TMDs at JLab : present and future

Pavia, 19-20 December 2018

HAS QCD
HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

Jefferson Lab

3DSPIN
MAPPING THE PROTON IN 3D

TRANSVERSITY and TENSOR CHARGE

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Marco Radici
INFN - Pavia

why transversity (PDF / TMD) ?

1st Mellin moment of transversity $\Rightarrow$ tensor "charge"

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

tensor charge connected to tensor operator

$$\langle p, S_p | \, \bar{q} \, \sigma^{\mu\nu} \, q \, | p, S_p \rangle = \left(P^\mu S_p^\nu - P^\nu S_p^\mu \right) \; g_T^q(Q^2)$$

$$= \left(P^\mu S_p^\nu - P^\nu S_p^\mu \right) \; \int dx \; h_1^{q-\bar{q}}(x,Q^2)$$

tensor operator not accessible in tree-level Standard Model
low-energy footprint of new physics at higher scales ?

why di-hadron mechanism ?

collinear framework

- simple product of PDF and IFF

Ex.: SIDIS $$A_{\text{SIDIS}}^{\sin(\phi_R+\phi_S)}(x,z,M_h^2) \sim -\frac{\sum_q e_q^2\; h_1^q(x)\; \frac{|\boldsymbol{R}_T|}{M_h}\; H_{1,q}^{\sphericalangle}(z,M_h^2)}{\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z,M_h^2)}$$

x-dependence of A_{SIDIS} all in PDF

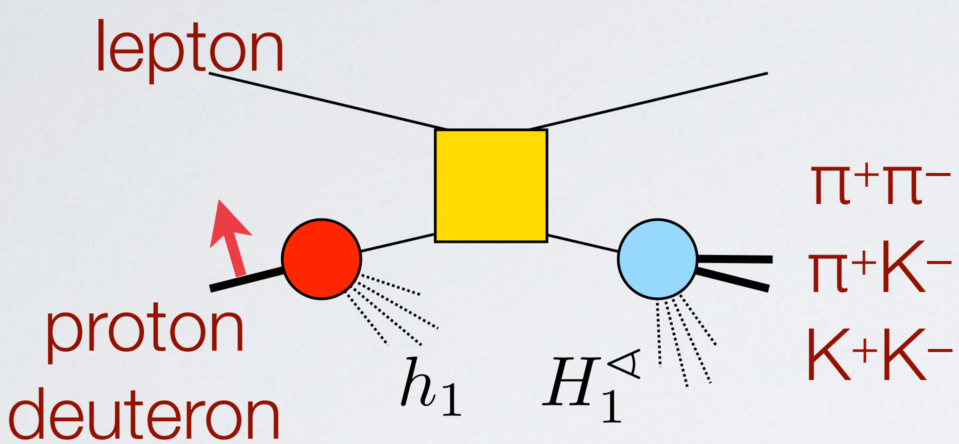
- factorization theorems for all hard processes
  → universality of h_1 $H_1^{\sphericalangle}$ mechanism

available experimental data

factorization theorems for all hard processes

<u>data used in the global fit</u>

SIDIS



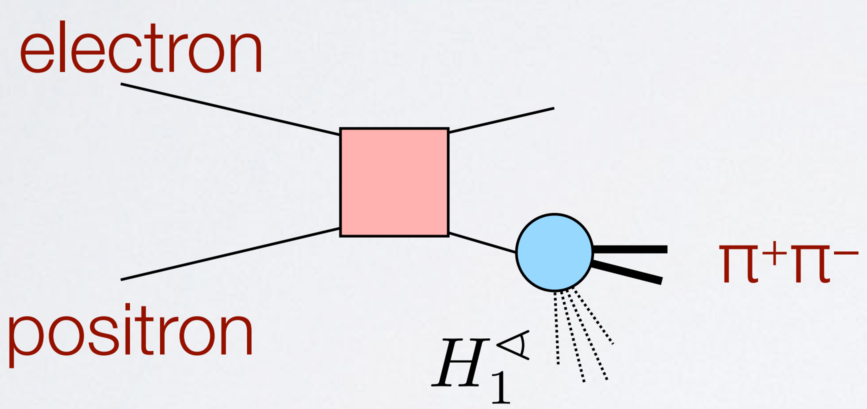
hermes

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

COMPASS

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

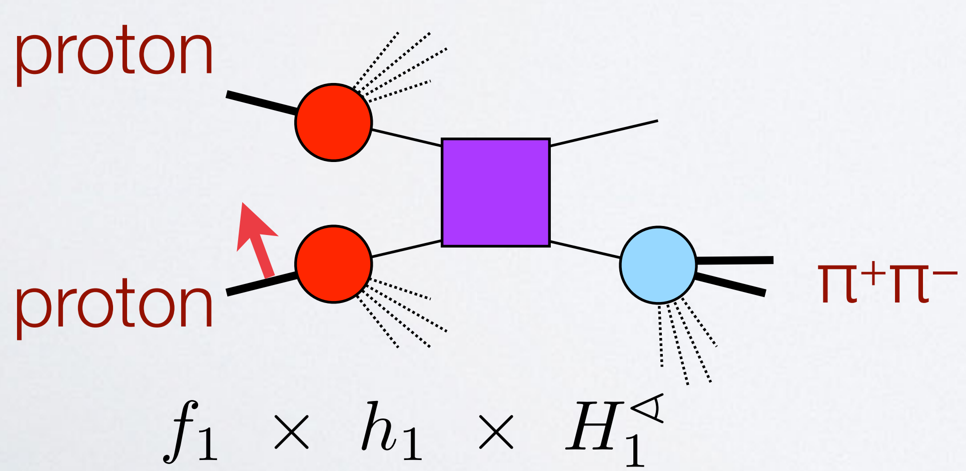
e+e−



BELLE

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

p p↑

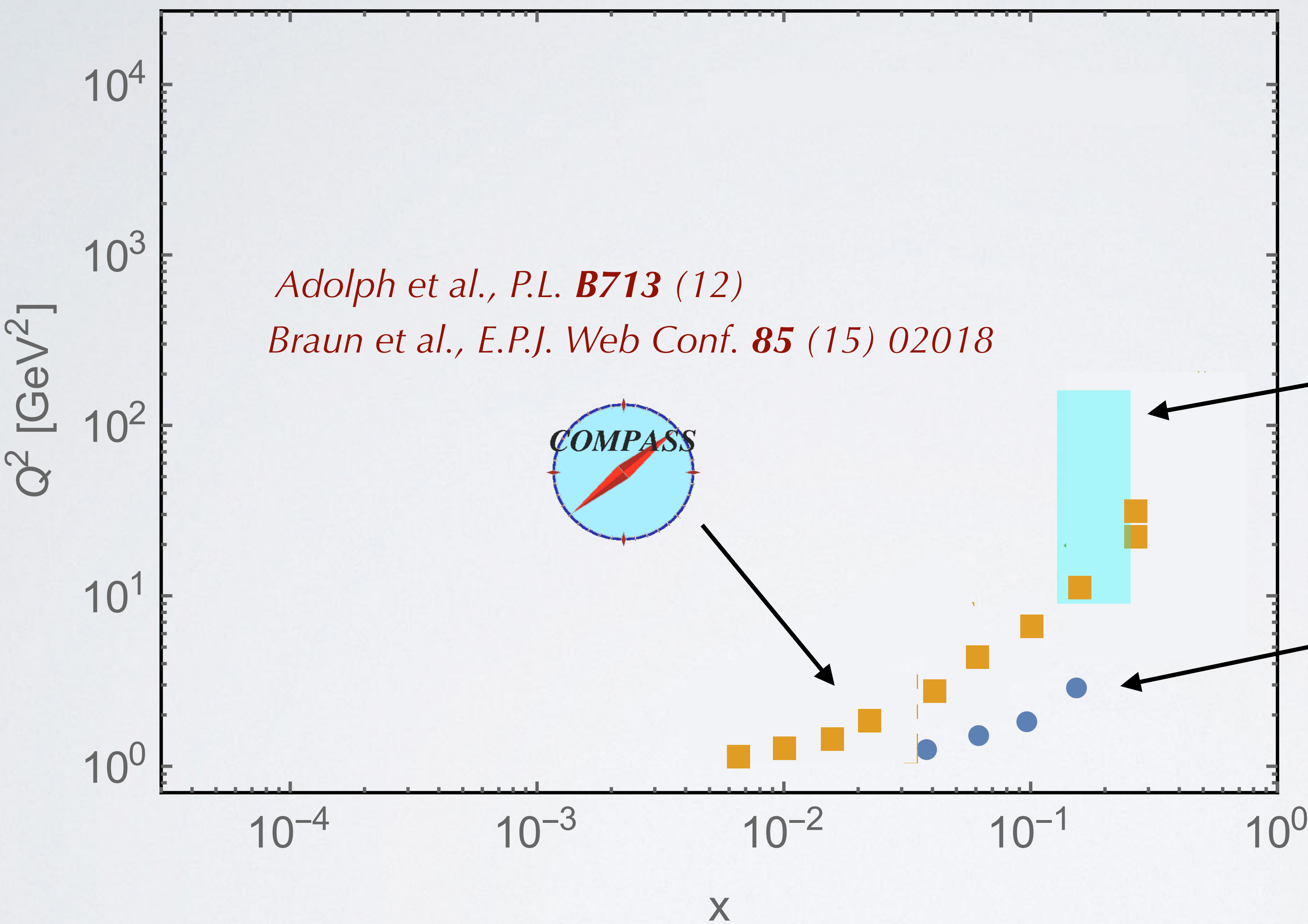


STAR

run 2006 (s=200)

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

the phase space



STAR

run 2006

s=200 GeV^2

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

hermes

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

- mostly medium/high x → not enough for sea quark explorations
- guess low-x behavior (relevant for calculation of tensor charge)

choice of functional form

functional form whose Mellin transform can be computed analytically and complying 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

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MSTW08 DSSV

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

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

10 fitting parameters

constrain parameters

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

low-x behavior

$$\left.\begin{array}{l}\lim_{x\to 0} x\mathrm{SB}^q(x) \propto x^{a_q} \\ \lim_{x\to 0} F^{q_v}(x) \propto x^{A_q}\end{array}\right\}$$

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

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

constrain parameters

low-x behavior

$$\lim_{x\to 0} x\mathrm{SB}^q(x) \propto x^{a_q}$$

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

constrain parameters

1) δq finite => $A_q + a_q > 0$

2) "massive" jet in DIS → h_1 at twist 3

violation of Burkardt-Cottingham s.r. $\int_0^1 dx\, g_2(x) \propto \int_0^1 dx\, \frac{h_1(x)}{x}$ $\longrightarrow$ $A_q + a_q > 1$

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

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

Kovchegov & Sievert, arXiv:1808.10354

low-x behavior

$$\left.\begin{array}{l}\lim_{x\to 0} x\mathrm{SB}^q(x) \propto x^{a_q} \\ \lim_{x\to 0} F^{q_v}(x) \propto x^{A_q}\end{array}\right\} \qquad h_1^q(x) \overset{x\,\to\,0}{\approx} x^{A_q + a_q - 1}$$

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

low-x behavior important

constrain parameters

1) δq finite => $A_q + a_q > 0$

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our choice $A_q + a_q > \frac{1}{3}$ $\left|\int_0^{x_{\min}} dx\right| \sim 1\%$ of $\left|\int_{x_{\min}}^1 dx\right|$

for $x_{\min}=10^{-6}$ from MSTW08

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 $D_1^g (Q_0) = \begin{cases} 0 \\ D_1^u (Q_0) / 4 \\ D_1^u (Q_0) \end{cases}$ ← ~ 1-hadron $D_1^g(Q_0)$

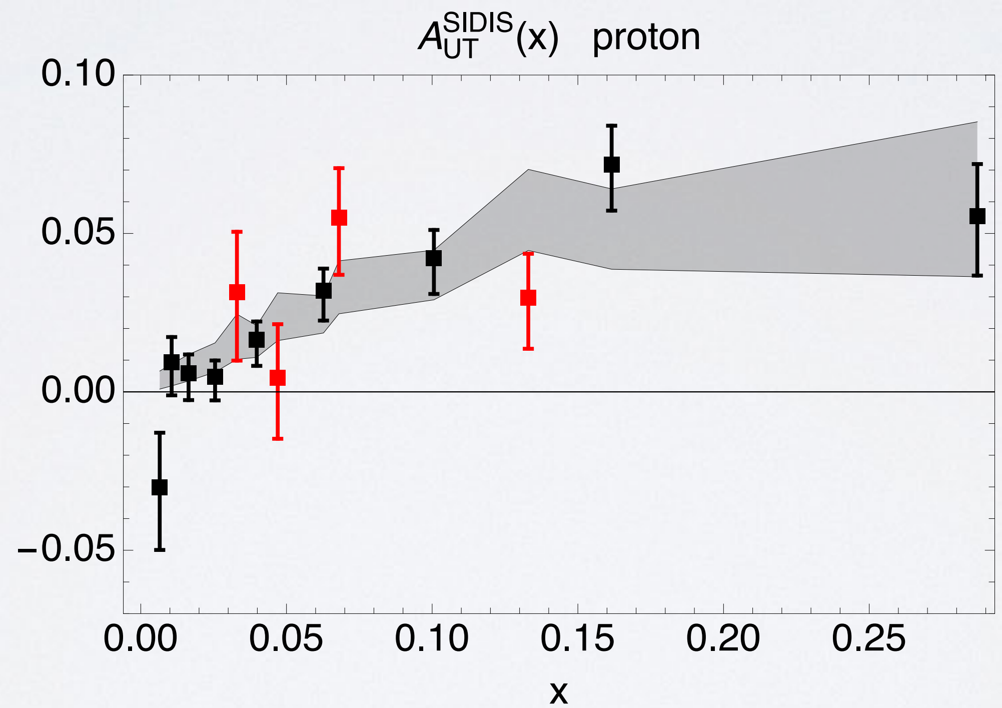
deteriorates our e^+e^- fit as $\chi^2/\mathrm{dof} =$

background	ρ channels
1.69	1.28
1.81	1.37
2.96	2.01

statistical uncertainty

the bootstrap method

- shift each exp. point by Gaussian noise within exp. variance
- create sets of virtual points to be fitted: 50, 100, 200 sets… until average and standard deviation reproduce original exp. points (here, 200x3=600)
- exclude largest and smallest 5% => 90% band



automatically accounts for correlations

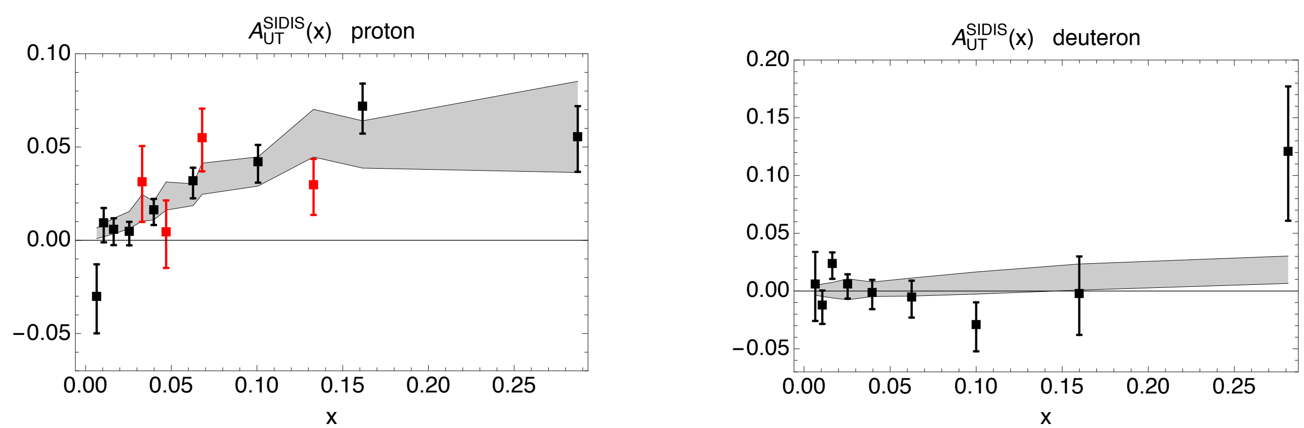
global fit published in

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

SIDIS

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

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



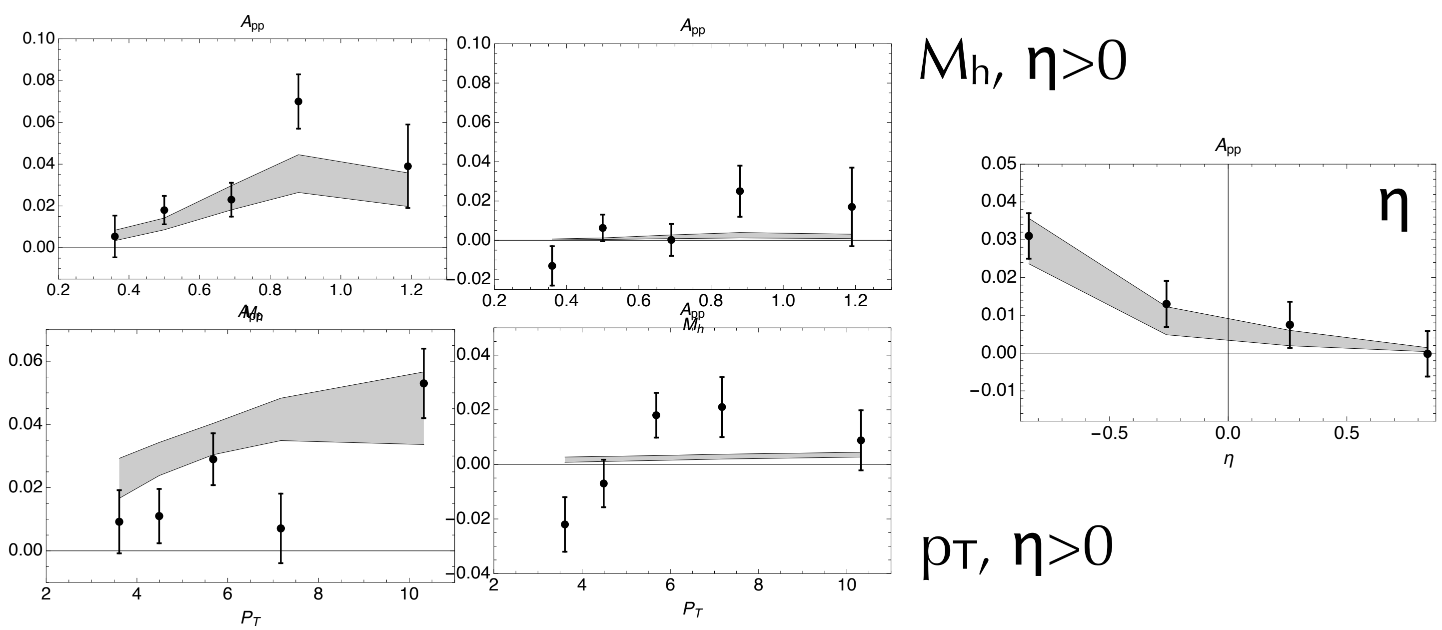
pp collisions

STAR

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

M_h, η<0

M_h, η>0



p_T, η<0

p_T, η>0

χ^2 of the fit

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

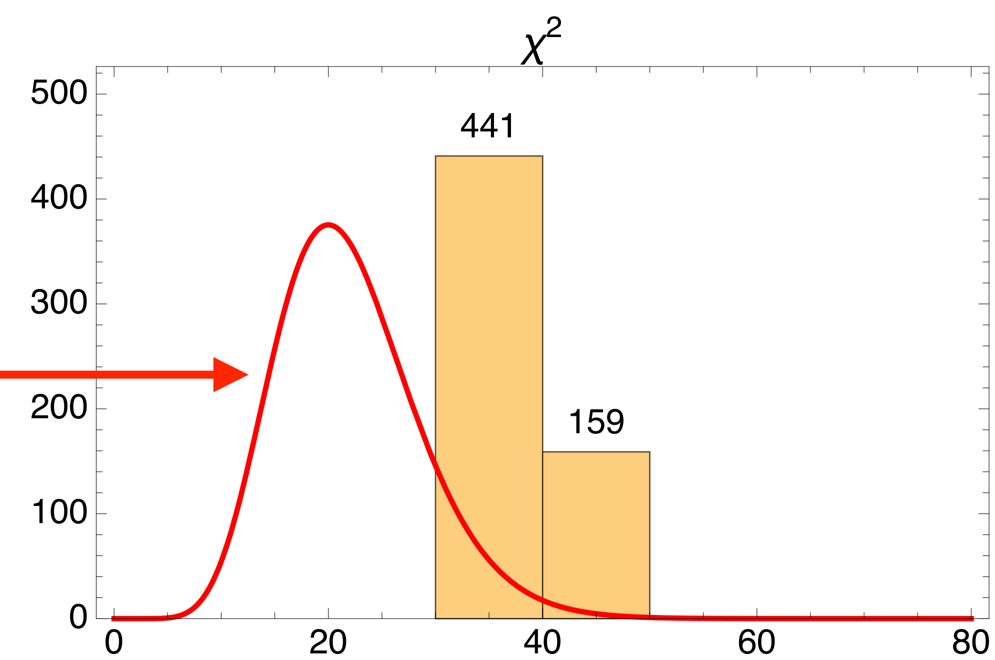
deuteron SIDIS **9** data points = + **9**

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

global fit **10** parameters

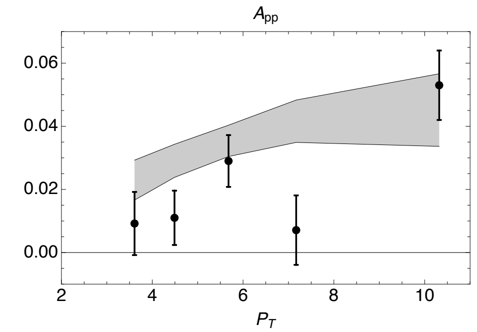
d.o.f. **22**

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



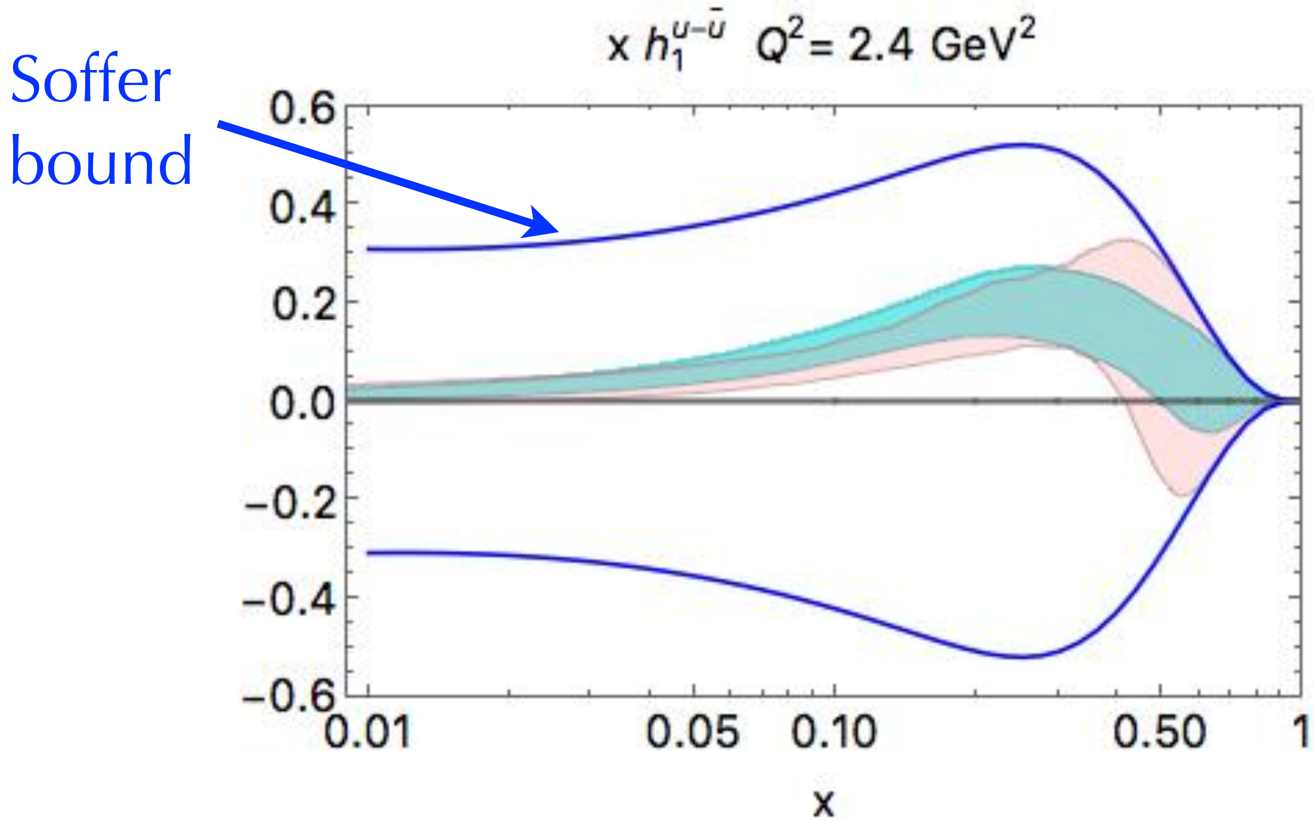
for χ^2/dof = 1 perfect overlap

STAR p_T, $\eta<0$



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

comparison with previous fit



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

global fit

up

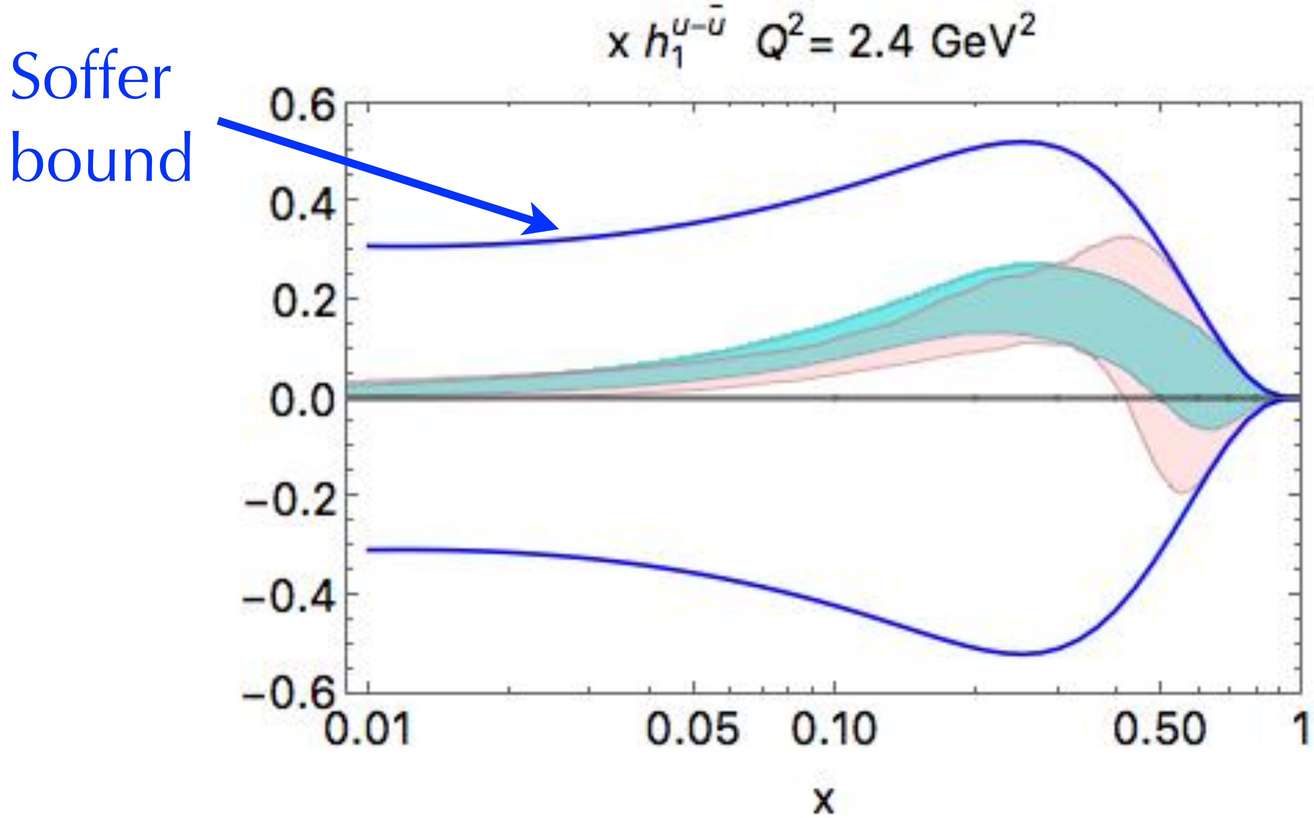
higher precision

old fit (only SIDIS data)

