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Search for a new bottomonium state decaying to $\Upsilon(1S)\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 8$ TeV ☆

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ABSTRACT

The results of a search for the bottomonium counterpart, denoted as X_b, of the exotic charmonium state X(3872) is presented. The analysis is based on a sample of pp collisions at $\sqrt{s} = 8$ TeV collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 20.7 fb^{-1}. The search looks for the exclusive decay channel $X_b \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to \mu^+\mu^-$. No evidence for an X_b signal is observed. Upper limits are set at the 95% confidence level on the ratio of the inclusive production cross sections times the branching fractions to $\Upsilon(1S)\pi^+\pi^-$ of the X_b and the $\Upsilon(2S)$. The upper limits on the ratio are in the range 0.9–5.4% for X_b masses between 10 and 11 GeV. These are the first upper limits on the production of a possible X_b at a hadron collider.

1. Introduction

In the past decade, several unexpected charmonium states, such as the X(3872) and the Y(4260), have been discovered [1,2] and then confirmed [3,4] by the Belle and BaBar experiments. The X(3872) state has also been seen by hadron collider experiments [5–8]. These exotic states are not predicted in well-established theoretical models, and progress in this area has been mostly driven by experiments. Interpretations as tetraquark states or hadronic molecules have been proposed [9–12]. It is therefore natural to look for similar states in the bottomonium system [9–14]. Finding such exotic bottomonium states may provide a more complete picture of exotic quarkonia and help to clarify their production mechanisms and intrinsic properties.

The exotic resonance X(3872) was discovered in the final state $J/\psi\pi^+\pi^-$. The CDF [5] and CMS [8] experiments have shown that the X(3872) is produced not only through B-meson decays, but also through prompt production. At the Large Hadron Collider (LHC), CMS has measured the prompt production of the X(3872) to be about 80% of the total production [8]. A bottomonium counterpart of the X(3872), denoted as X_b, would be expected to decay through $X_b \to \Upsilon(1S)\pi^+\pi^-$. Several known properties of the X(3872) state provide clues in the search for the X_b. The X(3872) has a small natural width < 1.2 MeV [15] and its production rate times the $X(3872) \to J/\psi\pi^+\pi^-$ branching fraction is $(6.56 \pm 0.29 \pm 0.65)\%$ of the corresponding $\psi(2S) \to J/\psi\pi^+\pi^-$ value [8], roughly independent of transverse momentum (p_T). In analogy, the X_b state could also be a narrow resonance, with a sizable decay rate in the $\Upsilon(1S)\pi^+\pi^-$ final state. The mass of the X_b is predicted in some models [9,13] to be close to either the $B\bar{B}$ or $B\bar{B}^*$ thresholds, 10.562 and 10.604 GeV, respectively. Alternative models [10–12] suggest other possibilities in the 10–11 GeV range.

A search in the $\Upsilon(1S)\pi^+\pi^-$ final state has been performed by the Belle experiment in the mass region around the $\Upsilon(10860)$ resonance [16]; a statistically significant excess of events was found but its origin remains inconclusive [17]. The BaBar experiment found an $\Upsilon(1D)$ bottomonium resonance in the same final state at 10.165 GeV [18]. However, the production rates for these two states are expected to be very small at the LHC [19,20], and they are not expected to be seen in the present analysis.

This Letter presents the results of a search for the exotic bottomonium state X_b through its decay $X_b \to \Upsilon(1S)\pi^+\pi^-$, using a data sample of pp collisions at $\sqrt{s} = 8$ TeV collected by the CMS experiment at the LHC and corresponding to an integrated luminosity of 20.7 fb^{-1}.

The strategy of this analysis is to search for a peak, other than the known $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances, in the $\Upsilon(1S)(\mu^+\mu^-)\pi^+\pi^-$ invariant-mass spectrum. The results are presented in terms of the relative inclusive production cross sections of the X_b and $\Upsilon(2S)$ states times their decay branching fractions to $\Upsilon(1S)\pi^+\pi^-$, $\sigma(\mathrm{pp} \to X_b \to \Upsilon(1S)\pi^+\pi^-)/\sigma(\mathrm{pp} \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)$, as a function of the X_b mass between 10 and 11 GeV. Many systematic uncertainties cancel in this ratio. The analysis probes the kinematic region $p_T(\Upsilon(1S)\pi^+\pi^-) > 13.5$ GeV and $|y(\Upsilon(1S)\pi^+\pi^-)| < 2.0$, where y denotes the rapidity.

