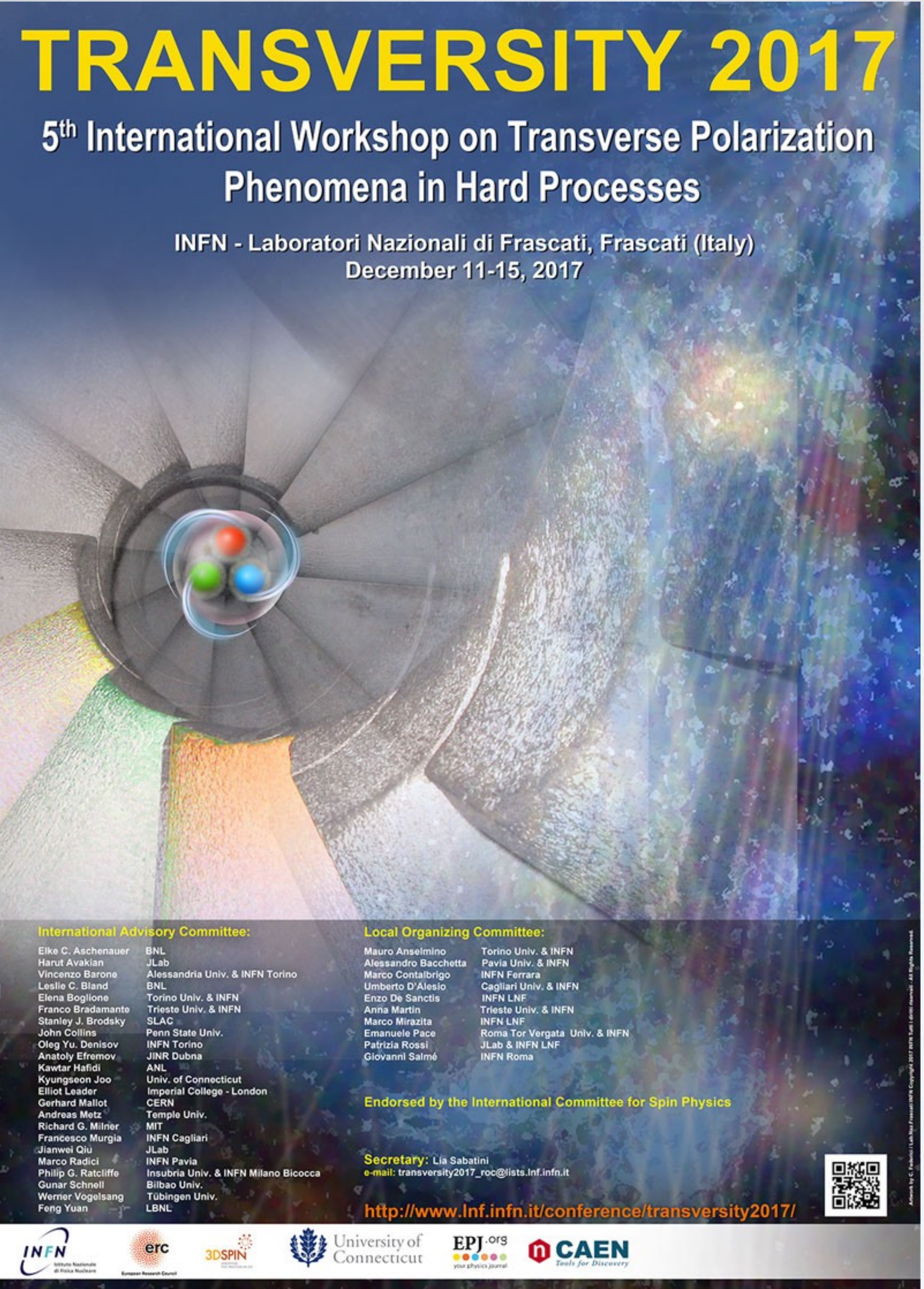

TRANSVERSITY 2017

5th International Workshop on Transverse Polarization Phenomena in Hard Processes

INFN - Laboratori Nazionali di Frascati, Frascati (Italy)
December 11-15, 2017

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Giovanni Salmé	INFN Roma

Endorsed by the International Committee for Spin Physics

Secretary: Lia Sabatini
e-mail: transversity2017_roc@lists.lnf.infn.it

http://www.lnf.infn.it/conference/transversity2017/

First extraction of Transversity from a global fit

Marco Radici
INFN - Pavia

in collaboration with
A. Bacchetta (Univ. Pavia)

the first workshop on Transversity: ECT* 2004

excerpt from CERN Courier **44** n.8 (2004) 51

organizers:
- E. De Sanctis
- W.-D. Novak
- M. Radici
- G. van der Steenhoven

the workshop of the famous
Trento Conventions

*Bacchetta et al., P.R. D**70** (04) 117504*

CONFERENCE

The Transversity Council of Trento at the ECT* (2004)

In a recent workshop at the ECT* in Trento on New Developments in Nucleon Spin Structure memories of the famous Council of Trento (1530) were revived.

During workshops experts get together to present the outcome of recent work, confront and discuss (new) ideas, get inspiration for further work, and incidentally start new collaborations. However, sometimes the conditions are so favorable that all workshop activities seem to be oriented towards a unique common goal. Each participant feels like being a member of one team cooperating to accomplish a well defined goal.

The latter feeling occurred during the International Workshop on *Transversity: New Developments in Nucleon Spin Structure* in June 2004 that brought together some 40 leading experimental and theoretical physicists in the field of nucleon spin structure at the European Center for Theoretical Physics (ECT*). The ECT* is located in the beautiful recently renovated Villa Tambosi in Villazzano, which is a nice suburb in the hills above Trento, Italy.

At the workshop many very interesting talks were presented by renown experts (among them M. Anselmino, J. Collins, M. Diehl, N.C.R. Makins, C.A. Miller, P.J.G. Mulders), supplemented by shorter -but not less inspiring- talks of PhD students and postdocs. The talks illustrated and substantiated the rapid developments in the new field of transverse spin physics. In fact, the results presented were so encouraging that the spontaneous idea emerged to devote part of the scheduled (and unscheduled) discussion time to the preparation of a document, soon christened *The Trento Convention*, containing all relevant notations and conventions that are crucial to achieve further progress in this field.

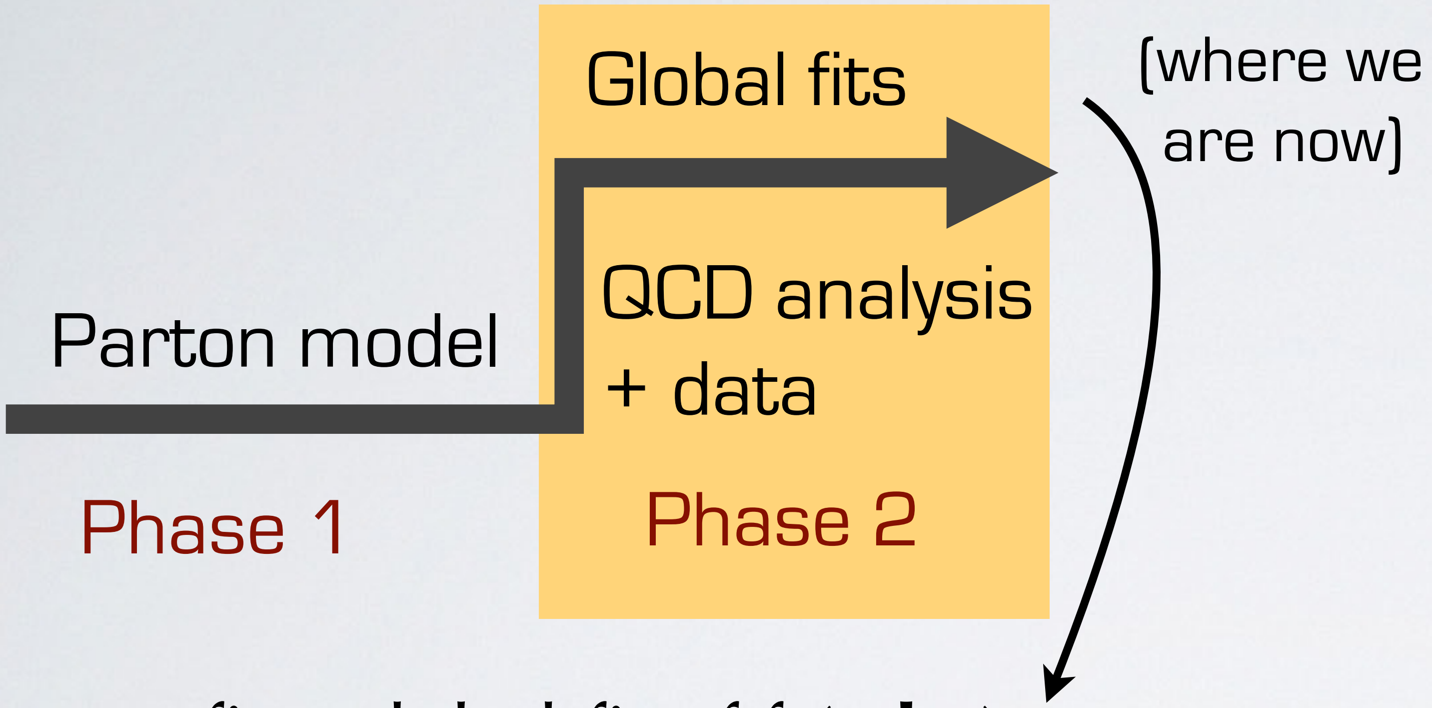
John Collins and Andy Miller discussing spin physics during the workshop dinner.

Such a document, which is now well under way, will soon be submitted to the e-print archives. It has been set up by a few representatives (A. Bacchetta and others), but it is virtually co-authored by all the workshop participants. Just like the famous First Vatican Council that took place in Trento almost 500 year ago (1530), the document represents a common frame, and a common language for an unambiguous comparison between theory and experiment. It will be an indispensable tool to boost further developments in this area.

But why is a seemingly technical subject as transverse spin physics so fascinating? From recent cosmological observations (by the WMAP satellite for instance), we know that visible matter represents only a small fraction (4%) of the universe. Of this small percentage only a minute fraction can be attributed to the mass of the quarks, for which -most likely- the Higgs mechanism has to be invoked. In fact, the remaining, *i.e.* by far largest, part of the mass of the visible universe has a dynamical origin. It is the dynamics of the quarks and gluons in the nucleon, as governed by the theory of strong interactions - Quantum Chromodynamics (QCD),

a phase transition in 3D studies as in PDFs

3D (TMDs)



Parton model

Phase 1

Global fits

QCD analysis
+ data

Phase 2

(where we
are now)

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

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

talk by Delcarro

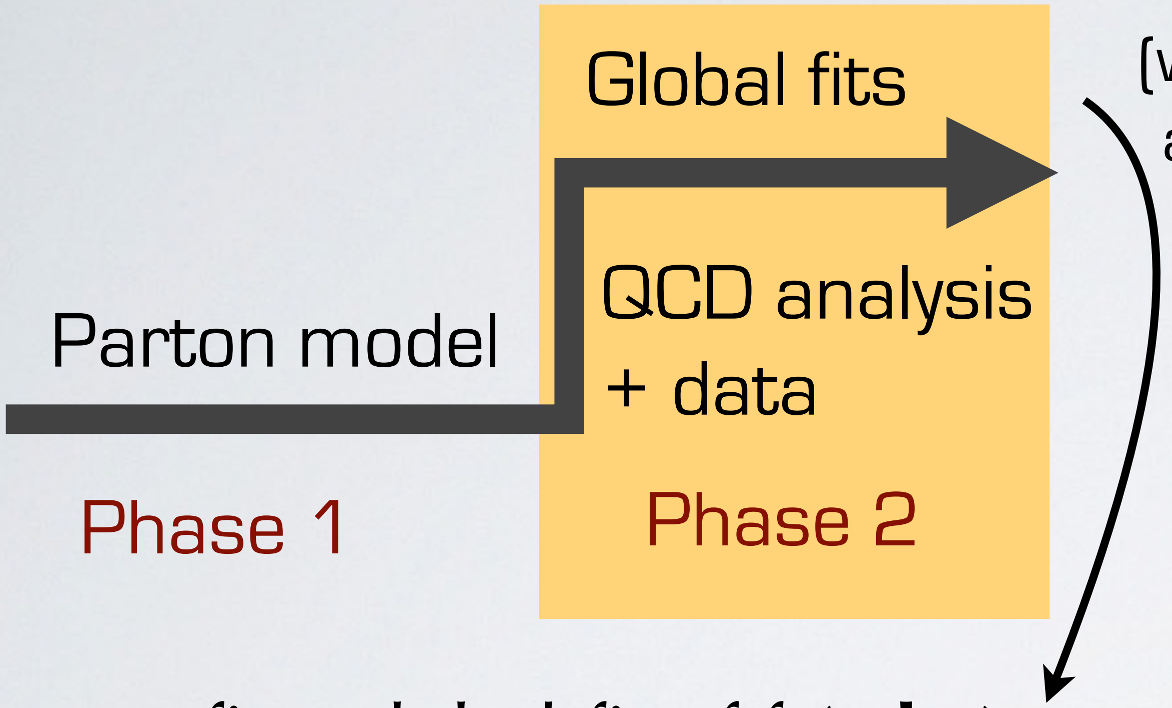
quark polarization

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 $h_{1T}^\perp$

a phase transition in 3D studies as in PDFs

3D (TMDs)



Global fits

Parton model

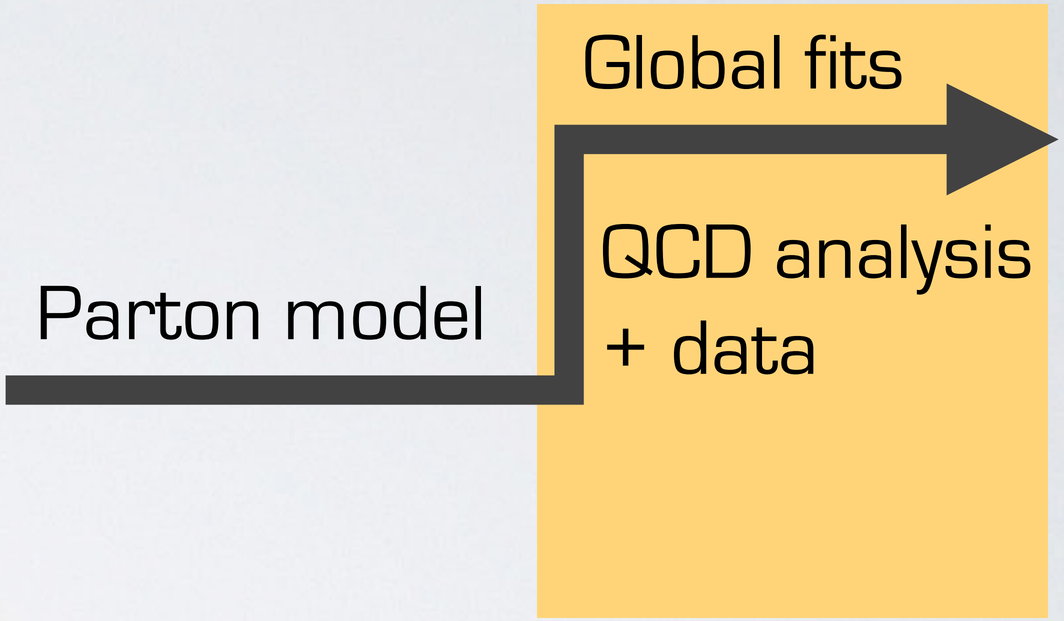
QCD analysis + data

Phase 1

Phase 2

(where we are now)

1D (PDFs)



Global fits

Parton model

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

talk by Delcarro

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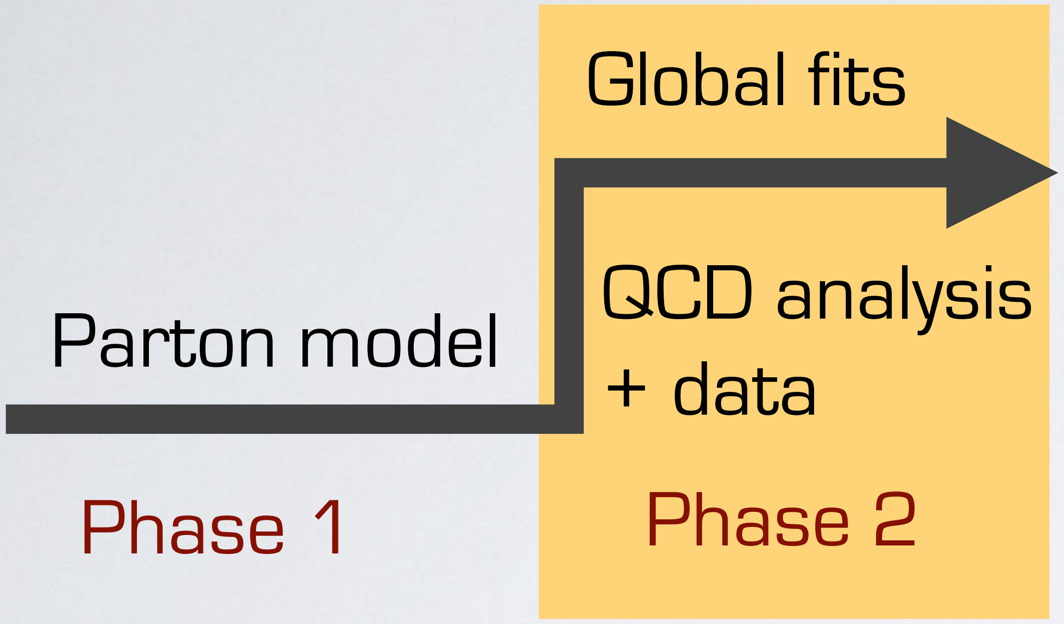
	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

talk by Nocera

for $\mathbf{f_1}$ and $\mathbf{g_1}$

a phase transition in 3D studies as in PDFs

3D (TMDs)



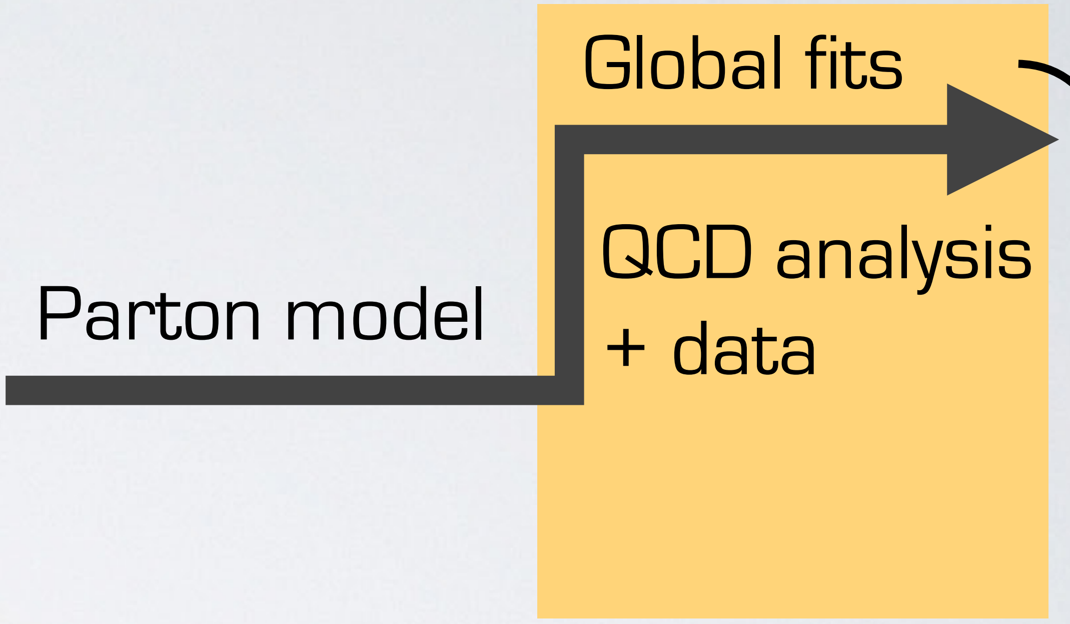
(where we are now)

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

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

talk by Delcarro

1D (PDFs)



