ATLAS/CMS b-hadron production

Zheng Wang for the ATLAS, and CMS collaborations ( B physics )

Abstract

The ATLAS and CMS analyses of B productions at $\sqrt{s} = 7$ TeV and 8 TeV are summarized. The production cross section measurements include inclusive b production and exclusive production measurements of $\Upsilon(1S, 2S, 3S)$, $B^+$, $B^0$, $B^0_s$, $B^\pm$, $\Lambda_b$. The ATLAS and CMS search results of new b-quark states with RUN-I data are also introduced. Observation of the rare $B^0_s \rightarrow \mu^+\mu^-$ decay from CMS and combined result of CMS and LHCb data are presented.

Presented at LHCP2015 The 3rd Conference on Large Hadron Collider Physics
ATLAS/CMS: b-hadron production

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Abstract. The ATLAS and CMS analyses of b-hadron production at $\sqrt{s} = 7$ TeV and 8 TeV are summarized. The production cross section measurements include inclusive b production and exclusive production measurements of $\Upsilon (1S, 2S, 3S)$, $B^+, B^0, B_s^0, B^\pm, \Lambda_b$. The ATLAS and CMS search results of new b-quark states with RUN-I data are also introduced. Observation of the rare $B^0_s \rightarrow \mu^+\mu^-$ decay from CMS and combined result of CMS and LHCb data are presented.

INTRODUCTION

Production of hadrons containing the b-quark has been predicted with NLO (Next-Leading Order) accuracy for more than twenty years. However, the dependence on the factorization and renormalization scales, and on the value of $m_b$ results in theoretical uncertainties of up to 40%. The large production cross sections for b-hadron particles in $pp$ collisions at LHC energies provides opportunities for testing the perturbative and non-perturbative QCD model predictions on the b-hadron production and fragmentation accurately, and studying the dynamics of heavy quarks inside b-hadrons, decay models and spectroscopy. It is also possible for physicists to search for some quarkonium-like exotic states and other new physics phenomena.

The detailed description of the CMS and ATLAS detectors, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [1] [2] The ATLAS and CMS detectors have excellent capabilities to reconstruct b-hadron decays due to the highly efficient muon detection system and the high-resolution silicon tracker. For both experiments, the trackers have good momentum, impact parameter and vertex resolutions, and good b-tagging capability. ATLAS and CMS also have robust muon identification performance. Muon detection down to low $p_T$ (transverse momentum) and low mis-identification of muon particle. In the LHC RUN-I running, ATLAS and CMS have collected the largest $pp$ collision data samples, which corresponds to integrated luminosities of $\sim 5$ fb\textsuperscript{-1} at $\sqrt{s} = 7$ TeV and $\sim 20$ fb\textsuperscript{-1} at $\sqrt{s} = 8$ TeV, respectively. Therefore, ATLAS and CMS may fully exploit the highest Beauty Flavor production with high accuracy.

With the highest LHC luminosities, and access regimes and phase space, ATLAS and CMS analyses on B production are complementary to those by B factories [3], experiments on Tevatron [4] and LHCb [5].

MEASUREMENT OF PRODUCTION CROSS SECTION

This section introduces ATLAS and CMS results of inclusive and exclusive b-hadron reconstruction measurements, angular analysis of $B^0 \rightarrow K^0\mu^+\mu^-$, measurements of the CP-violating weak phase $\phi$ and of the decay width difference $\Delta\Gamma$, using the $B^0 \rightarrow J/\psi\phi(1020)$ decay channel. The measurement of the parity-violating asymmetry parameter $\alpha_b$ and of the helicity amplitudes for the decay $\Lambda_b^0 \rightarrow J/\psi\Lambda^0$ at $\sqrt{s} = 7$ TeV and 8 TeV is also introduced.

Inclusive b production measurements

Inclusive b production measurements were performed by ATLAS and CMS at the beginning of LHC running from 2010. The typical data samples used for the inclusive process measurements are from $\sim nb^{-1}$ to $\sim pb^{-1}$. CMS measured differential production cross sections of inclusive b-hadron with muon with $85 nb^{-1}$ data at 7 TeV [6], the
inclusive \( bb \to X \to \mu \mu X \) with 27.9 pb\(^{-1}\) data at 7 TeV [7], and the inclusive b-jet production with 34 pb\(^{-1}\) data at 7 TeV [8]. ATLAS measured the production cross section of hadrons containing the b-quark using decays to \( D^\pm \mu^- X \) final states [9], as well as the inclusive and di-jet cross-sections of b-jets at 7 TeV [10]. Differential cross sections have been measured as a function of muon (b-jet) transverse momentum and (pseudo)rapidity. The results of inclusive cross section measurement were compared with MC@NLO, POWHEG, Pythia predictions. Predictions are in agreement with ATLAS and CMS results within uncertainties.

