

IWHSS 2020

XVII International Workshop
on Hadron Structure
and Spectroscopy

Spectroscopy
Spin and 3D Structure of the Nucleon
Fragmentation Functions
Generalized Parton Distributions
Emergence of Hadronic Mass
Proton Radius
New experimental techniques

☞ <https://agenda.infn.it/event/20446>
✉ iwhss2020@ts.infn.it

Trieste
16-18 November 2020

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Last news about
Transversity
& **Sivers**
functions

Marco Radici
INFN - Pavia



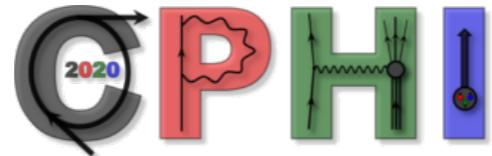
Organized by
INFN - Division of Trieste, in collaboration with
Physics Department of the Trieste University,
in the context of the proESOF initiative

Sponsored by
INFN, ECSAC, Physics Consortium, proESOF, COMPASS



New developments despite Covid-19

talk on
Sivers & transversity



my last trip to a workshop
before lockdown



several developments
despite Covid-19

talk on
Sivers & transversity



4th YR
workshop
19-21 Nov.



<https://indico.bnl.gov/event/9913/>

The “exotic” parton densities

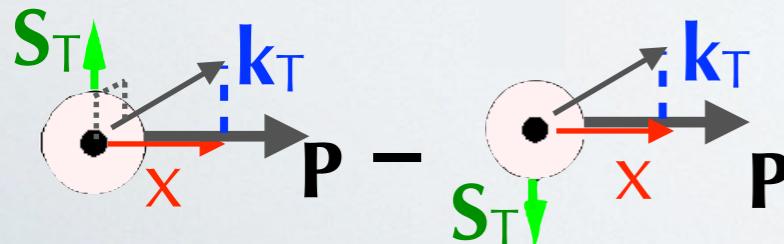
TMDs @twist=2

quark polarization

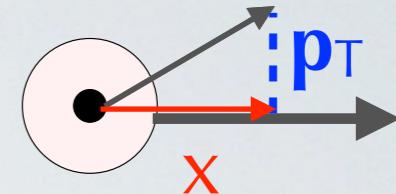
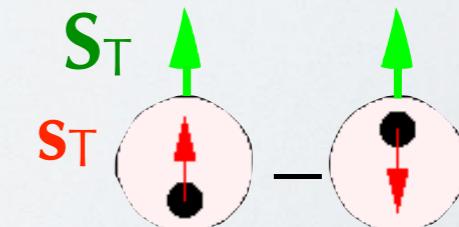
	U	L	T
U	f_1		$h_{1\perp}$
L		g_{1L}	$h_{1L\perp}$
T	$f_{1T\perp}$	g_{1T}	$h_1 \ h_{1T\perp}$

prototype of
naïve T-odd structures

$$S_T \cdot (P \times k_T)$$



prototype of
chiral-odd structures



The EIC Golden and Silver Measurements



The EIC White Paper

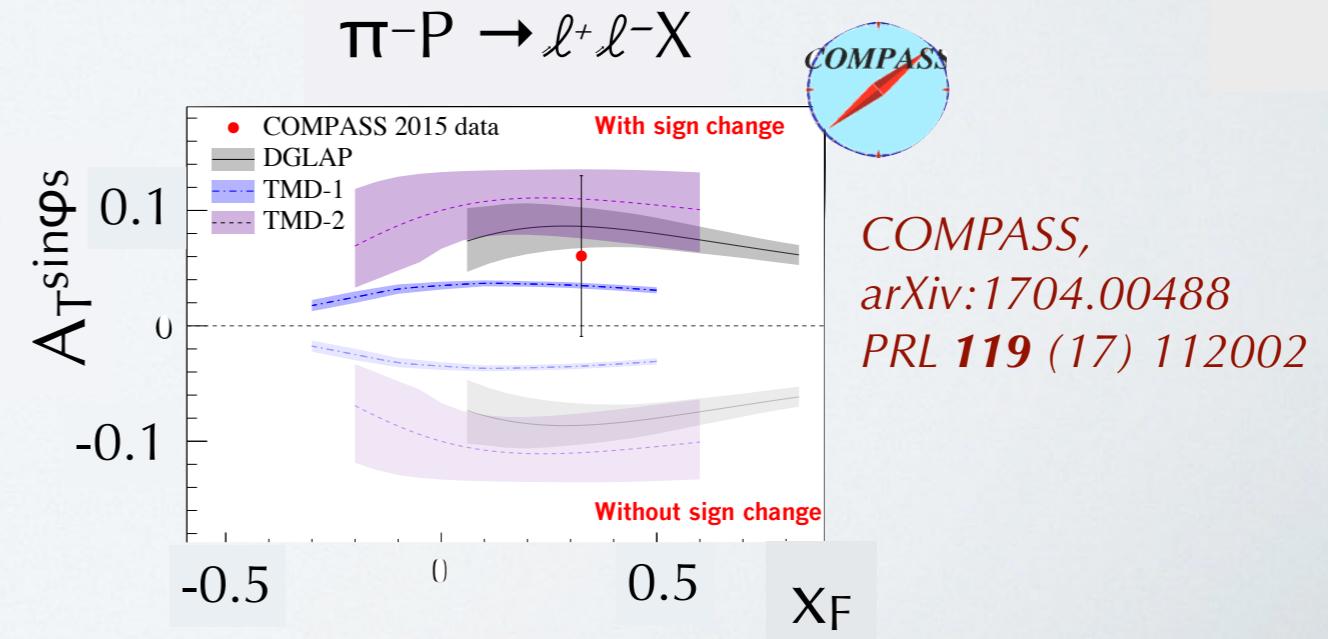
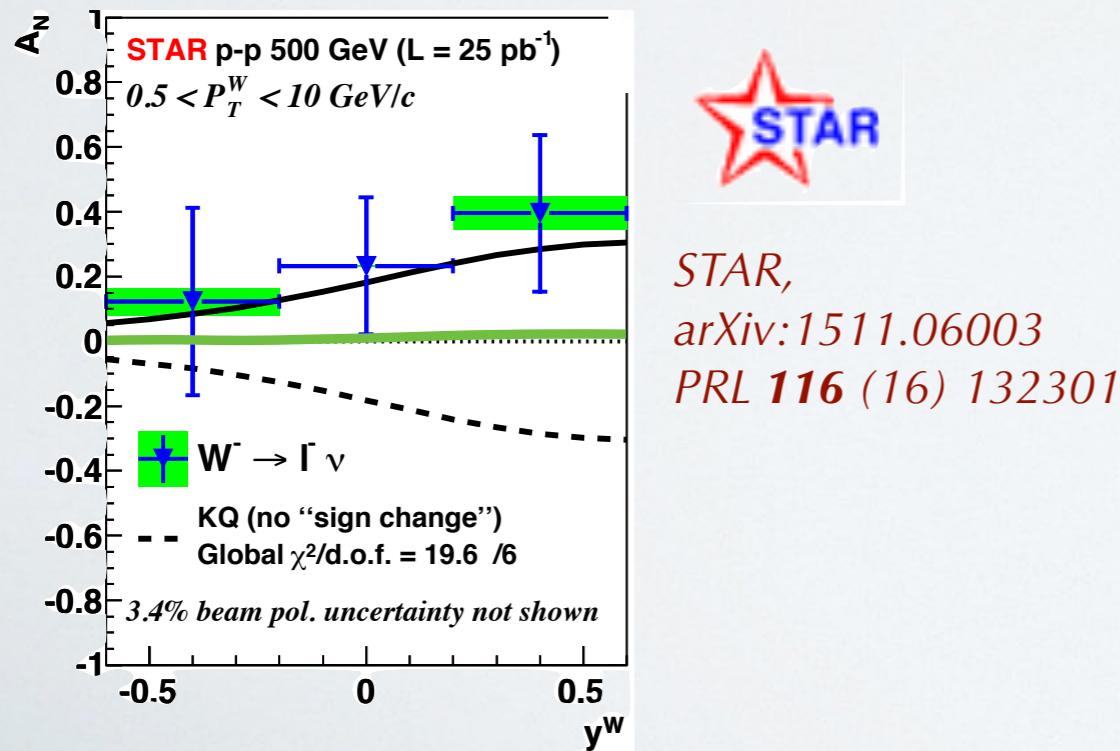
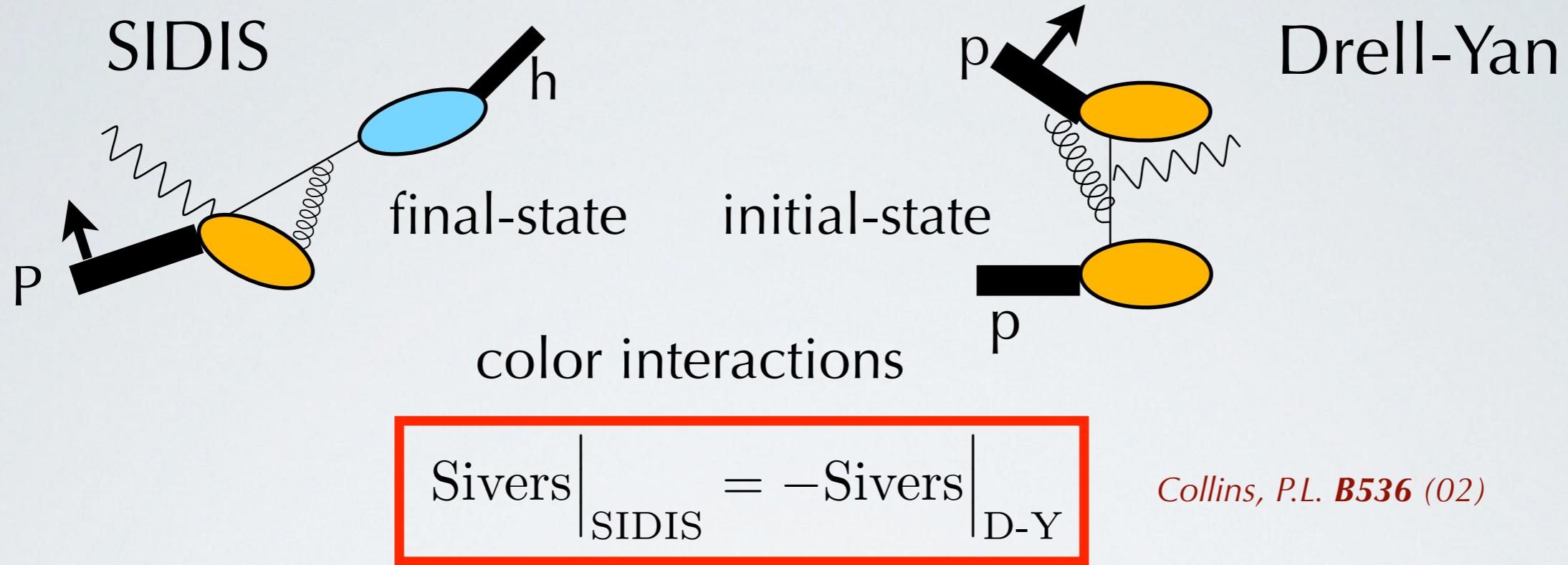
Accardi et al., E.P.J. A52 (16) 268, arXiv:1212.1701 , see also Boer et al., arXiv:1108.1713



Deliverables	Observables	What we learn
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations 3D Imaging of quark's motion: valence + sea 3D Imaging of gluon's motion QCD dynamics in a unprecedented Q^2 (P_{hT}) range
Chiral-odd functions: Transversity; Boer-Mulders	SIDIS with Transverse polarization	3 rd basic quark PDF: valence + sea, tensor charge Novel spin-dependent hadronization effect QCD dynamics in a chiral-odd sector with a wide Q^2 (P_{hT}) coverage

Table 2.2: Science Matrix for TMD: 3D structure in transverse momentum space: (upper) the golden measurements; (lower) the silver measurements.

Why Sivers: 1) predicted non-universality



Why Sivers: 2) Sivers \leftrightarrow quark total J

Ji, P.R.L. 78 (97) 610

Ji's sum rule

$$J_z^q(Q^2) = \frac{1}{2} \int_0^1 dx x [H^q(x, 0, 0; Q^2) + E^q(x, 0, 0; Q^2)]$$

model lensing funct. $L(x)$ + fit f_{1T^\perp}

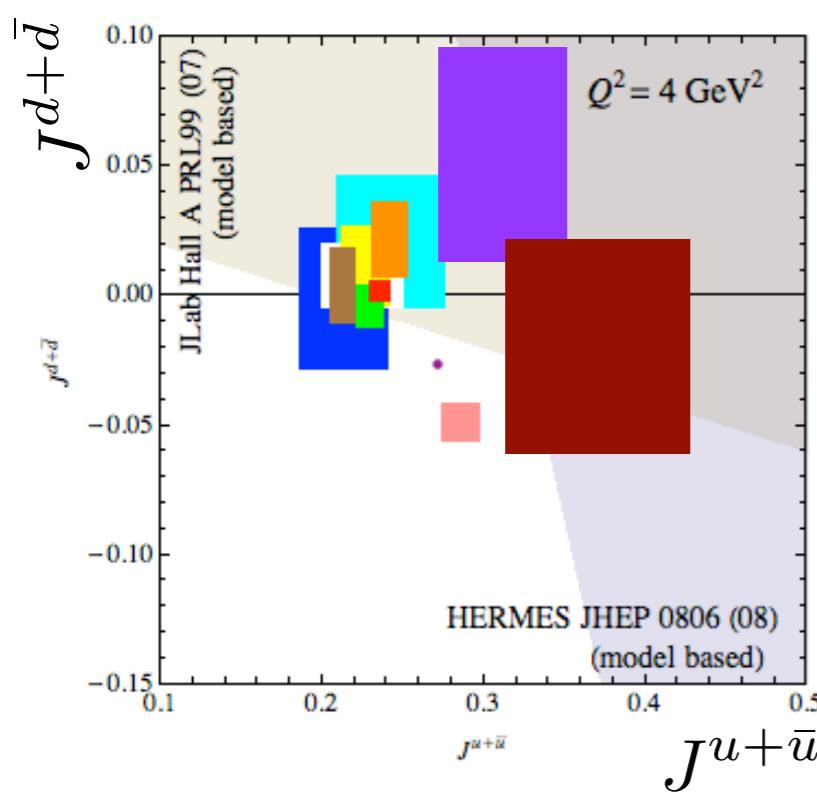
(applicable only to 2-body systems)

