FIRST extraction of TRANSVERSITY from data on lepton-hadron SCATTERING + 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

Istituto Nazionale di Fisica Nucleare

3DSPIN MAPPING THE PROTON IN 3D

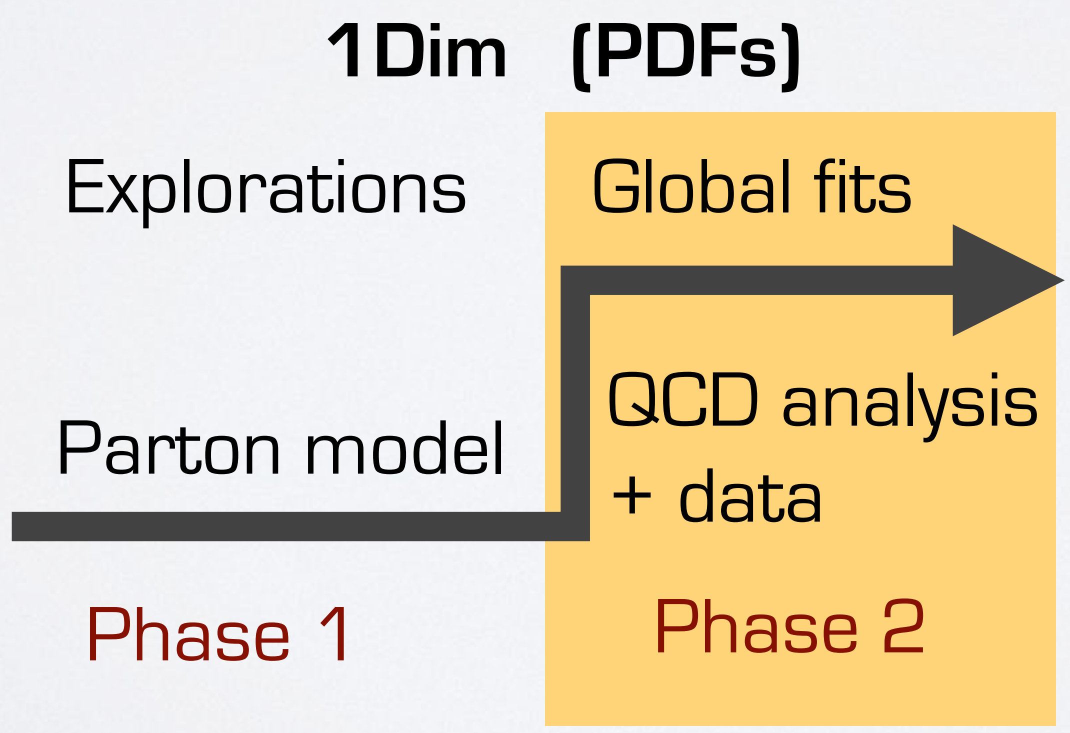
erc European Research Council

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**



Motivation

searches for BSM New Physics

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

hadron level

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

quark level

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

$$C_T \leftrightarrow g_T \epsilon_T$$

exp. data

?

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

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

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

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.
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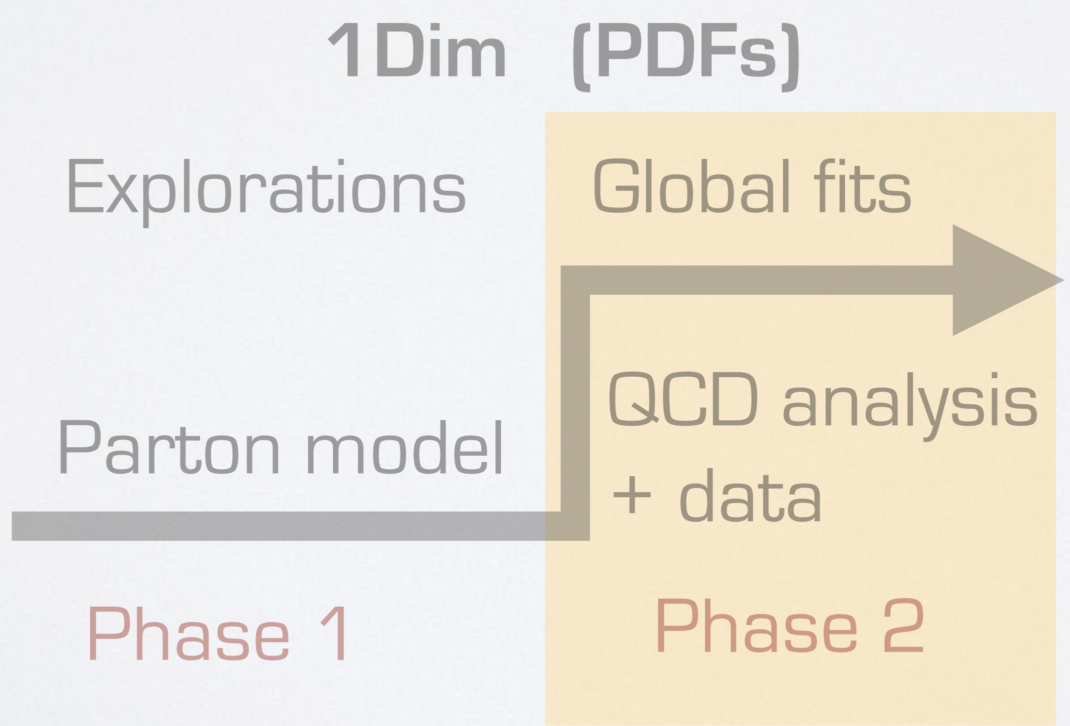
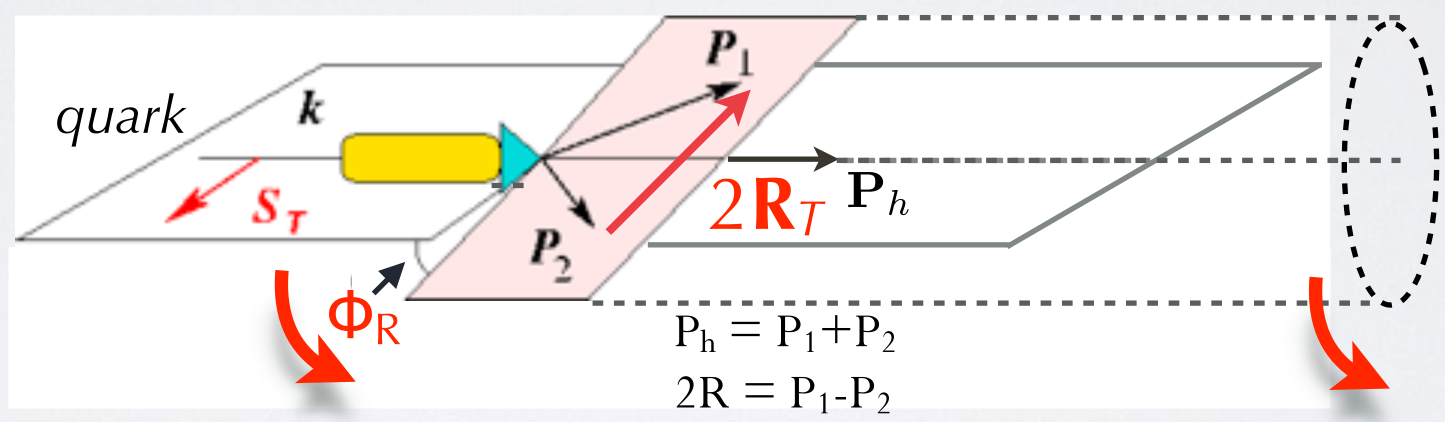


2-hadron-inclusive production

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

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



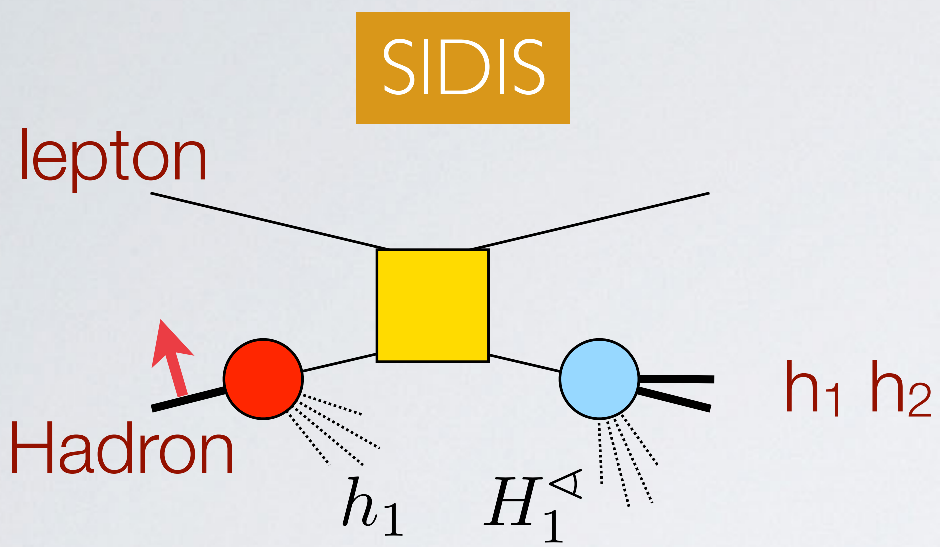
$\updownarrow$

M_h

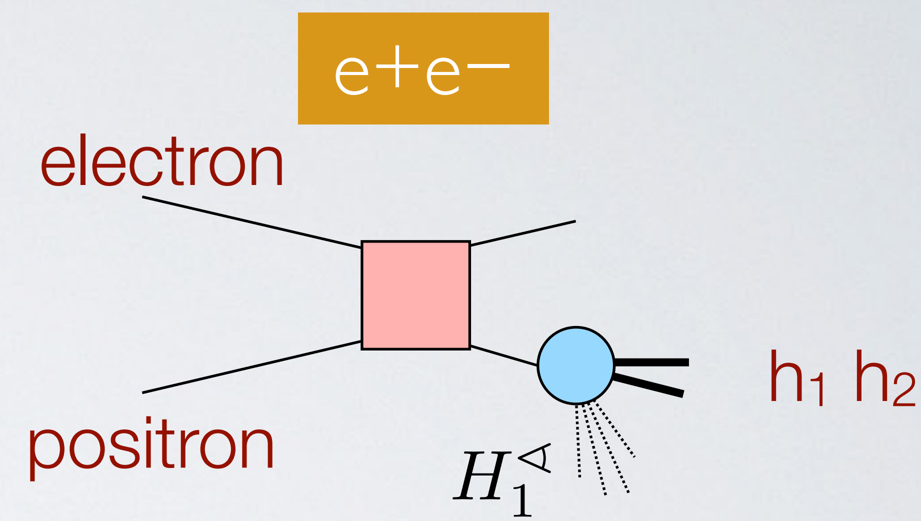
invariant mass

correlation S_T and R_T → **azimuthal asymmetry**

2-hadron-inclusive production



framework
collinear
factorization

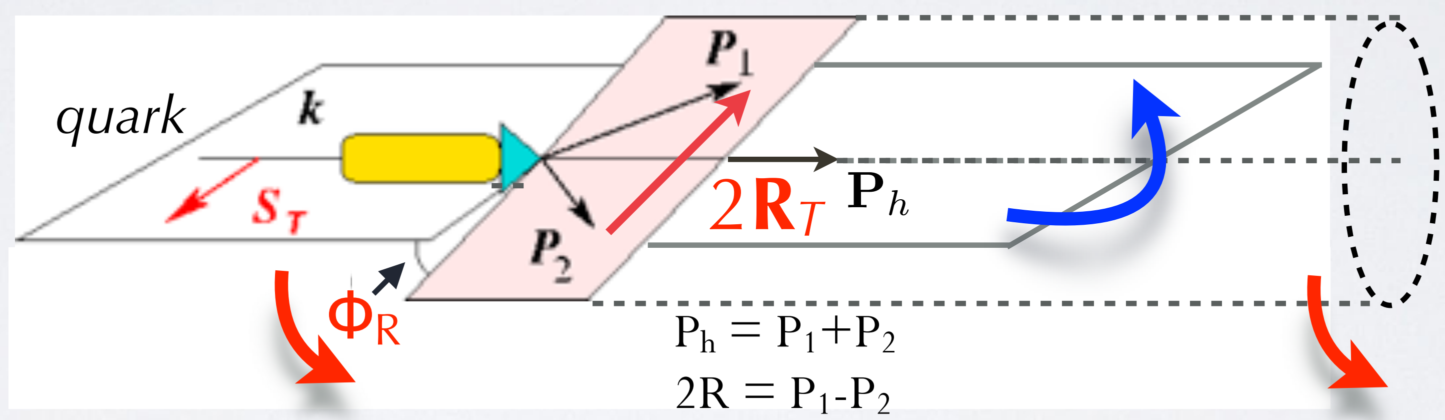


$R_T \ll Q$ $H_1^{\sphericalangle}$

↕

M_h

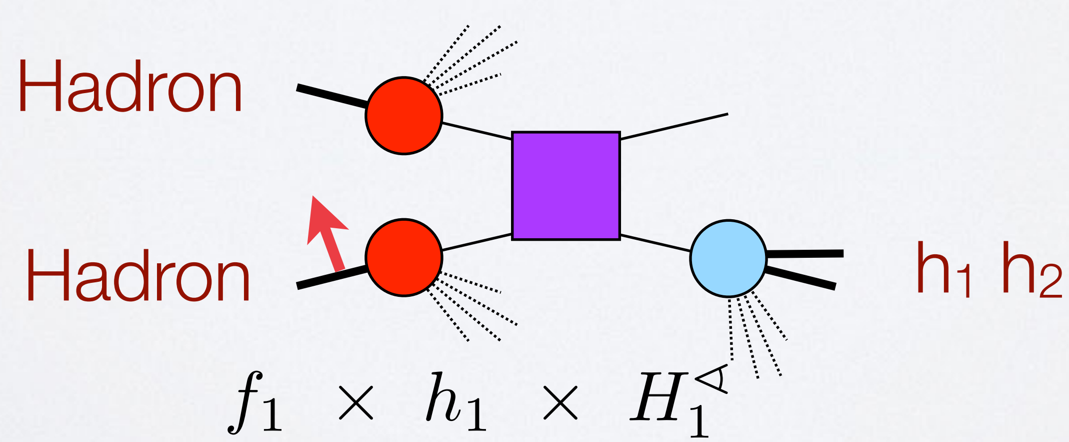
invariant mass



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

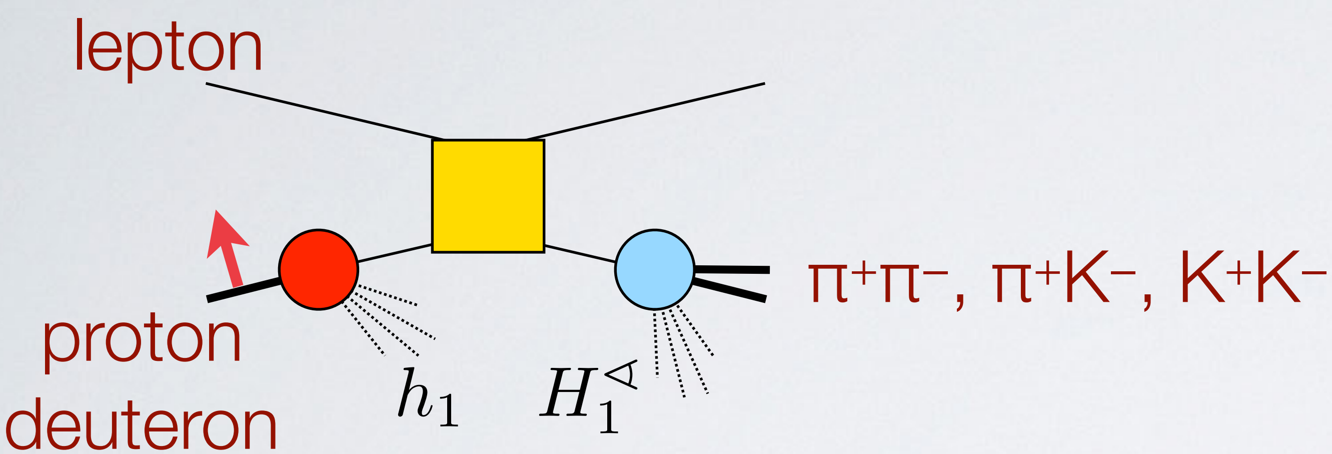
correlation S_T and R_T → **azimuthal asymmetry**

