On the nature of the $\pi_1(1400)$ exotic meson

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We show that the P wave enhancement observed in several experiments in the $\eta\pi$ mass spectrum can be interpreted as the equivalent of the σ meson seen in the S-wave $\pi\pi$ system.

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The role of low energy gluonic degrees of freedom in confinement, hadron mass and spin generation and in the residual hadron-hadron interactions still awaits a quantitative description. Any theoretical approach is complicated by the strong character of the soft interactions in QCD and phenomenology of gluonic excitations is challenging because gluons do not carry electromagnetic or weak charge to which one can directly couple. The spectroscopy of hadrons with excited gluonic degrees of freedom should therefore provide crucial information about the nature of the soft gluonic modes. In this context the spectroscopy of exotic mesons is of fundamental importance. Exotic mesons have quantum numbers that cannot be attributed to valence quarks alone and it is expected, based on lattice gauge simulations, that the additional contribution comes from exciting the gluon field flux tube confining the quarks. The theoretical expectation is that the spin (J), parity (P) and charge conjugation (C) quantum numbers of the lightest exotic isovector should be $J^{PC} = 1^{-+}$ and have mass around 1.9 GeV [1–3]. It is possible, however, that corrections due to extrapolation of the lattice mass predictions to the physical light quark masses could introduce a $100 - 200$ MeV downward shift [4]. Based on the large N_C expansion it has been shown that exotic mesons ought to have hadronic decay widths comparable to the other mesonic resonances [5] *i.e.* to be of the order of $\Gamma = 100 - 250$ MeV. Lattice simulation also indicate that at least one exotic meson multiplet should exist below the threshold energy for string breaking and quark production [6].

In this context the current experimental situation appears to be puzzling. There have been observations of an exotic meson candidate, the $\pi_1(1400)$, with $J^{PC} = 1^{-+}$ quantum numbers and an unusually light mass and a large width. There is evidence of an exotic wave, P-wave in the $\eta\pi^-$ and $\eta\pi^0$ channels [7–11]. The classification of this wave as an exotic meson resonance comes from a Breit-Wigner (BW) fit of the $\eta\pi^-$ [9] spectrum produced in the reaction $\pi^- p \to \eta\pi^- p$ and the $\eta\pi$ spectrum in the reaction $\bar{p}n \to \pi^-\pi^0\eta$ [10]. In both cases a broad P-wave was extracted, centered at $M_{\eta\pi} \sim 1.4$ GeV and width of $\Gamma \sim 300 - 400$ MeV. In the simultaneous analysis of the partial waves amplitudes and the spin density matrix of the $\eta\pi^0$ [11] spectrum in the $\pi^- p \to \eta\pi^0 n$ reaction, however, it was found that no selfconsistent set of BW parameters describing the observed P-wave could be found.

From a point of view of QCD and the quark structure a typical meson resonance $e.g$ the ρ or the a_2 is not much different from a bound state. The quark wave functions are compact and a small width arises from coupling to a few open channels. Compared with those a broad resonance like the $\pi_1(1400)$ seems likely to be of different origin. We will argue here that in fact it might be very similar to the σ meson used to parameterize the low energy S-wave $\pi\pi$ spectrum. It is widely accepted, however, that the σ meson does not originate from a quark bound state but instead is a dynamical resonance arising from residual, low energy $\pi\pi$ interactions.

We will therefore start by discussing briefly the S-wave, low energy $\pi\pi$ scattering. The low energy interactions are well constrained by chiral symmetry and have been extensively studied [12–14]. Keeping only the lowest order in the chiral expansion will minimize possible contributions from preexisting resonances, and to further eliminate the overlap with high energy channels the effective theory needs to be cut-off at $\beta \sim 4\pi f_\pi \sim 1$ GeV. Considering just a single, $\pi\pi$ channel the potential matrix element can be written as,

$$\langle S(\pi\pi), p|V|S(\pi\pi), q\rangle = -4\pi\lambda_0 t_0^{\frac{1}{2}}(p) g_0(p) g_0(q) t_0^{\frac{1}{2}}(q) \quad (1)$$