Pasquini, Rodini, Bacchetta, PR D100 (19) 054039

$$\int d\mathbf{k}_T f_{1T^\perp}^{\perp q}(x, \mathbf{k}_T; Q_L^2) = -L(x) E^q(x, 0, 0; Q_L^2)$$

distortion in momentum space \longleftrightarrow distortion in position space

Burkardt, P.R. D66 (02) 114005



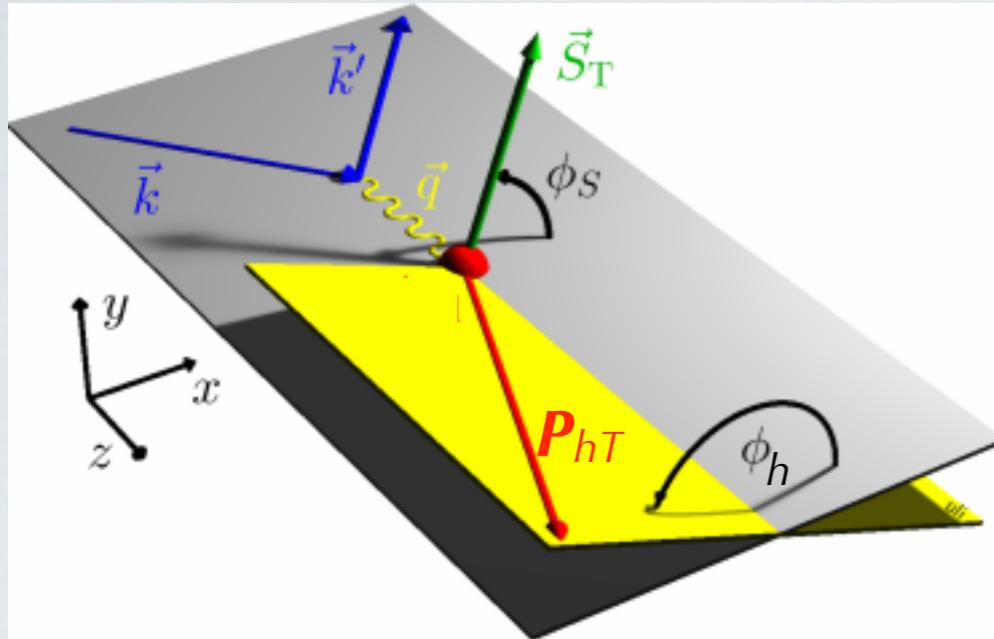
- [cyan square] Goloskokov & Kroll, EPJ C59 (09) 809
- [white square] Diehl & Kroll, E.P.J. C73 (13) 2397
- [brown square] Diehl et al., EPJ C39 (05) 1
- [purple square] Guidal et al., PR D72 (05) 054013
- [pink square] Liuti et al., PRD 84 (11) 034007
- [orange square] Bacchetta & Radici, PRL 107 (11) 212001
- [blue square] LHPC-1, PR D77 (08) 094502
- [red square] LHPC-2, PR D82 (10) 094502
- [green square] QCDSF, arXiv:0710.1534
- [yellow square] Wakamatsu, EPJ A44 (10) 297
- [purple square] Alexandrou et al., arXiv:1706.02973
- [dark red square] Deka et al., arXiv:1312.4816

models
of
GPD

color lensing

lattice

the Sivers Spin Asymmetry in SIDIS



$$A_T^{\sin(\phi_h - \phi_S)} \propto \frac{f_{1T}^\perp \otimes D_1}{f_1 \otimes D_1}$$

long record of extractions of the
Sivers moment $f_{1T}^{\perp(1)}(x)$:

Vogelsang & Yuan, P.R. **D72** (05) 054028
Collins et al., P.R. **D73** (06) 014021
Bacchetta & Radici, P.R.L. **107** (11) 212001
Anselmino, Boglione, Melis, P.R. **D86** (12) 014028
Aybat, Prokudin, Rogers, P.R.L. **108** (12) 242003
Sun & Yuan, P.R. **D88** (13) 034016
Boer, N.P. **B874** (13) 217
.....

Sivers recent extractions: JAM20

global fit of all Sivers/Collins SSA in SIDIS, DY, W/Z-production, e+e-

*Cammarota et al. (JAM20),
PR D102 (20) 054002, arXiv:2002.08384*

standard “extended parton model” : $TMD(x, k_T; Q) = PDF(x; Q) \text{Gauss}(k_T)$

$$\begin{array}{ccc} & \nearrow & \nearrow \\ & \text{DGLAP evo} & \text{no evo} \end{array}$$

SIDIS DY W/Z

SIDIS cuts => total **517** SSA pts: **126 + 12 + 17** Sivers

$Q^2 \geq 1.6 \text{ GeV}^2$ $0.2 \leq z \leq 0.6$

$0.2 < P_{hT} < 0.9 \text{ GeV}$

$$\downarrow$$

$$A_T^{\text{Sivers}} \propto \frac{f_{1T}^\perp \otimes D_1}{f_1 \otimes D_1}$$

$$\uparrow$$

parameters fitted to HERMES π and K multiplicities

SIDIS cuts => total **807** pts

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$Q^2 \geq 1.6 \text{ GeV}^2 \quad 0.2 \leq z \leq 0.6$

$0.2 < P_{hT} < 0.9 \text{ GeV}$

↓

not all independent

$$A_T^{\text{Sivers}} \propto \frac{f_{1T}^\perp \otimes D_1}{f_1 \otimes D_1}$$

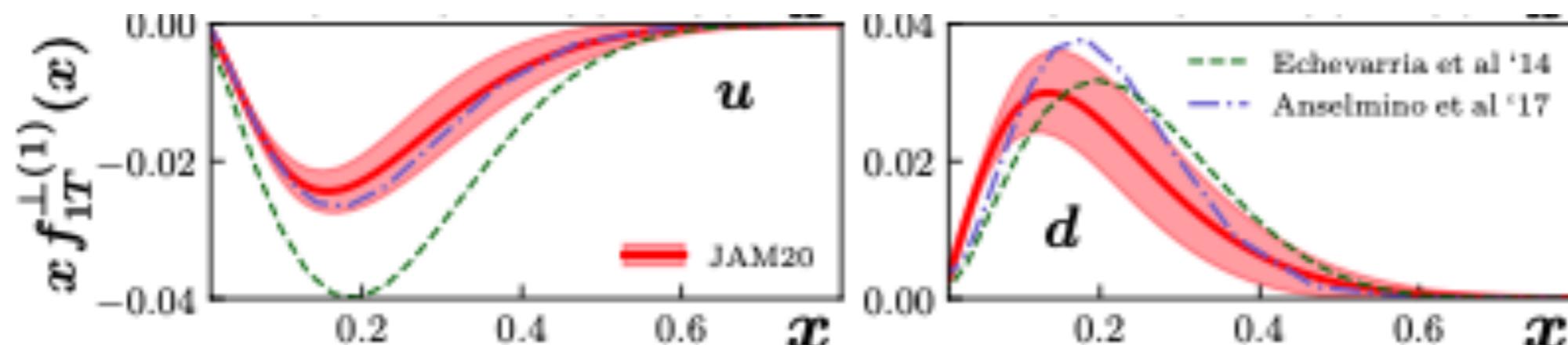
parameters fitted to HERMES π and K multiplicities
SIDIS cuts => total **807** pts

↑
DGLAP evo ↑
no evo



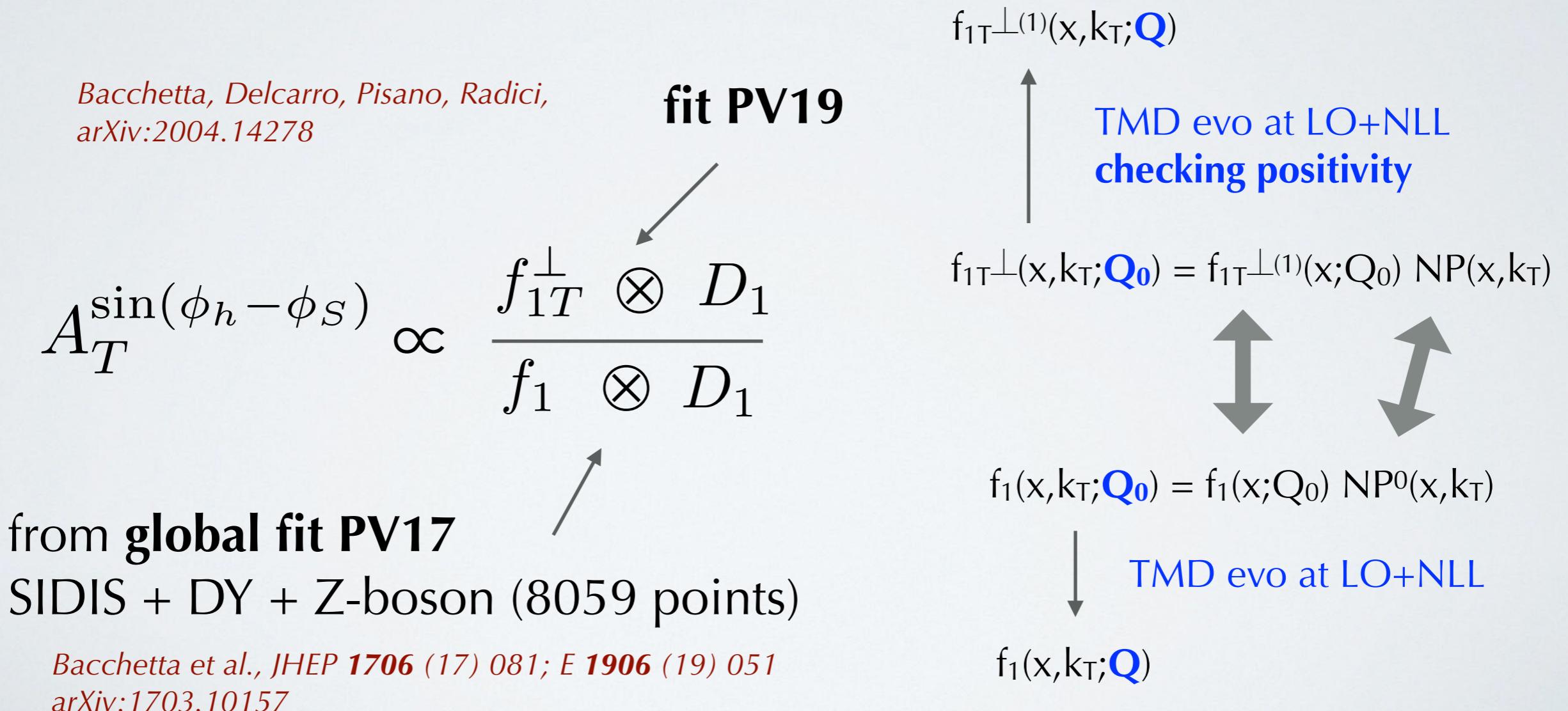
Sivers recent extractions: JAM20

*Cammarota et al. (JAM20),
PR D102 (20) 054002, arXiv:2002.08384*



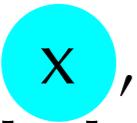
Sivers recent extractions: PV19

Full TMD framework
First extraction of Sivers function
with consistent TMD description



Sivers recent extractions: PV19

fit of Sivers SSA only in SIDIS

but **only**  , z, P_{hT} projections included

Same cuts as in PV17 global fit

$$Q^2 \geq 1.4 \text{ GeV}^2 \quad 0.2 \leq z \leq 0.7$$

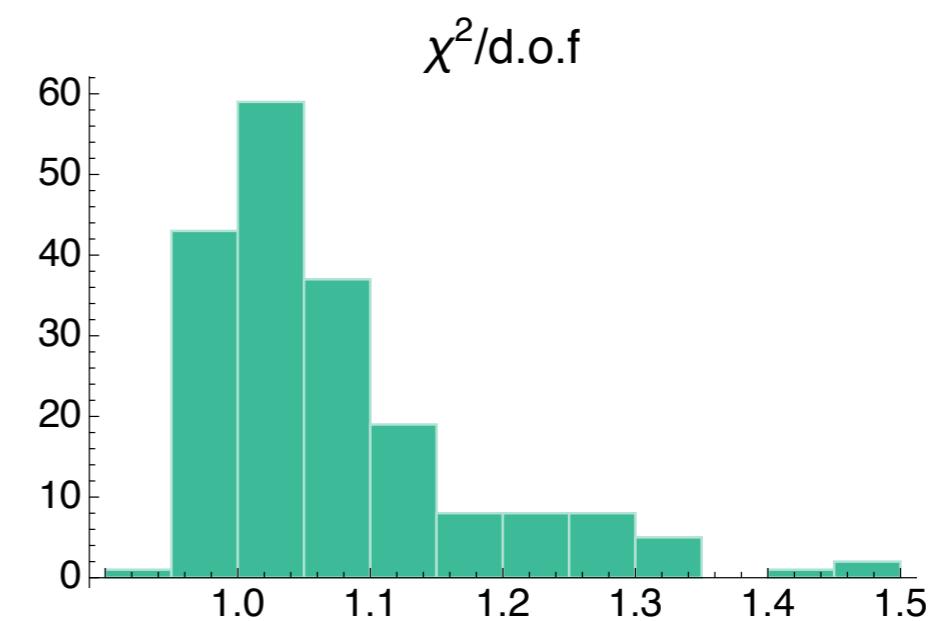
$$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5 \text{ GeV}$$

