Chiral-Odd Generalized Parton Distributions and Transversity in Light Front Constituent Quark Models

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Second Workshop on the QCD Structure of the Nucleon
(Monte Porzio Catone, ROME, 12-16 June)

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- Very few model calculations,
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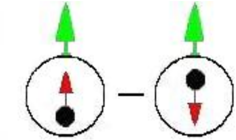
$$\mathcal{H}_T(x, 0, 0) = h_1(x) =$$



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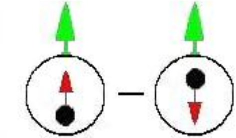

- Test of relativistic effects, i.e. $h_1(x) \neq g_1(x) \Rightarrow$

  Possibility of measure the relativistic nature of quarks inside the nucleon.

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$Q^2 \to \infty$, x_B fixed

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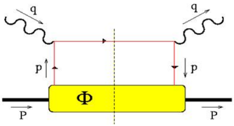

Compton **S**cattering Handbag
PDs

$$\Phi(p,P,S) = \int \frac{d^4z}{(2\pi)^4}\, e^{ip\cdot z} \times \langle PS|\bar{\psi}(0)\Gamma\psi(z)|PS\rangle$$

P,S = P',S'

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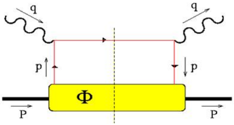

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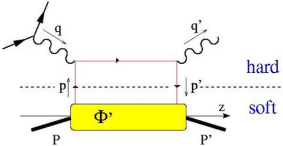
and
$t = (P - P')^2 \neq 0$

$\Rightarrow$ Not Forward Scattering



DVCS Handbag
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$$\Phi'(\bar{p}, P, P', S', S) = \int \frac{d^4 z}{(2\pi)^4}\, e^{i\bar{p}\cdot z} \times \langle P'S'|\bar{\psi}\left(-\frac{z}{2}\right)\Gamma\psi\left(\frac{z}{2}\right)|PS\rangle$$

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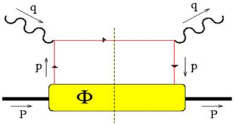

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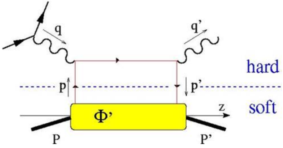

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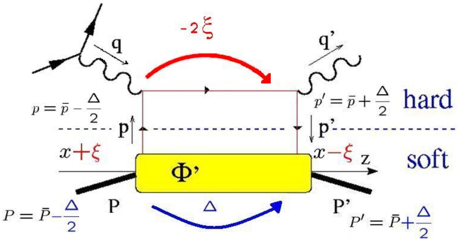
$\Rightarrow$ GPD $\doteq$ Nondiagonal hadronic matrix elements of bilocal products of the light-front quark field operators. Thus, they don't represent probability density (like PDF), but interference between amplitudes describing different quantum fluctuaction of a nucleon.

Kinematics and Correlation Functions



"Average Momentum" FRAME

- $\bar{P} = \frac{1}{2}(P+P') = (\bar{P}^+, \bar{P}^-, \mathbf{0}_\perp)$ "average momentum"
- $\xi = \frac{(P-P')^+}{(P+P')^+}$ "skewedness" (SPDs)
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Depending on which Γ structure we substitute $\Rightarrow$ 8 different GPDs:

Diehl, EPJ **C 19** '01

- Unpolarized GPDs $\Phi'^{[\gamma^+]} \Rightarrow \mathcal{H}(x,\xi,t)$ & $\mathcal{E}(x,\xi,t)$
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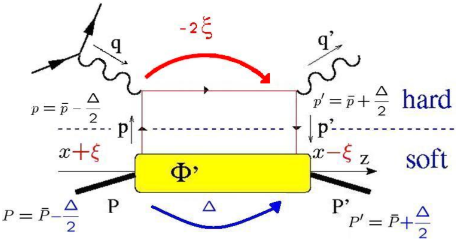

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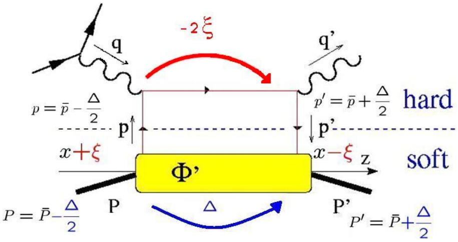

