

First Global Extraction of Generalized Parton Distributions from Experiment and Lattice Data with Next-to-Leading-Order Accuracy

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We report the first global extraction of generalized parton distributions, GUMP 1.0, by combining deeply virtual Compton scattering and ρ -meson production data from Jefferson Lab and the Hadron-Electron Ring Accelerator with global fits of parton distribution functions, charge form factors, and lattice quantum chromodynamics simulations. Using a conformal moment space parametrization, we achieve a unified description across low- and high- x regions at next to leading order accuracy in perturbative corrections. The results provide state-of-the-art generalized parton distributions consistent with almost all known facts, enabling three-dimensional nucleon imaging in impact parameter space and, at the same time, establishing a benchmark for future theoretical and experimental studies of the nucleon structure.

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Introduction—The multidimensional structures of the nucleon have drawn growing interest in the past decades as the new frontier for the study of strong interactions and quantum chromodynamics (QCD). Generalized parton distributions (GPDs) that encode the three-dimensional (3D) distributions of partons in the nucleon have been one of the most sophisticated tools for such a purpose [1–8], together with their momentum-space counterpart—transverse momentum distributions [9]. In particular, GPDs correspond to parton distributions localized in the impact parameter space [10–13], and contain important information about the nucleon, such as the spin and mechanical properties [1,2,14,15]. Experimentally, GPDs can be constrained by hard exclusive scattering processes off the nucleon, such as deeply virtual Compton scattering (DVCS) [16] and deeply virtual meson production (DVMP) [17,18], among other hard exclusive processes [19–31]. Experimental studies of GPDs have been one of the crucial

physics motivations for future upgrades at Jefferson Lab (JLab) [32] and the upcoming Electron-Ion Collider (EIC) in the United States [33,34] and in China [35].

Despite their physical significance, a complete determination of even the leading-twist GPDs has remained challenging due to the well-known inverse problem [36]. This is because measurements of DVCS and DVMP, even when combined with forward inputs, do not uniquely determine the GPDs. Meanwhile, recent novel developments have made it possible to access parton distributions directly through first-principles lattice QCD simulations [37–40]. Especially, lattice simulations mainly constrain GPDs in the regions that experiments cannot access easily [41], and therefore provide crucial complementary input for the extraction of GPDs. In this spirit, the GPD through universal moment parametrization (GUMP) program was put forward a few years ago [42–44], aiming to develop advanced extractions of GPDs from global inputs.

We recognize the important and extensive efforts that have been devoted to studying exclusive processes in the GPD framework [45–54], and progress has been made to extract zero-skewness GPDs from various inputs as well [42,55,56]. Nevertheless, uncovering the 3D structure of the nucleon with a unified description across all inputs requires access to the full GPDs.

In this Letter, we present the first global extraction of GPDs with comprehensive inputs that cover the major experimental and lattice constraints on GPDs. Specifically,

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we complement the large amount of precise DVCS measurements from JLab in the relatively high- x region [57–61] with the Hadron-Electron Ring Accelerator (HERA) measurement of both DVCS [62] and deeply virtual ρ -meson production (DV ρ P) [63,64] in the low- x region at next-to-leading order accuracy of perturbative QCD corrections for the exclusive cross sections and GPD evolutions. Moreover, as GPD functions reduce to parton distribution functions (PDFs) in the forward limit and their first moments become charge form factors, we also include in our analysis the global PDFs [65] and nucleon charge form factors [66]. These constraints are reinforced by the most recent lattice simulations of generalized form factors and x -dependent GPDs at zero and nonzero skewness [67–72]. With the GPD parametrization in the conformal moment space, we present a state-of-the-art extraction of GPDs across sea and valence regions. The results enable three-dimensional nucleon imaging in impact parameter space, establish a benchmark for the future study of nucleon tomography, and also provide crucial theoretical inputs for the GPD programs at JLab and the future electron-ion colliders.

