
JAM ($Q^2=2$)
Torino ($Q^2=1$)
TMD ($Q^2=10$)

JAM includes constraint
from ‘‘lattice g_T ’’

- 1) **ETMC '19** *Alexandrou et al., arXiv:1909.00485*
- 2) **Mainz '19** *Harris et al., P.R. D100 (19) 034513*
- 3) **LHPC '19** *Hasan et al., P.R. D99 (19) 114505*
- 4) **JLQCD '18** *Yamanaka et al., P.R. D98 (18) 054516*
- 5) **PNDME '18** *Gupta et al., P.R. D98 (18) 034503*
- 6) **ETMC '17** *Alexandrou et al., P.R. D95 (17) 114514;
E P.R. D96 (17) 099906*
- 7) **RQCD '14** *Bali et al., P.R. D91 (15) 054501*
- 8) **LHPC '12** *Green et al., P.R. D86 (12) 114509*

Comparison on tensor charge



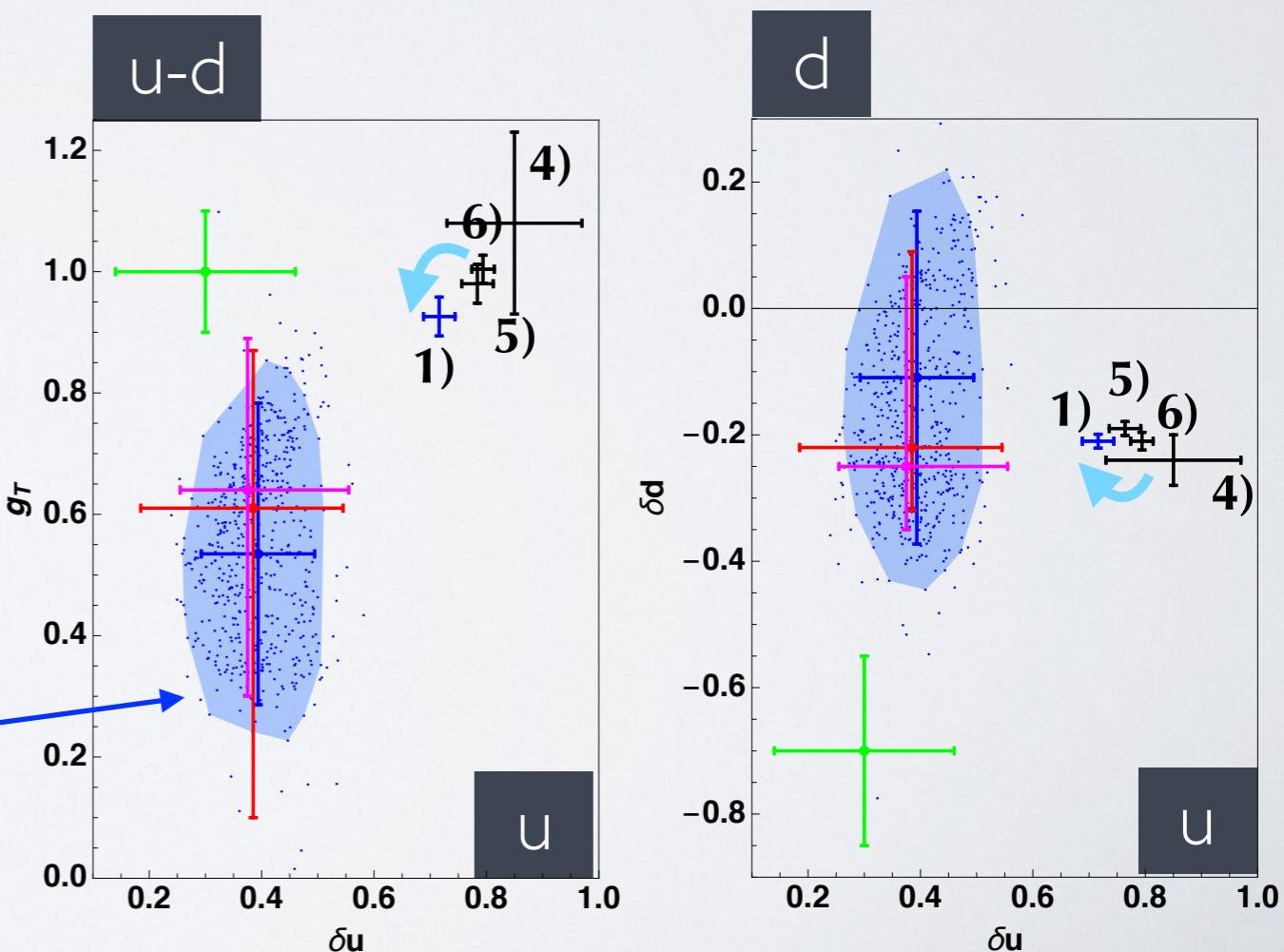
Collins effect
no p-p data

{ JAM ($Q^2=2$)
 Torino ($Q^2=1$)
 TMD ($Q^2=10$)

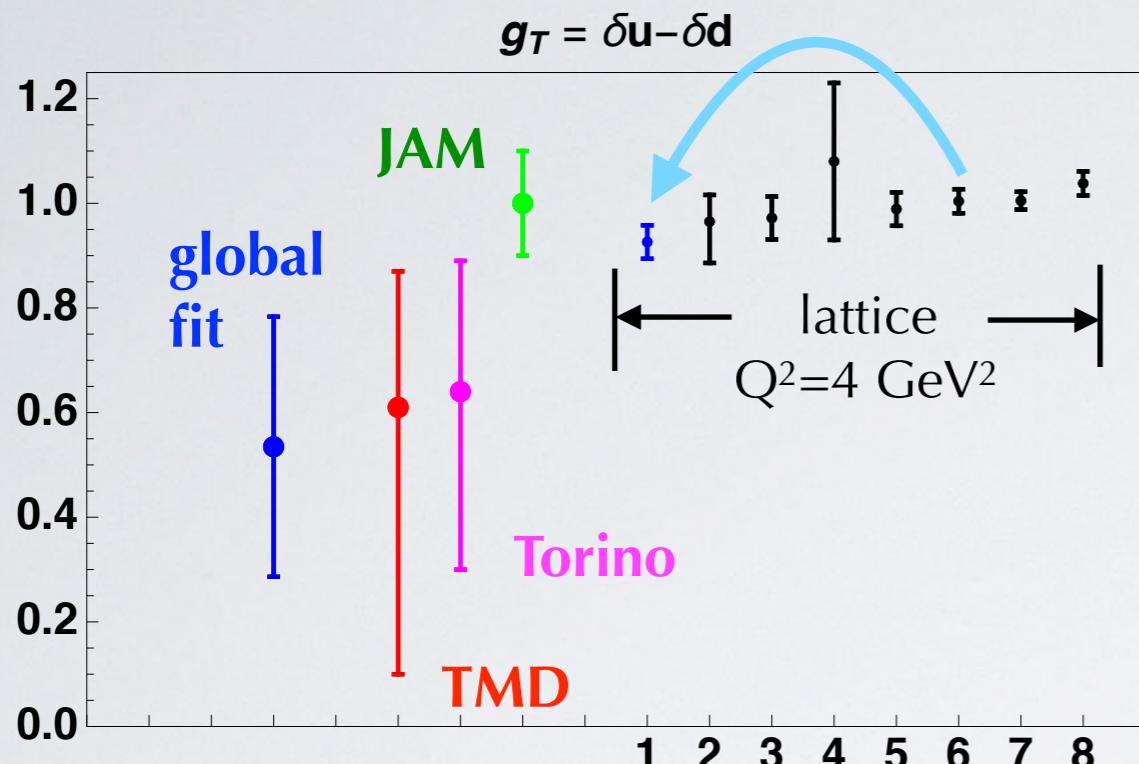
JAM includes constraint
from “lattice g_T ”

