First global extraction of the worm-gear TMD g_{1T}

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SPIN2021

Matsue, Japan

Outline

- **Introduction**
- **Theoretical predictions**
- **Overview of fitting procedure: Monte-Carlo technique**
- **Final results and comparison with theoretical predictions**
- **Summary/ Outlook**

Introduction

Quark polarization →

Nucleon polarization ↓

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

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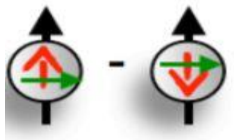
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

"Worm-gear TMD": One of the least known TMDs



Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Theoretical predictions

1.

2.

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1. Large $\mathrm{N_c}$ analysis: (Pobylitsa, hep-ph/ 0301236)

$$g_{1T}^{u}(x,\vec{k}_{\perp}^{2}) = - g_{1T}^{d}(x,\vec{k}_{\perp}^{2}) + 1/N_c\text{-suppressed}$$

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2. Wandzura-Wilczek-type (WW-type) relation: (Avakian et. al., 0709.3253, Kanazawa et. al., 1512.07233, …)

$$g_{1T}^{(1)q}(x) \equiv \int d^2\vec{k}_\perp \left(\frac{k_\perp^2}{2M^2}\right) g_{1T}^{q}(x,\vec{k}_\perp^2) \overset{\text{EOM}}{=} x\int_x^1 \frac{dy}{y} g_1^q(y) + x\,\tilde{g}_T^q(x)$$

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Semi-inclusive Deep Inelastic Scattering: $\ell(l) + N(P,S) \rightarrow \ell'(l') + h(P_h) + X$

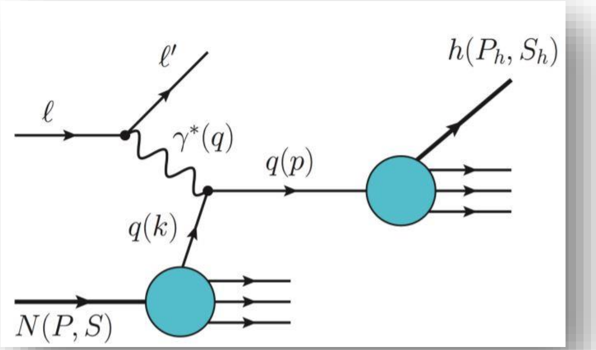

Fig. courtesy:
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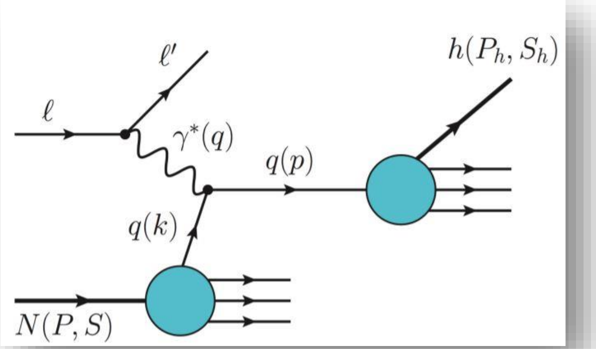

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Model-independent decomposition of cross-section: **(Bacchetta et. al. 2007, …)**

$$\frac{d\sigma}{dx\, dy\, d\phi_S\, dz_h\, d\phi_h\, dP_{hT}^2} = \frac{\alpha_{\rm em}^2}{x\, y\, Q^2}\left\{\left(1 - y + \frac{1}{2}y^2\right) F_{UU} + \lambda_l\, |\vec{S}_\perp|\, y\left(1 - \frac{1}{2}y\right)\cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \ldots\right\}$$

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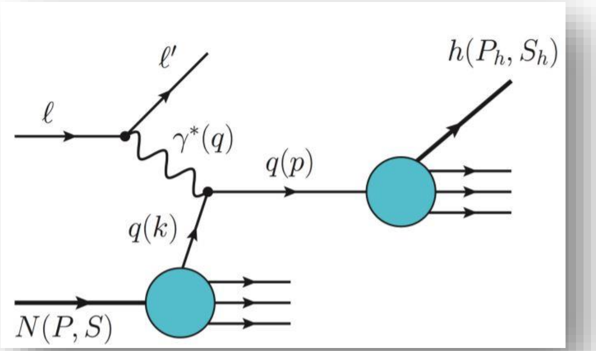

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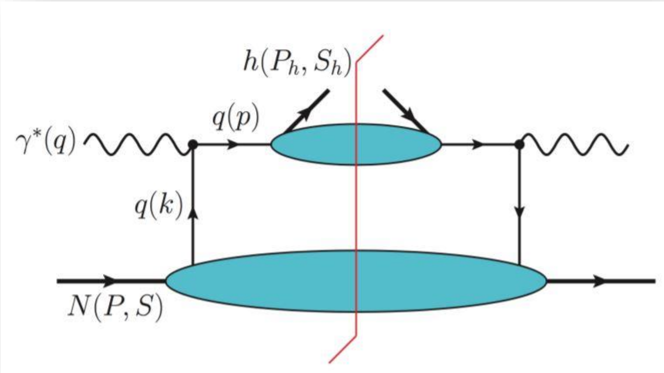

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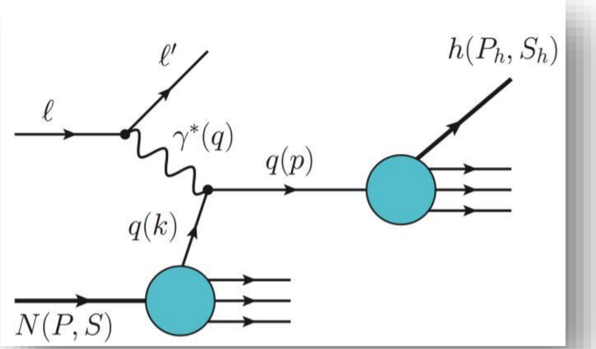

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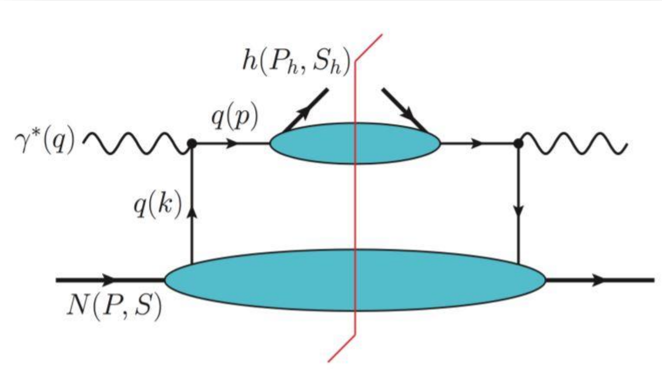

Connection between structure functions and TMDs: (Bacchetta et. al. 2007, …)

$$F_{UU} = C\left[f_1(x,\vec{k}_\perp^2)\, D_1(z,\vec{P}_\perp^2)\right] \qquad F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\vec{P}_{hT}\cdot\vec{k}_\perp}{|\vec{P}_{hT}|M}\, g_{1T}(x,\vec{k}_\perp^2)\, D_1(z,\vec{P}_\perp^2)\right]$$

$$C\Big[w\, f\, D\Big] = x\sum_q e_q^2 \int d^2\vec{k}_\perp \int d^2\vec{P}_\perp\, \delta^{(2)}\big(z\vec{k}_\perp + \vec{P}_\perp - \vec{P}_{hT}\big)\, w(\vec{k}_\perp,\vec{P}_\perp)\, f^q(x,\vec{k}_\perp^2)\, D^q(z,\vec{P}_\perp^2)$$

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$$g_{1T}^{q}(x,\vec{k}_{\perp}^{2},Q^2) = g_{1T}^{(1)q}(x,Q^2)\,\frac{2M_N^2\,e^{-\frac{\vec{k}_{\perp}^{2}}{\pi\langle k_{\perp}^{2}\rangle}}}{\pi\big(\langle k_{\perp}^{2}\rangle\big)^2}$$

$q = (u,d)$

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$$g_{1T}^{(1)}(x, Q^2) = \frac{n}{\int_0^1 dy\, y^{\alpha+1}(1-y)^{\beta} f_1(y, Q_0^2)}\, x^{\alpha}(1-x)^{\beta} f_1(x, Q^2)$$

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- **Fix TMD width:** $\dfrac{\langle k_\perp^2\rangle\big|_{g_1}}{\langle k_\perp^2\rangle\big|_{f_1}} \approx 0.76$

Lattice QCD Hagler et. al., hep-lat/ 0908.1283 (See also Bastami et. al., 1807.10606 that uses this idea to get $\langle k_\perp^2\rangle\big|_{g_{1T}}$)

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$$\approx \frac{\langle k_\perp^2\rangle\big|_{g_{1T}}}{\langle k_\perp^2\rangle\big|_{f_1}} \xrightarrow{\langle k_\perp^2\rangle|_{f_1} = 0.53} \therefore \langle k_\perp^2\rangle\big|_{g_{1T}} \approx 0.40$$

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Helicity & unpolarized PDFs have similar large-x behavior

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3 free parameters:

$$n^u, \quad n^d, \quad \alpha$$

where, $g_{1T}^{(1)}(x, Q$ ... $x)^\beta f_1(x, Q^2)$

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$$g_{1T}^{(1)q}(x) \overset{x\to 1}{\approx} (1-x) f_1^q(x) \longrightarrow \therefore \beta^u = \beta^d = 1$$

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SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Experimental data

Dataset	Target	Identified hadron	No. of points
HERMES	p	π^+	26
Airapetian et. al., arXiv: 2007.07755		π^-	26
		π^0	8
COMPASS	p	$h^+ \approx (\pi^+, \mathrm{K}^+)$	33
Parsamyan, PoS: QCDEV2017		$h^- \approx (\pi^-, \mathrm{K}^-)$	31
JLab	n	π^+	2
Huang, arXiv: 1108.0489		π^-	2

Cut:

$$\frac{q_T}{Q} < 0.50$$

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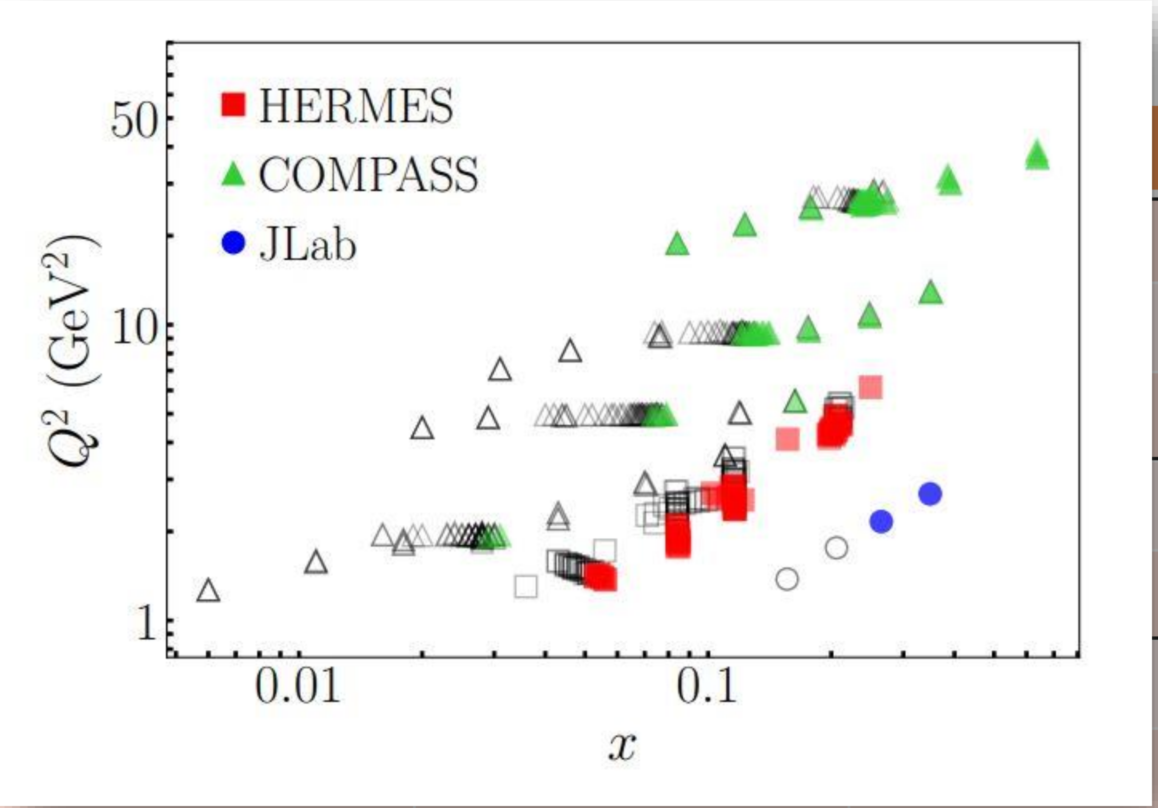
SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Experimental data

Dataset
HERMES
Airapetian et. al., arXiv: 2007.07755
COMPASS
Parsamyan, PoS: QCDEV2017
JLab
Huang, arXiv: 1108.0489



Cut:

$$\frac{q_T}{Q} < 0.50$$

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Fitting procedure: Monte-Carlo technique

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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Fitting procedure: Monte-Carlo technique

Theory

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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Theory

Fit to exp. data

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Fitting procedure: Monte-Carlo technique

Theory

Fit to exp. data

Minimize:

$$\chi^2 = \sum_{\mathrm{H+C+J}} \frac{(\mathrm{exp.\,data} - \mathrm{theory})^2}{(\mathrm{exp.\,error})^2}$$

