Heavy flavor physics with CMS

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Abstract

Recent results from CMS Collaboration on quarkonia physics and heavy quark production are presented. All these results have been obtained analyzing the data from pp collisions at $\sqrt{s} = 7$ TeV provided by the LHC and collected by the CMS detector in the year 2010. The measurements of B-mesons, charmed meson and open beauty production cross sections are illustrated, together with the analysis techniques and the estimation of the systematics uncertainties, and compared with the predictions of the available theoretical models. A recent result from CDF on the $Y$ polarization is also reported.

PRESENTED AT

The Ninth International Conference on Flavor Physics and CP Violation
(FPCP 2011)
Maale Hachamisha, Israel, May 23–27, 2011
1 Introduction

The study of heavy-quark production in high-energy hadronic interactions plays a key role in testing next-to-leading order (NLO) Quantum Chromodynamics (QCD) calculations. In the past, discrepancies were observed between experimental data and theoretical predictions, e.g. at Tevatron [1, 2, 3, 4] and HERA [5, 6, 7, 8]. Substantial progress has been achieved in the understanding of heavy-quark production at Tevatron energies [9], but large theoretical uncertainties still remain, mainly due to the dependence of the calculations on the renormalization and factorization scales. The observed large scale dependence of the NLO calculations is considered to be a symptom of large contributions from higher orders: small-$x$ effects [10, 11], where $x \sim m_b/\sqrt{s}$, are possibly relevant in the low transverse momentum ($p_T$) domain, while multiple-gluon radiation leads to large logarithms of $p_T/m_b$ and may be important at high $p_T$ [12]. The resummed logarithms of $p_T/m_b$ at next-to-leading-logarithmic accuracy have been matched to the fixed-order NLO calculation for massive quarks [13]. At the non-perturbative level, the b-hadron $p_T$ spectrum depends strongly on the parametrization of the fragmentation function [14]. The b-quark production cross section has also been studied in the general-mass variable-flavor-number scheme [15] and the $k_T$ factorization QCD approach [16, 17].

Measurements of B-hadron production at higher energies than before, provided by the Large Hadron Collider (LHC), represent an important test of the new theoretical calculations just mentioned. Measurements of inclusive b-quark production cross section require identification of inclusive events in which a b-quark has been produced in $pp$ collisions. In results reported here, the discrimination of the heavy quark events has been achieved either exclusively, reconstructing the whole decay channel of a B meson, or inclusively, considering hard jets. In this context, two different tagging techniques have been applied: reconstruction of a displaced secondary vertex, and analysis of the transverse momentum spectrum of an energetic muon with respect to the closest jet.

Concerning the charmed and beauty bound states, it is well known that the mechanisms of quarkonia production are still not fully understood, and despite of the considerable progress made in recent years, none of the existing theoretical models describes satisfactorily prompt $J/\psi$ and $\Upsilon$ differential cross sections [15], nor the polarization values obtained with the Tevatron data. Therefore, measurements at the LHC will contribute to shed light to the quarkonium production mechanisms, by providing differential cross sections in wider rapidity ranges and to higher transverse momenta than before. They also allow for important tests of several alternative theoretical approaches: these include non-relativistic QCD (NRQCD) factorization [19], where quarkonium production includes colour-octet (CO) components, and calculations made in the colour-singlet (CS) model including next-to-leading order (NLO) corrections [20] which reproduce the differential cross sections measured at the Teva-
tron experiments \cite{21,22} without requiring a significant colour-octet contribution.

2 The CMS detector

A detailed description of the CMS detector can be found elsewhere \cite{25}. Some of the most relevant features for heavy flavor physics are summarized here.

