Transversity 2024
Round Table 1

Alessandro Bacchetta, Carlo Flore, Gunar Schnell

Umberto’s wishlist

- use/misuse of the Soffer bound
- impact/use/relevance of lattice calculations
- tensor charge (comparisons, new physics?)
- uncertainties beyond statistics (parametrizations, unpolarised FFs & diFFs, Collins FFs,...),
- different statistical approaches (replica method vs. MC approach, chi2's and correlations, bands...)
- role of kinematical cuts imposed to select SIDIS data in the fitting procedure
- compatibility of the extractions of h1 via the Collins effect (TMD approach) and dihadron production (Collinear approach)
- data binning, large-x region, Q2 coverage...
- ...

Positivity bounds

Soffer bound

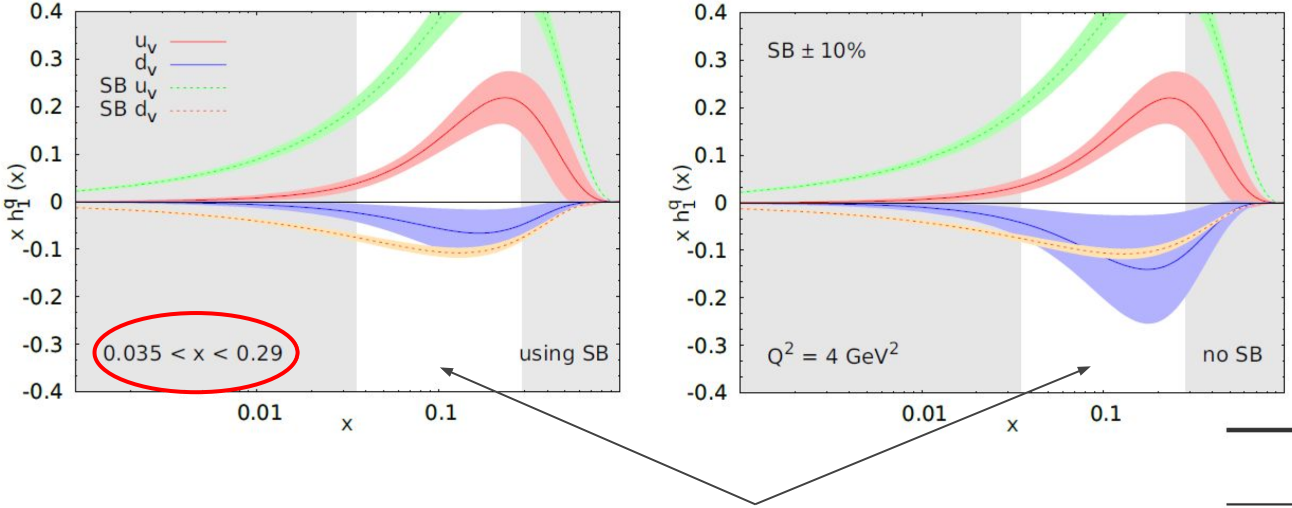
$$|h_1^q(x,Q^2)| \leq \frac{1}{2}\left[f_{q/p}(x,Q^2) + g_{1L}^q(x,Q^2)\right] \equiv SB^q(x,Q^2)$$

- positivity bound linking the 3 independent collinear PDFs at leading twist
- useful constraint for phenomenology
- how to properly use it?
- it depends on the adopted PDF and helicity extractions – always consistent choices? –
- unnatural shrinkage of uncertainties observed if SB automatically fulfilled by adopted parametrizations (e.g. in SIDIS when fitted w/ Collins function [D'Alesio, Flore, Prokudin] or in 2h production w/ diFF function [Benel, Courtoy, Ferro-Hernandez])
- positivity bounds useful for checking theory consistency [De Florian, Forte, Vogelsang]
- most stringent positivity requirement is on actual cross sections (or asymmetries); PDFs are only derived quantities subject to various assumptions

⇒ better to fit without bound and then check consistency?

Soffer bound

$$|h_1^q(x,Q^2)| \leq \frac{1}{2}\left[f_{q/p}(x,Q^2) + g_{1L}^q(x,Q^2)\right] \equiv SB^q(x,Q^2)$$

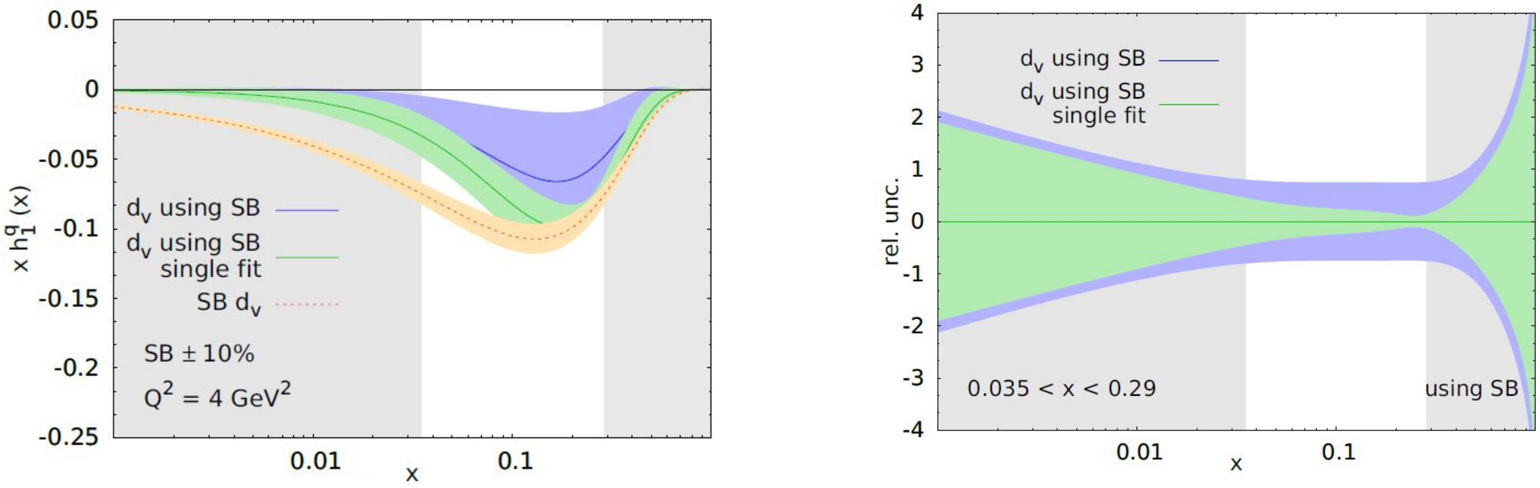


SIDIS data

$Q^2 = 4$ GeV^2		
	using SB	no SB
δu_v	0.42 ± 0.09	0.40 ± 0.09
δd_v	-0.15 ± 0.11	-0.29 ± 0.22
g_T	0.57 ± 0.13	0.69 ± 0.21

Soffer bound

$$|h_1^q(x,Q^2)| \leq \frac{1}{2}\left[f_{q/p}(x,Q^2) + g_{1L}^q(x,Q^2)\right] \equiv SB^q(x,Q^2)$$



- "using SB single fit": SB a priori, corresponding normalization parameter saturates ⇒ uncertainty underestimated
- "using SB": SB applied a posteriori, configuration not explored when enforcing SB in the fit now explored
- underestimation of uncertainty more severe in the x-region probed by experimental data !!

Positivity constraints

on the other hand, need to be careful if positivity is not imposed and check for severe violations

DE FLORIAN, FORTE, and VOGELSANG PHYS. REV. D **109,** 074007 (2024)

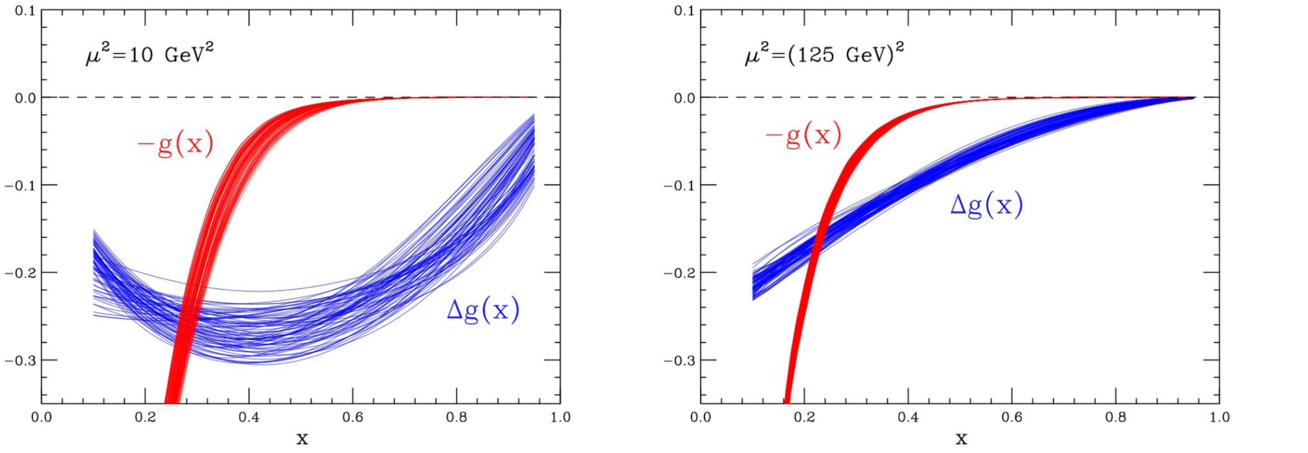
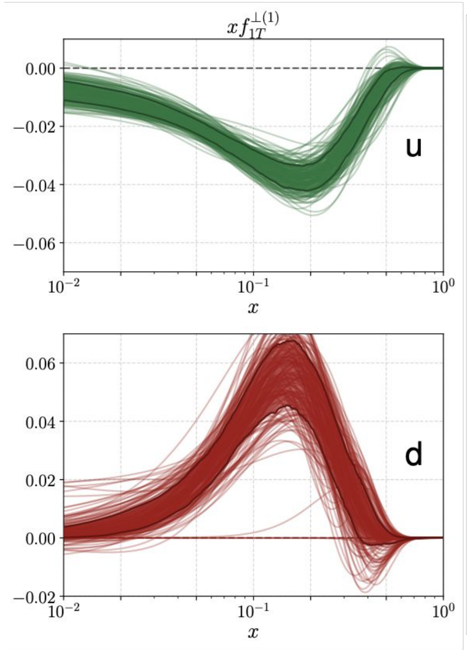


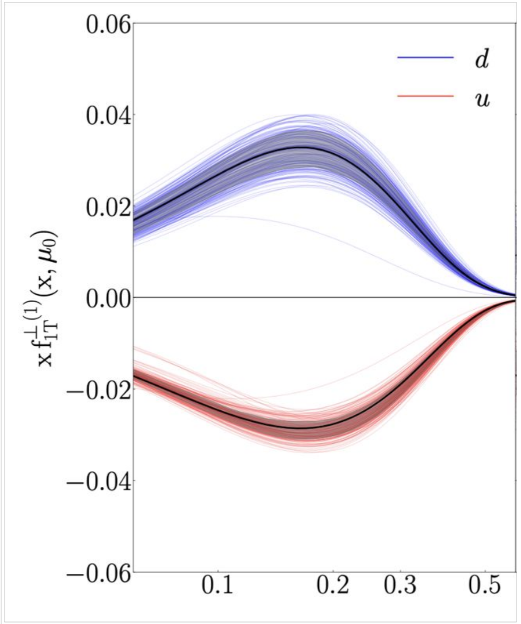
FIG. 1. PDF replicas of Ref. [7] for $-g(x,\mu)$ and $\Delta g(x,\mu)$ at $\mu = \sqrt{10}$ GeV (left) and $\mu = 125$ GeV (right).

Positivity and Sivers function

Without RHIC W & Z data



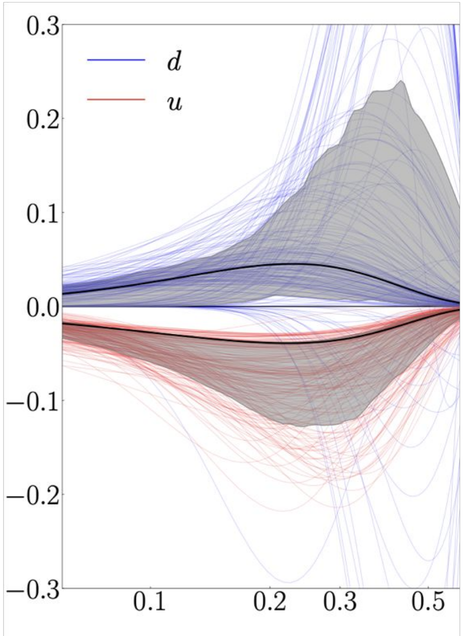
Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278



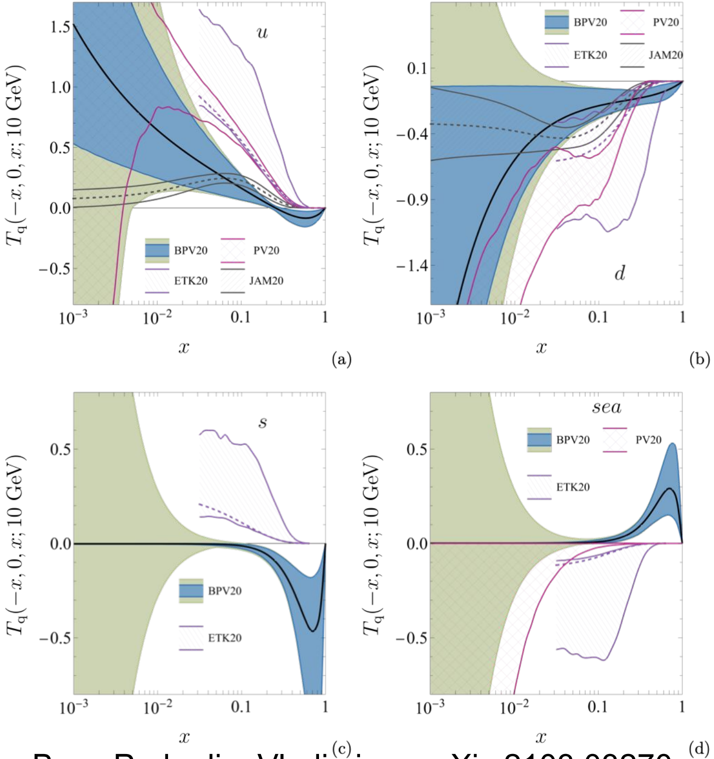
Echevarria, Kang, Terry, arXiv:2009.10710

