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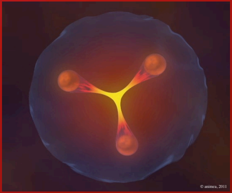

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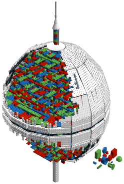
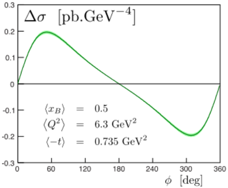
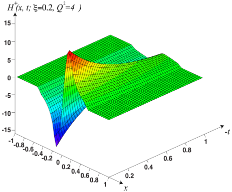
Representations of Generalized Parton Distributions in the Dyson-Schwinger Formalism





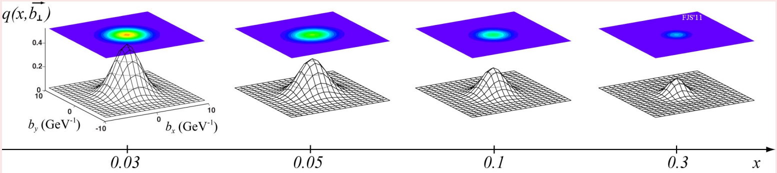


Few-Body Problems 2015 | Hervé MOUTARDE

May 19$^{\mathrm{th}}$, 2015

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in the nucleon.
- Insights on:
  - **Spin** structure,
  - **Energy-momentum** structure.
- **Probabilistic interpretation** of Fourier transform of GPD$(x, \xi = 0, t)$ in **transverse plane**.

Transverse plane density (Goloskokov and Kroll model)



- Important topic for several **past, existing and future** experiments: H1, ZEUS, HERMES, CLAS, CLAS12, JLab Hall A, COMPASS, EIC, ...
- GPD modeling / parameterizing is an essential ingredient for the interpretation of experimental data.
- **Recent applications** of the Dyson-Schwinger and Bethe-Salpeter framework to **hadron structure studies**.

- Important topic for several **past, existing and future** experiments: H1, ZEUS, HERMES, CLAS, CLAS12, JLab Hall A, COMPASS, EIC, ...
- GPD modeling / parameterizing is an essential ingredient for the interpretation of experimental data.
- **Recent applications** of the Dyson-Schwinger and Bethe-Salpeter framework to **hadron structure studies**.

- Here develop **pion GPD model** for simplicity.
- No planned experiment on pion GPDs but existing proposal of DVCS on a virtual pion.

Amrath *et al.*, Eur. Phys. J. **C58**, 179 (2008)

Overview.

Development of a new GPD model in the Dyson-Schwinger and Bethe-Salpeter framework.

- Important topic for several **past, existing and future** experiments: H1, ZEUS, HERMES, CLAS, CLAS12, JLab Hall A, COMPASS, EIC, ...
- GPD modeling / parameterizing is an essential ingredient for the interpretation of experimental data.
- **Recent applications** of the Dyson-Schwinger and Bethe-Salpeter framework to **hadron structure studies**.

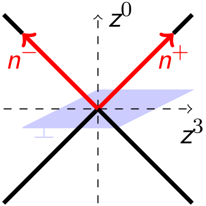
Steps towards a **pion GPD** model:

1. GPDs: Theoretical Framework
2. GPDs in the Dyson-Schwinger and Bethe-Salpeter Approach
3. Results: Theoretical Constraints and Phenomenology

GPDs: Theoretical Framework

$$H^q_\pi(x,\xi,t) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P+\frac{\Delta}{2} \middle| \bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right) \middle| \pi, P-\frac{\Delta}{2} \right\rangle_{\substack{z^+=0\\ z_\perp=0}}$$

with $t = \Delta^2$ and $\xi = -\Delta^+/(2P^+)$.



References

Müller *et al.*, Fortschr. Phys. **42**, 101 (1994)
Ji, Phys. Rev. Lett. **78**, 610 (1997)
Radyushkin, Phys. Lett. **B380**, 417 (1996)

- From **isospin symmetry**, all the information about pion GPD is encoded in $H^u_{\pi^+}$ and $H^d_{\pi^+}$.
- Further constraint from **charge conjugation**: $H^u_{\pi^+}(x,\xi,t) = -H^d_{\pi^+}(-x,\xi,t)$.

