Generalised Partons Distributions: Modelling and Lattice Computations

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A brief introduction to Generalised Partons Distributions (GPDs)

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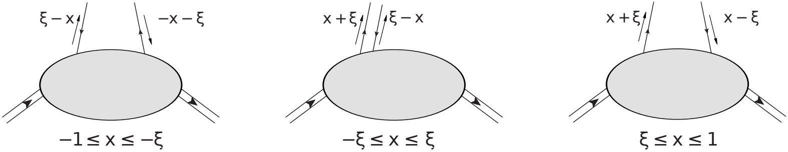
  - "hadron-parton" amplitudes which depend on three variables (x, ξ, t) and a scale μ,



- ★ x: average momentum fraction carried by the active parton
- ★ ξ: skewness parameter $\xi \simeq \frac{x_B}{2-x_B}$
- ★ t: the Mandelstam variable

- Generalised Parton Distributions (GPDs):
  - "hadron-parton" amplitudes which depend on three variables (x, ξ, t) and a scale μ,
  - are defined in terms of a non-local matrix elements,

$$\frac{1}{2}\int \frac{e^{ixP^+z^-}}{2\pi}\langle P+\frac{\Delta}{2}|\bar{\psi}^q(-\frac{z}{2})\gamma^+\psi^q(\frac{z}{2})|P-\frac{\Delta}{2}\rangle \mathrm{d}z^-|_{z^+=0,\mathbf{z}=0}$$
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}\gamma^+u + E^q(x,\xi,t)\bar{u}\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u\right].$$

$$\frac{1}{2}\int \frac{e^{ixP^+z^-}}{2\pi}\langle P+\frac{\Delta}{2}|\bar{\psi}^q(-\frac{z}{2})\gamma^+\gamma_5\psi^q(\frac{z}{2})|P-\frac{\Delta}{2}\rangle \mathrm{d}z^-|_{z^+=0,\mathbf{z}=0}$$
$$= \frac{1}{2P^+}\left[\tilde{H}^q(x,\xi,t)\bar{u}\gamma^+\gamma_5 u + \tilde{E}^q(x,\xi,t)\bar{u}\frac{\gamma_5\Delta^+}{2M}u\right].$$

D. Müller *et al.*, Fortsch. Phy. 42 101 (1994)
X. Ji, Phys. Rev. Lett. **78**, 610 (1997)
A. Radyushkin, Phys. Lett. **B380**, 417 (1996)

4 GPDs without helicity transfer + 4 helicity flip GPDs

Generalised Parton Distributions

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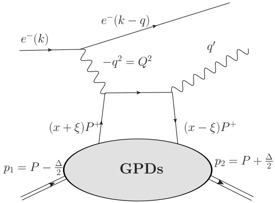
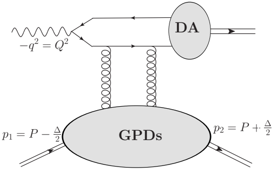
  - can be split into quark flavour and gluon contributions,
  - are related to PDF in the forward limit $H(x, \xi = 0, t = 0; \mu) = q(x; \mu)$
  - are universal, *i.e.* are related to the Compton Form Factors (CFFs) of various exclusive processes through convolutions

$$\mathcal{H}(\xi, t) = \int \mathrm{d}x \; C(x, \xi) H(x, \xi, t)$$





Properties

- Polynomiality property:

$$\int_{-1}^{1} \mathrm{d}x\, x^m H^q(x,\xi,t;\mu) = \sum_{j=0}^{\left[\frac{m}{2}\right]} \xi^{2j} C^q_{2j}(t;\mu) + mod(m,2)\xi^{m+1} C^q_{m+1}(t;\mu)$$

X. Ji, J.Phys.G 24 (1998) 1181-1205
A. Radyushkin, Phys.Lett.B 449 (1999) 81-88

Special case :

$$\int_{-1}^{1} \mathrm{d}x\; H^q(x,\xi,t;\mu) = F^q_1(t)$$

Lorentz Covariance

Properties

- Polynomiality property:

Lorentz Covariance

- Positivity property:

$$\left|H^q(x,\xi,t) - \frac{\xi^2}{1-\xi^2}E^q(x,\xi,t)\right| \leq \sqrt{\frac{q\left(\frac{x+\xi}{1+\xi}\right)q\left(\frac{x-\xi}{1-\xi}\right)}{1-\xi^2}}$$

A. Radysuhkin, Phys. Rev. **D59**, 014030 (1999)
B. Pire *et al.*, Eur. Phys. J. **C8**, 103 (1999)
M. Diehl *et al.*, Nucl. Phys. **B596**, 33 (2001)
P.V. Pobilitsa, Phys. Rev. **D65**, 114015 (2002)

Positivity of Hilbert space norm

Properties

- Polynomiality property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

- Support property:

$$x \in [-1; 1]$$

M. Diehl and T. Gousset, Phys. Lett. **B428**, 359 (1998)

Relativistic quantum mechanics

Properties

- Polynomiality property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

- Support property:

Relativistic quantum mechanics

- Scale evolution property
  $\rightarrow$ generalization of DGLAP and ERBL evolution equations

D. Müller *et al.*, Fortschr. Phys. 42, 101 (1994)

Renormalization

Properties

- Polynomiality property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

- Support property:

Relativistic quantum mechanics

- Scale evolution property

Renormalization

Challenge

Fullfilling all these property is a challenge
for both modelling and lattice computations

Modelling GPDs

Double Distribution Modeling

- GPDs are related to Double Distributions (DDs) through:

$$H(x,\xi,t) = \int_\Omega \mathrm{d}\beta \mathrm{d}\alpha \left(F(\beta,\alpha,t) + \xi G(\beta,\alpha,t) \right) \delta\left(x - \beta - \xi\alpha \right)$$

The Dirac δ insures that the polynomiality is fulfilled, independently of our choice of F and G

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- DDs have been widely used for phenomenological purposes (VGG, GK...)
- They also appear naturally in covariant modelling attempts

Positivity property is not guaranteed, and may be violated.

- On the light front, hadronic states can be expanded on a Fock basis:

$$|P,\pi\rangle \propto \sum_\beta \Phi_\beta^{q\bar{q}}|q\bar{q}\rangle + \sum_\beta \Phi_\beta^{q\bar{q},q\bar{q}}|q\bar{q},q\bar{q}\rangle + \dots$$

$$|P,N\rangle \propto \sum_\beta \Phi_\beta^{qqq}|qqq\rangle + \sum_\beta \Phi_\beta^{qqq,q\bar{q}}|qqq,q\bar{q}\rangle + \dots$$

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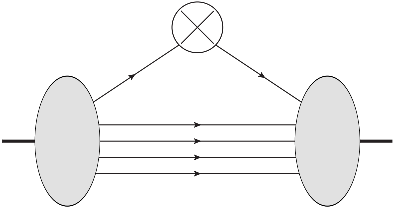
- Non-perturbative physics is contained within the N-particle LFWFs Φ^N
- This formalism allows to recover the probabilistic picture of non-relativistic quantum mechanics

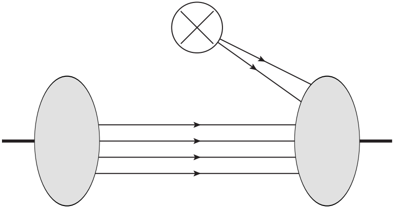
- On the light front, hadronic states can be expanded on a Fock basis

DGLAP: $|x| > |\xi|$



- Same N LFWFs
- No ambiguity

ERBL: $|x| < |\xi|$



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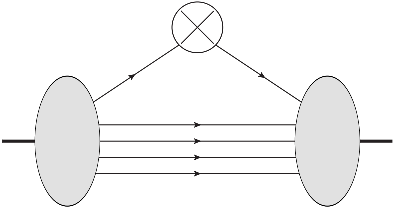

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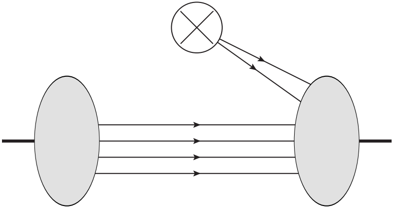

