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Sezione Pavia

Transversity: Theory / Phenomenology Overview

Outline

Transversity overview:

- properties
- ways to extract it from exp. data
- current knowledge
- tensor charge: comparison with lattice
- new data available
- future data and related impact

In 30 min., overview far from exhaustive…

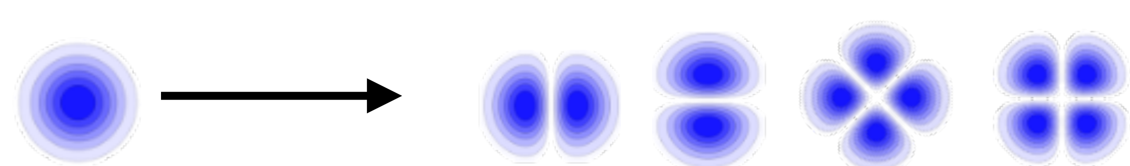
Transversity properties

The quark TMD "zoo" at leading twist

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$	✘	$h_1^\perp =$ −
	L	✘	$g_1 =$ −	$h_{1L}^\perp =$ −
	T	$f_{1T}^\perp =$ −	$g_{1T} =$ −	$h_1 =$ − $h_{1T}^\perp =$ −

similar table for gluons

deformations induced by spin-momentum correlations



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

each TMD is connected to a specific measurable SIDIS spin asymmetry

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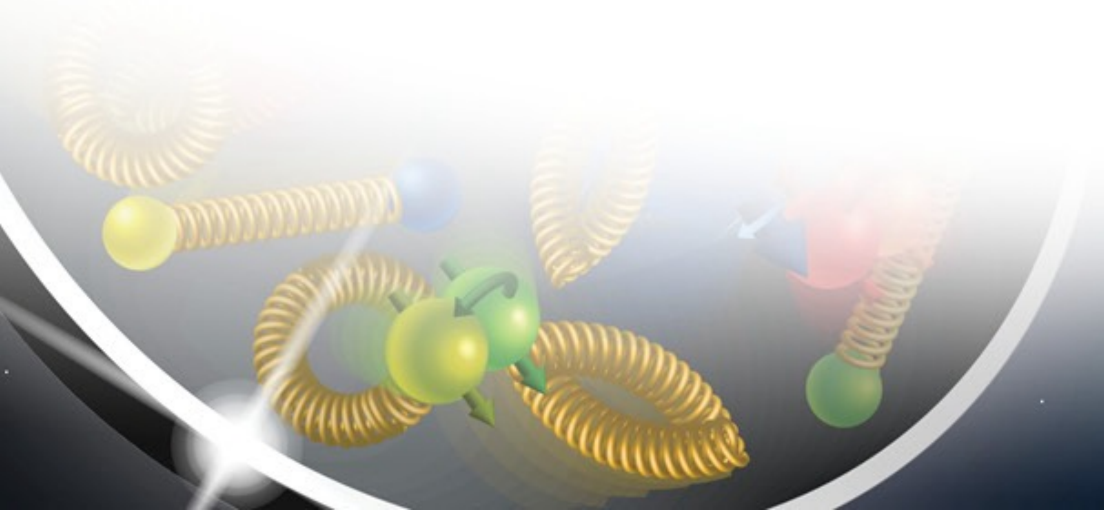
T-odd



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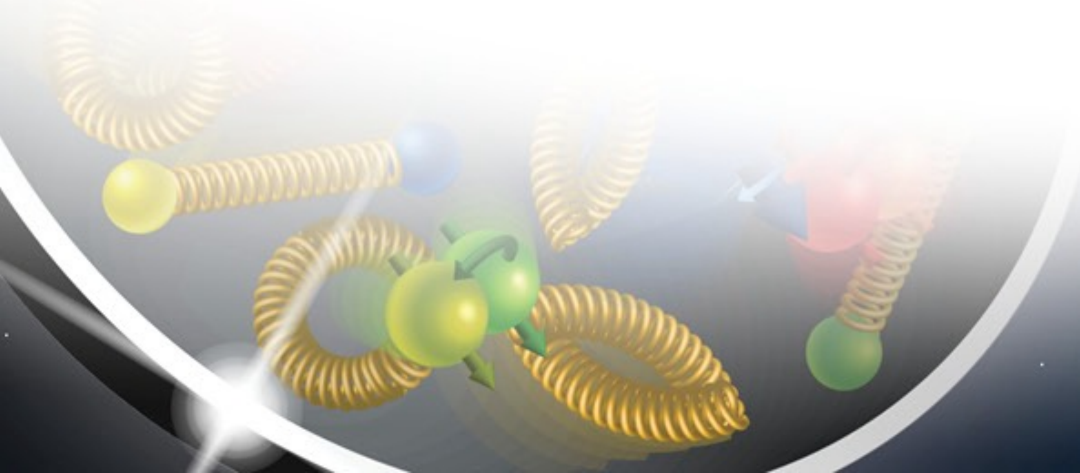
chiral-odd



Electron-Ion Collider

Integrating k_T : the collinear quark PDFs

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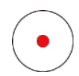
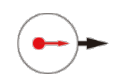
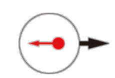
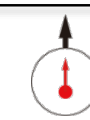
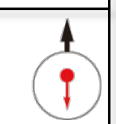
Nucleon Polarization	U	$f_1 =$ 		
	L		$g_1 =$  - 	
	T			$h_1 =$  - 

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	U	$f_1 =$		
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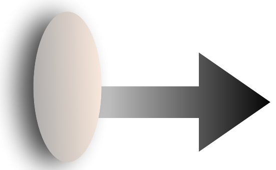
	T			$h_1 =$ -

transversity

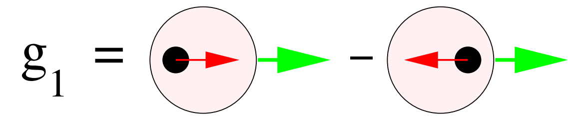
- the only chiral-odd structure that survives in collinear kinematics
- only way to determine the tensor charge $\delta^q(Q^2) = \int_0^1 dx\, h_1^{q-\bar{q}}(x, Q^2)$

Transversity properties

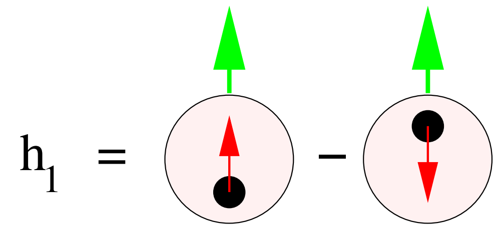
both defined in
Infinite Mom. Frame



boosted Nucleon



helicity



transversity

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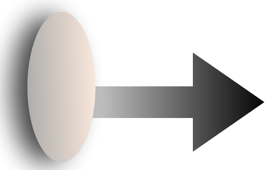

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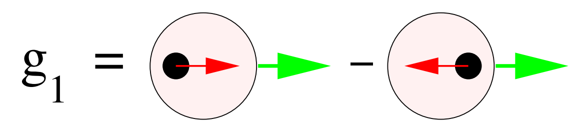

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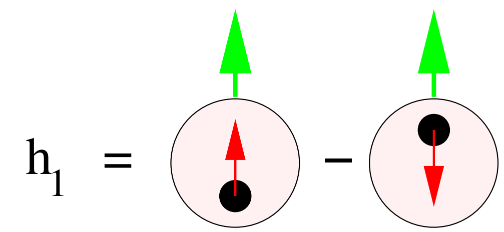

transversity

=

Non-relativistic theory:
boosts & rotations commute

Differences
=> info on relativistic motion of quarks

Transversity properties

both defined in
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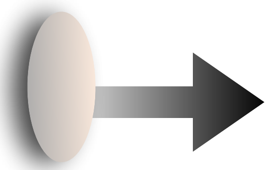
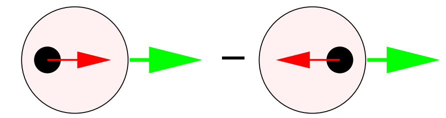


boosted Nucleon

$g_1 =$ 

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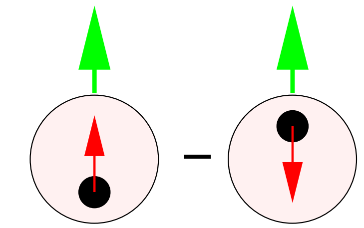
$h_1 =$ 

transversity

Non-relativistic theory:
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Differences
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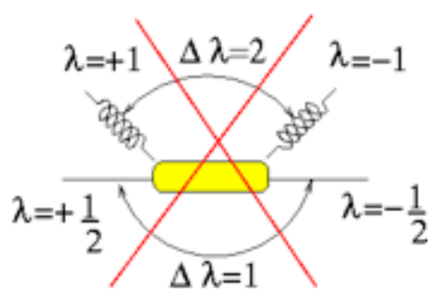
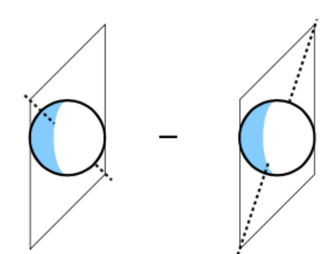
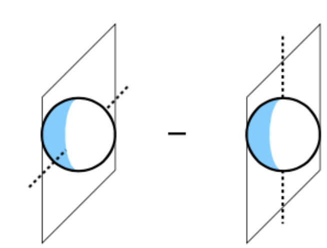
In a spin-1/2 hadron,
no transversity of gluons



singlet and
non-singlet
evolution

only
non-singlet
evolution

In a spin-1 hadron, gluon transversity possible
because transverse tensor polariz. => Δλ=2
but $h^g_{1,TT} \equiv h^g_1$ is only a TMD and T-odd

$S^{xy}_{TT} =$  $S^{xx}_{TT} =$ 

Jaffe & Manohar (1989), Artru & Mekhfi (1990), Bacchetta & Mulders (2000)

Transversity properties

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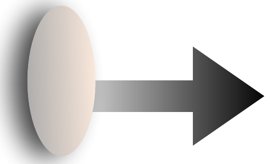

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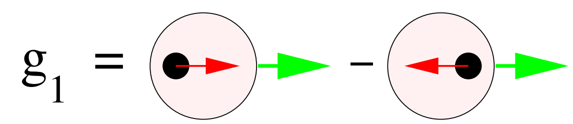

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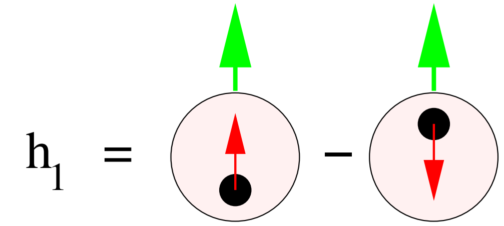

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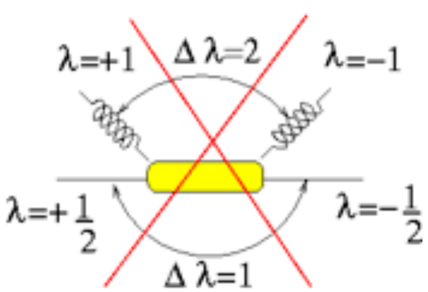

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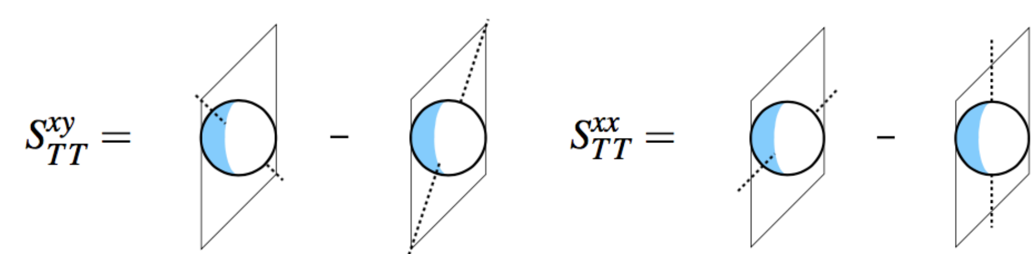
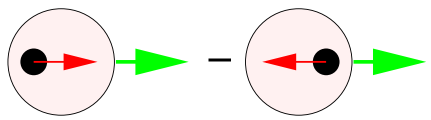


Jaffe & Manohar (1989), Artru & Mekhfi (1990), Bacchetta & Mulders (2000)

Soffer bound: $|h_1| \leq \frac{1}{2}(f_1 + g_1)$ for any (x,Q²)

Transversity properties

g_1 = 

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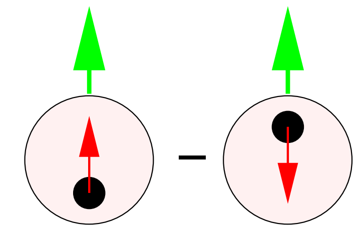
h_1 = 

transversity

charges connected to hadronic matrix elements of local operators (calculable on lattice)

$$\langle P, S_L \,|\, \bar{q}\, \gamma^\mu \gamma_5\, q \,|\, P, S_L \rangle = S_L P^\mu \, g_A^q$$

axial current <=> axial charge

$$= S_L P^\mu \int_0^1 dx\, g_1^{q+\bar{q}}(x, Q^2)$$

connected to C-even structure

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

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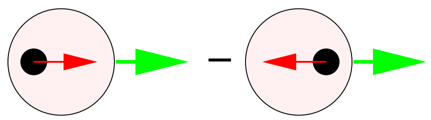
g_1 = 

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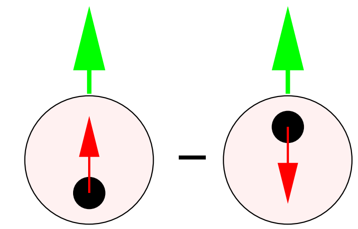
h_1 = 

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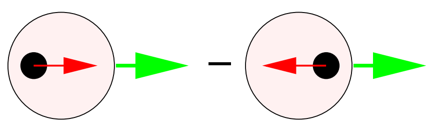
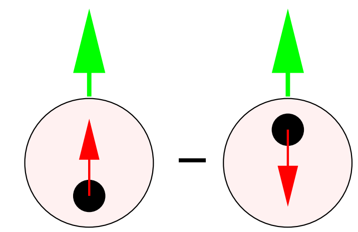
$$C_F = \frac{N_c^2 - 1}{2N_c}$$

=> δ^q scales with Q^2

Transversity properties

g_1 = 

$\neq$

h_1 = 

helicity | transversity

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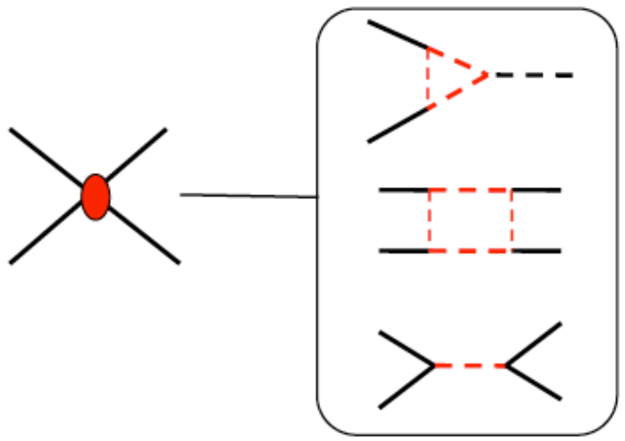
helicity and transversity are very different !

Potential for BSM discovery ?

Tensor (and chiral-odd) structures do not appear in the Standard Model Lagrangian at tree level.

Is it a possible low-energy footprint of BSM physics at higher scale ?



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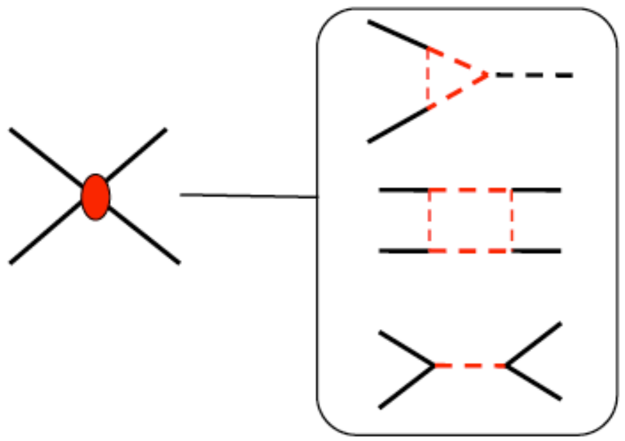

neutron β-decay

$n \to p\, e^- \bar{\nu}_e$

$$\mathcal{L}_{\rm SM} \sim G_F V_{ud}\, \bar{e}\gamma^\mu(1-\gamma_5)\nu_e\, \bar{p}\gamma_\mu(1-\gamma_5)n$$

$$+\mathcal{L}_{\rm eff} \sim G_F V_{ud}\, g_T\, \varepsilon_T\, \bar{e}\sigma^{\mu\nu}\nu_e\, \bar{p}\sigma_{\mu\nu}n \quad ?$$

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

BSM coupling

$$g_T\, \varepsilon_T \approx \frac{M_W^2}{M_{\rm BSM}^2}$$

precision => BSM scale

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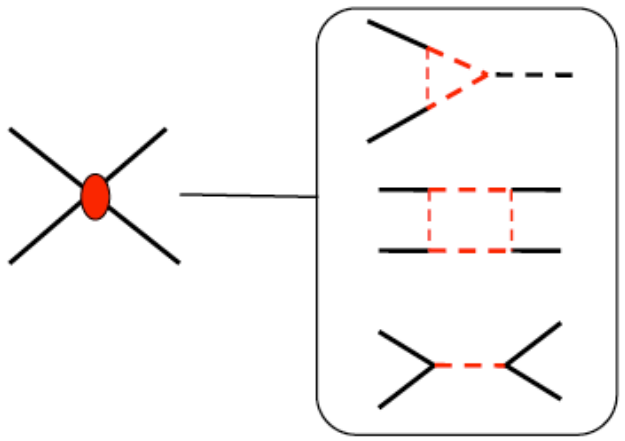

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<u>SMEFT with strong CP violation</u>

permanent Electric Dipole Mom.

$$\mathcal{L}_{\rm SMEFT} \to \sum_{f=u,d,s,c} d_f\, \bar{\Psi}_f\, \sigma_{\mu\nu}\gamma_5 \Psi_f\, F^{\mu\nu} \quad ?$$

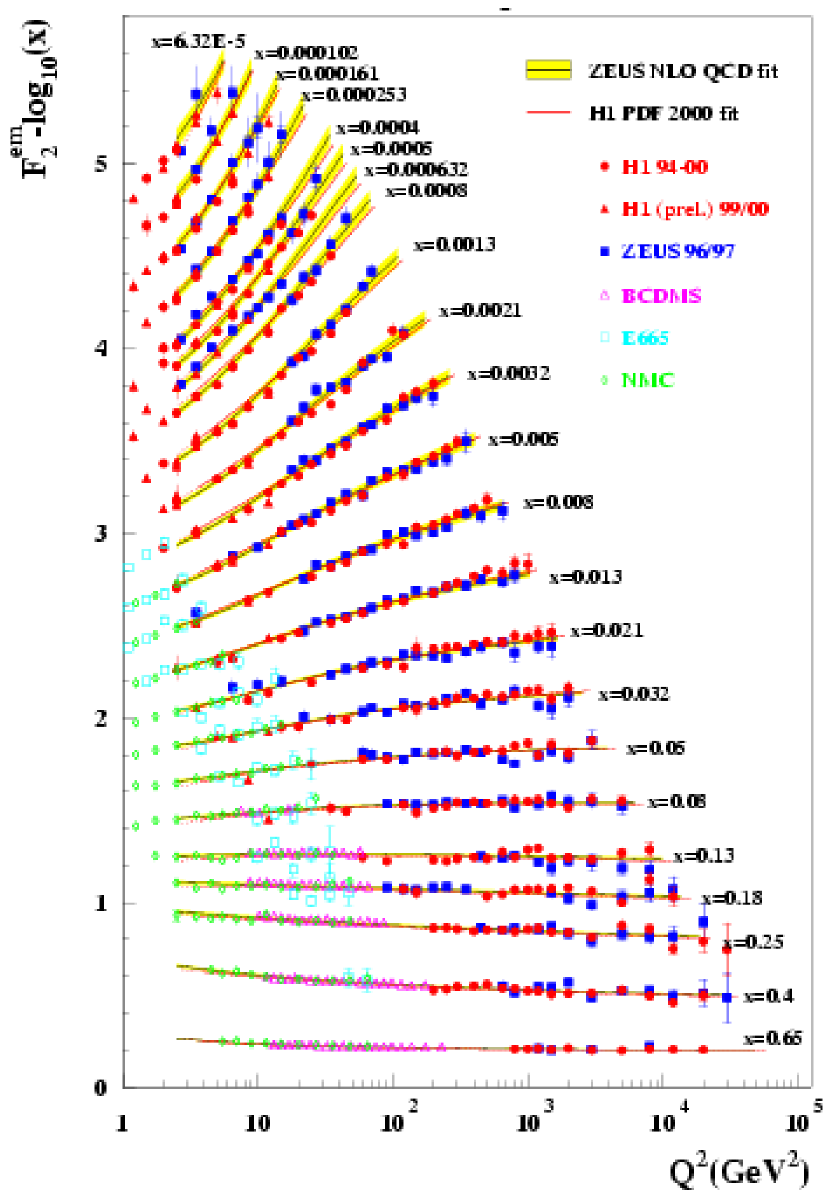
neutron EDM $d_n = \delta u\, d_u + \delta d\, d_d + \delta s\, d_s + \ldots$

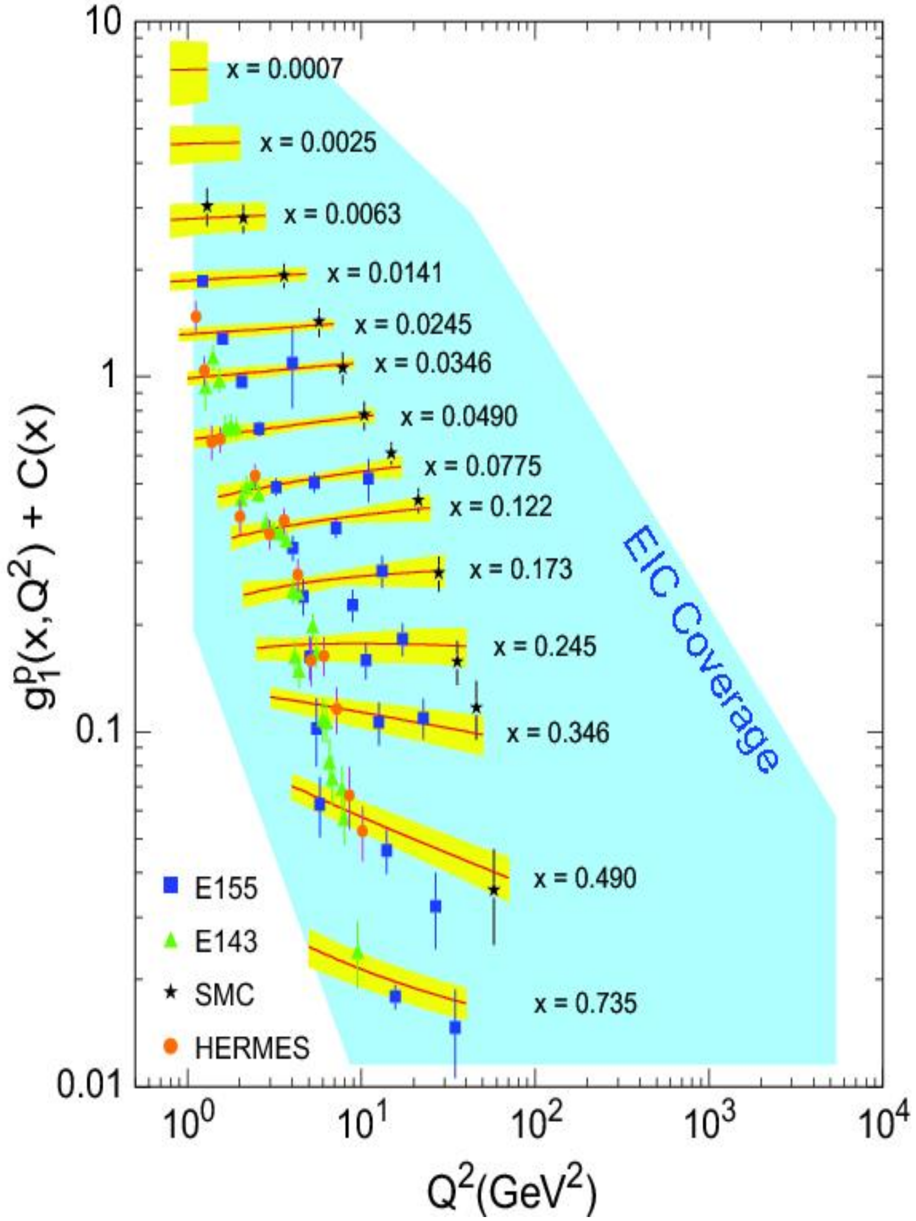
exp. data + tensor charge => constrain amount of CP violation