90% uncertainty
band

- | | |
|--------------|--|
| 1) ETMC '19 | Alexandrou <i>et al.</i> , arXiv:1909.00485 |
| 2) Mainz '19 | Harris <i>et al.</i> , P.R. D100 (19) 034513 |
| 3) LHPC '19 | Hasan <i>et al.</i> , P.R. D99 (19) 114505 |
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| 5) PNDME '18 | Gupta <i>et al.</i> , P.R. D98 (18) 034503 |
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| 8) LHPC '12 | Green <i>et al.</i> , P.R. D86 (12) 114509 |



Comparison on tensor charge



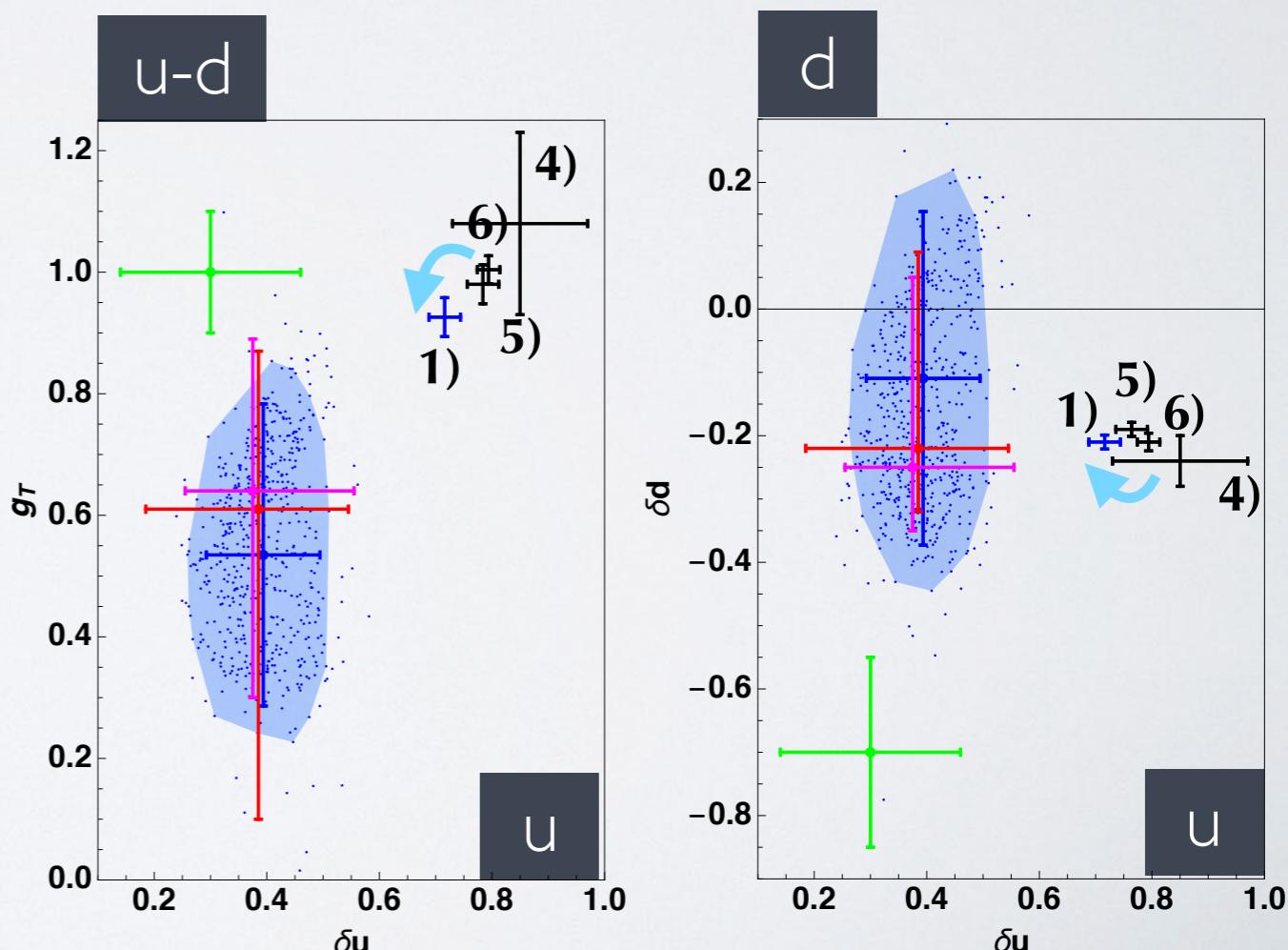
Collins effect
no p-p data

JAM ($Q^2=2$)
Torino ($Q^2=1$)
TMD ($Q^2=10$)

JAM includes constraint
from “lattice g_T ”

no simultaneous compatibility
between
“pheno δq ” and “lattice δq ”

