Light-front quark distributions in the nucleon and nucleon electromagnetic form factors

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Nucleon form factors

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Pion form factors

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Motivations

A wealth of information on the partonic structure of protons and neutron is encoded in the Generalized Parton Distributions
Extensive theoretical and experimental research programs are being pursued to gain information on GPD's

Our strategy :

- to obtain the quark-nucleon vertex function from an investigation of nucleon EM form factors in the space- and timelike regions, within the light-front dynamics,
- to use the nucleon light-front wave function to evaluate GPD's

Light-front dynamics opens a unique possibility to study the hadronic state, in both the valence and the nonvalence sector (Brodsky, Pauli & Pinsky, Phys. Rep. **301** (1998) 299)

$$|meson\rangle = \ |q\bar{q}\rangle + |q\bar{q}q\bar{q}\rangle + |q\bar{q}\ g\rangle.....$$

$$|baryon\rangle = \underbrace{|qqq\rangle}_{\text{valence}} + \underbrace{|qqq\ q\bar{q}\rangle + |qqq\ g\rangle.....}_{\text{nonvalence}}$$

★ A meaningful Fock expansion within LF framework
no spontaneous pair production

First step : unpolarized parton distributions

Outline

- A covariant expression for the EM current:
  the Mandelstam Formula

  Pion
  Nucleon

- Nucleon EM Form Factors in the spacelike and timelike regions
  including valence and nonvalence vertex functions

- Longitudinal and transverse quark momentum distributions in the nucleon

- Conclusion & Perspectives

The Mandelstam Formula for the EM current

It yields a covariant expression of the em current for hadrons.

A first application $\Rightarrow$ Pion

In the TL region one has

$$j^\mu = -\imath 2e\frac{m^2}{f_\pi^2}N_c\int\frac{d^4k}{(2\pi)^4}\Lambda_{\overline{\pi}}(k-P_\pi,P_{\overline{\pi}})\overline{\Lambda}_\pi(k,P_\pi)\times$$
$$Tr[S(k-P_\pi)\,\gamma^5 S(k-q)\,\mathcal{I}^\mu(k,q)\,S(k)\,\gamma^5]$$

- $S(p)=\dfrac{1}{\not p - m + \imath\epsilon}$ is the constituent quark propagator
- $\gamma_5\,\Lambda_\pi(k,P_\pi)=\lambda_\pi(k,P_\pi)$ is the pion vertex function;

  P^μ_π and $P^\mu_{\overline{\pi}}$ are the pion momenta.

  γ_5 is the Dirac structure in $\lambda_\pi(k,P_\pi)$, from a simple effective quark-pion Lagrangian
- $\mathcal{I}^\mu(k,q)$ is the quark-photon vertex (q^μ the virtual photon momentum)

Instead of the $q^+=0$ frame (the usual choice within LF) for a unified investigation of SL and TL regions we use a reference frame where

$$q^+>0\,,\quad \mathbf{q}_\perp=0$$

(F.M. Lev, E. Pace and G. Salme', NPA 641 (1998) 229).

Nucleon

The Dirac structure of the quark-nucleon vertex is suggested, as in the case of the quark-pion vertex, by an effective Lagrangian (de Araujo et al., PLB B478 (2001) 86)

$$\mathcal{L}_{eff}(x) = \frac{\epsilon_{abc}}{\sqrt{2}} \int d^4x_1\, d^4x_2\, d^4x_3\; \mathcal{F}(x_1, x_2, x_3, x) \times$$
$$\sum_{\tau_1,\tau_2,\tau_3} \Big[m_N\, \alpha\; \bar{q}^a_{\tau_1}(x_1)\, \gamma^5\, q^{b\,C}_{\tau_2}(x_2)\, \bar{q}^c_{\tau_3}(x_3)\; -$$
$$\frac{(1-\alpha)}{\sqrt{3}}\, \bar{q}^a_{\tau_1}(x_1)\, \gamma^5\, \gamma_\mu\, q^{b\,C}_{\tau_2}(x_2) \cdot \bar{q}^c_{\tau_3}(x_3)\, (-\imath\, \partial^\mu) \Big]\, \psi^N_{\tau_N}(x)$$
$$+\; \ldots$$

which corresponds to a $T_{12} = 0$, $S_{12} = 0$ quark pair.

For the present time : $\alpha = 1.$

Then, the Bethe-Salpeter amplitude for the nucleon can be approximated as follows

$$\Phi^\sigma_N(k_1, k_2, k_3, P_N) = \imath \Big[S(k_1)\, \tau_y\, \gamma^5\, S_C(k_2)C \otimes S(k_3) +$$
$$S(k_3)\, \tau_y\, \gamma^5\, S_C(k_1)C \otimes S(k_2) + S(k_3)\, \tau_y\, \gamma^5\, S_C(k_2)C \otimes S(k_1) \Big]$$
$$\times\; \Lambda(k_1, k_2, k_3)\, \chi_{\tau_N}\, U_N(P_N, \sigma)$$

with a symmetrized Dirac structure of the qqq-nucleon vertex.

$\Lambda(k_1, k_2, k_3)$ describes the symmetric momentum dependence of the vertex function upon the quark momentum variables, k_i

$U_N(P_N, \sigma)$ and χ_{τ_N} are the nucleon spinor and isospin eigenstates.

Spacelike nucleon em form factors

are evaluated from the matrix elements of the macroscopic current

$$\langle \sigma', P'_N | j^\mu \, | P_N, \sigma \rangle = \bar{U}_N(P'_N, \sigma') \left[-F_2(q^2) \, \frac{{P'_N}^\mu + {P_N}^\mu}{2M_N} + \right.$$

$$\left. \left(F_1(q^2) + F_2(q^2)\right) \, \gamma^\mu \right] U_N(P_N, \sigma)$$

which are approximated microscopically by the Mandelstam formula

$$\langle \sigma', P'_N | j^\mu \, | P_N, \sigma \rangle = \int \frac{d^4 k_1}{(2\pi)^4} \int \frac{d^4 k_2}{(2\pi)^4} \, \Sigma \left\{ \bar{\Phi}^{\sigma'}_N(k_1, k_2, k'_3, P'_N) \right.$$

$$\left. \times \, S^{-1}(k_1) \, S^{-1}(k_2) \, \mathcal{I}^\mu(k_3, q) \;\; \Phi^\sigma_N(k_1, k_2, k_3, P_N) \right\} \;\; 3 \, N_c$$

where $\mathcal{I}^\mu(k_3, q)$ is the quark-photon vertex.

⋆ ⋆ ⋆ An important issue: the instantaneous contributions.

Let us consider the free Dirac propagator

$$\frac{\not{k} + m}{k^2 - m^2 + \imath\epsilon} \;=\; \frac{\not{k}_{on} + m}{k^+(k^- - k^-_{on} + \frac{\imath\epsilon}{k^+})} \;+\; \frac{\gamma^+}{2k^+}$$

Instantaneous term in the free propagator ↑

The Fourier transform on k^- of the second term contains: $\delta(x^+)$.