Analyses of exclusive b-hadron production by ATLAS and CMS

Total and differential cross sections \( \sigma / dp_T^0 \) and \( \sigma / dyB \) for \( B^+ \) mesons produced in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV are measured by CMS [11]. The data correspond to an integrated luminosity of 5.8 pb\(^{-1}\) collected by the CMS experiment. The exclusive decay \( B^+ \to J/\psi K^+ \), with \( J/\psi \to \mu \mu \), is used to detect \( B^+ \) mesons and to measure the production cross section as a function of \( p_T^0 \) and \( y^0 \). The total cross section for \( p_T^0 > 5 \) GeV and \( |y^0| < 2.4 \) is measured to be \( 28.1 \pm 2.4 \) (stat.) \( \pm 2.0 \) (sys.) \( \pm 3.1 \) (lum.) mb. The result is in reasonable agreement with theoretical predictions in terms of shape, but has an absolute normalization approximately 1.5 times larger than the MC@NLO calculation. ATLAS as well measured \( B^+ \) differential production cross-section with 2.4 fb\(^{-1}\) data at \( \sqrt{s} = 7 \) TeV [12]. The integrated \( B^+ \) production cross-section in the kinematic range \( 9 \) GeV < \( p_T^0 < 120 \) GeV and \( |y| < 2.25 \) is measured to be \( 10.6 \pm 0.3 \) (stat.) \( \pm 0.7 \) (sys.) \( \pm 0.2 \) (lum.) \( \pm 0.4 \) (Br) \( \mu \bar{\mu} \). The next-to-leading-order QCD calculation is compatible with the measured differential cross-section. The predictions are obtained within the Powheg and MC@NLO frameworks and are quoted with an uncertainty from renormalization and factorization scales and b-quark mass of the order of 20\%-40\%. Within these uncertainties, Powheg+Pythia is in agreement with the measured integrated cross-sections and with the dependence on \( p_T \) and \( y \). At low \( |y| \), MC@NLO+Herwig predicts a lower production cross-section and a softer \( p_T \) spectrum than the one observed in data, while for \( |y| > 1 \) the predicted \( p_T \) spectrum becomes harder than observed in data. The FONLL calculation for \( \sigma(pp \to bX) \) is compared to the data, assuming a hadronisation fraction \( f_{b \to \Lambda}\) of \((40.1 \pm 0.8)\% \) [13], and is in good agreement with the measured differential cross-section \( \sigma / dp_T \), within the theoretical uncertainty.

The CMS measured of \( B^0 \) and \( B^0 \) differential production cross sections \( \sigma / dp_T^0 \) and \( \sigma / dyB \) with 40 pb\(^{-1}\) data at \( \sqrt{s} = 7 \) TeV [14] [15]. The \( B^0 \) meson are reconstructed in the exclusive final state \( J/\psi K_S^0 \), with \( J/\psi \to \mu \mu \) and \( K_S^0 \to \pi^+ \pi^- \), while \( B^0 \) are reconstructed from the decay \( B^0 \to J/\psi \phi \) with \( J/\psi \to \mu \mu \), \( \phi \to K^+ K^- \). The integrated \( B^0 \) cross section times \( B^0 \to J/\psi \phi \) branching fraction in the range \( 8 < p_T^0 < 50 \) GeV/c and \( |y| < 2.4 \) is measured to be \( 6.9 \pm 0.6 \) (stat.) \( \pm 0.6 \) (sys.) nb. For the \( B^0 \) with \( p_T^0 > 5 \) GeV and \( |y| < 2.2 \), the total cross section is measured to be \( 33.2 \pm 2.5 \) (stat.) \( \pm 3.5 \) (sys.) \( \mu \bar{\mu} \). The cross sections are compared with predictions based on perturbative QCD calculations at next-to-leading order. The \( B^0 \) result lies between the theoretical predictions of MC@NLO \((4.6^{+1.7}_{-1.3} \pm 1.4 \) nb) and PYTHIA \((9.4 \pm 2.8 \) nb), where the last uncertainty is from the \( B^0 \to J/\psi \phi \) branching fraction. CMS cross-section measurements of \( B^0 \) and \( B^0 \) production in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV gave values between the two theory predictions, indicating internal consistency amongst the three different \( B \)-meson \((B^+, B^0, B^0)\) results.

At ATLAS, the ratio of b-quark fragmentation fractions \( f_s / f_d \) was measured in \( pp \) collisions with 2.47 fb\(^{-1}\) data at \( \sqrt{s} = 7 \) TeV [16]. From the observed yields of 6640 ± 100 (stat.) \( \pm 220 \) (sys.) \( B_s^0 \to J/\psi \phi \) events and 36290 ± 320 (stat.) \( \pm 650 \) (sys.) \( B_d^0 \to J/\psi K^{*0} \) events, the quantity \( f_s / f_d = \frac{\text{BR}(B_s^0 \to J/\psi \phi)}{\text{BR}(B_d^0 \to J/\psi K^{*0})} \) is estimated to be 0.199 ± 0.004 (stat.) \( \pm 0.010 \) (sys.) Figure 1, taken from [16], shows the measurements of \( f_s / f_d \) versus \( B \) meson \( p_T \) for CDF, LHCb, ATLAS and LEP experiments. ATLAS measurement agrees with results from LHCb, CDF, and the LEP average [17]. The ATLAS data show no dependence on \( p_T \) nor on \( |y| \) within the kinematic range tested.

CMS measured the ratio \( \frac{\text{BR}(B_s^0 \to J/\psi \phi(980))}{\text{BR}(B_d^0 \to J/\psi \phi(1020))} \) using the data of integrated luminosity of 5.3 fb\(^{-1}\) at \( \sqrt{s} = 7 \) TeV [18]. Total 873 ± 49 events of \( B_s^0 \to J/\psi (\mu^+ \mu^-) \) \( \phi (\pi^+ \pi^-) \) and 8377 ± 107 events of \( B_d^0 \to J/\psi (\mu^+ \mu^-) \phi (K^+ K^-) \) are observed. The ratio of the branching fraction of \( B_s^0 \to J/\psi (\mu^+ \mu^-) \phi (K^+ K^-) \) to the branching fraction of \( B_d^0 \to J/\psi (\mu^+ \mu^-) \phi (K^+ K^-) \), \( R_{B_d/B_s} \), is determined to be \( \frac{\text{BR}(B_s^0 \to J/\psi \phi(980))}{\text{BR}(B_d^0 \to J/\psi \phi(1020))} \) = 0.140 ± 0.013 (stat) \( \pm 0.018 \) (sys.). This result is consistent with the theoretical prediction of about 0.2 [19] and with previous measurements [20].

