Generalized Parton Distributions and their implications for observables relevant to baryon junction dynamics

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In collaboration with

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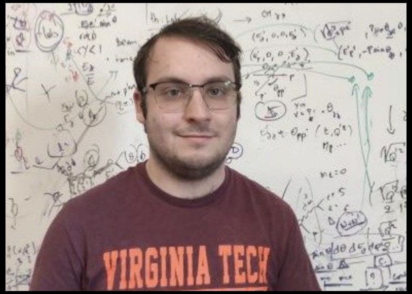


Brannon Semp

Zaki Panjsheeri

Literature

arXiv:2511.03065 Hessian based GPD parametrization

arXiv: 2512.20853 Disconnected contributions

arXiv: 2605.06994 NNGPD

arXiv:2504.13289 Symbolic regression study of LQCD GPDs

Outline

1. **Motivation**: providing a unified picture within QCD from complementary insights into spatial 3D structure of hadrons

    - Flavor content of nucleon form factors
    - Role of antiquarks
    - Role of gluons: baryon junctions (work in progress)

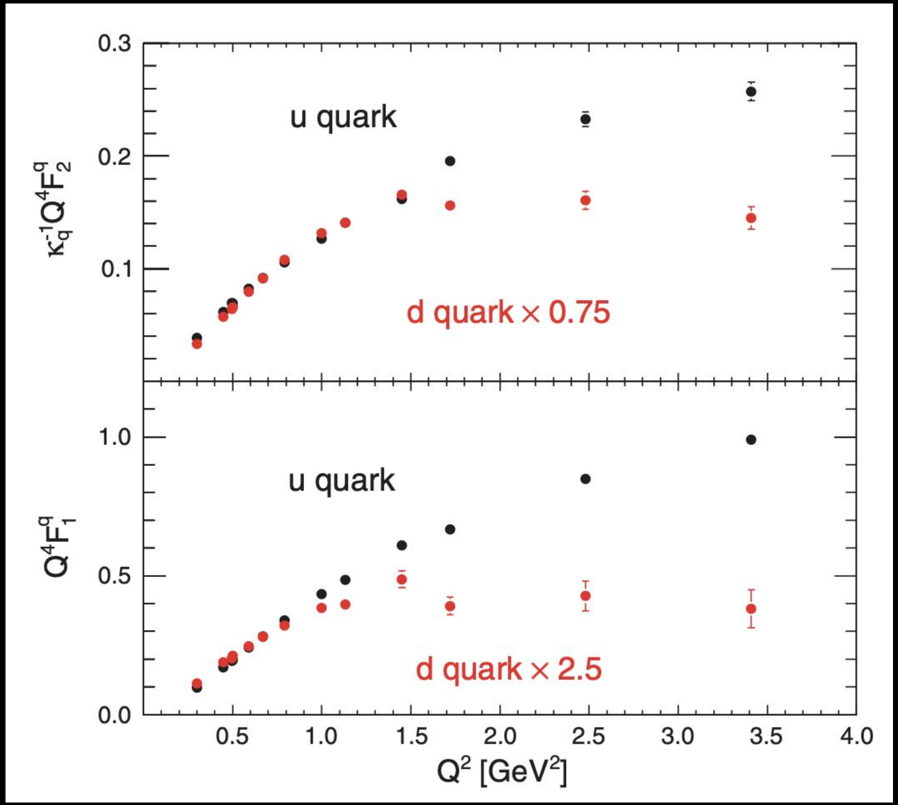
2. **Generalized Parton Distributions (GPDs)**: accessing QCD correlations underlying the dynamical picture

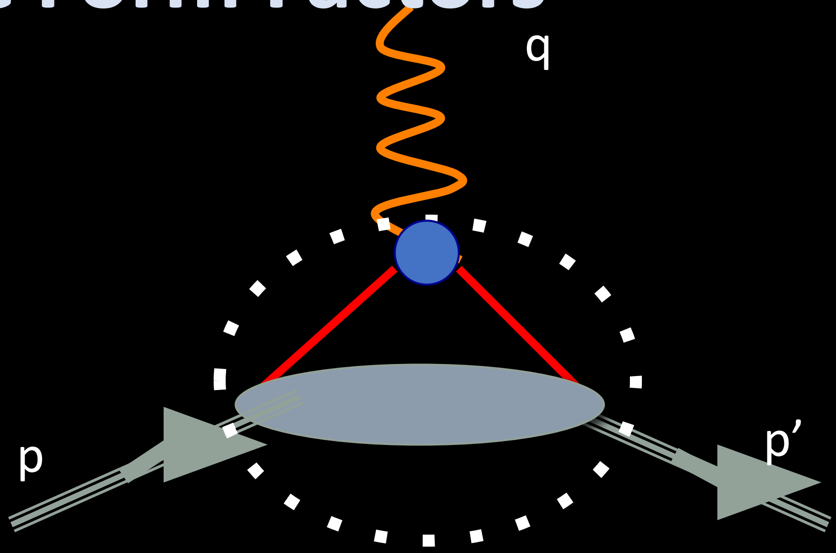
    - What quantities are needed, and what can be extracted from data
        - x-dependence is needed to test the partonic property and to do images.
        - For the problem of extracting OAM from data we might not need a full x-coverage: going from CFFs to Mellin moments directly

