TMDs and Azimuthal Spin Asymmetries
in
Light-Cone Quark Models

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in collaboration with:

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Outline

- Three-Quark Light-Cone Wave function of the Nucleon
- Spin-Spin and Spin-Orbit Correlations in T-even TMDs
  - overlap representation in terms of three-quark light-cone amplitudes which are eigenstates of orbital angular momentum
  - results in a light-cone CQM
- Leading-Twist Single Spin Asymmetries in SIDIS due to T-even TMDs
  - Comparison with available experimental data from CLAS, COMPASS, HERMES
- Conclusions
Light-Cone Fock Expansion

\[ | \Psi \rangle = \Psi_{3q} | qqq \rangle + \Psi_{3q \bar{q}} | 3q \bar{q} \rangle + \Psi_{3qg} | qqqg \rangle + \cdots \]

Fixed light-cone time

\[ | (P^+, \vec{P}_\perp), \lambda \rangle = \sum_{N, \beta} \int [dx]_N [d\vec{k}_\perp]_N \Psi^f_{\lambda, N, \beta}(x_i, \vec{k}_{\perp, i}) | N, \beta; x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp, i}, \lambda \rangle \]

- Internal variables:
  \[ x_i = \frac{p_i^+}{P^+}, \quad \sum_{i=1}^{N} x_i = 1, \quad \sum_{i=1}^{N} \vec{k}_{\perp, i} = \vec{0}_\perp \]

- \( \Psi^f_{\lambda, N, \beta}(x_i, \vec{k}_{\perp, i}) \): frame INdependent

\[ J^z = \sum_{i=1}^{n} s_i^z + \sum_{i=1}^{n-1} L_i^z \]

In the light-cone gauge \( A^+ = 0 \), the total angular momentum is conserved. Fock state by Fock state.

⇒ each Fock-state component can be expanded in terms of eigenfunction of the light-front orbital angular momentum operator.
Three Quark Light Cone Amplitudes

\[ P^+, \vec{P}_\perp \]

\[ |P, \lambda\rangle = \sum_\beta \int d[1]d[2]d[3] \Psi^\lambda_{i, j}(x_i, \vec{k}_\perp) \varepsilon^{ijk} \frac{1}{\sqrt{6}} u_{i, \lambda_1} (1) u_{j, \lambda_2} (2) d_{k, \lambda_3} (3) |0\rangle \]

\[ J_z = J_z^q + L_z^q \]

classification of LCWFs in orbital angular momentum components

\[ |P, \uparrow\rangle = |P, \uparrow\rangle^{L_z=2}_{-\frac{3}{2}} + |P, \uparrow\rangle^{L_z=1}_{-\frac{1}{2}} + |P, \uparrow\rangle^{L_z=0}_{\frac{1}{2}} + |P, \uparrow\rangle^{L_z=-1}_{\frac{3}{2}} \]

6 independent wave function amplitudes: \( \psi^{(i)} \ i = 1, \ldots, 6 \)

\[ L_z^q = -1 \quad L_z^q = 0 \quad L_z^q = 1 \quad L_z^q = 2 \]

\[ J_z^q \rightarrow (\uparrow \uparrow \uparrow)_{LC} \quad (\uparrow \uparrow \downarrow)_{LC} \quad (\uparrow \downarrow \downarrow)_{LC} \]

parity

time reversal
isospin symmetry

\[ 0 | \varepsilon^{ijk} u_{i, \lambda_1} (1) \Gamma u_{j, \lambda_2} (2) d_{k, \lambda_3} (3) |P\rangle \]

\[ |P \uparrow\rangle^{L_z=-1}_{\frac{3}{2}} = \int d[1]d[2]d[3] \left( k_x^x - i k_y^y \right) \psi^{(5)}(1, 2, 3)^6(1, 2, 3)^{\mathbf{(2)}}(1, 2, 3)^{(2)}(2, 3) \right) \]

\[ \times \frac{\varepsilon^{ijk}}{\sqrt{6}} u_{i \uparrow} (1) \left( u_{j \uparrow} (2) d_{k \uparrow} (3) - d_{j \uparrow} (2) u_{k \uparrow} (3) \right) |0\rangle \]