The\( B_s^0 \to J/\psi \phi \) process is also a “golden” mode to explore CP violation because it is a flavor non-specific and experimentally clean final state. CMS measured the CP-violating weak phase \( \phi_s \) of the \( B_s^0 \) meson and the decay width difference \( \Delta \Gamma_s \) of the \( B_s^0 \) light and heavy mass eigenstates using a data sample of \( B_s^0 \to J/\psi \phi(1020) \to \mu^+ \mu^- K^+ K^- \) decays at a centre-of-mass energy of 8 TeV [21]. A total of 49200 reconstructed \( B_s^0 \) decays are used to extract the values of \( \phi_s \) and \( \Delta \Gamma_s \) by performing a time-dependent and flavour tagged angular analysis of the \( \mu^+ \mu^- K^+ K^- \) final
state. ATLAS’s measurement is based on 4.9 fb\(^{-1}\) of integrated luminosity at \(\sqrt{s} = 7\) TeV. Table 1 shows the ATLAS, CMS, as well as LHCb [23] measurements of CP-violating weak phase \(\phi_s\) and the decay width difference \(\Delta\Gamma_s\). It may be seen that the measured value of \(\phi_s\) agrees with the SM prediction [24], in which it is assumed that subleading contributions to the decay amplitude are negligible. Results confirm \(\Delta\Gamma_s\) to be nonzero, with a value consistent with theoretical predictions. Three experiments provide independent reference measurements of \(\phi_s\) and \(\Delta\Gamma_s\), and contribute to improving the overall precision of these quantities and thereby probing the SM further.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\Delta\Gamma_s) (ps(^{-1}))</th>
<th>(\phi_s) (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (4.9) fb(^{-1}) [22]</td>
<td>0.053 ± 0.021 ± 0.010</td>
<td>0.12 ± 0.25 ± 0.5</td>
</tr>
<tr>
<td>CMS (20) fb(^{-1}) [21]</td>
<td>0.095 ± 0.013 ± 0.007</td>
<td>-0.075 ± 0.097 ± 0.031</td>
</tr>
<tr>
<td>LHCb (3) fb(^{-1}) [23]</td>
<td>0.0805 ± 0.0091 ± 0.0032</td>
<td>-0.058 ± 0.049 ± 0.006</td>
</tr>
</tbody>
</table>

Using 20.5 fb\(^{-1}\) pp collision data at \(\sqrt{s} = 8\) TeV, CMS studied the angular distributions and the differential branching fraction of the decay \(B^0 \to K^0\mu^+\mu^-\). In the analysis, The \(K^{*0}\) is reconstructed through its decay to \(K^+\pi^-\), and the \(B^0\) is reconstructed by fitting the two identified muon tracks and the two hadron tracks to a common vertex. From 1430 signal decays, the forward-backward asymmetry of the muons (\(A_{FB}\)), the \(K^{*}(892)^0\) longitudinal polarization fraction (\(F_L\)), and the differential branching fraction are determined as a function of the dimuon invariant mass squared, \(dB/dq^2\). Table 2 shows the measurements from CMS (the 7 TeV [25], 8 TeV results [26], and the combination), LHCb [27], BaBar [28], CDF [29], and Belle [30] of \(F_L\), \(A_{FB}\), and \(dB/dq^2\) in the region \(1 < q^2 < 6\) GeV\(^2\) for the decay \(B^0 \to K^{0}\mu^+\mu^-\). CMS results are among the most precise to date and are consistent with Standard Model (SM) predictions and previous measurements.

For the \(B^\pm\) meson, CMS measured the ratio of the cross sections times branching fractions for \(B^\pm \to J/\psi K^\pm\) at a center-of-mass energy of 7 TeV and integrated luminosity of 5.1 fb\(^{-1}\) [33]. The analysis, performed for \(B^\pm\) mesons with \(p_T > 15\) GeV and in the central rapidity region \(|y| < 1.6\), gives a measured ratio of \(R_{\psi/K} = [0.48 \pm 0.05(stat) \pm 0.03(syst) \pm 0.05(syst)]\). A similar measurement from LHCb in the kinematic region \(p_T > 4\) GeV, \(2.5 < y < 4.5\) gives [0.68 ± 0.10(stat) ± 0.03(syst) ± 0.05(syst)] \% [34]. The two measurements, performed in different kinematic regions, are expected to differ because of the softer \(p_T\) distribution of the \(B^*\) with respect to that of the \(B^0\), implying a lower value of the ratio at higher \(p_T\). The measurements are consistent with this expectation. Measurements of the production cross section times branching fraction for \(B^\pm \to J/\psi l^\pm\nu\) relative to that