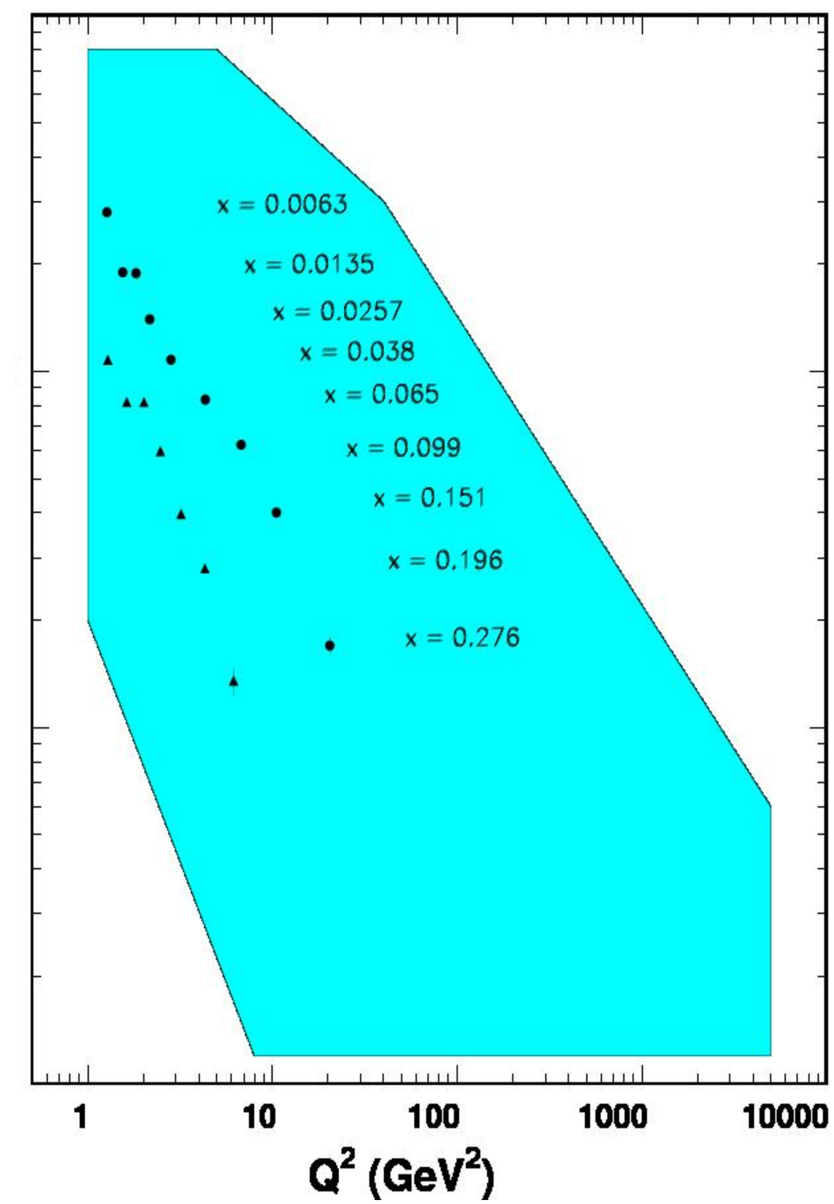
How to extract transversity from exp. data

Available dataset is scarce…

unpolarized f_1 | helicity g_1 | transversity h_1







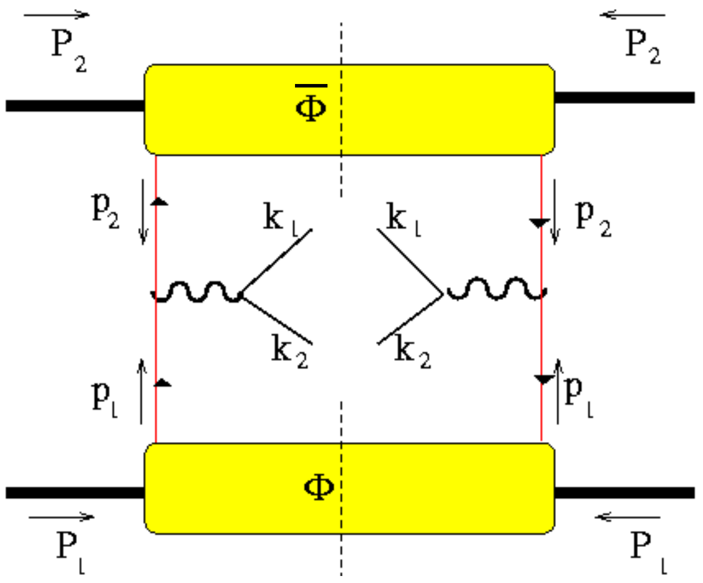
thousands | hundreds | tenths

Analyzers of transversity at leading twist

Ideal situation: fully transversely polarized Drell-Yan

$$p^{\uparrow}\,\bar{p}^{\uparrow} \to \ell + \bar{\ell} + X$$

not technically doable
at the moment..



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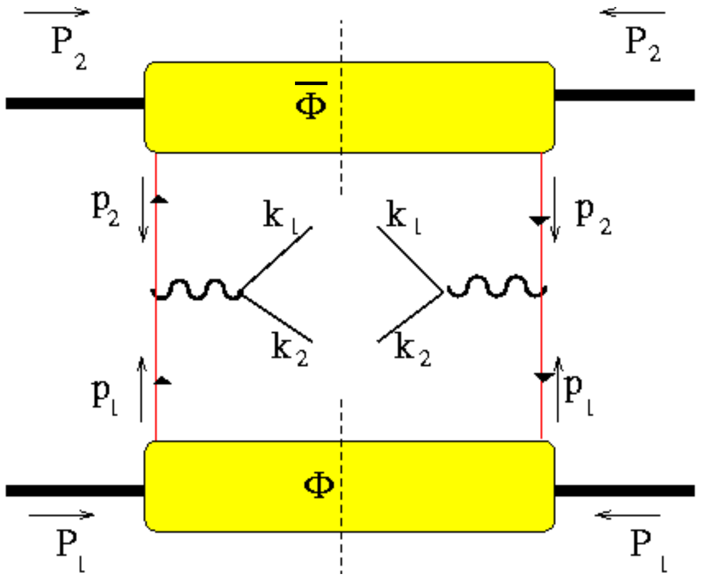


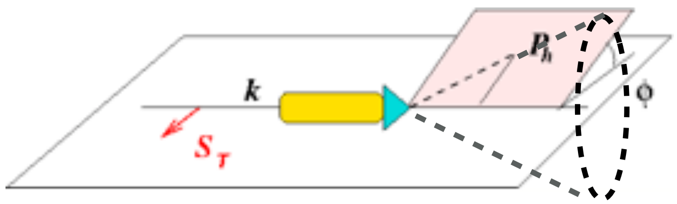
Alternative (at RHIC) $p^\uparrow p^\uparrow \to \ell + \bar{\ell} + X$

$$A_{TT} = \frac{d\sigma(p^\uparrow p^\uparrow) - d\sigma(p^\uparrow p^\downarrow)}{d\sigma(p^\uparrow p^\uparrow) + d\sigma(p^\uparrow p^\downarrow)} = |S_{T_1}|\,|S_{T_2}| \frac{\sin^2\theta \, \cos 2\phi_\ell}{1+\cos^2\theta} \frac{\sum_q e_q^2\, h_1^q(x_1)\, \bar{h}_1^{\bar{q}}(x_2) + (1 \leftrightarrow 2)}{\sum_q e_q^2\, f_1^q(x_1) \bar{f}_1^{\bar{q}}(x_2) + (1 \leftrightarrow 2)}$$

But $\bar{h}_1^{\bar{q}} \ll h_1^q$ $\quad |h_1^q| \le \frac{1}{2}(f_1^q + g_1^q)$ make A_{TT} too small..

Martin et al., P.R.D60 (99) 117502

Analyzers of transversity at leading twist



Collins effect

$\mathbf{S}_\mathrm{T} \cdot \mathbf{k} \times \mathbf{P}_{\mathrm{hT}}$

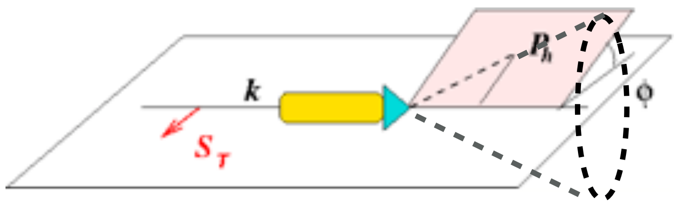
Collins, N.P. **B396** (93) 161

$$\propto h_1(x, k_\perp) \otimes H_1^\perp(z, P_\perp)$$

TMD framework

SIDIS

Analyzers of transversity at leading twist



Collins effect

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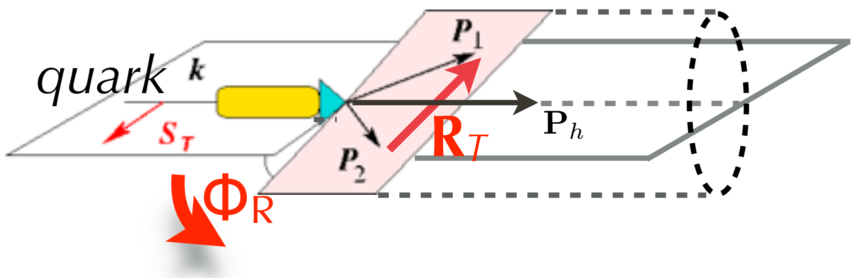
$\propto\ h_1(x, k_\perp) \otimes H_1^\perp(z, P_\perp)$

TMD framework

SIDIS



di-hadron mechanism

$\mathbf{S}_\mathrm{T} \cdot \mathbf{P}_2 \times \mathbf{P}_1 = \mathbf{S}_\mathrm{T} \cdot \mathbf{P}_\mathrm{h} \times \mathbf{R}_\mathrm{T}$

Collins et al., N.P. **B420** (94)

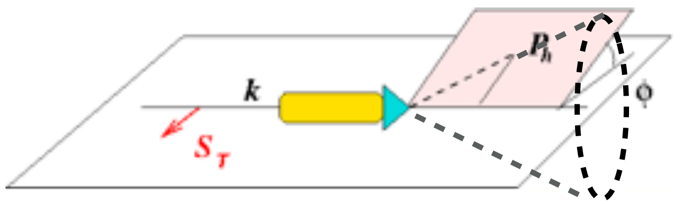
$\propto\ h_1(x)\, H_1^{\sphericalangle}(z, R_T^2)$

collinear framework

SIDIS

$p\, p^\uparrow$

Analyzers of transversity at leading twist



Collins effect

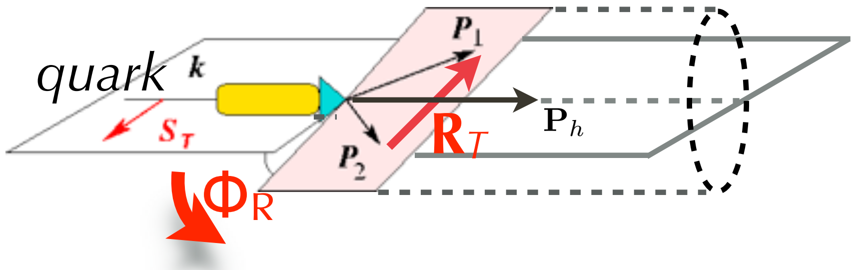
$\mathbf{S}_T \cdot \mathbf{k} \times \mathbf{P}_{hT}$

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

$\propto h_1(x, k_\perp) \otimes H_1^\perp(z, P_\perp)$

TMD framework

SIDIS



di-hadron mechanism

$\mathbf{S}_T \cdot \mathbf{P}_2 \times \mathbf{P}_1 = \mathbf{S}_T \cdot \mathbf{P}_h \times \mathbf{R}_T$

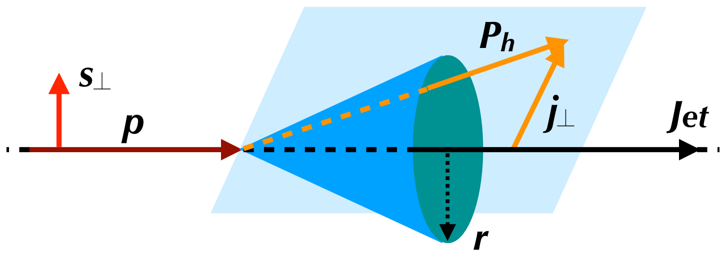
Collins et al., N.P. **B420** (94)

$\propto h_1(x)\, H_1^{\sphericalangle}(z, R_T^2)$

collinear framework

SIDIS

p p↑



hadron-in-jet Collins effect

$j_T^2 \ll Q^2 = (P_T^{jet})^2$

Yuan, P.R.L. **100** (08)

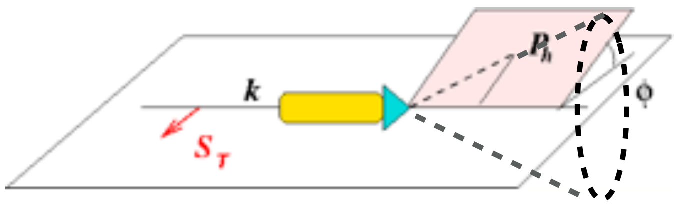
$\propto h_1(x)\, [C(z,\mu) \otimes H_1^\perp(z_h, j_T, P_T^{\rm jet} r)]$

hybrid framework

SIDIS

p p↑

Analyzers of transversity at leading twist



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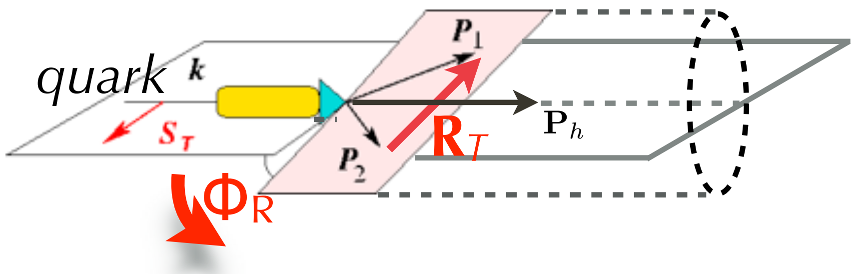

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SIDIS

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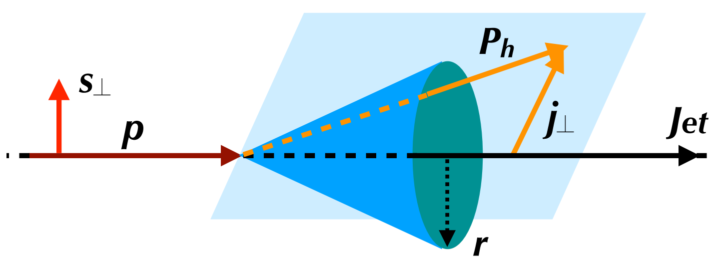

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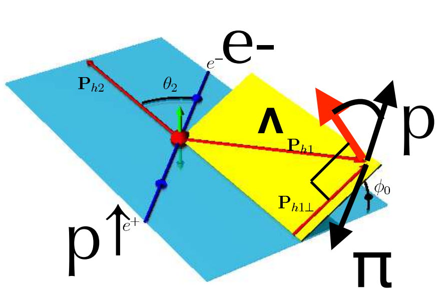


Λ spin transfer

Jaffe, P.R. D**54** (96)

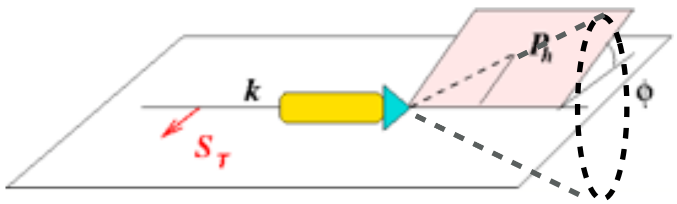
$\propto \; h_1(x)\, H_1(z)$

collinear framework

SIDIS

$p\,p^\uparrow$

Analyzers of transversity at leading twist



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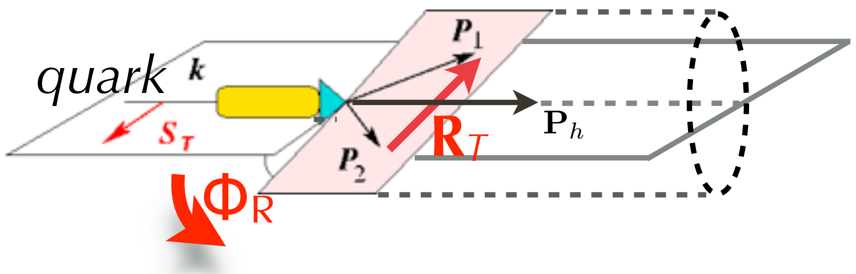
TMD framework

SIDIS



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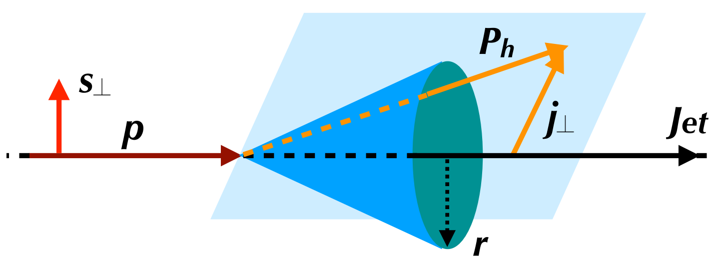

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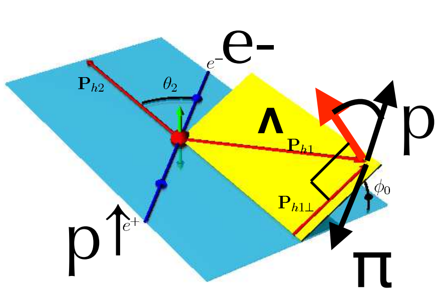

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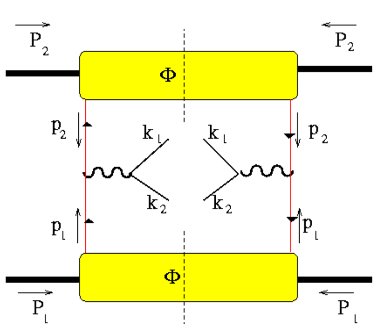


single-polarised Drell-Yan

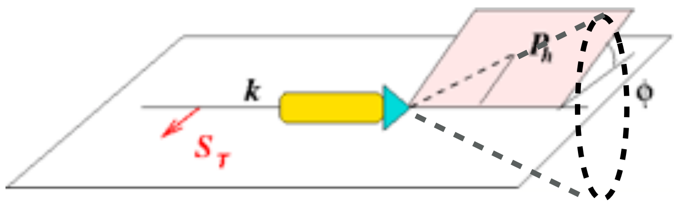
Boer, P.R. D**60** (99)

$\propto h_1^\perp(x_1, k_{\perp 1}) \otimes h_1(x_2, k_{\perp 2})$

TMD framework

$\pi\, p^\uparrow$

Analyzers of transversity at leading twist



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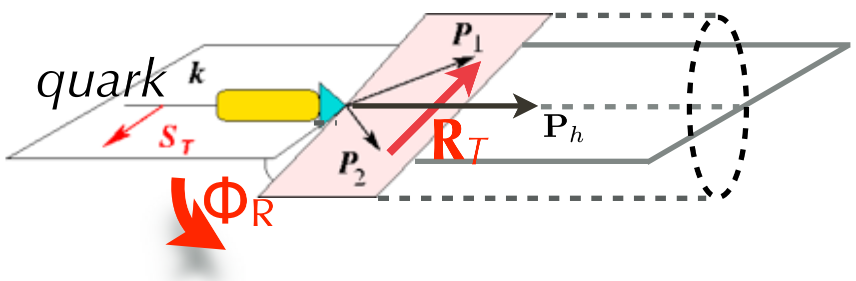

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SIDIS

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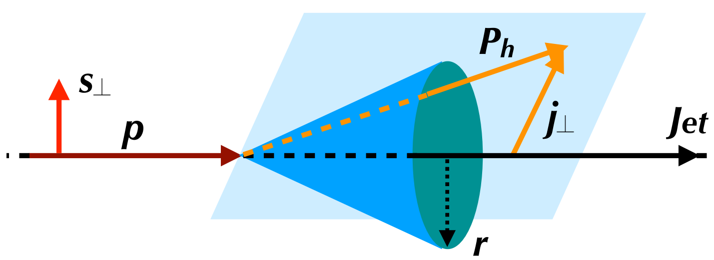

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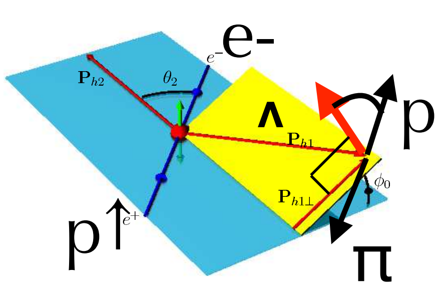
hybrid framework

SIDIS

$p\,p^\uparrow$



Λ spin transfer

Jaffe, P.R. **D54** (96)

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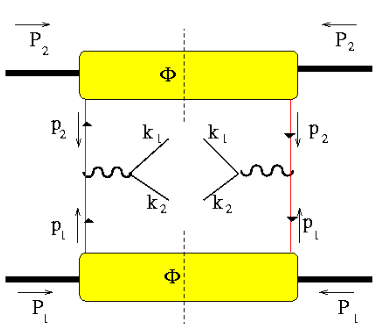
collinear framework

SIDIS

$p\,p^\uparrow$



single-polarised Drell-Yan

Boer, P.R. **D60** (99)

$\propto\ h_1^\perp(x_1,k_{\perp 1})\otimes h_1(x_2,k_{\perp 2})$

TMD framework

$\pi\, p^\uparrow$

+ forward limit of chiral-odd GPD $\quad \lim_{t\to 0} H_T(x,\xi,t) = h_1(x)$

see Thursday afternoon session

current knowledge of transversity and tensor charge

Collins effect

most recent extractions

	Framework	e+e-	SIDIS	A_N	Lattice	Soffer bound
Anselmino 2015 P.R. D**92** (15) 114023	parton model	✔	✔	✘	✘	✔
Kang et al. 2016 P.R. D**93** (16) 014009	TMD / CSS	✔	✔	✘	✘	✔
Lin et al. 2018 P.R.L. **120** (18) 152502	parton model	✘	✔	✘	✔ g_T	✘
D'Alesio et al. 2020 (CA) P.L. **B803** (20) 135347	parton model	✔	✔	✘	✘	✘ , ✔
JAM3D-20 P.R. D**102** (20) 054002	parton model	✔	✔	✔	✘	✘
JAM3D-22 P.R. D**106** (22) 034014	parton model	✔	✔	✔	✔ g_T	✔ $\leq \Delta f_1, \Delta g_1$
Boglione et al. 2024 (TO) P.L. **B854** (24) 138712	parton model	✔	✔	✔ reweighing	✘	✔ a posteriori

