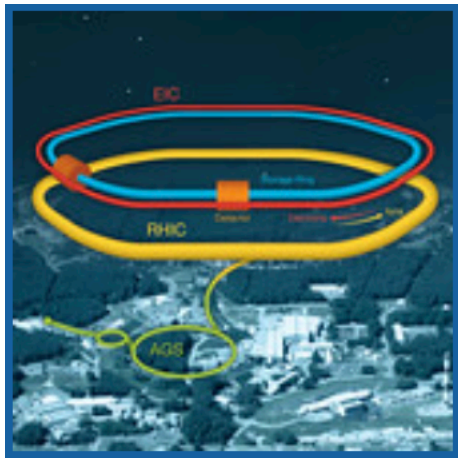


The 2025 CFNS-SURGE Summer Workshop on the Physics of the Electron-Ion Collider

Lattice QCD (selected topics)

Lecture 2

Martha Constantinou

Temple University

Center for Frontiers in Nuclear Science

Stony Brook University, USA

June 2 - 13, 2025

OUTLINE OF LECTURE 2

- ★ **Types of quantities we study in lattice QCD for hadron structure**
- ★ **Proton spin crisis**
- ★ **Accessing x-dependent distributions**
- ★ **Key points of Lectures 2**

OUTLINE OF LECTURE 2

★ Types of quantities we study in lattice QCD for hadron structure

★ Proton spin crisis But not really

★ Accessing x-dependent distributions

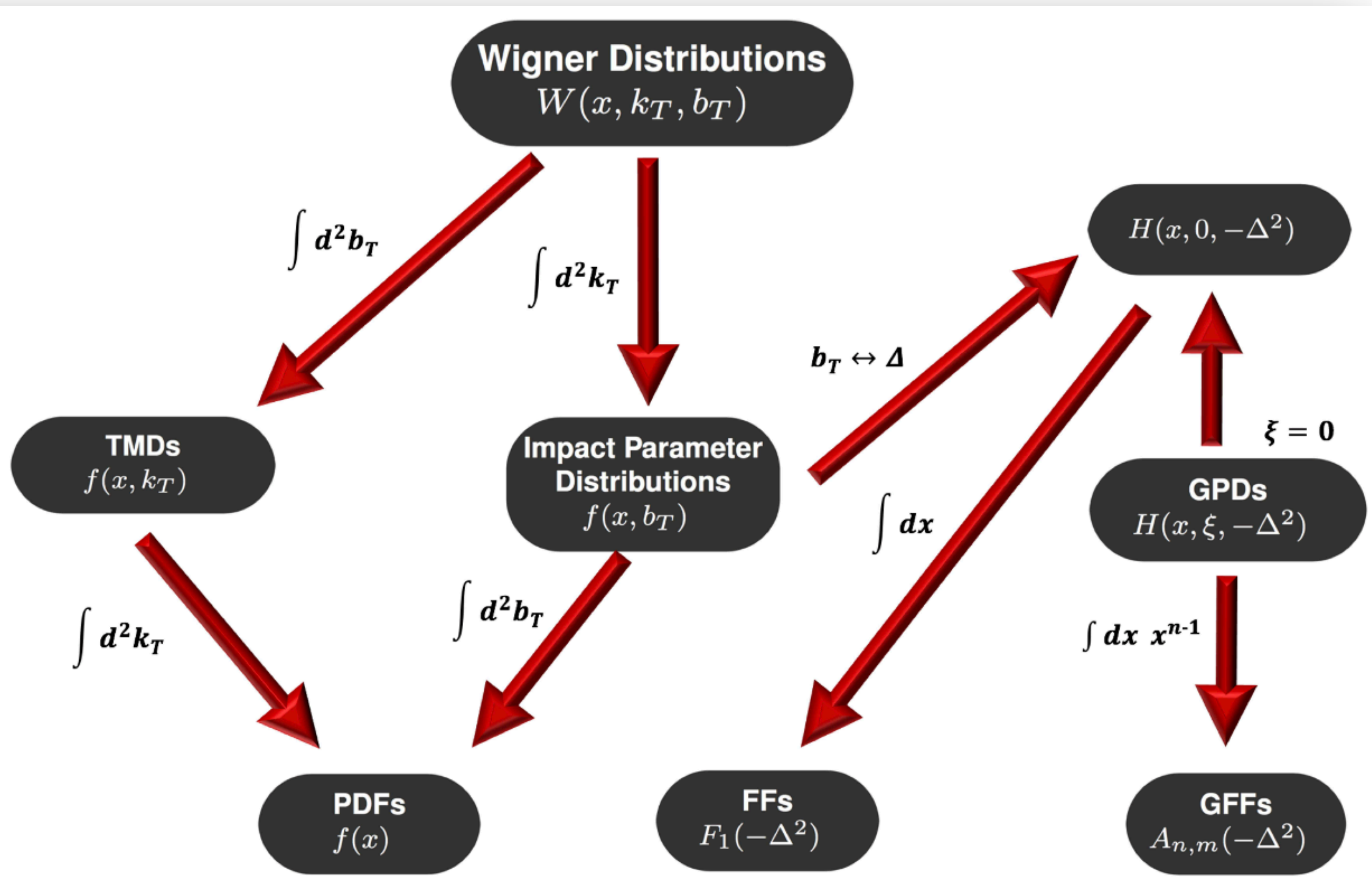
★ Key points of Lectures 2

How to study Hadron Structure

Nucleon Characterization

Wigner distributions

- ★ Fully characterize partonic structure of hadrons
- ★ Provide multi-dim images of the parton distributions in phase space



- ★ Correlations between momenta, positions, spins
- ★ Information on the hadron's mechanical properties (OAM, pressure, etc.)

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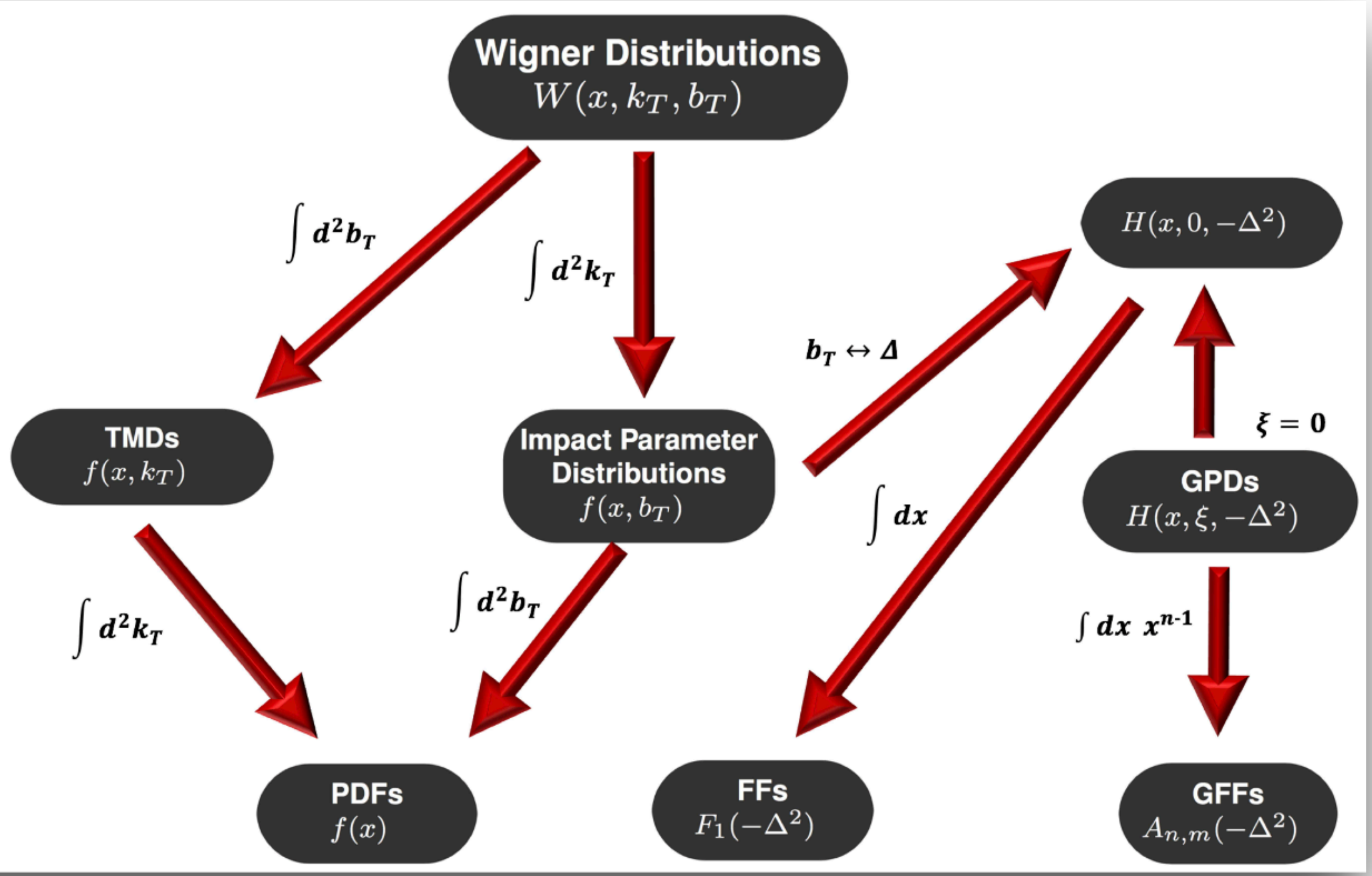
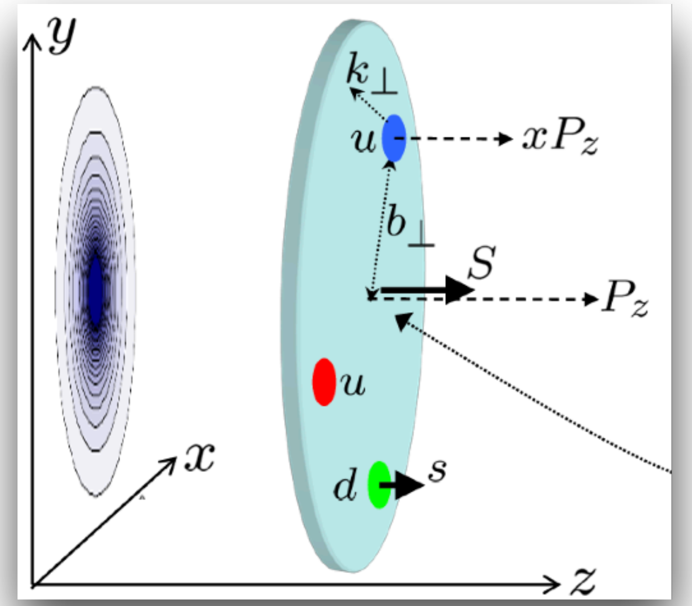


★ Partons contain information on

x: longitudinal momentum fraction

k_T: transverse momentum

$b_\perp$: impact parameter



★ Correlations between momenta, positions, spins

★ Information on the hadron's mechanical properties (OAM, pressure, etc.)

Accessing information on PDFs/GPDs

- ★ Parton model: physical picture valid for infinite momentum frame

[R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1969)]

- ★ PDFs via matrix elements of nonlocal light-cone operators ($-t^2 + \vec{r}^2 = 0$)

$$f(x) = \frac{1}{4\pi} \int dy^- e^{-ixP^+y^-} \langle P, S | \bar{\psi}_f \gamma^+ \mathcal{W} \psi_f | P, S \rangle$$

- ★ Light-cone correlations inaccessible from Euclidean lattices ($\tau^2 + \vec{r}^2 = 0$)

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local operators

$$\bar{q}(-\tfrac{1}{2}z)\, \gamma^\sigma W[-\tfrac{1}{2}z, \tfrac{1}{2}z]\, q(\tfrac{1}{2}z) \quad = \quad \sum_{n=0}^{\infty} \frac{1}{n!}\, z_{\alpha_1} \ldots z_{\alpha_n} \left[\bar{q} \gamma^\sigma \overleftrightarrow{D}^{\alpha_1} \ldots \overleftrightarrow{D}^{\alpha_n} q \right]$$

$$\langle N(P') | \mathcal{O}_V^{\mu\mu_1\cdots\mu_{n-1}} | N(P) \rangle \sim \sum_{\substack{i=0 \\ \text{even}}}^{n-1} \left\{ \gamma^{\{\mu} \Delta^{\mu_1} \cdots \Delta^{\mu_i} \overline{P}^{\mu_{i+1}} \cdots \overline{P}^{\mu_{n-1}\}} A_{n,i}(t) - i \frac{\Delta_\alpha \sigma^{\alpha\{\mu}}{2m_N} \Delta^{\mu_1} \cdots \Delta^{\mu_i} \overline{P}^{\mu_{i+1}} \cdots \overline{P}^{\mu_{n-1}\}} B_{n,i}(t) \right\} + \frac{\Delta^\mu \Delta^{\mu_1} \cdots \Delta^{\mu_{n-1}}}{m_N} C_{n,0}(\Delta^2) \Big|_{n\ \text{even}} \Big) \Big\} + \frac{\Delta^\mu \Delta^{\mu_1} \cdots \Delta^{\mu_{n-1}}}{m_N} C_{n,0}(\Delta^2) \Big|_{n\ \text{even}} \Big] U(P)$$

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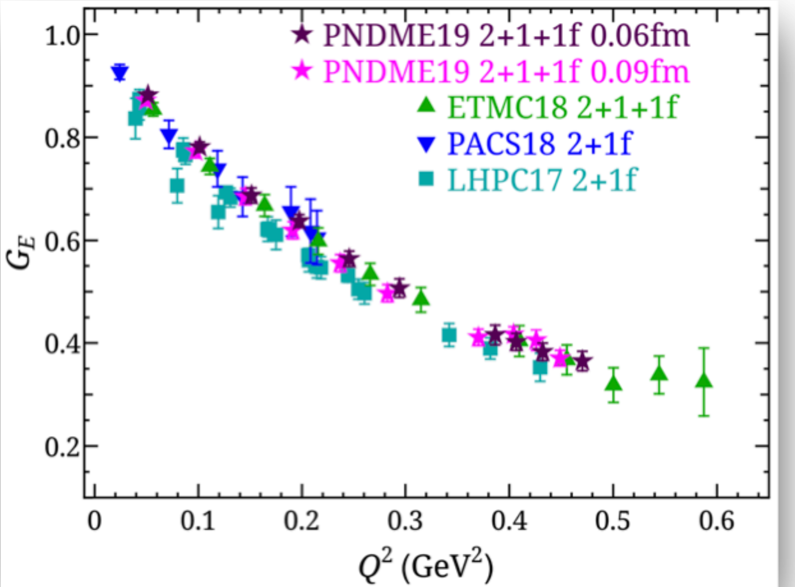
- 👍 Statistical uncertainty can be controlled
- 👍 contain physical information
- 👎 No direct access to x
- 👎 skewness independent
- 👎 Power-divergent mixing for high Mellin moments (derivatives > 3)
- 👎 Signal-to-noise ratio decays with the addition of covariant derivatives
- 👎 Number of GFFs increases with order of Mellin moment

Accessing information on PDFs/GPDs

Computationally efficient extraction of Q^2 dependence



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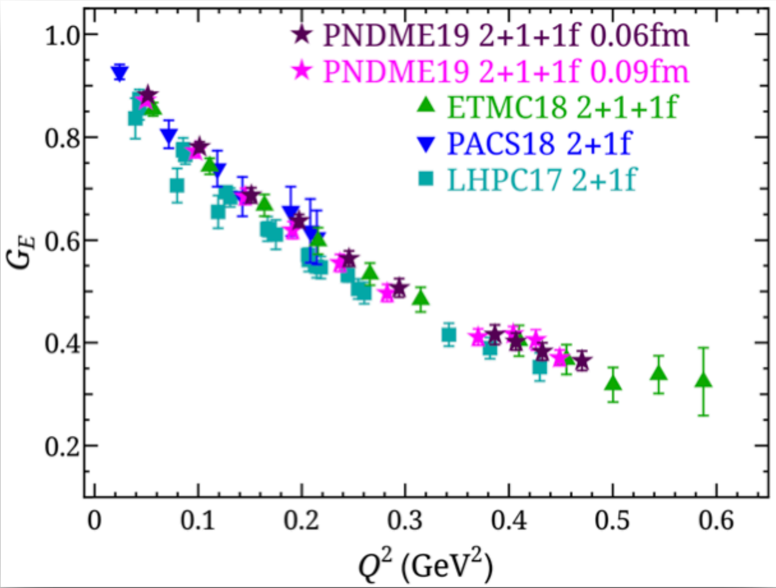

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Reconstruction of PDFs/GPDs very challenging

Accessing information on PDFs/GPDs

B. Matrix elements of nonlocal operators (quasi-GPDs, pseudo-GPDs)

$$\langle N(P_f) \,|\, \underbrace{\bar{\Psi}(z)\,\Gamma\,\mathscr{W}(z,0)\Psi(0)}_{} \,|\, N(P_i)\rangle_\mu$$

Nonlocal operator with Wilson line

$$\langle N(P')|O_V^\mu(x)|N(P)\rangle = \overline{U}(P')\left\{\gamma^\mu H(x,\xi,t) + \frac{i\sigma^{\mu\nu}\Delta_\nu}{2m_N}E(x,\xi,t)\right\}U(P) + \mathrm{ht}\,,$$

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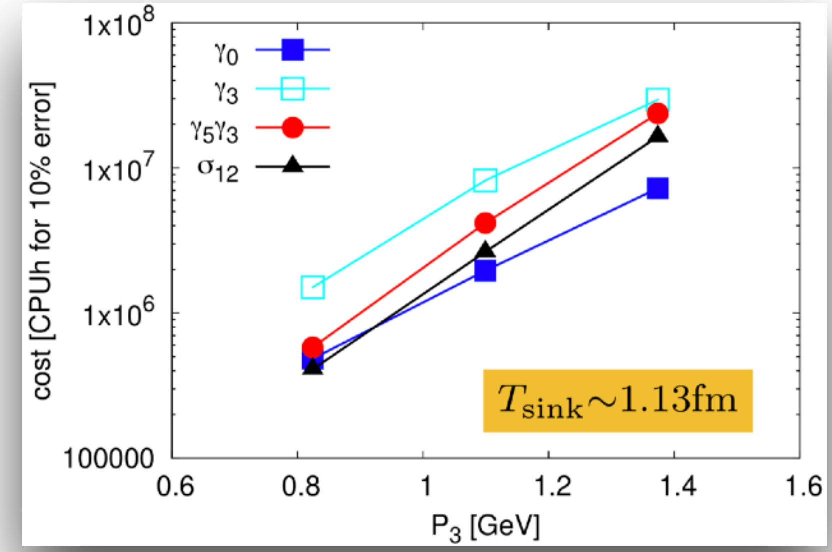
Calculation challenges

- Standard definition of GPDs in symmetric frame
  separate calculations at each t
- Statistical noise increases with P_3, t
  Projection:
  billions of core-hours for physical point at $P_3 = 3\,\mathrm{GeV}$



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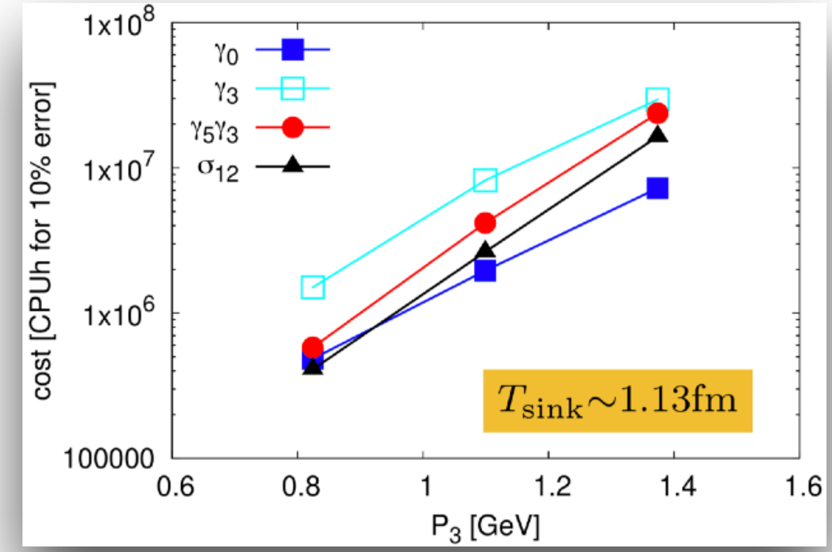
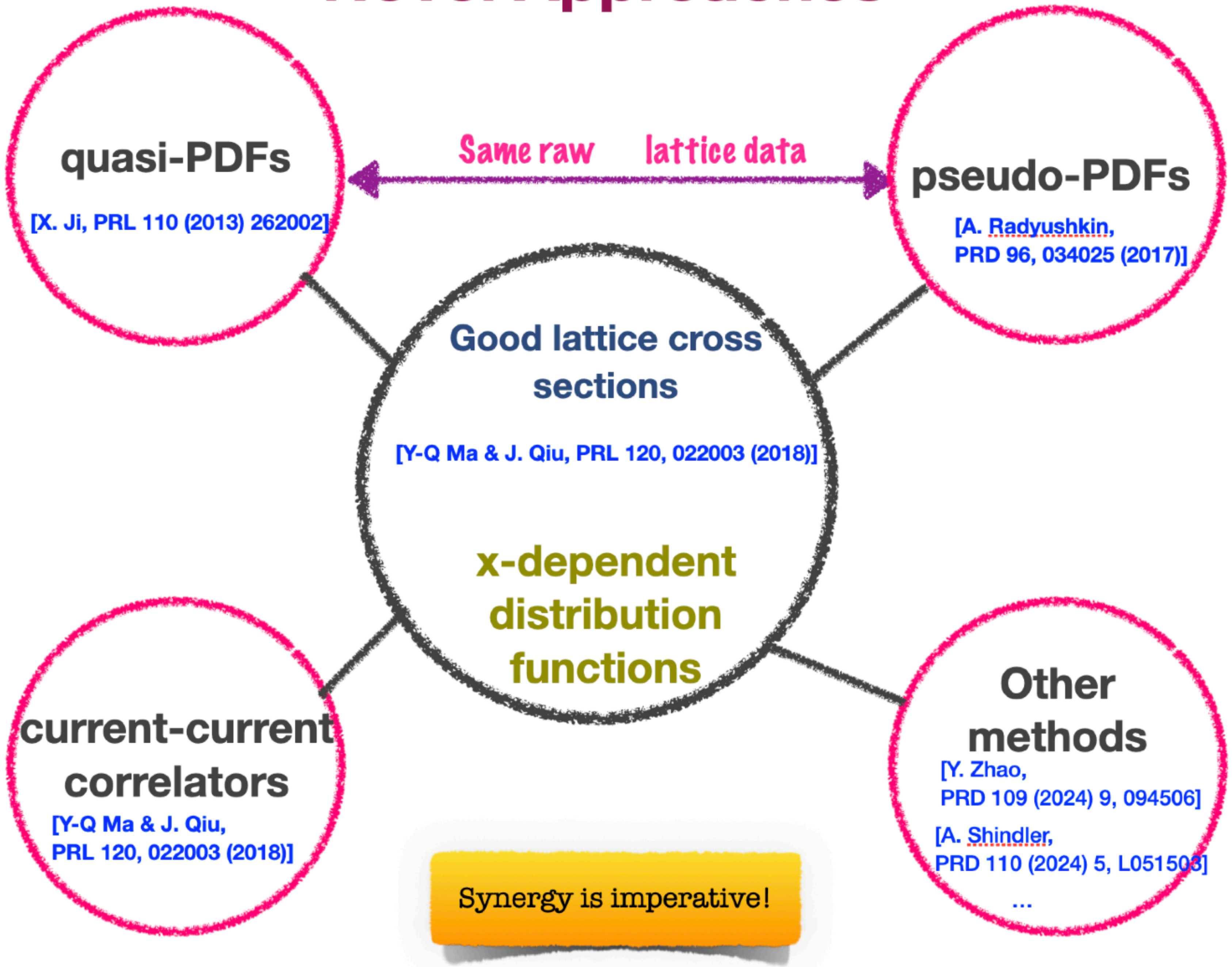


C. Other methods

See next slide

Novel Approaches



Hadronic tensor	[K.F. Liu, S.J. Dong, PRL 72 (1994) 1790, K.F. Liu, PoS(LATTICE 2015) 115]
Auxiliary scalar quark	[U. Aglietti et al., Phys. Lett. B441, 371 (1998), arXiv:hep-ph/9806277]
Fictitious heavy quark	[W. Detmold, C. J. D, Lin, Phys. Rev. D73, 014501 (2006)]
Auxiliary scalar quark	[V. Braun & D. Mueller, Eur. Phys. J. C55, 349 (2008), arXiv:0709.1348]
Higher moments	[Z. Davoudi, M. Savage, Phys. Rev. D86, 054505 (2012)]
Quasi-distributions (LaMET)	[X. Ji, PRL 110 (2013) 262002, arXiv:1305.1539; Sci. China PPMA. 57, 1407 (2014)]
Compton amplitude and OPE	[A. Chambers et al. (QCDSF), PRL 118, 242001 (2017), arXiv:1703.01153]
Pseudo-distributions	[A. Radyushkin, Phys. Rev. D 96, 034025 (2017), arXiv:1705.01488]
Good lattice cross sections	[Y-Q Ma & J. Qiu, Phys. Rev. Lett. 120, 022003 (2018), arXiv:1709.03018]
PDFs without Wilson line	[Y. Zhao Phys.Rev.D 109 (2024) 9, 094506, arXiv:2306.14960]
Moments of PDFs of any order	[A. Shindler, Phys.Rev.D 110 (2024) 5, L051503, arXiv:2311.18704]

Reviews of methods and applications

- ***A guide to light-cone PDFs from Lattice QCD: an overview of approaches, techniques and results***
  K. Cichy & M. Constantinou (invited review) Advances in HEP 2019, 3036904, arXiv:1811.07248
- ***Large Momentum Effective Theory***
  X. Ji, Y.-S. Liu, Y. Liu, J.-H. Zhang, and Y. Zhao (2020), 2004.03543
- ***The x-dependence of hadronic parton distributions: A review on the progress of lattice QCD***
  M. Constantinou (invited review) Eur. Phys. J. A 57 (2021) 2, 77, arXiv:2010.02445

Well-studied "novel" methods for PDFs/GPDs in LQCD

Matrix elements of non-local operators (space-like separated fields) with boosted hadrons

$$\mathcal{M}(P_f, P_i, z) = \langle N(P_f) \,|\, \bar{\Psi}(z)\,\Gamma\,\mathcal{W}(z,0)\Psi(0) \,|\, N(P_i)\rangle_\mu$$

Calculation very taxing!

