First extraction of g_{1T}

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BNL

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Correlations in Partonic and Hadronic Interactions (CPHI-2022)

Duke University

In Collaboration with:

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Daniel Pitonyak (Lebanon Valley College)

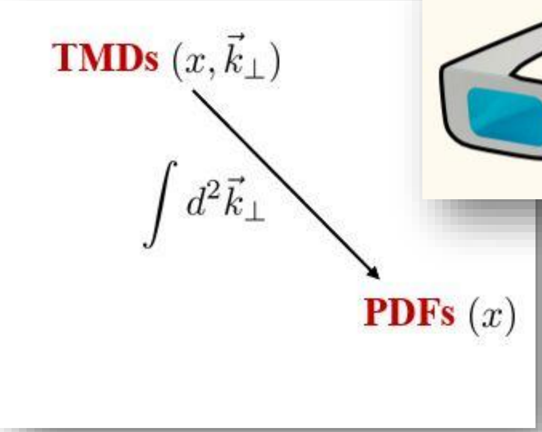
Based on Physical Review D 105 (2022) 3, 034007

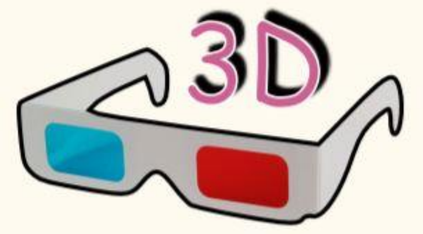
Outline

- Introduction to TMDs
- Previous knowledge on g_{1T} : Theoretical predictions
- Main extraction: Fit through Monte-Carlo technique
- Main fit results
- Comparison with theoretical predictions
- Comparison with Lattice QCD results
- Summary/Outlook

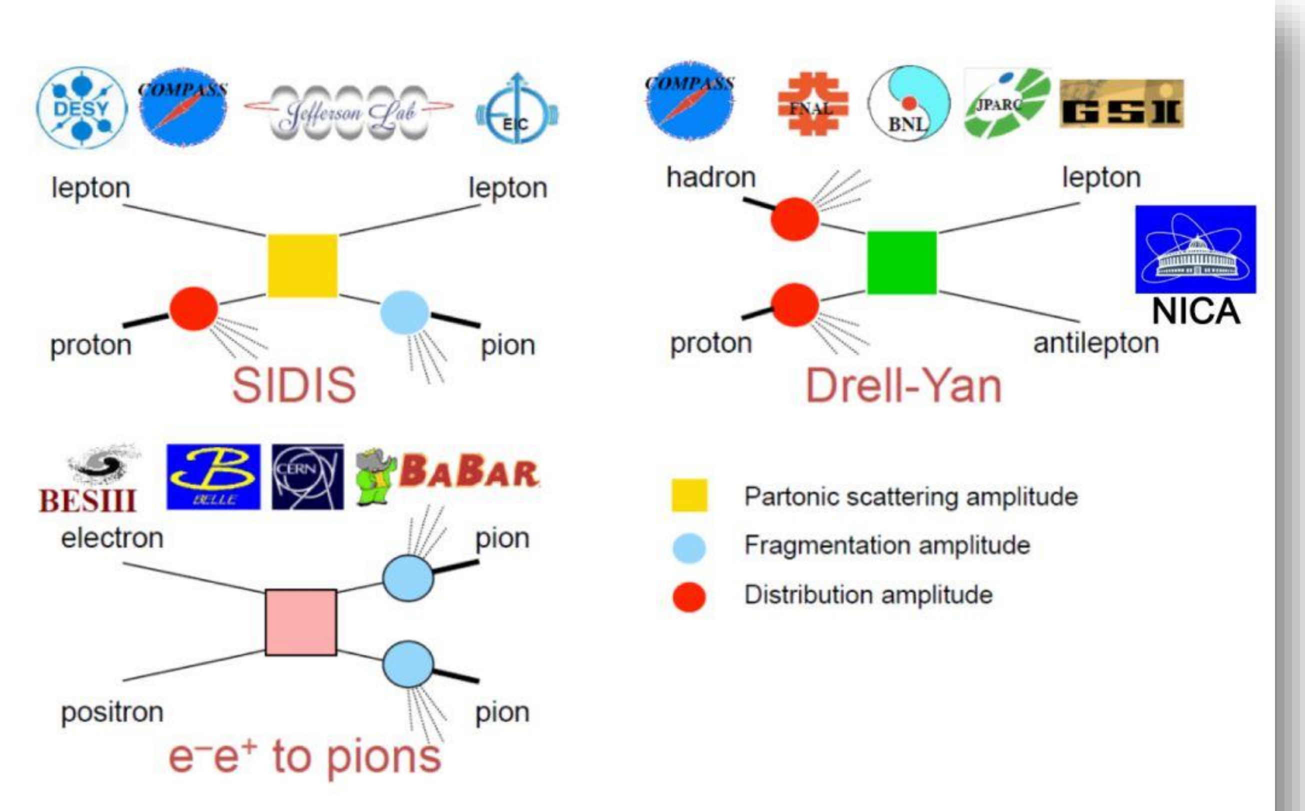
Introduction

- **TMDs: Interest in 3D rather than 1D parton structure of hadrons**





- **TMDs appear in the QCD description of many scattering processes:**



(from M. Grosse Perdekamp, talk at TMD Summer School, 2017)

- **TMDs allow one to study interesting non-trivial aspects like universality**

Introduction

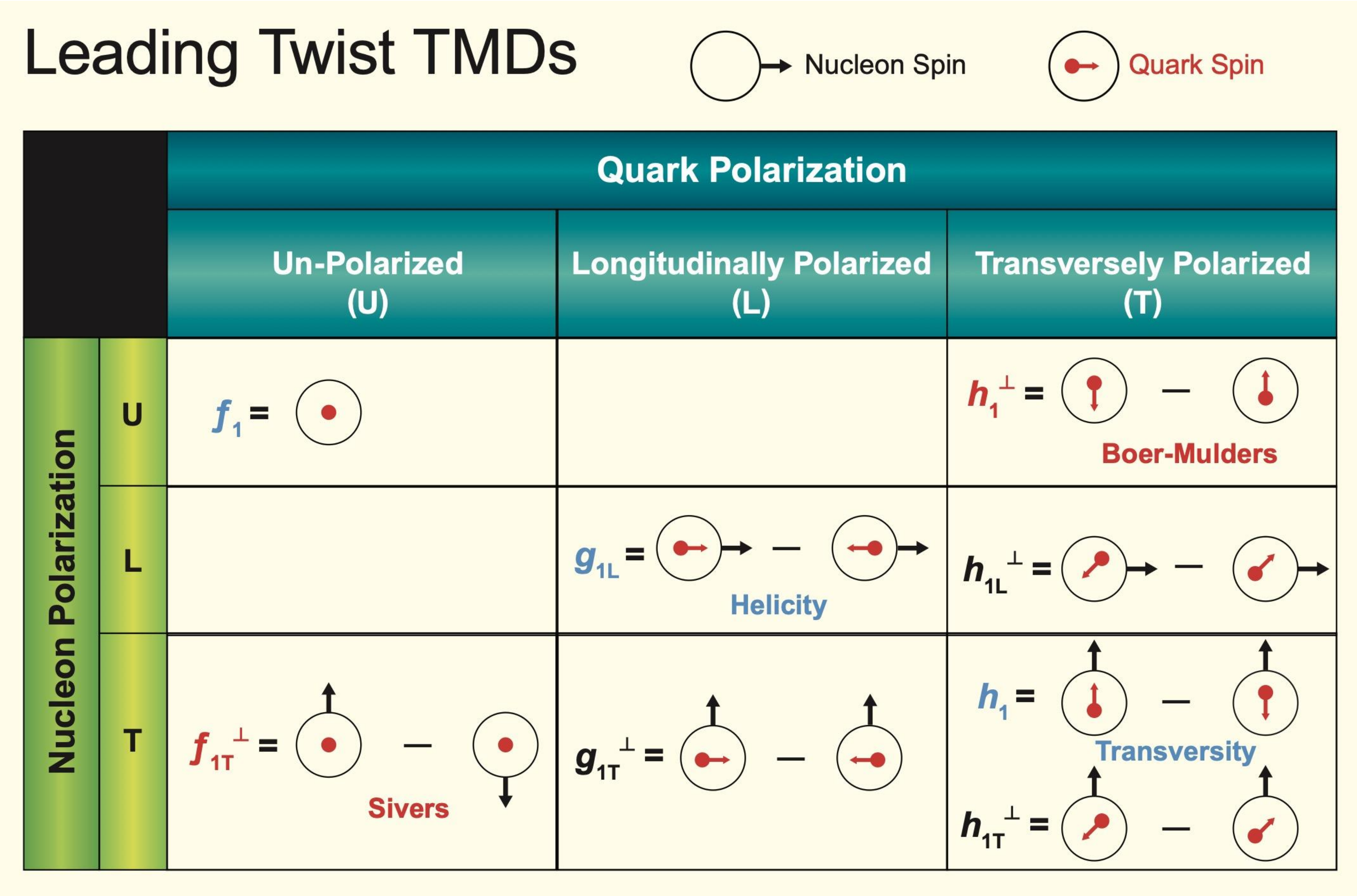
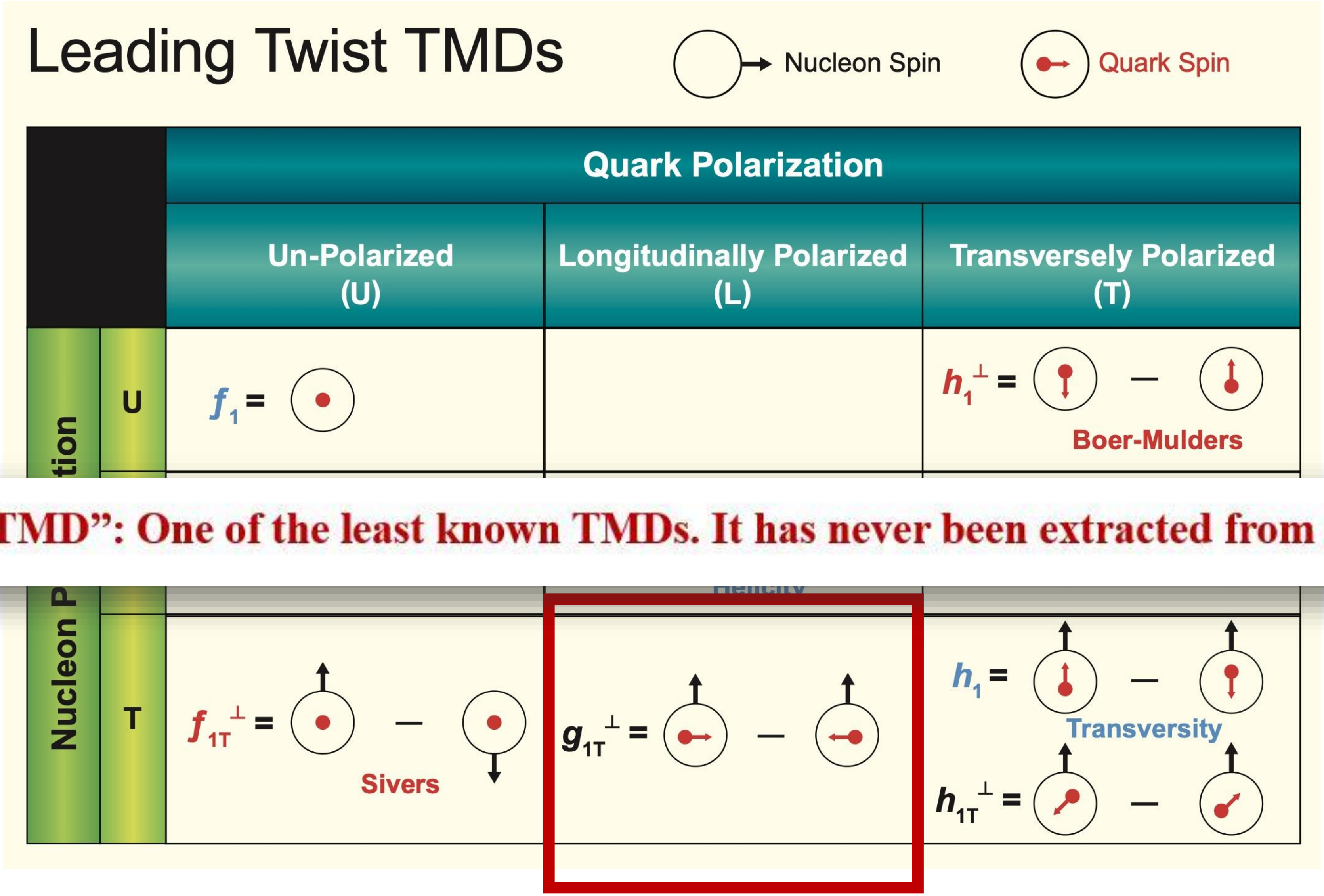


Fig. courtesy:
D. Pitonyak

Introduction



"Worm-gear TMD": One of the least known TMDs. It has never been extracted from experimental data.

Fig. courtesy:
D. Pitonyak

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

Theoretical predictions

1.

2.

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

Theoretical predictions

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

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

Fundamentals

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

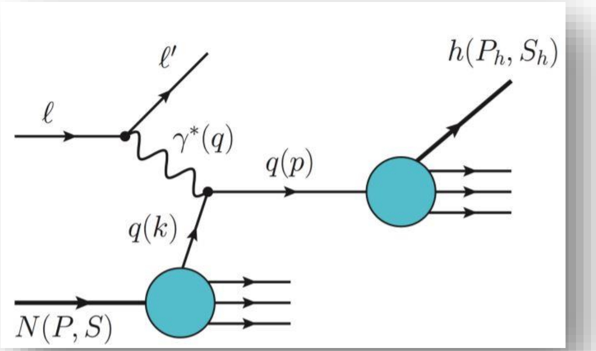

Fig. courtesy:
A. Metz

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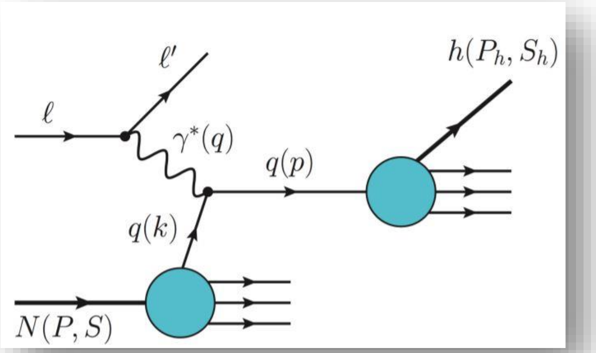

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Model-independent decomposition of cross-section: (Bacchetta et. al. 2007, …)

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz_h\,d\phi_h\,dP_{hT}^2} = \frac{\alpha_{\rm em}^2}{x\,y\,Q^2}\left\{\left(1-y+\frac{1}{2}y^2\right)F_{UU}\right.$$

$$\left. + \lambda_l\,|\vec{S}_\perp|\,y\left(1-\frac{1}{2}y\right)\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots\right\}$$

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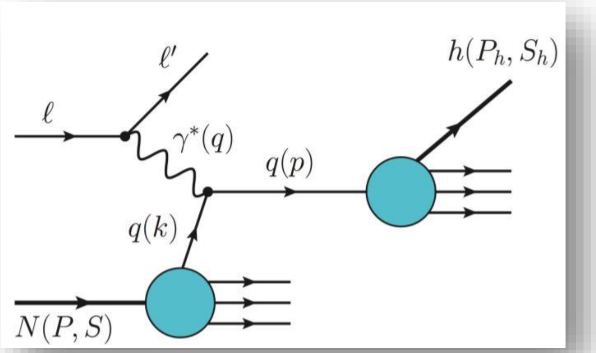
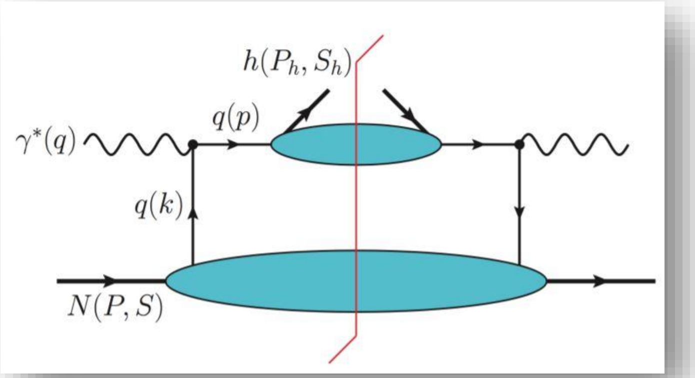


$q_T \ll Q$



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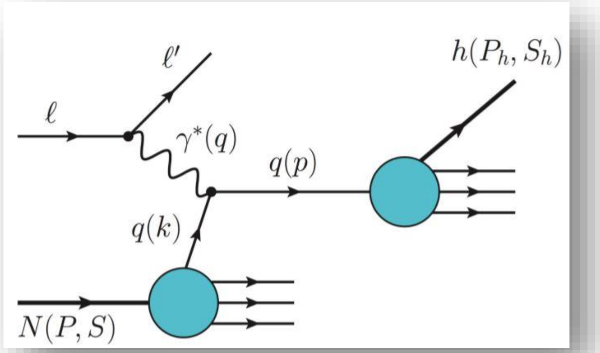

