PacificSpin2019

The 11th Circum-Pan-Pacific Symposium on High Energy Spin Physics

August 27 - 30, 2019 Miyazaki, Japan

Topics

- Spin Structure of the Proton and Neutron
- Polarized Deep Inelastic Scattering, p-p Collision, Drell-Yan Process
- Generalized Parton Distributions
- Transverse Momentum Dependent Parton Distributions
- Perturbative QCD, Lattice QCD

https://sites.google.com/quark.kj.yamagata-u.ac.jp/pacspin2019

Contact: pacificspin2019@nucl.phys.titech.ac.jp

Deadline for early registration and Deadline for abstract submission for contributed talks: June 27, 2019

Latest results in the extraction of the Sivers and Transversity distributions

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INFN - Pavia

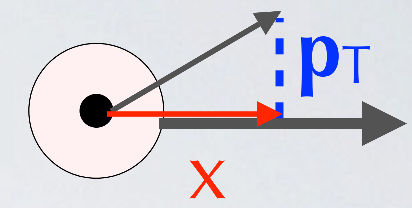
INFN Istituto Nazionale di Fisica Nucleare

In collaboration with
A. Bacchetta (Univ. Pavia)
F. Delcarro (JLab)

erc European Research Council
3DSPIN MAPPING THE PROTON IN 3D
HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

the Sivers function

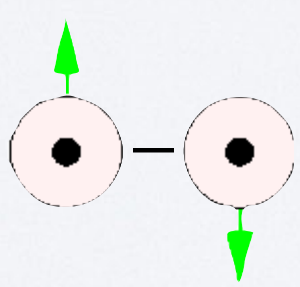
TMDs @twist=2



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 $h_{1T}^\perp$

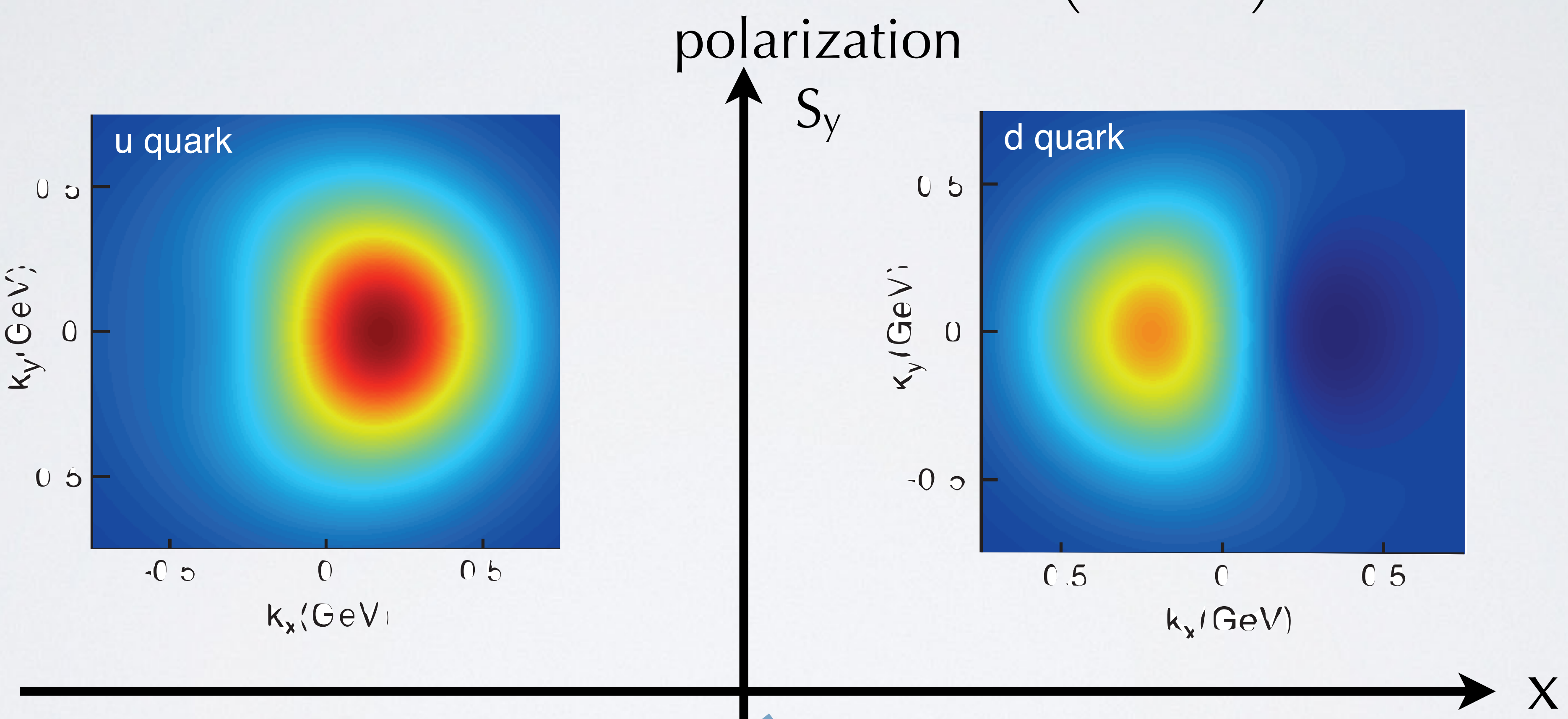


the Sivers function

distortion of quark distribution in polarized proton P↑
along direction $\perp$ polarization ("spin-orbit")

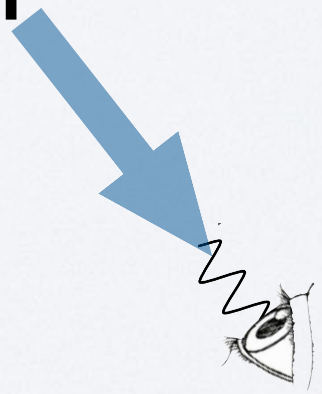
$$f_{q/p^\uparrow}(x, \boldsymbol{k}_T) = f_1^q(x, \boldsymbol{k}_T) - f_{1T}^{\perp q}(x, \boldsymbol{k}_T)\, \boldsymbol{S} \cdot \left(\frac{\hat{\boldsymbol{P}}}{M} \times \boldsymbol{k}_T \right)$$

*Sivers, P.R. D**41** (90) 83*



$$f_{1T}^{\perp u} < 0$$

$$f_{1T}^{\perp d} > 0$$



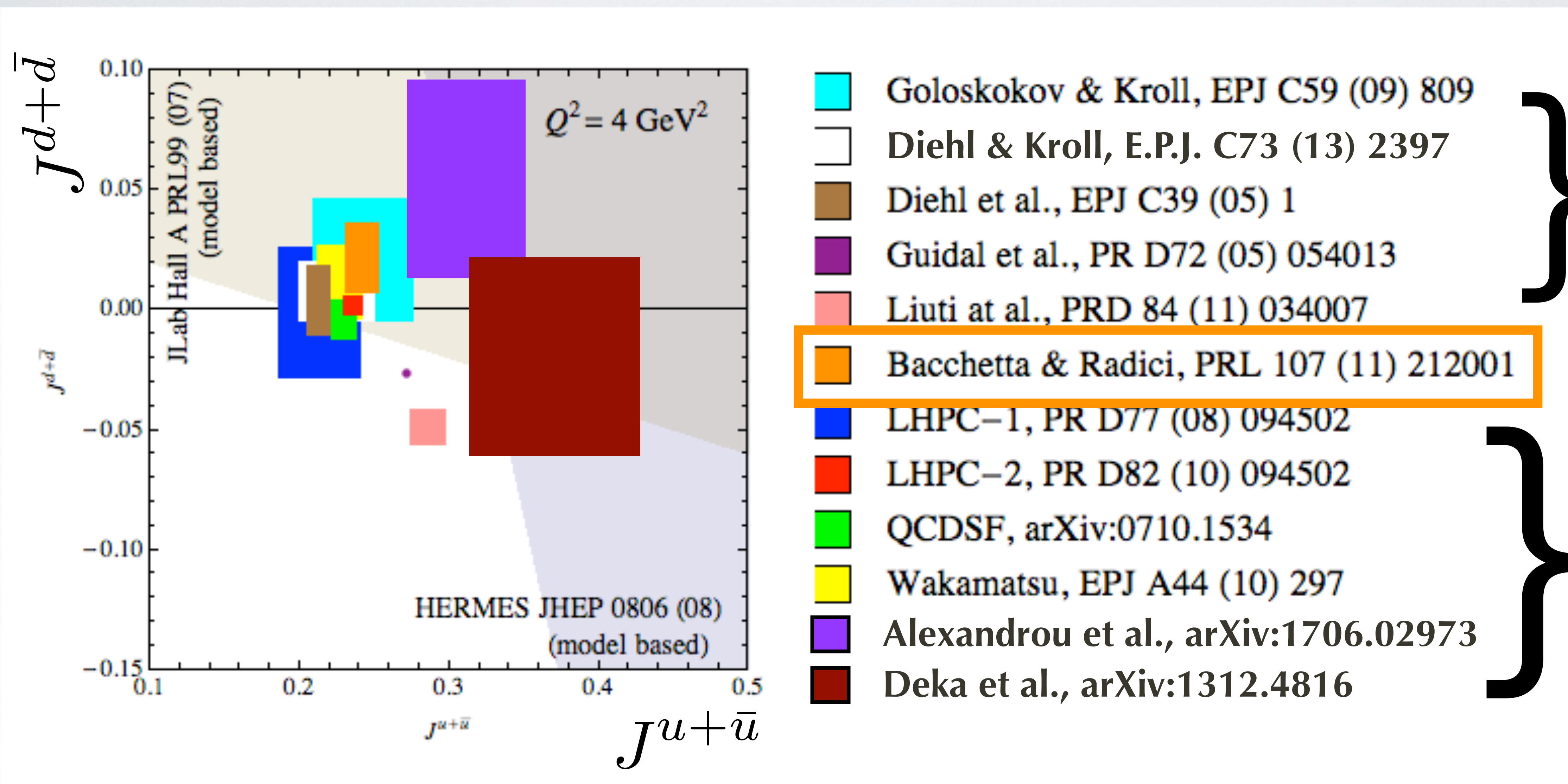
deformation along x
depends on flavor

EIC White Paper
Boer et al., arXiv:1108.1713
Accardi et al., arXiv:1212.1701

Sivers function ↔ quark total J

Ji's sum rule $\quad J_z^q(Q^2) = \frac{1}{2}\int_0^1 dx\, x\,\left[H^q(x,0,0;Q^2) + E^q(x,0,0;Q^2)\right]$

model lensing funct. L(x) + fit $f_{1T^\perp}$ $\quad \int d\boldsymbol{k}_T\, f_{1T}^{\perp q}(x, \boldsymbol{k}_T; Q_L^2) = -L(x)\; E^q(x,0,0;Q_L^2)$

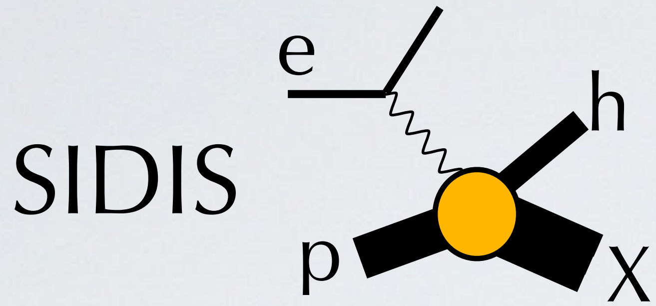


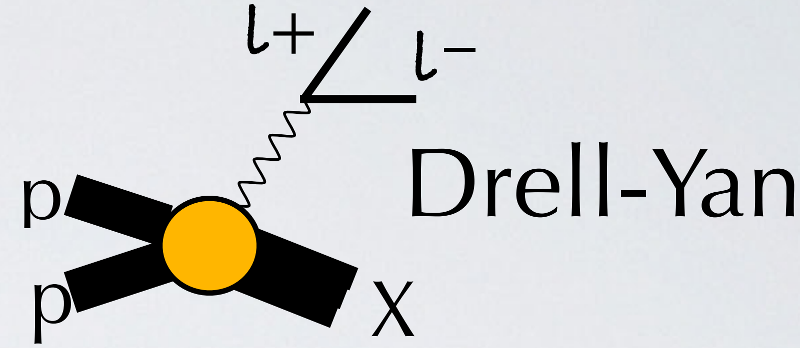
models of GPD

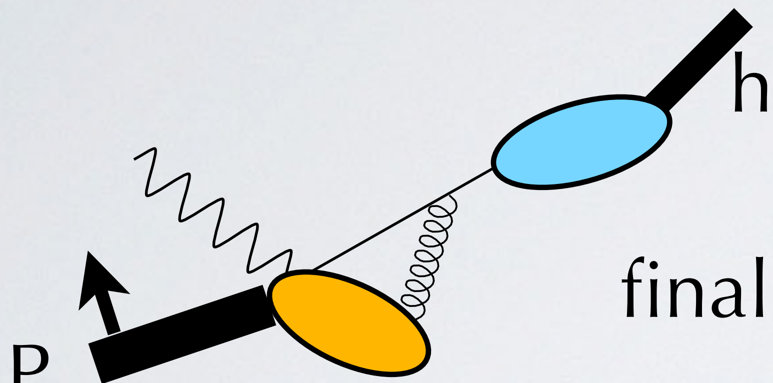
color lensing

lattice

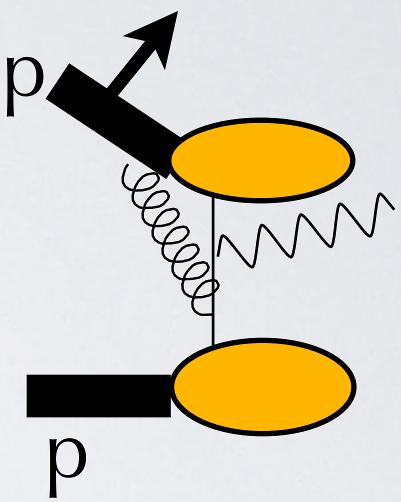
non-universality of Sivers function





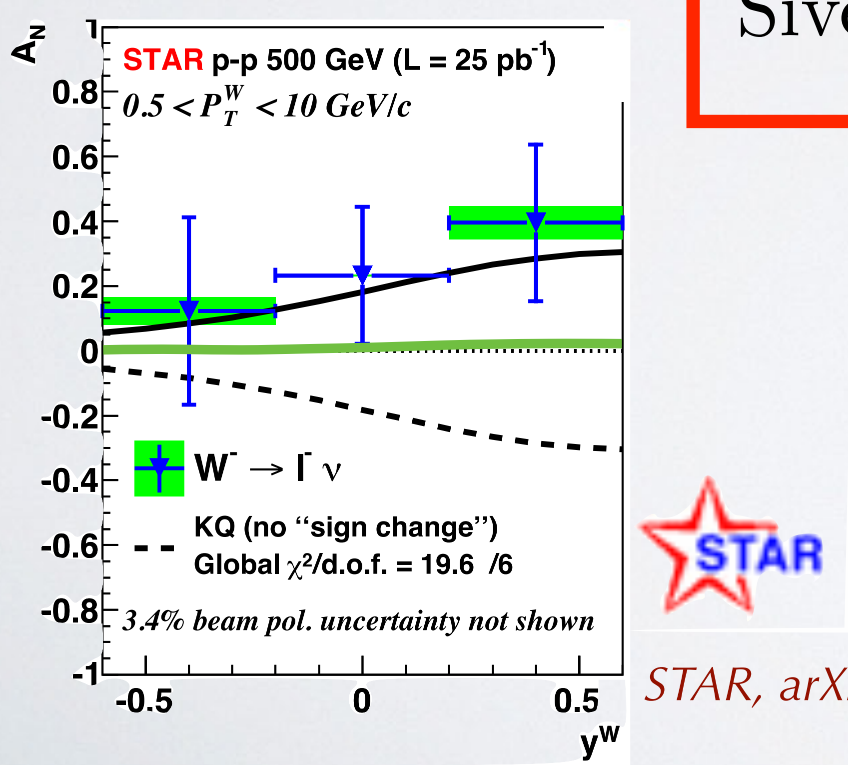


final-state color interactions initial-state



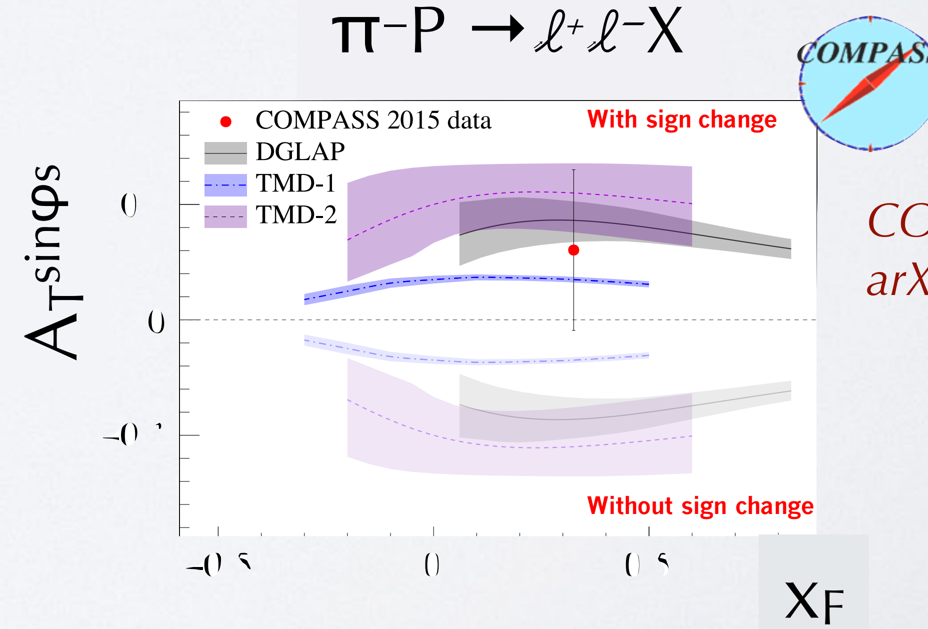
$$\boxed{\text{Sivers}\Big|_{\text{SIDIS}} = -\text{Sivers}\Big|_{\text{D-Y}}}$$

*Collins, P.L. **B536** (02)*



STAR, arXiv:1511.06003

$\pi^- P \rightarrow \ell^+ \ell^- X$

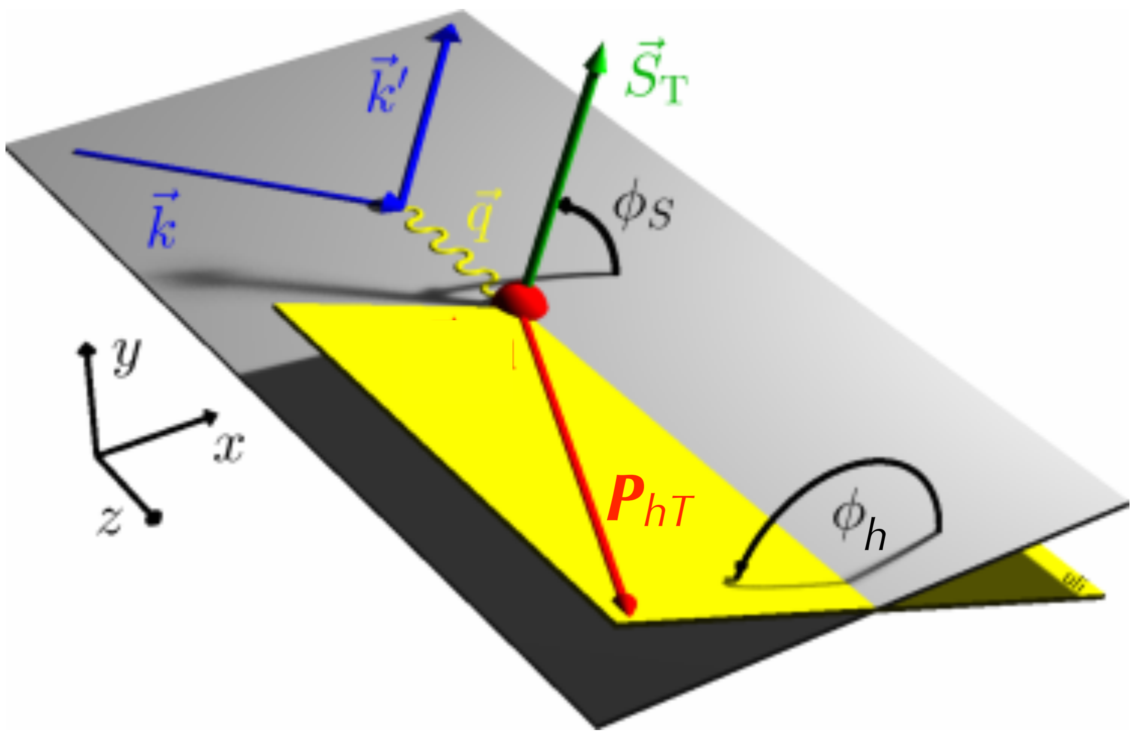


COMPASS, arXiv:1704.00488

the Sivers effect in SIDIS

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h d\boldsymbol{P}_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}$$

$$+\sin(\phi_h-\phi_S)|\boldsymbol{S}_T|\left[F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right]+\dots\Big\}$$



hard part

convolution

$$F_{UN,\gamma^*} = \sum_q H^q(Q^2)\,\mathcal{C}\left[w_{\gamma^*}\,f_N^q\,D_1^q\right]$$

$$+\,Y_{UN,\gamma^*}(Q^2,P_{hT}^2)+\mathcal{O}(M^2/Q^2)$$

matching Y term

$$\mathcal{C}[wfD] = x\sum_a e_a^2\int d^2\boldsymbol{k}_\perp d^2\boldsymbol{P}_\perp \delta^2(z\boldsymbol{k}_\perp+\boldsymbol{P}_\perp-\boldsymbol{P}_{hT})w(\boldsymbol{k}_\perp,\boldsymbol{P}_\perp)f^a(x,\boldsymbol{k}_\perp^2;Q^2)D^{a\to h}(z,\boldsymbol{P}_\perp^2;Q^2)$$

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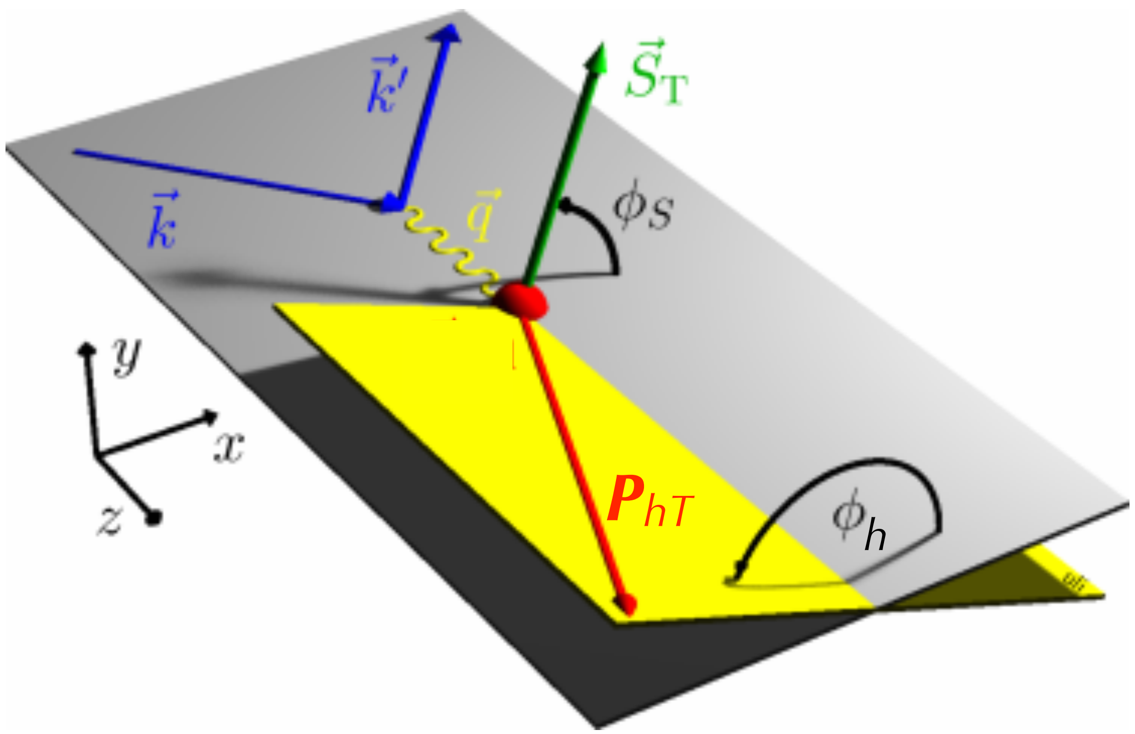
$$+\sin(\phi_h-\phi_S)|\boldsymbol{S}_T|\left[F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right]+\ldots\Big\}$$



hard part

~ 1

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"theoretical cuts": LO , twist=2, $P_{hT}^2 \ll Q^2$, NLL

