Time- and spacelike nucleon e.m. form factors beyond relativistic constituent quark models

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Pion ff in the spacelike and timelike regions $\longrightarrow$ J.P.B.C. de Melo, T. Frederico, E. Pace, G. Salme', Phys. Lett. **B 581** (2004) 75

Spacelike and timelike pion electromagnetic form factor and Fock state components within the light-front dynamics $\longrightarrow$ J.P.B.C. de Melo, T. Frederico, E. Pace, G. Salme', Phys. Rev. **D 73**, 074013 (2006)

Electromagnetic Hadron Form Factors and Higher Fock Components $\longrightarrow$ J.P.B.C. de Melo, T. Frederico, E. Pace, S. Pisano, G. Salme', Nucl. Phys. **A 782** (2007) 69

Timelike and spacelike hadron ff's, Fock state components and LF dynamics E. Pace, G. Salme', T. Frederico, S. Pisano, Nucl. Phys. **A 790** (2007) 606c

E. Pace, G. Salme', T. Frederico, S. Pisano, J. de Melo, hep-ph 08041511

Motivations

The investigation of hadron EM form factors in the space- and timelike regions, within the 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

- yields the possibility to address the vast phenomenology of hadronic resonances (Vector Meson propagation...) in the timelike region

Why "beyond relativistic constituent quark models" ?

We tried to describe nucleon ff's in a relativistic constituent quark model within a Poincare' covariant light-front approach, but using only the nucleon valence vertex function we met serious difficulties

E. Pace, G. Salme', A. Molochkov, Nucl. Phys. **A 721** (2003) 405, Nucl. Phys. **A 699** (2002) 156

Outline

- A covariant expression for the EM current: the Mandelstam Formula
- Pion EM Form Factor in the spacelike and timelike regions
- Nucleon EM Form Factors in the spacelike and timelike regions including valence and non valence vertex functions
- Conclusion & Perspectives

The Mandelstam Formula for the EM current

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

A first application $\Rightarrow$ Pion

In the TL region one has

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

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

  P_π^μ and $P_{\bar\pi}^\mu$ are the pion momenta.

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

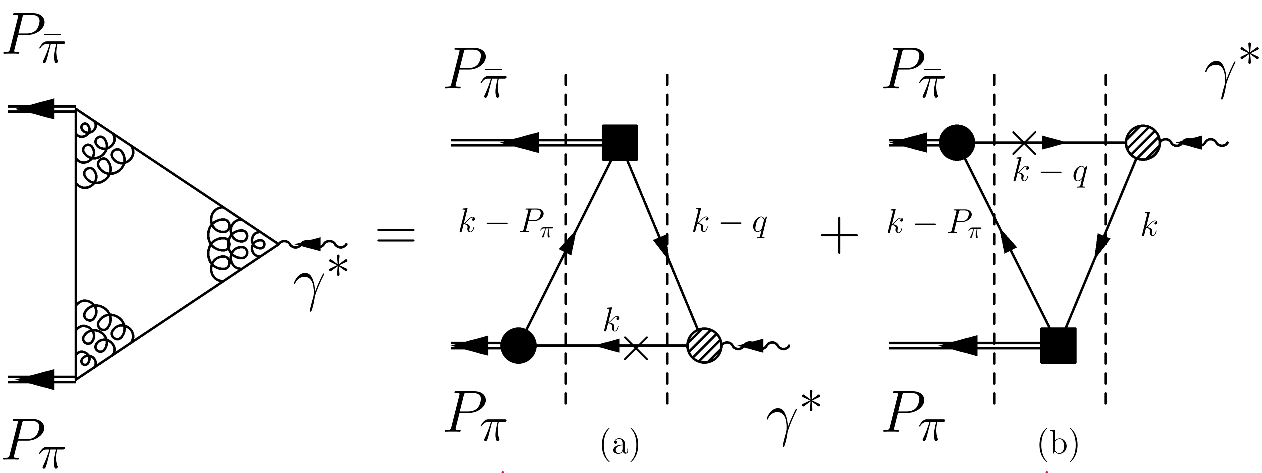
Instead of the usual $q^+ = 0$ frame (the standard choice within LF) for a unified investigation of SL and TL regions we use a reference frame where

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

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

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.

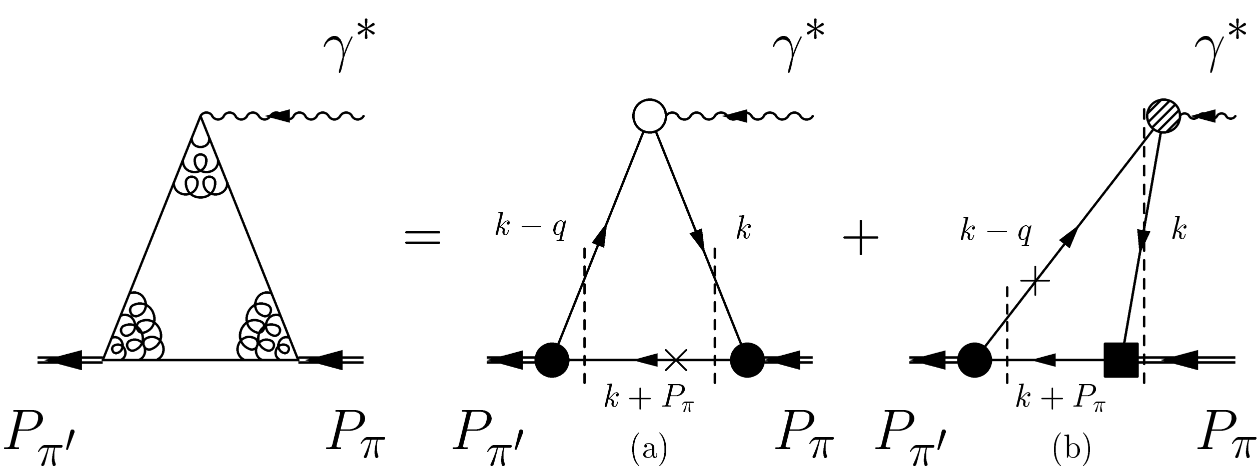
Timelike region



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

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

Spacelike region



$\uparrow$ (non-val.)

