Transversity from Dihadron Transverse-Spin Observables

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Pitonyak, Cocuzza, Metz, Prokudin, NS, `24 (PRL)
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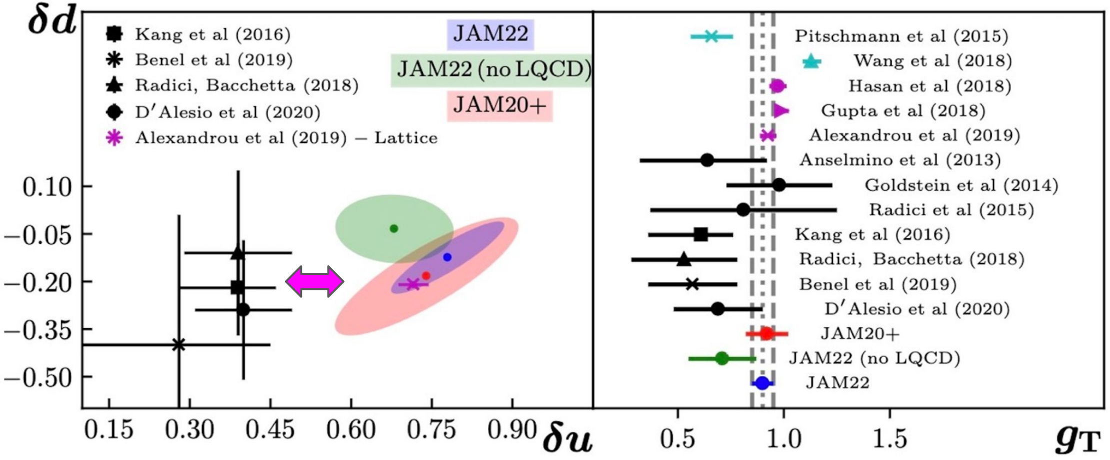
Transversity,
Trieste IT Jun 3 2024

Motivations

Gamberg, Malda, Miller, Pitonyak, Prokudin, NS, `22 (PRD)



- TMD+CT3 pheno in tension with other analyzes (delta u)
- Radici, Bacchetta, and Benel, Courtoy, Ferro-Hernandez used collinear di-hadron observables to extract tensor charges
- New fresh look at collinear di-hadron pheno

Observable	Reactions	Non-Perturbative Function(s)	χ^2/npts	Exp. Refs.
$A_{UT}^{\sin(\phi_h-\phi_S)}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$182.9/166=1.10$	[22, 24, 27]
$A_{UT}^{\sin(\phi_h+\phi_S)}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,\vec{k}_T^2), H_1^\perp(z,z^2\vec{p}_T^2)$	$181.0/166=1.09$	[22, 24, 27]
${}^*A_{UT}^{\sin\phi_S}$	$e+p^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x), \tilde{H}(z)$	$18.6/36=0.52$	[22, 24, 27]
$A_{UC/UL}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^\perp(z,z^2\vec{p}_T^2)$	$154.9/176=0.88$	[29–32]
$A_{T,\mu^+\mu^-}^{\sin\phi_S}$	$\pi^- + p^\uparrow \to \mu^+\mu^- + X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$6.92/12=0.58$	[34]
$A_N^{W/Z}$	$p^\uparrow + p \to (W^+,W^-,Z)+X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$30.8/17=1.81$	[35]
A_N^π	$p^\uparrow + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x)=\frac{1}{\pi}f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z), \tilde{H}(z)$	$70.4/60=1.17$	[7, 9, 10, 13]
Lattice g_T	——	$h_1(x)$	$1.82/1=1.82$	[89]

Analysis setup

Collaboration	References	Observable	Process	Nonperturbative function(s)
Belle	[64]	$d\sigma/dz\,dM_h$	$e^+e^- \to (\pi^+\pi^-)X$	D_1
Belle	[112]	$A^{e^+e^-}$	$e^+e^- \to (\pi^+\pi^-)(\pi^+\pi^-)X$	$D_1, H_1^{\sphericalangle}$
HERMES	[118]	A_{UT}^{SIDIS}	$ep^\uparrow \to e'(\pi^+\pi^-)X$	$D_1, H_1^{\sphericalangle}, h_1$
COMPASS	[117]	A_{UT}^{SIDIS}	$\mu\{p,D\}^\uparrow \to \mu'(\pi^+\pi^-)X$	$D_1, H_1^{\sphericalangle}, h_1$
STAR	[97,121]	A_{UT}^{pp}	$p^\uparrow p \to (\pi^+\pi^-)X$	$D_1, H_1^{\sphericalangle}, h_1$
ETMC	[77]	$\delta u,\ \delta d$	LQCD	h_1
PNDME	[71]	$\delta u,\ \delta d$	LQCD	h_1

$$\frac{d\sigma}{dz\,dM_h} = \frac{4\pi N_c \alpha_{\mathrm{em}}^2}{3s} \sum_q \bar{e}_q^2 D_1^q(z, M_h),$$

$h_1(x;\mu^2)$ Transversity (TPDF)

$H_1^{\sphericalangle}(z, M_h; \mu^2)$ Interference FF (IFF)

$D_1(z, M_h; \mu^2)$ Dihadron FF (DiFFs)

$$A^{e^+e^-}(z, M_h, \bar{z}, \bar{M}_h) = \frac{\sin^2\theta \sum_q e_q^2 H_1^{\sphericalangle,q}(z, M_h) H_1^{\sphericalangle,\bar{q}}(\bar{z}, \bar{M}_h)}{(1+\cos^2\theta)\sum_q e_q^2 D_1^q(z, M_h) D_1^{\bar{q}}(\bar{z}, \bar{M}_h)}$$

$$A_{UT}^{\mathrm{SIDIS}} = c(y) \frac{\sum_q e_q^2 h_1^q(x) H_1^{\sphericalangle,q}(z, M_h)}{\sum_q e_q^2 f_1^q(x) D_1^q(z, M_h)}$$