Surviving

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = 2\pi\sum_a e_a^2 x\int_0^\infty d\xi_T\xi_T J_0(\xi_T|\boldsymbol{P}_{hT}|/z)\boxed{\tilde{f}_1^a(x,\xi_T^2;Q^2)}\tilde{D}_1^{a\to h}(z,\xi_T^2;Q^2)$$

position space

$$F_{UT,T}^{\sin(\phi_h-\phi_S)}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = -2\pi M\sum_a e_a^2 x\int_0^\infty d\xi_T\xi_T^2 J_1(\xi_T|\boldsymbol{P}_{hT}|/z)\boxed{\tilde{f}_{1T}^{\perp(1)a}(x,\xi_T;Q^2)}\tilde{D}_1^{a\to h}(z,\xi_T^2;Q^2)$$

the Sivers Single-Spin Asymmetry

$$f_{1T}^{\perp} \qquad D_1$$

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{A(x,y)\, F_{UT,T}^{\sin(\phi_h-\phi_S)}(x,z,\boldsymbol{P}_{hT}^2,Q^2)}{A(x,y)\, F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)}$$

$$f_1 \qquad D_1$$

First extraction of Sivers function using unpolarized TMDs f_1 and D_1 extracted from global fit of (SIDIS + Drell-Yan + Z-boson) data

Bacchetta, Delcarro, Pisano, Radici, in preparation

parametrization of unpolarized f_1 & D_1

At **LO** $\tilde{f}_1^q(x,\xi_T^2;Q^2) = \underbrace{f_1^q(x,\mu_\xi^2)\, e^{S(\mu_\xi^2,Q^2)}}_{\text{perturbative}}\, e^{g_K(\xi_T)\,\log(Q^2/Q_0^2)}\, \tilde{f}_{1NP}^q(x,\xi_T^2)$ and similar for D_1

Collins, "Foundations of Perturbative QCD" (11)

DSEHS15@NLO

f_1 = collinear PDF GJR08FFnloE

S = Sudakov form factor,

at **NLL** includes A_1, A_2, B_1

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$$\tilde{f}_{1NP} = \mathrm{F.T.}\left(\frac{1}{\pi}\,\frac{1+\lambda \boldsymbol{k}_T^2}{g_1+\lambda g_1^2}\, e^{-\boldsymbol{k}_T^2/g_1}\right)$$

$$\tilde{D}_{1NP} = \mathrm{F.T.}\left(\frac{1}{\pi}\,\frac{e^{-\boldsymbol{P}_T^2/g_3} + \lambda_F\, \boldsymbol{P}_T^2/z^2\, e^{-\boldsymbol{P}_T^2/g_4}}{g_3+\lambda_F/z^2\, g_4^2}\right)$$

$$g_1(x) = g_1(0.1)\,\frac{(1-x)^\alpha\, x^\sigma}{(1-0.1)^\alpha\, 0.1^\sigma}$$

$$g_{3/4}(z) = g_{3/4}(0.5)\,\frac{(1-z)^\gamma\,(z^\beta+\delta)}{(1-0.5)^\gamma\,(0.5^\beta+\delta)}$$

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1 + 4 + 6 = 11 parameters

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1 + 4 + 6 = 11 parameters

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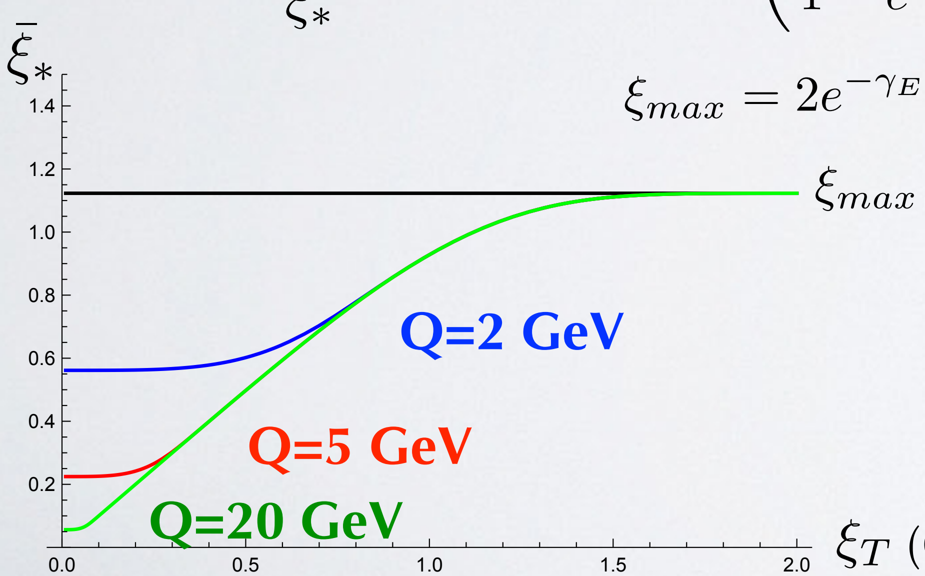
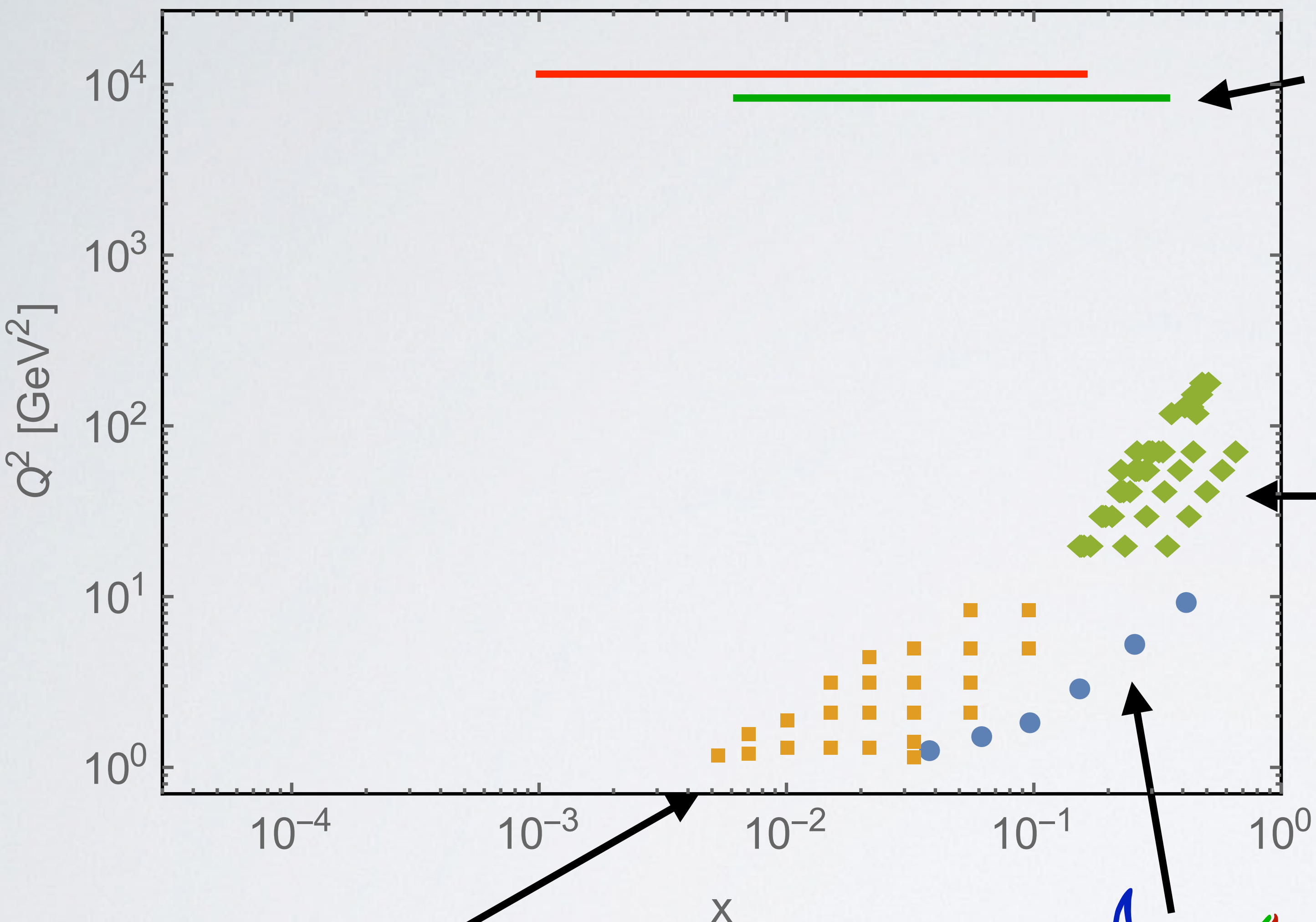
$$\xi_{max} = 2e^{-\gamma_E} \qquad \xi_{min} = \frac{2e^{-\gamma_E}}{Q}$$



$$1 \le \mu_\xi \le Q$$

(x, Q²) - coverage

(Z @LHC)



Z production

Abbot et al., P.R.L. 84 (00) 2792
Affolder et al., P.R.L. 84 (00) 845
Abazov et al., P.R.L. 100 (08) 102002
Aaltonen et al., P.R. D86 (12) 052010

Drell-Yan

Fermilab

Ito et al., P.R. D23 (81) 604
Moreno et al., P.R. D43 (91)
Antreyan et al., P.R.L. 47 (81)

COMPASS

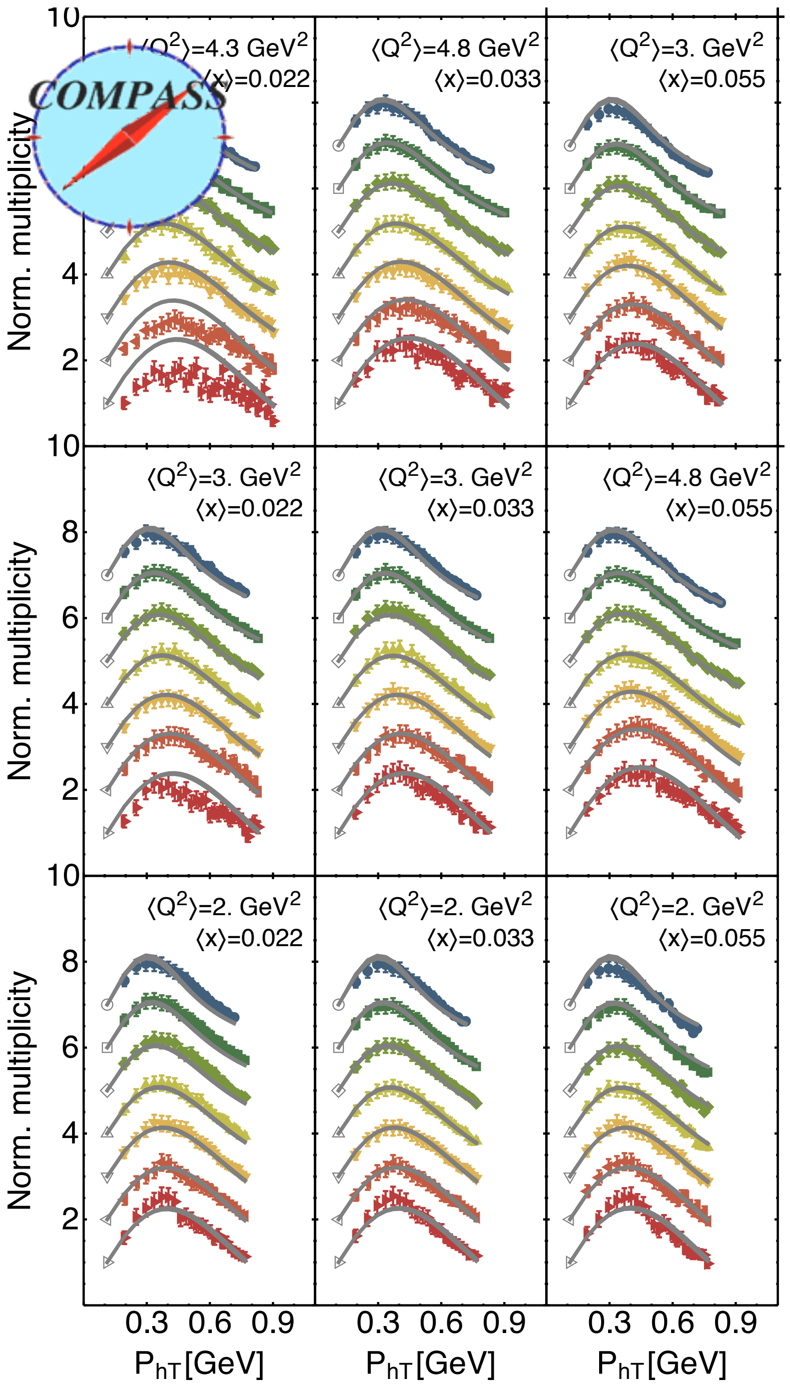
hermes

Adolph et al., E.P.J. C73 (13)

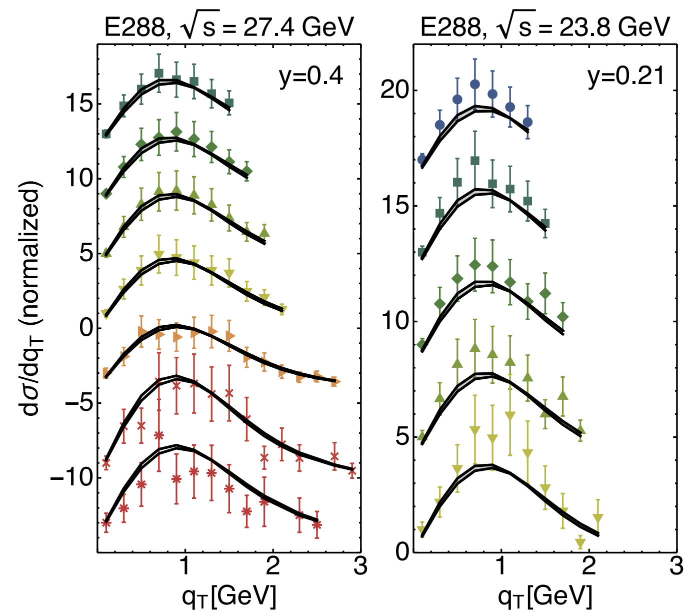
Airapetian et al., P.R. D87 (13)

first unpolarized TMD global fit

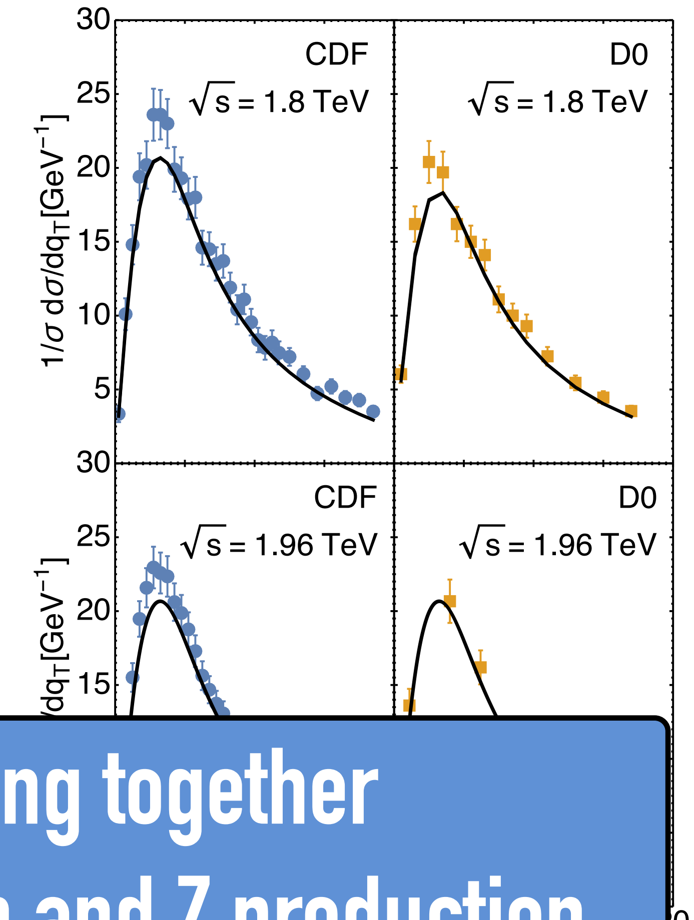
SIDIS



Drell-Yan



Z production



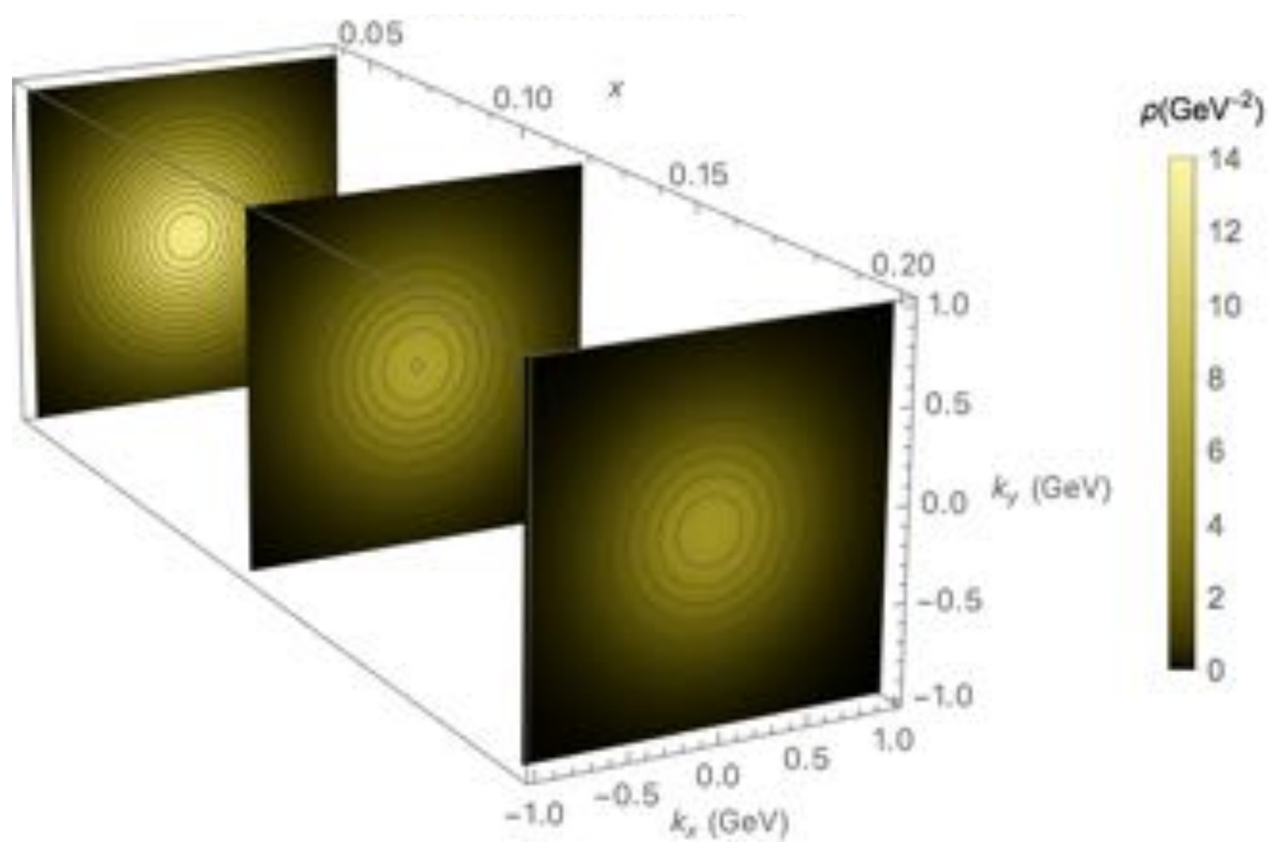
Number of data points: 8059

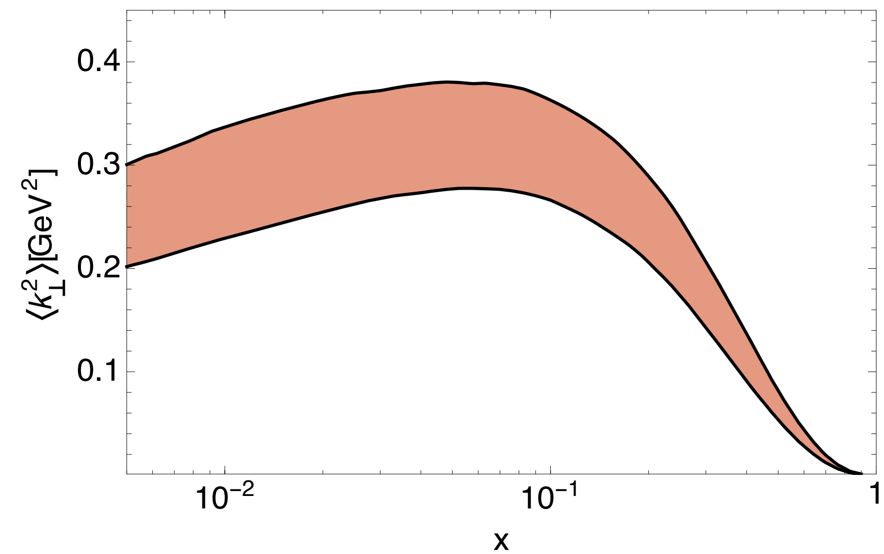
Global χ^2/dof = 1.55 ± 0.05

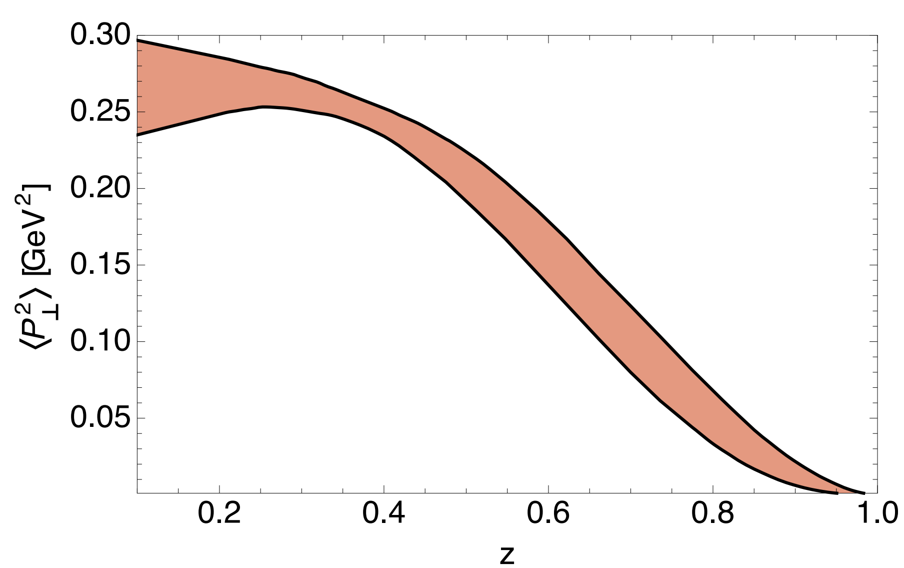
Pavia2016: first fit putting together semi-inclusive DIS, Drell-Yan and Z production