H H↑



exp. data for 2-hadron-inclusive production

SIDIS ℓ H↑ → ℓ' (h_1 h_2) X

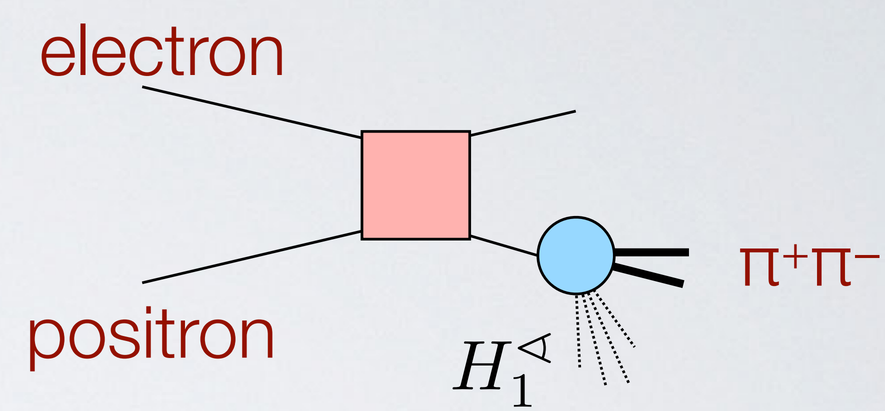


Airapetian et al., JHEP **0806** (08) 017

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

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

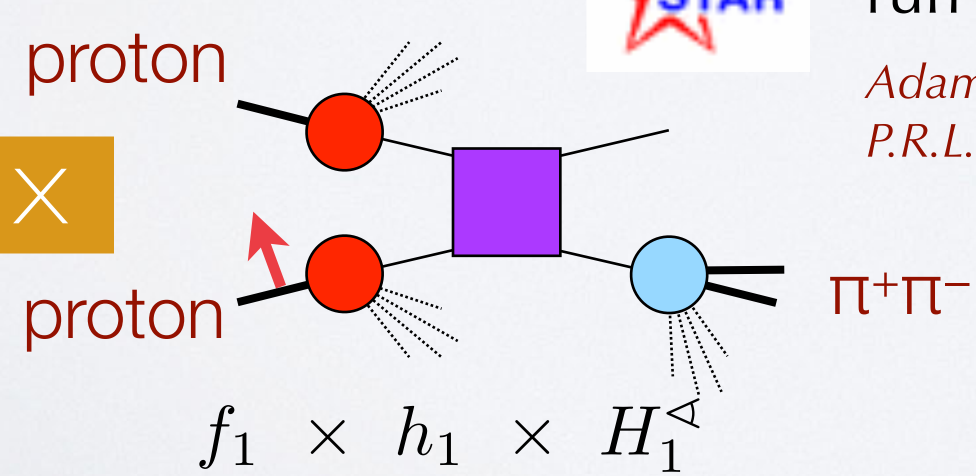
e+e− → (h_1 h_2) X



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

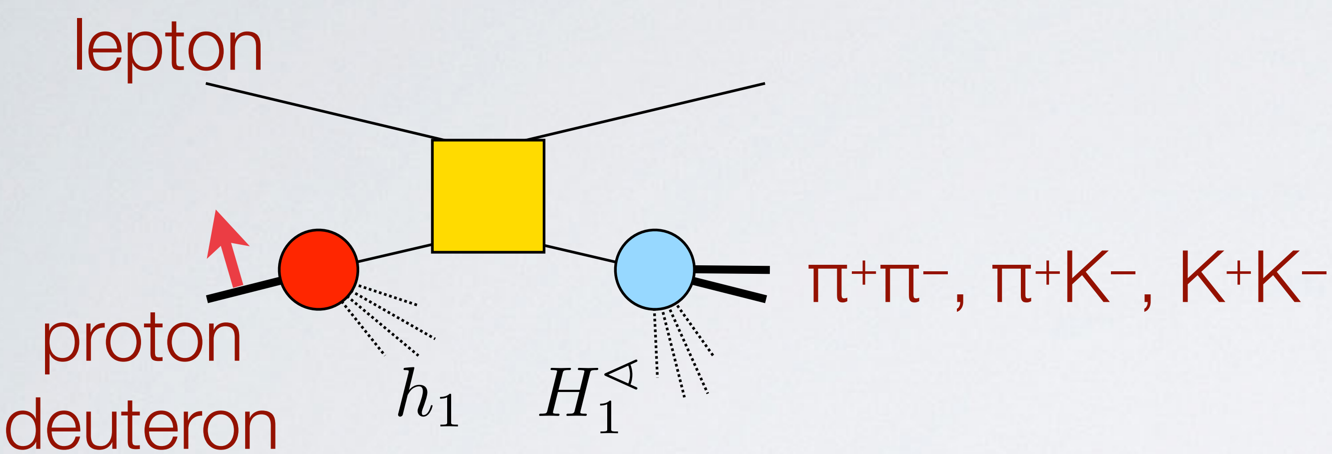
run 2011 (s=500)

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 $H^\uparrow \to \ell'$ $(h_1\, h_2)$ X



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

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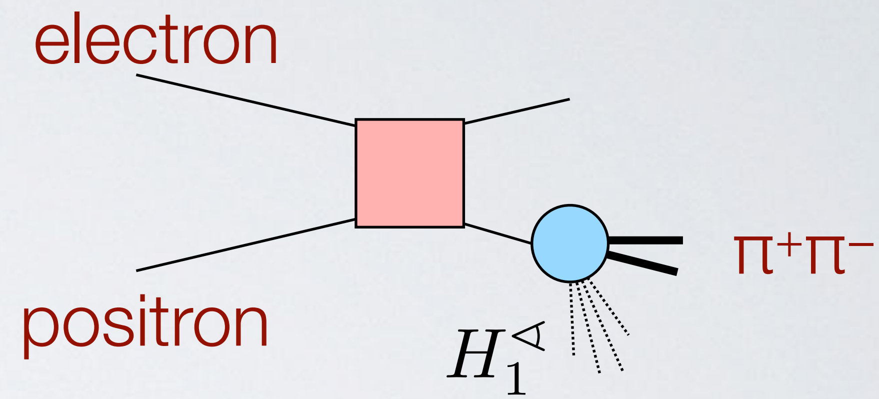

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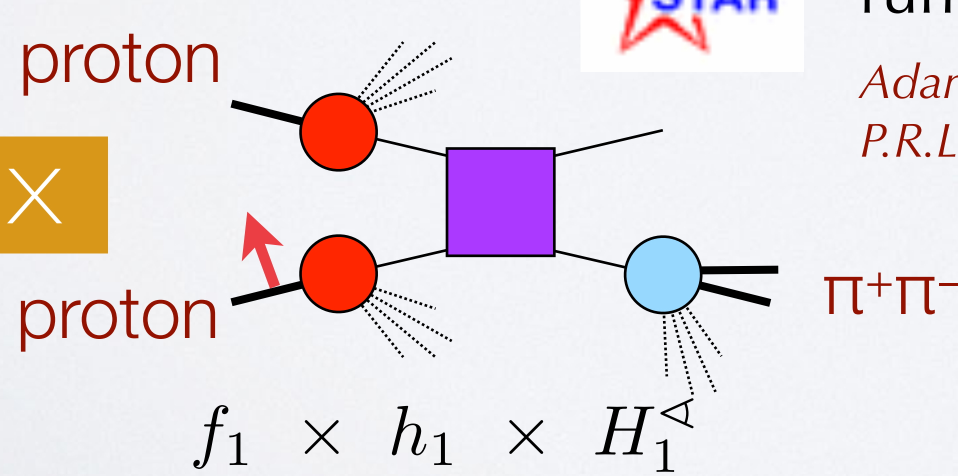

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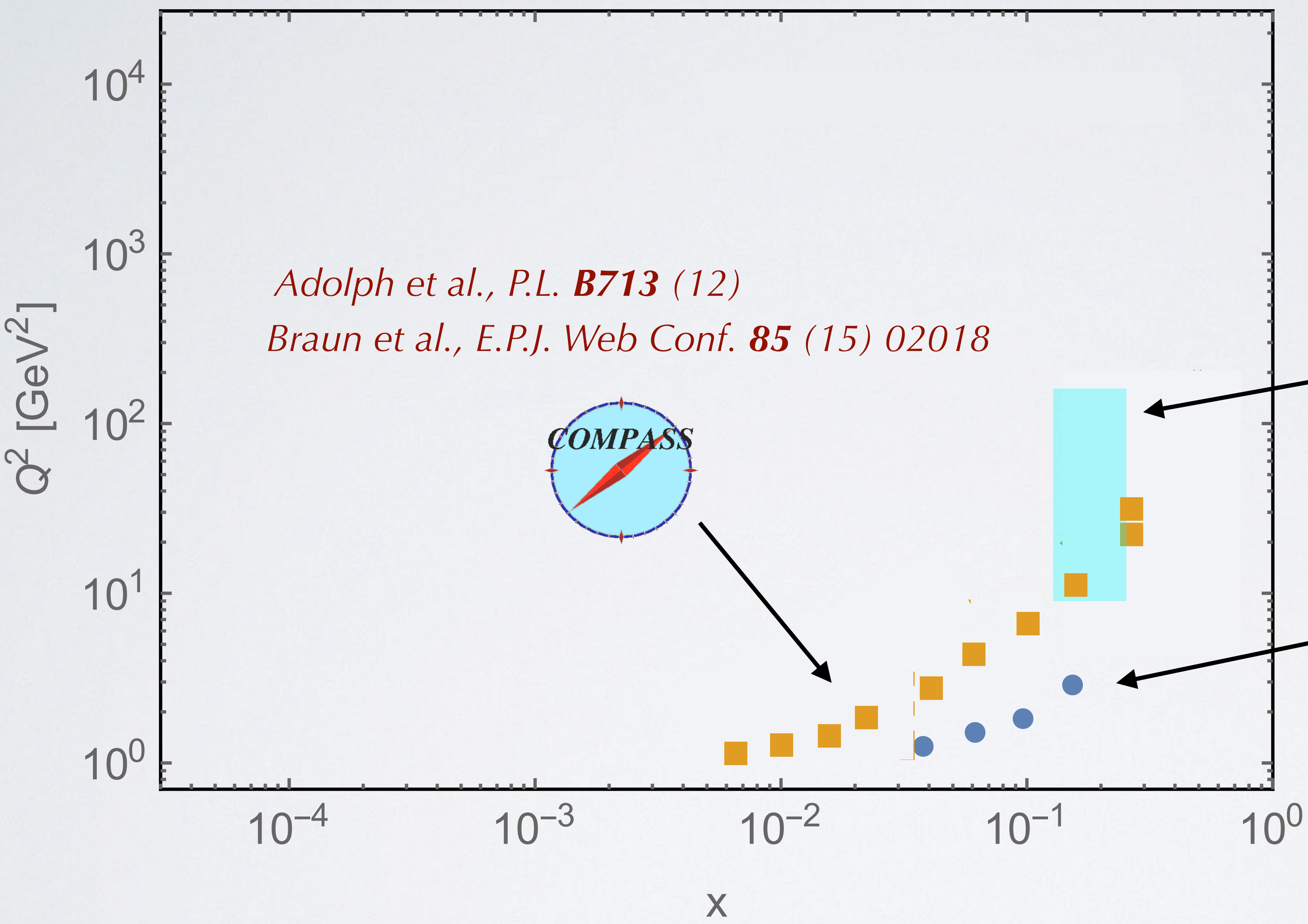
~~run 2011 (s=500)~~

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

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

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*

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

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

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 Q^2

choice of functional form

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

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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

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

1) δq finite => $A_q + a_q > 0$

choice of functional form

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2) small-x dipole picture => $h_1^{q_v}(x) \underset{x\to 0}{\approx} x^{1-2\sqrt{\frac{\alpha_s(Q^2)N_c}{2\pi}}}$ at Q_0 $A_q + a_q \sim 1$

Kovchegov & Sievert, arXiv:1808.10354

consistent with lattice *Kirschner et al., Z.Phys.* ***C74*** *(97) 501*

consistent with "massive" jet in DIS *Accardi and Bacchetta, P.L.* ***B773*** *(17) 632*

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

choice of functional form

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

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

our choice $A_q + a_q > \frac{1}{3}$

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

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

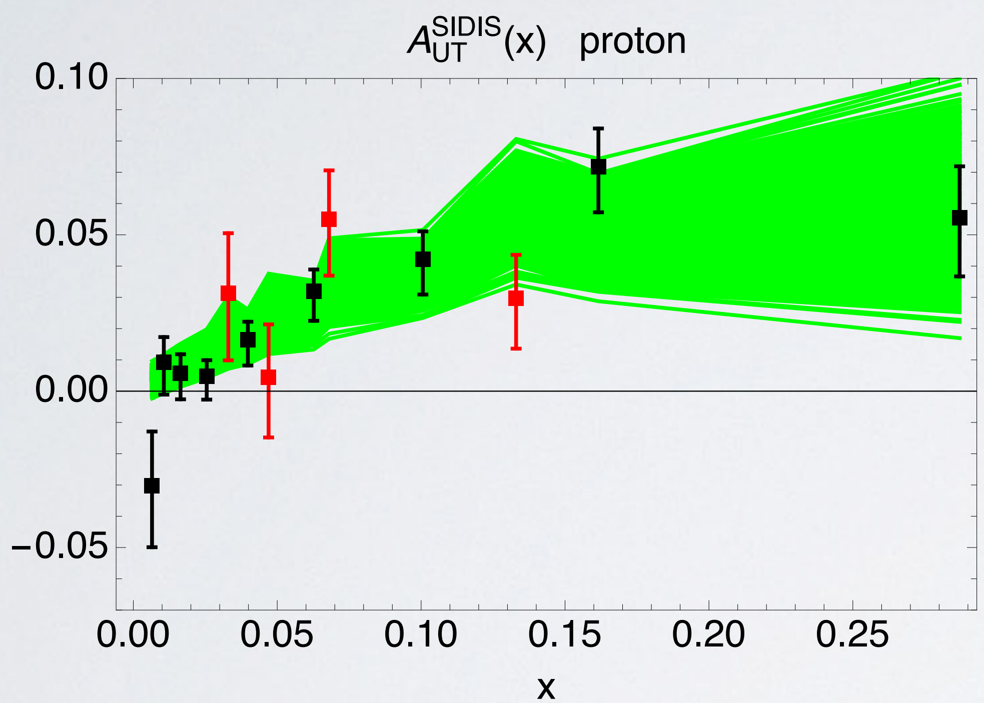
deteriorates our e^+e^- fit as $\chi^2/\mathrm{dof} = \begin{cases} 1.69 & 1.28 \\ 1.81 & 1.37 \\ 2.96 & 2.01 \end{cases}$

