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

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di Fisica Nucleare

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in collaboration with A. Bacchetta (Univ. Pavia)

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

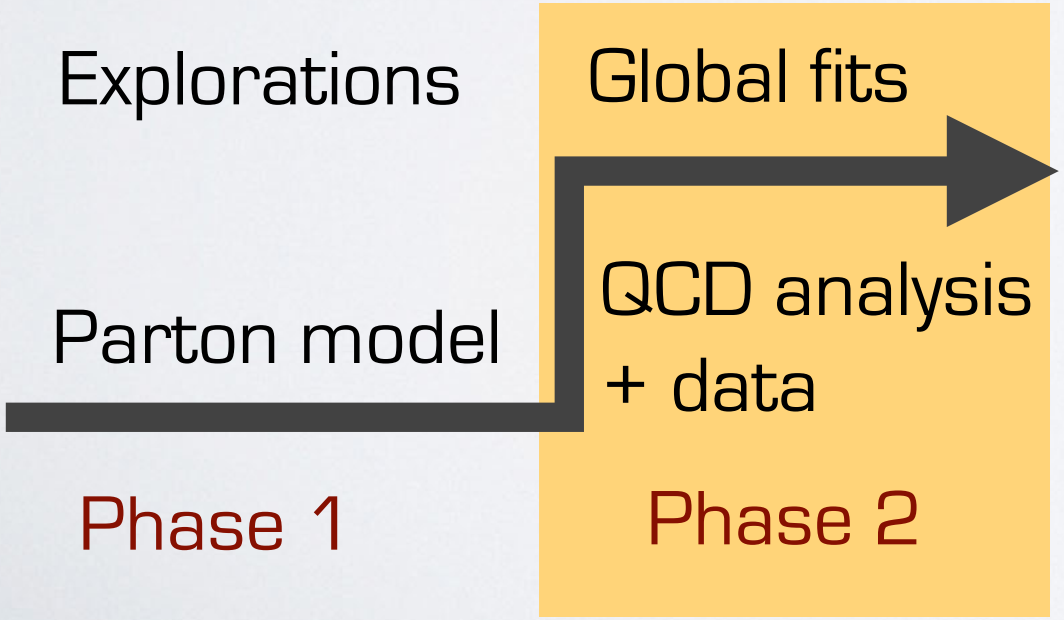
a phase transition

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 $h_{1T}^\perp$

1Dim (polarized) PDFs



Explorations

Global fits

Parton model

QCD analysis
+ data

Phase 1

Phase 2

3Dim TMDs

first global fit
of $f_1(x, \mathbf{k}_\perp)$

Bacchetta et al.,
*JHEP **1706** (17) 081*

a phase transition

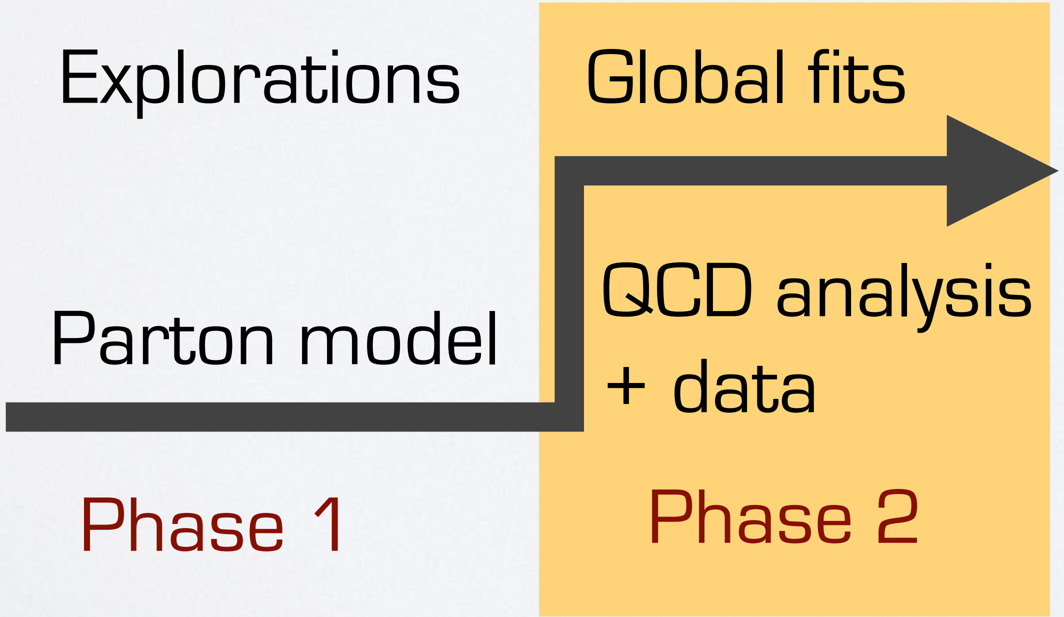
quark polarization

nucleon polarization

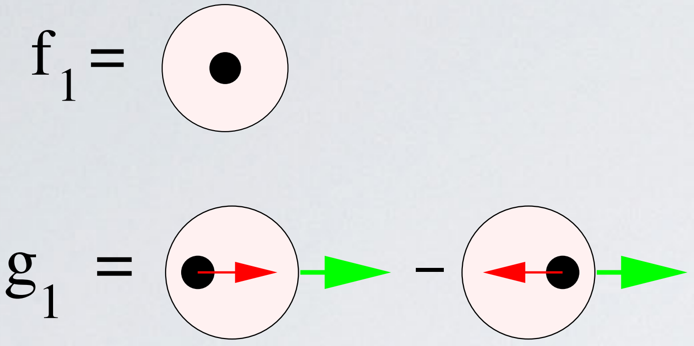
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

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

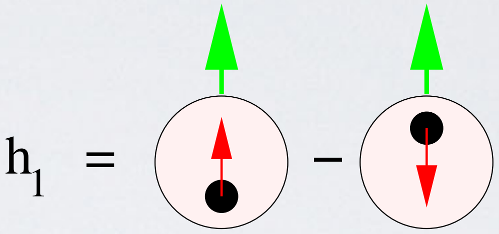
1Dim chiral-odd PDFs



transversity: a chiral-odd PDF



transversity PDF $h_1(x)$



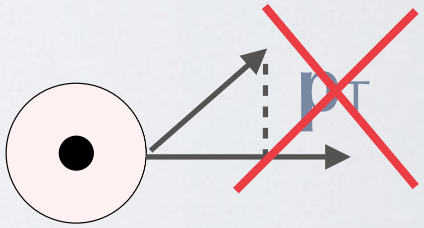
it is a **chiral-odd** function (flips quark helicity)

→ needs a chiral-odd partner

→ suppressed in inclusive DIS

which channel addresses it at leading twist as a **PDF** ?

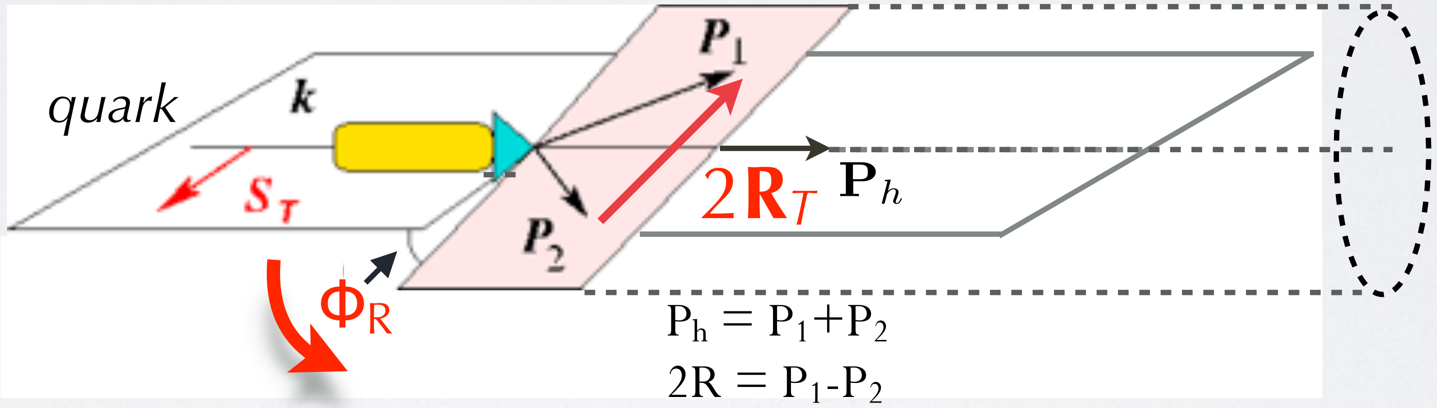
di-hadron semi-inclusive production



2-hadron-inclusive production

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

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



$P_h = P_1 + P_2$

$2R = P_1 - P_2$

↕

M_h

invariant mass

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

2-hadron-inclusive production

framework
collinear
factorization

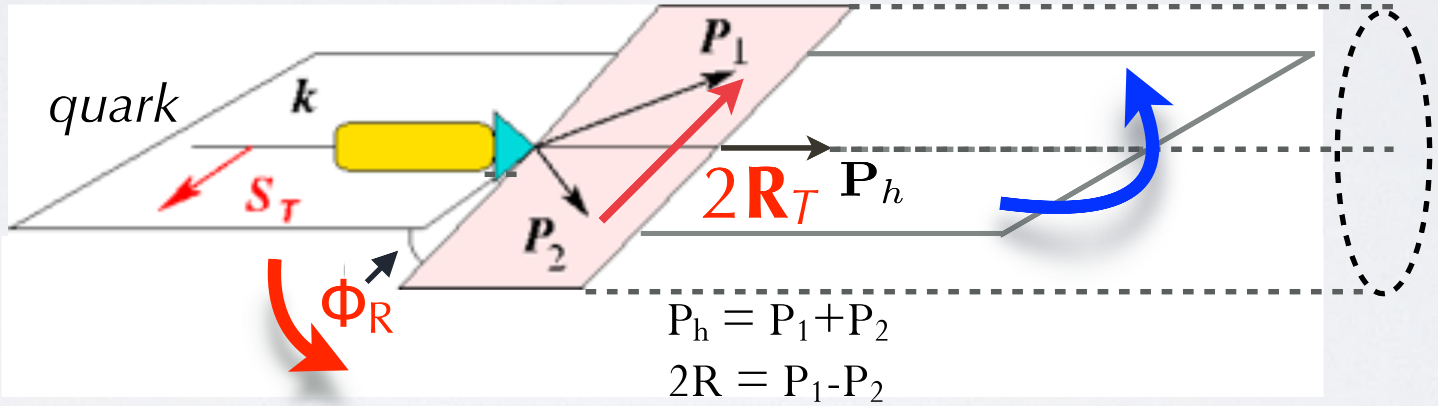
Collins, Heppelman, Ladinsky,
N.P. ***B420*** *(94)*

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

↕

M_h

invariant mass

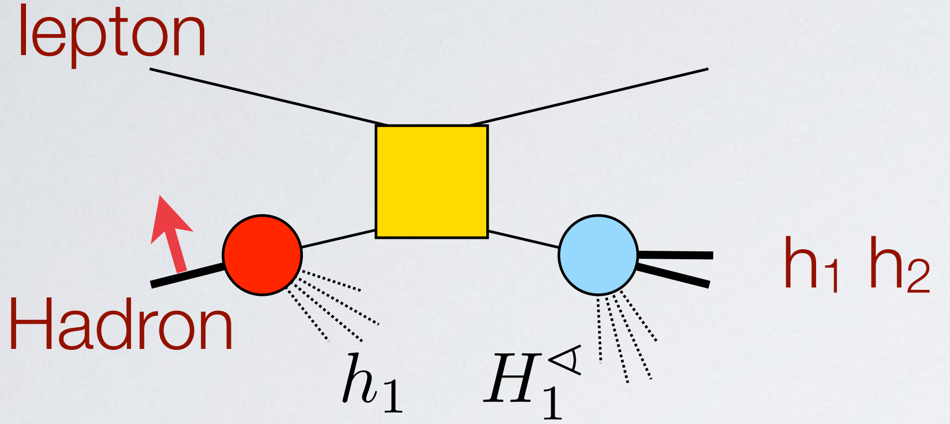


survives to
polar symmetry
($\int dP_{hT}$)
$P_h \parallel k$

correlation S_T and R_T → **azimuthal asymmetry**

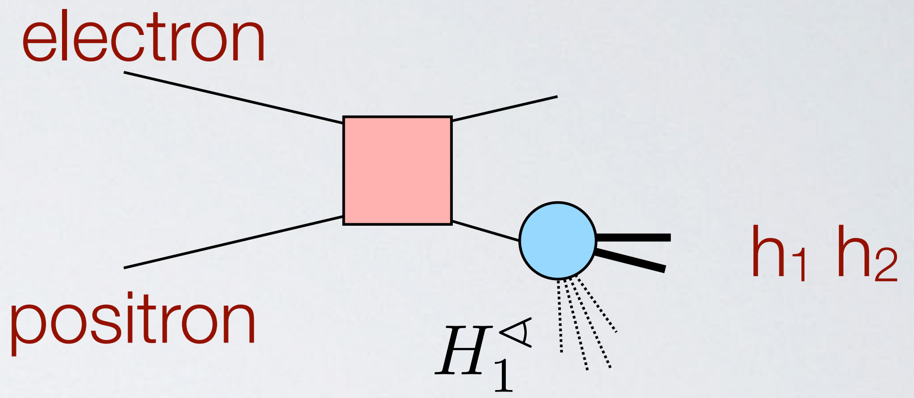
2-hadron-inclusive production

SIDIS



framework
collinear
factorization

e+e−



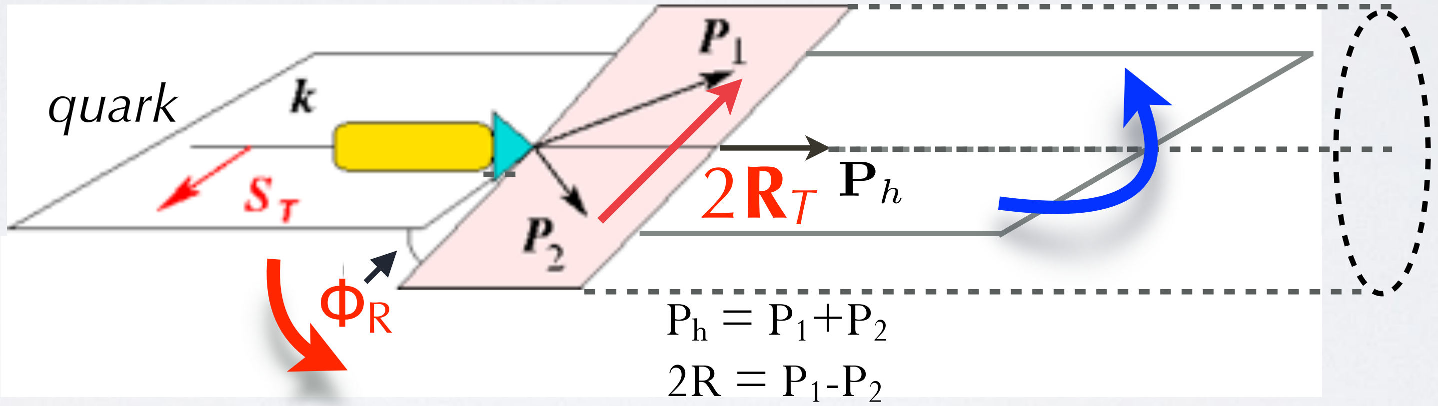
$R_T \ll Q$

↕

M_h

invariant mass

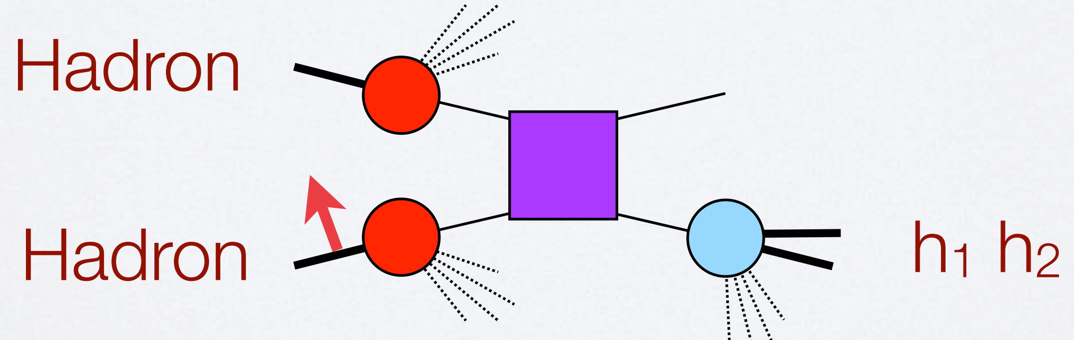
$H_1^{\sphericalangle}$



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

correlation S_T and R_T → **azimuthal asymmetry**

H H↑

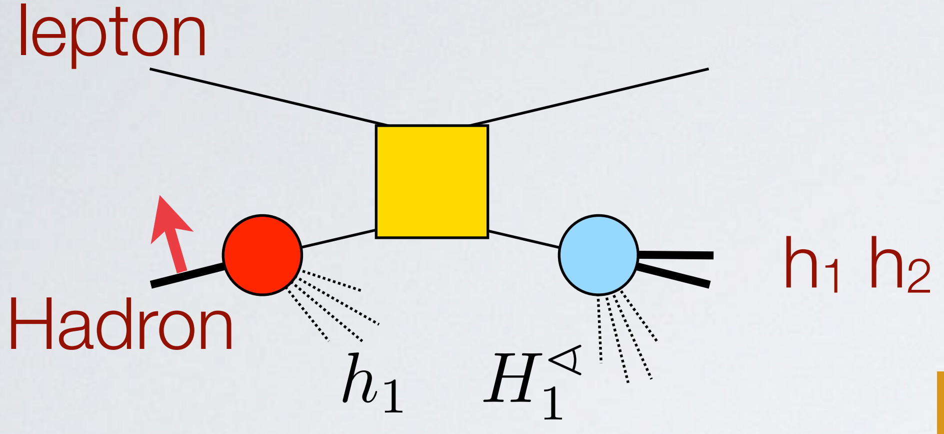


$f_1 \times h_1 \times H_1^{\sphericalangle}$

2-hadron-inclusive production

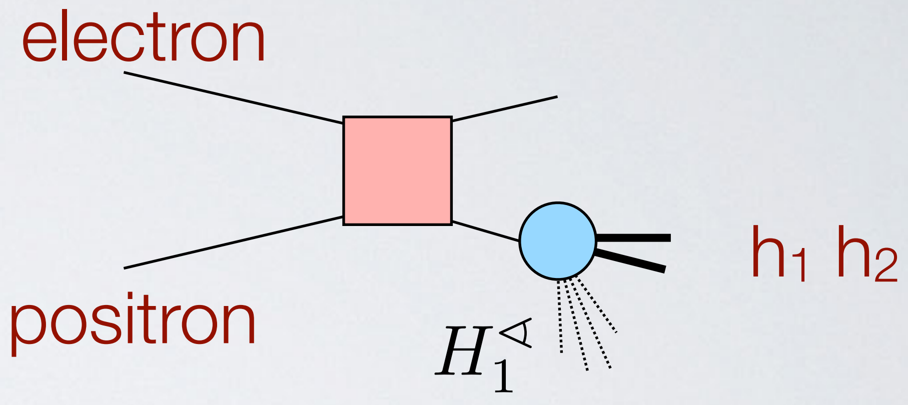
factorized formulas

SIDIS



*Jaffe, Jin, Tang, P.R.L.**80** (98) 1166*
*Radici, Jakob, Bianconi, P.R.D**65** (02) 074031*
*Bacchetta & Radici, P.R. D**67** (03) 094002*

e+e−

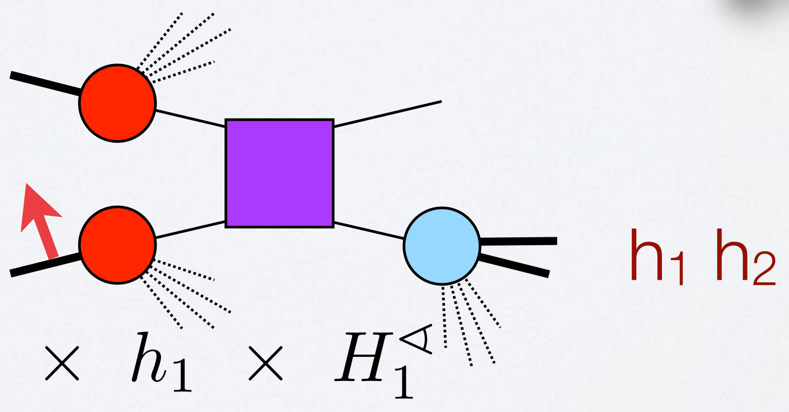


*Artru & Collins, Z.Phys. **C69** (96) 277*
*Boer, Jakob, Radici, P.R.D**67** (03) 094003*
*Matevosyan et al., P.R.D**97** (2018) 074019*

DGLAP evolution
connects $h_1(x,\mathbf{Q})$
& $H_1^{\sphericalangle}(z,\mathbf{M_h},\mathbf{Q})$
at different scales $\mathbf{Q}$

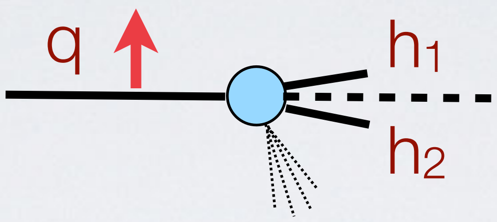
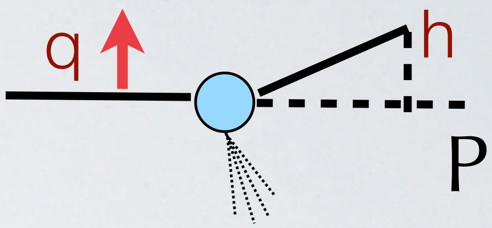
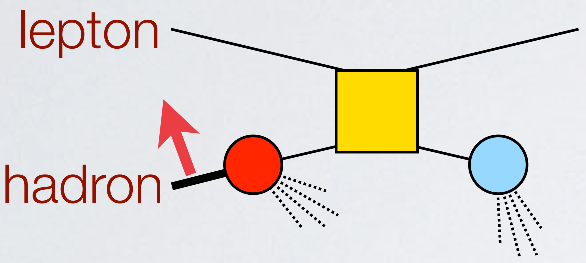
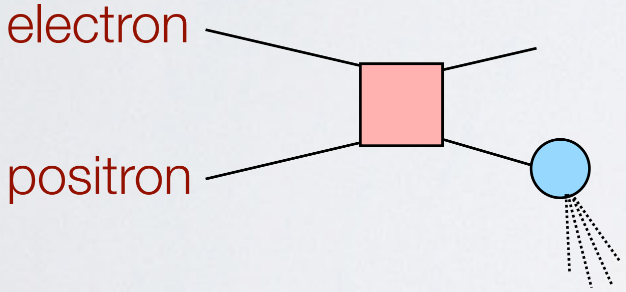
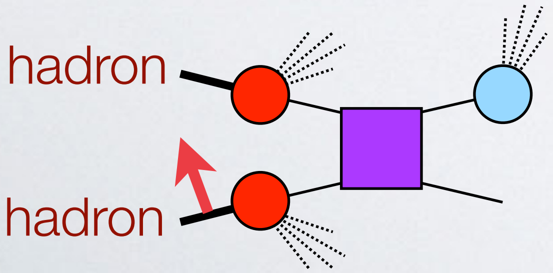
*Ceccopieri, Radici, Bacchetta, P.L.**B650** (07) 81*

H H↑



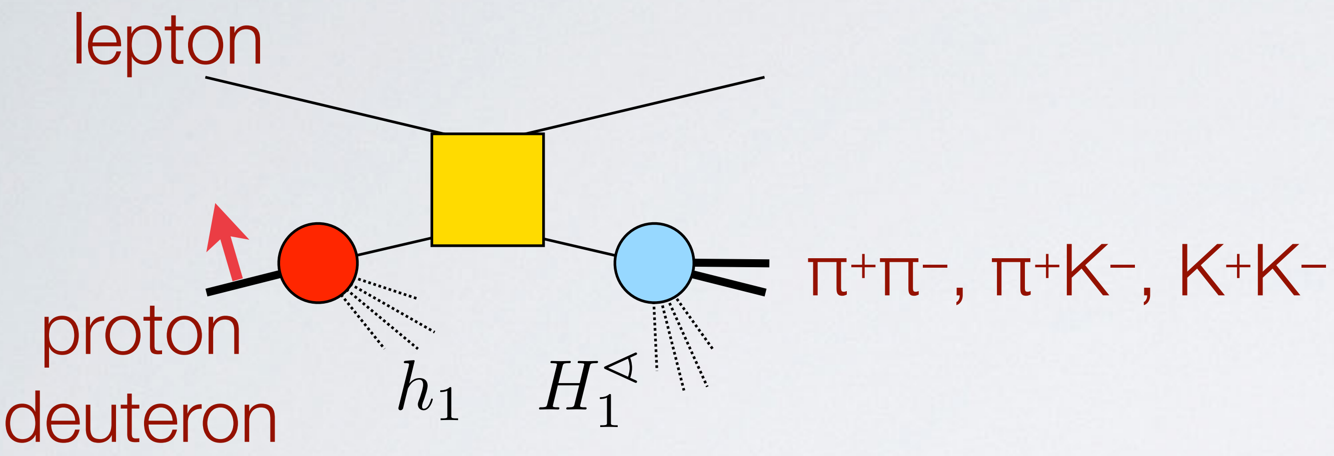
*Bacchetta & Radici, P.R. D**70** (04) 094032*

advantage of 2-hadron-inclusive mechanism

factorized formulas	**Dihadron** fragmentation **collinear** framework  $R_T \ll Q$	Collins effect **TMD** framework  $P_{hT} \ll Q$
 SIDIS	✔	✔
 e+e−	✔	✔
 H H↑	✔	✘

exp. data for 2-hadron-inclusive production

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



lepton

proton

deuteron

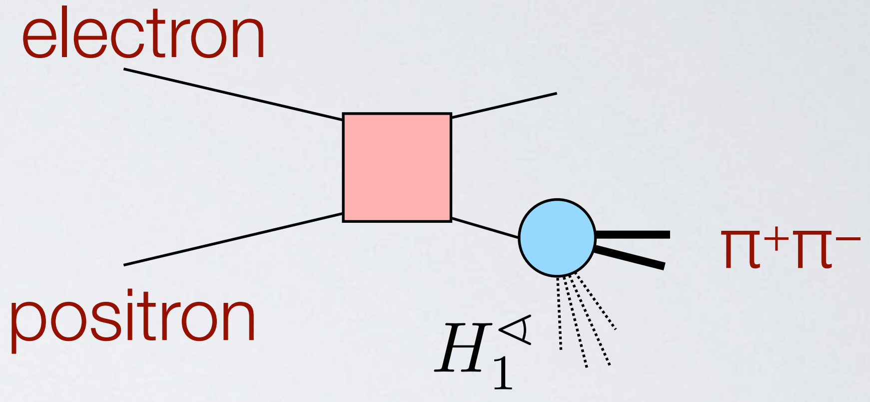
h_1 $\quad H_1^{\sphericalangle}$

$\pi^+\pi^-$, π^+K^-, K^+K^-

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

Adolph et al., P.L. ***B713*** *(12); P.L.* ***B736*** *(14)*
Braun et al., E.P.J. Web Conf. ***85*** *(15) 02018*

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



electron

positron

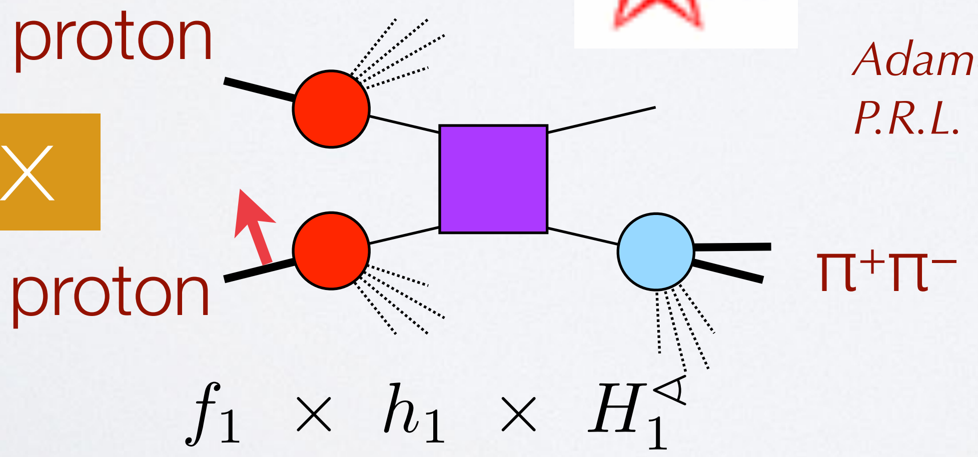
$H_1^{\sphericalangle}$

$\pi^+\pi^-$

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

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

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



proton

proton

$\pi^+\pi^-$

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

run 2006 (s=200)

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

run 2011 (s=500)

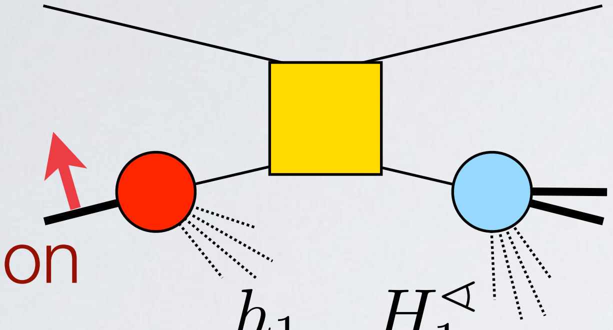
Adamczyk et al. (STAR),
P.L. ***B780*** *(18) 332*

