First extraction of Transversity from data on lepton-hadron scattering and hadronic collisions

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CIPANP 2018

cipanp18.berkeley.edu

13th Conference on the Intersections of Particle and Nuclear Physics

May 29 - June 3

Hyatt Regency Indian Wells Resort and Spa, Palm Springs, CA

Parallel Session Topics

International Scientific Advisory Board

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3DSPIN MAPPING THE PROTON IN 3D

erc European Research Council

based on

P.R.L. **120** (2018) 192001, arXiv:1802.05212

plus updates

U.S. DEPARTMENT OF ENERGY Office of Science

Motivation

searches for BSM New Physics

- **nuclear β-decay**: effective field theory including operators not in SM Lagrangian; for example, tensor operator

talk Gonzalez-Alonso

hadron level

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

exp. data

$$C_T \leftrightarrow g_T\,\epsilon_T$$

quark level

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

?

$g_T = \delta u - \delta d$ **isovector tensor charge**

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

talks Mereghetti, Syristsyn,..

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

tensor charge

lattice

$\langle P,S|\,\bar{q}\sigma^{\mu\nu}q\,|P,S\rangle$
$= (P^\mu S^\nu - P^\nu S^\mu)\,\delta q$

pheno

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

transversity

a phase transition

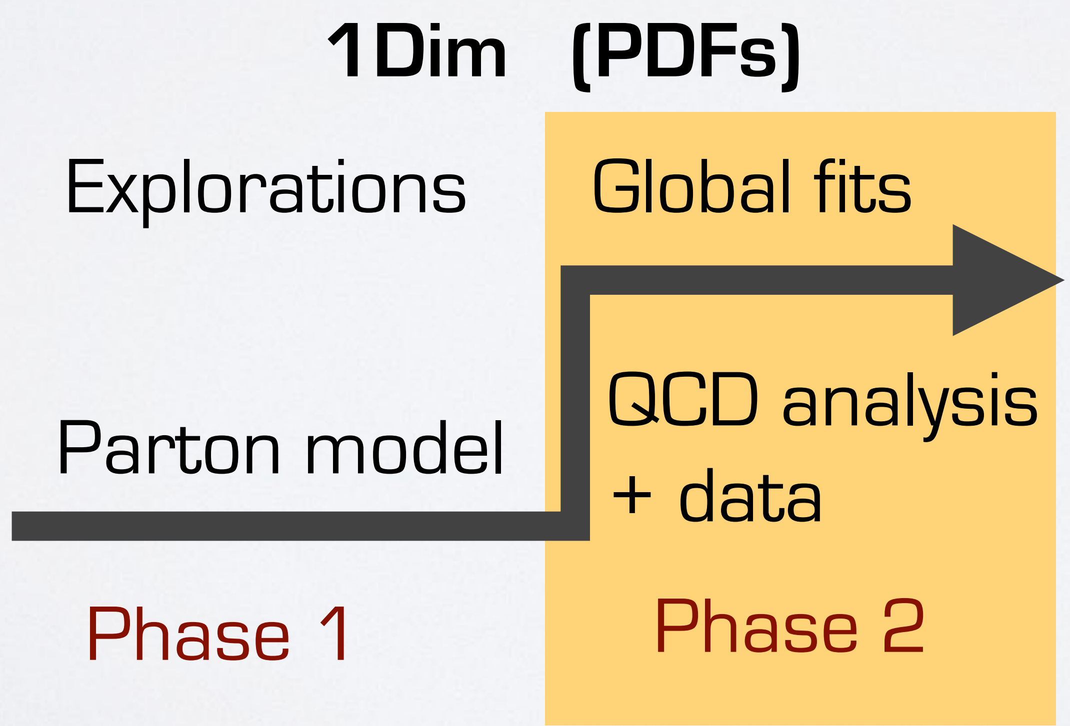
quark polarization

nucleon polarization

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

chiral-odd → **SIDIS**

first global fit
(= lepton-hadron scatt.
and hadron collisions)
of **PDF h_1**



2-hadron-inclusive production

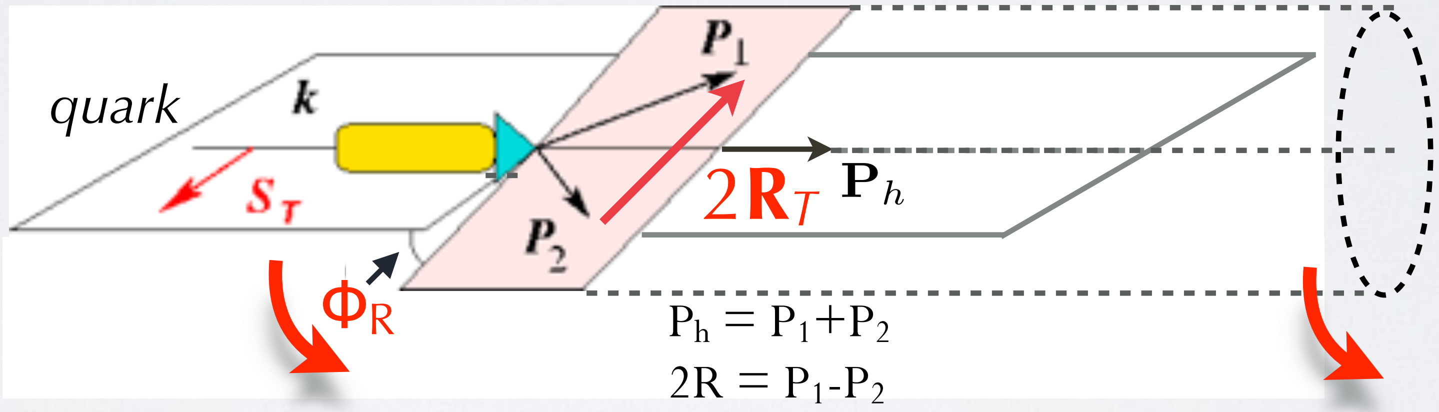
Collins, Heppelman, Ladinsky,
N.P. ***B420*** *(94)*

$R_T \ll Q$ $\quad H_1^{\sphericalangle}$

$\updownarrow$

M_h

invariant mass



correlation S_T and R_T → **azimuthal asymmetry**

2-hadron-inclusive production

framework
collinear
factorization

Collins, Heppelman, Ladinsky, ***N.P. B420*** *(94)*

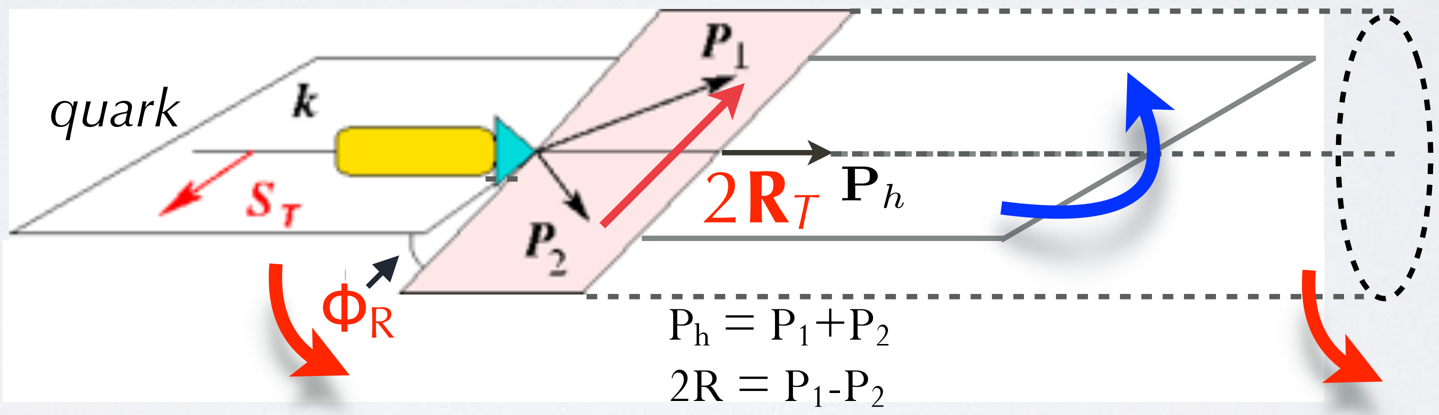
$R_T \ll Q$

↕

M_h

invariant mass

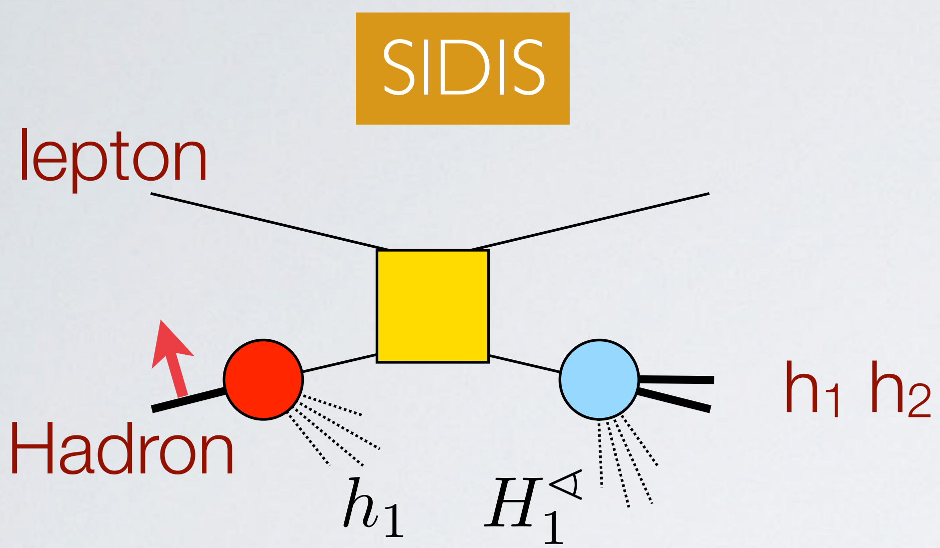
$H_1^{\sphericalangle}$



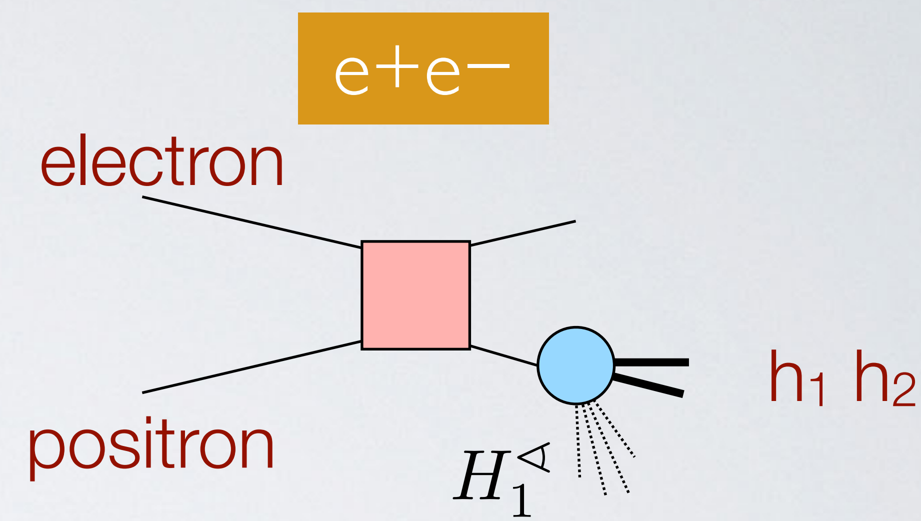
survives to polar symmetry ($\int d\boldsymbol{P}_{hT}$)

correlation $\boldsymbol{S}_T$ and $\boldsymbol{R}_T$ → **azimuthal asymmetry**

2-hadron-inclusive production



framework
collinear
factorization

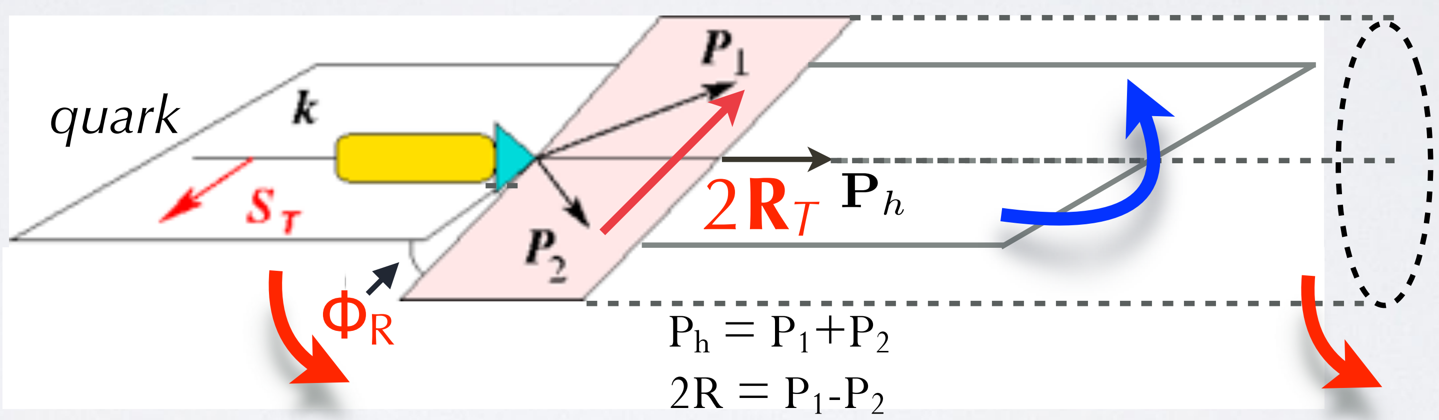


$R_T \ll Q$ $H_1^{\sphericalangle}$

↕

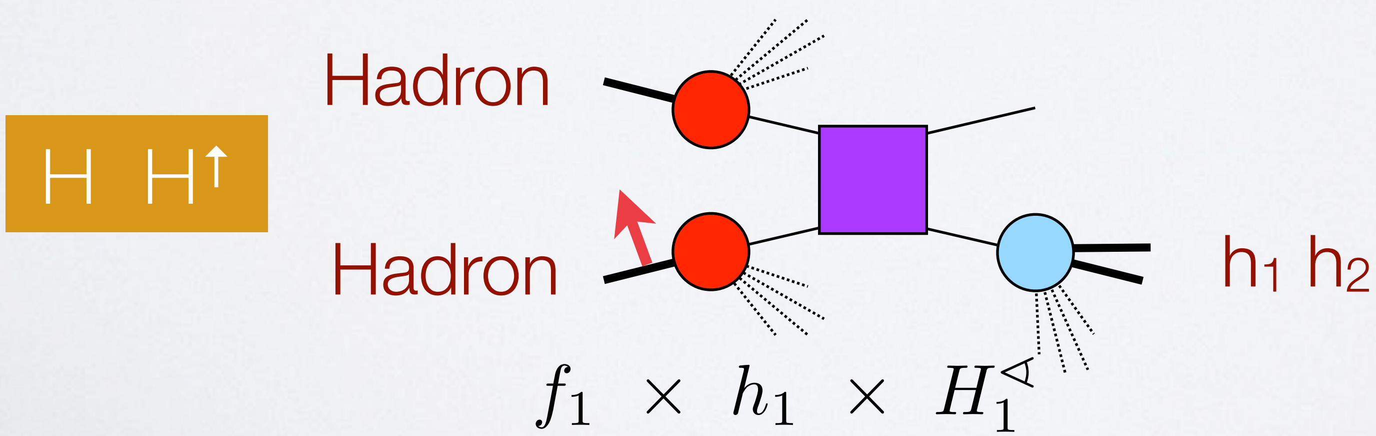
M_h

invariant mass



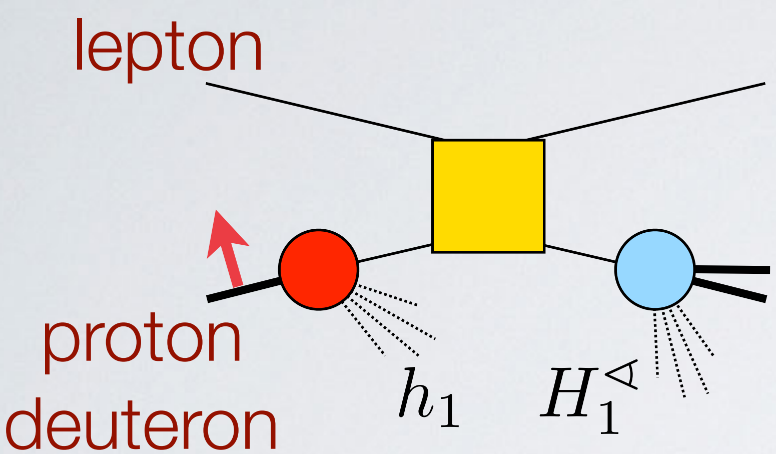
survives to
polar
symmetry
($\int dP_{hT}$)

