PROCEEDINGS OF SCIENCE

Exotic quarkonium states in CMS experiment

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Using large data samples of di-muon events, CMS can perform detailed measurements and searches for new states in the field of exotic quarkonium. We present our results on the production of prompt and non-prompt X(3872), detected in the $J/\psi\pi^+\pi^-$ decay channel, which extend to higher p_T values than in any previous measurement. The cross-section ratio with respect to the $\psi(2S)$ is given differentially in p_T, as well as p_T integrated. For the first time at the LHC, the fraction of X(3872) coming from B hadron decays has been measured. After these studies of the charmonium X, we present a new search for its bottomonium counterpart, denoted as X_b, based on a data sample of pp collisions at 8 TeV collected by CMS in 2012. In analogy to the X(3872) studies, the analysis uses the $X_b \to \Upsilon(1S)\pi\pi$ exclusive decay channel, with the $\Upsilon(1S)$ decaying to $\mu^+\mu^-$ pairs. No evidence for X_b is observed and upper limits at a confidence level of 95% on the production cross section of X_b times the decay branching fraction have been set.

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1. Introduction

The exotic meson X(3872) was first discovered in the final state of $\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-$ [1], and attracted many interests in quarkonium spectroscopy since it was the first observation of an unexpected charmonium state. Following this discovery several new states have been found [2], but the exact theory of these exotic resonances has not yet been fully established. There are several possible interpretations of the X(3872) state: a conventional charmonium state, a $\mathrm{D}^*\mathrm{D}$ molecule, or could be a tetraquark candidate. The X(3872) is not only produced through B-meson decays, but also through a direct prompt production at hadron colliders [3, 4, 5, 6]. Prompt and non-prompt productions can be distinguished according to the displacement of the X(3872) decay vertex. The prompt productions can be described in the framework of non-relativistic quantum chromodynamics (NRQCD) in pp collisions, and differential production cross section of the X(3872) has been calculated [7]. It is a good test of the NRQCD if the prompt X(3872) production cross section as a function of transverse momentum is measured at the Large Hadron Collider (LHC).

In addition to the X(3872) studies, one can also look for a similar resonance in the bottomonium system [8, 9, 10, 11, 12]. The discovery of exotic bottomonium mesons would provide some more information for the underlying mechanism of those discovered new states. The bottomonium counterpart of X(3872), denoted by $\mathrm{X_b}$, is expected to decay through $\mathrm{X_b} \to \Upsilon(1S)\pi^+\pi^-$. Based on the known properties of X(3872), the $\mathrm{X_b}$ meson could be a narrow resonance, and with a sizable production rate in the $\Upsilon(1S)\pi^+\pi^-$ final state, as an analogy to the discovery channel of $\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-$. However the exact mass of $\mathrm{X_b}$ is unknown. The strategy to search for a peak in the invariant mass spectrum of $\Upsilon(1S)(\to \mu^+\mu^-)\pi^+\pi^-$, other than the known $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances. Since there is no evidence found, we report the limits on the ratio of the production cross section times branching ratio of $\mathrm{X_b}$ to $\Upsilon(2S)$.

2. Measurement of X(3872) Productions

A measurement of the differential production cross section of $\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-$ is presented [6]. The study is based on the data recorded by the Compact Muon Solenoid (CMS) experiment [13] in pp collisions at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 4.8 fb^{-1}. The analysis is performed in the kinematic range of $10 < p_\mathrm{T} < 50$ GeV and the rapidity $|y| < 1.2$ of the X(3872) candidates. The measurement is carried out by determining the ratio of the X(3872) and $\psi(2S)$ cross sections times their branching fractions to the final state $\mathrm{J}/\psi\pi^+\pi^-$. In this ratio many common systematic uncertainties are cancelled. In addition to the ratio of cross sections times branching fractions, the fraction of non-prompt X(3872) events is measured. The differential cross section as a function of transverse momentum for the prompt X(3872) production is measured for the first time.

