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Measurement of the production cross section ratio $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$ in pp collisions at $\sqrt{s} = 8$ TeV

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ABSTRACT

A measurement of the production cross section ratio $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$ is presented. The $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ bottomonium states, promptly produced in pp collisions at $\sqrt{s} = 8$ TeV, are detected by the CMS experiment at the CERN LHC through their radiative decays $\chi_{b1,2}(1P) \to \Upsilon(1S) + \gamma$. The emitted photons are measured through their conversion to e^+e^- pairs, whose reconstruction allows the two states to be resolved. The $\Upsilon(1S)$ is measured through its decay to two muons. An event sample corresponding to an integrated luminosity of 20.7 fb^{-1} is used to measure the cross section ratio in a phase-space region defined by the photon pseudorapidity, $|\eta^{\gamma}| < 1.0$; the $\Upsilon(1S)$ rapidity, $|y^{\Upsilon}| < 1.5$; and the $\Upsilon(1S)$ transverse momentum, $7 < p_T^{\Upsilon} < 40$ GeV. The cross section ratio shows no significant dependence on the $\Upsilon(1S)$ transverse momentum, with a measured average value of $0.85 \pm 0.07\,(\text{stat} + \text{syst}) \pm 0.08\,(\text{BF})$, where the first uncertainty is the combination of the experimental statistical and systematic uncertainties and the second is from the uncertainty in the ratio of the χ_b branching fractions.

1. Introduction

Despite considerable efforts over the last decades, hadron formation, which is part of the nonperturbative sector of quantum chromodynamics (QCD), remains poorly understood within the standard model of particle physics. Heavy-quarkonium production is an excellent probe of hadron formation. In the past years, significant progress has been made in the theory sector [1], especially in the framework of nonrelativistic QCD (NRQCD) [2]. This framework factorizes into distinct processes the short-distance creation of a heavy quark–antiquark pair, in either a color-singlet or a color-octet configuration, and the long-distance formation of the quarkonium bound-state. The first process is presently calculated to next-to-leading order in perturbative QCD [3]. The bound-state formation is described by transition probabilities, called long-distance matrix elements (LDMEs), which are assumed to be constant (independent of quarkonium transverse momentum and rapidity) and universal (independent of the collision system and energy). In the Fock-state expansion of the heavy-quarkonium state, only a small number of color-singlet and color-octet terms contribute in the limit of small relative quark velocity v. The color-octet LDMEs are not easily calculable and the dominant ones are, therefore, treated as free parameters and adjusted to agree with the experimental data [4–6].

The ratio of P-wave quarkonia production cross sections is a reliable test of predictions because many theoretical, as well as experimental, uncertainties cancel out. Prompt χ_c measurements in hadron collisions were not possible until the advent of precise vertex detectors that allowed the separation of promptly produced χ_c from those coming from the decay of B mesons [7]. This ability is important, as NRQCD predictions are valid only for promptly produced χ_c. In the case of bottomonium, measurements are more difficult owing to the reduced production cross sections and the small separation in mass (19.4 MeV) between the $\chi_{b1}(1P)$ and the $\chi_{b2}(1P)$ (for readability the 1P is dropped hereafter). The production ratio of χ_{c2} and χ_{c1} is discussed in recent theoretical papers [3,8], but the debate on the importance of color-octet contributions remains open. In the bottomonium sector, the NRQCD velocity expansion is more rigorously valid given the smaller relative quark velocity. Therefore, the measurement of the χ_{b2} to χ_{b1} production cross section ratio should give further insight into the mechanism that governs quarkonium production [8]. At the LHC, the charmonium χ_{c2}/χ_{c1} production cross section ratio was measured by the LHCb [9], CMS [10], and ATLAS [11] experiments, using data collected in pp collisions at $\sqrt{s} = 7$ TeV. More recently, the LHCb

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experiment also reported a measurement of the χ_{b1} and χ_{b2} production cross section ratio using combined $\sqrt{s} = 7$ and 8 TeV data [12].