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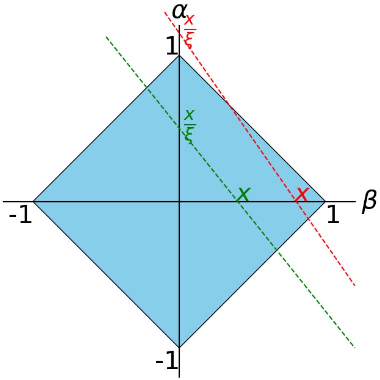
LFWFs formalism has the positivity property inbuilt but polynomiality is lost by truncating both in DGLAP and ERBL sectors.

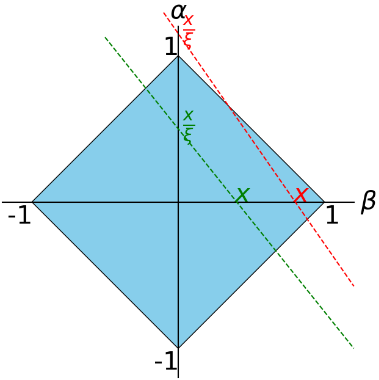
$$H(x,\xi) = \int_\Omega \mathrm{d}\beta \mathrm{d}\alpha \delta(x-\beta-\alpha\xi)\left[F(\beta,\alpha)+\xi G(\beta,\alpha)\right]$$



- DGLAP (red) and ERBL (green) lines cut $\beta = 0$ outside or inside the square
- Every point $(\beta \neq 0, \alpha)$ contributes **both** to DGLAP and ERBL regions
- For every point $(\beta \neq 0, \alpha)$ we can draw an infinite number of DGLAP lines.

Intuitive picture

$$H(x,\xi) = \int_\Omega \mathrm{d}\beta \mathrm{d}\alpha \delta(x - \beta - \alpha\xi) \left[F(\beta,\alpha) + \xi G(\beta,\alpha)\right]$$



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Is it possible to recover the DDs from the DGLAP region only?

GPD properties from Radon Transform

- Double Distribution representation:

$$H(x,\xi) = D(x/\xi) + \int_\Omega \mathrm{d}\beta \mathrm{d}\alpha \delta(x - \beta - \alpha\xi) F_D(\beta,\alpha)$$

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- Since DD are compactly supported, we can use the **Boman and Todd-Quinto theorem** which tells us

$$H(x,\xi) = 0 \quad \text{for} \quad (x,\xi) \in \text{DGLAP} \Rightarrow F_D(\beta,\alpha) = 0 \quad \text{for all} \quad (\beta \neq 0, \alpha) \in \Omega$$

Boman and Todd-Quinto, Duke Math. J. 55, 943 (1987)

insuring the uniqueness of the extension up to D-term like terms.

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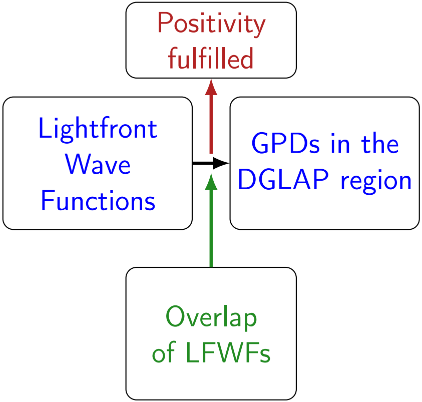
New modeling strategy

- Compute the DGLAP region through overlap of LFWFs
  $\Rightarrow$ **fulfilment of the positivity property**
- Extension to the ERBL region using the Radon inverse transform
  $\Rightarrow$ **fulfilment of the polynomiality property**