|0\rangle
Light-Cone Quark Model

- Phenomenological LCWF for the valence (qqq) component:
  - momentum-space component: $S$ wave
    \[ \tilde{\Psi} = \frac{N}{(M_0^2 + \beta^2)^2} \]
    \[ M_0 = \sum_i^3 \sqrt{m_i^2 + k_i^2}, \quad m = 0.267 \text{ GeV} \]
    \[ \beta = 0.61 \text{ GeV}, \quad \gamma = 3.4 \quad \text{fitted to anomalous magnetic moments of the nucleon} \]
    \[ N : \text{normalization constant} \]
  - spin and isospin component in the rest frame: $SU(6)$ symmetric
    \[ uud [\uparrow \downarrow \uparrow + \downarrow \uparrow \uparrow - 2 \uparrow \uparrow \downarrow] \quad J_z = J_z^q \]
    \[ \Rightarrow \text{Melosh rotation to convert the rest-frame spins of quarks in LF spins} \]
    \[ q_I^\uparrow = w \left[ (k^+ + m_q) q_{LC}^\uparrow - (k_x + i k_y) q_{LC}^\downarrow \right] \]
    \[ q_I^\downarrow = w \left[ (k_x - i k_y) q_{LC}^\uparrow + (k^\dagger + m_q) q_{LC}^\downarrow \right] \]
    \[ J_z = J_z^q + L_z^q \]

Six independent wave function amplitudes:
- eigenstates of the total orbital angular momentum operator in Light-Front dynamics

\[ L_z^q = -1 \quad (\uparrow \uparrow \uparrow)_{LC} \]
\[ L_z^q = 0 \quad (\uparrow \uparrow \downarrow)_{LC} \]
\[ L_z^q = 1 \quad (\uparrow \downarrow \downarrow)_{LC} \]
\[ L_z^q = 2 \quad (\downarrow \downarrow \downarrow)_{LC} \]

The six independent wave function amplitudes obtained from the Melosh rotations satisfy the model independent classification scheme in four orbital angular momentum components.
Time-Even TMDs

\[ \lambda, x, k \perp \lambda', x, k \perp \]

Light-cone Gauge $A^+ = 0$ and advanced boundary condition for $A_\perp$ → no gauge link

\[
T(x, k_\perp) = \langle (P^+, \Delta_\perp = 0), \Lambda' \mid \mathcal{O}^q_{\lambda', \lambda} \mid (P^+, \Delta_\perp = 0), \Lambda \rangle
\]

\[
\mathcal{O}^q_{\lambda', \lambda} = \int \frac{dz^- dz_\perp}{(2\pi)^3} \bar{q}_{\lambda'}(\frac{z^-}{2}) \Gamma q_{\lambda}(\frac{z_\perp}{2}) e^{i(k^+ z^- - k_\perp \cdot z_\perp)}
\]

\[
\Gamma = \begin{cases} 
\gamma^+ & \Rightarrow q^\dagger q^\dagger + q^\dagger q_\perp \quad \text{quark-number density} \\
\gamma^+ \gamma^5 & \Rightarrow q^\dagger q^\dagger - q^\dagger q_\perp \quad \text{quark-helicity density} \\
i\sigma^{x+} \gamma^5 & \Rightarrow q^\dagger q_\perp + q^\dagger q^\dagger \quad \text{transverse-spin density}
\end{cases}
\]
Light Cone Amplitudes Overlap Representation of TMDs

\[ f_1 = \begin{array}{c}
\Delta L_z=0
\end{array} \]

\[ f_1^q(x, k^2_\perp) = L_{z=0}(P \uparrow \sum_\lambda q^\dagger_\lambda q_\lambda | P \uparrow)^{L_z=0} + L_{z=1}(P \uparrow \sum_\lambda q_\lambda^\dagger q_\lambda | P \uparrow)^{L_z=1} \]

\[ + L_{z=-1}(P \uparrow \sum_\lambda q_\lambda^\dagger q_\lambda | P \uparrow)^{L_z=-1} + L_{z=2}(P \uparrow \sum_\lambda q_\lambda^\dagger q_\lambda | P \uparrow)^{L_z=-2} \]

\[ g_{1L}^q(x, k^2_\perp) = L_{z=0}(P \uparrow \sum_\lambda (-1)^{1/2} \lambda q_\lambda^\dagger q_\lambda | P \uparrow)^{L_z=0} + L_{z=1}(P \uparrow \sum_\lambda (-1)^{1/2} \lambda q_\lambda^\dagger q_\lambda | P \uparrow)^{L_z=1} \]

\[ + L_{z=-1}(P \uparrow \sum_\lambda (1)^{1/2-\lambda} q_\lambda^\dagger q_\lambda | P \uparrow)^{L_z=-1} + L_{z=2}(P \uparrow \sum_\lambda (1)^{1/2-\lambda} q_\lambda^\dagger q_\lambda | P \uparrow)^{L_z=-2} \]

\[ h_1 = \begin{array}{c}
\Delta L_z=0
\end{array} \]

