Timelike and spacelike electromagnetic form factors of nucleons, a unified description

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevD.85.113004">http://dx.doi.org/10.1103/PhysRevD.85.113004</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Sat Dec 22 22:59:32 EST 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/72143">http://hdl.handle.net/1721.1/72143</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td></td>
</tr>
</tbody>
</table>
The extended Lomon-Gari-Krümpelmann model of nucleon electromagnetic form factors, which embodies $ρ$, $ρ'$, $ω$, $ω'$, and $ϕ$ vector meson contributions and the perturbative QCD high momentum transfer behavior has been extended to the timelike region. Breit-Wigner formulas with momentum-dependent widths have been considered for broad resonances in order to have a parametrization for the electromagnetic form factors that fulfills, in the timelike region, constraints from causality, analyticity, and unitarity. This analytic extension of the Lomon-Gari-Krümpelmann model has been used to perform a unified fit to all the nucleon electromagnetic form factor data, in the spacelike and timelike region (where form factor values are extracted from $e^+e^-\to N\bar{N}$ cross sections data). The knowledge of the complete analytic structure of form factors enables predictions at extended momentum transfer, and also of timelike observables such as the ratio between electric and magnetic form factors and their relative phase.

I. INTRODUCTION

Nucleon electromagnetic form factors (EMFFs) describe modifications of the pointlike photon-nucleon vertex due to the structure of nucleons. Because the virtual photon interacts with single elementary charges, the quarks, it is a powerful probe for the internal structure of composite particles. Moreover, as the electromagnetic interaction is precisely calculable in QED, the dynamical content of each vertex can be compared with the data. The study of EMFFs is an essential step towards a deep understanding of the low-energy QCD dynamics. Nevertheless, even in case of nucleons, the available data are still incomplete. The experimental situation is twofold:

(i) In the spacelike region many data sets are available for elastic electron scattering from nucleons ($N$), both protons ($p$) and neutrons ($n$). Recently, the development of new polarization techniques (see e.g. Ref. [1]) provides an important improvement to the accuracy, giving a better capability of disentangling electric and magnetic EMFFs than the unpolarized differential cross sections alone.

(ii) In the timelike region there are few measurements, mainly of the total cross section (in a restricted angular range) of $e^+e^-\to N\bar{N}$, one set for neutrons and nine sets for protons, one of which includes a produced photon. Only two attempts, with incompatible results, have been made to separate the electric and magnetic EMFFs in the timelike region.

Many models and interpretations for the nucleon EMFFs have been proposed. Such a wide variety of descriptions reflects the difficulty of connecting the phenomenological properties of nucleons, parametrized by the EMFFs, to the underlying theory which is QCD in the nonperturbative (low-energy) regime. The analyticity requirement, which connects descriptions in both space ($q^2 < 0$) and timelike ($q^2 > 0$) regions, drastically reduces the range of models to be considered. In particular, the more successful ones in the timelike region are the vector-meson-dominance (VMD) based models [2,3] (see, e.g., Ref. [4] for a review on VMD models) that, in addition, because of their analytic form, have the property of being easily extendable to the whole $q^2$ domain: spacelike, timelike, and asymptotic regions.

In this paper we propose an analytic continuation to the timelike region of the last version of the Lomon model for the spacelike nucleon EMFFs [5]. This model has been developed by improving the original idea, due to Iachello, Jackson, and Landé [2] and further developed by Gari and Krümpelmann [3], who gave a description of nucleon EMFFs which incorporates VMD at low momentum transfer and asymptotic freedom in the perturbative QCD (pQCD) regime. As we will see in Sec. III, in this model EMFFs are described by two kinds of functions: vector meson propagators, dominant at low-$q^2$ and hadronic form factors (FFs) at high-$q^2$. The analytic extension of the model only modifies the propagator part and consists in defining more accurate expressions for propagators that account for finite-width effects and give the expected resonance singularities in the $q^2$-complex plane.

II. NUCLeon ELECTROMAGNETIC FORM FACTORS

The elastic scattering of an electron by a nucleon $e^-N\to e^-N$ is represented, in Born approximation, by the diagram of Fig. 1 in the vertical direction. In this
kinematic region the 4-momentum of the virtual photon is spacelike: \( q^2 = -2 \omega_1 \omega_2 (1 - \cos \theta_e) \leq 0 \), where \( \omega_{1(2)} \) is the energy of the incoming (outgoing) electron and \( \theta_e \) is the scattering angle.

The annihilation \( e^+ e^- \rightarrow N \bar{N} \) or \( N \bar{N} \rightarrow e^+ e^- \) is represented by the same diagram of Fig. 1 but in the horizontal direction, in this case the 4-momentum of the virtual photon is timelike: \( q^2 = (2 \omega)^2 \geq 0 \), where \( \omega = \omega_1 = \omega_2 \) is the common value of the lepton energy in the \( e^+ e^- \) center of mass frame.

The Feynman amplitude for the elastic scattering is

\[
M = \frac{1}{q} [e \bar{u}(k_2) \gamma^\mu u(k_1)] e \bar{U}(p_2) \Gamma_\mu(p_1, p_2) U(p_1),
\]

where the 4-momenta follow the labelling of Fig. 1, and \( U \) and \( \bar{U} \) are the electron and nucleon spinors, and \( \Gamma_\mu \) is a nonconstant matrix which describes the nucleon vertex. Using gauge and Lorentz invariance, the most general form of such a matrix is [6]

\[
\Gamma_\mu = \gamma^\mu F^N_1(q^2) + \frac{i \sigma^{\mu \nu} q_\nu}{2M_N} F^N_2(q^2),
\]

where \( M_N \) is the nucleon mass (\( N = n, p \)), and \( F^N_1(q^2) \) and \( F^N_2(q^2) \) are the so-called Dirac and Pauli EMFFs; they are Lorentz scalar functions of \( q^2 \) and describe the nonhelicity-flip and the helicity-flip part of the hadronic current, respectively. Normalizations at \( q^2 = 0 \) follow from total charge and static magnetic moment conservation and are

\[
F^N_1(0) = Q_N, \quad F^N_2(0) = \kappa_N,
\]

where \( Q_N \) is the electric charge (in units of \( e \)) and \( \kappa_N \) the anomalous magnetic moment (in units of the Bohr magneton \( \mu_B \)) of the nucleon \( N \).