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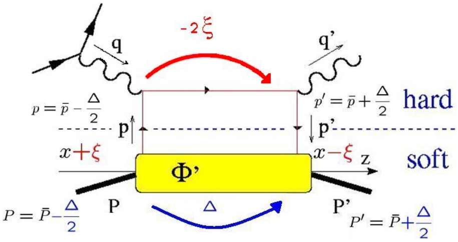

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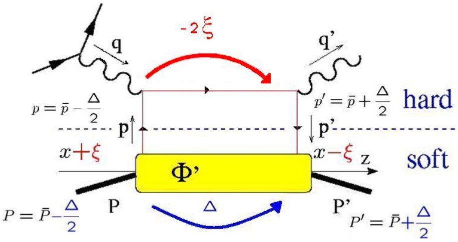

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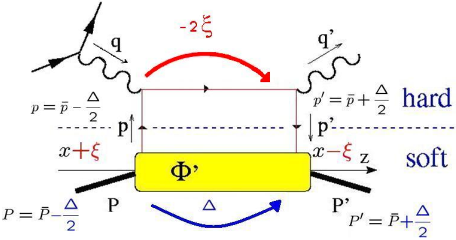

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GPDs with helicity flip (Chiral-odd)

$$\frac{1}{2}\int \frac{dz^-}{2\pi} e^{i\bar{x}P^+z^-} \langle p',\lambda'|\bar{\psi}(-z/2)\sigma^{+i}\gamma_5\psi(z/2)|p,\lambda\rangle|_{z^+=0,\vec{z}_\perp=0}$$

$$= \frac{1}{2P^+}\bar{u}(p',\lambda')\left[\mathcal{H}_T^q\sigma^{+i}\gamma_5 + \tilde{\mathcal{H}}_T^q\frac{\epsilon^{+i\alpha\beta}\Delta_\alpha P_\beta}{M^2} + \mathcal{E}_T^q\frac{\epsilon^{+i\alpha\beta}\Delta_\alpha\gamma_\beta}{2M} + \tilde{\mathcal{E}}_T^q\frac{\epsilon^{+i\alpha\beta}P_\alpha\gamma_\beta}{M}\right]u(p,\lambda)$$

GPDs can be related to the following helicity amplitudes

M. Diehl, EPJ **C 19**, ('01)

$$\mathbf{A}_{\lambda'+,\lambda-} = \int \frac{dz^-}{2\pi} e^{i\bar{x}P^+z^-}\langle p',\lambda'|\,\mathcal{O}_{+,-}(z)\,|p,\lambda\rangle\Big|_{z^+=0,\,\vec{z}_\perp=0}$$

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⇒ **CHIRAL-ODD Nature**

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(cont'ed)

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- $\mathbf{A}_{-+,--} = \epsilon \frac{(t_0-t)^{1/2}}{2M}[\tilde{\mathcal{H}}_T^q + (1+\xi)\frac{\mathcal{E}_T^q-\tilde{\mathcal{E}}_T^q}{2}]$
- $\mathbf{A}_{++,--} = (1-\xi^2)^{1/2}[\mathcal{H}_T^q + \frac{t_0-t}{4M^2}\tilde{\mathcal{H}}_T^q - \frac{\xi^2}{1-\xi^2}\mathcal{E}_T^q + \frac{\xi}{1-\xi^2}\tilde{\mathcal{E}}_T^q]$
- $\mathbf{A}_{-+,+-} = -(1-\xi^2)^{1/2}\frac{(t_0-t)}{4M^2}\tilde{\mathcal{H}}_T^q$

$\Longrightarrow$

Thus inverting:

- $\mathcal{E}_T^q = \frac{2M}{\epsilon\sqrt{t_0-t}}(\frac{1}{(1-\xi)}\mathbf{A}_{++,+-} + \frac{1}{(1+\xi)}\mathbf{A}_{-+,--})$
  $+ \frac{8M^2}{(t_0-t)(1-\xi^2)\sqrt{1-\xi^2}}\mathbf{A}_{-+,+-}$
- $\tilde{\mathcal{E}}_T^q = \frac{2M}{\epsilon\sqrt{t_0-t}}(\frac{1}{(1-\xi)}\mathbf{A}_{++,+-} - \frac{1}{(1+\xi)}\mathbf{A}_{-+,--})$
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- $\mathcal{H}_T^q = \frac{1}{\sqrt{1-\xi^2}}(\mathbf{A}_{++,--} + \mathbf{A}_{-+,+-})$
  $+ \frac{2M\xi}{\epsilon\sqrt{t_0-t}(1-\xi^2)}(\mathbf{A}_{-+,--} - \mathbf{A}_{++,+-})$
- $\tilde{\mathcal{H}}_T^q = \frac{-4M^2}{\sqrt{1-\xi^2}(t_0-t)}(\mathbf{A}_{-+,+-})$