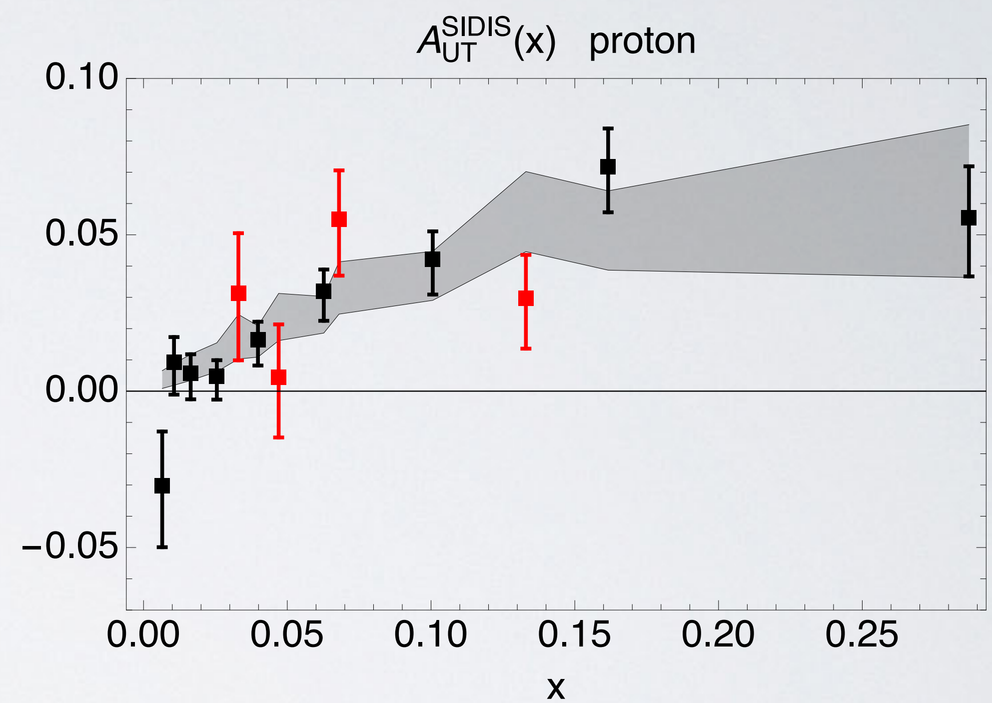
background ρ channels

statistical uncertainty

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

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



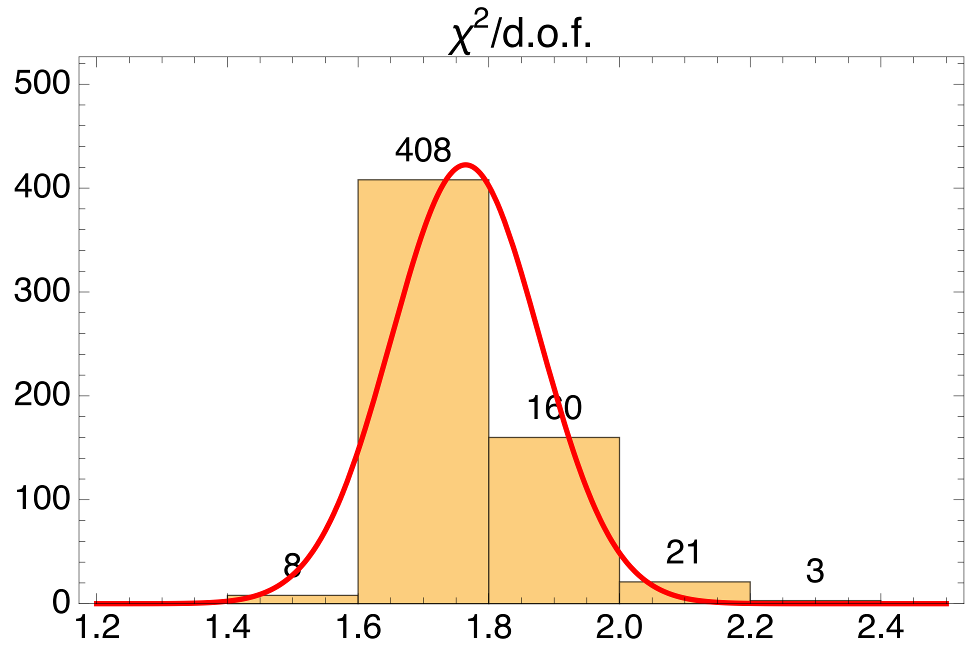


all 600 replicas → 90% of replicas

<u>the bootstrap method</u>

χ^2 of the fit

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



proton SIDIS **13** data points = **4** hermes + **9** COMPASS

deuteron SIDIS **9** data points = + **9**

STAR **24** data points (**4** η)x $\frac{\mathbf{4}}{\mathbf{24}}$ + (**10** M_h)x$\frac{\mathbf{10}}{\mathbf{24}}$ + (**10** p_T)x$\frac{\mathbf{10}}{\mathbf{24}}$

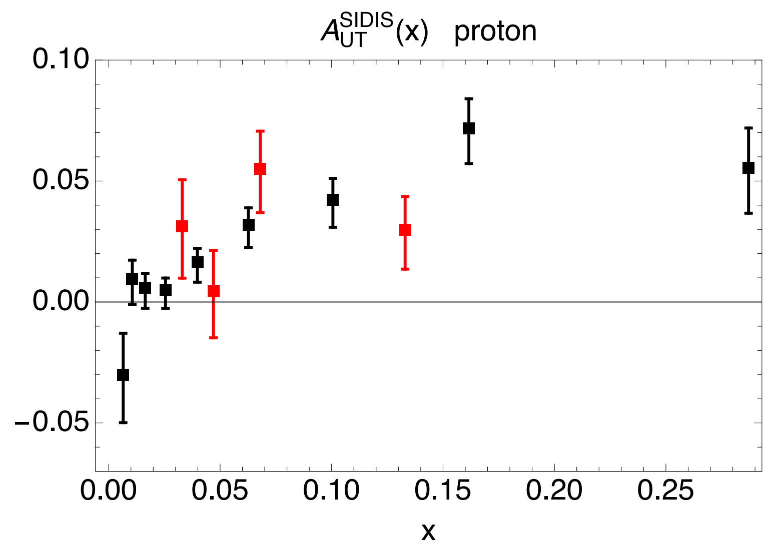
global fit **10** parameters

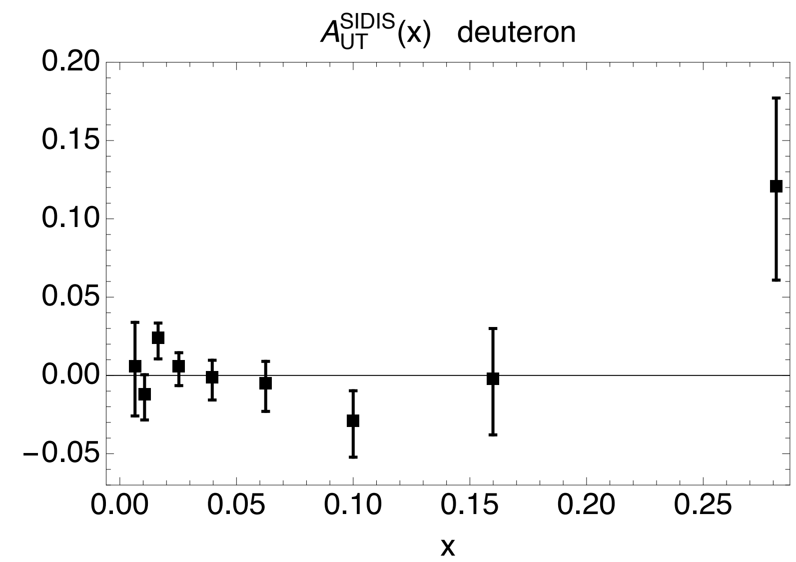
results

SIDIS

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

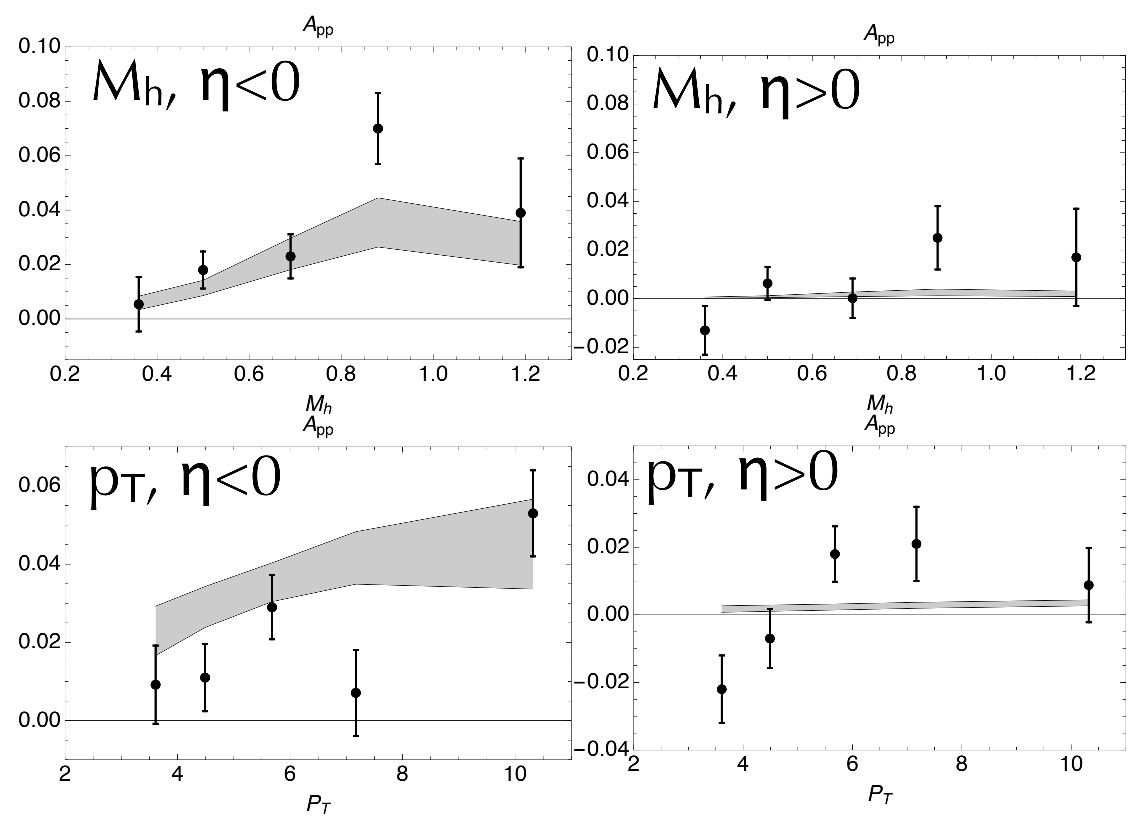
Airapetian et al.,
JHEP ***0806*** *(08) 017*

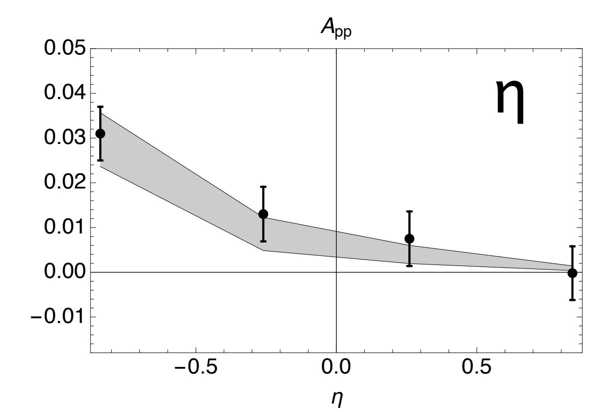




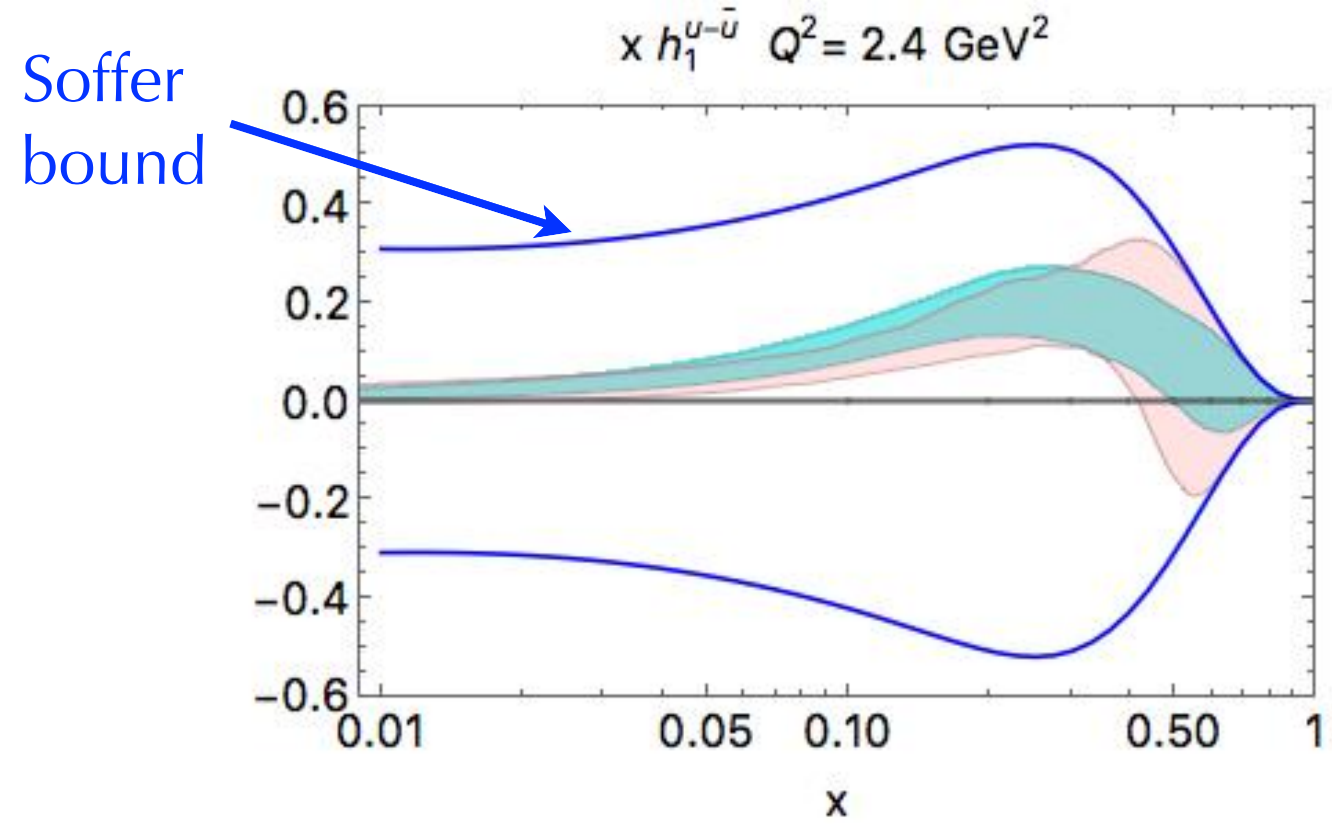
pp collisions

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





comparison with previous fit



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

global fit

up

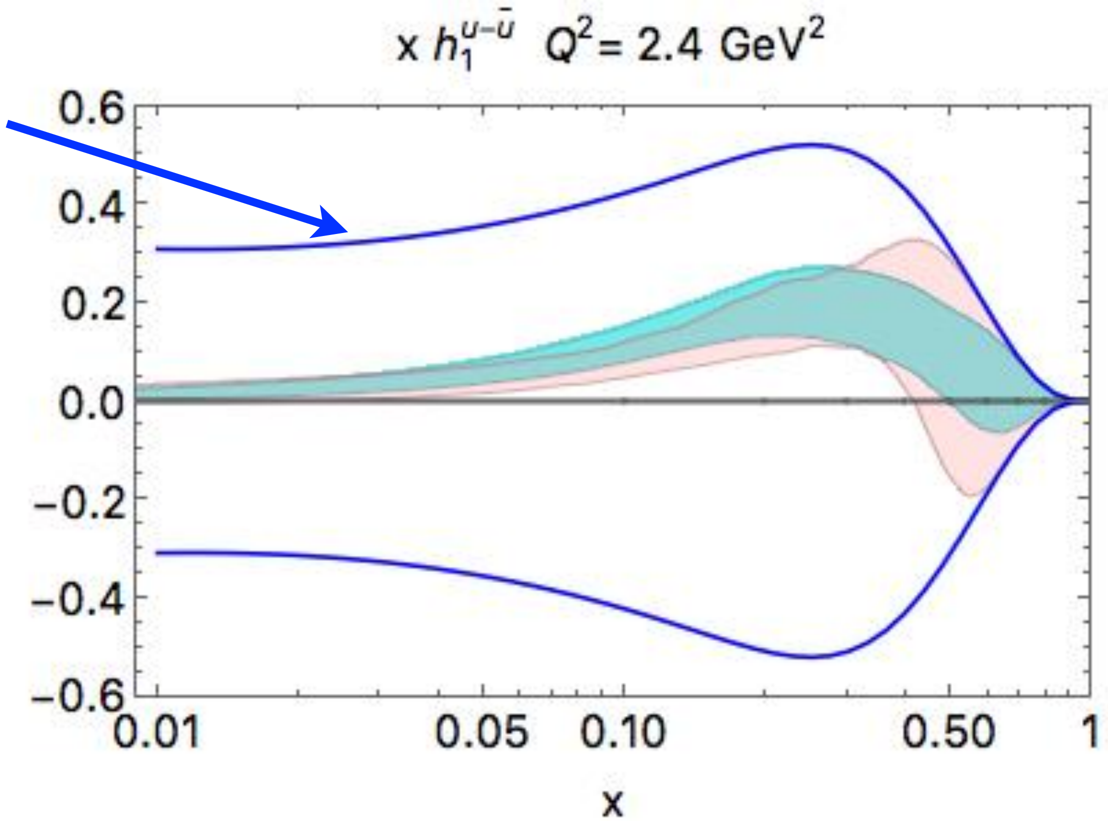
higher precision

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)