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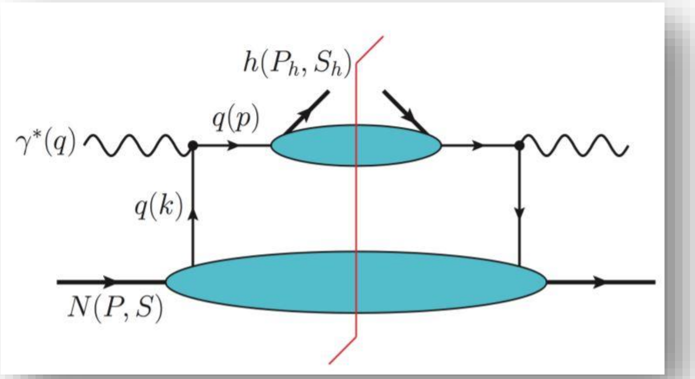

Connection between structure functions and TMDs: (Bacchetta et. al. 2007, …)

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

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

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Parameterization of g_{1T}

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Gaussian ansatz:

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

$q = (u,d)$

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where,

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

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

Presently available data insufficient to pin down the parameters:

$$\langle k_\perp^2 \rangle, \quad \alpha^d, \quad \beta^{u/d}$$

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- **Fix TMD width:**

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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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$$\langle k_\perp^2 \rangle\big|_{f_1} = 0.53$$

Cammarota et. al., arXiv 2002.08384

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

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$\langle k_\perp^2 \rangle|_{f_1} = 0.53$ →

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$$\therefore \langle k_\perp^2 \rangle|_{g_{1T}} \approx 0.40$$

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Helicity & unpolarized PDFs have similar large-x behavior

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Gaussian ansatz: $g_{1T}^q(x, \vec{k}_\perp^2, Q^2)$ … $q = (u, d)$

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

3 free parameters:

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

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Gaussian ansatz: $g_{1T}^q(x, \vec{k}_\perp^2, Q^2)$ … $q = (u, d)$

3 free parameters:

We checked explicitly that using different values of TMD width and beta does not change the qualitative conclusions of our results

- Fix TMD width: $\langle k_\perp^2 \rangle \big|_{g_{1T}} \approx 0.40$
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Remarks about evolution

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- **The quantity $g_{1T}^{(1)}(x)$ evolves according to $f_1(x)$:**

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

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$$g_{1T}^{(1)}(x) \equiv \tilde{g}(x)$$

$$\begin{aligned}\frac{\partial \tilde{g}(x_B,\mu^2)}{\partial \ln\mu^2} &= \frac{\alpha_s}{2\pi}\int\frac{dxdy}{x}\left\{\tilde{g}(x)\delta(y-x)\left[C_F\left(\frac{1+z^2}{(1-z)_+}+\frac{3}{2}\delta(1-z)\right)-\frac{C_A}{2}\frac{1+z^2}{1-z}\right]\right.\\ &+\tilde{G}_D(x,y)\left[C_F\left(\frac{x_B^2}{x^2}+\frac{x_B}{y}-\frac{2x_B^2}{xy}-\frac{x_B}{x}-1\right)+\frac{C_A}{2}\frac{(x_B^2+xy)(2x_B-x-y)}{(x_B-y)(x-y)y}\right]\\ &\left.+G_D(x,y)\left[C_F\left(\frac{x_B^2}{x^2}+\frac{x_B}{y}-\frac{x_B}{x}-1\right)+\frac{C_A}{2}\frac{x_B^2-xy}{(y-x_B)y}\right]\right\}\end{aligned}$$

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DGLAP kernel

$$\frac{\partial \tilde{g}(x_B,\mu^2)}{\partial \ln\mu^2} = \frac{\alpha_s}{2\pi}\int \frac{dxdy}{x}\left\{\boxed{\tilde{g}(x)\delta(y-x)\left[C_F\left(\frac{1+z^2}{(1-z)_+}+\frac{3}{2}\delta(1-z)\right)\right.}-\frac{C_A}{2}\frac{1+z^2}{1-z}\right]$$
$$+\tilde{G}_D(x,y)\left[C_F\left(\frac{x_B^2}{x^2}+\frac{x_B}{y}-\frac{2x_B^2}{xy}-\frac{x_B}{x}-1\right)+\frac{C_A}{2}\frac{(x_B^2+xy)(2x_B-x-y)}{(x_B-y)(x-y)y}\right]$$
$$\left.+G_D(x,y)\left[C_F\left(\frac{x_B^2}{x^2}+\frac{x_B}{y}-\frac{x_B}{x}-1\right)+\frac{C_A}{2}\frac{x_B^2-xy}{(y-x_B)y}\right]\right\}$$

$$g_{1T}^{(1)}(x) \equiv \tilde{g}(x)$$

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

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:

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

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

Fitting procedure: Monte-Carlo technique

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

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Theory

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Theory

Fit to exp. data

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

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Theory

Fit to exp. data

Minimize:

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

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

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Fit to exp. data

Minimize weighted chi-squared:

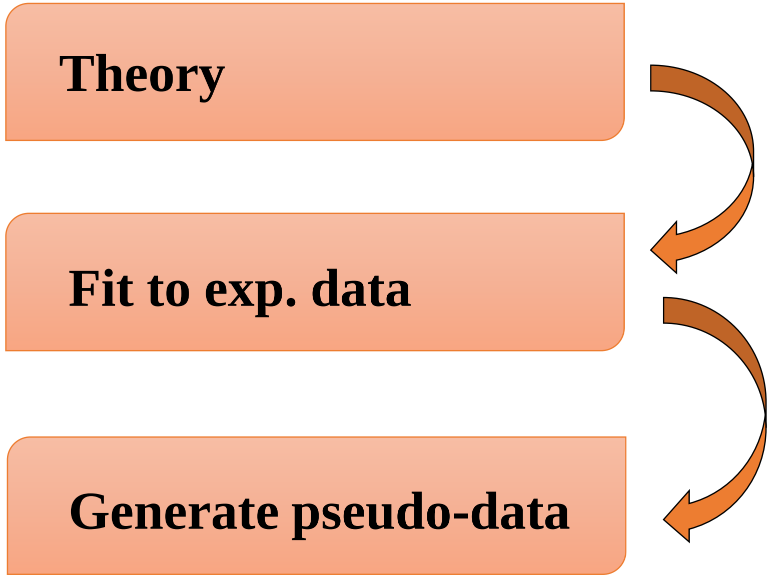
$$\chi^2 = \sum_{\mathrm{H+C}} \frac{(\mathrm{exp.\,data} - \mathrm{theory})^2}{(\mathrm{exp.\,error})^2} + w \sum_{\mathrm{J}} \frac{(\mathrm{exp.\,data} - \mathrm{theory})^2}{(\mathrm{exp.\,error})^2}$$

(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

Fitting procedure: Monte-Carlo technique



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

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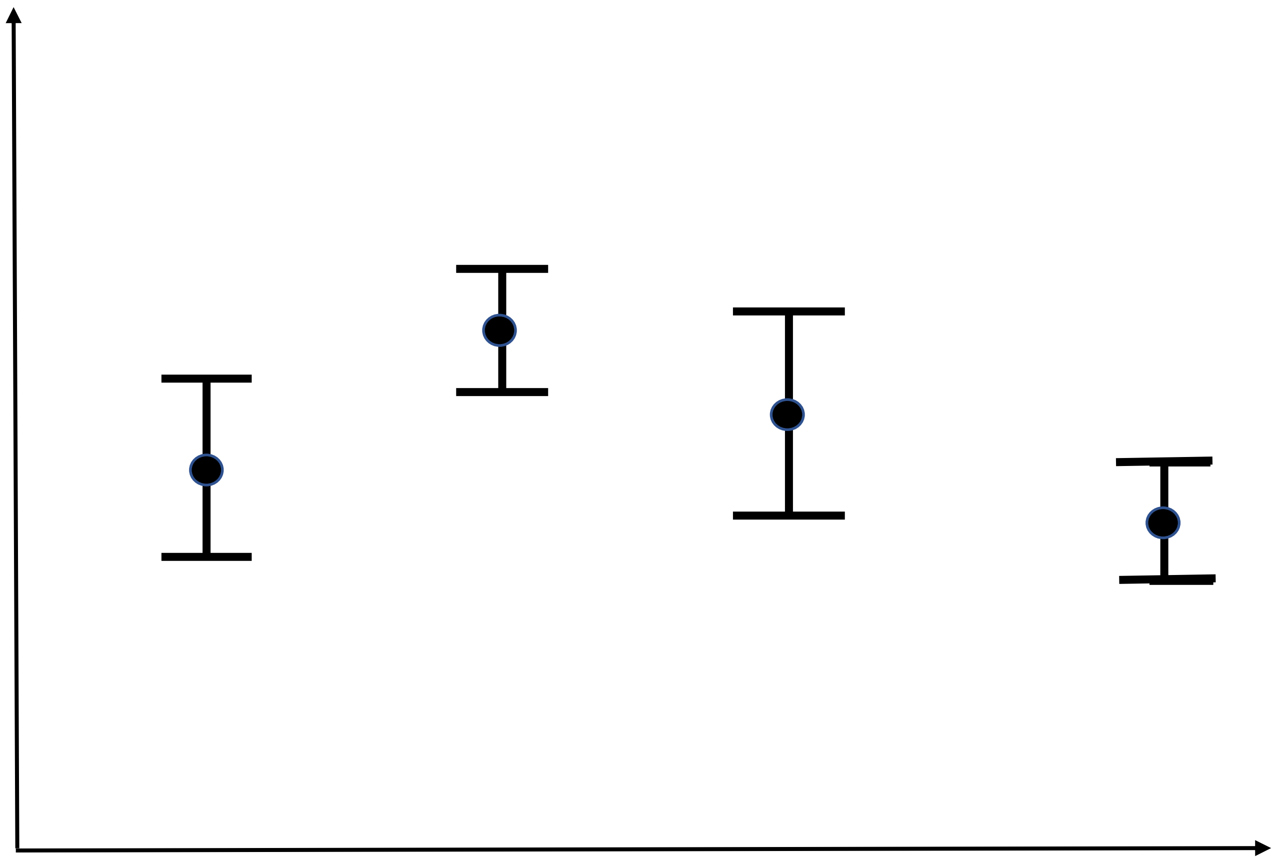
Theory

Fit to exp. data

Generate pseudo-data



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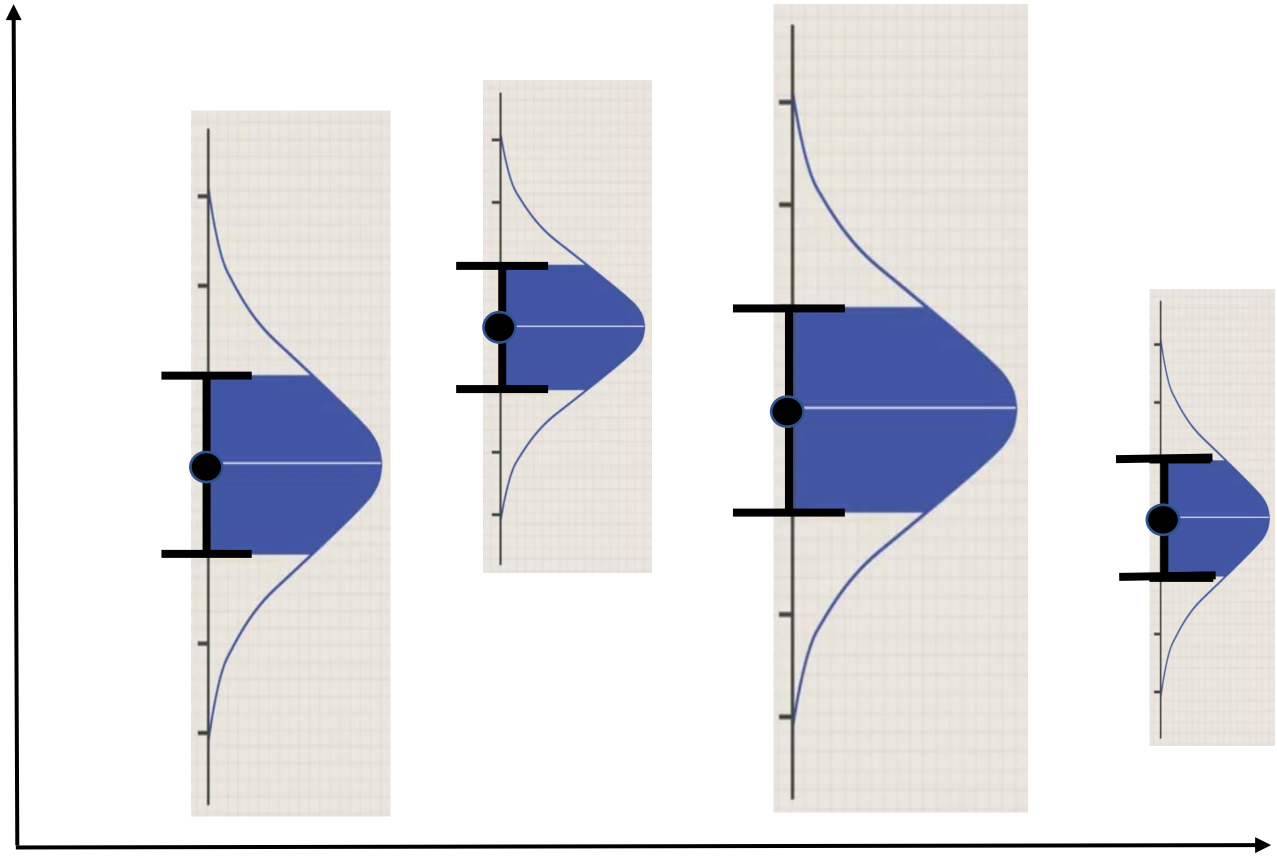

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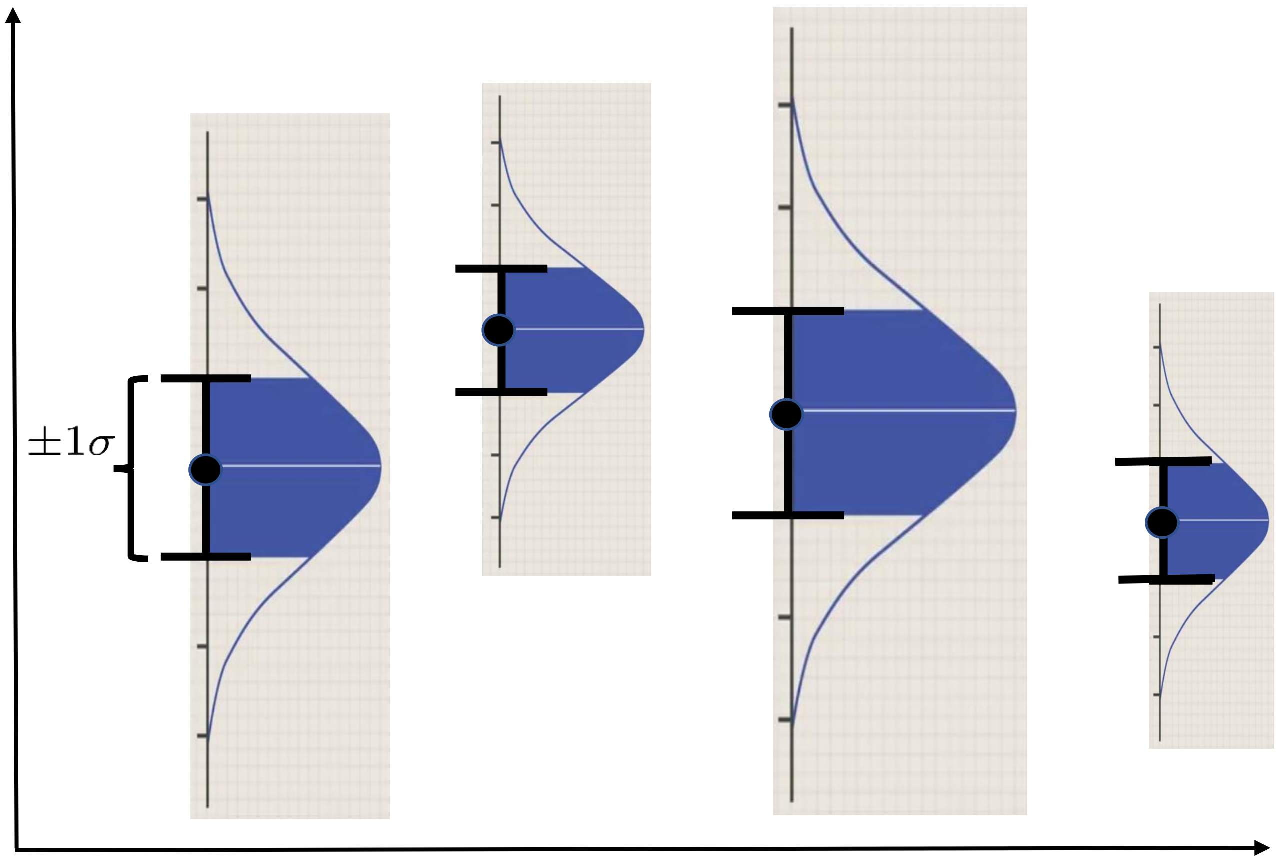

