PROCEEDINGS OF SCIENCE

Measurements of b-Quark Production and $\mathrm{B\overline{B}}$ Angular Correlations

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Measurements performed by the CMS experiment of the cross section for inclusive b-quark production in proton-proton collisions at $\sqrt{s} = 7$ TeV are presented. The measurements are based on different methods, such as inclusive jet measurements with secondary vertex tagging or selecting a sample of events containing jets and at least one muon, where the transverse momentum of the muon with respect to the closest jet axis discriminates b events from the background. In addition, measurements of the angular correlations between beauty and anti-beauty hadrons produced in LHC pp collisions at $\sqrt{s} = 7$ TeV are presented, probing for the first time the small angular separation region. The results are compared with predictions based on perturbative QCD calculations at leading and next-to-leading order.

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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.

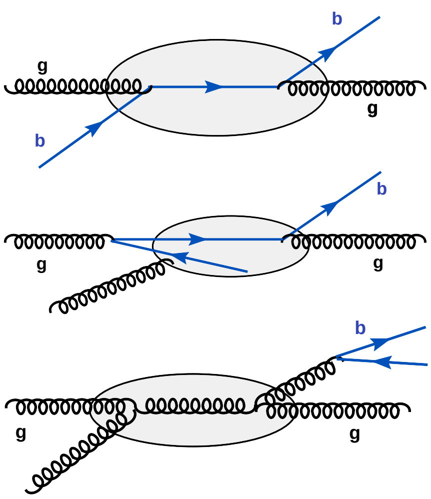

Figure 1: Examples of schematic Feynman diagrams for the three subprocesses: flavour creation (FCR, top), flavour excitation (FCR, middle) and gluon splitting (GSP, bottom).

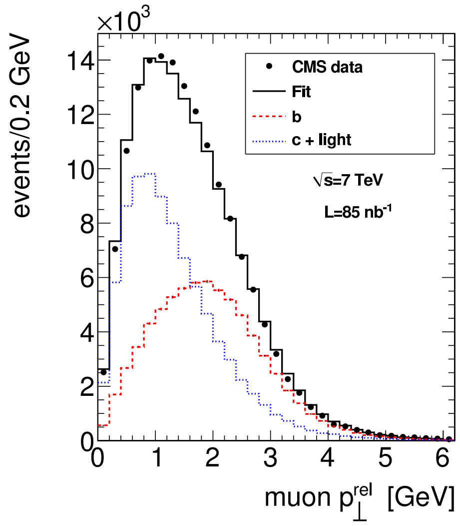

Figure 2: Distribution of muon transverse momentum $p_{T,rel}$ in data (solid points) and the results of the likelihood fit (black line). The simulated distributions are shown separately for the b quarks (red dashed) and for the combined charm and light quarks (blue dotted line).

Within the leading-order 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 each other. FCR pertains to the $2 \rightarrow 2$ processes gluon-fusion and $q\overline{q}$ annihilation, where the b and $\overline{b}$ are emitted in a back-to-back configuration. FEX refers to the $2 \rightarrow 3$ process, where one b quark of a $b\overline{b}$ 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 $b\overline{b}$ 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 $B\overline{B}$ pairs will become the major source of b quark production.

All analyses presented below are based on CMS data, collected in 2010 at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. A detailed description of the CMS detector can be found in Ref. [1].

2. Inclusive b production with muons

The first measurement of the b-hadron production cross section based on semimuonic decays at $\sqrt{s} = 7\,\text{TeV}$ in the central rapidity range is presented [2]. The dataset corresponds to $85\,\text{nb}^{-1}$ and is based on data triggered with a low-threshold ($p_T > 3$ GeV) single-muon trigger.