This Letter presents a measurement of the χ_{b2}/χ_{b1} production cross section ratio. The χ_{b1} and χ_{b2} states are reconstructed by detecting their radiative decays $\chi_{b1,2} \to \Upsilon(1S) + \gamma$, which is the dominant decay mode, with the $\Upsilon(1S)$ decaying into two muons. An accurate measurement of the photon energy (typically in the range 0.5–2 GeV) is obtained from the reconstruction of the momentum of the electron–positron pair originating from the photon conversion in the beam pipe or in the inner layers of the CMS silicon tracker. The resulting mass resolution of the χ_b candidates, around 5 MeV, is sufficient to resolve the two $\chi_{b1,2}$ peaks at the expense of a limited yield, given the small reconstruction efficiency for such low-energy photons. The cross section ratio is obtained as

$$\begin{aligned}\mathcal{R} &\equiv \frac{\sigma(\mathrm{pp} \to \chi_{b2} + X)}{\sigma(\mathrm{pp} \to \chi_{b1} + X)} \\ &= \frac{N_{\chi_{b2}}}{N_{\chi_{b1}}} \cdot \frac{\varepsilon_{\chi_{b1}}}{\varepsilon_{\chi_{b2}}} \cdot \frac{\mathcal{B}(\chi_{b1} \to \Upsilon(1S) + \gamma)}{\mathcal{B}(\chi_{b2} \to \Upsilon(1S) + \gamma)}, \end{aligned} \tag{1}$$

where $N_{\chi_{b1,2}}$ are the yields of $\chi_{b1,2}$ signal candidates, simultaneously obtained from an unbinned maximum likelihood fit of the $\mu\mu\gamma$ invariant-mass spectrum, $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$ is the ratio of the acceptance and efficiency corrections for the two processes obtained from a full detector simulation, and $\mathcal{B}(\chi_{b1,2} \to \Upsilon(1S) + \gamma)$ are the branching fractions of the corresponding radiative decays [13]. The results are presented in four bins of $\Upsilon(1S)$ transverse momentum, p_T^{Υ}, in the range 7–40 GeV. This choice was driven by the trigger requirements at low p_T, and the amount of available data at high p_T.

2. CMS detector and event samples

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 superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Muons are measured in the pseudorapidity range $|\eta^{\mu}| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events. The high-level trigger processor farm further decreases the event rate before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [14].

The analysis is based on the $\sqrt{s} = 8$ TeV pp data sample collected by CMS in 2012 at the CERN LHC, corresponding to an integrated luminosity of 20.7 fb^{-1}. The events have been selected at the trigger level by requiring opposite-sign muon pairs of invariant mass in the range 8.5–11.5 GeV, dimuon p_T larger than 6.9 GeV, a distance of closest approach of each muon track to the beam axis of less than 5 mm, and a χ^2 probability from the kinematic fit of the muons to a common vertex larger than 0.5%.

To parameterize the reconstructed $\chi_{b1,2}$ mass distributions and evaluate the reconstruction efficiency, a detailed Monte Carlo (MC) simulation based on GEANT4 [15] was performed. About 40 million events for each χ_b state were propagated through an accurate description of the CMS detector, including realistic trigger emulations and reconstruction algorithms identical to those used to process the collected data. Since the photon conversion probability multiplied by the reconstruction efficiency is less than 1% for photons of energy below 1 GeV, a large number of events is needed. To reduce CPU usage, the χ_b mesons were generated alone, without any "underlying event". This simplification should have no influence on the results of the analysis because any possible effect of accompanying particles on the track reconstruction efficiencies is identical for the two χ_b states, canceling in the ratio. Both χ_b samples were produced using the PYTHIA event generator [16], with the χ_b p_T distributions parameterized on the basis of the $\Upsilon(2S)p_T$ spectrum measured by CMS [17]. The χ_b mesons were generated in the rapidity range $|y| < 2.0$ and forced to decay into $\Upsilon(1S) + \gamma$, with the $\Upsilon(1S)$ mesons decaying to dimuons. Only simulated events where a photon conversion occurred were further processed and reconstructed.

