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Flavor Physics with CMS at LHC

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Abstract

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Flavor Physics with CMS at LHC

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The investigation of heavy flavor physics represents an alternative approach to direct New Physics searches at LHC. The CMS experiment concentrates its effort on decays with muons in the final state, that can be efficiently selected by the multiple-level triggers. We summarize here the perspective and expected results on different processes, from rare beauty hadron decays, τ decays and $q\bar{q}$ production, using data which will be collected in the first years of LHC running.

1. Introduction

There are several reasons why a general purpose detector like CMS designed for high p_T physics could be efficiently used to study heavy flavor physics. First of all, there will be about 10^{11} $b\bar{b}$ pairs produced at the initial luminosity year of $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ thanks to the high $b\bar{b}$ x-section which is $\sigma_{b\bar{b}} \sim 500 \mu\text{b}$ at $\sqrt{s} = 14 \text{ TeV}$. So, very rare decays like $B_s^0 \rightarrow \mu^+\mu^-$ and $B_s^0 \rightarrow \gamma\mu^+\mu^-$ could be searched even with the Standard Model (SM) decay rate. In different scenarios of New Physics (NP) the branching fraction of these decays could be enhanced by orders of magnitude, which makes the observation of these channels even more probable.

From the detector point of view heavy flavor physics is also an attractive field. Thanks to the low p_T (di)-muon triggers, precise vertex detector and efficient tracker system, the CMS detector is capable of efficiently recognizing and reconstructing specific topologies of b -decays. On the other hand, the study of b -jets provides with an important knowledge which might be crucial in searches for Higgs boson and supersymmetric particles. Also, one should not forget that b - and heavy onia-decay channels provide an excellent calibration opportunity for the vertex and tracker systems.

And finally, at the low luminosity phase there

are no expectations to observe Higgs decays, but as it is mentioned above there are plenty of $b\bar{b}$. So, first real physics results at LHC could be obtained in the heavy flavor sector. Even at a high luminosity, thanks to efficient (di)-muon trigger, CMS is able to continue such studies.

2. The CMS Detector

The complete description of the CMS detector can be found elsewhere [1]. Here only the main characteristics are mentioned. The CMS detector is a standard general purpose hadron collider detector composed of the following subsystems: vertex and tracker systems, electro-magnetic and hadron calorimeters and muon system. The full length is 22 m and outer diameter is 15 m. The total weight of the detector is 12.5 kton. All subsystems but the muon detector are placed inside a superconducting magnetic coil which able to reach a 3.8 T-field. In the following, the most crucial subsystems for heavy flavor physics are briefly discussed.

2.1. Muon system

The CMS muon system is composed of three types of gaseous particle detectors for muon identification. Drift tubes (DT) chambers in a central barrel region and cathode strip chambers (CSC) in two end-cap regions, thanks to a high spatial resolution, are used for position and momentum measurements. Because of their fast response

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time, both systems also provide the Level-1 trigger with good efficiency and high background rejection. Resistive plate chambers (RPC), which are placed in both the barrel and end-cap regions, combine an adequate spatial resolution with an excellent (≤ 5 ns) time resolution. Along with the DT and CSC systems, the RPC system provides the Level-1 trigger. It is also capable of identifying unambiguously the relevant bunch-crossing to which a muon track is associated even in the presence of the high rate and background at a full LHC luminosity.

Muon identification efficiency in the central region ($|\eta| < 1$) is above 70% for muons with $p_T > 5$ GeV/c. In the endcap regions ($1 < |\eta| < 2.5$) identification efficiency is above 70% already for muons with $p_T > 3$ GeV/c.

2.2. Tracker system

The CMS tracker system is based only on silicon detectors (220 m² of Si): micro-strip and pixel. The strip detector consists of 10 barrel layers and 9 disks positioned both forward and backward. Depending on rapidity the high p_T tracks leave 10 to 14 hits. The hit resolution is ~ 50 μm in $r - \phi$ direction and ~ 500 μm in z -direction. The pixel system is placed closer to the interaction point and consists of 3 barrel layers and 2 disks positioned both forward and backward. Since pixel dimension is 100×150 μm^2 the detector provides precise 2D information. The hit resolution is ~ 10 μm in $r - \phi$ direction and ~ 17 μm in z -direction. Momentum resolution of the CMS tracker system varies from 0.5% in the central region to 2% in the endcaps for tracks with $p_T = 1 \div 10$ GeV/c. The primary and secondary vertex resolution is event dependent. Usually, for b -decay channels the primary vertex resolution in the transverse plane is about 20 μm and the secondary one is $70 \div 100$ μm .