\[ h_1^q(x, k^2_\perp) = \text{Re}[L_{z=0}(P \downarrow |q^\dagger_\lambda q_\lambda| P \downarrow)^{L_z=0}] + 2\text{Re}[L_{z=-1}(P \downarrow |q^\dagger_\lambda q_\lambda| P \downarrow)^{L_z=-1}] \]
\[ g_{1T}(x, k_\perp^2) = \]
\[ \Delta L_z = 1 \]
\[ \frac{2M}{k_\perp^2} \left( k^x \text{Re}[^{L_z=0}\langle P \uparrow | \sum_\lambda (-1)^{1/2-\lambda} q_\lambda^{\dagger} q_\lambda | P \downarrow \rangle^{L_z=-1}] + k^y \text{Im}[^{L_z=0}\langle P \uparrow | \sum_\lambda (-1)^{1/2-\lambda} q_\lambda^{\dagger} q_\lambda | P \downarrow \rangle^{L_z=-1}] \right) \]
\[ + k^x \text{Re}[^{L_z=-2}\langle P \downarrow | \sum_\lambda (-1)^{1/2-\lambda} q_\lambda^{\dagger} q_\lambda | P \uparrow \rangle^{L_z=-1}] + k^y \text{Im}[^{L_z=-2}\langle P \downarrow | \sum_\lambda (-1)^{1/2-\lambda} q_\lambda^{\dagger} q_\lambda | P \uparrow \rangle^{L_z=-1}] \]

\[ h_{1L}^\parallel = \]
\[ |\Delta L_z| = 1 \]
\[ S \rightarrow P \]
\[ S \rightarrow P \]
\[ \frac{2M}{k_\perp^2} \left( \text{Re}[^{L_z=1}\langle P \uparrow | q_\lambda^{\dagger} q_\lambda | P \uparrow \rangle^{L_z=0}] - k^y \text{Im}[^{L_z=1}\langle P \uparrow | q_\lambda^{\dagger} q_\lambda | P \uparrow \rangle^{L_z=0}] \right) \]
\[ P \rightarrow D \]
\[ P \rightarrow D \]
\[ + k^x \text{Re}[^{L_z=2}\langle P \uparrow | q_\lambda^{\dagger} q_\lambda | P \uparrow \rangle^{L_z=1}] - k^y \text{Im}[^{L_z=2}\langle P \uparrow | q_\lambda^{\dagger} q_\lambda | P \uparrow \rangle^{L_z=1}] \]

\[ h_{1T}^\parallel = \]
\[ |\Delta L_z| = 2 \]
\[ P \rightarrow P \]
\[ D \rightarrow S \]
\[ -\text{Re}[^{L_z=1}\langle P \uparrow | q_\lambda^{\dagger} q_\lambda | P \downarrow \rangle^{L_z=-1}] - 2\text{Re}[^{L_z=0}\langle P \uparrow | q_\lambda^{\dagger} q_\lambda | P \downarrow \rangle^{L_z=-2}] \]
TMDs in a Light-Cone CQM

\[ f_1^q(x, k_{\perp}^2) = N^q \int d[1]d[2]d[3] \sqrt{x_1 x_2 x_3} |\tilde{\Phi}(\{x_i\}, \{k_{\perp,i}\})|^2 \delta(x - x_3) \delta^2(k_{\perp} - k_{\perp,3}) \]

\[ g_{1L}^q(x, k_{\perp}^2) = P^q \int d[1]d[2]d[3] \sqrt{x_1 x_2 x_3} |\tilde{\Phi}(\{x_i\}, \{k_{\perp,i}\})|^2 \frac{(m + x M_0)^2 - k_{\perp}^2}{(m + x M_0)^2 + k_{\perp}^2} \delta(x - x_3) \delta^2(k_{\perp} - k_{\perp,3}) \]

\[ h_1^q(x, k_{\perp}^2) = P^q \int d[1]d[2]d[3] \sqrt{x_1 x_2 x_3} |\tilde{\Phi}(\{x_i\}, \{k_{\perp,i}\})|^2 \frac{(m + x M_0)^2}{(m + x M_0)^2 + k_{\perp}^2} \delta(x - x_3) \delta^2(k_{\perp} - k_{\perp,3}) \]

\[ g_{1T}^q(x, k_{\perp}^2) = P^q \int d[1]d[2]d[3] \sqrt{x_1 x_2 x_3} |\tilde{\Phi}(\{x_i\}, \{k_{\perp,i}\})|^2 \frac{2 M (m + x M_0)}{(m + x M_0)^2 + k_{\perp}^2} \delta(x - x_3) \delta^2(k_{\perp} - k_{\perp,3}) \]

