The Compact Muon Solenoid Experiment

Conference Report

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Exclusive B production at CMS with the first LHC data

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Abstract

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Exclusive B production at CMS with the first LHC data

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B physics will be one of the key physics themes at the Large Hadron Collider (LHC). In this talk, we present the estimated sensitivities of CMS for observing and measuring properties of exclusive final states $B \rightarrow J/\Psi + X$ during the first LHC running period. Apart from probing the heavy quarks at the LHC center-of-mass energy, these measurements are also important standard candles for upcoming measurements.

1. Introduction

Since the Large Hadron Collider (LHC) established the first proton-proton collisions with 7 TeV center-of-mass (CM) energy, on 30 March 2010, a completely new energy frontier is being explored. The machine luminosity is steeply increasing and it is envisaged that in 2010 instantaneous luminosities of the order of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ will be reached, integrating a luminosity of a few tens of inverse picobarn. By the end of 2011 a total integrated luminosity of the order of 1 fb^{-1} will be probably available.

The LHC experiments are expected to provide important contributions to presently “hot” topics in B physics, like the study of oscillations and CP violation in the B_s sector and the search for rare B decays, such as the flavor changing neutral current (FCNC) decays: $B_s \rightarrow \mu^+ \mu^-$ and $B_d \rightarrow \mu^+ \mu^-$. New physics might be unveiled by these processes. These studies require high statistics (order of few fb^{-1} of integrated luminosity), perfectly commissioned detectors and accurate control of the background sources. The performance of the detectors is a key factor in pursuing these studies.

One important task to be accomplished with the first few pb^{-1} of collected data is to assess the b production mechanism at $\sqrt{s} = 7 \text{ TeV}$, measuring the relevant cross sections up to a large transverse momentum (p_T) range and with high angular acceptance. To this respect the study of exclusive decays of the $B^\pm$ and B^0 mesons into a J/ψ plays an important role. The presence

of a $J/\psi \rightarrow \ell^+ \ell^-$ decay in the final state is a clean signature providing a useful trigger primitive. The properties of the $B^\pm$ and B^0 mesons (masses, lifetimes, decay branching fractions) are well known from previous experiments, so that the reconstruction of their decays and the measurement of their lifetimes can be used to test the commissioning of the detectors with early data. B production differential cross sections can be measured using exclusive decay channels, benefiting from a better control of the background and reduced systematic uncertainties with respect to the inclusive channels. Finally some B^+ and B^0 exclusive decays are either important background sources or reference channels for studies in the B_s sector, like the search for $B_s \rightarrow \mu^+ \mu^-$ decays.

2. The CMS experiment

The Compact Muon Solenoid (CMS) is a general-purpose detector, primarily designed for the search of the Standard Model Higgs Boson and New Physics in the high p_T region. It is equipped with a super-conducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Inside the solenoid volume are located the brass/scintillator hadron calorimeter (HCAL), the crystal electromagnetic calorimeter (ECAL), the inner tracker. Muons are measured outside the solenoid, in gas-ionization detectors embedded in the steel return yoke. The inner tracker consists of 1440 silicon pixel and 15148 silicon strip detector modules and provides an impact

parameter resolution of $\sim 15 \mu\text{m}$ and a p_T resolution of about 1.5 % for 100 GeV/c particles. The muon detectors cover the pseudorapidity window $|\eta| < 2.4$, deploying detection planes made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. More information about the CMS detector can be found elsewhere [1].

2.1. The trigger system

The first level (L1) of the CMS trigger system, composed of custom hardware processors, is designed to select, in less than 1 μs , the most interesting events, using information from the calorimeters and muon detectors. The High Level Trigger (HLT) processor farm further decreases the event rate from up to 100 kHz to 100 Hz, before data storage.

Figure 1. Trigger efficiency (L1 + HLT) for the reconstruction of $B^+ \rightarrow J/\psi K^+$ events, in various trigger scenarios, as a function of p_T^B [2].