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

exp. data for 2-hadron-inclusive production

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

lepton



$\pi^+\pi^-$, π^+K^-, K^+K^-

proton

deuteron

h_1 $H_1^{\sphericalangle}$

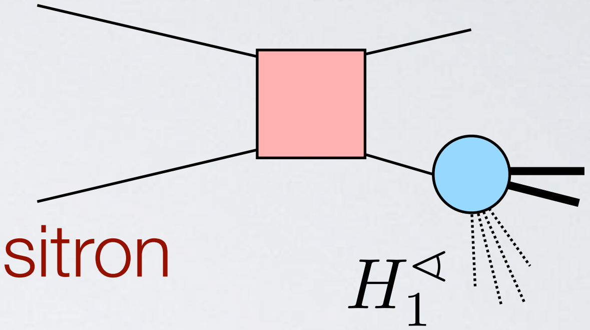
Airapetian et al., JHEP **0806** (08) 017

Adolph et al., P.L. **B713** (12); P.L. **B736** (14)

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

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

electron



$\pi^+\pi^-$

positron

$H_1^{\sphericalangle}$

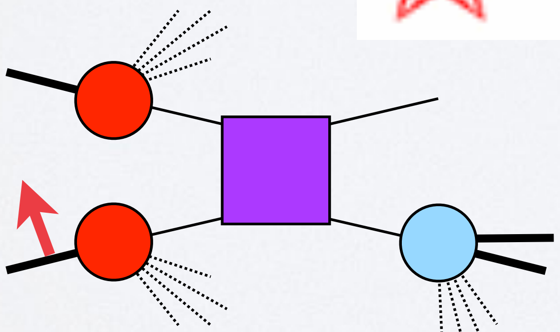
Vossen et al., P.R.L. **107** (11) 072004

D_1 Seidl et al., P.R. **D96** (17) 032005

from Montecarlo

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

proton



proton

$\pi^+\pi^-$

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

run 2006

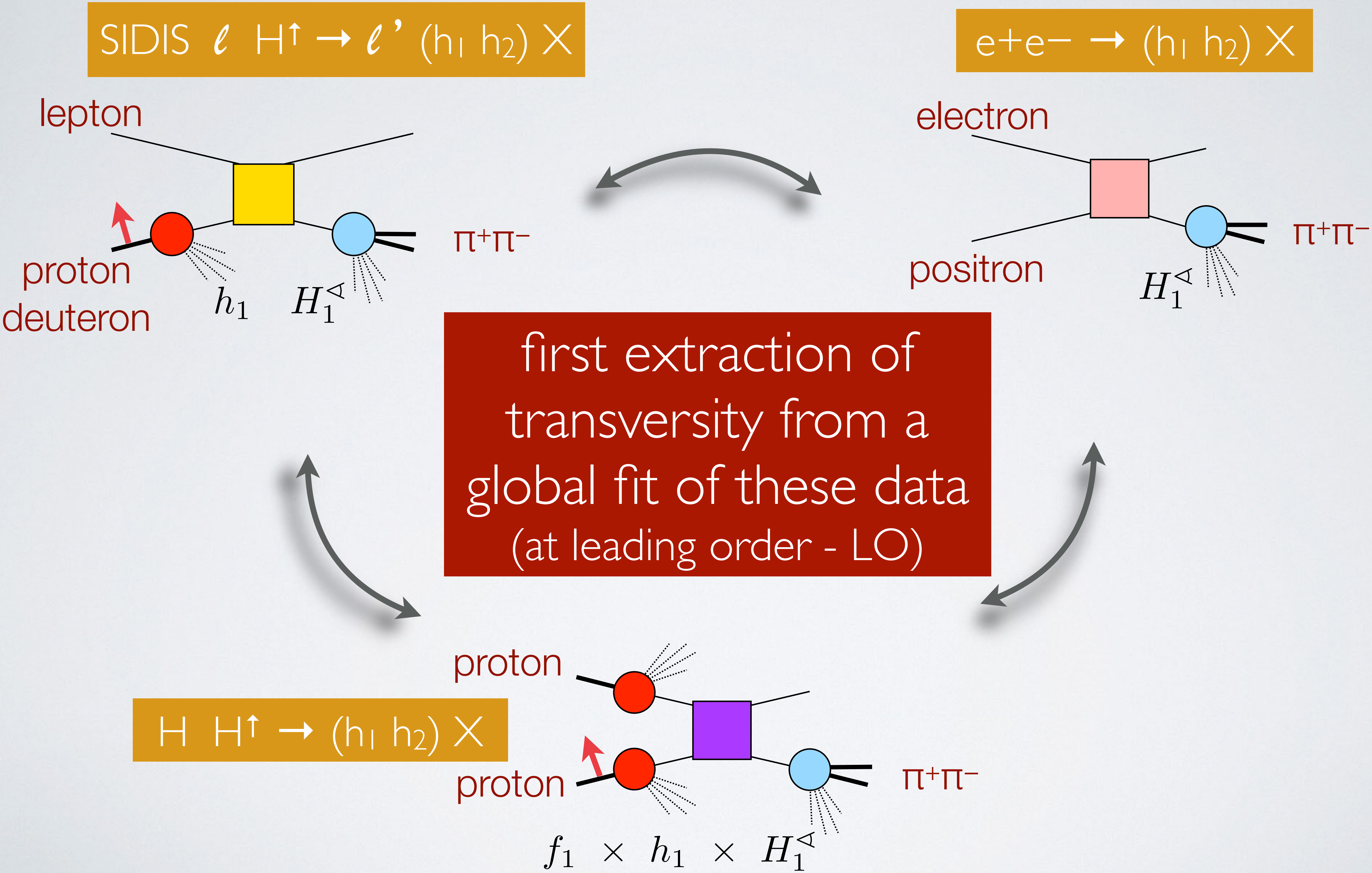
Adamczyk et al. (STAR), P.R.L. **115** (2015) 242501

run 2011

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

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

take–away message



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

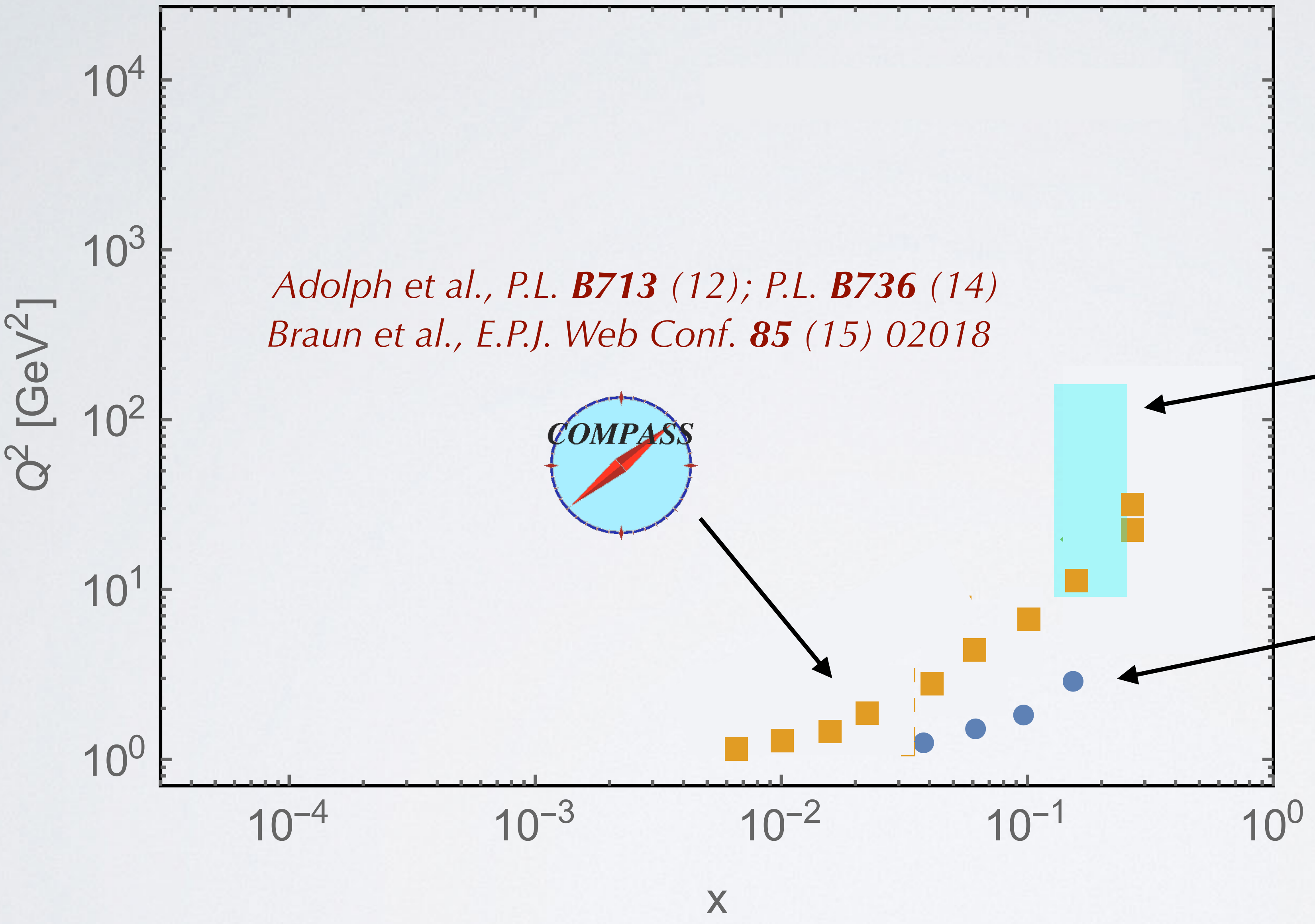
$e^+e^- \to (h_1\ h_2)\ X$

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

first extraction of transversity from a global fit of these data

(at leading order - LO)

the kinematics



Adolph et al., P.L. ***B713*** *(12); P.L.* ***B736*** *(14)*
Braun et al., E.P.J. Web Conf. ***85*** *(15) 02018*

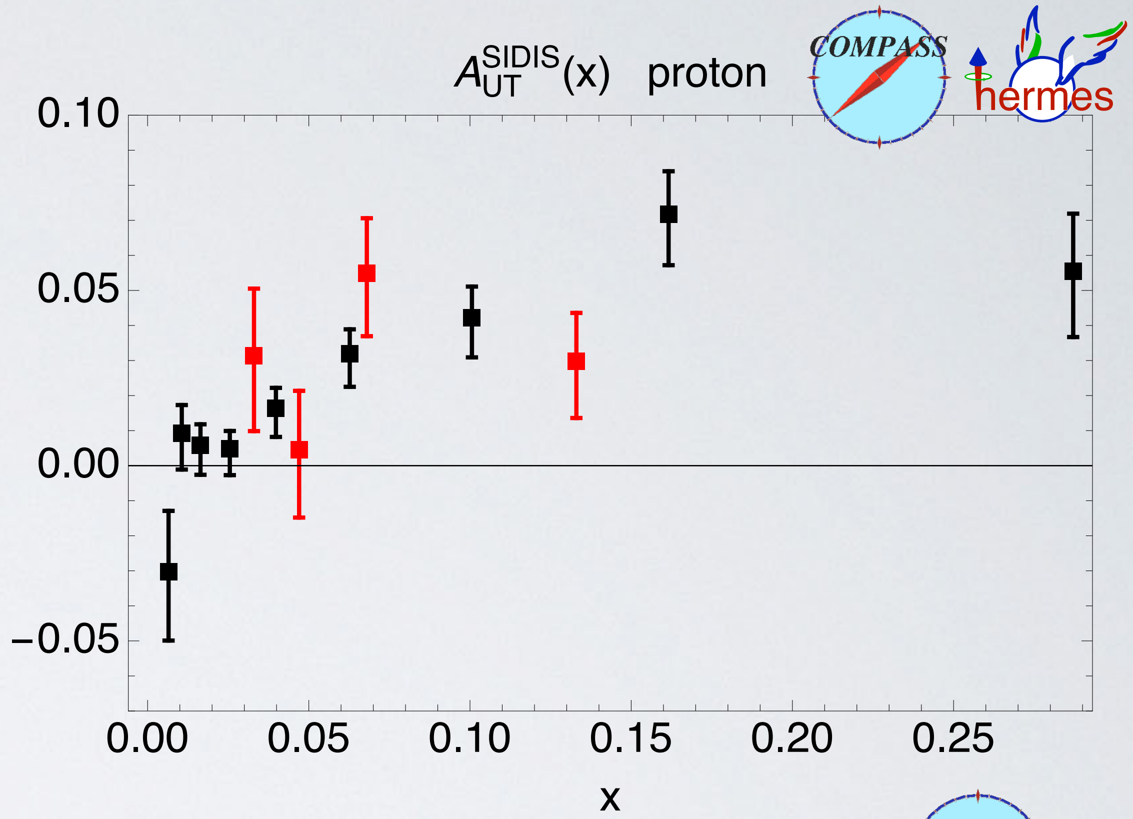
run 2006
s=200 GeV^2

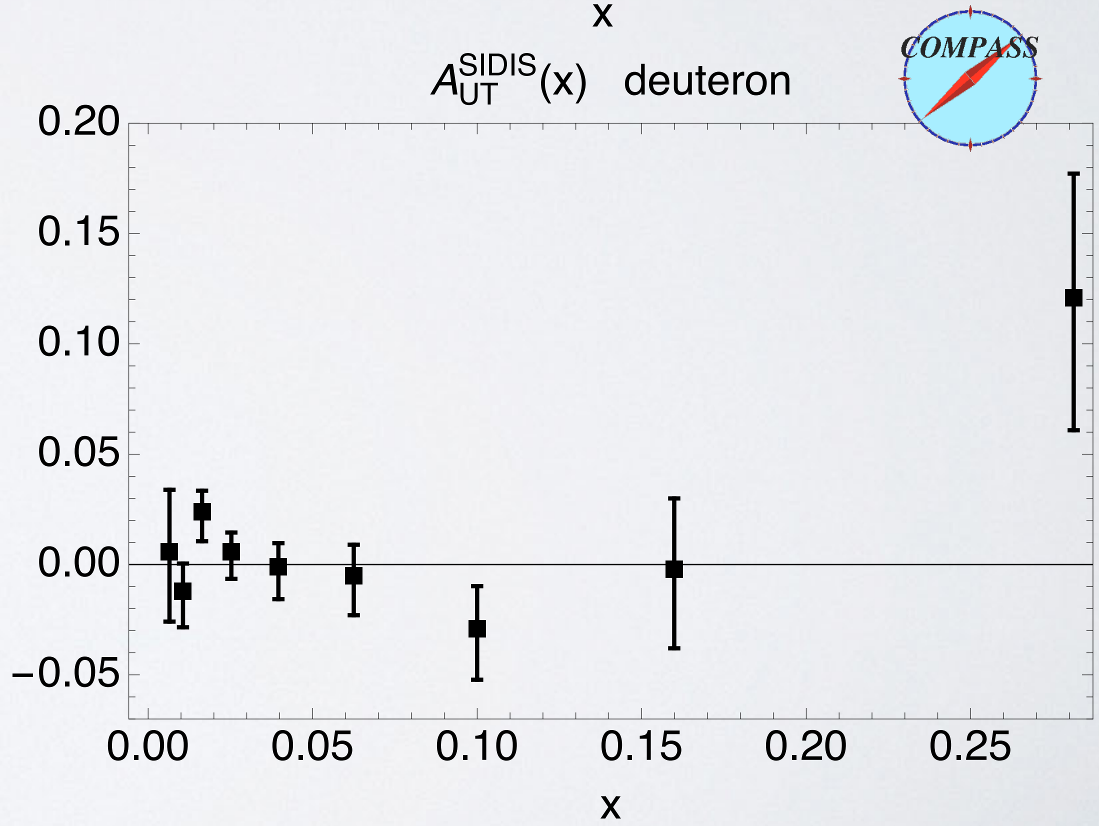
Adamczyk et al. (STAR),
P.R.L. ***115*** *(2015) 242501*

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

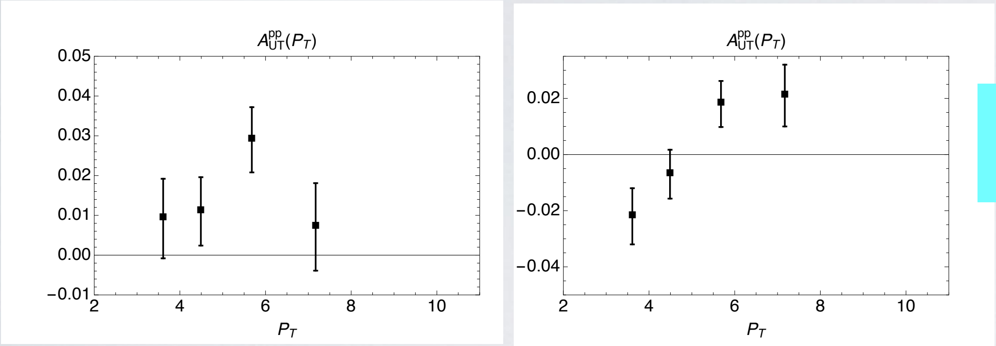
explore only valence quarks

the data set in more detail



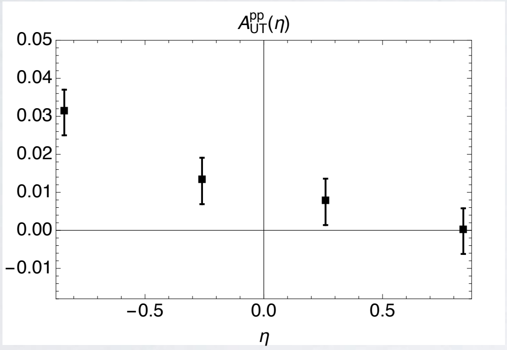


the data set in more detail



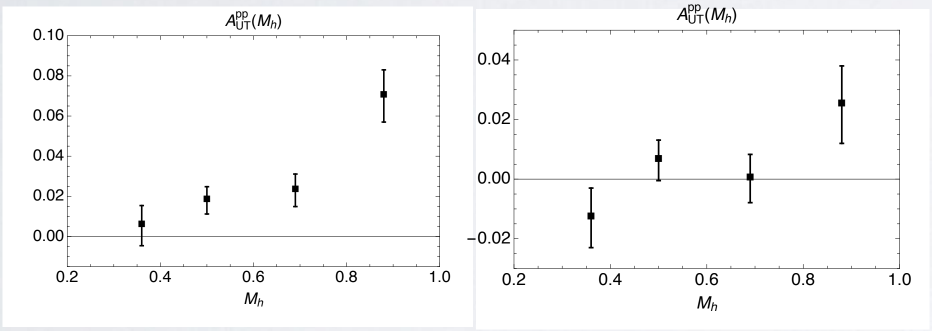
A_{ut}^{pp} (P_T)

η<0



η>0

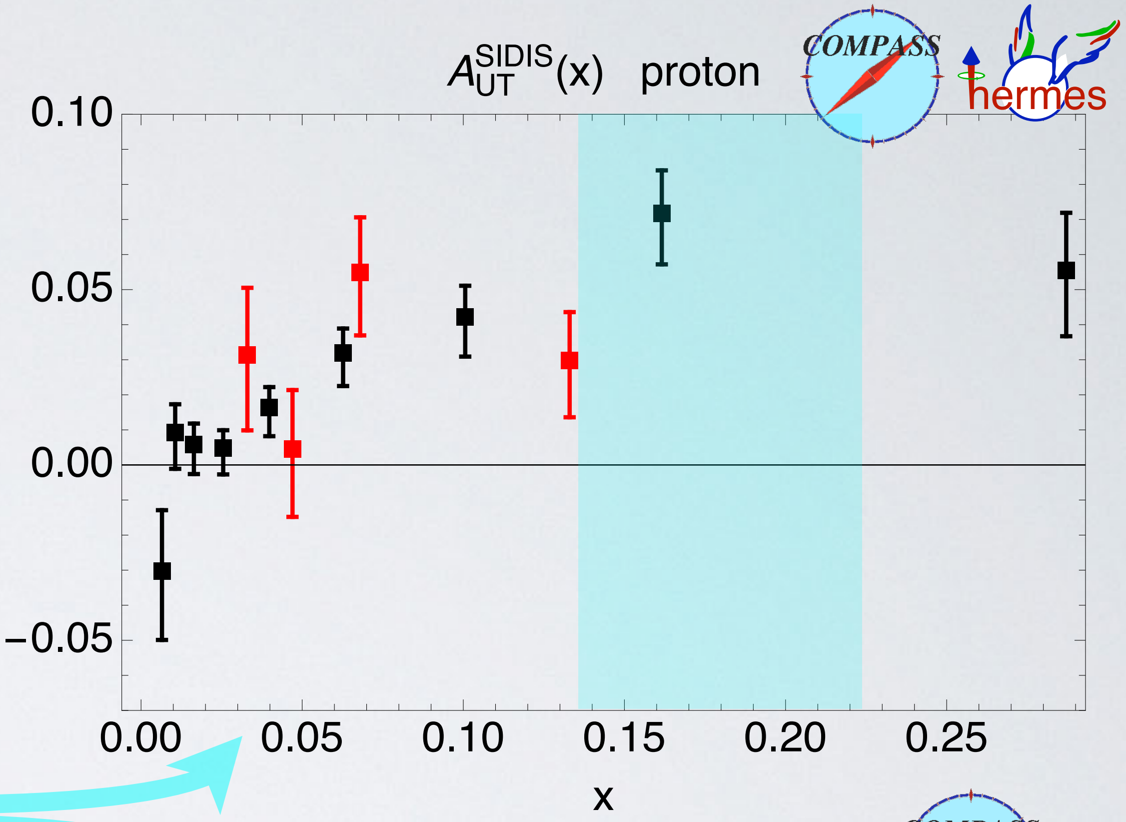
A_{ut}^{pp} (η)

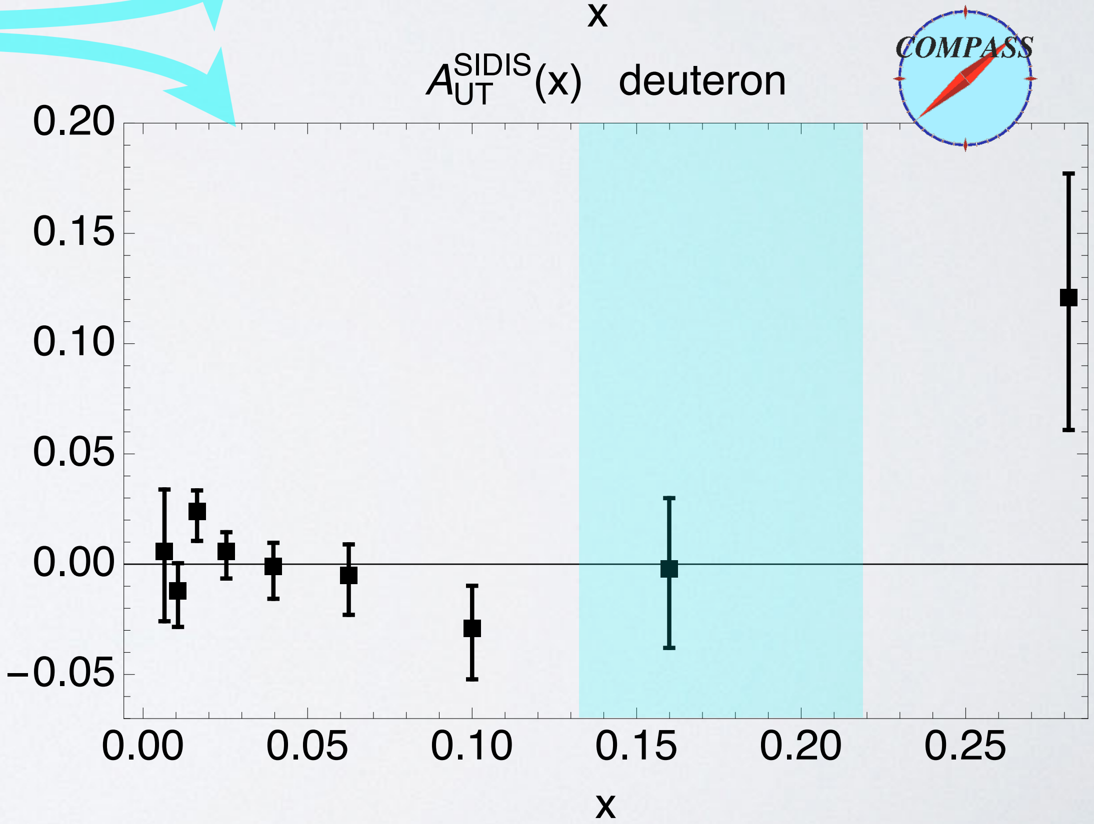


A_{ut}^{pp} (M_h)

run 2006 s=200 GeV^2

(effective coverage in x 🟦)





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

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

$$\big\downarrow$$

Soffer Bound

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

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 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

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

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

$|N_{q_v}| \leq 1 \ \Rightarrow\ |F^{q_v}(x)| \leq 1$ **Soffer Bound ok at any Q²**

choice of functional form

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

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

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

low-x behavior is important outside data range

constrain parameters

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

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

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 $\chi^2/\mathrm{dof} = \begin{cases} 1.69 & 1.28 \\ 1.81 & 1.37 \\ 2.96 & 2.01 \end{cases}$

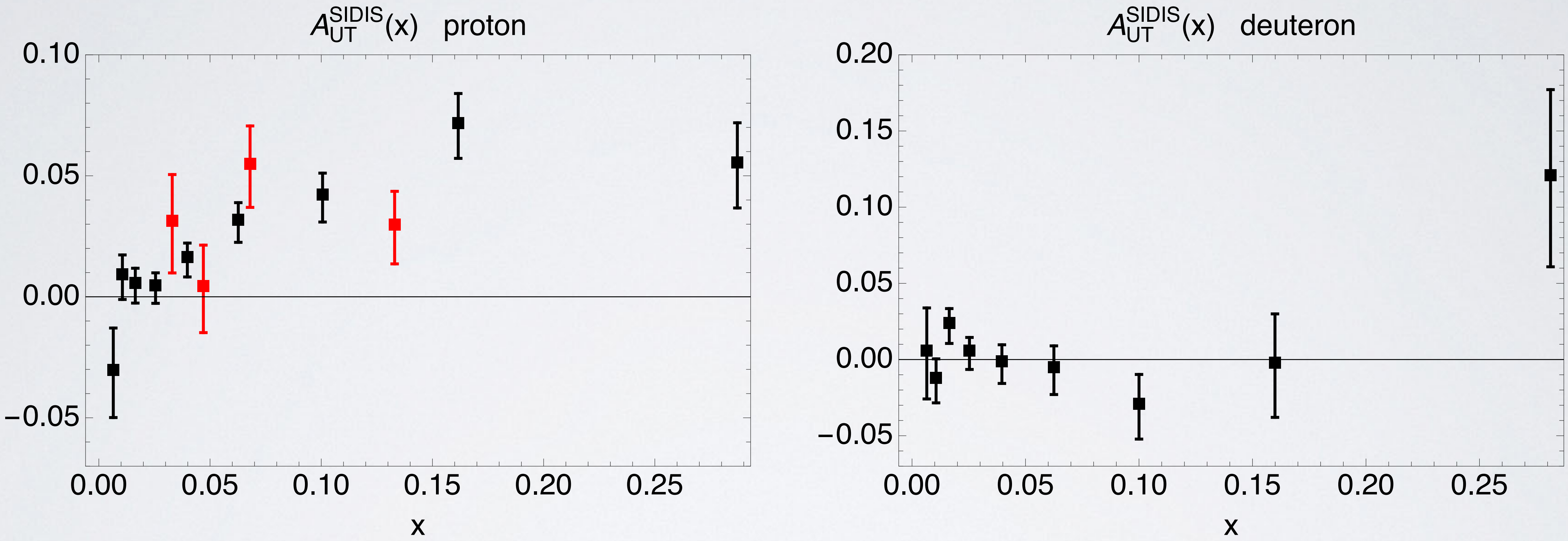
background ρ channels

statistical uncertainty: the bootstrap method

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

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

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



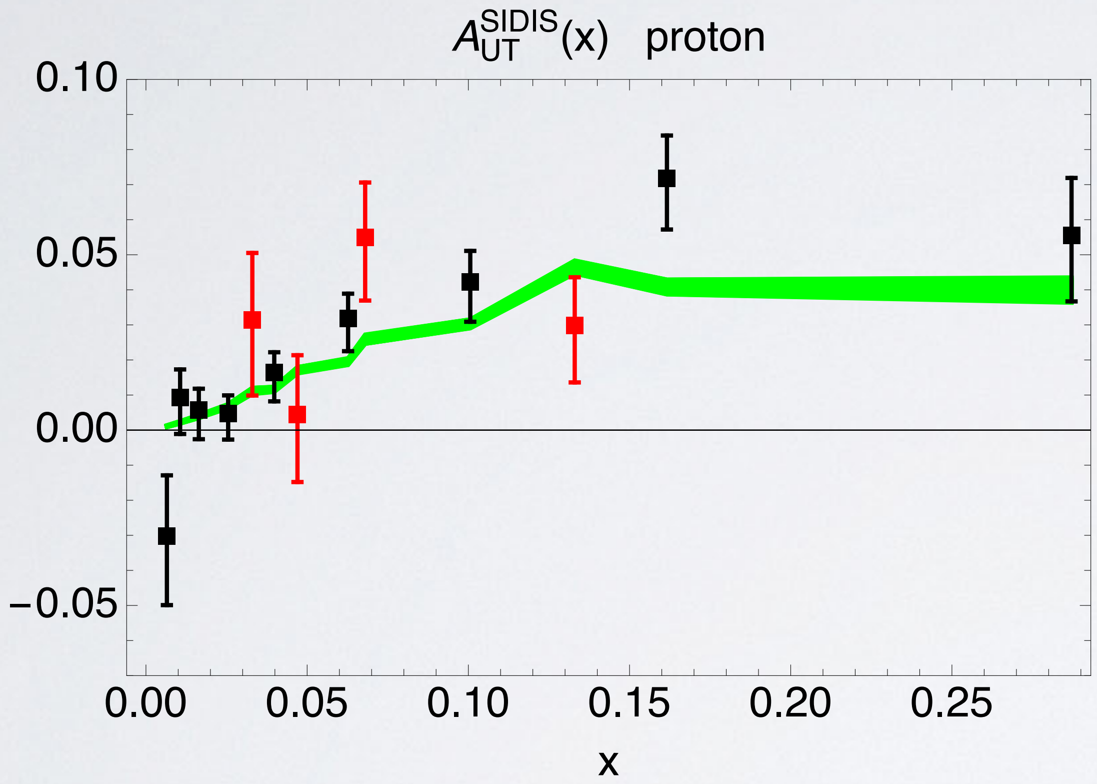
shift each exp. data point by Gaussian noise within exp. variance
→ create a replica of all exp. data points and fit them

statistical uncertainty: the bootstrap method

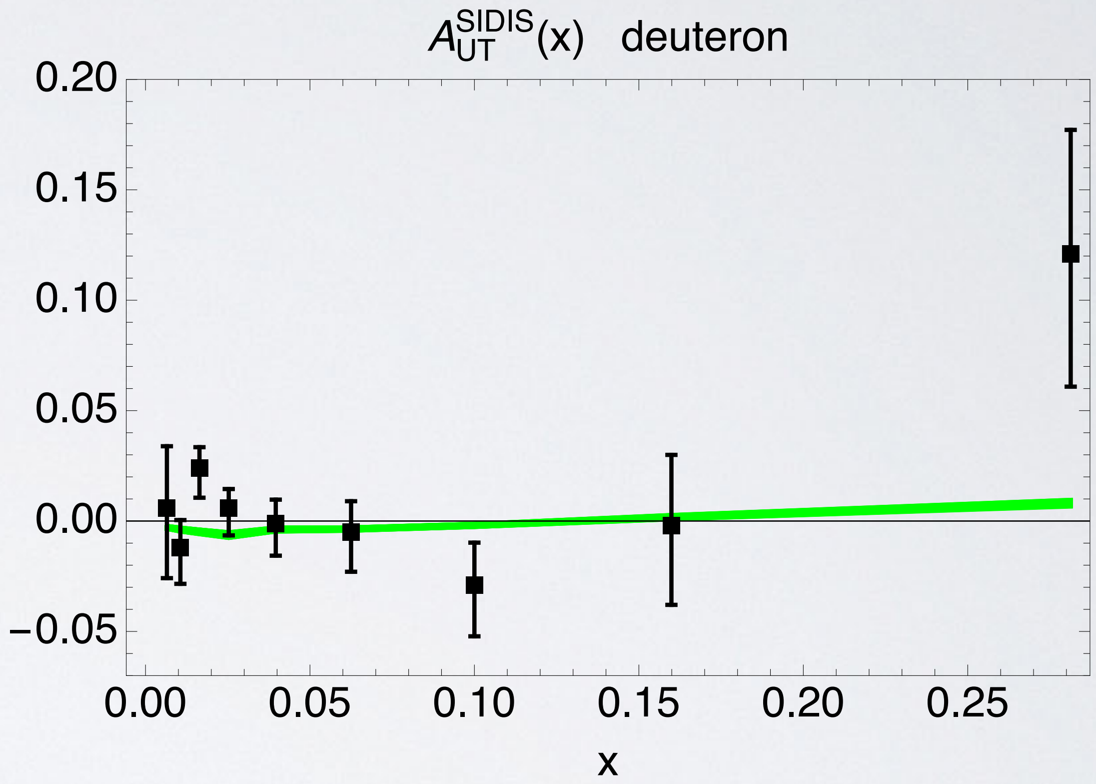
■ COMPASS *Braun et al., E.P.J. Web Conf.* ***85*** *(15) 02018*