The core CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume there are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass/scintillator hadron calorimeter. Muons are detected by three types of gas-ionization detectors embedded in the steel return yoke: Drift Tubes (DT), Cathode Strip Chambers (CSC), and Resistive Plate Chambers (RPC). The muon detectors cover a pseudorapidity window $|\eta| < 2.4$, where $\eta = -\ln[\tan(\theta/2)]$, where the polar angle $\theta$ is measured from the $z$-axis, which points along the counterclockwise beam direction. The silicon tracker is composed of pixel detectors (three barrel layers and two forward disks on each side of the detector, made of 66 million $100 \times 150 \mu m^2$ pixels) followed by microstrip detectors (ten barrel layers plus three inner disks and nine forward disks on each side of the detector, with 10 million strips of pitch between 80 and 184 $\mu m$). Thanks to the strong magnetic field and the high granularity of the silicon tracker, the transverse momentum, $p_T$, of the muons matched to reconstructed tracks is measured with a resolution of about 1\% for the typical muons used in this analysis. The silicon tracker also provides the primary vertex position, with $\sim 20 \mu m$ accuracy.

The first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events. The High Level Trigger (HLT) further decreases the rate before data storage.

3 CMS results on $J/\psi$ and $\Upsilon$

In the first weeks of the LHC operation at 7 TeV in 2010, the CMS detector was able to promptly observe and reconstruct the standard candles for the heavy quark physics, the $J/\psi$ and $\Upsilon$ states, in a quasi-on-line fashion. Then soon after, with 0.314 and 3 pb$^{-1}$ of integrated luminosity, respectively, full analyses were performed and published \cite{23,24}. In both $J/\psi$ and $\Upsilon$ analyses, the data were collected with a trigger requiring the detection of two muons at the hardware level, without any further selection at higher level\footnote{The coincidence of two muon signals, without any explicit $p_T$ requirement, is sufficient to maintain the dimuon trigger without prescaling.}, the resonant states were reconstructed through their
decay in two opposite sign muons, and the production cross sections were measured
differentially in $p_T$ and $y$ intervals.

Concerning the datasets analysed, quality requirements are applied on the status
of all the sub–components involved, on the reconstructed Primary Vertex (PV), as
well as on the reconstructed muons. The kinematic requirements on the muons are
chosen to ensure that the trigger and muon reconstruction efficiencies are high and
not rapidly changing within the acceptance window considered: for the muons in the
$J/\psi$ analysis, the minimum $p_T$ ranges from 3.3 GeV in the central $\eta$ region, down to
2.4 GeV in the endcap regions, whereas in the $\Upsilon$ study, one asks for muons with $p_T$
> 3.5 GeV in the barrel and $p_T > 2.5$ GeV in the endcaps.

The detector systems have been aligned and calibrated using LHC collision data
and cosmic ray muons [26, 27, 28]. Further residual effects are determined by studying
the dependence of the reconstructed $J/\psi$ dimuon invariant-mass distribution on the
muon kinematics. The transverse momentum is then corrected for the residual scale,
for both analyses, the parameters having been evaluated through a likelihood fit
performed to the peak of the invariant mass shape. To reduce the combinatorial
background, one also requires the invariant mass of the two muons to lie in a certain
window centered around the nominal value of the mass for the considered resonance.

3.1 Acceptance and efficiency

The muon acceptance, defined here as the fraction of detectable muons from the
meson decay as a function of the dimuon transverse momentum and rapidity, reflects
the finite geometrical coverage of the CMS detector and the limited kinematical reach
of muon trigger and reconstruction systems.

To compute the acceptance, $J/\psi$ and $\Upsilon$ simulated events have been generated
with no cut on $p_T$ and within a pseudorapidity region extending beyond the muon
detector coverage. In the signal Monte Carlo (MC) sample, the meson decays into two
muons are generated with the EVTGEN [29] package, including effects of final-state
radiation, fully simulated and then reconstructed with the CMS detector simulation
software, to assess multiple scattering and finite resolution effects. In general, the
acceptance varies with the resonance’s mass, and moreover the meson polarization
strongly influences the muon angular distributions, expected to change as a function
of $p_T$. In order to account for all of this, the acceptance is calculated for five extreme
polarization scenarios [30]: unpolarized, polarized longitudinally and transversely
with respect to two different reference frames: the helicity frame, defined by the
flight direction of the meson in the center-of-mass system of the colliding beams, and
the Collins-Soper frame [32], given by the direction of the incoming protons direction
in the meson’s rest frame. Fig. 1 shows the expected values of the acceptance for
muons coming from the $J/\psi$ and $\Upsilon$ decays, as a function of the meson’s $p_T$ and $y$, for
the unpolarized scenario.
The total muon efficiency can be factorized into three terms, accounting for the trigger efficiency, the muon identification efficiency and of good quality track reconstruction, respectively. All the three components are evaluated with the “Tag and Probe” data-driven method [33], considering a data sample selected with looser trigger requirements. In events with two muon candidates, one candidate, called the “tag”, is required to satisfy tighter identification criteria. The other candidate, called the “probe”, is selected with criteria depending on the measured efficiency. The efficiency to detect a given J/ψ or Υ event is thus dependent on the value of the muon-pair kinematic variables.

