First study of twist-3 PDFs & GPDs for the proton from Lattice QCD

Martha Constantinou

Temple University

In collaboration with:

S. Bhattacharya[1], K. Cichy[2], J. Dodson[1], A. Metz[1], A. Scapellato[1], F. Steffens[3]

1. Temple University, 2. Adam Mickiewicz University, 3. University of Bonn

LATTICE 21

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Twist-classification of PDFs

$$f_i = f_i^{(0)} + \frac{f_i^{(1)}}{Q} + \frac{f_i^{(2)}}{Q^2} \cdots$$

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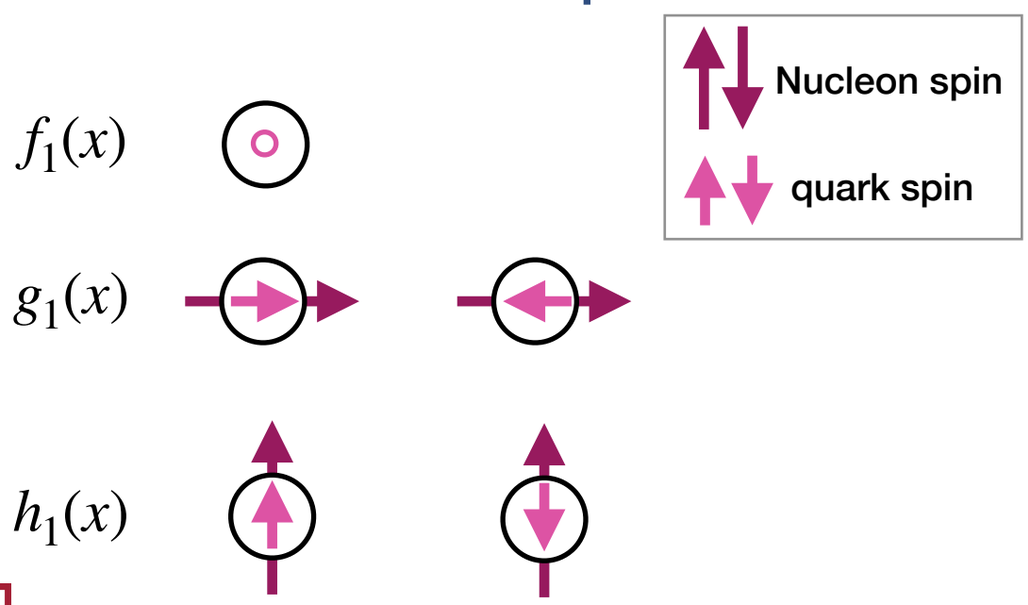
Twist-2 $(f_i^{(0)})$

Nucleon \ Quark	U (γ^+)	L ($\gamma^+\gamma^5$)	T (σ^{+j})
U	$f_1(x)$ number density		
L		$g_1(x)$ helicity	
T			$h_1(x)$ transversity

Probabilistic interpretation



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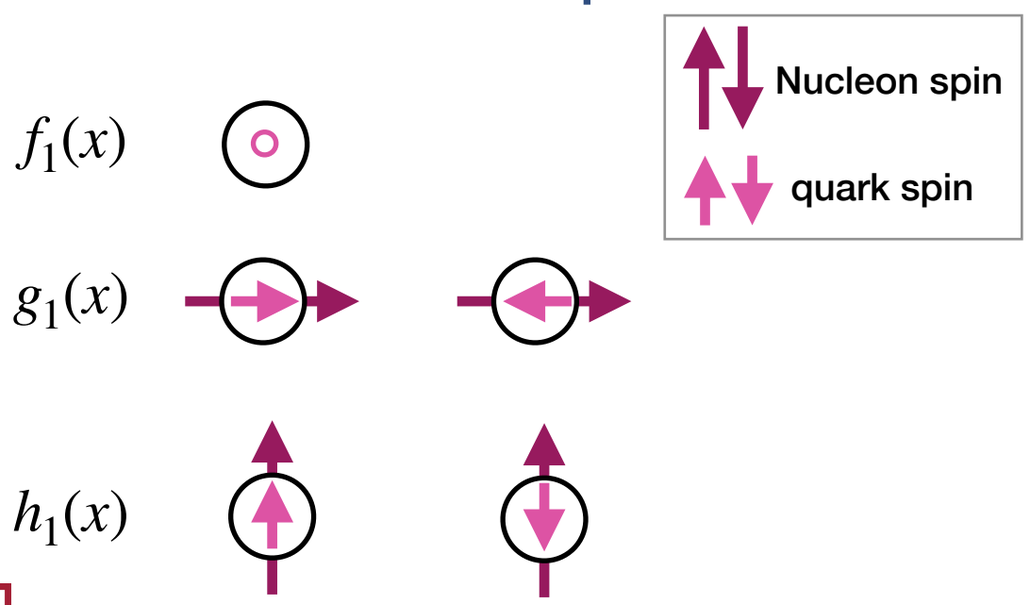

- ★ Lack density interpretation, but can be sizable
- ★ Kinematically suppressed
  Difficult to isolate experimentally
- ★ Theoretically: contain $\delta(x)$ singularities
  (see A. Metz talk)
- ★ Contain info on quark-gluon-quark correlators

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This talk

+ twist-3 $\widetilde{G}_i$ GPDs

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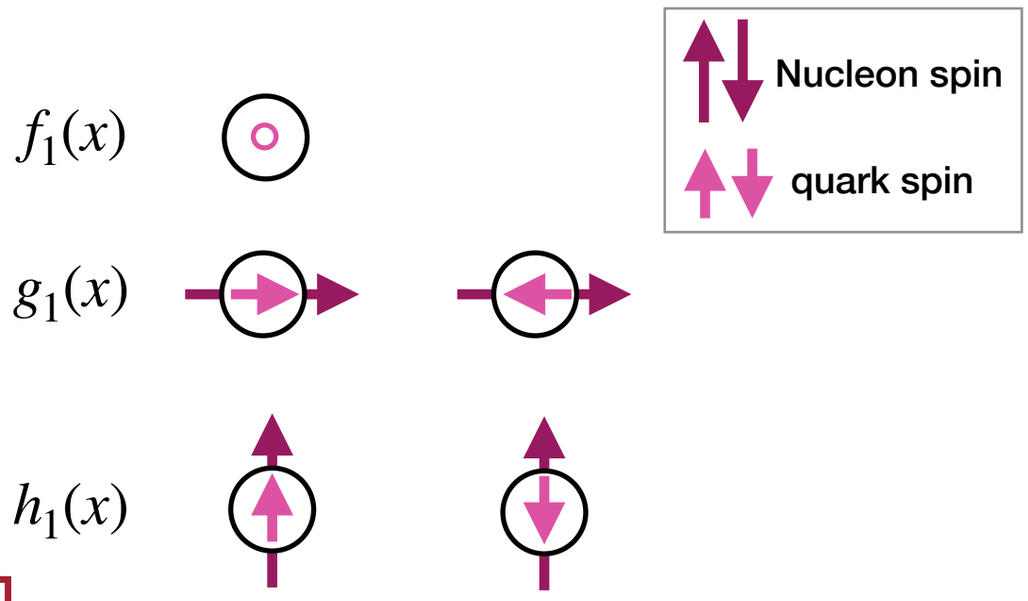

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Parameters of calculations

- ★ Nf=2+1+1 twisted mass (TM) fermions & clover term
- ★ Ensemble parameters:

Name	β	N_f	$L^3 \times L_T$	a [fm]	M_π	$m_\pi L$
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★ Twist-3 u-d PDFs: $g_T(x)\,, \quad h_L(x)$

P_3 $[\frac{2\pi}{L}]$	P_3 [GeV]	N_{conf}	N_{meas}
2	0.83	194	1552
3	1.25	731	11696
4	1.67	1644	105216

- Double statistics for $g_T(x)$: $\gamma^1\gamma^5$ & $\gamma^2\gamma^5$
- $T_{\text{sink}} = 1.12\,\text{fm}$

★ Twist-3 u-d GPDs: $\widetilde{G}_1(x,\xi,t)\,, \widetilde{G}_2(x,\xi,t)\,, \widetilde{G}_3(x,\xi,t)\,, \widetilde{G}_4(x,\xi,t)$

P_3 [GeV]	$\vec{Q} \times \frac{L}{2\pi}$	$-t$ [GeV^2]	ξ	N_{meas}
0.83	(2,0,0)	0.69	0	4288
1.25	(2,0,0)	0.69	0	4288
1.25	(2,2,0)	1.39	0	4288
1.67	(2,0,0)	0.69	0	4288

- We utilize $\gamma^1\gamma^5$ & $\gamma^2\gamma^5$ $\pm\vec{Q}, \pm P_3$
- $T_{\text{sink}} = 1\,\text{fm}$

Twist-3 PDFs

- *New insights on proton structure from lattice QCD: the twist-3 parton distribution function $g_T(x)$*
  S.Bhattacharya, K.Cichy, M.C, A.Metz, A.Scapellato, F.Steffens, PRD 102 (2020), 111501 (Editors' Suggestion), [arXiv:2004.04130]

- *One-loop matching for the twist-3 parton distribution $g_T(x)$*
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- *The role of zero-mode contributions in the matching for the twist-3 PDFs $e(x)$ and $h_L(x)$*
  S. Bhattacharya, K. Cichy, M.C, A. Metz, A. Scapellato, F. Steffens, PRD 102 (2020) 114025, [arXiv:2006.12347]

- *Parton distribution functions beyond leading twist from lattice QCD:The $h_L(x)$ case*
  S. Bhattacharya, K. Cichy, M.C, A. Metz, A. Scapellato, F. Steffens, [arXiv:2107.02574]

Twist-3 $g_T(x)$ PDF

- $g_2(x)$ ($g_2(x) = g_T(x) - g_1(x)$) related to the transverse force acting on the active quark in DIS off a transversely polarized nucleon immediately after it has absorbed the virtual photon [M. Burkardt, *Phys.Rev.D* 88 (2013) 114502, arXiv:0810.3589]

- can be separated from twist-2 helicity PDF in scattering longitudinally polarized leptons from a transversely polarized target
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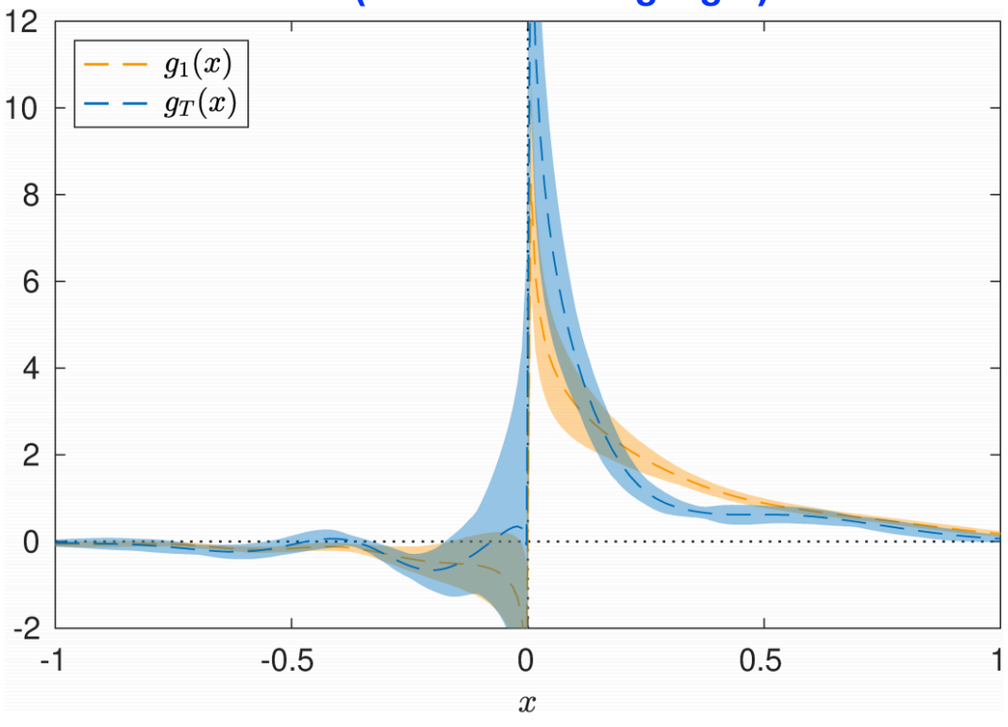

