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Recent Developments in Tetraquark Studies at LHCb

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This proceeding presents recent developments in tetraquark studies, with a focus on analyses conducted by the LHCb collaboration. Key highlights include the observation of the $T_{\psi\psi}(6900)$ tetraquark candidate in the di-J/ψ prompt production channel in pp collisions being the first $cc\overline{cc}$ exotic candidate. Furthermore, the discovery of the first open flavor tetraquarks, the $T_{\overline{cs}0}(2870)^0$ and $T_{\overline{cs}1}(2900)^0$ in the $B^+ \to D^+D^-K^+$ decay is reported. This decay does not only provide an excellent environment to study exotic hadrons in the D^-K^+ channel, but also gives insight into charmonium(-like) states in the D^+D^- production system. This is also exploited in the $D^{*\pm}D^{\mp}K^+$ channel where a simultaneous description of the charge conjugate modes provides a fit sensitive to the spin-parity quantum numbers of the resonances. Three new charmonium(-like) states have been confirmed while also measuring their J^{PC} quantum numbers and previously observed tetraquark states in a new production system.

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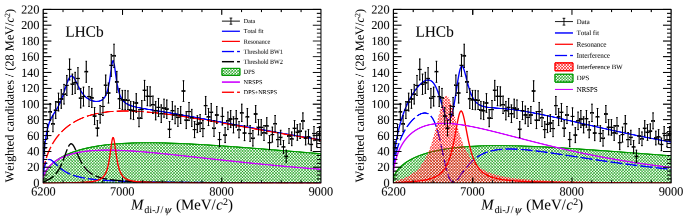
1. Observation of the $T_{\psi\psi}(6900)$ in Prompt di-J/ψ Production

Evidently, $cc\overline{cc}$ tetraquark candidates can be studied in the di-J/ψ invariant mass spectrum where contributions could arise either from a direct decay to two J/ψ mesons or from feed-down effects from heavier charmonia.

At the LHC using proton-proton collisions, a di-J/ψ can be produced in two separate interactions of gluons or quarks (double-parton scattering (DPS) [3–5]), or in a single interaction (single-parton scattering (SPS) [5–7]). In case of SPS production, it can take into account both resonant production via the $T_{cc\overline{cc}}$ tetraquark state and non-resonant production. The DPS contributions dominates the high $M_{\mathrm{di}-J/\psi}$ region which is in agreement with expectation. Using the full LHCb Run 1 and Run 2 proton-proton collision dataset, two J/ψ candidates are reconstructed in prompt production directly searching for a fully charmed tetraquark state.

The di-J/ψ transverse momentum of SPS production is, on average, predicted to be higher than DPS production [8]. Since it is expected that resonant contributions arise from SPS production, one can enhance SPS production by choosing high p_T regions. Figure 1 shows the invariant mass of the di-J/ψ candidates , which covers the predicted masses of $T_{cc\overline{cc}}$ states decaying to a J/ψ pair. There are evident structures in the spectrum. First, a broad structure just above the di-J/ψ threshold around 6.2 GeV. Then, at 6.9 GeV, there is a narrow peak (referred to as $X(6900)$) and a less distinct structure around 7.2 GeV.



(a) (b)

Figure 1: Invariant mass spectra of the weighted di-J/ψ candidates with an additional $p_T^{\mathrm{di}-J/\psi}$ requirement. The fit components are from (a) model I and (b) model II.

The background-subtracted di-J/ψ mass spectrum in the mass region where tetraquarks are expected is seen in Figure 1. The contributions are predominantely from non-resonant SPS (NRSPS) and DPS production. They are modeled by a two-body phase-space distribution multiplied by an exponential function. For the DPS production, a second order polynomial is also multiplied, whose parameters are fixed by di-J/ψ mass distributions from J/ψ differential cross section measurements. Both contributions make up the baseline model, which is rejected with a significance of 3.4σ.

