

Measurement of $B\bar{B}$ Angular Correlations at $\sqrt{s} = 7$ TeV with the CMS Experiment

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Measurements of the angular correlations between beauty and anti-beauty hadrons produced in LHC pp collisions at $\sqrt{s} = 7$ TeV are presented. These results probe for the first time the small angular separation region and show sensitivity to collinear particle emission. The results are compared with predictions based on perturbative QCD calculations at leading and next-to-leading order.

1 Introduction

Studies of production properties of beauty quarks (b) at the CERN LHC collider are of twofold interest. Firstly, the b production process provides an excellent opportunity to study details of perturbative Quantum Chromodynamics (pQCD). Over the years, the various tensions between the predictions and the measurements, that existed in data at lower energies such as the HERA or the Tevatron collider, have been reduced, however not completely resolved. Studies at the LHC collider with higher centre-of-mass energies complement the previous data, but also expand the reach and provide tests at precisions below the present theoretical uncertainties.

Secondly, b quark production constitutes one of the major backgrounds in many of the searches for new physics. Any production channel of exotic states, that produces top quarks or W -bosons, will inherently have a large b production rate. It is of importance not only to understand the absolute production rates, but also to be able to describe the details of the b production dynamics. Thus, a solid understanding of the topology of the final states will be crucial to constitute efficient criteria to distinguish possible signal signatures from b -induced background configurations.

Within the leading-order (LO) QCD picture, the production of $b\bar{b}$ in pp collisions at LHC can be attributed to three parton level production subprocesses, commonly denoted by flavour creation (FCR), flavour excitation (FEX) and gluon splitting (GSP) (see Fig. 1). At higher orders, the distinction becomes scale dependent, and is thus less well defined. Due to the different dynamics of these components, the final state topologies differ substantially from

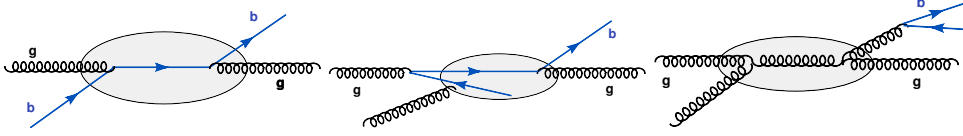


Figure 1: Examples of schematic Feynman diagrams for the three subprocesses: flavour creation (FCR, top), flavour excitation (FCR, middle) and gluon splitting (GSP, bottom).

each other. FCR pertains to the $2 \rightarrow 2$ processes gluon-fusion and $q\bar{q}$ annihilation, where the b and \bar{b} are emitted in a back-to-back configuration. FEX refers to the $2 \rightarrow 3$ process, where one b quark of a $b\bar{b}$ pair from the proton sea participates in the hard scattering, thereby producing an asymmetry in the momentum and angular distribution of the final state. The GSP contribution on the other hand describes gluons from either initial or final state, that split into a $b\bar{b}$ pair, which in turn are emitted preferentially at small opening angles and low p_T . Furthermore, the relative production rates themselves vary also as a function of the energy scale. It is expected, that at higher energies the gluon splitting contributions dominate, ie. processes with a collinear branching of gluons into $B\bar{B}$ pairs will become the major source of b quark production.

2 Measurements of $B\bar{B}$ Angular Correlations

CMS has performed the first measurement [1] of the angular correlations between beauty and anti-beauty hadrons ($B\bar{B}$) produced in pp collisions at $\sqrt{s} = 7$ TeV, thereby probing for the first time the region of small angular separation. The analysis is based on a data sample corresponding to an integrated luminosity of $3.1 \pm 0.3 \text{ pb}^{-1}$. A detailed description of the CMS detector can be found in Ref. [2].

The measurements are done differentially as a function of the opening angle for different event scales, which are characterised by the leading jet transverse momentum in the event (independently of b hadrons). The leading jet of the event is used to trigger. The trigger thresholds are chosen such as to reach an efficiency over 99% for all three energy scale bins, which correspond to a leading jet p_T in excess of 56, 84 and 120 GeV, respectively, when using corrected jet energies.

The cross sections are determined by applying efficiency corrections and normalising to the total integrated luminosity. The angular correlations between the two B hadrons are measured in terms of the difference in azimuthal angles ($\Delta\phi$) in radians and the combined separation variable $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\eta$ is the pseudorapidity. The analysis results are quoted for the visible kinematic range defined by the phase space at the B hadron level by the requirements $|\eta(B)| < 2.0$ and $p_T(B) > 15$ GeV for both of the B hadrons. The leading jet used to define the minimum energy scale is required to be within a pseudorapidity of $|\eta(\text{jet})| < 3.0$.