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 $h_{1T}^\perp$

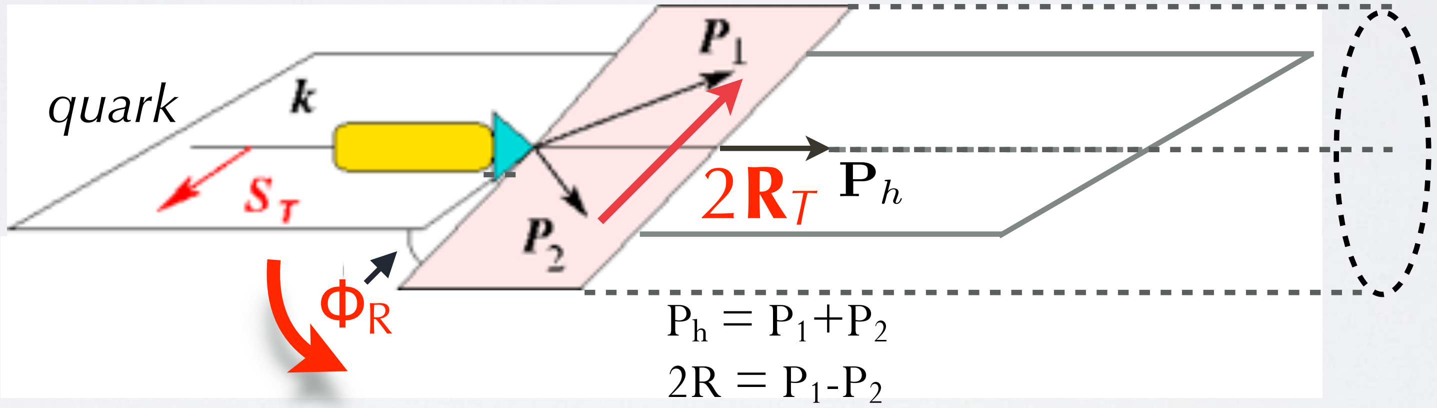
talk by Nocera

for **f_1** and **g_1**

but for **h_1** ??
(as a **twist-2 PDF**)

extraction from 2-hadron-inclusive data

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



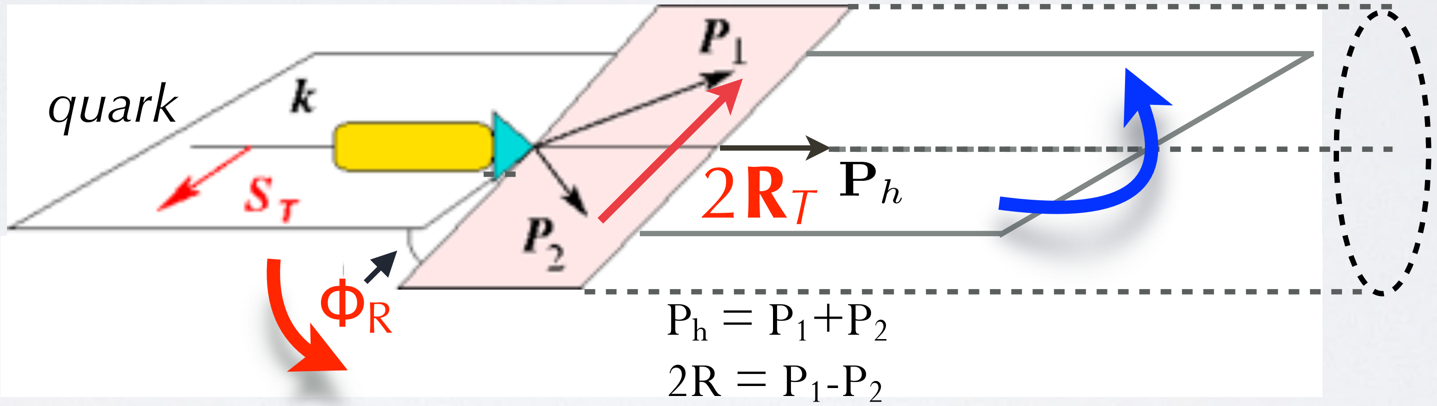
$P_h = P_1+P_2$

$2R = P_1-P_2$

correlation S_T and R_T → **azimuthal asymmetry**

extraction from 2-hadron-inclusive data

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

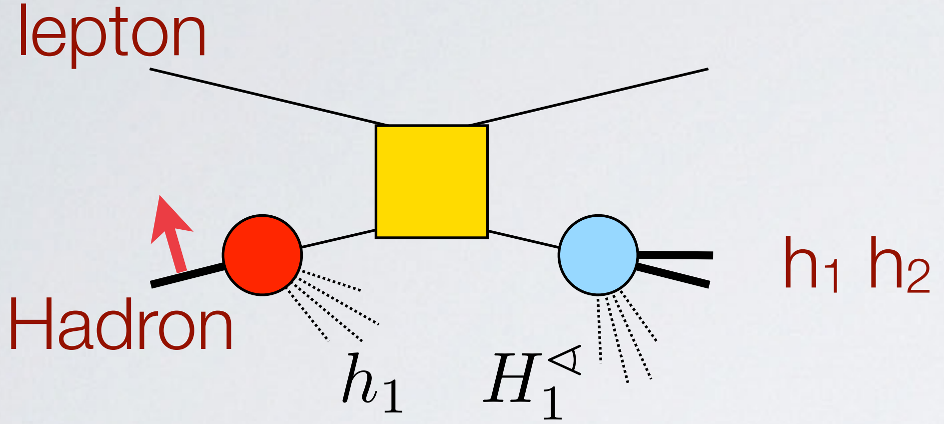


survives to
polar symmetry
($\int d\boldsymbol{P}_{hT}$)

correlation S_T and R_T → **azimuthal asymmetry**

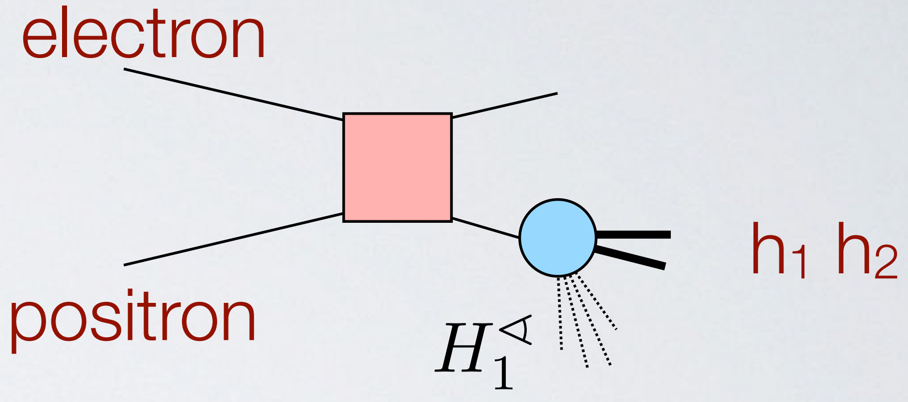
extraction from **2-hadron**-inclusive data

SIDIS

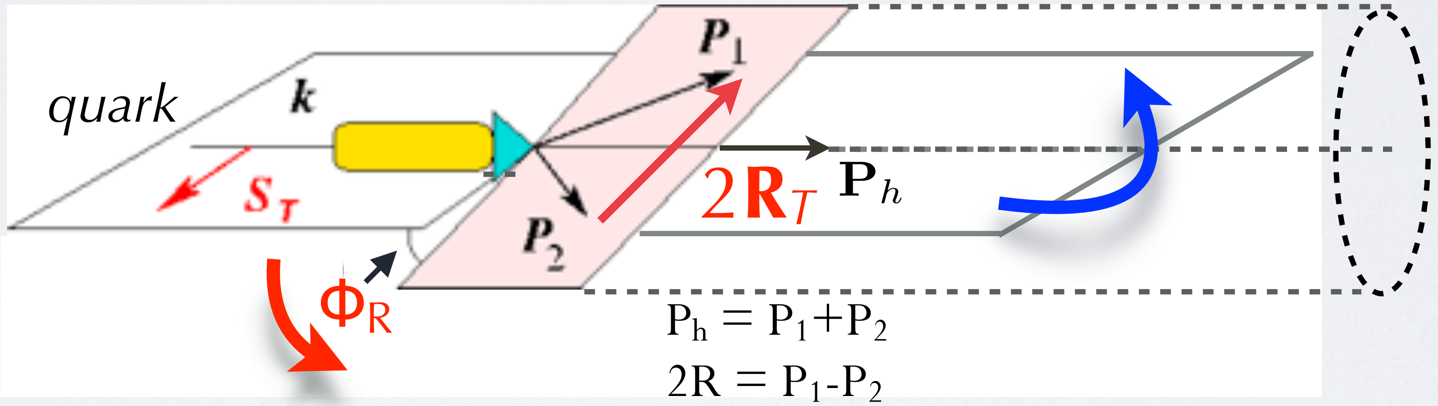


framework
collinear
factorization

e+e−



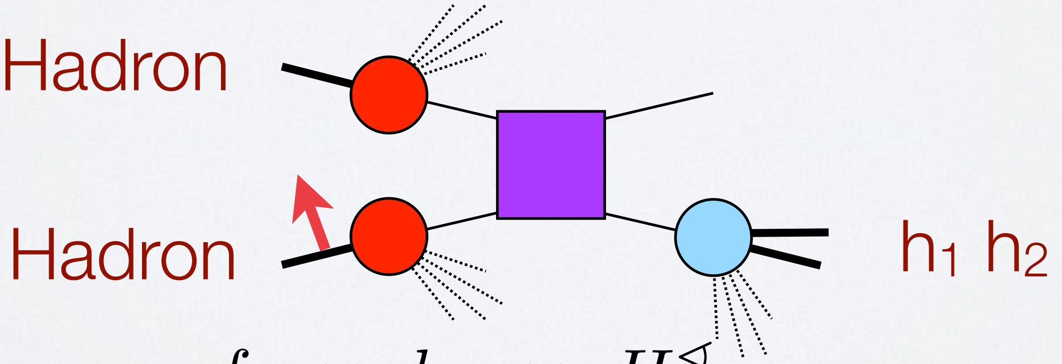
$R_T \ll Q$ $H_1^{\sphericalangle}$



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

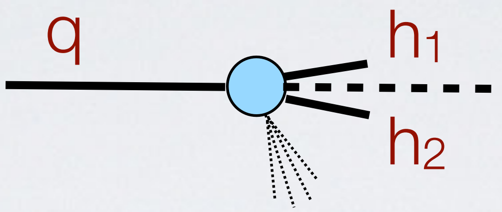
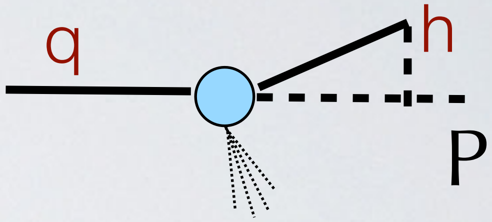
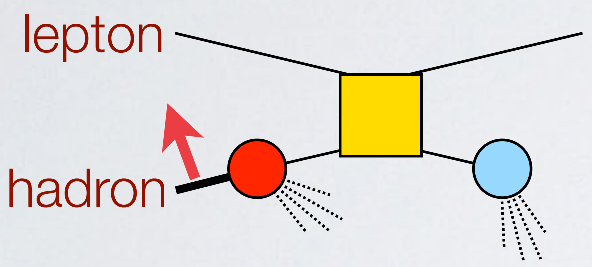
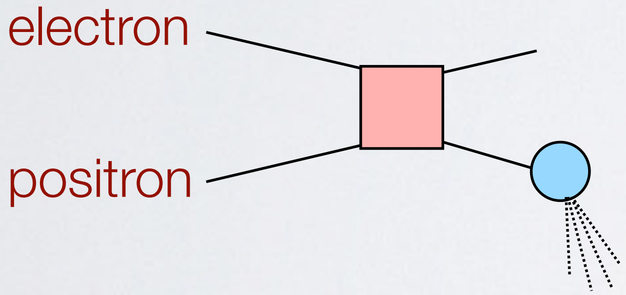
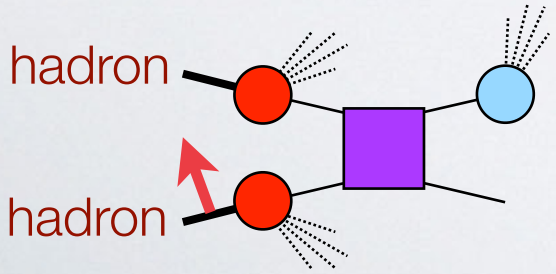
correlation S_T and R_T → **azimuthal asymmetry**

H H↑



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

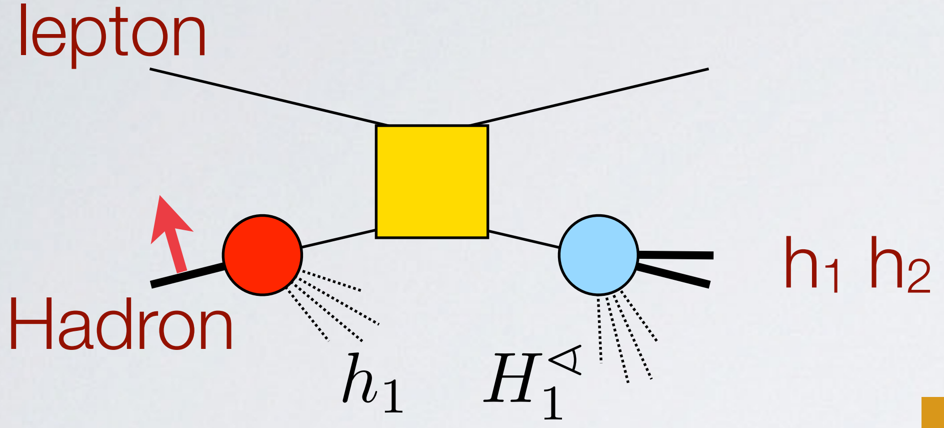
advantage of 2-hadron-inclusive mechanism

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

extraction from 2-hadron-inclusive data

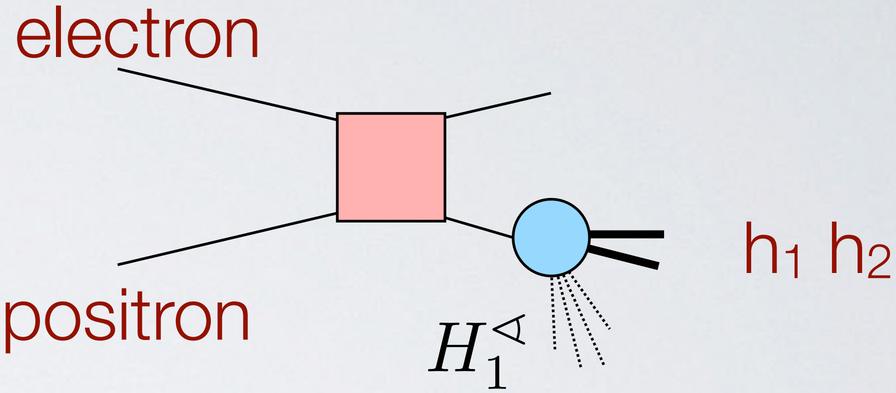
factorized formulas

SIDIS



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

e+e−

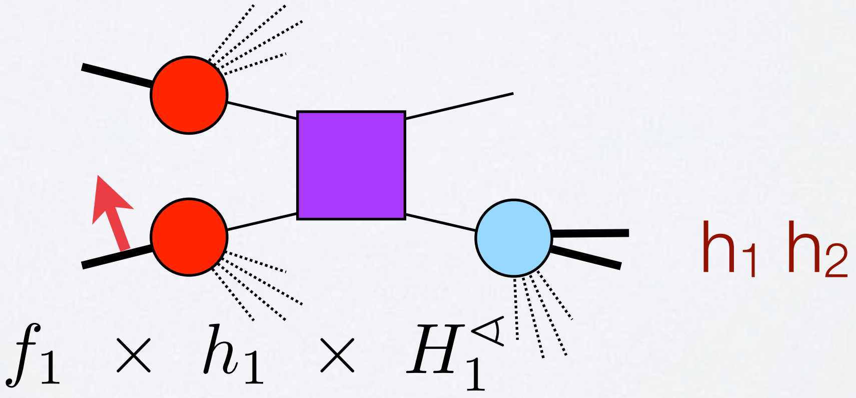


*Artru & Collins, Z.Phys. **C69** (96) 277*
*Boer, Jakob, Radici, P.R.D**67** (03) 094003*

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

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

H H↑



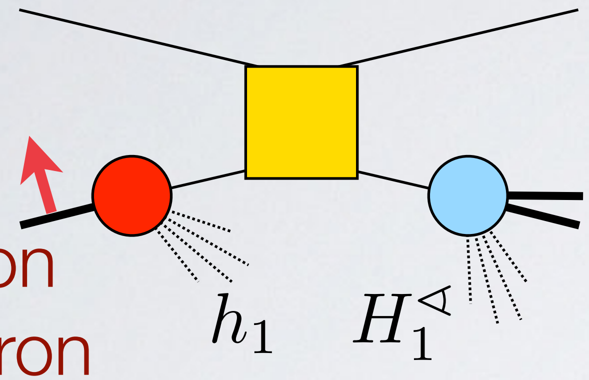
$f_1 \times h_1 \times H_1^{\sphericalangle}$

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

extraction from 2-hadron-inclusive data

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

lepton



proton
deuteron

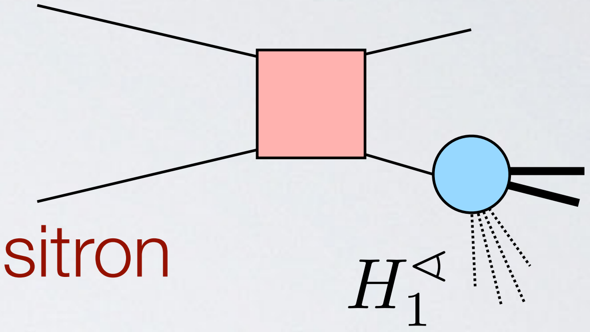
$\pi^+\pi^-$, π^+K^-, K^+K^-

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*

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

electron



positron

$\pi^+\pi^-$

*Vossen et al., P.R.L. **107** (11) 072004*
*Seidl et al., P.R. D**96** (17) 032005*

run 2006 (s=200)

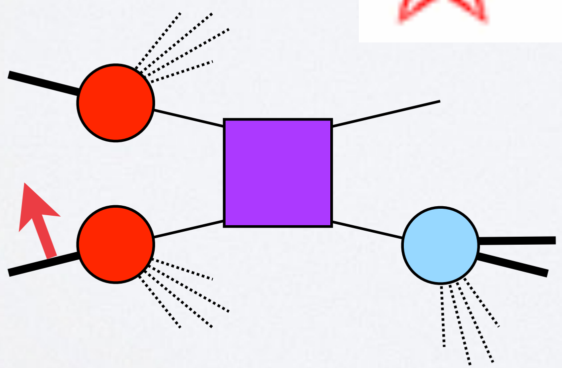
Adamczyk et al. (STAR),
*P.R.L. **115** (2015) 242501*

run 2011 (s=500)

Adamczyk et al. (STAR),
arXiv:1710.10215

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

proton



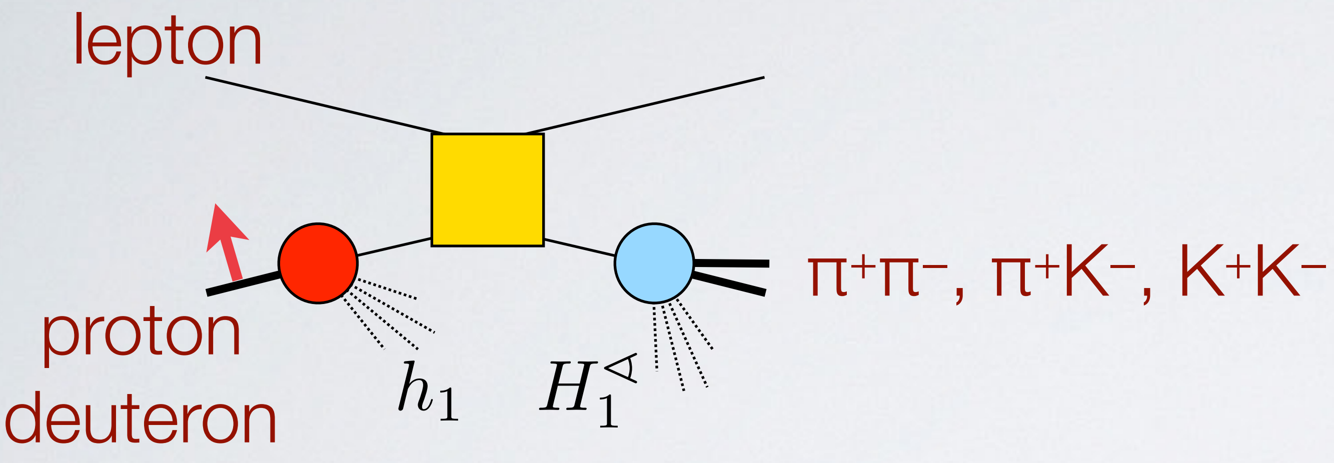
proton

$\pi^+\pi^-$

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

extraction from 2-hadron-inclusive data

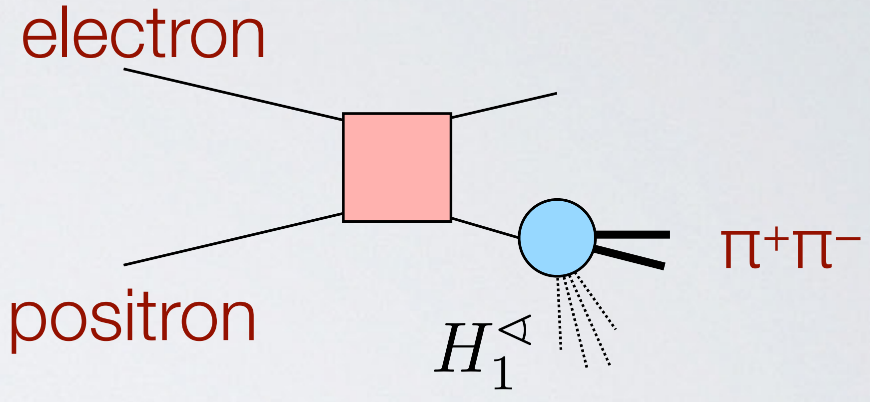
SIDIS $\ell\ H^{\uparrow} \to \ell' (h_1 h_2) X$



*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*

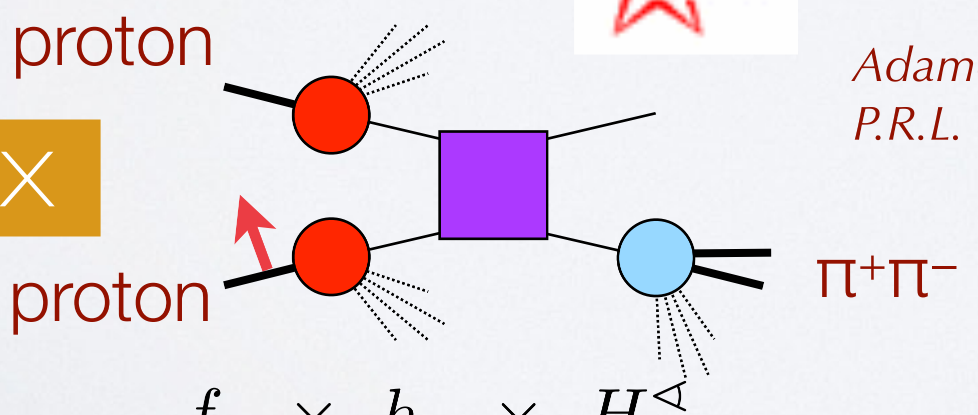
$e^+e^- \to (h_1 h_2) X$



*Vossen et al., P.R.L. **107** (11) 072004*
*Seidl et al., P.R. D**96** (17) 032005*

