QCD EVOLUTION
Workshop

May 20 - 24, 2018
Santa Fe, NM,
Drury Plaza Hotel

TOPICS:
- Hadron structure: theory & experiment
- Transverse momentum dependent distributions
- Generalized parton distributions
- Effective theories, SCET
- Lattice QCD
- Multi-parton interactions
- Resummation techniques
- Nuclear effects, small-x

Organizing Committee

Ian Balitsky	Alexei Prokudin
Martha Constantinou	Anatoly Radyushkin
Leonard Gamberg	Matt Sievert
Chris Lee	Ivan Vitev (Chair)
Duff Neill	Shinsuke Yoshida

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qcdevolution2018@lanl.gov
www.jlab.org/conferences/qcd-evolution2018

First extraction of Transversity from a global analysis of lepton-hadron scattering and hadronic collisions

Marco Radici
INFN - Pavia

in collaboration with
A. Bacchetta (Univ. Pavia)

based on
P.R.L. **120** (2018) 192001
arXiv:1802.05212
plus updates

a phase transition

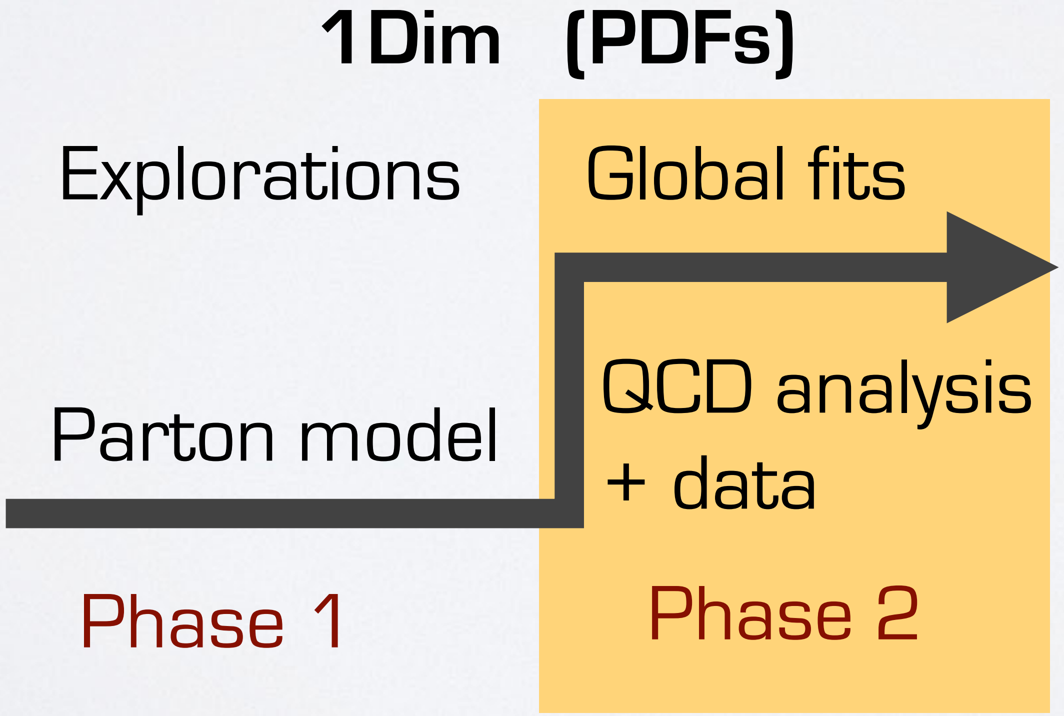
quark polarization

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**



1Dim (PDFs)

Explorations

Global fits

Parton model

QCD analysis
+ data

Phase 1

Phase 2

2-hadron-inclusive production

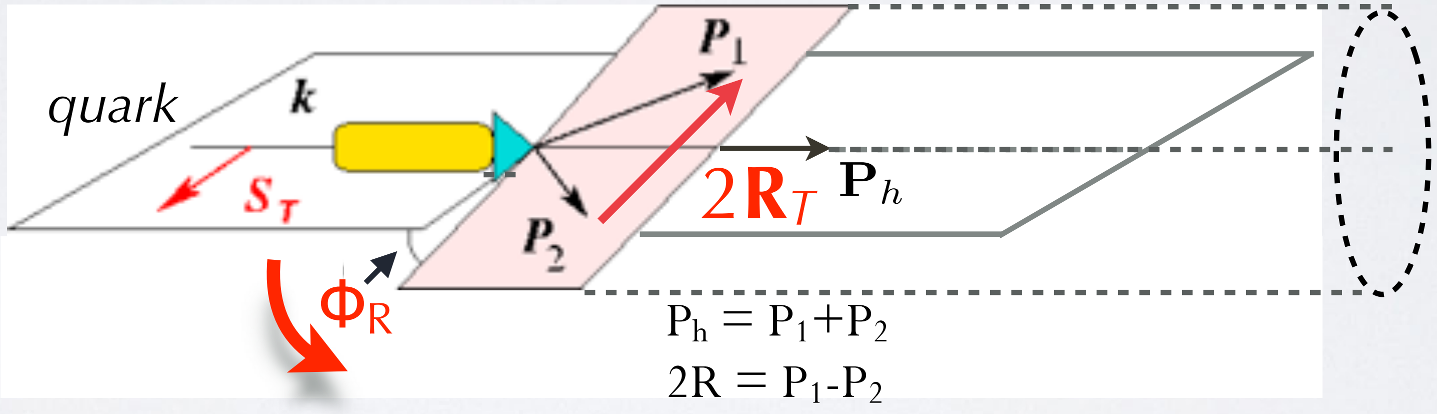
Collins, Heppelman, Ladinsky,
N.P. ***B420*** *(94)*

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

↕

M_h

invariant mass



correlation $\boldsymbol{S_T}$ and $\boldsymbol{R_T}$ → **azimuthal asymmetry**

2-hadron-inclusive production

framework
collinear
factorization

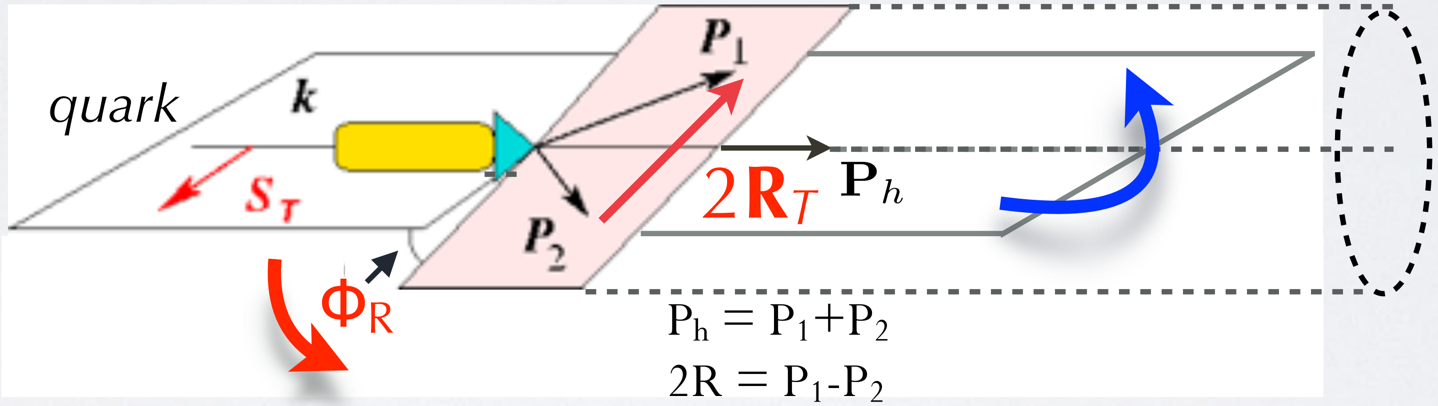
Collins, Heppelman, Ladinsky,
N.P. ***B420*** *(94)*

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

↕

M_h

invariant mass

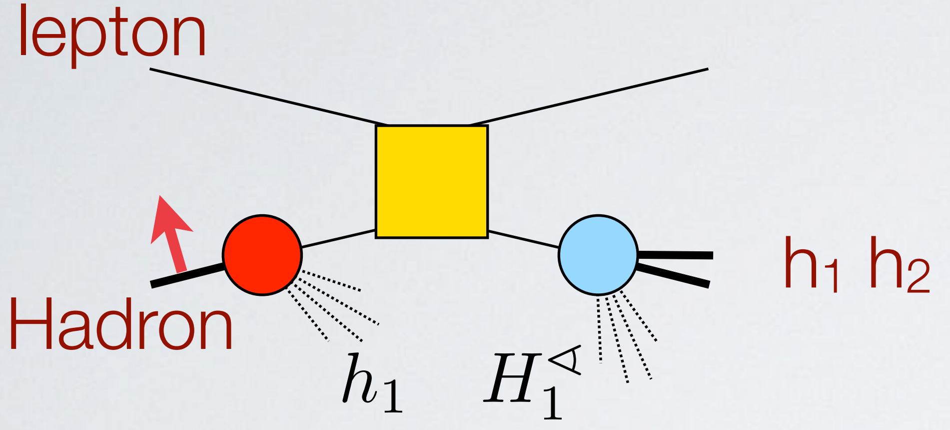


survives to
polar
symmetry
($\int dP_{hT}$)

correlation S_T and R_T → **azimuthal asymmetry**

2-hadron-inclusive production

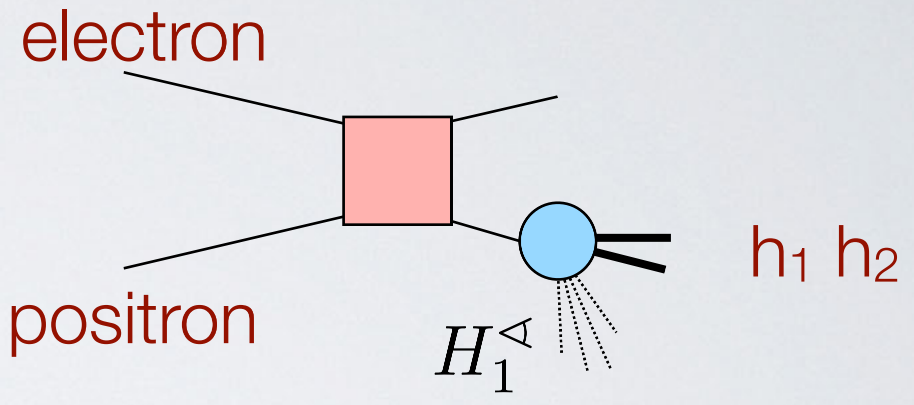
SIDIS



h_1 $H_1^{\sphericalangle}$

framework
collinear
factorization

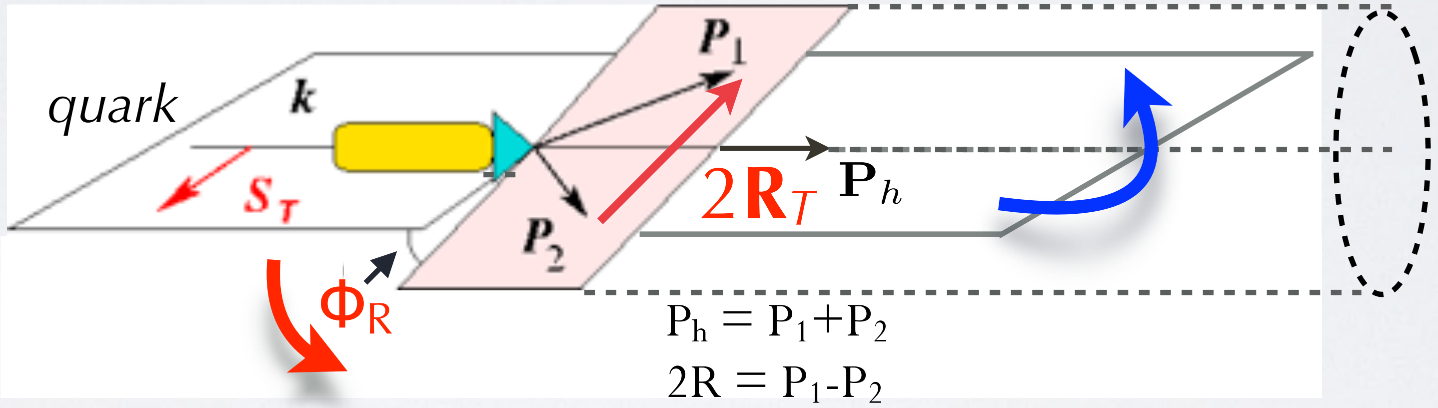
e+e−



$H_1^{\sphericalangle}$

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

↕



$P_h = P_1 + P_2$

$2R = P_1 - P_2$

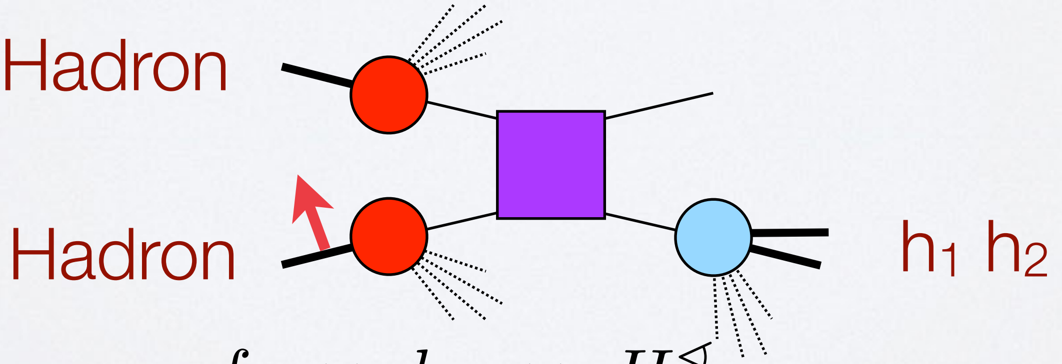
survives to
polar
symmetry
($\int dP_{hT}$)

M_h

invariant mass

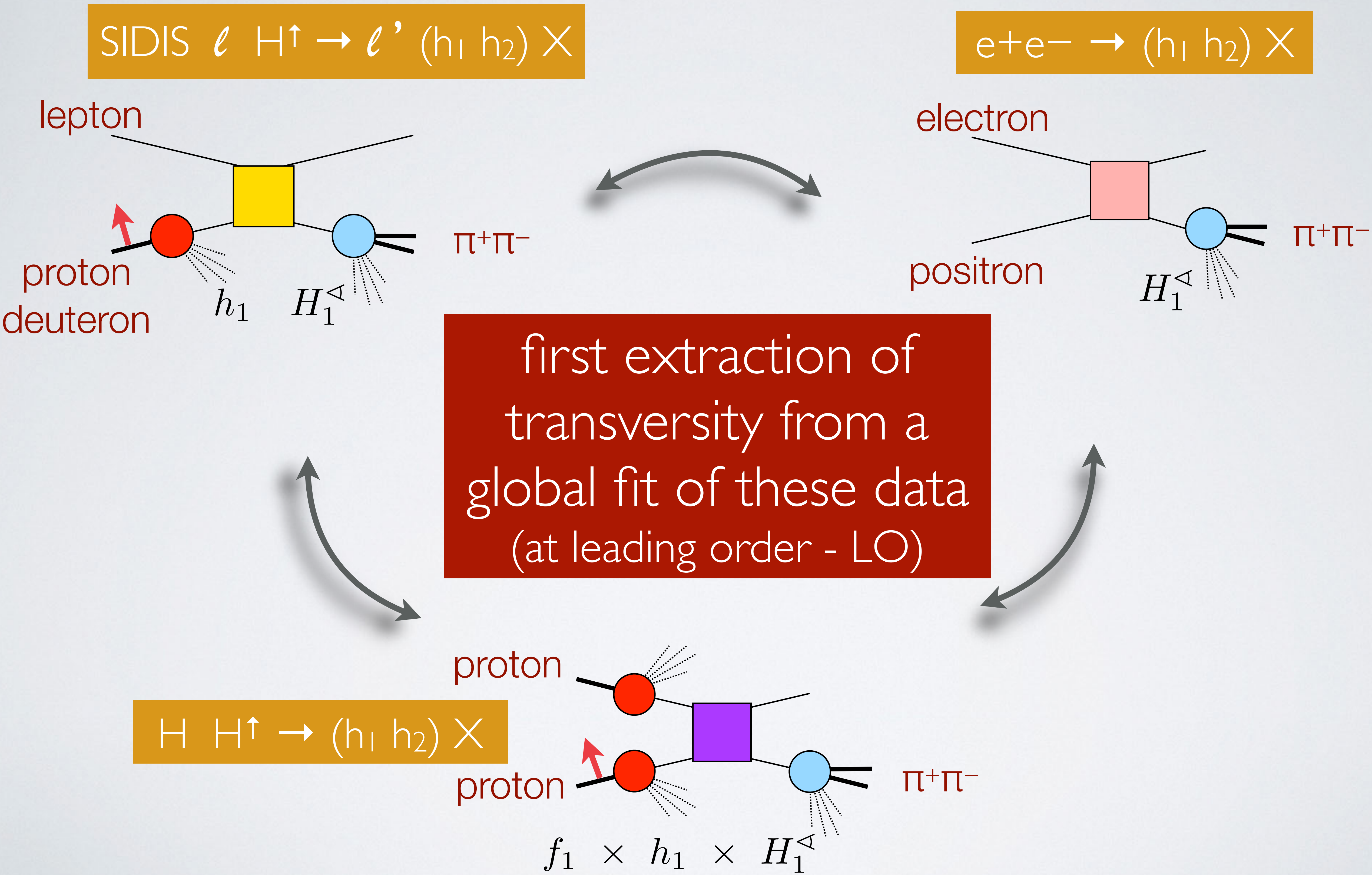
correlation S_T and R_T → **azimuthal asymmetry**