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

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



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



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

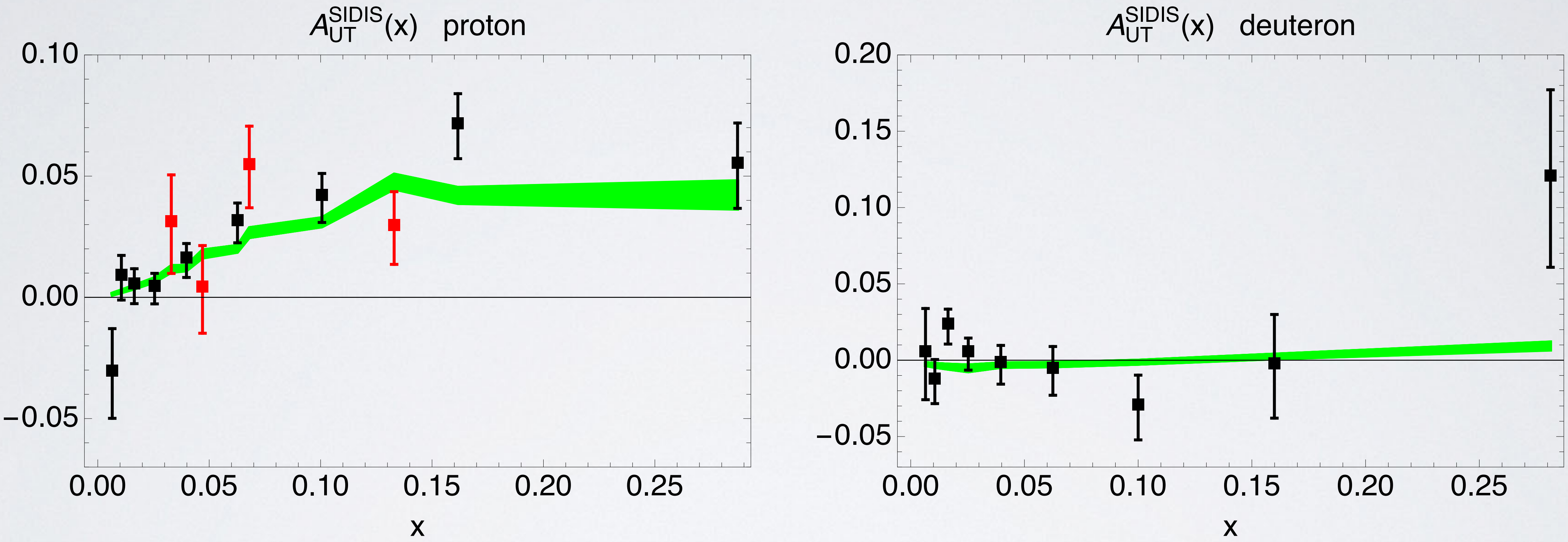
50 replicas

statistical uncertainty: the bootstrap method

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

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

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



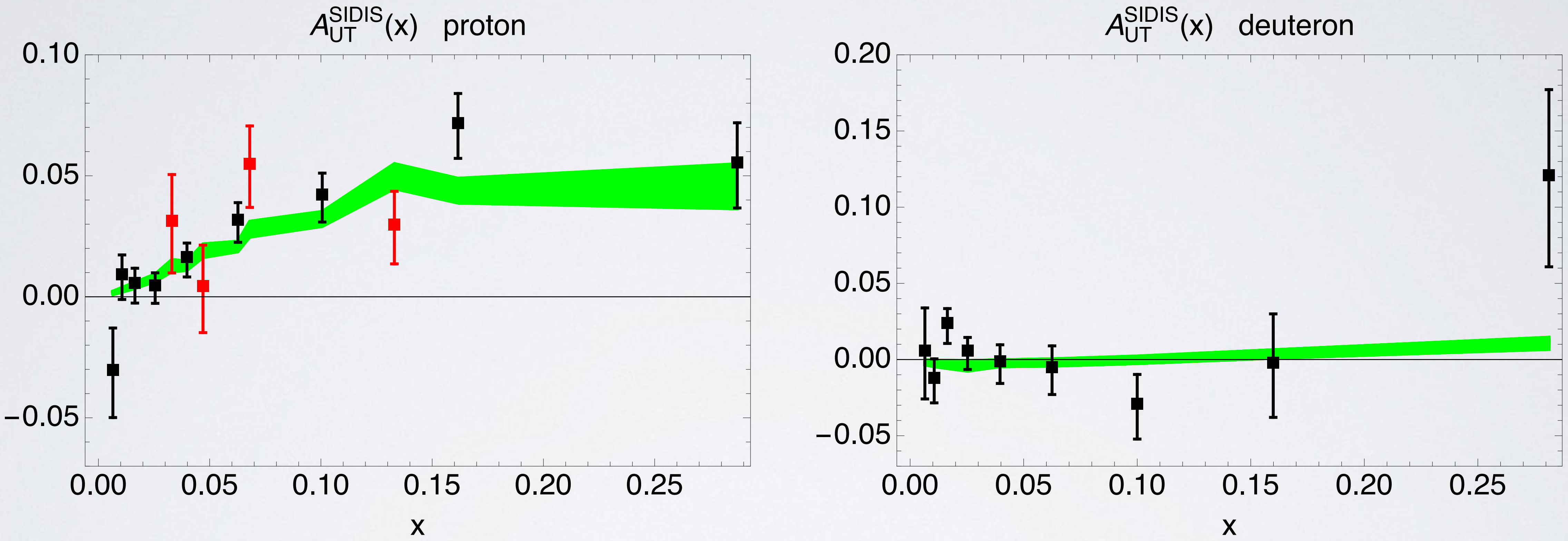
100 replicas

statistical uncertainty: the bootstrap method

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

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

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



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

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

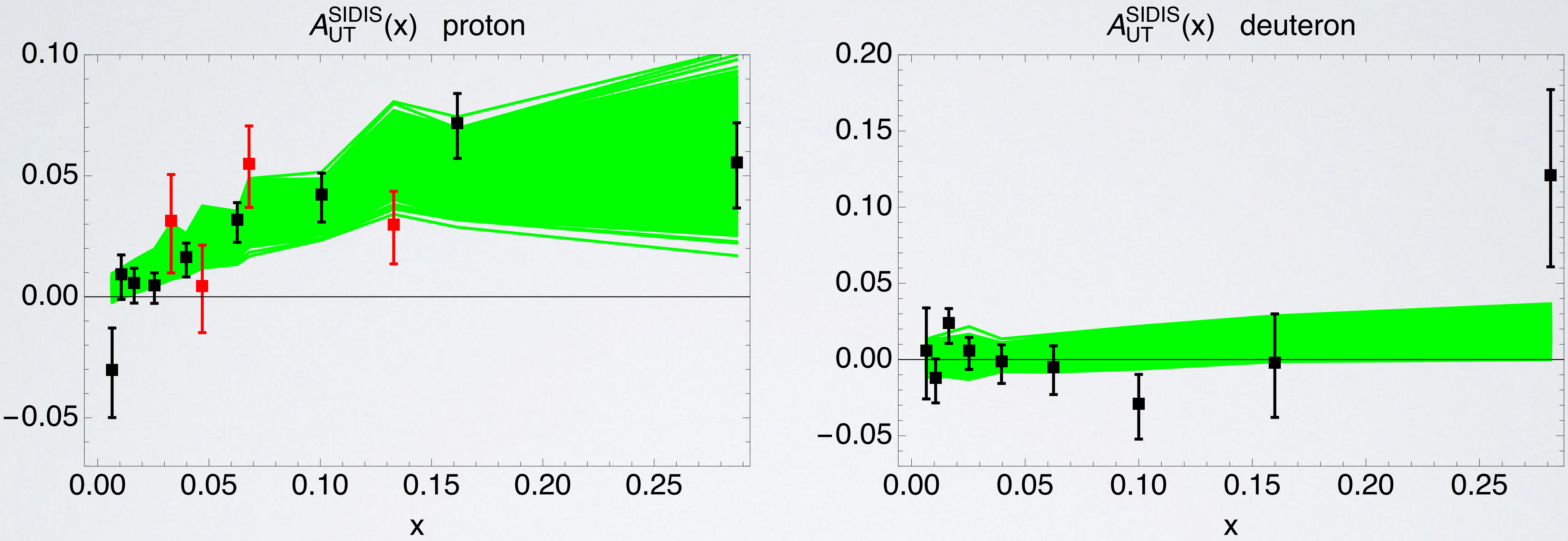
200 replicas

statistical uncertainty: the bootstrap method

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

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

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



all 600 replicas

statistical uncertainty: the bootstrap method

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

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

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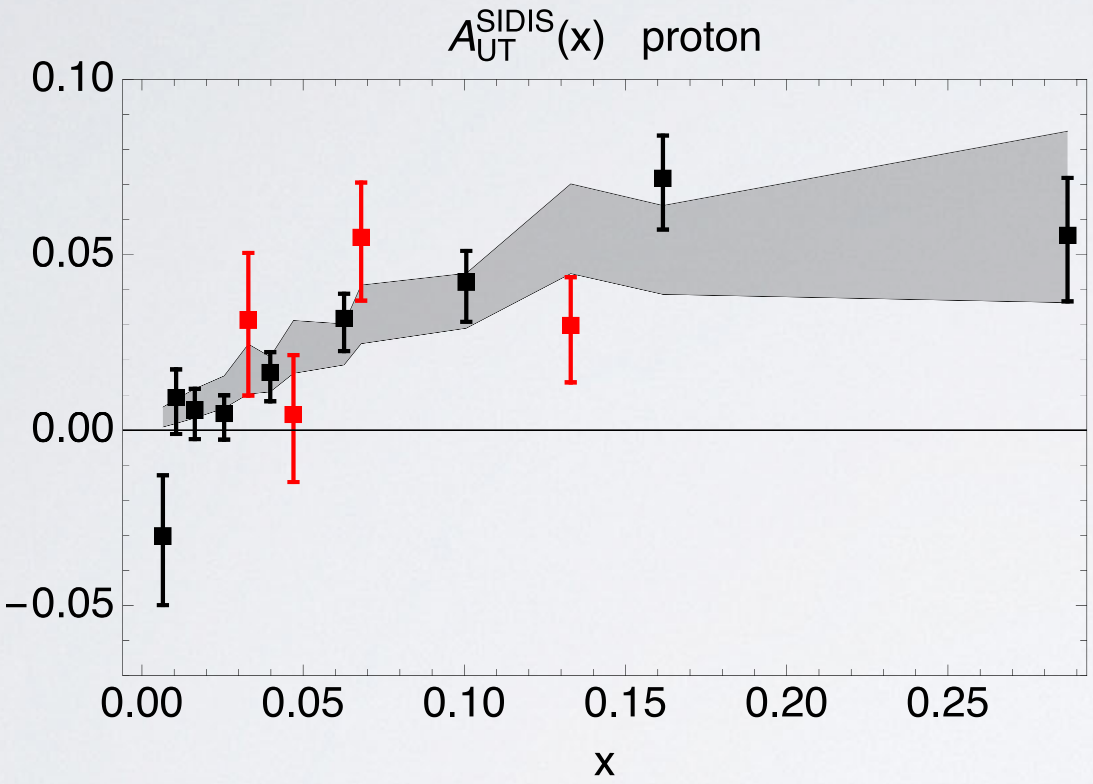
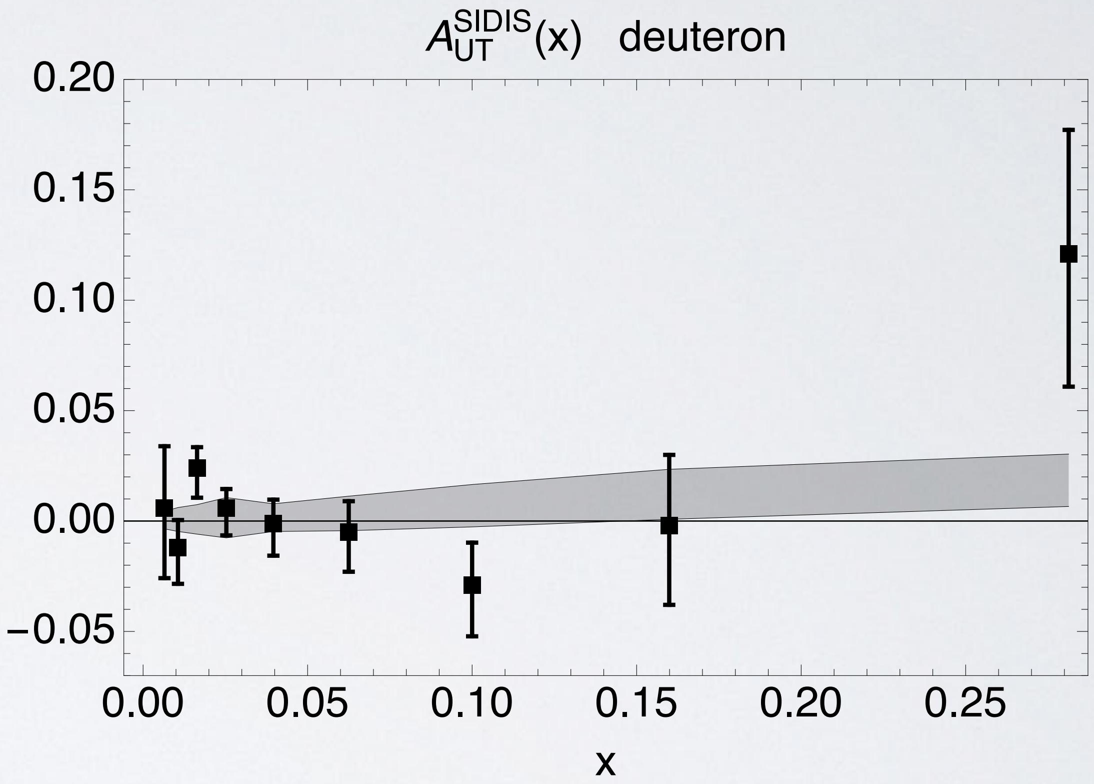
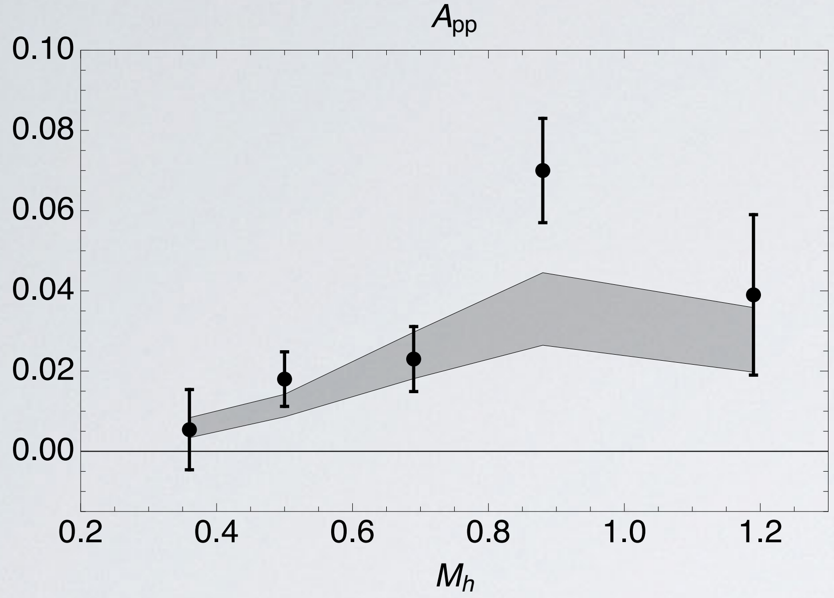


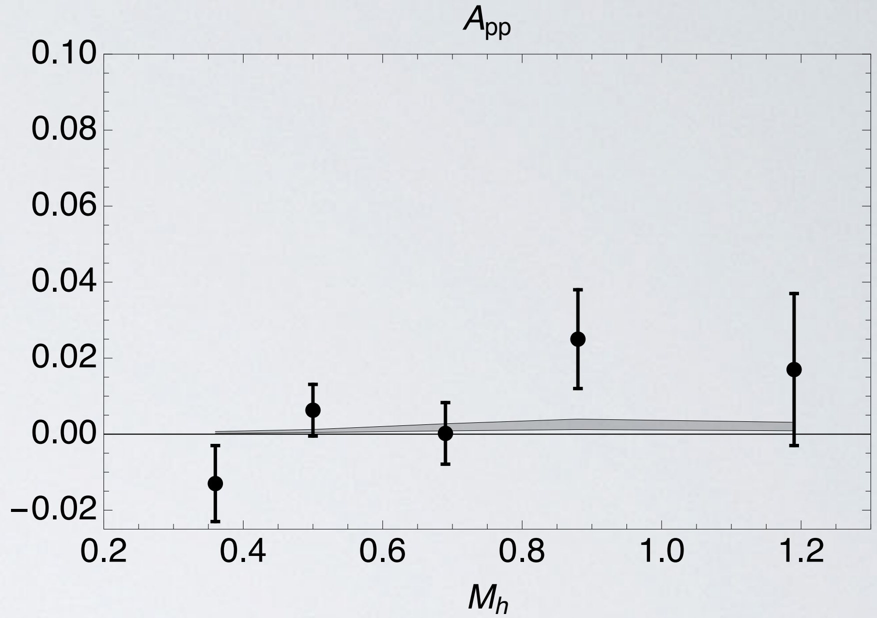


90% replicas

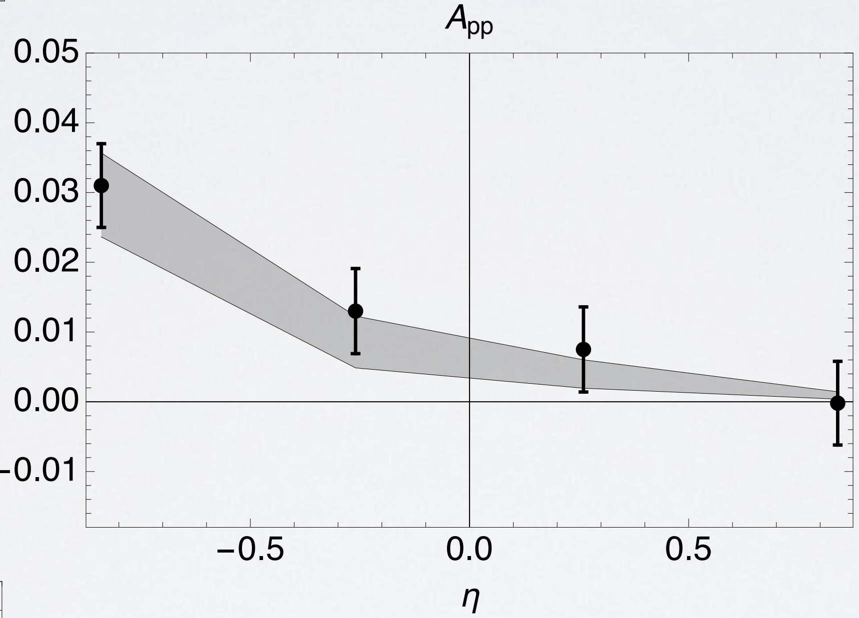
fit STAR asymmetry



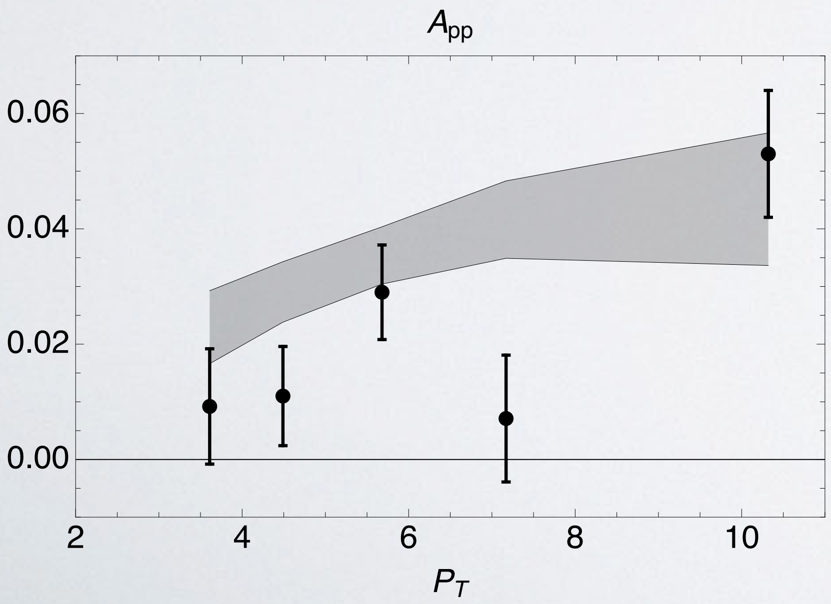
Adamczyk et al. (STAR), P.R.L. ***115*** *(2015) 242501*



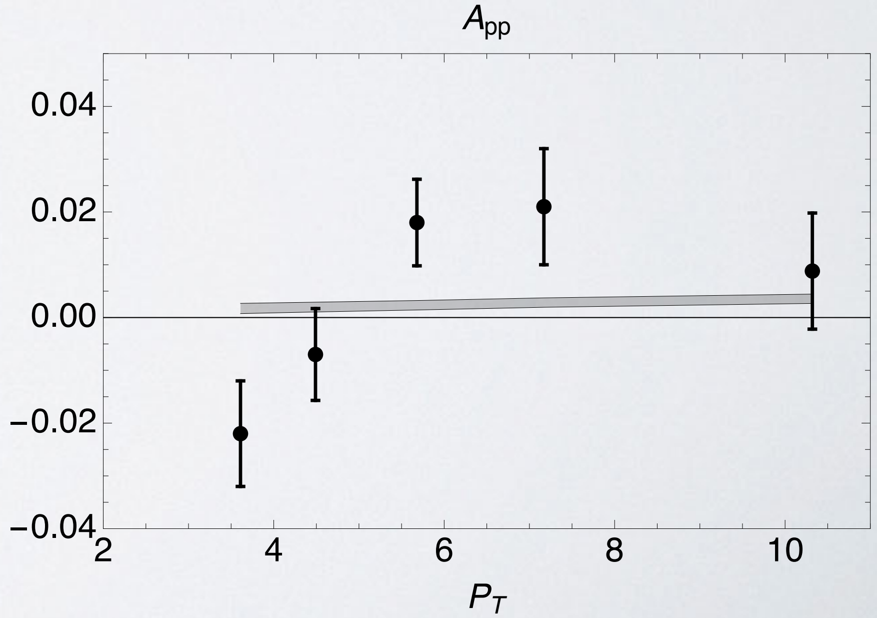
η<0



η>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%

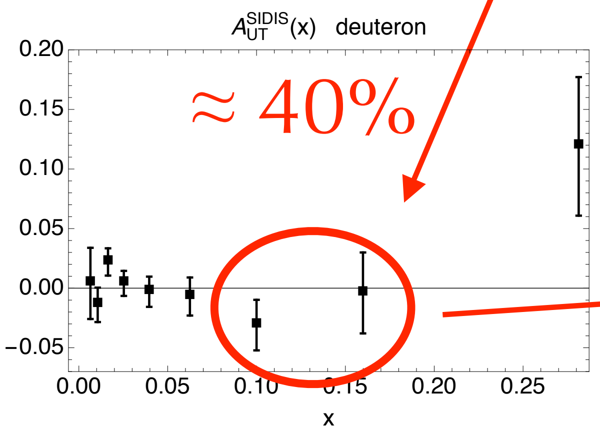
COMPASS

≈ 60%
rest

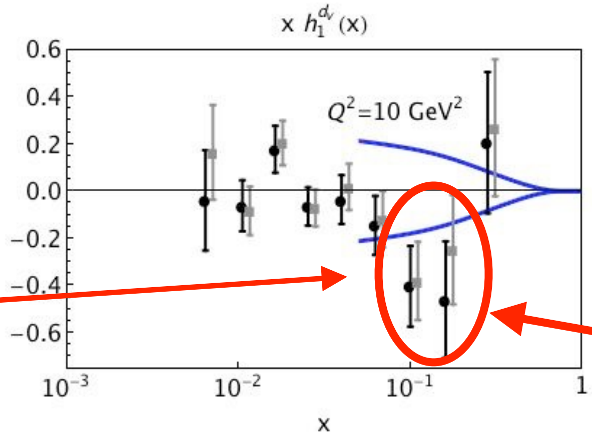
≈ 62%

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)

