INT-17-3 week 5

Hadron Imaging at JLab and at future EIC

Sept. 25-29, 2017

Transversity and tensor charge

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in collaboration with

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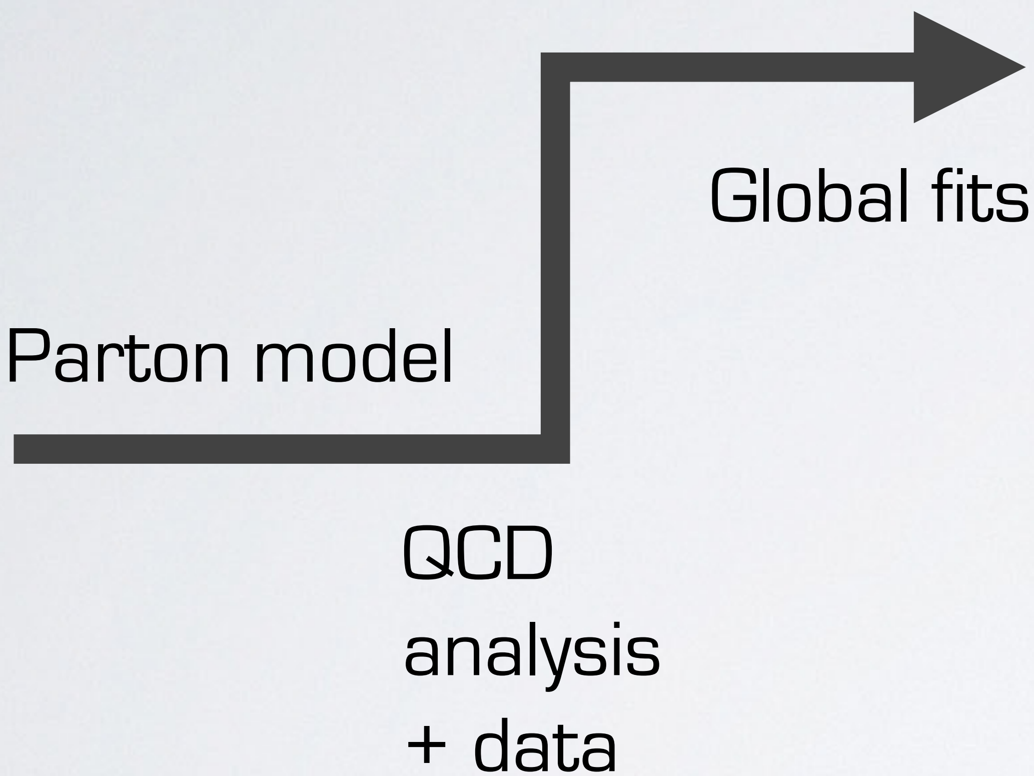
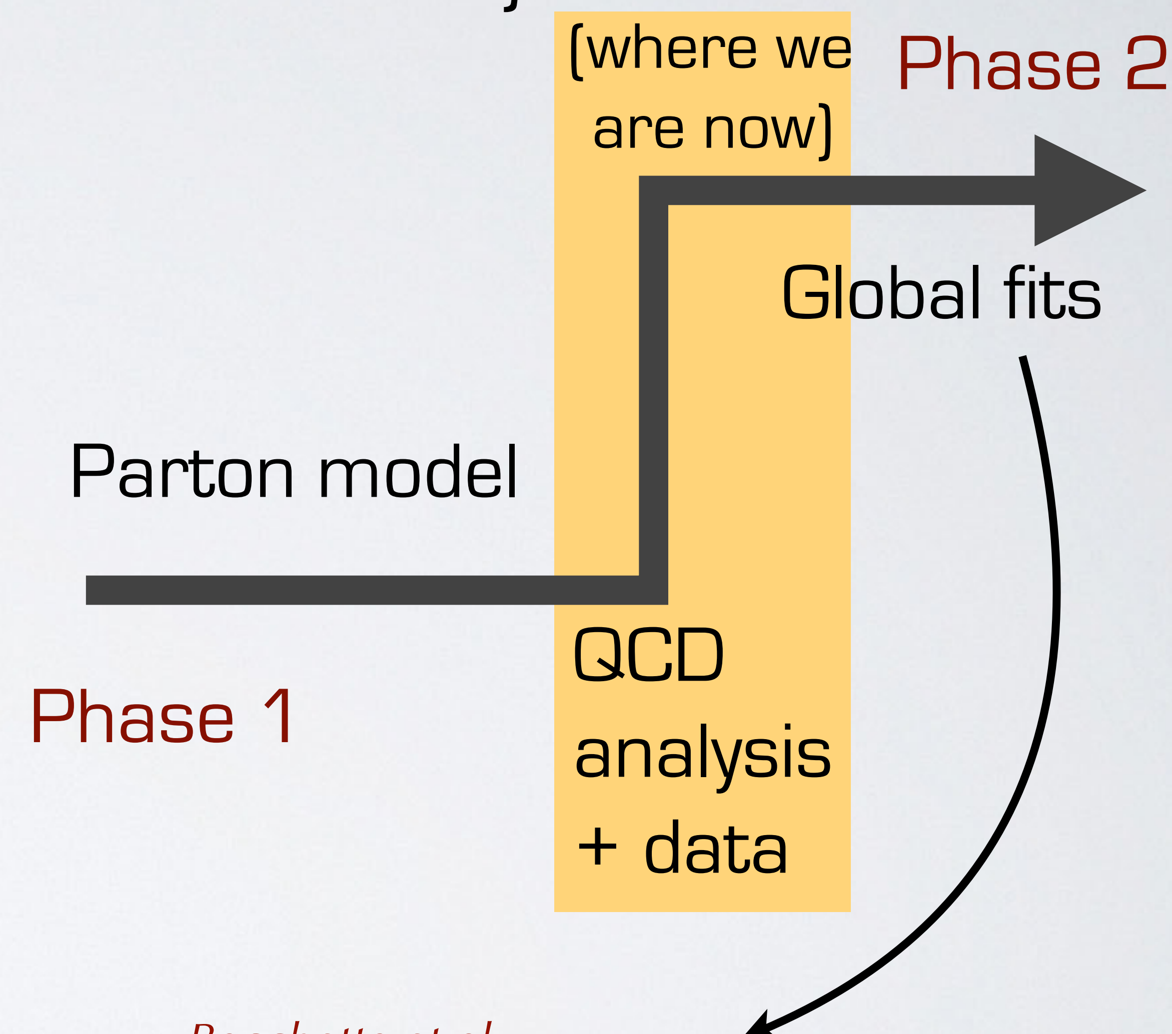
Istituto Nazionale di Fisica Nucleare

a phase transition in 3D studies

1D
(standard parton distribution functions - PDFs)



3D
(transverse momentum distributions - TMDs)



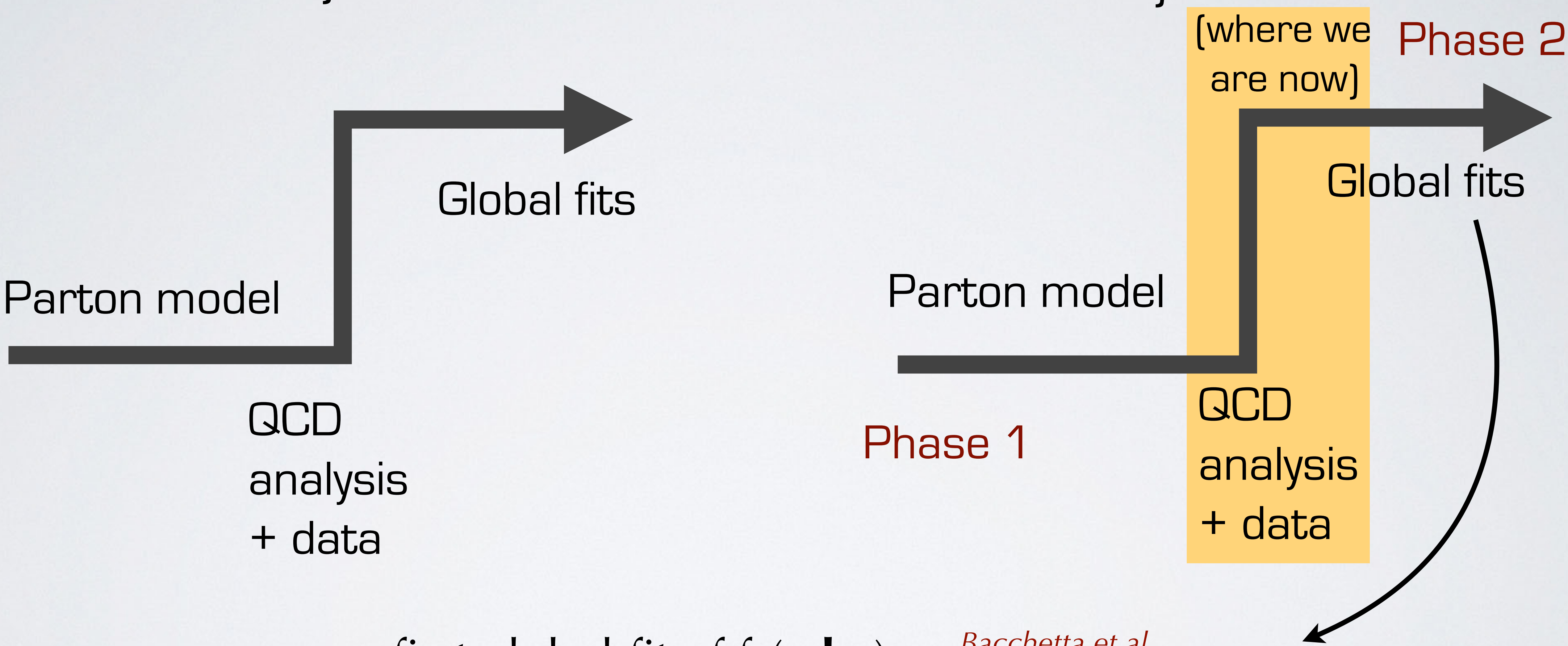
first global fit of $f_1(x,\mathbf{k}_\perp)$

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

a phase transition in 3D studies

1D
(standard parton distribution functions - PDFs)

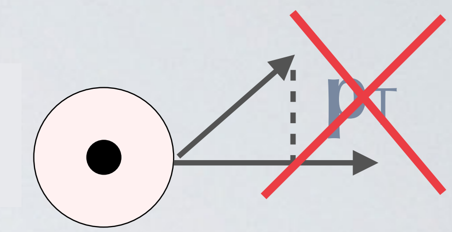
3D
(transverse momentum distributions - TMDs)



first global fit of $f_1(x,\mathbf{k}_\perp)$ *Bacchetta et al., JHEP **1706** (17) 081*

but there is another missing global fit for leading-order PDFs: the transversity!

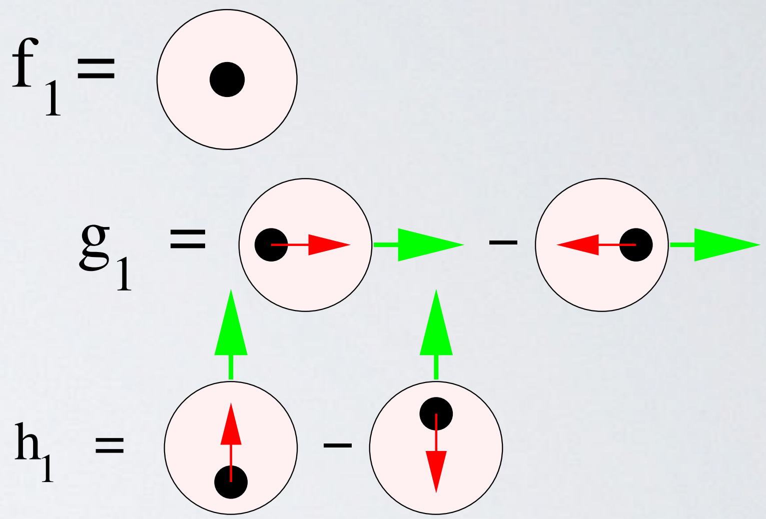
leading-twist PDF map



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 $h_{1T}^\perp$



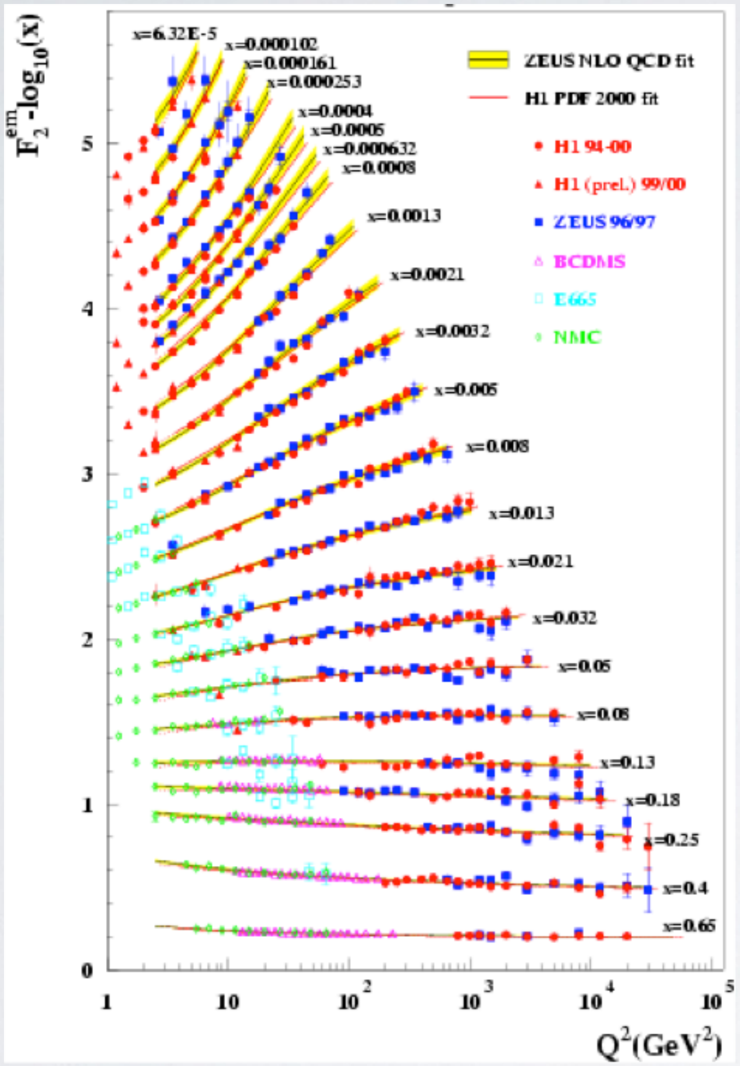
transversity distribution $h_1(x)$

flips helicity (chiral-odd)
→ suppressed in inclusive DIS

all three PDFs needed for a complete description
of proton (spin) structure at leading order