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Fitting procedure: Monte-Carlo technique

Theory

Fit to exp. data

Minimize weighted chi-squared:

$$\chi^2 = \sum_{\text{H+C}} \frac{(\text{exp. data} - \text{theory})^2}{(\text{exp. error})^2} + w \sum_{\text{J}} \frac{(\text{exp. data} - \text{theory})^2}{(\text{exp. error})^2}$$

(Echevarria, Kang, Terry, arXiv: 2009.10710)

Give JLab data weight similar to HERMES & COMPASS data

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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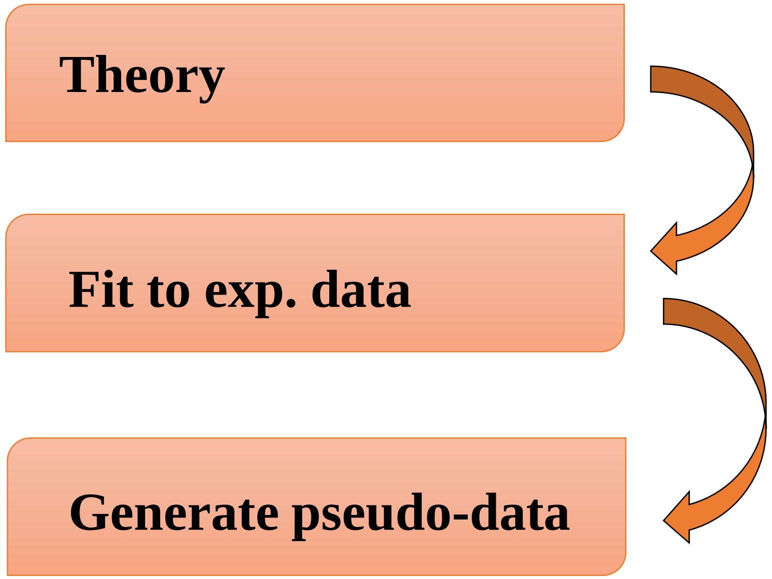
Fitting procedure: Monte-Carlo technique



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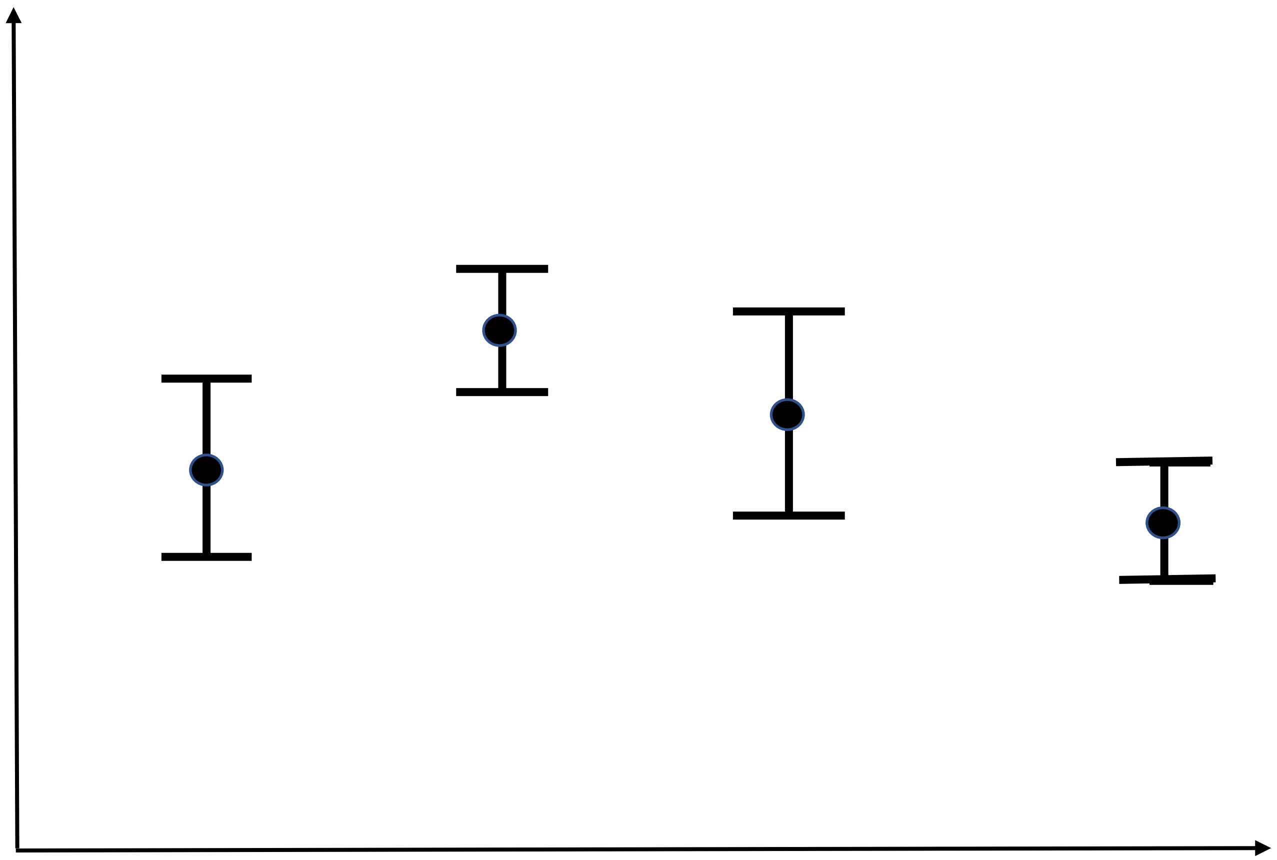
Fitting procedure: Monte-Carlo technique

Theory

Fit to exp. data

Generate pseudo-data



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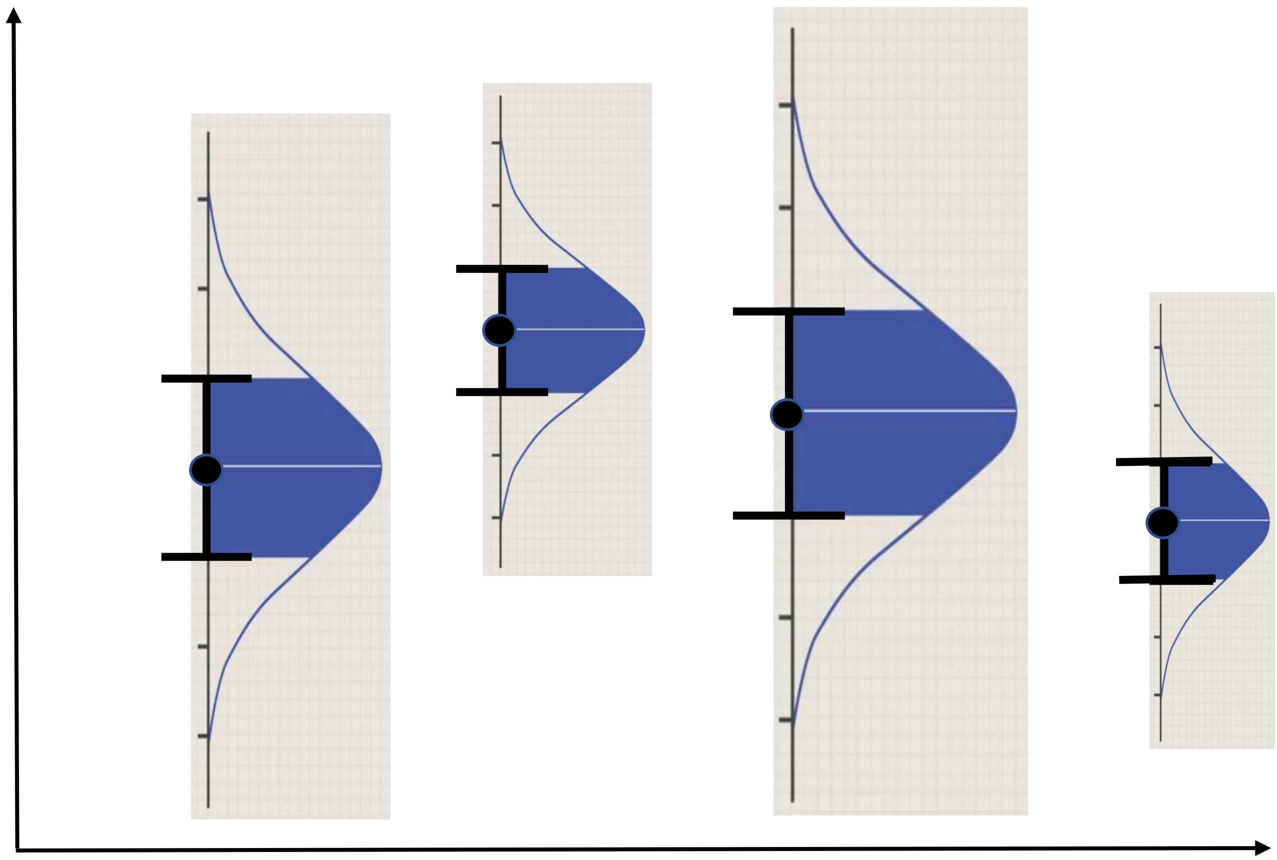

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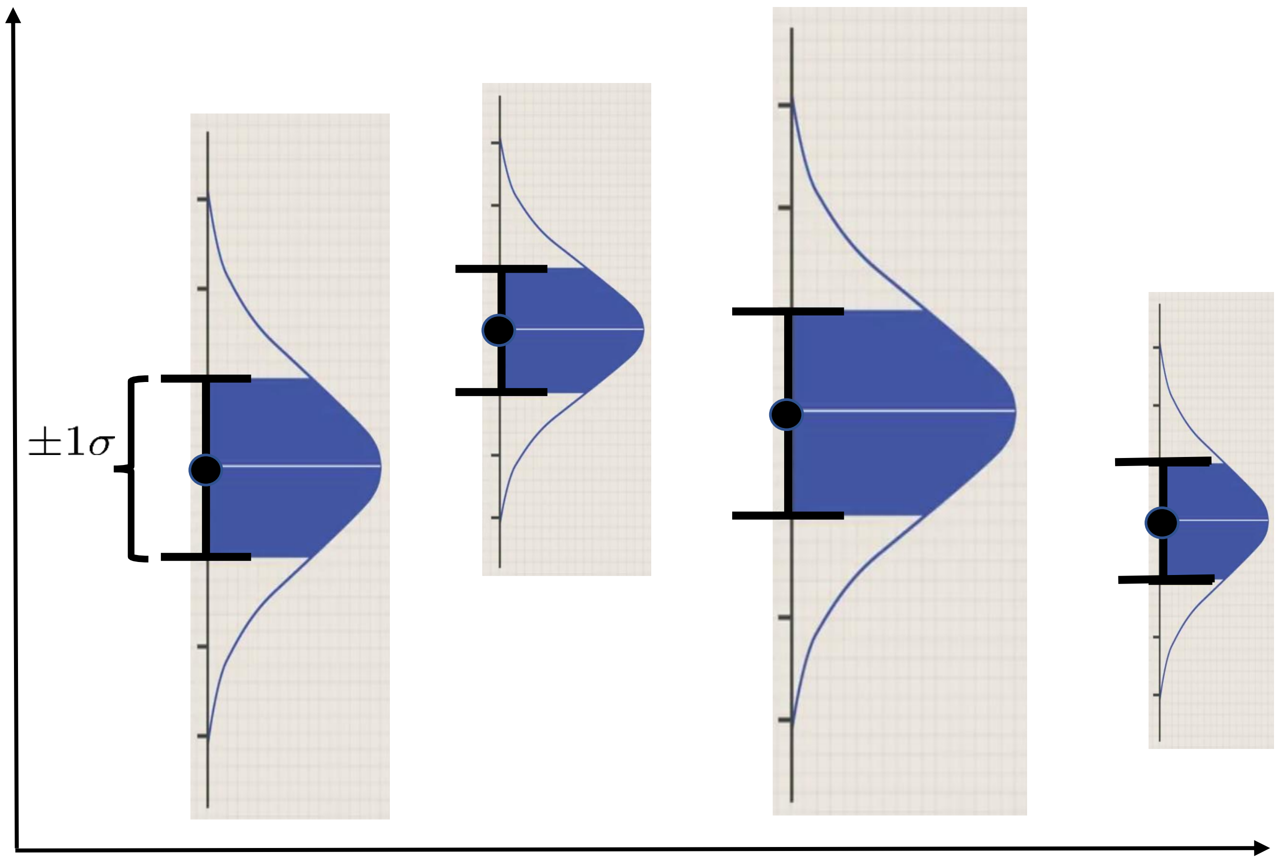
Generate pseudo-data