Theoretical framework and GPD parametrization—GPDs are the generalization of PDFs with nonzero momentum transfer, defined as

$$F_{q,g} \equiv \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | O_{q,g}(\lambda n) | P \rangle, \quad (1)$$

where the initial and final nucleon momenta are labeled as P and P' , respectively, and the average momentum $\bar{P} \equiv (P + P')/2$ and momentum transfer $\Delta \equiv P' - P$ are also defined, using the notations and conventions in Ref. [16]. The nonlocal correlators $O_{q,g}(\lambda n)$ are distributed along the direction of the lightlike vector $n^2 = 0$ with gauge links in between. Then each GPD, collectively denoted as $F(x, \xi, t)$, depends on three variables: the average parton momentum fraction x , the longitudinal projection of the momentum transfer $\xi \equiv -n \cdot \Delta / (2n \cdot \bar{P})$, and the momentum transfer squared $t \equiv \Delta^2 \leq 0$.

Conventionally, GPDs are defined to be symmetric in ξ due to parity and time-reversal symmetry. Therefore, we consider GPDs on the phase space $x \in [-1, 1]$, $\xi \in [0, 1]$, and $t \in (-\infty, 0]$ without loss of generality. Additionally, GPDs are subject to further physical constraints, such as the endpoint constraint, kinematic constraint, and polynomiality constraint [4], among others.

It has been extensively discussed in the literature [45,46,73] that the conformal moments of GPDs can help one utilize these physical constraints, including the evolution properties of GPDs, to construct or parametrize GPDs. This idea naturally motivates one to consider a global analysis of GPDs by parametrizing their conformal moments. In particular, the Kumerički-Müller model was proposed and has been successful in fitting the DVCS and

DVMP measurements [45–47,74,75], with a focus on the sea distributions. Lately, the GUMP program was put forward for the global analysis of full GPDs [42–44], encompassing both the sea and valence regions from extensive inputs.

In the conformal moment expansion framework, GPDs are formally expanded with respect to a set of conformal partial wave functions $p_j(x, \xi)$ as [73]

$$F(x, \xi, t) = \sum_{j=0}^{\infty} (-1)^j p_j(x, \xi) \mathcal{F}_j(\xi, t), \quad (2)$$

where $\mathcal{F}_j(\xi, t)$ are the corresponding partial wave amplitudes or so-called conformal moments of GPDs. To actually construct GPDs in the x space, analytical resummation of all moments $\mathcal{F}_j(\xi, t)$ is required, which can usually be done through a Mellin-Barnes integral,

$$F(x, \xi, t) = \frac{1}{2i} \int_{c-i\infty}^{c+i\infty} dj \frac{p_j(x, \xi)}{\sin(\pi[j+1])} \mathcal{F}_j(\xi, t). \quad (3)$$

Then, GPDs can be established equivalently in the moment space. One crucial feature of constructing GPDs in moment space is that GPD moments are polynomials of ξ [4] and can therefore be expanded in terms of ξ as

$$\mathcal{F}_j(\xi, t) = \sum_{k=0, \text{even}}^{j+1} \xi^k \mathcal{F}_{j,k}(t). \quad (4)$$

For the typical kinematics of interest, such as the JLab, HERA, and future EIC, $\xi \lesssim 1/2$ is small. Thus, we can truncate the above series to $k = 4$ for simplicity.

For the forward moments $\mathcal{F}_{j,0}(t)$ with $k = 0$, we employ a simple parametrization of them as

$$\mathcal{F}_{j,0}(t) = \sum_{i=1}^{i_{\max}} N_i \frac{B(j+1-\alpha_i(t), 1+\beta_i)}{B(2-\alpha_i, 1+\beta_i)} R_i(t), \quad (5)$$

that corresponds to the *Ansätze* $N_i x^{-\alpha_i} (1-x)^{\beta_i}$ in the forward limit and x space, commonly used in PDF global analysis [76]. The choice of $i_{\max}$ depends on the anticipated flexibility of the x dependence. We set $i_{\max} = 2$ for the H GPD of $\bar{u}, \bar{d}, g$ to accommodate the wide coverage of $x \in [0.0005, 0.6]$ and $i_{\max} = 1$ for the rest. We note that fewer parameters are required to achieve a satisfactory fit in this analysis compared to global PDF analyses. This likely reflects the more limited kinematic coverage in x and the fact that the fit is not performed directly to all experimental data.

