Search for QCD exotic states at CMS

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The search for an exotic tetraquark state decaying into $\Upsilon(1S)\mu^+\mu^-$ performed at the CMS experiment is reported. An evidence for the X(3872) exotic state production in PbPb collisions is also presented, as well as the first observation of the $B_s^0 \to X(3872)\phi$ decay and the measurement of its branching fraction. The latter is found to be about two times smaller than $\mathcal{B}(B^+ \to X(3872)K^+)$, indicating the difference in the production dynamics of X(3872) in B_s^0 and B^+ decays.

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The CMS experiment [1] at the LHC is providing new important results in the Exotic Heavy Flavor physics sector. In this work, we report the search for a tetraquark state decaying into $\Upsilon(1S)\mu^+\mu^-$ (Section 1), an evidence for X(3872) production in nuclei collisions (Section 2), and the observation of the $B_s^0 \to X(3872)\phi$ decay (Section 3). Charge-conjugate states are implied throughout the text.

1. Search for tetraquarks decaying into $\Upsilon(1S)\mu^+\mu^-$

A number of theoretical predictions exist for compact tetraquarks composed of two heavy quarks and two corresponding anti-quarks. In particular, the masses of $\mathrm{bb\bar{b}\bar{b}}$ tetraquarks are predicted to be around twice the η_b mass, slightly below twice the $\Upsilon(1S)$ mass. The CMS experiment performed a search [2] for such states in their decays into $\Upsilon(1S)\mu^+\mu^-$, followed by the $\Upsilon(1S) \to \mu^+\mu^-$ decays, using the data collected in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. Four muons of high quality, having $p_T > 2.5$ GeV, are selected and fit to a common vertex with χ^2 probability in excess of 5%. The mass of the first dimuon is required to be compatible with the known $\Upsilon(1S)$ meson mass. If any opposite-sign dimuon is compatible with being a decay product of J/ψ, the event is discarded.

The double-$\Upsilon(1S)$ production process is one of the background sources to the tetraquark search. Its contribution is estimated in data and its shape in the $\Upsilon(1S)\mu^+\mu^-$ mass distribution is evaluated using the simulated event samples. To improve the invariant mass resolution, the mass difference variable $M(\mu^+\mu^-\mu^+\mu^-) - M(\mu^+\mu^-) + m_{\Upsilon(1S)}$ is used, where the second term corresponds to the mass of the dimuon associated with $\Upsilon(1S) \to \mu^+\mu^-$ decay and $m_{\Upsilon(1S)}$ is the world-average mass of the $\Upsilon(1S)$ bottomonium state.

The observed distribution of $\Upsilon(1S)\mu^+\mu^-$ mass, presented in Fig. 1 (left), is fit with a sum of smooth background, $\Upsilon(1S)\Upsilon(1S)$ contribution, and a signal component.

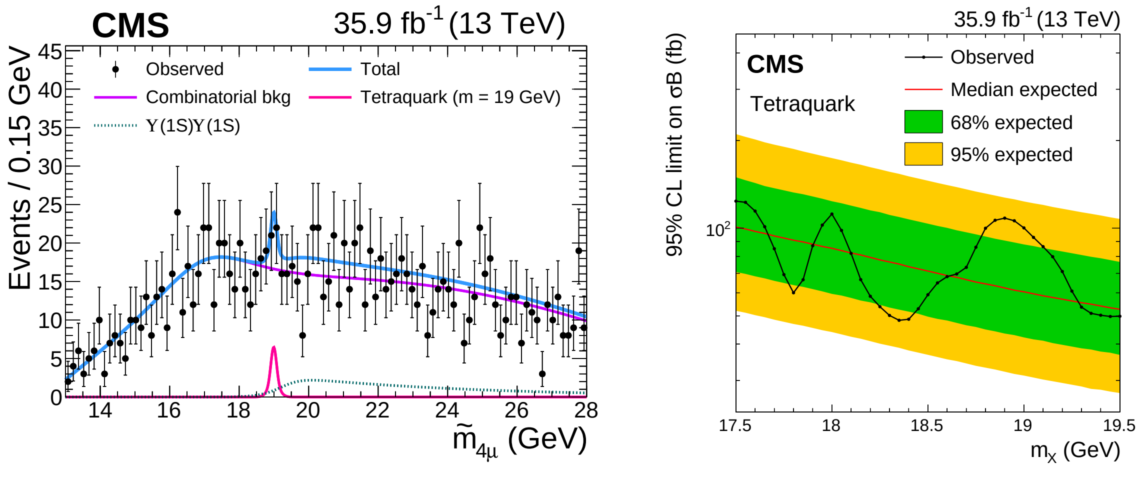

Figure 1: Left: the reconstructed $\Upsilon(1S)\mu^+\mu^-$ invariant mass distributions with the fit results overlaid [2]. Right: mass-dependent upper limit on the tetraquark production [2].