\+ point-by-point extraction from data
Martin et al., P.R. D**91** (15) 014034

see talk by Bradamante
in the afternoon

Di-hadron mechanism

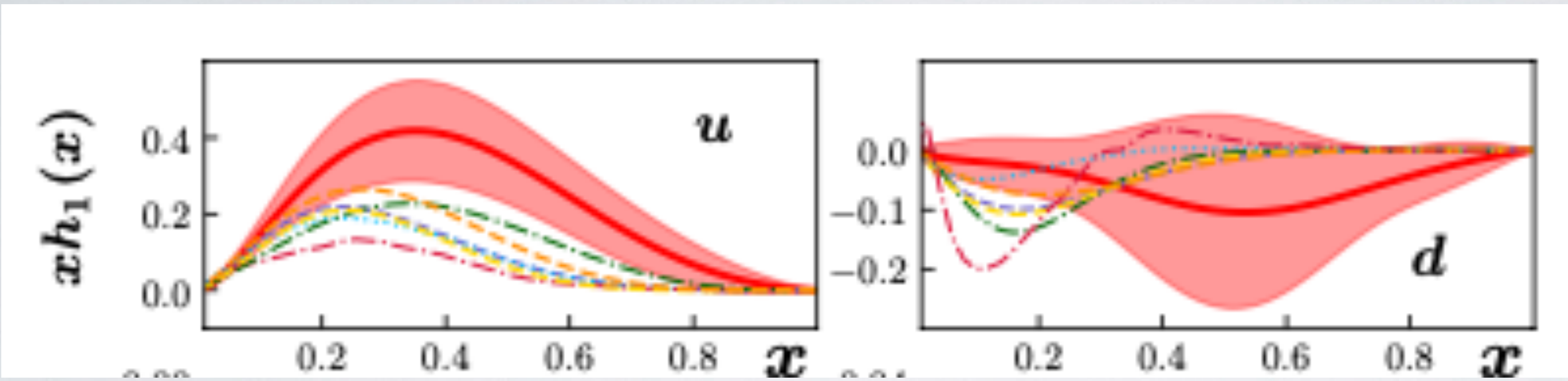
available extractions

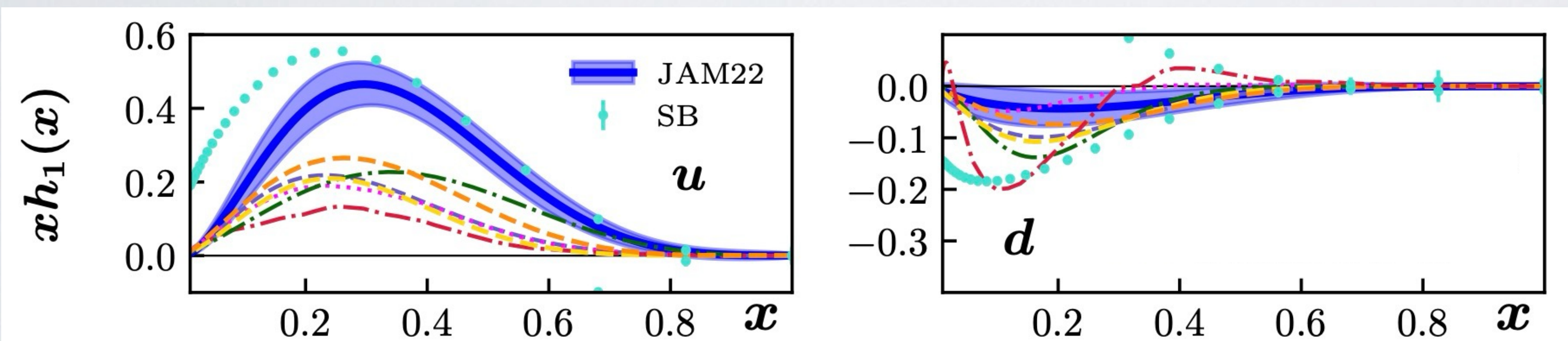
	e+e- unpol. $d\sigma^0$	e+e- asymmetry	SIDIS	p-p collisions	Lattice	Soffer bound
Radici & Bacchetta 2018 P.R.L. **120** (18) 192001	PYTHIA (separately)	✔ (separately)	✔	✔	✘	✔
Benel et al. 2020 E.P.J. **C80** (20) 5	PYTHIA (separately)	✔ (separately)	✔	✘	✘	✔ $\leq \Delta f_1, \Delta g_1$
JAMDIFF 2024 P.R.L. **132** (24) 091901	✔	✔	✔	✔	✔ δu, δd	✔ $\leq \Delta f_1, \Delta g_1$

see round table on Tuesday afternoon for discussion on use of SB, lattice data..

see talk by Schnell (and Vossen?) on Thursday for di-hadron fragmentation

Transversity



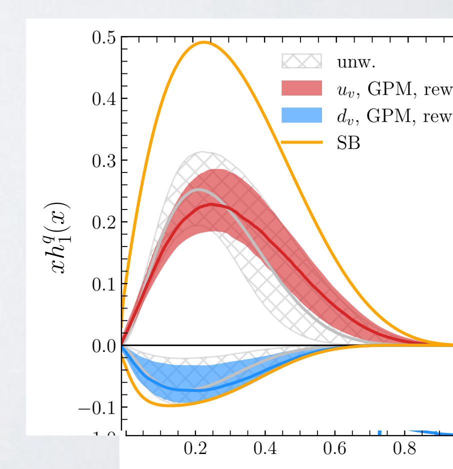


	Soffer bound
JAM20	✘
Anselmino 15	✔
Kang 16	✔
D'Alesio 20	✔
Radici 18	✔
Anselmino 13	✔
Benel 19	✔
JAM22	✔ $\leq \Delta f_1, \Delta g_1$

Anselmino 15

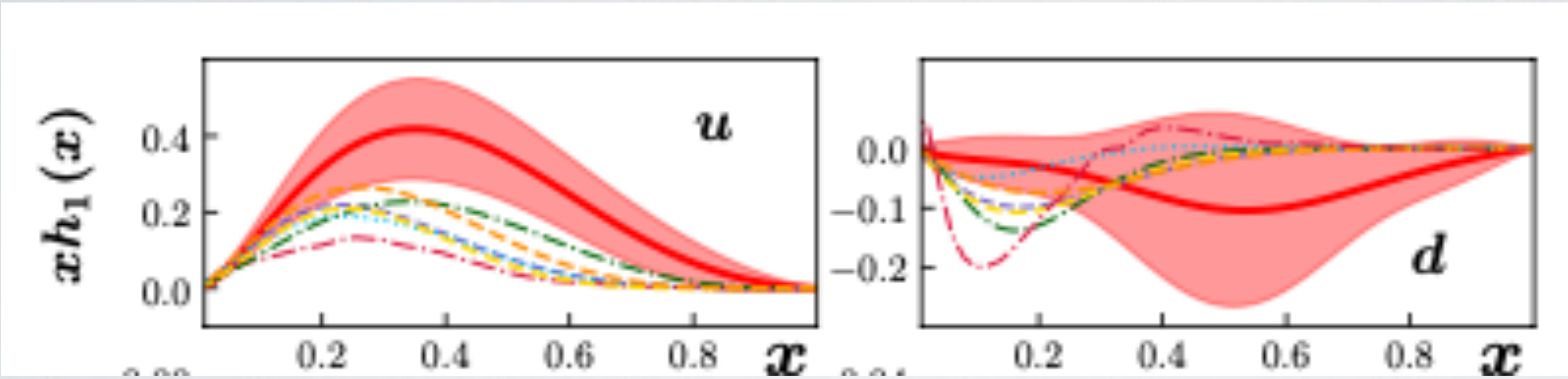
Boglione 24 ✔ a posteriori

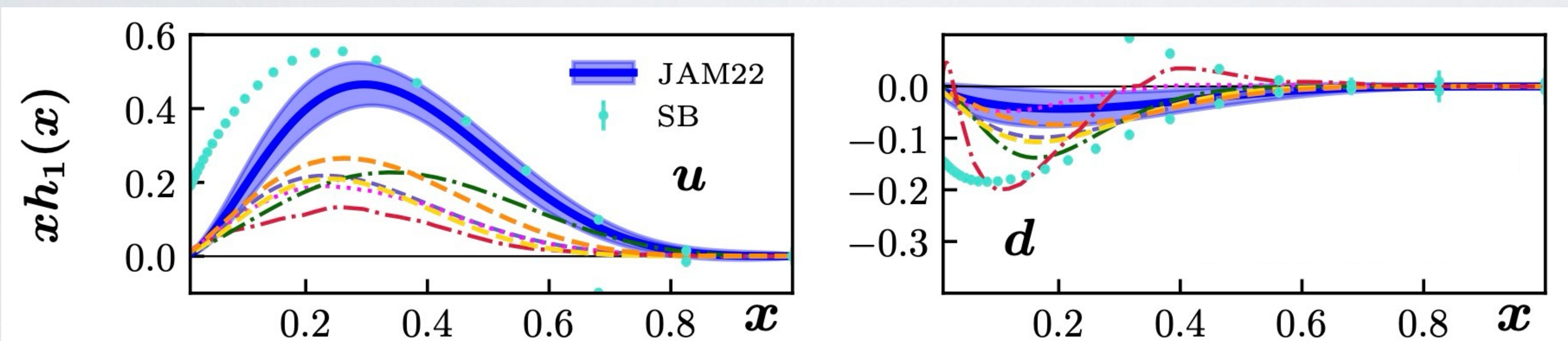
D'Alesio 20

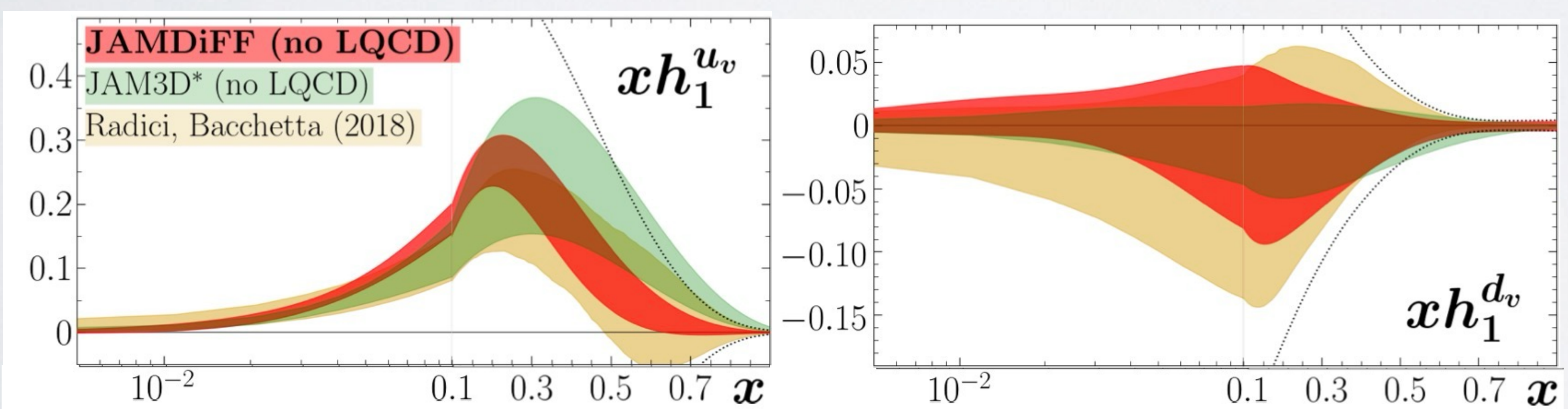


D. Pitonyak, QCD Evolution 24

Transversity



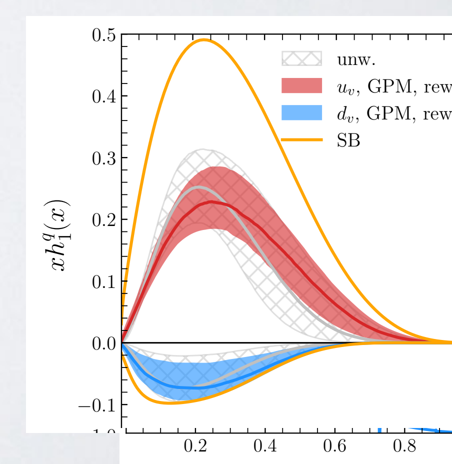




Soffer bound

		Soffer bound
—	JAM20	✘
- -	Anselmino 15	✔
-•-	Kang 16	✔
- -	D'Alesio 20	✔
·····	Radici 18	✔
- -	Anselmino 13	✔
-•-	Benel 19	✔
—	JAM22	✔ $\leq \Delta f_1, \Delta g_1$

Anselmino 15
Boglione 24 ✔ a posteriori
D'Alesio 20

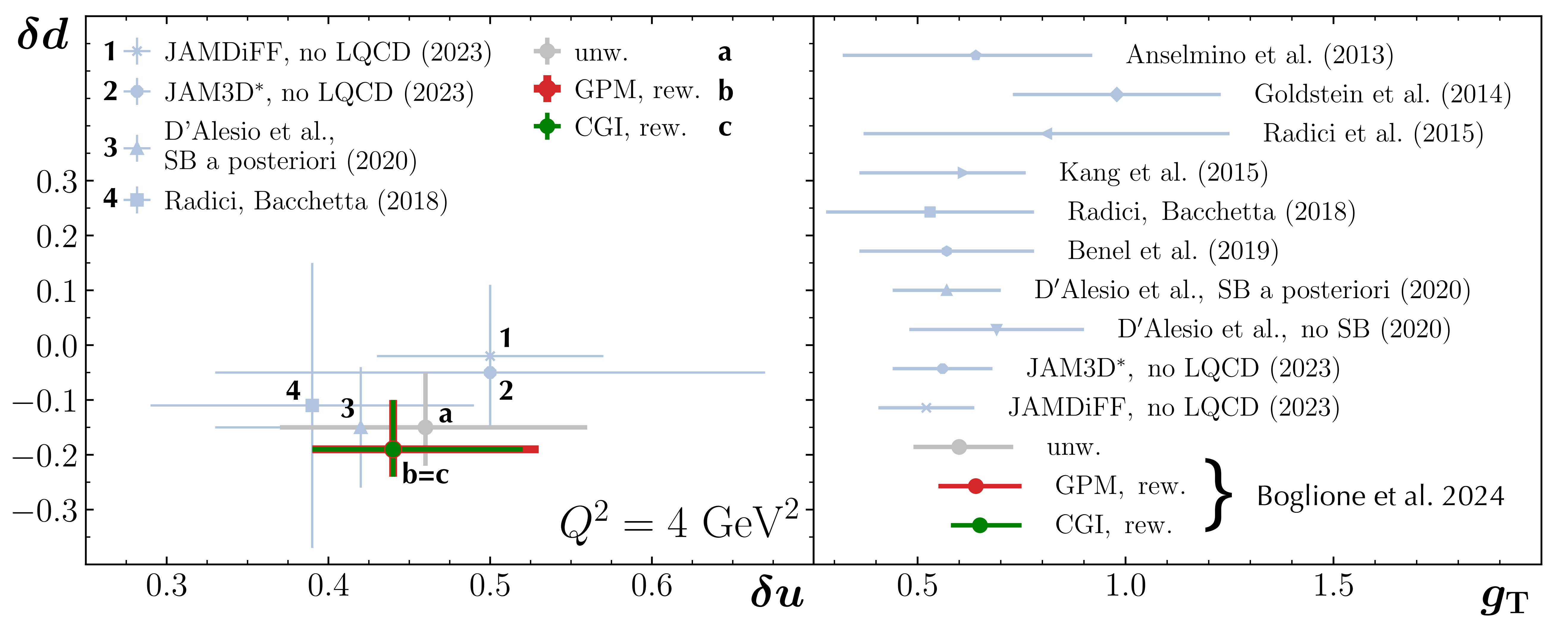


* JAM3D includes $\bar{u} = -\bar{d}$ w.r.t. JAM22

D. Pitonyak, QCD Evolution 24

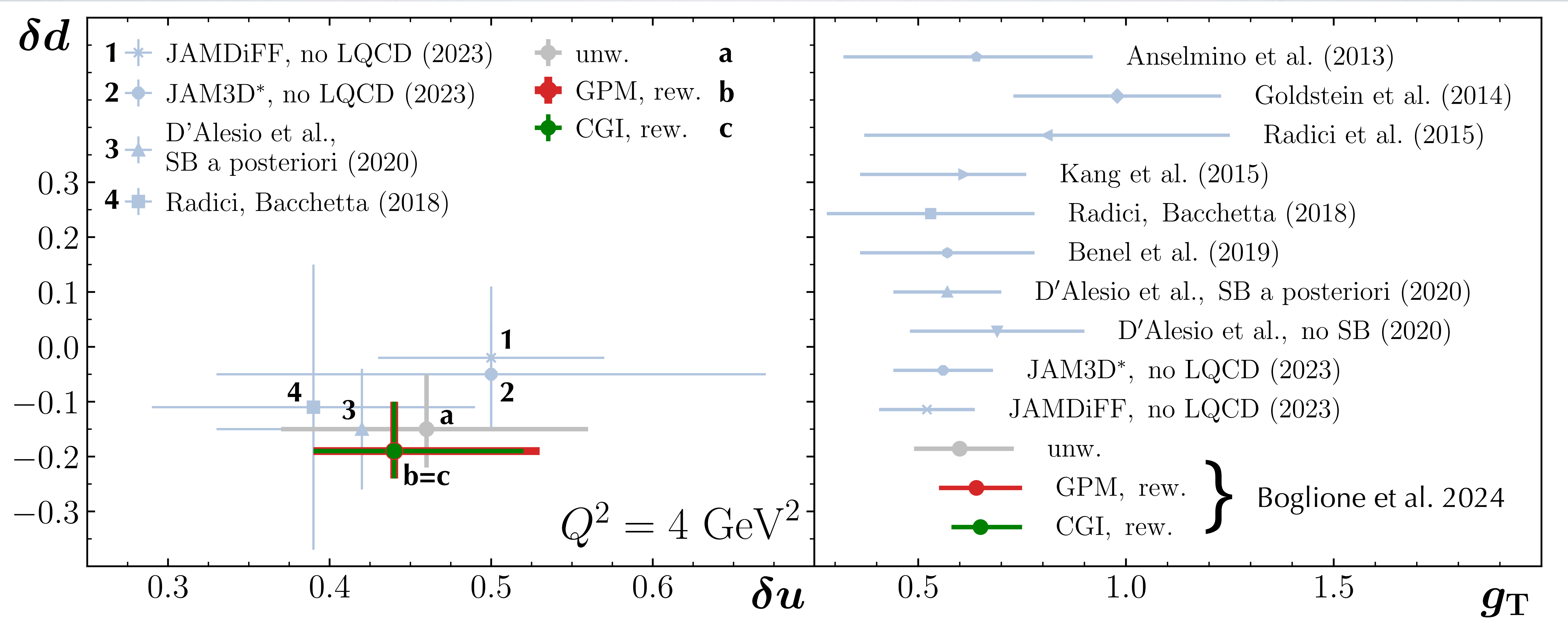
Tensor charge

C. Flore, QCD Evolution 24



Tensor charge

C. Flore, QCD Evolution 24

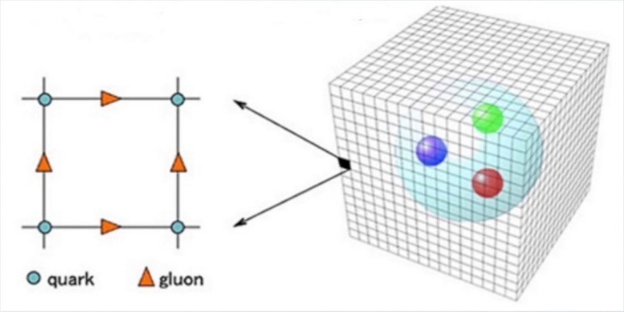


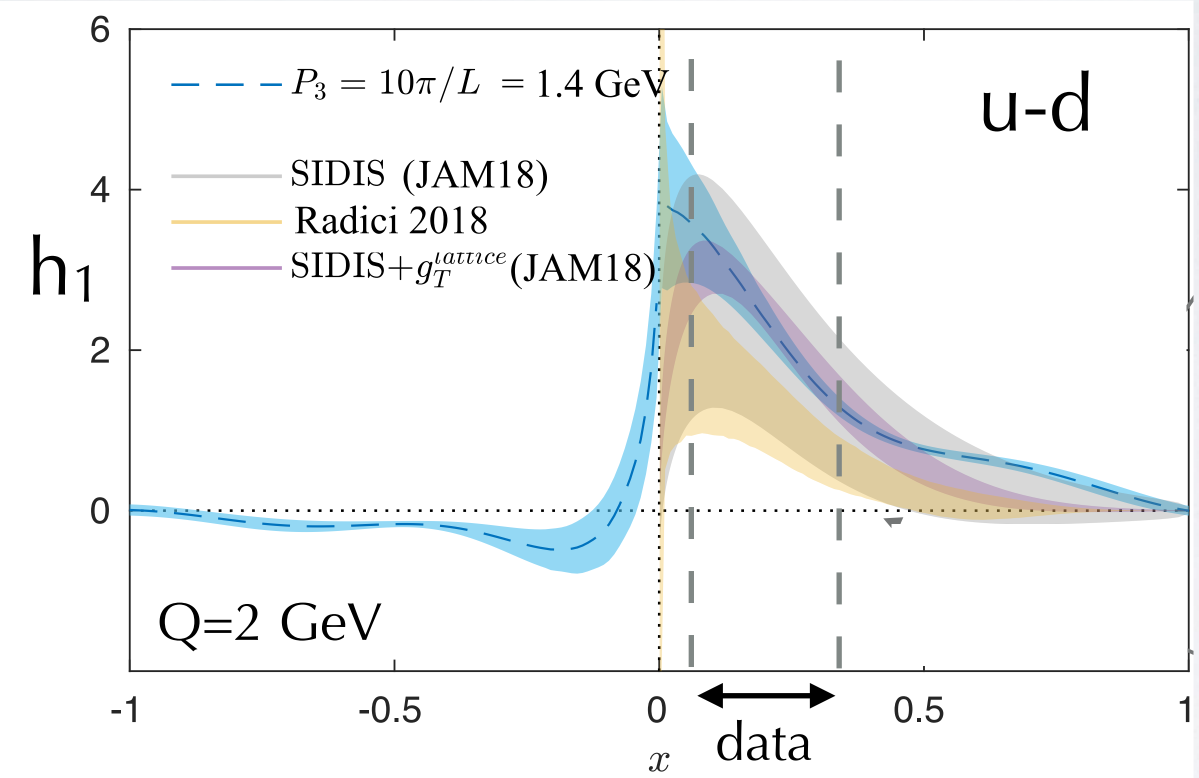
- consistency of phenomenological extractions from a variety of exp. data with different approaches
- increasing precision

see talk by Flore in the afternoon

Pheno — Lattice : transversity

direct calculation on lattice of x-dependence using LaMET





courtesy of F. Steffens

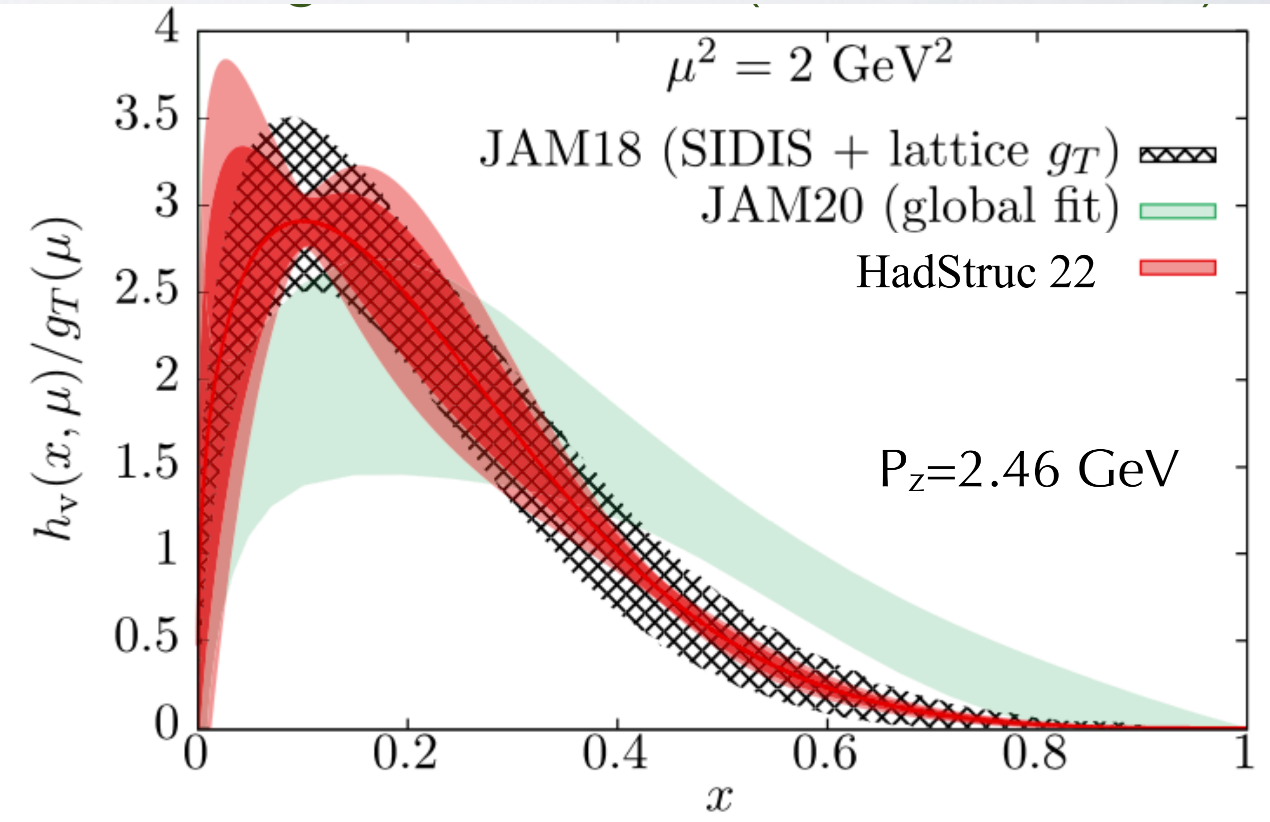
JAM18 = Lin *et al.*, P.R.L. **120** (18) 152502