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

Nucleon tomography in momentum space







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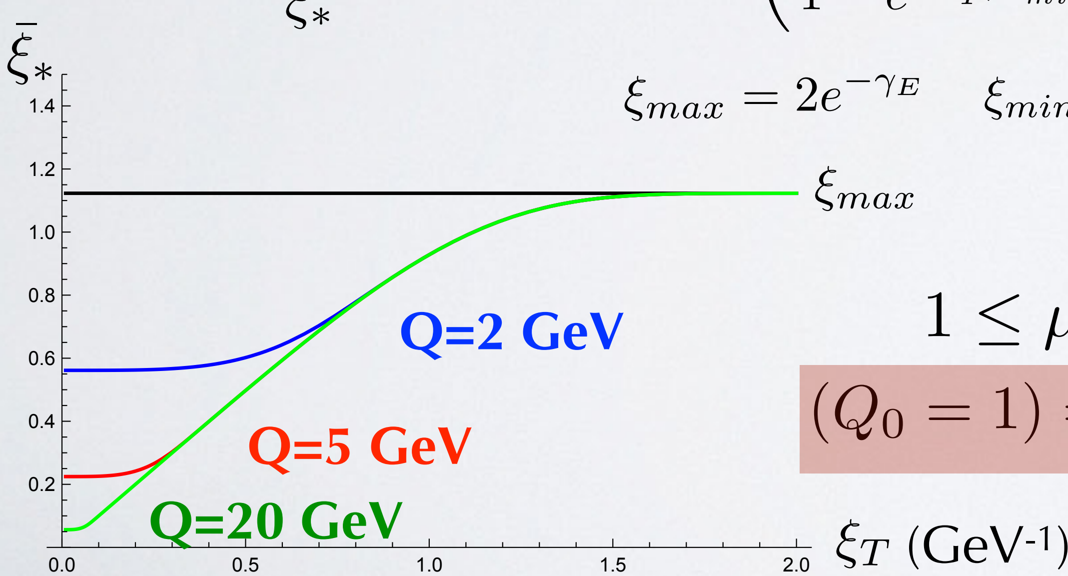

$$1 \le \mu_\xi \le Q$$

$$(Q_0 = 1) \Rightarrow (\mu_\xi = 1)$$

$$\tilde{f}_1^q(x,\xi_T^2;Q_0^2) = f_1^q(x,Q_0^2)\,\tilde{f}_{1NP}(x,\xi_T^2)$$

parametrization of Sivers $f_{1T}^{\perp}$

scale Q_0 $\quad \tilde{f}_{1T}^{\perp q}(x,\xi_T^2;Q_0^2) = f_{1T}^{\perp(1)q}(x,Q_0^2)\,\tilde{f}_{1TNP}^{\perp}(x,\xi_T^2)$

$$\left(\frac{1}{N_T}\,\frac{1}{\pi}\,\frac{1+\lambda_S \boldsymbol{k}_T^2}{M_1^2+\lambda_S M_1^4}\,e^{-\boldsymbol{k}_T^2/M_1^2} \quad f_{1NP}(x,\boldsymbol{k}_T^2)\right)$$

normalized flavor-independent double Gaussian on top of f_{1NP}

parametrization of Sivers $f_{1T}^{\perp}$

scale Q_0 $\quad \tilde{f}_{1T}^{\perp q}(x, \xi_T^2; Q_0^2) = f_{1T}^{\perp(1)q}(x, Q_0^2)\, \tilde{f}_{1TNP}^{\perp}(x, \xi_T^2)$

normalization

$$f_{1T}^{\perp(1)q} = \frac{1}{N_x^q}\, f_{Siv}^q(x) \quad f_1^q(x, Q_0^2)$$

$$f_{Siv}^q(x) = x^{\alpha_q}\, (1-x)^{\beta_q}\, [1 + A_q T_1(x) + B_q T_2(x)]$$

Chebyshev polynomials

F.T. $\left(\frac{1}{N_T} \frac{1}{\pi} \frac{1 + \lambda_S \boldsymbol{k}_T^2}{M_1^2 + \lambda_S M_1^4}\, e^{-\boldsymbol{k}_T^2/M_1^2} \quad f_{1NP}(x, \boldsymbol{k}_T^2) \right)$

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q = u_v, d_v, s (= sea)

Chebyshev polynomials

further **multiply** by $\frac{1}{N_{Tmax}} \frac{1}{N_{xmax}}$

$$\begin{cases} N_{Tmax} = \max\limits_{\boldsymbol{k}_T^2} \left[\frac{k_T}{M} \frac{1}{N_T} \frac{1}{\pi} \frac{1 + \lambda_S \boldsymbol{k}_T^2}{M_1^2 + \lambda_S M_1^4} e^{-\boldsymbol{k}_T^2/M_1^2} \right] \\ N_{xmax} = \max\limits_{x,q} \left[\frac{1}{N_x^q} f_{Siv}^q(x) \right] \end{cases}$$

to grant **positivity** $\left(f_{1T}^{\perp(1)}(x, \boldsymbol{k}_T^2) \right)^2 \leq \frac{\boldsymbol{k}_T^2}{4M^2} \left(f_1(x, \boldsymbol{k}_T^2) \right)^2$

parametrization of Sivers $f_{1T}^{\perp}$

scale Q_0 $\quad \tilde{f}_{1T}^{\perp q}(x,\xi_T^2;Q_0^2) = f_{1T}^{\perp(1)q}(x,Q_0^2)\, \tilde{f}_{1TNP}^{\perp}(x,\xi_T^2)$

F.T. $\left(\frac{1}{N_T}\, \frac{1}{\pi}\, \frac{1+\lambda_S \boldsymbol{k}_T^2}{M_1^2+\lambda_S M_1^4}\, e^{-\boldsymbol{k}_T^2/M_1^2} \quad f_{1NP}(x,\boldsymbol{k}_T^2) \right)$

normalized flavor-independent double Gaussian on top of f_{1NP}

normalization

$$f_{1T}^{\perp(1)q} = \frac{1}{N_x^q}\, f_{Siv}^q(x) \quad f_1^q(x,Q_0^2)$$

$$f_{Siv}^q(x) = x^{\alpha_q}(1-x)^{\beta_q}\left[1 + A_q T_1(x) + B_q T_2(x)\right]$$

randomly fixed

Chebyshev polynomials

q = u_v, d_v, s (= sea)

further **multiply** by $\frac{1}{N_{Tmax}}\, \frac{1}{N_{xmax}}$

$$\begin{cases} N_{Tmax} = \max\limits_{\boldsymbol{k}_T^2}\left[\frac{k_T}{M}\, \frac{1}{N_T}\, \frac{1}{\pi}\, \frac{1+\lambda_S \boldsymbol{k}_T^2}{M_1^2+\lambda_S M_1^4}\, e^{-\boldsymbol{k}_T^2/M_1^2}\right] \\ N_{xmax} = \max\limits_{x,q}\left[\frac{1}{N_x^q}\, f_{Siv}^q(x)\right] \end{cases}$$

to grant **positivity** $\left(f_{1T}^{\perp(1)}(x,\boldsymbol{k}_T^2)\right)^2 \leq \frac{\boldsymbol{k}_T^2}{4M^2}\, \left(f_1(x,\boldsymbol{k}_T^2)\right)^2$

2 + 3x4 = 14 parameters

evolution of Sivers $f_{1T}^{\perp}$

At **LO** $$\tilde{f}_{1T}^{\perp q}(x,\xi_T^2;Q^2) = \underbrace{f_{1T}^{\perp(1)q}(x,\mu_\xi^2)\, e^{S(\mu_\xi^2,Q^2)}}_{\text{perturbative}}\; \underbrace{e^{g_K(\xi_T)\,\log(Q^2/Q_0^2)}\, \tilde{f}_{1TNP}^{\perp}(x,\xi_T^2)}_{\text{nonperturbative}}$$

S = Sudakov form factor,
at **NLL** includes A_1, A_2, B_1

$$f_{1T}^{\perp(1)q}(x,\mu_\xi^2) = -\frac{1}{2M}\, T_F^q(x,x,\mu_\xi^2)$$

Ji, Qiu, Vogelsang, Yuan, hep-ph/0602239

Qiu-Sterman

approximate evolution of T_F as DGLAP evolution of f_1

data used in the fit

hermes — proton [H]

95 data points

Jefferson Lab — neutron [^{3}He]

6 data points

COMPASS 2009 — deuteron [^{6}LiD]

88 data points

COMPASS 2017 — Proton [NH_3]

111 data points

analysis of statistical error
with replica method (200)
68% confidence level

Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

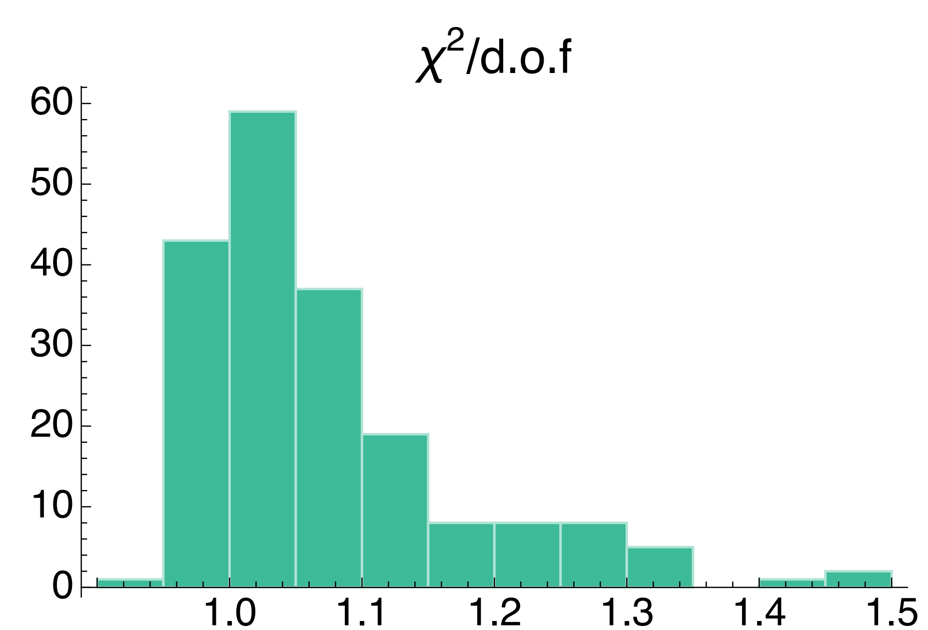
$Q^2 \geq 1.4$ GeV^2 $0.2 \leq z \leq 0.7$

$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

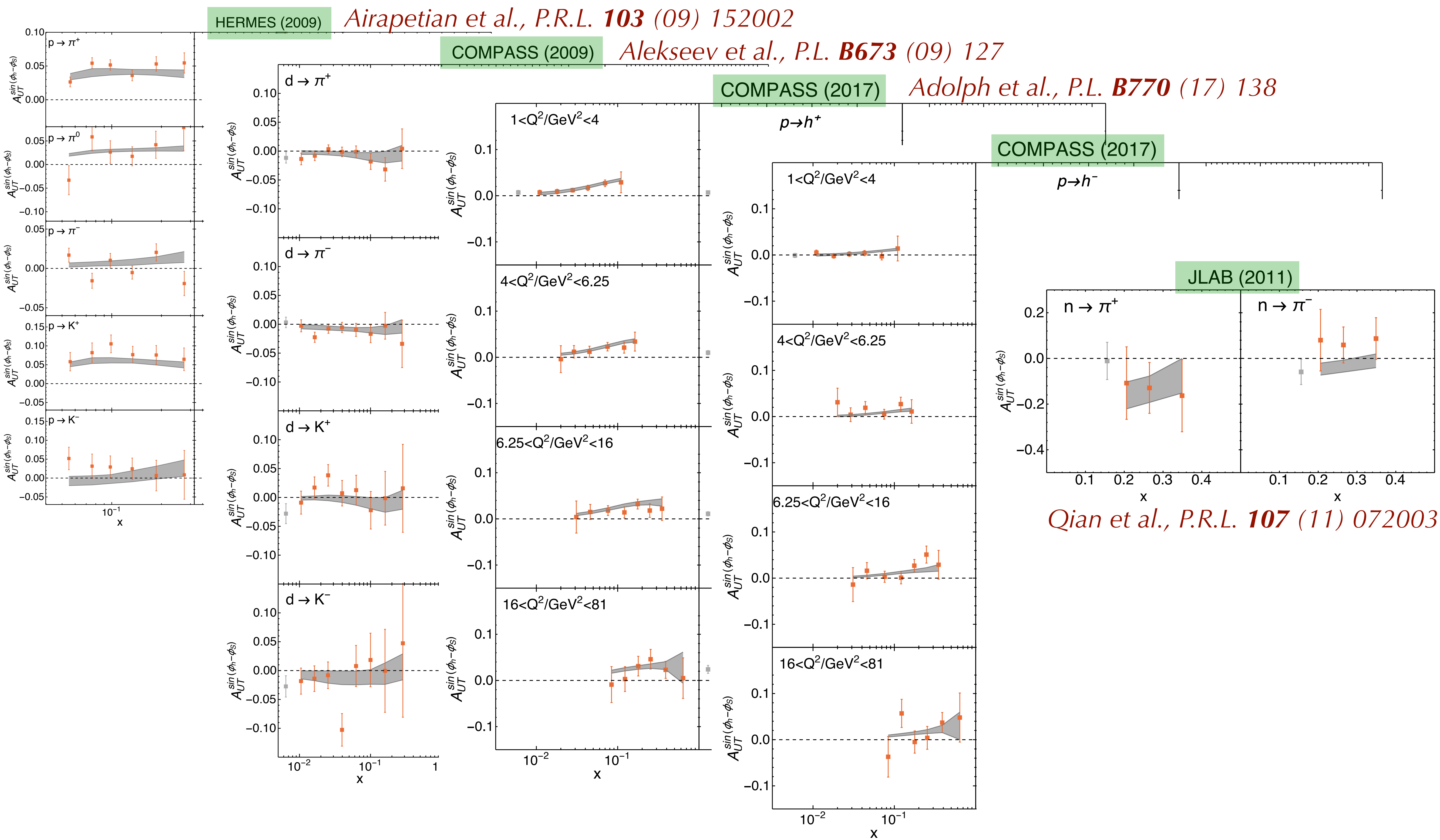
300 data points → **118** data fitted

14 free parameters

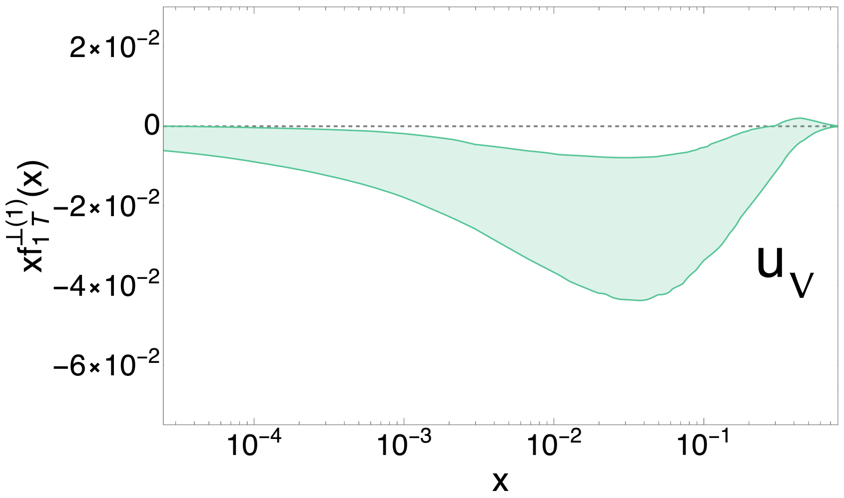
χ^2/d.o.f. = 1.06 ± 0.10



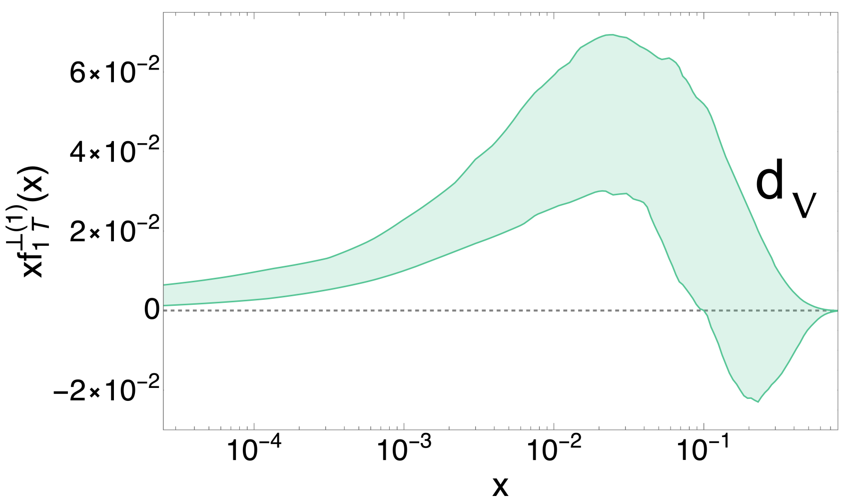
sample of fit



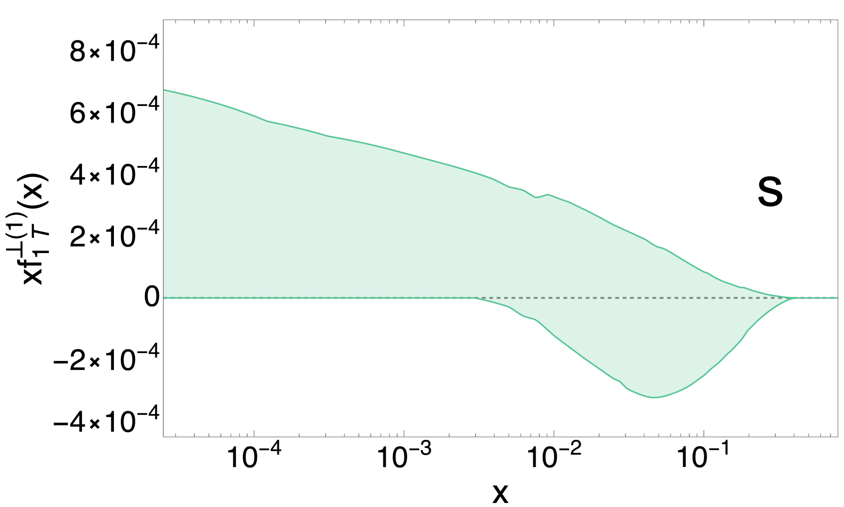
results

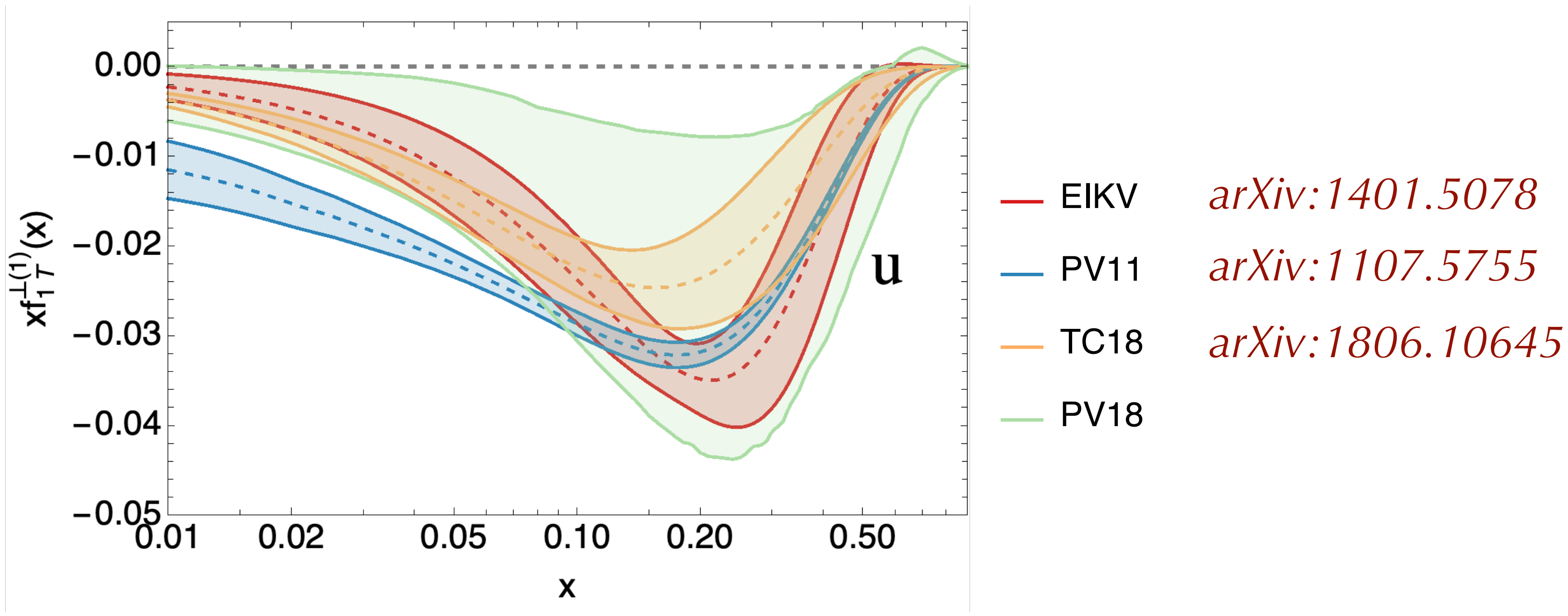

u_V
x
$xf_{1T}^{\perp(1)}(x)$

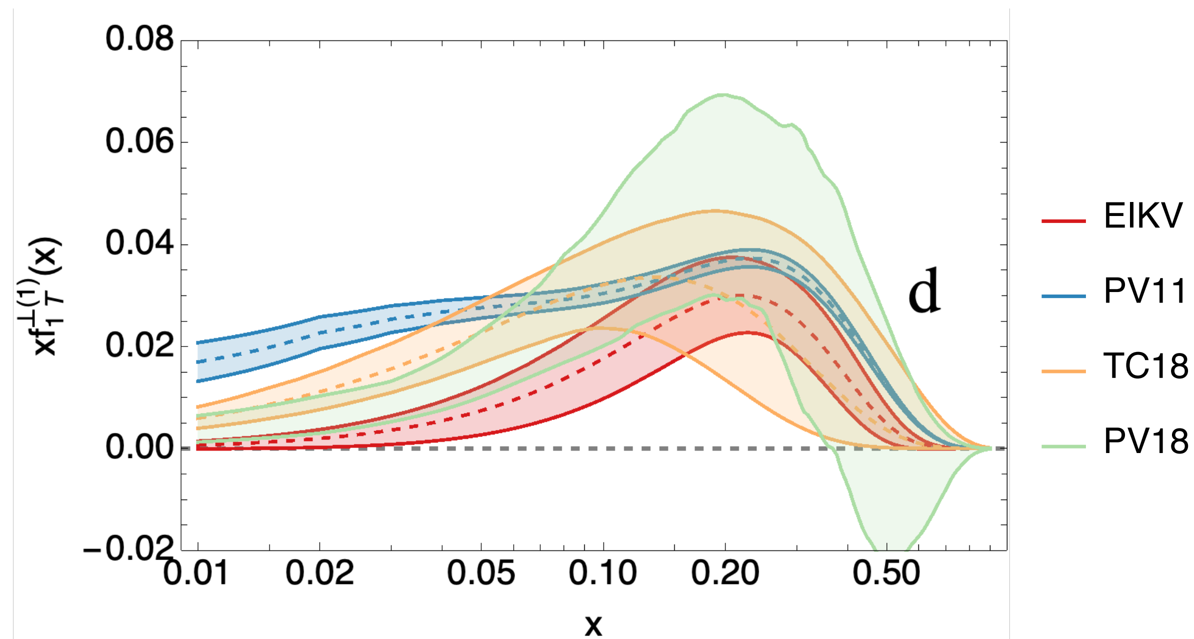
(a)


d_V
x
$xf_{1T}^{\perp(1)}(x)$

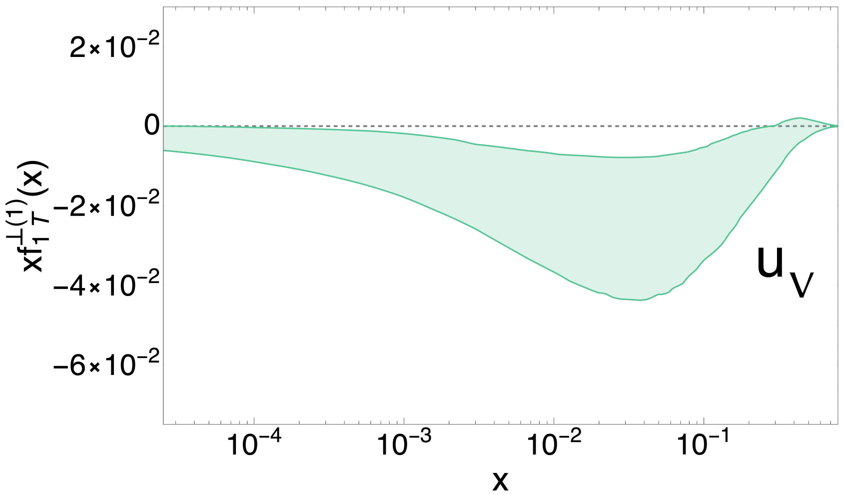
(c)