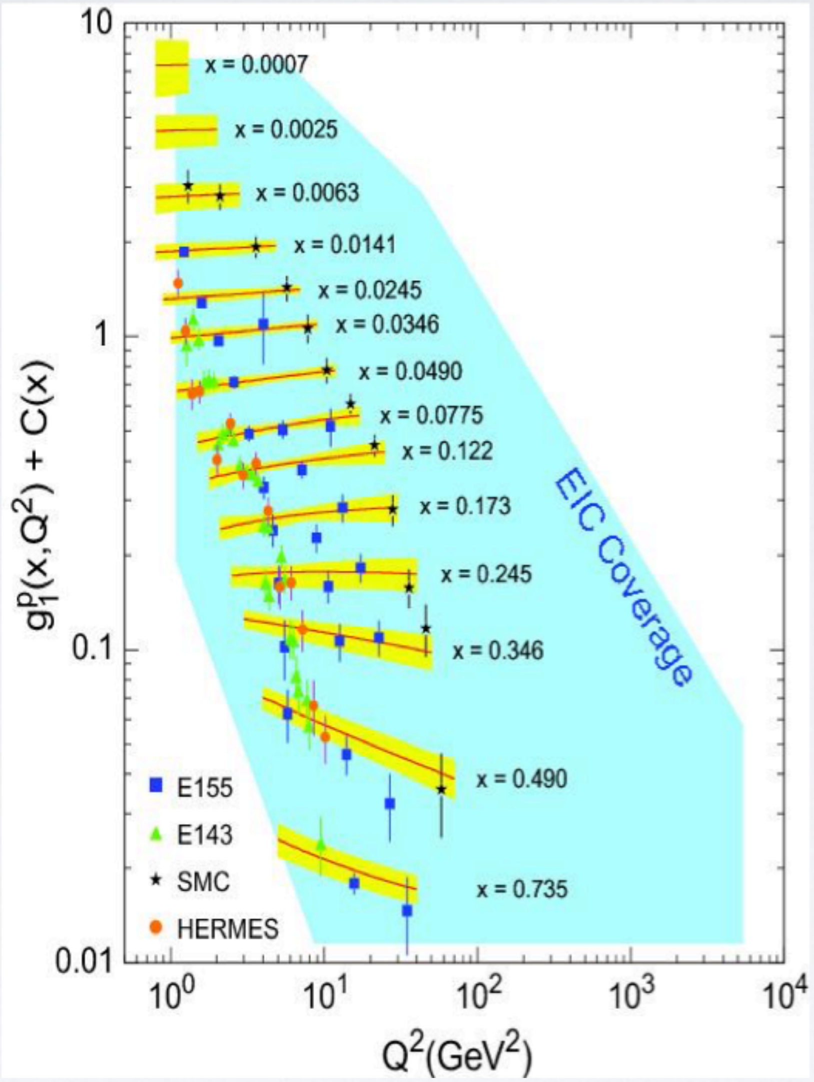
Transversity poorly known

World data for F_2^p



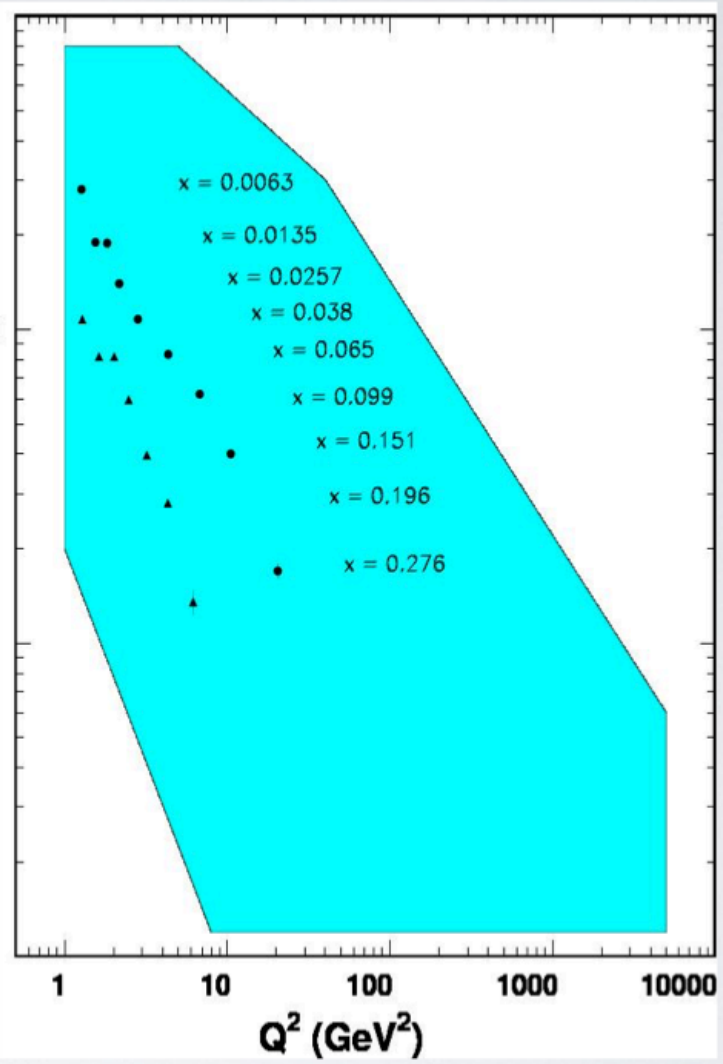
f_1 from fits of **thousands** data

World data for g_1^p



g_1 from fits of **hundreds** data

World data for **h_1**

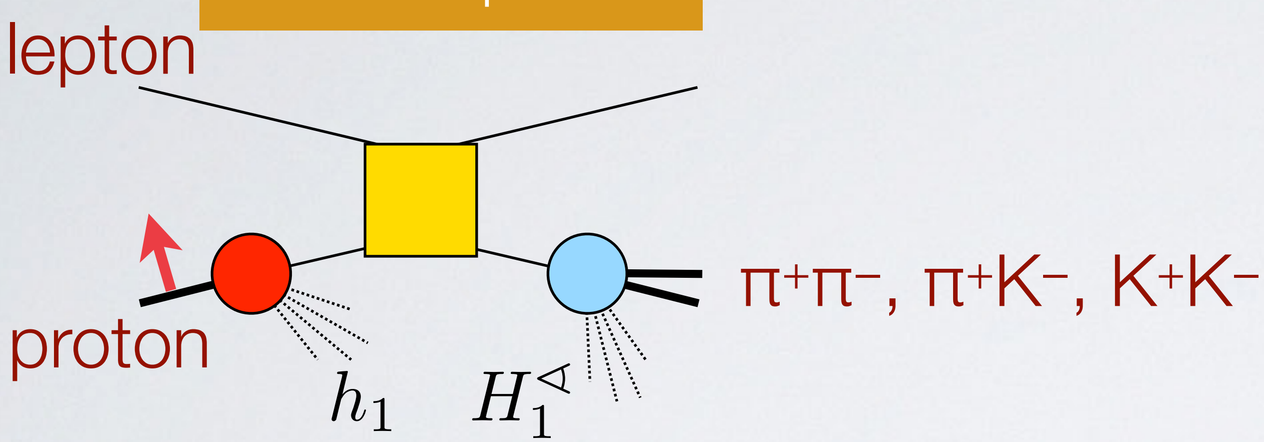


h_1 from fits of **tens** data

slide from H.Montgomery, QCD Evolution 2016

extraction from 2-hadron-inclusive data

SIDIS ℓ-p$^\uparrow$, D$^\uparrow$

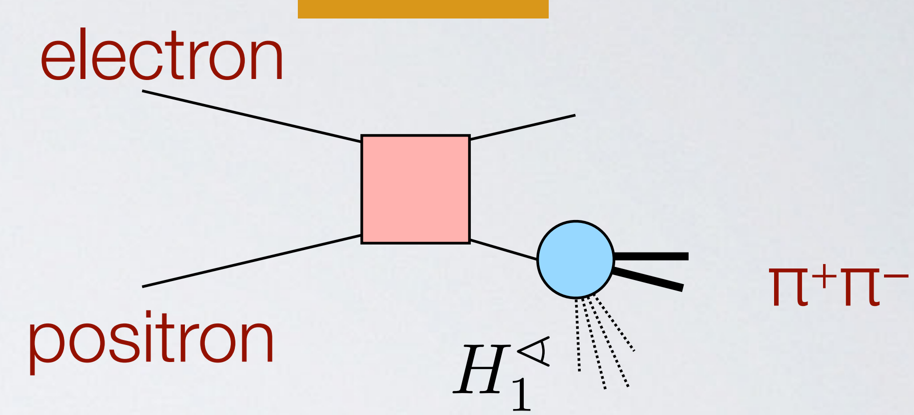


Airapetian et al., JHEP ***0806*** *(08) 017*

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

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

e+e−

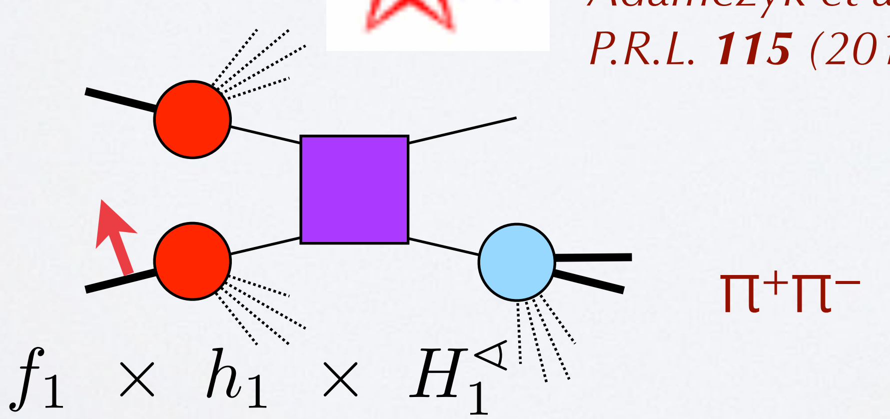


Vossen et al., P.R.L. ***107*** *(11) 072004*

run 2006

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

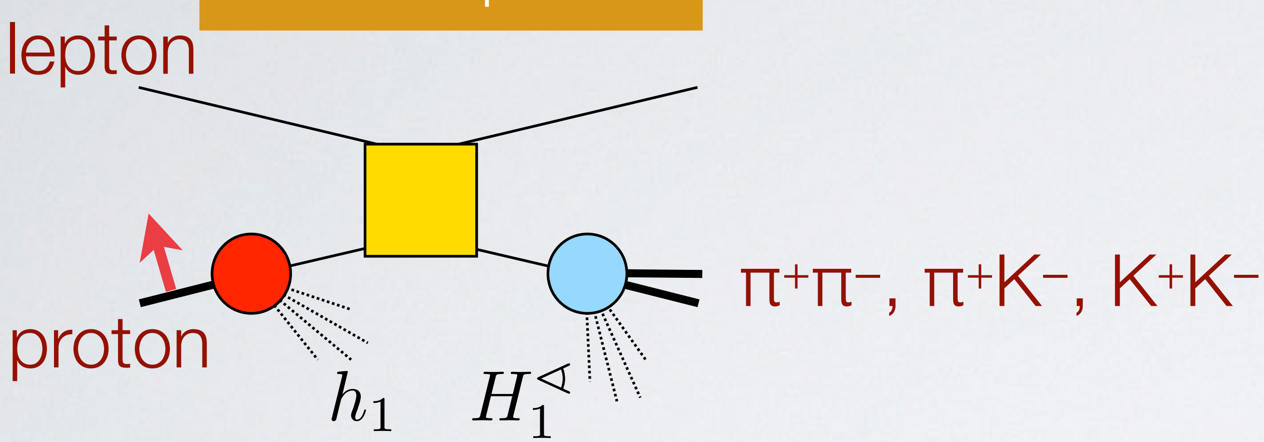
p-p$^\uparrow$



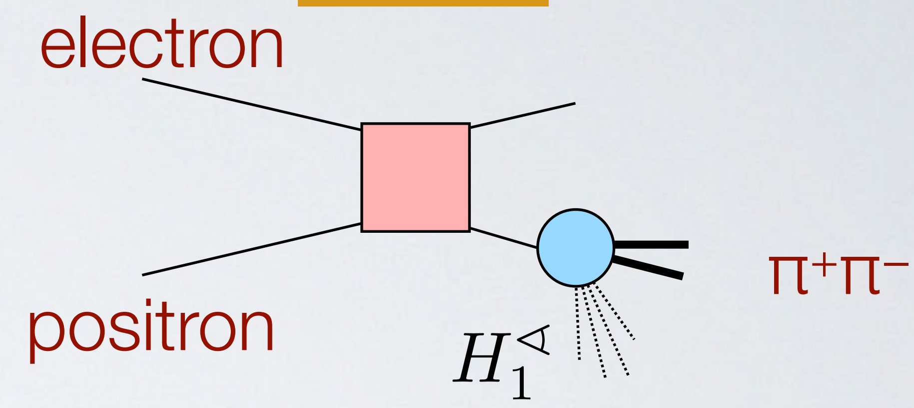
more data (hopefully) soon to be released

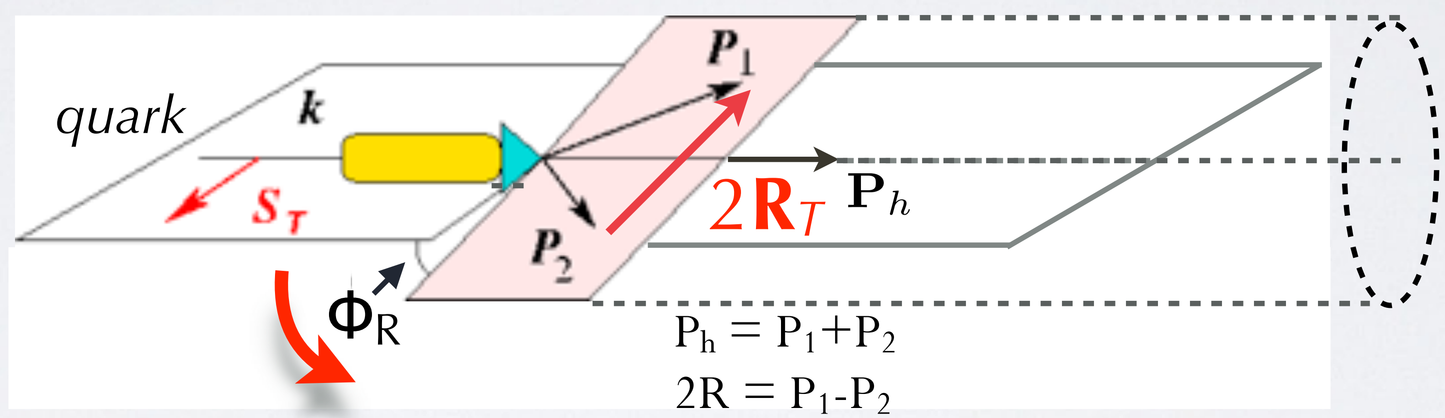
extraction from 2-hadron-inclusive data

SIDIS ℓ-p↑, D↑



e+e−

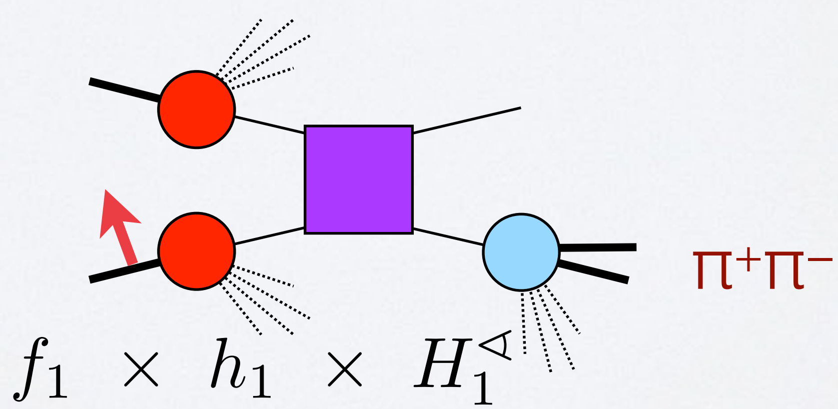




Collins, Heppelman, Ladinsky, N.P. ***B420*** *(94)*

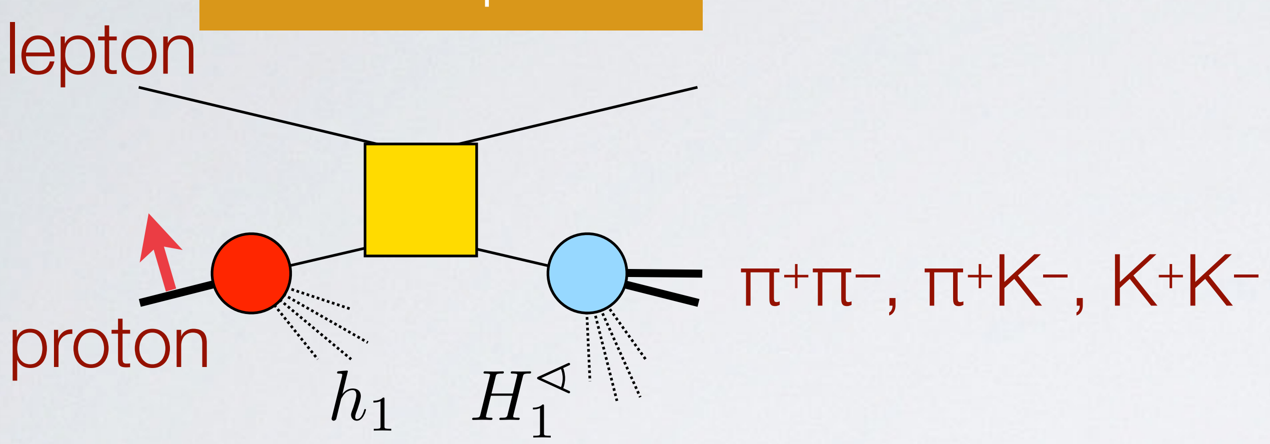
correlation S_T and R_T → azimuthal asymmetry

p-p↑

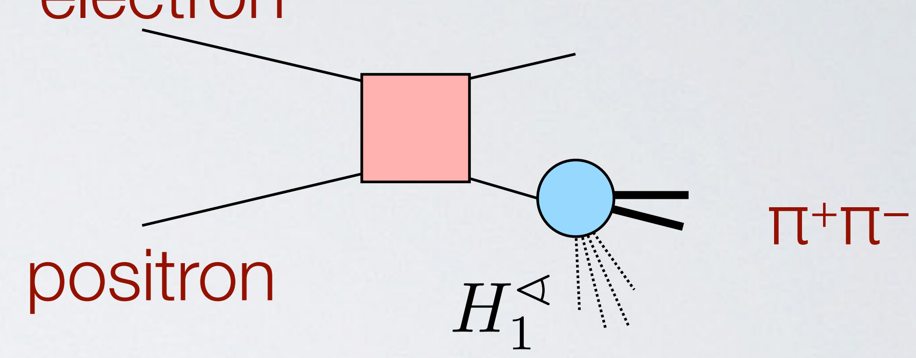


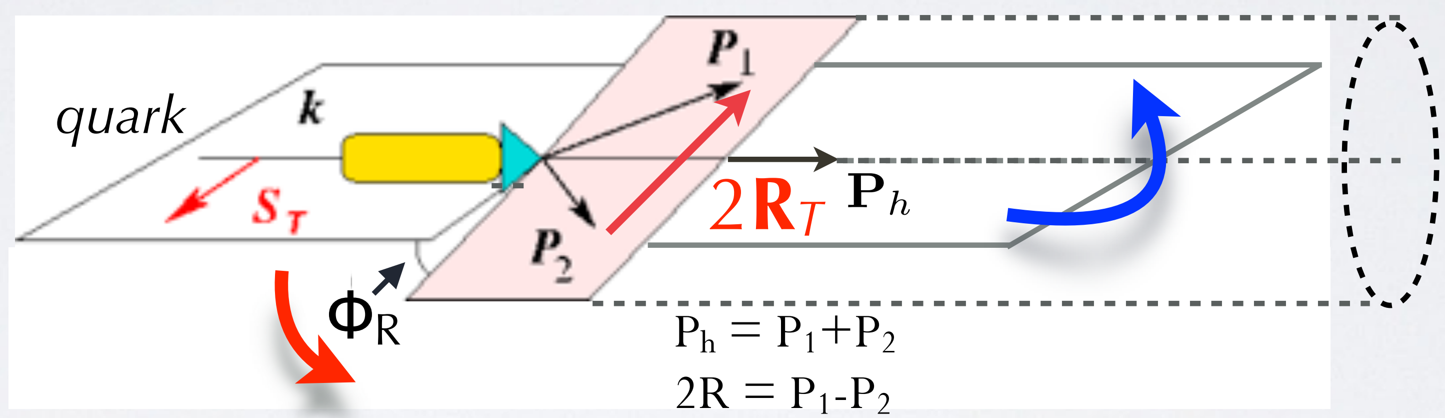
extraction from 2-hadron-inclusive data

SIDIS ℓ-p↑, D↑



e+e−

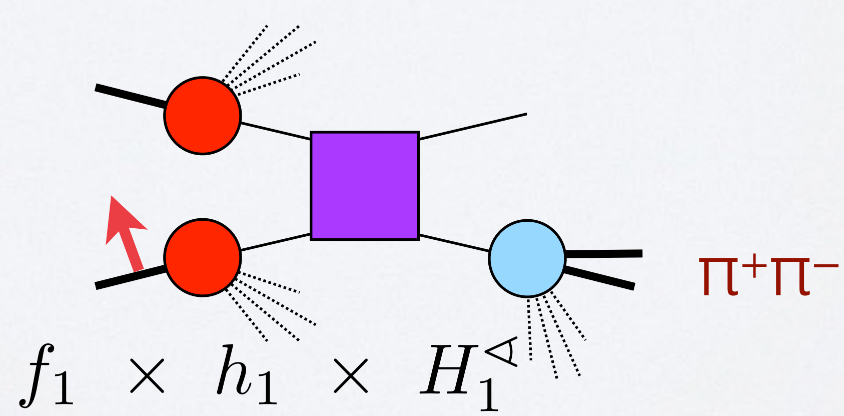




survives to polar symmetry ($\int dP_{hT}$)

correlation S_T and R_T → azimuthal asymmetry

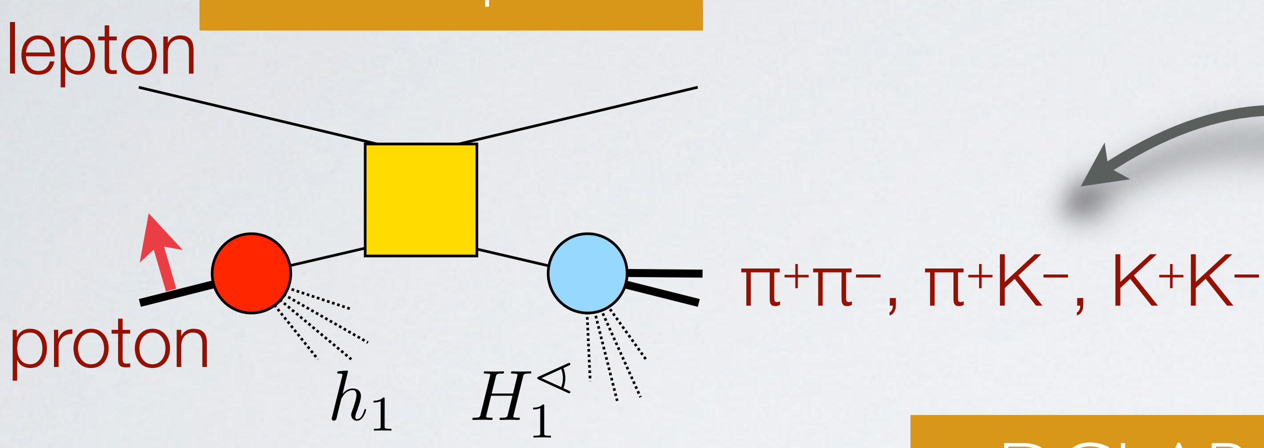
p-p↑



framework collinear factorization $R_T \ll Q$

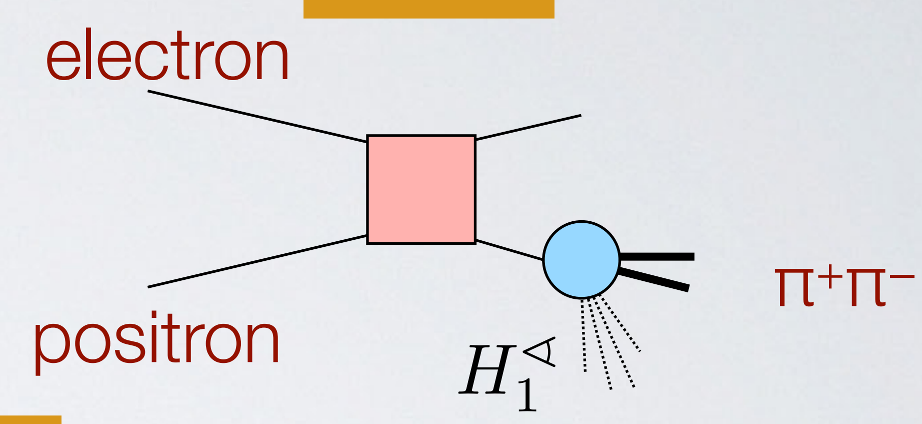
extraction from 2-hadron-inclusive data

SIDIS ℓ-p↑, D↑



*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−

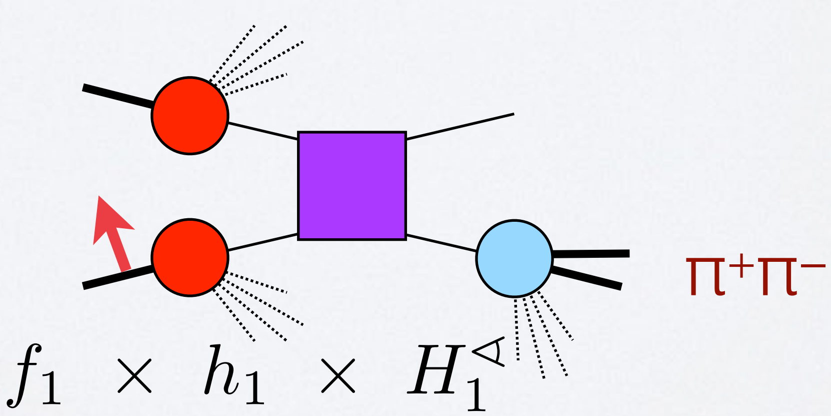


*Artru & Collins, Z.Phys. **C69** (96) 277*
*Boer, Jakob, Radici, P.R.D**67** (03) 094003*

DGLAP evolution
connects h_1 & $H_1^{\sphericalangle}$
at different scales

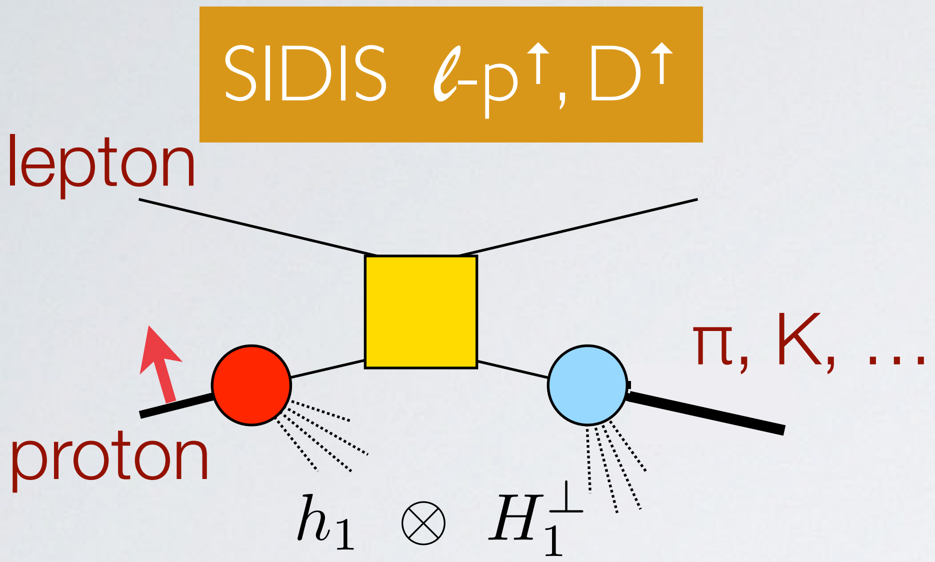
*Ceccopieri, Radici, Bacchetta, P.L.**B650** (07) 81*

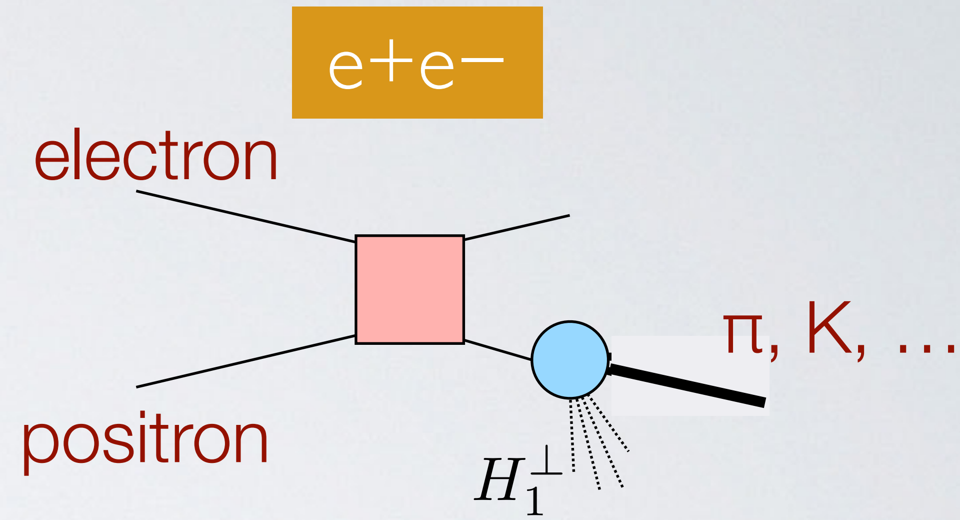
p-p↑



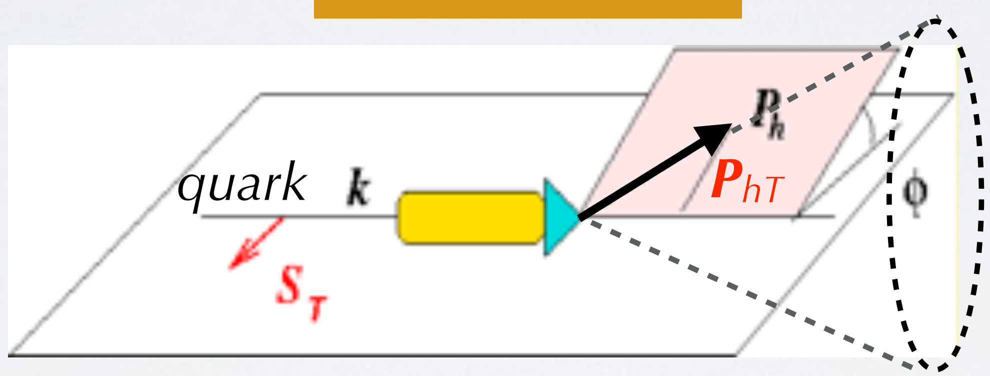
*Bacchetta & Radici, P.R. D**70** (04) 094032*

