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# Measurement of the cross section for production of $b\bar{b}X$ decaying to muons in $pp$ collisions at $\sqrt{s} = 7$ TeV

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ABSTRACT: A measurement of the inclusive cross section for the process  $pp \rightarrow b\bar{b}X \rightarrow \mu\mu X'$  at  $\sqrt{s} = 7$  TeV is presented, based on a data sample corresponding to an integrated luminosity of  $27.9 \text{ pb}^{-1}$  collected by the CMS experiment at the LHC. By selecting pairs of muons each with pseudorapidity  $|\eta| < 2.1$ , the value  $\sigma(pp \rightarrow b\bar{b}X \rightarrow \mu\mu X') = 26.4 \pm 0.1$  (stat.)  $\pm 2.4$  (syst.)  $\pm 1.1$  (lumi.) nb is obtained for muons with transverse momentum  $p_T > 4$  GeV, and  $5.12 \pm 0.03$  (stat.)  $\pm 0.48$  (syst.)  $\pm 0.20$  (lumi.) nb for  $p_T > 6$  GeV. These results are compared to QCD predictions at leading and next-to-leading orders.

KEYWORDS: Hadron-Hadron Scattering

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## 1 Introduction

The measurement of the cross section for inclusive b-quark production at the Large Hadron Collider (LHC) is a powerful probe of quantum chromodynamics (QCD) at very high energies. In addition, knowledge of the inclusive b-production rate from QCD processes helps to understand the background in searches for massive particles decaying into b quarks, such as the Higgs boson or new heavy particles.

The b-quark production cross section can be computed at next-to-leading order (NLO) in a perturbative QCD expansion [1–3]. The sizeable scale dependence of the result suggests that the contribution from the neglected higher-order terms is large [4–6]. The measurements performed at the Tevatron in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  and 1.96 TeV [7, 8], and at the LHC by the Compact Muon Solenoid (CMS) [9–11] and LHCb [12, 13] collaborations in pp collisions at  $\sqrt{s} = 7$  TeV in different rapidity ranges are generally consistent with

the theoretical calculations. However, the comparisons are affected by large theoretical uncertainties.

The measurements of the cross section for the inclusive process  $pp \rightarrow b\bar{b}X \rightarrow \mu\mu X'$  at  $\sqrt{s} = 7 \text{ TeV}$  presented here allow for a comparison with QCD predictions in a kinematic domain where NLO calculations are more reliable because of the suppressed contribution of the gluon-splitting production mechanism (as discussed in [14] and the references therein).

Experimentally, the dimuon final state allows for the selection of a sample with high  $b\bar{b}$  event purity in the following wide kinematical region: muon pseudorapidity  $|\eta| < 2.1$ , where  $\eta = -\ln[\tan(\theta/2)]$  and  $\theta$  is the angle between the muon momentum and the counterclockwise beam direction, and muon momentum in the plane transverse to the beam axis  $p_T > 4 \text{ GeV}$  or  $p_T > 6 \text{ GeV}$ . Discrimination of the background from charm and light quark decays and from the Drell-Yan process is accomplished using the two-dimensional distribution of the two muon impact parameters ( $d_{xy}$ ), defined as the distance of closest approach of each muon track to the interaction point projected onto the plane transverse to the beam axis.

This paper is structured as follows. A brief description of the CMS detector is presented in section 2. Section 3 describes the collision and simulated data used for this measurement and the selection criteria. Section 4 contains a detailed description of the categories in which events are grouped according to each muon's production process and kinematic features, while the fit to the impact parameter distributions is discussed in section 5. Section 6 describes how the efficiency is computed and section 7 is devoted to the determination of the systematic uncertainties. Section 8 reports the cross section measured in data and expected from QCD predictions.

## 2 The CMS detector

A detailed description of the CMS experiment can be found elsewhere [15]. The central feature of the CMS apparatus is a superconducting 3.8 T solenoid of 6 m internal diameter. Within the field volume are the silicon tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are detected in the pseudorapidity range  $|\eta| < 2.4$  by gaseous detectors utilizing three technologies: drift tubes (DT), cathode strip chambers (CSC), and resistive plate chambers (RPC), embedded in the steel return yoke. The silicon tracker is composed of pixel detectors (three barrel layers and two forward disks on either side of the detector, made of 66 million  $100 \mu\text{m} \times 150 \mu\text{m}$  pixels) followed by microstrip detectors (ten barrel layers, three inner disks and nine forward disks on either side of the detector, with the strip pitch between 80 and  $180 \mu\text{m}$ ). Thanks to the strong magnetic field and high granularity of the silicon tracker, the transverse momentum  $p_T$  of muons matched to reconstructed tracks is measured with the resolution better than 1.5% for  $p_T < 100 \text{ GeV}$ . The silicon tracker also provides the vertex position with  $\sim 15 \mu\text{m}$  accuracy. The impact parameter resolution is measured with a sample of muons from  $\Upsilon(1S) \rightarrow \mu^+\mu^-$  decays to be  $28 \mu\text{m}$  and  $21 \mu\text{m}$  for muons with  $p_T > 4 \text{ GeV}$  and  $p_T > 6 \text{ GeV}$ , respectively.

The first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interest-

ing events. The rapidity coverage of the L1 muon triggers used in this analysis is  $|\eta| < 2.4$ . The high-level-trigger processor farm further decreases the event rate before data storage.

### 3 Data selection and Monte Carlo simulation

The data employed for this measurement were collected with the CMS detector during the 2010 running period of the LHC. They correspond to an integrated luminosity  $\mathcal{L} = 27.9 \pm 1.1 \text{ pb}^{-1}$  [16]. A sample of events with two muons, each with transverse momentum  $p_T > 3 \text{ GeV}$  were selected at the trigger level. Further requirements, designed to increase the purity of the muon candidates and to increase the fraction of muons from b decay in the sample, are applied at the analysis stage. A muon candidate is selected by matching information from the silicon tracker and muon chambers. The track must contain at least 12 hits from the silicon tracker, with signals in at least two pixel layers, and a normalized  $\chi^2$  not exceeding 2. The overall  $\chi^2$  obtained by combining the information from the tracker and the muon chambers should not exceed 10 times the number of degrees of freedom. Finally, each muon must be contained in the kinematical region defined by  $|\eta| < 2.1$  and  $p_T > 4 \text{ GeV}$ . We perform the measurement in this region and in a higher  $p_T$  region where both the muons have  $p_T > 6 \text{ GeV}$ .