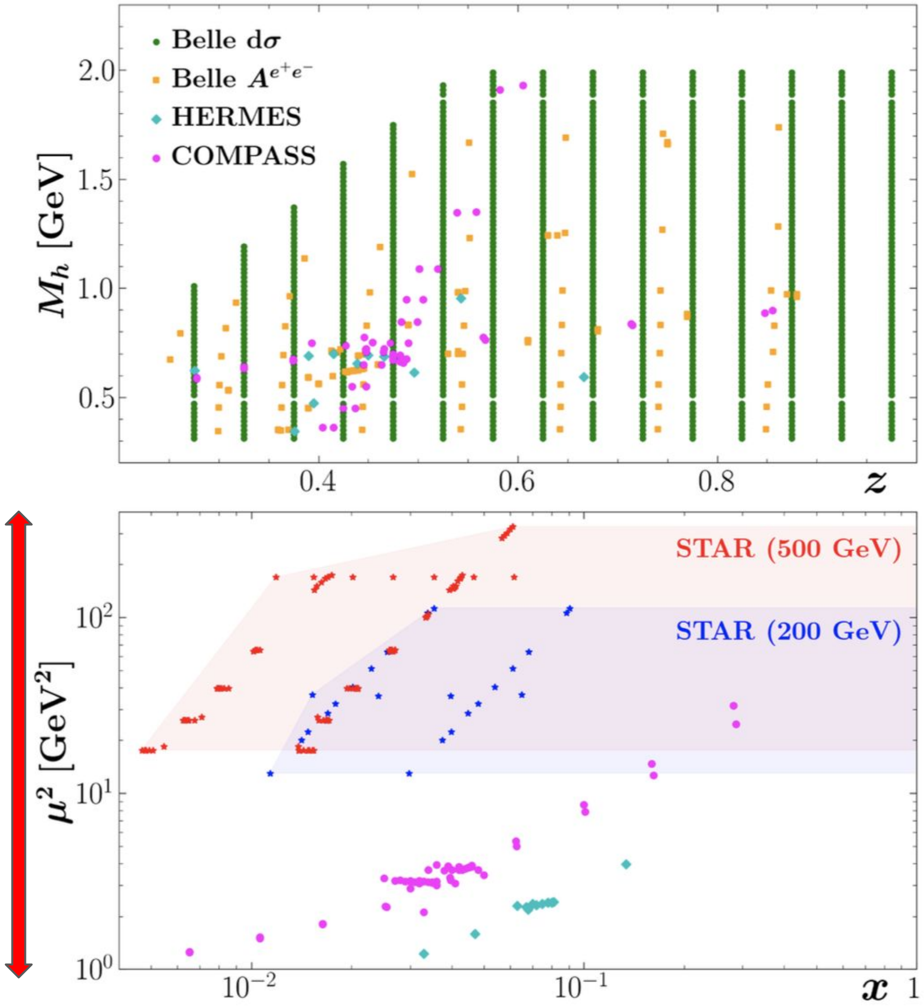
$$A_{UT}^{pp} = \frac{2P_{hT} \sum_i \sum_{a,b,c,d} \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 \frac{dx_b}{z} h_1^a(x_a) f_1^b(x_b) \frac{d\Delta\hat{\sigma}_{a^\uparrow b \to c^\uparrow d}}{d\hat{t}} H_1^{\sphericalangle,c}(z, M_h)}{2P_{hT} \sum_i \sum_{a,b,c,d} \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 \frac{dx_b}{z} f_1^a(x_a) f_1^b(x_b) \frac{d\hat{\sigma}_{ab \to cd}}{d\hat{t}} D_1^c(z, M_h)}$$

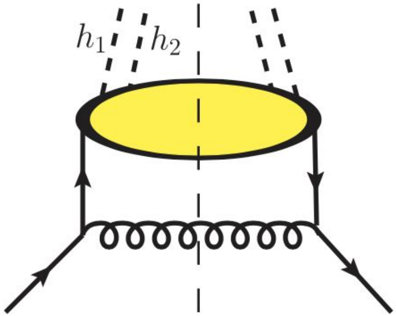
$$h_1(x;\mu^2)$$

$$H_1^{\sphericalangle}(z, M_h;\mu^2)$$

$$D_1(z, M_h;\mu^2)$$

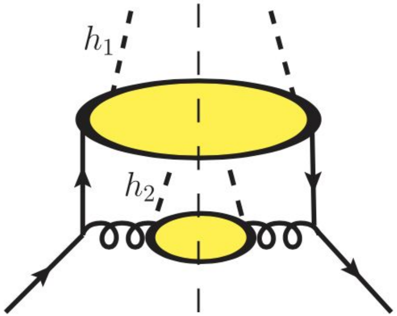
Need to address scale dependence





(a)

homogeneous



(b)

inhomogeneous

- We work at LO in pQCD hence we only consider homogeneous evolution
- The scale dependence obeys standard timelike DGLAP evolution
- DGLAP only changes the z dependence

$$\frac{\partial D_1^{h_1 h_2/i}(z, M_h; \mu^2)}{\partial \mu^2} = \sum_j \int_z^1 \frac{dw}{w} D_1^{h_1 h_2/i}\left(\frac{z}{w}, M_h; \mu^2\right) P_{i \to j}(w)$$

Same for $H_1^{\sphericalangle}(z, M_h; \mu^2)$ with transversely polarized splitting kernels

Model assumptions in TPDF $h_1(x;\mu_0^2)$

- Traditional parametrization

$$h_1^i(x) = \frac{N^i}{\mathcal{M}^i} x^{\alpha^i}(1-x)^{\beta^i}(1+\gamma^i\sqrt{x}+\delta^i x)$$

- Reconstructed flavors

$$h_1^{u_v} \quad h_1^{d_v} \quad h_1^{\bar{u}_v} \quad h_1^{\bar{d}_v}$$

- Flavor assumptions (due to lack of observables)

$$h_1^{\bar{u}} = -h_1^{\bar{d}}$$

Expectations from large Nc limit

- Impose Soffer bounds

$$|h_1^i(x;\mu)| \le \frac{1}{2}[f_1^i(x;\mu) + g_1^i(x;\mu)]$$

- Impose small-x constraints (Kovchegov, Sievert `19)

$$\alpha^i \xrightarrow{x\to 0} 1 - 2\sqrt{\frac{\alpha_s N_c}{2\pi}}. = 0.170 \pm 0.085$$

