PROCEEDINGS OF SCIENCE

Exotic Charmonium Physics At SuperB

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In the past few years the B Factories and the Tevatron have provided evidence for states that do not admit the conventional mesonic interpretation and that instead could be made of a larger number of constituents. While this possibility has been considered since the beginning of the quark model, the actual identification of such states would represent a major revolution in our understanding of elementary particles. It would also imply the existence of a large number of additional states that have not yet been observed. This paper reviews the steps needed towards the understanding of this picture and discusses the role of SuperB in it.

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1. Introduction

It is now almost seven years since the first heavy quarkonium exotic state has been observed and the number of observed such states has significantly increased. In order to explain all these states one needs to go beyond the assumption that mesons can only be made of a quark and an anti-quark and consider the possibility to be observing bound states of four quarks or two quarks and valence gluons. These novel states of aggregation are not a new idea and it was indeed already in the foundations of the quark model [1]. Also, the hypothesis that the mesons of the scalar nonet are actually tetraquarks can be dated back to the '70s [2]. But only now, with the presence of several exotic candidates with heavy quarks the possibily to have a global picture is becoming real. Nonetheless the currently available statistics is not sufficient to be conclusive and a Super-Flavour-Factory with a luminosity 50 times larger would contribute critically in understanding this picture.

2. Towards a global picture

The path towards such global picture comprises several steps. First all relevant experimental observations need be considered. Fig 1, from Ref. [3], summarizes such observations in the charmonium sector, the richest of exotic candidates. Next, a complete set of theoretical predictions

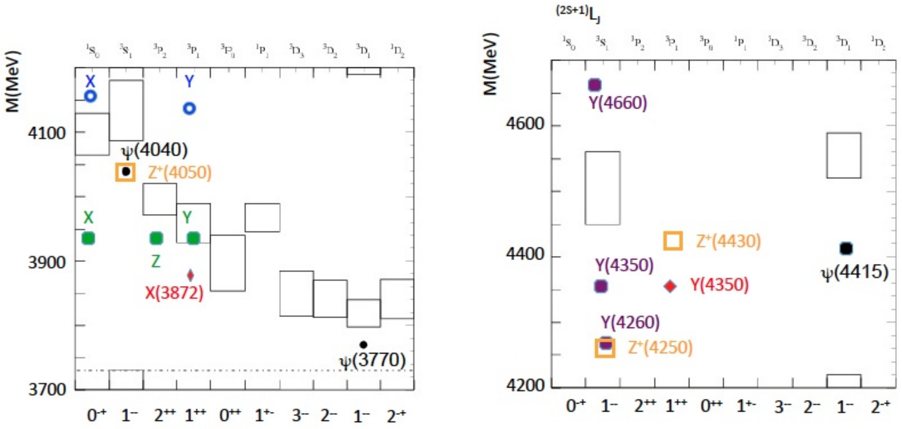
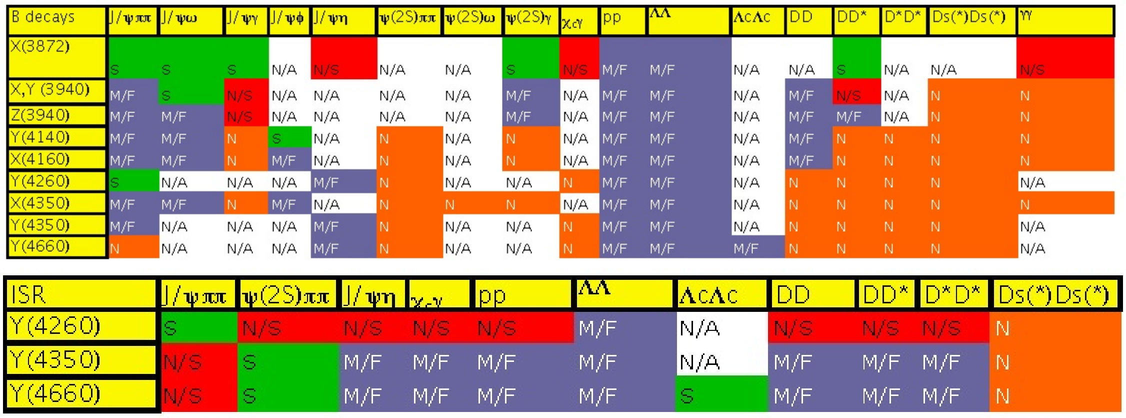


Figure 1: Observed states with hidden charm above the open charm threshold. The theory predictions are according to the potential models described in Ref. [4].

and a systematic experimental search is needed. The work in the theoretical path is progressing although strong interactions are extremely hard to compute, even in presence of heavy quarks, and therefore predictions are extremely hard and uncertain. Finally, additional states predicted by the theoretical models need to be searched for. This paper sketches the path towards this last goal.