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

equivalent to Collins extraction

comparison with previous fit



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global fit

up

higher precision

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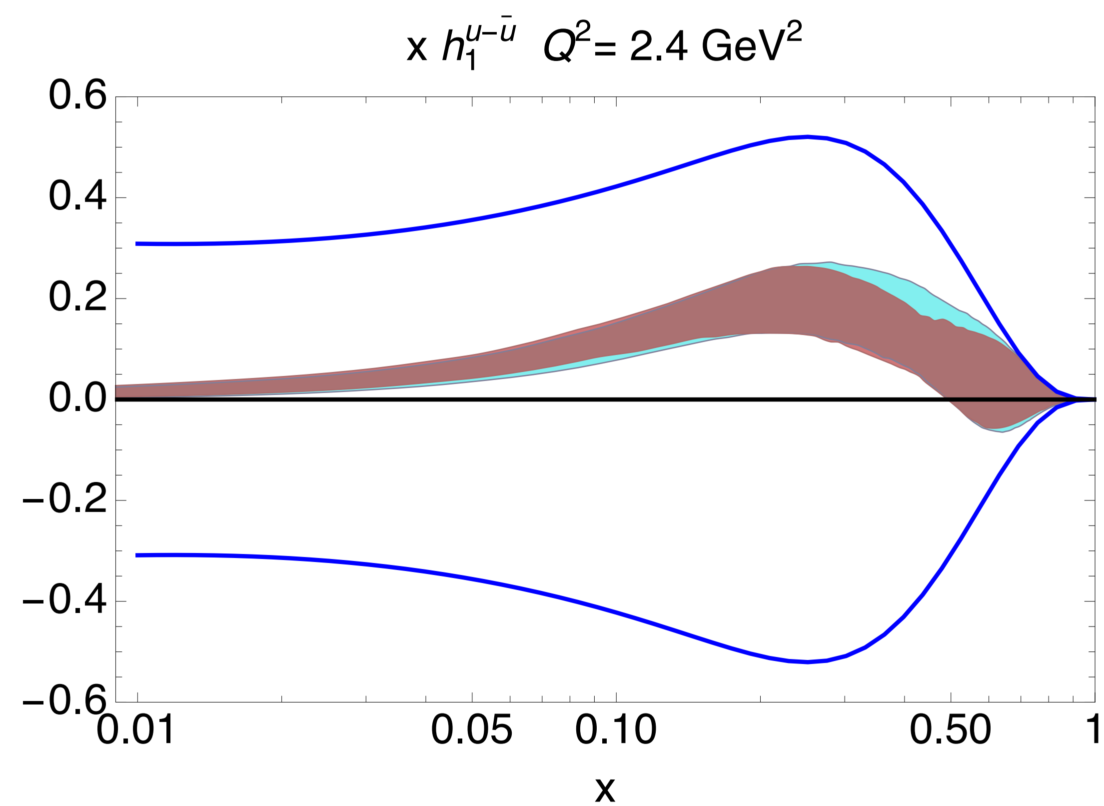
equivalent to Collins extraction

up

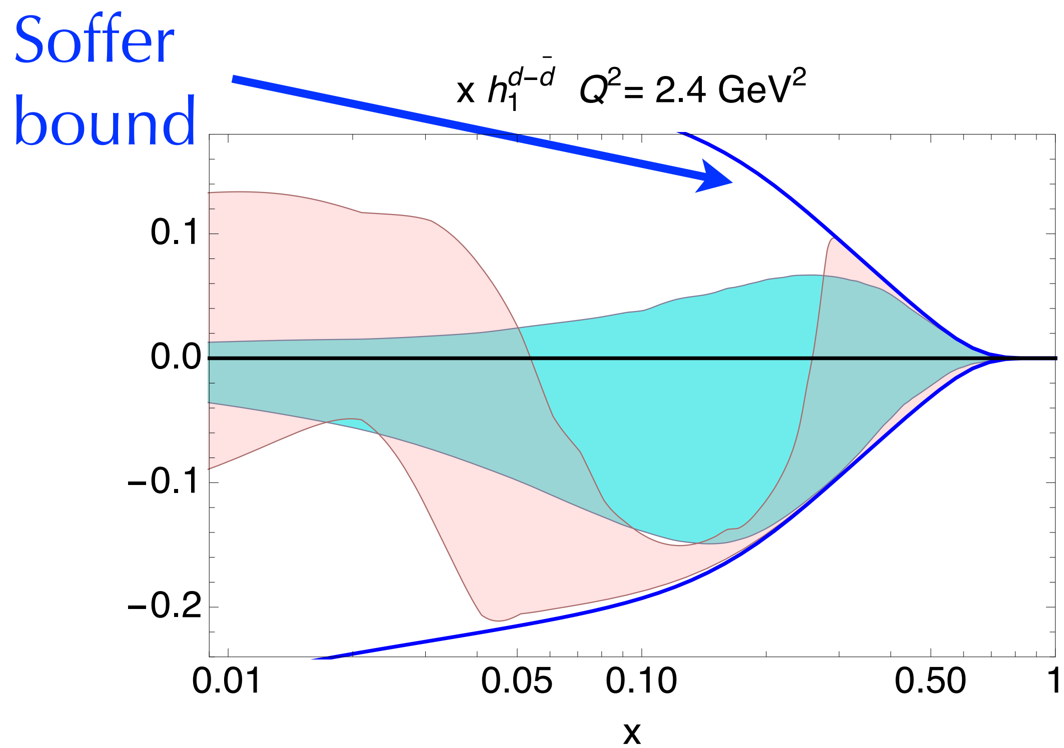
insensitive to uncertainty on gluon D_1

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

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



comparison with previous fit



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

global fit

old fit

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

down

down

sensitive to uncertainty on gluon D_1

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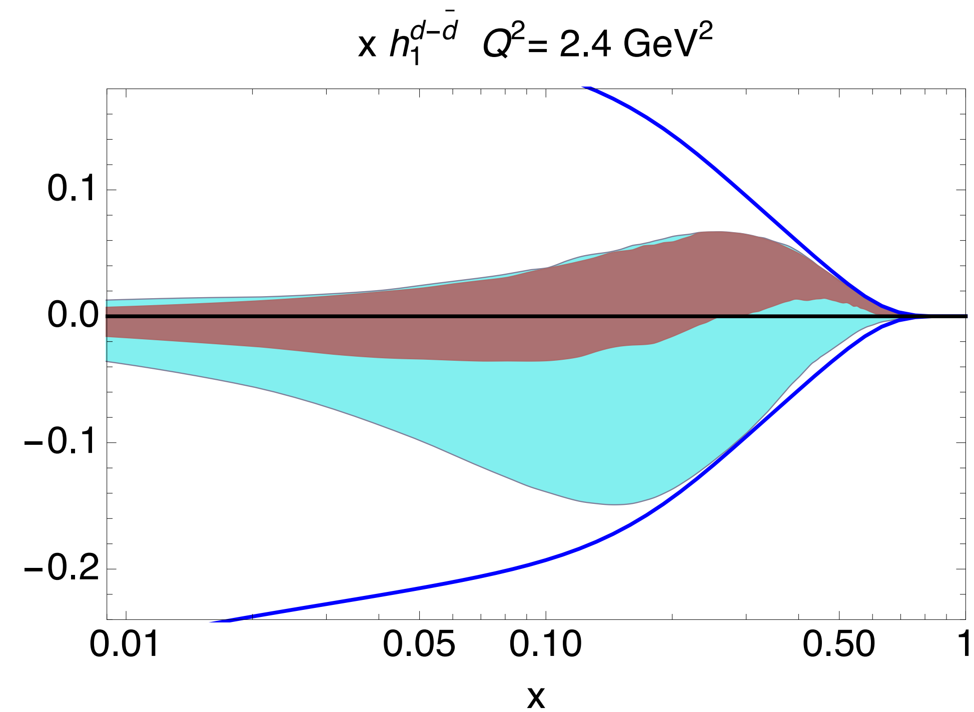
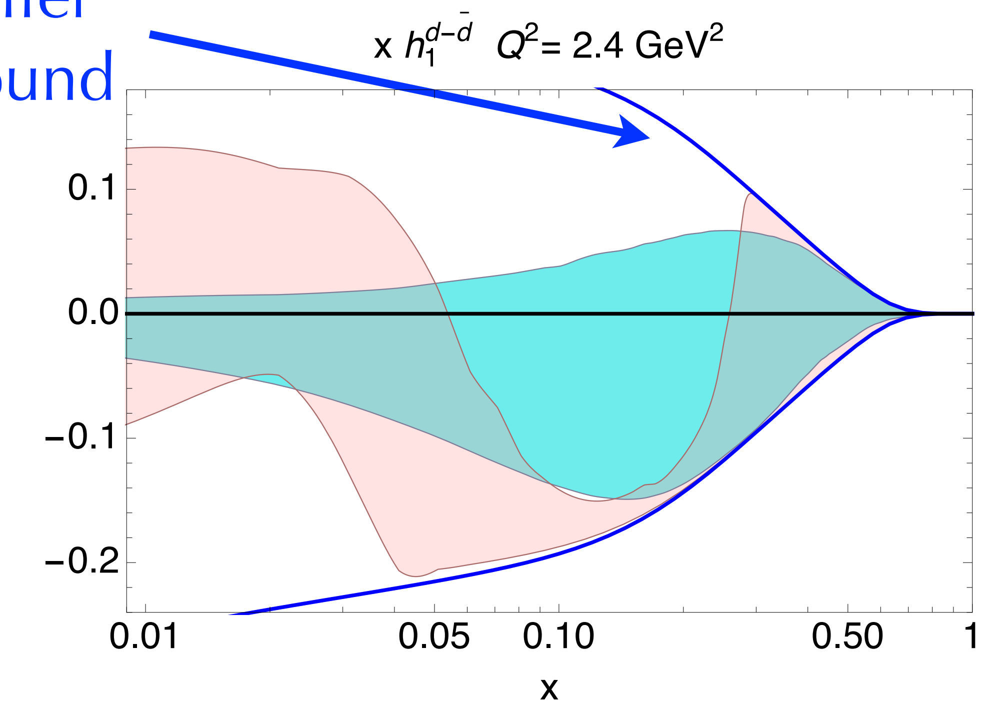


comparison with previous fit

Soffer bound



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

global fit

old fit

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

down

p-p: up~down , gluon @LO
but
SIDIS: up~(8x)down , gluon @NLO

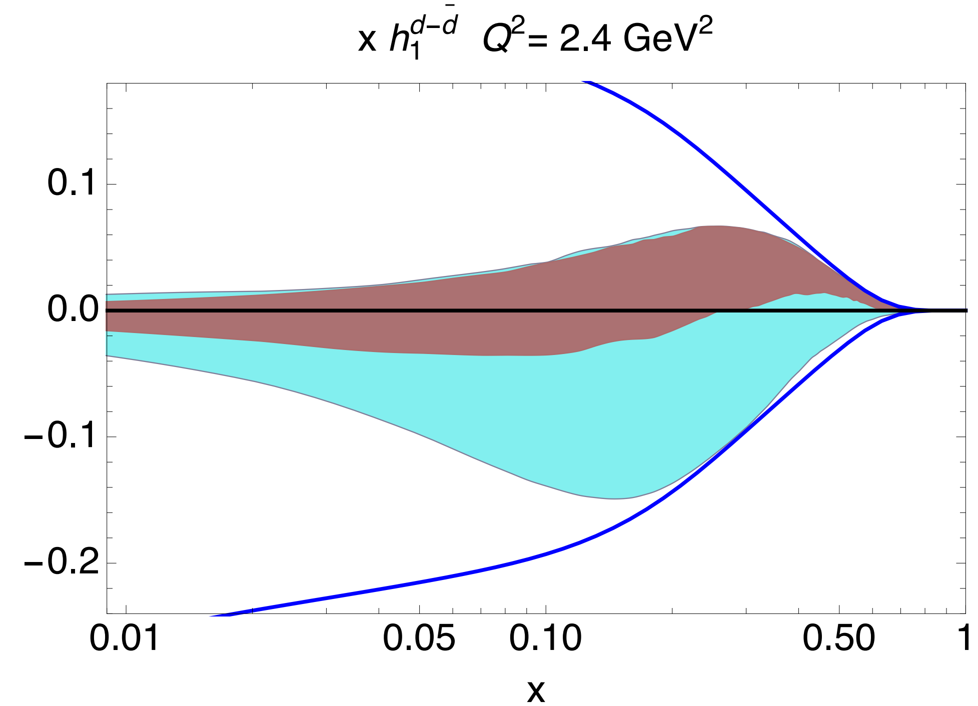
need data from target more sensitive to down : deuteron, ^{3}He …

down

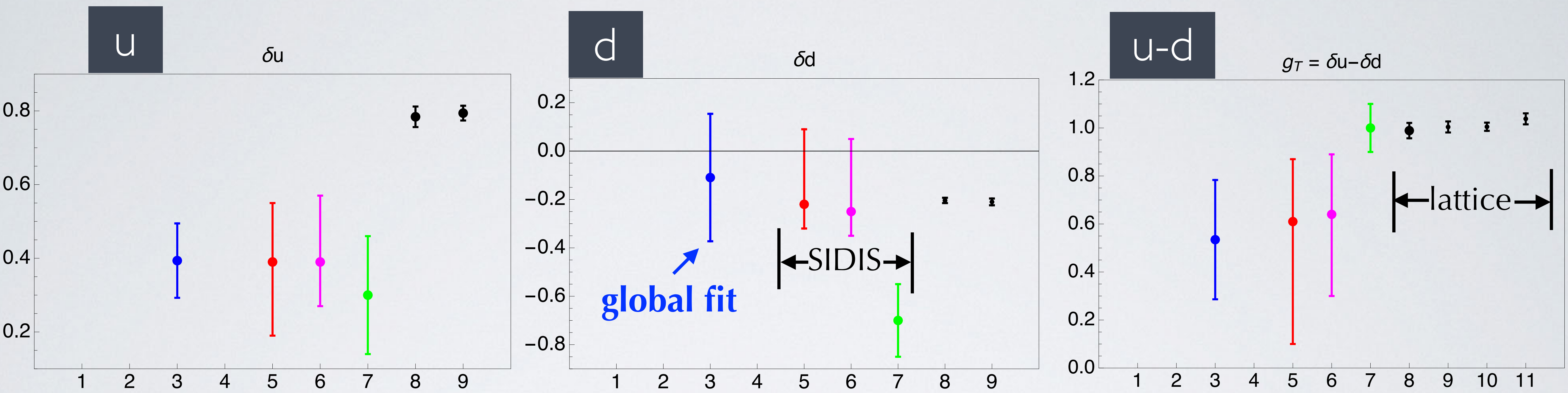
sensitive to uncertainty on gluon D_1

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

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



tensor charge



Q^2=4 GeV^2 *

JAM includes
"lattice data"

Radici & Bacchetta, *P.R.L.* **120** (18) 192001 — 3) **global fit '17**

Kang et al., P.R. D **93** *(16) 014009* — 5) **"TMD fit" * Q^2=10**

Anselmino et al., P.R. D **87** *(13) 094019* — 6) **Torino fit * Q^2=1**

Lin et al., P.R.L. **120** *(18) 152502* — 7) **JAM fit '17 * Q_0^2=2**

8) **PNDME '18** — *Gupta et al., P.R. D* **98** *(18) 034503*

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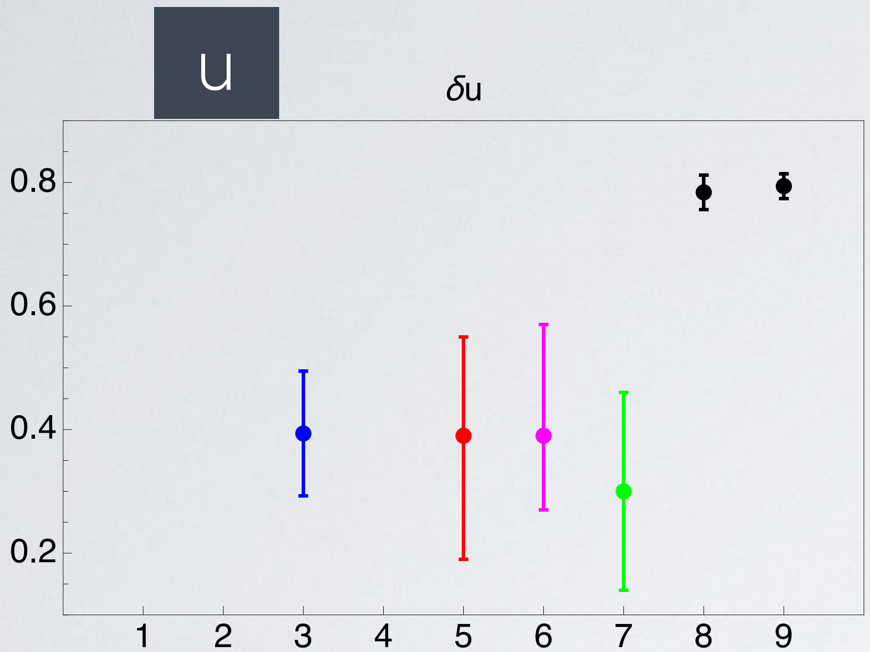
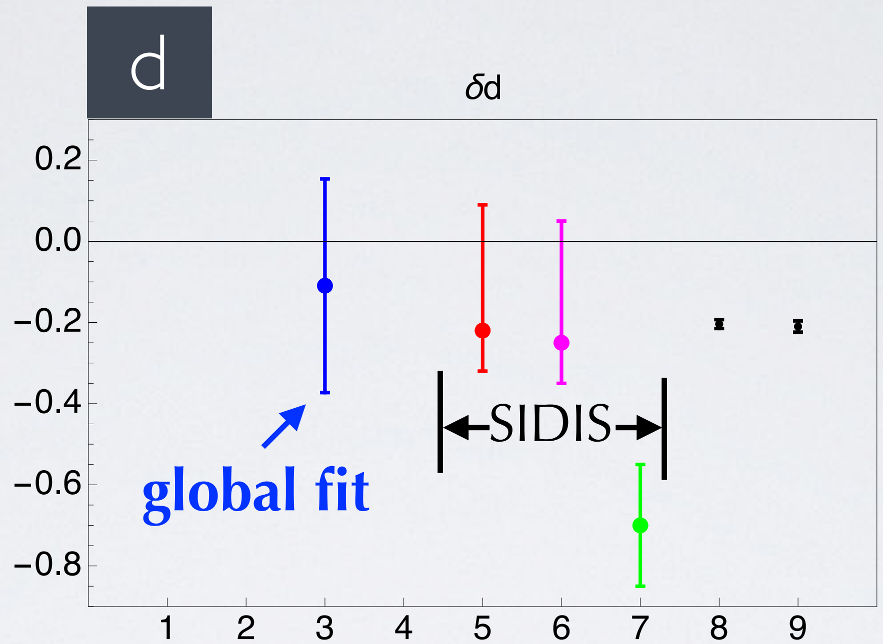
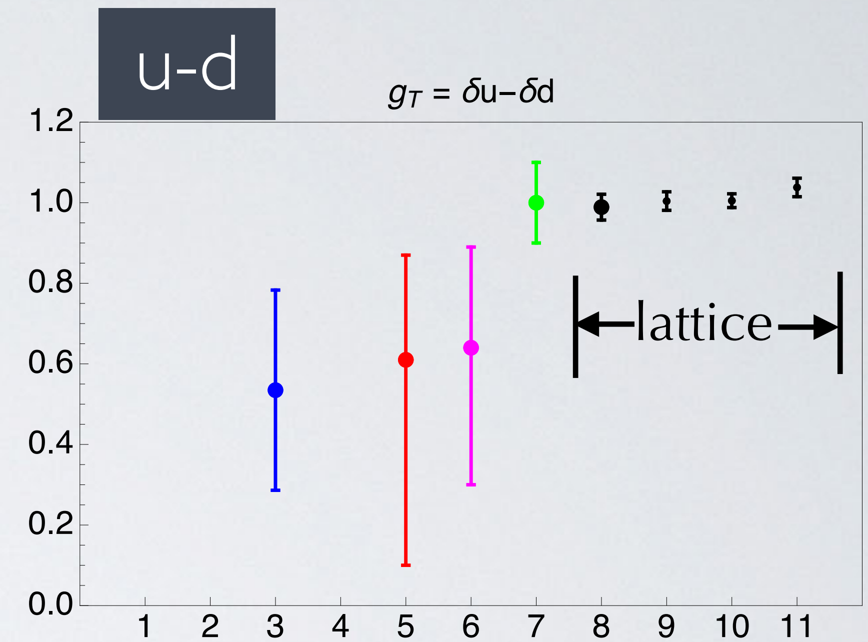
tensor charge







no simultaneous compatibility between lattice and phenomenology

Q^2=4 GeV^2 *

JAM includes "lattice data"

Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — **3) global fit '17**

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results

global fit published in

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

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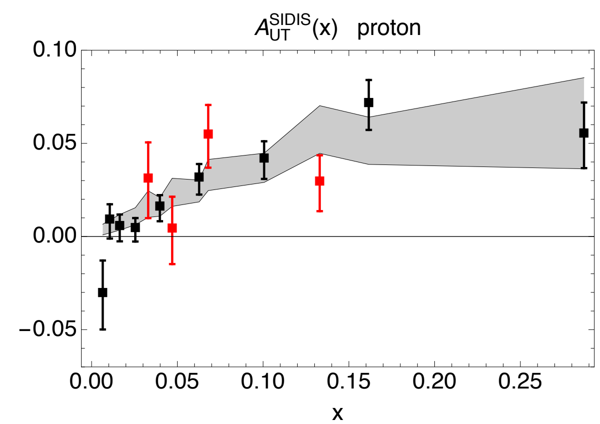

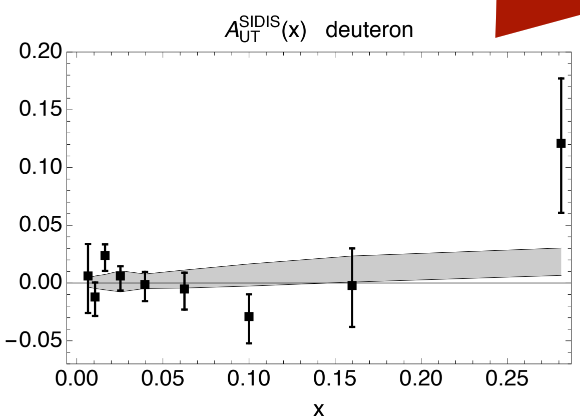

pp collisions

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

M_h, $\eta<0$

M_h, $\eta>0$

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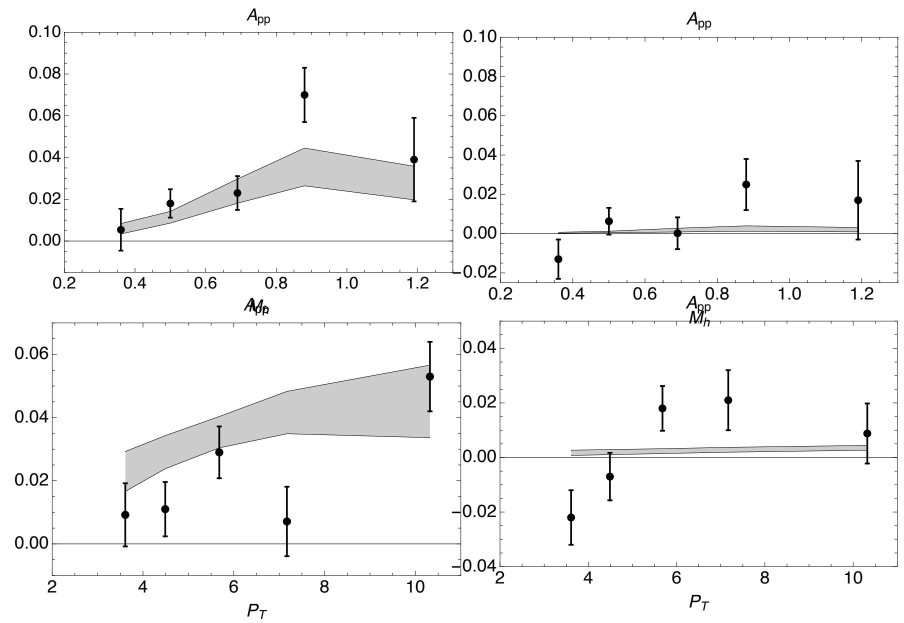
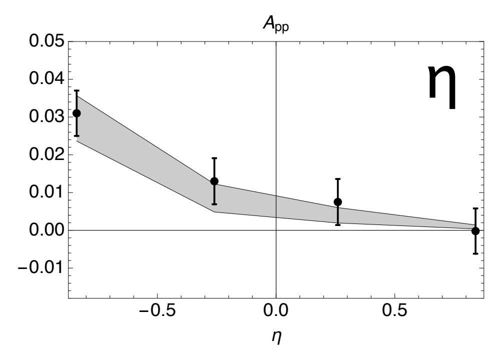


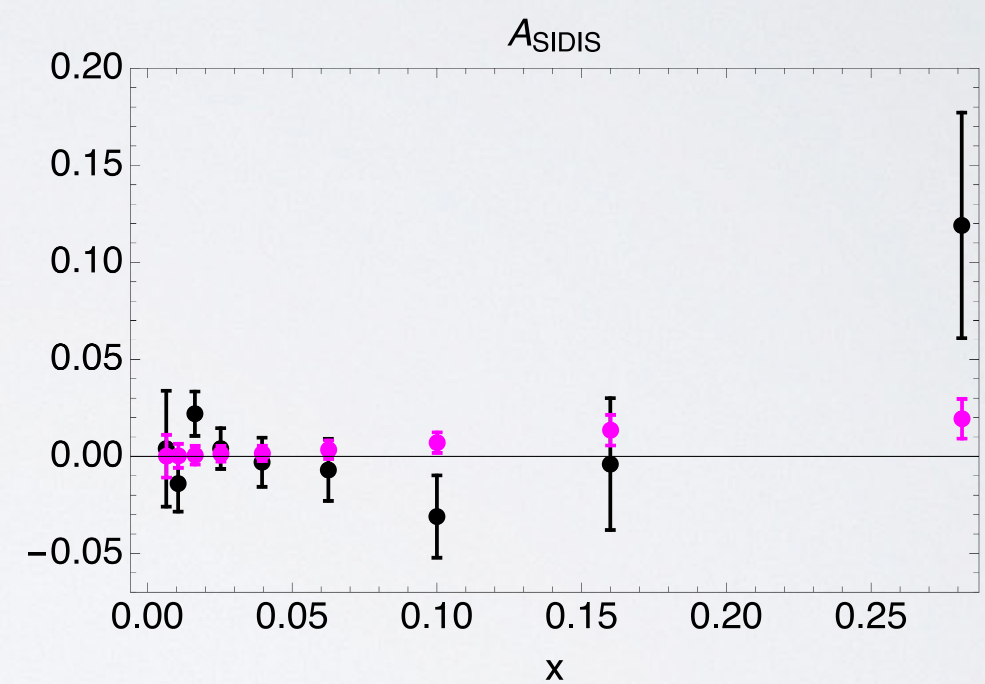


Compass pseudo-data

add to previous set of data
a new set of SIDIS pseudo-data for **deuteron** target

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

pseudodata



statistical error ~ 0.6 x [error in 2010 proton data]
<A> = average value of replicas in previous global fit

study impact on precision of previous global fit

impact of pseudo-data for deuteron

global fit + pseudodata

global fit

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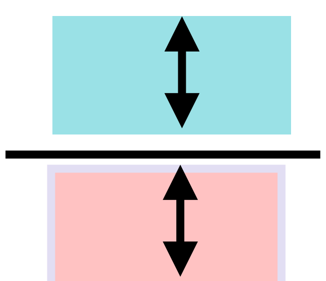
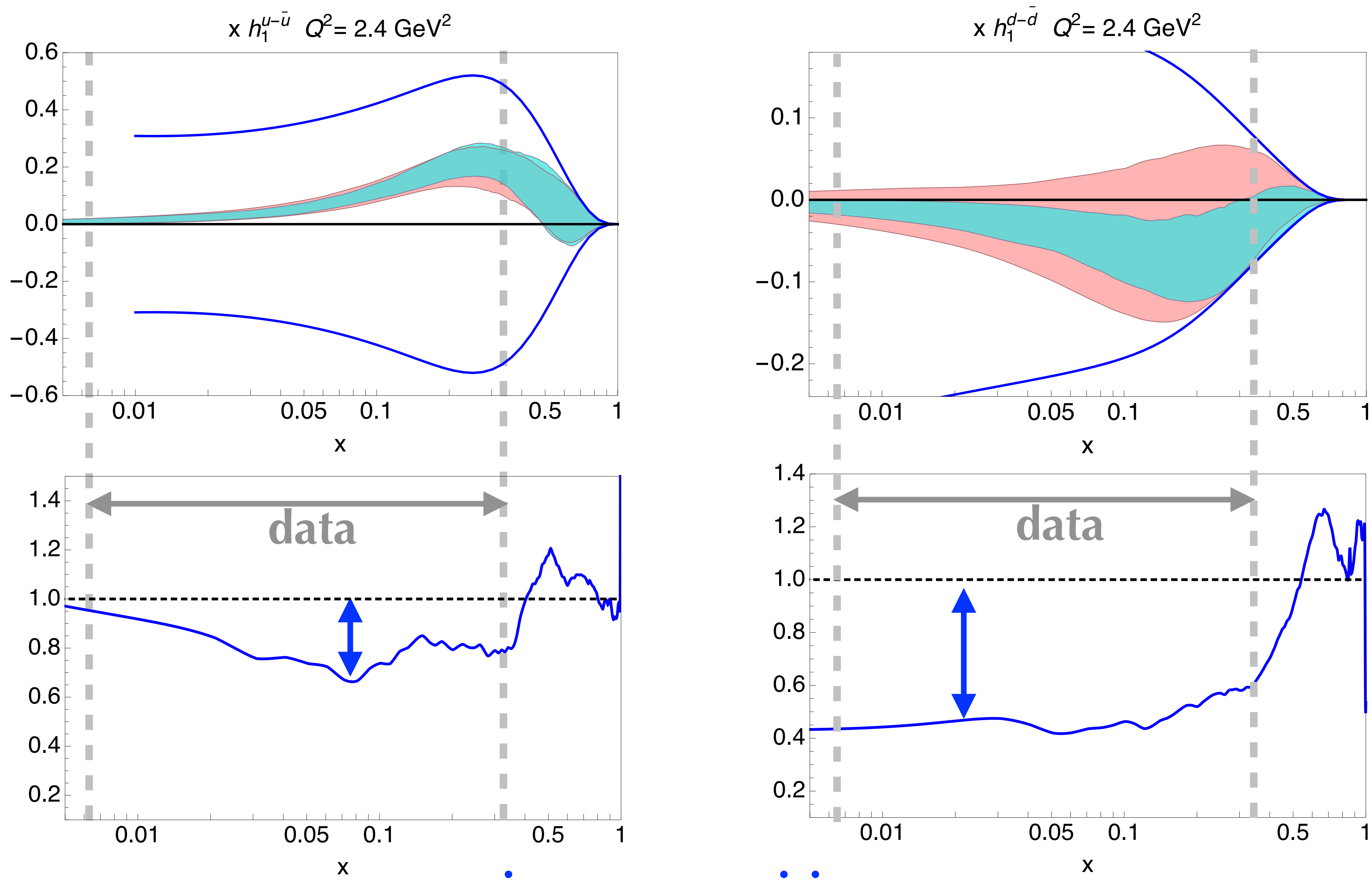