3. Event reconstruction and selection

The CMS muon reconstruction procedure [18] identifies muons by requiring that tracks reconstructed in the silicon tracker be matched with at least one muon segment in any muon detector. To ensure an accurate p_T measurement and to suppress the contribution from decays-in-flight of pions and kaons, the number of silicon tracker layers with at least one hit must be larger than five, with two of them in the silicon pixel layers, and the track-fit χ^2 per degree of freedom must be smaller than 1.8. Loose selections are applied to the transverse and longitudinal muon impact parameters, $d_{xy} < 3$ cm and $|d_z| < 30$ cm, respectively, to further suppress decays in flight and cosmic ray muons. The selected muons must have a transverse momentum p_T^{μ} and pseudorapidity η^{μ} in the fiducial kinematic region $p_T^{\mu} > 3.5$ GeV and $|\eta^{\mu}| < 1.9$. Each event containing a pair of opposite-sign muons is kept in the analysis sample if the dimuon invariant mass $m_{\mu\mu}$ is between 8.5 and 11 GeV, its absolute rapidity is less than 1.5, and the χ^2 probability of the dimuon kinematic fit (with the two muon tracks constrained to a common vertex) is larger than 1%. To select $\Upsilon(1S)$ candidates, $m_{\mu\mu}$ is required to be within 3σ of the $\Upsilon(1S)$ mass, where the dimuon mass resolution σ is parameterized as a function of the $\Upsilon(1S)$ rapidity, and is obtained by fitting the dimuon mass distribution in narrow dimuon rapidity bins. This parameterization accounts for the significant rapidity dependence of the dimuon mass resolution, from around 65 MeV at $y = 0$ to around 120 MeV at $|y| = 1.5$.

The low-energy photons produced in the χ_b radiative decays that convert into electrons and positrons often produce tracks that are rather asymmetric, with one of the two tracks carrying a small fraction of the photon's energy. Given that these tracks rarely reach the calorimeter, they are reconstructed exclusively using information from the silicon tracker. An algorithm optimized for the reconstruction of low-p_T displaced tracks has been used, relying on an iterative tracking procedure [19].

The track pairs used to reconstruct the converted photons are required to fulfill the following selection criteria: the two tracks must be of opposite charge; one must have at least four hits in the silicon tracker layers and the other at least three hits; the innermost hits of the two tracks must be less than 5 cm apart along the beam direction; both tracks must have a reduced track-fit χ^2 smaller than 10; the two tracks should be almost parallel to each other, having angular separations $\Delta(\cot\theta) < 0.1$ and $\Delta\phi < 0.2$ rad, where θ and ϕ are the polar and azimuthal angles, respectively, defined at the common vertex; the primary pp vertex associated with the photon conversion is required to lie outside both track helices; defining d_m as the distance between the centers of the two circles formed by the tracks in the transverse plane minus the sum of their radii, the condition $-0.25 < d_m < 1$ cm must be satisfied; finally, the conversion vertex must be at least 1.5 cm away from the beam axis in the transverse plane, in order to suppress the background from π^0 Dalitz decays.

Table 1
Parameters extracted from the fits to the measured $\mu\mu\gamma$ invariant mass distributions, in the four $\Upsilon(1S)$ p_T bins considered. The quoted uncertainties are statistical only. The parameters are defined in the text.

p_T^{Υ} [GeV]	7–11	11–16	16–20	20–40
$N_{\chi_{b2}}/N_{\chi_{b1}}$	0.65 ± 0.12	0.51 ± 0.06	0.49 ± 0.08	0.54 ± 0.07
$N_{\chi_{b1}}$	392 ± 37	655 ± 39	343 ± 27	474 ± 31
N_{bkg}	5772 ± 86	3909 ± 72	1401 ± 43	1431 ± 44
λ	3.50 ± 0.23	2.08 ± 0.45	0.78 ± 0.72	0.79 ± 0.71
ν [GeV^{-1}]	6.01 ± 0.66	4.09 ± 1.17	1.59 ± 1.80	3.19 ± 1.85

The analysis is performed on events having a photon with pseudorapidity $|\eta^{\gamma}| < 1.0$, where the photon energy is measured with the best resolution, an important factor for a clean separation between the two χ_b peaks. When the $\Upsilon(1S)$, loosely selected as described in above, and converted photons are paired to form χ_b candidates, the distance along the beam axis between the dimuon vertex and the extrapolated photon trajectory is required to be less than 1 mm. The invariant mass of the χ_b candidate, $m_{\mu\mu\gamma}$, is calculated through a kinematic fit, which constrains the dimuon invariant mass to the $\Upsilon(1S)$ mass and the electron–positron invariant mass to zero. In addition, the electron and positron are constrained to a common vertex, as are the two muons and the photon. The χ_b candidates are retained if the χ^2 probability of the kinematic fit is larger than 2%. This approach significantly reduces the effect of the muon momentum resolution on the χ_b mass resolution.