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2. CMS detector and trigger

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the magnet volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. The inner tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the counterclockwise proton beam direction. Muons are measured with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a p_T resolution better than 1.5% for a typical muon in this analysis. Extensive forward calorimetry complements the angular coverage provided by the barrel and endcap detectors. A more detailed description of the CMS detector can be found in Ref. [21].

A two-level trigger system [22] selects events for further analysis. The events analyzed in this search are collected with a trigger requiring at least two oppositely charged muon candidates. The invariant mass of the muon pair is required to be in the range between 8.5 and 11.5 GeV. The transverse momentum of the muon pair must be above 6.9 GeV, and the dimuon vertex fit χ^2 probability must be greater than 0.5%.

3. Reconstruction and event selection

The reconstruction of the X_b and $\Upsilon(2S)$ candidates begins with the reconstruction of an $\Upsilon(1S) \to \mu^+\mu^-$ candidate and two additional charged tracks in the event, assuming the pion mass hypothesis for the latter. The $\Upsilon(1S)$ candidate is reconstructed as a pair of oppositely charged muons. Each muon is required to leave hits in at least six tracker layers, at least two of which must be in the silicon pixel detector, and to be matched with at least one segment in the muon system. Muons are required to have $p_T > 2.5$ GeV, $|\eta| < 2.1$, and good track-fit quality. The muon tracks are required to intersect the beam line within a cylinder of 3 cm in radius and 30 cm in length around the primary vertex position, which is selected as the vertex with the largest sum of p_T^2 of the tracks associated with it. The rapidity of the muon pair is required to be within $|y(\mu^+\mu^-)| < 2.0$. Each $\Upsilon(1S)$ candidate must have $p_T > 13.5$ GeV and the χ^2 probability from the dimuon vertex fit is required to be larger than 1%; these requirements are more stringent than those used by the trigger. The $\Upsilon(1S)$ invariant-mass window is defined as the region within $\pm 2.5\sigma_M$ of the $\Upsilon(1S)$ mass [15], where the dimuon mass resolution, σ_M, is measured to increase from 65 to 125 MeV as $|y(\mu^+\mu^-)|$ changes from 0 to 2.

The $\Upsilon(1S)\pi^+\pi^-$ candidate is reconstructed by combining two oppositely charged tracks with the $\Upsilon(1S)$ candidate. The pions must each have a minimum p_T of 400 MeV, be in the region $|\eta| < 2.5$, have a track fit $\chi^2/\text{ndf} < 5$, and at least 11 strip tracker hits and two silicon pixel hits. In order to reduce the combinatorial background from additional tracks in the event, the χ^2 probability of the dipion vertex fit is required to be larger than 10% and the pions are required to be within a radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.7$ with respect to the $\Upsilon(1S)$ direction, where $\Delta\eta$ ($\Delta\phi$) is the difference in pseudorapidity (azimuthal angle in radians) between the pion direction and the $\Upsilon(1S)$ momentum. A common-vertex constrained fit is applied to the tracks forming the $\Upsilon(1S)(\mu^+\mu^-)\pi^+\pi^-$ candidate, together with the constraint that the dimuon invariant mass be equal to the world-average $\Upsilon(1S)$ mass [15]. The χ^2 probability from the vertex-mass constrained fit is required to be greater than 10%. There are on average 2.3 reconstructed candidates per event for the events with at least one candidate; all of the reconstructed candidates are included in the analysis. From simulations the combinatorial background candidates are found to be randomly distributed in mass and do not introduce any bias in the extraction of the signal. The selection criteria described above were optimized using a genetic algorithm [23] that maximized the expected significance of the signal in the mass region near the $\Upsilon(2S)$. The statistical significance of the signal is expected to be more than five standard deviations if the X_b branching fraction times production cross section relative to the $\Upsilon(2S)$ is 6.56% (or higher), analogous to that of the X(3872) relative to the $\psi(2S)$.