ratio of widths

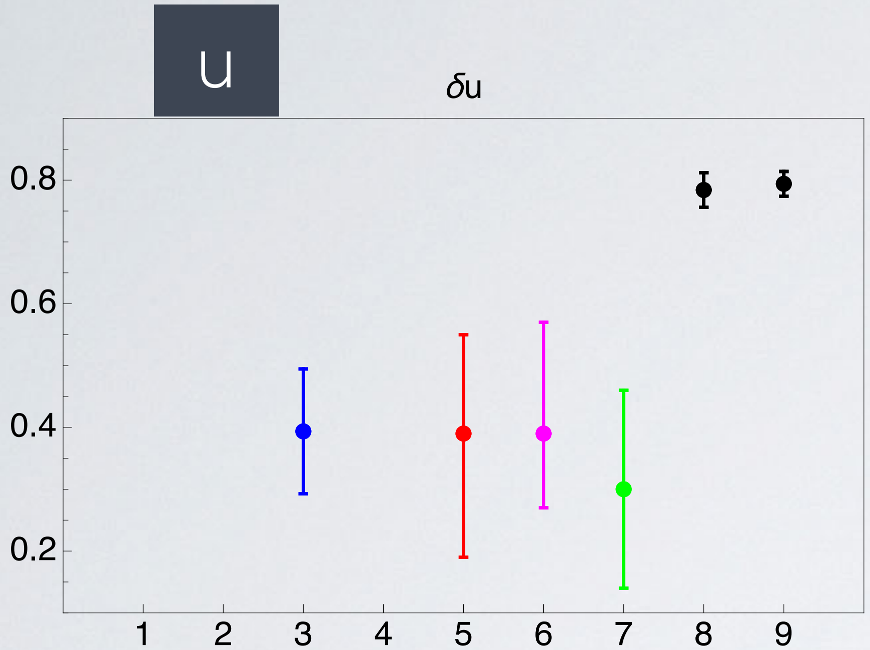
up

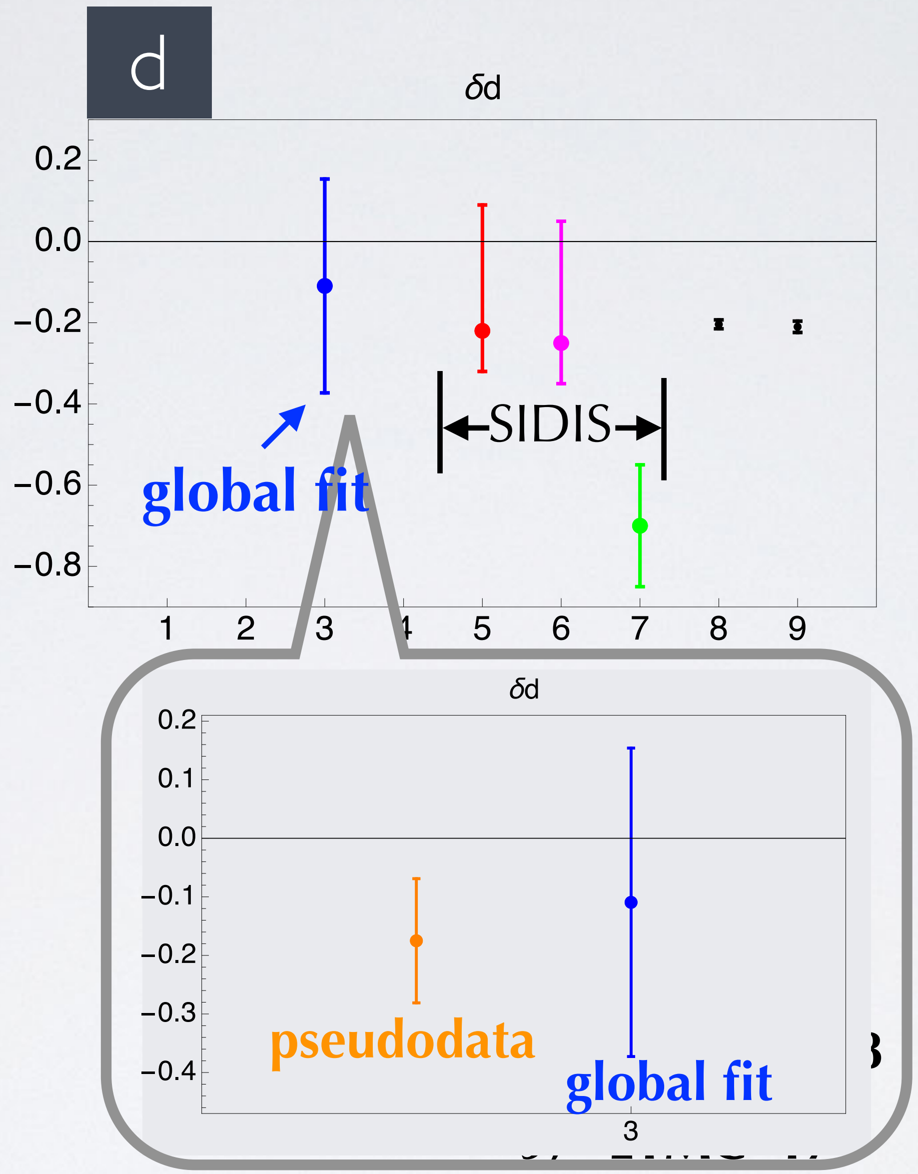
down

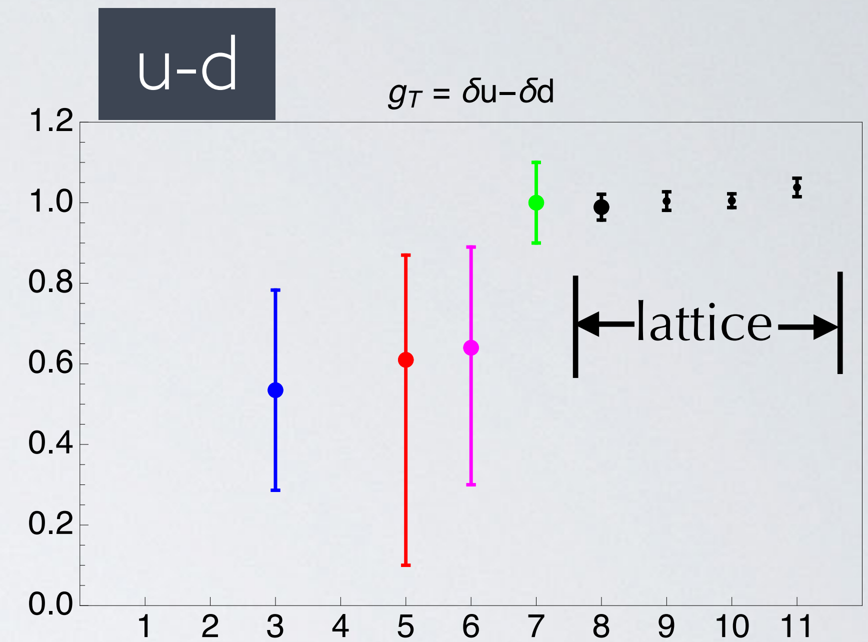


increase precision

tensor charge







JAM includes "lattice data"

*Radici & Bacchetta, P.R.L. **120** (18) 192001*	3) **global fit '17**		*Gupta et al., P.R. D**98** (18) 034503*
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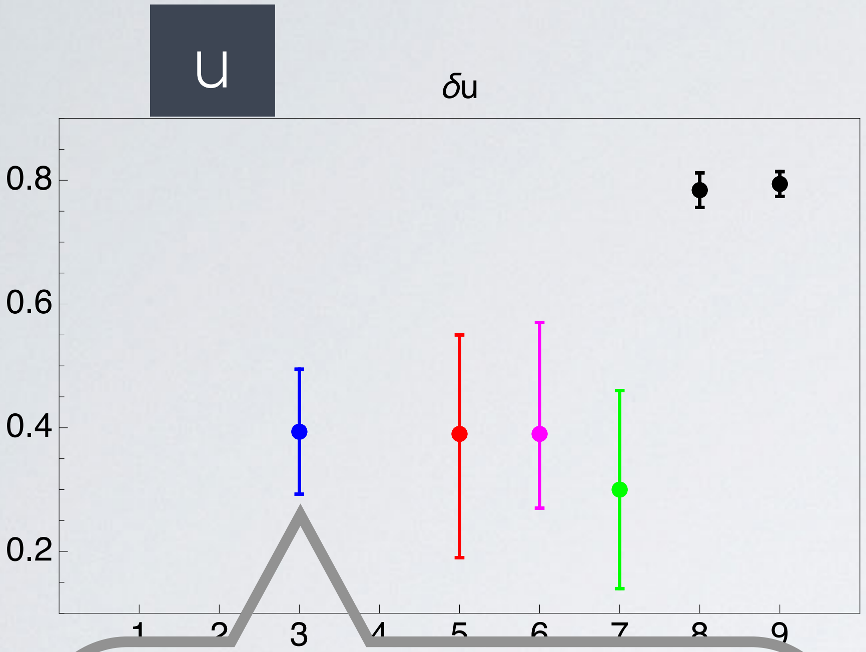
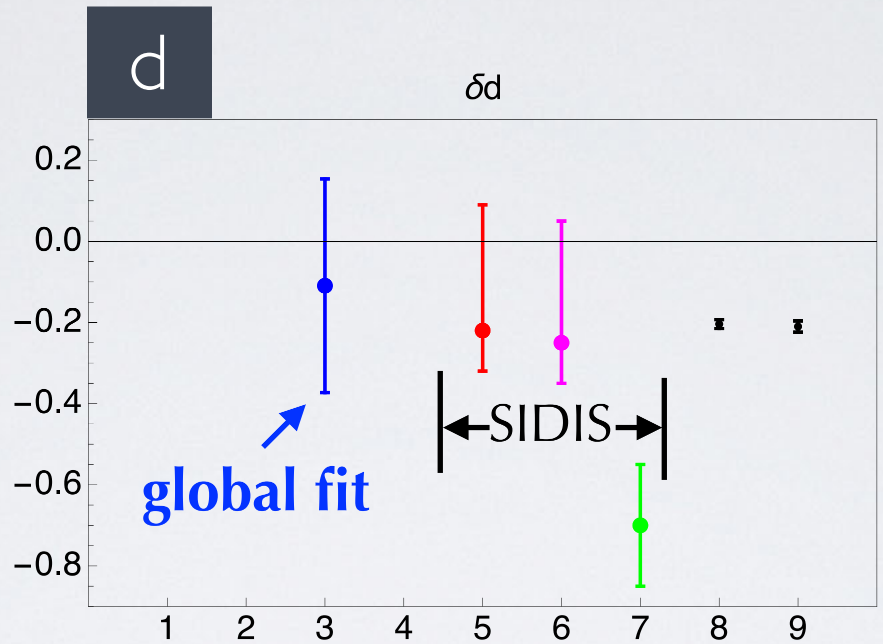
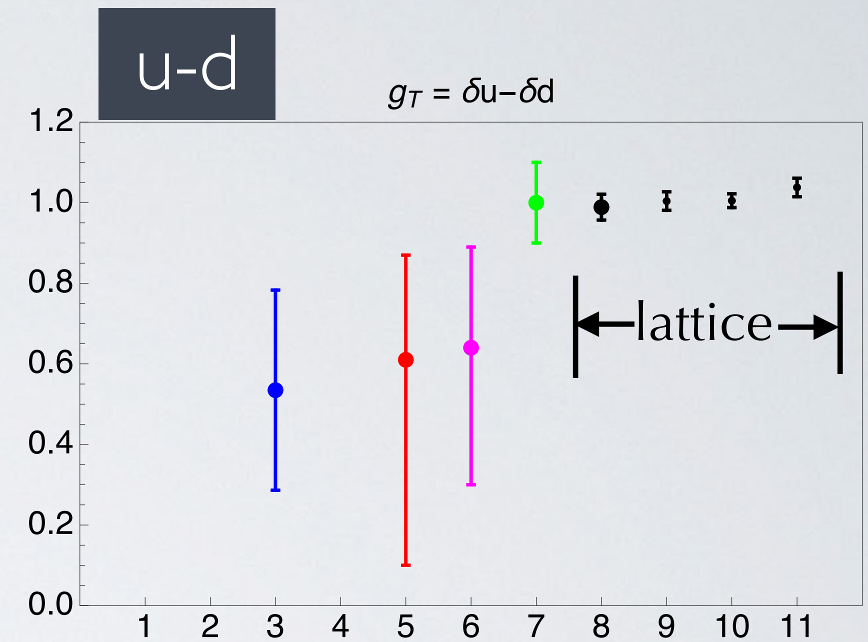
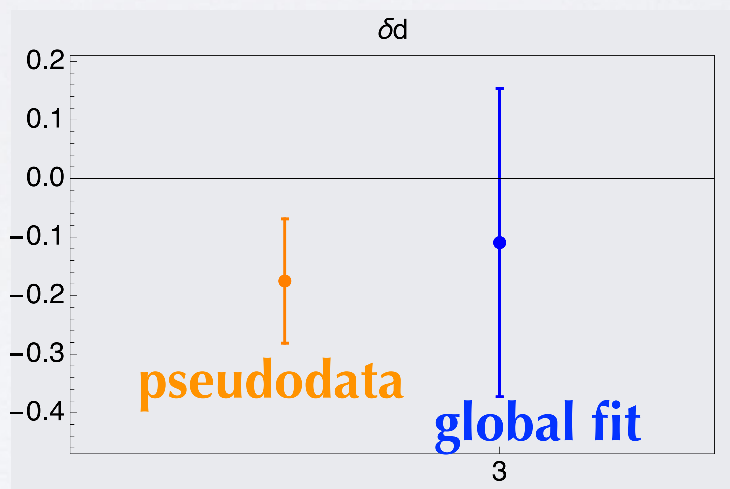
*Lin et al., P.R.L. **120** (18) 152502*	7) **JAM fit '17 * Q_0^2=2**		

tensor charge









JAM includes "lattice data"

Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — 3) global fit '17

*Kang et al., P.R. D****93*** *(16) 014009* — 5) "TMD fit" * $Q^2=10$

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Lin et al., P.R.L. ***120*** *(18) 152502* — 7) JAM fit '17 * $Q_0^2=2$

*Gupta et al., P.R. D****98*** *(18) 034503*

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

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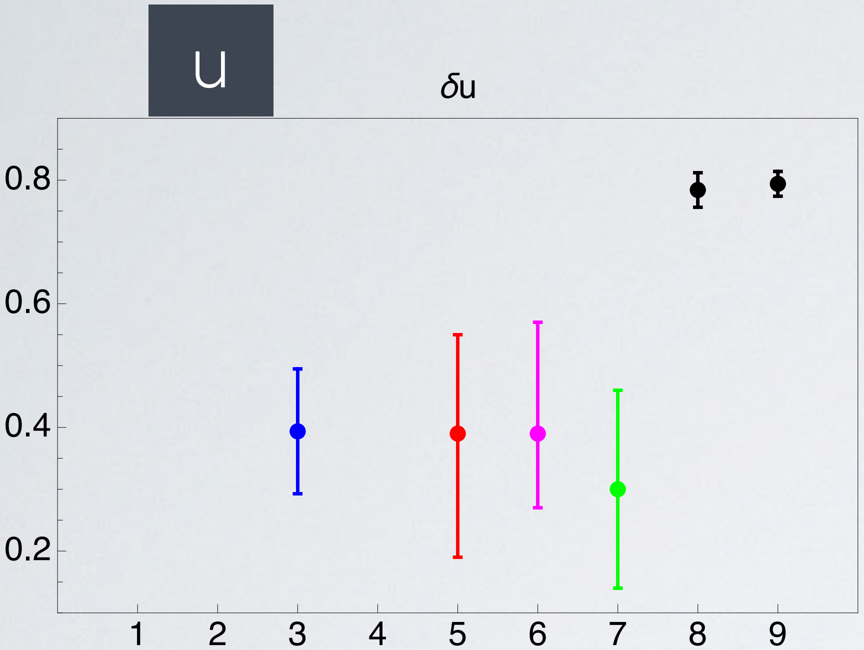
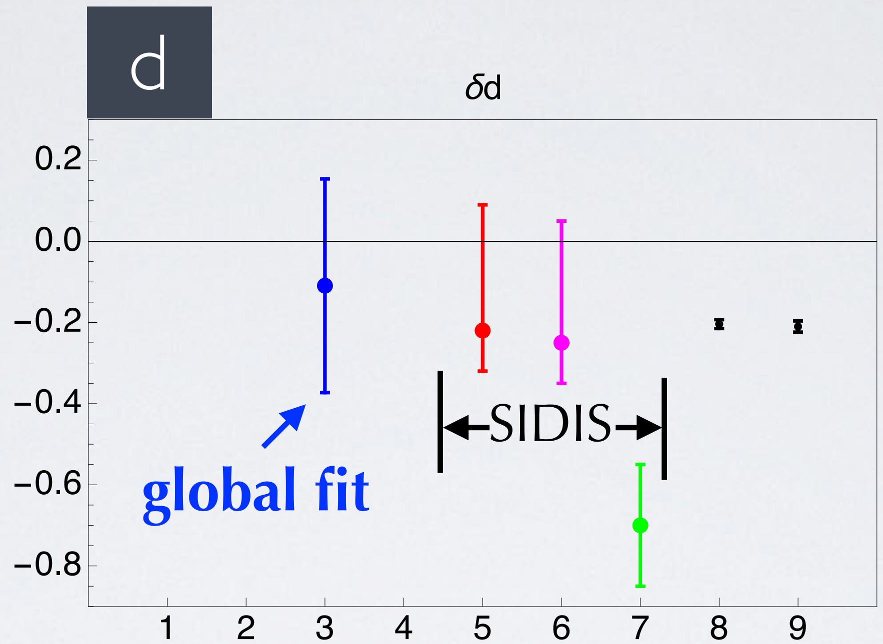
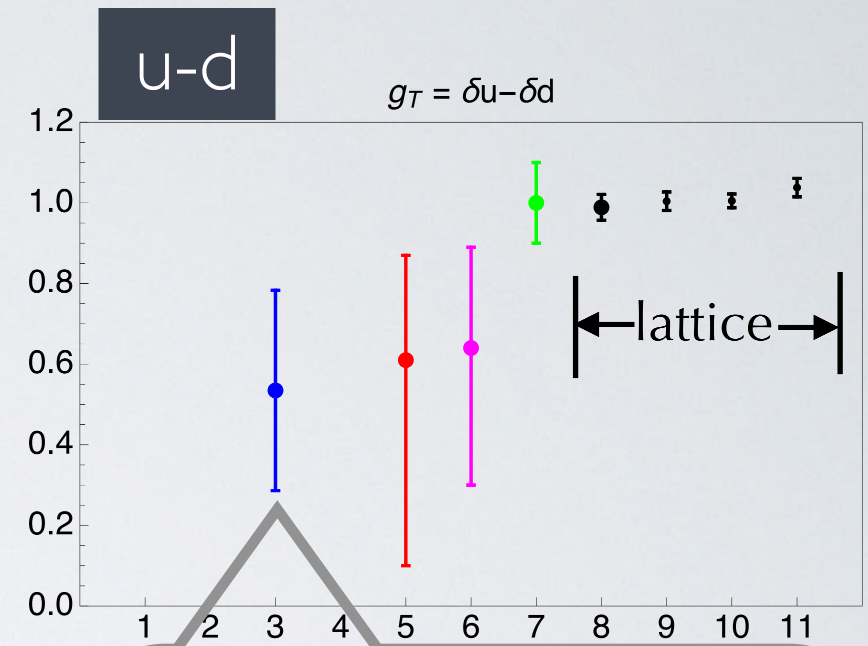
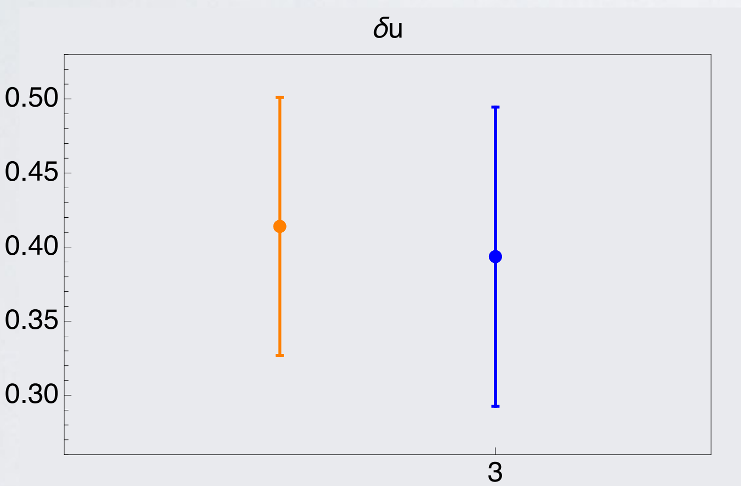
11) LHPC '12 — *Green et al., P.R. D****86*** *(12)*

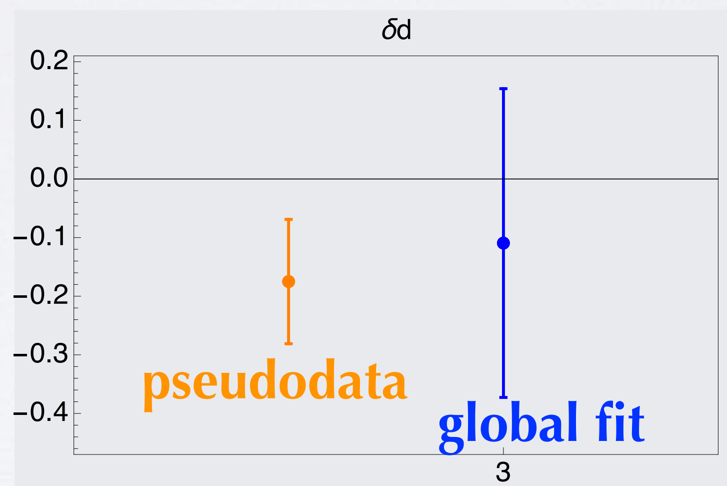
tensor charge











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*P.R. D**96** (17) 099906*

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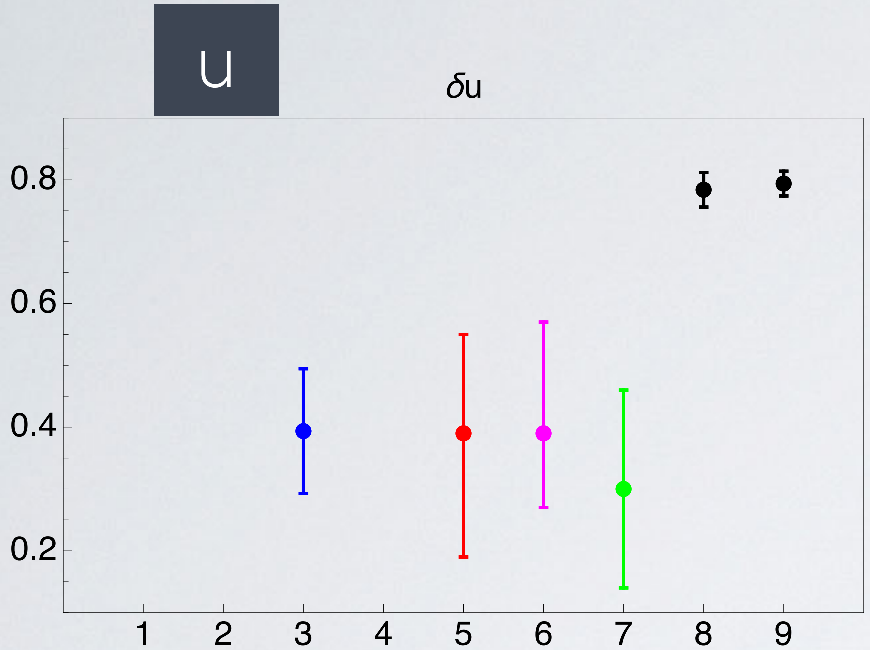
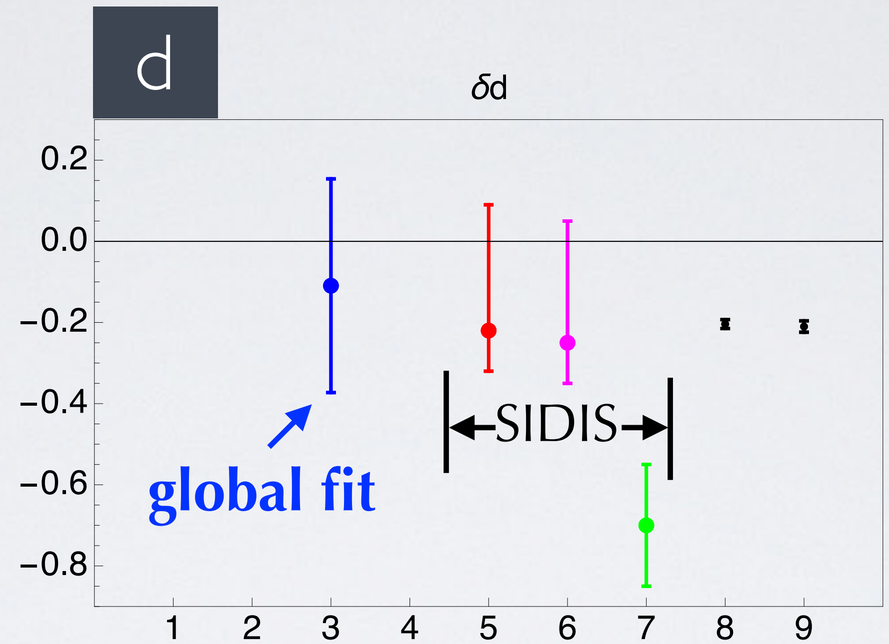
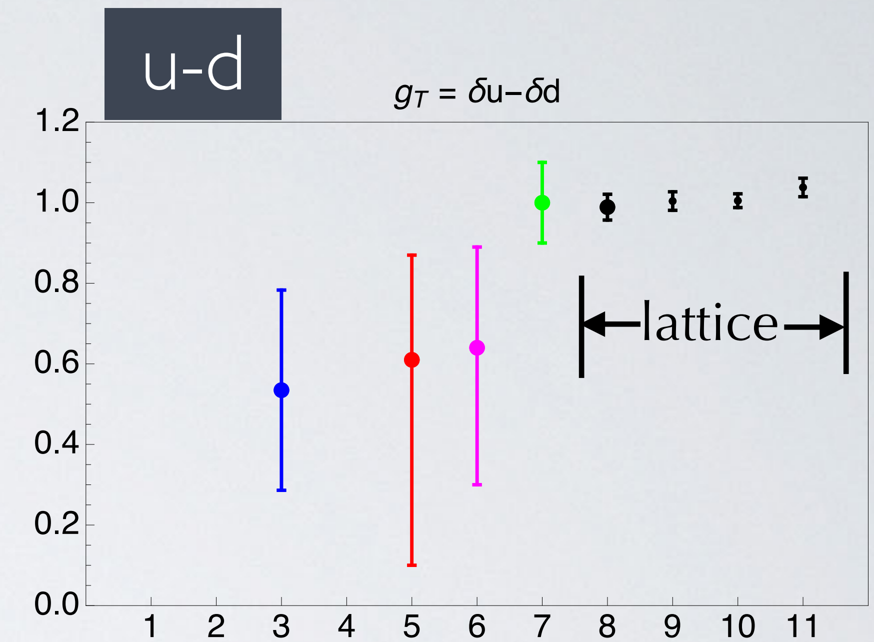
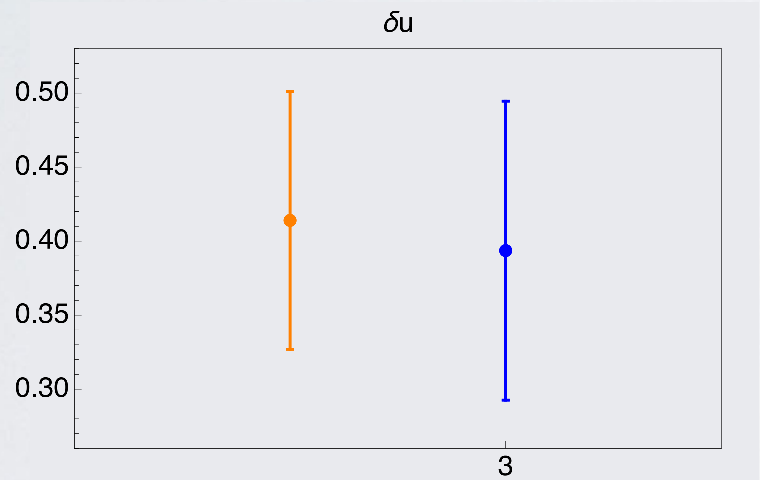
4) SoLID — *Ye et al., P.L.* ***B767*** *(17) 91*

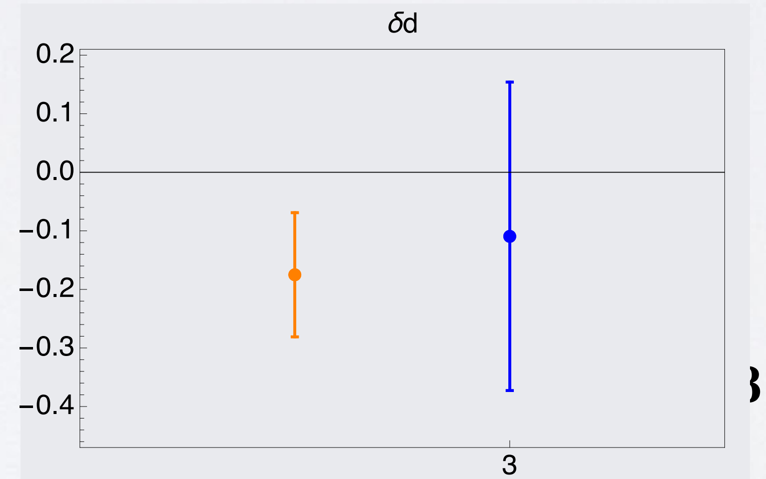
tensor charge

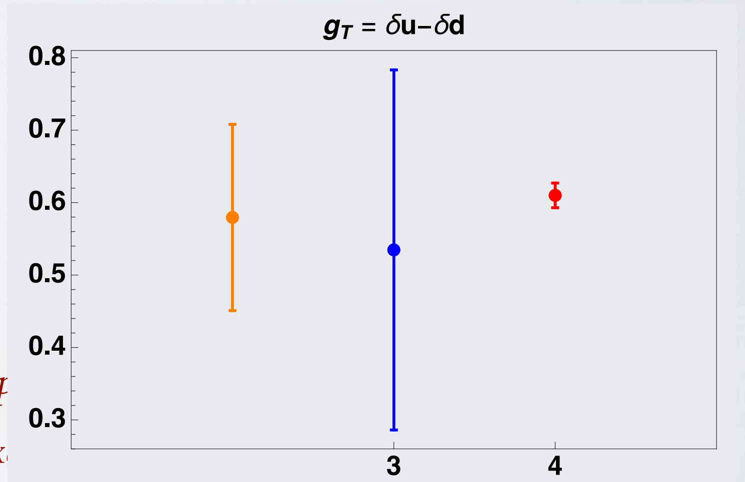












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Lin et al., P.R.L. ***120*** *(18) 152502* — 7) **JAM fit '17 * Q_0^2=2**