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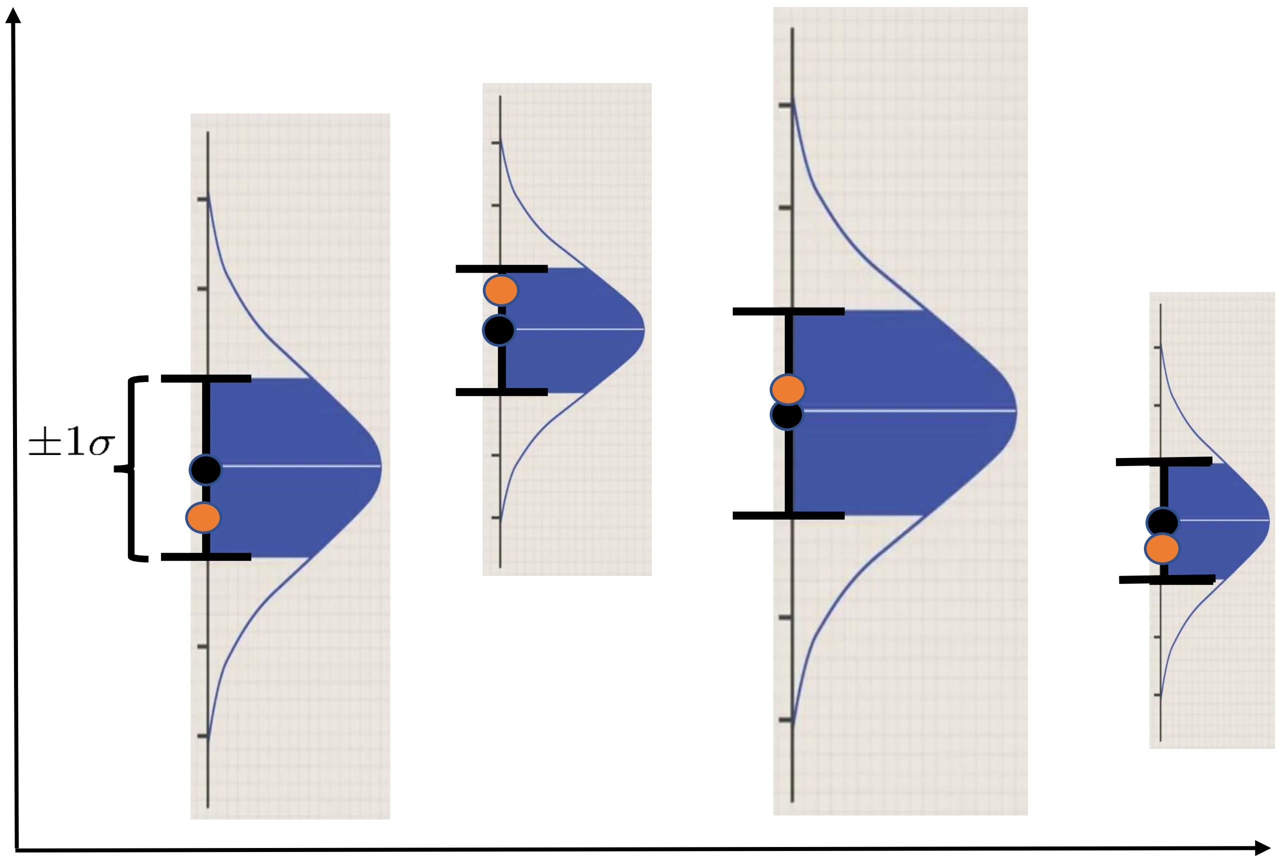

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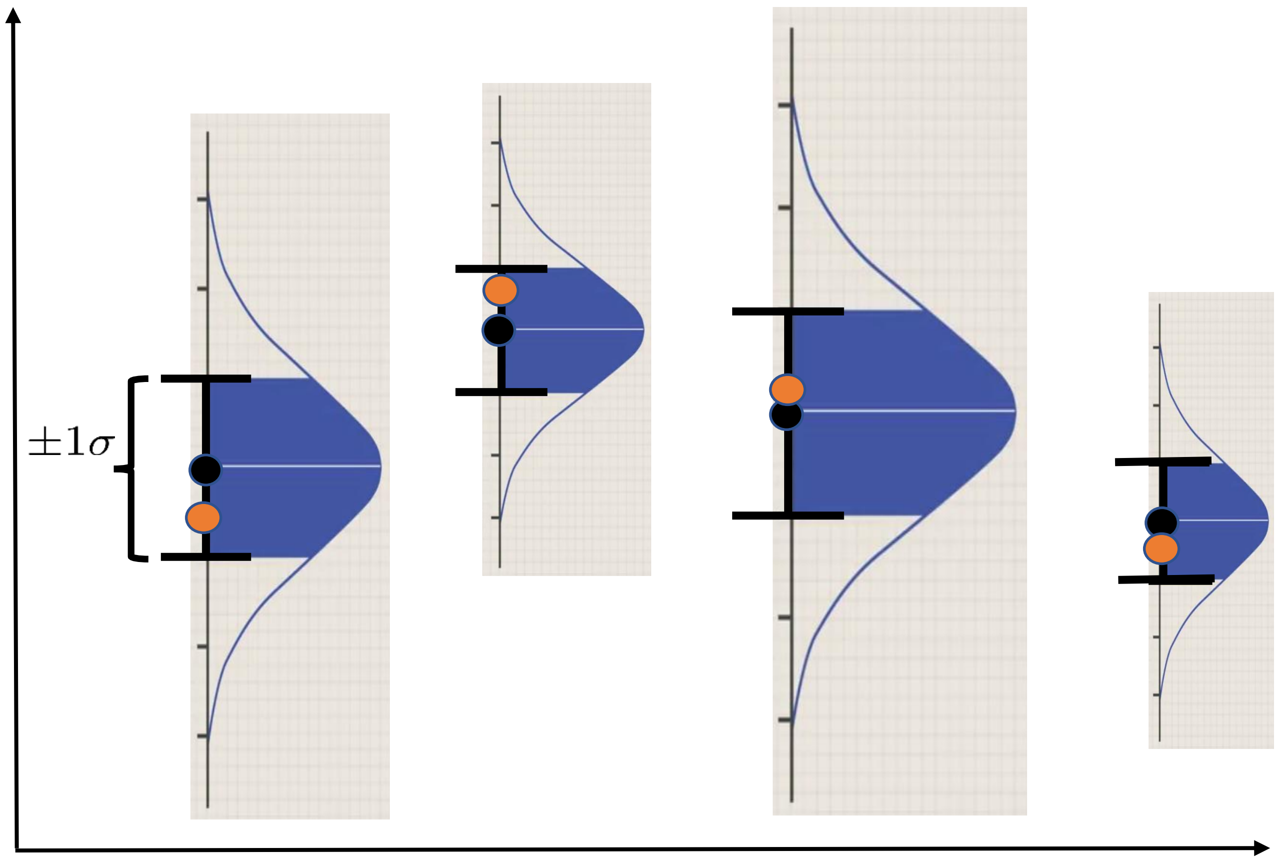

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Fitting procedure: Monte-Carlo technique

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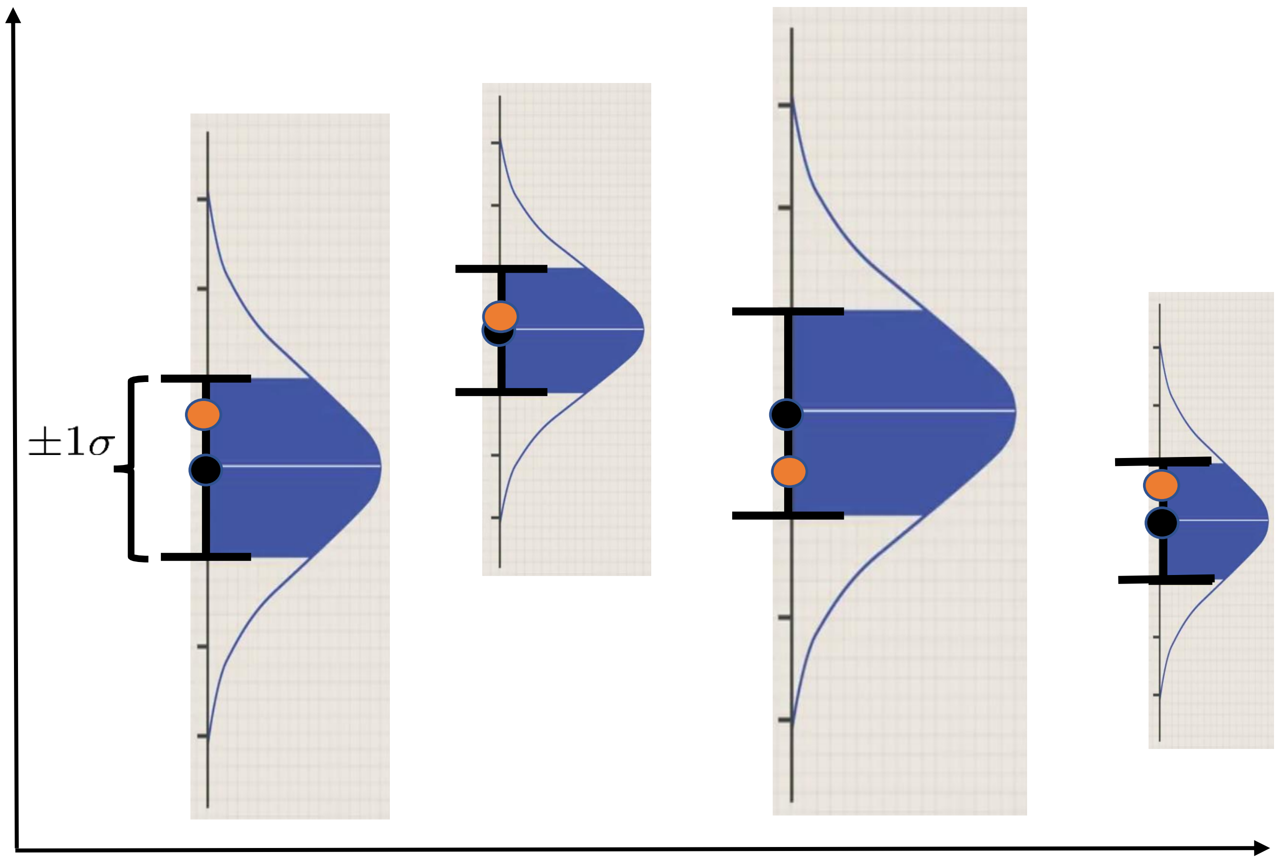
Fit to exp. data

Generate pseudo-data

Fit to pseudo-data



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

Fitting procedure: Monte-Carlo technique

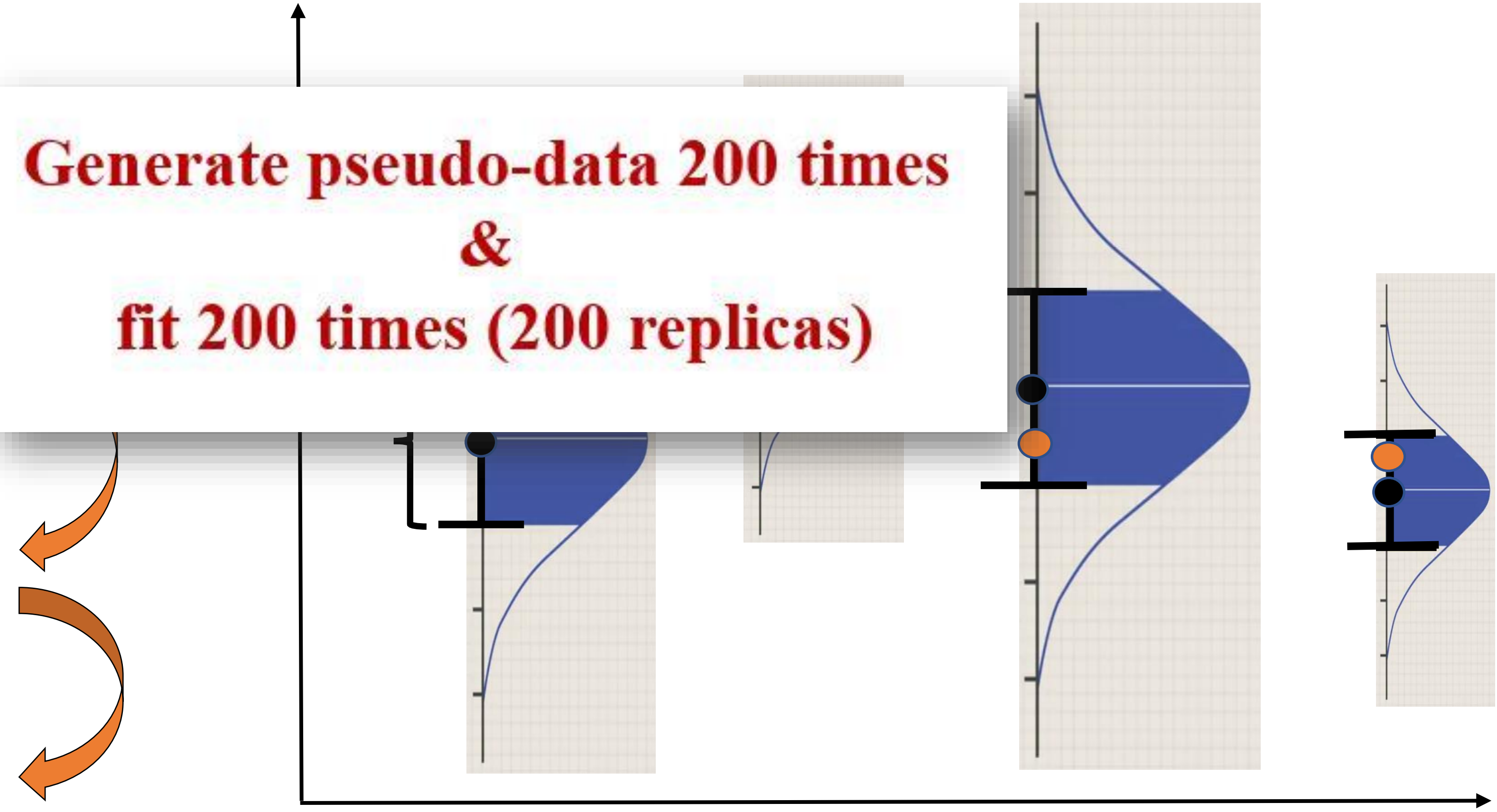
Theory

Fit to exp. data

Generate pseudo-data

Fit to pseudo-data

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



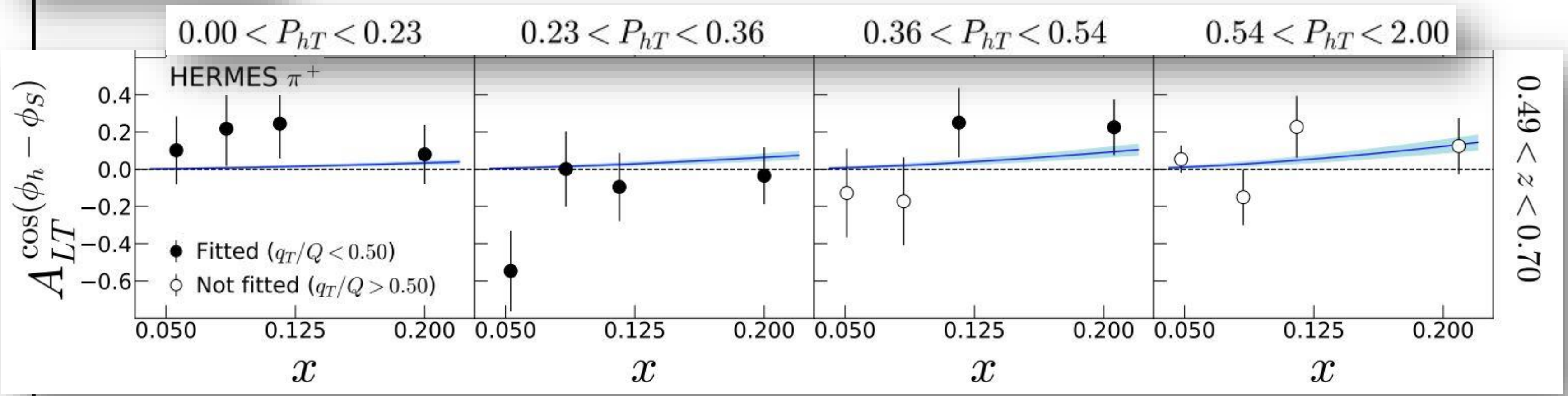
Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