Twist-3 counterpart as sizable as twist-2

Burkhardt-Cottingham sum rule important check

[S.Bhattacharya, K.Cichy, M.C, A.Metz, A.Scapellato, F.Steffens, PRD 102 (2020), 111501, [arXiv:2004.04130]

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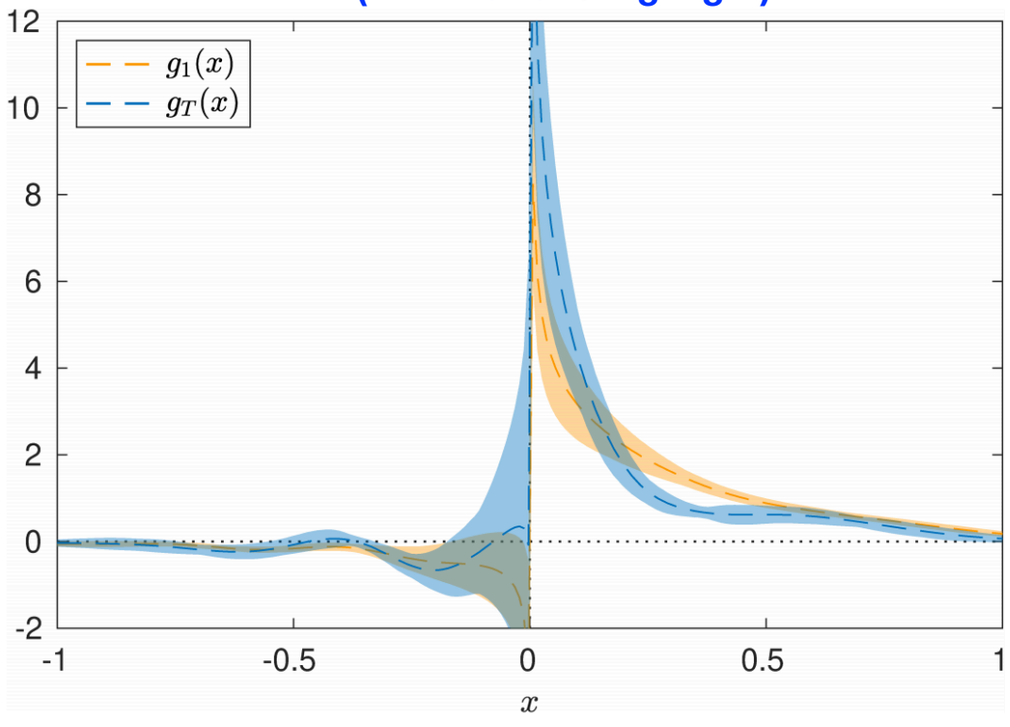

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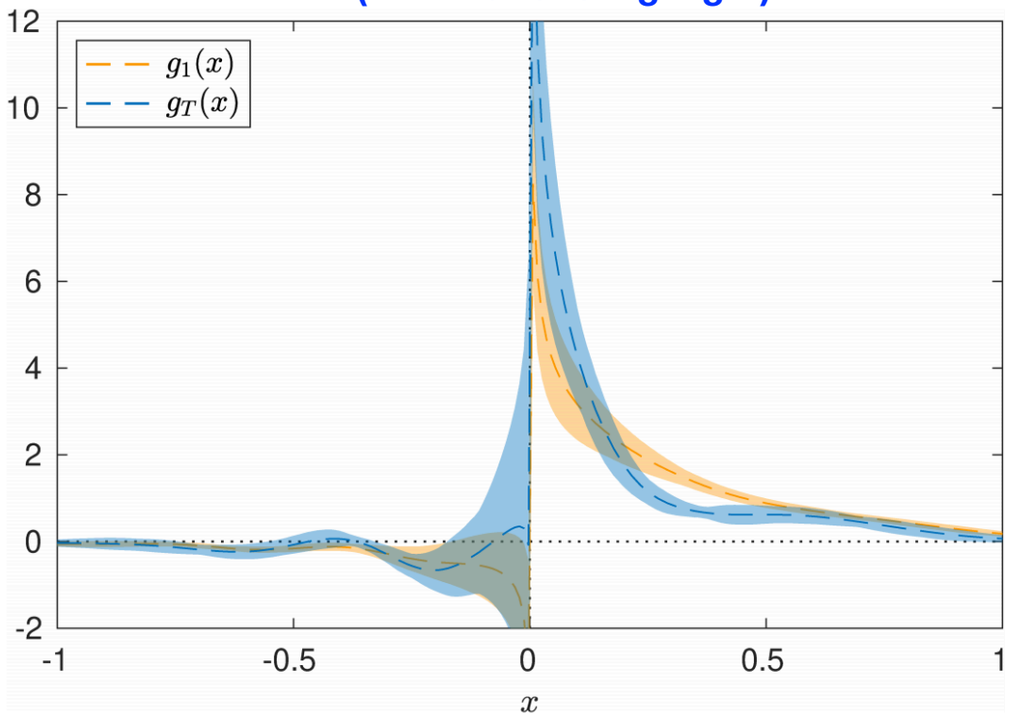

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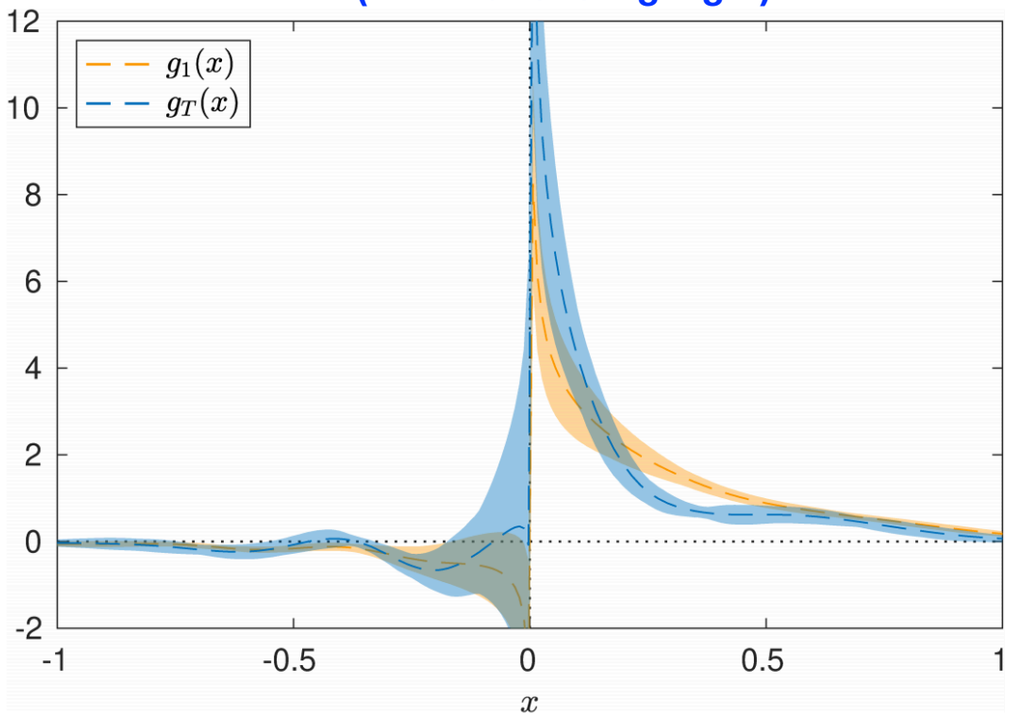

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$$\int_{-1}^{1} dx\, g_1(x) - \int_{-1}^{1} dx\, g_T(x) = 0.01(20)$$

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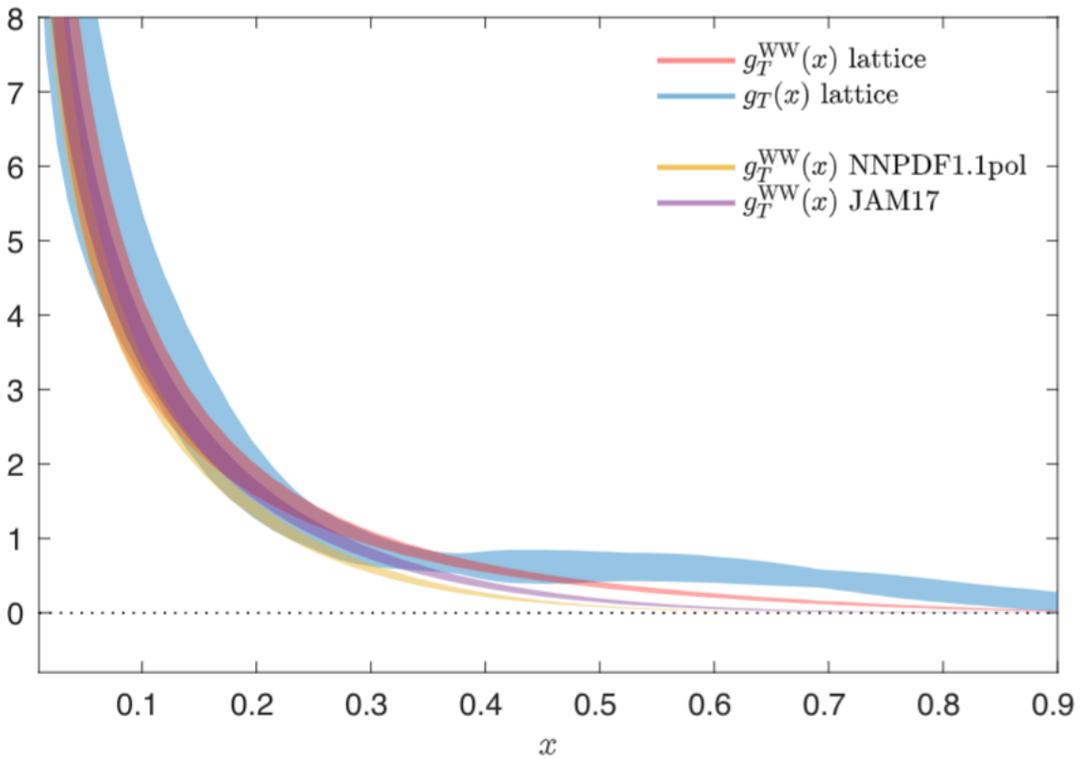