In the Breit frame, i.e. when the transferred 4-momentum \( q \) is purely spacelike, \( q = (0, \vec{q}) \), the hadronic current takes the standard form of an electromagnetic 4-current, where the time and the space component are Fourier transformations of a charge and a current density, respectively:

\[
\rho_q = J^q = e \left[ F^N_1 + \frac{q^2}{2M^2} F^N_2 \right],
\]

\[
\tilde{J}_q = e \bar{U}(p_2) \gamma U(p_1) [F^N_1 + F^N_2].
\]

We can define another pair of EMFFs through the combinations

\[
G^N_E = F^N_1 + \frac{q^2}{2M^2} F^N_2, \quad G^N_M = F^N_1 + F^N_2.
\]

These are the Sachs electric and magnetic EMFFs [7], that, in the Breit frame, correspond to the Fourier transformations of the charge and magnetic moment spatial distributions of the nucleon. The normalizations, which reflect this interpretation, are

\[
G^N_E(0) = Q_N, \quad G^N_M(0) = \mu_N,
\]

where \( \mu_N = Q_N + \kappa_N \) is the nucleon magnetic moment. Moreover, Sachs EMFFs are equal to each other at the timelike production threshold \( q^2 = 4M^2_N \), i.e.,

\[
\]

Finally, we can consider the isospin decomposition for the Dirac and Pauli EMFFs:

\[
F^i_s = \frac{1}{2} (F^p_i + F^n_i), \quad F^i_v = \frac{1}{2} (F^p_i - F^n_i), \quad i = 1, 2.
\]

\( F^i_s \) and \( F^i_v \) are the isoscalar and isovector components.

### III. THE MODEL

The model presented here is based on simpler versions designed for the spacelike EMFFs of Iachello, Jackson and Landé [2] and of the Gari and Krümpelmann idea [3], which describes nucleon EMFFs by means of a mixture of VMD, for the electromagnetic low-energy part, and strong vertex FFs for the asymptotic behavior of superconvergent or pQCD. The Lomon version [5], which fits well all the spacelike data now available included two more well identified vector mesons and an analytic correction to the form of the \( \rho \) meson propagator suitable for describing the effect of its decay width in the spacelike region fitted to a dispersive analysis by Mergell, Meissner, and Drechsel [8].

This model describes the isospin components, Eq. (3), in order to separate different species of vector meson contributions. For the isovector part, the Lomon model used the \( \rho \) and \( \rho'(1440) \) or \( \rho' \) contribution, while for the isoscalar the \( \omega, \omega(1420) \) or \( \omega' \) and \( \phi \) were considered. In detail these are the expressions:
where
(i) $\text{BW}^\alpha_0(q^2)$ is the propagator of the intermediate vector meson $\alpha$ in pole approximation

$$
\text{BW}^\alpha_0(q^2) = \frac{g_\alpha}{f_\alpha} \frac{M^2_\alpha}{M^2_\alpha - q^2}, \quad \alpha = \rho, \omega, \omega^\prime, \phi,
$$

(5)

$M^2_\alpha g_\alpha/f_\alpha$ are the couplings to the virtual photon and the nucleons;
(ii) $\text{BW}^{\rho\omega}_\text{MMD}(q^2)$ are dispersion-integral analytic approximations for the $\rho$ meson contribution in the spacelike region [8]

$$
\text{BW}^{\rho\omega}_\text{MMD}(q^2) = \frac{1.0317 + 0.0875(1 - q^2/0.3176)^{-2}}{2(1 - q^2/0.5496)},
$$

$$
\text{BW}^{\rho\omega}_\text{MMD}(q^2) = \frac{5.7824 + 0.3907(1 - q^2/0.1422)^{-1}}{2\kappa_\rho(1 - q^2/0.5362)};
$$

(iii) the last term in each expression of Eq. (4) dominates the asymptotic QCD behavior and also normalizes the EMFFs at $q^2 = 0$ to the charges and anomalous magnetic moments of the nucleons;
(iv) the functions $F^{\alpha}_i(q^2)$, $\alpha = \rho, \omega, \omega^\prime$ and $i = 1, 2$, are meson-nucleon FFs which describe the vertices $\alpha NN$, where a virtual vector meson $\alpha$ couples with two on-shell nucleons. Noting that the same meson-nucleon FFs are used for $\rho^\prime$ and $\omega^\prime$ as for $\rho$ and $\omega$, we have

$$
F^{\rho,\omega}_i(q^2) = f_i(q^2) = \frac{\Lambda^2_i}{\Lambda^2_i - q^2}\left(\frac{\Lambda^2_i}{\Lambda^2_i - q^2}\right)^{i-1}, \quad i = 1, 2,
$$

$$
F^{\phi}_1(q^2) = f_1(q^2)\left(\frac{q^2}{q^2 - \Lambda^2_1}\right)^{3/2},
$$

$$
F^{\phi}_2(q^2) = f_2(q^2)\left(\frac{\Lambda^2_2 - \mu^2_\phi}{\sqrt{\mu^2_\phi - q^2}}\right)^{3/2},
$$

(6)

where $\Lambda_1$ and $\Lambda_2$ are free parameters that represent cutoffs for the general high energy behavior and the helicity-flip, respectively, and

$$
\tilde{q}^2 = q^2 \frac{\ln((\Lambda^2_D - q^2)/\Lambda^2_{\text{QCD}})}{\ln(\Lambda^2_D/\Lambda^2_{\text{QCD}})},
$$

(7)

where $\Lambda_D$ is another free cutoff which controls the asymptotic behavior of the quark-nucleon vertex, the extra factor in $F^{\phi}_i(q^2)$ imposes the Zweig rule; the functions $F^\phi_i(q^2)$ can be interpreted as quark-nucleon FFs that parametrize the direct coupling of the virtual photon to the valence quarks of the nucleons,

$$
F^\phi_i(q^2) = \frac{\Lambda^2_i}{\Lambda^2_i - \tilde{q}^2}\left(\frac{\Lambda^2_i}{\Lambda^2_i - \tilde{q}^2}\right)^{i-1}, \quad i = 1, 2,
$$