not possible for 1-hadron-inclusive data



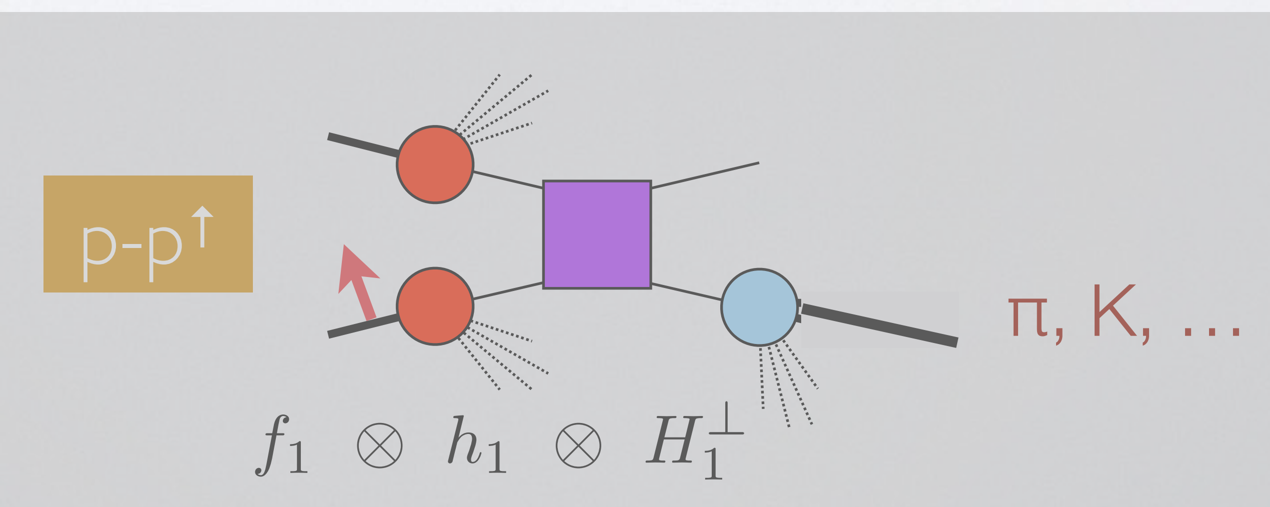


Collins effect

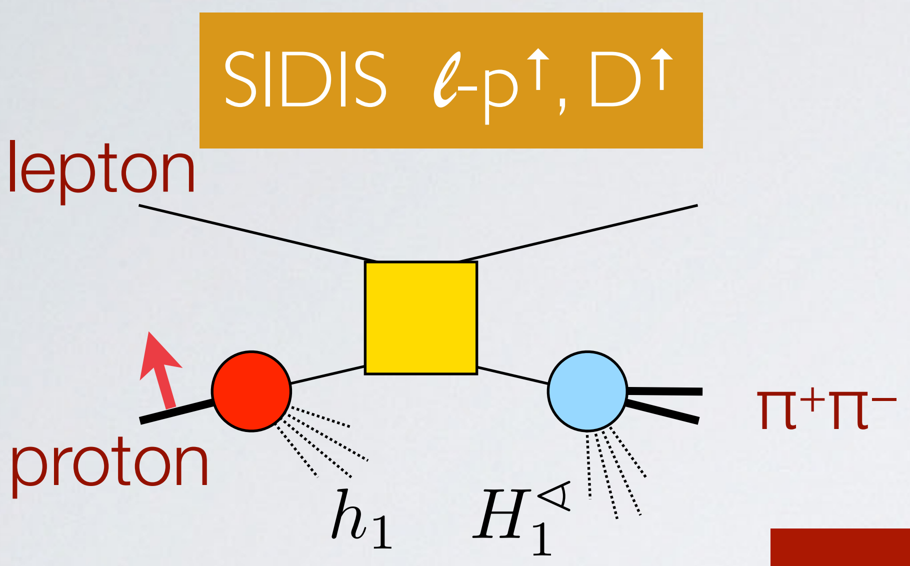


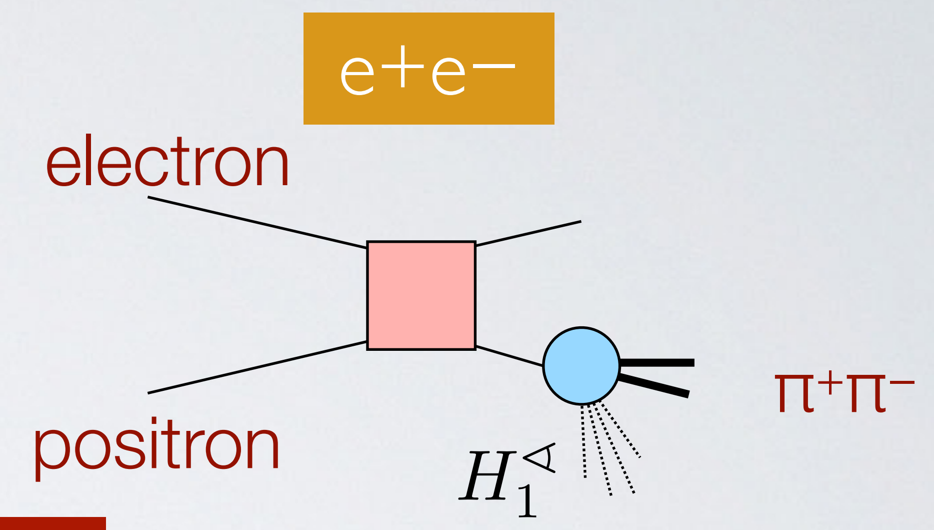
correlation S_T and P_{hT} → azimuthal asymmetry

factorization theorem not yet proved

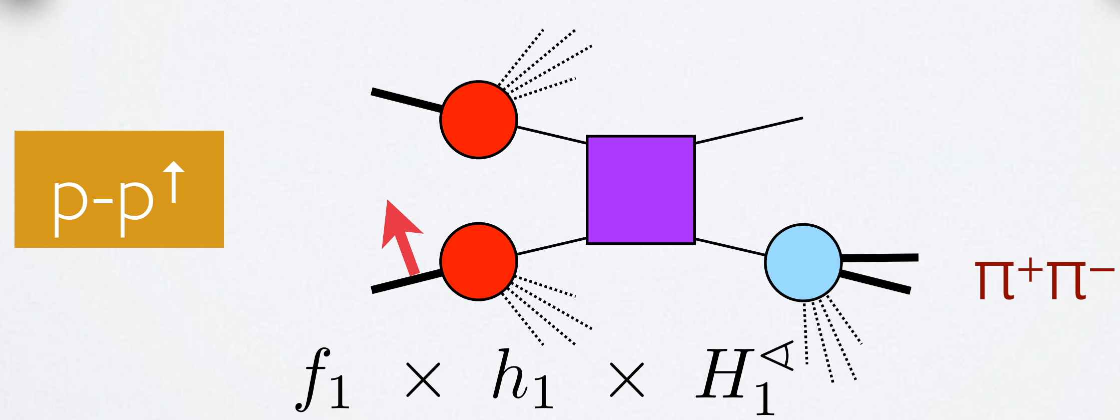


take–away message



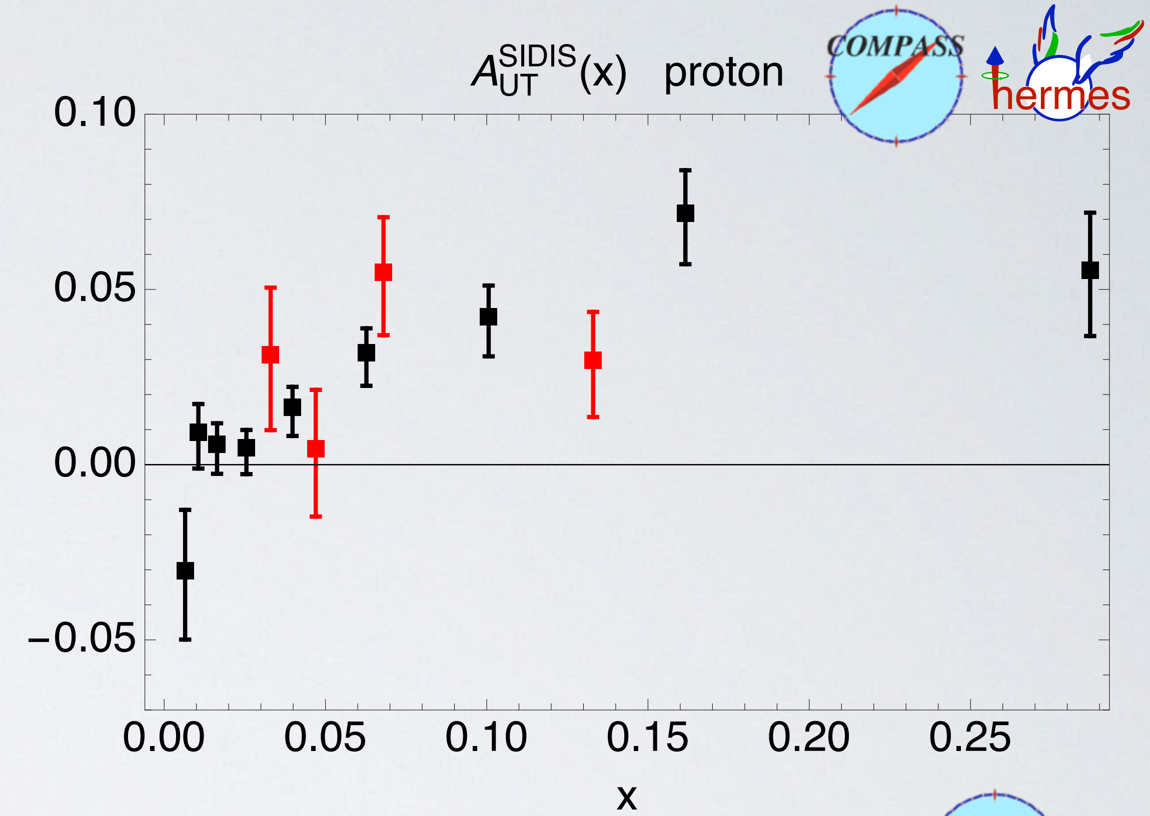


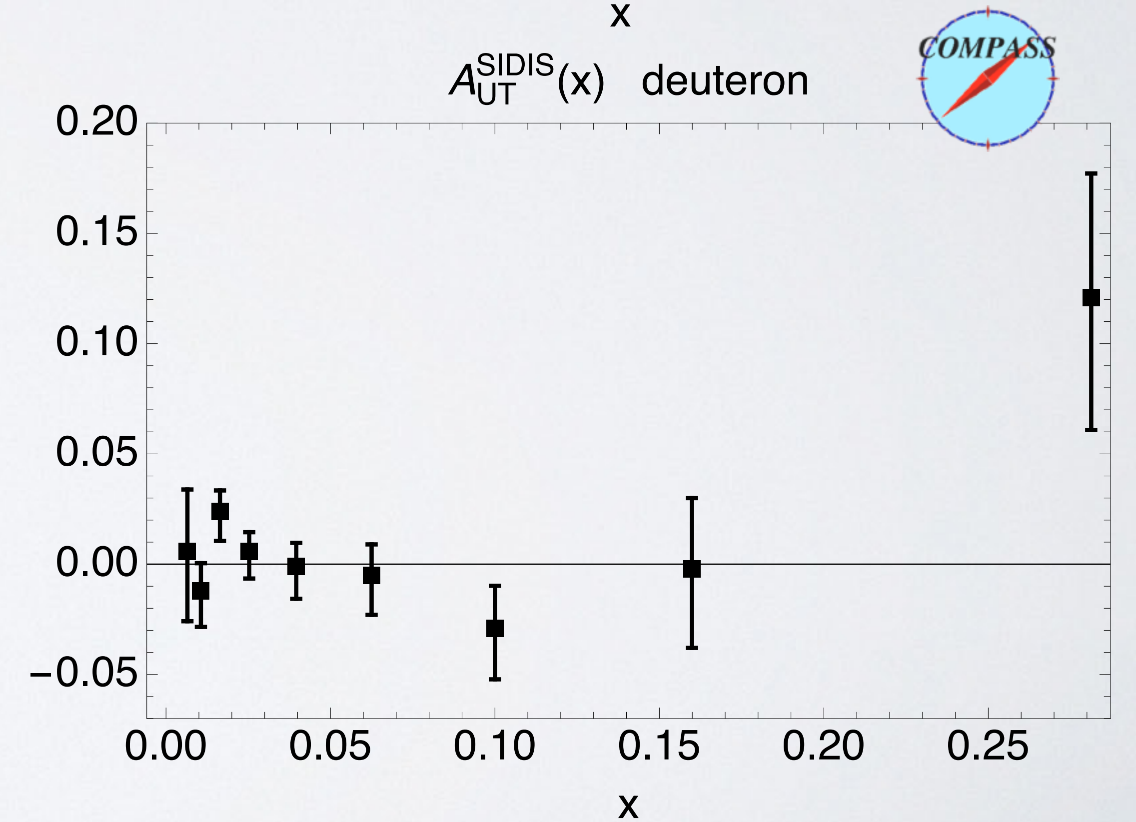
first extraction
of transversity
from a global fit
of these data



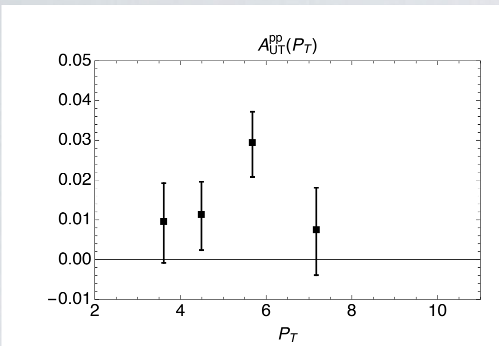
PRELIMINARY !

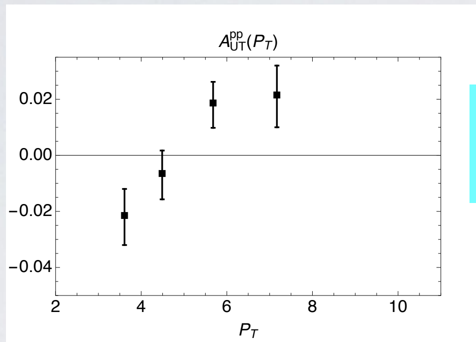
the data set in more detail





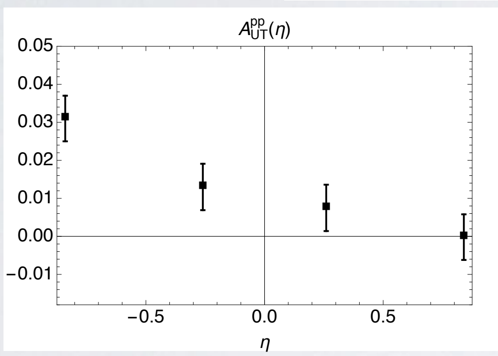
the data set in more detail





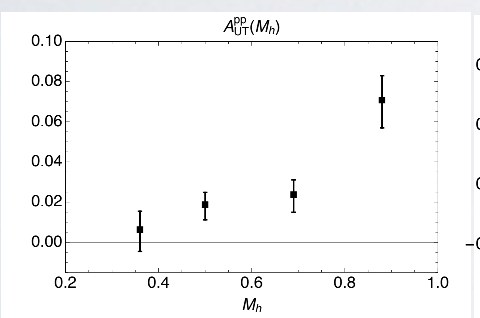
A_{ut}^{pp} (P_T)

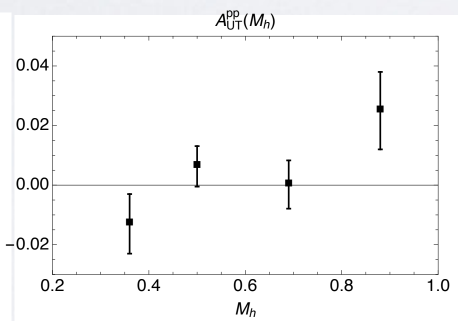
$\eta<0$



$\eta>0$

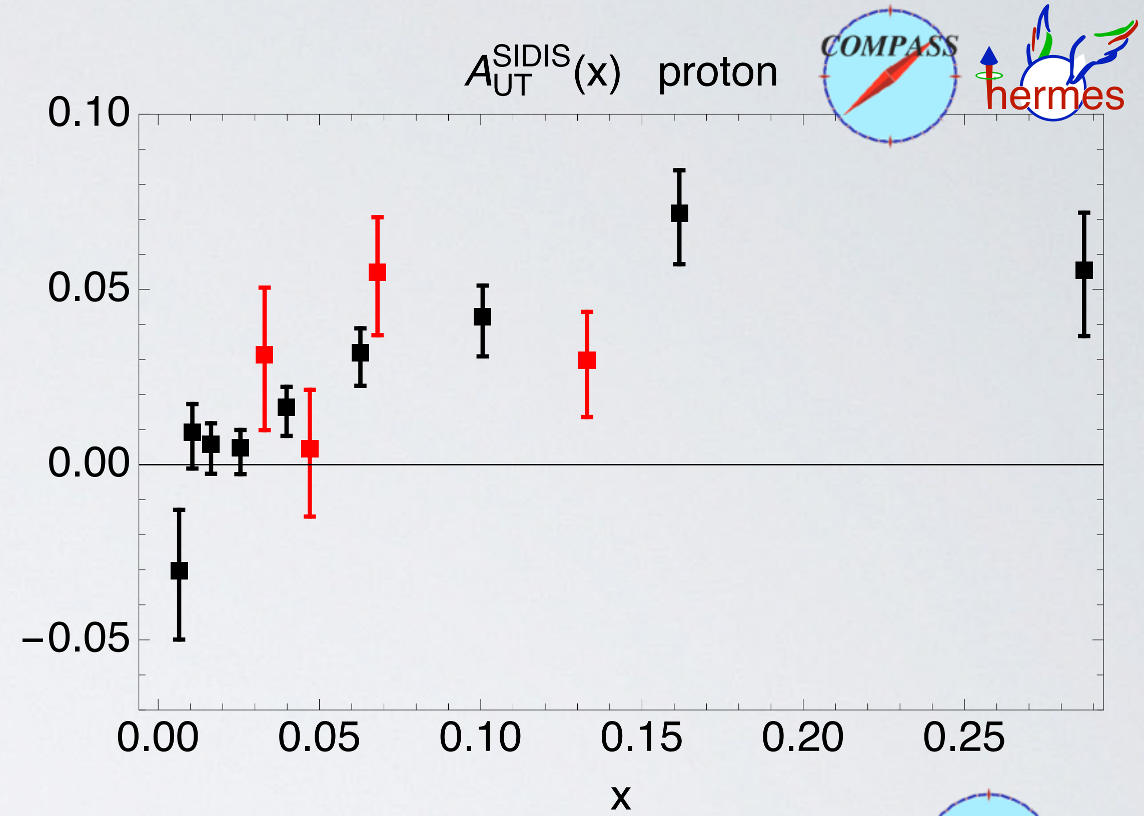
A_{ut}^{pp} (η)

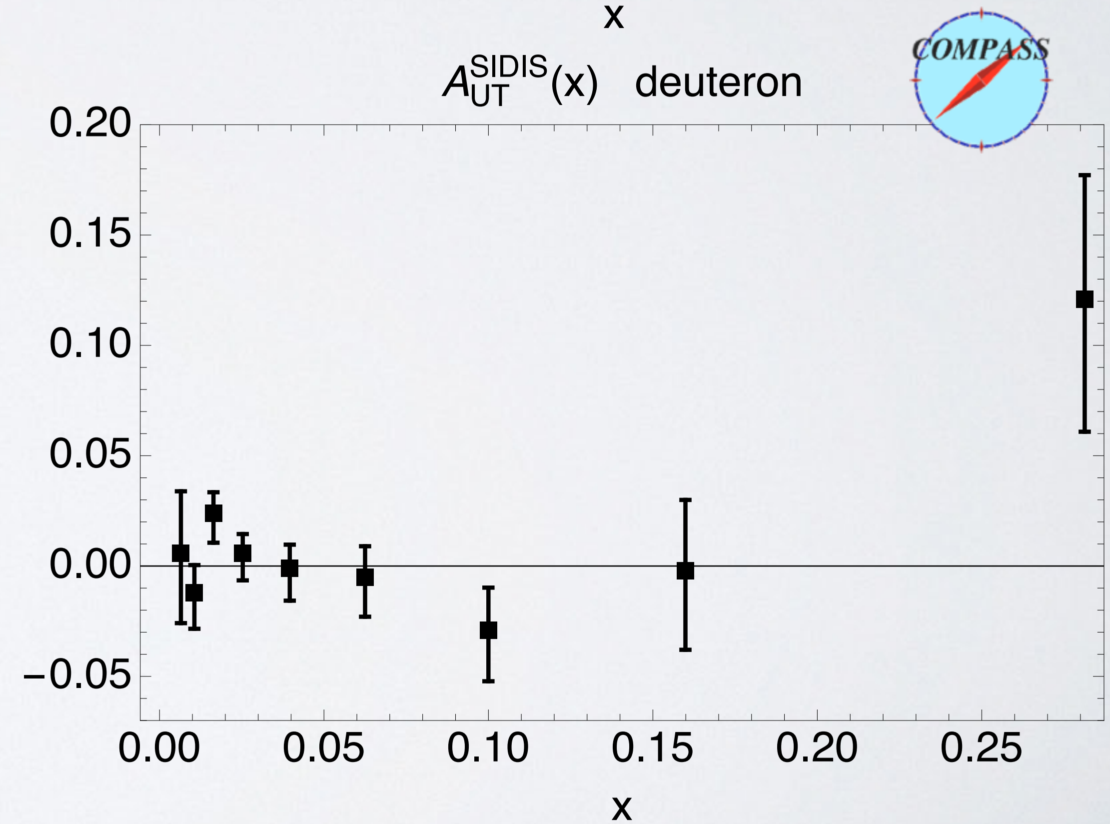




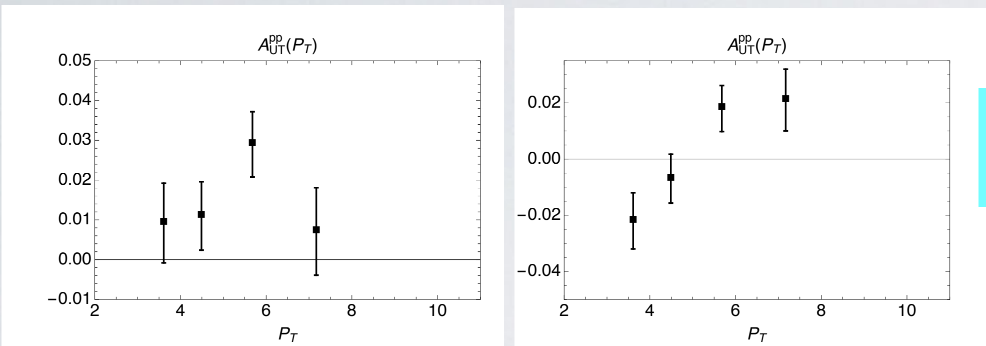
A_{ut}^{pp} (M_h)

run 2006 s=200 GeV^2



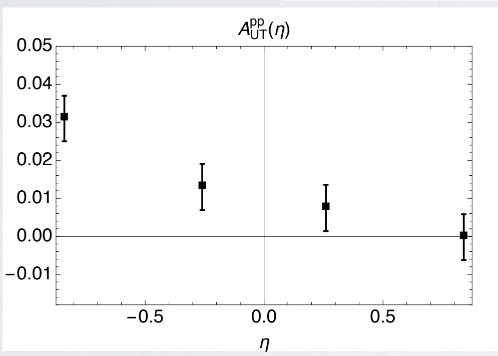


the data set in more detail



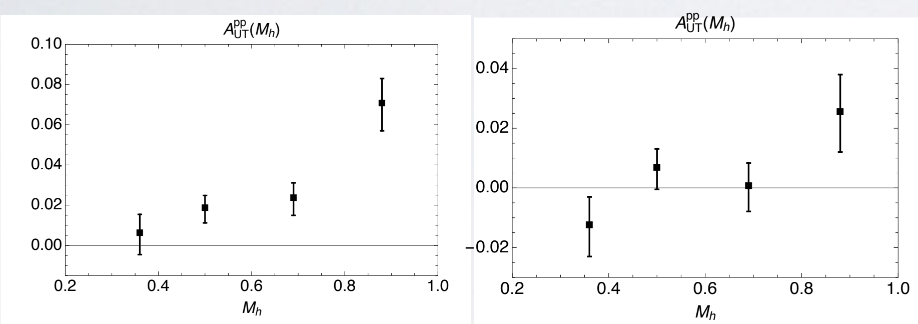
A_{ut}^{pp} (P_T)