\[ h_{1L}^q(x, k_{\perp}^2) = -P^q \int d[1]d[2]d[3] \sqrt{x_1 x_2 x_3} |\tilde{\Phi}(\{x_i\}, \{k_{\perp,i}\})|^2 \frac{2 M (m + x M_0)}{(m + x M_0)^2 + k_{\perp}^2} \delta(x - x_3) \delta^2(k_{\perp} - k_{\perp,3}) \]

\[ h_{1T}^q(x, k_{\perp}^2) = -P^q \int d[1]d[2]d[3] \sqrt{x_1 x_2 x_3} |\tilde{\Phi}(\{x_i\}, \{k_{\perp,i}\})|^2 \frac{2 M^2}{(m + x M_0)^2 + k_{\perp}^2} \delta(x - x_3) \delta^2(k_{\perp} - k_{\perp,3}) \]

- SU(6) symmetry \[ N^u = 2 \quad N^d = 1 \quad P^u = 4/3 \quad P^d = -1/3 \]
- momentum dependent wf factorized from spin-dependent effects
- 3 relations between the TMDs

B.P., Cazzaniga, Boffi, PRD78, 2008
Total results obey SU(6) symmetry relations:

\[ f_1^u = 2f_1^d, \quad g_{1L}^u = -4g_{1L}^d, \quad h_1^u = -4h_1^d \]

The partial wave contributions do not satisfy SU(6) symmetry relations!
ONLY TOTAL results (and not partial wave contr.) obey SU(6) symmetry relations:
\[ g_{1T}^{(1)} u = -4 g_{1T}^{(1)} d, \quad h_{1L}^{\perp(1)} u = -4 h_{1L}^{\perp(1)} d, \quad h_{1T}^{\perp(1)} u = -4 h_{1T}^{\perp(1)} d \]
Relations of TMDs in Valence Quark Models

(1) \[ 2h_1^q(x, k_{\perp}^2) = g_{1L}^q(x, k_{\perp}^2) + \frac{P^q}{N_q} f_1^q(x, k_{\perp}^2) \]

(2) \[ \frac{P^q}{N_q} f_1^q(x, k_{\perp}^2) = h_1^q(x, k_{\perp}^2) - \frac{k_{\perp}^2}{2M^2} h_{1T}^q(x, k_{\perp}^2) \]

(3) \[ h_{1T}^q(x, k_{\perp}^2) = -g_{1T}^q(x, k_{\perp}^2) \]

(1), (2), and (3) hold in Light-Cone CQM Models

BP, Pincetti, Boffi, PRD72, 2005;
BP, Cazzaniga, Boffi, PRD78, 034025 (2008)

(1) and (2) hold in Bag Model

Avakian, Efremov, Yuan, Schweitzer, PRD78, 114024 (2008)

(1) and (2) hold in the diquark spectator model for the separate scalar and axial-vector contributions, (3) is valid more generally for both u and d quarks

Gamberg, Goldstein, Schlegel, PRD77, 094016 (2008)
She, Zhu, Ma, PRD 79, 054008 (2009)

(1) and (2) holds in covariant quark-parton model

Efremov, Schweitzer, Teryaev, Zavada, PRD80, 014021 (2009)

(1) and (2) are not valid in more phenomenological versions of the diquark spectator model for the axial-sector, but hold for the scalar contribution

Bacchetta, Conti, Radici, PRD78, 074010 (2008)

\( \checkmark \) no gluon dof
\( \leftarrow \) valid at low hadronic scale
\( \downarrow \) there are NO EXACT relations between TMDs in QCD, but having well-motivated approximations is valuable!
\[ g_1^q(x) - h_1^q(x) = h_{1T}^{(1)\perp q}(x) \]

- Positivity constraint:
  \[ |h_{1T}^{(1)\perp q}(x)| \leq \frac{1}{2}(f_1^q(x) - g_1^q(x)) \]

Soffer inequality
\[ |h_{1T}^{(1)\perp q}(x)| + |h_1^q(x)| \leq f_1^q(x) \]

scale of the model:
\[ Q_0^2 = 0.079 \text{ GeV}^2 \text{ where } \sum_q \langle x^q \rangle = 1 \]

“approximate” evolution for \( h_{1T}^{(1)\perp} \), using evolution equations of transversity
BP, Cazzaniga, Boffi, PRD78 (2008)