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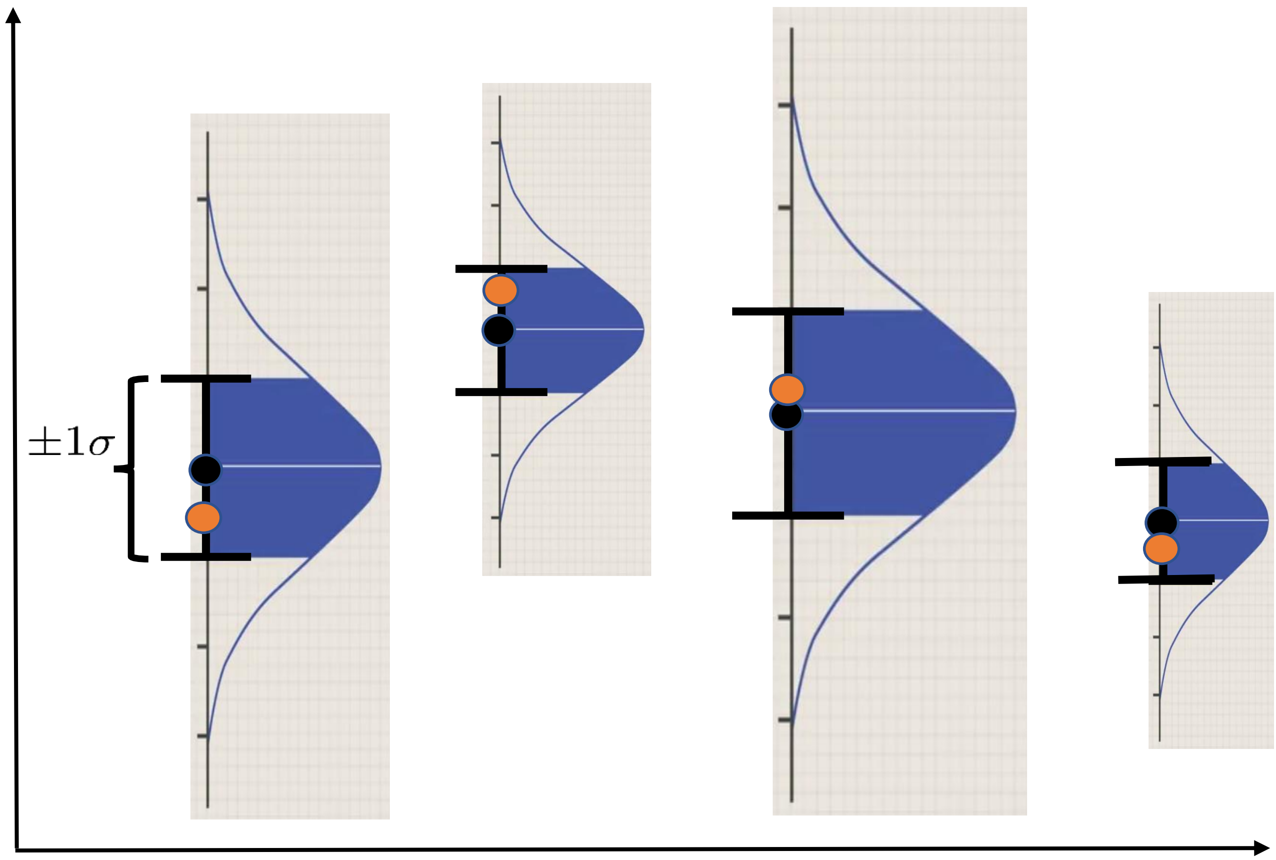
Fitting procedure: Monte-Carlo technique

Theory

Fit to exp. data

Generate pseudo-data



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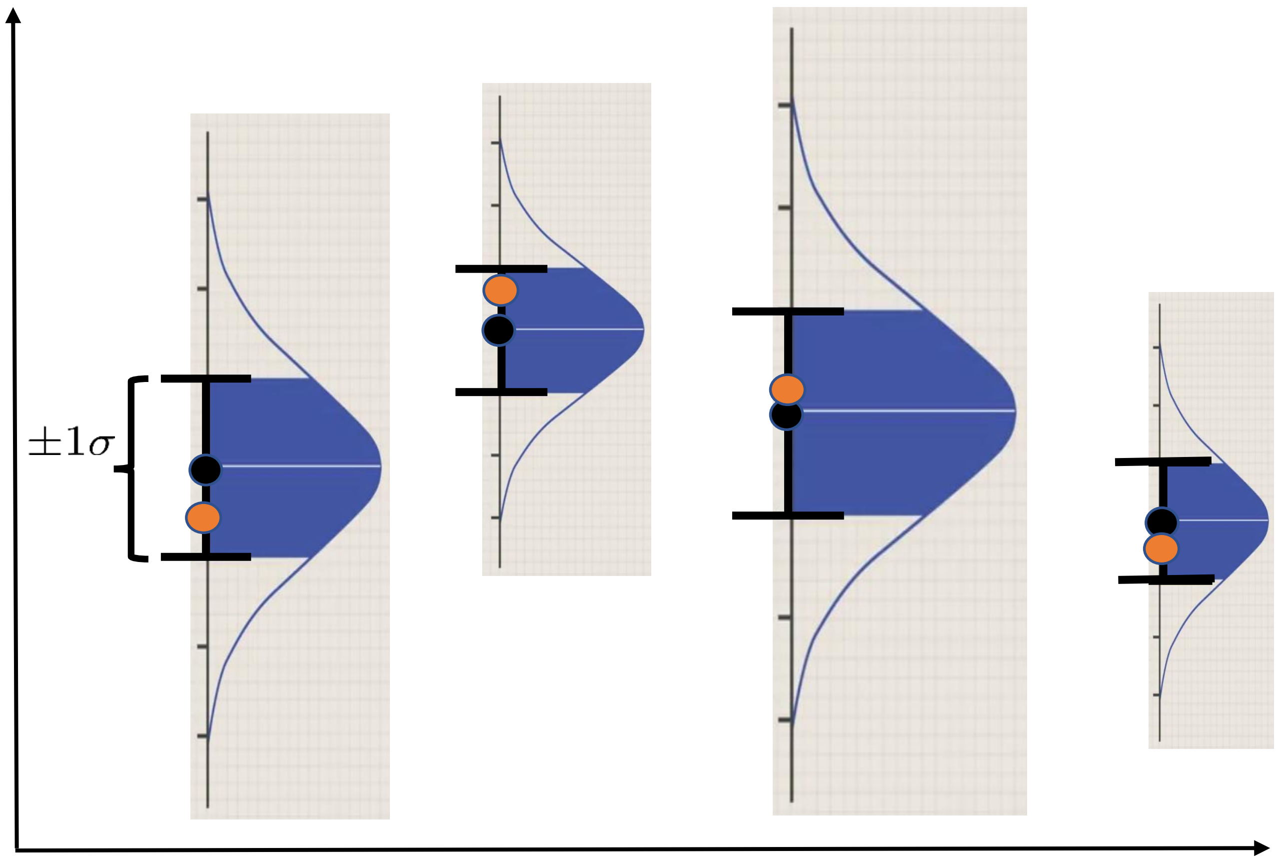
Fitting procedure: Monte-Carlo technique

Theory

Fit to exp. data

Generate pseudo-data

Fit to pseudo-data



Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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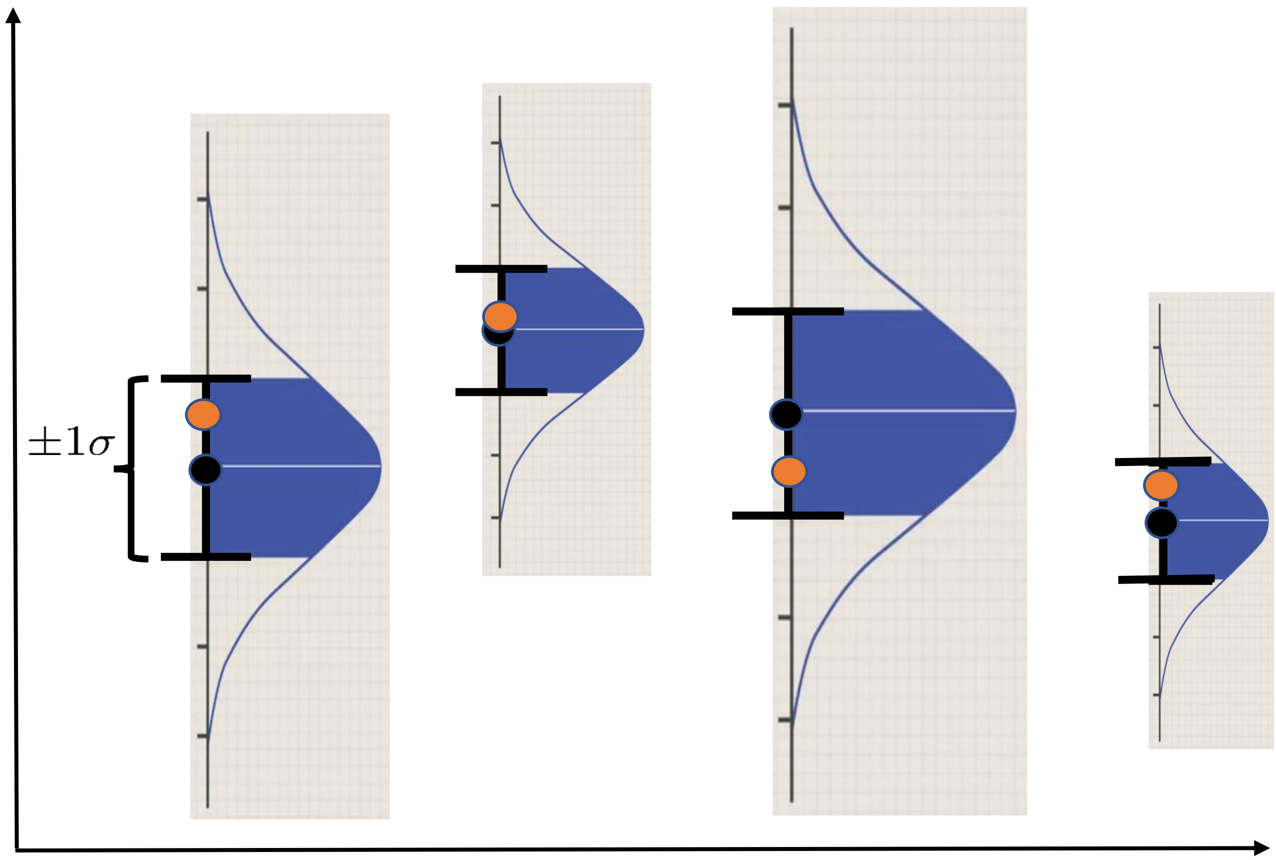
Fitting procedure: Monte-Carlo technique

- Theory
- Fit to exp. data
- Generate pseudo-data
- Fit to pseudo-data



Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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Fitting procedure: Monte-Carlo technique

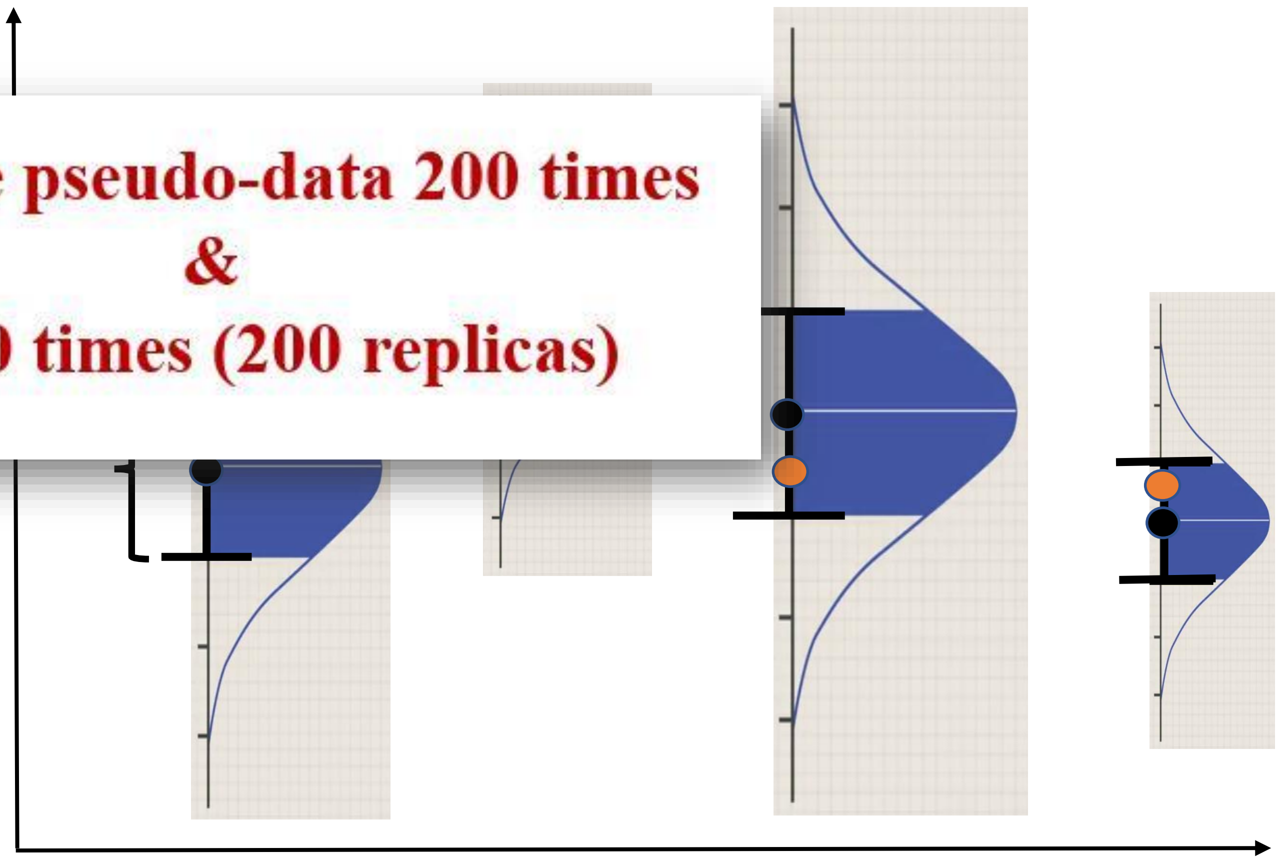
Theory

Fit to exp. data

Generate pseudo-data

Fit to pseudo-data

Generate pseudo-data 200 times
&
fit 200 times (200 replicas)



Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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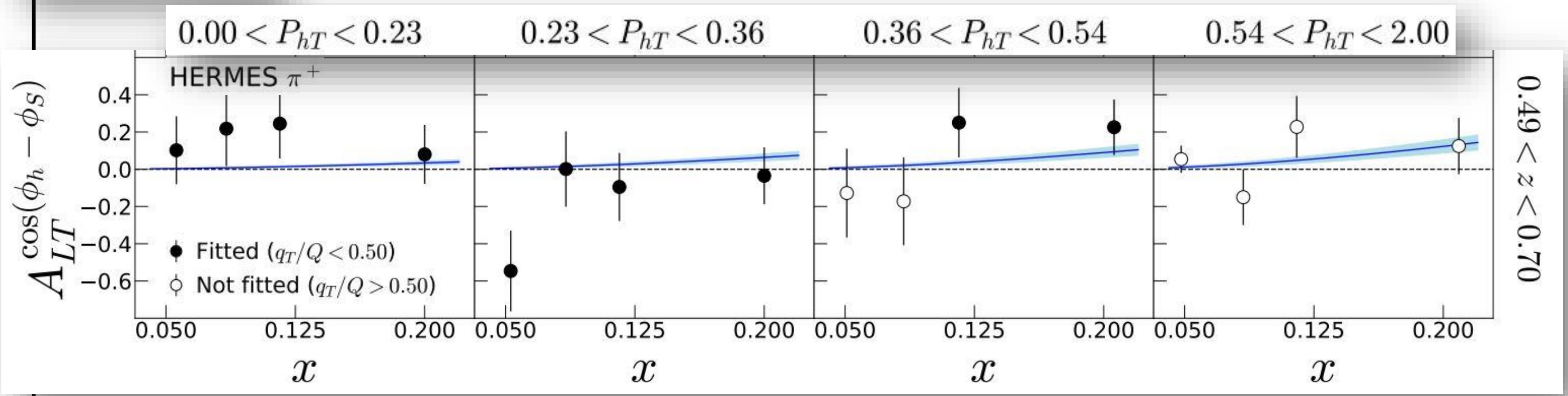
Theory versus data

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Sample results

Theory versus data



Data set	$\chi^2_w/N_{\text{pts.}}\vert_{\text{Main}}$
HERMES π^+	1.20

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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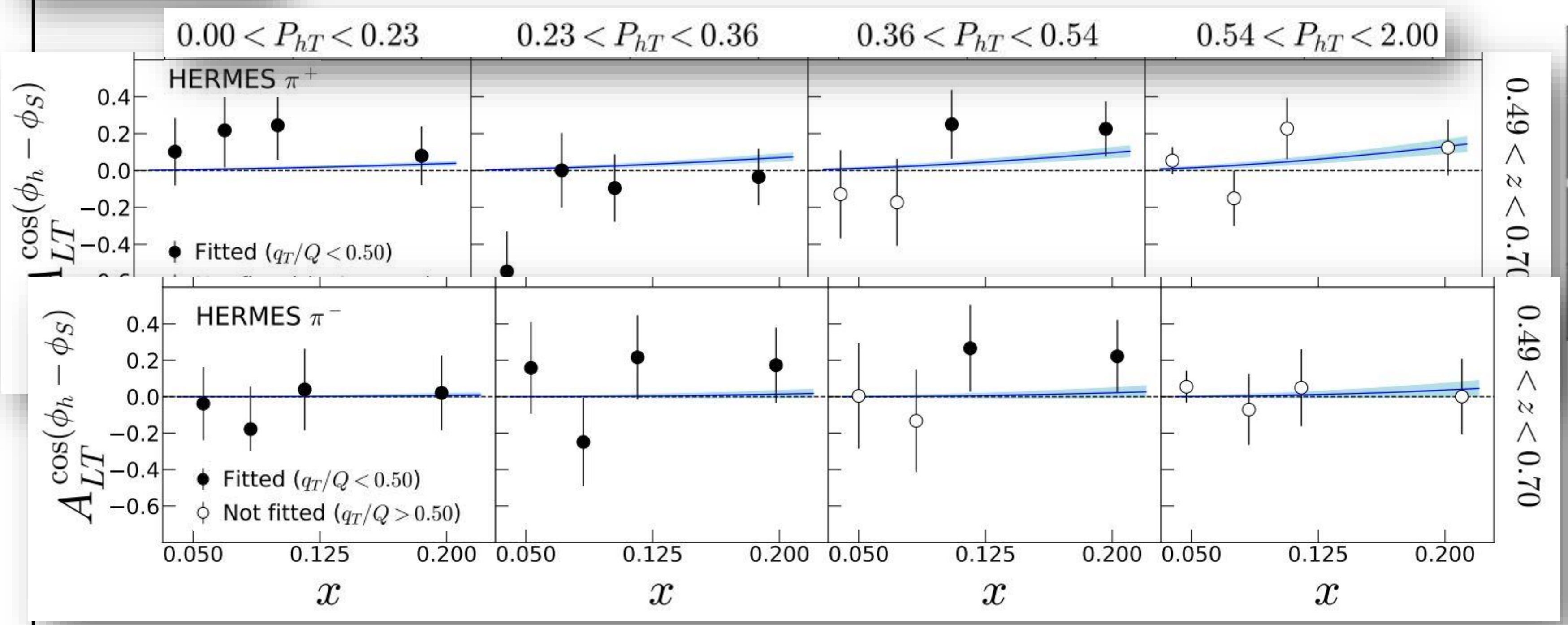
Sample results

Theory versus data



Data set	$\chi^2_w/N_{\text{pts.}}\big\vert_{\text{Main}}$
HERMES π^+	1.20
HERMES π^-	0.88

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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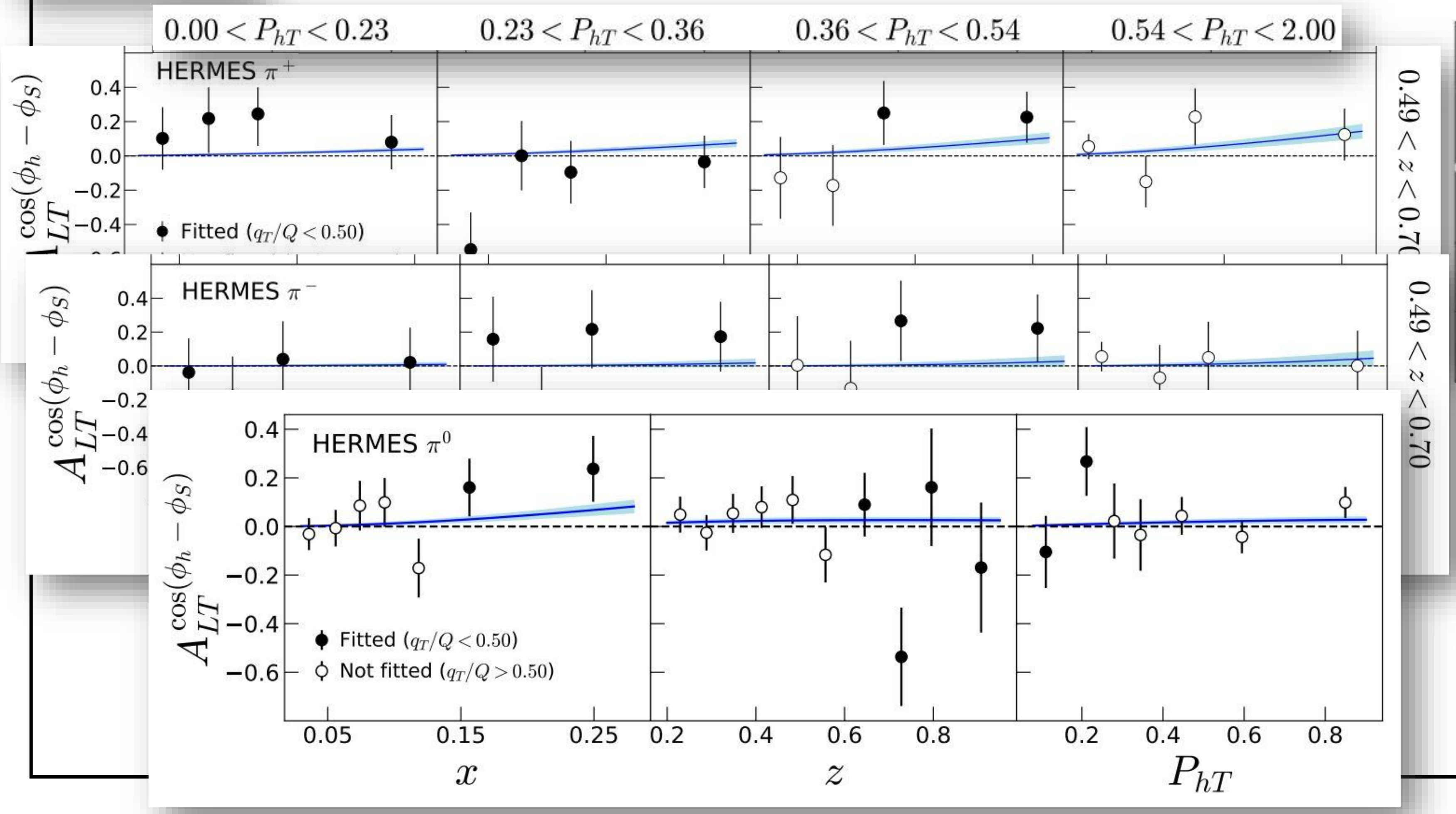
Theory versus data

Sample results



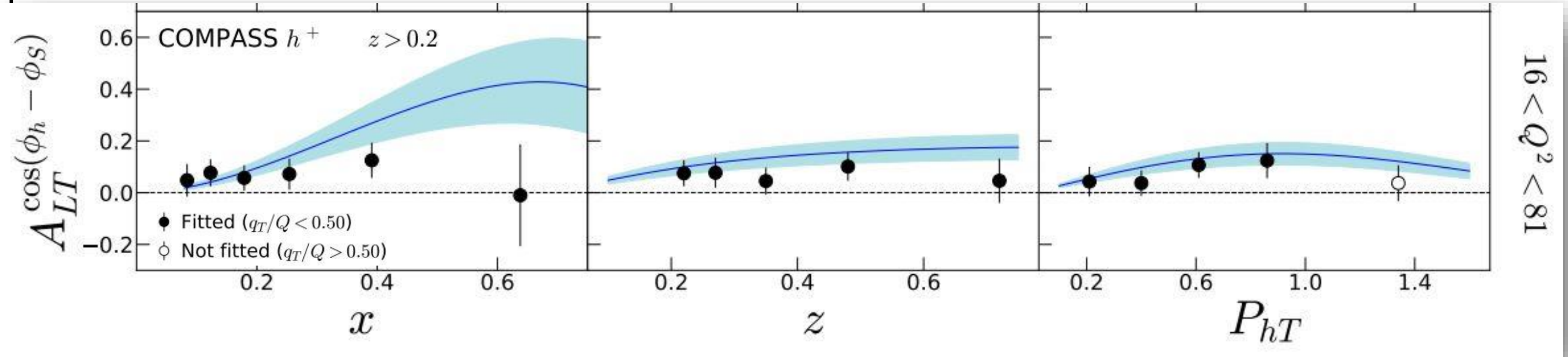
Data set	$\chi^2_w/N_{\text{pts.}}\vert_{\text{Main}}$
HERMES π^+	1.20
HERMES π^-	0.88
HERMES π^0	1.94

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Sample results

Theory versus data



Data set	$\chi^2_w/N_{pts.}\vert_{Main}$
HERMES π^+	1.20
HERMES π^-	0.88
HERMES π^0	1.94
COMPASS h^+	0.97