D_1^q from Montecarlo

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



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

run 2006

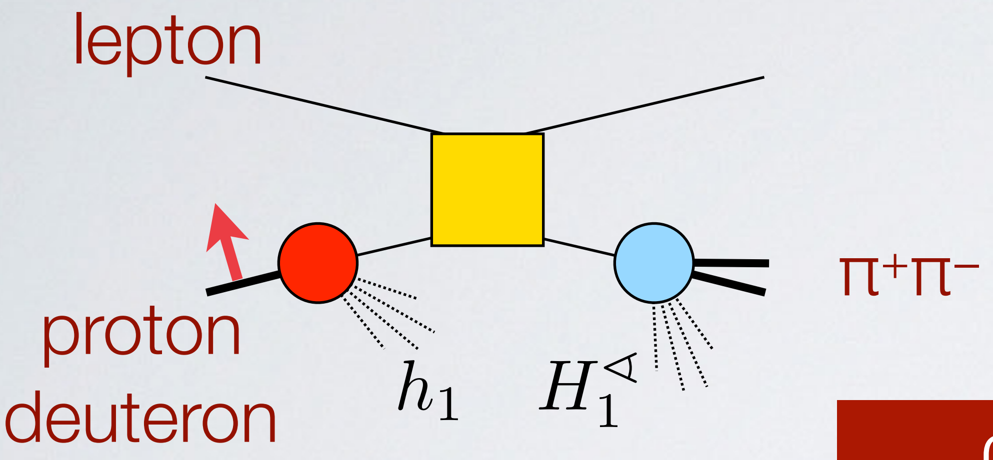
*Adamczyk et al. (STAR), P.R.L. **115** (2015) 242501*

run 2011

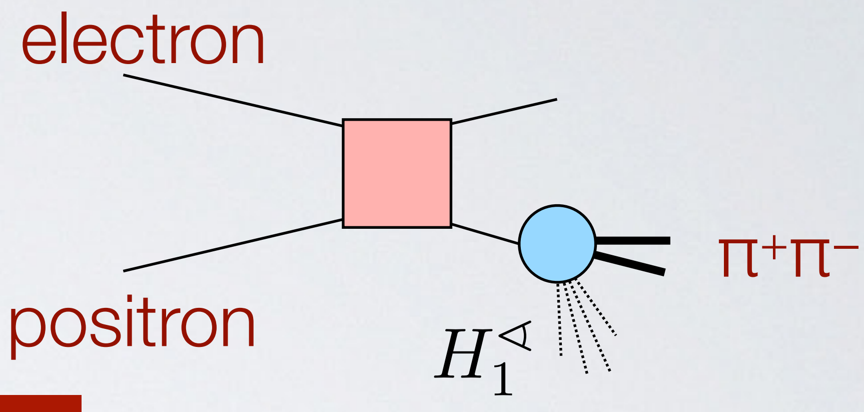
Adamczyk et al. (STAR), arXiv:1710.10215

take–away message

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

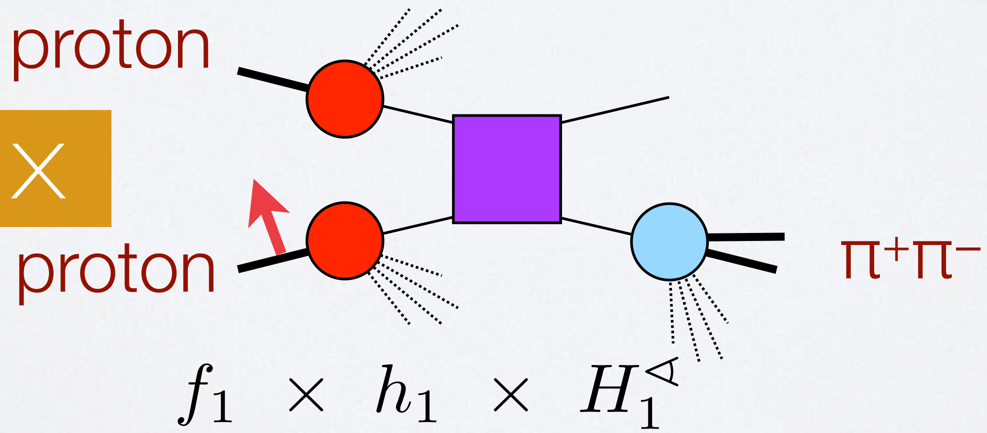


e+e− → $(h_1\ h_2)\ X$



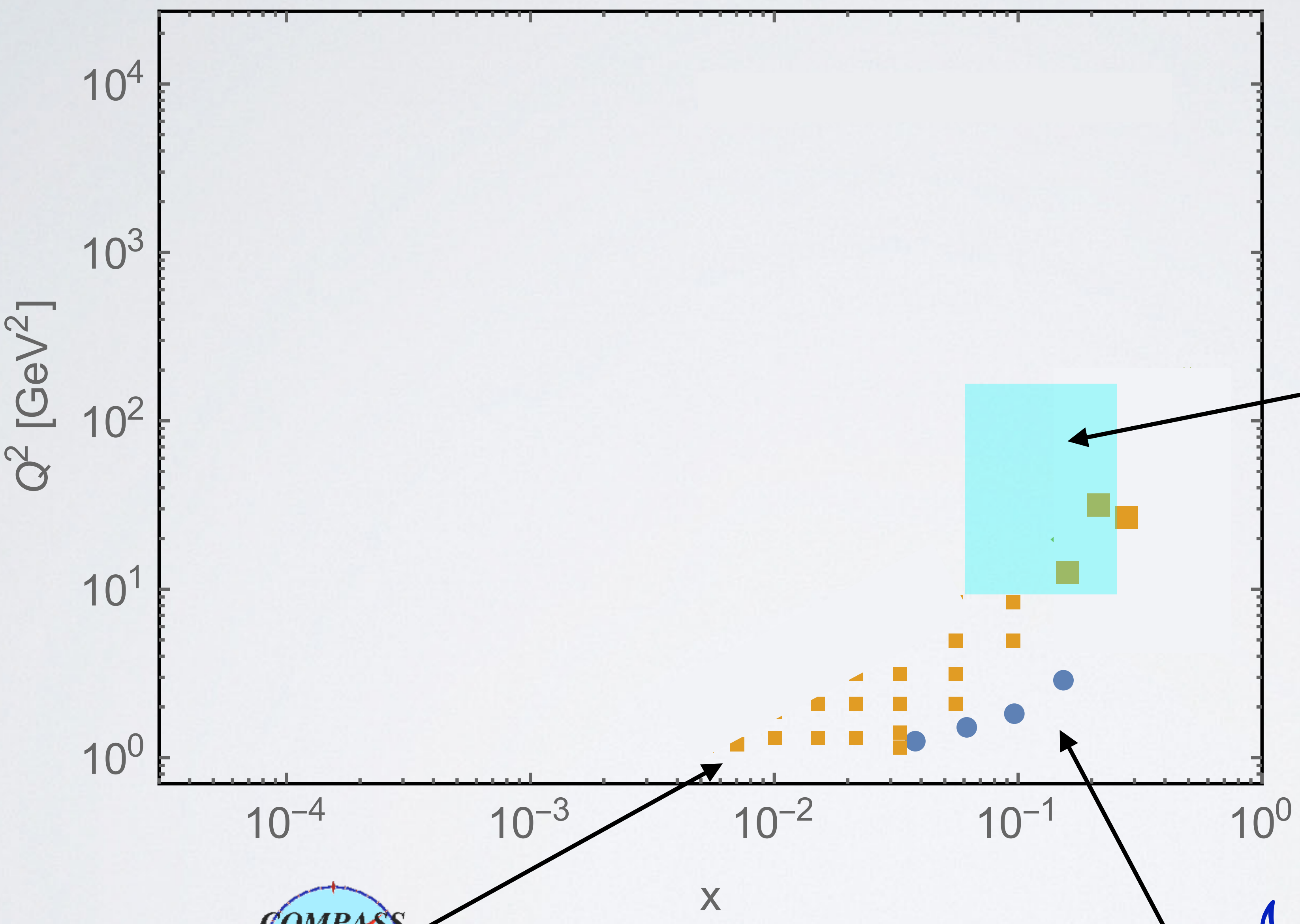
first extraction
of transversity
from a global fit
of these data

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



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

the kinematics



run 2006
s=200 GeV^2

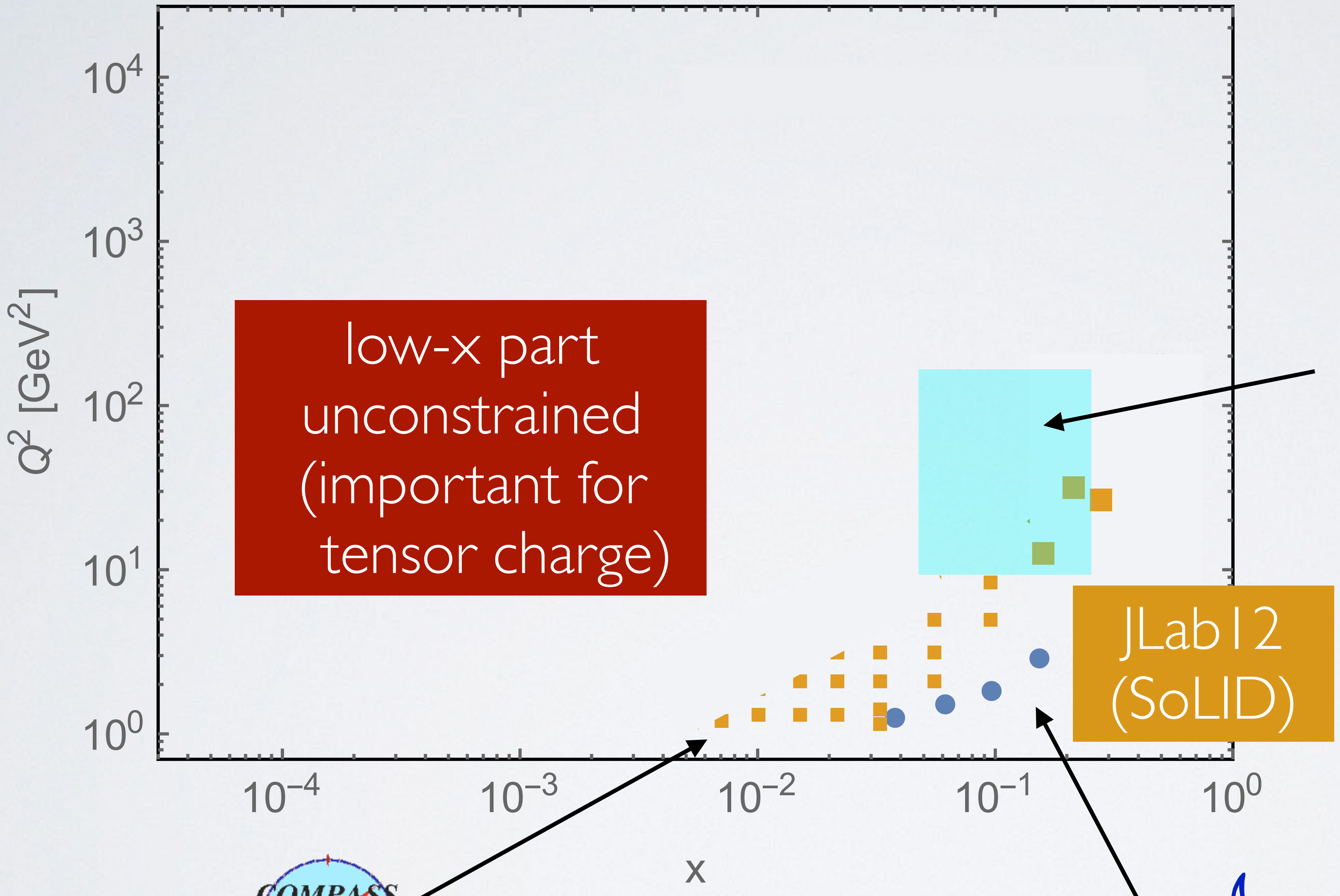
Adamczyk et al. (STAR),
*P.R.L. **115** (2015) 242501*

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

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

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

the kinematics



low-x part
unconstrained
(important for
tensor charge)

JLab12
(SoLID)

STAR run 2006
s=200 GeV^2

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

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

$\big\downarrow$ Soffer Bound

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

MSTW08 DSSV

choice of functional form

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

Soffer Bound

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MSTW08 DSSV

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

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

Soffer Bound satisfied at any Q^2

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

10 fitting parameters

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

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

MSTW08 DSSV

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

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

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 $A + \bar{a} > 0.3$ 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

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

dσ (η,M_h,P_T) typical cross section for a+b↑→c↑+d process

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

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

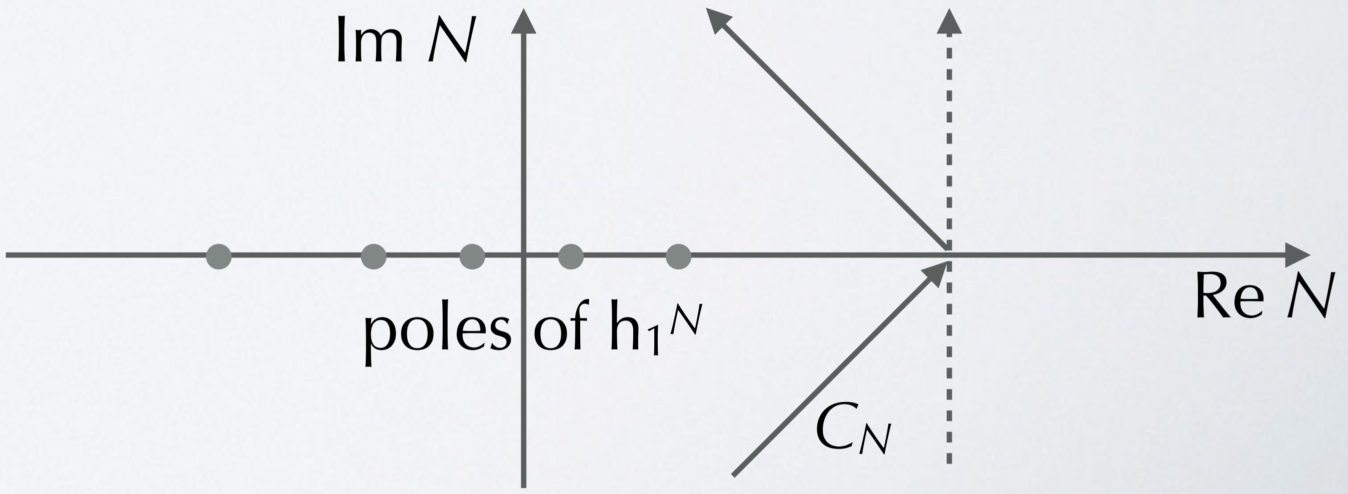
$$h_1(x, Q^2) = \int_{\mathcal{C}_N} dN\ x^{-N}\ h_1^N(Q^2) \qquad N \in \mathbb{C}$$

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

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

pre-compute F_b only one time on contour C_N

this speeds up convergence and facilitates ∫ dN , provided that h_1^N is known analytically



theoretical uncertainties

Single-Spin Asymmetry
in p-p↑ collisions

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

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

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

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

theoretical uncertainties

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

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

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

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

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

our choice: compute $d\sigma_0$ with $D_1^g(Q_0) = \begin{cases} 0 \\ D_1^u(Q_0)\,/\,4 \\ D_1^u(Q_0) \end{cases}$

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

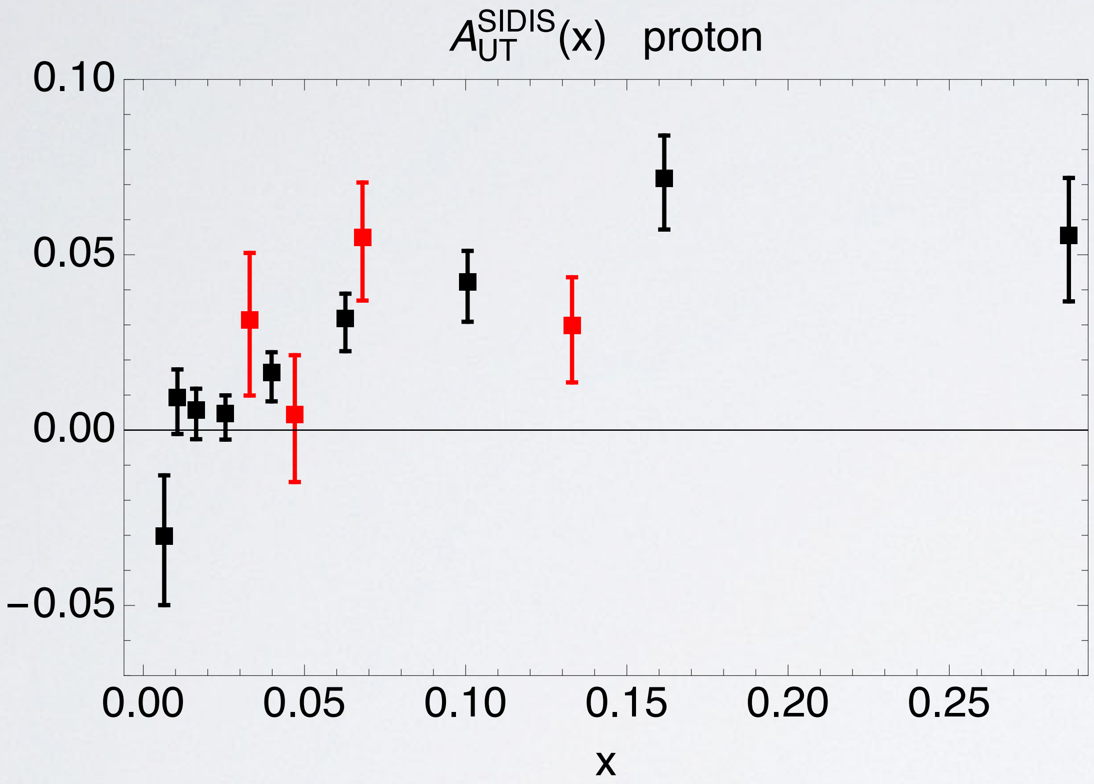
background ρ channels

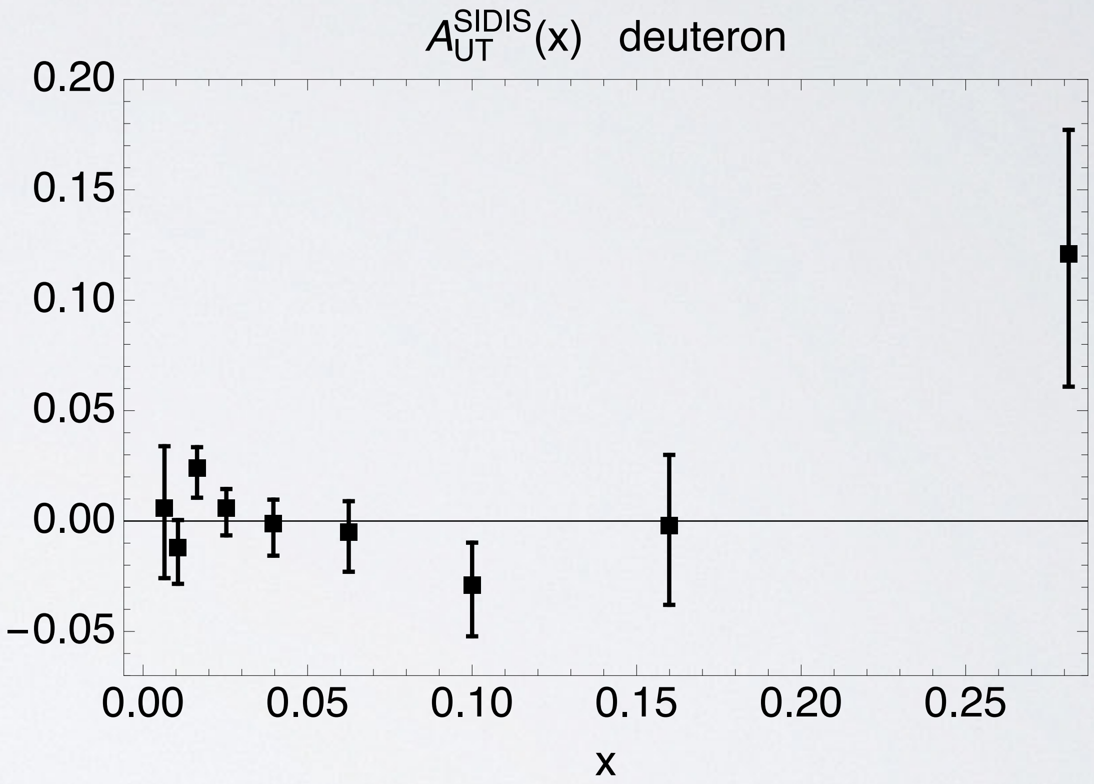
statistical uncertainty: the bootstrap method