$g_{1T} = - h_{1L\perp}$

$\langle k_x \rangle = 55.81 \text{ MeV (up)}$

$\langle k_x \rangle = -28.14 \text{ MeV (down)}$

• Light-cone quark model: $g_{1T}(x, k_{\perp}^2) = - h_{1L\perp}(x, k_{\perp}^2)$

• Lattice calculation: $g_{1T}(x, k_{\perp}^2) \approx - h_{1L\perp}(x, k_{\perp}^2) \Rightarrow$ supports predictions from light-cone QM

Haegler, Musch, Negele, Schaefer, arXiv:0908.1283 [hep-lat]

$g_{1T}: \langle k_x \rangle = 67(5) \text{ MeV; } h_{1L\perp} = \langle k_x \rangle = -60(5) \text{ MeV (up)}$

$g_{1T}: \langle k_x \rangle = -30(5) \text{ MeV; } h_{1L\perp} = 16(5) \text{ MeV (down)}$
\[ \rho(x, k_\perp, S_\perp) = \frac{1}{2} [f_1 + S^i \varepsilon^{ijk} k^j \frac{1}{M} f_{1T}] \]

\[ \rho(x, k_\perp, s_\perp) = \frac{1}{2} [f_1 + s^i \varepsilon^{ijk} k^j \frac{1}{M} h^1_1] \]

\[ \rho(x, k_\perp, S_\perp, s_\perp) = \frac{1}{2} [f_1 + S^i s^j h_1 + S^i (2k^i k^j - k^2_\perp \delta^{ij}) s^j \frac{1}{2M^2} h^1_{1T}] \]

\[ \rho(x, k_\perp, \Lambda, s_\perp) = \frac{1}{2} [f_1 + \Lambda s^i k^i \frac{1}{M} h^1_{1L}] \]

\[ \rho(x, k_\perp, S_\perp, \lambda) = \frac{1}{2} [f_1 + S^i \lambda k^i \frac{1}{M} g^1_{1T}] \]

\[ \rho(x, b_\perp, S_\perp) = \frac{1}{2} [H - S^i \varepsilon^{ijk} b^j \frac{1}{M} E'] \]

\[ \rho(x, b_\perp, s_\perp) = \frac{1}{2} [H - s^i \varepsilon^{ijk} b^j \frac{1}{M} (E'_T + 2 \tilde{H}'_T)] \]

\[ \rho(x, b_\perp, S_\perp, s_\perp) = \frac{1}{2} [\Pi - S^i s^j (\Pi_T - \frac{1}{4M^2} \Delta_b \tilde{H}_T) + S^i (2b^i b^j - b^2 \delta^{ij}) s^j \frac{1}{M^2} \tilde{H}''_T] \]

\[ \Lambda s^i b^i \quad \text{time-reversal odd} \Rightarrow \text{GPD}=0 \]

\[ S^i \lambda b^i \quad \text{time-reversal odd} \Rightarrow \text{GPD}=0 \]

Diehl, Haegler, 2005; Meissner, Metz, Schlegel, 2009
correlations in $k_\perp, S_\perp, s_\perp$

$$\rho(x, k_\perp, S_\perp, s_\perp) = \frac{1}{2} \left[ f_1 + S^i s^i h_1 \right. \\
+ \left. S^i (2k^i k^j - k_\perp^2 \delta^{ij}) s^j \frac{1}{2M^2} h_{1T}^\perp \right]$$

trivial relations:

$$\int dk_\perp f_1(x, k_\perp^2) = f_1(x) = H(x, 0, 0)$$

$$\int dk_\perp h_1(x, k_\perp^2) = h_1(x) = H_T(x, 0, 0)$$

no Fourier transform

correlations in $b_\perp, S_\perp, s_\perp$

$$\rho(x, b_\perp, S_\perp, s_\perp) = \frac{1}{2} \left[ H - S^i s^i (H_T - \frac{1}{4M^2} \Delta_b \tilde{H}'_T) \right. \\
+ \left. S^i (2b^i b^j - b^2 \delta^{ij}) s^j \frac{1}{M^2} \tilde{H}''_T \right]$$

nontrivial, model-dependent relation:

$$\int dk_\perp h_{1T}^q(x, k_\perp^2) = \frac{2}{(1-x)^2} \tilde{H}^q_T(x, 0, 0)$$