- PDF **forward limit**

$$H^q(x, 0, 0) = q(x)$$

- PDF **forward limit**
- Form factor **sum rule**

$$\int_{-1}^{+1} dx\, H^q(x, \xi, t) = F_1^q(t)$$

- PDF **forward limit**
- Form factor **sum rule**
- **Polynomiality**

$$\int_{-1}^{+1} dx\, x^n H^q(x, \xi, t) = \text{polynomial in } \xi$$

- PDF **forward limit**
- Form factor **sum rule**
- **Polynomiality**
- **Positivity**

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

- PDF **forward limit**
- Form factor **sum rule**
- **Polynomiality**
- **Positivity**
- H^q is an **even function** of ξ from time-reversal invariance.

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- H^q is an **even function** of ξ from time-reversal invariance.
- H^q is **real** from hermiticity and time-reversal invariance.

- PDF **forward limit**
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- H^q is an **even function** of ξ from time-reversal invariance.
- H^q is **real** from hermiticity and time-reversal invariance.
- H^q has support $x \in [-1, +1]$.

Properties.

Generalization of form factors and Parton Distribution Functions.

- PDF **forward limit**
- Form factor **sum rule**
- **Polynomiality**
- **Positivity**
- H^q is an **even function** of ξ from time-reversal invariance.
- H^q is **real** from hermiticity and time-reversal invariance.
- H^q has support $x \in [-1, +1]$.
- **Soft pion theorem** (pion target)

$$H^q(x, \xi = 1, t = 0) = \frac{1}{2}\phi_\pi^q\left(\frac{1+x}{2}\right)$$

- PDF **forward limit**
- Form factor **sum rule**
- **Polynomiality**
- **Positivity**
- H^q is an **even function** of ξ from time-reversal invariance.
- H^q is **real** from hermiticity and time-reversal invariance.
- H^q has support $x \in [-1, +1]$.
- **Soft pion theorem** (pion target)

Numerous theoretical constraints on GPDs.

- There is no known GPD parameterization **relying only on first principles**.
- Modeling becomes a key issue.

Polynomiality.

Mixed constraint from Lorentz invariance and discrete symmetries.

- Introduce **isovector** and **isoscalar** GPDs:

$$
\begin{aligned}
H^{I=0}(x,\xi,t) &= H^u_{\pi^+}(x,\xi,t) + H^d_{\pi^+}(x,\xi,t) \\
H^{I=1}(x,\xi,t) &= H^u_{\pi^+}(x,\xi,t) - H^d_{\pi^+}(x,\xi,t)
\end{aligned}
$$

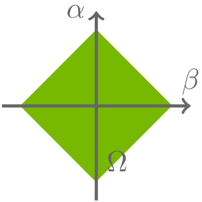
- Compute Mellin moments of GPDs:

$$
\begin{aligned}
\int_{-1}^{1} \mathrm{d}x\, x^m H^{I=0}(x,\xi) &= 0 \ (m \text{ even}) \\
\int_{-1}^{1} \mathrm{d}x\, x^m H^{I=0}(x,\xi) &= \sum_{\substack{i=0 \\ \text{even}}}^{m} (2\xi)^i C^{I=0}_{mi} + (2\xi)^{m+1} C^{I=0}_{m\,m+1} \ (m \text{ odd}) \\
\int_{-1}^{1} \mathrm{d}x\, x^m H^{I=1}(x,\xi) &= \sum_{\substack{i=0 \\ \text{even}}}^{m} (2\xi)^i C^{I=1}_{mi} \ (m \text{ even}) \\
\int_{-1}^{1} \mathrm{d}x\, x^m H^{I=1}(x,\xi) &= 0 \ (m \text{ odd})
\end{aligned}
$$

- Define Double Distributions F^q and G^q as matrix elements of **twist-2 quark operators**:

$$\left\langle P+\frac{\Delta}{2}\middle|\bar{q}(0)\gamma^{\{\mu}i\overset{\leftrightarrow}{D}{}^{\mu_1}\dots i\overset{\leftrightarrow}{D}{}^{\mu_m\}}q(0)\middle|P-\frac{\Delta}{2}\right\rangle = \sum_{k=0}^{m}\binom{m}{k}$$

$$\left[F^q_{mk}(t)2P^{\{\mu}-G^q_{mk}(t)\Delta^{\{\mu}\right]P^{\mu_1}\dots P^{\mu_{m-k}}\left(-\frac{\Delta}{2}\right)^{\mu_{m-k+1}}\dots\left(-\frac{\Delta}{2}\right)^{\mu_m\}}$$



with

$$F^q_{mk} = \int_\Omega \mathrm{d}\beta\mathrm{d}\alpha\,\alpha^k\beta^{m-k}F^q(\beta,\alpha)$$

$$G^q_{mk} = \int_\Omega \mathrm{d}\beta\mathrm{d}\alpha\,\alpha^k\beta^{m-k}G^q(\beta,\alpha)$$