![Figure 1](image-url)
for $B^+ \to J/\psi K^*$ are also available from the CDF experiment in the kinematic region $p_T > 4$ GeV and $|y| < 1$. With the present $B^+_c(p_T,|y|)$ coverage, these experimental results can give guidance to improve the theoretical calculations still affected by large uncertainties and constrain the various $B^+_c$ production models. The ratio of the $B^+_c \to J/\psi\pi^+\pi^-$ and $B^+_c \to J/\psi\pi^+$ branching fractions has been measured to be $B_{B_c} = 2.55 \pm 0.80$ (stat) $\pm 0.33$ (syst) $\pm 0.01(|\tau_{B_c}|)$, which is in good agreement with the result from the LHCb experiment, $2.41 \pm 0.30$ (stat) $\pm 0.33$ (syst) [35], and represents its first confirmation. This measurement can be compared with the theoretical predictions, which assume factorization into $B_{B_c} \to J/\psi W^+ W^*$ and $W^+ W^* \to n\pi^*$ ($n = 1, 2, 3, 4$). In particular, Ref. [36] predicts 1.5 for the ratio, whereas Ref. [37] predicts three different values, 1.9, 2.0, and 2.3, depending on the chosen set of $B_{B_c}$ meson form factors. More precise measurements are needed to determine if one of the predictions is favored by the data. The model-independent method implemented for the efficiency evaluation of the five-body final state can be considered in future high-statistics analyses to reduce systematic uncertainties associated with the unknown multibody decay dynamics.

For the $b$-baryons, CMS measured the differential cross sections times branching fraction $\sigma dp_T^{\Lambda_b} \times B(\Lambda_b \to J/\psi\Lambda)$ and $\sigma dp_T^{B_c} \times B(\Lambda_c \to J/\psi\Lambda)$ for $\Lambda_b$ baryons produced in $pp$ collisions at $\sqrt{s} = 7$ TeV [38]. The measurements are given for $p_T^{\Lambda_b} > 10$ GeV and $|y^{\Lambda_b}| < 2.0$. The $p_T^{\Lambda_b}$ distribution falls faster than both the measured $p_T$ spectra from $b$ mesons and the predicted spectra from the NLO MC POWHEG and the leading-order MC PYTHIA. The measured value of $\sigma(\Lambda_b) \times B(\Lambda_b \to J/\psi\Lambda)$ for $p_T^{\Lambda_b} > 10$ GeV and $|y^{\Lambda_b}| < 2.0$ is $1.16 \pm 0.06$ (stat) $\pm 0.12$ (syst) nb, and the integrated $\sigma(\Lambda_b)/\sigma(\Lambda_c)$ ratio is $1.02 \pm 0.07$ (stat) $\pm 0.09$ (syst). The total cross section and rapidity distribution are consistent with both predictions within large uncertainties. The measured $\sigma(\Lambda_b)/\sigma(\Lambda_c)$ ratio is consistent with unity and constant as a function of both $p_T^{\Lambda_b}$ and $|y^{\Lambda_b}|$.

At ATLAS, measurements of the parity-violating decay asymmetry parameter $a_0$ and the helicity amplitudes for the decay $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(\pi^+\pi^-)$ has been performed using the $4.6 fb^{-1}$ $pp$ collisions data at a center-of-mass energy of 7 TeV [39]. The measured values of $a_0$, and the ratio parameters of the helicity amplitudes $k_+ \text{ and } k_- \text{ are } a_0 = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst}) \text{ and } k_+ = 0.21^{+0.14}_{-0.21}(\text{stat}) \pm 0.13(\text{syst}) \text{ and } k_- = 0.13^{+0.10}_{-0.19}(\text{stat}) \pm 0.15(\text{syst}), \text{ corresponding to the value of the helicity parameters } [a_{+/}] = 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst}), [a_{-}] = 0.59^{+0.68}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}), [b_{+}] = 0.79^{+0.04}_{-0.03}(\text{stat}) \pm 0.02(\text{syst}), [b_{-}] = 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst}), \text{ The } \Lambda_b^0 \text{ decay has large amplitudes } [a_{+/}] \text{ and } [b_{+}], \text{ which means the negative-helicity states for } \Lambda_b^0 \text{ are preferred. The } \Lambda_b^0 \text{ and } J/\psi \text{ from } \Lambda_b^0 \text{ decay are highly polarized. Adding in quadrature the statistical and systematic uncertainties, the observed value of } a_0 \text{ is consistent with the measurement } a_0 = 0.05 \pm 0.17(\text{stat}) \pm 0.07(\text{syst}) \text{ by LHCb [40] at the level of one standard deviation. However, it is not consistent with the expectation from pQCD (a_0 \text{ in the range from } -0.17 \text{ to } -0.14) [41], and HQET (a_b = 0.78) [42] at a level of about 2.6 and 2.8 standard deviations, respectively.}

The ATLAS experiment observed the decay $\Lambda_b^0 \to \psi(2S)\Lambda^0$ at $\sqrt{s} = 8$ TeV using an integrated luminosity of $20.6 fb^{-1}$ data [43]. The $J/\psi$ and $\psi(2S)$ mesons are reconstructed in their decays to a muon pair, while the $\Lambda^0 \to \pi^+\pi^-\pi^+$ decay is exploited for the $\Lambda_b^0$ baryon reconstruction. The $\Lambda_b^0$ baryons are reconstructed with transverse momentum.

**TABLE 2.** Measurements from CMS, LHCb, BaBar, CDF, and Belle of $F_L$, $A_{FB}$, and $dB/dq^2$ in the region $1 < q^2 < 6$ GeV$^2$ for the decay $B^0 \to K^{(*)}\mu^+\mu^-$.  