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

Alexandrou *et al.*, P.R. D**99** (19) 114504

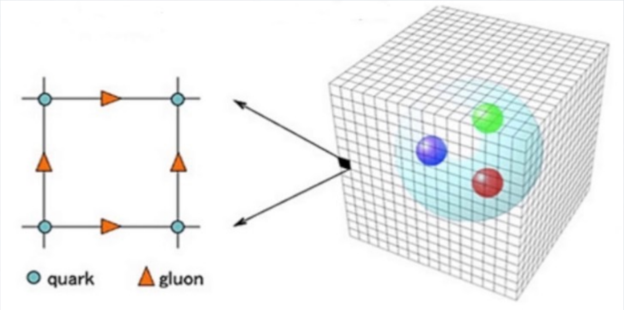
JAM20 = Cammarota *et al.*, P.R. D**102** (20) 054002

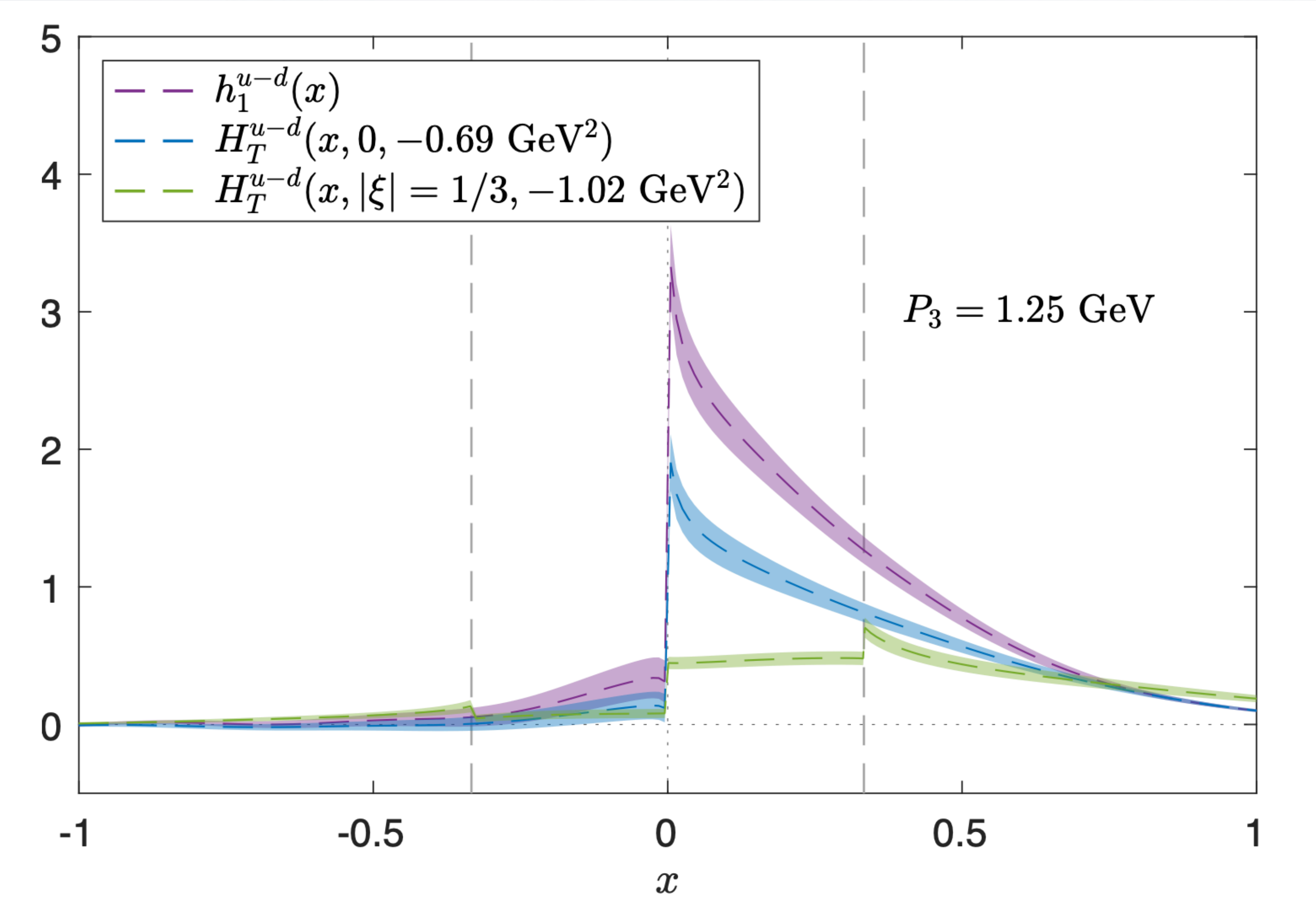
HadStruc22 = Egerer *et al.*, P.R. D**105** (22) 034507



Lattice : chiral-odd GPD

direct calculation of x-dependence using LaMET
at ξ = 0, 1/3



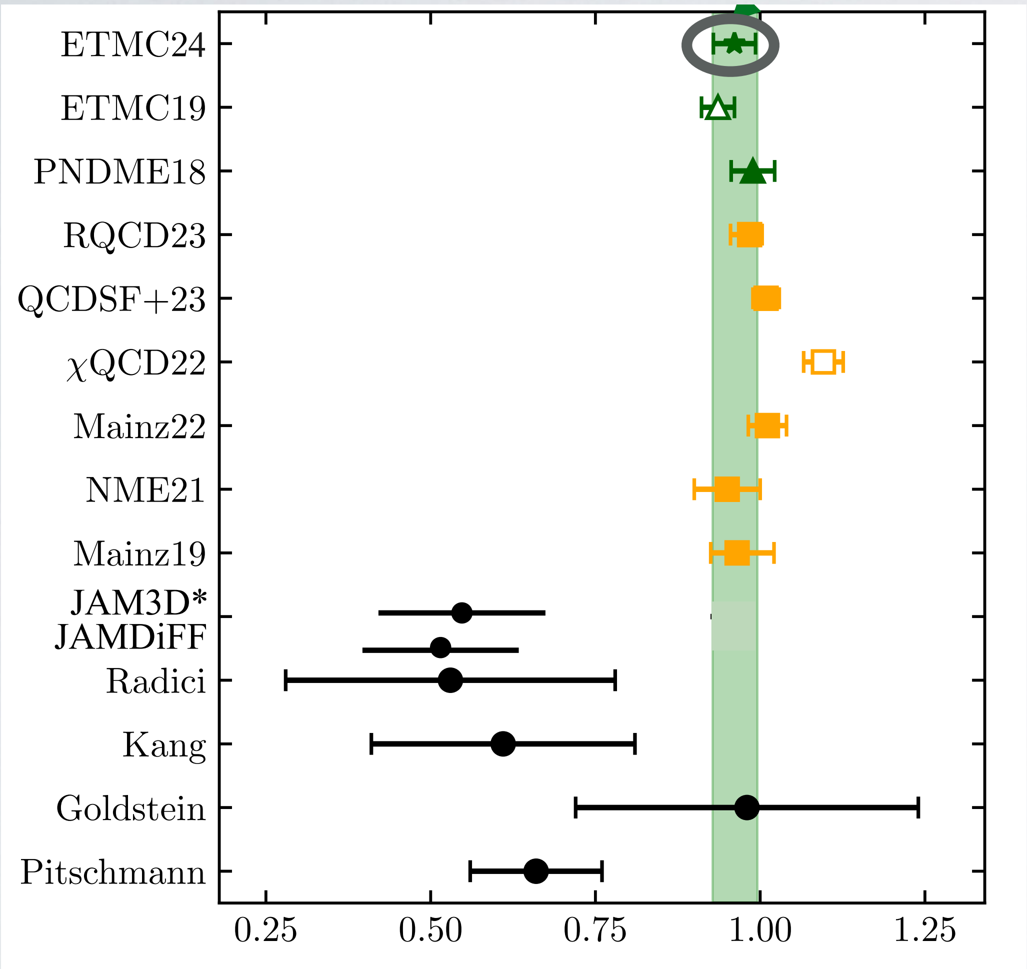


Alexandrou *et al.* (ETMC), P.R. D**105** (22) 034501

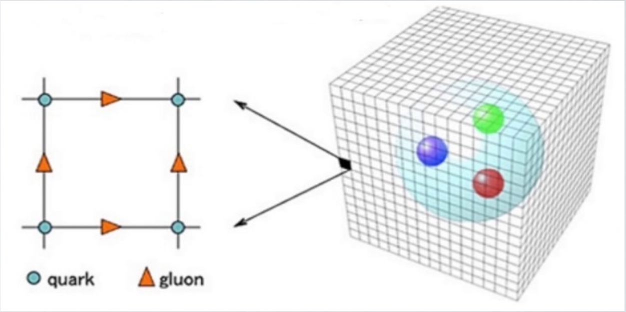
see next talk by Alexandrou

Pheno — Lattice : tensor charge

$g_T = \delta u - \delta d$



green N_f=2+1+1

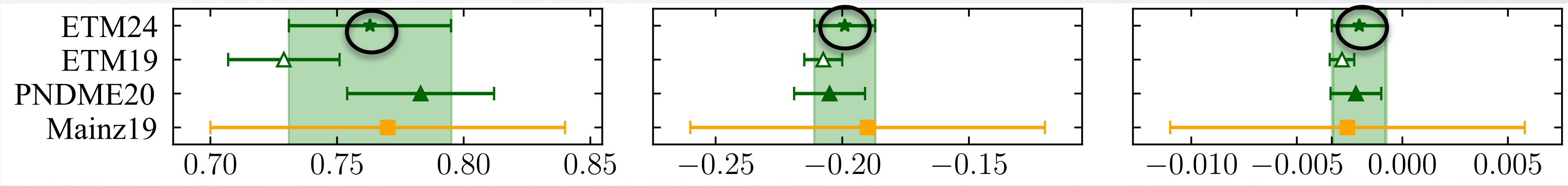


open symbols = no continuum extrapolation

yellow N_f=2+1

adapted from
C. Alexandrou, QCD Evolution 24

δu δd δs



Pheno — Lattice : tensor charge

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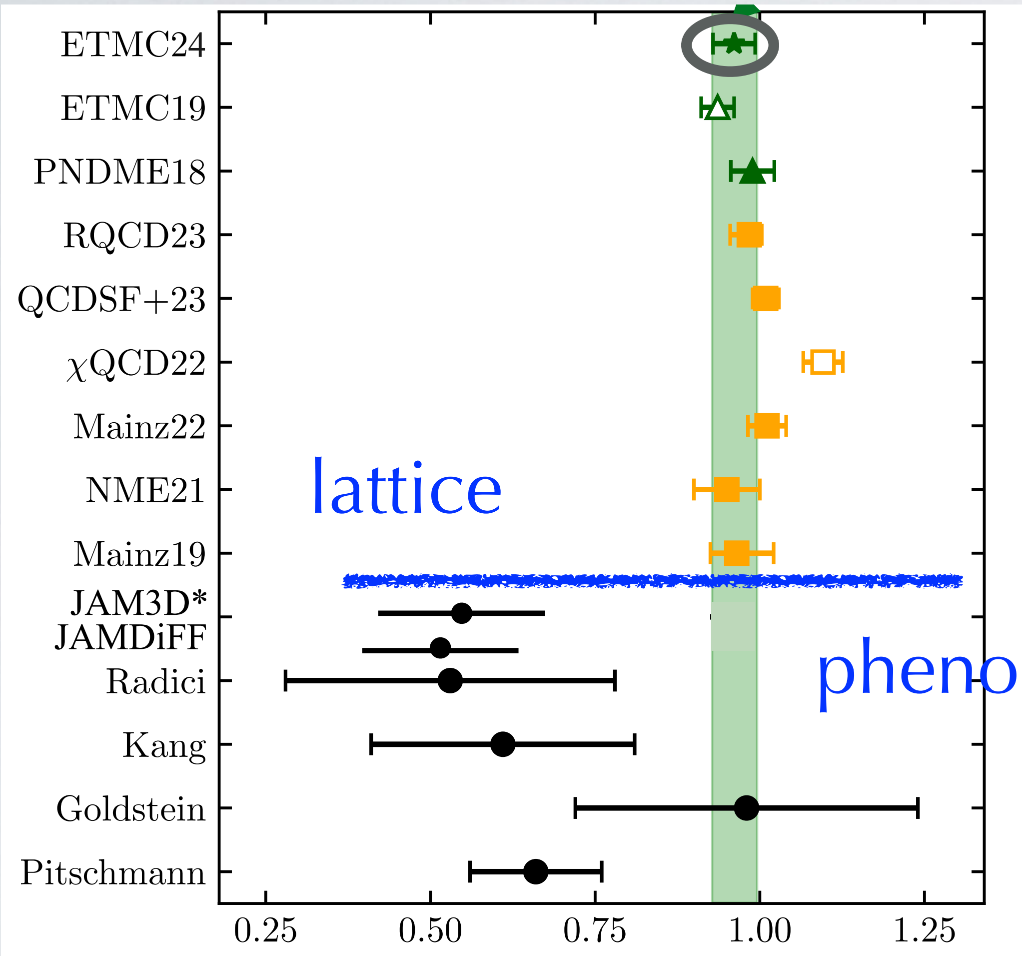

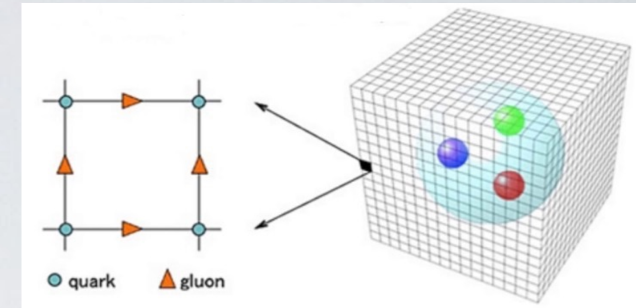

green $N_f=2+1+1$

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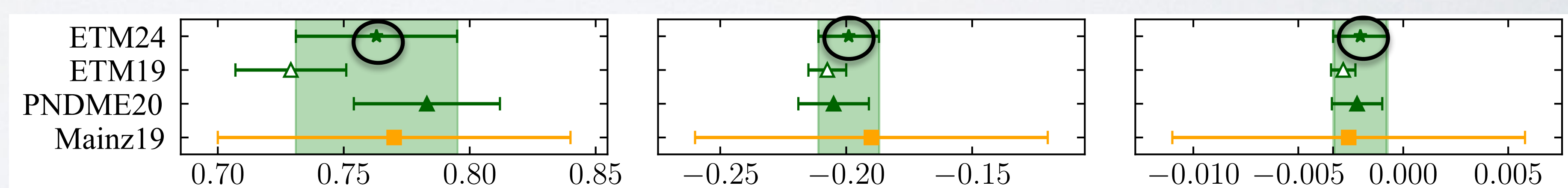
tension between pheno and lattice ?

adapted from
C. Alexandrou, QCD Evolution 24

δu δd δs



Pheno — Lattice : tensor charge

Probing Nucleons and Nuclei in High Energy Collisions

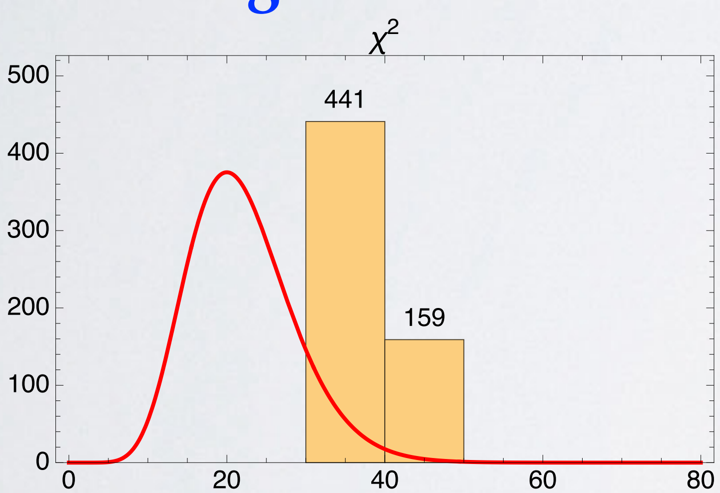
INT 18-3 Oct. 1 - Nov. 16 2018, Seattle

Eds. Y. Hatta, Y.V. Kovchegov, C. Marquet, A. Prokudin

arXiv:2002.12333

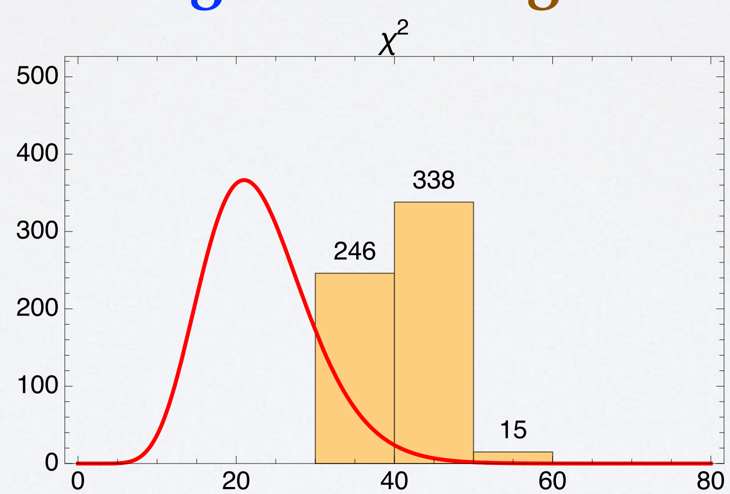
tension between pheno and lattice is an old story; my exercise of 2018:

global fit



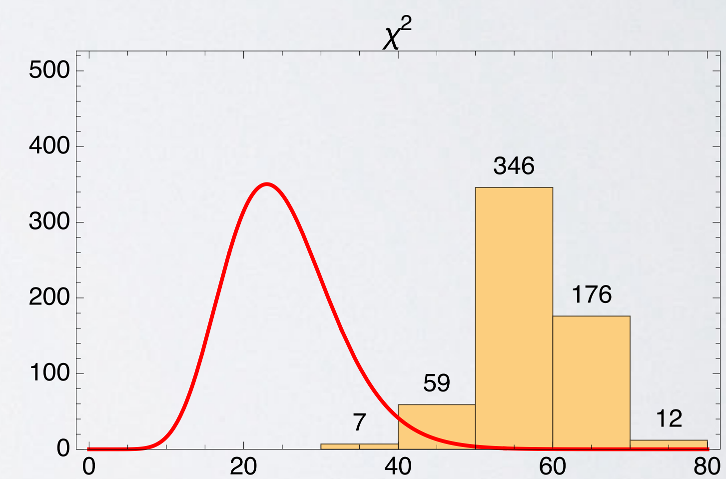
χ^2/dof = 1.76 ± 0.11

global fit + g_T



χ^2/dof = 1.82 ± 0.25

global fit + g_T + δu + δd



χ^2/dof = 2.29 ± 0.25

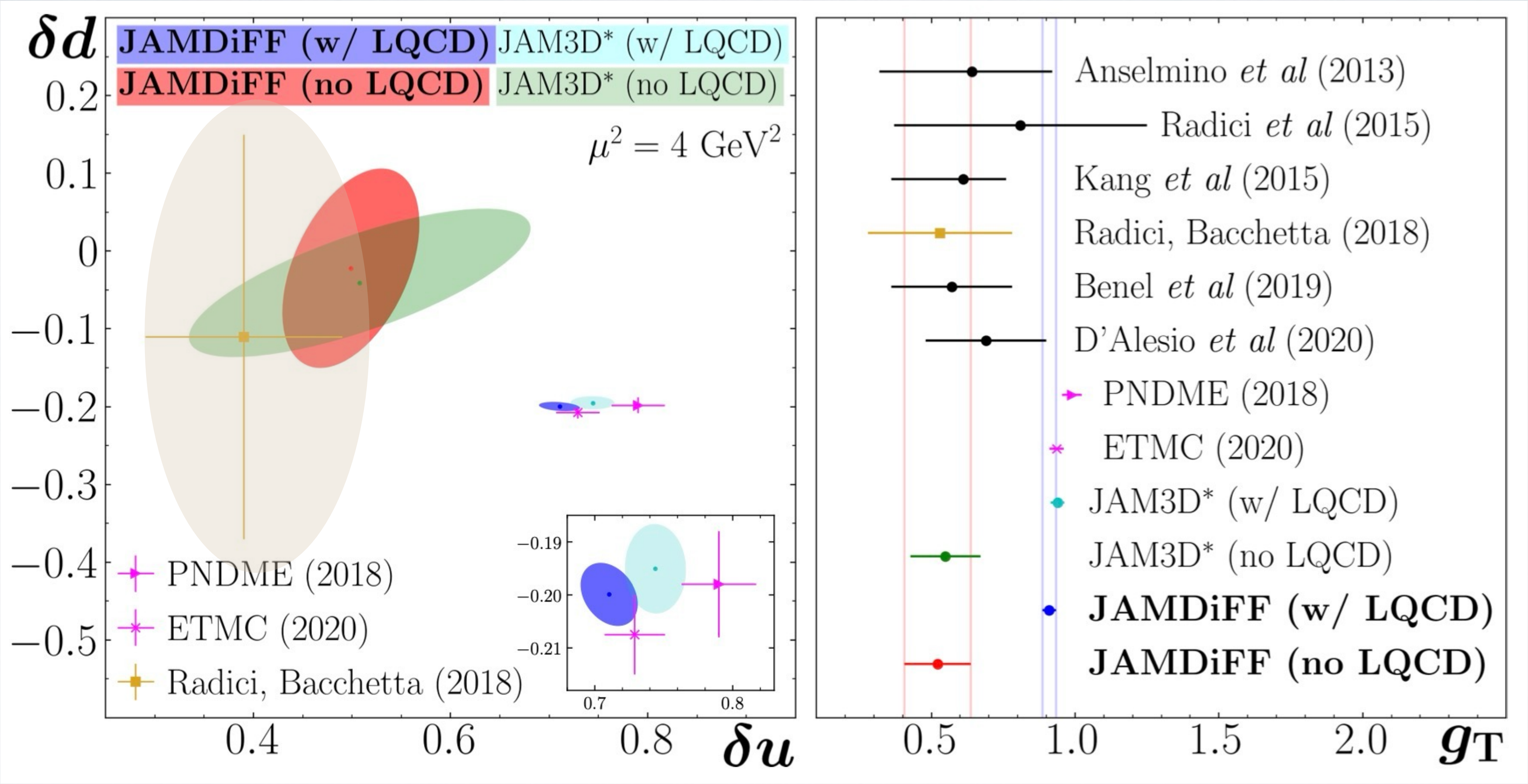
probability density function of χ^2 distribution