The t dependence of the *Ansätze* is implemented in two ways: a nonfactorized Regge trajectory: $\alpha_i(t) \equiv \alpha_i + \alpha'_i t$ with a Regge slope α'_i , and another factorized $R(t)$ that can be parametrized separately. Recent studies of GPD parametrization with the holographic QCD model suggest a

similar form [77,78]. Here, we additionally implement $R(t)$ to ensure sufficient flexibility in the GPD model. Specifically, we pick an exponential form $R(t) = \exp(-bt)$ for sea quarks and gluons, and a dipole form $R(t) = (1 - t \cdot M^{-2})^{-2}$ for valence quarks, to account for the different t dependence of them.

The off-forward moments $F_{j,k}(t)$ with $k \neq 0$, more specifically $k = 2, 4$, receive fewer constraints. Accordingly, we model them as $F_{j,k}(t) \equiv R_k F_{j-k,0}(t)$, proportional to the forward ones, as originally proposed in [45,46]. This choice can be relaxed if further constraints on GPDs are obtained from, for instance, lattice simulations. We note that the so-called $C_{q,g}$ terms are not implemented in this way, the investigation of which is left for separate future work.

Lastly, we note that among the four leading-twist H , E , $\tilde{H}$, and $\tilde{E}$ GPDs, the E and $\tilde{E}$ GPDs are much less constrained due to the lack of forward constraints, e.g., from unpolarized and polarized PDFs. In particular, the flavor separation appears challenging. Therefore, we impose empirical constraints, such as $E_g \propto H_g$, to avoid unconstrained GPDs. Again, such choices can be relaxed in the future with more constraints on the E and $\tilde{E}$ GPDs. The details of the GPD parametrization can be found in Supplemental Material (SM) of this work [79], where we present all the parameters and their best-fit values, along with the full fit results.

Setup of the analysis and results—In this section, we outline the setup of the global analysis and present the results. The analysis is performed using a χ^2 minimization with the IMINUIT interface of Minuit2 [80,81]. We employ the formulas in [82,83] for DVCS cross sections and asymmetries with leading-twist GPDs and kinematical accuracy of twist three. For DV ρ P, we use leading-twist formulas, appropriate for the small- x_B HERA kinematics. Both Compton and transition form factors are computed with next-to-leading-order Wilson coefficients and GPD evolution, of which the expressions in conformal moment space are collected in [45–47].

In this first analysis, some GPD-related observables have not been included for various considerations, such as the timelike Compton scattering [19,20], doubly DVCS [21–23], and other two-to-three processes [24–31] discussed in the literature. These could be incorporated in future work once more data are available. The exclusive J/ψ productions also provide constraints on the gluon GPDs [44,84–95]. However, including these data requires extending the factorized t dependence assumed in this analysis. For the same reason, we omit the lattice results on gluon gravitational form factors [69]. Furthermore, recent near-threshold J/ψ measurements have advanced the study of gluon gravitational form factors [96–102], but as they mainly probe the large- ξ region, a dedicated analysis is again left to future work.