- 1) **ETMC '19** *Alexandrou et al., arXiv:1909.00485*
- 2) **Mainz '19** *Harris et al., P.R. D100 (19) 034513*
- 3) **LHPC '19** *Hasan et al., P.R. D99 (19) 114505*
- 4) **JLQCD '18** *Yamanaka et al., P.R. D98 (18) 054516*
- 5) **PNDME '18** *Gupta et al., P.R. D98 (18) 034503*
- 6) **ETMC '17** *Alexandrou et al., P.R. D95 (17) 114514; E P.R. D96 (17) 099906*
- 7) **RQCD '14** *Bali et al., P.R. D91 (15) 054501*
- 8) **LHPC '12** *Green et al., P.R. D86 (12) 114509*



Tension “pheno” - “lattice”

main problem of “pheno δq ”
is extrapolating outside data..

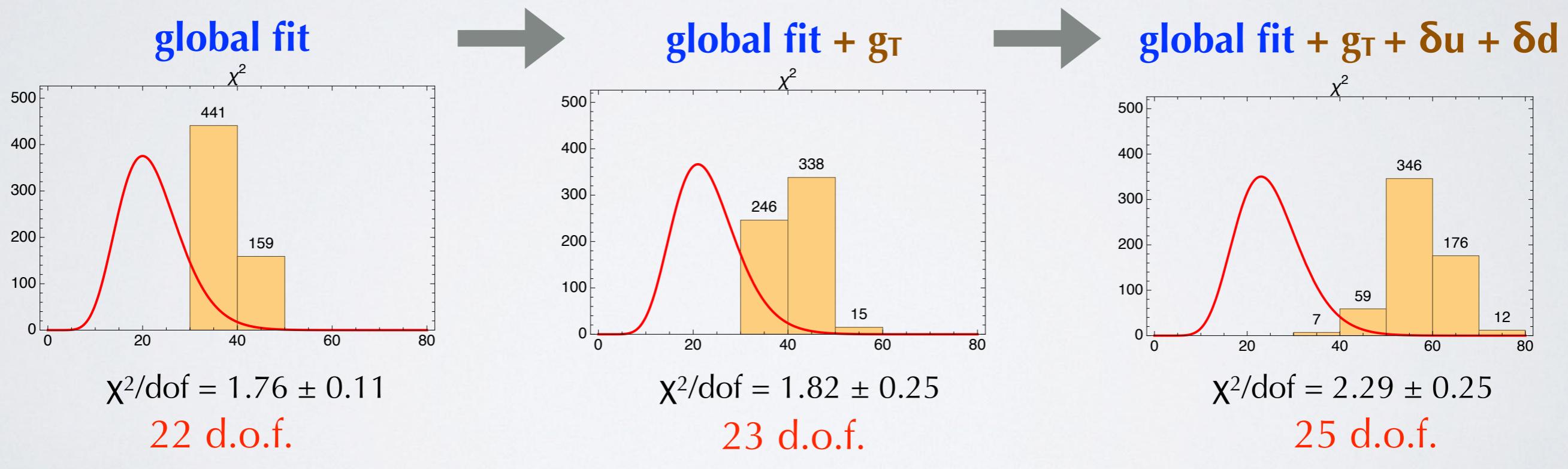
$$\delta q = \int_0^{x_{\min}} dx h_1^{q-\bar{q}} + \int_{x_{\min}}^{x_{\max}} dx h_1^{q-\bar{q}} + \int_{x_{\max}}^1 dx h_1^{q-\bar{q}}$$