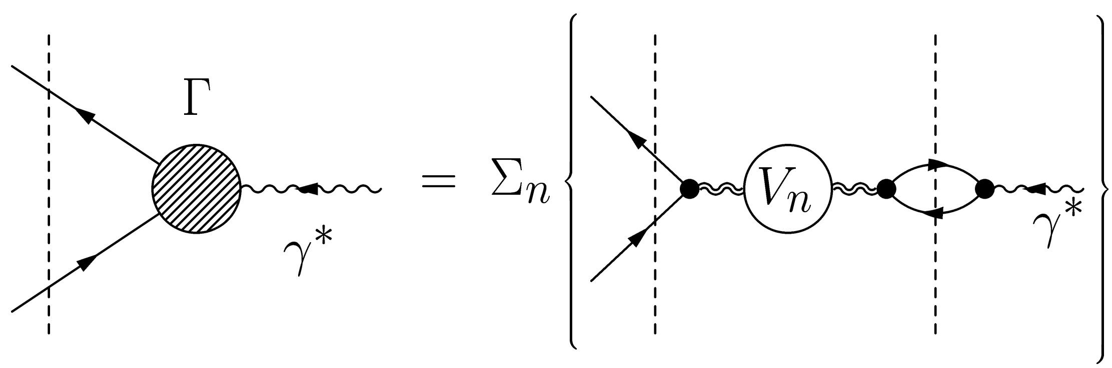
(val.) $0 < k^+ + P_\pi^+ < P_\pi^+$ $P_\pi^+ < k^+ + P_\pi^+ < P_{\pi'}^+$

⋆ First Problem: How to model the quark-photon vertex ? ⋆

⋆ ⋆ Second 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)? ⋆ ⋆

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

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



⋆ A Vector Meson Dominance approximation has been applied to the quark-photon vertex, when a $q\bar{q}$ pair is produced

$$\Gamma^{\mu}(k,q) \;=\; \sqrt{2}\sum_{n,\lambda} \left[\epsilon_{\lambda}\cdot \widehat{V}_{n}(k,k-P_{n})\right] \Lambda_{n}(k,P_{n}) \;\times$$

$$\frac{[\epsilon^{\mu}_{\lambda}]^{*} f_{Vn}}{(q^{2}-M_{n}^{2}+\imath M_{n}\tilde{\Gamma}_{n}(q^{2}))} \qquad (1)$$

- 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 on-shell amplitude of the VM has been related to the light-front VM wave function

$$\frac{P^+_n \ \ \Lambda_n(k, P_n)|_{[k^- = k^-_{on}]}}{[M^2_n - M^2_0(k^+, \mathbf{k}_\perp; P^+_n, \mathbf{P}_{n\perp})]} = \psi_n(k^+, \mathbf{k}_\perp; P^+_n, \mathbf{P}_{n\perp})$$

$\psi_n(k^+, \mathbf{k}_\perp; P^+_n, \mathbf{P}_{n\perp})$ 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" ($M^2_n \sim M^2_{gr} + \omega\ (n-1)$; n is the radial quantum number) is obtained. No isospin breaking is considered in the π form factor calculation ($\rho \equiv \omega$).

- normalized to the probability of the lowest ($q\bar{q}$) Fock state (i.e. the valence component). The $q\bar{q}$ probability can be 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.

⋆ ⋆ In order to describe the emission (absorption) of a pion by a quark (■ - nonvalence component), 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

$$\psi_\pi(k^+, \mathbf{k}_\perp; P^+_\pi, \mathbf{P}_{\pi\perp}) = \frac{m}{f_\pi} \frac{P^+_\pi \ [\Lambda_\pi(k, P_\pi)]_{[k^- = k^-_{on}]}}{[m^2_\pi - M^2_0(k^+, \mathbf{k}_\perp; P^+_\pi, \mathbf{P}_{\pi\perp})]}$$

⋆ ⋆ ⋆ A new issue: the instantaneous contributions.

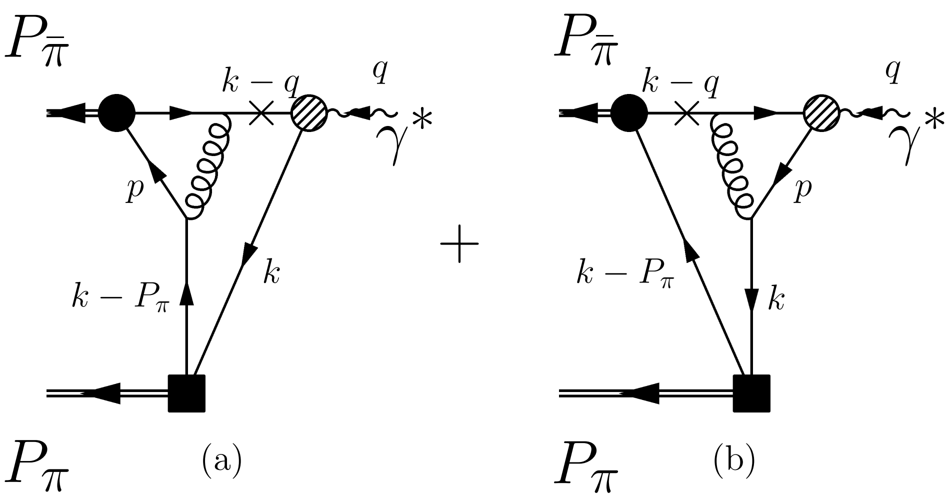
Let us consider the free Dirac propagator

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

Instantaneous term in the free propagator ↑

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

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.

Pion EM Form Factor

in the space- and time-like regions

The pion EM form factor can be extracted using the definitions

$$j^{\mu}_{TL} = \langle \pi\bar{\pi} | \bar{q}(0)\gamma^{\mu} q(0) | 0 \rangle = e \, (P^{\mu}_{\pi} - P^{\mu}_{\bar{\pi}}) \, F_{\pi}(q^2) \quad ,$$
$$j^{\mu}_{SL} = \langle \pi | \bar{q}(0)\gamma^{\mu} q(0) | \pi' \rangle = e \, \left(P^{\mu}_{\pi} + P^{\mu}_{\pi'}\right) \, F_{\pi}(q^2)$$

Then,

i) from the Mandelstam formula,

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

and iii) in the limit $m_\pi \to 0$ one obtains the following expression for the EM pion form factor

calculated $\downarrow$

$$F_{\pi}(q^2) = \sum_n \frac{f_{Vn}}{q^2 - M_n^2 + \imath M_n \Gamma_n(q^2)} \, g^{+}_{Vn}(q^2)$$

calculated $\uparrow$

Note, for $q^2 = M_n^2$, $g^{+}_{Vn}(M_n^2)$ yields the decay constant $VM \to \pi\bar{\pi}$.