The tracking efficiency is found to be constant in the momentum range defined by the acceptance cuts, and it varies only slightly in the |η| plane. The muon identification and trigger efficiencies have a stronger p_T and |η| dependence, which is mapped with a fine granularity (from nine to twelve bins in p_T and five in |η|).

3.2 J/ψ cross-sections measurements

The differential cross sections are determined from the signals yields, obtained directly from a weighted unbinned maximum likelihood fit to the dimuon invariant-mass spectrum, once corrected for the acceptance and the overall efficiency. In the mass fits, the shape assumed for the signal is a “Crystal Ball” [34] function, which takes into account the detector resolution as well as the radiative tail from bremsstrahlung.
Figure 2: Differential prompt $J/\psi$ cross section as function of $p_T$ for the three different rapidity intervals reported in the figures, for the unpolarized production scenario. The data are compared with the available theoretical predictions, from Pythia, Cascade MC and Colour Evaporation Model. The error bars represent the statistical and systematic errors added in quadrature. The 11% uncertainty due to the luminosity determination is not shown and is common to all bins.

Besides the uncertainty of the luminosity normalization, about 11% for measurements in the first data taking and analysis period, the largest source of systematic uncertainty arises from the determination of the muon efficiencies from the data. It’s worth noticing that both the uncertainties reduce with additional data.

The total cross section for inclusive $J/\psi$ production, obtained by integrating over $p_T$ between 6.5 and 30 GeV and over rapidity between $-2.4$ and $2.4$, in the unpolarized production hypothesis, gives:

$$\sigma(pp \to J/\psi X) \cdot BR(J/\psi \to \mu^+\mu^-) = (97.5 \pm 1.5(stat) \pm 3.4(syst) \pm 10.7(lumi)) \text{ nb}$$

The inclusive $J/\psi$ decays include a prompt and a non–prompt component. Figure 2 shows the prompt differential cross section $\frac{d\sigma}{dp_Tdy} \cdot BR(J/\psi \to \mu^+\mu^-)$ in three rapidity ranges, together with statistical and systematic uncertainties (except the luminosity one), added in quadrature. The prompt $J/\psi$ differential production cross sections have been compared with theoretical predictions from Pythia [35], Cascade [36] Event Generator and the Colour Evaporation Model (CEM) [37, 38, 39, 40, 41]. These calculations include contributions to the prompt $J/\psi$ yield due to feed-down decays from heavier charmonium states ($\chi_c$ and $\psi(2S)$) and can, therefore, be directly compared to the measured data points, as shown in Fig. 2. At forward rapidity and low $p_T$ the calculations underestimate the measured yield.

Since the measurements of prompt $J/\psi$ include a significant contribution from feed-down decays, of the order of 30% [42, 43], it is not possible to compare the prompt measurement with the predictions of models such as the Colour-Singlet Model (including higher-order corrections) [31] or the LO NRQCD model (which includes singlet and octet components), available only for the direct $J/\psi$. 

5
3.3 Non-prompt J/ψ cross section

The estimation of non-prompt J/ψ coming from b–hadron decays can be performed by discriminating J/ψ mesons produced away from the pp collision vertex, that means observing the distance between the dimuon vertex and the primary vertex in the plane orthogonal to the beam line. To determine the non-prompt J/ψ production cross-section, an unbinned maximum-likelihood fit in each \( p_T \) and rapidity bin was performed to the distributions of the invariant mass of the muon pair and to the quantity \( l_{J/\psi} = L_{xy} \cdot m_{J/\psi}/p_T \) where \( L_{xy} \) is the most probable transverse decay length in the laboratory frame.