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- **Violations of 15-40% expected from experimental data**

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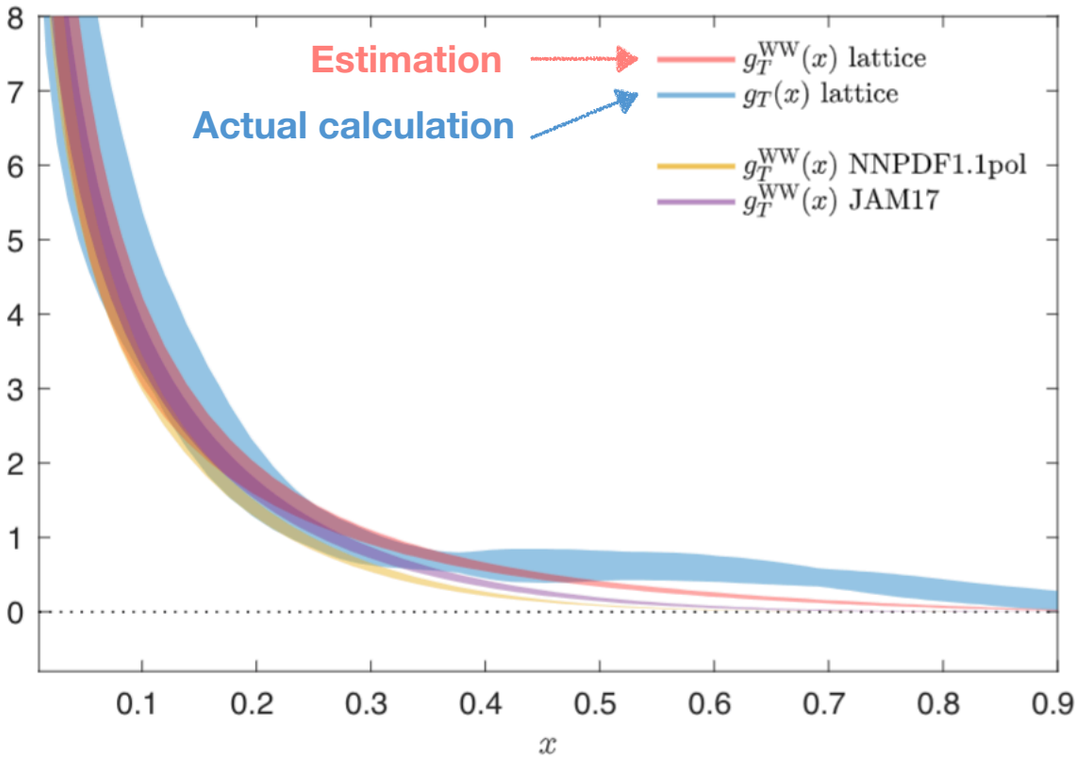

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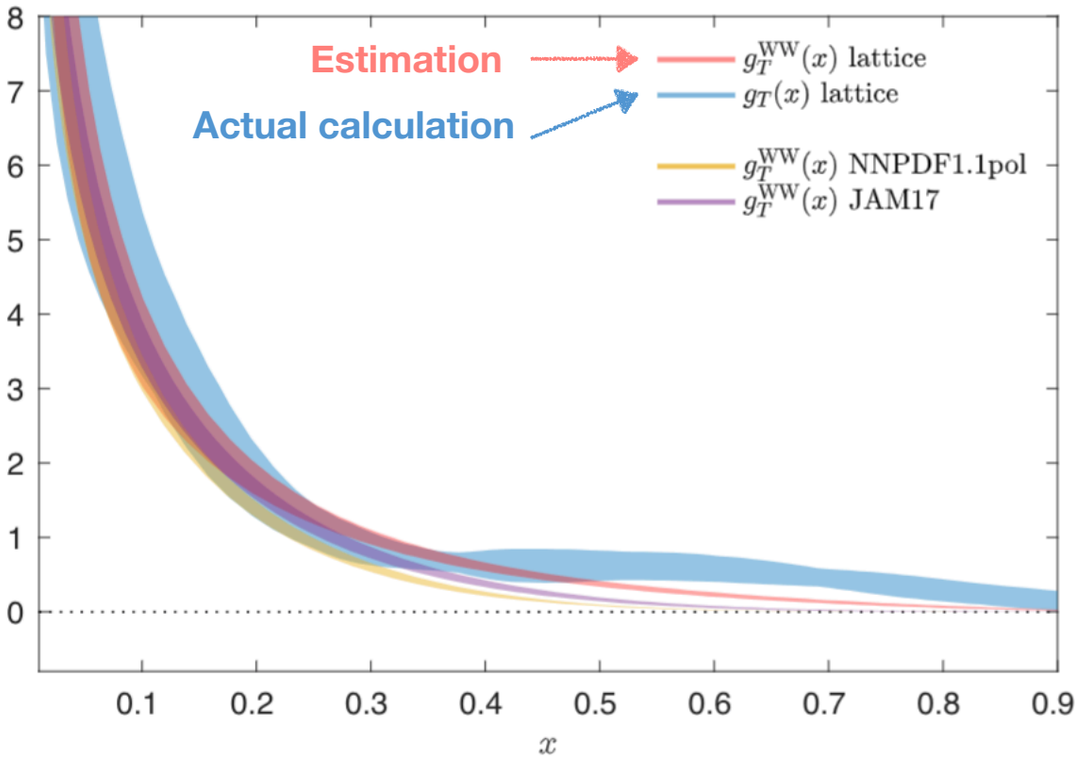

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d_2-moment: $d_2 = \int dx\, 3\, x^2\, [g_T(x) - g_T^{\rm WW}(x)]$

- **Investigated experimentally (JLab Hall A) and found $\mathcal{O}(10^{-3})$**

[D. Flay et al., PRD 94, 5 (2016) 052003, arXiv:1603.03612]

- **High-accuracy results are required to calculate d_2**

Twist-3 $h_L(x)$ PDF

- Chiral odd: decouple from usual DIS, thus not trivial to extract

- $h_L(x)$ accessed via:

  - di-hadron single spin asymmetries (CLAS)

  [Gliske et al., PRD 90 (2014) 11, 114027, arXiv:1408.5721; A. Vossen, CIPANP 2018, arXiv: 1810.02435]

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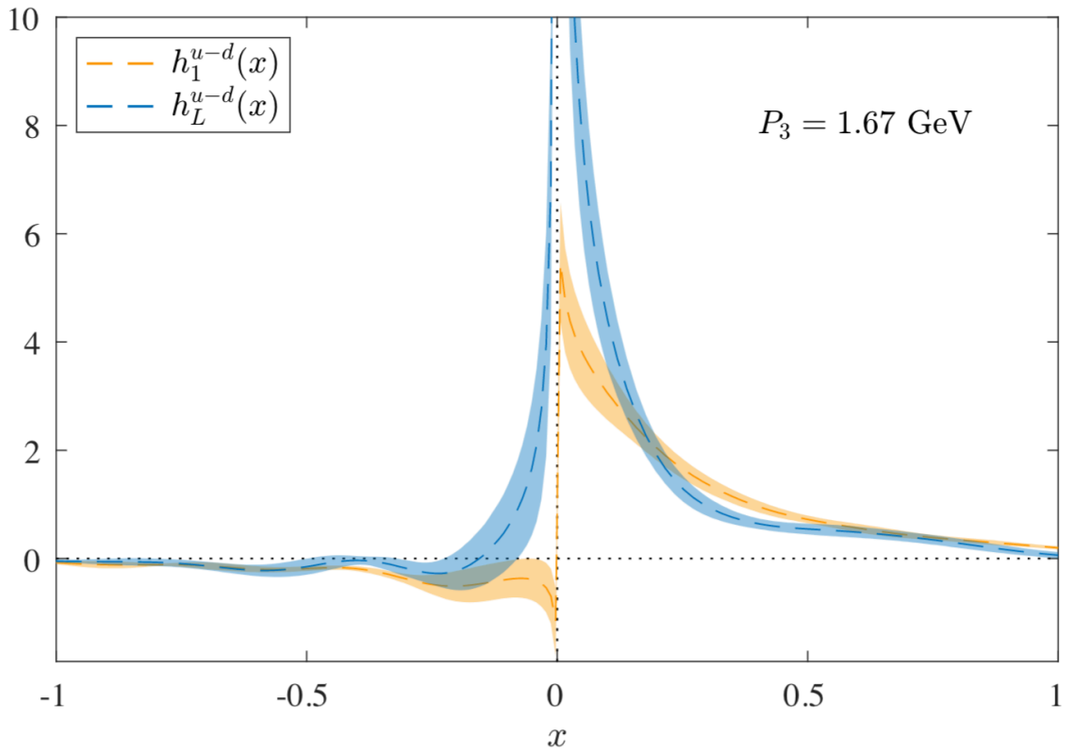

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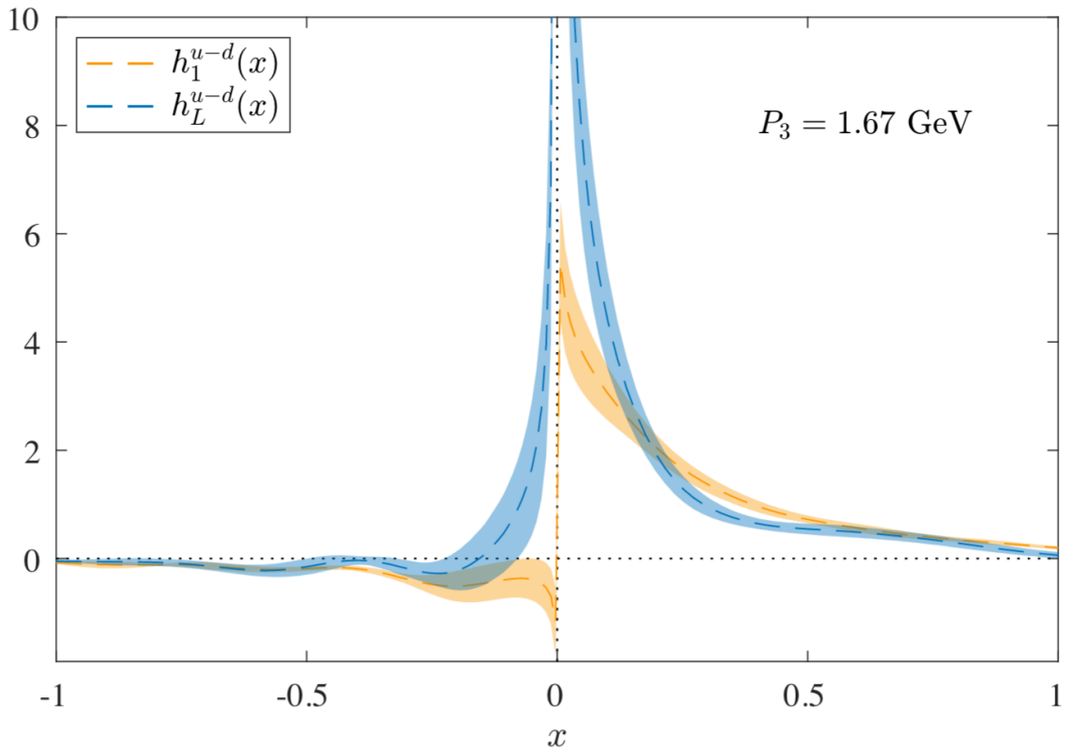