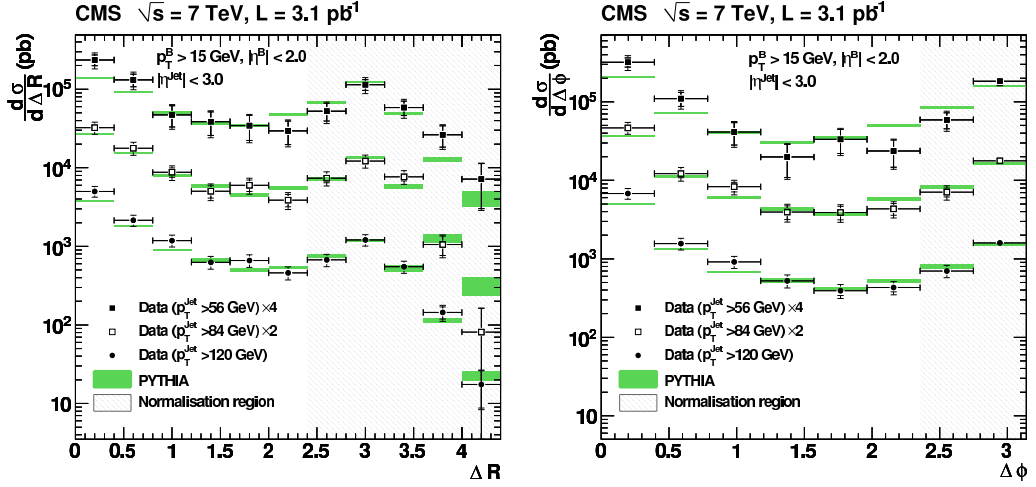


Figure 2: Differential $B\bar{B}$ production cross sections as a function of ΔR (left) and $\Delta\phi$ (rad) (right) for the three leading jet p_T regions. For clarity, the $p_T > 56$ and 84 GeV bins are offset by a factor 4 and 2, respectively. The error bars of the data show the statistical (inner) and the total (outer bars) uncertainties. A common uncertainty of 47% due to the absolute normalisation on the data points is not included. The PYTHIA prediction is normalised to the region $\Delta R > 2.4$ or $\Delta\phi > 2.4$. The widths of the shaded bands indicate the statistical uncertainties of the predictions.

In order to measure the angular correlations also in the collinear regime, the reconstruction of the B hadrons is done independently of jet algorithms. The method uses the B hadron decays and is based on an iterative inclusive secondary vertex finder that exploits the excellent CMS tracking information [3]. This allowed to approximate the flight direction of the original B hadron by the vector between the primary (PV) and the secondary vertices (SV). A resolution of 0.02 rad in ΔR could be achieved that way. The average overall event reconstruction efficiencies (for both B hadrons) are found to be of order 10% at an average purity of 84%. Detailed studies were performed to ensure high accuracy in the B-hadron kinematics description. In addition, the angular dependence of the efficiency description was verified by a special event mixing technique, both in data and the simulation.

The measured cross sections are presented in Fig.2. Overlaid are the predictions by the PYTHIA calculations, which are normalised to the $\Delta R > 2.4$ or $\Delta\phi > 2.4$ (rad) regions, where the calculations are expected to be more reliable. Note, that an overall common uncertainty of 47% due to the absolute normalisation is not shown in the figures.

We find that the cross sections at small ΔR or $\Delta\phi$ are substantial and even exceed the values observed at large L angular separation values. Hence, the configurations where the two B hadrons are emitted in opposite directions are much less likely than the collinear configuration.

The measurements are compared to various predictions, based on LO and next-to-leading

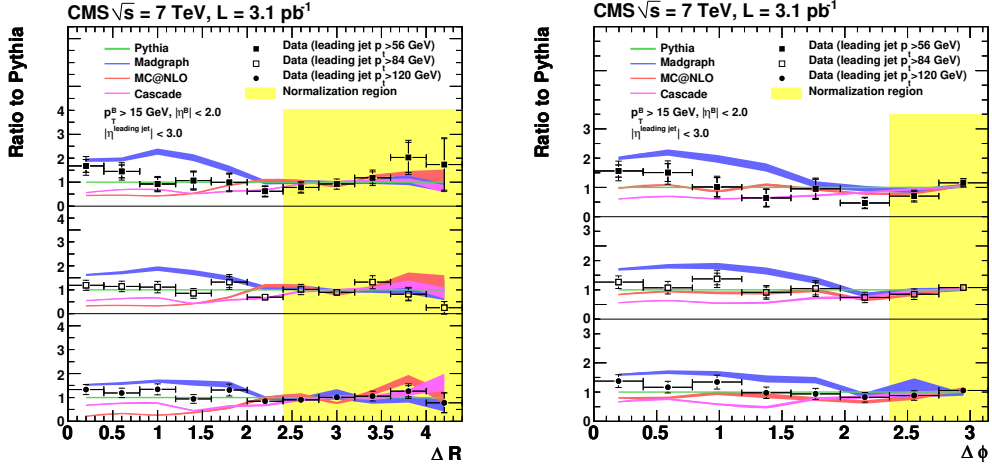


Figure 3: Ratio of the differential $B\bar{B}$ production cross sections, as a function of ΔR (left) and $\Delta\phi$ (rad) (right), for data, MADGRAPH, MC@NLO and CASCADE, with respect to the PYTHIA predictions, shown also for the three leading jet p_T bins. The simulation is normalised to the region $\Delta R > 2.4$ and $\Delta\phi > 2.4$ (rad) (FCR region), as indicated by the shaded normalisation region. The widths of the theory bands indicate the statistical uncertainties of the simulation.