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

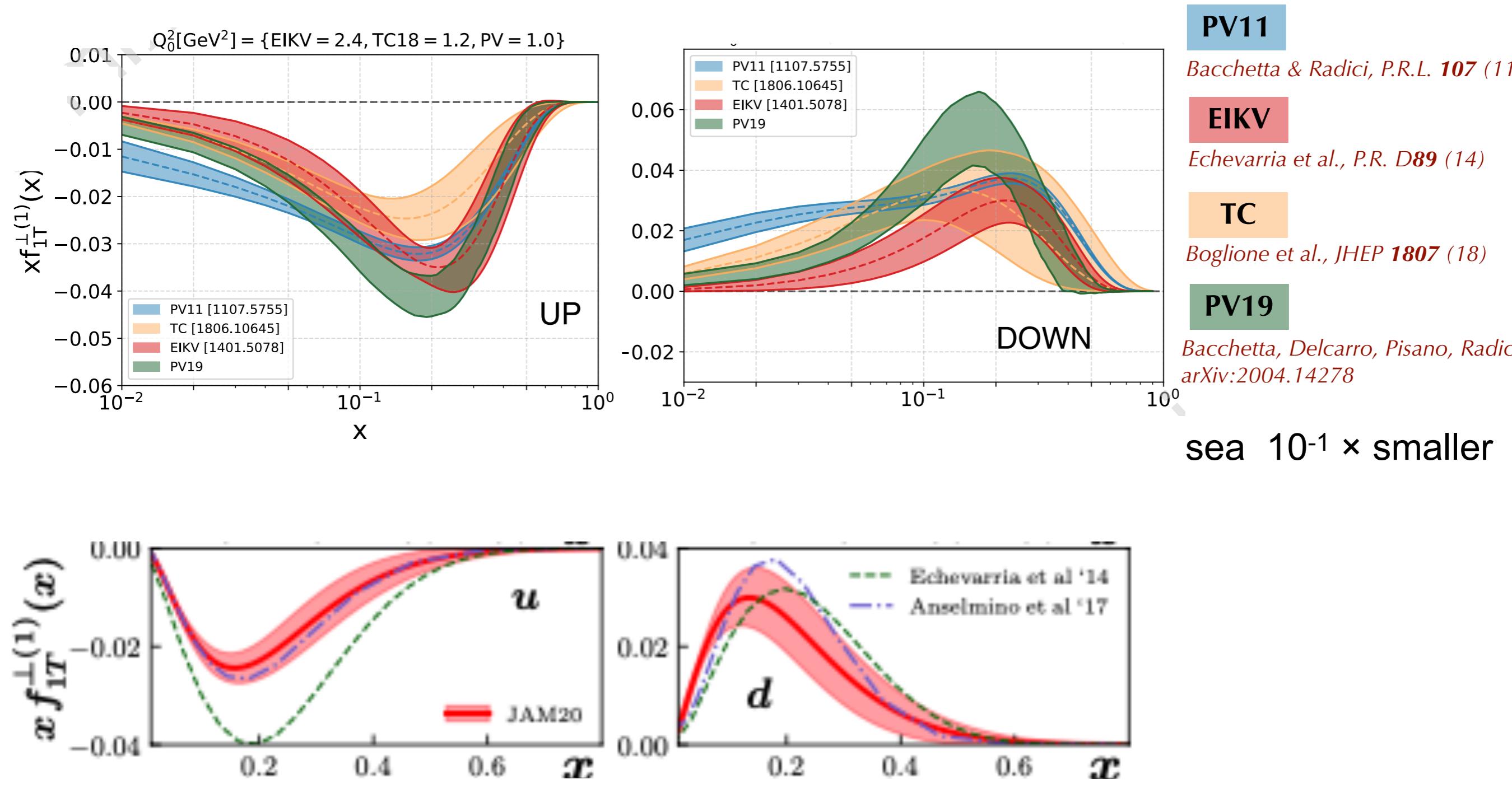
*Bacchetta, Delcarro, Pisano, Radici,
arXiv:2004.14278*



300 data points → **118** data fitted
14 free parameters
 $\chi^2/\text{d.o.f.} = 1.06 \pm 0.10$

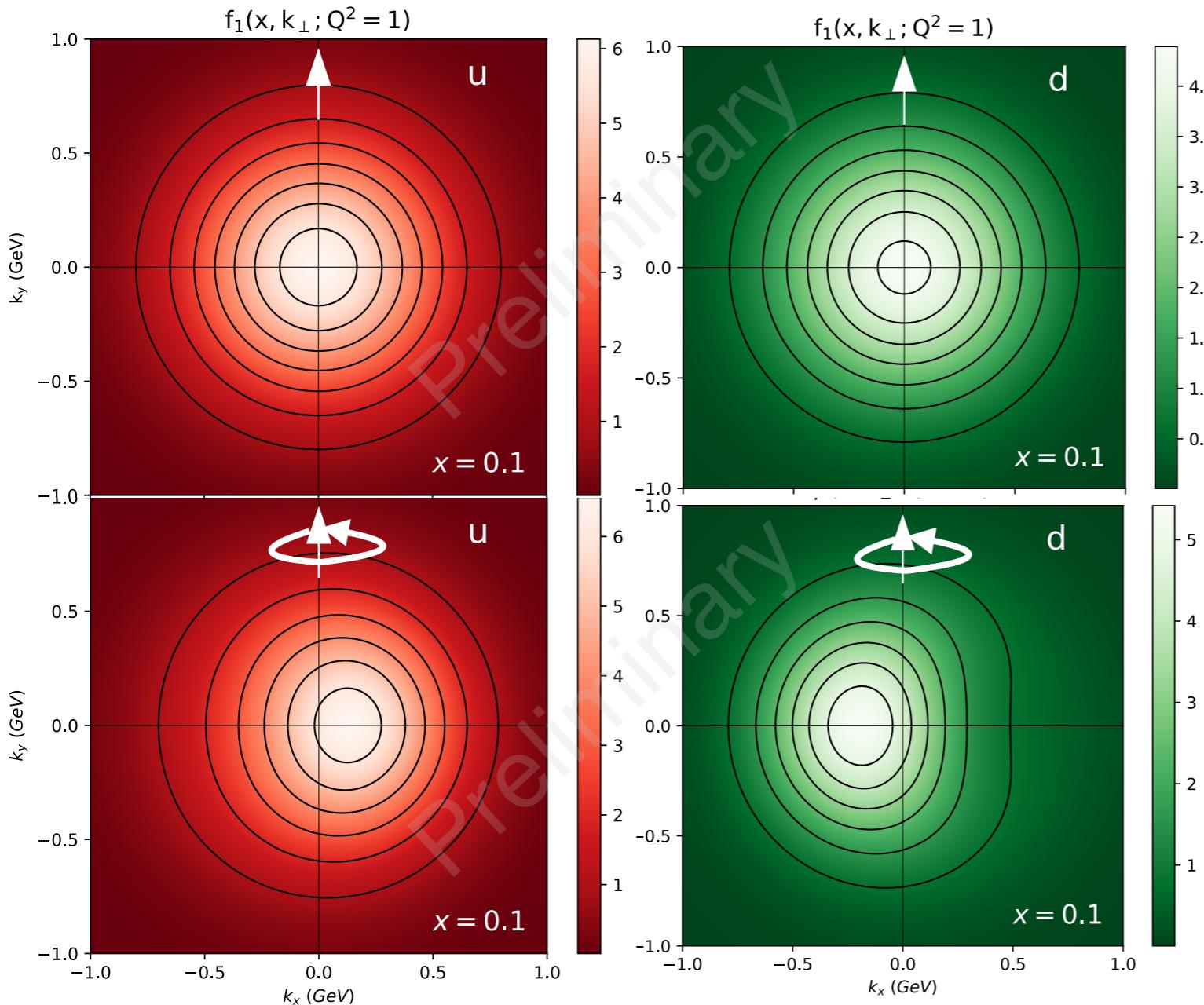


Sivers recent extractions: PV19



Cammarota et al. (JAM20),
PR D**102** (20) 054002, arXiv:2002.08384

Sivers effect from PV19



Bacchetta, Delcarro, Pisano, Radici,
arXiv:2004.14278

$$f_{q/p^\uparrow}(x, \mathbf{k}_T) = f_1^q(x, \mathbf{k}_T^2)$$

$$f_{q/p^\uparrow}(x, \mathbf{k}_T) = f_1^q(x, \mathbf{k}_T^2) - f_{1T}^{\perp q}(x, \mathbf{k}_T^2) \mathbf{S} \cdot \left(\frac{\hat{\mathbf{P}}}{M} \times \mathbf{k}_T \right)$$

Sivers recent extractions: EKT

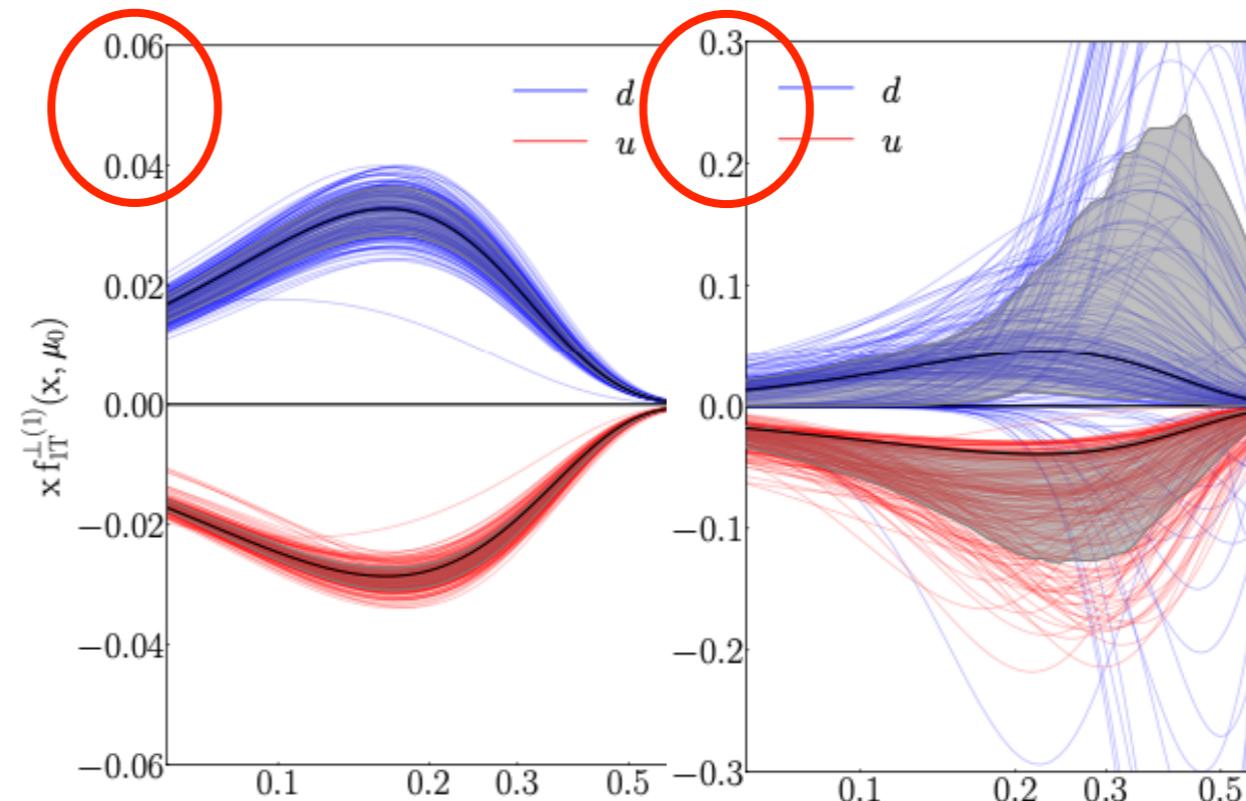
fit of all Sivers SSA in SIDIS, DY with/without W/Z-production

Echevarria, Kang, Terry, arXiv:2009.10710

Full TMD framework; analysis at NLO+NNLL

see next talk
by Terry

impact of STAR data



same doubts as for JAM20:

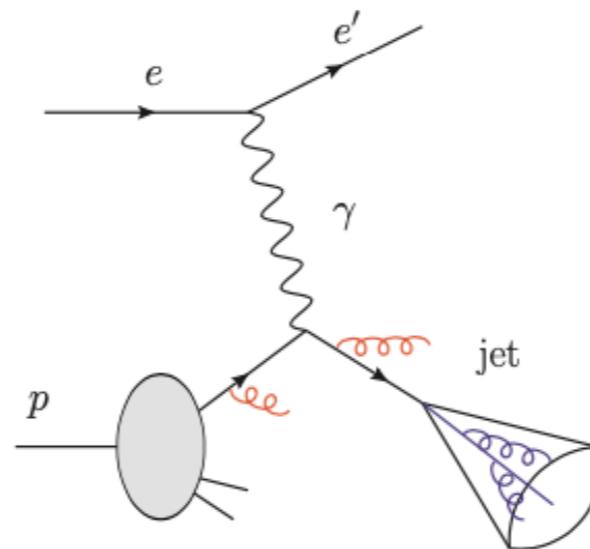
- not all data used for DY and W/Z are independent
- TMD (pion) ?



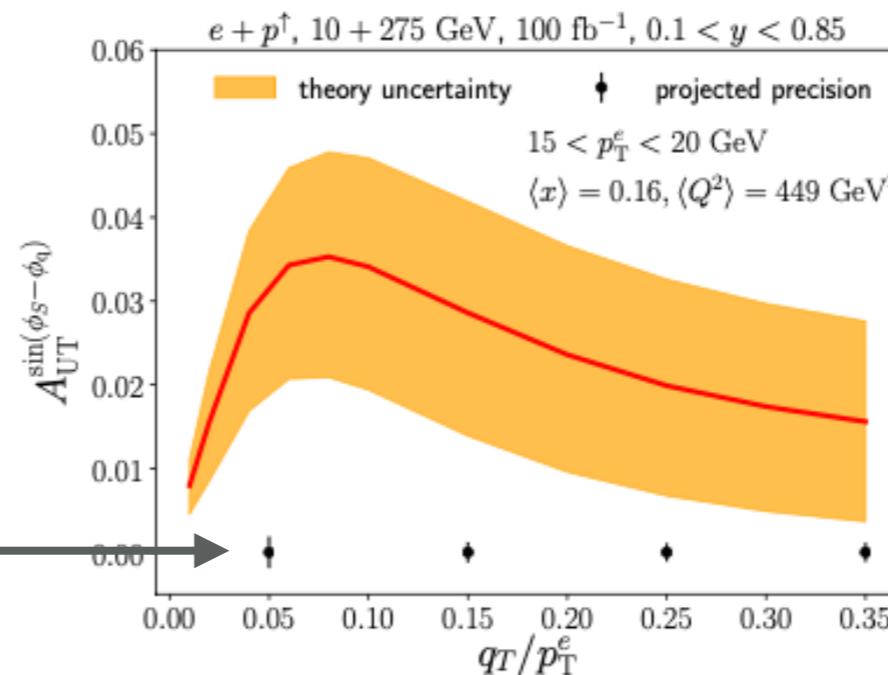
New methods: jets

electron-jet azimuthal correlations => Sivers effect

see talk
by Scimemi
on Wednesday



*Arratia et al.,
PR D102 (20) 074015, arXiv:2007.07281*



potential impact of EIC

based on

EIKV

Echevarria et al., P.R. D89 (14)