Primary interaction vertices are reconstructed event-by-event from the reconstructed tracks. A candidate vertex is accepted if its fit has at least four degrees of freedom and its distance from the beam spot does not exceed 24 cm along the beam line and 1.8 cm in the plane transverse to the beams. Tracks are assigned to the primary vertex for which the track's distance to the vertex along the beam direction is smallest at the point of closest approach in the transverse plane. Muon tracks are required to have an impact parameter  $d_{xy}$  perpendicular to the beam direction and with respect to its assigned primary vertex of less than 0.2 cm. Events are kept only if both muon tracks are assigned to the same primary vertex and both cross the beam axis within 1 cm of that vertex position along the beam direction.

To remove muons from  $Z^0$  decays, a selection on the dimuon mass  $M_{\mu\mu} < 70 \text{ GeV}$  is applied. The mass range contributed by the  $\Upsilon$  resonances,  $8.9 < M_{\mu\mu} < 10.6 \text{ GeV}$ , is also rejected. Charmonium resonances and sequential semileptonic decays from a single b quark (for example  $b \rightarrow J/\psi X \rightarrow \mu\mu X$ , or  $b \rightarrow c\mu X \rightarrow \mu\mu X'$ ) are rejected by removing dimuons with  $M_{\mu\mu} < 5 \text{ GeV}$ . Events are selected if one and only one pair of muons is found satisfying all the criteria defined above. A total of 537 734 events for  $p_T > 4 \text{ GeV}$  and 151 314 events for  $p_T > 6 \text{ GeV}$  pass these requirements.

Two samples of simulated Monte Carlo (MC) events were generated using the minimum-bias settings of PYTHIA 6.422 [17] (parameter MSEL=1), with the Z2 tune [18, 19], and incorporating the CTEQ6L1 parton distribution functions (PDF) [20]. To increase the generation efficiency within the selected acceptance, a filter was applied at the generator level requiring two muons with  $p_T^{\text{gen}} > 2.5 \text{ GeV}$  and  $|\eta^{\text{gen}}| < 2.5$  for the measurement with  $p_T > 4 \text{ GeV}$ , or  $p_T^{\text{gen}} > 5 \text{ GeV}$  and  $|\eta^{\text{gen}}| < 2.5$  for the measurement with  $p_T > 6 \text{ GeV}$ . The generated samples include events with muons originating from the decay of light mesons (mostly charged pions and kaons) within the tracker volume. A third MC

sample was produced to simulate the Drell–Yan process. MC events, including the full simulation of the CMS detector and trigger via the GEANT4 package [21], are subjected to the same reconstruction and selection as the real data.

## 4 Templates for different muon classes

The fraction of signal events ( $pp \rightarrow b\bar{b}X \rightarrow \mu\mu X'$ ) in the data is obtained from a fit to the 2D distribution of the impact parameters of the two muons. For this purpose, reconstructed muons in the simulated events are separated into four different classes, defined according to their origin. The single-particle distributions of the transverse impact parameter  $d_{xy}$  are obtained for each class from simulation and fit using analytical functions. From these functions, the 2D templates are built symmetrically. This procedure is described in the following section.

### 4.1 Definition of muon classes

Information from the generation process is used to assign each reconstructed muon in the simulation to a well-defined category. Reconstructed muon candidates are linked to the corresponding generated charged particles with a hit-based associator, which reduces the probability of incorrect associations to a negligible level. Tracks are assigned to one of the following classes:

1. B-hadron decays (B): muons produced in the decay of a B hadron, including both direct decays ( $b \rightarrow \mu^- X$ ) and cascade decays ( $b \rightarrow cX \rightarrow \mu X'$ ,  $b \rightarrow \tau X \rightarrow \mu X'$ ,  $b \rightarrow J/\psi X \rightarrow \mu^\pm X$ );
2. Charmed hadron decays (C): muons from the semileptonic decays of charmed hadrons produced promptly;
3. Prompt tracks (P): candidates originating from the primary vertex, mostly muons from the Drell-Yan process and quarkonia decays. This category also includes punch through of primary hadrons, and muons from decays of charged pions and kaons in the volume between the silicon tracker and the muon chambers;
4. Decays in flight (D): muons produced in decays of charged pions or kaons (which may come either from light- or heavy-flavor hadrons) in the silicon tracker volume.

Table 1 gives the single-muon sample composition from the simulation for MC events passing the full selection and dimuon trigger. While the fraction of muons from decays in flight (D) decreases at larger  $p_T$ , the prompt component (P) increases due to the Drell-Yan muons.

The predicted composition of the dimuon events from the simulation is shown in table 2, where PX is defined as the sum of the PB, PC, and PD contributions. The uncertainties given in the table are the statistical uncertainties from the simulated samples.

Figure 1 shows the  $d_{xy}$  distributions for muons with  $p_T > 4$  GeV from the simulation for all the classes above except for the prompt tracks, where muons from decays of  $\Upsilon(1S)$

Source	Fraction in simulation (%)	
	$p_T > 4 \text{ GeV}$	$p_T > 6 \text{ GeV}$
B hadron (B)	$77.8 \pm 0.2$	$79.8 \pm 0.4$
C hadron (C)	$14.0 \pm 0.1$	$12.6 \pm 0.1$
Prompt sources (P)	$1.84 \pm 0.04$	$3.44 \pm 0.08$
Decays in flight (D)	$6.37 \pm 0.07$	$4.21 \pm 0.09$

**Table 1.** Percentage of each muon class in the simulated events for two  $p_T$  requirements. The uncertainties are statistical only.