Fixed parameters

$m_u = m_d$ = 0.265 GeV

Experimental vector-meson masses, M_n , and widths, Γ_n , for the first four vector mesons.

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

From PDG 04, *Akhmetshin et al., PLB **509**, 217 (2001) and **Anisovich et al., PLB **542**, 8 (2002).

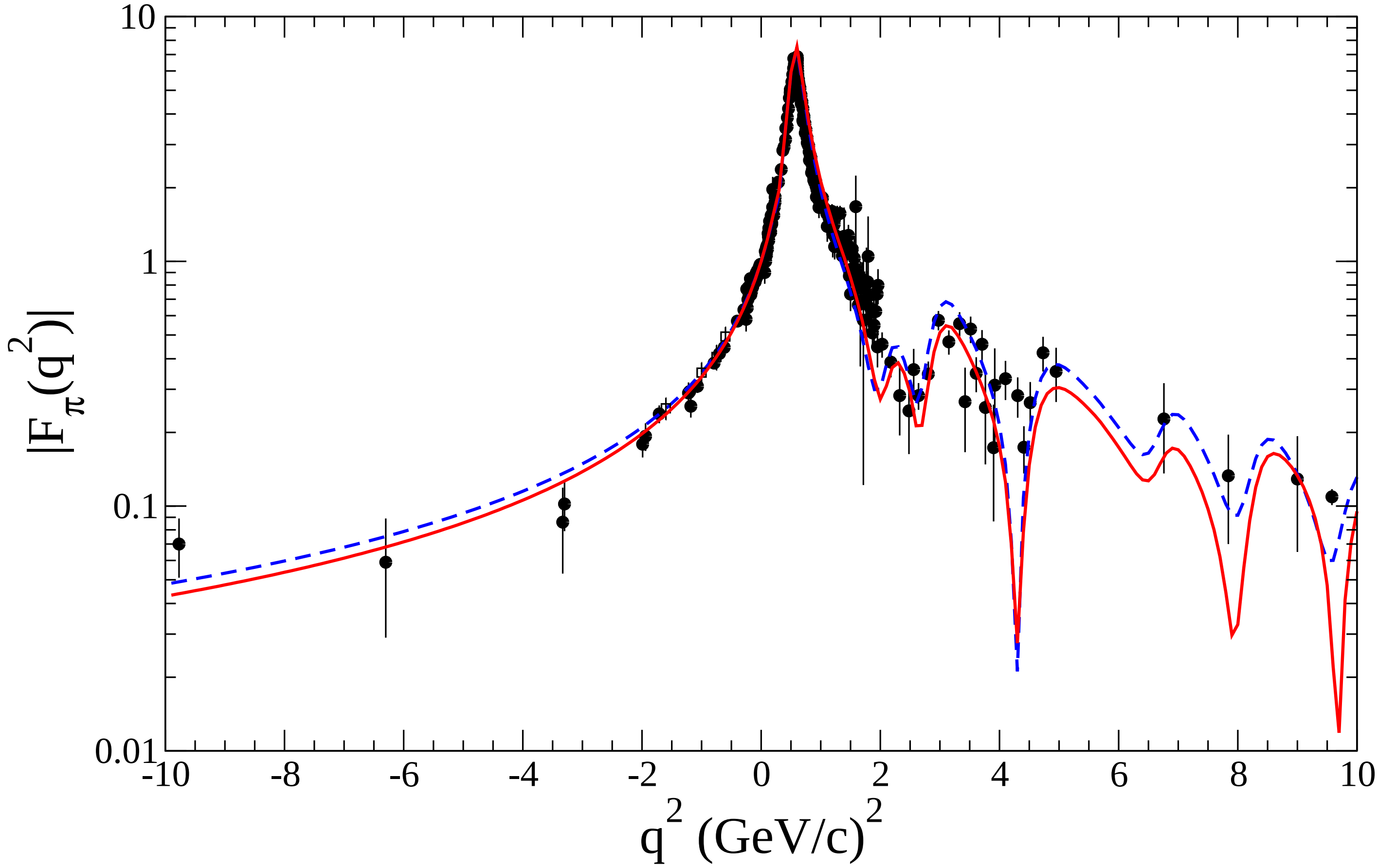
20 vector mesons are taken into account to reach convergence up to $q^2 = 10\ (GeV/c)^2$. The VM masses for $M_n > 2150\ MeV$ are from the Frederico, Pauli, Zhou model (PRD 66 (2002) 116011).

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 $w_{VM} = -0.7$ for a global fit, and $w_{VM} = -1.5$ for an improved description of the ρ peak region.

Pion EM Form Factor in the SL and TL regions
Comparison with Experimental Data



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

Solid line: calculation with the pion w.f. from the FPZ model for the Bethe-Salpeter amplitude in the valence region ($w_{VM} = -0.7$).

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 heights of the bumps in the TL region are well reproduced in our model. This feature is related to the calculated value, $g^{+}_{Vn}(q^2)$, of the decay form factor $VM \to \pi\bar{\pi}$.
- A more refined description of the instantaneous contribution could help to fill the deep near 2 $(GeV/c)^2$.
- The introduction of ω-like and ϕ-like mesons could obviously improve the description of the data in the TL region.
- In the TL region, at high values of the momentum transfer, the agreement with the data is quite reasonable.

Results for $\Gamma_{e^+e^-} = \frac{8\pi\alpha^2 \; f^2_{Vn}}{(3M^3_n)}$

Meson	$\Gamma_{e^+e^-}$ (KeV)	$\Gamma^{exp}_{e^+e^-}$ (KeV)
$\rho(770)$	6.98	7.02 ± 0.11
$\rho(1450)$	1.04	1.47 ± 0.4
$\rho(1700)$	0.98	$> 0.23 \pm 0.1$
$\rho(2150)$	0.65	-

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

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)

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

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

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 eigenstate.