The short-term future

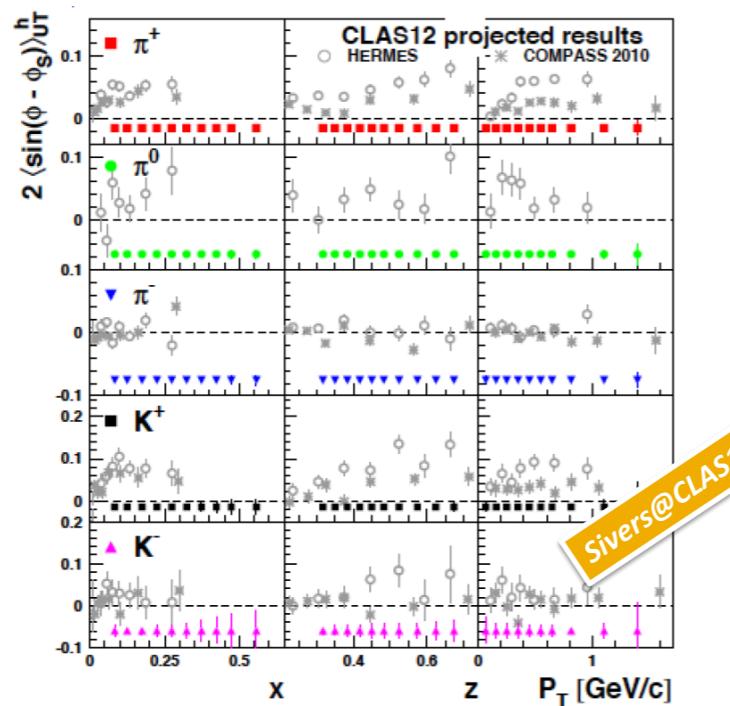
Compass



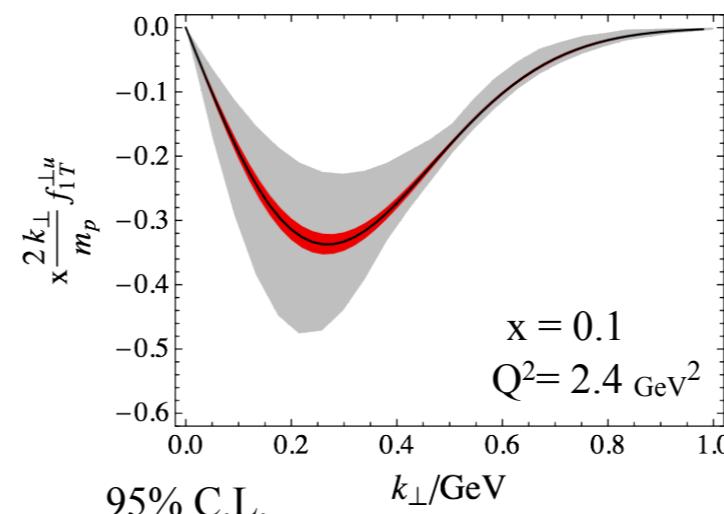
of course

JLab12

Hall B clas



Hall A SoLID



see talks
by Rossi
and Gao
on Tuesday

gluon Sivers function

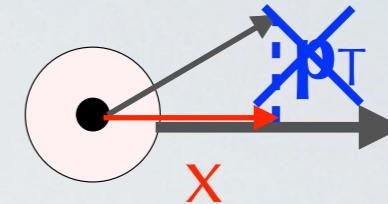
see talk
by Boer
on Tuesday

Transversity : both PDF and TMD

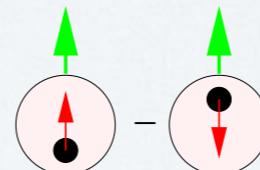
PDFs @twist=2

quark polarization

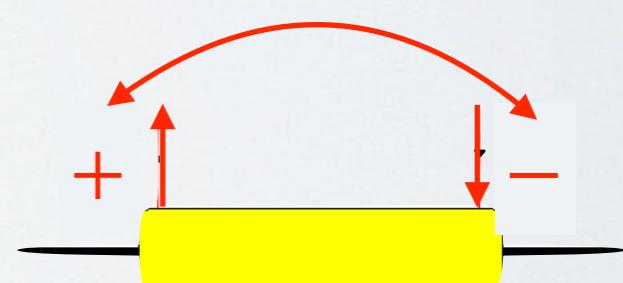
	U	L	T
U	f_1		$h_{1\perp}$
L		g_{1L}	$h_{1L\perp}$
T	$f_{1T\perp}$	g_{1T}	$h_1 \ h_{1T\perp}$



- chiral-odd structure in spin-1/2 hadron
- no gluon transversity $\rightarrow h_1$ is a non-singlet object



$$\max \Delta S_L = |S'_L - S_L|$$



see talk
by Kumano
on Wednesday

Why Transversity : BSM connections

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

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

exp. bounds

+ tensor charge

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

- **nuclear β -decay:** EFT can include tensor operator

hadron level : $n \rightarrow p e^- \bar{\nu}_e$

exp. bounds

C_T

$\leftrightarrow g_T \epsilon_T$

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

isovector tensor charge

quark level : $d \rightarrow u e^- \nu_e$

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

unknown ϵ_T

Di-hadron PV18 fit : $h_1(x)$ as a PDF

global PV18 fit (with IFF fixed to e+e-)

*Radici and Bacchetta, P.R.L. **120** (18) 192001
arXiv:1802.05212*

SIDIS



18 data points



4 data points

pp collisions



run 2006
($s=200 \text{ GeV}^2$)

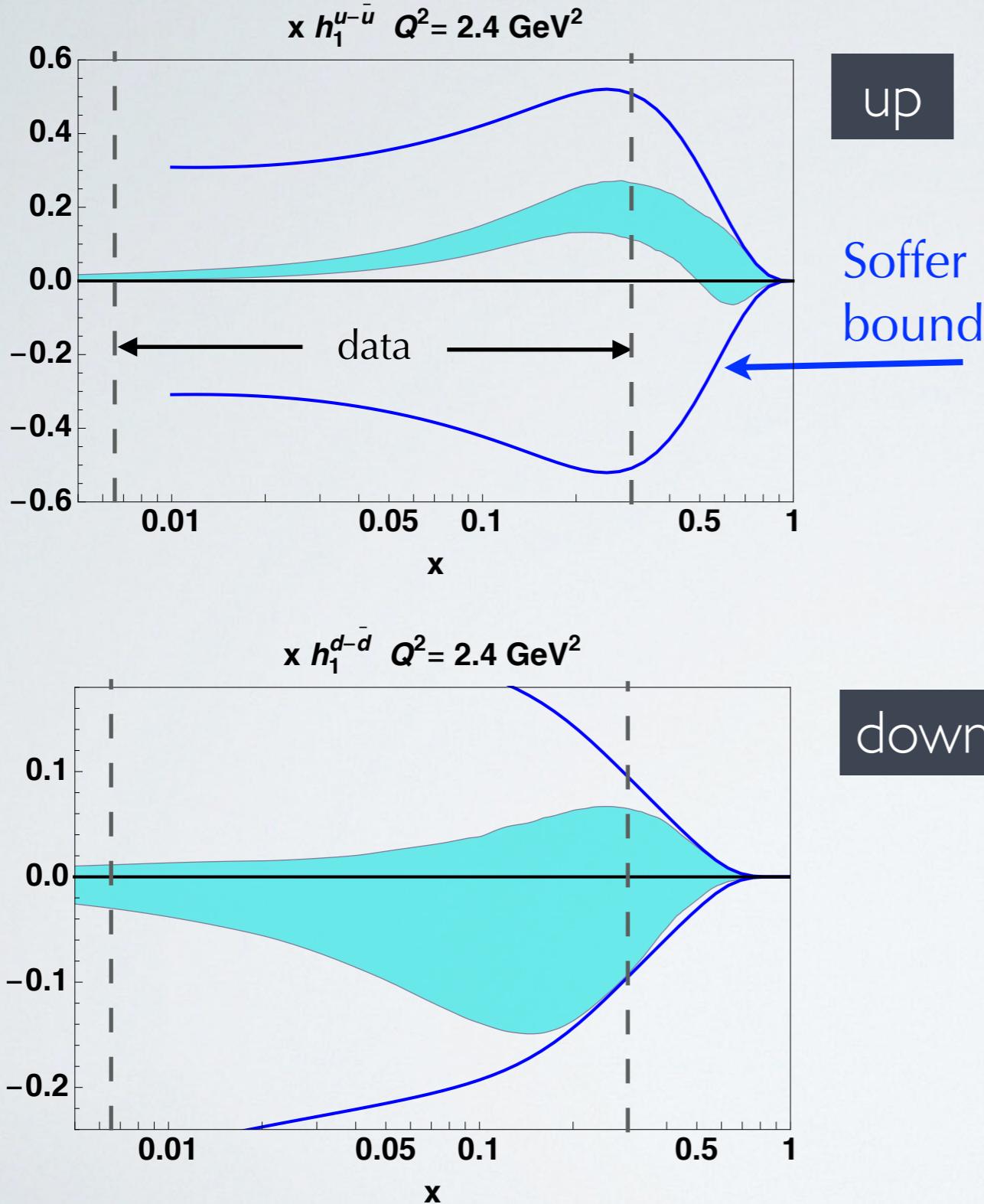
10 independent data points

10 fitting parameters

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

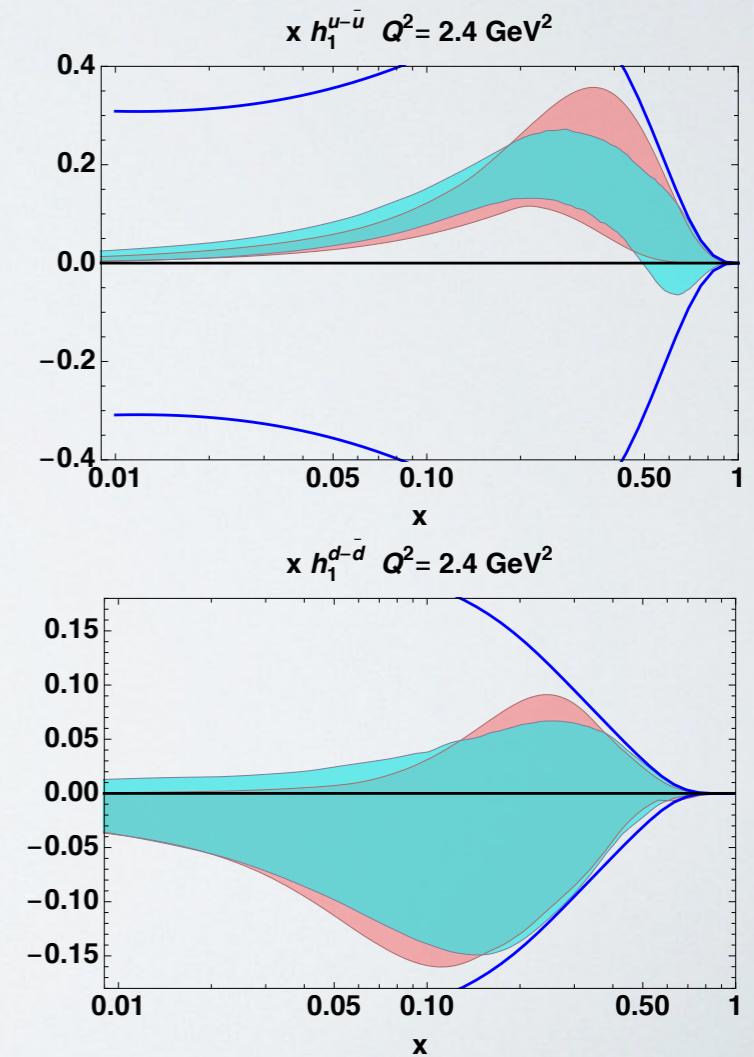
- functional form fulfilling Soffer bound at any (x, Q^2) + constraint at low x to give finite 1st Mellin moment
- LO analysis + error estimate on unknown D_{1g}
- replica method for statistical error analysis

Di-hadron PV18 fit : $h_1(x)$ as a PDF



- uncertainty band from 90% of 600 replicas = max uncertainty on $D_{1g}(Q_0)$
- diverges less than $1/x$
- compares very well with extraction from Collins effect in TMD framework
- similarly for Torino group

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



di-hadron D_1^q \Leftrightarrow Belle (PRELIMINARY)

- take functional forms used to fit yield of ($\pi^+\pi^-$) from PYTHIA at BELLE kin.

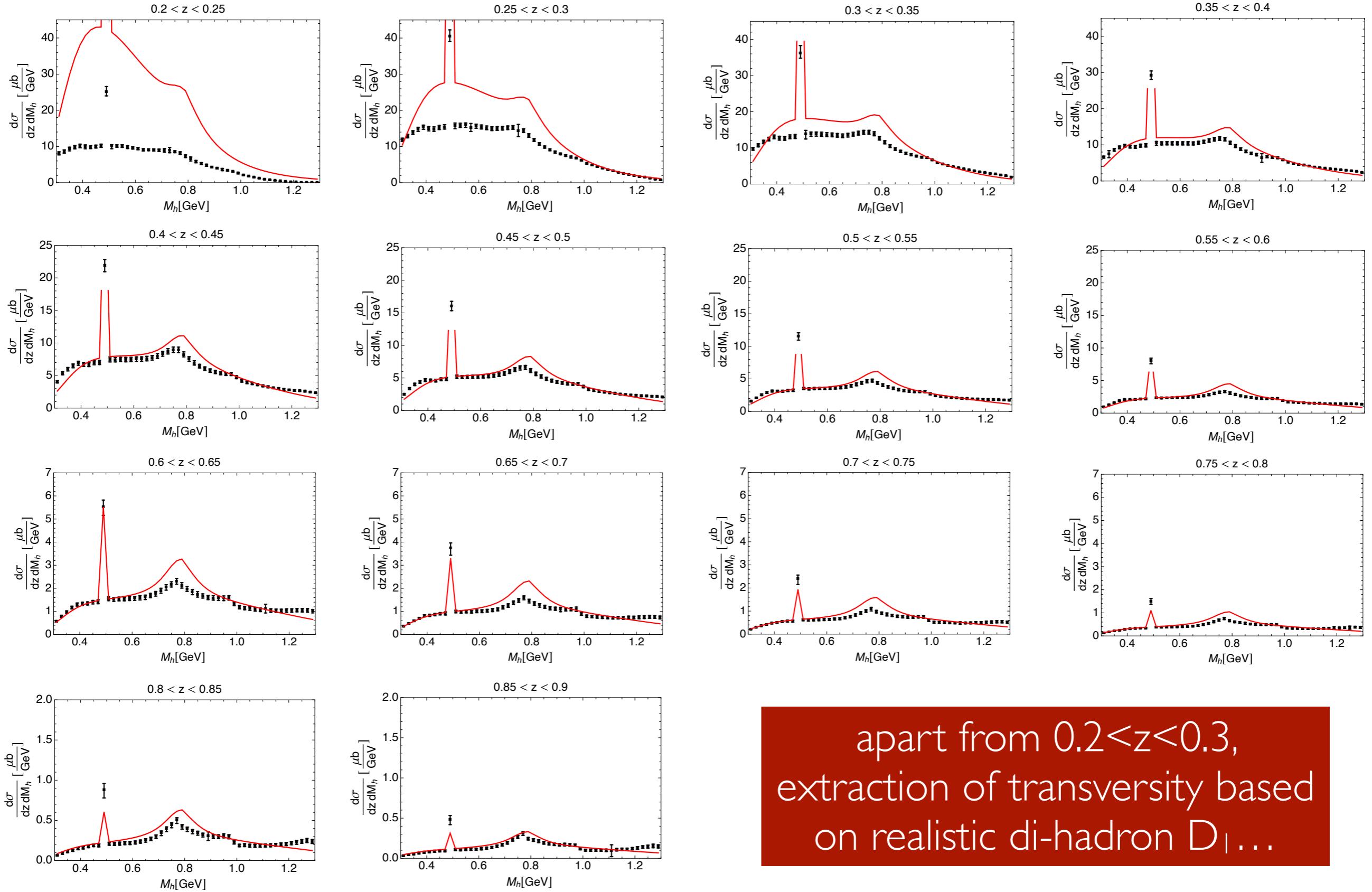
Courtoy et al., P.R. D85 (12) 114023

- evolve up to NLO and build unpolarized cross section as function of (z, M_h) $z = z_{\pi^+} + z_{\pi^-}$ M_h = pair invariant mass
- compare prediction with BELLE data for unpolarized cross section
(need to adjust normalization)