η<0

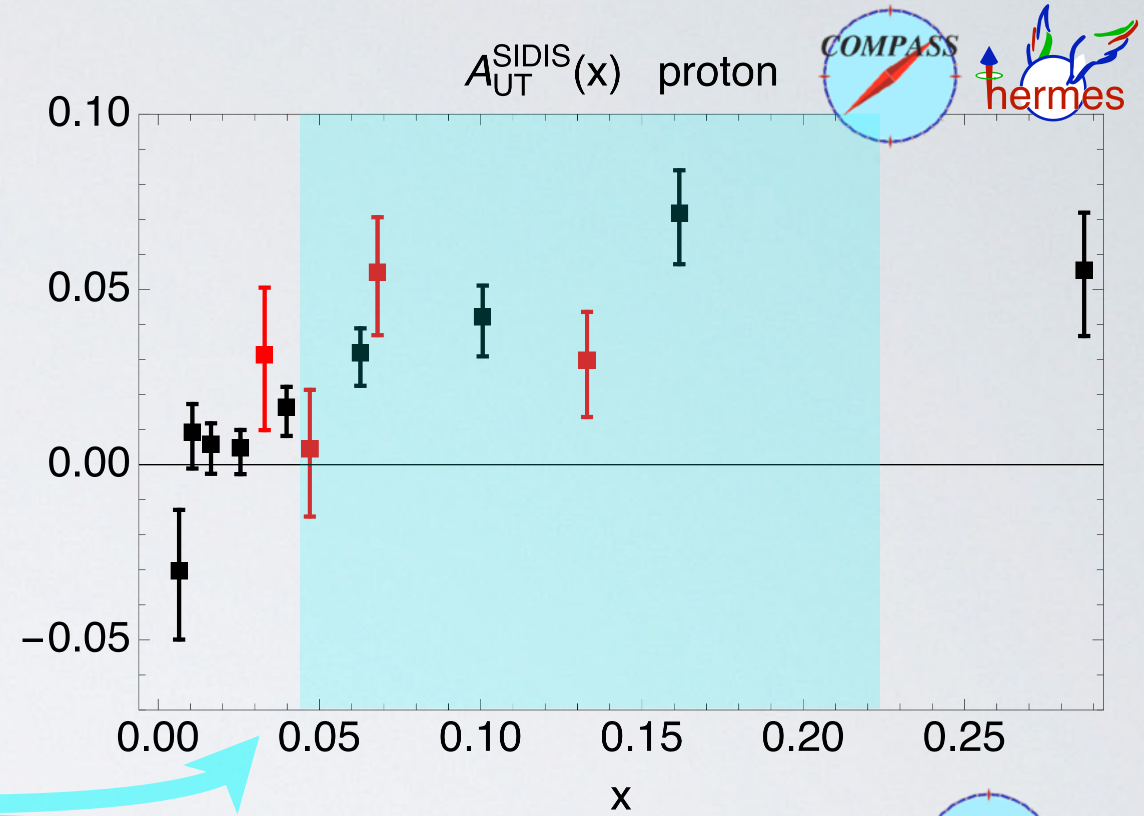


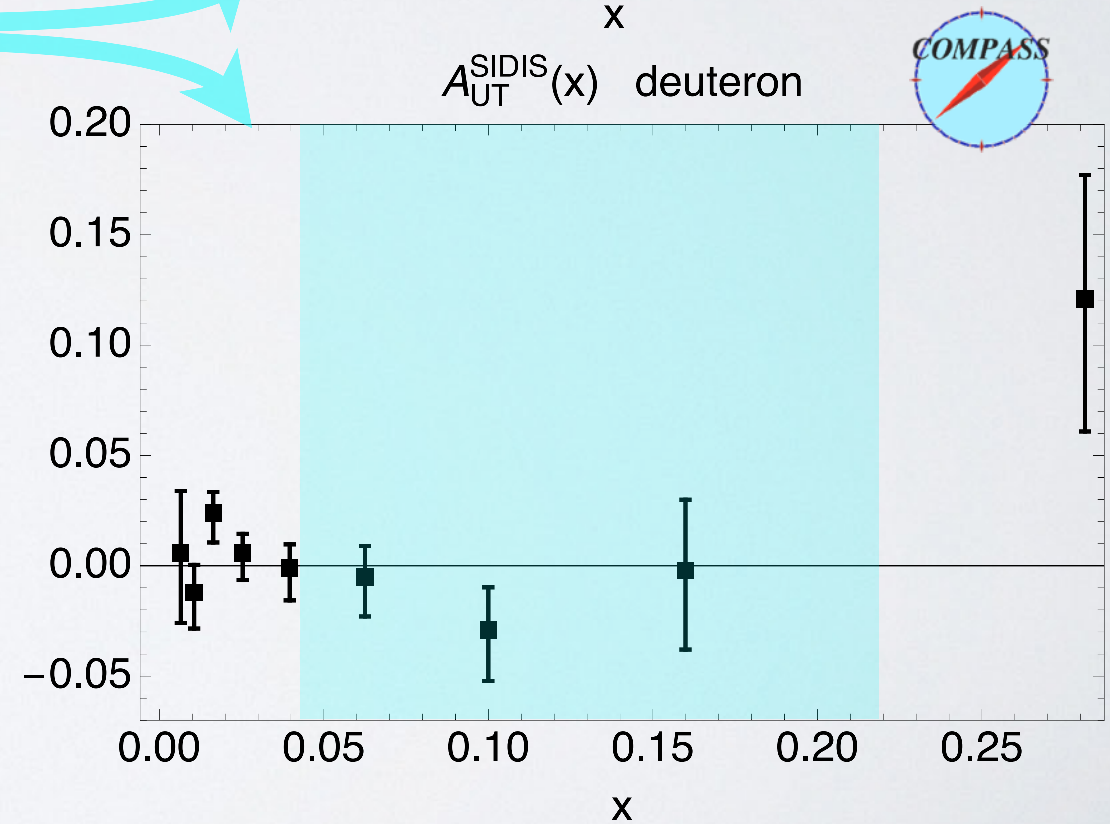
η>0

A_{ut}^{pp} (η)



A_{ut}^{pp} (M_h)

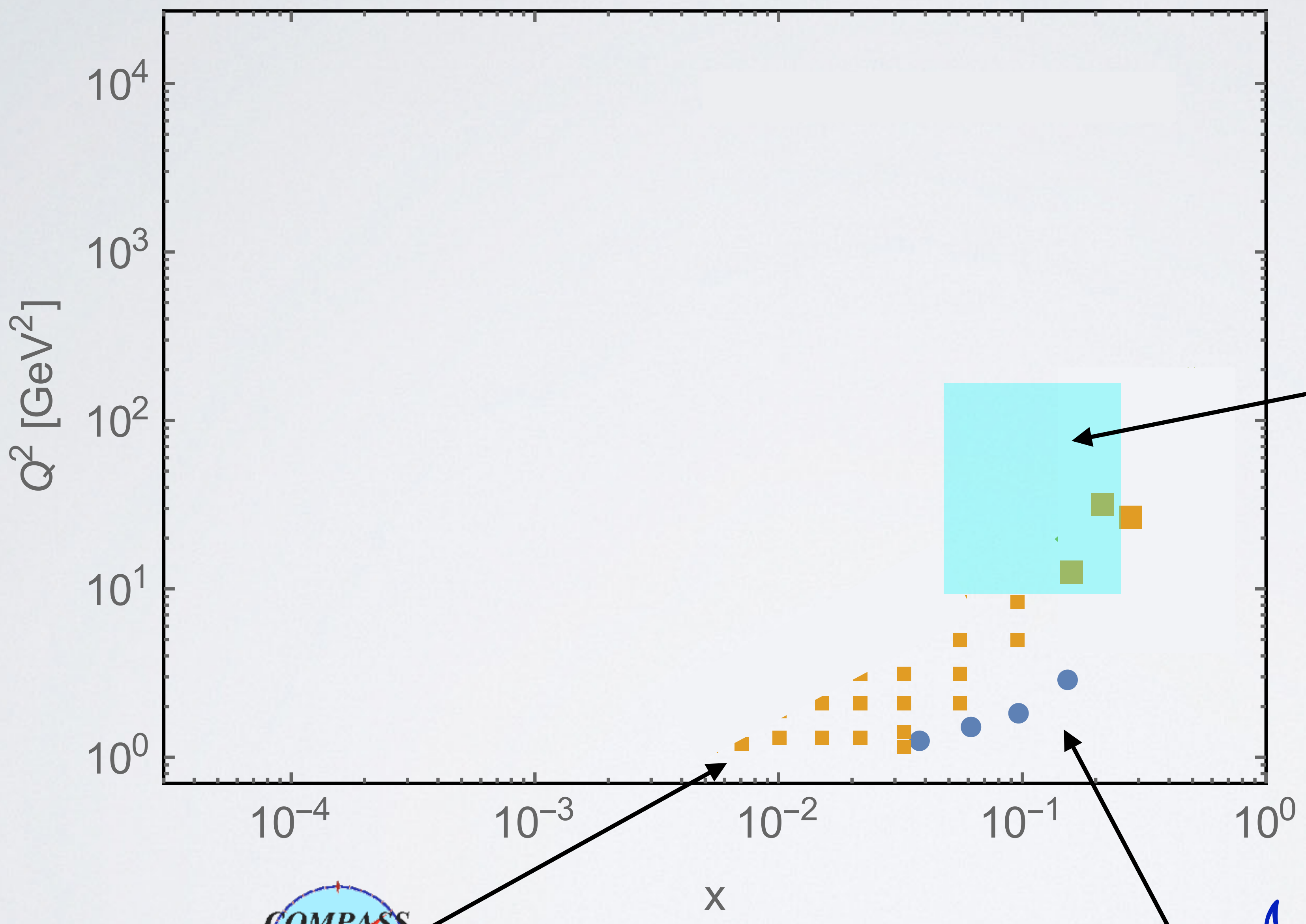




STAR run 2006 s=200 GeV^2

(effective coverage in x)

the kinematics

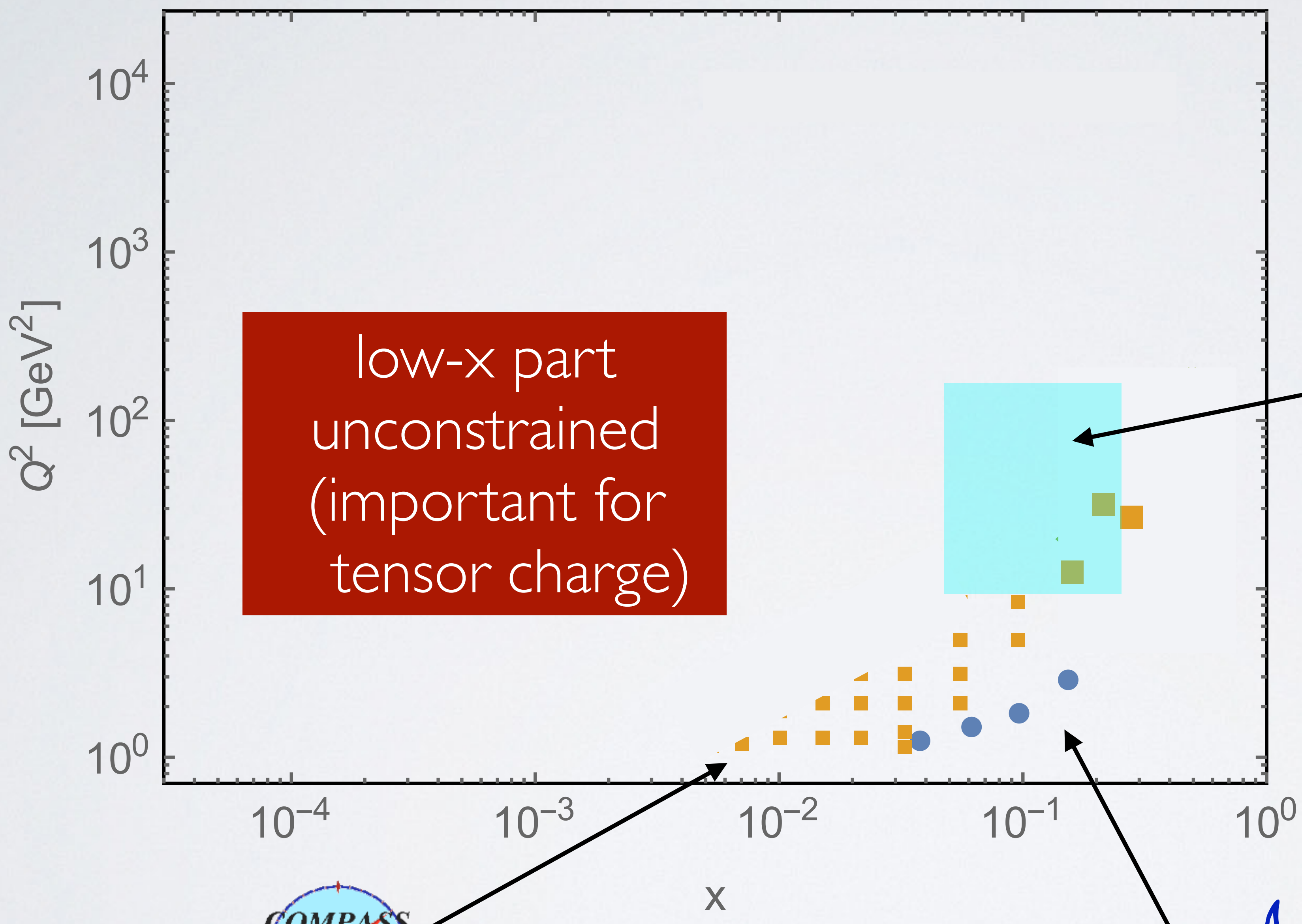


Adamczyk et al. (STAR),
P.R.L. ***115*** *(2015) 242501*

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

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

the kinematics



low-x part unconstrained (important for tensor charge)

STAR

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

COMPASS

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

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

hermes

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

choice of functional form

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

Soffer Bound

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

choice of functional form

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Soffer Bound

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$$F(x) = \frac{N}{\max_x[|F(x)|]}\, x^A\, [1 + B\,\mathrm{Ceb}_1(x) + C\,\mathrm{Ceb}_2(x) + D\,\mathrm{Ceb}_3(x)]$$

$$|N| \leq 1 \ \Rightarrow\ |F(x)| \leq 1$$

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

10 fitting parameters

Soffer Bound satisfied at any Q^2

choice of functional form

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

Soffer Bound

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

$$F(x) = \frac{N}{\max_x[|F(x)|]}\, x^A\, [1 + B\,\mathrm{Ceb}_1(x) + C\,\mathrm{Ceb}_2(x) + D\,\mathrm{Ceb}_3(x)]$$

$$|N| \le 1 \ \Rightarrow\ |F(x)| \le 1$$

Soffer Bound satisfied at any Q^2

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

10 fitting parameters

if $\lim_{x\to 0} x\,\mathrm{SB}(x) \propto x^{\bar{a}}$ then $A + \bar{a} > 0$ grants $\int_0^1 dx\ h_1^q(x;Q^2) \equiv \delta q(Q^2)$ is finite

this bound drastically constrains the tensor charge

with new functional form, Mellin transform can be computed analytically

choice of functional form

typical cross section for a+b$^\uparrow$→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*

choice of functional form

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

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

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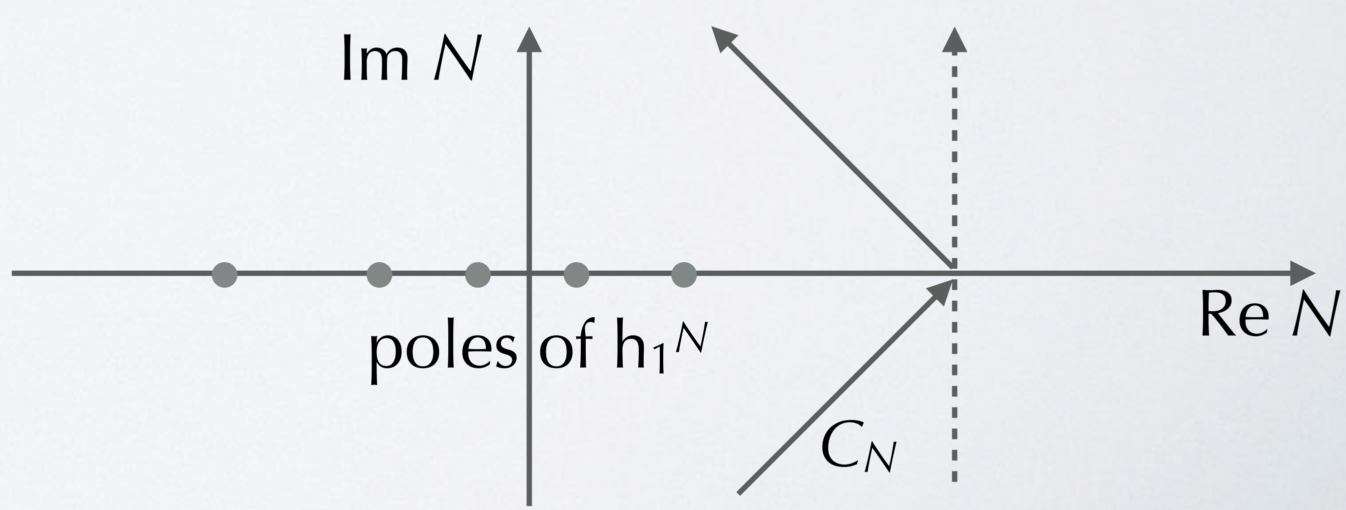
*Stratmann & Vogelsang, P.R. D**64** (01) 114007*

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

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

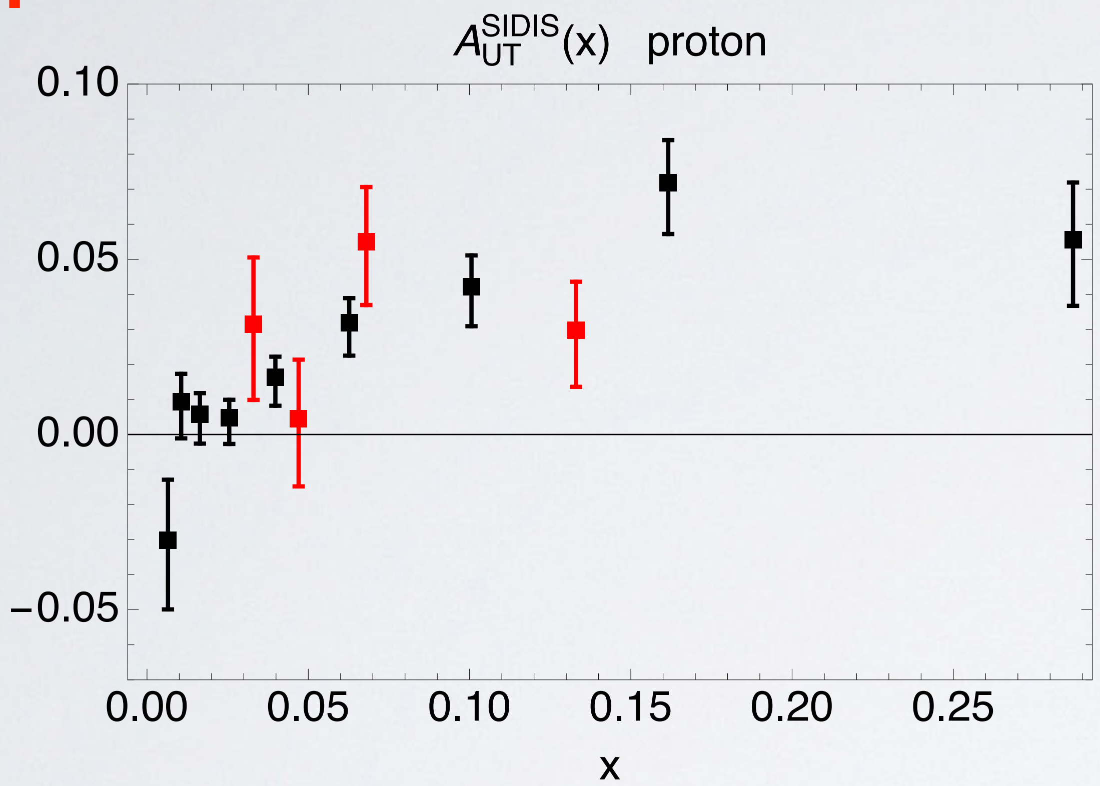


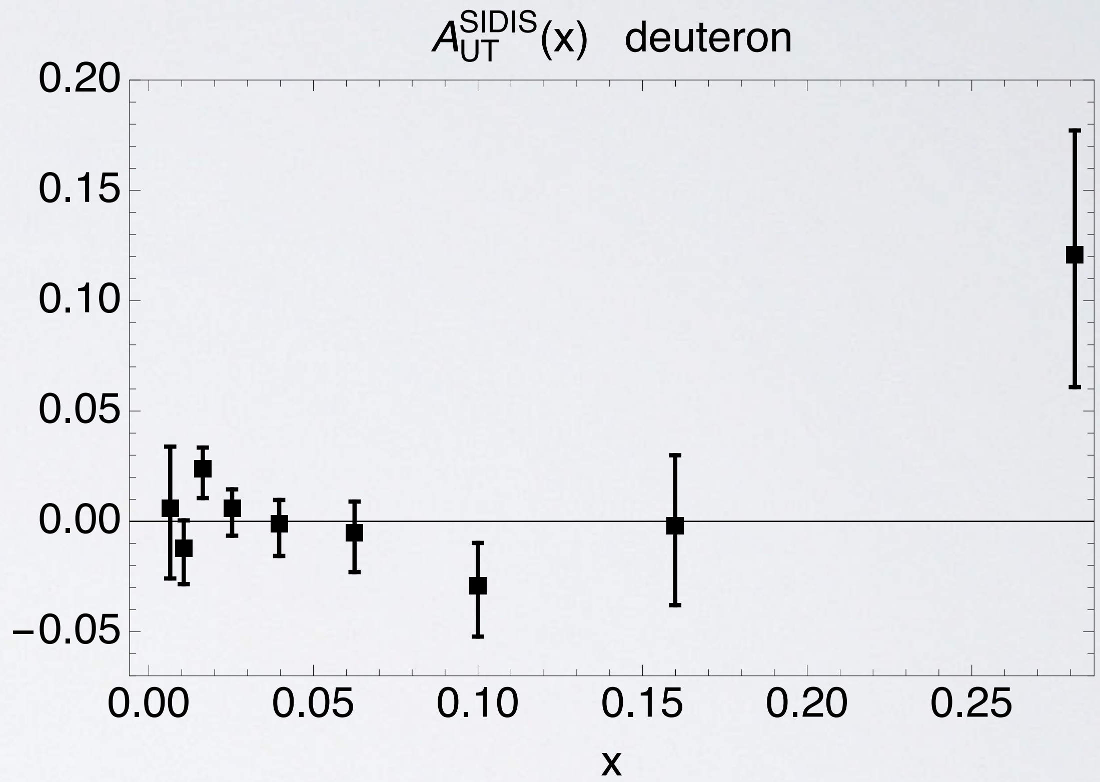
fit SIDIS asymmetry

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

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

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





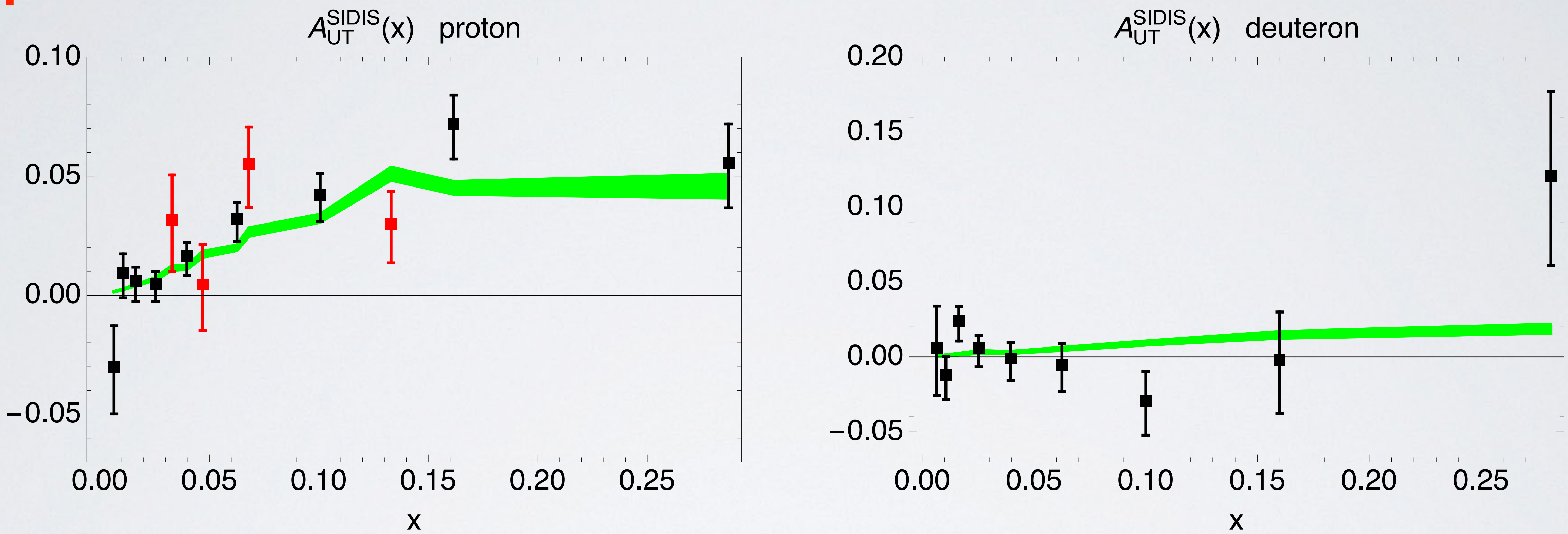
the replica method

fit SIDIS asymmetry

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)*



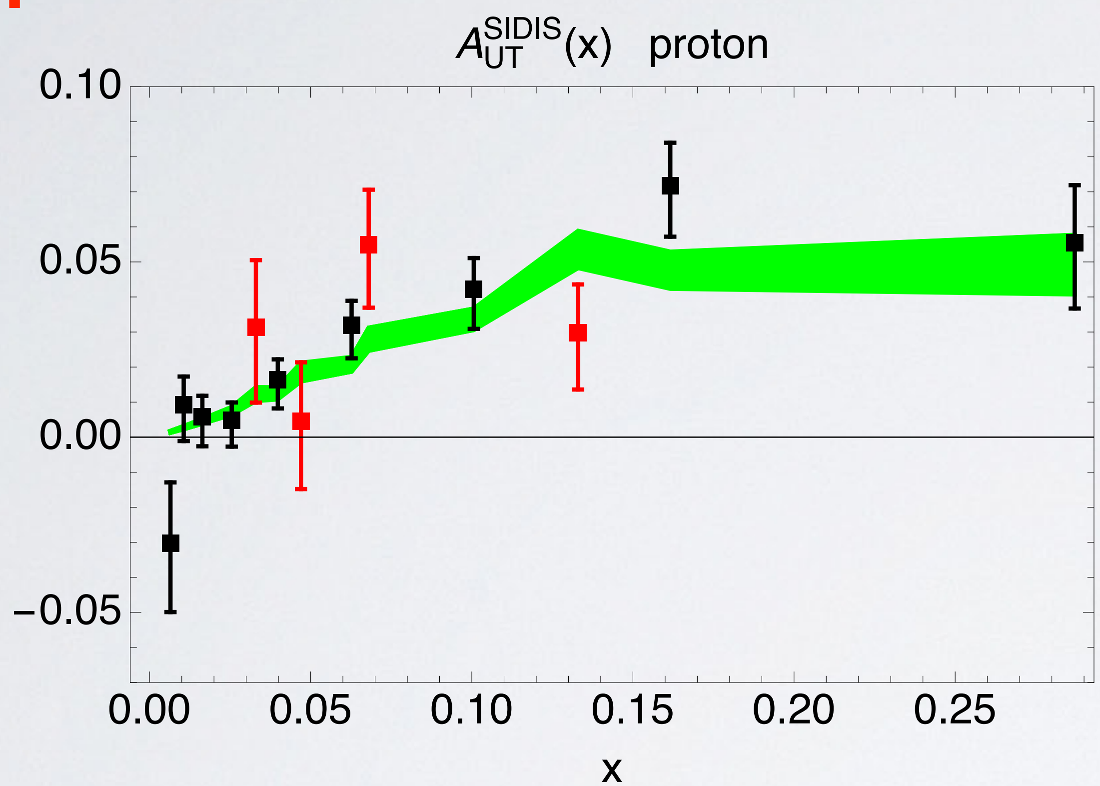
the replica method (50)