Positivity and Sivers function

With RHIC W & Z data



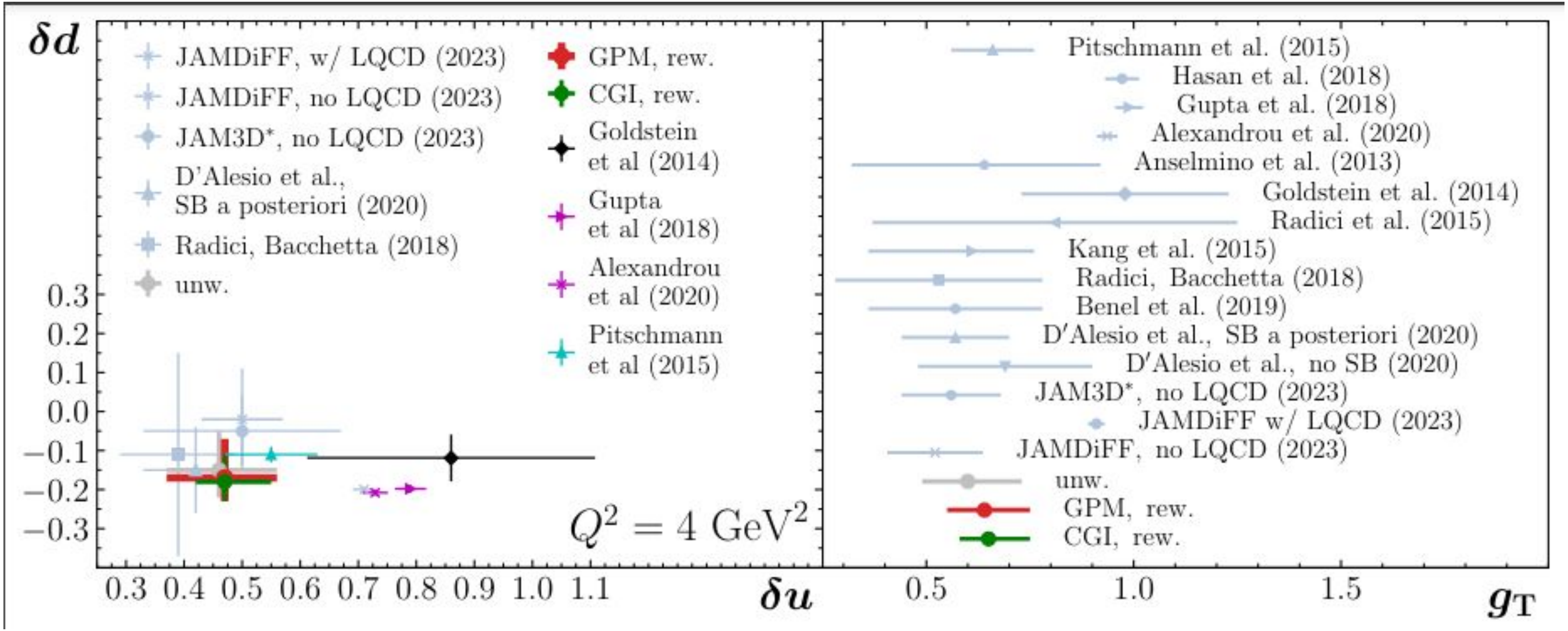
Echevarria, Kang, Terry, arXiv:2009.10710



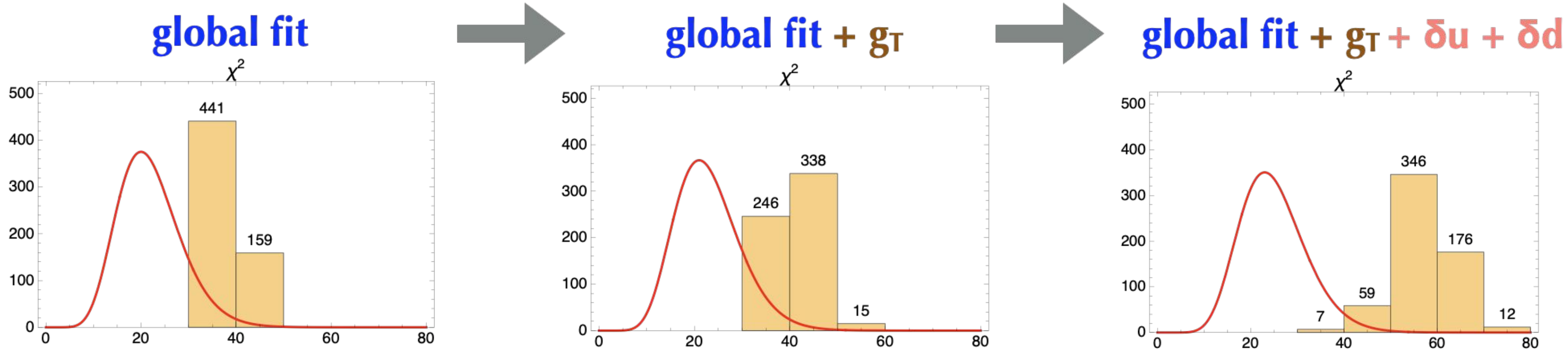
Bury, Prokudin, Vladimirov, arXiv:2103.03270

Lattice and phenomenology

Lattice-phenomenology tension?



Lattice-phenomenology tension?

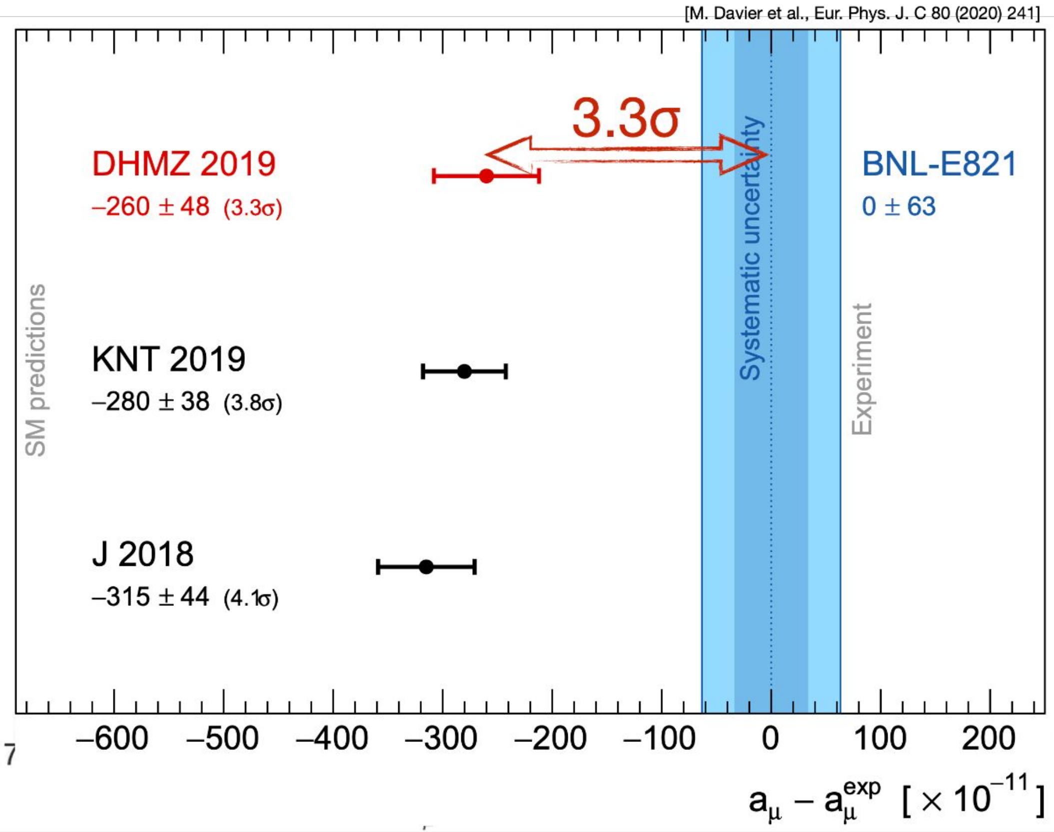


$\chi^2/\text{dof} = 1.76 \pm 0.11$ $\chi^2/\text{dof} = 1.82 \pm 0.25$ $\chi^2/\text{dof} = 2.29 \pm 0.25$

probability density function of χ^2 distribution

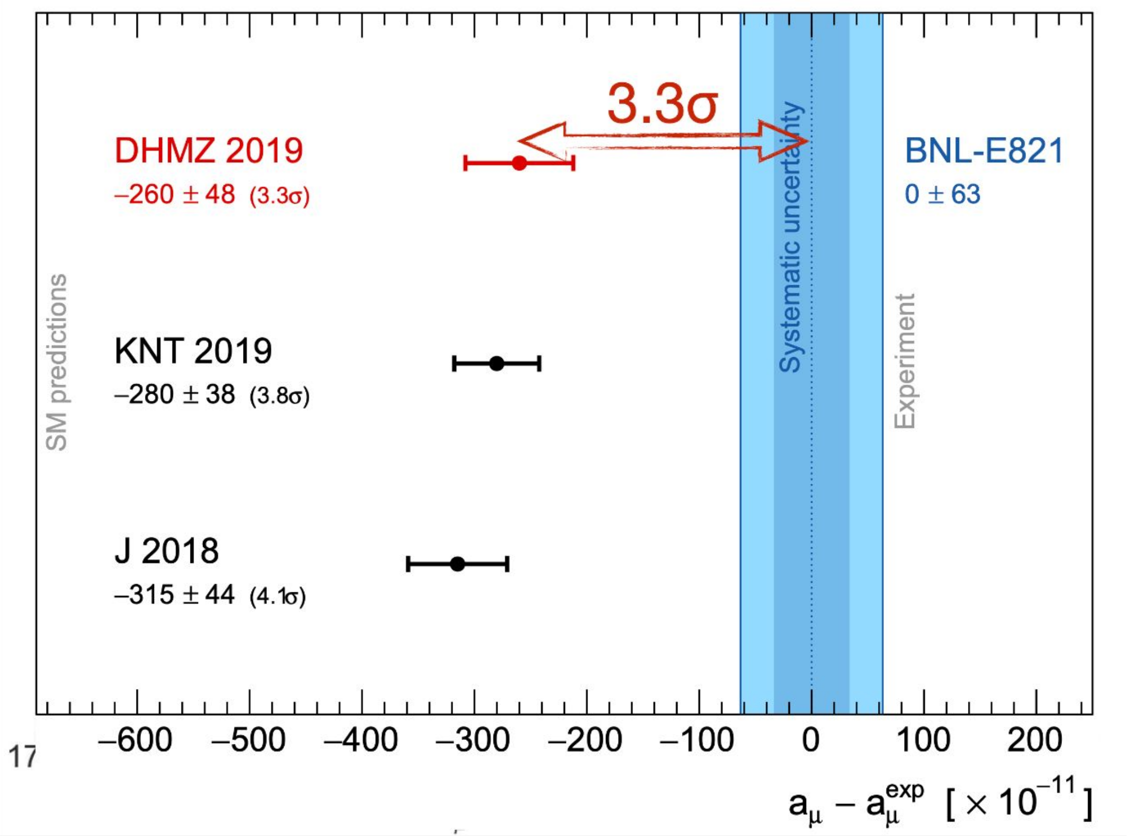
consistency of data sets

- 3.3σ tension:



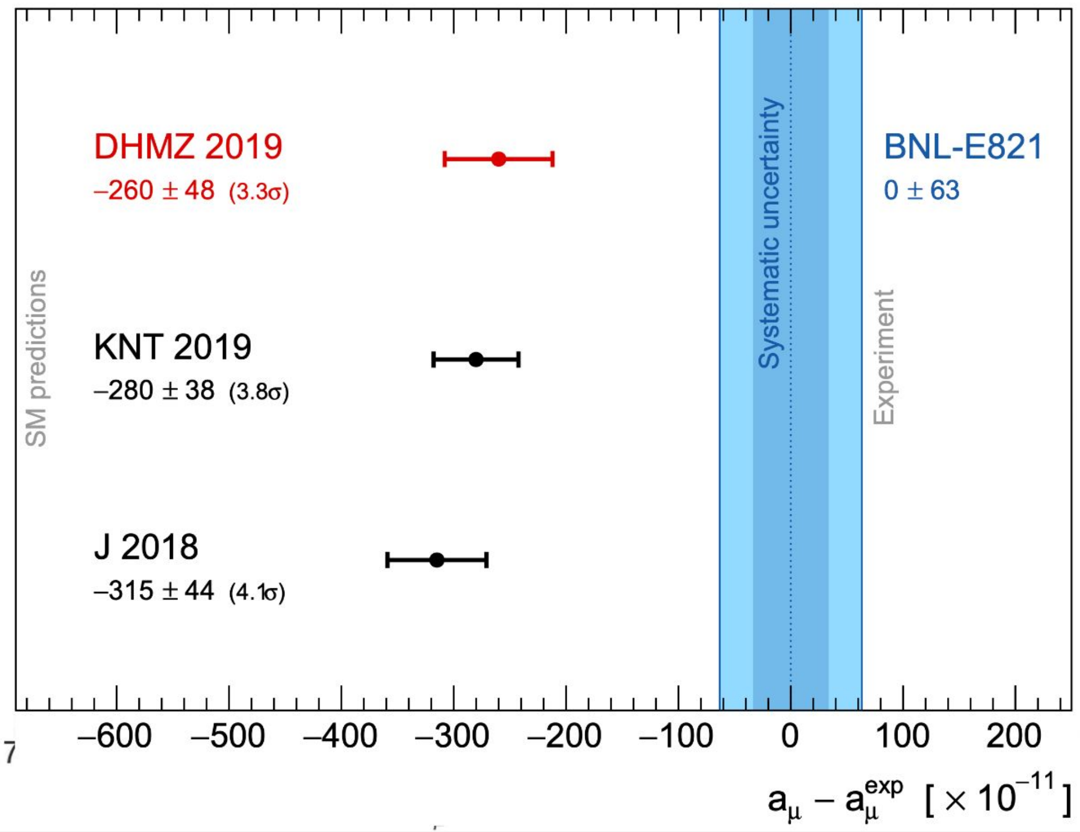
consistency of data sets

- 3.3σ tension:
  - new physics!