where $t_0(p) = (2s(p) - m_\pi^2)/2f_\pi^2$ is the $O(p^2)$ chiral amplitude, ($\sqrt{s(p)} = 2e_\pi(p) = 2\sqrt{m_\pi^2 + p^2}$), $g_0(p)$ provides the high-momentum cutoff and is chosen to be of the Yamaguchi form, $g_0(p) = \beta_0^2/(p^2 + \beta_0^2)$ [15]. This potential leads to the S-wave $\pi\pi$ phase shift, $\delta^0_{\pi\pi}(q)$ given by,

$$q \cot \delta^0_{\pi\pi}(q) = 8\pi\sqrt{s(q)}[1 + \lambda_0 J_0(q)]/\lambda_0 t_0(q) g_0^2(q), \quad (2)$$

where

$$J_0(q) = \frac{2}{(4\pi)^2}\Re\int_0^\infty dk \frac{k^2}{e_\pi^2(k)} \frac{t_0(k) g_0^2(k)}{\sqrt{s(q)} - \sqrt{s(k)} + i\epsilon} \quad (3)$$

To be consistent with chiral expansion the coupling constant λ_0 is fixed by requiring that the scattering length agrees with the $O(p^2)$ chiral perturbation theory result,

$a^0_{\pi\pi} = 7m_\pi^2/32\pi f_\pi^2$. This is automatically satisfied if λ_0 is replaced by the renormalized coupling, $\hat{\lambda}$ defined by $1 = \hat{\lambda} = \lambda_0/(1 + \lambda_0 J_0(0))$.

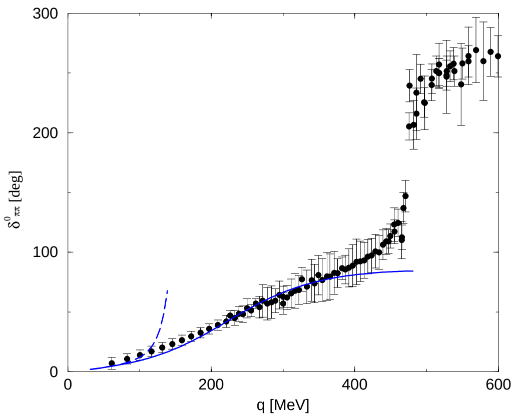

FIG. 1: S-wave $\pi\pi$ elastic phase shift. Solid line show the result of fitting the data below $\sqrt{s} = 700$ MeV to the formula given by Eq 2. The fit gives $\beta_0/4\pi f_\pi = 1.14$. The dashed line corresponds to an effective range expansion $q \cot \delta^0_{\pi\pi} = 1/a^0_{\pi\pi} + r^0_{\pi\pi} q^2/2 + O(q^4)$ with $a^0_{\pi\pi} = 0.152 m_\pi^{-1}$, and $r^0_{\pi\pi} = r^0_{\pi\pi}(\beta_0) = -12.077 m_\pi^{-1}$.

In Fig. 1 we show the result of the one-parameter fit to the elastic $\pi\pi$ S-wave phase shift from threshold up to $\sqrt{s} = 700$ MeV, which results in $\beta_0 = 1.33$ GeV. We also show the resulting effective range approximation. The result of the fit suggests that the interpretation of the $\pi\pi$ spectrum in terms of an effective theory expansion works very well up to energies where other dynamical effects become relevant. In this case it is the proximity of the $K\bar{K}$ channel. The smooth, albeit significant growth of the phase is a dynamical effect of the soft $\pi\pi$ rescattering. Since these rescattering effects are quite strong (due to quadratic dependence of t_0 on energy) the effective range approximation breaks down at much lower energy than the fully iterated amplitude. The situation is similar in the $\pi\pi$ P-wave channel. There the leading amplitude is weaker in the S-wave and the iterated solution gives slower growing phases. Additionally, there is a rapid growth of the phase at $\sqrt{s} = 770$ MeV due to the preexisting quark bound state –the ρ meson, *i.e.* the ρ meson cannot be accounted for by low order $\pi\pi$ rescattering.