(cont'ed)

$\Rightarrow$

- $\mathbf{A}_{++,+-} = \epsilon \frac{(t_0-t)^{1/2}}{2M}[\tilde{\mathcal{H}}_T^q + (1-\xi)\frac{\mathcal{E}_T^q + \tilde{\mathcal{E}}_T^q}{2}]$
- $\mathbf{A}_{-+,--} = \epsilon \frac{(t_0-t)^{1/2}}{2M}[\tilde{\mathcal{H}}_T^q + (1+\xi)\frac{\mathcal{E}_T^q - \tilde{\mathcal{E}}_T^q}{2}]$
- $\mathbf{A}_{++,--} = (1-\xi^2)^{1/2}[\mathcal{H}_T^q + \frac{t_0-t}{4M^2}\tilde{\mathcal{H}}_T^q - \frac{\xi^2}{1-\xi^2}\mathcal{E}_T^q + \frac{\xi}{1-\xi^2}\tilde{\mathcal{E}}_T^q]$
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Thus inverting:

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Change of base

Helicity Basis

$$\phi_R = P_R\phi = \frac{1}{\sqrt{2}}(1+\gamma_5)\phi$$

$$\phi_L = P_L\phi = \frac{1}{\sqrt{2}}(1-\gamma_5)\phi$$

Transversity Basis

$$\mathcal{Q}_\pm = \frac{1}{\sqrt{2}}(1 \pm \gamma^1\gamma_5)$$

$$\mathcal{Q}_+\phi \equiv \phi_\uparrow$$

$$\mathcal{Q}_-\phi \equiv \phi_\downarrow$$

Introducing the transversity basis also for the nucleon spin states, i.e.

$$|p,\uparrow\rangle = \frac{1}{\sqrt{2}}(|p,+\rangle + |p,-\rangle)$$

$$|p,\downarrow\rangle = \frac{1}{\sqrt{2}}(|p,+\rangle - |p,-\rangle)$$

and defining the following matrix elements

$$T^q_{\lambda_t'\lambda_t} = \langle p',\lambda_t'|\int\frac{dz^-}{2\pi}e^{i\bar{x}P^+z^-}\bar{\psi}(-z/2)\gamma^+\gamma^1\gamma_5\psi(z/2)|p,\lambda_t\rangle$$

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(cont'ed)

we find:

$\spadesuit$ $T^q_{\uparrow\uparrow} = -T^q_{\downarrow\downarrow}$ $\quad$ $T^q_{\uparrow\downarrow} = T^q_{\downarrow\uparrow}$

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"Parity invariance"

and in terms of the matrix elements "A"

$\star$ $T^q_{\uparrow\uparrow} = A_{++,--} + A_{-+,+-}$ $\quad$ $T^q_{\uparrow\downarrow} = A_{++,+-} - A_{-+,--}$

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Finally, we obtain the chiral-odd GPDs from the transverse matrix elements through the relations

- $\mathcal{H}^q_T = \frac{1}{(1-\xi^2)^{1/2}} T^q_{\uparrow\uparrow} - \frac{2M\xi}{\epsilon\sqrt{t_0-t}(1-\xi^2)} T^q_{\uparrow\downarrow}$
- $\mathcal{E}^q_T = \frac{2M\xi}{\epsilon\sqrt{t_0-t}} \frac{1}{1-\xi^2} T^q_{\uparrow\downarrow} + \frac{2M}{\epsilon\sqrt{t_0-t}(1-\xi^2)} \tilde{T}^q_{\uparrow\uparrow} - \frac{4M^2}{(t_0-t)(1-\xi^2)^{3/2}} (\tilde{T}^q_{\downarrow\uparrow} - T^q_{\uparrow\uparrow})$
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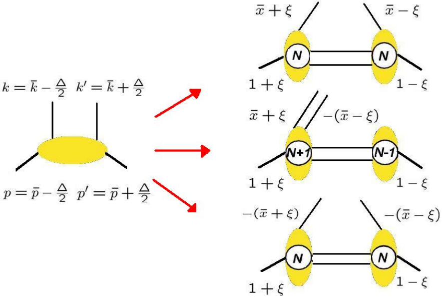
OVERLAP REPRESENTATION