(8)

$\tilde{q}^2$ is defined as in Eq. (7);
(vi) finally, $\kappa_\alpha$ is the ratio of tensor to vector coupling at $q^2 = 0$ in the $\alpha NN$ matrix element, while the isospin anomalous magnetic moments are

$$
\kappa_s = \kappa_\rho + \kappa_\omega, \quad \kappa_t = \kappa_\rho - \kappa_\omega.
$$

The spacelike asymptotic behavior ($q^2 \to -\infty$) for the Dirac and Pauli EMFFs of Eq. (4) is driven by the $F^{\phi}_i(q^2)$ contribution, given in Eq. (8). In particular, we get

$$
F^{\rho,\omega}_i(q^2) \sim \frac{1}{q^2 - \infty} \frac{1}{[q^2 \ln((-q^2/\Lambda^2_{\text{QCD}}))]^2},
$$

$$
F^{\phi}_1(q^2) \sim \frac{F^{\phi}_i(q^2)}{q^2 - \infty} \frac{F^{\phi}_i(q^2)}{q^2 - \Lambda^2_{\text{QCD}}},
$$

as required by the pQCD [9].

In principle, this model can be extended also to the timelike region, positive $q^2$, to describe data on cross sections for the annihilation processes: $e^+ e^- \to N\bar{N}$. However, a simple analytic continuation of the expressions given in Eq. (4) involves important issues mainly concerning the analytic structure of the vector meson components of the EMFFs that, in the timelike region, are complex functions of $q^2$. The hadronic FFs of Eqs. (6) and (8) may also have real poles as a function of $q^2$. In fact, as defined above, $F^\rho_i$ has a real pole at $q^2 = \Lambda^2_\rho$. In the other denominators of Eqs. (6) and (8), as in $F^{\rho,\omega}_i$ and $F^\phi_1$, $q^2$ is replaced by $\tilde{q}^2$. The latter as a function of $q^2$ has a maximum in its real range $0 < q^2 < \Lambda^2_D$, which, for reasonable values of $\Lambda_D$ and $\Lambda_{\text{QCD}}$, may be smaller than $\Lambda^2_\omega, \Lambda^2_\rho$ and $\Lambda^2_D$. Therefore, all the hadronic FFs real poles may be avoided by also replacing $q^2$ by $\tilde{q}^2$ in the factors of $F^\phi_i$. This does not effect the asymptotic behavior required by the Zweig rule and will be adopted in the model used here. The results
in Sec. VI show that with this modification real poles can be avoided in every case examined, although in half the cases mild constraints on $\Lambda_1$ or $\Lambda_{QCD}$ are needed which affect the quality of the fit negligibly. A detailed treatment of the possibility of extending the model from the spacelike to the timelike region will be given in Sec. V.

IV. ANALYTICITY OF BREIT-WIGNER FORMULAS

The standard relativistic Breit-Wigner (BW) formula for an unstable particle of mass $M$ and energy independent width $\Gamma$ is

\[
\text{BW}(s) = \frac{1}{M^2 - s - i\Gamma M};
\]

it has a very simple analytic structure, only one complex pole and no discontinuity cut in its domain. Once this formula is improved to include energy dependent widths, one immediately faces problems concerning the analyticity.

We consider explicitly the case of the $\rho$ resonance in its dominant decay channel $\pi^\pm \pi^\mp$. A realistic way to formulate an energy dependent width is to extend the $\rho$ mass off shell, making the substitution $M_\rho^2 = s$, in the first order decay rate

\[
\Gamma(\rho \rightarrow \pi^\pm \pi^\mp) = \frac{|g_{\rho\pi\pi}|^2}{48\pi} \frac{M_\rho^2 - 4M_\pi^2}{M_\rho^2},
\]

where $g_{\rho\pi\pi}$ is the coupling constant and, $M_\rho$ and $M_\pi$ are the $\rho$ and pion mass, respectively. Such a decay rate has been obtained by considering, for the vertex $\rho \pi^\pm \pi^\mp$, the point-like amplitude

\[
\mathcal{M} = g_{\rho\pi\pi} e_\rho (p_+ - p_-)^\mu,
\]

where $e_\rho$ is the polarization vector of the vector meson $\rho$, and $p_\pm$ is the 4-momentum of $\pi^\pm$. Finally, assuming the $\pi^\pm \pi^\mp$ as the only decay channel and using Eq. (9) for the corresponding rate, the energy dependent width can be defined as

\[
\Gamma(s) = \frac{M_\rho^2}{s} (s - s_0) \left( \frac{M_\rho^2 - 4M_\pi^2}{s_0} \right)^{(3/2)} = \Gamma_0 \left( \frac{s - s_0}{s_0} \right)^{(3/2)},
\]

\[
\gamma = \frac{\Gamma(s)}{(M_\rho^2 - s_0)^{(3/2)}},
\]

where the subscript “$s$” indicates the factor $1/s$ appearing in the width definition, $\Gamma_0$ is the total width of the $\rho$, and $s_0 = 4M_\pi^2$. It follows that the BW formula becomes

\[
\text{BW}(s) = \frac{s}{s(M_\rho^2 - s) - i\gamma(s - s_0)^{(3/2)}}.
\]

In this form the BW has the “required” [10] discontinuity cut $(s_0, \infty)$ and maintains a complex pole $s_p$. Because of the more complex analytic structure, the new pole position $s_p$ turns out to be slightly shifted with respect to the original position $s_0$. Moreover, these are not the only complications introduced by using $\Gamma_0(s)$ instead of $\Gamma_0$, the power 3/2 in the denominator and the factor 1/s [see Eq. (10)] also generate additional physical poles which, in agreement with dispersion relations, must be subtracted, as discussed below.