In Fig. 1, we present representative fits to various experimental measurements, including the unpolarized

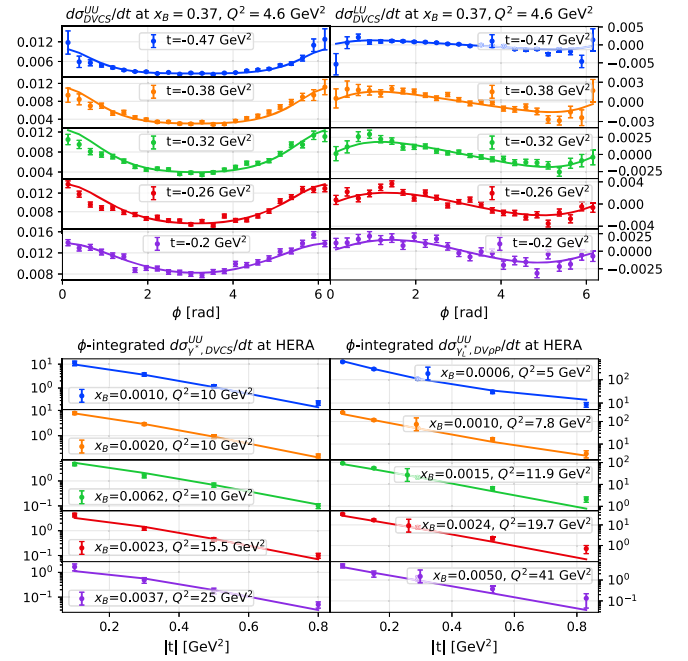


FIG. 1. Representative fits to differential cross sections: unpolarized DVCS at JLab (top left), beam-polarized DVCS at JLab (top right), unpolarized DVCS at HERA (bottom left), and unpolarized DV ρ P at HERA (bottom right). JLab data are ϕ -differential electroproduction cross sections [57–60], while HERA data are ϕ -integrated photoproduction cross sections [62–64].

and beam-polarized DVCS differential cross sections measured at JLab [57–60] and the ϕ -integrated differential cross sections of DVCS and DV ρ P measured by H1 and ZEUS at HERA [62–64]. We also note the development of a GPD database [103] and include the asymmetry measurements [61]. All DV ρ P data are converted to longitudinal cross sections using the longitudinal-to-transverse ratio R extracted from experimental measurements [63,64]. Generally, we observe excellent agreement with the data. In particular, we find a consistent description between the DVCS and DV ρ P measurements of HERA. This also aligns with the observations by the Kumerički-Müller model [47]. The main challenge appears to be the presence of possible higher-order sinusoidal behaviors in the ϕ dependence of the JLab data, which could indicate higher-twist effects that are beyond the scope of this work and warrant further investigation.

In Fig. 2, we present representative fits to the globally fitted PDFs by the JLab Angular Momentum Collaboration [65] as well as lattice-calculated GPDs [72,104,105]. We also consider the global nucleon charge form factors [66] and a systematic lattice QCD simulation of generalized form factors up to the fifth moments [70]. The detailed fit results that do not fit here are collected in SM of this letter [79]. Such integrated constraints on GPDs across different species and flavors are essential for a robust extraction, since the experimental observables are generally insensitive to these distinctions unless measurements are performed with varying beam and target polarization