3. **Future: quantitative application to baryon junctions**

1. Understanding flavor structure of Elastic Form Factors

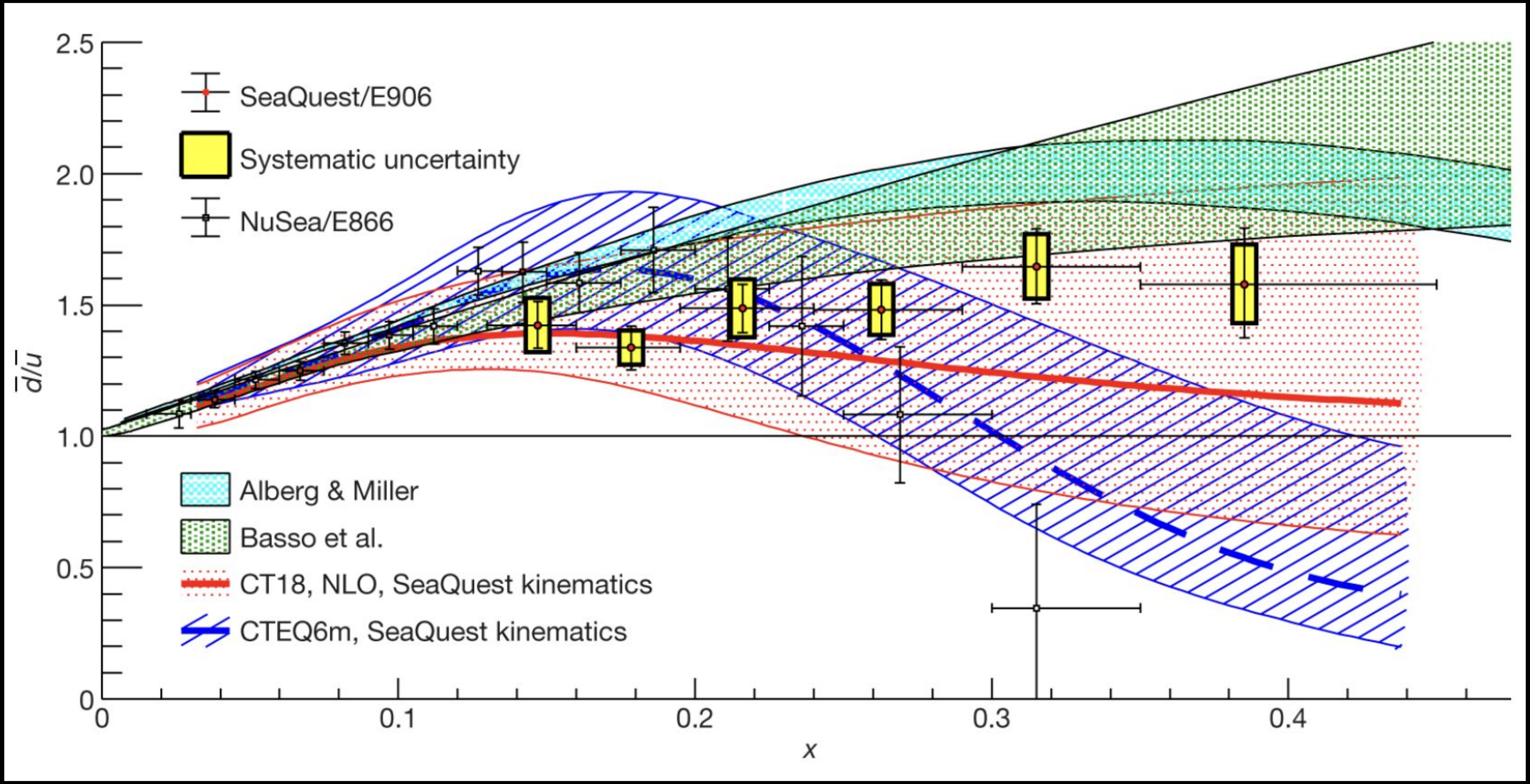
Unexpected Q^2 dependence





Cates et al., Phys.Rev.Lett. 106 (2011)

… and flavor structure of anti-quark contributions



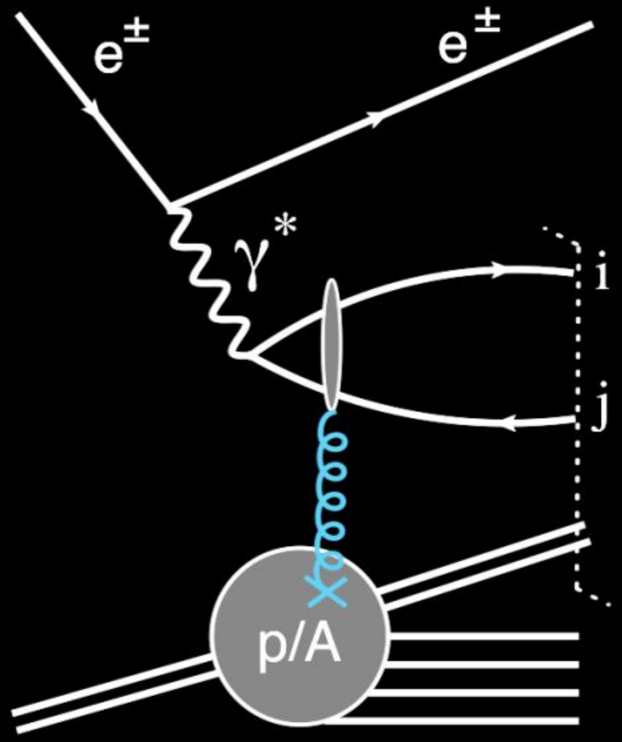
Baryon stopping

<ins>Experimental Evidence</ins>

- Baryon number is transported less efficiently than charge with predicted ratio from valence-quark models of 0.5-0.7
- Ratio is closer to 1 at mid-rapidity
- Net (baryon transport)/(particle - charge - yield) is further diluted by the large s-sbar production

<ins>QCD Picture, beyond valence-quark model</ins>

- Many color strings (flux tubes) are created and can reconnect: instead of simple quark–antiquark strings, one has junction topologies
- By allowing color strings to reconnect into junction configurations, baryon number is no longer tied to valence quarks and can be transported more efficiently to mid-rapidity, increasing the baryon-to-charge transport ratio.
- “Extending the content of color strings” lets baryon number be transported farther than the quarks themselves
- Junction transport brings baryon number to mid-rapidity, where it recombines with sea quarks produced at low x, linking strange production to disconnected dynamics.



Magdy, Tribedy, Lewis

(Kharzeev, Veneziano, et al.)