No significant signal is observed, and a mass-dependent upper limit is set on the production cross section multiplied by the branching fraction of the tetraquark decay into $\Upsilon(1S)\mu^+\mu^-$ and $\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$, presented in Fig. 1 (right). The limit calculation relies on the reconstruction and identification efficiencies, estimated in simulations and verified in data. The limits are also set in a wider mass range on possible exotic particles decaying into $\Upsilon(1S)\mu^+\mu^-$ [2].

2. Evidence for X(3872) production in relativistic heavy ion collisions

Production of excited states of charmonium and bottomonium states is known to be suppressed in nucleus-nucleus collisions due to interactions with the hot medium. Moreover, higher excited states are suppressed more than lower excited states, for example, $\Upsilon(2S)$ is suppressed by a larger factor than $\Upsilon(1S)$ [3]. The X(3872) state, observed by the Belle experiment in 2003, is known to be inconsistent with a pure charmonium state due to its mass above double open charm threshold and small natural width. A number of interpretations exist, including molecule or tetraquark models of a superposition of those with a conventional charmonium state. Study of X(3872) production in nucleus-nucleus collisions and comparison to the $\psi(2S)$ production could bring additional information to improve the understanding of the X(3872) nature.

The CMS experiment performed such a study using $1.7\,\mathrm{nb}^{-1}$ of PbPb collisions collected in 2018 at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$. Both $\psi(2S)$ and X(3872) states are reconstructed through their decays into $J/\psi\pi^+\pi^-$ with a subsequent decay $J/\psi \to \mu^+\mu^-$. The observed $J/\psi\pi^+\pi^-$ mass distribution is presented in Fig. 2, showing $\psi(2S)$ and X(3872) signals. The distribution is fit with a sum of a smooth background functions and two signal contributions. The statistical significance of the X(3872) signal is estimated to be about 4 standard deviations (s.d.), corresponding to the first evidence of X(3872) production in nuclei collisions [4]. The efficiency-corrected ratio of yields $N^{\mathrm{corr}}(\mathrm{X}(3872))/N^{\mathrm{corr}}(\psi(2S))$, after subtraction of non-prompt contribution, is measured to be $r = 1.10 \pm 0.51\,(\mathrm{stat}) \pm 0.53\,(\mathrm{syst})$ [4]. This value is noticeably larger than that measured in pp collisions of $\sim 0.05 - 0.1$, however, due to large uncertainty in r, it is consistent with the pp value.

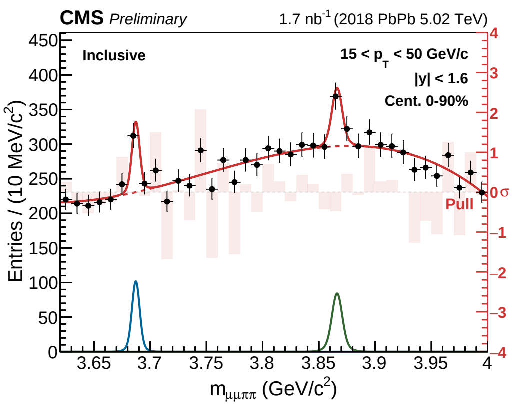

Figure 2: The $J/\psi\pi^+\pi^-$ invariant mass distribution observed in PbPb collisions. The left peak corresponds to the $\psi(2S)$ signal, the right peak – to the X(3872) [4].

3. Observation of the $B_s^0 \to X(3872)\phi$ decay

Studies of the X(3872) production in b hadron decays can provide important information for establishing the X(3872) internal structure. The exotic state has been previously observed in B^+, B^0, Λ_b^0 decays, and in prompt production at hadron colliders.

The CMS experiment performed a search [5] for the $B_s^0 \to X(3872)\phi$ decay using pp collision data collected at $\sqrt{s} = 13$ TeV in 2016–2018 and corresponding to an integrated luminosity of about 140 fb^{-1}. The signal decay is reconstructed using the $X \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$ and $\phi \to K^+K^-$ decays, and the normalization channel $B_s^0 \to \psi(2S)\phi \to J/\psi\pi^+\pi^-K^+K^- \to \mu^+\mu^-\pi^+\pi^-K^+K^-$ is chosen thanks to its identical final-state particles and very similar decay topology and kinematics.

The signal is extracted using a two-dimensional (2D) fit to $M(K^+K^-)$ and $M(J/\psi\pi^+\pi^-)$, after requiring $M(J/\psi\pi^+\pi^-K^+K^-)$ to be in a narrow interval around the known B_s^0 meson mass. The measured $J/\psi\pi^+\pi^-$ invariant mass distribution is shown in Fig. 3 (left), overlaid with the projection of the 2D fit.