if we constrain our **global fit** with lattice results for all components of tensor charge (up, down, isovector) the χ^2 clearly deteriorate

$$\overline{g_T}^{\text{latt}} = 1.004 \pm 0.057$$

$$\overline{\delta u}^{\text{latt}} = 0.782 \pm 0.031$$

$$\overline{\delta d}^{\text{latt}} = -0.218 \pm 0.026$$

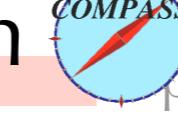


statistically very unlikely

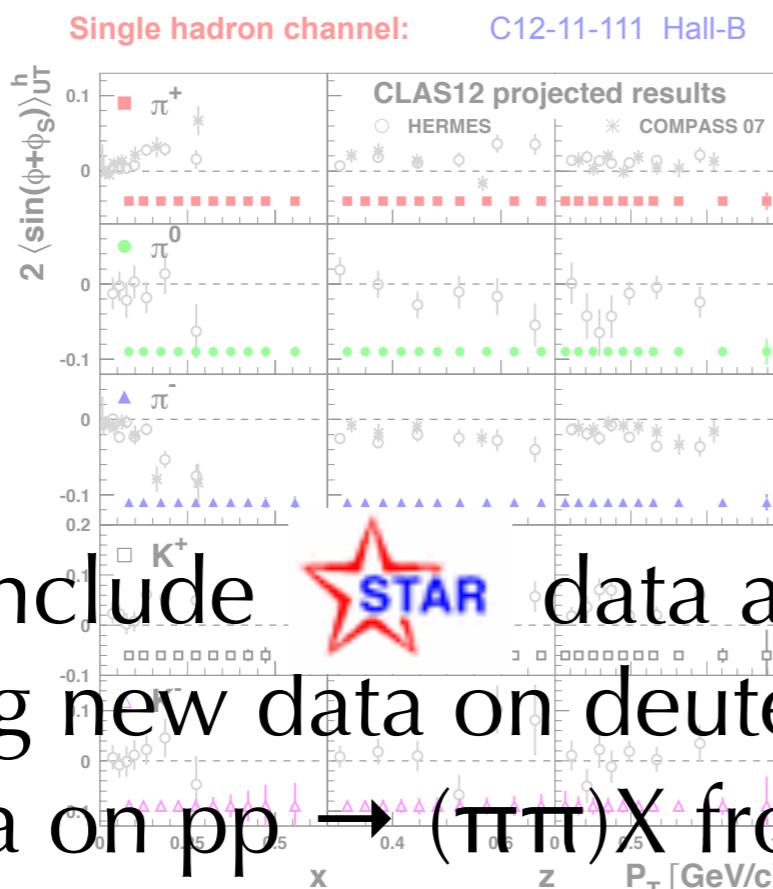
The Future

Mid-Term
JLab12

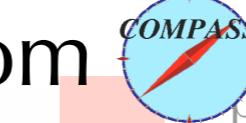
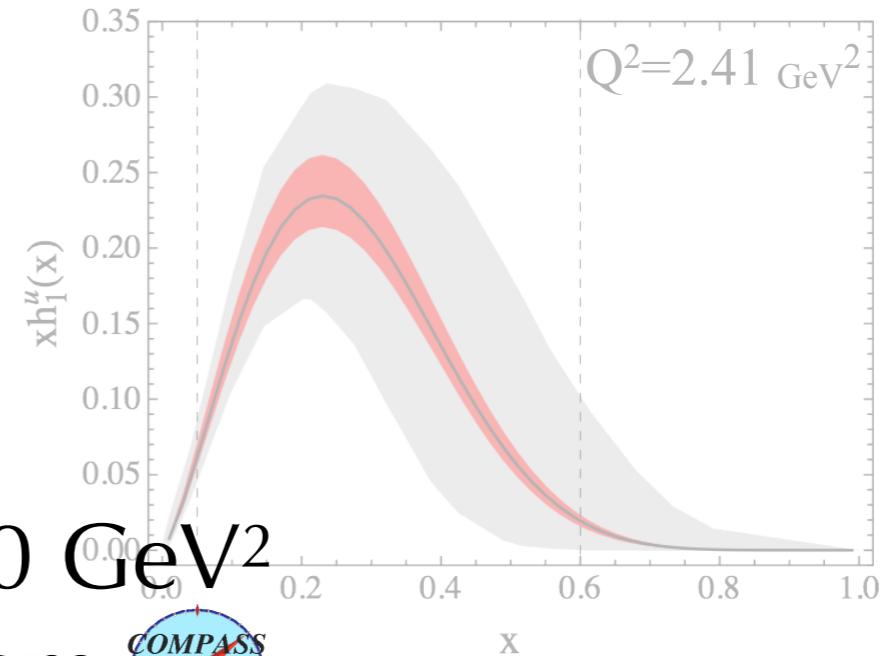
also:

- need to include  data at $s=500 \text{ GeV}^2$
- upcoming new data on deuteron from  projection with ${}^3\text{He}^\uparrow$ and p^\uparrow data
- need data on $\text{pp} \rightarrow (\pi\pi)\text{X}$ from  to constrain D_1 gluon

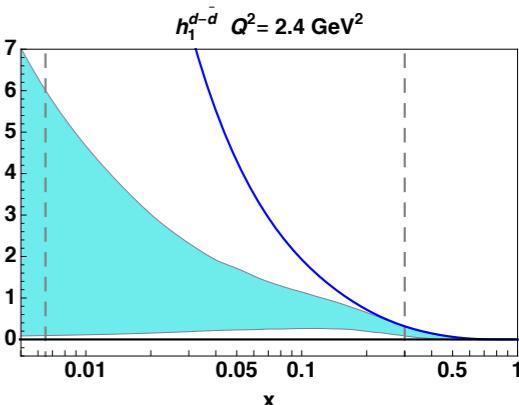
Hall B 



Hall A SoLID



projection with ${}^3\text{He}^\uparrow$ and p^\uparrow data
Anselmino et al., P.R.D. 92 (15) 114023