B decays into a J/ψ are naturally triggered by the muons from the $J/\psi \rightarrow \mu^+ \mu^-$ decay. Since B-physics events are relatively soft, the trigger efficiency depends critically on the p_T thresholds applied, which are adjusted depending on of the instantaneous luminosity of LHC. As an example, figure 1 shows a study of the trigger efficiency in a simulation of $B^+ \rightarrow J/\psi K^+$ decays in p-p collisions at $\sqrt{s} = 10 \text{ TeV}$ [2]. The Monte Carlo

sample is preselected requiring two muons at the generator level with p_T exceeding 2.5 GeV/c and $|\eta| < 2.4$. The trigger efficiency is shown as a function of the simulated B momentum, for several trigger choices. Most part the signal lies in the p_T region between 10 and 15 GeV/c. Two HLT muons, with $p_T > 3 \text{ GeV}/c$, are considered as a trigger requirement in the analysis, resulting in a trigger efficiency between 20 % and 30 %. Considerably higher efficiencies may be obtained by relaxing the trigger requirement to a single muon with $p_T > 3 \text{ GeV}/c$, which is still sufficient to keep the trigger rate sustainable in the startup phase of LHC.

3. $b\bar{b}$ angular correlations

The dominant source of B hadrons at LHC is $b\bar{b}$ pair production through the strong interaction. The QCD production mechanisms are usually divided in the following categories: flavor creation, flavor excitation, gluon splitting. Flavor creation is a leading order process generating back-to-back, high p_T , $b\bar{b}$ pairs. Flavor excitation and gluon splitting are next to leading order processes which generate, respectively, $b\bar{b}$ pairs with asymmetric p_T and $b\bar{b}$ pairs at low p_T and close in direction. The angular correlation between the b and the $\bar{b}$ quark is sensitive to the relative contribution of the three mechanisms (see figure 2).

CMS plans to measure the $b\bar{b}$ angular correlations in the plane transverse to the beams ($\Delta\phi$) in decays where one b flavor decays into a J/ψ and the opposite flavor decays semileptonically into a muon. This is a clean 3-muon signature, easily accessible since the LHC startup, providing good efficiency and granularity specially in the small $\Delta\phi$ region, where next to leading order contributions dominate. The analysis [3] requires two HLT muons with $p_T > 3 \text{ GeV}/c$ and impact parameter with respect to the beam spot lower than 2 cm. A third muon is required, with $p_T > 3 \text{ GeV}/c$. The estimated effective cross section for $b\bar{b} \rightarrow J/\psi \mu X$ decays, after the selection, is about 145 pb for p-p collisions at $\sqrt{s} = 10 \text{ TeV}$.

Three variables are considered to separate the signal from the main background processes: the invariant mass of the two muons forming the

Figure 2. Distribution of $\Delta\phi$ for the $b\bar{b} \rightarrow J/\psi \mu X$ process, after all selection criteria are applied (see text). The different signal and background components are stacked and shown in different colors [3].

J/ψ candidate ($M_{\mu^+\mu^-}$), the vertex displacement of the J/ψ from the primary vertex in the plane transverse to the beams (L_{xy}) and the impact parameter in the transverse plane (d_{xy}) of the muon originating from the semi-leptonic b decay. The following background categories are identified: “prompt J/ψ ” produced in QCD events, “fake J/ψ ” events, and processes where the third muon is not originating from the decay of a b quark (“fake muon”). Probability density functions for the $M_{\mu^+\mu^-}$, L_{xy} and d_{xy} variables are worked out from Monte Carlo events for the signal and each of the background categories. The data sample with $J/\psi + \mu$ candidates is divided into bins of $\Delta\phi(J/\psi, \mu)$, the angle in the plane transverse to the beams between the J/ψ and the third muon. For each bin the signal and background yields are derived through a simultaneous unbinned maximum likelihood fit to $M_{\mu^+\mu^-}$, L_{xy} and d_{xy} . An unfolding procedure, based on MC templates, is then adopted to infer the $\Delta\phi(b, \bar{b})$ distribution from $\Delta\phi(J/\psi, \mu)$.

Analysis of data at the CM energy of 7 TeV is ongoing. A Monte Carlo simulation performed at $\sqrt{s} = 10$ TeV [3] shows that, with an integrated luminosity of 50 pb^{-1} , it is possible to

collect more than 7000 signal events measuring the $b\bar{b}$ azimuthal correlation differential cross section, $d\sigma/d\Delta\phi$, with an accuracy of the order of 15-20 % in each $\Delta\phi$ bin, combining statistical and systematic uncertainties (see figure 3).

Figure 3. Simulation of the differential cross section measurement $d\sigma/d\Delta\phi$ with 50 pb^{-1} integrated luminosity at $\sqrt{s} = 10$ TeV.

