Measurements of BB Angular Correlations with CMS

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Abstract. A measurement of the angular correlations between beauty and anti-beauty hadrons produced in LHC pp collisions at $\sqrt{s} = 7$ TeV is presented, probing for the first time the small angular separation region. The B hadrons are identified by the presence of secondary vertices and their kinematics are reconstructed combining the decay vertex with the primary interaction vertex. The results are compared with predictions based on perturbative QCD calculations at leading and next-to-leading order.

INTRODUCTION

Beauty quarks are abundantly produced through strong interactions in pp collisions at the CERN Large Hadron Collider (LHC). The hadroproduction of $b\overline{b}$ pairs is measured to have a large cross section (of the order of $100\,\mu$b) at a centre-of-mass energy of 7 TeV [1, 2, 3]. Detailed b quark production studies provide substantial information about the dynamics of the underlying hard scattering subprocesses within perturbative Quantum Chromodynamics (pQCD). In lowest order pQCD, i.e. in $2 \to 2$ parton interaction subprocesses, momentum conservation requires the b and $\overline{b}$ quarks to be emitted in a back-to-back topology. However, higher order $2 \to N$ subprocesses with additional partons (notably gluons) emitted, give rise to different topologies of the final state b quarks. Consequently, measurements of $b\overline{b}$ angular and momentum correlations provide information about the underlying production subprocesses and allow for a sensitive test of pQCD leading-order (LO) and next-to-leading order (NLO) cross sections and their evolution with event energy scales. Studies of b quark production at the LHC may provide insight into the hadronisation properties of heavy quarks at these new energy scales, as well as better knowledge of the heavy quark content of the proton. In this report, a method used by the CMS collaboration to measure the BB angular correlation is presented [4]. The analysis is based on an iterative inclusive secondary vertex finder that exploits the excellent tracking capabilities of the CMS detector.

A detailed description of the CMS detector can be found in Ref. [5]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m inner diameter, with a 3.8 T axial magnetic field. The subdetectors used in the present analysis are tracking detectors and calorimeters, located within the field volume. The tracker consists of a silicon pixel and silicon strip tracker covering the pseudorapidity range $|\eta| < 2.5$. The pixel tracker consists of three barrel layers and two endcap disks at each barrel end. The strip tracker has 10 barrel layers and 12 endcap disks. The basic Monte Carlo event generator used in this analysis is the LO Pythia program (version 6.422 [6]), which is used to determine selection efficiencies and to optimise the vertexing algorithm for B hadron reconstruction. The results are then compared with other predictions from different generators.

MEASUREMENT OF ANGULAR CORRELATION WITH SECONDARY VERTICES

The analysis relies on the single-jet trigger in both the hardware-level (L1) and the software high-level (HLT) components of the CMS trigger system. At least one HLT jet should have uncorrected transverse calorimetric energy E_{T}^{U} above a trigger threshold of 15, 30 or 50 GeV. The event sample is then divided into three energy scale bins corresponding to the $p_T$ranges where the different jet triggers are over 99% efficient. These correspond to samples where the transverse momenta of the leading jet, within $|\eta(\text{jet})| < 3.0$ and using corrected jet energies, exceed 56, 84 and 120 GeV, respectively.

The effective integrated luminosity, taking into account the trigger prescale factors, corresponds to 0.031, 0.313 and 3.069 pb^{-1}, respectively, for the three samples, including some overlap.

The primary vertex is reconstructed from tracks of low impact parameter with respect to the nominal interaction region. In cases of multiple interactions in the same bunch crossing (pile-up events), the primary interaction vertex is chosen to be the one with the largest squared transverse momentum sum $S_{\mathrm{T}} = \sum p_{\mathrm{T}i}^{2}$, where the sum runs over all tracks associated with the vertex.

The events are required to have at least two reconstructed secondary vertices. An inclusive secondary vertex finding (IVF) technique, not using any jet information, is applied for this purpose. This technique reconstructs secondary vertices by clustering tracks around the so-called seeding tracks characterized by high three-dimensional impact parameter significance $S_d = d/\sigma(d)$, where d and $\sigma(d)$ are the impact parameter and its uncertainty at the PV. The tracks are clustered to a seed track based on their compatibility given their separation distance in three dimensions, the separation distance significance (distance normalised to its uncertainty), and the angular separation. The clustered tracks are then fitted to a common vertex with an outlier-resistant fitter. The vertices sharing more than 70% of the tracks compatible within the uncertainties are merged. As a final step, all tracks are assigned to either the primary or the secondary vertices on the basis of the significance of the track to vertex distance.