Fig. 3 shows the projection of the likelihood fits in two sample bins. The non-prompt J/ψ differential production cross sections have also been compared with calculations made with the Pythia and CASCADE Monte Carlo generators, and in the FONLL framework \[45\]. The results are presented in Fig. 4, showing a good agreement with the calculations.

Different sources of systematic errors contribute to the total uncertainty of the extraction of the non–prompt component, and in general they depend on the considered \( y \) interval. In rough order of relevance, they are:

- primary vertex estimation;
- decay length resolution function;
- background fit;
- residual misalignments in the tracker;
- b-hadron lifetime model;
- efficiencies for prompt and non–prompt J/ψ.

3.4 \( \Upsilon \) cross section measurements

The \( \Upsilon \) states 1S, 2S and 3S were observed with evident signals above the background in the 3 pb\(^{-1}\) of data analyzed. The mass resolution provided by the full CMS detector reconstruction is \( \sim 70 \) MeV for \( \eta(\mu) < 1.0 \). The yields are extracted simultaneously with a maximum likelihood fit in \( p_T \) and \( y \) intervals, and the double differential cross sections in \( p_T \) and \( y \) are measured after having corrected the data for the acceptance and efficiency as for the J/ψ analysis. The measured values of the \( \Upsilon(nS) \) integrated production cross sections for the rapidity range \(|y| < 2\) are:

\[
\begin{align*}
\sigma(p \, p \rightarrow \Upsilon(1S)X) \cdot B(\Upsilon(1S) \rightarrow \mu^+\mu^-) &= (7.37 \pm 0.13(\text{stat})^{+0.61}_{-0.42}(\text{syst}) \pm 0.81(\text{lumi}))\text{nb}; \\
\sigma(p \, p \rightarrow \Upsilon(2S)X) \cdot B(\Upsilon(2S) \rightarrow \mu^+\mu^-) &= (1.90 \pm 0.09(\text{stat})^{+0.20}_{-0.11}(\text{syst}) \pm 0.24(\text{lumi}))\text{nb}; \\
\sigma(p \, p \rightarrow \Upsilon(3S)X) \cdot B(\Upsilon(3S) \rightarrow \mu^+\mu^-) &= (1.02 \pm 0.07(\text{stat})^{+0.11}_{-0.08}(\text{syst}) \pm 0.11(\text{lumi}))\text{nb}.
\end{align*}
\]
Figure 3: Projection of the two-dimensional likelihood fit (in mass and $l_{J/\psi}$) to the $l_{J/\psi}$ dimension for bins $2 < p_T < 4.5$ GeV, $1.2 < |y| < 1.6$ (left) and $6.5 < p_T < 10$ GeV, $1.6 < |y| < 2.4$ (right), with their pull distributions (bottom).

Figure 4: Differential non-prompt $J/\psi$ production cross section, as a function of $p_T$ for three different rapidity intervals. The data points are compared with three different models, using the PYTHIA curve to calculate the abscissa where they are plotted [46].
The Υ (1S) and Υ (2S) measurements include feed-down from higher-mass states, such as the χ_b family and the Υ (3S). These measurements assume unpolarized production. Assumptions of fully-transverse or fully-longitudinal polarizations change the cross sections by about 20%.

The results are shown in Fig. 5, that presents the differential production cross sections for the Υ(nS) states as a function of the meson’s p_T, and the relative ratio between the 2S and 3S states over the ground 1S state. The fraction of 2S and 3S with respect to the 1S clearly increases with p_T. The measured values are found to be in good agreement with previous Tevatron findings [21, 22]. The normalized p_T spectrum prediction from PYTHIA is consistent with the measurements, while it overestimates the integrated cross section by about a factor of two.