The status of the experimental observations is extremely fragmented. Pictorial summaries, separated by production mechanisms, are in Figs. 2-4. The exotic states have been observed always in only one production mechanism and often in only one final state. None of the states has been searched systematically in all final states. Sometimes the analysis of a given final state for a given production mechanism is missing, but often it has either been performed only in a limited mass range or the invariant mass spectrum has been published without a fit to the possible new state. This is mostly due to the fact that some of the analyses did not show a significant signal themselves and they were published before a new state was observed. As an example, the invariant mass spectra of a charmonium and a photon in Refs. [5, 6] are focussed on the $X(3872)$ region and no information is available outside it. On the other side in Ref. [7] the $J/\psi\eta$ invariant mass spectrum is published, but not fitted for all the possible new states. Whatever the cause is, the critical point is that building a global picture requires having either an observation or a limit in each final state for each candidate new state: limits allow to quantify the level at which a decay mode has not been observed and can show whether a signal could have been observed in a final state or the efficiency, the branching fraction or the background level would make it unobservable. It is also worth remarking that although finding new decay modes of these states might not necessarily cast light on the nature of these particles, they would in any case concur to the evidence of the existence of the states that suffer from lack of statistics.



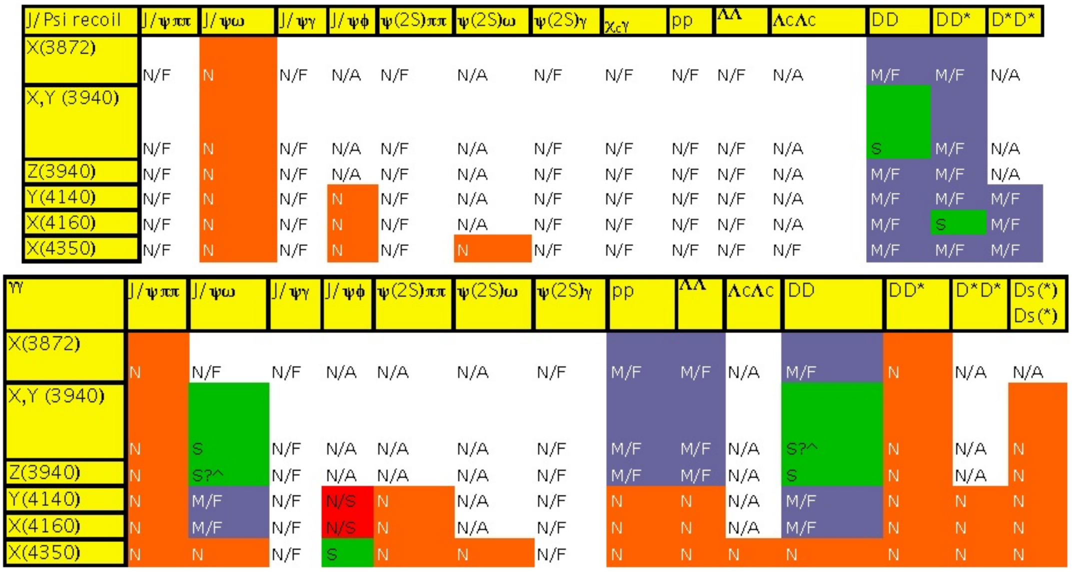
B decays	J/ψππ	J/ψω	J/ψγ	J/ψφ	J/ψη	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	χcγ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*)Ds(*)	γγ
X(3872)	S	S	S	N/A	N/S	N/A	N/A	S	N/S	M/F	M/F	N/A	N/A	S	N/A	N/A	N/S
X,Y (3940)	M/F	S	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	N/S	N/A	N	N
Z(3940)	M/F	M/F	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	M/F	N/A	N	N
Y(4140)	M/F	M/F	N	S	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
X(4160)	M/F	M/F	N	M/F	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
Y(4260)	S	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
X(4350)	M/F	M/F	N	M/F	N/A	N	N	N	N/A	M/F	M/F	N/A	N	N	N	N	N
Y(4350)	M/F	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
Y(4660)	N	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	M/F	N	N	N	N	N/A

ISR	J/ψππ	ψ(2S)ππ	J/ψη	χcγ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*)Ds(*)
Y(4260)	S	N/S	N/S	N/S	N/S	M/F	N/A	N/S	N/S	N/S	N
Y(4350)	N/S	S	M/F	M/F	M/F	M/F	N/A	M/F	M/F	M/F	N
Y(4660)	N/S	S	M/F	M/F	M/F	M/F	S	M/F	M/F	M/F	N