H H↑



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

take–away message



SIDIS $\ell\ H^{\uparrow} \to \ell'\ (h_1\ h_2)\ X$

$e^+e^- \to (h_1\ h_2)\ X$

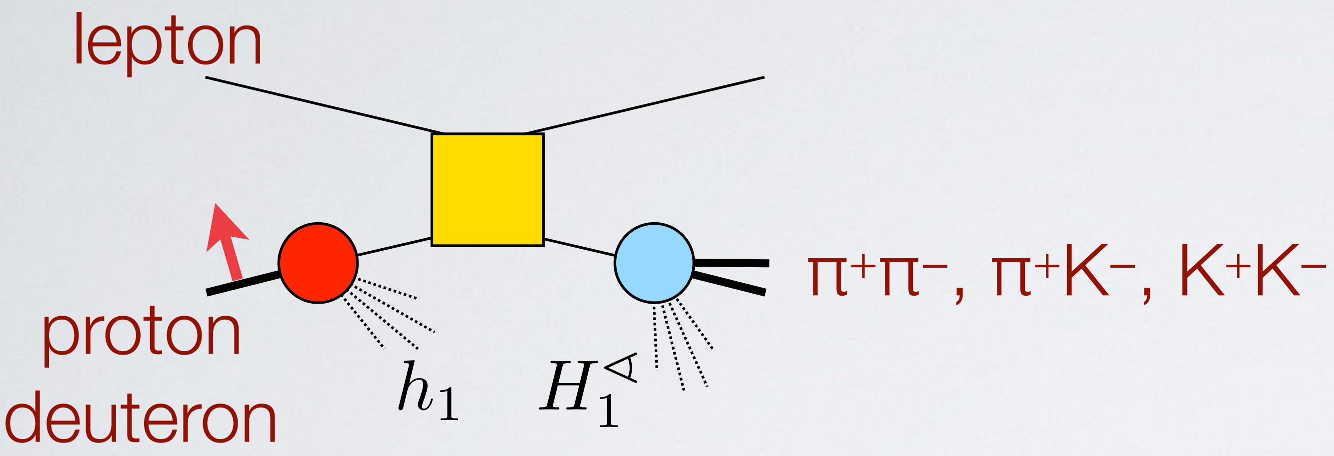
$H\ H^{\uparrow} \to (h_1\ h_2)\ X$

first extraction of transversity from a global fit of these data

(at leading order - LO)

exp. data for 2-hadron-inclusive production

SIDIS ℓ H↑ → ℓ' (h_1 h_2) X

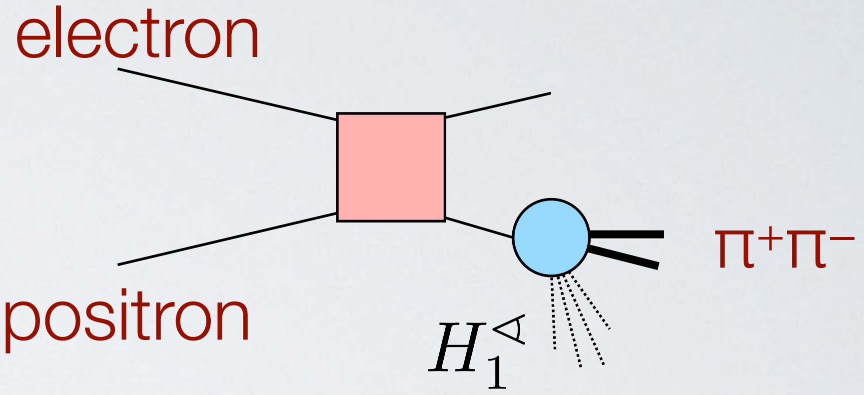


*Airapetian et al., JHEP **0806** (08) 017*

*Adolph et al., P.L. **B713** (12)*

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

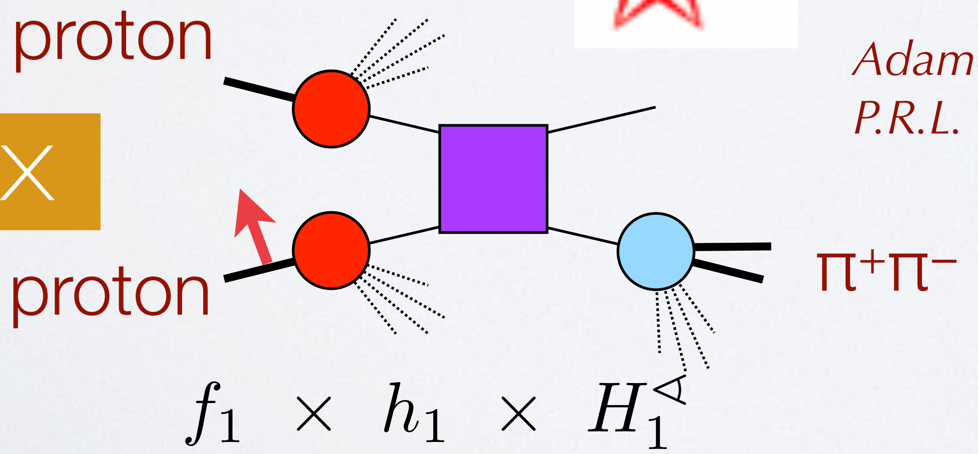
e^+e^- → (h_1 h_2) X



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

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

H H↑ → (h_1 h_2) X



run 2006 (s=200)

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

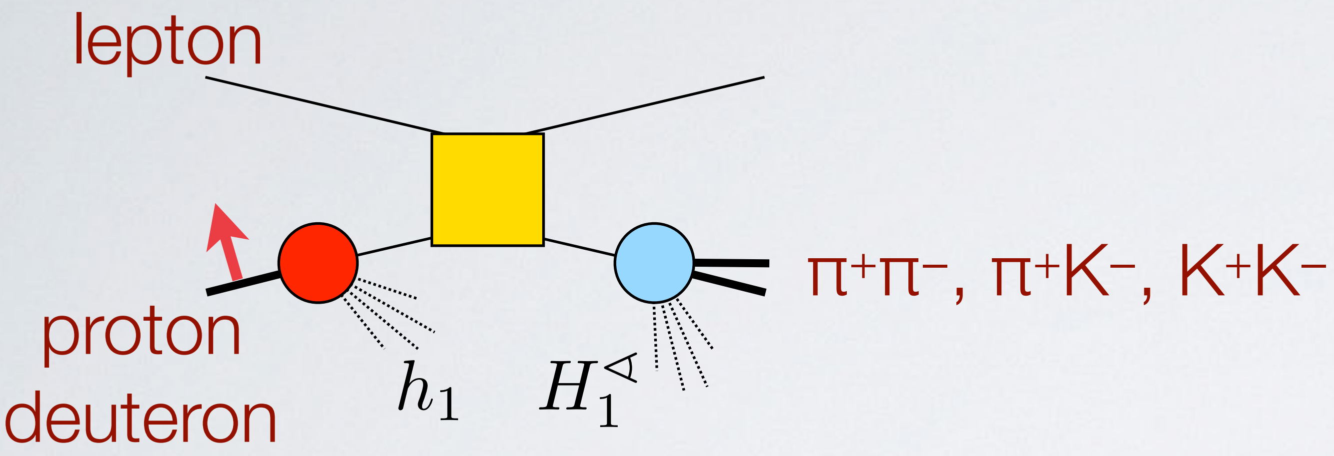
run 2011 (s=500)

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

A_{UT} (η, M_h, P_T)

exp. data for 2-hadron-inclusive production

SIDIS ℓ H$^\uparrow$ → ℓ' (h_1 h_2) X

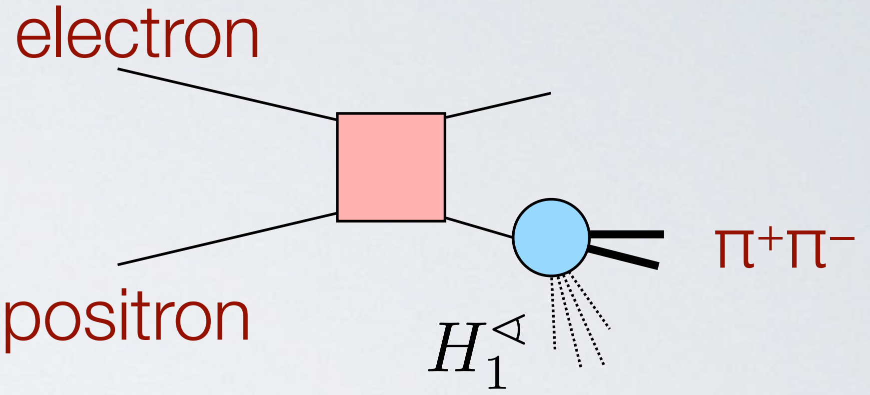


Airapetian et al.,
JHEP ***0806*** *(08) 017*

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

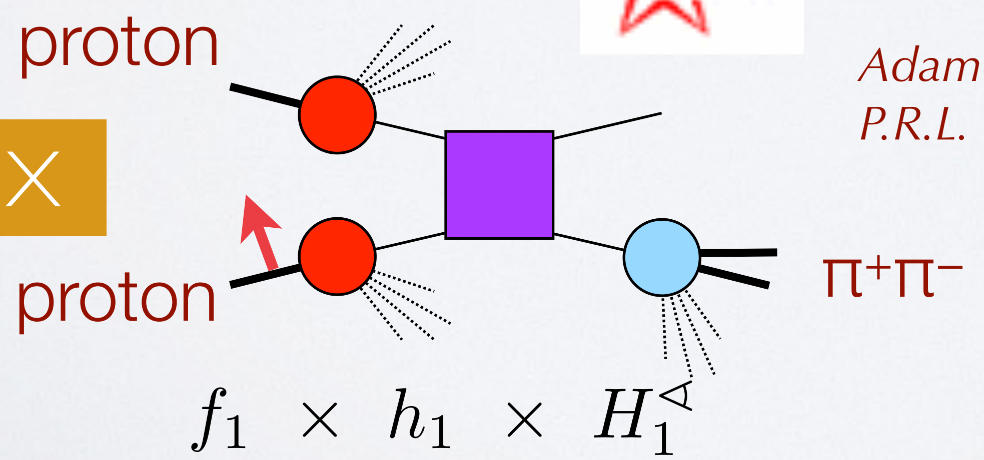


Vossen et al., P.R.L. ***107*** *(11) 072004*

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

from Montecarlo

H H$^\uparrow$ → (h_1 h_2) X



run 2006

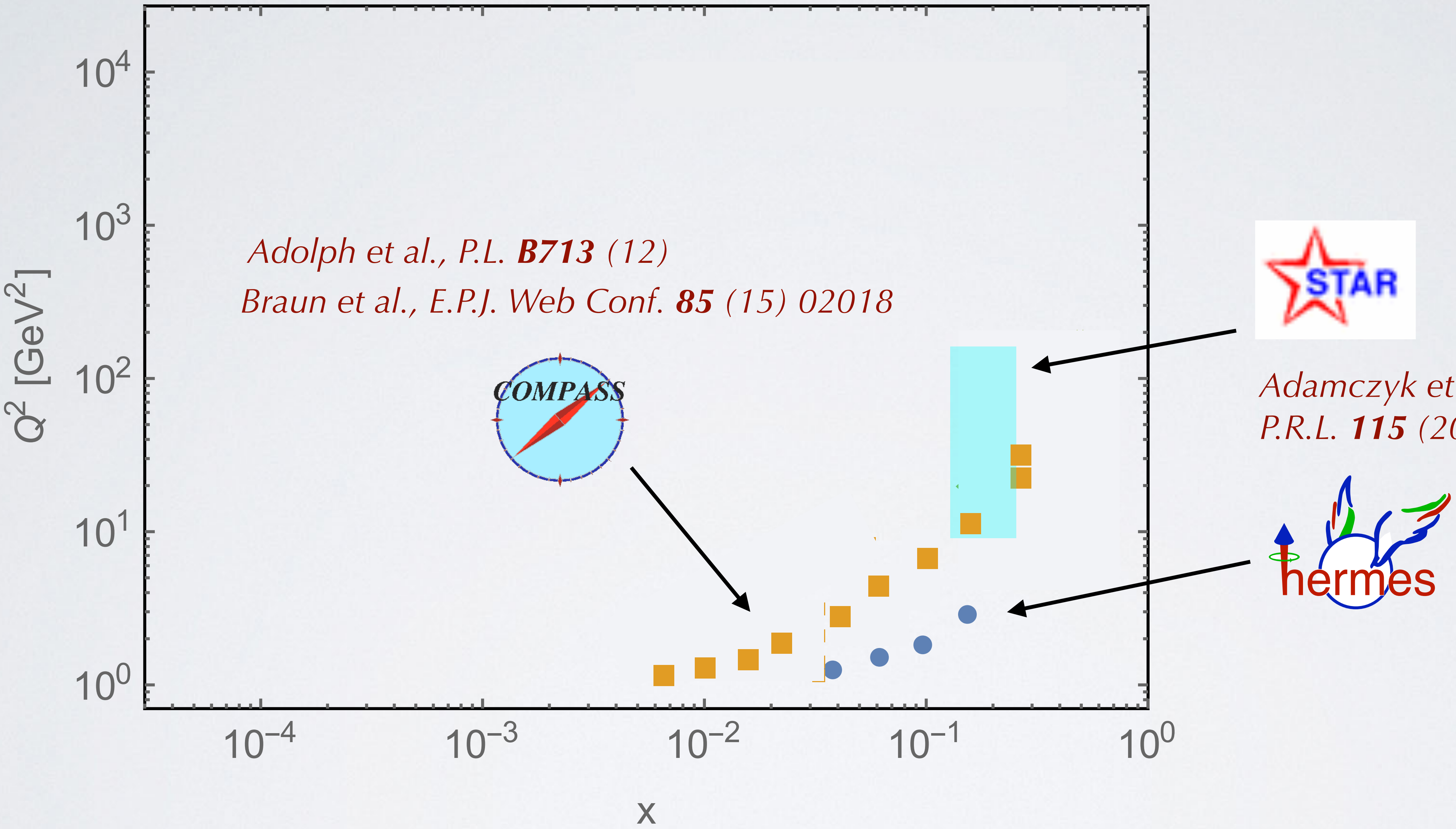
Adamczyk et al. (STAR),
P.R.L. ***115*** *(2015) 242501*

run 2011

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

$A_{UT}\,(\eta, M_h, P_T)$

the kinematics



Adolph et al., P.L. ***B713*** *(12)*

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

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

different funct. form whose Mellin transform can be computed analytically but keep main feature: comply with Soffer Bound at any x and scale Q²

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

↓ 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

choice of functional form

different funct. form whose Mellin transform can be computed analytically but keep main feature: comply with Soffer Bound at any x and scale Q^2

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MSTW08 DSSV

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

$$|N_{q_v}| \leq 1\ \Rightarrow\ |F^{q_v}(x)| \leq 1$$

Ceb$_n$(x) Cebyshev polynomial

10 fitting parameters

Soffer Bound satisfied at any Q^2

choice of functional form

different funct. form whose Mellin transform can be computed analytically but keep main feature: comply with Soffer Bound at any x and scale Q²

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

Soffer Bound

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

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$$|N_{q_v}| \leq 1 \ \Rightarrow\ |F^{q_v}(x)| \leq 1$$

Ceb$_n$(x) Cebyshev polynomial

10 fitting parameters

Soffer Bound satisfied at any Q²

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

$A_q + a_q > \frac{1}{3}$ grants that tensor charge $\delta q(Q^2) = \int_{x_{\min}}^{1} dx\, h_1^{q-\bar{q}}(x,Q^2)$ is finite and error $O(1\%)$

constrain parameter

MSTW08 x$_{\min}$=10^{-6}

theoretical uncertainties

quark D_1^q is well constrained by e^+e^- (Montecarlo) but

we don’t know anything about the gluon D_1^g (e^+e^- doesn’t help..)

Single-Spin Asymmetry
in p-$p^\uparrow$ collisions

$$A_{UT}(\eta, M_h, P_T) = \frac{d\sigma_{UT}}{\boxed{d\sigma_0}}$$

chiral-odd
not important

important !

typical cross section for a+b→c+d process

$$d\sigma_0 \propto \sum_{a,b,c,d} \int \frac{dx_a dx_b}{8\pi^2 \bar{z}} \, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} \, D_1^c(\bar{z}, M_h)$$

theoretical uncertainties

quark D_1^q is well constrained by e^+e^- (Montecarlo) but

we don't know anything about the gluon D_1^g (e^+e^- doesn't help..)

