The Light-front constituent quark model and the electromagnetic properties of the nucleon: beyond the valence component ?

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Relativistic quark models for the pion form factor in SL and TL

Phys. Lett. **B 581** (2004) 75; Phys. Rev. **D 73**, 074013 (2006)

J.P.B.C. de Melo, T. Frederico, E. Pace, G. S.

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Phys. Lett. **B 671** (2009) 153,

J.P.B.C. de Melo, T. Frederico, E. Pace, S. Pisano, G.S.

Nucleon electromagnetic form factors in the timelike region

Prog, Part. Nucl. Phys. **68**, 113-157 (2013),

Achim Denig and G.S.

Motivations and Outline

The non perturbative regime appears the most challenging, in view of the still non fully understood confinement mechanism $\Rightarrow$

Mikhail Shifman in a 2010-talk in honor of Murray Gell-Mann's 80th birthday emphasized: *Although the underlying QCD Lagrangian and asymptotic freedom, it implies at short distances, are established beyond any doubt, the road from this starting point to theoretical control over the large-distance hadronic world is long and difficult* (M. Shifman, arXiv:1007.0531)

Goal: developing a covariant framework, based on the Bethe-Salpeter Amplitudes of hadrons, or equivalently on the Light-Front wave functions (Fock expansion) that allows one to include information on hadron dynamics, extracted from processes involving em probes in both space- and time-like regions This provides a new tool for paving the way from a purely phenomenological microscopic description of the hadronic states to the one with a more consistent dynamical content.

Our strategy was:

first modeling the quark-photon vertex and the quark-hadron amplitude from an investigation of the pion EM form factor, within a Mandelstam-inspired approach. Then, moving to the nucleon case, producing true predictions for the timelike region (it contains a lot of information on mesonic spectra to be extracted...).

N.B. the approach have been extended to both Generalized Parton Distributions and transverse-momentum distributions (presently applied to the pion case, PRD **D 80** (2009) 05444021, and first results for the nucleon)

Why "beyond relativistic constituent quark models" ?

Our personal experience:the attempt to describe nucleon ff's in a relativistic constituent quark model, within a Poincare' covariant Light-front approach, using only the nucleon valence vertex function, compelled us to introduce CQ form factors..... Expected from the quasi-particle nature of CQ's (PLB **357**, 267 (1995))

Can we phenomenologically resolve the Constituent Quark ?

The Light-front framework is very suitable for an investigation of hadron EM form factors in both space- and timelike regions, beyond the valence contribution, since

one can exploits the almost "simple" LF vacuum

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

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

LF advantages:

★ A meaningful Fock expansion can be constructed: the vacuum is largely trivial, without spontaneous pair production

★ ★ The LF boosts do not contain the dynamics, and the initial and final hadronic states, in a given process, can be trivially related to their intrinsic description

The Mandelstam Formula for the EM current

Our guidance $\Rightarrow$ the Mandelstam formula, that provides a covariant expression of the em current for hadrons.

A first application $\Rightarrow$ **Pion**

In the TL region one has

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

- $S(p) = \dfrac{1}{\not p - m + \imath\epsilon}$ is the constituent quark propagator
- $\gamma_5\,\Lambda_\pi(k,P_\pi) = \lambda_\pi(k,P_\pi)$ is the pion vertex function (known caveats...), i.e.the Bethe-Salpeter Amplitude $\times\ S^{-1}(quark)S^{-1}(\overline{quark})$

  P_π^μ and $P_{\overline{\pi}}^\mu$ are the pion momenta.
- $\Gamma^\mu(k,q)$ is the quark-photon vertex (q^μ the virtual photon momentum)

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

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

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

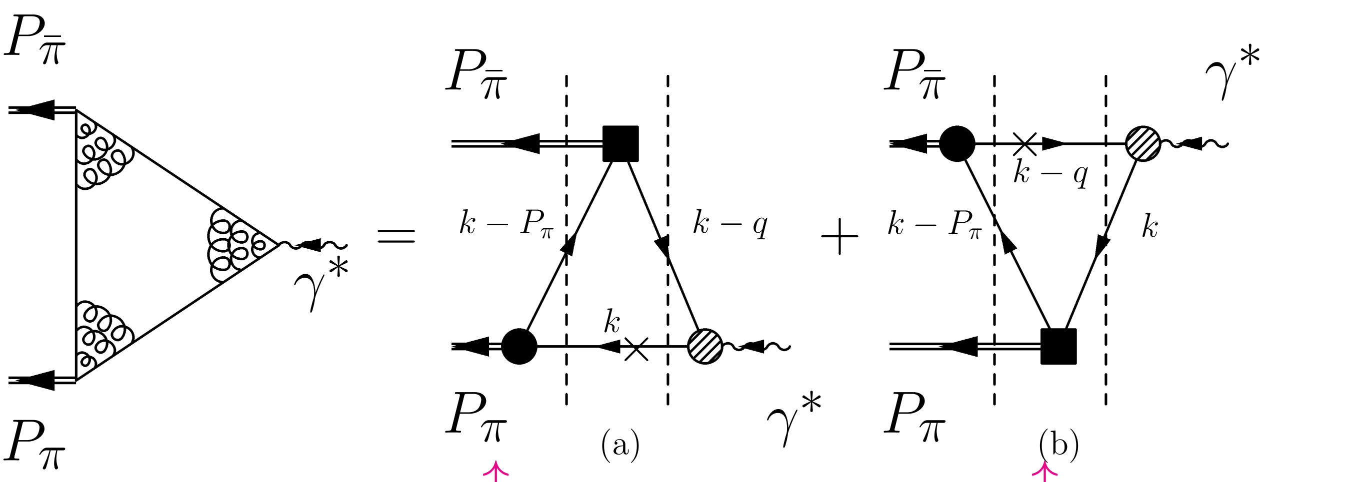
In this frame, the photon (hadronic component) allows transitions from valence to nonvalence components!

Projecting out the Mandelstam Formula onto the Light Front

...through the k^- integration. Only the poles of the Dirac propagators are considered in the k^- integration. We proved in a simple model that our reference frame is the best one for this approximation.

LF-time flows from R$\rightarrow$ L

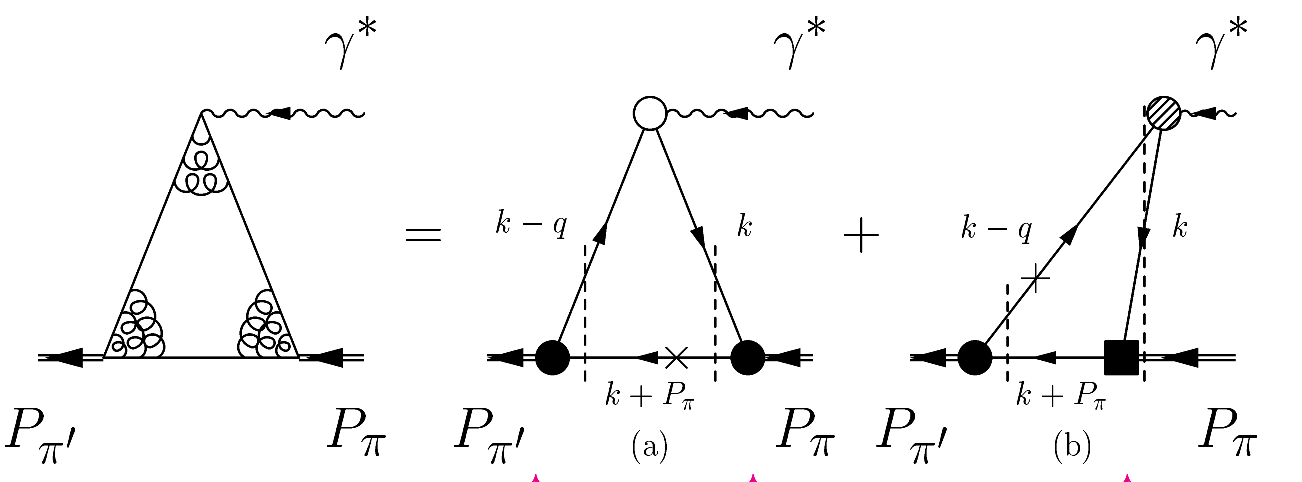
Timelike region



(●=val) ↑ $0 < k^+ < P_\pi^+$ (■ =nonval) ↑ $P_\pi^+ < k^+ < q^+$

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

Spacelike region



↑ (●=val) ↑ (■ =nonval) ↑

$0 < k^+ + P_\pi^+ < P_\pi^+$ $P_\pi^+ < k^+ + P_\pi^+ < P_{\pi'}^+$

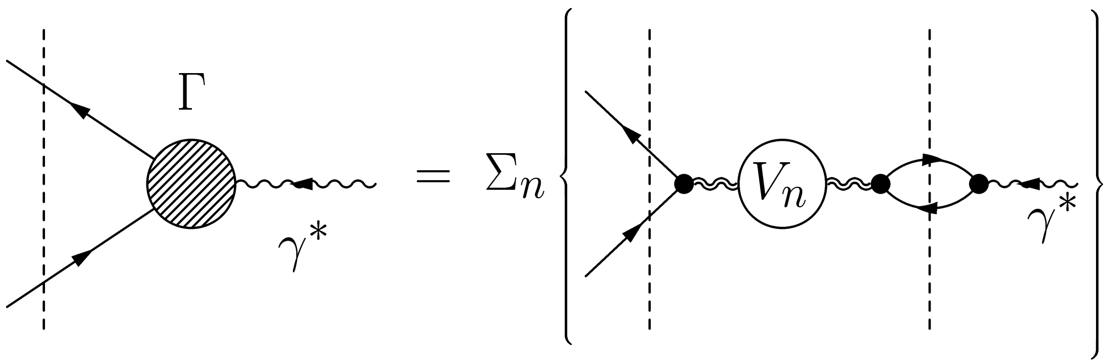
★ First Problem: How to describe the amplitude for the emission or absorption of a pion by a quark, ■ (non valence vertex), and the $q\bar{q}$-pion vertex, ● (valence vertex)

The non valence component (■) of the pion state is given by the emission (absorption) of a pion by a quark, we assume a constant interaction [Choi & Ji (PLB 513 (2001) 330)]. The coupling constant is fixed by the normalization of the pion form factor.