Müller *et al.*, Fortschr. Phys. **42**, 101 (1994)
Radyushkin, Phys. Rev. **D59**, 014030 (1999)
Radysuhkin, Phys. Lett. **B449**, 81 (1999)

- Representation of GPD:

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

- Support property: $x \in [-1,+1]$.
- Discrete symmetries: F^q is α-even and G^q is α-odd.

- Decompose an hadronic state $|H; P, \lambda\rangle$ in a Fock basis:

$$|H; P, \lambda\rangle = \sum_{N,\beta} \int [\mathrm{d}x\mathrm{d}\mathbf{k}_\perp]_N \psi_N^{(\beta,\lambda)}(x_1, \mathbf{k}_{\perp 1}, \ldots, x_N, \mathbf{k}_{\perp N}) \, |\beta, k_1, \ldots, k_N\rangle$$

- Derive an expression for the pion GPD in the DGLAP region $\xi \leq x \leq 1$:

$$H^q(x, \xi, t) \propto \sum_{\beta,j} \int [\mathrm{d}\bar{x}\mathrm{d}\bar{\mathbf{k}}_\perp]_N \delta_{j,q} \delta(x - \bar{x}_j) \big(\psi_N^{(\beta,\lambda)}\big)^* (\hat{x}', \hat{\mathbf{k}}'_\perp) \psi_N^{(\beta,\lambda)}(\tilde{x}, \tilde{\mathbf{k}}_\perp)$$

  with $\tilde{x}, \tilde{\mathbf{k}}_\perp$ (resp. $\hat{x}', \hat{\mathbf{k}}'_\perp$) generically denoting incoming (resp. outgoing) parton kinematics.

  Diehl *et al.*, Nucl. Phys. **B596**, 33 (2001)

- Similar expression in the ERBL region $-\xi \leq x \leq \xi$, but with overlap of N- and $(N+2)$-body LFWF.

Overlap representation.

Advantages and drawbacks.

- Physical picture.
- Positivity relations are fulfilled **by construction**.
- Implementation of **symmetries of N-body problems**.

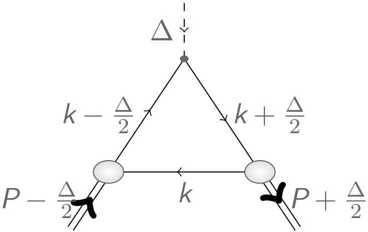
What is not obvious anymore

What is *not* obvious to see from the wave function representation is however the **continuity of GPDs at** $x = \pm\xi$ and the **polynomiality** condition. In these cases both the DGLAP and the ERBL regions must cooperate to lead to the required properties, and this implies **nontrivial relations between the wave functions** for the different Fock states relevant in the two regions. An *ad hoc* Ansatz for the wave functions would **almost certainly lead** to GPDs that **violate the above requirements**.

Diehl, Phys. Rept. **388**, 41 (2003)

GPDs in the Dyson-Schwinger and Bethe-Salpeter Approach

$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \left| \bar{q}(0) \gamma^+ (i \overleftrightarrow{D}^+)^m q(0) \right| \pi, P - \frac{\Delta}{2} \right\rangle$$

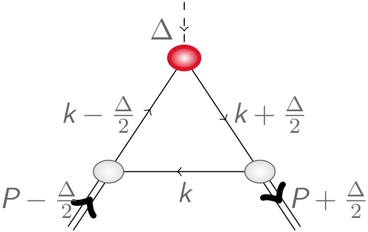


- Compute **Mellin moments** of the pion GPD H.

GPDs in the rainbow ladder approximation.

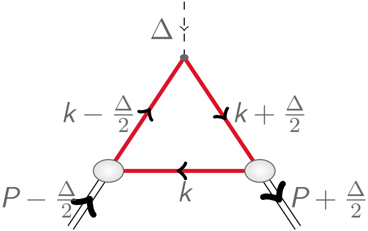
Evaluation of triangle diagrams.