Added 50% conservative uncertainties

Model assumptions in DiFFs

$$D_1^{\pi^+\pi^-/i}(z, M_h; \mu_0^2)$$

- Mh grid based parametrization

$$D_1^i(z, \mathrm{M}_h^{i,j}) = \sum_{k=1,2,3} \frac{N_{jk}^i}{\mathcal{M}_{jk}^i} z^{\alpha_{jk}^i}(1-z)^{\beta_{jk}^i}$$

- Reconstructed flavors

$$D_1^u \quad D_1^s \quad D_1^c \quad D_1^b \quad D_1^g$$

- Flavor assumptions

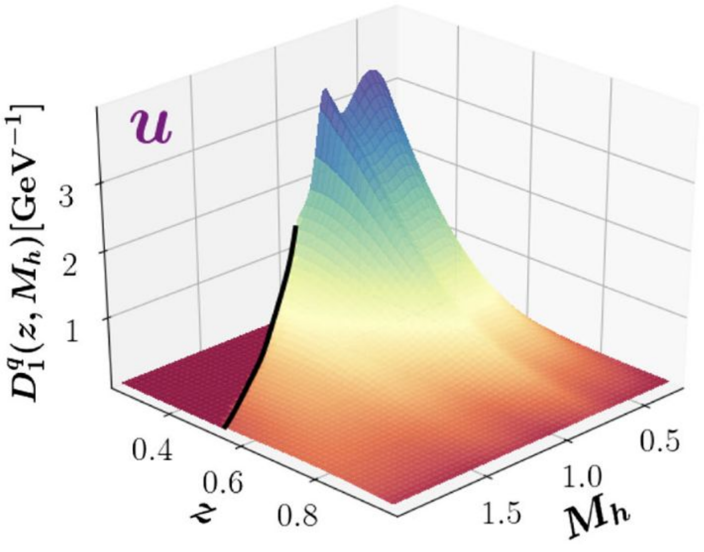
$$D_1^u = D_1^d = D_1^{\bar{u}} = D_1^{\bar{d}},$$

$$D_1^s = D_1^{\bar{s}}, \qquad D_1^c = D_1^{\bar{c}}, \qquad D_1^b = D_1^{\bar{b}},$$

- Flavor separation using Pythia 6&8

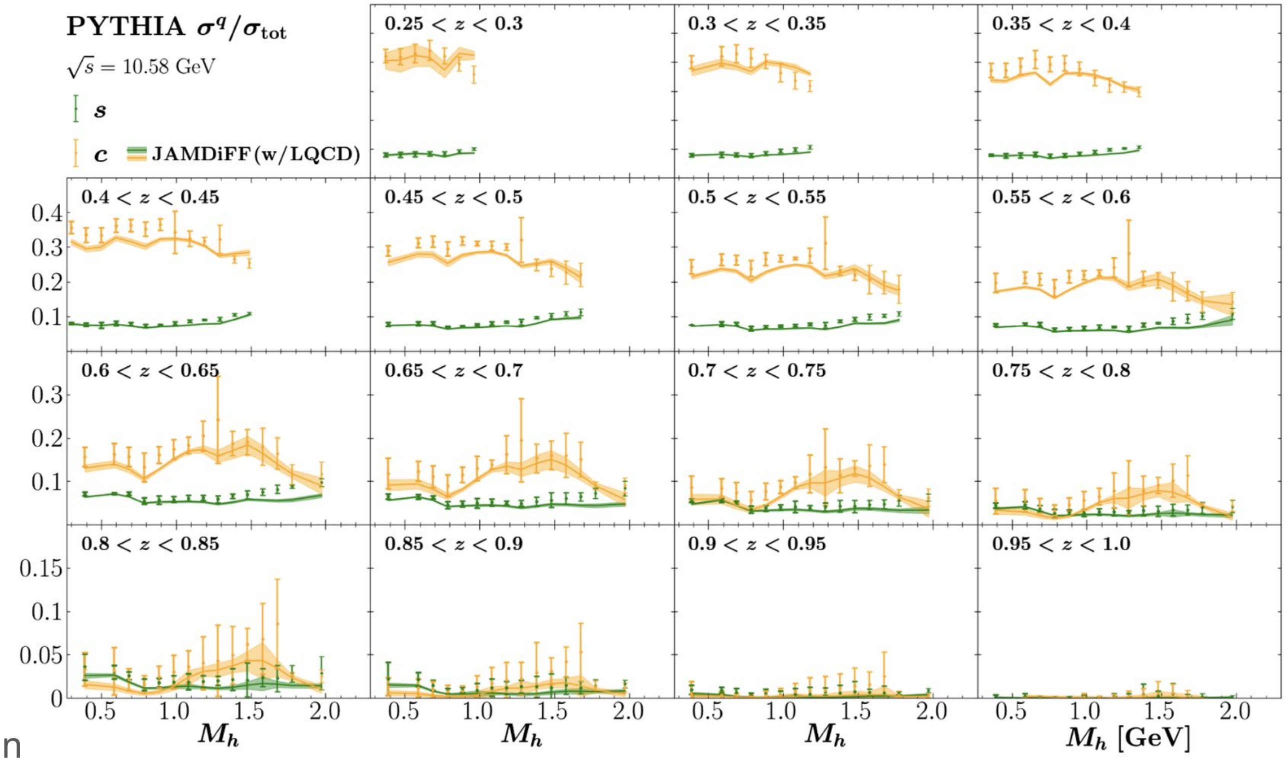
$$\frac{\sigma^{q=s,c,b}}{\sigma^{\text{tot}}} \Rightarrow$$

Generate Pythia data and assign uncertainties from various tunes



- Impose positivity

$$D_1^i(z, M_h; \mu) > 0,$$



- Error bars on Pythia stemming from different tunes.
- Simulated Pythia data at different energies to constrain the gluon DiFF Q=10.58 - 91.19 GeV

Model assumptions in IFFs

$$H_1^{\sphericalangle,\pi^+\pi^-/i}(z, M_h; \mu_0^2)$$

- Mh grid based parametrization

$$H_1^{\sphericalangle,u}(z, \mathrm{M}_h^{u,j}) = \sum_{k=1,2} \frac{N_{jk}^u}{\mathcal{M}_{jk}^u} z^{\alpha_{jk}^u} (1-z)^{\beta_{jk}^u}$$

