Possible experimental signatures of stable double beauty tetraquarks

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A new method is proposed to search for the double beauty tetraquark $bbud$ with a mass below the $BB$ threshold. The $bd$-$bd$ mixing can result in evolution of the tetraquark content to $bbud$ with the following strong decay into the $\Upsilon(1S)\pi^-$ and $\Upsilon(2S)\pi^-$ final states in a secondary vertex displaced from the primary $pp$ collision vertex. This experimental signature is clean, has a high selection efficiency and can be well separated from backgrounds. Experimental signatures for searches for other double heavy tetraquarks are also discussed, suggesting the possibility of the $bd$ or $bs$ mixing.

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I. INTRODUCTION

The double beauty tetraquark $bbud$ with a mass below the $BB$ threshold has been predicted within the framework of various theoretical approaches [1,17]. There is a consensus regarding the negative binding energy of the ground state of the tetraquark, which is clearly demonstrated in Fig. 8 of [1]. This tetraquark has to be stable against strong and electromagnetic decays, therefore the state will decay weakly with a lifetime typical for hadrons containing constituent $b$-quarks. Since the tetraquark contains two $b$-quarks, the lifetime is naively expected to be $\sim (0.4 – 0.8)$ ps, which is about half of the $B$ meson lifetime. In has to be noted that theoretical predictions for the lifetime value vary within a wide range from 0.367 ps [1] to 7.6 ps [8].

The discovery of the $\Xi^{++}_c$ baryon by the LHCb collaboration [18] gave more confidence in the possibility of the experimental observation of the double beauty tetraquark at LHC. Based on this LHCb measurement, the cross section for the $bbud$ tetraquark production at LHC was estimated in [13] as $\sim 1$ nb. Taking into account the large data samples collected by the LHCb experiment ($\sim 9$ fb$^{-1}$) and the ATLAS and CMS experiments ($> 150$ fb$^{-1}$ each), the prospects to observe the tetraquark are not hopeless. However, the double beauty tetraquark will decay weakly in many channels with small branching fractions of about $10^{-2} – 10^{-3}$. In addition to this, the efficiencies to reconstruct the produced $D$ and $B$ mesons are $\sim 10^{-2}$ and $\sim 10^{-4}$, respectively, including all branching fractions and track reconstruction efficiencies. This makes the observation of this state experimentally difficult, even with the large data samples collected by the LHC experiments.

II. PROPOSED METHOD

In this paper a new method is proposed to search for the $bbud$ tetraquark. The size of the double heavy compact tetraquark is expected to be less than 1 fm, and the distances between constituent quarks should be approximately the same as in $B$ mesons. Therefore the $bd$ mixing has to be of the same order as for the $B^0$ mesons. The mixing can change the quark content of the $bbud$ state to the $bbud$ configuration. Then this $bbud$ state immediately decays strongly into the $\Upsilon(1S)\pi^-$ or $\Upsilon(2S)\pi^-$ final state with a whole branching fraction close to 100%. The charge conjugate states are implied throughout this paper. The tetraquark decay process is illustrated in Fig. 1.

The $\Upsilon(1S)$ or $\Upsilon(2S)$ mesons can be reconstructed in the muonic decay modes, this also allows to trigger these events with a high efficiency. The corresponding branching fractions are large, $Br(\Upsilon(1S)\rightarrow \mu^+\mu^-) = (2.48\pm 0.05)\%$ and $Br(\Upsilon(2S)\rightarrow \mu^+\mu^-) = (1.93\pm 0.17)\%$. This experimental signature for the tetraquark searches is very clean: two muons and a pion form a secondary vertex displaced from the primary $pp$ collision vertex. $\Upsilon$ mesons are not produced in the displaced vertex in any other processes, therefore this condition provides strong background suppression. It is interesting to note, that the signals in the mass distributions $m(\Upsilon(1S)\pi^-)$ and $m(\Upsilon(2S)\pi^-)$ have to be narrow, although the decays are strong.

FIG. 1: The experimental signature of the mixing induced decay of the $bbud$ tetraquark.
III. MIXING PROBABILITY DENSITY FUNCTION

The decay rate as a function of the decay time for the studied state is calculated taking into account two possible processes: the weak decays of the $b$-quarks and the strong decays induced by the $b\bar{d}$ mixing. Both processes result in decays of the tetraquarks but in different final states. In the case of only weak decays, the fraction of the remaining events $R_w(t)$ and the probability density function (PDF) $f_w(t)$ as a function of the decay time $t$ are described as:

$$R_w(t) = \exp(-t/\tau)$$

$$f_w(t) = 1/\tau \cdot \exp(-t/\tau)$$  \hspace{1cm} (1)

In the case of only mixing process, the fraction of the remaining events $R_m(t)$ and the mixing PDF $f_m(t)$ as a function of the decay time $t$ are:

$$R_m(t) = (1 + \cos(\Delta m \cdot t))/2$$

$$f_m(t) = \Delta m \cdot \sin(\Delta m \cdot t)/2$$  \hspace{1cm} (2)

If both effects are enabled simultaneously, the combined PDF $f_2(t)$ will be:

$$f_2(t) = f_m(t) \cdot R_w(t) + f_w(t) \cdot R_m(t)$$  \hspace{1cm} (3)

As mentioned above, after mixing the quark configuration $b\bar{b}ud$ decays immediately, therefore, the obtained distribution differs significantly from that obtained for the conventional $B^0$-mixing process.