The simulated samples of the $\Upsilon(2S)$ and X_b events are generated with the PYTHIA 6.426 [24] event generator, and the particle decays are modeled using the EVTGEN package [25], assuming that the $\Upsilon(2S)$ and X_b states have the same production mechanism and are both produced unpolarized. The unpolarized assumption for the $\Upsilon(2S)$ is supported by a recent CMS measurement [26]. In the event generation, the X_b state is assumed to be a narrow resonance with the same quantum numbers as the $\Upsilon(2S)$. Generated events are processed through a full detector simulation based on GEANT4 [27]. The simulated $\Upsilon(2S)$ events are reweighted according to the dipion invariant-mass spectrum in $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ decays measured by the CLEO experiment [28]. The kinematic distributions in the simulated $\Upsilon(2S)$ sample are compared with the corresponding distributions in the data and found to be in good agreement. The X_b events are assumed to have the same dipion mass distribution as the $\Upsilon(2S)$ events, which is very similar to the dipion mass distribution of the X(3872) [8]. Other possible X_b decay models are considered as systematic uncertainties, as described in Section 4.1.

Significant mass resolution and background level differences are observed for the $\Upsilon(1S)\pi^+\pi^-$ candidates in the barrel ($|y| < 1.2$) and endcap ($1.2 < |y| < 2.0$) regions. Therefore, the events are separated into these two classes. Fig. 1 shows the reconstructed invariant-mass distributions of the $\Upsilon(1S)\pi^+\pi^-$ candidates in the barrel and endcap regions. Apart from the peaks corresponding to the $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ decays, the mass spectrum does not show any other outstanding structure. Unbinned maximum-likelihood fits are performed on the invariant-mass distributions using single Gaussian functions to describe the $\Upsilon(2S)$ and $\Upsilon(3S)$ states, and third-degree polynomials to describe the combinatorial background, whose parameters were left free in the fit. The means and widths of the Gaussian functions are allowed to float in the fit. The resulting fit values of the widths are consistent with the mass resolutions obtained from the simulated events. The centers of the Gaussian functions are consistent with the world-average values [15] for the two Υ masses. The resulting numbers of $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ events are 7100 ± 150 and 3840 ± 160 for the barrel and endcap regions, where the uncertainties are statistical. The invariant-mass distributions around the $\Upsilon(2S)$ resonance are shown in Fig. 2 for the barrel and endcap regions, with the results of the fits superimposed.

4. Results

The search for the X_b is performed in the mass regions 10.06–10.31 and 10.40–10.99 GeV, excluding the mass intervals around the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances. Fits are performed to the data by shifting the mean mass of the hypothetical X_b signal in 10 MeV intervals and letting the signal strength float. The invariant-mass distribution of the reconstructed $\Upsilon(1S)\pi^+\pi^-$ is modeled with a Gaussian function. The intrinsic width of the X_b is assumed to be small compared to the detector mass resolution. In the fits, the width of the Gaussian is fixed to the values obtained from simulation. Depending on the X_b mass, the signal width is estimated to be in the range 3.8–10.6 MeV (6.8–16.4 MeV) for

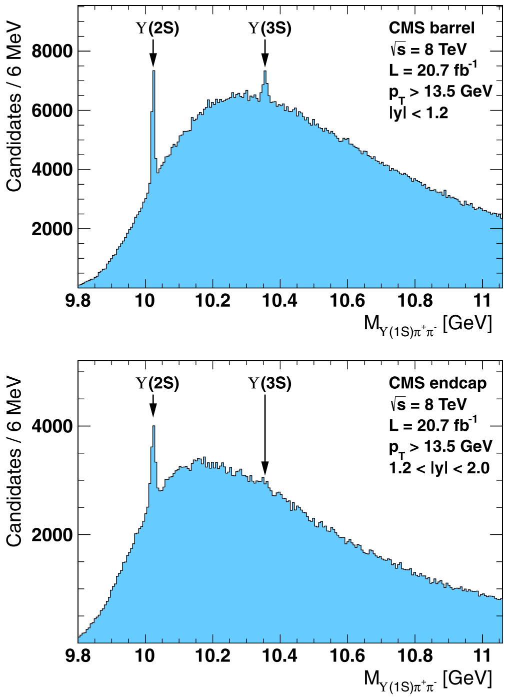

Fig. 1. The reconstructed invariant-mass distributions of the candidates in the barrel (top) and endcap (bottom) regions. Peaks corresponding to $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ decays are indicated with the arrows.