A. Regularization of Breit-Wigner formulas

We consider the general case where there is a number $N$ of poles lying in the physical Riemann sheet. We may rewrite the BW by separating the singular and regular behaviors as

\[
\text{BW}(s) = \frac{P_N(s)}{\prod_{k=1}^N (s - z_j)(s^2 - s - i\gamma(s - s_0)^\beta)},
\]

where $P_N(s)$ is a suitable $N$ degree polynomial, $\beta$ is a noninteger real number which defines the discontinuity cut (in the previous case we had $\beta = 3/2$), $\gamma = \Gamma_0 / (M_\rho^2 - s_0)^\beta$, and the $z_j$ are the real axis (physical) poles. To avoid divergences in our formulas, we may define a simple regularization procedure consisting in subtracting these poles. In other words we add counterparts that at $z = z_j$ behave as the opposite of the $i$th pole. In more detail, we may define a regularized BW as

\[
\tilde{\text{BW}}(s) = \text{BW}(s) - \sum_{k=1}^N \frac{P_N(z_k)}{(s - z_k)(s^2 - s - i\gamma(s - s_0)^\beta)} \times \frac{1}{s - z_k}.
\]

In Appendix A we show how dispersion relations (DRs) offer a powerful tool to implement this procedure without the need to know where the poles are located. However, in this paper we show that an analytic expression also contains the information.

B. Two cases for $\Gamma(s)$

In our model for nucleon EMFFs, widths are used only for the broader resonances; $\rho(770)$, $\rho(1450)$, and $\omega(1420)$ [11]. We explicitly consider two expressions for $\Gamma(s)$ which entail different analytic structures for the BW formulas. Besides the form we discussed in Sec. IV, Eq. (10), we consider also a simpler expression (closer to the nonrelativistic form); hence, for a generic broad resonance, we have
\[ \Gamma_s(s) = \Gamma_0 \left( \frac{s - \bar{s}_0}{M^2 - \bar{s}_0} \right)^{3/2} = \frac{\gamma_s}{M} \left( s - \bar{s}_0 \right)^{3/2}, \]
with: \[ \gamma_s = \frac{\Gamma_0 M^3}{(M^2 - \bar{s}_0)^{3/2}} \]
\[ \Gamma_1(s) = \Gamma_0 \left( \frac{s - \bar{s}_0}{M^2 - \bar{s}_0} \right)^{3/2} = \frac{\gamma_1}{M} \left( s - \bar{s}_0 \right)^{3/2}, \]
with: \[ \gamma_1 = \frac{\Gamma_0 M}{(M^2 - \bar{s}_0)^{3/2}}. \]  

(12)

In both cases we assume that such a resonance decays predominantly into a two-body channel whose mass squared equals \( \bar{s}_0 \). The subscript “1” in the second expression of Eq. (12) indicates that there is no extra factor \( 1/s \) in the definition of the energy dependent width.

As already discussed, the BW formulas acquire a more complex structure as functions of \( s \); as a consequence, unwanted poles are introduced. Such poles spoil analyticity, hence, they must be subtracted by hand or, equivalently, by using the DR procedure defined in Appendix A.

In more detail, for both BW formulas, we only have one real pole, that we call \( s_s \) and \( s_1 \), respectively, (both less than \( \bar{s}_0 \)). The corresponding residues, that we call \( R_{s,1} \), are

\[ R_s = \frac{s_s}{M^2 - 2s_s + \frac{3}{2} \gamma_s \sqrt{\bar{s}_0 - s_s}} \]
\[ R_1 = -1 + \frac{1}{2} \gamma_1 \sqrt{\bar{s}_0 - s_1}. \]

Following Eq. (11), the regularized BW formulas read

\[ \tilde{\text{BW}}_{s,1}(s) = \text{BW}_{s,1}(s) - \frac{R_{s,1}}{s - s_{s,1}}. \]

In particular, below the threshold \( \bar{s}_0 \), where BWs are real, we have

\[ \tilde{\text{BW}}_{s}(s < \bar{s}_0) = \frac{s}{s(M^2 - s) - \gamma_s(\bar{s}_0 - s)^{3/2}} - \frac{R_s}{s - s_s}, \]
\[ \tilde{\text{BW}}_{1}(s < \bar{s}_0) = \frac{1}{M^2 - s - \gamma_1(\bar{s}_0 - s)^{3/2}} - \frac{R_1}{s - s_1}. \]  

(14)

Above \( \bar{s}_0 \) BWs become complex; real and imaginary parts are obtained as the limit of \( \tilde{\text{BW}}_{s,1}(s) \) over the upper edge of the cut (\( \bar{s}_0, \infty \)). Since the poles \( s_{s,1} \) are real, only the real parts have to be corrected as

\[ \text{Re}[\tilde{\text{BW}}_{s}(s > \bar{s}_0)] = \frac{s^2(M^2 - s)}{s^2(M^2 - s)^2 + (\gamma_s^2(s - \bar{s}_0)^3)^2} - \frac{R_s}{s - s_s}, \]
\[ \text{Re}[\tilde{\text{BW}}_{1}(s > \bar{s}_0)] = \frac{M^2 - s}{s^2(M^2 - s)^2 + (\gamma_1^2(s - \bar{s}_0)^3)^2} - \frac{R_1}{s - s_1}, \]  

while the imaginary parts remain unchanged

\[ \text{Im}[\tilde{\text{BW}}_{s}(s > \bar{s}_0)] = \frac{s \gamma_s^2(s - \bar{s}_0)^{3/2}}{s^2(M^2 - s)^2 + (\gamma_s^2(s - \bar{s}_0)^3)^2}, \]
\[ \text{Im}[\tilde{\text{BW}}_{1}(s > \bar{s}_0)] = \frac{\gamma_1^2(s - \bar{s}_0)^{3/2}}{(M^2 - s)^2 + (\gamma_1^2(s - \bar{s}_0)^3)^2}. \]

(15)

(16)

The parameters of the subtracted poles for the three vector mesons are reported in Table I. A third case is discussed in Appendix B. It is not fitted to the data because its resonance structure is intermediate between the two above cases.

Figures 2 and 3 show comparisons between the two descriptions in case of \( \rho \) in the spacelike and timelike regions, respectively. On the left of each figure is the modulus of each, on the right the relative difference with respect to BWs.

