Abstract Due to the angular condition in the light-front dynamics (LFD), the extraction of the electromagnetic form factors for spin-1 particles can be uniquely determined taking into account implicitly non-valence and/or the zero-mode contributions to the matrix elements of the electromagnetic current. No matter which matrix elements of the electromagnetic current is used to extract the electromagnetic form factors, the same unique result is obtained. As physical observables, the electromagnetic form factors obtained from matrix elements of the current in LFD must be equal to those obtained in the instant form calculations. Recently, the Babar collaboration [1] has analyzed the reaction $e^+ + e^- \rightarrow \rho^+ + \rho^-$ at $\sqrt{s} = 10.58$ GeV to measure the cross section as well as the ratios of the helicity amplitudes $F_{\lambda' \lambda}$. We present our recent analysis of the Babar data for the rho meson considering the angular condition in LFD to put a stringent test on the onset of asymptotic perturbative QCD and predict the energy regime where the subleading contributions are still considerable.

Keywords Light-Front Dynamics, Electromagnetic form factors, electromagnetic observables, $\rho$-meson, Perturbative QCD

1 Introduction

The quantum field theory of strong interactions is Quantum Chromodynamics (QCD) and the main purpose of this theory is to explain the bound state hadronic systems in terms of quarks and gluons, the degrees of freedom of QCD. However, this task is not so easily fulfilled [2]. The light-front dynamics is one useful approach to describe hadronic bound states, mesons or baryons, in particular, because of the trivial kinematic boost properties [3; 4; 5]. Nevertheless, the light-front description with a truncated Fock space breaks the rotational symmetry as the rotation operator in LFD is dynamical [6; 7; 8; 9]. The main consequence from the violation of the rotational symmetry appears as the loss of the covariance of calculated matrix elements (i.e. the helicity amplitudes) of the electromagnetic (EM) current [2; 3; 4; 10]. To restore the covariance of the electromagnetic current matrix elements in any effective model calculation of LFD, it is crucial to take into account the non-valence contribution as well as the zero-mode contribution. Once covariance is restored, then the observables calculated with these matrix elements will have the same results as in an instant form basis calculation [2; 3; 4; 11; 12].

In the case of spin-1 particles, the LFD satisfying both parity and time-reversal invariance may yield four matrix elements for the electromagnetic current for the plus component of the electromagnetic

J. P. B. C. de Melo
Laboratorio de Física Teórica e Computação Científica, Universidade Cruzeiro do Sul, 01506-000, São Paulo, Brazil.

T. Frederico
Instituto Tecnológico de Aeronáutica, 12228-900, São José dos Campos, Brazil.

Chueng-Ryong Ji
Department of Physics, Box 8202, North Carolina State University, Raleigh, NC 27695-8202, USA.
current, $J^+$, while only three form factors, i.e., charge, magnetic and quadrupole form factors exist. However, the requirement of the angular momentum conservation provides the angular condition in LFD and due to the angular condition the number of independent matrix elements in LFD gets identical to the number of independent physical observables or form factors. While we have many possibilities to combine the matrix elements of the electromagnetic current in the Drell-Yan frame, the extraction of the physical electromagnetic form factors is unique due to the angular condition \cite{13, 14, 15, 16, 17}. Because of the freedom in choosing different matrix elements or the helicity amplitudes, one should be very careful in taking into account the non-valence contribution and/or zero-modes for the correct extraction of the form factors from matrix elements of the electromagnetic current \cite{10, 15, 18}.

Unlike the case of the pseudoscalar mesons (e.g., the pion), vector mesons (in particular, the $\rho$-meson that we discuss here) do not have much experimental data in order to compare with models or theory. Some time ago, however, the Babar collaboration has extracted some helicity amplitudes for the reaction $e^+e^-\rightarrow \rho^+\rho^-$ \cite{1} and also the cross-section at $\sqrt{s} = 10.58$ GeV. In the present work, those experimental data are analyzed to get some insight on the onset of perturbative QCD (pQCD).

