

XXVI International Workshop on Deep Inelastic Scattering and Related Subjects

DIS

16-20 April 2018
Port Island, Kobe, Japan

WG1 Structure Functions and Parton Densities

WG2 Low x and Diffractive Physics

WG3 Higgs and BSM Physics in Hadron Collisions

WG4 Hadronic and Electroweak Observables

WG5 Physics with Heavy Flavours

WG6 Spin and 3D Structure

WG7 Future of DIS

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First extraction of Transversity from electron-proton and proton-proton data



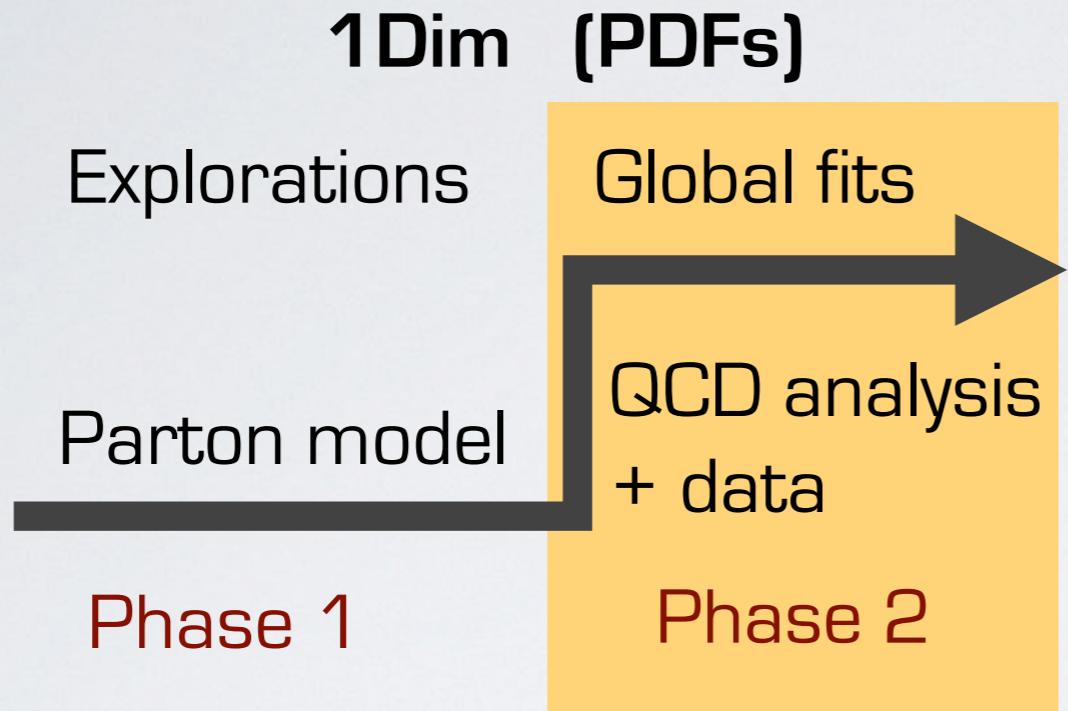
Marco Radici
INFN - Pavia

in collaboration with
A. Bacchetta (Univ. Pavia)



based on
arXiv:1802.05212
to appear in Phys. Rev. Lett.

a phase transition

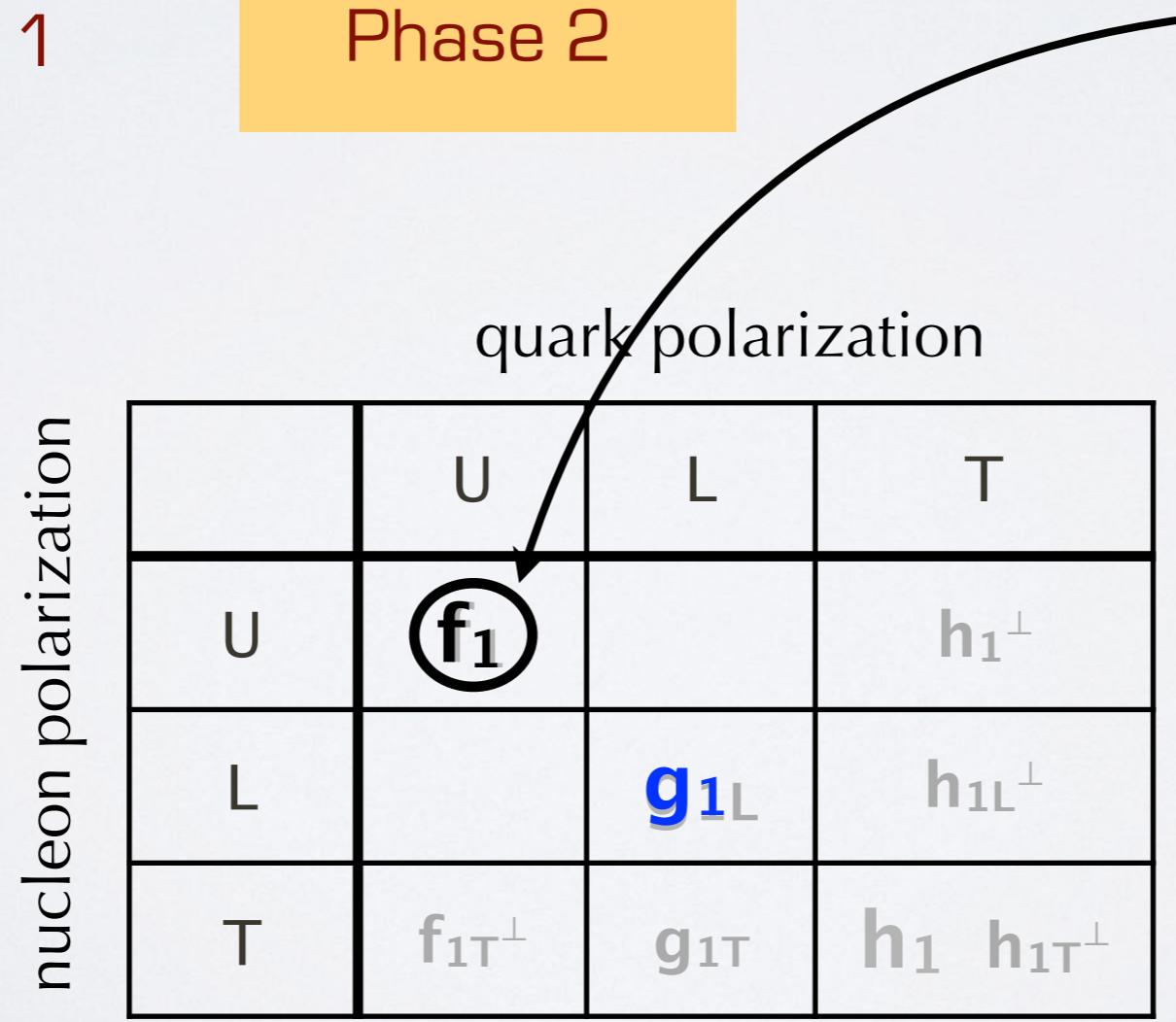
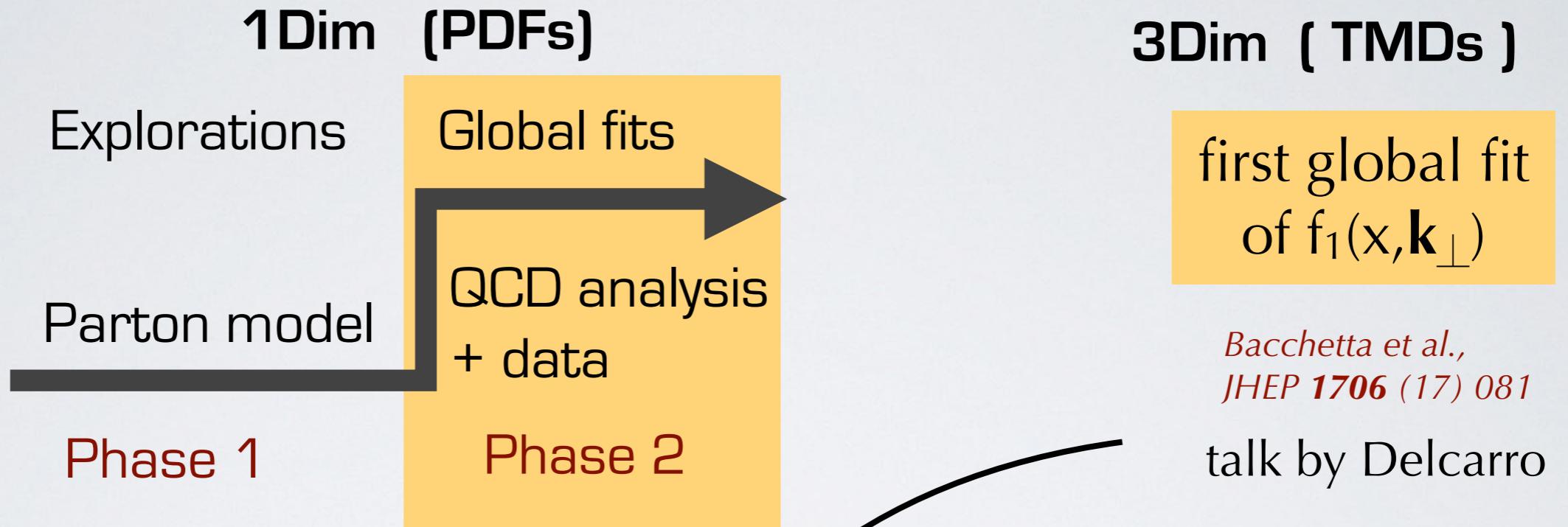


quark polarization

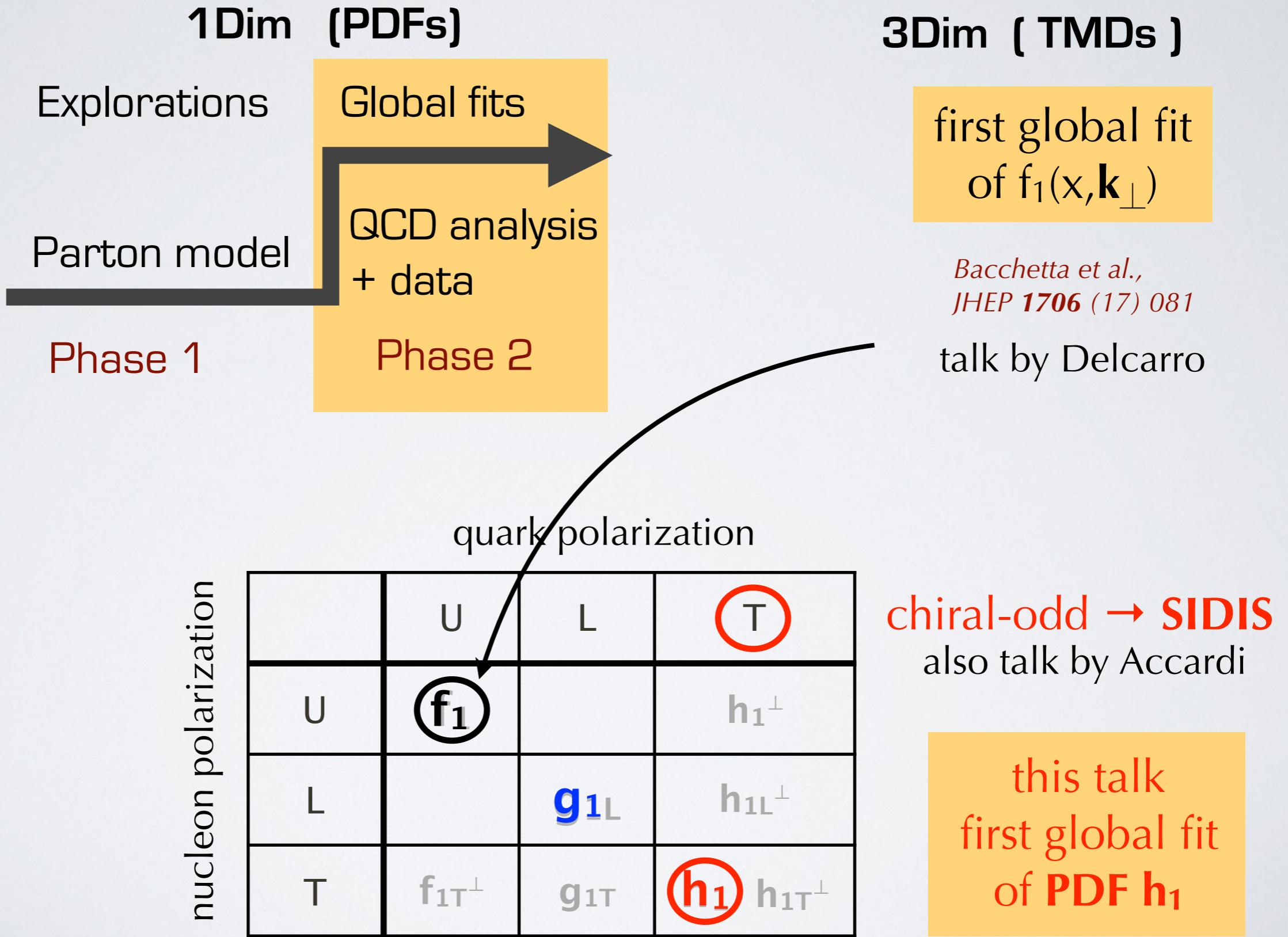
nucleon polarization

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

a phase transition



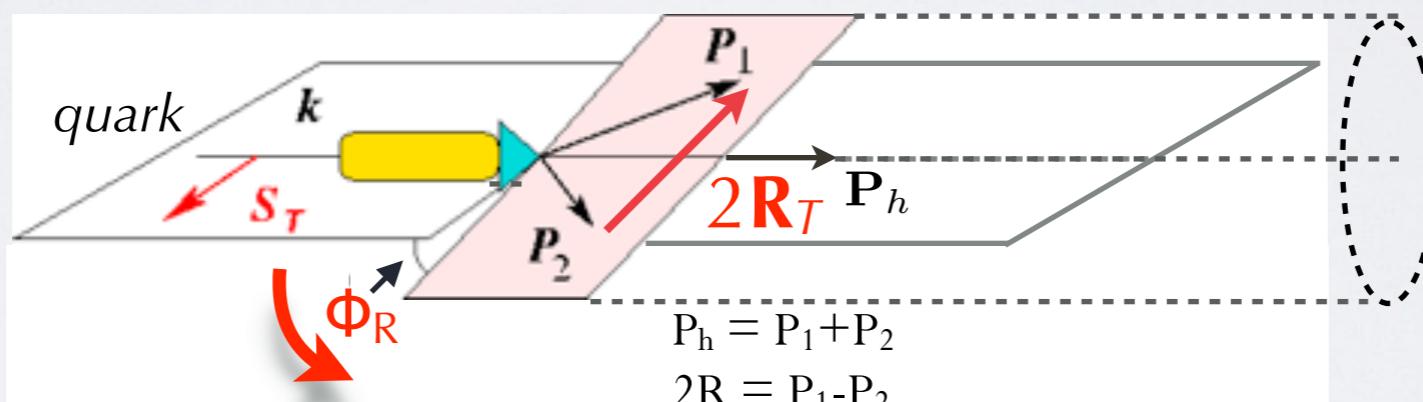
a phase transition



2-hadron-inclusive production

$$H_1^<$$

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



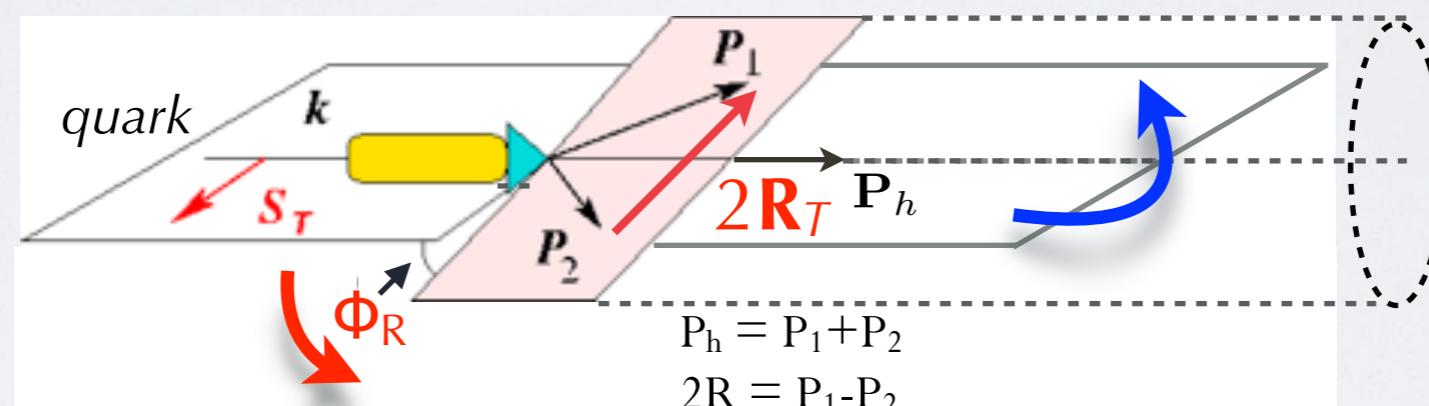
correlation S_T and $R_T \rightarrow$ azimuthal asymmetry