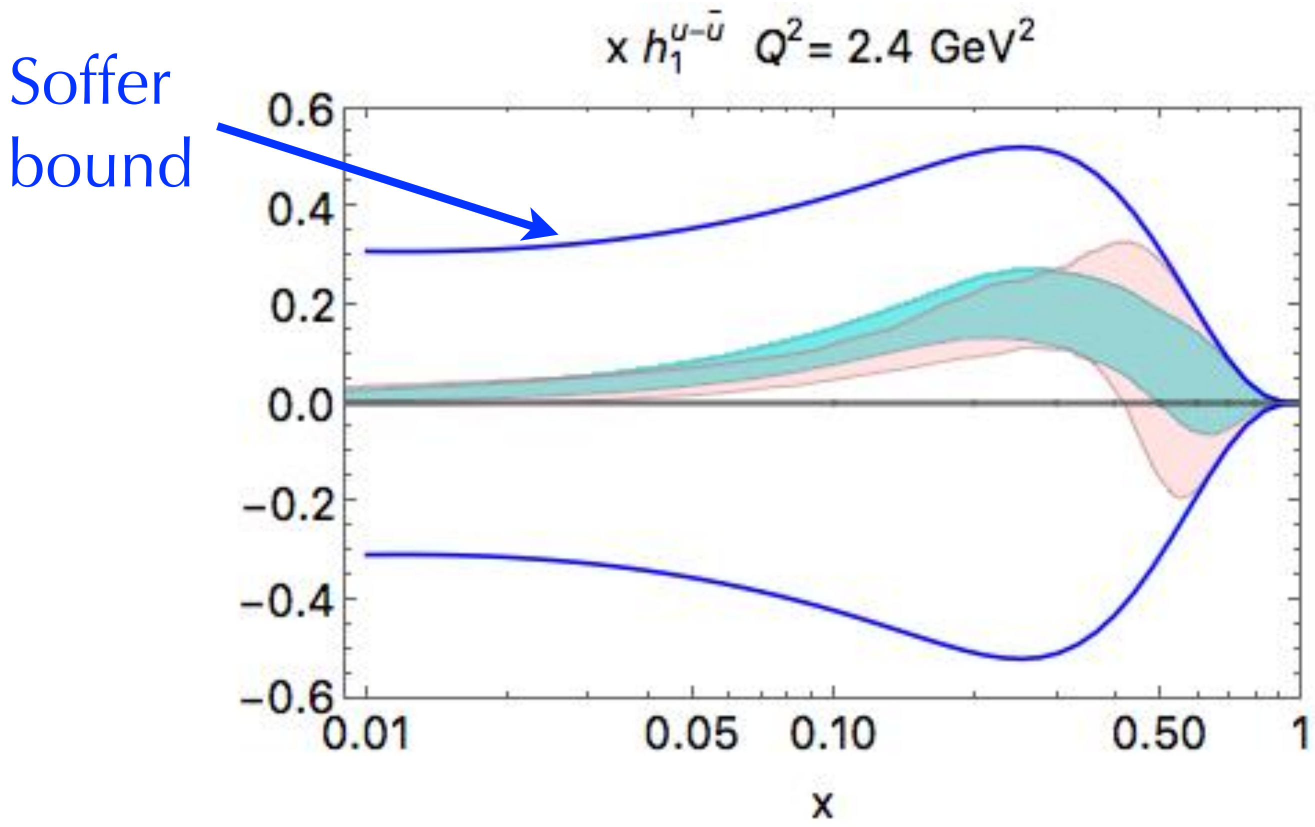
results

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

- 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



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

global fit

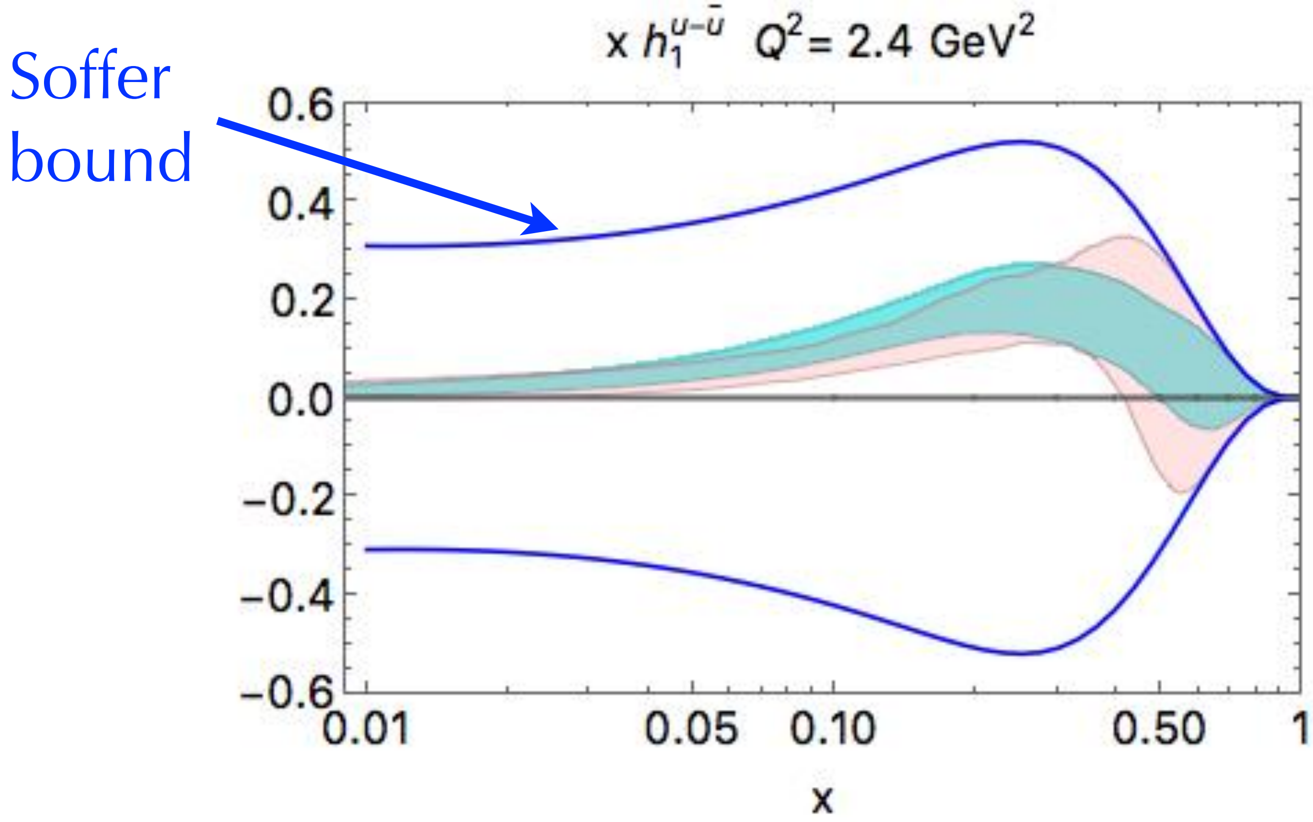
up

higher precision

old fit (only SIDIS data)

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

comparison with previous fit



Soffer bound

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

global fit

up

higher precision

old fit (only SIDIS data)

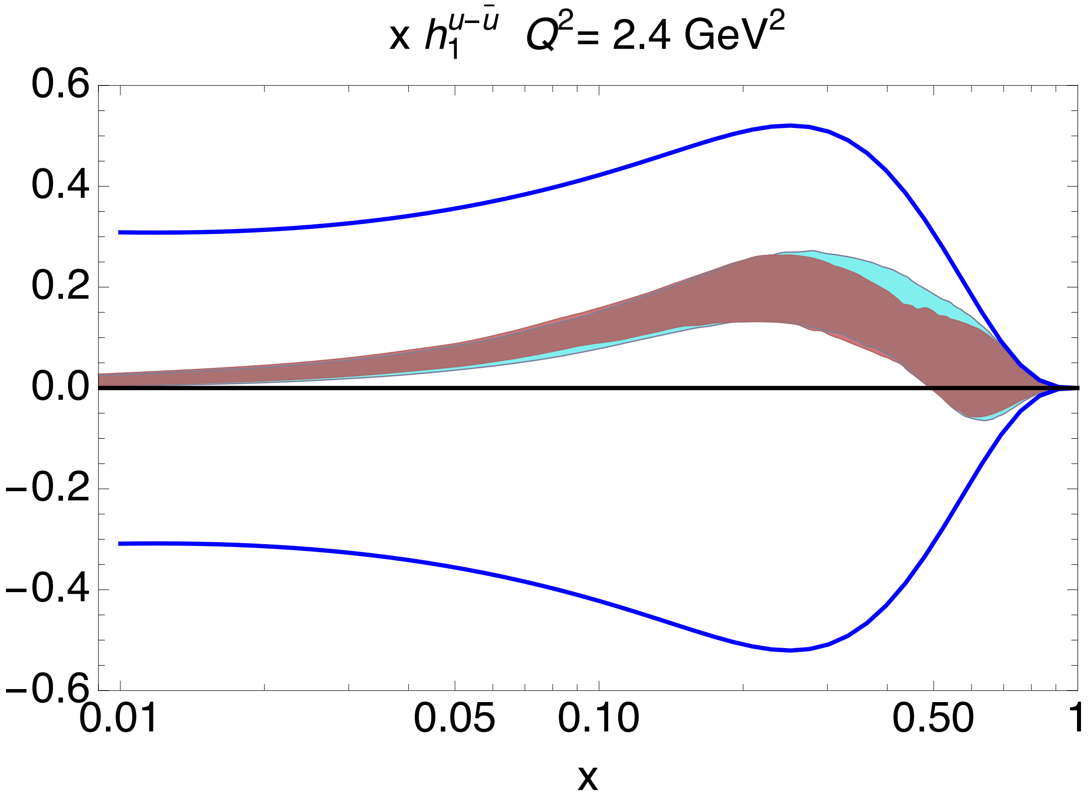
Radici et al.,
JHEP ***1505*** *(15) 123*

up

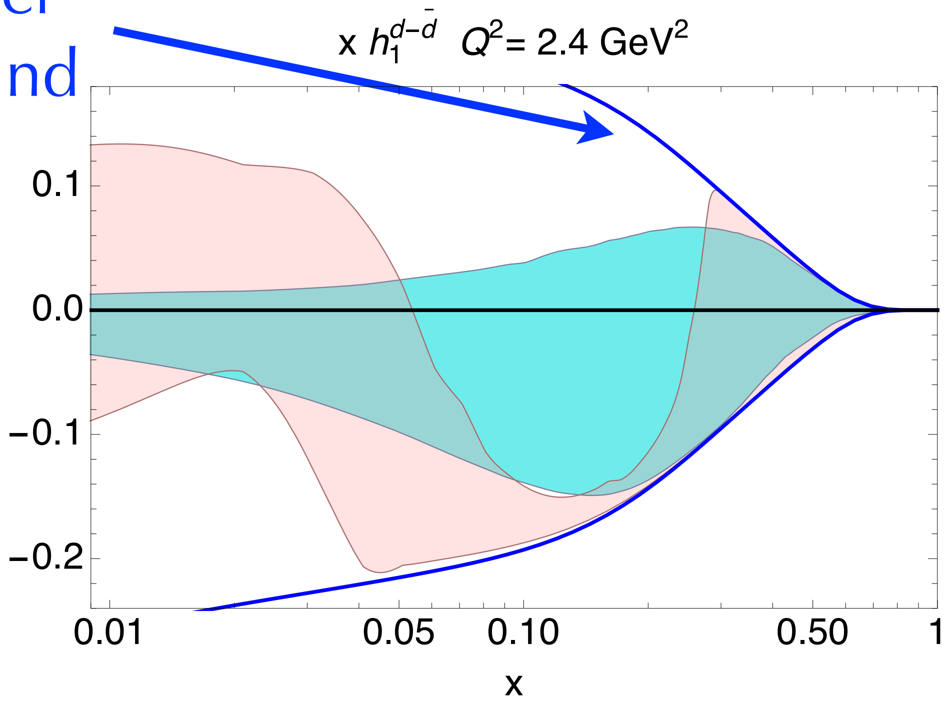
insensitive to uncertainty on gluon D_1

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

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



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*

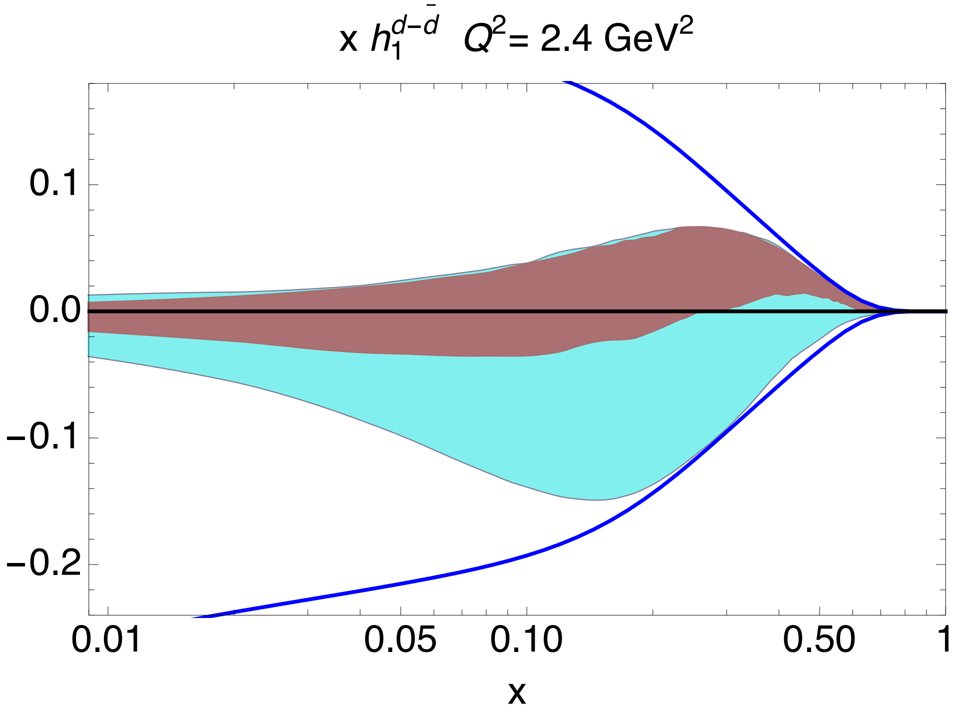
down

down

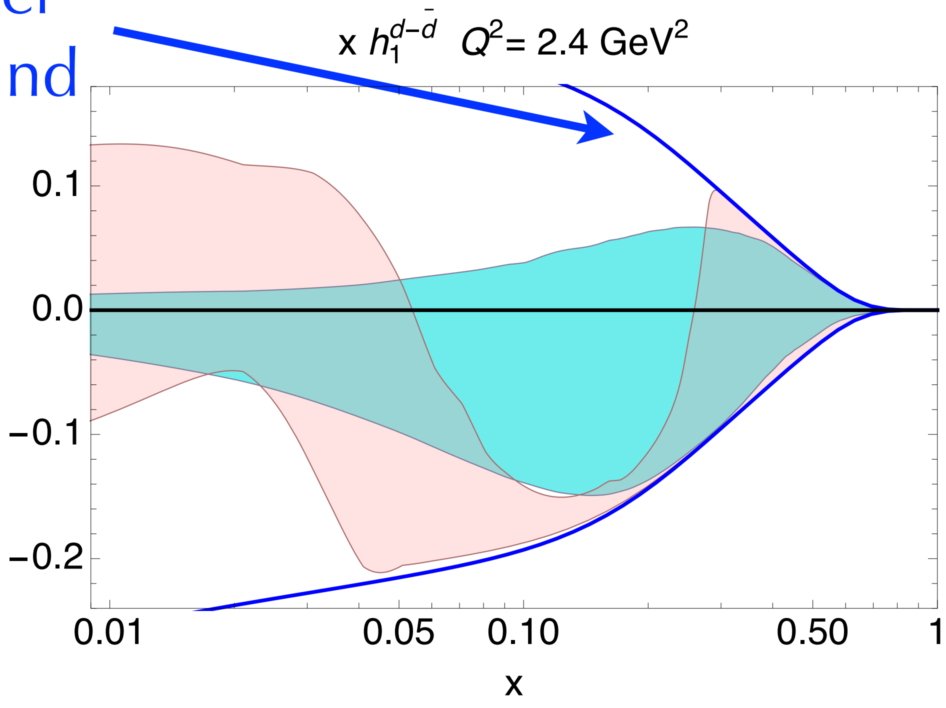
sensitive to uncertainty on gluon D_1

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

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



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

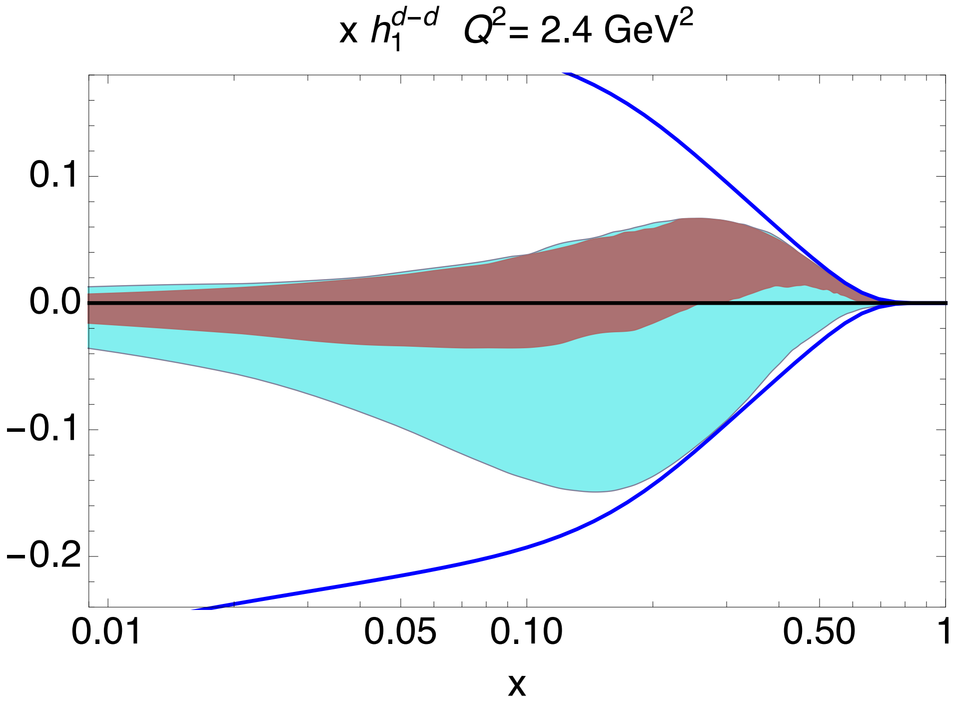
need NLO analysis
+
dihadron multiplicities in pp

down

sensitive to
uncertainty on
gluon D_1

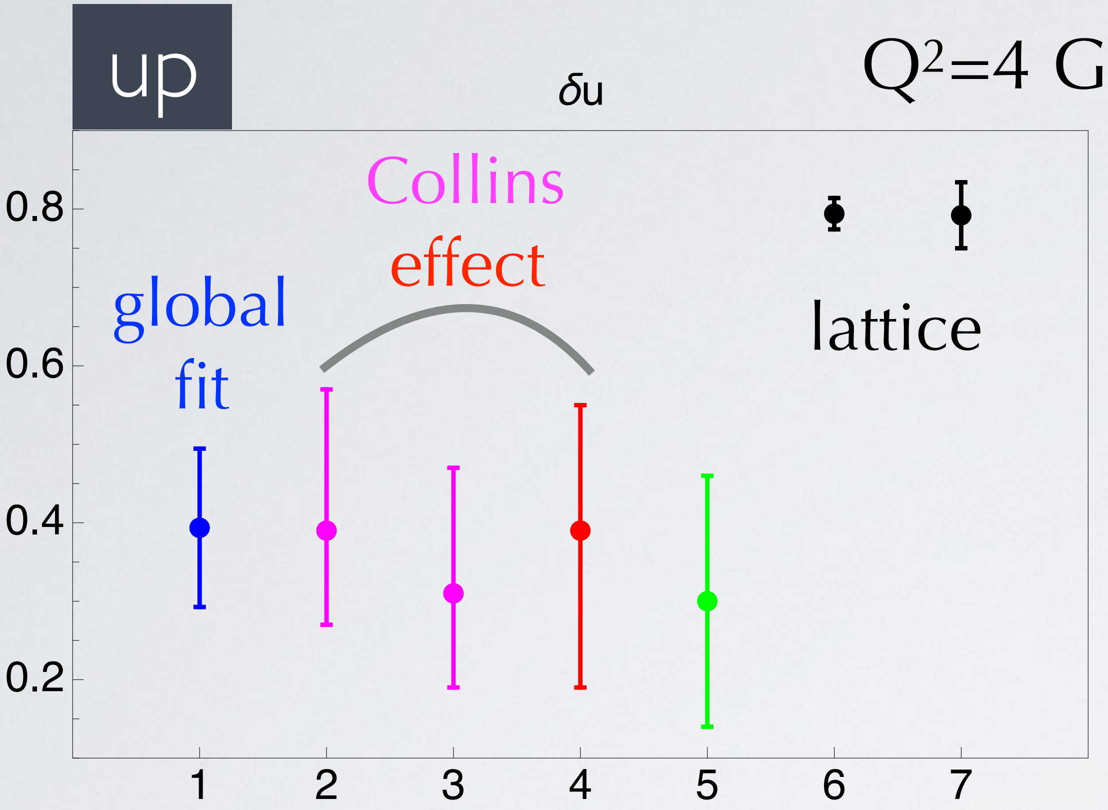
$$D_1^g(Q_0) = 0$$

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



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*

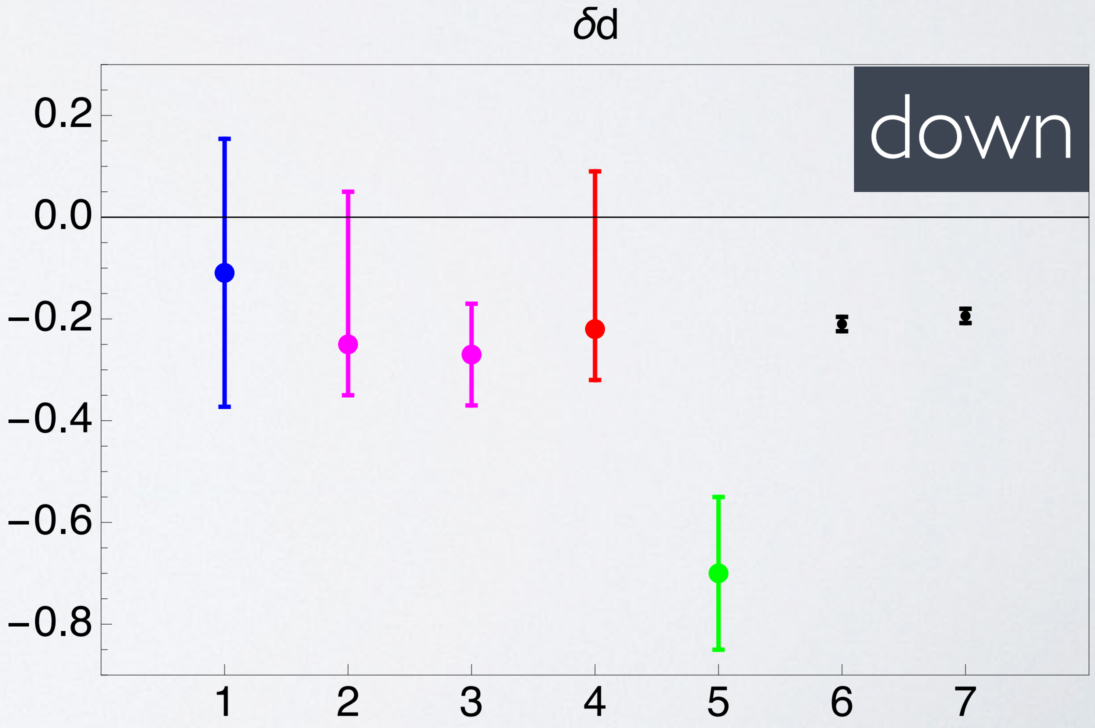
2,3- Torino *Anselmino et al., P.R. D****87*** *(13) 094019* *** Q^2=1**

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

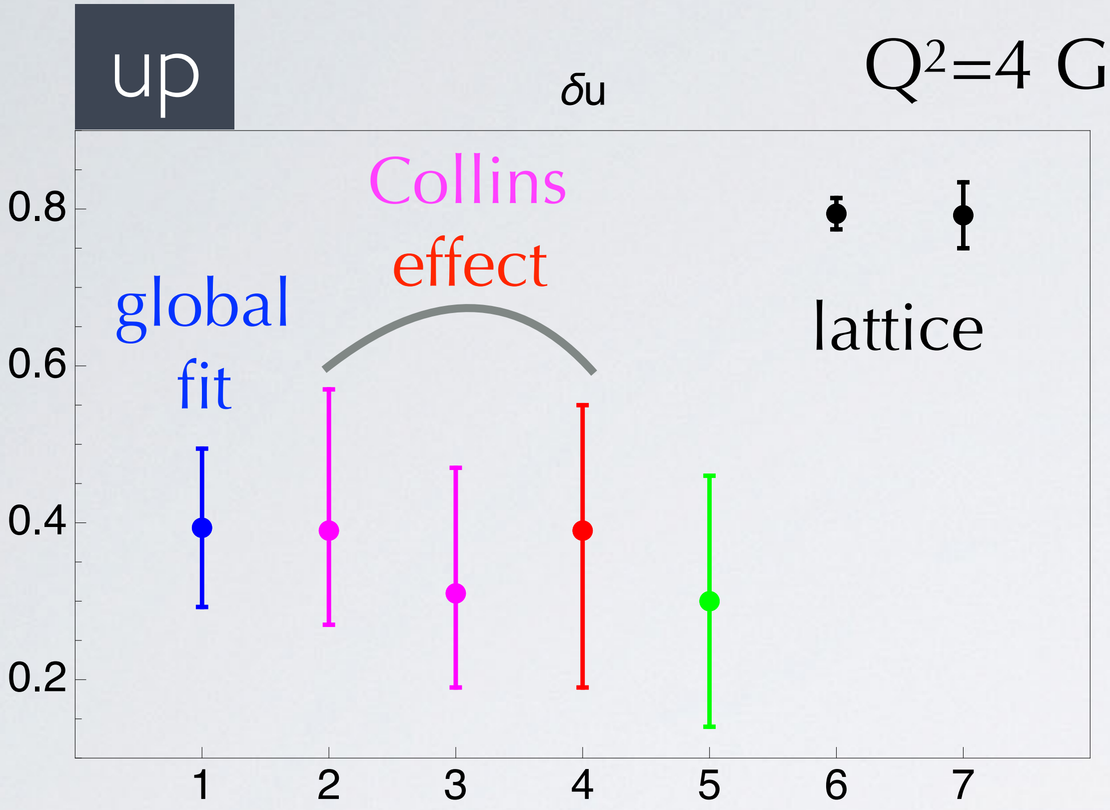
5- JAM fit *Lin et al., P.R.L.****120*** *(18) 152502* **{Collins effect + lattice g_T=δu-δd** *** Q_0^2=2**

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*



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**

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**

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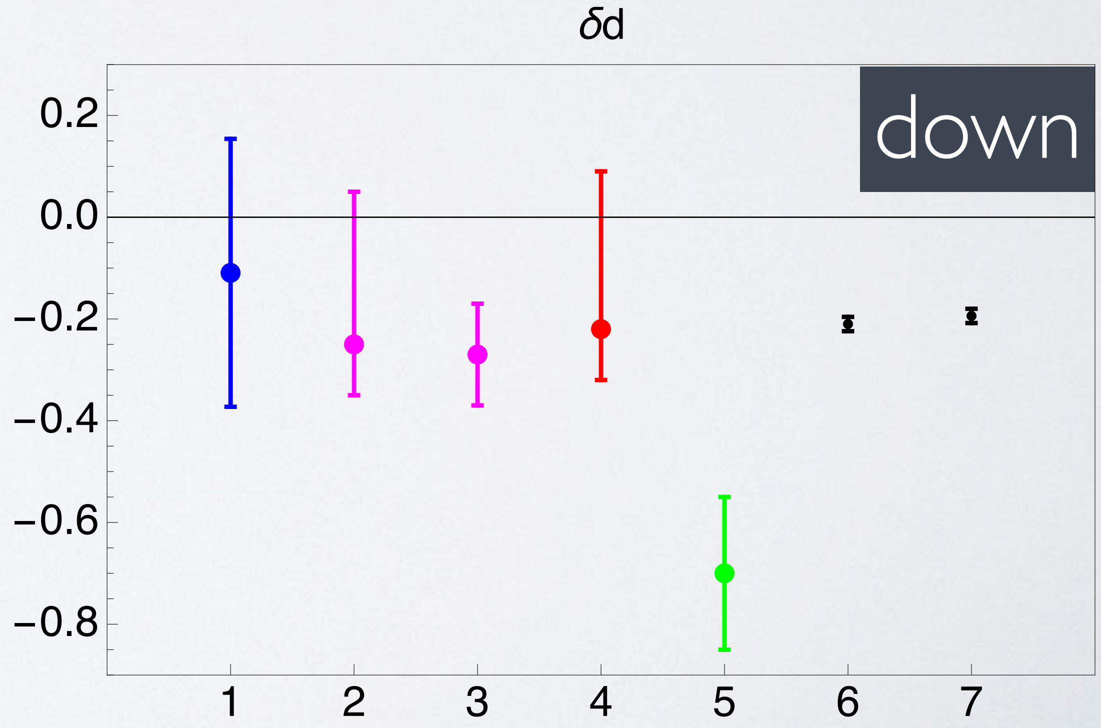
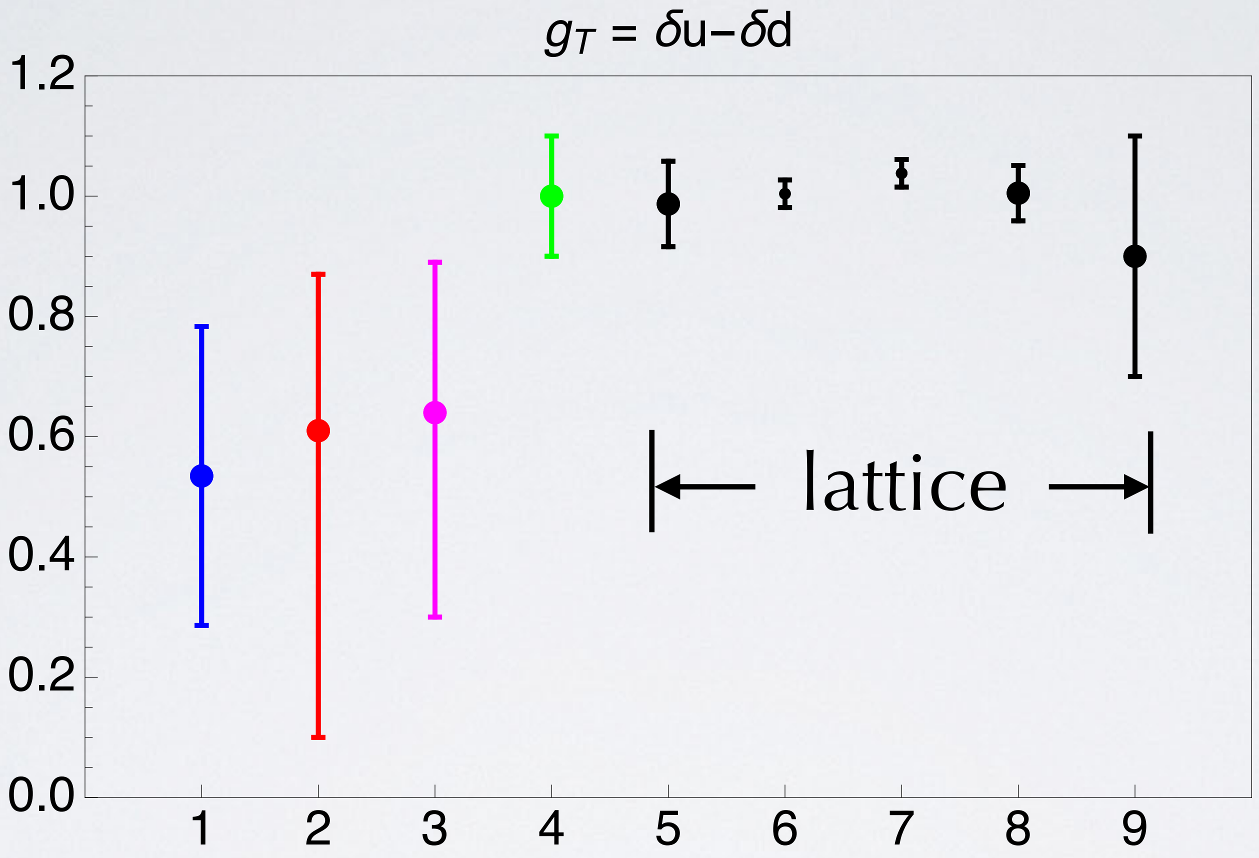