Single-Spin Asymmetry
in p-p↑ collisions

$$A_{UT}(\eta, M_h, P_T) = \frac{d\sigma_{UT}}{\boxed{d\sigma_0}}$$

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$$d\sigma_0 \propto \sum_{a,b,c,d} \int \frac{dx_a dx_b}{8\pi^2 \bar{z}} \, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} \, D_1^c(\bar{z}, M_h)$$

our choice: compute $d\sigma_0$ with $D_1^g(Q_0) = \left\{\begin{array}{l} 0 \\ D_1^u(Q_0)/4 \\ D_1^u(Q_0) \end{array}\right.$

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

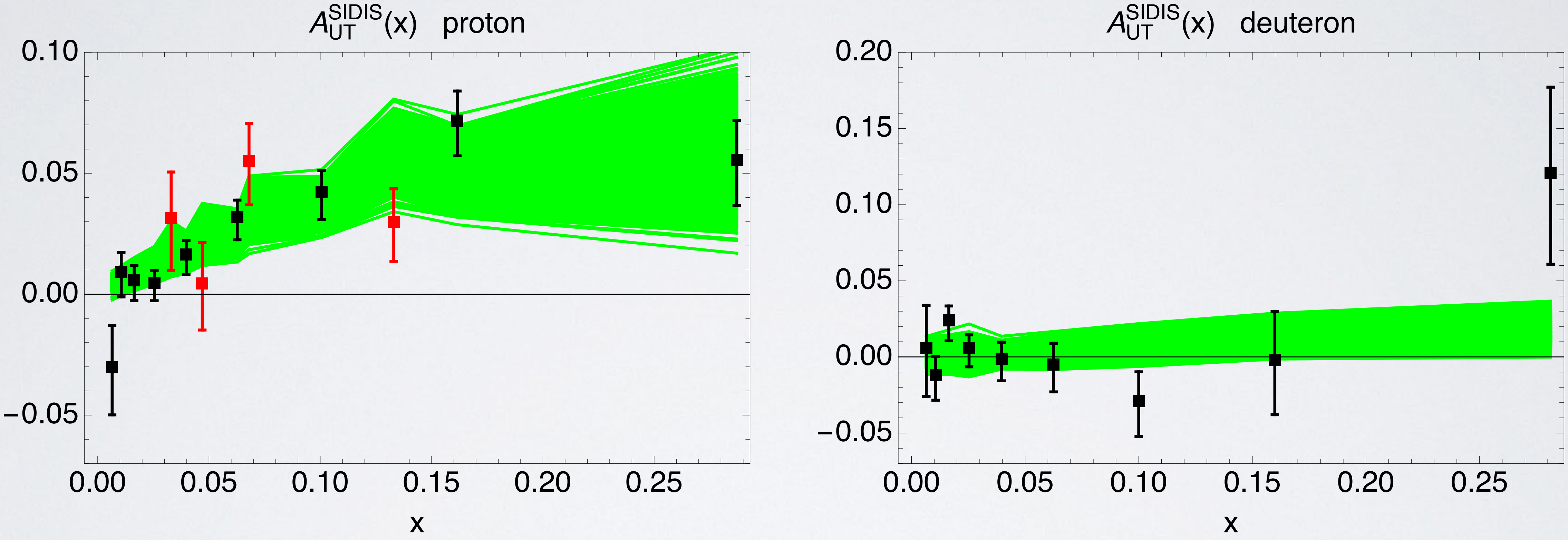
background ρ channels

statistical uncertainty: the bootstrap method

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

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

Adolph et al., P.L. ***B713*** *(12)*



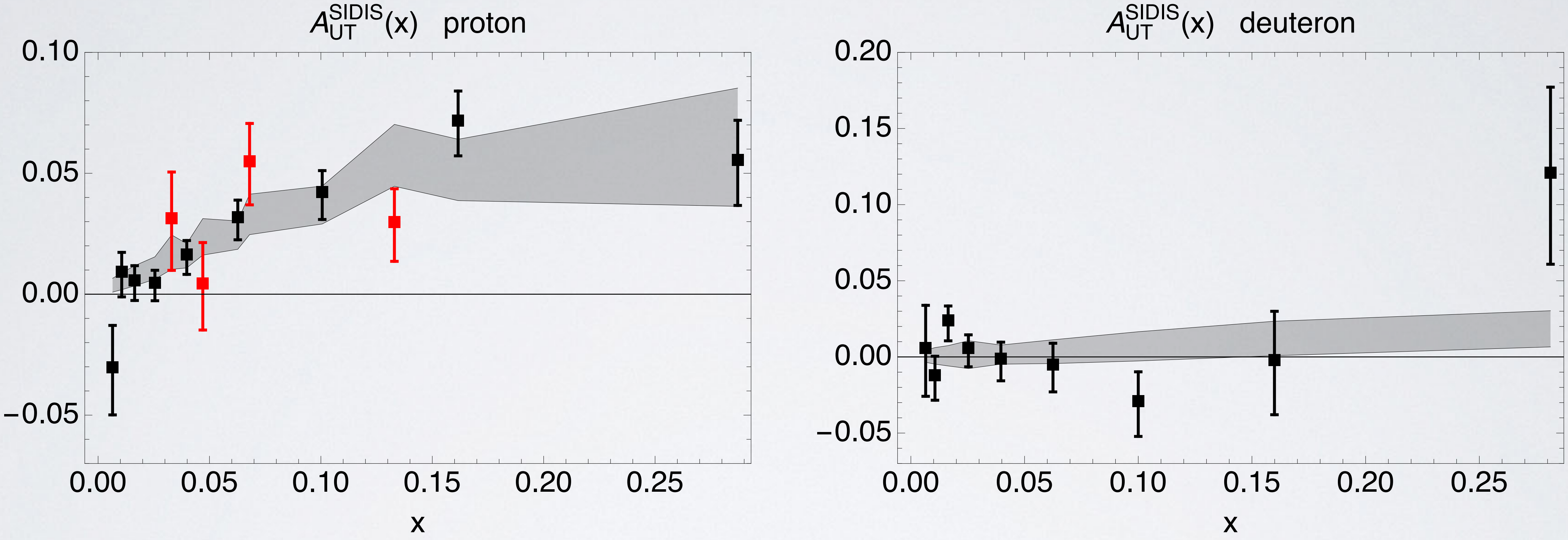
all 600 replicas

statistical uncertainty: the bootstrap method

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

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

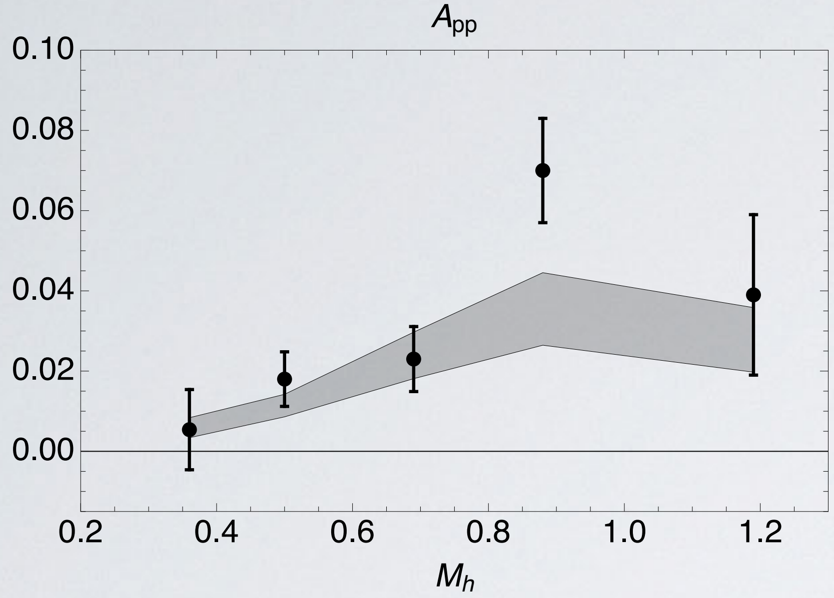
*Adolph et al., P.L. **B713** (12)*


$A_{UT}^{SIDIS}(x)$ proton

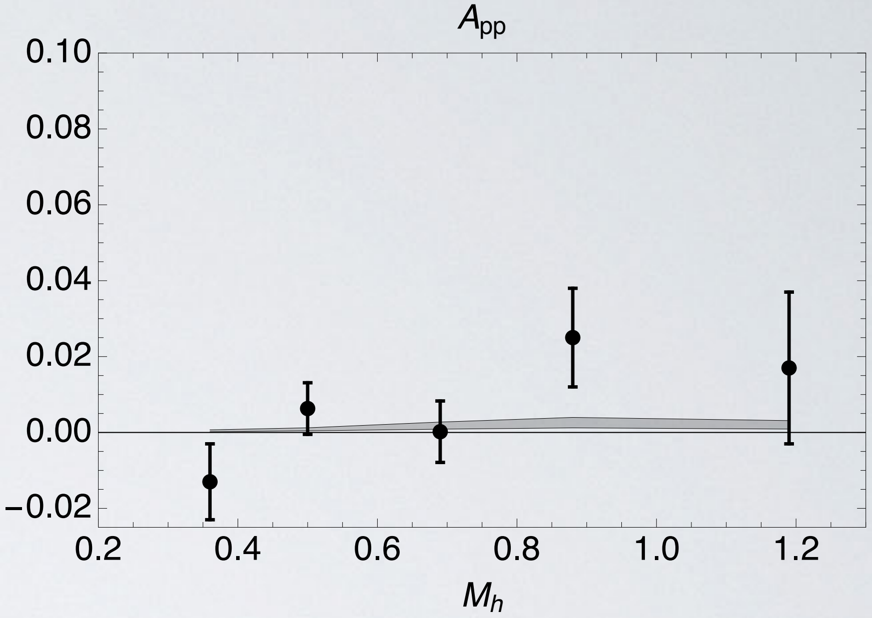
$A_{UT}^{SIDIS}(x)$ deuteron

90% replicas

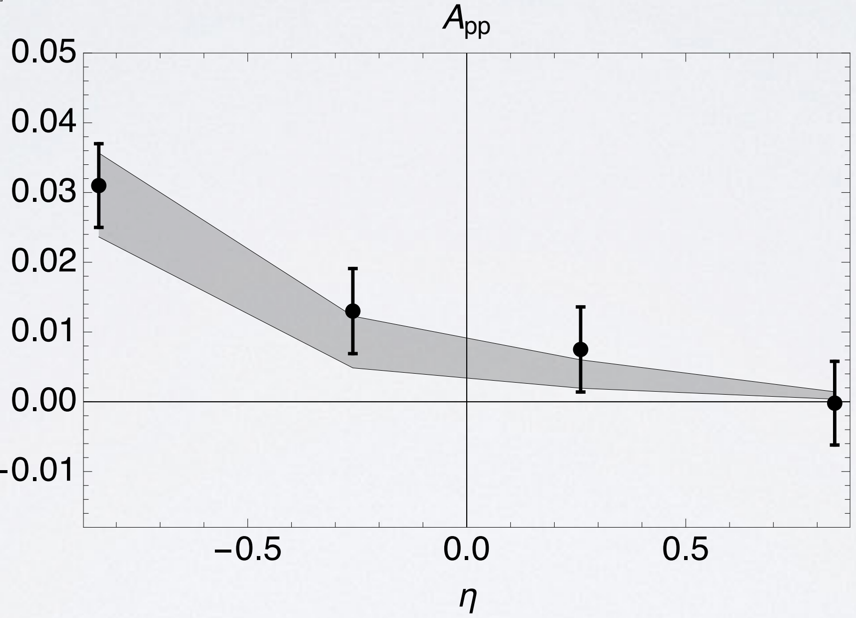
fit STAR asymmetry



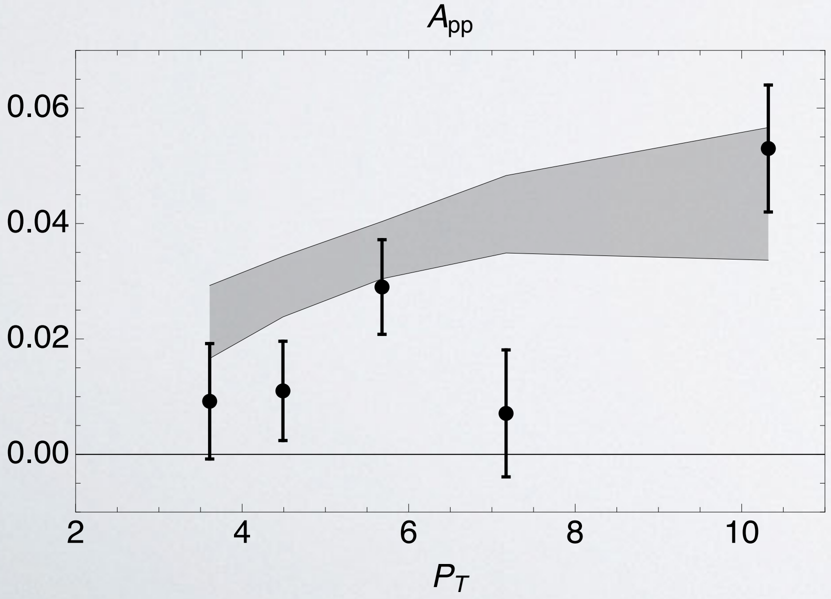
Adamczyk et al. (STAR), P.R.L. ***115*** *(2015) 242501*



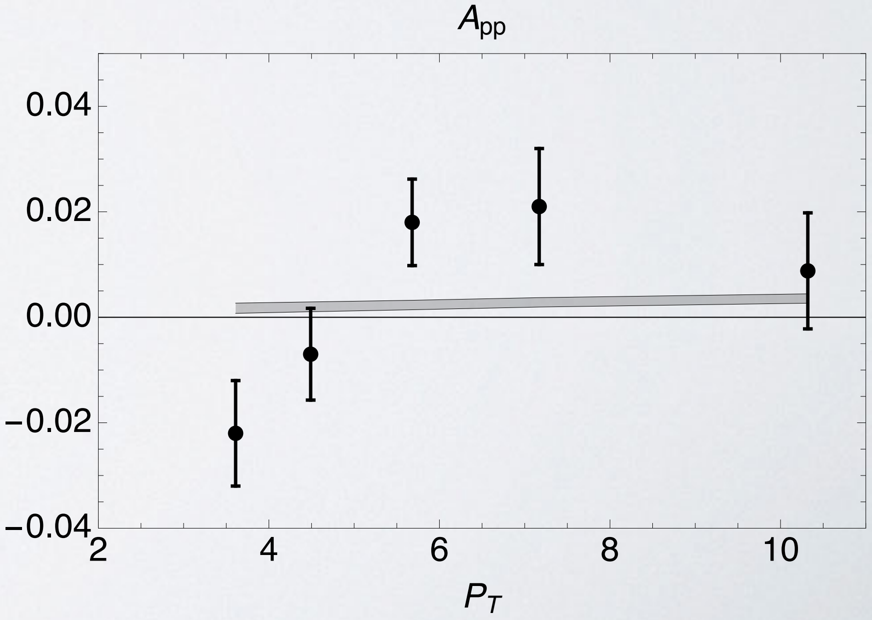
$\eta<0$



$\eta>0$



90% uncertainty band



χ^2 of the fit

46 data points, **10** parameters
global **χ^2/dof** = 2.08 ± 0.09

≈ 38%

SIDIS

≈ 24%

hermes

≈ 76%

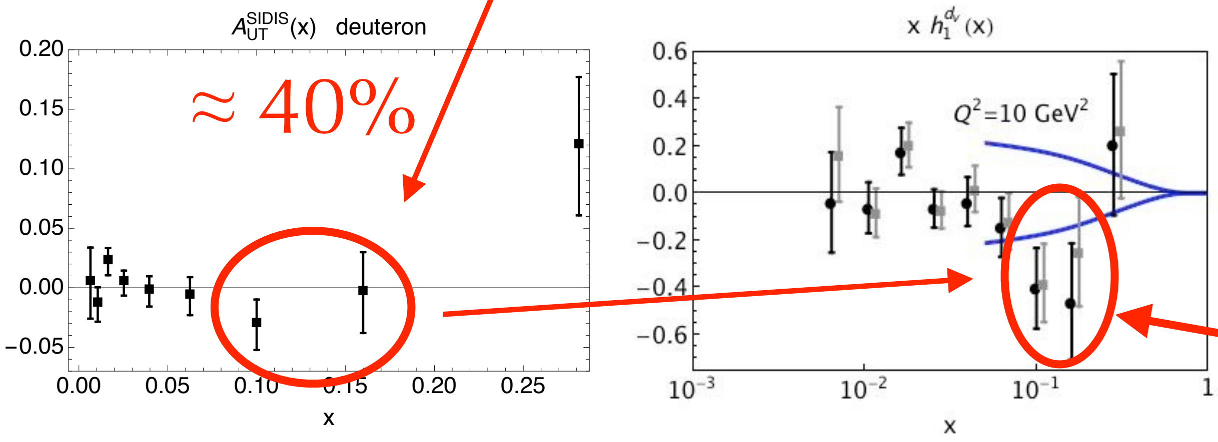
COMPASS

≈ 60%
rest

≈ 62%

STAR

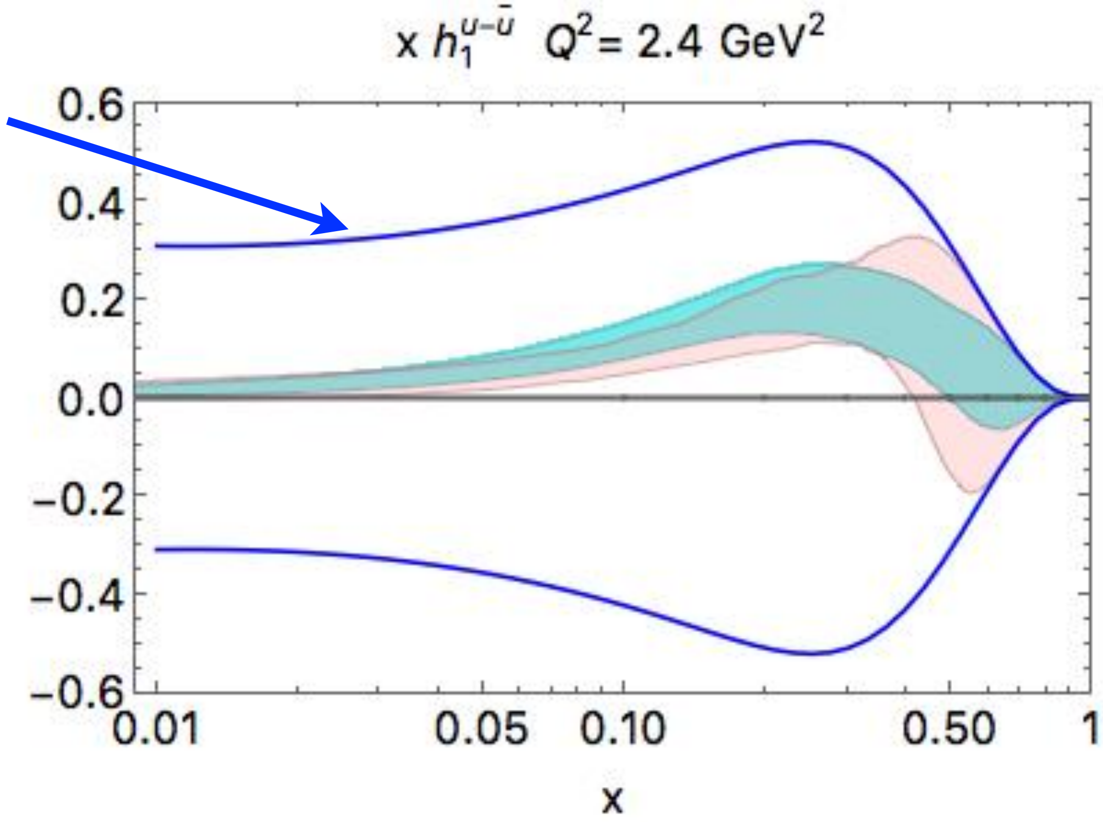
- P_T bins ≈ 70%
- M_h bins ≈ 28%
- η bins ≈ 2%