Figure 2: Status of the searches of the new states in the processes $B \to XK$ (top) and $e^+e^- \to X\gamma_{ISR}$, $X \to f$, for several final states f. Final states where each exotic states were observed ("S") or excluded ("N/S") are indicated. A final states is marked as "N" if the analysis has not been performed in a given mass range and with "M/F" if the spectra are published but a fit to a given state has not been performed. Finally "N/A" indicates that quantum numbers forbid the decay and "N/F" if an analysis is experimentally too challenging.

Looking into this "observational" tables in detail, B decays (top of Fig. 2) are the most studied, but there is a significant amount of missing fits ("M/F"). Particularly severe is the lack of analysis of the baryonic spectra since baryonic decays are a signature of tetraquark states. Some other modes have never been studied, mostly because the number of expected events is very low. Nonetheless the study of $B \to \psi(2S)\pi\pi K$ decays should be relatively clean, while $D^*\bar{D}^*$ and above all $D_s^{(*)}\bar{D}_s^{(*)}$ suffer from the low branching fractions of the observed states.

States produced in conjunction with an initial state radiation (ISR) photon (bottom of Fig. 2) have an unambigous J^{CP} assignment and therefore fewer analyses are needed to establish their properties. Nonetheless it is striking to see that a large fraction of analyses have been carried out exclusively for the first observed exotic state, the $Y(4260)$. It can also be noticed that no search is published involving $D_s^{(*)}$ mesons: while the efficiency is expected to be very low, background should be low as well and surprises can always arise. Finally the $Y(4660)$ has been object of one of the combined analyses we are advocating here [8]: two states apparently different, observed in $\psi(2S)$ and $\Lambda_c\bar{\Lambda}_c$ final states, if fitted under the same ansatz were found to be consistent with being the same and interesting ratios of branching fractions were measured.



J/Psi recoil	J/ψππ	J/ψω	J/ψγ	J/ψφ	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	χcγ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*
X(3872)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	N/A
X,Y (3940)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	S	M/F	N/A
Z(3940)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	N/A
Y(4140)	N/F	N	N/F	N	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	M/F
X(4160)	N/F	N	N/F	N	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	S	M/F
X(4350)	N/F	N	N/F	N	N/F	N	N/F	N/F	N/F	N/F	N/F	M/F	M/F	M/F

γγ	J/ψππ	J/ψω	J/ψγ	J/ψφ	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*) Ds(*)
X(3872)	N	N/F	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	M/F	N	N/A	N/A
X,Y (3940)	N	S	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	S?^	N	N/A	N
Z(3940)	N	S?^	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	S	N	N/A	N
Y(4140)	N	M/F	N/F	N/S	N	N/A	N/F	N	N	N/A	M/F	N	N	N
X(4160)	N	M/F	N/F	N/S	N	N/A	N/F	N	N	N/A	M/F	N	N	N
X(4350)	N	N	N/F	S	N	N	N/F	N	N	N	N	N	N	N

Figure 3: Status of the searches of the new states in collisions $e^+e^- \to XJ/\psi$(top) and $\gamma\gamma \to X$ (bottom), $X \to f$, for several final states f. Symbols are explained in the caption of Fig.2.

On the recoil of a J/ψ and in $\gamma\gamma$ interactions (Fig. 3) only $C = +$ neutral states can be observed. This restricts the number of final states of interest. Also, the low multiplicity of these decays and the large missing momentum in the case of $\gamma\gamma$ decays makes these analyses experimentally challenging. On the other side $C = +$ states are the least known and reinforcing the evidence of the signals would help. It is also interesting to notice that, mostly due to statistics, the recoil to any other particle but the J/ψ has not been investigated. Given the selection rules the recoil to χ_{c0} or χ_{c2} would be very interesting.

Concerning the searches of charged exotic states, the most striking signature of states made of more than two quarks, very few searches have been conducted in B decays. We believe that for each exotic neutral spectrum the corresponding charged state should be searched for completeness and, as shown in the bottom of Fig. 4 only five combinations of final states and exotic states has been searched for. As an example, no information has been extracted from Refs. [9, 10] on the charged partner of the $X(3872)$, $Z(3870)$ in our table, which has long been pointed out as a critical state to search for. Moreover among the four quark bound states there must be states that contain a single s quark, their mostly distinctive signature being a charmonium plus a charged kaon. These states could be searched in B decays in association with a $s\bar{s}$ state or inclusively in $p\bar{p}$ collisions.