In the valence sector $0 < k^+ < P_\pi^+$ (●), we relate the pion vertex function $\Lambda_\pi(k, P_\pi)$ to the pion Light-Front wave function

$$\psi_\pi(k^+, \mathbf{k}_\perp; P_\pi^+, \mathbf{P}_{\pi\perp}) = \frac{m}{f_\pi} \frac{P_\pi^+ \left[\Lambda_\pi(k, P_\pi)\right]_{[k^- = k_{on}^-]}}{[m_\pi^2 - M_0^2(k^+, \mathbf{k}_\perp; P_\pi^+, \mathbf{P}_{\pi\perp})]}$$

★ ★ Second Problem: How to model the quark-photon vertex ?



⋆ When a $q\bar{q}$ pair is produced, a microscopical Vector Meson Dominance model has been adopted.

$$\Gamma^{\mu}_{VMD}(k,q) = \sqrt{2}\sum_{n,\lambda} \left[\epsilon_\lambda \cdot \widehat{V}_n(k,k-P_n)\right] \Lambda_n(k,P_n) \times \frac{[\epsilon^{\mu}_{\lambda}]^* f_{Vn}}{(q^2 - M_n^2 + \imath M_n \tilde{\Gamma}_n(q^2))}$$

★ f_{Vn} is the decay constant of the n-th vector meson into a virtual photon (to be calculated in our model !), M_n the mass, $\tilde{\Gamma}_n(q^2) = \Gamma_n\; q^2/M_n^2$ (for $q^2 > 0$) the corresponding total decay width and $\epsilon_\lambda(P_n)$ the VM polarization

★★ $\left[\epsilon_\lambda(P_n) \cdot \widehat{V}_n(k,k-P_n)\right] \Lambda_n(k,P_n) \equiv$ VM vertex function.

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

generates the proper Melosh rotations for ${}^3S_1$ states. M_0 is the standard Light-Front free mass. [W. Jaus, PRD 41 (1990) 3394)]

★★★ $\Lambda_n(k,q)$ is the momentum-dependent part of the VM Bethe-Salpeter amplitude.

In the valence sector, $0 < k^+ < P_n^+$, the (3D) on-shell amplitude of the VM has been related to the Light-Front VM wave function

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

N.B. M_n and ψ_n are eigenvalues and eigenvectors of a LF Maas operator obtained by Frederico, Pauli, Zhou model (PRD 66 (2002) 116011)

Pion EM Form Factor

in the space- and time-like regions

Fixed parameters

$m_u = m_d = 0.200\ GeV$ in this presentation. According to the choice for the nucleon. Results very close to the old ones (PLB (2004) and PRD (2006))

Experimental vector-meson masses, M_n , and widths, Γ_n , for the first four vector mesons (PDG '08).

Meson	M_n (MeV)	M_n^{exp} (MeV)	Γ_n (MeV)	Γ_n^{exp} (MeV)
$\rho(770)$	770	775.8 ± 0.5	146.4	146.4 ± 1.5
$\rho(1450)$	1497^{*}	1465.0 ± 25.0	226^{*}	400 ± 60
$\rho(1700)$	1720	1720.0 ± 20.0	220	250 ± 100
$\rho(2150)$	2149	2149.0 ± 17	230^{**}	363 ± 50

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

20 vector mesons are taken into account to reach convergence up to $q^2 = 10\ (GeV/c)^2$. The VM masses for $M_n > 2150\ MeV$ are from the Frederico, Pauli, Zhou model (PRD 66 (2002) 116011).

Adjusted parameters

1. The width, Γ_n, of the vector mesons with mass $> 2.150\ GeV$. The chosen value $\Gamma_n = 0.15\ GeV$ is similar to the width of the first four VM's

2. w_{VM}, that weights the two instantaneous contributions. We used $w_{VM} = -1.0$ for a global fit. For an improved description of the ρ peak region one should add IS mesons, ϕ and the triangle term, disregarded for $m_\pi \to 0$.

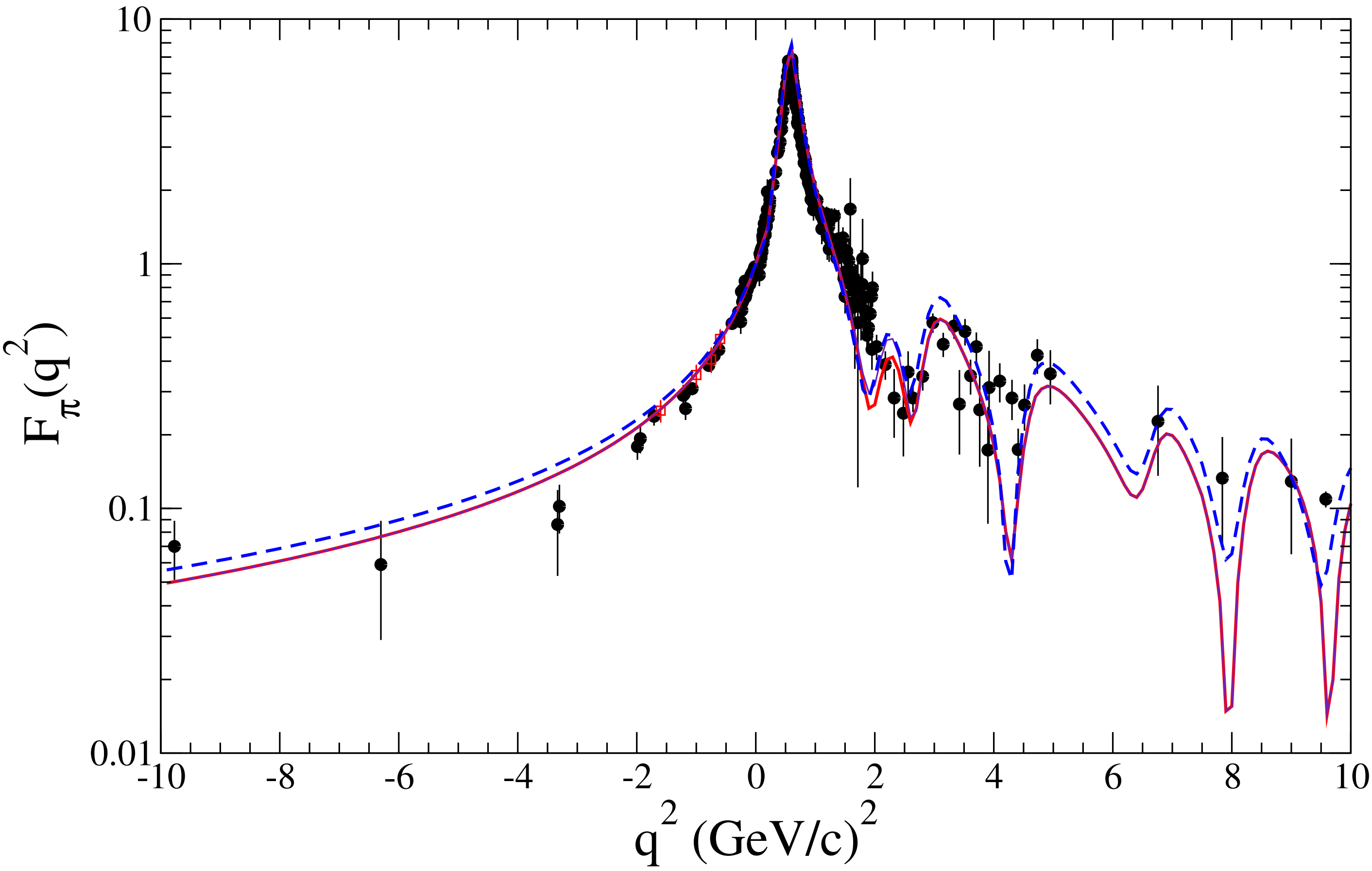
Results - PRD 73(2006) 074013

$$\Gamma_{e^+e^-} = \frac{8\pi\alpha^2\ f_{Vn}^2}{(3M_n^3)}$$

Meson	$\Gamma_{e^+e^-}$ (KeV)	$\Gamma_{e^+e^-}^{\exp}$ (KeV)
$\rho(770)$	6.98	7.02 ± 0.11
$\rho(1450)$	0.97	1.47 ± 0.4
$\rho(1700)$	0.99	$> 0.23 \pm 0.1$
$\rho(2150)$	0.62	-

Pion EM Form Factor in the SL and TL regions

Comparison with Experimental Data



●: Compilation from R. Baldini et al. (EPJ. C11 (1999) 709, and Refs. therein.)