isovector tensor charge $g_T = \delta u - \delta d$

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)*

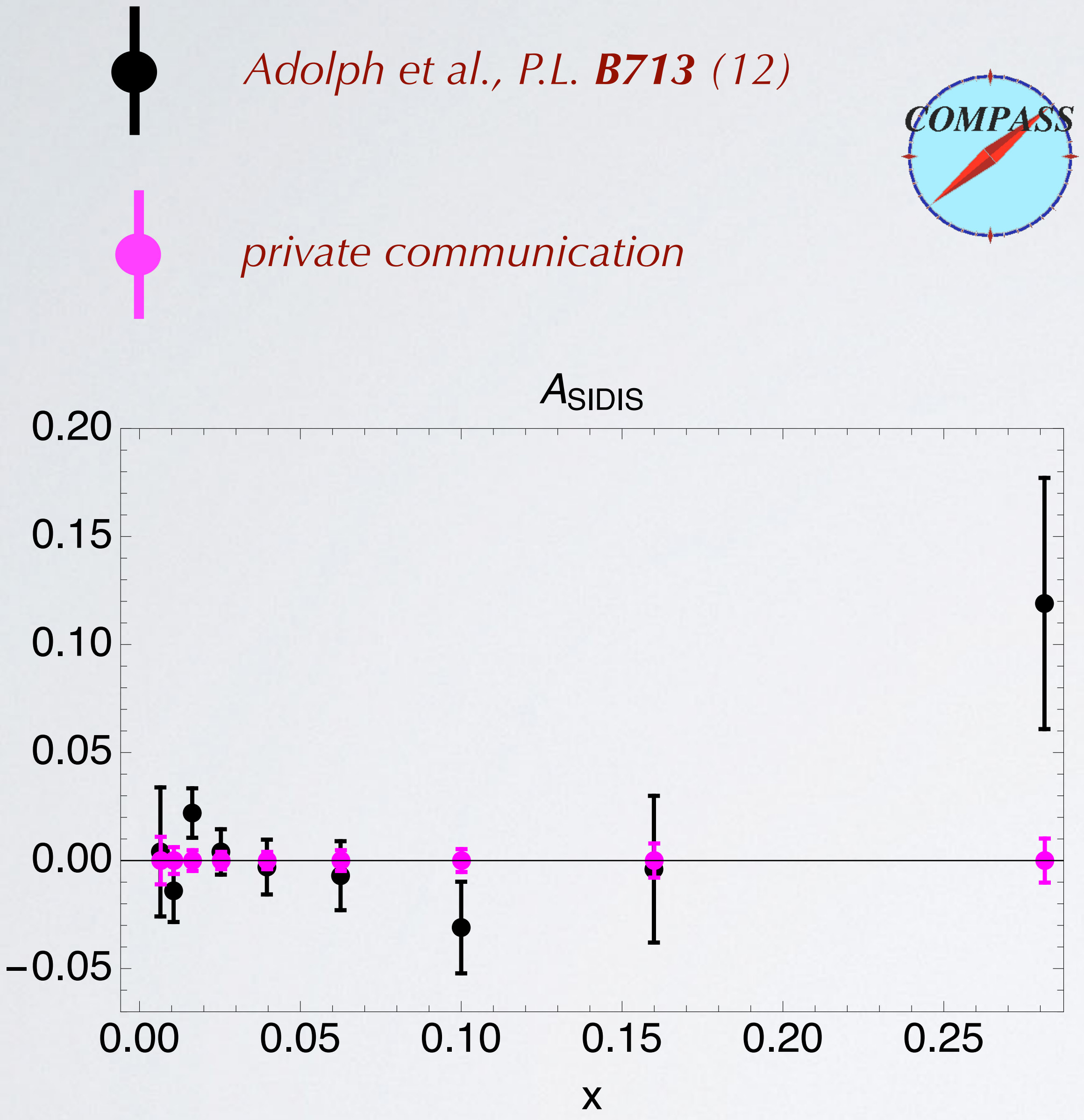
9) RBC-UKQCD — *Aoki et al., P.R. D****82*** *(10)*

“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

so far, shown results from published PRL paper

add Compass deuteron pseudodata



1) recall: <u>deuteron</u> $A_{\mathrm{SIDIS}} \sim h_1^{u_v} + h_1^{d_v}$

<u>proton</u> $A_{\mathrm{SIDIS}} \sim 4h_1^{u_v} - h_1^{d_v}$

2) pseudodata with central value = 0

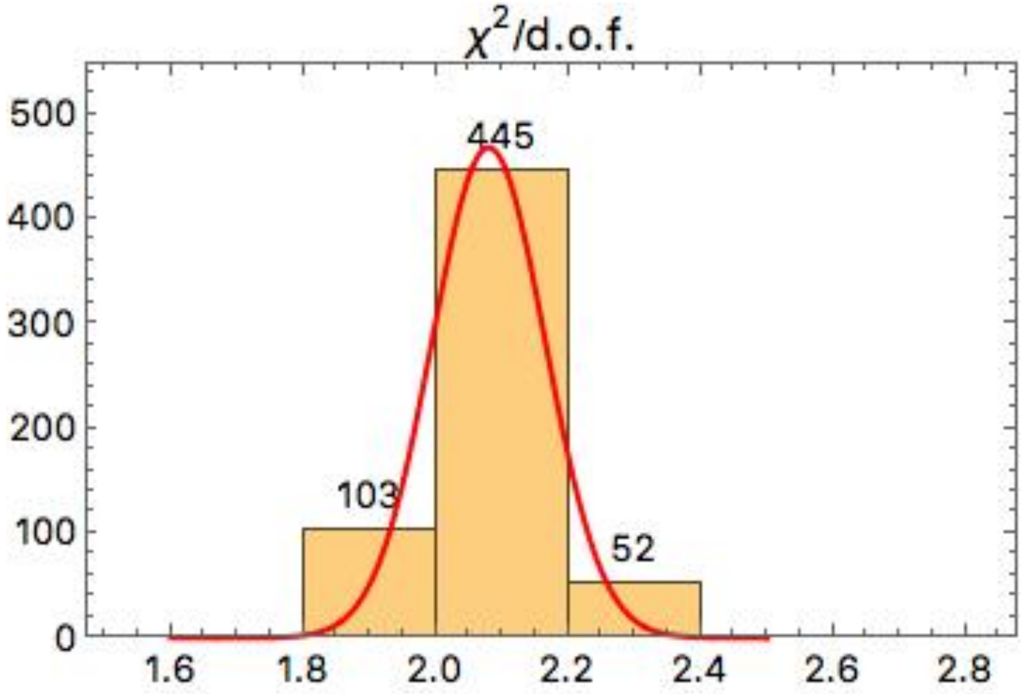
tried with values of old run 2004,
but too strong tension with other data
→ $\chi^2/\mathrm{dof} \gtrsim 3\text{-}4$

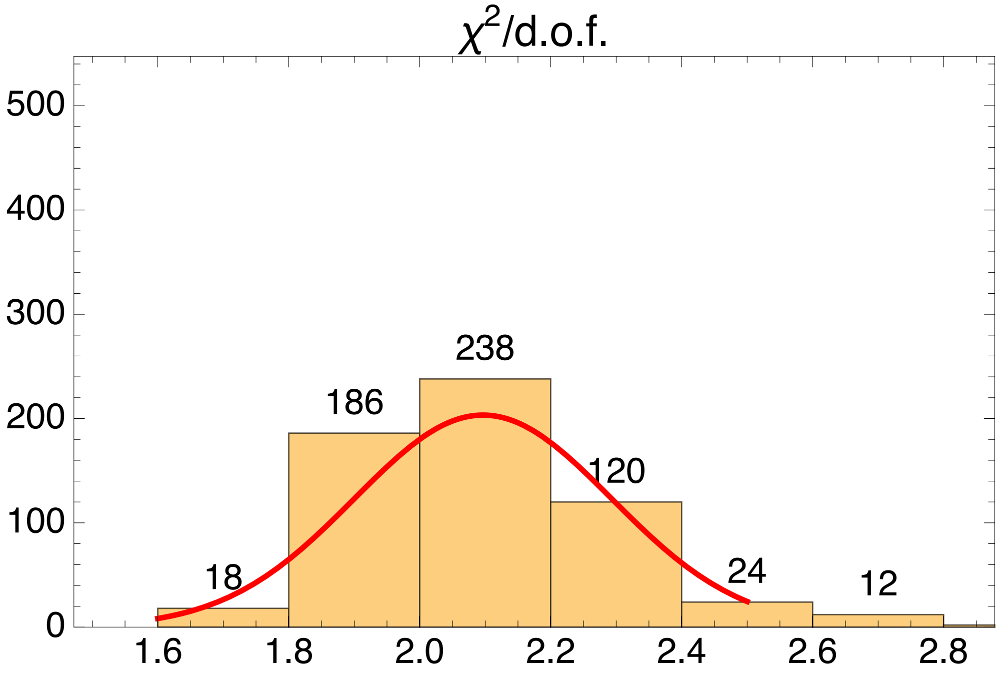
future deuteron measurement will have strong selective impact on replicas

χ^2 of the fit

global fit

+ pseudodata





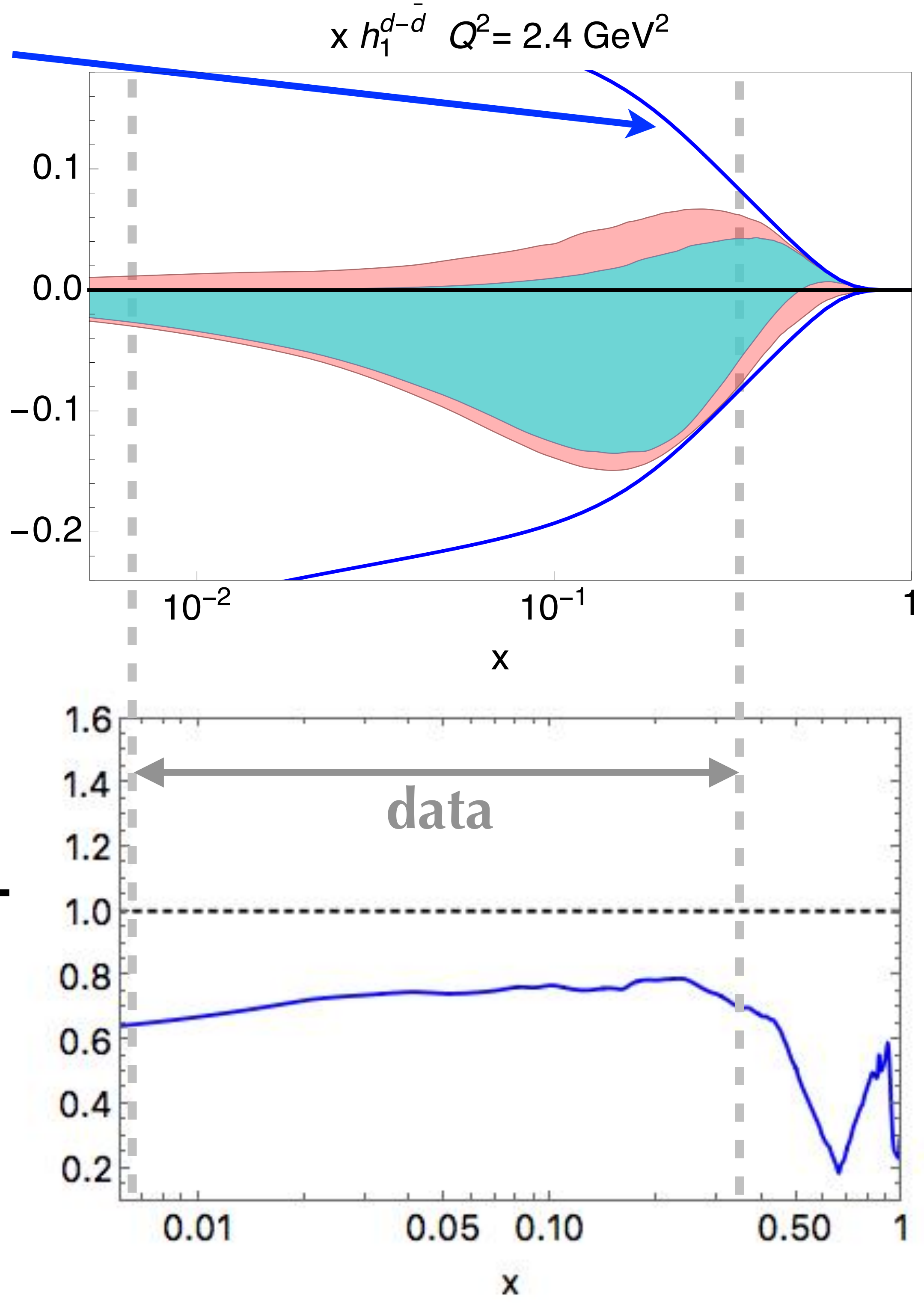
χ^2/dof = 2.08 ± 0.09

χ^2/dof = 2.10 ± 0.20

pseudodata impact on down

Soffer bound

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

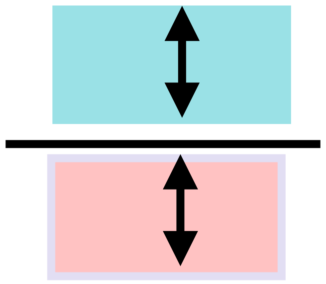


global fit + pseudodata

global fit

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

down



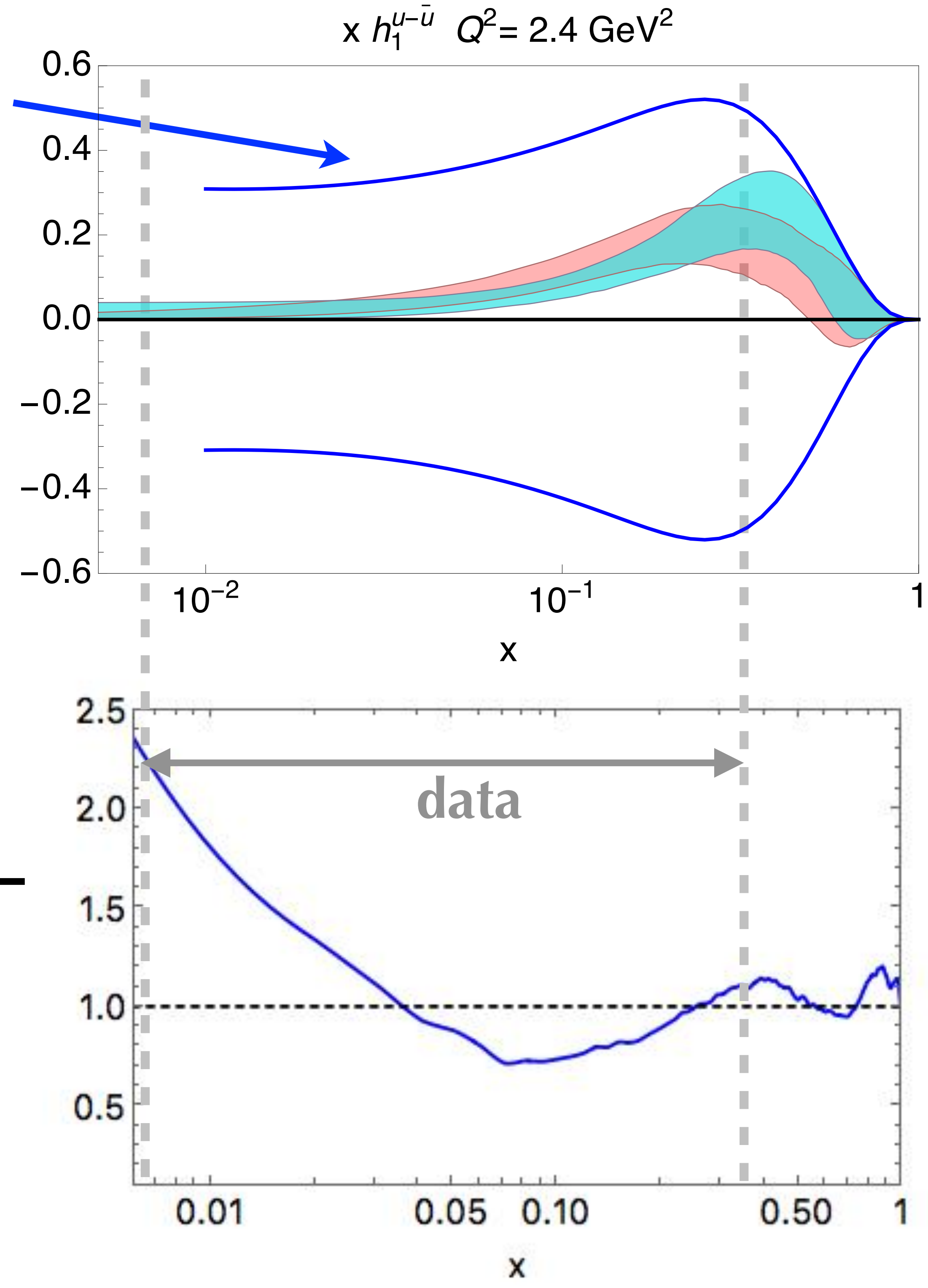
ratio of widths

< 20% >
increase in
precision

pseudodata impact on up

Soffer bound

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

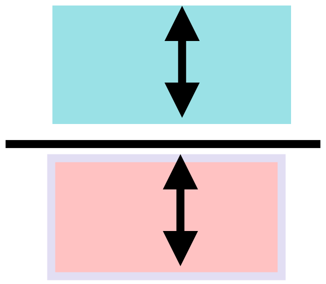


global fit + pseudodata

global fit

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

up

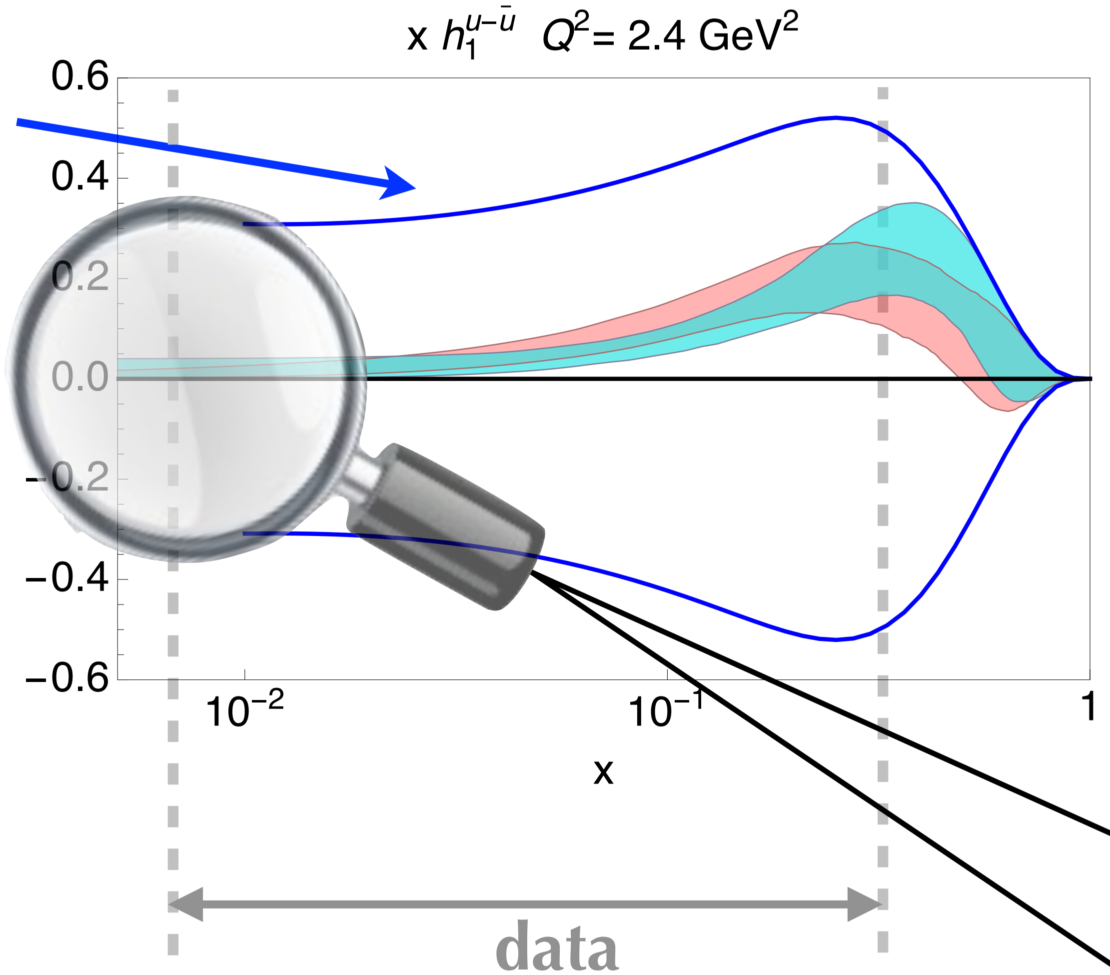


ratio of widths

pseudodata impact on up

Soffer bound

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

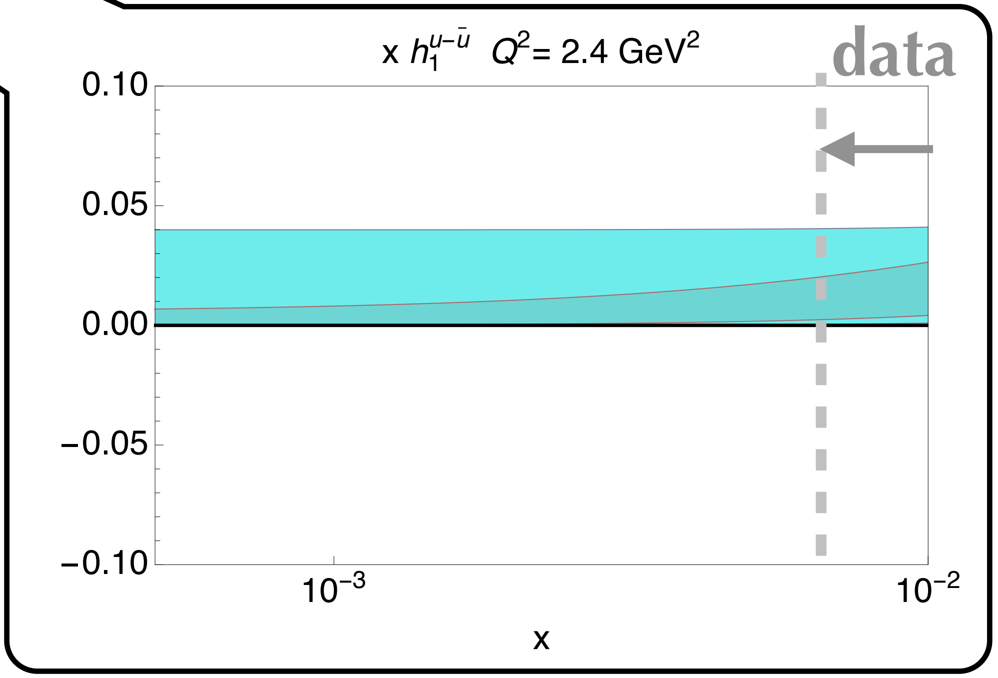


global fit + pseudodata

global fit

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

up



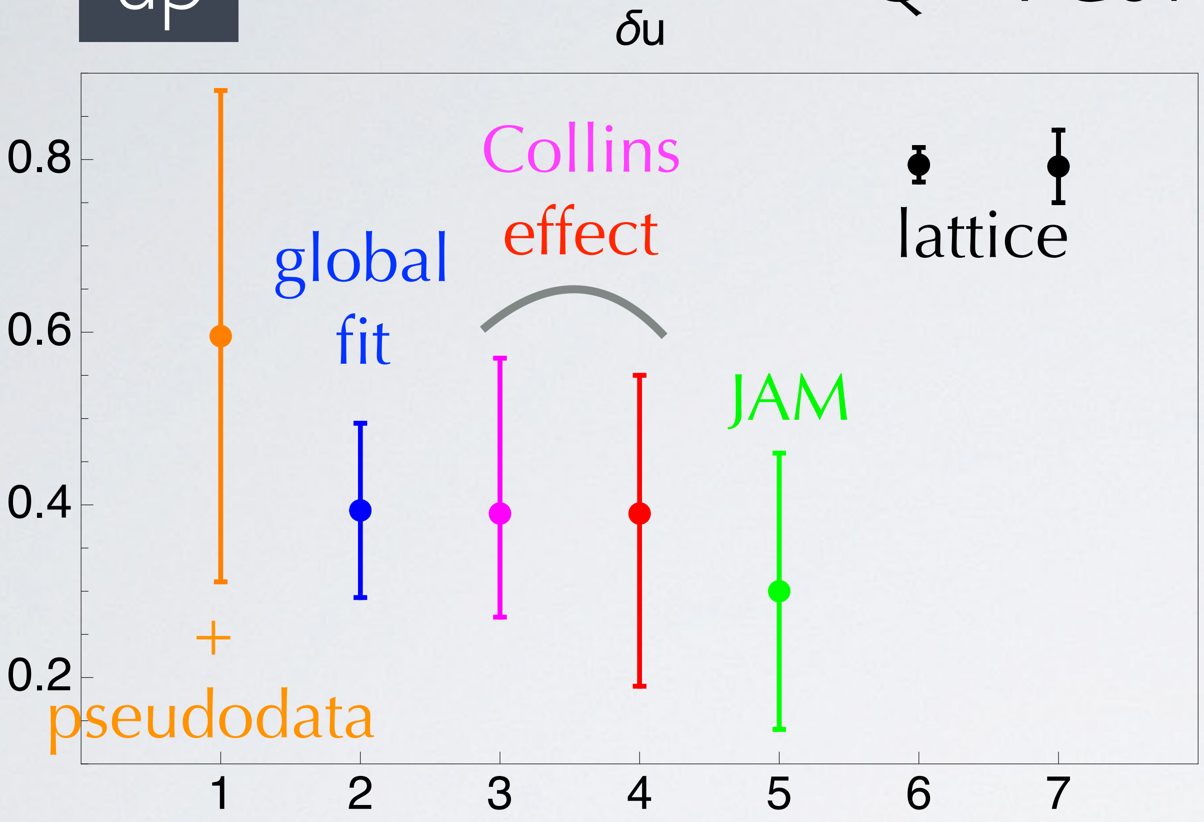
$$h_1^q(x) \overset{x \to 0}{\approx} x^{A_q+a_q-1} \qquad A_q + a_q > \frac{1}{3}$$

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

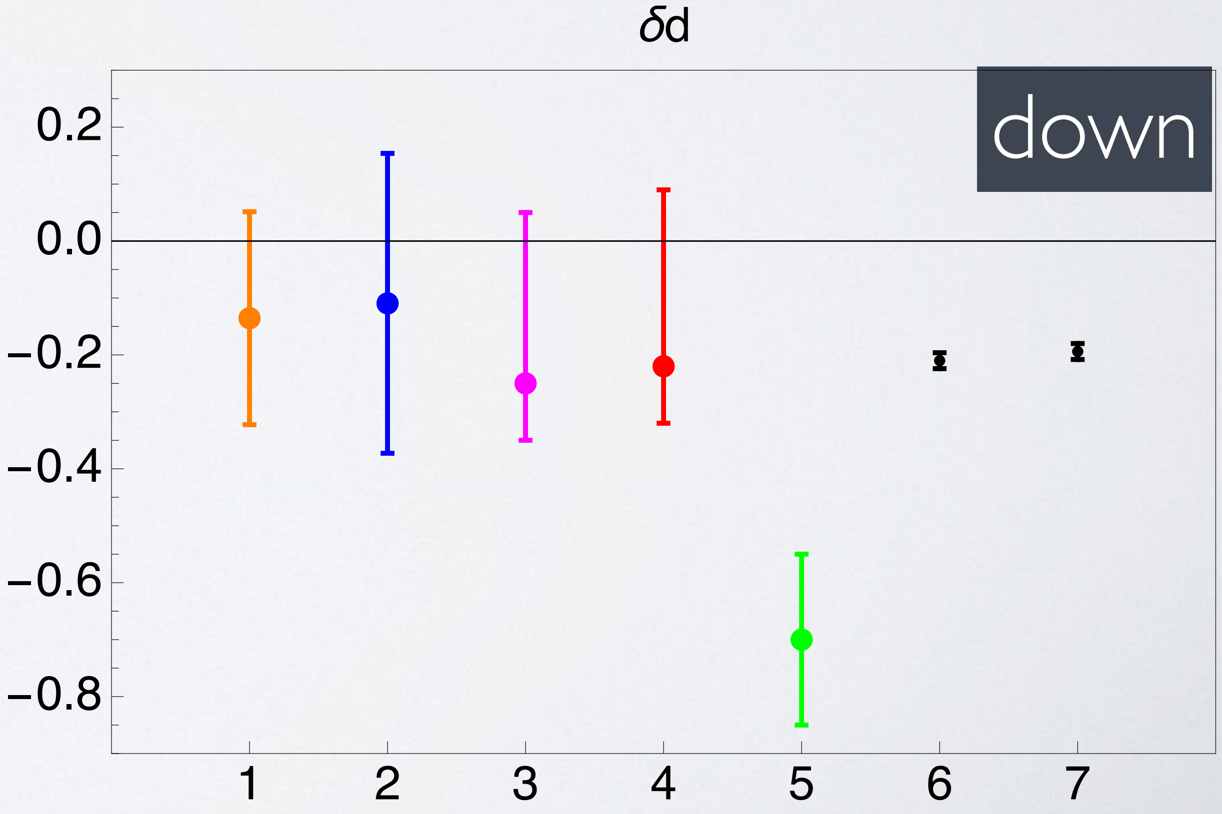
pseudodata impact on tensor charge

up

Q^2=4 GeV^2 *



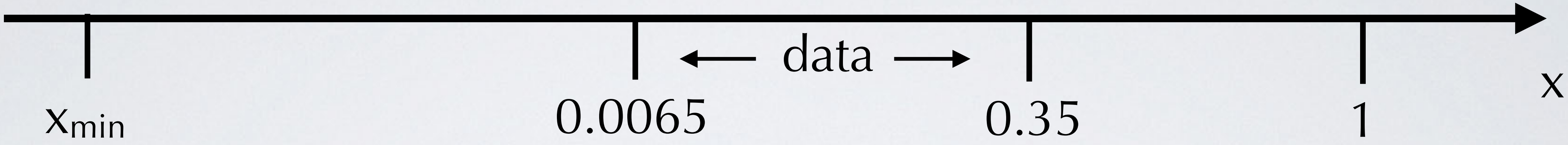
better precision on down
larger uncertainty on up
("reversed role" of flavors..)



full compatibility
with lattice ??