Reference frame : $\mathbf{q}_\perp = 0 \qquad q^+ = |q^2|^{1/2}$

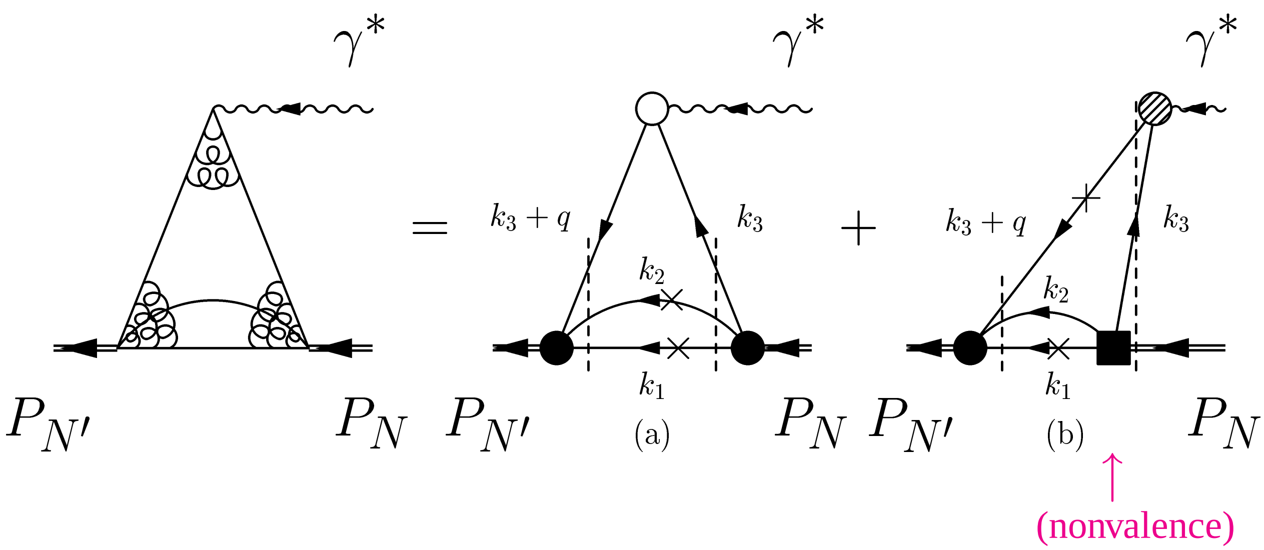
Quark mass : $m_u = m_d = 200 \; MeV$.

Projection of the Mandelstam Formula on the Light Front

We project out the Mandelstam Formula by the integration on k_1^- and k_2^-, taking into account only the poles of the propagators. Then the vertex functions have only a three-momentum dependence.

Spacelike Region

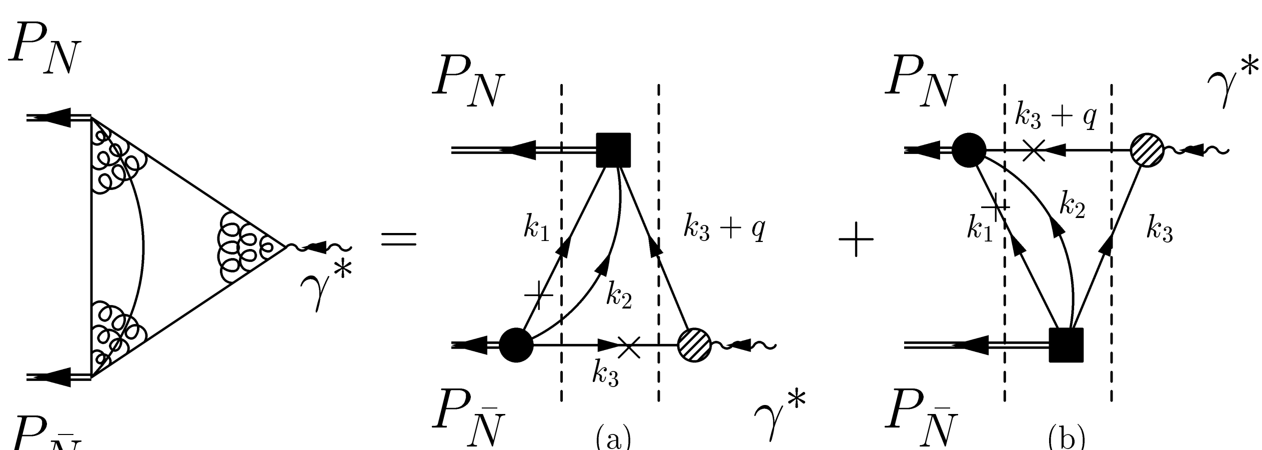
Triangle contr. Pair contr. (Z-diagr.)



(val.) $0 < k_i^+ < P_N^+$ $\qquad$ $0 > k_3^+ > -q^+$

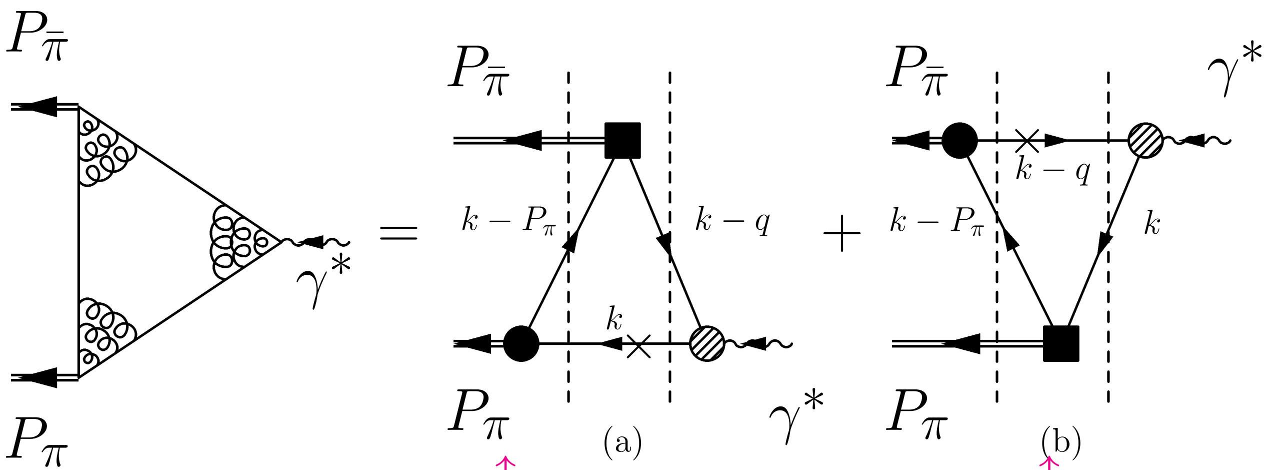
$\times \quad \Rightarrow \quad k$ on the mass shell : $k_{on}^- = (m^2 + k_\perp^2)/k^+$

Timelike Region



$P_N^+ < k_3^+ + q^+ < q^+$ $\qquad$ $0 < k_3^+ + q^+ < P_N^+$

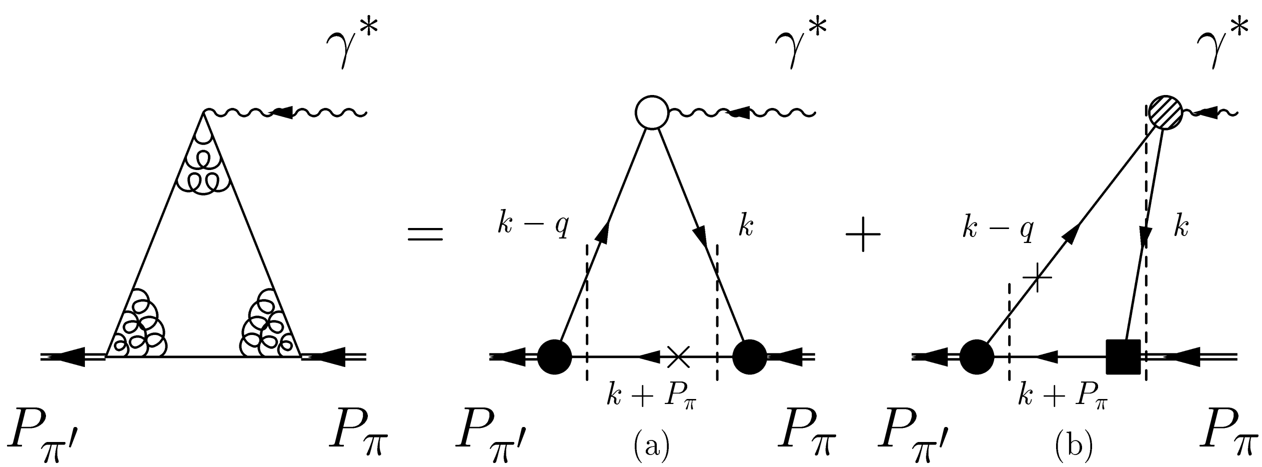
Timelike region



(val.) $\uparrow$ $0 < k^+ < P_\pi^+$ (nonval.) $\uparrow$ $P_\pi^+ < k^+ < q^+$

$\times \Rightarrow k$ on its mass shell : $k^-_{on} = (m^2 + k^2_\perp)/k^+$

Spacelike region



$\uparrow$ (nonvalence)

