Modeling new XYZ states at JPAC

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Abstract. The observation of the unexpected $XYZP$ resonances has challenged the usual heavy quarkonium framework. One of the most studied exotic states, the $X(3872)$, happens to be copiously produced in high-energy hadron collisions. We discuss how this large prompt production cross-section, together with the comparison with light nuclei production data, disfavors a loosely-bound molecule interpretation, and calls for a new interpretation for the exotic hadron resonances. We also present the research of the Joint Physics Analysis Center in Hadron Spectroscopy.

1. Introduction

The last decade witnessed the observation of many unexpected $XYZP$ resonances in the heavy quarkonium sector. Their production and decay rates are not compatible with a standard charmonium interpretation [1–3]. The most popular phenomenological interpretation for many of these states is the so-called *hadron molecule*, *i.e.* a loosely bound state of two mesons, interacting via long-range light meson exchange. The main antagonistic model is the *compact tetraquark*, which is dominated by short-range color interaction [4–6]. Also, the possibility for some of these states to be mere kinematical effects has been discussed [7–9].

2. Production of $X(3872)$ at hadron colliders

The $X(3872)$ is known to have a large prompt production cross section at hadron colliders, similar to the one of the ordinary $\psi(2S)$ charmonium state.

The closeness of the $X(3872)$ to the $\bar{D}^0 D^{*0}$ threshold might suggest for this state to be a $\bar{D}^0 D^{*0}$ molecule [1], with a binding mechanism provided by some inter-hadron potential (one-pion exchange). If this is the case, one can derive a model-independent relation between the partial width of $X \to \bar{D}^0 D^{*0}$ and the binding energy, which can be tested in future high-statistics experiments [10]. Nevertheless, it is hard to explain the formation a loosely bound molecule, with a binding energy of -3 ± 192 keV, at the vertex of hard collisions at energies of some TeVs. This issue was firstly raised in [11], which used MC simulations to find a cross section ~ 300 times smaller than the experimental value, if one considered all the $\bar{D}^0 D^{*0}$ pairs with relative momentum $\lesssim 50$ MeV to be molecular candidates.

Ref. [12] bridged the gap considering the final state interactions between the two mesons, in the Migdal-Watson framework. The authors argued that the very presence of strong rescattering allows for a relative momentum between the constituents of the order of the mass of the mediator

[1] The charge-conjugate mode is understood

(pion). Since the cross section scales as $(k_0^{\rm max})^3$, the experimental value is rapidly reached. This approach was criticised in [13], by noticing that the presence Migdal-Watson approach requires the two rescattering hadrons to be separated in phase space from the debris of the reaction, whereas in hadron collisions a huge number of pions interferes with the $\bar{D}^0 D^{*0}$ rescattering. The controversy remained somehow unsolved [14]. Similar approaches appeared in the literature to estimate the production for several exotic hadrons [15–17]; however, in the absence of precise final state interactions calculations, the uncertainty in $k_0^{\rm max}$ reflects in a $> O(10)$ uncertainty in the cross sections, which makes any estimate of sizeable cross sections unreliable.

Refs. [18, 19] proposed a more mechanistic way to take into account final state interactions: it was considered that some of the large number of pions produced might elastically interact with the would-be-molecule constituents, thus changing the relative momentum in the center of mass of the pair. If this interaction reduces the relative momentum of even a small part of the many large-k_0 pairs, there could be a significant effect of feed-down of pairs towards lower bins, even in the far low energy region below 50 MeV. Populating that region means increasing the formation probability of the loosely bound X. The simulations show that this effects indeed occurs, but is not large enough to justify the large cross section.