The SV are required to be made up of at least three tracks, to have a maximal two-dimensional flight distance $D_{xy} = |\overrightarrow{SV}_{xy}| < 2.5$ cm, a minimal two-dimensional flight distance significance $S_{2D} = D_{xy}/\sigma(D_{xy}) > 3$ (see Figure 1), and to possess a vertex mass $m_{SV} < 6.5$ GeV. The vector $\overrightarrow{SV}$ is defined as the one joining the PV to the SV.

A B hadron candidate is built from the four-momentum of the vertex, defined as the sum $p_{SV} = \sum p_i$ over all tracks fitted to that vertex, with $p_i = (E_i, \vec{p}_i)$, using the pion mass hypothesis. Events with at least two secondary vertices may originate from any of the following processes: a) true 'signal' BB events; b) true BB events where at least one B hadron is not correctly reconstructed (SV from other sources); c) QCD events with light quark and gluon jets, which enter through misidentification of vertices

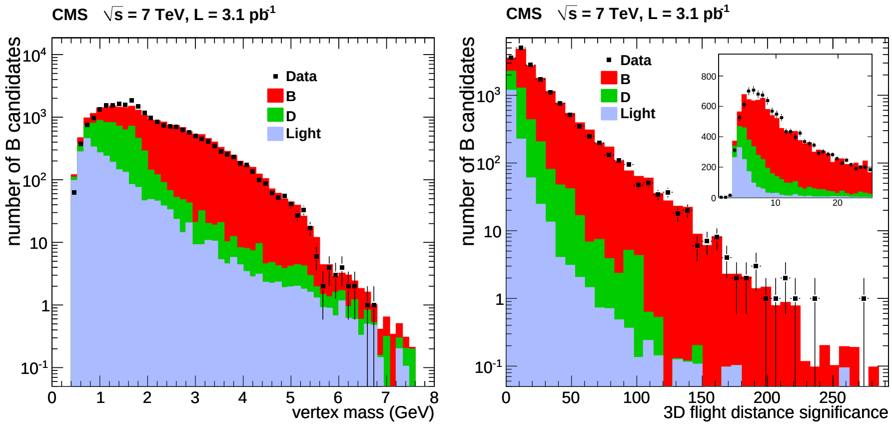

FIGURE 1. Properties of the reconstructed B candidates: vertex mass distribution (left) and flight distance significance distribution (right). The decomposition into the different sources, beauty, charm and light quarks, is shown for the Pythia Monte Carlo simulation.

not originating from B decay; d) direct $c\bar{c}$ production with long lived D hadrons; e) sequential $B \to D \to X$ decay chains, where B hadrons decay to long lived D hadrons, and both B and D vertices are reconstructed. The BB signal events contain a fraction from top quark pair production of less than 1%.

It can happen that both the B and D decay vertices are reconstructed by the IVF in $b \to c$ decay. Such topologies need to be distinguished from events with two quasi-collinear B hadrons. To achieve this, an iterative merging procedure is applied to vertices with $\Delta R < 0.4$. The procedure is optimised to yield a single B candidate associated with a decay chain $B \to D \to X$, while successfully retaining two B candidates also in events where two real B hadrons are emitted nearly collinearly.

RESULTS

In order to measure the angular separation the B hadron flight direction is measured by the vector vector $\overrightarrow{SV}$ (connecting the position of B hadron production to the position of the B hadron decay).

The angular differential cross section measurement is obtained by counting the events with two B candidates as a function of their angular separation. The distribution is then corrected for the efficiency and purity defined with respect to the visible kinematic range of $|\eta(\mathrm{B})| < 2.0$ and $p_T(\mathrm{B}) > 15$ GeV for both of the B hadrons. The correction is derived from simulation as a function of the angular separation ΔR, independently for each leading jet p_T bin.