s
x
$xf_{1T}^{\perp(1)}(x)$

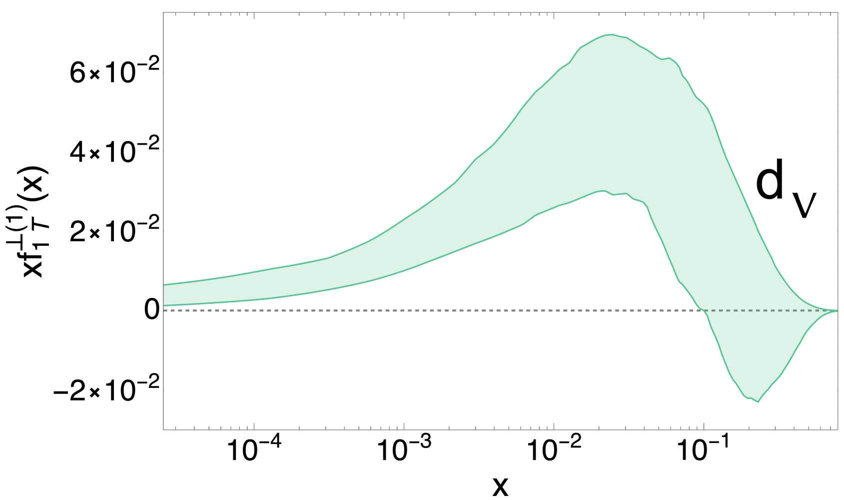

u
x
$xf_{1T}^{\perp(1)}(x)$
EIKV
PV11
TC18
PV18
arXiv:1401.5078
arXiv:1107.5755
arXiv:1806.10645


d
x
$xf_{1T}^{\perp(1)}(x)$
EIKV
PV11
TC18
PV18

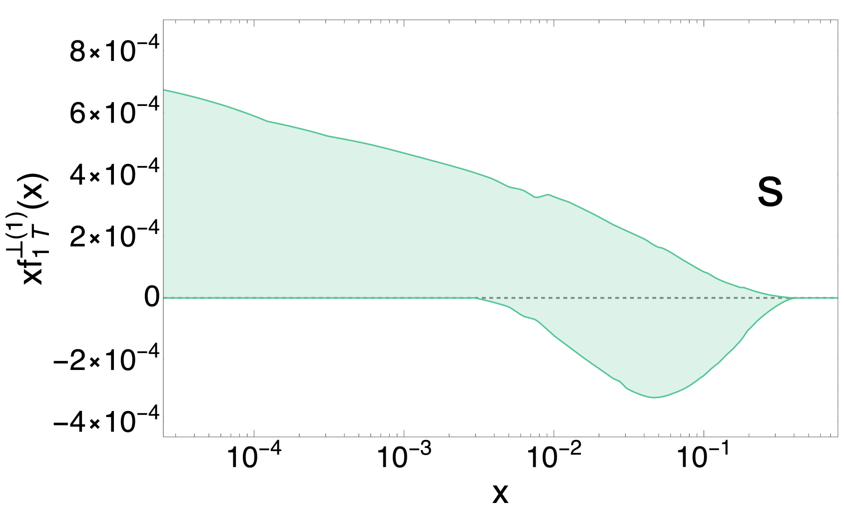
results

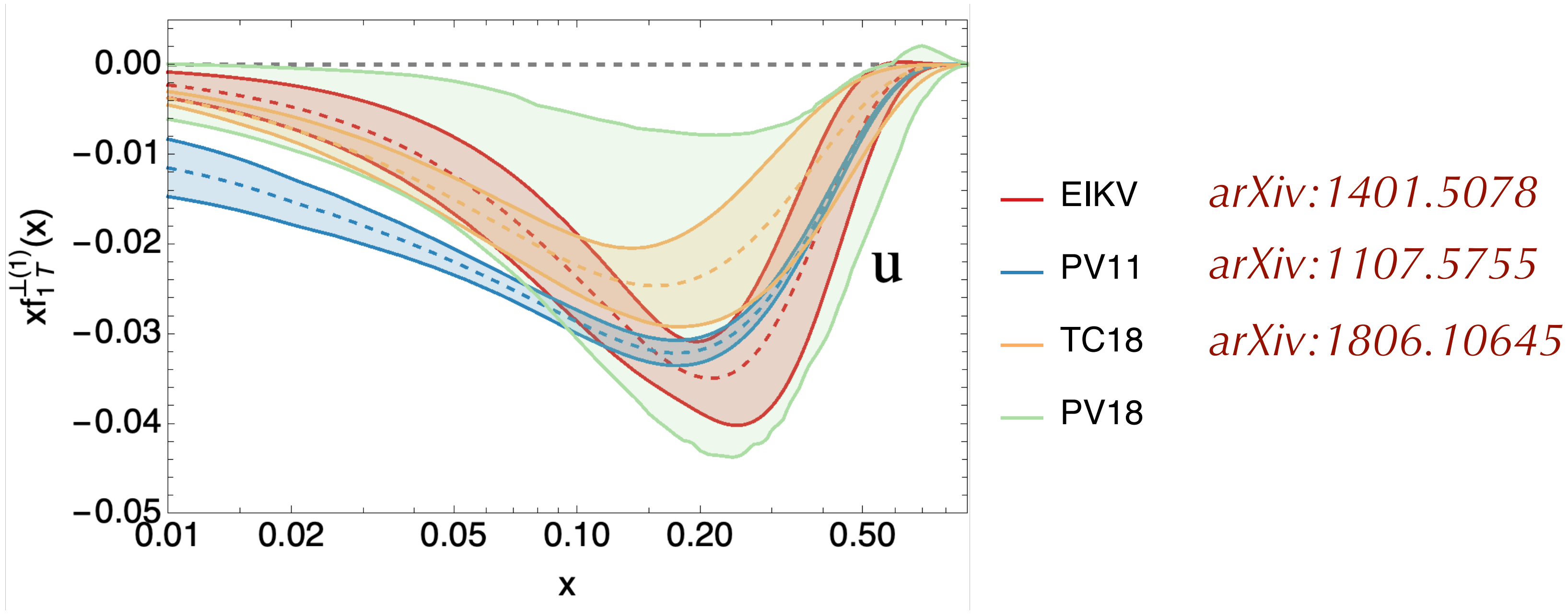


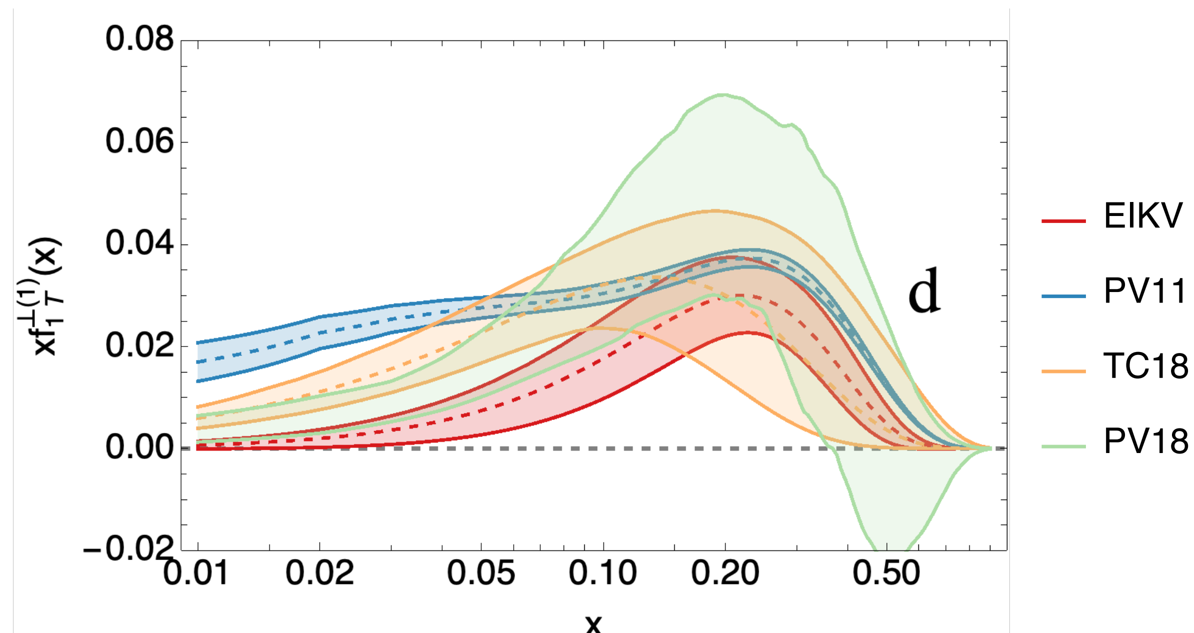
(a)



(c)



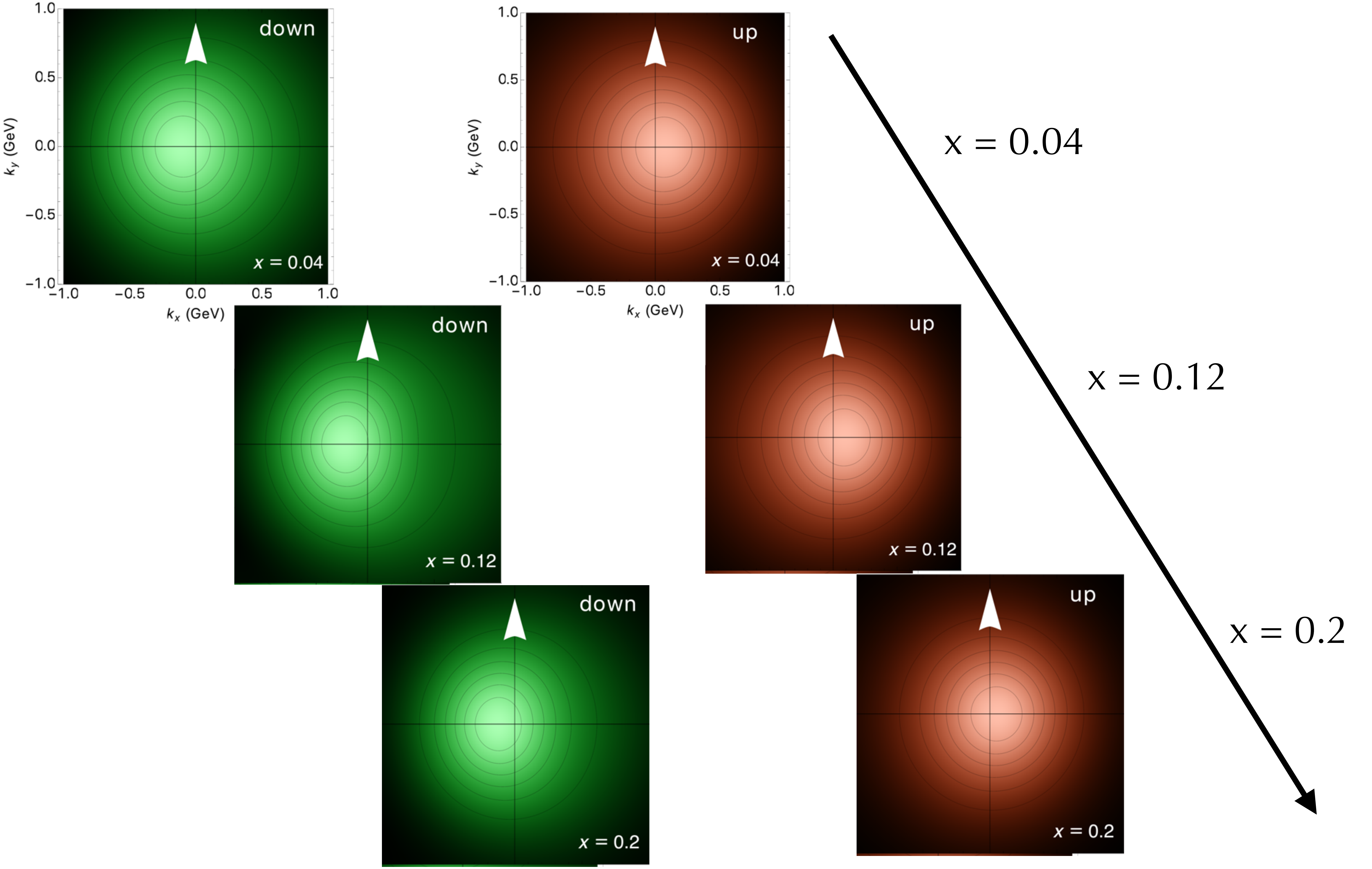




wider uncertainty band because of uncertainty in extraction of unpolarized TMD f_1

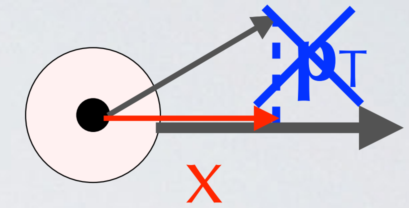
→ more realistic…

tomography of transversely polarized proton



the Transversity function

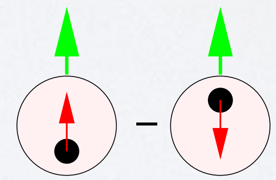
PDFs @twist=2



quark polarization

nucleon polarization

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



chiral-odd → suppressed

1st Mellin moment (tensor charge) not directly accessible in $\mathcal{L}_{SM}$

→ low-energy footprint of BSM physics at higher scale ?

h_1 from first global fit of SIDIS + p-p data

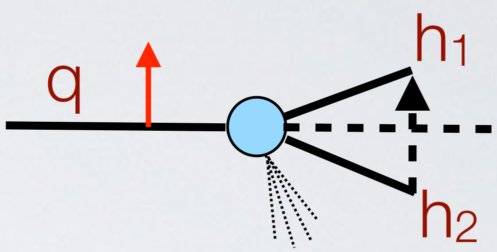
*Radici and Bacchetta, P.R.L. **120** (18) 192001*

the di-hadron mechanism

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

- the di-hadron mechanism: IFF $H_1^{\sphericalangle}$

  2-hadrons semi-inclusive production



collinear framework

- h_1 probed as PDF

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

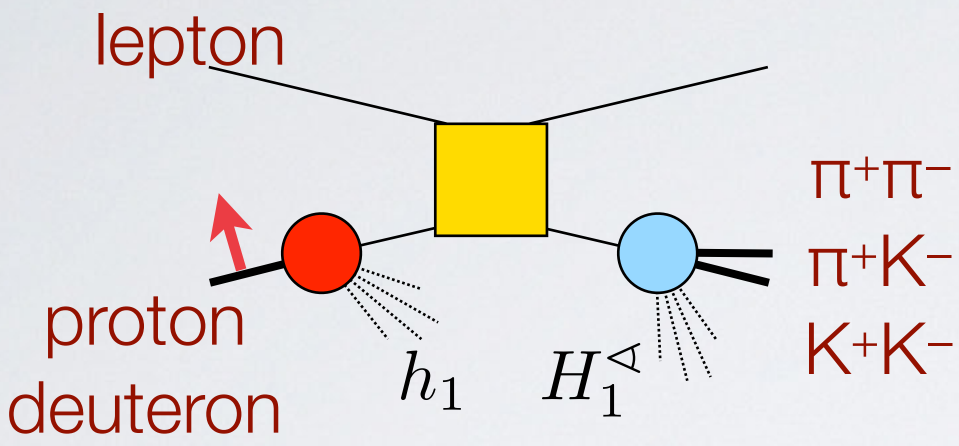
)

advantages of di-hadron mechanism

factorization theorems for all hard processes

data used in the global fit

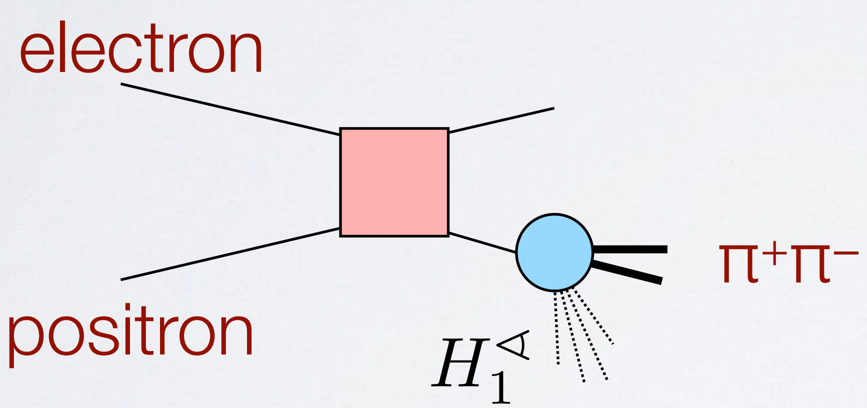
SIDIS



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

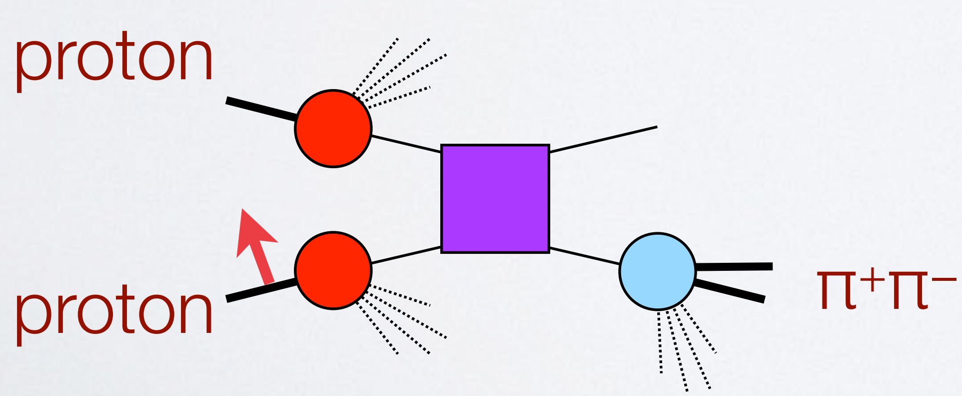
COMPASS: *Adolph et al., P.L. **B713** (12)*
*Braun et al., E.P.J. Web Conf. **85** (15)*

e+e−



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

p p↑



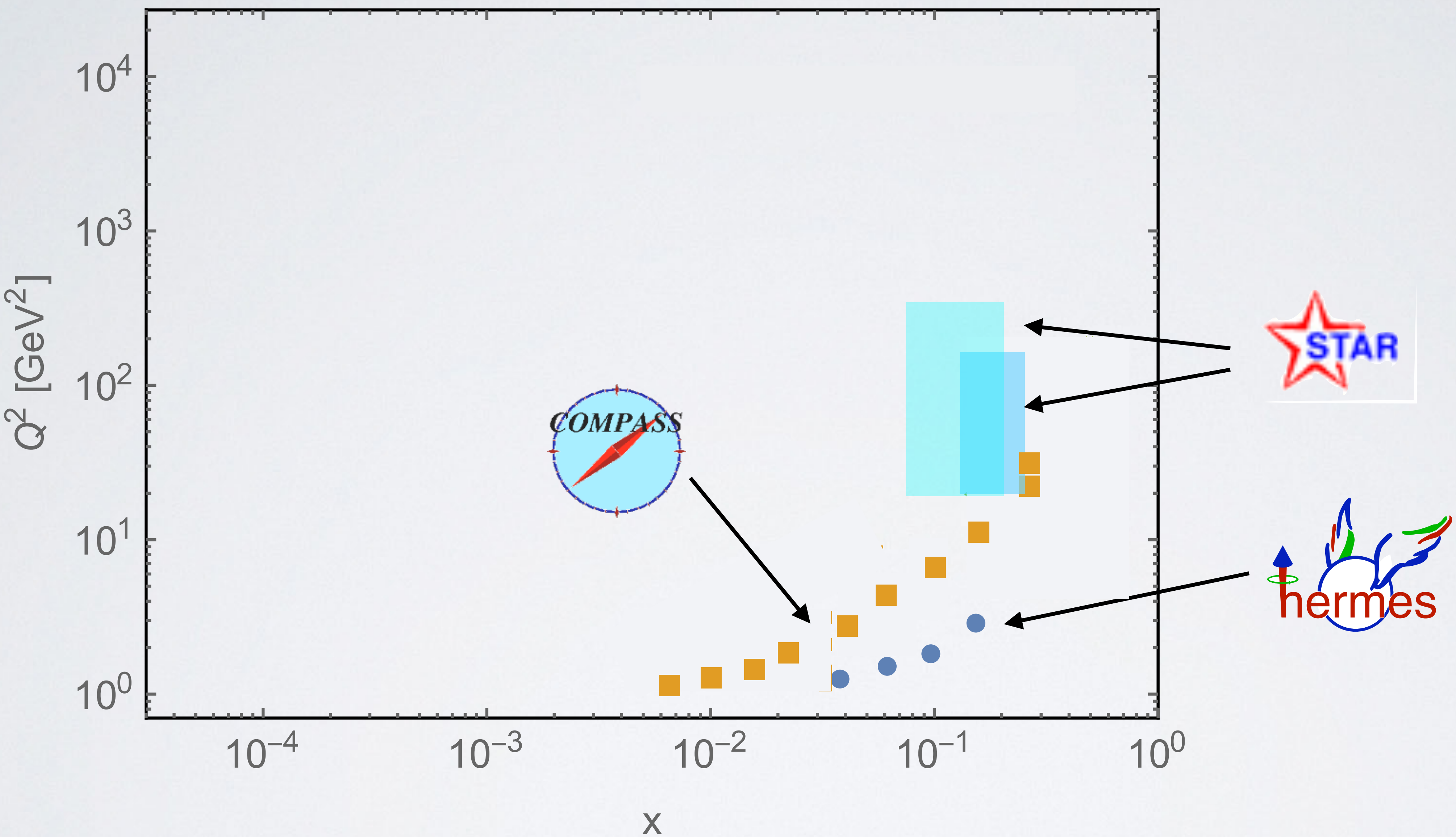
$f_1 \times h_1 \times H_1^{\sphericalangle}$

STAR

run 2006 (s=200 GeV^2): *Adamczyk et al. (STAR), P.R.L. **115** (2015) 242501*

run 2011 (s=500 GeV^2): *Adamczyk et al. (STAR), P.L. **B780** (18) 332*

the phase space

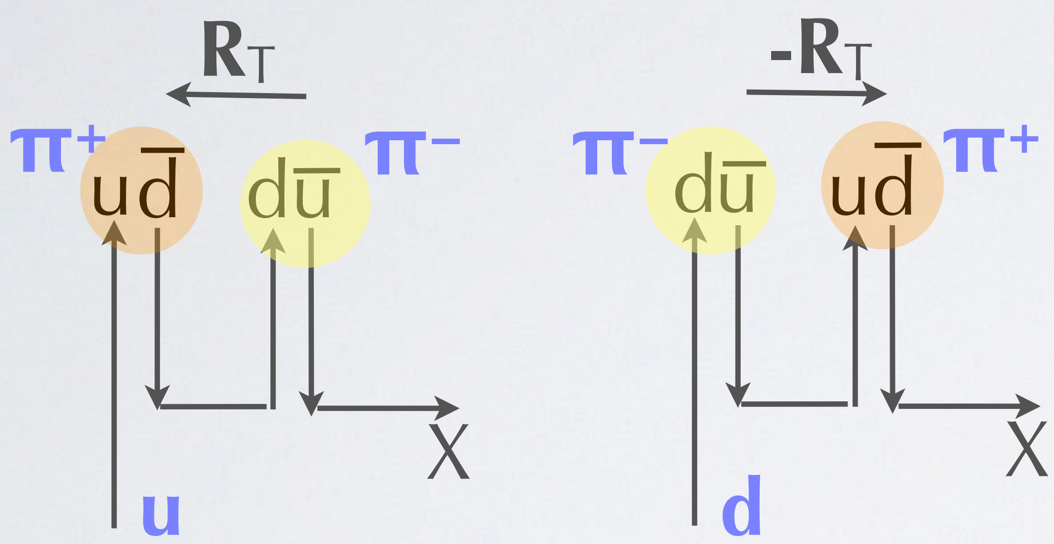


- limited to mostly medium/high x
- guess low-x behavior (relevant for calculation of tensor charge - see later)

currently, only LO analysis

$$A_{UT}^{\sin(\phi_R+\phi_S)}(x,z,M_h^2) \propto -\frac{|\mathbf{R}|}{M_h}\frac{\sum_q e_q^2\, h_1^q(x)\; H_1^{\sphericalangle q}(z,M_h^2)}{\sum_q e_q^2\, f_1^q(x)\; D_1^q(z,M_h^2)}$$