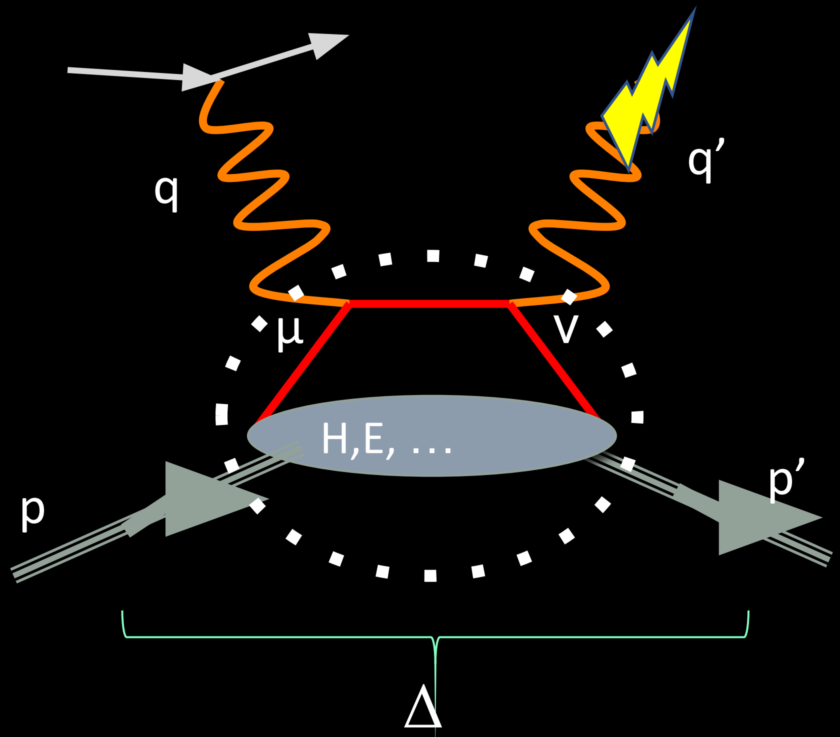
Is there a common mechanism based in non-perturbative QCD structure?

2. GPDs

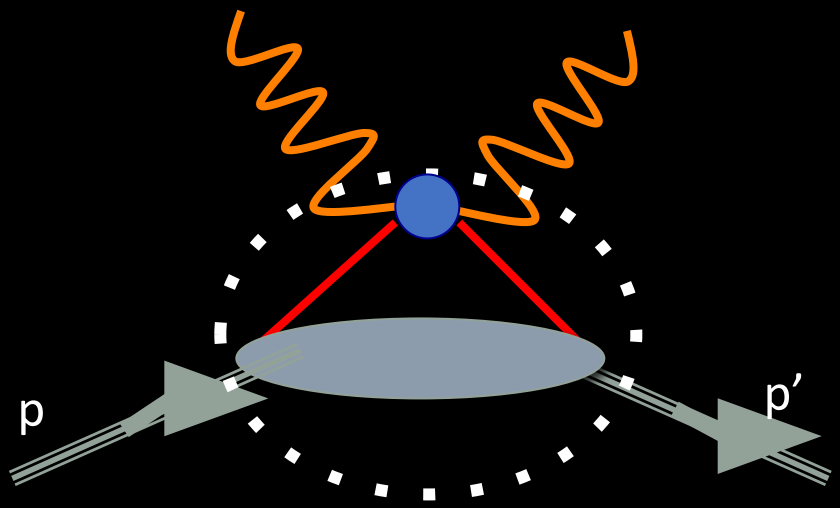
GPDs represent an paradigm for exploring this question

They allow us to access both “s and t channels”, and spatial and spin structure of partonic configurations

QCD matrix element

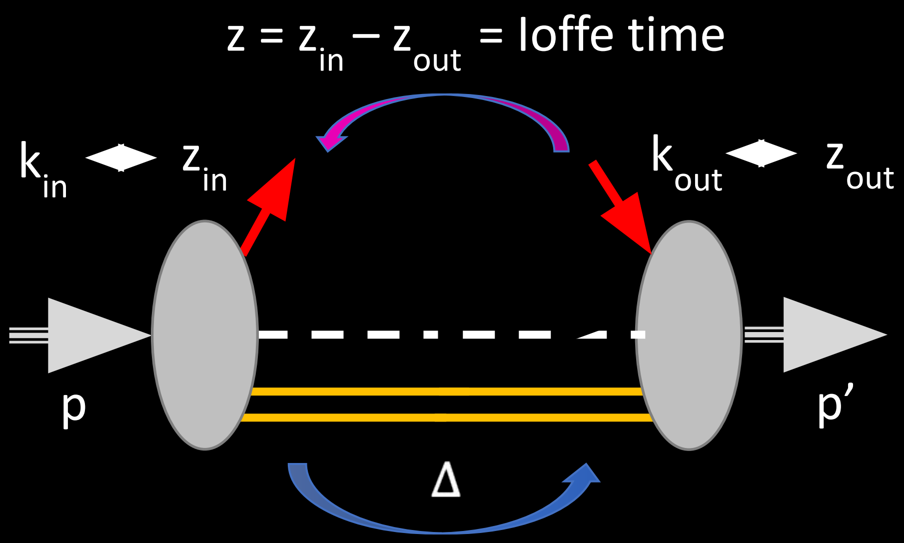


Local Operator



Generalized Parton Distribution → 2^{nd} GPD Moment → (EMT) Form Factor

$$W^{\Gamma}_{\Lambda,\Lambda'} = \int \frac{dz_{in}}{(2\pi)} \int \frac{dz_{out}}{(2\pi)^2}\, e^{i(k_{in} z_{in})}\, e^{-i(k_{out} z_{out})}\, \langle p', \Lambda' | \overline{\psi}(z_{out}) \Gamma \mathcal{U}(z_{in}, z_{out}) \psi(z_{in}) | p, \Lambda \rangle \Big|_{z^{+}_{in(out)}=0},$$



