Heavy flavor production in CMS

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Abstract

Measurements of heavy flavor production in $pp$ collisions at $\sqrt{s} = 7.0$ TeV recorded at the CMS experiment are presented. Double differential cross sections with respect to transverse momentum and rapidity are shown for $J/\psi$ and $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. The inclusive open beauty rate is measured with two different techniques, including a study of the angular correlations between $b$ jets in events with two identified $b$ jets. Lastly, the $B^+$, $B^0$, and $B^0_s$ production rates are measured from the reconstruction of exclusive final states.

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HEAVY FLAVOR PRODUCTION AT CMS

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1 Introduction

Cross sections for heavy quark production in hard scattering interactions provide an interesting testing ground for QCD calculations. Theoretically, large uncertainties remain due to the dependence on the renormalization and factorization scales. Measurements from the LHC at the center of mass energy of \( \sqrt{s} = 7.0 \) TeV provide new opportunities to test and further our understanding of the heavy quark production mechanisms.

CMS is a general purpose experiment at the Large Hadron Collider. The main detector components used in these analyses are the silicon tracker and the muon systems. The silicon tracker measures charged particles in the pseudorapidity range \( |\eta| < 2.5 \) within a 3.8 T field of the superconducting solenoid. It provides an impact parameter resolution of \( \sim 15 \) \( \mu \)m and a \( p_T \) resolution of about 1.5\% for particles with transverse momenta up to 100 GeV. Muons are measured in the pseudorapidity range \( |\eta| < 2.4 \) with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers.

2 Onia production

The first heavy flavor production measurements at CMS were made by reconstructing \( J/\psi^2 \) and \( \Upsilon^3 \) mesons in their decays to two muon final states. Candidates are formed by fitting pairs of oppositely-signed muons to a common vertex and event yields are obtained by fitting invariant mass distributions. The observed yields are corrected for detector acceptance, reconstruction inefficiencies, and trigger inefficiencies in bins of candidate transverse momentum \( p_T \) and rapidity \( y \) to measure double differential cross sections. The fraction of \( J/\psi \) mesons produced from long-lived \( B \) decays is also measured by fitting the lifetime distribution of the reconstructed \( J/\psi \) mesons. The three lowest \( \Upsilon \) states are all visible due to the excellent mass resolution of the CMS detector. The yields of the \( \Upsilon(2S) \) and \( \Upsilon(3S) \) states are measured with respect to the \( \Upsilon(1S) \) state as functions of the \( \Upsilon p_T \) and \( y \).
Two independent techniques are used to measure inclusive beauty production. The first technique makes use of semi-muonic decays of $B$ hadrons.\(^4\) Reconstructed charged tracks with $p_T > 300\text{ MeV}$ are clustered into jets with the anti-$k_T$ algorithm with $R = 0.5$. Events are then selected where the jet contains a reconstructed muon with $p_T > 6\text{ GeV}$ and $|\eta| < 2.1$. For jets originating from $b$ quarks, the decay kinematics demand that, on average, the muon direction will be further displaced from the jet direction than for muons from lighter jets ($udscg$). The observed distribution of the quantity $p_T^{ref} = |\vec{p}_\mu \times \vec{p}_j|/|\vec{p}_\mu|$ is fit to separate signal $b$ jets from background. Templates for the signal and background $p_T^{ref}$ shapes are obtained from simulation (for signal and $c$ quark backgrounds) or data ($uds$ quark and gluon backgrounds) and are crosschecked in data for those obtained from simulation.

The inclusive $b$-quark production cross section is obtained by correcting the measured $b$-quark yield by the selection efficiency in bins of muon $p_T$ as shown in Figure 1. The total visible cross section is measured to be $(1.32 \pm 0.01(\text{stat.}) \pm 0.30(\text{syst.}) \pm 0.15(\text{lumi.})) \mu b$ for $b$-jet decays with a muon with $p_T > 6\text{ GeV}$ and $|\eta| < 2.1$. The measured cross section is larger than that predicted by MC@NLO $(0.95^{+0.42}_{-0.24}\mu b)$ and smaller than that predicted by Pythia $(1.9\mu b)$.

The second technique used to measure the inclusive beauty production rate relies on the identification of displaced secondary vertices within reconstructed jets to tag them as $b$ jets.\(^5\) An inclusive jet sample is used to search for jets containing a secondary vertex. The secondary vertex is required to contain at least three charged tracks and the vertex must be well separated from the primary event vertex since long-lived $B$ hadrons give rise to a larger separation than lighter jets. A separation cut is chosen such that $\approx 60\%$ efficiency is obtained with $\approx 0.1\%$ rate for mistagging light jets as $b$ jets.