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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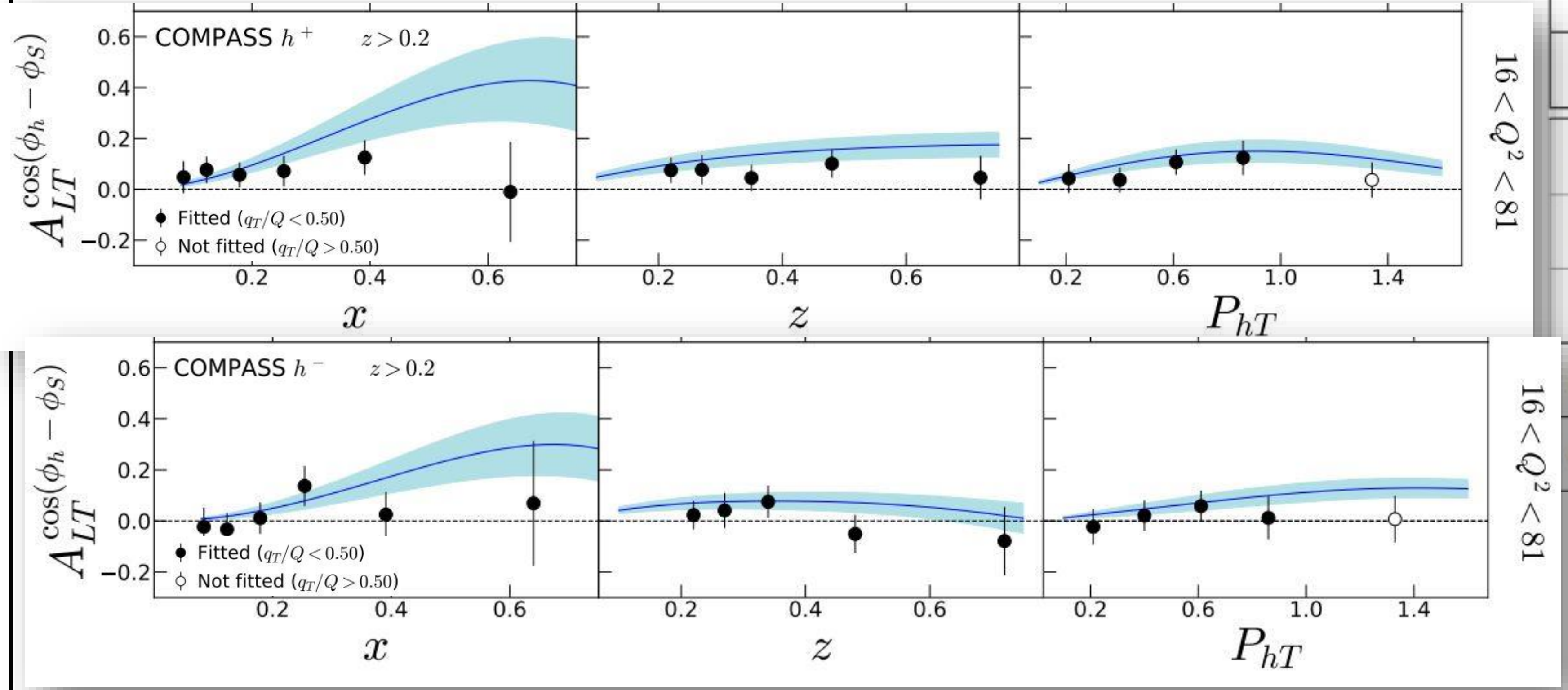
Sample results

Theory versus data

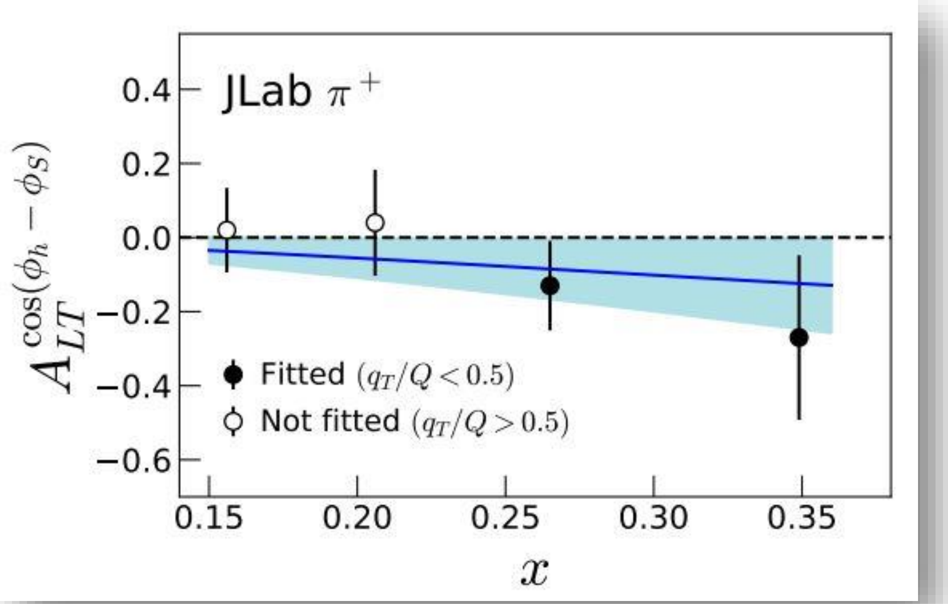


Data set	$\chi^2_w/N_{pts.}\vert_{Main}$
HERMES π^+	1.20
HERMES π^-	0.88
HERMES π^0	1.94
COMPASS h^+	0.97
COMPASS h^-	0.71

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Theory versus data



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HERMES π^+	1.20
HERMES π^-	0.88
HERMES π^0	1.94
COMPASS h^+	0.97
COMPASS h^-	0.71
JLab π^+	0.31

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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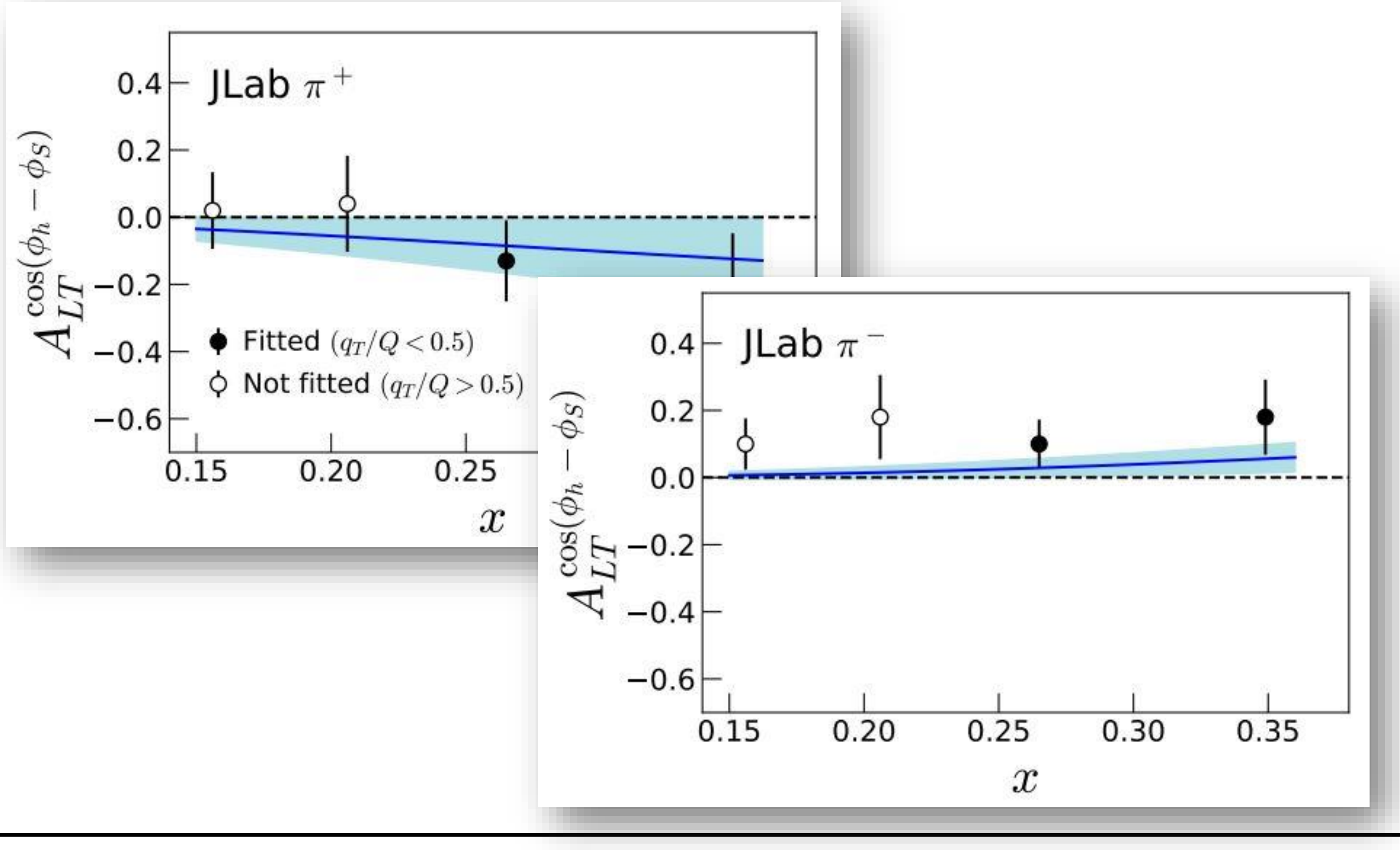
Theory versus data



Data set	$\chi^2_w/N_{pts.}\vert_{Main}$
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HERMES π^0	1.94
COMPASS h^+	0.97
COMPASS h^-	0.71
JLab π^+	0.31
JLab π^-	1.13

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Theory versus data

Strong compatibility between our theory and data

Data set	$\chi^2_w/N_{\text{pts.}}\vert_{\text{Main}}$
HERMES π^+	1.20
HERMES π^-	0.88
HERMES π^0	1.94
COMPASS h^+	0.97
COMPASS h^-	0.71
JLab π^+	0.31
JLab π^-	1.13
Global	**0.86**

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

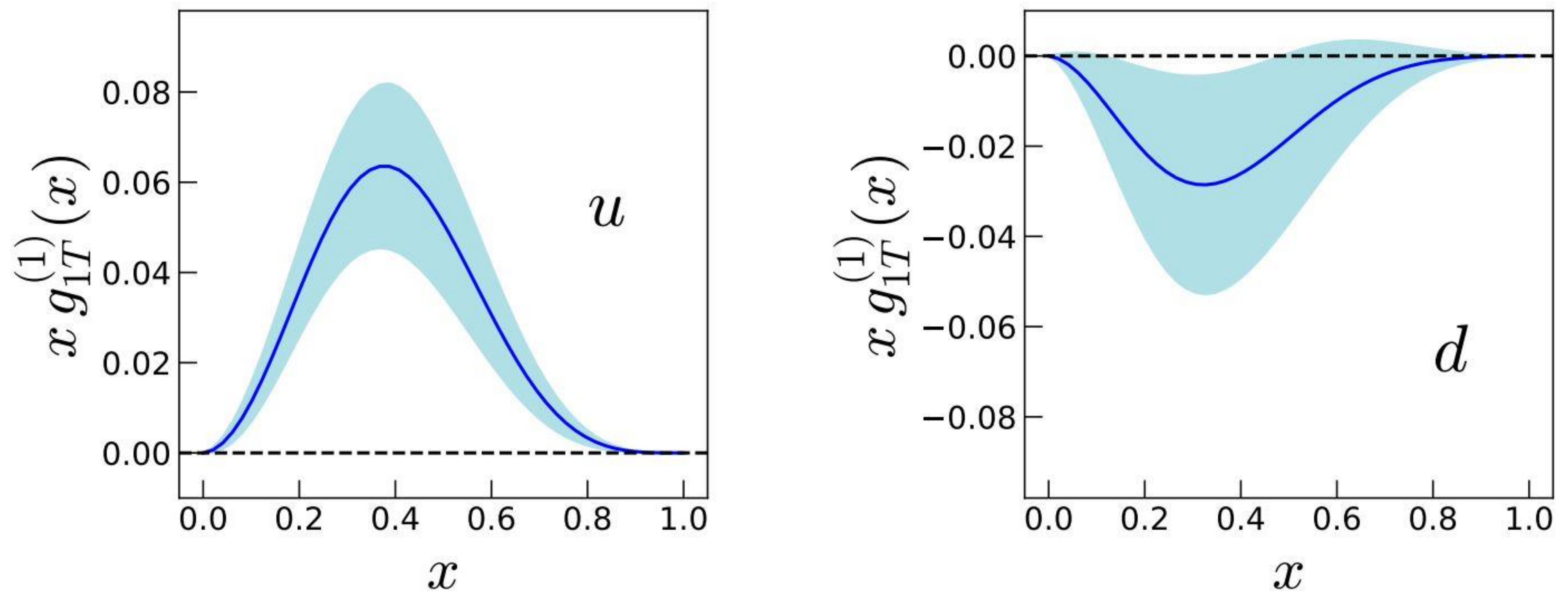
SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Results for the x-dependence

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Results for the x-dependence

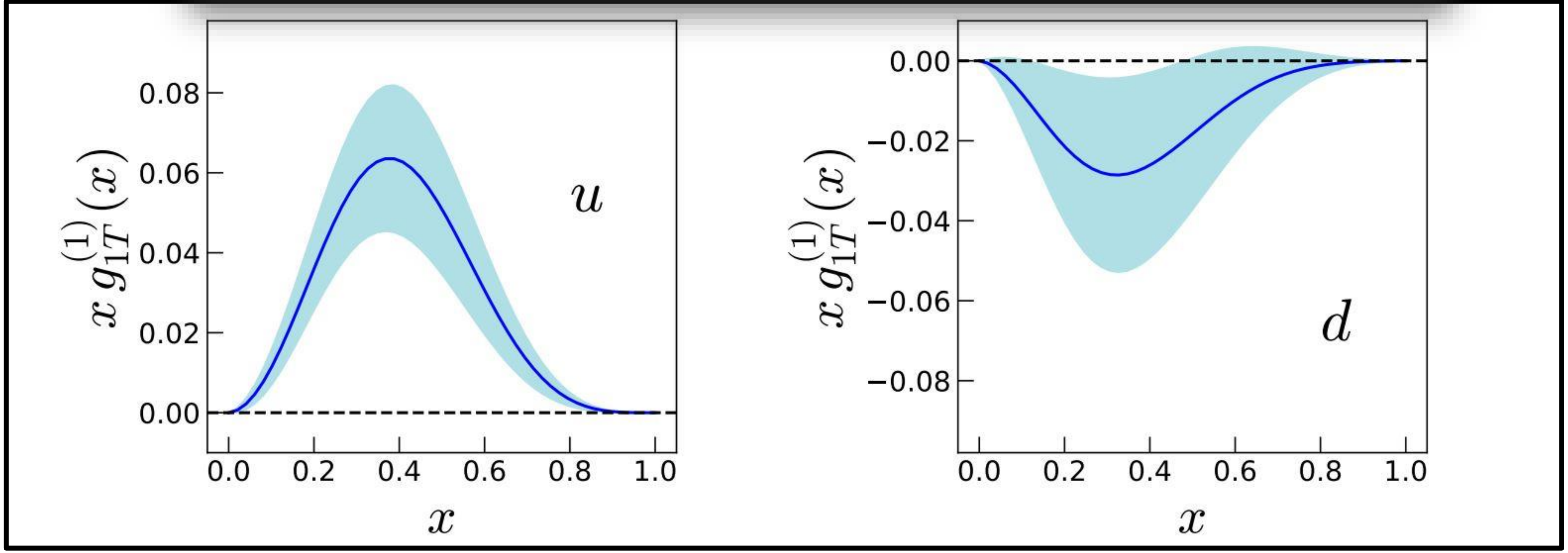


- **Up quark distribution is positive**
- **Down quark distribution is negative**