Gup

Alex

*E P.R. D**96** (17) 099906*

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

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

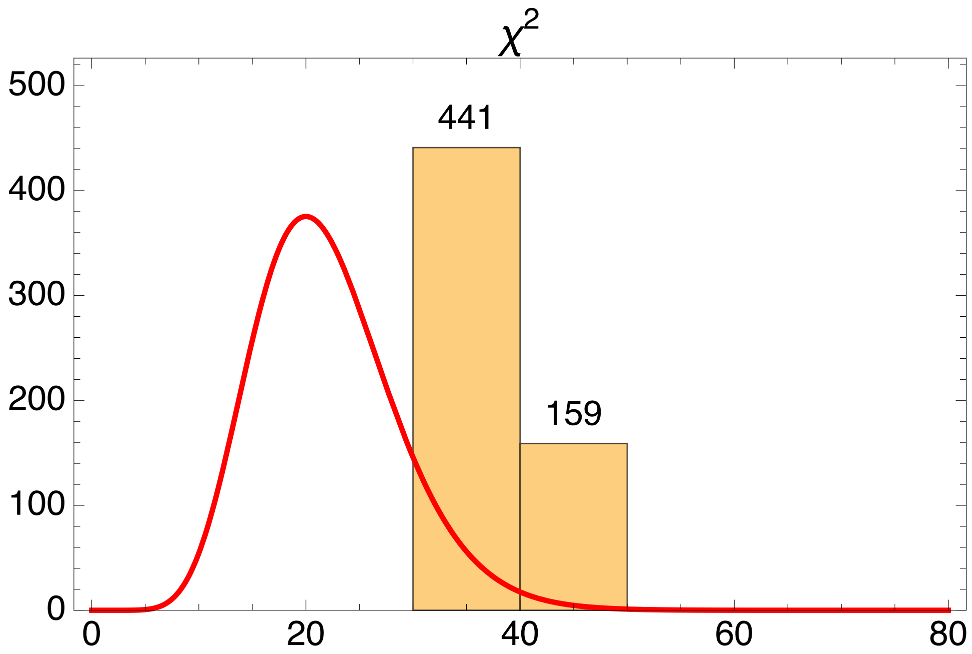
91

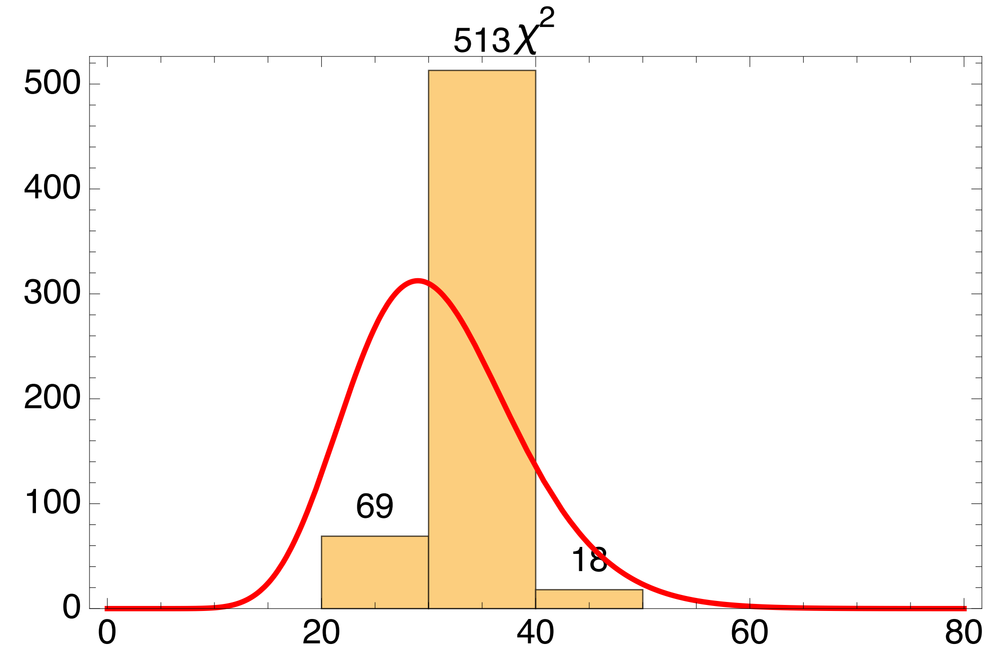
better precision
but tension with lattice confirmed

better χ^2

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

$\chi^2/\text{dof} = 1.12 \pm 0.09$





probability density function of
χ^2 distribution for
22 d.o.f. 31 d.o.f.

but central value of pseudodata not known
→ only spreading is meaningful

results

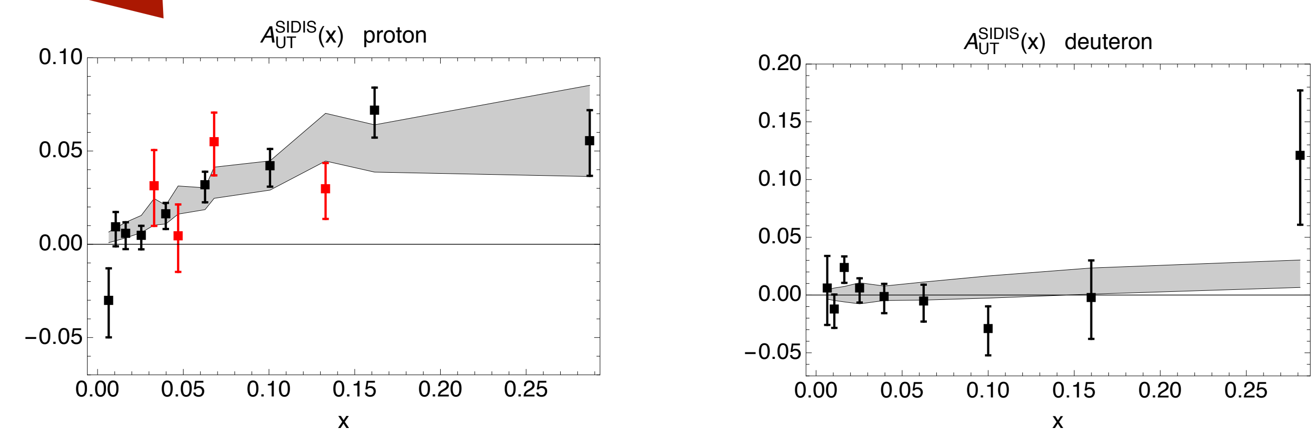
global fit published in

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

SIDIS

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

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

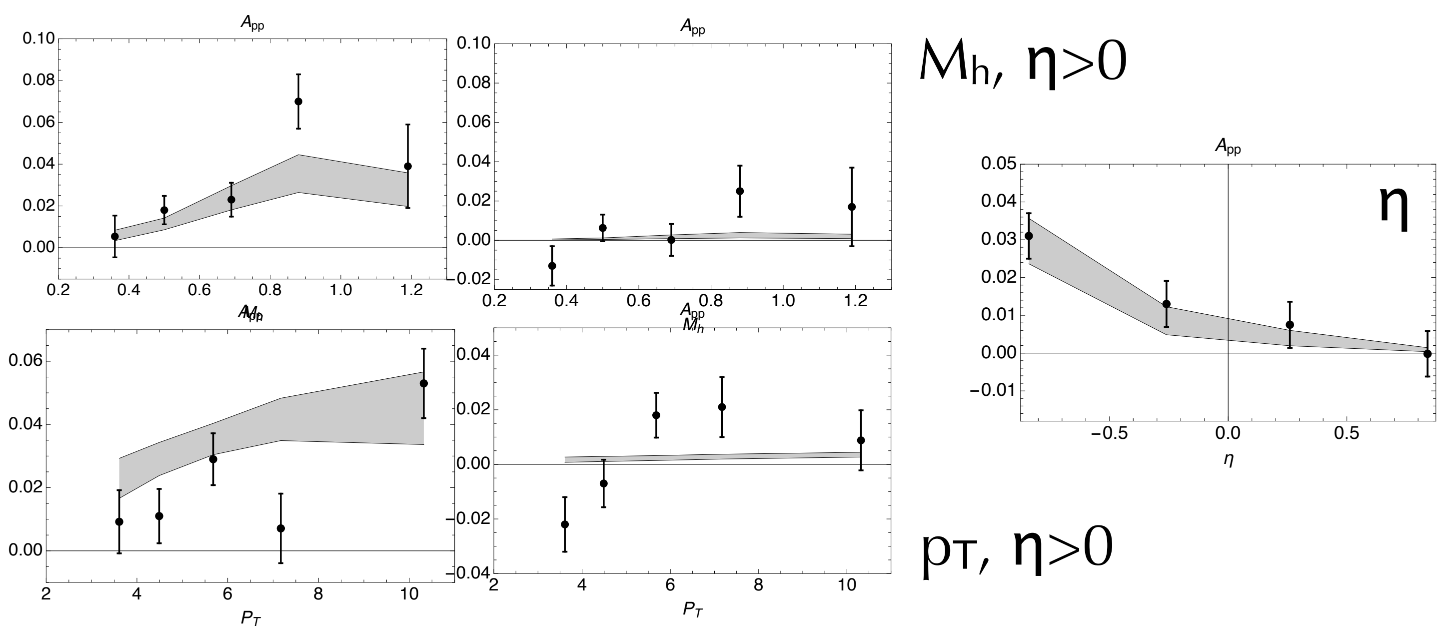


pp collisions

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

M_h, η<0

M_h, η>0



p_T, η<0

p_T, η>0

CLAS12 pseudo-data

add to previous set of data
a new set of SIDIS pseudo-data for **proton** target

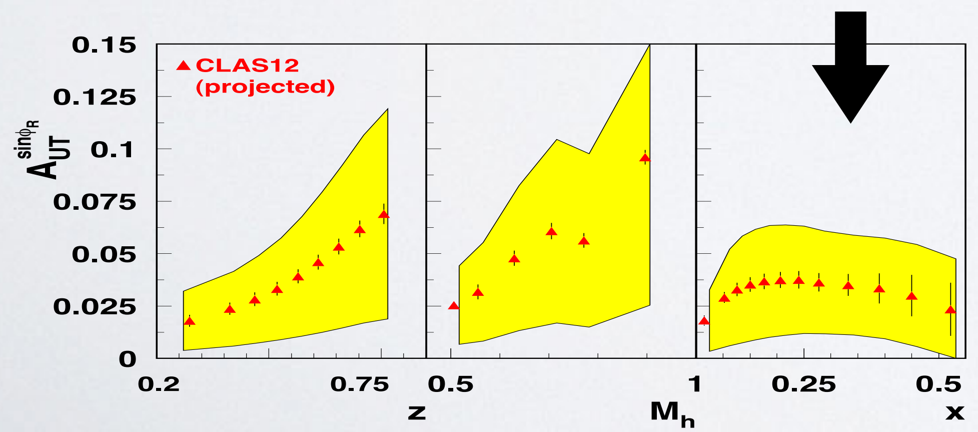
Adolph et al., P.L. ***B713*** *(12)*

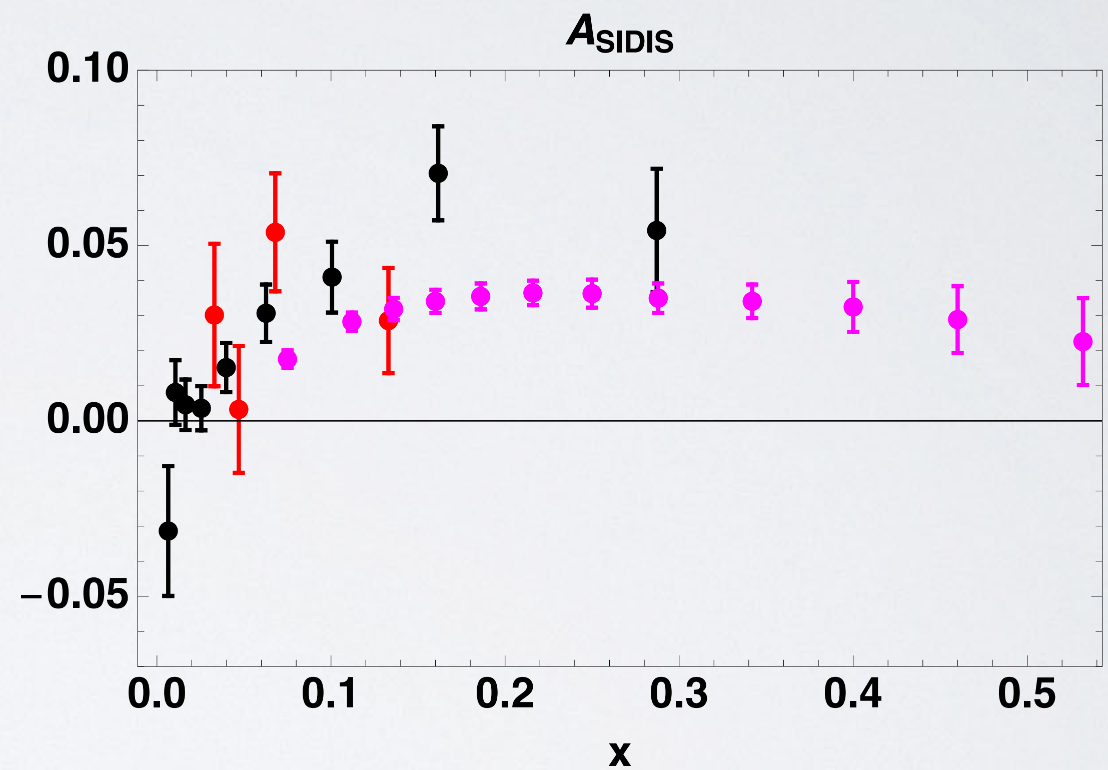
Airapetian et al.,
JHEP ***0806*** *(08) 017*

pseudodata C12-12-009

A 12 GeV Research Proposal to Jefferson Lab (PAC 39)

Measurement of transversity with dihadron production
in SIDIS with transversely polarized target





study impact on precision
of published global fit

impact of pseudo-data for proton

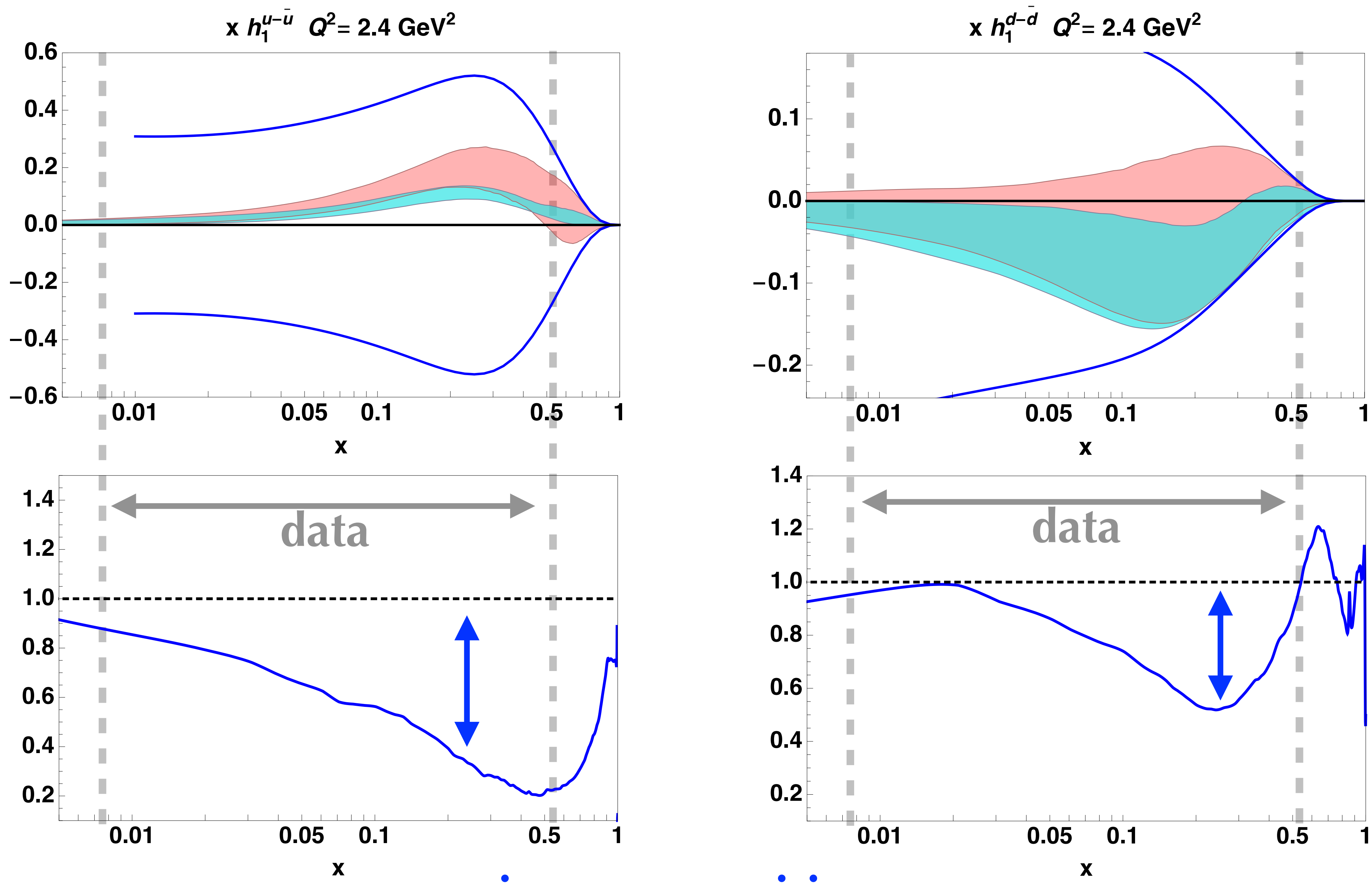
global fit + pseudodata

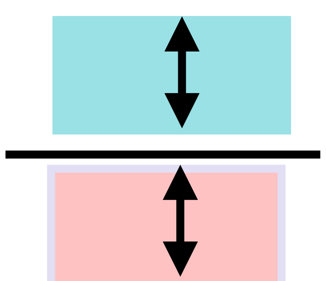
global fit

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

up

down





ratio of widths

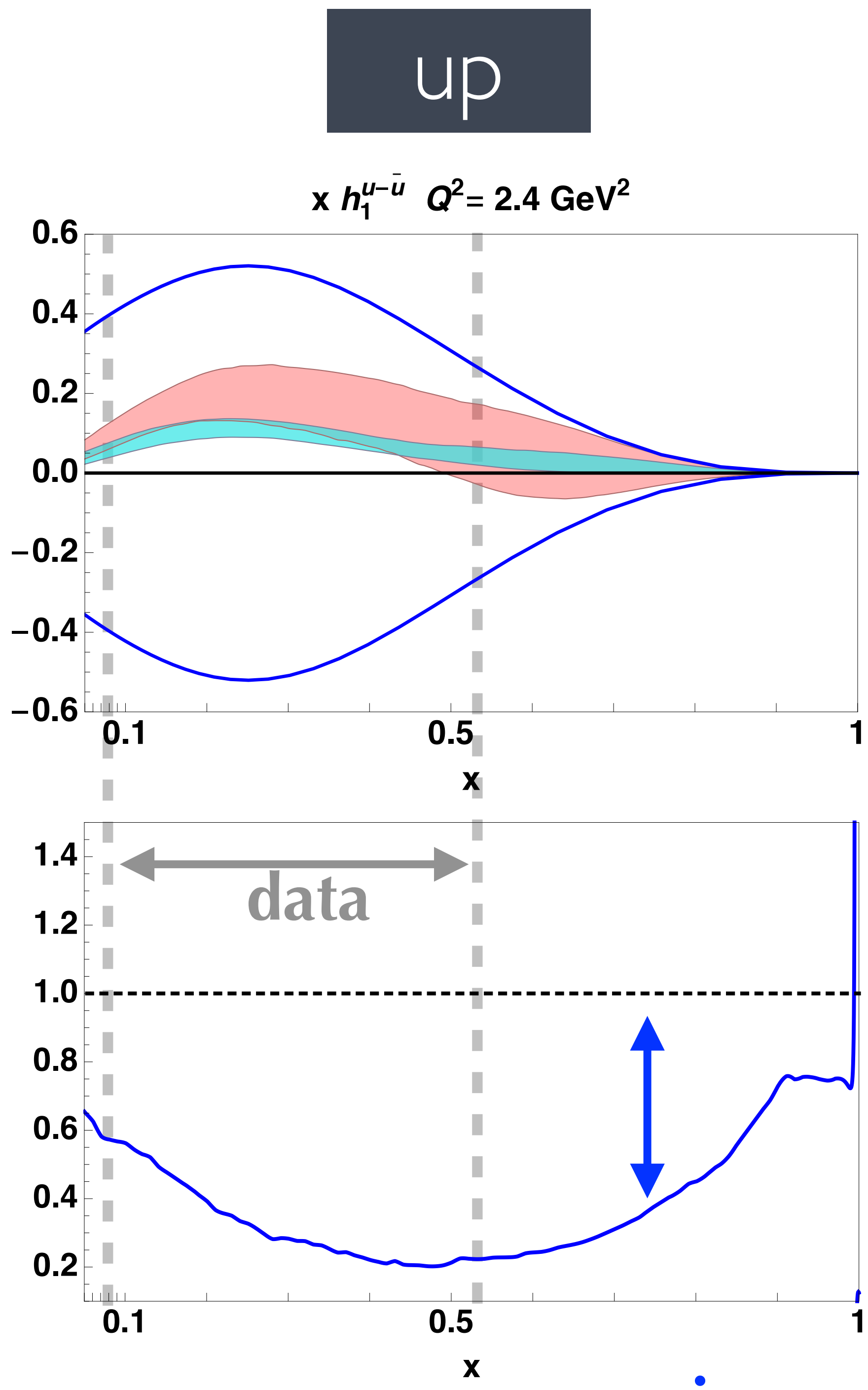
increase precision

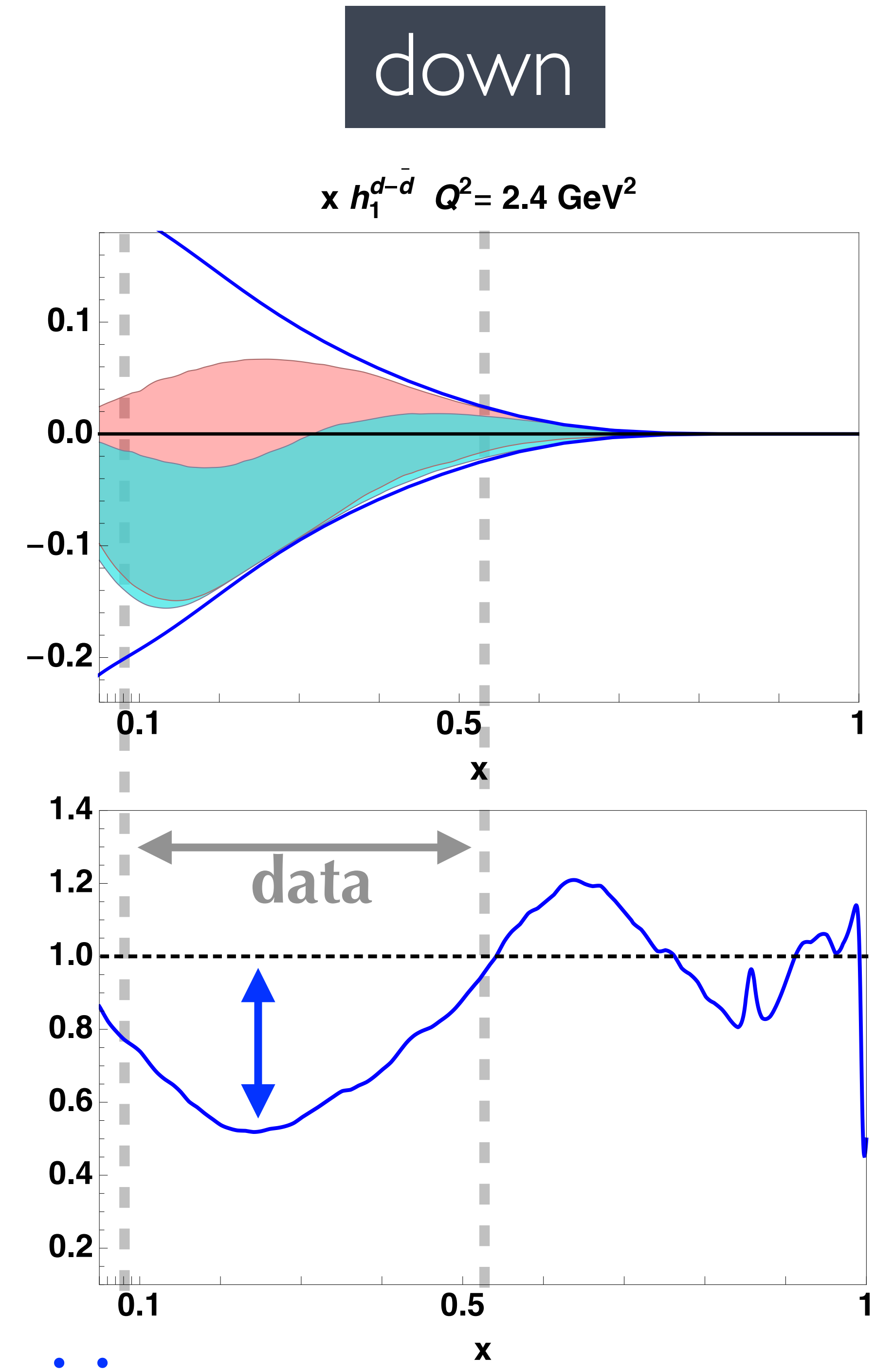
linear scale

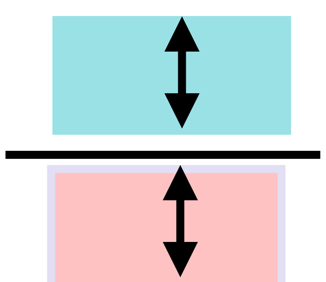
global fit + pseudodata

global fit

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



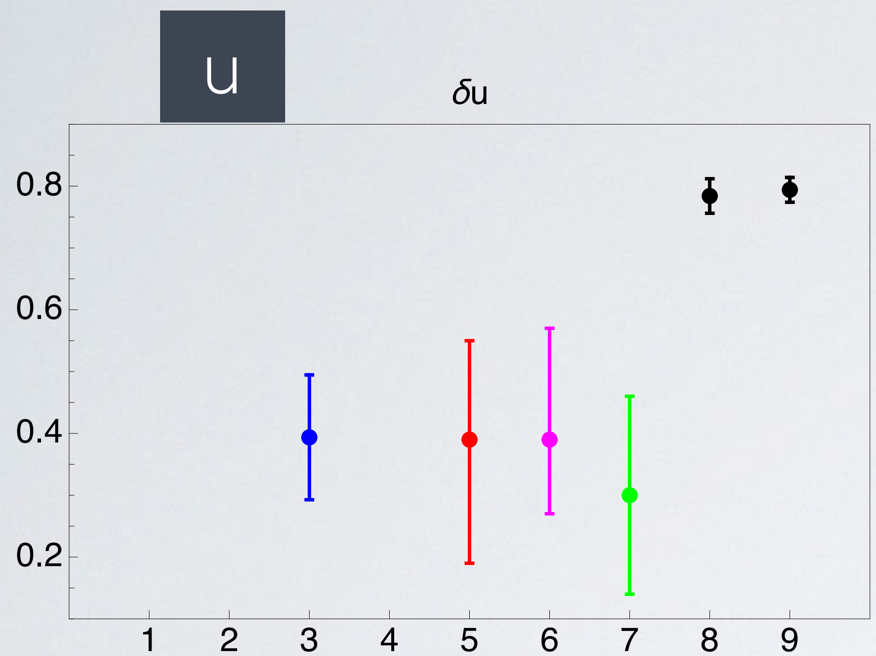


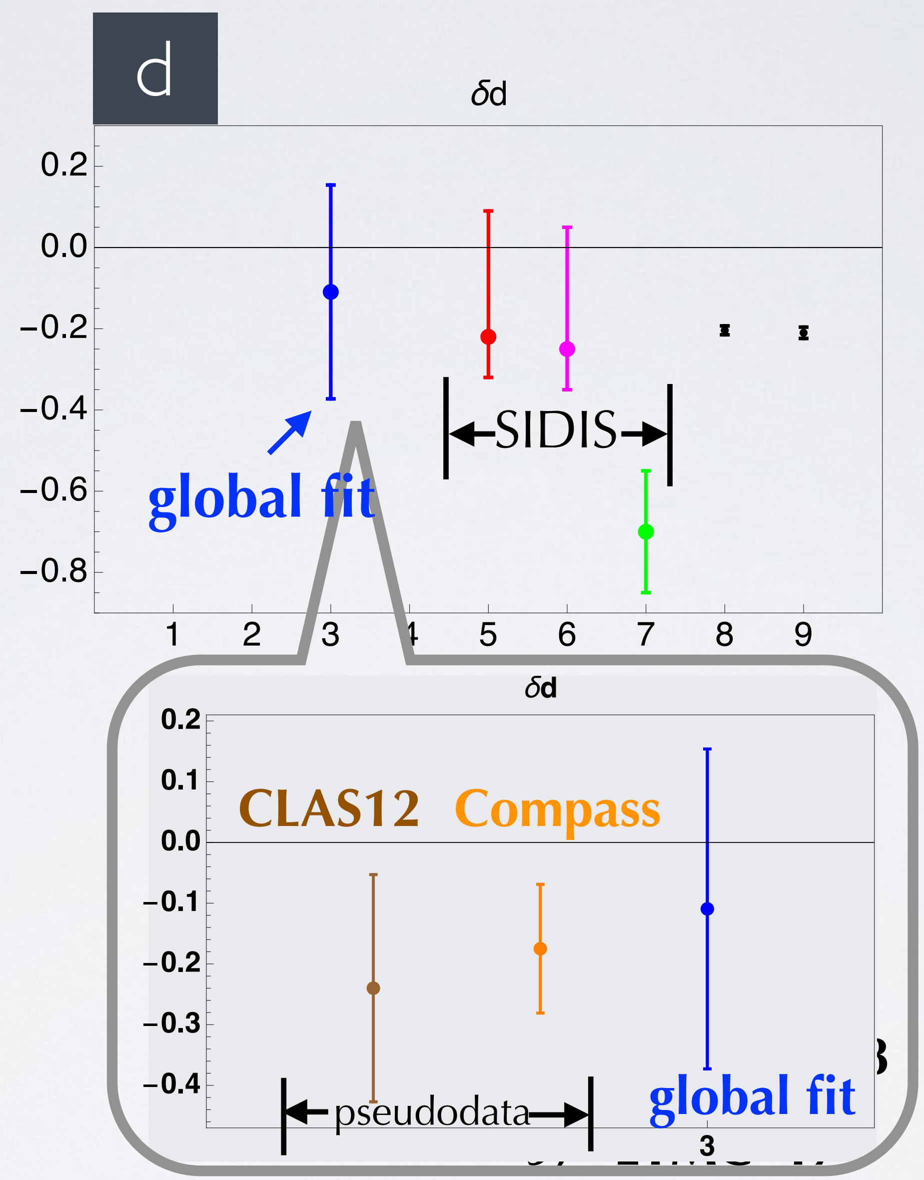


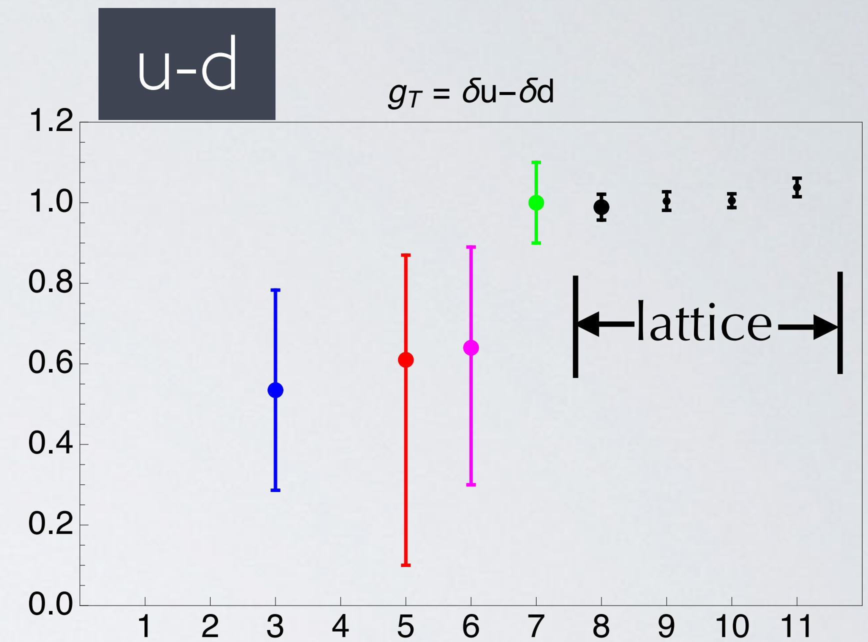
ratio of widths

increase precision

tensor charge







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Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — 3) **global fit '17**