(val.) $0 < k^+ + P_\pi^+ < P_\pi^+$ $\quad$ $P_\pi^+ < k^+ + P_\pi^+ < P_{\pi'}^+$

We adopt a frame where $\mathbf{P}_{\pi\perp} = \mathbf{q}_\perp = \mathbf{0}$.

In the limit $m_\pi \to 0$, both in TL and SL regions, only diagram (b) contributes, i.e the one where the nonvalence component (higher Fock component) is acting. Therefore, the quark-photon vertex is dominated by the $q\bar{q}$ production.

Quark-Photon Vertex

$$\mathcal{I}^{\mu} = \mathcal{I}^{\mu}_{IS} + \tau_z \mathcal{I}^{\mu}_{IV}$$

each term contains a purely valence contribution (in the SL region only) and a contribution corresponding to the pair production (or Z-diagram).

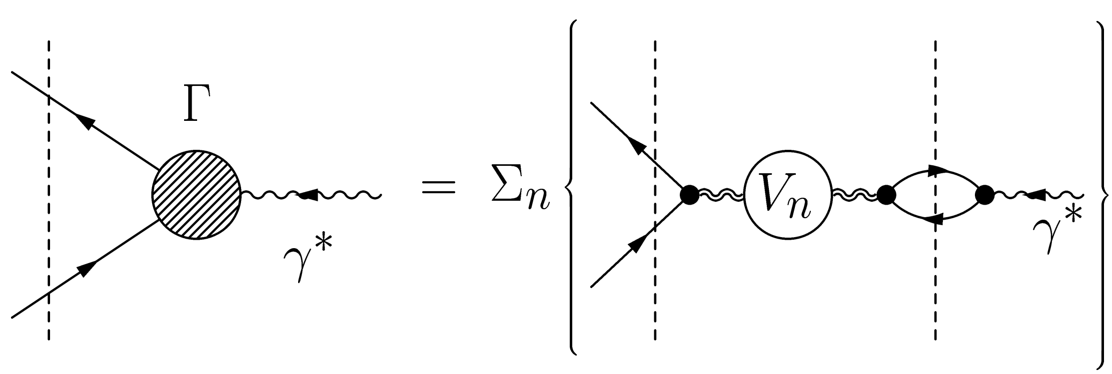
The Z-diagram contribution can be decomposed in a bare term + a Vector Meson Dominance term (according to the decomposition of the photon state in bare, hadronic [and leptonic] contributions), viz

$$\mathcal{I}^{\mu}_{i}(k,q) = \mathcal{N}_i \, \theta(P^+_N - k^+) \, \theta(k^+) \, \gamma^{\mu} \; +$$
$$+ \, \theta(q^+ + k^+) \, \theta(-k^+) \, \left\{ Z_B \, \mathcal{N}_i \, \gamma^{\mu} + Z^i_{VM} \, \Gamma^{\mu}[k,q,i] \right\}$$

$$i = IS, IV$$

with $\mathcal{N}_{IS} = 1/6$ and $\mathcal{N}_{IV} = 1/2$. The constants Z_B (bare term) and Z^i_{VM} (VMD term) are unknown weights to be extracted from the phenomenological analysis of the data.

According to i the VMD term $\Gamma^{\mu}[k,q,i]$ includes isovector or isoscalar mesons.



$$\Gamma^\mu(k,q,i) = \sqrt{2}\sum_{n,\lambda} [\epsilon_\lambda \cdot \mathcal{V}(k,q)]\ \Lambda^i_n(k,P^i_n) \times$$
$$\frac{[\epsilon^\mu_\lambda]^* f^i_{Vn}}{(q^2 - M^2_{i,n} + \imath\, M_{i,n}\tilde{\Gamma}^i_n(q^2))} \qquad (1)$$

- f^i_{Vn} is the decay constant of the n-th vector meson into a virtual photon (to be calculated in our model **!**), $M_{i,n}$ the mass, $\tilde{\Gamma}^i_n(q^2) = \Gamma^i_n\ q^2/M^2_{i,n}$ (for $q^2 > 0$) the corresponding total decay width and $\epsilon_\lambda(P^i_n)$ the VM polarization
- $\left[\epsilon_\lambda(P^i_n) \cdot \mathcal{V}(k,q)\right]\ \Lambda^i_n(k,P^i_n) \equiv$ VM vertex function.

To have a conserved current, we take

$$\mathcal{V}^\mu(k,q) = V^\mu(k,q) - \frac{q^\mu}{q^2}\, q\cdot V(k,q) \qquad (q\cdot\mathcal{V}=0)$$

This definition generate no divergence at the photon point in our reference frame : $\mathbf{q}_\perp = 0 \qquad q^+ = |q^2|^{1/2}$

We assume

$$V^\mu(k,q) = \gamma^\mu - \frac{k^\mu_{on} - (q-k)^\mu_{on}}{M_0(k^+,\mathbf{k}_\perp;q^+,\mathbf{q}_\perp) + 2m}\ ,$$

to generate the proper Melosh rotations for $^3S_1$ states. M_0 is the standard light-front free mass. [W. Jaus, PRD 41 (1990) 3394)]

$\Lambda^i_n(k,P^i_n)$ is the momentum-dependent part of the VM Bethe-Salpeter amplitude.

In the valence sector, $0 < k^+ < P_n^{i+}$, the on-shell amplitude of the VM has been related to the light-front VM wave function

$$\frac{P_n^{i+} \quad \Lambda_n^i(k, P_n^i)\big|_{[k^-=k^-_{on}]}}{[M_n^2 - M_0^2(k^+, \mathbf{k}_\perp; P_n^{i+}, \mathbf{P}^i_{n\perp})]} = \psi_n^i(k^+, \mathbf{k}_\perp; P_n^{i+}, \mathbf{P}^i_{n\perp})$$

$$\psi_n^i(k^+, \mathbf{k}_\perp; P_n^{i+}, \mathbf{P}^i_{n\perp}) \quad \text{is}$$

- eigenfunction of a relativistic CQ square mass operator (Frederico, Pauli & Zhou, PRD 66 (2002) 116011), with confinement (harmonic oscillator potential) and $\pi - \rho$ splitting (Dirac-delta interaction in the pseudoscalar channel). A natural explanation of the "Iachello-Anisovitch law" ($M_n^2 \sim M_{gr}^2 + \omega\ (n-1)$; n is the radial quantum number) is obtained. In the π form factor calculation no isospin breaking was considered ($\rho \equiv \omega$).

- normalized to the probability of the lowest $(q\bar{q})$ Fock state (i.e. the valence component), roughly estimated in a simple model (de Melo et al., PRD 73 (2006) 074013) that reproduces the "Iachello-Anisovitch law", for the VM mass spectra.