$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \middle| \bar{q}(0)\gamma^+ (i\overleftrightarrow{D}^+)^m q(0) \middle| \pi, P - \frac{\Delta}{2} \right\rangle$$



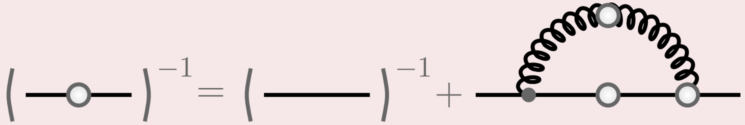
- Compute **Mellin moments** of the pion GPD H.
- Triangle diagram approx.

$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \middle| \bar{q}(0)\gamma^+ (i\overleftrightarrow{D}^+)^m q(0) \middle| \pi, P - \frac{\Delta}{2} \right\rangle$$

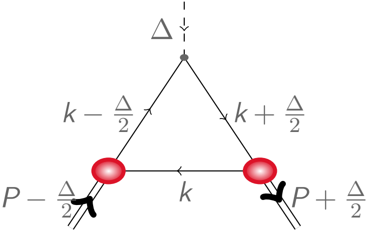


- Compute **Mellin moments** of the pion GPD H.
- Triangle diagram approx.
- Resum **infinitely many** contributions.

Dyson - Schwinger equation

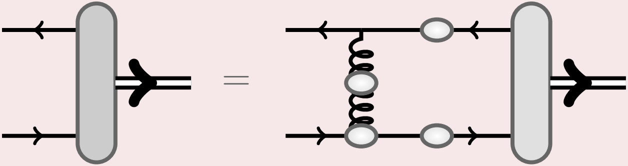


$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \middle| \bar{q}(0)\gamma^+(i\overleftrightarrow{D}^+)^m q(0) \middle| \pi, P - \frac{\Delta}{2} \right\rangle$$

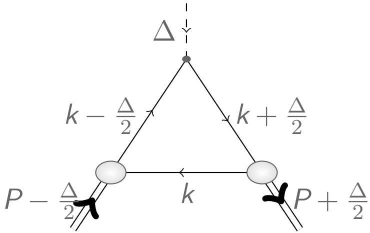


- Compute **Mellin moments** of the pion GPD H.
- Triangle diagram approx.
- Resum **infinitely many** contributions.

Bethe - Salpeter equation



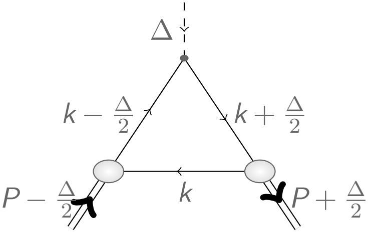
$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P+\frac{\Delta}{2} \middle| \bar{q}(0)\gamma^+(i\overleftrightarrow{D}^+)^m q(0) \middle| \pi, P-\frac{\Delta}{2} \right\rangle$$



- Compute **Mellin moments** of the pion GPD H.
- Triangle diagram approx.
- Resum **infinitely many** contributions.
- **Nonperturbative** modeling.

- Most GPD properties **satisfied by construction**.

$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \left| \bar{q}(0) \gamma^+ (i \overleftrightarrow{D}^+)^m q(0) \right| \pi, P - \frac{\Delta}{2} \right\rangle$$



- Compute **Mellin moments** of the pion GPD H.
- Triangle diagram approx.
- Resum **infinitely many** contributions.
- **Nonperturbative** modeling.

- Most GPD properties **satisfied by construction**.
- Also compute crossed triangle diagram.

Mezrag *et al.*, arXiv:1406.7425 [hep-ph] and Phys. Lett. **B741**, 190 (2015)

Algebraic model.

Intermediate step before using numerical solutions of Dyson-Schwinger and Bethe-Salpeter equations.

- Expression for GPD Mellin moments:

$$2(P^+)^{m+1}\langle x^m\rangle^u = \mathrm{tr}_{CFD}\int\frac{\mathrm{d}^4k}{(2\pi)^4}(k^+)^m\, i\Gamma_\pi\left(k-\frac{\Delta}{2},P-\frac{\Delta}{2}\right)$$
$$\times S(k-\frac{\Delta}{2})i\gamma^+\, S(k+\frac{\Delta}{2})i\bar{\Gamma}_\pi\left(k+\frac{\Delta}{2},P+\frac{\Delta}{2}\right)S(k-P)$$

- Expressions for vertices and propagators:

$$S(p) = \left[-i\gamma\cdot p+M\right]\Delta_M(p^2)$$
$$\Delta_M(s) = \frac{1}{s+M^2}$$
$$\Gamma_\pi(k,p) = i\gamma_5\frac{M}{f_\pi}M^{2\nu}\int_{-1}^{+1}\mathrm{d}z\,\rho_\nu(z)\,\left[\Delta_M(k_{+z}^2)\right]^\nu$$
$$\rho_\nu(z) = R_\nu(1-z^2)^\nu$$

with R_ν a normalization factor and $k_{+z}=k-p(1-z)/2$.

