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Prospects for B Physics Measurements using the CMS Detector at the LHC

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Abstract

The LHC provides new opportunities to improve our understanding of the *b* quark using high statistics data samples and the 14 TeV center-of-mass energy. The prospects to measure the cross section for inclusive *b* production in events containing jets and at least one muon are presented. Additionally, the feasibility for CMS to measure the mass and the lifetime of the B_c meson and to search for the rare leptonic decay $B_s \to \mu\mu$ are presented. Detailed studies of detector systematic effects and theoretical uncertainties are included

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PROSPECTS FOR B PHYSICS MEASUREMENTS USING THE CMS DETECTOR AT THE LHC

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The LHC provides new opportunities to improve our understanding of the *b* quark using high statistics data samples and the 14 TeV center-of-mass energy. The prospects to measure the cross section for inclusive *b* production in events containing jets and at least one muon are presented. Additionally, the feasibility for CMS to measure the mass and the lifetime of the B_c meson and to search for the rare leptonic decay $B_s \to \mu\mu$ are presented. Detailed studies of detector systematic effects and theoretical uncertainties are included.

Keywords: B Physics; LHC; CMS.

1. Inclusive b-quark production

B production will be one of the most copious sources of hadrons at LHC. A study [1] has been performed on Monte Carlo events generated with PYTHIA to investigate methods in CMS of identifying *b*-jets (*b* "tagging") in an inclusive sample of events containing jets and at least one muon. We present the capability to measure the inclusive *b*-quark production cross section as a function of the *B*-hadron transverse momentum p_T and pseudorapidity η.

The study of the CMS capability to measure the inclusive *b* production is based on full detector simulation. The measurement of the differential cross sections is studied for *B*-hadrons of $p_T > 50$ GeV/c and within the fiducial volume of $|\eta| < 2.4$. The event selection requires a *b*-tagged jet in the fiducial volume to be present in the event. *B* tagging is based on inclusive secondary vertex reconstruction in jets [2]. At Level-1 (L1) trigger, the single muon trigger is used. At the High Level Trigger (HLT) we require the "muon + *b*-jet" trigger.

The most energetic *B*-hadron inside the phase space defined above is selected. Good correspondence between the generated *B*-particle and the reconstructed *b*-tagged jet is observed. The corresponding p_T and pseudorapidity relative resolutions are shown in Figure 1 for *B*-particles with $p_T > 170$ GeV/c. The resolutions are 13% and 6% for p_T and η, respectively.

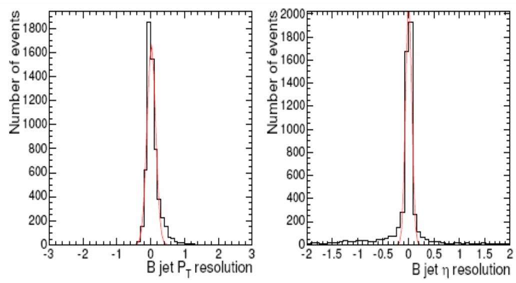

Fig. 1. Relative resolution, (Reconstructed − True) / True, for p_T and pseudorapidity of *b* tagged jets in CMS.

The average *b* tagging efficiency is 65% in the barrel region, while the efficiency is about 10 % less for the endcap region.

The signal fraction is determined from a fit to the data distribution using the simulated shapes for the signal and background. To do so we apply a lepton tag by selecting inclusive muons. Each reconstructed muon is associated to the most energetic *b* tagged jet. The muon must be closer to this *b* tagged jet than to any other jet in the event. Otherwise the event is discarded. In most cases the tagged muon is inside the b jet. The average efficiency of associating the muon with the b tagged jet is

75 %. We calculate the transverse momentum of the muon with respect to the *b*-jet axis which effectively discriminates between *b* events and background. Figure 2 shows an example of the fit of the distribution of the muon p_T with respect to the closest jet, using the expected shapes for the muons from *b* events, charm events and light quark events. The normalisation of the three contributions are free parameters in the fit. The event fractions are well reproduced within statistical errors [1].

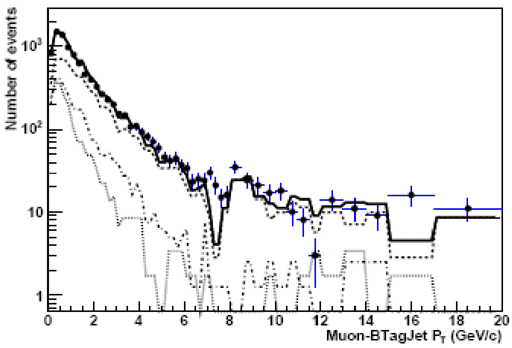

Fig. 2. Fit of the muon p_T spectrum with respect to the closest *b* tagged jet. The contributions of tagged muons from *b* events (dashed curve), *c* events (dot-dashed curve) and light quark events (dotted curve) as defined by the fit are shown. The solid curve is the sum of the three contributions.