Burkhardt-Cottingham valid for quasi-$h_L(x)$

[S. Bhattacharya, A. Metz, arXiv:2105.07282]

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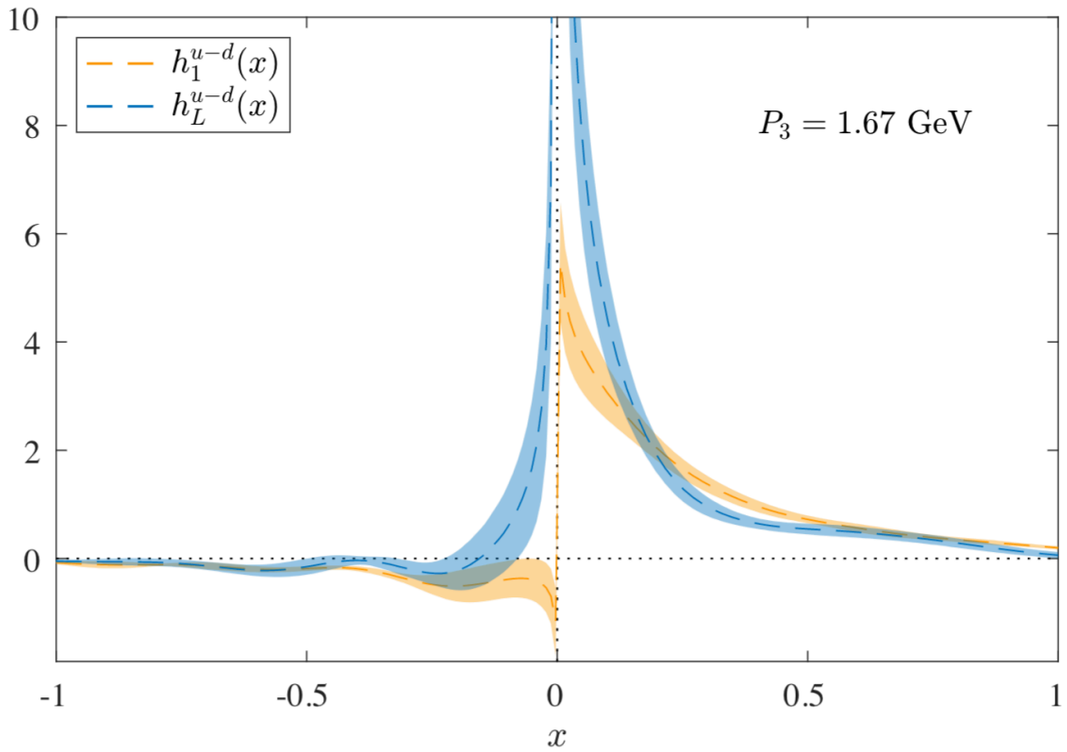

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$$\int dx\, \tilde{h}_L(x, 0.83\,\text{GeV}) = 1.13(08)\,, \qquad \int dx\, \tilde{h}_1(x, 0.83\,\text{GeV}) = 1.02(07)$$

$$\int dx\, \tilde{h}_L(x, 1.25\,\text{GeV}) = 1.09(10)\,, \qquad \int dx\, \tilde{h}_1(x, 1.25\,\text{GeV}) = 1.07(08)$$

$$\int dx\, \tilde{h}_L(x, 1.67\,\text{GeV}) = 1.03(16)\,, \qquad \int dx\, \tilde{h}_1(x, 1.67\,\text{GeV}) = 0.94(10)$$

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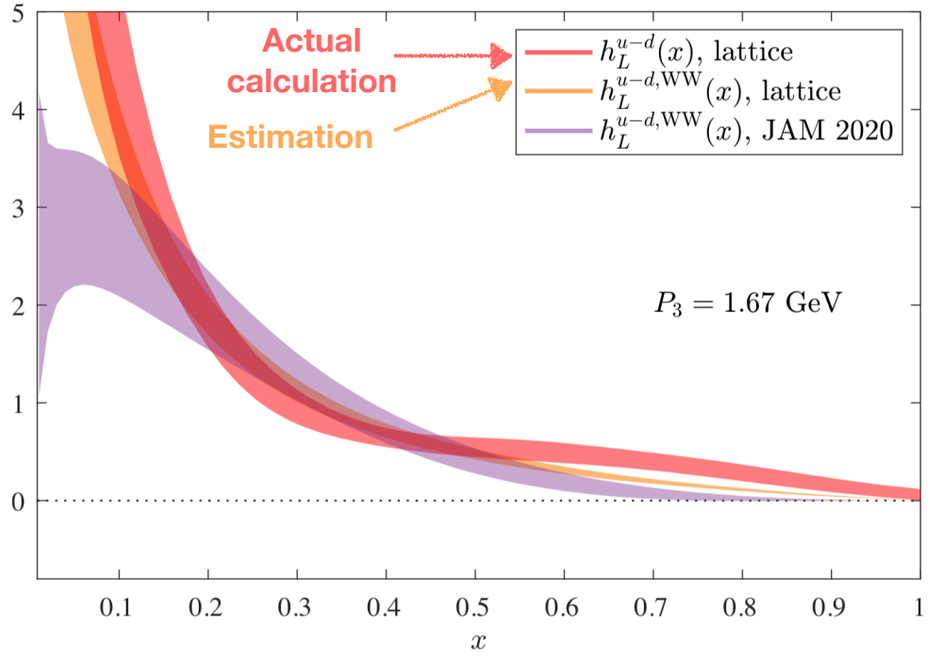

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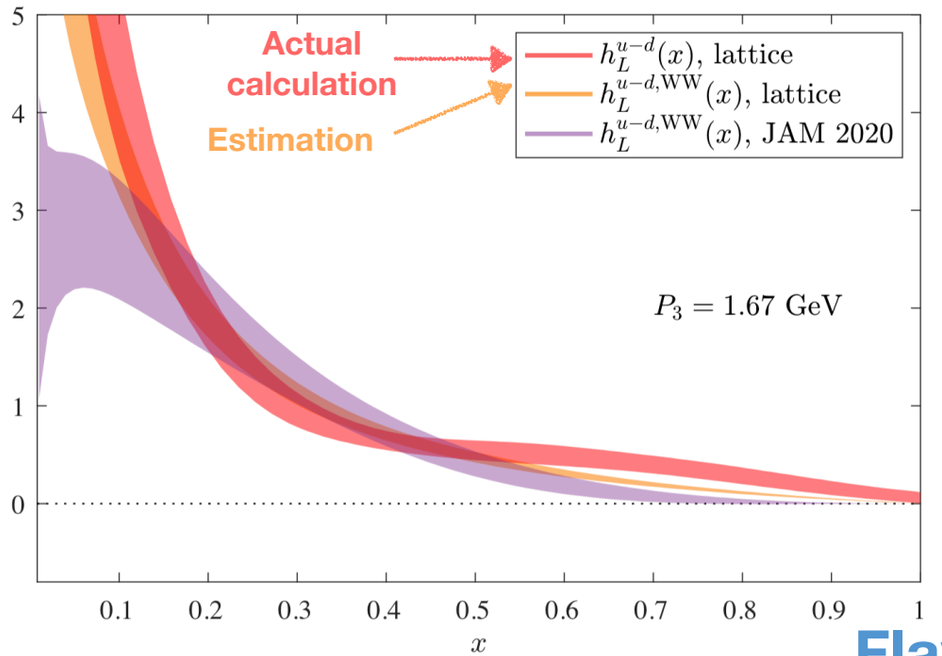

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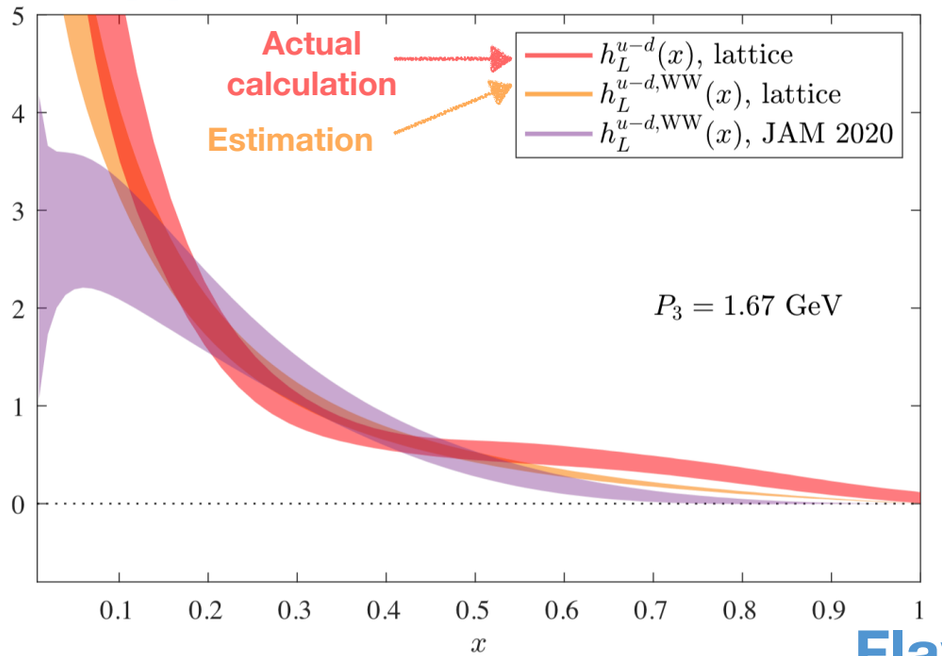