Quark-quark correlation function

*Analogous treatment for gluons

Two sets of variables/Fourier conjugates

$$b = \frac{z_{in} + z_{out}}{2}$$

$$\Delta = k_{in} - k_{out} = p - p'$$

External d.o.f., directly measurable

$$z = z_{in} - z_{out}$$

Ioffe time

$$k = \frac{k_{in} + k_{out}}{2} \rightarrow X p^{+}$$

Loop variables

Non local quark/gluon operator between different proton states

$$W^{\Gamma}_{\Lambda,\Lambda'} = \delta^3(\Delta - p + p') \int \frac{d^2\mathbf{z}_T}{(2\pi)^2} \int \frac{dz^-}{(2\pi)} e^{i(k^+ + \Delta^+/2)z^-} \, e^{-i(\mathbf{k}_T + \boldsymbol{\Delta}_T/2)\cdot\mathbf{z}_T} \langle p', \Lambda' | \overline{\psi}\,(0,0,0)\ \Gamma\,\psi\,(0, z^-, \mathbf{z}_T)\,|p, \Lambda$$

Underlying partonic structure in Green's function formalism

$$H_q(X,0,t) = \int d^2\mathbf{k}_T^{\mathcal{X}}\, dk_{\mathcal{X}}^+\, \delta(k_{\mathcal{X}}^+ - (1-X)p^+)\, \langle p-\Delta \mid \bar{\psi}_+(0) \mid \mathcal{X}\rangle \langle \mathcal{X} \mid \psi_+(0) \mid p\rangle$$

$$\phi(k_{\mathcal{X}}^+, \mathbf{k}_{T,\mathcal{X}}) \to \phi(X, \mathbf{k}_{T,in}) = \langle \mathcal{X} \mid \psi_+(0) \mid p\rangle,$$

$$H_q(X,0,t) = \int d^2\mathbf{k}_{T,in}\, \phi^*(X, \mathbf{k}_{T,in} - \mathbf{\Delta})\phi(X, \mathbf{k}_{T,in}).$$

one-body non-diagonal density in transverse momentum

$$H_q(X,0,t) = \int d^2\mathbf{b}\, e^{i\mathbf{b}\cdot\mathbf{\Delta}}\, \tilde{\phi}^*(X,\mathbf{b})\, \tilde{\phi}(X,\mathbf{b})$$

one-body diagonal density in transverse space

3D Coordinate Space Representation

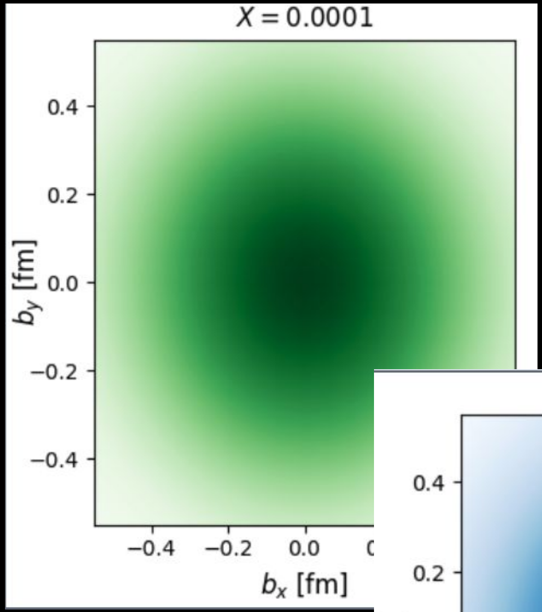
GPDs can be Fourier transformed from momentum space into coordinate space, providing insight into the spatial distributions of quarks and gluons inside the proton, besides matter and charge distributions.

Slice of Wigner phase space distribution

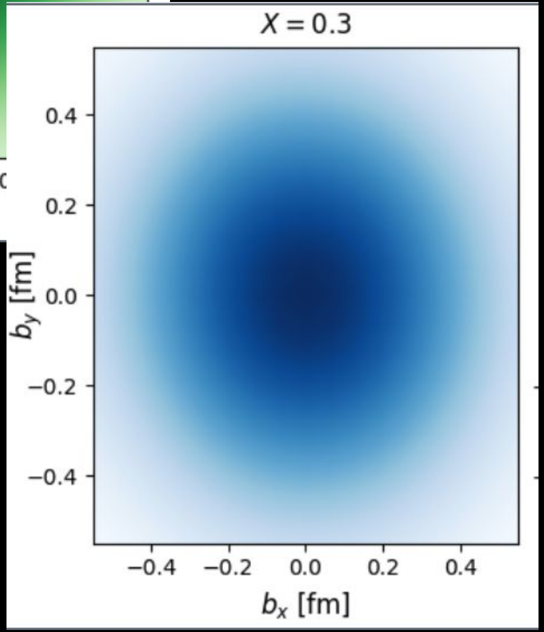
$$\mathcal{H}^q(X, 0, b_T) = \int \frac{d^2\Delta_T}{(2\pi)^2} H^q(X, 0, \Delta_T) e^{-i\Delta_T \cdot b_T}$$