The total event selection efficiency is about 5 %. By correcting for the semi-leptonic branching ratio of *b* quarks and *c* quarks it amounts to about 25 % on average. It turns out that the total efficiency is almost independent of transverse momentum and angle of the *B*-particle. Therefore the measurement of the differential cross section is less affected by systematic uncertainties due to bin-by-bin efficiency corrections.

Several potential sources for systematic uncertainties are considered and their impact on the observed cross section is detailed in [1]. The largest uncertainty arises from the 3 % error on the jet energy scale which leads to a cross section error of 12 % at $E_T > 50$ GeV/c. The estimated statistical, systematic and total uncertainty as function of the *b* tagged jet transverse momentum with respect to the beam line is shown in Figure 3.

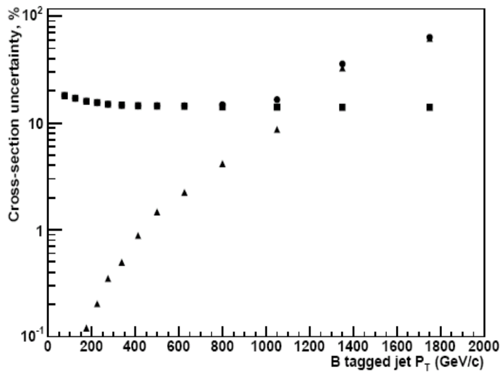

Fig. 3. The statistical uncertainty for the cross section measurement (triangles), systematic (squares) uncertainty and total (dots) uncertainty as function of the *b* tagged jet transverse momentum with respect to the beam line. Total uncertainty comprises the statistical and systematic uncertainties added in quadrature.

The event selection for inclusive *b* production measurement at CMS will allow to study *b* production mechanisms on an event sample of 16 million *b* events for 10 fb^{-1} of integrated luminosity. The *b* purity of the selected events varies as function of the transverse momentum in a range from 70 % to 55 %. Our estimate shows that with the CMS detector we can reach 1.5 TeV/c as the highest measured transverse momentum of *B* hadrons.

2. Study of B_c hadrons

The B_c meson is the ground state of the $\bar{b}c$ system, which is doubly heavy flavoured. This unique character provides a window for studying heavy-quark dynamics that is very different from the one of quarkonium. The experimental study of B_c will help to understand heavy quark dynamics and to test the spin symmetry derived in non-relativistic quantum chromodynamics (NRQCD). CMS has the potential to collect much more B_c mesons than the Tevatron experiments do, due to the higher production cross section and luminosity.

The study the B_c meson through $B_c^+ \rightarrow J/\Psi\, \pi^+$, with $J/\Psi \rightarrow \mu^+\mu^-$ is proposed. The goal is to measure the mass and lifetime, and to compare the results with theoretical predictions which do have large uncertainties at the moment.

The selection starts from two muon tracks. The two muons should have different charge and share the same vertex. To form a *J/Ψ* candidate the invariant mass of the muons should be in a window between 3.0 and 3.2 GeV/c^2. An additional track must be found at the same vertex of the *J/Ψ* which is inconsistent with a muon or an electron. A kinematic fit is applied to the selected events imposing a *J/Ψ* mass constraint and forcing the two muon tracks as well as the pion track to share the same vertex. After the kinematic fit the invariant mass of the *J/Ψ* – pion system is shown in Figure 4. The distribution of the proper decay length together with the fit result is also shown in Figure 4. Backgrounds from *B* hadrons and prompt *J/Ψ* are included in the plot, while other backgrounds are neglected here. More details on the analysis can be found in reference [3].

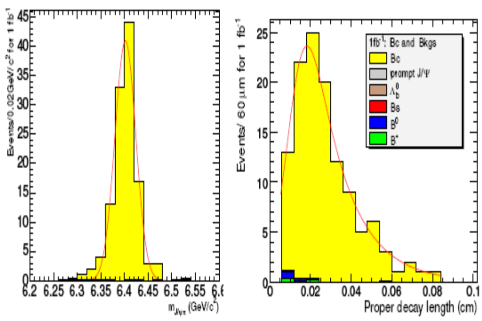

Fig. 4. Left: The invariant mass of the *J/Ψ* and pion candidate for the selected B_c. Right: The B_c proper decay length distribution. Both plots correspond to 1 fb^{-1}.

With the first fb^{-1} of data CMS is expected to measure the B_c mass with an uncertainty of 22.0(stat.) ± 14.9(syst.) MeV/c^2 and $c\tau$ with 13.1(stat.) ± 3.0(syst.) μm, corresponding to a lifetime uncertainty of 0.044(fit) ± 0.010(syst.) ps. About 120 $B_c^+ \rightarrow J/\Psi \pi^+$, with $J/\Psi \rightarrow \mu^+\mu^-$, events would be observed. At the moment, the theoretical calculation is at the leading order without the colour-octet contribution. Therefore the uncertainties on the total cross section and the p_T distribution are large. In the real data analysis, *J/Ψ* plus one track with $J/\Psi \rightarrow \mu^+\mu^-$ will be selected as a control sample, $B^+ \rightarrow J/\Psi K^+$ will be used to estimate the efficiency, and the side band of the *J/Ψ* peak will be used to estimate the background to B_c.