Source	Fraction in simulation (%)	
	$p_T > 4 \text{ GeV}$	$p_T > 6 \text{ GeV}$
BB	$71.6 \pm 0.2$	$74.6 \pm 0.4$
CC	$9.24 \pm 0.08$	$8.67 \pm 0.14$
BC	$5.66 \pm 0.07$	$5.22 \pm 0.11$
PP	$1.84 \pm 0.04$	$3.43 \pm 0.08$
DD	$1.49 \pm 0.04$	$0.73 \pm 0.04$
BD	$6.01 \pm 0.07$	$4.40 \pm 0.10$
CD	$3.69 \pm 0.05$	$2.53 \pm 0.08$
PX	$0.48 \pm 0.02$	$0.40 \pm 0.03$

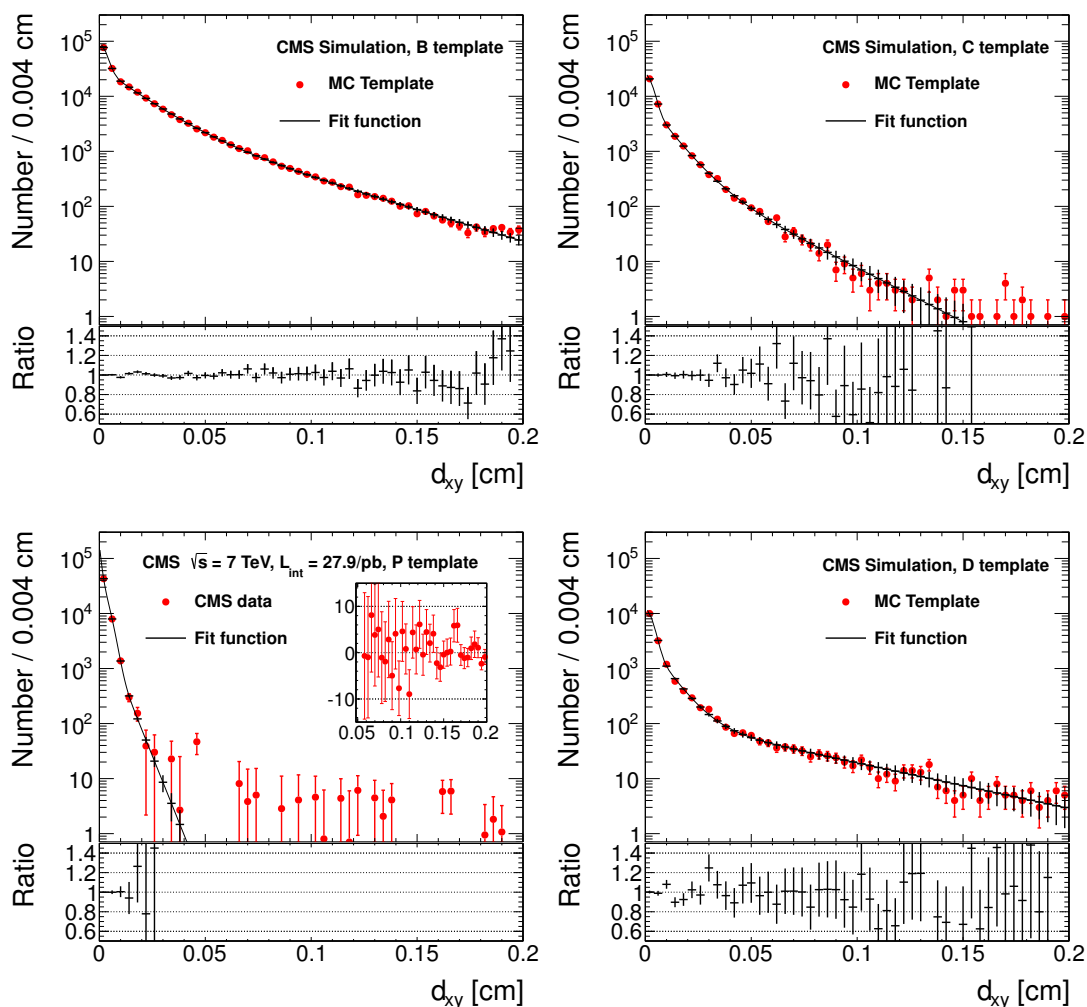
**Table 2.** Percentage of dimuon event sources in the simulation for two different  $p_T$  requirements. PX represents the sum of the contributions from PB, PC, and PD. The uncertainties are statistical only.

in the collision data are used after removing the background with a sideband subtraction technique.

The prompt  $d_{xy}$  distribution is fit with the sum of a Gaussian centered at zero and an exponential function. This combination of functions accounts for the detector resolution effects. The distributions of the other classes are fit using, in addition, a second exponential term. The functions are shown by continuous black lines overlaid on the histograms in figure 1, while the black points represent the template histograms obtained by evaluating the fit functions at each bin center. The ratio of the MC distribution to the fit values are shown in the lower plots of figure 1. The templates for muons with  $p_T > 6 \text{ GeV}$  are obtained in a similar way.