correlation S_T and R_T → **azimuthal asymmetry**



exp. data for 2-hadron-inclusive production

SIDIS ℓ H$^{\uparrow}$ → ℓ' (h_1 h_2) X



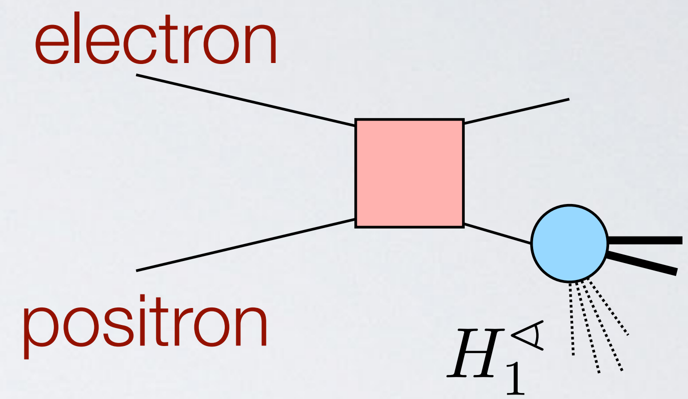
$\pi^+\pi^-$, π^+K^-, K^+K^-

*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*

e+e− → (h_1 h_2) X

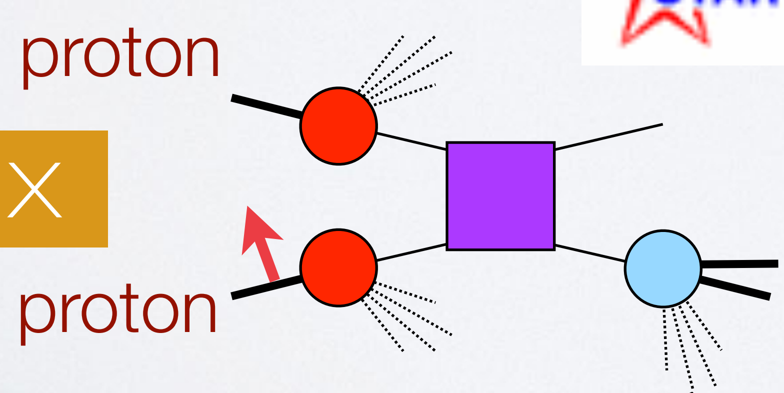


$\pi^+\pi^-$

*Vossen et al., P.R.L. **107** (11) 072004*

~~D_1 *Seidl et al., P.R. D**96** (17) 032005*~~

H H$^{\uparrow}$ → (h_1 h_2) X



$\pi^+\pi^-$

$$f_1 \times h_1 \times H_1^{\sphericalangle}$$

run 2006 (s=200)

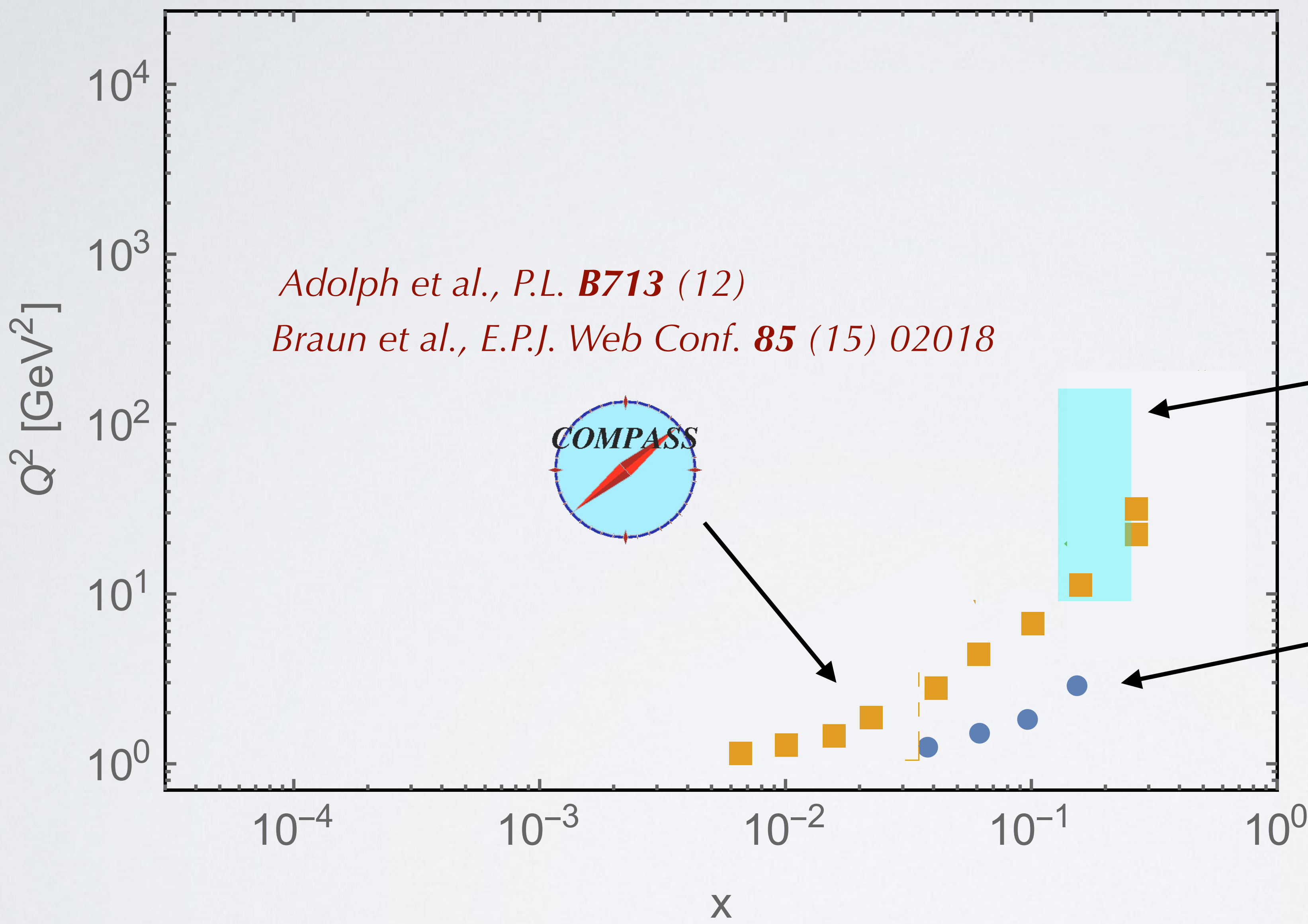
*Adamczyk et al. (STAR), P.R.L. **115** (2015) 242501*

~~run 2011 (s=500)~~

~~*Adamczyk et al. (STAR), P.L. **B780** (18) 332*~~

A_{UT} (η,M_h,P_T)

the kinematics



run 2006

s=200 GeV^2

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

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

explore only valence quarks

choice of functional form

functional form whose Mellin transform can be computed analytically and complying with Soffer Bound at any x and scale Q^2

$$h_1^{q_v}(x;Q_0^2) = F^{q_v}(x) \left[\mathrm{SB}^q(x) + \overline{\mathrm{SB}}^{\bar{q}}(x)\right]$$

Soffer Bound

$$2|h_1^q(x,Q^2)| \le 2\ \mathrm{SB}^q(x,Q^2) = |f_1^q(x,Q^2) + g_1^q(x,Q^2)|$$

MSTW08 DSSV

$$F^{q_v}(x) = \frac{N_{q_v}}{\max_x[|F^{q_v}(x)|]}\, x^{A_{q_v}}\, [1 + B_{q_v}\,\mathrm{Ceb}_1(x) + C_{q_v}\,\mathrm{Ceb}_2(x) + D_{q_v}\,\mathrm{Ceb}_3(x)]$$

$\mathrm{Ceb}_n(x)$ Cebyshev polynomial

10 fitting parameters

constrain parameters

$|N_{q_v}| \le 1 \Rightarrow |F^{q_v}(x)| \le 1$ Soffer Bound ok at any Q^2

choice of functional form

$$h_1^{q_v}(x;Q_0^2) = F^{q_v}(x)\ \left[\mathrm{SB}^q(x) + \overline{\mathrm{SB}}^{\bar{q}}(x)\right]$$

$$F^{q_v}(x) = \frac{N_{q_v}}{\max_x[|F^{q_v}(x)|]}\, x^{A_{q_v}}\ [1 + B_{q_v}\,\mathrm{Ceb}_1(x) + C_{q_v}\,\mathrm{Ceb}_2(x) + D_{q_v}\,\mathrm{Ceb}_3(x)]$$

constrain parameters

tensor charge $\delta q(Q^2) = \int_{x_{\min}}^1 dx\, h_1^{q-\bar{q}}(x,Q^2)$

low-x behavior is important outside data range

if $\lim_{x\to 0} x\mathrm{SB}^q(x) \propto x^{a_q}$ then $h_1^q(x) \overset{x\to 0}{\approx} x^{A_q + a_q - 1}$

- 1st option: finite tensor charge $\longrightarrow$ $A_q + a_q > \frac{1}{3}$

grants also error $O(1\%)$ for MSTW08 $x_{min}=10^{-6}$

- 2nd option: finite violation of Burkhardt-Cottingham sum rule

Accardi and Bacchetta, P.L. ***B773*** *(17) 632*

$$\int_0^1 dx\, g_2(x) \propto \int_0^1 dx\, \frac{h_1(x)}{x} \quad \longrightarrow \quad A_q + a_q > 1$$

theoretical uncertainties

unpolarized Di-hadron Fragmentation Function D_1

- **quark** D_1^q is **well** constrained by $e^+e^- \to (\pi^+\pi^-)\,X$ (Montecarlo)
- **gluon** D_1^g is **not** constrained by $e^+e^- \to (\pi^+\pi^-)\,X$ (currently, LO analysis)
- **no data** available yet for $p\,p \to (\pi^+\pi^-)\,X$

we don't know anything about the gluon D_1^g

our choice: set $D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u(Q_0)/4 \\ D_1^u(Q_0) \end{cases}$

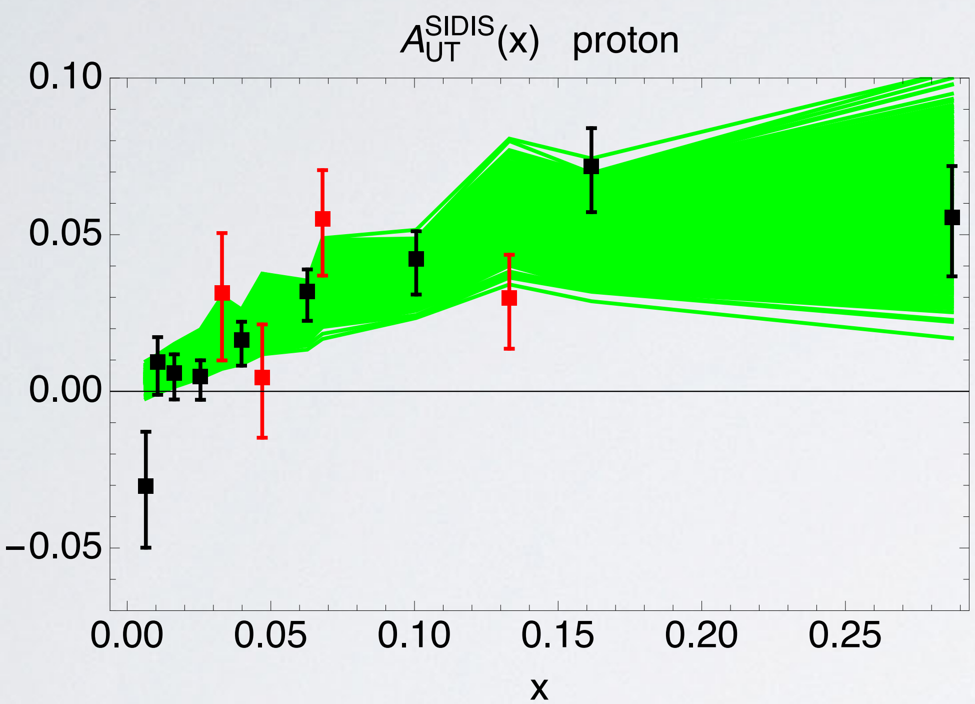
deteriorates our e^+e^- fit as $\chi^2/\text{dof} = \begin{cases} 1.69 & 1.28 \\ 1.81 & 1.37 \\ 2.96 & 2.01 \end{cases}$