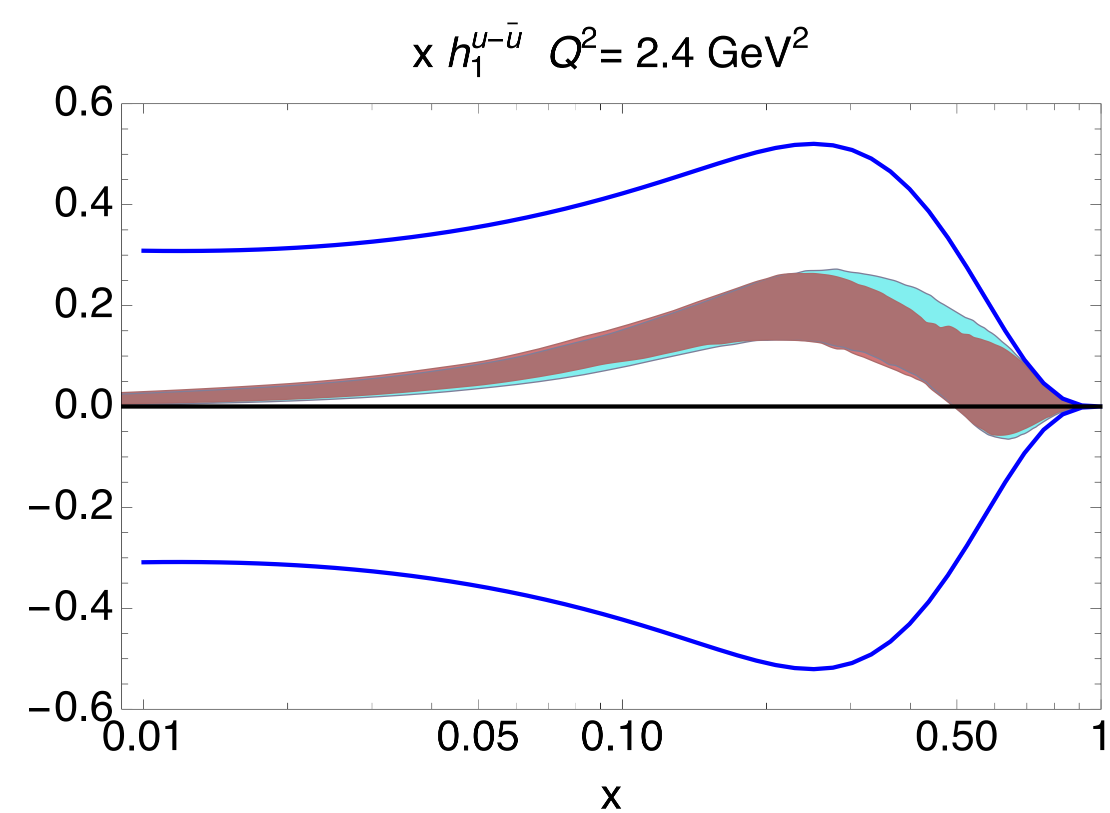
Radici et al., JHEP ***1505*** *(15) 123*

up

insensitive to uncertainty on gluon D_1

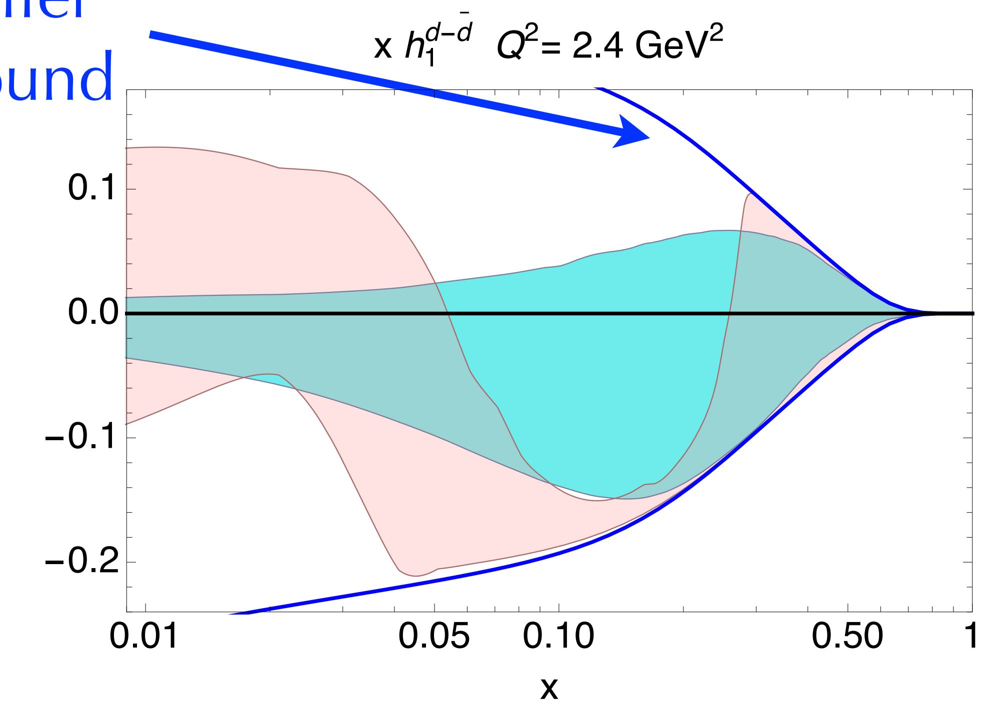
$D_1^g(Q_0) = 0$

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



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

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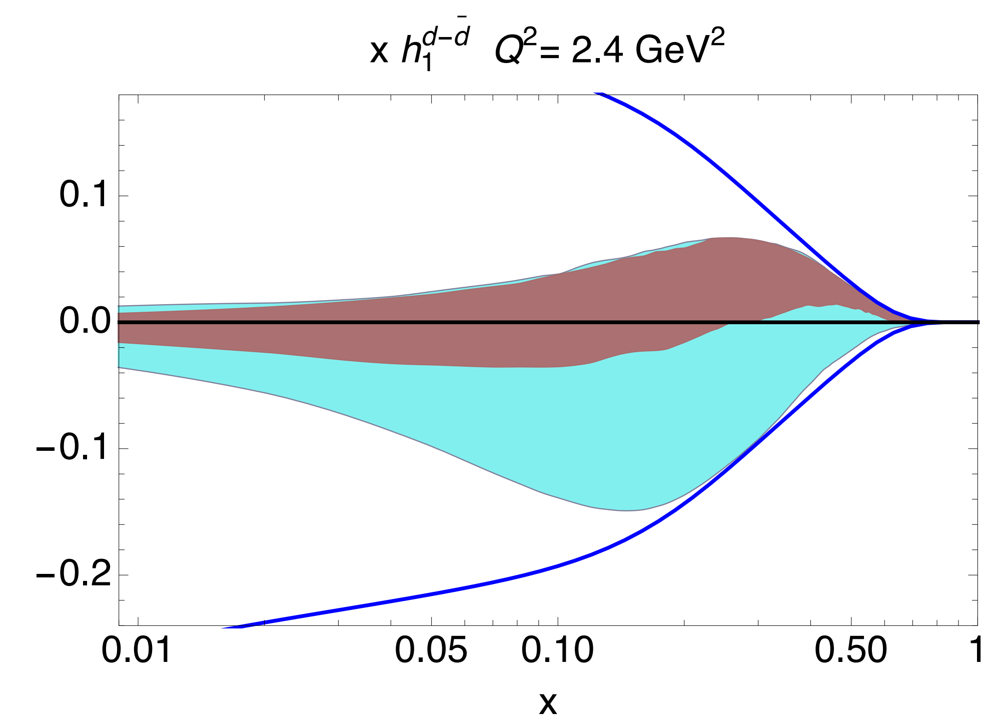
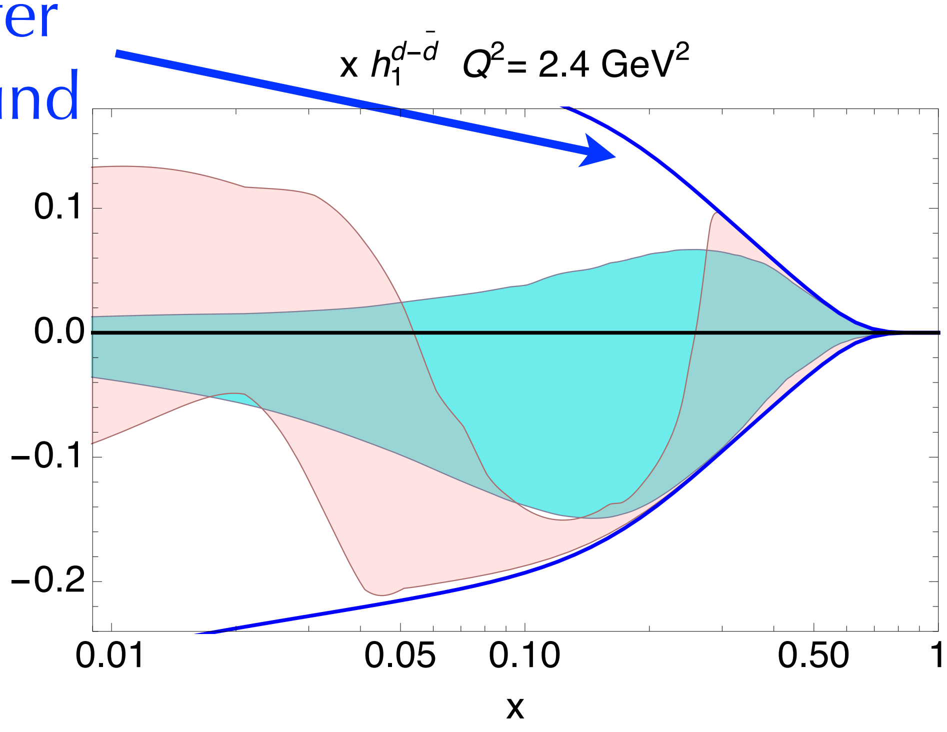


comparison with previous fit

Soffer bound



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

global fit

old fit

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

down

need better control on
$g \rightarrow \pi^+\pi^-$

down

sensitive to uncertainty on gluon D_1

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

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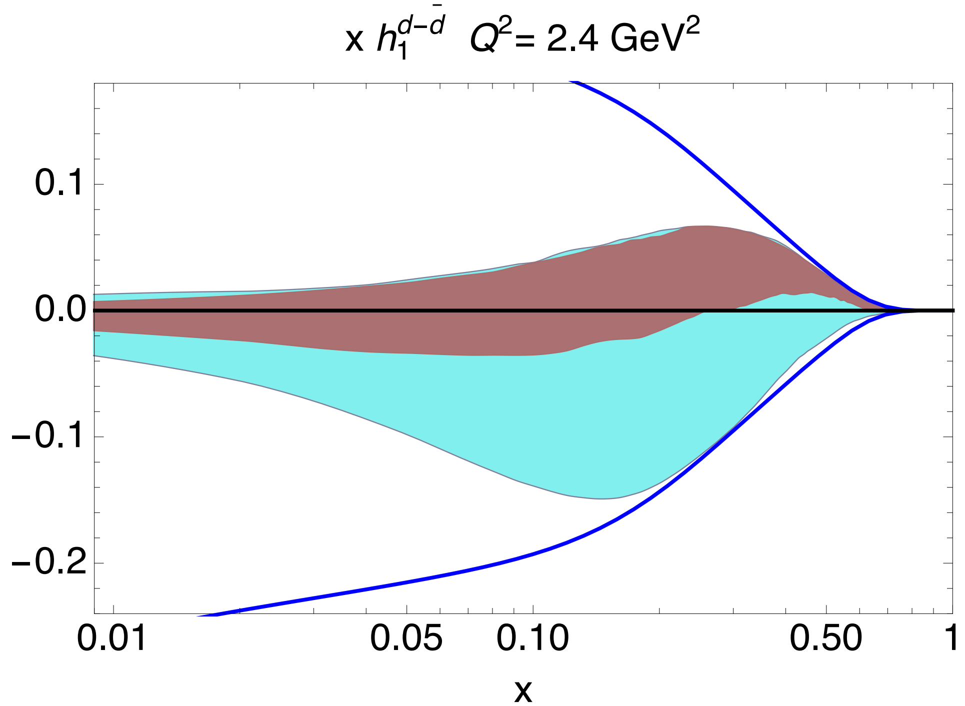
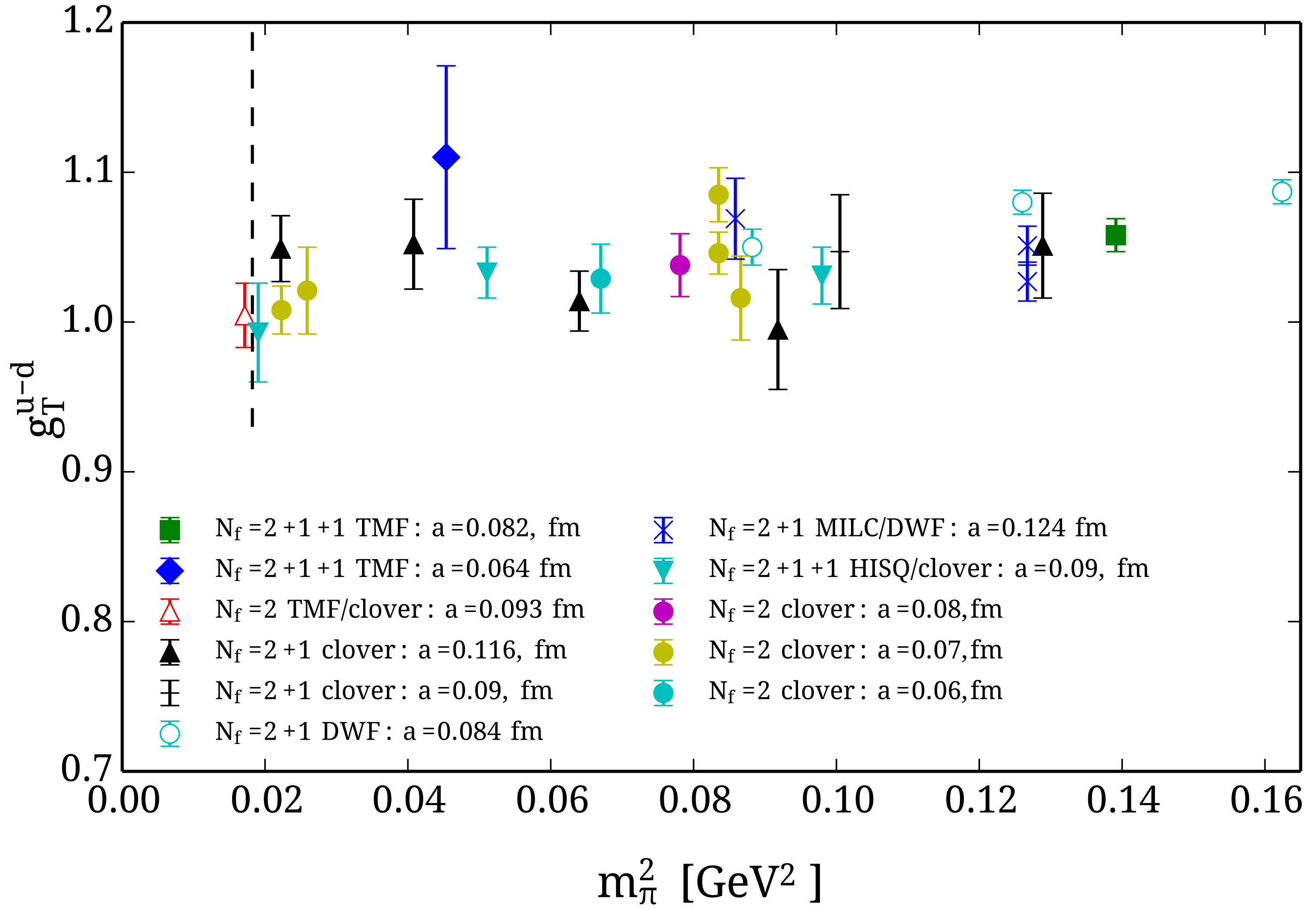