- length of the Wilson line (z) } PDFs, GPDs
- nucleon momentum boost (P_3) } PDFs, GPDs
- momentum transfer (t) } GPDs
- skewness (ξ) } GPDs

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quasi-PDFs

pseudo-ITD

[A. Radyushkin, PRD 96, 034025 (2017)]

$$\tilde{q}_\Gamma^{\mathrm{GPD}}(x, t, \xi, P_3, \mu) = \int \frac{dz}{4\pi} e^{-i\,x\,P_3\,z}\,\mathscr{M}(P_f, P_i, z)$$

$$\mathfrak{M}(\nu, \xi, t; z_3^2) \equiv \frac{\mathscr{M}(\nu, \xi, t; z_3^2)}{\mathscr{M}(0,0,0; z^2)} \qquad (\nu = z \cdot p)$$

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Matching in momentum space
(Large Momentum
Effective Theory)

Matching in ν space

$$Q(\nu, \mu^2) = \int_{-1}^{1} dx\, e^{i\nu x} q(x, \mu^2)$$

Light-cone PDFs & GPDs

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Matching resembles factorization:

$$\sigma_{\rm DIS}(x, Q^2) = \sum_i \left[H^i_{\rm DIS} \otimes f_i\right](x, Q^2)$$

$$\tilde{q}^{\rm GPD}_\Gamma(x, t, \xi, P_3, \mu) = \int \frac{dz}{4\pi} e^{-i\,x\,P_3\,z}\,\mathscr{M}(P_f, P_i, z)$$

$$\mathfrak{M}(\nu, \xi, t; z_3^2) \equiv \frac{\mathscr{M}(\nu, \xi, t; z_3^2)}{\mathscr{M}(0,0,0; z^2)} \qquad (\nu = z \cdot p)$$

Matching in momentum space
(Large Momentum
Effective Theory)

Matching in ν space

$$Q(\nu, \mu^2) = \int_{-1}^{1} dx\, e^{i\nu x} q(x, \mu^2)$$

Light-cone PDFs & GPDs

Calculation very taxing!

- length of the Wilson line (z)
- nucleon momentum boost (P_3)

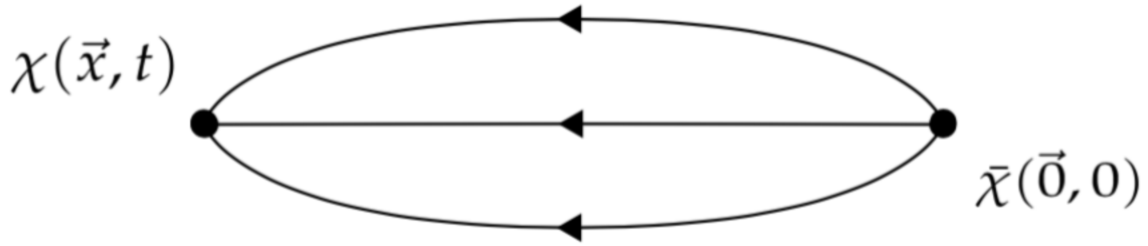
} PDFs, GPDs

- momentum transfer (t)
- skewness (ξ)

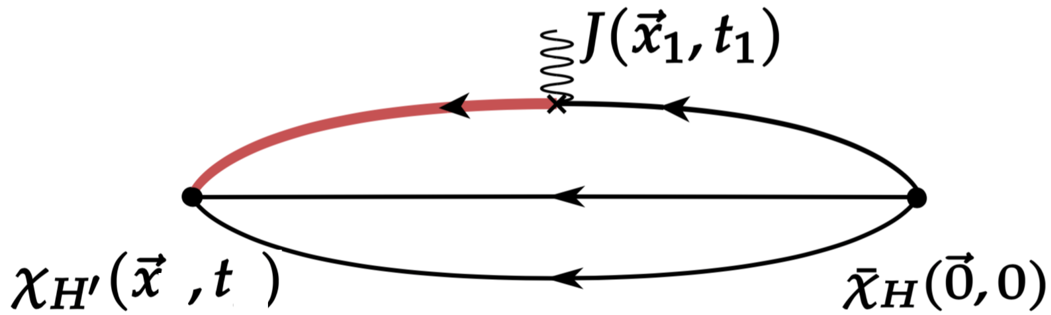
} GPDs

Correlation functions in lattice QCD

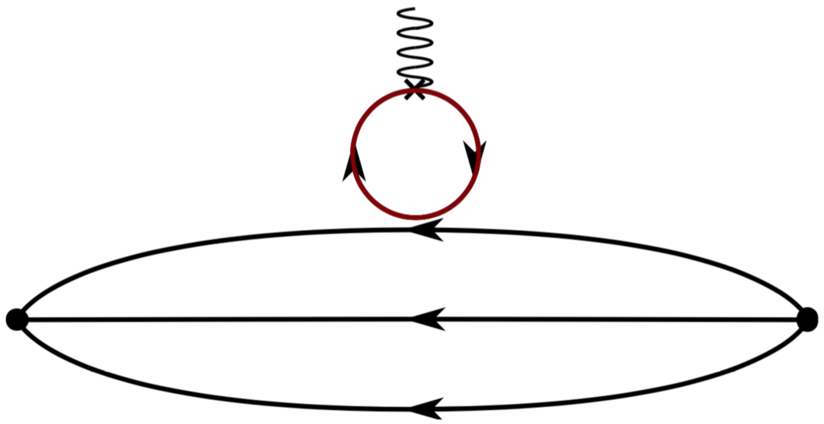
2pt-functions



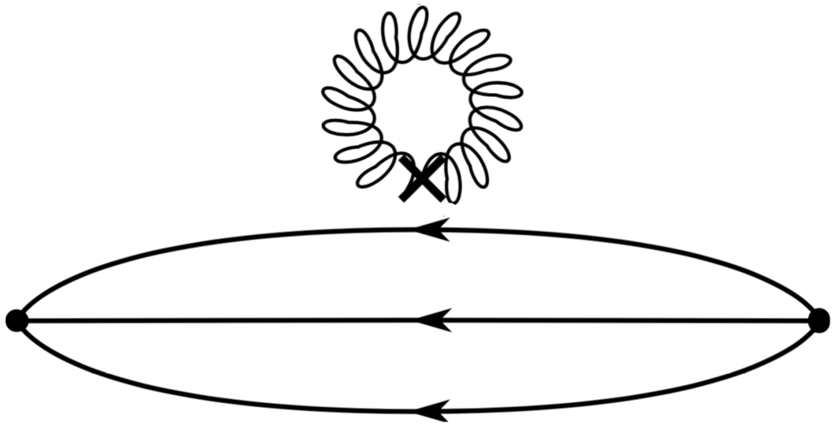
3pt-functions



Connected



Disconnected Quark loop

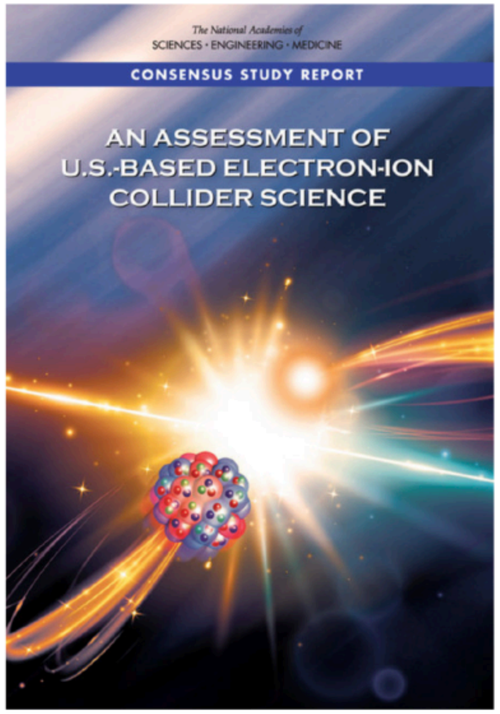


Disconnected Gluon loop

Understanding how lattice calculations support EIC physics:

the proton spin

Hadron structure at core of nuclear physics

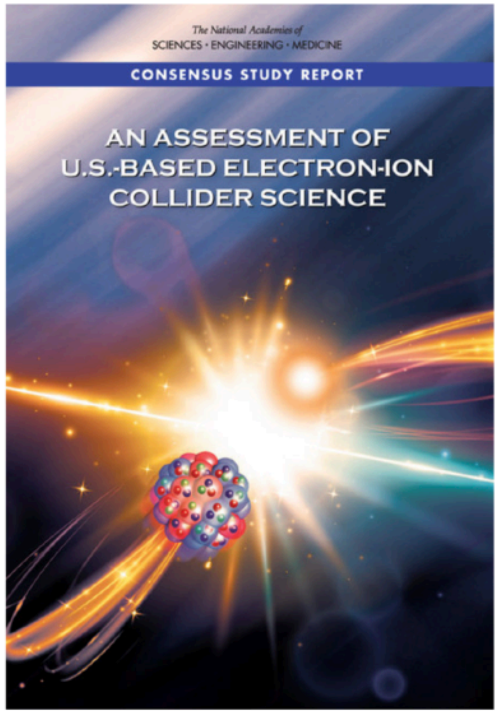


Main Pillar of NAS: Assessment report for EIC

Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Hadron structure at core of nuclear physics



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Advances of Lattice QCD are timely

Lattice QCD is featured in the EIC Yellow Report
- 900-page document
- scientist from 151 Institutions

Lattice QCD can provide input in the proton mass and spin decomposition from first principles

Proton spin "puzzle"

- ★ Fundamental degree of freedom (from space-time symmetry) Proton spin:1/2
- ★ Spin plays an important role in determining the structure of composite particles, like the proton
- ★ Simple models predict that the 3 quarks responsible for the proton's quantum numbers carry 1/3 of its spin
- ★ DIS experiments (1988) show surprising results for proton spin

[J. Ashman et al., Phys. Lett., vol. B206 (1988) 364]

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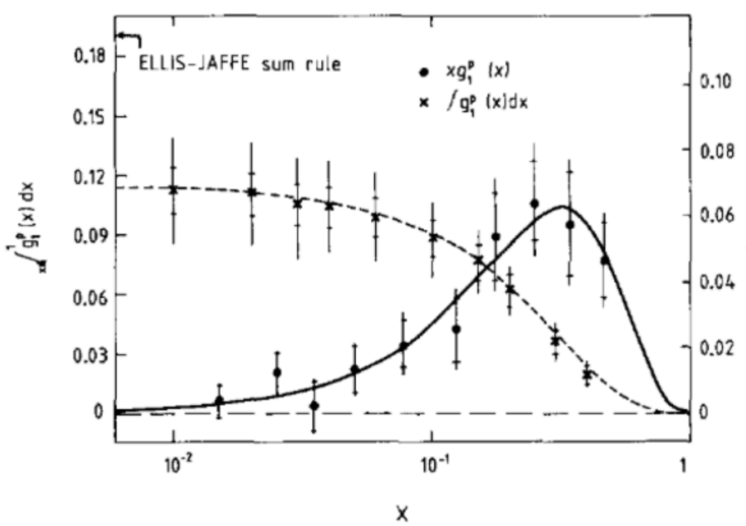

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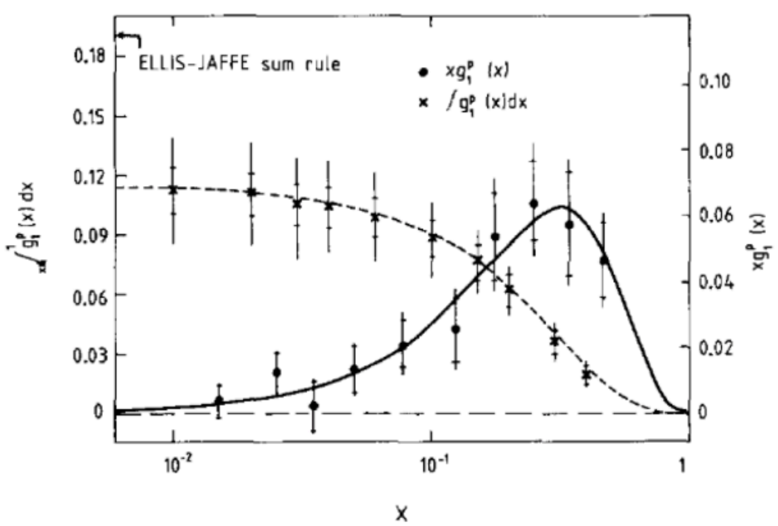

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SPIN CRISIS !

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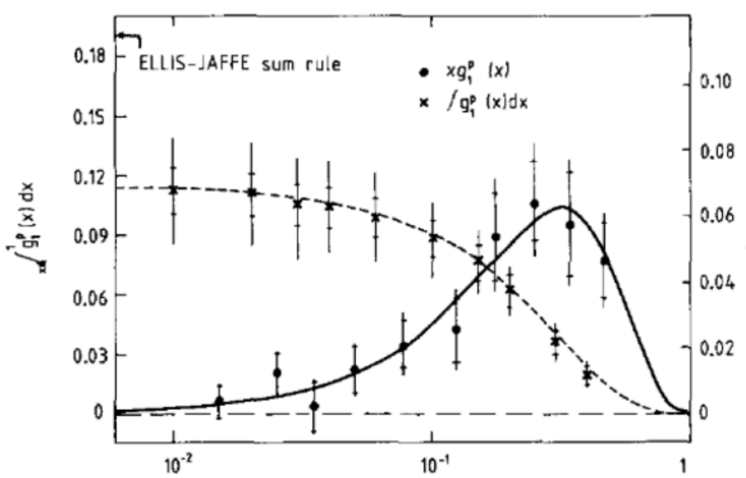

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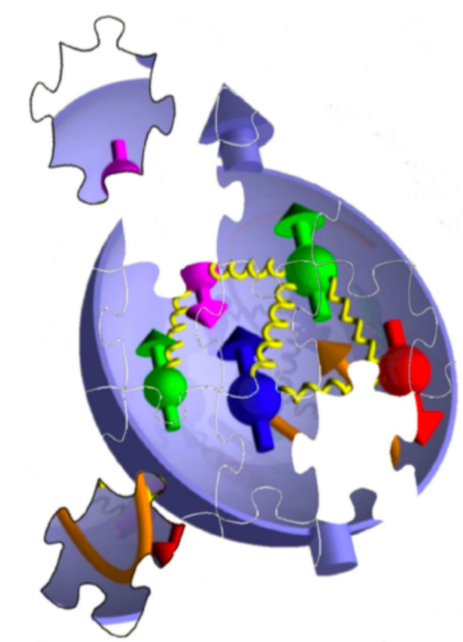

Still open questions:

- Sea quark and gluon contributions
- Parton orbital angular momentum

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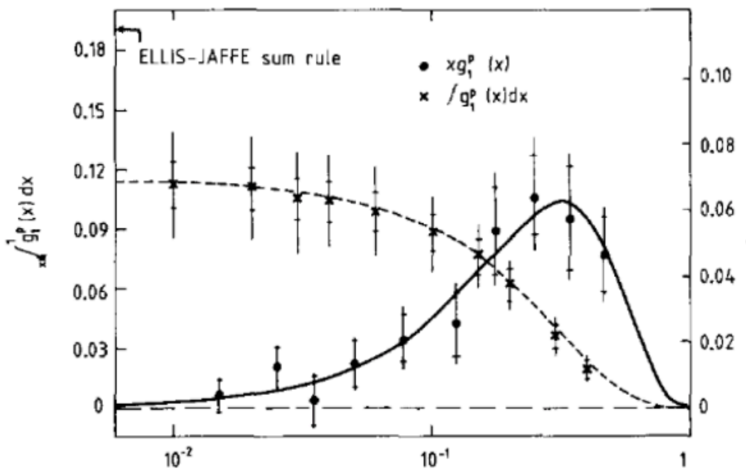

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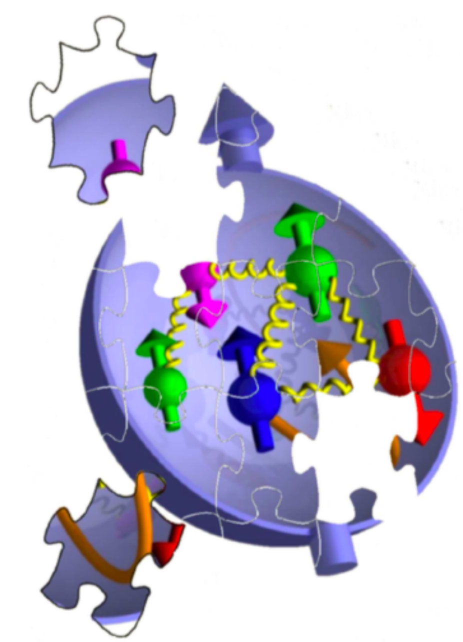

Still open questions:

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We must quantify the proton spin decomposition

Spin structure from first principles

Lattice QCD can provide important information on the spin

Ji's Spin Decomposition

$$\frac{1}{2} = \sum_q J^q + J^G = \sum_q \left(L^q + \frac{1}{2}\Delta\Sigma^q \right) + J^G$$

L_q: Quark orbital angular momentum

$\Delta\Sigma_q$: Intrinsic spin

J_g: Gluon spin

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All these quantities can be computed within Lattice QCD

Extraction from Lattice QCD:

$$J^q = \frac{1}{2}\left(A_{20}^q + B_{20}^q \right)$$

$$L^q = J^q - \Sigma^q$$

$$\Sigma^q = g_A^q$$

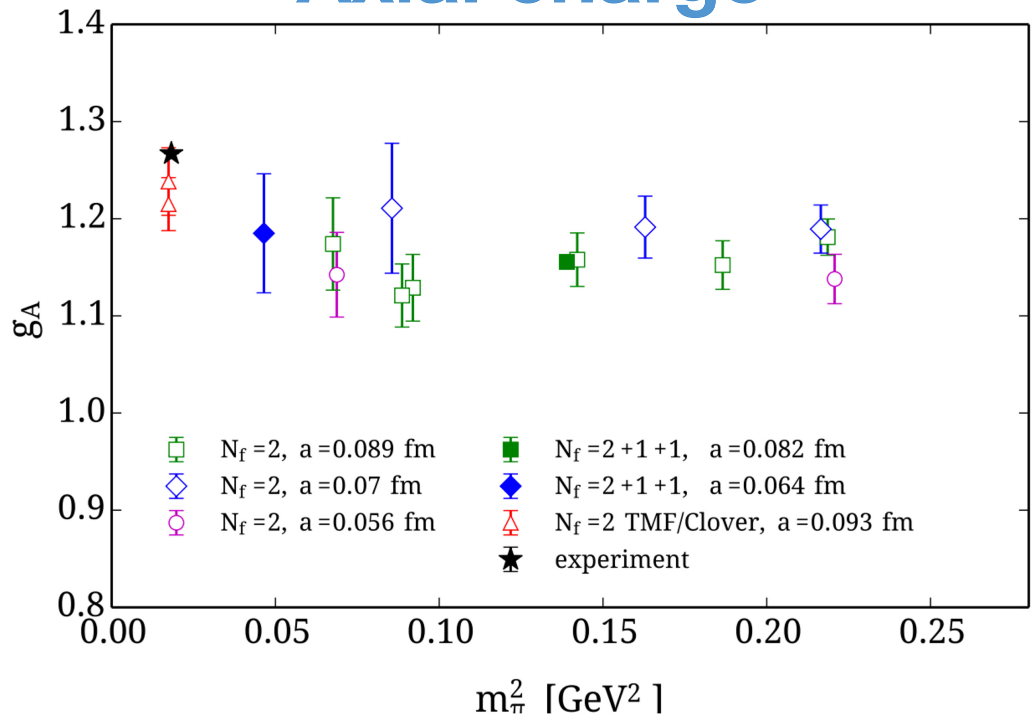
Necessary computations:

- Axial Charge
- Quark momentum fraction
- Gluon momentum fraction

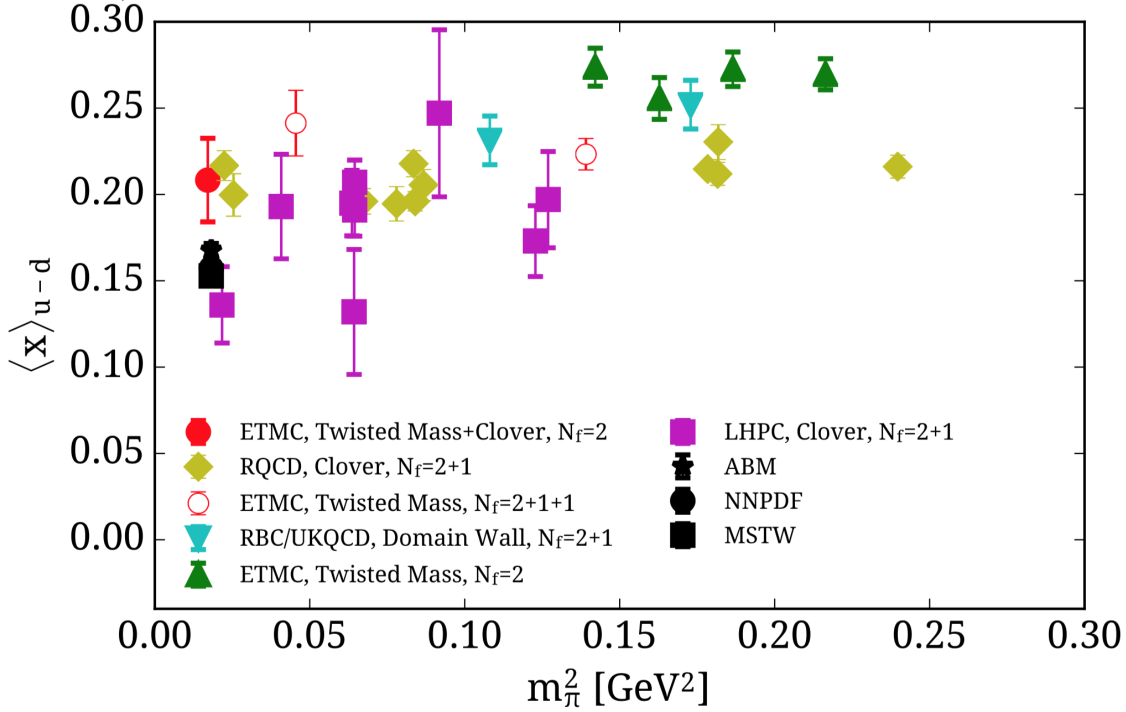
Quark Orbital Angular extracted indirectly

Spin components in Lattice QCD

Axial charge



Quark momentum fraction



Spin components in Lattice QCD

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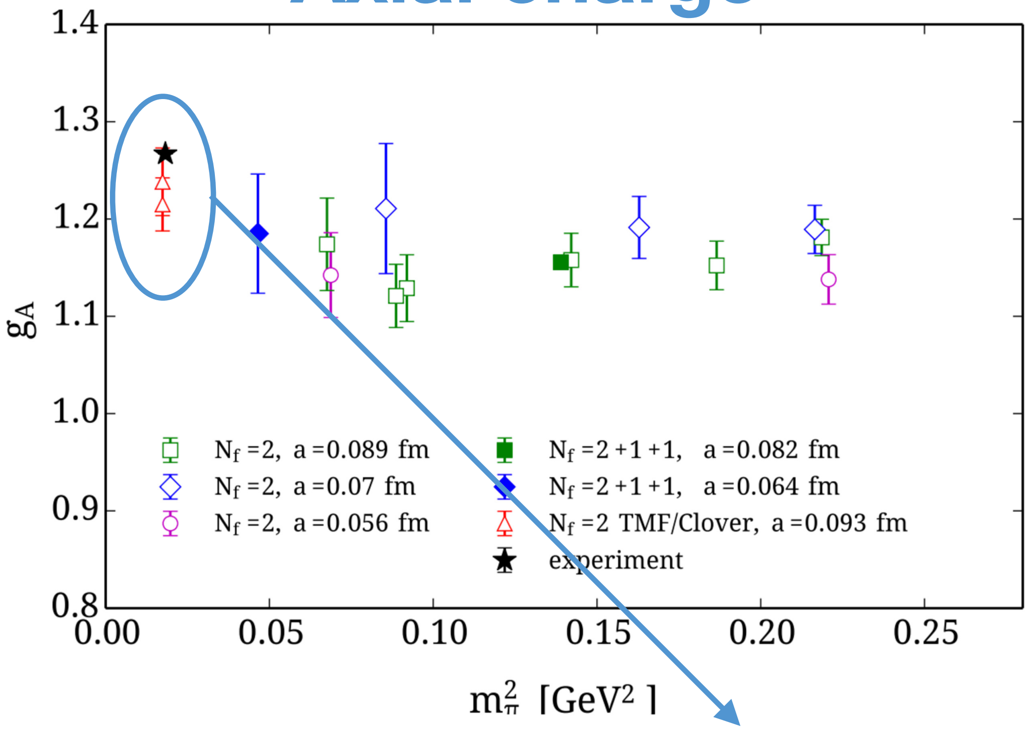