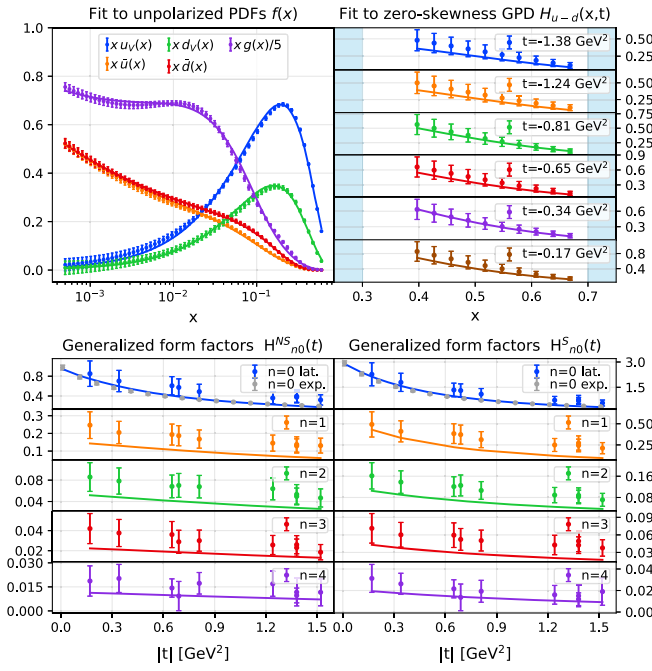


FIG. 2. Representative fits to global PDFs and lattice QCD simulations: fits to global unpolarized PDFs (top left) [65], lattice simulations of GPDs at zero skewness (top right) [72,104,105], and global charge form factor [66] and lattice simulations of generalized form factors for flavor nonsinglet $H_{n0}^{u-d}(t)$ (bottom left) and flavor singlet (S) $H_{n0}^{u+d}(t)$ (bottom right) [70].

configurations [106]. This is one substantial improvement anticipated from the future EIC, which will enable high-precision measurements with different polarization configurations.

We remark that when combining the experimental data with the lattice results, a moderate relative 30% uncertainty has been added to the reported uncertainty of the lattice results to account for systematic uncertainties (continuum limit, physical quark mass, infinite volume, excited state contamination, large momentum extrapolation, etc.) not included in the original analysis. It serves as a rough estimate, whereas further quantitative studies of systematic uncertainties are undoubtedly crucial to analyze experimental and lattice data simultaneously, which, nevertheless, is beyond the scope of this work.

Finally, in Fig. 3, we summarize the fit results by presenting the number of data points, N_{pts} , from all the inputs used in this analysis, together with the corresponding χ^2/N_{pts} for each of them. Overall, this analysis incorporates a total of 2646 data points from experiments, lattice simulations, and global PDFs and form factors, yielding a χ^2/N_{pts} value close to unity. The overall χ^2 per degree of freedom is about 1.09, demonstrating a good level of agreement among all the inputs.

We note that the uncertainty analysis in this work is limited to the Hessian errors from the χ^2 minimization, propagated via a standard Monte Carlo procedure while

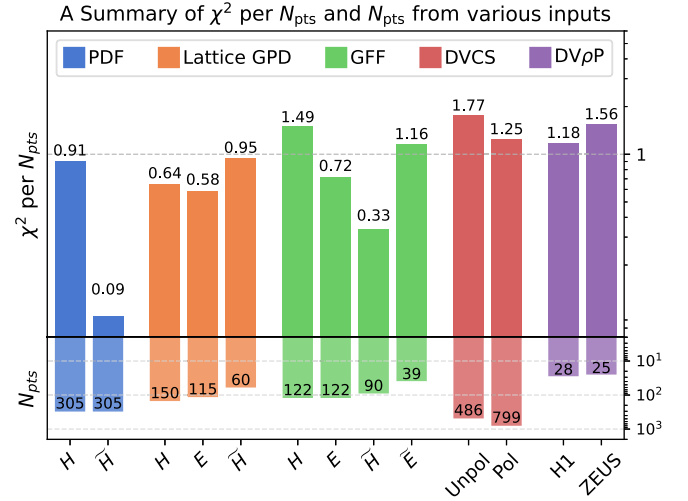


FIG. 3. A summary of contributions to the χ^2 from all inputs used in the analysis, normalized by the number of data points N_{pts} , which are shown in the lower panel.

neglecting error correlations and other systematic errors. A more comprehensive treatment using Bayesian inference or the replica method is left for future work due to its substantial computational cost. Recent studies exploring systematic errors such as parametrization biases in GPD extraction with neural networks [53] also point to important directions for future development.