Spacelike nucleon em form factors

are evaluated from the matrix elements of the macroscopic current

$$\langle \sigma', P'_N | j^\mu \, | P_N, \sigma \rangle = \bar{U}_N(P'_N, \sigma') \left[-F_2(Q^2) \, \frac{{P'_N}^\mu + {P_N}^\mu}{2M_N} + \left(F_1(Q^2) + F_2(Q^2) \right) \, \gamma^\mu \right] U_N(P_N, \sigma)$$

which are approximated microscopically by the Mandelstam formula

$$\langle \sigma', P'_N | j^\mu \, | P_N, \sigma \rangle = \int \frac{d^4 k_1}{(2\pi)^4} \int \frac{d^4 k_2}{(2\pi)^4} \, \Sigma \left\{ \bar{\Phi}^{\sigma'}_N(k_1, k_2, k'_3, P'_N) \times S^{-1}(k_1) \, S^{-1}(k_2) \, \mathcal{I}^\mu(k_3, q) \;\; \Phi^\sigma_N(k_1, k_2, k_3, P_N) \right\} \;\; 3 \, N_c$$

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

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.

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

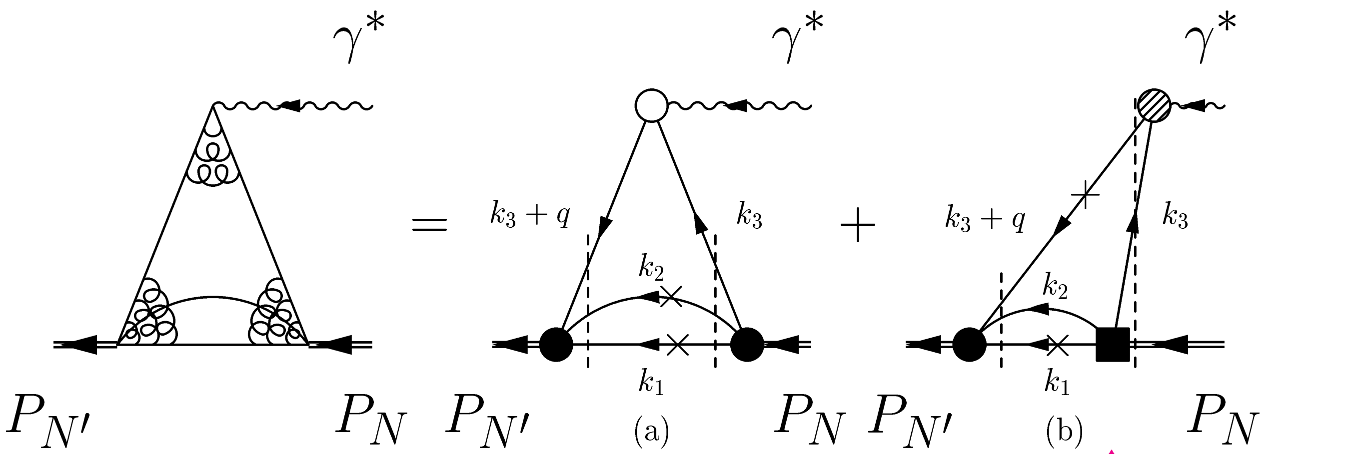
Quark mass : $m_u = m_d = 200 \; MeV$.

The relativistic CQ model for the vector meson square mass operator gives the experimental VM masses and VM decay constants, f_{Vn}, also for this value of the quark mass.

As result of the k^- integrations one has

Spacelike Region

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

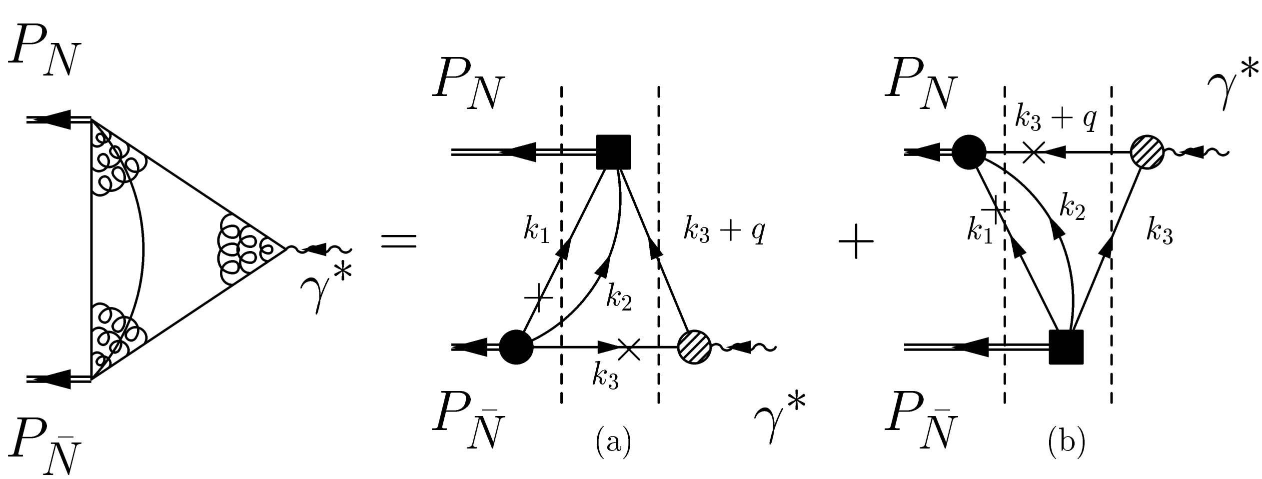


↑ (non-val.)

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

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

Timelike Region



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

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

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.

The VMD term $\Gamma^\mu[k,q,i]$ is the same already used in the pion case, but now includes isoscalar mesons.

Isoscalar VM masses, M_n, and widths, Γ_n, for the first IS mesons.

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

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

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

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

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

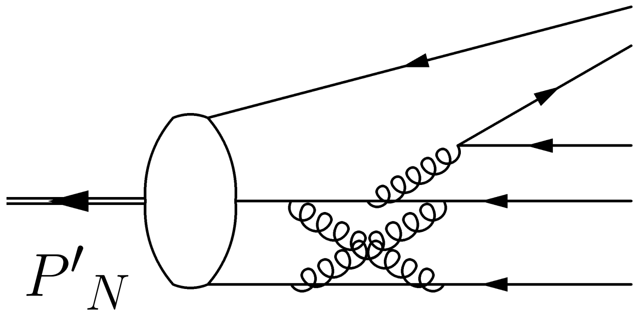
and $\mathcal{N}$ a normalization constant.

