Recent B-Physics results from CMS

Franco Simonetto

c/o Dip. Fisica, via Marzolo 8, 35131, Padova, Italy
E-mail: franco.simonetto@pd.infn.it

Abstract. The CMS experiment has measured the production of heavy flavored hadrons and jets at 7 TeV. A large range of inclusive and exclusive cross-section measurements (Quarkonia, charged and neutral B hadrons) as well as studies of $b\bar{b}$ angular correlations were made and compared to theoretical predictions at Leading Order and Next to Leading Order precision. These results are here reviewed.

1. Introduction

There are several reasons to study heavy flavour Physics at the LHC. First the measurement of $b$-jets and $b$-hadrons production provides a valuable test of QCD predictions, complementing the measurements performed at lower centre of mass energies in $p\bar{p}$ collisions at the Tevatron. In addition, hints of new Physics might show up in the evolution and decay of B-hadrons. While the $B_d, B_u$ properties have been studied in detail at the B-factories, $B_s$ properties, still largely unknown, can best be measured in a hadron collider. Finally, the top quark, the Higgs boson, and new particles expected in several New Physics models (SUSY Higgs, fourth generation quarks, etc.) decay preferentially to $b$-jets: proper understanding of the production of $b$-quarks in the Standard Model is therefore mandatory to understand the SM background to these new Physics searches.

Out of the four detectors operating at the Large Hadron Collider at CERN, only LHCb was explicitly designed for Heavy Flavour Physics, while ATLAS and CMS are omni-purpose detectors, primarily devoted to the search for new Physics processes taking place at the highest possible energy. However, due to the refined self-triggering muon system, the high resolution silicon tracker, and the precise vertex reconstruction provided by the three layers of inner pixels, CMS provides competitive results also in the B-Physics sector. I review here some of these results. A detailed description of the CMS detector can be found in [1].

For the reader’s ease, results are grouped in three sections: inclusive measurements, where $b$-jets are tagged by high $p_T$ muons or displaced secondary vertices, semi-inclusive measurements of $b \to J/\psi X$ decays, and exclusive measurements of fully reconstructed $B \to J/\psi h$ decays, where the hadron $h$ can be either a charged kaon, a neutral kaon or a $\phi$, and the $J/\psi$ is reconstructed in its $\mu^+\mu^-$ decay.

1 On behalf of the CMS Collaboration
2. Measurements of $b$-jet production properties with inclusive tags

2.1. Inclusive $b \to \mu \bar{\nu}_\mu X$ decays

In the first stage of LHC operation at 7 TeV, the low luminosity allowed CMS to run a single muon trigger with loose requirements: the projection of the muon momentum in the direction perpendicular to the beam axis, $p_{T\mu}$, should exceed 3 GeV. Muons are identified by matching a track reconstructed in the silicon tracker to that reconstructed in the muon chambers. To improve track quality and background rejection, at the analysis stage tighter requirements are imposed on the muon transverse momentum, $p_{T\mu} > 6$ GeV, and pseudorapidity $|\eta\mu| = -\ln(tan(\theta/2)) < 2.1$ ($\theta$ is the polar angle between the track direction and the beam line).

Signal events are discriminated from muons produced in background processes (from charm decay, from the decays of charged pions and kaons, from hadron sailing through the detector to the muon chambers, or from the decays of $Q\bar{Q}$ bound states, “onia”), using jet information. Jets with $p_{Tjet} > 1$ GeV are reconstructed using all good quality charged tracks in the event (with $p_{Ttrack} > 0.3$ GeV), using the anti-$k_T$ algorithm [2] with threshold $R=0.5$. Due to the large $b$-quark mass, the momentum of the muon, projected along the direction perpendicular to the jet axis ($p_{T\mu,rel}$) is on average larger for signal events than for background. A fit to the $p_{T\mu,rel}$ distribution determines the amount of signal and background in the data. Template shapes for the signal and for each background source are taken from the simulation. The fit result is displayed on Figure 1. Muon trigger, tracking and identification efficiencies are measured with a “Tag & Probe” method, using a sample of muons from $J/\psi \to \mu^+\mu^-$ decays [3]. One of the two muons (the “Tag”) is identified. The Probe is then defined as a second track in the same event, with opposite charge to the Tag, which, combined to the Tag, has an invariant mass compatible with the $J/\psi$ world average value [4]. The efficiency is determined in bins of the Probe $p_T$ and $\eta$ by comparing the number of probes passing and falling the selection criteria. After background subtraction and efficiency correction, with an integrated luminosity of $L = 0.85 \pm 0.09$ nb$^{-1}$ CMS measures [5]:

$$
\sigma(pp \to b\bar{b}X \to \mu Y) = 1.32 \pm 0.01_{stat} \pm 0.15_{syst} \pm 0.15_{L} \mu b,
$$

(1)
where the first error is statistical, the second is the quadratic sum of the systematic uncertainties (mostly due to the parameterisation of the $p_{T}^{\mu,rel}$ distributions), and the last term is the uncertainty on the luminosity, known, at the time of that measurement, with ±11% precision.

The result is consistent with the prediction of NLO QCD, $0.95^{+0.42}_{-0.21}$ pb [6] while the PYTHIA [7] prediction is somewhat larger ($\sim 19 \mu$b). Figure 2 shows the variation of the cross section, as a function of the muon transverse momentum, compared to the model predictions.

An independent inclusive cross section measurement is performed exploiting the single jets trigger. Jets with transverse momentum in the range $18 < p_{T}^{jet} < 300$ GeV are reconstructed combining informations from charged tracks, electromagnetic and hadronic calorimetric clusters with a Particle Flow technique [8]. While ensuring the same performance as that of the traditional calorimetric methods at high energy, the PF sizeably improves efficiency and resolution at low momentum ($p_{T}^{jet} < 100$ GeV). Jets from $b$ are tagged reconstructing secondary vertices formed by at least three charged tracks and displaced by at least four standard deviations from the collision point. The vertex mass, computed from the tracks belonging to the secondary vertex, is used to separate $b$-jets from light quarks (see Figure 3). The efficiency for vertex reconstruction is measured as a function of $p_{T}^{jet}$, $\eta^{jet}$ in a subset of muon tagged jets. The fraction of jets from $b$ in the sample is measured in ranges of $p_{T}^{jet}$ and $\eta^{jet}$ with a fit to the vertex mass: an example is shown in Figure 3. Preliminary results [9] obtained from an integrated luminosity of $60 \text{ nb}^{-1}$ are well consisted both with PYTHIA and with NLO calculations, which are however affected by large systematic uncertainties. Figure 4 shows the fraction of jets from $b\bar{b}$ events as a function of $p_{T}^{jet}$, compared to PYTHIA and NLO calculations.

Measuring the angular correlation between $b$-jets may shed light on the production of $b\bar{b}$ in proton proton interactions: gluon splitting (an $o(\alpha_s^3)$ process) favours the production of collinear $b$-jets, whereas jets from flavour creation ($o(\alpha_s^2)$) or flavour excitation ($o(\alpha_s^3)$), should be produced at larger angles. To improve the angular resolution, the $b$-jet direction is computed from the line connecting the primary to the secondary vertex. All events containing two secondary vertices, each composed by at least three charged tracks, an invariant mass exceeding

![Figure 3](image.png)

**Figure 3.** Invariant mass of the tracks at the secondary vertex. Points with error bands are data, overlayed to the contributions from $b$ (red histogram), $c$ (green) and light quarks (blue).

![Figure 4](image.png)

**Figure 4.** Measured $b$-jet cross section as a ratio to inclusive jet cross section. The NLO theory and Pythia MC predictions are shown for comparison.
1.4 GeV, $p_T^{vertex} > 8$ GeV, $|\eta^{vertex}| < 2$, and missing the primary vertex by at least five standard deviations, are employed. The angular distance between the two $b$ vertices is measured by the quantity $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$, where $\phi$ is the azimuthal angle. The data show a large excess of events at low $\Delta R$ as compared to the model expectation [10] (see Figure 5,6), hinting that gluon splitting contribution is significantly larger than expected.