2-hadron-inclusive production

framework
collinear
factorization

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

↑
 M_h

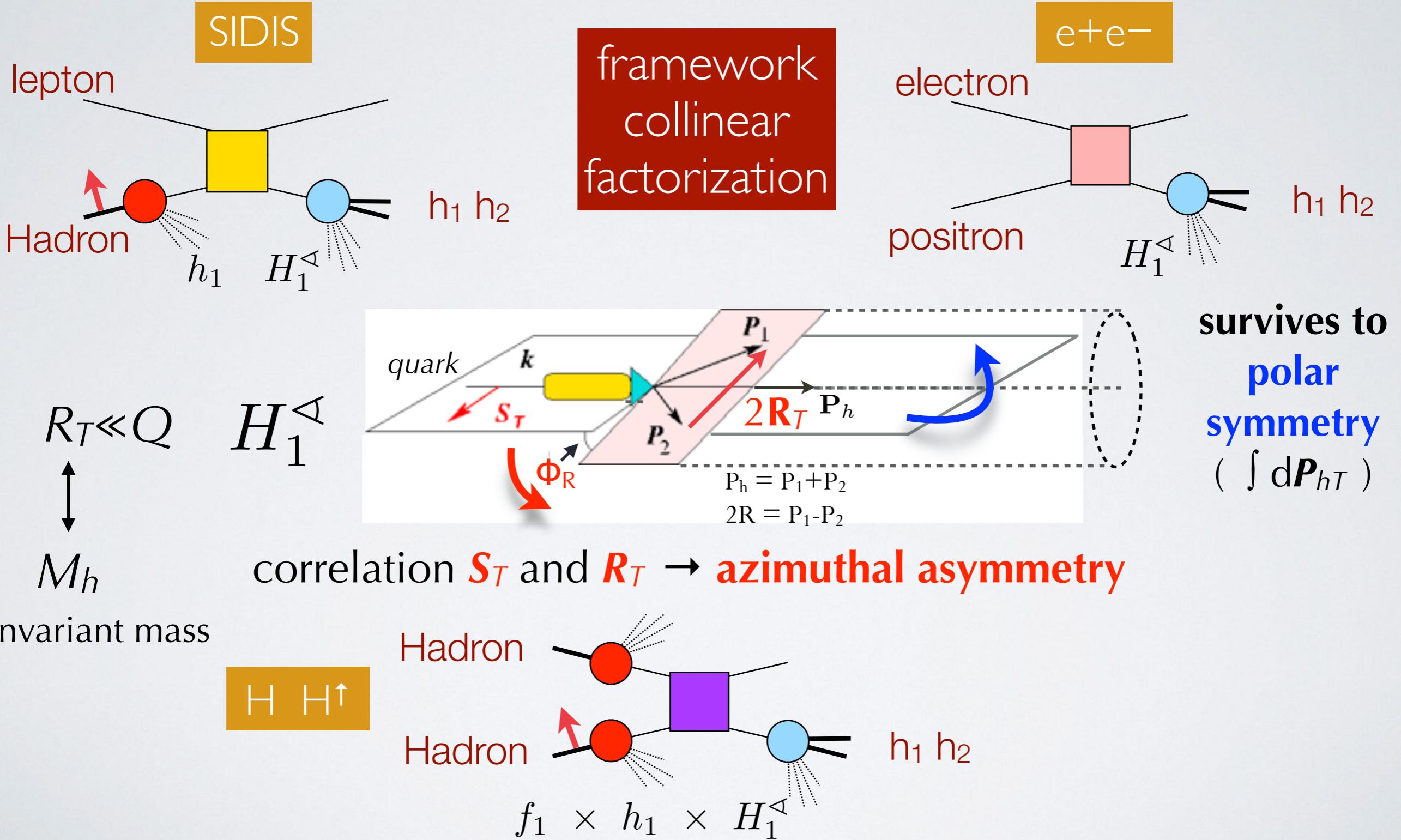


survives to
polar
symmetry
($\int dP_{hT}$)

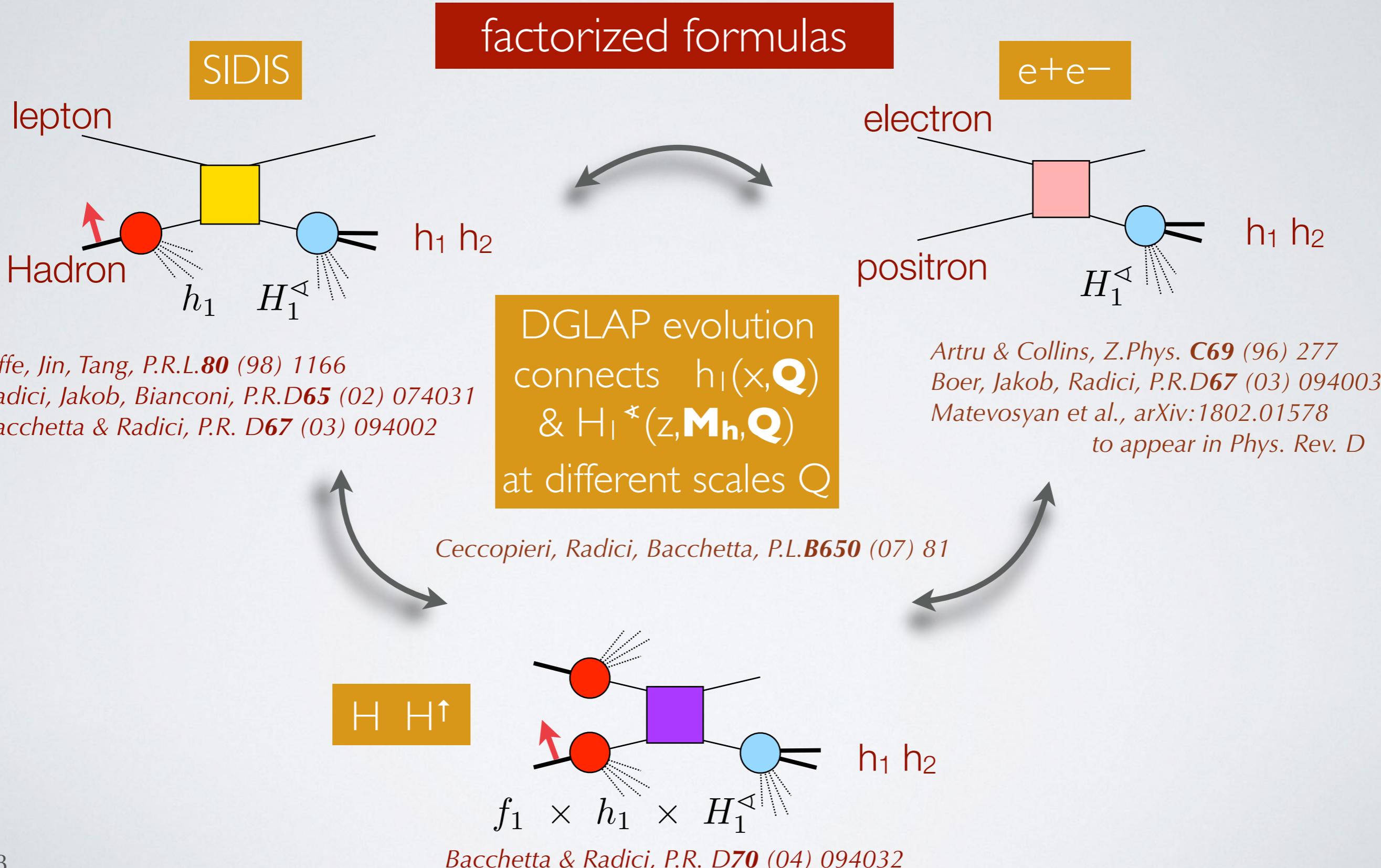
correlation s_T and $R_T \rightarrow$ azimuthal asymmetry

invariant mass

2-hadron-inclusive production



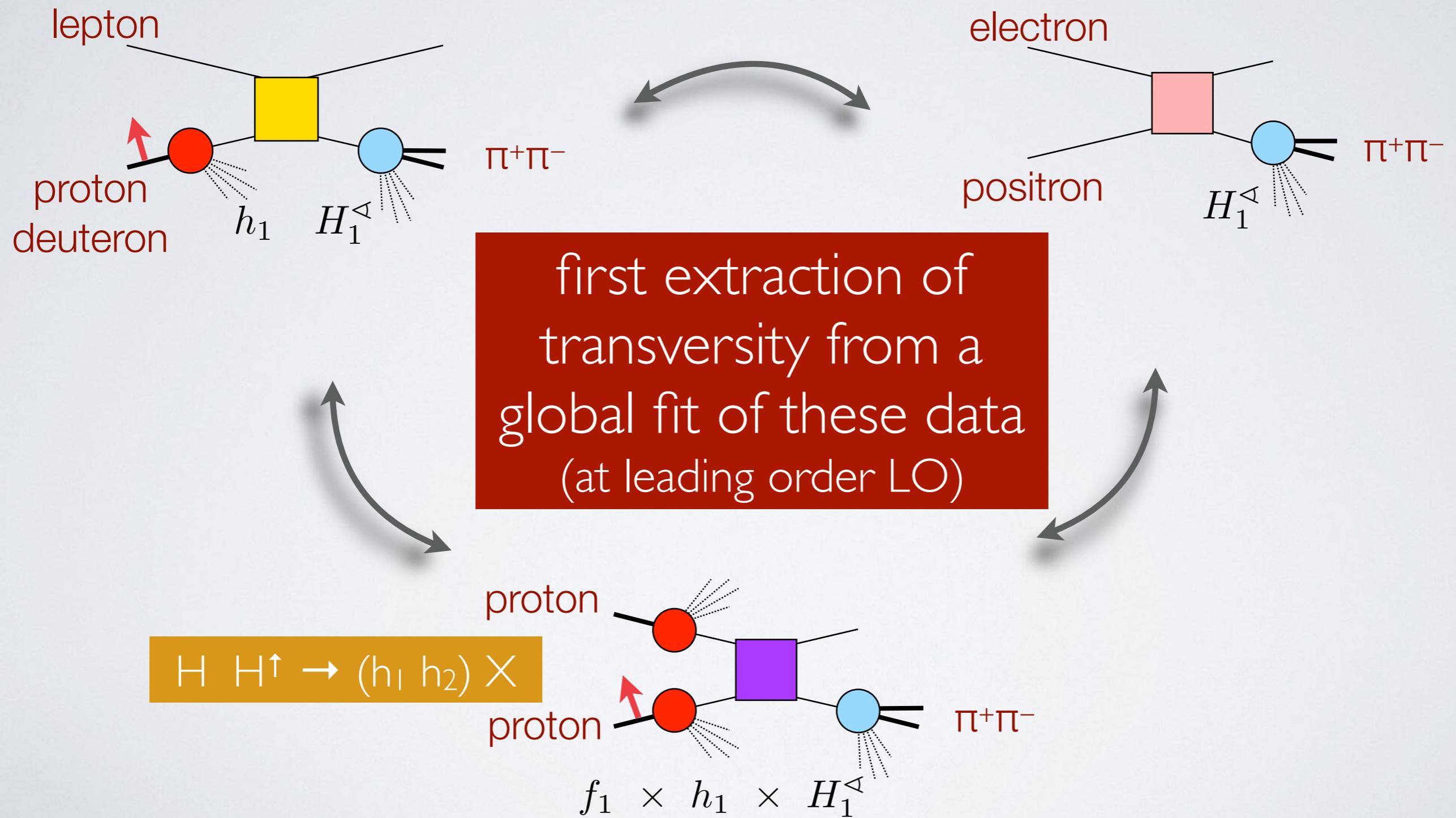
extraction from 2-hadron-inclusive production



take-away message

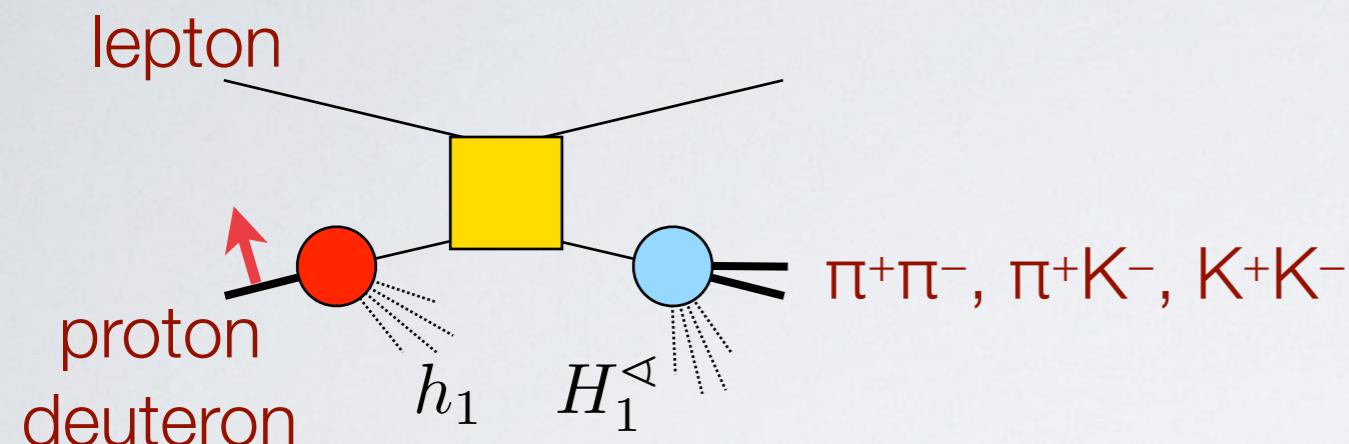
SIDIS $\ell^- H^\uparrow \rightarrow \ell' (h_1 h_2) X$

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



exp. data for 2-hadron-inclusive production

SIDIS $\ell^- H^\uparrow \rightarrow \ell^+ (h_1 h_2) X$

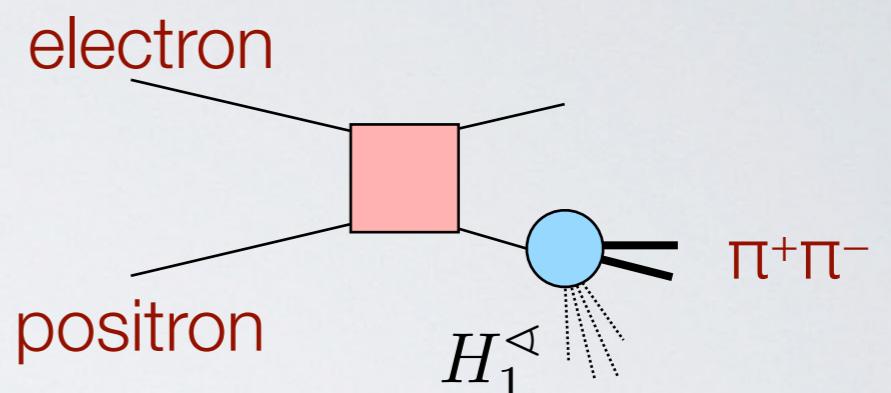


Airapetian et al.,
JHEP **0806** (08) 017



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

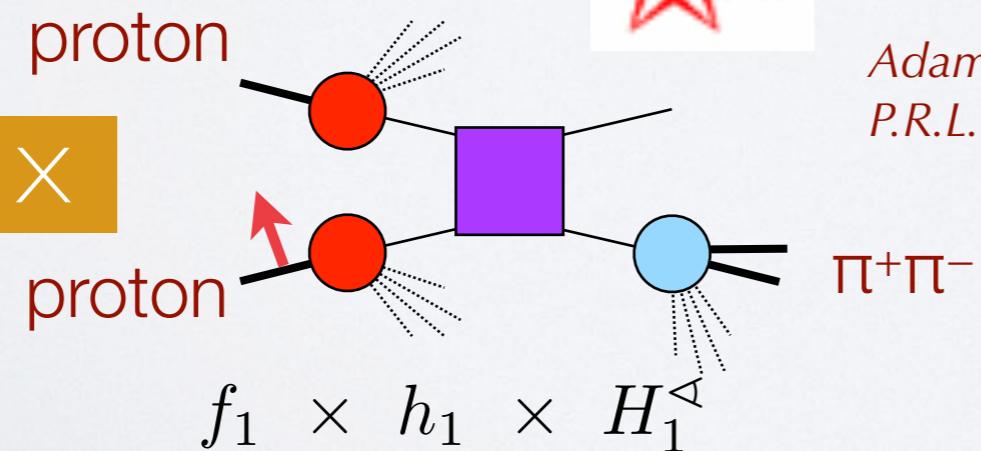
$e^+e^- \rightarrow (h_1 h_2) X$



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

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

$H^- H^\uparrow \rightarrow (h_1 h_2) X$



run 2006 ($s=200$)