π+π−
tree level



$$\left.\begin{aligned} H_1^{\sphericalangle\, u} &= -H_1^{\sphericalangle\, d} \\ H_1^{\sphericalangle\, q} &= -H_1^{\sphericalangle\, \bar q} \\ D_1^q &= D_1^{\bar q} \end{aligned}\right.$$

isospin symmetry

charge conjugation

access only q-q̄ = q_V , q=u,d
valence flavors in SIDIS A_{UT}

theoretical uncertainties

unpolarized Di-hadron Fragmentation Function D_1

- **quark** D_1^q is **well** constrained by $e^+e^- \to (\pi^+\pi^-)\, X$ (Montecarlo)
- **gluon** D_1^g is **not** constrained by $e^+e^- \to (\pi^+\pi^-)\, X$ (currently, LO analysis)
- **no data** available yet for $p\, p \to (\pi^+\pi^-)\, X$

we don't know anything about the gluon D_1^g

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

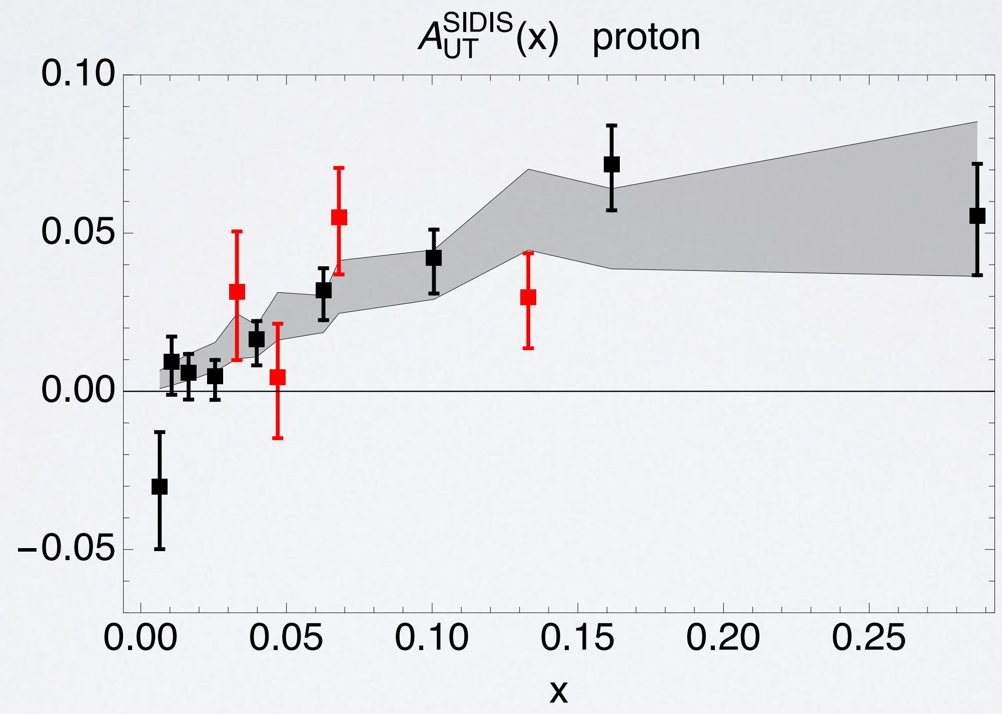
deteriorates our e^+e^- fit as $\chi^2/\text{dof} = \begin{cases} 1.69 & 1.28 \\ 1.81 & 1.37 \\ 2.96 & 2.01 \end{cases}$

background	ρ channels
1.69	1.28
1.81	1.37
2.96	2.01

statistical uncertainty

the bootstrap method

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



automatically accounts for correlations

choice of functional form

functional form whose Mellin transform can be computed analytically and complying with Soffer Bound at any x and scale Q^2

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

Soffer Bound

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

MSTW08 DSSV

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

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

10 fitting parameters

constrain parameters

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

constrain parameters : low-x trend

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

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

low-x behavior important

constrain parameters

δq finite => $A_q + a_q > 0$

our choice

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

$$\left| \int_0^{x_{\min}} dx \right| \sim 1\% \text{ of } \left| \int_{x_{\min}}^1 dx \right|$$

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

Other choices

"massive" jet in DIS → h_1 at twist 3
violation of Burkardt-Cottingham s.r.
Accardi and Bacchetta, P.L. ***B773*** *(17) 632*

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

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

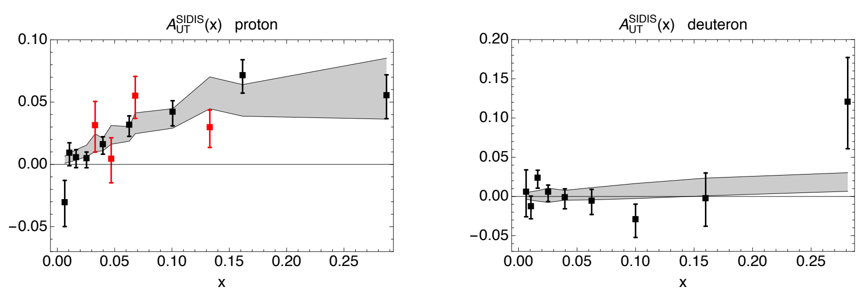
Kovchegov & Sievert, arXiv:1808.10354

Results

Our first global fit

first ever extraction of transversity from data of SIDIS and proton-proton collisions

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



SIDIS

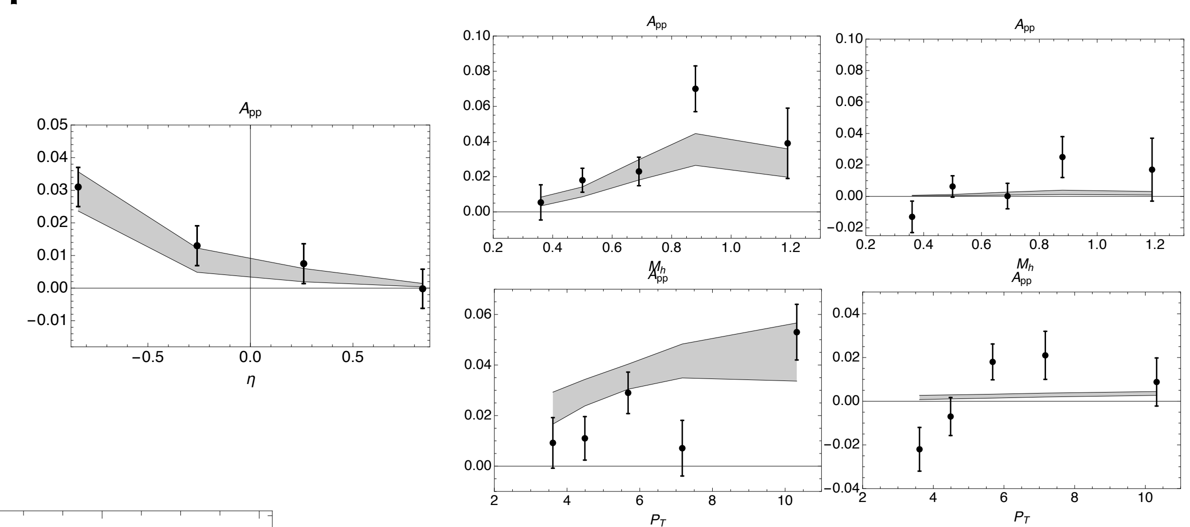
COMPASS — **18** data points

hermes — **4** data points

pp collisions

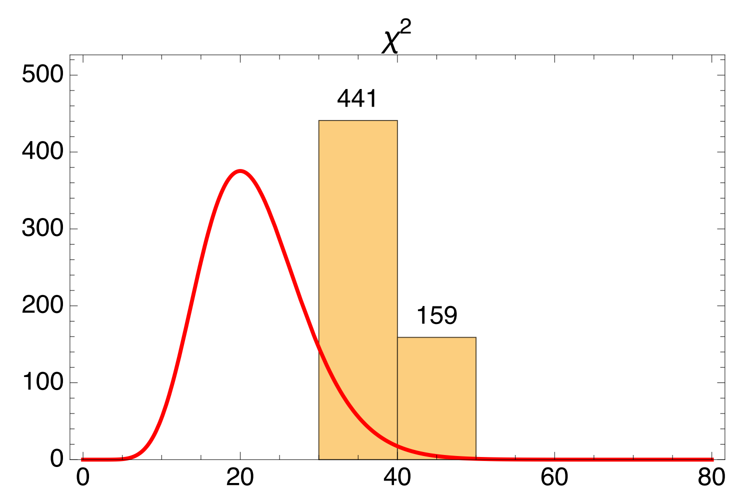
STAR — run 2006 (s=200 GeV^2)

10 independent data points



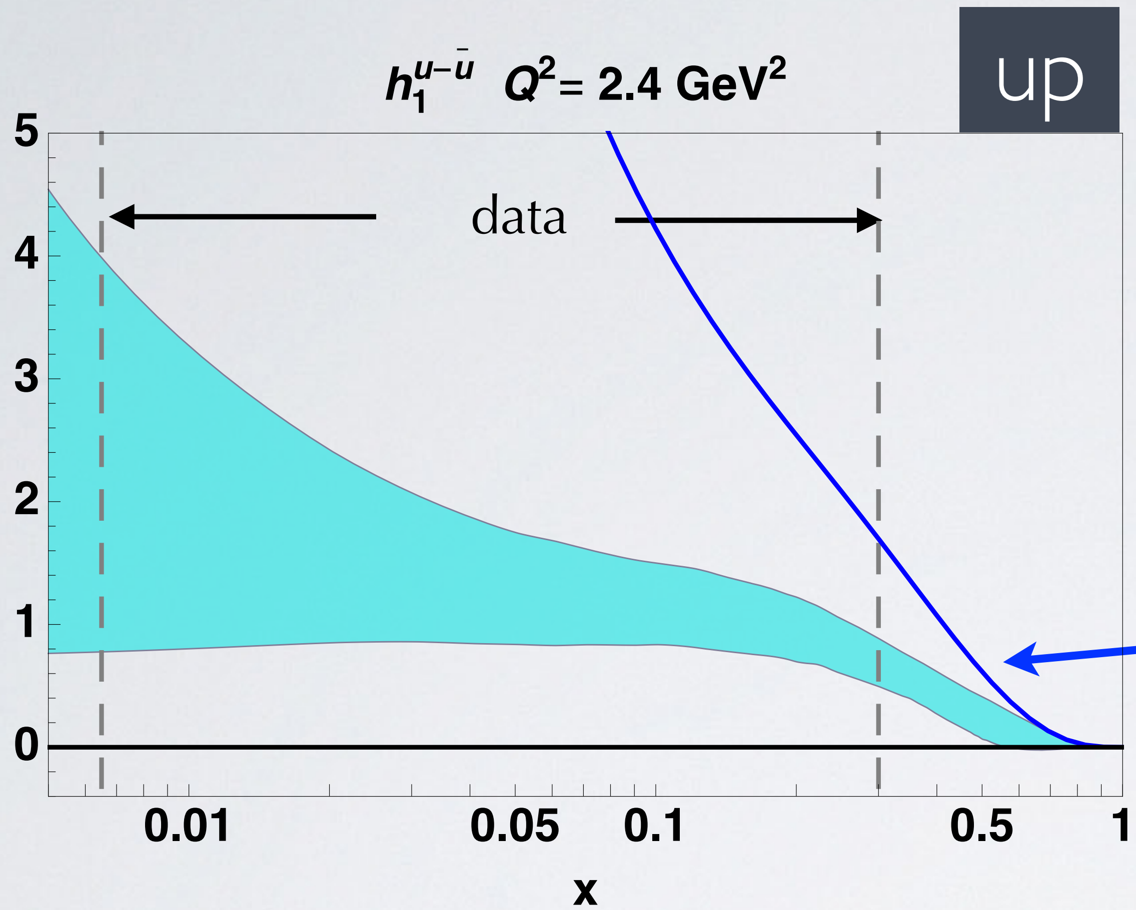
probability density function of χ^2 distribution for 22 d.o.f.

(for χ^2/dof = 1 perfect overlap)



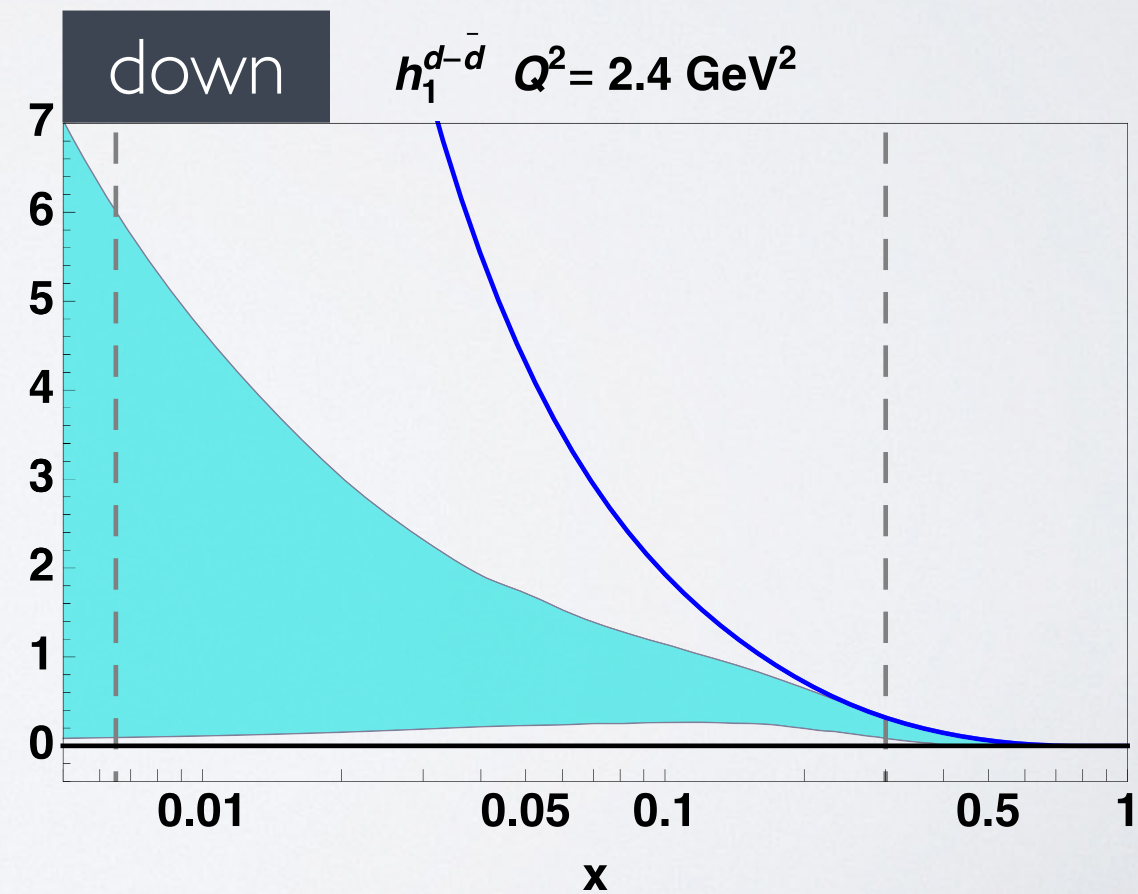
χ^2/dof = 1.76 ± 0.11

the extracted transversity

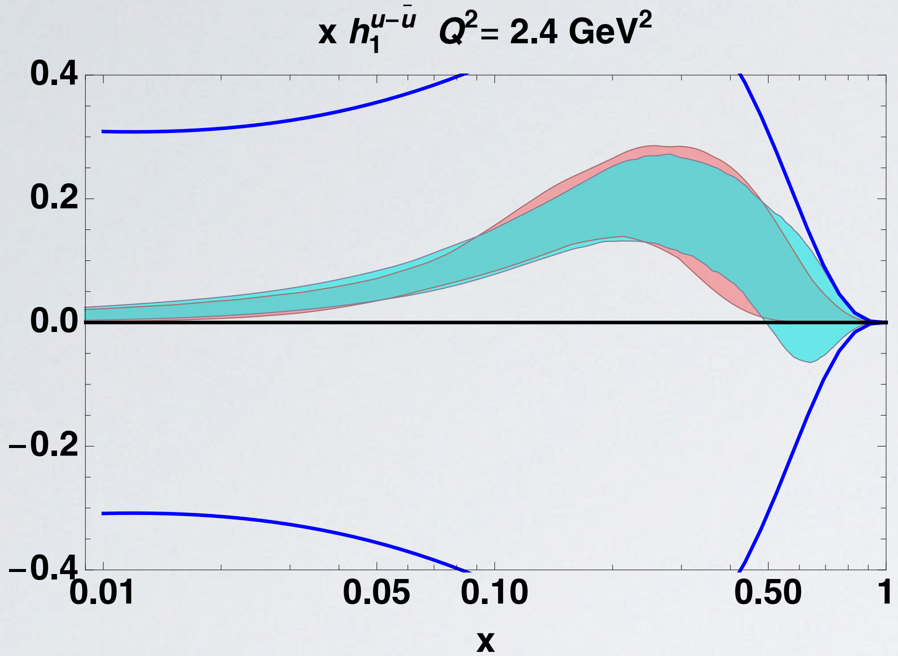


Soffer
bound

uncertainty band from
90% of 600 replicas
= max uncertainty on $D_1{}^g(Q_0)$

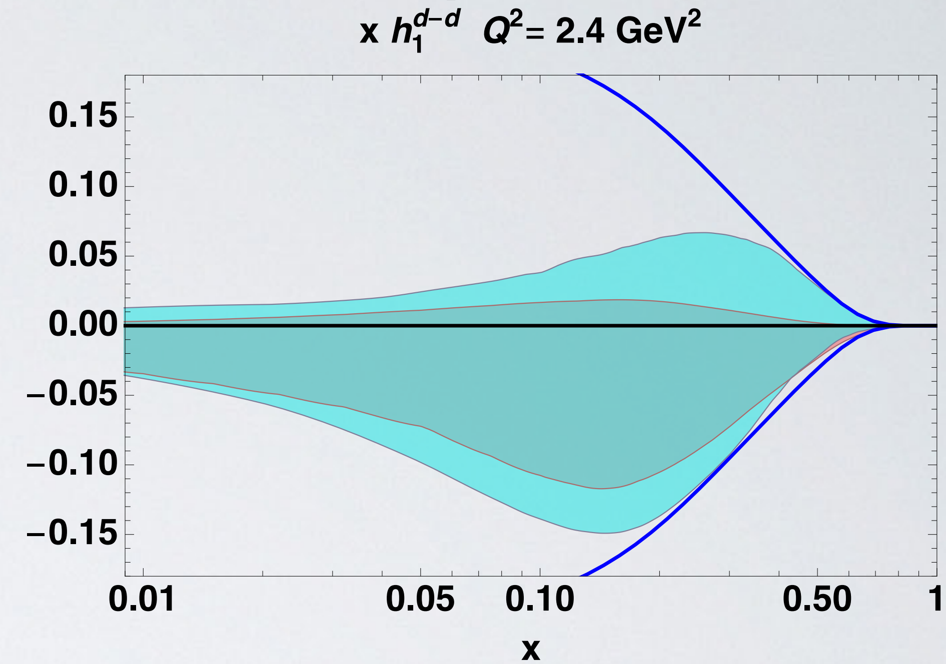


Comparison with other extractions



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

Torino

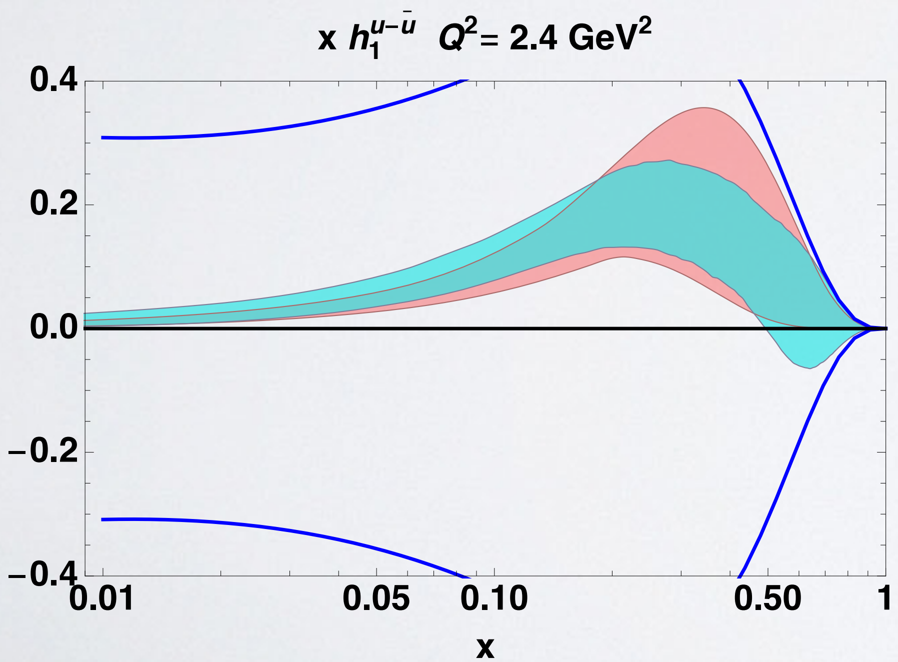


up

global fit

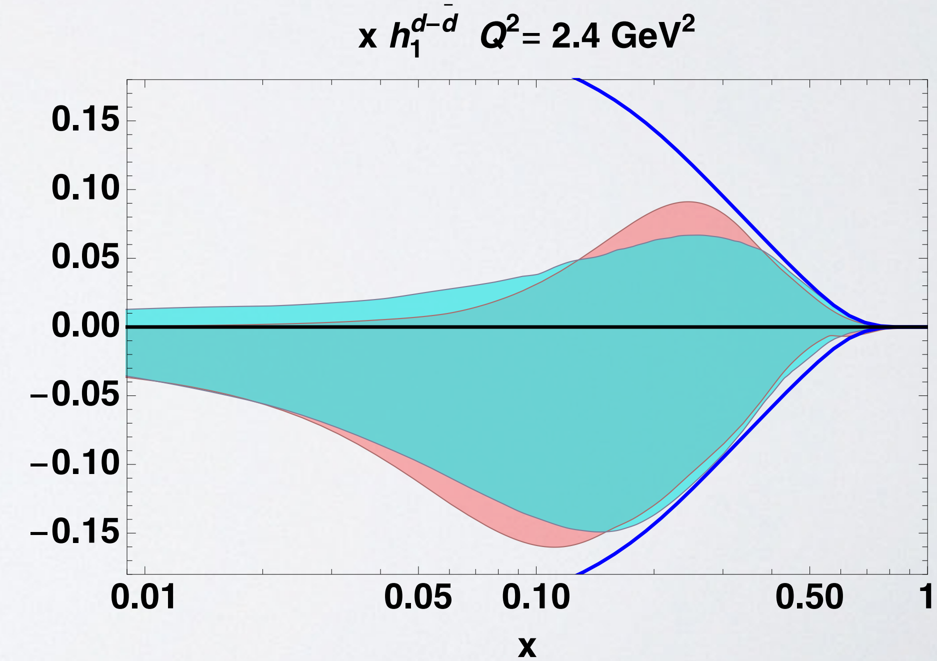
Radici and Bacchetta,
*P.R.L. **120** (18) 192001*

