# Quasi-GPDs using twisted mass fermions


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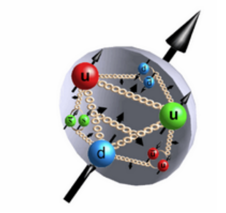
# Outline

- Introduction
- Quasi-GPD approach
- Exploratory study of nucleon GPDs
- Summary

# Generalized parton distributions (GPDs)

D. Muller, A. Radyushkin, X. Ji (1994-1997)

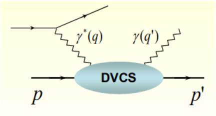



- Wealth of information contained in GPDs:
  - form factors and PDFs
  - longitudinal and transverse distribution of partons in a hadron
  - orbital angular momentum of quarks and gluons

- Part of physics program of EIC, COMPASS and JLAB 12GeV

- Experimentally accessed from e.g. DVCS and DVMP, but with uncertainties

  [see e.g. [K. Kumericki et al., Eur. Phys. J. A52 6 (2016) 157, arXiv:1602.02763]]
  - limited coverage of kinematic region
  - independent measurements to disentangle different GPDs




DVCS: $ep \to ep\gamma$

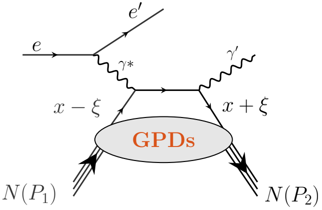
# Definitions of GPDs

- Matrix elements of quarks and gluons operators at a light-like separation

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle P_2|\bar{\psi}(0)\gamma^+ e^{ig\int_0^z dx' A^+}\psi(z)|P_1\rangle|_{z^+=0,\vec{z}=0}$$
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}(P_2)\gamma^+ u(P_1) + E^q(x,\xi,t)\bar{u}(P_2)\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}u(P_1)\right]$$

Notation:

- $P^+ = \frac{P_1^+ + P_2^+}{2}$ : momentum boost
- $t = \Delta^2 = (P_2 - P_1)^2$
- $\xi = -\frac{\Delta^+}{2P^+}$ : skewness




- In the forward limit ($P_1 = P_2$), GPDs reduce to parton densities: $H^q(x,0,0) = q(x)$
- Form factors are moments of GPDs, e.g. $\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1(t)$

# How can we study GPDs?

- GPDs are non-perturbative quantities $\Rightarrow$ Lattice QCD ?
- Light-cone dominance prevents a direct implementation of GPDs definition
- GPDs mostly studied through their moments (GFFs) and form factors ($F_1$ and $F_2$) [see Talk by G. Koutsou on Wed.]
- A tower of moments is needed to extract $x$-dependence, else information about longitudinal structure is lost
- New fields are growing up:

quasi-GPDs **[X.-D. Ji et al., Phys.Rev. D92 (2015) 014039]**

pseudo-GPDs **[A. Radyushkin, arXiv:1909.08474 [hep-ph]]**

lattice cross-sections with momentum transfer

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lattice cross-sections with momentum transfer

Extensions of approaches used to study PDFs

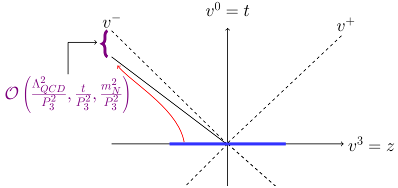
[see Talk by K. Cichy on Thu.]

# Quasi-GPDs in a nutshell

- Quasi-GPDs extracted from purely spatial matrix elements of fast moving hadrons

$$\tilde{q}_\Gamma^{GPD}(x,\xi,t,P_3,\mu^2) = \int \frac{dz}{4\pi} e^{-ixP_3 z} \langle H(P_3\hat{z}+\vec{Q}/2)|\,\bar{\psi}(z)\Gamma W(z,0)\psi(0)|\,H(P_3\hat{z}-\vec{Q}/2)\rangle_{\mu^2}$$

  - ⋆ $W(z)$: Wilson line of lenght $z$
  - ⋆ $P_3$: hadron momentum boost (finite)
  - ⋆ $t=\Delta^2=-Q^2$
  - ⋆ $\tilde{\xi}=-\frac{Q_3}{2P_3}$: quasi-skewness $\quad \tilde{\xi}=\xi+\mathcal{O}(1/P_3^2)$