In the next sections, Sect. 2, we briefly discuss the universal ratio for spin-1 electromagnetic form factors. In Sect. 3, the form factors are related to the helicity amplitudes. In Sect. 4, the sub-leading pQCD contributions are constrained by the light-front angular condition. In Sect. 5, the available BaBar data are analyzed by taking into account the sub-leading pQCD contributions. Summary and conclusion follows in Sect. 6.

2 Universal ratios and spin-1 EM form factors

In the reference \cite{14}, the authors eliminate the helicity amplitude $I_{11}^+$ in the light-front spin basis, and obtain the following expressions for the rho meson electromagnetic form factors (FFs), where the charge, magnetic and quadrupole form factors are given respectively by:

$$G_C^{(BH)} = \frac{1}{3(2p^+)(1 + 2\eta)} \left[ (3 - 2\eta)I_{60}^+ + 8\sqrt{2\eta}I_{10}^+ + 2(2\eta - 1)I_{1}^{-1} \right],$$

$$G_M^{(BH)} = \frac{2}{2p^+(1 + 2\eta)} \left[ I_{60}^+ - I_{1}^{-1} + \frac{(2\eta - 1)}{\sqrt{2\eta}} I_{10}^+ \right],$$

$$G_Q^{(BH)} = \frac{1}{(2p^+)(1 + 2\eta)} \left[ \frac{2}{\sqrt{2\eta}} I_{10}^+ - I_{60}^+ - \left( \frac{\eta - 1}{\eta} \right) I_{1}^{-1} \right],$$

(1)

here $\eta = q^2/4m_\rho^2$.

Within the pQCD, the helicity conservation dominates at very large momentum. From Eq.(1), the predicted universal ratios for the charge form factor, $G_C$, magnetic form factor, $G_M$, and quadrupole form factor, $G_Q$, are obtained as

$$G_C : G_M : G_Q = \left( 1 - \frac{2}{3}\eta \right) : 2 : -1,$$

(2)

and the asymptotic relation \cite{19} given by

$$G_c \approx \frac{2\eta}{3} G_Q$$

(3)

is consistent with perturbative relations for the EM FFs, at high momentum transfers, i.e, $\eta >> 1$.

In the present work, using the experimental amplitudes from the reaction $e^+e^-\rightarrow \rho^+\rho^-$, measured by Babar collaboration \cite{1}, at $\sqrt{s} = \sqrt{q^2} = 10.58$ GeV, we study the onset of the perturbative regime of QCD. The Babar data amplitudes are given in the time-like regime. Nevertheless, as stated by the Phragmén-Lindelöf theorem \cite{20} for analytic functions, space-like (SL) and time-like (TL) amplitudes are the same at very high momentum transfers. As a consequence, the EM FFs are the same for both regimes. A previous analysis for Babar data was done in Ref. \cite{21}. However, their parametrization of the data was not fully consistent with pQCD, and they concluded that their analysis does not take care of other reaction mechanisms that could contribute to the $\rho$-meson production in order to satisfy the helicity conservation (see this discussion in \cite{22}).
In the case of spin-1 particles, the electromagnetic form factors could be calculated with the plus component of the current within the light-front approach. In this case, the angular condition must be satisfied, which relates the matrix elements of the electromagnetic current used in Ref. [10] as well as the other prescriptions given in references [13, 14, 15], such that the electromagnetic form factors for spin-1 particles are uniquely extracted from the helicity amplitudes in the Drell-Yan frame.