Theory versus data

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

Sample results

Theory versus data

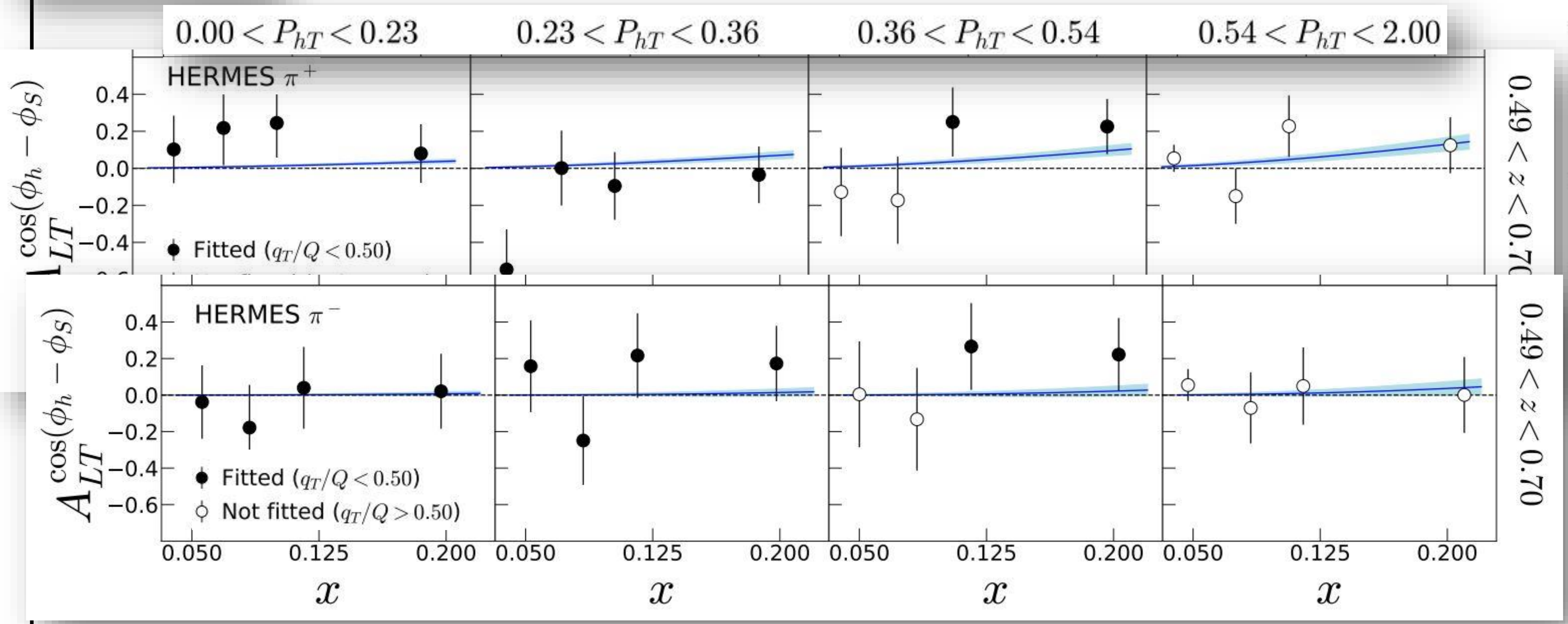


Data set	$\chi^2_w/N_{\text{pts.}}\|_{\text{Main}}$
HERMES π^+	1.20

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

Theory versus data

Sample results

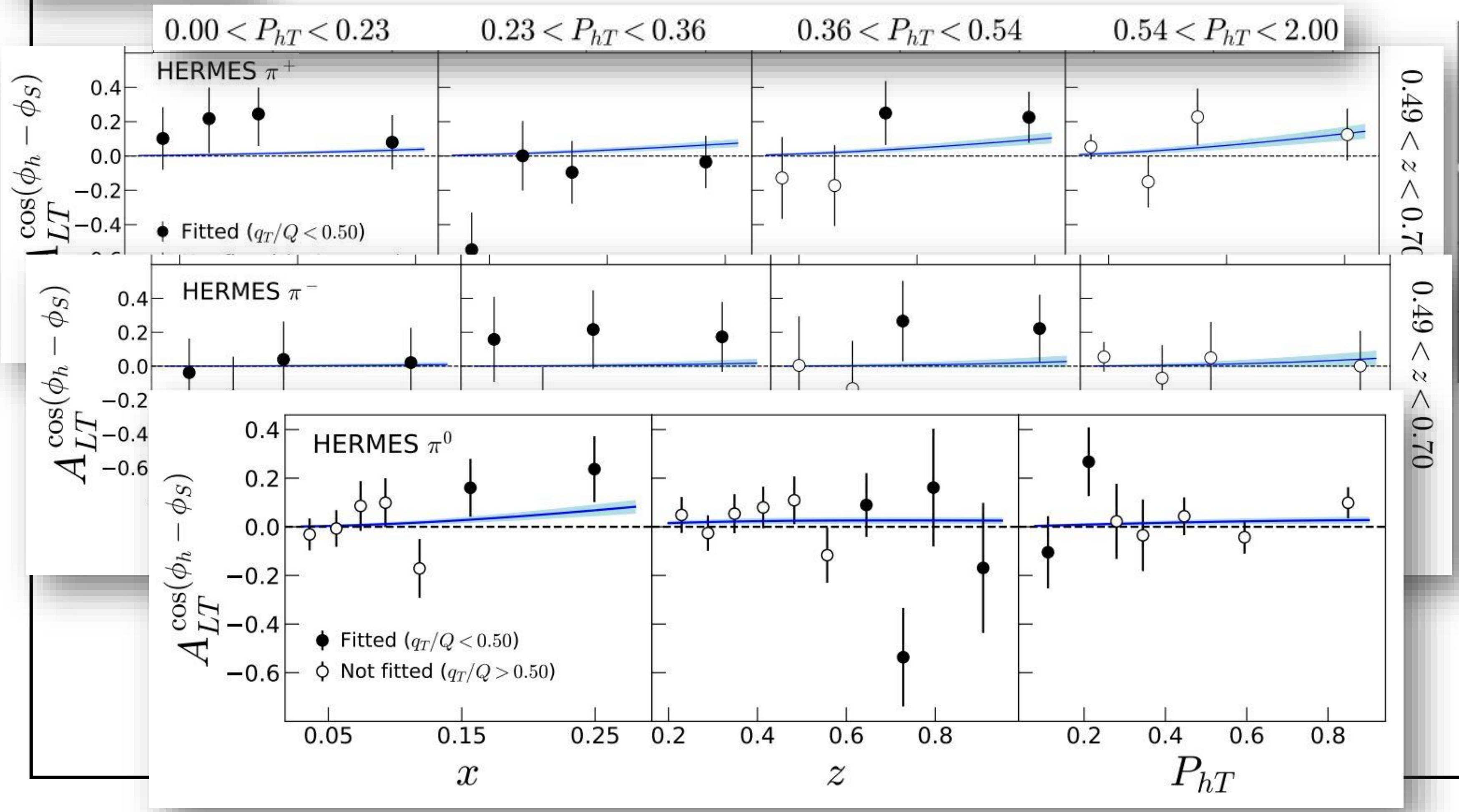


Data set	$\chi^2_w/N_{\text{pts.}}\vert_{\text{Main}}$
HERMES π^+	1.20
HERMES π^-	0.88

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

Sample results

Theory versus data

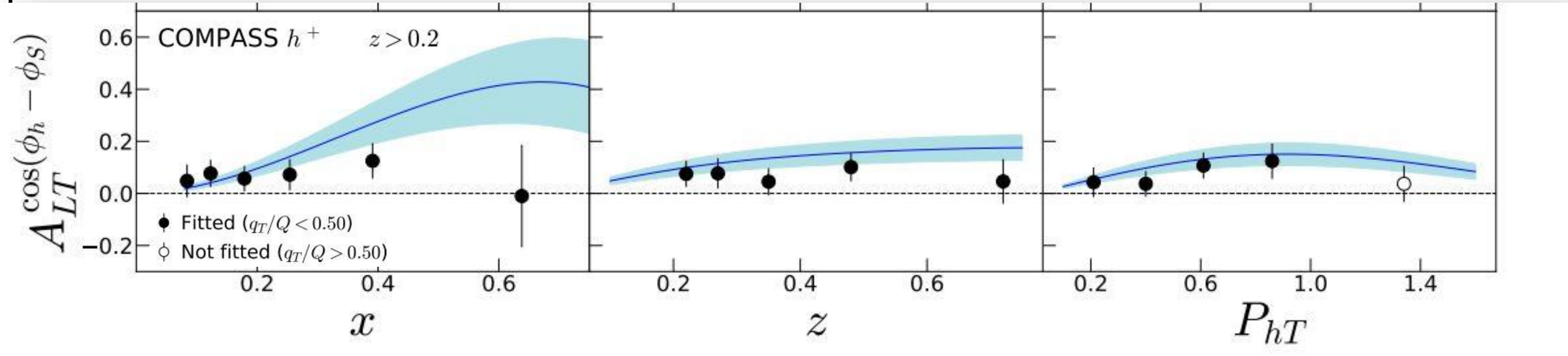


Data set	$\chi^2_w/N_{\text{pts.}}\big\vert_{\text{Main}}$
HERMES π^+	1.20
HERMES π^-	0.88
HERMES π^0	1.94

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

Sample results

Theory versus data



Data set	$\chi^2_w/N_{pts.}\vert_{Main}$
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Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

Sample results

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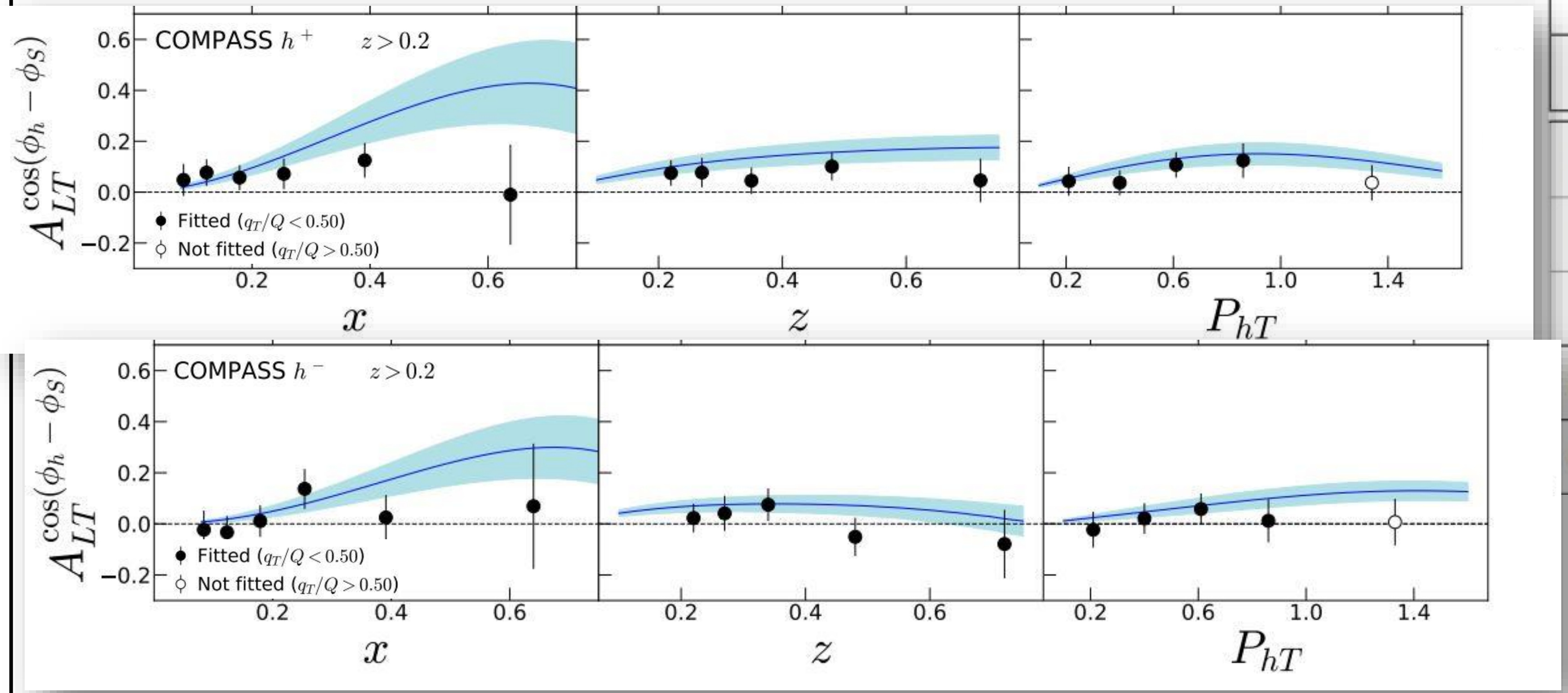

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Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

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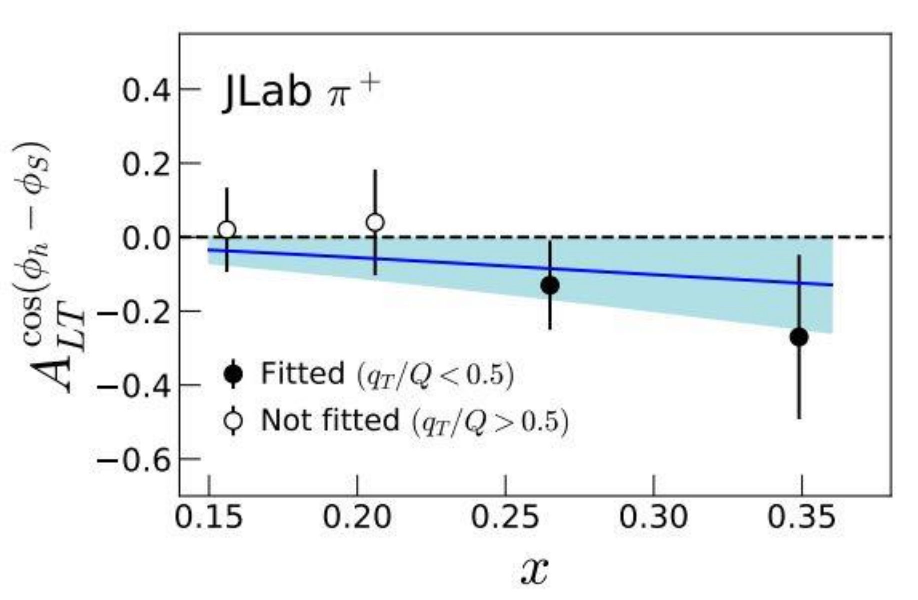

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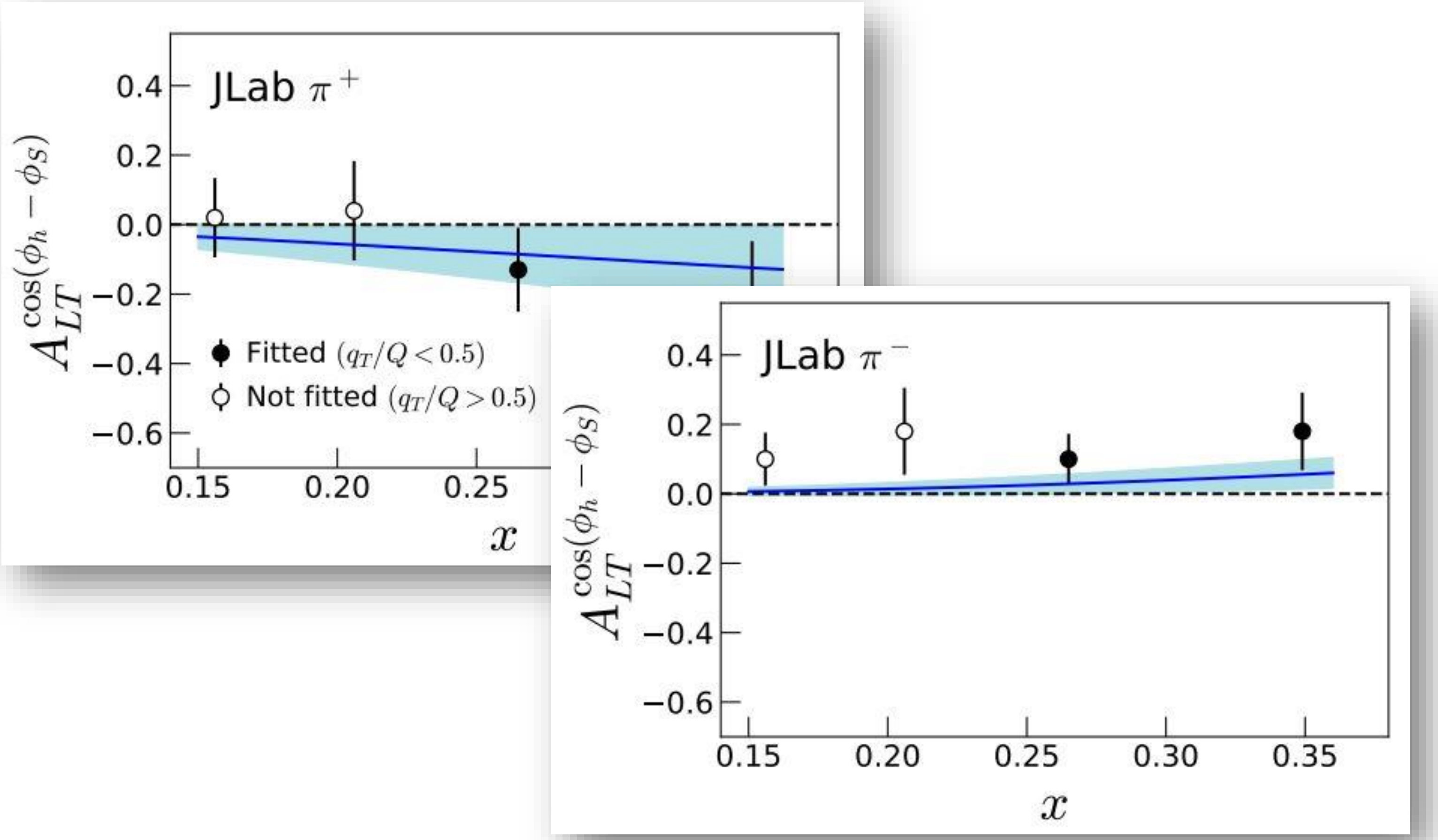