Events are selected requiring a pair of oppositely charged muons, corresponding to a J/ψ candidate. The rapidity of the muon pair is required to be within the central detector region of $|y(\mu^+\mu^-)| < 1.25$. There are two different transverse momentum thresholds: $p_\mathrm{T}(\mu^+\mu^-) > 7$ GeV for the first part of the data and $p_\mathrm{T}(\mu^+\mu^-) > 10$ GeV for the second part of data. The integrated luminosities are 2.1 fb^{-1} and 2.7 fb^{-1}, respectively. Each candidate muon must have a minimum p_T of 4 GeV in the interval of $|\eta| < 1.2$, or a minimum p_T of 3.3 GeV in the forward region

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$(1.2 < |\eta| < 2.4)$, where η denotes the pseudorapidity. The muon track must have at least two hits in the silicon pixel layers, and 11 tracker hits in total. The track is required to have a maximum χ^2 per degree of freedom of 1.8. A vertex fit is performed to determine the dimuon vertex. The χ^2-probability of the fit is required to be larger than 1%. The dimuon invariant mass is required to be within ± 75 MeV window from the fitted J/ψ mass.

The X(3872) candidate is reconstructed by combining the J/ψ candidate and pairs of oppositely charged pions. The pion tracks must have a maximum χ^2 per degree of freedom of 5, at least two (seven) silicon pixel (strip) hits, and a minimum p_T of 0.6 GeV. A kinematic constrained fit is applied and the resulting χ^2-probability is required to be larger than 5%. The pions are also required to have a maximum distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ of 0.55 between the pion and the J/ψ candidate. The Q-value of the decay is required to be smaller than 300MeV. The X(3872) candidate is required to be in the region $|y| < 1.2$ and in $10 < p_T < 50$ GeV ($13.5 < p_T < 50$ GeV) for the first (second) period of data.

2.1 Measurement of the cross section ratio

The ratio of the cross section times the branching fraction in the $J/\psi\pi^+\pi^-$ final state is obtained from the signal yields for X(3872) and $\psi(2S)$, denoted by $N_{X(3872)}$ and $N_{\psi(2S)}$ as following

$$R = \frac{\sigma(pp \to X(3872)) \times \mathscr{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S)) \times \mathscr{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} \times \frac{A_{\psi(2S)}}{A_{X(3872)}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{X(3872)}}, \quad (2.1)$$

after correcting with the efficiencies (ε) and acceptance (A) which are estimated with simulated events. The acceptance correct the kinematic coverage of the dimuon trigger and the acceptance of the CMS detector. The results are shown in Fig. 1. The measured R shows no significant dependence on p_T. The integrated value of R in the kinematic range is measured to be $0.0656 \pm 0.0029 \pm 0.0065$. The systematic uncertainties are discussed in Ref. [13].

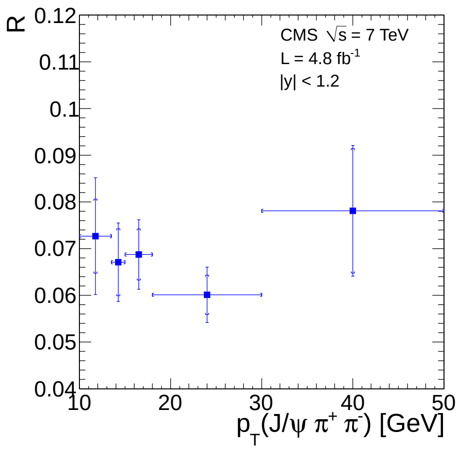

Figure 1: Ratios of the X(3872) and $\psi(2S)$ cross sections times their branching fractions as a function of p_T. The inner error bars are the statistical uncertainties and the outer error bars are the total uncertainties.