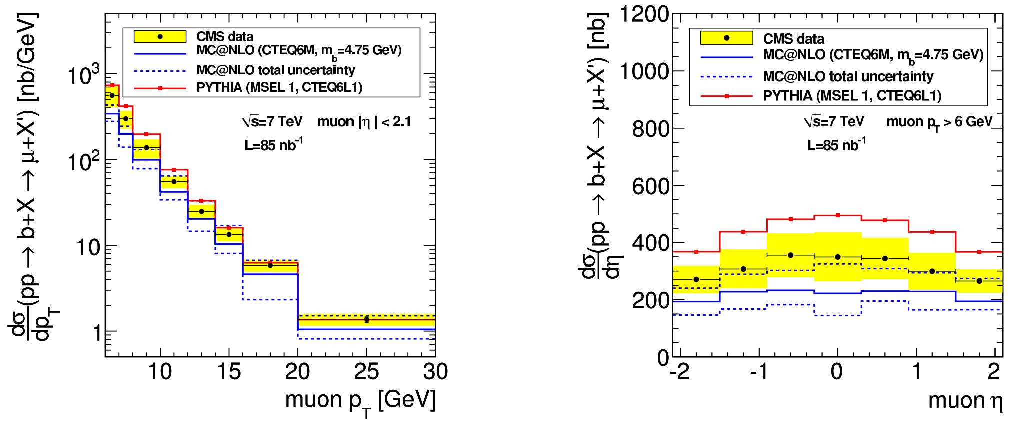

Figure 3: Differential cross section $\frac{d\sigma}{dp_T^\mu}(\mathrm{pp} \rightarrow \mathrm{b} + X \rightarrow \mu + X', |\eta^\mu| < 2.1)$ (left), and $\frac{d\sigma}{d\eta^\mu}(\mathrm{pp} \rightarrow \mathrm{b} + X \rightarrow \mu + X', p_T^\mu > 6$ GeV (right). Vertical error bars showing the statistical error are smaller than the point size in most bins, the horizontal bars indicate the bin width. The yellow band shows the quadratic sum of statistical and systematic uncertainties. The systematic uncertainty (11%) of the luminosity measurement is not included. Also shown is the MC@NLO prediction (solid blue line) with its theoretical uncertainty (dashed lines), and the PYTHIA predictions (in red).

The events are considered for the analysis, if they have a track-jet and at least one muon. The measurements are done in the visible kinematic region, defined by the jet transverse momentum of $p_{T,\mathrm{jet}} > 1$ GeV and a muon with transverse momentum $p_T^\mu > 6\,\text{GeV}$ with respect to the beam direction and pseudorapidity $|\eta^\mu| < 2.1$.

The discriminating variable to efficiently separate beauty events from background contributions, such as light quarks and gluons, is the so-called $p_{\mathrm{T,rel}}$ variable. It is the transverse momentum of the muon (of momentum $\vec{\mathrm{p}}_{\mu}$) with respect to the closest track-jet (of momentum $\vec{\mathrm{p}}_{j}$), defined by $p_{\mathrm{T,rel}} = |\vec{\mathrm{p}}_{\mu} \times \vec{\mathrm{p}}_{j}|/|\vec{\mathrm{p}}_{j}|$.

The total fraction of beauty events in the data sample is extracted by a binned log-likelihood fit to the observed $p_{\mathrm{T,rel}}$ distribution as shown in Fig. 2. The shape templates of the distributions are obtained from simulation (beauty signal and charm) or extracted from data (for the remaining background, strange, light and others).

The total cross section has been measured in the visible kinematic region defined above and resulted in $\sigma(\mathrm{pp} \to \mathrm{b} + X \to \mu + X') = (1.32 \pm 0.01(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.15(\mathrm{lumi}))\ \mu\mathrm{b}$. Note, that the cross section definition includes both muon charges, and it also includes both charge conjugate states, beauty and anti-beauty quarks, decaying to muons. For comparison, the inclusive b-quark production cross section predicted by the NLO pQCD calculation MC@NLO is $\sigma_{\mathrm{MC@NLO}} = (0.84^{+0.36}_{-0.19}(\mathrm{scale}) \pm 0.08(m_b) \pm 0.04(\mathrm{pdf}))\ \mu\mathrm{b}$, whereas the LO calculation PYTHIA predicts 1.8 μb. The inclusive b production cross sections are quoted as a function of the muon transverse momentum and muon pseudorapidity, and are shown in Fig.3.

The shape of the distributions are reasonably described by the theoretical calculations, however PYTHIA overestimates the absolute normalization, whereas MC@NLO underestimates it. In general, the agreement appears to be better at high p_{T} values.

3. Inclusive b production with jets

The inclusive b-jet production cross section has also been measured [3] with jets, tagged as b-jets, using a data set of an integrated luminosity of 60 nb^{-1}. Jets with a transverse momentum in the range $18 < p_{\mathrm{T}} < 300$ GeV are reconstructed with the anti-kT algorithm with cone size R=0.5 using Particle Flow objects [4]. These b-jets are identified with the CMS secondary vertex tagger [5] with an efficiency around 60% at a jet-p_{T} of 100 GeV. The measurements are performed in several rapidity intervals within the tracker acceptance.