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

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

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


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

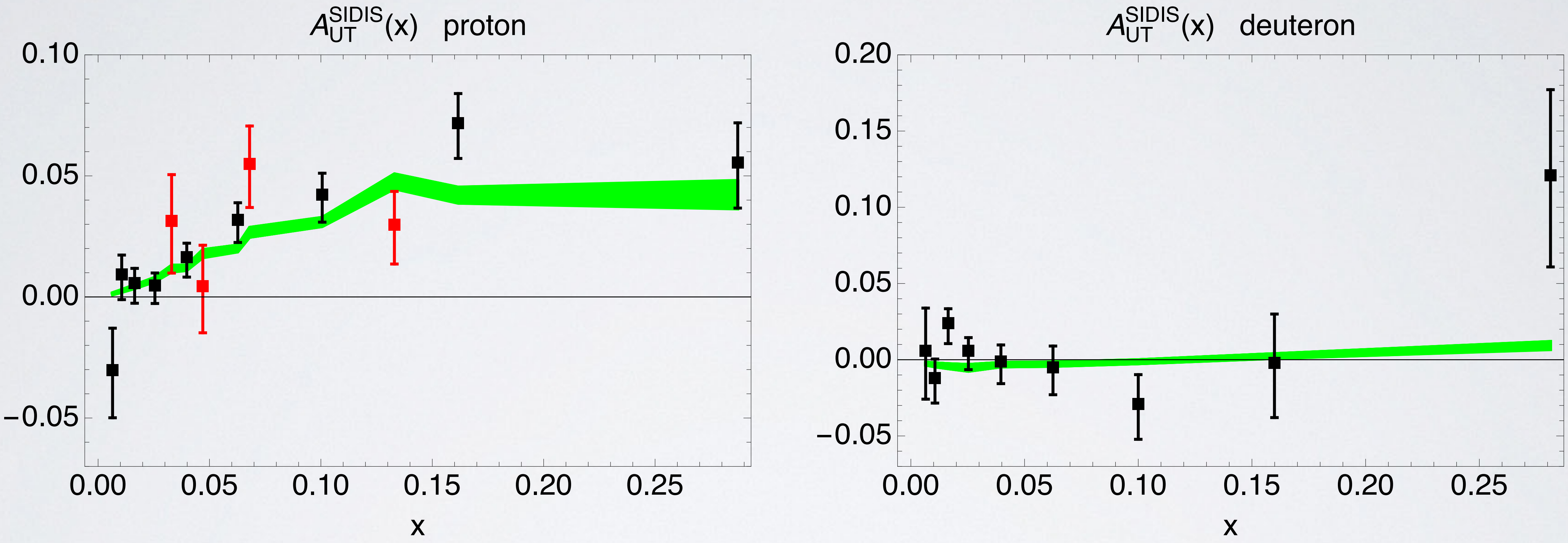

$A_{UT}^{SIDIS}(x)$ deuteron

statistical uncertainty: the bootstrap method

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

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

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



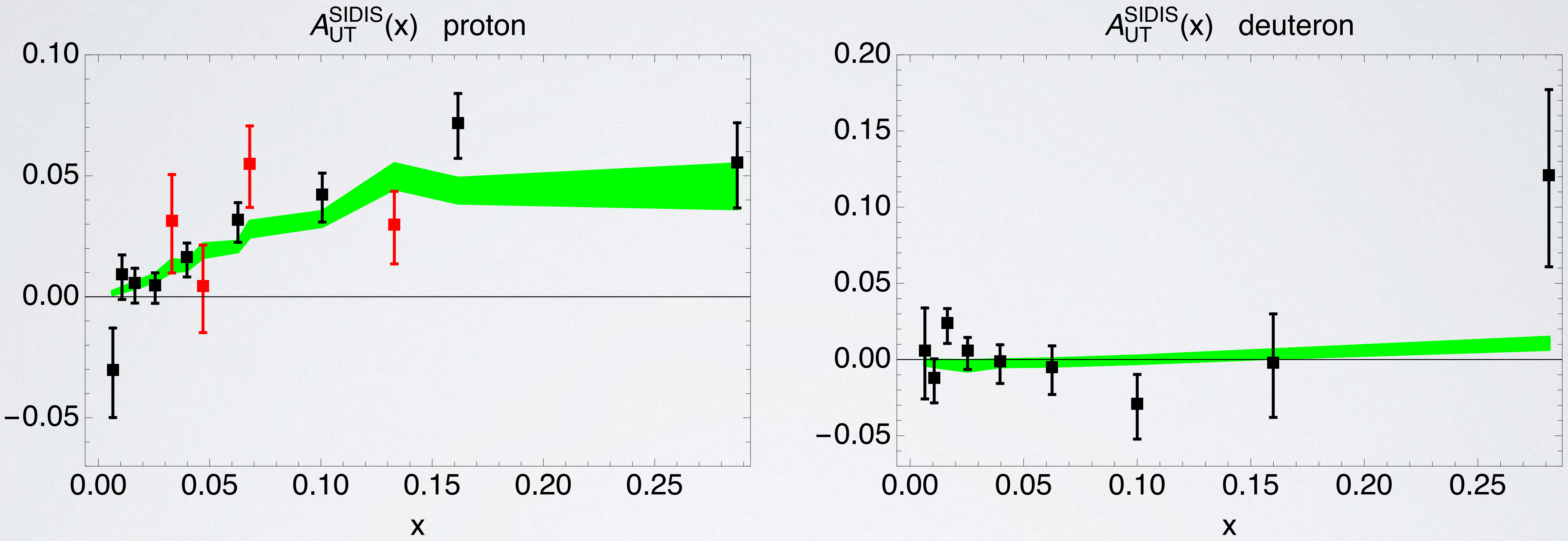
100 replicas

statistical uncertainty: the bootstrap method

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

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

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



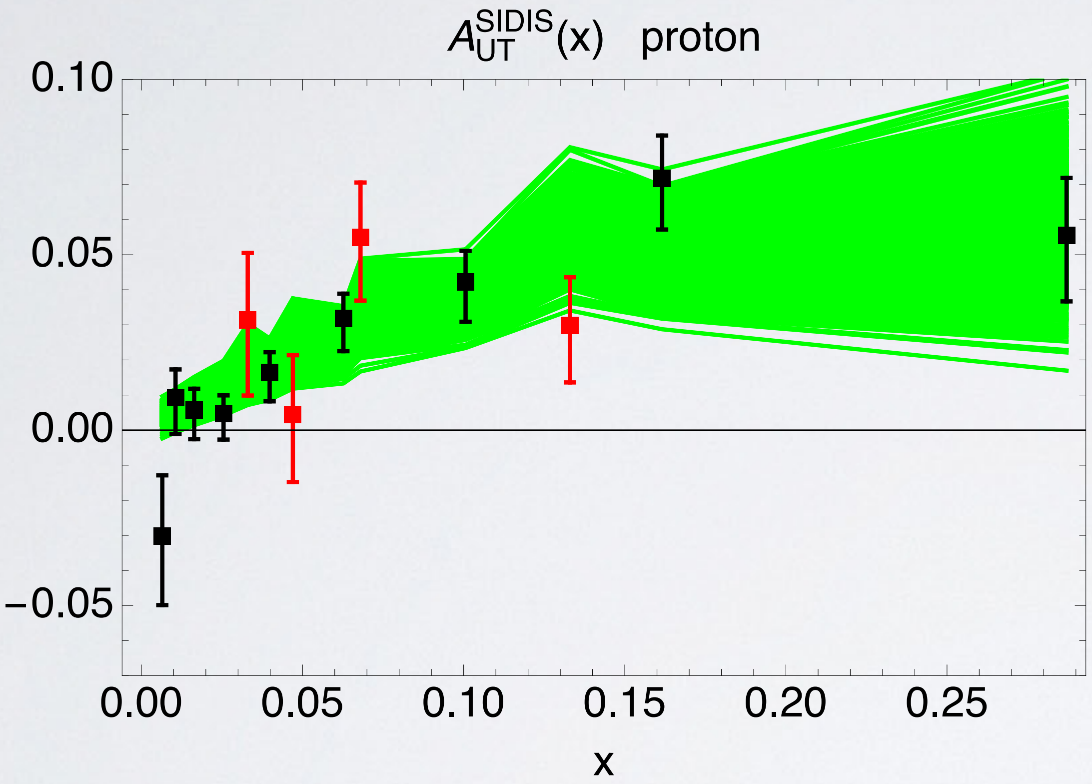
200 replicas

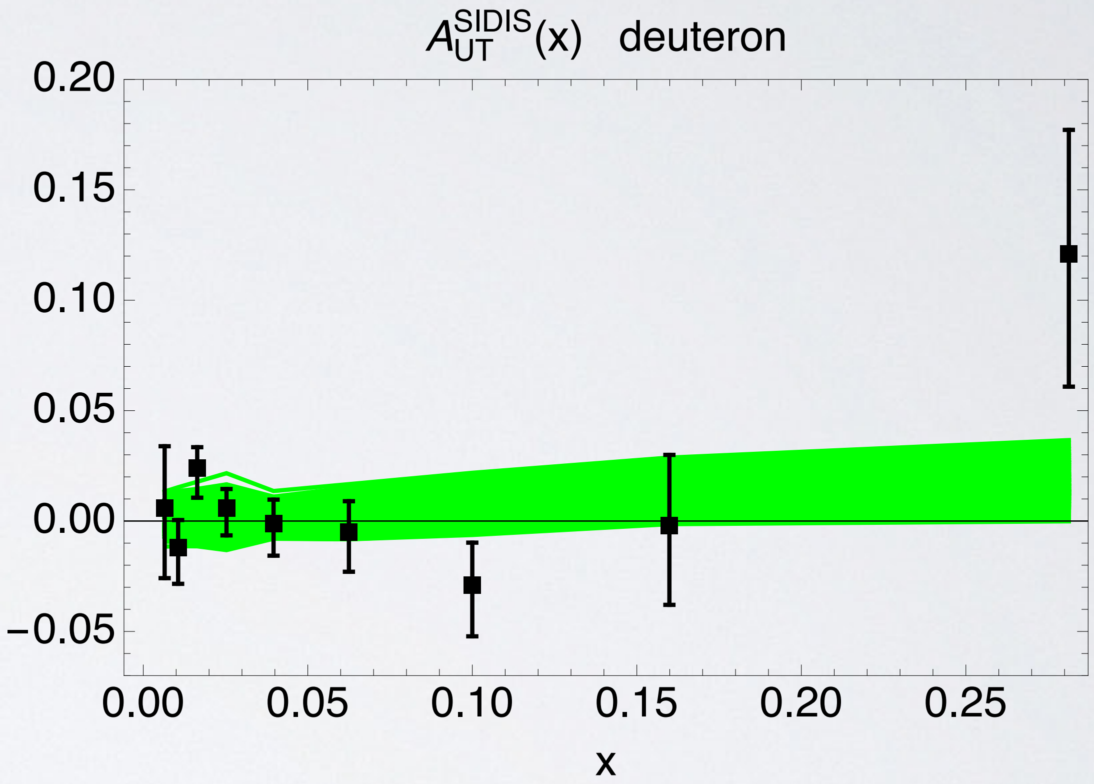
statistical uncertainty: the bootstrap method

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

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

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





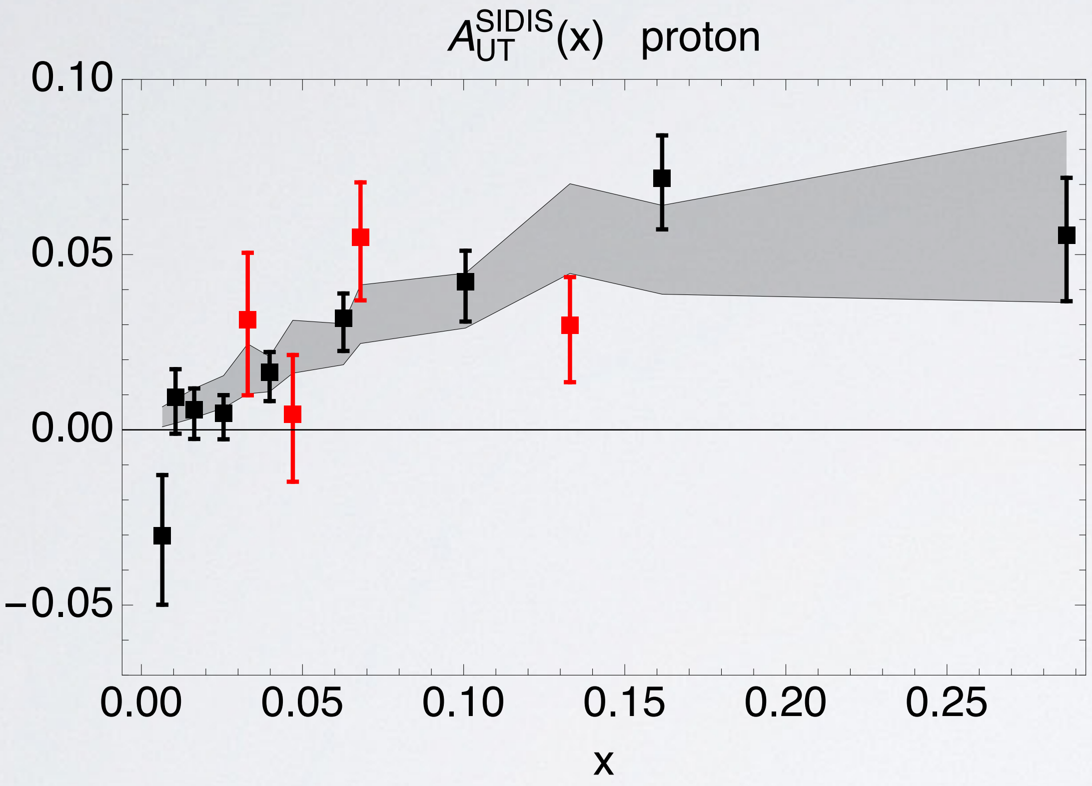
all 600 replicas

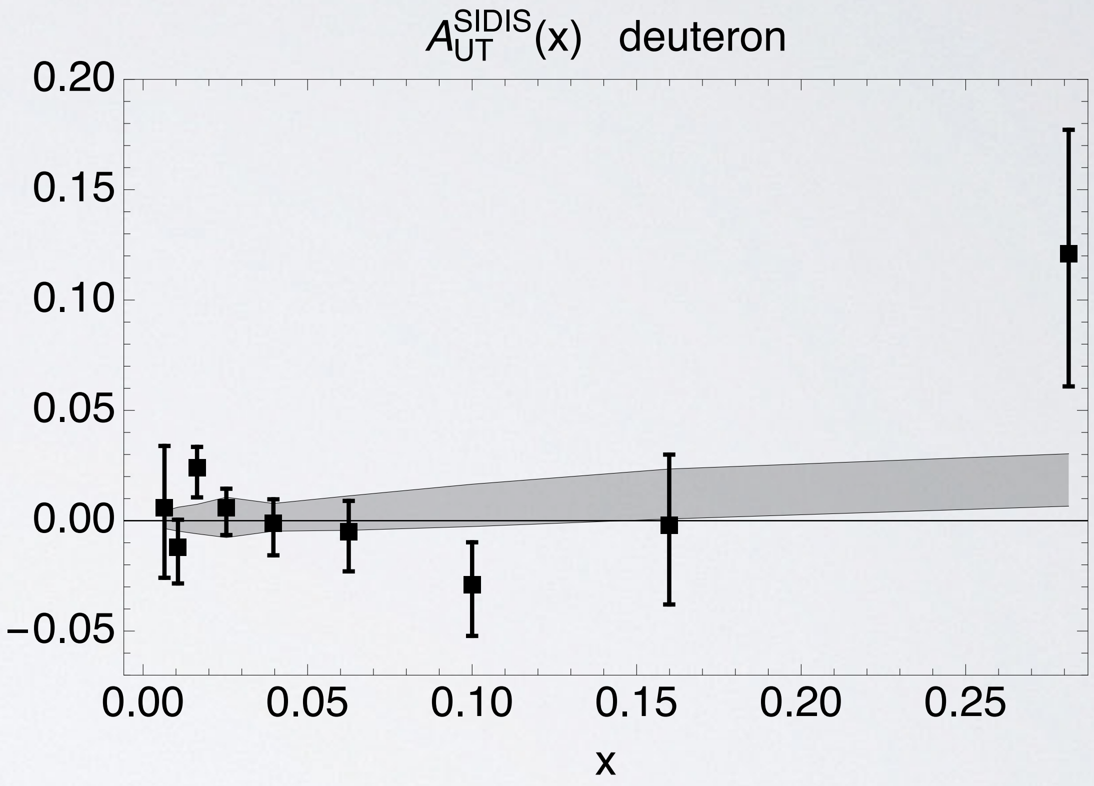
statistical uncertainty: the bootstrap method

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

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

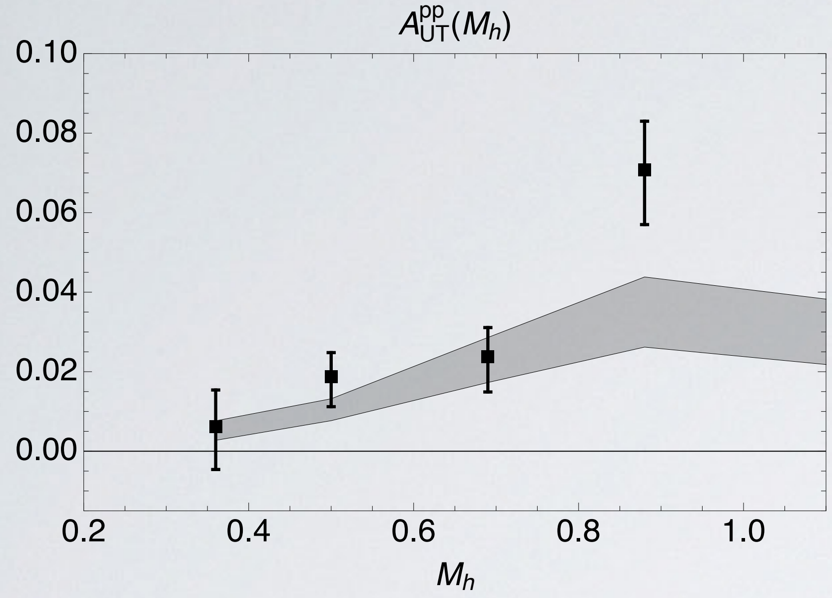
COMPASS *Adolph et al., P.L. **B713** (12)*



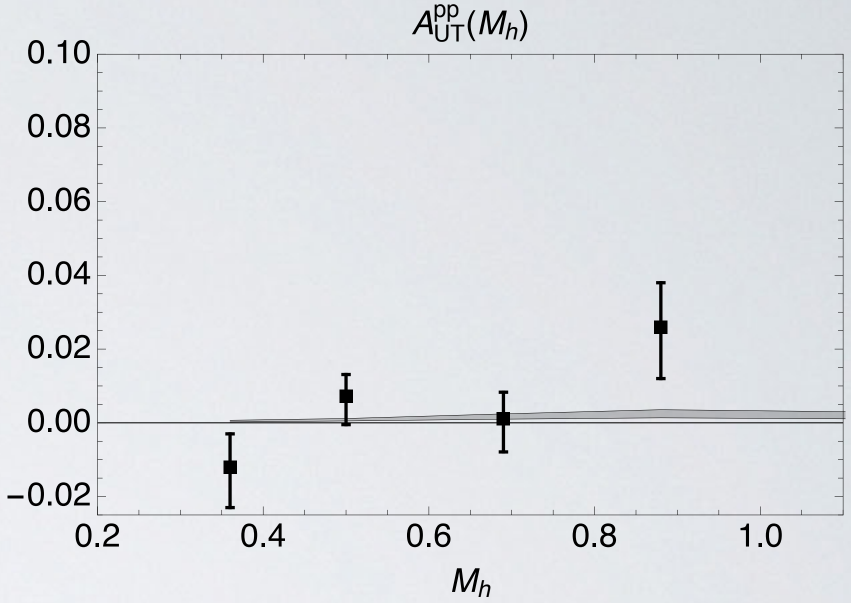


90% replicas

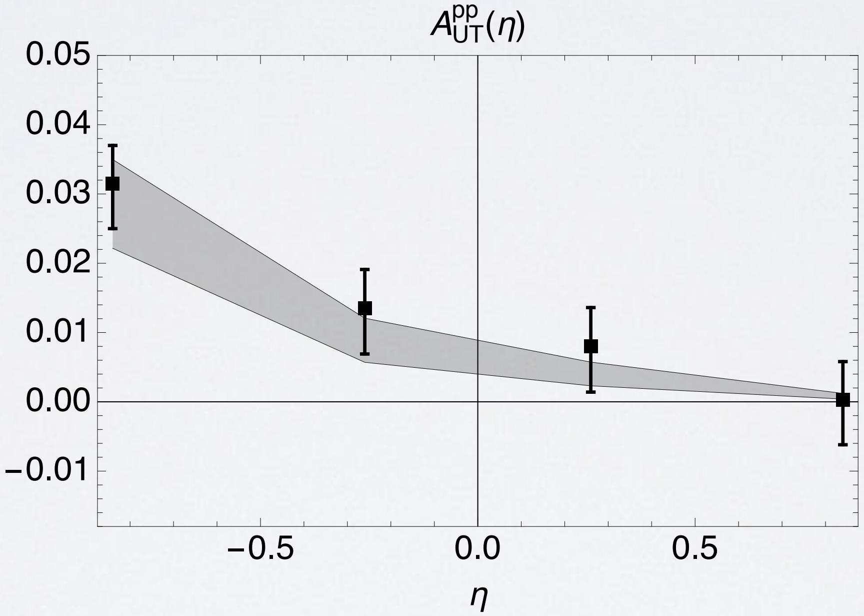
fit STAR asymmetry



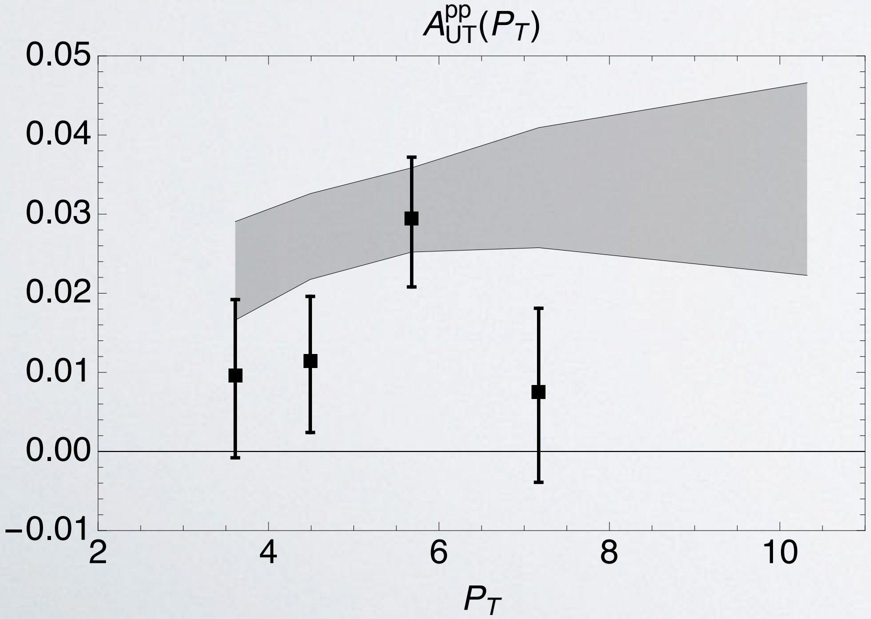
Adamczyk et al. (STAR),
P.R.L. ***115*** *(2015) 242501*