2.2 Measurement of the non-prompt fraction and prompt production cross section

The contribution from the decays of B hadrons (the non-prompt fraction) is determined from the decay lifetime distribution. The proper decay length ℓ_{xy} is defined in the transverse plane as the distance between the X(3872) vertex and the closest reconstructed primary vertex, and corrected by the Lorentz boost of the X(3872) candidate. A B-decay enriched sample is selected by requiring $\ell_{xy} > 100\ \mu$m, which keeps about 80% of the non-prompt candidates and the prompt contribution is smaller than 0.1%. The non-prompt fraction is determined from the ratio between the X(3872) yields in the B-enriched sample and the yields in the inclusive sample. The corrections for the efficiencies are applied. The X(3872) yields are extracted from the fits to the reconstructed invariant mass spectrum. The result is given in Fig. 2.

The prompt X(3872) production is determined from the measured cross section ratio, the non-prompt fraction, and the prompt $\psi(2S)$ cross section [14]. The formula for the prompt production cross section is given by

$$\sigma^{\text{prompt}}_{\text{X}(3872)} \times \mathscr{B}(\text{X}(3872) \to \text{J}/\psi\pi^+\pi^-) = \frac{1 - f^{\text{B}}_{\text{X}(3872)}}{1 - f^{\text{B}}_{\psi(2S)}} \cdot R \cdot \left[\sigma^{\text{prompt}}_{\psi(2S)} \times \mathscr{B}(\psi(2S) \to \mu^+\mu^-)\right] \cdot \frac{\mathscr{B}(\psi(2S) \to \text{J}/\psi\pi^+\pi^-)}{\mathscr{B}(\psi(2S) \to \mu^+\mu^-)} . \quad (2.2)$$

The results are also shown in Fig. 2, with a comparison to the predicted differential cross section for prompt X(3872) production using the NRQCD factorization formalism [7]. The shape of the differential cross section is reasonably described, but the predicted rate is much larger than the observed data.

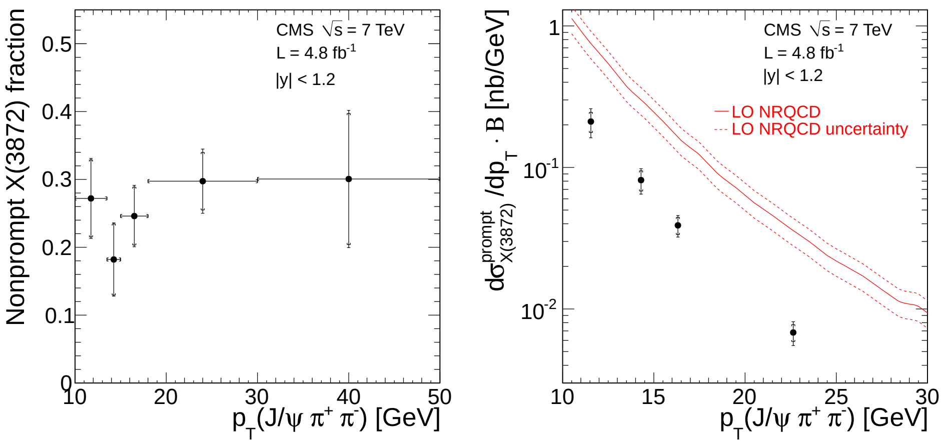

Figure 2: The measured non-prompt fraction for X(3872) (left) as a function of the transverse momentum and the measured differential cross section for prompt X(3872) production times branching fraction (right). The inner error bars are the statistical uncertainties and the outer error bars are the total uncertainties. Predictions from a NRQCD model [7] are shown by the solid line, with the dotted lines representing the uncertainty.

3. Search for a new bottomonium state decaying to $\Upsilon(1S)\pi^+\pi^-$

We present the search for a bottomonium counterpart of the exotic charmonium state X(3872), denoted as X_b, based on a data sample collected by the CMS experiment in pp collisions at $\sqrt{s} =$

8 TeV. The analysis is focused on an exclusive decay channel, $X_b \to \Upsilon(1S)\pi^+\pi^-$, followed by the $\Upsilon(1S) \to \mu^+\mu^-$ decay. A data set corresponding to an integrated luminosity of 20.7 fb^{-1} is used. The analysis is performed in the kinematic range of $p_T[\Upsilon(1S)\pi^+\pi^-] > 13.5$ GeV and $|y[\Upsilon(1S)\pi^+\pi^-]| < 2.0$.