We will now take this approach and apply it to the P-wave $\eta\pi$ scattering. To lowest order in the chiral expansion, the $\eta\pi$ interaction is given by

$$\langle P(\eta\pi), p|V|P(\eta\pi), q\rangle = -4\pi\lambda_1 t_1^{\frac{1}{2}}(p) g_1(p) g_1(q) t_1^{\frac{1}{2}}(q) \tag{4}$$

with $t_1(q) = q^2/f_\pi^2$ and $g_1(q) = \beta_1^2/(q^2 + \beta_1^2)$. The elastic $\eta\pi$ phase shift is then given by,

$$q^3 \cot \delta^1_{\eta\pi}(q) = 8\pi q^2 \sqrt{s}\left[1 + \lambda_1 J_1(q)\right]/\lambda_1 t_1(q) g_1^2(q) \tag{5}$$

with

$$J_1(q) = \frac{2}{(4\pi)^2} \Re \int_0^\infty dk \frac{k^2}{e_\pi(k) e_\eta(k)} \frac{t_1(k) g_1^2(k)}{\sqrt{s(q)} - \sqrt{s(k)} + i\epsilon} \tag{6}$$

and $\sqrt{s(q)} = e_\pi(q) + e_\eta(q) = \sqrt{m_\pi^2 + q^2} + \sqrt{m_\eta^2 + q^2}$. As before, $\lambda_1 = 1/(1 - J_1(0))$ is fixed by the threshold behavior,

$$q^2 \cot \delta^1_{\eta\pi} = 1/a^1_{\eta\pi} + r^1_{\eta\pi} q^2/2 + O(q^4) \tag{7}$$

with $1/a^1_{\eta\pi} = 8\pi(m_\pi + m_\eta) f_\pi^2$.

The production of the $\eta\pi$ system in the $\pi^- p$ reaction is dominated by the $a_2(1320)$ (D-wave) and the $a_0(980)$ (S-wave) resonances [9, 11]. The a_2 is produced via both natural, D_+ and unnatural, D_-, D_0 parity exchanges and the a_0 is produced via unnatural exchange only. The set of naturally and unnaturally produced waves do not interfere. In addition, an exotic P-wave has been added to the mix of waves in both natural P_+ and unnatural P_-, and P_0 sets. It is found that D_+ is the strongest wave and it leads to a clear interference signal due to presence of a P_+ wave in the data. This interference can be extracted directly from the data (corrected by the detector acceptance) via the spin density matrix. Independently from the spin density matrix analysis, a partial wave analysis has been performed on the $\eta\pi^-$ and $\eta\pi^0$ data sets. In Figs. 2 and 3 we compare the phase motion of the P_+ and D_+ waves extracted from the partial wave analysis of the $\eta\pi^0$ and $\eta\pi^-$ data with the theoretical predictions based on Eq. 7 constrained by the $\eta\pi^0$ data alone. The solid line corresponds to a global fit to twelve spin density matrix elements of the $\eta\pi^0$ data using the relativistic BW parameterization for the a_0 and a_2 mesons and the rescattering formula of Eq. 7 for the P waves. The fit yields $\chi^2/dof = 360/281$ and the single parameter determining the shape of the P-wave phase motion, β_1 is found to be, $\beta_1/4\pi f_\pi = 1.6$. Since this fit does not include the amplitudes the phase motion shown by the solid line is a prediction. In contrast the dashed line represents a fit to the $P_+ - D_+$ phase difference alone. The slight change in the parameter β_1 found in the two approaches should be attributed to an unphysical leakage of the D_+ in the partial wave analysis due to an imperfect detector acceptance. This is best seen in a combined mass a momentum transfer-t analysis [11]. The P_+ wave production is suppressed at low-$|t|$ due to angular momentum conservation. In the low-$|t|$ region ($|t| \le 0.13$ GeV^2) the partial wave analysis does however lead to a significant P_+ wave but with a much flatter $P_+ - D_+$ phase difference then for higher-$|t|$. This indicates that the P_+ wave primarily comes from the leakage from the D_+ wave due to an imperfect acceptance.