The main systematic uncertainty for the shape of the distribution arise from the shape of the efficiency and purity correction. The main contributions are: algorithmic effects on the vertex finding efficiency for quasi collinear hadrons, effect of the Jet Energy Scale, correct modelling in the simulation of the B hadron momenta, definition of the visible phase space and some bin migration effect for residual $B \to D$ events with the D reconstructed as a B.

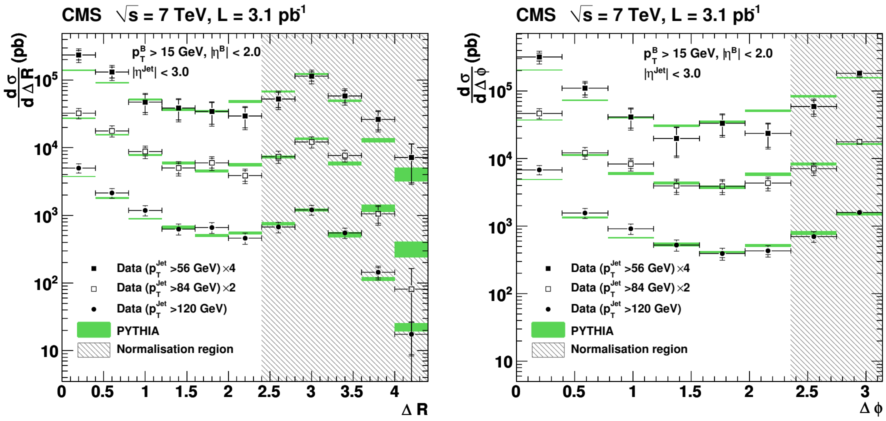

FIGURE 2. Differential BB production cross sections as a function of ΔR (left) and $\Delta\phi$ (right) for the three leading jet p_T regions. The Pythia simulation (shaded bars) is normalised to the region $\Delta R > 2.4$ or $\Delta\phi > \frac{3}{4}\pi$.

The uncertainties have been estimated from simulation and from data as detailed in [4].

The kinematic regions with $\Delta R < 0.8$ and with $\Delta R > 2.4$ are used for comparisons or normalisations of the simulation. This is inspired by the theoretical predictions, since at low ΔR values the gluon splitting process is expected to contribute significantly, whereas at high ΔR values flavour creation prevails.

The results of the measurements and comparisons with expectations from simulation are shown in Figures 2 and 3. A substantial amount of small angle production is found in data, as predicted, with large uncertainties, by the different generators. The collinear production tend to increase with respect to the back to back topology, at higher event energy scale.

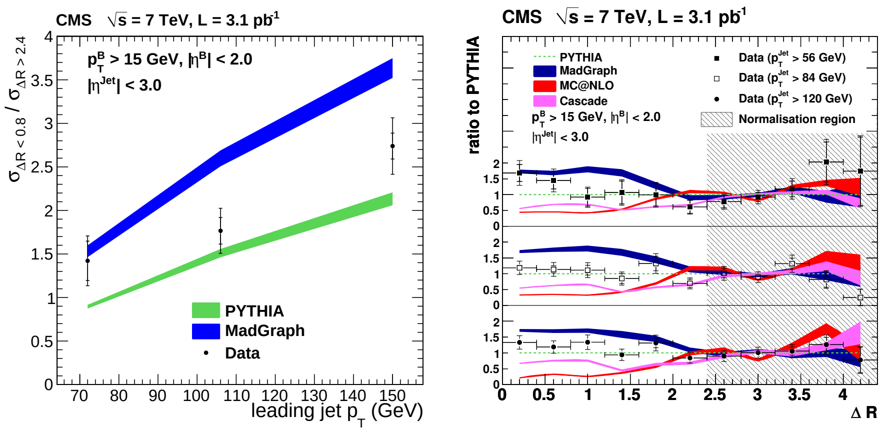

FIGURE 3. Left: ratio between the BB production cross sections in $\Delta R < 0.8$ and $\Delta R > 2.4$, $\rho_{\Delta R} = \sigma_{\Delta R<0.8}$ / $\sigma_{\Delta R>2.4}$, as a function of the leading jet p_T. Right: ratio of the differential BB production cross sections, as a function of ΔR for data, MagGraph, MC@NLOand CASCADE , with respect to the Pythia predictions.

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