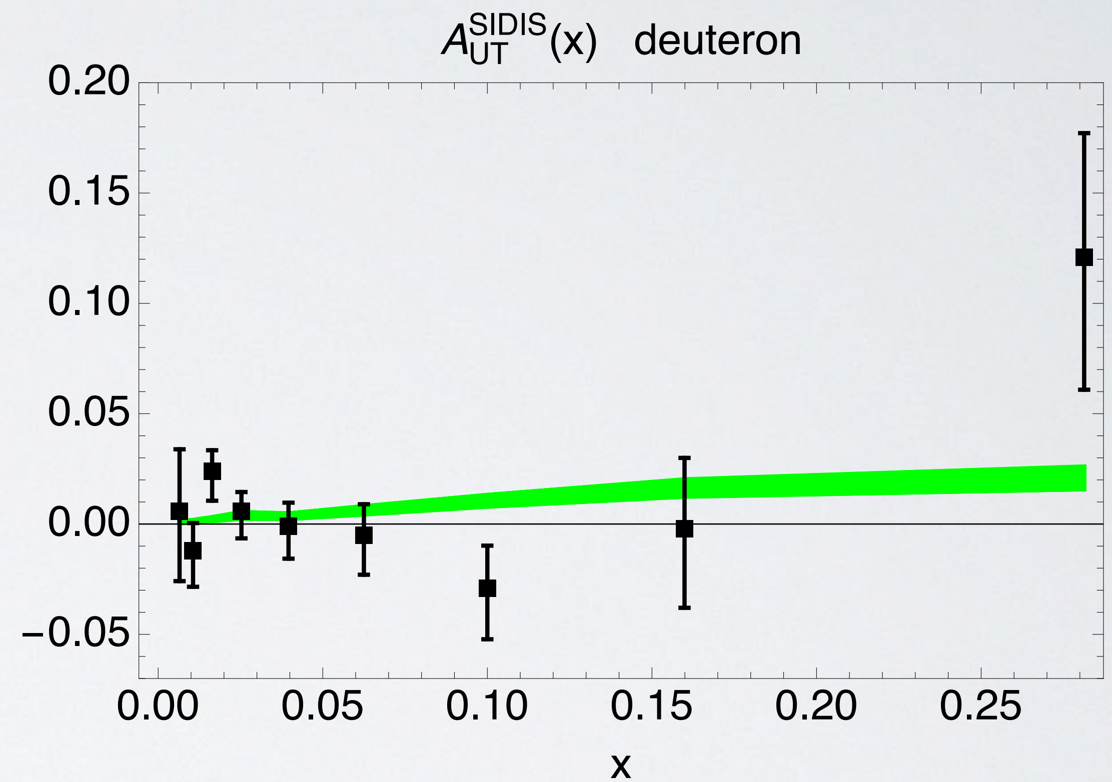
fit SIDIS asymmetry

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

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

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





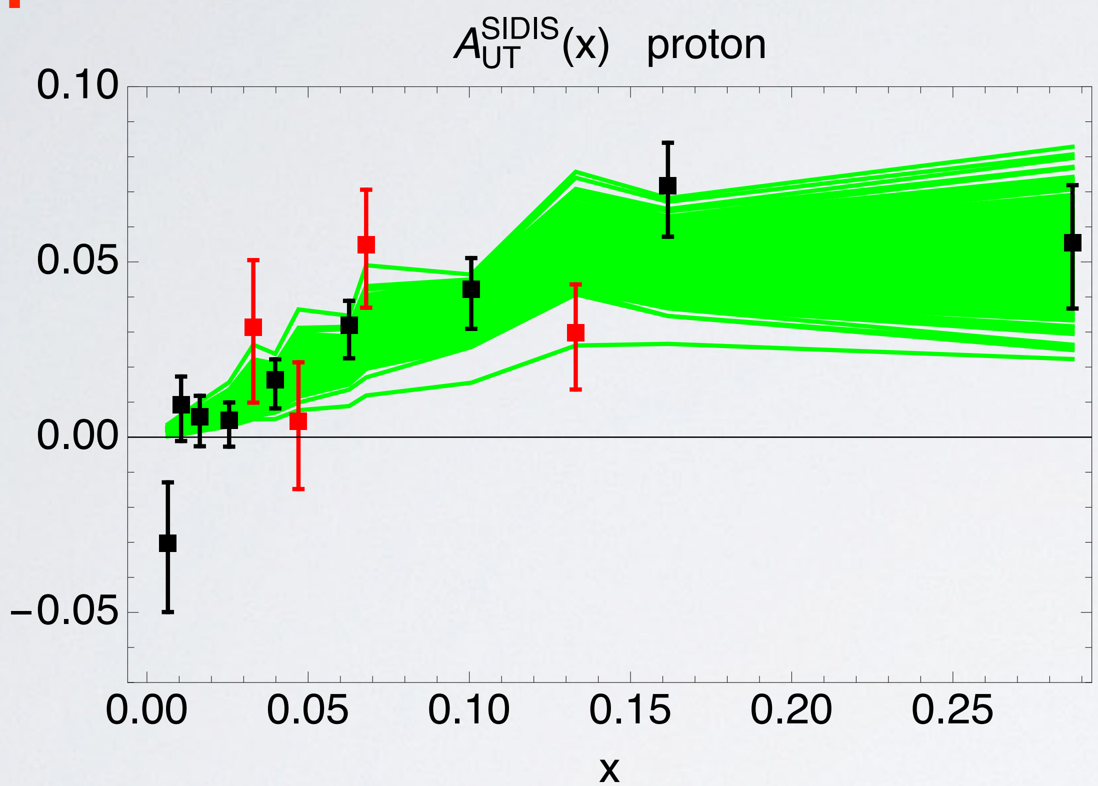
the replica method (100)

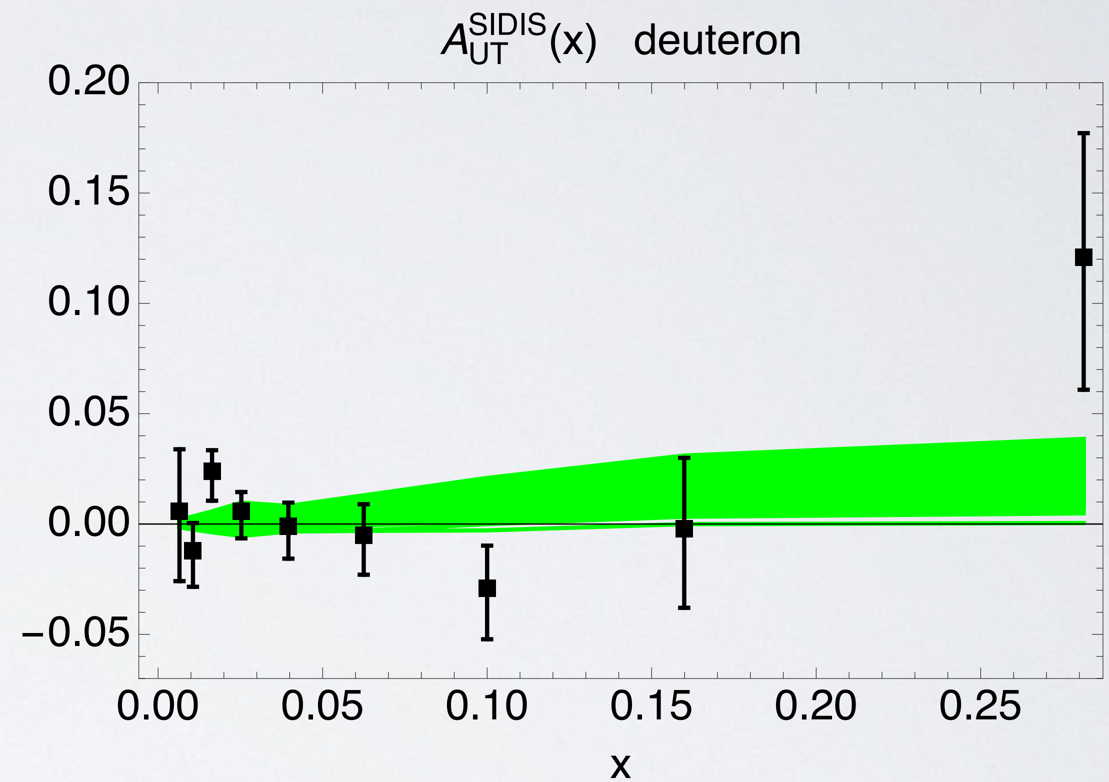
fit SIDIS asymmetry

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)*





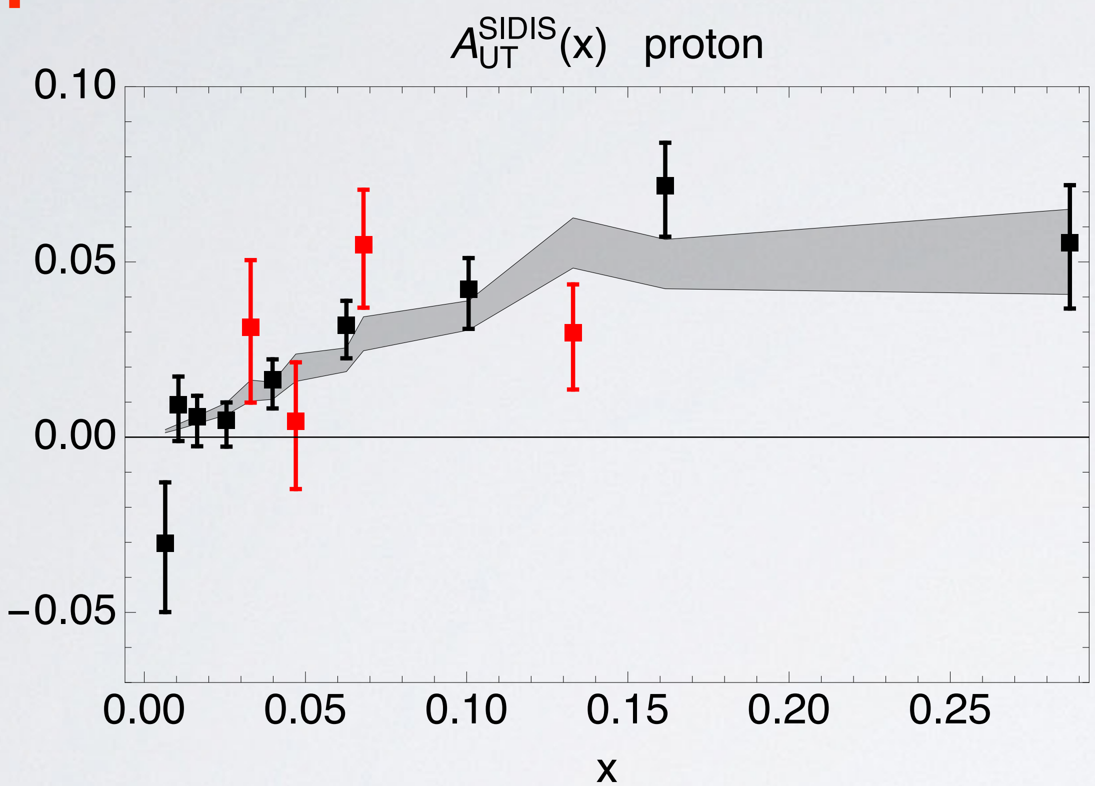
the replica method (200)

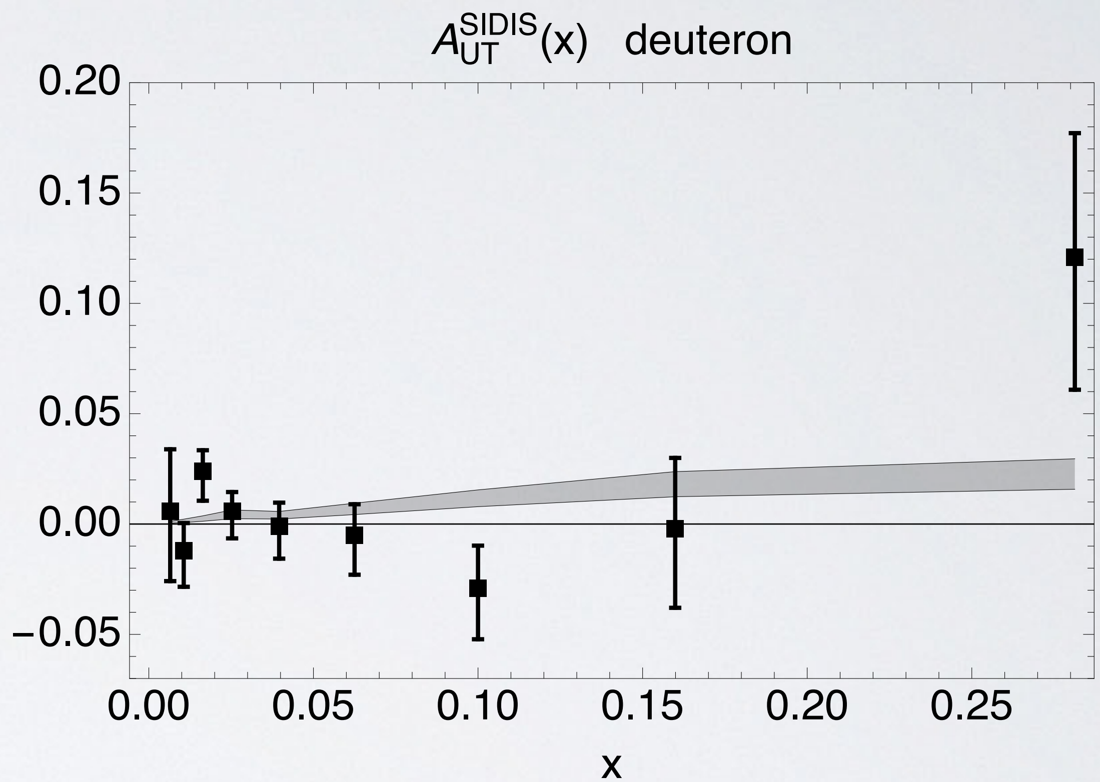
fit SIDIS asymmetry

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

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

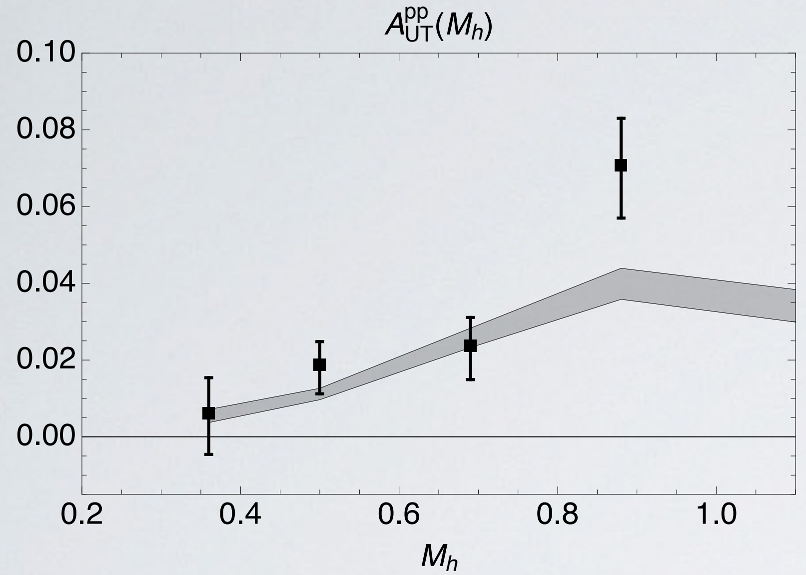
Adolph et al., P.L. ***B713*** *(12)*



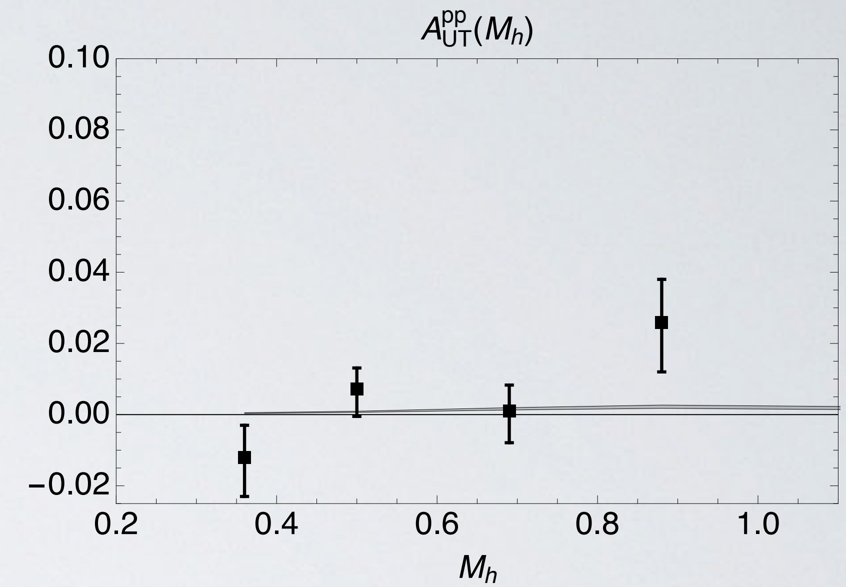


the replica method (68%)

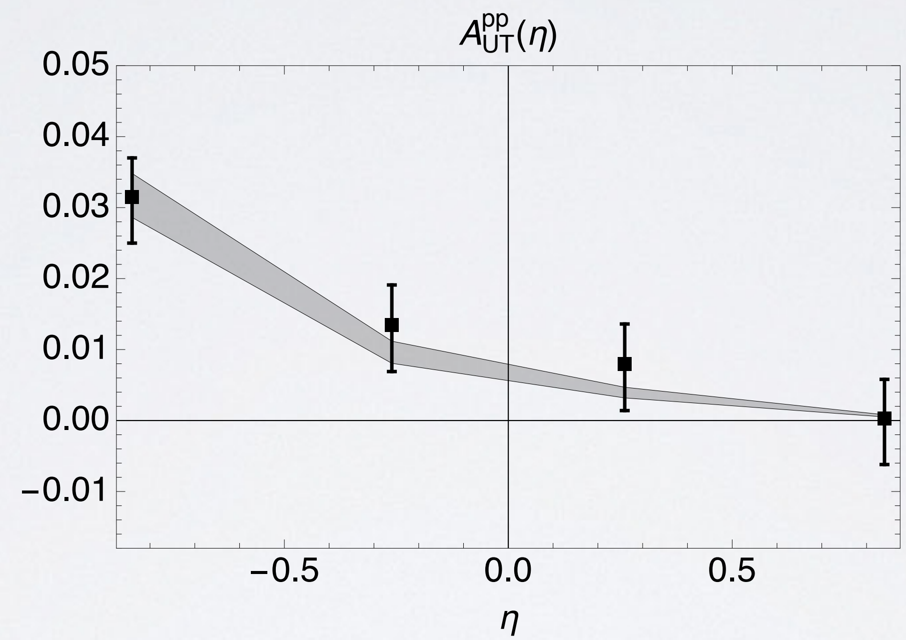
fit STAR asymmetry



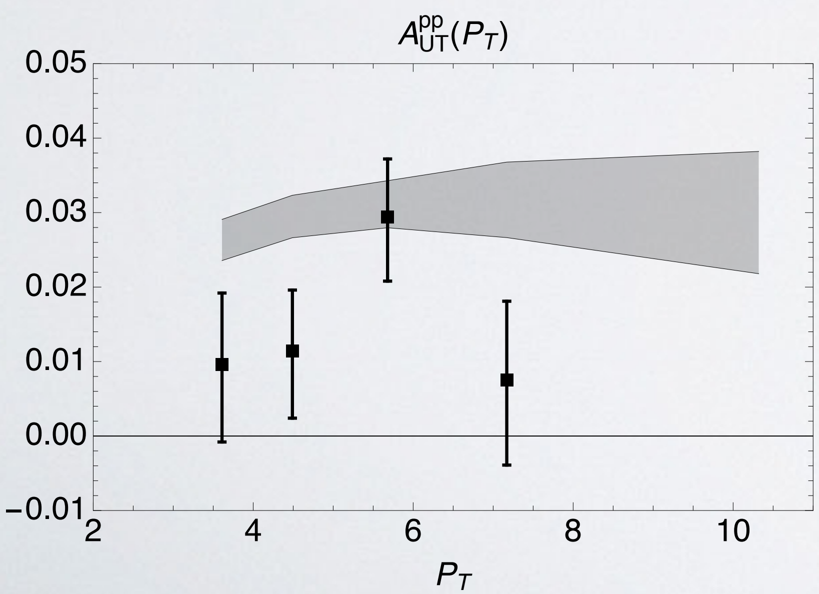
Adamczyk et al. (STAR), P.R.L. ***115*** *(2015) 242501*