GPD

gluon

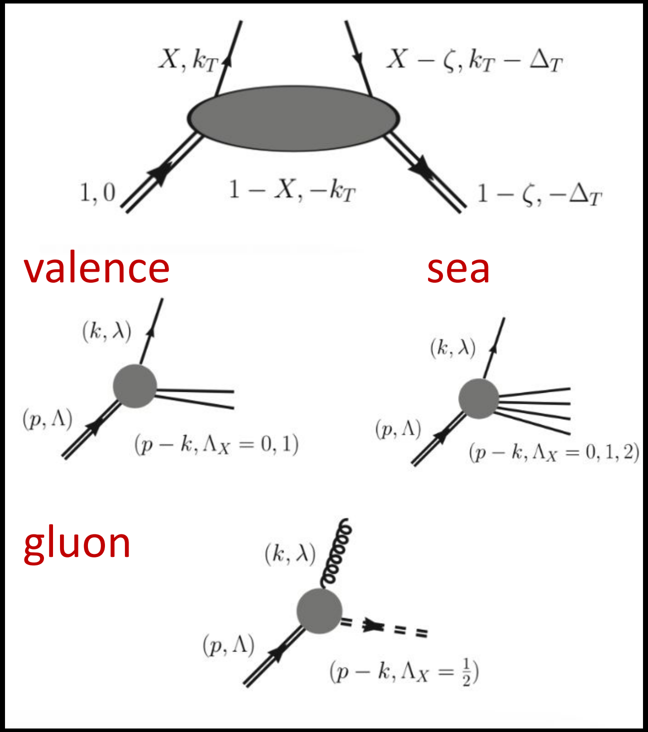


d-quark



With Z. Panjsheeri and J. Bautista

Modeling GPDs from low x to large x



Reggeized spectator model-based, with all flavor components + gluons

Spectator model

$$H_q = H_q^C + H_q^D = \mathcal{N}_q^H \, x^{-\left[\alpha_q + \alpha_q'^H \, t \, (1-x)^{p_q^H}\right]} F_q^H(x, \xi, t)$$

Regge term

B.Kriesten et al, Phys. Rev. D1055, 056022 (2022)
J.O. Gonzalez Hernandez, S. Liuti, G. Goldstein, K. Kathuria, Phys. Rev. C88, 065206 (2013)
G.Goldstein, J.O.Gonzalez Hernandez and S. Liuti, Phys. Rev. D84, 034007 (2011)
S. Ahmad, H. Honkanen, S. Liuti and S.K. Taneja, EPJC 63 , 407 (2009)

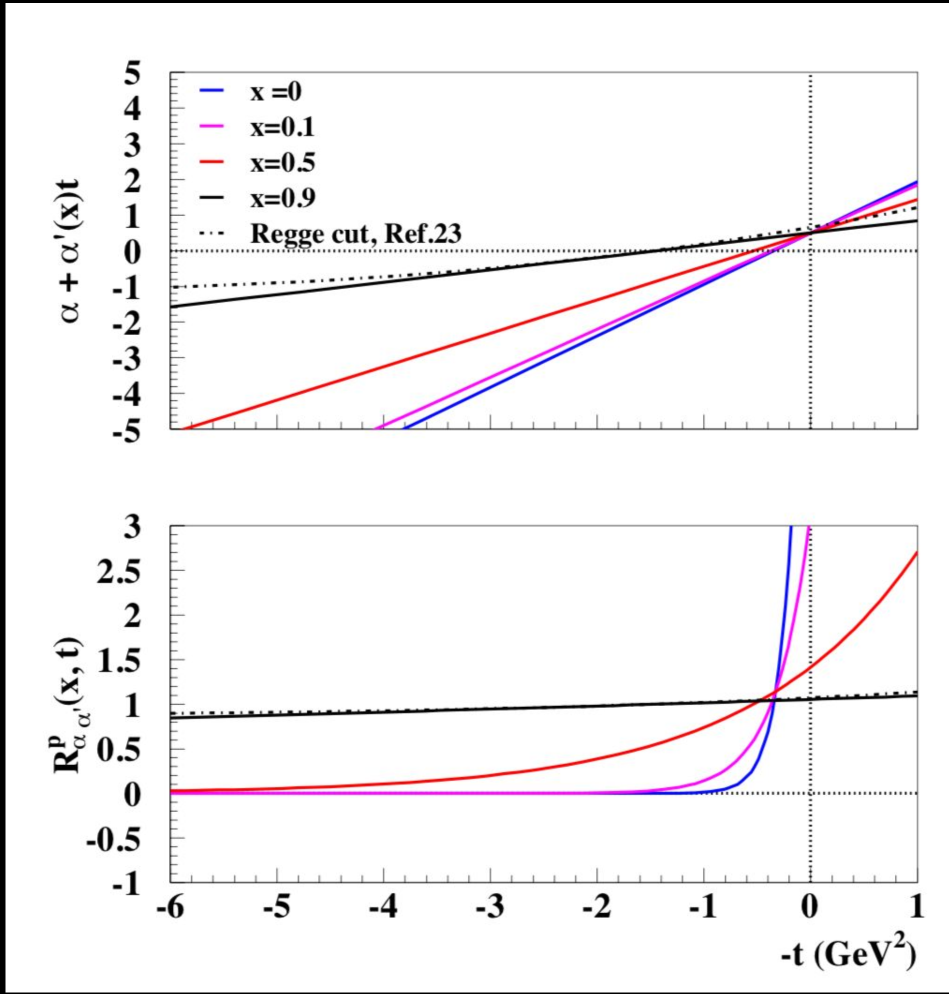
Panjsheeri et al. arXiv:2511.03065

$$R_p^{\alpha,\alpha'} = X^{-[\alpha+\alpha'(1-X)^p t]}$$

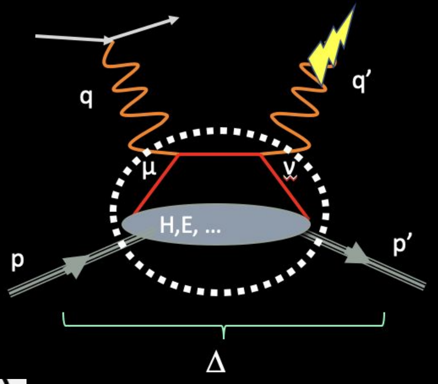
Interpretation of the flavor dependence of nucleon form factors in a generalized parton distribution model