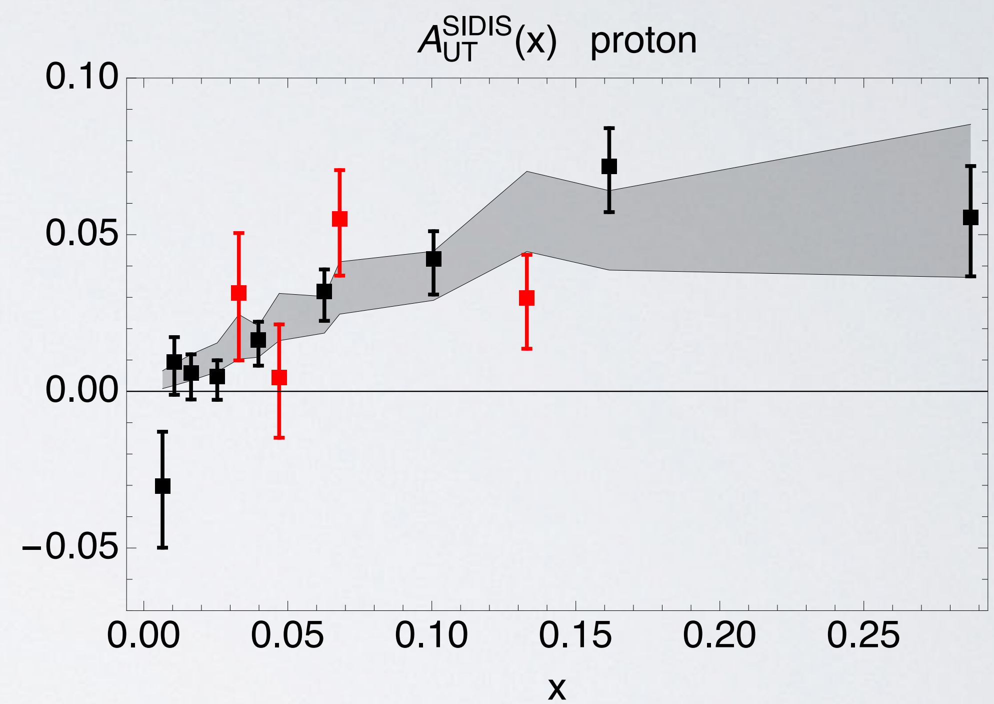
background	ρ	channels
1.69	1.28	
1.81	1.37	
2.96	2.01	

statistical uncertainty

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

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





all 600 replicas → 90% of replicas

<u>the bootstrap method</u>

46 data points, **10** parameters, global $\boldsymbol{\chi^2/\mathrm{dof}} = 2.08 \pm 0.09$

results

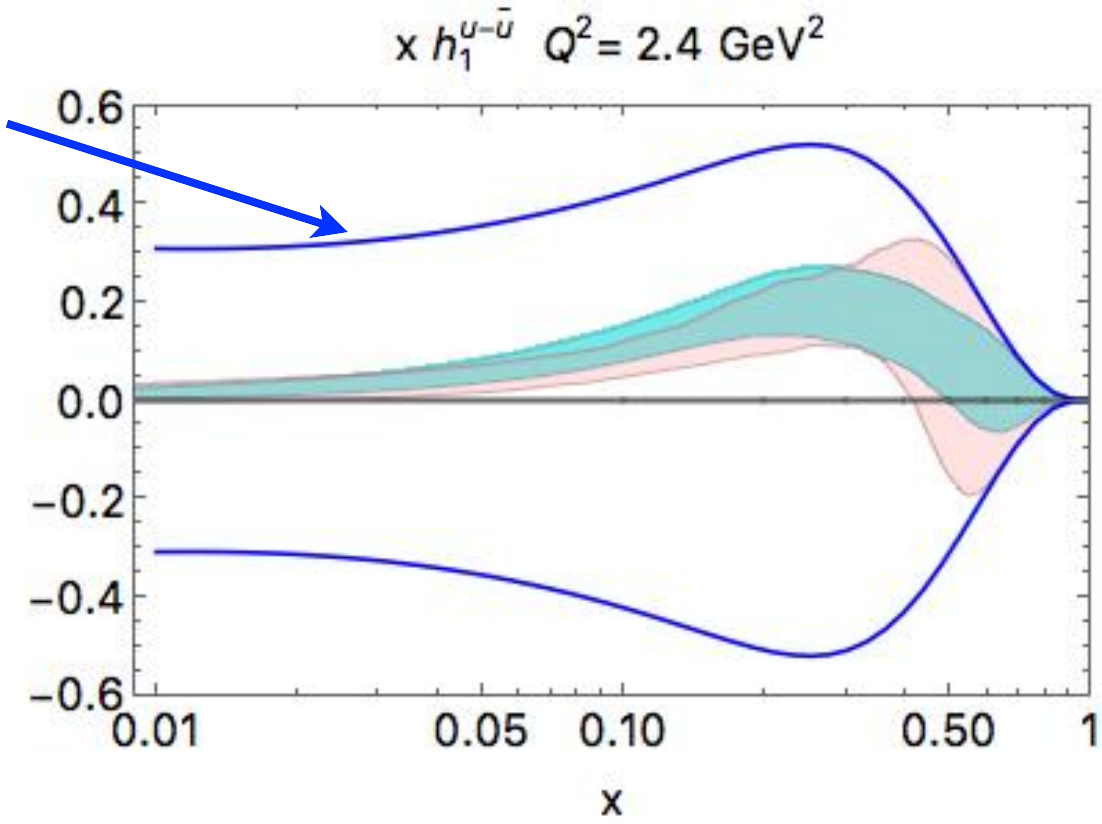
$$h_1^q(x) \overset{x \to 0}{\approx} x^{A_q + a_q - 1}$$

- 1st option: finite tensor charge $\longrightarrow$ $A_q + a_q > \frac{1}{3}$

grants also error $O(1\%)$ in calculation of tensor charge for MSTW08 $x_{min}=10^{-6}$

comparison with previous fit

Soffer bound



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

global fit

up

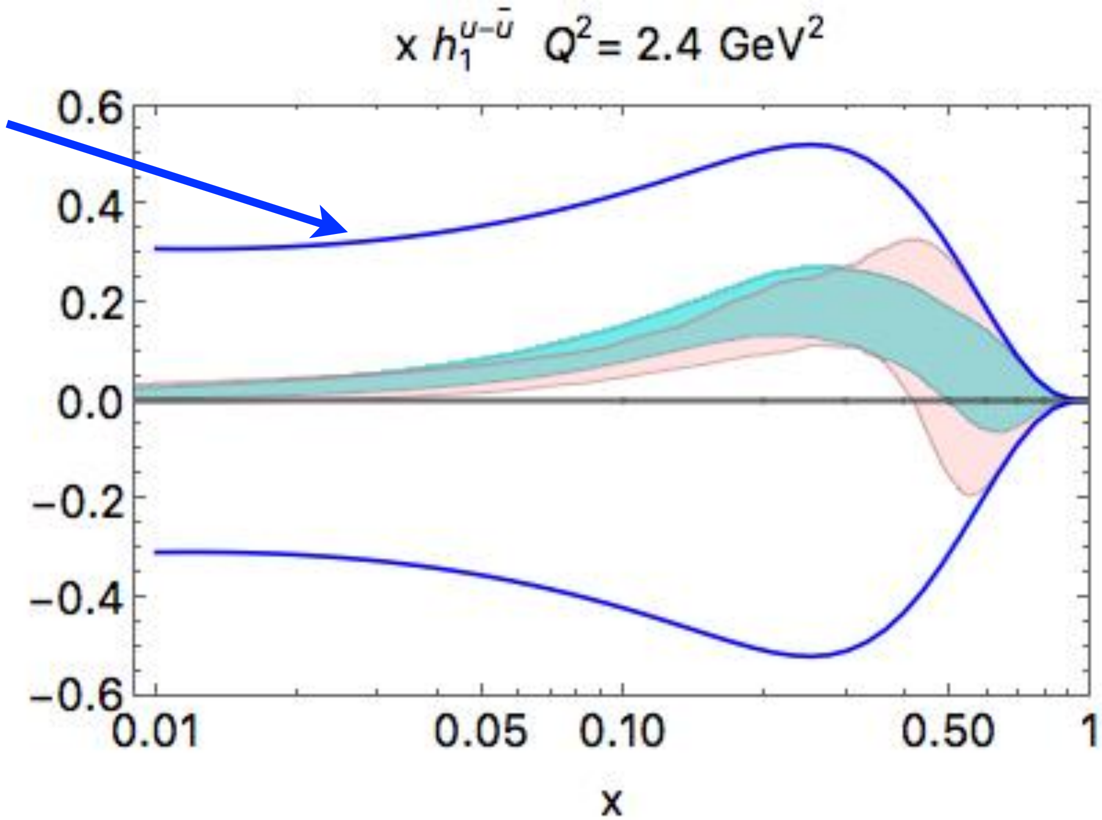
higher precision

old fit (only SIDIS data)

Radici et al.,
JHEP ***1505*** *(15) 123*

comparison with previous fit

Soffer bound



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global fit

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higher precision

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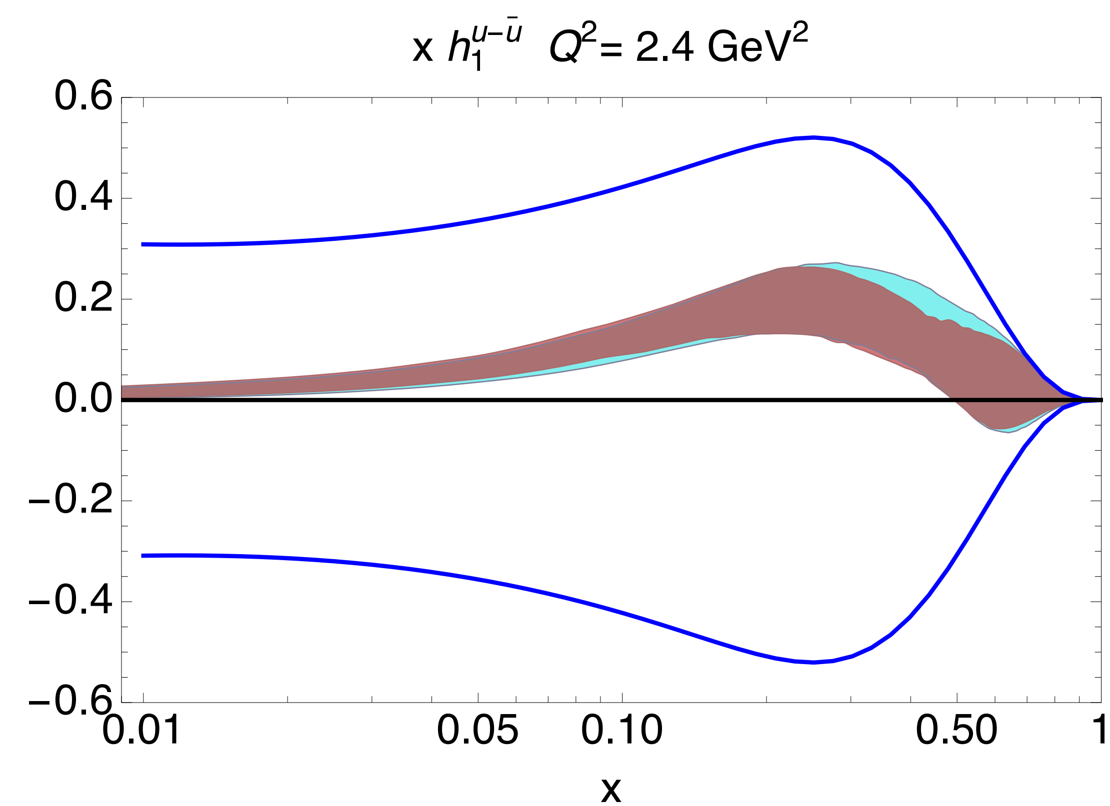
Radici et al., JHEP ***1505*** *(15) 123*