Chang *et al.*, Phys. Rev. Lett. **110**, 132001 (2013)

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\rho_\nu(z) &= R_\nu (1 - z^2)^\nu
\end{aligned}
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with R_ν a normalization factor and $k_{+z} = k - p(1 - z)/2$.

Chang *et al.*, Phys. Rev. Lett. **110**, 132001 (2013)

- Only two parameters:

Algebraic model.

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$$

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Chang *et al.*, Phys. Rev. Lett. **110**, 132001 (2013)

- Only two parameters:
  - Dimensionful parameter M.

Algebraic model.

Intermediate step before using numerical solutions of Dyson-Schwinger and Bethe-Salpeter equations.

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\rho_\nu(z) &= R_\nu (1 - z^2)^\nu
\end{aligned}
$$

  with R_ν a normalization factor and $k_{+z} = k - p(1-z)/2$.

  Chang *et al.*, Phys. Rev. Lett. **110**, 132001 (2013)

- Only two parameters:
  - Dimensionful parameter M.
  - Dimensionless parameter ν

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- Expressions for vertices and propagators:

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\rho_\nu(z) &= R_\nu (1 - z^2)^\nu
\end{aligned}
$$

  with R_ν a normalization factor and $k_{+z} = k - p(1-z)/2$.

  Chang *et al.*, Phys. Rev. Lett. **110**, 132001 (2013)

- Only two parameters:
  - Dimensionful parameter M.
  - Dimensionless parameter ν. **Fixed to 1** to recover asymptotic pion DA.

Results: Theoretical Constraints and Phenomenology

Verification of theoretical constraints.

Analytic expressions for the GPD H.

- **Analytic expression** in DGLAP and ERBL regions.

$$
\begin{aligned}
H^u_{x\geq\xi}(x,\xi,0) = \frac{48}{5}\Bigg\{ & \frac{3\left(-2(x-1)^4\left(2x^2-5\xi^2+3\right)\log(1-x)\right)}{20\left(\xi^2-1\right)^3} \\
& \frac{3\left(+4\xi\left(15x^2(x+3)+(19x+29)\xi^4+5(x(x(x+11)+21)+3)\xi^2\right)\tanh^{-1}\left(\frac{(x-1)\ldots}{x-\xi^2}\ldots\right.\right.}{20\left(\xi^2-1\right)^3} \\
& + \frac{3\left(x^3(x(2(x-4)x+15)-30)-15(2x(x+5)+5)\xi^4\right)\log\left(x^2-\xi^2\right)}{20\left(\xi^2-1\right)^3} \\
& + \frac{3\left(-5x(x(x(x+2)+36)+18)\xi^2-15\xi^6\right)\log\left(x^2-\xi^2\right)}{20\left(\xi^2-1\right)^3} \\
& + \frac{3\left(2(x-1)\left((23x+58)\xi^4+(x(x(x+67)+112)+6)\xi^2+x(x((5-2x)x+15)+3\ldots\right.\right.}{20\left(\xi^2-1\right)^3} \\
& + \frac{3\left(\left(15(2x(x+5)+5)\xi^4+10x(3x(x+5)+11)\xi^2\right)\log\left(1-\xi^2\right)\right)}{20\left(\xi^2-1\right)^3} \\
& + \frac{3\left(2x(5x(x+2)-6)+15\xi^6-5\xi^2+3\right)\log\left(1-\xi^2\right)}{20\left(\xi^2-1\right)^3}\Bigg\}
\end{aligned}
$$

- **Analytic expression** in DGLAP and ERBL regions.
- **Explicit check** of **support property** and **polynomiality** with correct powers of ξ.

- **Analytic expression** in DGLAP and ERBL regions.
- **Explicit check** of **support property** and **polynomiality** with correct powers of ξ.
- Also direct verification using Mellin moments of H.

Verification of theoretical constraints.

Analytic expressions for the GPD H.