J. Osvaldo Gonzalez-Hernandez, Simonetta Liuti, Gary R. Goldstein, and Kunal Kathuria

Phys. Rev. C **88**, 065206 – Published 27 December 2013



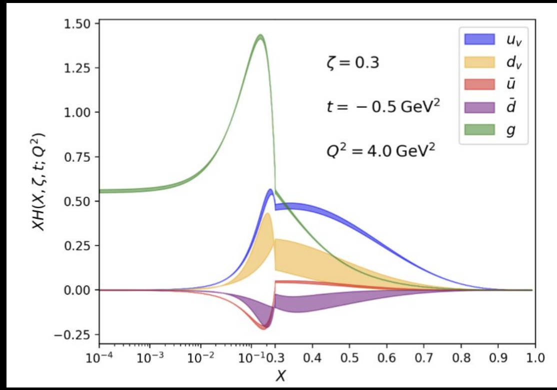
Quantitative results

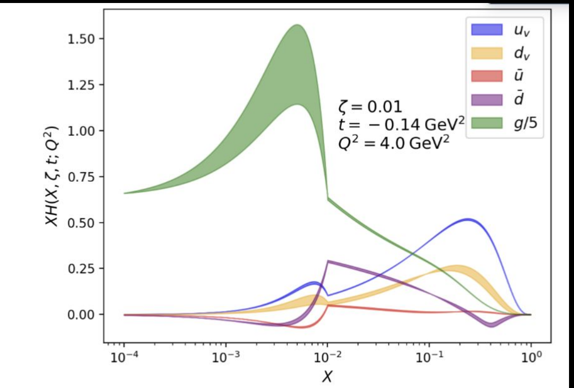


$$\mathrm{CFF}(\mathrm{x_{Bj}}, \mathrm{t}, \mathrm{Q}^2) = \int (\mathrm{QCDKernel}) \times \mathrm{GPD}(\mathrm{x}, \mathrm{x_{Bj}}, \mathrm{t}, \mathrm{Q}^2)$$

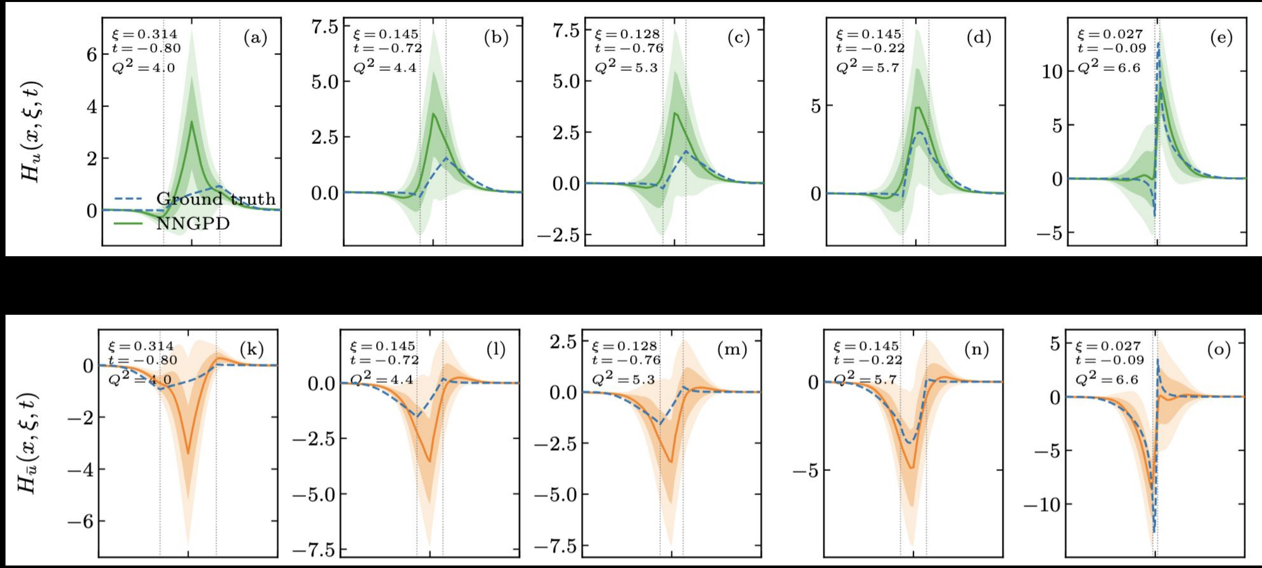
Hessian based fit (Z.Panjsheeri et al.,)

$$\chi^2_E(a,\lambda) = \sum_{k=1}^{N_{pt}} \frac{1}{s_k^2}\left(D_k - T_k(a) - \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha \beta_{k\alpha}\right)^2 + \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha^2$$

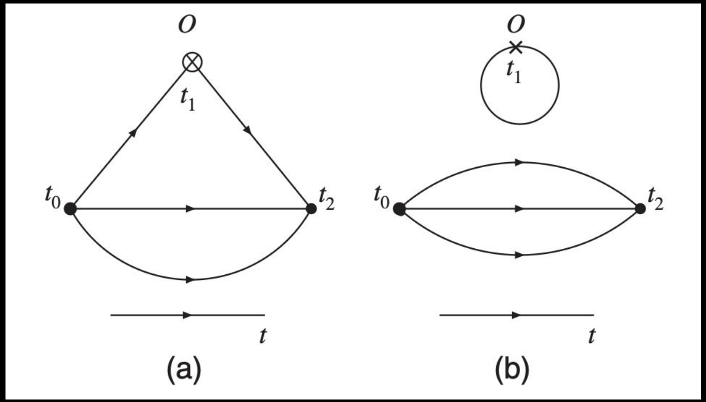




NNGPD (Xu, Jang, Panjsheeri et al.)