up

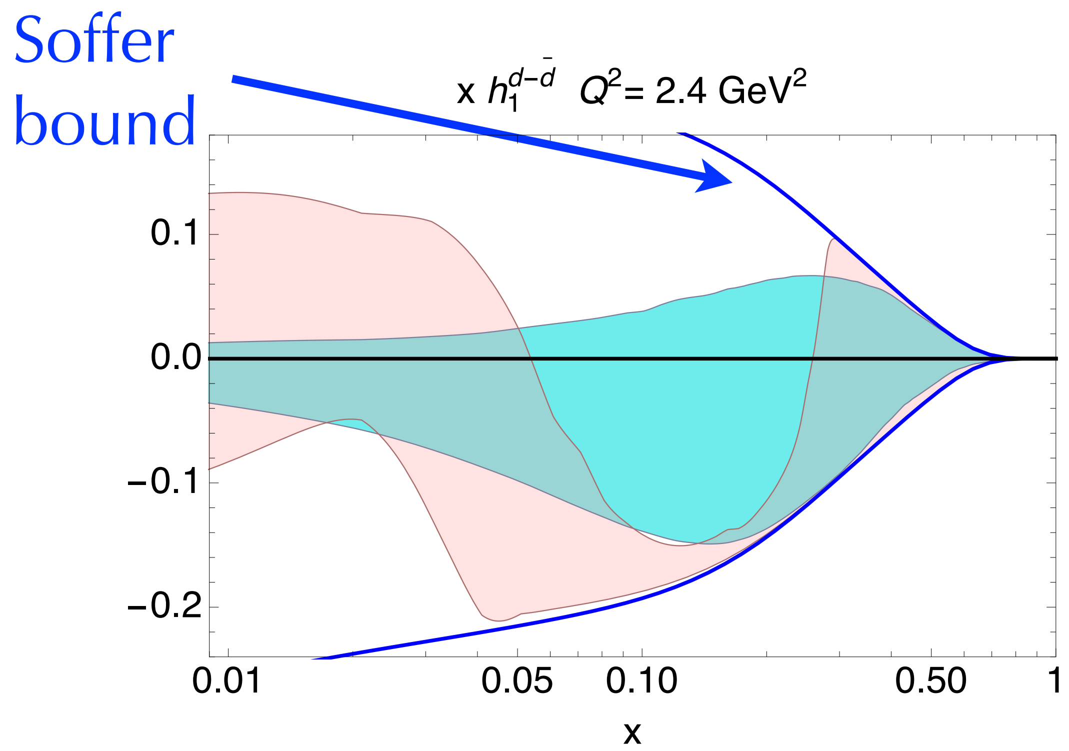
insensitive to uncertainty on gluon D_1

$D_1{}^g(Q_0) = 0$

$$D_1{}^g(Q_0) = \begin{cases} 0 \\ D_1{}^u/4 \\ D_1{}^u \end{cases}$$



comparison with previous fit



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

global fit

old fit

*Radici et al., JHEP **1505** (15) 123*

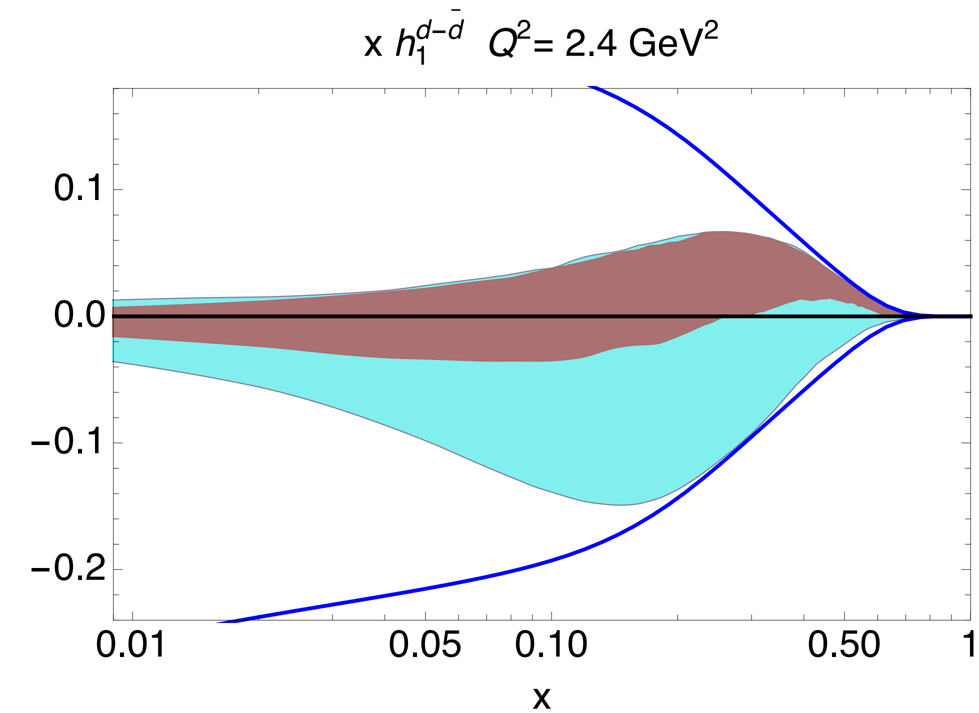
down

down

sensitive to uncertainty on gluon D_1

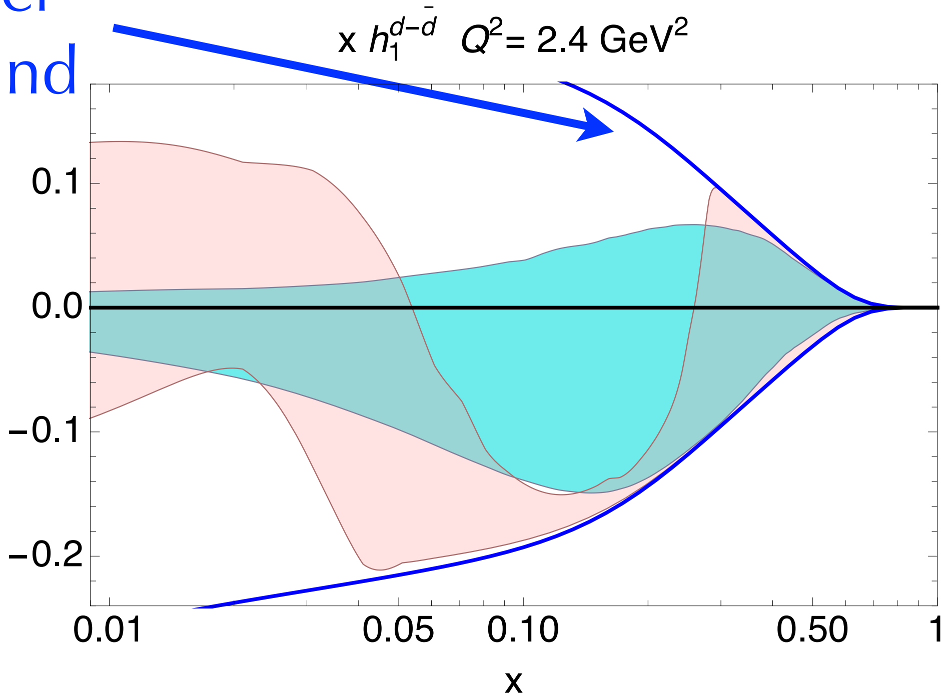
$$D_1^g(Q_0) = 0$$

$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$



comparison with previous fit

Soffer bound



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

global fit

old fit

Radici et al., JHEP ***1505*** *(15) 123*

down

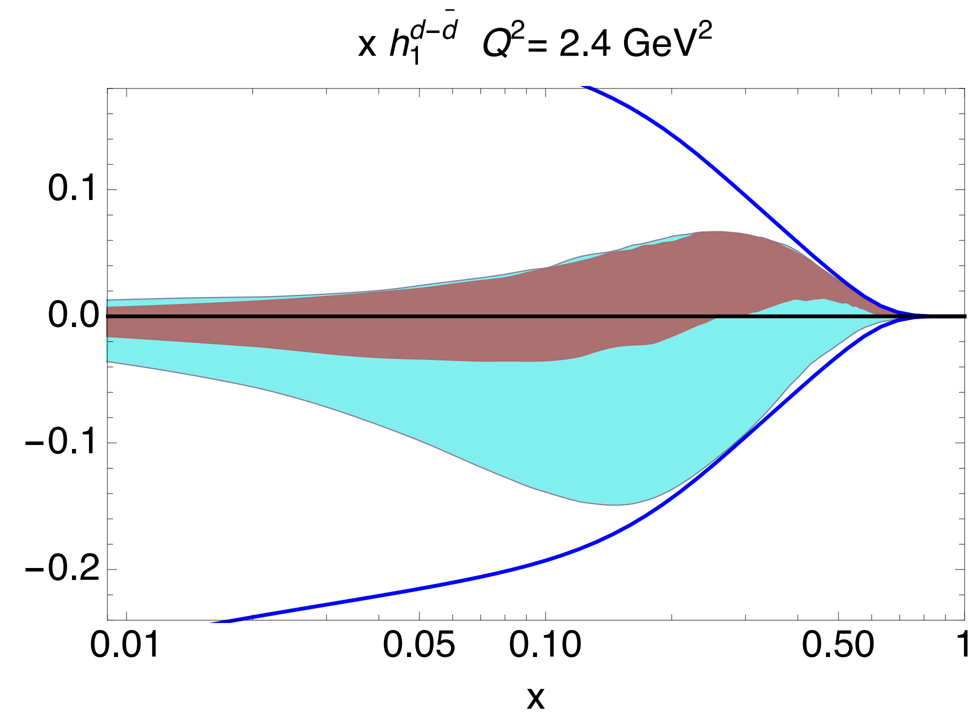
need NLO analysis + dihadron multiplicities in pp

down

sensitive to uncertainty on gluon D_1

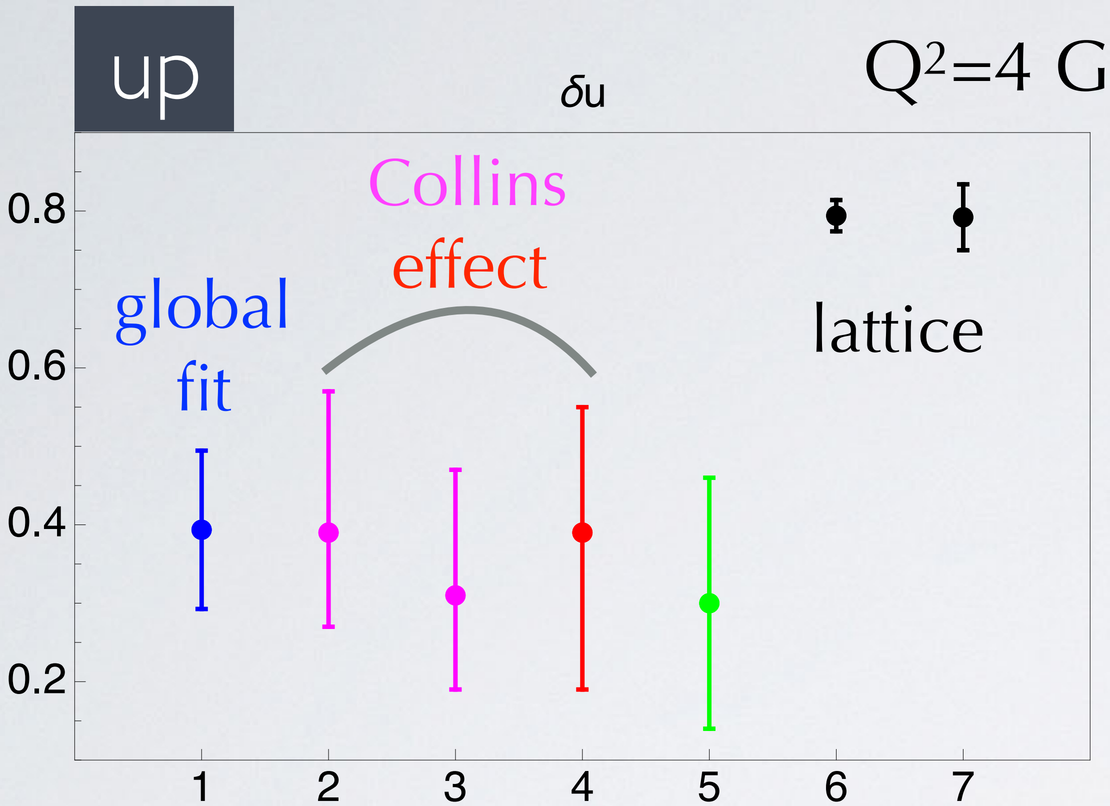
$D_1^g(Q_0) = 0$

$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$



tensor charge $\delta q(Q^2) = \int dx\, h_1^{q-\bar{q}}(x,Q^2)$

Q^2=4 GeV^2 *



1- global fit *Radici & Bacchetta, P.R.L.* ***120*** *(18) 192001*

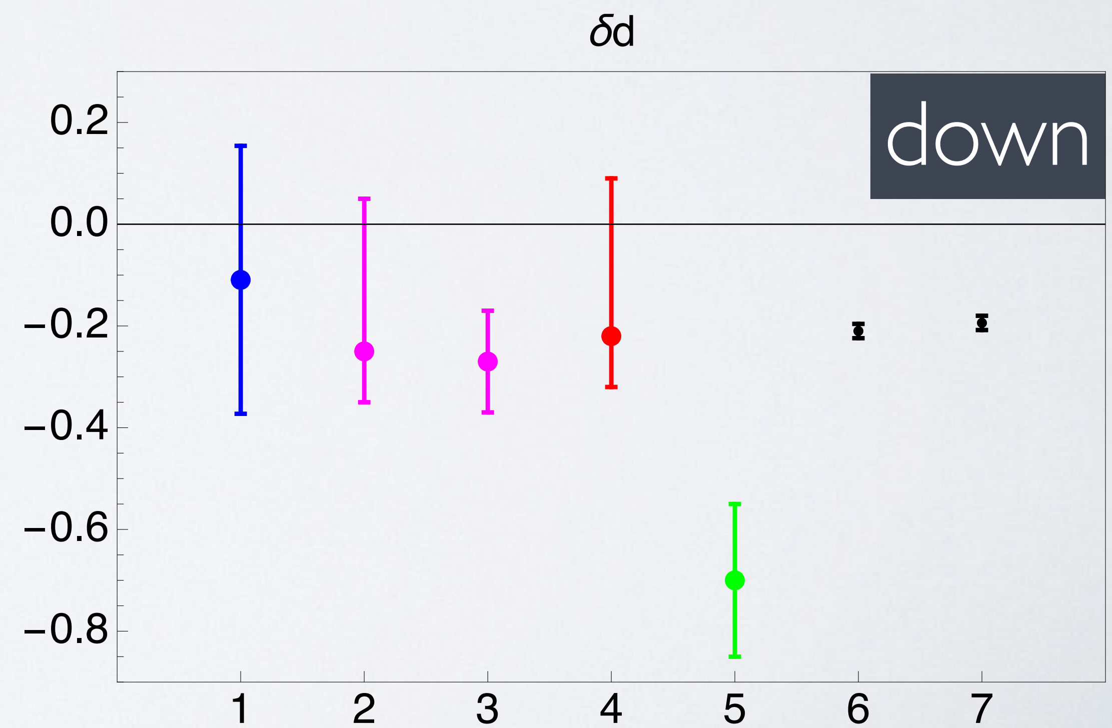
2,3- Torino *Anselmino et al., P.R. D****87*** *(13) 094019* *** Q^2=1**

4- TMD fit *Kang et al., P.R. D****93*** *(16) 014009* *** Q^2=10**

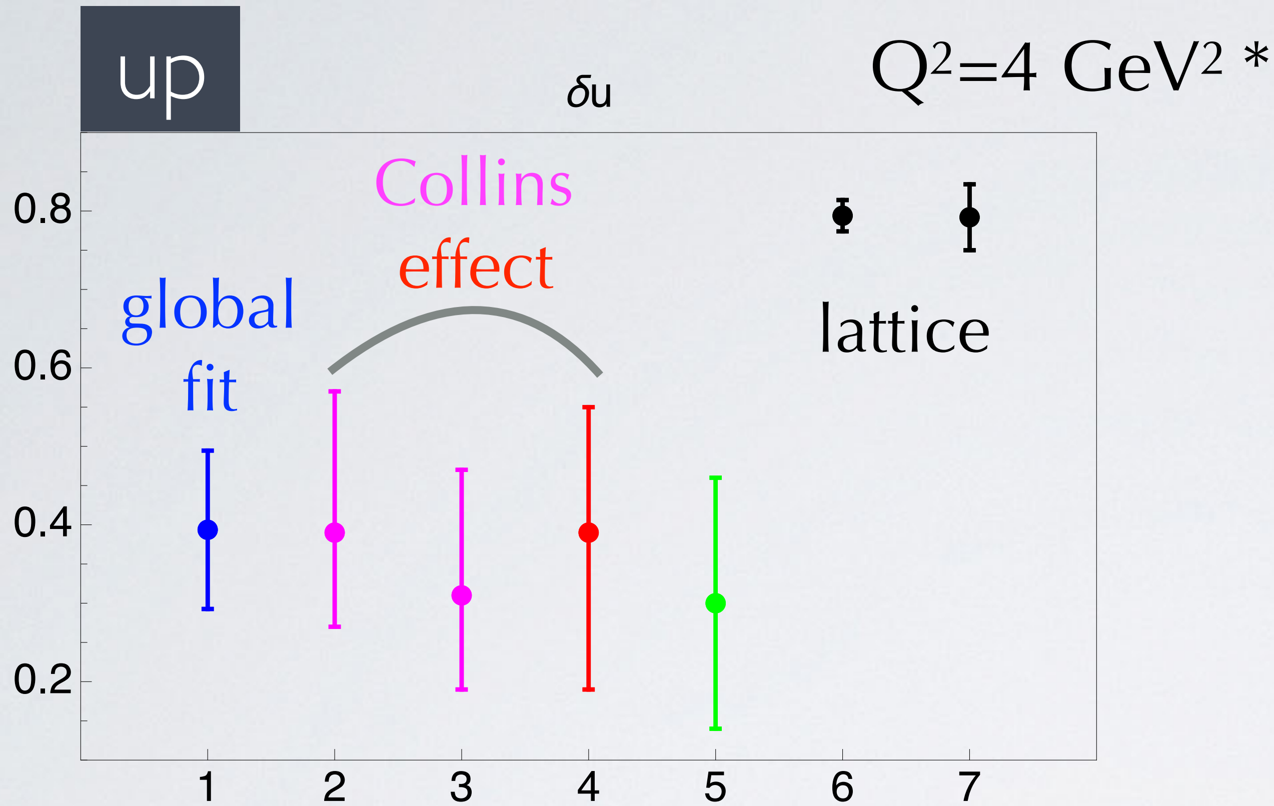
5- JAM fit *Lin et al., P.R.L.****120*** *(18) 152502* {**Collins effect + lattice $g_T=\delta u-\delta d$** *** Q_0^2=2**