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

lattice

PNDME18 Gupta *et al.*, P.R. D**98** (18) 034503
ETMC17 Alexandrou *et al.*, P.R. D**95** (17) 114514
E P.R. D**96** (17) 099906

Pheno — Lattice : tensor charge

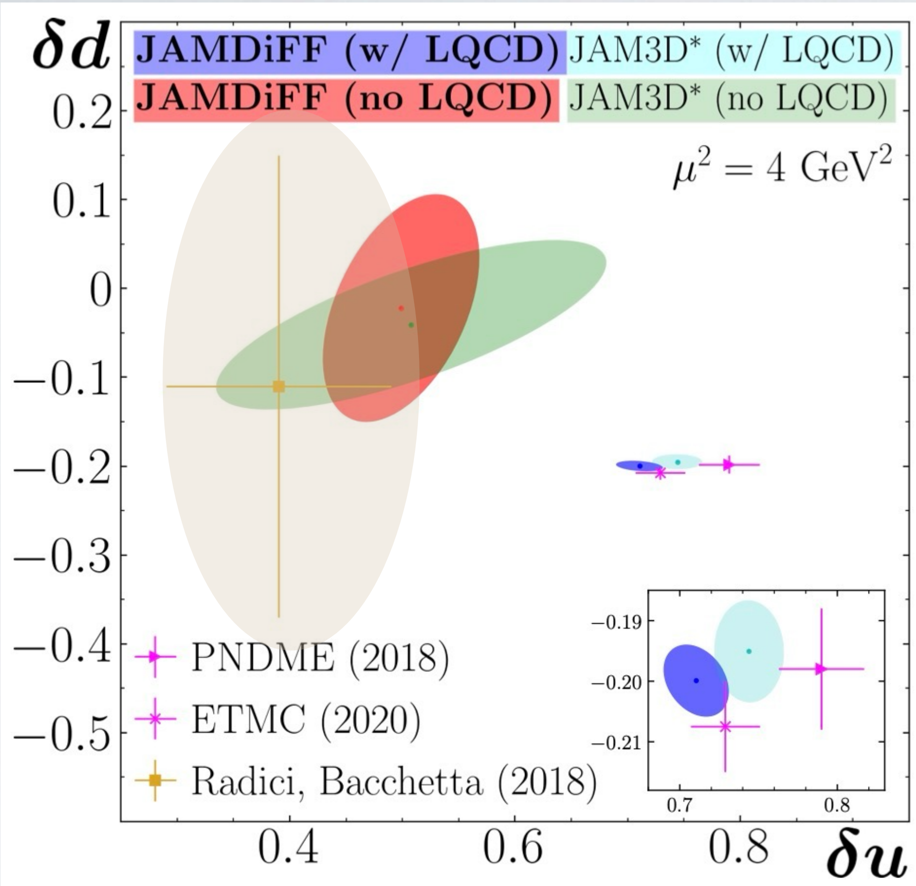


adapted from D. Pitonyak, QCD Evolution 24

see talks by Pitonyak & Sato in the afternoon

- approximate compatibility of JAM with other phenomenology when using both Collins effect and di-hadron mechanism but not including lattice results in the fit
- including lattice as prior, JAM still compatible with exp. data with both Collins effect and di-hadron mechanism

Pheno — Lattice : tensor charge

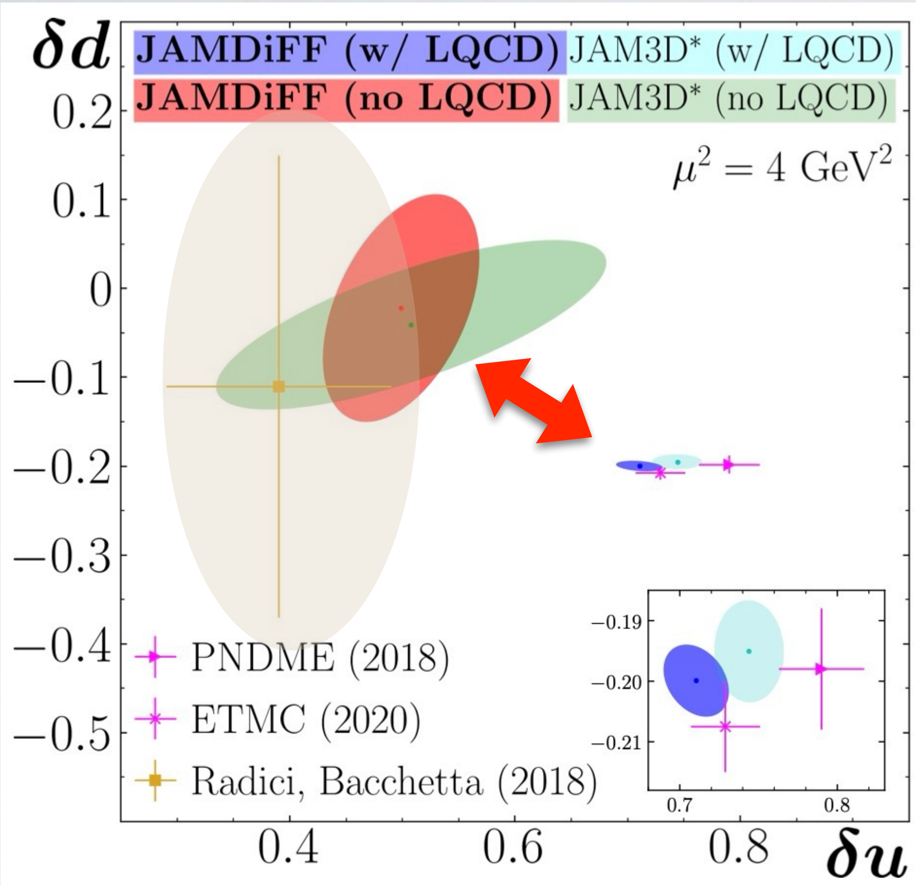


Experiment	Binning	N_{dat}	χ^2_{red} JAMDiFF (w/ LQCD)	(no LQCD)	(SIDIS only)
Belle (cross section)[64]	z, M_h	1094	1.01	1.01	1.01
Belle (Artru-Collins) [111]	z, M_h	55	1.27	1.24	1.28
	$M_h, \overline{M}_h$	64	0.60	0.60	0.60
	$z, \bar{z}$	64	0.42	0.42	0.41
HERMES [117]	x_{bj}	4	1.77	1.70	1.67
	M_h	4	0.41	0.42	0.47
	z	4	1.20	1.17	1.13
COMPASS (p) [116]	x_{bj}	9	1.98	0.65	0.59
	M_h	10	0.92	0.94	0.93
	z	7	0.77	0.60	0.63
COMPASS (D) [116]	x_{bj}	9	1.37	1.42	1.22
	M_h	10	0.45	0.37	0.38
	z	7	0.50	0.46	0.46
STAR [120] $\sqrt{s} = 200$ GeV $R < 0.3$	$M_h, \eta < 0$	5	2.57	2.56	—
	$M_h, \eta > 0$	5	1.34	1.55	—
	$P_{hT}, \eta < 0$	5	0.98	1.00	—
	$P_{hT}, \eta > 0$	5	1.73	1.74	—
	η	4	0.52	1.46	—
STAR [96] $\sqrt{s} = 500$ GeV $R < 0.7$	$M_h, \eta < 0$	32	1.30	1.10	—
	$M_h, \eta > 0$	32	0.81	0.78	—
	$P_{hT}, \eta > 0$	35	1.09	1.07	—
	η	7	2.97	1.83	—
ETMC δu [77]	—	1	0.71	—	—
ETMC δd [77]	—	1	1.02	—	—
PNDME δu [71]	—	1	8.68	—	—
PNDME δd [71]	—	1	0.04	—	—
Total χ^2_{red} (N_{dat})			**1.01** (1475)	**0.98** (1471)	0.96 (1341)

- lattice = 4 pts vs. total = 1475 pts. => statistical weight irrelevant
  => does not alter quality of fit on exp. data…

see round table on Tuesday afternoon

Pheno — Lattice : tensor charge



Experiment	Binning	$N_{\rm dat}$	$\chi^2_{\rm red}$ JAMDiFF (w/ LQCD)	(no LQCD)	(SIDIS only)
Belle (cross section) [64]	z, M_h	1094	1.01	1.01	1.01
	z, M_h	55	1.27	1.24	1.28
Belle (Artru-Collins) [111]	$M_h, \overline{M}_h$	64	0.60	0.60	0.60
	$z, \bar{z}$	64	0.42	0.42	0.41
	$x_{\rm bj}$	4	1.77	1.70	1.67
HERMES [117]	M_h	4	0.41	0.42	0.47
	z	4	1.20	1.17	1.13
	$x_{\rm bj}$	9	1.98	0.65	0.59
COMPASS (p) [116]	M_h	10	0.92	0.94	0.93
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Total $\chi^2_{\rm red}$ ($N_{\rm dat}$)			**1.01** (1475)	**0.98** (1471)	0.96 (1341)

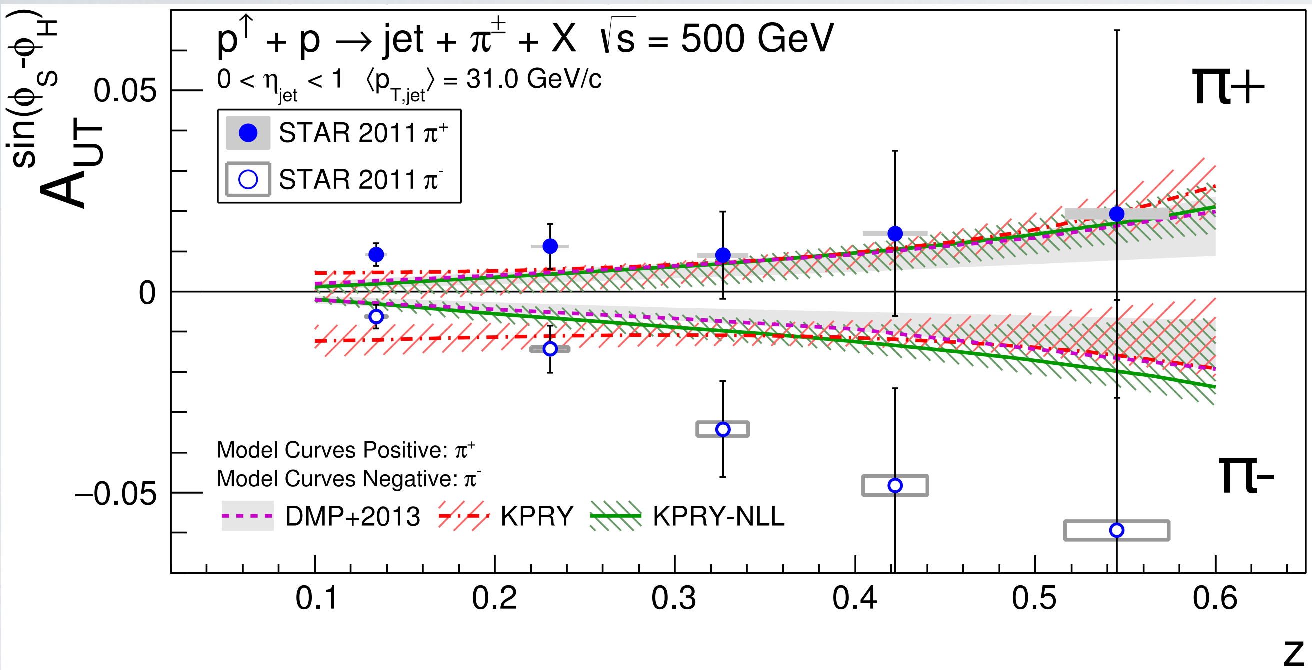
- lattice = 4 pts vs. total = 1475 pts. => statistical weight irrelevant
  => does not alter quality of fit on exp. data…
- χ^2~8.7 on δu of PNDME => **compatibility ??**

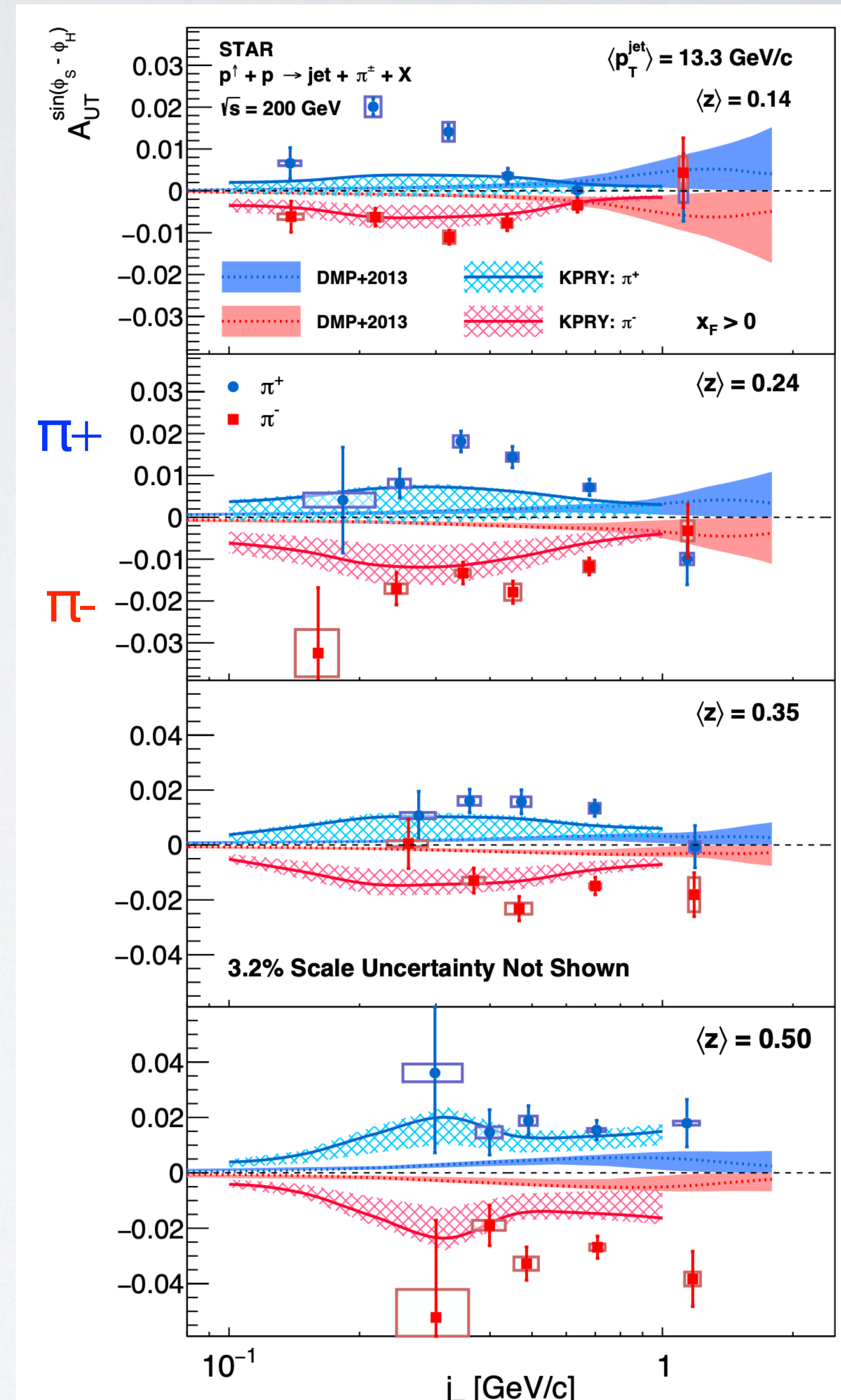
see round table on Tuesday afternoon

Hadron-in-jet Collins effect

$p^{\uparrow} + p \rightarrow \text{jet} + \pi^{\pm} + X$

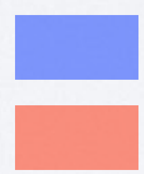
M. Grosse-Perdekamp, Transversity 2022





STAR 2010-11 $\sqrt{s} = 500$ GeV

D'Alesio et al., P.L. **B773** (17) 300



π+

π-

no evolution

TMD evolution

Kang et al., P.L. **B774** (17) 635

π+

π-

see talk by Murgia (?) on Tuesday

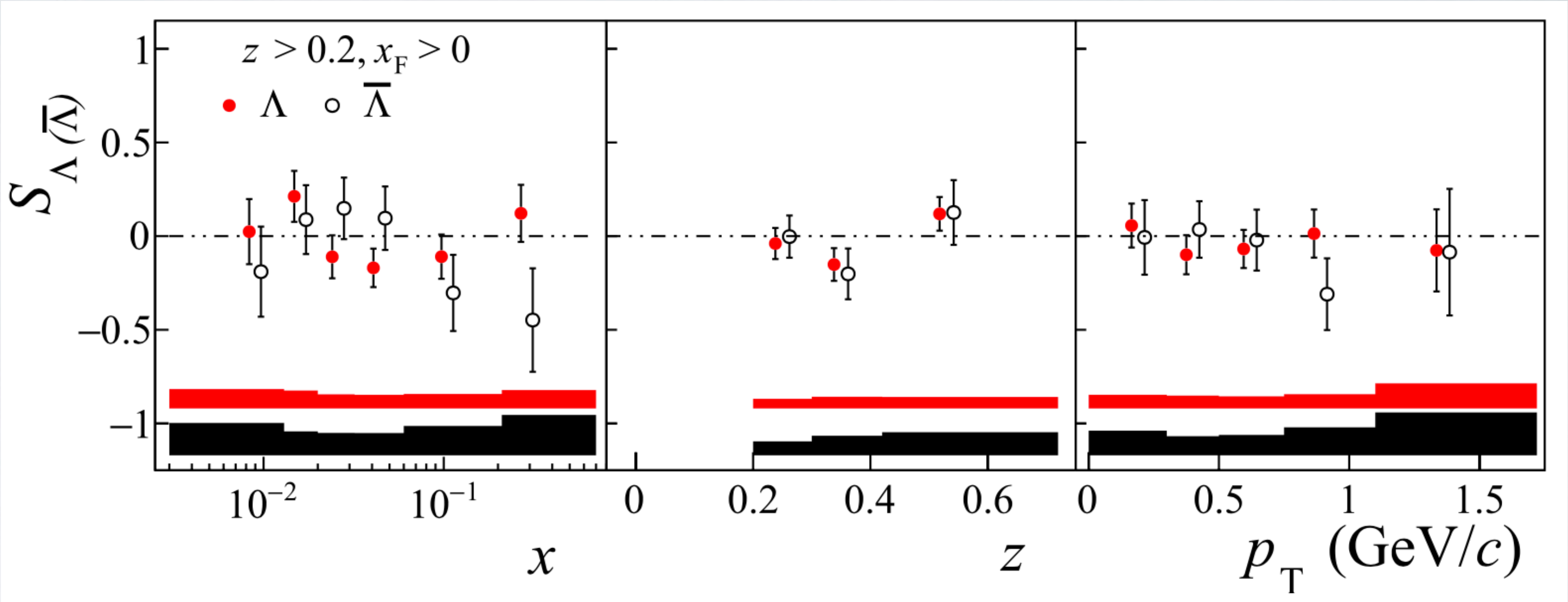
STAR 2012-15 $\sqrt{s} = 200$ GeV

Λ spin transfer

$$\ell + p^{\uparrow} \rightarrow \ell' + \Lambda(\bar{\Lambda})^{\uparrow} + X$$

$$S_{\Lambda} = \frac{1}{f P_T D_{NN}(y)} \frac{d\sigma(\Lambda^{\uparrow}) - d\sigma(\Lambda^{\downarrow})}{d\sigma(\Lambda^{\uparrow}) + d\sigma(\Lambda^{\downarrow})}$$

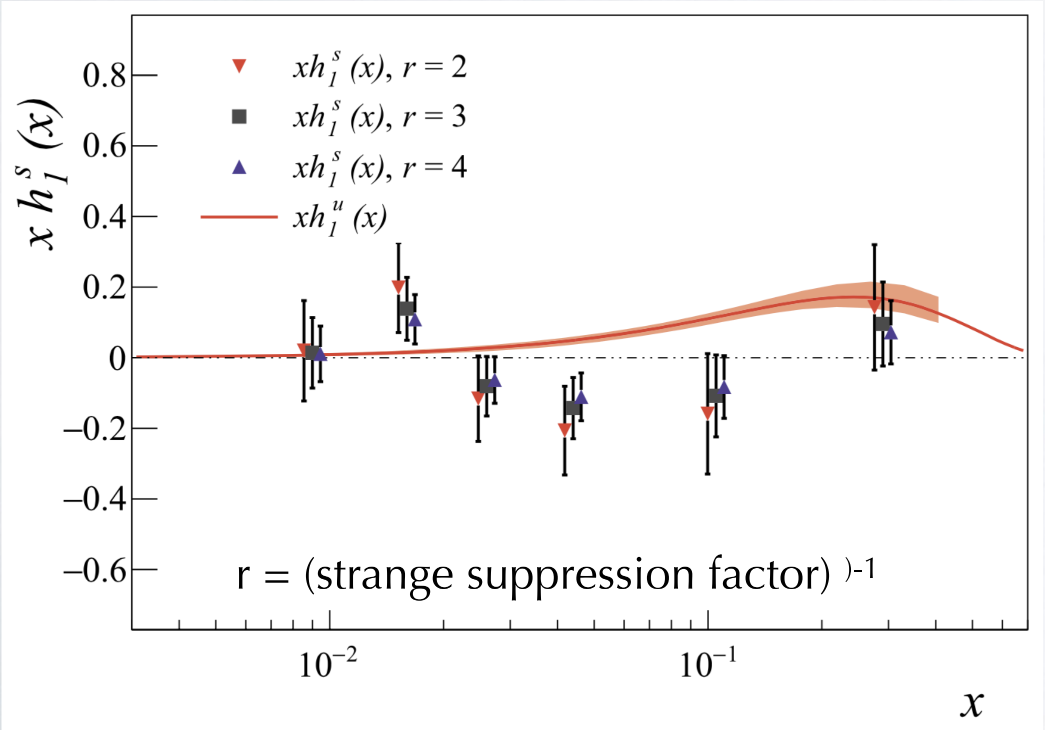
$$= \frac{\sum_q e_q^2 h_1^q H_{1q}^{\Lambda}}{\sum_q e_q^2 f_1^q D_{1q}^{\Lambda}}$$