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

For a better flavor separation, we need more precise neutron data



- **Up quark distribution is positive**
- **Down quark distribution is negative**

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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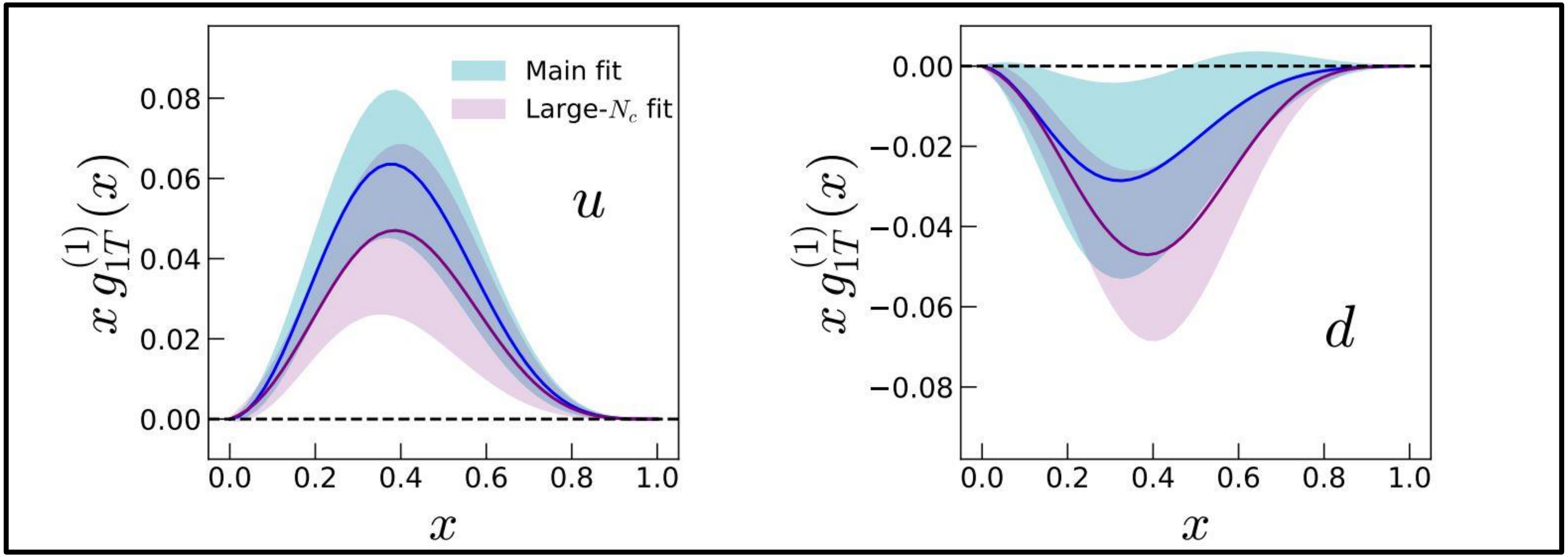
Test of theoretical predictions



- Qualitative agreement with large-N_c fit
- Slight preference to violate large-N_c approx.

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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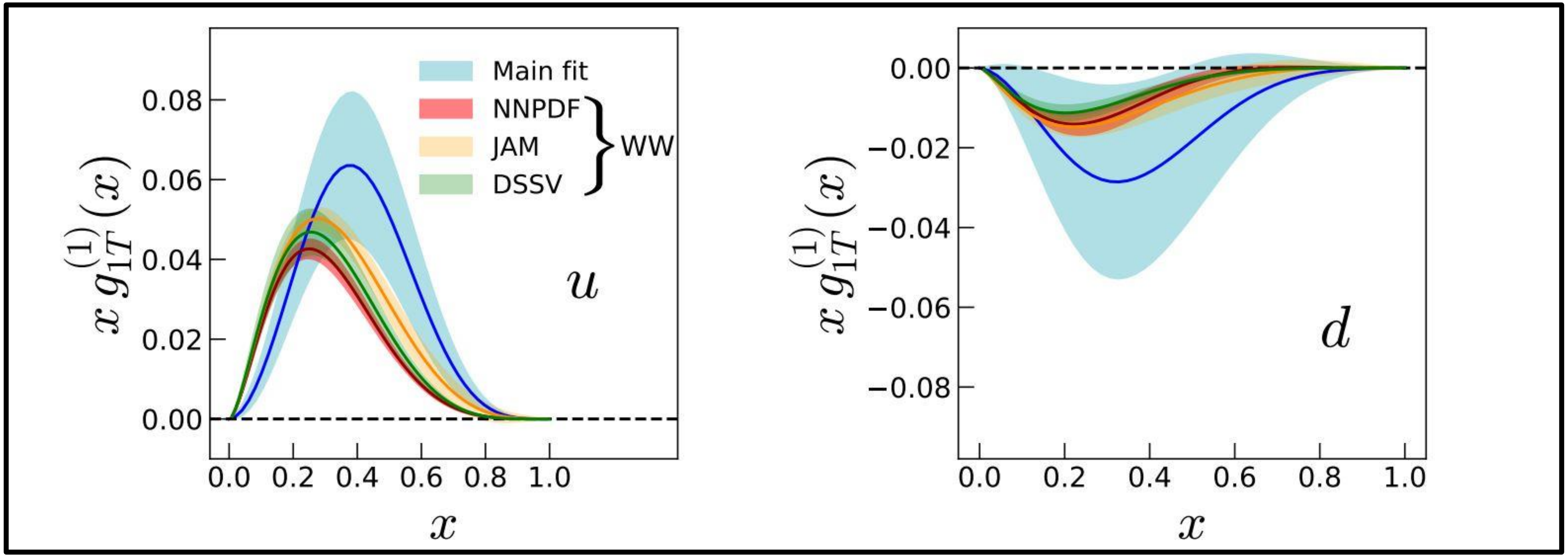
Test of theoretical predictions



- Qualitative agreement with WW-type approx.
- Hints of slight violation of WW-type approx.

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Violation of existing theoretical predictions?

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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Violation of existing theoretical predictions?

Summary of $\chi^2_w/N_{\text{pts.}}$					
Data set	$\chi^2_w/N_{\text{pts.}}\big\|_{\text{Main}}$	$\chi^2_w/N_{\text{pts.}}\big\|_{\text{Large-}N_c}$	$\chi^2_w/N_{\text{pts.}}\big\|_{\text{NNPDF}}$	$\chi^2_w/N_{\text{pts.}}\big\|_{\text{JAM}}$	$\chi^2_w/N_{\text{pts.}}\big\|_{\text{DSSV}}$

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Summary of $\chi^2_w/N_{pts.}$					
Data set	$\chi^2_w/N_{pts.}\|_{Main}$	$\chi^2_w/N_{pts.}\|_{Large-N_c}$	$\chi^2_w/N_{pts.}\|_{NNPDF}$	$\chi^2_w/N_{pts.}\|_{JAM}$	$\chi^2_w/N_{pts.}\|_{DSSV}$
HERMES π^+	1.20	1.23			
HERMES π^-	0.88	0.88			
HERMES π^0	1.94	2.01			
COMPASS h^+	0.97	0.51			
COMPASS h^-	0.71	0.53			
JLab π^+	0.31	0.06			
JLab π^-	1.13	2.23			

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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cal predictions?

Similar or better chi-squared for some data sets

Summary of $\chi^2_w/N_{pts.}$					
Data set	$\chi^2_w/N_{pts.}\|_{Main}$	$\chi^2_w/N_{pts.}\|_{Large\text{-}N_c}$	$\chi^2_w/N_{pts.}\|_{NNPDF}$	$\chi^2_w/N_{pts.}\|_{JAM}$	$\chi^2_w/N_{pts.}\|_{DSSV}$
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Summary of $\chi^2_w/N_{\text{pts.}}$

Data set	$\chi^2_w/N_{\text{pts.}}\vert_{\text{Main}}$	$\chi^2_w/N_{\text{pts.}}\vert_{\text{Large-}N_c}$	$\chi^2_w/N_{\text{pts.}}\vert_{\text{NNPDF}}$	$\chi^2_w/N_{\text{pts.}}\vert_{\text{JAM}}$	$\chi^2_w/N_{\text{pts.}}\vert_{\text{DSSV}}$
HERMES π^+	1.20		1.19	1.19	1.19
HERMES π^-	0.88		0.85	0.85	0.85
HERMES π^0	1.94		1.98	1.95	1.96
COMPASS h^+	0.97		0.71	1.02	0.89
COMPASS h^-	0.71		0.71	0.81	0.80
JLab π^+	0.31		0.81	0.78	0.96
JLab π^-	1.13		1.15	0.93	0.93

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Violation of existing theoretical predictions?

Summary of $\chi^2_w/N_{\text{pts.}}$					
Data set	$\chi^2_w/N_{\text{pts.}}\|_{\text{Main}}$	$\chi^2_w/N_{\text{pts.}}\|_{\text{Large-}N_c}$	$\chi^2_w/N_{\text{pts.}}\|_{\text{NNPDF}}$	$\chi^2_w/N_{\text{pts.}}\|_{\text{JAM}}$	$\chi^2_w/N_{\text{pts.}}\|_{\text{DSSV}}$
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HERMES π^-	0.88	0.88	0.85	0.85	0.85
HERMES π^0	1.94	2.01	1.98	1.95	1.96
COMPASS h^+	0.97	0.51	0.71	1.02	0.89
COMPASS h^-	0.71	0.53	0.71	0.81	0.80
JLab π^+	0.31	0.06	0.81	0.78	0.96
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Summary of $\chi^2_w/N_{\rm pts.}$					
Data set	$\chi^2_w/N_{\rm pts.}\|_{\rm Main}$	$\chi^2_w/N_{\rm pts.}\|_{\text{Large-}N_c}$	$\chi^2_w/N_{\rm pts.}\|_{\rm NNPDF}$	$\chi^2_w/N_{\rm pts.}\|_{\rm JAM}$	$\chi^2_w/N_{\rm pts.}\|_{\rm DSSV}$
HERMES π^+	1.20	1.23	1.19	1.19	1.19
HERMES π^-	0.88	0.88	0.85	0.85	0.85
HERMES π^0	1.94	2.01	1.98	1.95	1.96
COMPASS h^+	0.97	0.51	0.71	1.02	0.89
COMPASS h^-	0.71	0.53	0.71	0.81	0.80
JLab π^+	0.31	0.06	0.81	0.78	0.96
JLab π^-	1.13	2.23	1.15	0.93	0.93
Global	**0.86**	**0.99**	**0.95**	**0.94**	**0.97**

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Violation of existing theoretical predictions?