□: TJLAB SL data (J. Volmer et al., PRL. 86, 1713 (2001).)

Solid line: calculation with the pion w.f. from the FPZ model for the Bethe-Salpeter amplitude in the valence region ($w_{VM} = -1.0$).

Dashed line: the same as the solid line, but with the asymptotic pion w.f. $(\Lambda_\pi(k; P_\pi) = 1)$

$$\psi_\pi(k^+, \mathbf{k}_\perp; P_\pi^+, \mathbf{P}_{\pi\perp}) = \frac{m}{f_\pi} \frac{P_\pi^+}{[M_\pi^2 - M_0^2(k^+, \mathbf{k}_\perp; P_\pi^+, \mathbf{P}_{\pi\perp})]}$$

The Nucleon EM Form Factors

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)

$$\mathcal{L}_{eff}(x) = \frac{\epsilon_{abc}}{\sqrt{2}} \int d^4x_1\, d^4x_2\, d^4x_3 \mathcal{F}(x_1, x_2, x_3, x) \sum_{\tau_1, \tau_2, \tau_3} \times$$

$$\Big[m_N\, \alpha\;\bar{q}^a(x_1, \tau_1)\, \gamma^5\, q^b_C(x_2, \tau_2)\, \bar{q}^c(x_3, \tau_3) - \frac{(1-\alpha)}{\sqrt{3}} \times$$

$$\bar{q}^a(x_1, \tau_1)\, \gamma^5\, \gamma_\mu\, q^b_C(x_2, \tau_2) \cdot \bar{q}^c(x_3, \tau_3)\, (-\imath\, \partial^\mu) \Big]\, \psi_N(x, \tau_N)$$

$$+ \;\; \ldots$$

For the present time $\alpha = 1$, i.e. no derivative coupling

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

$$\Phi^\sigma_N(k_1, k_2, k_3, P_N) = \imath \left[S(k_1)\, \tau_y\, \gamma^5\, S_C(k_2) C \otimes S(k_3) + \right.$$

$$\left. S(k_3)\, \tau_y\, \gamma^5\, S_C(k_1) C \otimes S(k_2) + S(k_3)\, \tau_y\, \gamma^5\, S_C(k_2) C \otimes S(k_1) \right]$$

$$\times\; \Lambda(k_1, k_2, k_3)\, \chi_{\tau_N}\, U_N(P_N, \sigma)$$

with a properly 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 eigenstate.

Spacelike nucleon em form factors

are evaluated from the matrix elements of the macroscopic current

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

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

which are approximated microscopically by the Mandelstam formula

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

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

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

As in the pion case, we integrate on k_1^- and on k_2^- taking into account only the poles of the propagators. Then we are left with a three-momentum dependence of the vertex functions.

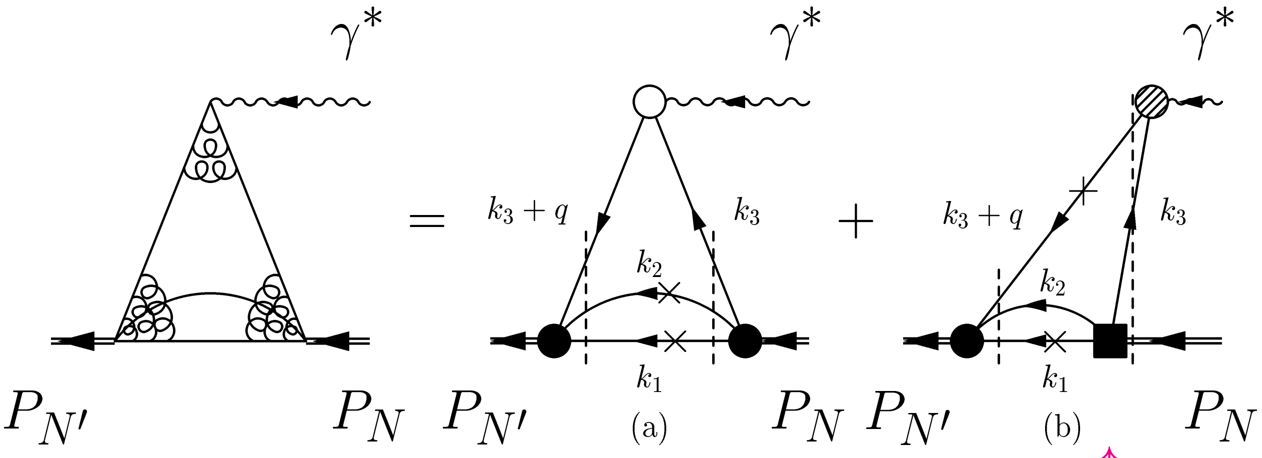
Frame : $\quad \mathbf{q}_\perp = 0 \qquad q^+ = |q^2|^{1/2}$

Quark mass : $m_u = m_d = 200 \; MeV$. As in the case of the pion.

As result of the k^- integrations one has

Spacelike Region

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

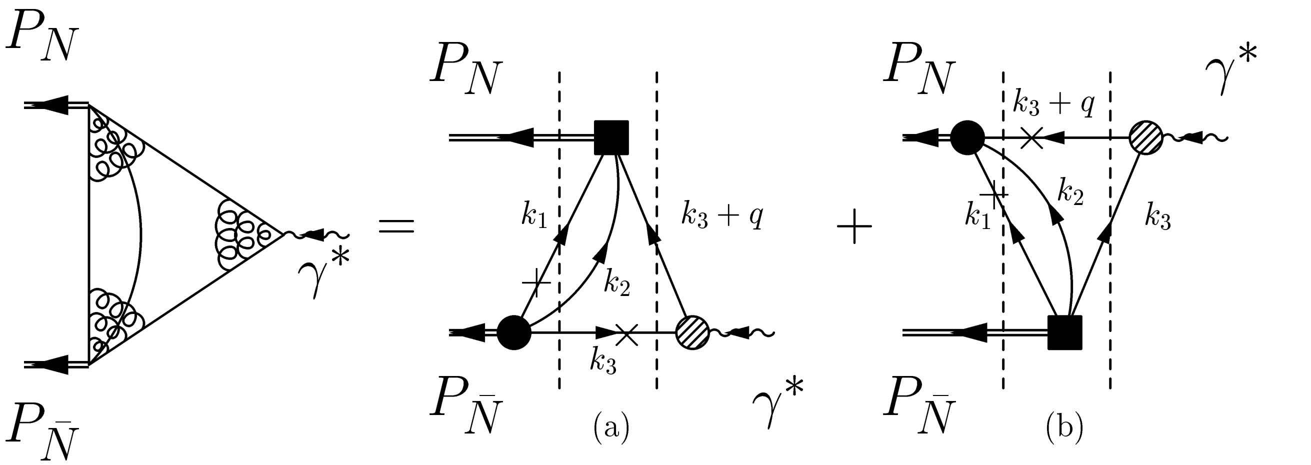


↑ (non-val.)