M. Diehl, Th. Feldmann, R. Jakob and P. Kroll, Eur. Phys. J. **C 8**, '99; Nucl. Phys. **B 596**, '01.



- $\xi < \bar{x} < 1$
- $-\xi < \bar{x} < \xi$
- $-1 < \bar{x} < -\xi$

We restrict our calculation to the region $\xi < \bar{x} < 1$ of plus-momentum fraction, where the GPDs describe the emission of a quark with plus-momentum $(\bar{x} + \xi)\bar{P}^{+}$ and its reabsorption with plus-momentum $(\bar{x} - \xi)\bar{P}^{+}$.

At the light-cone time $z^{+} = 0$, Fourier expansion of the free quark field (Fock Decomp.):

$$\phi_{\uparrow}(z^{-}, \vec{z}_{\perp}) = \int \frac{dk^{+} d^{2}\vec{k}_{\perp}}{k^{+} 16\pi^{3}} \Theta(k^{+}) \Big\{ b_{\uparrow}(k^{+}, \vec{k}_{\perp}) u_{+}(k, \uparrow) \exp(-i k^{+} z^{-} + i\vec{k}_{\perp} \cdot \vec{z}_{\perp})$$

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with $b_{\uparrow}$ ($d^{\dagger}_{\uparrow}$) annihilation (creation) operator for an on-shell (anti)quark with transverse pol. and u_{+} (v_{+}) "good" projection of the (anti)quark spinor.

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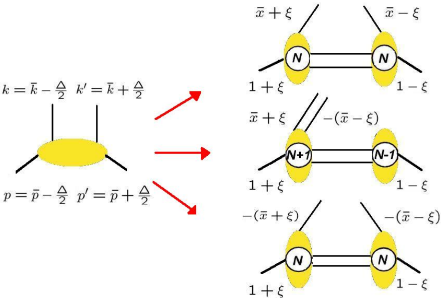

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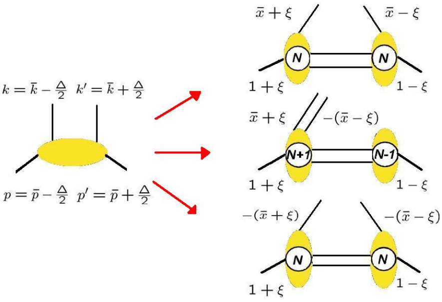

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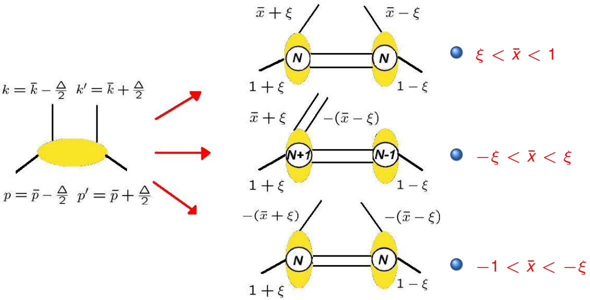

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with $b_\uparrow$ ($d_\uparrow^\dagger$) annihilation (creation) operator for an on-shell (anti)quark with transverse pol. and u_+ (v_+) "good" projection of the (anti)quark spinor.

The representation of the nucleon state reads:

$$|p, \lambda_t\rangle = \sum_{N,\beta} \int [dx]_N [d^2\vec{k}_\perp]_N \, \Psi_{\lambda_t,N,\beta}(r) \, |N, \beta; k_1, \ldots, k_N\rangle,$$

- $\Psi_{\lambda_t,N,\beta}$, Light-Cone Wave Function (LCWF) of the N-parton Fock state;
- $|N, \beta; k_1, \ldots, k_N\rangle$, N-parton Fock state.