up

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\[
\frac{d^4\sigma}{dx\,dy\,dz\,d\phi_h} = \frac{d^4\sigma_0}{dx\,dy\,dz\,d\phi_h} \left\{ 1 + \cos(2\phi_h) p_1(y) A_{UU}^{\cos(2\phi_h)} + S_L \sin(2\phi_h) p_1(y) A_{UL}^{\sin(2\phi_h)} \\
+ \lambda S_L p_2(y) A_{LL} + \lambda S_T \cos(\phi_h - \phi_s) p_2(y) A_{LT}^{\cos(\phi_h - \phi_s)} + S_T \sin(\phi_h - \phi_s) A_{UT}^{\sin(\phi_h - \phi_s)} \\
+ S_T \sin(\phi_h + \phi_s) p_1(y) A_{UT}^{\sin(\phi_h + \phi_s)} + S_T \sin(3\phi_h - \phi_s) p_1(y) A_{UT}^{\sin(3\phi_h - \phi_s)} \right\} + \ldots
\]

\[A_{XY}^{\text{weight}} = \frac{F_X^{\text{weight}}}{F_{UU}}\]

X = beam polarization  
Y = target polarization  
weight = ang. distr. hadron

\[F_{UU} \propto \sum_a e_a^2 f_1^a \otimes D_1^a\]

\[F_{LL} \propto \sum_a e_a^2 g_1^a \otimes D_1^a\]

\[F_{LT}^{\cos(\phi_h - \phi_s)} \propto \sum_a e_a^2 g_{1T}^a \otimes D_1^a\]

\[F_{UT}^{\sin(\phi_h - \phi_s)} \propto \sum_a e_a^2 f_{1T}^a \otimes D_1^a\]

\[F_{UU}^{\cos(2\phi_h)} \propto \sum_a e_a^2 h_{1L}^a \otimes H_{1L}^a\]

\[F_{UL}^{\sin(2\phi_h)} \propto \sum_a e_a^2 h_{1L}^a \otimes H_{1L}^a\]

\[F_{UT}^{\sin(\phi_h + \phi_s)} \propto \sum_a e_a^2 h_1^a \otimes H_1^a\]

\[F_{UT}^{\sin(3\phi_h - \phi_s)} \propto \sum_a e_a^2 h_{1T}^a \otimes H_{1T}^a\]

Bacchetta, et al., JHEP0702, 2007
Collinear double spin-asymmetries $A_{LL}$ and $A_1$

- Convolution integrals between parton distributions and fragmentation functions can be solved analytically without approximation.

\[
A_{LL} = \frac{\sum_a e_a^2 x g_1^a(x) D_1^a(z)}{\sum_a e_a^2 x f_1^a(x) D_1^a(z)}
\]

\[
A_1^p = \frac{\sum_a e_a^2 x g_1^a(x)}{\sum_a e_a^2 x f_1^a(x)}
\]

- No complications due to $k_\perp$ dependence.

- Evolution equations and fragmentation functions are known.

We can test the model under "controlled conditions":

- In which range and with what accuracy is the model applicable?
- How stable are the results under evolution?
$A_{LL}$ and $A_1$

\[
A_{LL} = \frac{\sum_a e_a^2 x g_1^a(x) D_1^a(z)}{\sum_a e_a^2 x f_1^a(x) D_1^a(z)}
\]

$D_1(z)$ at $Q^2 = 2.5 \text{ GeV}^2$ [Kretzer, PRD62, 2000]

$g_1(x), f_1(x)$ evolved to exp. $<Q^2> = 3 \text{ GeV}^2$

$g_1(x), f_1(x)$ initial scale $Q^2_0 = 0.079 \text{ GeV}^2$ where $\sum_q <x^q> = 1$

Inclusive longitudinal asymmetry

\[
A_1^P = \frac{\sum_a e_a^2 x g_1^a(x)}{\sum_a e_a^2 x f_1^a(x)}
\]

[Boffi, Efremov, Pasquini, Schweitzer, PRD79, 2009]

- description of exp. data within accuracy of 20-30% in the valence region
- very weak scale dependence
Gaussian Ansatz

$$f(x, k_{\perp}^2) = f(x) \frac{\exp\left(-\frac{k_{\perp}^2}{\langle k_{\perp}^2 \rangle}ight)}{\pi \langle k_{\perp}^2 \rangle}$$

- $k_{\perp}$ dependence of the model is not of gaussian form
- how well can it be approximated by a gaussian form?