B decays	$J/\psi\pi$	$J/\psi\pi\pi^0$	$\psi(2S)\pi$	$\psi(2S)\pi\pi^0$	$\chi_{c1}\pi$	DD	DD*	D*D*
Z+(3870)	M/F	N/S	M/F	N	M/F	N	N	N/A
Z+ (3940)	M/F	N	M/F	N	M/F	N	N	N/A
Z+(4050)	M/F	N	M/F	N	S	N	N	M/F
Z+(4140)	M/F	N	M/F	N	M/F	N	N	M/F
Z+(4250)	M/F	N	M/F	N	S	N	N	M/F
Z+(4350)	M/F	N	M/F	N	M/F	N	N	M/F
Z+(4430)	N/S	N	S	N	M/F	N	N	M/F
Z+(4660)	M/F	N	M/F	N	M/F	N	N	M/F

Figure 4: *Status of the searches for new charged states for several final states. Symbols are explained in the caption of Fig.2.*

3. Interplay with other experiments

SuperB is not the only next generation experiment capable of investigating heavy quark spectroscopy.

The LHCb experiment is starting to investigate its potentialities in the field. The complementarity of these studies with SuperB are evident, considering the present interplay between B-Factories and the Tevatron: the larger number of mesons produced allows detailed studies of the decay modes with final states made of charged particles. All other modes are best investigated by e^+e^- machines.

The only other next generation experiment at an e^+e^- machine is BES-III, but their current plan is to run below the energies of interest, at the $\psi(3770)$ [11], where they expect to collect $5 fb^{-1}$ per year. Even if a plan to run at the energies of the exotic states were developed, given the lower luminosity the complementarity of SuperB and BES-III would be the same as the B-Factories and CLEO-c.

A separate mention is deserved by the PANDA experiment at FAIR [12], a proton-antiproton collider which could produce the exotic resonances at threshold (i.e. $e^+e^- \to X,Y$). This production mechanism allows for copious production without the hindrance of fragmentation products as demonstrated at Fermilab for instance at the E760 and E835 experiments. Considering the expected characteristics of the antiproton beam and an integrated luminosity of 2 fb^{-1} per year, running at the J/ψ mass would yield 3.5 10^9 J/ψ mesons per year. Considering that $\Gamma_{ee}[Y(4260)] * \mathscr{B}(Y(4260) \to p\bar{p}) < 0.05\Gamma_{ee}[J/\psi] * \mathscr{B}(J/\psi \to p\bar{p})$@90% C.L. [13] and assuming $\Gamma_{ee}[Y(4260)] = \Gamma_{ee}[J/\psi]$, we could expect as many as 30K $Y(4260) \to J/\psi\pi\pi$ with a J/ψ decaying leptonically per year. Besides the large uncertainty on the assumption, this estimate can be compared with the 60K events in the same decay chain produced in a year at SuperB via ISR. The complementarity of the two experiments is guaranteed by the fact that the final states that can be studied by the two experiments are different and that the PANDA experiment can more easily access the narrow states while SuperB can study in detail larger states if the production mechanism is favorable. Furthermore, in case the center-of-mass-energy of SuperB is changed to the $Y(4260)$ mass, assuming a factor 10 loss in luminosity with respect to running at the $\Upsilon(4S)$, the number of events produced in the decay chain used as example would raise to 700K per year: a few weeks scan would then be equivalent to the PANDA dataset.

4. Conclusions

In summary, there are several reasons why a run at fifty to a hundred times the existing integrated luminosity is decisive to convert the hints for a new spectroscopy into a solid picture:

- All the new states, apart from the $X(3872)$, have been observed in only a single decay channel, each with a significance barely above 5σ. A hundredfold increase in statistics would allow searches in several other modes. In particular, it is important to observe both the decay to charmonium and to D-meson pairs and/or D_s meson pairs. Since the branching fractions of observable final states for the D and especially for the D_s mesons are particularly small, current experiments do not have the sensitivity to observe all the decays.
- Most models predict several other states, such as the neutral partners of the $Z(4430)$ and the nonet partners, for instance $[cd][\bar{c}\bar{s}]$ candidates decaying into a charmonium state and a kaon, at a significantly lower rate (see e.g. Ref. [14]) than the observed modes. Furthermore, several of these states decay into particles (in particular neutral pions and kaons) that have a low detection efficiency.
- SuperB is expected to be able to run also at lower center-of-mass energies, thus allowing to produce the 1^{--} resonances directly. This would be an invaluable and unprecedented means of exploration of this physics.

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