After some calculations we find the overlap representation for the matrix elements

$$\begin{aligned} T^q_{\lambda'_t\lambda_t} &= \sum_{N,\beta=\beta'} \left(\sqrt{1-\xi}\right)^{2-N} \left(\sqrt{1+\xi}\right)^{2-N} \sum_{j=1}^{N} \mathrm{sign}(\mu^t_j)\delta_{s_j q} \\ &\times \int [d\bar{x}]_N [d^2\vec{k}_\perp]_N \delta(\bar{x} - \bar{x}_j) \Psi^*_{\lambda'_t,N,\beta'}(\hat{r}') \Psi_{\lambda_t,N,\beta}(\tilde{r}) \end{aligned}$$

$$\begin{aligned} \tilde{T}^q_{\lambda'_t\lambda_t} &= \sum_{\beta,\beta',N} \left(\sqrt{1-\xi}\right)^{2-N} \left(\sqrt{1+\xi}\right)^{2-N} \sum_{j=1}^{N} \delta_{\mu^{t\prime}_j - \mu^t_j} \delta_{\mu^{t\prime}_i \mu^t_i} \mathrm{sign}(\mu^t_j)\delta_{s_j q} \\ &\times \int [d\bar{x}]_N [d^2\vec{k}_\perp]_N \delta(\bar{x} - \bar{x}_j) \Psi^*_{\lambda'_t,N,\beta'}(\hat{r}') \Psi_{\lambda_t,N,\beta}(\tilde{r}) \end{aligned}$$

In $\tilde{T}^q_{\lambda'_t\lambda_t}$, “ $\delta_{\mu^{t\prime}_j - \mu^t_j}$ ” $\Rightarrow$ the flip of the transverse spin polarization μ^t_j of the active quark.

The representation of the nucleon state reads:

$$|p, \lambda_t\rangle = \sum_{N,\beta} \int [dx]_N [d^2\vec{k}_\perp]_N \, \Psi_{\lambda_t,N,\beta}(r) \, |N, \beta; k_1, \ldots, k_N\rangle,$$

- $\Psi_{\lambda_t,N,\beta}$, Light-Cone Wave Function (LCWF) of the N-parton Fock state;
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$$T^q_{\lambda_t'\lambda_t} = \sum_{N,\beta=\beta'} \left(\sqrt{1-\xi}\right)^{2-N} \left(\sqrt{1+\xi}\right)^{2-N} \sum_{j=1}^{N} \mathrm{sign}(\mu_j^t)\delta_{s_j q} \times \int [d\bar{x}]_N [d^2\vec{k}_\perp]_N \delta(\bar{x} - \bar{x}_j) \Psi^*_{\lambda_t',N,\beta'}(\hat{r}')\Psi_{\lambda_t,N,\beta}(\tilde{r})$$

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Light-Cone Wave Function in Constituent Quark Models

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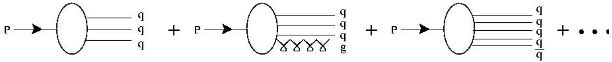

CQM are quantomechanical models with a fixed number of constituents and relativity-consistent, based on two fundamental hypotesis:

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In such models "relativity" can be incorporated in a straightforward way and the wave functions can be calculated solving the Hamiltonian eigenvalues equation in different forms of relativistic dynamic linked by an unitary transformation.

S. Boffi, B. Pasquini and M. Traini, Nucl. Phys. **B 649**,('03).

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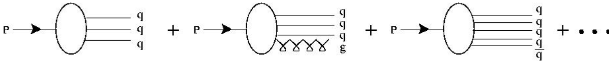

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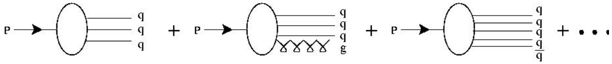

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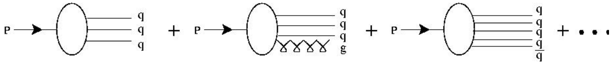

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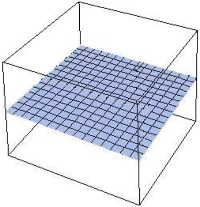

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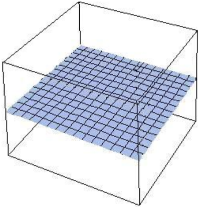

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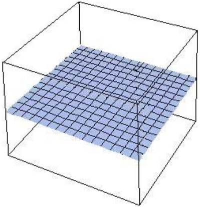

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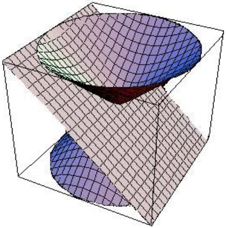

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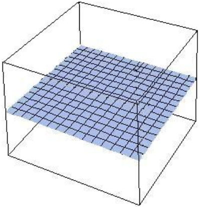