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$F_L$</th>
<th>$A_{FB}$</th>
<th>$dB/dq^2$ $(10^{-8}$ GeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS (7 TeV) [25]</td>
<td>$0.68 \pm 0.10 \pm 0.02$</td>
<td>$-0.07 \pm 0.12 \pm 0.01$</td>
<td>$4.4 \pm 0.6 \pm 0.4$</td>
</tr>
<tr>
<td>CMS (8 TeV) [26]</td>
<td>$0.72 \pm 0.05 \pm 0.05$</td>
<td>$-0.15^{+0.10}_{-0.08} \pm 0.03$</td>
<td>$3.6 \pm 0.3 \pm 0.3$</td>
</tr>
<tr>
<td>CMS (7 TeV + 8 TeV)</td>
<td>$0.71 \pm 0.06$</td>
<td>$-0.12^{+0.07}_{-0.08}$</td>
<td>$3.8 \pm 0.4$</td>
</tr>
<tr>
<td>LHCb [27]</td>
<td>$0.65^{+0.08}_{-0.07} \pm 0.03$</td>
<td>$-0.17 \pm 0.06 \pm 0.01$</td>
<td>$3.4 \pm 0.3^{+0.4}_{-0.5}$</td>
</tr>
<tr>
<td>BaBar [28]</td>
<td>$</td>
<td>$</td>
<td>$-$</td>
</tr>
<tr>
<td>CDF [29]</td>
<td>$0.69^{+0.10}_{-0.21} \pm 0.08$</td>
<td>$0.29^{+0.20}_{-0.23} \pm 0.07$</td>
<td>$3.2 \pm 1.1 \pm 0.3$</td>
</tr>
<tr>
<td>Belle [30]</td>
<td>$0.67 \pm 0.23 \pm 0.05$</td>
<td>$0.26^{+0.32}_{-0.32} \pm 0.07$</td>
<td>$3.0^{+0.9}_{-0.8} \pm 0.2$</td>
</tr>
<tr>
<td>SM (LCSR) [31]</td>
<td>$0.79^{+0.09}_{-0.12}$</td>
<td>$-0.02^{+0.03}_{-0.02}$</td>
<td>$4.6^{+0.7}_{-1.7}$</td>
</tr>
<tr>
<td>SM (Lattice) [32]</td>
<td>$0.73^{+0.08}_{-0.10}$</td>
<td>$-0.03^{+0.04}_{-0.03}$</td>
<td>$3.8^{+0.12}_{-1.0}$</td>
</tr>
</tbody>
</table>
$p_T > 10 \text{ GeV}$ and pseudorapidity $|\eta| < 2.1$. Figure 2 shows the invariant mass distributions for the combined sample of the selected $\Lambda_b^0$ and $\bar{\Lambda}_b^0$ candidates obtained after their fits to the $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ (left) and $\bar{\Lambda}_b^0 \rightarrow \psi(2S) \bar{\Lambda}^0$ (right) at ATLAS [43].

For the $\Upsilon$ production, ATLAS measured differential production cross sections and relative production rates for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons in $pp$ collisions at $\sqrt{s} = 7 \text{ TeV}$ at the LHC up to $p_T^\Upsilon < 70 \text{ GeV}$ in the rapidity interval $|y^\Upsilon| < 2.25$ [46]. The possible impact of the $\Upsilon$ spin alignment on these measured spectra is also quantified. These measurements are compatible with measurements by the CMS and LHCb collaborations. The integrated corrected cross sections multiplied by the $\Upsilon \rightarrow \mu^+\mu^-$ branching fractions within the rapidity region $|y^\Upsilon| < 2.25$ have been measured to be $8.01 \pm 0.02 \pm 0.36 \pm 0.31 \text{ nb}$, $2.05 \pm 0.01 \pm 0.12 \pm 0.08 \text{ nb}$, and $0.92 \pm 0.01 \pm 0.07 \pm 0.04 \text{ nb}$ for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, respectively. Uncertainties correspond to statistical, systematic, and luminosity measurement effects. These cross sections are obtained assuming unpolarized production. If the production polarization is fully transverse or longitudinal with no azimuthal dependence in the helicity frame, the integrated cross sections may vary by up to $(+19, -23)\%$, $(+18, -21)\%$, and $(+17, -19)\%$, respectively, for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. If a nontrivial azimuthal dependence is considered, integrated cross sections may be significantly enhanced by a factor of 2 or more. ATLAS results compared to predictions from two theoretical approaches describing $\Upsilon$ production. Measurements find both the NNLO* CSM and the CEM predictions have some problems in describing the normalization and shape of the differential spectra. In particular, the NNLO* dramatically underestimates the rate at high transverse momenta, where the data tend to agree better with the CEM. The inclusion of $P$-wave feed-down contributions in the theoretical calculation may help to improve the description. Large scale uncertainties in these predictions allow possible contributions from color-octet terms to contribute to the production rate in addition to singlet diagrams. The differential production ratios indicate that the increase in the production of higher $\Upsilon$ states as a function of $p_T^\Upsilon$ relative to the $\Upsilon(1S)$ observed previously begins to saturate at $30-40 \text{ GeV}$. Above $\sim 40 \text{ GeV}$, the envelope of possible variations in the differential cross sections due to spin alignment is reduced to below $\pm 10\%$. This, along with the expected reduction in feeddown contributions, results in a relatively well-controlled region in which to study quarkonium production without the dominant experimental and theoretical effects that complicate such studies at lower $p_T$.