Including connected and disconnected contributions in GPD phenomenology



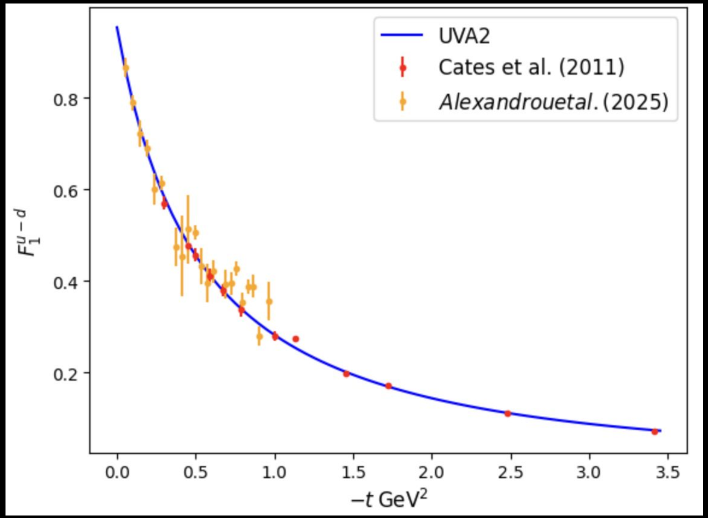
$$F_1^q(t) = A_{10}^q(t) = \int_{-1}^{1} dx H_q(x,\xi,t),$$
$$F_2^q(t) = B_{10}^q(t) = \int_{-1}^{1} dx E_q(x,\xi,t)$$

$$F_1^q(t) \;=\; F_1^{q,C} + F_1^{q,D} = \int_{-1}^{1} dx\, H_q^C + \int_{-1}^{1} dx\, H_q^D$$

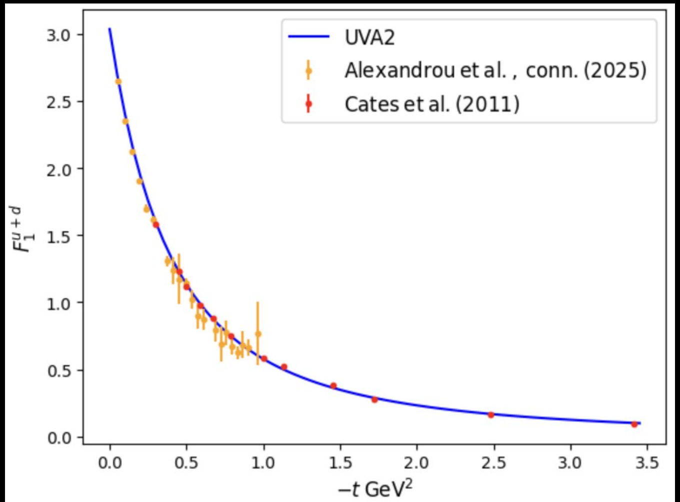
$$H_q^C \;=\; \frac{1}{2}(H_{q_v} + H_{q_{sea}}^C) = \frac{1}{2}(H_q^{-,C} + H_q^{+,C})$$
$$H_q^D \;=\; \frac{1}{2}(H_q^{-,D} + H_q^{+,D}).$$