Vector-meson valence probabilities $P_{q\bar{q};n}$ for the first resonances.

n	0	1	2	3	4	5	6
$P_{q\bar{q};n}$	0.77	0.31	0.29	0.27	0.22	0.18	0.18

Fixed parameters

$m_u = m_d = 0.200\ GeV$

Experimental vector-meson masses, M_n^{IV} , and widths, Γ_n^{IV} , for the first four isovector vector mesons.

Meson	M_n^{IV} (MeV)	$M_n^{\exp}$ (MeV)	Γ_n^{IV} (MeV)	$\Gamma_n^{\exp}$ (MeV)
$\rho(770)$	770	775.8 ± 0.5	146.4	146.4 ± 1.5
$\rho(1450)$	1497*	1459.0 ± 11.0	226*	147 ± 40
$\rho(1700)$	1720	1720.0 ± 20.0	220	250 ± 100
$\rho(2150)$	2149	2149.0 ± 17	230**	363 ± 50

Isoscalar masses, M_n^{IS}, and widths, Γ_n^{IS}, for the first 3 IS mesons.

Meson	M_n^{IS} (MeV)	$M_n^{\exp}$ (MeV)	Γ_n^{IS} (MeV)	$\Gamma_n^{\exp}$ (MeV)	Γ
$\omega(782)$	782	782.65 ± 0.12	8.44	8.49 ± 0.08	
$\omega'(1420)$	1420	1425.0 ± 25.0	225	215 ± 35	
$\omega''(1650)$	1720	1670.0 ± 30.0	250	315 ± 35	

From PDG 06, *Akhmetshin et al., PLB **509**, 217 (2001) and **Anisovich et al., PLB **542**, 8 (2002).

The higher VM masses are from the Frederico, Pauli, Zhou model (PRD 66 (2002) 116011).

20 isoscalar and 20 isovector vector mesons are taken into account to reach convergence up to $q^2 = 10\ (GeV/c)^2$.

We choose a unique value $\Gamma_n = 0.15\ GeV$ for the unknown vector mesons widths.

Momentum Dependence of the Bethe-Salpeter Amplitudes

In the valence vertex ● the spectator quarks are on the k^--shell, and the momentum dependence, reduced to a 3-momentum dependence by the k^- integrations, is approximated through a Nucleon Wave Function a la Brodsky (PQCD inspired), namely

$$\Psi_N(\tilde{k}_1, \tilde{k}_2, P_N) = P_N^+ \frac{\Lambda(k_1, k_2, k_3)|_{(k_{1on}^-, k_{2on}^-)}}{[M_N^2 - M_0^2(1,2,3)]} =$$

$$= P_N^+ \mathcal{N} \frac{(9\, m^2)^{7/2}}{(\xi_1 \xi_2 \xi_3)^p \; [\beta^2 + M_0^2(1,2,3)]^{7/2}}$$

where $\tilde{k}_i \equiv (k_i^+, \mathbf{k}_{i\perp})$, $M_0(1,2,3)$ is the free mass of the three-quark system,

$\xi_i = k_i^+/P_N^+ \qquad (i = 1, 2, 3)$

and $\mathcal{N}$ a normalization constant.

The power $7/2$ and the parameter $p = 0.13$ are chosen to have an asymptotic decrease of the triangle contribution faster than the dipole.

Only the triangle diagram determines the magnetic moments, weakly dependent on p. Then $\beta = 0.645$ can be fixed by μ_p and μ_n

Proton : 2.87±0,02 (Exp. 2.793)

Neutron : -1.85±0,02 (Exp. -1.913)

For the Z-diagram contribution, the nonvalence vertex ■ is needed. It can depend on the available invariants. In the spacelike region it can depend on the free mass of the (1,2) quark pair, $M_0(1,2)$, and the free mass of the (nucleon - quark $\bar{3}$) system entering the nonvalence vertex, $M_0(N,\bar{3})$.

Then in the spacelike region we approximate the momentum dependence of the nonvalence vertex by

$$\Lambda^{SL}_{NV}(k_1,k_2,k_3) = [g_{12}]^2\ [g_{N\bar{3}}]^{7/2-2}\ \left[\frac{k^+_{12}}{P'^+_N}\right]\left[\frac{P'^+_N}{k^+_{\bar{3}}}\right]^r\left[\frac{P^+_N}{k^+_{\bar{3}}}\right]^r$$

$$k^+_{12} = k^+_1 + k^+_2 \qquad g_{AB} = \frac{(m_A\, m_B)}{[\beta^2 + M^2_0(A,B)]}$$

The power 2 of $[g_{12}]^2$ is suggested from counting rules.
The power 3/2 of $[g_{N\bar{3}}]^{3/2}$ and the parameter $r = 0.17$ are chosen to have a dipole behavior for the nonvalence contribution.

In the timelike region the nonvalence vertex can depend on the mass of the (nucleon - qq pair) system . Then by analogy we approximate the nonvalence vertex in diagram (a) by

$$\Lambda^{TL}_{NV}(k_1,k_2,k_3) = 2\ [g_{\bar{1}\bar{2}}]^2\ [g_{N,\overline{12}}]^{3/2}\left[\frac{-k^+_{12}}{P^+_{\bar{N}}}\right]\left[\frac{P^+_N}{k'^+_3}\right]^r\left[\frac{P^+_{\bar{N}}}{k'^+_3}\right]^r$$

An analogous expression is used for diagram (b).

Adjusted parameters (in the SL region)

- the weights for the pair-production terms :

$Z_B = Z^{IV}_{VM} = 2.283$ and

$Z^{IS}_{VM} / Z^{IV}_{VM} = 1.12$

- the power $p = 0.13$ of ξ_i in the valence amplitude
- the power $r = 0.17$ of the ratio P^+_N / k^+_3 in the spacelike nonvalence vertex, to have a dipole asymptotic behaviour of the pair-production contribution