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



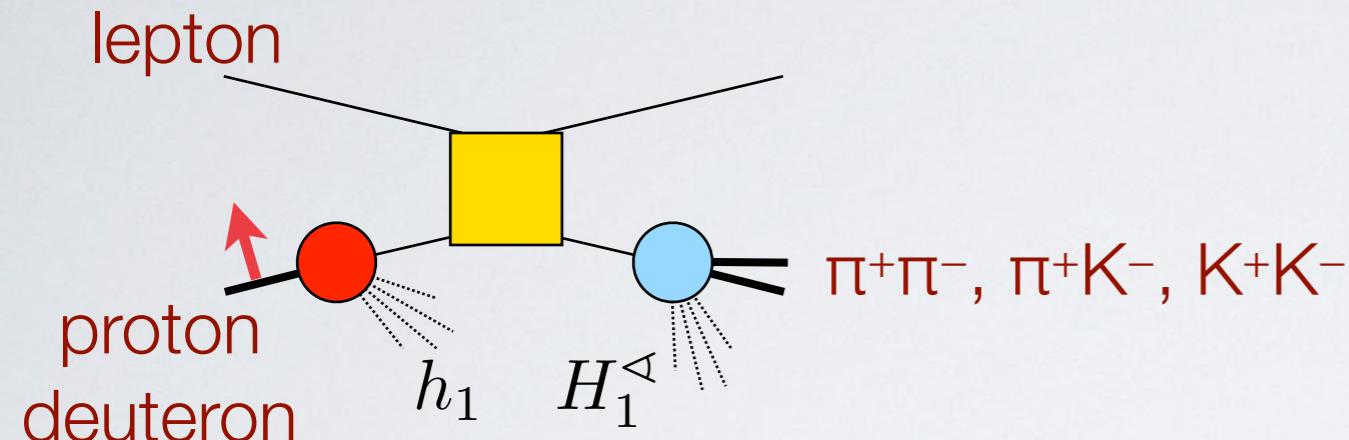
run 2011 ($s=500$)

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

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

exp. data for 2-hadron-inclusive production

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

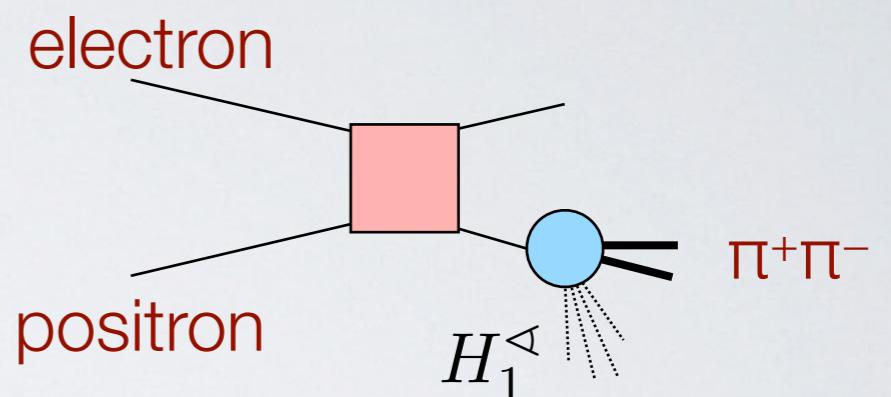


Airapetian et al.,
JHEP **0806** (08) 017



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

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

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

$H^- H^\uparrow \rightarrow (h_1 h_2) X$

proton

proton

$f_1 \times h_1 \times H_1^<$



run 2006

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

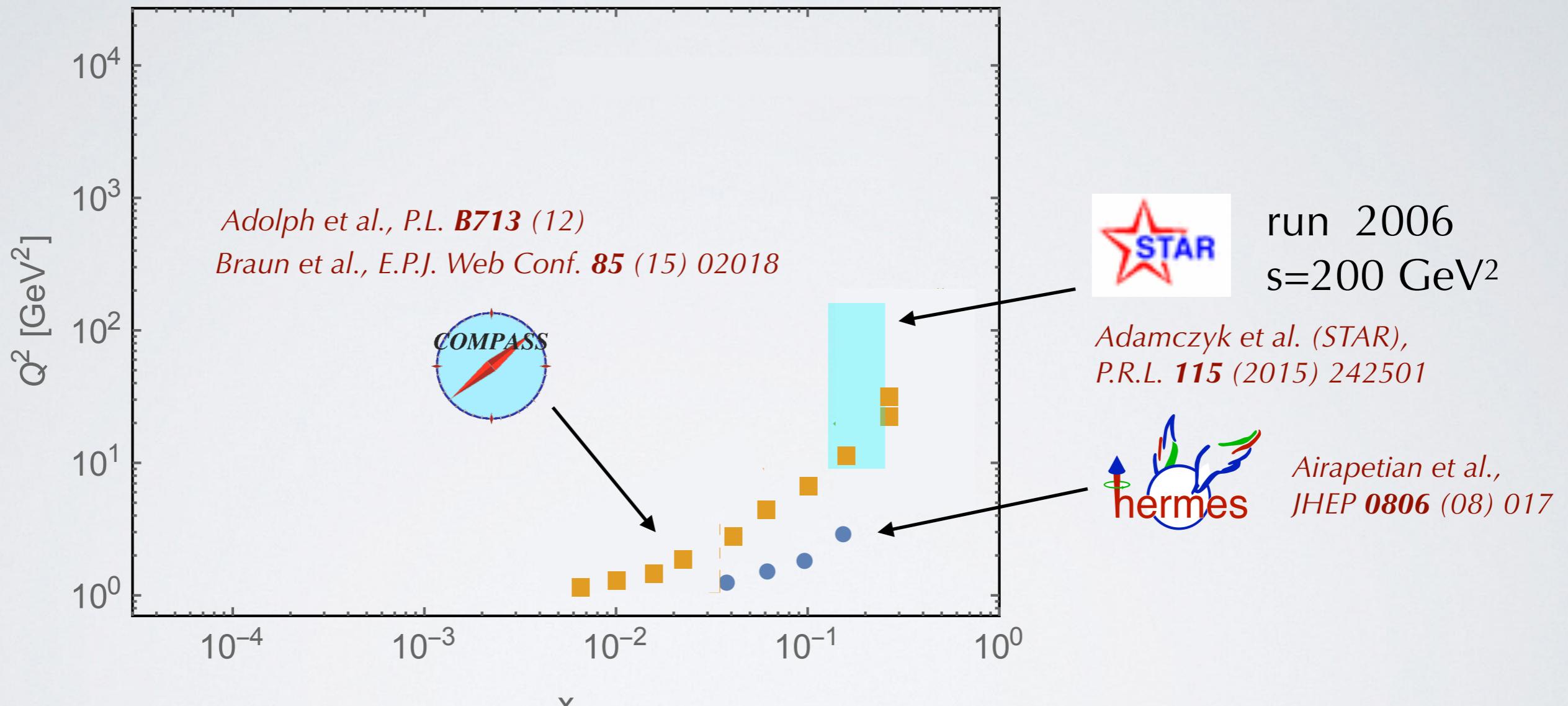
run 2011

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

$\pi^+\pi^-$

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

the kinematics



explore only valence quarks

choice of functional form

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

↓
Soffer Bound

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

MSTW08 DSSV

choice of functional form

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

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MSTW08 DSSV

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

$$|N_{q_v}| \leq 1 \Rightarrow |F^{q_v}(x)| \leq 1$$

Ceb_n(x) Cebyshev polynomial
10 fitting parameters

Soffer Bound satisfied at any Q²

choice of functional form

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

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Soffer Bound

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Ceb_n(x) Cebyshev polynomial
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Soffer Bound satisfied at any Q²

if $\lim_{x \rightarrow 0} x \text{SB}(x) \propto x^{\bar{a}}$ then $A_{q_v} + \bar{a} > \frac{1}{3}$ 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

hadronic collisions in Mellin space

$d\sigma(\eta, M_h, P_T)$ typical cross section for $a+b^\uparrow \rightarrow c^\uparrow + d$ process

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

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

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

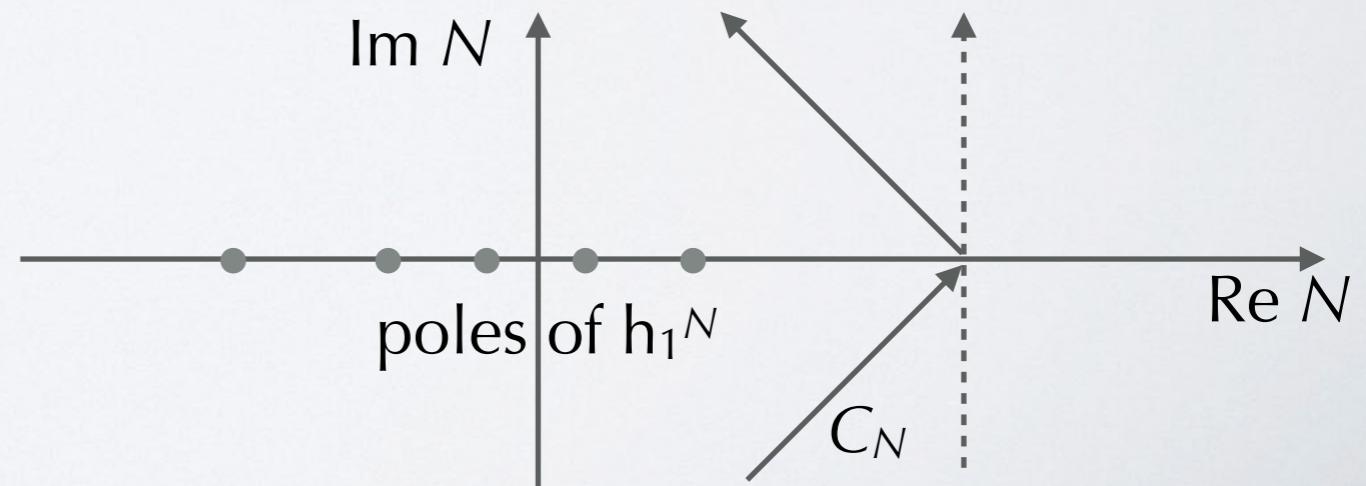
Stratmann & Vogelsang,
P.R. D64 (01) 114007

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

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

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**



theoretical uncertainties

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..)

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

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

typical cross section for $a+b \rightarrow c+d$ process

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

important !

theoretical uncertainties

quark D_{1q} is well constrained by e^+e^- (Montecarlo) but

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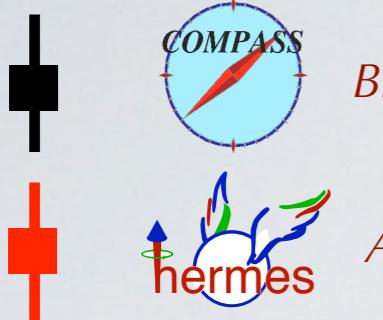
our choice: compute $d\sigma_0$ with $D_{1g}(Q_0) = \begin{cases} 0 \\ D_{1u}(Q_0) / 4 \\ D_{1u}(Q_0) \end{cases}$

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

background ρ channels

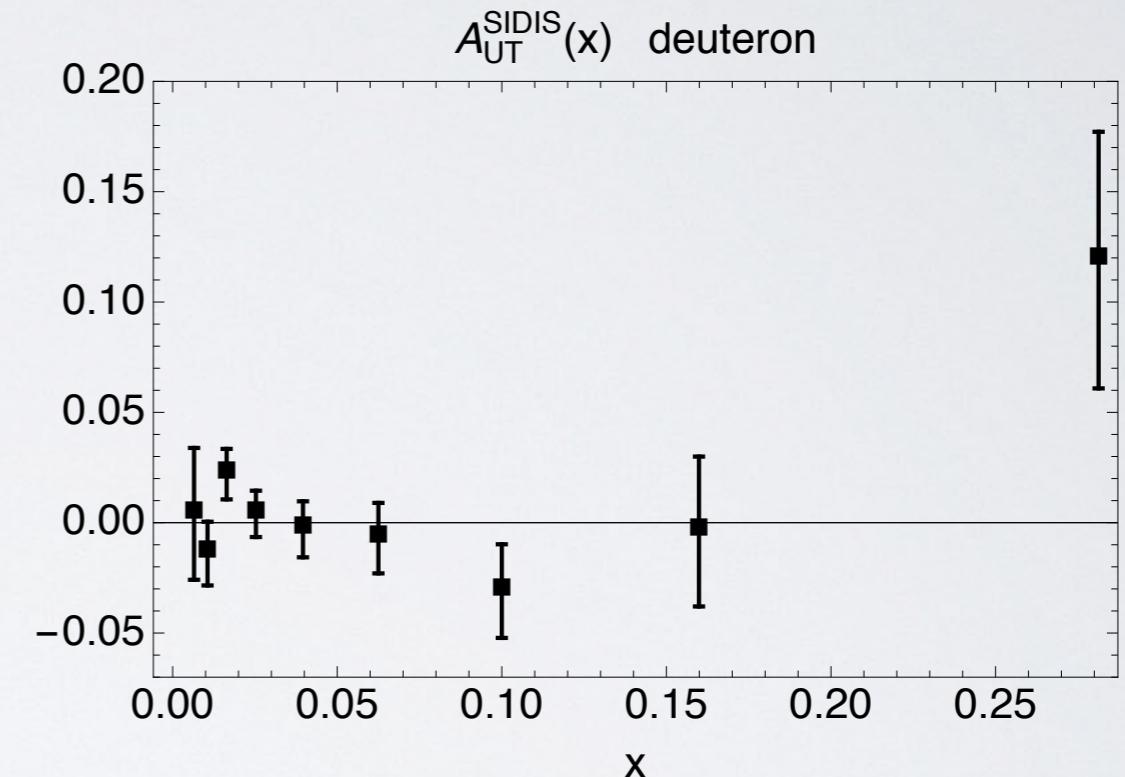
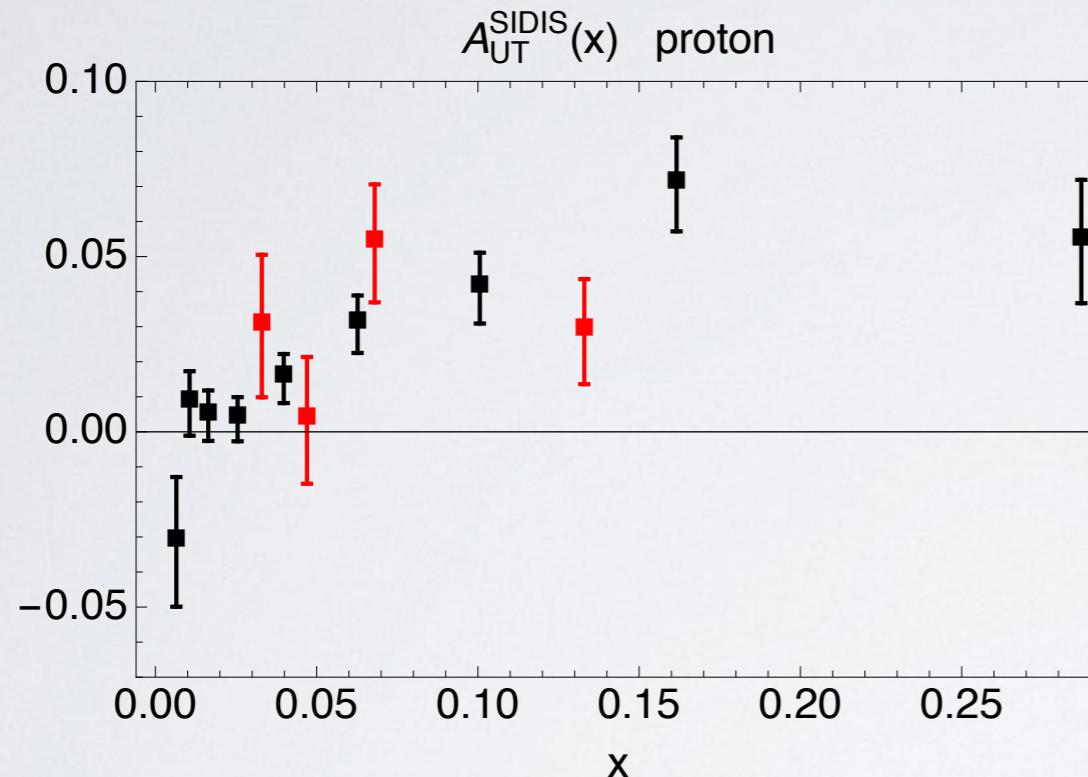
important !