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)

For the Z-diagram contribution, the non-valence vertex is needed



The non-valence vertex can depend on the available invariants, namely in the spacelike region on the free mass of quarks 1 and 2, $M_0(1,2)$, and the free mass of the (nucleon - quark $\bar{3}$) system entering the non-valence vertex, $M_0(N,\bar{3})$

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

$$\Lambda^{SL}_{NV}(k_1,k_2,k_3) = [g_{12}]^2 \, [g_{N\bar{3}}]^{7/2-2} \left[\frac{k^+_{12}}{P'^+_N}\right]^{1-r} \left[\frac{P^+_N}{k^+_{\bar{3}}}\right]^r \left[\frac{k^+_{12}}{k^+_{\bar{3}}}\right]^r$$

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

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

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

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

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

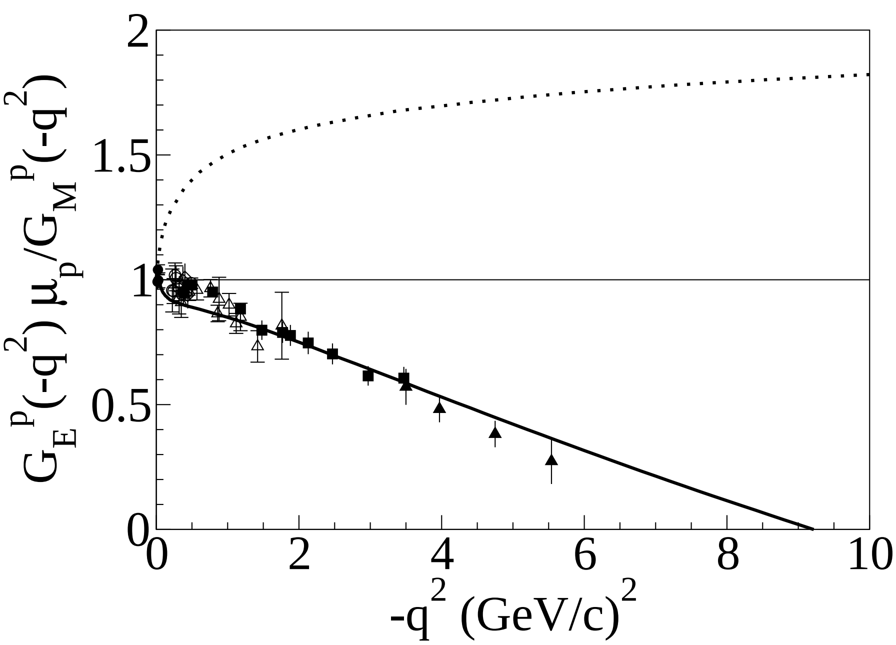
Results for nucleon radii

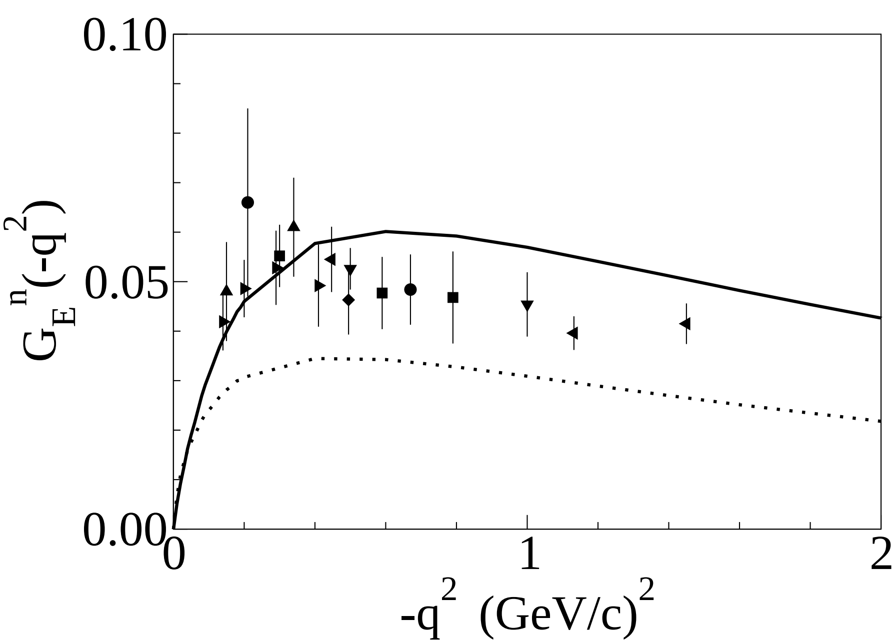
$r_p = (0.903 \pm 0.004)\ fm \qquad r^{exp}_p = (0.895 \pm 0.018)\ fm$

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

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

Nucleon electric form factors





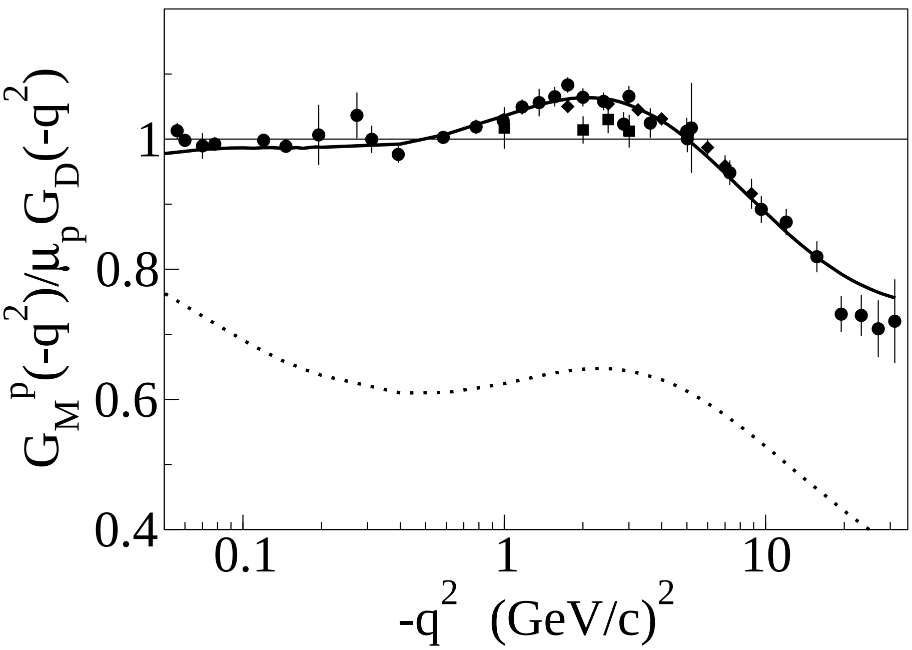
Solid line: full calculation $\equiv \mathcal{F}_\triangle + Z_B\, \mathcal{F}_{bare} + Z_{VM}\, \mathcal{F}_{VMD}$