A new modelling procedure

Lightfront
Wave
Functions

A new modelling procedure



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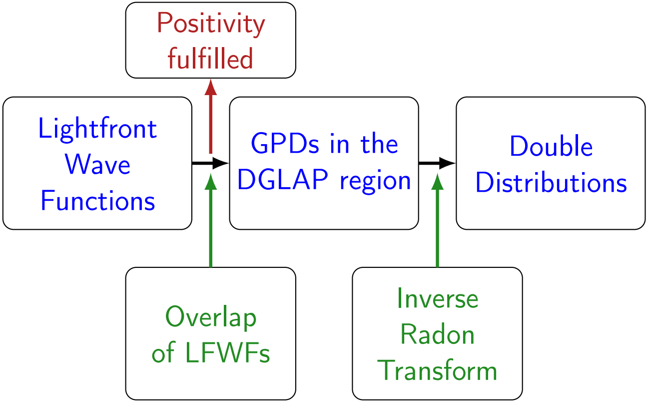

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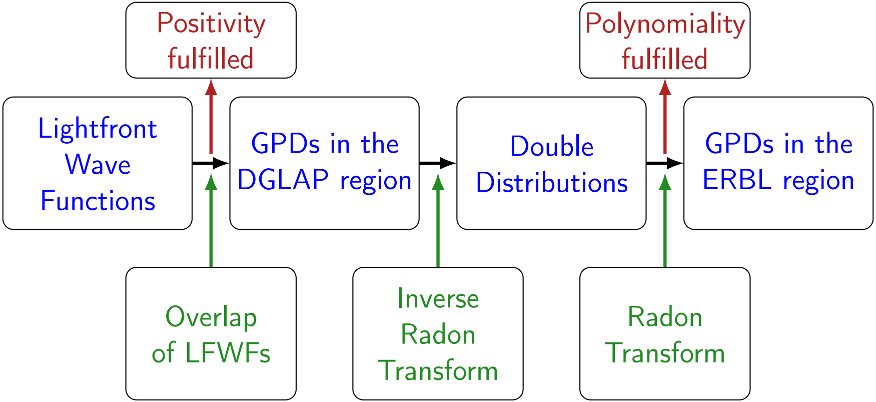

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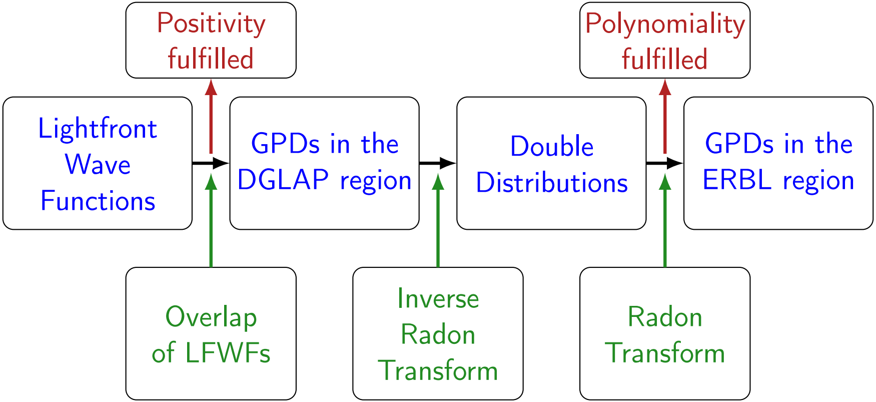
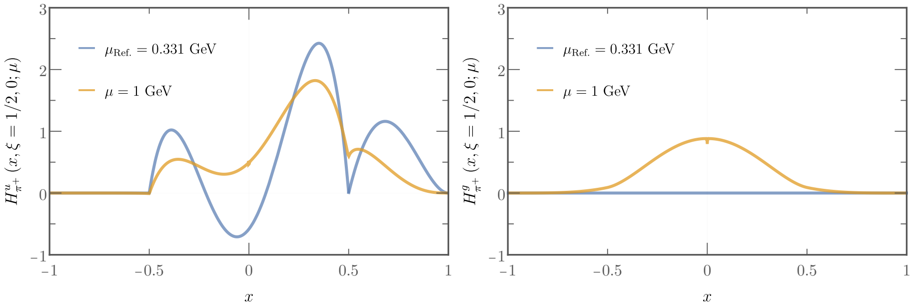