3. Trigger strategies

Triggering in CMS is done in two steps. The Level-1 trigger is based on muon and calorimetry information. It has a latency of 3.2 μs with a goal to reduce an event rate from 40 MHz to 100 kHz. At the second step called High-Level Trigger

(HLT), information from all subsystems are read-out and used in the event reconstruction. The reconstruction should be fast, therefore it is done locally: topologically around Level-1 pattern. At HLT the event rate decreases from 100 kHz to 100 Hz.

B-physics events are relatively soft. Hence, Level-1 calorimetry triggers having high E_T thresholds do not 'see' such events. Only events with one or two muons in the final state can be triggered with high selection efficiency for soft $b\bar{b}$ events (see, for example, the Level-1 trigger menu in [2]). The transverse momentum thresholds of these triggers depend on an instantaneous luminosity, but will be kept as low as possible in the range $p_T > 7 \div 14$ GeV/c for single and $p_T > 3 \div 7$ GeV/c for di-muon triggers. At HLT, exclusive and inclusive b -triggers, based on partial reconstruction of searched b -decay channels, are used. For the final states with two muons, a selection procedure which uses the reconstructed di-muon secondary vertex significantly improves a signal over background ratio. The detailed description of the trigger algorithms can be found in [3].

4. Physics channels

The CMS heavy flavor menu could be subdivided into two categories. The first one is approved results, which will be reported further. The second category is not finished or not yet approved by the Collaboration active studies. The last category will be only mentioned below.

4.1. Inclusive b production

Three different mechanisms contribute to the heavy flavor production at hadron colliders: gluon splitting, gluon/quark fusion and flavor excitation. Each of these production mechanisms has its own final state topology. It is important to measure the B-hadron p_T spectra within a large range to be able to disentangle the contributions of those mechanisms. In CMS the measurement of the inclusive b production cross section will be done with events containing jets and at least one muon.

The measurement of the differential cross sec-

tions is studied for B-hadrons of $p_T > 50$ GeV/ c and within the rapidity region of $|\eta| < 2.4$. The event selection requires a b -tagged jet to be present in the event. B tagging is based on inclusive secondary vertex reconstruction in jets [4]. As the Level-1 trigger, the single muon one is used with the threshold of 19 GeV/ c . At HLT in addition to the muon a b -jet with $p_T > 50$ GeV/ c is required.

The signal fraction is determined from a fit to the data distribution using the simulated shapes for the signal and background. Each reconstructed muon is associated to the most energetic b -tagged jet. The average efficiency of associating the muon with the b -tagged jet is 75%. The transverse momentum of the muon with respect to the b -jet axis discriminates signal against background.

Several sources of systematic uncertainties are considered in the study [5]. The largest uncertainty arises from the 3% error on a jet energy scale which leads to a cross section error of 12% at $p_T > 50$ GeV/ c .

1.6 million b -events for 1 fb^{-1} of an integrated luminosity will be collected to investigate the b production mechanism in CMS. The b production cross-section at $p_T = 1.2$ TeV/ c can be measured with 20% uncertainty.

4.2. $B_s^0 \rightarrow \mu^+ \mu^-$

Purely leptonic B -decays are theoretically very clean, thus providing an ideal environment for seeking indirect hints of NP effects. The SM branching ratio of $B_s^0 \rightarrow \mu^+ \mu^-$ is very small, $(3.42 \pm 0.54) \cdot 10^{-9}$ [6], while in large- $\tan \beta$ NP models it can be enhanced by orders of magnitude [7]. Up to now only the upper limit on the branching ratio is set by the CDF Collaboration: 4.7×10^{-8} at the 90% C.L. [8].