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

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

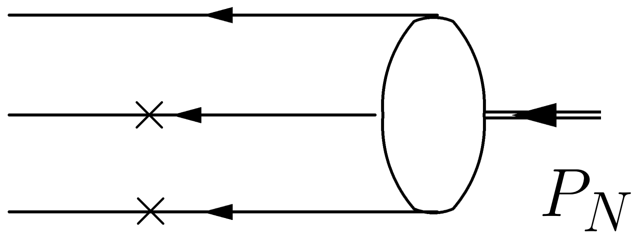
Timelike Region



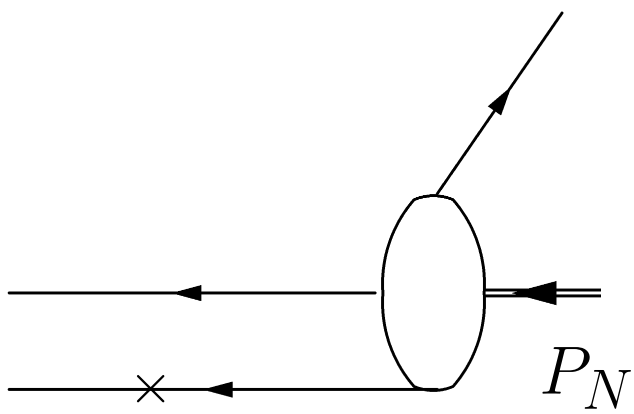
$P_N^+ < k_3^+ + q^+ < q^+$ $\quad$ $0 < k_3^+ + q^+ < P_N^+$

A non-valence contribution of the photon is involved: $|qqq, \bar{q}\bar{q}\bar{q}\rangle$

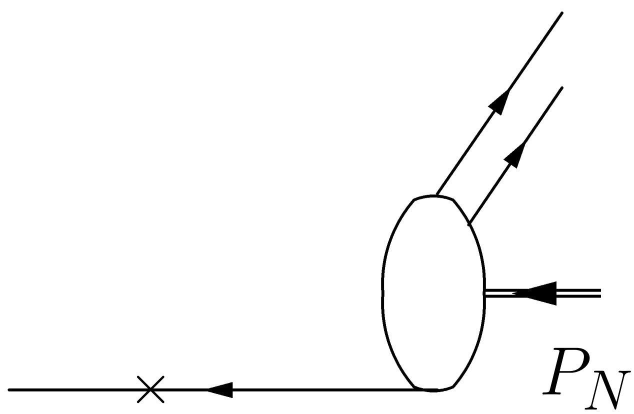
Ansatzes for the following 3D projections of the Nucleon 4D Bethe-Salpeter amplitude will be needed



The onshell vertex function ($\rightarrow$ valence component), with all the three legs as quark legs (two of them on the k^--shell)



Off-shell nucleon vertex in the SL region



Off-shell nucleon vertex in the TL region

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, $\theta(-Q^2)$) 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

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

with i = IS, IV, $\mathcal{N}_{IS} = 1/6$ 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.

The VMD term $\Gamma^{\mu}[k,q,i]$ is the same already used in the pion case, but now includes isoscalar mesons. Up to 20 IS and IV mesons

Inputs: masses, M_n , and total widths, Γ_n , for the first three IS mesons. For the remaining 17, masses from FPZ model, and total width $\Gamma_n = 0.15\ MeV$ as for the IV sector. We calculate microscopically $\Gamma^i_{e^-e^+}$ and the amplitudes $VM \to N\bar{N}$ and $VM + N \to N$

Meson	M_n (MeV)	Γ_n (MeV)
ω	782	8.44
ω'	1420	174
ω''	1720	220

Momentum Dependence of the Bethe-Salpeter Amplitudes

In the valence vertex the spectator quarks are on their-own 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

$$\Psi_N(k_1, k_2, k_3) = P_N^+ \frac{\Lambda_V(k_1, k_2, k_3)}{[M_N^2 - M_0^2(1,2,3)]} =$$

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

where $M_0(1,2,3)$ is the free mass of the three-quark system,

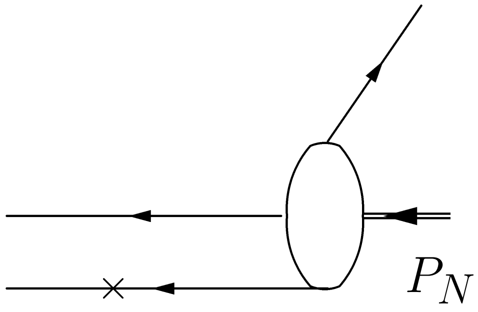
$\xi_i = k_i^+ / P_N^+$

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

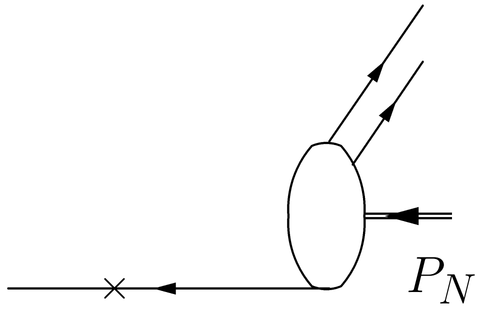
The power $7/2$ and the parameter $p = 0.13$ are chosen to have an asymptotic decrease of the triangle contribution faster than the dipole.

Only the triangle diagram determines the magnetic moments, weakly dependent on p. Then $\beta = 0.65$ can be fixed by μ_p and μ_n

Proton: 2.87 (Exp. 2.793) Neutron : -1.85 (Exp. -1.913)



SL off-shell vertex



TL off-shell vertex

The non-valence vertex can depend on the available invariants. in the spacelike region, one can single out the free mass of quarks 1 and 2, $M_0(1,2)$, and the free mass of the N-$\bar{q}$ system $M_0(N,\bar{3})$

Then in the spacelike region we approximate the momentum dependence of the non-valence vertex by

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

$$k^+_{12} = k^+_1 + k^+_2 \qquad g_{AB} = \frac{(m_A\, m_B)}{[\beta^2 + M_0^2(A,B)]}$$

In the timelike region the non-valence vertex can depend on the mass of the (nucleon - diquark) system . Then by analogy we approximate the non-valence 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 :

$$Z_B = Z^{IV}_{VM} = 2.283 \quad \text{and}$$
$$Z^{IS}_{VM}/Z^{IV}_{VM} = 1.12$$

- 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 non-valence vertex, to have a dipole asymptotic behavior of the pair-production contribution

By using in the fitting procedure the experimental data (updated to 2009) for $\mu_p G^p_E/G^p_M$, G^n_E, G^p_M and G^n_M

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

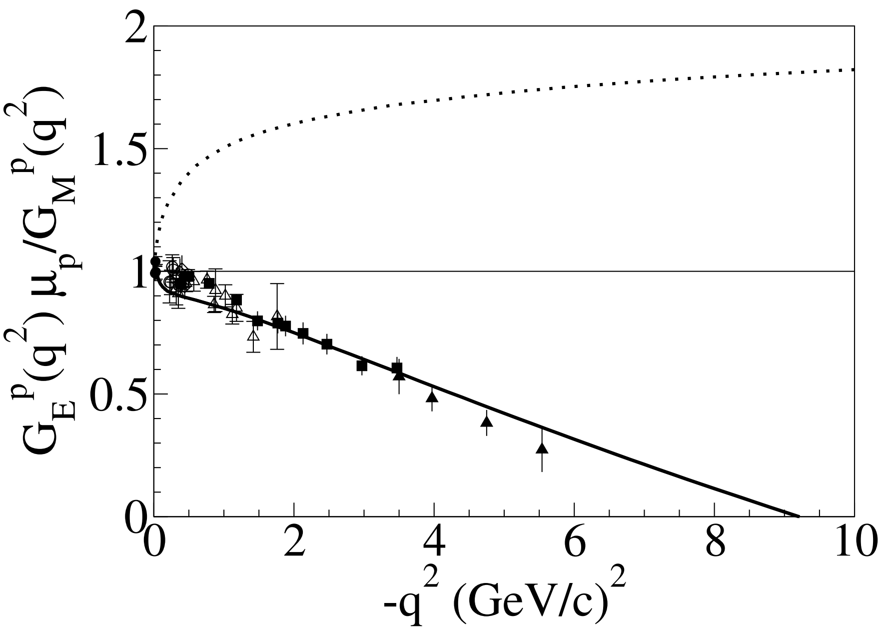
Results from PLB **671**, 153 (2009)

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

$$-\left[\frac{dG^n_E(Q^2)}{dQ^2}\right]^{th}_{Q^2=0} = (0.501 \pm 0.002)\ (GeV/c)^{-2}$$

$$-\left[\frac{dG^n_E(Q^2)}{dQ^2}\right]^{exp}_{Q^2=0} = (0.512 \pm 0.013)\ (GeV/c)^{-2}$$

Proton Ratio $\mu_p G_E^p / G_M^p$

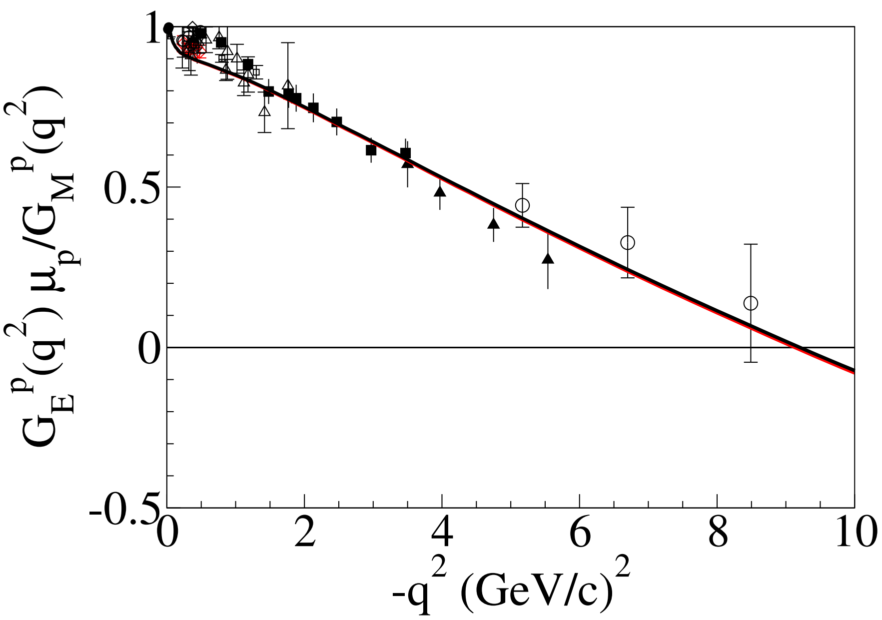


Solid line: full calculation $\equiv \mathcal{F}_{\triangle} + Z_B\ \mathcal{F}_{bare} + Z_{VM}\ \mathcal{F}_{VMD}$