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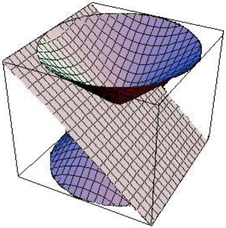

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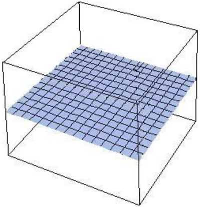

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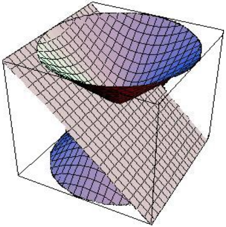

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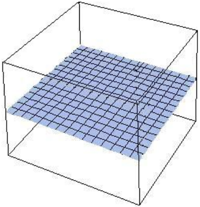

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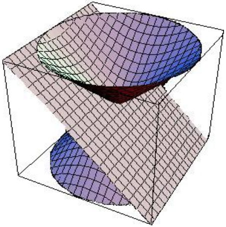

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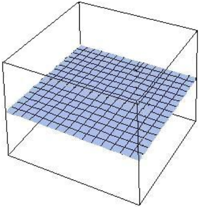

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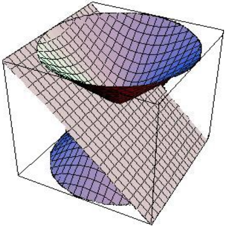

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RESULTS

B. Pasquini, M. P. and S. Boffi,
Phys. Rev **D 72**, '05

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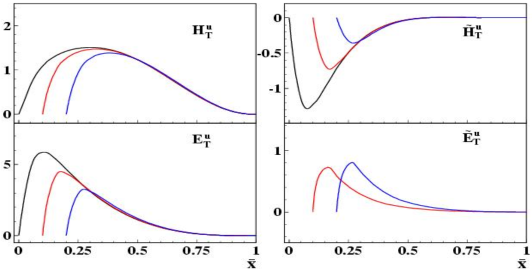

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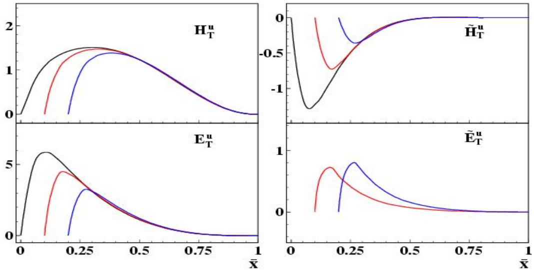

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Phys. Rev **D 72**, ’05

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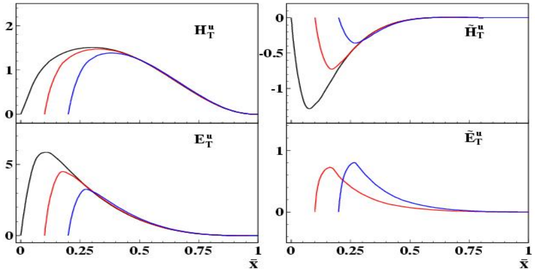

Ex.: C-O GPDs calculated in the CQM for the flavour “**u**”, for fixed $t = -0.5$ (GeV)^2 and different values of ξ:
$\xi = 0$ (black curves), $\xi = 0.1$ (blue), $\xi = 0.2$ (red).

$\Rightarrow$“Not only $\mathcal{H}_T^q(x,0,0) \neq 0$, (Scopetta in MIT bag model)”.

- **Forward Limit:**

$$\mathcal{H}_T^q(x,0,0) \quad = \quad h_1^q(x) = \sum_{\lambda_i^t \tau_i} \sum_{j=1}^{3} \delta_{\tau_j \tau_q} \mathrm{sign}(\lambda_j^t) \int [d\bar{x}]_3 [d\mathbf{k}_\perp]_3 \delta(x - x_j) \left| \psi_{\lambda^t}^{[f]} \left(x_i, \mathbf{k}_{\perp i}; \lambda_i^t, \tau_i \right) \right|^2$$

$$\tilde{\mathcal{H}}^q(x,0,0) \quad = \quad g_1^q(x) = \sum_{\lambda_i \tau_i} \sum_{j=1}^{3} \delta_{\tau_j \tau_q} \mathrm{sign}(\lambda_j) \int [d\bar{x}]_3 [d\mathbf{k}_\perp]_3 \delta(x - x_j) \left| \psi_{\lambda}^{[f]} \left(x_i, \mathbf{k}_{\perp i}; \lambda_i, \tau_i \right) \right|^2$$