V. THE ANALYTIC EXTENSION

The original model, described in Sec. III and constructed in the spacelike region, can be analytically continued in the timelike region using the regularized BW formulas obtained in Sec. IV. We consider then a new set of expressions for \( F_{\gamma,2}(q^2) \) and \( F_{\gamma,1}(q^2) \), homologous to those of Eq. (4) where now we use regularized BW formulas instead of the MMD [8] \( \rho \) width form or the zero-width approximation given in Eq. (5), and also two additional vector meson contributions, \( \rho(1450) \) and \( \omega(1420) \) here simply \( \rho' \) and \( \omega' \), as in the last version of the Lomon model [5]. Such BWs have the expected analytic structure and reproduce in both spacelike and timelike regions the finite-width effect of broad resonances. The narrow widths of the \( \omega \) and \( \phi \) have negligible effects, so we use these modified propagators only for broader vector mesons, namely: the isovectors \( \rho \) and \( \rho' \), and the isoscalar \( \omega' \). These are the new expressions for the isospin components of nucleon EMFFs:
where case = s and case = 1 correspond to the parametrizations of the energy dependent width described in Sec. IV B. Following Eqs. (14)–(16) for the definition of \(BW(q^2)\), and including the coupling constants, we have
TIMELIKE AND SPACELIKE ELECTROMAGNETIC FORM

TABLE II. Measured quantities, numbers of data points and \( \chi^2 \) contributions. The values in parentheses indicate the number of data points in the case “No BABAR.”

<table>
<thead>
<tr>
<th>( Q_i )</th>
<th>( N_i )</th>
<th>case = s With BABAR</th>
<th>case = 1 With BABAR</th>
<th>case = ( s ) No BABAR</th>
<th>case = ( 1 ) No BABAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>spacelike</td>
<td>( G_M^s )</td>
<td>68</td>
<td>48.7</td>
<td>50.1</td>
<td>54.6</td>
</tr>
<tr>
<td></td>
<td>( G_E^s )</td>
<td>36</td>
<td>30.4</td>
<td>27.6</td>
<td>26.2</td>
</tr>
<tr>
<td></td>
<td>( G_M^p )</td>
<td>65</td>
<td>154.6</td>
<td>154.2</td>
<td>158.2</td>
</tr>
<tr>
<td></td>
<td>( G_E^p )</td>
<td>14</td>
<td>22.7</td>
<td>23.2</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td>( \mu_p G_M^p / G_M^s )</td>
<td>25</td>
<td>13.9</td>
<td>12.9</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>( \mu_n G_M^p / G_M^s )</td>
<td>13</td>
<td>11.3</td>
<td>10.7</td>
<td>8.2</td>
</tr>
<tr>
<td>timelike</td>
<td>( G_M^{eff} )</td>
<td>81 (43)</td>
<td>162.5</td>
<td>166.7</td>
<td>62.2</td>
</tr>
<tr>
<td></td>
<td>( G_E^{eff} )</td>
<td>5</td>
<td>8.4</td>
<td>8.3</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>313(275)</td>
<td>452.5</td>
<td>451.7</td>
<td>347.3</td>
</tr>
</tbody>
</table>

\[
\mathcal{M}(q^2) = \frac{1}{q^2-s} \left( \frac{G^s}{M} - \frac{R^s}{q^2-s} \right) \quad \text{case = } s
\]

where \( q^2 \) is defined in the usual form as

\[
\chi^2 = \sum_{i=1}^{9} \tau_i \cdot \chi_i^2,
\]

where the coefficients \( \tau_i \) weight the ith contribution, we use \( \tau_i = 1 \) or \( \tau_i = 0 \) to include or exclude the ith data set. The single contribution \( \chi_i^2 \) is defined in the usual form as

\[
\chi_i^2 = \sum_{k=1}^{N_i} \left( \frac{Q_i(q_k^2) - \nu_k^i}{\delta \nu_k^i} \right)^2,
\]

VI. RESULTS

Nine sets of data have been considered; six of them lie in the spacelike region [12], and three lie in the timelike region [13–21]. The data determine the Sachs EMFFs and their ratios. The fit procedure consists in defining a global \( \chi^2 \) as a sum of nine contributions, one for each set. In more detail, we minimize the quantity

where magnetic EMFFs are also normalized to the magnetic moment. This normalization decreases the range of variation, but the curves clearly demonstrate deviations from the dipole form. The observable \( R_N \) is defined as the ratio \( R_N = G_N^s / G_M^s \) for the nucleon \( N \). As \( N \) stands for both neutron and proton, there are six spacelike observables. A departure from scaling is shown in the deviation of \( R_p \) and \( R_n \) from unity.
TABLE III. Best values of fit parameters and constants.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>case = s With BABAR</th>
<th>case = 1 With BABAR</th>
<th>case = s No BABAR</th>
<th>case = 1 No BABAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_ρ/\rho$</td>
<td>2.766</td>
<td>2.410</td>
<td>0.9029</td>
<td>0.4181</td>
</tr>
<tr>
<td>$κ_ρ$</td>
<td>−1.194</td>
<td>−1.084</td>
<td>0.8267</td>
<td>0.6885</td>
</tr>
<tr>
<td>$M_ρ$ (GeV)</td>
<td>0.7755 (fixed)</td>
<td>0.1491 (fixed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Γ_ρ$ (GeV)</td>
<td>0.1941 (fixed)</td>
<td>0.1491 (fixed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g_ω/\omega$</td>
<td>−1.057</td>
<td>−1.043</td>
<td>−0.2308</td>
<td>−0.4894</td>
</tr>
<tr>
<td>$κ_ω$</td>
<td>−3.240</td>
<td>−3.317</td>
<td>−9.859</td>
<td>−1.398</td>
</tr>
<tr>
<td>$M_ω$ (GeV)</td>
<td>0.78263 (fixed)</td>
<td>0.78263 (fixed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g_φ/\phi$</td>
<td>0.1871</td>
<td>0.1445</td>
<td>0.0131</td>
<td>0.1156</td>
</tr>
<tr>
<td>$κ_φ$</td>
<td>−2.004</td>
<td>−3.045</td>
<td>37.218</td>
<td>−0.2613</td>
</tr>
<tr>
<td>$M_φ$ (GeV)</td>
<td>2.015</td>
<td>1.974</td>
<td>1.265</td>
<td>1.649</td>
</tr>
<tr>
<td>$Γ_φ$ (GeV)</td>
<td>−2.053</td>
<td>−2.010</td>
<td>−2.044</td>
<td>−0.6712</td>
</tr>
<tr>
<td>$g_ρ'/\rho'$</td>
<td>−2.745</td>
<td>−3.274</td>
<td>−0.8730</td>
<td>−0.0369</td>
</tr>
<tr>
<td>$κ_ρ'$</td>
<td>−1.657</td>
<td>−1.724</td>
<td>−2.832</td>
<td>−104.35</td>
</tr>
<tr>
<td>$M_ρ'$ (GeV)</td>
<td>1.465 (fixed)</td>
<td>0.400 (fixed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Γ_ρ'$ (GeV)</td>
<td>1.465 (fixed)</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Λ_1$ (GeV)</td>
<td>0.4801</td>
<td>0.5000</td>
<td>0.6474</td>
<td>0.6446</td>
</tr>
<tr>
<td>$Λ_2$ (GeV)</td>
<td>3.0536</td>
<td>3.0562</td>
<td>3.0872</td>
<td>3.6719</td>
</tr>
<tr>
<td>$Δ$ (GeV)</td>
<td>0.7263</td>
<td>0.7416</td>
<td>0.8573</td>
<td>0.8967</td>
</tr>
<tr>
<td>$Λ_{QCD}$ (GeV)</td>
<td>0.050</td>
<td>0.050</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The timelike effective FF, $|G_{eff}^N(q^2)|$, is defined as