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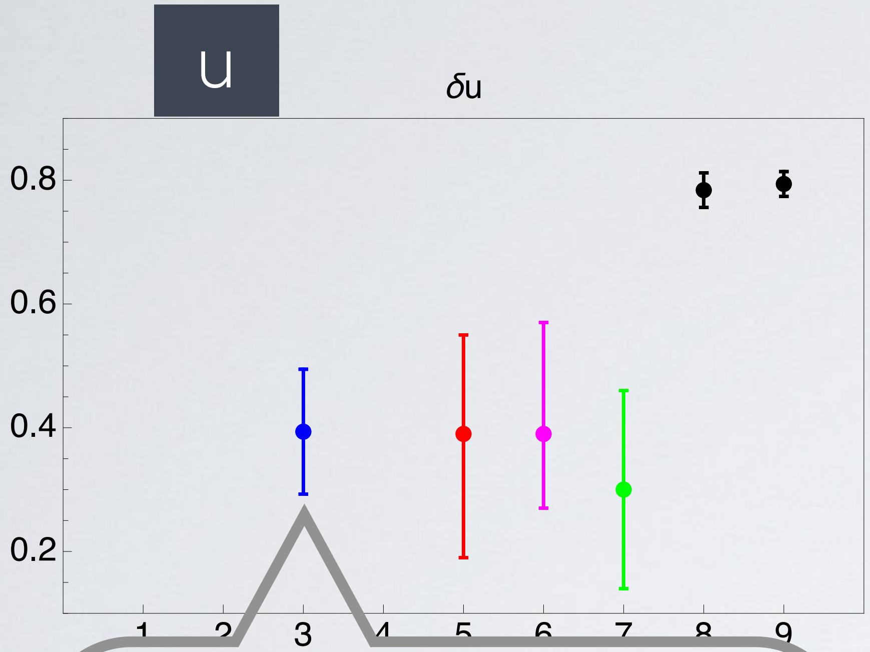
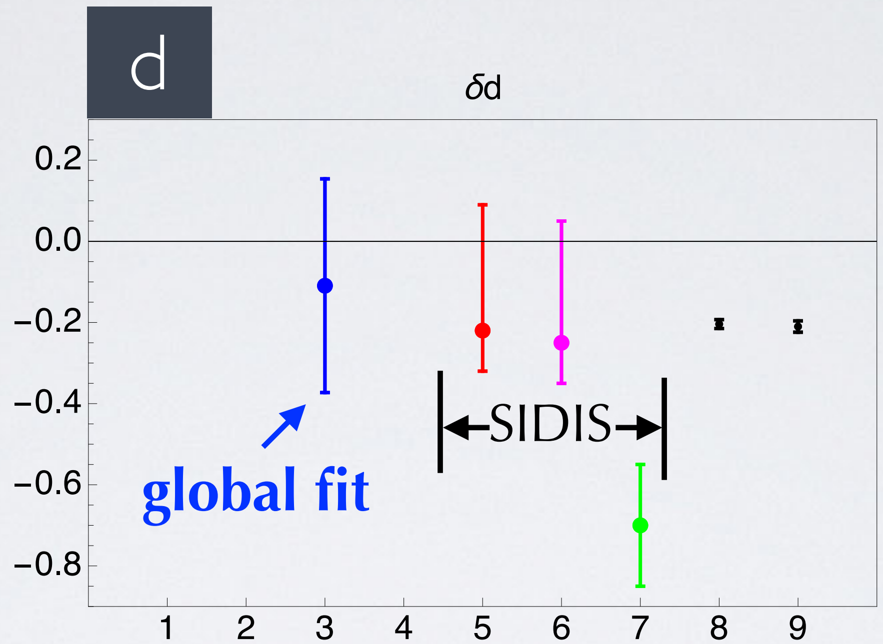
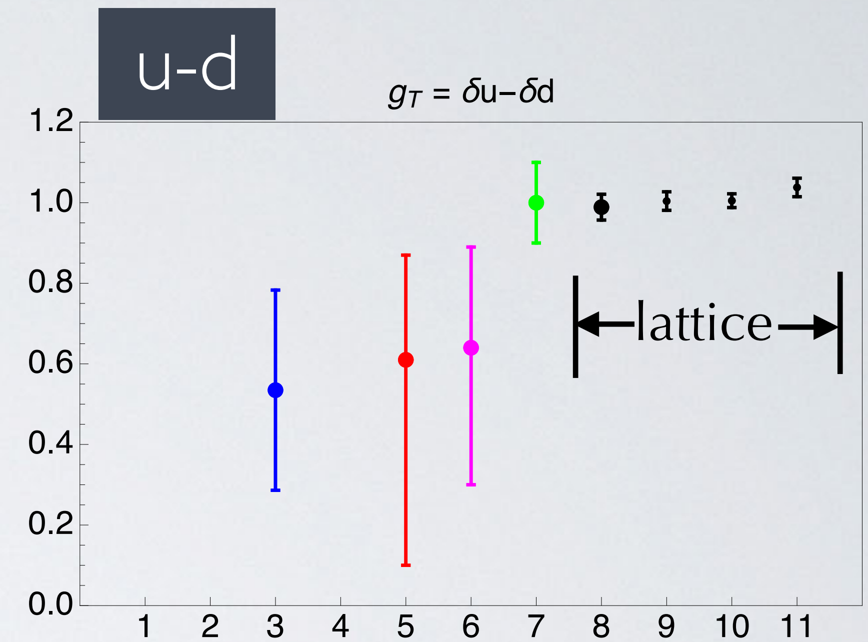
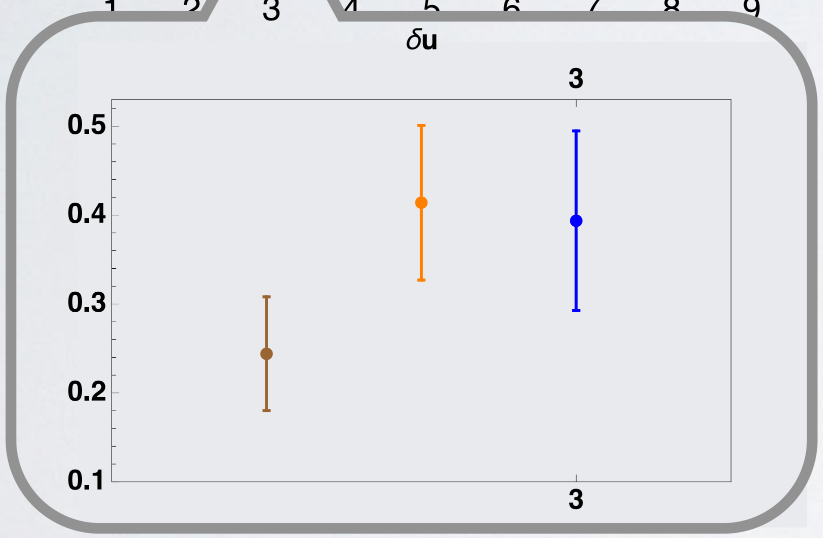
4) **SoLID** — *Ye et al., P.L. **B767** (17) 91*

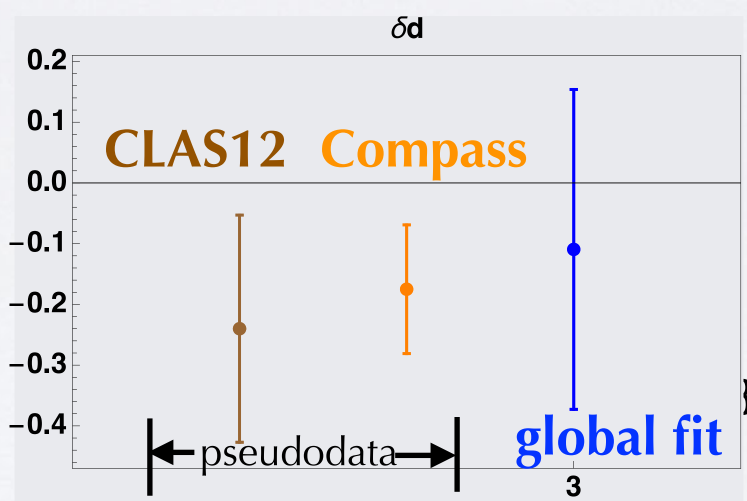
tensor charge











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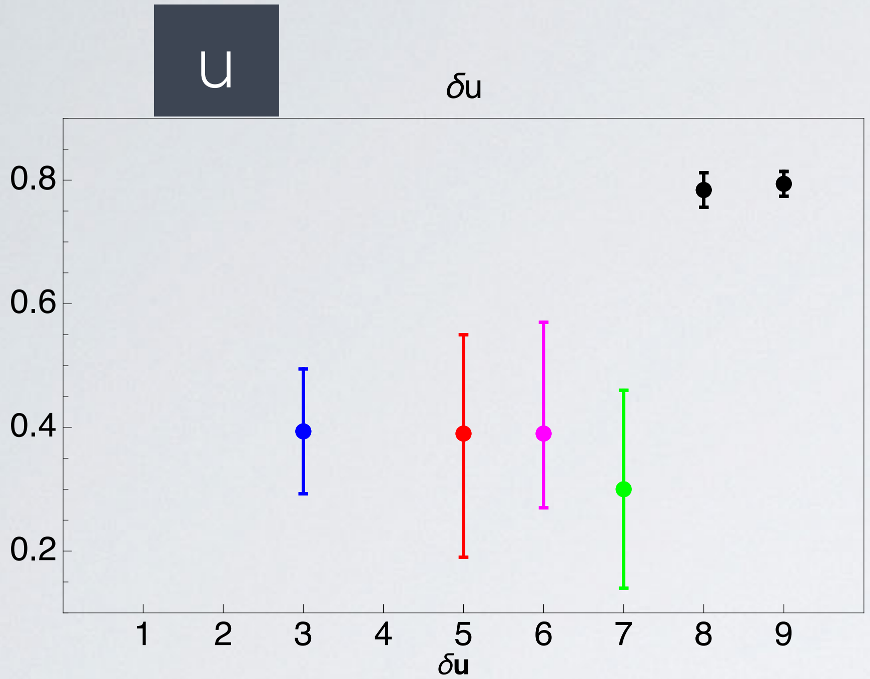

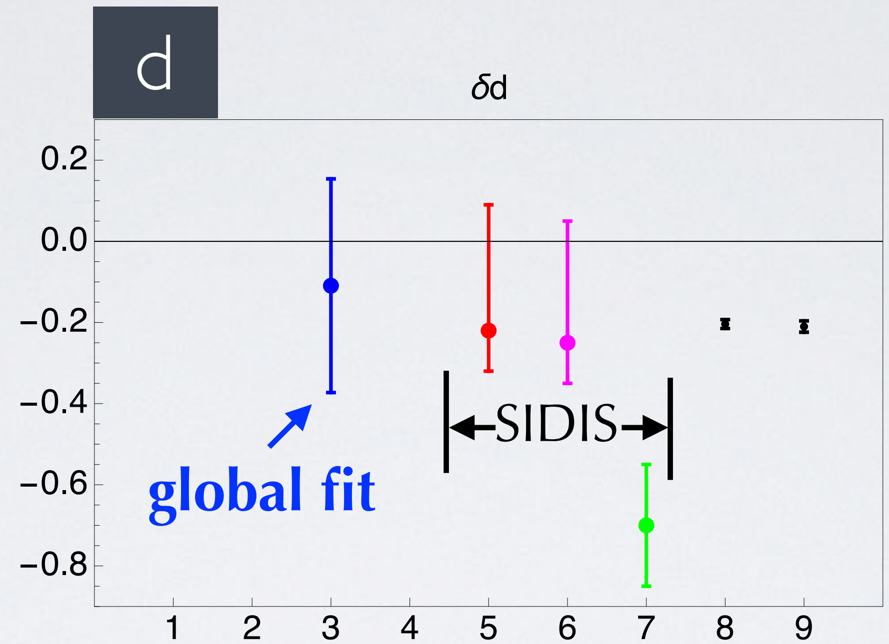

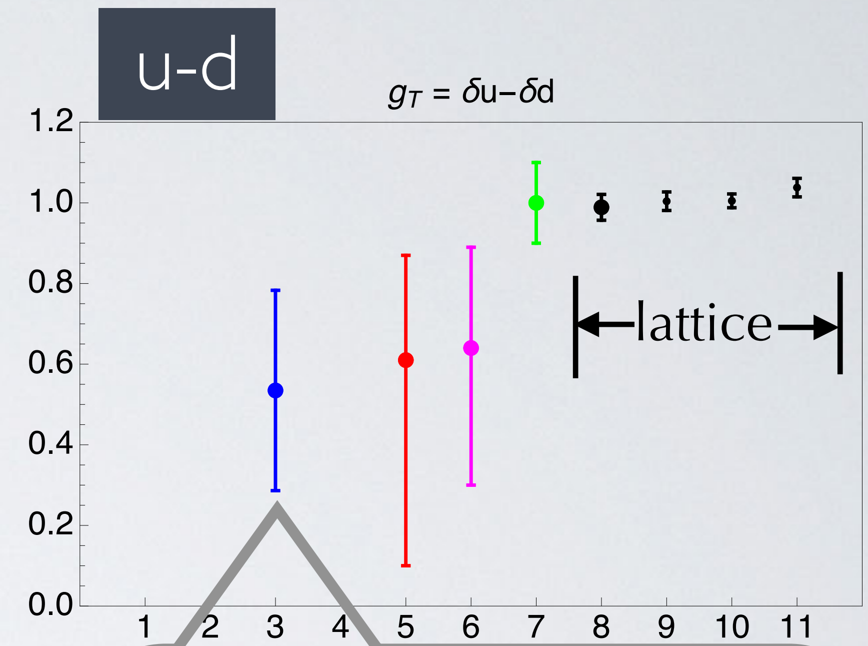

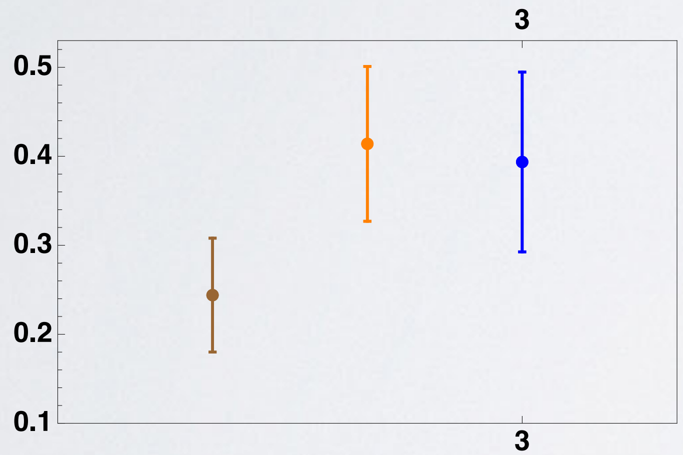

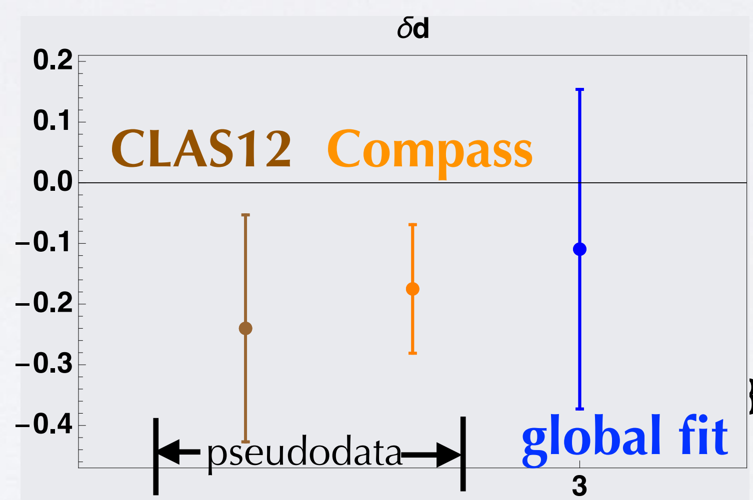

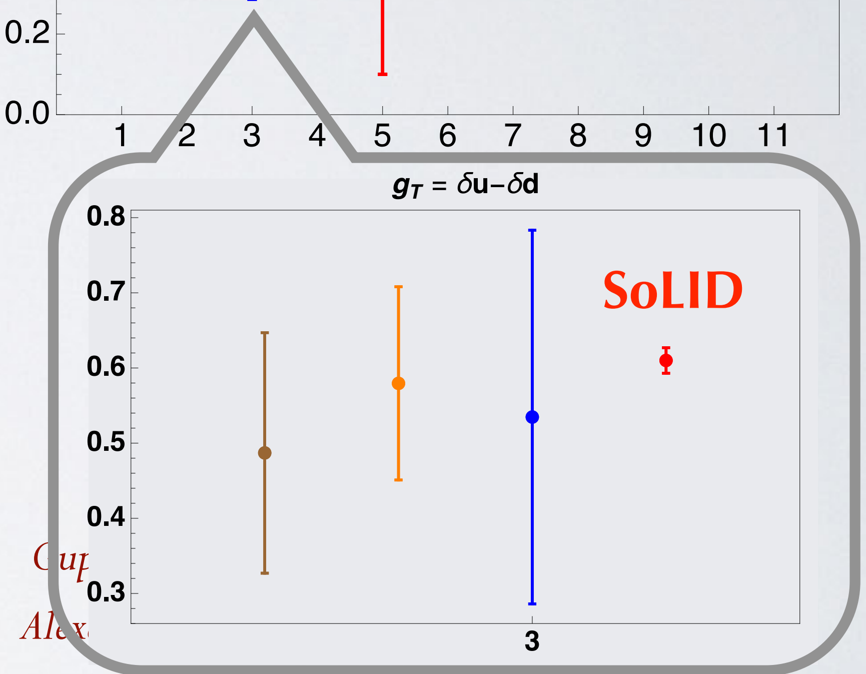

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Cup…
Ale…
*E P.R. D**96** (17) 099906*

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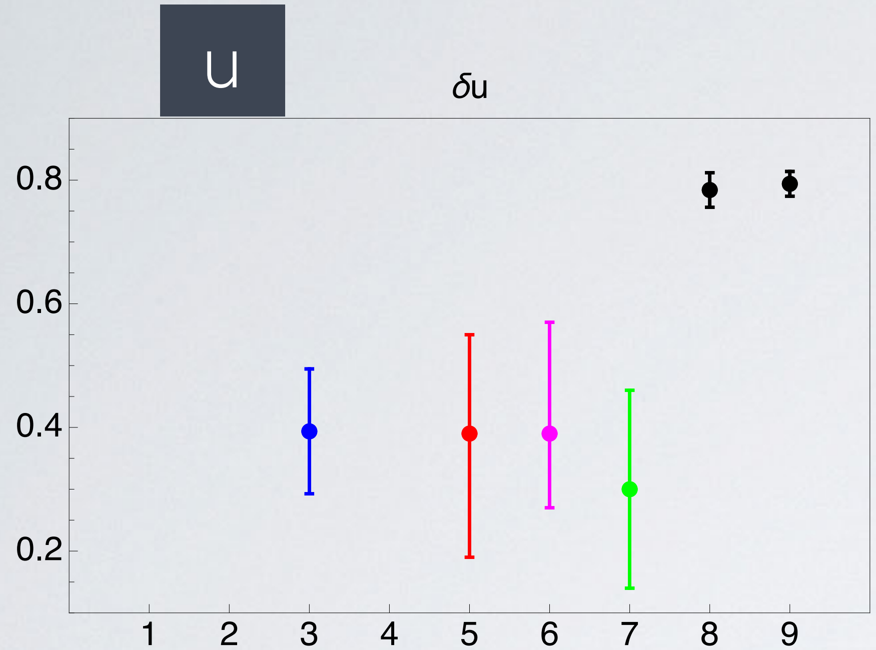
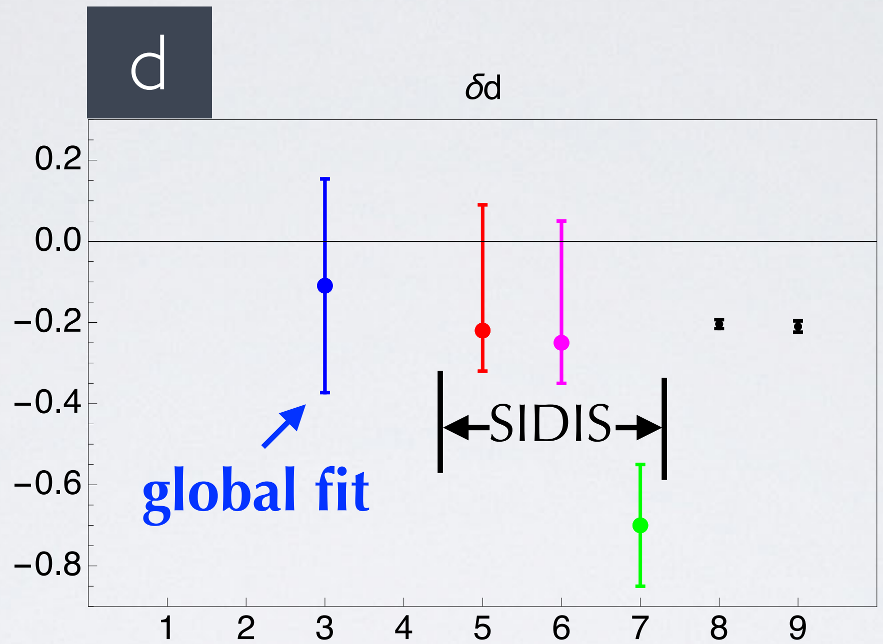
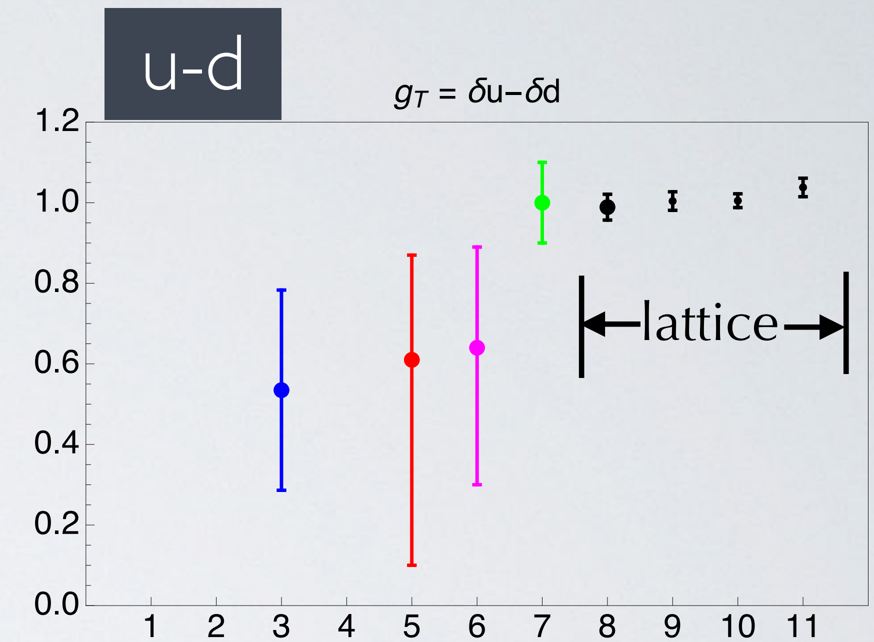
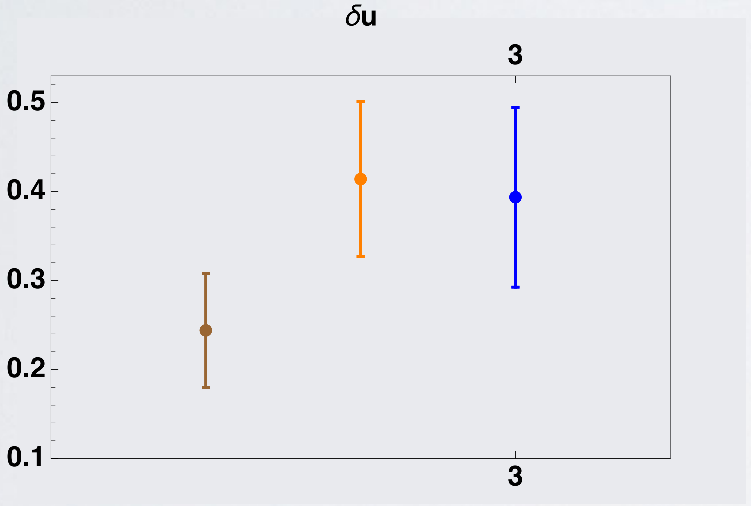
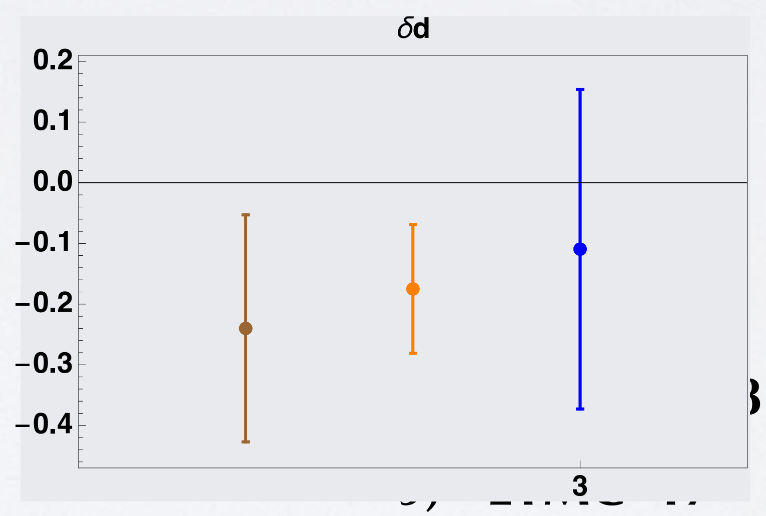
tensor charge

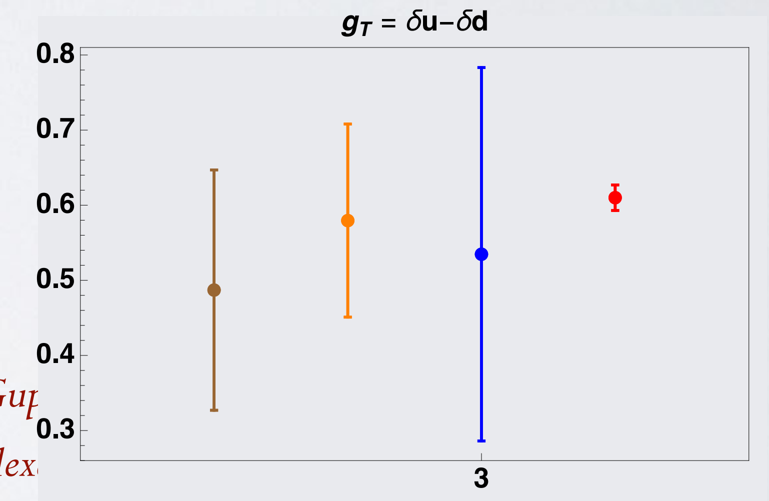












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*Gup... Alex... E P.R. D**96** (17) 099906*

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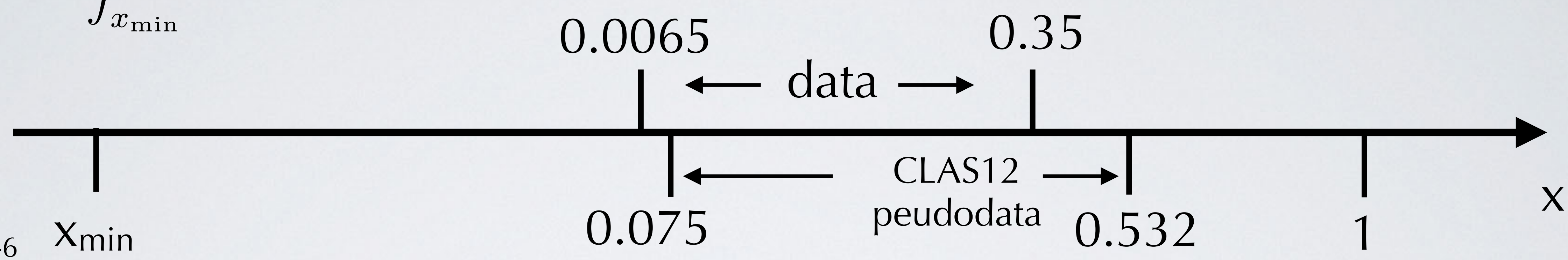
...) 91

better precision

but tension with lattice confirmed

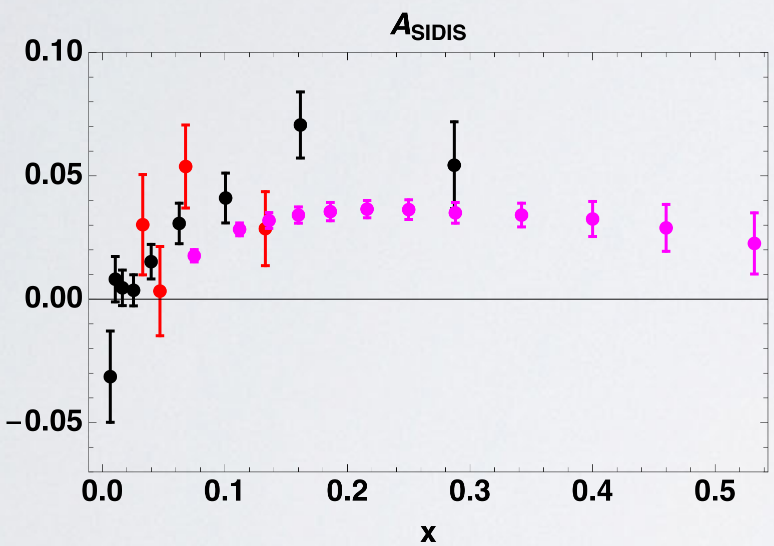
break down of Mellin moment

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



MSTW

x_{min}=10^{-6}



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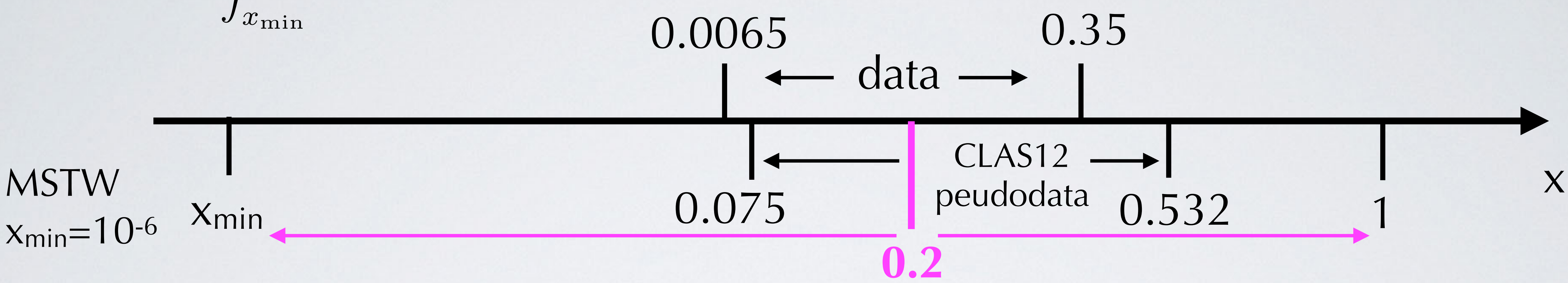