The applicability of low momentum expansion used here is well justified since, as shown in Fig. 2 after subtracting the $\eta\pi$ threshold the relevant momentum range is comparable to the one in $\pi\pi$ case and the two analysis are completely consistent. We have also checked model dependence. For example our formulas are certainly noncovariant which could be worrisome. Their noncovariant nature effectively results from an approximation $1/(\sqrt{s(q)}+\sqrt{s(k)})$ of the Z-diagram propagator, by $1/2\sqrt{s(k)}$ To verify this approximation we have also used fully covariant approach of the Valencia group and found identical description [13, 14, 16]

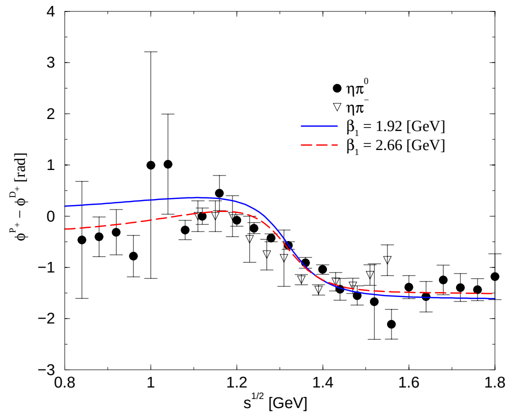

FIG. 2: The phase difference between P_+ and D_+ waves from partial wave analysis of the $\eta\pi^0$ (circles) and $\eta\pi^-$ (triangles) spectrum in the reaction $\pi^-(18\text{ GeV})p \to \eta\pi N$. The solid line is the fit of Eq. 5 to the spin density matrix elements and the dashed line is the fit to the $P_+ - D_+$ phase difference. Both fits are to the $\eta\pi^0$ data.

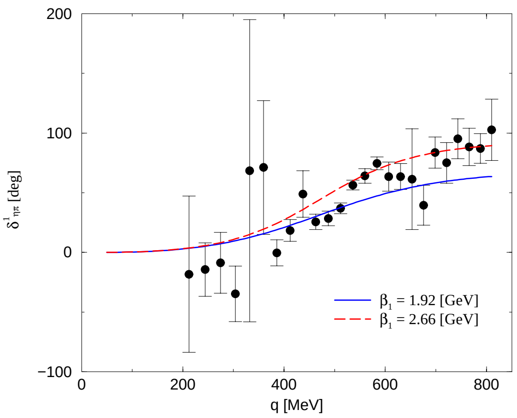

FIG. 3: The $\eta\pi^0$ P-wave phase obtained by adding a BW D_+ wave the the $P_+ - D_+$ phase difference shown in Fig. 2.

In conclusion we find that the broad P wave in the $\eta\pi$ system can be well accounted for by low energy rescattering effects. Comparing to the $\pi\pi$ channel we interpreted this enhancement as the equivalent to the effect of the σ meson, *i.e.* arising from correlated meson-meson state and not from a QCD bound state.

In this context we can also speculate as to the nature of the other exotic mesons in particular the $\pi_1(1600)$ seen in the $\eta'\pi^-$ and in the $\rho\pi$ channels. In the $\eta'\pi$ it was measured to have a rather large with, $\Gamma \sim 350$ MeV [17] and in the $\rho\pi$ channel has been found to be quite narrow with $\Gamma \sim 170$ MeV [18]. Taking into account the mass difference in between the $\eta'\pi$ and $\eta\pi$ thresholds it might be possible that the broad $\pi_1(1600)$ state in the $\eta'\pi$ has the same dynamical origin as the $\pi_1(1400)$ studied here. This may or may not be the case of the narrow state seen in the $\rho\pi$ system which as discussed in the introduction appears to be quite close to what is expected for a genuine QCD exotic.

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