Numerical calculations are performed assuming that the mixing parameter is $\Delta m = 0.513$ ps$^{-1}$, similar to the $B^0$ mixing, and the lifetime is $\tau = 0.5 \times 1.519$ ps, which is half of the $B^0$ meson lifetime. The results are shown in Fig. 2: the PDF curve $f_w(t)$ (Eq. 1) for the weak decays only, the PDF curve $f_2(t)$ (Eq. 3) for the combination of both effects, and the PDF curve for the fraction of mixing induced decays (first term in Eq. 3), when both processes are allowed. Fig. 2 demonstrates that PDF for the mixing induced decays is distributed over a wide decay time interval, i.e. the decay vertex formed by the $\mu^+\mu^-\pi^-$ track can be significantly displaced from the primary $pp$ collision vertex. This can provide strong background suppression, because the excellent vertex resolutions in LHC experiments allow to separate the signal events from backgrounds.

Using these calculations, the integrated fraction of the mixing induced decays relative to all tetraquark decays is estimated at the level $\sim 5\%$. As can be seen from Table 1, the integrated fraction of the mixing induced decays within the ranges of the parameter values is at least a few percent.

With a large statistics, the distribution of the mixing decay time can be measured experimentally using the proposed method, and the mixing parameter and the weak decay lifetime can be obtained from this distribution. Taking into account the whole $b\bar{b}ud$ tetraquark decay chain, the efficiency to reconstruct the mixing induced decays relative to the number of all produced $b\bar{b}ud$ tetraquarks is estimated at the level $\sim 10^{-4}$. Backgrounds can be strongly suppressed by the requirement of the displaced vertex, therefore a signal with several tens of reconstructed events can be observed.

If this signal will be observed with a large number of events, the decay time distributions should be studied separately for the $\Upsilon(1S)\pi^+$ and $\Upsilon(1S)\pi^-$ candidates to search for $CP$-violation effects. In the studied process the $b$-quark flavor is fixed by the charge of pion.

TABLE I: The integrated fraction of the mixing induced decays relative to all tetraquark decays for different $\Delta m$ and lifetime values.

| Mixing parameter $\Delta m$, ps$^{-1}$ | Weak decay lifetime, ps | Integrated mixing fraction |
|----------------------------------------|-------------------------|---------------------------|
| $0.513$                                | $0.751$                 | $7.5\%$                   |
| $0.3$                                  | $0.751$                 | $3.5\%$                   |
| $0.7$                                  | $0.751$                 | $12\%$                    |
| $0.513$                                | $0.4$                   | $3.0\%$                   |
| $0.513$                                | $2.0$                   | $27\%$                    |
IV. SIGNATURES FOR OTHER DOUBLE HEAVY TETRAQUARKS

Double heavy tetraquarks with different quark contents have been discussed theoretically. As predicted, some of them can have masses below the corresponding thresholds and decay weakly. If the $b\bar{d}$ or $bs$ combinations are included in the quark content, mixing can result in strong decays of these states. If such states exist, their decay time distributions can be very different. The shape of the mixing induced decay time distribution depends on the ratio of the lifetime value and the mixing period $\pi/\Delta m$. If the mixing period is approximately the same or less than the lifetime, then the final states will be produced close to the primary vertex with a large fraction of the mixing induced decays. If the mixing period is about an order of magnitude larger than the lifetime value, the fraction of the decays is small, but the secondary vertex will be displaced from the primary $pp$ vertex. If the mixing period is very large compared to the lifetime value, the fraction of the mixing induced decays will become very small. Double beauty tetraquarks with the $s$-quark and a mass below the $B_sB$ mass threshold, such as the $b\bar{b}s\bar{s}$ and $bb\bar{s}\bar{s}$ states, can evolve quickly via the $b\bar{s}$ mixing. Then the requirement of the displaced vertex cannot be applied to suppress backgrounds. However, the fraction of the mixing induced decays should be large. The mass distributions of the $\Upsilon(1S/2S)K^-/0$ combinations can be studied to search for these tetraquarks, but the corresponding decay vertex has to be located in proximity of the primary $pp$ vertex.

Also, the tetraquarks $bc\bar{u}\bar{d}$ or $bs\bar{u}\bar{d}$ are discussed in literature, and negative binding energies for their ground states are obtained in some theoretical models. The requirement of a displaced vertex can be applied to search for these states. This vertex has to be formed by a $B^-_s$ or $B^0_s$ meson and a charged pion. This signature is similar to that shown in Fig. 1, where the $\Upsilon(1S)$ meson is replaced by the $B^-_s$ or $B^0_s$ meson. Since the predicted values of the masses, lifetimes and mixing parameters for double heavy tetraquarks depend on parameters of theoretical models, wide ranges of possible values should be tested experimentally.

V. CONCLUSIONS

The clean experimental signature is proposed to search for the double beauty tetraquark $b\bar{b}u\bar{d}$ with a mass below the $BB$ threshold. As a result of the $b\bar{d} - b\bar{d}$ mixing, the state decays into the $\Upsilon(1S/2S)\pi^-$ combination originating from a displaced vertex. If the mixing parameter $\Delta m$ is not too small, the signal can be observed with statistics already collected by the LHC experiments. Signatures for other double heavy tetraquarks are also proposed and can be searched for at the LHC experiments.

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