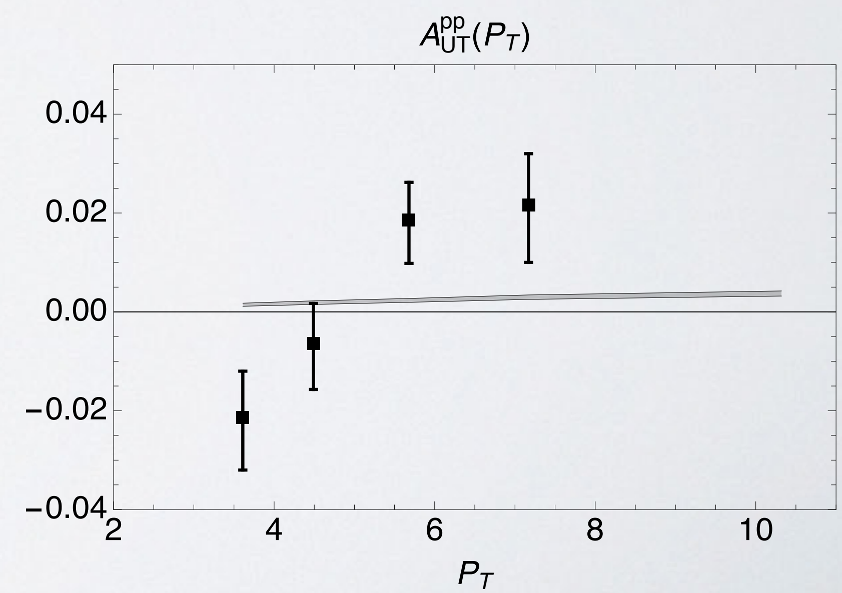
η<0



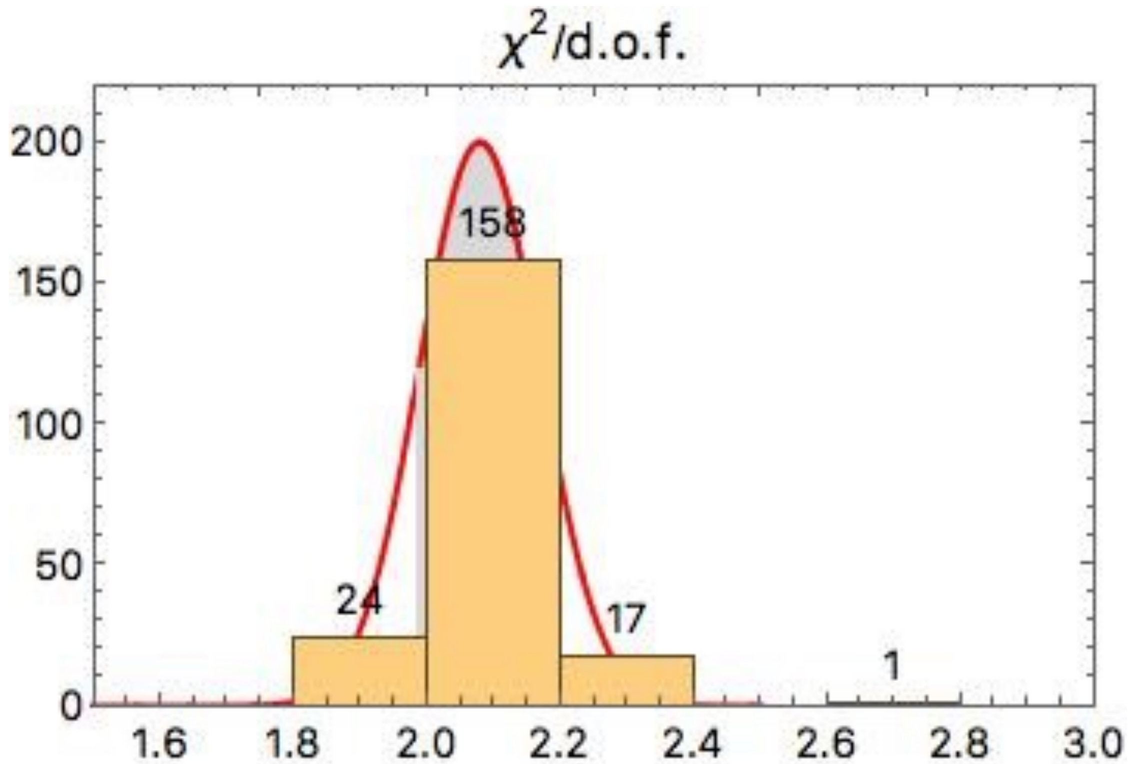
η>0

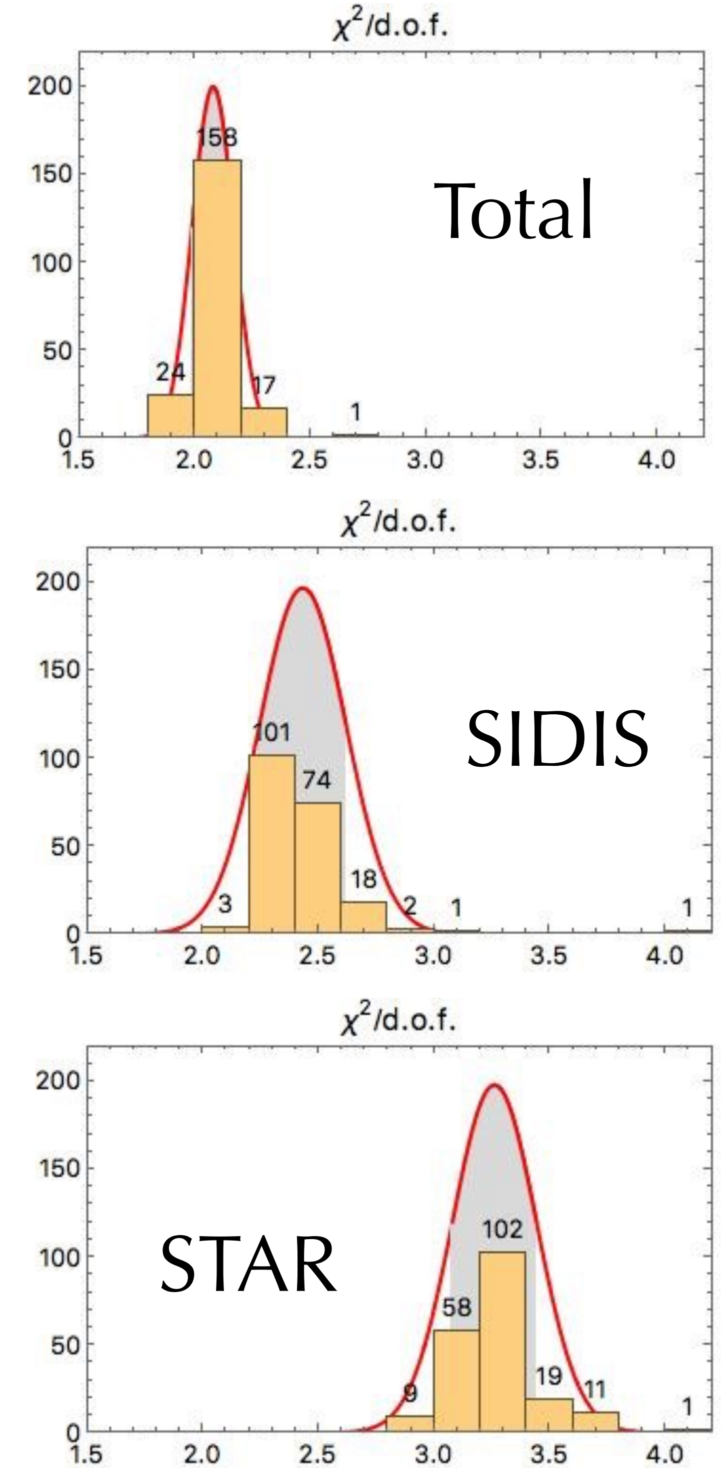


68% uncertainty band



χ^2 of the fit

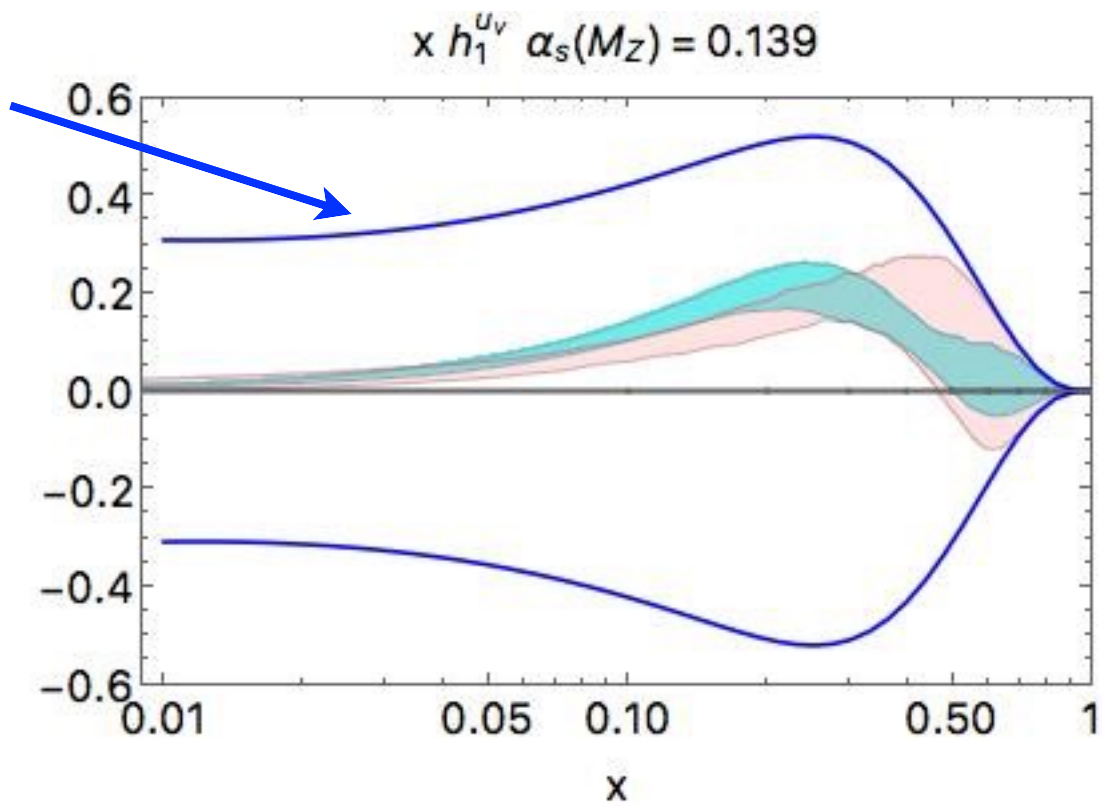




$\chi^2/\mathrm{dof} = 2.08 \pm 0.09$

comparison with previous fit

Soffer bound



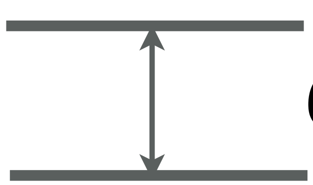
global fit

old fit

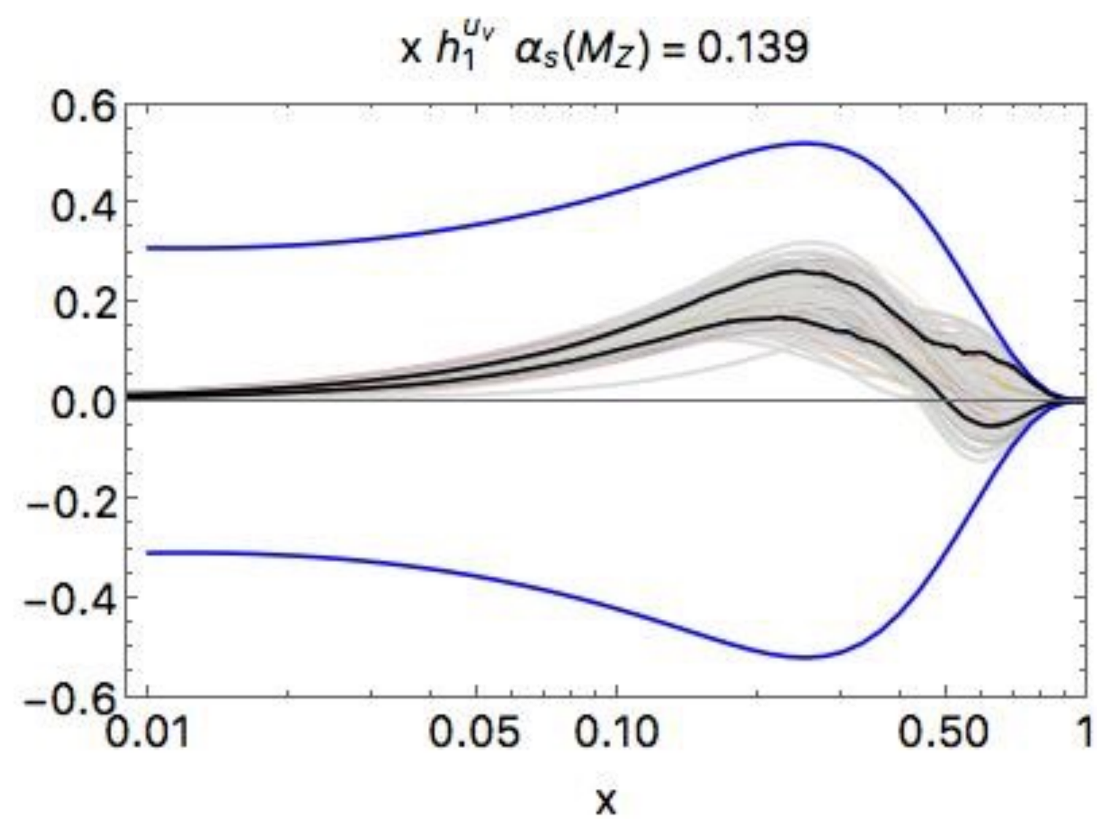
up

higher precision

all 200 replicas

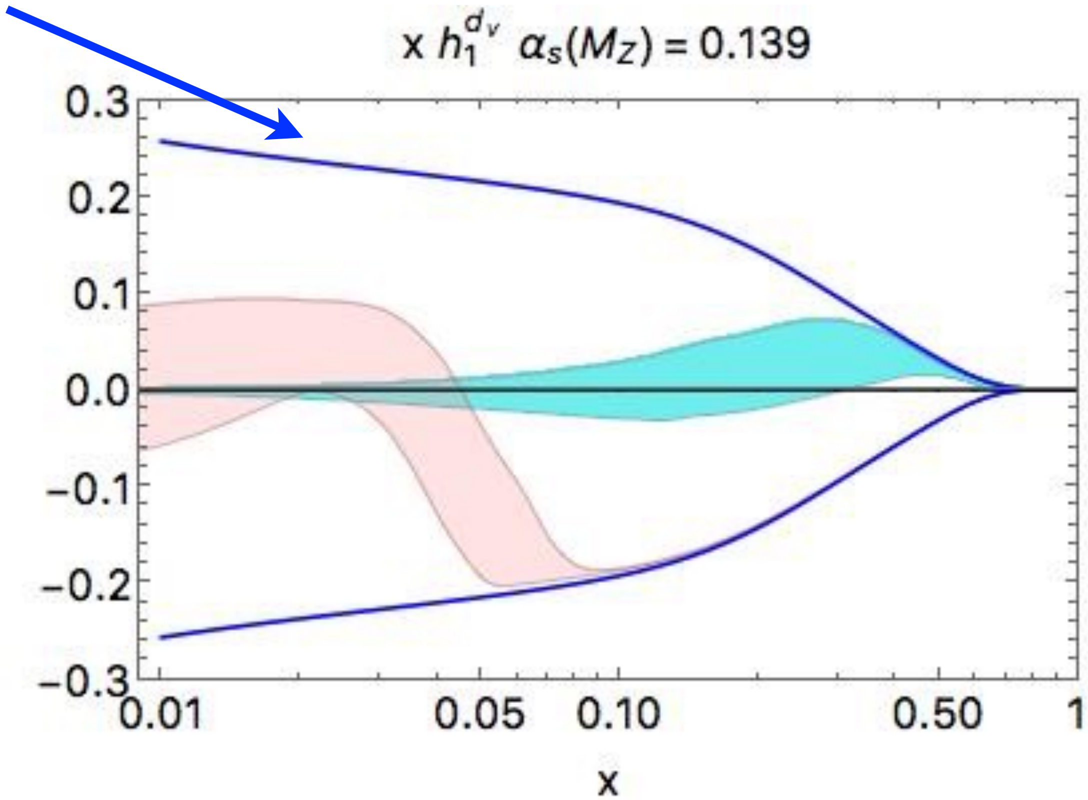


68% band



comparison with previous fit

Soffer bound



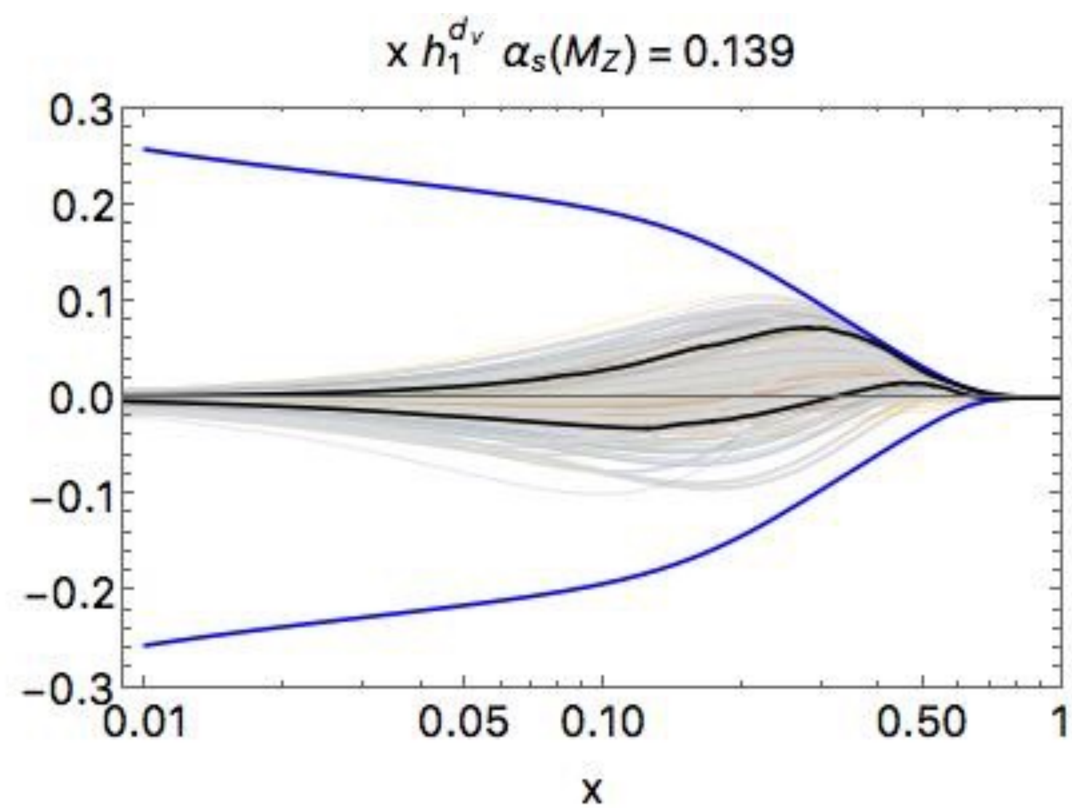
down

global fit

old fit

all 200 replicas

68% band



effect of STAR data :
saturation of Soffer bound
practically disappeared !