- Reconstructed flavors

$$H_1^{\sphericalangle,u}$$

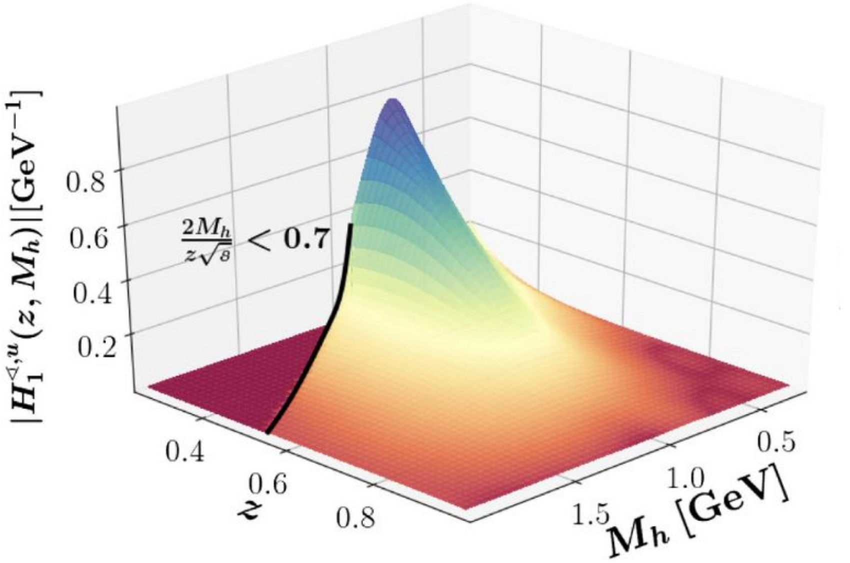
- Flavor assumptions

$$H_1^{\sphericalangle,u} = -H_1^{\sphericalangle,d} = -H_1^{\sphericalangle,\bar{u}} = H_1^{\sphericalangle,\bar{d}},$$

$$H_1^{\sphericalangle,s} = H_1^{\sphericalangle,\bar{s}} = H_1^{\sphericalangle,c} = H_1^{\sphericalangle,\bar{c}} = H_1^{\sphericalangle,b} = H_1^{\sphericalangle,\bar{b}} = 0.$$

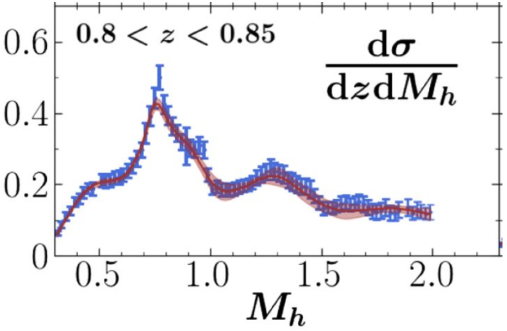
- Impose positivity bounds

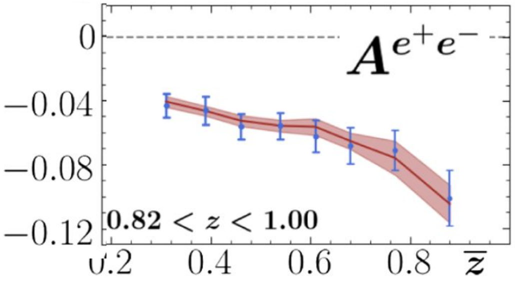
$$|H_1^{\sphericalangle,i}(z, M_h; \mu)| < D_1^i(z, M_h; \mu)$$

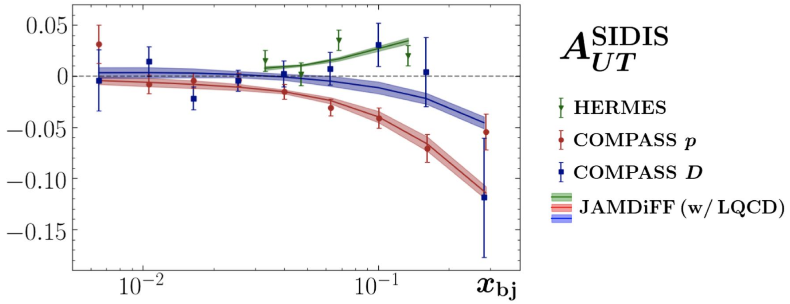


The results

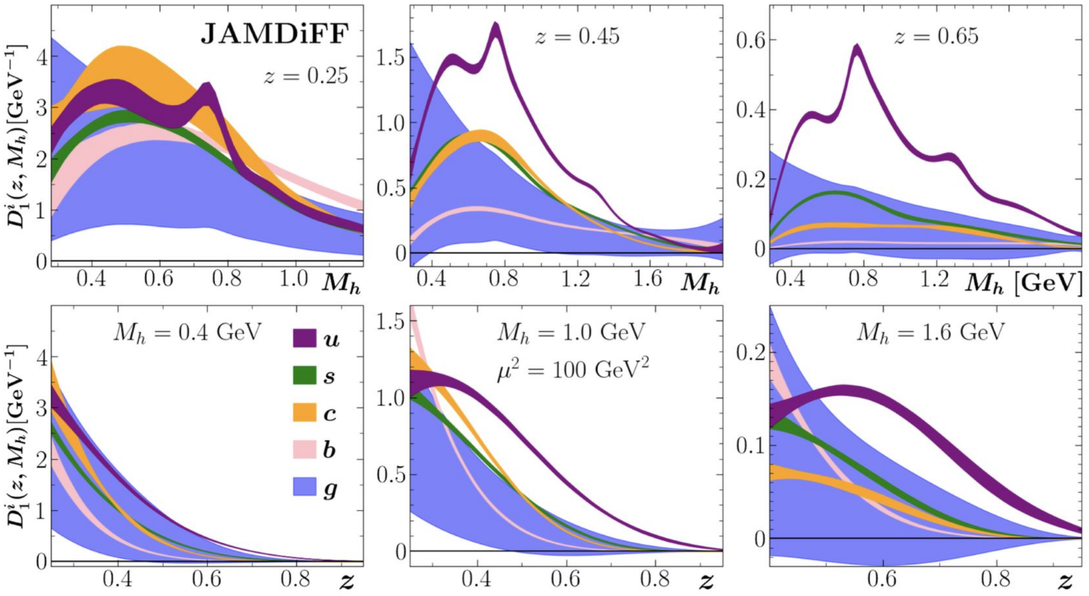
			$\chi^2_{\rm red}$		
			JAMDiFF		
Experiment	Binning	$N_{\rm dat}$	**(w/ LQCD)**	**(no LQCD)**	(SIDIS only)
Belle (cross section) [64]	z, M_h	1094	1.01	1.01	1.01
Belle (Artru-Collins) [112]	z, M_h	55	1.27	1.24	1.28
	$M_h, \overline{M}_h$	64	0.60	0.60	0.60
	$z, \bar{z}$	64	0.42	0.42	0.41
HERMES [118]	$x_{\rm bj}$	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) [117]	$x_{\rm bj}$	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) [117]	$x_{\rm bj}$	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 [121] $\sqrt{s} = 200$ 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 [97] $\sqrt{s} = 500$ 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 $\chi^2_{\rm red}$ ($N_{\rm dat}$)			**1.01** (1475)	**0.98** (1471)	0.96 (1341)