CMS collaboration measured the differential production cross sections as a function of $p_T$ for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ at $\sqrt{s} = 7 \text{ TeV}$ based on a data sample corresponding to an integrated luminosity of 4.9 fb$^{-1}$ in 2015 [47]. Figure 3 shows the $\Upsilon(nS)$ differential $p_T$ cross sections times dimuon branching fractions at CMS. The analysis selects events with dimuon rapidity $|y| < 1.2$ and dimuon transverse momentum in the range $10 < p_T < 100 \text{ GeV}$. Significantly improve the precision of the results in previously analyzed $p_T$ ranges [46] [48], and also extend the maximum $p_T$ range from 70 to 100 $\text{ GeV}$. The measurements show a transition from an exponential to a power-law behavior at $p_T = 20 \text{ GeV}$ for the three $\Upsilon$ states. Above that transition, the $\Upsilon(3S)$ spectrum is significantly harder than...
mass distribution gives a branching fraction $B$ distribution of the dimuon invariant mass, $f_b$ with data samples corresponding to integrated luminosities of 5 and 20

**FIGURE 3.** The $\Upsilon(nS)$ differential $p_T$ cross sections times dimuon branching fractions for $|y| < 1.2$ by CMS [47]. The $\Upsilon(2S)$ and $\Upsilon(3S)$ measurements are scaled by 0.1 and 0.01, respectively, for display purposes.

that of the $\Upsilon(1S)$. The ratios of the $\Upsilon(3S)$ and $\Upsilon(2S)$ differential cross sections to the $\Upsilon(1S)$ cross section show a rise as $p_T$ increases at low $p_T$, then become flatter at higher $p_T$. Combined with the CMS $\Upsilon(nS)$ polarization results [49], the new bottomonium measurements are a formidable challenge to our theoretical understanding of the production of heavy-quark bound states.

**SEARCH AND OBSERVATION FOR NEW b-STATES AND RARE DECAY**

In the SM of particle physics, tree level diagrams do not contribute to flavor-changing neutral-current (FCNC) decays. However, FCNC decays may proceed through higher-order loop diagrams, and this opens up the possibility for contributions from non-SM particles. In the SM, the rare FCNC decays $B^0_l(\bar{B}^0_l) \rightarrow \mu^+\mu^−$ have small branching fractions of $\mathcal{B}(B^0_l \rightarrow \mu^+\mu^-) = (3.57 \pm 0.30) \times 10^{-9}$, corresponding to the decay-time integrated branching fraction, and $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$ [50] [51]. Several extensions of the SM, such as supersymmetric models with nonuniversal Higgs boson masses [52], specific models containing leptoquarks [53], and the minimal supersymmetric standard model with large $\tan \beta$ [54], predict enhancements to the branching fractions for these rare decays. The decay rates can also be suppressed for specific choices of model parameters [55].

CMS searched the rare decays $B^0 \rightarrow \mu^+\mu^−$ and $\bar{B}^0 \rightarrow \mu^+\mu^−$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV [56], with data samples corresponding to integrated luminosities of 5 and 20 fb$^{-1}$, respectively. Fig. 4 shows the weighted distribution of the dimuon invariant mass, $m_{\mu^+\mu^-}$ at CMS. An unbinned maximum-likelihood fit to the dimuon invariant mass distribution gives a branching fraction $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.0^{+0.9}_{-0.6}) \times 10^{-9}$, where the uncertainty includes both statistical and systematic contributions. An excess of $B^0 \rightarrow \mu^+\mu^−$ events with respect to background is observed with a significance of 4.3 standard deviations. For the decay $B^0 \rightarrow \mu^+\mu^−$, an upper limit of $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9}$ at the 95% confidence level is determined. Both results are in agreement with the expectations from the SM. The combined analysis [57] from CMS and LHCb [58], taking advantage of their full statistical power, establishes conclusively the existence of the $B^0 \rightarrow \mu^+\mu^-$ decay and provides an improved measurement of its branching fraction. The combined fit leads to the measurements $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ and $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.4}_{-1.3}) \times 10^{-10}$, where the uncertainties include both statistical and systematic sources, the latter contributing 35% and 18% of the total uncertainty for the $B^0_s$ and $B^0$ signals, respectively. Using Wilks’ theorem [59], the statistical significance in unit of standard deviations, $\sigma$, is computed to be 6.2 for the $B^0_s \rightarrow \mu^+\mu^-$ decay mode and 3.2 for the $B^0 \rightarrow \mu^+\mu^-$ mode. The fit for the ratios of the branching fractions relative to their SM predictions yields $S_{B^0_s} = 0.76^{+0.20}_{-0.16}$ and $S_{B^0} = 3.7^{+1.6}_{-1.4}$. The measurements are compatible with the SM branching fractions of the $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ decays at the 1.2$\sigma$ and 2.2$\sigma$ level, respectively, when computed from the one dimensional hypothesis tests. Finally, the fit for the
ratio of branching fractions yields \( \mathcal{R} = 0.14^{+0.08}_{-0.06} \), which is compatible with the SM at the 2.3\( \sigma \) level. This concludes a search that started more than three decades ago, and initiates a phase of precision measurements of the properties of this decay. It also produces three standard deviation evidence for the \( B^0 \rightarrow \mu^+\mu^- \) decay.