4. Analysis procedure

The shape of the reconstructed invariant-mass distributions of the χ_b candidates is evaluated through MC simulation, performed under the assumption that the intrinsic width of the χ_b states, predicted to be smaller than 1 MeV [20], is negligible compared to the mass resolution, which is of the order of 5 MeV. Since the low-mass tail of the χ_{b2} shape falls under the χ_{b1} peak, it is important to use a reliable parameterization of the resolution function when evaluating the ratio of the χ_{b2} and χ_{b1} yields, $N_{\chi_{b2}}/N_{\chi_{b1}}$. The χ_b mass resolution is dominated by the energy resolution of the converted photon and has a clear low-mass tail, typical of processes involving radiative losses (the electrons and positrons lose energy when traversing the tracker material). The simulated signal shape also reveals the presence of a small high-mass tail due to multiple scattering; the signal response is parameterized by a double-sided Crystal Ball (CB) function [21] consisting of a Gaussian core with two power-law tails, with independent exponents and transition points.

The ratio $N_{\chi_{b2}}/N_{\chi_{b1}}$ is measured with an unbinned maximum likelihood fit to the $\mu\mu\gamma$ invariant-mass distribution, in four bins of $\Upsilon(1S) p_T$. The χ_{b1} and χ_{b2} probability density functions are modeled by double-sided CB functions with shape parameters fitted to the simulated distributions in each p_T bin of the $\Upsilon(1S)$. The total χ_{b1} yield, the $N_{\chi_{b2}}/N_{\chi_{b1}}$ ratio, and the total number of background events N_{bkg} are free parameters when fitting the data. The underlying continuum background, composed predominantly of events where the $\Upsilon(1S)$ and photon are unrelated, is modeled by a probability distribution function proportional to $(m - m_0)^{\lambda} \cdot \exp(-\nu(m - m_0))$, where m is the $\mu\mu\gamma$ invariant mass obtained from the four-track kinematic fit, $m_0 = 9.5$ GeV, and λ and ν are free parameters. The fit is performed in the $\mu\mu\gamma$ mass region 9.7–10.1 GeV. Fig. 1 shows the fitted invariant-mass distributions from data for each of the four $\Upsilon(1S) p_T$ bins considered, while Table 1 gives the corresponding fit results.

The measurement of the cross section ratio $\mathcal{R}$, defined in Eq. (1), depends on the ratio of the χ_{b1} and χ_{b2} measurement acceptance and efficiencies, $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}} = (N^{\mathrm{rec}}_{\chi_{b1}}/N^{\mathrm{gen}}_{\chi_{b1}})\big/(N^{\mathrm{rec}}_{\chi_{b2}}/N^{\mathrm{gen}}_{\chi_{b2}})$, where, for each p_T^{Υ} bin, N^{rec} is the number of simulated candidates that are reconstructed and pass the event selection criteria, while N^{gen} is the corresponding number of generated candidates, in the kinematic window $|y^{\Upsilon}| < 1.5$, $p_T^{\mu} > 3.5$ GeV, $|\eta^{\mu}| < 1.9$, and $|\eta^{\gamma}| < 1.0$. The reconstructed kinematic distributions of the simulated decay products are found to be in agreement with the measured ones. The values of the acceptance and efficiency ratios, $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$, are shown in Table 2. The ratio of the acceptances times efficiencies differs from unity owing to the increased detection efficiency of the higher-energy photon from the χ_{b2} decay.