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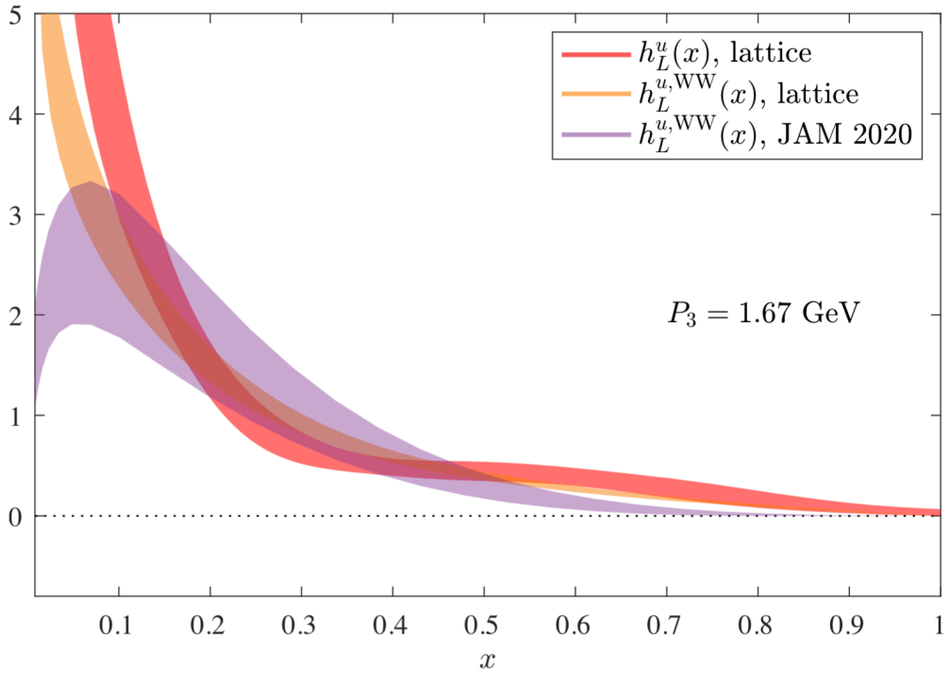
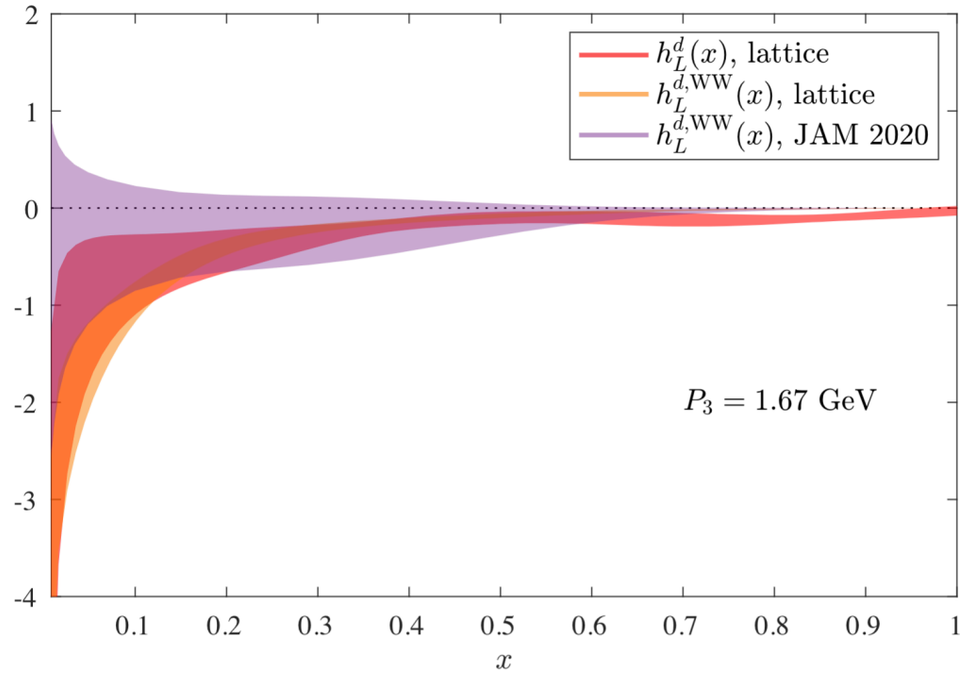
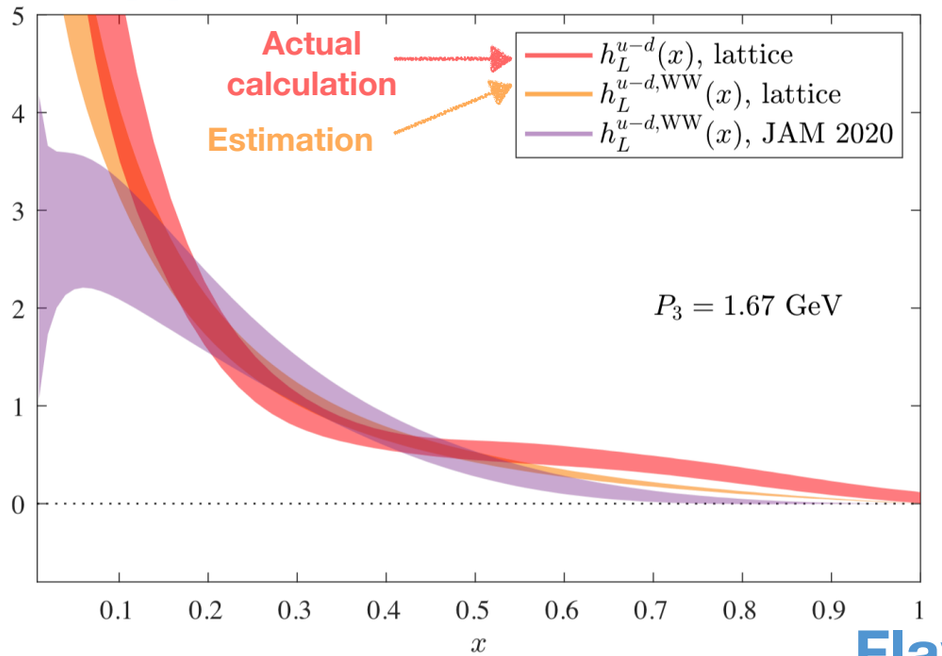




Twist-3 $h_L(x)$ PDF

WW approximation:

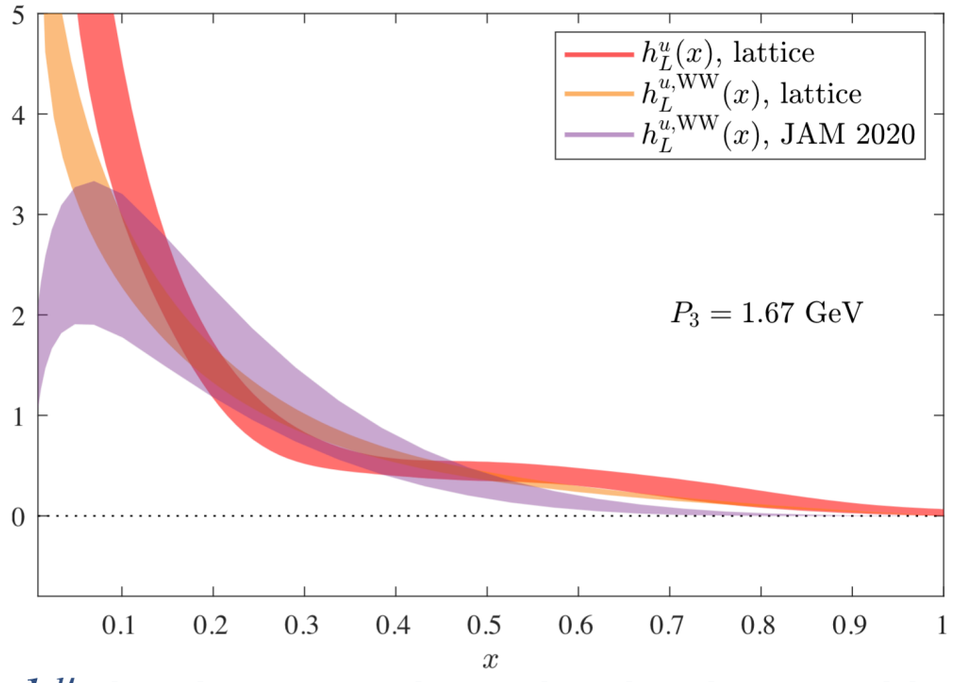


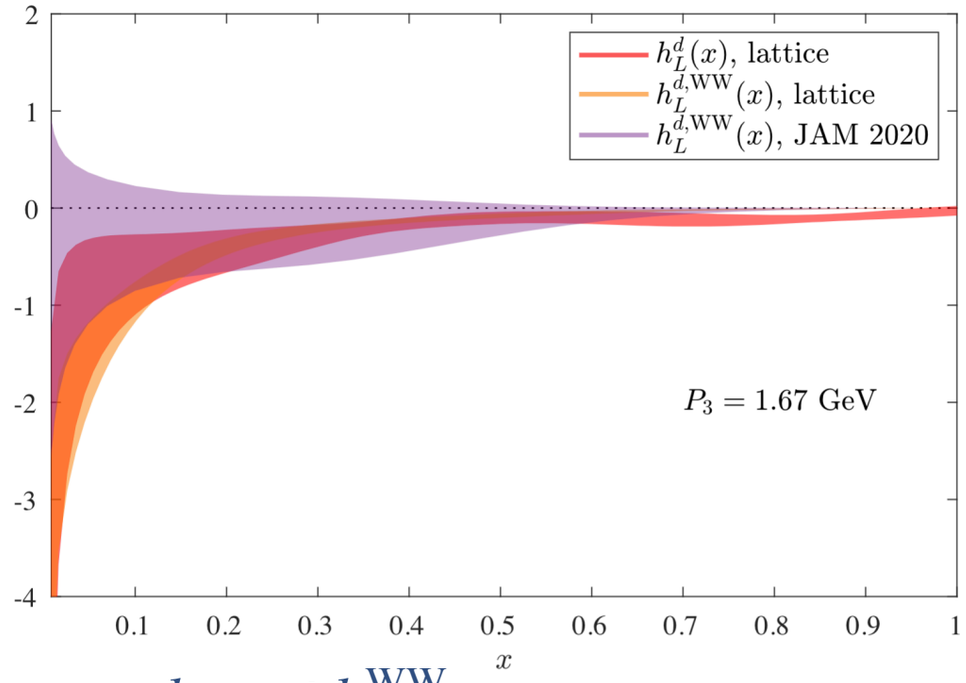
$$h_L^{\mathrm{WW}}(x) = 2x \int_x^1 dy \, \frac{h_1(y)}{y^2}$$

- Lattice data suggest that twist-3 $h_L(x)$ determined from twist-2 counterpart within uncertainties

Flavor decomposition

- Disconnected contributions negligible for transversity PDF **F. Manigrasso talk** [C. Alexandrou et al., arXiv:2106.16065]





- h_L^u dominant, and tension is observed between h_L and h_L^{WW}
- h_L^d negative and approaches zero faster then h_L^u

Twist-3 GPDs

- *Twist-3 partonic distributions from lattice QCD*
  S. Bhattacharya, K. Cichy, M. Constantinou, A. Metz, A. Scapellato, F. Steffens, [arXiv:2107.12818]

Twist-3 GPDs

see also J. Dodson's poster

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Twist-3 GPDs ($\gamma^\mu\gamma^5$)

★ Transverse matrix element of axial operator

$$\widetilde{F}^\mu = P^\mu \frac{\tilde{h}^+}{P^+} \widetilde{H} + P^\mu \frac{\tilde{e}^+}{P^+} \widetilde{E}$$

$$+ \Delta_\perp^\mu \frac{\tilde{b}}{2m} (\widetilde{E} + \widetilde{G}_1) + \tilde{h}_\perp^\mu (\widetilde{H} + \widetilde{G}_2) + \Delta_\perp^\mu \frac{\tilde{h}^+}{P^+} \widetilde{G}_3 + \tilde{\Delta}_\perp^\mu \frac{h^+}{P^+} \widetilde{G}_4 \qquad \boxed{\mu = 1,2}$$

$$h^\mu = \bar{u}(p')\,\gamma^\mu\,u(p)\,, \qquad e^\mu = \bar{u}(p')\,\frac{i\sigma^{\mu\nu}\Delta_\nu}{2m}\,u(p)\,, \qquad b = \bar{u}(p')\,u(p)\,,$$

$$\tilde{h}^\mu = \bar{u}(p')\,\gamma^\mu\gamma_5\,u(p)\,, \qquad \tilde{e}^\mu = \frac{\Delta^\mu}{2m}\,\tilde{b}\,, \qquad \tilde{b} = \bar{u}(p')\,\gamma_5\,u(p)$$

[D. Kiptily and M. Polyakov, Eur. Phys. J. C37 (2004) 105, arXiv:hep-ph/0212372]