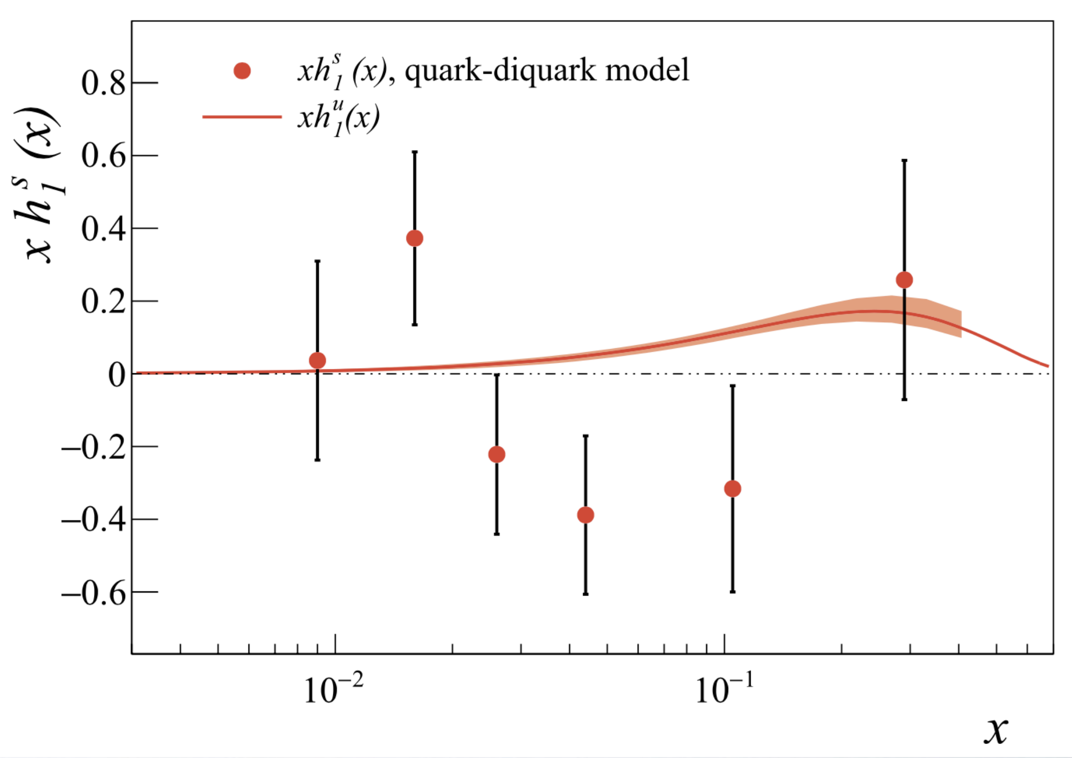


COMPASS Alexeev et al., P.L. **B824** (22) 136834

Λ polarisation carried only by s quark

Λ polarisation described in quark-diquark model

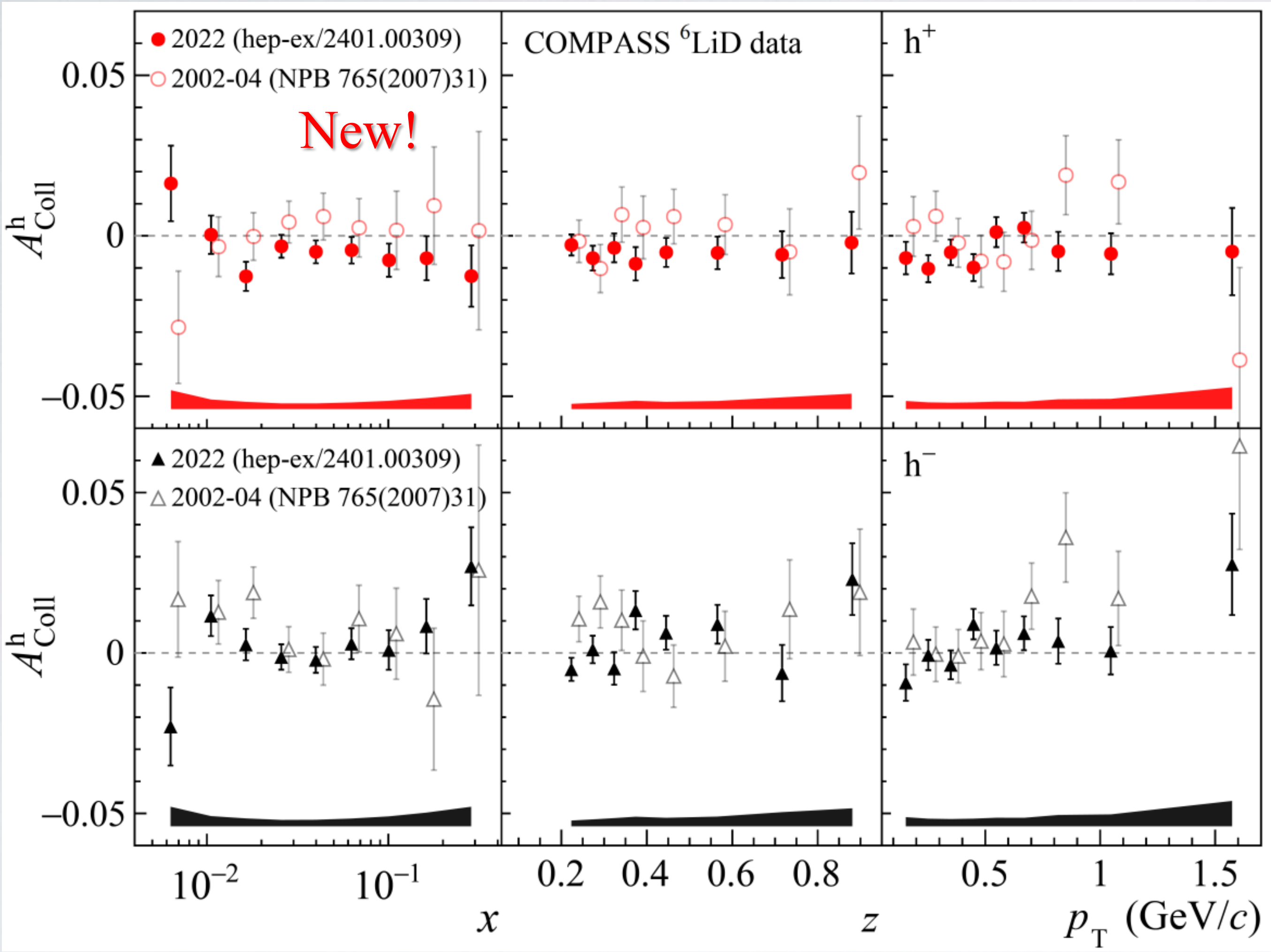




New available exp. data

New data : Compass SIDIS with deuteron target

B. Parsamyan, DIS 2024



Collins effect

COMPASS Alexeev *et al.*, arXiv:2401.00309

Also updated HERMES data

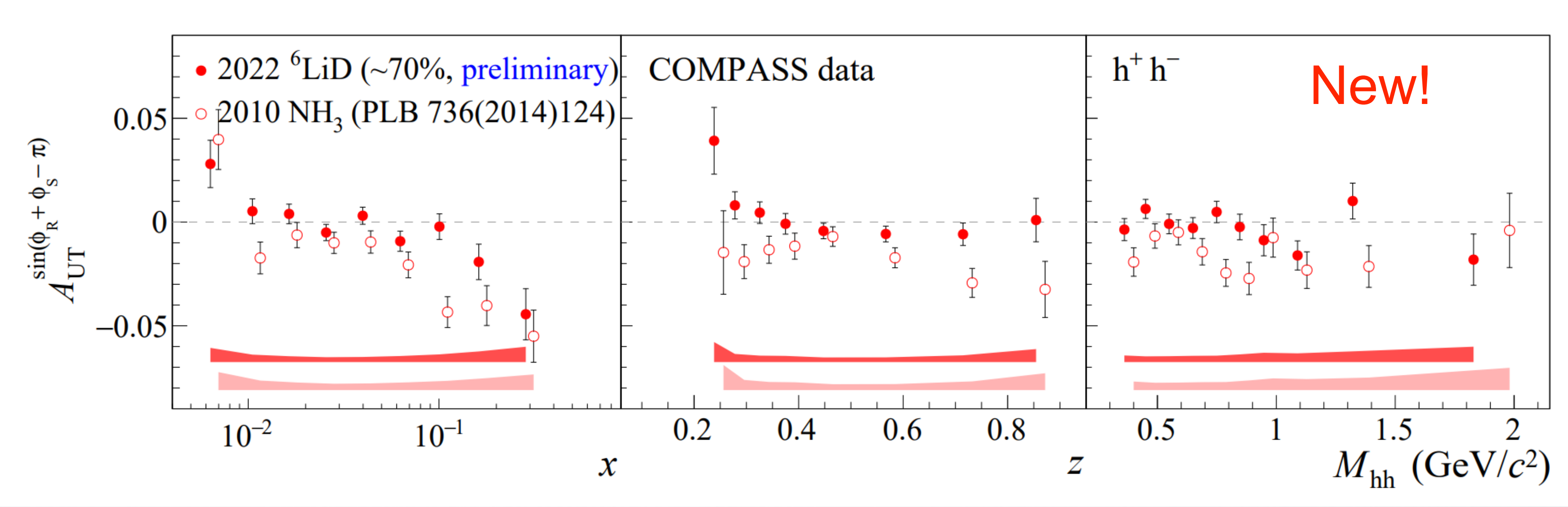
Airapetian *et al.*, JHEP **12** (20) 010

used by Boglione et al. 24

see talks by Vijayakumar (afternoon) and Parsamyan (Tuesday)

di-hadron mechanism

S. Asatryan, DIS 2024



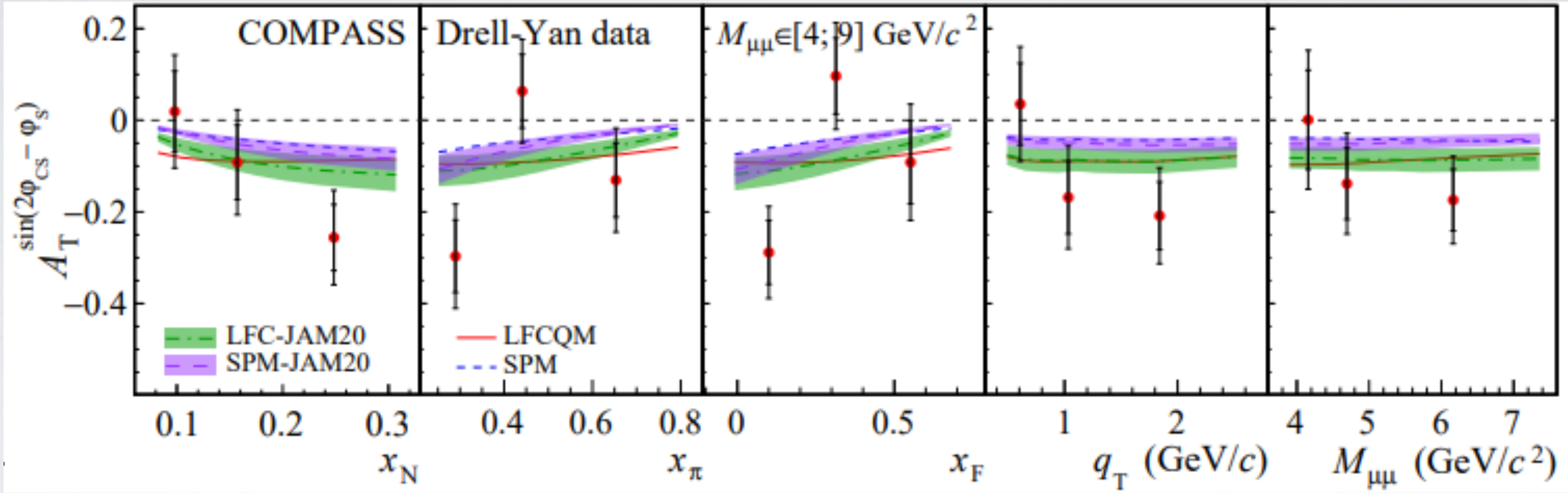
New data : Compass (π- N) Drell-Yan

$$\pi^- + p^\uparrow \to \ell \, \bar{\ell} + X$$

$$A_T = \frac{d\sigma(p^\uparrow) - d\sigma(p^\downarrow)}{d\sigma(p^\uparrow) + d\sigma(p^\downarrow)} \propto \frac{h_{1\pi}^\perp \otimes h_{1p}}{f_{1\pi} \otimes f_{1p}}$$

see talk by Quintans on Wednesday

COMPASS Alexeev *et al.*, arXiv:2312.17379



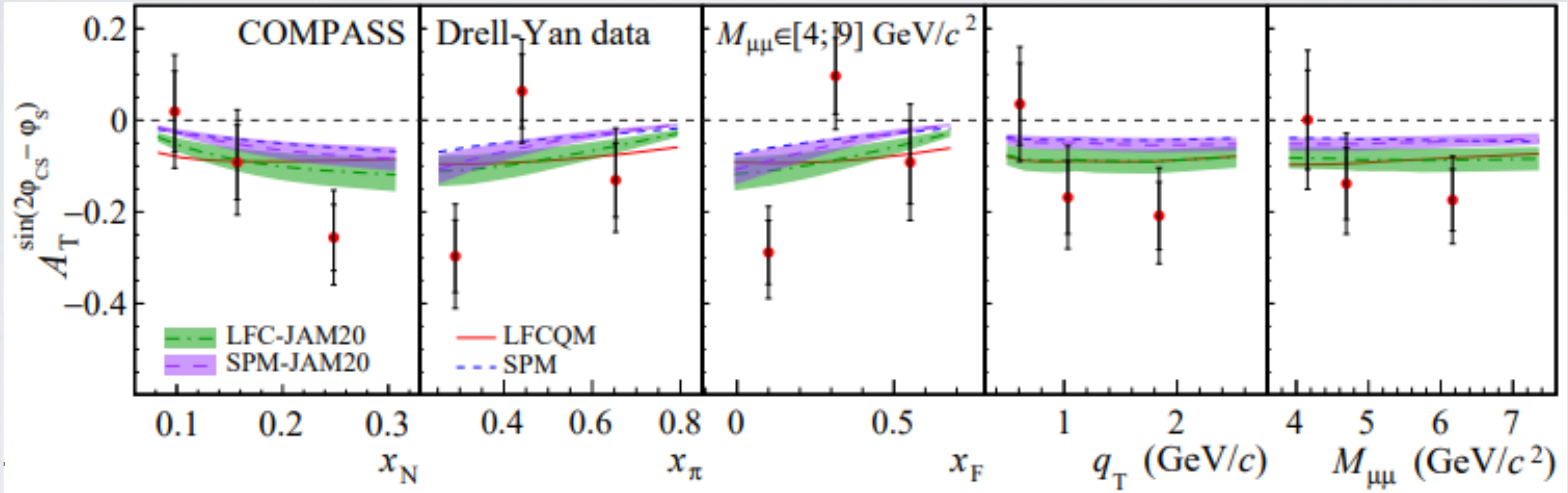
New data : Compass (π- N) Drell-Yan

$$\pi^- + p^\uparrow \to \ell\,\bar{\ell} + X$$

$$A_T = \frac{d\sigma(p^\uparrow) - d\sigma(p^\downarrow)}{d\sigma(p^\uparrow) + d\sigma(p^\downarrow)} \propto \frac{h^\perp_{1\,\pi} \otimes h_{1\,p}}{f_{1\,\pi} \otimes f_{1\,p}}$$

see talk by Quintans on Wednesday

COMPASS Alexeev *et al.*, arXiv:2312.17379

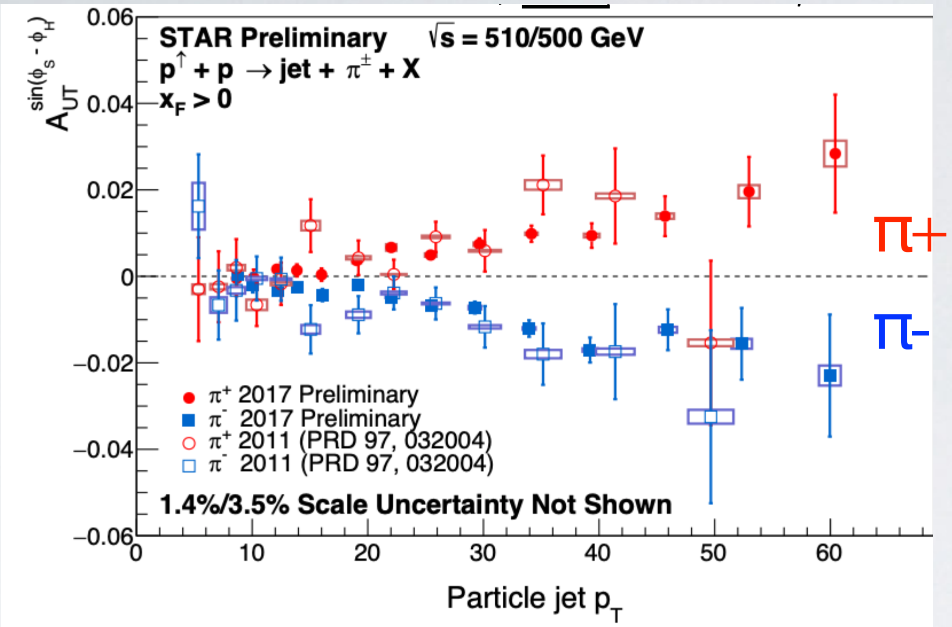


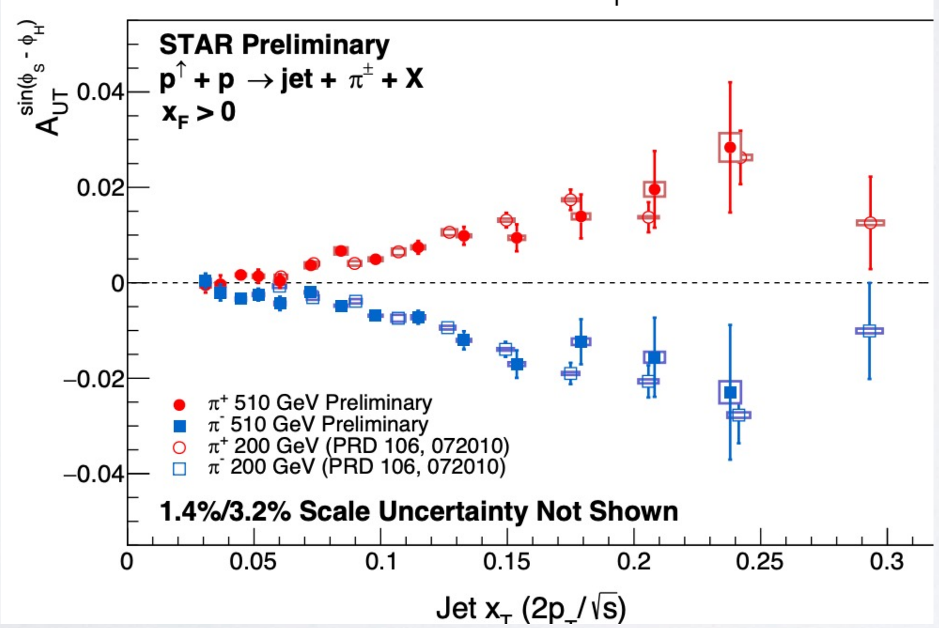
Similar spin asymmetry will be explored at:

- AMBER (including also K beams)
- FermiLab “LongQuest” (with proton-deuteron Drell-Yan)
- LHCspin (with proton-proton Drell-Yan)

see talk by Denisov on Friday

New data : STAR





X. Chu, DIS 2024

hadron-in-jet Collins effect

$p^{\uparrow} + p \rightarrow \text{jet} + \pi^{\pm} + X$

2017 preliminary $\sqrt{s} = 500$ GeV

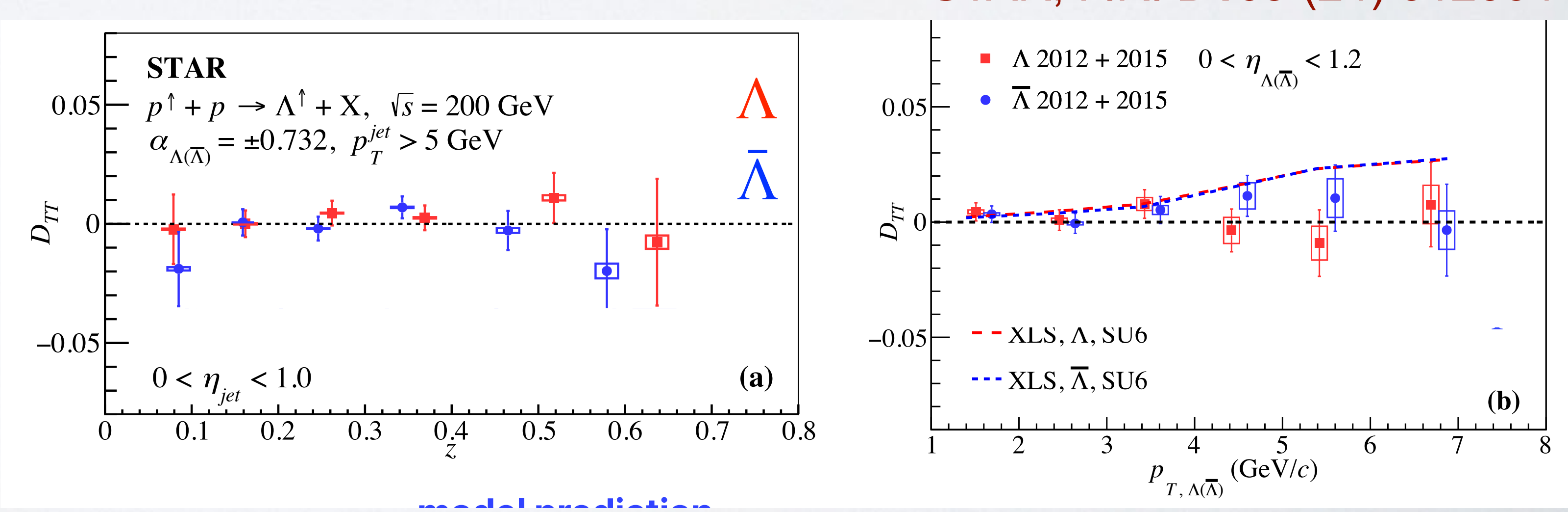
see talk by Zaccheddu on Tuesday

Λ spin transfer $p^{\uparrow} + p \rightarrow \Lambda^{\uparrow} + X$

2012-15 $\sqrt{s} = 200$ GeV

$$D_{TT} = \frac{d\sigma(\Lambda^{\uparrow}) - d\sigma(\Lambda^{\downarrow})}{d\sigma(\Lambda^{\uparrow}) + d\sigma(\Lambda^{\downarrow})} \propto \frac{h_1^a \otimes f_1^b \otimes \delta\sigma^{ab\rightarrow cd} \otimes H_1^c}{f_1^a \otimes f_1^b \otimes \sigma^{ab\rightarrow cd} \otimes D_1^c}$$

STAR, P.R. D**109** (24) 012004



see talks by Eyser, Aboona, Jeongsu (sPHENIX) today

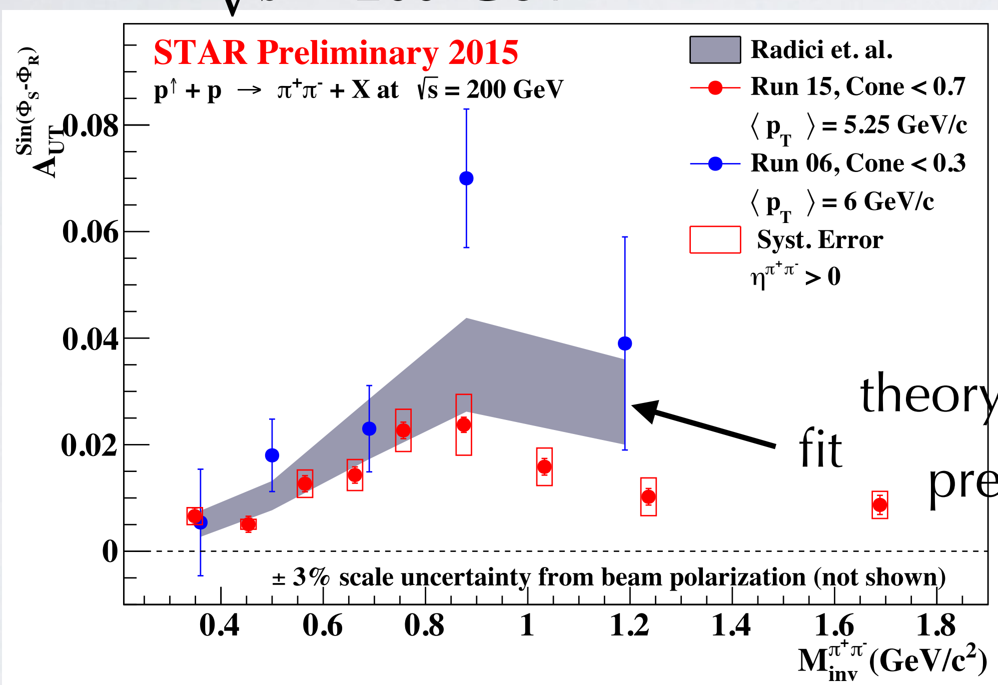
New data : STAR

di-hadron mechanism $p^{\uparrow} + p \to \pi^+ \pi^- + X$

$$A_{UT} = \frac{d\sigma(p^{\uparrow}) - d\sigma(p^{\downarrow})}{d\sigma(p^{\uparrow}) + d\sigma(p^{\downarrow})} \propto \frac{h_1^a \otimes f_1^b \otimes \delta\sigma^{ab\to cd} \otimes H_1^{\sphericalangle c}}{f_1^a \otimes f_1^b \otimes \sigma^{ab\to cd} \otimes D_1^c}$$