down

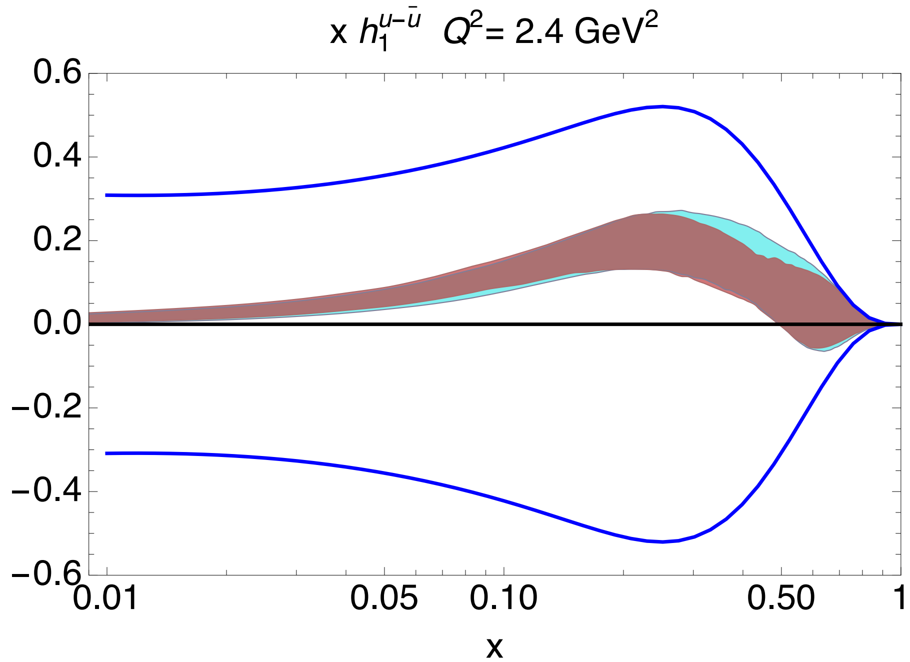


TMD

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

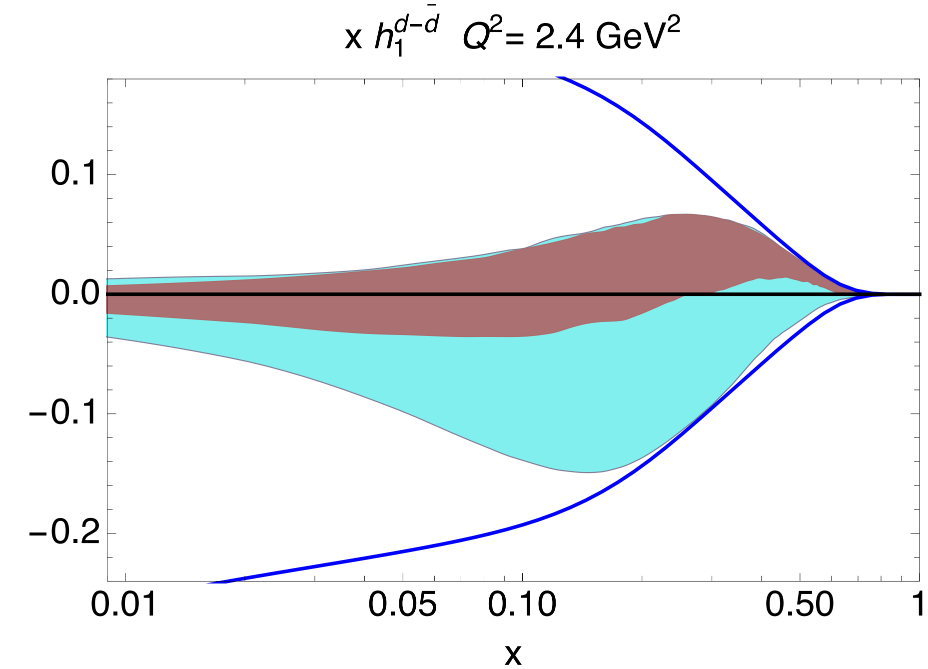


sensitivity to th. uncertainty



$D_1^g(Q_0) = 0$

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



global fit

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

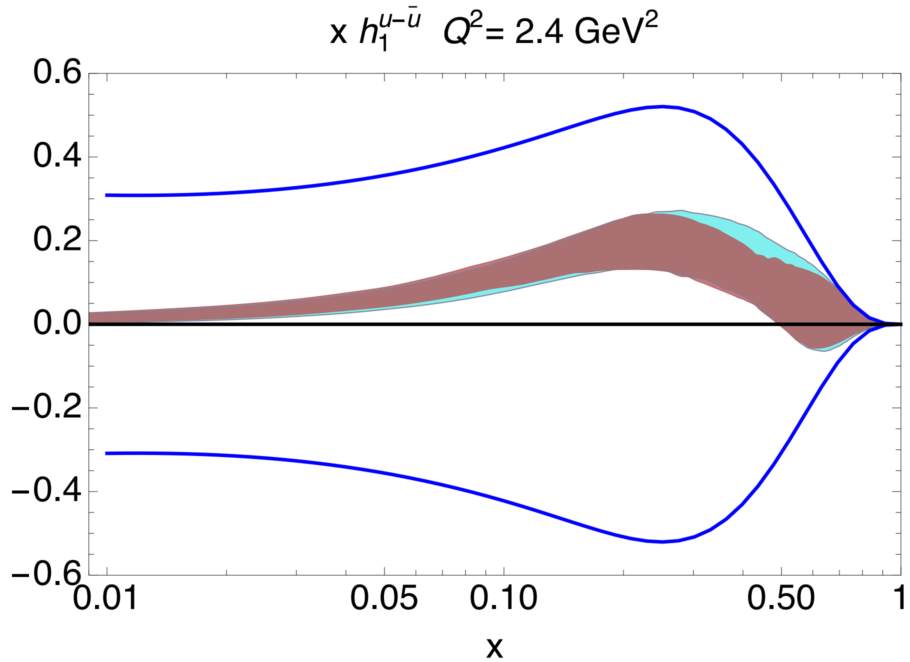
up

insensitive to uncertainty on gluon D_1

down

sensitive to uncertainty on gluon D_1

sensitivity to th. uncertainty

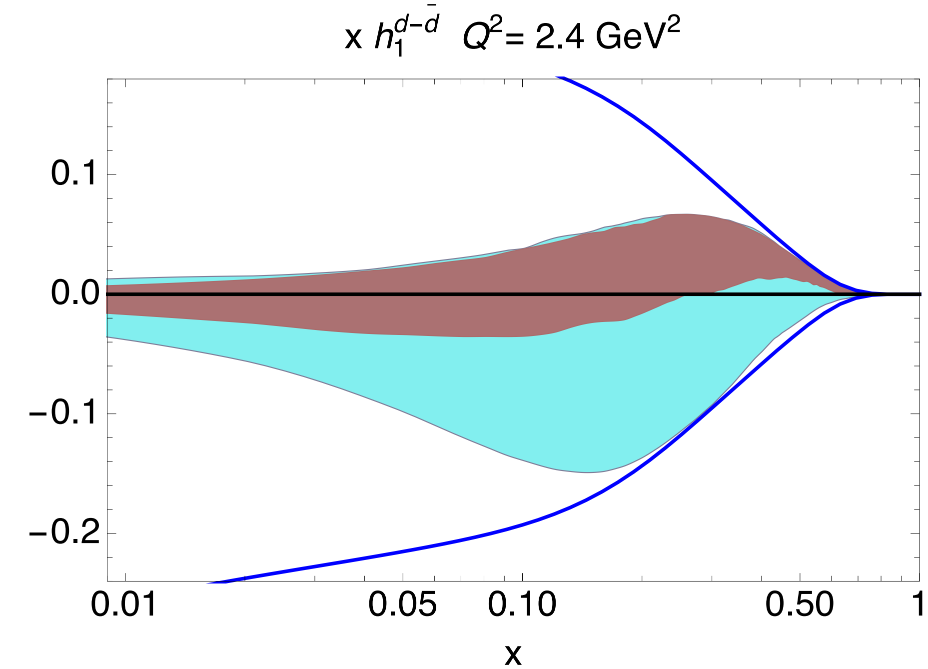


$D_1{}^g\,(Q_0) = 0$

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

global fit

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



up

insensitive to uncertainty on gluon D_1

down

sensitive to uncertainty on gluon D_1

p-p : u~d , gluon @LO but **SIDIS :** u~(8x)d , gluon @NLO

need data from target more sensitive to down (deuteron, ^{3}He) and
need data from multiplicities in p+p → (ππ)+X

The tensor "charge" of the proton

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

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

tensor charge connected to tensor operator

$$\begin{aligned}\langle P, S_p | \, \bar{q} \sigma^{\mu\nu} q \, | P, S_p \rangle &= (P^\mu S_p^\nu - P^\nu S_p^\mu) \, \delta q \\ &= (P^\mu S_p^\nu - P^\nu S_p^\mu) \int dx \, h_1^{q-\bar{q}}(x,Q^2)\end{aligned}$$

compute on lattice

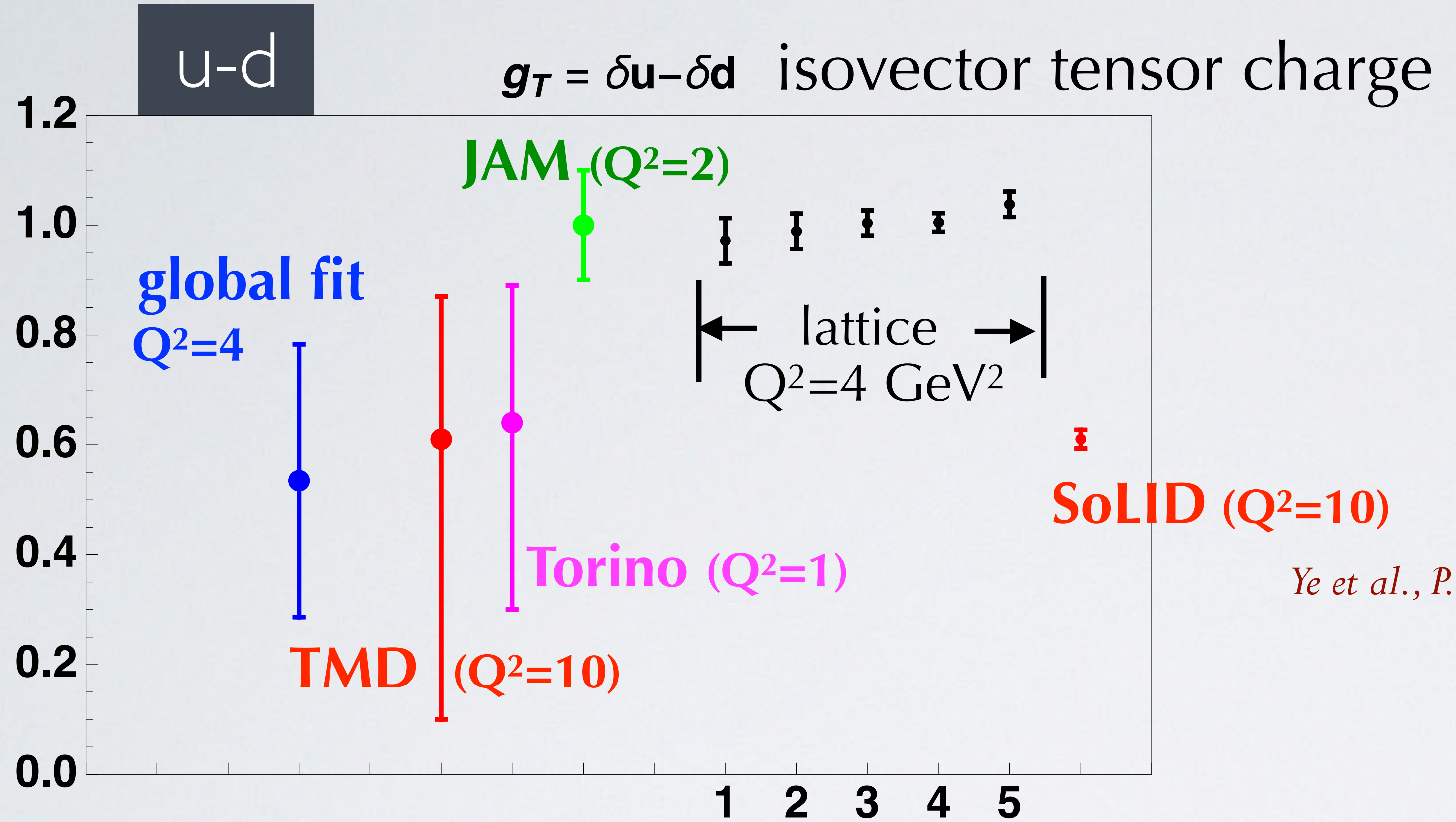
lattice δq

preferably the isovector $g_T = \delta u - \delta d$
(cancellation of "disconnected" diagrams)

extract transversity from data with transversely polarized protons

pheno δq

Results for our global fit



1) "MILC" '19 *Hasan et al., arXiv:1903.06487*

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

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

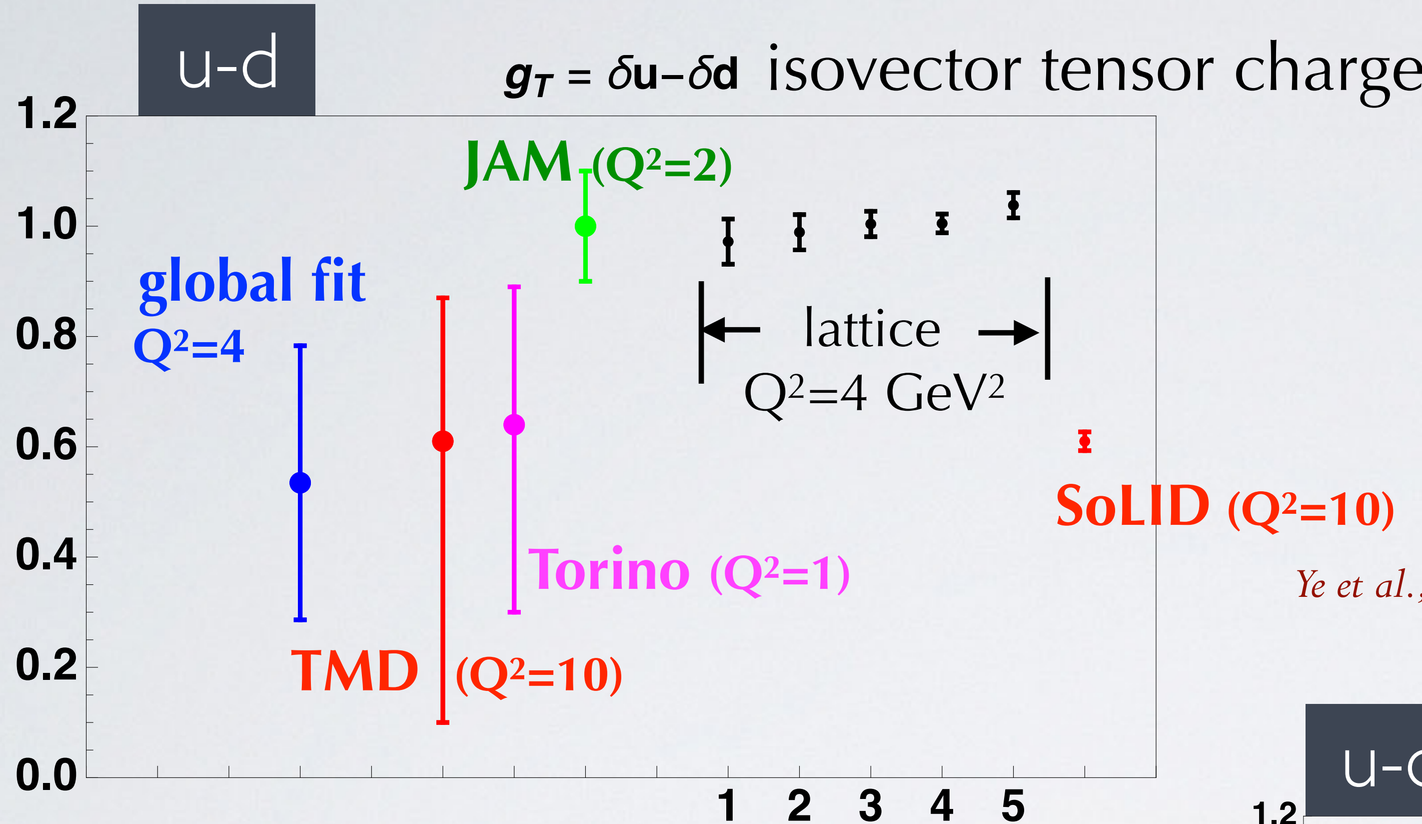
4) RQCD '14 *Bali et al., P.R. D**91** (15)*

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

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

Torino, TMD, JAM from SIDIS data only

Results for our global fit



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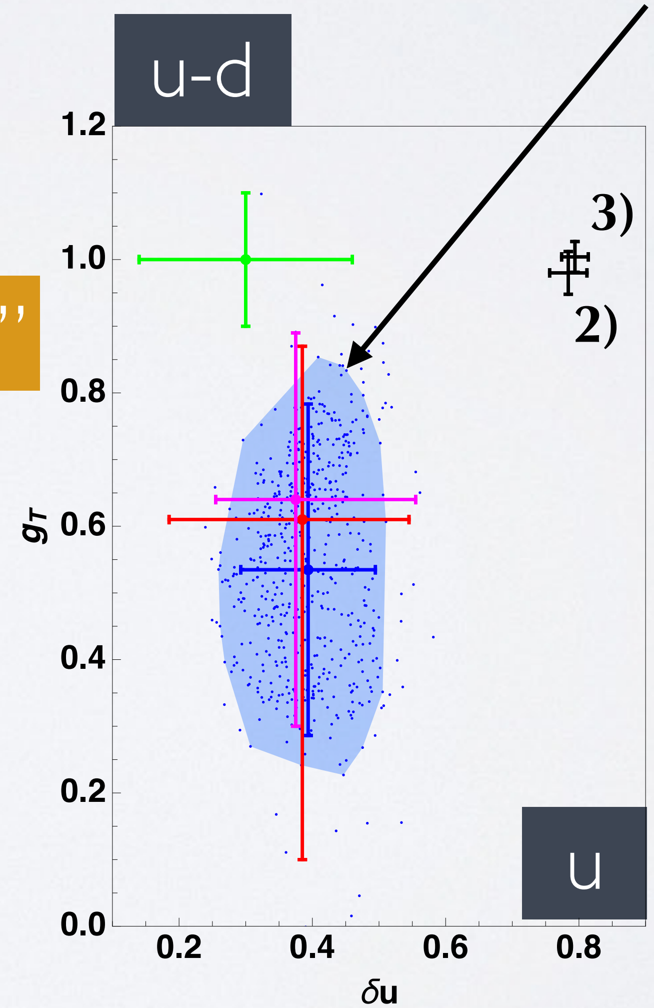
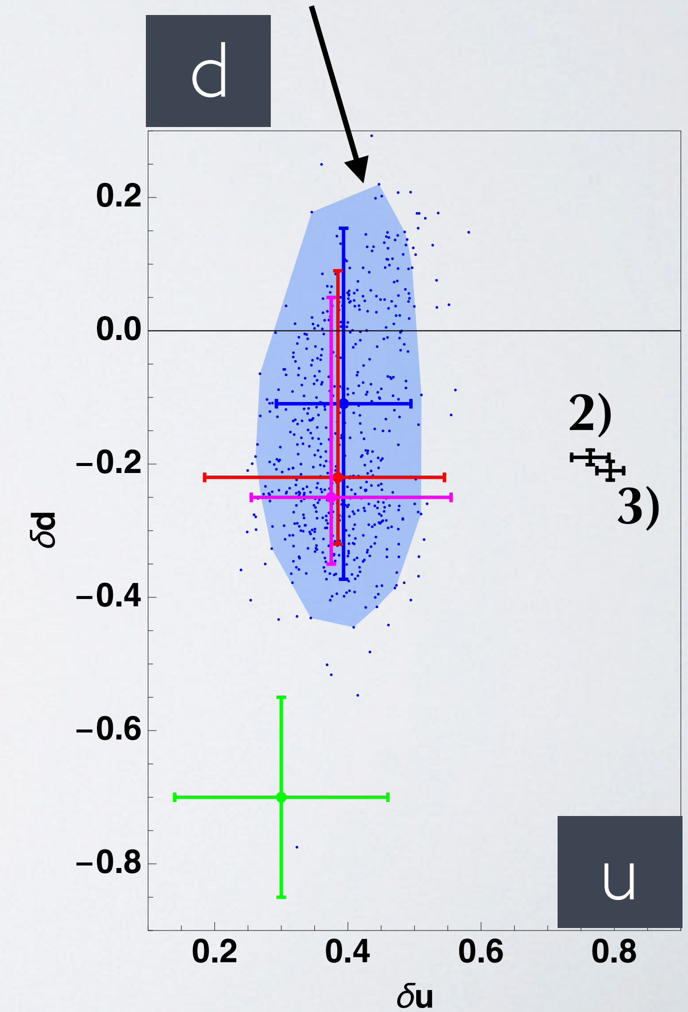
Torino, TMD, JAM from SIDIS data only

JAM includes constraint from "lattice g_T"

*Lin et al., P.R.L. **120** (18) 152502*

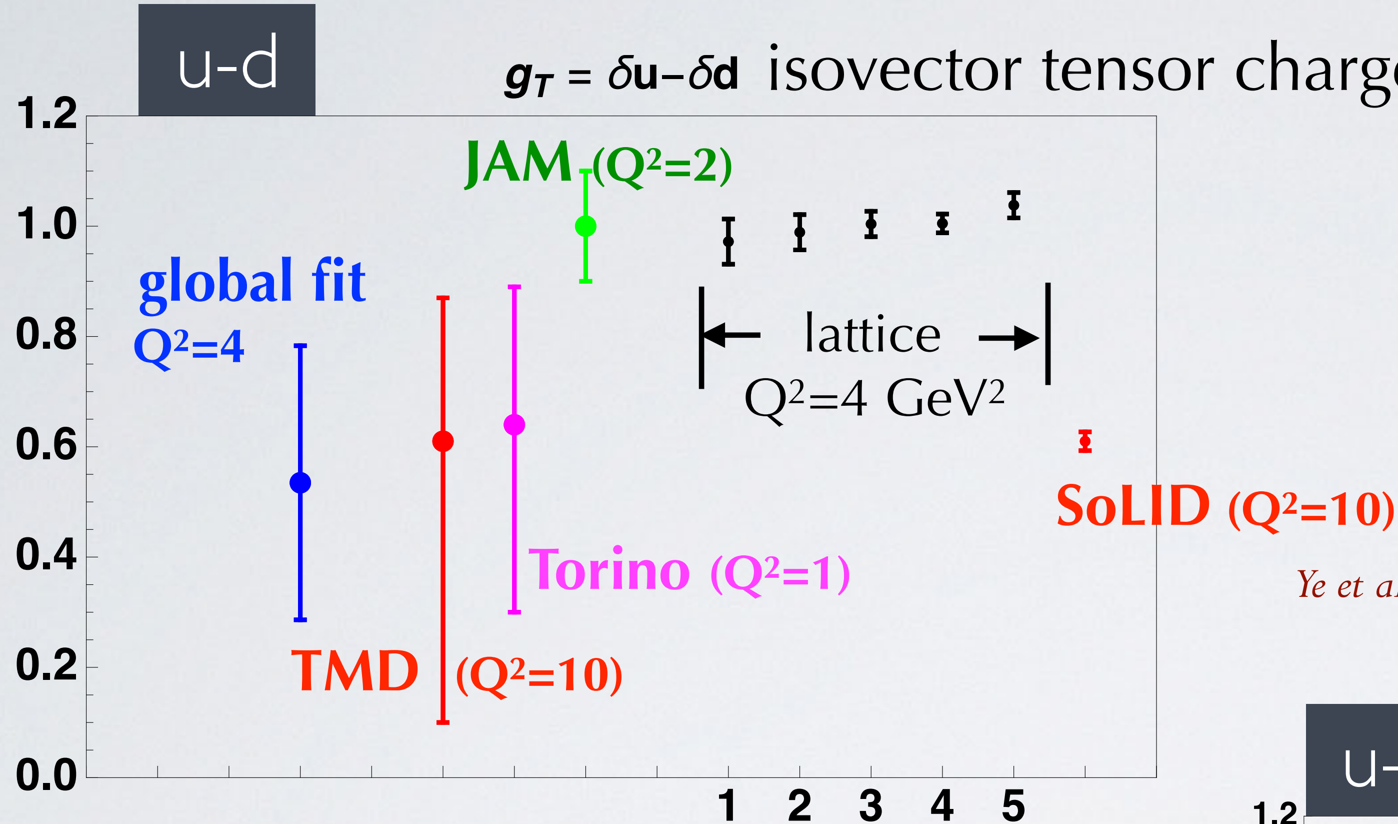
shaded area = 90% C.L.