- **Analytic expression** in DGLAP and ERBL regions.
- **Explicit check** of **support property** and **polynomiality** with correct powers of ξ.
- Also direct verification using Mellin moments of H.
- Soft pion theorem obtained by construction in a **symmetry-preserving** treatment.

Mezrag *et al.*, Phys. Lett. **B741**, 190 (2015)

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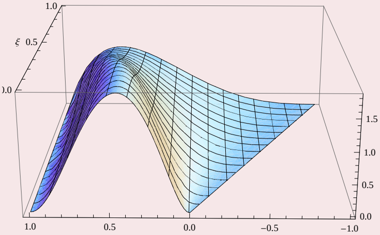
Mezrag *et al.*, Phys. Lett. **B741**, 190 (2015)

Valence $H^u(x, \xi, t)$ as a function of x and ξ at vanishing t.

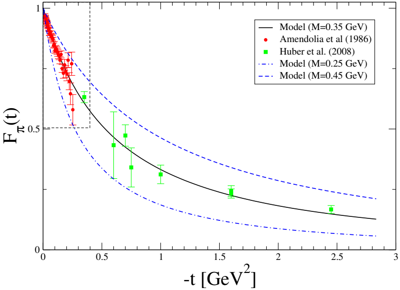


Mezrag *et al.*, arXiv:1406.7425 [hep-ph]

- Pion form factor obtained from isovector GPD:

$$\int_{-1}^{+1} \mathrm{d}x\, H^{I=1}(x, \xi, t) = 2F_\pi(t)$$

- Single dimensionful parameter $M \simeq 350$ MeV.



Mezrag *et al.*, arXiv:1406.7425 [hep-ph]

- Pion form factor obtained from isovector GPD:

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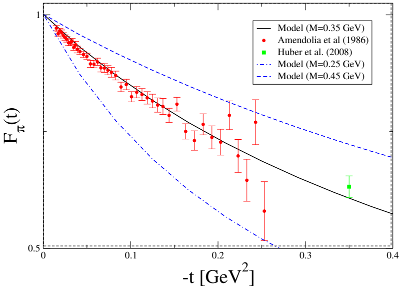

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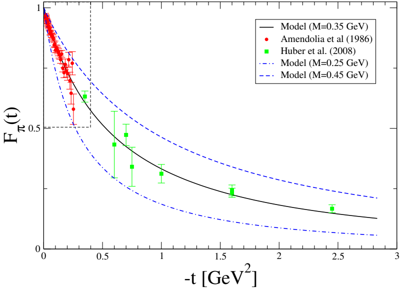

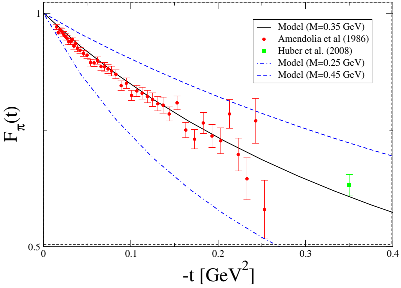

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Pion Parton Distribution Function.

Algebraic model in the overlap representation.

- Evaluate LFWF in algebraic model:

$$\psi(x, \mathbf{k}_\perp) \propto \frac{x(1-x)}{[(\mathbf{k}_\perp - x\mathbf{P}_\perp)^2 + M^2]^2}$$

- Expression for the GPD at $t = 0$:

$$H(x, \xi, 0) \propto \frac{(1-x)^2(x^2-\xi^2)}{(1-\xi^2)^2}$$

- Expression for the PDF:

$$q(x) = 30x^2(1-x)^2$$

- Compare to "naive" triangle diagram computation:

$$q(x) = \frac{72}{25}\Big((30 - 15x + 8x^2 - 2x^3)x^3 \log x$$
$$+ (3 + 2x^2)(1-x)^4 \log(1-x) + (3 + 15x + 5x^2 - 2x^3)x(1-x)\Big)$$

Chang *et al.*, Phys. Lett. **B737**, 23 (2014)

Conclusions

- Computation of GPDs, DDs, PDFs, LFWFs and form factors in the **nonperturbative framework** of Dyson-Schwinger and Bethe-Salpeter equations.
- **Explicit check** of several theoretical constraints, including polynomiality, support property and soft pion theorem.
- Simple algebraic model exhibits **most features of the numerical solutions** of the Dyson-Schwinger and Bethe-Salpeter equations.
- **Very good agreement** with existing pion form factor and PDF data.
- **Clear limits** of impulse approximation in the evaluation of quark twist-2 matrix elements.

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