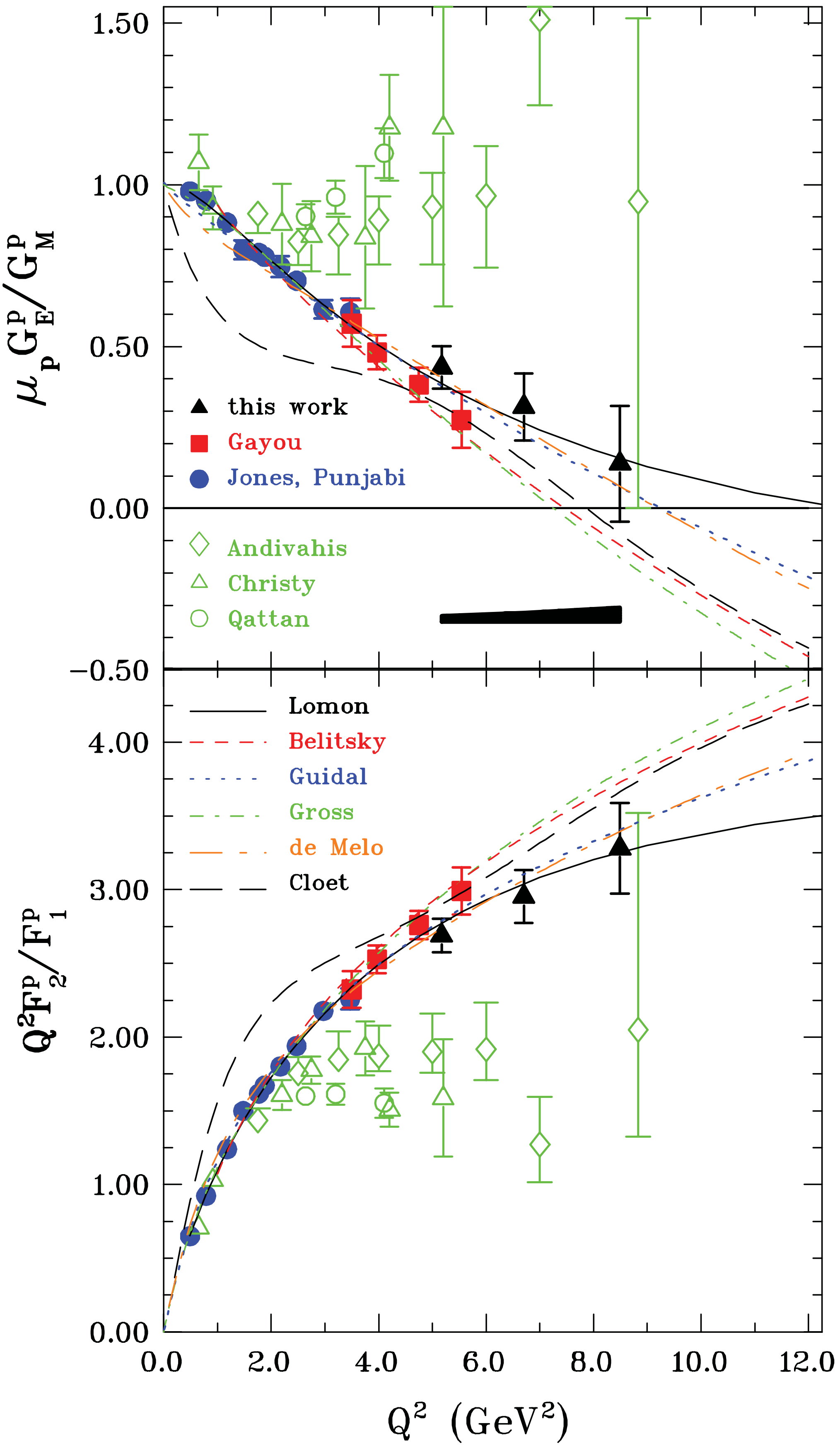
Dotted line: $\mathcal{F}_{\triangle}$ (triangle contribution only)

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

Interference between triangle and Z-diagram contributions, i.e. higher Fock components produces our zero.



Red line: only G_E^n, G_M^p and G_M^n in the fit for fixing the 4 parms.


1.50
1.00
0.50
0.00
−0.50
$\mu_p G_E^p / G_M^p$
this work
Gayou
Jones, Punjabi
Andivahis
Christy
Qattan
Lomon
Belitsky
Guidal
Gross
de Melo
Cloet
4.00
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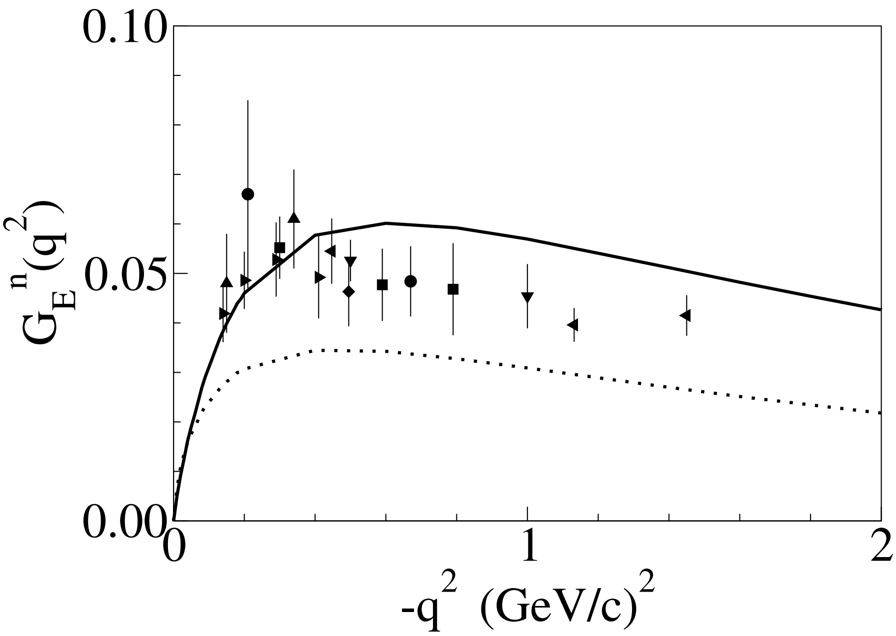
2.00
1.00
0.00
$Q^2 F_2^p / F_1^p$
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Q^2 (GeV^2)

SL Nucleon form factors: G_E^n, G_M^p G_M^n



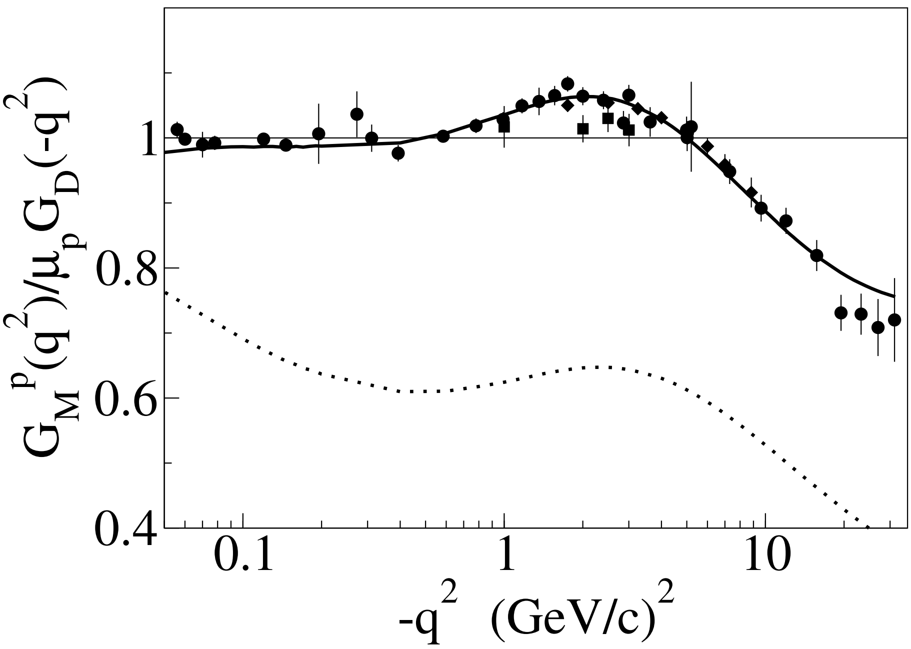
Solid line: full calculation $\equiv \mathcal{F}_\triangle + Z_B\, \mathcal{F}_{bare} + Z_{VM}\, \mathcal{F}_{VMD}$