≈ 40%

Soffer bound
@10 GeV^2

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

comparison with previous fit



Soffer bound

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

global fit

up

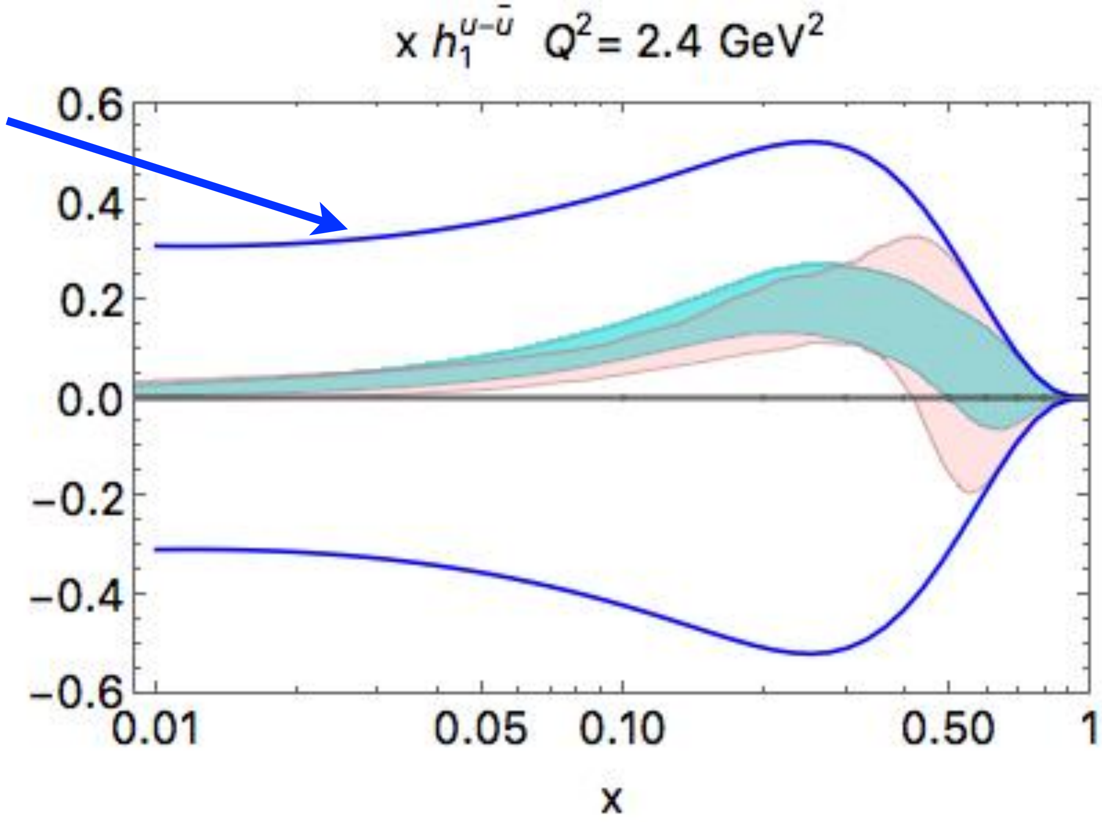
higher precision

old fit (only SIDIS data)

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

comparison with previous fit

Soffer bound



Radici & Bacchetta,
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global fit

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higher precision

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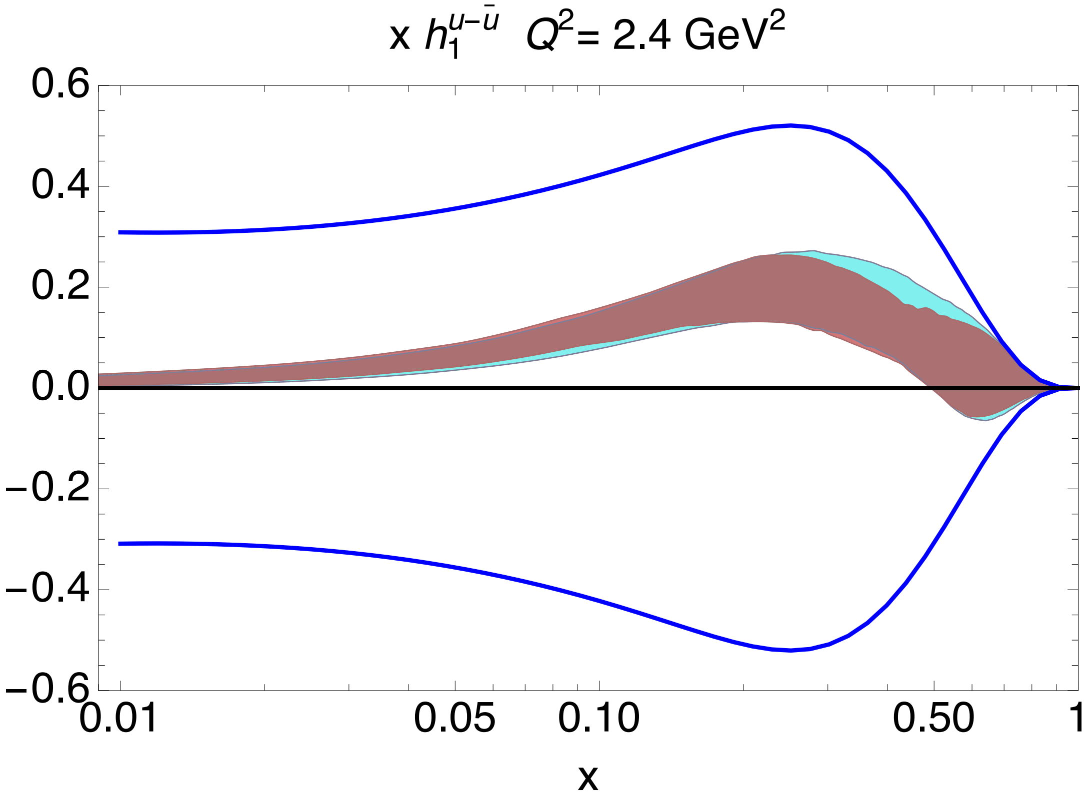
Radici et al.,
JHEP ***1505*** *(15) 123*

up

insensitive to uncertainty on gluon D_1

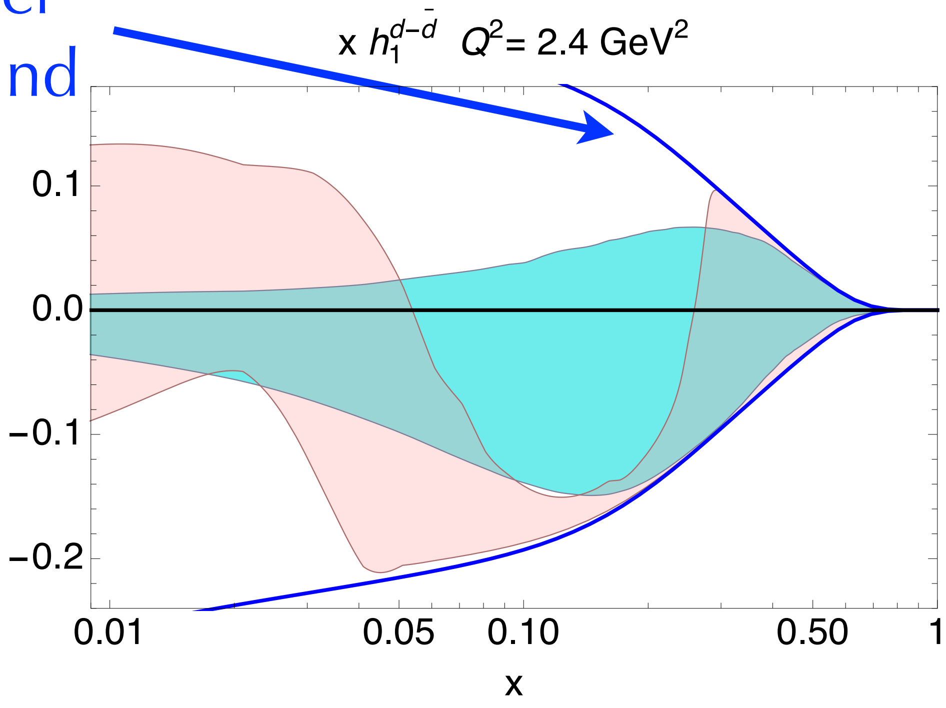
$$D_1^g(Q_0) = 0$$

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



comparison with previous fit

Soffer bound



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

global fit

old fit

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

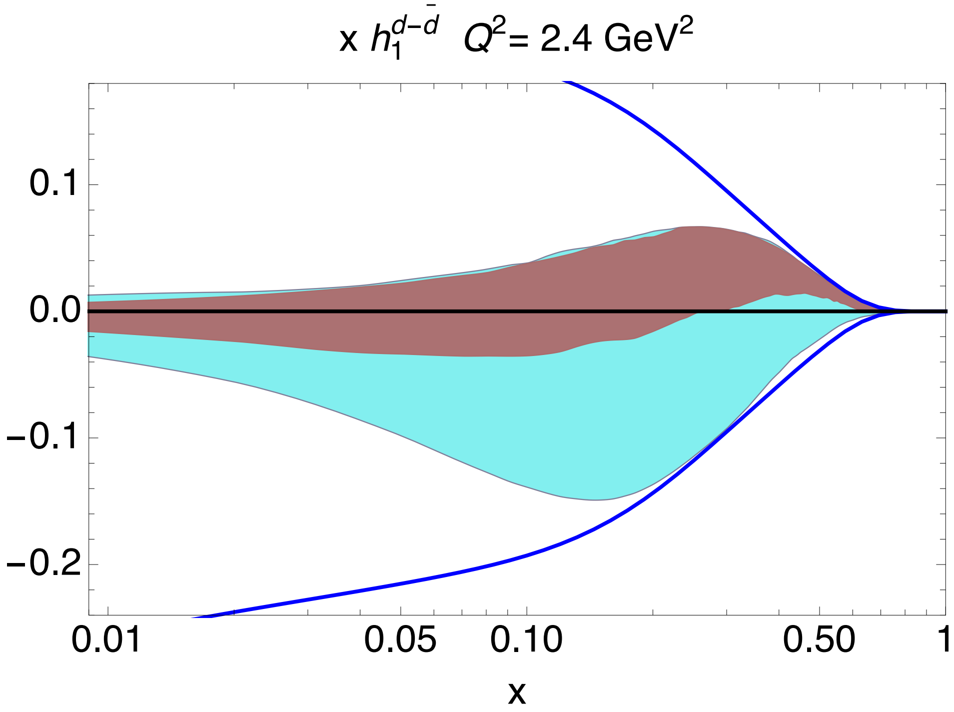
down

down

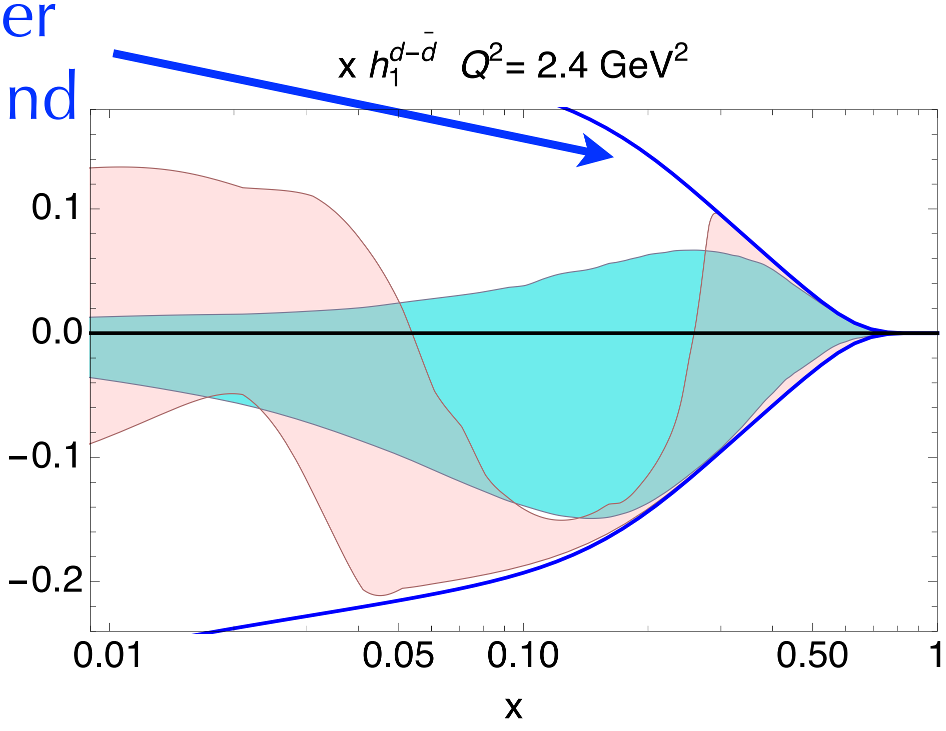
sensitive to uncertainty on gluon D_1

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

$$D_1^g(Q_0) = \left\{ \begin{array}{l} 0 \\ D_1^u/4 \\ D_1^u \end{array} \right.$$



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

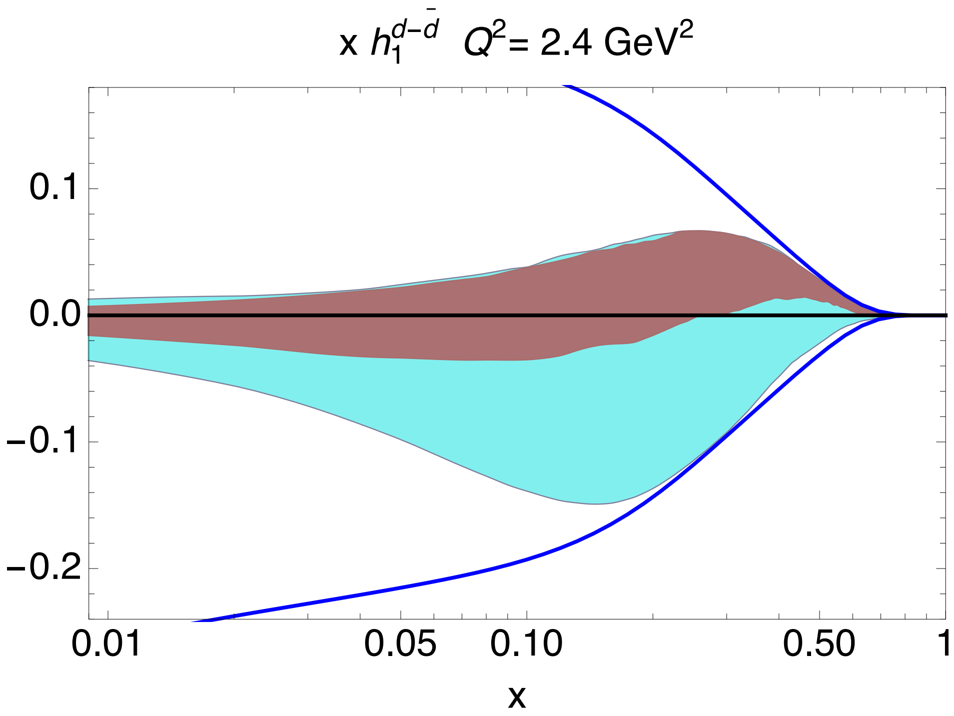
need dihadron multiplicities from RHIC

down

sensitive to uncertainty on gluon D_1

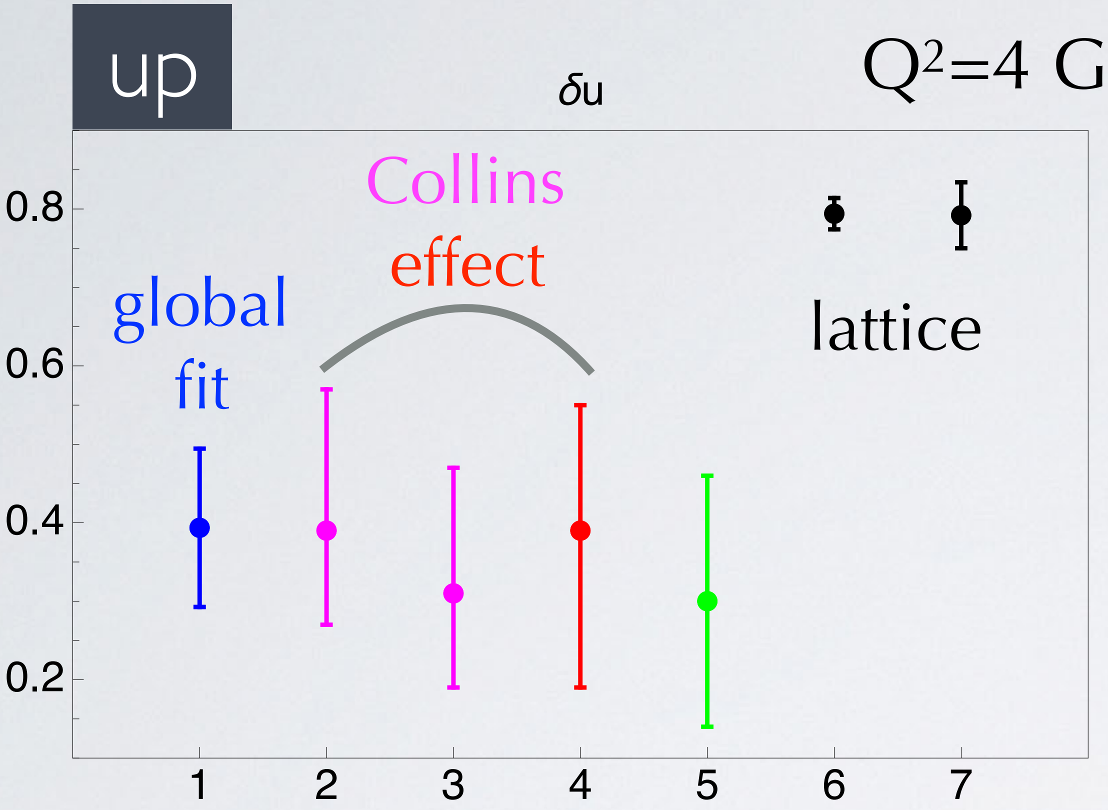
$D_1{}^g\,(Q_0) = 0$

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



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

Q^2=4 GeV^2 *



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

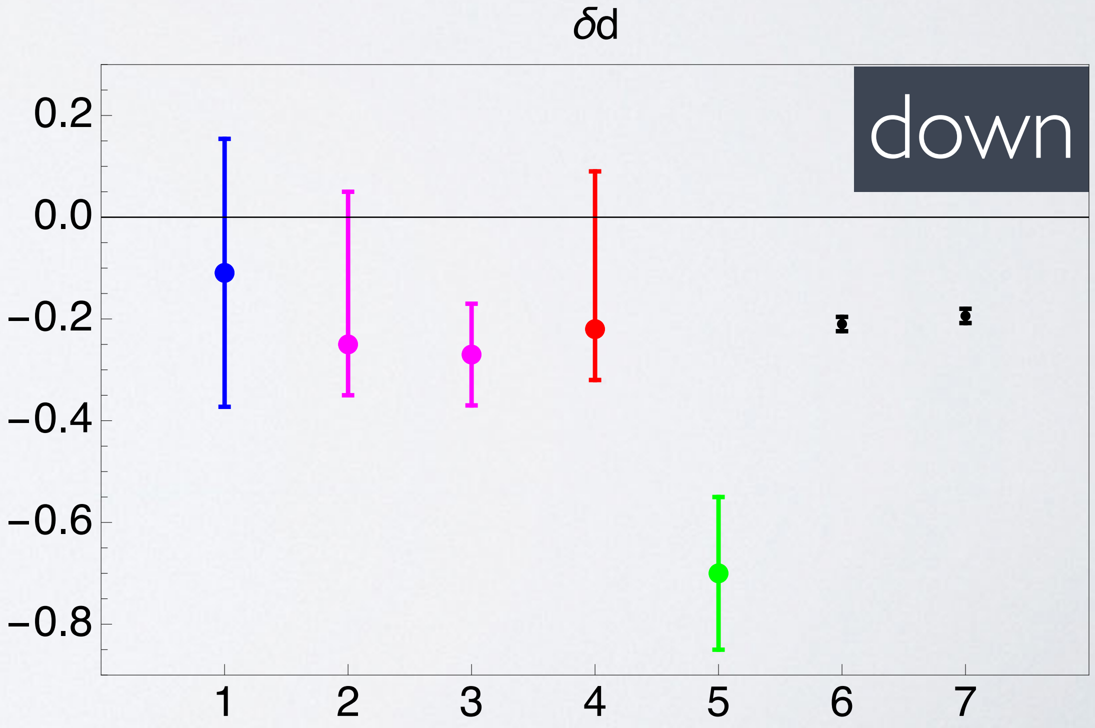
2,3- Torino *Anselmino et al., P.R. D* ***87*** *(13) 094019* *** Q^2=1**