Due to the freedom to chose three out of four matrix elements of the current, as long as the angular condition is satisfied, we have analyzed not only the contribution from $I^+_{-1}$, $I^+_{11}$, $I^+_{10}$ helicity amplitudes but also the contributions from $I^-_{-1}$, $I^0_{11}$, $I^-_{10}$ helicity amplitudes to the FFs. In order to generalize the universal ratios and still satisfy the asymptotic relation given by Eq. (3), we have now the following expressions for spin-1 ratios of EM FFs,

$$G_C : G_M : G_Q = \left(\alpha - \frac{2}{3} \eta \right) : \beta : -1 .$$  \hspace{1cm} (4)

The values for $\alpha$, and $\beta$ in Eq. (4) was found by analyzing the Babar experimental data [1]. The present analysis is based on completely model independent first principles: (i) the light-front angular condition is valid for any $Q^2$; (ii) the perturbative power counting rules are valid for $Q^2 \gg A^2_{FXCD}$; and, (iii) the analyticity of the FFs is valid for entire space-like and time-like regions.

3 Form factors and helicity amplitudes

With the notation and definitions given in Ref. [21], the EM current of the spin-one particle is written in terms of three Lorentz invariant FFs, in order to satisfy the covariance, current and parity conservation. In the TL region, the macroscopic EM current is given by [22]:

$$J_\mu = (p_1 - p_2)_\mu \left[ -G_1(q^2)U_1^* \cdot U_2^* + \frac{G_3(q^2)}{m_\rho^2} (U_1^* \cdot q U_2^* \cdot q - \frac{q^2}{2} U_1^* \cdot U_2^* ) + G_2(q^2) (U_1^* U_2^* \cdot q - U_2^* U_1^* \cdot q) \right] ,$$  \hspace{1cm} (5)

where the FFs $G_i(q^2)$ $(i = 1, 2, 3)$ are in general complex functions for TL momentum transfers $(q^2 > 0)$ and the polarization four-vectors of the $\rho$ mesons in the final state are $U_1^\mu$ and $U_2^\mu$. The electromagnetic FFs are given by

$$G_C = -\frac{2}{3} (G_2 - G_3) + \left( 1 - \frac{2}{3} \tau \right) G_1 , \quad G_M = -G_2 , \quad G_Q = G_1 + G_2 + 2G_3 ,$$  \hspace{1cm} (6)

where $\tau = q^2 / 4m_\rho^2$.

The helicity amplitudes, $F_{\lambda_1 \lambda_2}$, (with Jacob-Wick definitions), for the reaction $\gamma^* \rightarrow \rho^- \rho^+$, are given by

$$F_{\lambda_1 \lambda_2} = M_{\lambda_1 \lambda_2}^\lambda = M (\epsilon \rightarrow \epsilon (\lambda_1, \lambda_2) , U_1 \rightarrow U_1^{(\lambda_1)} , U_2 \rightarrow U_2^{(\lambda_2)} ) .$$  \hspace{1cm} (7)

The helicity states for the vector mesons, are, $\lambda_1 = \lambda_{\rho^+}$, and, $\lambda_2 = \lambda_{\rho^-}$. The virtual photon have the helicity, $\lambda = \lambda_{\gamma^*}$. Helicity conservation implies that $\lambda = \lambda_{\rho_1} - \lambda_{\rho_2}$ which leads to $F_{-1} = F_{-11} = 0$, because the virtual photon has spin 1. From symmetry properties, we have that $F_{-1-1} = F_{11}$, and, also, $F_{10} = -F_{01} = F_{-10} = -F_{-01}$, and thus only three independent helicities amplitudes remain.

In Ref. [21], instead of using the helicity amplitudes defined above, the authors used the Breit helicity amplitudes, $F_{\lambda_1 \lambda_2}^{B}$, which are given by

$$F_{00}^B = F_{00} - 2\tau F_{11} , \quad F_{10}^B = F_{10} , \quad F_{11}^B = F_{11} .$$  \hspace{1cm} (8)

Using the above definitions, the Breit helicity amplitude in terms of the EM FFs are written as:

$$F_{00}^B = 2m_\rho \sqrt{\tau - 1} \left[ G_C - \frac{4}{3} \tau G_Q \right] , \quad F_{11}^B = 2m_\rho \sqrt{\tau - 1} \left[ G_C + \frac{2}{3} \tau G_Q \right] , \quad F_{10}^B = 2m_\rho \sqrt{\tau (\tau - 1)} G_M .$$  \hspace{1cm} (9)