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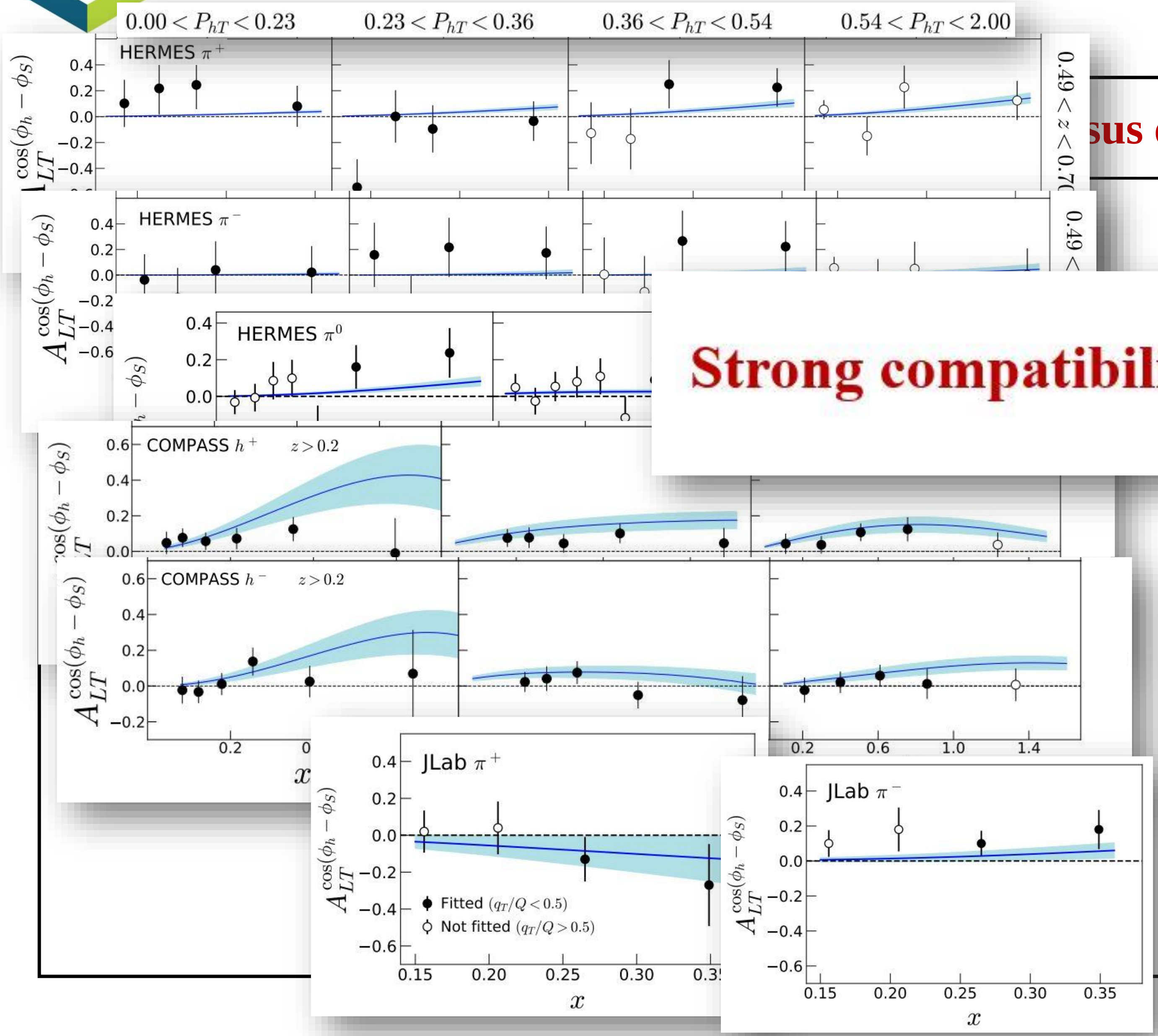


sus data

Strong compatibility between our theory and data

HERMES π^0	1.94
COMPASS h^+	0.97
COMPASS h^-	0.71
JLab π^+	0.31
JLab π^-	1.13
Global	**0.86**

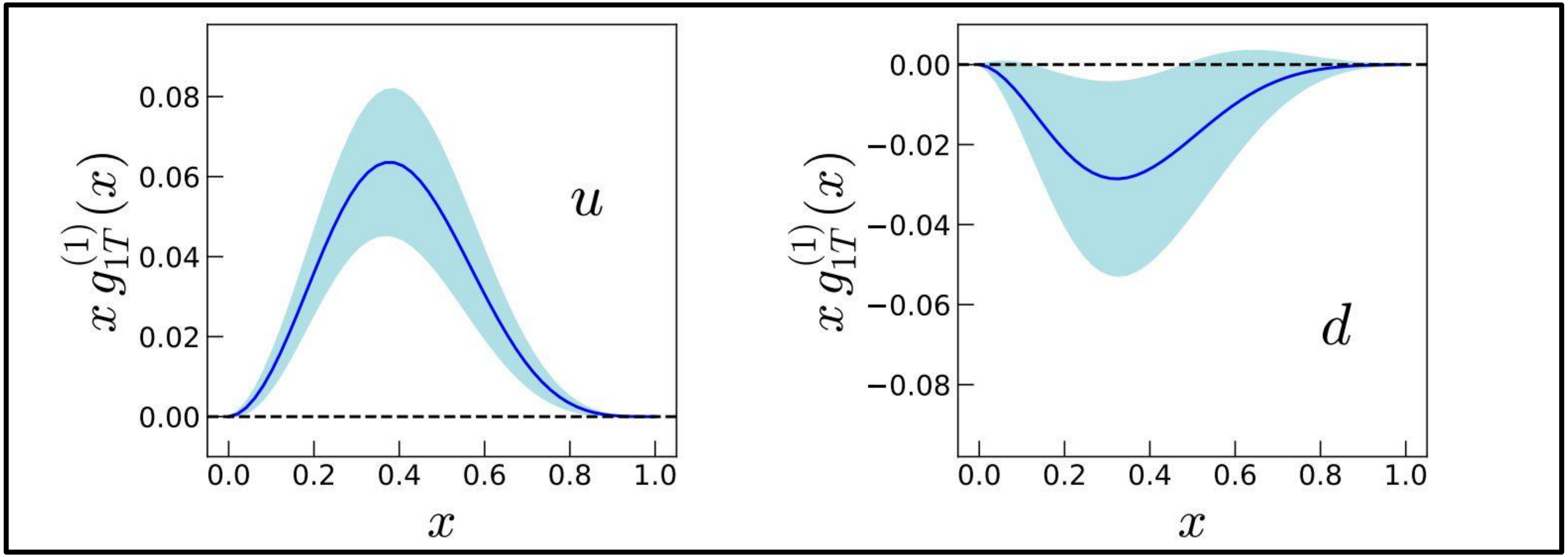
Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

Results for the x-dependence

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

Average value of all replicas at a given x + 1-sigma error band

Results for the x-dependence

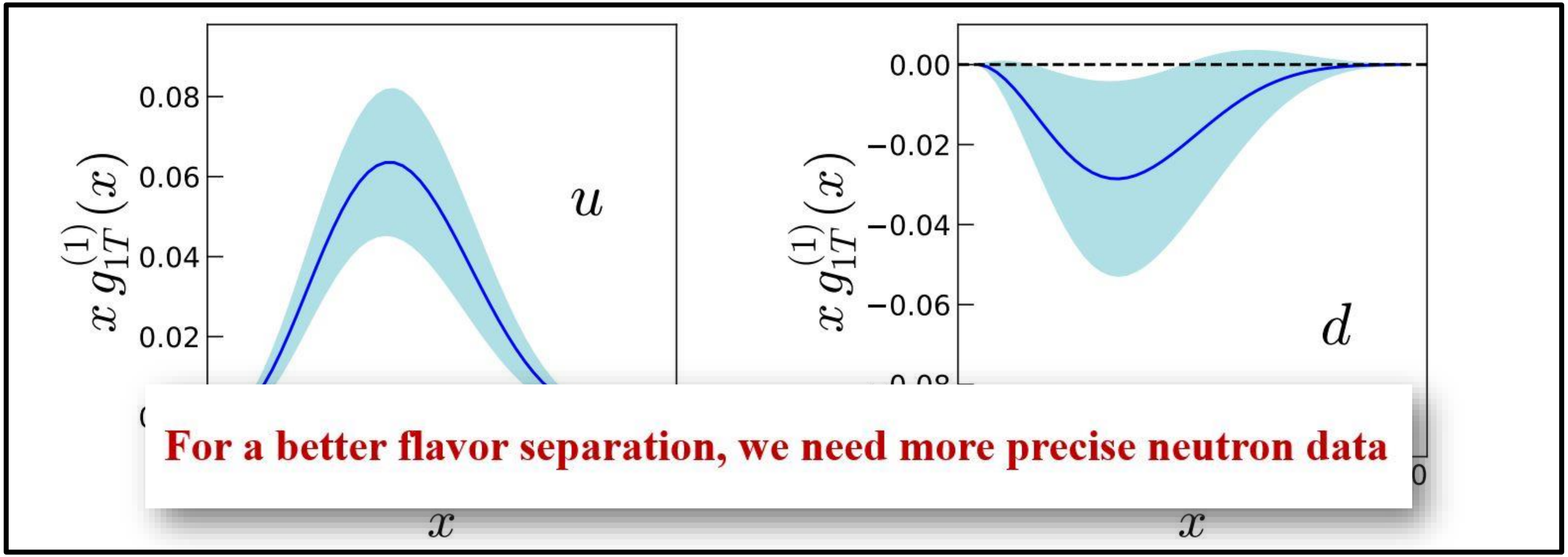


- **Up quark distribution is positive**
- **Down quark distribution is mostly negative**

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

Average value of all replicas at a given *x* + 1-sigma error band

Results for the x-dependence



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

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

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

Test of theoretical approximations

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

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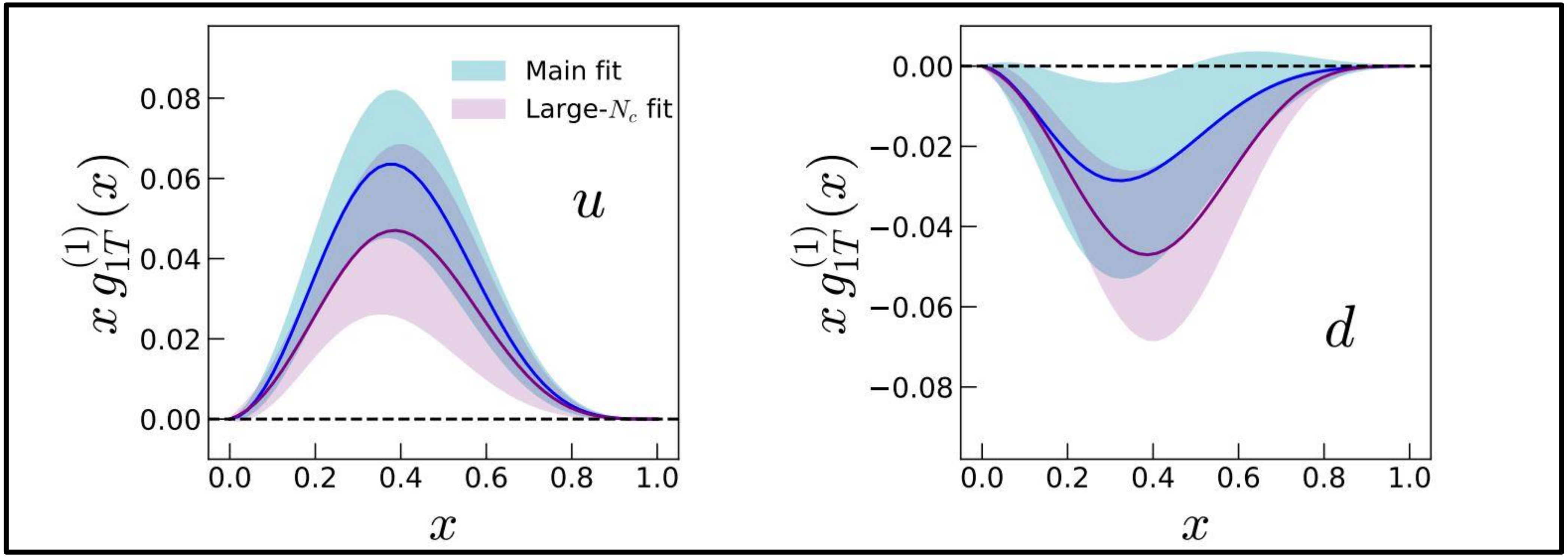
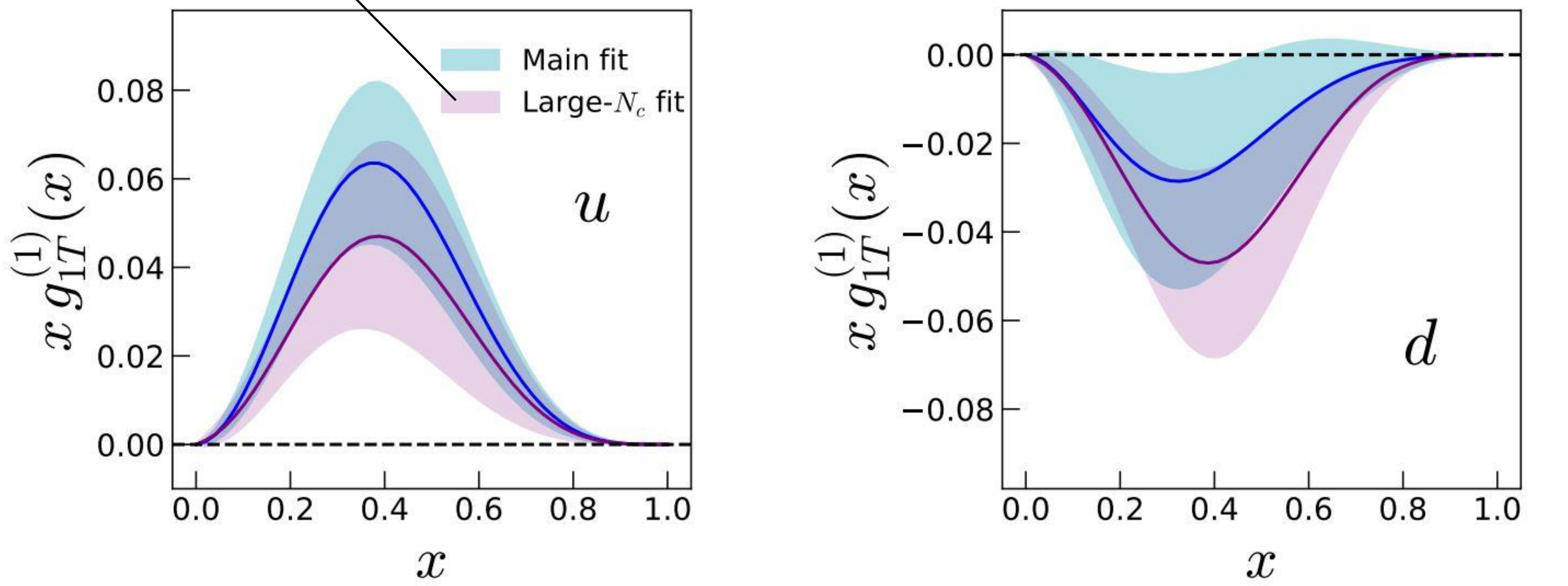