![Graph showing differential production cross section and ratio for Υ(nS) states.](image)

Figure 5: Differential production cross section of Υ(1S), Υ(2S) and Υ(3S) states, as a function of mesons’ p_T, on the left hand side, and the cross section ratio of Υ(2S) and Υ(3S) states relative to the ground state, on the right hand side.

4 Result from CDF Experiment on Υ(1S) polarization

The CDF Collaboration has a long record of studies about quarkonia physics. Knowledge of J/ψ and Υ production mechanisms has increased in the past decades with new data and with progress in theory. Still, almost 40 years after the J/ψ discovery, a comprehensive view of quarkonium production mechanisms and polarization is still missing, as already mentioned in Sec. 1.
The most recent results about the Υ polarization study at CDF [47], presented for the first time at this conference, are summarized here. The measurements were performed using 2.9 fb\(^{-1}\) of \(p\bar{p}\) collisions data at 1.96 TeV, making use of a template method, in which fully transverse and fully longitudinal Monte Carlo samples are generated and subjected to detector acceptance and efficiency effects, and then iteratively re-weighted to match the data \(p_T\) distributions. Based on the shapes of the polar distributions of the positive muon in the \(s\)-channel helicity frame, the polarization parameter is determined by matching a polarization-weighted combination of templates to data in different \(p_T(\Upsilon)\) bins. Events are selected using a mass fit, and backgrounds are evaluated using mass sidebands. The result is presented in Fig. 6, that represents the Υ polarization in terms of the parameter \(\alpha\), the polar angle of the positive muon in the \(s\)-channel helicity frame. Its values range from \(-1\), for a fully longitudinal polarized Υ, to \(+1\), for a fully transverse polarization. The Υ are found to be unpolarized at low \(p_T\), before developing a strongly longitudinal polarization at high \(p_T\), in obvious contrast with the NRQCD prediction. It is worth to mention that these findings are consistent with those from CDF Run I [48] and in disagreement with D0 run II ones [49].

![Diagram](image-url)

**Figure 6:** Υ polarization as a function of the parameter \(\alpha\), the polar angle of the positive muon in the \(s\)-channel helicity frame, as measured by the CDF Collaboration over 2.9 fb\(^{-1}\) of \(p\bar{p}\) collision data, compared with the predictions of the NRQCD calculations, represented by the colored band.
5 Other beauty hadrons

5.1 Exclusive production of B-mesons

The high production cross section of \(b\bar{b}\) pairs at the LHC energy, together with the good performance of the CMS detector, made possible the observation of \(B\)-hadrons such as \(B^+\), \(B^0\) and \(B_s\) rather early in the first year of data-taking, where the data samples used for the full analysis have been 5.8 pb\(^{-1}\) for the former [50], and 40 pb\(^{-1}\) for the latter two [51, 52].

The decay channels through which the \(B\)-mesons have been reconstructed are:

\[
\begin{align*}
B^+ &\rightarrow J/\psi K^+ \\
B^0 &\rightarrow J/\psi K_s(\rightarrow \pi^+\pi^-) \\
B_s &\rightarrow J/\psi \Phi(\rightarrow K^+K^-)
\end{align*}
\]

The \(J/\psi\) is always reconstructed via its decay to two opposite sign muons, which are also supposed to fire the di-muon trigger used to collect the data sample. Fig. 7 summarizes the results for the cross section measurements for the channels in (1), showing also the prediction of the MC@NLO.

Combined fit to the \(B\)-meson masses and lifetimes are used to reject the background, with most of the fit shapes derived directly from data; \(B\)-meson reconstruction efficiencies were taken from MC, whereas tracking, muon and trigger efficiencies were derived from data. The 2D maximum likelihood fits were performed in different bins of the mesons’ \(p_T\) and \(y\), in order to measure the differential production cross sections. The results of the measurements, shown in Fig. 8, are compared with the predictions of PYTHIA MC and MC@NLO calculation. In general the agreement with the latter is fair, but some differences in the \(y\) distributions are observed.