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

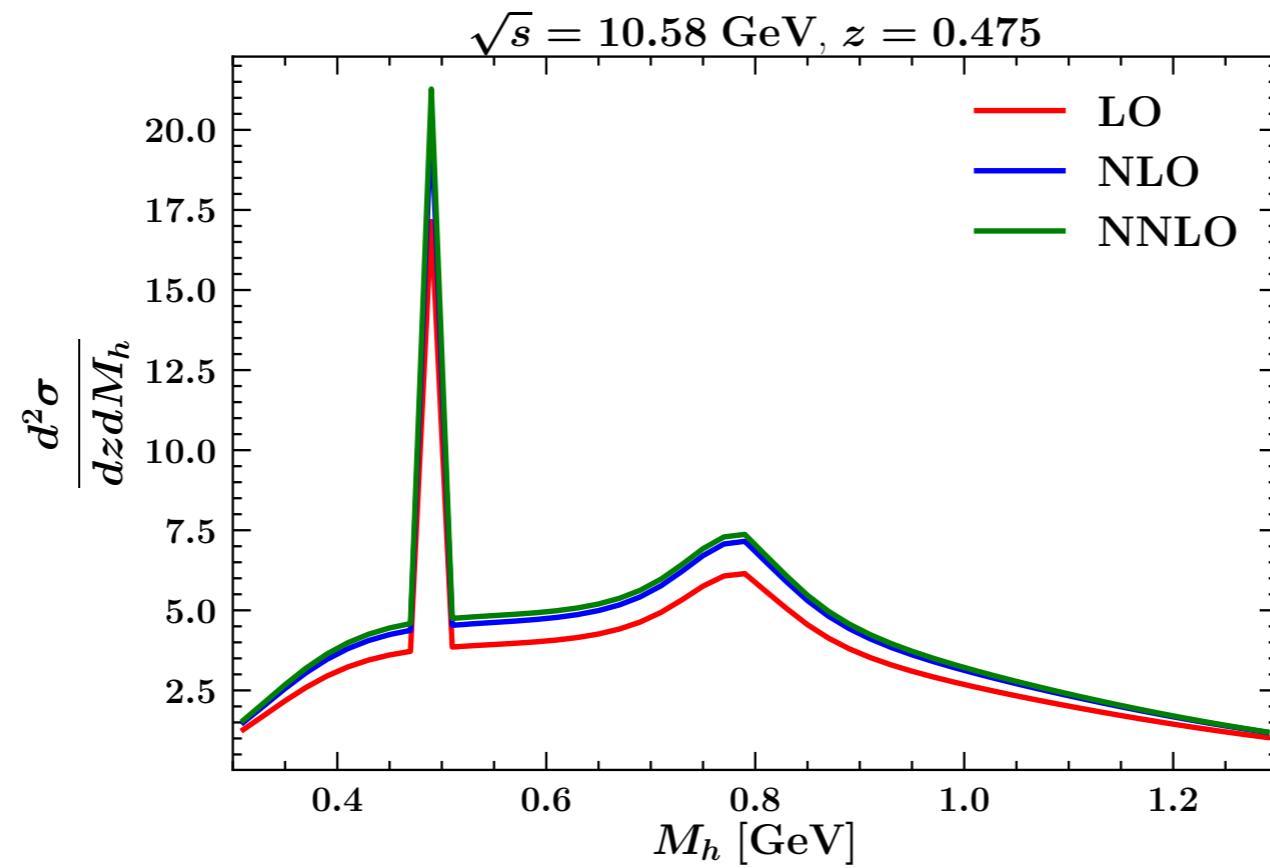
di-hadron D_1^q \Leftrightarrow Belle (PRELIMINARY)



apart from $0.2 < z < 0.3$,
extraction of transversity based
on realistic di-hadron D_1^q ...

di-hadron $D_1^q \leftrightarrow$ Belle (PRELIMINARY)

convergence of perturbative expansion:
NLO is already a good compromise

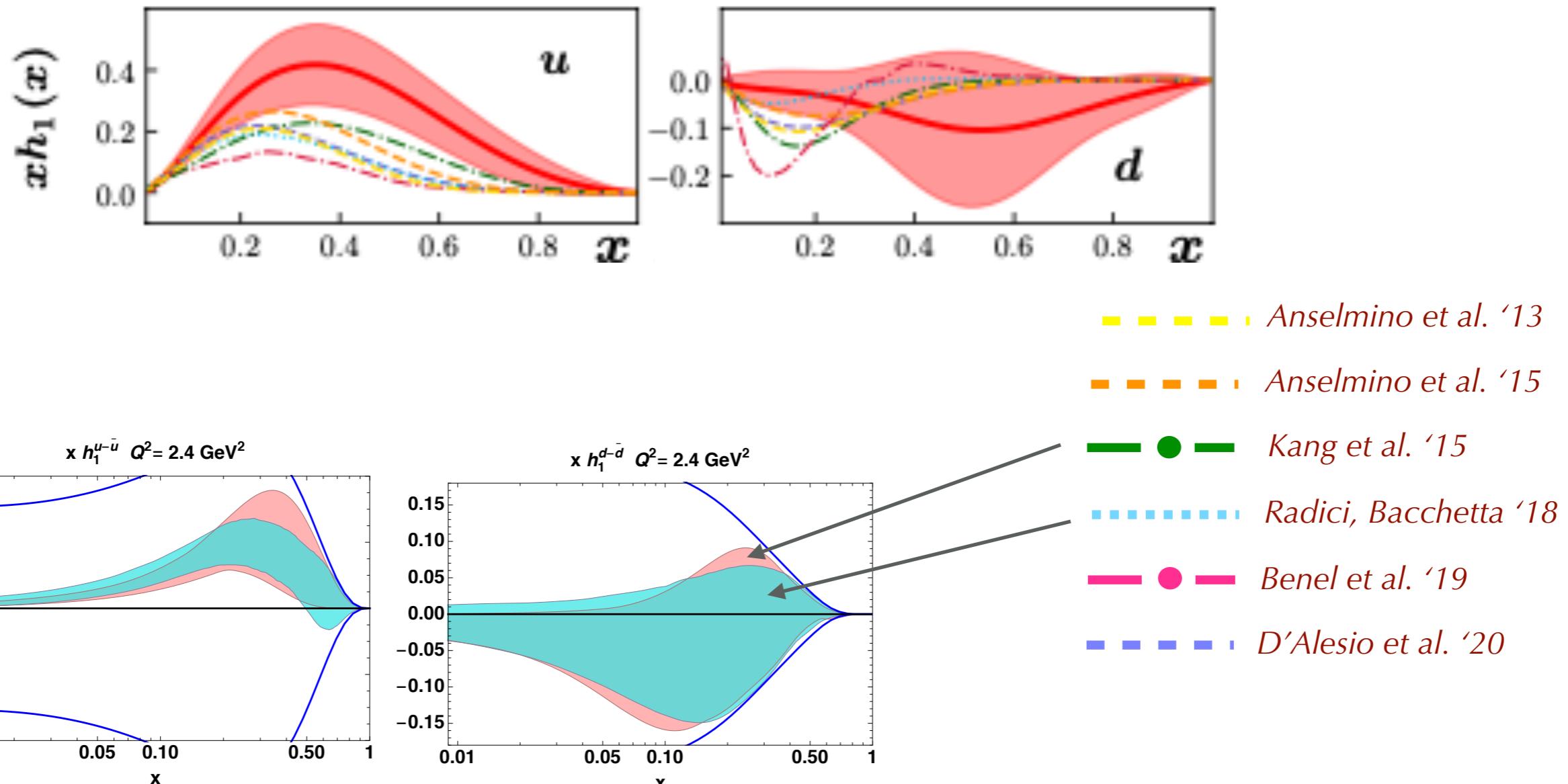


Transversity recent extractions: JAM20

global fit of all Sivers/Collins SSA in SIDIS, DY, W/Z-production, e+e-

*Cammarota et al. (JAM20),
PR D102 (20) 054002, arXiv:2002.08384*

no TMD framework

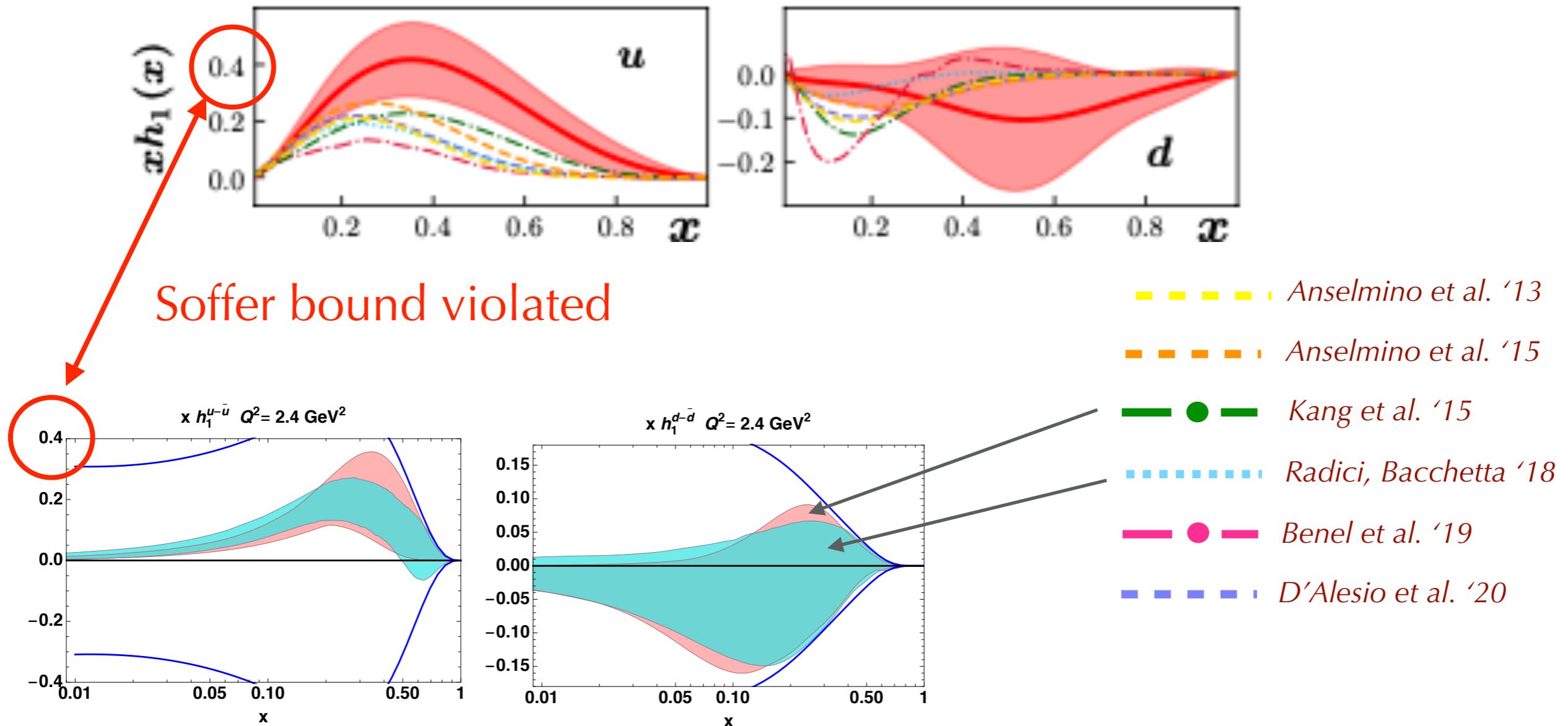


Transversity recent extractions: JAM20

global fit of all Sivers/Collins SSA in SIDIS, DY, W/Z-production, e+e-

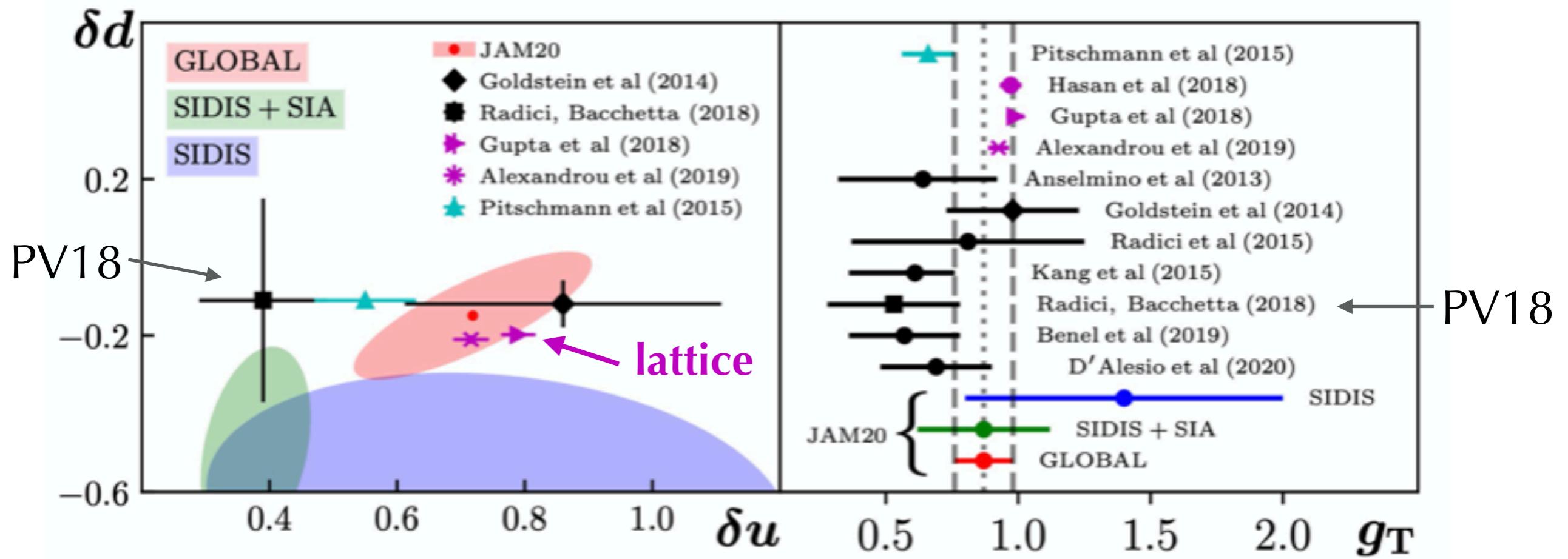
*Cammarota et al. (JAM20),
PR D102 (20) 054002, arXiv:2002.08384*

no TMD framework



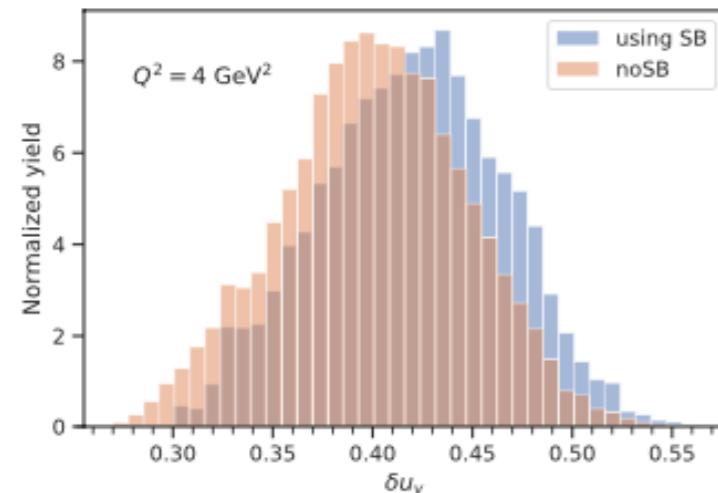
Tensor charges

Cammarota et al. (JAM20),
PR D102 (20) 054002, arXiv:2002.08384



discrepancy with lattice \Leftrightarrow Soffer bound ?