- **Qualitative agreement with large-$\mathrm{N_c}$ fit**
- **Slight preference to violate large-$\mathrm{N_c}$ approx.**

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

Set: $g_{1T}^{u}(x, \vec{k}_{\perp}^{2}) = -g_{1T}^{d}(x, \vec{k}_{\perp}^{2})$

Test of theoretical approximations



- **Qualitative agreement with large-N_c fit**
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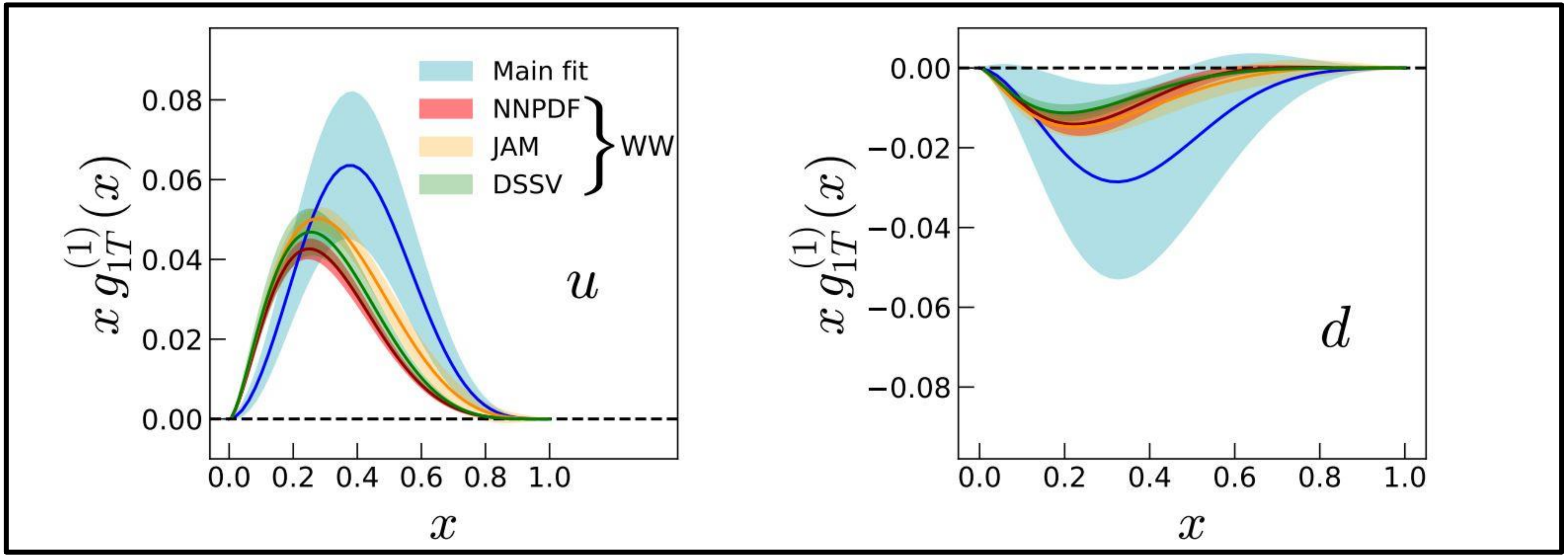
Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

Test of theoretical approximations

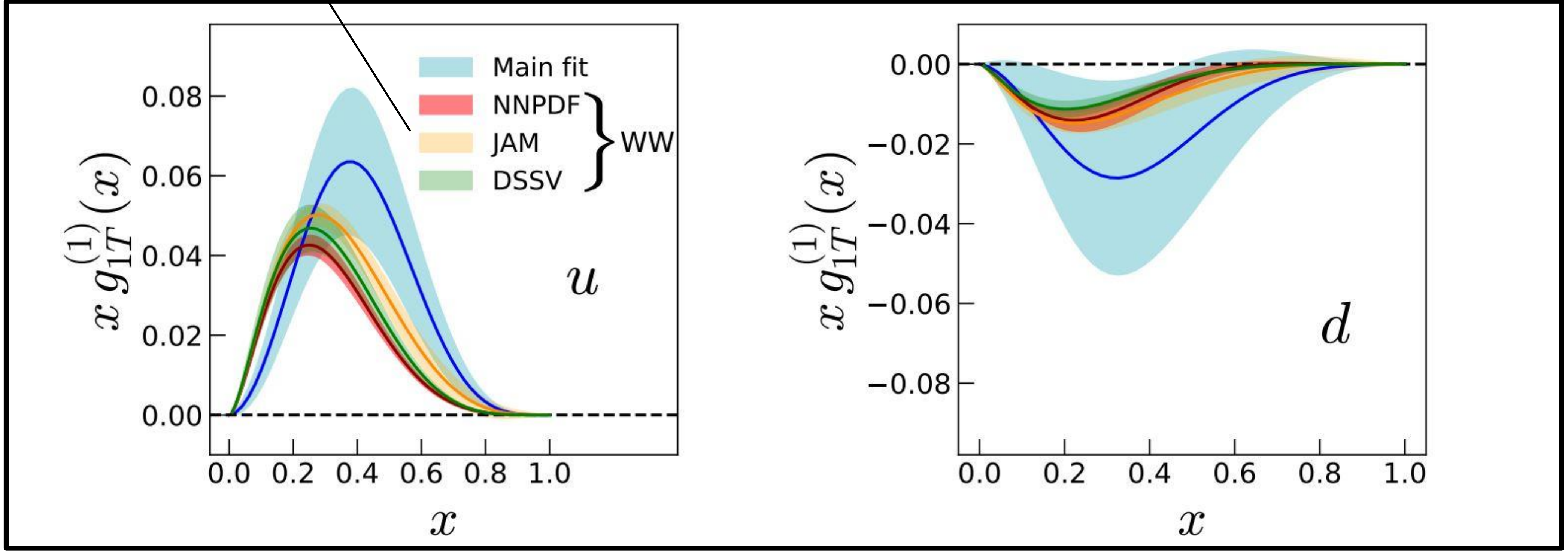


- **Qualitative agreement with WW-type approx.**
- **Hints of slight violation of WW-type approx.**

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

Set: $g_{1T}^{(1),q}(x) = x \int_x^1 dy \, \frac{g_1^q(y)}{y}$

Test of theoretical approximations



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

Deviation from theoretical approximations?

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

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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

pproximations?

Similar or better chi-squared for some data sets

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HERMES π^+	1.20		1.19	1.19	1.19
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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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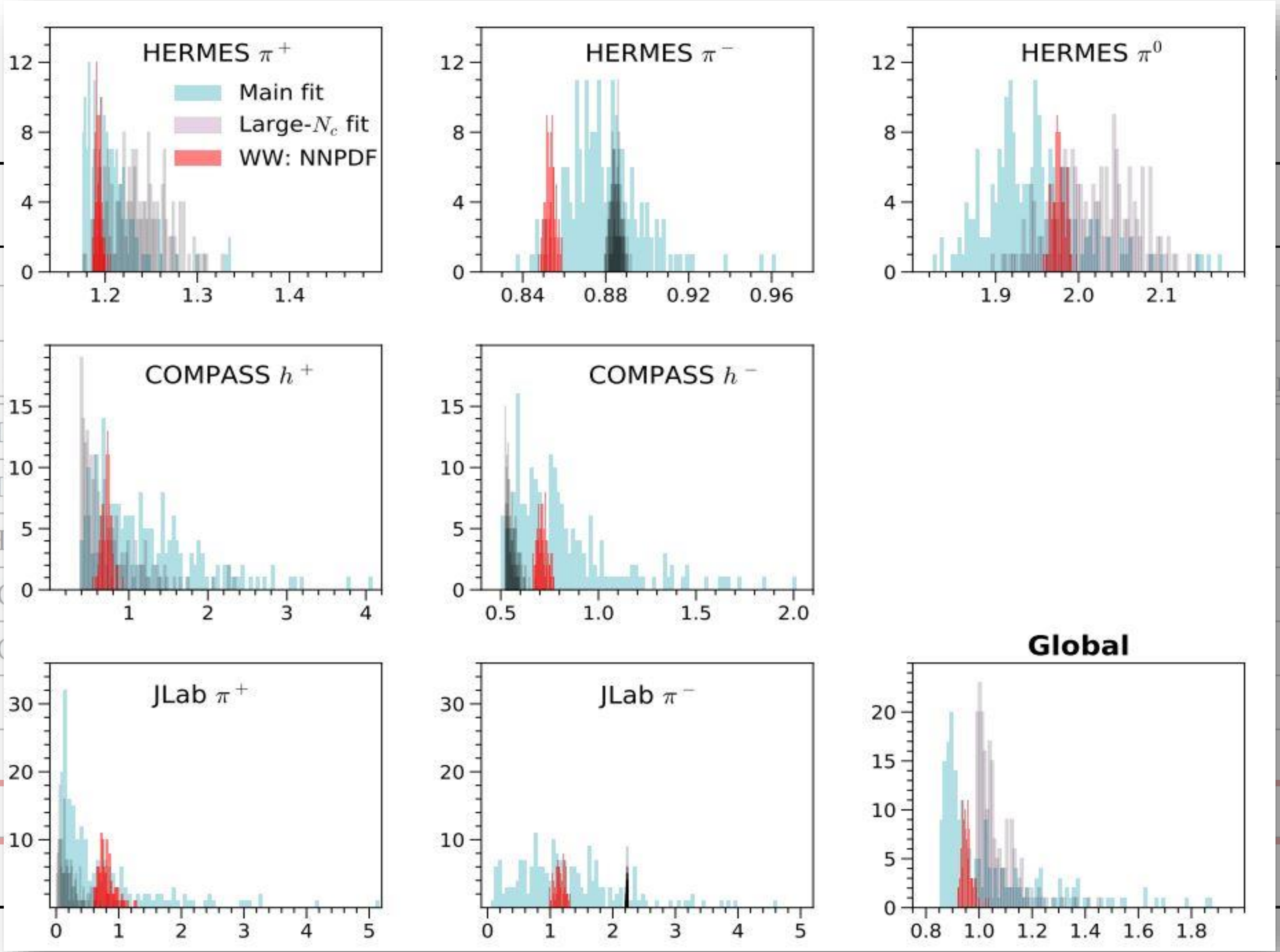
HERMES π^0	1.94	2.01	1.98	1.95	1.96
COMPASS h^+	0.97	0.51	0.71	1.02	0.89
COMPASS h^-	0.71	0.53	0.71	0.81	0.80
JLab π^+	0.31	0.06	0.81	0.78	0.96
JLab π^-	1.13	2.23	1.15	0.93	0.93
Global	**0.86**	**0.99**	**0.95**	**0.94**	**0.97**

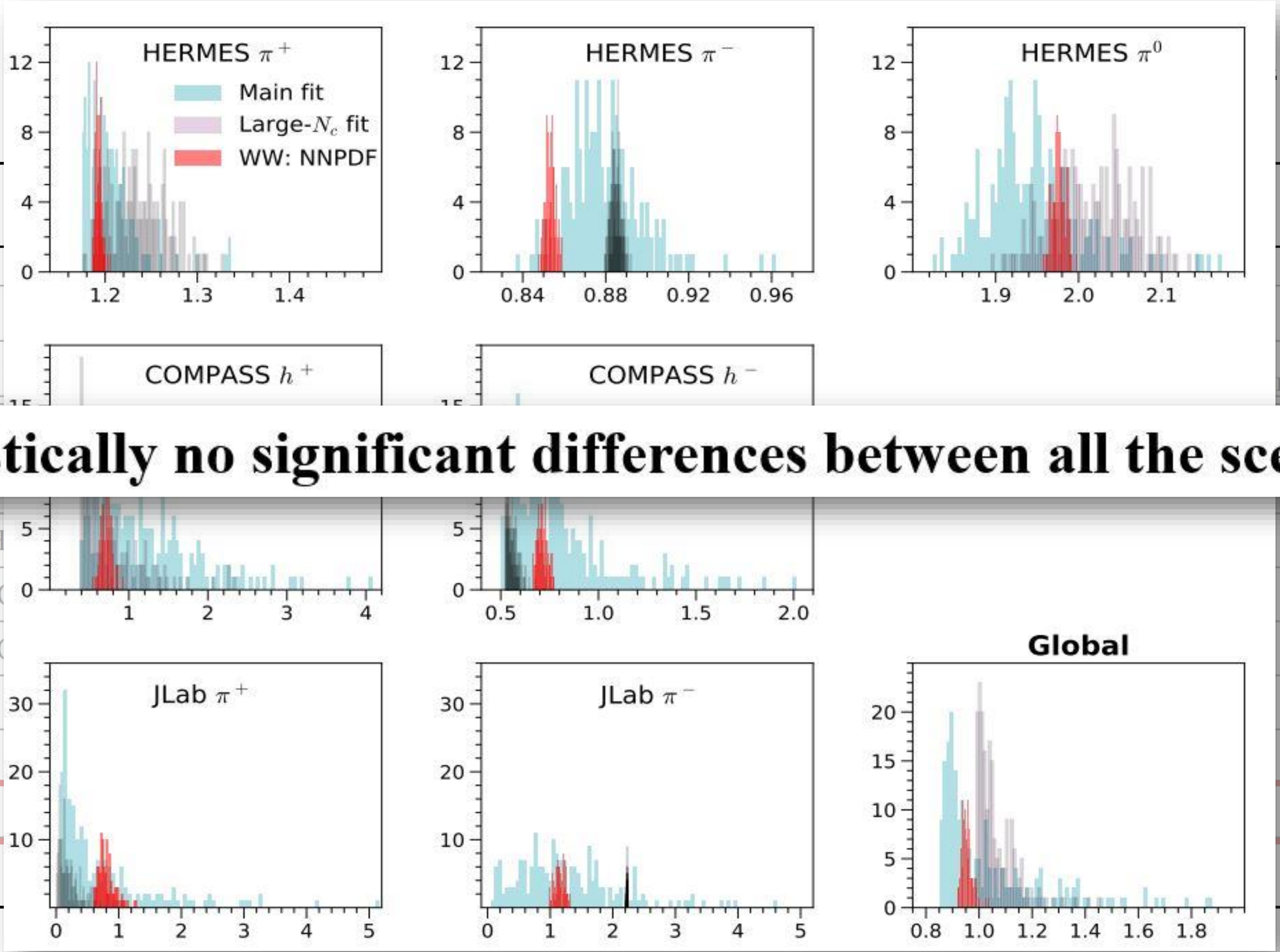
Extraction of g_{1T} TMD from HERMES, COMPASS & JLab data

Deviation from theoretical approximations?