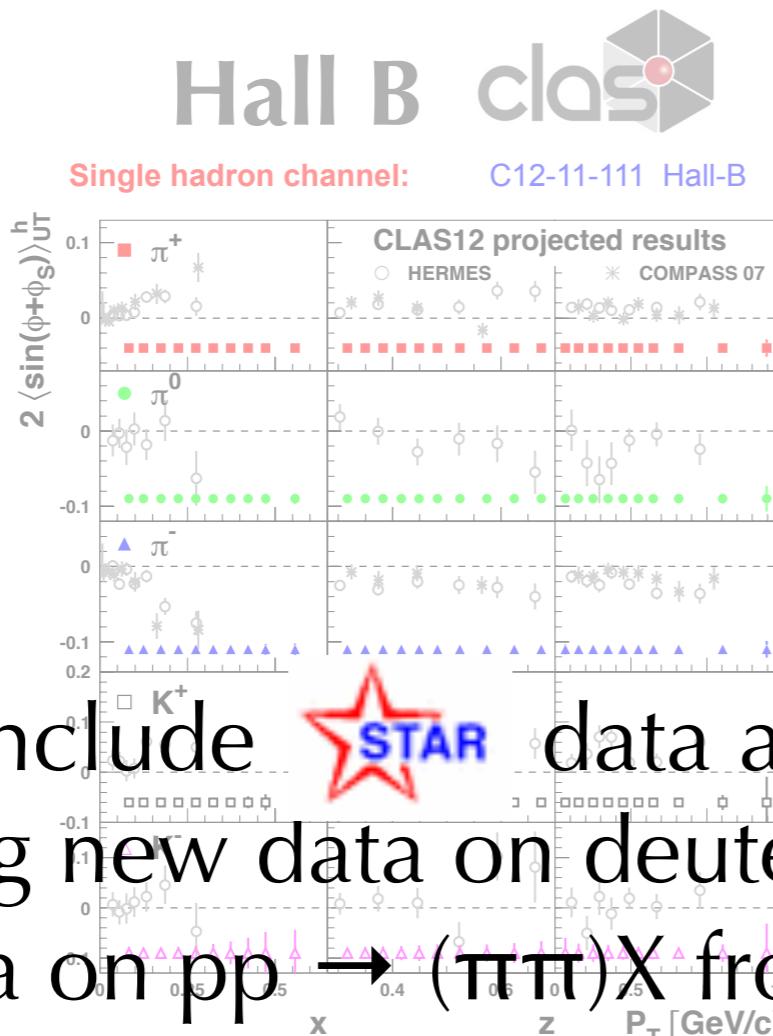


The Future

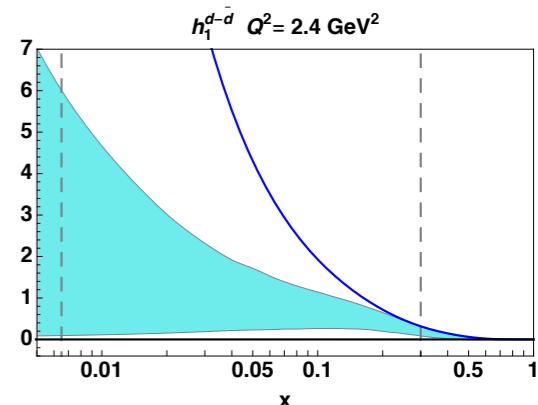
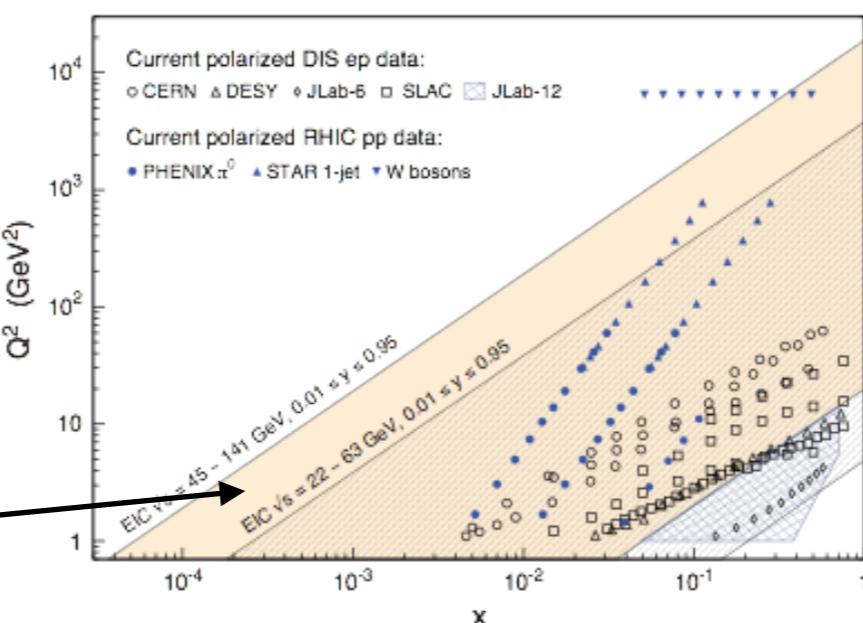
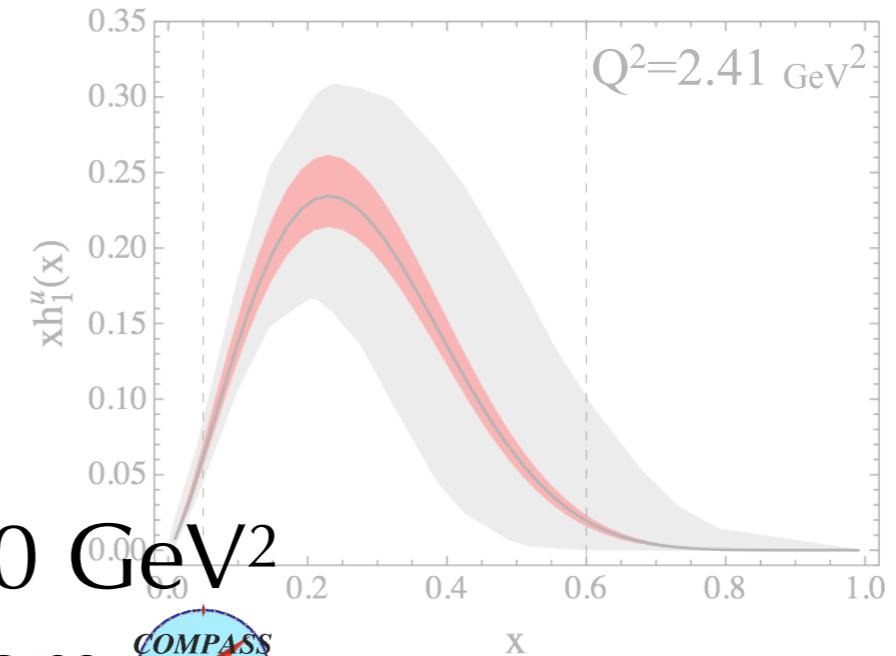
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Anselmino et al., P.R.D. 92 (15) 114023
- need data on $\text{pp} \rightarrow (\pi\pi)\text{X}$ from  to constrain D_1 gluon
- need EIC to extend (x, Q^2) coverage to have better handle on tensor charge