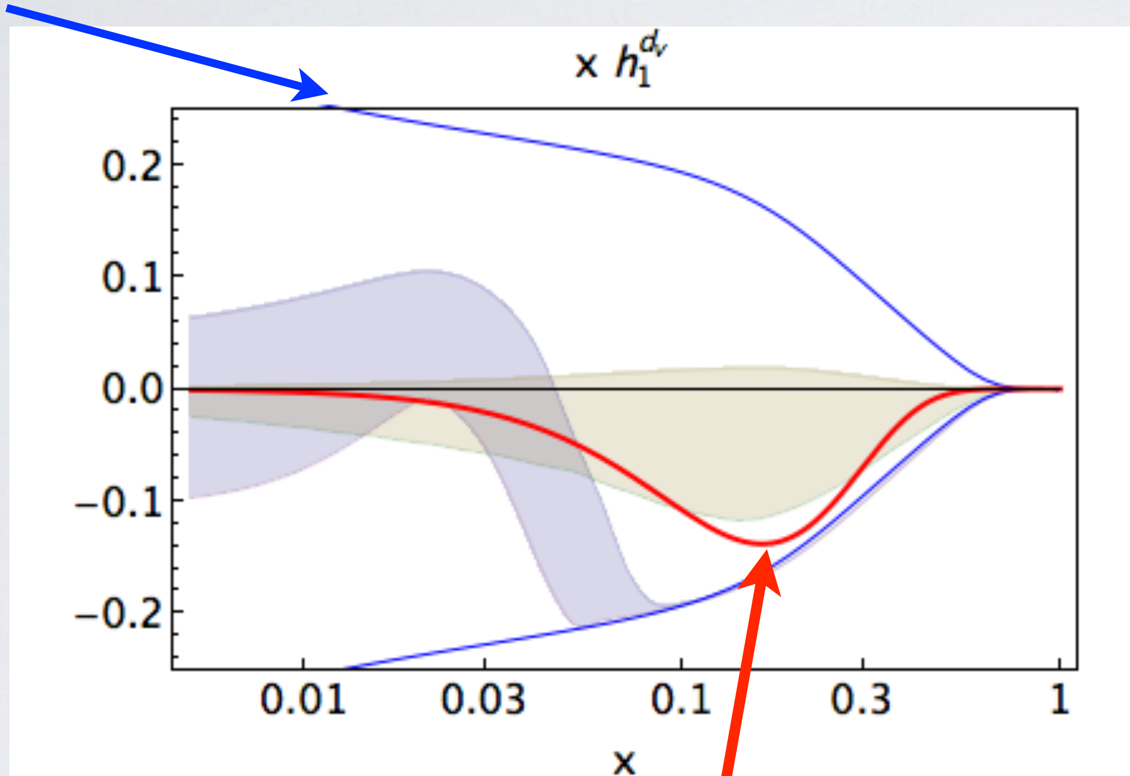
origin of saturation of Soffer bound

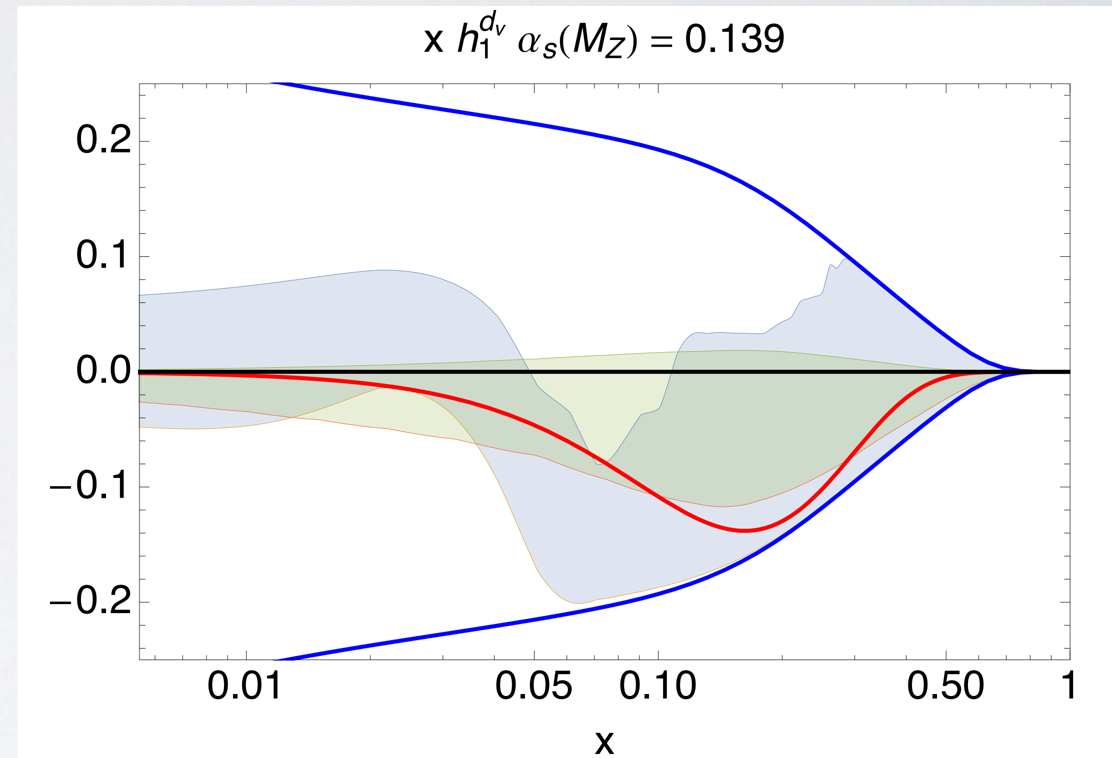
full SIDIS fit

down

"reduced" SIDIS fit :
no bins #7,8 with deuteron

Soffer
bound

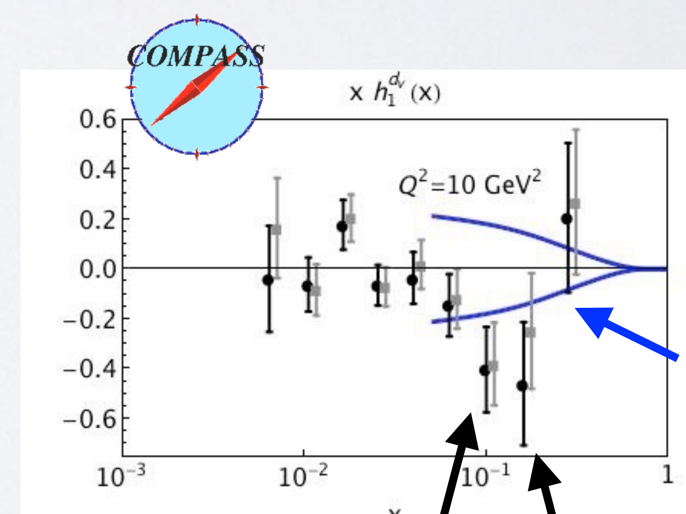




Radici et al.,
*JHEP **1505** (15) 123*

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

Anselmino et al.,
*P.R. D**87** (13) 094019*



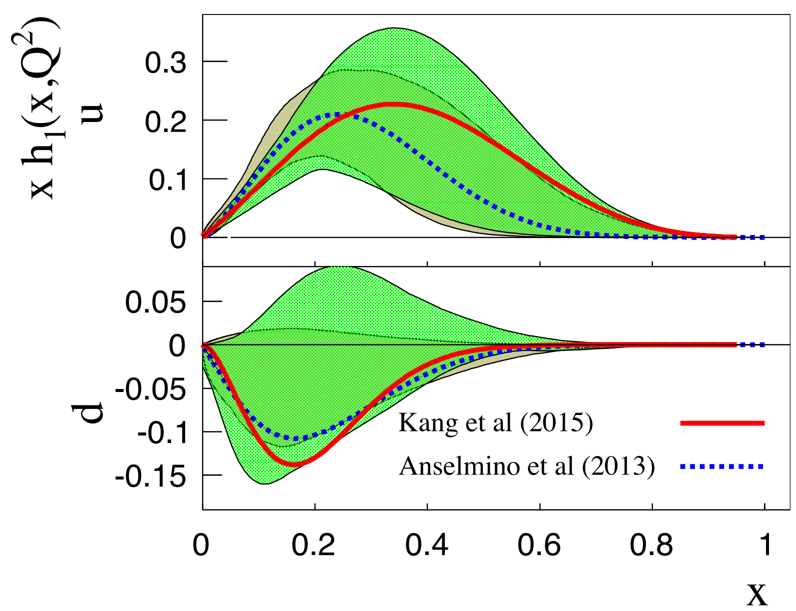
Soffer
bound

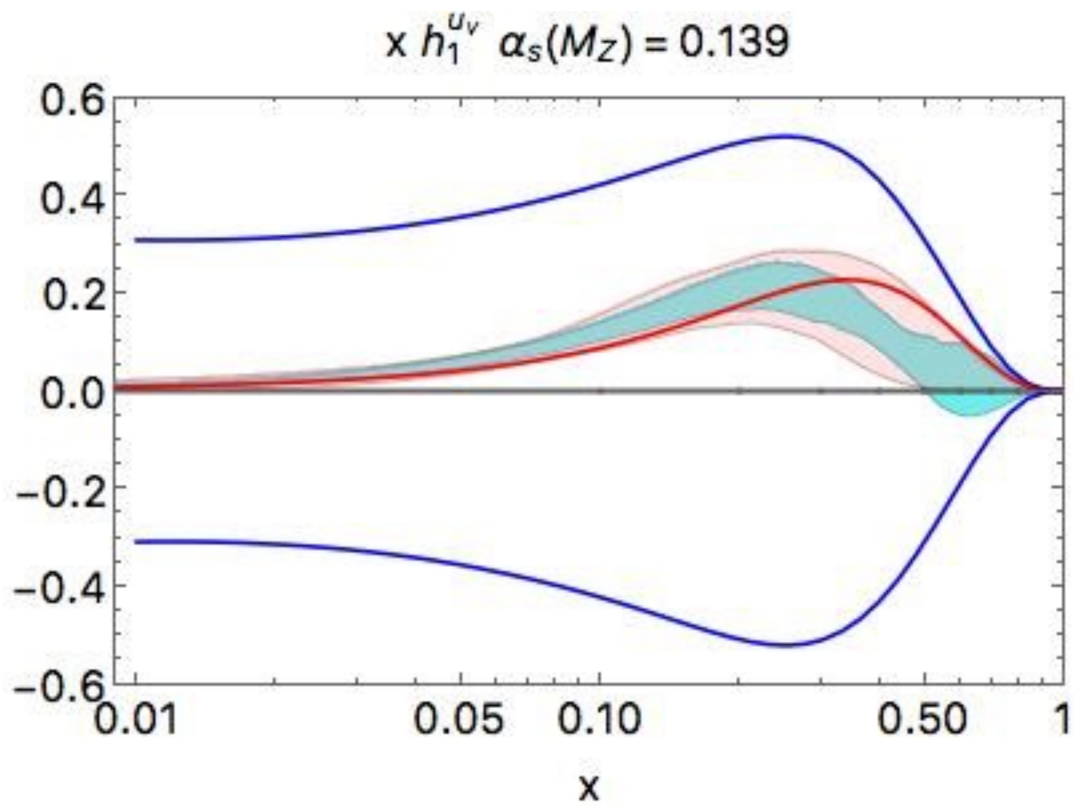
bins #7,8

Comparison with Collins effect

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

*Anselmino et al. (**Torino**), P.R. D**87** (13) 094019*



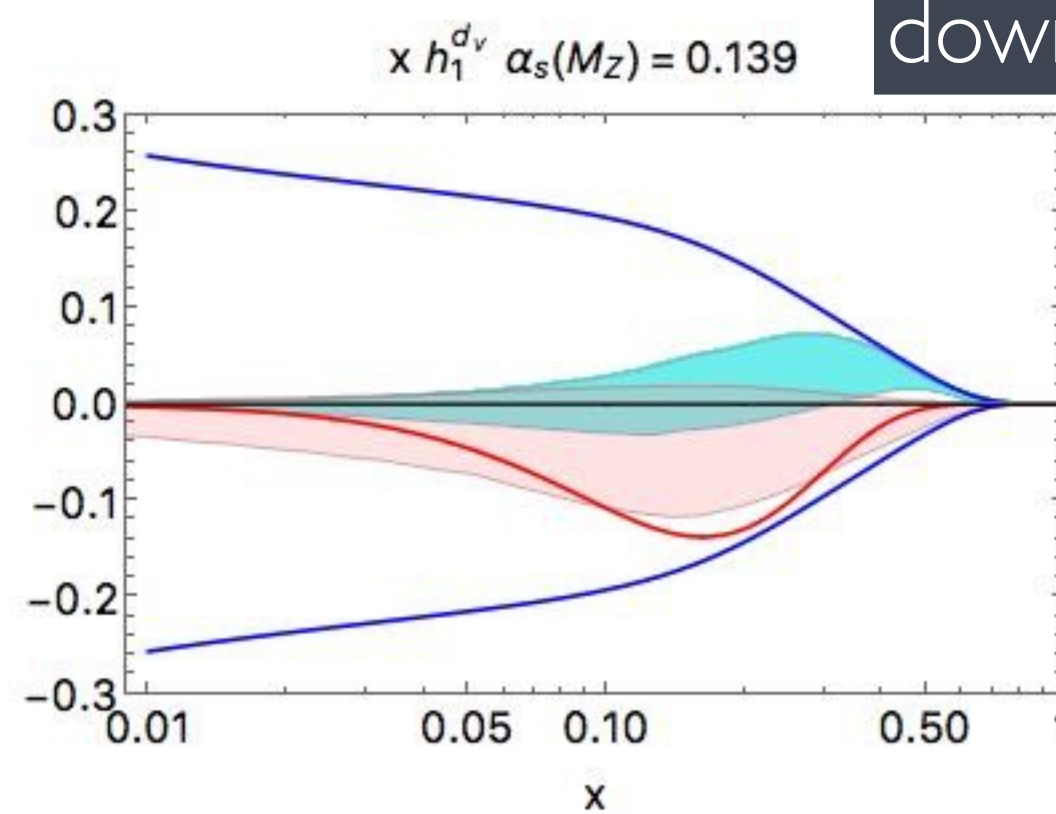


up

global fit

Torino

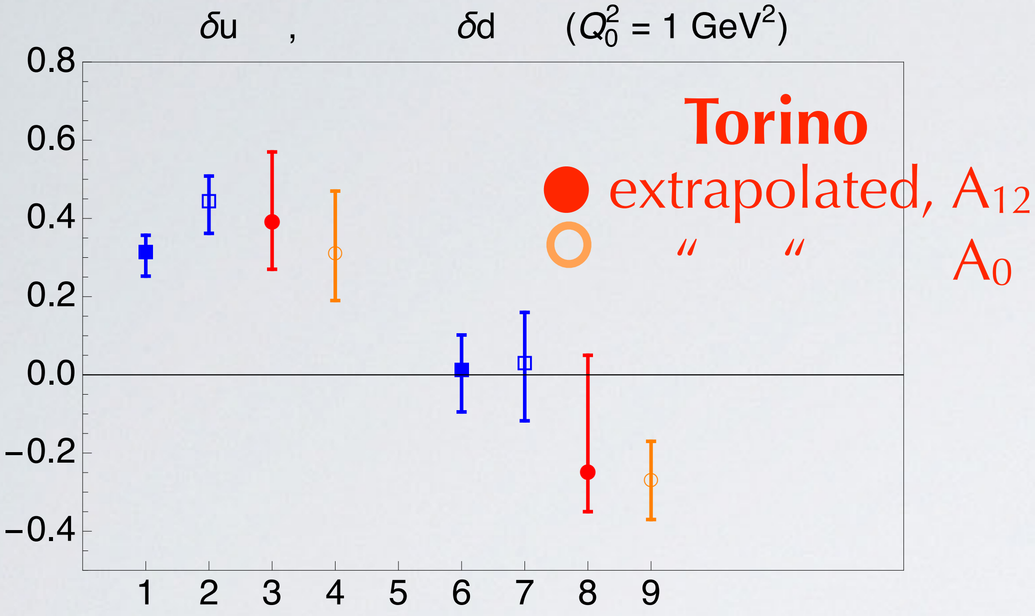
"TMDfit"



down

global fit : • gain in precision
• some tension with deuteron

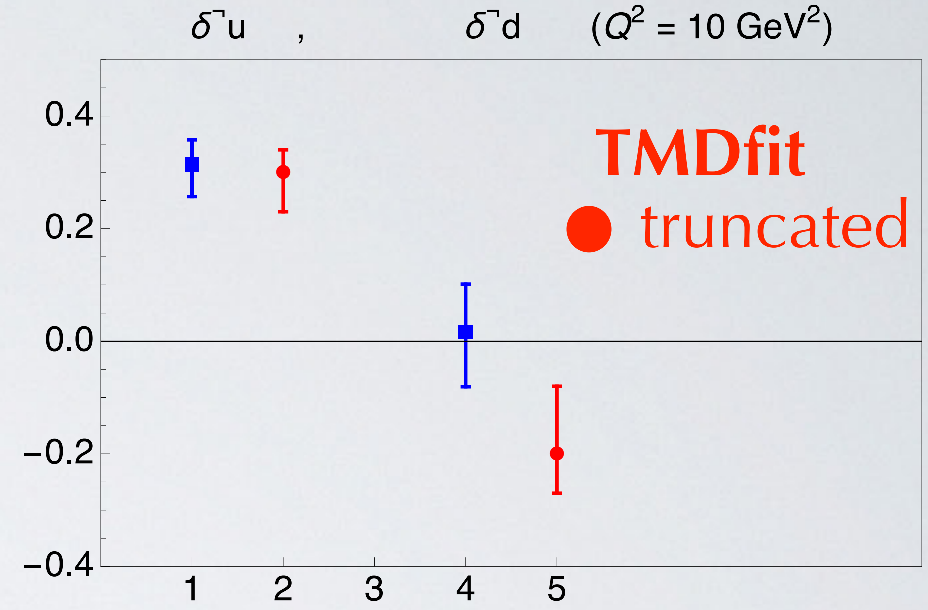
tensor charge $\delta q(Q^2) = \int dx\, h_1^{q-\bar{q}}(x,Q^2)$



global fit

■ truncated

□ extrapolated



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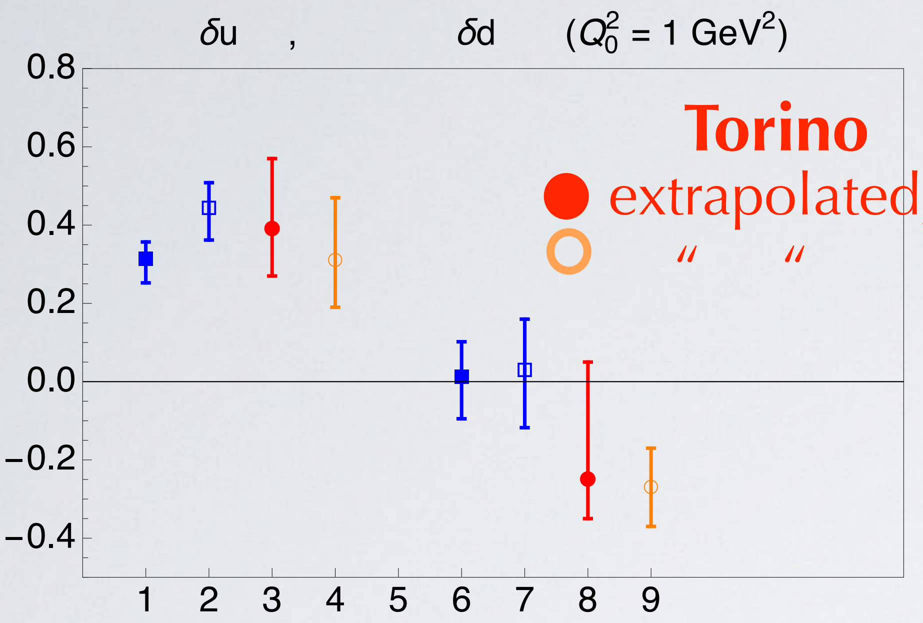
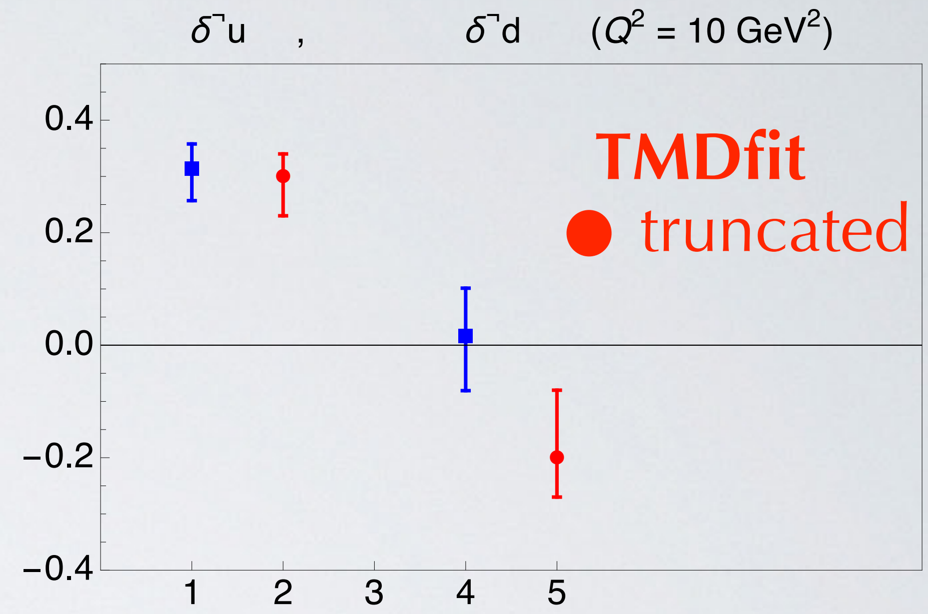


Torino
● extrapolated, A_{12}
○ " " A_0

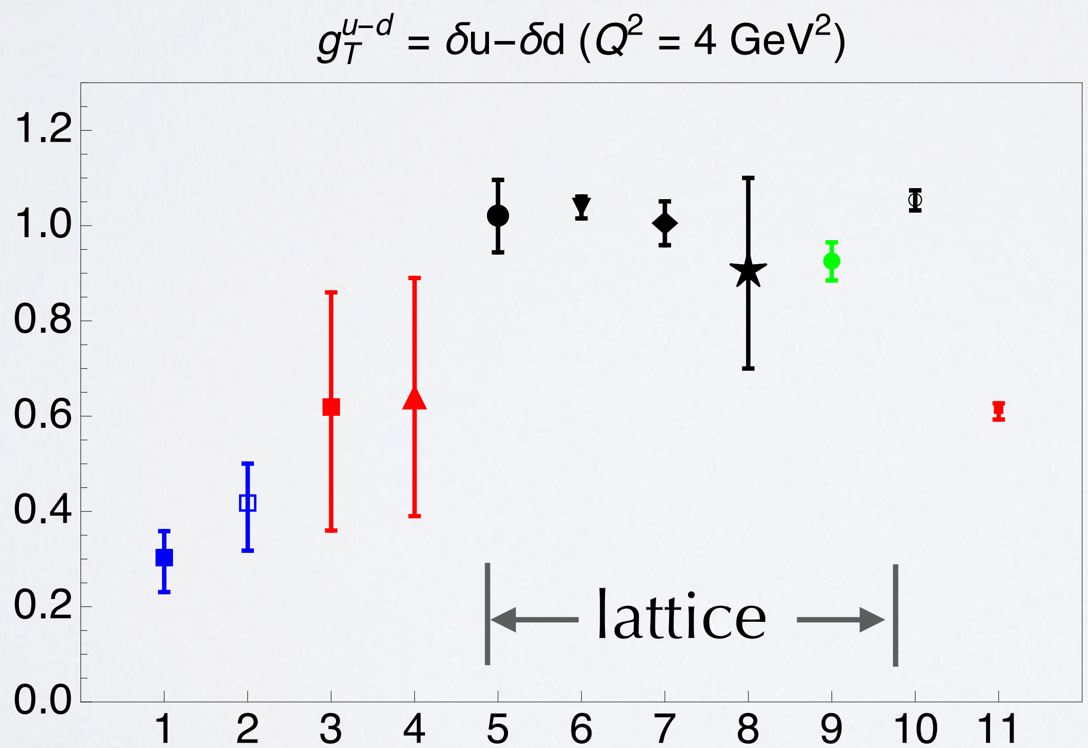
global fit
■ truncated
□ extrapolated



TMDfit
● truncated

global fit
1) truncated
2) extrapolated

3) "TMDfit"
4) Torino



5) PNDME '15 — *Bhattacharya et al., P.R. D**92** (15)*

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

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

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

9) ETMC '17 — *Alexandrou et al., arXiv:1703.08788*

10) ETMC '15 — *Abdel-Rehim et al., P.R.D**92** (15); E P.R.D**93** (16)*

11) SOLID — *Ye et al., P.L. **B767** (17) 91*

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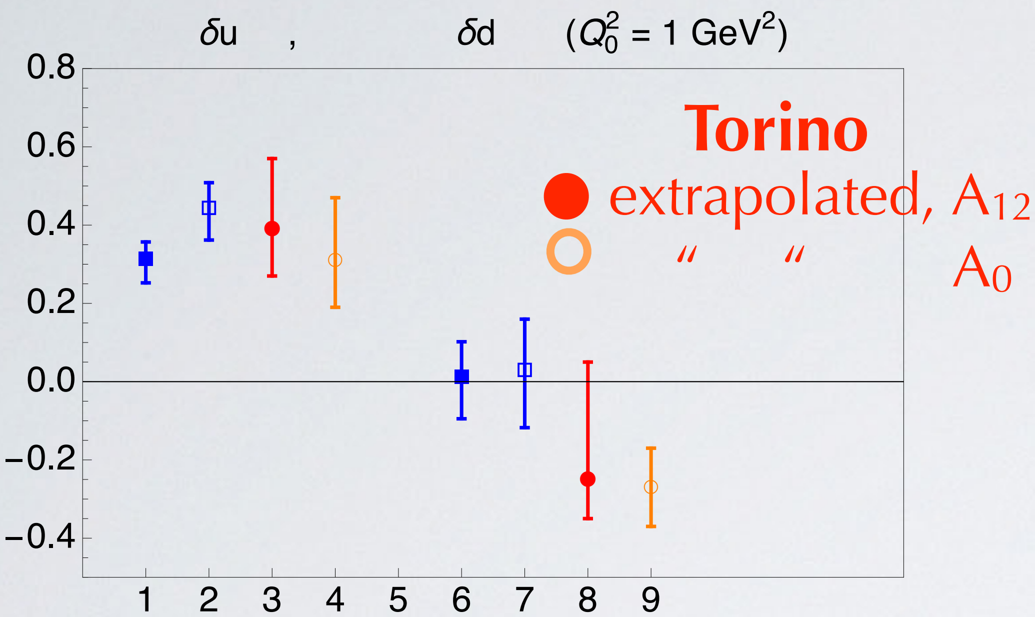
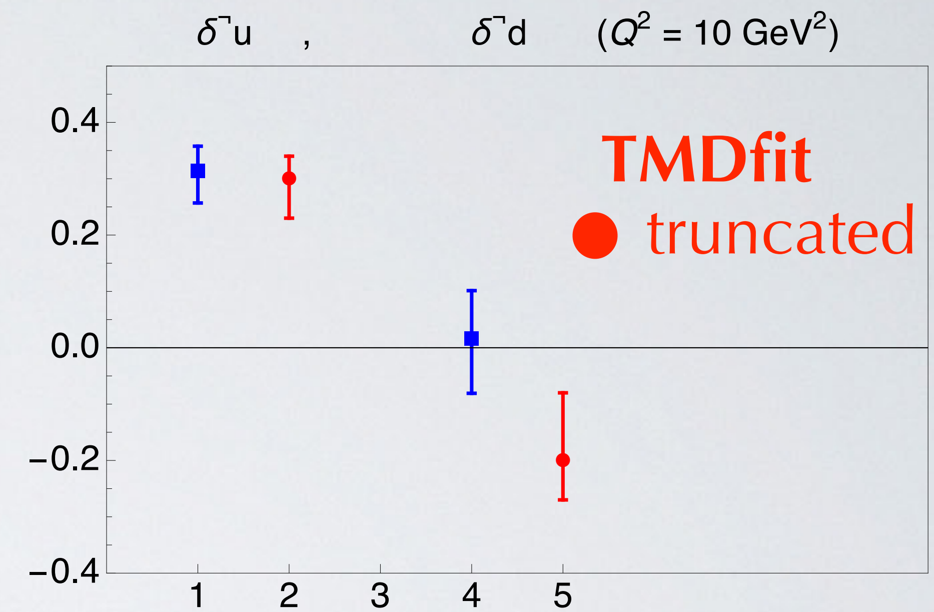


global fit

- ■ truncated
- □ extrapolated



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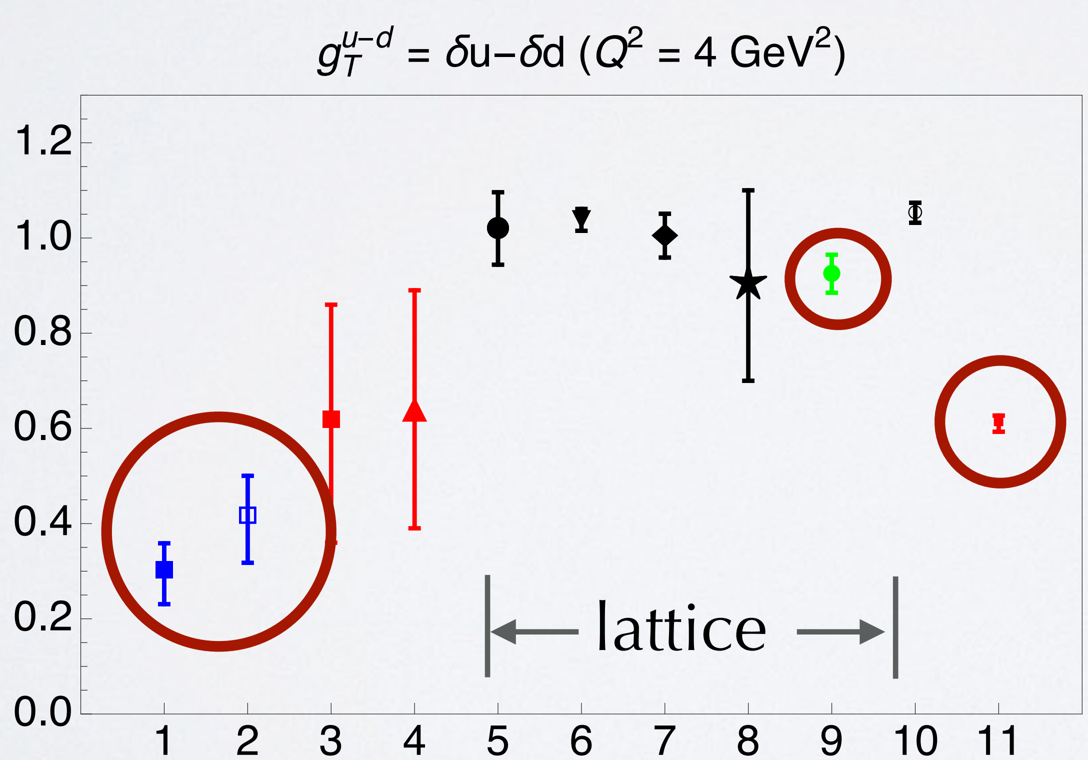

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precision !

precision : potential for BSM searches

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

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

tensor operator not directly accessible in $\mathcal{L}_{SM}$

low-energy footprint of new physics (BSM) at higher scales ?