**Figure 5.** $\Delta R$ distribution for $b\bar{b}$ data, for three different thresholds of the leading jet $p_T$. The green bands show Pythia predictions. The yellow band reflects the $\pm 47\%$ uncertainty in the absolute normalization.

**Figure 6.** Ratio between data and Pythia predictions, normalized to unity in the region $\Delta R > 2.4$. A sizeable deviation from unity is observed at low $\Delta R$ values. None of the other models considered reproduces the measured trend.

2.2. **Semi-Inclusive $b \to J/\psi(\to \mu^+ \mu^-)X$ decays**

B hadrons decays to a final state containing a $J/\psi$ have relatively large branching fractions and are easy to trigger. For these reasons, they are an interesting tool for studying B-Physics at hadron colliders. $J/\psi \to \mu^+ \mu^-$ decays are reconstructed with efficiency ranging from 2% to 40% with good signal to noise ratio (see Figure 7). Particles from B decays are separated from prompt production with a fit to the distance of the $J/\psi$ production point ($l_{J/\psi}$) from the primary vertex (see Figure 8). The contribution from combinatoric background is computed using opposite charge muon pairs with an invariant mass not compatible with the $J/\psi$ (“side bands”).

Efficiency is computed applying the Tag & Probe results to the two muons, accounting for correlations. The cross sections in the accepted region ($6.5 < p_T^{J/\psi} < 30$ GeV, and rapidity $|y| < 2.4$) are [11]:

$$\sigma(pp \to J/\psi X) = 70.9 \pm 2.1_{\text{stat}} \pm 3.0_{\text{syst}} \pm 7.8_{\triangle} \text{ nb}$$  \hspace{1cm} (2)

$$\sigma(pp \to b\bar{b}X \to J/\psi Y) = 26.0 \pm 1.4_{\text{stat}} \pm 1.6_{\text{syst}} \pm 2.0_{\triangle} \text{ nb}$$  \hspace{1cm} (3)

The fraction of $J/\psi$ produced in $b$ decays increases with the transverse momentum in any rapidity range, as shown in Figure 9, where the CMS results in different rapidity ranges are compared to those of ATLAS, CDF, and LHCb.
2.3. Fully reconstructed $B_q \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) h$ decays

The large cross section for $b$ hadrons production at the LHC allows the collection of large samples of fully reconstructed $b$-hadrons in $J/\psi h$ final states, where $h$ stands for a low mass hadron. Only the most recent measurement of the cross section $\sigma(pp \rightarrow B_s X, B_s \rightarrow J/\psi \phi)$ is described here: the previous measurements of $B^+ \rightarrow J/\psi K^+$ and $B_d \rightarrow J/\psi K_s$ proceed through similar steps.

The $J/\psi \rightarrow \mu^+ \mu^-$ decay triggers the event. Then pair of opposite charge particles are combined, assuming the Kaon mass hypothesis, to form the $\phi$ candidate. The four tracks are constrained to a common vertex, rejecting combinations with a probability smaller than 2%. Only combination with $p_{T,B_s} > 8$ GeV and rapidity $|y| < 2.4$ are retained. In case of multiple candidates in the same event, that with the largest probability is chosen. The signal event yield is computed with a two-dimensional fit to the system invariant mass ($M_{B_s}$) and proper decay length ($ct$) (see Figure 10, 11).

Besides the amount of signal, prompt and non-prompt background, the fit also determines some of the parameters of the pdfs employed to describe the background invariant mass distribution and signal and background proper time: the measured decay length for the signal ($ct = 478 \pm 26 \mu m$) is consistent within 1.4 standard deviations with its expected value. The measurement is repeated in several $p_T$ and $|y|$ ranges, with pdf parameters fixed to those obtained in the global fit. Using all the data collected during the first year of data taking at 7 TeV, for
Figure 10. $J/\psi \phi$ invariant mass for data (point with error bars), best fit (continous line), signal (dashed), prompt (dot-dashed) and non prompt (dotted) background. To enhance the signal contribution, only events with $ct > 100 \mu m$ are shown.