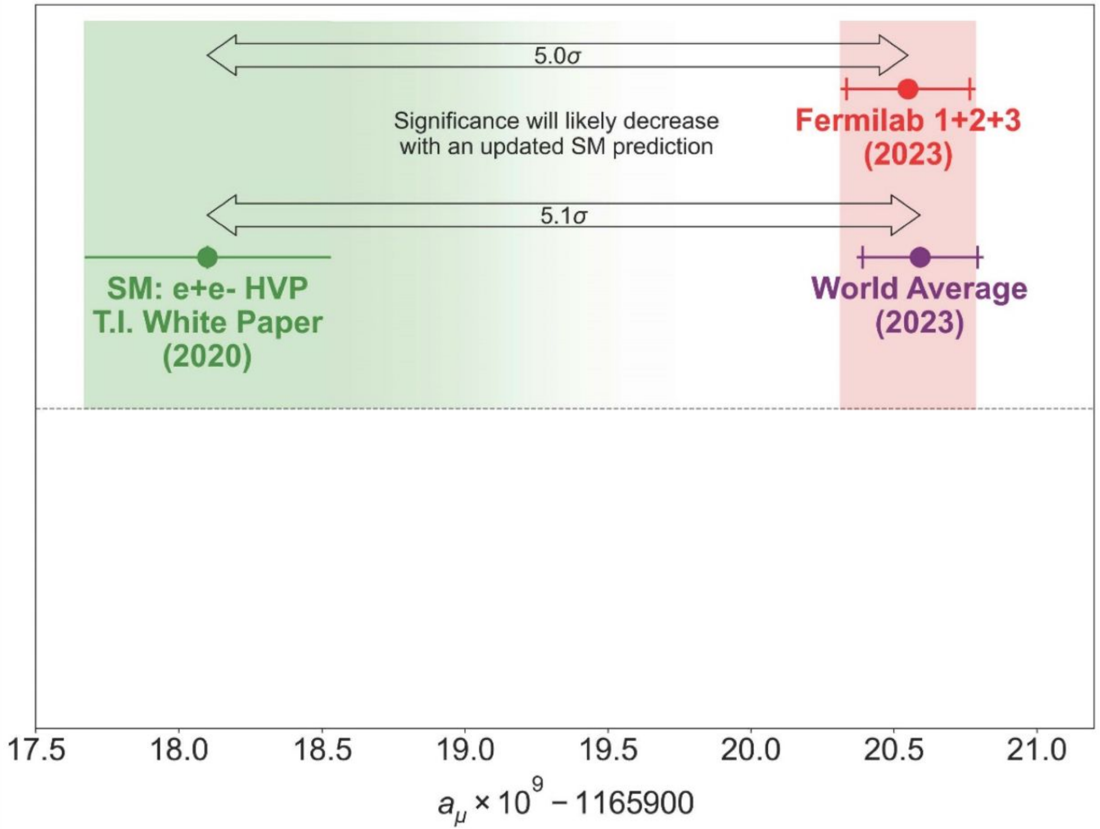
consistency of data sets

- 3.3σ tension:
  - new physics!
  - new experiments!



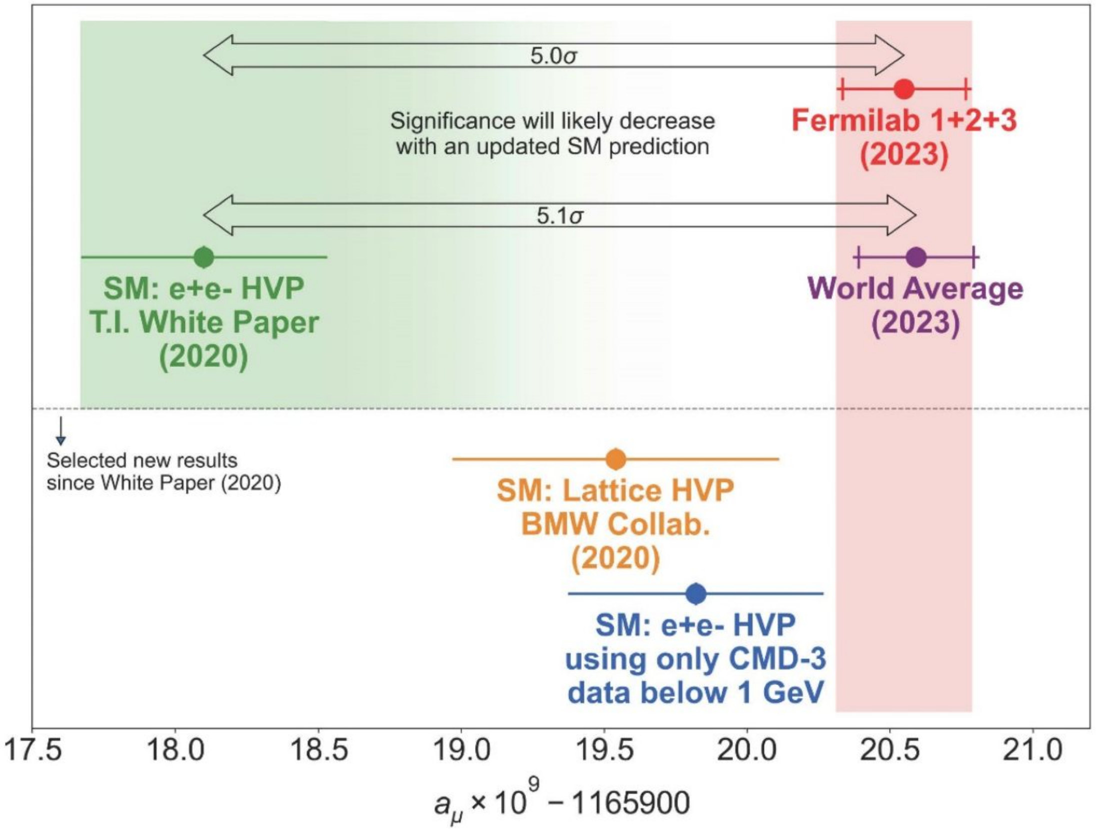
consistency of data sets

- 3.3σ tension:
  - new physics!!!
  - new experiments!



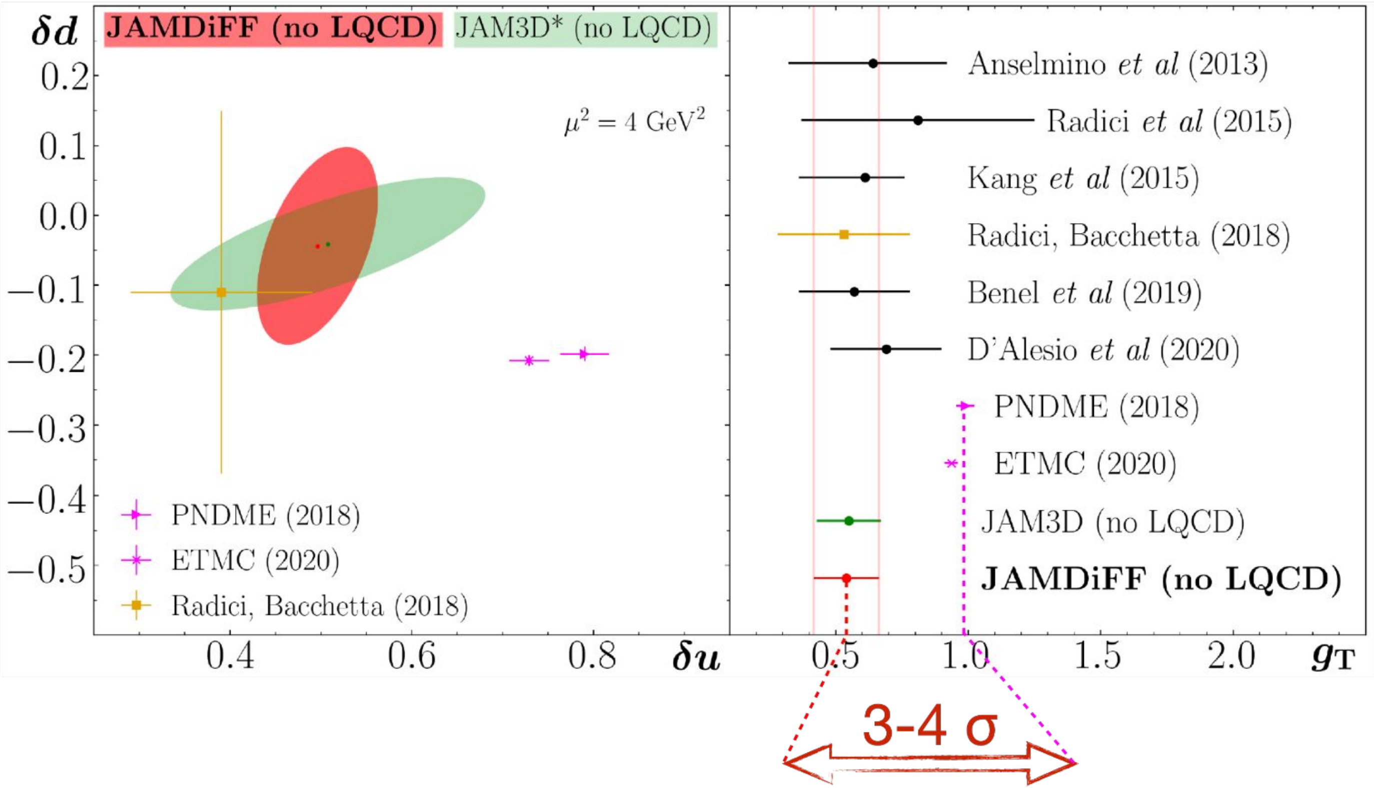
consistency of data sets

- 3.3σ tension:
  - new physics???
  - new experiments!
  - new calculations!



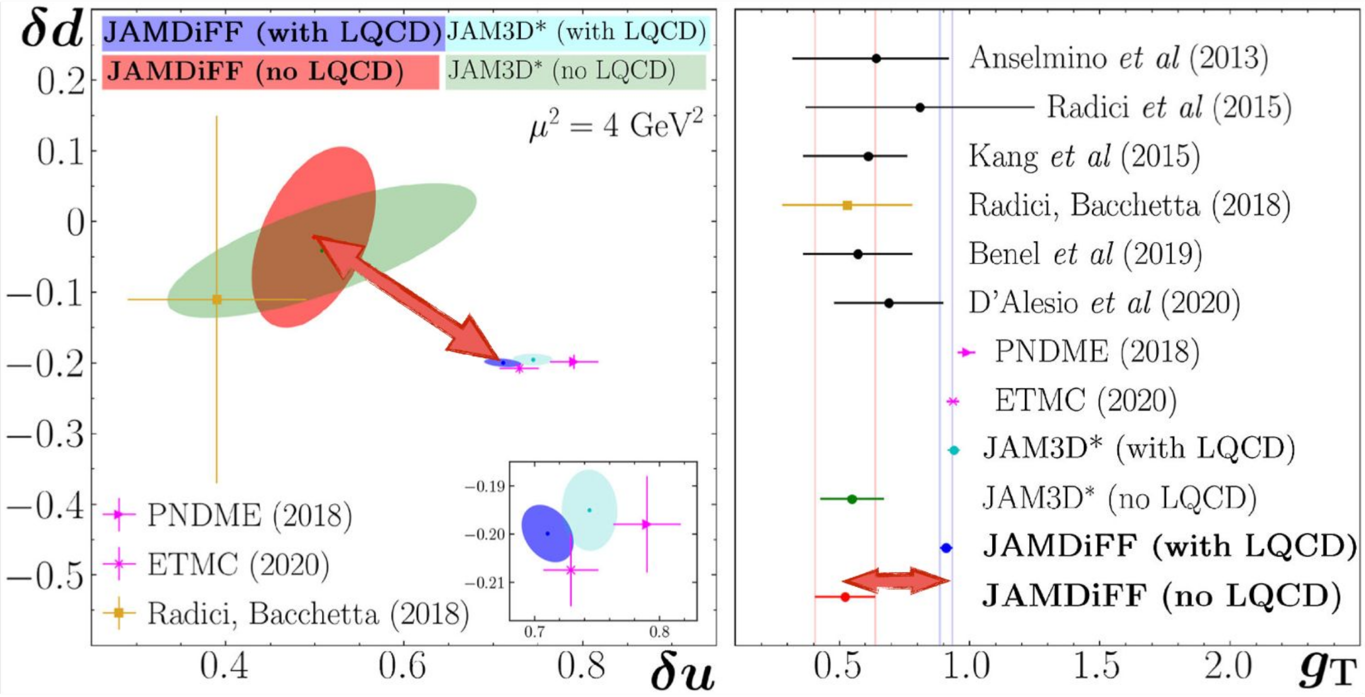
consistency of data sets

- 3-4 σ tension:



consistency of data sets

- 3-4 σ tension:
- combine!



consistency of data sets

TABLE I. Summary of χ^2_{red} values for the fits with and without LQCD data.

		χ^2_{red}	
Experiment	N_{dat}	With LQCD	No LQCD
Belle (cross section) [63]	1094	1.01	1.01
Belle (Artru-Collins) [92]	183	0.74	0.73
HERMES [94]	12	1.13	1.10
COMPASS (p) [95]	26	1.24	0.75
COMPASS (D) [95]	26	0.78	0.76
STAR (2015) [96]	24	1.47	1.67
STAR (2018) [64]	106	1.20	1.04
ETMC δu [28]	1	0.71	...
ETMC δd [28]	1	1.02	...
PNDME δu [25]	1	8.68	...
PNDME δd [25]	1	0.04	...
Total χ^2_{red} (N_{dat})		1.01 (1475)	0.98 (1471)

disclaimer: not a rigorous statistical analysis!

consistency of data sets

see, e.g., Maltoni & Schwetz, PRD 68 (2003) 033020

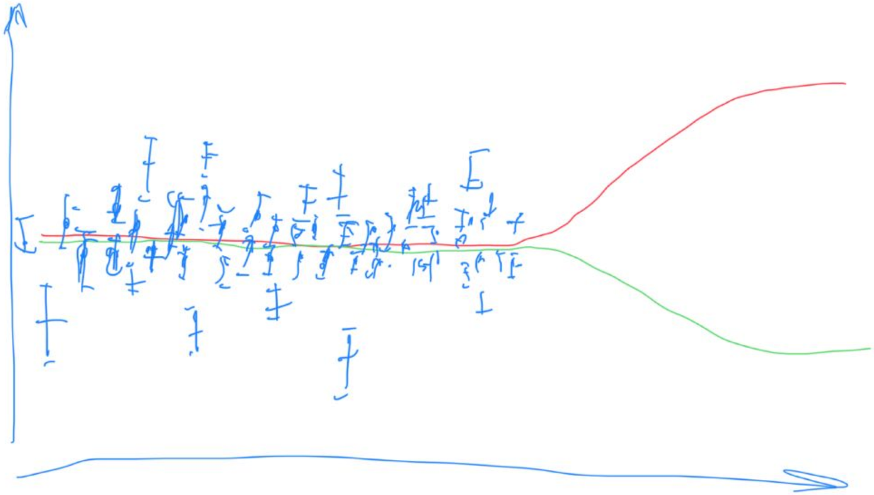


TABLE I. Summary of $\chi^2_{\rm red}$ values for the fits with and without LQCD data.