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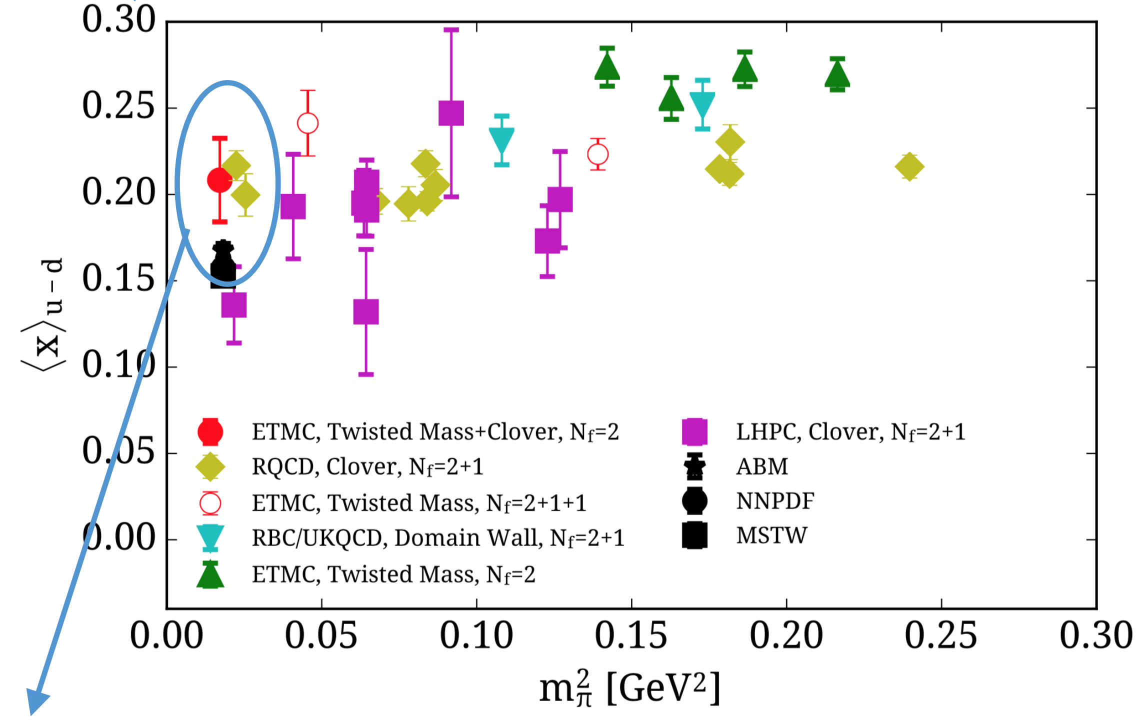
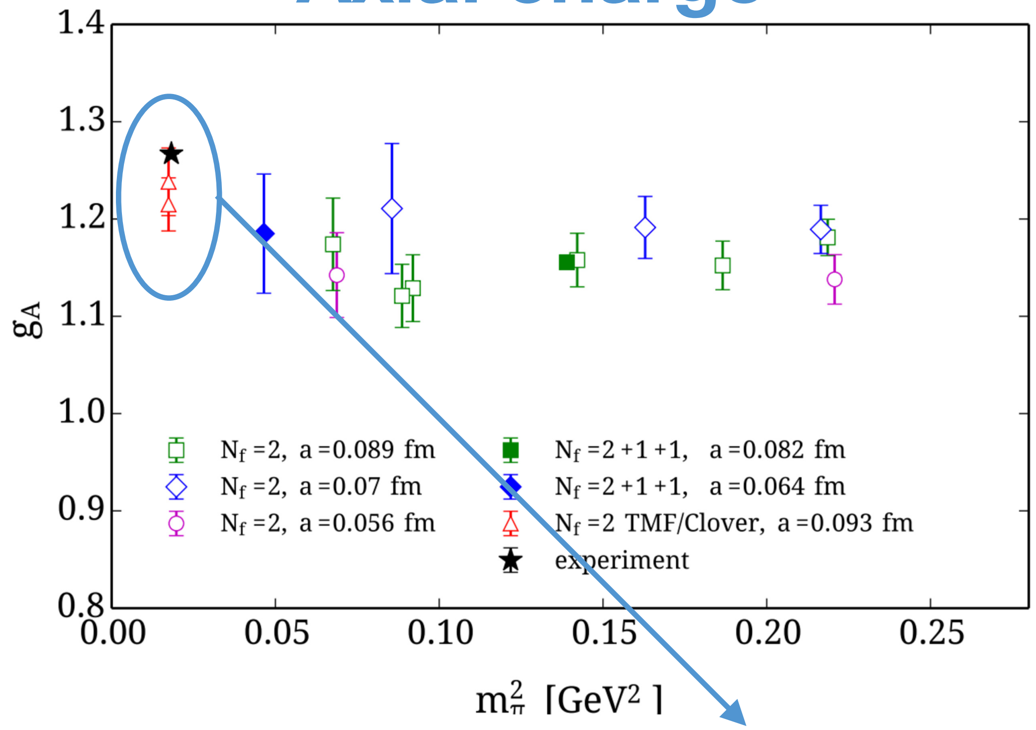


Simulations of nature enabled from new methods, algorithms, computer architecture

Spin components in Lattice QCD

Axial charge



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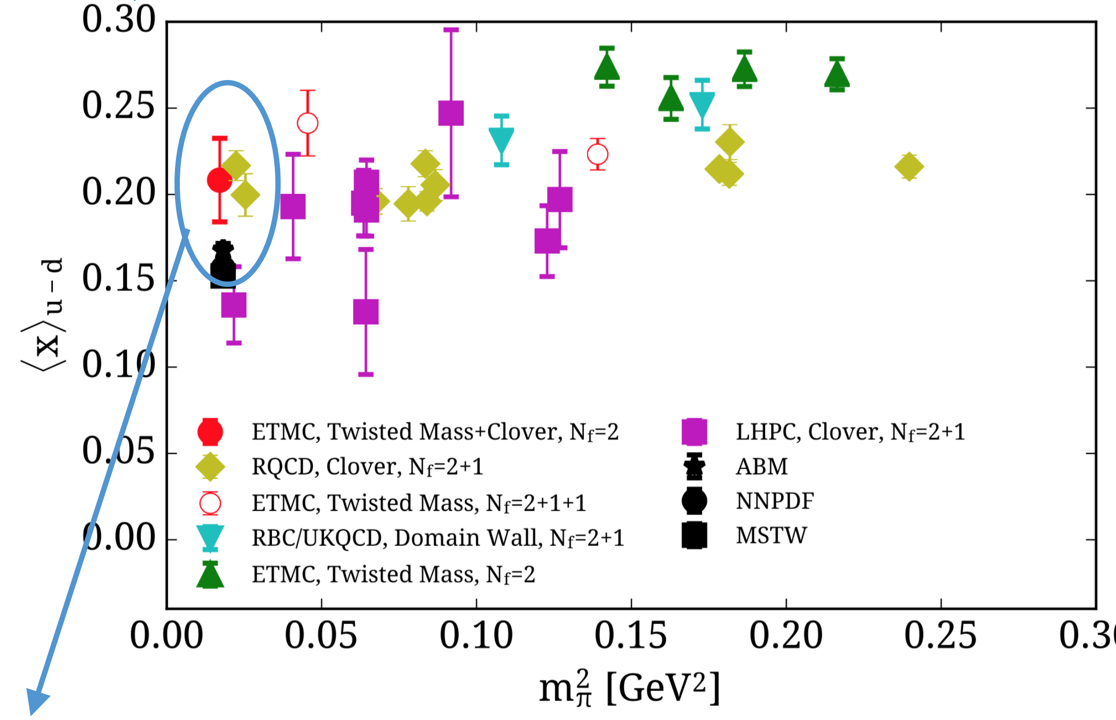
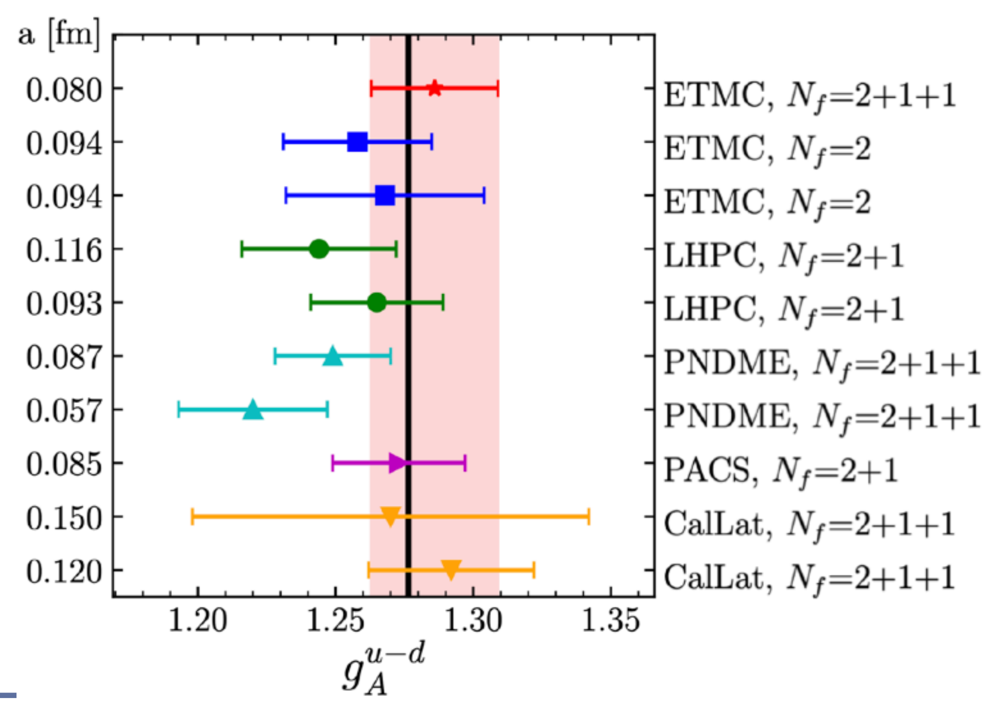


Simulations of nature enabled from new methods, algorithms, computer architecture

Summary of results

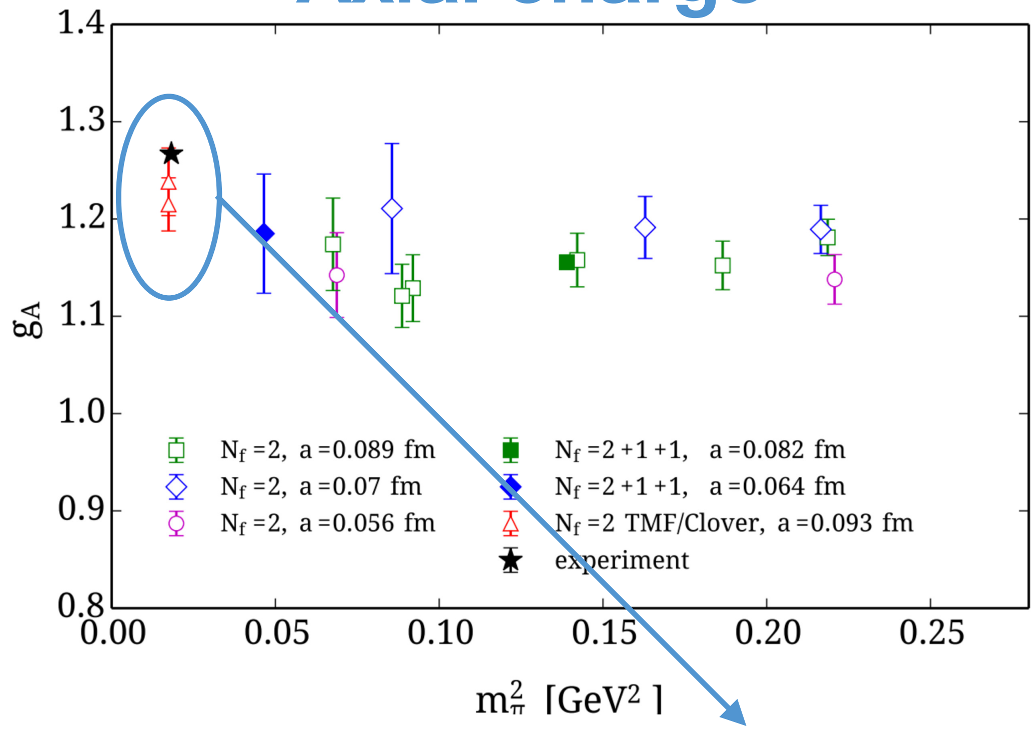


	u	d	s	c
g_A	0.862(17)	-0.424(16)	-0.0458(73)	-0.0098(34)

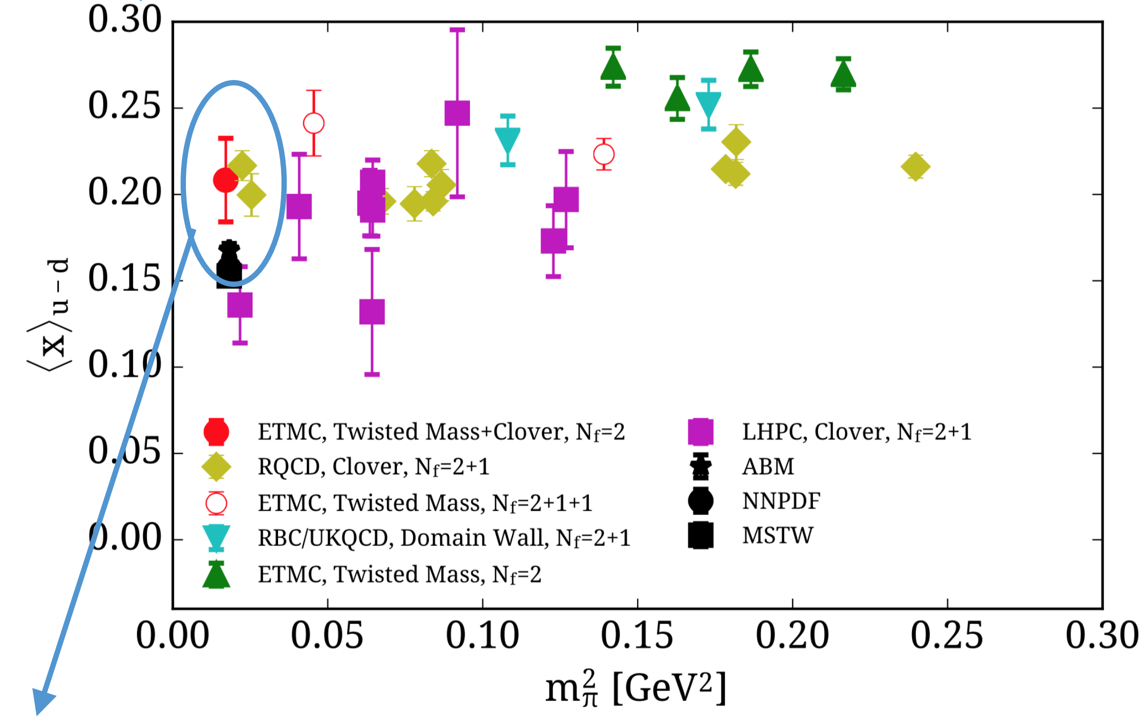
Taking into account the disconnected contributions is crucial for the spin

Spin components in Lattice QCD

Axial charge



Quark momentum fraction



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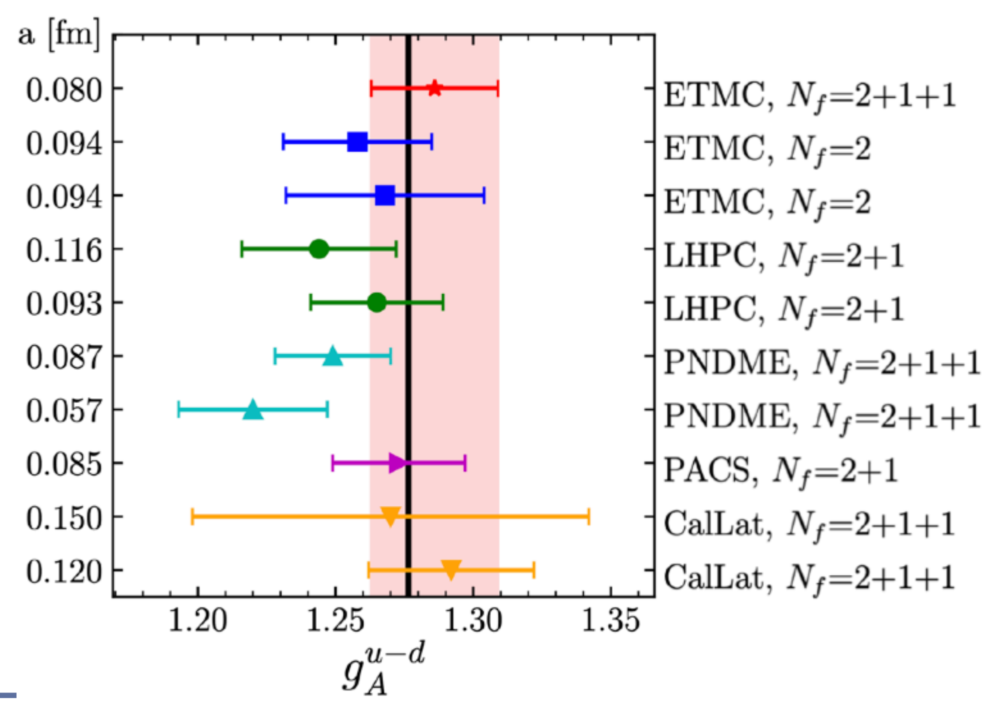

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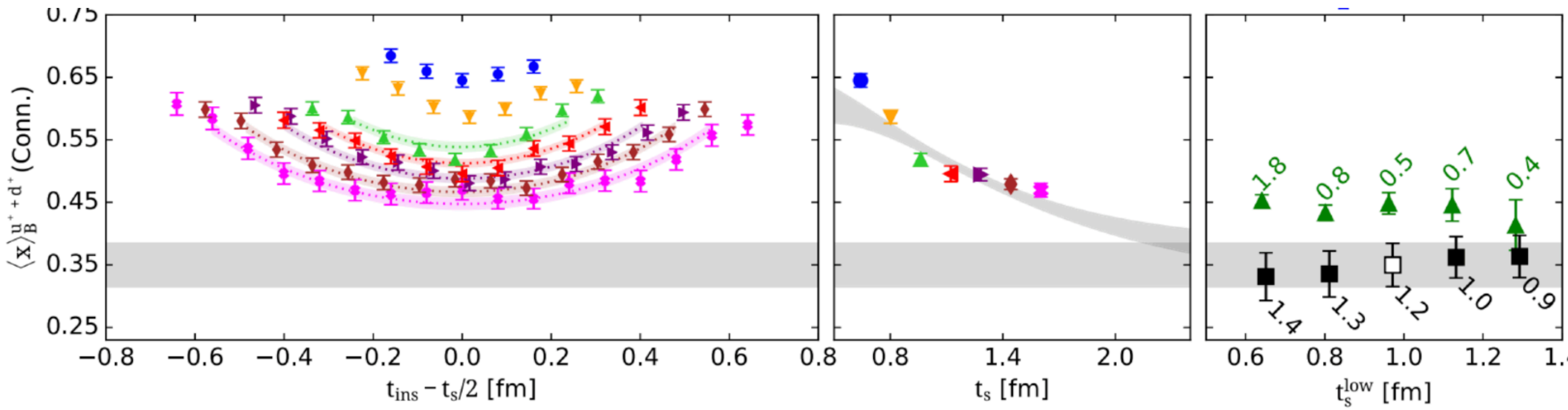
Quark momentum fraction

★ **connected contributions**



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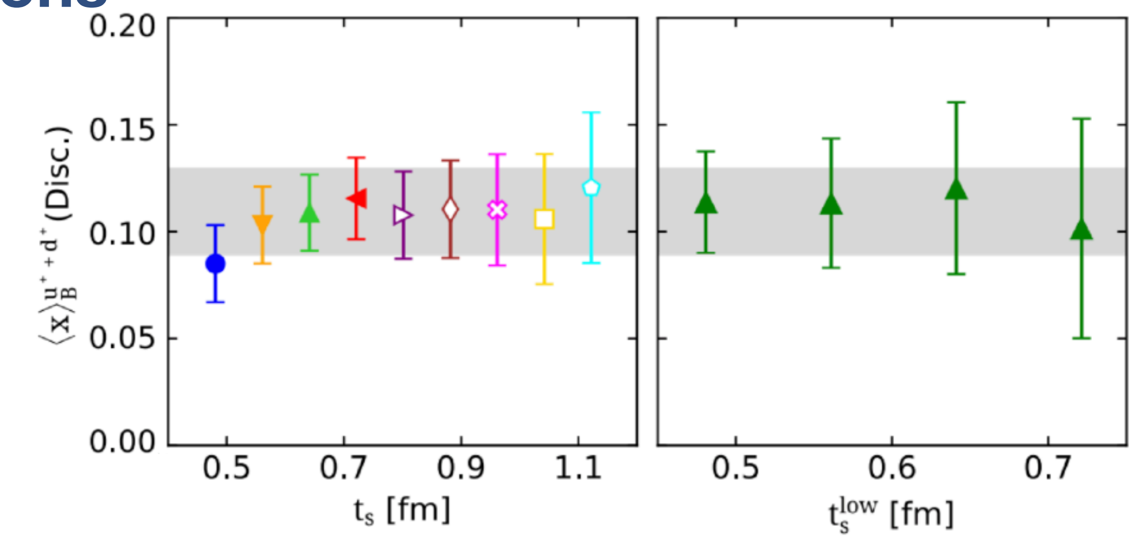