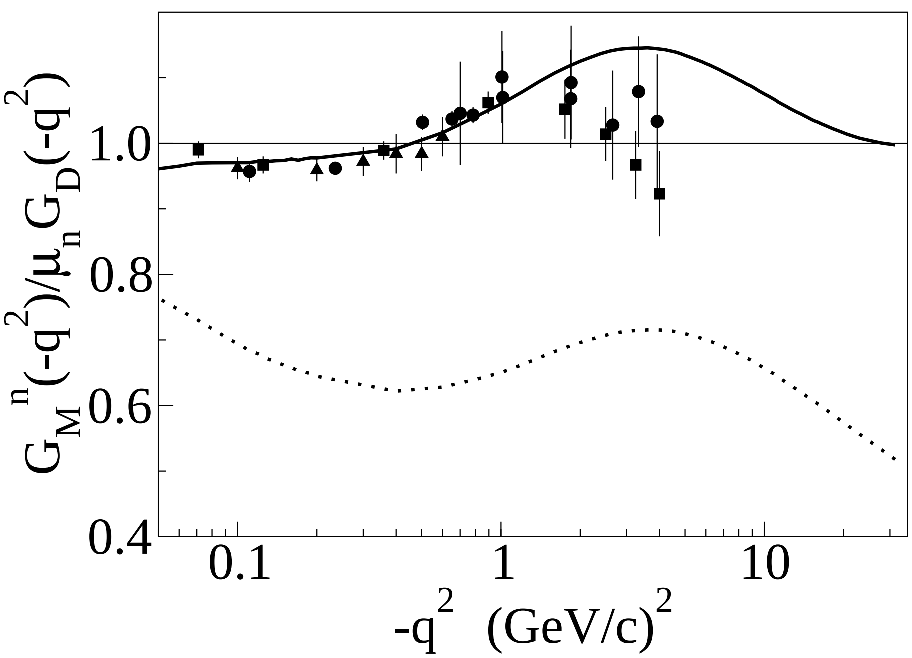
Dotted line: $\mathcal{F}_\triangle$ (triangle contribution only)

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

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 $\equiv \mathcal{F}_{\triangle} + Z_B\, \mathcal{F}_{bare} + Z_{VM}\, \mathcal{F}_{VMD}$

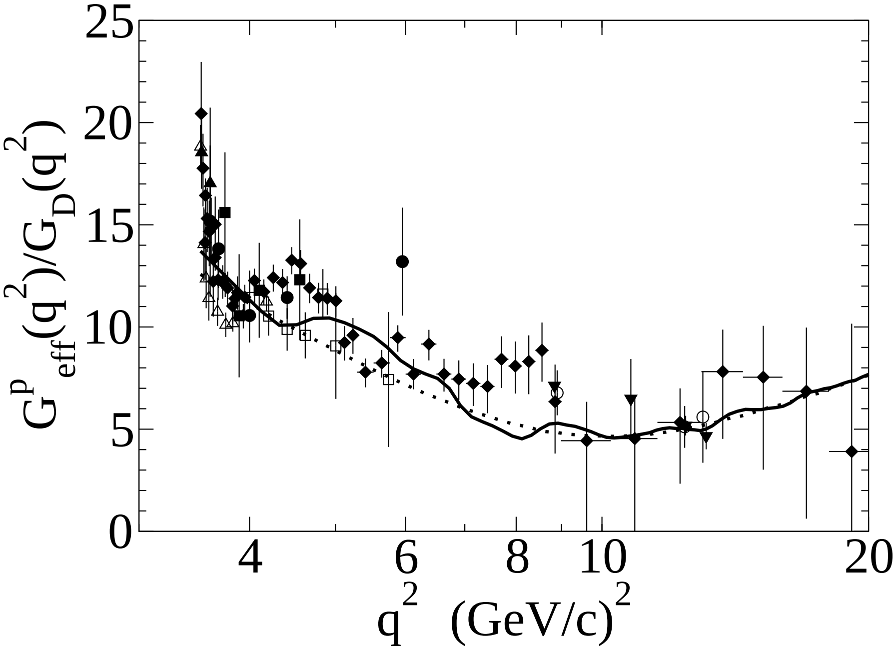
Dotted line: $\mathcal{F}_{\triangle}$ (triangle contribution only)