- Quasi-GPDs matched onto GPDs within LaMET framework

$$\tilde{q}_\Gamma^{GPD} = \int_{-1}^{1}\frac{dy}{|y|}\,\underbrace{\boxed{\mathcal{C}_\Gamma}}_{\text{matching kernel}}\; q_\Gamma^{GPD}(x,\xi,t,P_3,\mu^2)+\mathcal{O}\left(\frac{\Lambda_{QCD}^2}{P_3^2},\frac{t}{P_3^2},\frac{m_N^2}{P_3^2}\right)$$

  - ⋆ $\mathcal{C}_\Gamma$ independent on $Q^2$
  - ⋆ $\mathcal{C}_\Gamma$ reduces to the one of PDFs for $\xi=0$

**[X.Ji et al.,Phys.Rev. D92 (2015) 014039]**
**[X.Xiong, J-H. Zhang., Phys.Rev. D92 (2015) no.5, 054037]**
**[Y-S. Liu et al., Phys.Rev. D100 (2019) no.3, 034006]**

# Lattice setup

## Gauge ensemble

- Configurations of $N_f = 2 + 1 + 1$ flavors & clover term [ETMC collaboration]

| Ensemble | $N_f$ | $V(L^3 \times T)$ | lattice spacing $a$ | $m_\pi$ | $m_\pi L$ |
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| *cA211.32* | 4 | $32^3 \times 64$ | 0.093 fm | 270 MeV | 4 |

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## Nucleon momenta

- Breit frame

$$\vec{P}_i = P_3 \hat{z} - \vec{Q}/2$$

$$\vec{P}_f = P_3 \hat{z} + \vec{Q}/2$$

| $aP_3$ | $P_3$ [GeV] | $aP_i$ | $aP_f$ | $Q^2 = -t$ [GeV$^2$] | $\xi$ | $N_{\text{meas}}$ |
|---|---|---|---|---|---|---|
| 2 | 0.83 | (0,-1,2) | (0,1,2) | 0.69 | 0 | 1600 |
| 3 | 1.25 | (0,-1,3) | (0,1,3) | 0.69 | 0 | 7520 |
| 1.5 | 0.62 | (0,-1,1) | (0,1,2) | 0.87 | -1/3 | 1600 |
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*more will be added*

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- Classes chosen such that:
  1. different GPDs can be disentangled $(H(x,t,\xi), E(x,t,\xi), \tilde{H}(x,\xi,t), \ldots)$
  2. $P_3$-dependence and magnitude of the skewness can be studied

# Calculation on the lattice

- Matrix elements $\langle H(P_3\hat{z}+\vec{Q}/2)|\,\bar{\psi}(z)\Gamma W(z,0)\psi(0)|\,H(P_3\hat{z}-\vec{Q}/2)\rangle$ extracted from

$$\boxed{\begin{aligned}\Gamma_0 &= \frac{(1+\gamma_0)}{4}\\ \Gamma_k &= \frac{(1+\gamma_0)}{4}\gamma_5\gamma_k,\ k=1,2,3\end{aligned}}$$

$$C^{2pt}(\Gamma_0,\vec{p},t_f,t_i)=\sum_{\vec{x}_f} e^{-i(\vec{x}_f-\vec{x}_i)\cdot\vec{p}}\mathrm{Tr}[\Gamma_0\langle\mathcal{I}_N(\vec{x}_f,t_f)\bar{\mathcal{I}}_{\mathcal{N}}(\vec{x}_i,t_i)\rangle]$$

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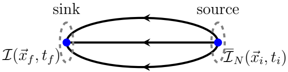

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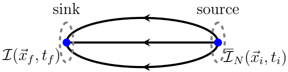


Lattice methods:

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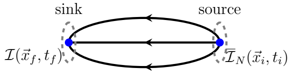


Lattice methods:

- Sequential inversions through the sink ($T_{sink}=12a\simeq 1.13$ fm)

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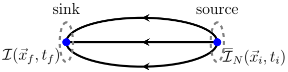



Lattice methods:

- Sequential inversions through the sink ($T_{sink}=12a \simeq 1.13$ fm)
- Momentum smearing

$$S_{mom} = \frac{1}{1+6\alpha}\left(\psi(x)+\alpha\sum_{j=\pm1}^{\pm3}U_j(x)\,e^{i\vec{\xi}\cdot\vec{P}}\,\psi(x+\hat{j})\right)$$

phase kept parallel to the nucleon momenta (at the source & sink)