$$|G_{eff}^N(q^2)| = \left[ \frac{σ(e^+e^−→N\bar{N})}{4π\alpha q^2 \sqrt{1-4M_{NN}^2/q^2(1+2M_N^2/q^2)}} \right]^{1/2},$$

where $σ(e^+e^−→N\bar{N})$ is the measured total cross section, and the kinematic factor at denominator is the Born cross section for a pointlike nucleon. In terms of electric and magnetic EMFFs, $G_E^N$ and $G_M^N$, i.e. considering the matrix element given in Eq. (1) and the definitions of Eq. (2), we have

$$|G_{eff}^N(q^2)| = \left( |G_M^N(q^2)|^2 + \frac{2M_N^2}{q^2} |G_E^N(q^2)|^2 \right)^{1/2} \times \left( 1 + \frac{2M_N^2}{q^2} \right)^{-1/2},$$

and this is the relation that we use to fit the data on $|G_{eff}^N|$ for both proton-antiproton and neutron-antineutron production.

The proton-antiproton production experiments were of two types, (1) the exclusive pair production [13–20] and (2) production of the pair with a photon [21]. In the latter case the pair production energy is obtained by assuming that the photon was produced by the electron or positron and that no other photons were emitted but undetected. Fits of the model were made both with and without the latter data [21]. In Figs. 5–12 the fit curves corresponding to the two possibilities: with and without BABAR data, are shown as solid and dashed lines, respectively.

The free parameters of this model are

(i) the three cutoffs: $Λ_1$, $Λ_2$, and $Λ_D$ which parametrize the effect of hadronic FFs and control the transition from nonperturbative to perturbative QCD regime in the $γNN$ vertex;

(ii) five pairs of vector meson anomalous magnetic moments and photon couplings ($κ_α, g_α/f_α$), with $α = ρ, ρ', ω, ω', φ$.

The best values for these 13 free parameters together with the constants of this model are reported in Table III.

The fixed parameters concern well-known measurable features of the intermediate vector mesons and dynamical quantities. Particular attention has to be paid to $Λ_{QCD}$. In fact we use the values $Λ_{QCD} = 0.15$ GeV in all cases but for the case $= 1$ without BABAR data, where instead $Λ_{QCD} = 0.10$ GeV. The use of such a reduced value is motivated by the requirement of having no real poles in meson-nucleon and quark-nucleon FFs (Sec. III). As $Λ_{QCD} = 0.15$ GeV is closer to the values preferred by high energy experiments, it suggests that case $= s$ is the more physical model. Another reason to prefer it on physical grounds is that the width formula of the vector meson decay in case $= s$ is determined by relativistic perturbation theory. Case $= 1$ was chosen because it is a simpler relativistic modification of the nonrelativistic Breit-Wigner form. This in our view is a less physical reason.
VII. DISCUSSION

The Lomon-Gari-Krupelman model [5] was developed for and fitted to spacelike EMFF data. To enable the model to include the timelike region, only the vector meson (of nonnegligible width) propagators needed revision to appropriately represent a relativistic BW form at their pole in the timelike region. Two such forms are discussed above, case \( s = 1 \), the minimal alteration from the nonrelativistic BW form, and case \( s \) derived from relativistic perturbation theory. The resulting modification in the spacelike region is minor and affected the fit there very little.

With the new form of the vector meson propagators, the simultaneous fit to the spacelike EMFF and the timelike nucleon-pair production data was satisfactory as seen in Figs. 4–11 and by the \( \chi^2 \) values of Table III.

The \( \chi^2 \) contributions from each spacelike EMFF differ little between case \( s = 1 \) and case \( s \) and are approximately the same as in the spacelike only fit of Ref. [12].
However, the fit in the timelike region, as measured by \( \chi^2/\text{d.o.f.} \), is qualitatively poorer when the BABAR data \([21]\) are included (\( \chi^2/\text{d.o.f.} = 2.5 \) than when that set of data is omitted (\( \chi^2/\text{d.o.f.} = 0.5 \) for case = 1, and is 1.0 for case = s). As the quality of the fit is poorer when the BABAR data are included, it may indicate an inadequacy in the model. However, the energy of the nucleon pairs produced in the BABAR experiment, unlike that of the exclusive pair production \([13–20]\), depends on the assumption that the observed photon is from electron or positron emission and is not accompanied by a significant amount of other radiation. The resultant theoretical error is not fully known although relevant calculations have been made \([22]\). The angular distributions may be sensitive to these radiation effects affecting the values of the \( |G_E/G_M| \) ratio whose data are displayed in Fig. 12 together with our prediction.