Role of Soffer bound

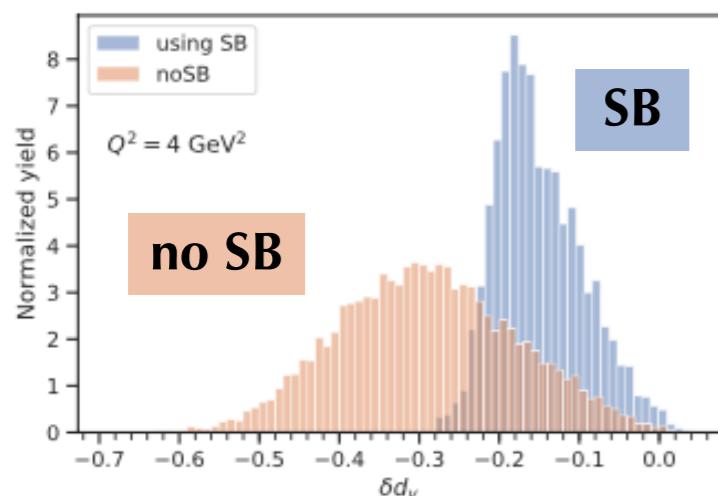


tensor charges

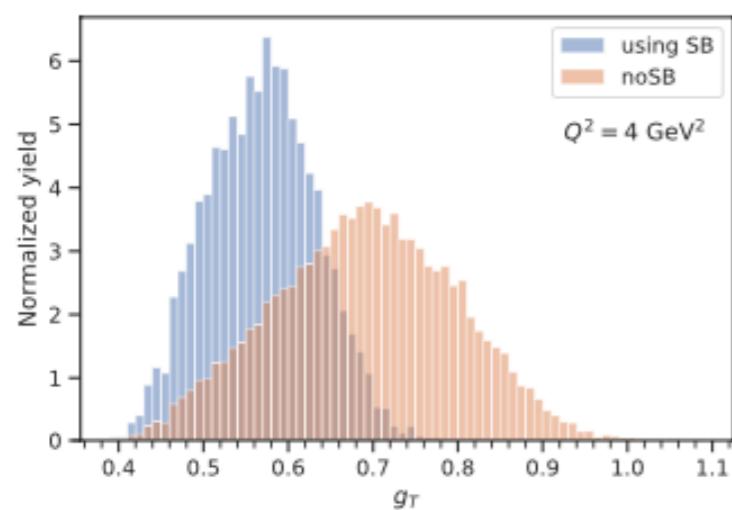
up
(δu)

D'Alesio et al.,
PL B802 (20) 135347, arXiv:2001.01573

fit of Compass & Hermes data
for Collins effect
no TMD framework

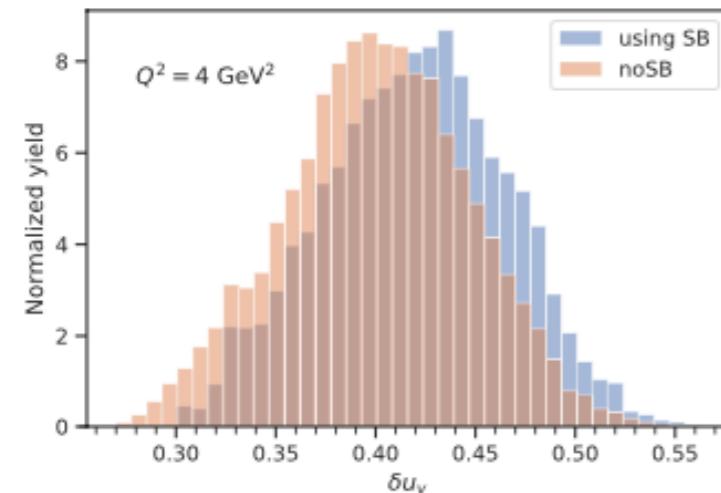


down
(δd)



g_T

Role of Soffer bound

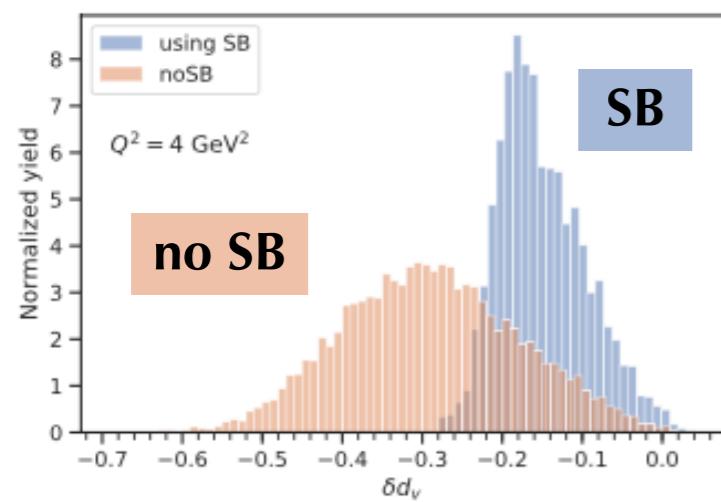


tensor charges

up
(δu)

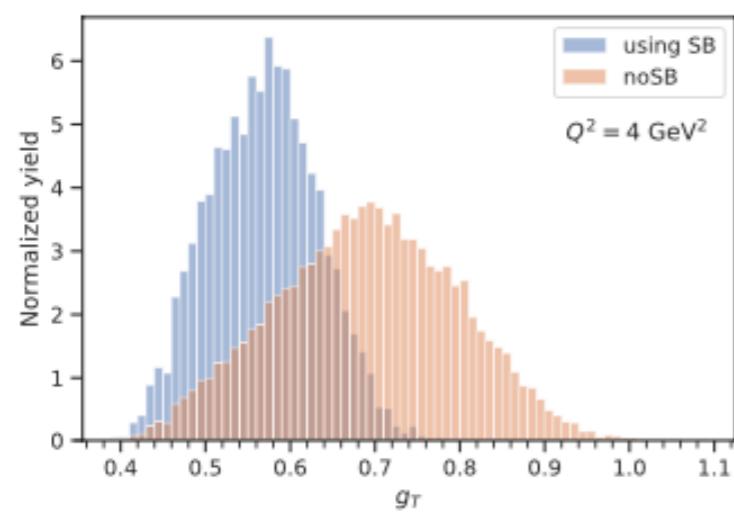
*D'Alesio et al.,
PL **B802** (20) 135347, arXiv:2001.01573*

fit of Compass & Hermes data
for Collins effect
no TMD framework



down
(δd)

relaxing Soffer bound constraint
largely affects down
and pushes g_T towards lattice pts.



g_T

see also *Benel et al., EPJ **C80** (20) 5, arXiv:1912.03289*
for error induced by
more flexible parametrization

Future perspectives

di-hadron channel

perspectives from **my** simulations
with some pseudo-data

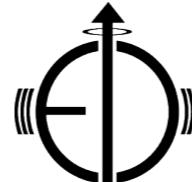
short-term =>



Jefferson Lab

BROOKHAVEN
NATIONAL LABORATORY

long-term =>



PV18 : impact of Compass pseudo-data

add to data of PV18 global fit
a new set of SIDIS pseudo-data for **deuteron** target

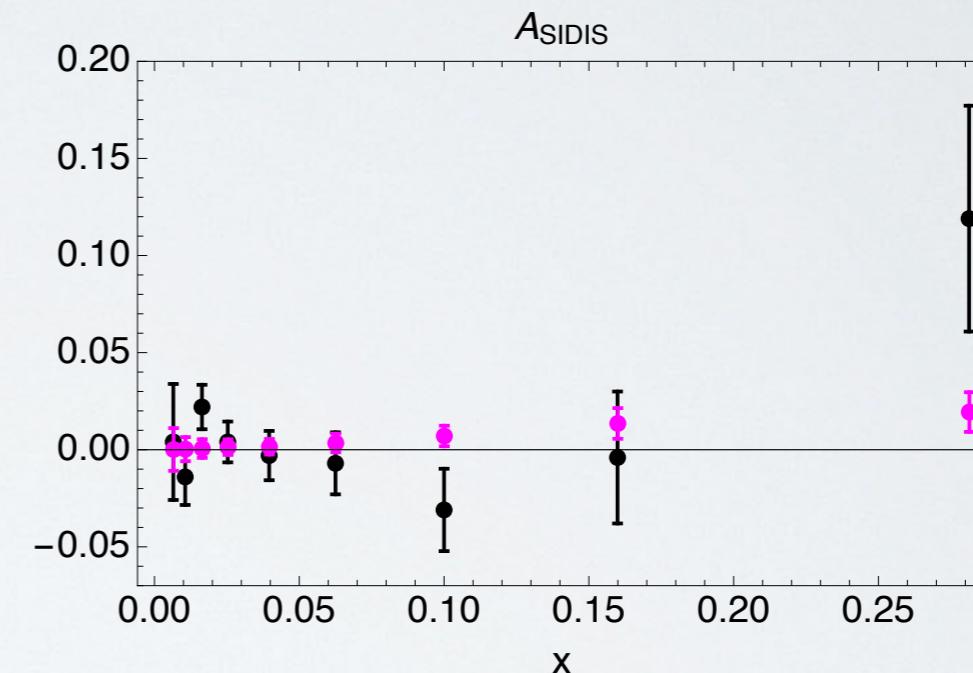


Adolph et al., P.L. B713 (12)



pseudodata

arXiv:1812.07281



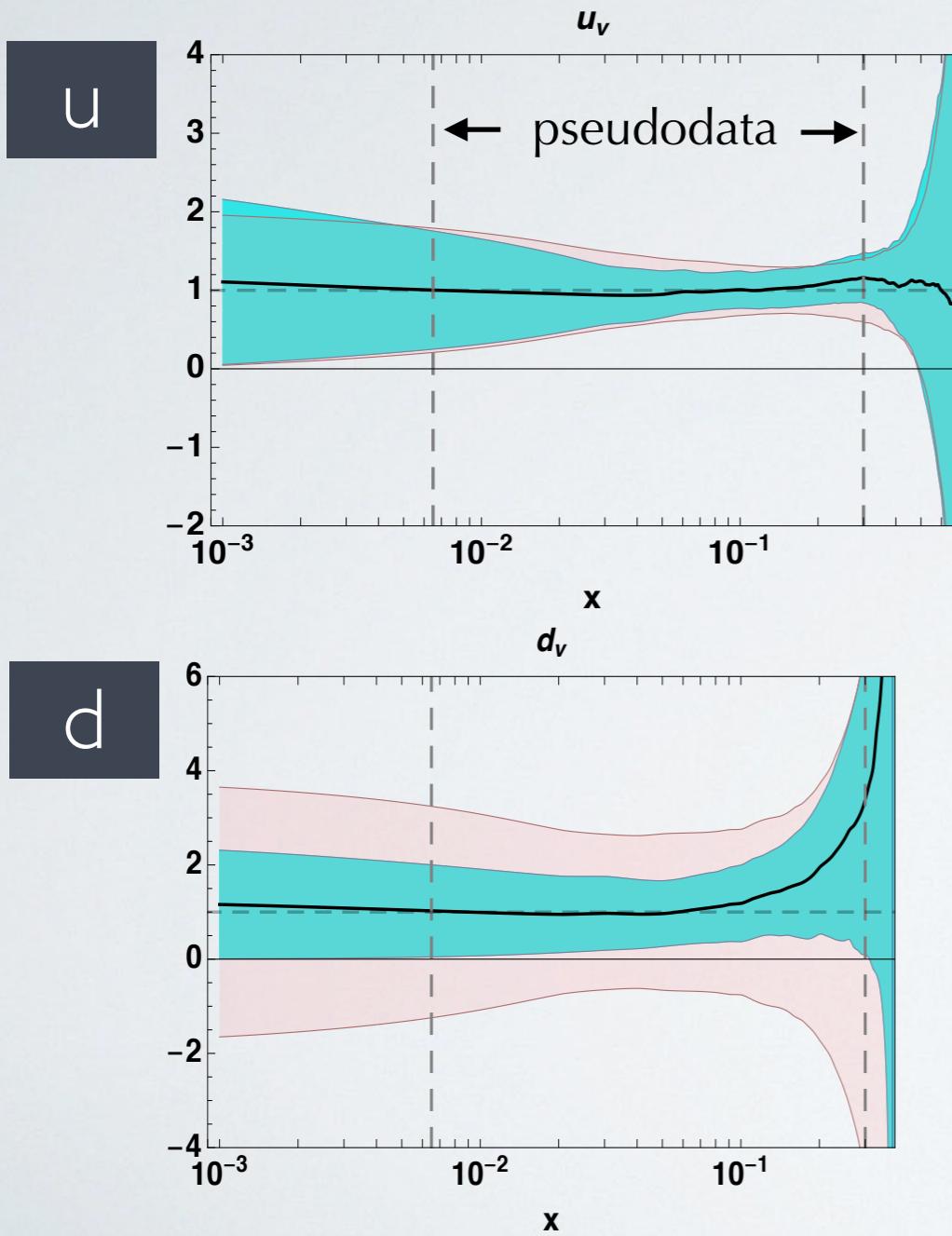
statistical error $\sim 0.6 \times$ [error in 2010 proton data]