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

$\sqrt{s} = 200$ GeV

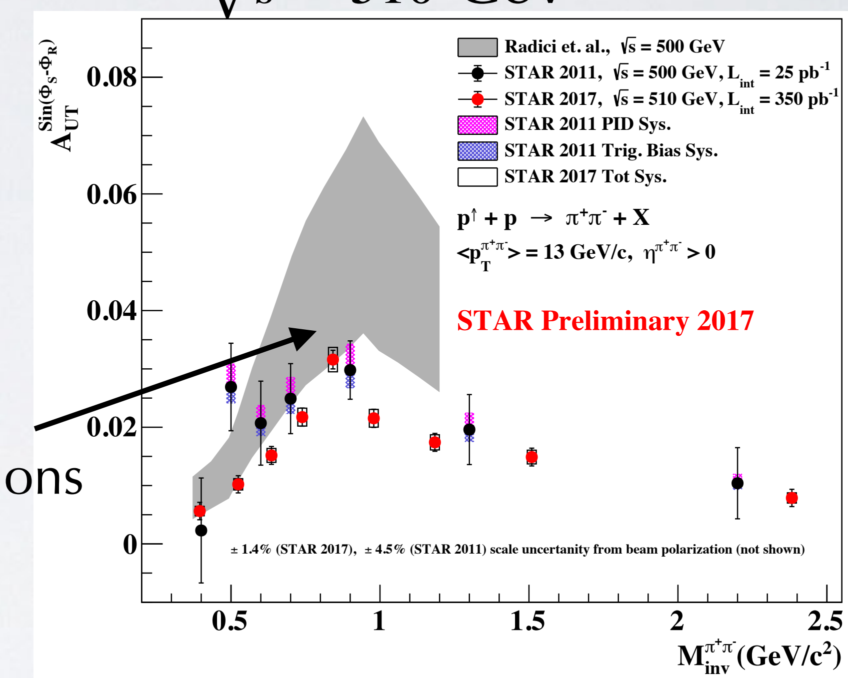


theory

fit

predictions

$\sqrt{s} = 510$ GeV



B. Surrow, DIS 2024

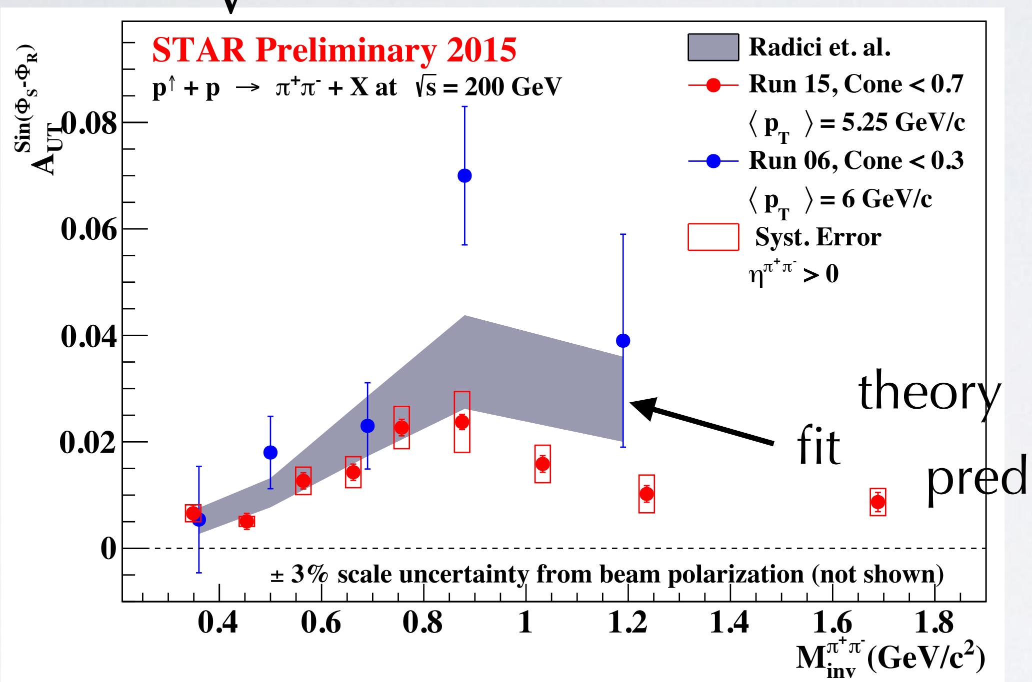
New data : STAR

di-hadron mechanism $p^{\uparrow} + p \rightarrow \pi^+ \pi^- + X$

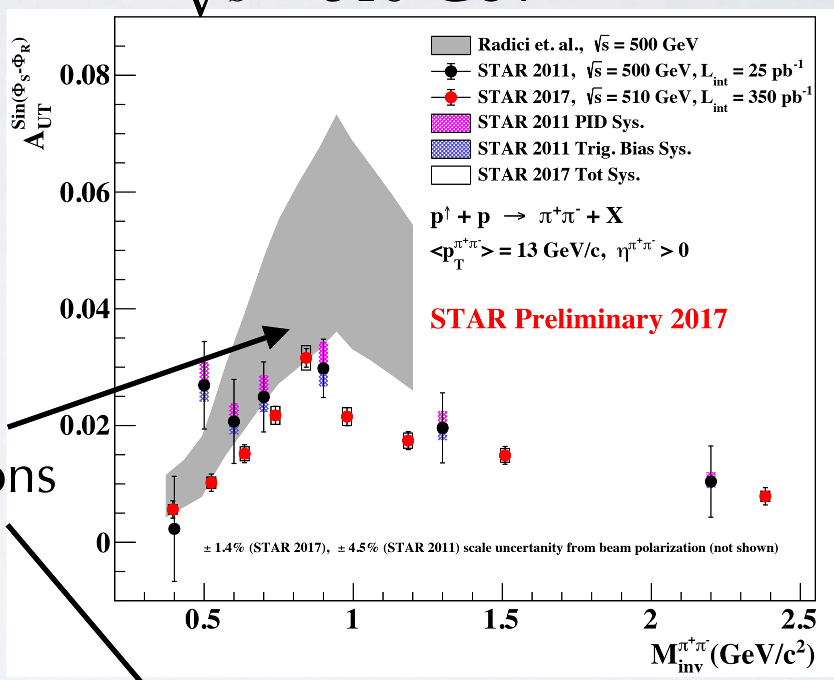
$$A_{UT} = \frac{d\sigma(p^{\uparrow}) - d\sigma(p^{\downarrow})}{d\sigma(p^{\uparrow}) + d\sigma(p^{\downarrow})} \propto \frac{h_1^a \otimes f_1^b \otimes \delta\sigma^{ab\rightarrow cd} \otimes H_1^{\sphericalangle c}}{f_1^a \otimes f_1^b \otimes \sigma^{ab\rightarrow cd} \otimes D_1^c}$$

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

$\sqrt{s} = 200$ GeV

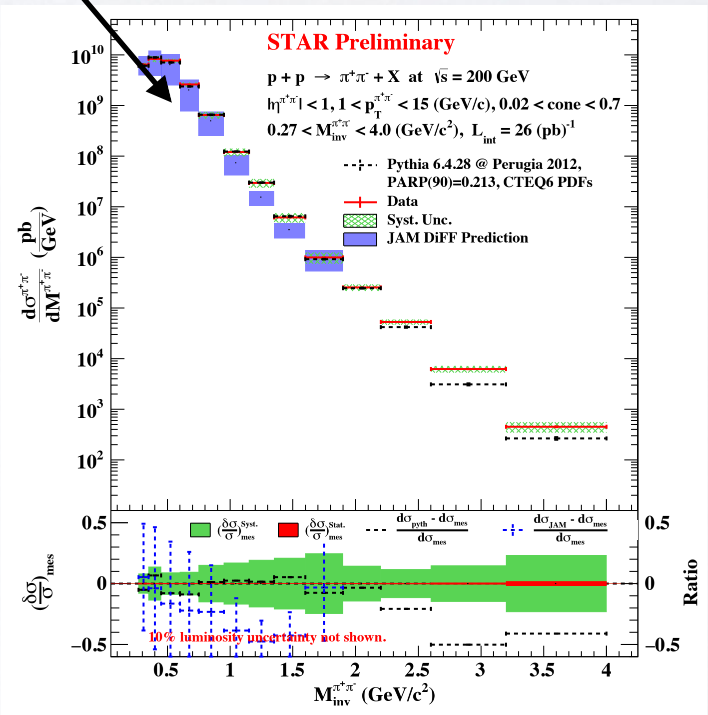


$\sqrt{s} = 510$ GeV



theory fit

predictions



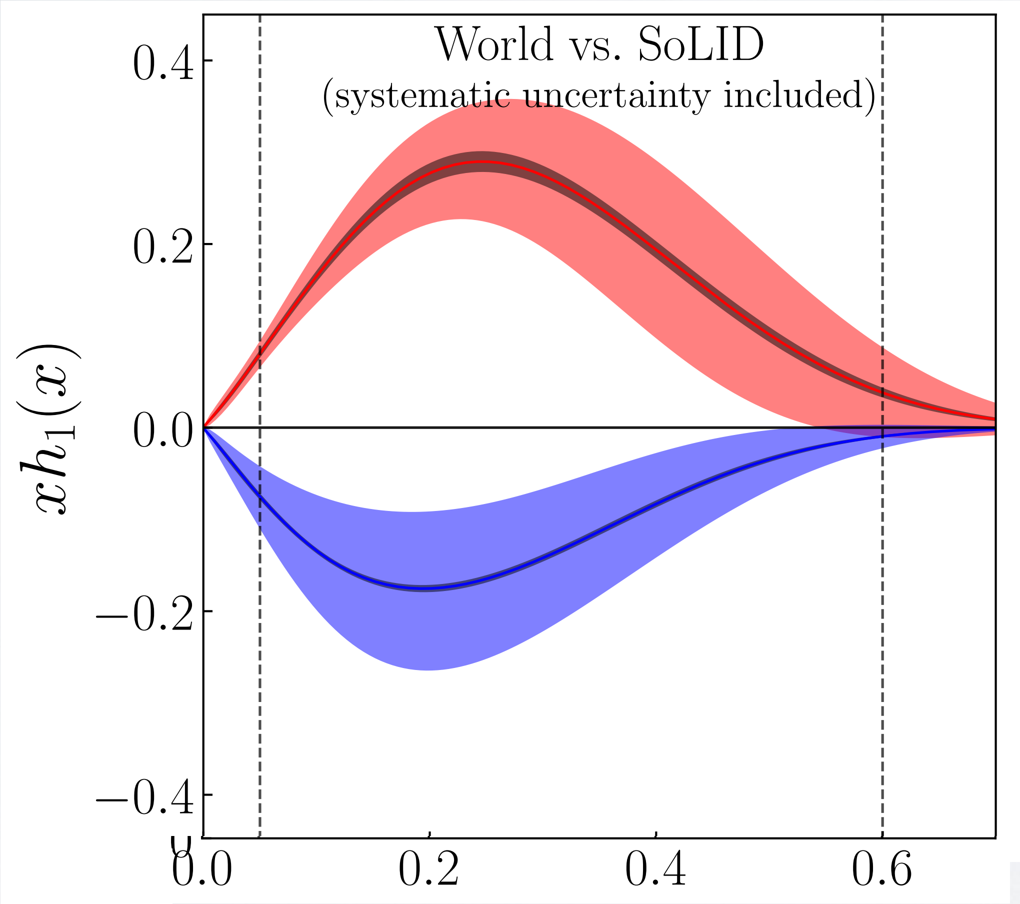
B. Surrow, DIS 2024

also unpolarized cross section

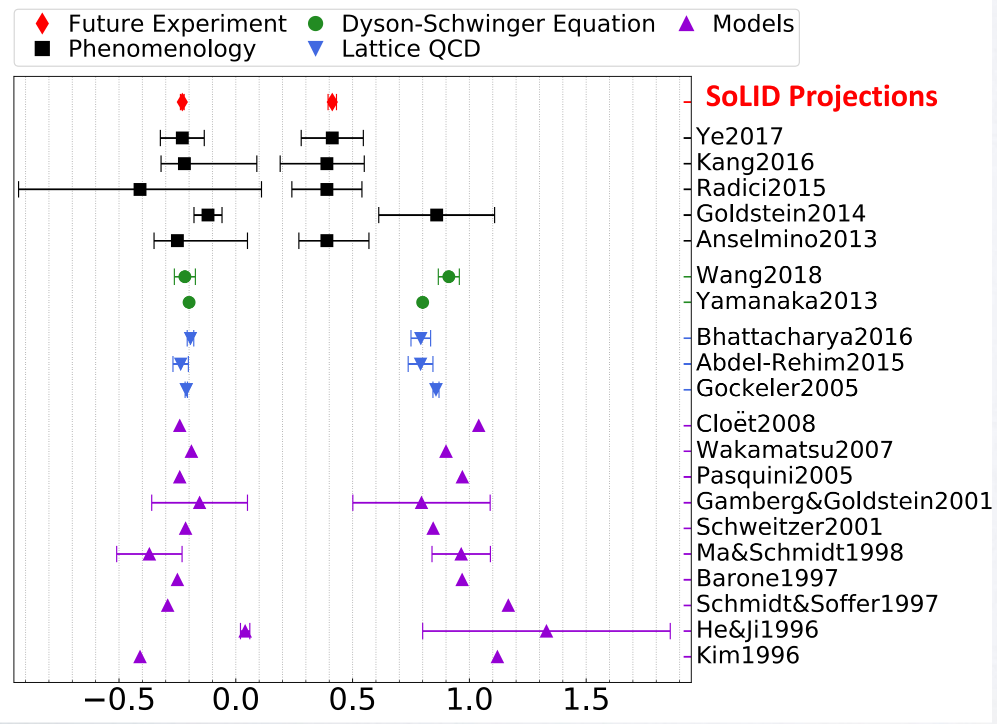
see talk by Surrow on Thursday morning

Future (and its impact)

Future: SoLID @JLab12

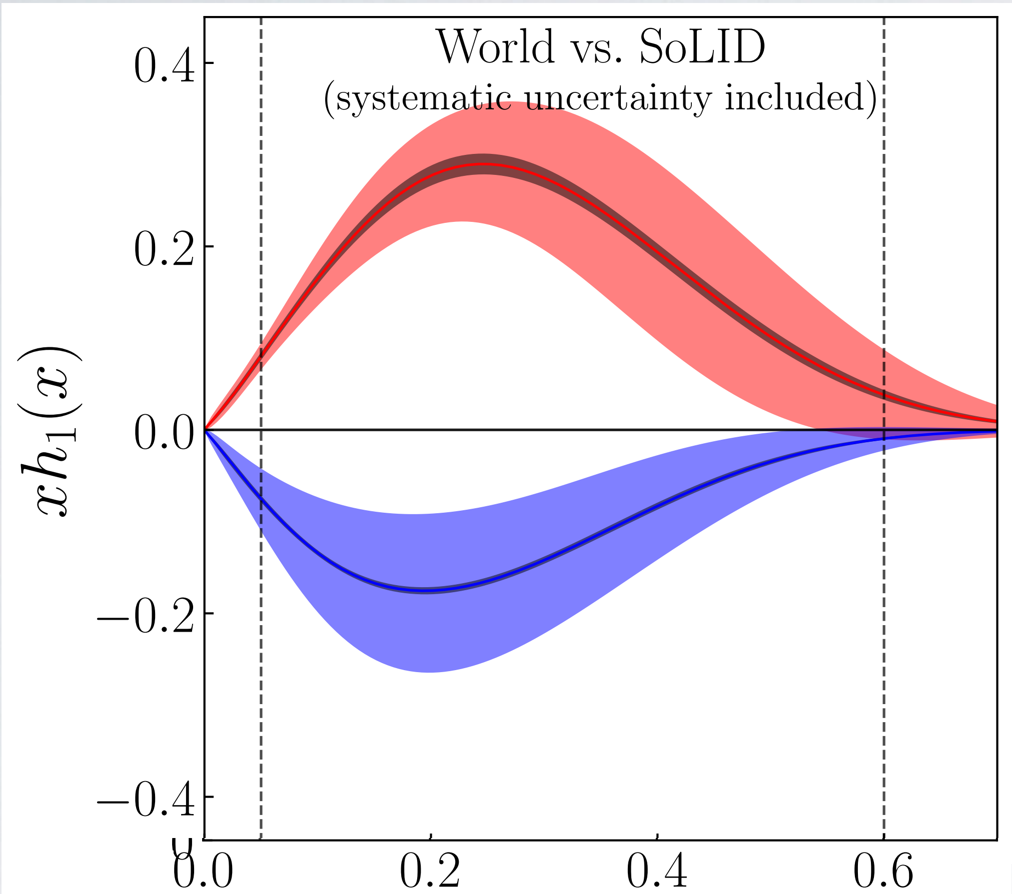


Z. Meziani, DIS 2024

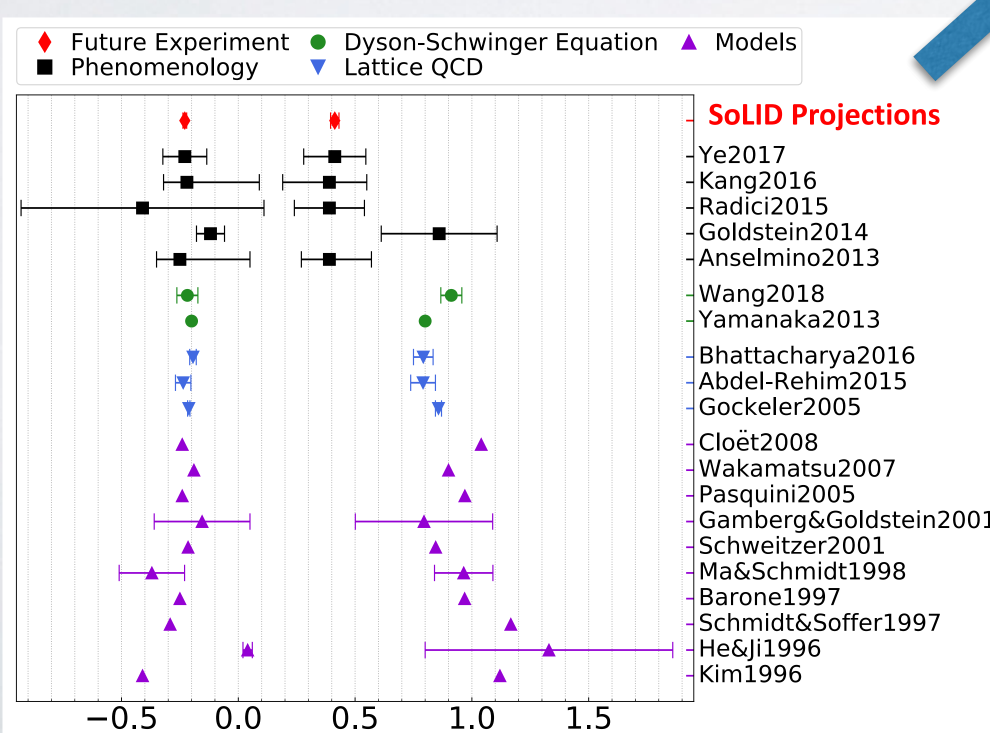


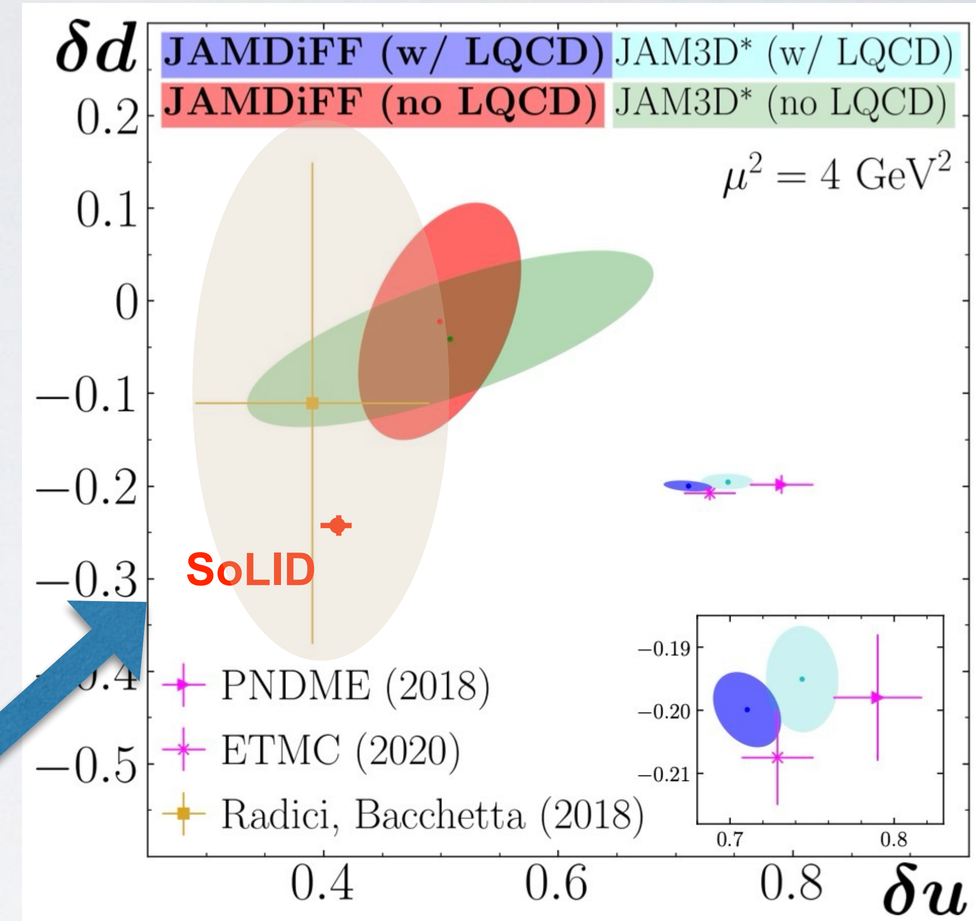
see talks by Avagyan, Gao, Diehl on Tuesday afternoon