$$\Rightarrow \qquad \chi^2 = 1.7$$

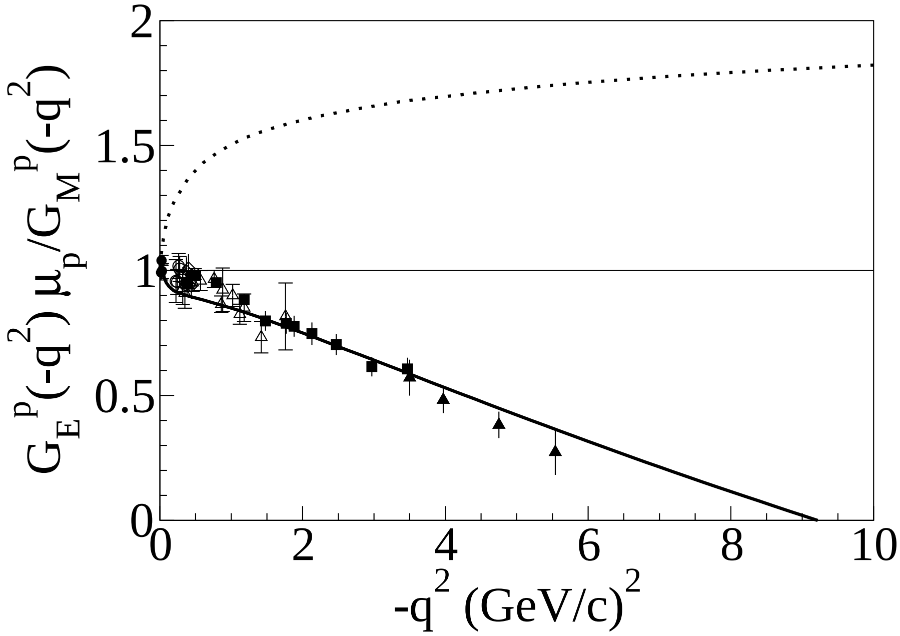
Results for nucleon radii

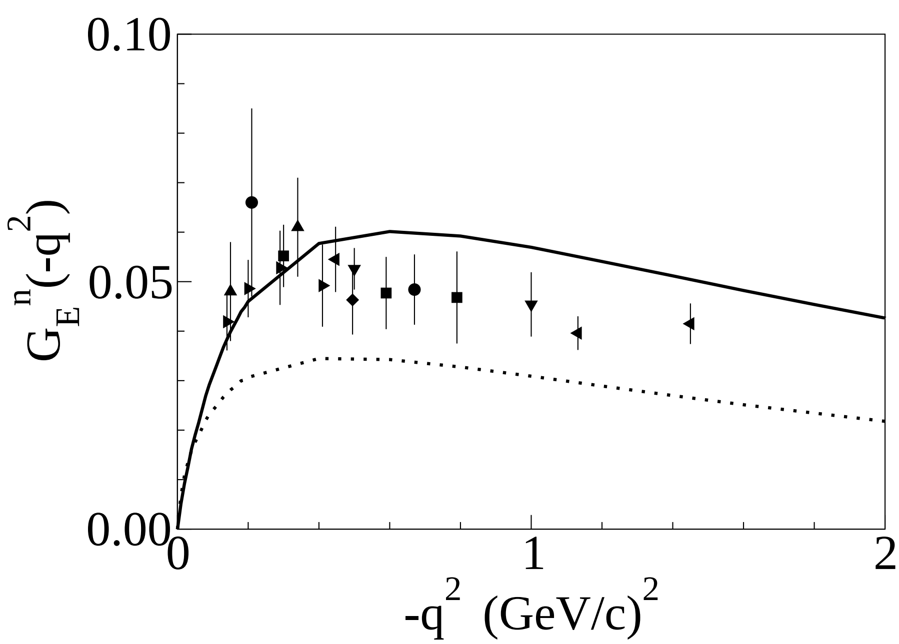
$r_p = (0.903 \pm 0.004)\ fm \qquad r_p^{exp} = (0.895 \pm 0.018)\ fm$

$$-\left[\frac{dG^n_E(Q^2)}{dQ^2}\right]^{th} = (0.501 \pm 0.002)\ (GeV/c)^{-2}$$

$$-\left[\frac{dG^n_E(Q^2)}{dQ^2}\right]^{exp} = (0.512 \pm 0.013)\ (GeV/c)^{-2}$$

Nucleon electric form factors





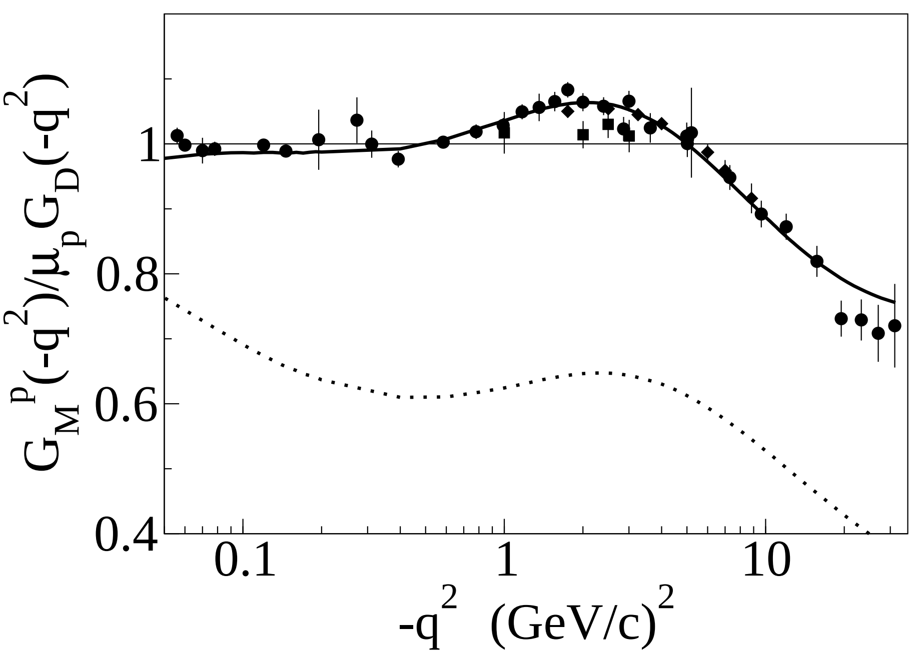
Solid line: full calculation $\equiv \mathcal{F}_{\triangle} + \mathcal{F}_{bare} + \mathcal{F}_{VMD}$

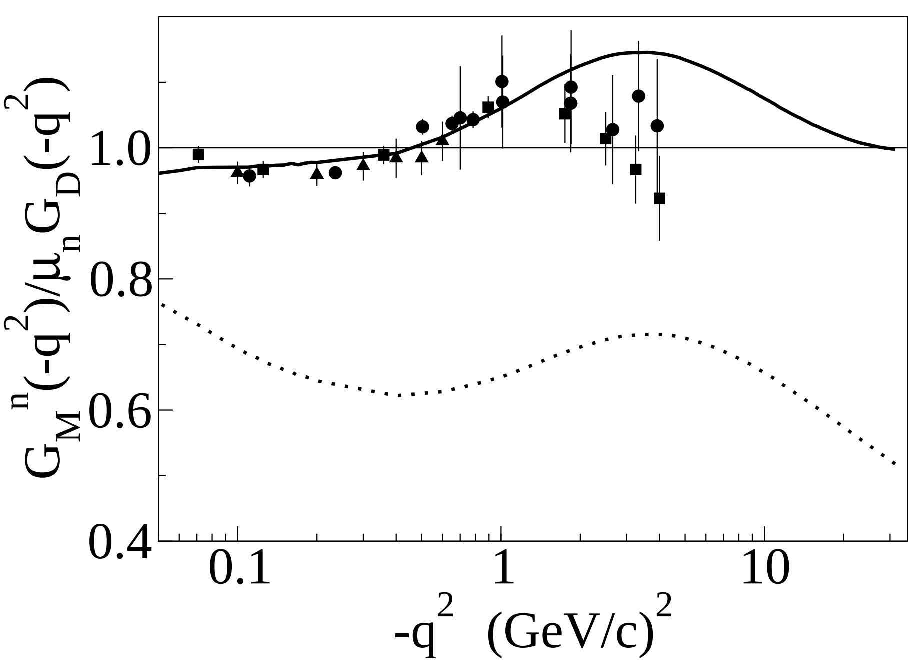
Dotted line: $\mathcal{F}_{\triangle}$ (triangle contribution only)

Data: www.jlab.org/ cseely/nucleons.html and Refs. therein.

The possible zero in $G_E^p \mu_p / G_M^p$ is strongly related to the Z-diagram contribution, i.e. higher Fock components.