The main challenge in the measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ decay rate is background suppression. Many background sources can mimic the signal topology. First, non-resonant $b\bar{b}$ events with each $b \rightarrow \mu X$ decays. Second, non-resonant QCD events, where two high p_T hadrons are misidentified as muons. And finally, rare B_d , B^+ , B_s and A_b decays, comprising hadronic, semileptonic, and radiative decays. Some of these de-

cays constitute a resonant background, like $B_s \rightarrow K^+ K^-$, others have a continuum di-muon invariant mass distribution. Potentially, the resonant background is the most dangerous one. But, as it is illustrated in Fig. 1, the contribution from such background is negligible due to the excellent mass resolution provided by the CMS detector. The current background simulation does not include muon samples due to hadronic in-flight decays or punch-through. It has been estimated that this hadronic component will increase the background level by about 10% (see Fig. 5.10.9 in [9]). Table 1 summarizes studied so far background samples. The probabilities for hadron misidentification used to calculate expected number of background events in CMS are found to be $\varepsilon_\pi = 0.5\%$, $\varepsilon_K = 1.0\%$, $\varepsilon_p = 0.1\%$.

Figure 1. Background $m_{\mu\mu}$ distribution before the application of selection criteria for the $B_s \rightarrow K^+ K^-$ decay channel.

As the Level-1 trigger the di-muon one with a threshold of $p_T > 3$ GeV/ c for each muon is used.

The HLT strategy relies critically on the tracker detector for a fast and high-efficiency reconstruction of the primary and secondary vertices, the determination of muon momenta and the mass of the muon pair. Two muons are reconstructed with only 6 hits per a track in the

Table 1

Background for $B_s^0 \rightarrow \mu^+ \mu^-$ samples used in the analysis. The visible cross-section, and the corresponding number of events for 10 fb^{-1} is given. The visible cross-sections include fragmentation, branching fractions, and (fake) muon p_T and $|\eta|$ selection criteria. The numbers $N_{\mu ID}$ do not yet include any selection criteria but hadron misidentification probability.

Sample	Generator cuts/channels	$\sigma_{vis} [\text{fb}]$	$N_{\mu ID} (10 \text{ fb}^{-1})$
$b\bar{b} \rightarrow \mu^+ \mu^- + X$	$p_T^\mu > 3 \text{ GeV}/c, \eta^\mu < 2.4$		
	$p_T^{\mu\mu} > 5 \text{ GeV}/c$	1.74×10^7	1.74×10^8
	$0.3 < \Delta R(\mu\mu) < 1.8$		
	$5 < m_{\mu\mu} < 6 \text{ GeV}/c^2$		
B_s decays	$B_s \rightarrow K^- K^+$	2.74×10^5	274
	$B_s \rightarrow \pi^- \pi^+$	9.45×10^3	3
	$B_s \rightarrow K^- \pi^+$	3.08×10^4	16
	$B_s \rightarrow K^- \mu^+ \nu$	2.80×10^5	2.80×10^4
	$B_s \rightarrow \mu^+ \mu^- \gamma$	1.29×10^1	130
B_d decays	$B_d \rightarrow \pi^- \pi^+$	8.34×10^4	21
	$B_d \rightarrow \pi^- K^+$	3.74×10^5	187
	$B_d \rightarrow \pi^- \mu^+ \nu$	1.25×10^6	6.25×10^4
	$B_d \rightarrow \mu^+ \mu^- \pi_0$	3.77×10^1	377
B_u decay	$B_u \rightarrow \mu^+ \mu^- \mu^+ \nu$	2.24×10^3	2.24×10^4
B_c decays	$B_c \rightarrow \mu^+ \mu^- \mu^+ \nu$	2.01×10^1	201
	$B_c \rightarrow J/\Psi \mu^+ \nu$	1.89×10^3	1.89×10^4
Λ_b decays	$\Lambda_b \rightarrow p \pi^-$	4.22×10^3	1
	$\Lambda_b \rightarrow p K^-$	8.45×10^3	1
QCD hadrons	$5 < M(hh) < 6 \text{ GeV}/c^2$	2.24×10^{11}	1.12×10^8

tracker system and required to have transverse momentum of $p_T > 4 \text{ GeV}/c$, to be in the central part of the detector $|\eta| < 2.4$ and to have opposite charges. Vertexing the two muons provides a powerful handle in the rate reduction: the quality of the vertex fit must be $\chi^2 < 20$. The three-dimensional flight length is required to be $l_{3D} > 150 \mu\text{m}$. The invariant mass of the muon pair is required to be in a tight window ($150 \text{ MeV}/c^2$) around the B_s meson mass.

