Recent and future experimental evidences for exotic mesons in hard reactions

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The QCD analysis of the recent experimental data (L3@LEP) of the hard exclusive $p\bar{p}$ production in two photon collisions shows that these data can be understood as a signal for the existence of an exotic isotensor resonance with a mass around 1.5 GeV. We also argue that hard exclusive reactions are a powerful tool for an experimental study of exotic hybrid mesons with $J^{PC} = 1^{-+}$.

Keywords: Hard reaction, exotic mesons, hybrids, GPDs, GDAs.

I. INTRODUCTION

Exclusive reactions $\gamma^* \gamma \to A + B$ which may be accessed in $e^+e^-$ collisions have been shown to have a partonic interpretation in the kinematical region of large virtuality of one photon and of small center of mass energy. First data on the $\rho^0 \rho^0$ channel at LEP have been published and analyzed, showing the compatibility of the QCD leading order analysis with experiment at quite modest values of $Q^2$.

We first focus on the comparison of processes $\gamma^* \gamma \to \rho^0 \rho^0$ and $\gamma^* \gamma \to \rho^+ \rho^-$ in the context of searching an exotic isospin 2 resonance decaying into two $\rho$ mesons; such channels have recently been studied at LEP by the L3 collaboration. A related study for photoproduction raised the problem of $\rho^0 \rho^0$ enhancement with respect to $\rho^+ \rho^-$ at low energies. One of the solutions of this problem was based on the prediction and further exploration of the possible existence of isotensor state, whose interference with the isoscalar state is constructive for neutral mesons and destructive for charged ones. The crucial property of such an exotic state is the absence of $q\bar{q}$ wave function at any momentum resolution. In other words, quark-antiquark component is absent both in its non-relativistic description and at the level of the light-cone distribution amplitude. An isotensor state on the light cone corresponds to the twist 4 or higher and its contribution is thus power suppressed at large $Q^2$. This is supported by the mentioned L3 data, where the high $Q^2$ ratio of the cross sections of charged and neutral mesons production points out an isoscalar state.

In both perturbative and non-perturbative ingredients of QCD factorization for the description of an isotensor state have been studied. Namely, the twist 4 coefficient function has been calculated and the non-perturbative matrix elements has been extracted from L3 data. The analysis of is compatible with the existence of an isotensor exotic meson with a mass around 1.5 GeV. Other exotic objects which can be investigated in hard reactions are the mesons with exotic quantum numbers, for example, with $J^{PC} = 1^{-+}$. These mesons, which have been called hybrids, cannot be described within the usual quark model. We have studied the hybrid mesons in the deep exclusive electroproduction processes which is well described in the framework of the collinear approximation where generalized parton distributions (GPDs) and distribution amplitudes describe the nonperturbative parts of a factorized amplitude. In , we showed that contrarily to naive expectations, the amplitude for the electroproduction of an exotic meson with $J^{PC} = 1^{-+}$ may be written in a very similar way as the amplitude for non-exotic vector meson electroproduction. The main observation of our work was that the quark-antiquark correlator on the light cone includes a gluonic component due to gauge invariance and leads to a leading twist hybrid light-cone distribution amplitude. We also studied the hybrid meson as a resonance in the reaction $e^+p \to e^+p (\pi^0\eta)$, the first experimental investigation of the hybrid with $J^{PC} = 1^{-+}$ as the resonance in $\pi^0\eta$ mode was implemented by the Brookhaven collaboration E852. Present candidates for the hybrid states with $J^{PC} = 1^{-+}$ include $\pi_1(1400)$ which is mostly seen through its $\pi\eta$ decay and $\pi_1(1600)$ which is seen through its $\pi\eta'$ and $\pi\rho$ decays.

II. SEARCHING ISOTENSOR EXOTIC MESONS IN $\gamma^* \gamma \to p\bar{p}$ PROCESS

The reaction which we study here is $e(k) + e(l) \to e(k') + e(l') + \rho(p_1) + \rho(p_2)$, where $\rho$ stands for the triplet $\rho$ mesons; the initial electron $e(k)$ radiates a hard virtual photon with momentum $q = k - k'$, with $q^2 = -Q^2$ quite large. This means that the scattered electron $e(k')$ is tagged. To describe the given reaction, it is useful to consider the subprocess $e(k) + \gamma(q') \to e(k') + \rho(p_1) + \rho(p_2)$. Regarding the other photon momentum $q' = l - l'$, we assume that,
firstly, its momentum is almost collinear to the electron momentum $l$ and, secondly, that $q^2$ is approximately equal to zero, which is a usual approximation when the second lepton is untagged. In two $\rho$ meson production, we are interested in the channel where the resonance corresponds to the exotic isospin, i.e., $I = 2$, and usual $J^{PC}$ quantum numbers. The $J^{PC}$ quantum numbers are not essential for our study. Because the isospin 2 state has only a projection on the four quark correlators, the study of mesons with the isospin 2 can help to throw light upon the four quark states. We thus, together with the mentioned reactions, study the following processes: $e(k) + e(l) \rightarrow e(k') + e(l') + R(p)$ and $e(k) + \gamma(q') \rightarrow e(k') + R(p)$, where meson $R(p)$ possesses isospin $I = 2$. The amplitudes for $\rho^0\rho^0$ and $\rho^+\rho^-$ productions can be written in the form of the decomposition over the amplitudes associated with the two and four quark correlators. The amplitudes corresponding to $\rho^+\rho^-$ production are not independent and can be expressed through the corresponding amplitudes of $\rho^0\rho^0$ production (see, [8]). Note that, in our case, only isospin 0 and 2 cases are relevant due to the positive $C$-parity of the initial and final states.