The pair-production contribution is essential for the result

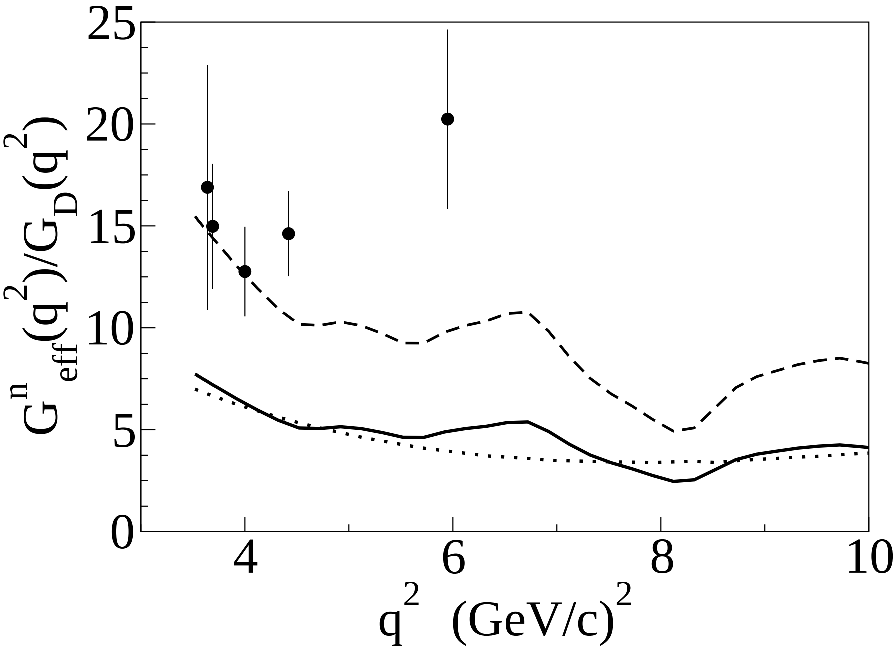
$G_D = 1/[1 - q^2/(0.71\ (GeV/c)^2)]^2$

Nucleon timelike form factors

parameter free results



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



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

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 VMD model plus a bare term
- The Z-diagram (higher Fock components) is essential for both pion and nucleon, in the adopted reference frame ($q^+ \neq 0$)
- Pion: results present a reasonable agreement with the TL data, while in the SL region the model works very well.
- Nucleon: 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.
- The parameter free calculations in the TL region give a fair description of the proton data, although some strength is lacking for $q^2 = 4.5\ (GeV/c)^2$ and $q^2 = 8\ (GeV/c)^2$
- The available TL neutron data are not reproduced by the present model

Next possible steps :

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

- different approximations for the nucleon wave function could be tested

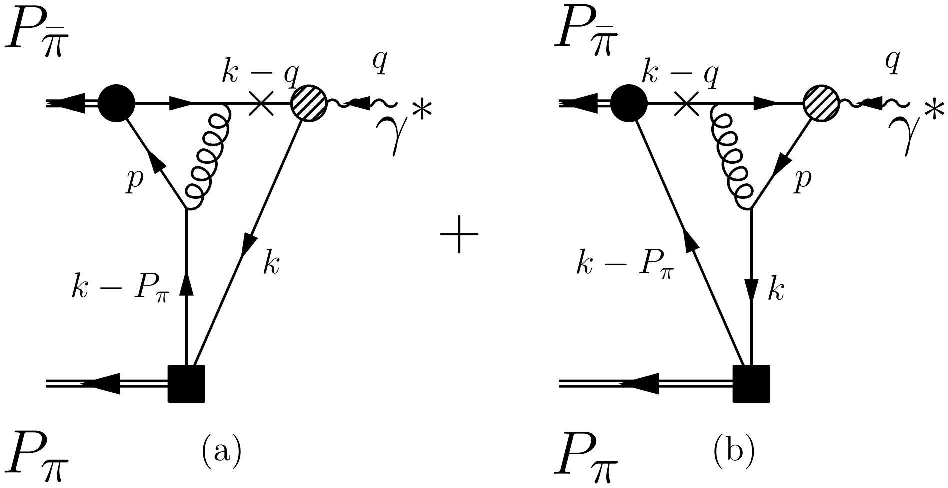
- a new model for the vector meson spectrum, able to account for the possible resonance at $M_n = 2.050\ GeV$ should be investigated and introduced in our calculation possibly for a better description of the quark-photon vertex.

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.

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



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.

The vertex functions with an instantaneous quark contribution is

$$\Lambda^{ist}_{\pi(n)} = \mathcal{K}^{ist}\, G_0\, \Lambda^{full}_{\pi(n)}$$

$\mathcal{K}^{ist}$ is the Bethe-Salpeter kernel for the instantaneous vertex function Λ^{ist}, G_0 the propagator of two free quarks and Λ^{full} the full vertex function (that we assume to be still related to the LF meson wave function).

We assume that the very short-range part of the one-gluon-exchange interaction, which includes spin-spin terms, is the dominant one and drastically simplify the above equation

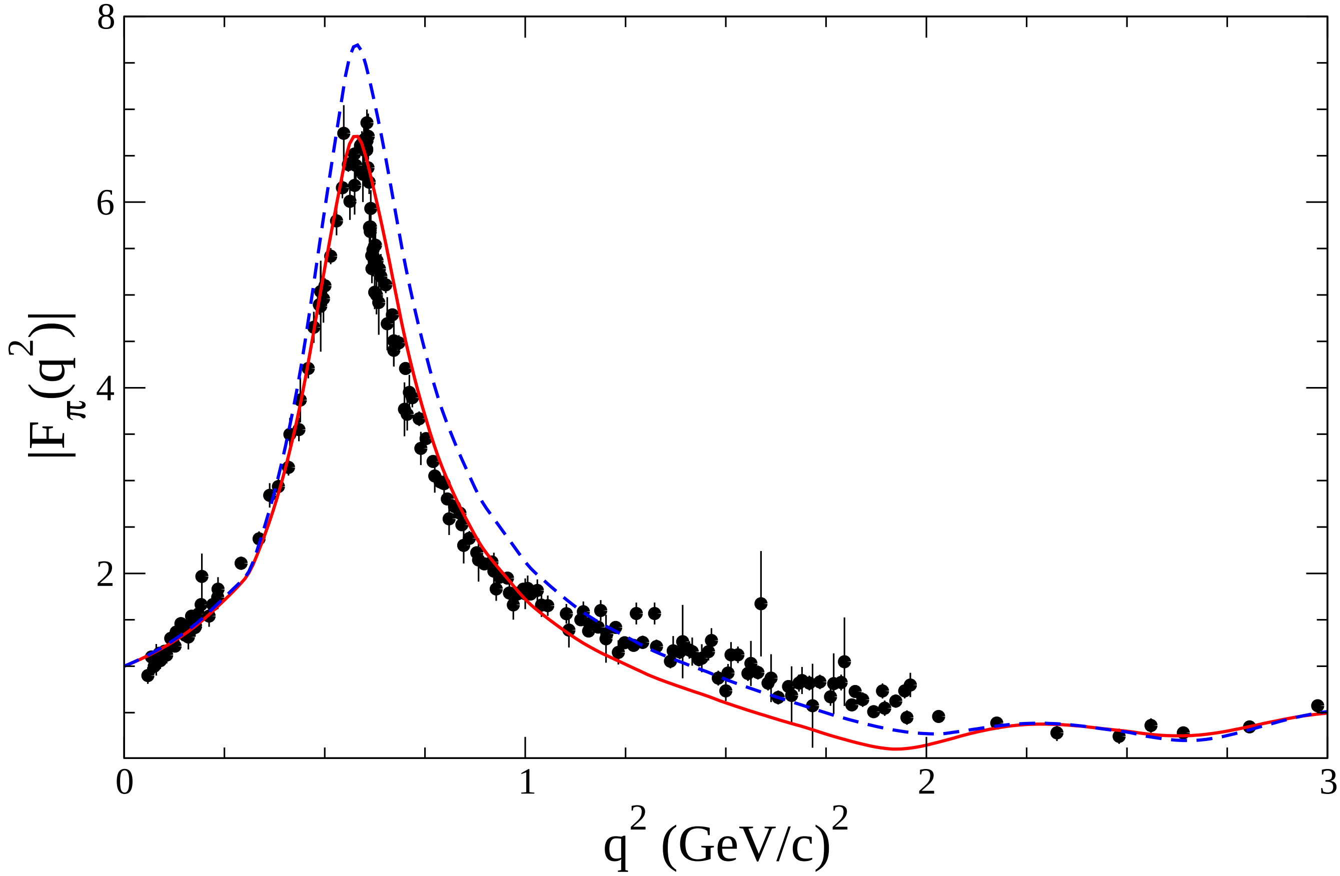
$$\Lambda^{ist} \sim \mathcal{C}\, \Lambda^{full}$$