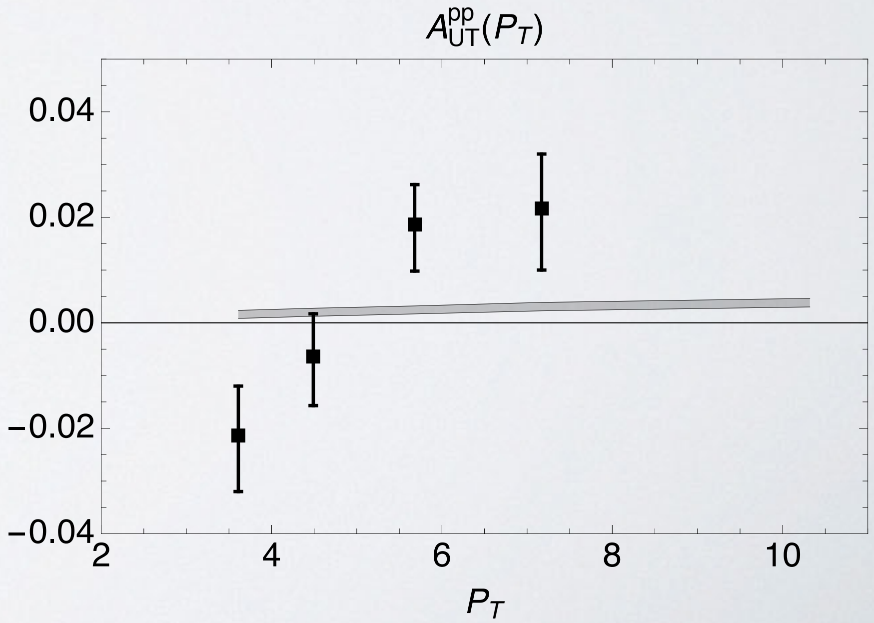
η<0



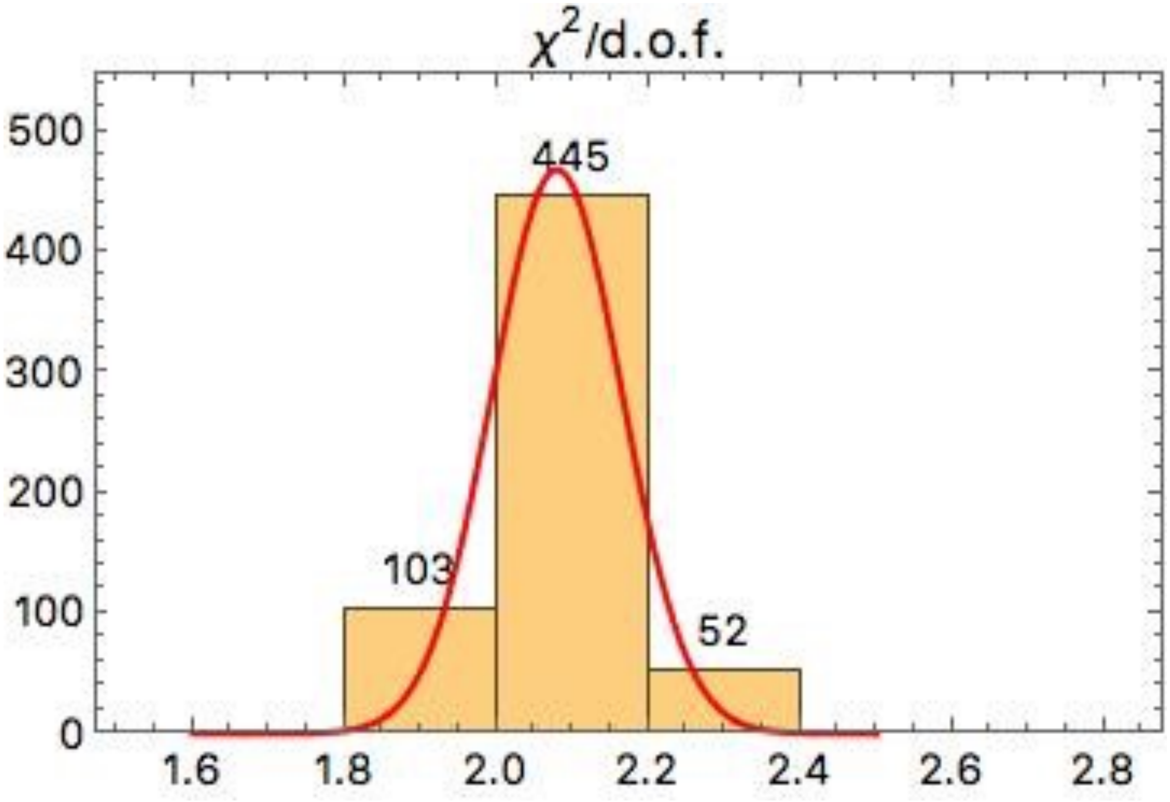
η>0



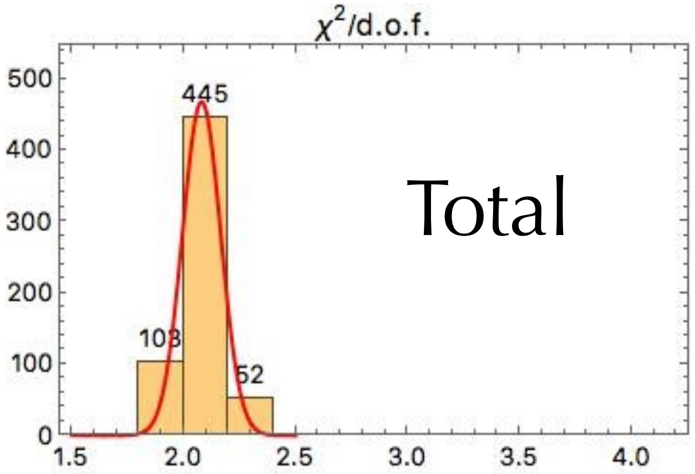
90% uncertainty band

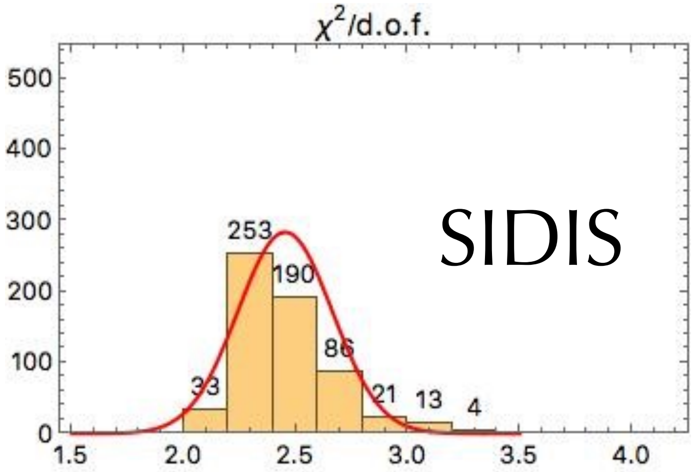


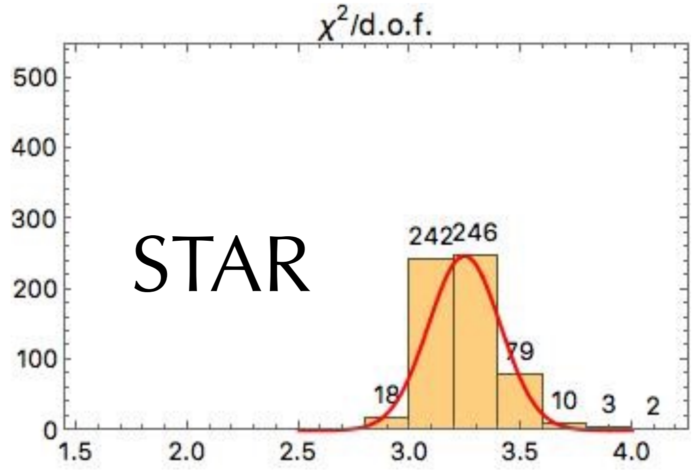
χ^2 of the fit



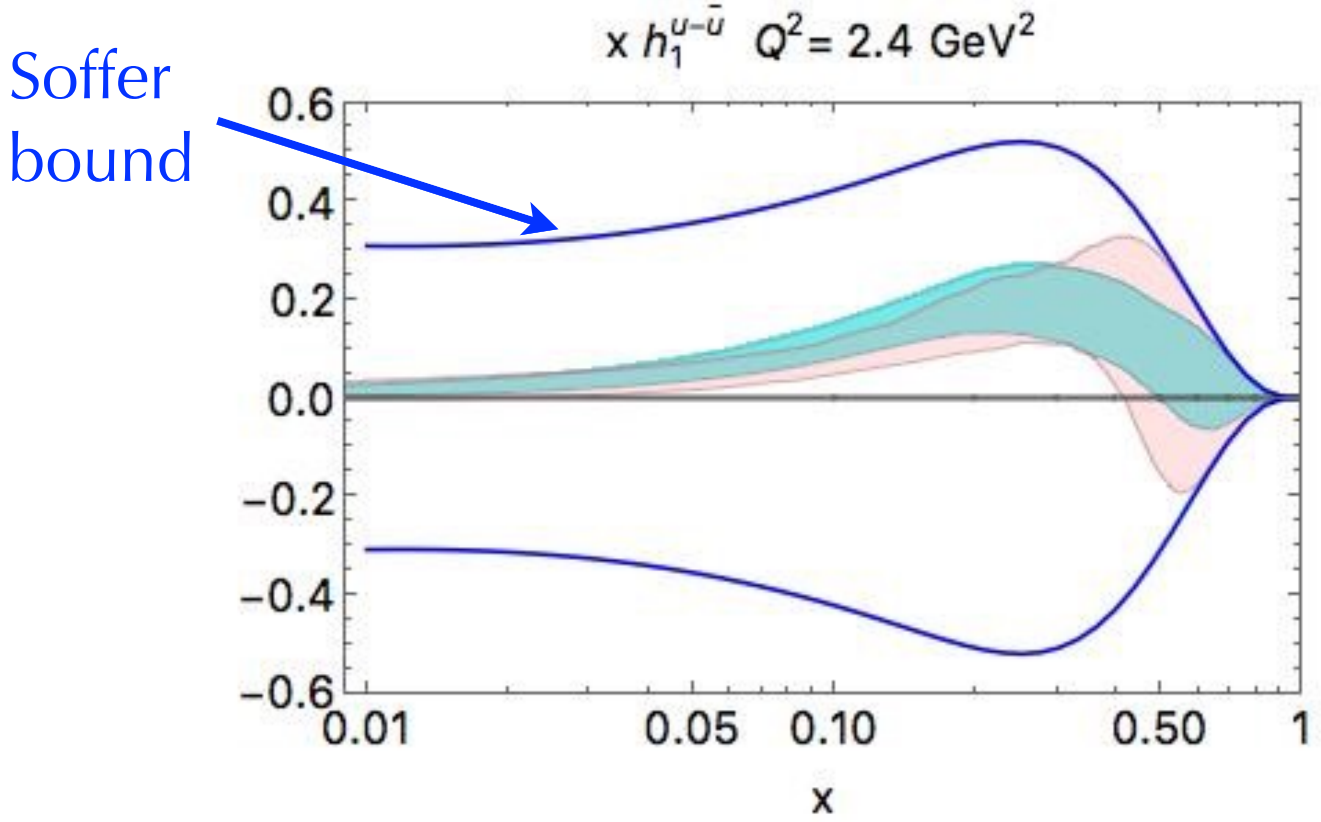
$$\chi^2/\text{dof} = 2.08 \pm 0.09$$







comparison with previous fit



Soffer bound

global fit

old fit

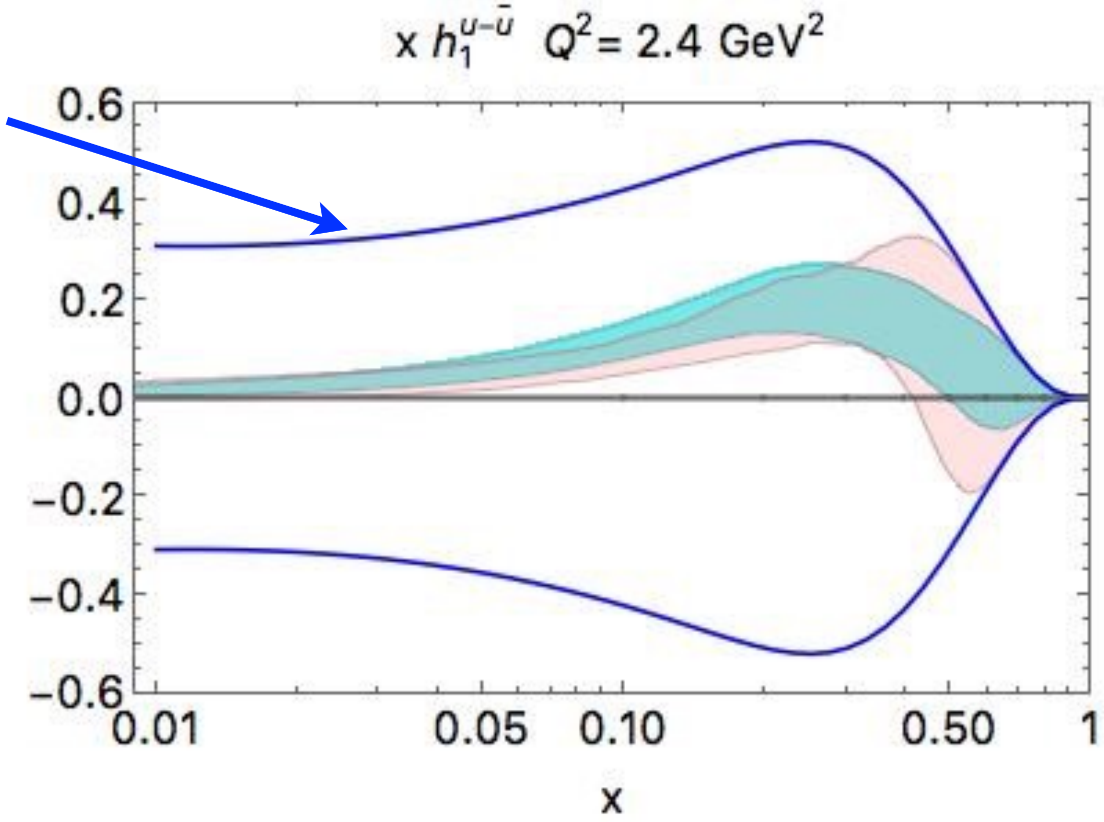
Radici et al.,
JHEP ***1505*** *(15) 123*

global fit

up

higher precision

comparison with previous fit



Soffer bound

global fit

old fit

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

global fit

up

higher precision

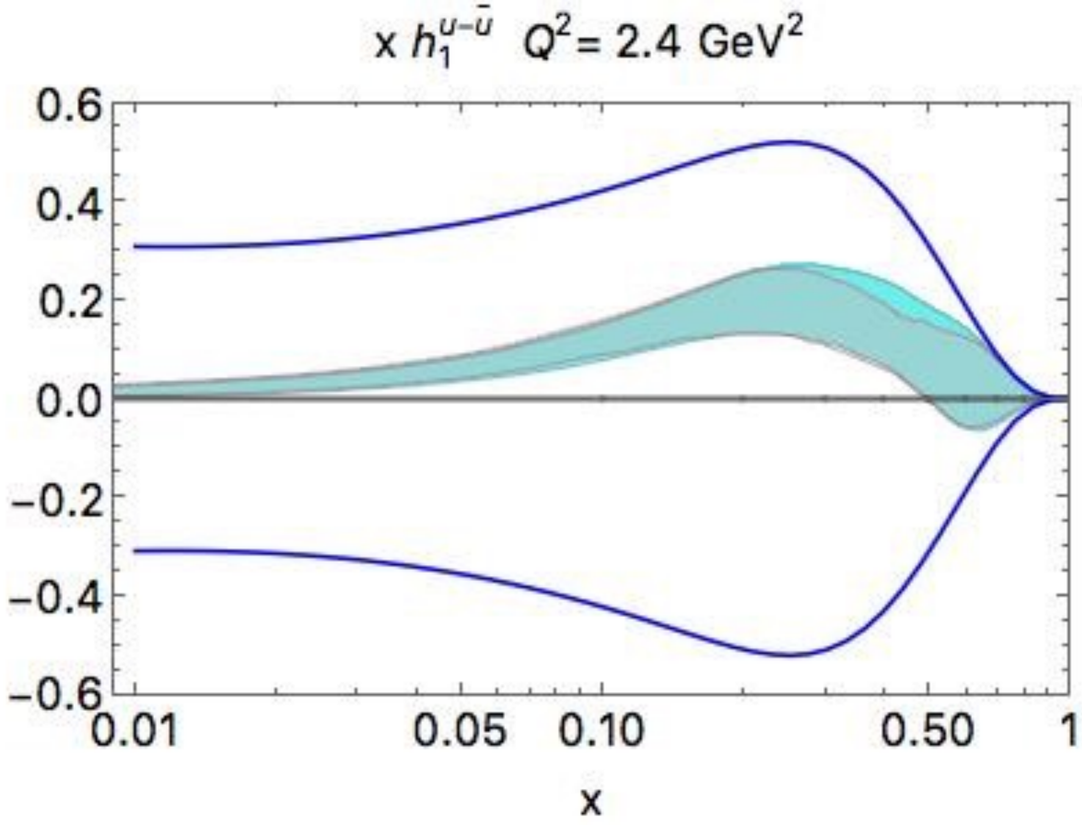
global fit

up

insensitive to uncertainty on gluon D_1

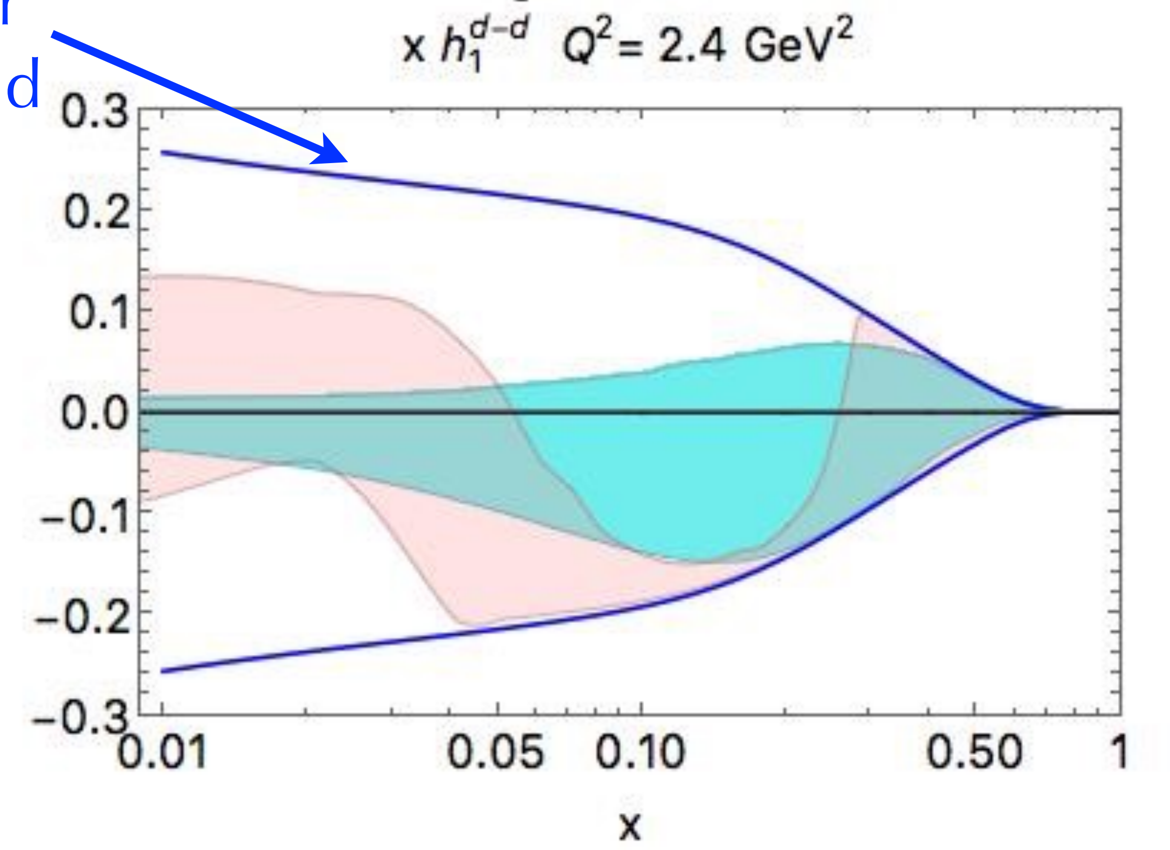
$$D_1^g(Q_0) = 0$$

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



comparison with previous fit

Soffer bound



down

global fit

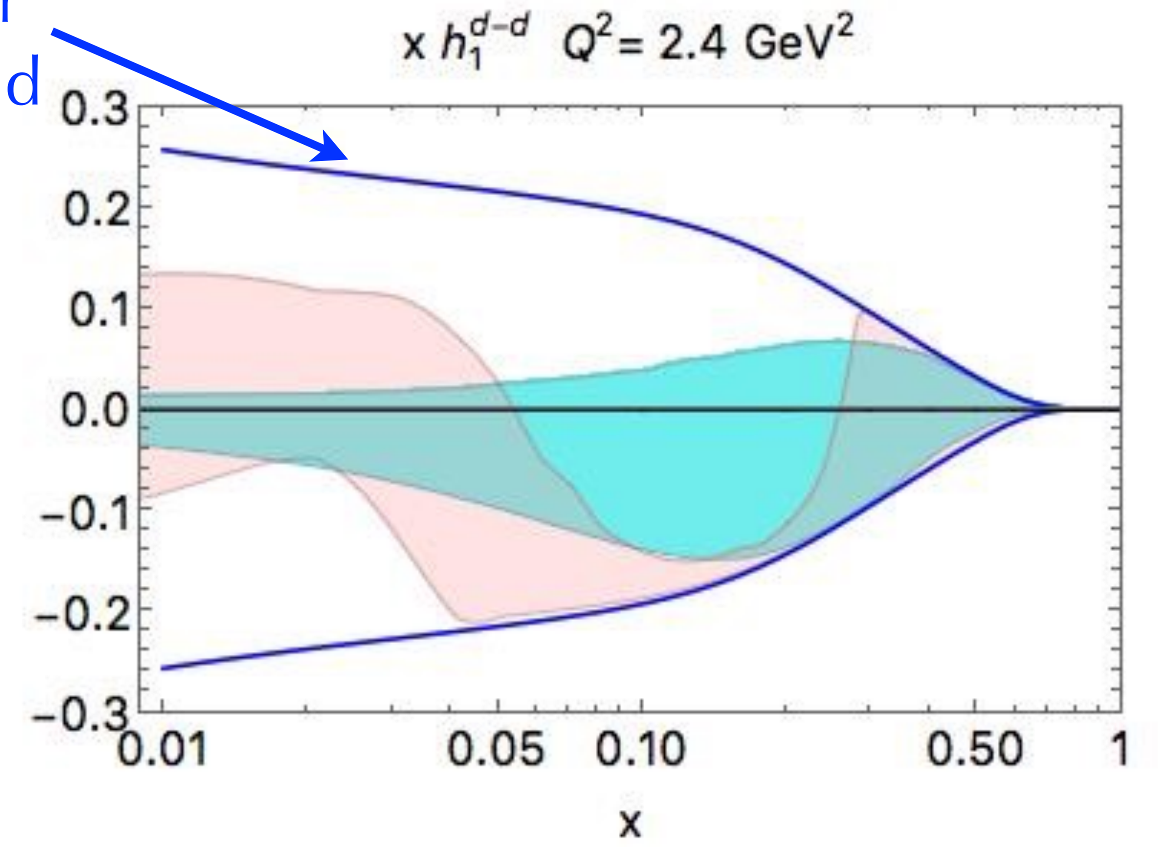
old fit

effect of STAR data :
saturation of Soffer bound
practically disappeared

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

comparison with previous fit

Soffer bound



global fit

old fit

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

down

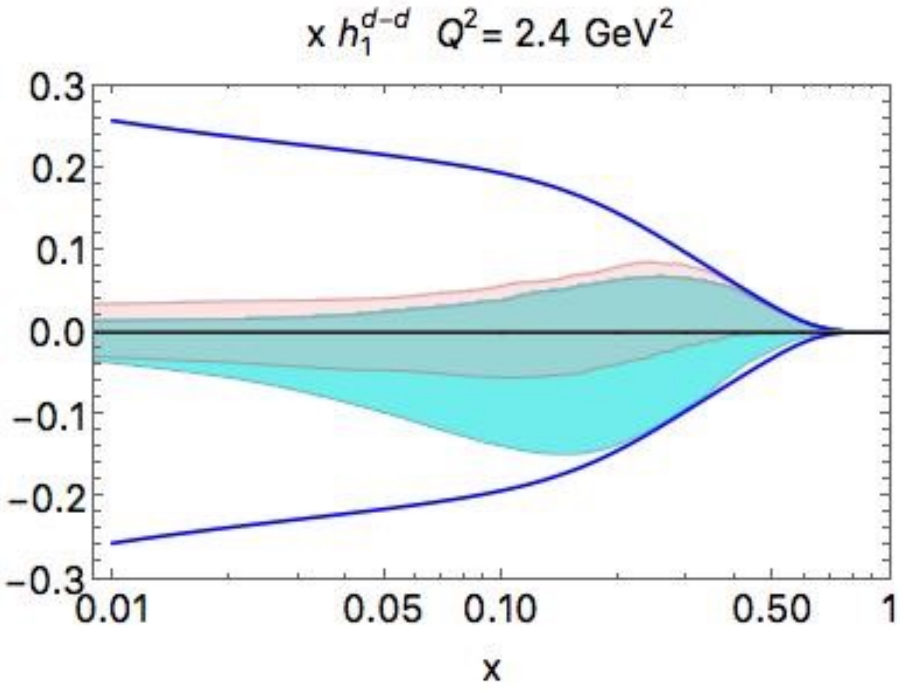
effect of STAR data :
saturation of Soffer bound
practically disappeared