		$\chi^2_{\rm red}$	
Experiment	$N_{\rm dat}$	With LQCD	No LQCD
Belle (cross section) [63]	1094	1.01	1.01
Belle (Artru-Collins) [92]	183	0.74	0.73
HERMES [94]	12	1.13	1.10
COMPASS (p) [95]	26	1.24	0.75
COMPASS (D) [95]	26	0.78	0.76
STAR (2015) [96]	24	1.47	1.67
STAR (2018) [64]	106	1.20	1.04
ETMC δu [28]	1	0.71	...
ETMC δd [28]	1	1.02	...
PNDME δu [25]	1	8.68	...
PNDME δd [25]	1	0.04	...
Total $\chi^2_{\rm red}$ ($N_{\rm dat}$)		1.01 (1475)	0.98 (1471)

disclaimer: not a rigorous statistical analysis!

consistency of data sets

see, e.g., Maltoni & Schwetz, PRD 68 (2003) 033020

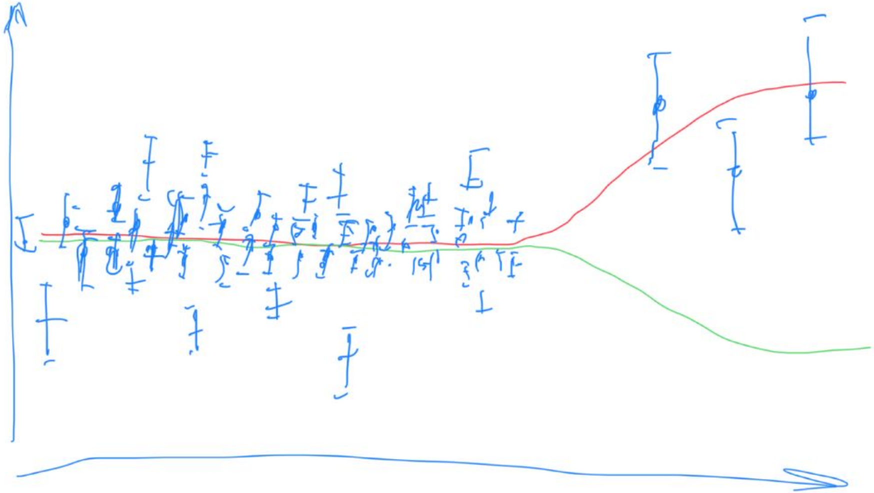


TABLE I. Summary of $\chi^2_{\rm red}$ values for the fits with and without LQCD data.

		$\chi^2_{\rm red}$	
Experiment	$N_{\rm dat}$	With LQCD	No LQCD
Belle (cross section) [63]	1094	1.01	1.01
Belle (Artru-Collins) [92]	183	0.74	0.73
HERMES [94]	12	1.13	1.10
COMPASS (p) [95]	26	1.24	0.75
COMPASS (D) [95]	26	0.78	0.76
STAR (2015) [96]	24	1.47	1.67
STAR (2018) [64]	106	1.20	1.04
ETMC δu [28]	1	0.71	...
ETMC δd [28]	1	1.02	...
PNDME δu [25]	1	8.68	...
PNDME δd [25]	1	0.04	...
Total $\chi^2_{\rm red}$ ($N_{\rm dat}$)		1.01 (1475)	0.98 (1471)

disclaimer: not a rigorous statistical analysis!

consistency of data sets

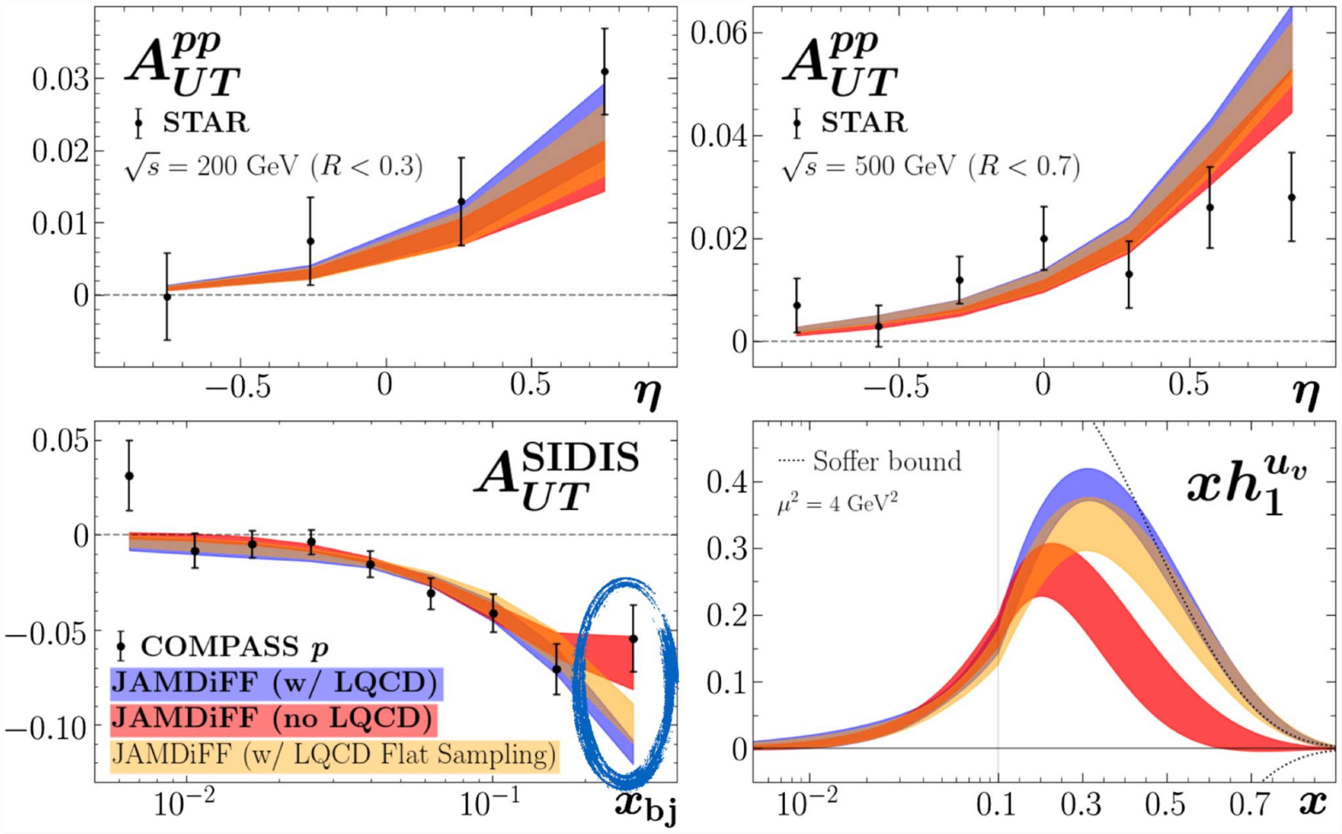
- majority of data points insensitive to tensor charge
  - basically irrelevant in discussion of compatibility of lattice and exp. data
- for tensor-charge related data: chi2 worsens from 203 to 239!
  - p-value from 0.314 to 0.022 (<0.05)
- if taking into account number of free (tensor-charge related) parameters:
  - p-value from 0.1055 to 0.0034 

TABLE I. Summary of χ^2_{red} values for the fits with and without LQCD data.

Experiment	N_{dat}	χ^2_{red} With LQCD	χ^2_{red} No LQCD
Belle (cross section) [63]	1094	1.01	1.01
Belle (Artru-Collins) [92]	183	0.74	0.73
HERMES [94]	12	1.13	1.10
COMPASS (p) [95]	26	1.24	0.75
COMPASS (D) [95]	26	0.78	0.76
STAR (2015) [96]	24	1.47	1.67
STAR (2018) [64]	106	1.20	1.04
ETMC δu [28]	1	0.71	...
ETMC δd [28]	1	1.02	...
PNDME δu [25]	1	8.68	...
PNDME δd [25]	1	0.04	...
Total χ^2_{red} (N_{dat})		1.01 (1475)	0.98 (1471)

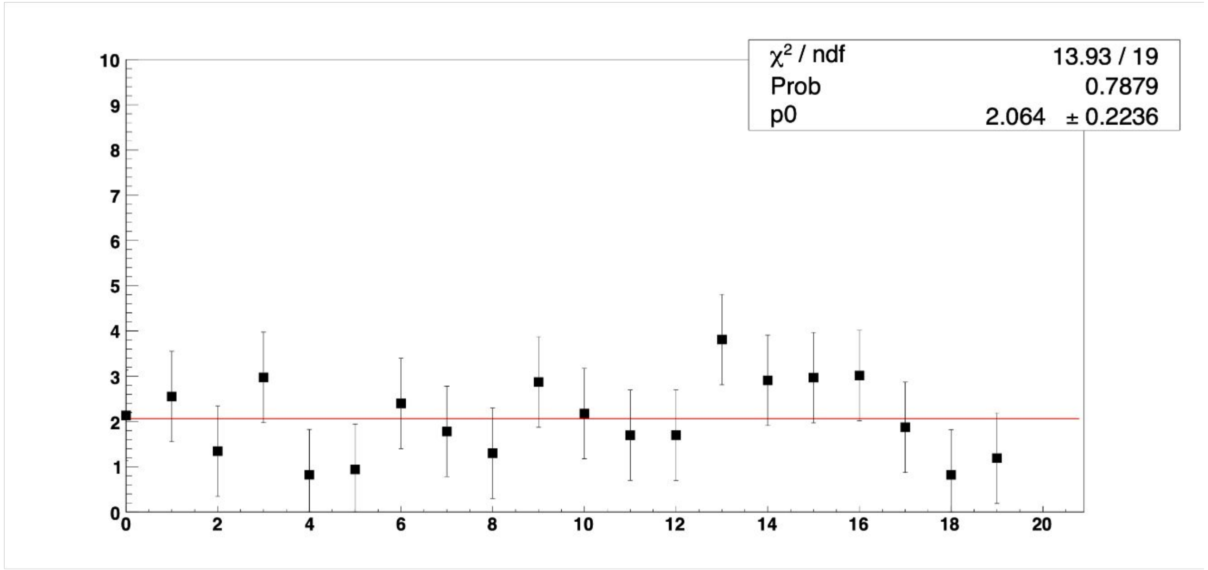
disclaimer: not a rigorous statistical analysis!

consistency of data sets



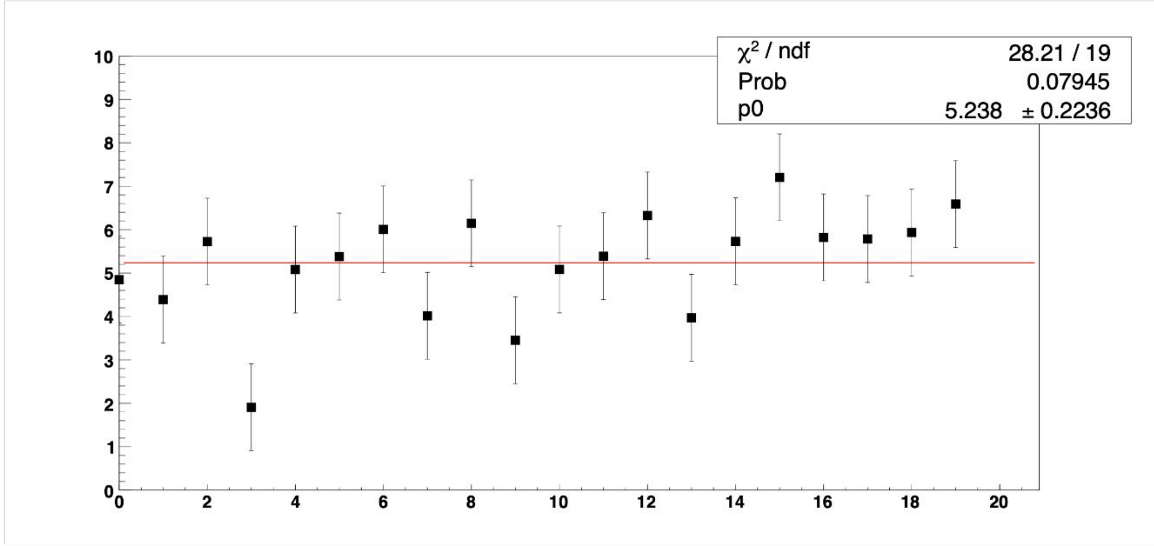
consistency of data sets

- 20 random data points around mean of 2.0
  - nicely reproduced by constant fit with uncertainty of 1/√20



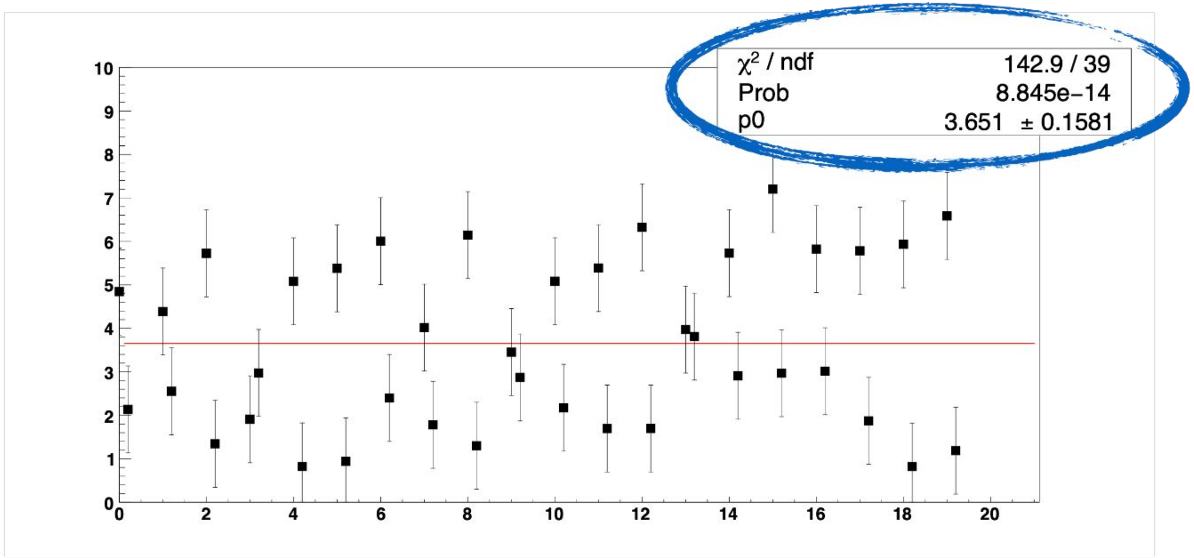
consistency of data sets

- 20 random data points around mean of 2.0
  - nicely reproduced by constant fit with uncertainty of $1/\sqrt{20}$
- 20 random data points around mean of 5.0
  - reproduced by constant fit with uncertainty of $1/\sqrt{20}$



consistency of data sets

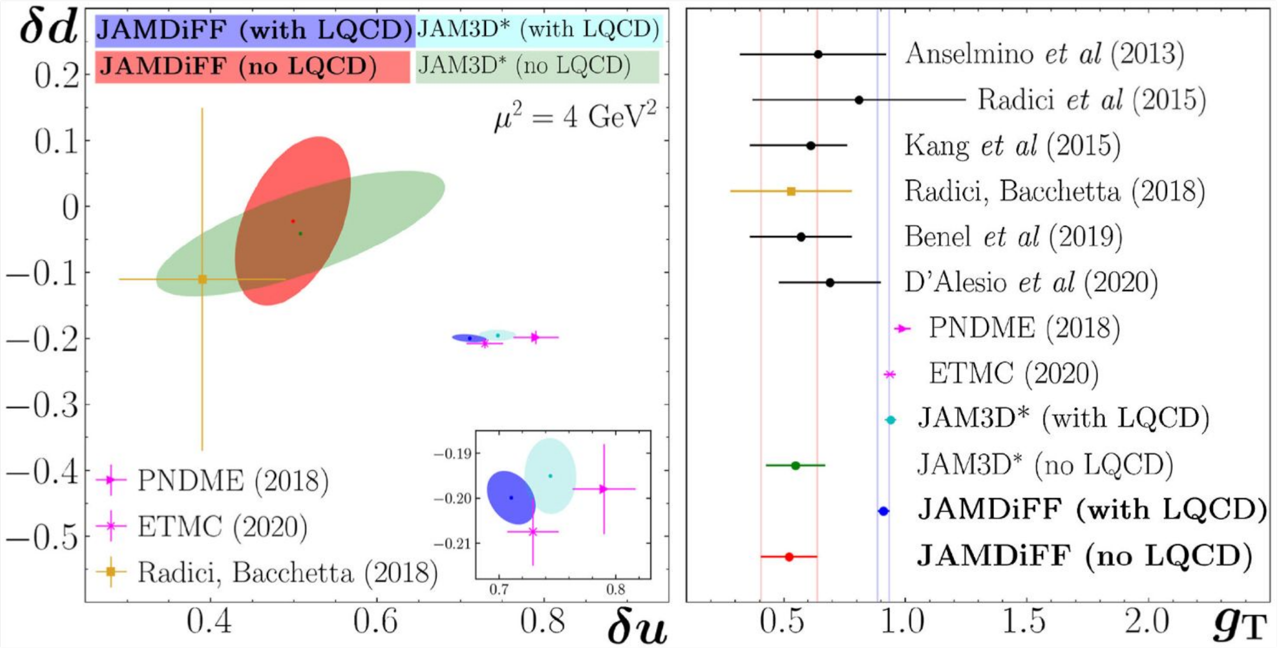
- 20 random data points around mean of 2.0
  - nicely reproduced by constant fit with uncertainty of 1/√20
- 20 random data points around mean of 5.0
  - reproduced by constant fit with uncertainty of 1/√20
- 40 inconsistent data points around means of 2.0 and 5.0
  - „nicely" reproduced by constant fit with uncertainty of 1/√40