Hall A SoLID



Conclusions

- with polarized TMDs many possible combinations allow to explore various aspects of motion of partons inside hadrons

Nucleon Polarization	Quark polarization		
	Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1 = \odot$		$h_1^\perp = \text{red dot} - \text{red dot}$
L		$g_1 = \text{red arrow} - \text{red arrow}$	$h_{1L}^\perp = \text{red arrow} - \text{red arrow}$
T	$f_{1T}^\perp = \text{red dot} - \text{red dot}$	$g_{1T} = \text{red arrow} - \text{red arrow}$	$h_1 = \text{red dot} - \text{red dot}$ $h_{1T}^\perp = \text{red arrow} - \text{red arrow}$

Conclusions

- with polarized TMDs many possible combinations allow to explore various aspects of motion of partons inside hadrons
- Sivers effect tests QCD at its fundamental level and gives indirect information on partonic contribution to proton spin
- first “tomography” of Sivers effect available from data in a consistent TMD framework

Bacchetta, Delcarro, Pisano, Radici, in preparation

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		$h_1^\perp = \text{red} \odot - \text{red} \odot$
	L		$g_1 = \text{red} \leftrightarrow - \text{red} \leftrightarrow$	$h_{1L}^\perp = \text{red} \leftrightarrow - \text{red} \leftrightarrow$
	T	$f_{1T}^\perp = \text{green} \odot - \odot \text{green}$	$g_{1T} = \text{green} \odot - \odot \text{green}$	$h_1 = \text{red} \odot - \text{red} \odot$ $h_{1T}^\perp = \text{red} \odot - \odot \text{red}$

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- Transversity as prototype of chiral-odd objects; its Mellin moment (tensor charge) is a potential doorway to BSM
*Radici and Bacchetta,
P.R.L. **120** (18) 192001
arXiv:1802.05212*
- apparently, tension between tensor charge extracted from data and computed on lattice

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P.R.L. 120 (18) 192001
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		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		$h_1^\perp = \text{---}$
	L		$g_1 = \odot\leftarrow - \odot\rightarrow$	$h_{1L}^\perp = \text{---}$
	T	$f_{1T}^\perp = \odot\uparrow - \odot\downarrow$	$g_{1T} = \odot\uparrow - \odot\downarrow$	$h_1 = \text{---}$ $h_{1T}^\perp = \text{---}$

Much more to come with