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

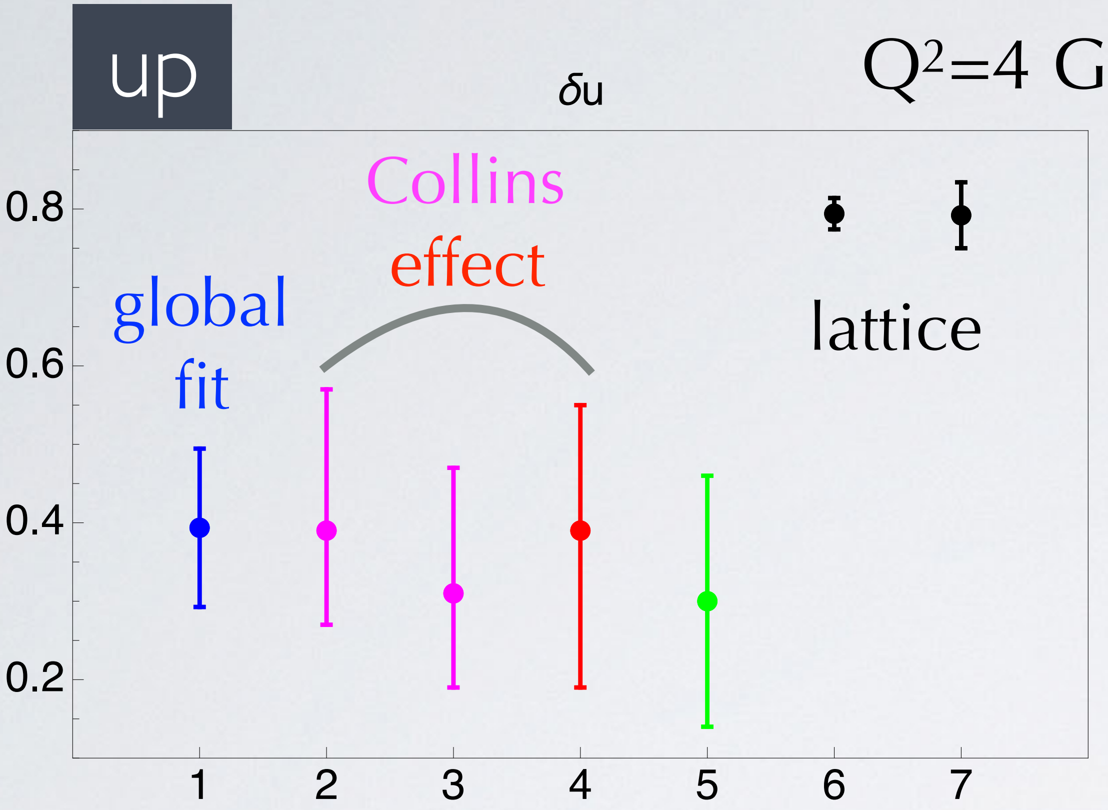
5- JAM fit *Lin et al., P.R.L.* ***120*** *(18) 152502* $\left\{\begin{array}{l}\textbf{Collins effect +}\\ \textbf{lattice } g_T=\delta u-\delta d\end{array}\right.$ *** Q_0^2=2**

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



Q^2=4 GeV^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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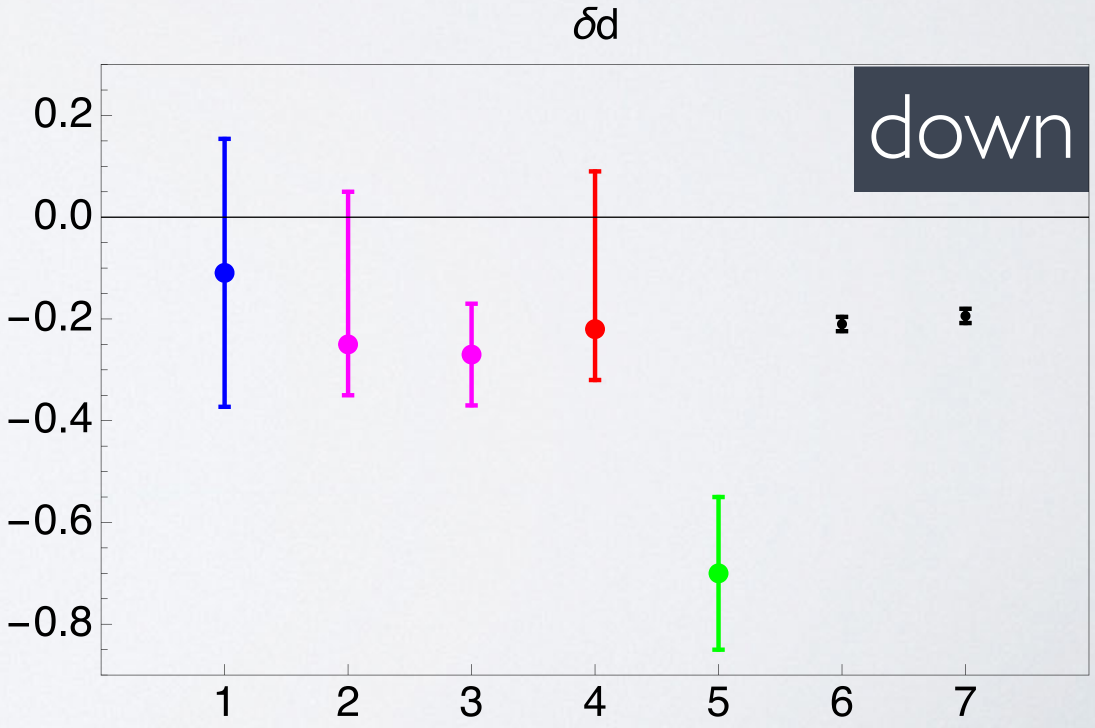
*P.R. D**93** (16) 014009* *** Q^2=10**

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

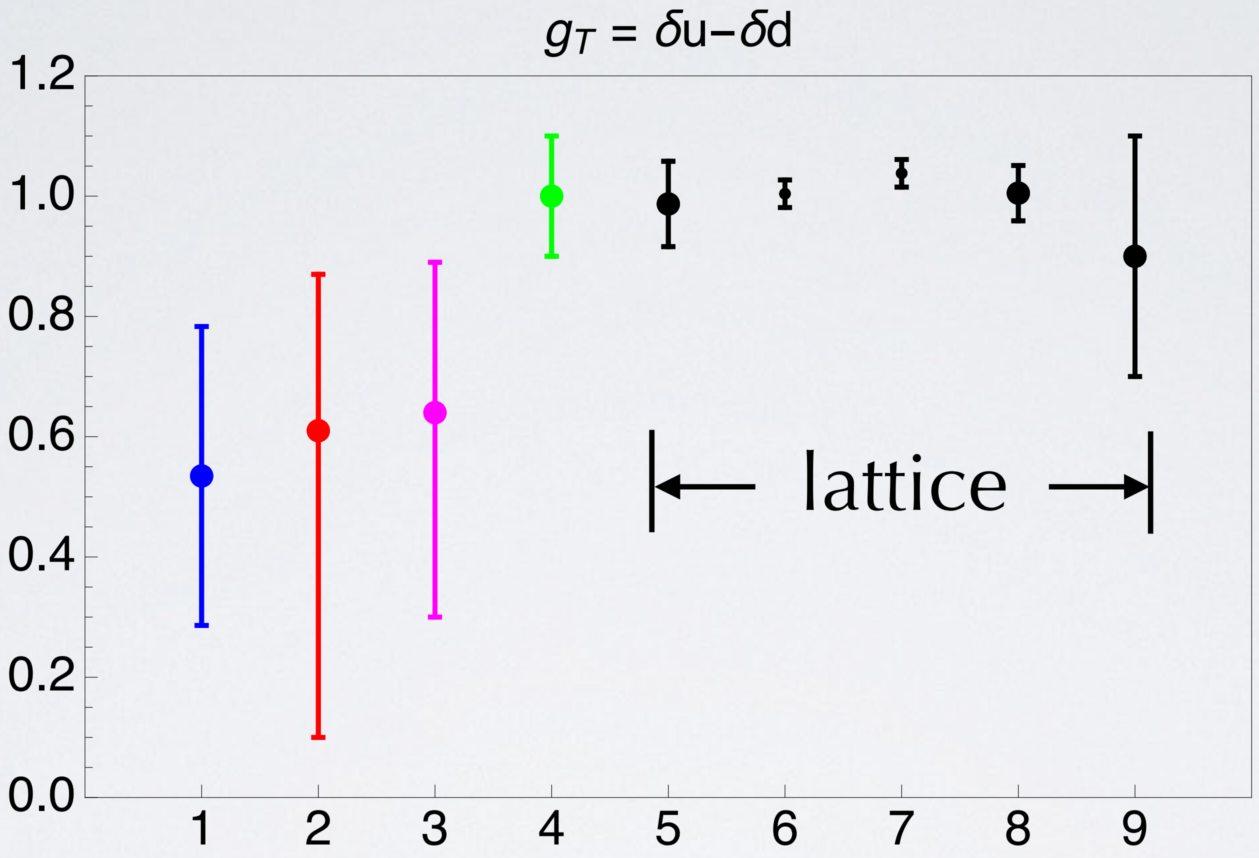
6- ETMC17 *Alexandrou et al., P.R. D**95** (17) 114514;*
*E P.R. D**96** (17) 099906*

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



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

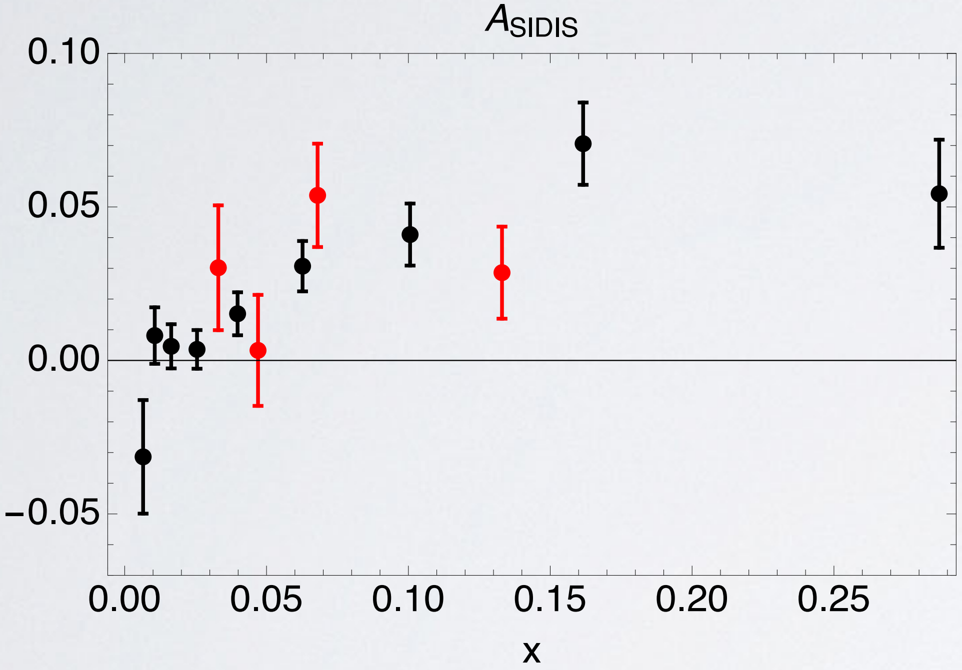
BUT

add Compass pseudodata for future deuteron run

● COMPASS

● hermes

proton

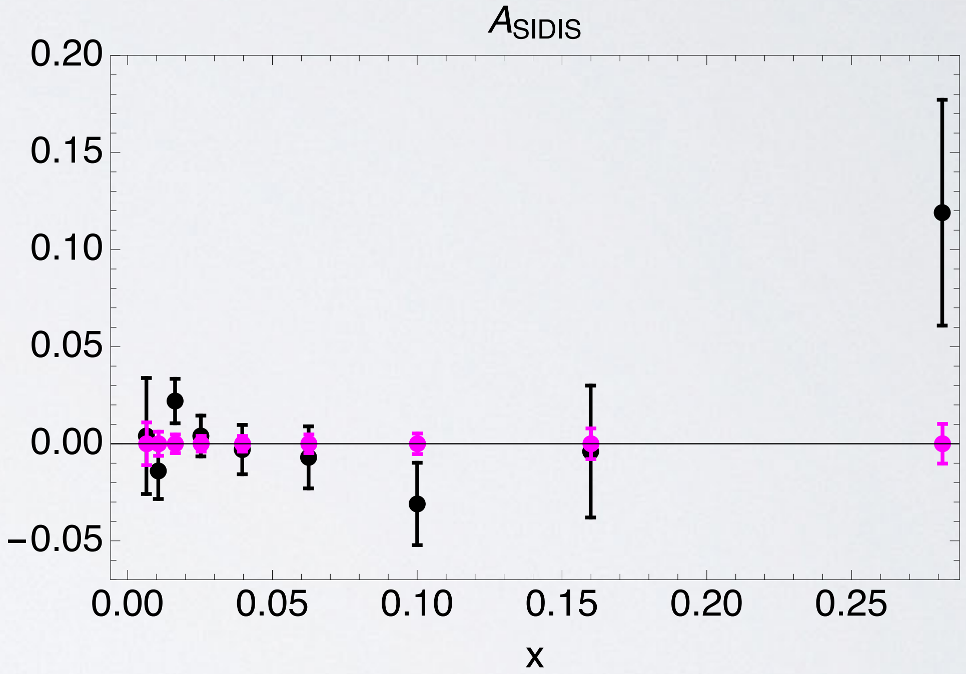


$$A_{\rm SIDIS} \sim 4h_1^{u_v} - h_1^{d_v}$$

● *Adolph et al., P.L.* ***B713*** *(12)*

● *private communication*

COMPASS

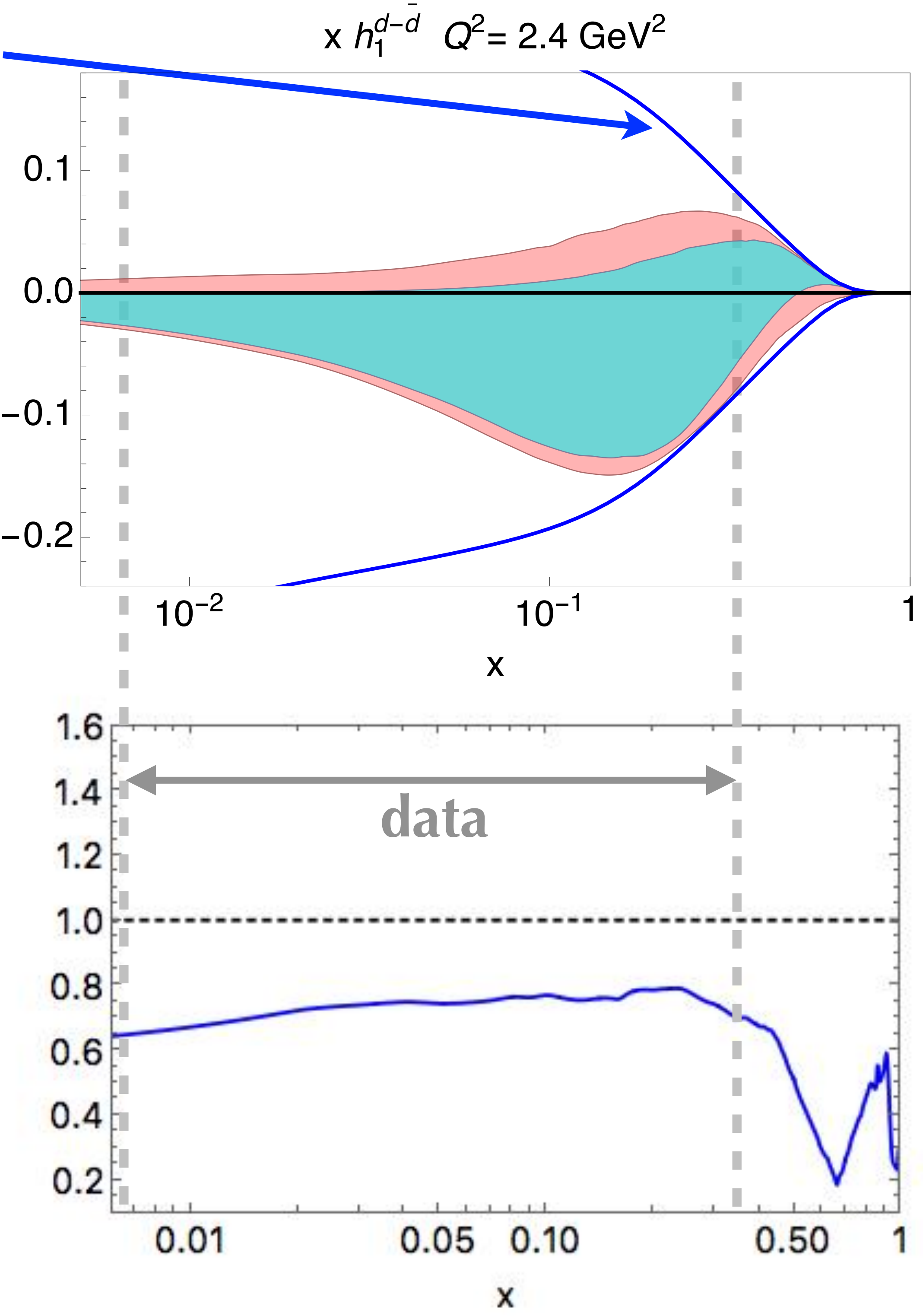


$$A_{\rm SIDIS} \sim h_1^{u_v} + h_1^{d_v}$$

pseudodata impact on down

Soffer bound

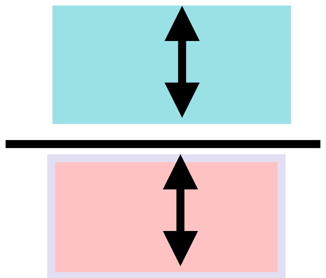
$$D_1^g(Q_0) = \left\{\begin{array}{l} 0 \\ D_1^u/4 \\ D_1^u \end{array}\right.$$