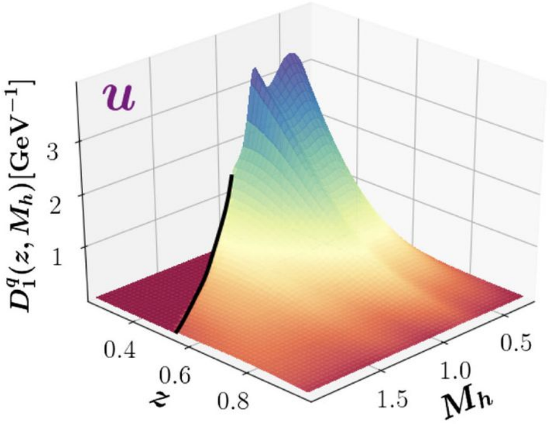




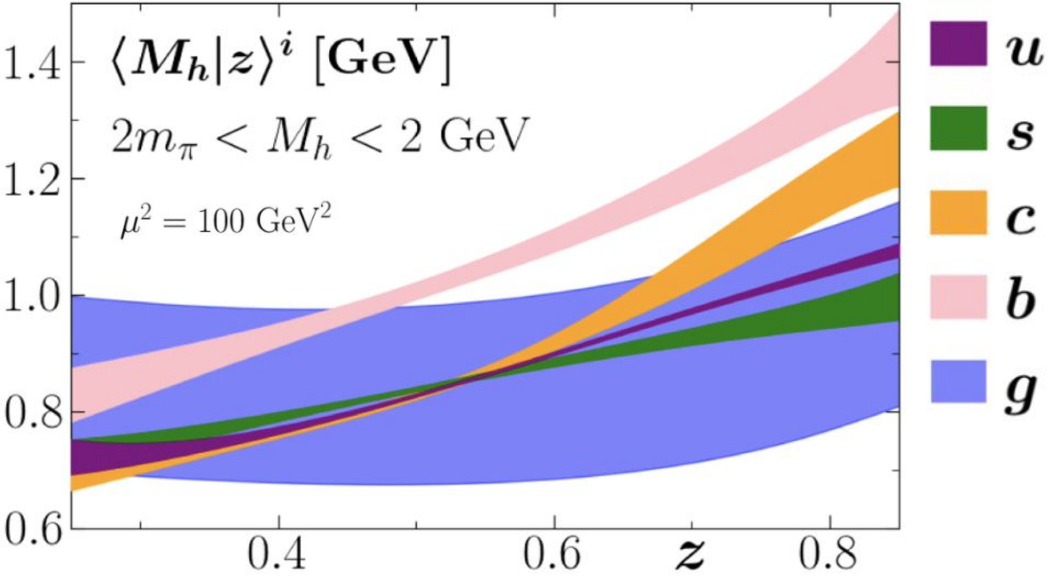


Reconstructed DiFFs





- More di-hadron pairs are produced at small z
- Clear reconstruction of the resonances
- DiFFs trend towards zero as we approach the physical threshold of 2mpi
- DiFFs goes to zero at large Mh as wide angle radiation is suppressed
- The gluon DiFF is not fully consistent with zero and more realistic than what was done in the past.