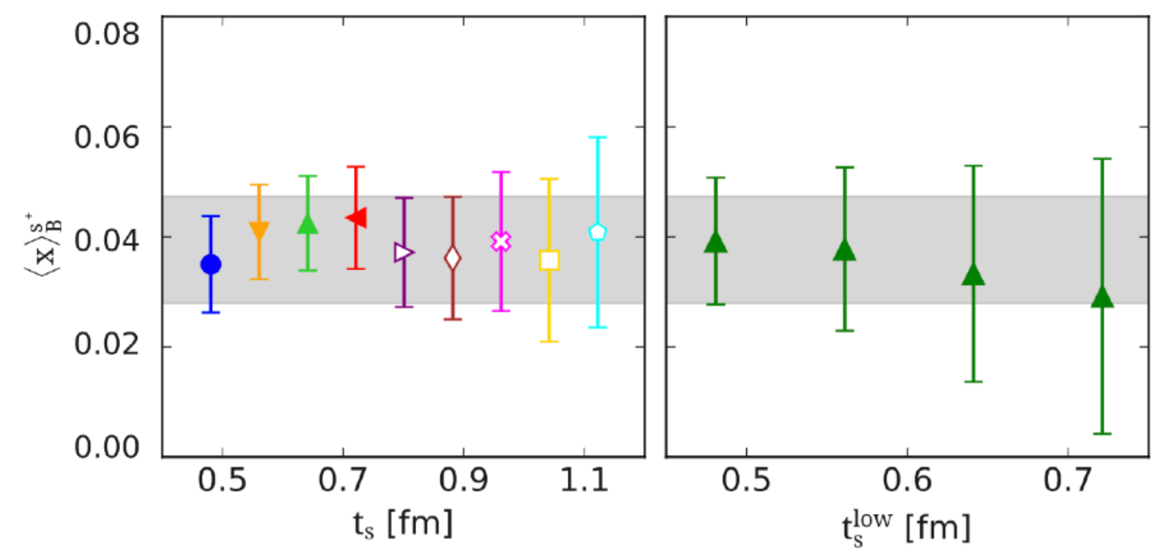

Quark momentum fraction

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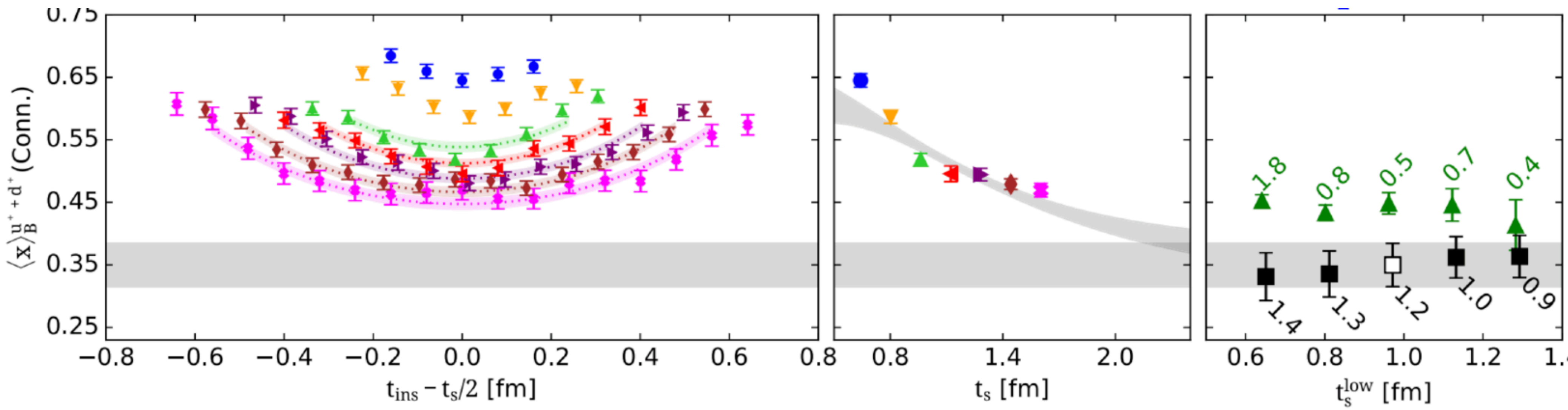
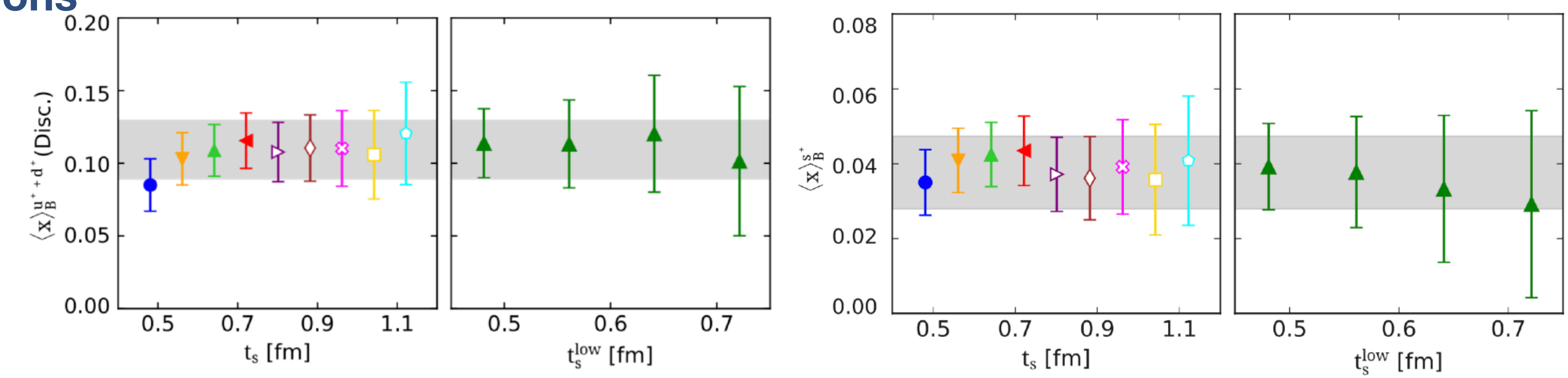
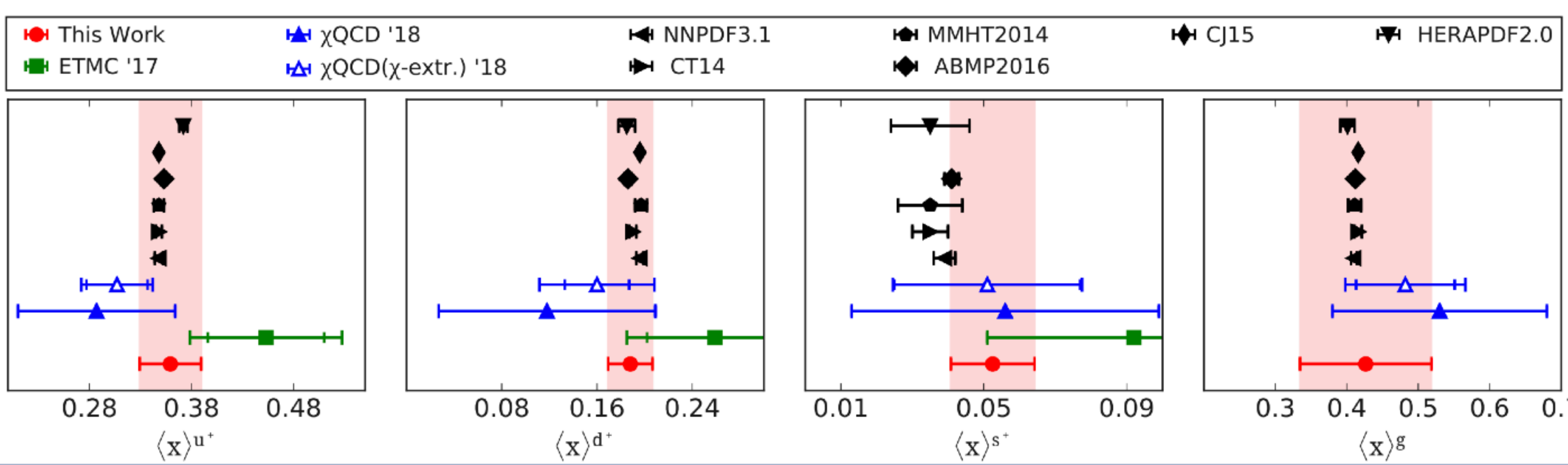


★ disconnected contributions

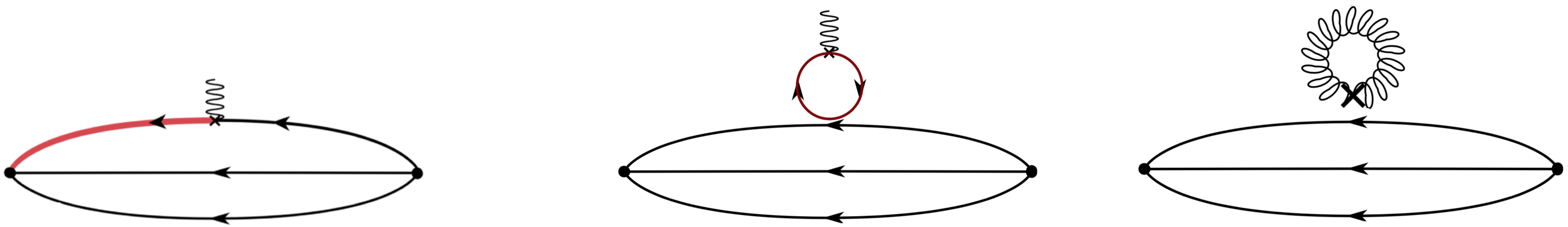


Collection of various results



Results @ physical pion mass

$\overline{MS}(2\text{GeV})$



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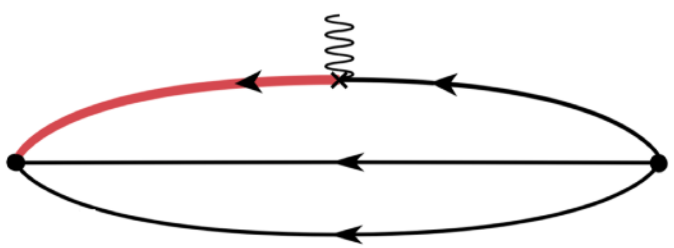
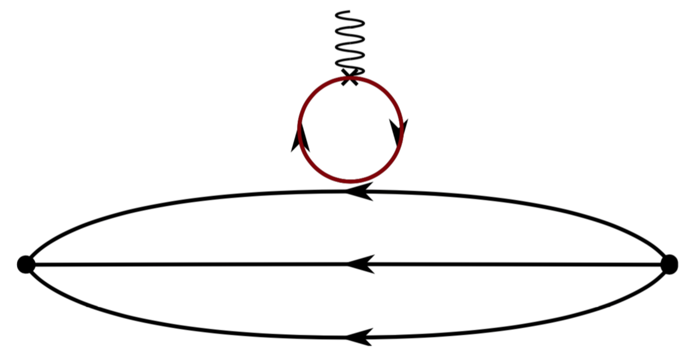


$\langle x \rangle^B_{u+d} = 0.350(35)$



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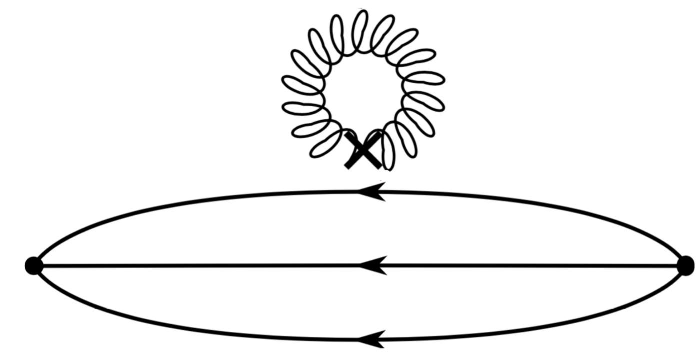

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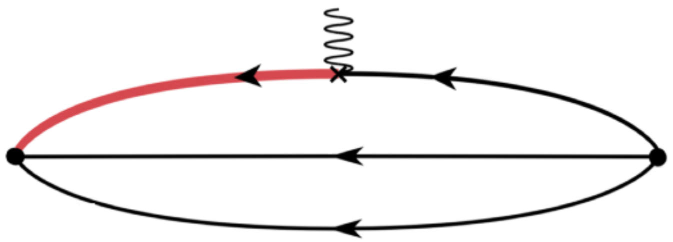

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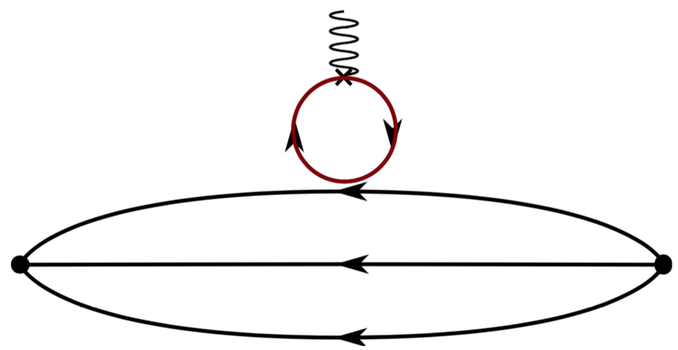

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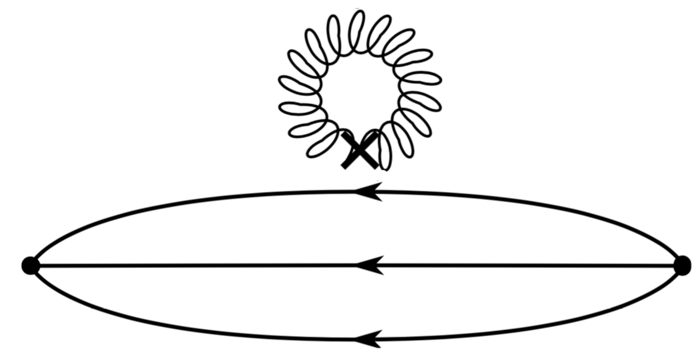

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★ **Mixing between quark and gluon contributions to $\langle x \rangle$**

$$\sum_q \langle x \rangle^R_q = Z_{qq} \sum_q \langle x \rangle^B_q + Z_{qg} \langle x \rangle^B_g \qquad \langle x \rangle^R_g = Z_{gg} \langle x \rangle^B_g + Z_{gq} \sum_q \langle x \rangle^B_q$$

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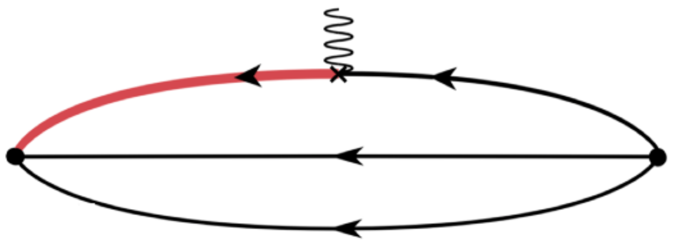

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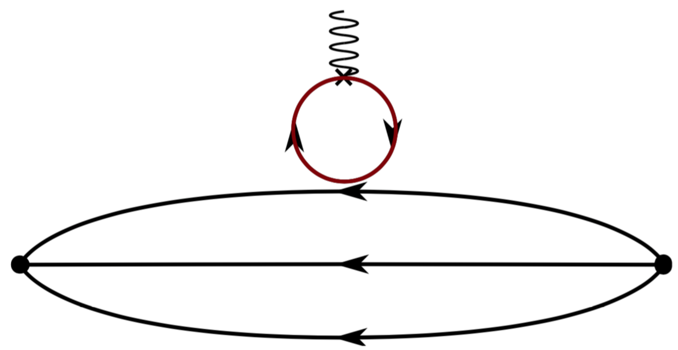

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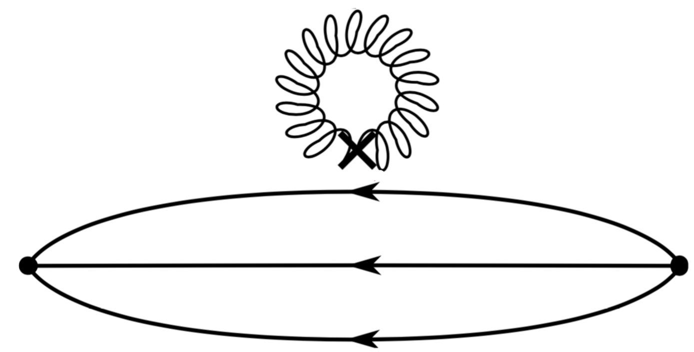

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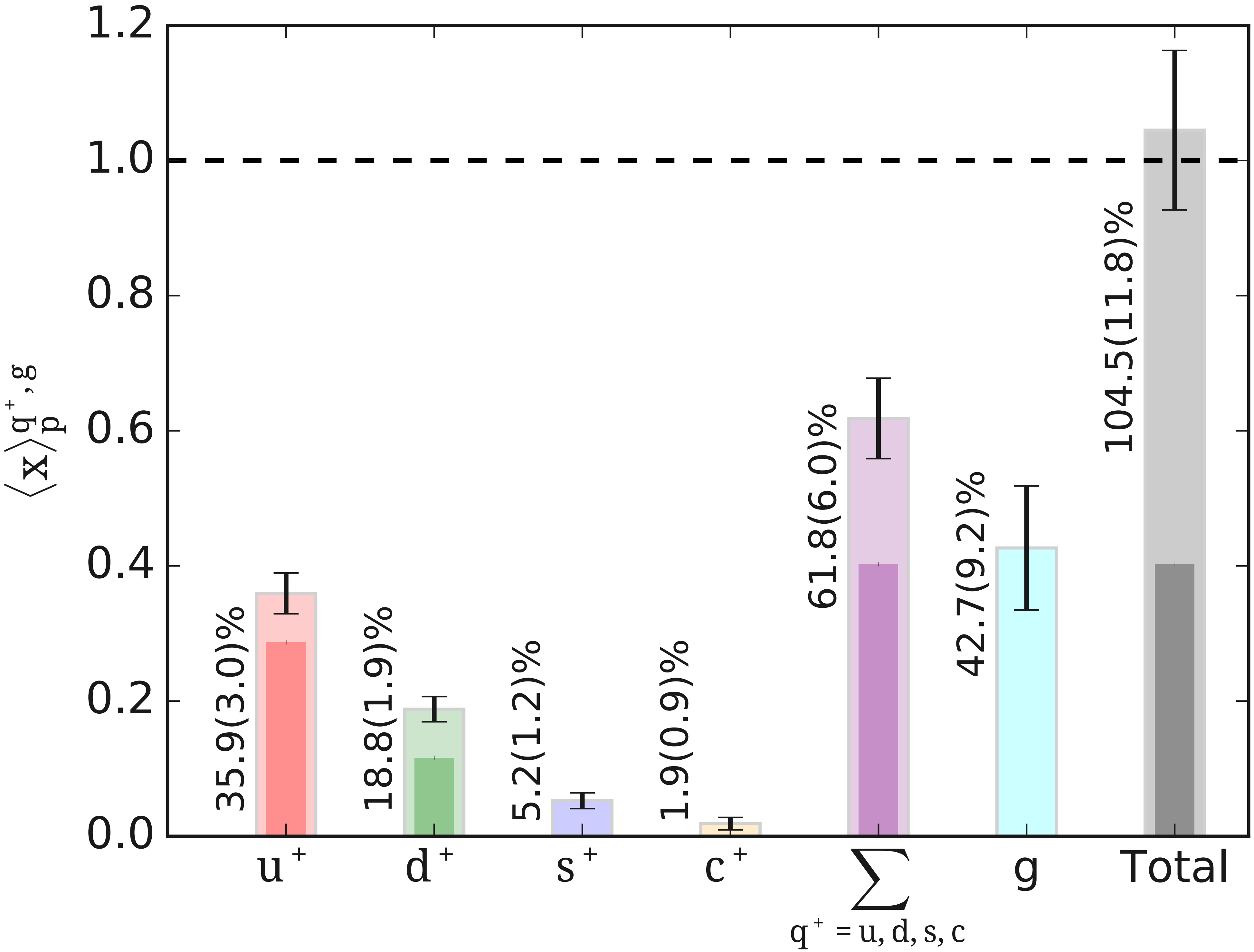
$\langle x \rangle_u = 0.359(30)$ $\quad \langle x \rangle_d = 0.188(19)$ $\quad \langle x \rangle_s = 0.052(12)$ $\quad \langle x \rangle_c = 0.019(9)$ $\quad \langle x \rangle_g = 0.427(92)$

Percentage of momentum



Momentum sum rule satisfied!

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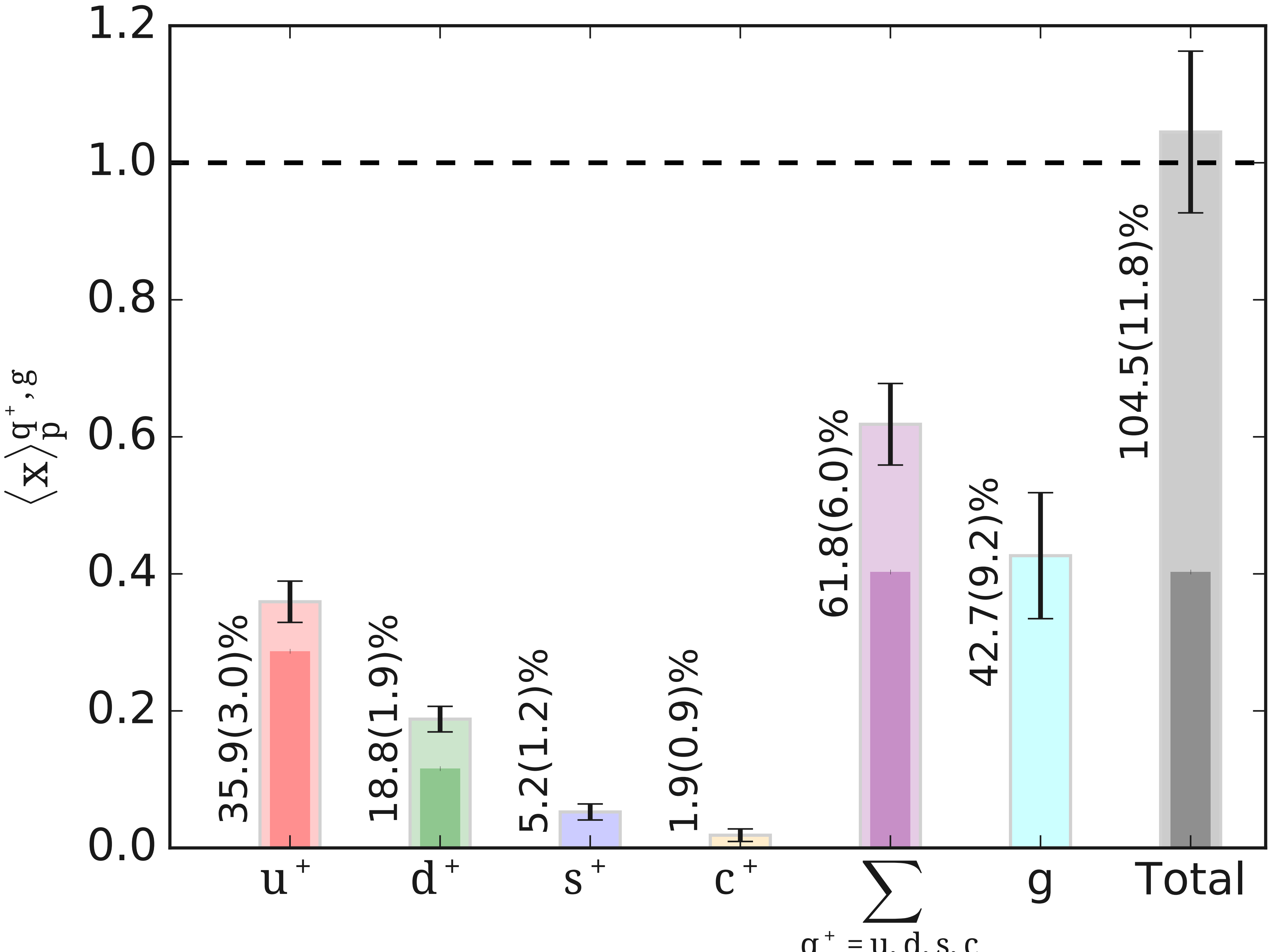

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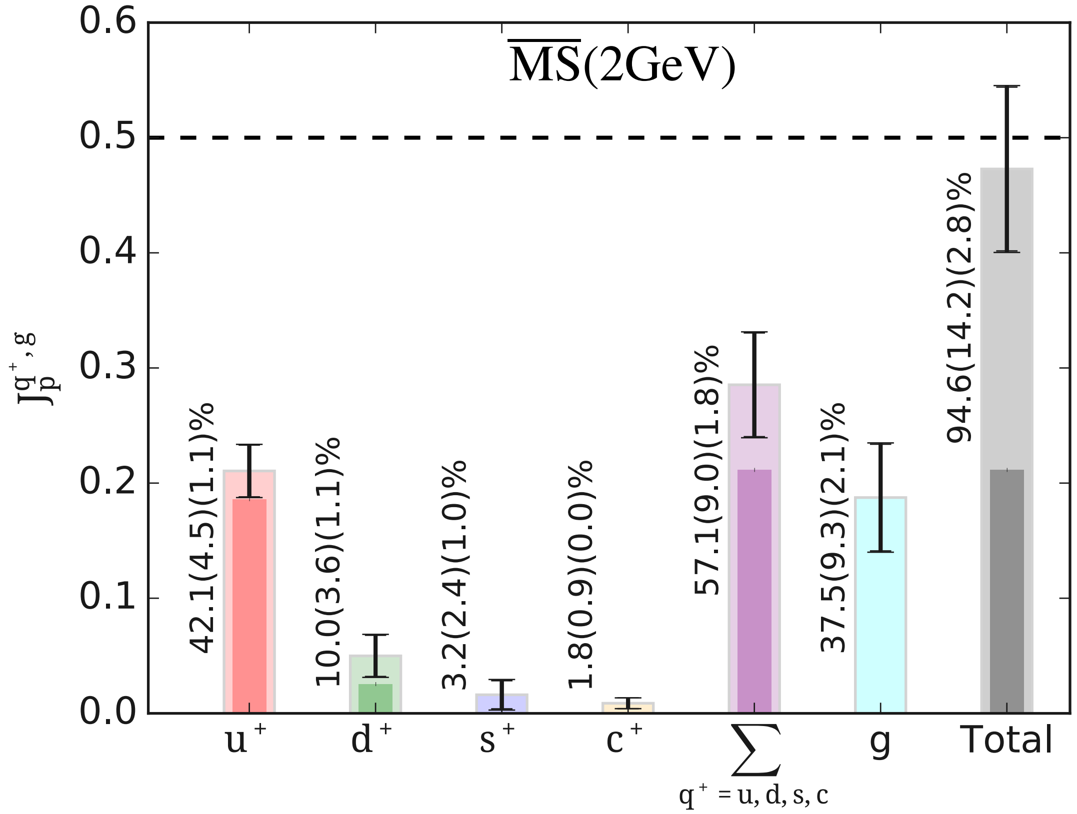
Spin decomposition