Not necessary to start from LFWFs

$\rightarrow$ Fulfilling the positivity and forward limit properties is enough

An example on the pion

Morgado *et al.*, in preparation



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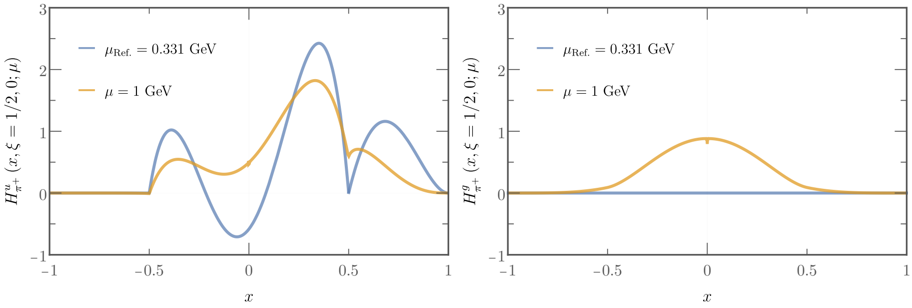

All theoretical constraints are fulfilled by construction !

An example on the pion

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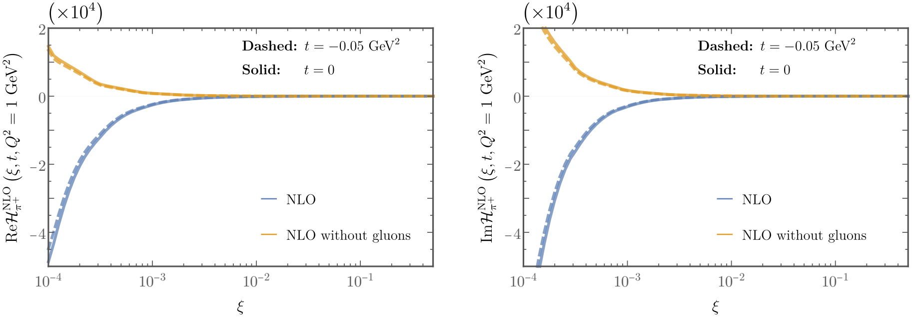

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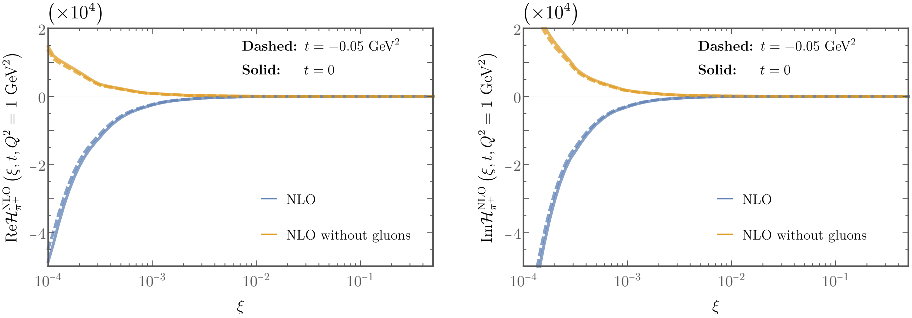

- The PARTONS framework allows us to study DVCS on virtual pion at LO (Sullivan process)
- Gluon in the pion dominates at EIC kinematics as expected
- Sullivan process measurable at EIC

Lattice QCD computations

- Lattice computation living in euclidean space "time-like" and "light-like" four vectors are not directly reachable
- Instead of computing matrix element of non-local operators, focus on local operators

$$n_\mu n_{\mu_1} \dots n_{\mu_n} \langle P | \bar{\psi}(0) \gamma^{\{\mu} \overleftrightarrow{D}^{\mu_1} \dots \overleftrightarrow{D}^{\mu_n\}} \psi(0) | P \rangle \propto \int \mathrm{d}x x^n q(x)$$

- Results on Mellin moments have been obtained for GPDs
  - Electromagnetic Form Factors
  - Axial Form Factors
  - Gravitational Form Factors