Nucleon magnetic form factors





Solid line: full calculation $\equiv \mathcal{F}_{\triangle} + \mathcal{F}_{bare} + \mathcal{F}_{VMD}$

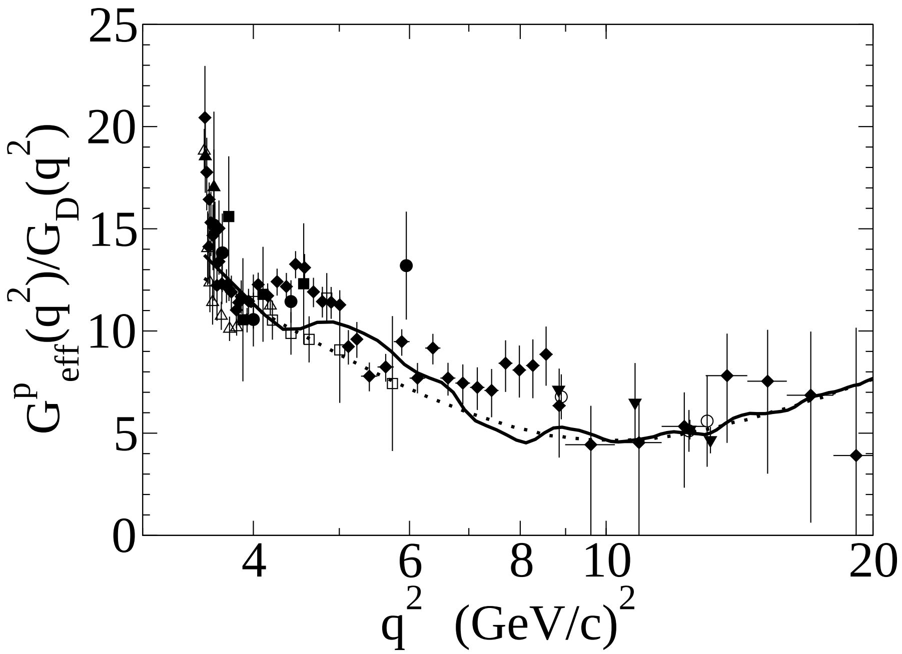
Dotted line: $\mathcal{F}_{\triangle}$ (triangle contribution only)

The pair-production contribution is essential for the result

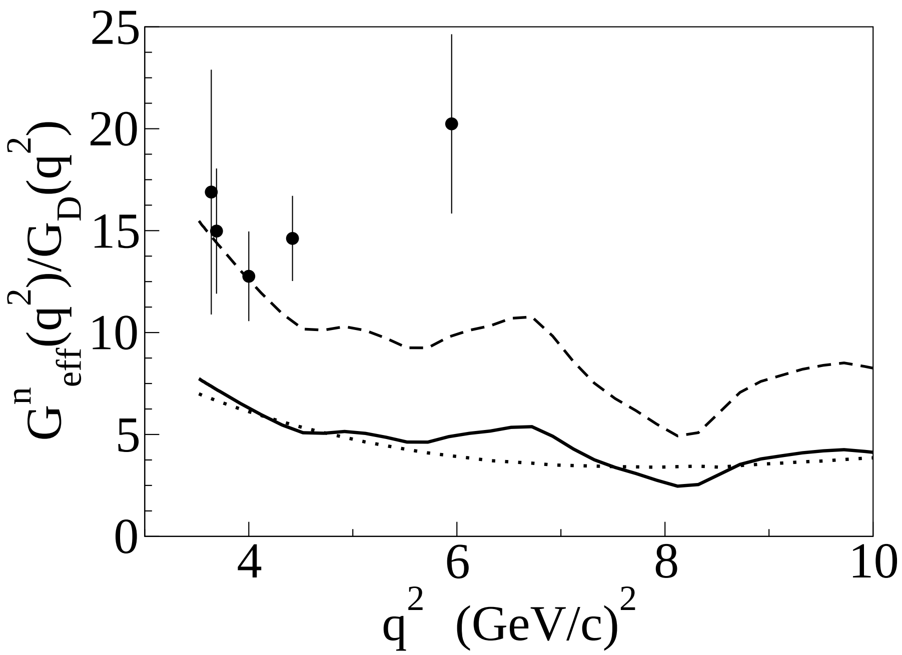
$G_D = 1/[1 - q^2/(0.71\ (GeV/c)^2)]^2$

Nucleon timelike form factors

parameter free results



Missing strength at $q^2 = 4.5\ (GeV/c)^2$ and $q^2 = 8\ (GeV/c)^2$

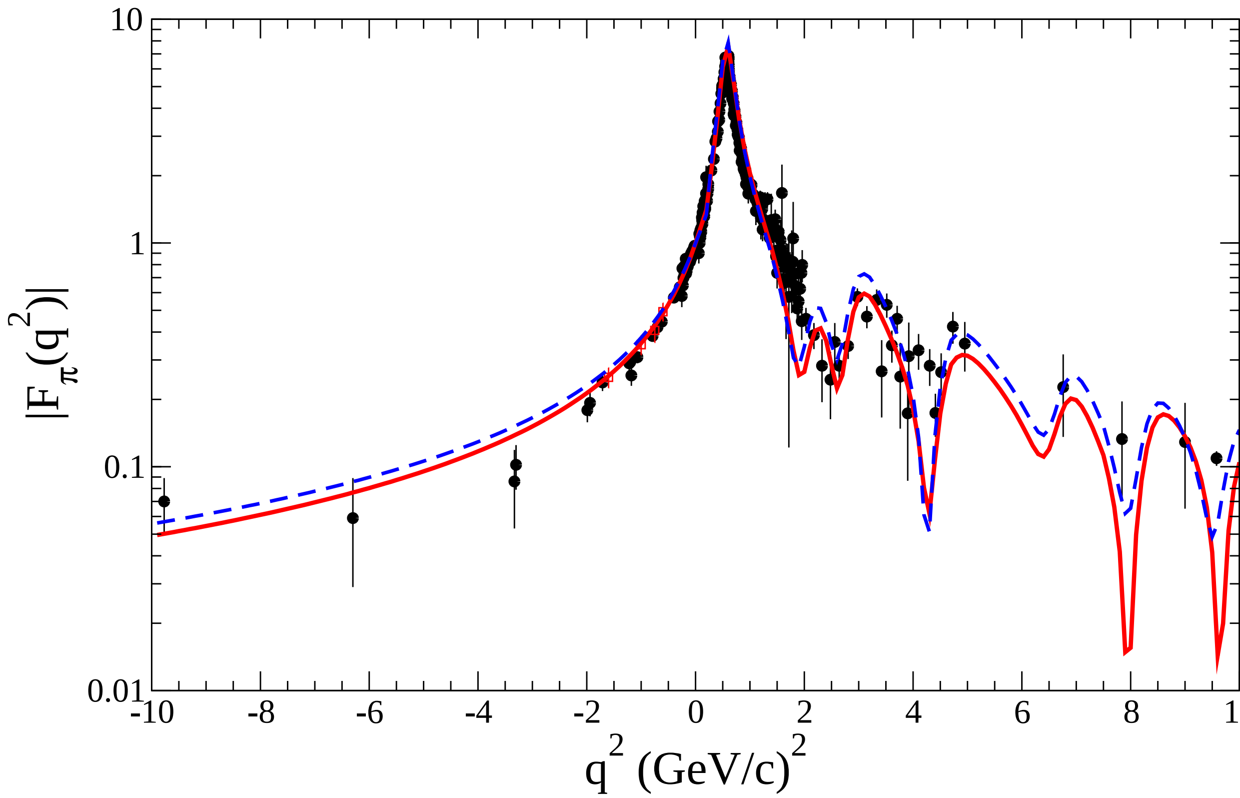


$$G^2_{eff}(q^2) = \frac{|G_M(q^2)|^2 + |G_E(q^2)|^2 \frac{2m_N^2}{q^2}}{1 + \frac{2m_N^2}{q^2}}$$

Pion EM Form Factor

i) From the Mandelstam formula, ii) taking into account only the poles of Dirac propagators in the k^- integration

and iii) in the limit $m_\pi \to 0$ we obtain



Data, R. Baldini et al. (EPJ. C11 (1999) 709, and Refs. therein.)

For the nonvalence vertex (■), we assumed a constant [Choi & Ji (PLB 513 (2001) 330)].