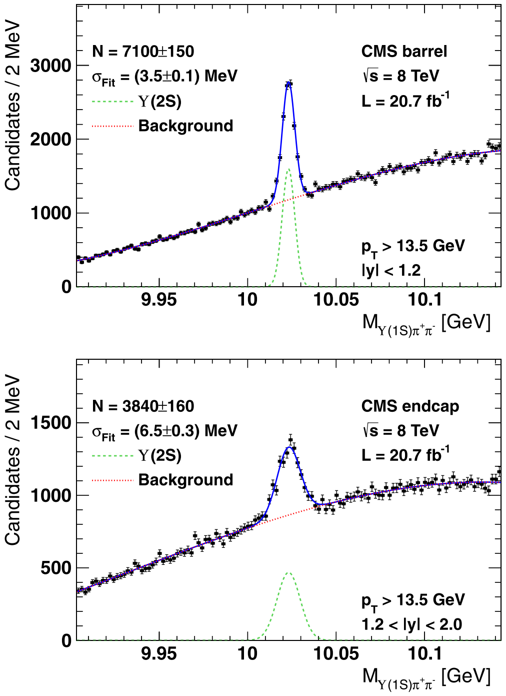

Fig. 2. The invariant-mass distributions of the candidates around the $\Upsilon(2S)$ resonance for the barrel (top) and endcap (bottom) regions. The result from the fit is shown as a solid curve; the $\Upsilon(2S)$ and background contributions from the fit are shown separately as the dashed and dotted curves, respectively.

the barrel (endcap) region. The background distribution is modeled separately for the low-mass (10.06–10.31 GeV) and high-mass (10.40–10.99 GeV) regions with a third-degree polynomial, whose coefficients are allowed to vary in the fit. The signal yields and the coefficients of the polynomials are determined from unbinned maximum-likelihood fits to the invariant-mass distributions for the barrel and endcap regions.

For a given X_b mass point, the relationship between the X_b and $\Upsilon(2S)$ yields is given by

$$N^{\rm obs}_{X_b} = R \times N^{\rm obs}_{\Upsilon(2S)} \times \frac{\epsilon_{X_b}}{\epsilon_{\Upsilon(2S)}}, \tag{1}$$

where $N^{\rm obs}_{X_b}$ and $N^{\rm obs}_{\Upsilon(2S)}$ are the observed X_b and $\Upsilon(2S)$ yields, respectively, and $\epsilon_{X_b}/\epsilon_{\Upsilon(2S)}$ is the ratio of overall efficiencies for X_b and $\Upsilon(2S)$ events. This ratio uses the acceptance and the trigger and reconstruction efficiencies estimated from simulated samples. In the barrel region, the ratio of efficiencies increases from about 1 to 2 for a hypothetical X_b mass in the range 10.06–10.31 GeV, mainly because of the increased acceptance for higher masses, and remains around 2 in the range 10.40–10.99 GeV. In the endcap region, the ratio of efficiencies stays around 1 for all the X_b mass values considered.

In tests of statistical significance, the p-value is the probability of obtaining a signal strength as large as (or larger than) the one that was actually observed, assuming that there is no signal. A signal-like distribution will result in a low observed p-value. In this analysis, the p-value is evaluated from simultaneous signal-plus-background fits to the observed invariant-mass distributions in the barrel and endcap regions. Significances of the X_b signal are evaluated for each hypothetical X_b mass. Given no strong hint of a signal in the present data, an upper limit on R, the ratio of the production cross sections times branching fractions of the X_b and $\Upsilon(2S)$, is calculated.

4.1. Systematic uncertainties

Several sources of systematic uncertainties are considered. The major sources are from the modeling of the signal decay, which includes the dipion invariant-mass distribution and the X_b mass resolution, the signal polarization, and the background shape.