statistical uncertainty: the bootstrap method

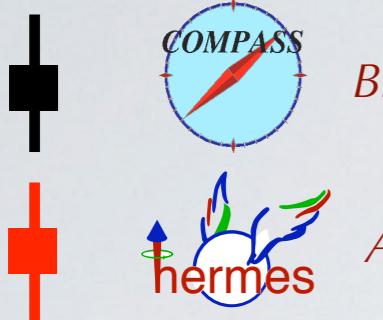


Braun et al., E.P.J. Web Conf. **85** (15) 02018

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

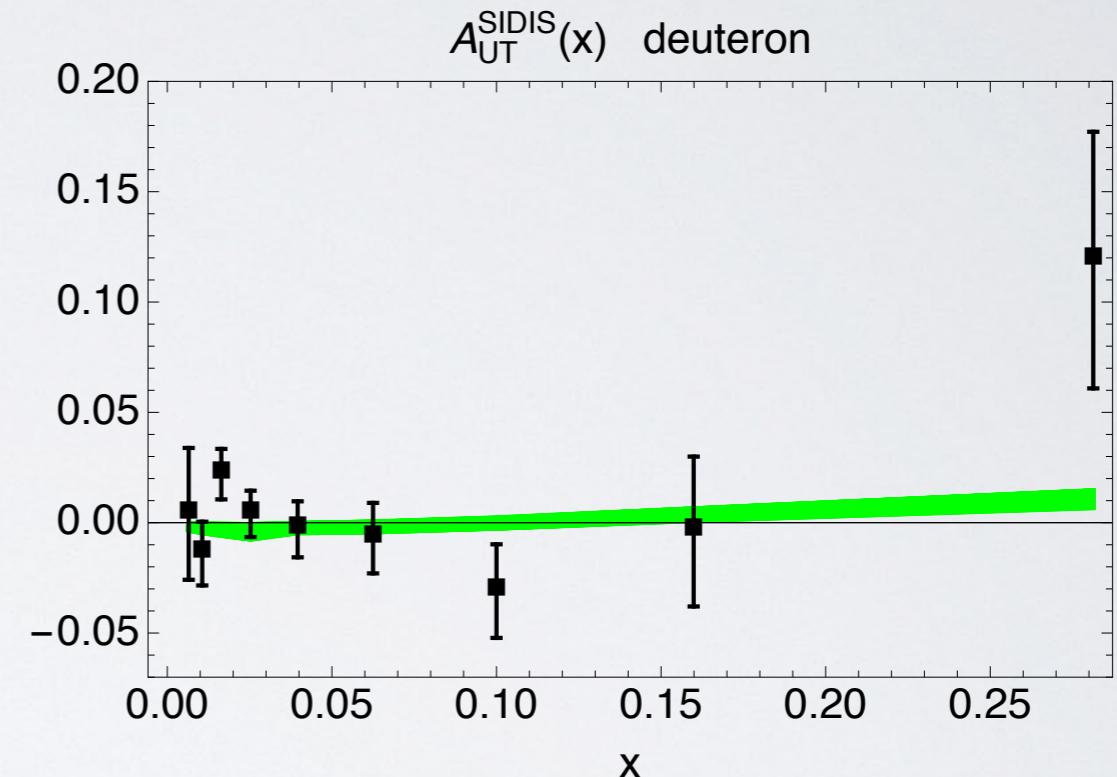
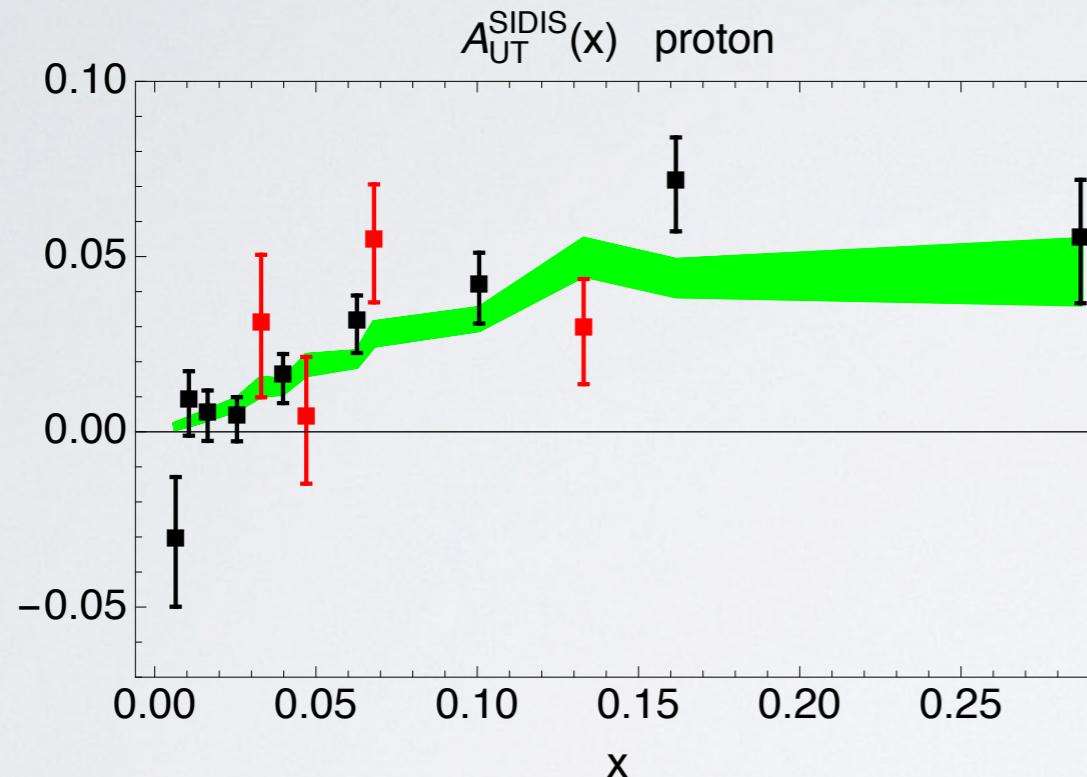


statistical uncertainty: the bootstrap method



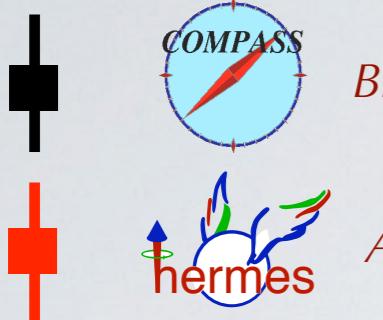
Braun et al., E.P.J. Web Conf. **85** (15) 02018

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



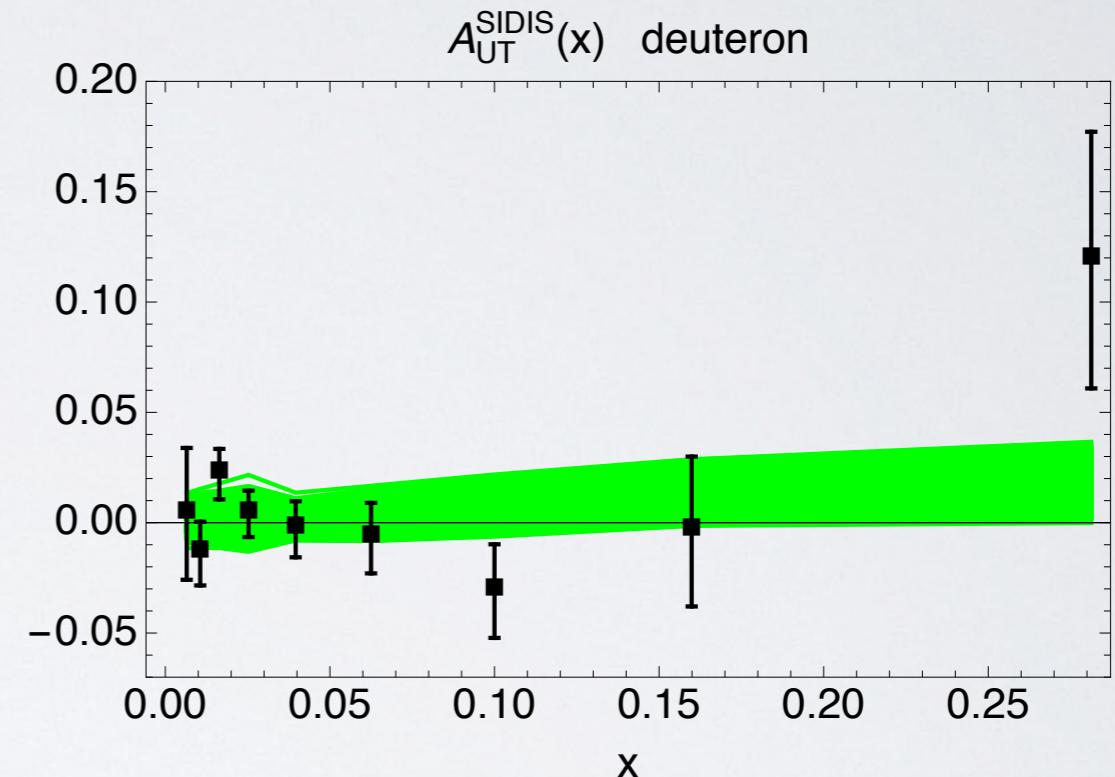
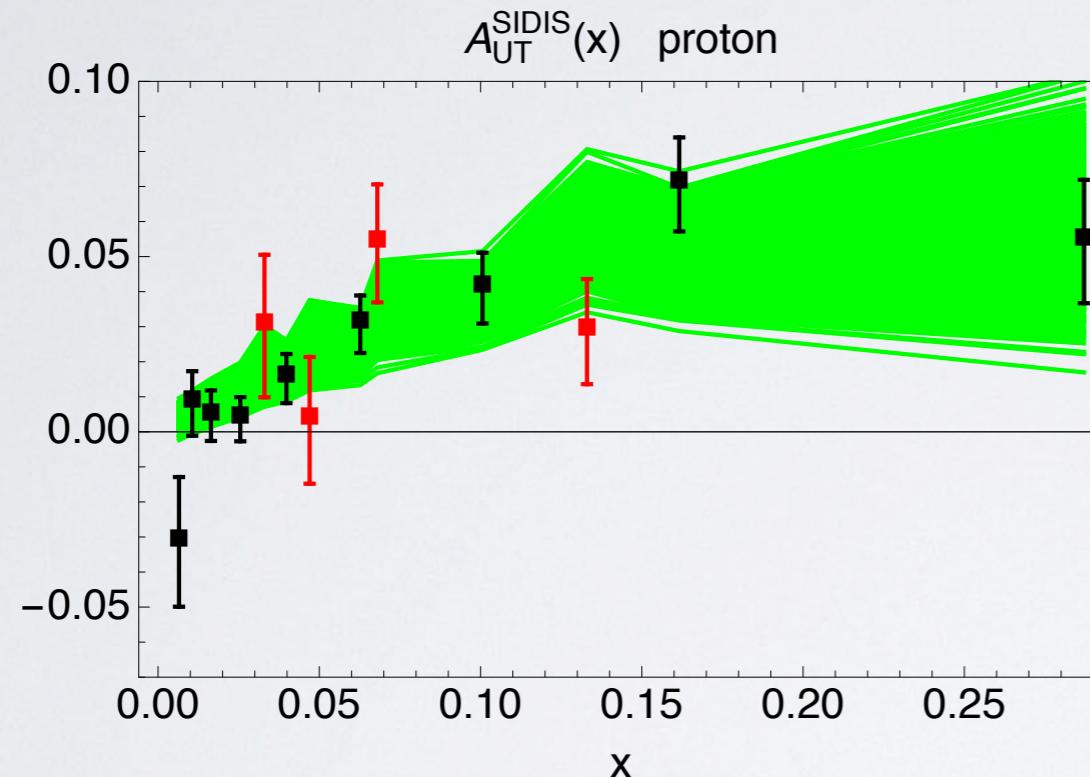
200 replicas

statistical uncertainty: the bootstrap method



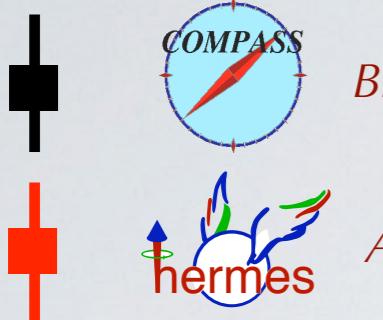
Braun et al., E.P.J. Web Conf. **85** (15) 02018

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



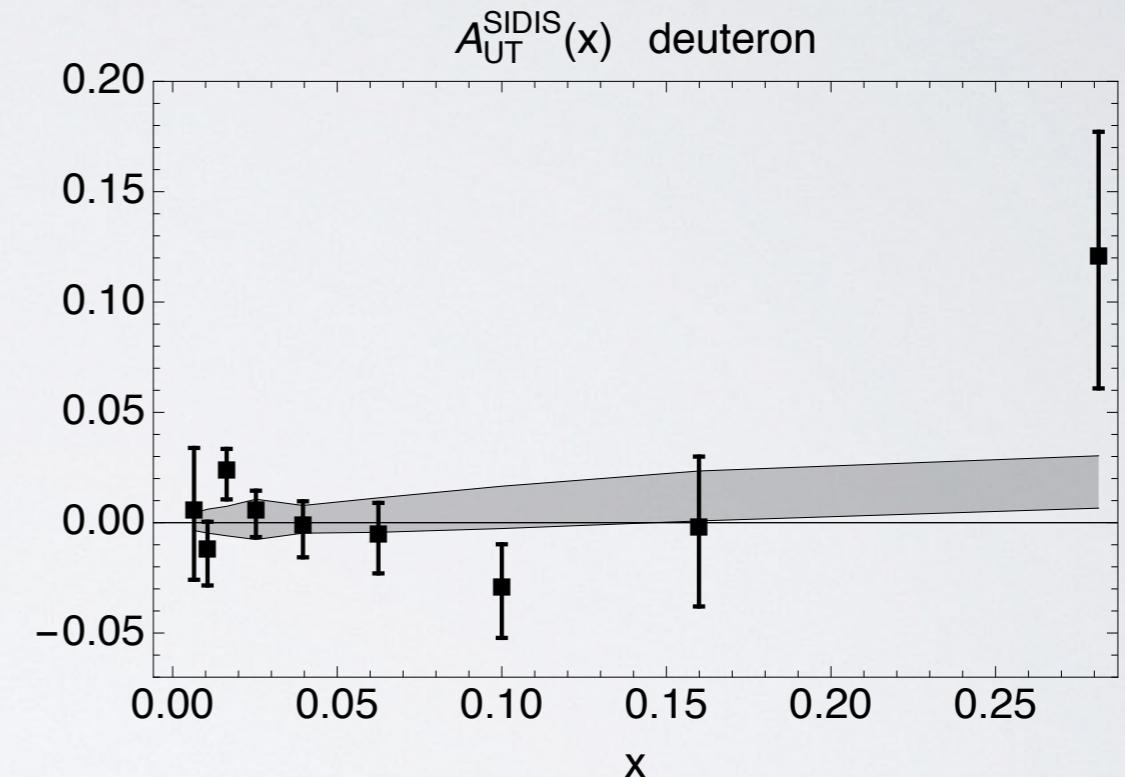
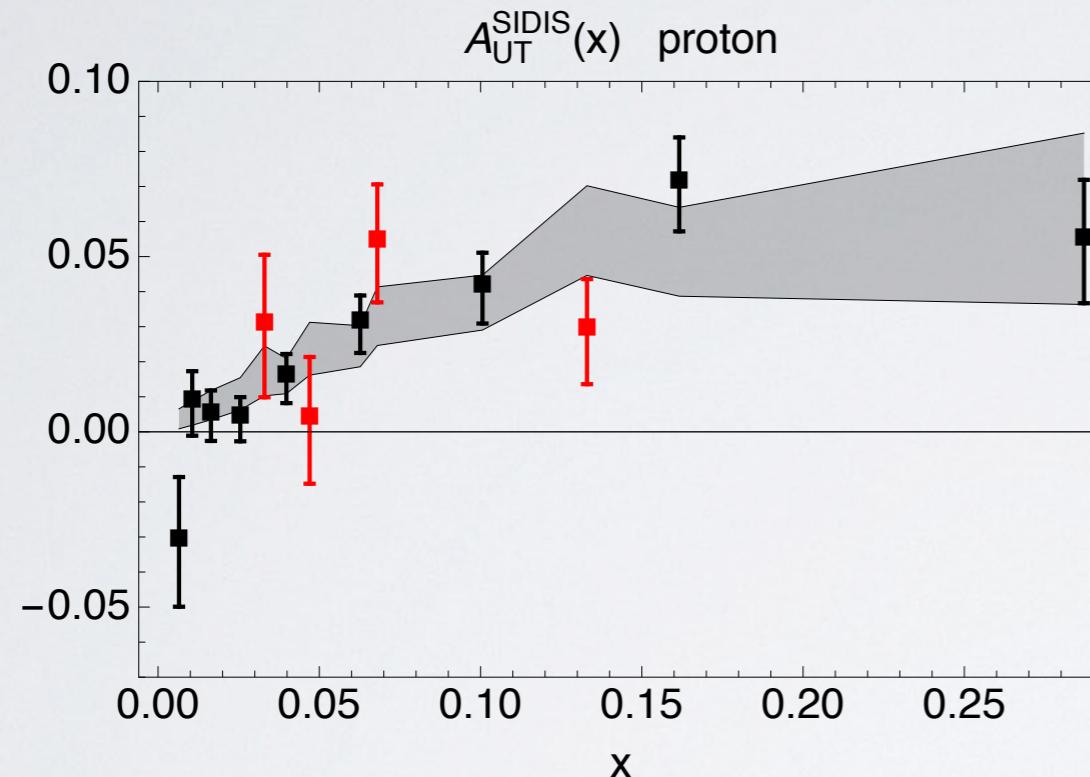
all 600 replicas