Solid line: calculation with the pion w.f. from the model of Frederico et al. PRD66 (2002) 116011 for the valence vertex (●)

Dashed line: $\Lambda_\pi(k; P_\pi) = 1$ in the valence vertex

One can define the distributions $H^q(x,\xi,t)$ and $E^q(x,\xi,t)$ for the quark q through the following relation

$$\bar{u}(P'_N,\lambda'_N)\left[H^q(x,\xi,t)\,\gamma^+ + E^q(x,\xi,t)\,\imath\,\frac{\sigma^{+\alpha}q_\alpha}{2M_N}\right]u(P_N,\lambda_N) =$$

$$2P^+\int\frac{dz^-}{4\pi}e^{ixP^+z^-}\ \langle P'_N,\lambda'_N|\bar{\psi}_q(-\frac{1}{2}z)\gamma^+\,\psi_q(\frac{1}{2}z)|P_N,\lambda_N\rangle\Big|_{\tilde{z}=0},$$

where λ_N is the nucleon helicity,

$$P = \frac{1}{2}(P'_N + P_N) \qquad t = q^2$$

$$\xi = -\frac{q^+}{2P^+}$$

$$x = \frac{k^+}{P^+}$$

and k is the average momentum of the active quark,

$$k = \frac{k_3 + k_3 + q}{2}$$

For $P'_N = P_N$, both q^+ and ξ are vanishing and $x = k_3^+/P_N^+ = \xi_3$ coincides with the Bjorken variable.

Then the unpolarized generalized parton distribution $H^q(x,\xi,t)$ reduces to the longitudinal parton distribution function $q(x)$.

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

$$q(x) = \int\frac{dz^-}{4\pi}e^{ixP_N^+z^-}\ \langle P_N|\bar{\psi}_q(0)\gamma^+\,\psi_q(z)|P_N\rangle\big|_{\tilde{z}=0}$$

where an average on the nucleon helicities is understood.

In our model it is easy to obtain the transverse momentum distribution and the longitudinal parton distribution of the active quark from the nucleon light-front wave function $\Psi_N(\tilde{k}_1, \tilde{k}_2, P_N)$:

$$f_1^u(x, k_{perp}) = -\frac{9\ N_c}{32\ (2\pi)^6} \int_0^{1-x} d\xi_2 \frac{1}{(1-x-\xi_2)\xi_2} \frac{1}{x^2} \int d\mathbf{p}_{2\perp} \times \frac{1}{P_N^{+2}} \left|\Psi_N(P_N^+\ \xi_1, \mathbf{p}_{1\perp}, P_N^+\ \xi_2, \mathbf{p}_{2\perp}, P_N)\right|^2 \ \ \mathcal{H}_u|_{(k_{1on}^-, k_{2on}^-)}$$

and

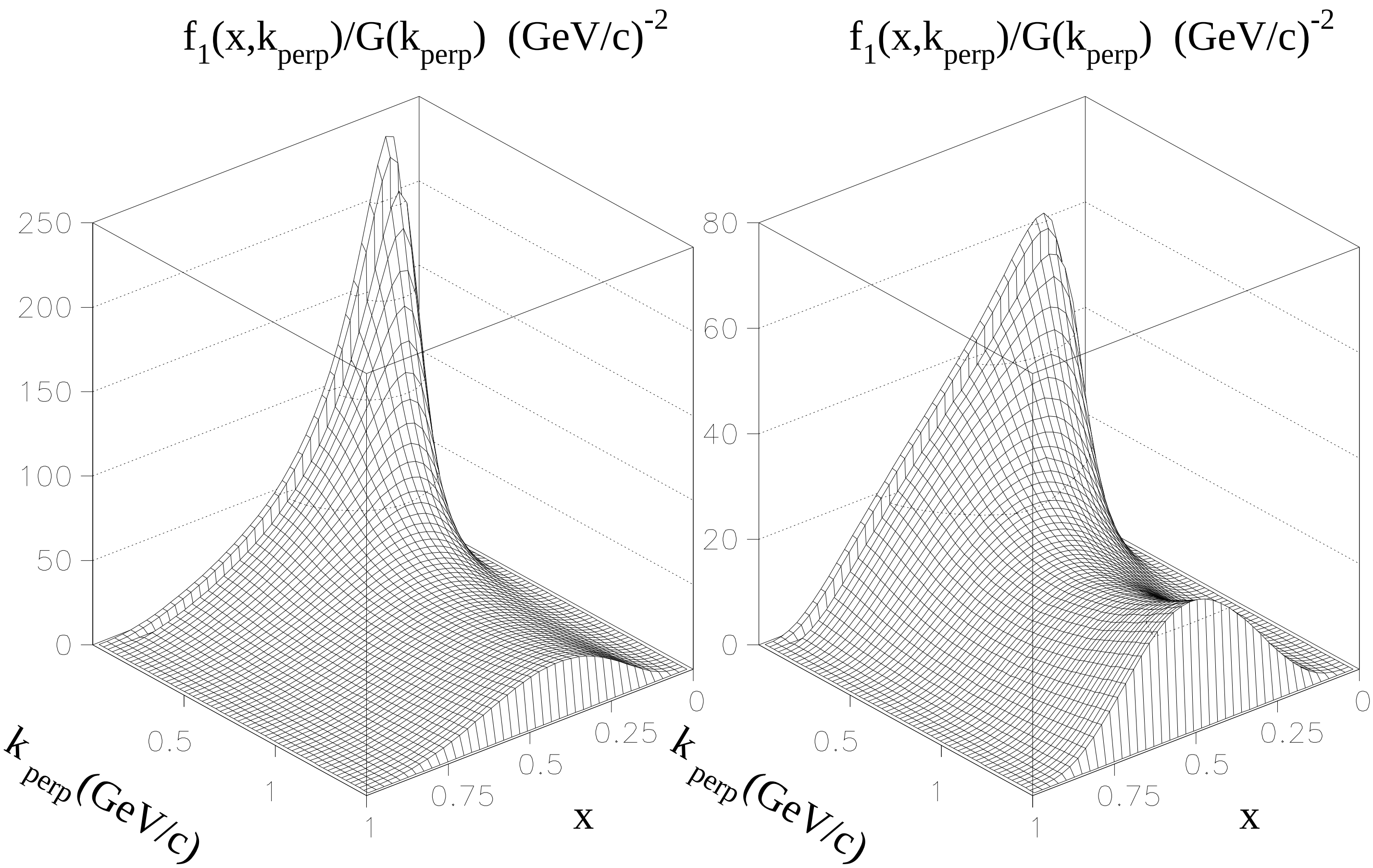
$$f_1^d(x, k_{perp}) = \frac{9\ N_c}{8\ (2\pi)^6} \int_0^{1-x} d\xi_2 \frac{1}{(1-x-\xi_2)\xi_2} \frac{1}{x^2} \int d\mathbf{p}_{2\perp} \times \frac{1}{P_N^{+2}} \left|\Psi_N(P_N^+\ \xi_1, \mathbf{p}_{1\perp}, P_N^+\ \xi_2, \mathbf{p}_{2\perp}, P_N)\right|^2 \ \ \mathcal{H}_d|_{(k_{1on}^-, k_{2on}^-)}$$

$$q(x) = \int d\mathbf{k}_{perp}\ \ f_1^q(x, k_{perp})$$

where $\mathcal{H}_u$ and $\mathcal{H}_d$ are proper traces of propagators and of the currents $\mathcal{I}_u^+$ and $\mathcal{I}_d^+$, respectively.