But if we look also at δu and δd …

Results for our global fit



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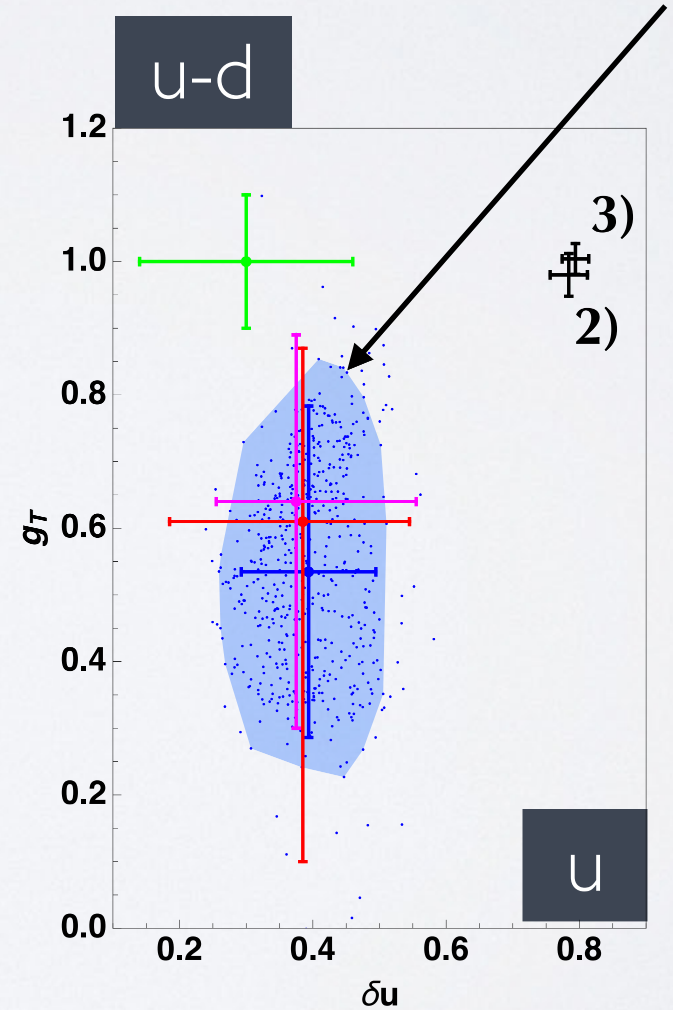
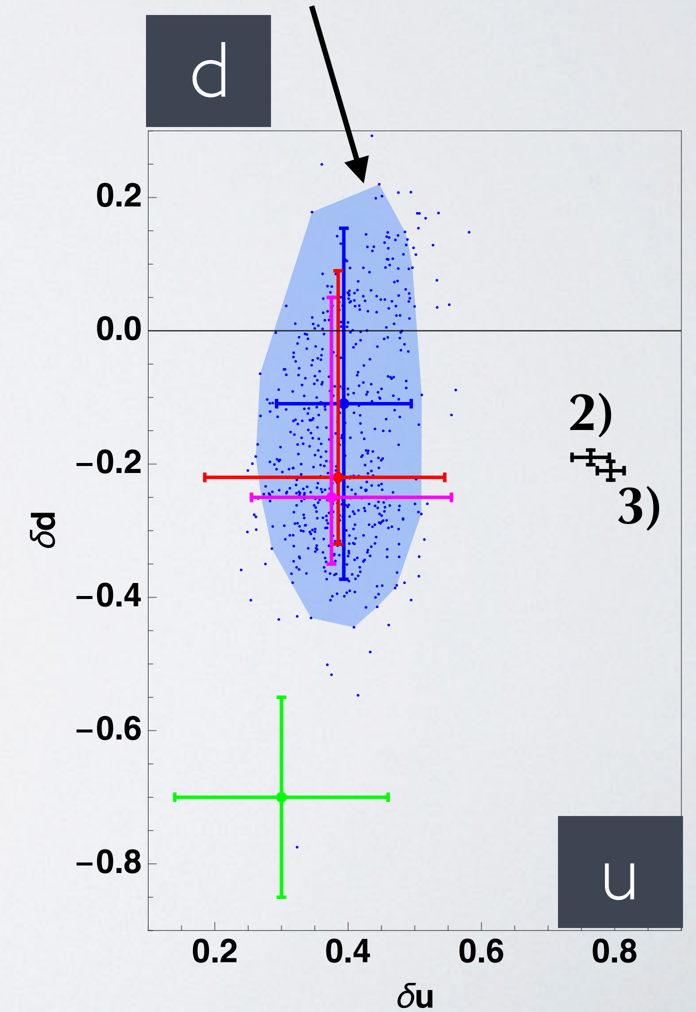




Torino, TMD, JAM from SIDIS data only

JAM includes constraint from "lattice g_T"

*Lin et al., P.R.L. **120** (18) 152502*

no simultaneous compatibility between "pheno δq" and "lattice δq"

pheno vs. lattice tensor charge

main problem of "pheno δq" is extrapolating outside data..

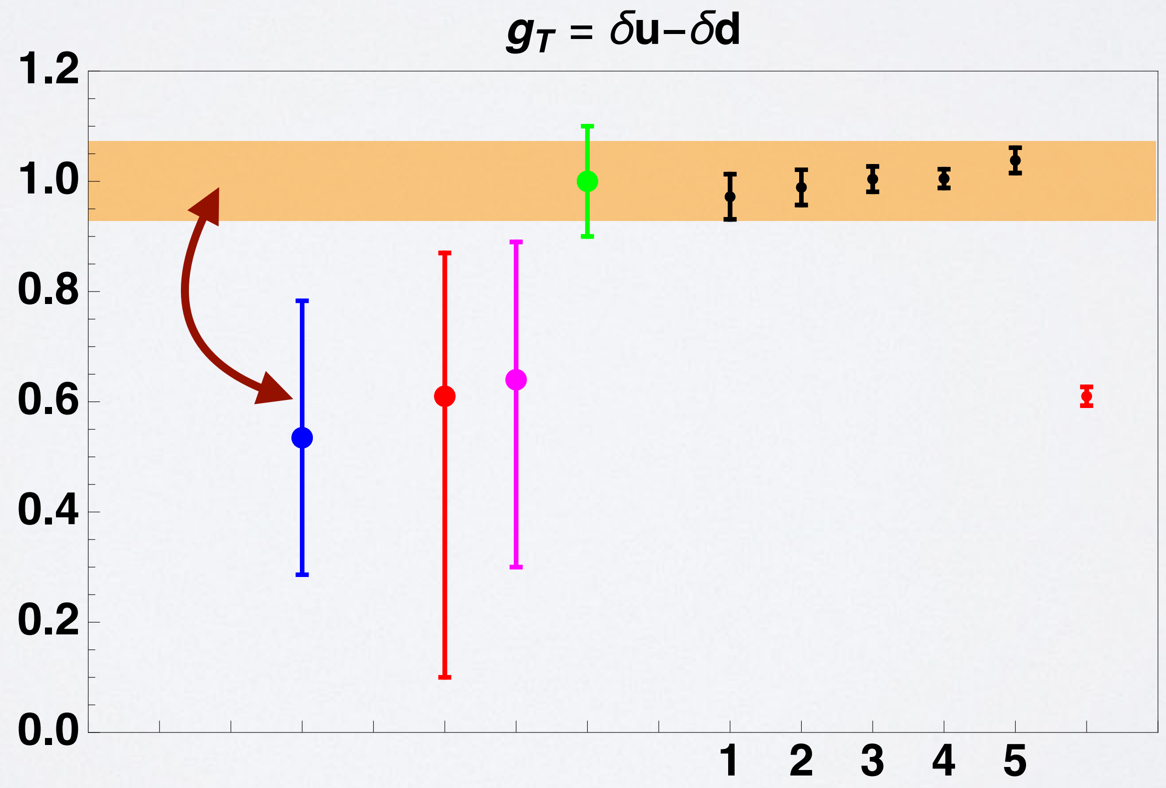
$$\delta q = \int_0^{x_{\min}} dx\, h_1^{q-\bar{q}} + \int_{x_{\min}}^{x_{\max}} dx\, h_1^{q-\bar{q}} + \int_{x_{\max}}^{1} dx\, h_1^{q-\bar{q}}$$

constraining "pheno g_T" with "lattice g_T"
as **JAM** Collaboration did ?

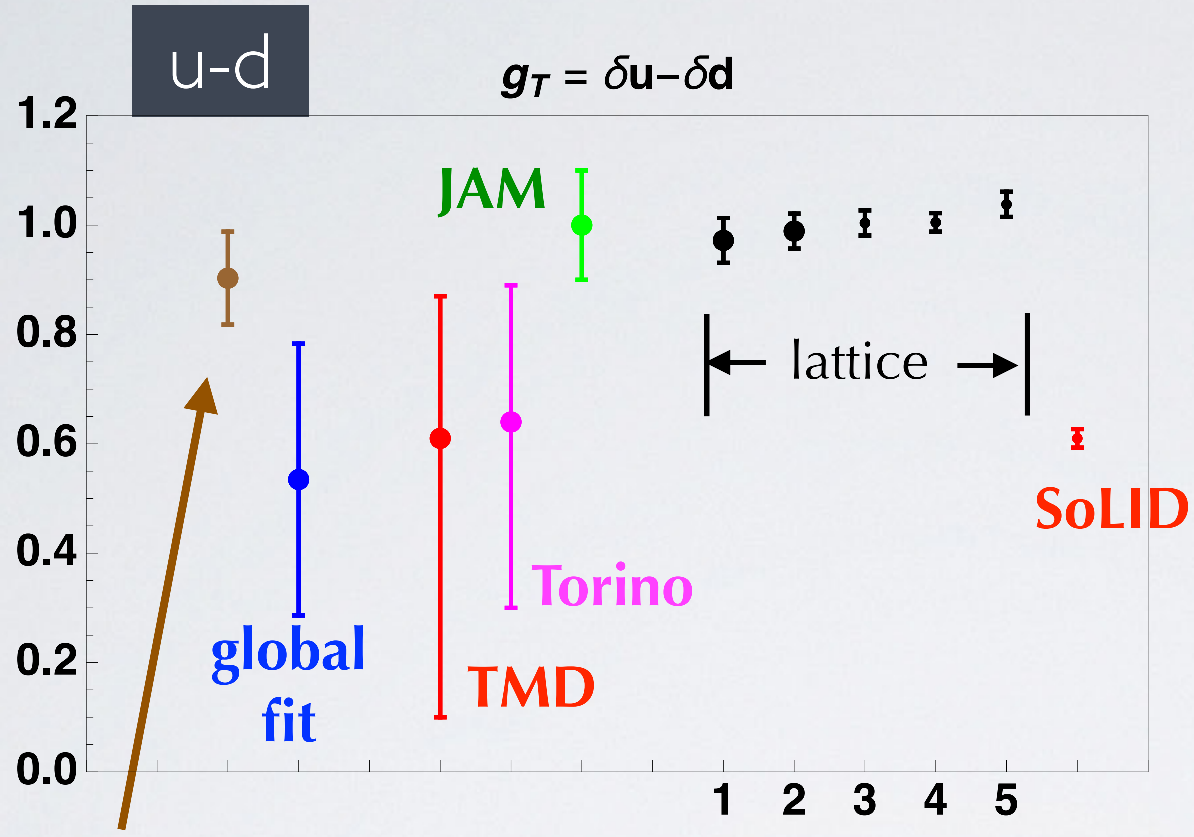
P.R.L. ***120*** *(18) 152502, arXiv:1710.09858*

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

are they compatible?

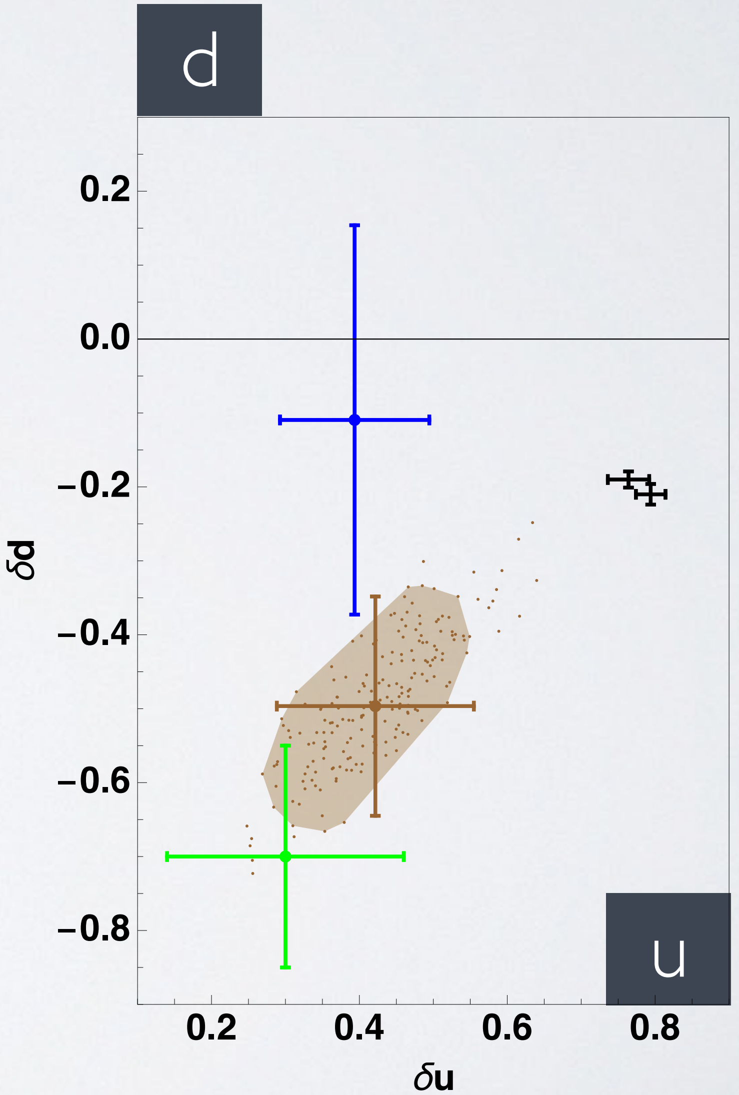


Constraining our global fit with "lattice g_T"



constraining **global fit** with lattice g_T

confirm JAM results:
constraining "pheno g_T" with "lattice gT"
at the price of
incompatibility for δu and δd



Tension "pheno" - "lattice"

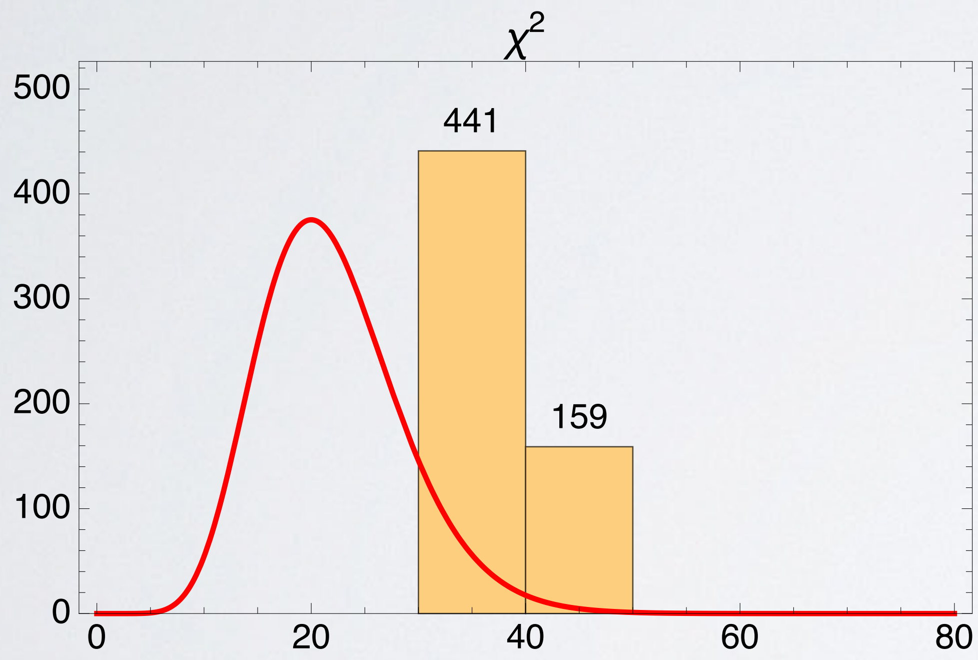
if we constrain our **global fit** with lattice results for all components of tensor charge (up, down, isovector) the χ^2 clearly deteriorate

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

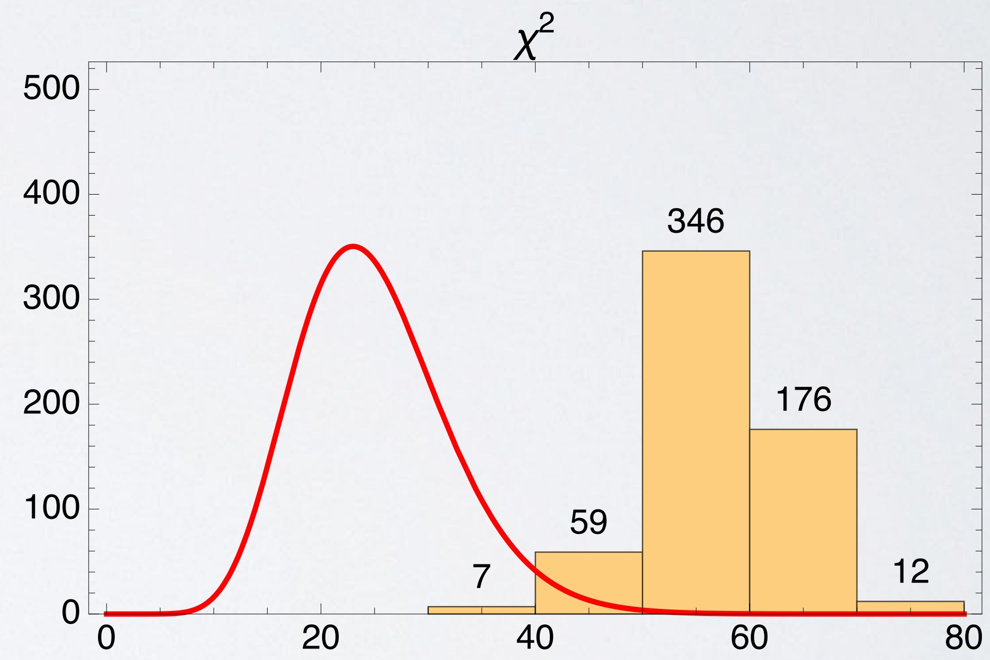
$\overline{\delta u}^{latt} = 0.782 \pm 0.031$

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

$\chi^2/dof = 1.76 \pm 0.11$



$\chi^2/dof = 2.29 \pm 0.25$



22 d.o.f.

probability density function of χ^2 distribution for

25 d.o.f.

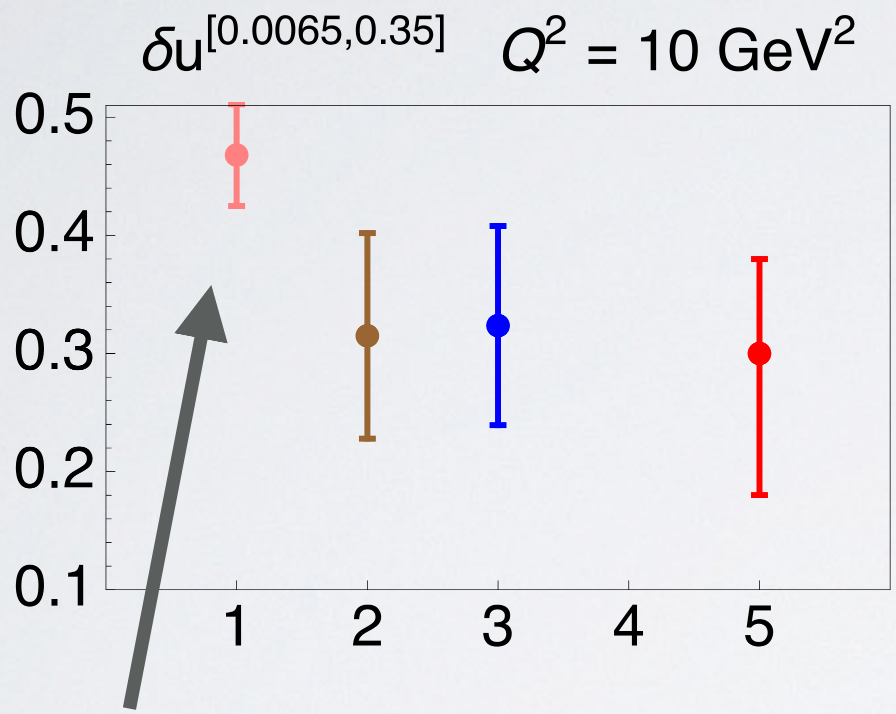
statistically very unlikely ....

truncated tensor charge

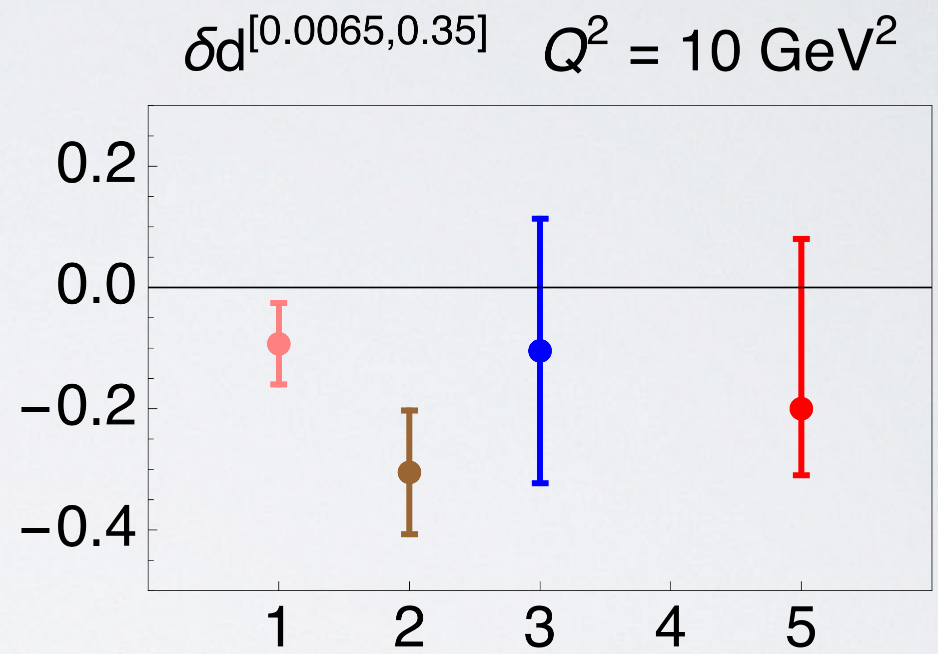
truncated

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

up



down



expect stability
when integrating
on x-range of
exp. data…

1) global fit + constrain g_T , δu , δd

2) global fit + constrain g_T

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

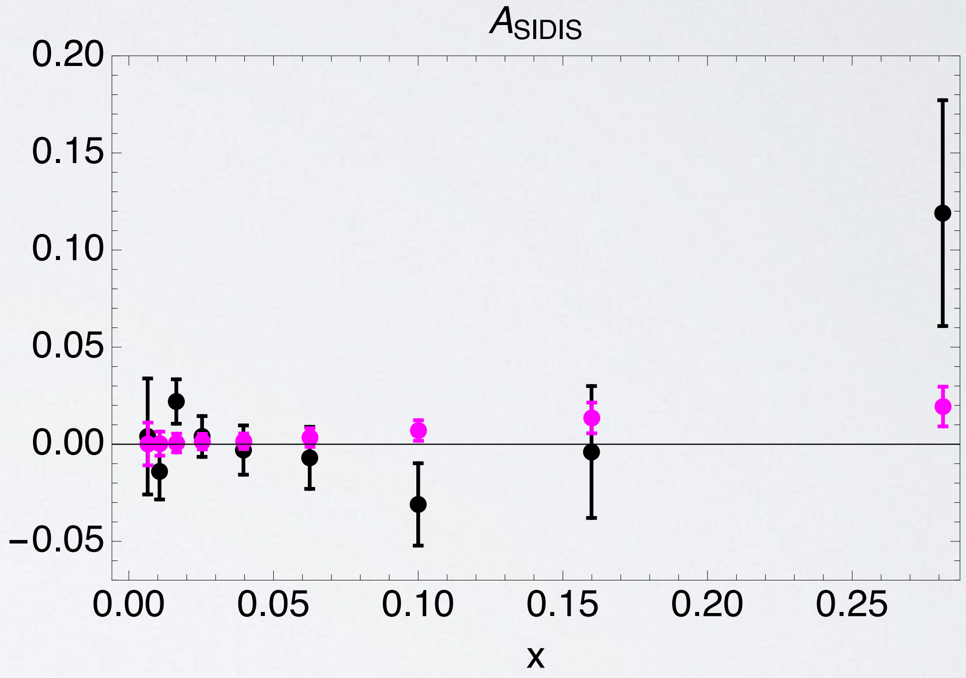
5) "TMD fit"   *Kang et al., P.R. D**93** (16) 014009*

Compass pseudo-data

add to data of our global fit
a new set of SIDIS pseudo-data for **deuteron** target