🟦 global fit + pseudodata

🟥 global fit

Radici & Bacchetta,
PRL ***120*** *(18) 192001*



ratio of widths

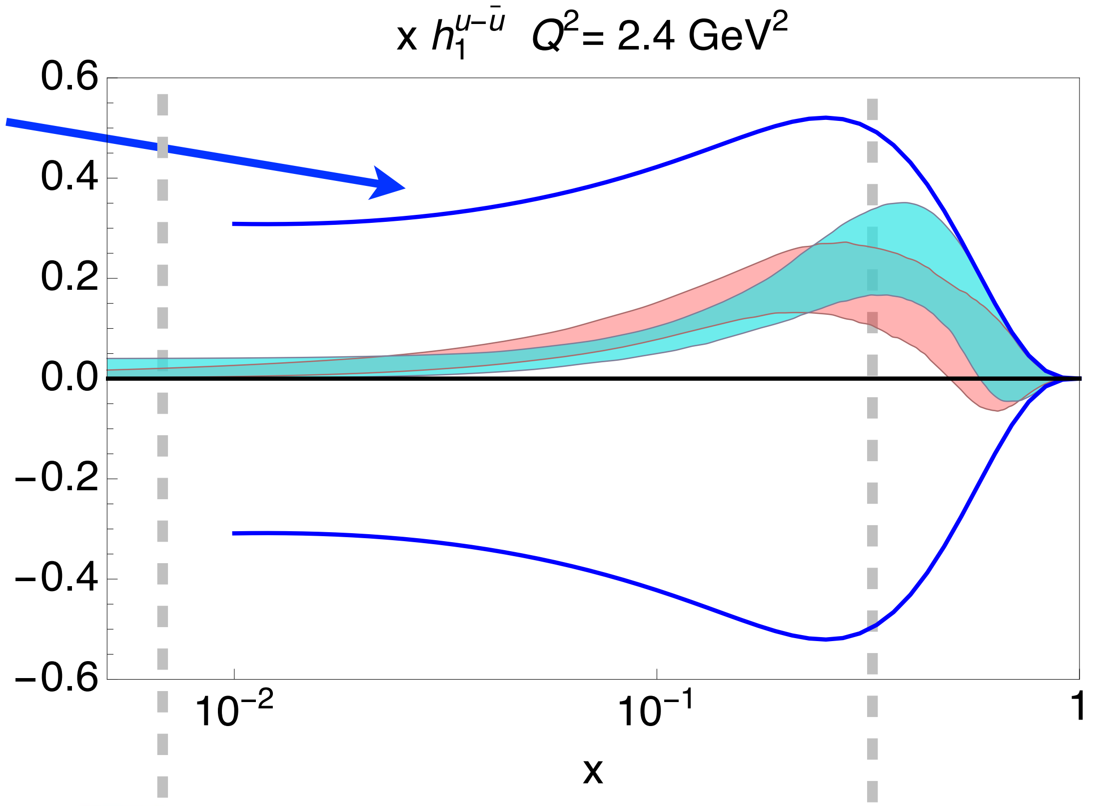
down

< 20% >
increase in
precision

pseudodata impact on up

Soffer bound

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

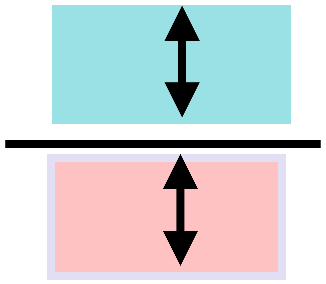


global fit + pseudodata

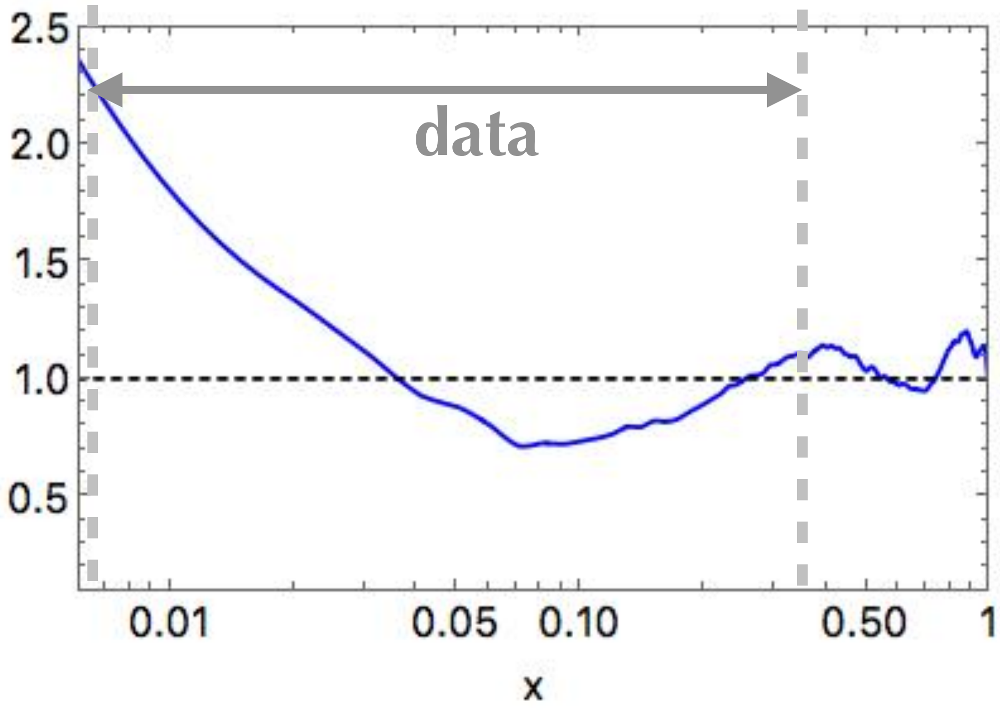
global fit

Radici & Bacchetta,
PRL ***120*** *(18) 192001*

up



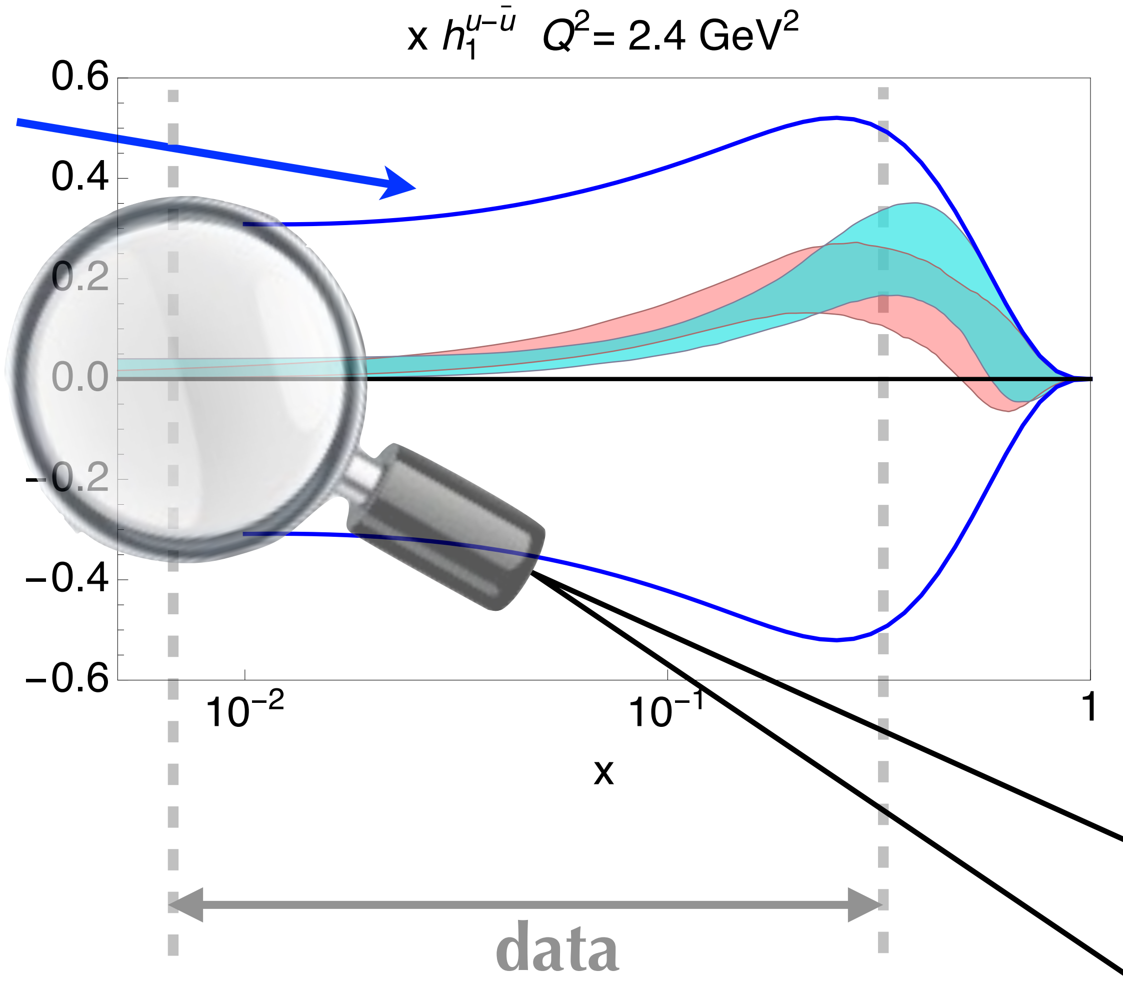
ratio of widths



pseudodata impact on up

Soffer bound

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

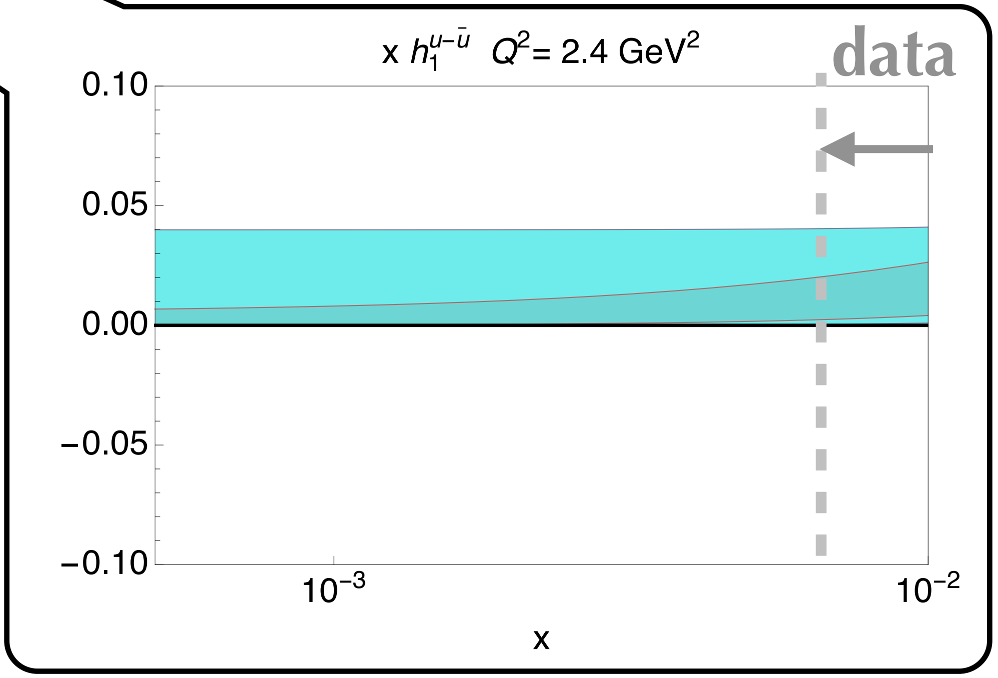


global fit + pseudodata

global fit

Radici & Bacchetta,
*PRL **120** (18) 192001*

up



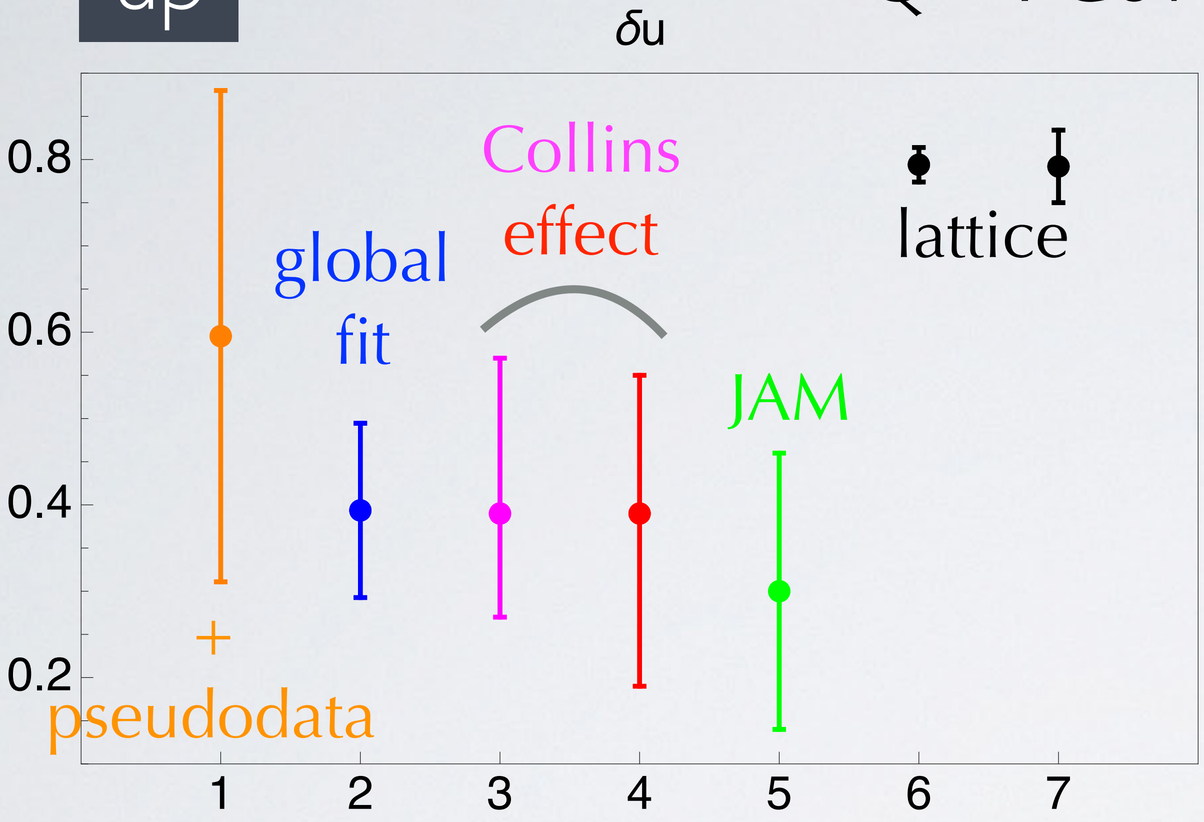
$$h_1^q(x) \overset{x\to 0}{\approx} x^{A_q+a_q-1} \qquad A_q + a_q > \frac{1}{3}$$

constraint not enough to avoid re-arrangement of replicas outside the range of new pseudodata

pseudodata impact on tensor charge

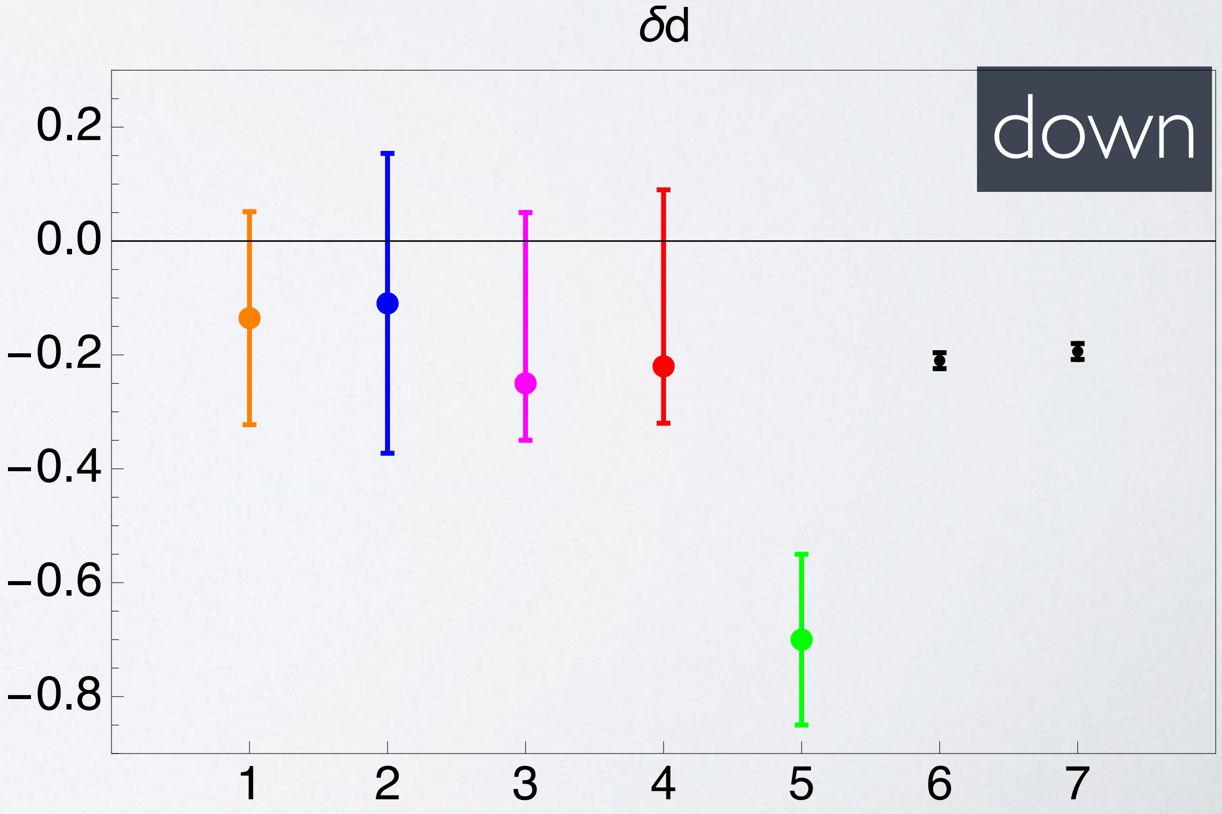
up

$Q^2=4\ \text{GeV}^2$ *



better precision on down
larger uncertainty on up
(“reversed role” of flavors..)