## 4.2 Two-dimensional template distributions

In principle, the dimuon events could be split into sixteen different categories by combining the four classes defined above for each muon. In order to reduce the number of categories to ten, the  $d_{xy}$  distributions are symmetrized (i.e.,  $BC=CB$ ,  $BD=DB$ , etc.) using a method originally developed by the CDF collaboration [8]. The one-dimensional (1D) histograms,

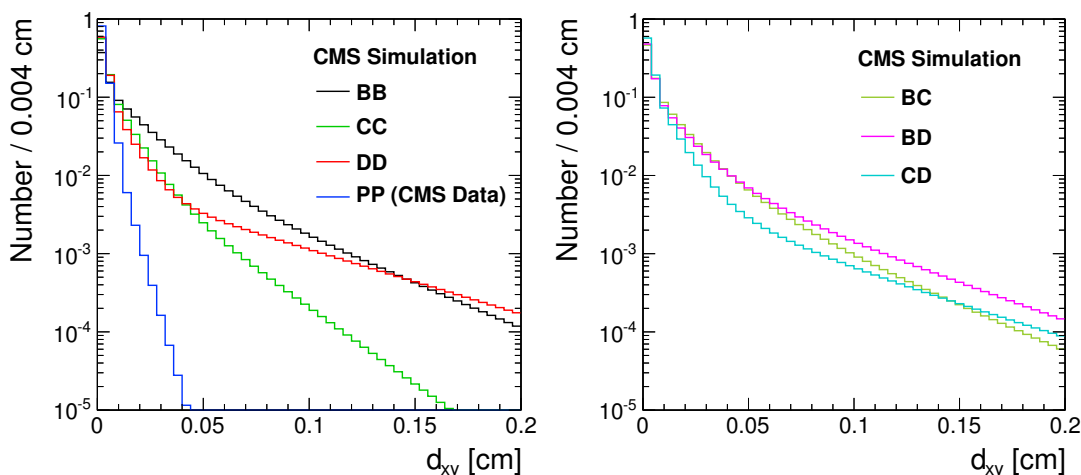


**Figure 1.** Comparison, for muons with  $p_T > 4$  GeV, between the template  $d_{xy}$  histogram (red) and the fitted function (black) for muons coming from B hadrons (class B, top left), charmed hadrons (class C, top right), prompt tracks (class P, bottom left), and decays in flight (class D, bottom right). The templates for B, C, and D come from simulation. For the prompt tracks, the distribution is obtained from data. An enlargement of the prompt-track distribution for  $d_{xy} > 0.05$  cm is shown on a linear scale as an insert in the lower-left plot. For each template, the ratio of the  $d_{xy}$  histogram to the fitted function is shown at the bottom.

built as described above, are normalized to unity within the fit range  $0 < d_{xy} < 0.2$  cm. The symmetrized 2D template histogram for the events with a muon of class  $\rho$  and another of class  $\sigma$  ( $\rho, \sigma = 1, \dots, 4$  according to the definition in section 4.1) is then constructed as

$$T_{ij}^{\rho,\sigma} = \frac{1}{2}(S_i^\rho S_j^\sigma + S_j^\rho S_i^\sigma), \quad (4.1)$$

where  $S_i^\rho$  is the content of the  $i^{\text{th}}$  bin of the histogram describing the class  $\rho$ , and analogously for index  $j$  and class  $\sigma$ . In this way, ten symmetric distributions are obtained.



**Figure 2.** 1D projections of the  $d_{xy}$  templates used in the fit for muons with  $p_T > 4$  GeV, for the BB, CC, PP, DD categories (left) and the BC, BD, CD ones (right).

In practice, the few events from the PX category are neglected, thus reducing the number of significant classes to seven.

The 1D projections of the seven templates are shown in figure 2 for muons with  $p_T > 4$  GeV.

## 5 Measurement of the sample composition

Consistent with the symmetric 2D templates, the data events are also randomized by taking the impact parameters of the two muons in each event, and filling the bin corresponding to  $[d_{xy}(\mu_1), d_{xy}(\mu_2)]$  or to  $[d_{xy}(\mu_2), d_{xy}(\mu_1)]$  according to the outcome of a random number generator.

The fractions of the individual contributions to the observed distribution are determined with a binned maximum-likelihood fit. The fit minimizes the function:

$$-2\ln(L) = -2 \left\{ \sum_{i,j=1}^7 [n_{ij} \ln(l_{ij}) - l_{ij}] - \frac{1}{2} \sum_{k'=1}^3 \left( \frac{r_{k'} - r_{k'}^{\text{MC}}}{\sigma_{r_{k'}}^{\text{MC}}} \right)^2 \right\}, \quad (5.1)$$

where  $n_{ij}$  is the content of the data histogram in the bin  $(i, j)$ ,  $l_{ij} = \sum_k [f_k \cdot T_{k,ij}]$ , where  $T_k$  is the  $k^{\text{th}}$  template ( $k = 1, \dots, 7$ ), and  $f_k$  is the fit parameter expressing the fraction of events from the  $k^{\text{th}}$  source. The fitted fractions are subject to the normalization condition  $\sum_{k=1}^7 f_k = 1$ . To reduce the number of fit parameters and ease the fit convergence, the three parameters  $f_{BC}$ ,  $f_{BD}$ , and  $f_{CD}$  are constrained so that the ratios  $f_{BC}/f_{BB}$ ,  $f_{BD}/f_{BB}$ , and  $f_{CD}/f_{CC}$  are compatible with the MC expectations within their statistical uncertainties. In eq. (5.1),  $k'$  is the index of the constrained templates (BC, BD, CD),  $r_{k'}$  is the ratio of the constrained fit fraction with respect to the reference fit fraction (for instance in the BC



Source	$p_T > 4 \text{ GeV}$	$p_T > 6 \text{ GeV}$
BB	$66.8 \pm 0.3$	$70.2 \pm 0.3$
CC	$9.2 \pm 0.6$	$5.5 \pm 1.2$
BC	$5.2 \pm 0.1$	$4.9 \pm 0.1$
PP	$1.7 \pm 0.3$	$4.0 \pm 0.4$
DD	$7.8 \pm 1.1$	$9.5 \pm 2.1$
BD	$5.6 \pm 0.1$	$4.2 \pm 0.1$
CD	$3.7 \pm 0.9$	$1.6 \pm 0.5$

**Table 3.** Results of the likelihood fit to data for the percentage of each dimuon source with two different muon  $p_T$  requirements. The BC, BD, and CD fractions are constrained to their ratios to BB and CC fractions as expected from the simulation.

case  $r_{BC} = f_{BC}/f_{BB}$ ),  $r_{k'}^{\text{MC}}$  is the ratio of the constrained fraction and reference fraction in the simulation, and  $\sigma_{r_{k'}^{\text{MC}}}$  its statistical uncertainty from the number of simulated events.