5.2 Observation of other heavy hadrons

beside \(B\)-mesons, other interesting particles have been observed and measured in the 40 pb\(^{-1}\) of \(pp\) collision data collected in 2010 by the CMS detector. The invariant mass peaks of the \(\chi_{c1}\) and \(\chi_{c2}\) states, separated by a \(\Delta m \simeq 45\) MeV, have been reconstructed through the decay channel \(\chi_{c} \rightarrow J/\psi + \gamma\) [53]. The \(\Lambda_b\) baryon has also been observed through its decay to \(J/\psi + \Lambda\) [54]. Furthermore, the puzzling \(X(3872)\) state has been observed in the decay channel to \(J/\psi \pi^+\pi^-\), and the ratio of its cross section over the \(\psi(2S)\) has been measured, giving: \(R = X(3872)/\psi(2S) = 0.087 \pm 0.017\) (stat.) \(\pm 0.009\) (syst.) [55]. Fig. 9 shows the invariant mass peaks of the aforementioned states.

6 Open beauty

b-jets play a key role in searches for new physics beyond the Standard Model. It took a while to fully establish a consistency between the Tevatron data and pQCD predictions for b-jet production cross section. Generally speaking, b-jets cross section measurements are highly
Figure 7: 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 are coming from the MC@NLO.

non-trivial, and sizable uncertainties affect both theory and experiment: on one side, one has to deal with a typical multi-scale problem, in which the center–of–mass collision energy, mass of the b–quark and the factorization and re–normalization scales are entangled in a subtle way; on the other hand, excellent performance of the tracking is required, challenging the detector full potential.

The CMS Collaboration has published results on b–jet production, which are briefly reviewed in the next sections: two complementary cross section measurements, making use of two different b–tagging techniques, and a study of the $B\bar{B}$ correlations, performed over $85 \text{ nb}^{-1}$, $60 \text{ nb}^{-1}$, and $3.1 \text{ pb}^{-1}$ of 2010 data, respectively [56, 57, 58]. These results were obtained using track or particle–flow jets. Typical values for the CMS performance at the time of the results presented here were: jet resolution about $10–15\%$, energy scale uncertainty below $3\%$. 

\[ \begin{align*}
\text{pp} & \rightarrow B^{+} X \\
P_{T}>5 \text{ GeV}, |y|<2.4 & \quad 28.3 \pm 2.4 \pm 1.0 \pm 1.1 \mu \text{b} \\
\text{(40 pb}^{-1}) & \\
\text{pp} & \rightarrow B^{0} X \\
P_{T}>5 \text{ GeV}, |y|<2.2 & \quad 33.2 \pm 2.5 \pm 1.3 \mu \text{b} \\
\text{(40 pb}^{-1}) & \\
\text{pp} & \rightarrow B_{s} X \rightarrow J/\psi \phi X \\
8<P_{T}<50 \text{ GeV}, |y|<2.4 (x1000) & \quad 6.9 \pm 0.6 \pm 0.3 \text{ nb} \\
\text{(40 pb}^{-1}) & \\
\end{align*} \]
Figure 8: Measured differential cross section $d\sigma/dp_T$ (left–hand side) and $d\sigma/dy$ (to the right), for $B^+$ (upper row), $B^0$ (center) and $B_s$ (bottom) mesons, compared to the theoretical predictions. The error bars correspond to the statistical uncertainties, and the (yellow) band represents the uncorrelated systematic uncertainties. Overall uncertainties from the luminosity and the branching fractions, reported in the plots, are not shown. The solid and dashed (blue) lines are the MC@NLO prediction and its uncertainty, respectively. The dotted (red) line is the PYTHIA prediction.
Figure 9: Invariant mass peaks of the $\chi_{c1}$ and $\chi_{c2}$ states (left), $\Lambda_b$ (center), the $\psi(2S)$ and the $X(3872)$ states (right). The reconstructed decay channels are reported in the text.

Figure 10: Ratio of the measured production cross sections over the predictions of the MC@NLO computation, as a function of the muon’s $p_T$ on the left hand side, and $\eta$ on the right, compared with the predictions provided by the Pythia, CASCADE MC and the FONLL calculations.