statistical uncertainty: the bootstrap method



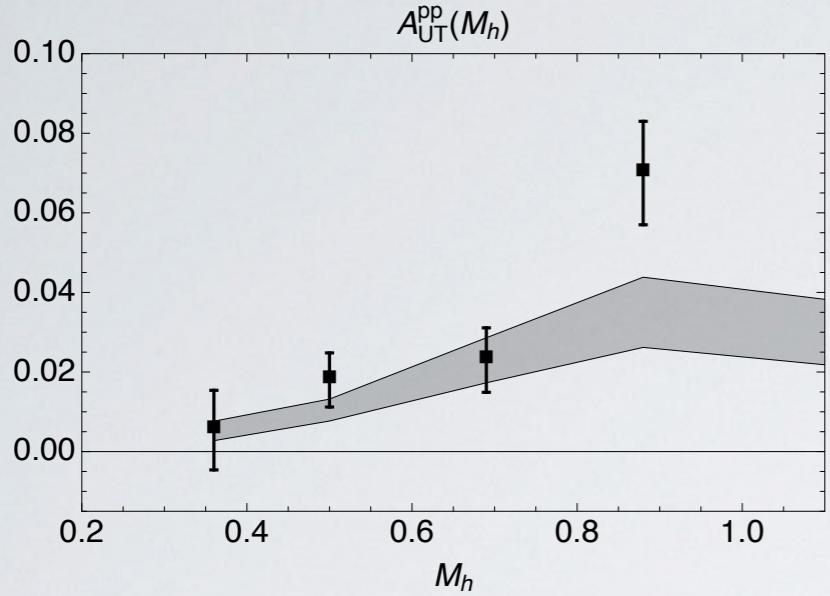
Braun et al., E.P.J. Web Conf. **85** (15) 02018

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



90% replicas

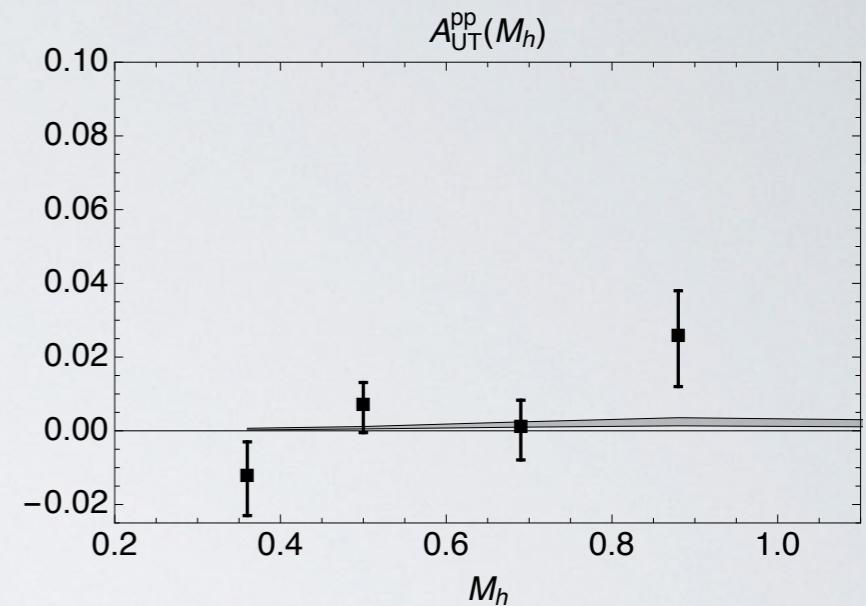
fit STAR asymmetry



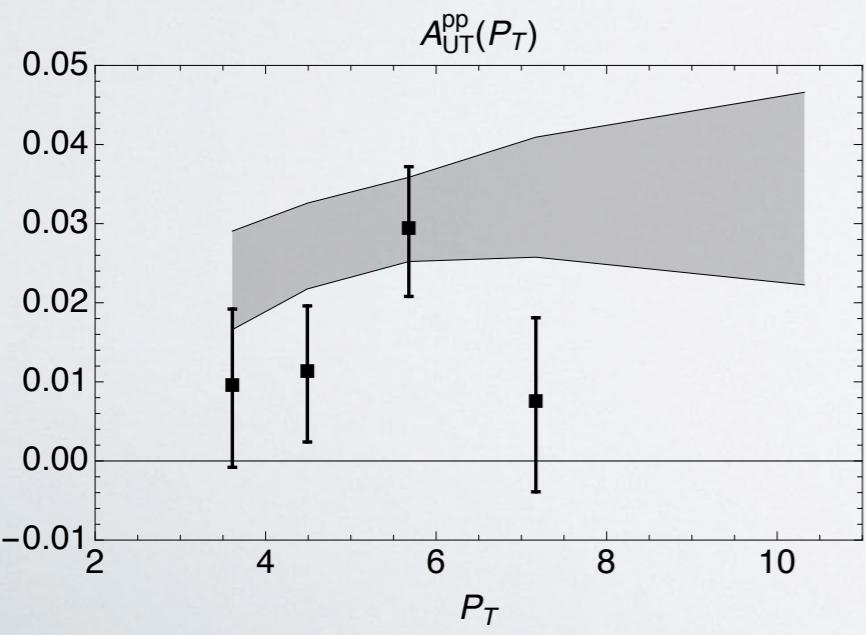
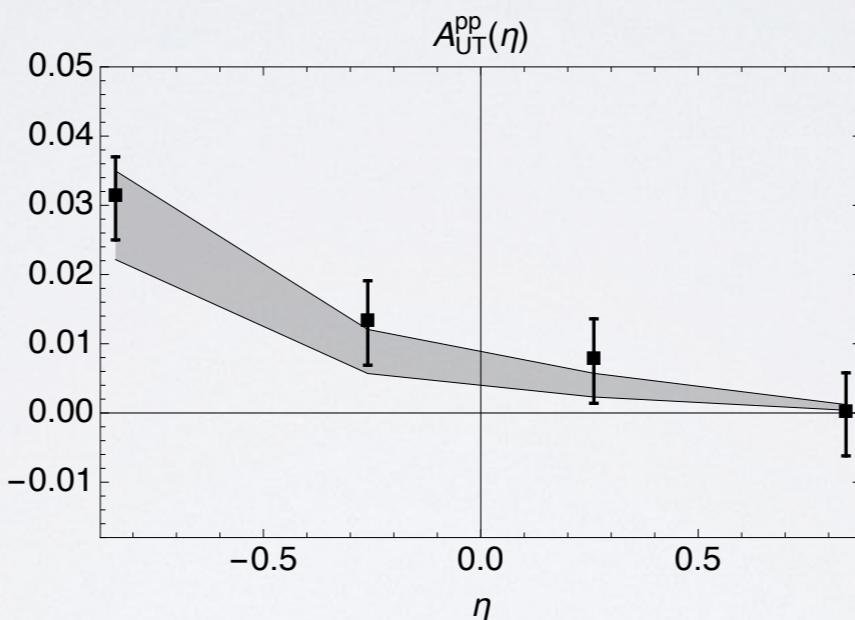
$\eta < 0$



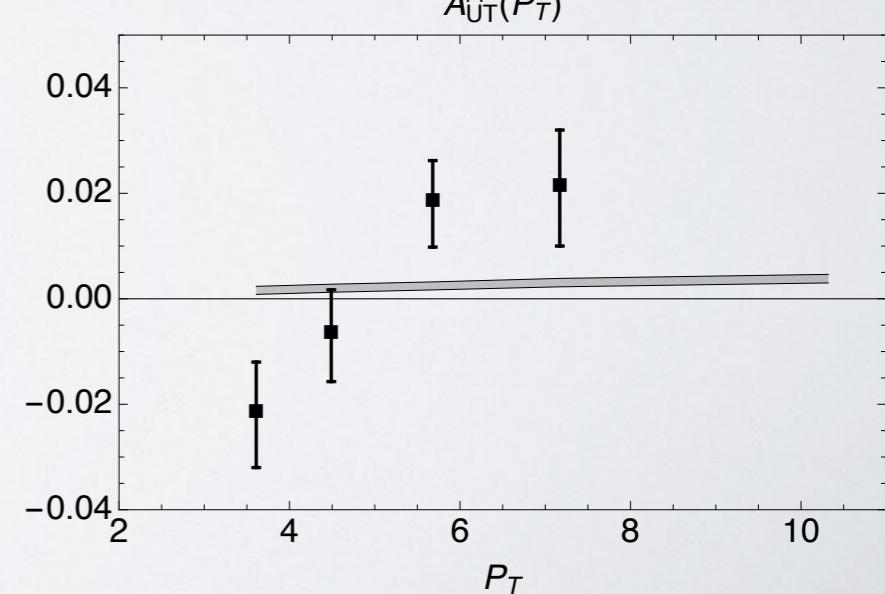
Adamczyk et al. (STAR),
P.R.L. 115 (2015) 242501



$\eta > 0$



90% uncertainty band



χ^2 of the fit

46 data points, **10** parameters
global $\chi^2/\text{dof} = 2.08 \pm 0.09$

$\approx 38\%$

$\approx 62\%$

SIDIS

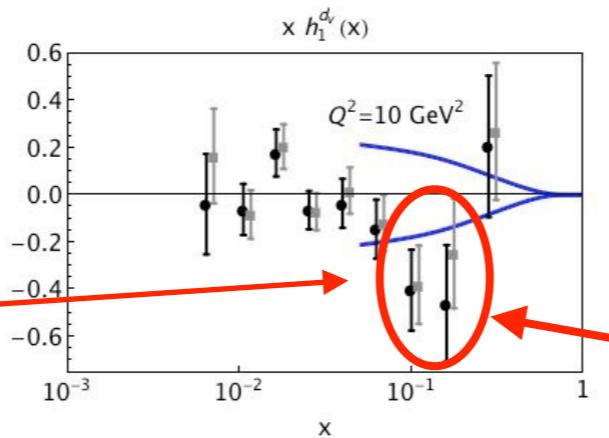
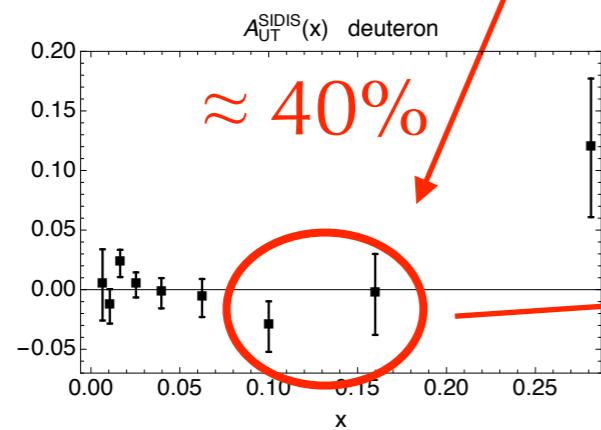


