

UNQUENCHING WEAK SUBSTRUCTURE*

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On assuming that weak substructure has a dynamics which is similar to quantum chromodynamics but much stronger, we conclude that unquenching is indispensable for predictions on the spectrum of weak-substructure resonances.

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1. Introduction

It is well known that compositeness may be studied from the appearance of resonance enhancements in the event distributions of scattering and production experiments. An extensive study on hadronic compositeness published by Godfrey and Isgur [1] gave us a good insight into the spectrum of quarkonia obtained by the scattering of mesons and by the event distributions of two or more hadrons produced in production experiments.

Nevertheless, at present, our knowledge of hadronic spectra is limited by the lack of accurate experimental data [2]. In particular, any bump in hadronic cross sections is usually interpreted as a resonance, whereas resonance structures that are not of a Breit–Wigner-like shape remain unrecognised in experimental analyses. Models like that of Ref. [1] are helpful

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in order to classify mesonic and baryonic resonances. However, several details of the spectra remain unsolved. Here, we shall concentrate on mesonic resonances.

Already as early as one decade after the introduction of the quark model by Zweig [3] and Gell-Mann [4], it was recognised that confinement models alone cannot explain the event distributions [5], since mesonic resonances are observed in scattering and production experiments. As a consequence, quark confinement and the scattering of hadrons have to be treated on the same footing. Scattering is most conveniently described by a scattering amplitude T as a function of the total invariant mass $\sqrt{s}$. Mesonic resonances appear as singularities (poles) of the analytic continuation of $T(\sqrt{s})$ into the complex $\sqrt{s}$ plane. The real and imaginary parts of a pole approximately correspond to the central mass and the width of a resonance, respectively. For the scattering of mesons, $T(\sqrt{s})$ must contain various distinct channels, because of the possible formation of different multi-hadron final states. Here, we shall limit ourselves to final states that contain pairs of mesons.

In Ref. [6], a model was developed that incorporates quark confinement in the construction of the scattering amplitude. The model represents confinement by binding the valence quarks via a harmonic-oscillator (HO) potential. Nevertheless, the pole spectrum of the resulting scattering amplitude is very different from the HO spectrum. Moreover, resonances are not represented by pure HO wave functions (see *e.g.* Ref. [7]), but rather by several components, namely for the allowed valence $q\bar{q}$ states with the resonance's quantum numbers and for the most relevant two-meson channels [6]. In this model, it is assumed that mesonic resonances and the free two-meson states resulting from decay couple to each other via the creation or annihilation of new $q\bar{q}$ pairs, with intensity represented by a parameter λ . In principle, λ has to be adjusted to experiment, but in practice it has been found to be rather independent of the meson's flavour content [8]. Furthermore, the internal hadronic dynamics, governed by glue, appears to be well represented by HO confinement, with an oscillator frequency $\omega = 190$ MeV, independent of the meson's flavour content.

Let us study, for example, resonances in the vector-charmonium sector. The quantum numbers of such systems are $c\bar{c}$ for flavour content and $J^{PC} = 1^{--}$ for spin, parity, and C -parity. A $1^{--} c\bar{c}$ system has total quark-antiquark spin $s = 1$, and relative quark-antiquark angular momentum $\ell = 0$ (S -wave) or $\ell = 2$ (D -wave). A convenient selection of open-charm two-meson states with $J^{PC} = 1^{--}$ may consist of $D\bar{D}$ with total two-meson spin $S = 0$ and relative two-meson angular momentum $L = 1$, $D\bar{D}^* + \bar{D}D^*$ ($S = 1/L = 1$), $D^*\bar{D}^*$ ($S = 0/L = 1$, $S = 2/L = 1$, or $S = 2/L = 3$), $D_s\bar{D}_s$ ($S = 0/L = 1$), $D_s\bar{D}_s^* + \bar{D}_sD_s^*$ ($S = 1/L = 1$), and $D_s^*\bar{D}_s^*$ ($S = 0/L = 1$, $S = 2/L = 1$, or $S = 2/L = 3$). We then obtain for the description of reso-

nances in the charmonium sector a coupled system of two quark–antiquark wave functions describing the probability of finding in the interaction region a $c\bar{c}$ pair in either of the two possible spatial configurations, and ten two-meson wave functions representing the probability of finding a pair of mesons in any of the ten flavour and spatial configurations.

In the model of Ref. [6], it was assumed that the two-meson states couple to the $c\bar{c}$ states exclusively through the creation/annihilation of $u\bar{u}$, $d\bar{d}$, or $s\bar{s}$ quark–antiquark pairs. No further final-state interactions within or among the two-meson channels were considered. Reality is, of course, somewhat more involved, but as in any model priorities must be set and further details left for future research. The used coupling constants were determined in Ref. [9] employing an HO approximation. Thus, we find that the $S = 2/L = 3$ two-meson configurations only couple to the D -wave $c\bar{c}$ states, whereas all the other two-meson configurations couple to both S - and D -wave $c\bar{c}$ states. Recently, similar results and some rather interesting consequences were derived in Refs. [10, 11].