The reconstruction of the X_b events starts with the reconstruction of an $\Upsilon(1S) \to \mu^+\mu^-$ candidate and two charged pion candidates. Each muon is required to associate at least six hits in the tracker layers and two in the pixel detector, and a minimum p_T of 2.5 GeV. The χ^2 per degree of freedom of the muon track fit should be smaller than 1.8. The transverse momentum of $\Upsilon(1S) \to \mu^+\mu^-$ candidate must be above 13.5 GeV, and the χ^2-probability of the vertex fit is required to be larger than 1%. The $\Upsilon(1S)$ invariant-mass window is defined as the region within $\pm 2.5\sigma_M$ of the nominal $\Upsilon(1S)$ mass, where σ_M is the dimuon mass resolution.

A $\Upsilon(1S)\pi^+\pi^-$ candidate is reconstructed by combining the $\Upsilon(1S)$ candidate with other two oppositely charged pions. The pions have a minimum p_T of 0.4 GeV, with a maximum track-fit χ^2 of 5 per degree of freedom, and at least 11 strip tracker hits and 2 silicon pixel hits. The χ^2-probability of dipion vertex fit is required to be >10%. The pions are also required to have a maximum distance ΔR of 0.7 between the pion and the $\Upsilon(1S)$. The χ^2-probability from the $\Upsilon(1S)\pi^+\pi^-$ vertex-mass constrained fit is required to be greater than 10%. Figure 3 shows the reconstructed invariant mass distributions in the barrel ($|y| < 1.2$) and endcap ($1.2 < |y| < 2.0$) channels. Peaks corresponding to $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ decays are observed. The number of $\Upsilon(2S)$ events is evaluated to be 7100 ± 150 (3840 ± 160) for the barrel (endcap) channel from a fit to the invariant mass distributions.

The mass spectrum does not show any other unrecorded resonances; in order to provide an assessment statistically the p-values are evaluated with an asymptotic approach [15]. Given no strong hint of signal found in data, the limit on R, the ratio of the production cross sections times branching fractions of X_b and of $\Upsilon(2S)$, is estimated. Signal-injected local expected p-values, which provide an estimate of expected discovery potential, are evaluated as well. The observed p-values are shown Fig. 4, together with the expected significance for $R = 0.0656$, which is motivated by the measurement of the X(3872). The expected and observed limits as a function of X_b mass are also shown in Fig. 4. The observed upper limits on R are in the range of 0.9–5.4% at 95% confidence level, depending on the assumed X_b mass. These are the first upper limits on the production of a possible X_b at a hadron collider.

References

[1] S. K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **91**, 262001 (2003) [arXiv:hep-ex/0309032].

[2] N. Brambilla, S. Eidelman, B. K. Heltsley, R. Vogt, G. T. Bodwin, E. Eichten, A. D. Frawley and A. B. Meyer *et al.*, Eur. Phys. J. C **71**, 1534 (2011) [arXiv:1010.5827 [hep-ph]].

[3] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. Lett. **93**, 072001 (2004) [arXiv:hep-ex/0312021].

[4] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **93**, 162002 (2004) [arXiv:hep-ex/0405004].

[5] R. Aaij *et al.* [LHCb Collaboration], Eur. Phys. J. C **72**, 1972 (2012) [arXiv:1112.5310 [hep-ex]].

[6] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1304**, 154 (2013) [arXiv:1302.3968 [hep-ex]].

[7] P. Artoisenet and E. Braaten, Phys. Rev. D **81**, 114018 (2010) [arXiv:0911.2016 [hep-ph]].