$\langle A \rangle$ = average value of replicas in previous global fit

study impact on precision of previous global fit

PV18 : impact of Compass pseudo-data

range [0.0065, x , 0.28]



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

deuteron target
→ better precision on down

global fit

global fit + pseudodata

PV18 : impact of CLAS12 pseudo-data

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



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



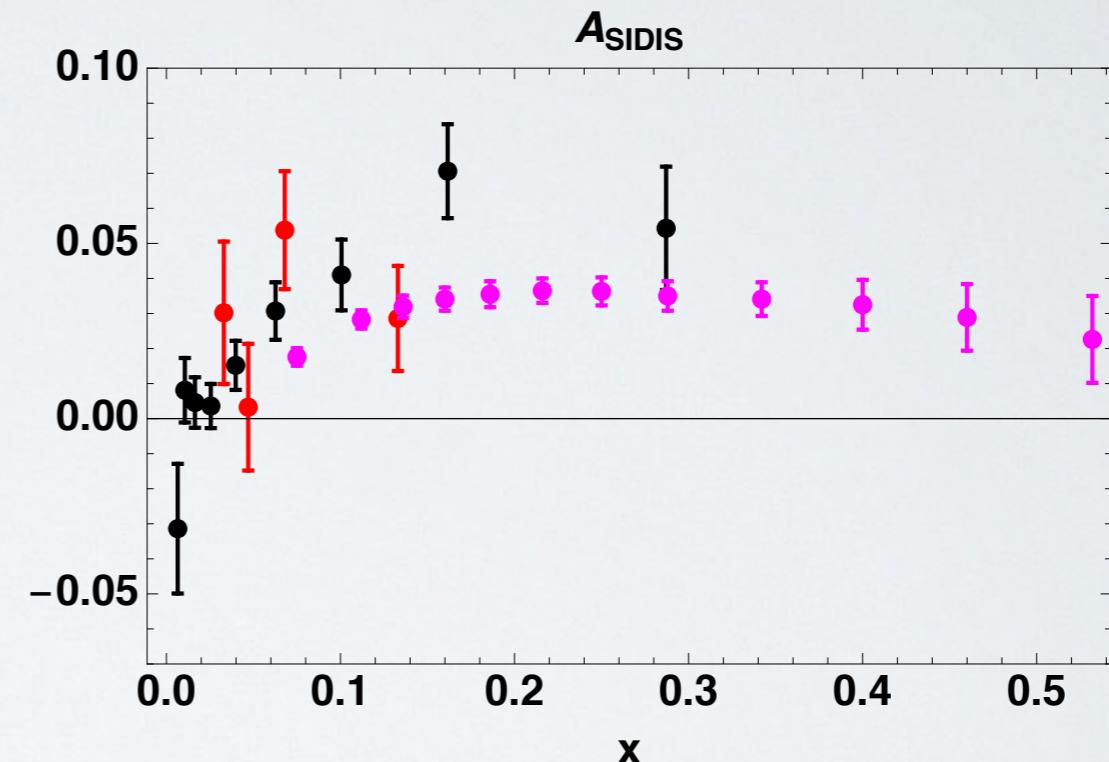
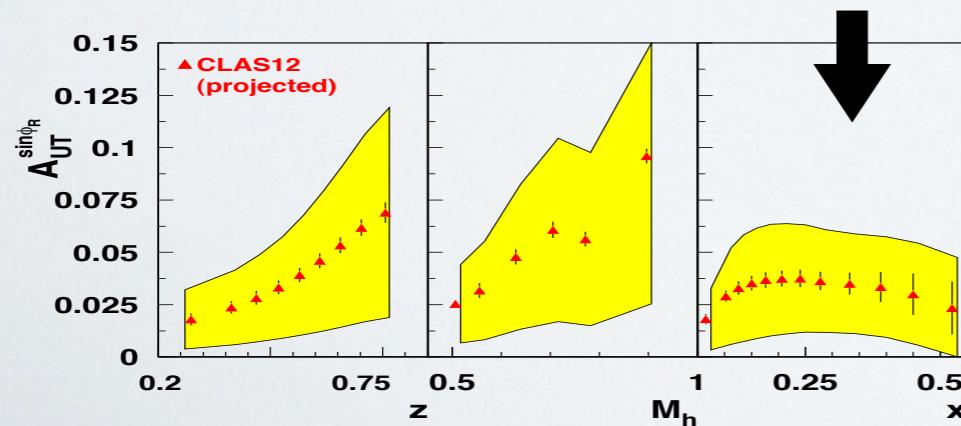
*Airapetian et al.,
JHEP **0806** (08) 017*



pseudodata C12-12-009

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

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



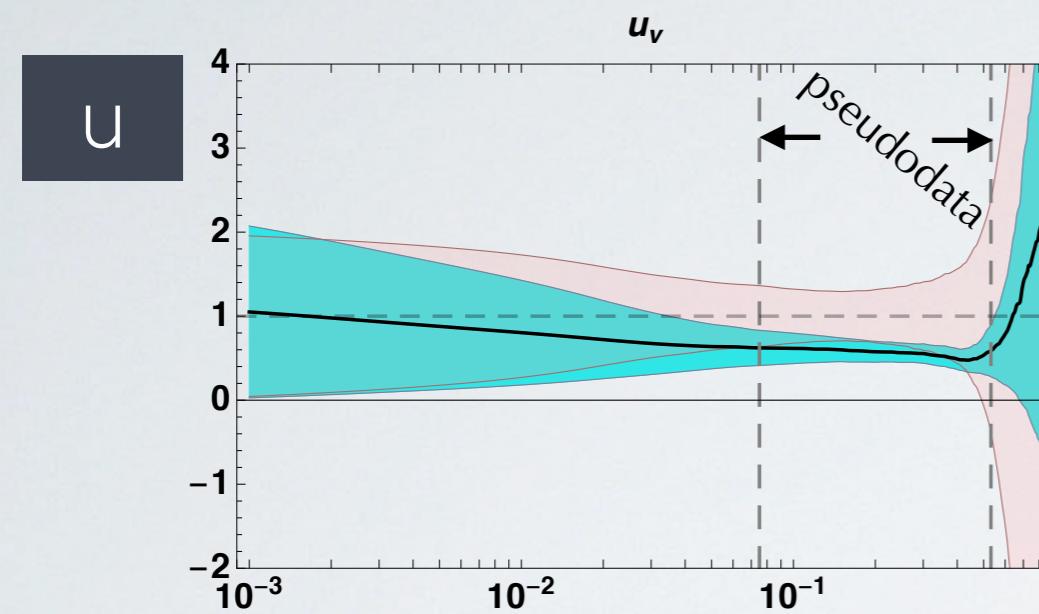
study impact on precision
of published global fit

PV18 : impact of CLAS12 pseudo-data

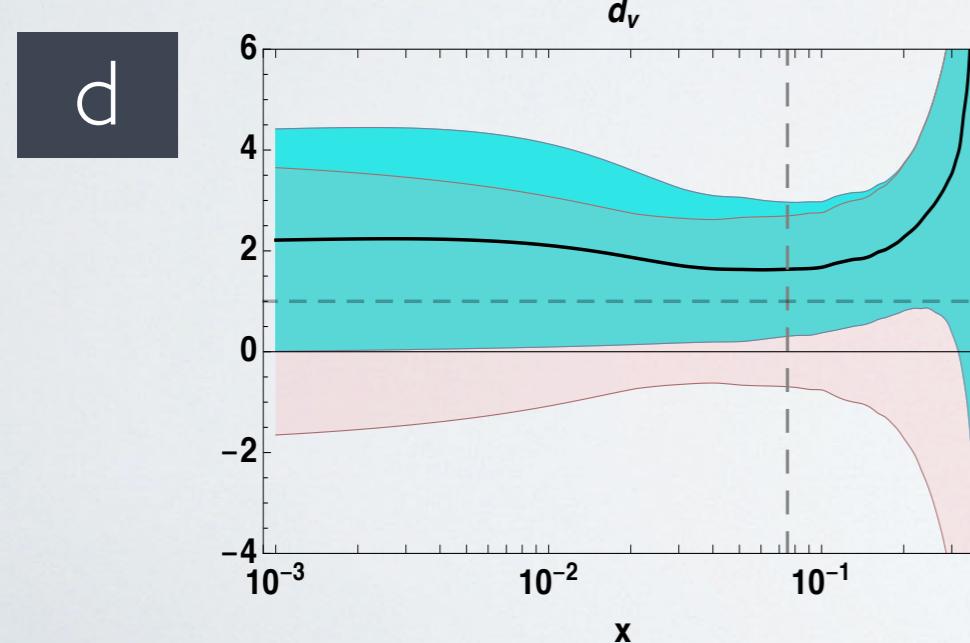
range [0.075, x , 0.53]



proposal C12-12-009



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



proton target
→ better precision on up

global fit

global fit + pseudodata

PRELIMINARY

add to data of PV18 global fit
the set of STAR data at $s=500 \text{ GeV}^2$

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



run 2011
($s=500 \text{ GeV}^2$) **32** indep.
data points

currently, $\chi^2/\text{dof} = 2.12 \pm 0.09$ still working on it...

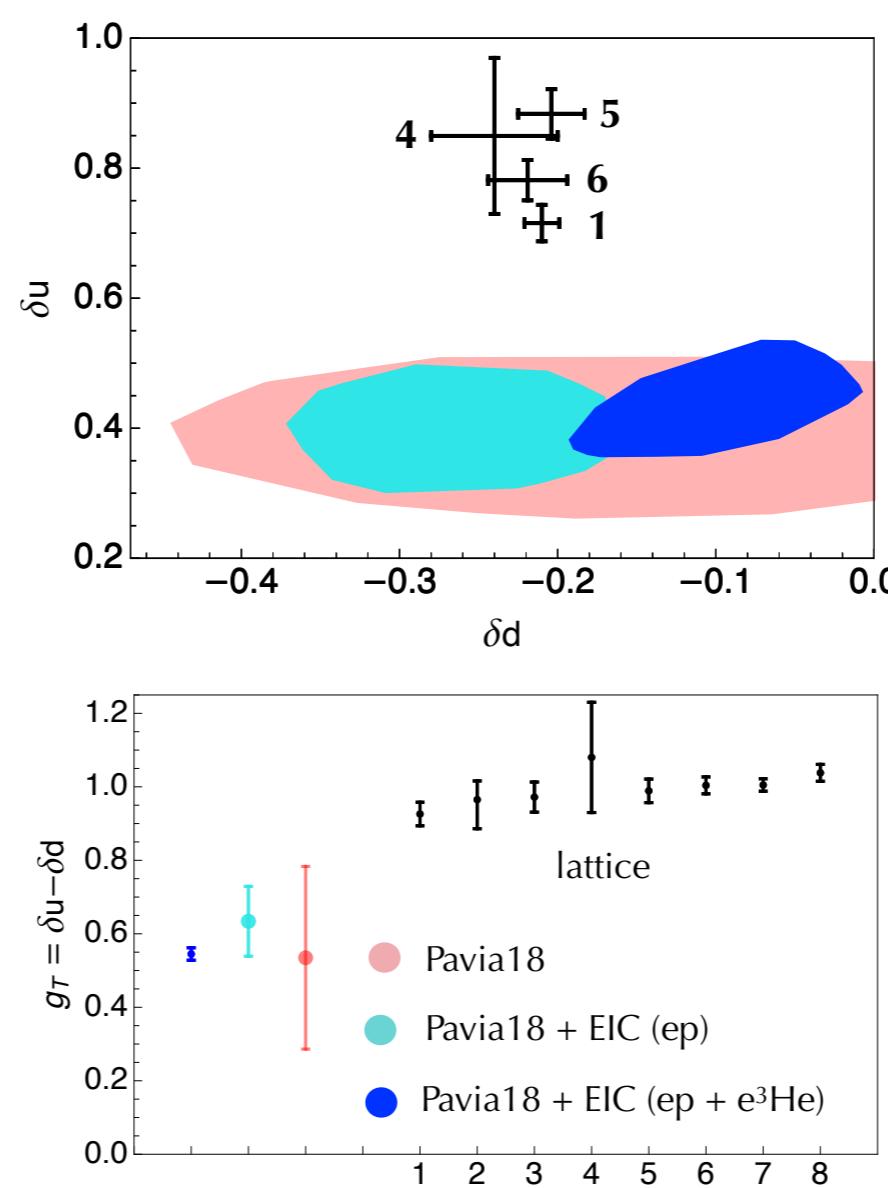
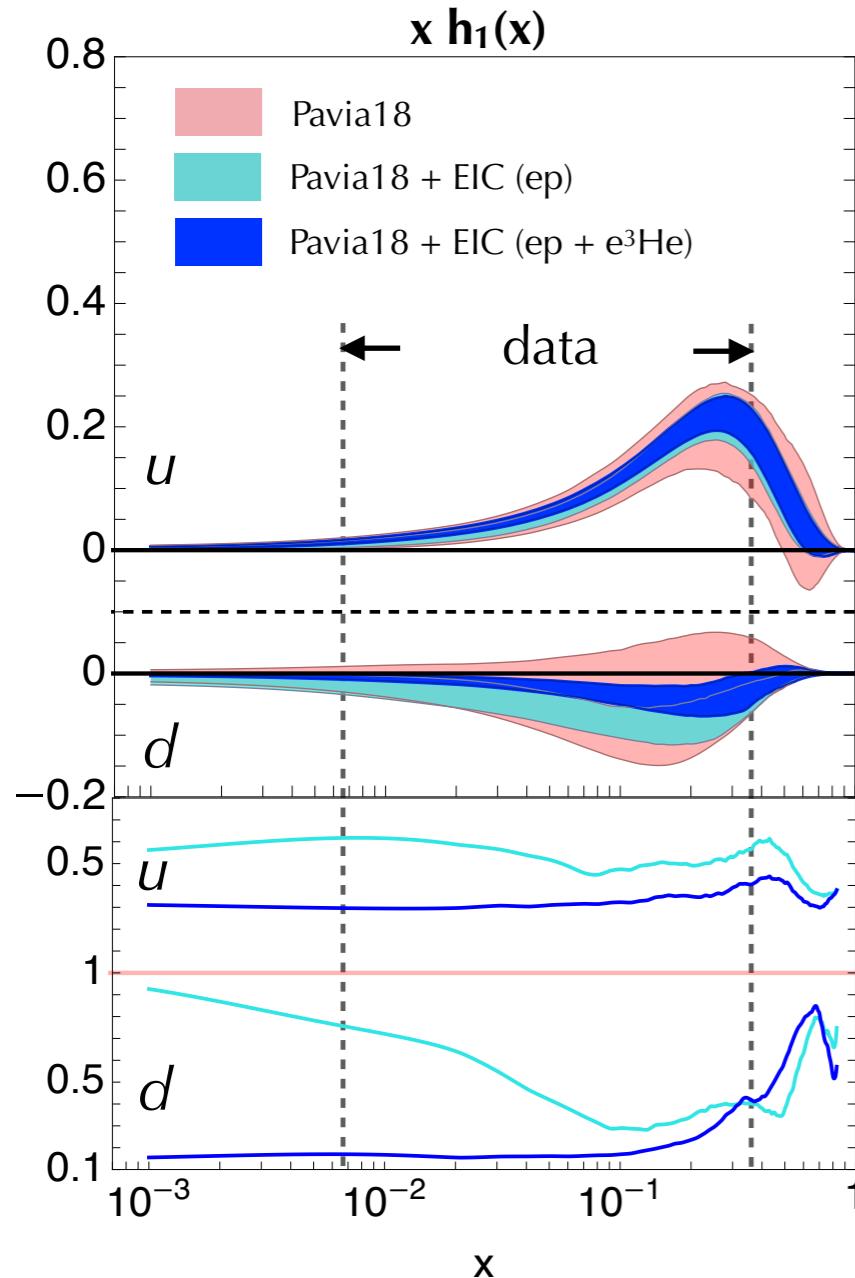
more data coming from