isovector tensor charge $g_T = \delta u - \delta d$

lattice results
with different
discretization schemes, lattice spacings, volumes

Q^2=4 GeV^2



Alexandrou, arXiv:1612.04644

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

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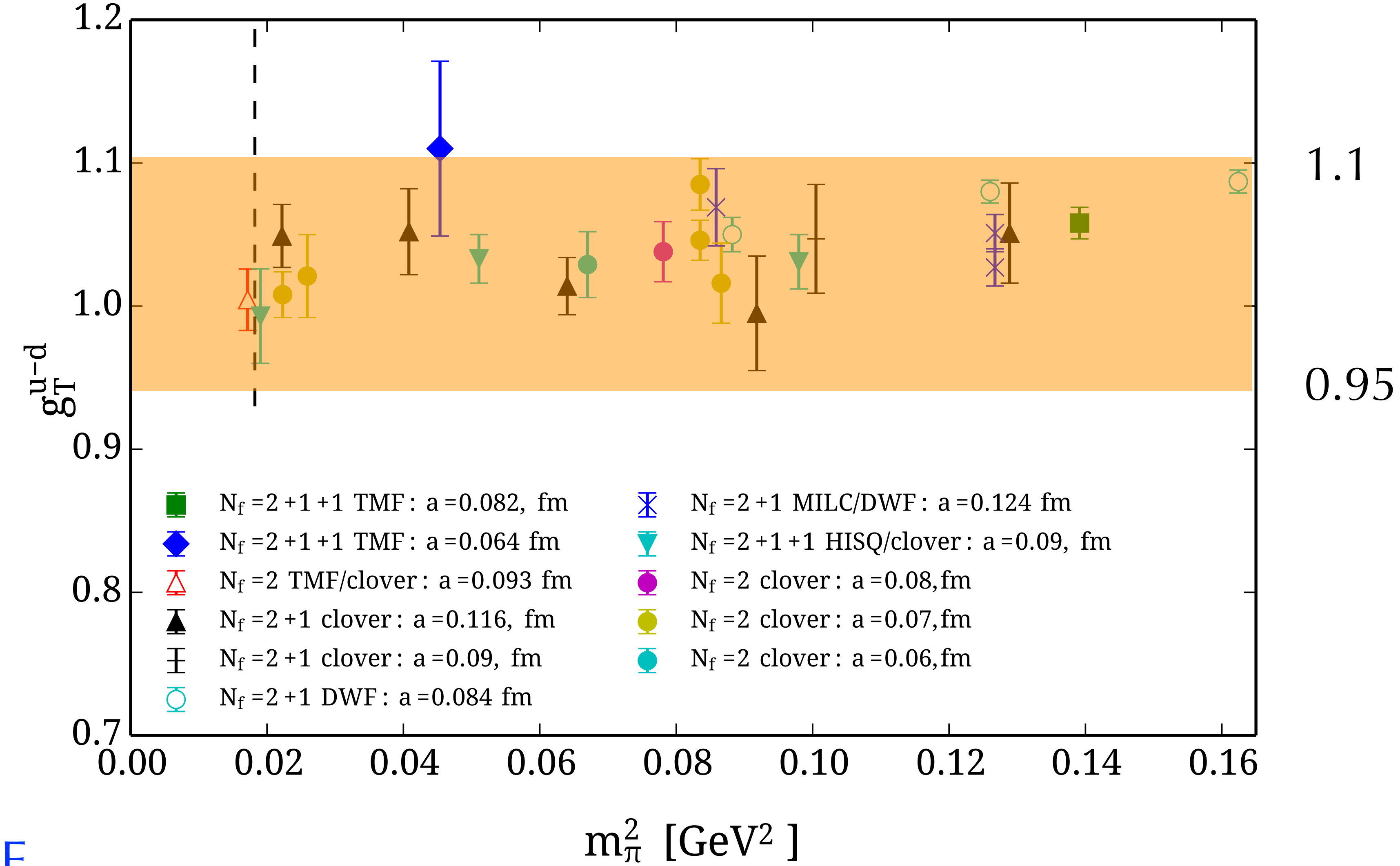


lattice quasi-PDF

see also talk by F. Steffens (ETMC)

see also arXiv:1803.04393 (LP^3)

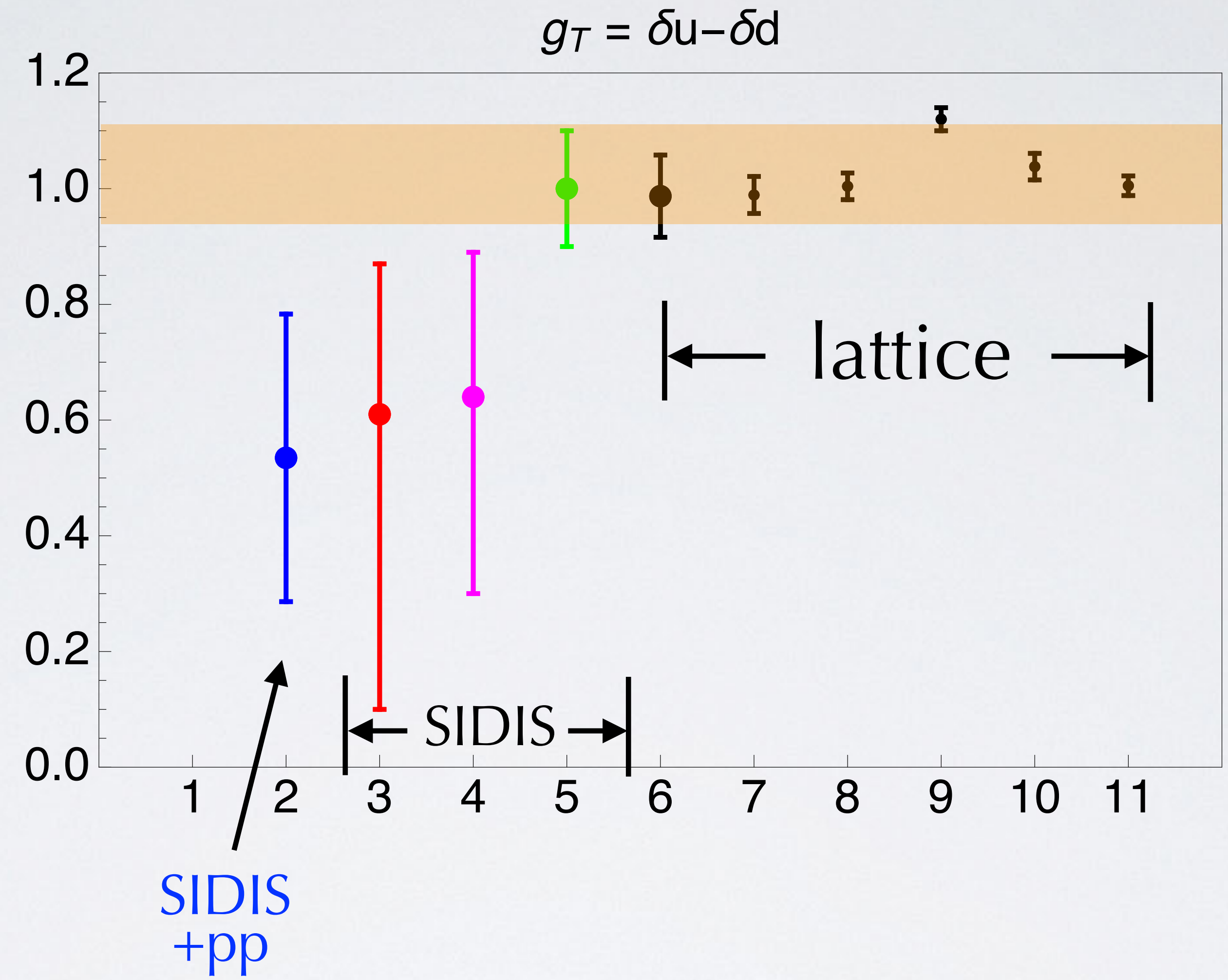
Alexandrou, arXiv:1612.04644

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

Q^2=4 GeV^2 *

?

JAM includes
"lattice data"



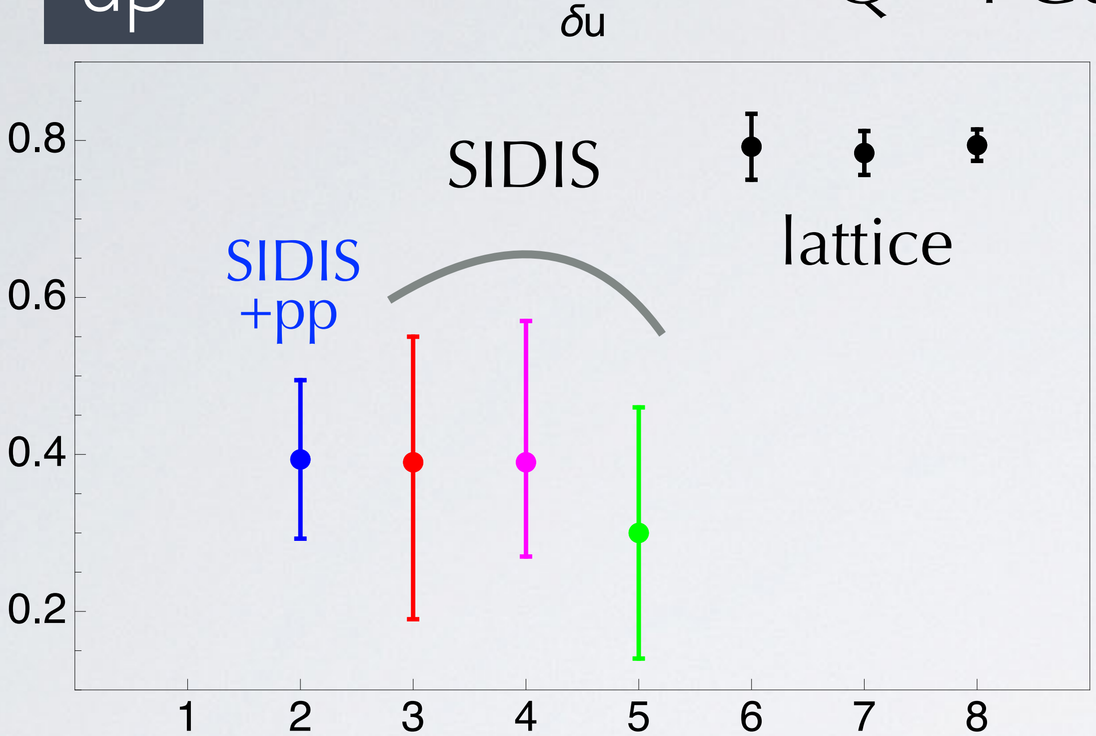
*Radici & Bacchetta, P.R.L. **120** (18) 192001*	2)	**global fit '17**	6)	PNDME '16	*Bhattacharya et al., P.R. D**94** (16) 054508*
			7)	PNDME '18	*Gupta et al., P.R. D**98** (18) 034503*
*Kang et al., P.R. D**93** (16) 014009*	3)	**"TMD fit" * Q^2=10**	8)	ETMC '17	*Alexandrou et al., P.R. D**95** (17) 114514; E P.R. D**96** (17) 099906*
*Anselmino et al., P.R. D**87** (13) 094019*	4)	**Torino fit * Q^2=1**	9)	NPLQCD '18	*Chang et al., P.R.L. **120** (18) 152002*
*Lin et al., P.R.L. **120** (18) 152502*	5)	**JAM fit '17 * Q_0^2=2**	10)	LHPC '12	*Green et al., P.R. D**86** (12)*
			11)	RQCD '14	*Bali et al., P.R. D**91** (15)*

from GPD
see also talk by S. Liuti

tensor charge : separate flavors

up

Q^2=4 GeV^2 *



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

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

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

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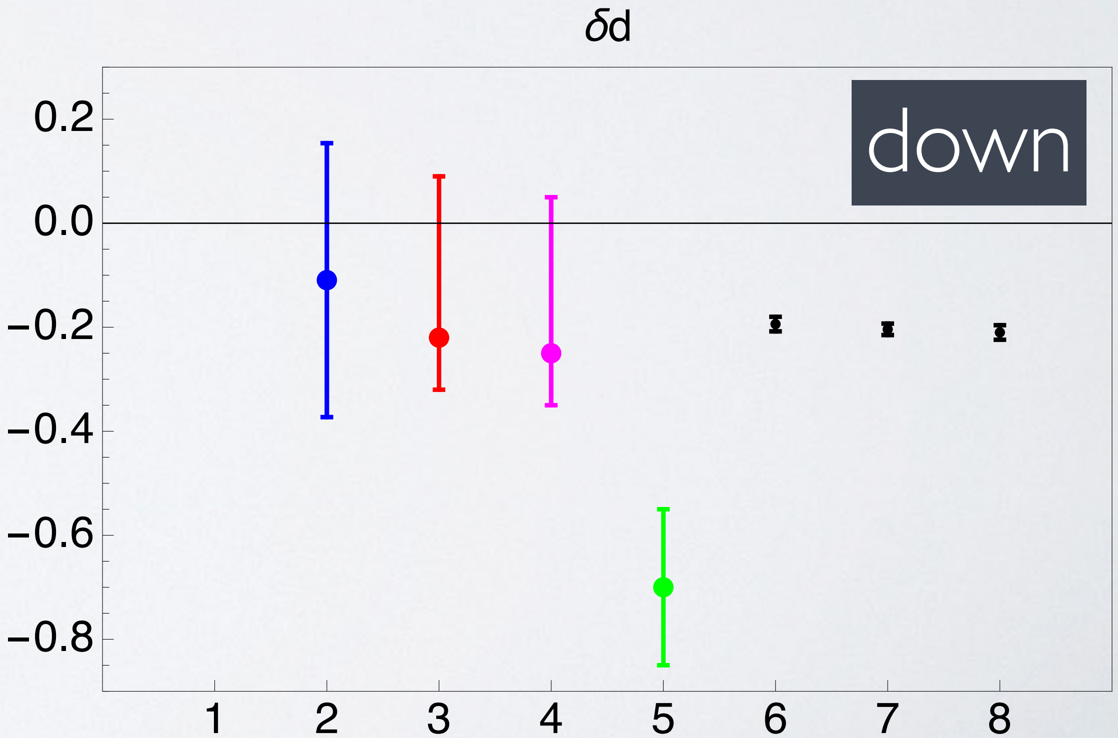
7- PNDME18 *Gupta et al., arXiv:1808.07597*

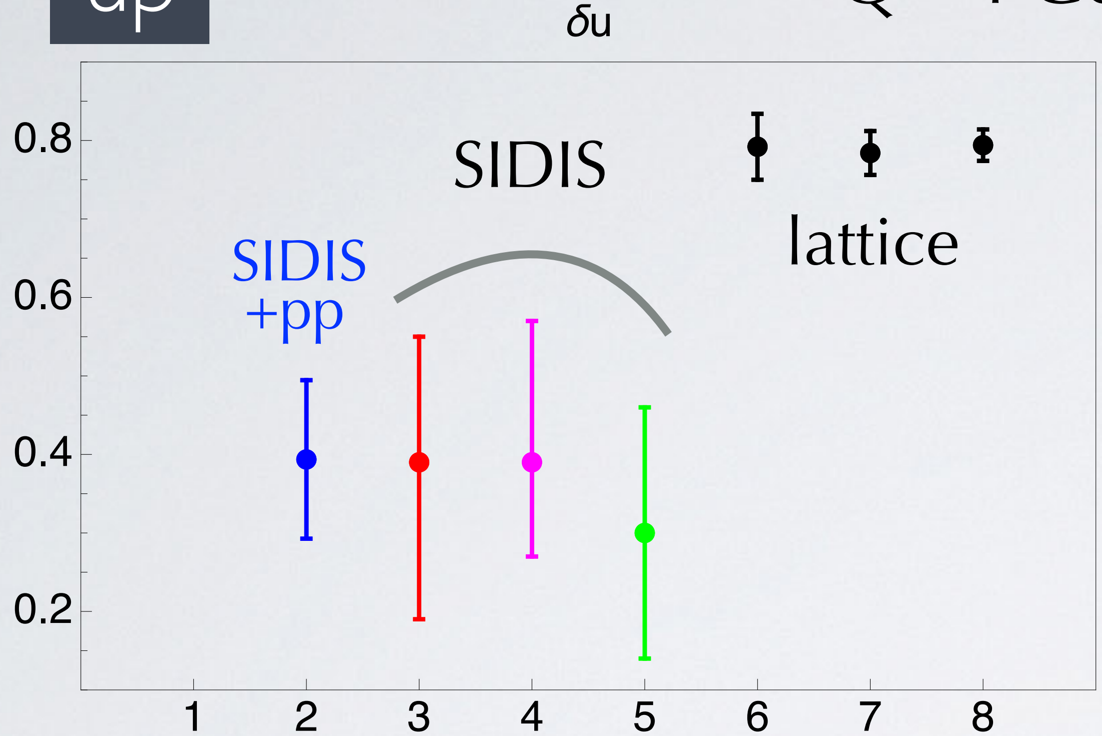
8- ETMC17 *Alexandrou et al., P.R. D****95*** *(17) 114514;*
*E P.R. D****96*** *(17) 099906*



tensor charge : separate flavors

up

Q^2=4 GeV^2 *



incompatibility for up

compatibility for down but within large errors (except JAM)