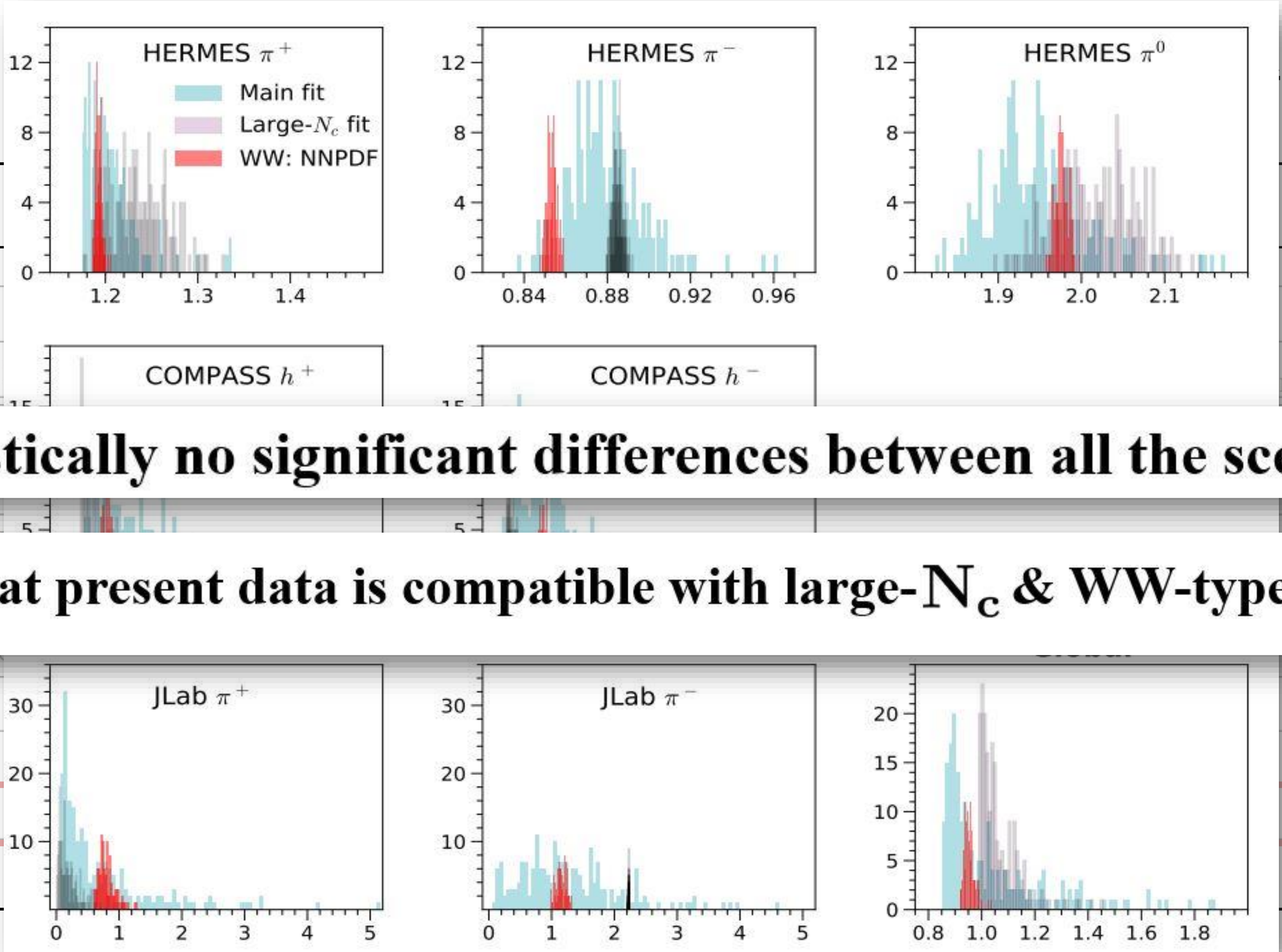
Summary of $\chi^2_w/N_{pts.}$					
Data set	$\chi^2_w/N_{pts.}\vert_{Main}$	$\chi^2_w/N_{pts.}\vert_{Large\text{-}N_c}$	$\chi^2_w/N_{pts.}\vert_{NNPDF}$	$\chi^2_w/N_{pts.}\vert_{JAM}$	$\chi^2_w/N_{pts.}\vert_{DSSV}$
HERMES π^+	1.20	1.23	1.19	1.19	1.19
HERMES π^-	0.88	0.88	0.85	0.85	0.85
HERMES π^0	1.94	2.01	1.98	1.95	1.96
COMPASS h^+	0.97	0.51	0.71	1.02	0.89
COMPASS h^-	[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^-
Global
JLab π^+
JLab π^-



Statistically no significant differences between all the scenarios



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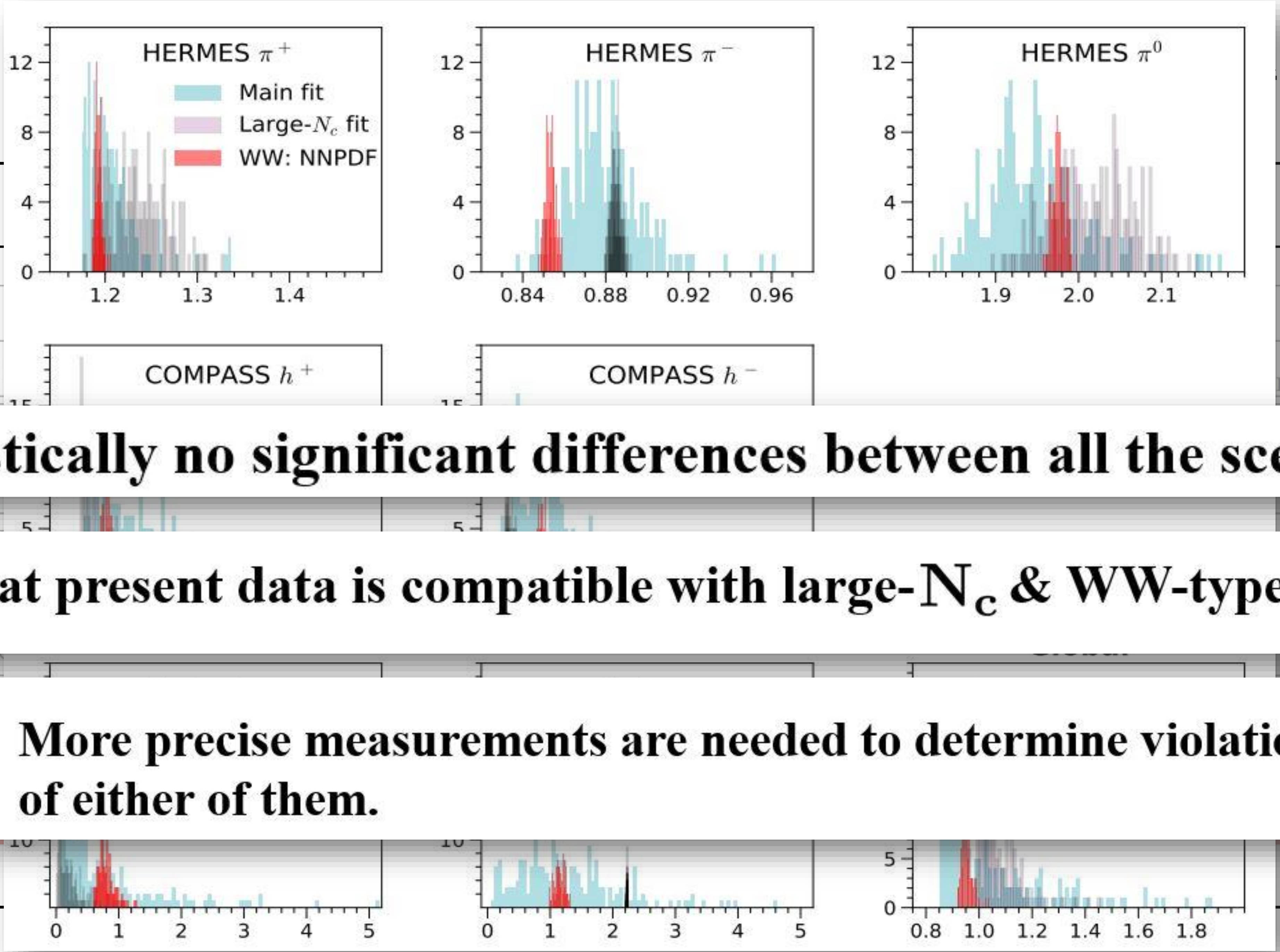
Hence, at present data is compatible with large-N_c & WW-type approx.



Statistically no significant differences between all the scenarios

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

More precise measurements are needed to determine violation of either of them.

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

Comparison with lattice QCD results

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

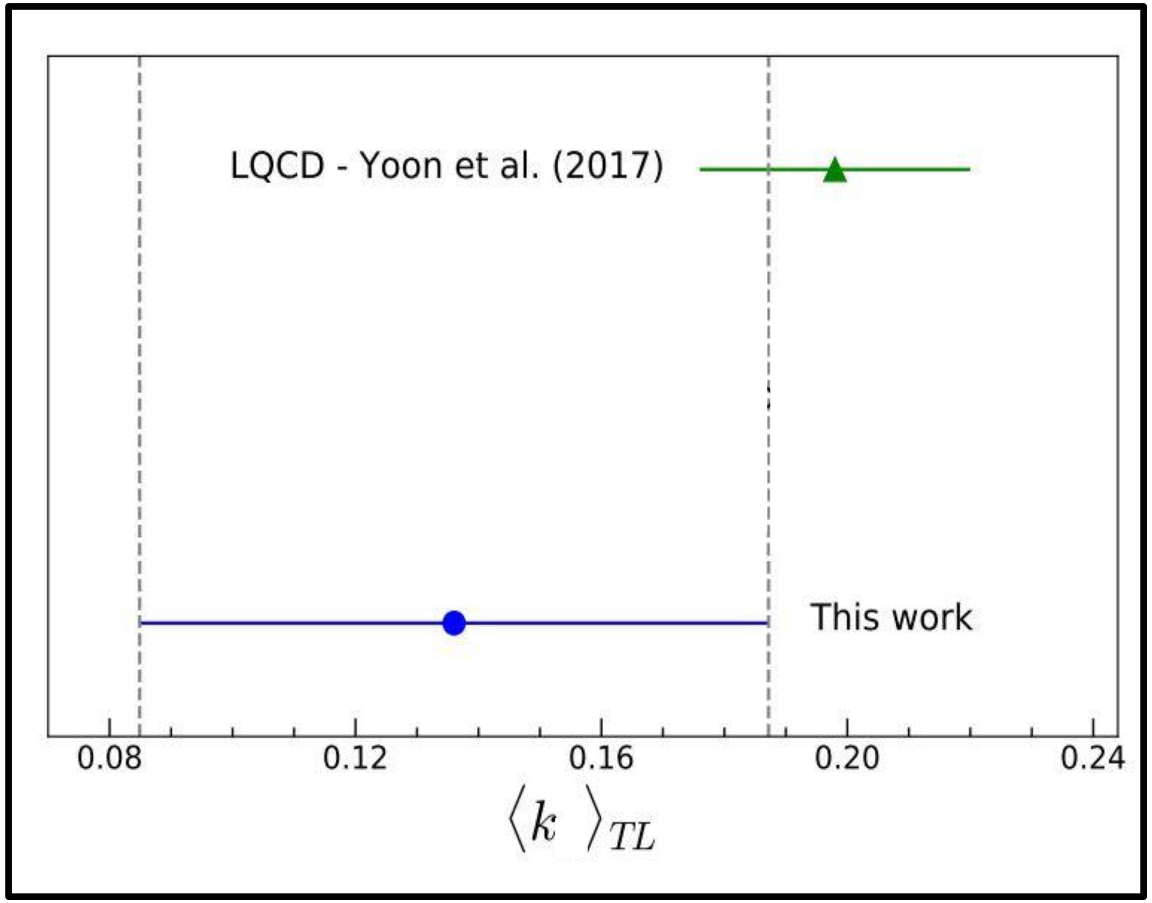
Comparison with lattice QCD results

Calculation of worm-gear shift:

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

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

Comparison with lattice QCD results



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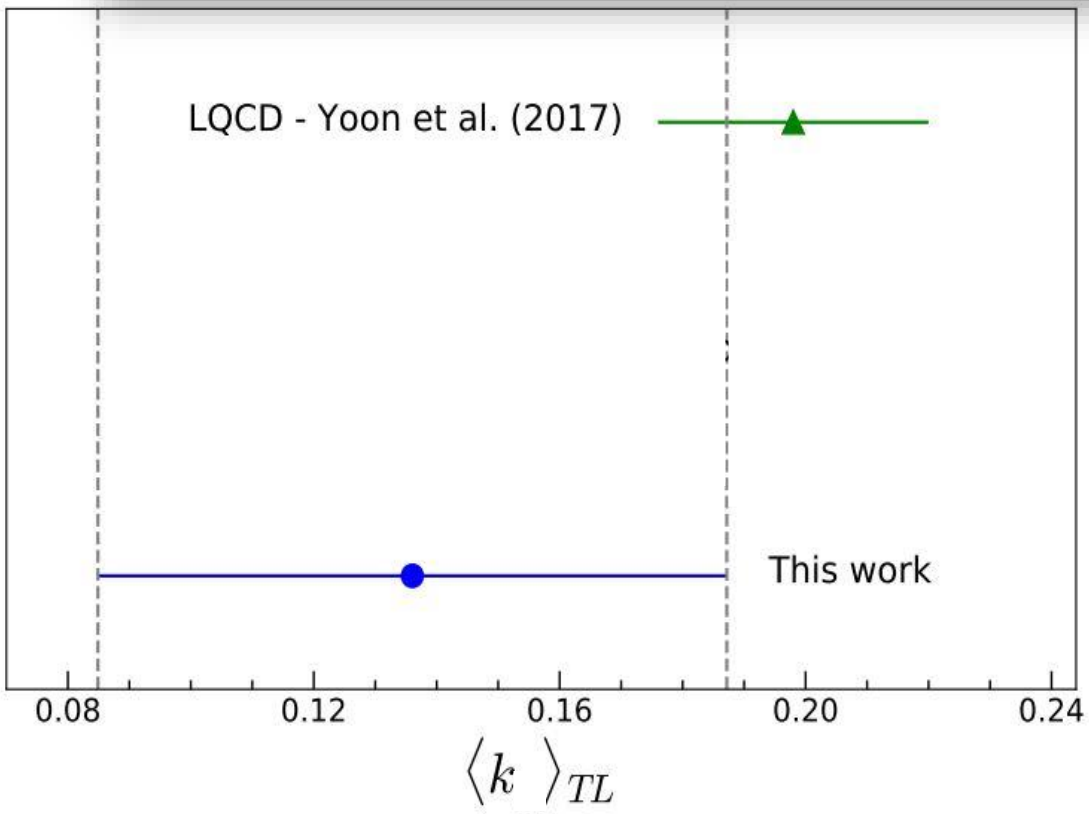
- **Consistency between lattice results & our main fit result**

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

…ce QCD results



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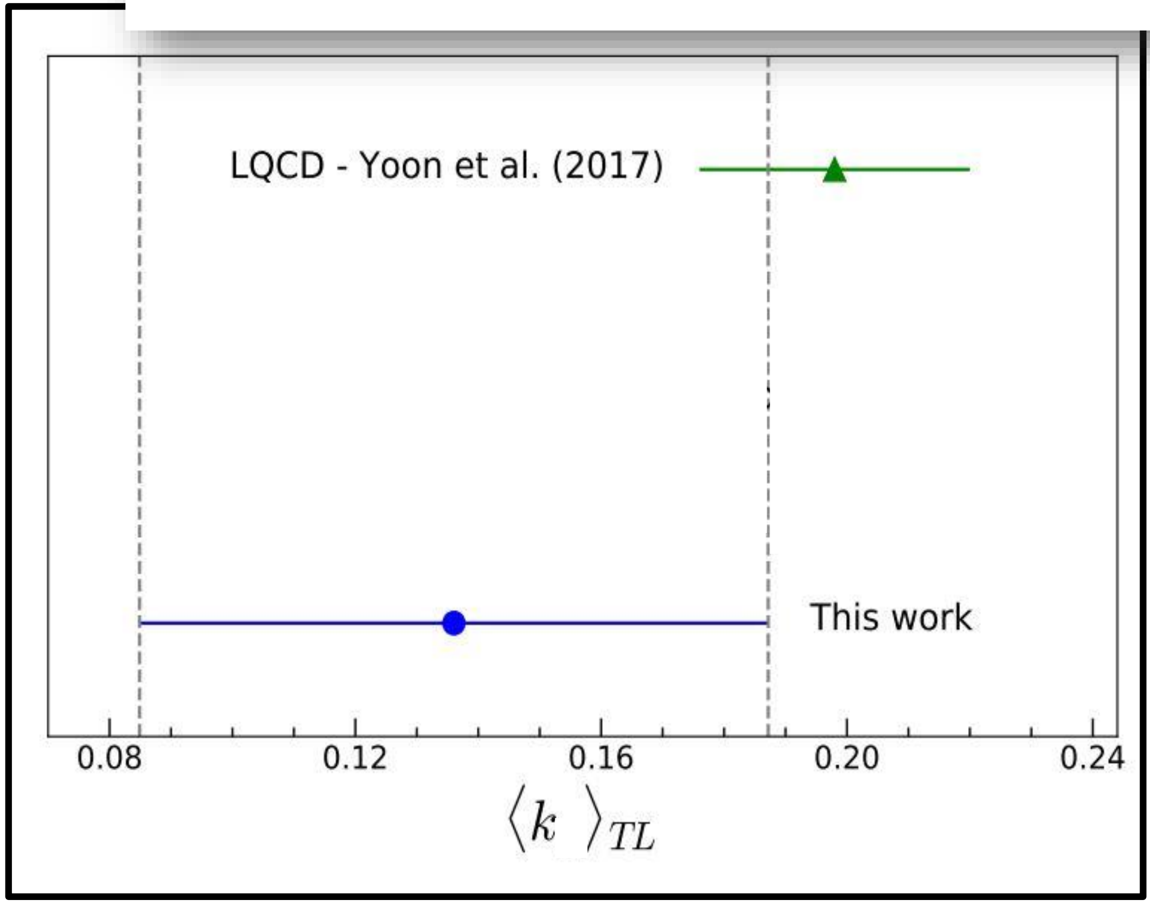