Extracted GPDs and proton tomography—One topic central to the study of GPDs is the nucleon tomography, where the impact parameter space distributions of partons in the nucleons can be written as [11]

$$\rho_{q/g}(x, \mathbf{b}) = \int \frac{d^2\Delta}{(2\pi)^2} e^{-i\Delta \cdot \mathbf{b}} H_{q/g}(x, -\Delta^2), \quad (6)$$

in terms of the corresponding zero-skewness GPDs. In this section, we present the extracted GPDs, denoted as the GUMP 1.0 extraction, and the proton tomography. Figure 4 shows an example of the extracted intrinsic transverse space gluon distributions, $\rho_g(x, \mathbf{b})$, in an unpolarized proton at $\mu = 2$ GeV, which will be one of the most important goals of the future EIC [33]. We note, however, that the factorized parametrization of the t dependence may limit the accuracy, as discussed above, and the errors due to parametrization bias have not been included.

Recently, the tomography of transversely polarized nucleons was revisited [107–111] and the intrinsic transverse space distribution in a transversely polarized (in the X direction) nucleon was defined as [108]

$$\rho_{q,\text{lin}}^X(x, \mathbf{b}) = \int \frac{d^2\Delta}{(2\pi)^2} e^{-i\Delta \cdot \mathbf{b}} \left[H_q(x, -\Delta^2) + \frac{i\Delta_y}{2M} (H_q + E_q)(x, -\Delta^2) \right], \quad (7)$$

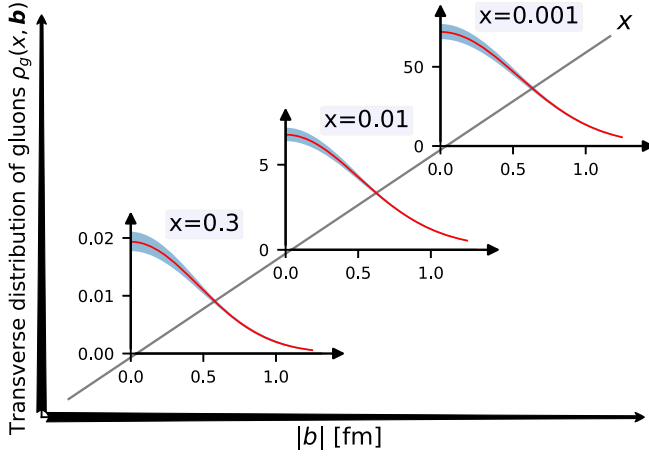


FIG. 4. The transverse space gluon distributions $\rho_g(x, \mathbf{b})$ in an unpolarized proton with GUMP 1.0 GPDs at $\mu = 2$ GeV. Bands correspond to 90% confidence intervals obtained via a standard Monte Carlo propagation of Hessian errors, neglecting error correlations and other systematic errors.

in terms of the zero-skewness GPDs, such that the contribution from the center-of-mass motion of the proton to its angular momentum is removed [107,108]. Correspondingly, the intrinsic contributions to the proton angular momentum are

$$J_q^X(x, \mathbf{b}) = \frac{\gamma}{2} (b^y \times x P^+) \rho_{q,\text{in}}^X(x, \mathbf{b}). \quad (8)$$

Here, γ is the boost factor of the proton, which will be omitted hereafter to normalize the proton spin to $\hbar/2$.

In Fig. 5, we present the intrinsic transverse distributions $\rho_{q,\text{in}}^X(x, \mathbf{b})$ of up and down quarks at $x = 0.3, 0.01$, and 0.001 , respectively, at the reference scale $\mu = 2$ GeV. The $\rho_{q,\text{in}}^X(x, \mathbf{b})$ are calculated via a numeric Fourier transform of the extracted zero-skewness GPDs according to Eq. (7). We label the transverse directions as $\mathbf{b} \equiv (X, Y)$ to distinguish them from the momentum fraction x , and assume the proton polarization along X .

From the intrinsic transverse quark distributions, it is clear that the quark contributions to the proton angular momentum are mainly from the up quark in the valence region. In contrast, the down quark contribution is minor and can potentially be negative. This picture gets rather different in the sea region. There appears to be a cancellation of up and down quarks' contributions to the proton angular momentum, as they are both distributed significantly off the Y axis but on opposite sides. Nevertheless, as the angular momentum contributions are suppressed by x in the sea region, as shown in Eq. (8), the quark contributions to the proton angular momentum are still dominated by the up quarks.