The BC component originates from the production of an extra  $c\bar{c}$  pair from gluon splitting in a  $b\bar{b}$  event. The production rate of  $c\bar{c}$  pairs from gluon splitting has been measured at LEP [22–24], and found to be 50% higher than theoretical predictions [25]. The measured  $b\bar{b}$  rate [26–28] is about 10 times smaller and has a negligible effect on the BC component. In contrast, the BD and CD contributions are related to the misidentified muon rate in events with true B and C production. These rates are determined from the MC simulation, and have been checked using direct measurements in the data [29]. The systematic uncertainties on the fit constraints are discussed in section 7.3.

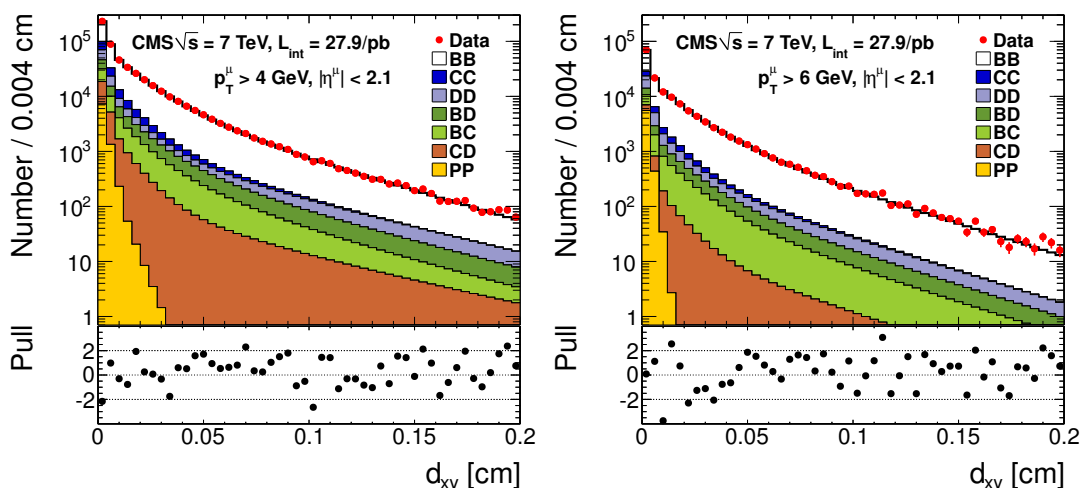
Table 3 gives the results of the fit to the data sample. The quoted uncertainties are obtained from the fit and are statistical only. The measured BB fraction is smaller than expected from the simulation, while the DD fraction is larger. Projections of the  $d_{xy}$  distributions with the results of the fits are shown in figure 3 for the two  $p_T$  selections.

## 6 Efficiency determination

The total efficiency  $\epsilon$  is defined as the fraction of signal events produced within the acceptance ( $p_T > 4 \text{ GeV}$  or  $p_T > 6 \text{ GeV}$ ,  $|\eta| < 2.1$  for each muon) that are retained in the analysis. In the simulation, the values of  $\epsilon^{\text{MC}} = (44.3 \pm 0.1)\%$  and  $(69.9 \pm 0.1)\%$  are computed for signal events with a  $p_T$  threshold of 4 and 6 GeV, respectively.

To compare these values to efficiencies measured in data, the selection procedure is divided into three steps, each defined relative to events passing the previous one:

1. muon selection (“MuSel”): events having at least two selected muons, each associated with a reconstructed vertex;
2. event selection (“EvSel”): events passing the dimuon invariant mass requirements, with both muons belonging to the same vertex;



**Figure 3.** Top: The projected  $d_{xy}$  distributions from data with the results of the fit for muons with  $p_T > 4$  GeV (left) and  $p_T > 6$  GeV (right). The distribution from each dimuon source is shown by the histograms. Bottom: The pull distribution from the fit.

Sample	$\epsilon_{\text{MuSel}}$	$\epsilon_{\text{EvSel}}$	$\epsilon_{\text{Trg}}$	$\epsilon$
$p_T > 4$ GeV, MC	$64.8 \pm 0.1$	$78.0 \pm 0.1$	$87.7 \pm 0.1$	$44.3 \pm 0.1$
$p_T > 4$ GeV, data	$69.5 \pm 3.6$	-	$86.1 \pm 2.0$	$48.8 \pm 2.9$
$p_T > 6$ GeV, MC	$83.6 \pm 0.1$	$90.1 \pm 0.1$	$92.8 \pm 0.1$	$69.9 \pm 0.1$
$p_T > 6$ GeV, data	$87.0 \pm 3.4$	-	$93.4 \pm 2.1$	$74.4 \pm 3.8$

**Table 4.** Efficiencies (in percent) at each step of the analysis found from the simulation and from the data. The last column reports the overall efficiency, obtained from the product of the three efficiencies shown. The event selection efficiency  $\epsilon_{\text{EvSel}}$  cannot be found with the data, so the MC simulation value is used. The bias and feed-through corrections described in the text are also included in the overall efficiency. Only statistical uncertainties are reported.

3. trigger selection (“Trg”): events passing the trigger requirements.

The efficiencies obtained by counting the signal events passing each step in the simulation are given in table 4.

The total efficiency can alternatively be expressed on an event-by-event basis by defining the efficiency  $\epsilon_i$  to select the  $i^{\text{th}}$  signal event as  $\epsilon_i = \epsilon_{i,\text{MuSel}} \cdot \epsilon_{i,\text{EvSel}} \cdot \epsilon_{i,\text{Trg}}$ . The  $(p_T, \eta)$  distribution of the signal events and the efficiency  $\epsilon_{i,\text{EvSel}}$  can only be extracted from simulation. The efficiencies  $\epsilon_{i,\text{MuSel}}$  and  $\epsilon_{i,\text{Trg}}$  can be found as the products of the single-muon efficiencies,  $\epsilon_i = \epsilon_{\mu_1}(p_T, \eta) \cdot \epsilon_{\mu_2}(p_T, \eta)$ , under the assumption that the single-muon efficiencies  $\epsilon_{\mu_i}$  only depend on the  $p_T$  and  $\eta$  of the muon. This assumption is found to be compatible with the efficiencies determined in the simulated sample, within their statistical uncertainties.