Trivially, the EM FFs can be also written in terms of the light-front helicity basis amplitudes.
4 Angular condition and sub-leading contributions

The present analysis of sub-leading order contributions to the helicity matrix elements of the EM current starts, for convenience, in SL region. The angular condition for the matrix elements of the plus component of the EM current in the Drell-Yan frame, and in light-front spin basis is given by

\[(1 + 2\eta)I_{11}^+ + I_{1-1}^+ - 2\sqrt{2\eta}I_{10}^- - I_{00}^+ = 0.\]  

(10)

In Ref. [13], the angular condition equation was used to eliminate the matrix element $I_{00}^+$, and the following expressions for the EM FFs were obtained:

\[G_C = \frac{1}{2p^+} \left[ \frac{3 - 2\eta}{3} I_{11}^+ + \frac{4\eta}{3} I_{10}^+ + \frac{1}{3} I_{1-1}^+ \right] \frac{f_0^+}{f_{00}^+}, \quad G_M = \frac{2}{2p^+} \left[ I_{11}^+ - \frac{1}{\sqrt{2\eta}} I_{10}^+ \right], \quad G_Q = \frac{1}{2p^+} \left[ -I_{11}^+ + \frac{1}{\sqrt{2\eta}} I_{10}^+ - I_{1-1}^+ \right].\]

(11)

The above expressions do not contain explicitly the matrix element $I_{00}^+$, used to derive the universal ratios for the EM FFs in Ref. [16]. Therefore, in order to bring consistency between (11) and the Brodsky-Hiller prescription (1) at large momentum transfers, we have to consider pQCD sub-leading contributions such that the angular condition is satisfied. We found the following relations from the angular condition constraint:

\[I_{10}^+ I_{00}^- = c_1 \sqrt{\eta} + c_2 \frac{I_{1-1}^+}{\eta \sqrt{\eta}}, \quad I_{11}^+ I_{00}^- = \sqrt{2c_1 + \frac{1}{\eta}}, \quad I_{00}^+ I_{00}^- = 2\sqrt{2c_2} - (\sqrt{2c_1 + \frac{1}{\eta}}),\]

(12)

which is analytically extended from the SL to the TL region, keeping the parameters $c_1$ and $c_2$ for both regions. The new parametrization of the SL FFs taking into account sub-leading contributions follows from the above relations and Eqs. (11):

\[G_C = \left[ 1 + 2\sqrt{2c_1} + 4\sqrt{2c_2} - \eta \right] \frac{f_0^+}{f_{00}^+}, \quad G_M = \left[ 1 + \sqrt{2c_1} - \sqrt{2c_2} \right] \frac{f_0^+}{2}, \quad G_Q = \left[ -1 + \frac{1 + \sqrt{2}(c_1 - c_2)}{\eta} \right] \frac{f_0^+}{4},\]

(13)

where $f_0^+ = I_{00}^+/(p^+\eta)$. With the generalized expression for the asymptotic ratios FFs, we have

\[\alpha = \frac{2}{3} \left( 1 + 2\sqrt{2}c_1 + 4\sqrt{2}c_2 \right) \quad \text{and} \quad \beta = 2(1 + \sqrt{2}c_1).\]

(14)

Also, writing $c_1$ and $c_2$ in terms of $(\alpha, \beta)$, one gets

\[c_1 = \frac{\beta - 2}{2\sqrt{2}}, \quad c_2 = \frac{1 + \frac{3}{4} \alpha - \beta}{4\sqrt{2}},\]

(15)

and then the electromagnetic FFs, in terms of $\alpha$ and $\beta$, are given by:

\[G_C = \left[ \alpha - \frac{2}{3} \right] \frac{f_0^+}{4}, \quad G_M = \left[ \beta + \frac{1}{2\eta}(\beta - 3\alpha - 2) \right] \frac{f_0^+}{4}, \quad G_Q = - \left[ 1 + \frac{3}{2\eta}(1 + \alpha - \beta) \right] \frac{f_0^+}{4}.\]