The peaking structures may have different interpretations. Multiple $T_{cc\overline{cc}}$ states could decay to a pair of J/ψ mesons or there might be feed-down effects, where a photon is not reconstructed, i.e. $T_{cc\overline{cc}} \to \chi_c(\to J/\psi\gamma)J/\psi$. While this would unlikely produce the narrow peak around 6900 MeV, it might explain the near-threshold enhancement. It is also possible that rescattering of two charmonium states produces such narrow peaks [9, 10]. The rescattering effects demand a complicated description of the lineshape and is subject of future investigation. Also, interference effects with NRSPS and resonant contributions alter the distribution. In the following, two models are used to describe the data. Due to small statistics, the peak around 7.2 GeV will be neglected.

In model I, the $X(6900)$ structure is considered as a resonance. The near-threshold enhancement is described through a superposition of two resonances. An S-Wave relativistic Breit-Wiger function multiplied by a two-body phase space distribution parametrizes the lineshape of the resonances corresponding to mass and width

$$m(X(6900)) = (6905 \pm 11 \pm 7)\,\text{MeV},\ \Gamma(X(6900)) = (80 \pm 19 \pm 33)\,\text{MeV},$$

respectively, where the first uncertainty is statistical and the second systematic. The fit quality is found to be $\chi^2/\text{ndof} = 112.7/89$ using a χ^2 test statistic. The left plot of Figure 1 shows the fit result of model I and reveals that the fit cannot describe the dip around 6.75 GeV. Thus, in model II in an attempt to describe the sharp drop of the data, interference effects between the NRSPS component and any resonance are included. The interference terms are then added to the remaining description of the spectrum yielding a mass and width of

$$m(X(6900)) = (6886 \pm 11 \pm 11)\,\text{MeV},\ \Gamma(X(6900)) = (168 \pm 33 \pm 69)\,\text{MeV},$$

respectively. Evidently, model II returns a larger width and yield. The fit quality is determined to be $\chi^2/\text{ndof} = 104.7/91$. The global significance of both models is evaluated by comparing the likelihood with and without additional resonances and yield 5.1σ for the $X(6900)$ state in model I. Determining the global significance for the resonances in model II can be subject of future studies.

2. Observation of the $X_{0(1)}(2900)$ in $B^+ \to D^+D^-K^+$ Decays

The $B^+ \to D^+D^-K^+$ decay is inherently interesting to study. In the D^-K^+ channel, resonances must have minimal valence quark content $\bar{c}d\bar{s}u$ and are, by default, of exotic nature. Exotic states consisting of a charm and strange quark have not been observed previously although predictions of such states exist [12, 13]. Furthermore, as conventional hadrons can also appear in the D^+D^- channel, the decay also offers a very clean environment to study charmonium(-like) resonances [14]. Using proton-proton collision data from the total Run 1 + 2 LHCb dataset, a full amplitude analysis of the decay $B^+ \to D^+D^-K^+$ is performed [11]. The offline selection consists of multiple kinematic cuts and a boosted decision tree (BDT) [15] algorithm to better separate signal from background. Opposed to the analysis described in Section 1, the final state particles originate from a b hadron making background suppression easier. An extended maximum-likelihood fit is applied to the invariant mass spectrum of the B candidates. Since the background yield is negligible (achieving a purity greater than 99.5%), it is removed in the following ensuring a more consistent fit stability.

The underlying distributions are described in an amplitude analysis formalism. The signal PDF is a function of the signal amplitude , which is built in the isobar formalism [16, 17] containing the resonant and non-resonant components of the model. It also contains information about the lineshape of a resonance, which is given by a relativistic BW distribution. Initially, only charmonium resonances in the D^+D^- channel are considered for the baseline model. Parity conservation enforces $J^P = 0^+, 1^-, 2^+, \ldots$ The initial resonances embedded into the model are taken from all known PDG [18] listings as well as other experimental results from Belle [20], BaBar [19] and LHCb [21]. Since the charmonium spectrum in this sector is not well understood, one cannot guarantee completeness. The corresponding Dalitz projections for Run 2 are shown in Figure 2.