6- ETMC17 *Alexandrou et al., P.R. D****95*** *(17) 114514; E P.R. D****96*** *(17) 099906*

7- PNDME16 *Bhattacharya et al., P.R. D****94*** *(16) 054508*



tensor charge $\delta q(Q^2) = \int dx\, h_1^{q-\bar{q}}(x,Q^2)$



incompatibility for up

compatible for down
but with large errors
(except JAM)

1- global fit *Radici & Bacchetta, P.R.L.* ***120*** *(18) 192001*

2,3- Torino *Anselmino et al., P.R. D**87** (13) 094019* *** Q^2=1**

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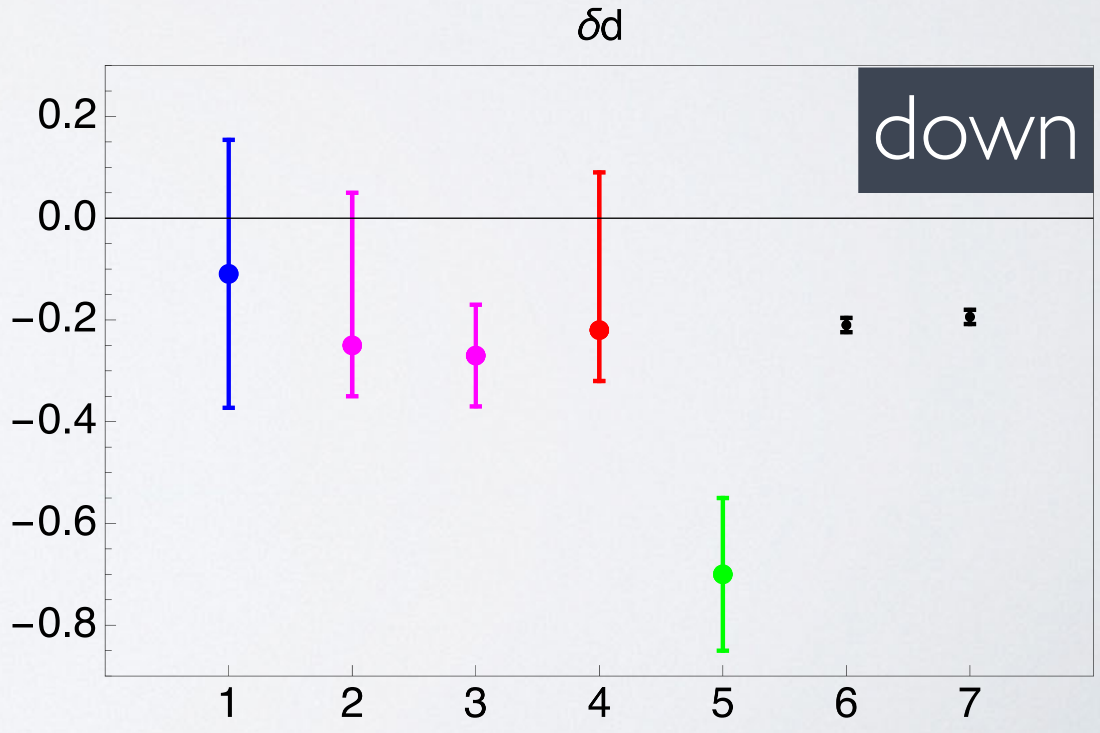
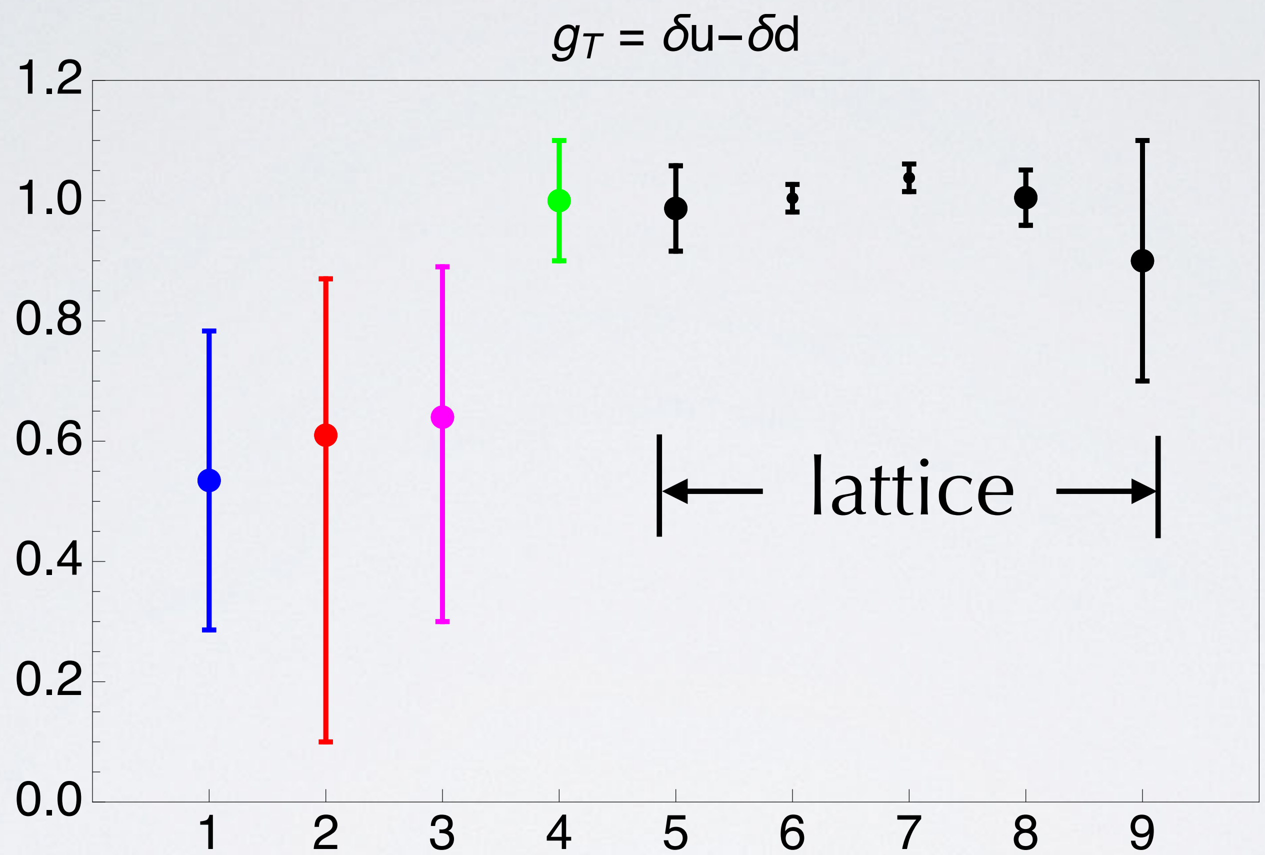


isovector tensor charge $g_T = \delta u - \delta d$

$Q^2=4\ GeV^2$ *



incompatibility (except JAM)

Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — **1) global fit '17**

*Kang et al., P.R. D****93*** *(16) 014009* — **2) "TMD fit" * $Q^2=10$**

*Anselmino et al., P.R. D****87*** *(13) 094019* — **3) Torino fit * $Q^2=1$**

Lin et al., P.R.L. ***120*** *(18) 152502* — **4) JAM fit '17 * $Q_0^2=2$**

5) PNDME '16 — *Bhattacharya et al., P.R. D****94*** *(16) 054508*

6) ETMC '17 — *Alexandrou et al., P.R. D****95*** *(17) 114514; E P.R. D****96*** *(17) 099906*

7) LHPC '12 — *Green et al., P.R. D****86*** *(12)*

8) RQCD '14 — *Bali et al., P.R. D****91*** *(15)*

9) RBC-UKQCD — *Aoki et al., P.R. D****82*** *(10)*

“transverse-spin puzzle” ?

there seems to be no simultaneous compatibility
about δu, δd, $g_T = \delta u - \delta d$
between lattice and
phenomenological extractions
of transversity

results

$$h_1^q(x) \overset{x \to 0}{\approx} x^{A_q + a_q - 1}$$

- 2nd option: finite violation of Burkhardt-Cottingham sum rule

$$\longrightarrow \quad A_q + a_q > 1$$

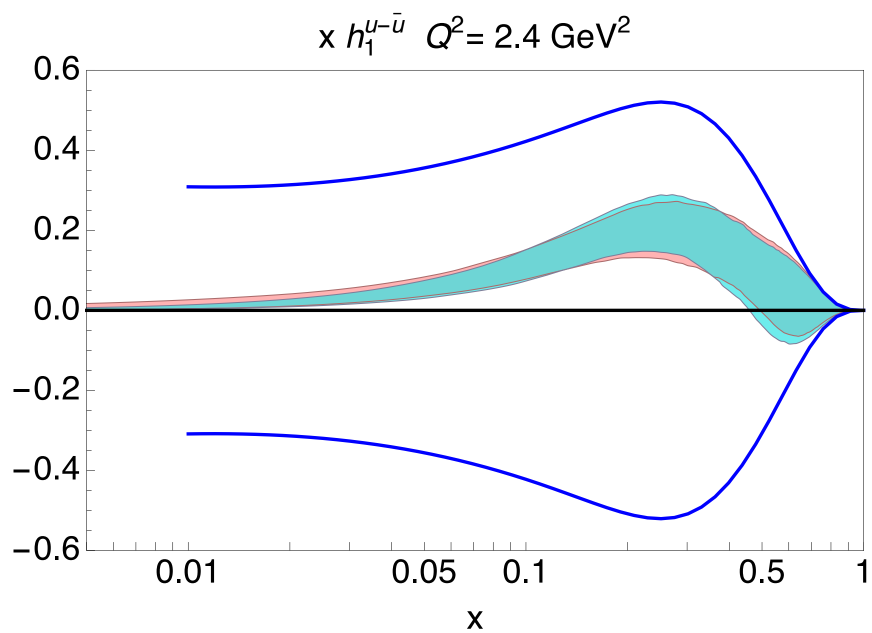
impact of low-x constraint

global fit 2nd option

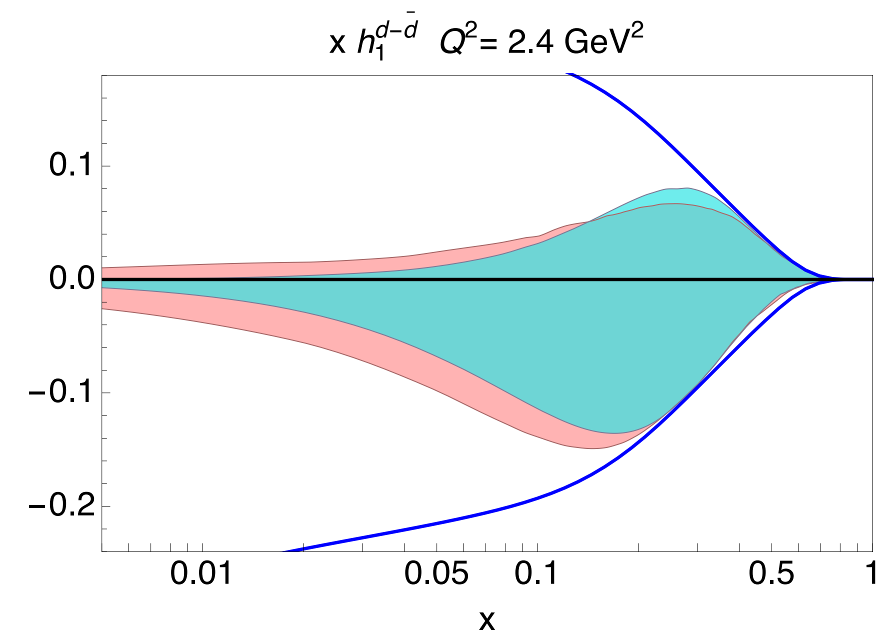
global fit 1st option

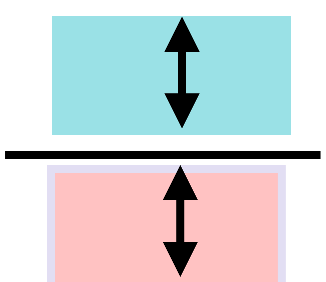
$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$