Difficulty with local operators

- In principle, one could compute local operator of degree as high as required
- In practice difficulties arise:
  - above $n = 3$ operators start mixing among them due to the breaking of rotational invariance $O(4)$ into a smaller symmetry group $H(4)$
  - This introduces power-like singularities in the lattice spacing which need to be treated non-perturbatively for each operator

see e.g. S. Capitani and G. Rossi, Nucl.Phys.B 433 (1995) 351-389

- In practice, only the first Mellin moments (n=1,2) are computed on the lattice
  $\rightarrow$ this compromises access to the x-dependence of the distributions through moments

Going beyond local operators

- Some approaches have been developed in the 2000s to try to by-pass this issue

see *e.g.* K. Cichy and M. Constantinou, Adv.High Energy Phys. 2019 (2019) 3036904

  - Direct computation of the hadronic tensor
  - Use of auxiliary quarks to "tame" divergences

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- In the last 10 years new approaches arose to compute PDF:
  - Large-Momentum Effective field theory (LaMET - quasi PDF-)
  - Ioffe-time pseudo distributions
  - OPE without OPE
  - Good Lattice cross section

X. Ji Phys. Rev. Lett., 2013, 110, 262002
Y.-Q. Ma and J.-W. Qiu Phys. Rev. D, 2018, 98, 074021
A. Radyushkin, Phys. Rev. D, 2017, 96, 034025
A. J. Chambers *et al.*, PRL 118 242001 (2017)

LaMET (quasi-PDF)

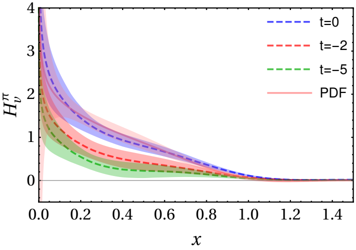
- Define non-local matrix element along a spatial direction:

$$\tilde{q}(\tilde{x}, P_3) = \int_{-\infty}^{\infty} \frac{\mathrm{d}z_3}{4\pi} e^{-iz_3\tilde{x}P_3} \langle p|\bar{\psi}(z_3)\gamma^3\mathcal{W}(z_3,0)\psi(0)|p\rangle$$

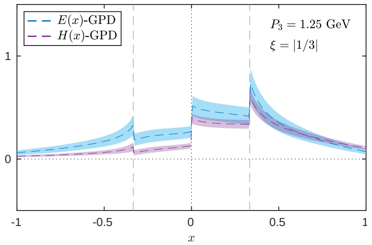
- Boost the hadron in a frame where $P_3^2 \gg \Lambda_{QCD}^2$ and $P_3^2 \gg M_H^2$
- Expand the quasi-PDF in terms of the Lightcone one plus corrections:

$$\tilde{q}(\tilde{x}, P_3, \mu^2) = \int_{-1}^{1} \frac{\mathrm{d}y}{|y|} C\left(\frac{x}{y}, \frac{\mu^2}{P_3^2}\right) q(y,\mu^2) + O\left(\frac{\Lambda_{QCD}^2}{P_3^2}, \frac{M_H^2}{P_3^2}\right)$$

- For $P_3 \to \infty$ one expects to recover the PDF through the matching condition
- Technical difficulties : linear divergences needs to be identified and subtracted (cut off in momentum space)
- The same formalism can be applied to GPDs

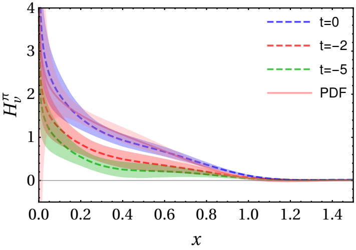


J.-W. Chen Nucl.Phys.B 952 (2020) 114940

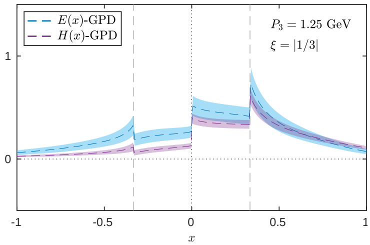


C. Alexandrou *et al.*, PRL 125 (2020) 26, 262001

- Pioneering works



J.-W. Chen Nucl.Phys.B 952 (2020) 114940



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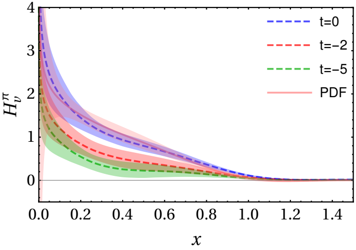
- Pioneering works
- Issues 1 large-x region
  - Support property violated ("by construction")
  - Positivity property violated