Parameter uncertainty (correctly) not punished by disagreement; only chi2 gets punished!

consistency of data sets

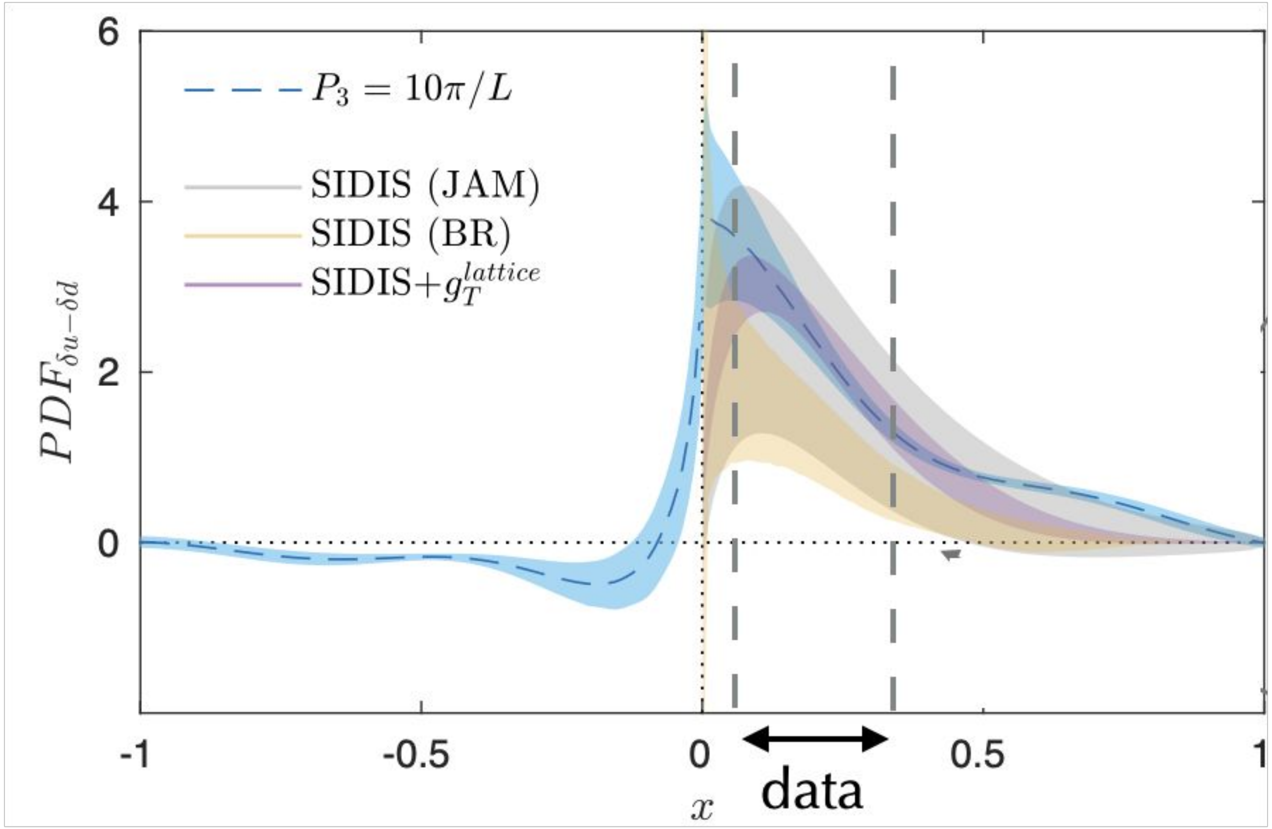
- 3-4 σ tension:
- combine!



➟ how much can we trust the shrunken uncertainties on the tensor charges?

➟ employ error inflation (cf. muon g-2 data combinations)?

Lattice transversity calculation



usage of lattice data

- on one side, have examples of using lattice data in phenomenology, e.g., muon (g-2)
- but what is confidence in accuracy of lattice data (and properly reflected in assigned uncertainties?)

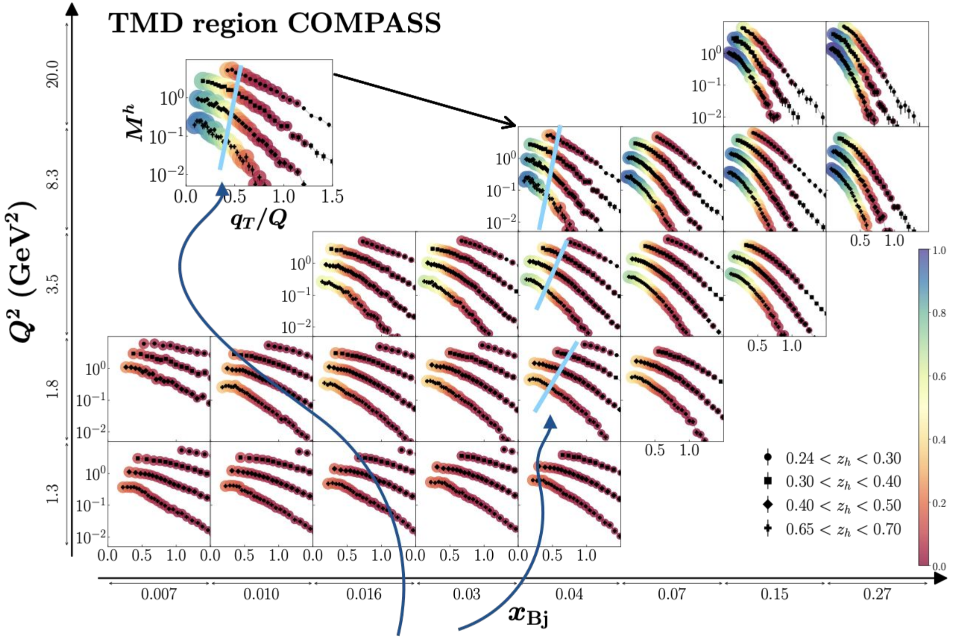
  ⇒ would we use also axial and vector charges from same calculation as constraints in other PDF fits?
  (is Soffer bound calculated in those fits consistent with axial and vector charges from lattice?)
  ⇒ why only total tensor charge and not also integrals of transversity of u and d separately, and of also s

- lattice data come with very small uncertainty; dominates the fit
  ⇒ if so much trust in lattice result, hardly need experimental data unless in studies of what functional form for lattice transversity is still in agreement with experimental data
- lattice points in combination with rigid parametrization can be difficult as the previous is an integral of the latter over the whole x range, e.g., also in regions where we have no data to guide choice of parametrization

Data selection

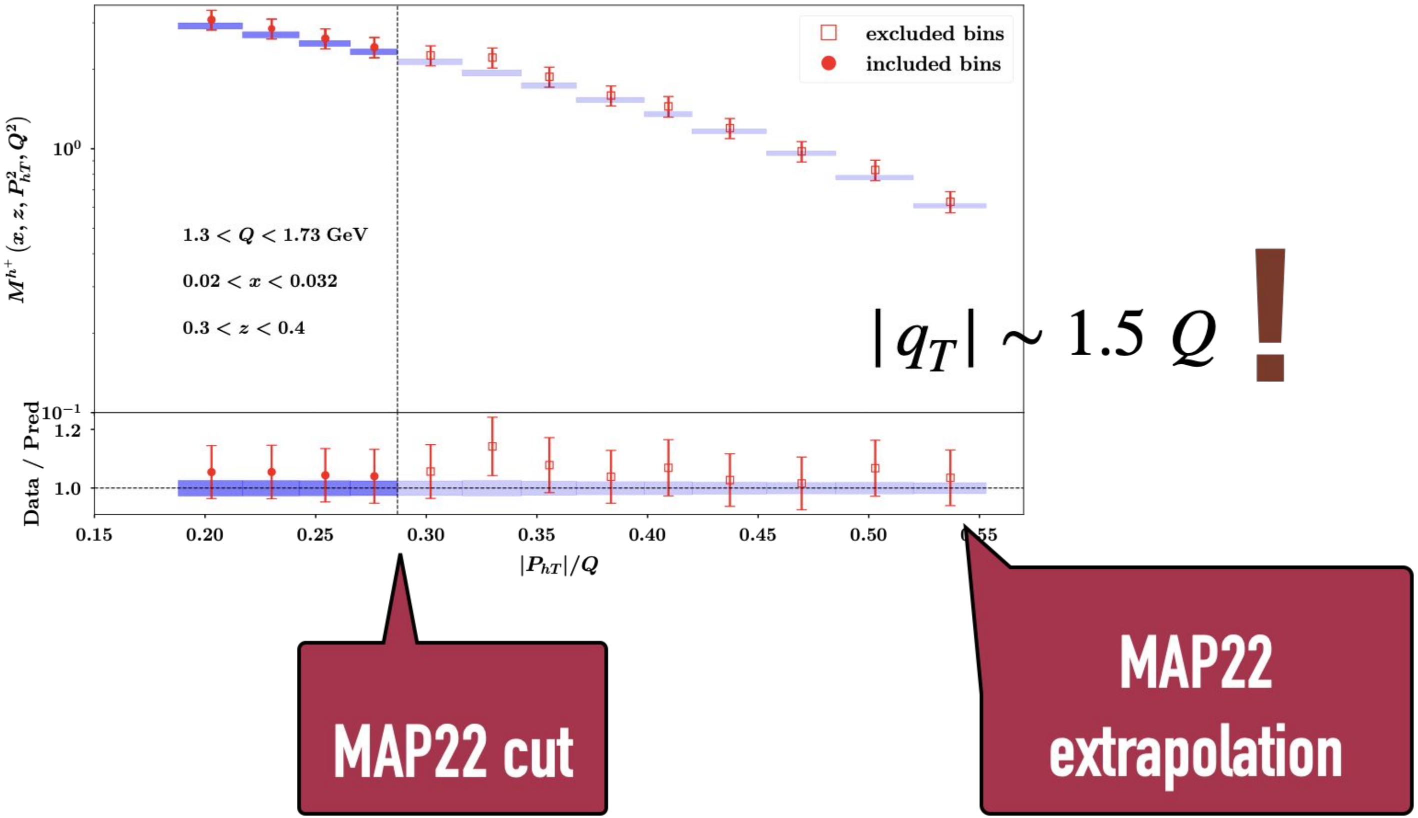
Data selection criteria: TMDs

Boglione, Diefenthaler, Dolan, Gamberg, Melnitchouk, arXiv:2201.12197

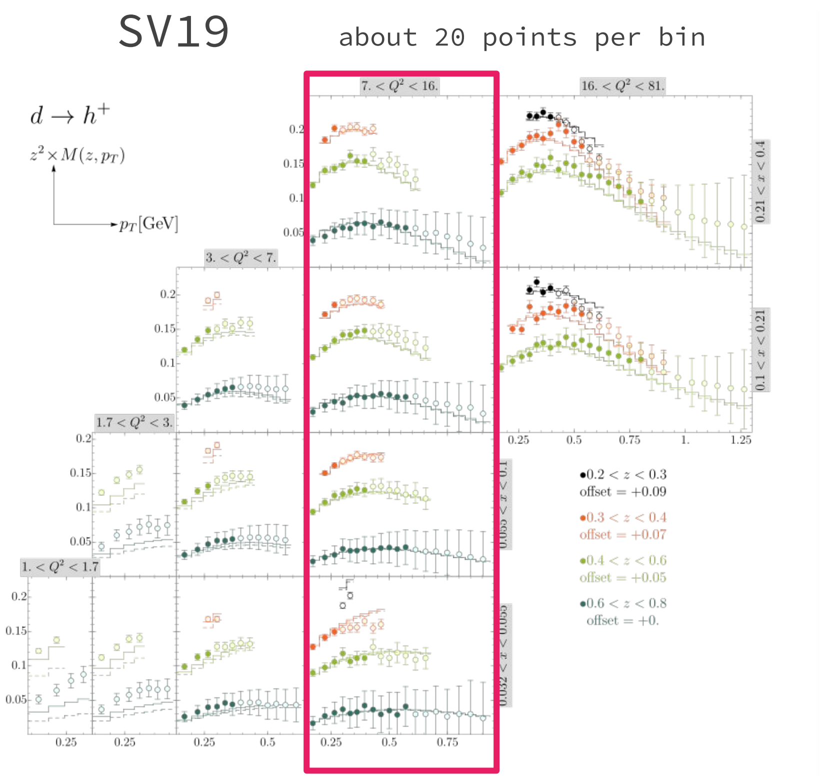


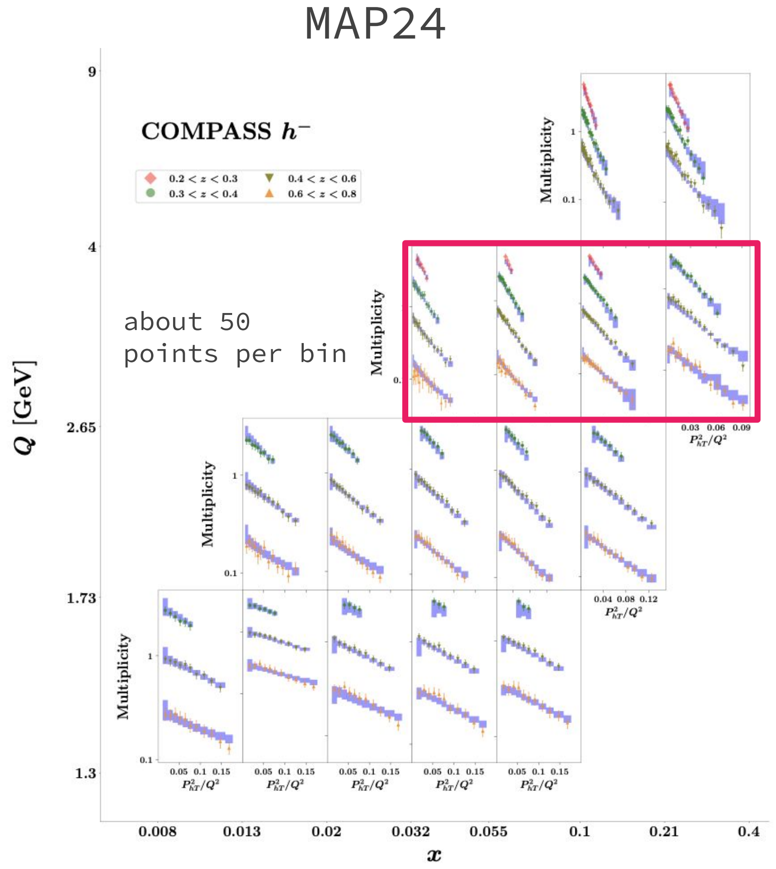
Approximate region included in MAP22 fit