The dipion distributions in the simulated $\Upsilon(2S)$ and X_b samples are reweighted according to the $\Upsilon(2S)$ data from CLEO [28], but the actual distribution of the X_b is unknown. This affects the value of the efficiency ratio $\epsilon_{X_b}/\epsilon_{\Upsilon(2S)}$ in Eq. (1). Several alternative models have been implemented, including a $\Upsilon(1S)\rho$ model, a model using the dipion invariant-mass distribution measured in X(3872) decay [8], and a three-body *S*-wave model. Since the actual quantum numbers for the X_b state are not known, the dipion invariant-mass distribution in the $X_b \to \Upsilon(1S)\rho$ decay we use (which is similar to the $X(3872) \to J/\psi\rho$ decay) in the systematic studies. The $X_b \to \Upsilon(1S)\rho$ process is modeled with a uniform two-body phase-space decay. The dipion mass distribution from X(3872) decay is scaled according to the mass difference between the X_b and the $\Upsilon(1S)$. A comparison between the alternative models and the default model using the $\Upsilon(2S)$ distribution leads to differences in the $\epsilon_{X_b}/\epsilon_{\Upsilon(2S)}$ efficiency ratio of up to 20% depending on the X_b mass, which is included as a systematic uncertainty. The reconstruction efficiency as a function of X_b mass is modeled with a simple analytical function. The systematic uncertainty in this modeling is estimated by comparing two different functions and is found to be negligible.

The $\Upsilon(2S)$ mass resolutions determined in data and simulation are consistent with each other. The statistical uncertainty in the $\Upsilon(2S)$ mass resolution from data of 2.9% (4.6%) in the barrel (endcap) region is larger than the difference between the measured and simulated values. The statistical uncertainty is taken as the systematic uncertainty from this source. While a single Gaussian function is used in the default modeling of the signal, a sum of two Gaussians is used as an alternative model, and the differences between the respective fits are taken as systematic uncertainties.

A recent CMS measurement [26] shows that $\Upsilon(2S)$ mesons are produced with negligible polarization. The daughter $\Upsilon(1S)$ mesons are expected to have a similar polarization [29]. However, the expected polarization of the $\mathrm{X_b}$ is unknown. Signal efficiencies evaluated using a simulated sample generated with unpolarized $\mathrm{X_b}$ are compared with efficiencies for the extreme cases of full transverse and full longitudinal polarizations in the helicity frame, assuming that the polarization of the daughter $\Upsilon(1S)$ is the same as that of the mother $\mathrm{X_b}$. The largest efficiency difference of 25% is taken as the systematic uncertainty from this source.

The fit model is composed of a background component, with floating coefficients, and a signal model, with the signal strength as a free parameter. The uncertainties in the coefficients from the fits are included as a systematic uncertainty in the statistical analysis. Furthermore, an alternative background parameterization, determined from a background-only fit to the candidates reconstructed with same-sign pions ($\Upsilon(1S)\pi^+\pi^+$ and $\Upsilon(1S)\pi^-\pi^-$) is also considered. The difference between the default and alternative background parameterizations is included as one of the systematic uncertainties.

Other systematic uncertainties, such as the uncertainty caused by the dependence of the efficiencies on the number of pp interactions per event (with an average of ≈21 interactions), have been considered and found to be negligible. Systematic uncertainties in the acceptance and trigger efficiency largely cancel out in the ratio R. As a check, the $\Upsilon(2S)$ yields, normalized to the integrated luminosity, are found to be stable for the different data-taking periods.

4.2. Determination of p-values and upper limits

The local p-values are calculated using an asymptotic approach [30] with the signal and background models described above and combining the results of the fits to the barrel and endcap regions. The systematic uncertainties mentioned above are implemented as nuisance parameters in the fit, assuming log-normal or flat priors. The expected discovery potential is estimated by injecting various amounts of signal events into the fits and evaluating the resulting p-values. The expected signal significance for the assumption $R = 6.56\%$, motivated by the ratio of production cross sections times branching fractions for X(3872) and $\psi(2S)$ reported in Ref. [8], is larger than five standard deviations (σ) across the explored $\mathrm{X_b}$ mass range, as shown by the dashed curve in Fig. 3. The observed p-values displayed in Fig. 3 by the solid line show no indication of an $\mathrm{X_b}$ signal. The smallest local p-value is 0.004 at 10.46 GeV, corresponding to a statistical significance of 2.6σ, which is reduced to 0.8σ when taking into account the "look-elsewhere effect" [31]. The expected and observed 95% confidence level upper limits on R, derived using a modified frequentist approach (CL_S) [32,33], are shown in Fig. 4 as a function of the $\mathrm{X_b}$ mass. The observed upper limits on R are in the range 0.9–5.4% at 95% confidence level. The expected upper limits, which are derived for a pure background hypothesis, are less stringent than those obtained from the p-value calculations. This is because the p-value calculations are only concerned with the probability of the background fluctuating to a signal-like peak in the invariant-mass distribution, while the upper limits on R also include the systematic uncertainties in the signal normalization from the signal decay model and $\mathrm{X_b}$ polarization assumptions.