global fit
down

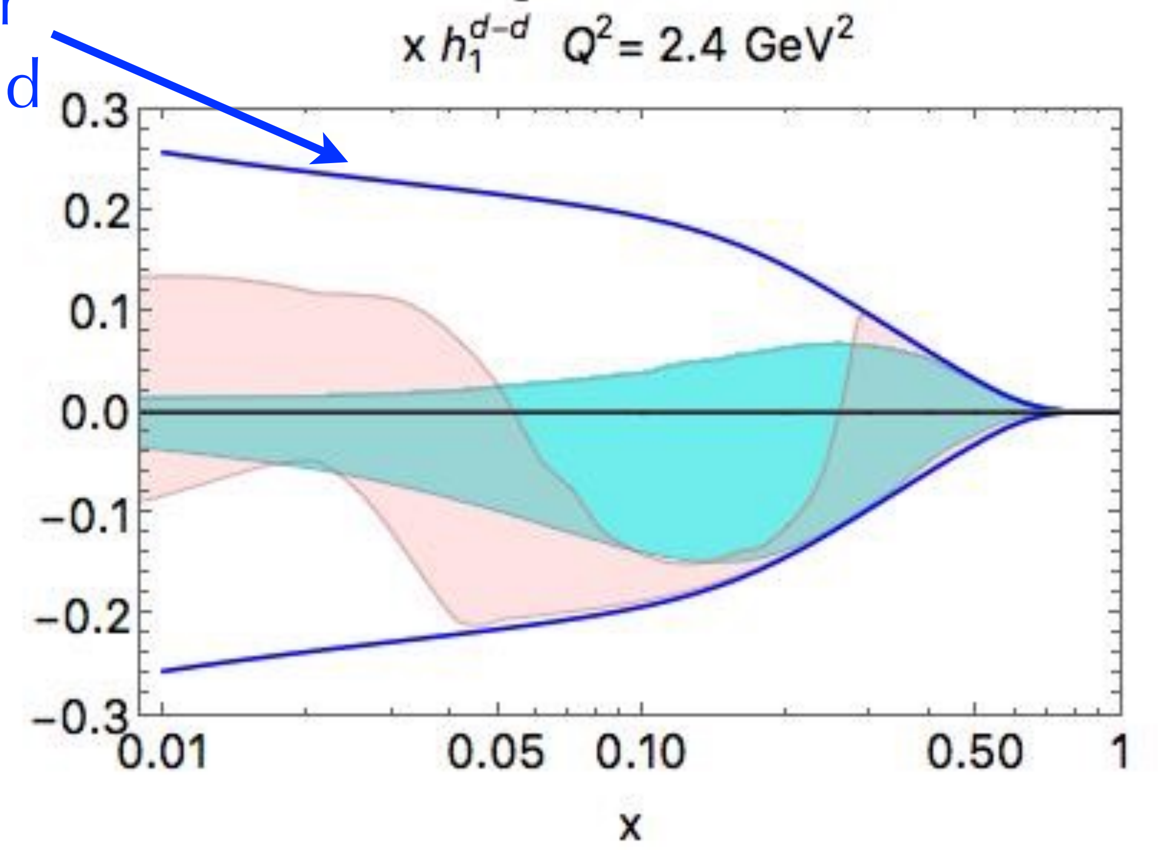
sensitive to
uncertainty on
gluon D_1

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

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



comparison with previous fit



Soffer bound

global fit

old fit

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

down

effect of STAR data :
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global fit

down

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$D_1^g(Q_0) = 0$

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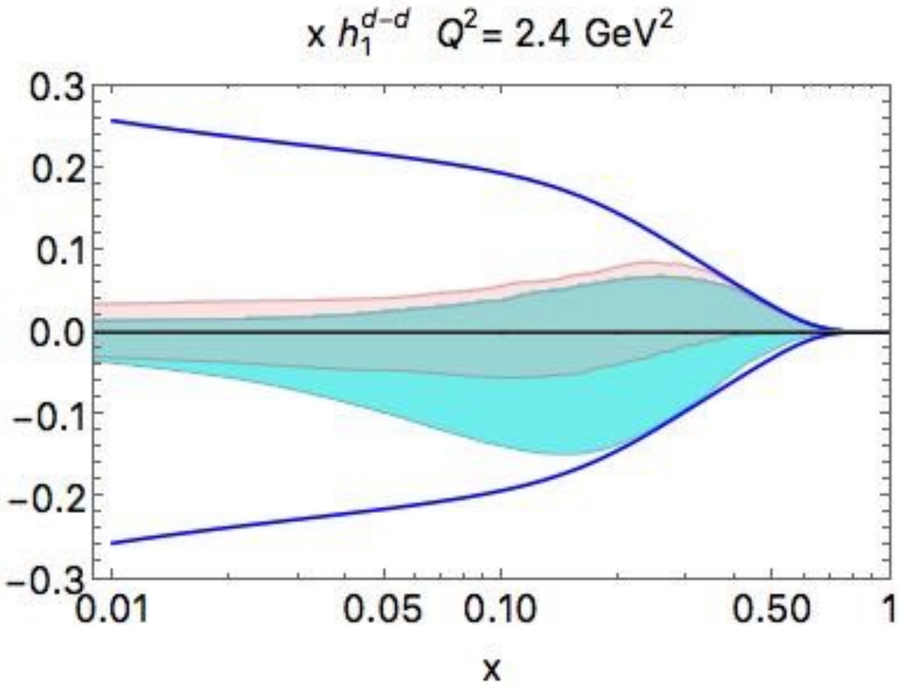
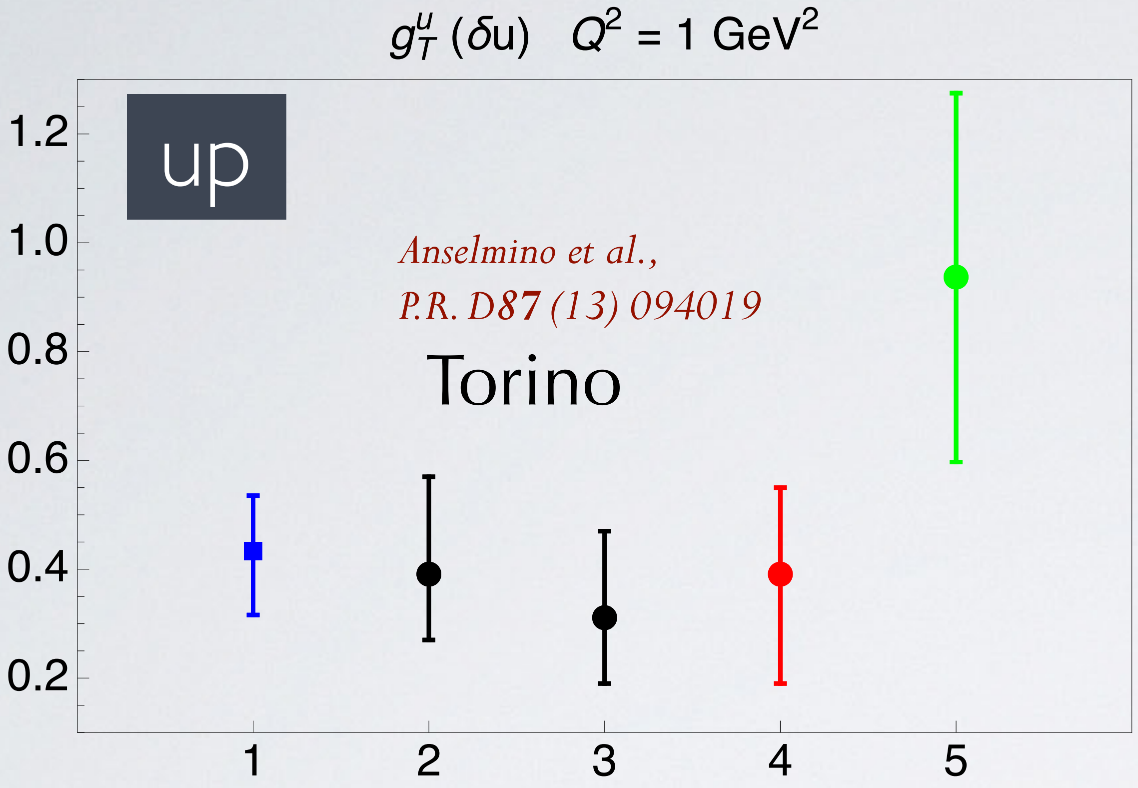


need dihadron multiplicities from RHIC
and better deuteron data from COMPASS

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



Anselmino et al., P.R. D87 (13) 094019

Torino

GPD "fit"

Goldstein et al., arXiv:1401.0438

global fit

TMD fit

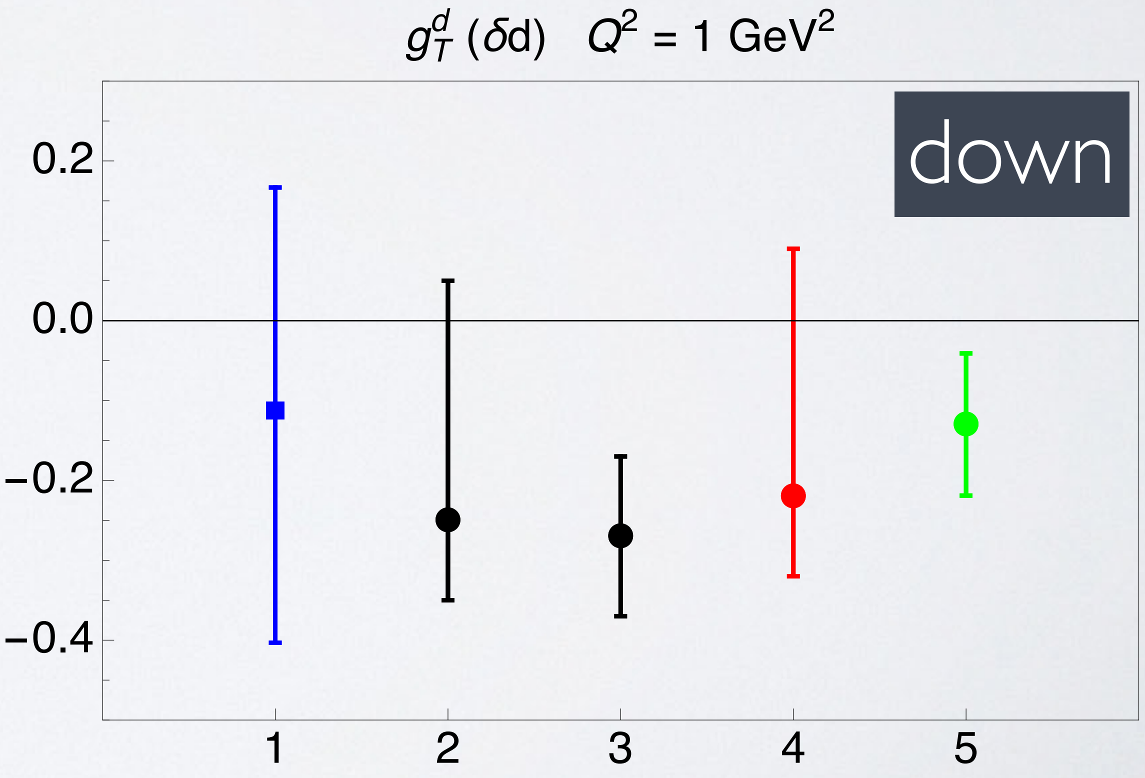
Kang et al., P.R. D93 (16) 014009

$\delta q^{[0,1]}$ $Q_0^2 = 1$

(except TMDfit)

best current precision on up

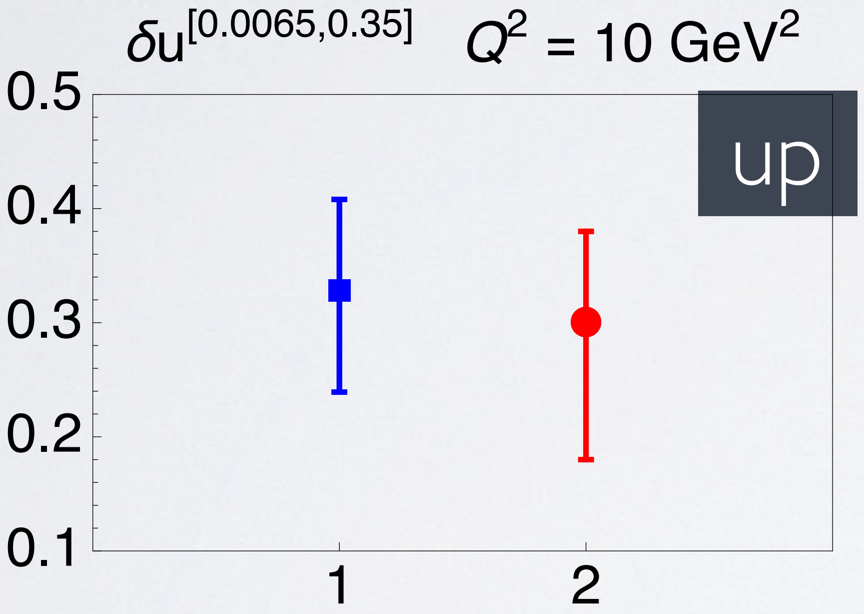
large (realistic) uncertainties on down

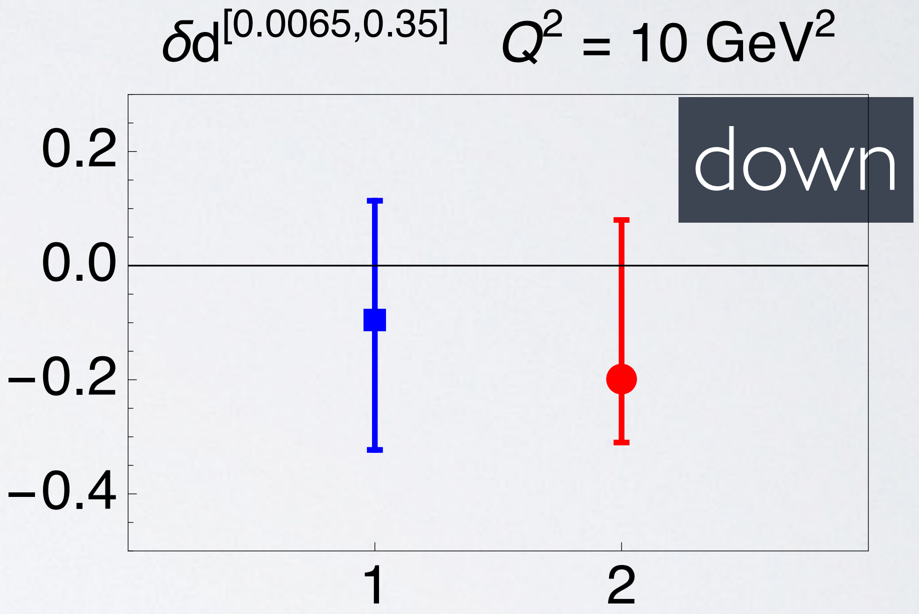


tensor charge $\delta q(Q^2) = \int dx\, h_1^{q\text{-}\bar{q}}(x,Q^2)$

truncated

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



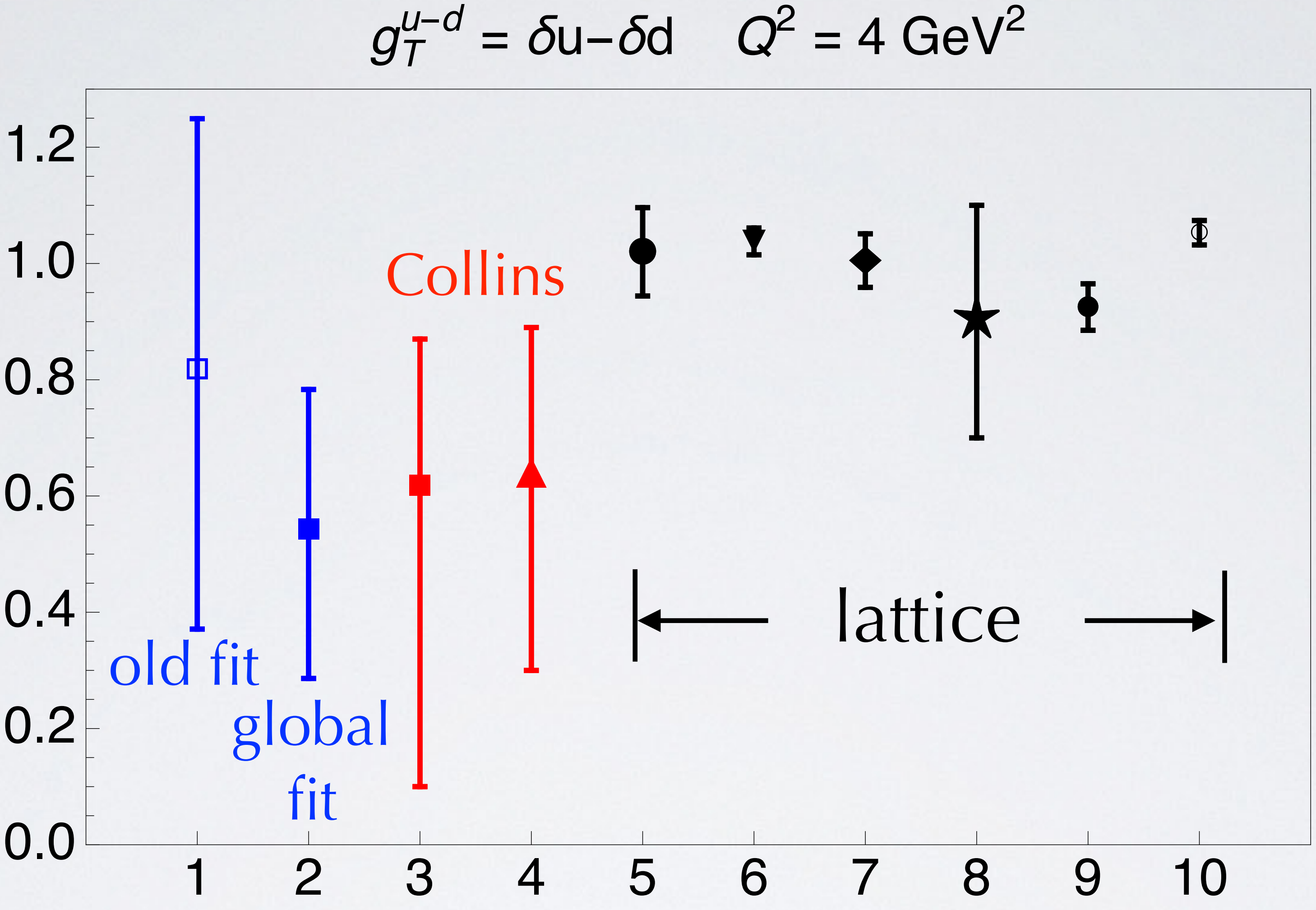


global fit

TMD fit

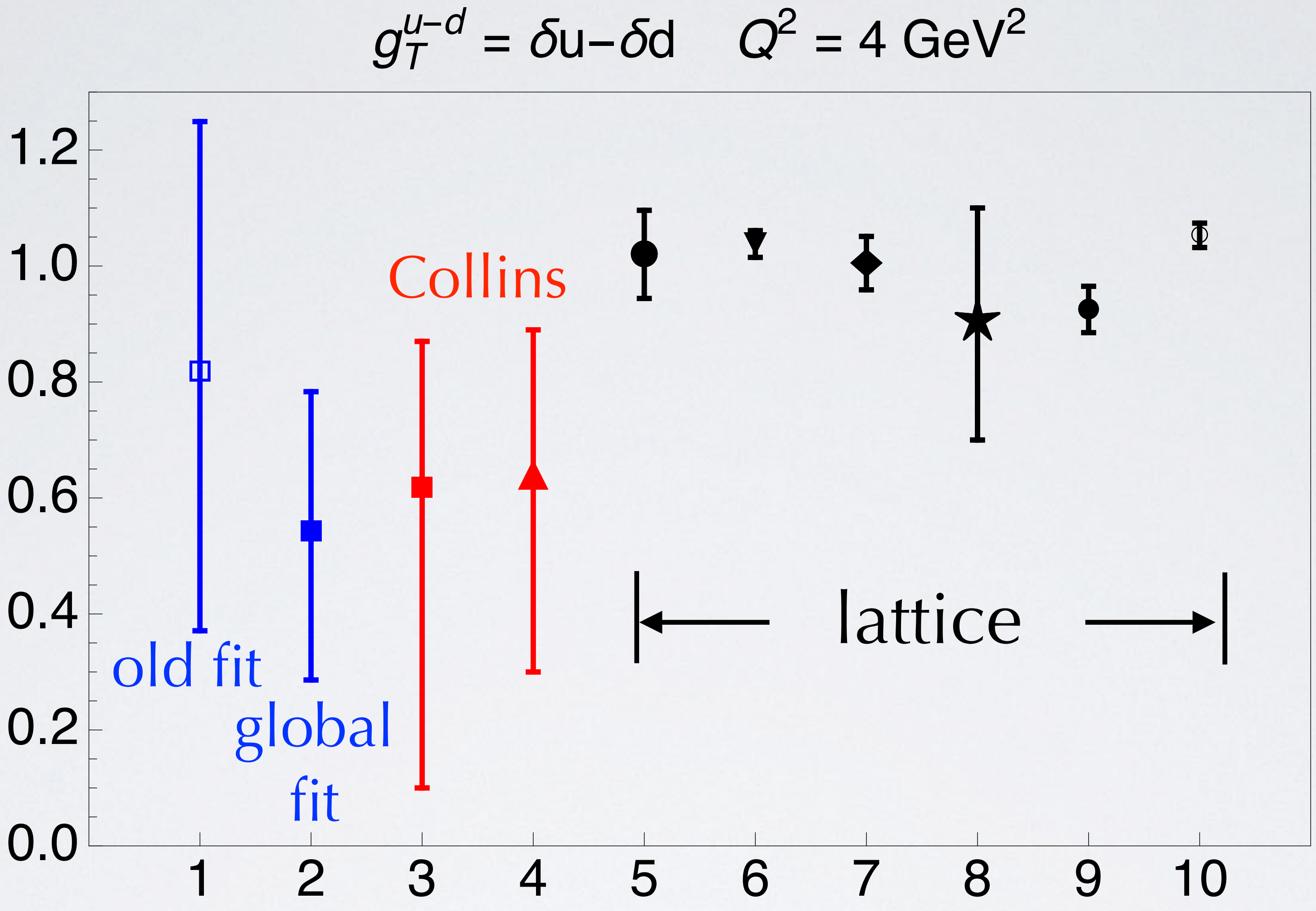
Kang et al.,
*P.R. D**93** (16) 014009*

isovector tensor charge $g_T^{u\text{-}d} = \delta u - \delta d$



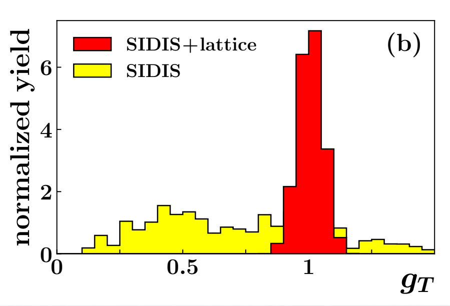
*Radici et al., JHEP **1505** (15) 123*	**1)** **old fit '15**	5)	PNDME '15	*Bhattacharya et al., P.R. D**92** (15)*
	2) **global fit '17**	6)	LHPC '12	*Green et al., P.R. D**86** (12)*
*Kang et al., P.R. D**93** (16) 014009*	**3)** **"TMD fit"**	7)	RQCD '14	*Bali et al., P.R. D**91** (15)*
*Anselmino et al., P.R. D**87** (13) 094019*	**4)** **Torino fit**	8)	RBC-UKQCD	*Aoki et al., P.R. D**82** (10)*
		9)	ETMC '17	*Alexandrou et al., P.R. D**95** (17) 114514;* *E P.R. D**96** (17) 099906*
		10)	ETMC '15	*Abdel-Rehim et al., P.R.D**92** (15);* *E P.R.D**93** (16)*

isovector tensor charge $g_T{}^{u\text{-}d} = \delta u - \delta d$



systematical discrepancy ?