Data selection criteria: TMDs



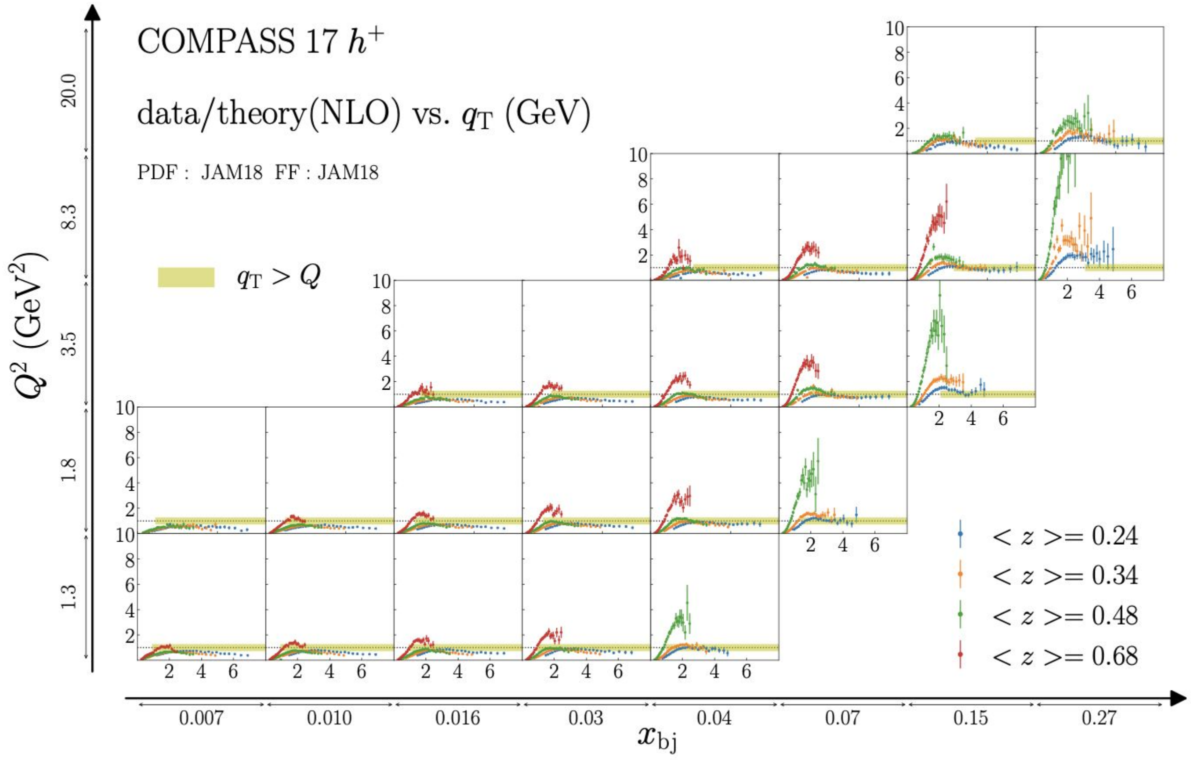
Data selection criteria



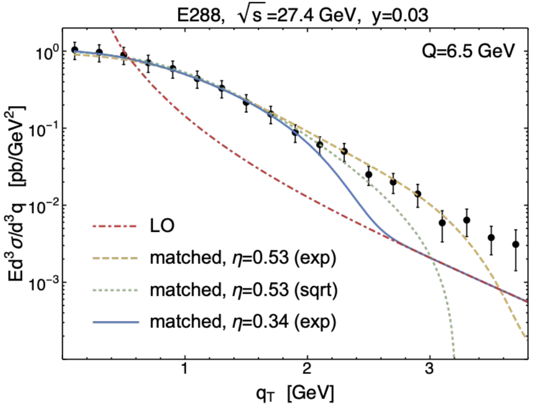


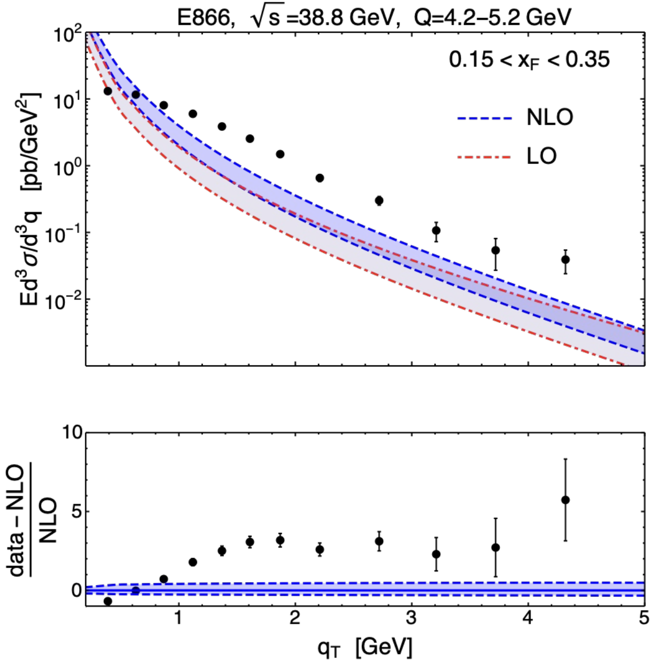
Data selection criteria: matching

Gonzalez-Hernandez, Rogers, Sato, Wang arXiv:1808.04396



Data selection criteria: matching

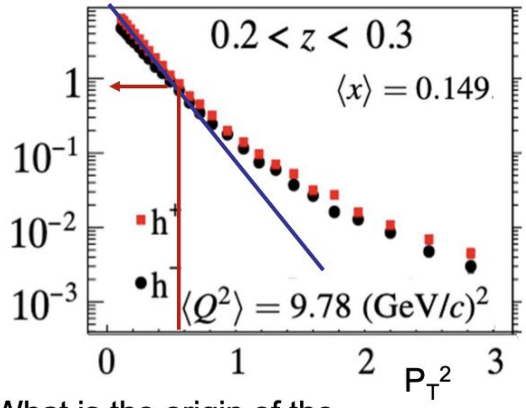




Bacchetta, Bozzi, Lambertsen, Piacenza, Steinglechner, Vogelsang arXiv:1901.06916

q_T-crisis or misinterpretation

https://arxiv.org/pdf/1709.07374.pdf

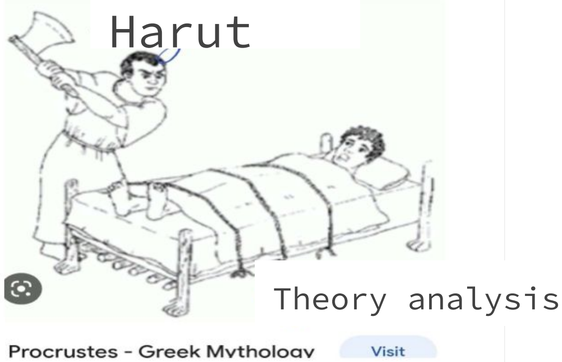


- What is the origin of the "high" P_T (0.8-1.8) tail?
  1) Perturbative contributions?
  2) Non perturbative contributions?

JLab: not enough energy to produce large P_T
HERMES: not enough luminosity to access large P_T

The q_T=P_T/z theory "trustworthy" cut:
1)Suppresses moderate Q^2 and large P_T (sensitive to k_T), where all kind of azimuthal modulations are most significant
2)Enhances large z region (ex. Exclusive Events) in TMD and low z in FO calculations

3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P_T samples , including ones from HERMES COMPASS, and even EIC.



Possible sources of large P_T behaviour

1) Perturbative contributions and p_T-dependence of unpolarized FFs (so far unlikely...)

2) Significantly wider in k_T distributions of u-quarks with spin opposite to proton spin (possible sign flips in asymmetries related to polarization of partons)

3) Significantly wider in k_T distributions of d-quarks (possible sign flips in asymmetries related to polarization of partons)

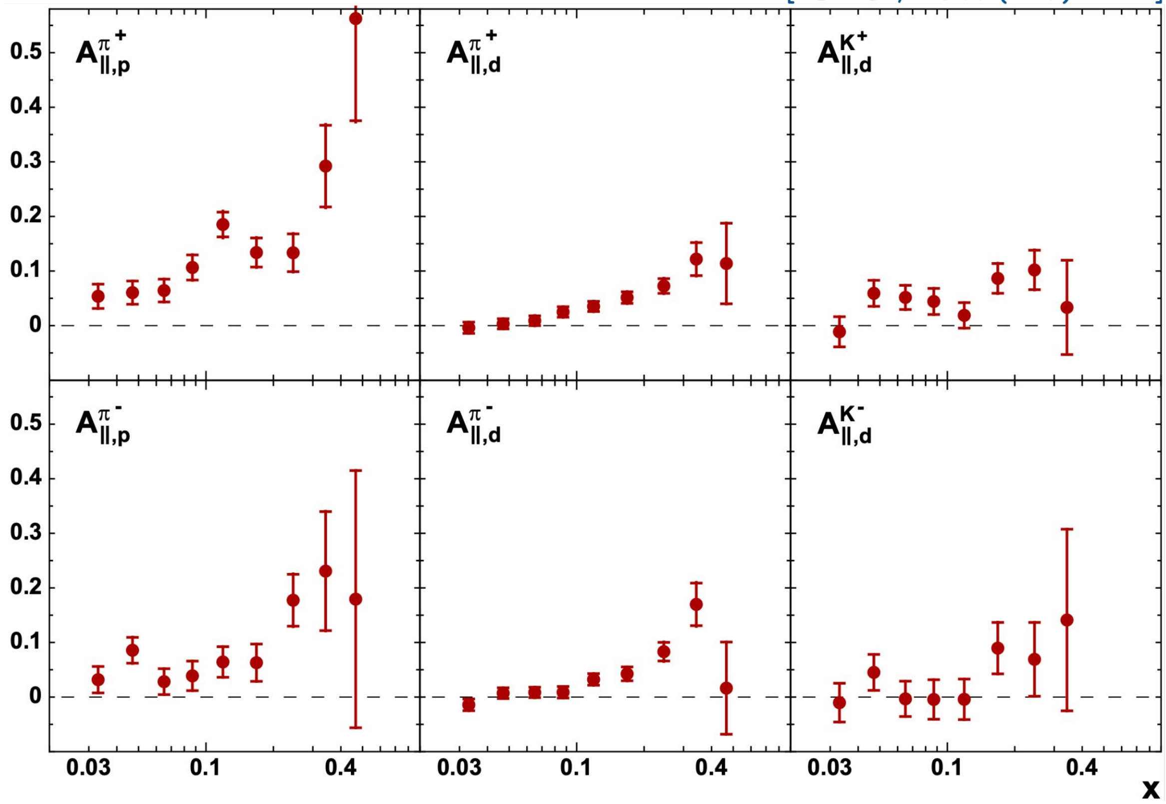
4) Significantly wider in k_T sea quark distributions (study contributions dominated by sea, K-,..)

---

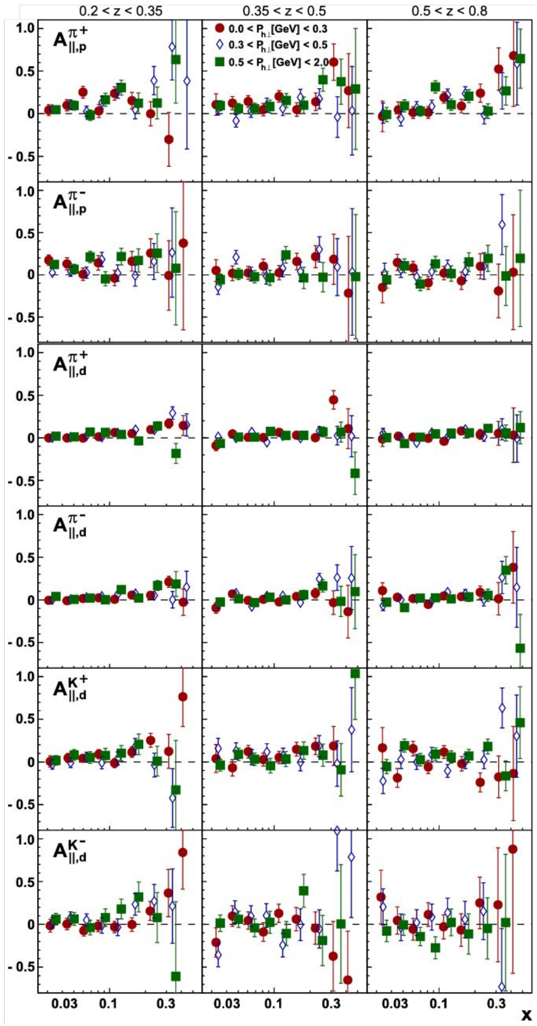
5) Increasing fraction of hadrons due to $F_{UU,L}$ (needed for proper interpretation → separation of $F_{UU,L}$ from total)
6) Significant contributions from VMs to low P_T pion multiplicities, with direct pions showing up at large P_T (needed for proper interpretation → much wider in k_T original parton distributions)
7) Radiative corrections (need the full x-section, typically applied to pions, while may be needed for underlying VMs,...)
8) Two photon exchange (will need positron beam)
....