(16)

It is easy to get the general asymptotic relations given in Eq. (4). We observe that the sub-leading contributions to the FFs in Ref. [24] are of the same order as the ones proposed in the present work.
5 BaBar data analysis with sub-leading order

The SL region FFs, $G_C, G_M,$ and $G_Q,$ are extended analytically to the TL region, i.e., $\eta \to -\tau,$ where $\eta = \frac{Q^2}{4m_e^2}, \tau = \frac{r^2}{4m_e^2},$ and $Q^2 = -q^2.$ The TL formulas are given below,

$$G_C = \left[ \alpha + \frac{2}{3} \right] \frac{f_{00}^+}{4}, G_M = \left[ \beta + \frac{1}{2\tau} (\beta - 3\alpha - 2) \right] \frac{f_{00}^+}{4}, G_Q = - \left[ 1 - \frac{3}{2\tau} (1 + \alpha - \beta) \right] \frac{f_{00}^+}{4}, \quad (17)$$

and the Breit helicity amplitudes used in [21], are

$$F_{10}^B = \frac{m_\rho}{8} \sqrt{1 - \tau^{-1}} \left[ 2 + 3\alpha + \beta (4\tau - 2) \right] f_{00}^+, \quad F_{00}^B = m_\rho \sqrt{\tau - 1} \left[ \beta + \tau - 1 \right] f_{00}^+, \quad F_{11}^B = \frac{m_\rho}{4} \sqrt{\tau - 1} \left[ 2 + 3\alpha - 2\beta \right] f_{00}^+. \quad (18)$$

The expressions above for the Breit helicity amplitudes are used to analyse the Babar experimental data at $\sqrt{s} = 10.58 \text{ GeV}$ [1]:

$$|F_{10}^B|^2 : |F_{11}^B|^2 = 0.51 \pm 0.14 \pm 0.07 : 0.10 \pm 0.04 \pm 0.01 : 0.04 \pm 0.03 \pm 0.01,$$  \quad (19)

given with the following normalization:

$$|F_{00}^B|^2 + 4|F_{10}^B|^2 + 2|F_{11}^B|^2 = 1. \quad (20)$$

If we chose the values from the “universal ratios” of the EM FFs, namely, $\alpha = 1,$ and $\beta = 2,$ we have the following relation:

$$|F_{10}^B|^2 : |F_{11}^B|^2 : (4 + 4\tau)^2 : \left( \frac{1}{2\sqrt{\tau}} + 4\sqrt{\tau} \right)^2 : 1. \quad (21)$$

Using the above relation together with the experimental value of $|F_{10}^B|^2 = 0.51$ and the normalization [20], we find the following relation among the Breit frame helicity amplitudes:

$$|F_{00}^B|^2 : |F_{10}^B|^2 : |F_{11}^B|^2 = 0.51 : 1.1 \times 10^{-2} : 1.4 \times 10^{-5}, \quad (22)$$

in evident disagreement with the Babar experimental data [19], which suggests that the asymptotic region is not yet reached at $\sqrt{s} = 10.58 \text{ GeV}.$ The values for $\alpha$ and $\beta$ with the quoted errors found by fitting the experimental Babar amplitudes with Eqs. [18] considering sub-leading corrections are shown in Table 1.

| Table 1 Extracted values of $\alpha$ and $\beta$ from the BaBar ratios [19] at $\sqrt{s} = 10.58 \text{ GeV}$ for $\gamma^* \to \rho^+ \rho^-$ using the expressions for the helicity amplitudes of Eq. [18], with the sub-leading contributions. The last line gives the zero of $G_C$ in the SL region. Two sets of $\{\alpha, \beta\}$ values with $\alpha < 0,$ i.e. (III) and (IV), have no zero of $G_C$ in the SL region. |
|---|---|---|---|---|
| Solution | (I) | (II) | (III) | (IV) |
| $\alpha$ | 23.1 $\pm$ 8.3 | 10.7 $\pm$ 6.4 | -15.6 $\pm$ 8.3 | -19.2 $\pm$ 6.4 |
| $\beta$ | 6.4 $\pm$ 2.0 | -5.4 $\pm$ 1.2 | 7.2 $\pm$ 2.0 | -5.0 $\pm$ 1.2 |
| $Q_0(\text{GeV})$ | 9.1 $\pm$ 1.6 | 6.2 $\pm$ 1.9 | - | - |