The \( B^\pm_c \) meson was observed by CDF and D0 experiments in the semileptonic decay and semileptonic decay, and then more decay modes have been observed by LHCb experiment in LHC. Excited states of the \( B^\pm_c \) meson have not previously been observed. The spectrum and properties of the \( B^\pm_c \) family are predicted by nonrelativistic potential models, perturbative QCD, and lattice calculations [60]. Measurements of the ground and excited states through fully reconstructed channels will provide tests of the predictions of these models and ultimately the opportunity to extract information on the strong interaction potential. ATLAS investigated the distribution of the mass difference 

\[
Q = m(B^\pm_c \pi^+\pi^-) - m(B^\pm_c) - 2m(\pi^+) \]

for events with the \( B^\pm_c \) meson reconstructed in its decay to \( J/\psi\pi^\pm \) in \( pp \) collisions at the LHC [61]. The analysis is based on an integrated luminosity of 4.9 (19.2) \( fb^{-1} \) of \( pp \) collisions at a center-of-mass energy of 7 (8) TeV. The distributions of the mass difference \( Q \) in ATLAS 7 TeV and 8 TeV data are shown in Figure 6. A new state is observed at \( Q = 288.3 \pm 3.5 \pm 4.1 \) MeV (calculated as the error weighted mean of the 7 and 8 TeV mass values) corresponding to a mass of 6842 \( \pm 4(\text{stat}) \pm 5(\text{syst}) \) MeV. The significance of the observation is 5.4\( \sigma \) within the uncertainties.
the mass of the resonance corresponding to the observed structure is consistent with the predicted mass of the second S-wave state, $B_c^+ (2S)$.

**FIGURE 6.** Distributions of the mass difference $Q = m(B_c^+\pi^+\pi^-) - m(B_c^+) - 2m(\pi^+)$ for events with the $B_c^+$ meson reconstructed in it decay to $J/\psi\pi^+$ at 7 TeV (left) and 8 TeV (right) at ATLAS experiment [61].

For the $b\bar{b}$ system, the quarkonium states with parallel quark spins ($s = 1$) include the S-wave $\Upsilon$ and the P-wave $\chi_b$ states, where the latter each comprise a closely spaced triplet of $J = 0$, 1, 2 spin states: $\chi_{b(0)}$, $\chi_{b1}$ and $\chi_{b2}$. The $\chi_b(1P)$ and $\chi_b(2P)$, with spin-weighted mass barycenters of 9.90 and 10.26 GeV, respectively, can be readily produced in the radiative decays of $\Upsilon(2S)$ and $\Upsilon(3S)$. ATLAS studied the $\chi_b(nP)$ quarkonium state at $\sqrt{s} = 7$ TeV using a data sample corresponding to an integrated luminosity of 4.4 fb$^{-1}$ [62]. The states are reconstructed through their radiative decays to $\Upsilon(1S, 2S)$ with $\Upsilon \rightarrow \mu^+\mu^-$, and the photon is reconstructed either through conversion to $e^+e^-$ or by direct calorimetric measurement. In addition to the mass peaks corresponding to the decay modes $\Upsilon(1P, 2P) \rightarrow \Upsilon(1S)\gamma$, a new structure centered at a mass of $10.530 \pm 0.005 (stat) \pm 0.009 (syst)$ GeV is also observed, in both the $\Upsilon(1S)$ and $\Upsilon(2S)$ decay modes. This structure is interpreted as the $\chi_b(3P)$ system. At CMS, the production cross section ratio $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$ was measured with an integrated luminosity data of 20.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV [63]. The $\chi_b$ states are detected by 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 $|y|^2 < 1.5$ and $p_T < 1.0$, in four bins of $\Upsilon(1S)$ $p_T$, spanning the range 7-40 GeV. The cross section ratio averaged over the $\Upsilon(1S)$ $p_T$ range is measured to be $0.85 \pm 0.07 (stat + syst) \pm 0.08 (BF)$, 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 $\chi_b$ 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 $\chi_{b2}$ and $\chi_{b1}$ relative production cross sections in hadron collisions, which complements and extends the LHCb results [64] obtained in the kinematic region $0.2 < \gamma(\chi_b) < 4.5, 5.0 < \gamma(\Upsilon) < 25$ GeV.

For the b-baryons, CMS observed a new $b\bar{b}$ baryon in $pp$ collisions at $\sqrt{s} = 7$ TeV with an integrated luminosity data of 5.3 fb$^{-1}$ [65]. The new b baryon decays into $\Xi_b^0\pi^+$ (plus charge conjugates), the known $\Xi_b^0$ baryon is reconstructed via the decay chain $\Xi_b^0 \rightarrow J/\psi\Xi^0 \rightarrow \mu^+\mu^-N\pi^+$, with $\Lambda^0 \rightarrow p\pi^-$. A peak is observed in the distribution of the difference between the mass of the $\Xi_b^0\pi^+$ system and the sum of the masses of the $\Xi_b^0$ and $\pi^+$, with a significance exceeding 5 standard deviations. The measured $Q = M(J/\psi\Xi^-\pi^+) - M(J/\psi\Xi^+) - M(\pi^-)$ value is $14.84 \pm 0.74 (stat) \pm 0.28 (syst)$ MeV. Given the charged-pion and $\Xi_b^0$ masses [66], the resulting b-baryon mass is $5945.0 \pm 0.7 (stat) \pm 0.3 (syst) \pm 2.7 (PDG)$ MeV, where the last uncertainty reflects the accuracy of the $\Xi_b^0$ mass measured from the Particle Data Group. While the width of the new baryon is not measured with good statistical precision, it is compatible with theoretical expectations [67]. Given its measured mass and decay mode, the new baryon is likely to be the $\Xi_b^{0*}$ with $J^P = 3/2^+$.}