A clear enhancement around $m^2(D^-K^+) \approx 8.25\,\mathrm{GeV}^2$ is visible in the D^-K^+ channel, which cannot be accounted for only using the charmonium resonances. The simplest way to change the model in order to closer match the data is adding resonances in the D^-K^+ channel. In the D^-K^+

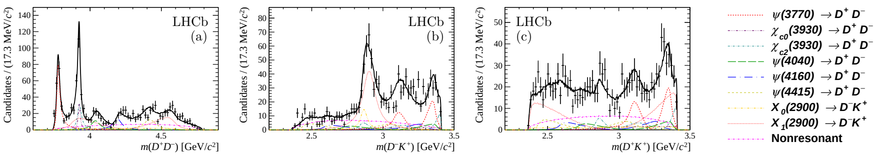


Figure 2: The Dalitz Plot projections with their contributions making up the fit model. The different embedded resonances are seen in the legend on the right. It is evident that the resonances in the D^-K^+ are necessary to give an accurate description of the data.

channel, spin 0 and spin 1 resonances are added. Figure 2 also displays the projections and the fit functions of the model including D^-K^+ resonances. It is evident that the resonances in the D^-K^+ channel are necessary to describe the data more accurately. The BW parameters of the peaking structure are determined to be

$$X_0(2900) : M = (2.866 \pm 0.007 \pm 0.002)\,\mathrm{GeV},\ \Gamma = (57 \pm 12 \pm 4)\,\mathrm{MeV},$$

$$X_1(2900) : M = (2.904 \pm 0.005 \pm 0.001)\,\mathrm{GeV},\ \Gamma = (110 \pm 11 \pm 4)\,\mathrm{MeV}$$

where the first uncertainty is statistical and the second error is systematic. The significances of these states are very high but further analyses are necessary to rule out that these structures are not produced in another way, e.g. rescattering effects. If interpreted as resonances, the first open flavor exotic states are reported. Furthermore, the model includes contributions from two charmonium(-like) states where previous measurements assumed a single $\chi_{c2}(3930)$ state. This model suggests to disentangle the state into one spin-0 and one spin-2 resonance $\chi_{c0}(3930)$ and $\chi_{c2}(3930)$, respectively.

3. Charmonium(-like) states in $B^+ \to D^{*\pm}D^{\mp}K^+$ Decays

Finally, the decays $B^+ \to D^{*+}D^-K^+$ and $B^+ \to D^{*-}D^+K^+$ are studied [22]. The analysis is also connected to Section 2 since it is important to confirm the existence of the $X_{0(1)}(2900)$ (referenced to as $T^*_{\overline{c}s0(1)}(2870(2900))^0$ in this work following the common nomenclature) in different production channels. Additionally, the $D^{*\pm}D^{\mp}$ decay again offers a clean environment to study charmonium(-like) resonances. Many observed charmonium(-like) states cannot be explained within the quark model [23, 24] and their valence quark content remains unclear. This work describes a simultaneous analysis of the $B^+ \to D^{*+}D^-K^+$ and $B^+ \to D^{*-}D^+K^+$ channels. This is the first time C-Parity conservation is exploited to employ a fit that is sensitive to the C-Parities of the resonances. Using LHCb Run 1 + 2 data corresponding to a integrated luminosity of $9\,\mathrm{fb}^{-1}$ and performing an offline selection similar to previous analyses [25], one obtains the mass spectrum that is displayed in Figure 3. An amplitude fit based on an unbinned maximum-likelihood method is employed to describe the data. The corresponding amplitude is also dependent on the C-Parity of the resonances