For the offline analysis all tracks are reconstructed with full detector information. The same as above but tighter (e.g. $\chi^2 < 1$) and additional selections are used to suppress background. The $\eta\phi$ separation of the two muons $\Delta R(\mu\mu) = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ must be in the range $0.3 \div 1.2$. The transverse momentum vector

of the B_s candidate must be close to the displacement of the secondary vertex from the primary vertex: the cosine of the opening angle between the two vectors must fulfill $\cos(\alpha) > 0.9985$. The isolation I is determined from the B_s candidate transverse momentum and charged tracks with $p_T > 0.9 \text{ GeV}/c$ in a cone with half-opening $r = 1.0$ around the di-muon direction as follows: $I = p_T^{\mu\mu} / (p_T^{\mu\mu} + \sum_{trk} |p_T|)$ and required to be $I > 0.85$. The significance of the flight length is required to be $l_{3D}/\sigma_{3D} > 18.0$. Mass separation between a di-muon candidate and the nominal B_s mass should not exceed $100 \text{ MeV}/c^2$.

For an integrated luminosity of 10 fb^{-1} , the expected number of signal events is $n_S = 6.1 \pm 0.6_{stat} \pm 1.5_{sys}$. The number of background events is $n_B = (14.1)^{+22.3}_{-14.1}$. An upper limit, extracted us-

ing the Bayesian approach, is $Br(B_s^0 \rightarrow \mu^+ \mu^-) < 1.4 \cdot 10^{-8}$ at the 90% CL [10].

4.3. $B_s \rightarrow J/\Psi \phi$

Important properties of B_s^0 system can be studied with the decay channel $B_s^0 \rightarrow J/\psi \phi$, such as the width and mass difference of the two weak eigenstates: $\Delta\Gamma_s, \Delta m_s$. In addition, the decay $B_s^0 \rightarrow J/\psi \phi$ is a golden channel for CP violation measurements. The particular spin structure of this decay allows to express its time dependence in a particular basis, called *transversity basis*, as the sum of 6 amplitudes where physical parameters enter differently. The most important of them is the weak phase ϕ_s which is at present strongly constrained by CKM fits [11] and could represent a clear hint of NP if found to be significantly different from this prediction. At present the flavor tagging tools required to extract the weak phase are not yet available in CMS and only the mixing measurement is considered here.

The Level-1 trigger is based on di-muon selection with $p_T > 3$ GeV/c each. HLT is the same as the one for $B_s^0 \rightarrow \mu^+ \mu^-$, with additional requirement for the di-muon invariant mass to be within 150 MeV/c² of the J/ψ mass. The J/ψ vertex is required to be 3σ away from the primary vertex. The cosine of the angle between the transverse momentum vector and the transverse decay length vector of the J/ψ candidate is required to exceed 0.9. ϕ candidates are reconstructed from all oppositely charged track pairs and all pairs with invariant mass within 20 MeV/c² of the ϕ mass are retained. All four tracks are then used for B_s^0 candidates, requiring invariant mass within 200 MeV/c² of nominal one. The transverse momentum of ϕ and B_s^0 candidates are required to be greater than 1.0 and 5.0 GeV/c, respectively.

The offline analysis follows the same criteria of HLT, but with complete information and tighter cuts. The main backgrounds arise from prompt J/ψ and $B_d^0 \rightarrow J/\psi K^*$ events. From an untagged time-dependent analysis of B_s^0 candidates the mixing parameters can be extracted. The result of the analysis shows that a first measurement of $\Delta\Gamma_s/\Gamma_s$ can be made with 20% precision with an integrated luminosity of 1.3 fb^{-1} , while

5% precision can be reached with 10 fb^{-1} [12].

4.4. $B_c^\pm \rightarrow J/\Psi \pi^\pm$

The interest to the B_c meson relates to the uniqueness of the heavy-heavy quark system which carries flavor. The B_c meson has been observed at Tevatron and its mass and lifetime have been measured [13]. But available statistics does not allow to make such measurements precise enough and investigate properties of this system in details.