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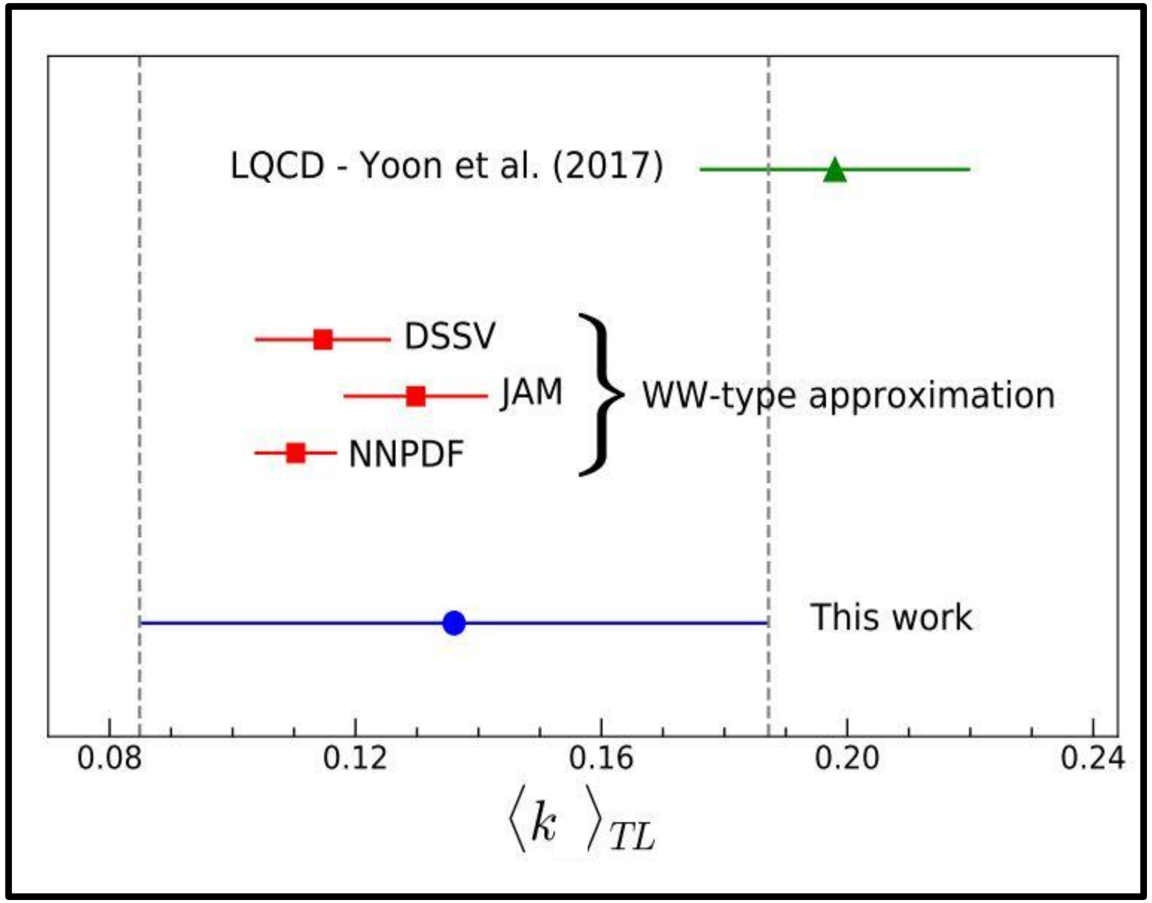
- **It is encouraging that lattice QCD & exp. data are in reasonable agreement**

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

Comparison with lattice QCD results



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

- **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 performed the first extraction of g_{1T} from experimental data, obtaining a very good fit simultaneously of HERMES, COMPASS, JLab data on SIDIS
- Additional deuteron and/or neutron measurements are needed for a cleaner flavor separation
- Qualitative agreements with large-$\mathrm{N_c}$ & WW-type approximation
- Although there is an indication of a slight violation of both the theoretical predictions, the data is not precise enough to affirm the degree of violation (if any)
- Any clear signal of violation of WW-type approximation would be a probe of quark-gluon-quark correlations
- Encouraging agreement in the worm-gear shift with lattice QCD results

Summary/Outlook

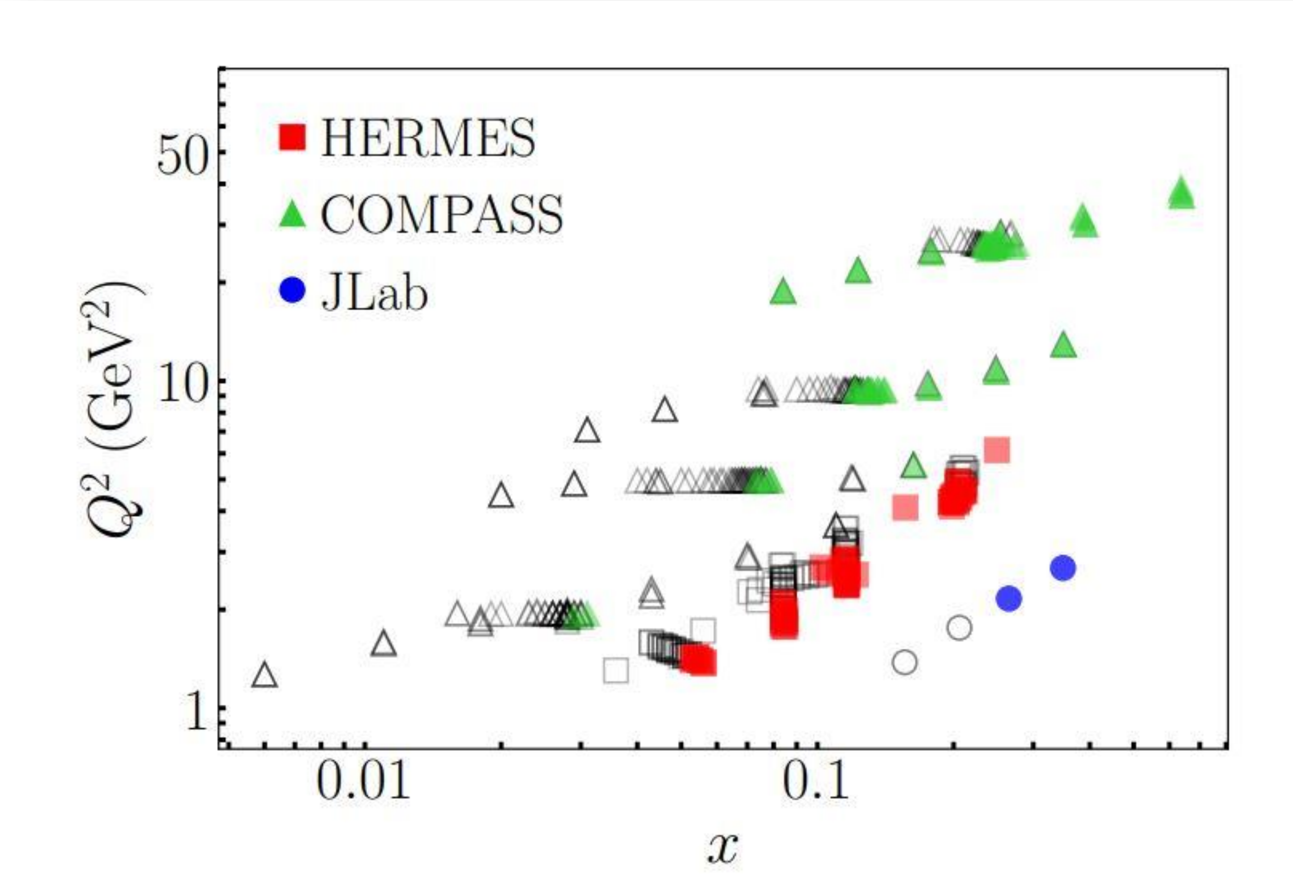
Outlook

- **Potential to access g_{1T} through asymmetries in weak gauge boson production: Study TMD evolution effects**
- **Extend analysis to extract $h_{1L}^{\perp}$**

…

Backup slides

Kinematic Coverage



Unweighted chi-squared technique results

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

Why "weighted" technique after-all?

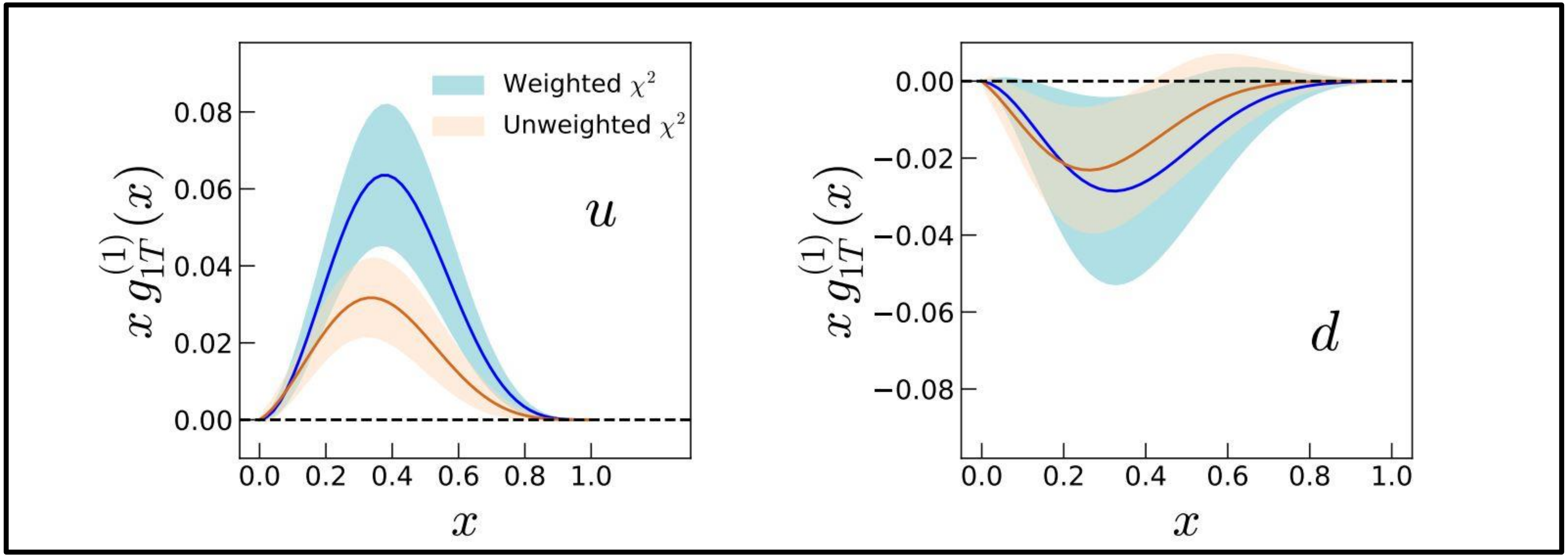
$$\chi^2 = \sum_{\mathrm{H+C+J}} \frac{(\mathrm{exp.\,data} - \mathrm{theory})^2}{(\mathrm{exp.\,error})^2}$$

Without weighting the chi-squared, we overfit COMPASS data, and we don't fit JLab π^- data particularly well.

HERMES π^-	0.89	0.88	0.85	0.85	0.85
HERMES π^0	2.03	2.03	1.98	1.95	1.96
COMPASS h^+	0.39	0.40	0.71	1.02	0.89
COMPASS h^-	0.54	0.53	0.71	0.81	0.80
JLab π^+	0.42	0.15	0.81	0.78	0.96
JLab π^-	1.88	2.23	1.15	0.93	0.93
Global	**0.83**	**0.83**	**0.93**	**1.02**	**0.99**

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

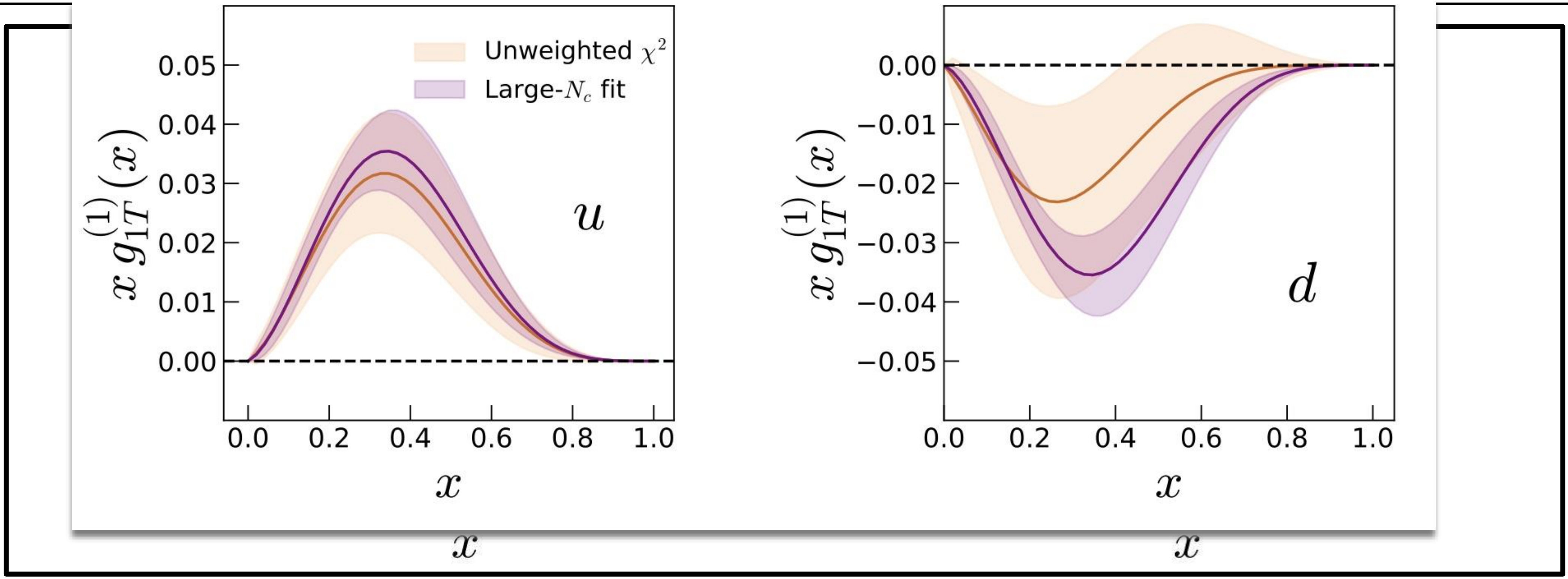
Weighted versus unweighted methods



- **Larger up quark distribution needed to describe JLab π^- data**

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

Weighted versus unweighted methods



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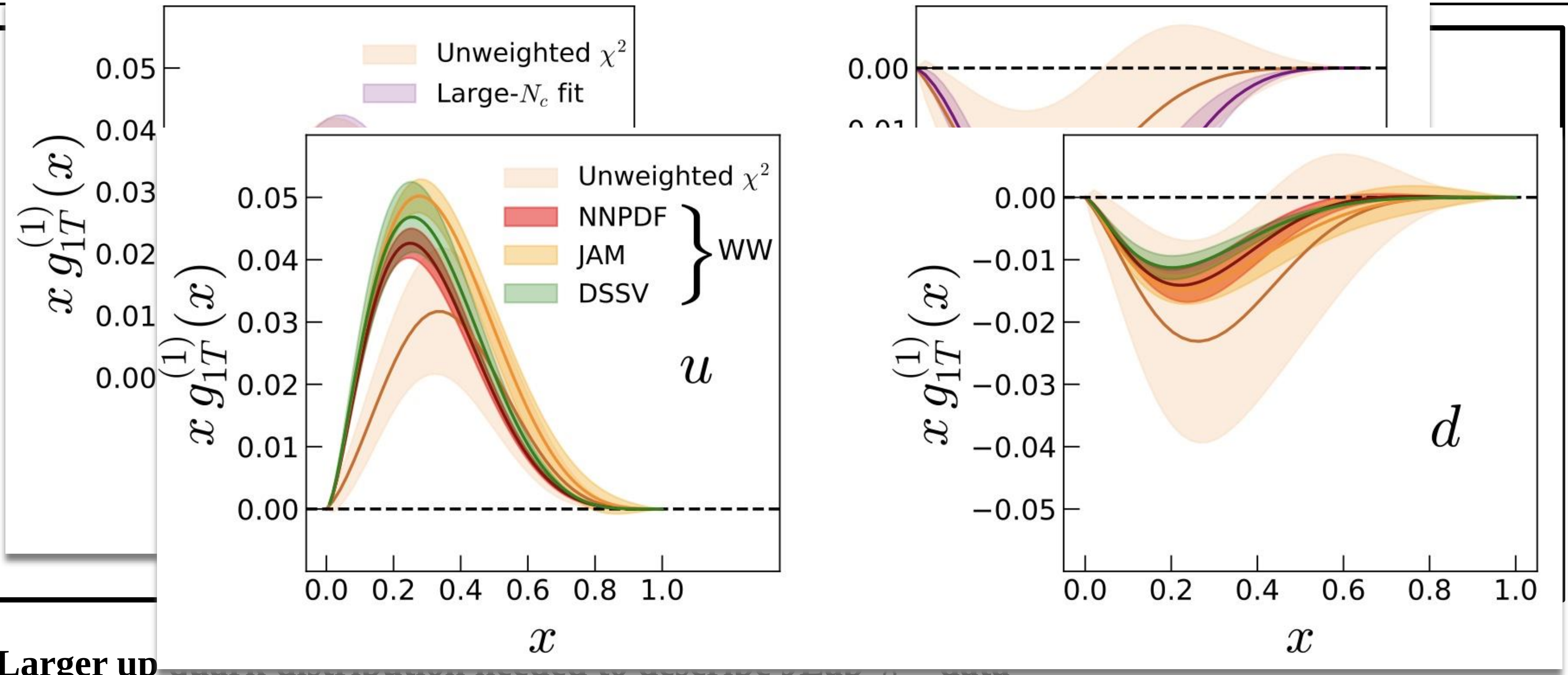

- Larger up