3. Comparison of $X(3872)$ with light nuclei production

If the $X(3872)$ is a real molecule, and if long-range final state interactions are indeed responsible for such a large cross section, one expects the cross sections of light nuclei to have a similar behavior, especially at high values of $p_\perp$. In Ref. [20], we used the Glauber theory to rescale the ALICE data on helium-3 (^{3}He) and hypertriton ($^3_\Lambda$H) production in Pb-Pb collisions to pp collisions, and we extrapolated these and the deuteron data to $p_\perp \gtrsim 15$ GeV. The comparison in Fig. 2 shows that the extrapolated hypertriton differential cross section in pp collisions would fall short by about $2 \div 3$ orders of magnitude with respect to the X production, and much more according to the blast-wave fit in the right panel. The drop of the deuteron cross section, which is directly measured in pp collisions, appears definitely faster. One might assume the very opposite point of view, *i.e.* that at high p_T the production is dominated by the short-range nature of the state, and expect the slope of the differential cross section to depend on the quark counting only. This would explain why the $X(3872)$ (4-quark state, either compact or molecule-like) is produced more than the deuteron (6-quark state), but is at odds with the steeper descent of the deuteron with respect to hypertriton (9-quarks).

The main problem for the production of loosely bound molecular states in proton-proton collisions is the difficulty in producing the constituents close enough in phase space. It is well known that the interaction of elementary partons with the collective hot dense medium causes relevant energy loss of the partons themselves. This effect is usually quantified by the nuclear modification factor R_{AA}, which compares the particle yield in Pb-Pb collisions with that in pp. While for ordinary hadrons medium effects generally lead to a suppression of the particle yield, conversely molecular states with small binding energy are expected to be enhanced. This would favor their coalescence into the final bound state by reducing their relative momenta directly at parton level. A naïve estimate based on available ALICE data suggests for values $R_{AA} \sim 5$ at $p_\perp = 5$ GeV. This confirms the enhancement for the production of hadron molecules. One naturally expects such an enhancement to be even more relevant for 3-body nuclei like ^{3}He and the hypertriton. Its role would be to further *decrease* the extrapolated cross section in prompt pp collisions. Even though qualitative conclusions can already be drawn, a quantitative analysis substantiated by data at higher $p_\perp$ is necessary for a definitive comparison with the X case.

4. Hybridized tetraquarks

In Ref. [21] we proposed a new interpretation for some of the XZ states: they would result from an hybridization between the discrete levels of the tetraquark potential and the levels of

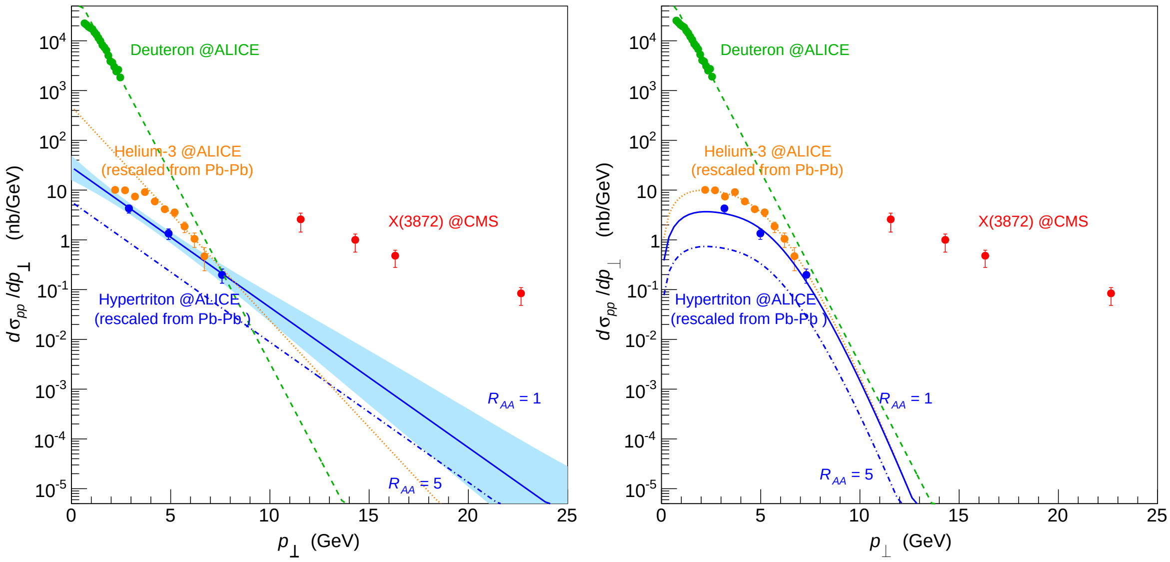


Figure 1. Comparison between the prompt production cross section in pp collisions of $X(3872)$ (red), deuteron (green), ^{3}He (orange), and hypertriton (blue) [20]. The hypertriton and ^{3}He data are fitted with an exponential curve (left panel), or with blast-wave functions (right panel).