The charge EM form factor for spin-1 particles, and in particular for the rho meson, has a zero at the momentum transfer $Q_0,$ and, with sub-leading contributions, the zero is given by $Q_0^2 = 6m_\rho^2\alpha,$ with values presented in Table 1 (last line), according the values for $\alpha$ and $\beta$ found. The results presented in the table show that the sub-leading corrections are extremely relevant for the Babar energy of $\sqrt{s} = 10.58 \text{ GeV}.$
6 Summary and Conclusion

The four solutions from the fitting of the experimental Babar amplitudes $F_{X\lambda}^{B\lambda}$ for $\sqrt{s} = 10.58$ GeV with Eq. (18) considering sub-leading corrections with the parameters given in Table 1 are presented in Fig. 1 as a function of the energy square $s$, where also the Babar experimental data \cite{1} are seen. The differences in the amplitudes calculated with sets (I)-(IV) are small in the region of $s$ between 60 and 160 GeV$^2$, but are significant enough to produce the zeros of $G_c$ for solutions (I) and (II). In the figure, we observe that the smooth predicted behaviour of the Breit frame amplitudes exhibit a variation of about one order of magnitude in the plotted range of $s$, and eventually could motivate future experiments to check the effect of the sub-leading pQCD contributions to the FFs, which were essential to fit the Babar data. However, the values of $\alpha$ and $\beta$ found are still far from the “universal” ones, clearly indicating that the asymptotic pQCD region is not yet reached at $\sqrt{s} = 10.58$ GeV. Therefore, data at higher energies will be necessary to be used as input to our expressions in order to check if $\alpha$ and $\beta$ converge to the “universal” values of 1 and 2, respectively. This constitutes an important verification of the pQCD universal ratios of spin-1 form factors.

In summary, we presented expressions for the spin-1 form factor and helicity amplitudes valid at large momentum in the SL region that are consistent with the angular condition by including sub-leading pQCD contributions. The expressions were analytically continued to the TL region and the
data for the Breit frame helicity amplitudes for the annihilation (production) process $e^+e^- \rightarrow \rho^+ \rho^-$, from the Babar experiment \cite{1} at $\sqrt{s} = 10.58$ GeV were analyzed. We hope that our discussion can motivate further experimental research on the asymptotic behavior of spin-1 electromagnetic form factors and the onset of pQCD predictions.

Acknowledgements. This work was partly supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) of Brazil. This work is a part of the project INCT-FNA Proc. No. 464898/2014-5. This work is also supported in part by the US Department of Energy (No. DE-FG02-03ER41260).