The differential cross sections $\frac{d\sigma_{\text{electro}}}{dQ^2\,dW^2}$ for both the $\rho^0\rho^0$ and $\rho^+\rho^-$ channels contain a number of unknown phenomenological parameters, which are intrinsically related to non perturbative quantities encoded in the generalized distribution amplitudes. We implemented a fit of these phenomenological parameters in order to get a good description of experimental data. We have obtained the following set of parameters for fitting: the masses and widths of isoscalar and isotensor resonances $M_{R0}$, $\Gamma_{R0}$, $M_{R2}$, $\Gamma_{R2}$, and the phenomenological parameters $S^\text{I}_2=0, I_3=0$, $S^\text{II}_3=0, I_3=0$, $S^\text{III}_4=0, I_3=0$, $S^\text{IV}_4=2, I_3=0$ which are related with the corresponding matrix elements of twist 2 and twist 4 operators (for more details, see [3]). Studying both the $W^-$ dependence and the $Q^2$ dependence of $\rho^0\rho^0$ and $\rho^+\rho^-$ production cross sections, it turned out that the best description is reached at $M_{R2} = 1.5$ GeV, $\Gamma_{R2} = 0.4$ GeV, $S^\text{I}_2=0, I_3=0$, $S^\text{II}_3=0, I_3=0$, $S^\text{III}_4=0, I_3=0$, $S^\text{IV}_4=0, I_3=0$, $S^\text{IV}_4=2, I_3=0$ = 0.018 GeV.

Thus, the fitting of LEP data based on the QCD factorization of the amplitude into a hard subprocess and a generalized distribution amplitude is consistent with the existence of an isospin $I = 2$ exotic meson with a mass in the vicinity of 1.5 GeV and a width around 0.4 GeV. The contributions of such an exotic meson in the two $\rho$ meson production cross sections are directly associated with some twist 4 terms that we have identified.

Analysing the $Q^2$ dependence, we can see that due to the presence of a twist 4 amplitude and its interference with the leading twist 2 component, the $\rho^0\rho^0$ cross section at small $Q^2$ is a few times higher than the $\rho^+\rho^-$ cross section. While for the region of large $Q^2$ where any higher twist effects are negligible the $\rho^0\rho^0$ cross section is less than the $\rho^+\rho^-$ cross section by the factor 2.

III. EXOTIC HYBRID MESON SEARCH IN HARD ELECTROPRODUCTION

Within quantum chromodynamics, hadrons are described in terms of quarks, anti-quarks and gluons. The usual, well-known, mesons are supposed to contain quarks and anti-quarks as valence degrees of freedom while gluons play the role of carrier of interaction, i.e. they remain hidden in a background. On the other hand, QCD does not prohibit the existence of the explicit gluonic degree of freedom in the form of a vibrating flux tube, for instance. The states where the $q\bar{q}q$ and $gg$ configurations are dominating, hybrids and glueballs, are of fundamental importance to understand the dynamics of quark confinement and the nonperturbative sector of quantum chromodynamics.

In [12], we proposed to study the exotic hybrid meson by means of its deep exclusive electroproduction, i.e., $e(k_1) + N(p_1) \rightarrow e(k_2) + H(p) + N(p_2)$, where we concentrate on the subprocess: $\gamma^*_L(q) + N(p_1) \rightarrow H_L(p) + N(p_2)$ when the baryon is scattered at small angle. This process is a hard exclusive reaction due to the transferred momentum $Q^2$ is large (Bjorken regime). Within this regime where a factorization theorem is valid, at the leading twist level, the crucial point is to properly define the hybrid meson distribution amplitude. The Fourier transform of the hybrid meson → vacuum matrix element of the bilocal vector quark operator may be written as

$$\langle H_L(p,0) | \bar{\psi}(-z/2) | -z/2; z/2 | \gamma_\mu \psi(z/2) | 0 \rangle = i f_H M_H e^{(0)}_{L,\mu} \int_0^1 dy e^{(y-y)p \cdot z/2} \phi^H_L(y),$$

where $e^{(0)}_{L,\mu} = (e^{(0)} \cdot z)/(p \cdot z)p_\mu$ and $y = 1 - y$ and $H$ denotes the isovector triplet of hybrid mesons; $f_H$ denotes a dimensionful coupling constant of the hybrid meson, of the order of 50 MeV, so that $\phi^H_L$ is dimensionless. $\phi^H_L$ is asymptotically equal to

$$\phi^H_L(u) = 30u(1-u)(1-2u).$$

We have calculated the leading twist contribution to exotic hybrid meson with $J^{PC} = 1^+$ electroproduction amplitude in the deep exclusive region. The resulting order of magnitude is somewhat smaller than the $\rho$ electroproduction but similar to the $\pi$ electroproduction. The obtained cross section is sizeable and should be measurable at dedicated experiments at JLab, Hermes or Compass.
We made a systematic comparison with the non-exotic vector meson production. To take into account NLO corrections, the differential cross-sections for these processes have been computed using the BLM prescription for the renormalization scale. In the case of $\rho$ production, our estimate is not far from a previous one which took into account kinematical higher twist corrections.

We have also discussed in detail the $\pi\eta$ mode corresponding to the $\pi_1(1400)$ candidate in the reaction $e p \rightarrow e p \pi^0\eta$. We have calculated an angular asymmetry implied by charge conjugation properties and got a sizeable hybrid effect which may be experimentally checked. We also considered the process $\gamma^*\gamma \rightarrow H \rightarrow \pi\eta$ which may be accessible in $e^+e^-$ collision.

In the region of small $Q^2$ higher twist contributions should be carefully studied and included. Note that they have already been considered in the case of deeply virtual Compton scattering where their presence was dictated by gauge invariance, and for transversely polarized vector mesons where the leading twist component vanishes.

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