the continuous spectrum of the two-meson potential. Consider a diquark-antidiquark state. An effective hamiltonian can give a rough estimate for the energy of these levels [4–6]. The wave function can be Fierz rearranged in a number of color singlet pairs which can be of the form hidden-flavor + light meson or two open flavor mesons, having quantum numbers compatible with the initial tetraquark state. For these meson pairs to have nonnegligible interaction and being able to rescatter into the diquarkonium, the relative kinetic energy cannot exceed an $E_{\max}$ of few tens of MeV. A level in the continuous spectrum of the two-body system and the near discrete level of the compact tetraquark can match, if their energy difference is smaller than $E_{\max}$. If this happens, a sort of 'hybridization' of the two-meson state into the compact structure occurs.

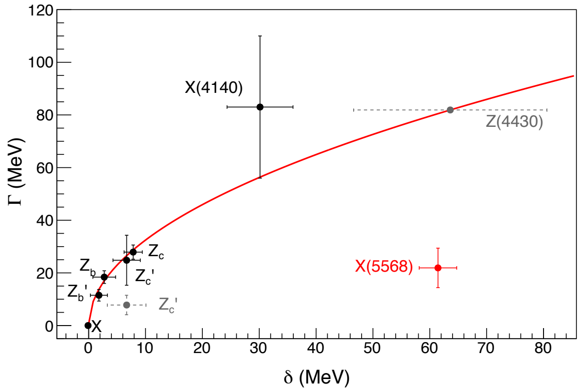
The possibility of having a true, shallow bound state enhancing the meson-meson scattering length is unfavored because of the prompt production issue. The Feshbach formalism provides an alternative mechanism (see some related discussions in [19, 22–24]). The scattering length in the meson-meson channel is given by

$$a \sim a_P - C\frac{|\langle\Psi_n|H_{QP}|\Psi_\alpha\rangle|^2}{E_n - E_\alpha + i\epsilon} \equiv \left(1 - \frac{\varkappa}{\delta - E + i\epsilon}\right) a_P \tag{1}$$

with $C > 0$ a positive constant (depending on the reduced mass of the would-be molecule). It is clear that the *detuning* δ, *i.e.* the distance in energy between the expected tetraquark discrete level and the onset of the continuous spectrum starting from the closest molecular threshold is positive and small. Conversely, $\delta < 0$ can suggest either the formation of a true bound state (unfavored by prompt production), or a repulsion in the meson-meson channel, which is incompatible with hybridization. This might be the reason which forbids the charged partners of the $X(3872)$ and provides isospin violation. The width of the state can thus be calculated,

$$d\Gamma \sim \delta(E - \delta)\ |\varkappa a_P|\ \frac{(2m)^{3/2}\sqrt{E}dE}{m} \tag{2}$$

which can be effectively estimated to be $\Gamma \sim A\sqrt{E}$. The square root dependence is given by



	Thr.	δ	$A\sqrt{\delta}$	Γ
$X(3872)$	$\bar{D}^0 D^{*0}$	0	0	0
$Z_c(3900)$	$\bar{D}^0 D^{*+}$	7.8	27.9	27.9
$Z_c'(4020)$	$\bar{D}^{*0} D^{*+}$	6.7	25.9	24.8
$X(4140)$	$J/\psi\ \phi$	30.1	54.7	83.0
$Z_b(10610)$	$\bar{B}^0 B^{*+}$	2.7	16.6	18.4
$Z_b'(10650)$	$\bar{B}^{*0} B^{*+}$	1.8	13.4	11.5
$X(5568)$	$B_s^0\,\pi^+$	61.4	78.4	21.9
X_{bs}	$B^+ \bar{K}^0$	5.8	24.1	—

Figure 2. Width of the observed exotic mesons as a function of their detuning, δ to the closest, from below, two-meson thresholds. The red point corresponds to the $X(5568)$ state whose observation has been claimed by D0. We also show the prediction for the $Z(4430)$ width, which underestimates the total width as expected. We show the value of the width of the $Z_c'(4020)$ measured in the $\bar{D}^{*0}D^{*+}$ channel, which is 2σ away from the one measured in the $h_c\pi$ channel.

the phase space. However, if the detuning δ falls outside the $[0, E_{\max}]$ interval, the integral is essentially zero and there is no significant contribution to the width: this contradicts the pure phase space prediction, according to which the further the threshold, the more it contributes to the decay width.