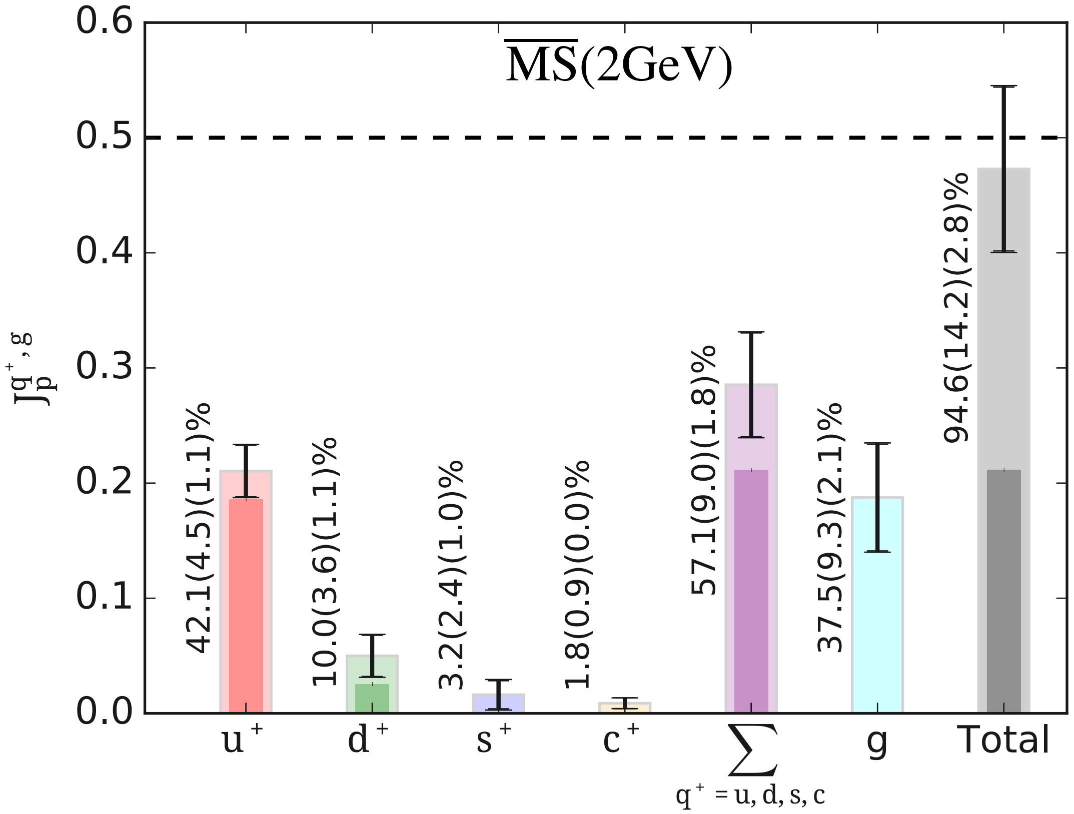
[C. Alexandrou et al., Phys. Rev. D 101, 094513 (2020), arXiv:2003.08486]

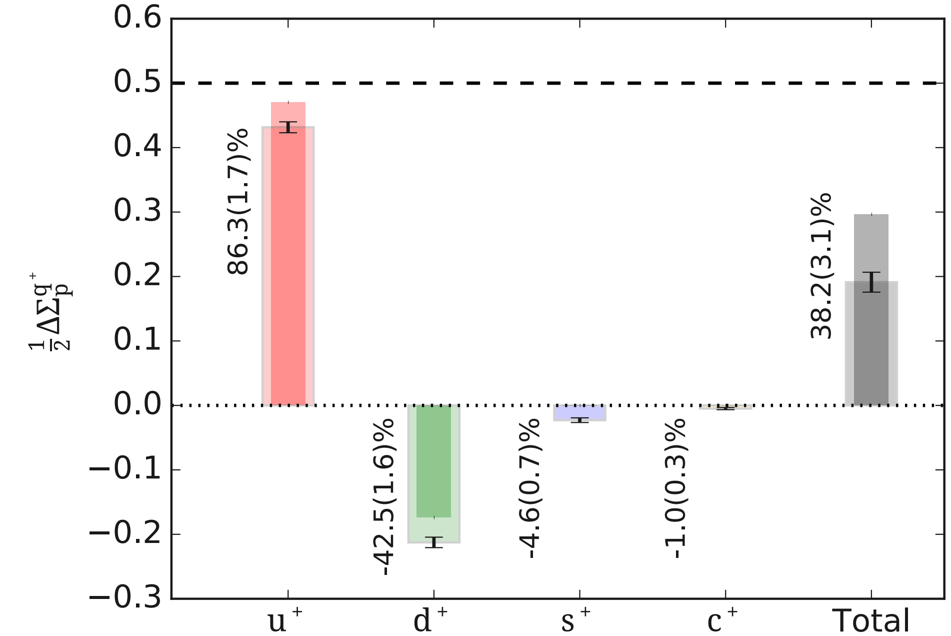


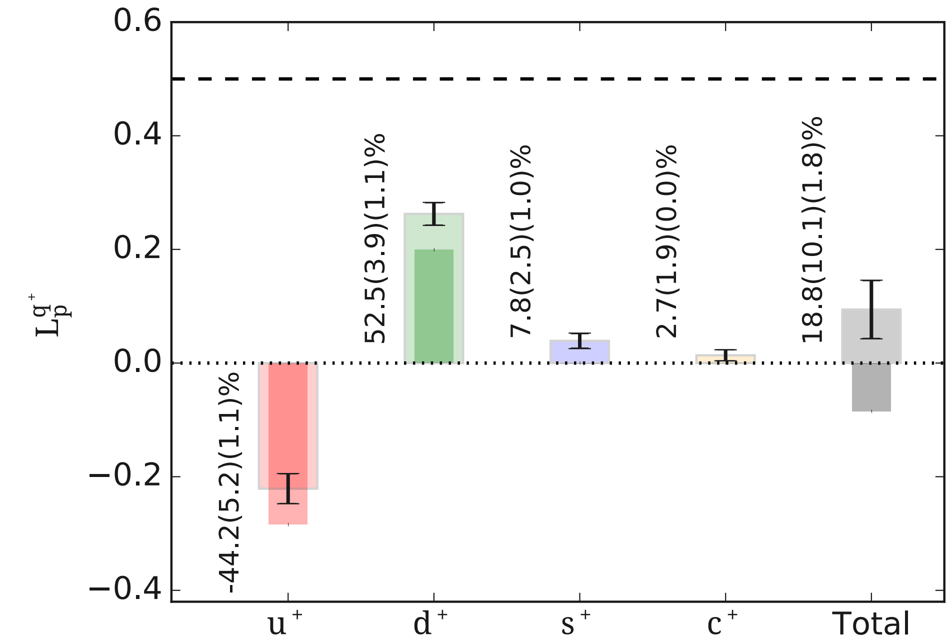
- ★ **Inner bars: connected contributions**
- ★ **Outer - Inner bars: disconnnected contributions**

Spin decomposition

[C. Alexandrou et al., Phys. Rev. D 101, 094513 (2020), arXiv:2003.08486]







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Quark orbital angular momentum extracted indirectly ($L_q = J_q - \Sigma_q$)

Spin decomposition

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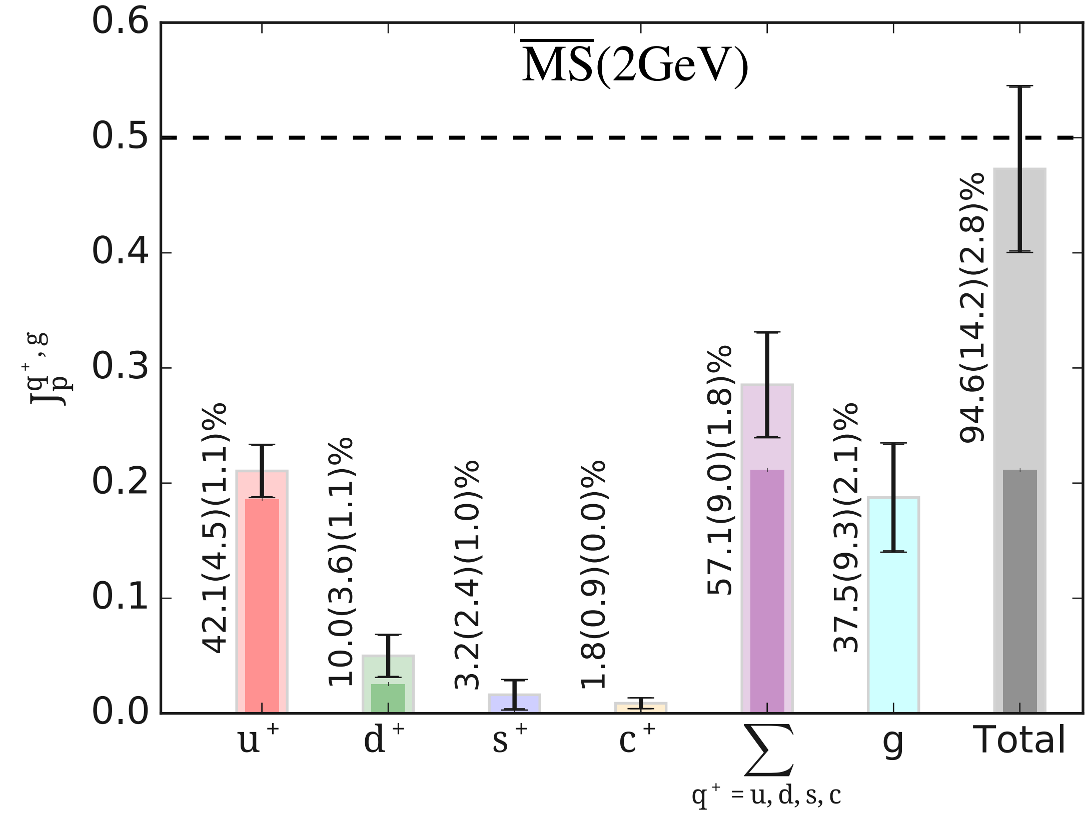

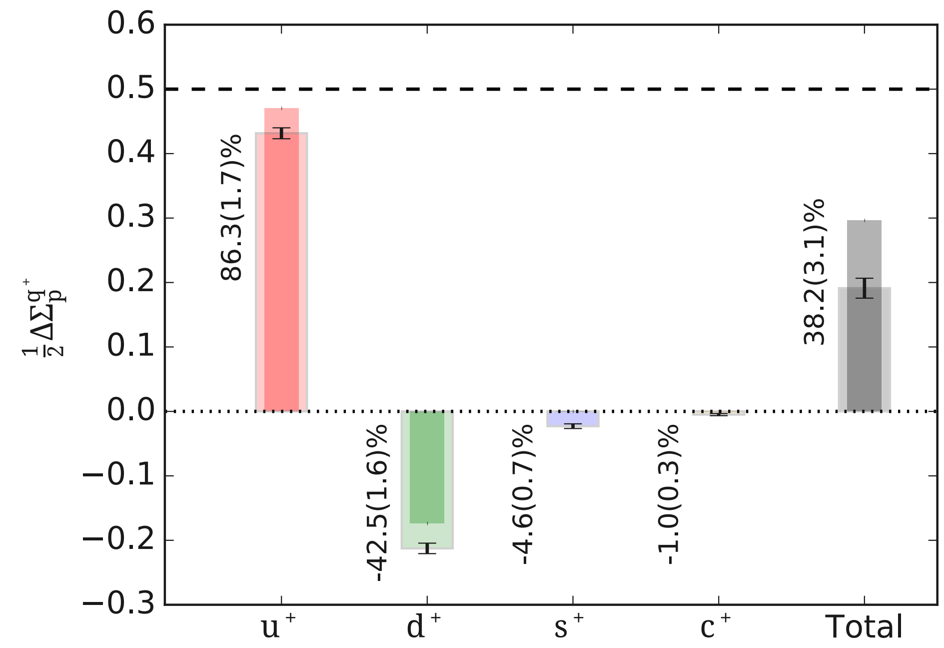

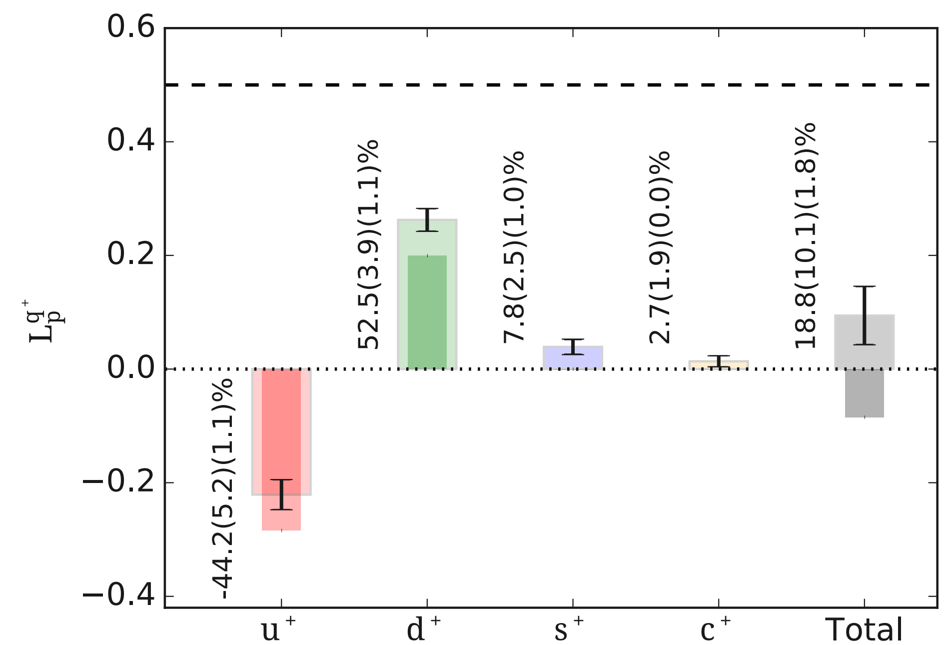

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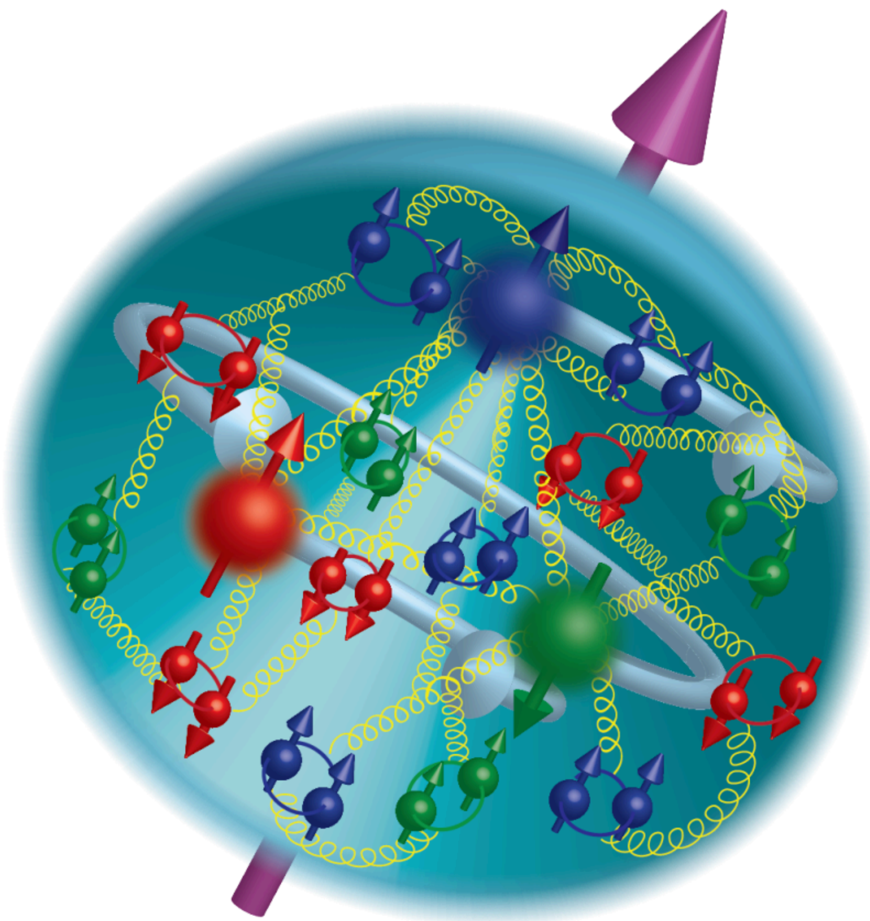
Quark orbital angular momentum extracted indirectly ($L_q = J_q - \Sigma_q$)

Satisfaction of spin and momentum sum rule is not forced

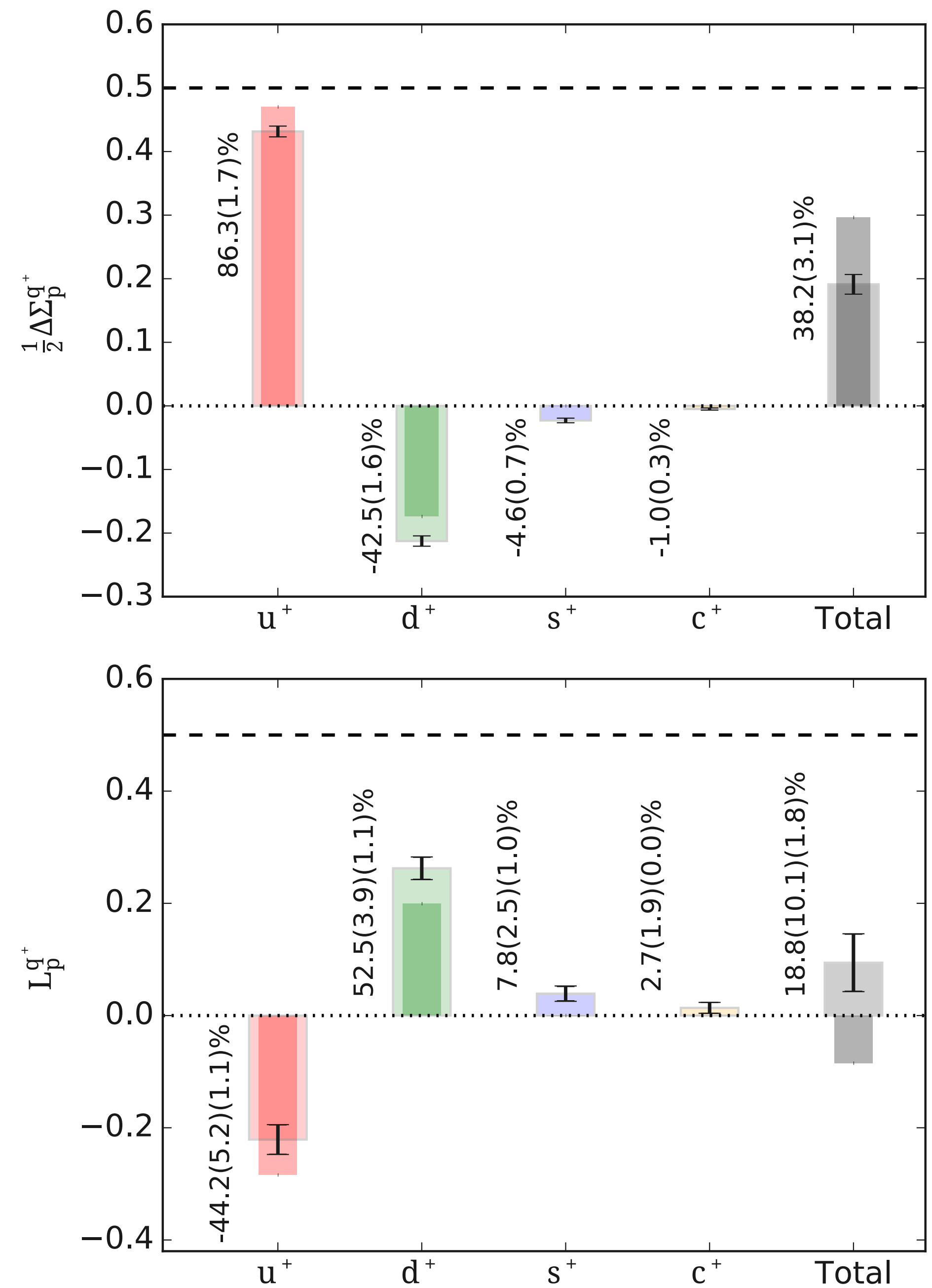
Spin decomposition

[C. Alexandrou et al., Phys. Rev. D 101, 094513 (2020), arXiv:2003.08486]

Better understanding of the spin distribution



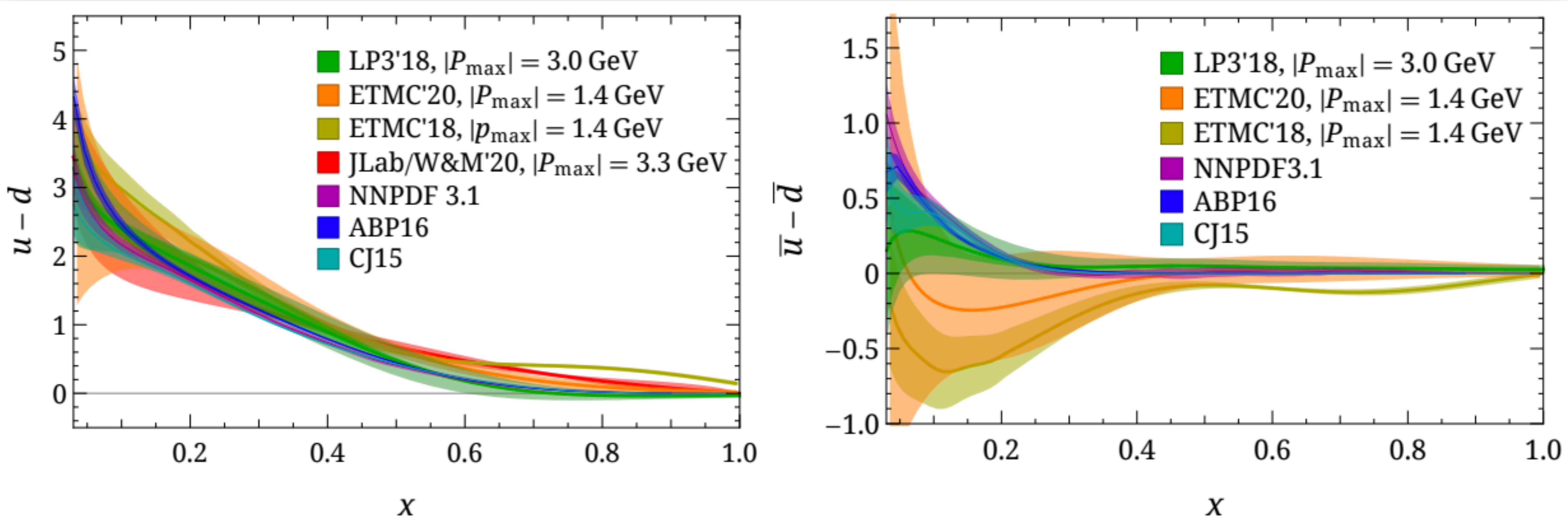
Designed by Z.-E. Meziani



Satisfaction of spin and momentum sum rule is not forced

Accessing PDFs/GPDs from lattice QCD

Collection of results for unpolarized PDF



[M. Constantinou et al. (2020 PDFLattice Report), Prog.Part.Nucl.Phys. 121 (2021) 103908]

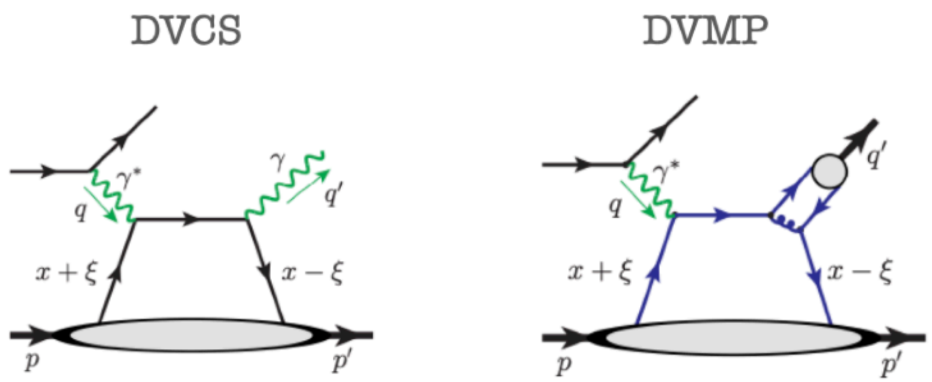
★ Several improvements:

- More calculations at physical quark masses
- Ensembles at various lattice spacings
- Addressing systematic uncertainties due to methodologies

★ Progress extended to gluon PDFs, GPDs, TMDs

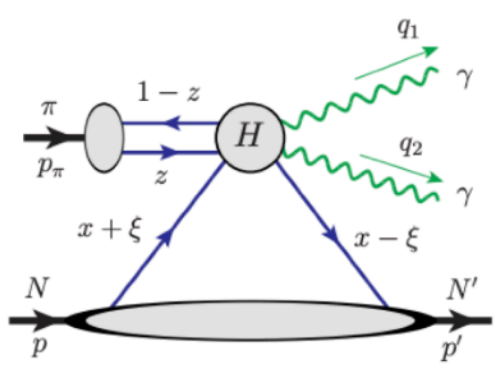
Generalized Parton Distributions

★ GPDs may be accessed via exclusive reactions (DVCS, DVMP)



[X.-D. Ji, PRD 55, 7114 (1997)]

★ exclusive pion-nucleon diffractive production of a γ pair of high $p_\perp$



[J. Qiu et al, arXiv:2205.07846]

★ GPDs are not well-constrained experimentally:

- x-dependence extraction is not direct. DVCS amplitude: $\mathscr{H} = \int_{-1}^{+1} \frac{H(x,\xi,t)}{x-\xi+i\epsilon} dx$

(SDHEP [J. Qiu et al, arXiv:2205.07846] gives access to x)

- independent measurements to disentangle GPDs
- GPDs phenomenology more complicated than PDFs (multi-dimensionality)
- and more challenges …