Table 2
Acceptance and efficiency ratios, $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$, computed from MC simulation. Uncertainties are statistical only.

p_T^{Υ} [GeV]	7–11	11–16	16–20	20–40
$\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$	0.85 ± 0.05	0.91 ± 0.05	0.91 ± 0.07	0.92 ± 0.04

5. Systematic uncertainties

The χ_{b1} and χ_{b2} signal shapes are derived from MC simulation. To evaluate the uncertainty in the $N_{\chi_{b2}}/N_{\chi_{b1}}$ ratio stemming from the imperfect parameterization of the MC signal shape, caused by the finite number of simulated events, a large number of pseudo-experiments are generated, randomly drawing sets of shape parameters using the covariance matrices of the fits to the simulated distributions. They are then used to fit the measured mass distributions, and the resulting $N_{\chi_{b2}}/N_{\chi_{b1}}$ distribution is fitted with a Gaussian function, the standard deviation of which is taken as the systematic uncertainty corresponding to the "signal parameters".

To account for possible discrepancies between the simulated and measured events regarding, in particular, the energy scale calibration and the measurement resolution, alternative data-fitting schemes are used, leaving some of the signal shape parameters free in the fit to the measured mass distributions. A Chebyshev polynomial function is also used as an alternative model for the shape of the mass distribution of the background. The maximum variation in the $N_{\chi_{b2}}/N_{\chi_{b1}}$ ratio with these different fitting strategies is taken as the "signal and background modeling" systematic uncertainty. The fitting procedure is found to be unbiased, as judged using pseudo-experiments where a certain $N_{\chi_{b2}}/N_{\chi_{b1}}$ value is injected; the fitted results deviate on average from the input values by less than 10% of the statistical uncertainty. It has also been verified that the $N_{\chi_{b2}}/N_{\chi_{b1}}$ ratio is insensitive to the addition of a signal term describing the χ_{b0} state. The possible influence of multiple primary vertices in the event ("pileup") on the $N_{\chi_{b2}}/N_{\chi_{b1}}$ measurement was investigated by repeating the analysis in subsamples of events with different numbers of reconstructed primary vertices. No statistically significant effect is observed.

Another source of systematic uncertainty in the evaluation of $\mathcal{R}$ is the statistical uncertainty in $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$, reflecting the finite size of the simulated event samples used to evaluate the measurement acceptances and efficiencies. The influence of the generated χ_{b1} and χ_{b2} p_T spectra on $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$ is evaluated by using alternative functions instead of the $\Upsilon(2S)$ spectrum. A reweighting procedure is used to obtain the values of $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$ corresponding to scenarios where the χ_{b1} and χ_{b2} are both produced according to the $\Upsilon(1S)$ or $\Upsilon(3S)$ p_T spectra, as well as to mixed scenarios where the two states have different spectra: $\Upsilon(1S)$ for the χ_{b1} and $\Upsilon(2S)$ for the χ_{b2}, or $\Upsilon(2S)$ for the χ_{b1} and $\Upsilon(3S)$ for the χ_{b2}. The maximum variation in the $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$ values obtained with all hypotheses is taken as the χ_b p_T spectra uncertainty. Possible dependencies of the $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$ determination on the description of the tracking de-