$\approx 24\%$



$\approx 76\%$

$\approx 60\%$
rest



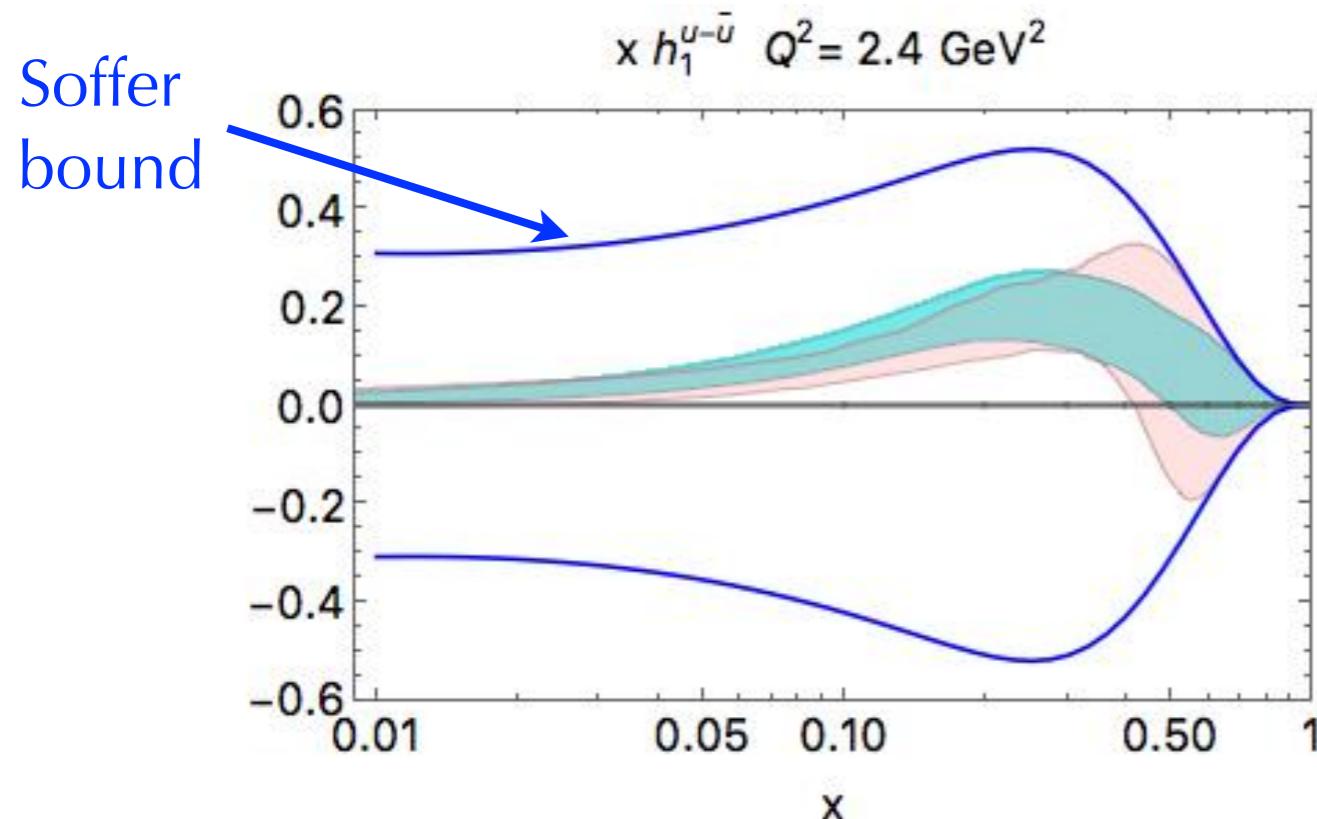
STAR

$\rightarrow P_T$ bins $\approx 70\%$

$\rightarrow M_h$ bins $\approx 28\%$

$\rightarrow \eta$ bins $\approx 2\%$

comparison with previous fit



*Radici et al.,
arXiv:1802.05212*

global fit

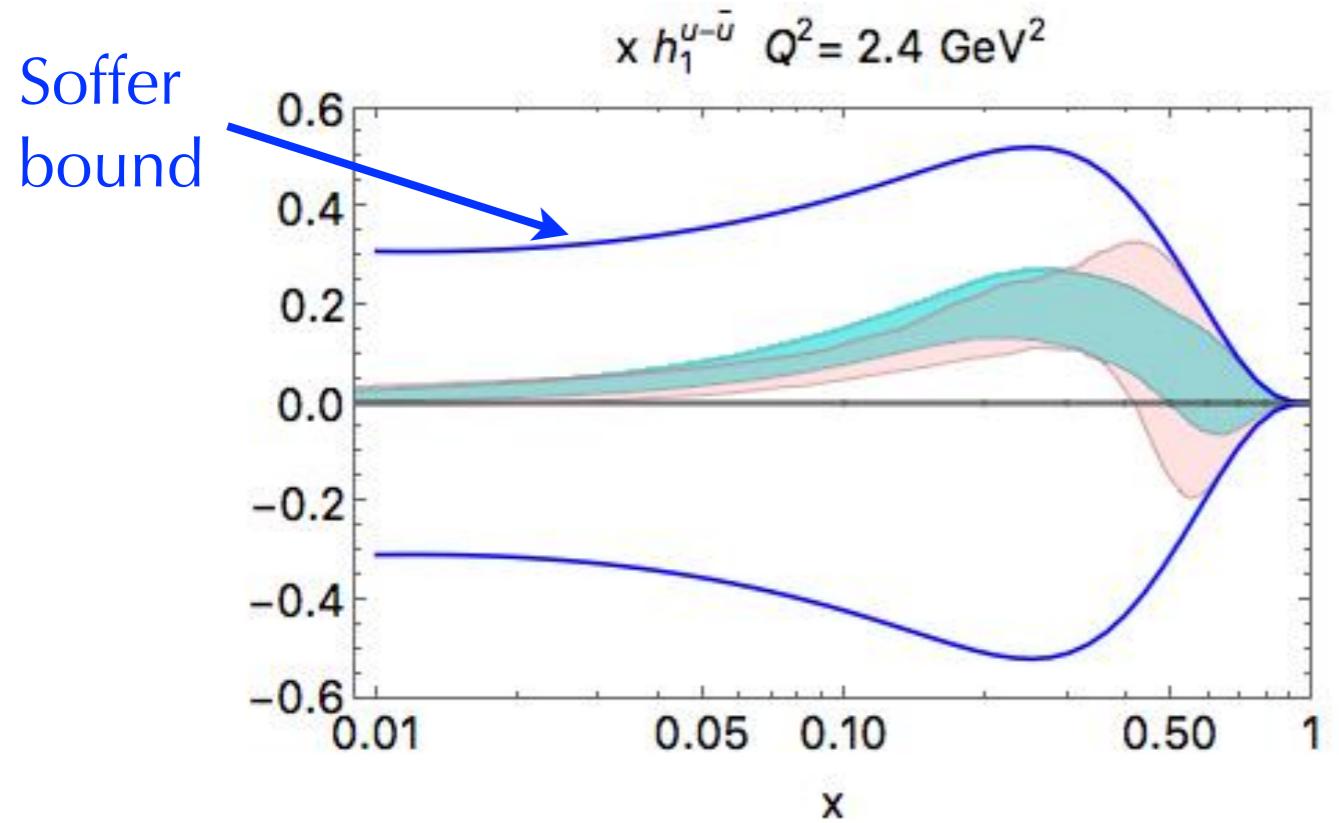
up

higher
precision

old fit (only SIDIS data)

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

comparison with previous fit



*Radici et al.,
arXiv:1802.05212*

global fit

up

higher
precision

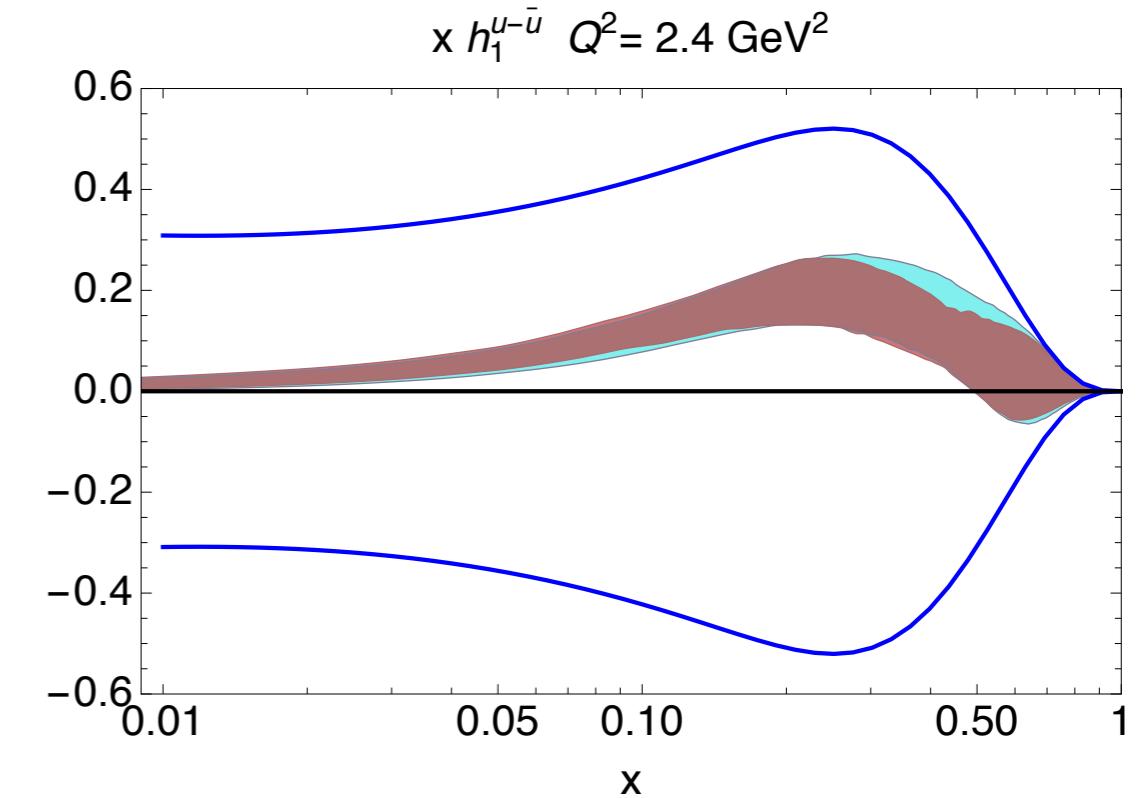
old fit (only SIDIS data)

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

up

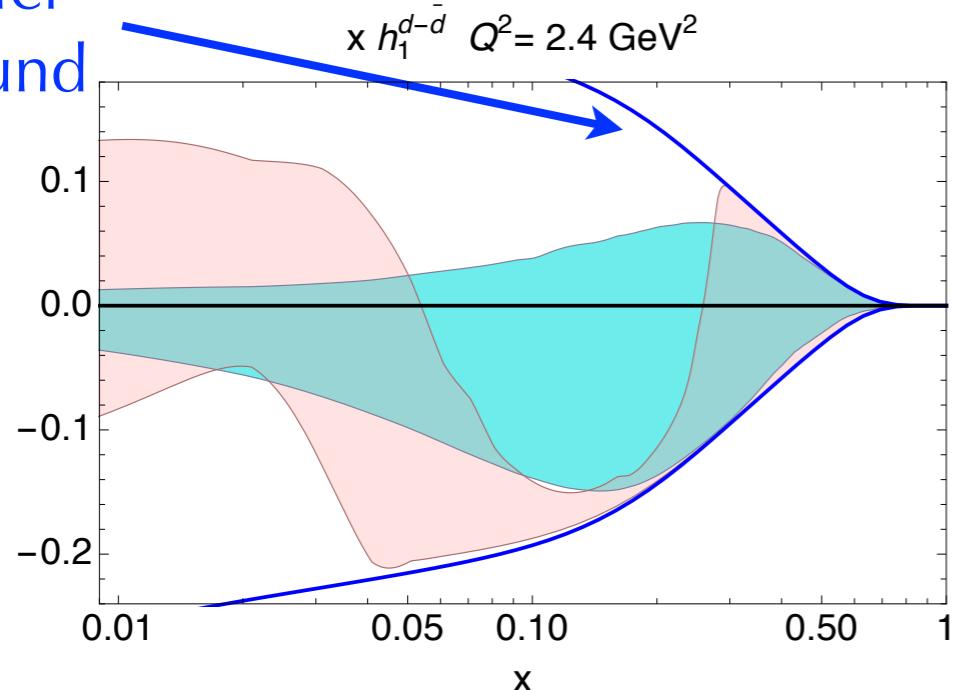
insensitive to
uncertainty on
gluon D_1

$$D_{1g}(Q_0) = \begin{cases} 0 \\ D_{1u}/4 \\ D_{1u} \end{cases}$$



comparison with previous fit

Soffer
bound



down

sensitive to
uncertainty on
gluon D_1

*Radici et al.,
arXiv:1802.05212*

global fit

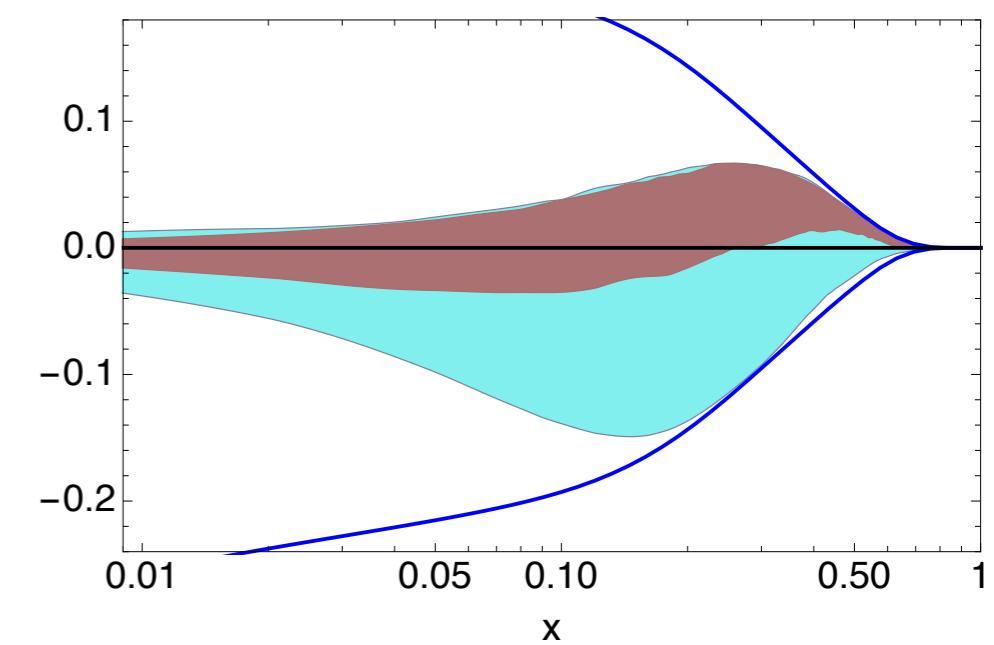
old fit

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

down

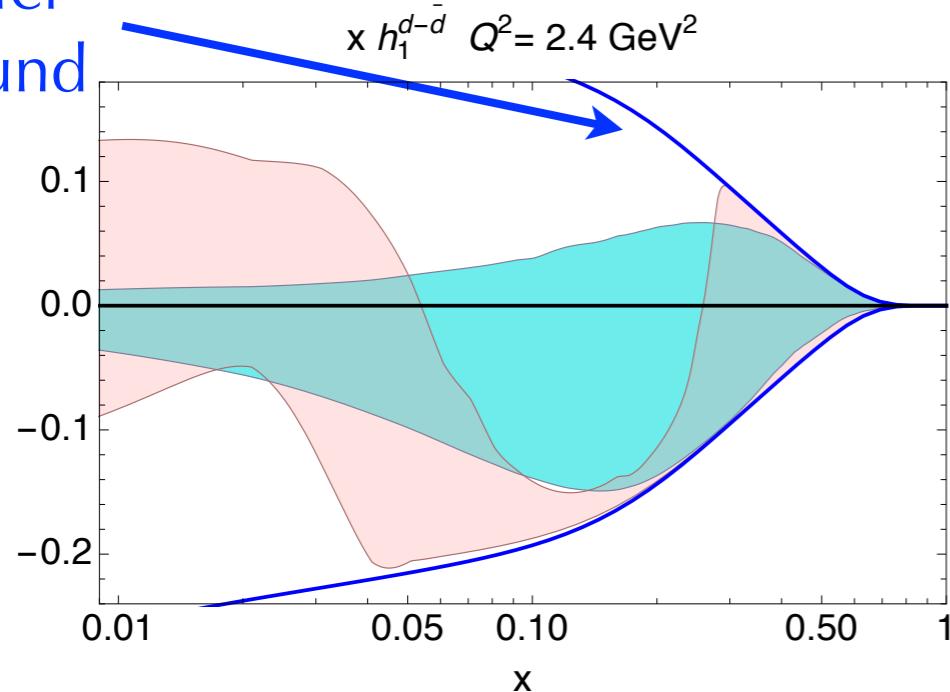
$$D_1g(Q_0) = \begin{cases} 0 \\ D_1^u / 4 \\ D_1^u \end{cases}$$