Figures 4–9 are extended to higher momentum transfers than the present data to show how the four different fits may be discriminated by new data. Figure 8 for \( R_p \) indicates that at the higher momentum-transfers extended data

---

**FIG. 8.** Spacelike ratio \( R_p = \mu_p G_E^p/G_M^p \) normalized to \( \mu_p \), in case = 1 and case = s, including and not the BABAR data.

**FIG. 10.** Timelike effective proton FF data (nine sets \([13–21]\)) and fit, in case = 1 and case = s, including and not the BABAR data.

**FIG. 9.** Spacelike ratio \( R_n = \mu_n G_E^n/G_M^n \) normalized to \( \mu_n \), in case = 1 and case = s, including and not the BABAR data.

**FIG. 11.** Timelike effective neutron FF data (only FENICE \([13]\)) and fit, in case = 1 and case = s, including and not the BABAR data.
may discriminate the smaller case = s no BABAR prediction from the larger case = 1 and case = s with BABAR predictions and from the still larger case = 1 no-BABAR prediction. Figure 9 for $R_s$ shows that at high momentum transfer the case = s predictions are higher than those for case = 1.

Figure 11 is extended in energy for the same reason. It clearly shows that at higher energy case = 1 no-BABAR may be discriminated from the other three fits by moderately precise data.

An extension of Fig. 10 would only show the production of proton pairs remaining very close to zero. However, in the range of energy already covered it is evident that the case = s no-BABAR result is difficult to reconcile with the BABAR data for $s = 5–7$ GeV$^2$. However, for $s = 7.5–8.5$ GeV$^2$ the no-BABAR fits are closer to the BABAR data than are the with-BABAR fits.

Figures 12 and 13 show that experiments in the timelike region for the ratio $|G_E^p/G_M^p|$ and the phase difference of $G_E^p$ and $G_M^p$ would be effective in discriminating between the models presented here and other models as well.

APPENDIX A: DISPERSION RELATIONS

Dispersion relations are based on the Cauchy theorem. Consider a function $F(z)$, analytic in the whole $z$ complex plane with the discontinuity cut $(s_0, \infty)$. If that function vanishes faster than $1/\ln|z|$ as $|z|$ diverges, we can write the spectral representation

$$F(z) = \frac{1}{\pi} \int_{s_0}^{\infty} \frac{\text{Im}[F(x)]dx}{x-z}.$$  \hspace{1cm} (A1)

This is the so-called DR for the imaginary part where it is understood that the imaginary part is taken over the upper edge of the cut.

The extension to the case where there is a finite number of additional isolated poles is quite natural. Indeed, considering a function with the set of poles $\{z_j\}$ ($j = 1, \ldots, N$) of Sec. IVA, under the same conditions, we obtain the spectral representation

$$F(z) + 2\pi i \sum_{j=1}^{N} \text{Res} \left[ \frac{F(z')}{z'-z}, z_j \right] = \frac{1}{\pi} \int_{s_0}^{\infty} \frac{\text{Im}[F(x)]dx}{x-z},$$  \hspace{1cm} (A2)

where $\text{Res}[g(z), z_0]$ stands for the residue of the function $g(z)$ at $z = z_0$. Furthermore, since we know the poles, we can use the more explicit form

$$F(z) = \frac{f(z)}{\prod_{j=1}^{N} (z-z_j)},$$

where $f(z)$ is the pole-free part of $F(z)$, but it has the same discontinuity cut. Using this form in the residue definition of Eq. (A2) and defining $\tilde{F}(z)$ as the regularized version of $F(z)$, we have

$$\tilde{F}(z) = F(z) + \sum_{k=1}^{N} \frac{f(z_k)}{\prod_{k'=1,k\neq k}^{N} (z_k - z_{k'})} \frac{1}{z_k - z} = \frac{1}{\pi} \int_{s_0}^{\infty} \frac{\text{Im}[F(x)]dx}{x-z},$$

which is exactly the same expression as Eq. (11). In other words, the DR procedure, using only the imaginary part of a generic function, which is suffering or not from the presence of unwanted poles, guarantees regularized
analytic continuations, the poles, even if unknown, are automatically subtracted.

**APPENDIX B: A THIRD CASE**

We consider a regularized vector meson propagator [23]

\[ D(s) = \frac{1}{M_0^2 - s + \Pi(s)}, \]

where \( M_0 \) is the bare mass of the meson and \( \Pi(s) \) is the scalar part of the tensor correlator. The imaginary part, due to the pion loop, can be obtained using the so-called Cutkosky rule [24] as

\[ \operatorname{Im}\Pi(s) = -\gamma_0 \sqrt{\frac{(s - \tilde{s}_0)^3}{s}} \theta(s - \tilde{s}_0), \]

\[ \gamma_0 = \frac{\Gamma_0 M^2}{\sqrt{(M^2 - \tilde{s}_0)^3}}. \]

(B1)

The real part of \( \Pi(s) \) represents the correction to the bare mass \( M_0 \) in such a way that the dressed mass becomes

\[ M^2 = M_0^2 + \operatorname{Re}\Pi(s). \]

It follows that the propagator can be written in terms of \( M^2 \) and the only imaginary part of \( \Pi(s) \)

\[ D(s) = \frac{1}{M^2 - s - i\operatorname{Im}\Pi(s)} = \frac{1}{M^2 - s - i\theta(s - \tilde{s}_0)\gamma_0\sqrt{(s - \tilde{s}_0)^3}/s}. \]

(B2)