The resulting cross sections are shown in Fig. 4 as a function of the b-jet p_{T} (left) for four different jet rapidity regions. The measurements are also compared with the predictions, based on MC@NLO and PYTHIA calculations.

The experimental uncertainties (jet energy reconstruction and luminosity) are substantially reduced by taking a ratio of the b-jet to the inclusive jet cross section. It is found that PYTHIA describes the data within 2% statistical and 21% systematic uncertainty. Comparing with MC@NLO, the overall b-jet fraction is reasonably described within errors, however the shapes in p_{T} and y are found to differ significantly.

4. Measurements of $\mathrm{B\overline{B}}$ Angular Correlations

CMS has presented the first measurement [6] of the angular correlations between beauty and anti-beauty hadrons ($\mathrm{B\overline{B}}$) 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 $3.1 \pm 0.3\,\mathrm{pb}^{-1}$.

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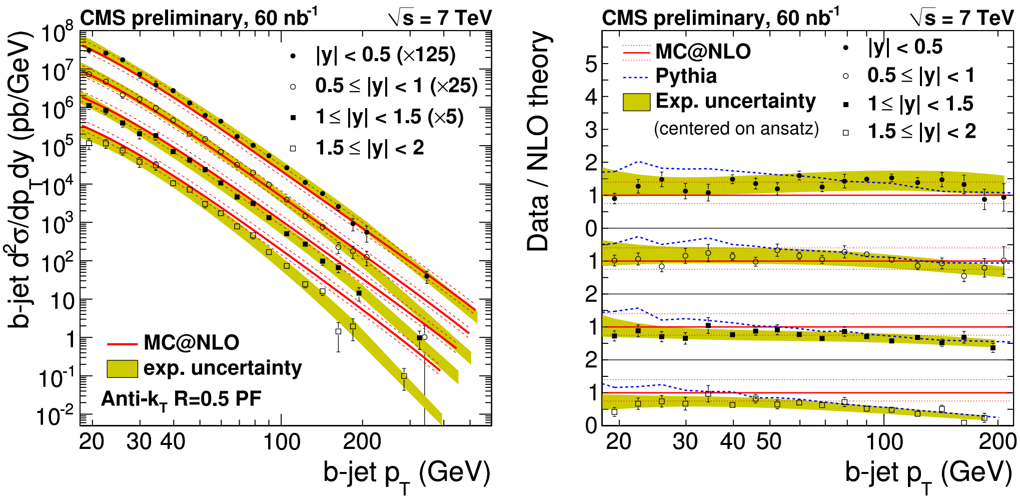

Figure 4: Differential b-jet production cross sections as a function of b jet-p_T (left) for the four different jet rapidity regions. At right the ratio of the data to the MC@NLO calculations are shown; for comparison also the PYTHIA predictions are plotted. The widths of the shaded bands indicate the experimental systematic uncertainties.

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 ($\Delta\phi$) 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 $|\eta(\mathrm{B})| < 2.0$ and $p_T(\mathrm{B}) > 15$ 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 $|\eta(\mathrm{jet})| < 3.0$.

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 [7]. This allowed to approximate the flight direction of the original B hadron by the vector between the primary (PV) and the secondary vertex (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.5. Overlaid are the predictions by the PYTHIA calculations, which are normalised to the $\Delta R > 2.4$ or $\Delta\phi > 2.4$ regions, where the calculations are