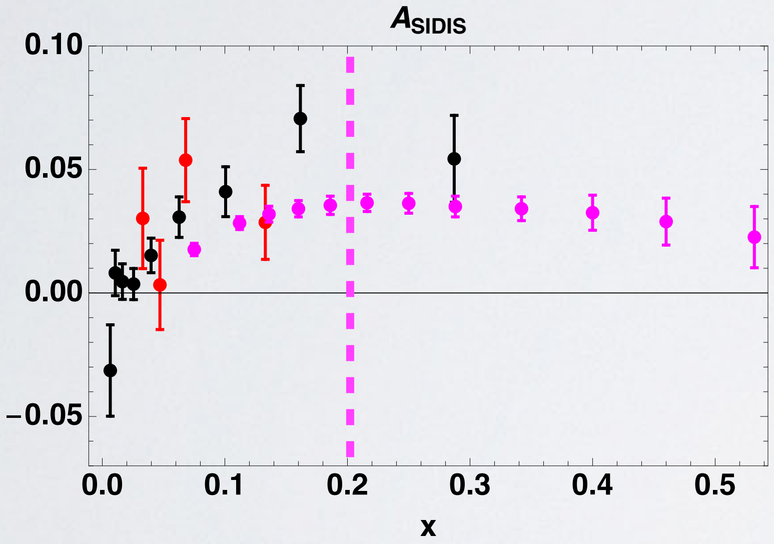

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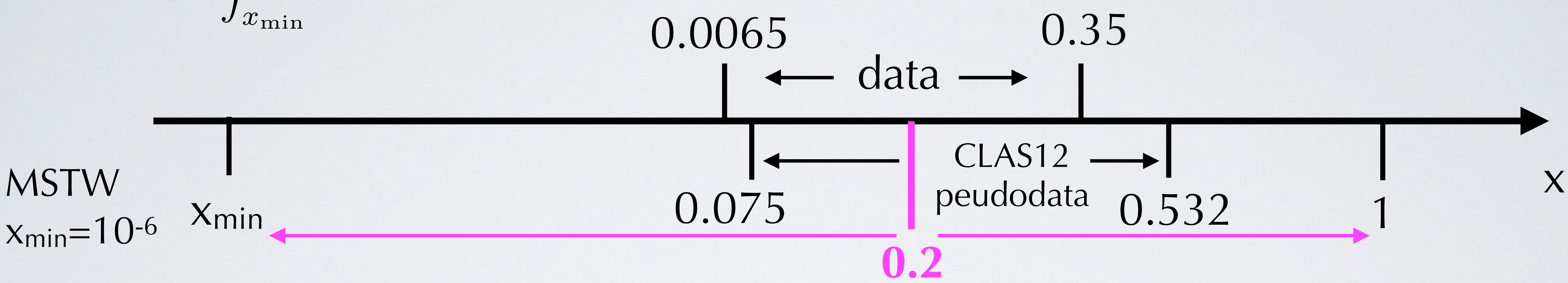
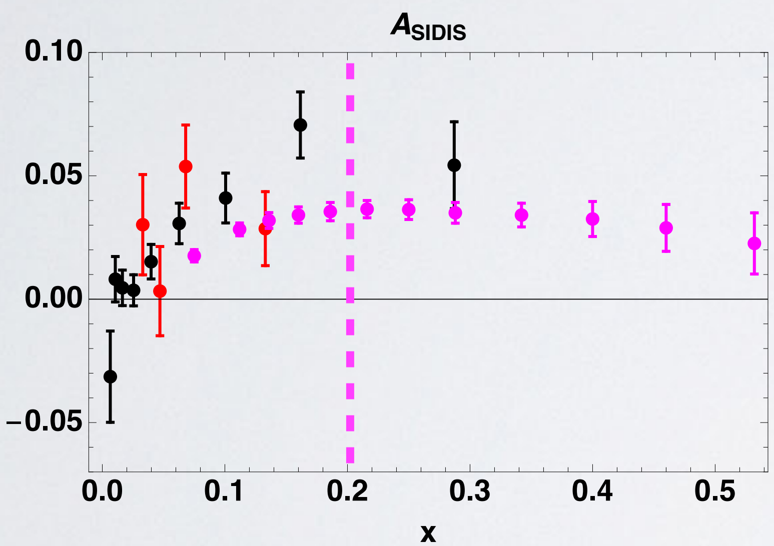
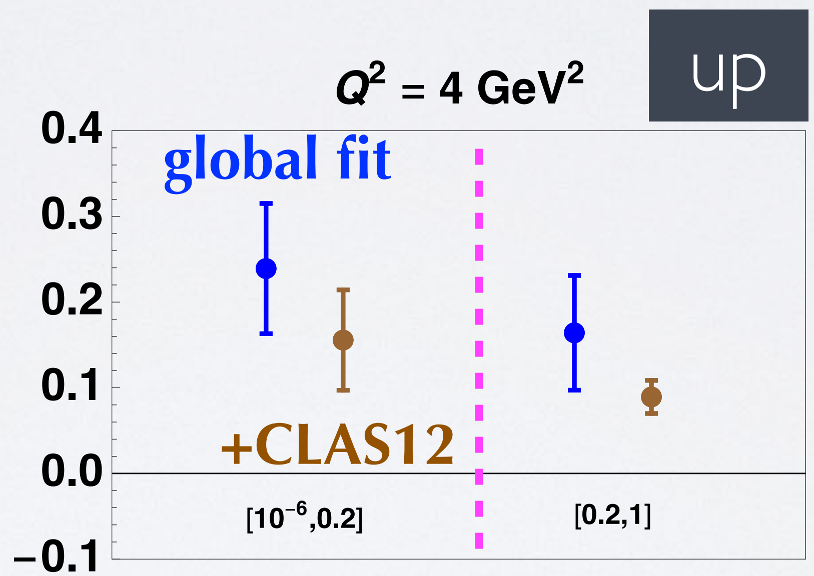
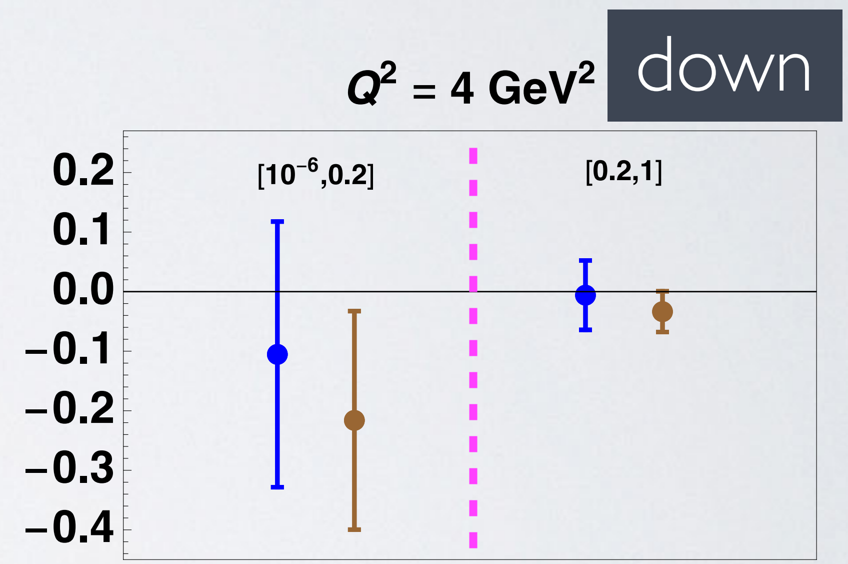




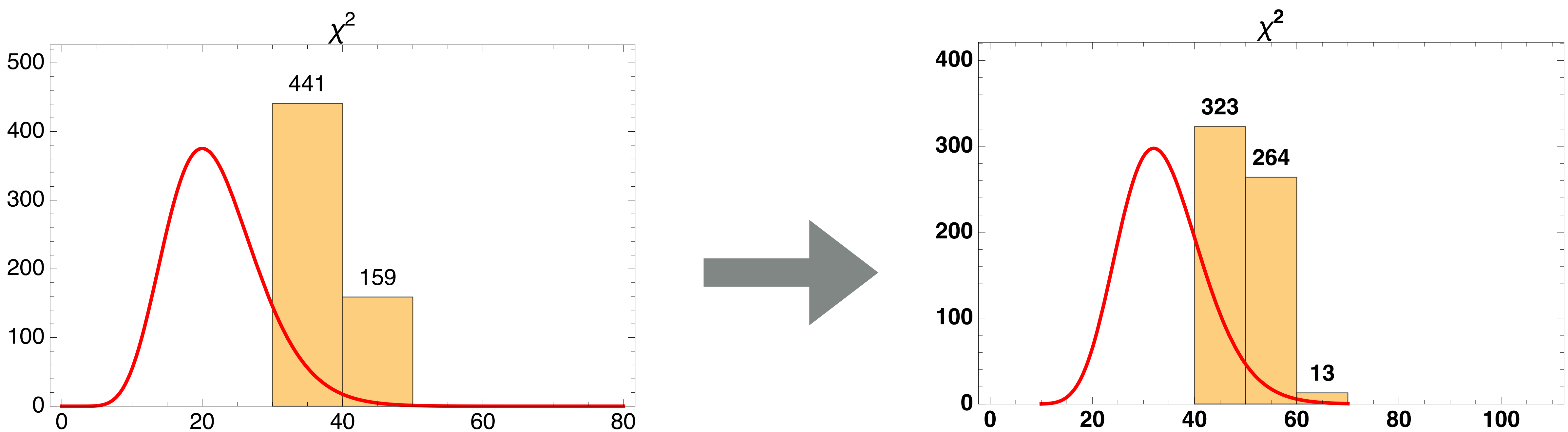




impact of CLAS12 pseudodata at large x (>0.2)
gives ~50% of up tensor charge
relative error $\Delta g_T/g_T$ from 82% → 43%

better χ^2

$\chi^2/\text{dof} = 1.76 \pm 0.11$ $\chi^2/\text{dof} = 1.48 \pm 0.10$

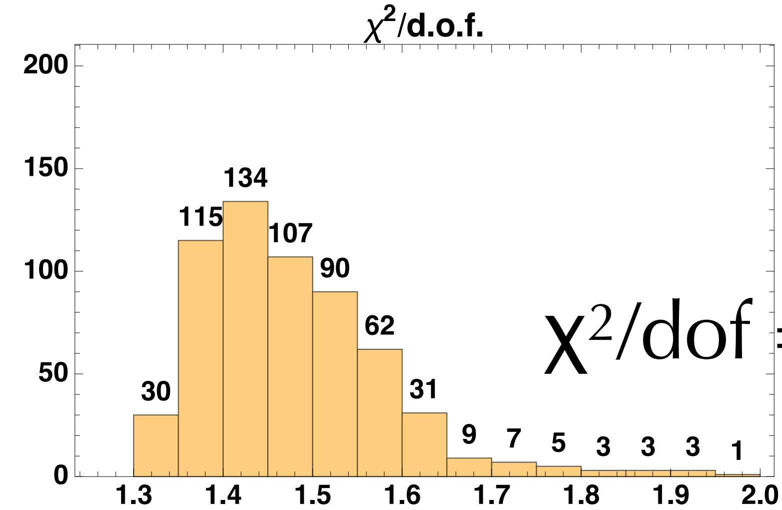


probability density function of
χ^2 distribution for
22 d.o.f. 34 d.o.f.

but central value of pseudodata not known
→ only spreading is meaningful

better χ^2

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



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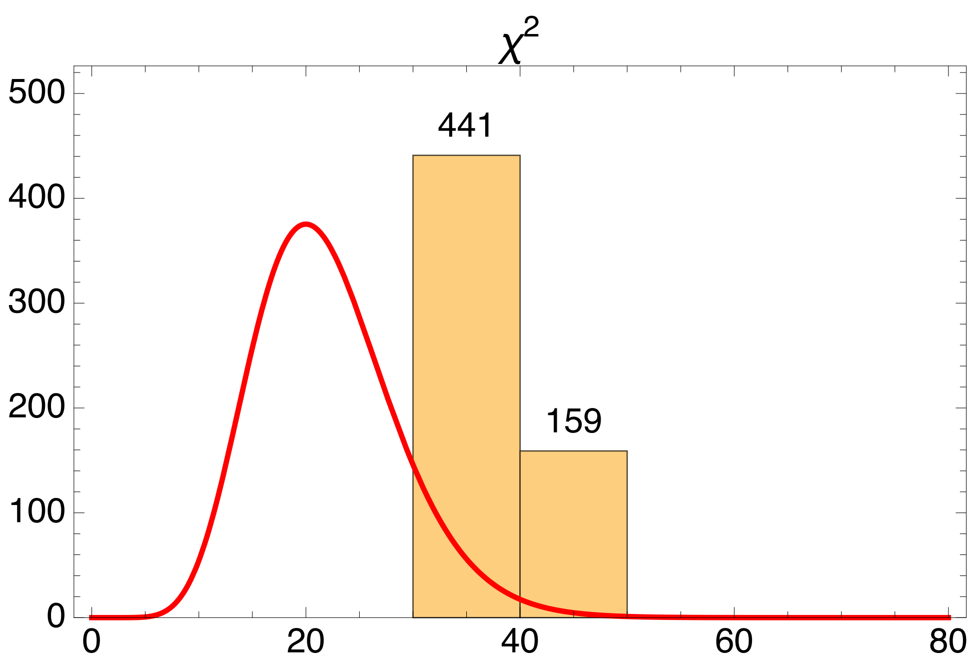
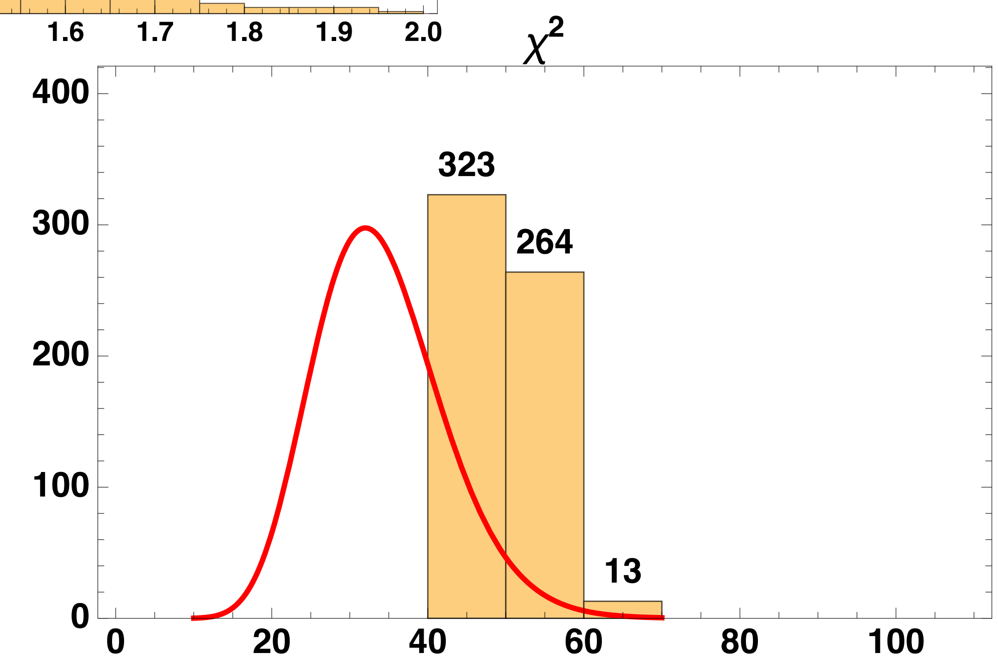




probability density function of

χ^2 distribution for

22 d.o.f. 34 d.o.f.

but central value of pseudodata not known

→ only spreading is meaningful

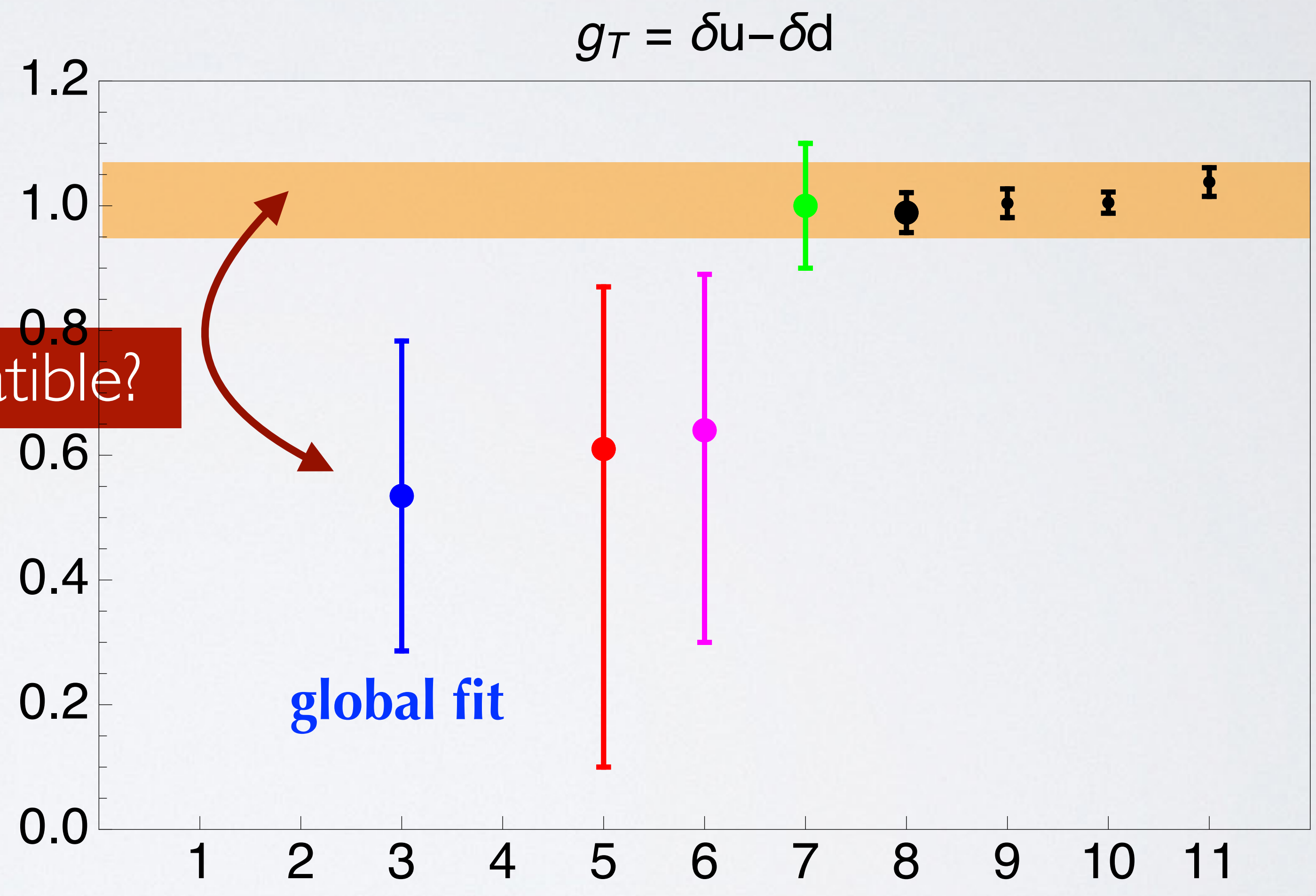
compatibility with lattice

add to SIDIS+pp data

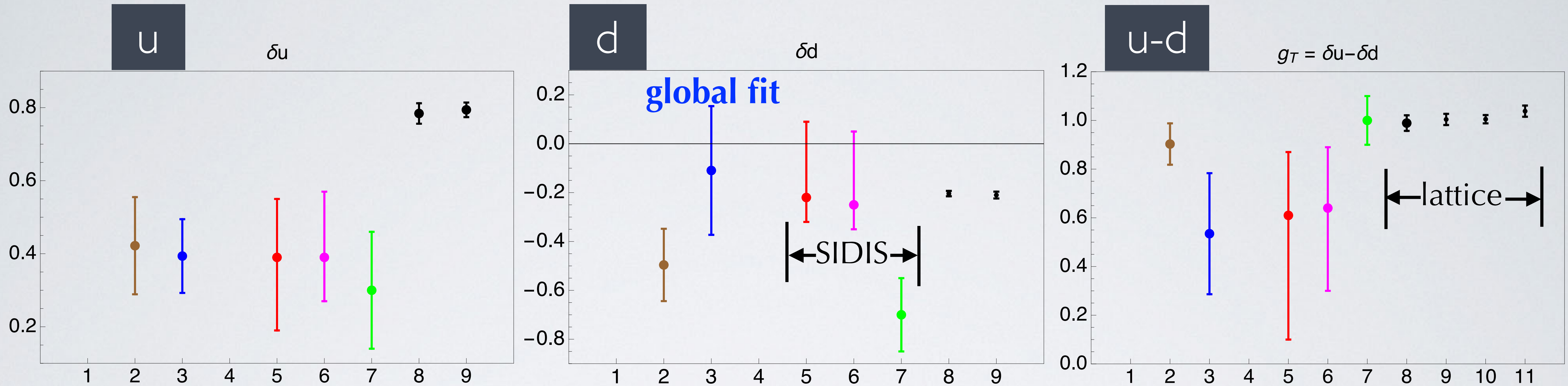
constraint to reproduce g_T from lattice

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

are they compatible?



tensor charge



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

2) global fit + constrain g_T

Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — 3) global fit '17

*Kang et al., P.R. D**93** (16) 014009* — 5) "TMD fit" * $Q^2=10$

*Anselmino et al., P.R. D**87** (13) 094019* — 6) Torino fit * $Q^2=1$

Lin et al., P.R.L. ***120*** *(18) 152502* — 7) JAM fit '17 * $Q_0^2=2$

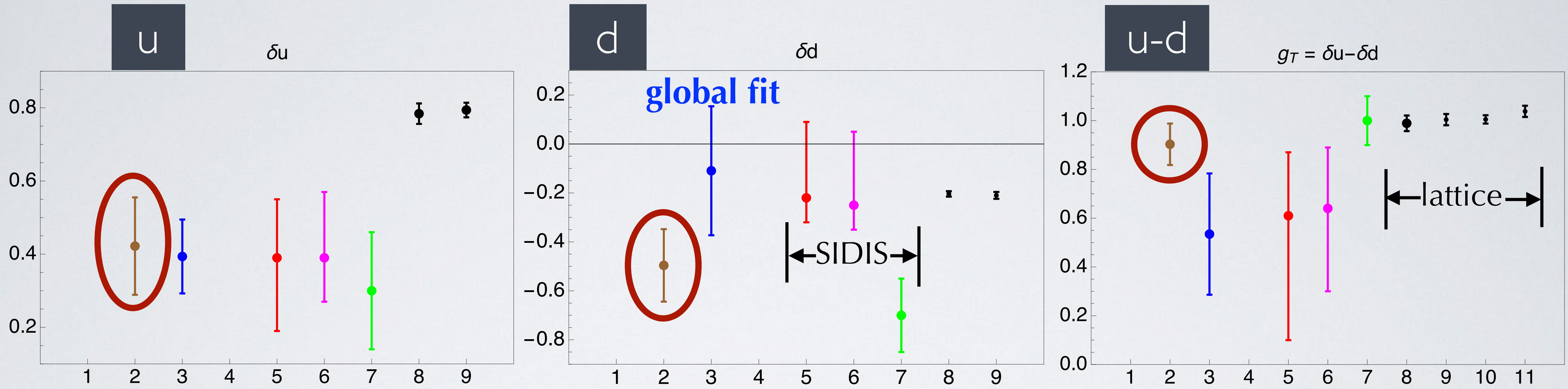
8) PNDME '18 — *Gupta et al., P.R. D**98** (18) 034503*

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

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

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

tensor charge



not yet full compatibility

Q^2=4 GeV^2 *

2) global fit + constrain g_T

Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — 3) global fit '17

*Kang et al., P.R. D**93** (16) 014009* — 5) "TMD fit" * Q^2=10

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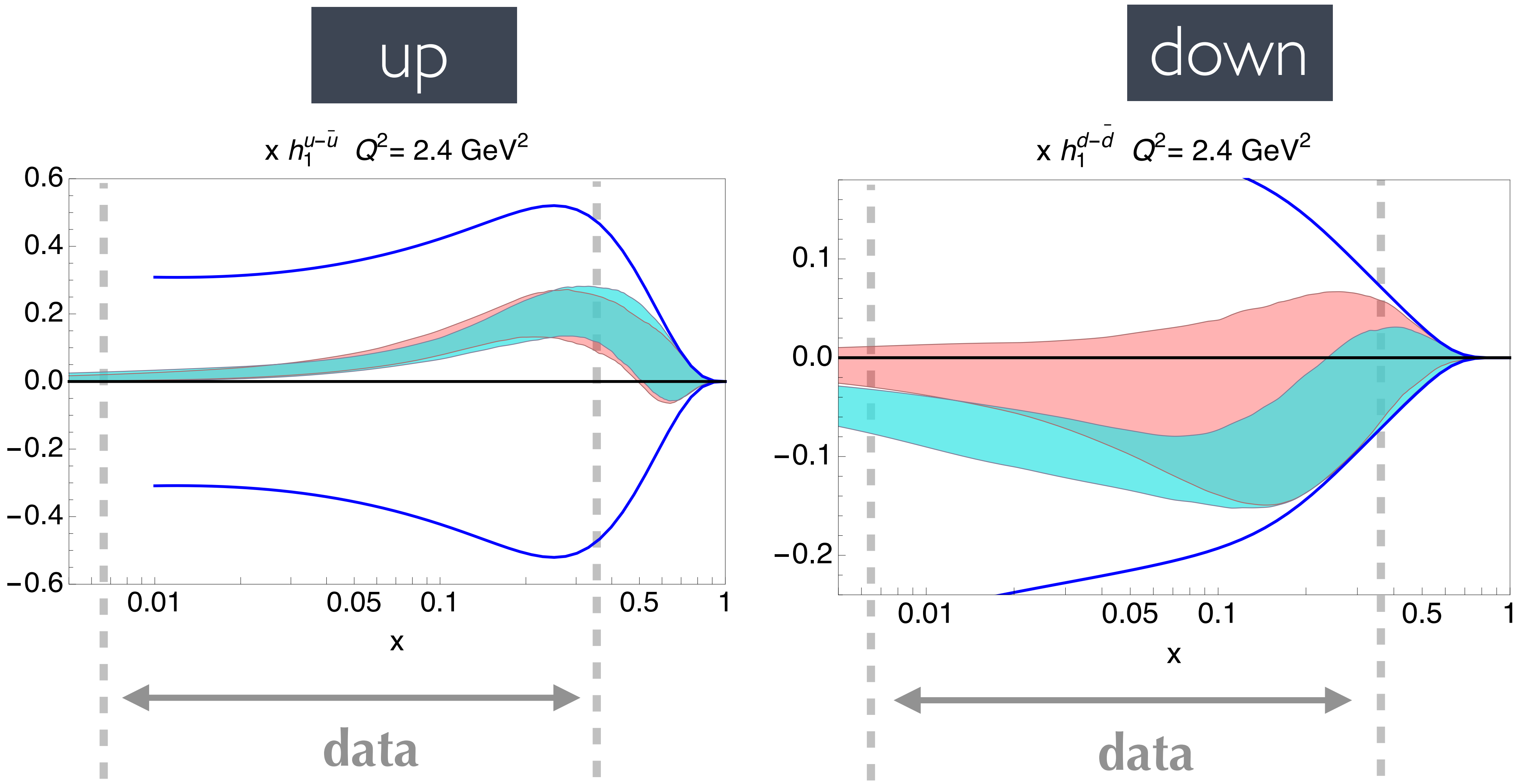
impact of lattice g_T constraint

global fit + lattice gT constraint

global fit

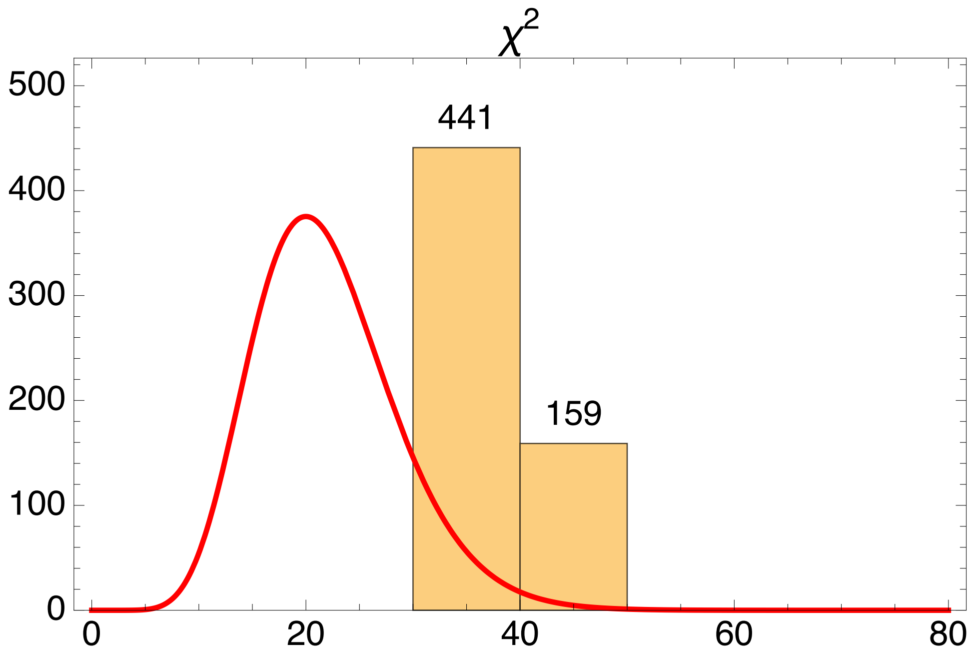
$$D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u/4 \\ D_1^u \end{cases}$$