3. Study of $B_s^0 \rightarrow \mu^+\mu^-$ in CMS

The $B_s^0 \rightarrow \mu^+\mu^-$ decay is a Flavor Changing Neutral Current (FCNC) process forbidden at tree-level. In the Standard Model the branching ratio of this decay is expected to be about 3.4 × 10^{-9} [4]. The rate of this process can be used to put constraints on CKM matrix elements or on the structure of FCNC processes, or to indicate new physics. Many theories that go beyond the standard model predict much larger FCNC effects in the heavy quark system. Current experimental limit for $B_s^0 \rightarrow \mu^+\mu^-$ decay branching ratio is < 1.0 × 10^{-7} at 95 % confidence level [5].

Figure 5 illustrates the rare decay $B_{s(d)}^0 \rightarrow \mu^+\mu^-$. In the SM, this decay proceeds through $W^{\pm}$ and Z^0 bosons in box (left) and loop (right) interactions. In SM extensions (*e.g.*, in the MSSM) new particles (*e.g.*, neutralinos and supersymmetric partners of the quarks and leptons) can contribute to the process and thereby increase the expected branching fraction by orders of magnitude.

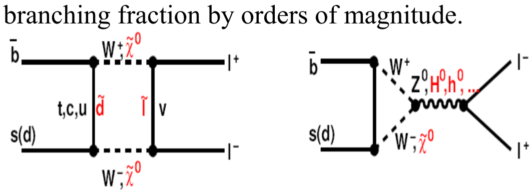

Fig. 5. Illustration of the rare decay $B_{s(d)}^0 \rightarrow \mu^+\mu^-$.

A study of measuring the rare $B_s \rightarrow \mu\mu$ decay has been performed with CMS experiment at the LHC [6]. Monte Carlo (MC) event samples were generated with PYTHIA 6.227 and passed through a full detector simulation based on GEANT 4. On average five pile-up events were included, appropriate for a luminosity of 2×10^{33} cm^{-2} s^{-1}. Both signal and background MC event samples have been generated as minimum bias QCD events. In the signal sample, B_s mesons decay as $B^0_{s\,(d)} \to \mu^+\mu^-$. The muons are required to have transverse momentum $p_T^{\mu} > 3$ GeV/c and $|\eta| < 2.4$; the B_s must have $p_T^{Bs} > 5$ GeV/c. The background is dominated by gluon splitting. In total 20000 signal events and about 15000 background events have been analyzed. The small size of the background sample is the limiting factor of the present study.

The L1 trigger strategy relies on the di-muon trigger stream. The high-level trigger (HLT) strategy relies critically on the pixel detector for a fast and high-efficiency determination of the primary vertex, the determination of large impact-parameter muons, and the mass of the muon pair. For the offline event selection, variables related to the primary vertex, the muon candidates, and the B_s candidate with its associated secondary vertex are calculated.

Figure 6 illustrates the mass resolution obtained on the signal MC event sample.

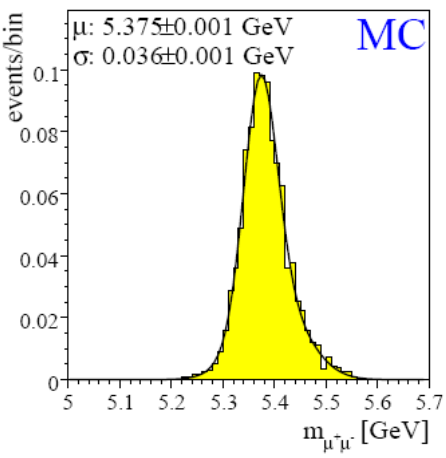

Fig. 6. Dimuon mass distribution in signal MC events. The curve is a fit of two Gaussians, the displayed parameters indicate the average mean and sigma. The histogram is normalized to unity.

Given the limited statistics of the background sample, no events remain after the application of all selection requirements. However, the absence of correlation to the other selection requirements allows a factorization of the isolation and χ^2 requirements with respect to the other cuts in the determination of the total background rejection factor.

The dominant sources of uncertainty on the signal (±25 %) and background ($^{+160}_{-100}$ %) yield are the statistical component of the background sample, the impact of the misalignment on the transverse flight length significance, and the assumption of factorizing cuts.

The total selection efficiency for signal events is 0.019 ± 0.002 and the background reduction factor is 2.7×10^{-7}. With 10 fb^{-1} luminosity the selection allows for 6.1 signal events and 14.3 background events. The corresponding upper limit on the branching fraction is $< 1.4 \times 10^{-8}$ at the 90 % C. L. This result promises an interesting start-up analysis with the possibility of setting tight constraints on the MSSM. With sufficient integrated luminosity, the precision measurement of the $B_s\to\mu\mu$ branching fraction will set constraints on models of new physics.

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