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<tr>
<th>TMD</th>
<th>$\langle k_{\perp} \rangle$ in GeV</th>
<th>$\langle k_{\perp}^2 \rangle$ in GeV$^2$</th>
<th>$\frac{4\langle k_{\perp} \rangle^2}{\pi \langle k_{\perp}^2 \rangle}$</th>
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<td>$h_{1T}$</td>
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<td>0.050</td>
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$=1$ in Gauss Ansatz

results agree within 20%

| $D_1(z)$ from Bacchetta et al., PLB659, 2008 |

with Gaussian Ansatz

exact result

Gaussian Ansatz gives uncertainty within typical accuracy of the model
Strategy to calculate the azimuthal spin asymmetries

- we focus on the $x$-dependence of the asymmetries, especially in the valence-$x$ region
- we adopt Gaussian Ansatz

- low hadronic scale $\rightarrow \langle k^2_{\perp} (f_1) \rangle_{\text{(MODEL)}} = 0.08 \text{ GeV}^2$ is much smaller than phenomenological value $\langle k^2_{\perp} (f_1) \rangle_{\text{(PHEN)}} = 0.33 \text{ GeV}^2$ (fit to SIDIS HERMES data assuming gaussian Ansatz) [Collins, et al., PRD73, 2006]

- we rescale the model results for $\langle k^2_{\perp} (TMD) \rangle$ with $\langle k^2_{\perp} (f_1) \rangle_{\text{(MODEL)}} / \langle k^2_{\perp} (f_1) \rangle_{\text{(PHEN)}}$

- we do not discuss the $z$ and $P_h$ dependence of azimuthal asymmetries because here integrals over the $x$ dependence extend to low $x$-region where the model is not applicable
Collins SSA

gaussian ansatz \[ A_{UT}^{\sin(\phi_h + \phi_S)}(x) = \frac{\sum_a e_a^2 x h_1^a(x) \langle B_1 H_{1}^{(1/2)a} \rangle}{\sum_a e_a^2 x f_1^a(x) \langle D_1^a \rangle} \]

- \( h_1(x) \) from Light-Cone CQM evolved at \( Q^2=2.5 \text{ GeV}^2 \), \( f_1(x) \) from GRV at \( Q^2=2.5 \text{ GeV}^2 \)

- \( H_{1}^{(1/2)} \) from HERMES & BELLE data

Efremov, Goeke, Schweitzer, PRD73 (2006); Anselmino et al., PRD75 (2007); Vogelsang, Yuan, PRD72 (2005)

HERMES data:
Diefenthaler, hep-ex/0507013

More recent HERMES and BELLE data not included in the fit of Collins function

COMPASS data:
Alekseev et al., PLB673, (2009)

\[ \phi_C = \phi_h + \phi_S + \pi \]
\[ A_{UT}^{\sin(\phi_C)} = -A_{UT}^{\sin(\phi_h + \phi_S)} \]
Transversity

- Dashed area: extraction of transversity from BELLE, COMPASS, and HERMES data
  Anselmino et al., PRD75, 2007

- Predictions from Light-Cone CQM evolved from the hadronic scale $Q^2_0$ to $Q^2= 2.5 \text{ GeV}^2$
  using two different momentum-dependent wf

\[
 h_1^q(x, \mu_0^2) = P^q \int d[X] \delta(x - x_3) |\tilde{\Psi}(\{x_i\}, \{k_{i,i}\})|^2 \frac{(m + xM_0)^2}{(m + xM_0)^2 + k_{1,3}^2}
\]

\[
 \tilde{\Psi} = \frac{N}{(M_0^2 + \beta^2)^\gamma}
\]

- phenomenological wf
- three fit parameters
- $\beta, \gamma$ and $m_q$ fitted to the anomalous magnetic moments of the nucleon
  and to $g_A$


Faccioli, et al., NPA656, 1999
Ferraris et al., PLB324, 1995

BP, Pincetti, Boffi, PRD72, 2005

\[ \tilde{\Psi} \text{ solution of relativistic potential model} \]

\[ \checkmark \text{no free parameters} \]

\[ \checkmark \text{fair description of nucleon form factors} \]
- chiral odd, no gluons
- $h_{1L}^{\perp}$: SP and PD interference terms
- $h_1$: SS and PP diagonal terms

$h_{1L}^{\perp} \leftrightarrow h_1$

- opposite sign of $h_1$
- $|h_{1L}^{\perp}(x, k_{\perp}^2)| >> |h_1(x, k_{\perp}^2)|$

With $P^q h_{1L}^{\perp} = h_{1L}^{\perp q}$

- Wandzura-Wilczek-type approximation
  Avakian, et al., PRD77, 2008

\[
\begin{aligned}
h_{1L}^{\perp(1) q}(x) &= \int d^2 k_{\perp} \frac{k_{\perp}^2}{2M} h_{1L}^{\perp q}(x, k_{\perp}) \\
&\approx x^2 \int_x^1 \frac{dy}{y^2} h_1^q(y)
\end{aligned}
\]