From the global extraction, we report the proton angular momentum decomposition to be $J_u = 0.334(9)$, $J_d = -0.108(12)$, and $J_g = 0.258(8)$ with $J_{\text{tot}} = 0.484(17)$, where uncertainties include the Hessian errors only.

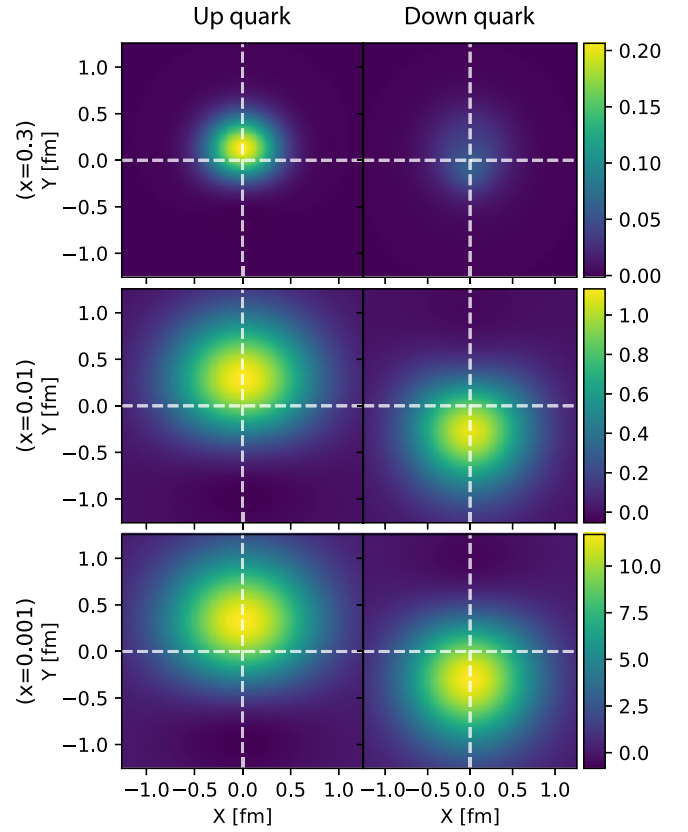


FIG. 5. The intrinsic transverse space distributions $\rho_{q,\text{in}}^X(x, \mathbf{b})$ of up and down quarks in a proton polarized in the X direction for $x = 0.3, 0.01$, and 0.001 with GUMP 1.0 GPDs at $\mu = 2$ GeV.

Comparing this to the lattice simulations [69], which reported $J_u = 0.2213(85)$, $J_d = 0.0197(85)$, and $J_g = 0.255(13)$, the difference is mainly caused by the global charge form factors that favor a negative $F_2^{u+d} \sim B_{10}^{u+d}(t)$. In contrast, the lattice favors positive or almost zero $B_{10}^{u+d}(t)$. The detailed comparison of the extracted E form factors can be found in SM. We leave a more careful investigation of this matter to future work.

Conclusion—To summarize, we present the first global analysis of GPDs using a comprehensive set of experimental and lattice inputs within the GUMP framework and its conformal moment parametrization. This work establishes a benchmark for future studies of nucleon tomography and internal structure, while providing essential input for GPD programs at current and upcoming facilities such as JLab, the EIC, and the EIC in China.

To demonstrate the power of the global extraction, we present the transverse spatial distributions of quarks in the proton, providing a direct tomographic image of its internal structure. This showcase highlights the unique capability of globally constrained GPDs to reveal the spatial dynamics of quarks with unprecedented fidelity.

The developments of this work will be released as open-source [112], aiming to provide a long-lasting resource designed to accelerate and support all future GPD studies.

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Data availability—The data that support the findings of this article are openly available [112].

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