References

1. B. Aubert et al. [BaBar Collaboration]: Observation of $e^+e^- \rightarrow \rho^+ \rho^-$ near $\sqrt{s} = 10.58$-GeV. Phys. Rev. D 78, 071103 (2008).
2. T. Muta: Foundations of Quantum Chromodynamics, An Introduction to Perturbative Methods in Gauge Theories, (World Scientific, Singapore, 1987).
3. M. V. Terentev: On the Structure of Wave Functions of Mesons as Bound States of Relativistic Quarks,' Sov. J. Nucl. Phys. 24 (1976) 106 [Yad. Fiz. 24 (1976) 207].
4. L. A. Kondratyuk and M. V. Terentev: The Scattering Problem For Relativistic Systems With Fixed Number Of Particles, Sov. J. Nucl. Phys. 31 (1980) 561 [Yad. Fiz. 31 (1980) 1087].
5. S. J. Brodsky, H. C. Pauli and S. S. Pinsky: Quantum chromodynamics and other field theories on the light cone. Phys. Rept. 301 (1998) 299.
6. Melo, J. P. B. C de, and Frederico,T.: Covariant and light front approaches to the rho meson electromagnetic form-factors. Phys. Rev. C 55, 2043 (1997).
7. J. P. B. C. de Melo, J. H. O. Sales, T. Frederico and P. U. Sauer: Pairs in the light front and covariance, Nucl. Phys. A 631, 574C (1998).
8. H. W. L. Naus, J. P. B. C. de Melo and T. Frederico: Ward-Takahashi identity on the light front. Few Body Syst. 24, 99 (1998).
9. J. P. C. B. de Melo, H. W. L. Naus and T. Frederico: Pion electromagnetic current in the light cone formalism, Phys. Rev. C 59 (1999) 2278.
10. H. M. Choi and C.-R. Ji: Electromagnetic structure of the rho meson in the light front quark model, Phys. Rev. D 70, 053015 (2004).
11. H. M. Choi and C.-R. Ji: Nonvanishing zero modes in the light front current, Phys. Rev. D 58, 071901 (1998).
12. B. L. G. Bakker, H. M. Choi and C.-R. Ji: The vector meson form-factor analysis in light front dynamics, Phys. Rev. D 65, 116001 (2002).
13. Grach, L. and Kondratyuk, L. A.: The electromagnetic form factor of the deuteron in relativistic dynamics. The two nucleon and the six components. Sov. J. Nucl. Phys. 39, 198 1984; L. L. Frankfurt, I. L. Grach, L. A. Kondratyuk, and M. F. Strikman: Is the structure in the deuteron magnetic form factor at $Q^2 \approx$ new evidence for nuclear core?. Phys. Rev. Lett. 62, 387 (1989).
14. Chung, P. L., Polyzou, W. N., Coester, F. and B. D. Keister, B. D.: Hamiltonian Light Front Dynamics of Elastic electron Deuteron Scattering. Phys. Rev. C 37, 2000 (1988).
15. L. L. Frankfurt, M. Strikman and T. Frederico: Deuteron form-factors in the light cone quantum mechanics 'good' component approach. Phys. Rev. C 48, 2182 (1993).
16. S. J. Brodsky and J. R. Hiller: Universal properties of the electromagnetic interactions of spin one systems, Phys. Rev. D 46, 2141 (1992).
17. V. A. Karmanov: On ambiguities of the spin-1 electromagnetic form-factors in light front dynamics, Nucl. Phys. A 608, 316 (1996).
18. P. Cardarelli, I. L. Grach, I. M. Narodetsky, G. Salme and S. Simula: Electromagnetic form-factors of the rho meson in a light front constituent quark model, Phys. Lett. B 349, 393 (1995).
19. C. E. Carlson and F. Gross, Phys. Rev. Lett. 53, 127 (1984) ; C. E. Carlson1984, Nucl.Phys. A 508, 481c (1990).
20. A. Dennig and G. Salmé, Progress in Particle and Nuclear Physics 68, 113 (2013).
21. A. Dbyessi, E. Tomasi-Gustafsson, G. I. Gakh, C. Adamus: Experimental constraint on the $\rho$ meson form factors in the time-like region. Phys. Rev. C 85 (2012) 048201.
22. J. P. B. C. de Melo, C.-R. Ji and T. Frederico: The $\rho$-meson time-like form factors in sub-leading pQCD, Phys. Lett. B 763, 87 (2016).
23. A. Akhiezer, M. P. Rekalo, "Electrodynamics of hadrons", (in Russian), Naukova Dumka, Kiev, 1977.
24. A. P. Kobushkin and A. I. Syamznomov: Deuteron electromagnetic form-factors in the transitional region between nucleon - meson and quark - gluon pictures, Phys. Atom. Nucl. 58 (1995) 1477.