up

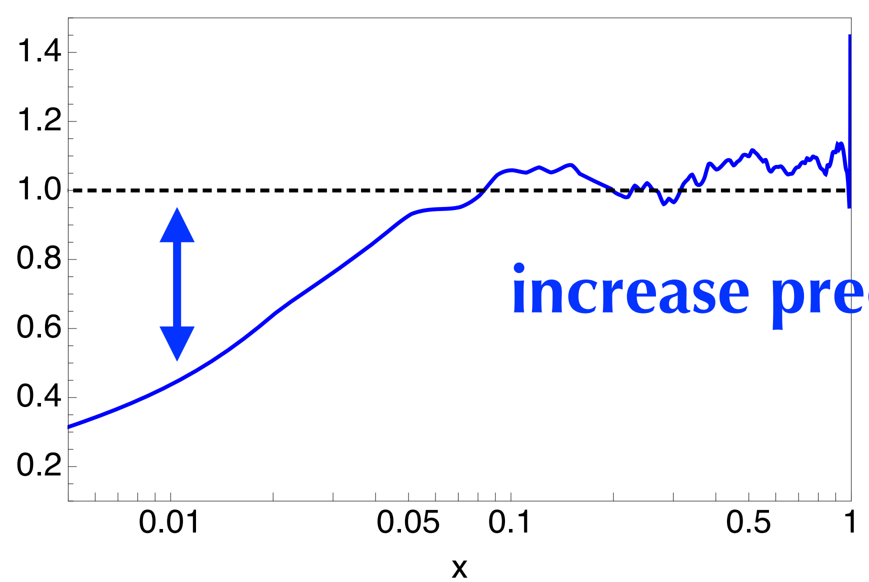


down

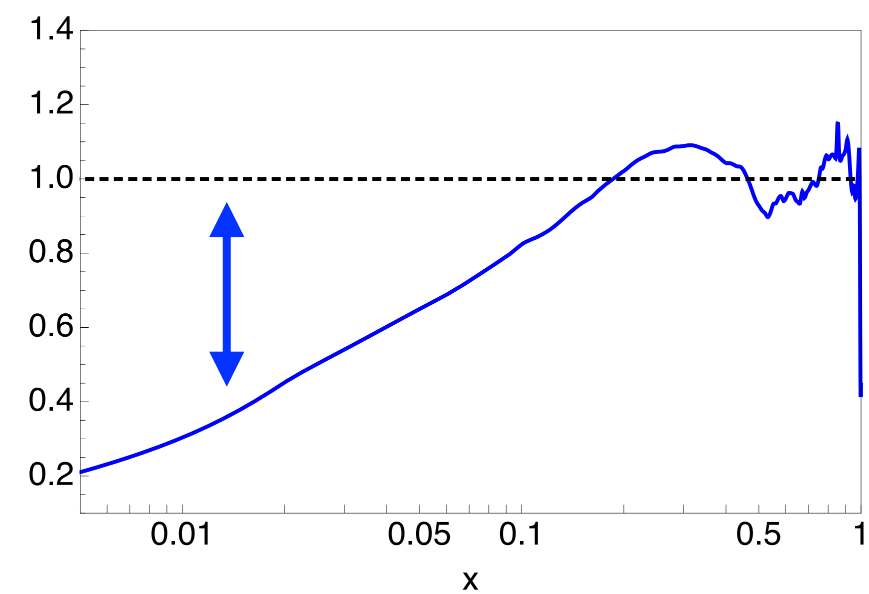




ratio of widths

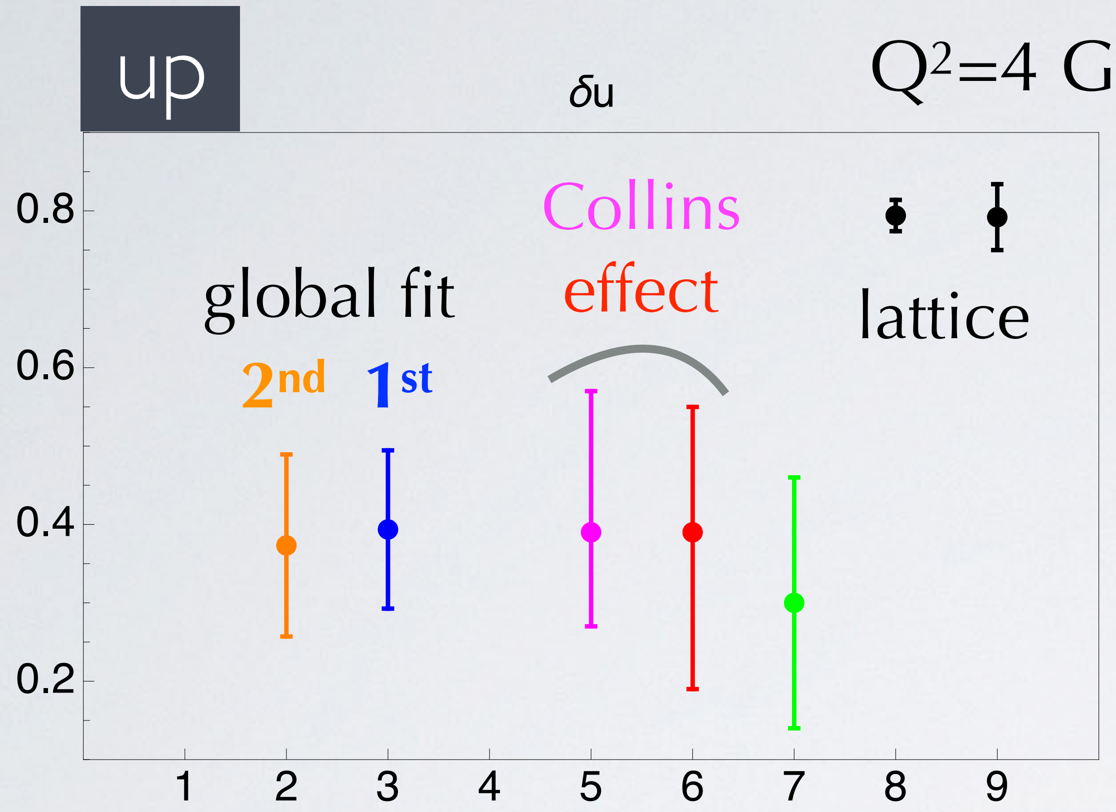


increase precision



impact of low-x constraint

Q^2=4 GeV^2 *



better down
up still incompatible
(similarly for isovector g_T)

general scenario confirmed

2- global fit 2nd option

3- global fit 1st option *Radici & Bacchetta, P.R.L.* ***120*** *(18) 192001*

5- Torino *Anselmino et al., P.R. D****87*** *(13) 094019* *** Q^2=1**

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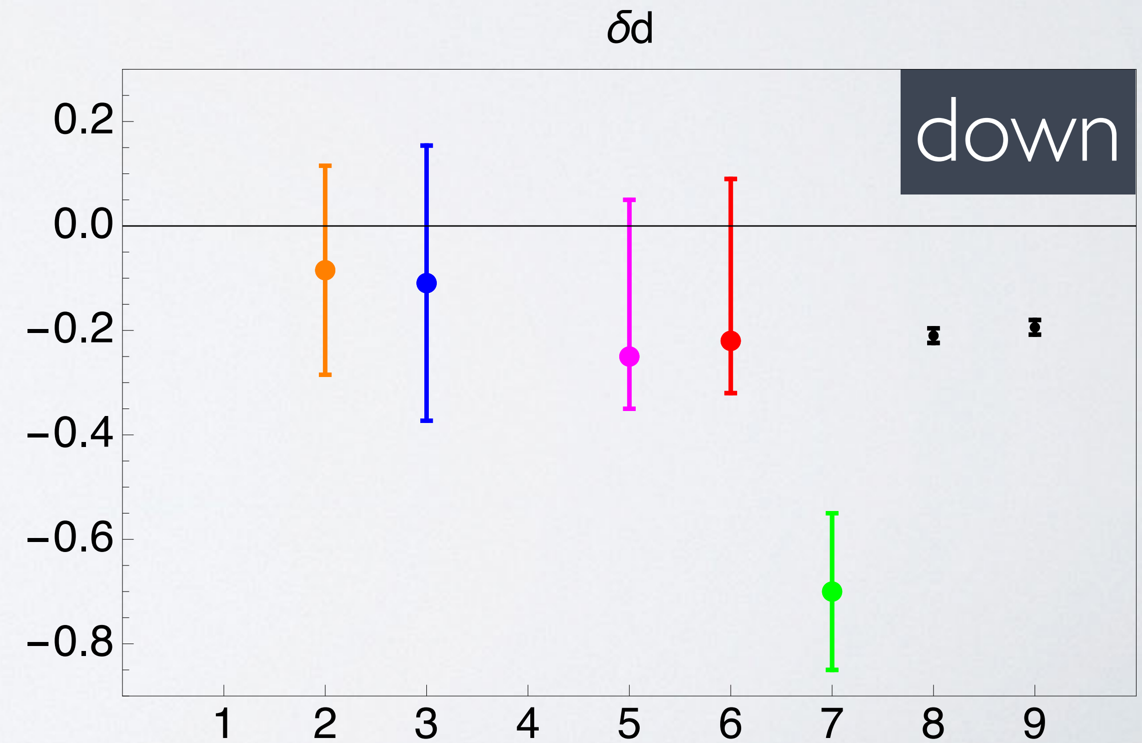
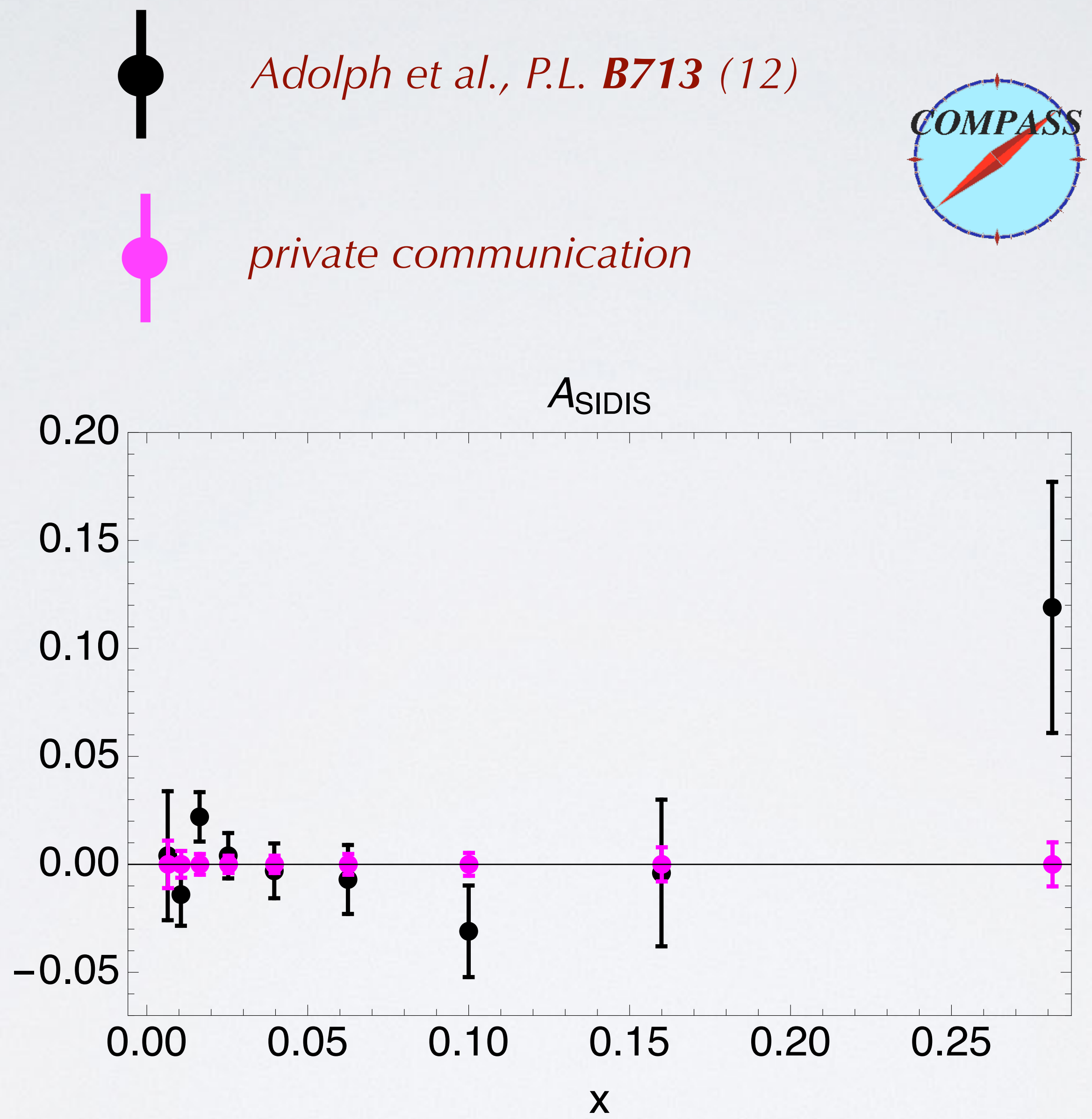


add Compass pseudodata for future deuteron run



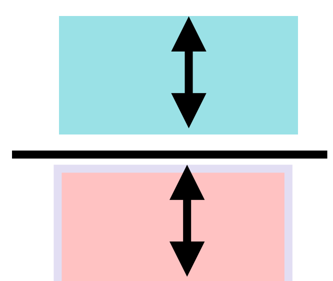
$$A_{\text{SIDIS}} \sim h_1^{u_v} + h_1^{d_v}$$