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

pseudodata
arXiv:1812.07281

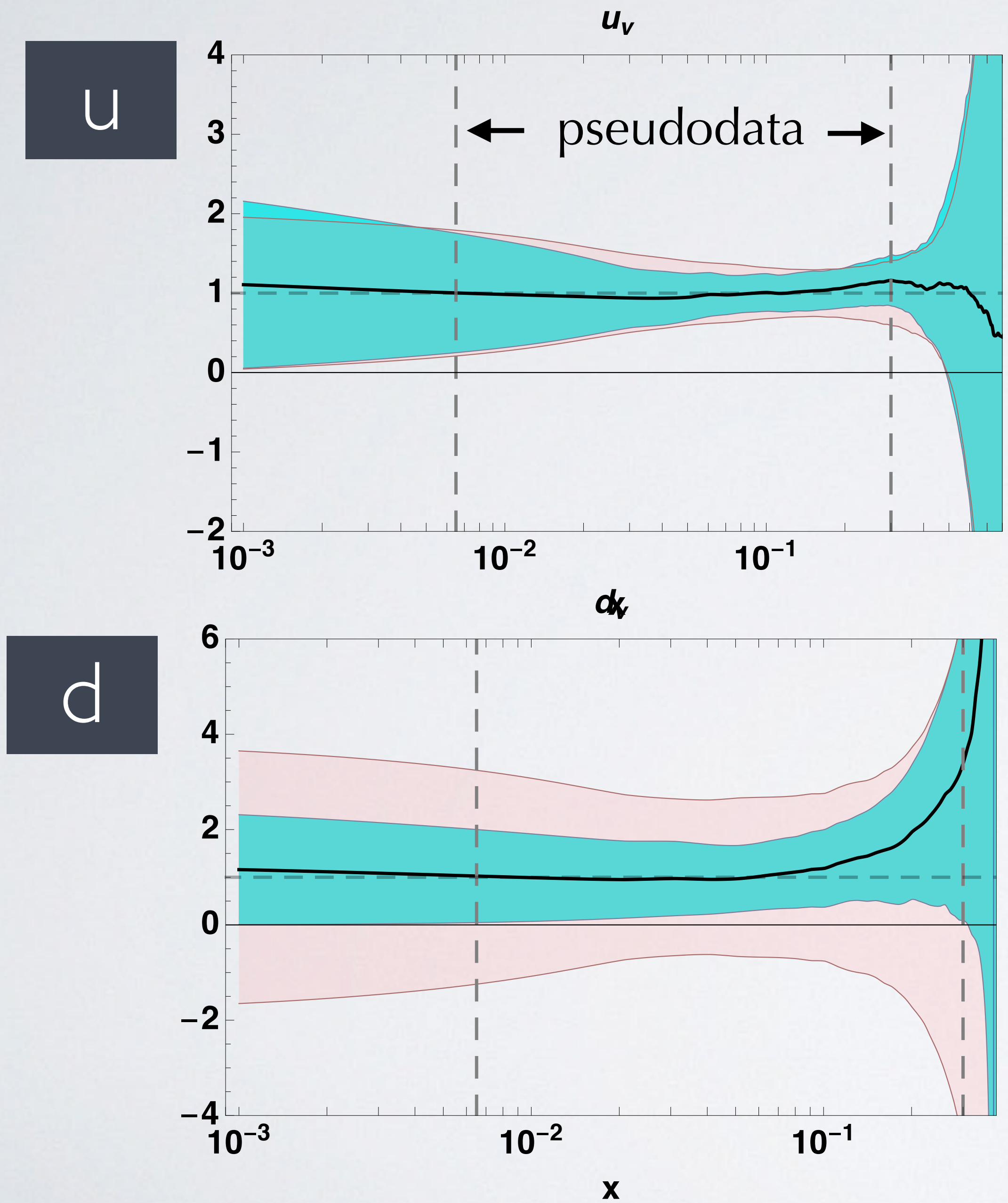


statistical error ~ 0.6 x [error in 2010 proton data]
<A> = average value of replicas in previous global fit

study impact on precision of previous global fit

Adding Compass pseudodata

range [0.0065, x , 0.28]



$$\left[\frac{h_{1min}}{\langle h_1\rangle_{\substack{global\\fit}}} \quad \frac{\langle h_1\rangle}{\langle h_1\rangle_{\substack{global\\fit}}} \quad \frac{h_{1max}}{\langle h_1\rangle_{\substack{global\\fit}}} \right]$$

deuteron target
→ better precision on down

global fit

global fit + pseudodata

CLAS12 pseudo-data

add to data of our global fit
a new set of SIDIS pseudo-data for **proton** target

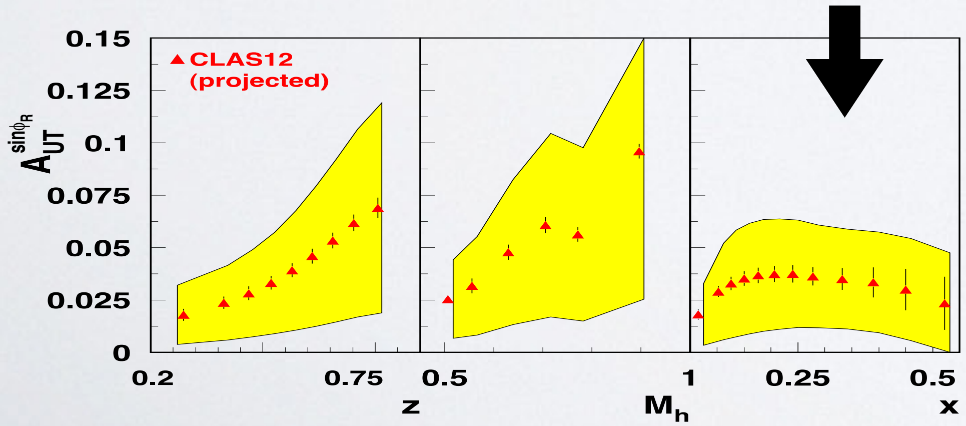
COMPASS — *Adolph et al., P.L.* ***B713*** *(12)*

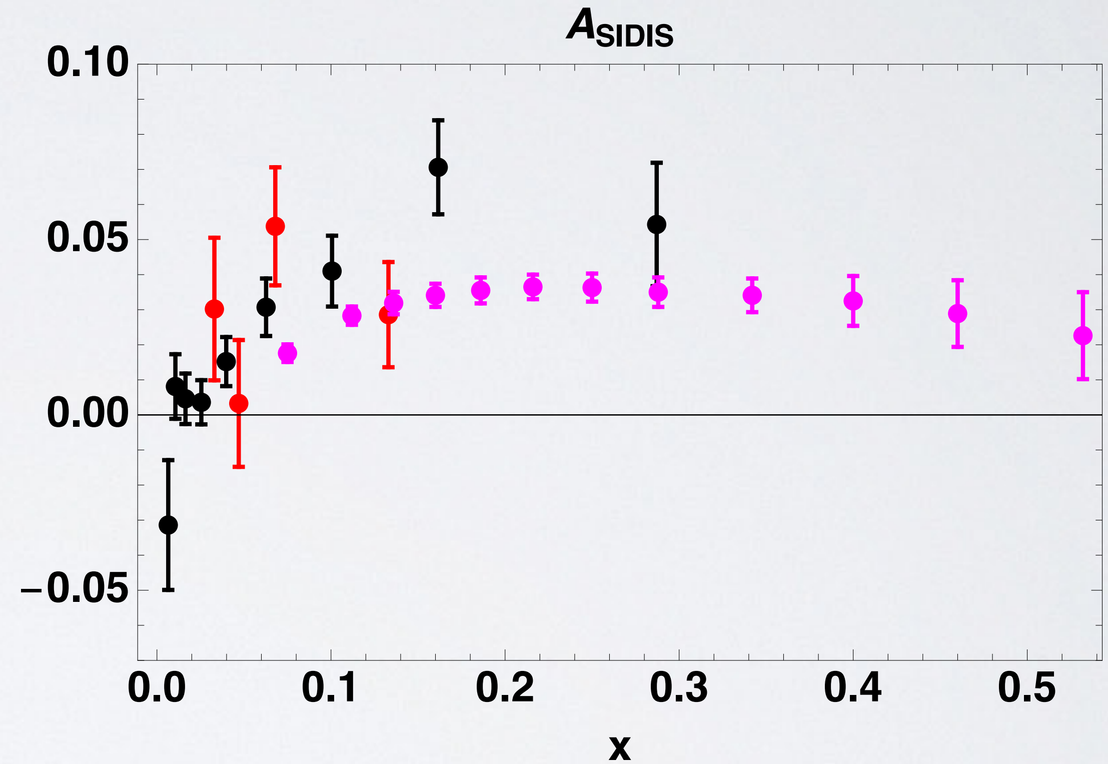
hermes — *Airapetian et al.,*
JHEP ***0806*** *(08) 017*

clas — pseudodata C12-12-009

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

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





study impact on precision
of published global fit

Adding CLAS12 pseudodata

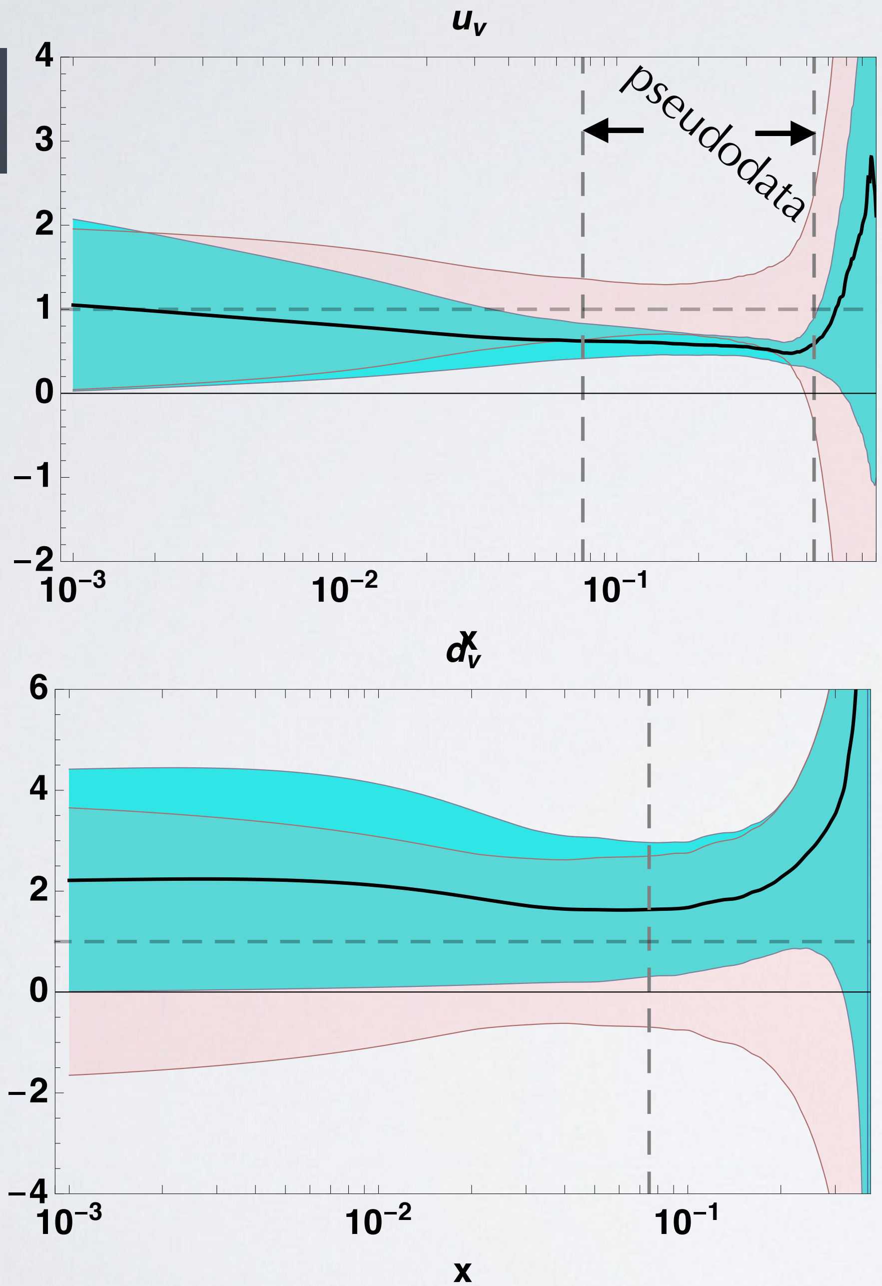
range $[0.075, \; x \;, 0.53]$

clas

proposal C12-12-009

u

d



$$\left[\; \frac{h_{1\min}}{\langle h_1 \rangle_{\substack{\text{global}\\ \text{fit}}}} \quad \frac{\langle h_1 \rangle}{\langle h_1 \rangle_{\substack{\text{global}\\ \text{fit}}}} \quad \frac{h_{1\max}}{\langle h_1 \rangle_{\substack{\text{global}\\ \text{fit}}}} \; \right]$$

proton target
→ better precision on up

global fit

global fit + pseudodata

PRELIMINARY

add to data of our global fit
the set of STAR data at s=500 GeV^2

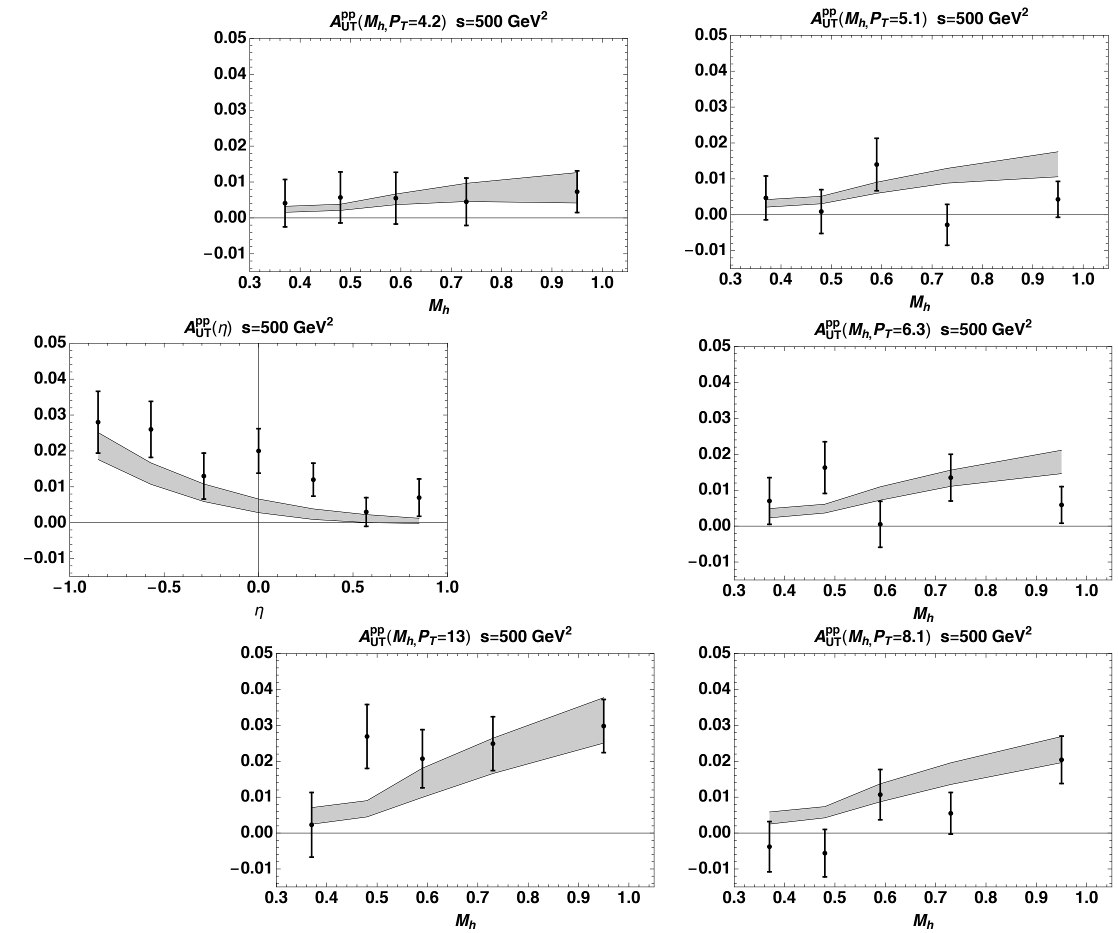
Adamczyk et al. (STAR), P.L. ***B780*** *(18) 332*

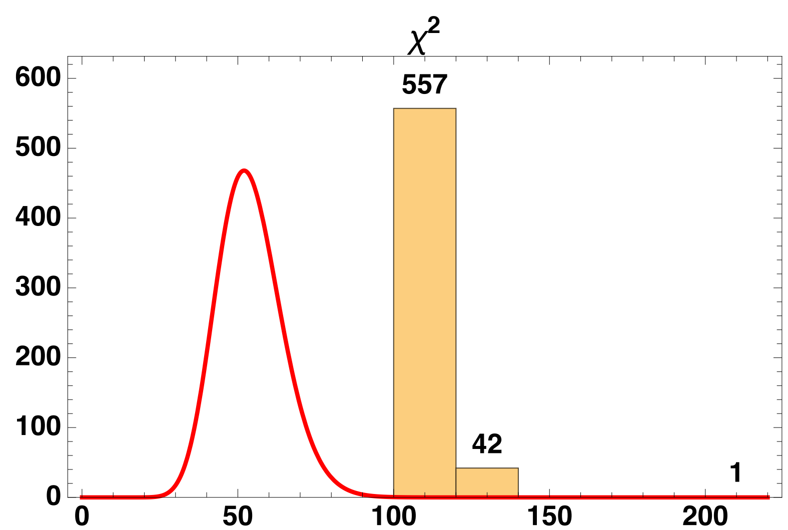
SIDIS **22** data points

pp collisions

run 2006 (s=200 GeV^2) — **10** indep. data points

run 2011 (s=500 GeV^2) — **32** indep. data points





(for χ^2/dof = 1 perfect overlap)

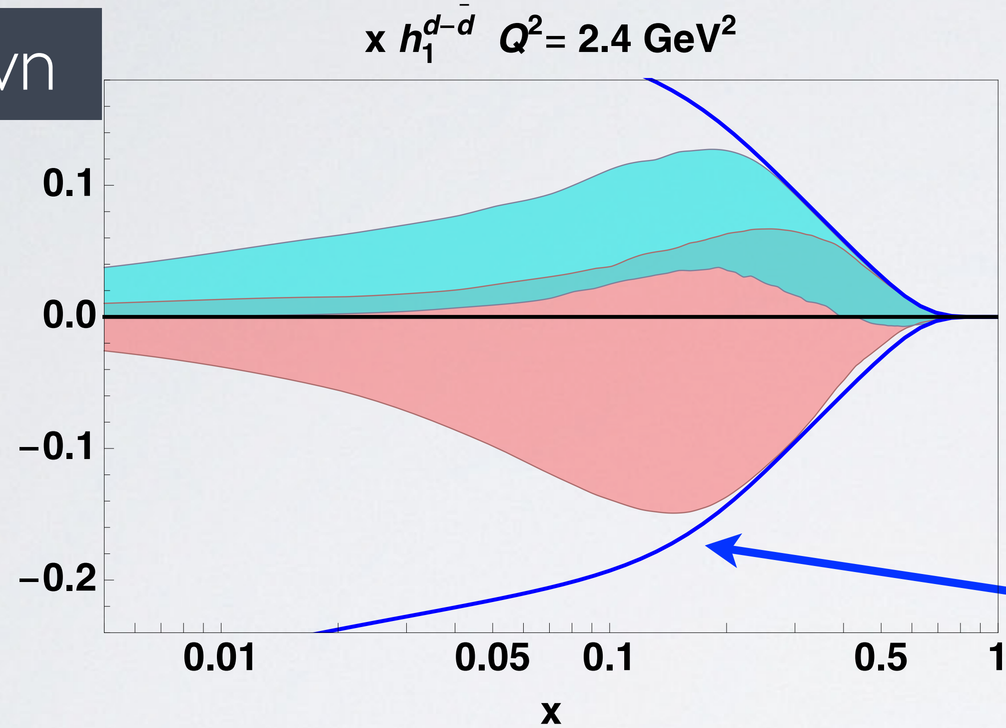
probability density function of χ^2 distribution for 54 d.o.f.

χ^2/dof = 2.12 ± 0.09

PRELIMINARY

up basically not modified

down



Soffer bound

global fit

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

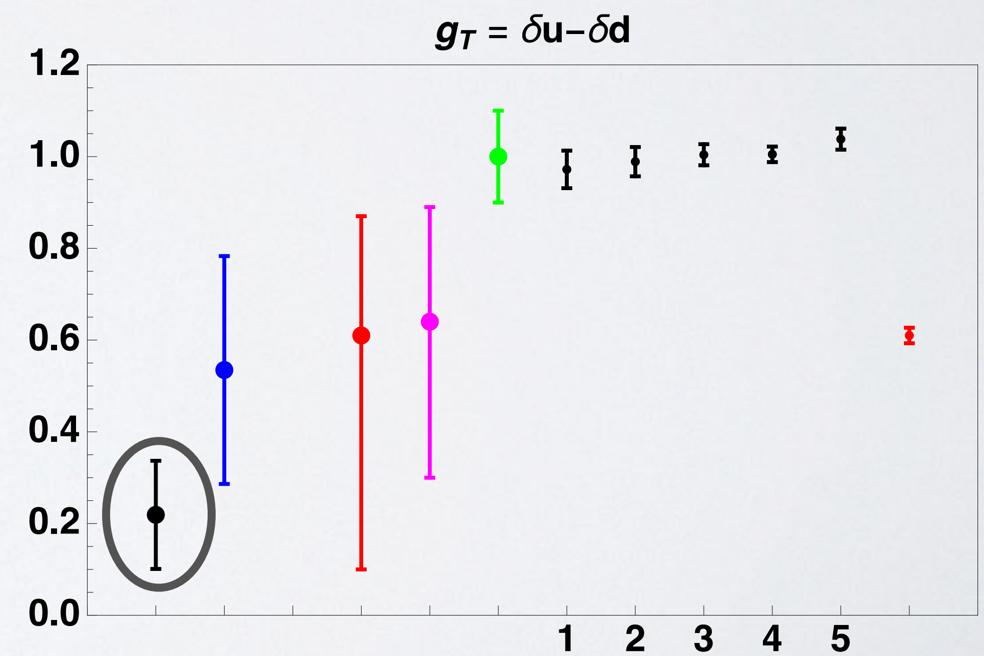
global fit + STAR s=500 data

more precise and fully positive

→ positive δd

→ smaller $g_T = \delta u - \delta d$!

unexpected opposite trend : need h_1 for sea quarks ?



Conclusions

Sivers

- **first extraction** using unpolarized TMD f_1 & D_1 extracted from global fit of data in a **consistent TMD framework**
- similar to other extractions but **more realistic** description of **uncertainties**
- **tomography** of transversely polarized proton

Transversity

- first **global fit** for chiral-odd transversity
- **NO** simultaneous **compatibility with lattice** for tensor charge in up, down, and isovector channels
- adding **Compass** and **CLAS12** SIDIS **pseudodata** increases precision of down and up, respectively
- adding **STAR** s=500 data gives **puzzling** results: need **sea quarks** ?

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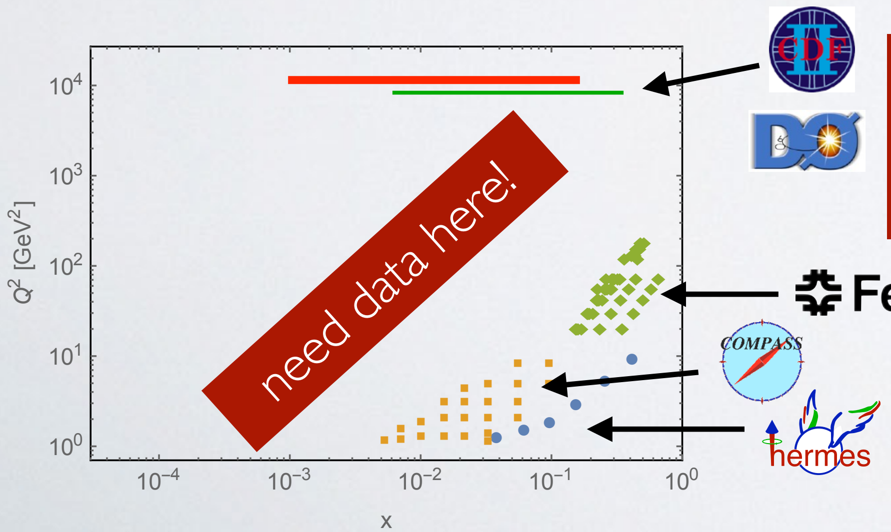

ultimate resource:
EIC