The above strategy of describing mesonic resonances via coupled-channel states was initially baptised the *unitarisation* scheme, as it leads to a unitary S -matrix instead of just energy levels. However, it is nowadays more often called *unquenching* the quark model [7], since mesonic resonances are described by coupling confined (quenched) quark–antiquark states to the meson–meson continuum, just like in fully unquenched lattice calculations [12].

Let us now assume for a moment that it was possible to scatter $\bar{D}$ mesons off a source of D mesons. Then, one could observe in experiment the $c\bar{c}$ resonances in the $D\bar{D}$ scattering cross sections. However, as it concerns a coupled-channel system, one might also observe $D_s\bar{D}_s$ final states, or any of the other flavour and spatial configurations that couple to $c\bar{c}$. For this reason, the scattering amplitude for $D\bar{D}$ scattering is described by a 10×10 complex symmetric matrix in the model of Ref. [6]. Each one of the 100 elements of that matrix, when analytically continued to complex invariant mass, contains the singularities that correspond to the various possible resonances.

For HO confinement, we have an equidistant $J^{PC} = 1^{--}$ $c\bar{c}$ spectrum with spacing 2ω , *i.e.*, one S -wave ground state and degenerate pairs of S - and D -wave excited states. As a consequence, we expect to find a similar resonance-pole spectrum for the model. To a certain extent, this is indeed what is observed in experiment, as we shall discuss below. In the model [6], the ground state is affected the most by unquenching and comes out several hundreds of MeV lower than the bare mass from confinement only. Its wave function contains sizable components in the two-meson channels, while the $c\bar{c}$ -channel is no longer a pure HO ground state. On the other hand, the

degenerate pairs of S - and D -waves show a very peculiar behaviour when the degeneracy is lifted upon unquenching, with the S - and D -wave components getting mixed. Namely, the dominantly D -wave mixture almost decouples from the two-meson channels, whereas the mainly S -wave one couples much more strongly. As a result, the mostly D -wave mixtures stay near the energy levels of pure HO confinement, while the others are shifted downwards about 150–200 MeV. A further consequence is that the resonance poles for the mainly D -wave mixtures do not have large imaginary parts and thus are narrow. This may well explain why they are not easily found in experiment.

So the dominantly D -wave mixtures of the $J^{PC} = 1^{--} c\bar{c}$ spectrum may serve as an indication for the bare quark-confinement spectrum. This represents a unique opportunity, since $J^{PC} = 1^{--}$ are precisely the quantum numbers for electron–positron annihilation. Hence, in e^-e^+ scattering experiments, one may find a straightforward feedback on quark confinement. Consequently, the $J^{PC} = 1^{--} c\bar{c}$ spectrum should form the backbone of meson spectroscopy. Now, what can the experimental state-of-the-art say about that? In Fig. 1 we depict the present situation. It clearly shows that the study of hadronic resonances is severely hampered by a lack of accurate data. The charmonium resonances at 4.03, 4.16, and 4.40 GeV were first observed almost four decades ago. The data in the invariant-mass interval 4.5–6.0 GeV do not have enough statistics for further analysis (see, however, Ref. [14]). This issue can only be solved with much better statistics, and bin sizes that do not exceed 1.0 MeV in order to discover the narrow D states.

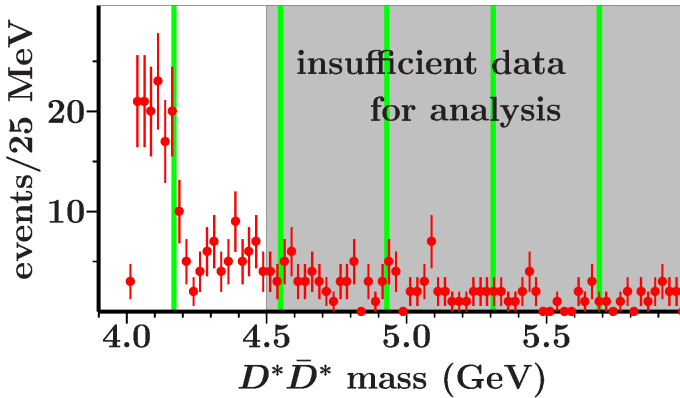


Fig. 1. Invariant-mass distribution for $J^{PC} = 1^{--} D^* \bar{D}^*$ states published by the BaBar Collaboration [13]. The vertical lines indicate the spectrum for HO confinement in the $J^{PC} = 1^{--} c\bar{c}$ sector. Resonances in the non-shaded area (3.9–4.5 GeV) are known for almost four decades. The data in the shaded area (4.5–6.0 GeV) do not have enough statistics.