Summary of $\chi^2_w/N_{\text{pts.}}$

Data set	$\chi^2_w/N_{\text{pts.}}\vert_{\text{Main}}$	$\chi^2_w/N_{\text{pts.}}\vert_{\text{Large-}N_c}$	$\chi^2_w/N_{\text{pts.}}\vert_{\text{NNPDF}}$	$\chi^2_w/N_{\text{pts.}}\vert_{\text{JAM}}$	$\chi^2_w/N_{\text{pts.}}\vert_{\text{DSSV}}$
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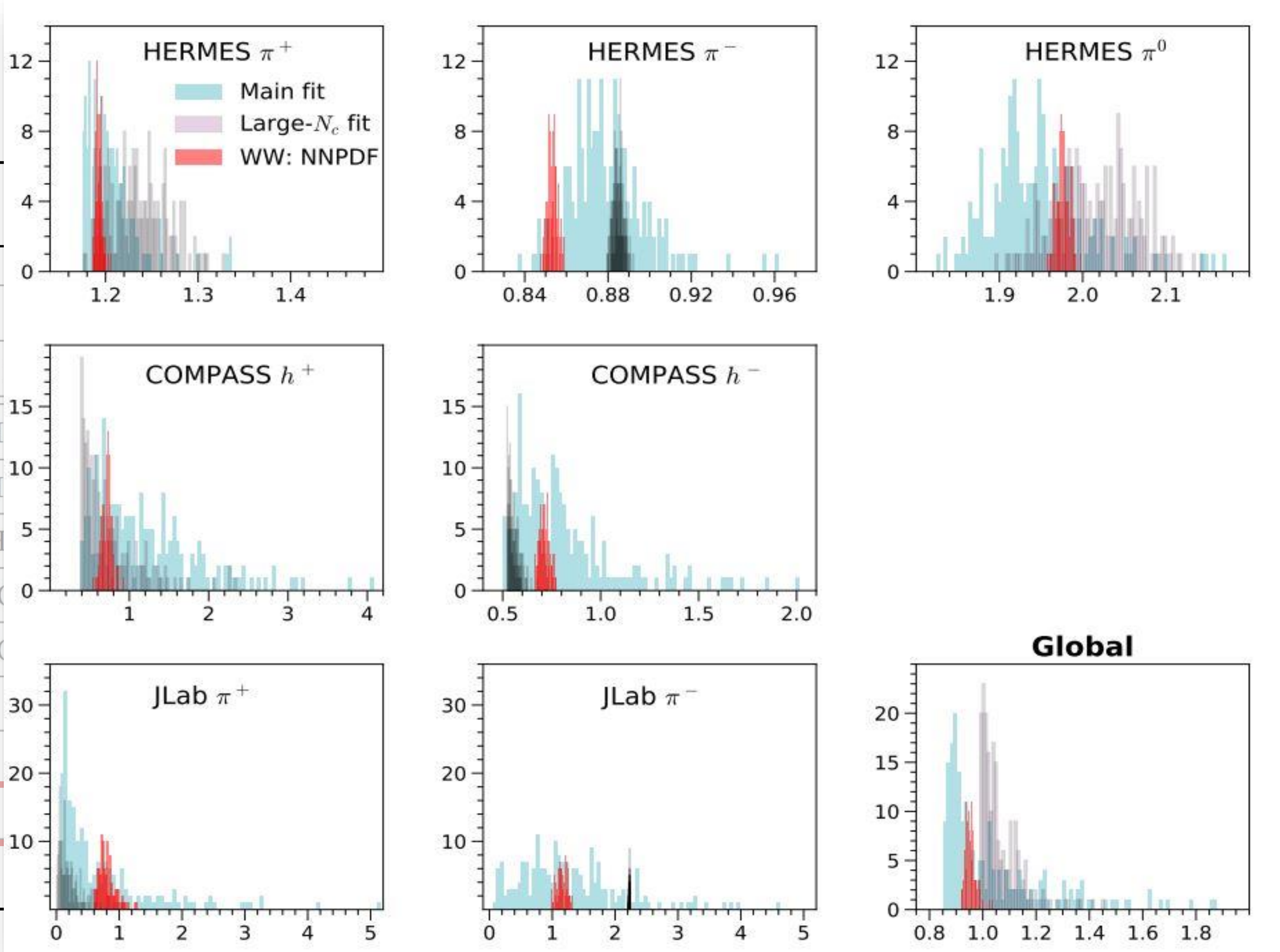
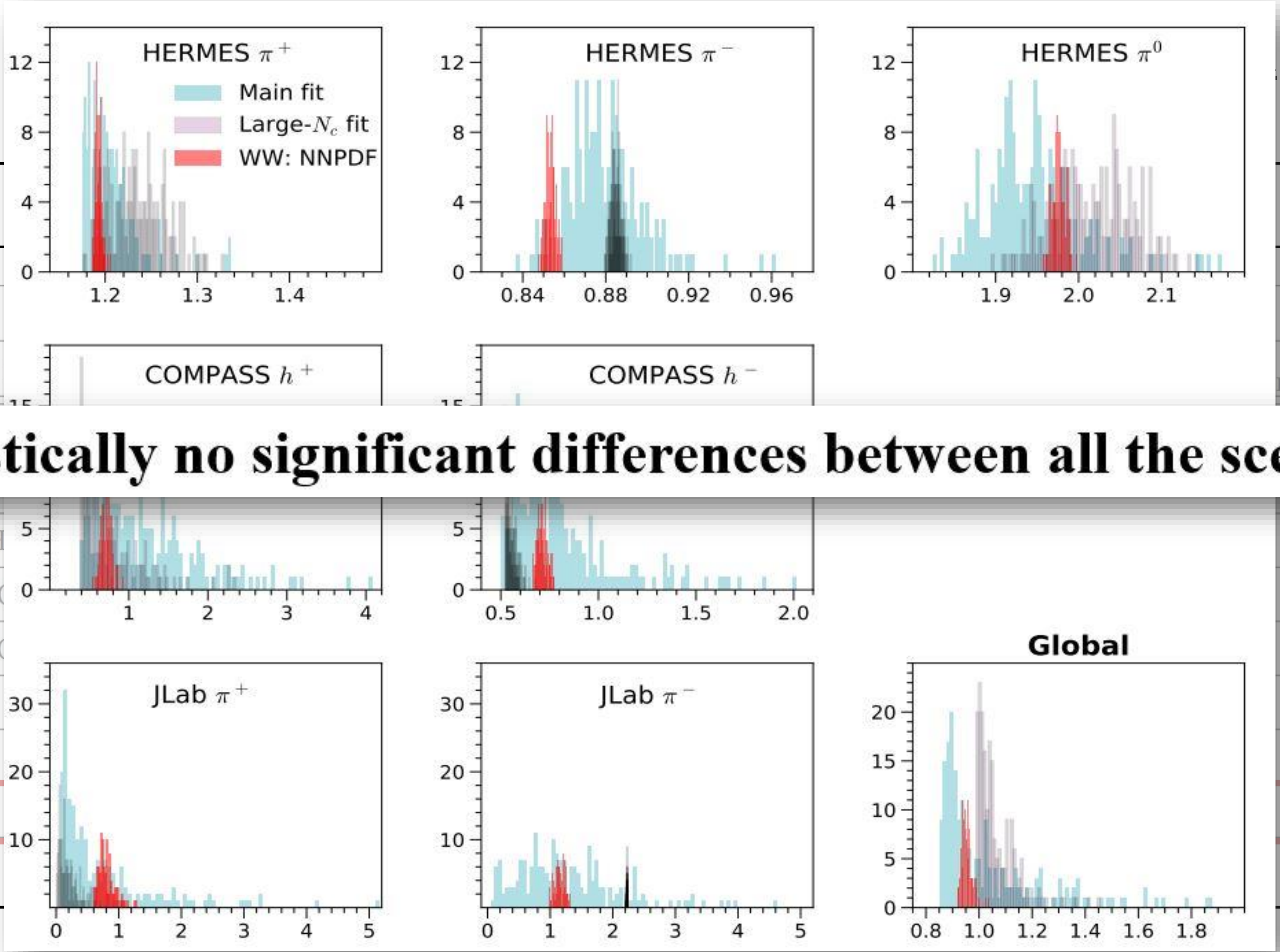
HERMES π^0	1.94	2.01	1.98	1.95	1.96
COMPASS h^+	0.97	0.51	0.71	1.02	0.89
COMPASS h^-	[illegible]	[illegible]	[illegible]	[illegible]	0.80
JLab π^+	0.31	0.06	0.81	0.78	0.96
JLab π^-	1.13	2.23	1.15	0.93	0.93
Global	**0.86**	**0.99**	**0.95**	**0.94**	**0.97**

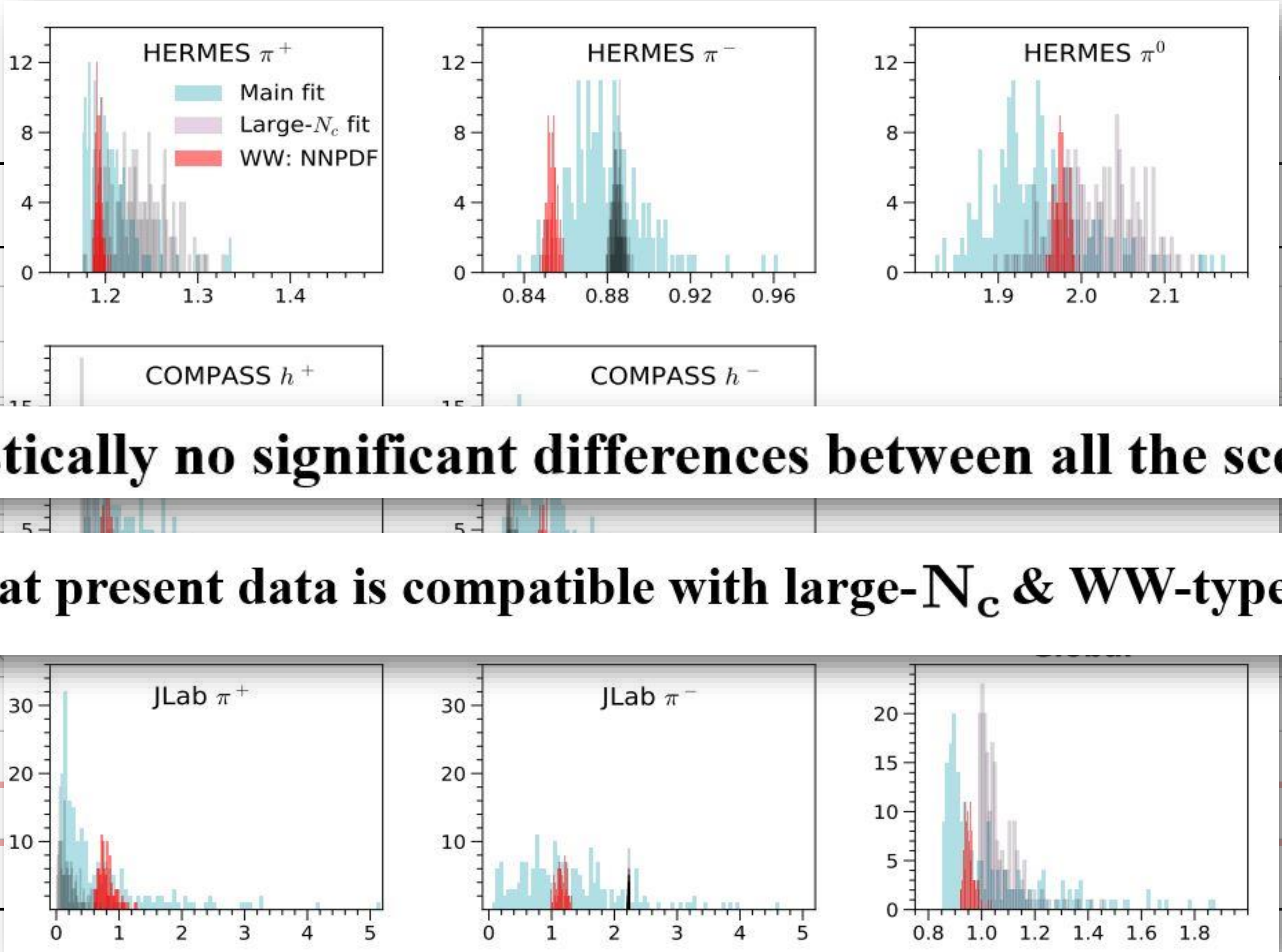
Our global chi-squared is consistently better



HERMES π^+
Main fit
Large-N_c fit
WW: NNPDF
HERMES π^-
HERMES π^0
COMPASS h^+
COMPASS h^-
JLab π^+
JLab π^-
Global



Statistically no significant differences between all the scenarios



Statistically no significant differences between all the scenarios

Hence, at present data is compatible with large-N_c & WW-type approx.

Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

SB, Kang, Metz, Penn, Pitonyak, arXiv: 2110.10253 (2021)

Comparison with lattice QCD results

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Calculation of worm-gear shift:

$$[\langle k_x \rangle_{TL}](Q^2) \equiv M \frac{\int_0^1 dx \left[g_{1T}^{(1)u}(x,Q^2) - g_{1T}^{(1)d}(x,Q^2) \right]}{\int_0^1 dx \left[f_1^u(x,Q^2) - f_1^d(x,Q^2) \right]}$$

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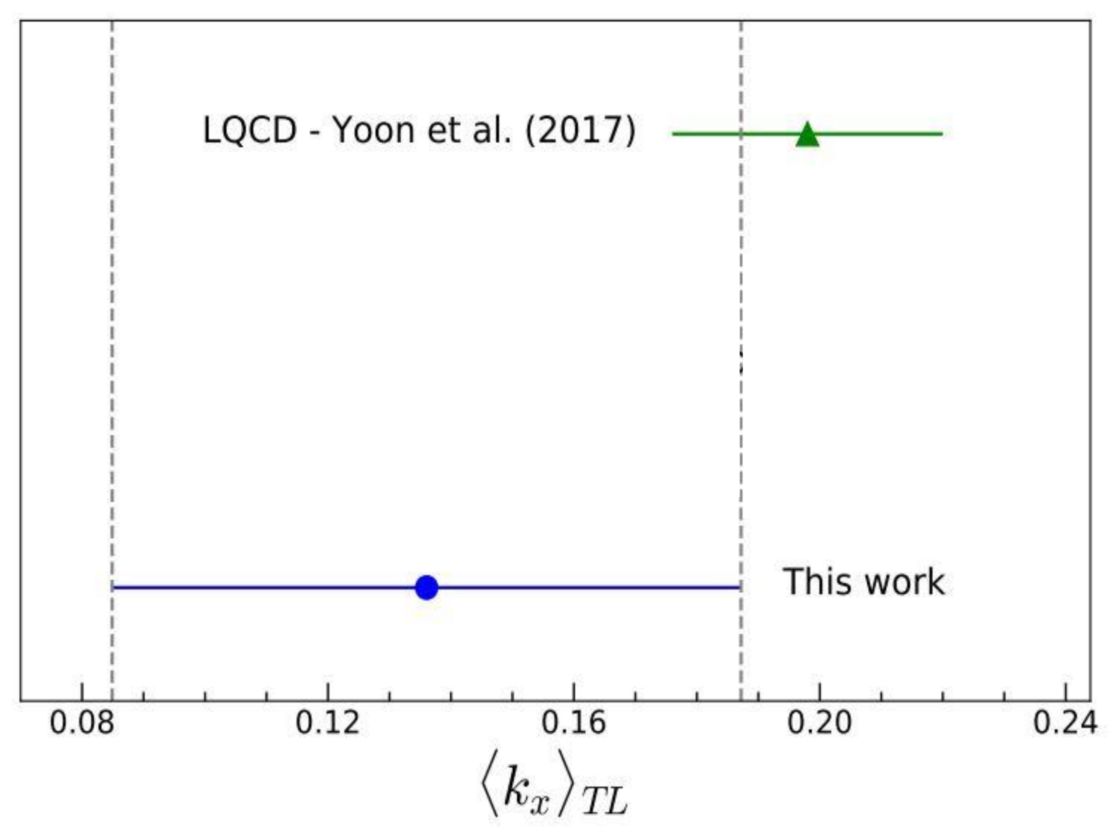