at $s=200 \text{ GeV}^2$



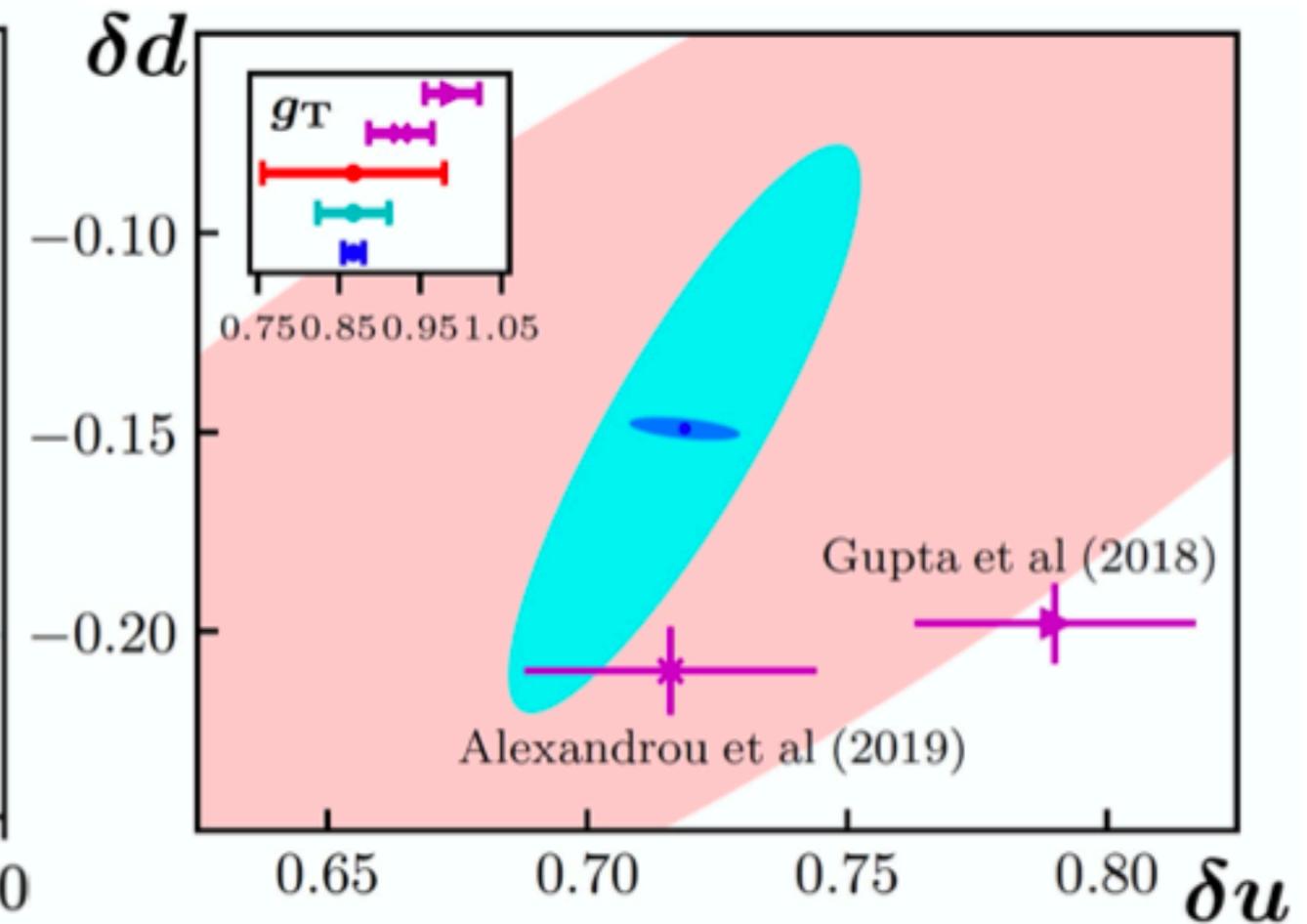
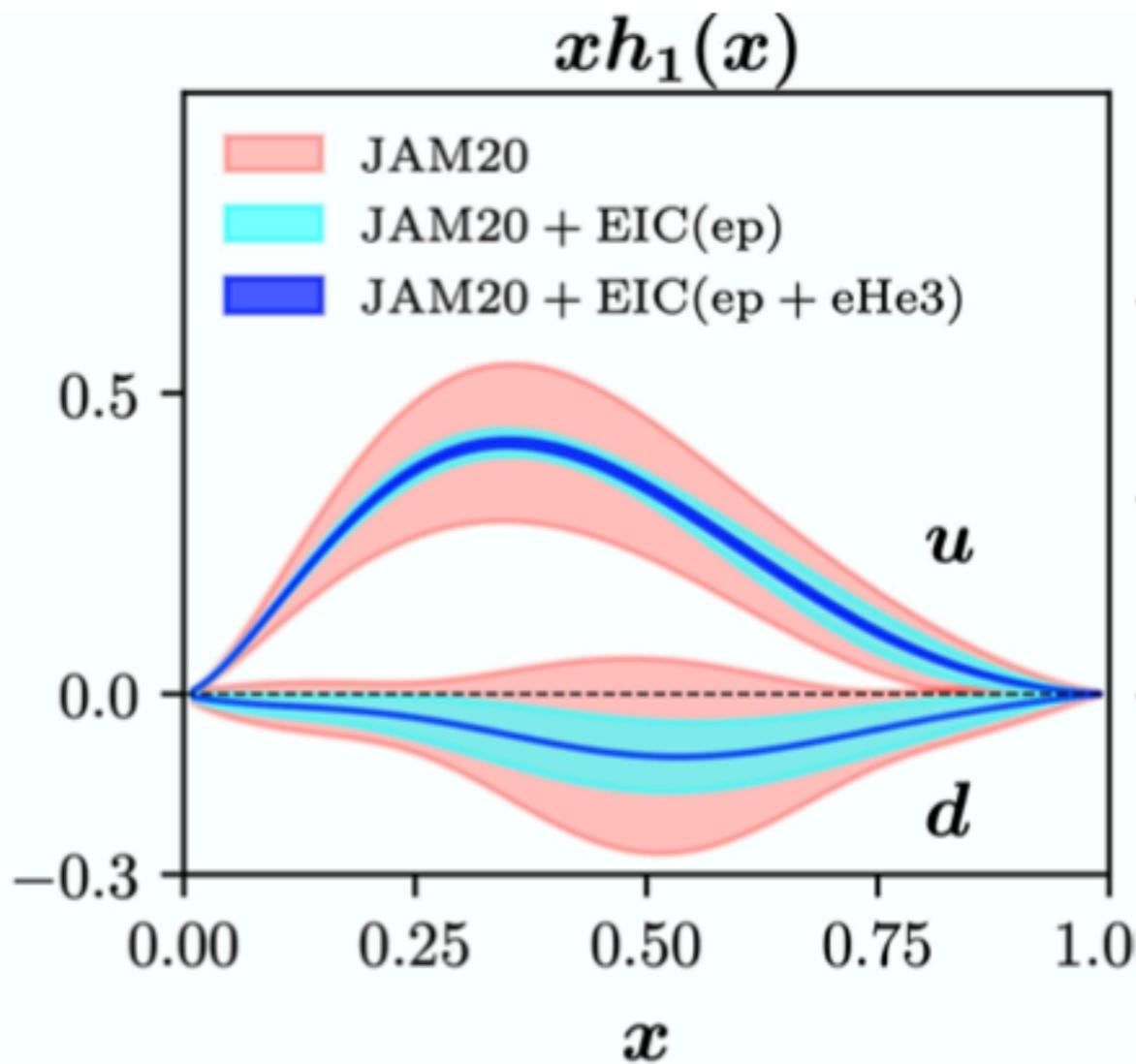
PV18 : impact of EIC pseudo-data



includes only 10x100 [GeV] energy configuration
for both proton and 3He ; total 3852 data pts.
error on IFF assumed scaling $\sim 2/\sqrt{N_{\text{pts}}}$

JAM20 : impact of EIC pseudo-data

figure by D. Pitonyak
EIC Yellow Report
in preparation



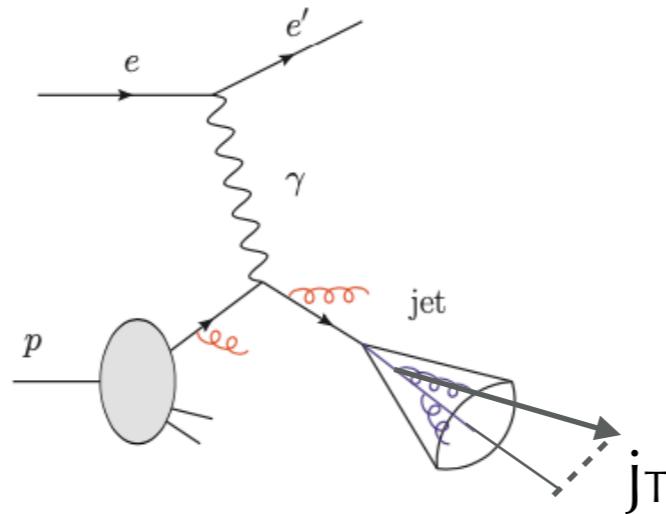
includes all EIC energy configurations:
proton [GeV]: 5x41, 5x100, 10x100, 18x275
 ^3He [GeV]: 5x41, 5x100, 18x100
total 8223 data pts.

precision on g_T can become comparable (or better) than lattice

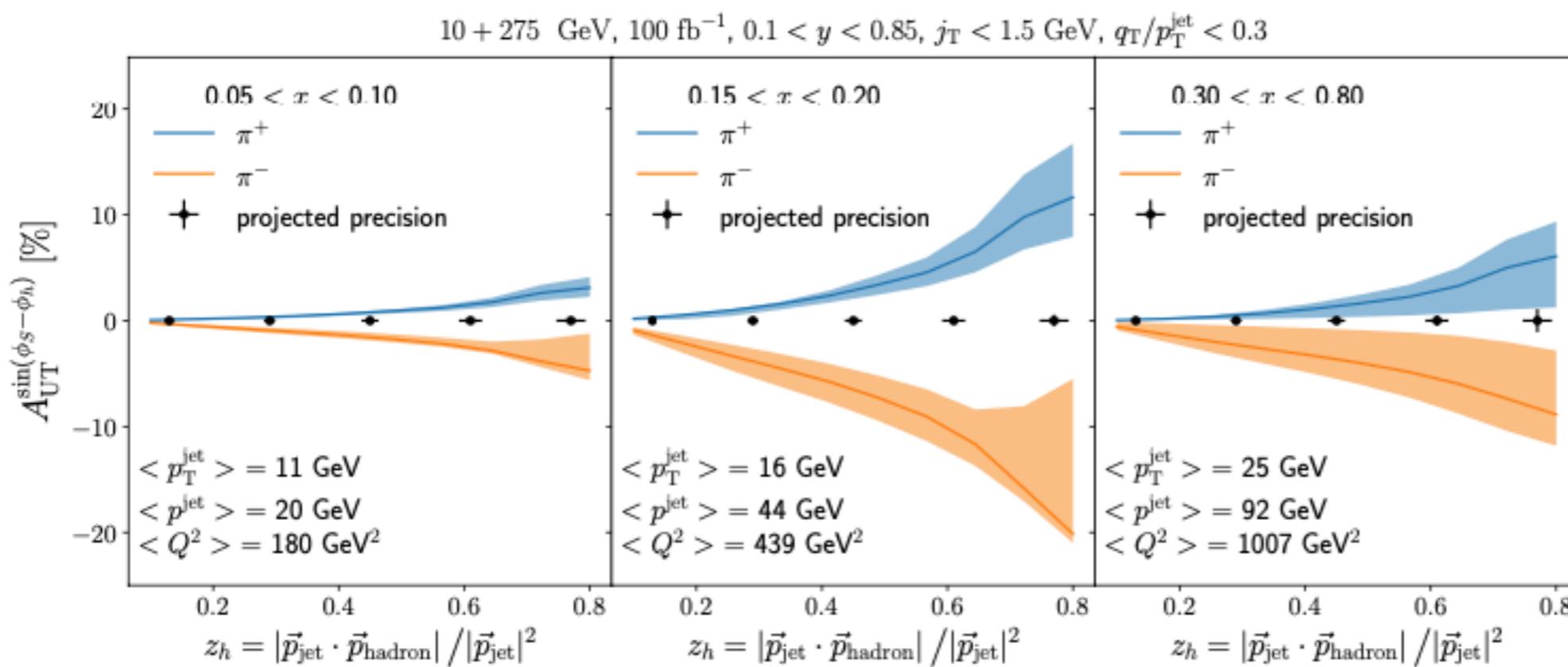
New methods: jets

electron - (hadron-in-jet) azimuthal correlations => Collins effect

see talk
by Scimemi
on Wednesday



*Arratia et al.,
PR D102 (20) 074015, arXiv:2007.07281*



potential
impact
of EIC

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

Conclusions

No conclusions.
Just stay tuned and have fun!