# Bare unpolarized matrix elements of quasi-GPDs

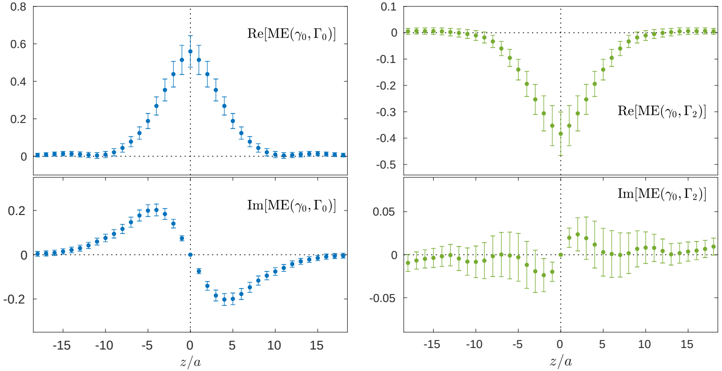
- To disentangle $E(x,\xi,t)$ and $H(x,\xi,t)$, two matrix elements are needed:

$$M(\gamma_0,\Gamma_0) = \mathcal{K}_H(P_i,P_f,\Gamma_0)H(z,t,\xi,t) + \mathcal{K}_E(P_i,P_f,\Gamma_0)E(z,t,\xi,t)$$

$$M(\gamma_0,\Gamma_2) = \mathcal{K}'_H(P_i,P_f,\Gamma_2)H(z,t,\xi,t) + \mathcal{K}'_E(P_i,P_f,\Gamma_2)E(z,t,\xi,t)$$

$\mathcal{K},\mathcal{K}'$ : kinematic factors

Example: $P_3 = 0.83$ GeV, $Q^2 = 0.69$ GeV $^2$, $\xi = 0$



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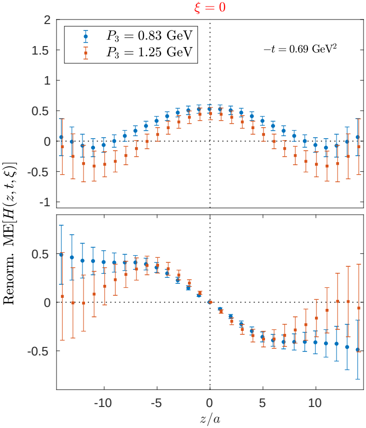

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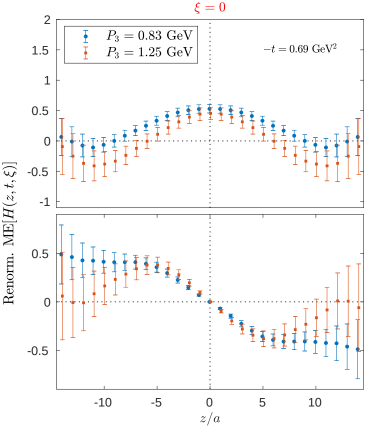


- Faster approach to zero as $P_3$ increases
- Increased noise at $P_3 = 1.25$ GeV ($\simeq 4$ times statistics than $P_3 = 0.83$ GeV)

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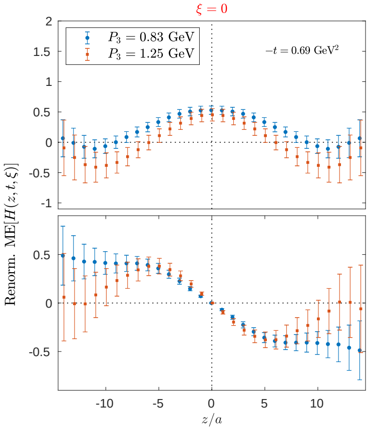