[F. Aslan et a., Phys. Rev. D 98, 014038 (2018), arXiv:1802.06243]

★ Sum Rules (generalization of Burkhardt-Cottingham)

$$\int_{-1}^{1} dx\, \widetilde{G}_i(x,\xi,t) = 0$$

[X. D. Ji, Phys. Rev. Lett. 78, 610 (1997), hep-ph/9603249]

★ Sum Rules (generalization of Efremov-Leader-Teryaev)

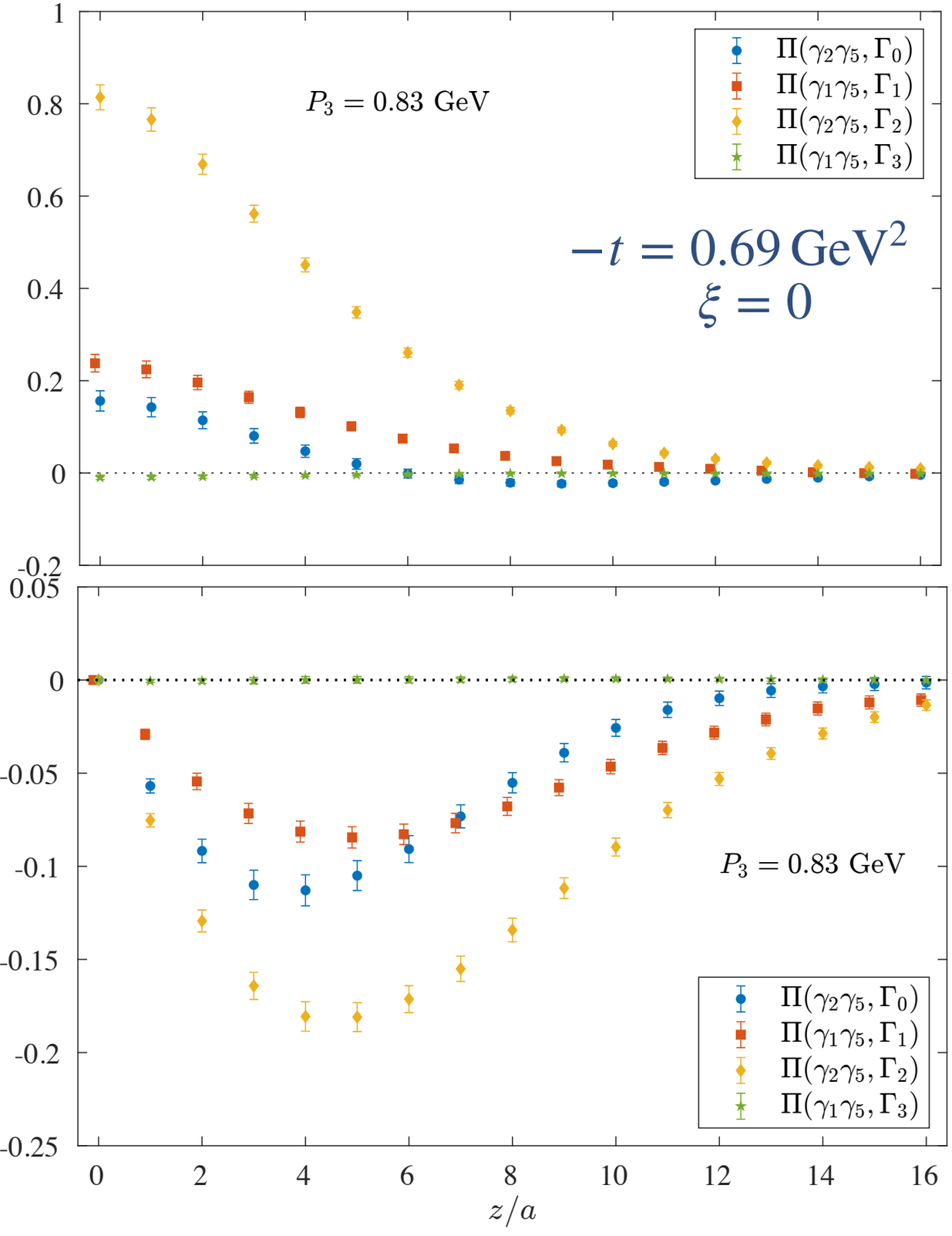
[A. Efremov, O. Teryaev , E. Leader, PRD 55 (1997) 4307, hep-ph/9607217]

$$\int_{-1}^{1} dx\, x\, \widetilde{G}_1(x,0,t) = \frac{1}{2}\left[F_2(t) - \int_{-1}^{1} dx\, x\, \widetilde{E}(x,0,t)\right], \qquad \int_{-1}^{1} dx\, x\, \widetilde{G}_2(x,0,t) = \frac{1}{2}\left[-\frac{t}{4m^2}F_2(t) - \widetilde{A}_{20}(t)\right],$$

$$\int_{-1}^{1} dx\, x\, \widetilde{G}_3(x,0,t) = 0 \qquad \int_{-1}^{1} dx\, x\, \widetilde{G}_4(x,0,t) = \frac{1}{4}G_E(t)$$

F_2 : Pauli FF
G_E : electric FF
$\widetilde{A}_{20}$, $\widetilde{B}_{20}$: axial GFFs

Bare matrix elements (ME)



★ $\Pi(\gamma^2\gamma^5, \Gamma_0)$ **&** $\Pi(\gamma^2\gamma^5, \Gamma_2)$**:**

disentangle $\widetilde{H} + \widetilde{G}_2,\ \widetilde{G}_4$

★ $\Pi(\gamma^1\gamma^5, \Gamma_1)$ **and** $\widetilde{H} + \widetilde{G}_2$**:**

disentangle $\widetilde{E} + \widetilde{G}_1$

★ $\Pi(\gamma^1\gamma^5, \Gamma_3)$ **gives** $\widetilde{G}_3$

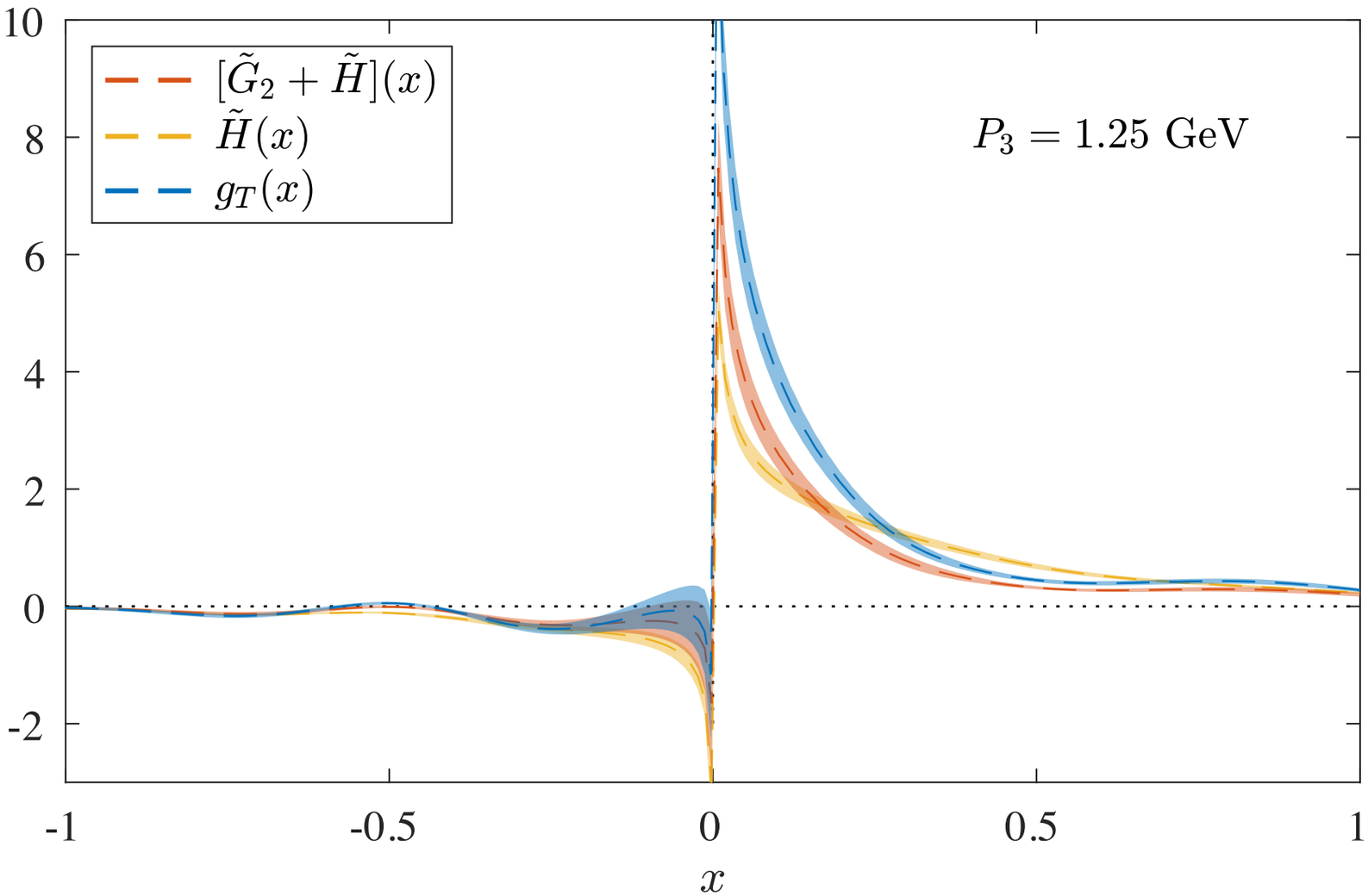
★ **Similar picture for $P_3 = 1.25$ GeV**