Actually, only the imaginary part of this expression makes sense because of the Heaviside step function in the definition of Eq. (B1); nevertheless, using DR, one can determine the complete propagator starting just from its imaginary part. The propagator is expected to be real below the threshold \( \tilde{s}_0 \). In particular, using Eq. (A1) for \( t < \tilde{s}_0 \), we have

\[ D(t) = \frac{1}{\pi} \int_{\tilde{s}_0}^{\infty} \frac{\operatorname{Im}D(s)ds}{s - t} = \frac{\gamma_0}{\pi} \int_{\tilde{s}_0}^{\infty} \frac{\sqrt{s(s - \tilde{s}_0)^3}ds}{s(M^2 - s - \gamma_0^2(s - \tilde{s}_0)^3)(s - t)}, \]

while the real part over the timelike cut (\( \tilde{s}_0, \infty \)), i.e. for \( s > \tilde{s}_0 \), is

\[ \operatorname{Re}D(s) = \frac{1}{\pi} \text{Pr} \int_{\tilde{s}_0}^{\infty} \frac{\operatorname{Im}D(s')ds'}{s' - s} = \frac{\gamma_0}{\pi} \text{Pr} \int_{\tilde{s}_0}^{\infty} \frac{\sqrt{s'(s' - \tilde{s}_0)^3}ds'}{s'(M^2 - s' - \gamma_0^2(s' - \tilde{s}_0)^3)(s' - s)}. \]

(B4)

In this case the “natural” spacelike extension of the original form given in Eq. (B2) is no more possible; in fact such a form, when we forget the Heaviside function in the denominator, develops a second cut which extends over the whole spacelike region. It follows that we can not write an expression like

\[ \mathbb{R} \ni \tilde{D}(s < \tilde{s}_0) = \frac{1}{M^2 - s - i\sqrt{(s - \tilde{s}_0)^3}/s} - \sum \frac{R_k}{s - s_k}, \]

Physical poles

where we get, in the spacelike region, a regular and real propagator simply by subtracting the physical poles.

The only possibility to go below threshold is to use the DRs of Eqs. (B3) and (B4). We compute explicitly the DR integrals using the substitution

\[ x = \sqrt{1 - \frac{\tilde{s}_0}{s}} \rightarrow \left\{ \begin{array}{l}
\frac{s}{s} = 2\tilde{s}_0 \frac{sd\tilde{s}_0}{(1 - x^2)^2}, \\
\frac{s}{s} \in (\tilde{s}_0, \infty) \rightarrow x \in (0, 1).
\end{array} \right. \]

The regularized form for \( D(s) \) is

\[ \tilde{D}(s) = \left\{ \begin{array}{l}
\frac{-1}{\pi s_0} \sum_{i=0}^{3} \frac{\xi_i^0 \ln(\xi_i^{0, t})}{\prod_{i=1}^{3} (x_i^0 - x_i)} \\
\frac{1}{\pi^2 s_0} \sum_{i=0}^{3} \frac{\xi_i^0 \ln(\xi_i^{0, t})}{\prod_{i=1}^{3} (x_i^0 - x_i)} + \frac{\gamma_0 \ln(\tilde{s}_0)^3}{s(M^2 - s)^2 + \gamma_0^2 (s - \tilde{s}_0)^3 s > \tilde{s}_0}
\end{array} \right. \]

The four values \( x_i^0 \) are the roots of the 4th-degree polynomial in \( x_0 \), which represents the denominator of the integrands in both DR’s:

\[ \{[(1 - x^2)M^2/\tilde{s}_0 - 1]/\gamma_0 + x^3 (\tilde{s}_0/t - 1 + x^2)\}, \]

in particular, \( x_0^2 = 1 - \tilde{s}_0/s \) is the only root that depends on \( s \), while the three \( x_i \) with \( i = 1, 2, 3 \), are the constant zeros of the first polynomial factor of 2 in Eq. (B5).

The value at \( s = 0 \) can be obtained as

\[ \tilde{D}(0) = \frac{-1}{\pi s_0} \sum_{i=0}^{3} \frac{\xi_i^0 \ln(\xi_i^{0, t})}{\prod_{i=1}^{3} (x_i^0 - x_i^0)} \]

Concerning the asymptotic behavior, when \( s \rightarrow \pm \infty \), i.e.

\[ \tilde{D}(s) \sim s |s|^{-\infty} \frac{1}{\pi s_0 \prod_{i=1}^{3} (1 - x_i^0)} \frac{\ln |s|}{s} = \frac{\gamma_0 \ln |s|}{\pi (1 + \gamma_0^2)} \]

where the last identity follows because the product at denominator is just the 3rd degree \( x^2 \) polynomial of Eq. (B5) evaluated at \( x^0 = 1 \).

A data fit was not made for this case because the resonance shape it produces is intermediate between the fitted case \( = 1 \) and case \( = s \).
APPENDIX C: THE THRESHOLD BEHAVIOR

The effective proton and neutron EMFFs extracted from the cross section data through the formula of Eq. (17) have a quite steep enhancement towards the threshold, i.e. when $q^2 \to (2M_N)^2$. This is a consequence of the almost flat cross section measured in the near-threshold region: $(2M_N)^2 \leq q^2 \leq (2\text{ GeV})^2$. Such a flat behavior is in contrast with the expectation in case of a smooth effective FF, which gives, near threshold, a cross section proportional to $\frac{1}{C_0^4 M^2 N \frac{q^4}{q^2}}$. Moreover, in the threshold region the formula of Eq. (17) has to be corrected to account for $N/f_{\text{final state interaction}}$. In particular, in the Born cross section formula, in case of proton-antiproton, we have to consider the correction due to their electromagnetic attractive interaction [25]. Such a correction, having a very weak dependence on the fermion pair total spin, factorizes and, in case of pointlike fermions, corresponds to the squared value of the Coulomb scattering wave function at the origin; it is also called the Sommerfeld-Schwinger-Sakharov rescattering formula [26]. Besides the Coulomb force, strong interaction could also be considered. Indeed, when final hadrons are produced almost at rest, they interact strongly with each other before getting outside the range of their mutual forces [27]. Indeed there is evidence for near threshold quasibound $NN$ states with widths in the tens of MeV [28]. It follows that EMFF values in this energy region are affected by different kinds of corrections whose form and interplay are not well-known. Hence, we decided to include in the present analysis only data above $q^2 = 4 \text{ GeV}^2$, to avoid the threshold region.

Figures 14 and 15 show the residue data over fit for the proton and neutron effective FF: $|G_{\text{eff, data}}^{p,n}|/|G_{\text{eff, fit}}^{p,n}|$, where $|G_{\text{eff, fit}}^{p,n}|$ has been obtained considering only data with $q^2 \geq 4 \text{ GeV}^2$.

---