In the data, the single-muon selection and trigger efficiencies are measured in intervals of  $p_T$  and  $\eta$  with the “tag-and-probe” (T&P) method [29, 30], which employs a sample of  $J/\psi \rightarrow \mu^+ \mu^-$  events selected with minimal trigger requirements. The selection efficiency found from this method is consistent with the value from the simulation ( $\epsilon_{\text{MuSel}}^{\text{data}}/\epsilon_{\text{MuSel}}^{\text{MC}} = 1.073 \pm 0.054$  for  $p_T > 4$  GeV and  $1.041 \pm 0.047$  for  $p_T > 6$  GeV), as is the trigger efficiency ( $\epsilon_{\text{Trg}}^{\text{data}}/\epsilon_{\text{Trg}}^{\text{MC}} = 0.982 \pm 0.028$  for  $p_T > 4$  GeV and  $1.006 \pm 0.023$  for  $p_T > 6$  GeV).

Differences in the kinematic distributions between the  $J/\psi$  sample and the  $b\bar{b}$  events might imply different bin-averaged efficiencies, causing biases in the region close to the acceptance thresholds. An overall bias correction of  $0.966 \pm 0.015$  ( $1.004 \pm 0.012$ ) is computed when comparing the efficiencies in the simulation computed with the T&P method and those obtained with the signal in the range  $p_T > 4$  GeV ( $p_T > 6$  GeV), where the uncertainties are statistical only.

Another correction to the total efficiency is applied to take into account the feed-through of events where one of the muons has a true  $p_T$  below the selection limit, whereas the reconstructed  $p_T$  is above it. This effect is computed using the simulation by finding the fraction of selected events with at least one muon generated outside of the acceptance, and is equal to 0.990 (0.980) for  $p_T > 4$  (6) GeV, with negligible uncertainties.

The overall efficiency is computed as the product of the efficiencies for the muon selection and trigger, as obtained with the T&P method in data, times the event selection efficiency found in the simulation, divided by the bias and the feed-through corrections. Results are shown in table 4.

## 7 Systematic uncertainties

Several sources of systematic uncertainties have been considered for this measurement. They are divided into uncertainties due to the model dependencies for both the signal and the backgrounds, the effects related to the impact parameter resolution, the fit method, and the measurement of the efficiency. Each of these is described separately in the subsections below.

### 7.1 Model-dependent uncertainties

The impact parameter projected onto the plane transverse to the beam axis of a muon produced in a hadron semileptonic decay is related to the parent hadron’s proper decay time  $t$  by:

$$d_{xy} = \beta\gamma ct \sin\delta \sin\theta, \tag{7.1}$$

where  $\beta$  is the ratio of the hadron velocity and the speed of light  $c$ ,  $\gamma = (1 - \beta^2)^{1/2}$ ,  $\delta$  is the angle between the muon and the hadron directions in the laboratory frame, and  $\theta$  is the polar angle between the hadron direction and the beam axis. Uncertainties in the parent lifetime affect the simulation of the proper distance distribution  $ct$ , and uncertainties in the parent hadron energy spectrum affect the Lorentz boost factor  $\beta\gamma$  and the angle  $\delta$ . The three general categories of systematic uncertainties due to these model dependencies are:

**b- and c-hadron properties:** four of the long-lived B hadrons produced at the LHC decay to muons at a non-negligible rate. While the  $B_d$  and  $B_u$  lifetimes are known with a precision better than 1%, the  $B_s$  and  $\Lambda_b$  lifetimes are measured with larger uncertainties. Simulated MC events with  $B_s$  and  $\Lambda_b$  decays are reweighted so as to vary the corresponding lifetimes by their uncertainties [31], the templates are recomputed, and the fit is repeated. The fit result changes by  $\pm 2.1\%$  ( $\pm 1.5\%$ ) for  $p_T > 4$  (6) GeV. The effects from uncertainties on the  $B_d$ ,  $B_u$ , and c-hadron lifetimes, similarly evaluated, are negligible. The b-hadron sample composition has been measured by experiments at LEP and the Tevatron [31], and by LHCb [32]. While substantial agreement has been found for the  $B_s/(B_u + B_d)$  fraction, a sizable discrepancy was observed for  $f_{\Lambda_b} = \Lambda_b/(B_u + B_d)$ . The results presented here are obtained using the averages between the LEP and LHCb results,  $f_{\Lambda_b} = 0.18 \pm 0.09$  ( $0.165 \pm 0.075$ ) for  $p_T > 4$  (6) GeV, where the uncertainties correspond to half the difference between LEP and LHCb. Varying  $f_{\Lambda_b}$  in these ranges affects the measurement by  $\pm 2.7\%$  ( $\pm 1.8\%$ ) for  $p_T > 4$  (6) GeV. Varying the other parameters affecting the b-hadron and c-hadron sample compositions by their uncertainties has a smaller effect for both  $p_T > 4$  GeV and  $p_T > 6$  GeV ( $\pm 0.7\%$ ,  $\pm 0.8\%$ , respectively).

**b-quark properties:** uncertainties in the production of B hadrons from the fragmentation of a b quark affect both the shape of the  $d_{xy}$  distribution and the efficiency estimate. The systematic uncertainty is computed as the difference between the default result and those obtained with two different hadronization models in the PYTHIA simulation: the Lund symmetric [17] and the Peterson [33] functions. Taking into account the effects on the b templates and those connected with the extraction of the efficiency, overall uncertainties of  $\pm 3.3\%$  ( $p_T > 4$  GeV) and  $\pm 3.6\%$  ( $p_T > 6$  GeV) are obtained. Using different PDFs to describe b-quark production in pp collisions has an effect of  $\pm 0.9\%$  ( $p_T > 4$  GeV) and  $\pm 0.5\%$  ( $p_T > 6$  GeV).