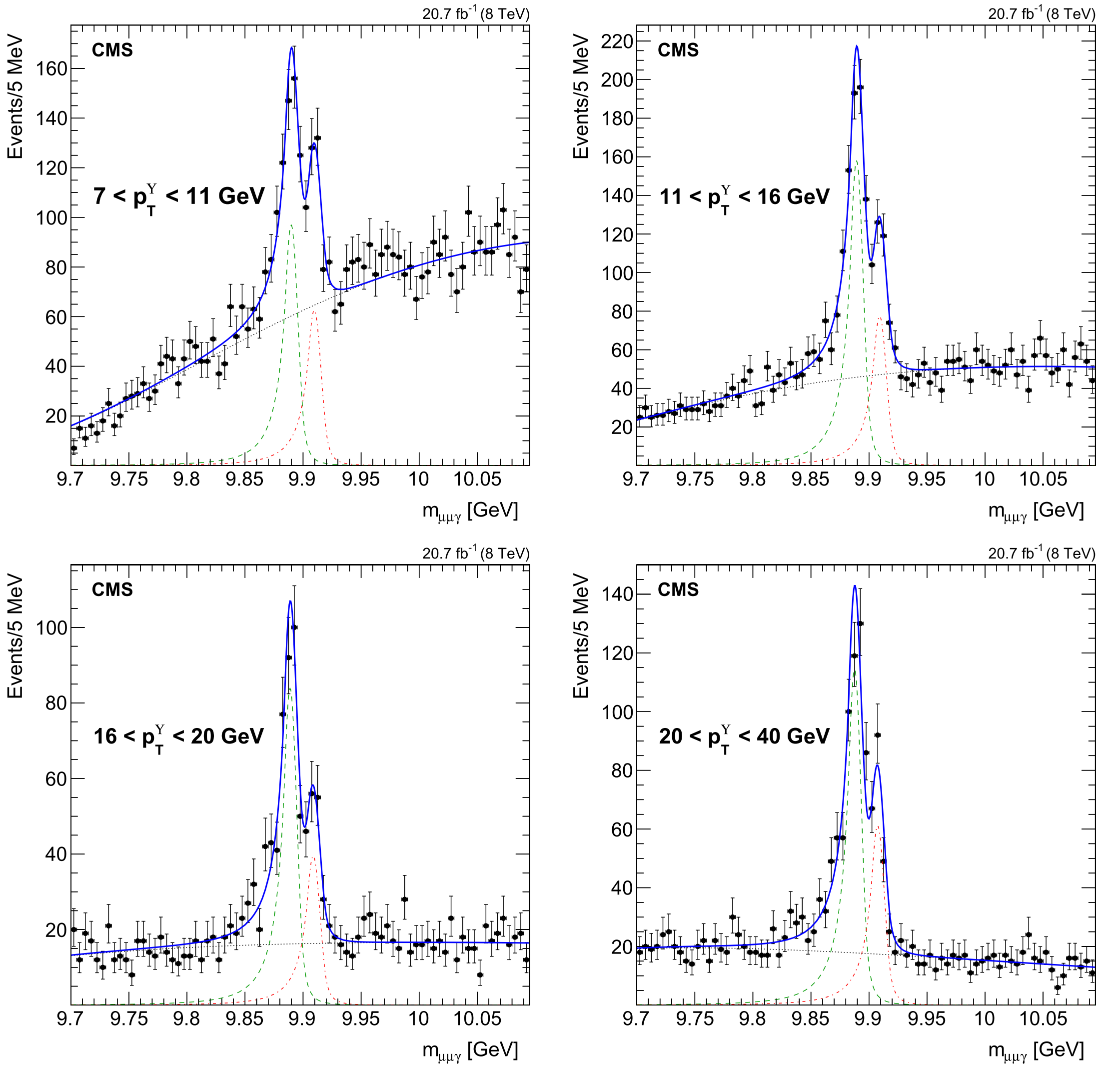

Fig. 1. Invariant-mass distributions of the $\mu\mu\gamma$ candidates for each of the four $\Upsilon(1S)$ p_T bins considered in the analysis. The fitted χ_{b1} and χ_{b2} signals are parameterized with double-sided CB functions determined using simulated events. The combinatorial background is described by the product of an exponential and a power-law function. The solid line gives the result of the overall fit, with the dashed and dashed–dotted lines showing the χ_{b1} and χ_{b2} contributions, respectively. The dotted line represents the background contribution.

tector material in the MC simulation have been found to be negligible.

The acceptances and efficiencies are evaluated under the assumption that the χ_{b1} and χ_{b2} are both produced unpolarized. Polarization affects the angular and p_T distributions of the radiated photon; since the photon reconstruction efficiency significantly depends on the photon p_T, especially at low p_T, the ratio of acceptances and efficiencies depends on the polarization scenario. In order to investigate this effect, the unpolarized MC distributions are reweighted to reproduce the theoretical angular distributions of χ_b decay products expected for different χ_b polarizations [22]. The acceptance and efficiency ratio is recalculated assuming that the χ_{b1} is produced unpolarized or with helicity $m_{\chi_{b1}} = 0, \pm1$, in combination with the assumption that the χ_{b2} is produced unpolarized or with helicity $m_{\chi_{b2}} = 0, \pm1, \pm2$, both in the helicity and Collins–Soper [23] frames. The maximal variations of $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$ in these 4 × 6 scenarios with respect to the "both unpolarized" case have a negligible influence (at the percent level) on the cross section ratio, well below the other uncertainties. Table 3 summarizes the systematic uncertainties considered in the analysis.