Data selection criteria: binning

[HERMES, PRD 99 (2019) 112001]

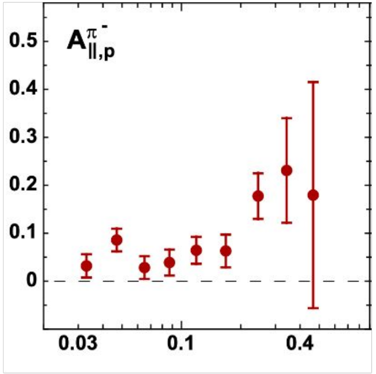


- **first-ever 3d binning** provides transverse-momentum dependence

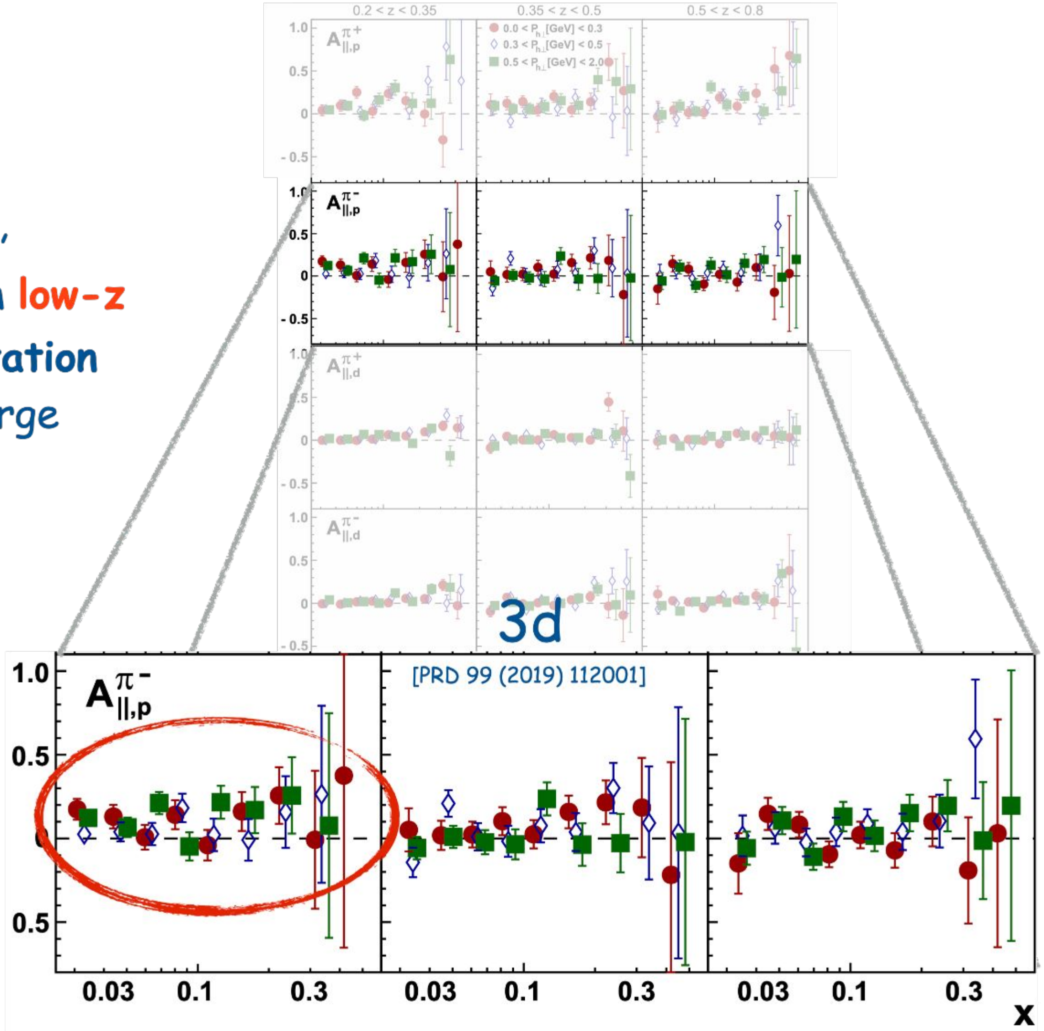


- **first-ever 3d binning** provides transverse-momentum dependence
- but also extra flavor sensitivity, e.g.,
  - π^- asymmetries mainly coming from low-z region where **disfavored fragmentation** large and thus **sensitivity** to the large **positive up-quark polarization**

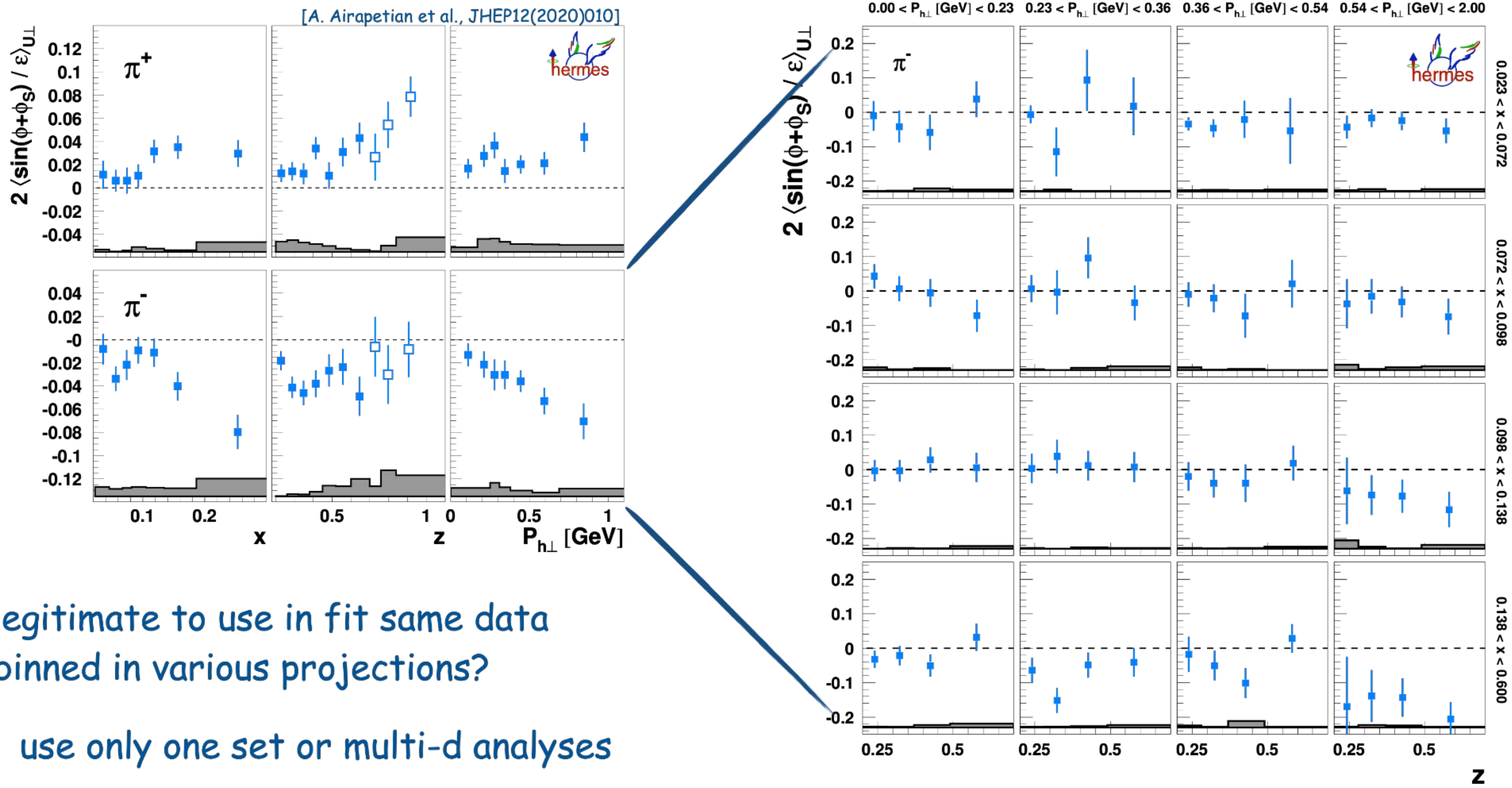
1d



3d



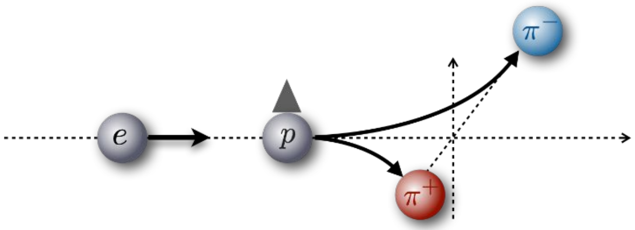
Data selection criteria: binning



- legitimate to use in fit same data binned in various projections?
  - use only one set or multi-d analyses

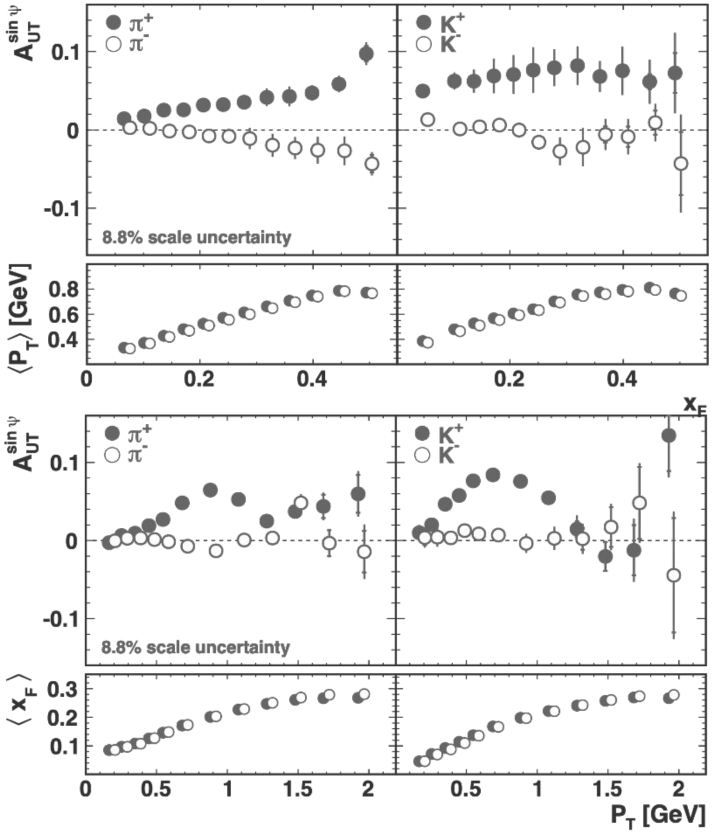
Data selection criteria: binning

- clear left-right asymmetries for pions and positive kaons
- increasing with x_F (as in pp)



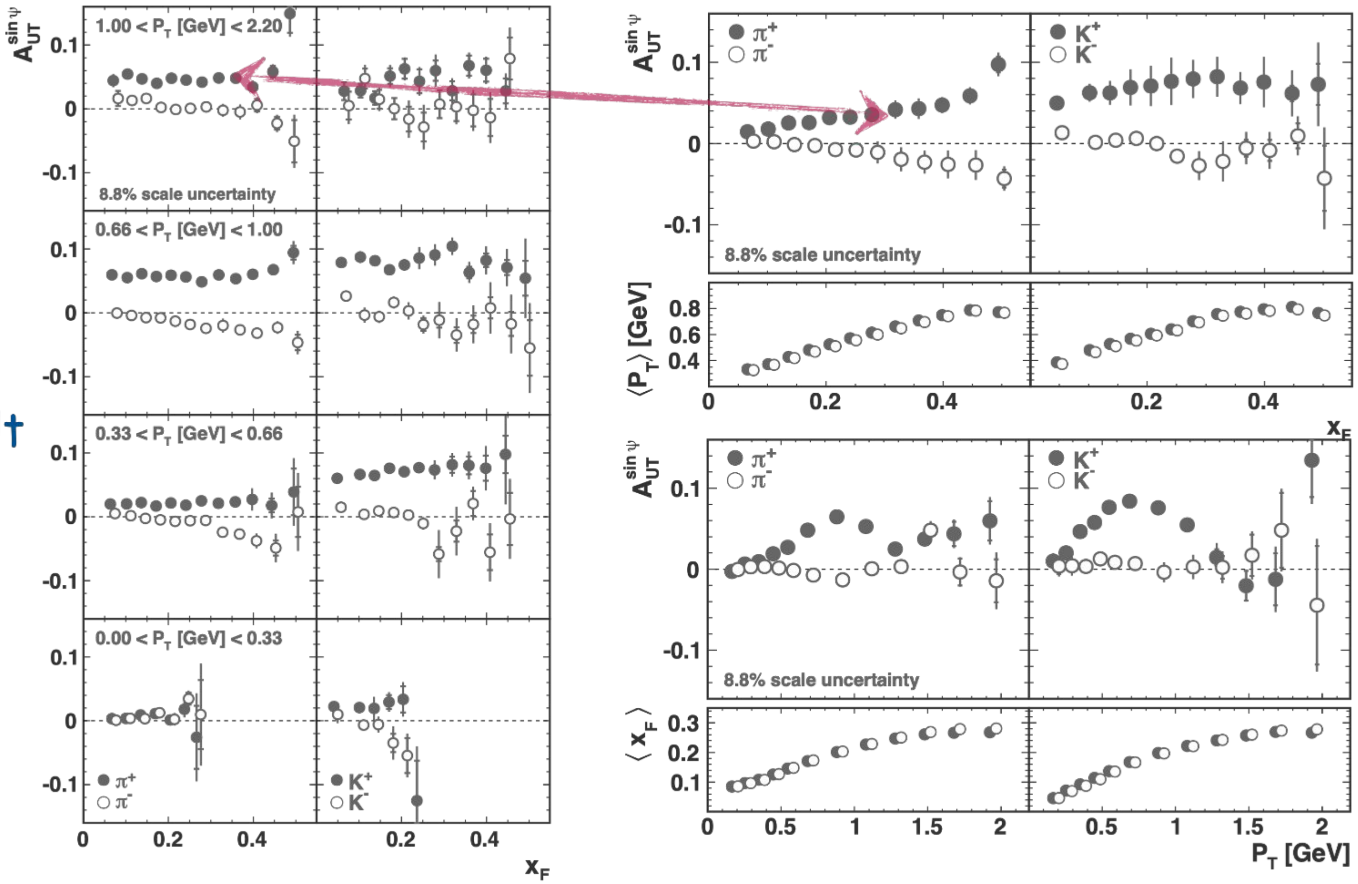
- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated

➥ look at 2D dependences



Data selection criteria: binning

- increase with x_F disappears in 2d binning
- increase in 1d presentation result of underlying P_T dependence