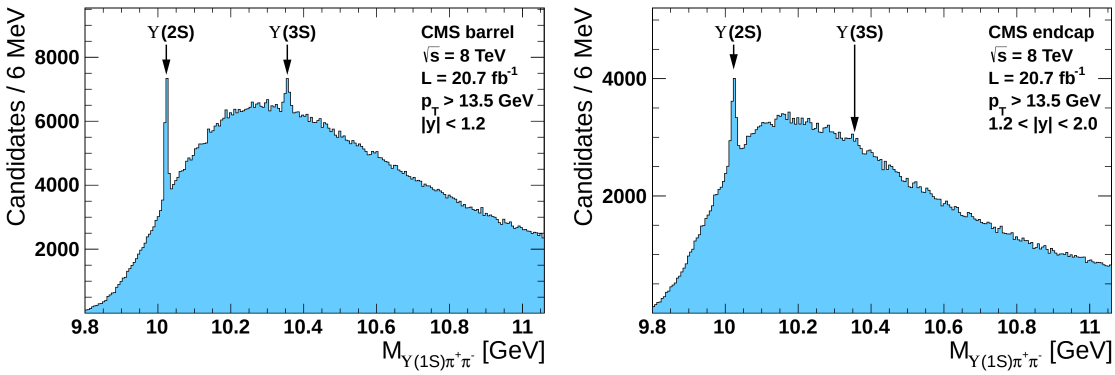

Figure 3: The reconstructed invariant mass distributions of the $\Upsilon(1S)(\rightarrow \mu^+\mu^-)\pi^+\pi^-$ candidates in the barrel (left) and endcap (right) channels.

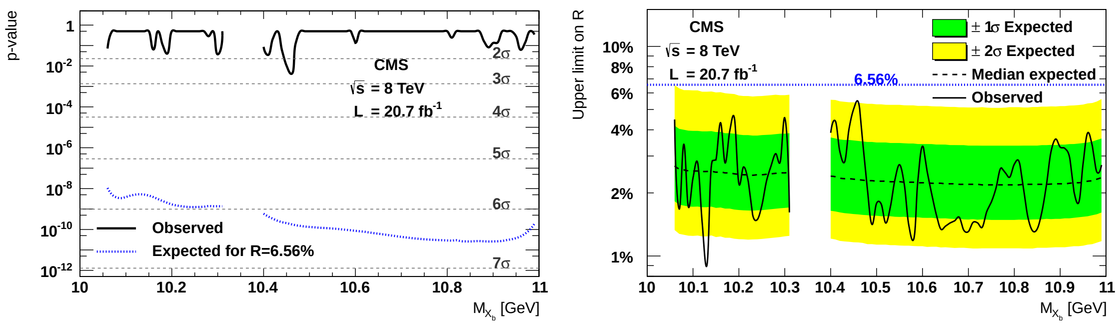

Figure 4: The p-values as a function of X_b mass (left) and the exclusion limits on R (right) as a function of X_b mass at 95% confidence level. The solid curve in the left figure shows the observed local p-values, and the dashed curve shows the expected p-values if the R is equal to 6.56%. The solid curve in the right figure shows the observed limits, while the dashed curve represents the limits expected for a pure background hypothesis.

[8] W. -S. Hou, Phys. Rev. D **74**, 017504 (2006) [arXiv:hep-ph/0606016].

[9] M. T. AlFiky, F. Gabbiani and A. A. Petrov, Phys. Lett. B **640**, 238 (2006) [arXiv:hep-ph/0506141].

[10] D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Lett. B **634**, 214 (2006) [arXiv:hep-ph/0512230].

[11] D. Ebert, R. N. Faustov and V. O. Galkin, Mod. Phys. Lett. A **24**, 567 (2009) [arXiv:0812.3477 [hep-ph]].

[12] R. D'E. Matheus, S. Narison, M. Nielsen and J. M. Richard, Phys. Rev. D **75**, 014005 (2007) [arXiv:hep-ph/0608297].

[13] S. Chatrchyan *et al.* [CMS Collaboration], JINST **3**, S08004 (2008).

[14] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1202**, 011 (2012) [arXiv:1111.1557 [hep-ex]].

[15] G. Cowan, K. Cranmer, E. Gross and O. Vitells, Eur. Phys. J. C **71**, 1554 (2011) [arXiv:1007.1727 [physics.data-an]].

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