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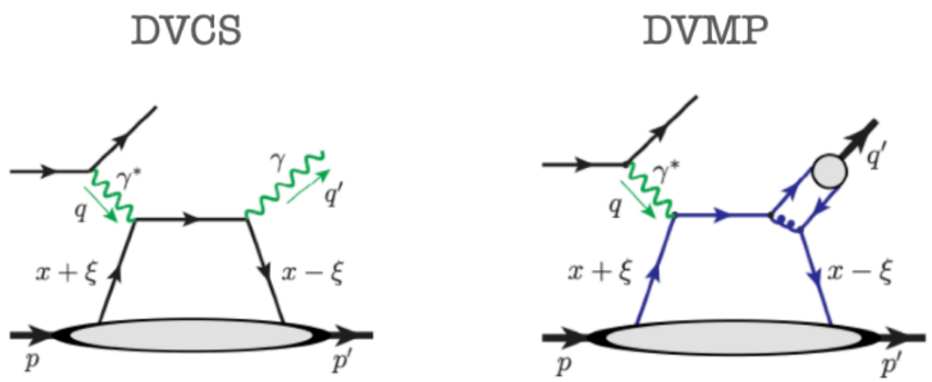

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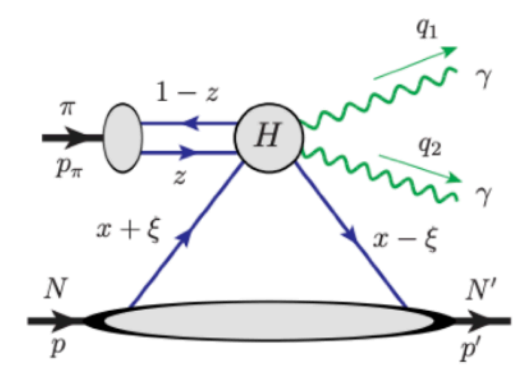

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★ Essential to complement the knowledge on GPD from lattice QCD

★ Lattice data may be incorporated in global analysis of experimental data and may influence parametrization of t and ξ dependence

Disclaimer

The field of GPDs is still developing and sources of systematic uncertainties have not been fully addressed

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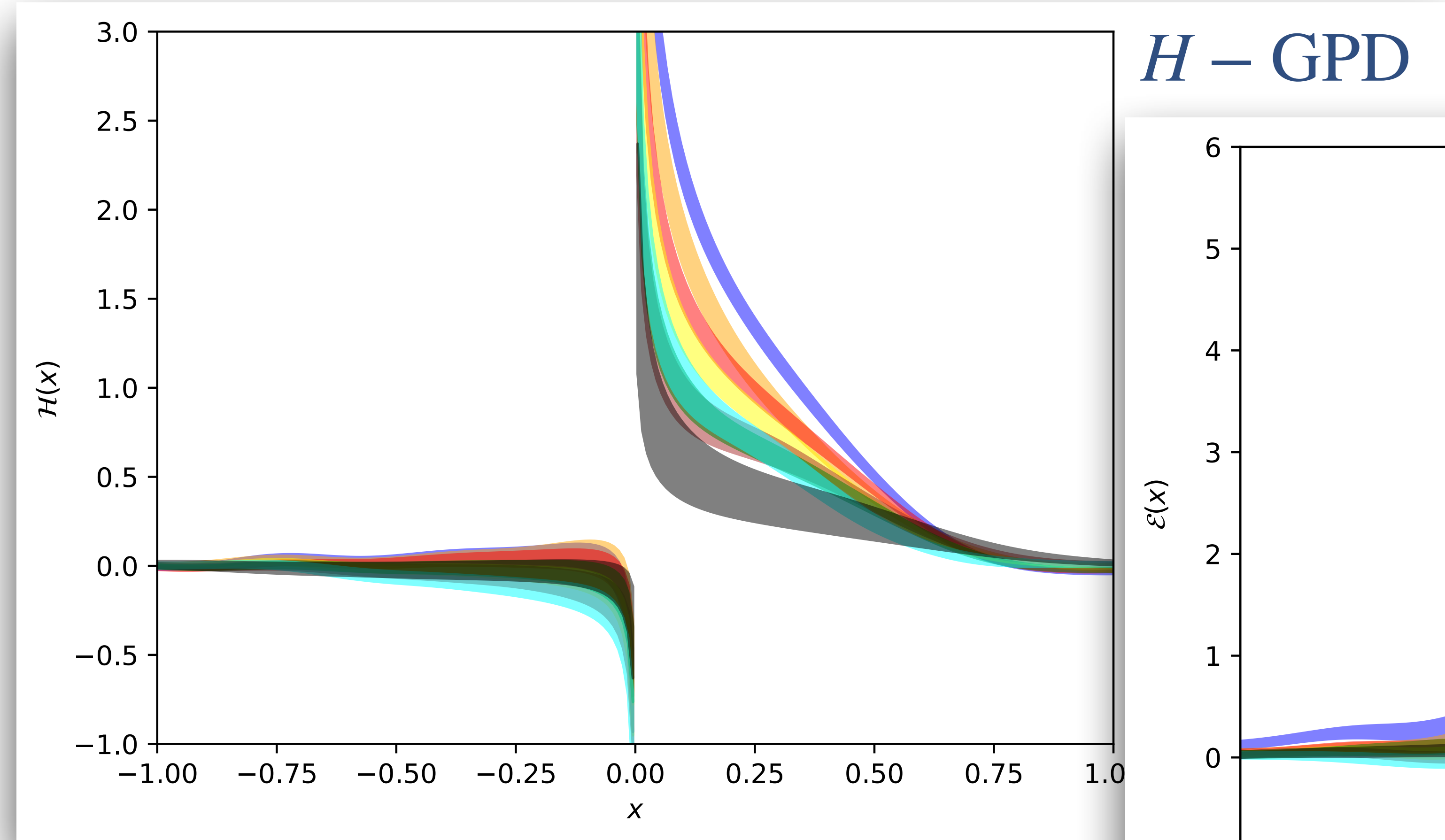
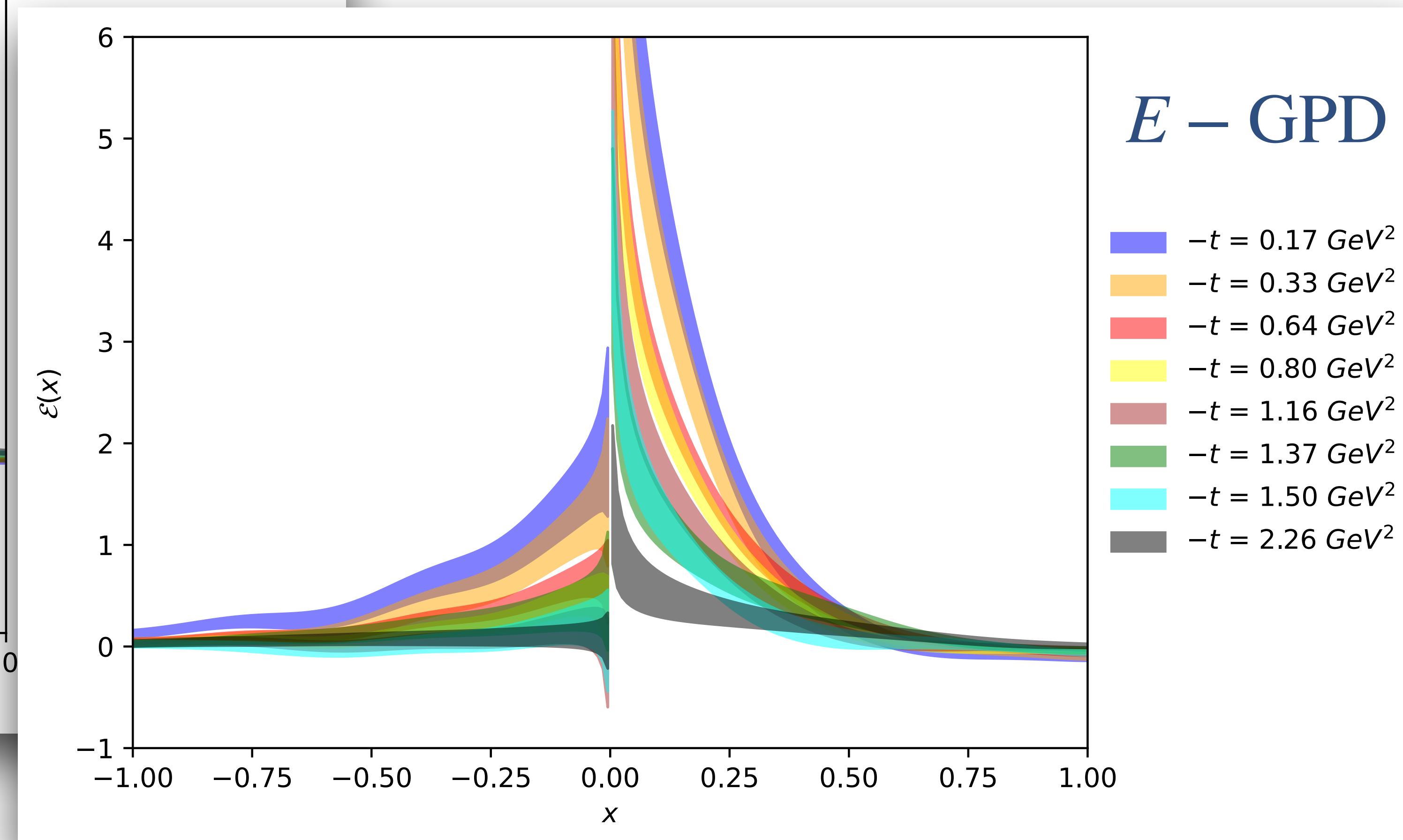
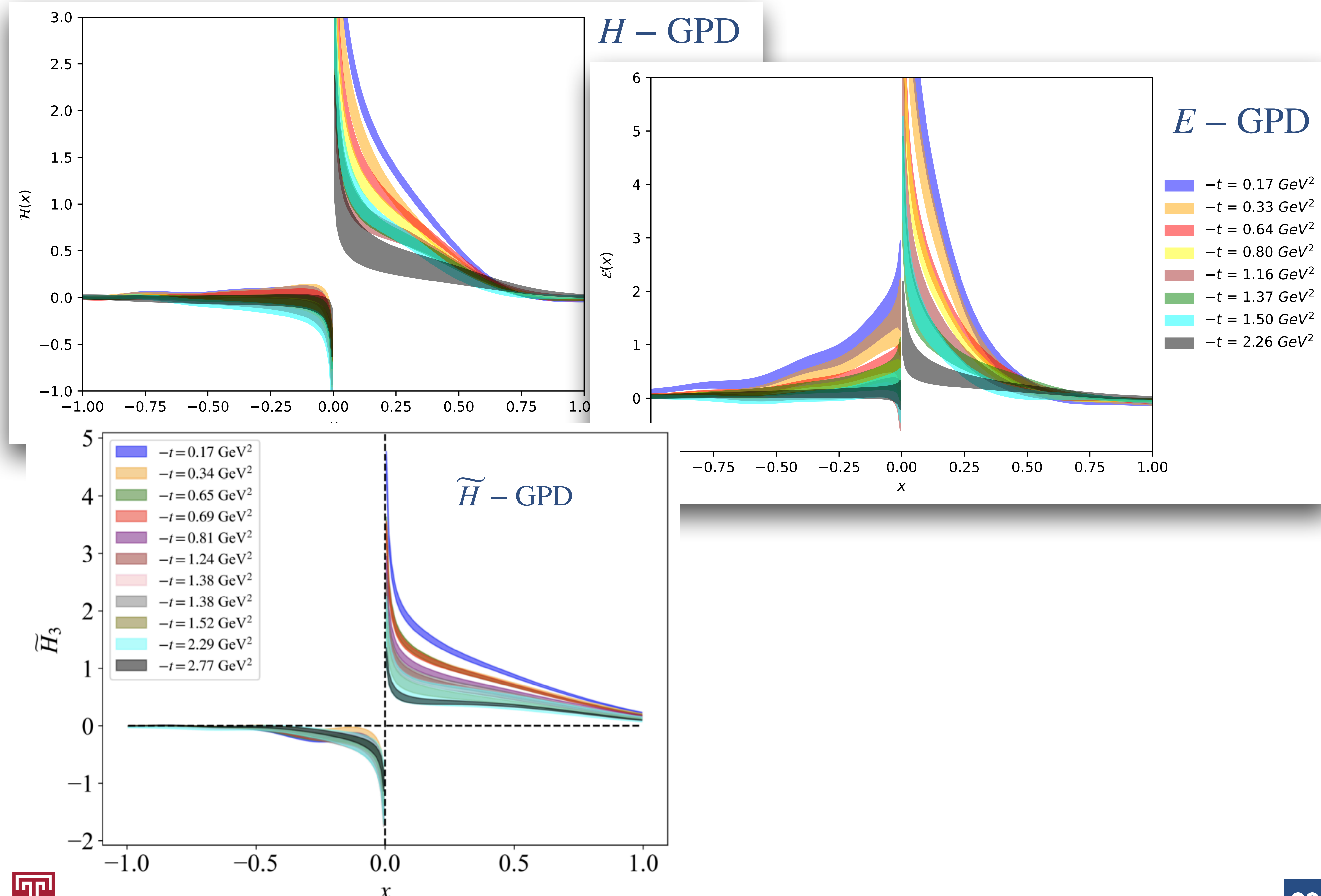
- Discretization effects
- physical pion mass
- volume effects
- inverse problem
- matching formalism
- connection to light-cone
- higher twist contaminations
- ...