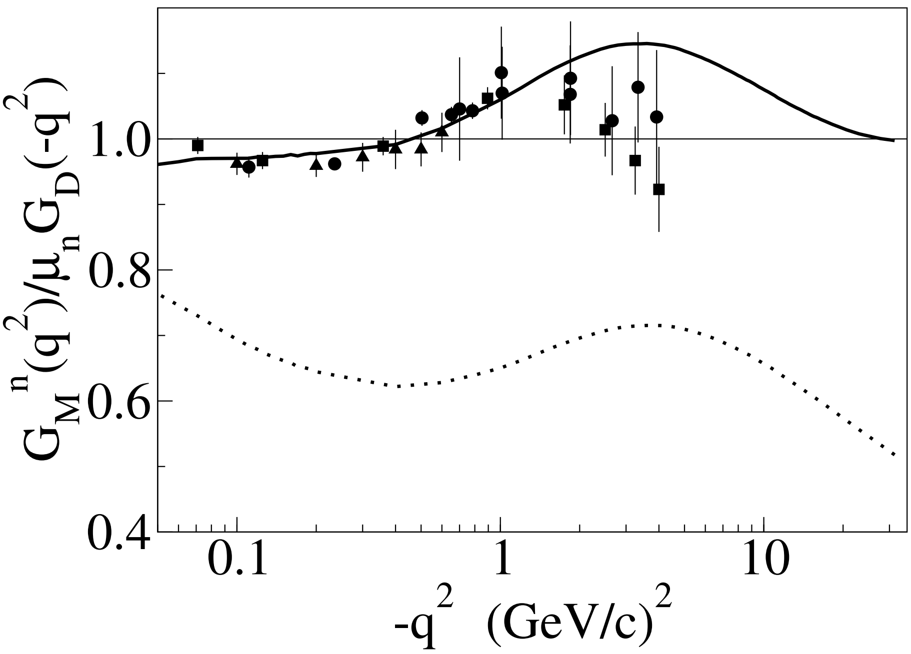
Dotted line: $\mathcal{F}_\triangle$ (triangle contribution only)

Values obtained from our model

$$-\left[\frac{dG_E^n(Q^2)}{dQ^2}\right]_{Q^2=0}^{th} = (0.501 \pm 0.002)\ (GeV/c)^{-2}$$

$$-\left[\frac{dG_E^n(Q^2)}{dQ^2}\right]_{Q^2=0}^{exp} = (0.512 \pm 0.013)\ (GeV/c)^{-2}$$





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

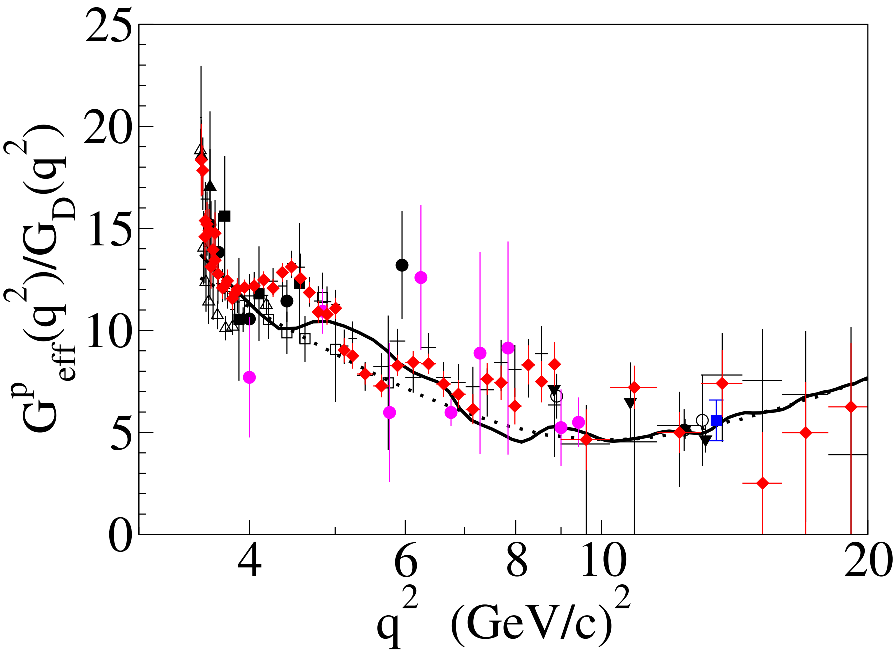
Dotted line: $\mathcal{F}_\triangle$ (triangle contribution only)

The pair-production contribution is essential for the result

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

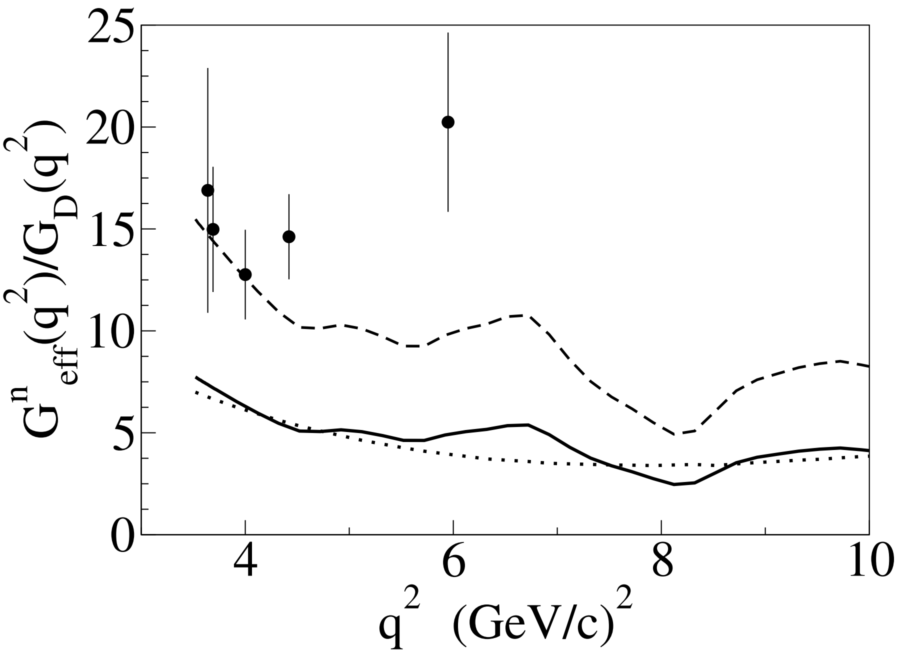
Nucleon timelike form factors

Parameter free results



Solid line: full calculation - Dotted line: bare production (no VM).

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



Dashed line: solid line arbitrarily $\times$ 2.

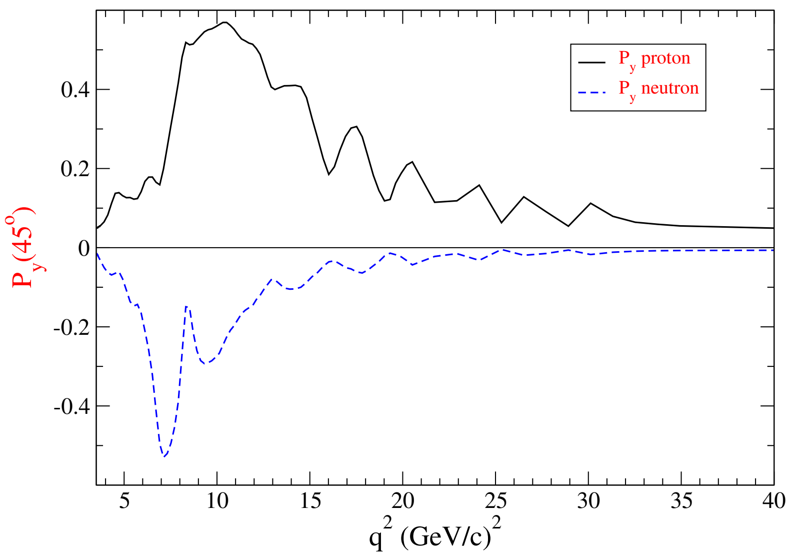
$$G_{eff}(q^2) = \sqrt{\frac{2\tau\ |G_M(q^2)|^2\ +\ |G_E(q^2)|^2}{2\tau\ +\ 1}}$$

Polarization orthogonal to the scattering plane: no polarized beam !