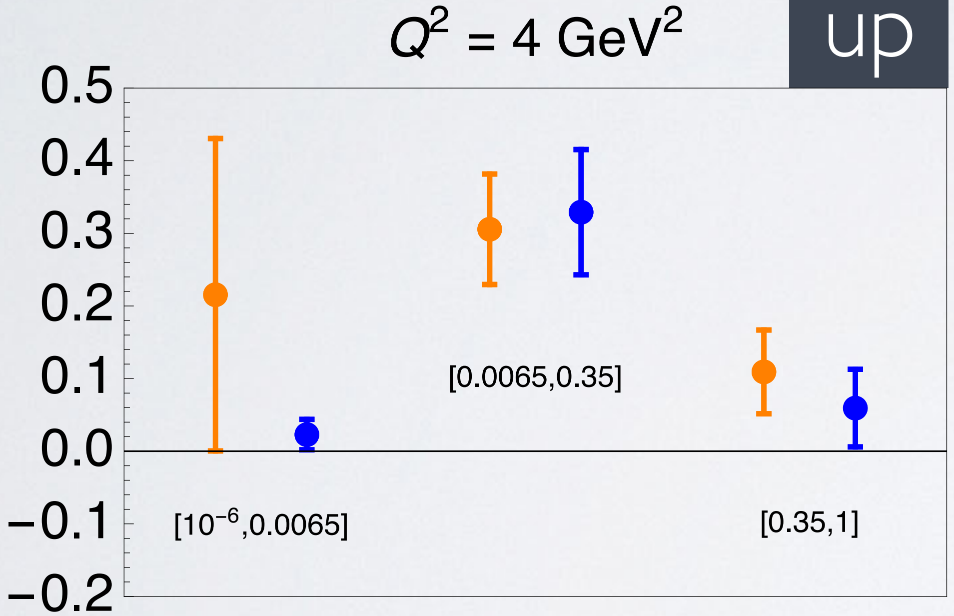
impact of extrapolation outside data

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



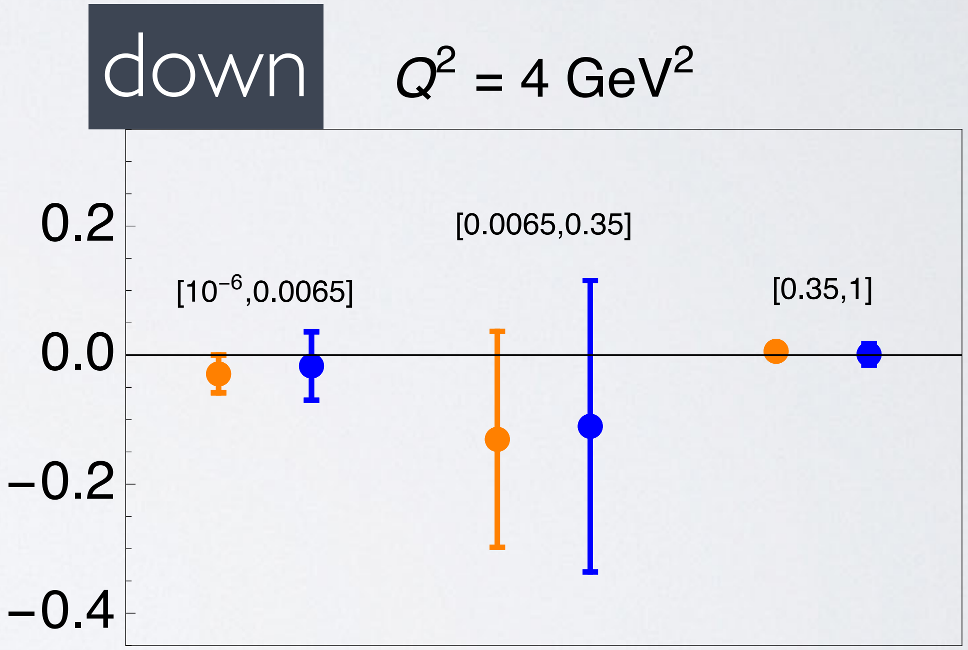
MSTW $x_{\min}$=10^{-6}

up



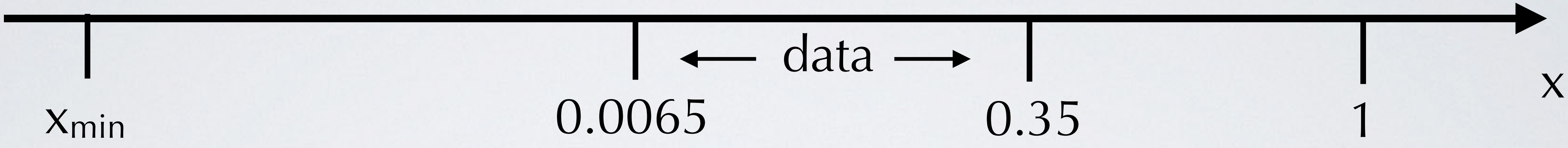
global
fit
+
pseudodata

down

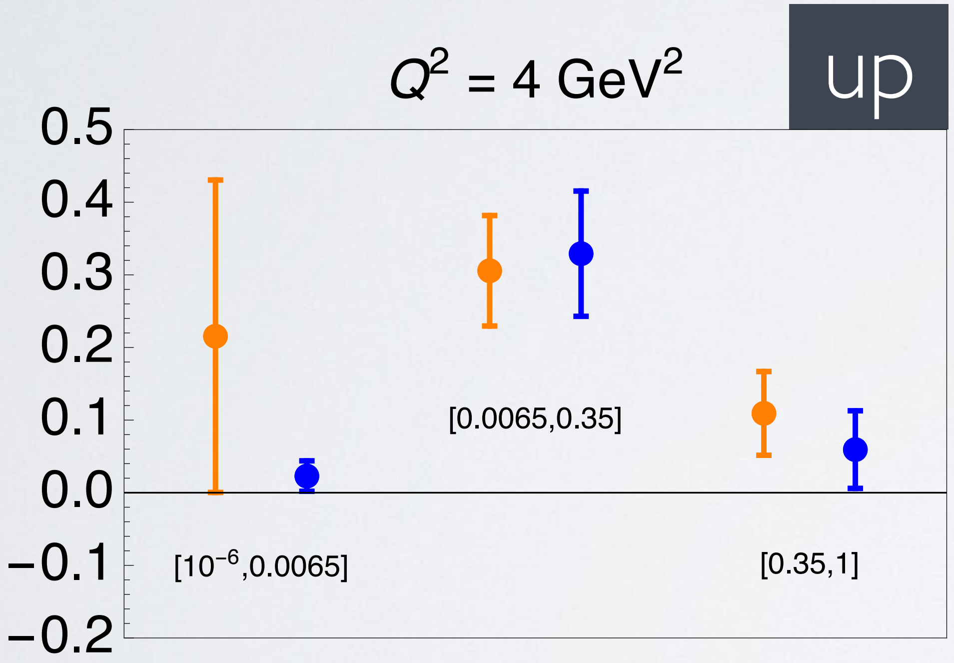


impact of extrapolation outside data

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

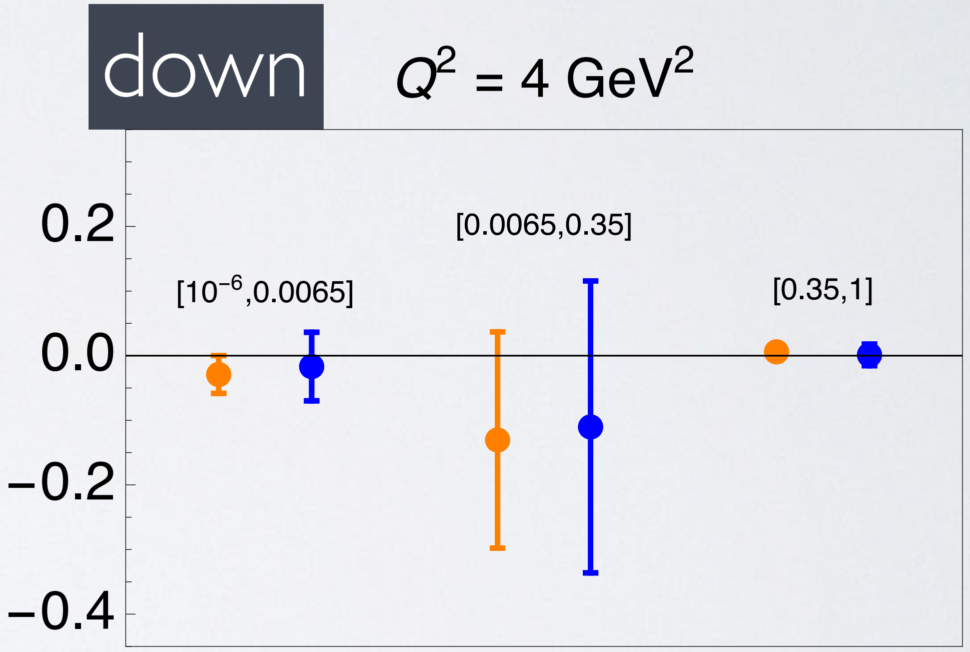


MSTW $x_{\min}=10^{-6}$



global fit

+ pseudodata

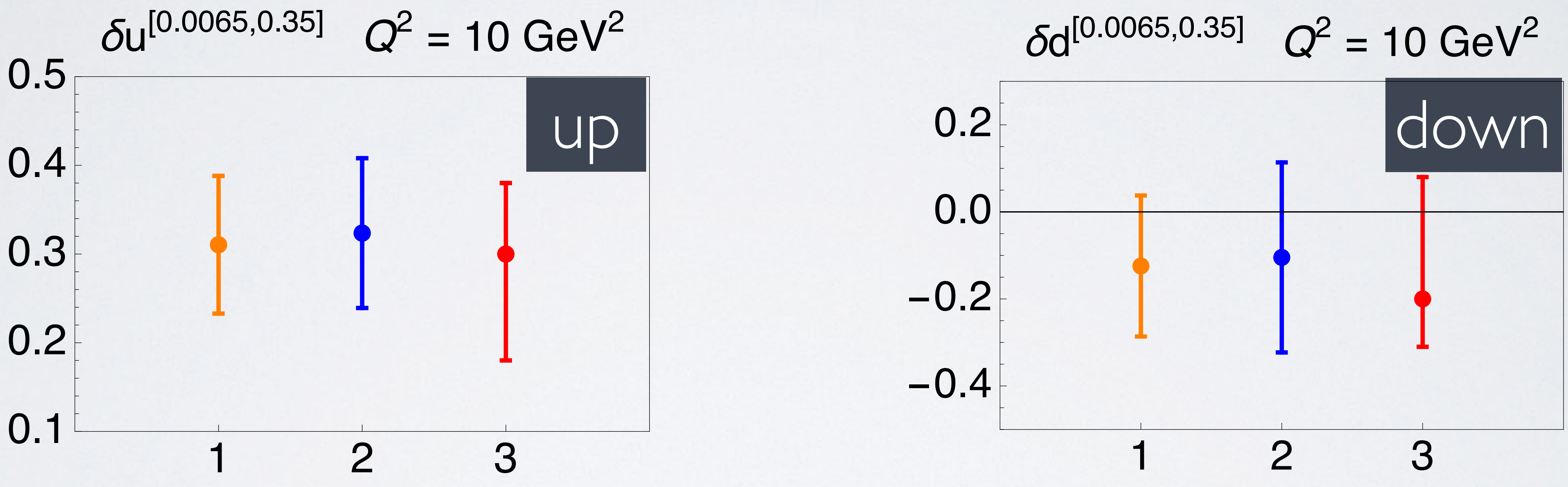


impact of pseudodata
for down: better precision everywhere
for up: large uncertainties in extrapolation at low x

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

truncated

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



\+
pseudodata

global fit

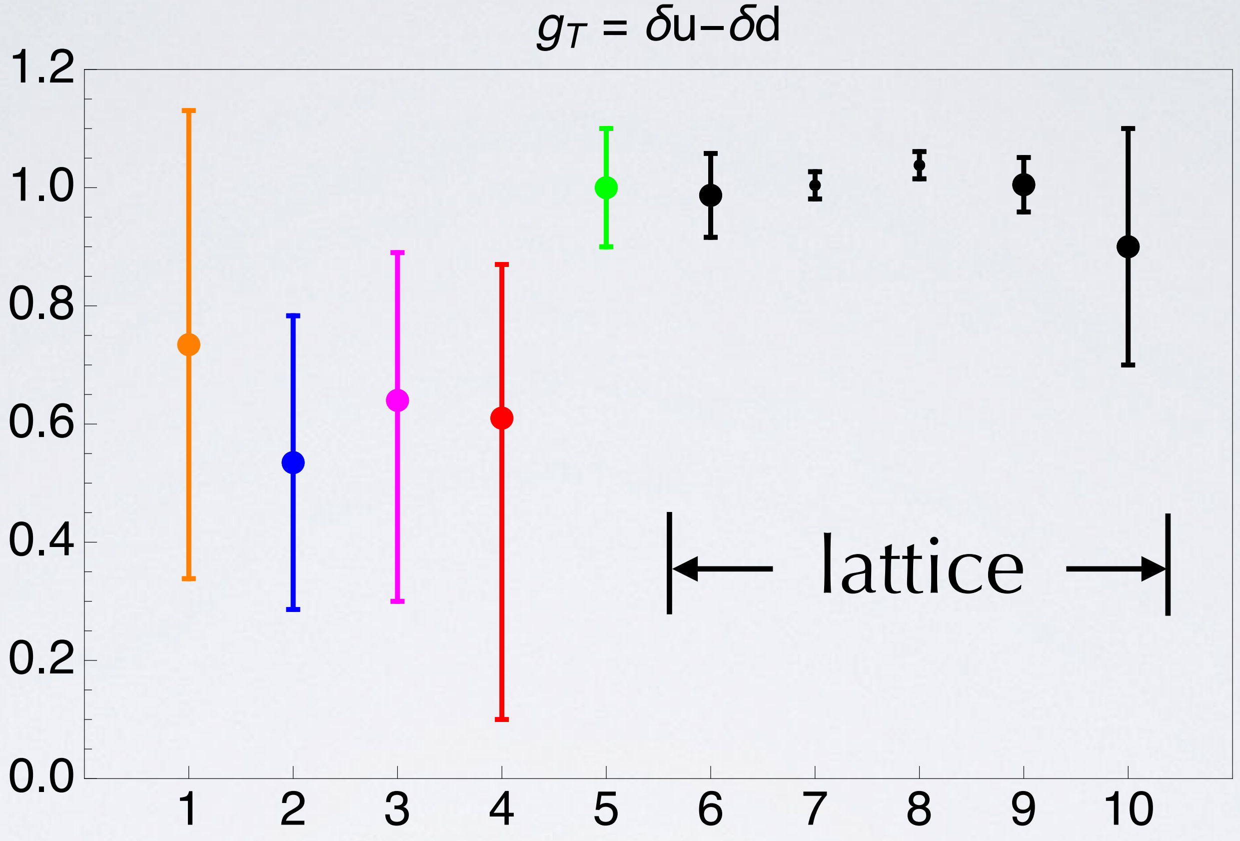
Radici & Bacchetta,
P.R.L. ***120*** *(18) 192001*

TMD fit

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

pseudodata impact on isovector tensor charge

Q^2=4 GeV^2 *



apparent simultaneous compatibility
because of large uncertainties coming from
extrapolation outside the x-range of data (mainly at low x)

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

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

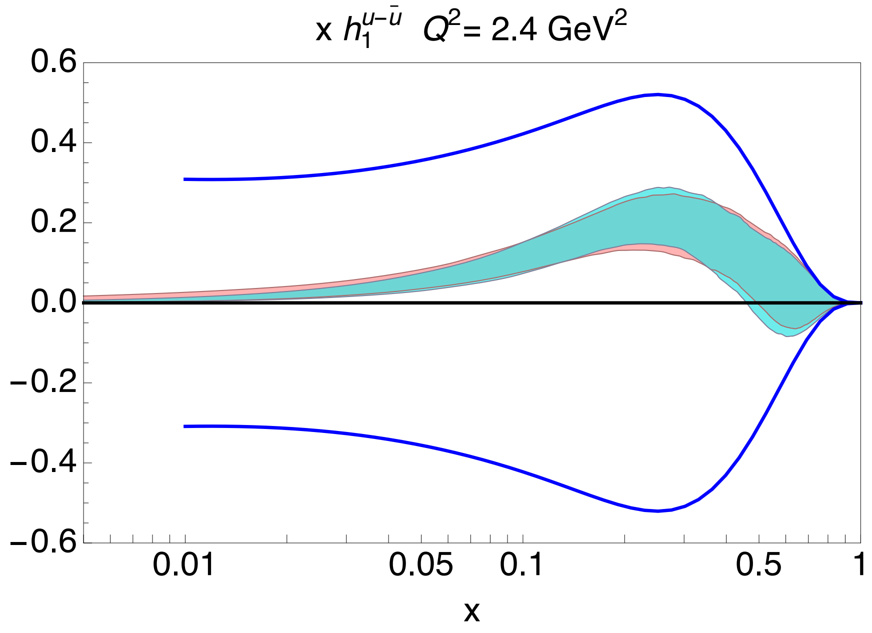
impact of low-x constraint

global fit 2nd option

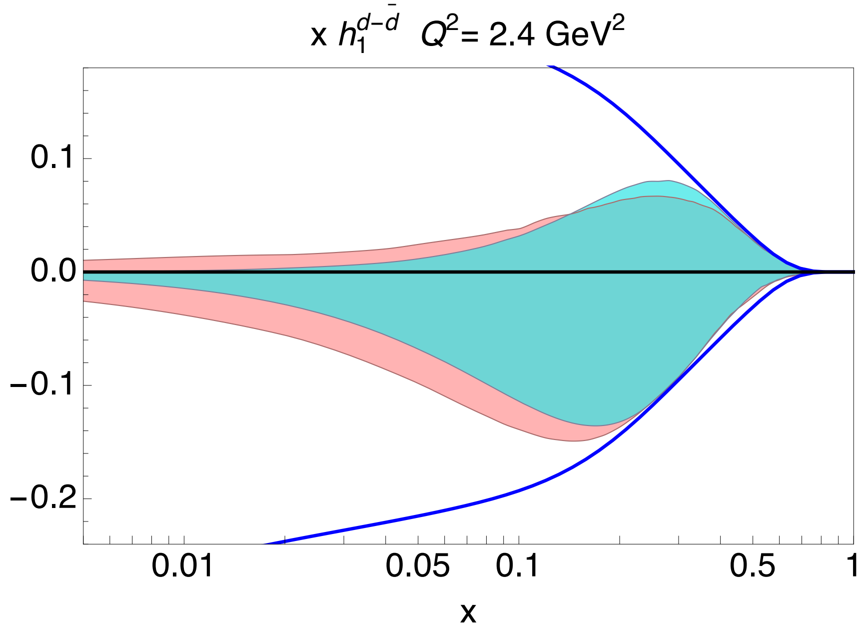
global fit 1st option

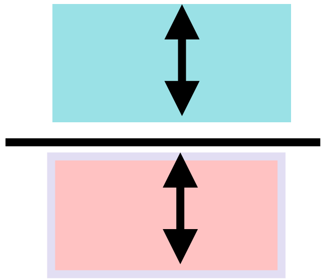
$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$

up

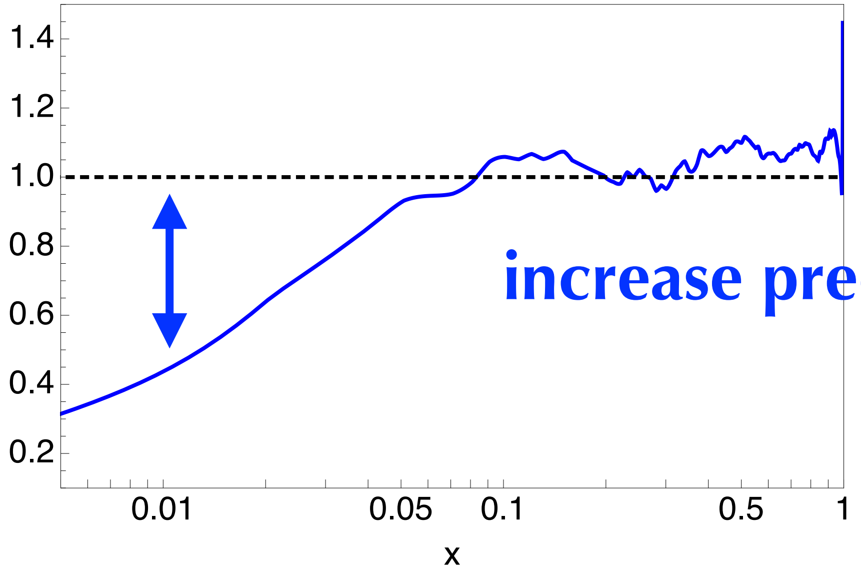


down

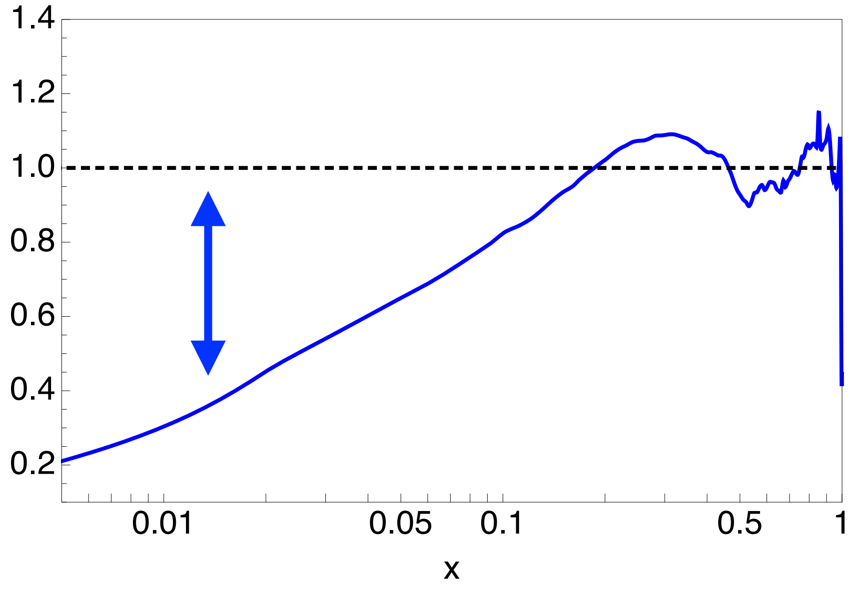




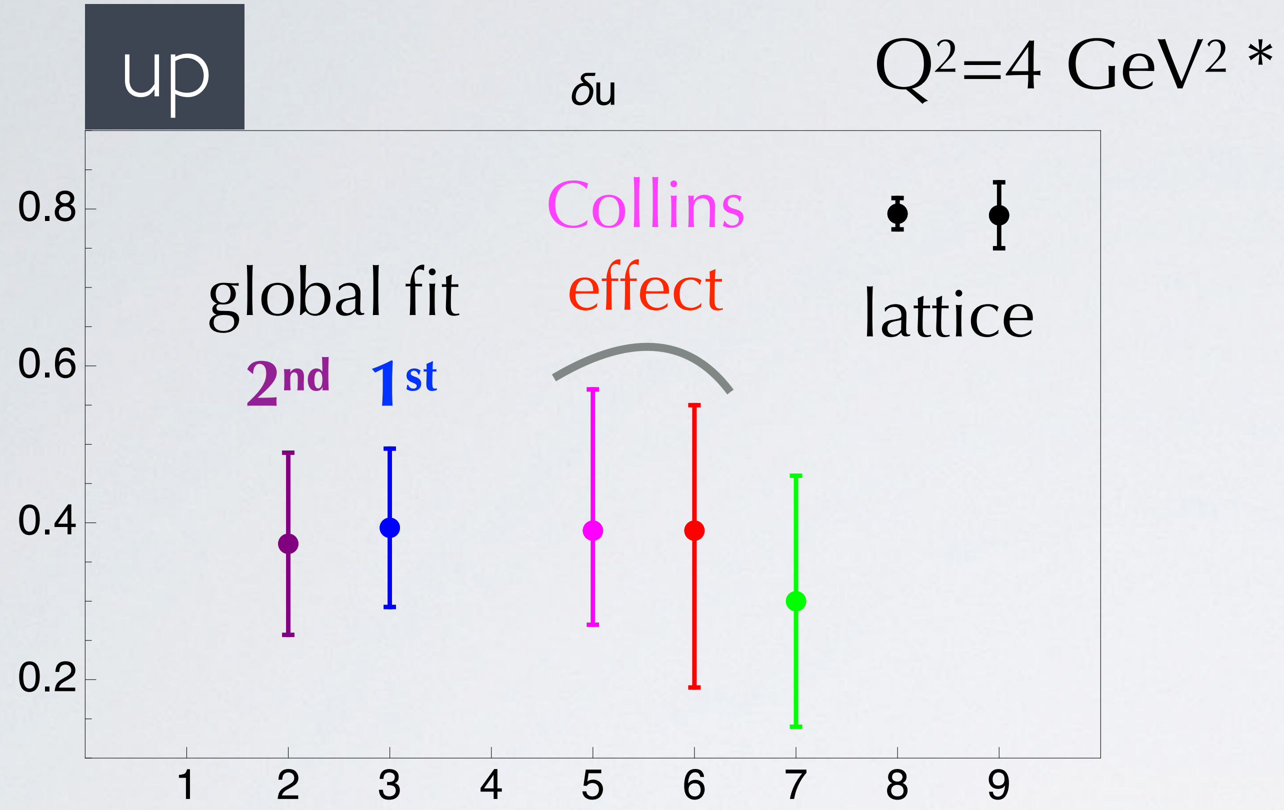
ratio of widths



increase precision



impact of low-x constraint



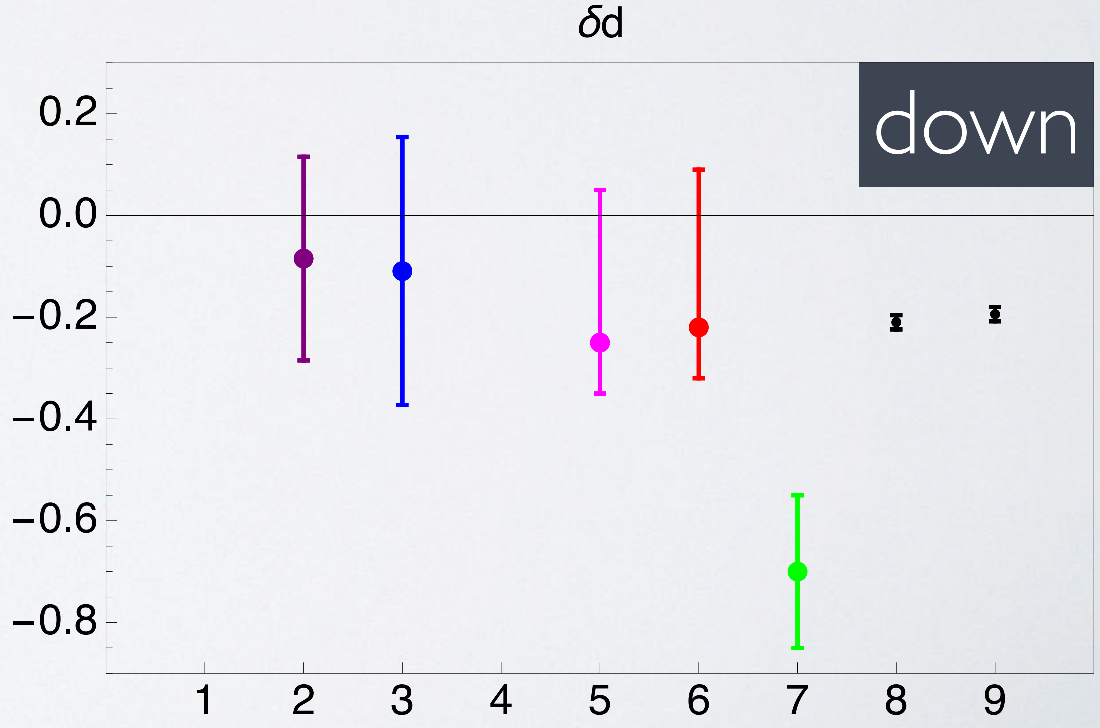
better down
up still incompatible
(similarly for isovector g_T)

general scenario confirmed

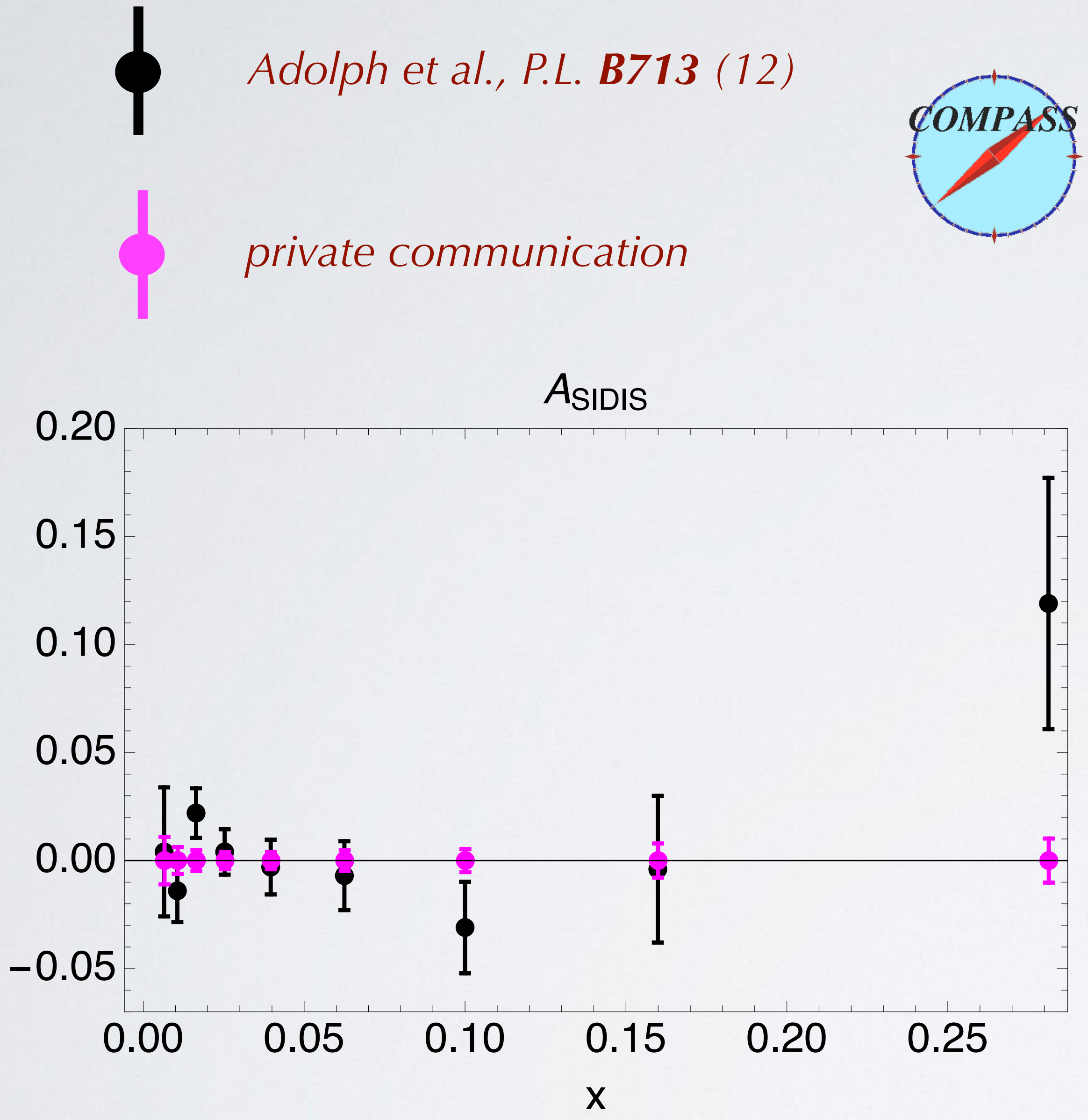
2- global fit 2nd option (finite violation of BC sum rule)