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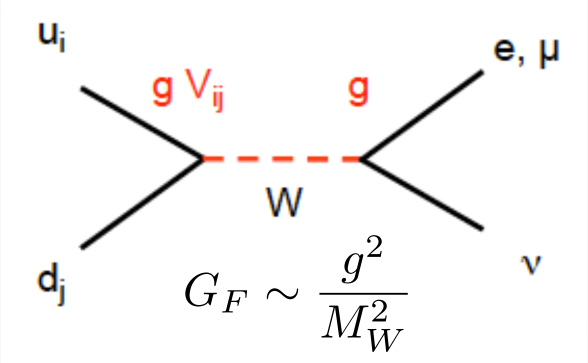
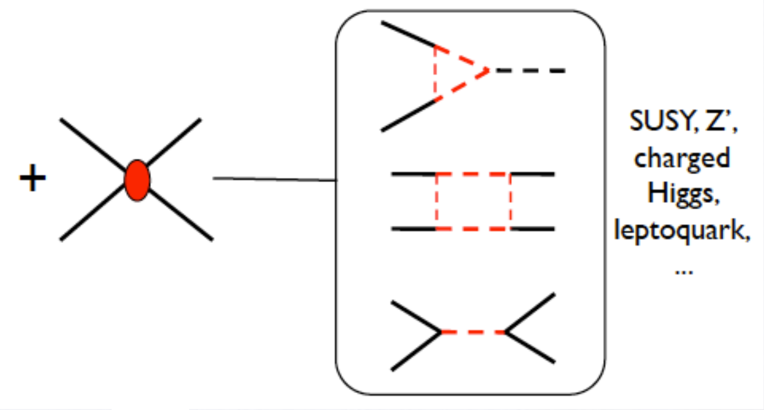
Example: neutron β–decay $n \to p\, e^- \bar{\nu}_e$





$\mathcal{L}_{SM}$ universal V-A

$\mathcal{L}_{BSM}$ new couplings: $\varepsilon_S\, 1,\ \ \varepsilon_{PS}\, \gamma_5\,,\ \ \varepsilon_T\, \sigma^{\mu\nu}$

$$\varepsilon_T\, g_T \approx M_W^2 / M_{BSM}^2$$

precision of 0.1% ⇒ [3-5] TeV bound for BSM scale

precision of $g_T^{\,u-d}$

current most stringent constraints on BSM tensor coupling come from

- Dalitz-plot study of radiative pion decay $\pi^+ \rightarrow e^+ \nu_e \gamma$

  Bychkov et al. (PIBETA), P.R.L. ***103*** *(09) 051802*

- measurement of correlation parameters in neutron β-decay of various nuclei

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$$| \varepsilon_T \, g_T | \lesssim 5 \times 10^{-4}$$

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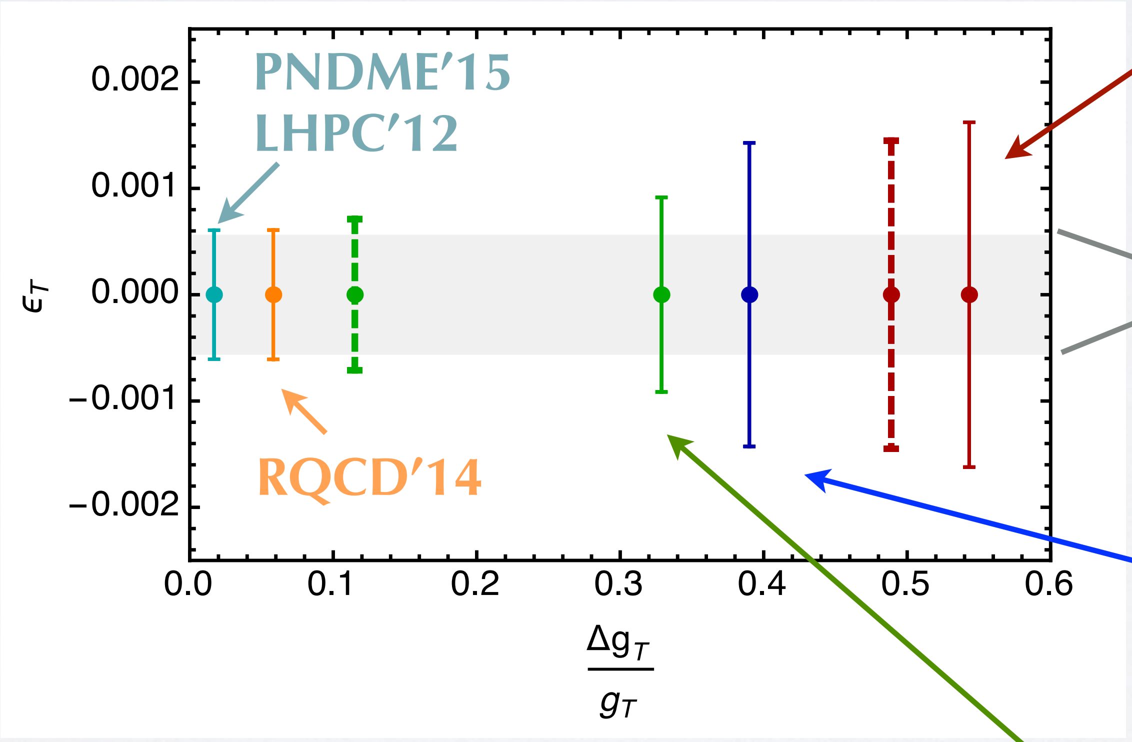
$\Delta\varepsilon_T$ from *Radici et al., JHEP* ***1505*** *(15) 123*



$\Delta\varepsilon_T$ assuming $\Delta g_T=0$

$\Delta\varepsilon_T$ from **Torino**

Goldstein et al., arXiv:1401.0438

Courtoy et al., P.R.L. ***115*** *(2015) 162001*

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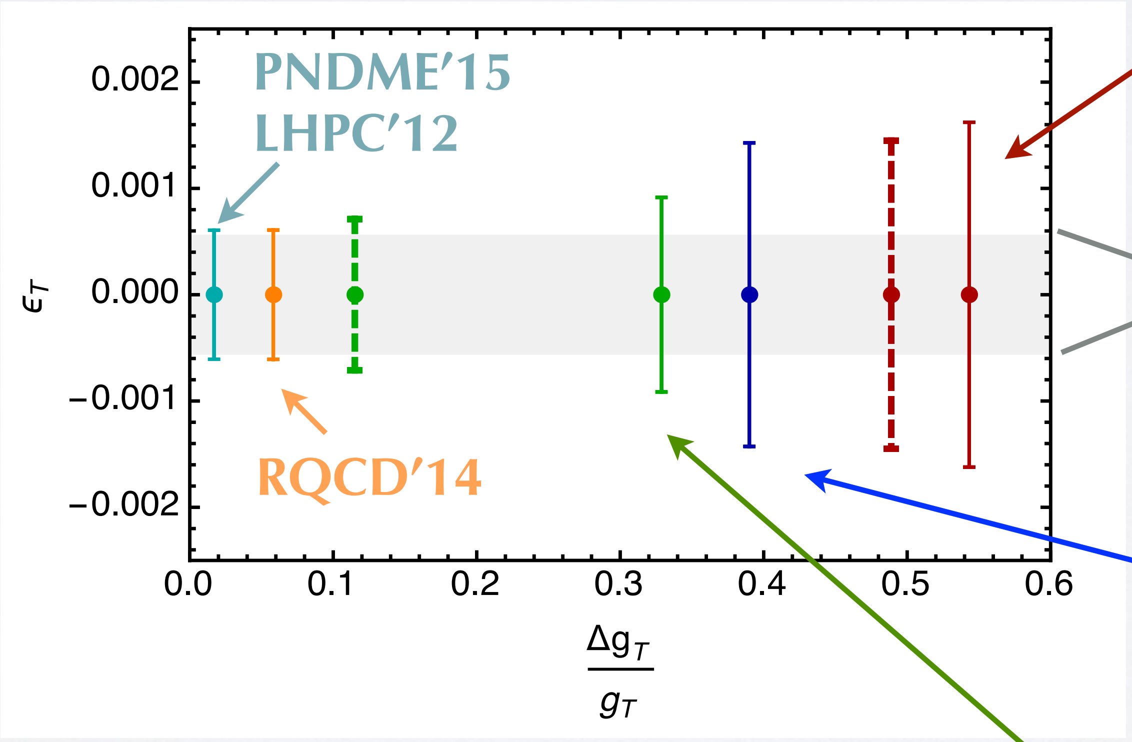
$| \varepsilon_T g_T | \lesssim 5 \times 10^{-4}$

need more data to adapt phenomenology to precision of measurements and lattice



$\Delta\varepsilon_T$ from *Radici et al., JHEP **1505** (15) 123*

(to be improved by global fit)

$\Delta\varepsilon_T$ assuming $\Delta g_T=0$

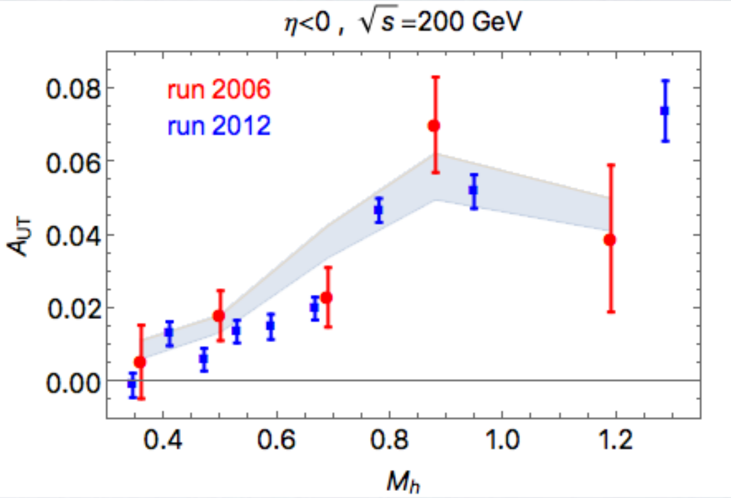
$\Delta\varepsilon_T$ from **Torino**

Goldstein et al., arXiv:1401.0438

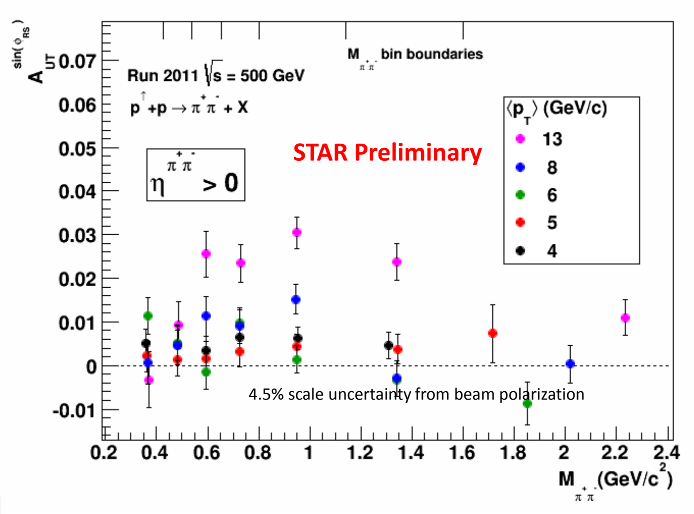
*Courtoy et al., P.R.L. **115** (2015) 162001*

To do list

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



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



M. Skoby, SPIN 2014

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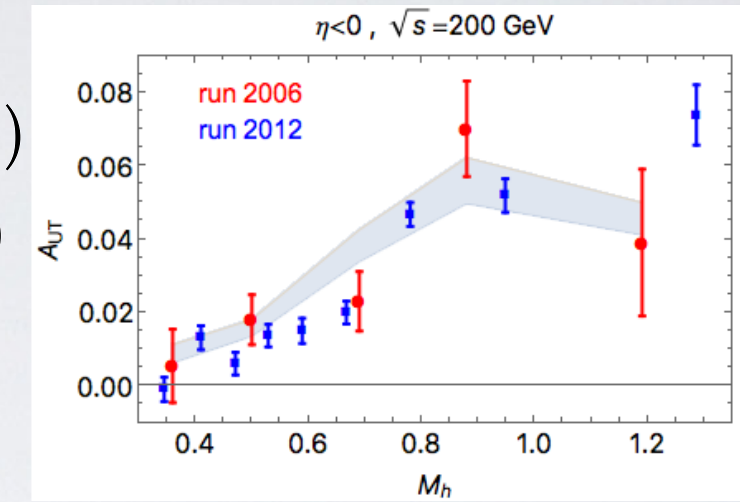
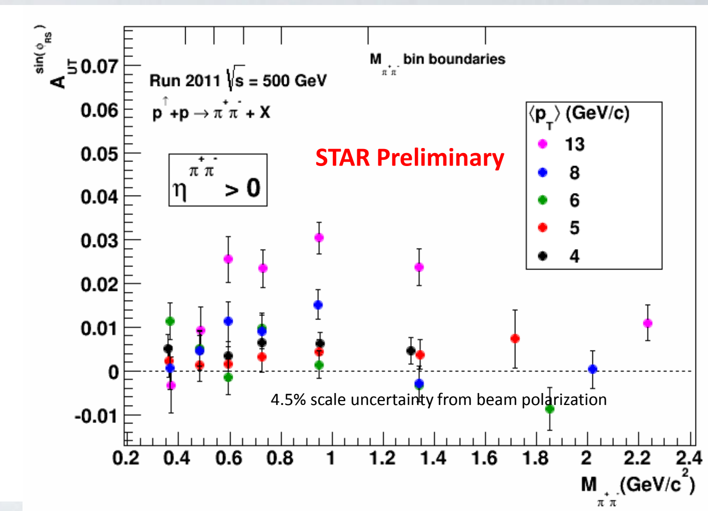


*Radici et al., P.R. D**94** (16) 034012*



M. Skoby, SPIN 2014

- ➡ wait for data on unpolarized cross section $d\sigma^0$:
  $e^+e^- \to (\pi\pi)\,X$ constrains D_1^q
  $p+p \to (\pi\pi)\,X$ constrains D_1^g

$$A_{UT} = \frac{d\sigma_{UT}}{d\sigma^0}$$

large K factor in $d\sigma^0$? (but not in $d\sigma_{UT}$)
uncertainty band probably underestimated
but no K factor can modify $A_{UT}(M_h)$

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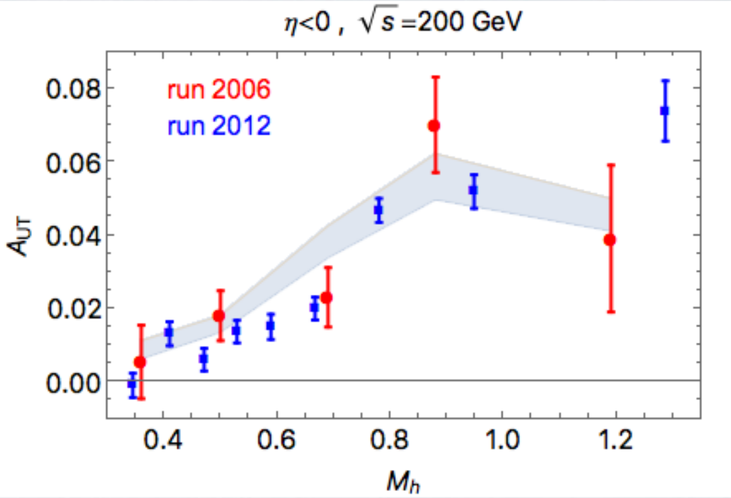
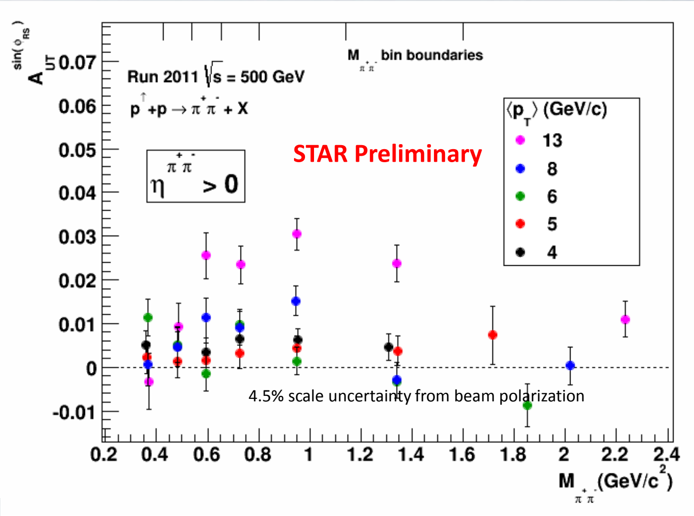


*Radici et al., P.R. D**94** (16) 034012*



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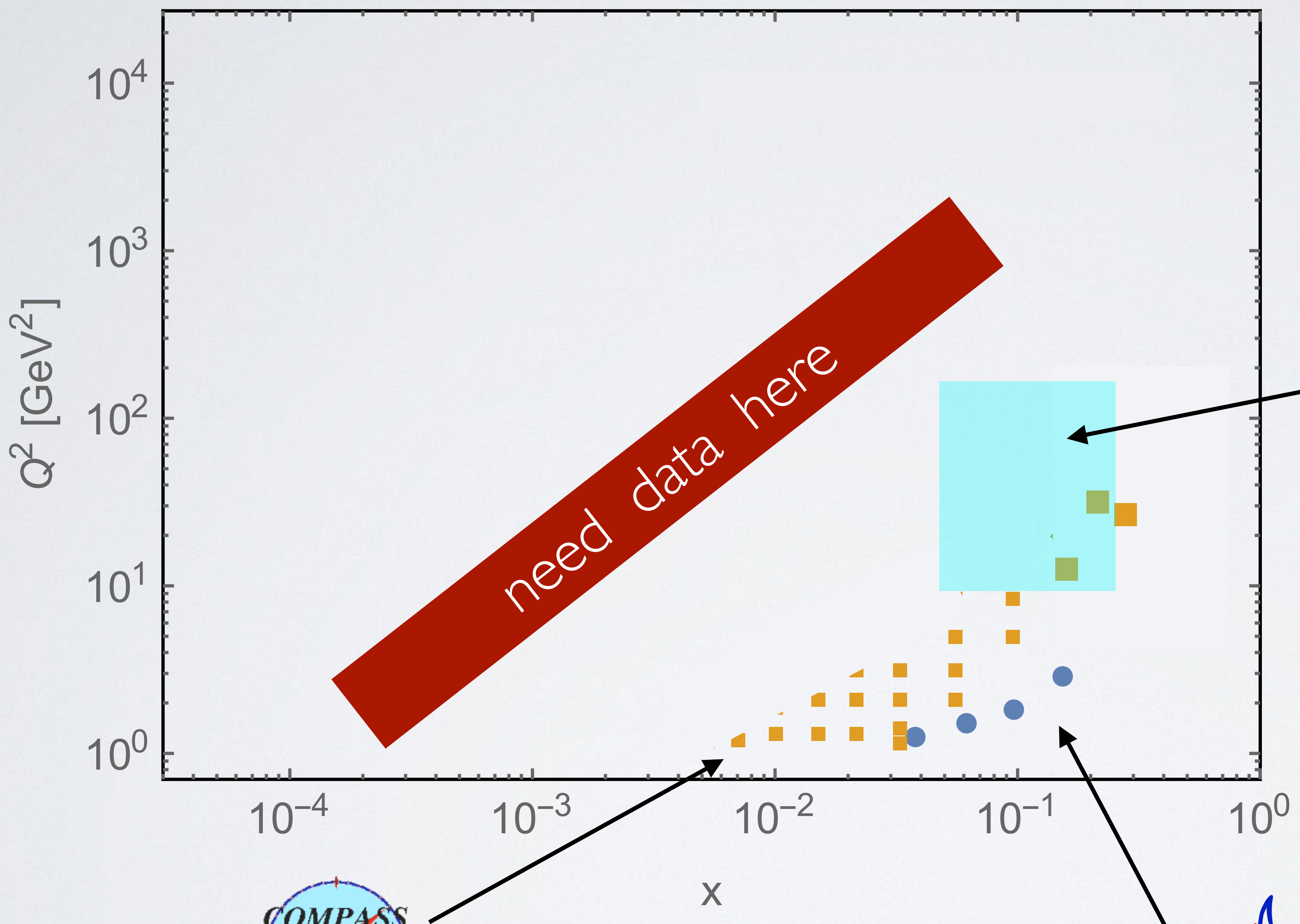
➡ use Compass data on πK and KK channels :
constrain strange contribution ?

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

Accardi and Bacchetta, arXiv:1706.02000

the kinematics



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

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

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

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

Conclusions

- first global fit of di-hadron inclusive data leading to extraction of transversity in collinear framework (PRELIMINARY!)

- inclusion of STAR p-p$^{\uparrow}$ data increases precision of extracted transversity and eliminates suspicious behavior of down channel; some tension with extraction from Collins effect

- tensor charge useful for low-energy explorations of BSM new physics ⇒ precision is an issue. In this respect, the global fit is a significant step forward

THANK YOU