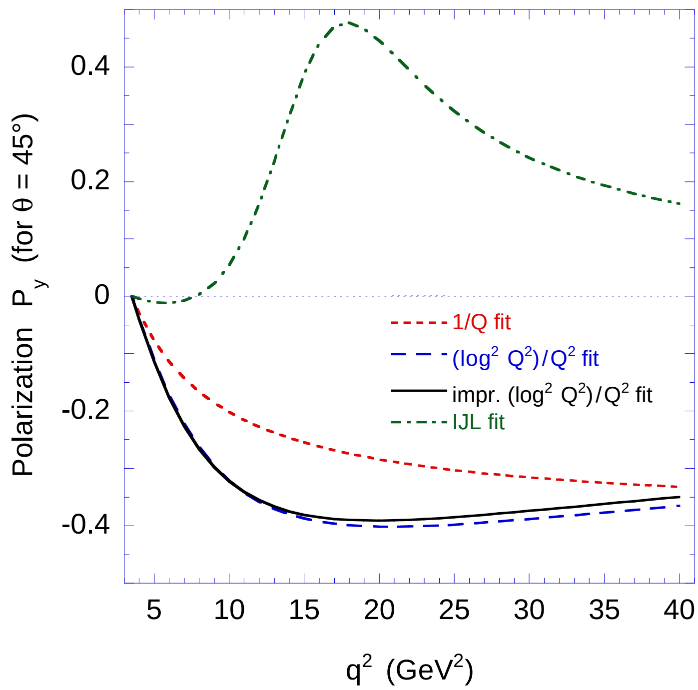
$$P_y(\theta_{CM}) = -\, sin\,(2\theta_{CM})\ \frac{\Im\{G_E(q^2)G_M^*(q^2)\}}{D\,\sqrt{\tau}}$$

where $\tau = q^2/4M^2$ and

$$D = \left[1 + cos^2\,(\theta_{CM})\right]\ |G_M(q^2)|^2 + sin^2\,(\theta_{CM})\ \frac{|G_E(q^2)|^2}{\tau}$$



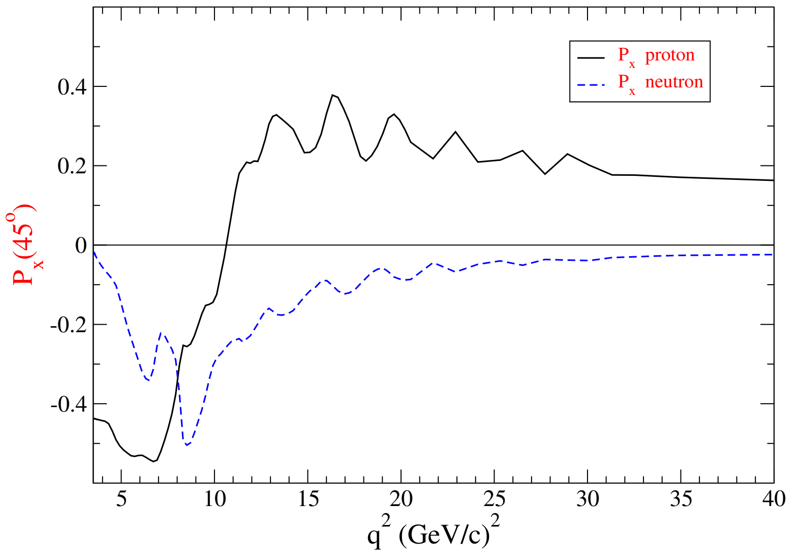
LF Constituent Quark Model



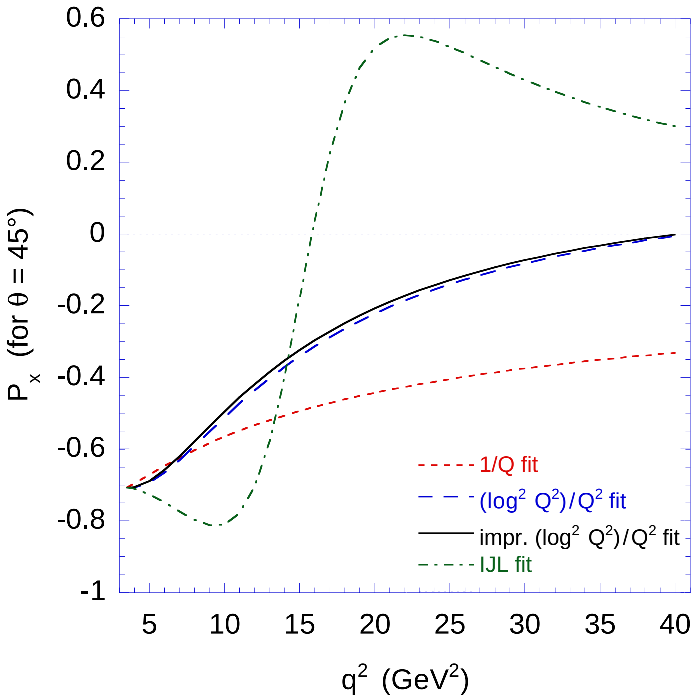
After Brodsky, Carlson, Hiller and Dae Sung Hwang PRD **69**, 054022 (2004).

Polarization orthogonal to incident beams in the scattering plane: polarized electron beam !

$$P_x(\theta_{CM}) = P_e\, 2sin\,(\theta_{CM})\ \frac{\Re\{G_E(q^2)G_M^*(q^2)\}}{D\,\sqrt{\tau}}$$



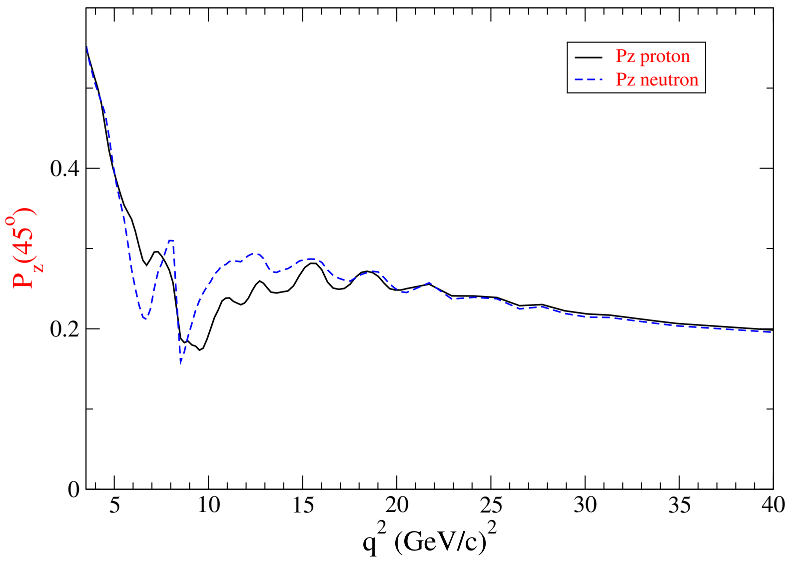
LF Constituent Quark Model



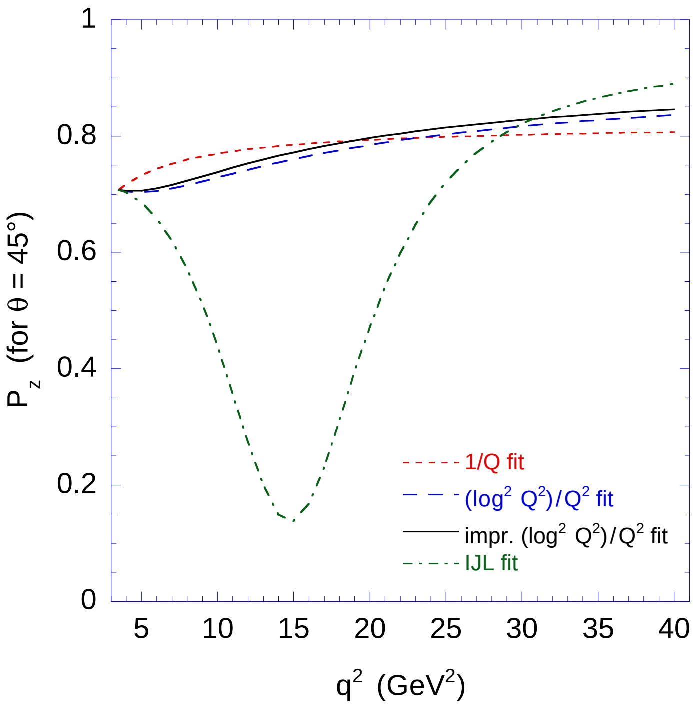
After Brodsky, Carlson, Hiller and Dae Sung Hwang PRD **69**, 054022 (2004).

Polarization along the incident beams: polarized electron beam !

$$P_z(\theta_{CM}) = P_e \; 2cos\,(\theta_{CM}) \; \frac{|G_M(q^2)|^2}{D}$$



LF Constituent Quark Model



After Brodsky, Carlson, Hiller and Dae Sung Hwang PRD **69**, 054022 (2004).