Using our parametrization we can fit connected and disconnected distributions

Connected+Disconnected u-d



Connected+Disconnected u+d



arXiv: 2512.20853

Panjsheeri, Pandey, Semp, SL

Modeling GPDs from low x to large x: disconnected contribution

$$q - \bar{q}$$

$$H_q^{-,D} = \mathcal{N}_D^{-}\, x^{-(\alpha_q + \alpha_q' t)}$$

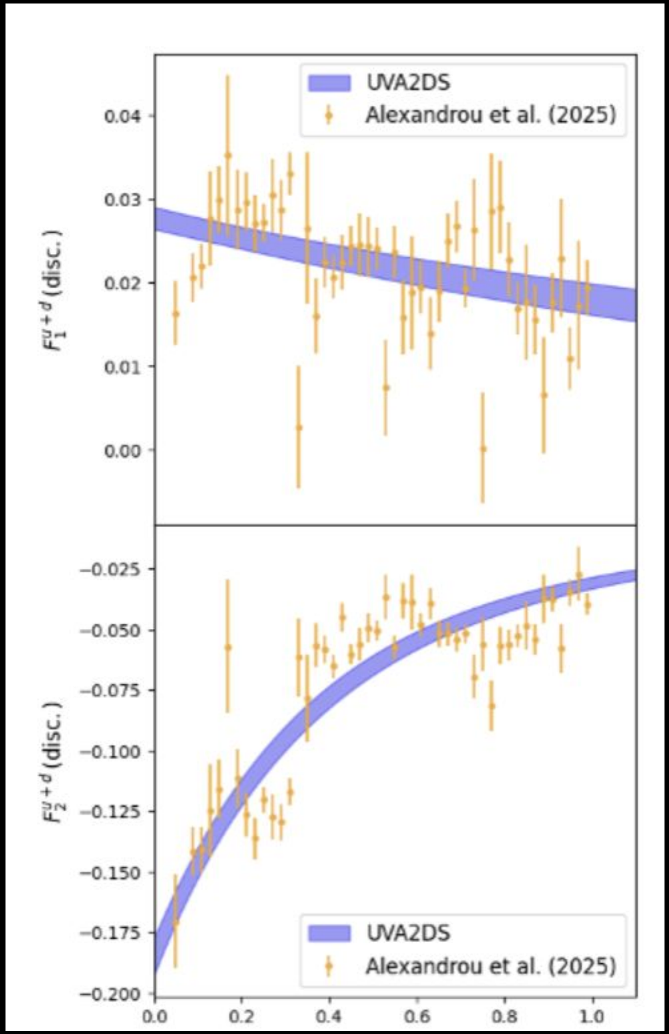
Valence in a standard PDF picture

$$q + \bar{q}$$

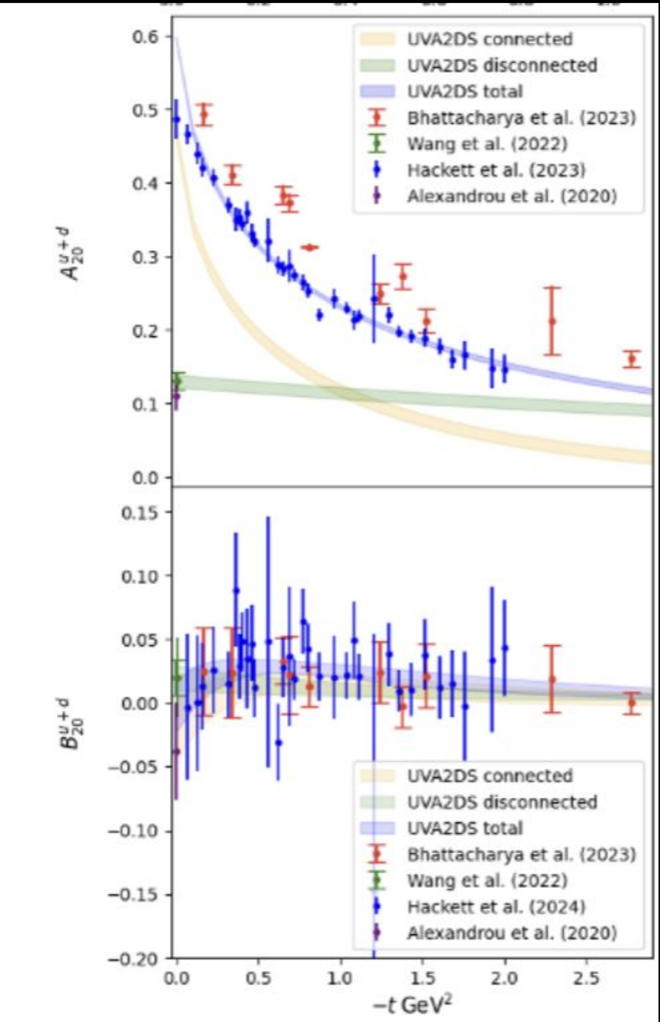
$$H_q^{+,D} = \mathcal{N}_D^{+}\, x^{-(\alpha_q + \alpha_q' t)} (1 - x)^{\beta}$$

Sea-quarks in standard PDF picture

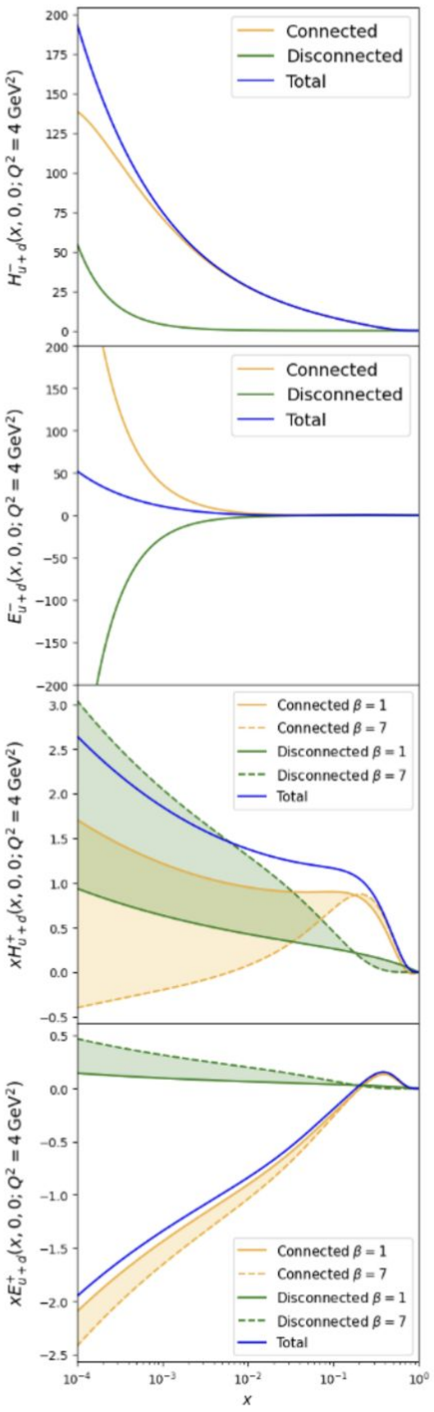
“-” disconnected n=1 Mellin moment



“+” connected and disconnected n=2 Mellin moment



GPDs/PDFs



Connected
Disconnected
Total
$H^-_{u+d}(x, 0, 0; Q^2 = 4\,\mathrm{GeV}^2)$
$E^-_{u+d}(x, 0, 0; Q^2 = 4\,\mathrm{GeV}^2)$
Connected $\beta = 1$
Connected $\beta = 7$
Disconnected $\beta = 1$
Disconnected $\beta = 7$
$xH^+_{u+d}(x, 0, 0; Q^2 = 4\,\mathrm{GeV}^2)$
$xE^+_{u+d}(x, 0, 0; Q^2 = 4\,\mathrm{GeV}^2)$
x

H^-

H^+

- In the baryon junction picture, a junction can be transported to mid-rapidity and coupled to quarks coming from the q q-bar pairs from the vacuum forming baryons resulting in the ratio close to unity.

- This gives us an intuition that the excess of anti-strangeness observed in experiments can be modeled as disconnected contributions at low x

- $$\frac{d^3\sigma}{dp^3} \propto \exp^{-\alpha \ln \sqrt{t-t_0}} \exp^{-\alpha y}$$

Modification of observable for c.m.s rapidity distribution of forward baryons

3.

Moving forward/work in progress

1) Is information on angular momentum directly extractable from data?
2) More specific connection to baryon junction dynamics

$$M_n = \int x^{n-1} \times GPD$$

angular momentum, calculable in lattice QCD

$$\mathrm{CFF} = \int (\mathrm{QCDKernel}) \times \mathrm{GPD}$$

experimental observable

$$\mathrm{GPD}$$

Same for other integral quantities involving GPDs in the chiral-odd sector: tensor charge

Conclusions

- Using the concept of GPDs, we present the first quantitative study of the impact of disconnected contributions to the PDFs -- calculated in LQCD -- and constrained by the values of their first (form factors) and second Mellin moments.

- The effect of disconnected sea quark distributions dominates the behavior of PDFs at low values of x.

- This study provides a QCD framework toward understanding the mechanisms responsible for the baryon–antibaryon asymmetry in QCD.