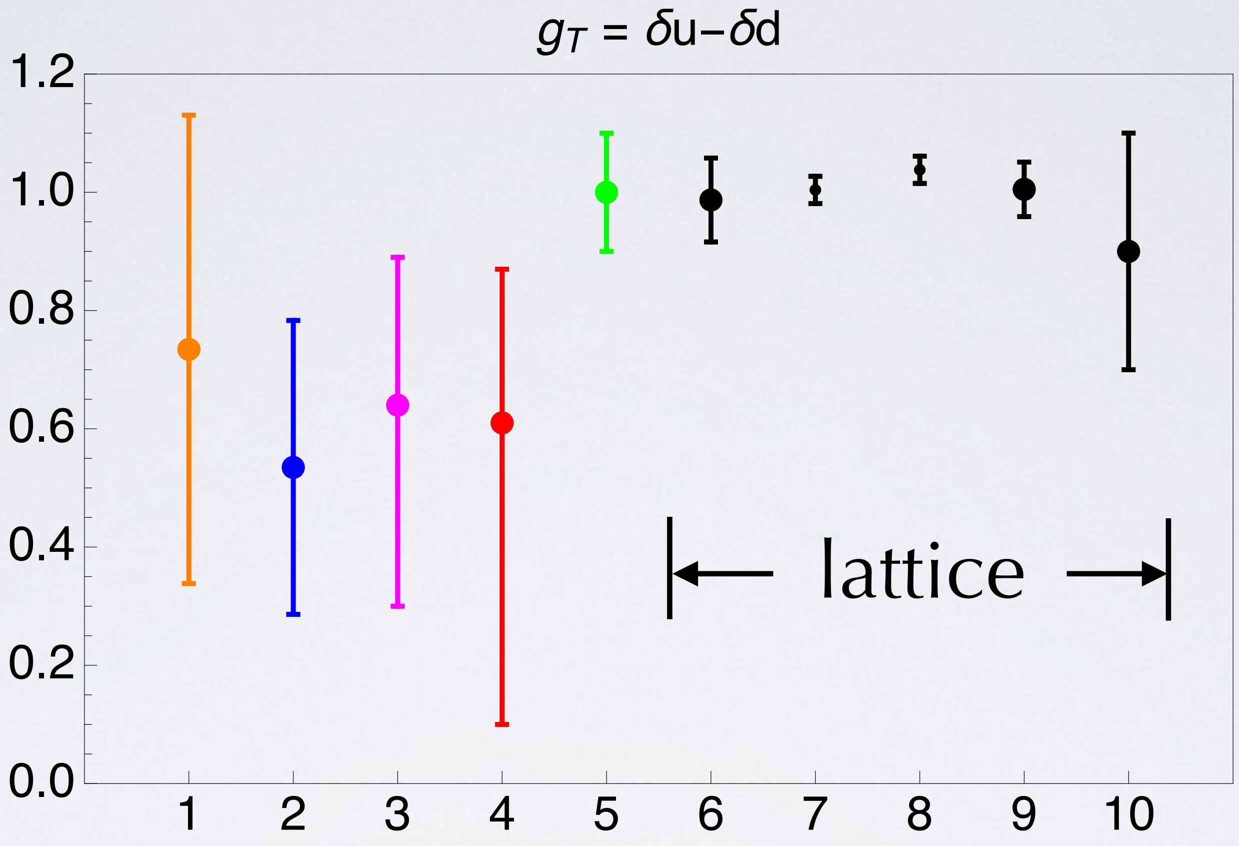
but global fit re-establishes
full compatibility
with lattice



down

pseudodata impact on isovector tensor charge

Q^2=4 GeV^2 *

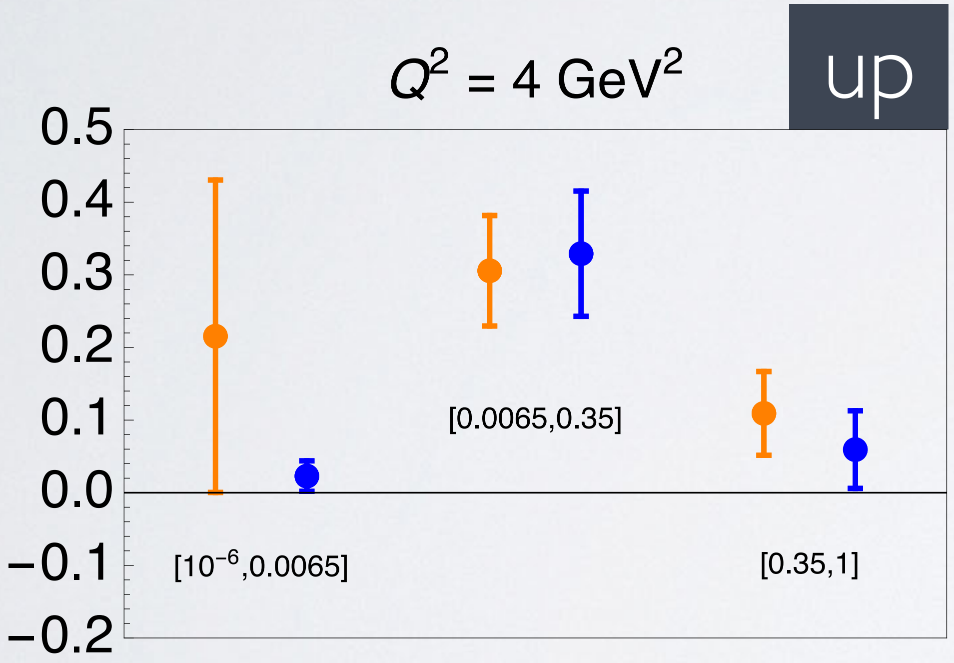


we can have simultaneous compatibility about δu, δd, g_T between lattice and our global fit, but because of large uncertainties coming from extrapolation outside the x-range of data (mainly at low x)

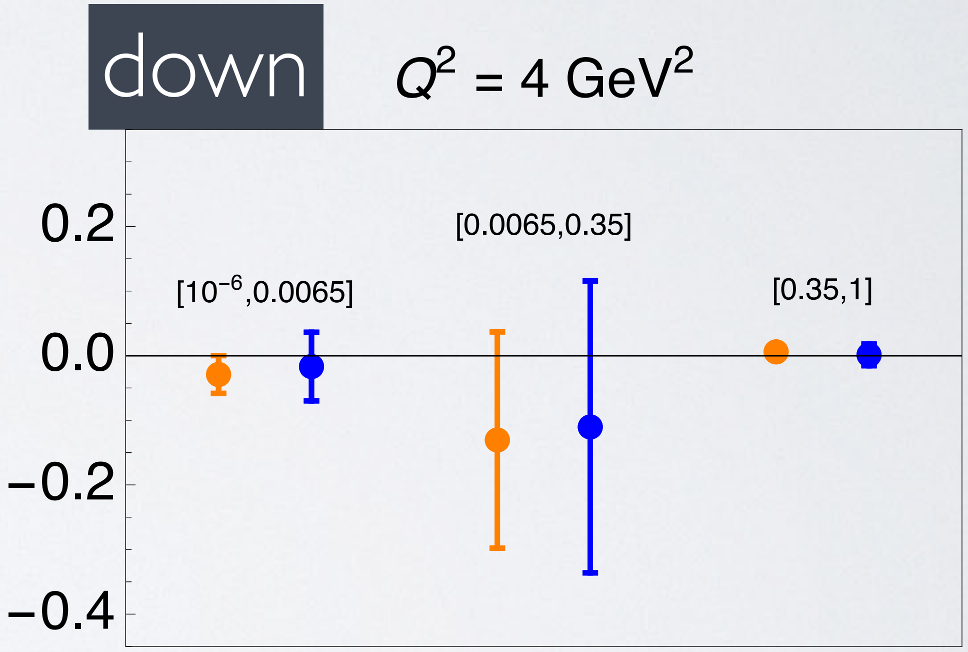
impact of extrapolation outside data

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

MSTW $x_{\min}=10^{-6}$



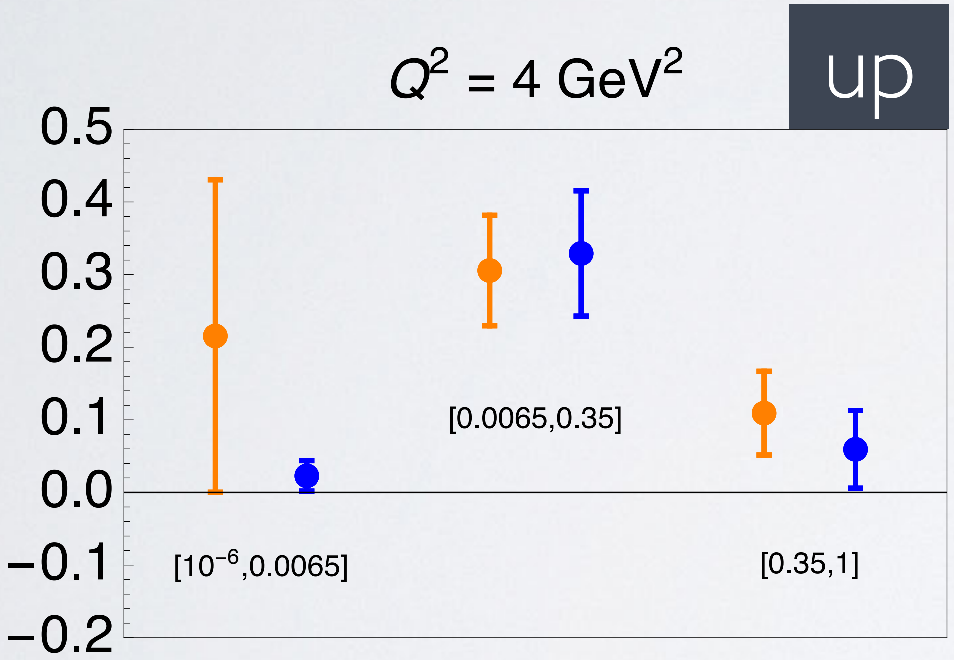
global
fit
+
pseudodata



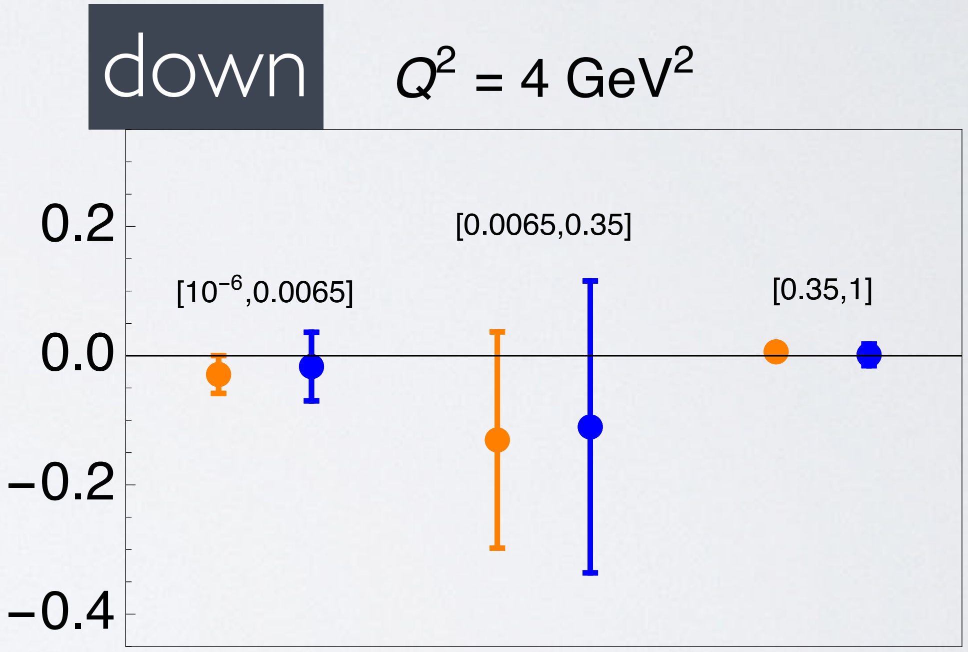
impact of extrapolation outside data

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

MSTW $x_{\min}=10^{-6}$

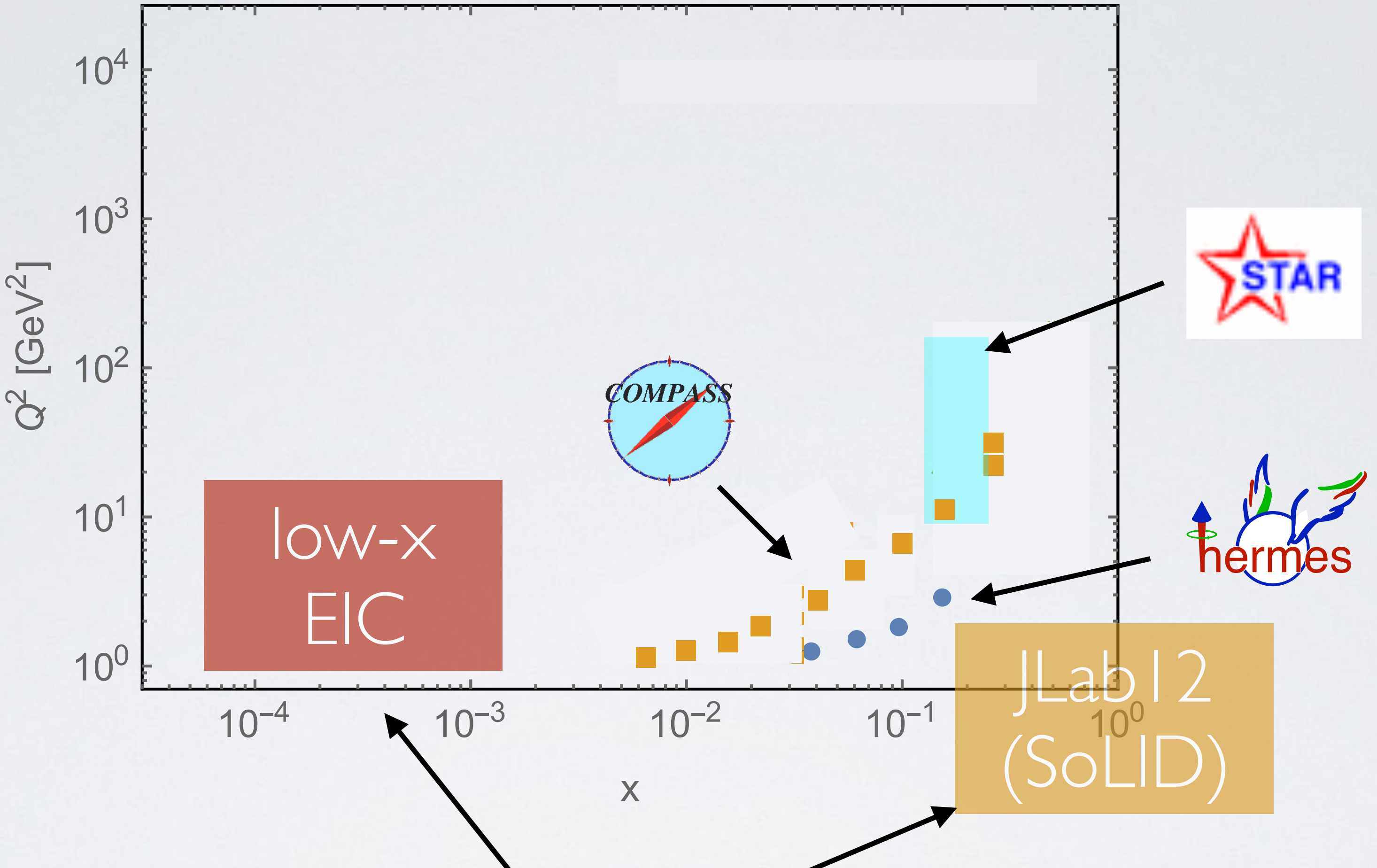


global
fit
+
pseudodata



impact of pseudodata
for down: better precision everywhere
for up: large uncertainties in extrapolation at low x

more constraints on extrapolation



run 2006
s=200 GeV^2

- 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*

- theoretical constraints from Burkardt-Cottingham sum rule

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

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

$$A_q + a_q > \frac{1}{3} \longrightarrow A_q + a_q > 1$$

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↑ 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 reverses the scenario: better down but larger uncertainties on up from extrapolation (mainly at low x); reach overall compatibility with lattice
- need data spanning larger x range; meantime, look for other theoretical constraints on extrapolation (mostly, at low x)