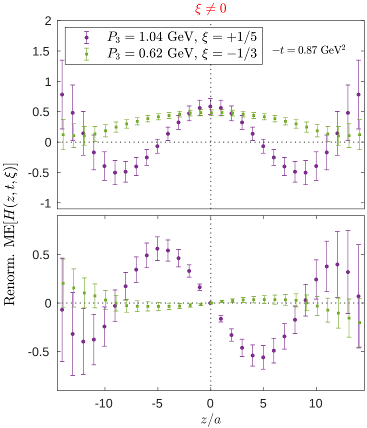


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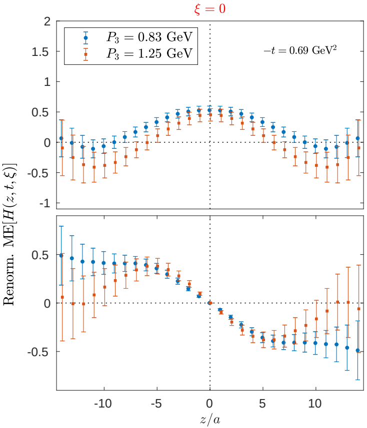


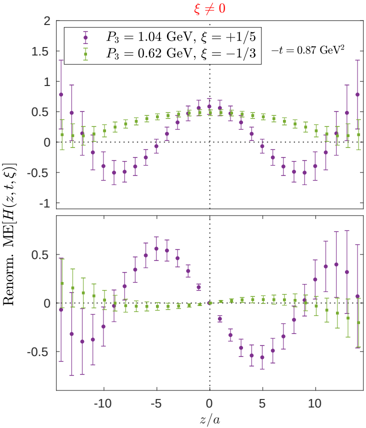


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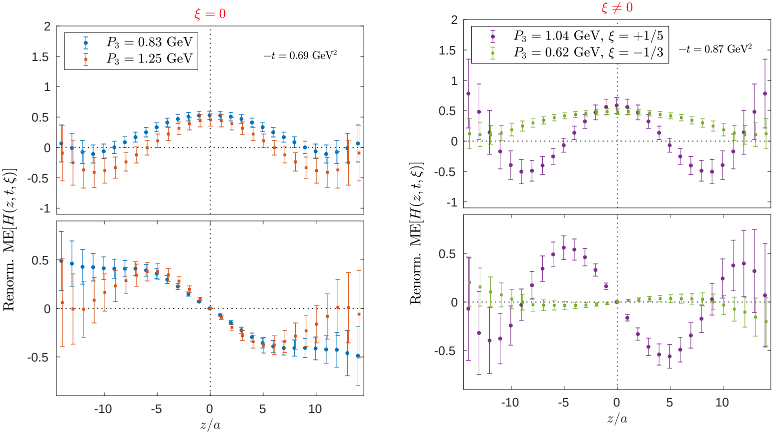


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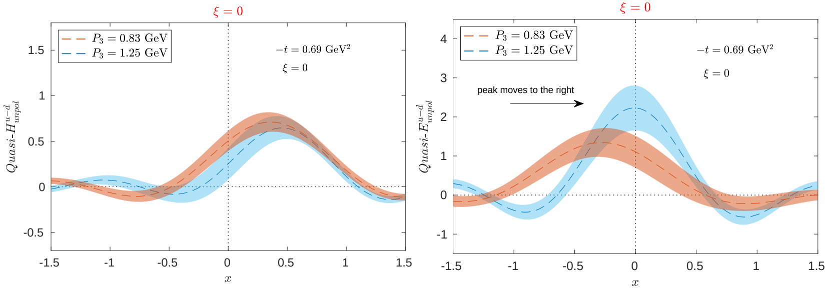
- Im$[H]$ sensitive to the magnitude of $P_3$ and $\xi$
- Real and imaginary parts play a crucial role upon Fourier transform

# Unpolarized quasi-GPDs

Upon Fourier transform

$$\tilde{q}^{GPD} = \frac{2P_3}{4\pi} \sum_{z=-z_{\max}}^{z=z_{\max}} e^{-ixP_3 z} ME^{GPD}(z,t,\xi)$$




- Quasi-H and -E affected differently on the momentum boost
  - quasi-H is compatible within errors
  - quasi-E becomes symmetric in $x$
    (larger momenta will shed light on the behavior of the quasi-$E$)

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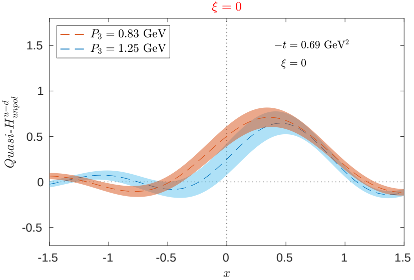