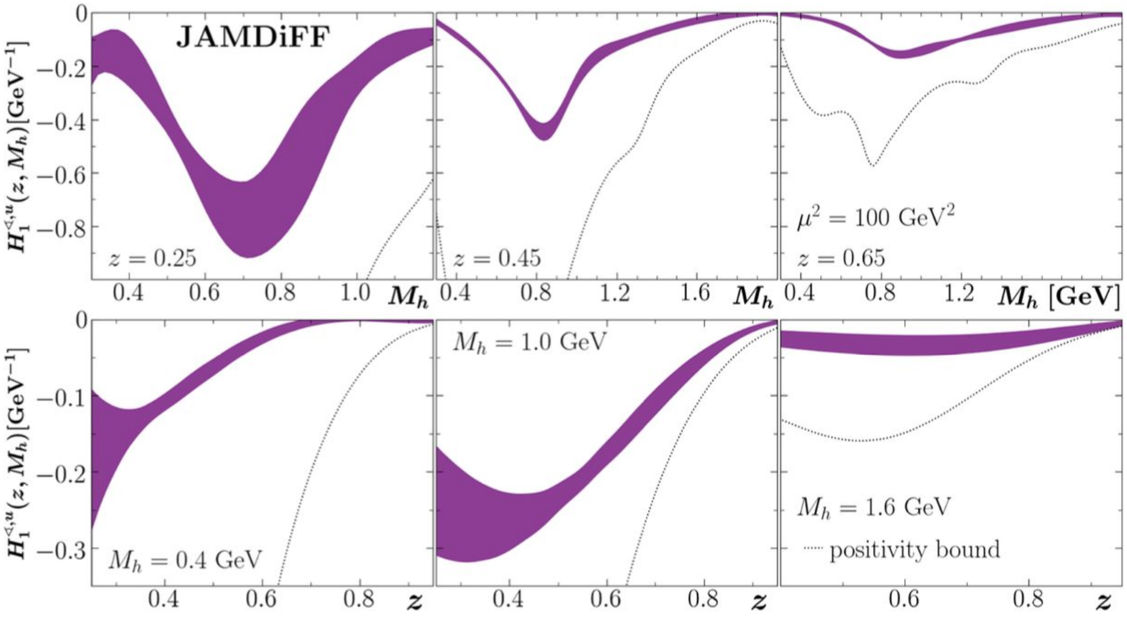


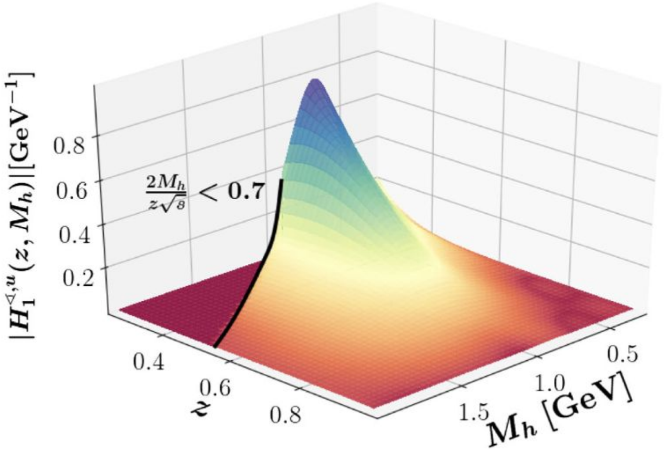
$$z = z_1 + z_2$$
$$M_h^2 = (P_{\pi^+} + P_{\pi^-})^2$$

$$\langle M_h|z\rangle^i = \frac{\int \mathrm{d}M_h\, M_h\, D_1^i(z, M_h)}{\int \mathrm{d}M_h\, D_1^i(z, M_h)}$$

- As expected, the invariant mass of the di-hadron pairs grows as z grows. Quark mass dependence becomes more important at large z
- At small z, large production of di-hadron pairs occurs, and quark masses does not influence the values of <Mh|z>
- Exception is the b-quark that due to its large mass generates larger Mh values

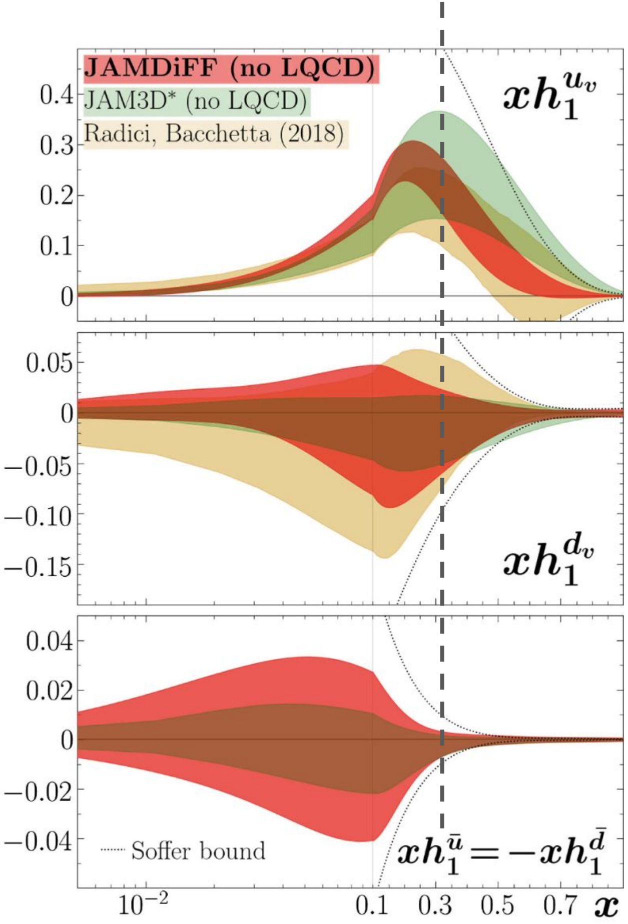
Reconstructed IFFs



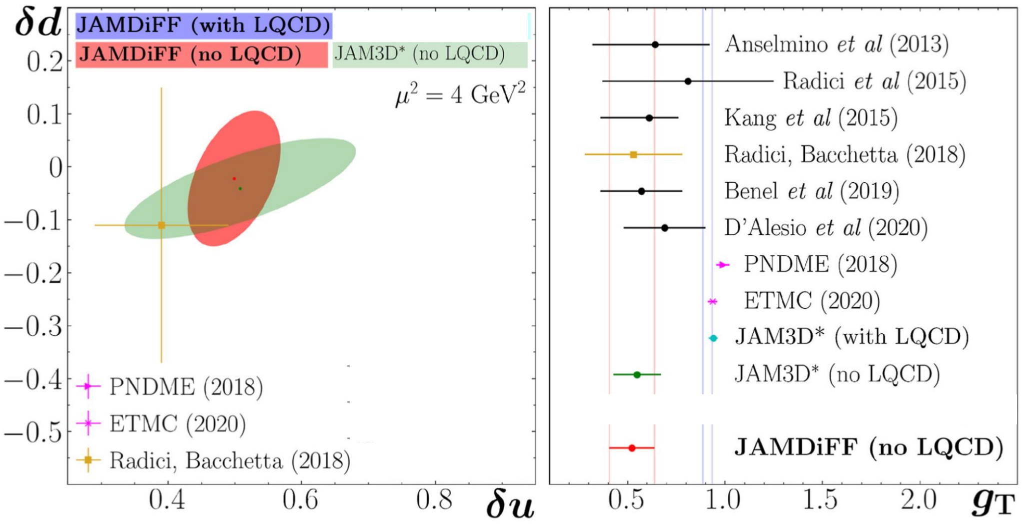


- Magnitude of IFF is proportional to DiFFs
- Marginal impact by positivity constraints
- The sign is not determined by the experimental data.