4. Measurement of the differential production cross section of $B^\pm$ and B^0 mesons

As demonstrated by a Monte Carlo study at $\sqrt{s} = 10$ TeV performed by CMS [2], B production differential cross section in p-p collisions can be measured using exclusive B decay channels already with 10 pb^{-1} of integrated luminosity.

4.1. Event selection

$B^\pm$ and B^0 mesons are reconstructed via $B^\pm \rightarrow J/\psi K^\pm$ and $B^0 \rightarrow J/\psi K^{0*}$ decays. Events with $\mu^+\mu^-$ pairs deriving from a common vertex and with $M(\mu^+, \mu^-) = M_{J/\psi} \pm 150 \text{ MeV}/c^2$ are selected. The reconstruction of $B^\pm \rightarrow J/\psi K^\pm$ decays requires the presence of a third track, of good quality and with $p_T > 0.8 \text{ GeV}/c$. In the $B^0 \rightarrow J/\psi K^{0*}$ decay the K^{0*} is reconstructed in its $K^{0*} \rightarrow K^+\pi^-$ decay, requiring two tracks of opposite charge with $p_T > 0.5 \text{ GeV}/c$ and

$M(K^+, \pi^-) = M(K^{0*}) \pm 120 \text{ MeV}/c^2$. A kinematic fit is performed to the three (four) tracks from the J/ψ decay and the K^+ (K^{*0}), constraining all tracks to originate from the same vertex and constraining the two muon tracks to the nominal J/ψ mass. Only one B candidate per event is selected, based on the best vertex probability from the fit. Its reconstructed mass (M_B) is required to lie in the $4.95 - 5.55 \text{ GeV}/c^2$ range. After all selection requirements, the efficiency for the B^+ (B^0) selection is 11.6 % (8.6 %). Out of a sample corresponding to 10 pb^{-1} integrated luminosity, 1750 B^+ and 903 B^0 candidates are expected.

The sample of events with the reconstructed transverse momentum of the B meson (p_T^B) exceeding $9 \text{ GeV}/c$ is selected. The proper decay length in the transverse plane is measured by projecting the two-dimensional distance L_{xy} between the primary and the secondary vertex onto the reconstructed B transverse momentum. The lifetime t is obtained by the ratio:

$$ct = L_{xy} \cdot \frac{M_B}{p_T^B} \quad (1)$$

4.2. Background evaluation

Four background categories are identified, based on the reconstructed B invariant mass and the vertex displacement. “Peaking B” background is the feed-down and feed-up from misreconstructed B decays that peak in the invariant mass spectrum. “Combinatorial B background” is the combinatorial background deriving from $b\bar{b}$ events that contain a real J/ψ at generator level, but do not peak in the B mass. “Prompt” background peaks at zero lifetime and does not peak in the reconstructed B invariant mass. It derives from “prompt” $J/\psi \rightarrow \mu^+\mu^-$ decays. Finally, the “QCD” background derives from $\mu^+\mu^-$ pairs not originating from a J/ψ decay. The $B \rightarrow J/\psi\pi$ decays (where the incorrect mass of a Kaon is assigned to the pion track) are treated as a constant fraction of the $B^\pm \rightarrow J/\psi K^\pm$ signal.

4.3. Measurement of cross sections and B lifetime ratios

Signal yields and lifetimes are determined using an unbinned maximum-likelihood fit to M_B and ct of the reconstructed candidates. Probability density functions of M_B and ct for the signal and each of the background processes are modeled “a priori” on independent Monte Carlo samples. Figure 4 shows the fitted distributions of M_B and ct for the B^+ and B^0 samples assuming an integrated luminosity of 10 pb^{-1} . Various contributions from signal and background components are shown.

In order to measure the differential production cross section the sample is divided into bins of the p_T of the B meson candidate and the fit procedure is repeated in each p_T bin. This time, in order to limit the statistical uncertainty, only signal and background yields are floated in the fit, while the B lifetimes are fixed to the global fit values. The differential cross section $d\sigma(pp \rightarrow B + X)/dp_T^B$ can be measured this way up to $p_T^B \simeq 30 \text{ GeV}/c$, with a statistical error lower than 10% in all bins. The systematic uncertainties are estimated to be order of 13% in all bins and are dominated by the LHC luminosity determination in the startup phase (order of 10%).