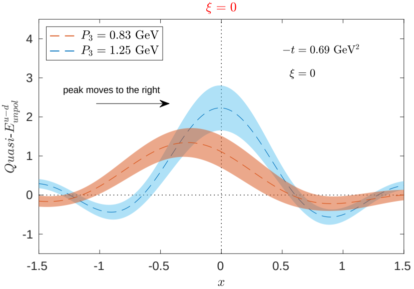


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  - quasi-H is compatible within errors
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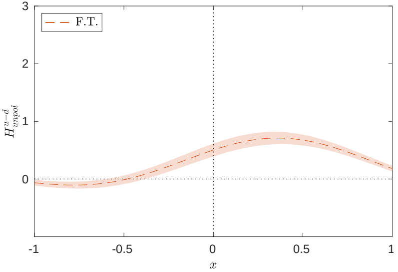
Still non-physical results, matching is needed

## Matching effect on the GPDs

- We apply the RI$\to\overline{\text{MS}}$ matching [Y-S Liu et al., Phys.Rev. D100 (2019) no.3, 034006]

$P_3 = 0.83$ GeV, $-t = 0.69$ GeV$^2$, $\xi = 0$



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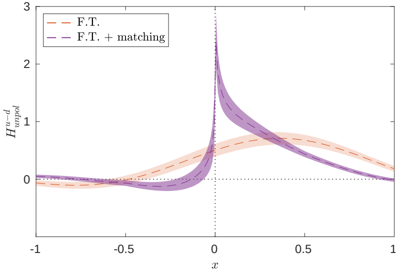

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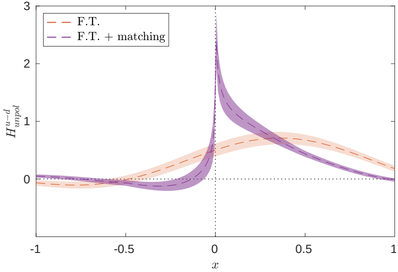
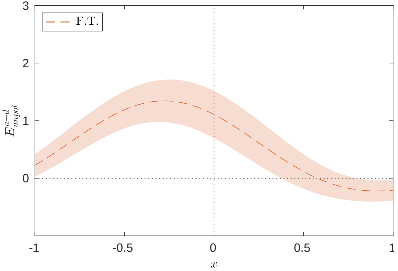
- We apply the RI→ $\overline{\text{MS}}$ matching [Y-S Liu et al., Phys.Rev. D100 (2019) no.3, 034006]

$P_3 = 0.83$ GeV, $-t = 0.69$ GeV$^2$, $\xi = 0$



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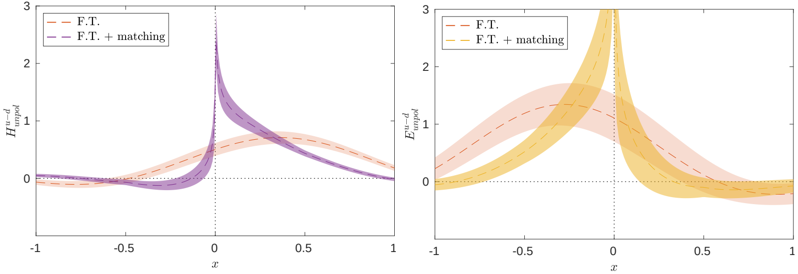


- Matching affects both $H$ and $E$ largely

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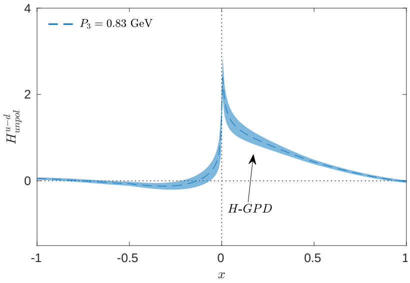
Momentum dependence on $H(x, \xi, t)$ and $E(x, \xi, t)$, at $-t = 0.69$ GeV$^2$




**antiquarks** **quarks**

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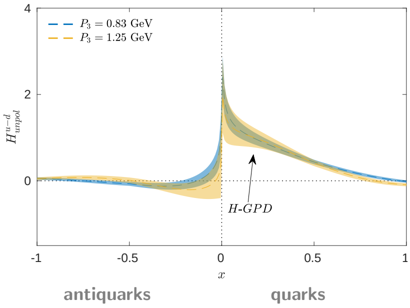