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.

Sensitivity to the choice of different weights for the instantaneous Bethe-Salpeter amplitudes of pion and VM's

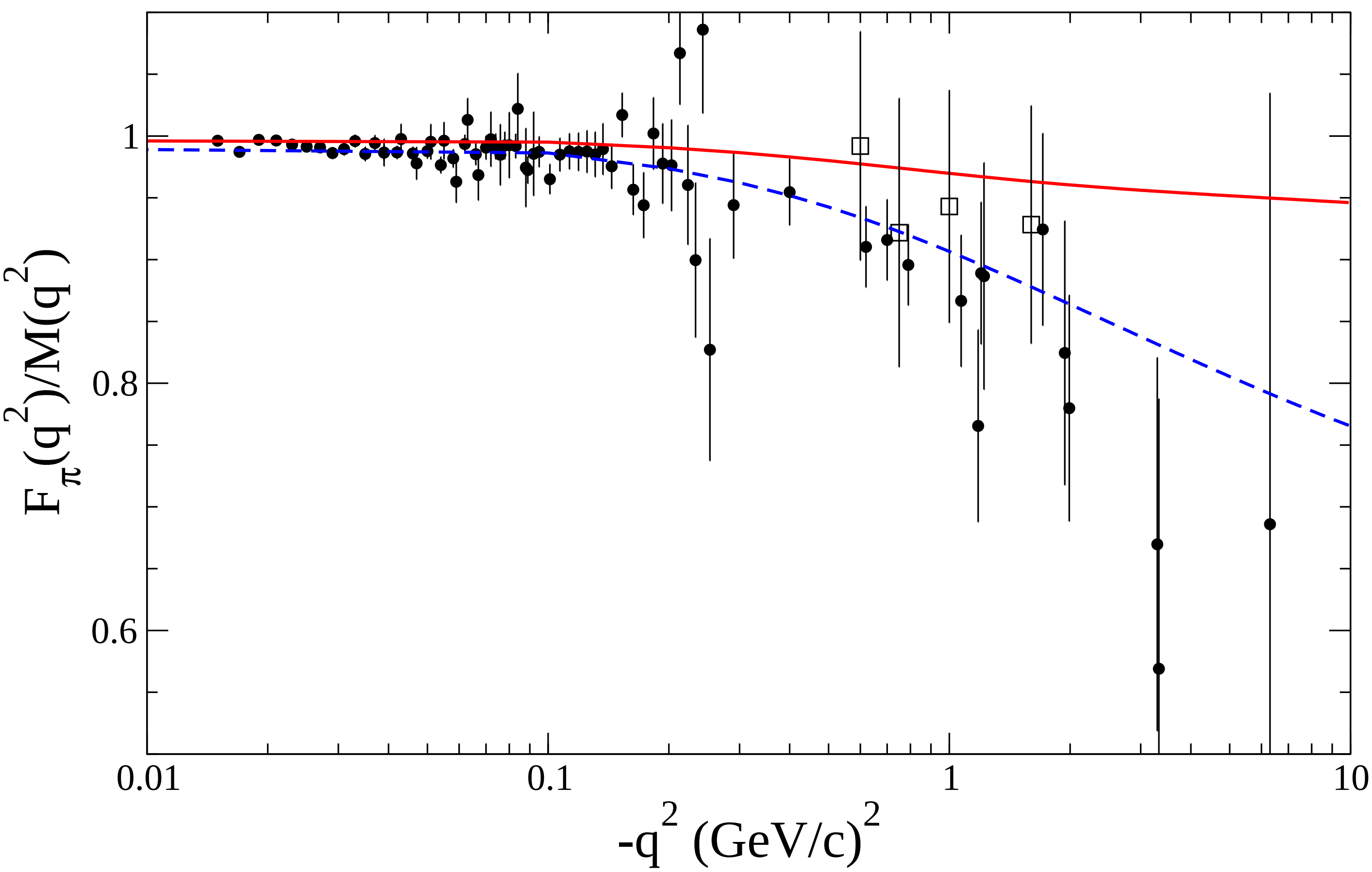
Pion form factor in the ρ-peak region



Solid line: calculation with the pion w.f. from the FPZ model for the Bethe-Salpeter amplitude in the valence region and $w_{VM} = -1.5$.

Dashed line: the same as the solid line but with $w_{VM} = -0.7$.

Pion form factor in the spacelike region.



The ratio $R_\pi(q^2) = F_\pi(q^2)/\left[1/(1 - q^2/m_\rho^2)\right]$ vs q^2, in the SL region. ●: Baldini et al.; □: TJLAB data, Volmer et al., PRL **86**, 1713 (2001).

Solid line: calculation with the pion w.f. from the FPZ model and $w_{VM} = -1.5$.

Dashed line: the same as the solid line but with $w_{VM} = -0.7$.

★ The good agreement with the experimental form factor at low momentum transfers is expected, since we have built-in the generalized ρ-meson dominance.