(NLO) pQCD calculations. Figure 3 illustrates the shape sensitivity by showing the ratio of the different ΔR distributions to the PYTHIA Monte Carlo predictions. It is found, that the overall tendency in shape is in general reasonably described by the predictions, however the normalizations and the details in shape, in particular at small opening angles are not described well by any of the calculations. Apart from MADGRAPH program, all predictions underestimate the amount of gluon splitting contributions in the collinear region.

Perturbative QCD predicts a back-to-back configuration for the production of the $B\bar{B}$ pair (i.e. large values of ΔR and/or $\Delta\phi$) for the LO processes. In contrast, the region of phase space with small opening angles between the B and \bar{B} hadrons provides strong sensitivity to collinear emission processes, such as the ones present in higher-order processes. Gluon radiation which splits into $b\bar{b}$ pairs is anticipated to have a smaller angular separation between the b quarks.

The measurements show that the $B\bar{B}$ production cross section ratio $\rho_{\Delta R} = \sigma_{\Delta R < 0.8} / \sigma_{\Delta R > 2.4}$ increases as a function of the leading jet p_T in the event (see Fig. 4). Larger p_T values lead to more gluon radiation and, hence, are expected to produce more gluon splitting into $B\bar{B}$ pairs. This general trend is described reasonably by the theoretical calculations.

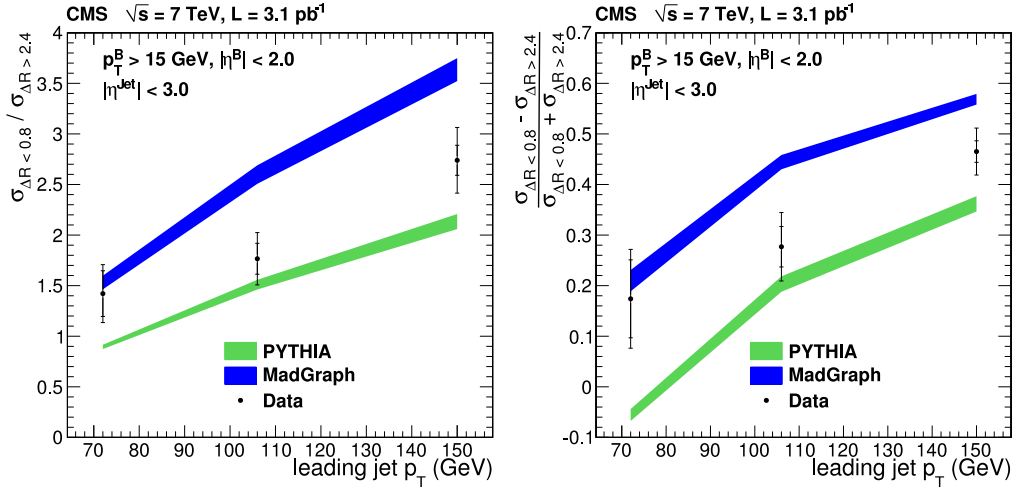


Figure 4: Left: ratio between the $B\bar{B}$ production cross sections in $\Delta R < 0.8$ and $\Delta R > 2.4$, $\rho_{\Delta R} = \sigma_{\Delta R < 0.8} / \sigma_{\Delta R > 2.4}$, as a function of the leading jet p_T . Right: asymmetry between the two regions, $(\sigma_{\Delta R < 0.8} - \sigma_{\Delta R > 2.4}) / (\sigma_{\Delta R < 0.8} + \sigma_{\Delta R > 2.4})$. The symbols denote the data averaged over the bins and are plotted at the mean leading jet p_T of the bins. For the data points, the error bars show the statistical (inner bars) and the total (outer bars) errors. Also shown are the predictions from the PYTHIA and MADGRAPH simulations, where the widths of the bands indicate the uncertainties arising from the limited number of simulated events.

3 Conclusions

The first measurements of inclusive beauty production have been performed at the LHC by the CMS experiment over a large range from very low transverse momenta up to 300 GeV in the central rapidity region. Comparisons with theoretical predictions, based on pQCD calculations have confirmed the large production cross section. The calculations in general describe the overall features of beauty production fairly well. However, the predictions do not yet adequately describe the differential measurements, neither in the B transverse momentum, nor the rapidity nor the $B\bar{B}$ opening angle distributions.

References

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