The production of $b$ jets is calculated as a double differential cross section versus jet $p_T$ and $y$, where the reconstructed values have been corrected to the particle $p_T$ and $y$. The measured results are shown in Figure 1. The leading systematic uncertainties arise from the $b$-jet energy scale corrections, the data-driven uncertainties on the $b$-tagging efficiency and from the mistag rates for light jets. The overall agreement with MC@NLO is reasonable, though the modeling of the rapidity dependence shows discrepancies between the data and simulation.
Figure 2: Correlation results between reconstructed pairs of $b$-tagged jets compared to Pythia simulation (left) and other theoretical predictions normalized to the Pythia result (right).

4  $b\bar{b}$ correlations

The secondary vertex finding technique also allows for the study of correlations between $b\bar{b}$ pairs. The correlations between two $B$ candidates can provide useful information about the $b\bar{b}$ pair production mechanism, where pairs produced from gluon splitting are expected to have small separations, while those from flavor creation are expected to dominate at large separation. Secondary vertices are reconstructed with at least three charged tracks and a 3D flight length from the primary vertex greater than five times its uncertainty. The flight length of the $B$ candidate is computed as the direction from the primary vertex to the secondary vertex. For events with exactly two such identified secondary vertices, the quantity $\Delta R$ is computed, where $\Delta \phi$ is the difference in polar angle and $\Delta \eta$ is the difference in pseudorapidity between the two $B$ candidate directions.

Results are shown in Figure 2 for events where both $B$ candidates have $p_T > 15$ GeV and $|\eta| < 2.0$. The reconstructed jet momentum is corrected back to the true value, and the results are reported for three different regions of leading jet $p_T$. The results are normalized to the region with $\Delta R > 2.4$, which is expected to be better understood theoretically. The data show an excess at low $\Delta R$ values compared to the prediction from Pythia suggesting that the contribution from gluon splitting is larger than expected.

5  Exclusive $B$ production

A fully exclusive reconstruction technique is used to measure the cross sections for $B^+$, $B^0$, and $B_s$ mesons. The three species are reconstructed by fitting to a common vertex a $J/\psi$ plus a $K^+$, $K^0_S$, or a $\phi$, respectively. The $J/\psi$ mesons are reconstructed in their decays to $\mu^+\mu^-$, while the $K^0_S$ and $\phi$ mesons are reconstructed in their decays to $\pi^+\pi^-$ and $K^+K^-$, respectively. The dominant backgrounds in each analysis arise from events with a prompt $J/\psi$. To distinguish the signals from these backgrounds, a two-dimensional fit to the $B$ mass and $B$ lifetime is used for each $B$ species to extract the signal yield in bins of $B$ $p_T$ and $y$. The fitted lifetimes in all three cases are consistent with the known values.

For $B^+$, 912 signal events are observed in 6 pb$^{-1}$ of data, while 809 and 549 events are observed for $B^0$ and $B_s^0$ in 40 pb$^{-1}$. The fitted signal yields are corrected for the detector acceptance and reconstruction and trigger inefficiencies to calculate the cross section. For the $B^+$ and $B^0$ measurements, candidates with $B$ $p_T > 5$ GeV are used, while for $B_s^0$, $p_T > 8$ GeV.
are considered. For $B^+$ and $B^0_s$ ($B^0$) $B$ candidates are required to have $|y| < 2.4$ (2.2). The total visible cross sections are measured to be $(28.1 \pm 2.4 \pm 2.0 \pm 3.1) \mu b$ for $B^+$ and $(33.2 \pm 2.5 \pm 3.5) \mu b$ for $B^0$, where the first error is statistical, the second is systematic, and the third for $B^+$ is the uncertainty in the luminosity, while the luminosity uncertainty is included in the systematic for $B^0$. The total visible cross section times the branching fraction for $B^0_s \rightarrow J/\psi \phi$ is measured to be $(6.9 \pm 0.6 \pm 0.5 \pm 0.3) \text{nb}$ for $B^0_s$. In all cases, the observed cross sections are found to be lower than those predicted by Pythia and higher than those predicted by MC@NLO, though compatible within uncertainties. The results for $B^0$ and $B^0_s$ versus $p_T$ are shown in Figure 3.

6 Conclusions

A variety of measurements of heavy flavor production have been made by CMS in $pp$ collisions at $\sqrt{s} = 7$ TeV. These include $J/\psi$ and $\Upsilon$ double-differential production cross sections, measurements of inclusive beauty production from multiple complementary methods, including $b\bar{b}$ correlation measurements, and three exclusive $B$ production cross section measurements. While the agreement with MC models is generally good, none of the theoretical models considered yet describe all of the features observed in the data.

References

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