We observe that the widths and detunings in a broad class of observed resonances strictly obey this law with a common value for the A parameter — this can be appreciated by the very good fit in Fig. 2. The fact that all data can be fitted with the same proportionality constant A, strongly supports for the described states to share the same nature. This does not straightforwardly generalize to excited tetraquarks, where the closed channel is itself not stable against a de-excitation into its allowed tetraquark ground state. Similarly, we do not extend the analysis to pentaquarks.

Tetraquarks in the form of diquarkonia might be difficult to be formed once a generic four-quark system is placed in a small region of space. That means that diquarkonia might not be formed independently of this resonant mechanism. More precisely, the hadronization state could contain diquarkonium in its mixture with such a small probability that, if not enhanced by some other mechanism, pure diquarkonium levels are not accessible in present experimental conditions. This might provide a set of 'dynamical selection rules': very little probability of being formed is translated into the experimental evidence of the fact that a particular state is not observed.

5. The Joint Physics Analysis Center

Given the experimental and theoretical interest on hadron spectroscopy, the Joint Physics Analysis Center (JPAC) was set up to develop theoretical and phenomenological analysis methods to support hadron physics experiments. The project started in 2013 as a joint venture between Indiana University, George Washington University and Jefferson Lab. Currently it has expanded to 20 researchers distributed among the three founding institutions plus Rheinischen Friedrich-Wilhelms Universität Bonn and Johannes Gutenberg Universität Mainz in Germany, IFIC/CSIC-Universidad de Valencia in Spain, Universiteit Gent in Belgium, and Universidad Nacional Autónoma de México in Mexico.

The JPAC researchers aim to apply S-matrix theory principles, *i.e.* analyticity, crossing symmetry and unitarity [25], to develop scattering amplitudes for several hadron reactions of theoretical and experimental interest The work is performed in close collaboration with experimentalists (from BESIII, COMPASS, CLAS, GlueX, KLOE and LHCb), to implement the amplitudes in the existing data-analysis software. The methods to write the amplitudes include the K-matrix and N/D parametrizations, complemented with chiral constraints or Regge asymptotics if needed. The amplitudes can be analytically continued from the real axis into the complex energy plane and the unphysical Riemann sheets, to unravel the existing resonances contributing to the physical reactions. We are focused on hadron spectroscopy delivering amplitudes for three-body meson decays [26–30], meson-baryon scattering [31, 32], Regge phenomenology to probe hadron structure [33], and meson photoproduction [34–36].

I briefly review the most recent worked published by our group. The $\eta \to 3\pi$ decay is of particular interest because it is isospin-breaking and provides insight on the light-quark mass difference. In [29] we performed a simultaneous global fit to the KLOE-2 and WASA-at-COSY data using the Khuri-Treiman equations, determining $Q^2 = \frac{m_s^2 - \bar{m}_{u,d}^2}{m_d^2 - m_u^2} = (21.6 \pm 0.4)^2$ [29]. The LHCb collaboration reported two pentaquarks in the $J/\psi p$ channel, but the nature of these states is still to be understood. In [36] we built up a full model for the $\gamma p \to J/\psi p$ reaction, and analyzed the scarce available experimental data. The $P_c(4450)$ was introduced as a Breit-Wigner amplitude and the background was modeled with a Pomeron exchange. We found that data allow for the existence of a pentaquark whose $J/\psi\, p$ branching ratio has to be $< 30\%$ (17%) at 95% confidence level, if $J^P = 3/2^-$ $(5/2^+)$. Jefferson Lab has just approved an experiment to measure this reaction [37].

To ease the exchange of information between JPAC and other theorists and experimentalists, we created a public interactive website [38]. The JPAC web page hosts downloadable versions of the codes to compute several of the reactions analyzed by the group [39]. The codes can also be run on the web page and the outputs downloaded.

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