3- global fit 1st option (finite tensor charge)

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



add Compass deuteron pseudodata



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

● *private communication*

adding again
Compass deuteron pseudodata

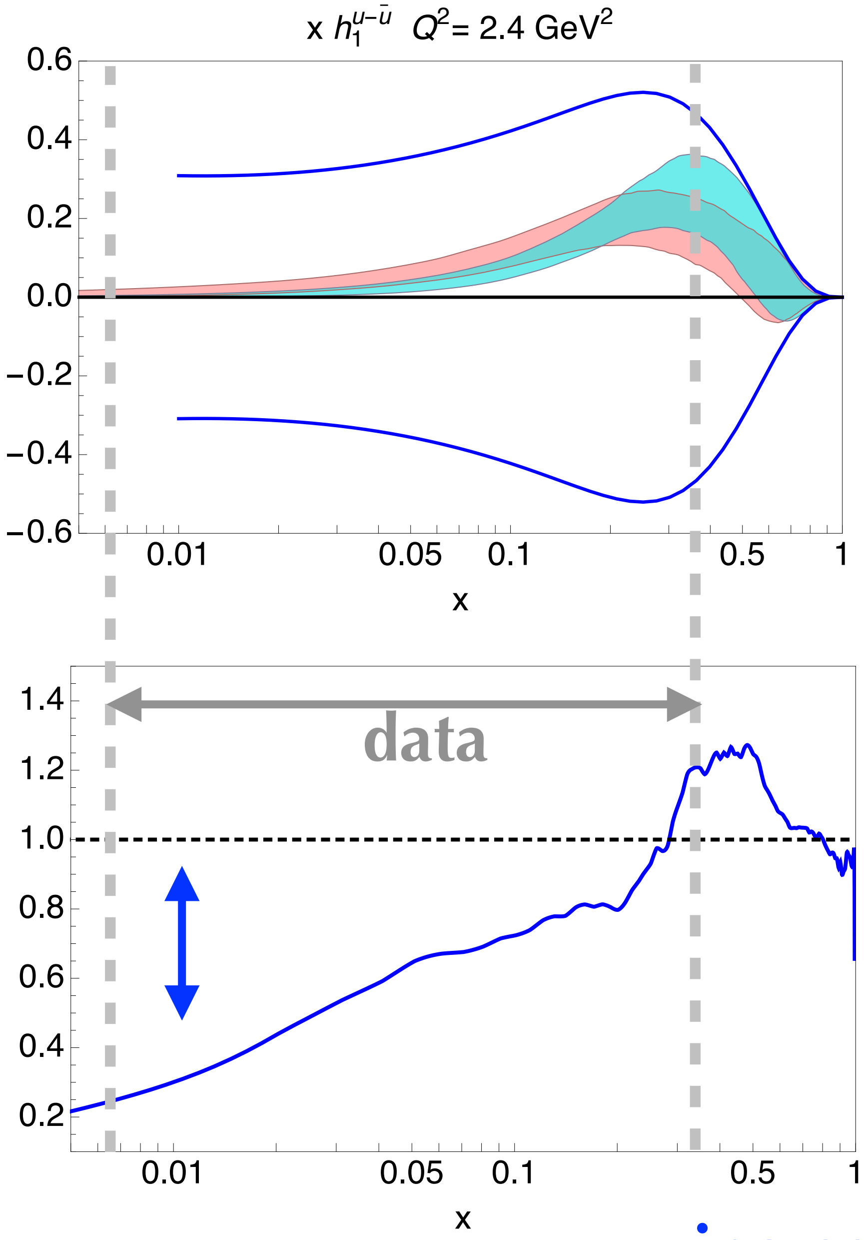
impact of pseudodata

global fit + pseudodata

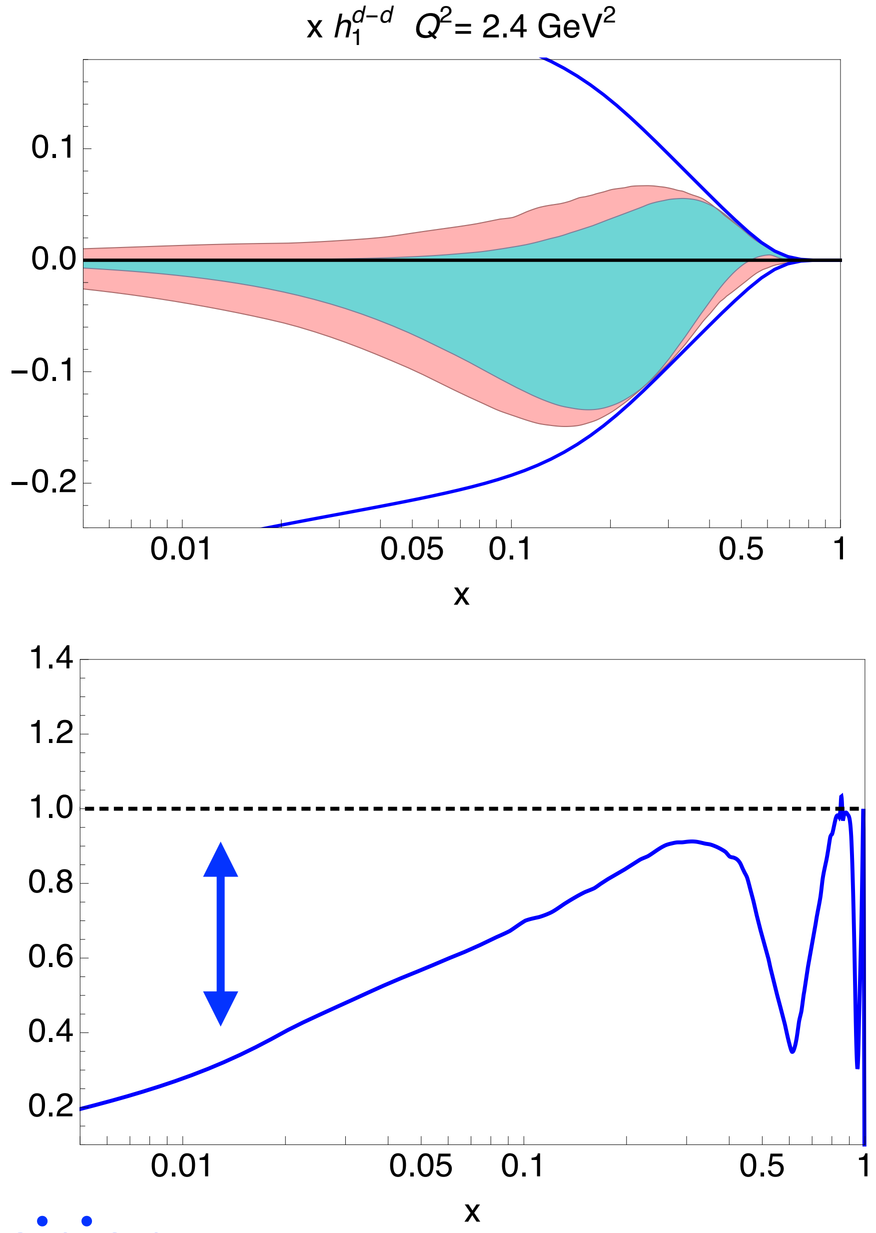
global fit

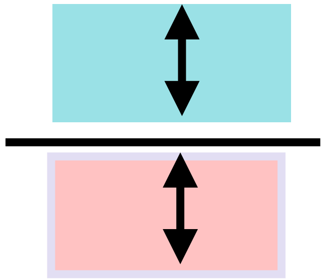
$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$

up



down



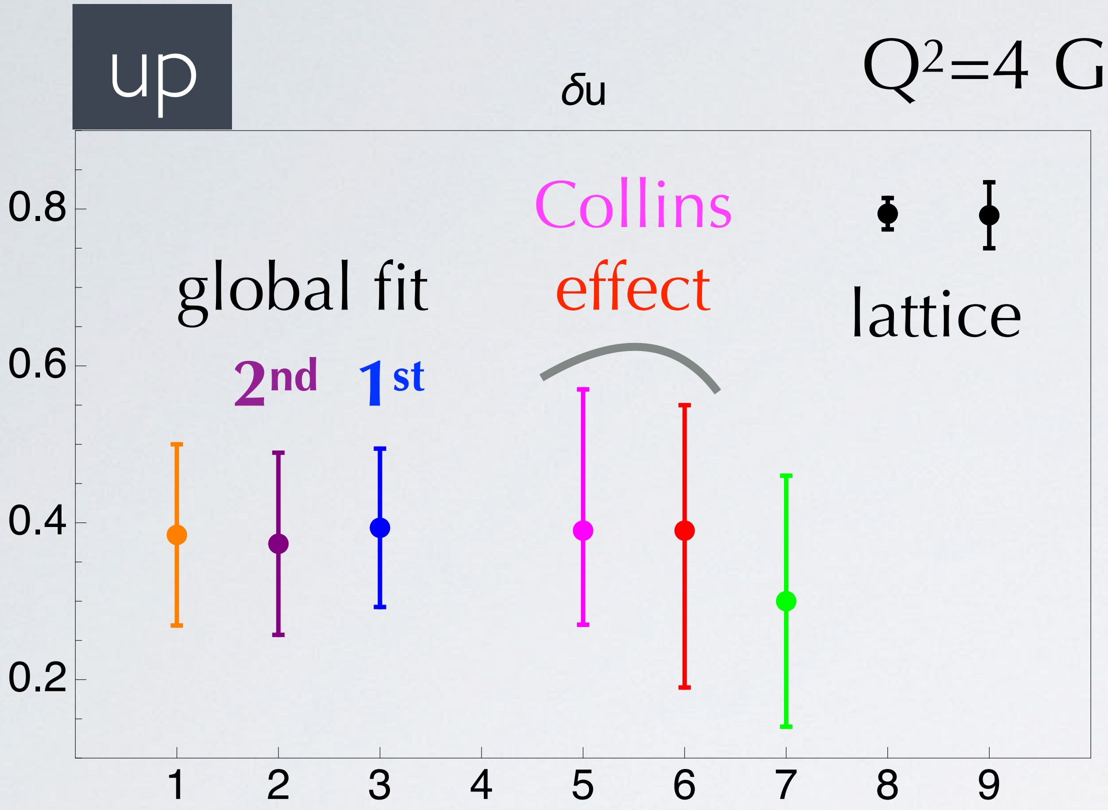


ratio of widths

increase precision

impact of pseudodata

Q^2=4 GeV^2 *



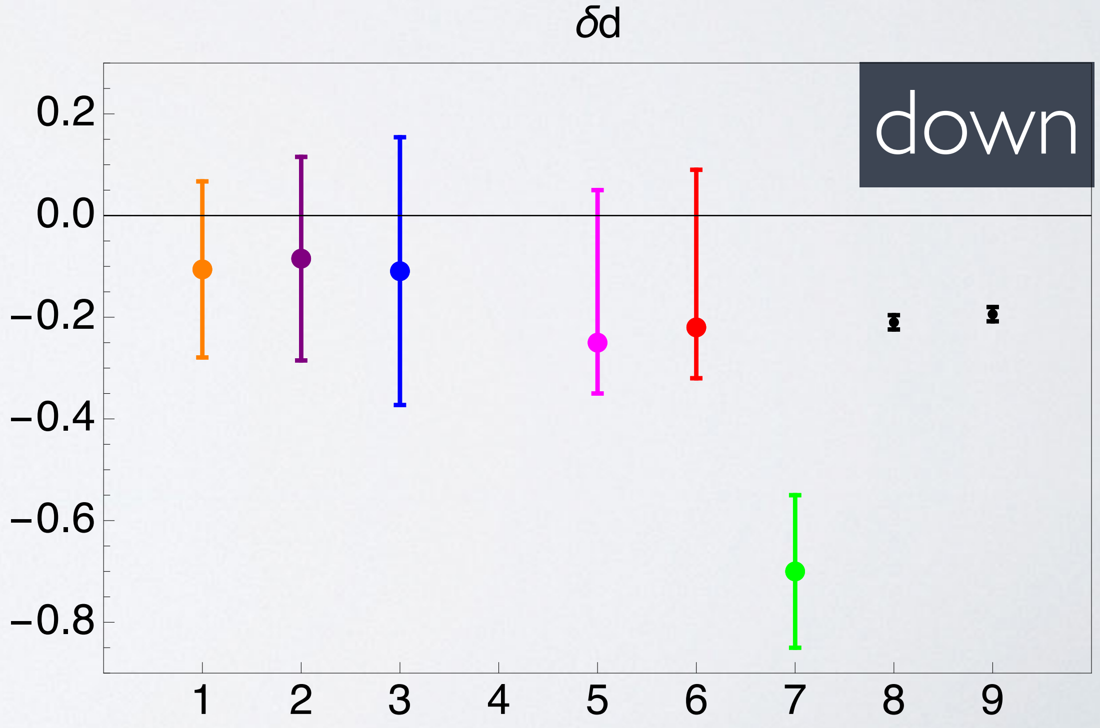
again better down
but confirm general picture

1- global fit 2nd option + pseudodata

2- global fit 2nd option (finite violation of BC sum rule)

3- global fit 1st option (finite tensor charge)

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



summarizing

color code of
global fit

global fit 1st option (finite tensor charge) *Radici & Bacchetta, P.R.L.* ***120*** *(18) 192001*

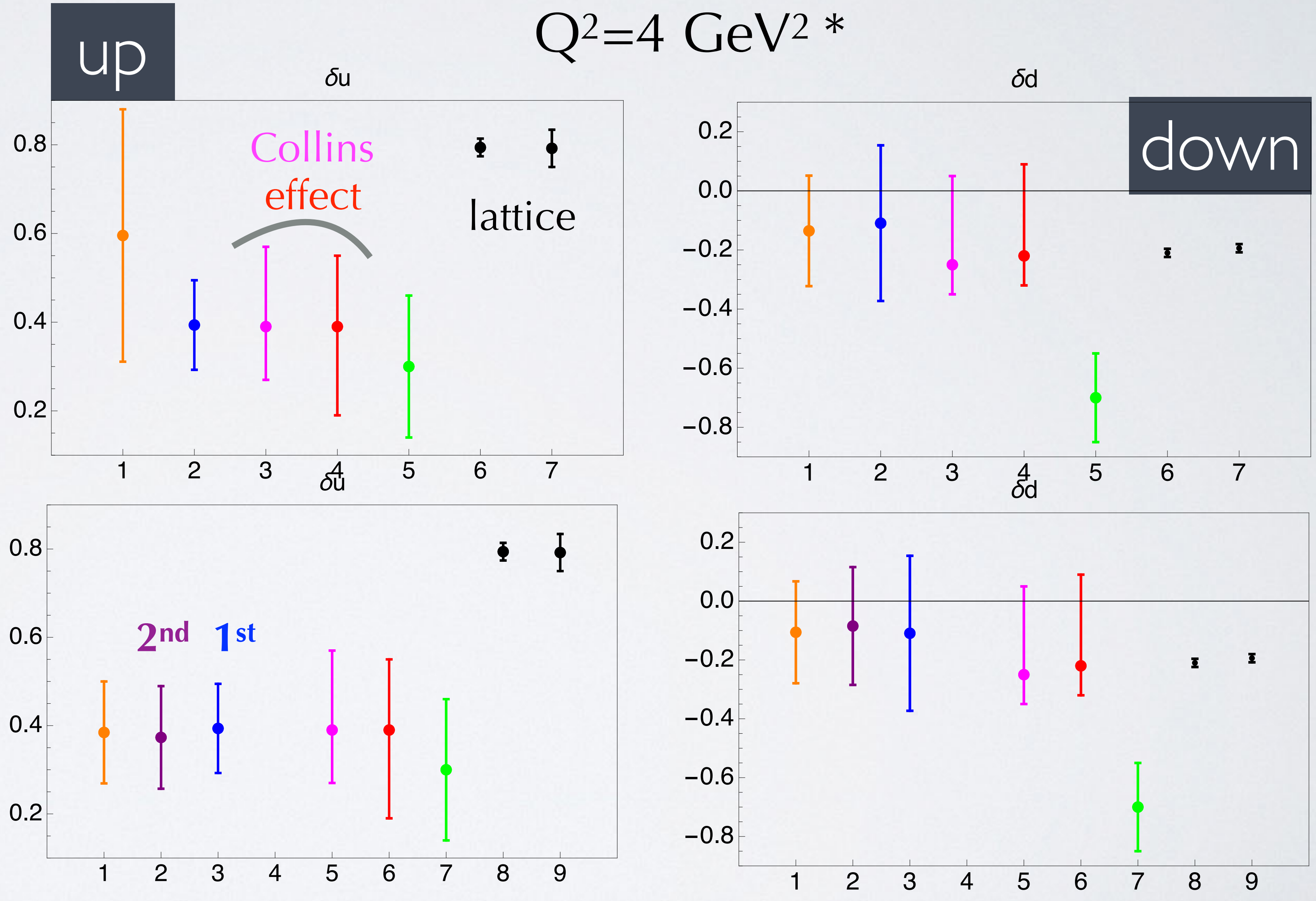
global fit 2nd option (finite violation of BC sum rule)

adding
pseudodata

1st option + pseudodata

2nd option + pseudodata

Q^2=4 GeV^2 *



summarizing

color code of global fit

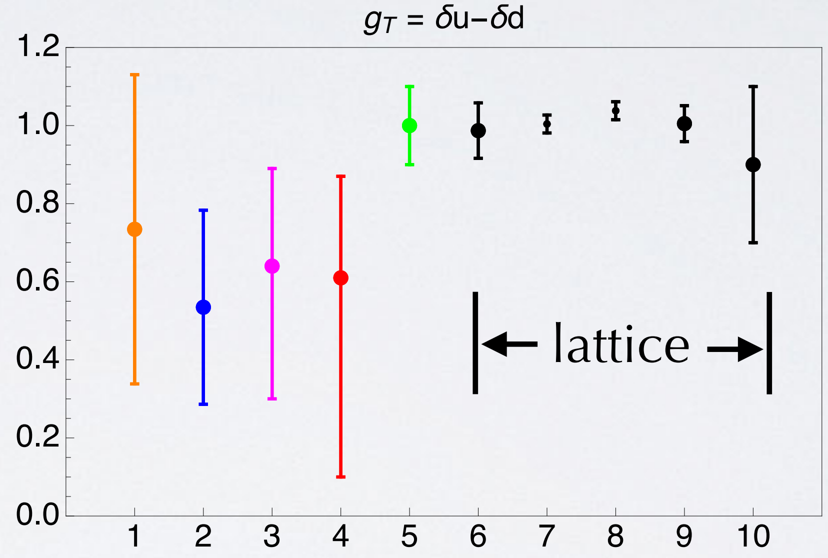
global fit 1st option (finite tensor charge)

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

global fit 2nd option (finite violation of BC sum rule)

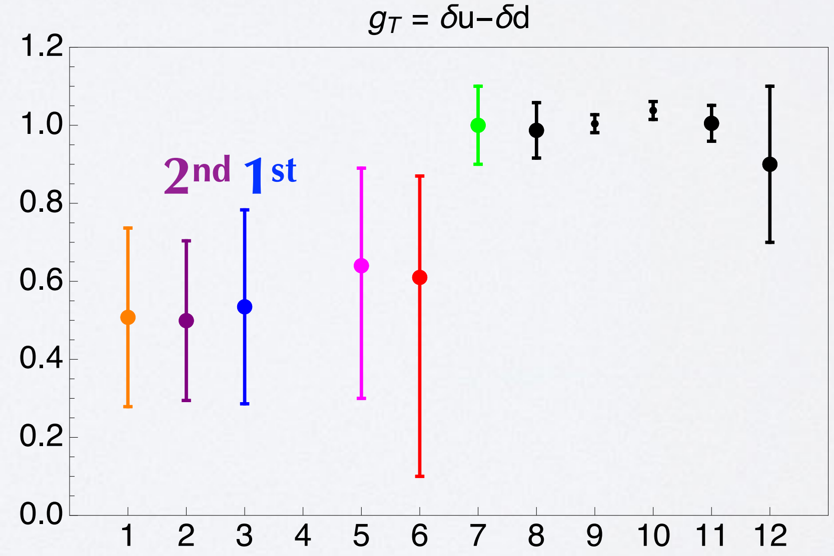
adding pseudodata COMPASS

1st option + pseudodata

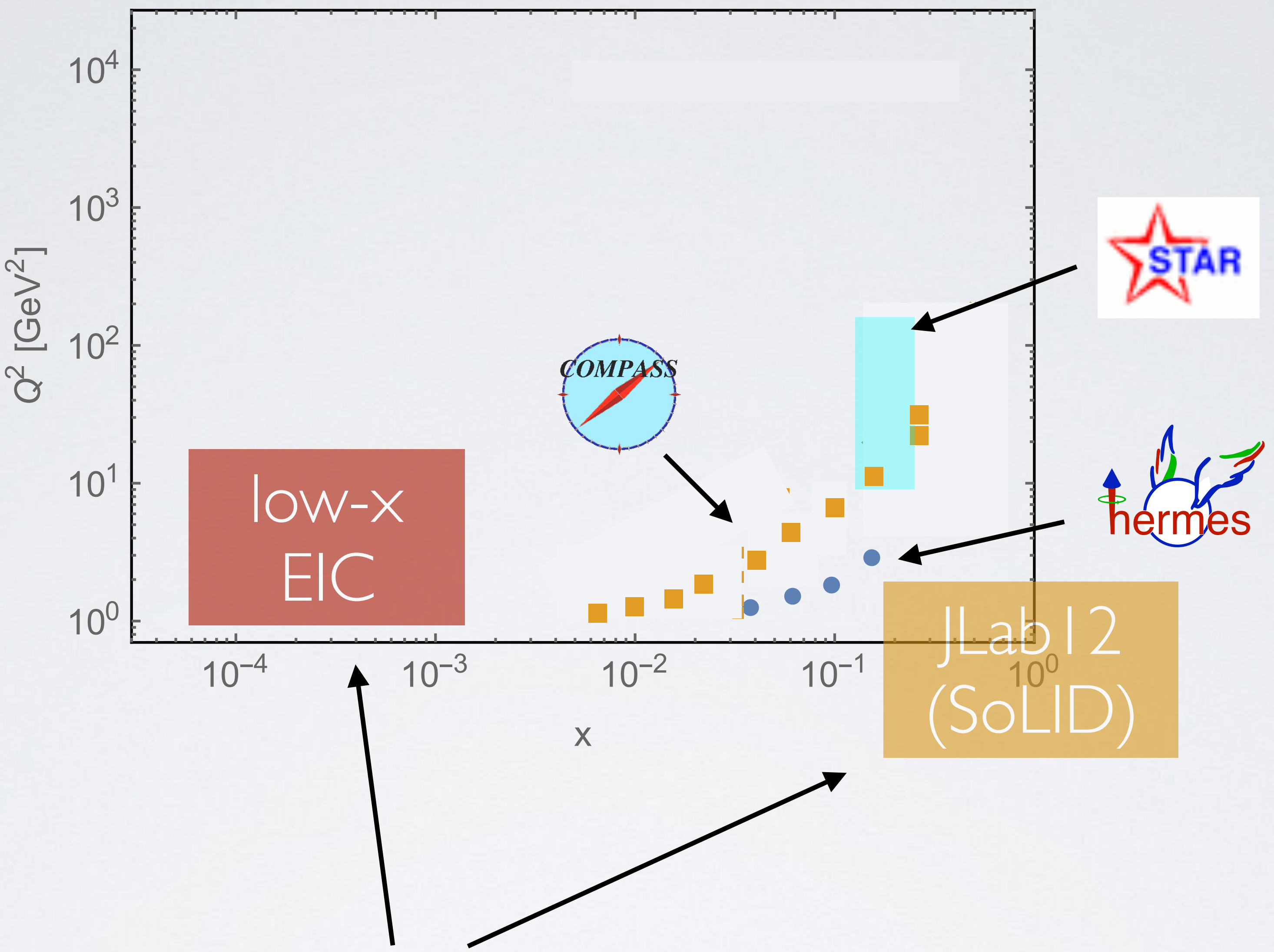


isovector

2nd option + pseudodata



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*

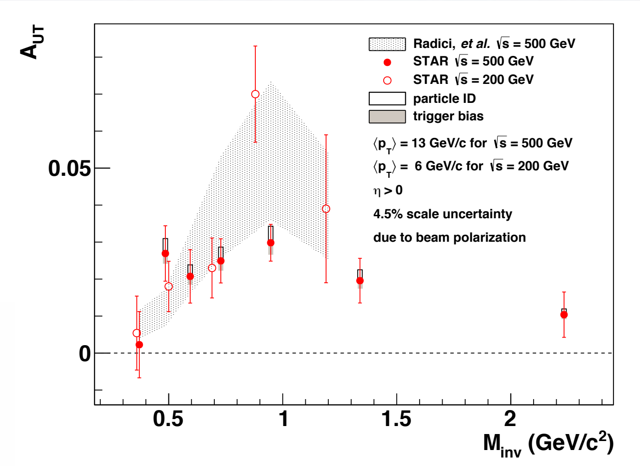
  polarized BFKL: from *S*(*inglet*) to *NS*(*inglet*) to δ*q*(*x*,*Q*^{2})

To do list

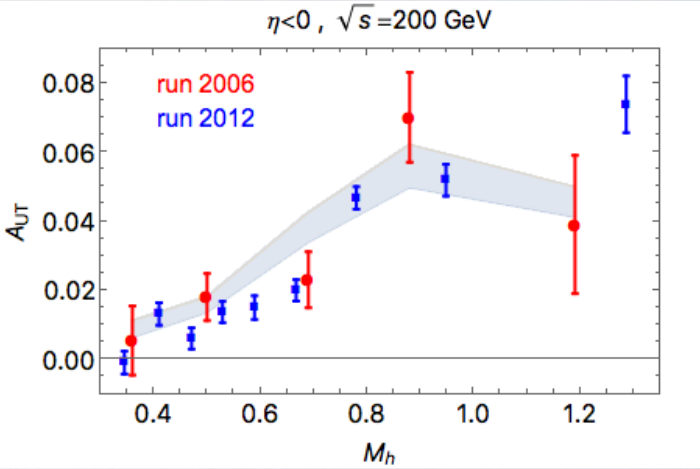
- ➡ refit di-hadron fragmentation functions using new data:
  $e^+e^- \to (\pi\pi)\,X$ constrains D_1^q
  (currently only by Montecarlo)

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

- ➡ 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*

- ➡ use COMPASS data on πK and KK channels, and from $\Lambda^\uparrow$ fragmentation: constrain strange contribution ?