CMS observed peaking structures in the $J/\psi\phi$ mass spectrum from $B^{*} \rightarrow J/\psi\phi K^*$ decays at $\sqrt{s} = 7$ TeV [68]. Picture 7 shows the distribution of mass difference $\Delta m = m(\mu^+\mu^- K^+K^-) - m(\mu^+\mu^-)$ in the CMS 7 TeV data. Two peaking structures are observed above the simulated phase-space (PS) continuum distribution shown by the dotted line. Assuming an S-wave relativistic BW lineshape for this structure above a three-body PS shape for the nonresonant background, a statistical significanc of greater than 5 standard deviations is found. Adding the $J/\psi$ mass to the extracted $\Delta m$ values, the mass and width are measured to be $m_1 = 4148.0 \pm 2.4 (stat.) \pm 6.3 (syst.)$ MeV and $\Gamma_1 =$
28^{+15}_{-8}(stat.) \pm 19(syst.)$ MeV. The measured mass and width are consistent with the Y(4140) values reported by CDF experiment [69]. The relative branching fraction of this peaking structure with respect to the total number of $B^+ \to J/\psi K^+$ events is estimated to be about 0.10, with a statistical uncertainty of about 30%. This is consistent with both the value measured by CDF of 15% \pm 5% and the upper limit reported by LHCb (0.07) [70]. In addition, evidence for a second peaking structure is found in the same mass spectrum, with measured mass and widths of $m_1 = 4313.8 \pm 5.3(stat.) \pm 7.3(syst.)$ MeV and $\Gamma_2 = 38^{+30}_{-16}(stat.) \pm 16(syst.)$ MeV. Because of possible reflections from two-body decays, the statistical significance of the second structure cannot be reliably determined. The two structures are well above the threshold of open charm ($D\bar{D}$) decays and have relatively narrow widths. Conventional charmonium mesons with these masses would be expected to have larger widths and to decay predominantly into open charm pairs with small branching fractions into $J/\psi$. Angular analyses of the $B^+ J/\psi K^+$ decays would help to elucidate the nature of these structures.

![Distribution of mass difference](image)

**FIGURE 7.** Distribution of mass difference $\Delta m = m(\mu^+ \mu^- K + K^+) - m(\mu^+ \mu^-)$ in the CMS 7 TeV data [68]. Two peaking structures are observed above the simulated phase-space (PS) continuum distribution shown by the dotted line.

In the past decade, several unexpected charmonium states, such as the X(3872) and the Y(4260), have been discovered [71] and then confirmed [72] by the Belle and BaBar experiments. The X(3872) state has also been seen by hadron collider experiments [73]. The exotic resonance X(3872) was discovered in the final state $J/\psi \pi^+ \pi^-$, and indicated that the X(3872) is produced not only through B-meson decays, but also through prompt production. A bottomonium counterpart of the X(3872), denoted as $X_b$, would be expected to decay through $X_b \to \Upsilon(1S) \pi^+ \pi^-$. CMS searched for the exotic bottomonium state in the decay channel $X_b \to \Upsilon(1S) \pi^+ \pi^-, \Upsilon(2S) \to \mu^+ \mu^-\pi^+$, in $pp$ collisions at $\sqrt{s} = 8$ TeV with an integrated luminosity data of 20.7 $fb^{-1}$ [74]. 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 $|\gamma(\Upsilon(1S) \pi^+ \pi^-)| < 2.0$. 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 $\Upsilon(1S)$ resonances, no significant excess above the background was observed for $X_b$ masses between 10 and 11 GeV. The expected sensitivity of the analysis was greater than five standard deviations for the explored $X_b$ 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 $\sigma(pp \to X_b \to \Upsilon(1S) \pi^+ \pi^-)/\sigma(pp \to \Upsilon(2S) \to \Upsilon(1S) \pi^+ \pi^-)$ is in the range 0.9-5.4%, depending on the assumed $X_b$ mass. ATLAS also searched for the hidden-beauty analogue of the X(3872) by reconstructing $\pi^+ \pi^- \Upsilon(1S)$($\to \mu^+ \mu^-$) events in 16.2 $fb^{-1}$ of $pp$ collision data recorded at $\sqrt{s} = 8$ TeV [75]. No evidence for new narrow states is found for masses 10.05-10.31 GeV and 10.40-11.00 GeV. Upper limits are also set on the ratio $R = [\sigma(pp \to X_b)_{\Upsilon}(X_b \to \Upsilon(1S) \pi^+ \pi^-)]/[\sigma(pp \to \Upsilon(2S))_{\Upsilon}(\Upsilon(2S) \to \Upsilon(1S) \pi^+ \pi^-)]$, with results ranging from 0.8% to 4.0% depending on the $X_b$ mass. The analogous ratio for the X(3872) is 6.56%: a value this large is excluded for all $X_b$ masses considered. Separate fits to the $\Upsilon(1^{3}D_2)$ triplet, $\Upsilon(10860)$, and $\Upsilon(11020)$ also reveal no significant signals, and a CL$_S$ upper limit of 0.55 is set on $\sigma(pp \to \Upsilon(1^{3}D_2))/\sigma(pp \to \Upsilon(2S))$. 
SUMMARY

CMS and ATLAS collaborations extensively measured inclusive and exclusive B productions with LHC run-I data. CMS and ATLAS main achievements include precision measurements of B hadron production and decay properties; Observation of new B meson, baryon states and decay modes. For the rare processes, CMS observed long-sought \( B_s \to \mu^+\mu^- \) decay. The results gave significant contribution to the stringent test of the Standard Model prediction, and new physics searches.

The higher energy, luminosity and pileup of coming LHC RUN-II runs will bring both challenges and new possibilities to ATLAS and CMS B physics studies.

ACKNOWLEDGMENTS

Congratulate colleagues in the CERN accelerator departments for the excellent RUN-I performance of the LHC and thank the technical and administrative staffs at CERN for their contributions to the success of the ATLAS and CMS effort. The author is supported by the Chinese Science Funds: 11061140514, 2013CB837801.

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