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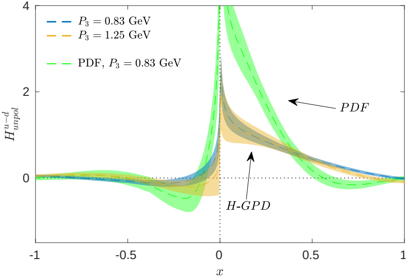


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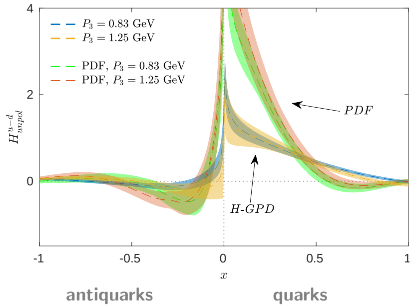


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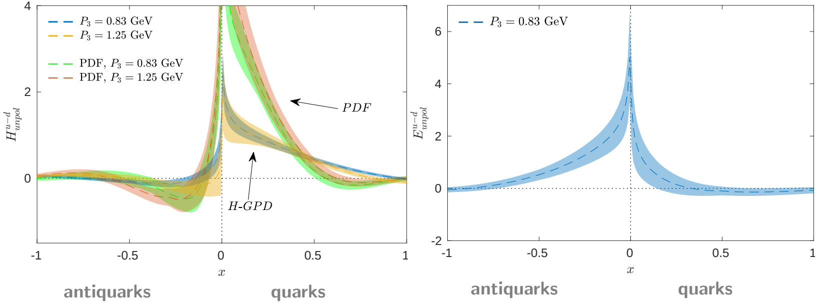


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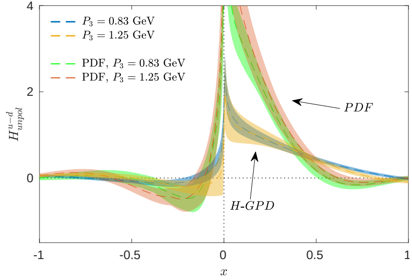


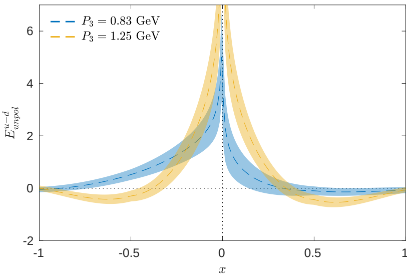


**antiquarks** **quarks** **antiquarks** **quarks**

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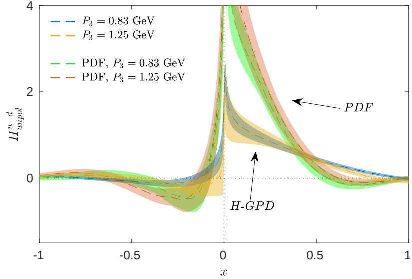


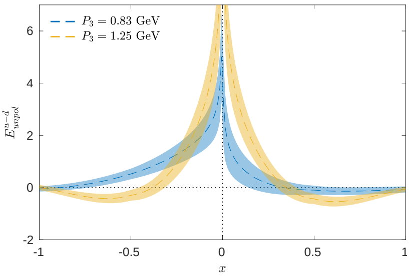


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★ Lattice results will be compared to global fits to DVCS data

# Summary

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**Exploratory study of nucleon GPDs**

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## Exploratory study of nucleon GPDs

- Computation performed using $N_f = 2 + 1 + 1$ twisted mass fermions, at $m_\pi = 270$ MeV
- Quasi-distribution approach extended to quasi-GPDs (pion GPDs studied in [J-W. Chen et al., arXiv:1904.12376])
- More laborious calculation than for PDFs
  - more variables to control
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**Future perspectives**

- increasing statistics for the kinematic setups already considered
- extending the kinematic coverage in $(P_3, \xi, t)$ space
- testing theoretical properties of GPDs, e.g. $H(x, -\xi, t) = H(x, \xi, t), \ldots$
- studying excited states contamination (other $T_{\text{sink}}$ must be added)
- applying advanced reconstruction methods for the Fourier transform **[J. Karpie et al., JHEP 1904 (2019) 057]**

*Thank you very much for your attention.*

# Helicity GPDs ($\xi = 0$)

At $\xi = 0$ only $\tilde{H}$ survives