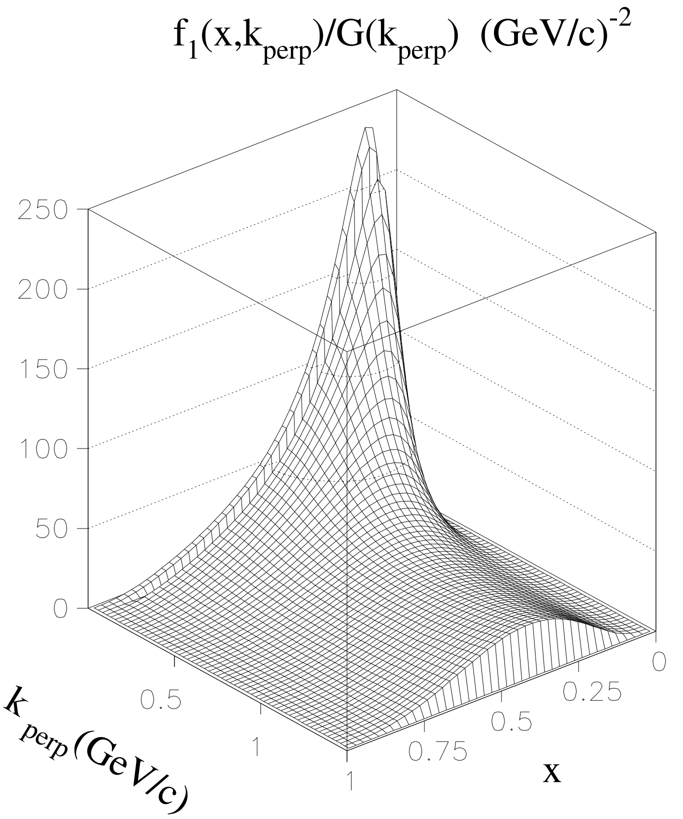
Transverse momentum distributions in the proton

$$f_1^{u(d)}(x, k_\perp) = -\frac{N_c}{(2\pi)^6} \int_0^{1-x} d\xi_2 \frac{C_{u(d)}}{(1-x-\xi_2)\xi_2} \frac{1}{x^2} \int d\mathbf{k}_{2\perp}$$

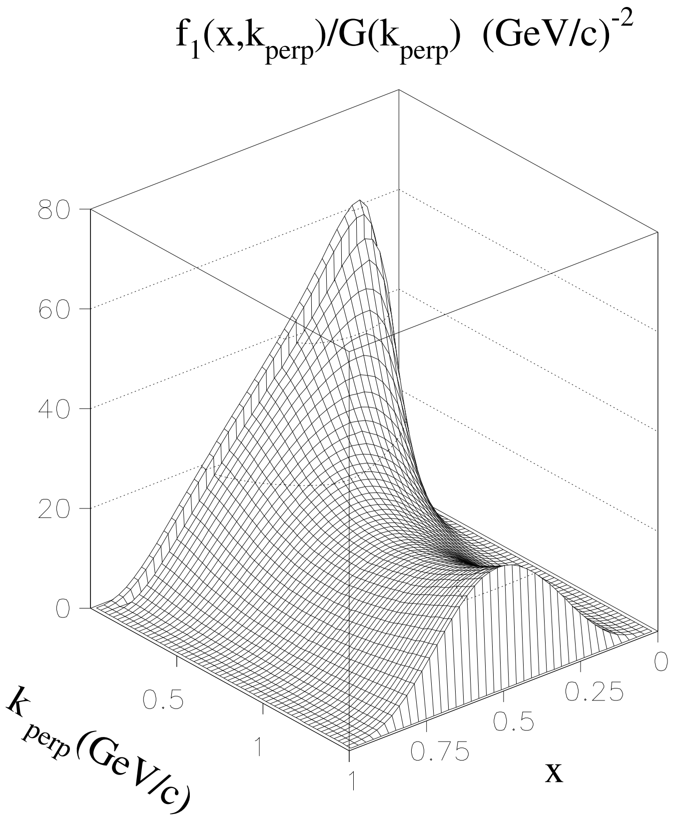
$$\times \frac{1}{P_N^{+2}} \, |\Psi_N(\tilde{k}_1, \tilde{k}_2, P_N)|^2 \quad \mathcal{H}_{u(d)}\Big|_{(k^-_{1on}, k^-_{2on})}$$

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

u quark



d quark



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

The decay of our $f_1(x, k_\perp)$ vs $k_\perp$ is faster than in diquark models of nucleon (Jacob et al., Nucl Phys. A626 (1997) 937), while it is slower than in factorization models for the transverse momentum distributions (Anselmino et al., PRD 74 (2006) 074015).

Longitudinal momentum distributions

For $P'_N = P_N$ the unpolarized GPD $H_q(x,\xi,t)$ reduces to the longitudinal parton distribution function $q(x)$

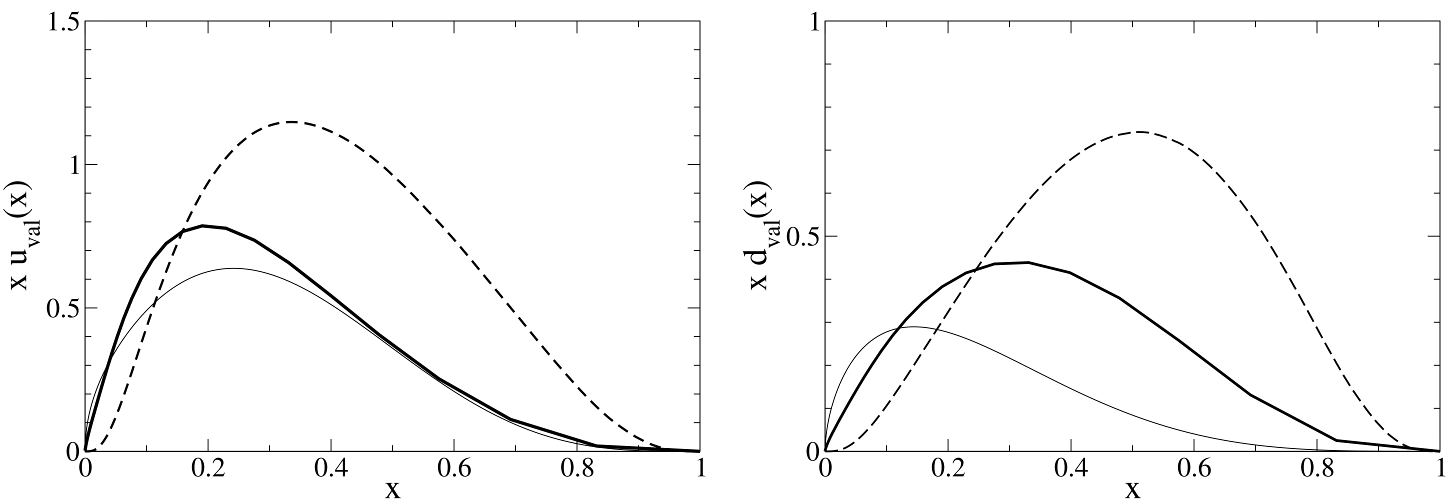
$$H^q(x,0,0) = \int \frac{dz^-}{4\pi} e^{ixP_N^+ z^-} \; \langle P_N | \bar{\psi}_q(0)\, \gamma^+ \, \psi_q(z) | P_N \rangle \big|_{\tilde{z}=0}$$

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

an average on the nucleon helicities is understood.

proton preliminary results

u quark $\qquad\qquad\qquad$ 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 relativistic Constituent Quark Model, based on phenomenological Ansatzes for the hadron Bethe-Salpeter amplitudes, have been applied for evaluating both pion and nucleon em form factors, in SL and TL regions.
- A microscopical Vector Meson Dominance model has been devised, exploiting masses and eigenfunction of a relativistic mass operator, able to reproduce the vector meson mass in PDG 08.
- Only 4 adjusted paramters are necessary to get $\chi^2 \sim 1.7$ in the SL region for the nucleon ff.
- It is predicted a zero for the SL ratio $\mu_p G_E^p / G_M^p$ around $Q^2 \sim 9\ (GeV/c)^2$. The interference between the valence and non valence component (pair production) of the proton state is the cause. Notice that the whole $\mu_p G_E^p / G_M^p$ should be considered a prediction.
- TL Nucleon ff are true predictions!
- The comparison with experimental data for the proton points to missing strength around 4.5 and 8 $(GeV/c)^2$
- Fenice data for the neutron ff is largely underestimated
- Calculations of the TL polarizations show interesting structures, related both to the realistic description of the SL nucleon ff's and to the VMD
- Extension to TMD and GPD is currently under progress. Pion done

Next steps :

- to develop more refined covariant models based on Nakanishi representation of the Bethe-Salpter amplitudes in Minkowski space (Frederico, Viviani G.S., PRD 85, 036009 (2012)

$$\Phi_b(k,p) = i \int_{-1}^{1} dz \int_{0}^{\infty} d\gamma \, \frac{g_b(\gamma, z; \kappa^2)}{[\gamma + \kappa^2 - k^2 - p \cdot kz - i\epsilon]^{2+n}}$$

  where κ^2 is defined $\kappa^2 = m^2 - \frac{M^2}{4}$.

- to calculate nucleon GPD's