Table 3
Relative systematic uncertainties in $\frac{N_{\chi_{b2}}}{N_{\chi_{b1}}} \cdot \frac{\varepsilon_{\chi_{b1}}}{\varepsilon_{\chi_{b2}}}$, in percent, for the four p_T^Υ bins considered.

p_T^Υ [GeV]	7–11	11–16	16–20	20–40
Signal parameters	3.2	3.5	3.3	3.5
Signal and background modeling	6.8	5.3	5.2	6.1
$\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$ statistical uncertainty	6.4	5.8	7.2	4.4
Choice of χ_b p_T spectra	3.0	3.0	2.8	4.8
Total	10.3	9.1	9.9	9.6

6. Results and discussion

The ratio $\mathcal{R}$ of the χ_{b2} and χ_{b1} production cross sections in the $\Upsilon(1S) + \gamma$ decay channel for each p_T^Υ bin is obtained by correcting the $N_{\chi_{b2}}/N_{\chi_{b1}}$ yield ratio (Table 1) with the corresponding acceptance and efficiency ratio $\varepsilon_{\chi_{b1}}/\varepsilon_{\chi_{b2}}$ (Table 2).

Fig. 2 shows the measured $\sigma(\chi_{b2})/\sigma(\chi_{b1})$ cross section ratio, as a function of p_T^Υ, before (left) and after (right) multiplying by the decay branching fractions, taken from Ref. [13]. The relative uncertainty in the ratio of the branching fractions is 9%. The numerical values are given in Table 4.

Table 4
The cross section ratio $\sigma(\chi_{b2})/\sigma(\chi_{b1})$ measured in four p_T^{Υ} bins before and after multiplying by the $\chi_b \to \Upsilon(1S)+\gamma$ branching fractions [13]. The second column gives the average p_T value for each bin. The first uncertainty is statistical, the second is systematic, and the third reflects the uncertainty in the branching fraction.

p_T^{Υ} [GeV]	$\langle p_T^{\Upsilon}\rangle$ [GeV]	$\sigma(\chi_{b2})/\sigma(\chi_{b1}) \times \mathcal{B}(\chi_{b2})/\mathcal{B}(\chi_{b1})$	$\sigma(\chi_{b2})/\sigma(\chi_{b1})$
7–11	8.7	0.56 ± 0.10 ± 0.06	0.99 ± 0.18 ± 0.10 ± 0.09
11–16	12.9	0.47 ± 0.06 ± 0.04	0.83 ± 0.10 ± 0.08 ± 0.07
16–20	17.5	0.45 ± 0.07 ± 0.04	0.80 ± 0.13 ± 0.08 ± 0.07
20–40	26.2	0.50 ± 0.06 ± 0.05	0.89 ± 0.11 ± 0.09 ± 0.08