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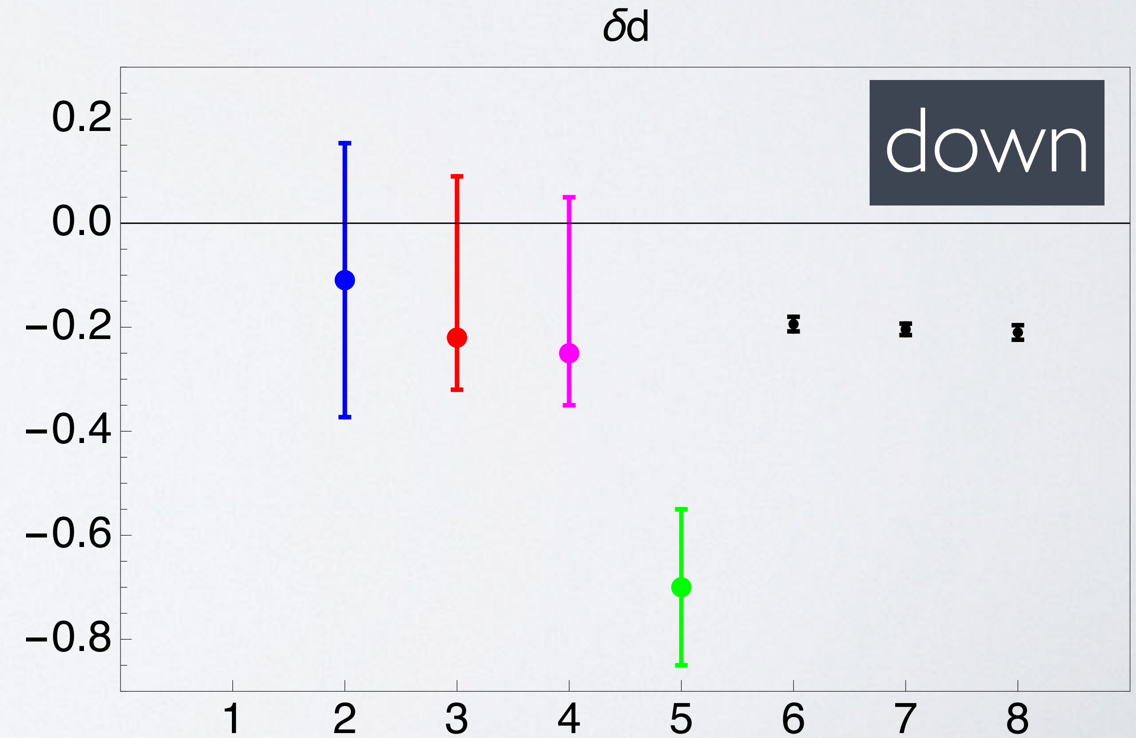


“transverse-spin puzzle” ?

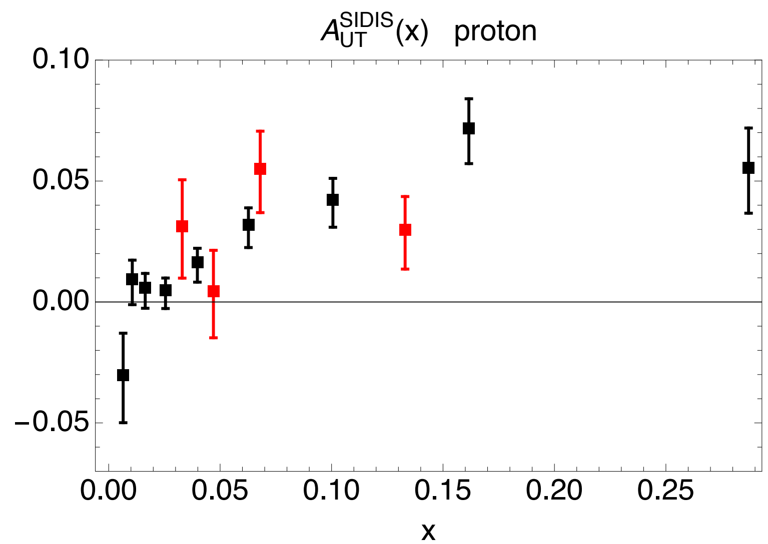
there seems to be no simultaneous compatibility
about δu, δd, $g_T = \delta u - \delta d$
between lattice and
phenomenological extractions
of transversity

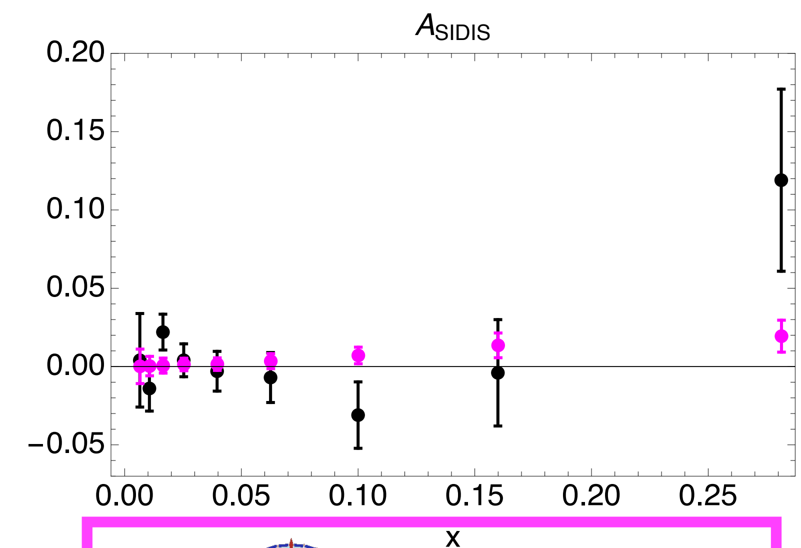
results

SIDIS

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

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



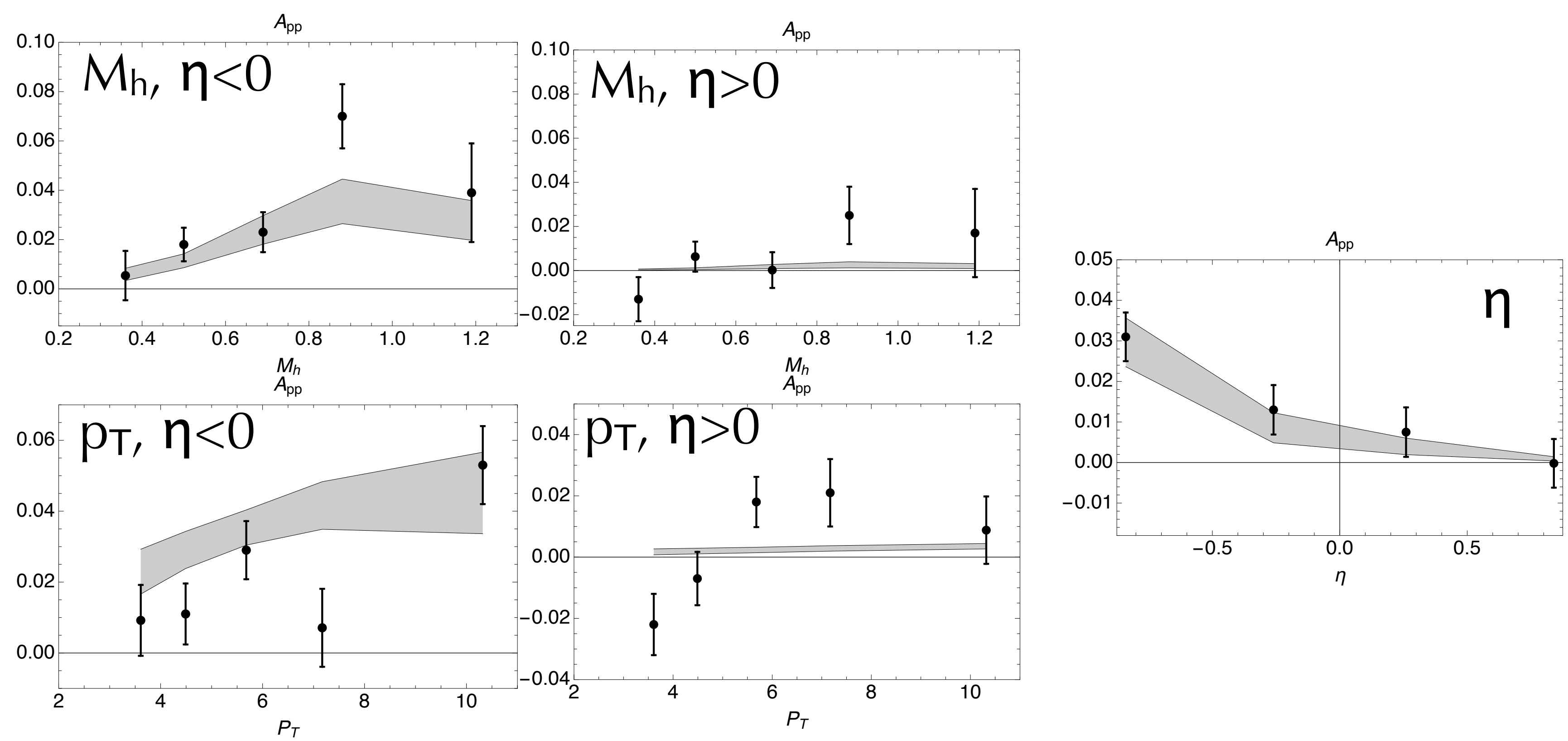


COMPASS pseudodata

pp collisions

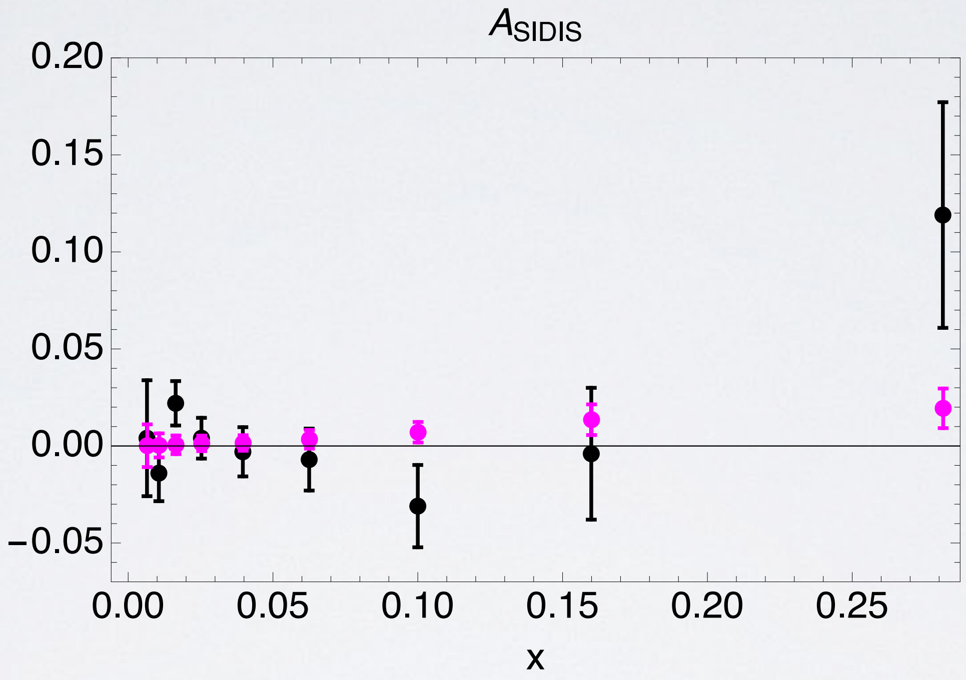
STAR

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



Compass pseudodata

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



COMPASS pseudodata

see next talk by F. Bradamante

statistical error ~ 0.6 x [error in 2010 proton run]

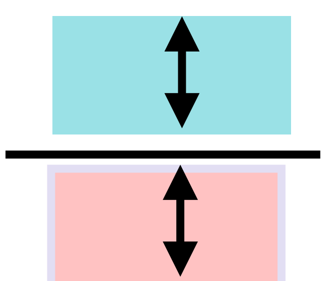
<A> = average value of replicas in previous global fit