A further consequence of hadronic compositeness is the appearance of non-resonant threshold enhancements. A theoretical model for threshold enhancements in hadronic production amplitudes, based on quark–antiquark pair creation, was formulated in Ref. [15] and further developed in Refs. [16, 17]. This model shows that one must expect non-resonant enhancements in the amplitudes just above pair-creation thresholds. In the case of stable hadrons, such enhancements are accompanied by clear minima right at the thresholds, as observed in experiment for the process $e^-e^+ \rightarrow b\bar{b}$, measured and analysed by the BaBar Collaboration [18]. As also remarked by BaBar in their paper, the large statistics and the small energy steps of the scan make it possible to clearly observe the dips at the opening of the thresholds corresponding to the $B\bar{B}^* + \bar{B}B^*$ and $B^*\bar{B}^*$ channels. However, experimental evidence of this phenomenon is scarce, since it needs event counts with high statistics and good resolution. Nevertheless, in some cases, signals, albeit often feeble, can be seen in experimental data for hadronic production [19].

In Ref. [15], the generic relation

$$P = \Im Z + TZ \tag{1}$$

between two-particle scattering (T) and production (P) amplitudes was studied in a microscopic multi-channel model for meson–meson scattering with coupling to confined quark–antiquark channels. The amplitude T in expression (1) is supposed to contain the resonance poles that occur in scattering, whereas Z is a smooth function of invariant mass. Threshold enhancements occur in production amplitudes as a consequence of the shape of $\Im Z$, which in the ideal case of no further nearby thresholds rises sharply just above threshold. For larger invariant masses, $\Im Z$ first reaches a maximum and then falls off exponentially. As a consequence, production amplitudes show non-resonant yet resonant-like enhancements just above threshold. In Fig. 1 one may observe such an enhancement at 4.66 GeV, just above the $\Lambda_c^+\Lambda_c^-$ threshold [14], while the large bump at 4.04 GeV may well consist of the enhancement above the $D^*\bar{D}^*$ threshold interfering with a $c\bar{c}$ resonance of modest size.

Besides threshold enhancements, unquenching may also dynamically generate resonances, *i.e.*, resonance poles in the scattering amplitude that are not directly related to the confinement spectrum. The low-lying scalar mesons are the classical example of this phenomenon [20]. So enhancements can be due to resonances that are either directly related to the confinement spectrum or dynamically generated, but may also correspond to non-resonant threshold effects. Consequently, analysing mesonic scattering/

production data is a rather difficult task, in particular when the spatial quantum numbers are completely/partly unknown, which unfortunately is most commonly the case.

2. Weak substructure

In Refs. [2, 21], we have indicated the possible existence of substructure in the weak sector, based on the observation that recurrences of the Z boson may exist. The corresponding data, published in Refs. [22–30], do not have sufficient statistics to definitely conclude the existence of weak substructure, except perhaps for a clear dip at about 115 GeV in diphoton, four-lepton, $\mu\mu$, and $\tau\tau$ invariant-mass distributions. The latter structure indicates the possible opening of a two-particle threshold, probably corresponding to a pseudo-scalar partner of the Z boson with a mass of about 57.5 GeV. Further possible recurrences of the Z boson, *viz.* at 210 and 240 GeV [21], certainly need a lot more statistics.

Composite heavy gauge bosons and their spin-zero partners, the latter with a mass in the range of 50–60 GeV, were considered long ago [31] and studied in numerous works (see *e.g.* Refs. [32–37]). To date, no experimental evidence of their existence has been reported. However, if a pseudo-scalar partner of the Z boson with mass of about 57.5 GeV exists and, consequently, part of the structure observed in the mass interval 115–135 GeV is interpreted as a threshold enhancement, then it must be possible to verify their existence at LHC, for example in four-photon events.

More recently the interest in weak substructure has revived [38–42]. Most popular among the proposed models is a so-called technicolour (TC) [43], for which one expects QCD-like dynamics but much stronger. From the structure of the threshold enhancement above 115 GeV, we deduced an interaction distance of the order of 0.008 fm [2]. Now, from QCD we have learned that self-interactions lead to an appreciable contribution to the masses of resonances. Hence, for yet much stronger dynamics, we must expect that the masses of resonances are basically determined by the self-interactions and not so much by the masses and binding forces of the constituents. This has indeed been recognised in Ref. [42], where, in a perturbative fashion, the mass of the TC scalar resonance is lowered by several hundreds of GeV. However, as we have argued that already for QCD unquenching should be incorporated beyond perturbative contributions, we assume that for weak substructure it is absolutely indispensable to do so. This also implies that the corresponding spectrum will contain dynamically generated resonances as well and may even be dominated by such poles, rather than by those stemming from confinement.

3. Conclusions

Modelling the dynamics of strong interactions is useful and certainly a lot of fun. However, it must be accompanied by the study of scattering and production [44]. Experiment, unfortunately, does not yet provide the necessary statistics to systematically confront model results with measured cross sections.

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