but Collins seems compatible with lattice



Lin et al., arXiv:1710.09858

Radici et al., JHEP ***1505*** *(15) 123* **1) old fit '15**

2) global fit '17

*Kang et al., P.R. D**93** (16) 014009* **3) "TMD fit"**

*Anselmino et al., P.R. D**87** (13) 094019* **4) Torino fit**

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)*

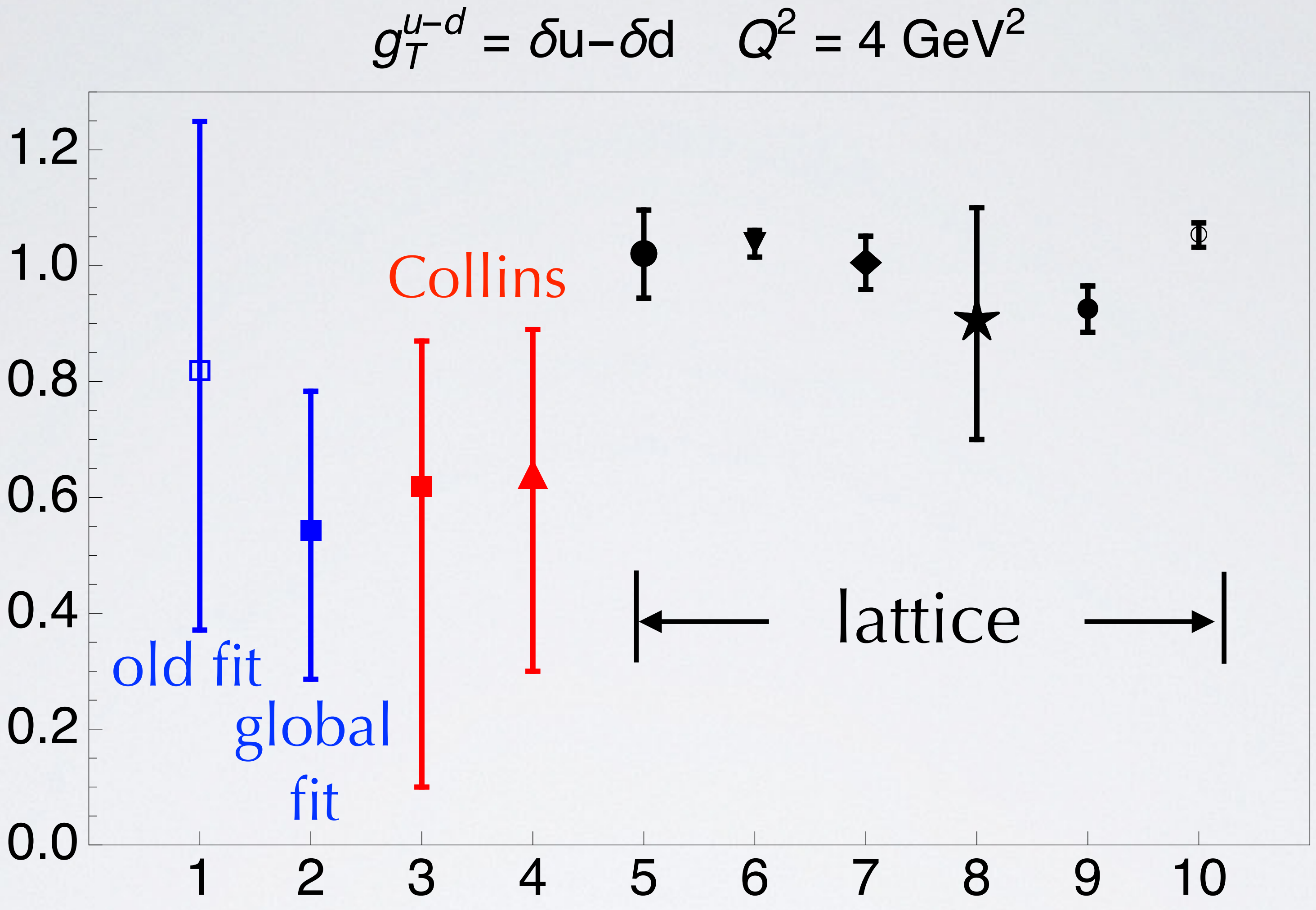
8) RBC-UKQCD *Aoki et al., P.R. D**82** (10)*

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

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

isovector tensor charge $g_T^{\text{u-d}} = \delta\text{u} - \delta\text{d}$

precision
is an issue !



systematical
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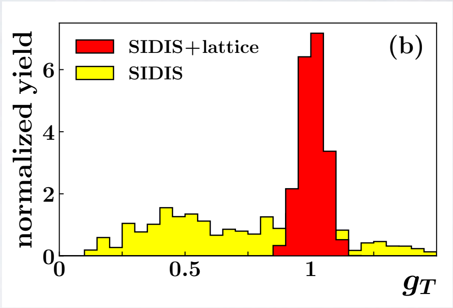
but Collins seems
compatible with lattice



Lin et al., arXiv:1710.09858

*Radici et al., JHEP **1505** (15) 123* **1) old fit '15**

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*Kang et al., P.R. D**93** (16) 014009* **3) "TMD fit"**

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

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

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 tree-level $\mathcal{L}_{\text{SM}}$
low-energy footprint of new physics (BSM) at higher scales ?

talk by Courtoy

precision : potential for BSM searches

$$
\begin{aligned}
P^{[\mu}\, S^{\nu]}\, g_T^q(Q^2) &= P^{[\mu}\, S^{\nu]} \int_0^1 dx\ \left[h_1^q(x,Q^2) - h_1^{\bar q}(x,Q^2)\right] \\
&= \langle P,S|\, \bar q\, \sigma^{\mu\nu}\, q\, |P,S\rangle
\end{aligned}
$$

tensor operator not directly accessible in tree-level $\mathcal{L}_{SM}$
low-energy footprint of new physics (BSM) at higher scales ?

talk by Courtoy

Example: neutron β–decay $n \rightarrow p\, e^-\, \bar\nu_e$

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

$\bar e \gamma^\mu (1-\gamma_5)\nu_e \quad \bar u \gamma^\mu (1-\gamma_5) d$

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

$\ldots + \varepsilon_T\ \bar e \sigma^{\mu\nu} \nu_e \quad \bar q \sigma^{\mu\nu} q \ldots$

$\varepsilon_T\, g_T^{u-d}$ $(\approx M_W^2 / M_{BSM}^2)$

current experimental constraint from

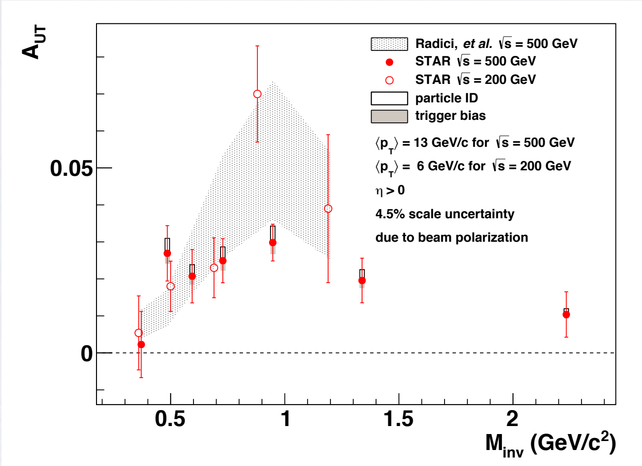
- radiative pion decay
  *Bychkov et al. (PIBETA), P.R.L. **103** (09) 051802*
- neutron β decay
  *Pattie et al., P.R. C**88** (13) 048501*

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

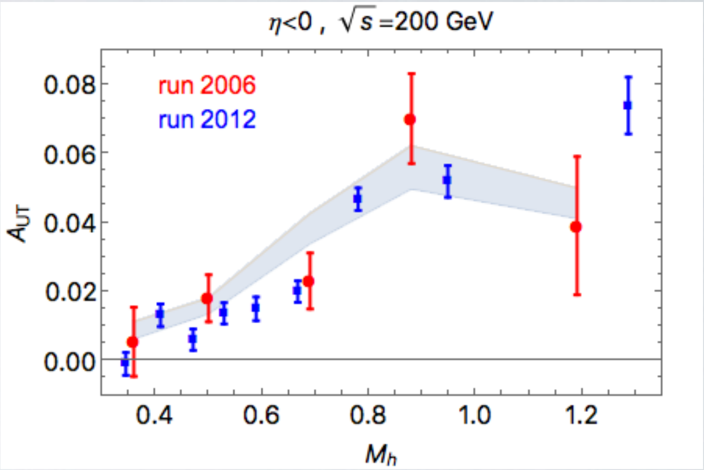
To do list

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

talk by Aschenauer & Surrow



Adamczyk et al. (STAR), arXiv:1710.10215



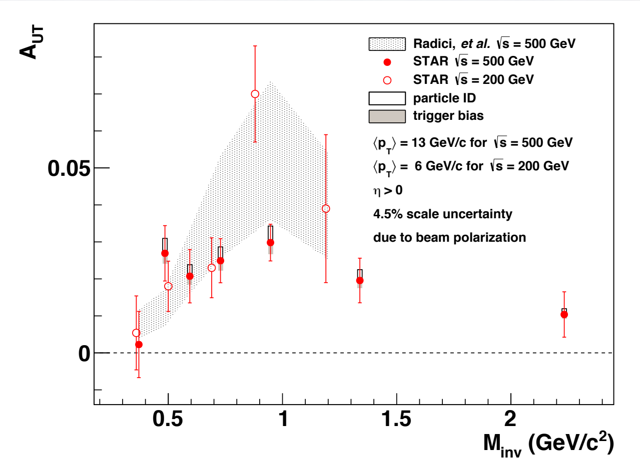
*Radici et al., P.R. D**94** (16) 034012*

- ➡ need data on p+p → (ππ) X constrains gluon $D_1{}^g$

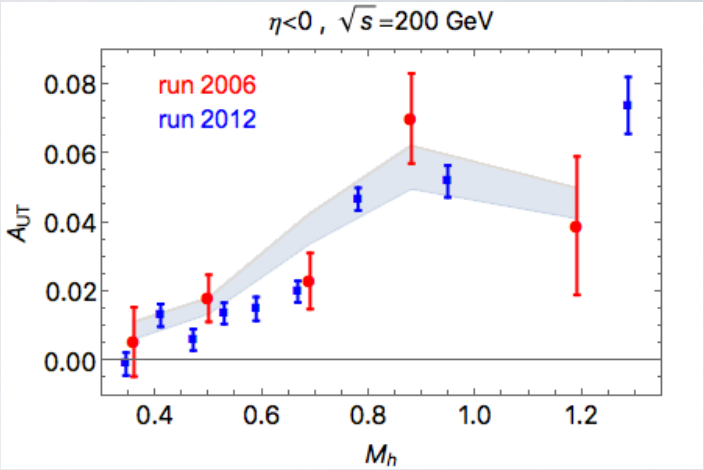
To do list

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

talk by Aschenauer & Surrow



Adamczyk et al. (STAR), arXiv:1710.10215



*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: $e^+e^- \to (\pi\pi)$ X constrains $D_1{}^q$ (currently only by Montecarlo)

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

talk by Vossen & Schnell

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

talk by Moretti

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

talk by Accardi

Conclusions

- first global fit of di-hadron inclusive data leading to extraction of transversity as a PDF in collinear framework

- inclusion of STAR p-p$^\uparrow$ data increases precision of up channel and eliminates suspicious behavior of down;
  large uncertainty on down due to unconstrained gluon di-hadron fragmentation function

- tensor charge useful for low-energy explorations of BSM new physics ⇒ precision is an issue.

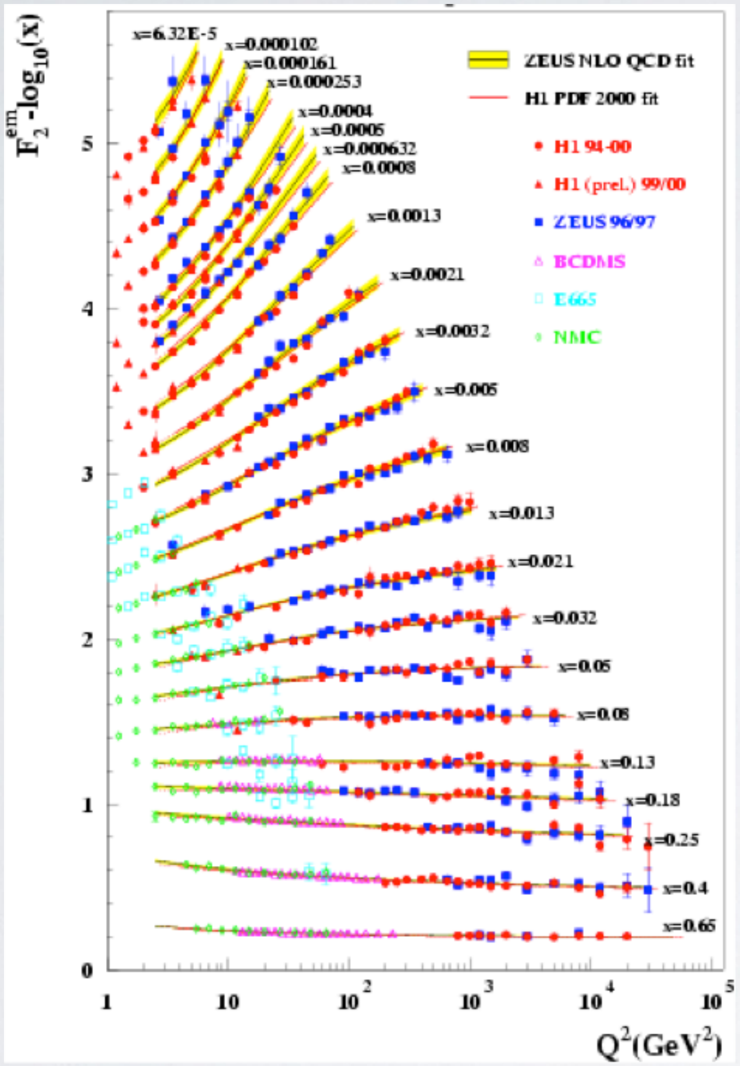
  This global fit is an important step forward

THANK YOU

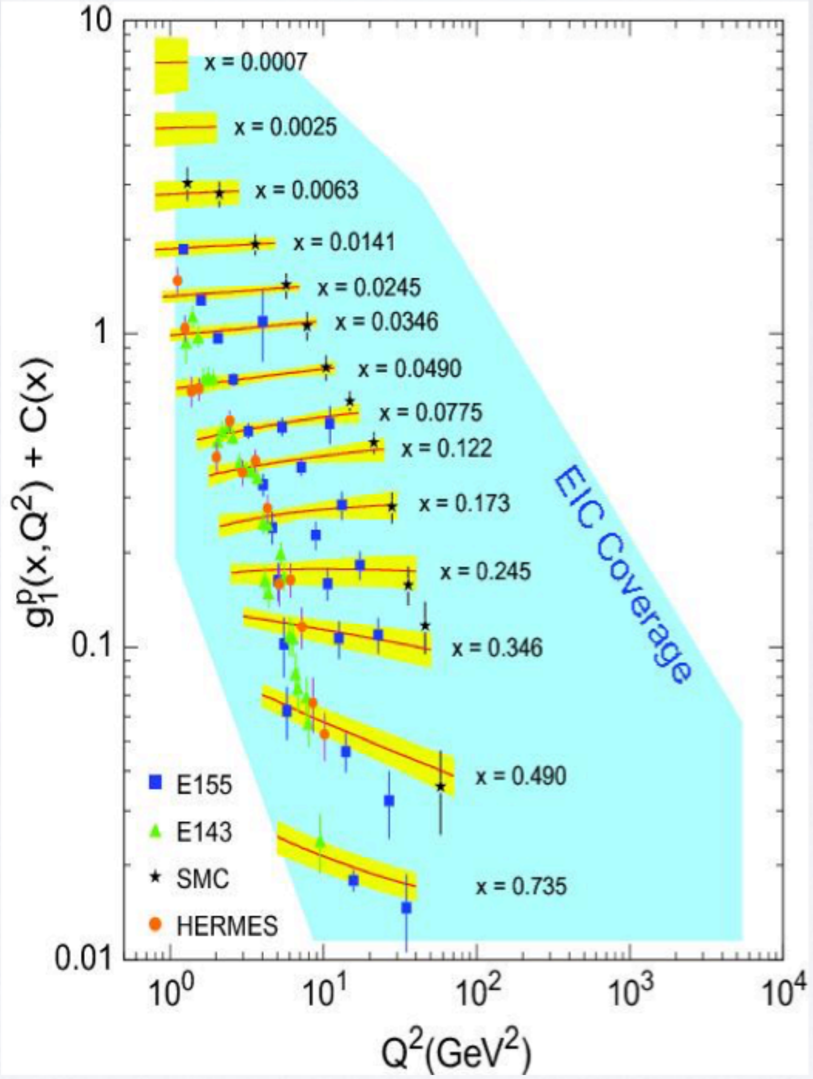
Back-up

Transversity poorly known

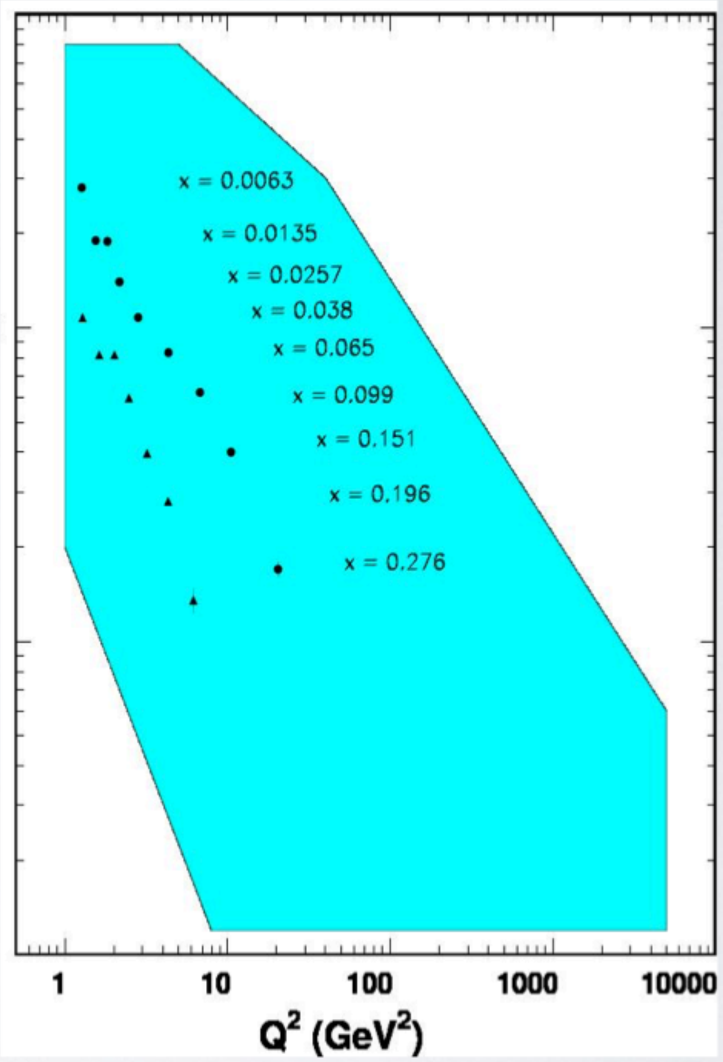
World data for F_2^p



World data for g_1^p



World data for **h_1**



f_1 from fits of **thousands** data

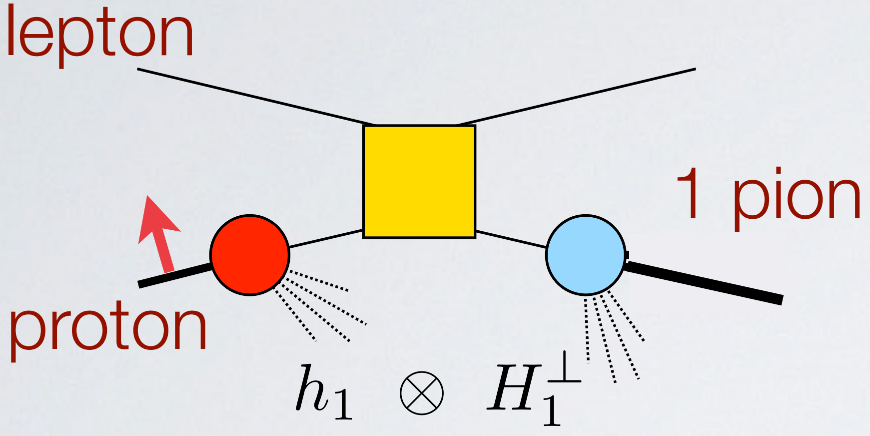
g_1 from fits of **hundreds** data

h_1 from fits of **tens** data

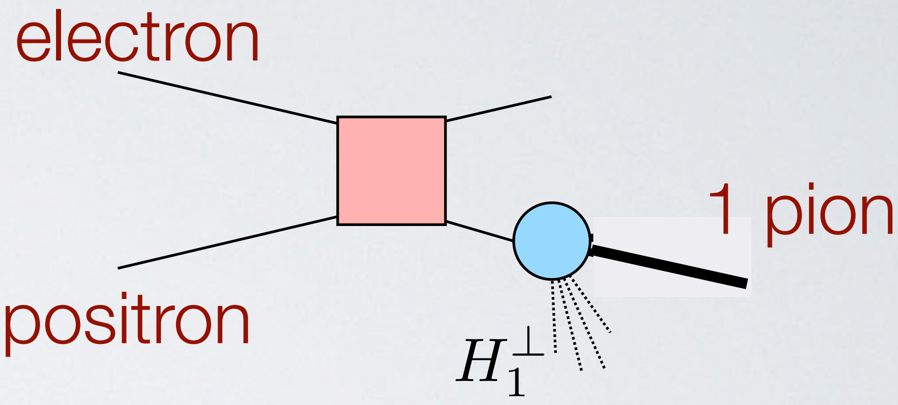
slide from H.Montgomery, QCD Evolution 2016