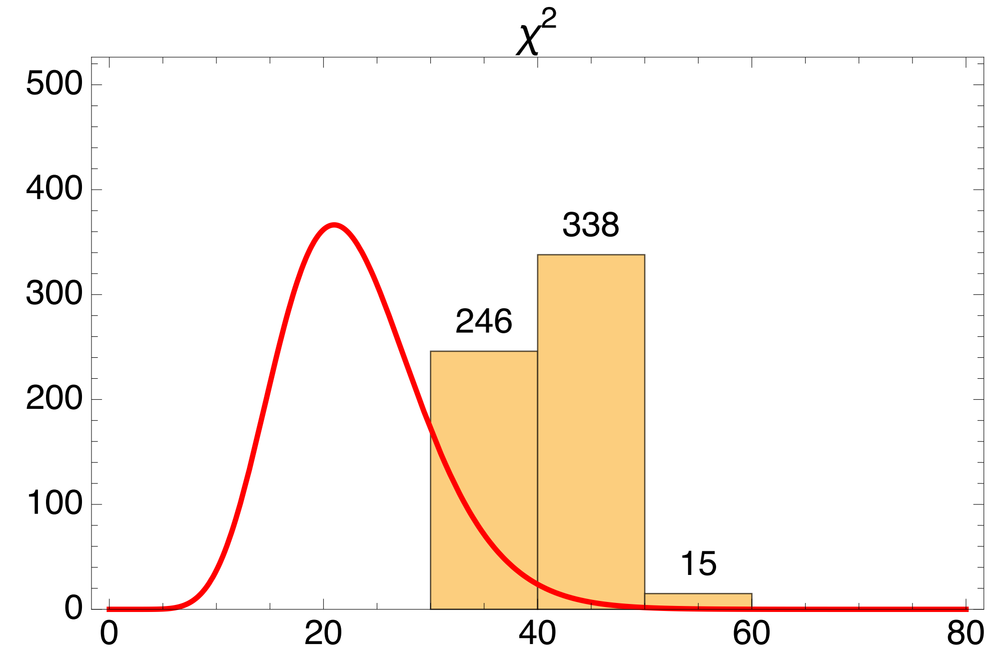


χ^2

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

$\chi^2/\text{dof} = 1.82 \pm 0.25$





probability density function of
χ^2 distribution for
22 d.o.f. 23 d.o.f.

compatibility with lattice

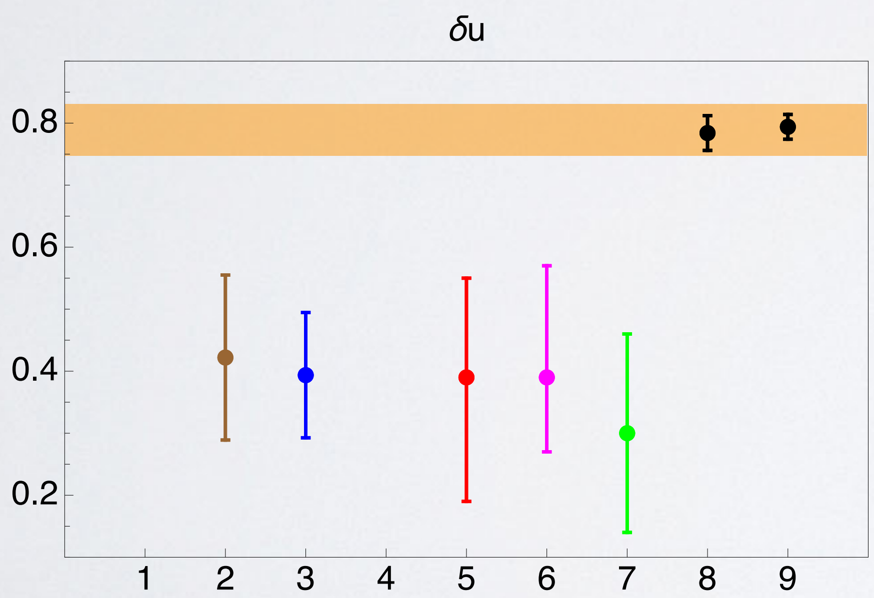
add to SIDIS+pp data

constraint to reproduce from lattice

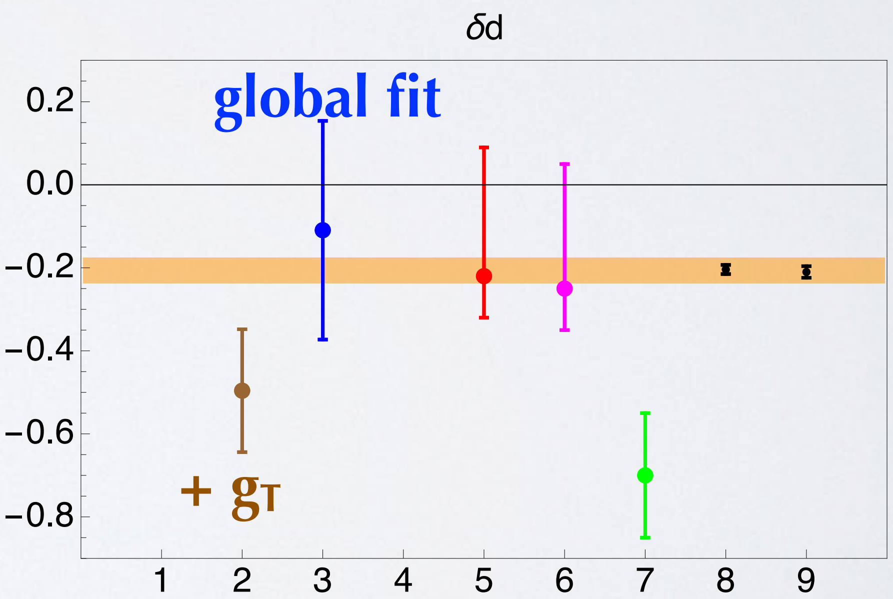
g_T , δu , δd

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

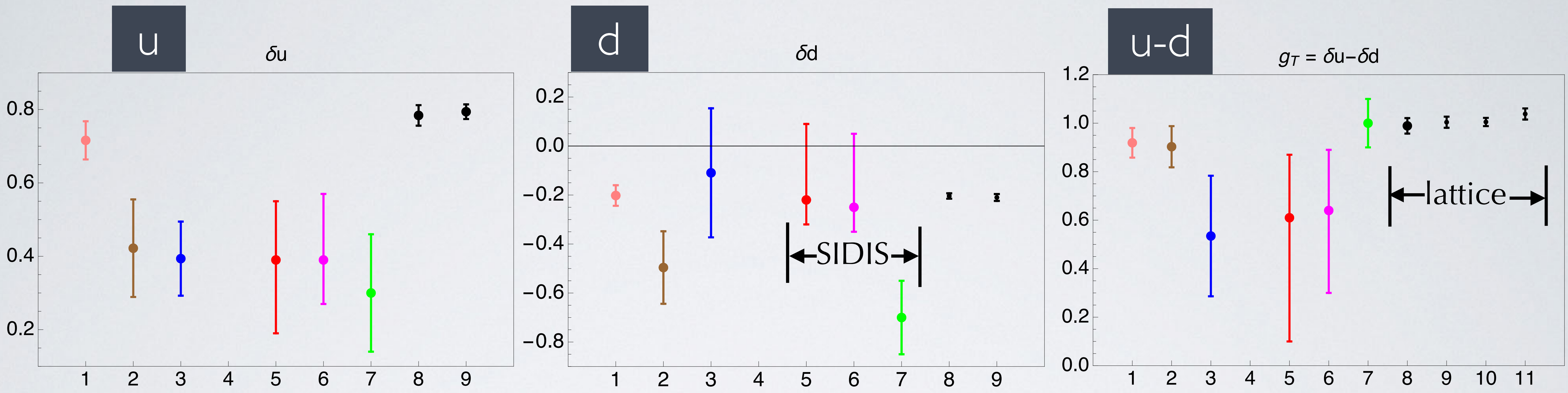
$\overline{\delta u}^{latt} = 0.782 \pm 0.031$



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



tensor charge



Q^2=4 GeV^2 *

1) **global fit + constrain g_T , δu , δd**

2) **global fit + constrain g_T**

Radici & Bacchetta, P.R.L. ***120*** *(18) 192001* — 3) **global fit '17**

*Kang et al., P.R. D****93*** *(16) 014009* — 5) **"TMD fit" * Q^2=10**

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Lin et al., P.R.L. ***120*** *(18) 152502* — 7) **JAM fit '17 * Q_0^2=2**

8) **PNDME '18** — *Gupta et al., P.R. D****98*** *(18) 034503*

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

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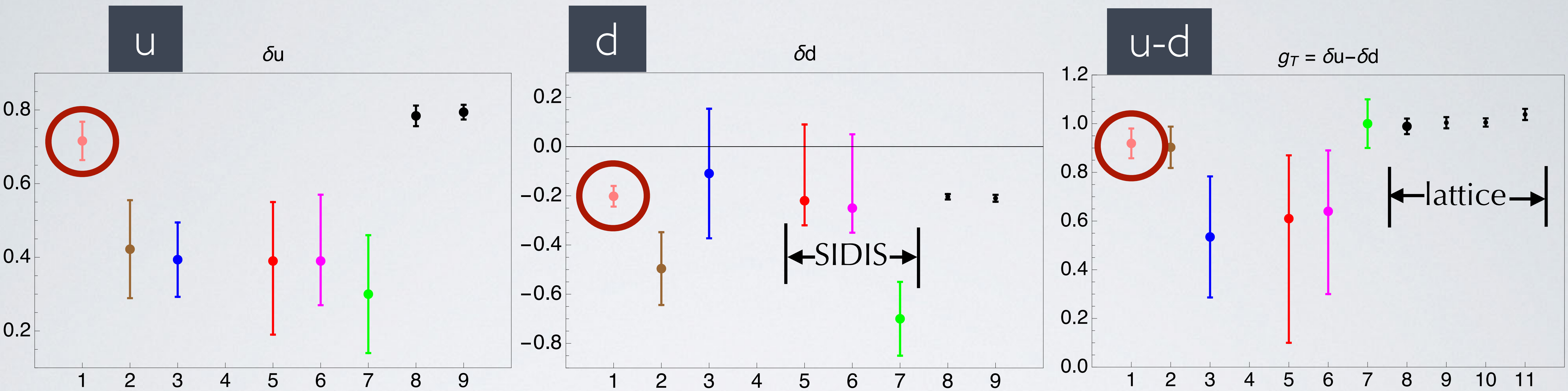
tensor charge



Q^2=4 GeV^2 *

compatible, but…

1) global fit + constrain g_T , δu , δd

2) global fit + constrain g_T

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

3) global fit '17

*Kang et al., P.R. D****93*** *(16) 014009* — 5) "TMD fit" * Q^2=10

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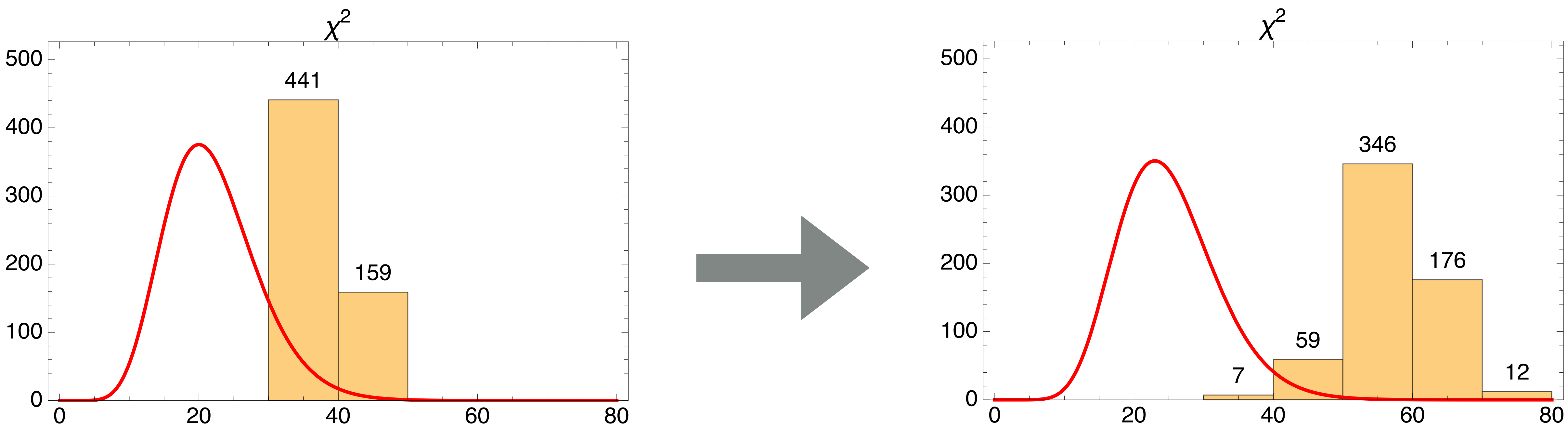
χ^2

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

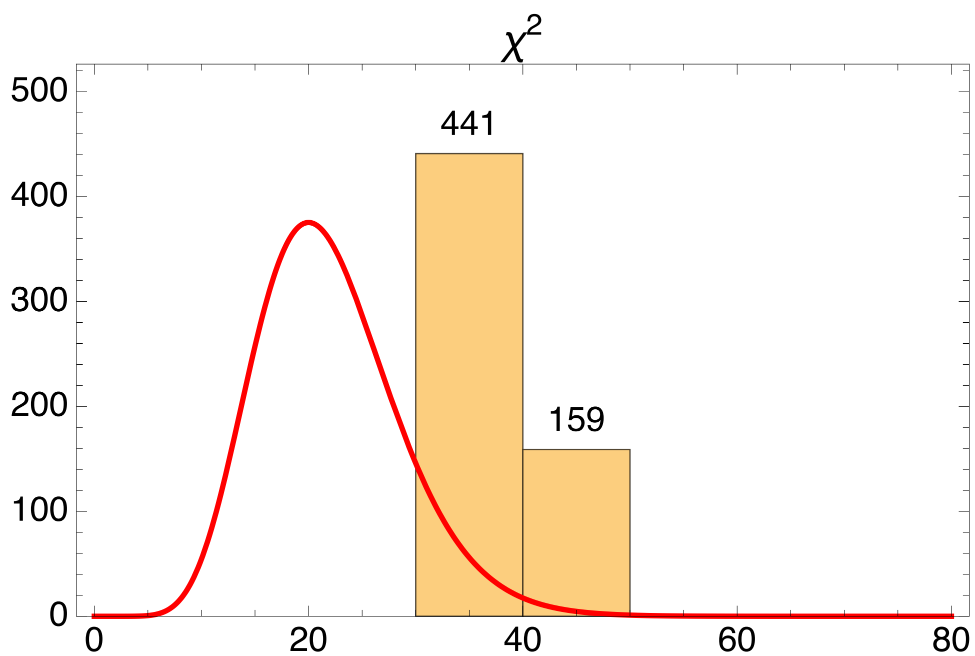
$\chi^2/\text{dof} = 2.29 \pm 0.25$



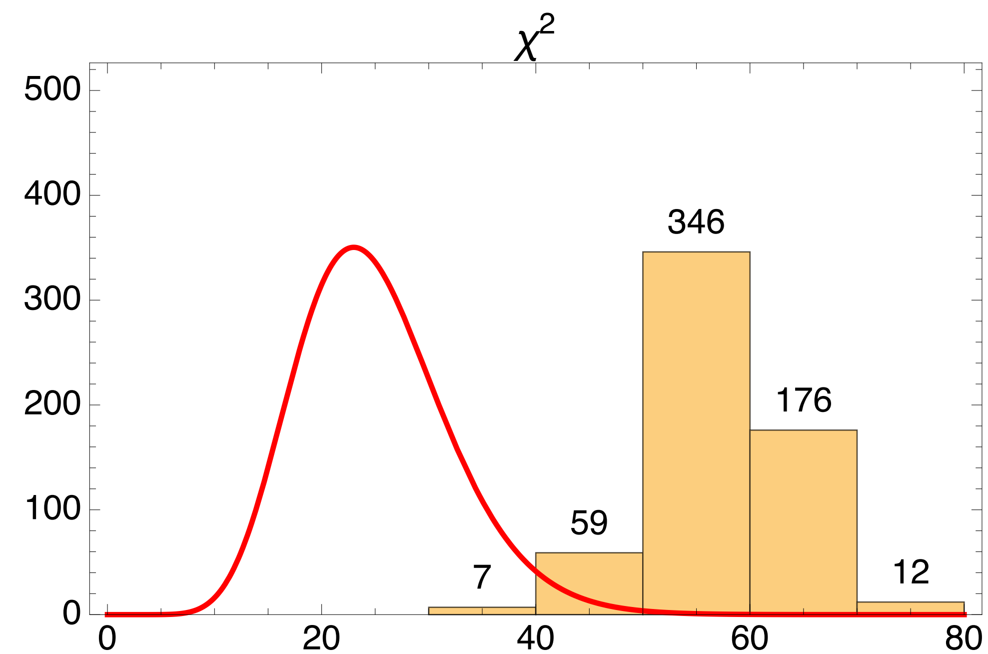
probability density function of
χ^2 distribution for
22 d.o.f. 25 d.o.f.

χ^2

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



$\chi^2/\text{dof} = 2.29 \pm 0.25$



probability density function of
χ^2 distribution for
22 d.o.f.   25 d.o.f.

compatible, but… statistically very unlikely !

More (existing) data …

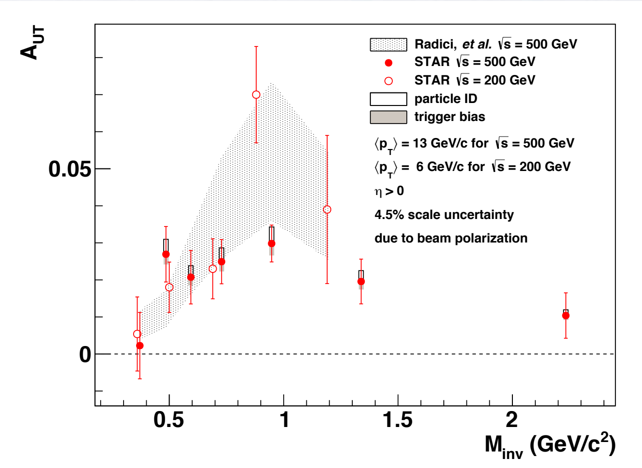
Di-hadron

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

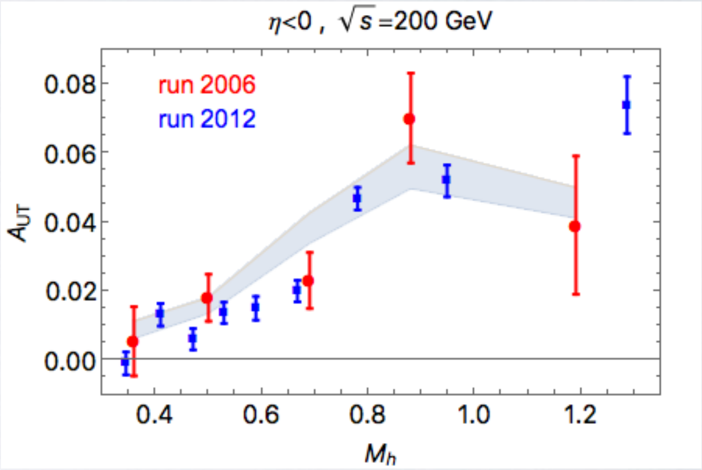
*Seidl et al., P.R. D**96** (17) 032005*

p-p↑ collisions

➡ 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*

SIDIS

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

Conclusions / Open Problems

- 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 → **need more/better "neutron target" data**
- **NO** apparent simultaneous **compatibility with lattice** for tensor charge in up, down, and isovector channels
- adding **Compass** SIDIS **pseudo-data for deuteron** increases precision of down, but leaves this scenario unaltered
- adding **CLAS12** SIDIS **pseudo-data for proton** affects large x (error of up tensor charge reduced by ~2x), but tension with lattice even increased
- it is possible to force replicas to be **compatible with data and lattice** but situation is **statistically very unlikely**

enlarging the covered x-range is crucial → (target)$^{\uparrow}$ program at JLab12 !

THANK YOU

Back-up

the leading-twist PDF / TMD map

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 $h_{1T}^\perp$

1- **h_1** needed as the 3rd basic quark **PDF** for spin-1/2 objects

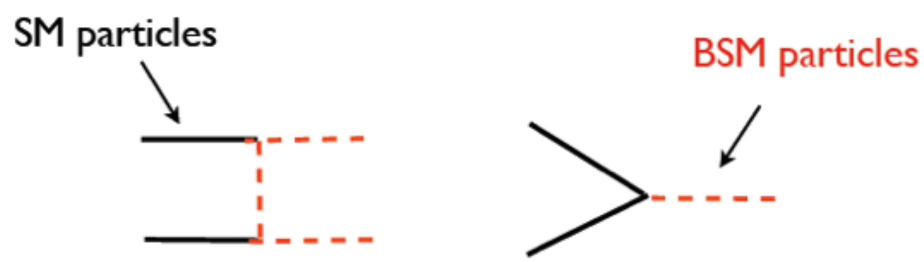
2- address novel QCD dynamics in the chiral-odd sector, also as **TMD**

potential for BSM discovery ?

E

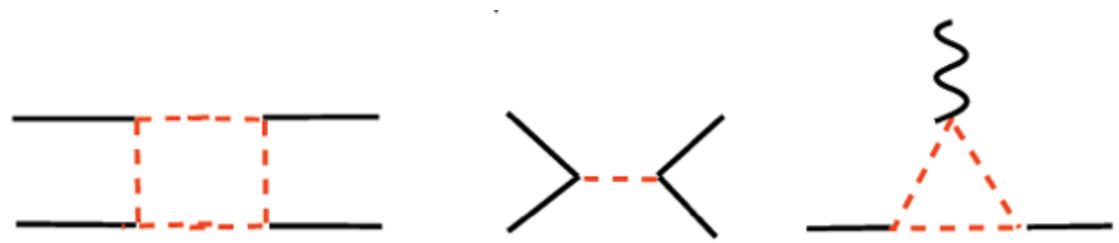
at least, two ways of searching :

M_{BSM}
high energy



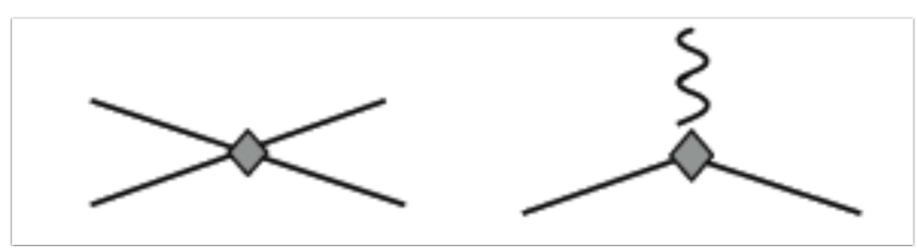
1- direct access
to new particles

$E_{exp} \ll M_{BSM}$
low energy
high precision

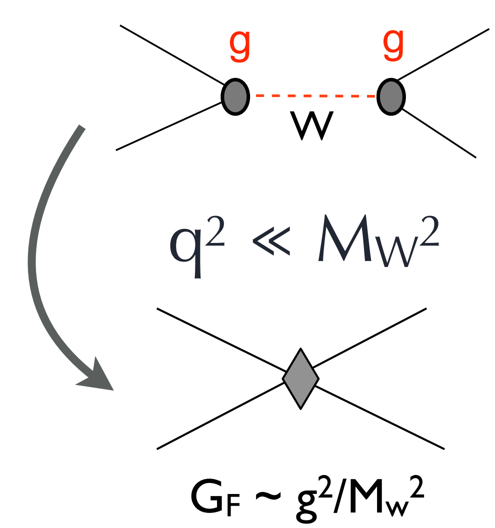


2- indirect access
virtual effects

footprint:
new local
operators



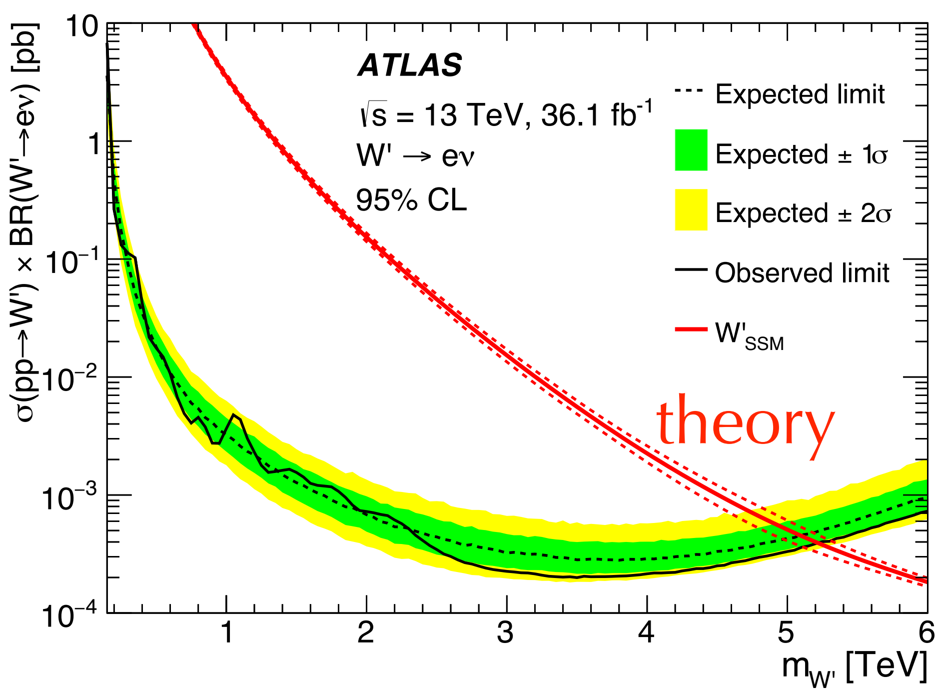
Example:
weak CC
interaction



Examples of direct access

- **p p → e⁻ ν + X**   search for W′ → e⁻ ν with W′ heavy partner of W

limits on cross section

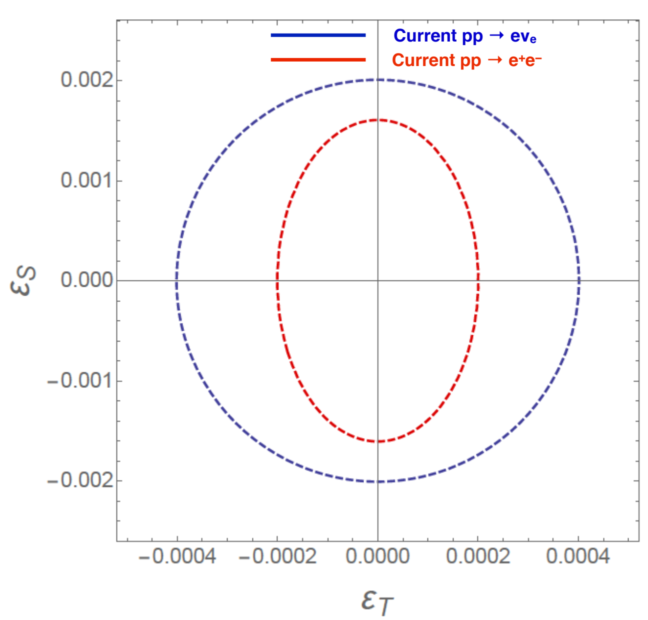


data / background

Aaboud et al. (ATLAS), E.P.J. ***C78*** *(18) 401*

$M_{W'}$ > 5.1–5.2 TeV at 95% C.L.

puts contraints on BSM operators including scalar (ε_S) & tensor (ε_T)



Gupta et al. (PNDME), P.R. ***D98*** *(18) 034503*

constraints reinforced including
p p → Z′ → e⁻ e⁺ + X

Examples of indirect access

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

hadron level

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

exp. data

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

$$\approx \frac{M_W^2}{M_{\rm BSM}^2}$$

quark level

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

?