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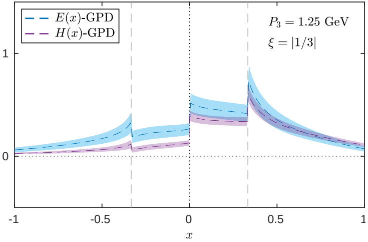

C. Alexandrou *et al.*, PRL 125 (2020) 26, 262001

- Pioneering works
- Issues 1 large-x region
  - Support property violated (“by construction”)
  - Positivity property violated
- Issues 2 crossover line $|x| = |\xi|$
  - Discontinuity $\rightarrow$ violation of factorisation theorem
  - Higher-twist pollution?

Pseudo-distributions

- Define a distribution with depending of Lorentz scalar quantities:

$$\mathcal{M}(\nu, -z^2) = \langle p|\bar{\psi}(-z)\gamma^{\alpha}\psi(z)|p\rangle \quad \text{with} \quad \nu = -p\cdot z$$

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- Taking $\alpha = 0$ and $z = (0, 0, 0, z_3)$, one can define de pseudo-distributions with the expected support in x:

$$\mathcal{P}(x, z_3^2) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \mathrm{d}\nu e^{-ix\nu}\mathcal{M}(\nu, z_3^2) \quad \text{with} \quad \mathcal{P}(x, 0) = q(x)$$

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- Issues with divergencies on the lattice bypass by the definition of RGI reduced distribution $\mathfrak{M}$:

$$\mathfrak{M}(\nu, z^2) = \frac{\mathcal{M}(\nu, z_3^2)}{\mathcal{M}(0, z_3^2)} \quad \rightarrow \quad \text{Good behaviour for } z_3^2 \rightarrow 0$$

- Define a distribution with depending of Lorentz scalar quantities:

$$\mathcal{M}(\nu, -z^2) = \langle p|\bar{\psi}(-z)\gamma^\alpha\psi(z)|p\rangle \quad \text{with} \quad \nu = -p \cdot z$$

- Taking $\alpha = 0$ and $z = (0, 0, 0, z_3)$, one can define de pseudo-distributions with the expected support in x:

$$\mathcal{P}(x, z_3^2) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \mathrm{d}\nu e^{-ix\nu}\mathcal{M}(\nu, z_3^2) \quad \text{with} \quad \mathcal{P}(x, 0) = q(x)$$

- Issues with divergencies on the lattice bypass by the definition of RGI reduced distribution $\mathfrak{M}$:

$$\mathfrak{M}(\nu, z^2) = \frac{\mathcal{M}(\nu, z_3^2)}{\mathcal{M}(0, z_3^2)} \quad \rightarrow \quad \text{Good behaviour for } z_3^2 \rightarrow 0$$

- Matching condition given on $\mathfrak{M}$

Rossi-Testa argument

- Criticisms were formulated by G. Rossi and M. Testa

see G. Rossi and M. Testa, PRD 98 (2018) 5, 054028

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Not being an expert, I remain neutral here

Conclusions

Summary

- After 25 years, GPDs formalism is well established . . .
- . . . but the GPDs themselves remain poorly known
- Modelling GPDs is challenging because of all theoretical constraints
- Lattice QCD starts going beyond few moments but difficulties remain

Perspectives

- Significant efforts in phenomenology remain be done (CFF and GPD)
- Exploiting models built to fulfill all theoretical constrains
- What lattice QCD could bring remains to be clarified

In the perspective of EIC and EICC, a lot of work remains to be done to exploit the forthcoming data.

Thank you for your attention