6.1 b–jets with muons

The measurement of the integrated and differential cross section of the reaction $pp \rightarrow b + X \rightarrow \mu + X$, has been performed on jets coming from b–quarks. The production of a b–quark decaying semi–leptonically is deduced by the identification of a rather energetic muon inside a jet, where the transverse momentum relative to the jet axis is quite sizable. For a muon from a b–decay, the transverse momentum relative to the jet axis is on average larger than when the muon comes from light quarks; through this property it is hence possible to
discriminate events in which b–quarks were produced.

A binned log-likelihood fit is performed on the spectrum of such a quantity, called \( p_{\text{rel}}^{T} \), using template distributions provided by the simulation for \( b \) and \( c \) quarks, and derived from the data for gluons and light quarks. This latter is dominated by hadrons misidentified as muons (mainly decay-in-flight), so they are reweighted by the misidentification rate measured in the data. Considering that the fit is not able to distinguish light quark, gluon and charm components, these are merged together.

The fit stability was tested against variation of the binning, repeating the fits on many simulated pseudo–experiments, cross–checking the results using jets from particle flow and performing the fits on the impact parameter distribution.

The \( b \)-jet tag efficiency achieved with this technique is about 74\% at \( p_{T} (\mu) \simeq 6 \text{ GeV} \), and close to 100\% above 20 GeV, whereas the contamination is \( \sim 7\% \) in lowest \( p_{T} \) bin, asymptotically decreasing towards 2\% at high \( p_{T} \). The uncertainties dominating the measurement are those coming from the approximate knowledge of the signal and the background \( p_{\text{rel}}^{T} \) shape.

Fig. 10 shows the ratio of the measured differential production cross sections in \( p_{T} \) and \( \eta \) over the predictions of the MC@NLO computation, as well as those provided by the Pythia, CASCADE MC and the FONLL calculations.

6.2 \( b \)-tagging with secondary vertices

The identification of jets coming from the hadronization of b–quarks is possible also through the reconstruction of secondary vertices (SV). Once a displaced SV is reconstructed, differ-
ent discriminators can be used to tag the jet as originating from a b–quark. In the analysis presented here, the discriminator adopted is a monotonic function of the 3D decay length. The decay length significance cut is chosen so that the corresponding tagging efficiency is about 60% at $p_T^{jet} = 100$ GeV, with a contamination of $\sim 0.1\%$. The b–tagging efficiency and the mistag rates from c or light jets are evaluated from simulated events and constrained by a data/MC scale factor obtained from data. The jet energy corrections for rapidity dependence, and those for absolute scale and $p_T$ dependence, come from real data and simulated events respectively. In order to evaluate the purity of the selected sample, a fit to the SV mass distribution is performed, taking the shapes from simulated events, and letting free the relative normalizations for c and b jets, with the (small) contribution from light quarks fixed to the Monte Carlo expectations (“template fit”).

![Figure 12: Production cross sections as a function of the opening angle $\Delta R$ between the two B mesons in different ranges of the leading jet $p_T$, with absolute normalization (left); ratio of the measured cross section with the predictions from Pythia, compared with MC@NLO, MadGraph and Cascade MC model predictions (right). The dashed area at high $\Delta R$ values is used as the normalization region.](image)

The data sample was collected using hadronic triggers with different thresholds of the jet $p_T$; to merge them, the individual $p_T$ spectra of jets have been normalized with the luminosity of their data taking periods, and then combined into a single spectrum with the jet $p_T$ bins corresponding to intervals where the triggers were fully efficient. The overall transverse jet energy range goes from 18 to 300 GeV, and the measurements have been performed in four $\eta$ intervals.

The leading systematic uncertainties are:

- the jet energy scale of b–jets relatively to the inclusive ones (45%);
- data-driven constraints on b-tagging efficiency (20%);
• mistag rate for charm (34 %) and for light jets (1 - 10%).

Fig. 11 shows the results for the production cross section measurements for b–jets as a function of the b–jet transverse momentum, compared with the MC@NLO predictions, and the ratio with the inclusive jets cross-section. While the agreement with Pythia and MC@NLO is reasonable, significant differences in shape are evident, the simulations predicting more b–jets at high $p_T$ than what is observed.