★ **Real part of ME: dominant**

★ $\widetilde{G}_3$ **is kinematically suppressed**

x-dependence of twist-3 GPDs

$$-t = 0.69\,\mathrm{GeV}^2, \qquad \xi = 0$$



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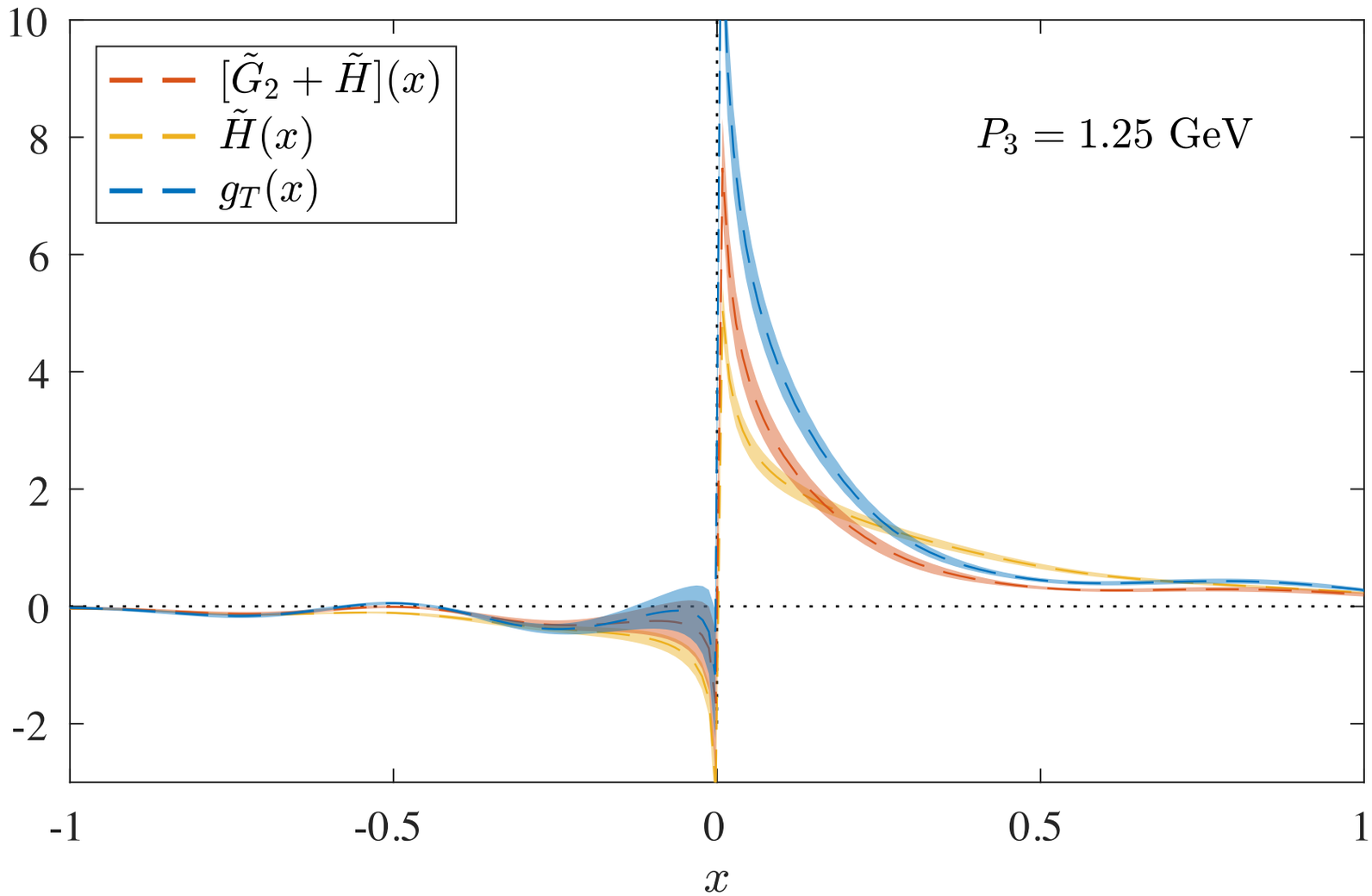

★ $g_T(x)$: **dominant distribution**

★ $\widetilde{H} + \widetilde{G}_2$ **similar in magnitude to** $\widetilde{H}$ **For twist-2 GPDs see A. Scapellato's talk**

★ $\widetilde{G}_2$ **is expected to be small**

Concluding Remarks

- ★ **quasi-PDFs formalism can be generalized beyond leading twist:**
  $g_T(x),\ h_L(x),\ e(x)$
- ★ **We address computationally expensive calculations**
  GPDs with signal comparable to PDFs
- ★ **Several improvements - mixing with quark-gluon-quark correlator**

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Thank you

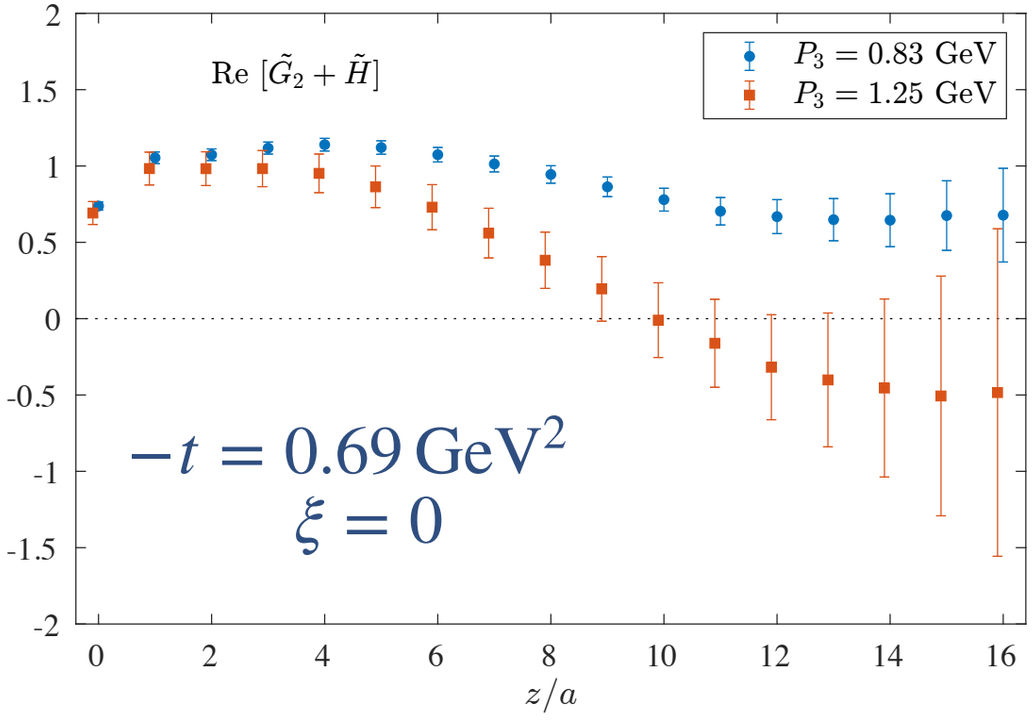
U.S. DEPARTMENT OF ENERGY | Office of Science

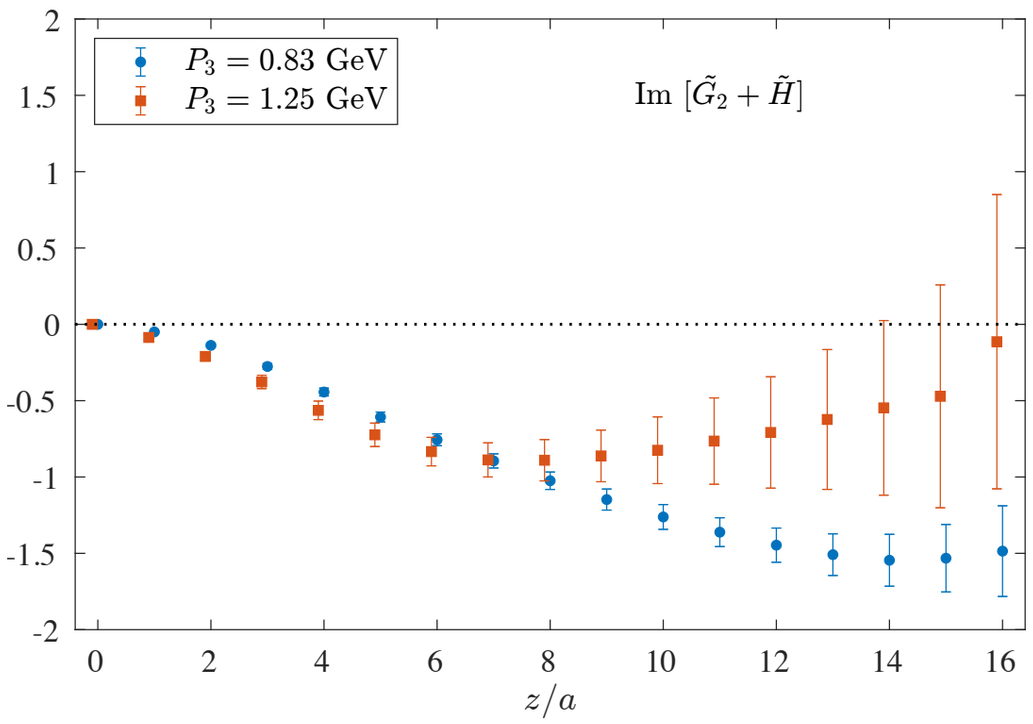
TMD Collaboration **TMD Topical Collab.**

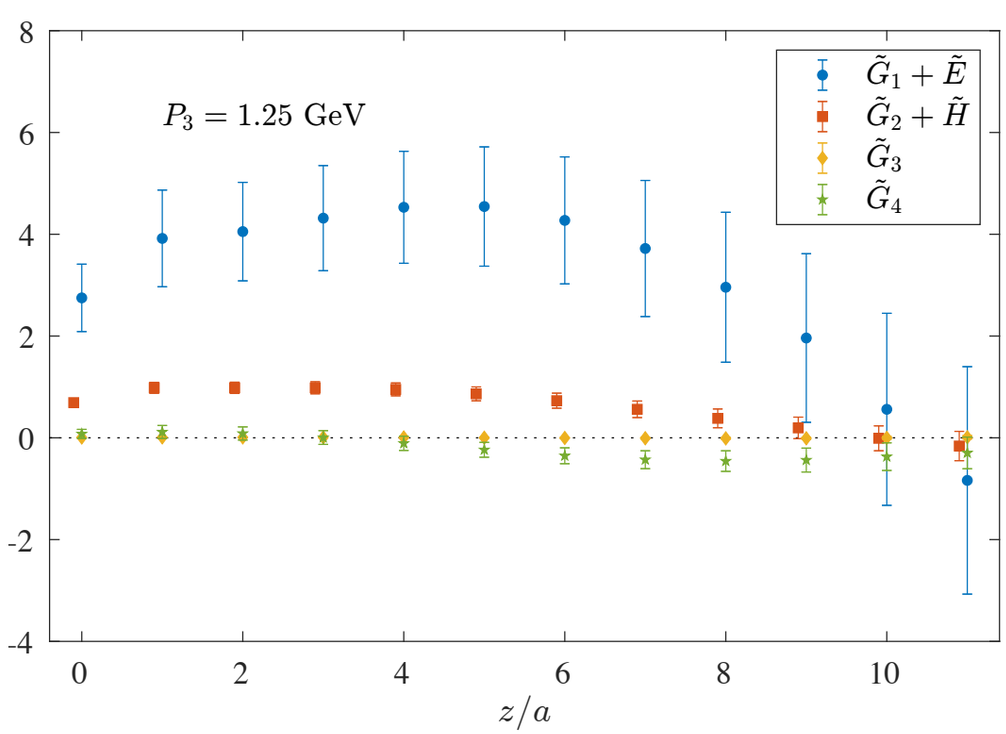
U.S. DEPARTMENT OF ENERGY | Office of Science