$x h_1^{d-\bar{d}} \quad Q^2 = 2.4 \text{ GeV}^2$



comparison with previous fit

Soffer
bound



*Radici et al.,
arXiv:1802.05212*

global fit

old fit

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

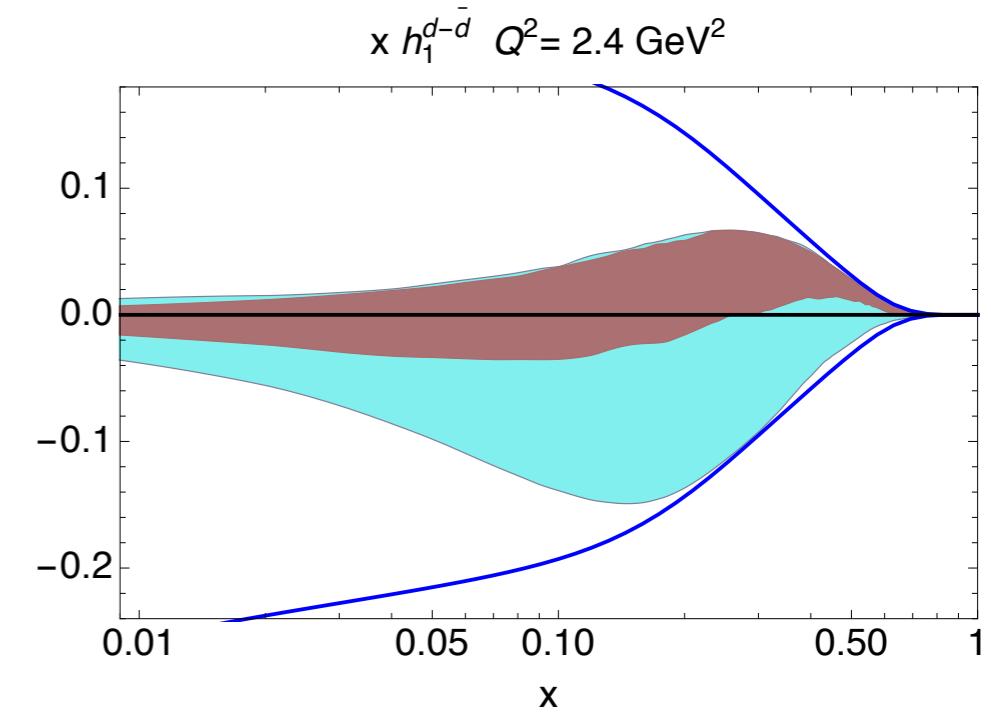
down

need dihadron multiplicities
from RHIC
and better deuteron data

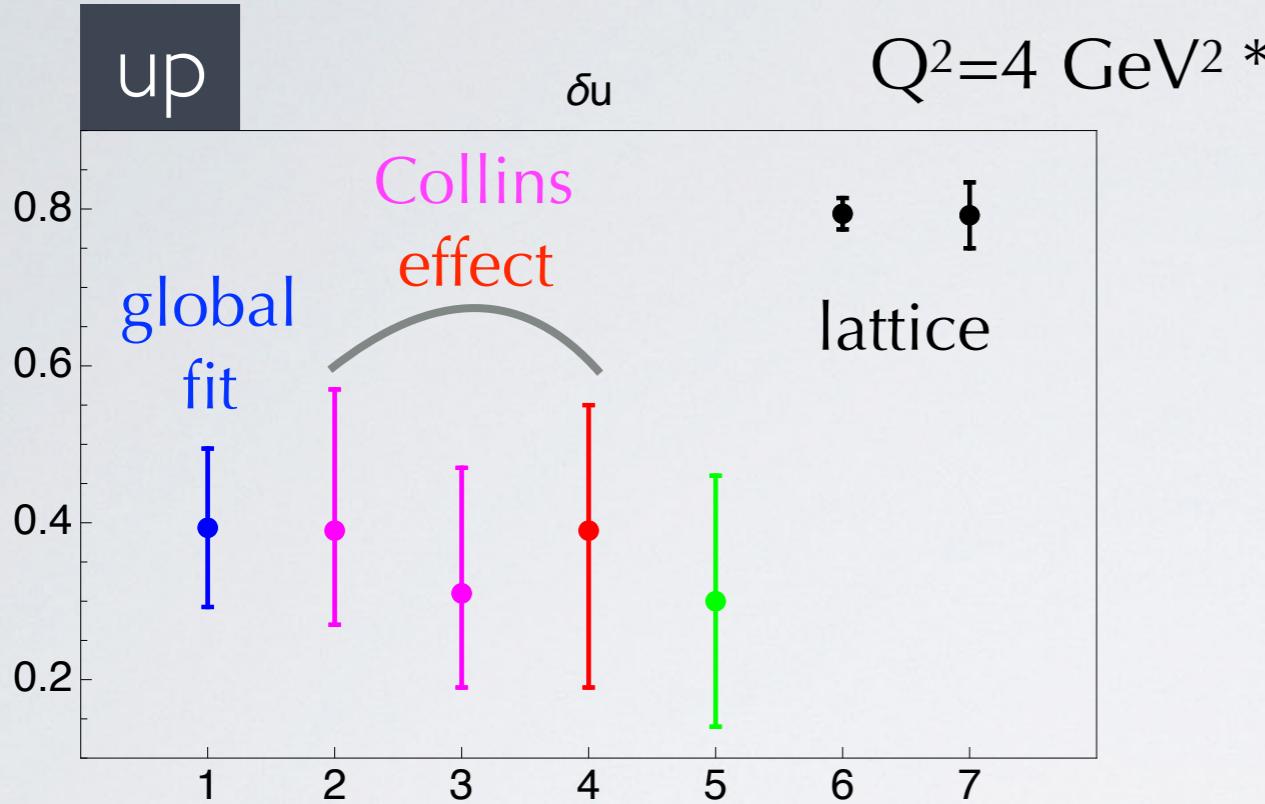
down

sensitive to
uncertainty on
gluon D_1

$$D_{1g}(Q_0) = 0$$
$$D_{1g}(Q_0) = \begin{cases} 0 \\ D_1^u / 4 \\ D_1^u \end{cases}$$



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



1- global fit

Radici et al., arXiv:1802.05212

2,3- Torino

Anselmino et al., P.R.D87(13)094019 * $Q^2=1$

4- TMD fit

Kang et al., P.R.D93(16)014009 * $Q^2=10$

5- JAM fit

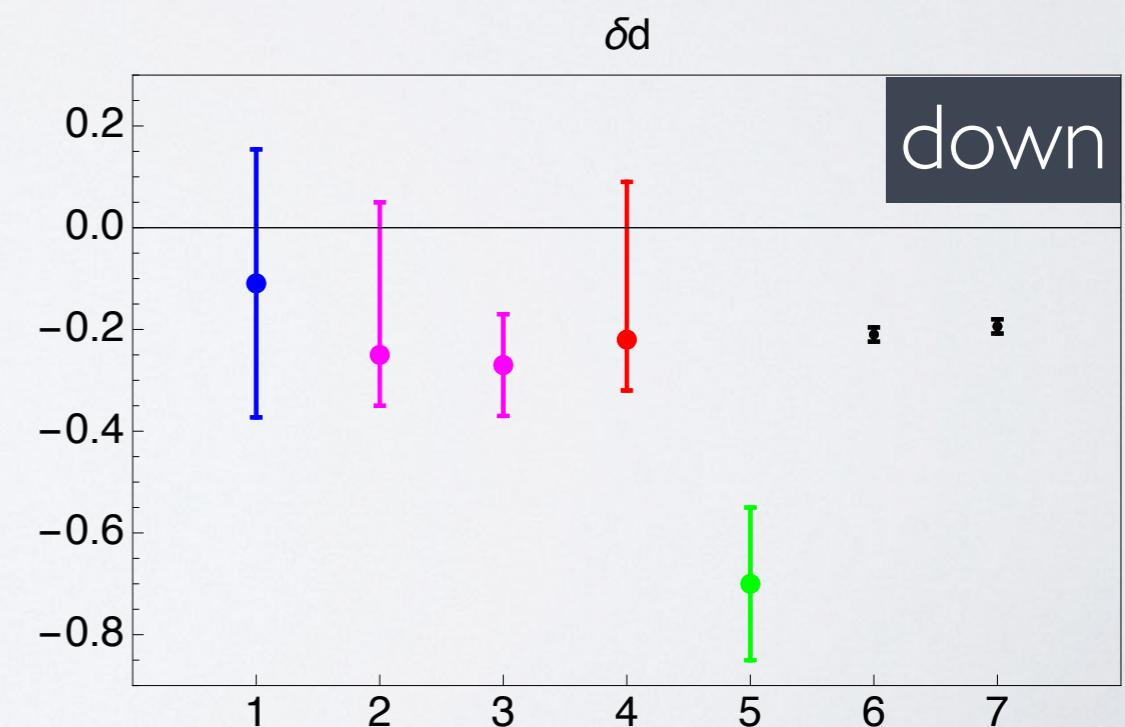
Lin et al., arXiv:1710.09858 {Collins effect + lattice $g_T = \delta u - \delta d$ * $Q_0^2=2$ }

6- ETMC17

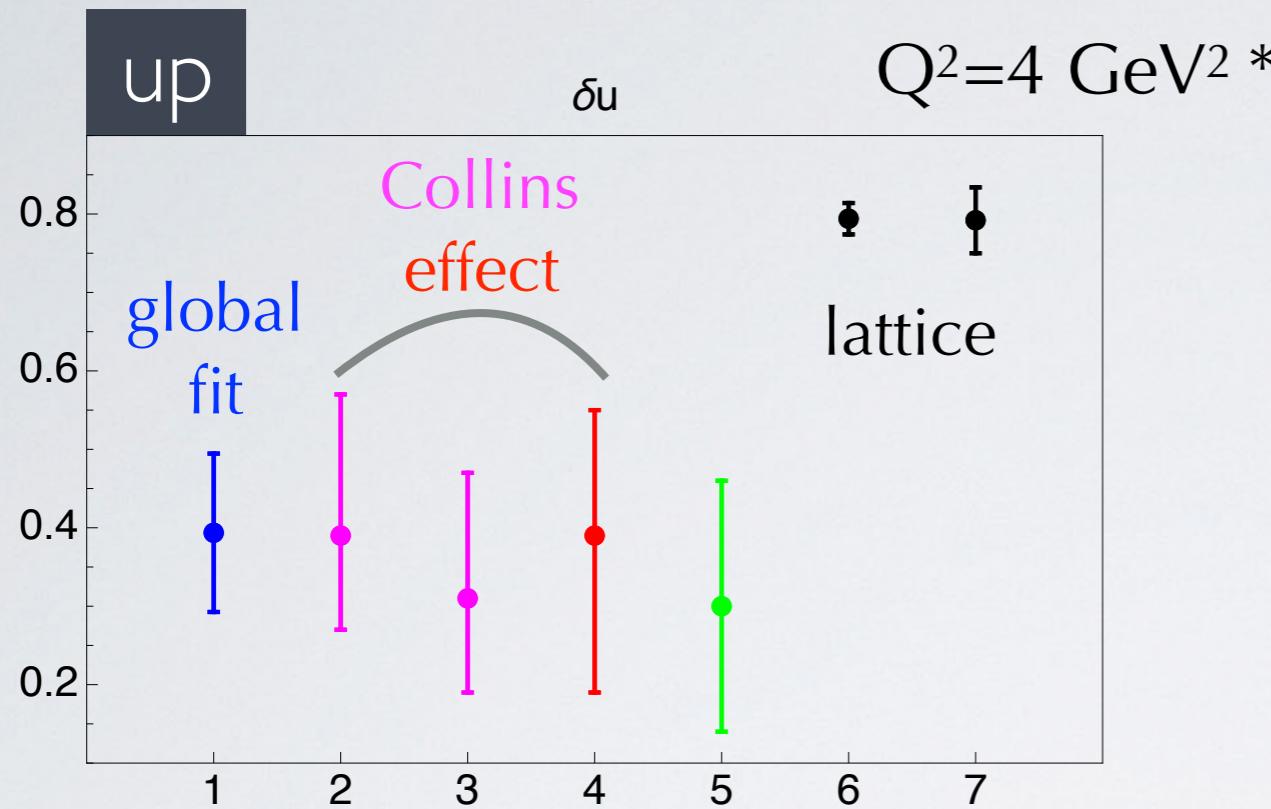
Alexandrou et al., P.R.D95(17)114514; E P.R.D96(17)099906

7- PNNDME16

Bhattacharya et al., P.R.D94(16)054508



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



incompatibility for up
compatible for down
but with large errors
(except JAM)

1- global fit

Radici et al., arXiv:1802.05212

2,3- Torino

Anselmino et al., P.R.D87(13)094019 * $Q^2=1$

4- TMD fit

Kang et al., P.R.D93(16)014009 * $Q^2=10$

5- JAM fit

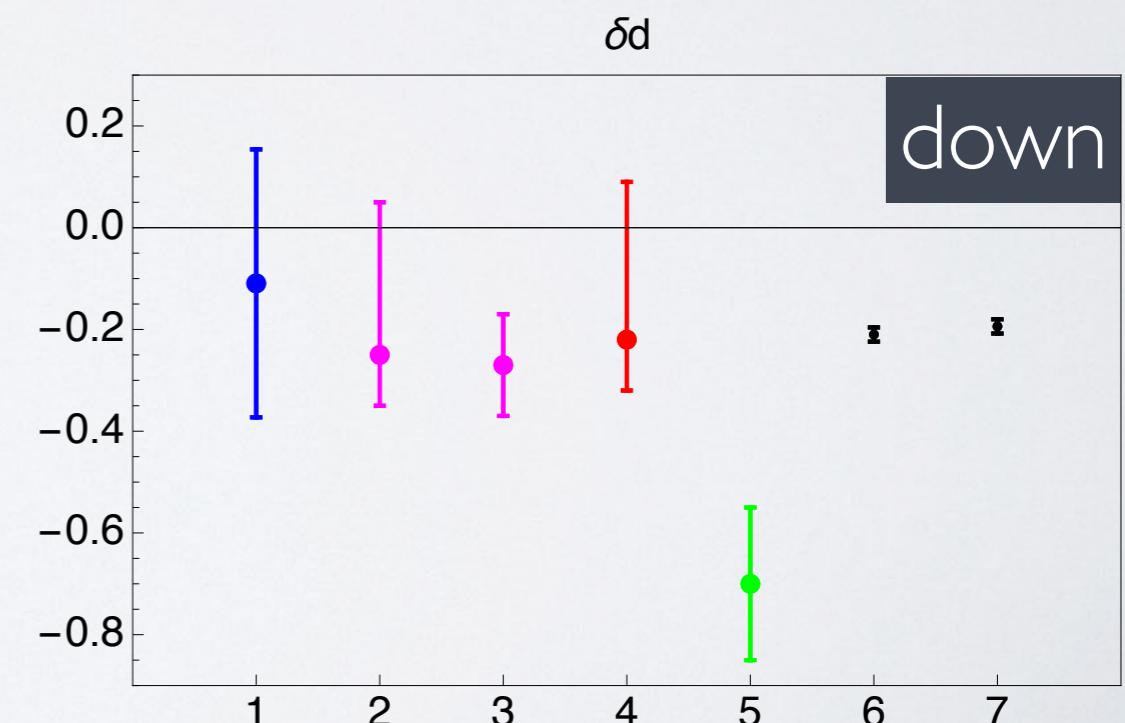
Lin et al., arXiv:1710.09858 $\left\{ \begin{array}{l} \text{Collins effect +} \\ \text{lattice } g_T = \delta u - \delta d \end{array} \right. * Q_0^2=2$

6- ETMC17

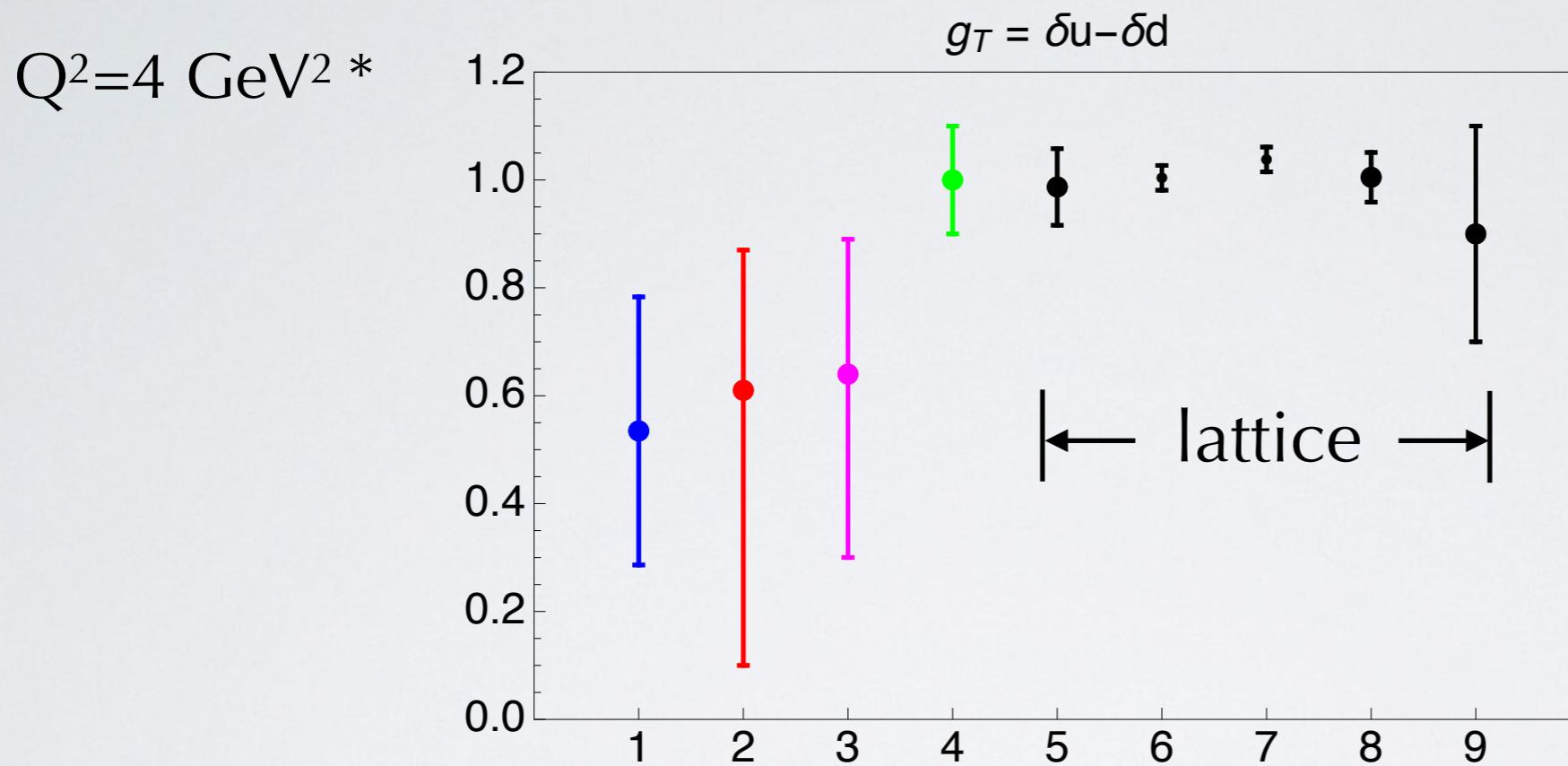
Alexandrou et al., P.R.D95(17)114514; E P.R.D96(17)099906