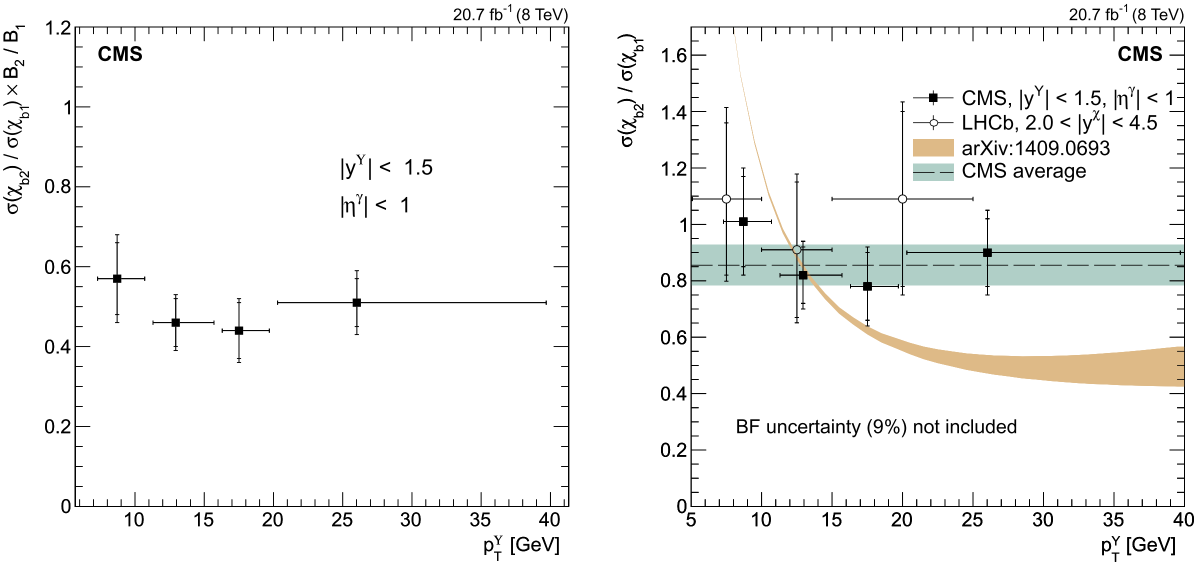

Fig. 2. The ratio of the χ_{b2} and χ_{b1} production cross sections, as a function of p_T^{Υ}, before (left) and after (right) multiplying by the ratio of the $\Upsilon(1S)+\gamma$ branching fractions, as measured by CMS and LHCb [12] (right only). The vertical bars represent the statistical (inner bars) and total (outer bars) experimental uncertainty, respectively. The horizontal bars show the width of each bin. The dashed line in the right plot is a fit of a constant to the CMS measurements, and the horizontal band is the total uncertainty in the fit result. The 9% uncertainty in the ratio of branching fractions, which applies to all bins of p_T^{Υ}, is not included. The curved band represents the result of a theoretical calculation [24].

The open circles in Fig. 2, right panel, show the LHCb measurement [12], which can be compared to the CMS result since no significant dependence of the ratio on the rapidity is expected. The shaded area in the right panel of Fig. 2 shows a theoretical calculation [24] performed in the framework of NRQCD. Since data on χ_b production were not available until recently, in this calculation the LDMEs are extracted from experimental data on the $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ cross section ratio [7,9,10] and extrapolated, using NRQCD scaling rules, to the case of P-wave bottomonium. The dashed line in Fig. 2 (right) gives the result of a fit of the CMS measurements to a constant, corresponding to 0.85 ± 0.07, where the uncertainty includes both statistical and systematic uncertainties, but not the uncertainty in the ratio of the χ_b branching fractions. A constant behavior is expected in the case of color-octet dominance. The measurements do not indicate the large increase in the ratio at low p_T^{Υ} and differ by more than two standard deviations from the asymptotic value at high p_T predicted by the theory. More precise measurements may be needed in order to thoroughly test the validity of NRQCD in the P-wave bottomonium sector.

7. Summary

The production cross section ratio $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$ has been measured in pp collisions by detecting the radiative decays to a $\Upsilon(1S)$ and a photon, with the $\Upsilon(1S)$ decaying to two muons. Events are selected where the $\Upsilon(1S)$ and photon are emitted in the phase-space region defined by $|y^{\Upsilon}| < 1.5$ and $|\eta^{\gamma}| < 1.0$, in four bins of $\Upsilon(1S)$ p_T, spanning the range 7–40 GeV. The measurement has been performed using a data sample collected by the CMS experiment in 2012, at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.7 fb^{-1}. The cross section ratio averaged over the $\Upsilon(1S)$ p_T range is measured to be $0.85 \pm 0.07\,(\text{stat}+\text{syst}) \pm 0.08\,(\text{BF})$, where the first uncertainty is the combination of the experimental statistical and systematic uncertainties and the second is from the uncertainty in the ratio of the χ_b branching fractions. The ratio does not show a significant dependence on the $\Upsilon(1S)$ p_T. This is the most precise measurement to date of the χ_{b2} and χ_{b1} relative production cross sections in hadron collisions, which complements and extends the results of Ref. [12] obtained in the kinematic region $2.0 < y(\chi_b) < 4.5$, $5.0 < p_T(\Upsilon) < 25$ GeV.

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