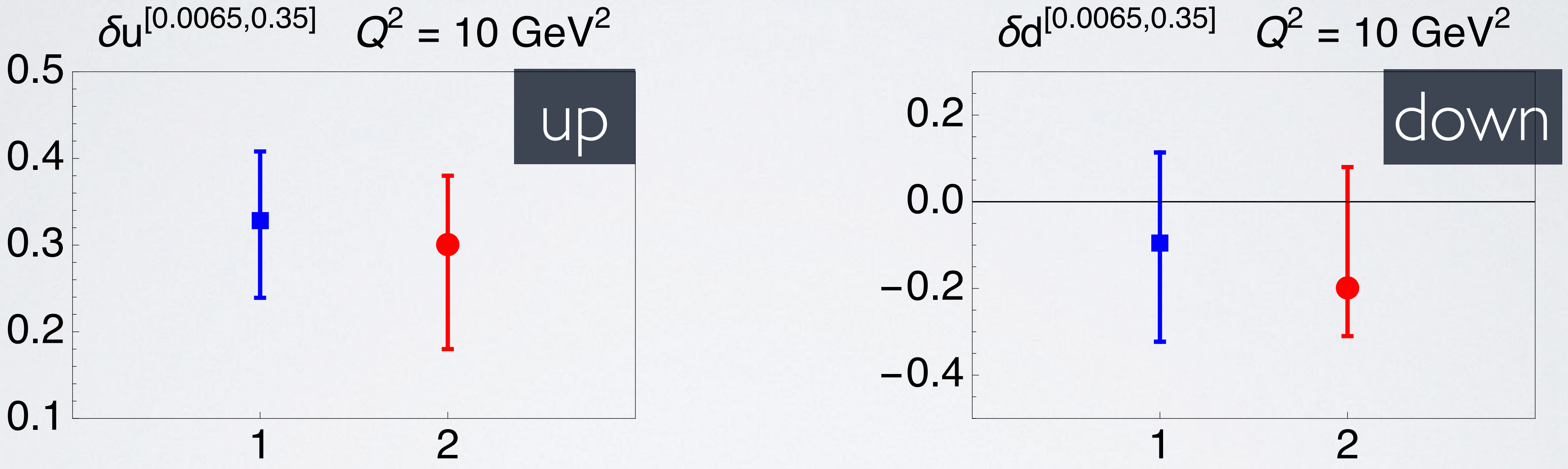
THANK YOU

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*

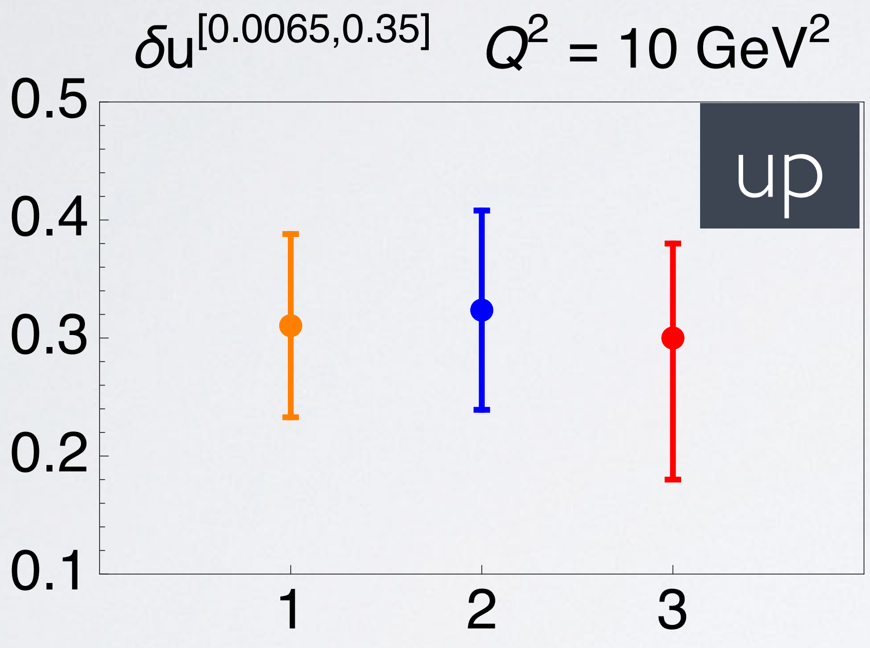
TMD fit

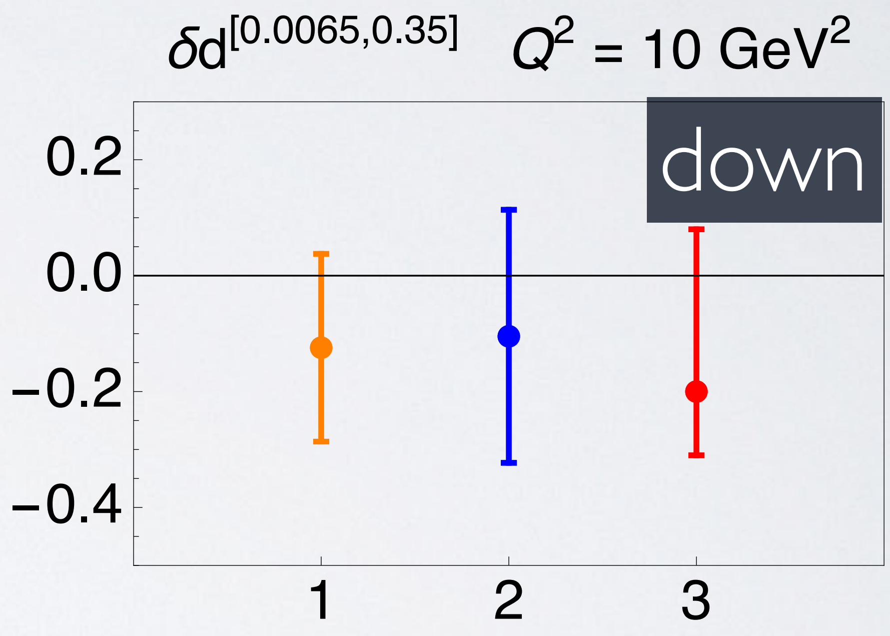
Kang et al.,
*P.R. D**93** (16) 014009*

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

truncated

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





\+
pseudodata

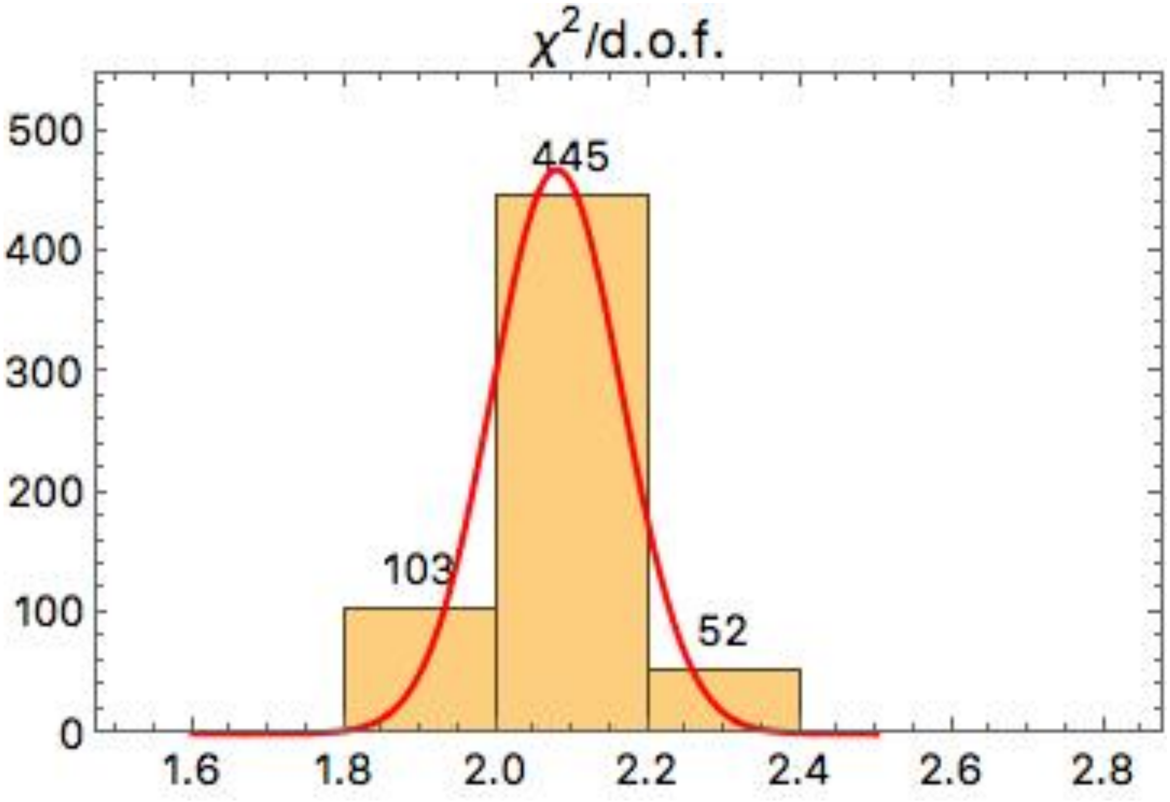
global fit

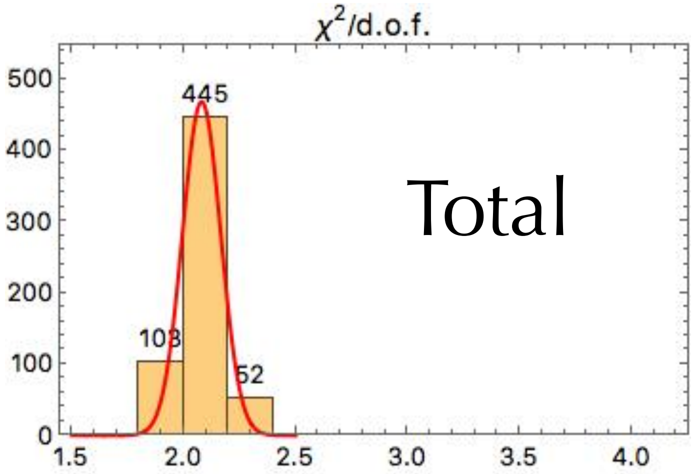
Radici & Bacchetta,
P.R.L. ***120*** *(18) 192001*

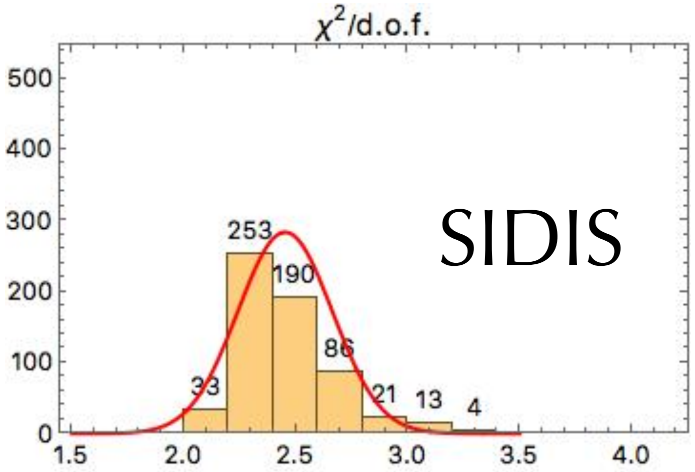
TMD fit

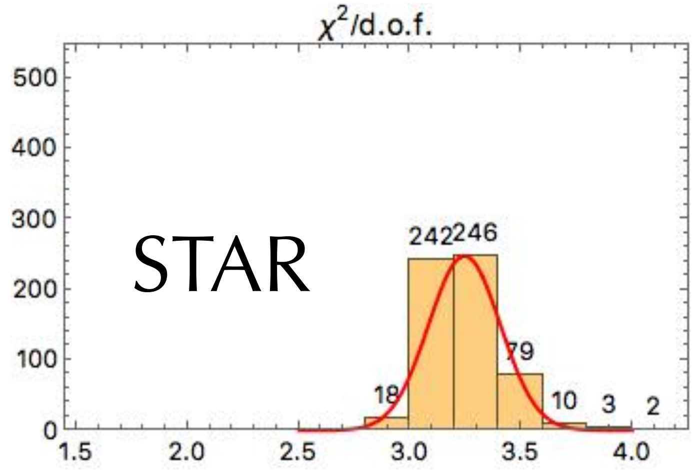
Kang et al.,
*P.R. D**93** (16) 014009*

χ^2 of the fit







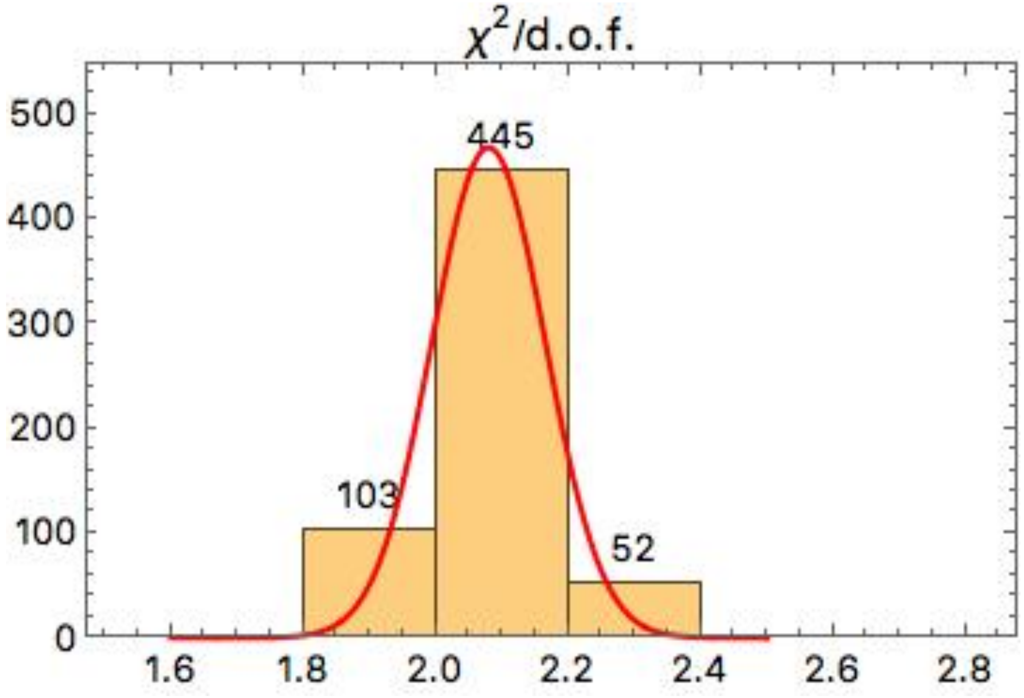


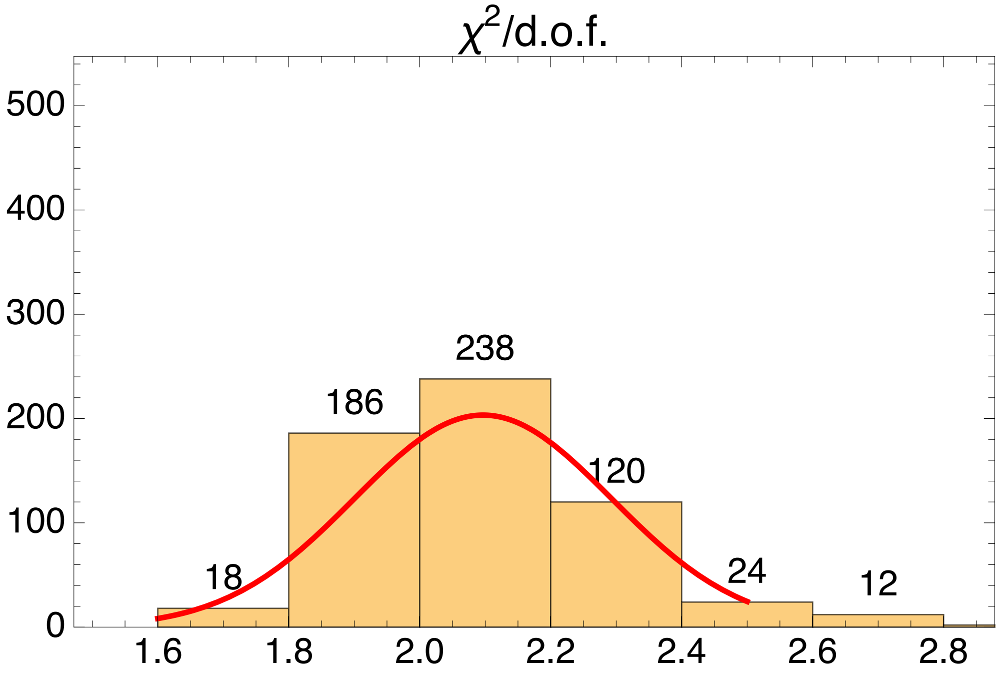
χ^2/dof = 2.08 ± 0.09

χ^2 of the fit

global fit

+ pseudodata



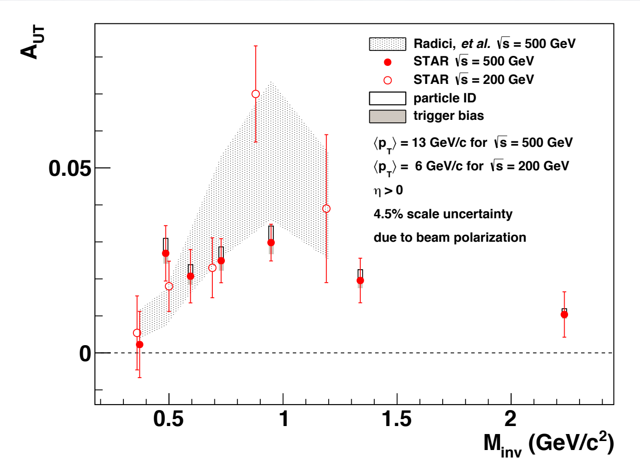


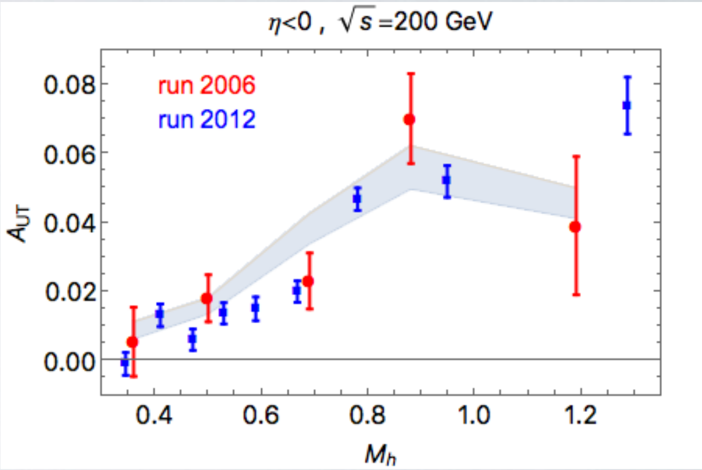
$\chi^2/\text{dof} = 2.08 \pm 0.09$

$\chi^2/\text{dof} = 2.10 \pm 0.20$

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