From the lifetimes determined in the global fit the lifetime ratio:

$$R_{+0} = \frac{\tau(B^+)}{\tau(B^0)} = 1.10 \pm 0.05 \pm 0.01 \quad (2)$$

is derived, consistent with the current world average value of 1.071 ± 0.009 [4] used in the simulation. Systematic uncertainties like the misalignment and ct resolution cancel out in the ratio, so that the error is still driven by the statistical uncertainty.

4.4. Perspective

Measurements with $\sqrt{s} = 7 \text{ TeV}$ collisions are ongoing. With respect to the 10 TeV simulation a 75% reduction of the B production cross section is expected, but the adoption of reduced trigger thresholds brings a substantial gain in the final yield of events. Analyses of $B^0 \rightarrow J/\psi K_S^0$, $B_s \rightarrow J/\psi \phi$, $\Lambda_b \rightarrow J/\psi \Lambda^0$ decays are also ongoing. Considering that more

Figure 4. Simulated distributions of M_B and ct for the B^+ (top) and B^0 (bottom) fits. Individual contributions from signal and background components are shown.

than 1000 $J/\psi \rightarrow \mu^+\mu^-$ decays were selected in the first 15 nb^{-1} of data analyzed by CMS [5], it can be estimated that a few B exclusive decays might be present in this data sample. Actually a convincing $B^- \rightarrow J/\psi K^- \rightarrow \mu^+\mu^- K^-$ candidate was already found (see figure 5). This result is very preliminary. The reconstructed invariant mass of the J/ψ and K^- candidate is $5.286 \text{ GeV}/c^2$, the measured invariant mass of the $\mu^+\mu^-$ pair is $3.135 \text{ GeV}/c^2$. The $\mu^+\mu^- K^-$ vertex has a χ^2 probability of 0.844 and it is displaced from the primary vertex by 1.93 mm, with a significance of 18 standard deviations.

5. $B_s \rightarrow \mu^+\mu^-$

The $B_s \rightarrow \mu^+\mu^-$ process is a sensitive probe for New Physics. In the Standard Model (SM) its branching ratio is very small, $(3.86 \pm 0.15) \times 10^{-9}$

[6], since it involves a flavor-changing neutral current $b \rightarrow s$ transition, it requires an internal quark annihilation within the B meson and it is helicity suppressed. The branching ratio can be considerably higher, by orders of magnitude, in New Physics models like, for example, the Minimal Supersymmetric extension of the Standard Model at large $\tan \beta$ [7]. To date this decay has not been observed; the current best limits by CDF and D0 [8,9] are still one order of magnitude above the SM expectation.

In a simulation study performed by CMS [10] the $B^\pm \rightarrow J/\Psi K^\pm$ decay is used as a reference channel, allowing to cancel out many systematic errors to first order, including those due to the knowledge of the $b\bar{b}$ production cross section and the luminosity measurements. Since the process is very rare, a thorough control of the

Figure 5. Very preliminary: $B^- \rightarrow J/\psi K^- \rightarrow \mu^+ \mu^- K^-$ candidate event. Left: side view of the event. Right: detail of the vertex reconstruction. The measured distance between the primary and the secondary vertex in the transverse plane is 1.93 mm.

background processes is needed. In the simulation, which considers a data sample corresponding to 1 fb^{-1} integrated luminosity at $\sqrt{s} = 14 \text{ TeV}$, it is expected to pose the 95% c.l. limit: $\text{Br}(B_s \rightarrow \mu^+ \mu^-) \leq 1.9 \times 10^{-8}$. While this is still a factor four higher than the SM expectation, it allows to pose constraints on New Physics models already with the first 1 fb^{-1} of integrated luminosity.

6. Summary

The Large Hadron Collider has opened a new exciting energy frontier and the CMS experiment is collecting data with excellent quality. Exclusive B decays into a J/ψ offer a clean experimental signature well suited to the startup phase. Exclusive B mass peaks can be already reconstructed since the first few inverse picobarns of data collected, while B production cross sections and $b\bar{b}$ correlations can be measured with $O(10 - 20 \%)$ accuracy with the first few tens of inverse picobarns. By the end of 2011 data equivalent to $\sim 1 \text{ fb}^{-1}$ integrated luminosity could be available, making possible the search for rare B decays, like the $B_s \rightarrow \mu^+ \mu^-$ decay, which could either unveil New Physics or pose stringent limits to current theories beyond the Standard Model.

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