Future: SoLID @JLab12



Z. Meziani, DIS 2024





see talks by Avagyan, Gao, Diehl on Tuesday afternoon

Future: EIC impact

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

Collins effect

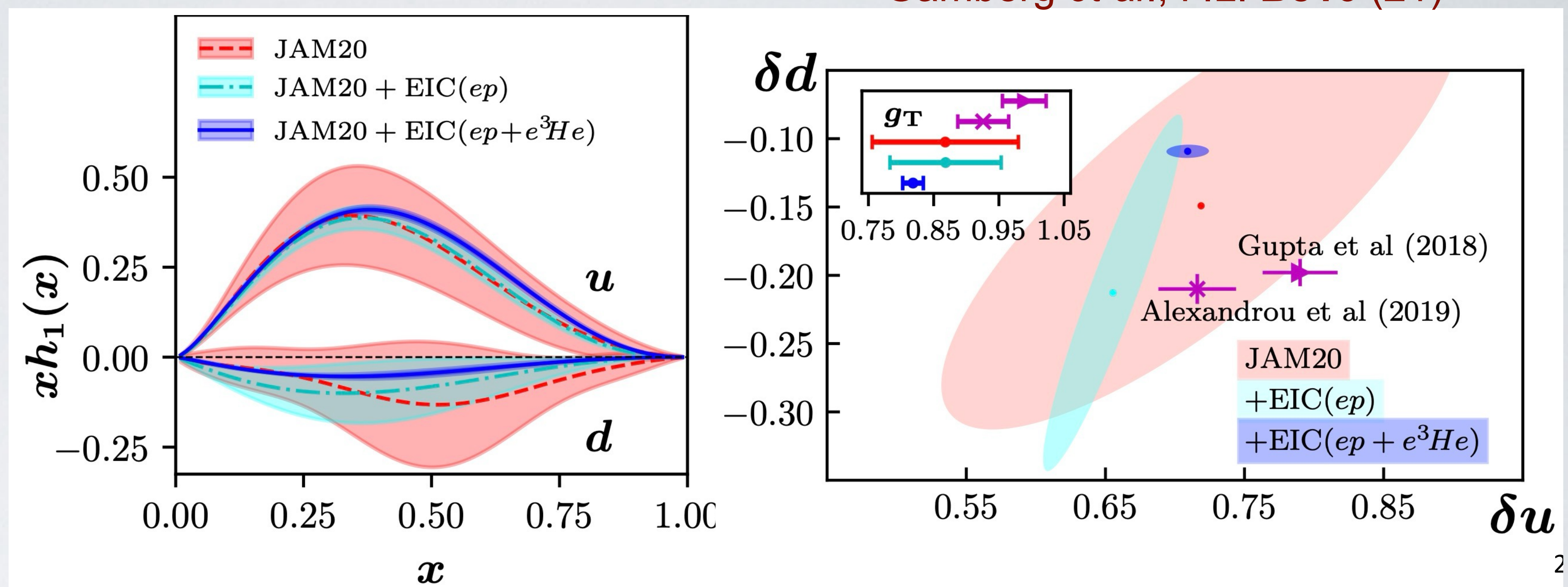
$\mathcal{L}$=10 fb^{-1} , 8223 data pts.

proton [GeV]:

5x41, 5x100, 10x100, 18x275

^{3}He [GeV]:

5x41, 5x100, 18x100



Future: EIC impact

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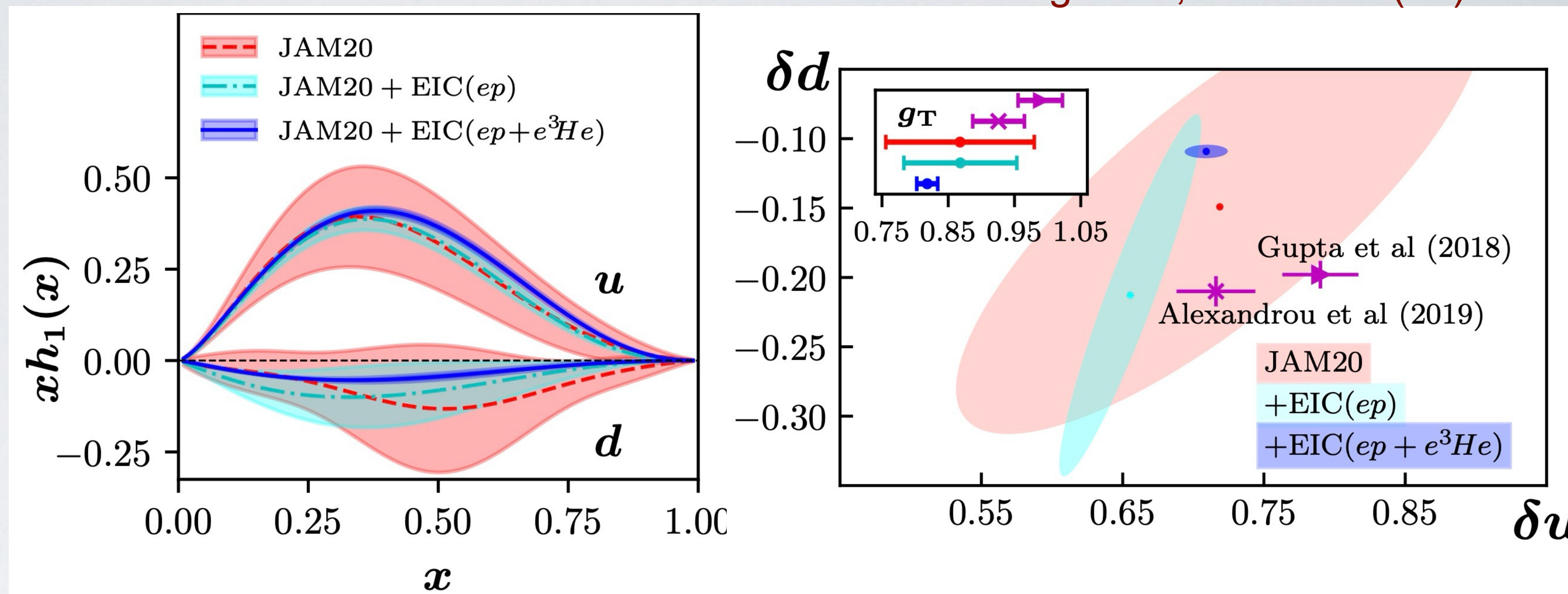
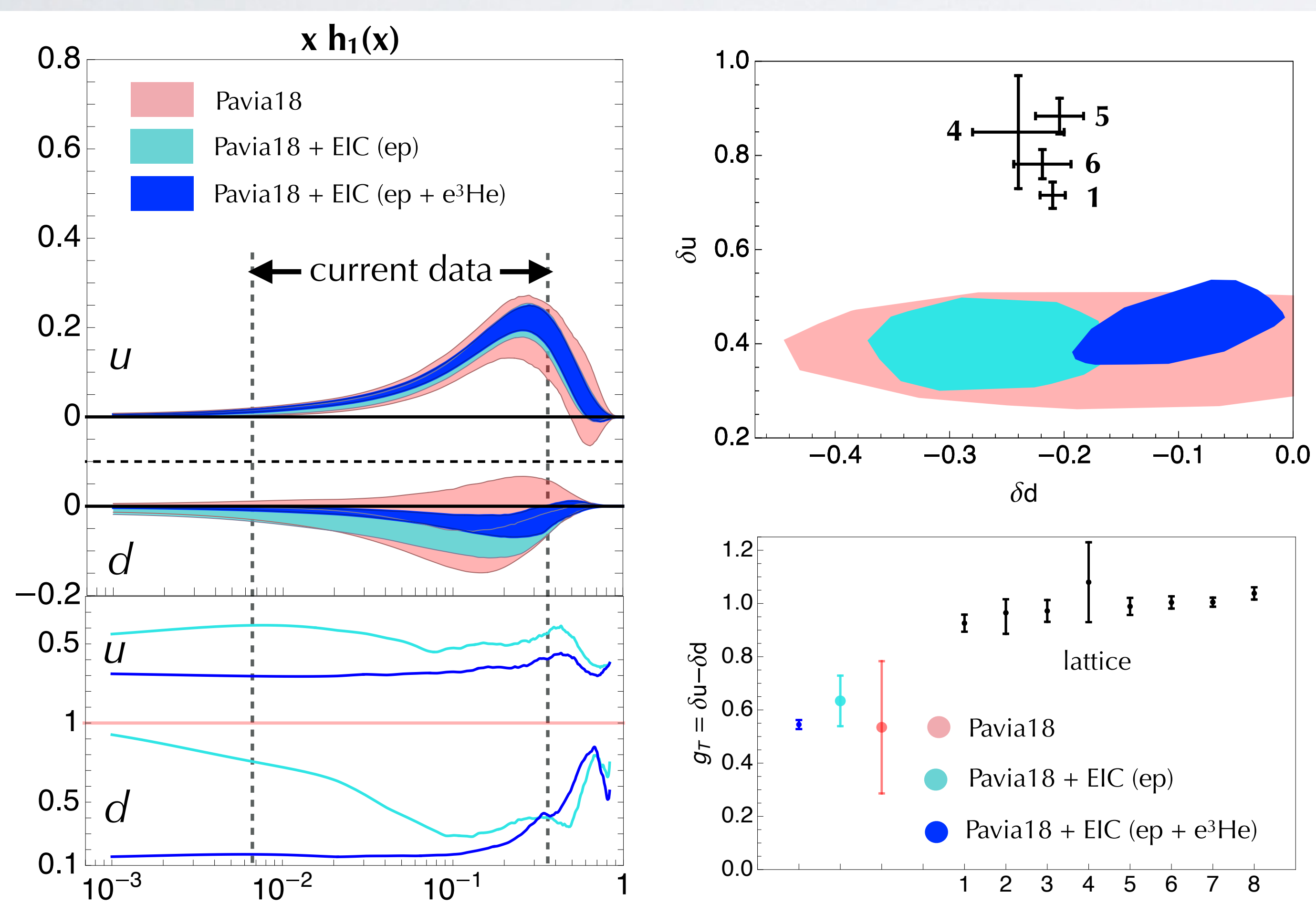
Gamberg *et al.*, P.L. **B816** (21)





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

di-hadron mechanism

$\mathcal{L}$=10 fb^{-1} , 3852 data pts
proton&^{3}He [GeV]: 10x100

Lattice results

1) **ETMC '19** Alexandrou et al., arXiv:1909.00485
2) **Mainz '19** Harris et al., P.R. D**100** (19) 034513
3) **LHPC '19** Hasan et al., P.R. D**99** (19) 114505
4) **JLQCD '18** Yamanaka et al., P.R. D**98** (18) 054516
5) **PNDME '18** Gupta et al., P.R. D**98** (18) 034503
6) **ETMC '17** Alexandrou et al., P.R. D**95** (17) 114514; (E) P.R. D**96** (17) 099906
7) **RQCD '14** Bali et al., P.R. D**91** (15) 054501
8) **LHPC '12** Green et al., P.R. D**86** (12) 114509

Future: EIC impact

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

Collins effect

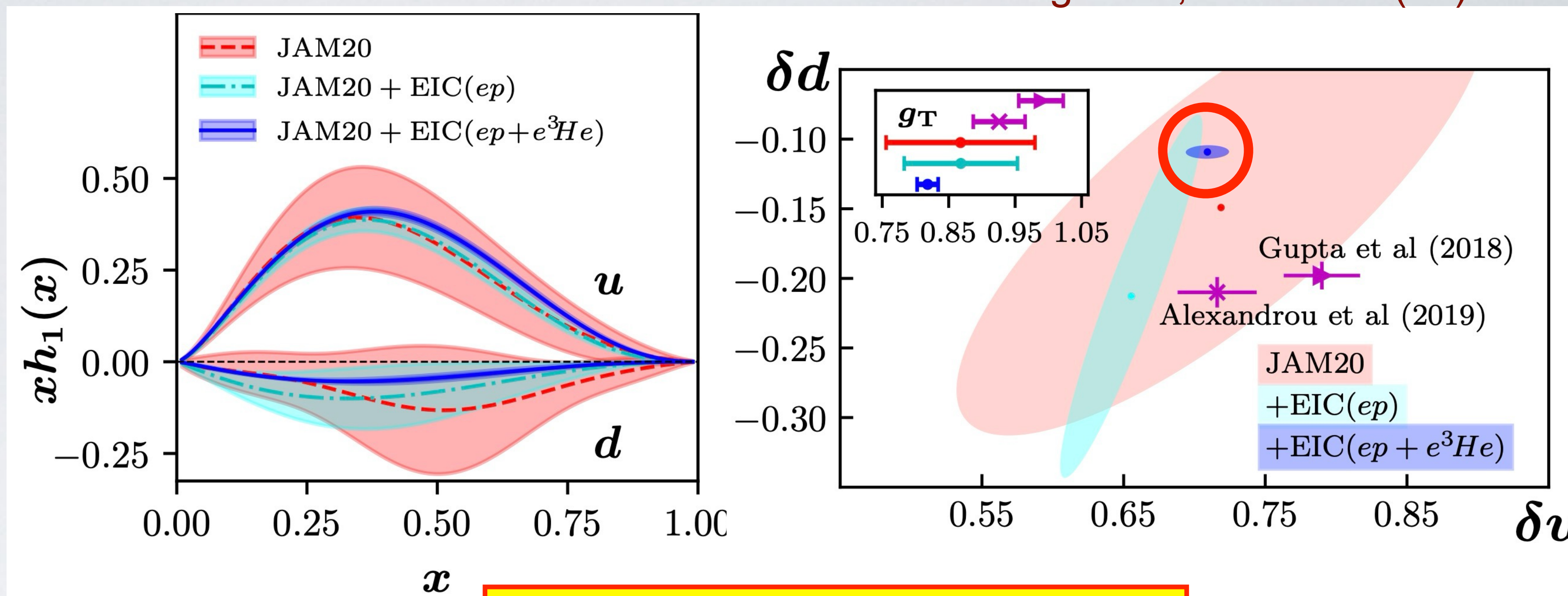
$\mathcal{L}$=10 fb^{-1} , 8223 data pts.

proton [GeV]:

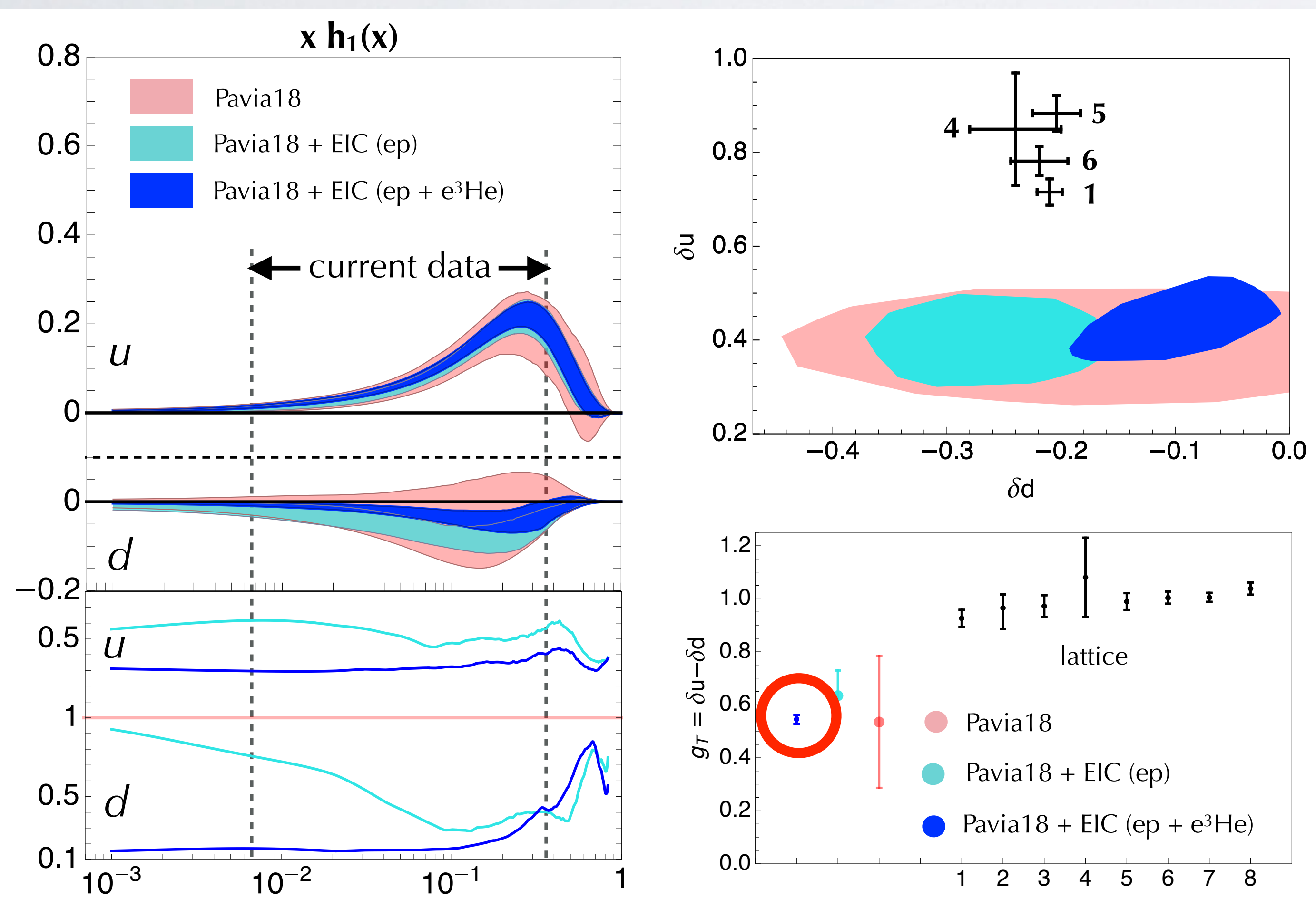
5x41, 5x100, 10x100, 18x275

^{3}He [GeV]:

5x41, 5x100, 18x100



expected precision close to (or higher than) lattice



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

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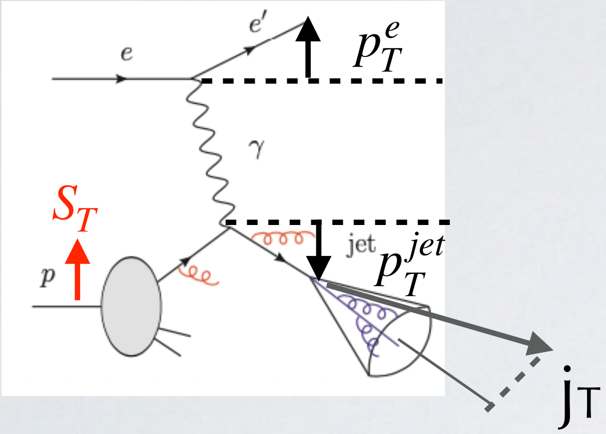
Future: EIC impact

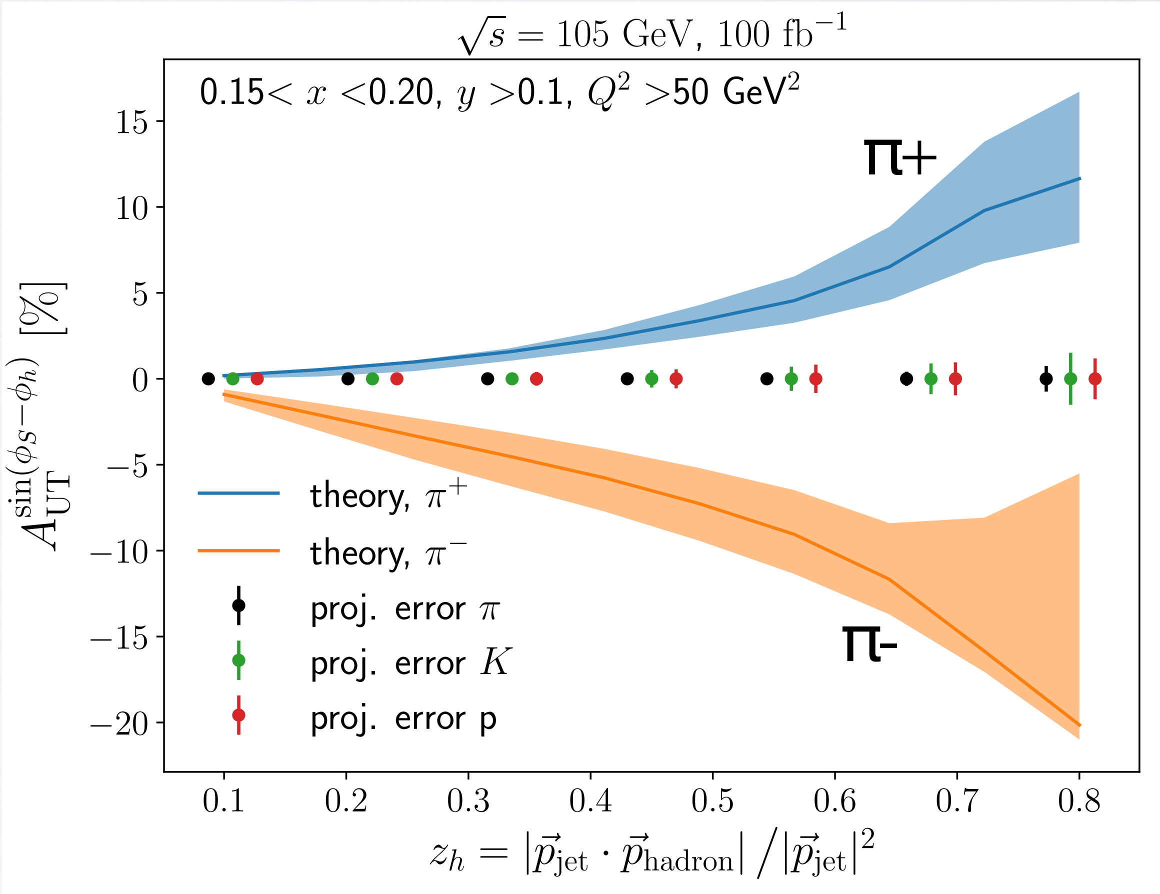
hadron-in-jet Collins effect



electron - hadron-in-jet azimuthal correlations

$|p_T^e + p_T^{\text{jet}}| \ll |p_T^e - p_T^{\text{jet}}|/2 \Rightarrow$ factorization theorem

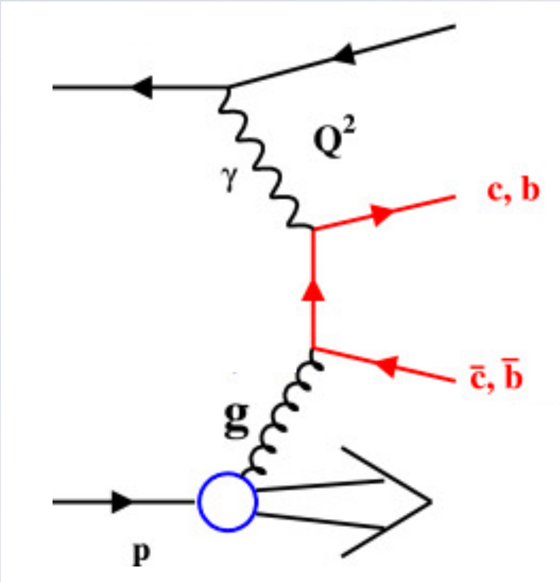
theory uncertainty bands from



Arratia *et al.*, P.R. D**102** (20) 074015

see overview of EIC by Aschenauer
on Tuesday afternoon

Future: EIC new channel



$$e + p^{\uparrow} \rightarrow Q + \bar{Q} + X$$

$$K_{\perp} = (K_{Q\perp} - K_{\bar{Q}\perp})/2$$

$$q_T = K_{Q\perp} + K_{\bar{Q}\perp}$$

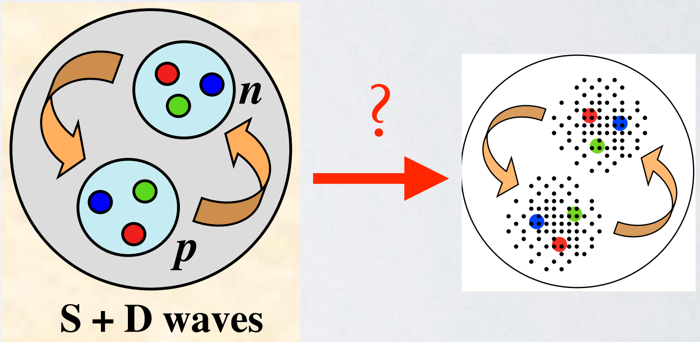
$|q_T| \ll |K_{\perp}| \Rightarrow$ factorization theorem

"Collins" $\sin(\phi_{q_T} + \phi_S)$ asymmetry

$$A_N^{\sin(\phi_S+\phi_T)} = \frac{2(1-y)\, \mathcal{B}_{0T}^{\gamma^* g \to Q\overline{Q}}}{[1+(1-y)^2]\, \mathcal{A}_{U+L}^{\gamma^* g \to Q\overline{Q}} - y^2 \mathcal{A}_{L}^{\gamma^* g \to Q\overline{Q}}} \frac{|\boldsymbol{q}_T|}{M_p} \frac{h_1^g(x, \boldsymbol{q}_T^2)}{f_1^g(x, \boldsymbol{q}_T^2)}$$

Boer *et al.*, JHEP **08** (16) 001

since standard convolution model for deuteron
does not reproduce data for the tensor struct. fnct. $b_1(x)$



Discovering the mechanism for the gluon transversity could help in solving the puzzle…

see talk by Boer on Wednesday

Enjoy the workshop