With $P^q h_1 = h_1^q$
\[
A_{UL}^{\sin(2\phi_h)} = \frac{\sum_a e_a^2 x \langle h_{1L}^{(1)} a(x) B_2' H_{1}^{(1/2)a} \rangle}{\sum_a e_a^2 x \langle f_1^a(x) D_1^a \rangle}
\]

- \( h_{1L}^{(1)} \) from Light-Cone CQM evolved at \( Q^2 = 2.5 \text{ GeV}^2 \), with the evolution equations of \( h_1(x) \)
- \( f_1(x) \) from GRV at \( Q^2 = 2.5 \text{ GeV}^2 \)
- \( H_{1}^{(1/2)} \) from HERMES & BELLE data

Efremov, Goeke, Schweitzer, PRD73 (2006); Anselmino et al., PRD75 (2007); Vogelsang, Yuan, PRD72 (2005)

HERMES Coll.
Airapetian, PRL84, 2000;
Avakian,

Model results compatible with preliminary CLAS data for \( \pi^+ \) and \( \pi^0 \)
but cannot explain the SSA for \( \pi^- \)
→ more precise data expected
gaussian ansatz $\Rightarrow A_{LT}^{\cos(2\phi_n-\phi_S)}(x) = \frac{\sum_a e_a^2 x g_{1T}^{(1)a}(x) \langle B_0^a D_1^a \rangle}{\sum_a e_a^2 x f_1^a(x) \langle D_1^a \rangle}$

- $g_{1T}^{(1)}(x), f_1(x)$ initial scale $Q^2_0=0.079 \text{ GeV}^2$
- $g_{1T}^{(1)}(x)$ evolved to $Q^2=2.5 \text{ GeV}^2$ using evolution eq. of $g_1(x)$
- $f_1(x)$ evolved to $Q^2=2.5$

$D_1(z)$ at $Q^2=2.5 \text{ GeV}^2$ [Kretzer, PRD62, 2000]

<table>
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<td>[Kotzinian, et al., arXiv:0705.2402]</td>
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\[ A_{UT}^{\sin(3\phi_n - \phi_S)} \]

gaussian ansatz \[ \Rightarrow A_{UT}^{\sin(3\phi_n - \phi_S)} = -\sum_a e_a^2 x \frac{h_{1T}^{(1)}(x)}{\sum_a e_a^2 x} \langle B_3 H_1^{(1/2)a} \rangle \]

- \( h_{1T}^{(1)} \) from Light-Cone CQM evolved at \( Q^2=2.5 \text{ GeV}^2 \), with the evolution equations of \( h_1(x) \)
- \( f_1(x) \) from GRV at \( Q^2=2.5 \text{ GeV}^2 \)
- \( H_1^{(1/2)} \) from HERMES & BELLE data

Efremov, Goeke, Schweitzer, PRD73 (2006); Anselmino et al., PRD75 (2007); Vogelsang, Yuan, PRD72 (2005)

- smaller predictions than expected from positivity bounds \[ |h_{1T}^{(1)}(x)| \leq (f_1(x) - g_1(x))/2 \]
with \( f_1 \) and \( g_1 \) from GRV at \( Q^2=2.5 \text{ GeV}^2 \)

- experiment planned at CLAS12 (H. Avakian at al., LOI 12-06-108)

- analysis in progress for HERMES data

COMPASS Coll.

Kotzinian, arXiv:0705.2402
Summary

- Model independent classification of TMDs in terms of three-quark Light-Cone amplitudes with different orbital angular momentum

- Model calculation in a Light-Cone CQM
  - Relativistic effects due to Melosh rotations in LCWF introduce a non trivial spin structure and correlations between quark spin and quark orbital angular momentum
  - Three non-trivial relations among T-even TMDs valid at low scale in a large class of relativistic quark models
  - One nontrivial model-dependent relation between pretzelosity and chiral-odd GPD

- Predictions for all Azimuthal Spin Asymmetries in SIDIS due to T-even TMDs
  - $A_{LL}$ and $A_1$: the model is capable to describe the data in the valence region with accuracy of 20-30%
  - TMDs in the light-cone CQM have not gaussian shape, but we checked that, within the accuracy of the model, the $k_\perp$ dependence in the azimuthal asymmetries can be approximated with gaussian Ansatz
  - Collins asymmetry is the only non-zero within the present day error bars
    - Very good agreement between model predictions and exp. data
  - $A_{LT}^{\cos(2\phi_h-\phi_S)}$, $A_{UL}^{\sin(2\phi_h)}$, $A_{UT}^{\sin(3\phi-\phi_S)}$: available exp. data compatible with zero within error bars
    - Model results with “approximate” evolution are compatible with data