impact of pseudodata

global fit + pseudodata

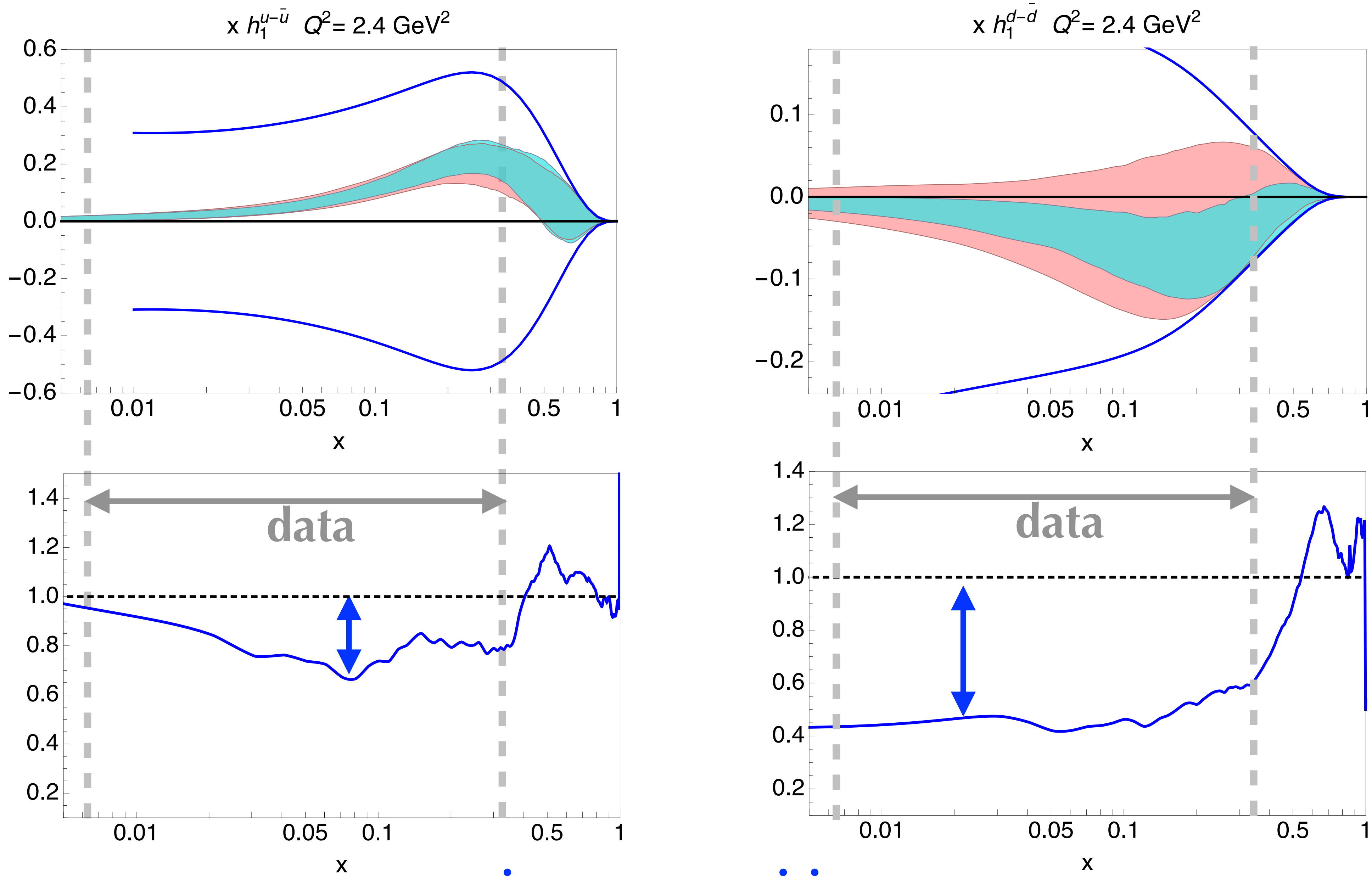
global fit

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



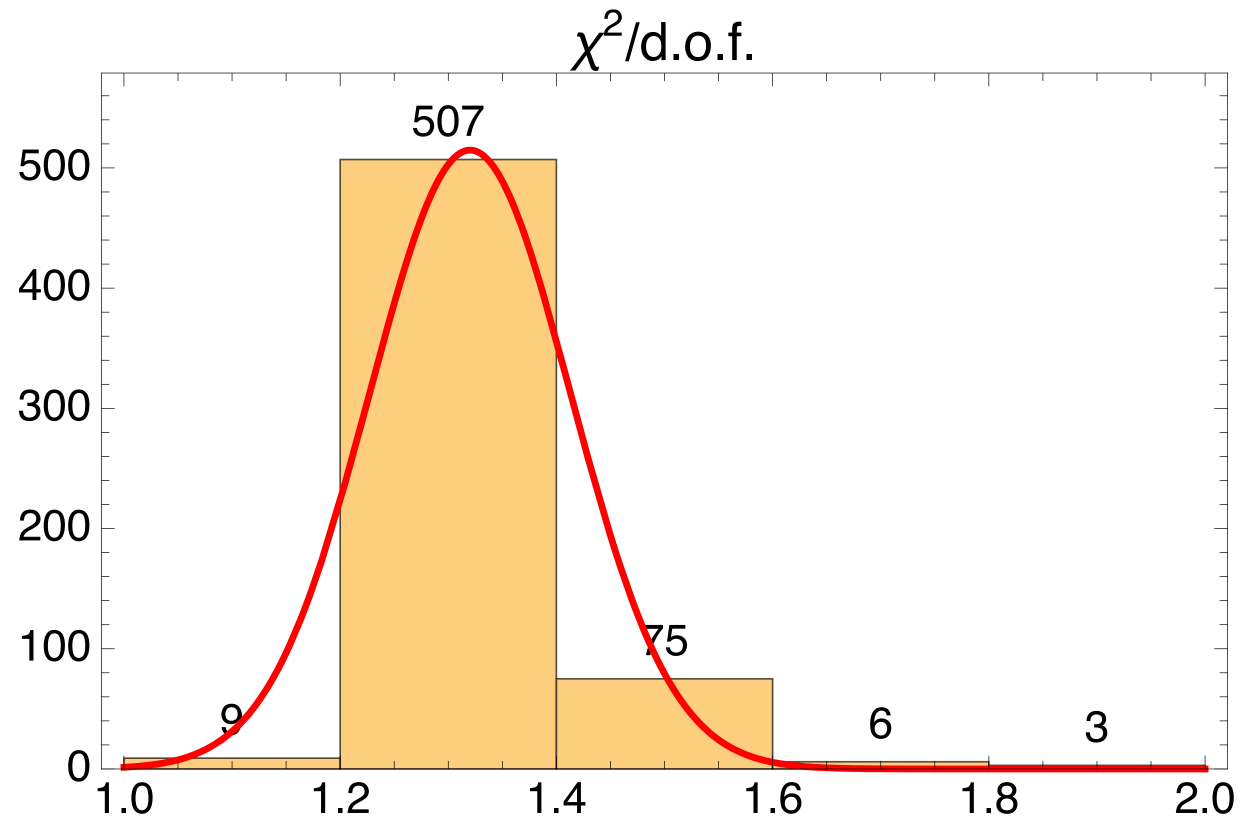
ratio of widths

up | down



increase precision

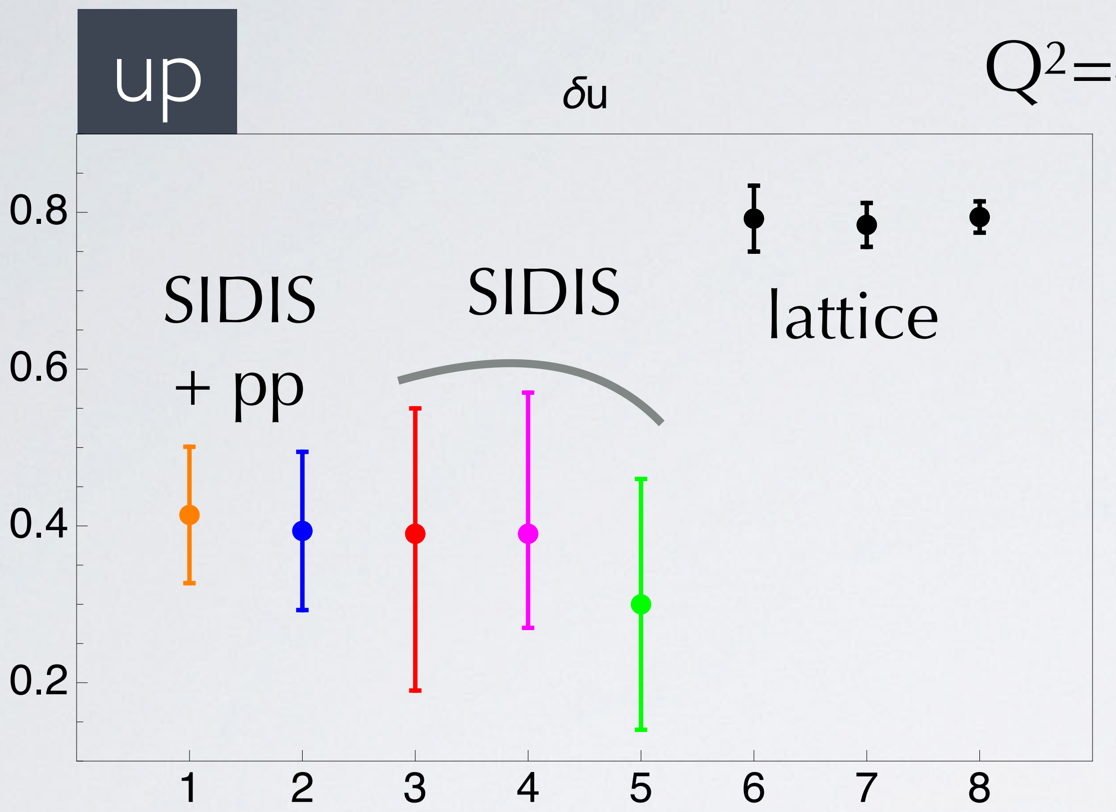
better χ^2

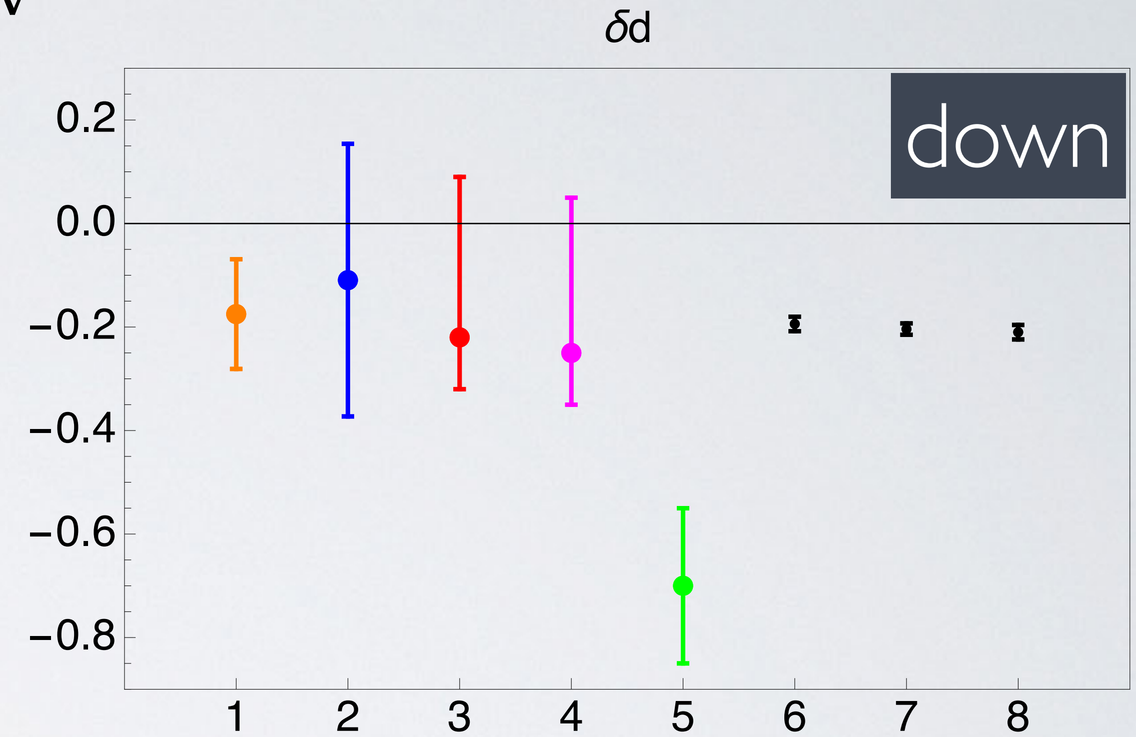


$\chi^2/\mathrm{dof} = 1.32 \pm 0.09$

impact of pseudodata

Q^2=4 GeV^2 *





1- global fit + pseudodata

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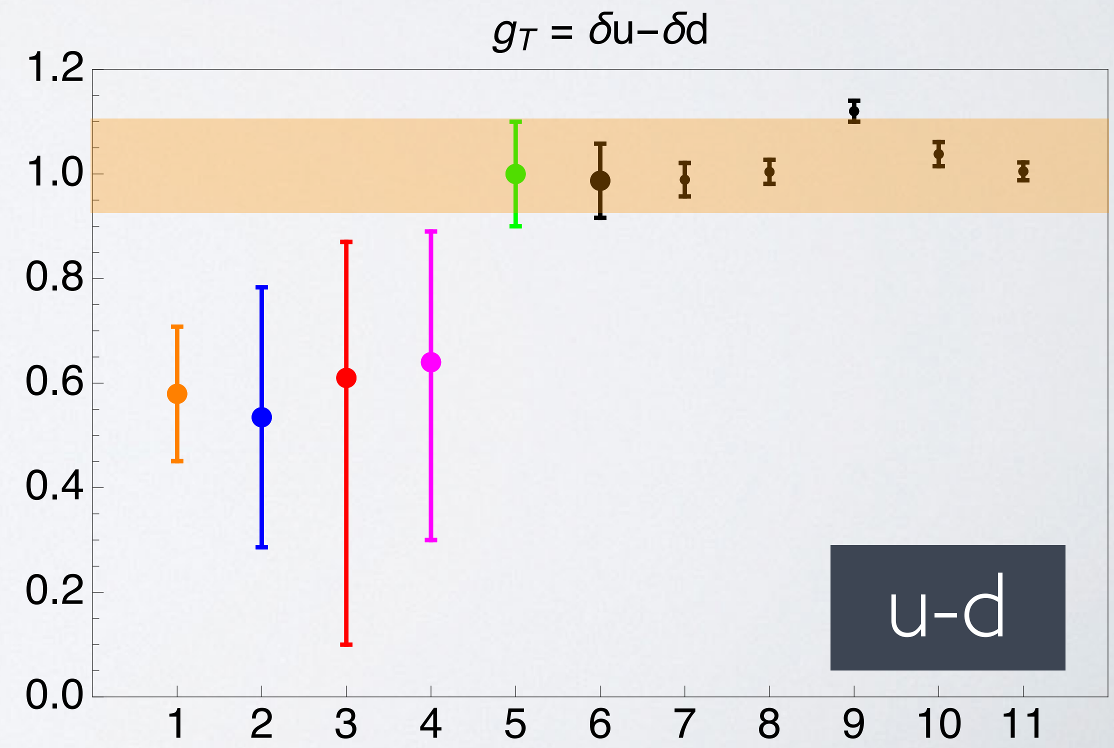
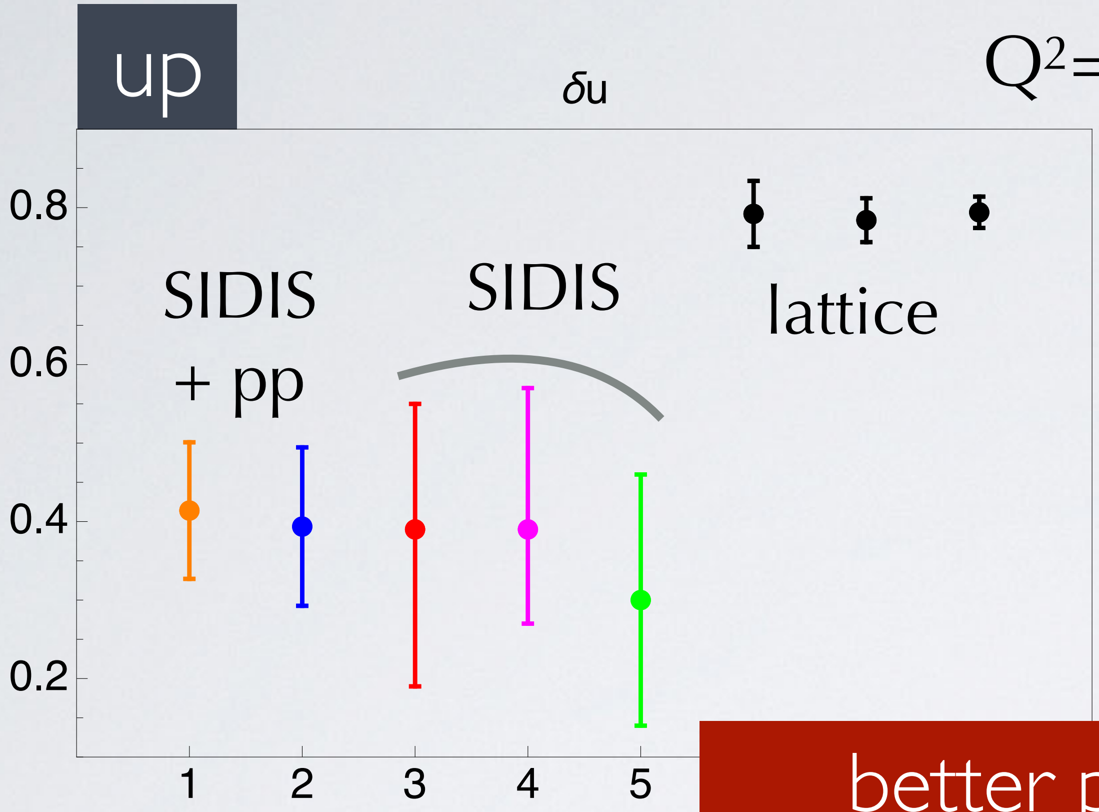
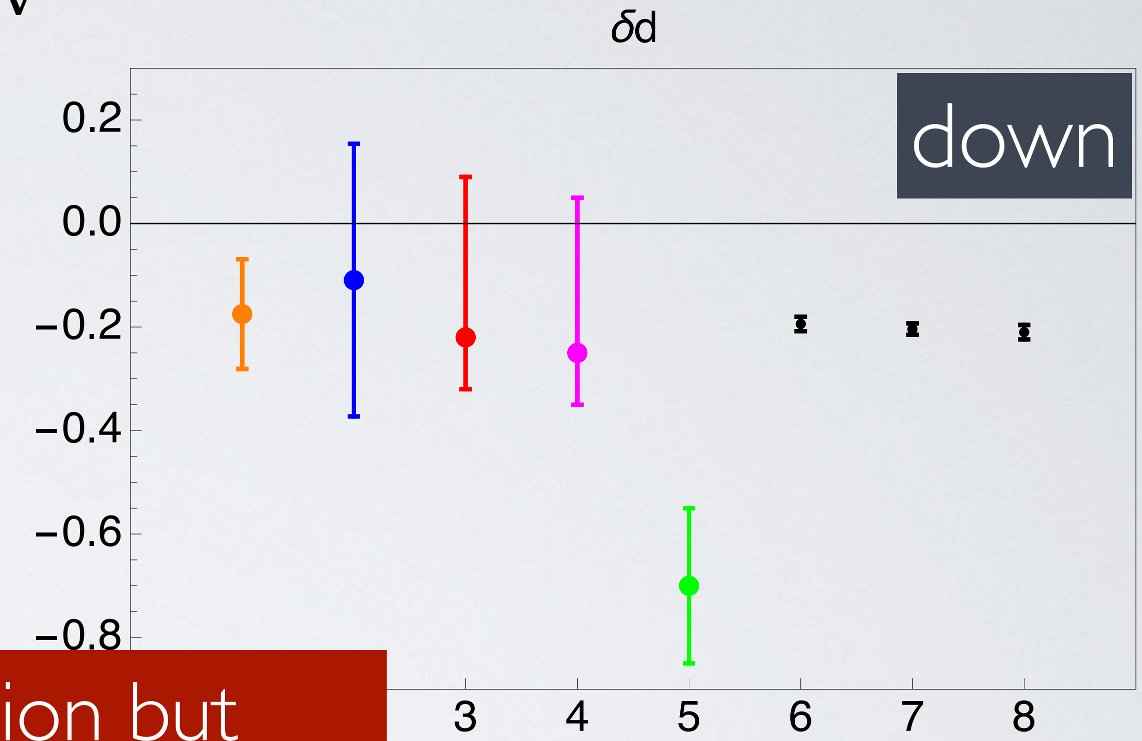