The 2D fit returns 299 ± 39 signal $X(3872)\phi$ events and allows to estimate the statistical significance of above 6.5 s.d., corresponding to the first observation of the $B_s^0 \to X(3872)\phi$ decay. The remaining non-B_s^0 background is verified to be negligible using the $_s\mathcal{P}$lot technique to subtract non-X(3872) and non-ϕ combinations $J/\psi\pi^+\pi^-K^+K^-$ and plotting the $J/\psi\pi^+\pi^-K^+K^-$ invariant mass distribution, as shown in Fig. 3 right. A similar signal extraction procedure is used in the normalization $B_s^0 \to \psi(2S)\phi$ channel to evaluate the yield $N(B_s^0 \to \psi(2S)\phi) = 15359 \pm 171$, which is then combined with the $B_s^0 \to X(3872)\phi$ yield and corrected for the efficiency ratio to obtain [5]

$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)\,\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)\,\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (2.21 \pm 0.29\,(\text{stat}) \pm 0.17\,(\text{syst}))\%.$$

After multiplying this ratio by the known denominator branching fractions, one obtains [5] $\mathcal{B}(B_s^0 \to X(3872)\phi)\,\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.14 \pm 0.54\,(\text{stat}) \pm 0.32\,(\text{syst}) \pm 0.46\,(\mathcal{B})) \times 10^{-6}$. This product is compared to the similar products of branching fractions for the $B^+ \to X(3872)K^+$ and $B^0 \to X(3872)K^{(*)0}$ decays in Fig. 4 (right). The $B^+ \to X(3872)K^+$ decay evidently has about two times larger branching fraction with respect to the $B^0 \to X(3872)K^{(*)0}$ and $B_s^0 \to X(3872)\phi$ decays,

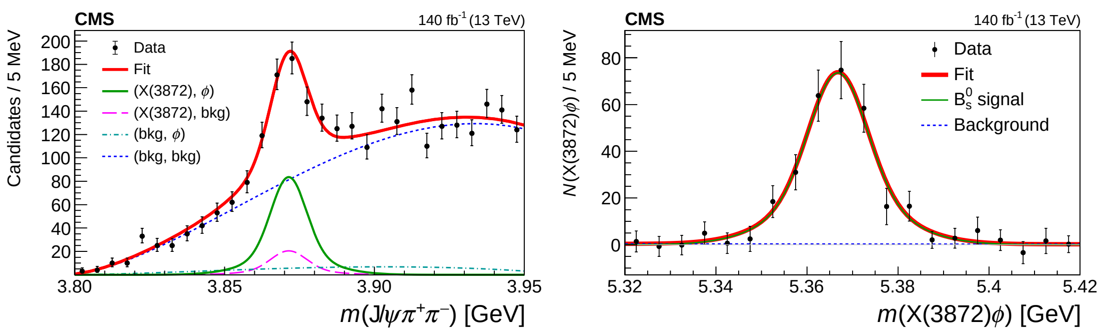

Figure 3: Left: $J/\psi\pi^+\pi^-$ invariant mass distribution in the selected $B_s^0 \to X(3872)\phi$ candidates in data [5]. Right: $X(3872)\phi$ invariant mass distribution after subtraction of non-ϕ K^+K^- combinations and non-X(3872) $J/\psi\pi^+\pi^-$ combinations [5].

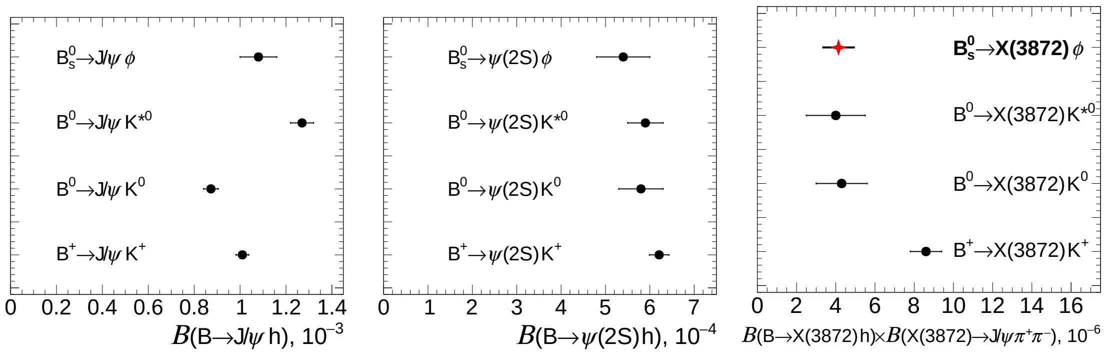

Figure 4: Comparison of branching fractions of B meson decays into a charmonium state (or X(3872)) and a light meson [5].

in contrast to the similar decays of B mesons into J/$\psi\,h$ and $\psi(2S)h$, which have approximately equal branching fractions as shown in Fig. 4 left and center [5]. This shows that X(3872) production in B meson decays is different from that of traditional charmonium states.

4. Summary

In summary, the exotic tetraquark states decaying into $\Upsilon(1S)\mu^+\mu^-$ are searched for, and mass-dependent limits are set on their production cross section multiplied by the branching fractions. The first evidence for X(3872) state production in PbPb collisions and the first observation of X(3872) state production in B_s^0 meson decays are reported. The branching fraction of the $B_s^0 \to X(3872)\phi$ is found to be about two times smaller than that of the $B^+ \to X(3872)K^+$ decay, indicating the difference in the production dynamics of X(3872) in B_s^0 and B^+ decays.

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