Light-cone GPDs

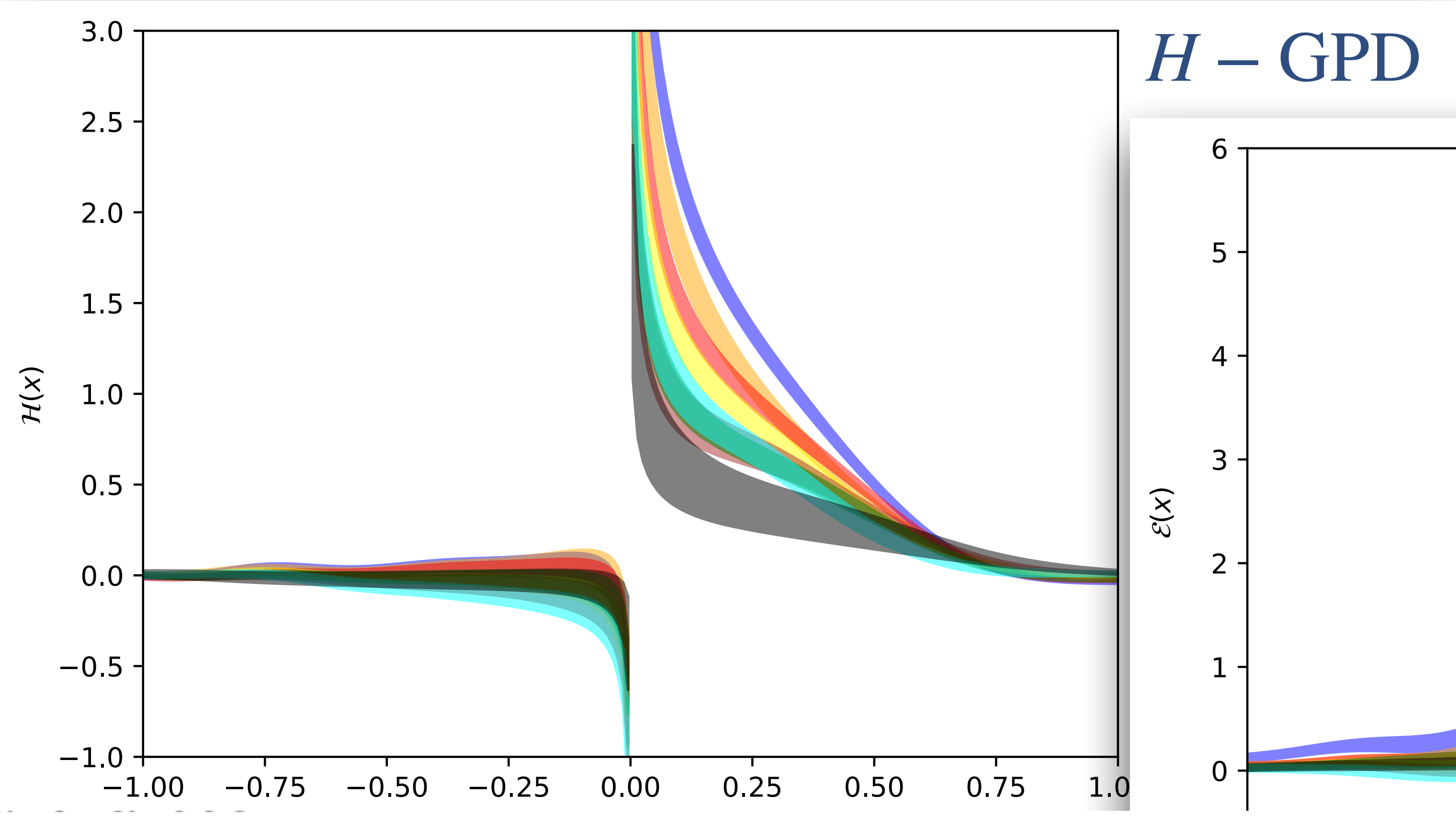


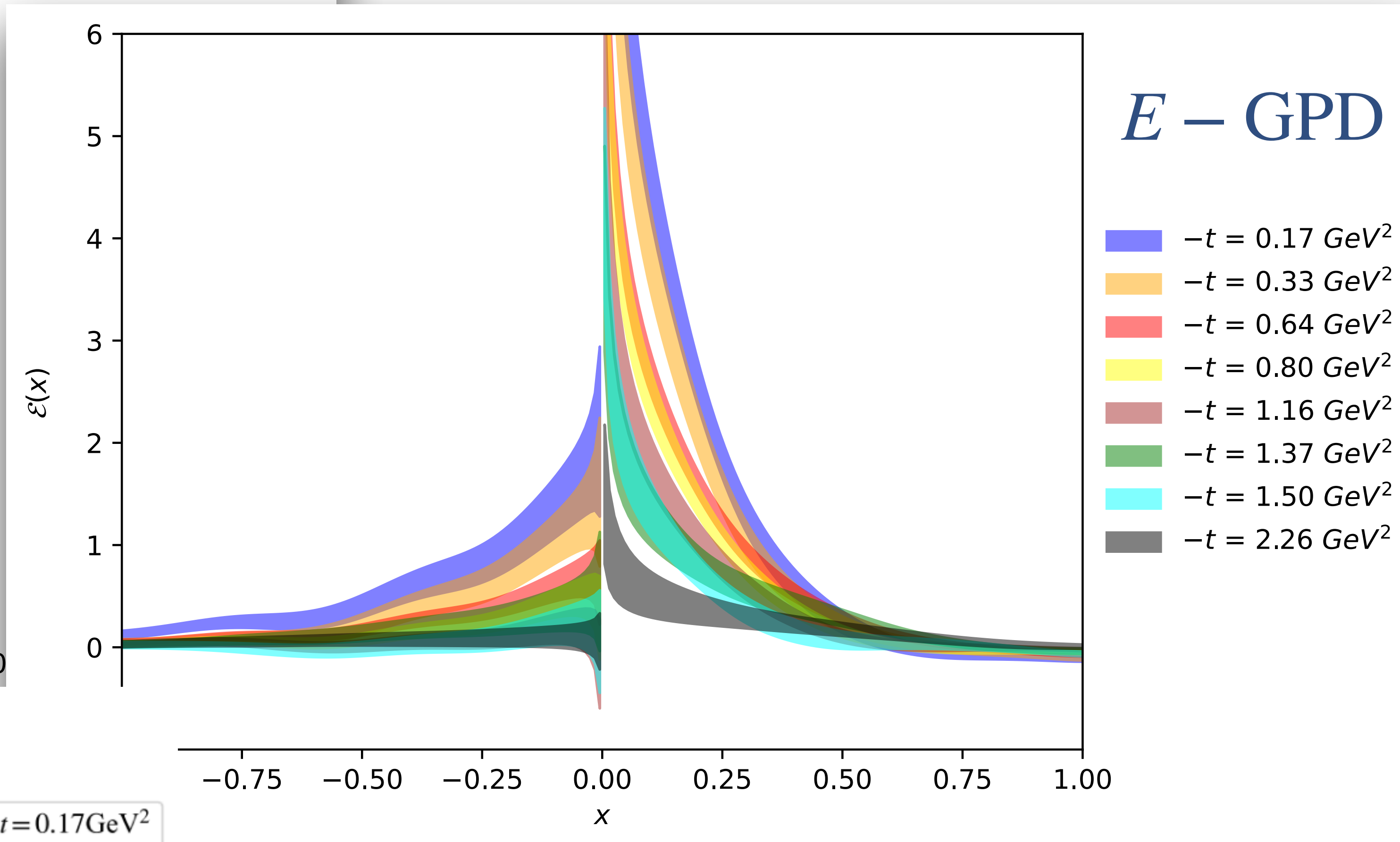


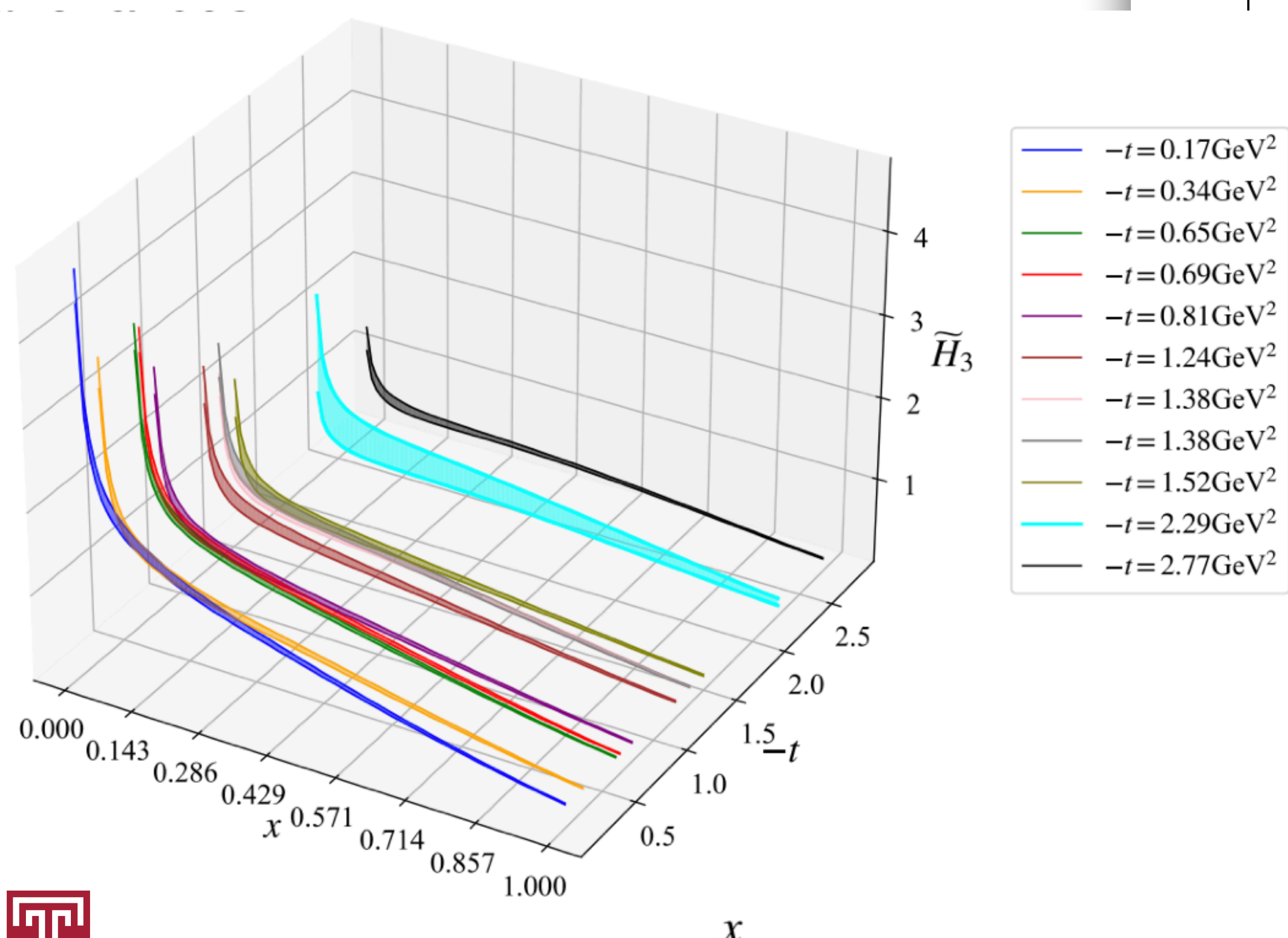
Light-cone GPDs



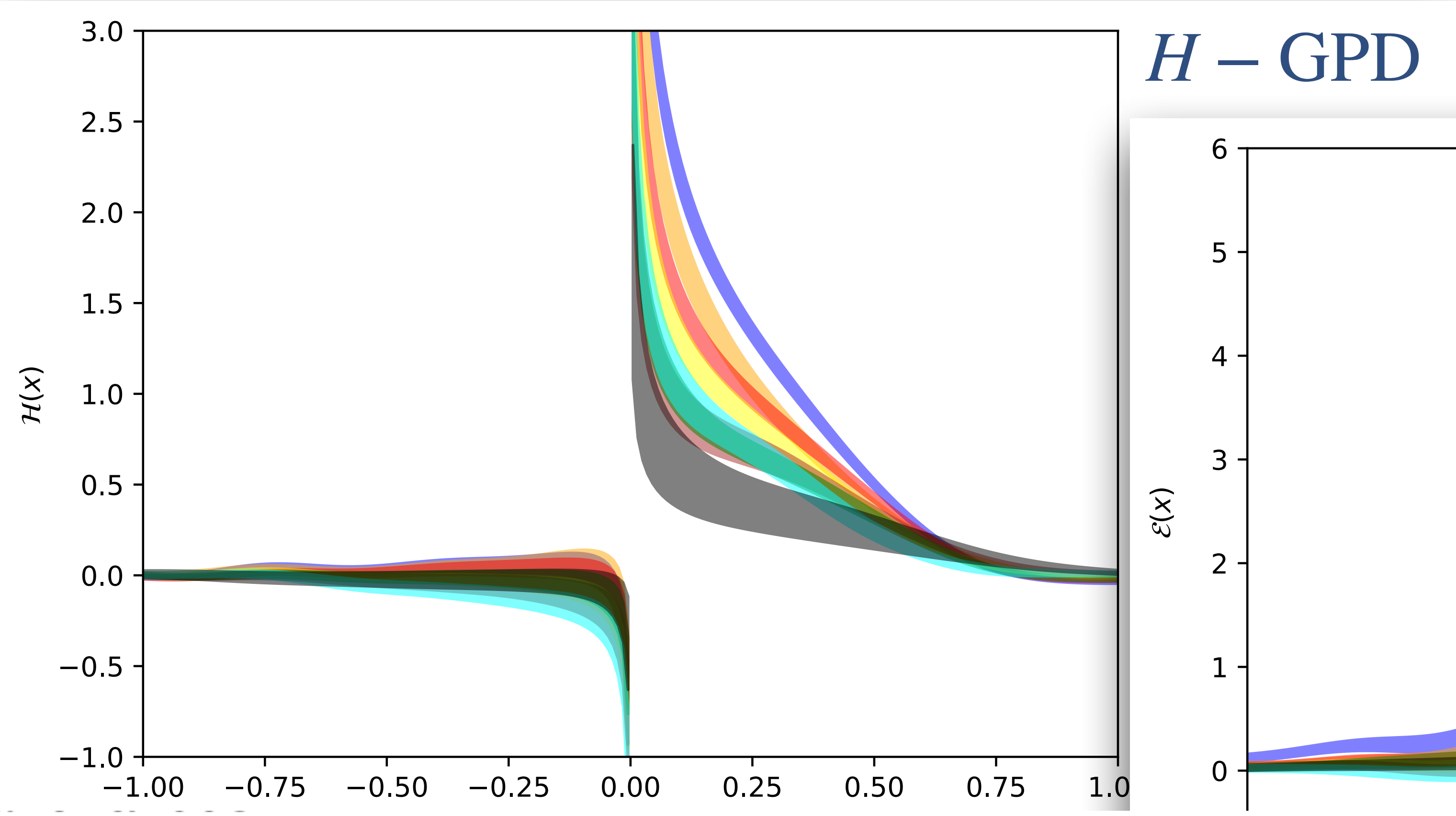
Light-cone GPDs

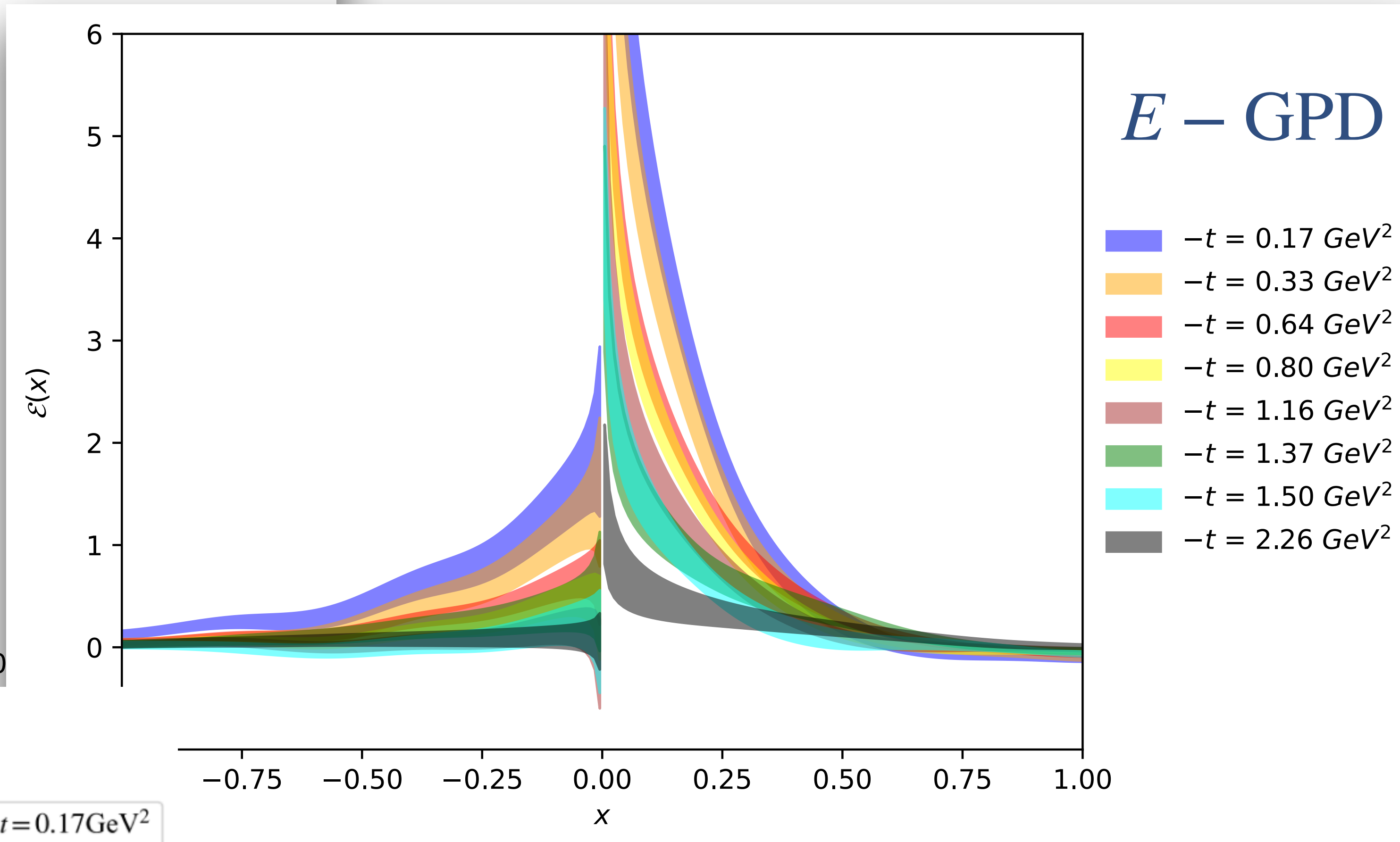


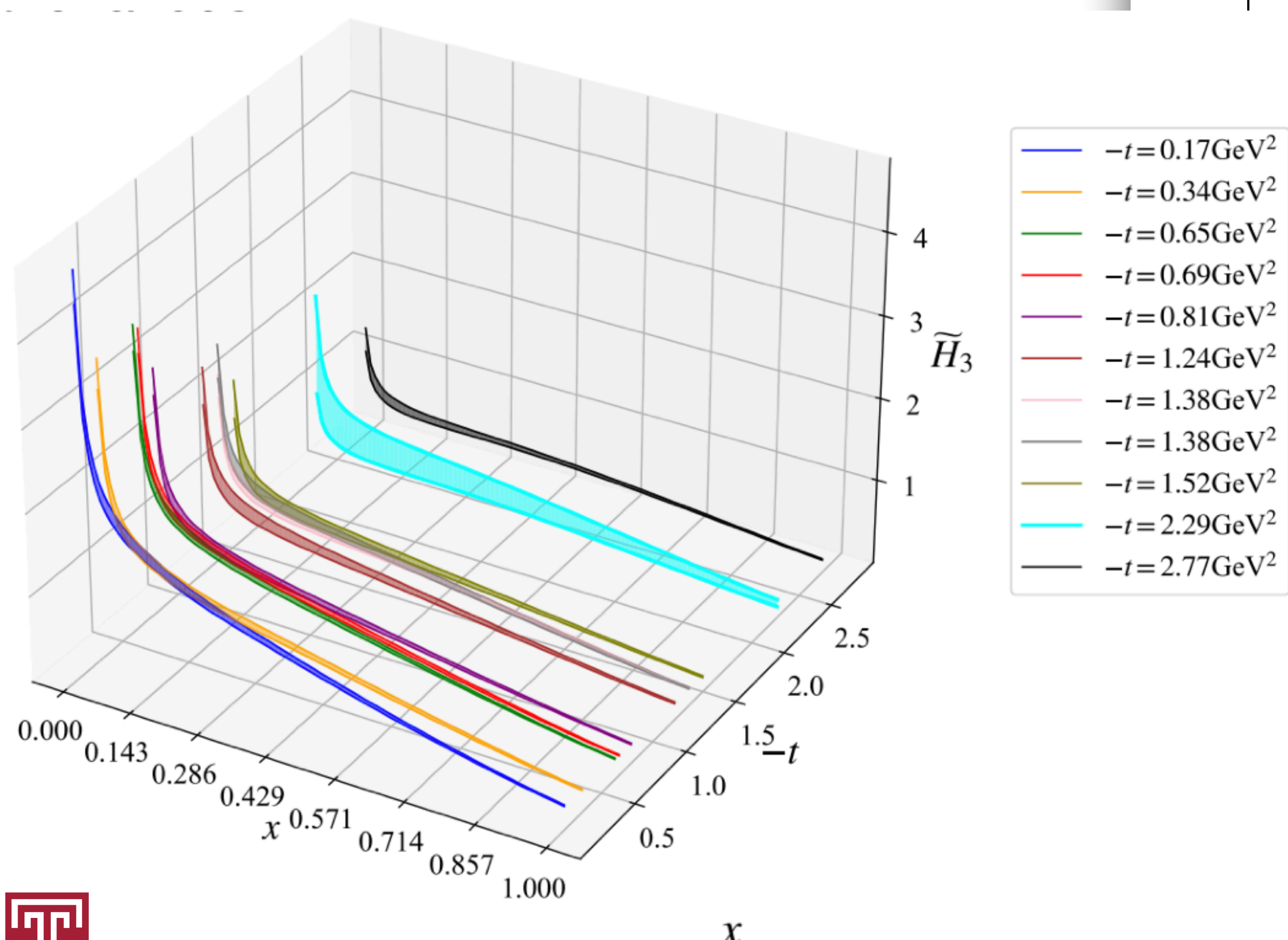




Light-cone GPDs

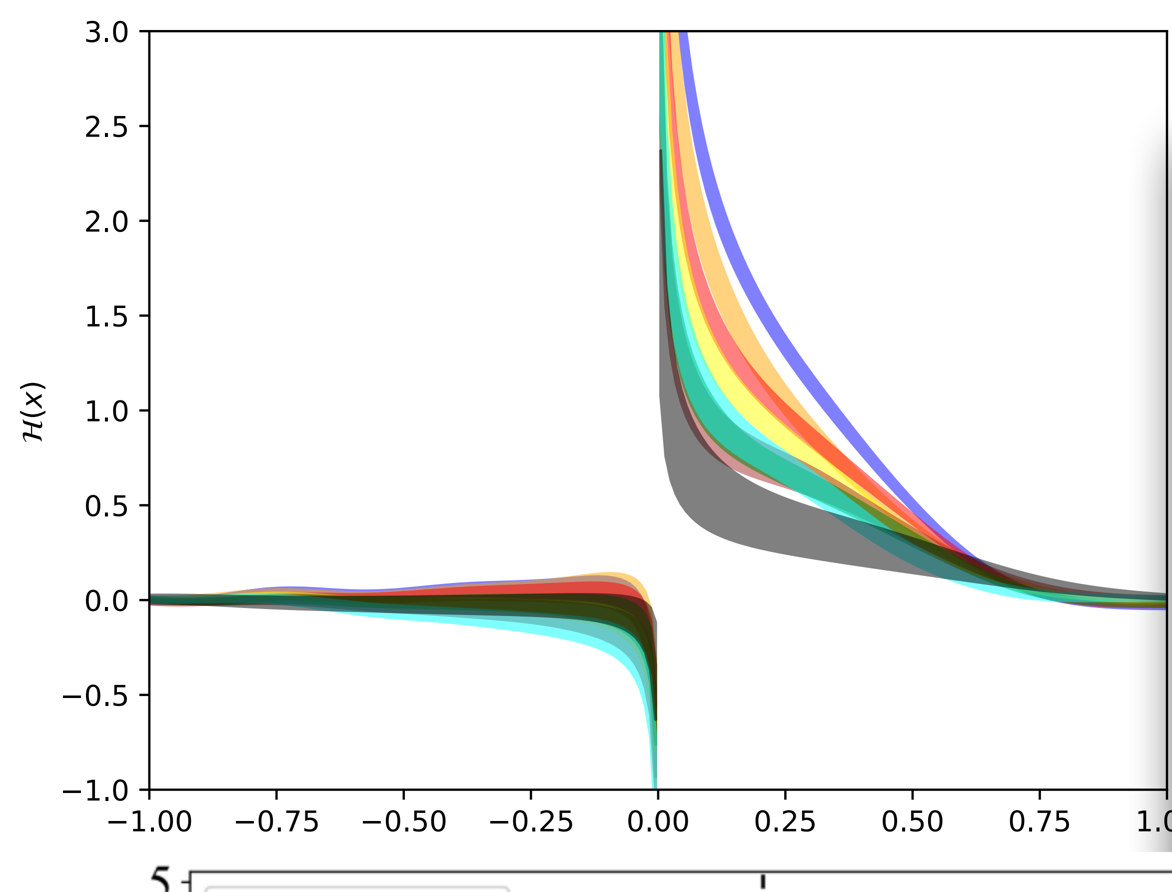




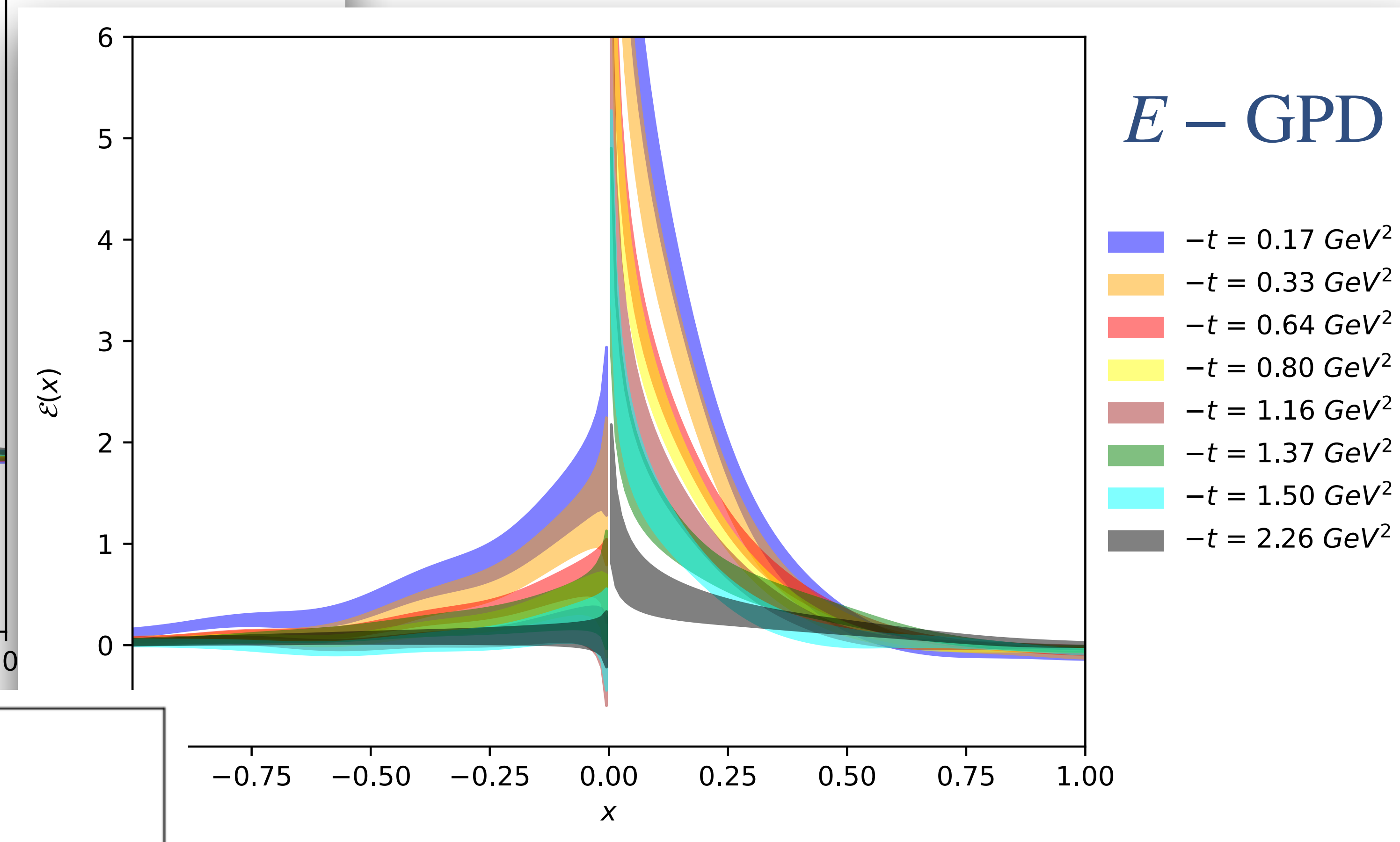


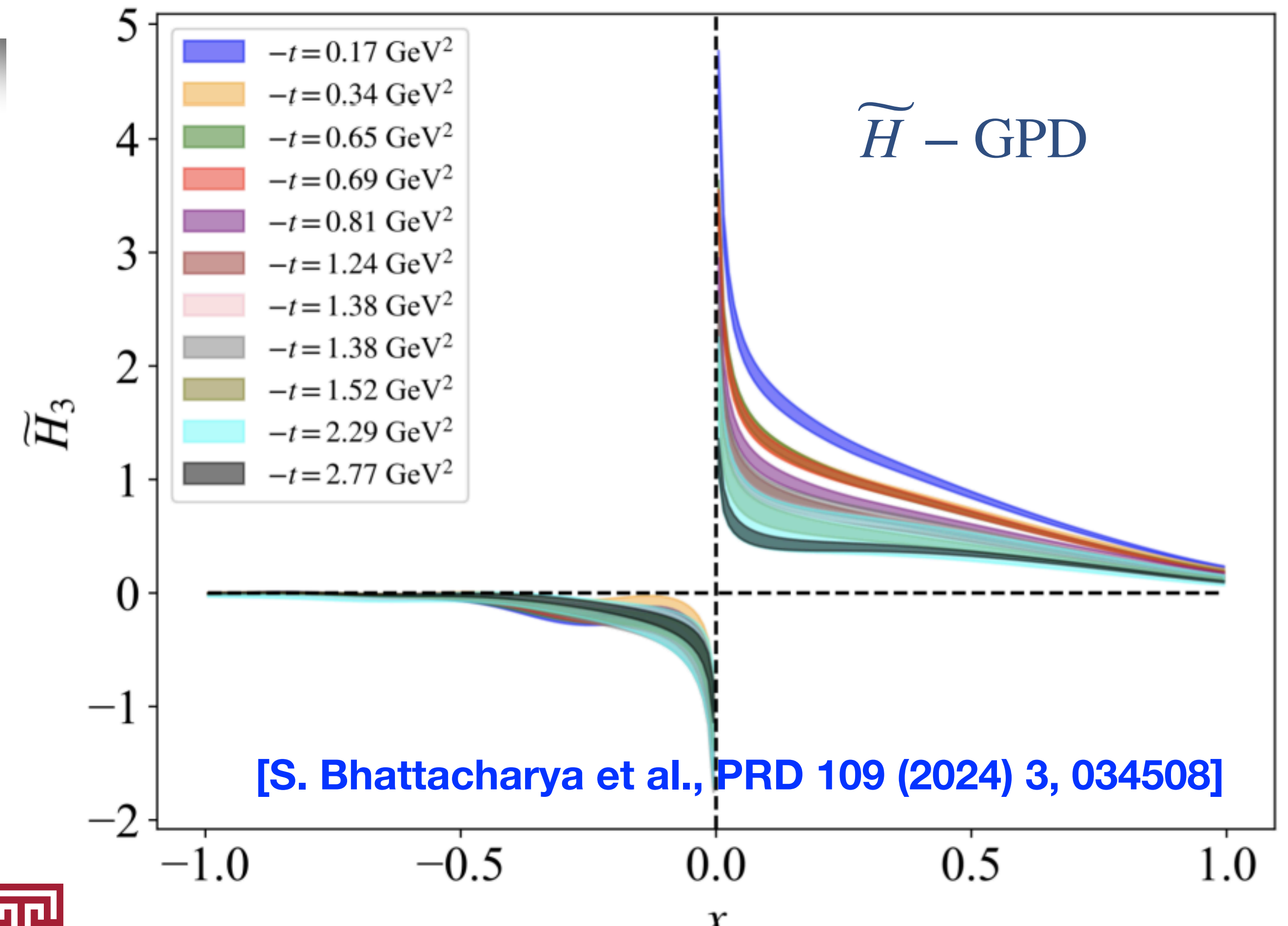
- ★ +x region: quarks
  -x region: anti-quarks
- ★ anti-quark region susceptible
  to more systematic uncertainties
- ★ small- and large-x region
  not reliably extracted
- ★ large -t values unreliable but free

Reminder: Unpolarized & Helicity GPDs



[S. Bhattacharya et al., PRD 106 (2022) 11, 114512]



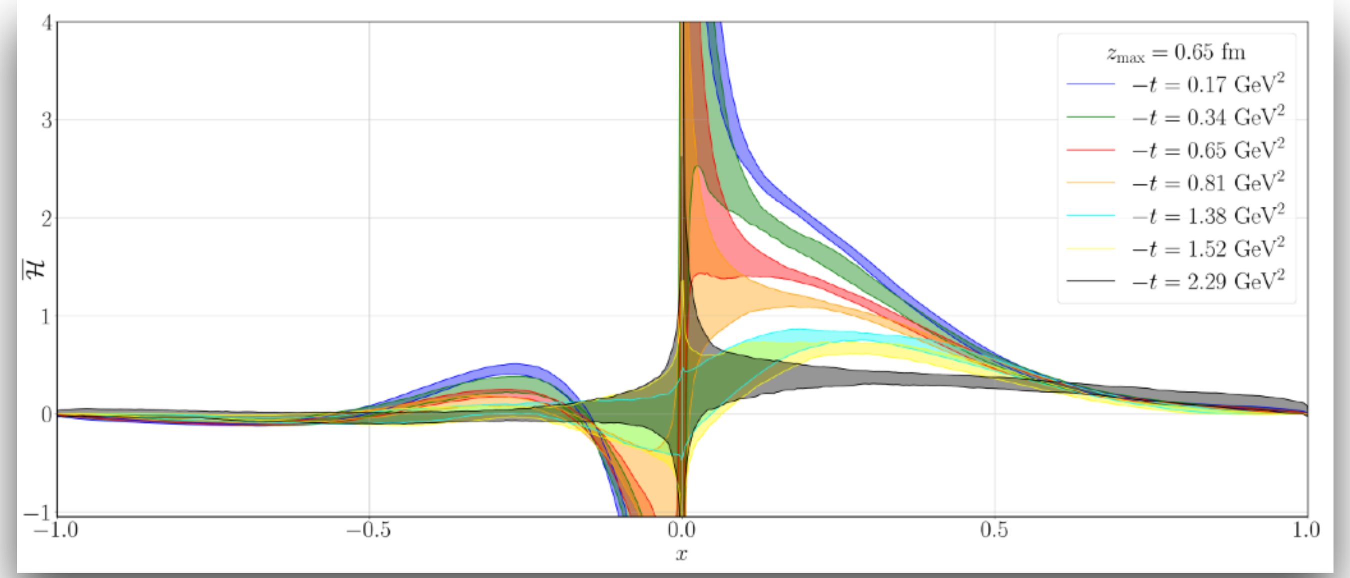


[S. Bhattacharya et al., PRD 109 (2024) 3, 034508]

★ Signal for H_T comparable with H, $\widetilde{H}$

★ $\widetilde{E}(\xi = 0) = 0$

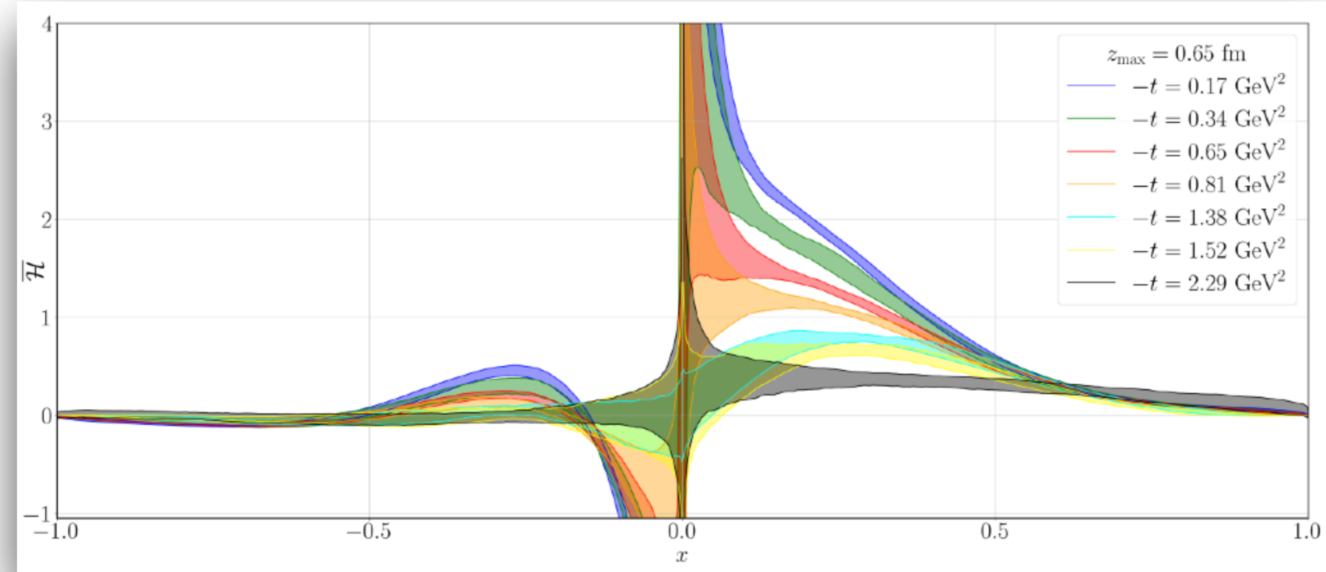
Alternative approach: pseudo-ITD



[Battacharya et al., PRD 110 (2024) 5, 054502]