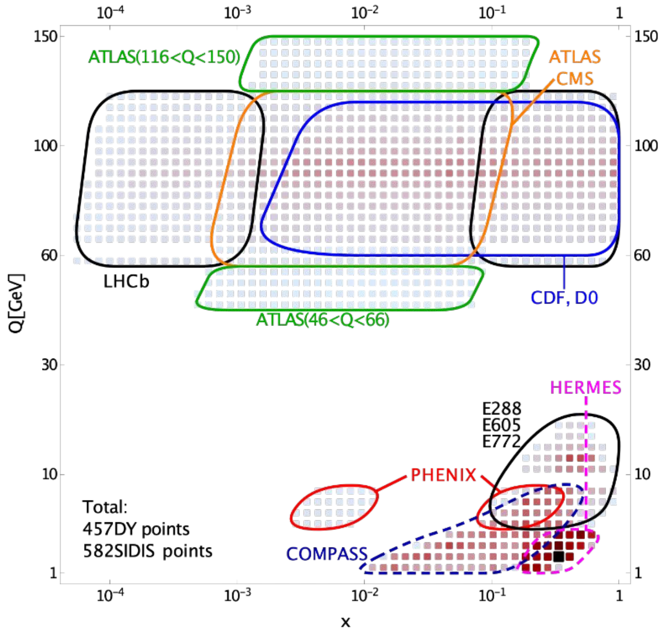


Future data

Experimental prospects

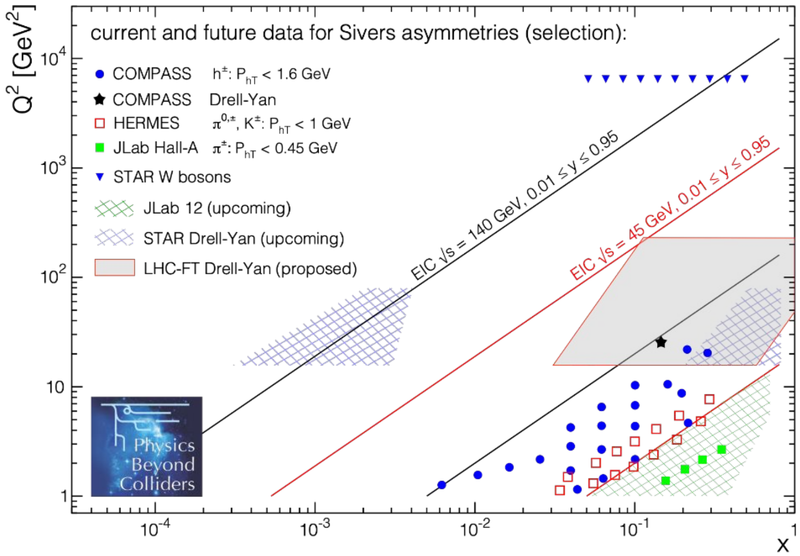
* Unpolarized TMDs experimental landscape

🔗 [I. Scimemi & A. Vladimirov JHEP06(2020)137]



* Future data from colliders (EIC, LHC, SuperKEKB) & fixed-target exp. (JLab12, Fermilab, LHC-FT,…)

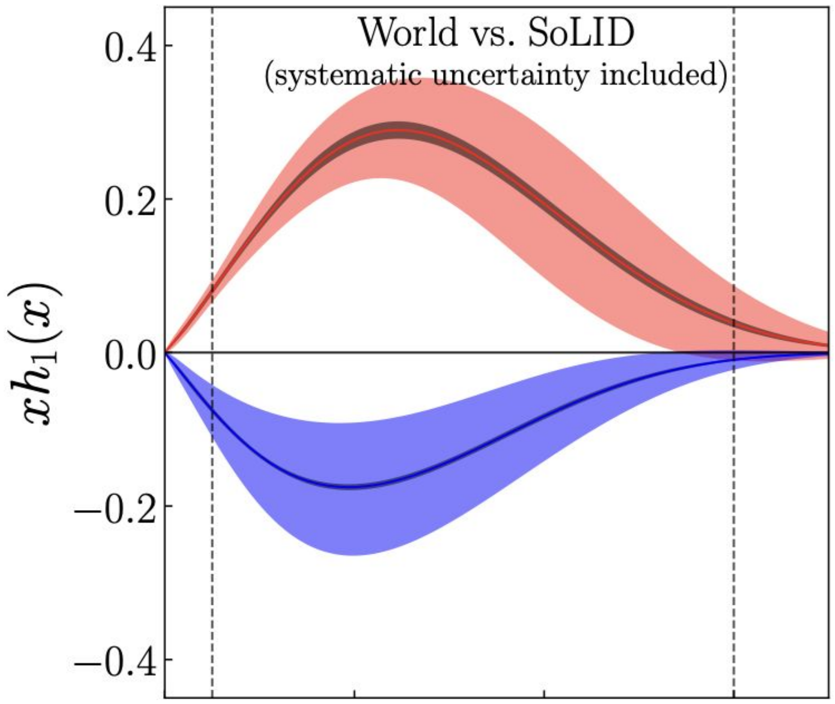
🔗 [A. Dainese et al., arXiv:1901.04482]

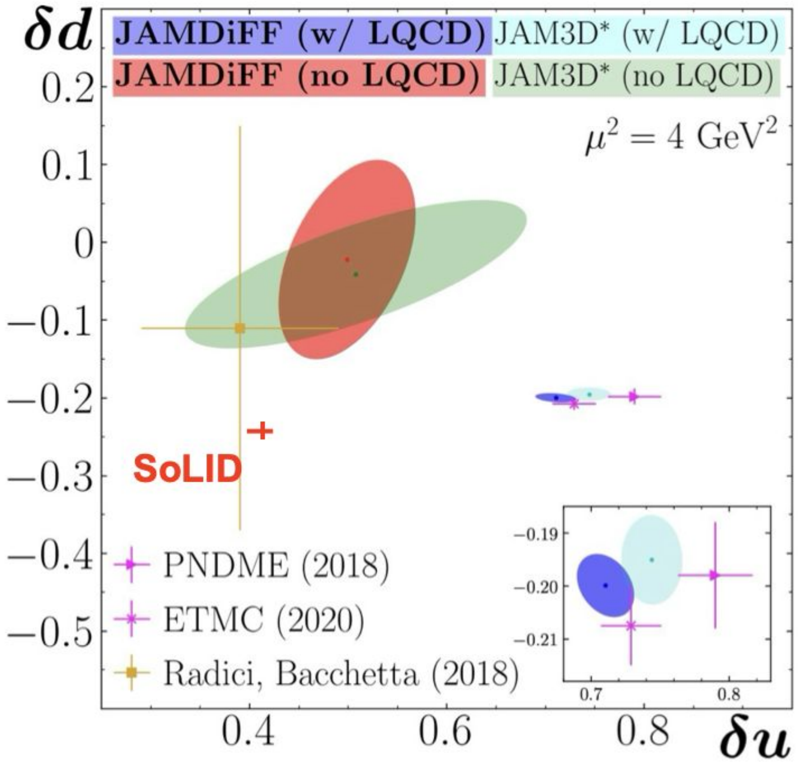


(ex. for polarized TMDs excludes high-Q LHC DY)

EIC but also DY and JLab12 data will contribute substantially and fill current phase-space holes

Impact of new data: SOLID

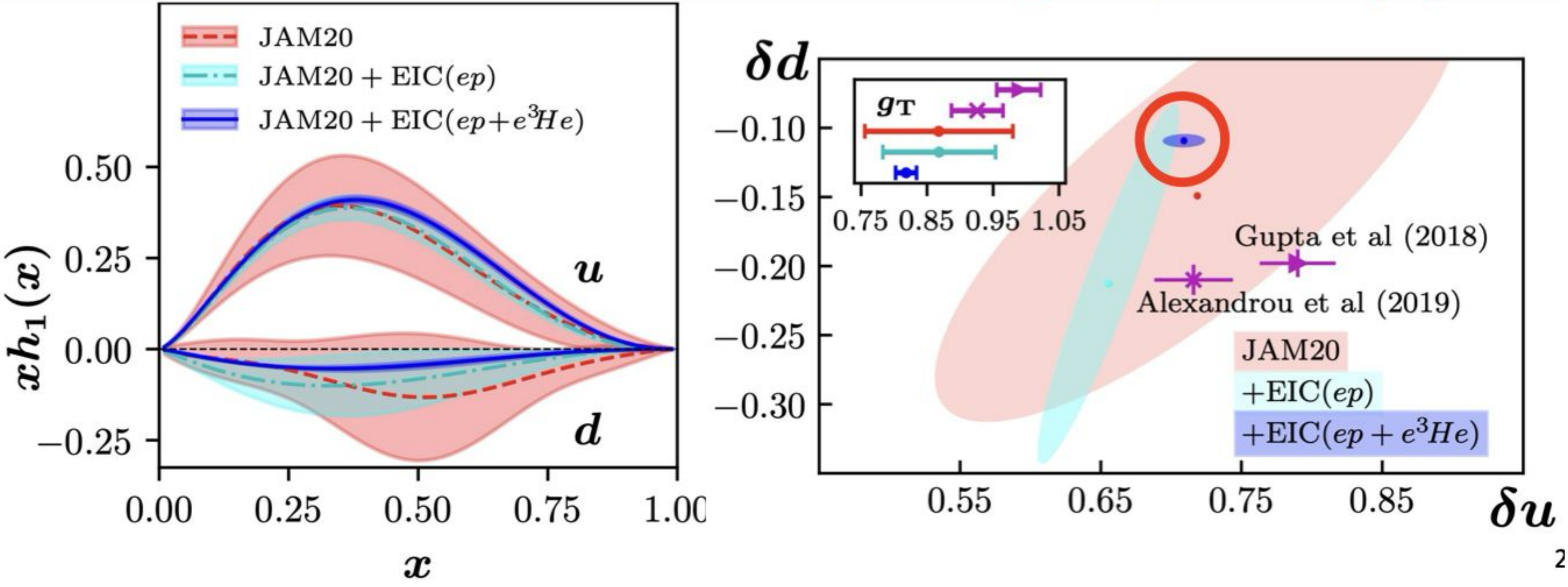




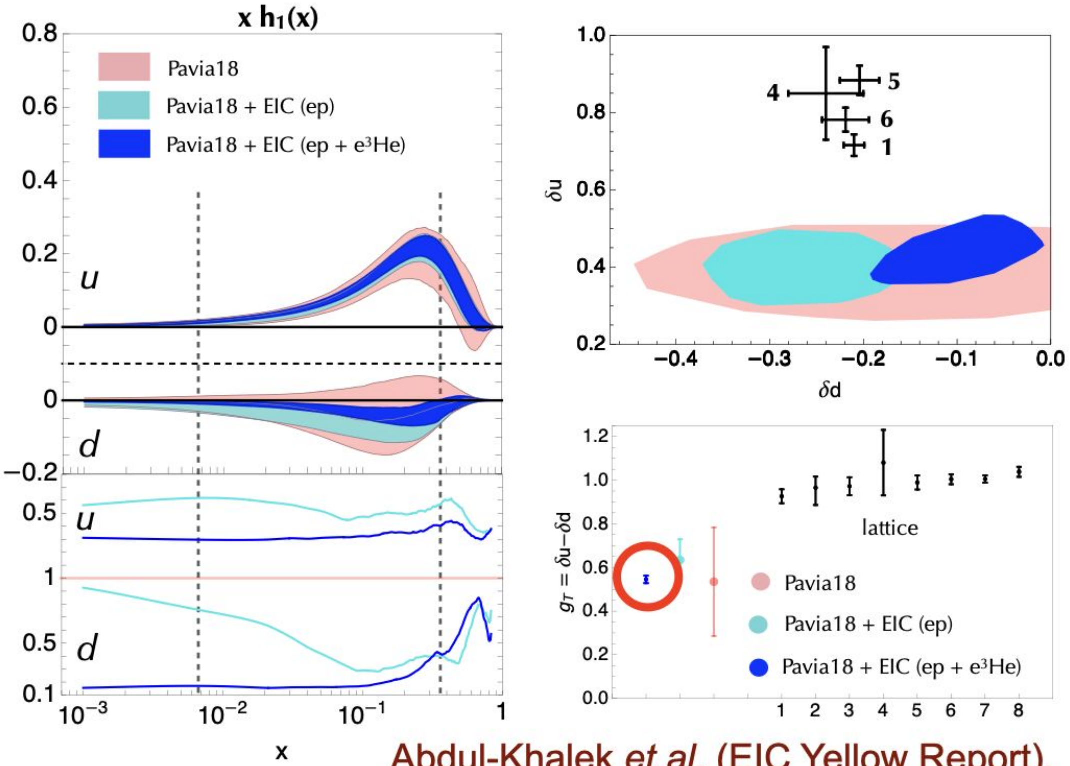
Z. Meziani, DIS 2024

Impact of new data: EIC

Gamberg *et al.*, P.L. **B816** (21)

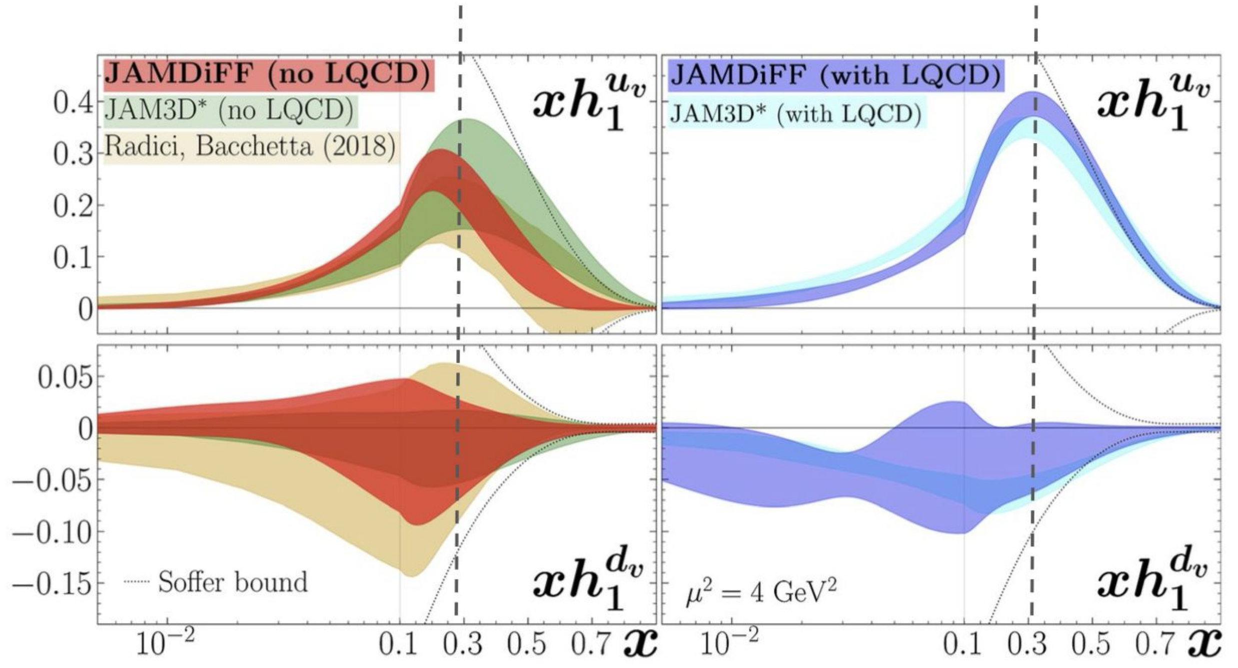


Impact of new data: EIC



Abdul-Khalek *et al.* (EIC Yellow Report), N.P. **A1026** (22) 122447

Impact of new data



Discussion

- how to properly use the Soffer Bound in phenomenological analyses?
- how to handle lattice information?
- more data to come at large-x (SoLID, LHCSpin?), what to expect?
- usage of complementary information from other processes (A_N in $p^{\uparrow}p \rightarrow h\,X$, hadron in jet in $p^{\uparrow}p$ collisions...)