Figure 11. $B_s$ decay length distribution for data (point with error bars), best fit (continous line), signal (dashed), prompt (dot-dashed) and non prompt (dotted) background, for events with an invariant mass compatible with the $B_s$.

an integrated Luminosity of 40 nb$^{-1}$, CMS measures [12]

$$\sigma(pp \rightarrow B_s X) \cdot B(B_s \rightarrow J/\psi \phi) = 6.9 \pm 0.6_{\text{stat}} \pm 0.5_{\text{syst}} \pm 0.3_{\ell} \text{ nb} \quad (4)$$

Figure 12 compares the cross sections measured by CMS for the three processes $B_u \rightarrow J/\psi K^+$ [13], $B_d \rightarrow J/\psi K_s$ [14], and $B_s \rightarrow J/\psi \phi$. The reader should note that the measurements have been performed in different $p_T$, $y$ regions, as indicated in the figure.

Figure 12. Summary of B meson cross section measurements performed by CMS with 7 TeV $pp$ collisions at LHC. The inner error bars of the data points correspond to the statistical uncertainty, while the outer (thinner) error bars correspond to the quadratic sum of statistical and systematic uncertainties. The outermost brackets correspond to the total error, including a luminosity uncertainty which is also added in quadrature. Theory predictions at NLO are obtained using MC@NLO.

3. Conclusions

The CMS collaboration has provided an impressive amount of results on B-Physics using the data collected so far at the LHC collider, including eight published measurements and four preliminary public notes. Comparison to existing calculations of the cross section and angular correlations permits deeper understanding of the means of $b\bar{b}$ quarks production and hadronisation in hadron colliders. These high quality results proof the detector potential for the future programme of Heavy Flavour Physics, including searching for rare B decays, CP violation in the $B_s$ sector, or using the $b$ jets as a tool in new Physics search.
References

[1] CMS collaboration, “The CMS experiment at the CERN LHC”, 2008 JINST 3 S08004.
[2] M. Cacciari, G.P. Salam and G. Soyez, “The anti-kt jet clustering algorithm”, JHEP 04 (2008) 063.
[3] CMS Collaboration, Performance of muon identification in pp collisions at \( \sqrt{s} = 7 \) TeV, CMS Physics Analysis Summary CMS-PAS-MUO-10-002 (2010).
[4] K. Nakamura et al. (Particle Data Group), "The Review of Particle Physics", J. Phys. G 37, 075021 (2010).
[5] CMS Collaboration, "Inclusive b-hadron production cross section with muons in pp collisions at \( \sqrt{s} = 7 \) TeV”, JHEP 1103 (2011) 090.
[6] S. Frixione, P. Nason and B.R. Webber, “Matching NLO QCD and parton showers in heavy flavour production”, JHEP 08 (2003) 007.
[7] T. Syöstrand, S. Mrenna and P.Z. Skands, "PYTHIA 6.4 Physics and Manual”, JHEP 05 (2006) 026.
[8] CMS Collaboration, Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and Missing ET, CMS PAS PFT-09-001 (2009).
[9] CMS Collaboration, “Inclusive b-jet production in pp collisions at \( \sqrt{s} = 7 \) TeV ”, CMS-PAS-BPH-10-009, (2009).
[10] CMS Collaboration, “Measurement of BB(bar) Angular Correlations based on Secondary Vertex Reconstruction at \( \sqrt{s} = 7 \) TeV”, JHEP 1103 (2011) 136.
[11] CMS Collaboration “J/ψ prompt and non-prompt cross sections in pp collisions at \( \sqrt{s} = 7 \) TeV”, Eur.Phys.J. C71 (2011) 1575.
[12] CMS Collaboration “Measurement of the B^0_b Production Cross Sections in pp Collisions at \( \sqrt{s} = 7 \) TeV”, CERN-PH-EP-2011-06, Submitted to PRD-RC.
[13] CMS Collaboration, “Measurement of the B^+ Production Cross Section in pp Collisions at \( \sqrt{s} = 7 \) TeV”, Phys.Rev.Lett.106:112001, (2011).
[14] CMS Collaboration, “Measurement of the B^0_d Production Cross Section in pp Collisions at \( \sqrt{s} = 7 \) TeV”, Phys. Rev. Lett. 106, 252001 (2011).