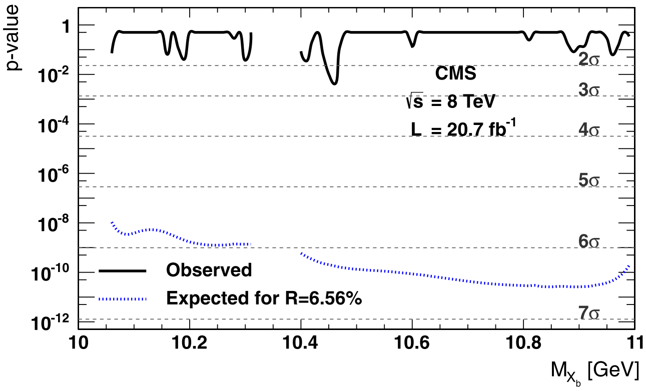

Fig. 3. Observed (solid curve) and expected for $R = 6.56\%$ (dotted curve) local p-values, as a function of the assumed $\mathrm{X_b}$ mass.

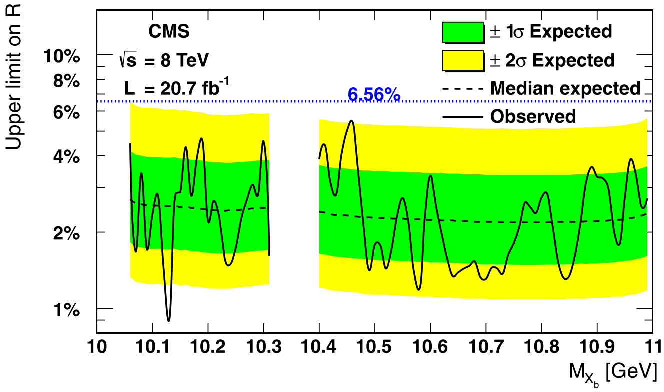

Fig. 4. Upper limits at the 95% confidence level on R, the production cross section for the $\mathrm{X_b}$ times its branching fraction to $\Upsilon(1S)\pi^+\pi^-$, relative to the $\Upsilon(2S)$, as a function of the $\mathrm{X_b}$ mass. The solid curve shows the observed limits, while the dashed curve represents the expected limits in the absence of a signal, with the two shaded regions giving the ±1 and ±2 standard deviation uncertainties on the expected limits. The measured value for the analogous X(3872) to $\psi(2S)$ ratio of 6.56% is shown by the dotted line.

5. Summary

A search for an exotic bottomonium state in the decay channel $\mathrm{X_b} \to \Upsilon(1S)\pi^+\pi^-$, followed by $\Upsilon(1S) \to \mu^+\mu^-$, in pp collisions at $\sqrt{s} = 8$ TeV at the LHC has been presented. This analysis was performed using data collected by the CMS experiment, corresponding to an integrated luminosity of 20.7 fb^{-1}. Candidates were reconstructed from two identified muons and two additional charged tracks assumed to be pions. The search was conducted in the kinematic region $p_T(\Upsilon(1S)\pi^+\pi^-) > 13.5$ GeV and $|y(\Upsilon(1S)\pi^+\pi^-)| < 2.0$. The $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ process was used as a normalization channel, canceling many of the systematic uncertainties. Excluding the known $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances, no significant excess above the background was observed for $\mathrm{X_b}$ masses between 10 and 11 GeV. The expected sensitivity of the analysis was greater than five standard deviations for the explored $\mathrm{X_b}$ mass range, if the relative signal strength is comparable to the corresponding value for the X(3872) of 6.56%. The resulting 95% confidence level upper limit on the ratio $\sigma(\mathrm{pp} \to \mathrm{X_b} \to \Upsilon(1S)\pi^+\pi^-)/\sigma(\mathrm{pp} \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)$ is in the range 0.9–5.4%, depending on the assumed $\mathrm{X_b}$ mass. These are the first upper limits on the production of a possible $\mathrm{X_b}$ at a hadron collider.

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