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- **Consistency between lattice results & our main fit result**

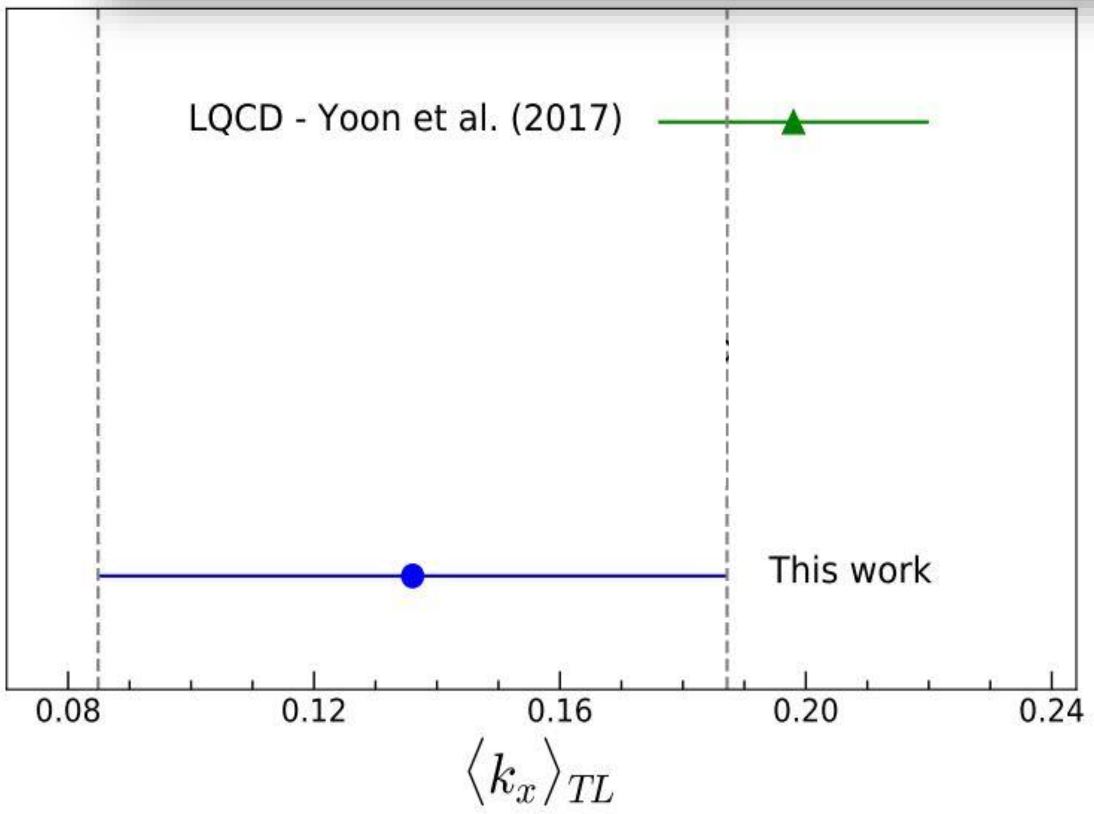
Caveats in LQCD calculations:

- **No definite scale:** $Q \approx \frac{1}{a}$
- **Limits** $\hat{\zeta} \to \infty$ **&** $b_T \to 0$ **cannot be taken**

…MES, COMPASS & JLab data

…ak, arXiv: 2110.10253 (2021)

…ce QCD results



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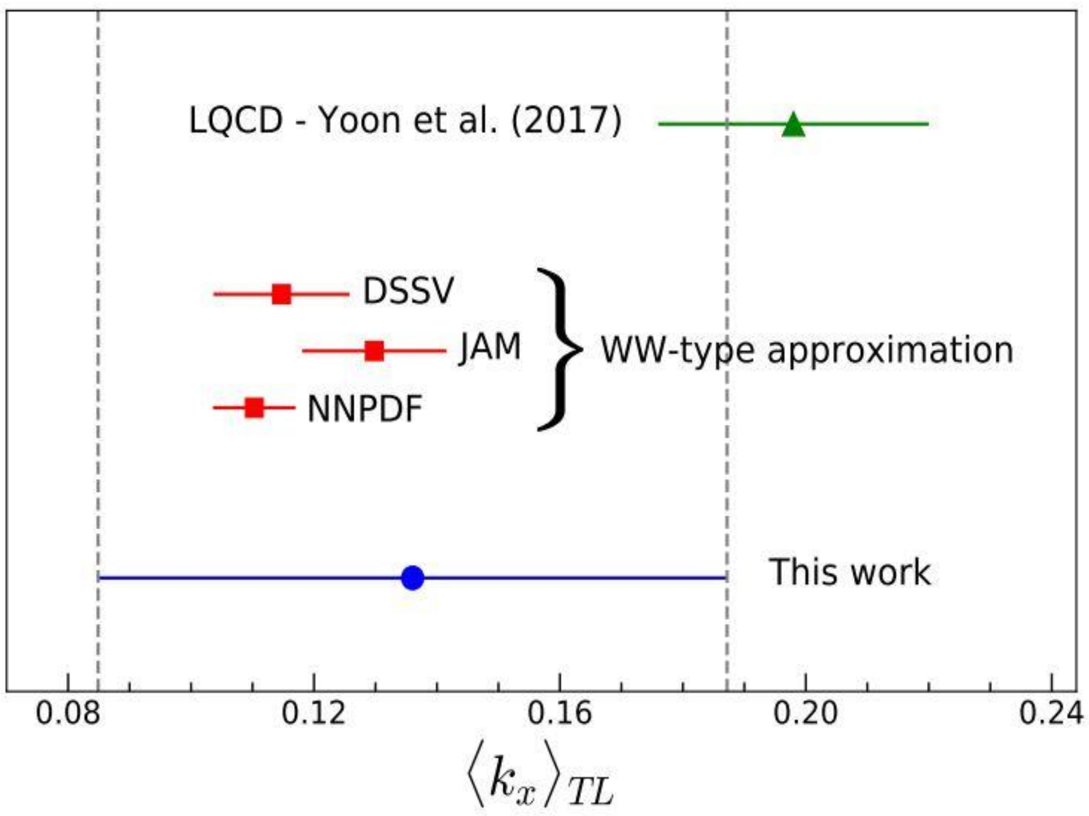

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- **Consistency between lattice results & our main fit result**
- **It is encouraging that lattice QCD & exp. data are in reasonable agreement**
- **Consistency between results from WW-type approx. & our main fit result**

Summary/ Outlook

Summary

- We have shown our final results for g_{1T}, obtained from a simultaneous fitting to HERMES, COMPASS & JLab data on SIDIS
- Qualitative agreements with large-N_c & WW-type approximation
- Although there is an indication of a slight violation of both large-N_c & WW-type approximation, the data is not precise enough to affirm the degree of violation
- Encouraging agreement in the worm-gear shift with lattice QCD results

Outlook

- Extend analysis to extract $h_{1L}^{\perp}$, …

Backup slides

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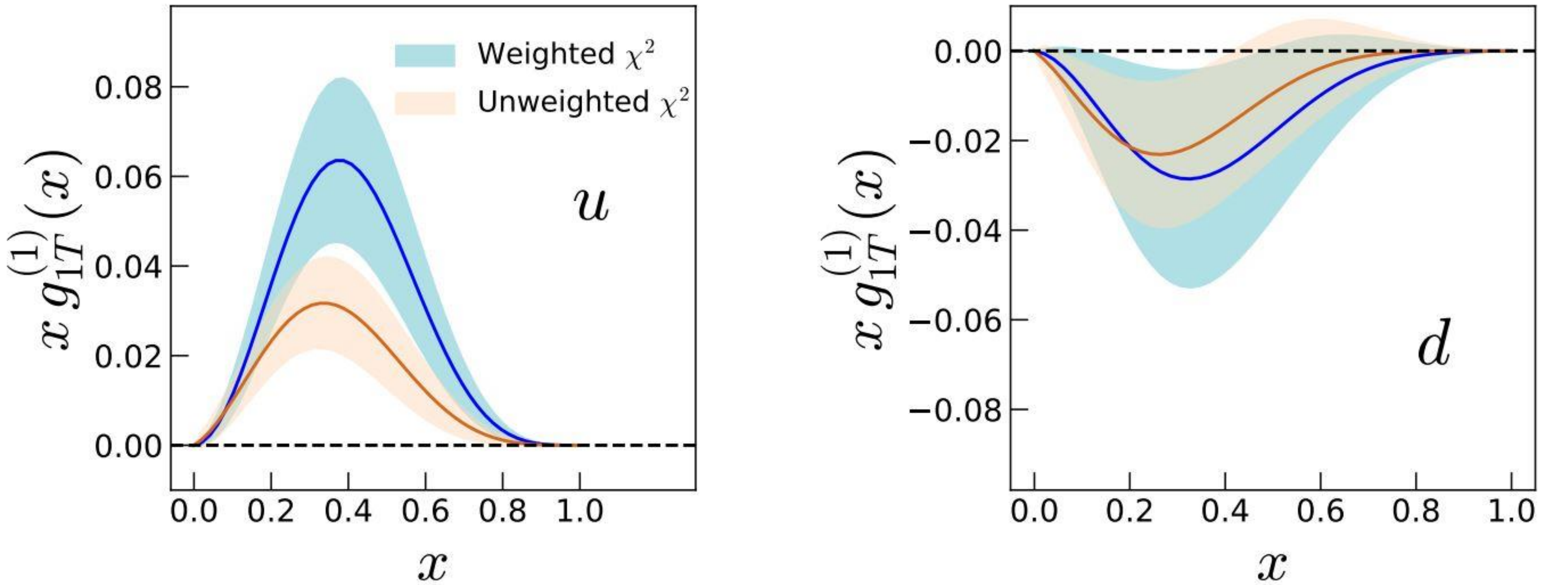
Weighted versus unweighted methods



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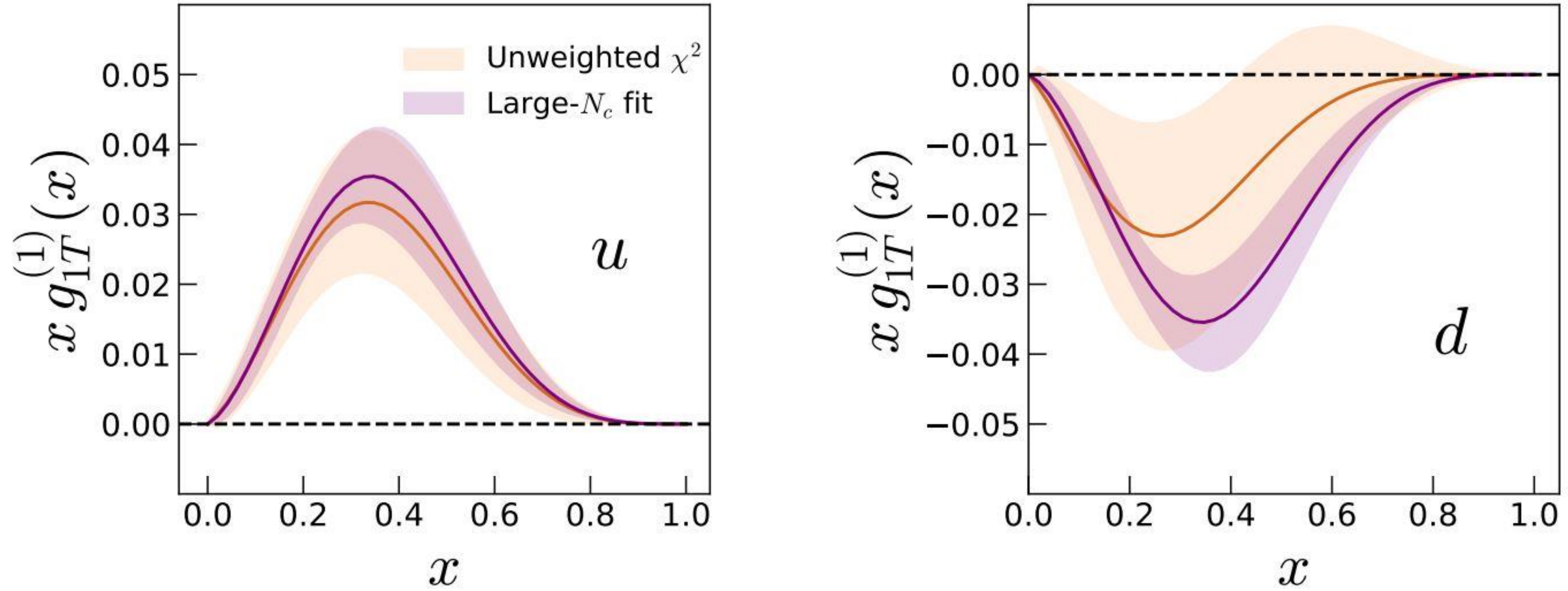
Additional plots from the unweighted method



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