In CMS a feasibility study has been performed in the decay channel $B_c^\pm \rightarrow J/\Psi \pi^\pm$ [14]. First J/Ψ candidates are composed by two muons with $p_T > 4$ GeV/c and $|\eta| < 2.2$ with opposite charge. The candidate invariant mass is required to be in the region from 3.0 to 3.2 GeV/c². Then, pion candidates are selected by requiring a third track coming from the same vertex as the two muons with $p_T > 2$ GeV/c and $|\eta| < 2.4$. The following selections are applied in addition: a proper decay length $L_{xy}^{PDL} > 60 \mu\text{m}$, a significance $L_{xy}/\sigma_{xy} > 2.5$ and a opening angle between the vector from primary to secondary vertex and the momentum vector of the reconstructed B_c : $\cos\theta > 0.8$.

For 1 fb^{-1} 120 signal and less than 3 background events are expected. The reconstructed B_c mass is 6.4 GeV/c² and the width of the mass peak is 15 MeV/c². To extract the B_c meson lifetime a binned likelihood fit was performed, resulting in $\tau = 460 \pm 45$ fs.

4.5. LFV in $\tau \rightarrow \mu\mu\mu$

Tau lepton decays which involves Lepton-flavor-violation with muons in the final state have branching ratios in the SM that are experimentally inaccessible. NP particles can enhance the values of their branching fractions up to $10^{-11} \div 10^{-7}$, depending on the particular model. The most stringent upper limit on $Br(\tau^+ \rightarrow \mu^+ \mu^- \mu^+)$ is currently set [15] to $5.3 \cdot 10^{-8}$ at the 90% CL.

The main production source of τ leptons that can be efficiently triggered with CMS at LHC is $pp \rightarrow W \rightarrow \tau \nu_\tau$ and $pp \rightarrow Z \rightarrow \tau\tau$ is considered. A trigger efficiency of 62% is obtained, requiring single (double) muon trigger with transverse momentum threshold of 19(7) GeV/c. The

τ invariant mass resolution is estimated to be $(23.8 \pm 0.6) \text{ MeV}/c^2$ (Fig. 2). A missing transverse energy in excess of $20 \text{ GeV}/c^2$ is required. The main background sources are combinatorial from W and Z and light meson decays ($\phi, \eta \rightarrow \mu^+ \mu^-$) from $c\bar{c}$ continuum, therefore a veto is applied on the ϕ mass. An upper limit of $Br(\tau^+ \rightarrow \mu^+ \mu^- \mu^+) < 3.8 \cdot 10^{-8}$ at the 90% CL [16] can be set for an integrated luminosity of 30 fb^{-1} .

Figure 2. Three muons invariant mass distribution for $\tau \rightarrow \mu\mu\mu$ decay channel

4.6. Additional heavy flavor decays

Although the following analysis are not yet finalized, it is worth while to list them here to demonstrate a future spectrum of heavy flavor activity in CMS.

Measurements of $b\bar{b}$ production cross-section and lifetimes of B-mesons will be done in the following decay channels: $B^\pm \rightarrow J/\Psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$, $B \rightarrow D^0 \mu X$, $b \rightarrow J/\Psi + X \rightarrow \mu^+ \mu^- + X$. The correlation study of J/Ψ vs μ provides clean measurements of $b\bar{b}$ production mechanisms. Searches for NP is also planned to be done in $B_s \rightarrow \mu^+ \mu^- \gamma$, $B \rightarrow (\phi, K^*, K_s) \mu^+ \mu^-$ decay channels.

5. Conclusions

While designed for high- p_T physics, the CMS has a broad heavy flavor program. Main features

which allow this program are 1) high $b\bar{b}$ event rate even at a low ($10^{32} - 10^{33}$) initial luminosity, 2) the efficient low p_T di-muon trigger and 3) excellent tracking that provides high momentum, mass, vertex resolution. Expected results are competitive with current B-physics experiments. The first measurements are expected to be done in 2009/2010.

Only approved results have been described above. But there are much more channels under investigations now, hence more heavy flavor topics will be studied in CMS.

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