Transverse momentum distributions in the proton
preliminary results

u quark　　　　*d* quark



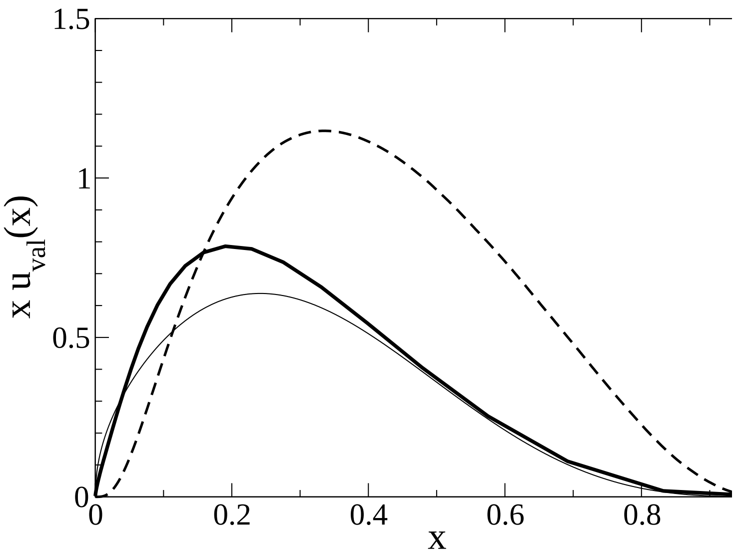
$G(k_{perp}) = (1 + k_{perp}^2/m_\rho^2)^{-5.5}$

The decay of our $f_1(x, k_{perp})$ as a function of k_{perp} is faster than in diquark models of nucleon (Jacob et al., Nucl Phys. A626 (1997) 937), while it decays slowly with respect to factorization models for thensverse momentum sistributions (Anselmino et al., PRD 74 (2006) 074015).

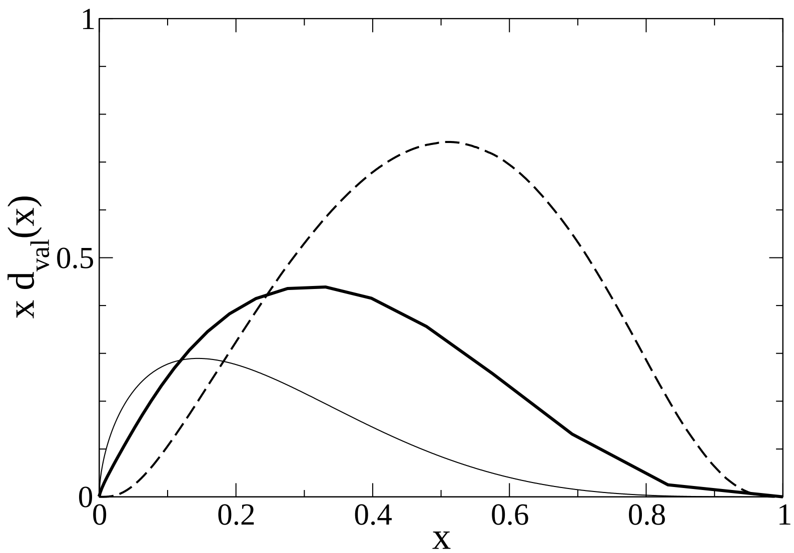
Longitudinal momentum distributions in the proton

preliminary results

u quark



d quark



Dashed lines : our longitudinal momentum distributions

Thick solid lines : our model after evolution to $Q^2 = 1.6$ (GeV/c)^2

Thin solid lines : CTEQ4 fit to data [Lai et al., PRD 51 (1995) 4753]

Conclusions & Perspectives

- A microscopical model for hadron em form factors in both SL and TL region has been proposed
- The quark-photon vertex for the process where a virtual photon materializes in a $q\bar{q}$ pair is approximated by a microscopic VMD model plus a bare term
- The Z-diagram (higher Fock component) is essential for both pion and nucleon, in the adopted reference frame ($q^+ \neq 0$)
- Nucleon and pion: good results in the SL region. The possible zero in $G_E^p \mu_p / G_M^p$ is related to the pair-production contribution.
- In the TL region our calculations give a fair description of the proton and pion data, although some strength is lacking for $q^2 = 4.5\ (GeV/c)^2$ and $q^2 = 8\ (GeV/c)^2$
- The analysis of nucleon form factors allows us to get a phenomenological Ansatz for the nucleon LF wave function
- This LF wave function is used to evaluate the unpolarized transverse momentum distributions and longitudinal momentum distributions in the nucleon

Next step :

the calculation of polarized momentum distributions

Further possible developments

- different Dirac structures of the effective quark-nucleon Lagrangian could be considered

- different approximations for the nucleon wave function could be tested

- a model for the vector meson spectrum, able to account for a possible resonance at $M_n = 2.050\ GeV$ should be investigated, possibly for a better description of the quark-photon vertex.

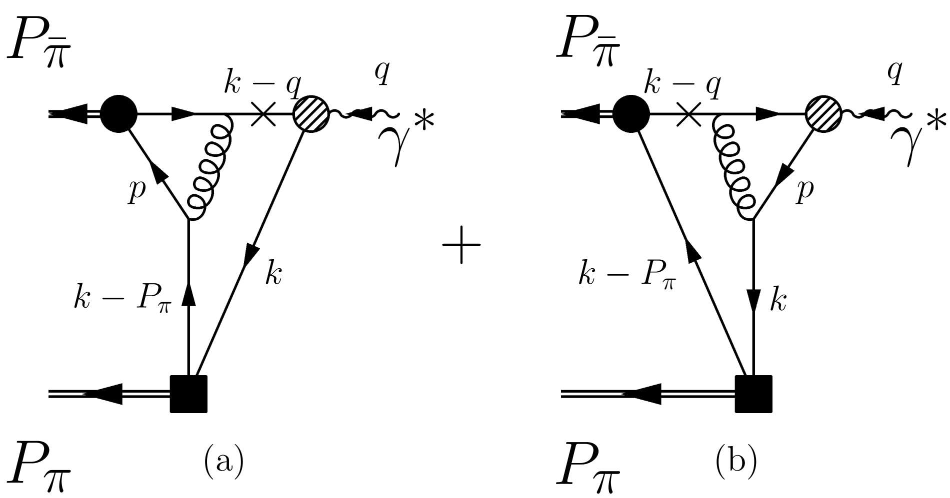
The decay constant, f_{Vn}, is evaluated assuming that:

i) $\Lambda_n(k, P_n)$ does not diverge in the k^- complex-plane for $|k^-| \to \infty$,

and ii) the contributions of its singularities in the k^- integration are negligible.

$$f_{Vn} = -\frac{N_c \, P_n^+}{4(2\pi)^3} \int_0^{P_n^+} \frac{dk^+ \, d\mathbf{k}_\perp}{k^+ \, (P_n^+ - k^+)} \frac{\Lambda_n(k, P_n)|_{[k^- = k^-_{on}]}}{[M_n^2 - M_0^2(k^+, \mathbf{k}_\perp; P_n^+, \mathbf{P}_{n\perp})]}$$
$$Tr\left[(\not k - \not P_n + m)\gamma^+(\not k + m)\widehat{V}_{nz}(k, k - P_n)\right] \, .$$

For $m_\pi \to 0$, only instantaneous contributions survive, since on-shell terms give vanishing contributions to the trace in j^μ.



Instantaneous contributions to the timelike em form factor of a massless pion. The instantaneous quark line (vertical line) is attached to the pion vertex in (a) and to VM vertex in (b). The shaded circle represents the dressed photon vertex.

We assume $\Lambda^{ist} \sim \mathcal{C}\, \Lambda^{full}$

The constant $\mathcal{C}$ is thought to roughly describe the effects of the short-range interaction.

We use the relative weight, $w_{VM} = \mathcal{C}_{VM}/\mathcal{C}_\pi$, as a free parameter.