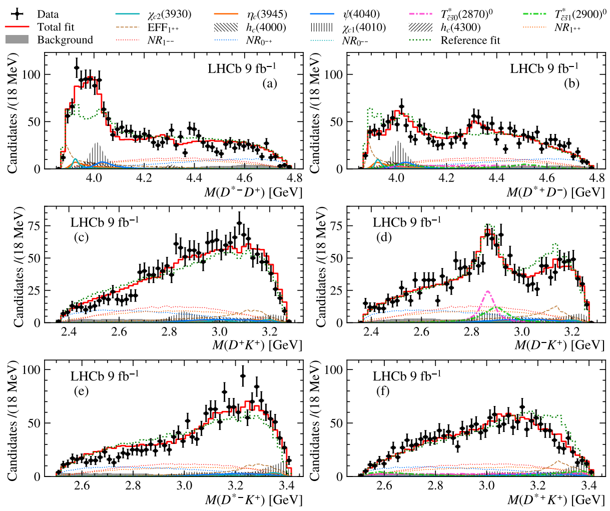


Figure 3: Distributions of the invariant masses: The first column the invariant masses in the $B^+ \to D^{*-}D^+K^+$ are seen while the second column displays the masses of the $B^+ \to D^{*+}D^-K^+$ decay. Black: Data, Red Solid Lines: Fit results, the resonant contributions can be seen in the legend. As a reference, the green-dotted line shows a model without the $h_c(4000)$, $\chi_{c1}(4010)$ and $h_c(4300)$.

decaying to $D^{\pm}D^{\mp}$, which is described in detail in the original work [22]. Evidently, Figure 3 shows clear differences around 4 GeV in the invariant mass spectra of $M(D^{*+}D^-)$ and $M(D^{*-}D^+)$ due to interference effects. In the $B^+ \to D^{*+}D^-K^+$ channel, the two resonant contributions also found in Section 2 are included to describe the data as seen in Figure 3(e). Their statistical significances are determined to be 11σ and 9.2σ for the $T^*_{\bar{c}s0}(2870)^0$ and $T^*_{\bar{c}s1}(2900)^0$, respectively, when fixing their lineshape parameters, confirming both states in a different production channel. Furthermore, the ratio of their branching fractions are found to be larger than in the $B^+ \to D^+D^-K^+$ channel. If the parameters are allowed to float in the fit, one obtains

$$m(T^*_{\bar{c}s0}(2870)^0) = (2914 \pm 11 \pm 15)\,\text{MeV},\ \Gamma(T^*_{\bar{c}s0}(2870)^0) = (128 \pm 22 \pm 23)\,\text{MeV},$$
$$m(T^*_{\bar{c}s1}(2900)^0) = (2887 \pm 8 \pm 6)\,\text{MeV},\ \Gamma(T^*_{\bar{c}s1}(2900)^0) = (92 \pm 16 \pm 16)\,\text{MeV}.$$

Additionally, four charmonium(-like) states are found with statistical significances of 10σ, 9.1σ, 16σ and 6.4σ. Following the nomenclature of $I = 0$ states, they correspond to the $\eta_c(3945)$, $h_c(4000)$, $\chi_{c1}(4010)$ and $h_c(4300)$ resonances, respectively. As the isospin quantum number is not measured directly, exotic contributions currently cannot be ruled out. Their quantum numbers J^{PC} are found to be 0^{-+}, 1^{+-}, 1^{++} and 1^{+-}, respectively, with other spin-parity combinations ruled out by at least 5.7σ.

The masses and widths obtained from the fit are given below.

$$\begin{aligned}
m(\eta_c(3945)) &= 3945^{+28+37}_{-17-28}\,\text{MeV},\ \Gamma(\eta_c(3945)) = 130^{+92+101}_{-49-70}\,\text{MeV},\\
m(h_c(4000)) &= 4000^{+17+29}_{-14-22}\,\text{MeV},\ \Gamma(h_c(4000)) = 184^{+71+97}_{-45-61}\,\text{MeV},\\
m(\chi_{c1}(4010)) &= 4012.5^{+3.6+4.1}_{-3.9-3.7}\,\text{MeV},\ \Gamma(\chi_{c1}(4010)) = 62.7^{+7.0+6.4}_{-6.4-6.6}\,\text{MeV},\\
m(h_c(4300)) &= 4307.3^{+6.4+3.3}_{-6.6-4.1}\,\text{MeV},\ \Gamma(h_c(4300)) = 58^{+28+28}_{-16-25}\,\text{MeV},
\end{aligned}$$

where the $\eta_c(3945)$ seems to be consistent with the previously found $X(3940)$ state [26, 27] while the other three are measured for the first time.

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