7- PNDME16

Bhattacharya et al., P.R.D94(16)054508



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



Radici et al., arXiv:1802.05212

1) global fit '17

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

2) "TMD fit" * $Q^2=10$

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

3) Torino fit * $Q^2=1$

Lin et al., arXiv:1710.09858

4) JAM fit '17 * $Q_0^2=2$

5) PNDME '16

Bhattacharya et al., P.R. D94 (16) 054508

6) ETMC '17

Alexandrou et al., P.R. D95 (17) 114514;
E P.R. D96 (17) 099906

7) LHPC '12

Green et al., P.R. D86 (12)

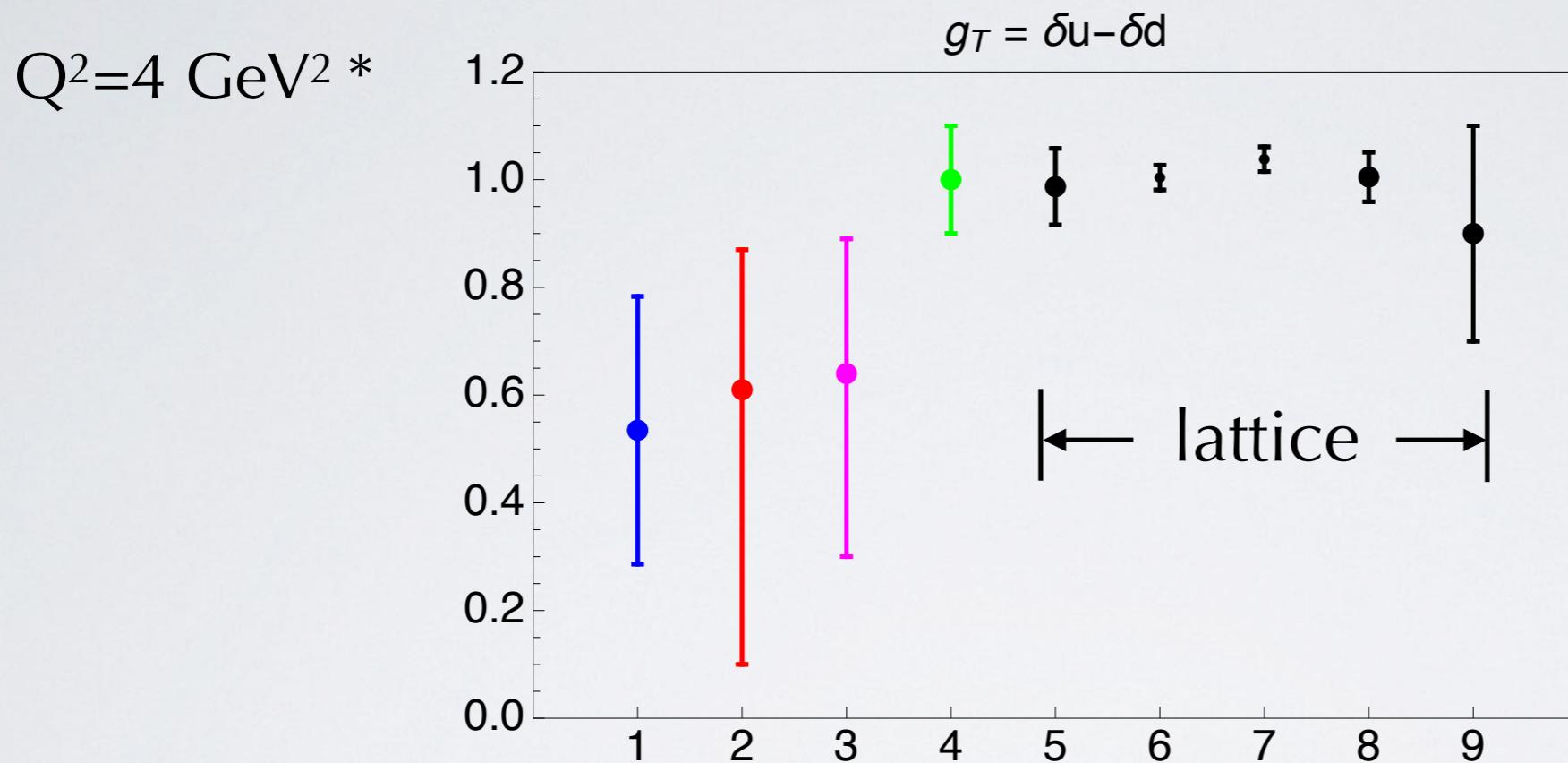
8) RQCD '14

Bali et al., P.R. D91 (15)

9) RBC-UKQCD

Aoki et al., P.R. D82 (10)

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



Radici et al., arXiv:1802.05212

1) **global fit '17**

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

2) **"TMD fit" * $Q^2=10$**

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

3) **Torino fit * $Q^2=1$**

Lin et al., arXiv:1710.09858

4) **JAM fit '17 * $Q_0^2=2$**

5) PNDME '16

6) ETMC '17

7) LHPC '12

8) RQCD '14

9) RBC-UKQCD

Bhattacharya et al., P.R. D94 (16) 054508

Alexandrou et al., P.R. D95 (17) 114514;

E P.R. D96 (17) 099906

Green et al., P.R. D86 (12)

Bali et al., P.R. D91 (15)

Aoki et al., P.R. D82 (10)

“transverse-spin puzzle” ?

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

potential for BSM searches

$$P^{[\mu} S^{\nu]} \delta q(Q^2) = P^{[\mu} S^{\nu]} \int_0^1 dx \ [h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)] \\ = \langle P, S | \bar{q} \sigma^{\mu\nu} q | P, S \rangle$$

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

talk H. Gao

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

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

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

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*

\mathcal{L}_{BSM} new couplings: ϵ_S 1, ϵ_{PS} γ_5 , $\epsilon_T \sigma^{\mu\nu}$

$$\dots + \epsilon_T \bar{e} \sigma_{\mu\nu} \nu_e \quad \bar{q} \sigma^{\mu\nu} q \dots$$

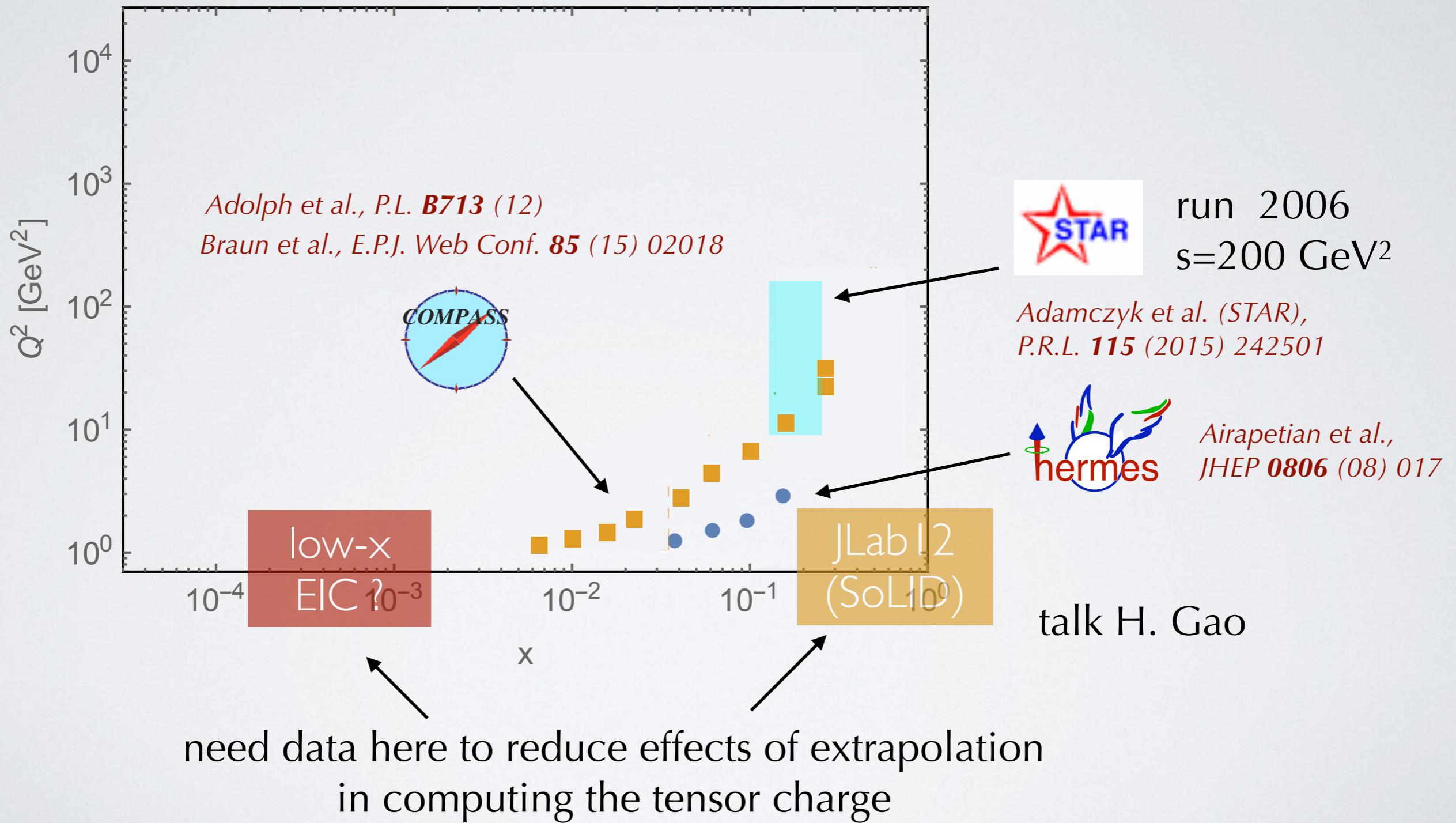
$\epsilon_T g_T$

$(\approx M_W^2 / M_{\text{BSM}}^2)$

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



the kinematics



Conclusions

- first global fit of di-hadron inclusive data leading to extraction of transversity as a PDF in collinear framework
- inclusion of STAR p-p[↑] data increases precision of up channel; large uncertainty on down due to unconstrained gluon unpolarized di-hadron fragmentation function
- no simultaneous compatibility with lattice for tensor charge of up, down, and isovector : “transverse spin puzzle”?
- tensor charge important for explorations of BSM new physics

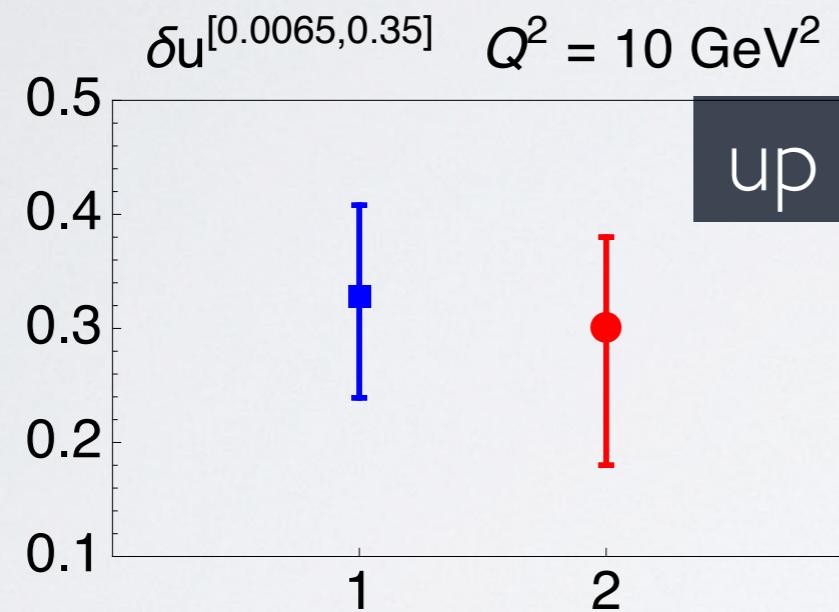
THANK YOU

Back-up

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

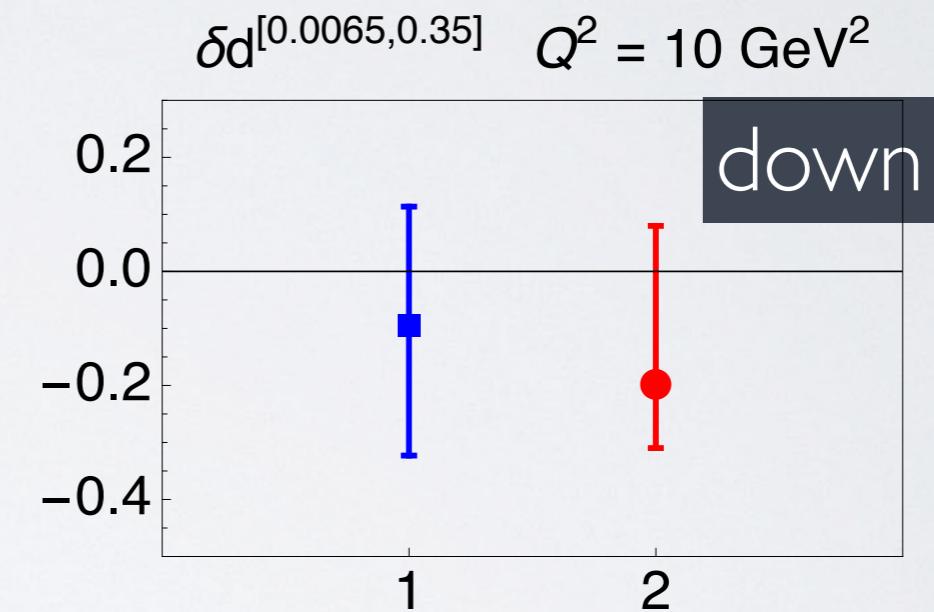
truncated

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



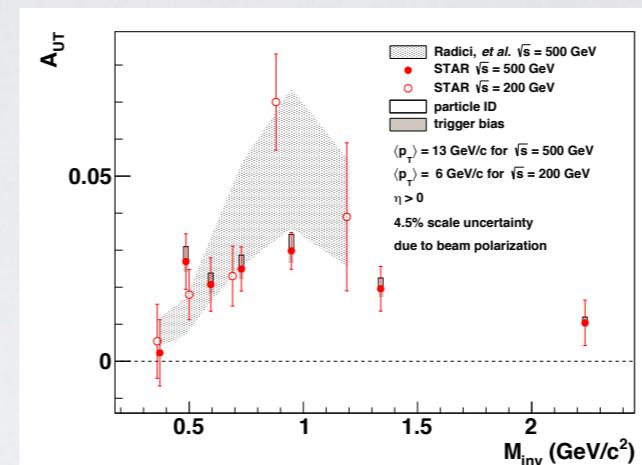
global fit
*Radici et al.,
arXiv:1802.05212*

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

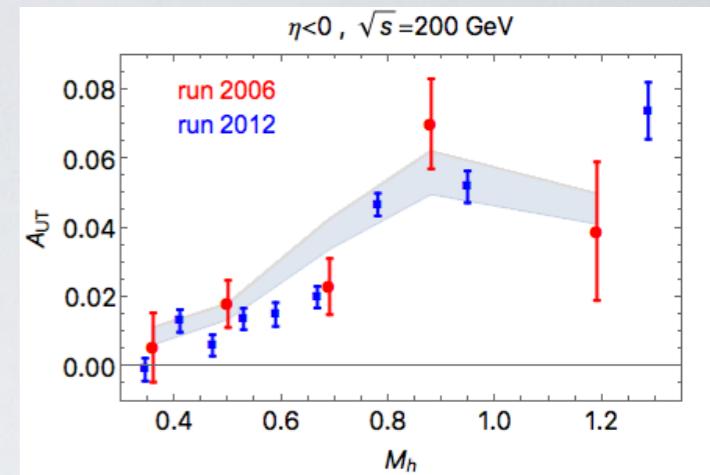


To do list

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



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



Radici et al., P.R. **D94** (16) 034012

- need data on $p+p \rightarrow (\pi\pi) X$ constrains gluon D_{1g}
- refit di-hadron fragmentation functions using new data:
 $e^+e^- \rightarrow (\pi\pi) X$ constrains D_{1q}
 (currently only by Montecarlo)
- use COMPASS data on πK and KK channels, and from Λ^\uparrow fragmentation:
 constrain strange contribution ?
- explore other channels, like inclusive DIS via Jet fragm. funct.'s



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