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$$\mathcal{M}_T = \frac{(m + x_3 M_0)^2}{(m + x_3 M_0)^2 + \vec{k}^2_{\perp,3}}$$

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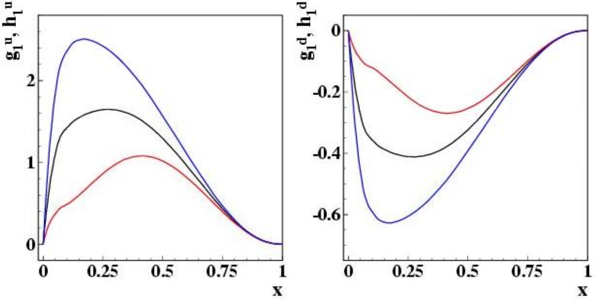

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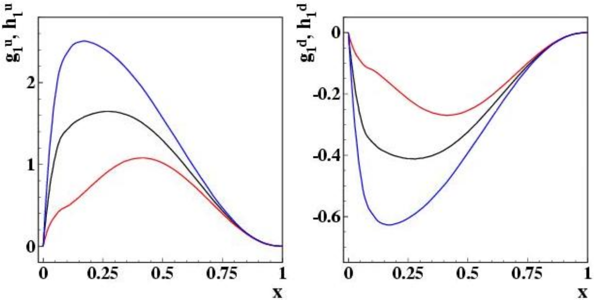

Helicity and Transversity distributions for the u (left panel) and d (right panel) quark. The blue lines correspond to h_1^q, the red lines show g_1^q, and the black lines are the nonrelativistic results when Melosh rotations reduce to the identity ($h_1^q = g_1^q$).

- Axial (Δq) and Tensor (δq) "Charges"

$$\Delta q = \int_{-1}^{1} dx\, g_1^q(x), \quad \delta q = \int_{-1}^{1} dx\, h_1^q(x).$$

The nucleon axial / tensor charge measures the net number of longitudinally / transversely polarized valence quarks in a longitudinally / transversely polarized nucleon.

	NR	HO	HYP
Δu	$4/3$	1.0	0.61
Δd	$-1/3$	-0.25	-0.15
δu	$4/3$	1.17	0.97
δd	$-1/3$	-0.29	-0.24

Valence contributions to the axial and tensor charge calculated within different SU(6)-symmetric quark models: the nonrelativistic quark model (NR), the harmonic oscillator model (HO), and the hypercentral (HYP) model.

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- Angolar Momentum Sum Rule

Recently Burkardt showed (PR**D 72**,'05) how the angular momentum J^x carried by quarks with transverse polarization in the $\hat{x}$ direction in an unpolarized nucleon at rest is related to the forward limit of chiral-odd GPDs through the following relation:

$$\langle \delta^{\mathbf{x}} \mathbf{J}^{\mathbf{x}}_{\mathbf{q}} \rangle = \langle \mathbf{J}^{\mathbf{x}}_{\mathbf{q},+\hat{\mathbf{x}}} - \mathbf{J}^{\mathbf{x}}_{\mathbf{q},-\hat{\mathbf{x}}} \rangle = \frac{1}{2}\left[A_{T20}(0) + 2\tilde{A}_{T20}(0) + B_{T20}(0)\right], \qquad (1)$$

where the invariant form factors A_{T20}, $\tilde{A}_{T20}$ and B_{T20} are the second "Mellin" moments of the chiral-odd GPDs:

$$A_{T20}(t) = \int_{-1}^{1} dx\, x H_T(x,\xi,t),\ \tilde{A}_{T20}(t) = \int_{-1}^{1} dx\, x \tilde{H}_T(x,\xi,t),\ B_{T20}(t) = \int_{-1}^{1} dx\, x E_T(x,\xi,t).$$