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

isovector tensor charge

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

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

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

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

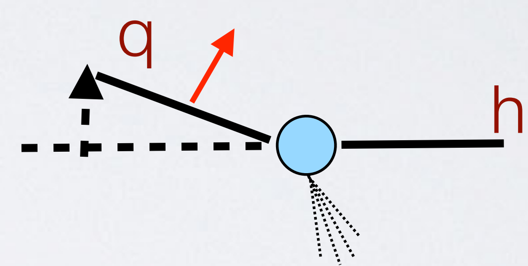
transversity

extraction of transversity

transversity is chiral-odd → need a chiral-odd partner

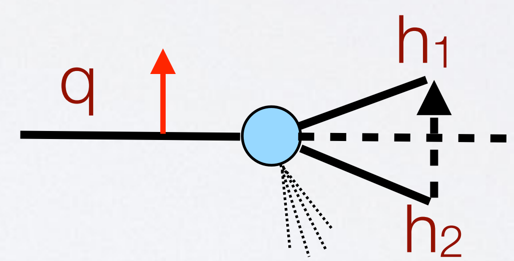
- itself : fully polarized Drell-Yan ✗

- Collins function : the Collins effect



TMD framework **h_1 as TMD**

- IFF : the di-hadron mechanism



collinear framework **h_1 as PDF**

- hadron-in-jet mechanism : mixed framework **h_1 as PDF**

2-hadron-inclusive production

framework
collinear
factorization

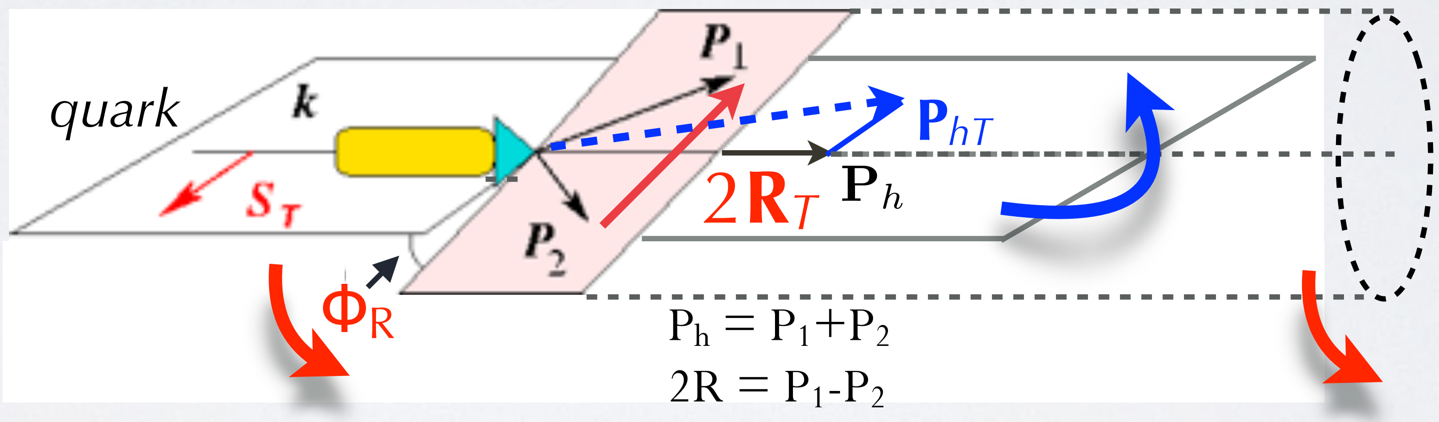
Collins, Heppelman, Ladinsky, ***N.P. B420*** *(94)*

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

↕

M_h

invariant mass



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

correlation S_T and R_T → **azimuthal asymmetry**

advantages of di-hadron mechanism

collinear framework

- simple product of PDF and IFF

Ex.: SIDIS

$$A_{\text{SIDIS}}^{\sin(\phi_R+\phi_S)}(x,z,M_h^2) \sim -\frac{\sum_q e_q^2\; h_1^q(x)\; \frac{|\boldsymbol{R}_T|}{M_h}\; H_{1,q}^{\sphericalangle}(z,M_h^2)}{\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z,M_h^2)}$$

x-dependence of A_{SIDIS} all in PDF

- flavor sum simplified by symmetries of IFF { isospin symmetry, charge conjugation }
  + data on proton and deuteron targets
  → separate valence up and down

- factorization theorems for all hard processes
  → universality of $h_1\ H_1^{\sphericalangle}$ mechanism

advantages of di-hadron mechanism

$$A_{\text{SIDIS}}^{\sin(\phi_R+\phi_S)}(x,z,M_h^2) \sim -\frac{\sum_q e_q^2\; h_1^q(x)\; \frac{|\boldsymbol{R}_T|}{M_h}\, H_{1,q}^{\sphericalangle}(z,M_h^2)}{\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z,M_h^2)}$$

$\pi^+\pi^-$ tree level

$$H_1^{\sphericalangle\, u} = -H_1^{\sphericalangle\, d}$$ isospin symmetry

$$H_1^{\sphericalangle\, q} = -H_1^{\sphericalangle\, \bar{q}}$$

$$D_1^q = D_1^{\bar{q}}$$

} charge conjugation

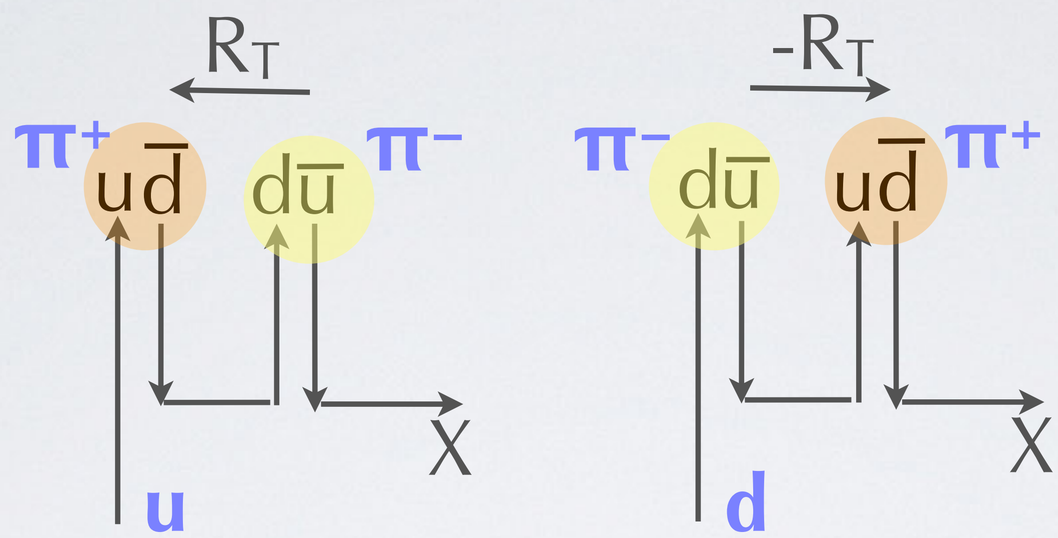
\+ data on proton and deuteron targets

proton $$x h_1^{u-\bar{u}} - \frac{1}{4} x h_1^{d-\bar{d}} = F\,[A_{\text{SIDIS}}^{p}\ \text{data},\ H_1^{\sphericalangle\, u},\ f_1^q D_1^q]$$

deuteron $$x h_1^{u-\bar{u}} + x h_1^{d-\bar{d}} = \tilde{F}\,\left[A_{\text{SIDIS}}^{D}\ \text{data},\ H_1^{\sphericalangle\, u},\ f_1^q D_1^q\right]$$

separate valence up and down

IFF symmetries



$$H_1^{\sphericalangle\, u} = -H_1^{\sphericalangle\, d} \quad \text{isospin symmetry}$$

$$\left.\begin{array}{rcl} H_1^{\sphericalangle\, q} & = & -H_1^{\sphericalangle\, \bar{q}} \\ D_1^{q} & = & D_1^{\bar{q}} \end{array}\right\} \text{charge conjugation}$$

valid only for $(\pi^+\pi^-)$ pairs and at tree level

hadronic collisions in Mellin space

$d\sigma\,(\eta, M_h, P_T)$ 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**

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

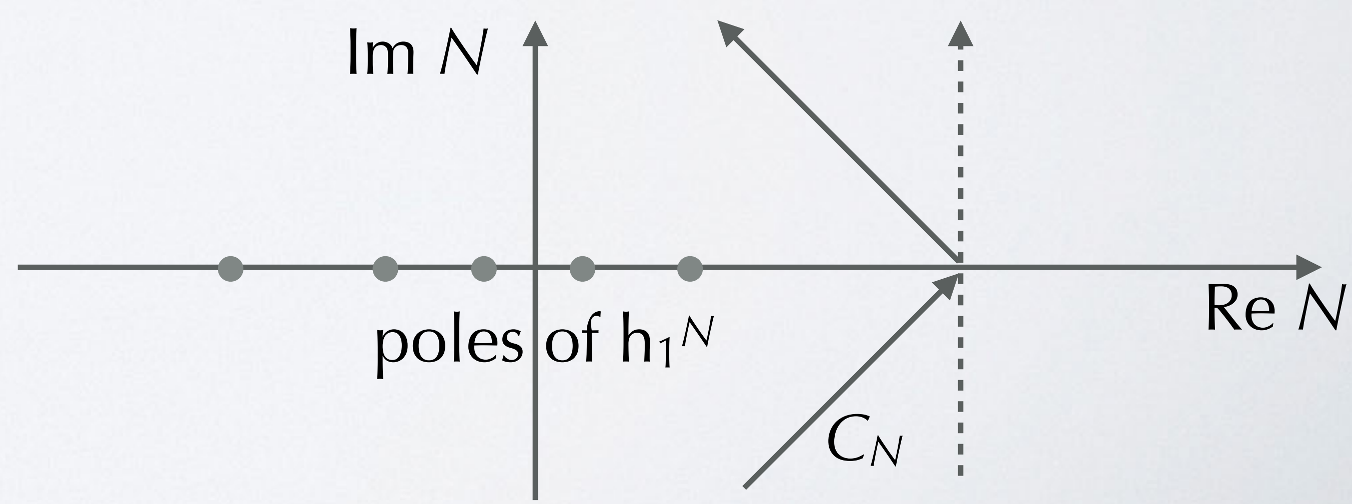
*Stratmann & Vogelsang, P.R. D**64** (01) 114007*

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

$$F_b(N, \eta, |\mathbf{P}_T|, M_h)$$

pre-compute F_b only one time on contour C_N

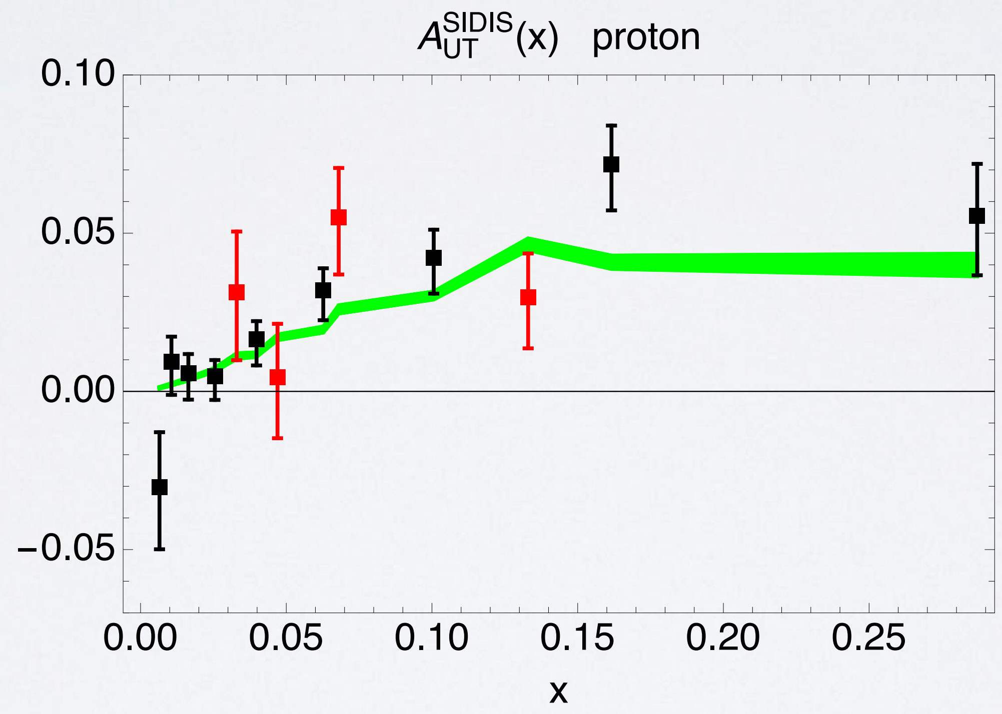
this **speeds up** convergence and facilitates $\int dN$, provided that **h_1^N is known analytically**



statistical uncertainty

the bootstrap method

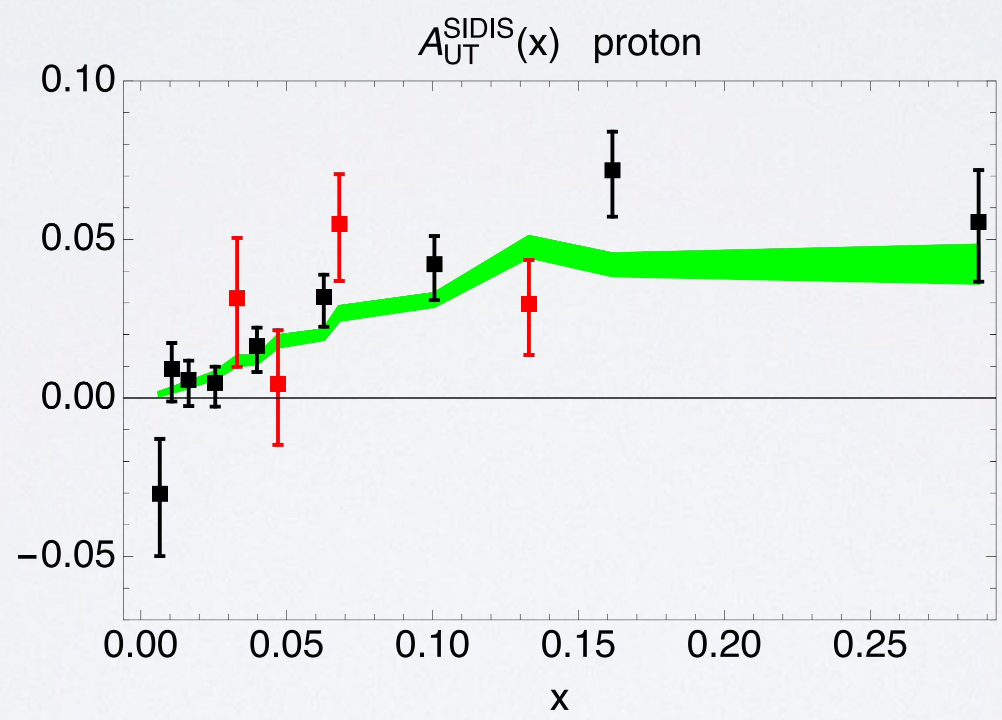
- shift each exp. point by Gaussian noise within exp. variance
- create sets of virtual points to be fitted: 50



statistical uncertainty

the bootstrap method

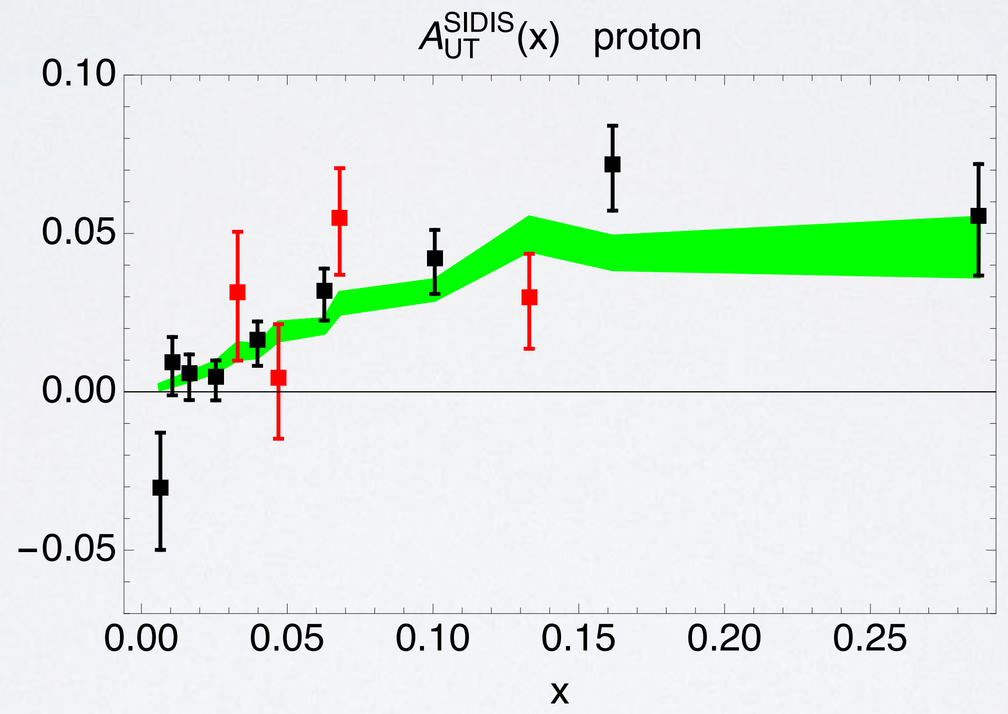
- shift each exp. point by Gaussian noise within exp. variance
- create sets of virtual points to be fitted: 50, 100



statistical uncertainty

the bootstrap method

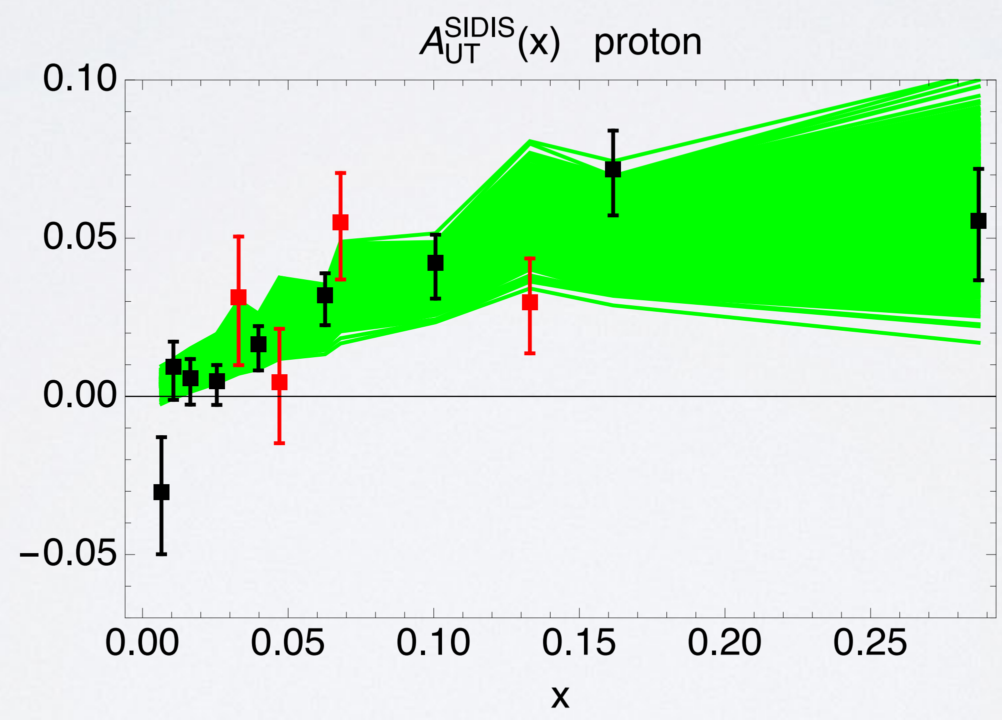
- shift each exp. point by Gaussian noise within exp. variance
- create sets of virtual points to be fitted: 50, 100, 200 sets…



statistical uncertainty

the bootstrap method

- shift each exp. point by Gaussian noise within exp. variance
- create sets of virtual points to be fitted: 50, 100, 200 sets… until average and standard deviation reproduce original exp. points (here, 200x3=600)



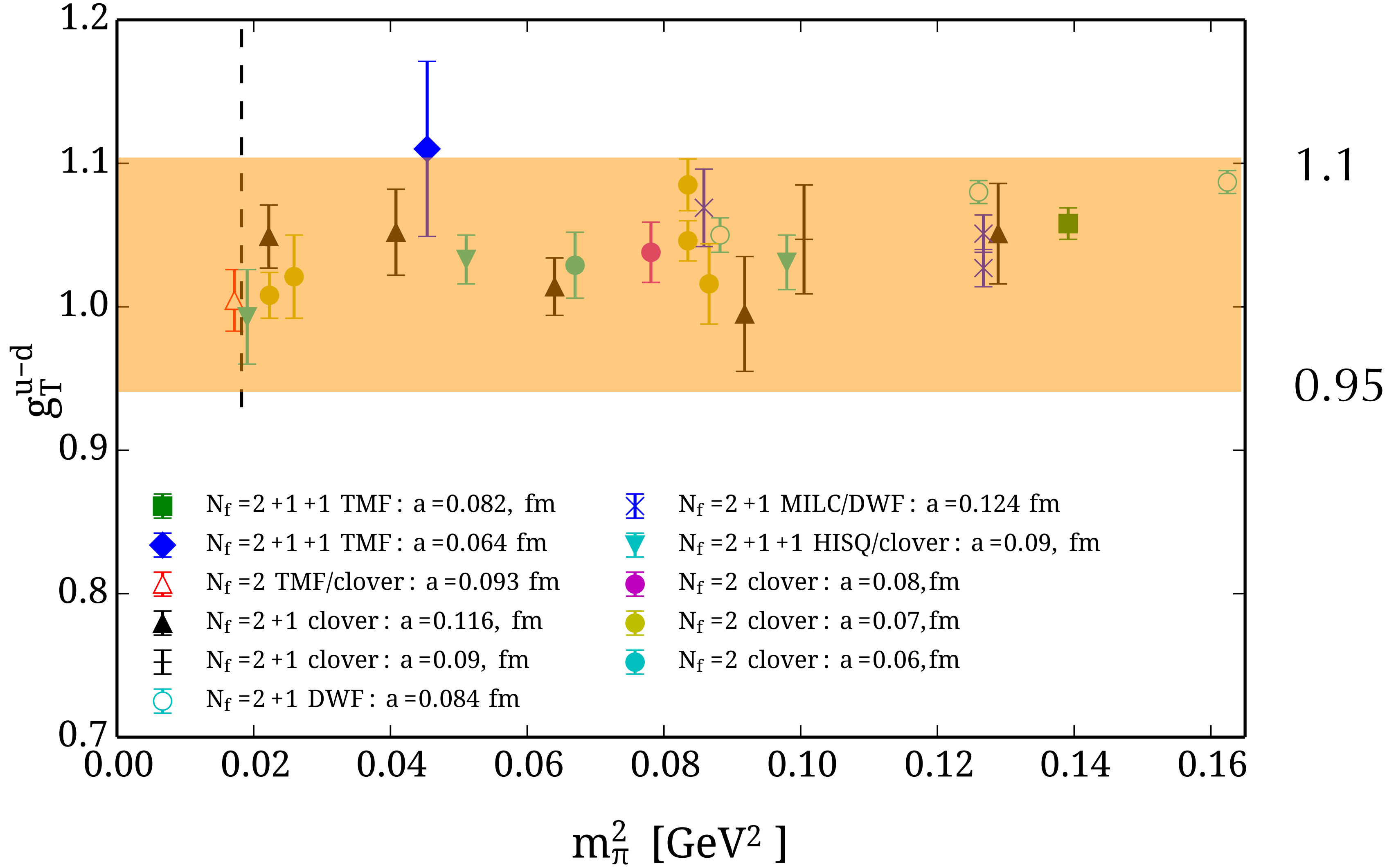
isovector tensor charge $g_T = \delta u - \delta d$

lattice results

with different

discretization schemes, lattice spacings, volumes

Q^2=4 GeV^2



lattice quasi-PDF

see also arXiv:1803.04393 (LP^3)

Alexandrou, arXiv:1612.04644

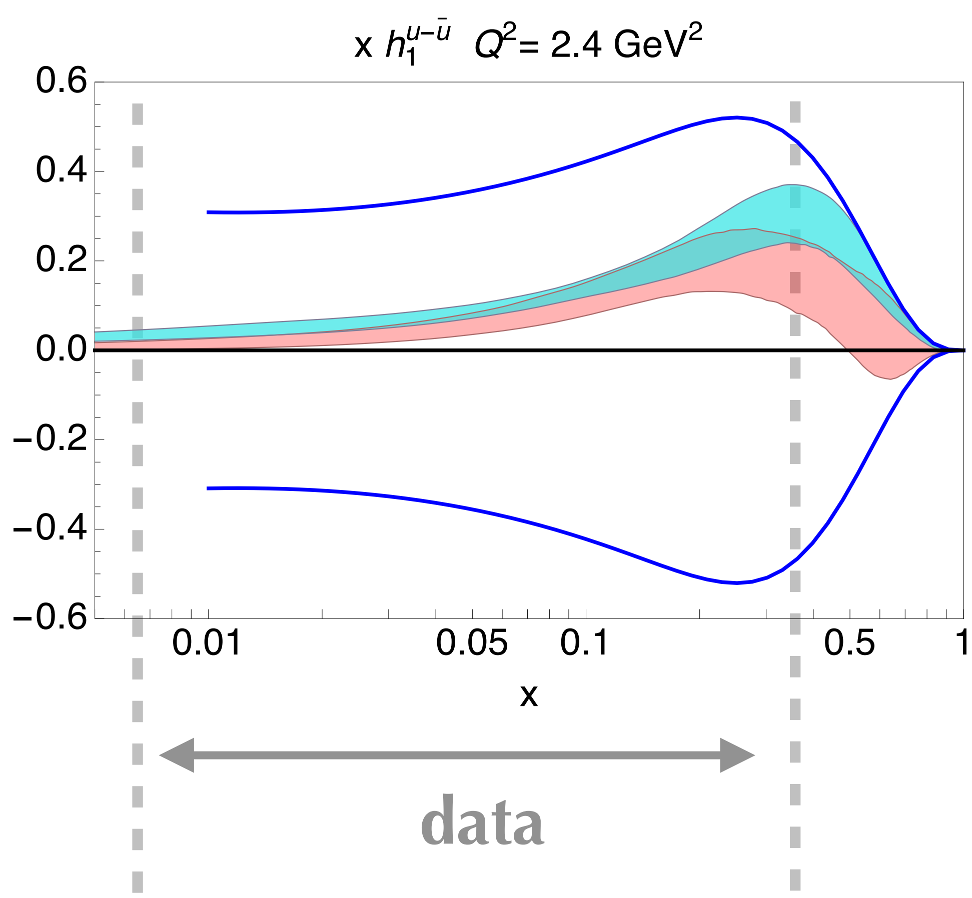
impact of "full" lattice constraint

global fit + lattice (g_T, δu, δd) constraint

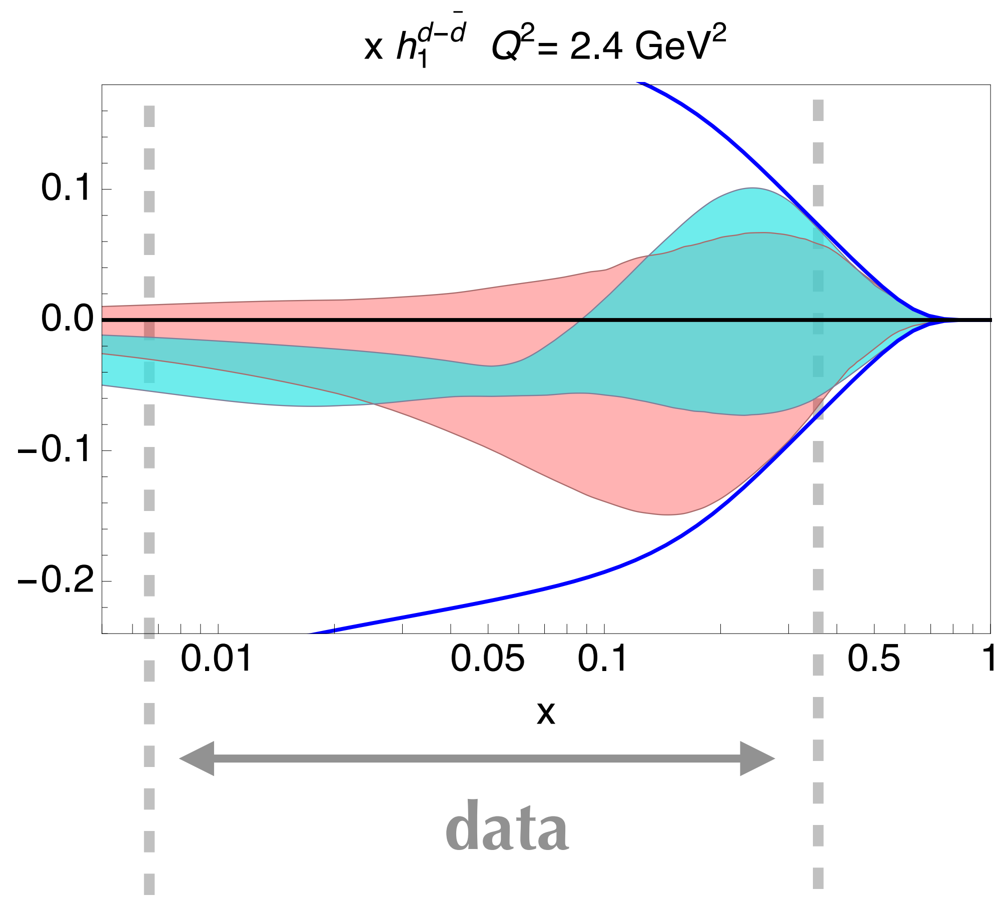
global fit

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

up



down



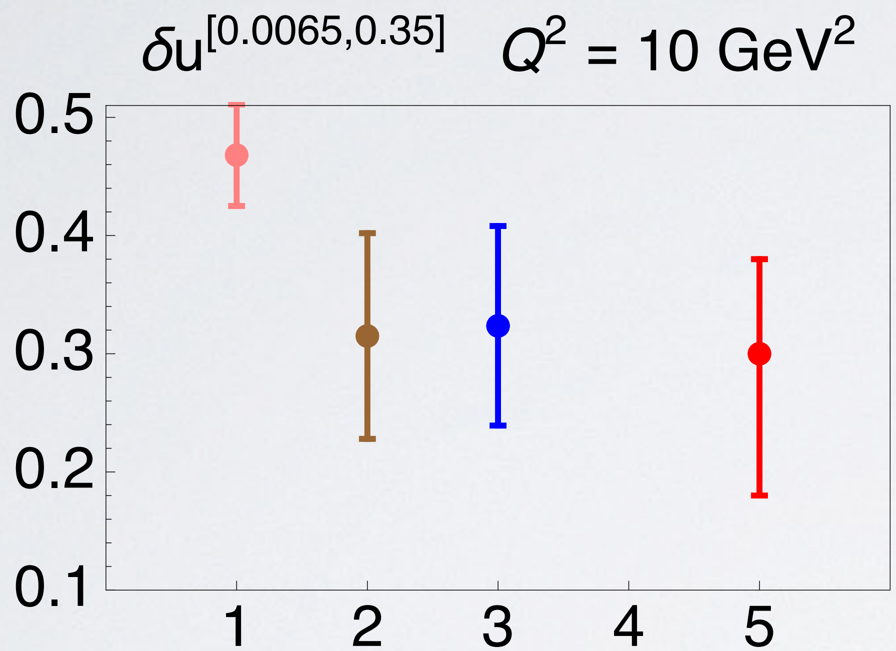
higher up, even within x-range of data

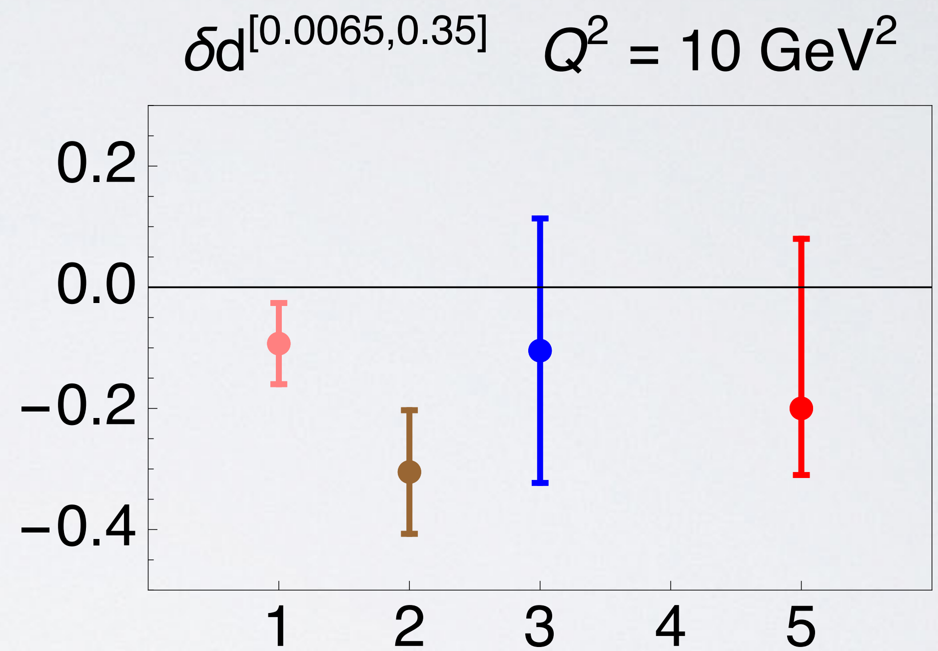
truncated tensor charge

truncated

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

up





down

1) global fit + constrain g_T , δu , δd

2) global fit + constrain g_T

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

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