![Graph showing production cross section measurements for b–jets](image)

Figure 13: Ratio between $B\bar{B}$ production cross section in $\Delta R < 0.8$ and $\Delta R > 2.4$ as function of leading jet $p_T$, compared with Pythia, in green, and MadGraph MC predictions, in blue (left). Asymmetry between $B\bar{B}$ production cross section in $\Delta R < 0.8$ and $\Delta R > 2.4$ as function of leading jet $p_T$ (right).

6.3 $B\bar{B}$ correlations

Among the parton–level mechanisms of $b\bar{b}$ production most relevant at LHC, there are the flavor creation, of order $\alpha_s^2$, in which the heavy quarks are produced directly from two primary gluons in a t–channel process, and, at order $\alpha_s^3$, the so–called flavor excitation and the gluon splitting. In the latter one, the $b\bar{b}$ comes from a single gluon through an s–channel process.

Considering B–hadrons coming from the hadronization of b–quarks, one important difference among the processes of direct flavor creation and the gluon splitting comes from the kinematic of the B’s. The opening angle between the two B mesons is expected to be rather different, being larger in the process of lowest order.

The CMS Collaboration has performed a detailed study of the $B\bar{B}$ correlations, providing a significant test of QCD and a further insight into the dynamics of $B\bar{B}$ production mechanisms. Making use of the SV–based b–tag techniques, the quantity $\Delta R$ defined as
the distance in the $\eta$–$\phi$ plane between the primary vertex and each SV, $\Delta R = \sqrt{\eta^2 + \phi^2}$, is used to study the angular correlation of the B mesons.

The production cross sections have been measured as a function of the opening angle $\Delta R$ among the two mesons; the results are presented in different ranges of the leading jet’s $p_T$, as in Fig. [12] where also the ratio with the predictions from Pythia is presented, together with the comparison with the MC@NLO, MadGraph and Cascade MC predictions. The dashed region at large $\Delta R$, in principle better known since it is dominated by LO processes, is used in this case to obtain the normalization of the remaining region of $\Delta R$.

Considering that the flavor creation is expected to dominate at high values in $\Delta R$, whereas the gluon splitting contributes more at low values, it is interesting to check the agreement between the data and the theoretical models. This is shown in Fig. [13] where the ratios of the cross sections in the regions $\Delta R < 0.8$ and $\Delta R > 2.4$, and the relative asymmetry, are shown. None of the predictions describes the data very well, that lie between the MadGraph and Pythia. The calculations from MC@NLO do not describe the shape of the $\Delta R$ distribution either, in particular at small values, and the Cascade predictions are significantly below the data everywhere.

7 Conclusions

Various recent results published by the CMS Collaboration have been summarized, all of them obtained analyzing the $pp$ collision data at 7 TeV collected in the year 2010.

Measurements have been performed on quarkonia states, studying the production of $J/\psi$ and $\Upsilon$ states, extracting the total and differential production cross sections as function of the mesons’ $p_T$ and $y$ for different polarization scenarios. The cross section of $J/\psi$ coming from $b$–hadrons was also measured and compared with the available theoretical computations. The latest result on the $\Upsilon$ polarization by the CDF Collaboration has also been presented. Exclusive reconstructions of different B–mesons such as $B^+$, $B^0$ and $B_s$ have been presented, together with the production cross section measurements versus $p_T$ and $y$. The observation of other beauty and charmed hadronic states, as the $\chi_{c1,2}$, the $\Lambda_b$ baryon and the $X(3872)$ state has also been reported.

Finally, the CMS results on open beauty production have been summarized, showing the studies made with two different techniques for $b$–tagging, together with those on the angular correlation of B–mesons, and comparing the data with the predictions of the available theoretical models.
ACKNOWLEDGEMENTS

The involvement in this work was made possible by the founding of the INFN, sezione di Padova. I am grateful to Prof. U. Gasparini for all the sustaining and encouraging, and to the entire CMS Padova group for the fruitful collaboration.
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