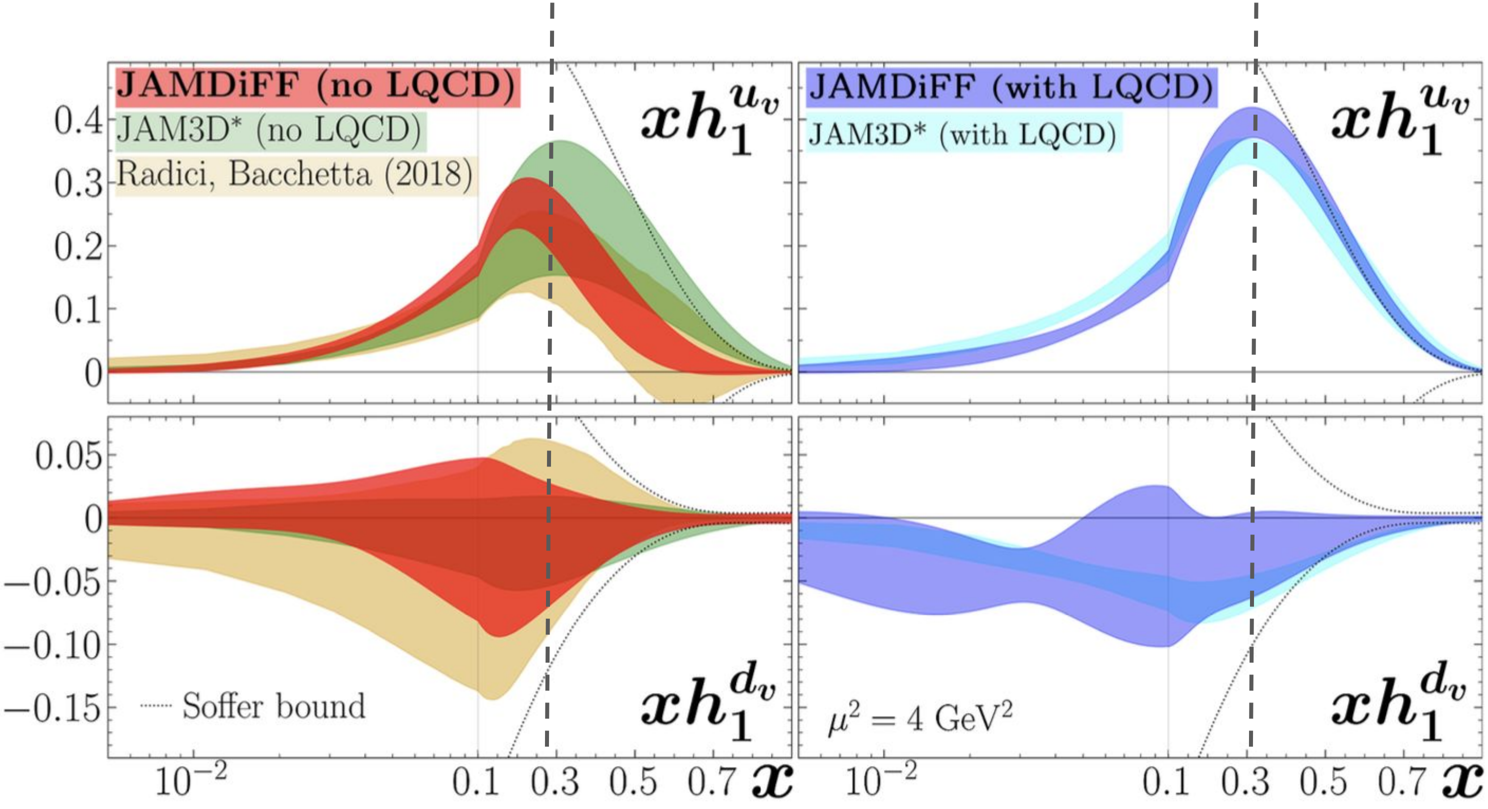
Reconstructed TPDF



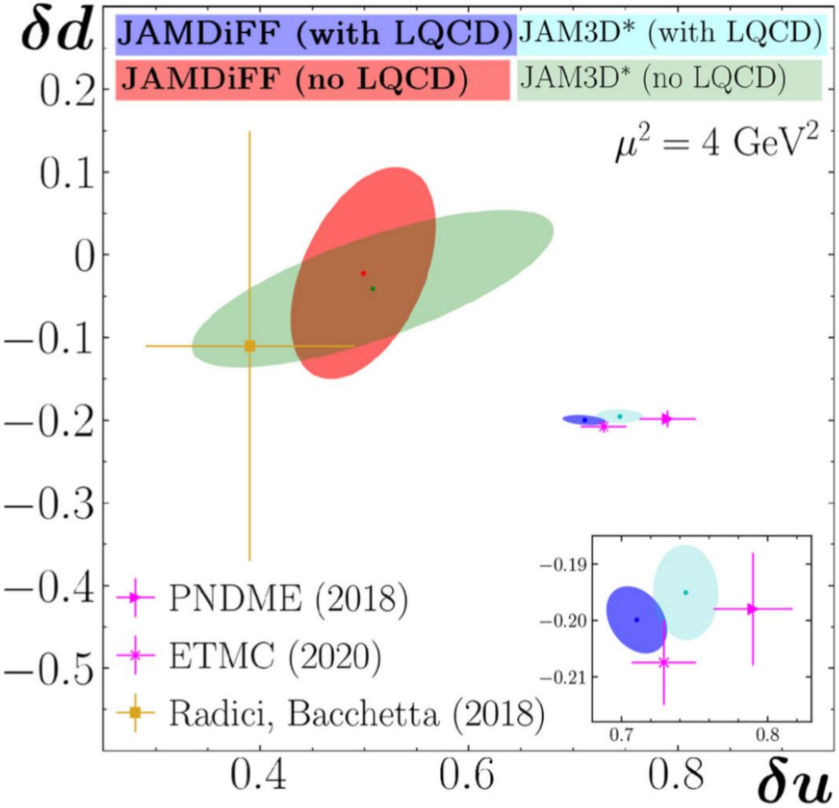
- Point-by-point in x constraints from data ends around x~0.3.
- Below x<0.3, the reconstructed transversity PDFs are consistent with Radici et al and TMD+CT3 (JAM3D) results.
- Beyond x>0.3, only the u quark PDF has non-vanishing signal with some differences wrt JAM3D*
- JAM3D* includes antiquarks and small x constraints