Using LCWFs derived from the hypercentral CQM we obtain

$$\langle \delta^{\mathbf{x}} \mathbf{J}^{\mathbf{x}}_{\mathbf{u}} \rangle = 0.39, \quad \langle \delta^{\mathbf{x}} \mathbf{J}^{\mathbf{x}}_{\mathbf{d}} \rangle = 0.10, \qquad \text{(HYP)} \qquad (2)$$

while using the Schmidt-Soffer harmonic oscillator wave function of the nucleon (PL**B 407**, '97), we obtain:

$$\langle \delta^{\mathbf{x}} \mathbf{J}^{\mathbf{x}}_{\mathbf{u}} \rangle = 0.68, \quad \langle \delta^{\mathbf{x}} \mathbf{J}^{\mathbf{x}}_{\mathbf{d}} \rangle = 0.28. \qquad \text{(HO)} \qquad (3)$$

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Summary

- Derivation of the Overlap representation for the chiral-odd Generalized Parton Distributions in a general (model indipendent) framework using the Fock-state decomposition in the transverse-spin basis;
- Application of the formalism to the case of Light Cone Wave Functions obtained by considering only valence quarks in a Costituent Quark Model;
- Different Helicity and Transversity distributions have been derived in the forward limit in agreement with the relativistic requirements and the Soffer inequality;
- Estimation of the axial and tensor "charges" confirming the different size and sign of the up and down quarks predicted within a relativistic quark models;
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...and Outlook

In the CQM we have taken into account only valence quarks and this limits the average longitudinal momentum fraction $\bar{x}$ between ξ and 1. Nevertheless the inclusion of "sea" contributions (to access ERBL region) is possible following, e.g., the lines of the papers: B. Pasquini and S. Boffi, PR**D 71** ('05) and PR**D 73** ('06).

THANKS TO THE ORGANIZERS OF THE WORKSHOP

FOR THE OPPORTUNITY GRANTED TO ME

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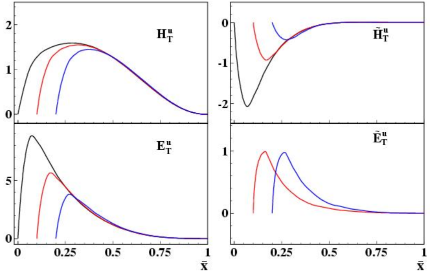
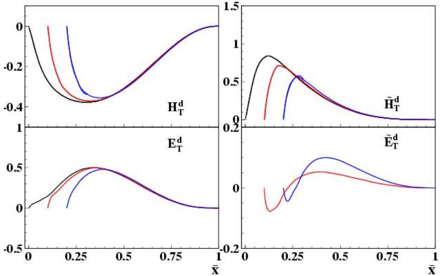


The chiral-odd GPDs calculated in the CQM for the flavour "*u*", for fixed $t = -0.2$ (GeV)^2 and different values of ξ: $\xi = 0$ (black curves), $\xi = 0.1$ (blue curves), $\xi = 0.2$ (red curves).



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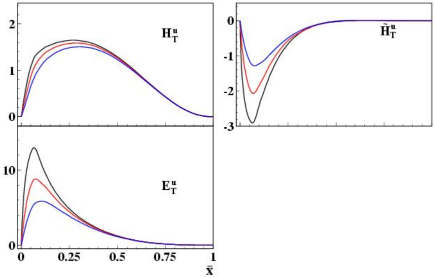

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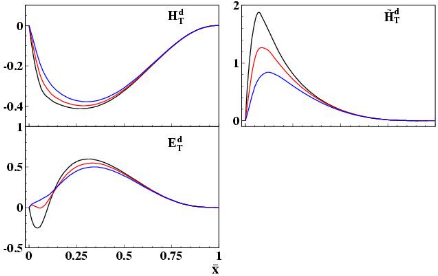

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Hypercentral Model

P. Faccioli, M. Traini and V. Vento, Nucl. Phys. **A 656**, '99

$$H = \sum_{i=1}^{3} \sqrt{\mathbf{k}_i^2 + m_i^2} - \frac{\tau}{\sqrt{\rho^2 + \lambda^2}} + k\sqrt{\rho^2 + \lambda^2},$$

with

$$\rho = \frac{\mathbf{r}_1 - \mathbf{r}_2}{\sqrt{2}} \qquad \mathrm{e} \qquad \lambda = \frac{\mathbf{r}_1 + \mathbf{r}_2 - 2\mathbf{r}_3}{\sqrt{6}}.$$

Features:

- Low energy spectrum, Form Factors;
- $SU(6)$ symmetric nucleon wave function;
- For $x \to 1$ (valence quark dominance), GPDs are obtained in a covariant approach and exibith the exact forward limit reproducing the parton distribution with the correct support and automatically fulfilling the particle number and momentum sum rule.