impact of pseudodata

Q^2=4 GeV^2 *





better precision but confirm general trend

1- global fit + pseudodata

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

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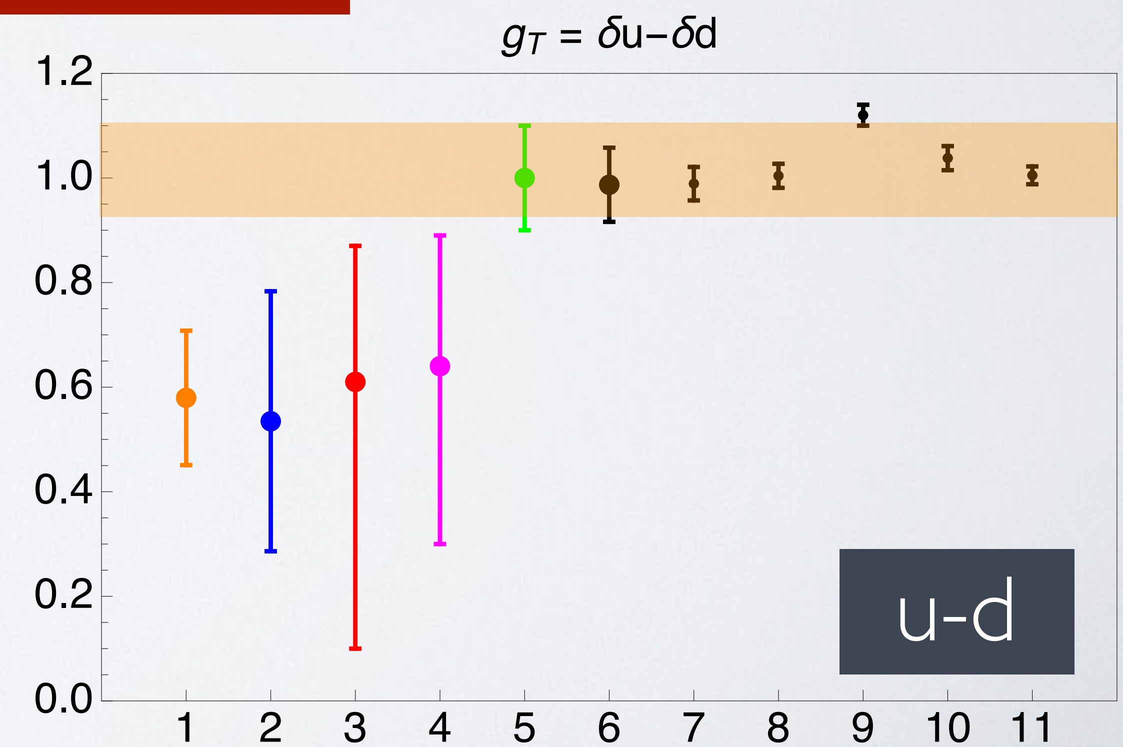


Conclusions

- 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 in up, down, and isovector channels
- adding Compass pseudodata for deuteron increases precision, particularly for down, but seems to confirm this scenario
- are lattice moments really compatible with di-hadron inclusive small/large-x data ? What's going on at very small x ?

THANK YOU

Back-up

2-hadron-inclusive production

framework
collinear
factorization

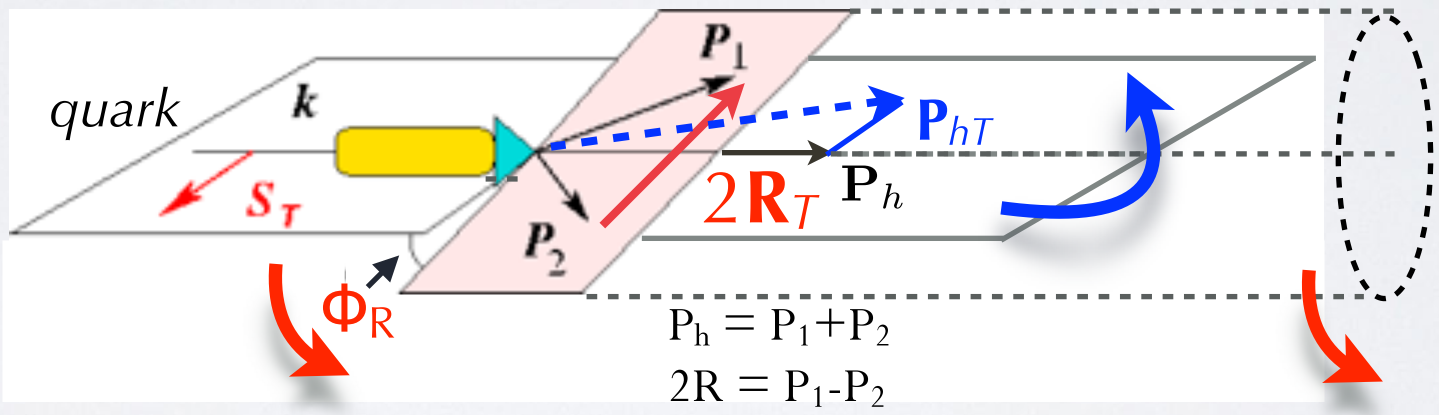
Collins, Heppelman, Ladinsky,
N.P. ***B420*** *(94)*

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

↕

M_h

invariant mass



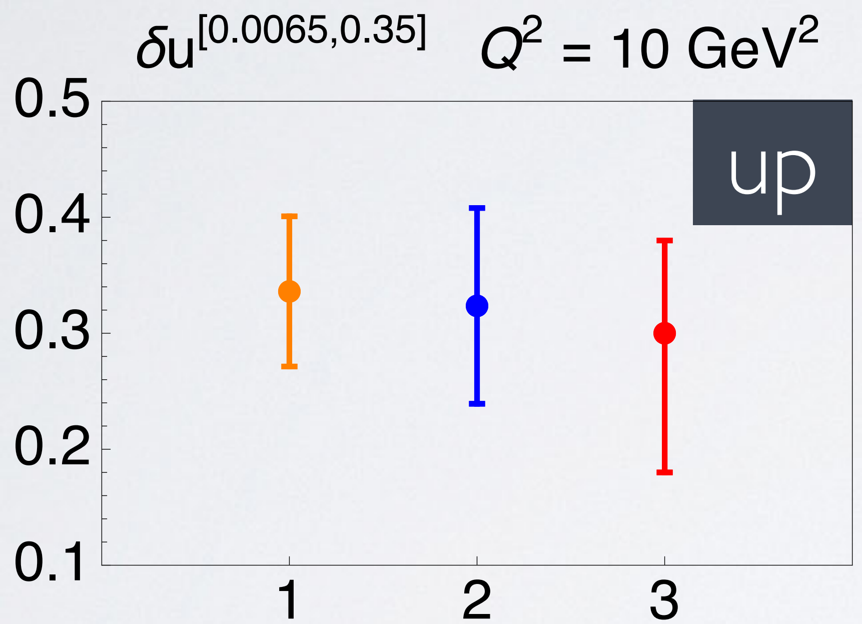
survives to
polar symmetry
($\int dP_{hT}$)

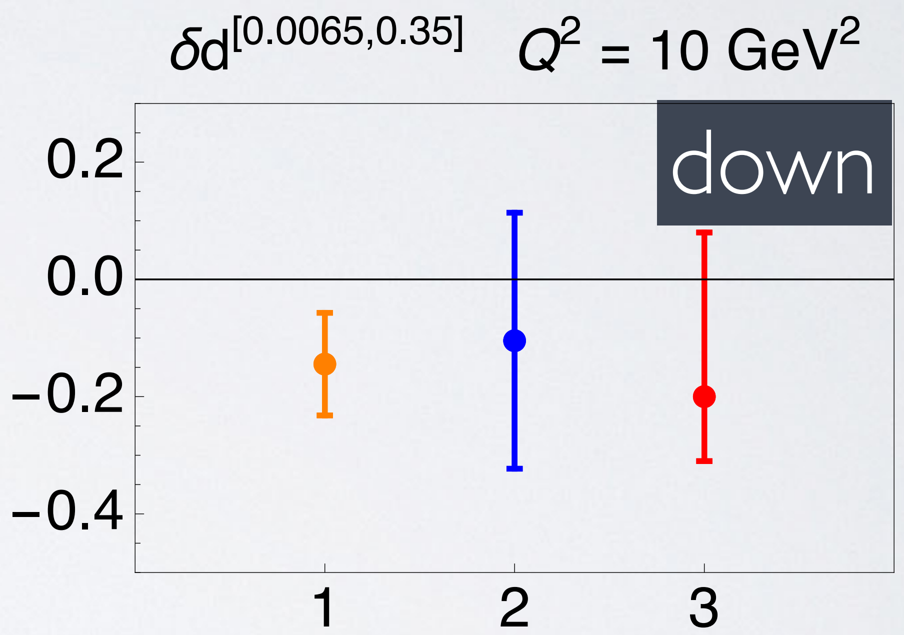
correlation S_T and R_T → **azimuthal asymmetry**

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

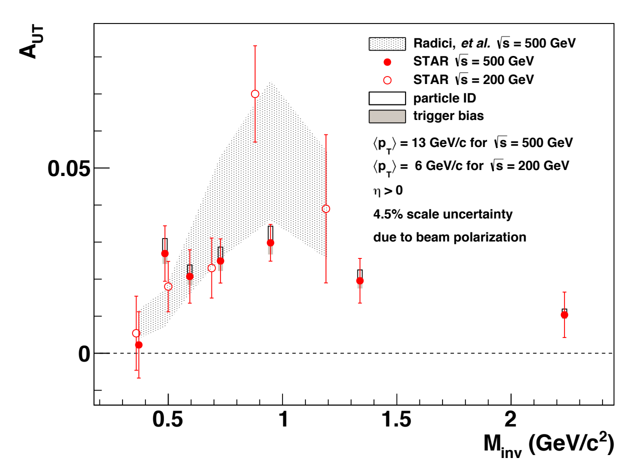
Radici & Bacchetta,
P.R.L. ***120*** *(18) 192001*

TMD fit

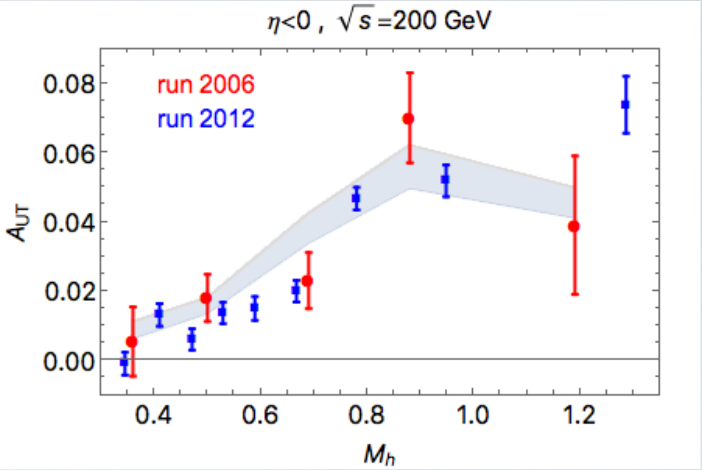
Kang et al.,
*P.R. D**93** (16) 014009*

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

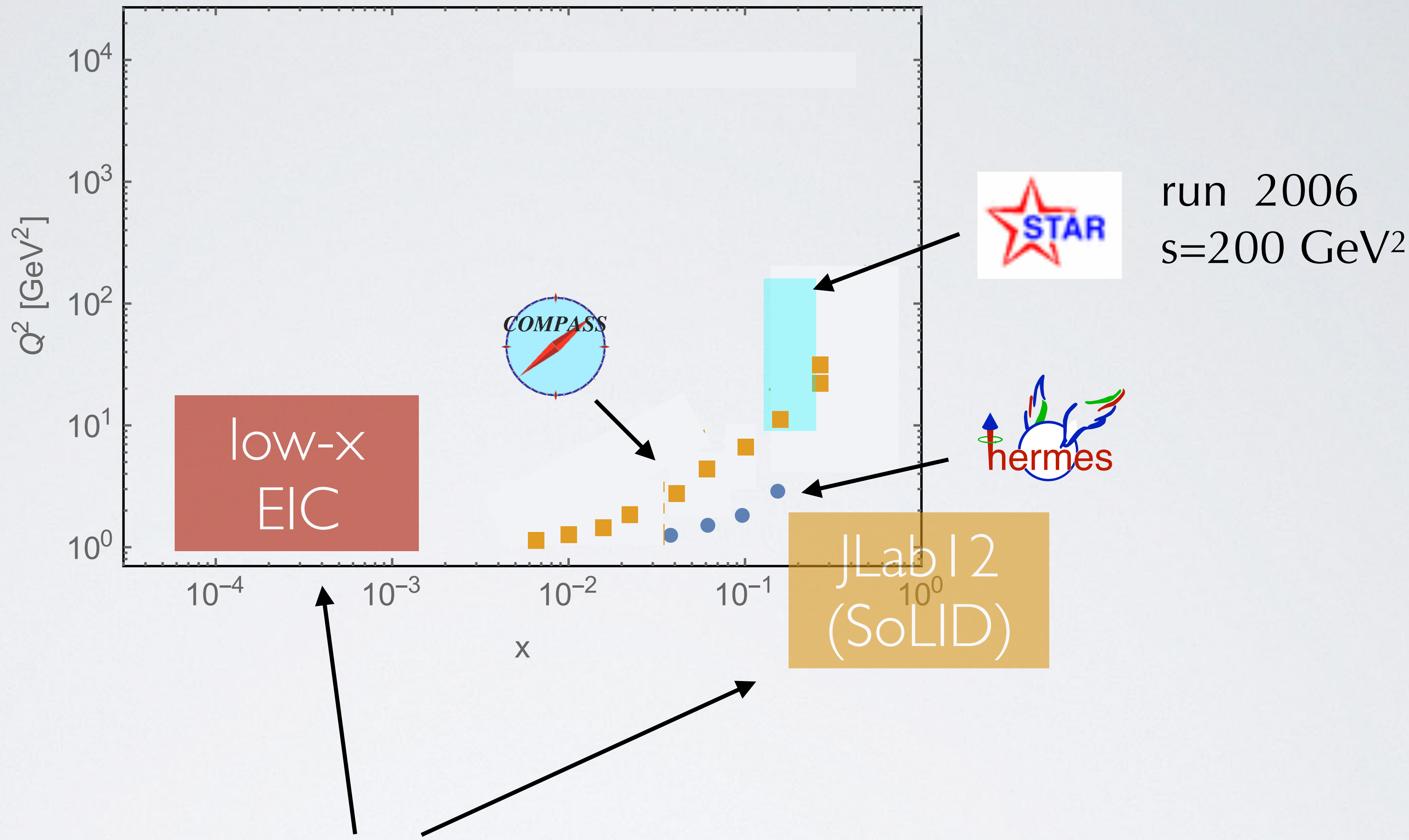
➡ refit di-hadron fragmentation functions using new data: e^+e^- → (ππ) X constrains D_1^q (currently only by Montecarlo)

*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

more constraints on extrapolation



- of course, need more data