impact of pseudodata

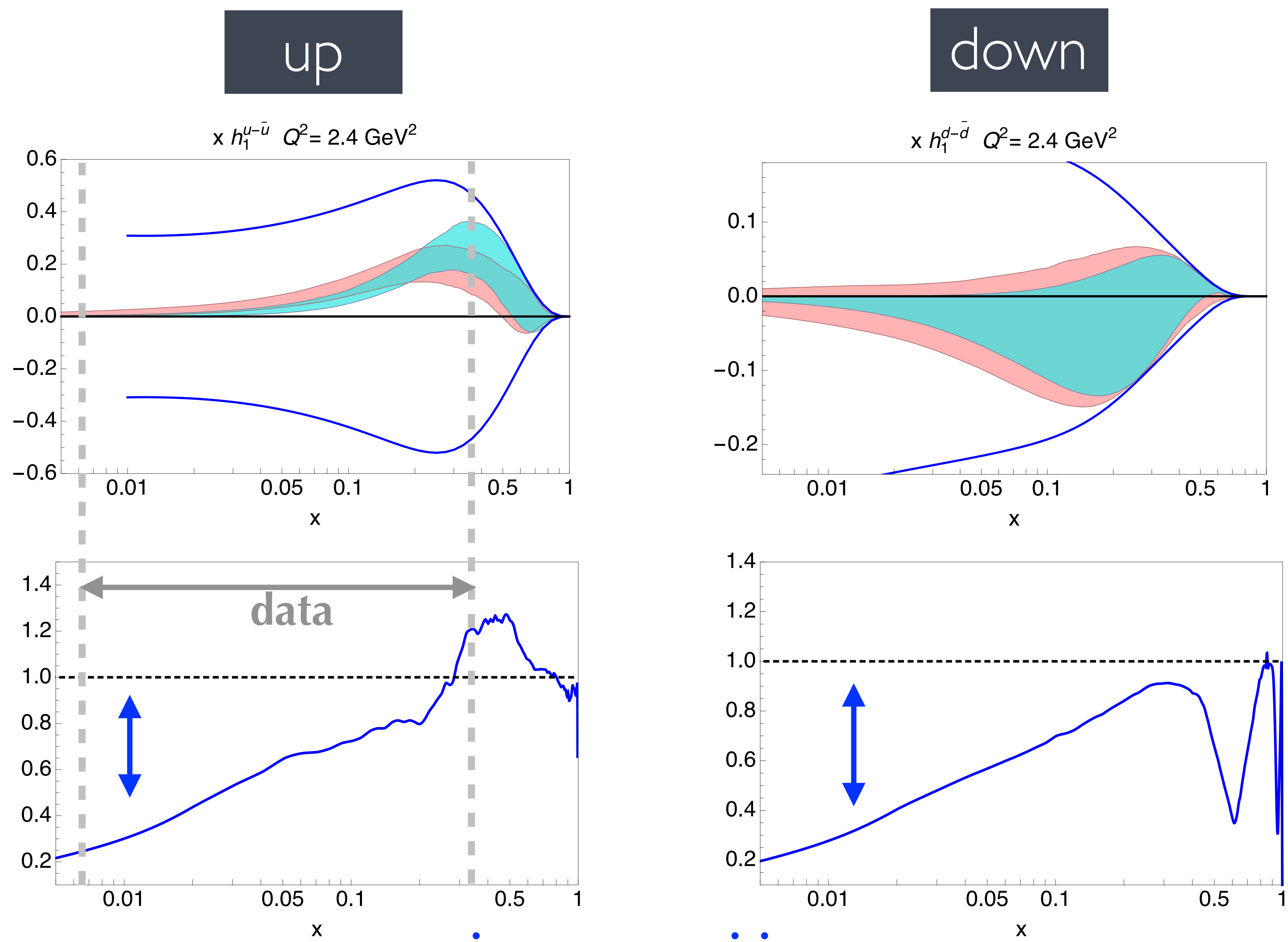
global fit + pseudodata

global fit

$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$

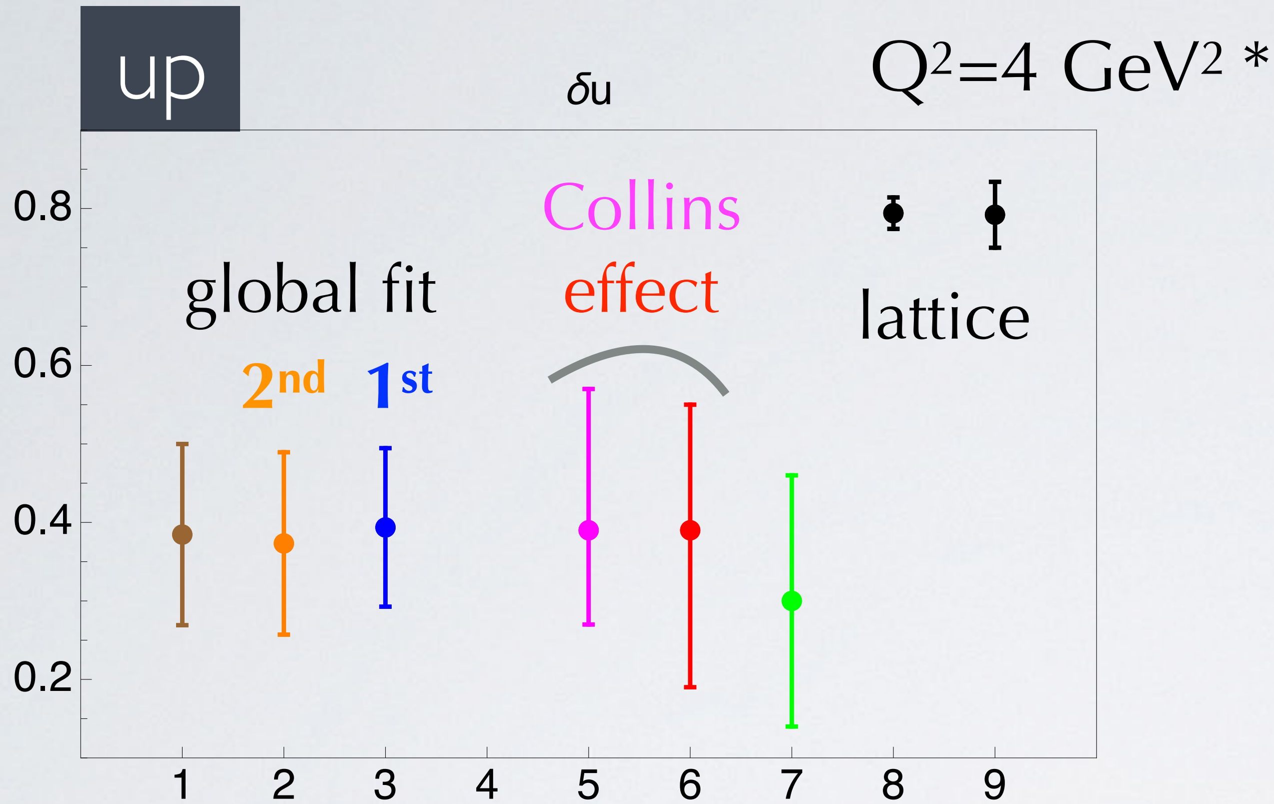


ratio of widths

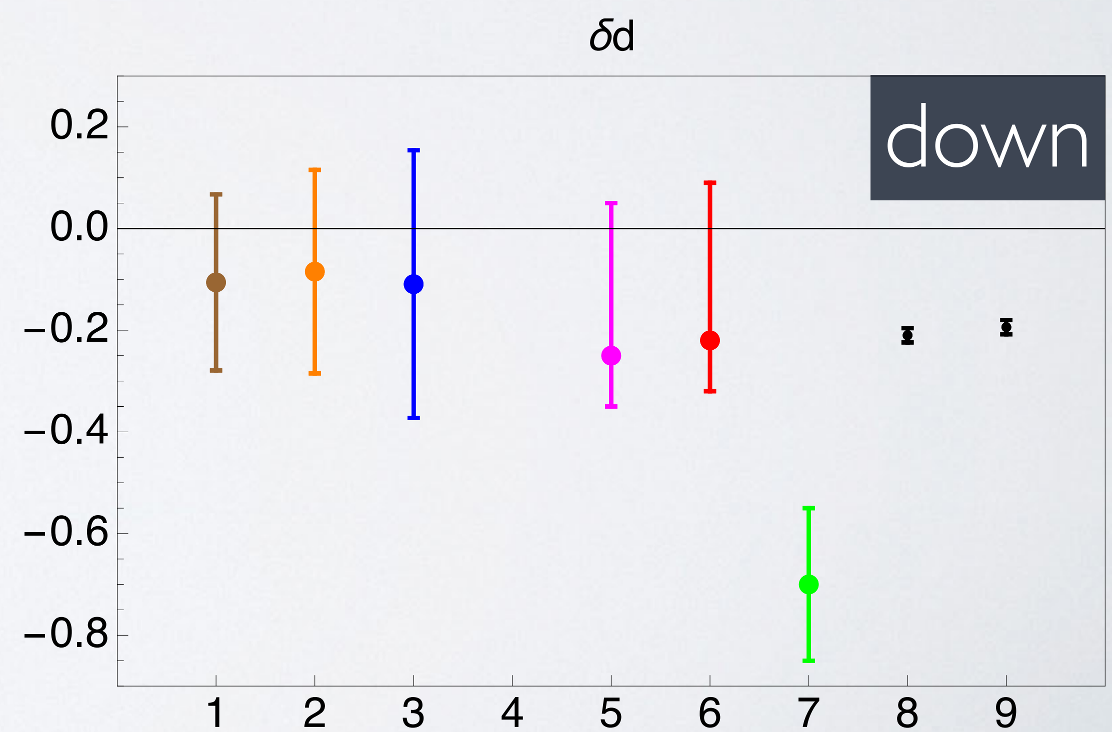


increase precision

impact of pseudodata



again better down
but confirm general picture



1- global fit 2nd option + pseudodata

2- global fit 2nd option

3- global fit 1st option *Radici & Bacchetta, P.R.L.* ***120*** *(18) 192001*

5- Torino *Anselmino et al., P.R. D****87*** *(13) 094019* * $Q^2=1$

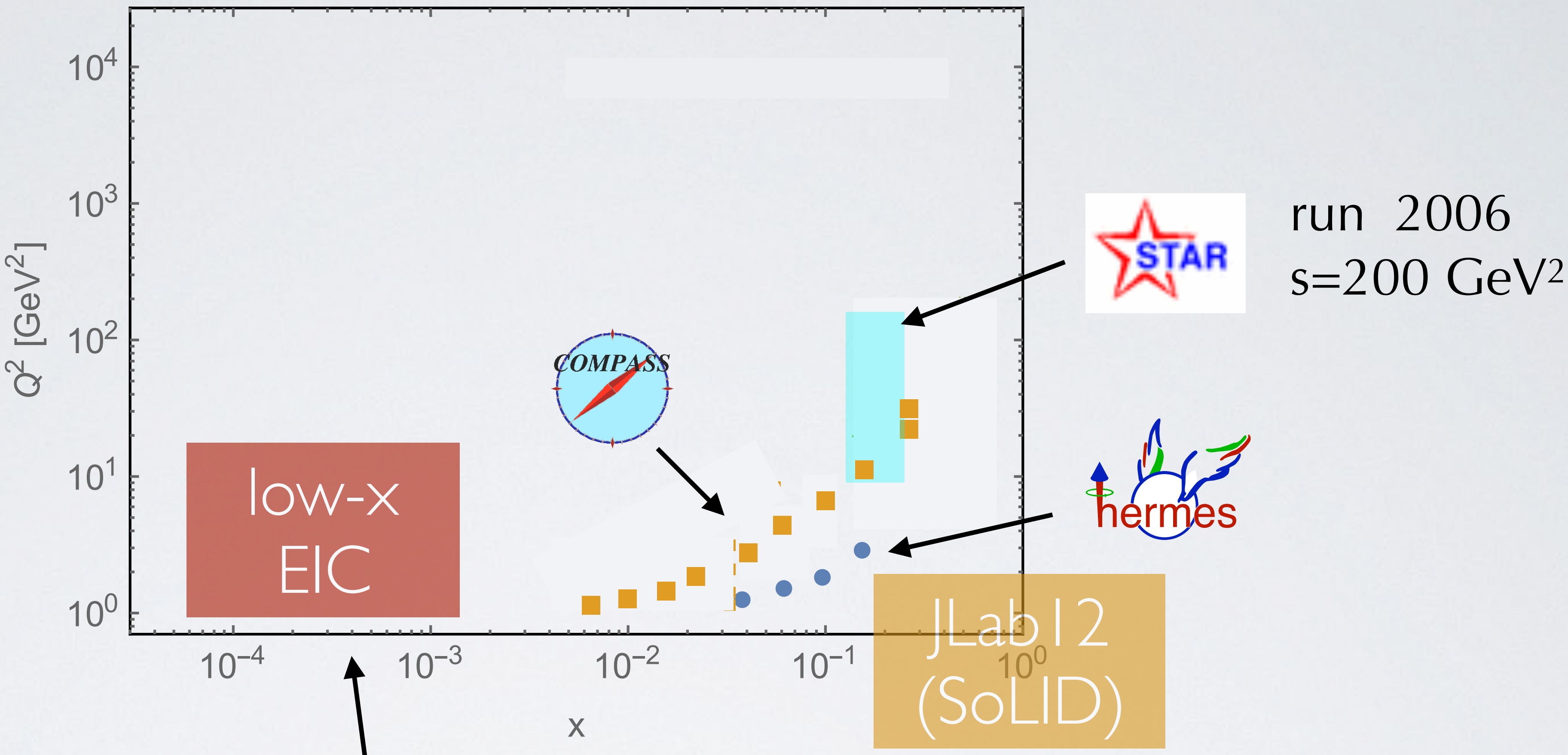
6- TMD fit *Kang et al., P.R. D****93*** *(16) 014009* * $Q^2=10$

7- JAM fit *Lin et al., P.R.L.****120*** *(18) 152502* {**Collins effect + lattice $g_T=\delta u-\delta d$** * $Q_0^2=2$

8- ETMC17 *Alexandrou et al., P.R. D****95*** *(17) 114514; E P.R. D****96*** *(17) 099906*

9- PNDME16 *Bhattacharya et al., P.R. D****94*** *(16) 054508*

more constraints on extrapolation



- of course, need more data

- theoretical constraints from low-x behavior in dipole picture (generalize work on helicity $\Delta q^S(x, Q^2) \approx \left(\frac{1}{x}\right)^{\alpha_h}$ $\alpha_h = \frac{4}{\sqrt{3}}\sqrt{\frac{\alpha_s N_c}{2\pi}}$ by

*Kovchegov et al., P.L. **B772** (17) 136*

Conclusions

- first global fit of di-hadron inclusive data leading to extraction of transversity as a PDF in collinear framework
- inclusion of STAR p-p$^{\uparrow}$ data increases precision of up channel; large uncertainty on down due to unconstrained gluon unpolarized di-hadron fragmentation function
- no apparent simultaneous compatibility with lattice for tensor charge of up, down, and isovector
- adding Compass pseudodata for deuteron confirms the scenario
- need data spanning larger x range; meantime, look for other theoretical constraints on extrapolation (mostly, at low x)