**Light-meson decays in flight:** muons from  $\pi$  and K decays have different  $d_{xy}$  distributions. The shape is also different for muons from light mesons produced in the hadronization of a light quark, or from the decay of a heavy hadron. Given the uncertainties on the pion and kaon fractions in the simulation, we vary the relative amounts by  $\pm 30\%$  and find a negligible effect on the final results. Similarly, we change the ratio of light mesons from heavy-flavor and light-flavor decays by  $\pm 50\%$ , and observe a 2.5% (2.6%) change in the results for  $p_T > 4$  (6) GeV. The generator-level filter applied to the simulated sample, requiring two muons to be produced within the tracker volume in each event, affects the shape and composition of the decays-in-flight template. The impact of the filter on the BB fraction is estimated by extracting the decays-in-flight template from an unbiased simulated sample in which only one generated muon is required to pass the filter and the other muon is used in determining the template. Repeating the analysis with this new template results in a 0.5% variation of the final result for both  $p_T$  selections.

The total model-dependent systematic uncertainty, found by adding in quadrature the contributions listed above, is 5.5% for  $p_T > 4$  GeV and 5.1% for  $p_T > 6$  GeV.

## 7.2 Uncertainties on the impact parameter resolution

The systematic uncertainty from the impact parameter resolution is determined by comparing the  $d_{xy}$  distribution from prompt  $\Upsilon(1S) \rightarrow \mu^+ \mu^-$  decay candidates reconstructed in collision data to the predicted distribution from MC simulation. A slight  $\phi$  dependence in the determination of the signed impact parameter with respect to the beam spot, where  $\phi$  is the azimuthal angle of the muon track, due to the CMS tracker not being perfectly centered around the beam pipe, is not reproduced by the simulation. The combined effect from the misalignment and the different resolution in data and simulation is evaluated by an additional smearing of the impact parameter consistent with the observed differences between data and simulation. A further check to avoid the region dominated by the resolution has been performed by moving the lower bound of the fit range from 0 to  $40 \mu\text{m}$ . The maximum deviation from the default result found with these two methods is 2.7% (4.0%) for  $p_T > 4$  (6) GeV, which is taken as the systematic uncertainty due to the detector resolution.

## 7.3 Uncertainties related to the Monte Carlo precision and the fit method

There are four general categories of systematic uncertainty caused by the MC statistical precision and the fitting procedure. These include:

**Monte Carlo precision:** the likelihood fit is validated using a set of 500 parameterized simulated datasets, each with the same number of events as the data sample. The fit results from these datasets reproduce the input values with uncertainties consistent with those obtained in data, and the pull distribution is well described by a normal function. The r.m.s. of the results obtained for the BB fraction is 0.3% (0.7%) for  $p_T > 4$  (6) GeV, which are taken as the systematic uncertainties related to the finite simulated sample.

**Template parameterization:** the  $d_{xy}$  distributions in the simulated data used for the fit are smoothed using a superposition of a Gaussian plus one or two exponential functions, depending on the extent of the tail. The associated systematic uncertainty, evaluated by using different parametrizations, is equal to  $\pm 0.7\%$  for both  $p_T$  selections. The systematic uncertainty from the use of symmetrized templates is estimated to be  $\pm 0.6\%$  ( $\pm 0.7\%$ ) for  $p_T > 4$  (6) GeV, by comparing the results obtained in the simulation when a sum of symmetrized templates is used as pseudo-data instead of the usual randomized distribution.

**Bin size and fit upper bound:** varying the  $d_{xy}$  bin size in the range  $0.002 - 0.008$  cm accounts for a systematic uncertainty of 1.0% (2.1%) for  $p_T > 4$  (6) GeV, while varying the fit upper bound in the range  $0.15 - 0.25$  cm accounts for 0.3% (0.4%).

**Fit constraints:** the BC, BD, and CD fractions are constrained in the fit so that their ratios with respect to the fitted BB fraction in the BC and BD cases, and the fitted CC fraction in the CD case, agree with the predicted values from the MC simulation, as described in section 5. The uncertainties from this procedure include those on the rate of  $c\bar{c}$  production from gluon splitting and the muon misidentification rates in the simulation. To estimate the uncertainty, we vary the constraints on the fractions by  $\pm 50\%$  around the simulation values, which induces a difference of 1.6% (1.2%) for  $p_T > 4$  (6) GeV in

Source	Uncertainty	
	$p_T > 4 \text{ GeV}$	$p_T > 6 \text{ GeV}$
Model dependency	5.5	5.1
Impact parameter resolution	2.7	4.0
Monte Carlo precision and fit method	2.2	2.7
Efficiencies and acceptance	6.1	6.2
Total	8.9	9.4

**Table 5.** Systematic uncertainties on the cross-section measurements in percent for the two  $p_T$  limits.

the fitted BB fraction. Since the 2D fit neglects the mixing of prompt and non-prompt muon components (PB, PC, PD), an additional systematic uncertainty is computed by assigning to the BB fraction an uncertainty equal to the missing contributions, as found in the simulation, of 0.7% (0.6%) for  $p_T > 4$  (6) GeV.

The total systematic uncertainty related to the fit method is found by adding the contributions in quadrature, which gives 2.2% (2.7%) for  $p_T > 4$  (6) GeV.

As a consistency check, an unconstrained 1D fit is performed on the  $d_{xy}$  distribution of the muons selected for the analysis, using the templates derived in section 4.1. The results are in agreement within the quoted systematic uncertainty with those from the 2D fit.

#### 7.4 Efficiencies from data and the dimuon invariant mass extrapolation

The statistical uncertainties of the efficiencies found from the T&P method of 6.0% (5.2%) for  $p_T > 4$  (6) GeV are taken as the systematic uncertainty on this procedure.