extraction from 1-hadron-inclusive data

SIDIS

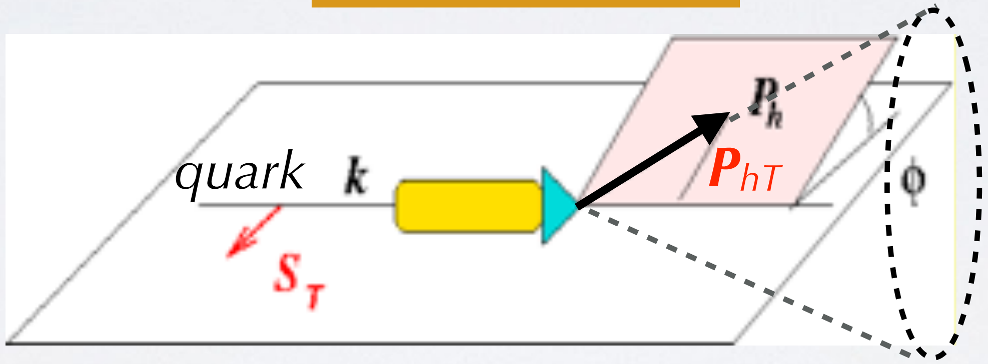


e+e−



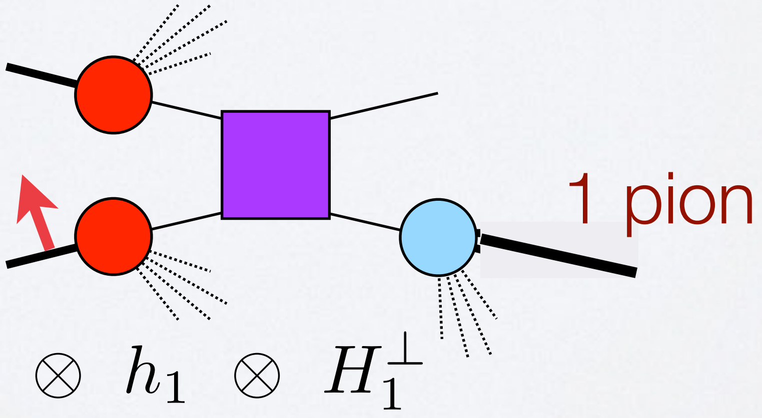
Collins effect

Collins,
N.P. ***B396*** *(93) 161*



correlation $\boldsymbol{S}_T$ and $\boldsymbol{P}_{hT}$ → azimuthal asymmetry

p-p↑



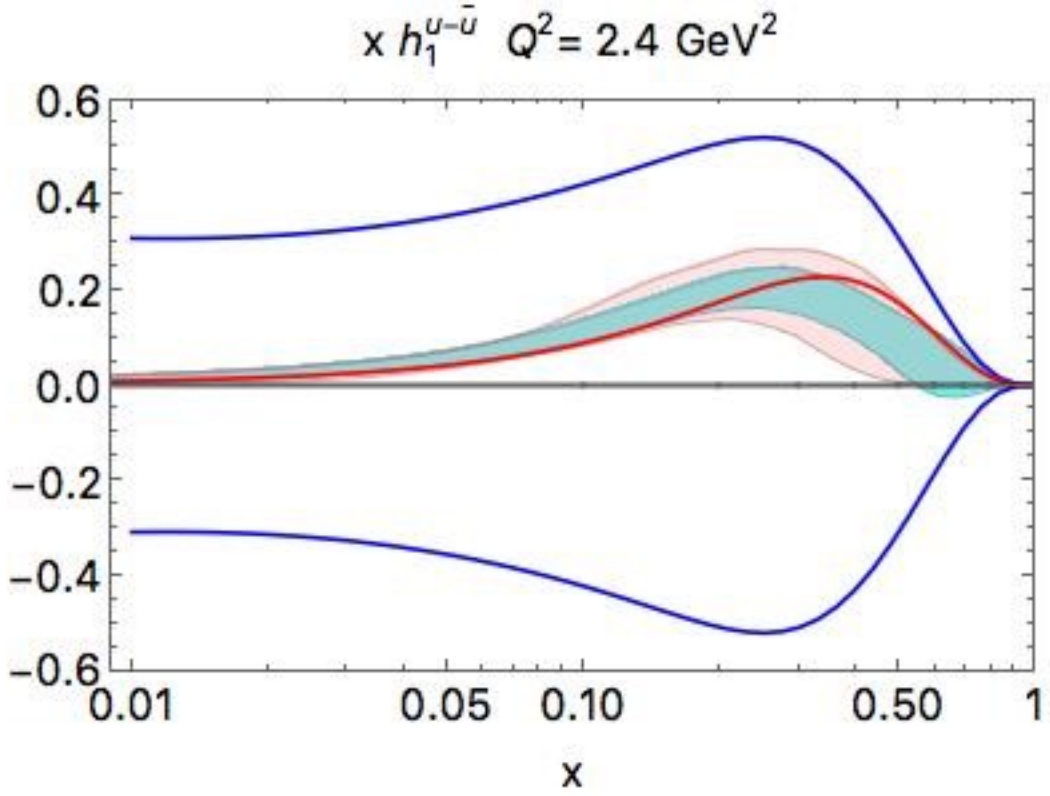
framework
TMD
factorization
$P_{hT} \ll Q$

Comparison with Collins effect

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

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

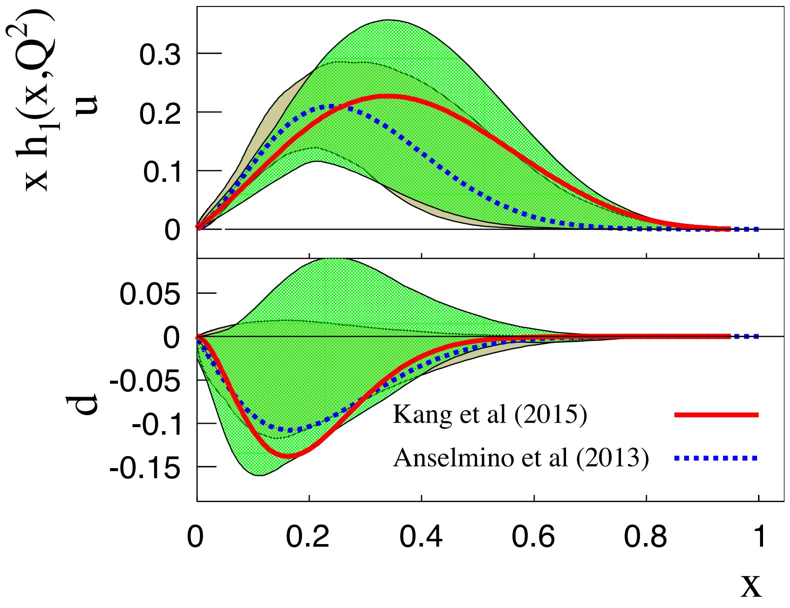
up



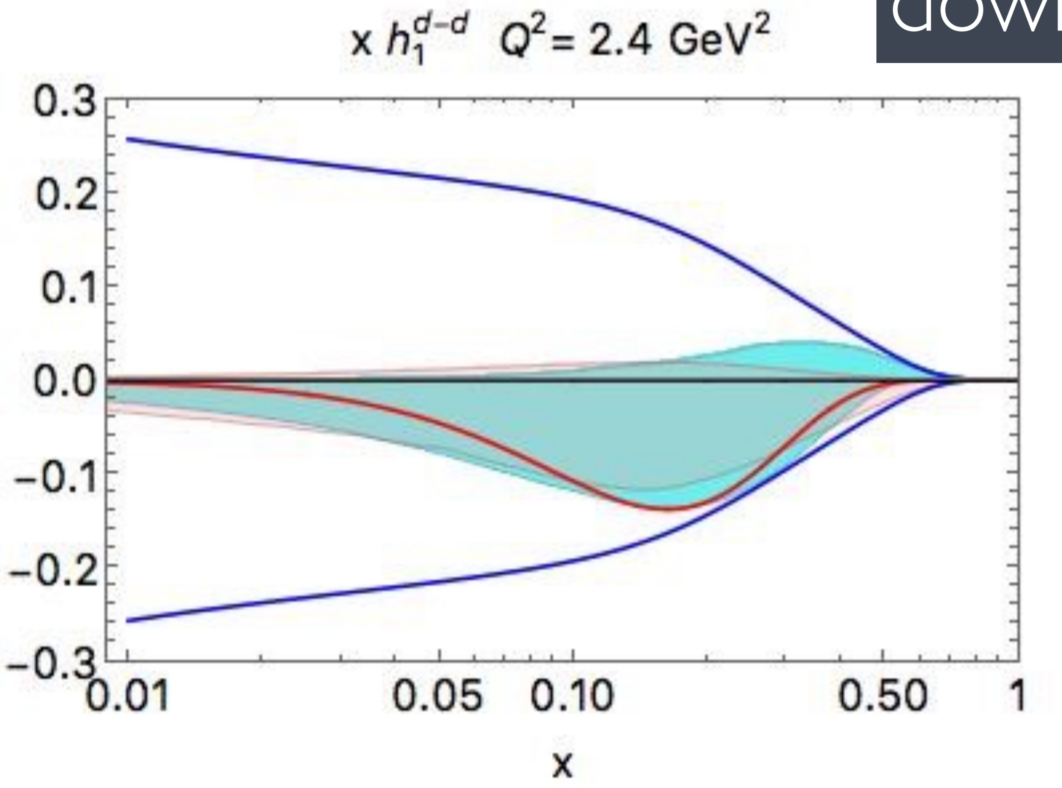
global fit

Torino

"TMDfit"



down



global fit : •up: gain precision
•down: compatible

also from forward limit of chiral-odd GPD H_T

*Goldstein et al., P.R. D**91** (15) 114013*

also possible on lattice (LAMET): "quasi-PDF"

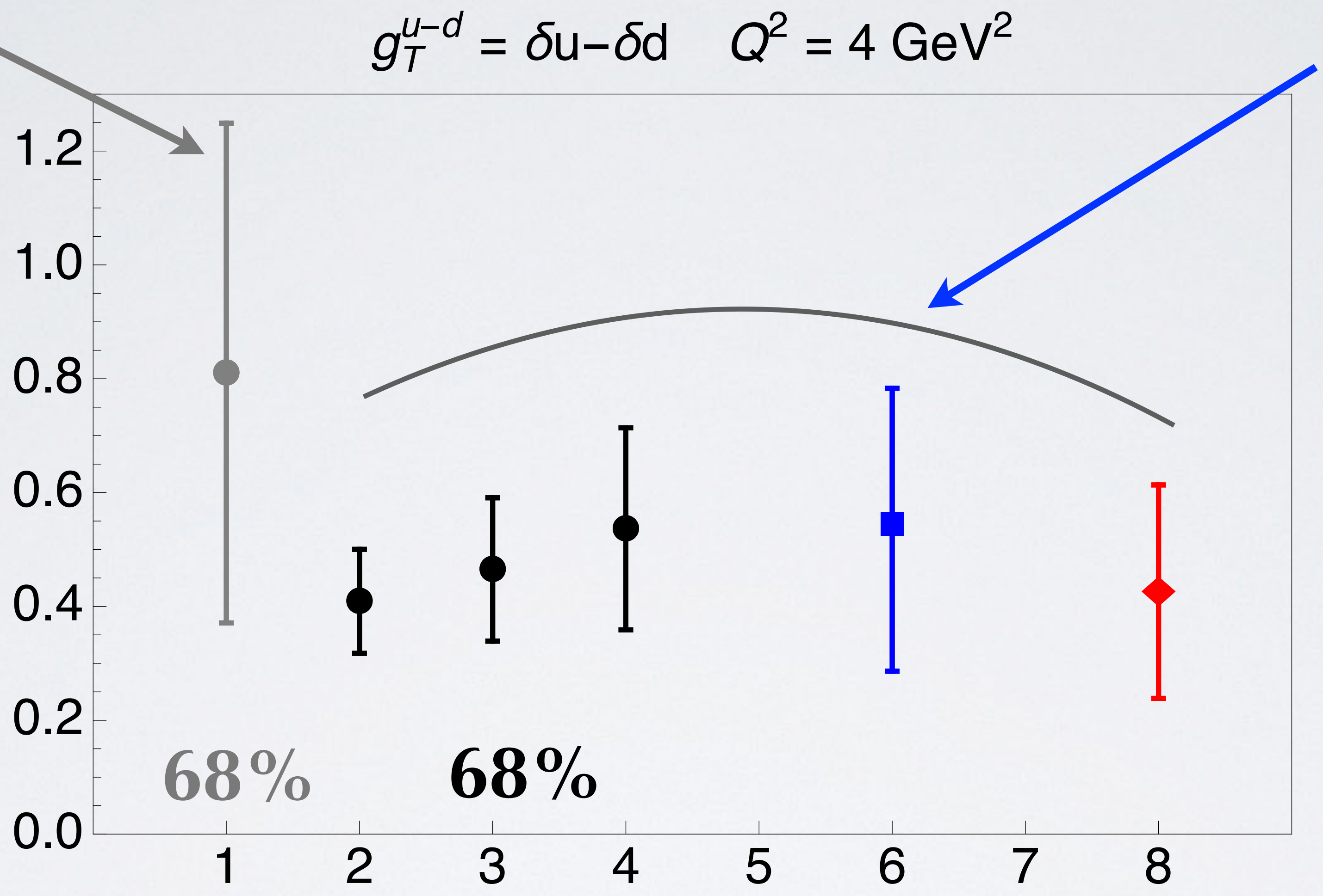
Chen et al., arXiv:1603.06664

isovector tensor charge $g_T^{u\text{-}d} = \delta u - \delta d$

old fit

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

global fit

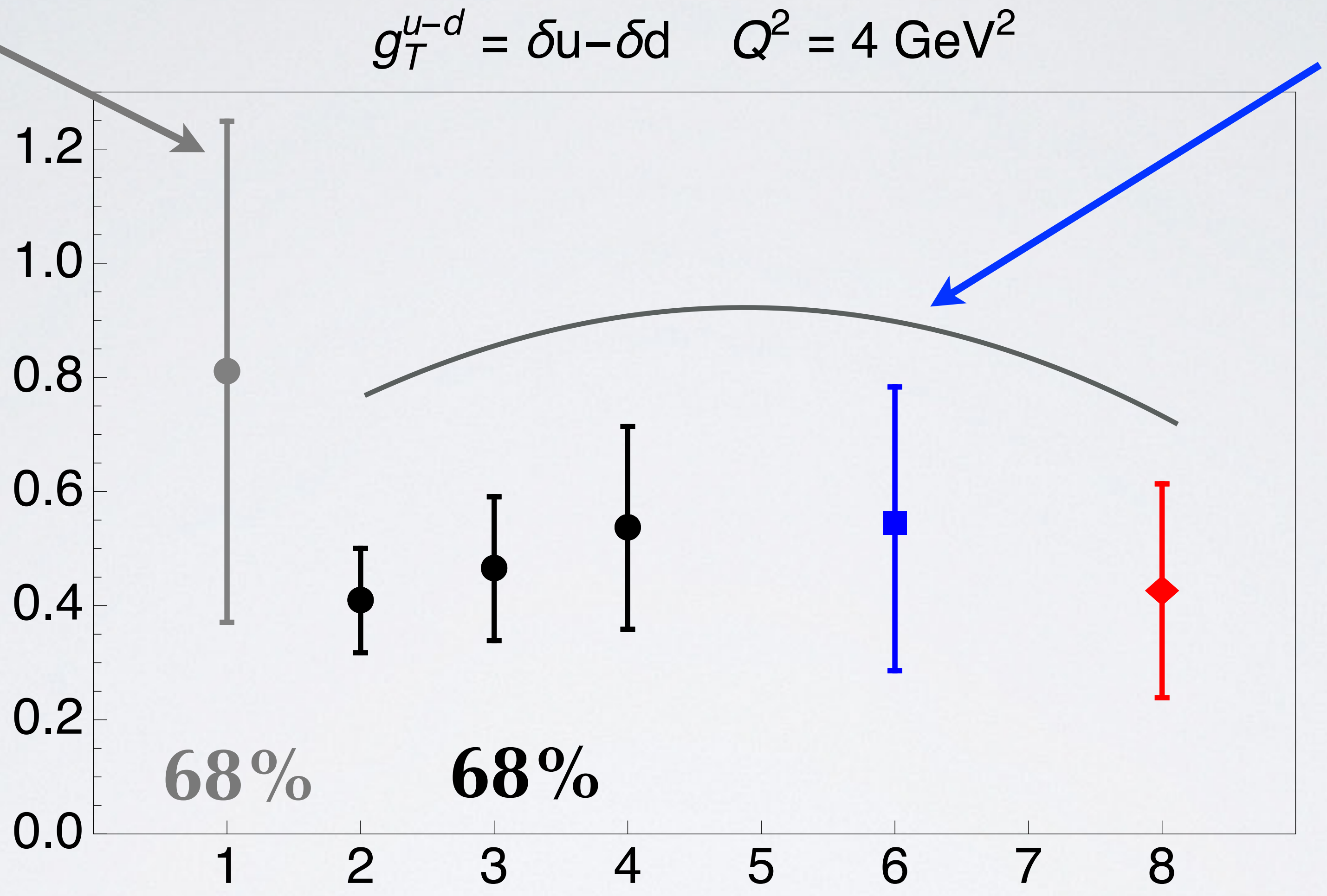


$D_1^g = 0$ **$D_1^g = 0$**

isovector tensor charge $g_T^{u-d} = \delta u - \delta d$

old fit

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



global fit

$D_1^g = 0$

$D_1^g = 0$

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

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

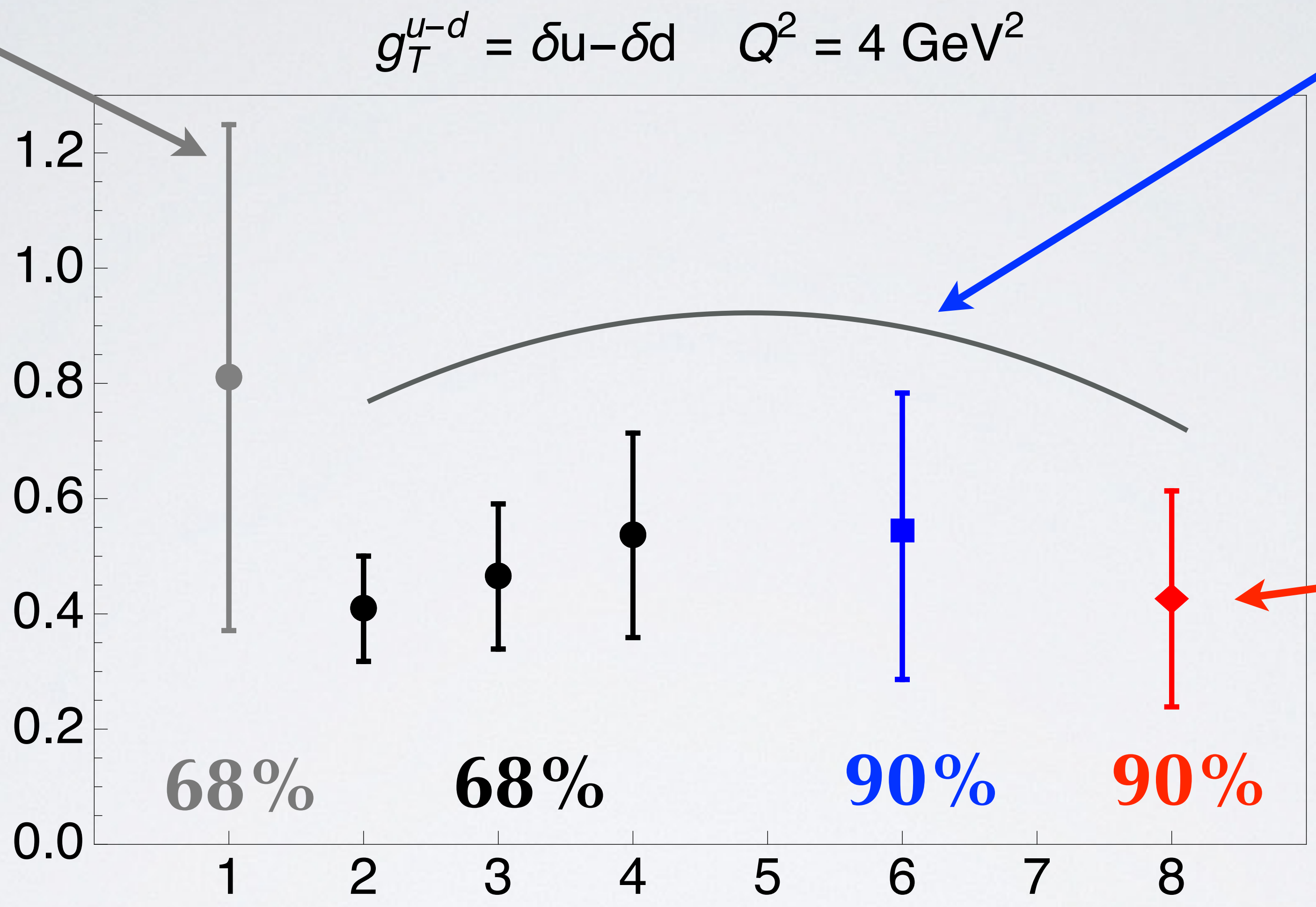
isovector tensor charge $g_T^{u\text{-}d} = \delta u - \delta d$

old fit

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

global fit

truncated



$D_1^g = 0$ $\quad D_1^g = 0$

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

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