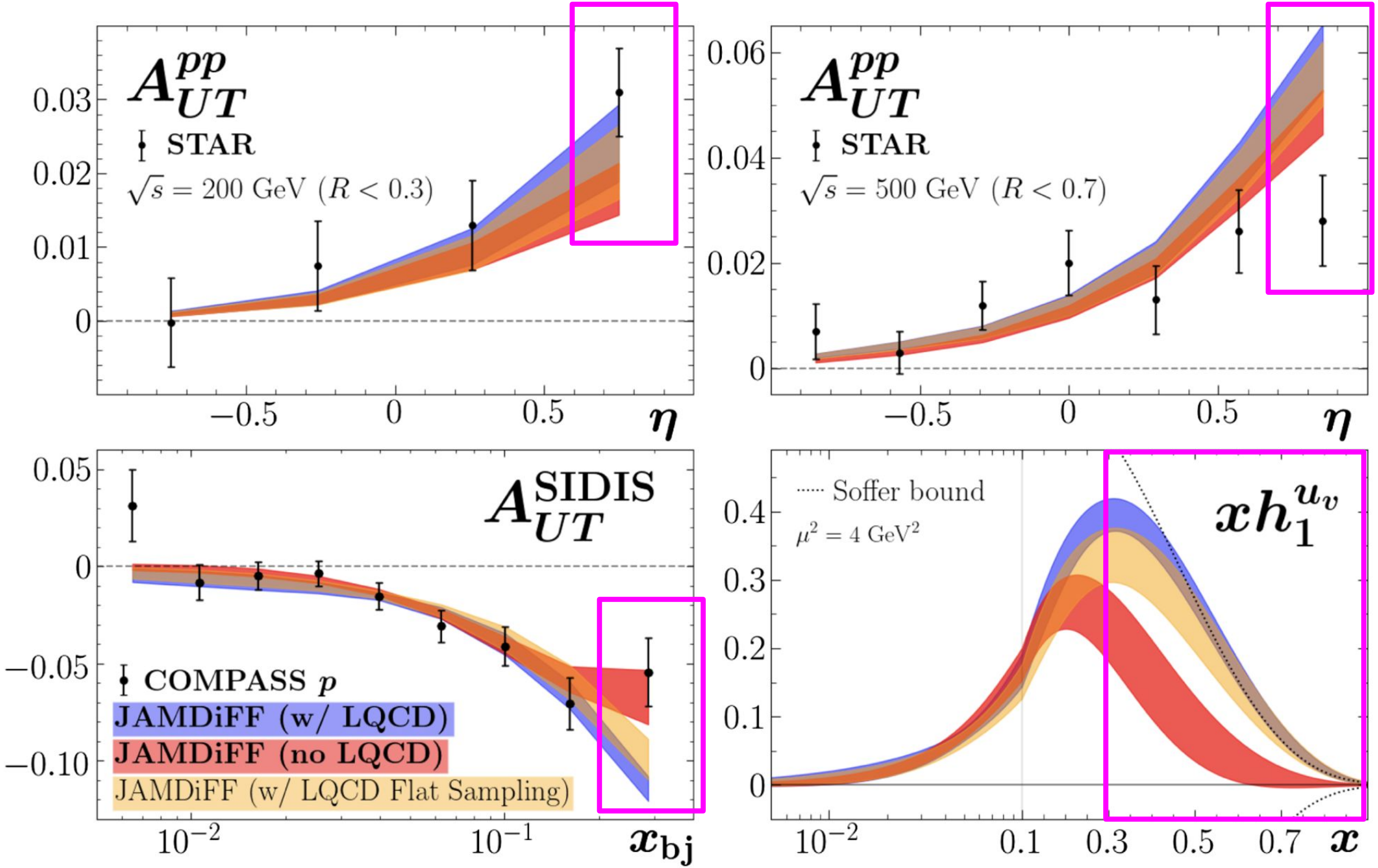
Reconstructed TPDF with LQCD



Reconstructed TPDF with LQCD



	χ^2_{red}	
	JAMDiFF	
Experiment	**(w/ LQCD)**	**(no LQCD)**
Belle (cross section) [64]	1.01	1.01
	1.27	1.24
Belle (Artru-Collins) [112]	0.60	0.60
	0.42	0.42
	1.77	1.70
HERMES [118]	0.41	0.42
	1.20	1.17
	1.98	0.65
COMPASS (p) [117]	0.92	0.94
	0.77	0.60
	1.37	1.42
COMPASS (D) [117]	0.45	0.37
	0.50	0.46
	2.57	2.56
STAR [121]	1.34	1.55
$\sqrt{s} = 200$ GeV	0.98	1.00
$R < 0.3$	1.73	1.74
	0.52	1.46
	1.30	1.10
STAR [97]	0.81	0.78
$\sqrt{s} = 500$ GeV	1.09	1.07
$R < 0.7$	2.97	1.83
ETMC δu [77]	0.71	
ETMC δd [77]	1.02	
PNDME δu [71]	8.68	
PNDME δd [71]	0.04	
Total χ^2_{red} (N_{dat})	**1.01** (1475)	**0.98** (1471)



A_{UT}^{pp}
STAR
$\sqrt{s} = 200$ GeV $(R < 0.3)$
η
A_{UT}^{pp}
STAR
$\sqrt{s} = 500$ GeV $(R < 0.7)$
η
A_{UT}^{SIDIS}
COMPASS p
JAMDiFF (w/ LQCD)
JAMDiFF (no LQCD)
JAMDiFF (w/ LQCD Flat Sampling)
x_{bj}
Soffer bound
$\mu^2 = 4$ GeV^2
$xh_1^{u_v}$
x

Summary & outlook

- At present there is no significant tension between LQCD and experimental reconstruction of nucleon tensor charges
- Different reconstructions of tensor charges are mostly driven by large x data
- More high x data is needed to reach accurate reconstruction of TPDF above x>0.3
- Inclusion of LQCD calculations as priors are very informative/useful in QCD phenomenology
- The JAMDiFF results and JAM3D* results are very similar and one can perform a combined analysis (TMD+CT3 & DiFF) **->** indicates possible **universal nature of all SSAs and nucleon tensor charges**