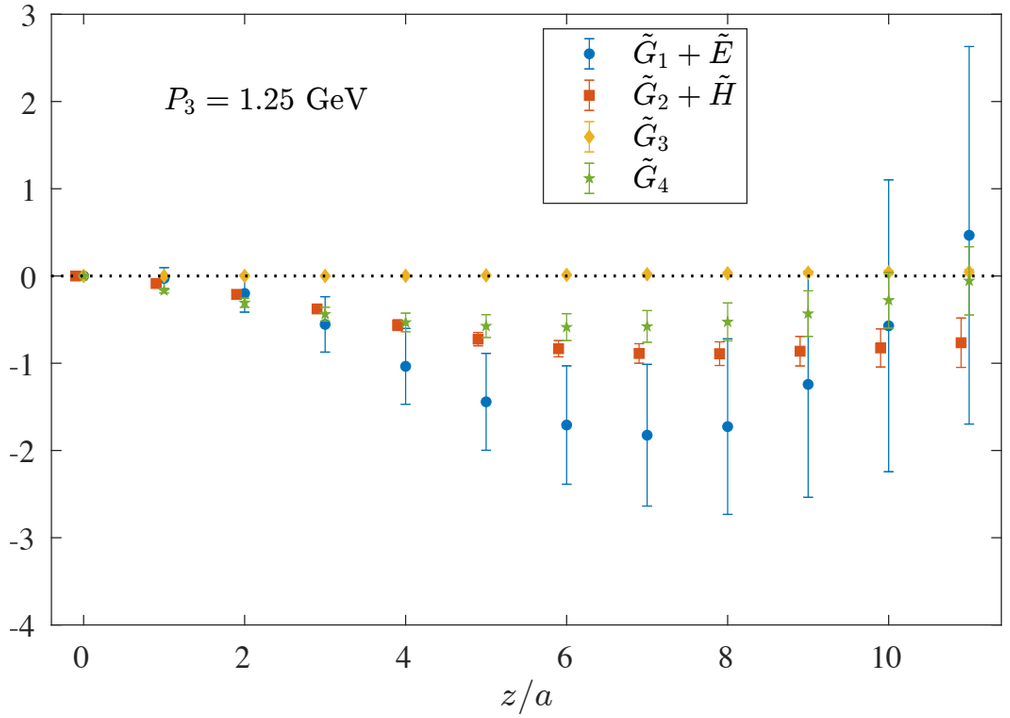
DOE Early Career Award (NP)
Grant No. DE-SC0020405

Matrix elements decomposition

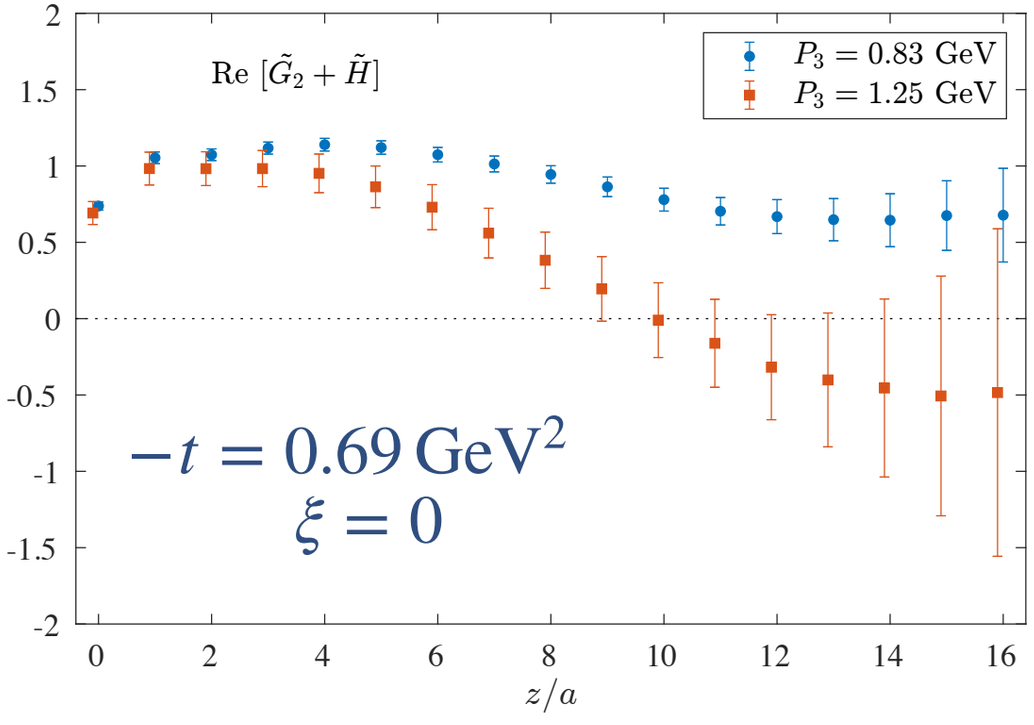


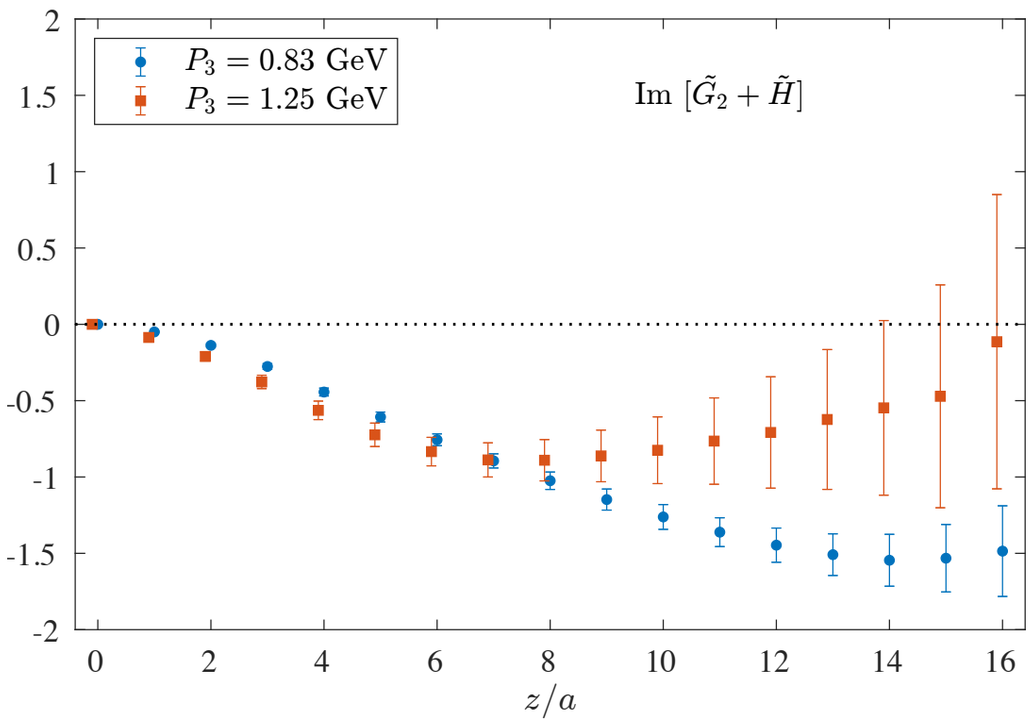


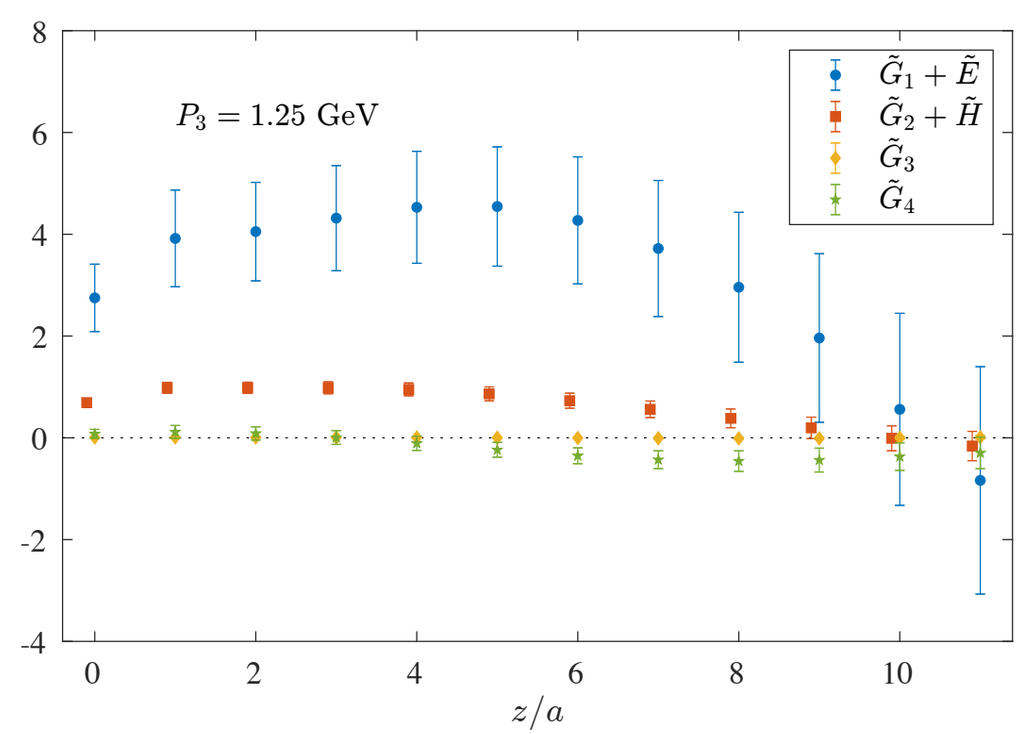


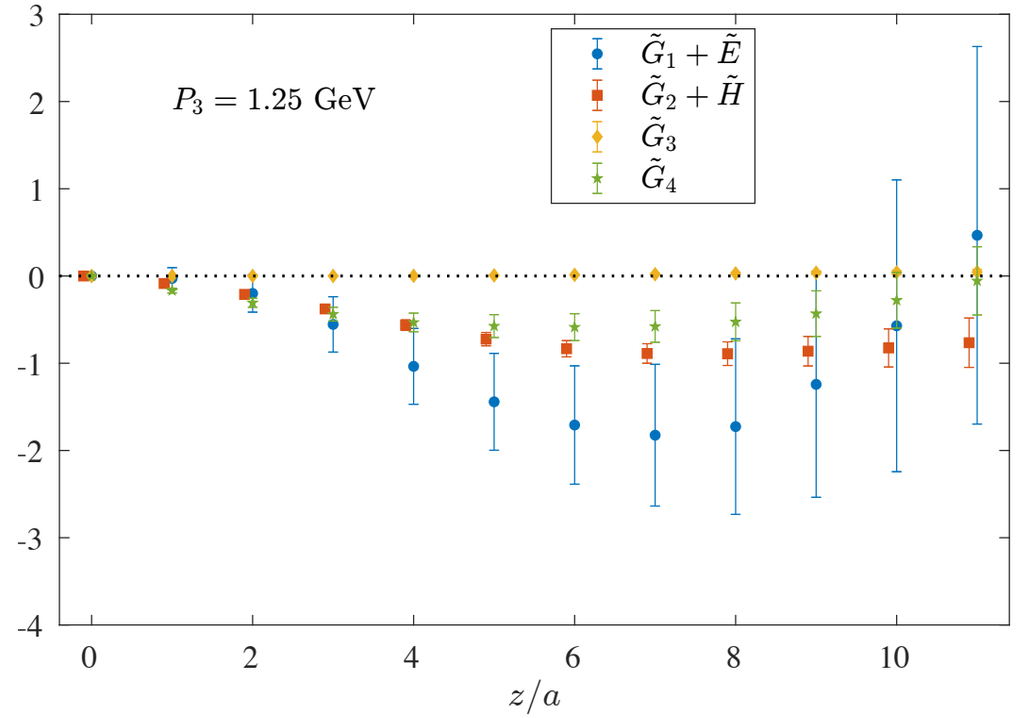


Matrix elements decomposition









★ $\widetilde{E} + \widetilde{G}_1$: **highest contribution**

★ $\widetilde{G}_3$, $\widetilde{G}_4$: **suppressed**