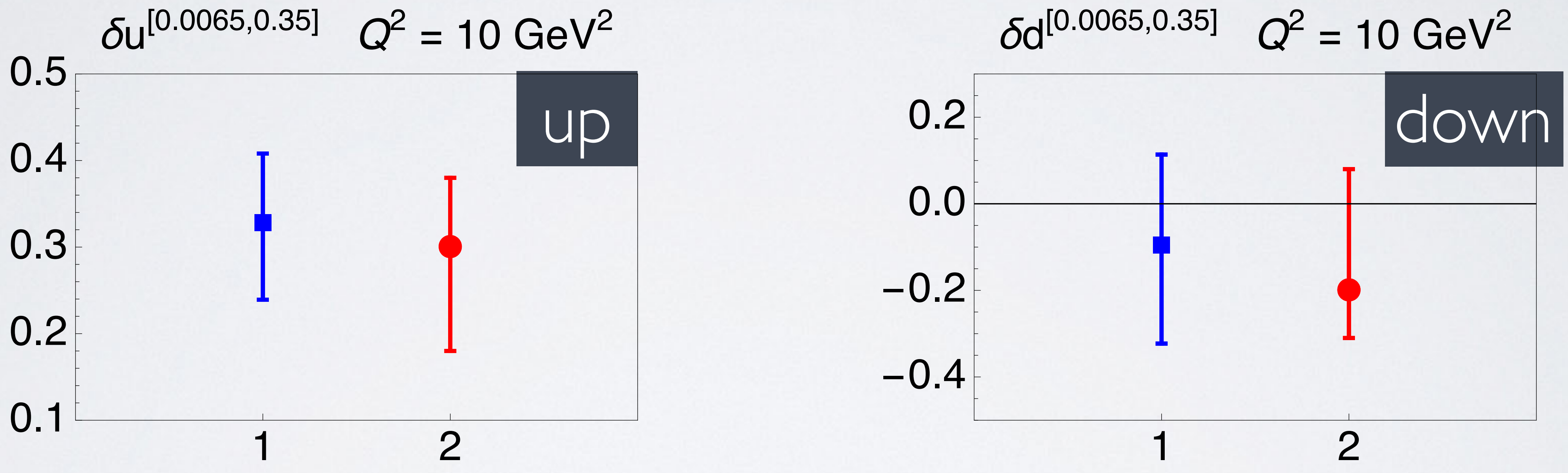
THANK YOU

Back-up

tensor charge $\delta q(Q^2) = \int dx\, h_1^{q-\bar{q}}(x,Q^2)$

truncated

$\delta q^{[0.0065,0.35]}$ $Q^2 = 10$



global fit
Radici & Bacchetta,
P.R.L. ***120*** *(18) 192001*

TMD fit
Kang et al.,
*P.R. D**93*** *(16) 014009*

tensor charge $\delta q(Q^2) = \int dx\ h_1^{q-\bar{q}}(x,Q^2)$

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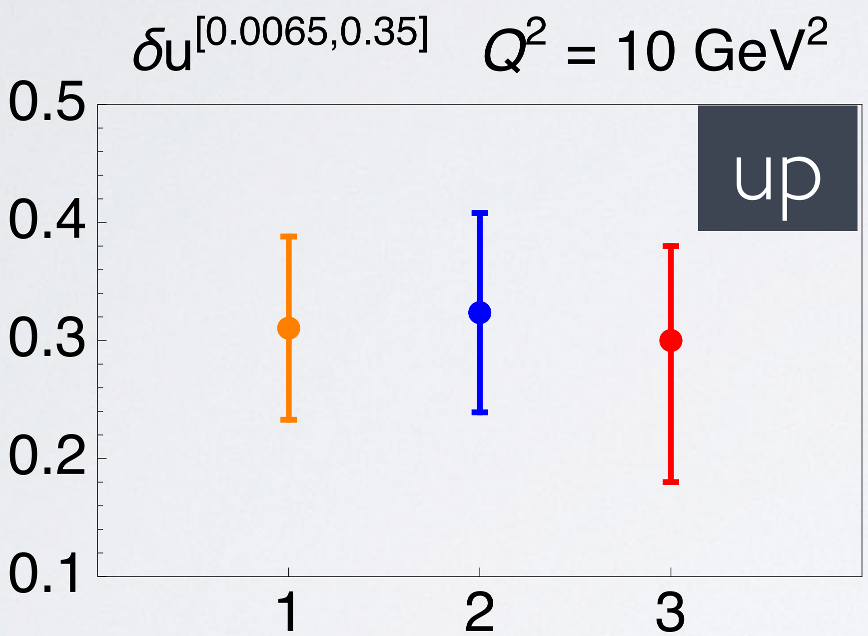
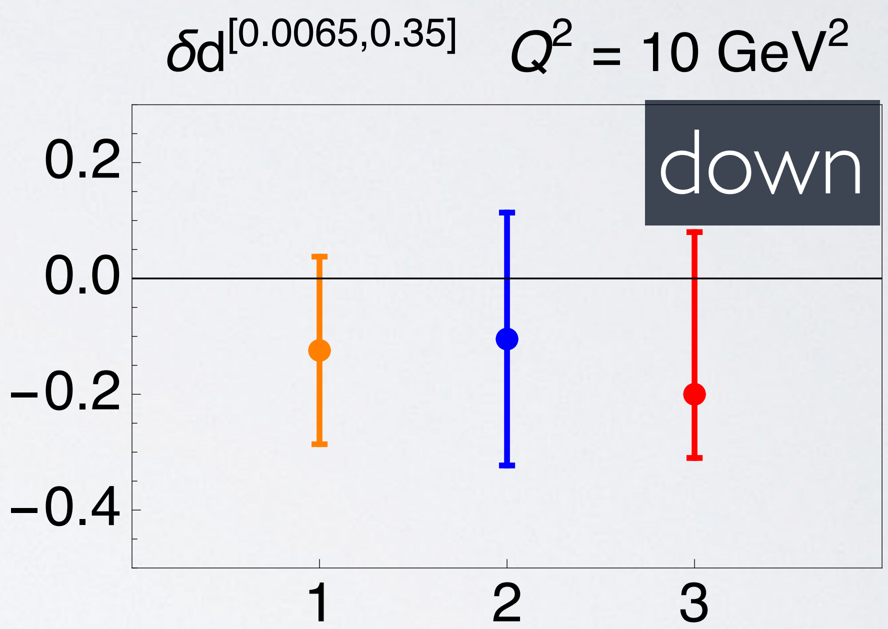
$\delta q^{[0.0065,0.35]}$ $Q^2 = 10$





+
pseudodata

global fit

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

TMD fit

Kang et al.,
*P.R. D**93** (16) 014009*

χ^2 of the fit

46 data points, **10** parameters

global **χ^2/dof** = 2.08 ± 0.09

≈ 38%

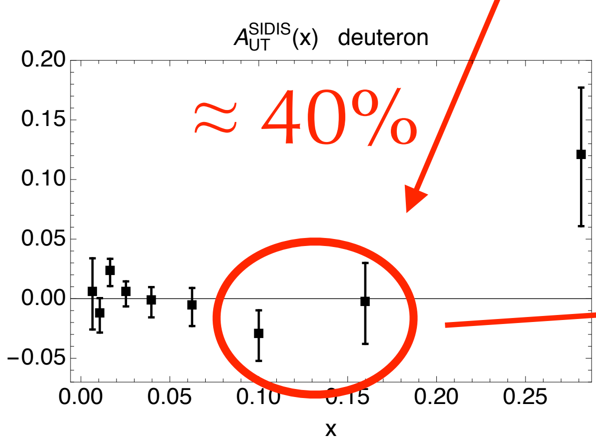
SIDIS

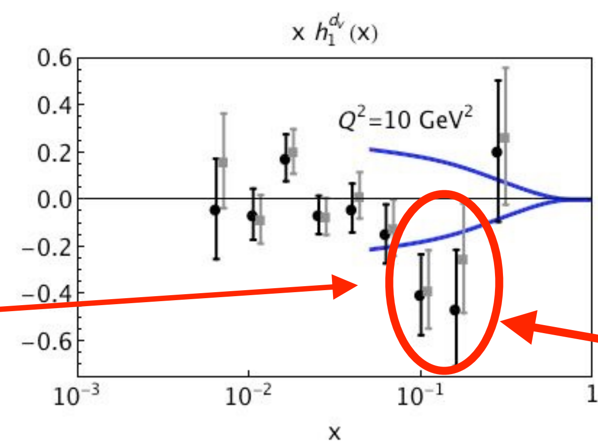
≈ 24% (hermes)

≈ 76% (COMPASS)

→ ≈ 60% rest

≈ 40%





Soffer bound
@10 GeV^2

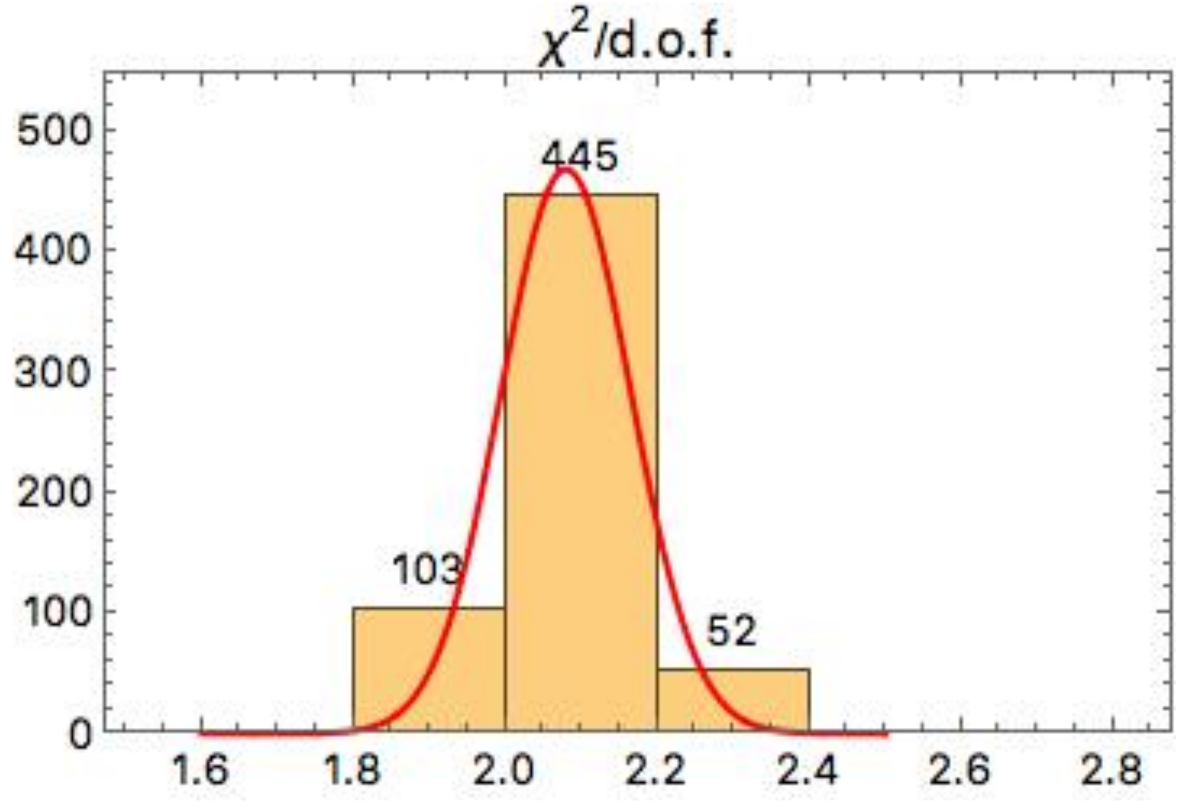
(x=0.1, Q^2~9 GeV^2)
(x=0.16, Q^2~15 GeV^2)

≈ 62%

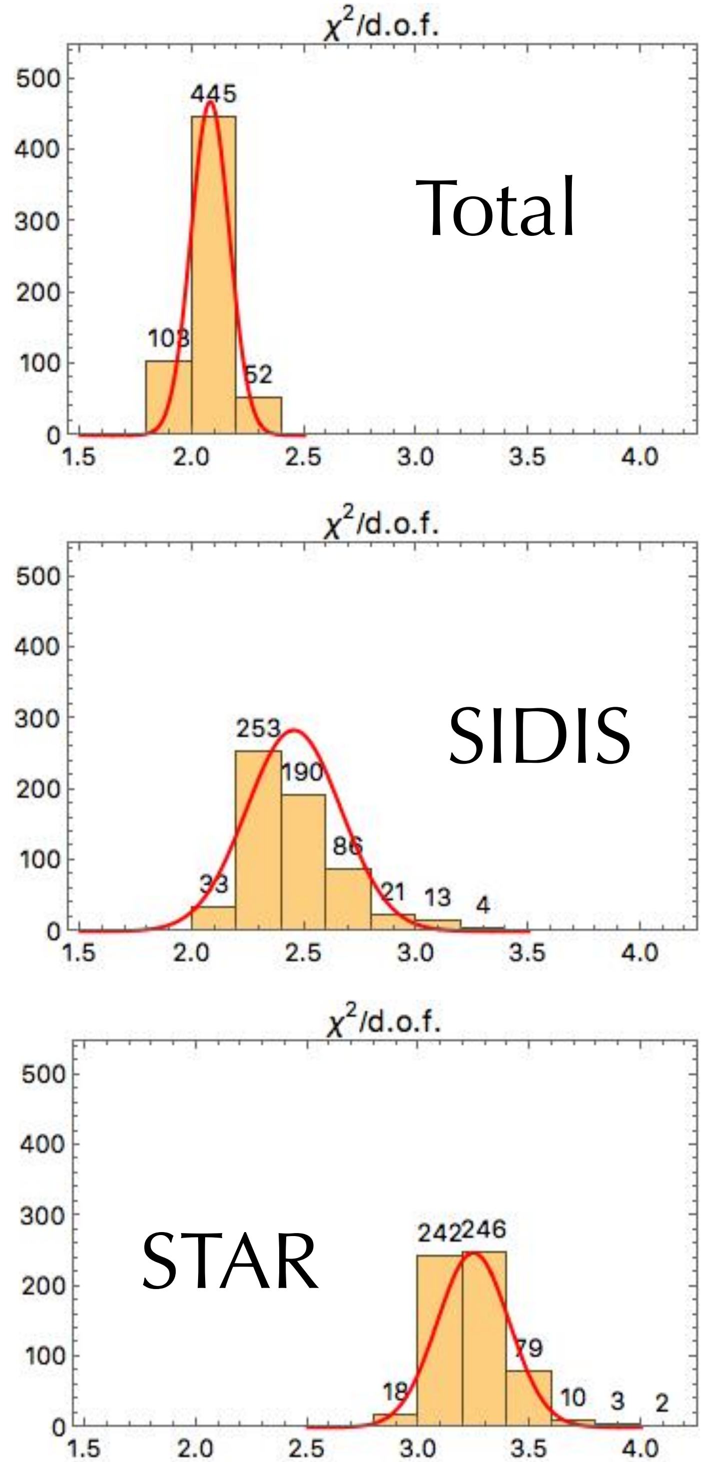
STAR

- P_T bins ≈ 70%
- M_h bins ≈ 28%
- η bins ≈ 2%

χ^2 of the fit

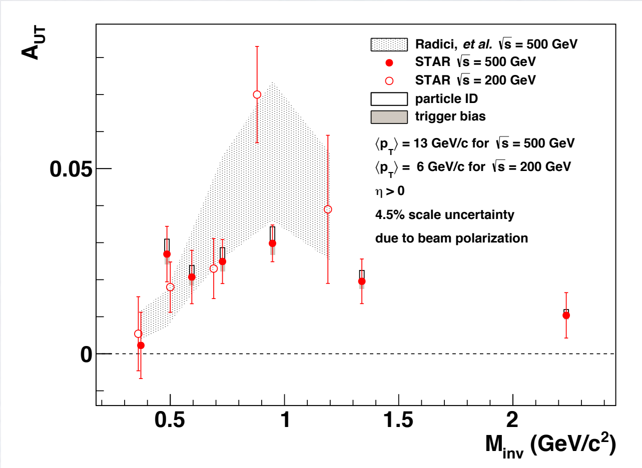


χ^2/dof = 2.08 ± 0.09

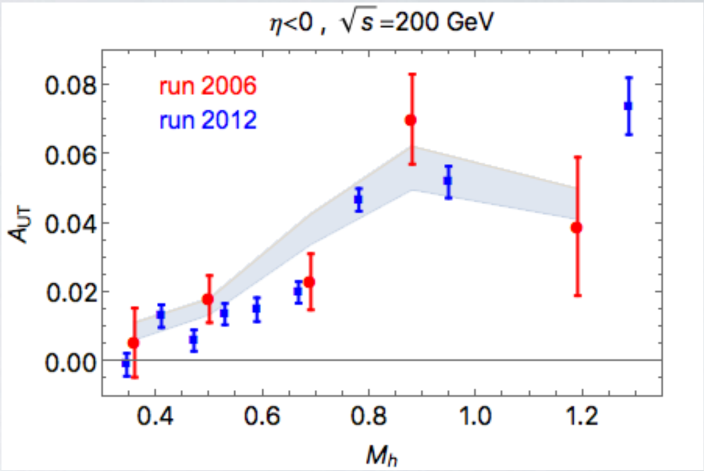


To do list

- ➡ use also other (multi-dimensional) data from STAR run 2011 (s=500) and (later) run 2012 (s=200)



Adamczyk et al. (STAR), P.L. ***B780*** *(18) 332*



*Radici et al., P.R. D**94** (16) 034012*

- ➡ need data on p+p → (ππ) X constrains gluon $D_1{}^g$

- ➡ refit di-hadron fragmentation functions using new data: e^+e^- → (ππ) X constrains $D_1{}^q$ (currently only by Montecarlo)

*Seidl et al., P.R. D**96** (17) 032005*

- ➡ use COMPASS data on πK and KK channels, and from Λ↑ fragmentation: constrain strange contribution ?

- ➡ explore other channels, like inclusive DIS via Jet fragm. funct.'s