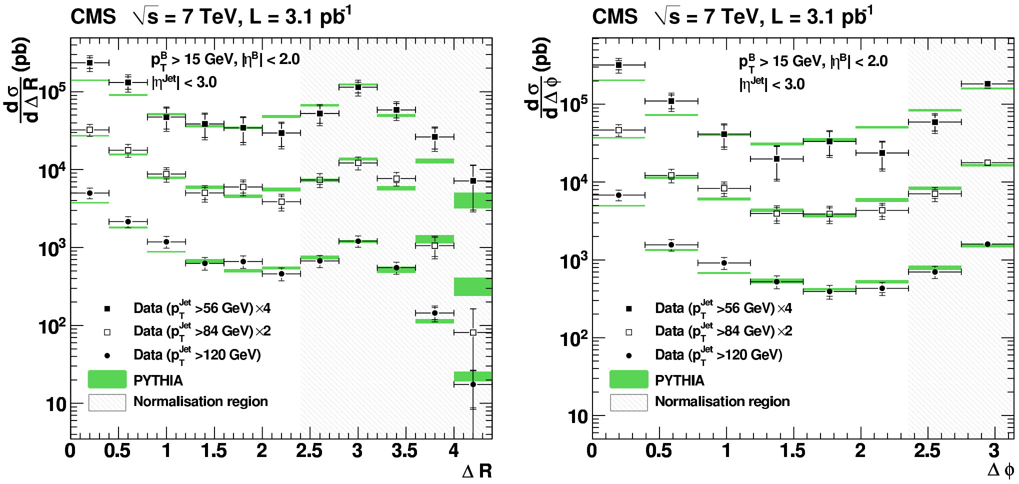

Figure 5: Differential B$\overline{\text{B}}$ production cross sections as a function of ΔR (left) and $\Delta\phi$ (right) for the three leading jet p_T regions. For clarity, the $p_T > 56$ and 84 GeV bins are offset by a factor 4 and 2, respectively. The error bars of the data show the statistical (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.

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 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 region of small opening angles between the two B hadrons provides strong sensitivity to collinear emission processes, as expected for higher-order processes, such as radiated gluons which split into $b\bar{b}$ pairs.

The measurements are compared to various predictions, based on LO and NLO pQCD calculations. Figure 6 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.

5. Conclusions

The first measurements of inclusive beauty production have been performed at the LHC by the CMS collaboration 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

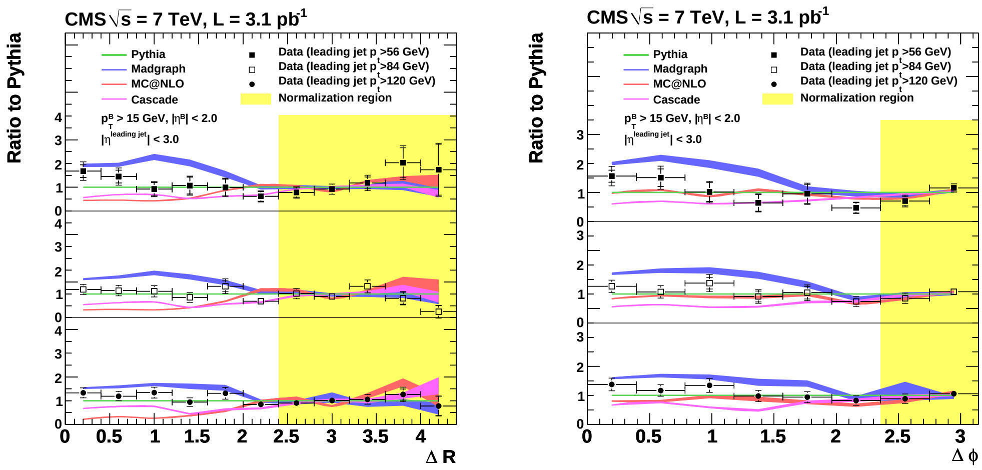

Figure 6: Ratio of the differential B$\overline{\text{B}}$ production cross sections, as a function of ΔR (left) and $\Delta\phi$ (right), for data, MADGRAPH, MC@NLO and CASCADE, with respect to the PYTHIA predictions, shown also for the three leading jet p_{T} bins. The simulation is normalised to the region $\Delta R > 2.4$ and $\Delta\phi > 2.4$ (FCR region), as indicated by the shaded normalisation region. The widths of the theory bands indicate the statistical uncertainties of the simulation.

the differential distributions, be it in B transverse momentum, rapidity or B$\overline{\text{B}}$ opening angle distributions.

References

[1] R. Adolphi *et al.* [CMS Collaboration], JINST **3** (2008) S08004.

[2] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1103** (2011) 090.

[3] V. Khachatryan *et al.* [CMS Collaboration], "Inclusive b-jet Production in pp Collisions at $\sqrt{s} = 7\,\text{TeV}$", CMS Note, CERN-CMS-PAS-BPH-10-009, 2010.

[4] V. Khachatryan *et al.* [CMS Collaboration], "Commissioning of the Particle-Flow Reconstruction in Minimum-Bias and Jet Events from pp Collisions at $\sqrt{s} = 7\,\text{TeV}$", CMS Note, CERN-CMS-PAS-PFT-10-002, 2010.

[5] V. Khachatryan *et al.* [CMS Collaboration], "Commissioning of b-jet Identification with pp Collisions at $\sqrt{s} = 7\,\text{TeV}$", CMS Note, CERN-CMS-PAS-BTV-10-001, 2010.

[6] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1103** (2011) 136.

[7] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. **C70** (2010) 1165-1192.