- ➡ need data on $p+p \to (\pi\pi)\,X$ constrains gluon D_1^g

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

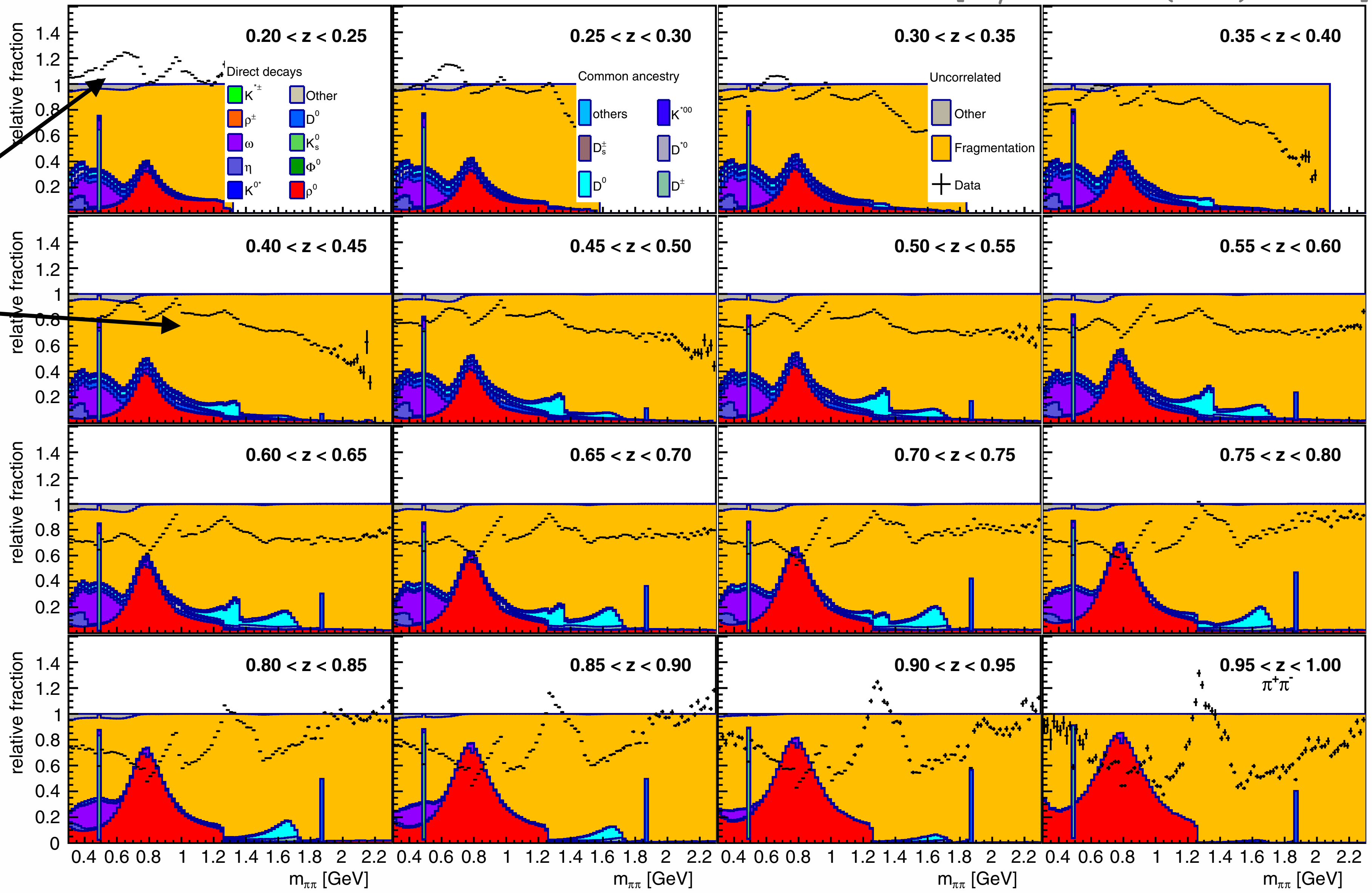
e^+e^- cross section for $(\pi\pi)$ in same hemisphere

same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
pion pairs

data ≠ MC



$T > 0.8$

$z_{1,2} > 0.1$

- decomposition based on PYTHIA simulation
- clear differences in invariant-mass dependence between MC and data

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, but can be potentially very selective when inserting real central values
- need data spanning larger x range; meantime, look for other theoretical constraints on extrapolation (mostly, at low x)

THANK YOU

Back-up

the SIDIS Single-Spin Asymmetry

$$A_{UT}^{\sin(\phi_R+\phi_S)} = -\frac{B(y)}{A(y)}\,\frac{|\mathbf{R}|}{M_h}\,\sin\theta\,\frac{\sum_q e_q^2\, h_1^q(x)\, H_{1,sp}^{\sphericalangle\, q}(z,M_h^2)}{\sum_q e_q^2\, f_1^q(x)\, D_1^q(z,M_h^2)}$$

x-dep. of SSA given by PDFs only

$$n_q^\uparrow = \int dz \int dM_h^2\, \frac{|\mathbf{R}|}{M_h}\, H_{1,sp}^{\sphericalangle\, q}(z,M_h^2)$$

$$n_q = \int dz \int dM_h^2\, D_1^q(z,M_h^2)$$

separate valence u and d using symmetry of DiFFs

$$n_q = n_{\bar q}$$

$$n_q^\uparrow = -n_{\bar q}^\uparrow$$

$$n_u^\uparrow = -n_d^\uparrow$$

proton

$$\boxed{xh_1^p(x)} \equiv xh_1^{u_v}(x) - \frac{1}{4}\, xh_1^{d_v}(x)$$

$$= -\frac{A(y)}{B(y)}\, \boxed{\frac{[A_{UT}^{\sin(\phi_R+\phi_S)}]_p}{e_u^2\, n_u^\uparrow}}\, \frac{9}{4} \sum_{q=u,d,s} e_q^2\, x f_1^{q+\bar q}(x)\, n_q$$

deuteron

$$\boxed{xh_1^D(x)} \equiv xh_1^{u_v}(x) + xh_1^{d_v}(x)$$

$$= -\frac{A(y)}{B(y)}\, \frac{\boxed{[A_{UT}^{\sin(\phi_R+\phi_S)}]_D}}{e_u^2\, n_u^\uparrow}\, 3 \sum_{q=u,d,s} \left[e_q^2\, n_q + e_{\tilde q}^2\, n_{\tilde q}\right] x f_1^{q+\bar q}(x)$$

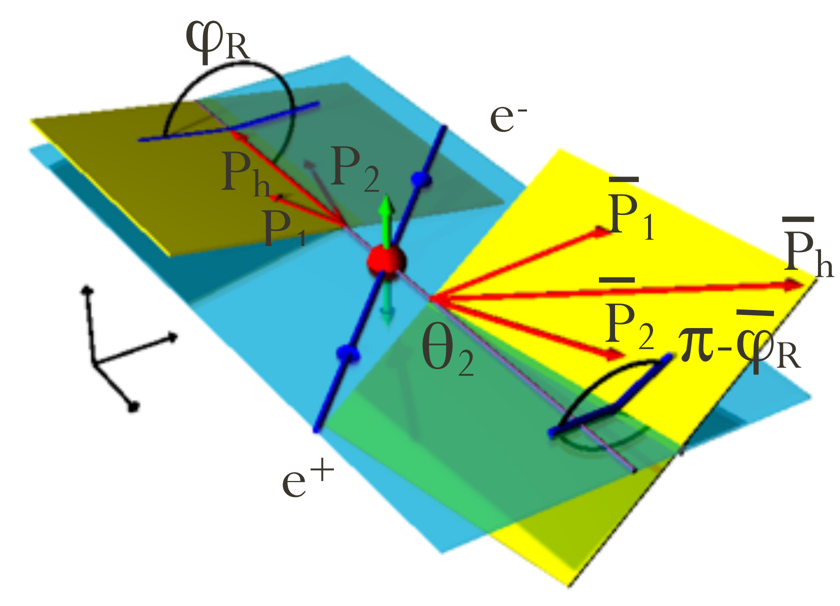
$$\tilde q = d, u, s$$

point-by-point extraction

Bacchetta, Courtoy, Radici, P.R.L. ***107*** *(11) 012001*

Martin, Bradamante, Barone, P.R. D ***91*** *(15) 014034*

extraction of DiFF from e+e−



*Artru & Collins, Z.Ph. C**69** (96) 277*

$$A^{\cos(\phi_R+\bar\phi_R)} = \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\,\frac{|\mathbf{R}_T|}{M_h}\,\frac{|\overline{\mathbf{R}}_T|}{\overline{M}_h}$$

*Boer, Jakob, Radici, P.R.D**67** (03) 094003*

*Matevosyan et al., P.R.D**97** (2018) 074019*

$$\times\,\frac{\sum_q e_q^2\, H_{1,sp}^{\triangleleft\, q}(z,M_h^2)\,\overline{H}_{1,sp}^{\triangleleft\, \bar q}(\bar z,\overline{M}_h^2)}{\sum_q e_q^2\, D_1^q(z,M_h^2)\,\overline{D}_1^q(\bar z,\overline{M}_h^2)}$$

integrate on one hemisphere

$$A^{\cos(\phi_R+\bar\phi_R)} = \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\,\frac{|\mathbf{R}|}{M_h}\,\sin\theta\,\langle\sin\bar\theta\rangle\,\frac{\sum_q e_q^2\, H_{1,sp}^{\triangleleft\, q}(z,M_h^2)\; n_{\bar q}^{\uparrow}}{\sum_q e_q^2\, D_1^q(z,M_h^2)\; n_{\bar q}}$$

$$n_q^{\uparrow} = \int dz \int dM_h^2\, \frac{|\mathbf{R}|}{M_h}\, H_{1,sp}^{\triangleleft\, q}(z,M_h^2)$$

$$n_q = \int dz \int dM_h^2\, D_1^q(z,M_h^2)$$

Belle data for $A^{\cos(\Phi_R+\overline{\Phi}_R)}$

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

→

symmetry of DiFFs

$n_q = n_{\bar q}$

$n_q^{\uparrow} = -n_{\bar q}^{\uparrow}$

$n_u^{\uparrow} = -n_d^{\uparrow}$

(determines the sign of $A^{\cos(\Phi_R+\overline{\Phi}_R)}$)

→

first extraction of DiFFs

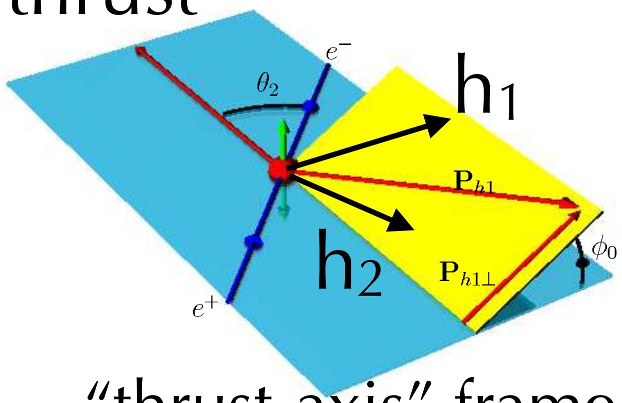
*Courtoy et al., P.R.D**85** (12) 114023*

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

e^+e^- cross section for ($\pi\pi$) in same hemisphere

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

thrust

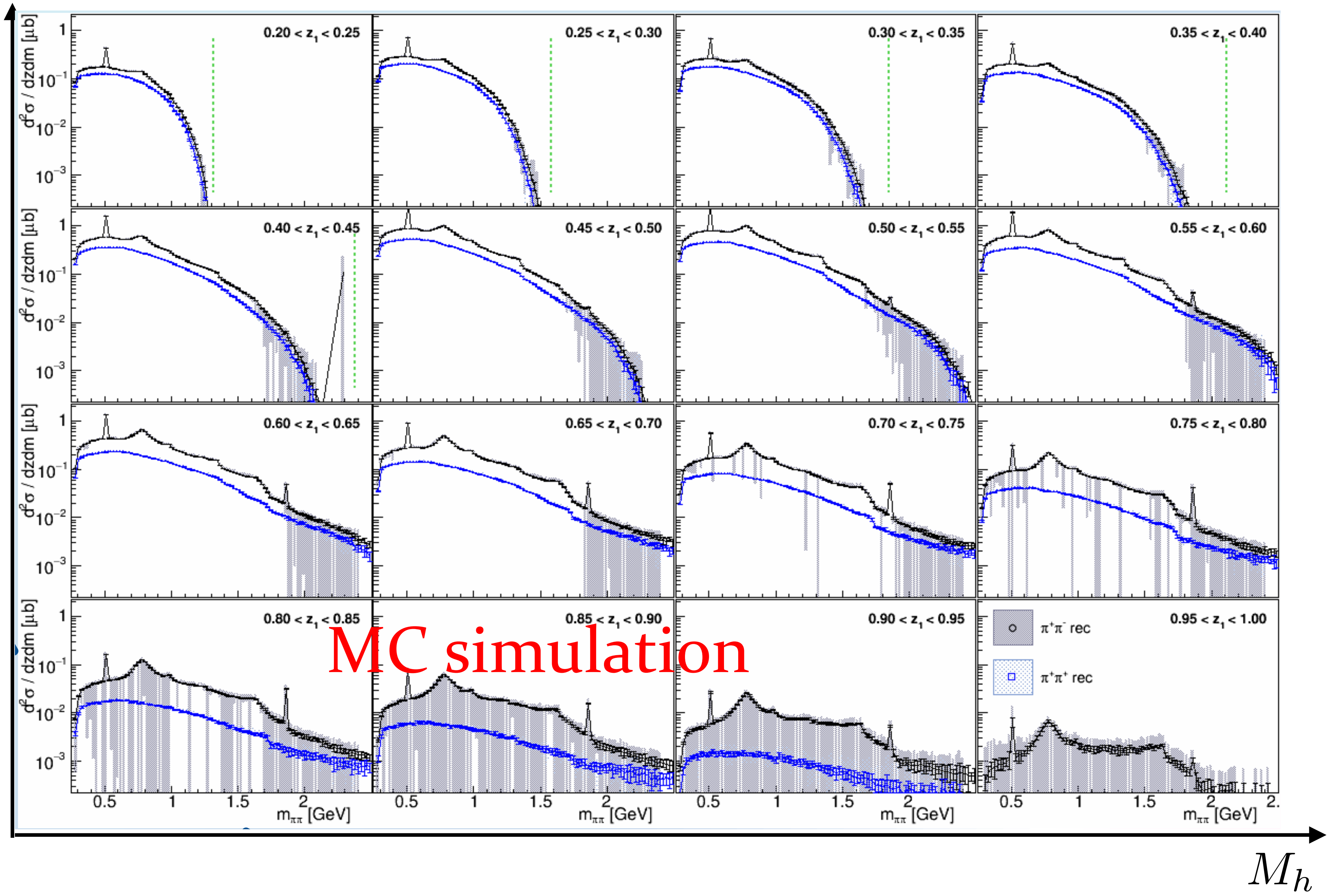


“thrust-axis” frame

● $\pi^+\pi^-$

● $\pi^+\pi^+$

$$\frac{d\sigma^0}{dz\, dM_h}$$



MC simulation

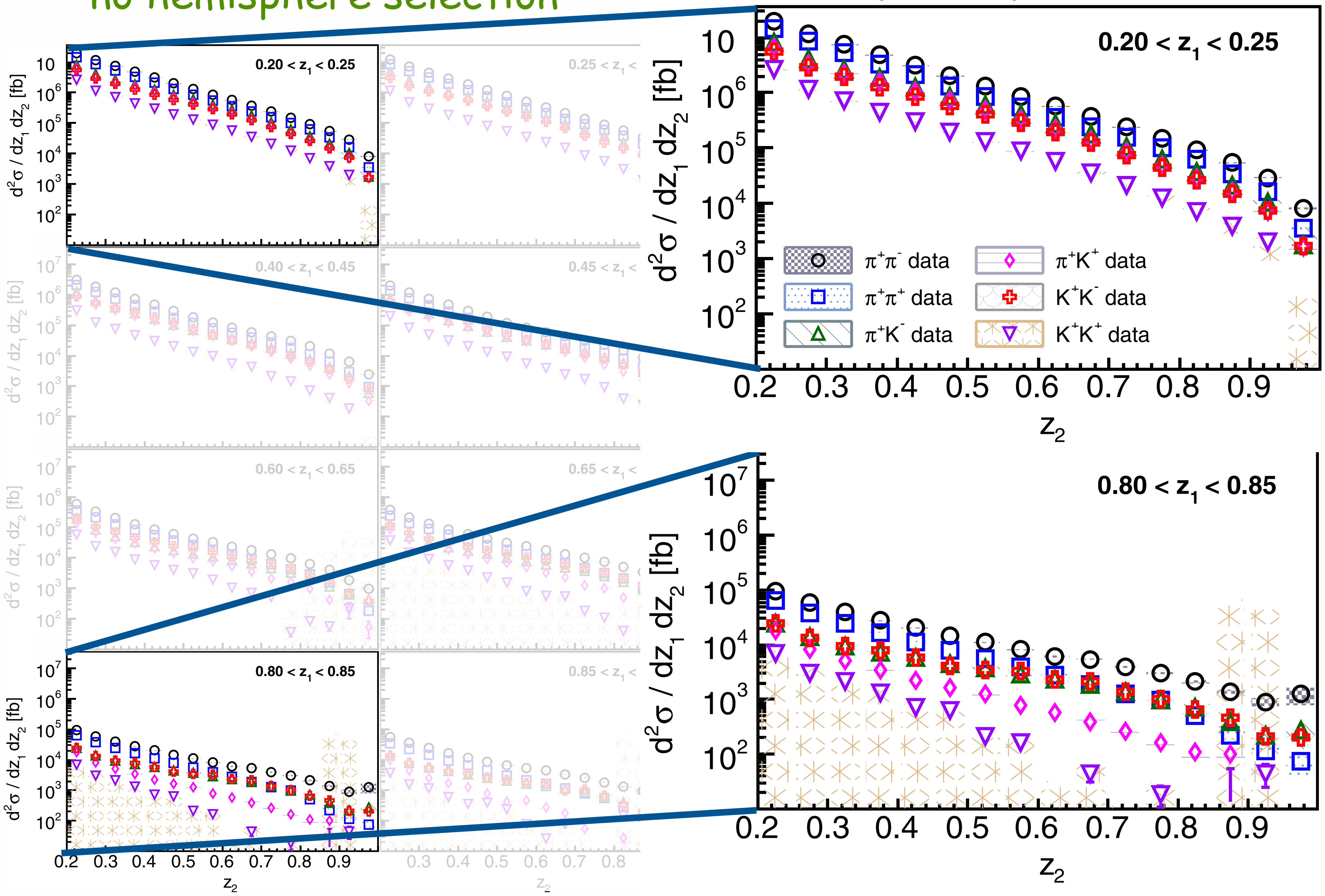
R. Seidl, talk at SPIN2016

upcoming Belle data for (z, M_h) binning of unpolarized di-hadron e^+e^- cross section

e^+e^- cross section for (hh) from all hemispheres

hadron-pair production

no hemisphere selection



$D_1(z_2)$ @low z_1 ≠ $D_1(z_2)$ @high z_1

e^+e^- cross section for (hh) in different hemispheres

hadron-pairs: topology comparison

- any hemisphere vs. opposite- & same-hemisphere pairs
  - same-hemisphere pairs with kinematic limit at $z_1=z_2=0.5$

[Phys. Rev. D92 (2015) 092007]

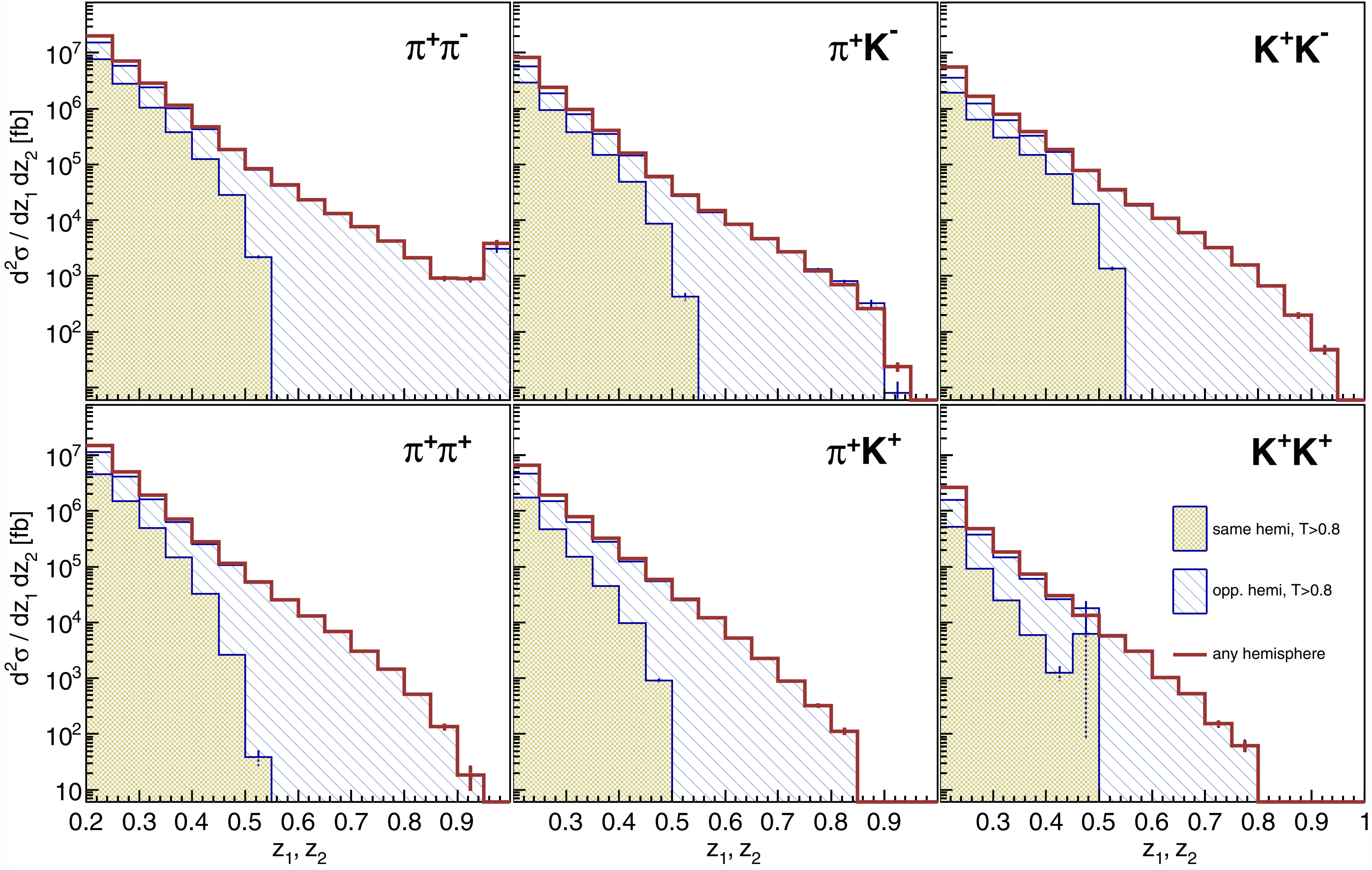
opposite hemisphere

$0 < z_1=z_2 < 1$

same hemisphere

$0 < z_1+z_2 < 1$

$0 < z_1=z_2 < 0.5$



gunar.schnell @ desy.de 18 FF18 - Feb 20th, 2018

DiFF $(z_1, z_2) \neq D_1(z_1)\ D_1(z_2)$

hadronic collisions in Mellin space

dσ (η,M_h,P_T) typical cross section for $a+b^\uparrow \to c^\uparrow + d$ process

$$\frac{d\sigma_{UT}}{d\eta} \propto \int d|\mathbf{P}_T|\, dM_h \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\hat{\sigma}_{ab^\uparrow \to c^\uparrow d}}{d\hat{t}}\, H_1^{\sphericalangle\, c}(\bar{z}, M_h)$$

to be computed thousands times… usual trick: use **Mellin anti-transform**

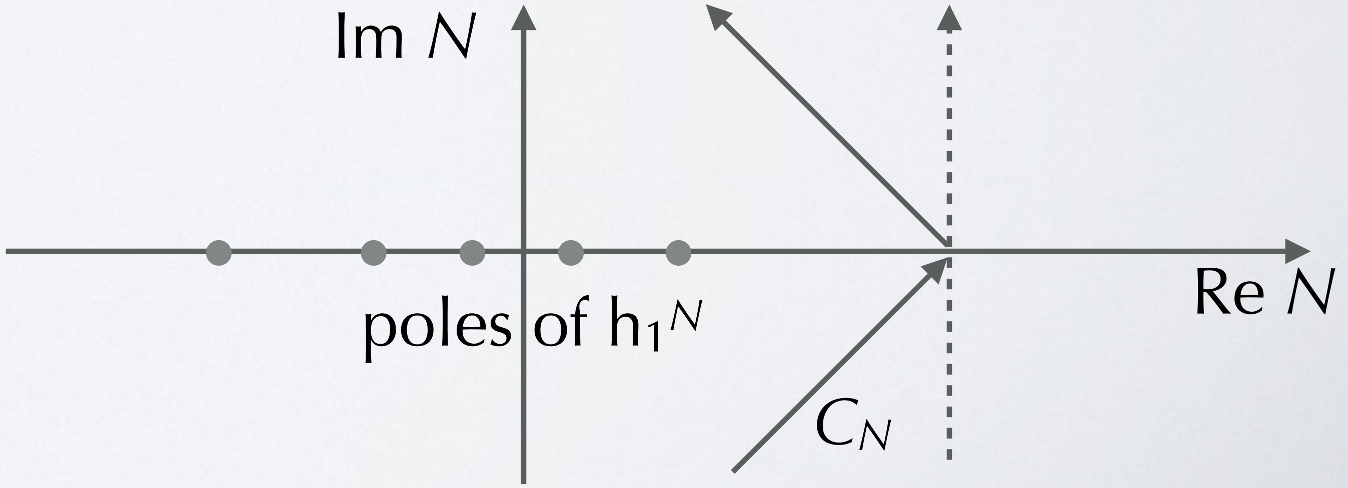
$$h_1(x, Q^2) = \int_{\mathcal{C}_N} dN\; x^{-N}\; h_1^N(Q^2) \qquad N \in \mathbb{C}$$

*Stratmann & Vogelsang, P.R. D**64** (01) 114007*

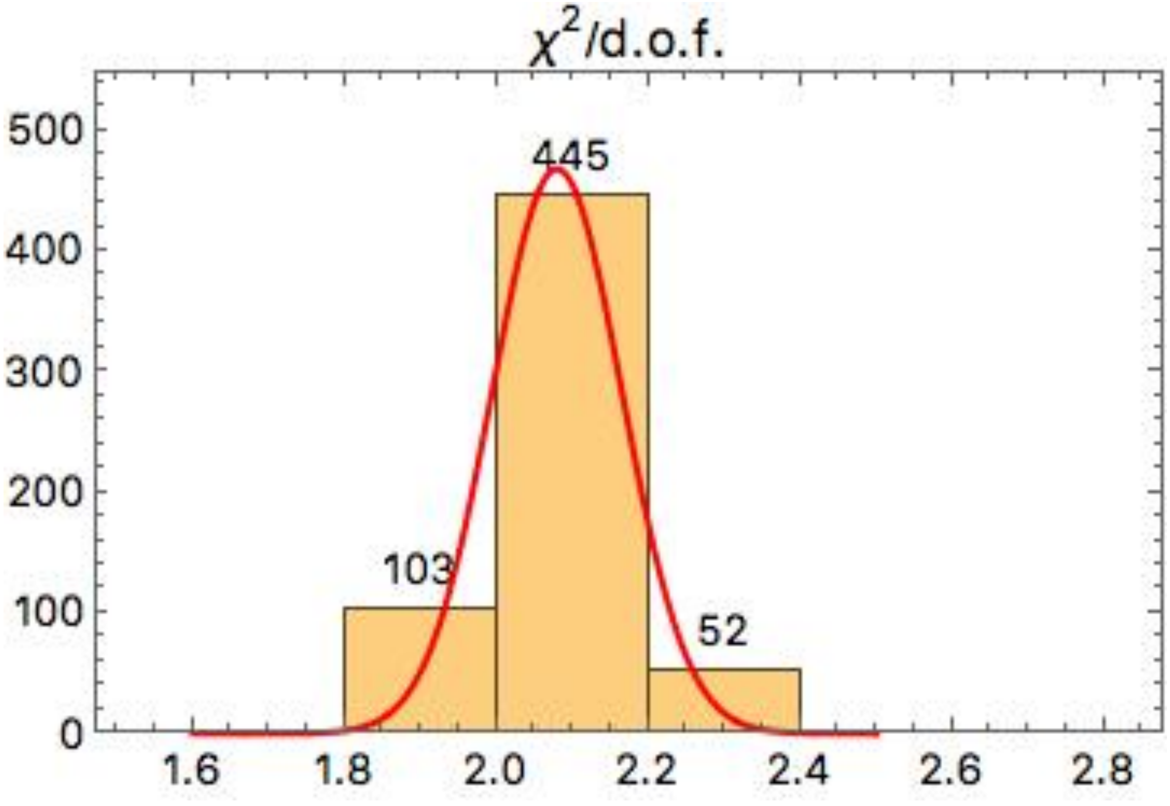
$$\frac{d\sigma_{UT}}{d\eta} \propto \sum_b \int_{\mathcal{C}_N} dN \int d|\mathbf{P}_T|\, h_{1b}^N(P_T^2) \int dM_h \underbrace{\sum_{a,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, x_b^{-N}\, \frac{d\hat{\sigma}_{ab^\uparrow \to c^\uparrow d}}{d\hat{t}}\, H_1^{\sphericalangle\, c}(\bar{z}, M_h)}_{F_b(N, \eta, |\mathbf{P}_T|, M_h)}$$

pre-compute F_b only one time on contour C_N

this **speeds up** convergence and facilitates $\int dN$, provided that **h_1^N is known analytically**



χ^2 of the fit



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