Different steps between approaches:
- *renormalization*
- *x-dependence reconstruction*
- *matching formalism*

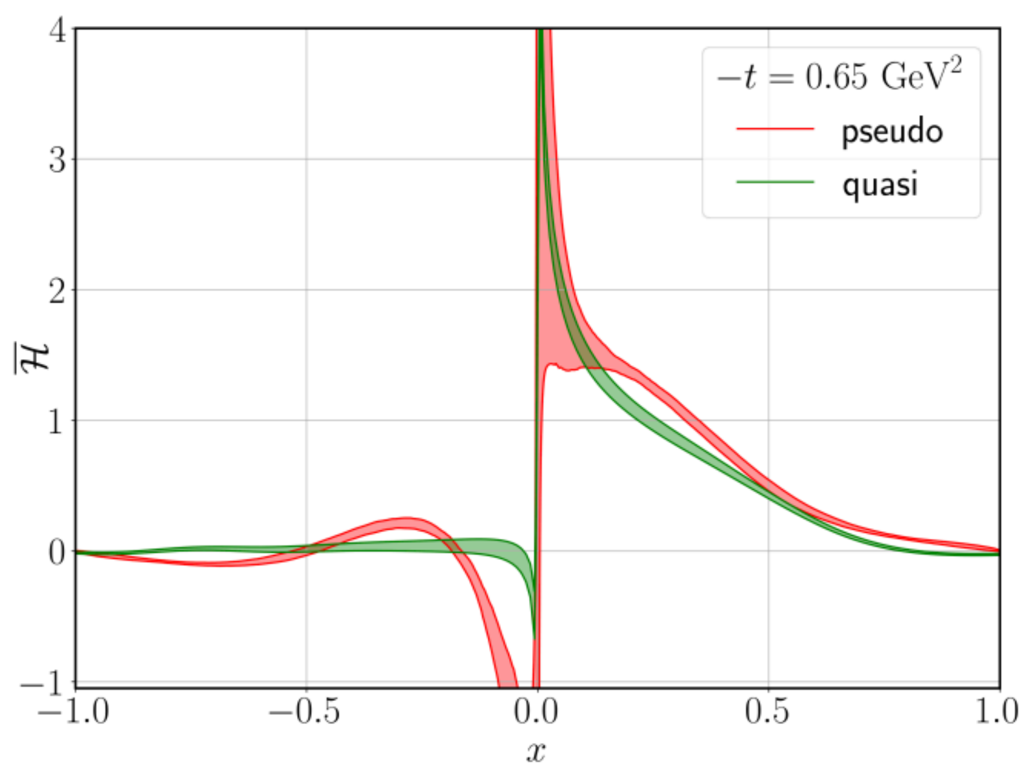
Alternative approach: pseudo-ITD

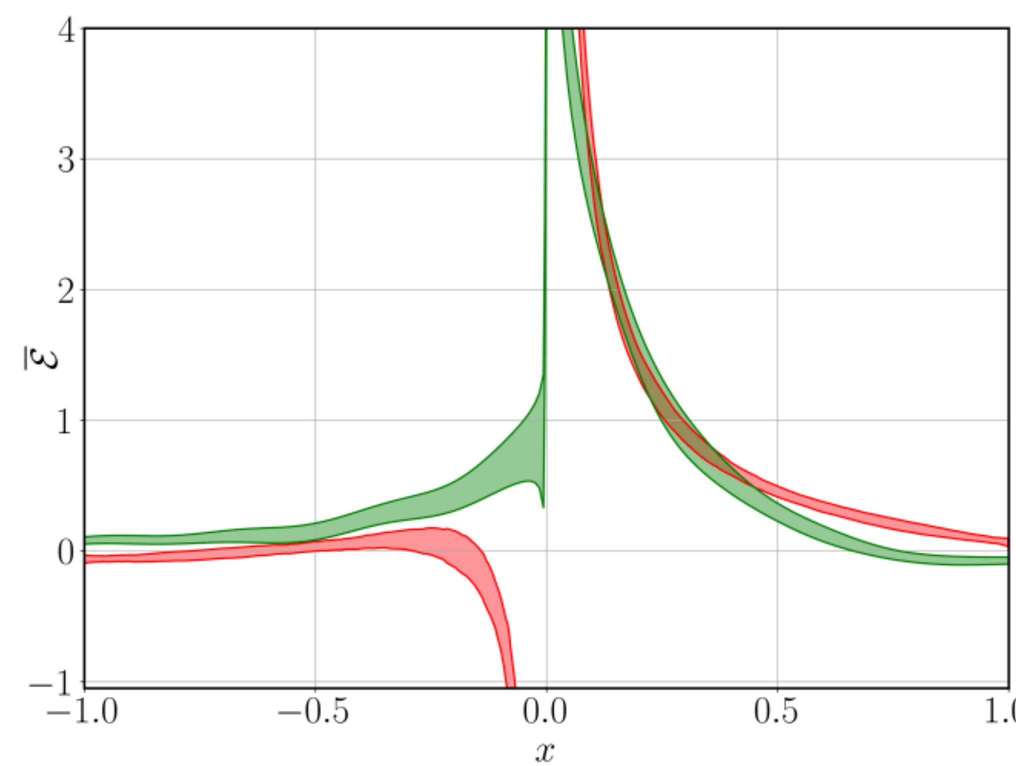


[Battacharya et al., PRD 110 (2024) 5, 054502]

Different steps between approaches:
- renormalization
- x-dependence reconstruction
- matching formalism

★ Comparison between methods helps assess systematic effects





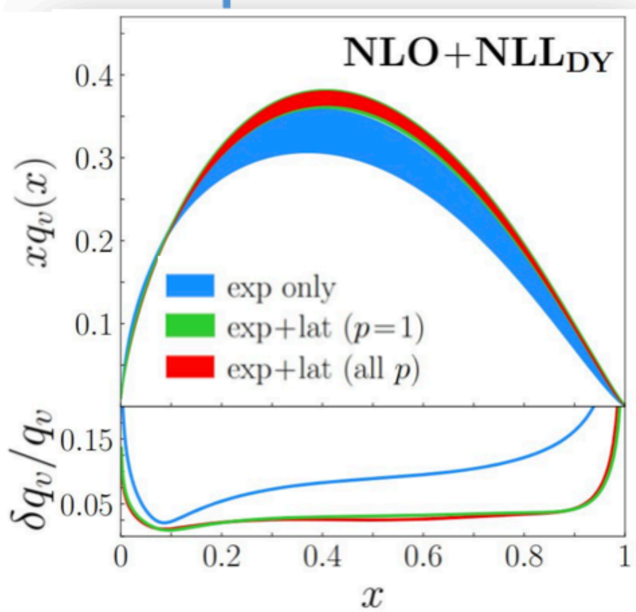
★ x<0 and small-x regions susceptible to systematic effects

★ Comparison only includes systematic uncertainties

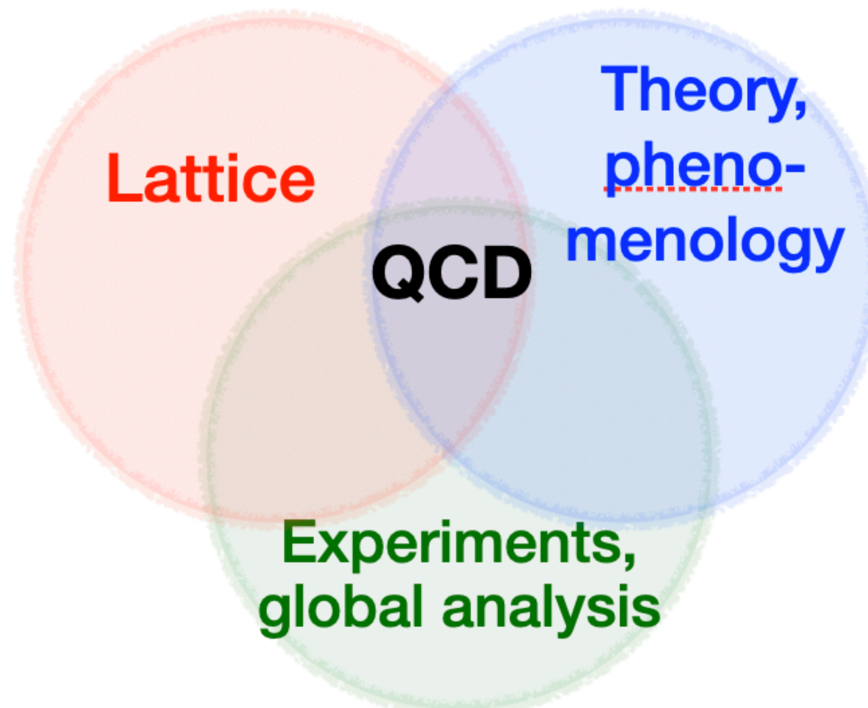
Synergy/Complementarity of lattice and phenomenology

Synergies: constraints & predictive power of lattice QCD

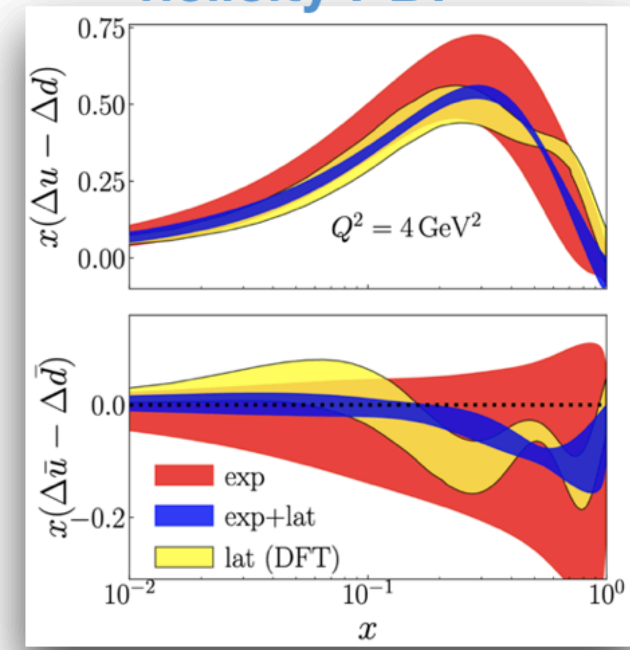
pion PDF



[JAM/HadStruc, PRD105 (2022) 114051]

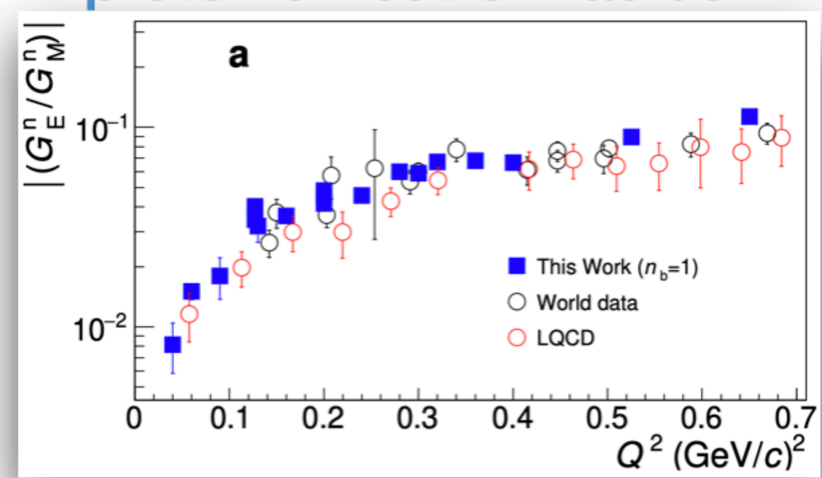


helicity PDF



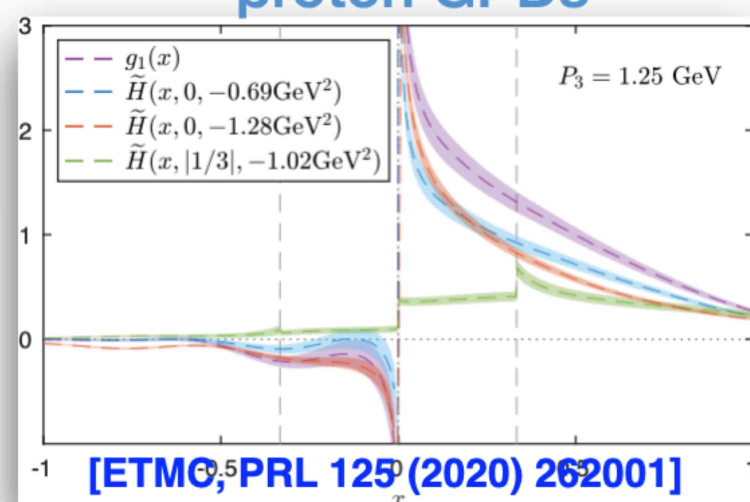
[JAM & ETMC, PRD 103 (2021) 016003]

proton & neutron radius



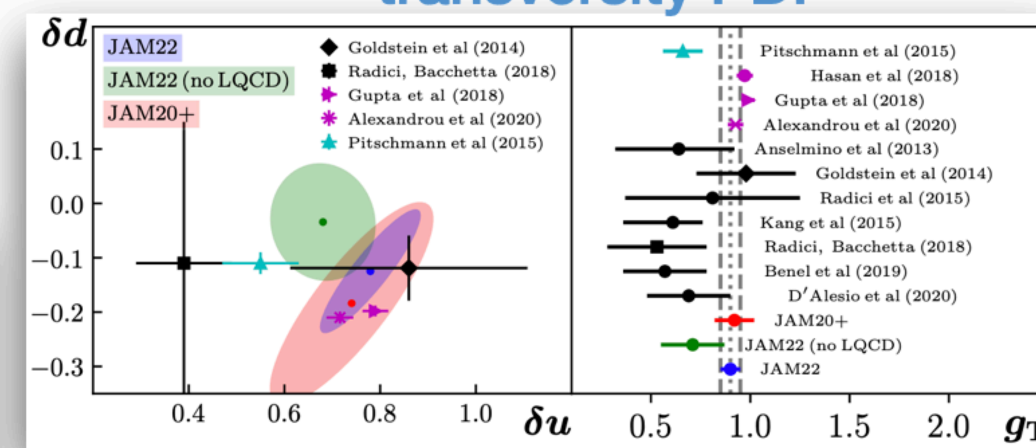
[Atac et al., Nature Comm. 12, 1759 (2021)]

proton GPDs



[ETMC, PRL 125 (2020) 262001]

transversity PDF



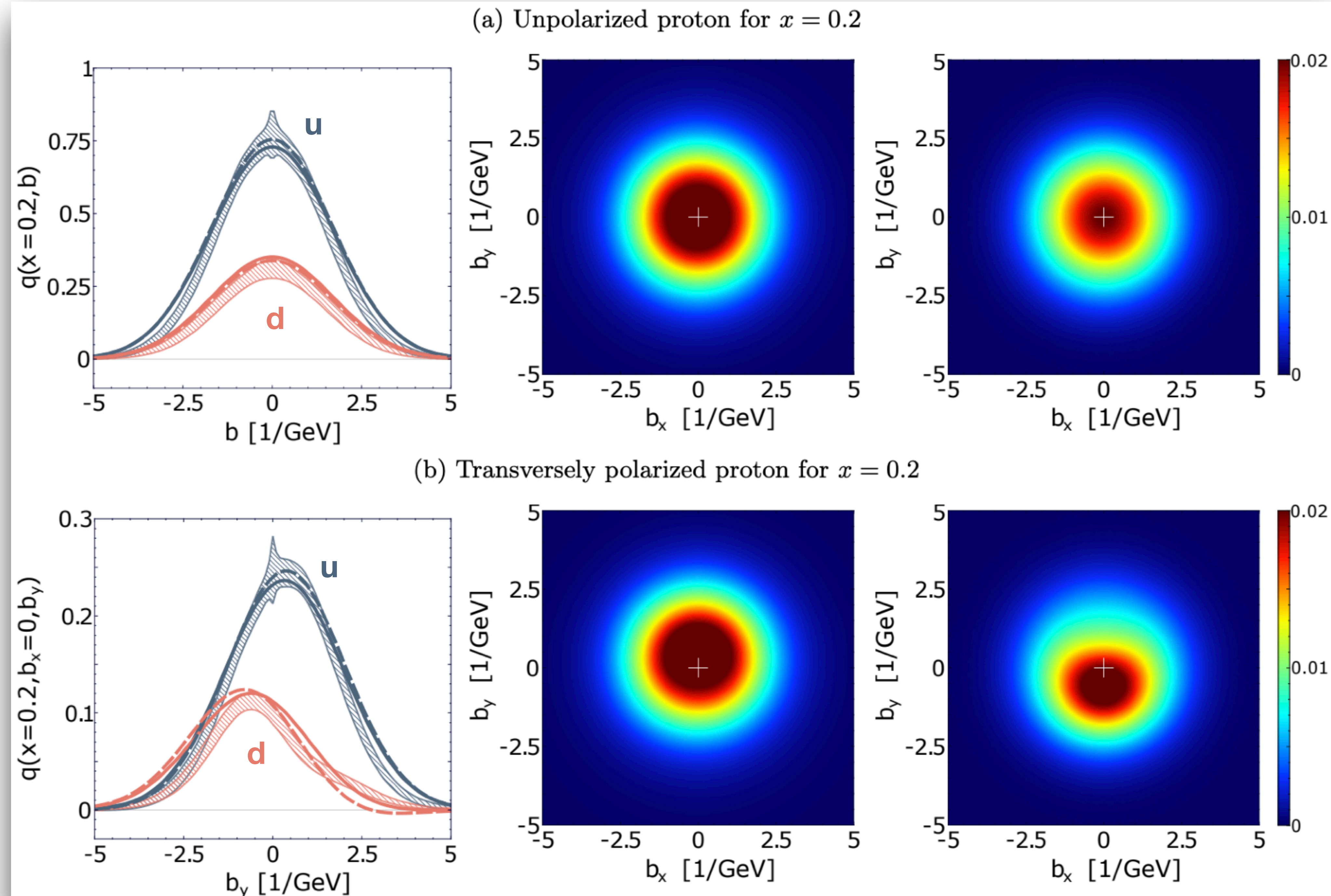
[JAM, PRD 106 (2022) 3, 034014]

And many more!

Toward synergy for GPDs

[K. Cichy et al., PRD 110 (2024) 11, 114025]

Example: unpolarized GPDs



- GK (solid line),
- VGG (dashed line)

- Good agreement for up quark; reasonable agreement for down quark
- Further study needed on how to combine lattice results with data

How to lattice QCD data fit into the overall effort for hadron tomography

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- ★ Lattice data may be incorporated in global analysis of experimental data and may influence parametrization of t and ξ dependence

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1. Theoretical studies of high-momentum transfer processes using perturbative QCD methods and study of GPDs properties
2. Lattice QCD calculations of GPDs and related structures
3. Global analysis of GPDs based on experimental data using modern data analysis techniques for inference and uncertainty quantification

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Other GPD global analysis efforts:

- Gepard [https://gepard.phy.hr/]
- PARTONS [https://partons.cea.fr]
- EXCLAIM [https://exclaimcollab.github.io/web.github.io/#/]

Summary of Lecture 2

Key points of Lecture 2

★ Hadron structure studies are critical for understanding the immensely rich and complex properties of the visible matter

★ The lattice formulation can provide first principle results for a very broad research program in Hot and Cold QCD, and beyond!

★ Many opportunities for synergies and complementarity.

U.S. DEPARTMENT OF ENERGY | Office of Science

DOE Early Career Award
Grant No. DE-SC0020405 &
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Abhyuday Sharda (University of Tennessee)
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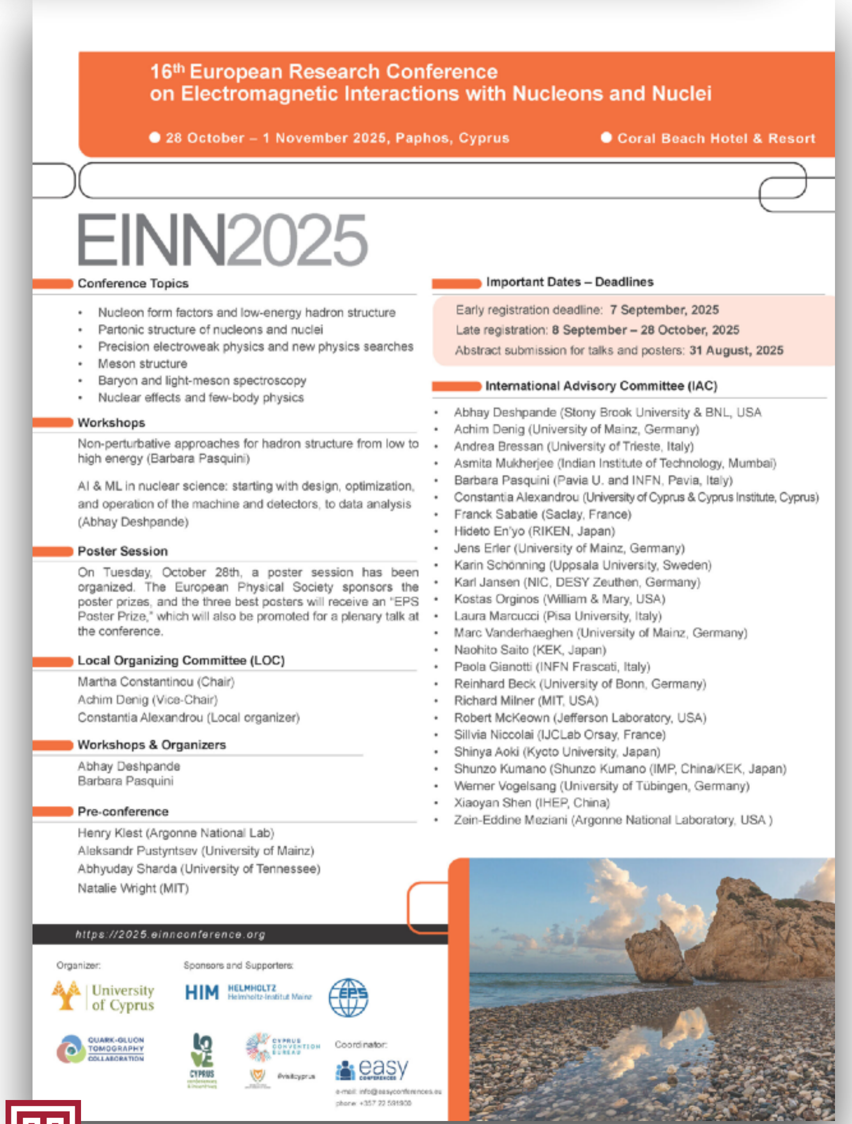
26 - 27 October, 2025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on Electromagnetic Interactions with Nucleons and Nuclei

28 October – 1 November 2025, Paphos, Cyprus
Coral Beach Hotel & Resort

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- Nucleon form factors and low-energy hadron structure
- Partonic structure of nucleons and nuclei
- Precision electroweak physics and new physics searches
- Meson structure
- Baryon and light-meson spectroscopy
- Nuclear effects and few-body physics

Workshops

Non-perturbative approaches for hadron structure from low to high energy (Barbara Pasquini)

AI & ML in nuclear science: starting with design, optimization, and operation of the machine and detectors, to data analysis (Abhay Deshpande)

Poster Session

On Tuesday, October 28th, a poster session has been organized. The European Physical Society sponsors the poster prizes, and the three best posters will receive an "EPS Poster Prize," which will also be promoted for a plenary talk at the conference.

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Constantia Alexandrou (Local organizer)

Workshops & Organizers

Abhay Deshpande
Barbara Pasquini

Pre-conference

Henry Klest (Argonne National Lab)
Aleksandr Pustyntsev (University of Mainz)
Abhyuday Sharda (University of Tennessee)
Natalie Wright (MIT)

Important Dates – Deadlines

Early registration deadline: **7 September, 2025**
Late registration: **8 September – 28 October, 2025**
Abstract submission for talks and posters: **31 August, 2025**

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Abstract submission is Open!

Other topics relevant to EINN
Poster
Talk in workshop 1 "Non-perturbative approaches for hadron structure from low t
Talk in workshop 2: "AI & ML in nuclear science: starting with design, optimization, a

Thank you