The dimuon invariant mass distribution predicted from the MC simulation, scaled to the fitted fractions in the data, does not agree with the observed distribution within the uncertainties. Attributing the entire difference as being due to extra  $b\bar{b}$  signal events, gives us the largest systematic uncertainty from this source of 1.1% (3.3%) for  $p_T > 4$  (6) GeV.

#### 7.5 Overall systematic uncertainty

All the systematic uncertainties described so far are summarized in table 5 and sum in quadrature to 8.9% (9.4%) for  $p_T > 4$  (6) GeV, with the larger contribution coming from the data-driven efficiency determination with the T&P method. The last source of systematic uncertainty to be considered is related to the integrated luminosity of the dimuon data sample, which is determined with a 4% uncertainty [16]. The total systematic uncertainty is therefore 9.8% for  $p_T > 4$  GeV and 10.2% for  $p_T > 6$  GeV.

## 8 Results and comparison with QCD predictions

The  $pp \rightarrow b\bar{b}X \rightarrow \mu\mu X'$  cross section within the accepted kinematic range is determined from the observed number of dimuon events passing the event selection  $\mathcal{N}_{\mu\mu}$ , the fraction of

signal events in the dimuon sample  $f_{\text{BB}}$ , the average efficiency for the trigger, muon identification, and event selection  $\epsilon$ , weighted by the  $p_{\text{T}}$  and  $\eta$  distributions, and the integrated luminosity  $\mathcal{L}$  according to the relation:

$$\sigma(\text{pp} \rightarrow \text{bb}\bar{\text{X}} \rightarrow \mu\mu\text{X}', p_{\text{T}} > 4 \text{ or } 6 \text{ GeV}, |\eta| < 2.1) = \frac{\mathcal{N}_{\mu\mu} \cdot f_{\text{BB}}}{\epsilon \cdot \mathcal{L}}. \quad (8.1)$$

By applying eq. (8.1) we measure:

$$\begin{aligned} \sigma(\text{pp} \rightarrow \text{bb}\bar{\text{X}} \rightarrow \mu\mu\text{X}', p_{\text{T}} > 4 \text{ GeV}, |\eta| < 2.1) = \\ 26.4 \pm 0.1 \text{ (stat.)} \pm 2.4 \text{ (syst.)} \pm 1.1 \text{ (lumi.) nb} \end{aligned} \quad (8.2)$$

and

$$\begin{aligned} \sigma(\text{pp} \rightarrow \text{bb}\bar{\text{X}} \rightarrow \mu\mu\text{X}', p_{\text{T}} > 6 \text{ GeV}, |\eta| < 2.1) = \\ 5.12 \pm 0.03 \text{ (stat.)} \pm 0.48 \text{ (syst.)} \pm 0.20 \text{ (lumi.) nb.} \end{aligned} \quad (8.3)$$

The cross sections predicted by the leading-order PYTHIA simulation are 48.2 nb for  $p_{\text{T}} > 4 \text{ GeV}$  and 9.2 nb for  $p_{\text{T}} > 6 \text{ GeV}$ , where the statistical uncertainties are negligible. That PYTHIA predicts a cross section value higher than the one measured in data has been seen in previous analyses [11], and is confirmed by our present findings.

The next-to-leading-order event generator MC@NLO [34] is used to estimate the NLO QCD prediction for this measurement, with the CTEQ6.6 PDF and a b-quark mass of 4.75 GeV. The generator is interfaced with HERWIG [35] for parton showering, hadronization, and decays. The systematic uncertainty for this prediction is obtained by varying the b-quark mass between 4.5 GeV and 5 GeV, and by changing the PDF to the MSTW2008 [36] set. The scale uncertainty is estimated by varying the QCD renormalization and factorization scales independently from half to twice their default values, as in ref. [37].

The predicted cross sections are:

$$\sigma_{\text{MC@NLO}}(\text{pp} \rightarrow \text{bb}\bar{\text{X}} \rightarrow \mu\mu\text{X}', p_{\text{T}} > 4 \text{ GeV}, |\eta| < 2.1) = 19.7 \pm 0.3 \text{ (stat.)} \begin{matrix} +6.5 \\ -4.1 \end{matrix} \text{ (syst.) nb} \quad (8.4)$$

and

$$\sigma_{\text{MC@NLO}}(\text{pp} \rightarrow \text{bb}\bar{\text{X}} \rightarrow \mu\mu\text{X}', p_{\text{T}} > 6 \text{ GeV}, |\eta| < 2.1) = 4.40 \pm 0.14 \text{ (stat.)} \begin{matrix} +1.10 \\ -0.84 \end{matrix} \text{ (syst.) nb.} \quad (8.5)$$

Both predictions are compatible with our results within the uncertainties of the NLO calculations and the measurements.

## 9 Summary

A measurement of the inclusive cross section for the process  $\text{pp} \rightarrow \text{bb}\bar{\text{X}} \rightarrow \mu\mu\text{X}'$  at  $\sqrt{s} = 7 \text{ TeV}$  has been presented, based on an integrated luminosity of  $27.9 \pm 1.1 \text{ pb}^{-1}$  collected by the CMS experiment at the LHC. Selecting pairs of muons each with pseudorapidity  $|\eta| < 2.1$ , the value  $\sigma(\text{pp} \rightarrow \text{bb}\bar{\text{X}} \rightarrow \mu\mu\text{X}') = 26.4 \pm 0.1 \text{ (stat.)} \pm 2.4 \text{ (syst.)} \pm 1.1 \text{ (lumi.) nb}$  was obtained for muons with transverse momentum  $p_{\text{T}} > 4 \text{ GeV}$ , and  $5.12 \pm 0.03 \text{ (stat.)} \pm 0.48 \text{ (syst.)} \pm 0.20 \text{ (lumi.) nb}$  for muons with  $p_{\text{T}} > 6 \text{ GeV}$ . This result is the most precise measurement of this quantity yet made at the LHC.

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