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Prospects for Measuring $B_s^0 \to \mu^+\mu^-$ with the CMS Detector

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The flavor-changing neutral current decay $B_s^0 \to \mu^+\mu^-$ is highly suppressed in the standard model, but its branching fraction of $3.4 * 10^{-9}$ could be significantly enhanced through contributions from new physics. At the LHC, this rare decay could be observed for the first time. In this contribution, the prospects for measuring $B_s^0 \to \mu^+\mu^-$ with the CMS detector are presented. In particular, some aspects of the experimental setup, the first and high level trigger selections, and the offline analysis are discussed.

1. INTRODUCTION

At the LHC design luminosity of 10^{34} cm^{-2}s^{-1}, around 10^6 pairs of b quarks are produced per second. This makes the LHC experiments ATLAS, LHC-B and CMS in principle ideal places to study CP violation, $B_s^0 - \bar{B}_s^0$-mixing and rare B decays. In particular, the experiments have looked into the prospects for measuring the purely leptonic decay $B_s^0 \to \mu^+\mu^-$. In the Standard Model (SM), it is highly suppressed, since this flavor-changing neutral current (FCNC) process is forbidden at the tree level and can only proceed through higher order diagrams. In this paper, we present the prospects of measuring $B_s^0 \to \mu^+\mu^-$ with the CMS detector, with a focus on several aspects on the experimental setup and the online and offline selections.

1.1. Motivation

The SM branching fraction for the decay $B_s^0 \to \mu^+\mu^-$ is only $\mathcal{B} = (3.42 \pm 0.54) * 10^{-9}$ [1,2], but it could be significantly enhanced through contributions from new physics beyond the Standard Model.

For example, in the minimal super-symmetric standard model (MSSM), $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \propto (\tan\beta)^6$, which leads to an enhancement of up to three orders of magnitude compared with the SM, even in the case of minimal flavor violation (MFV). An observation would immediately yield an upper bound on the heaviest mass in the MSSM Higgs sector. Significant enhancements of the branching fraction are also expected within minimal super-gravity, non-MFV or R-parity violating super-symmetric models.

1.2. Limits from Current Experiments

Since B_s decays are not accessible at the B-factories, the currently best limits on the decay $B_s^0 \to \mu^+\mu^-$ are obtained at the TEVATRON experiments CDF and D0 [3,4]. The most recent result from D0 [5] is based on a luminosity of 300 pb^{-1}. With 4 candidate events within a mass window of ± 90 MeV and 4.3 ± 1.2 of background, they obtain a limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.0 * 10^{-7}$. The best limit so far comes from CDF [6], which use 364 pb^{-1} and obtain $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5 * 10^{-7}$ for a mass resolution of ± 25 MeV. These limits are still around two orders of magnitude above the SM expectation, but are expected to improve with more luminosity.

2. EXPERIMENTAL ASPECTS

The analysis of the $B_s^0 \to \mu^+\mu^-$ decay requires the capability to keep the signal events while reducing the huge QCD background by many orders of magnitude. The main ingredients to achieve this are a very good invariant mass resolution in order to reconstruct the di-muon mass, muon isolation in both the tracker and the calorimeter, as well as a precise reconstruction of the secondary vertex from the B meson decay. Since the main

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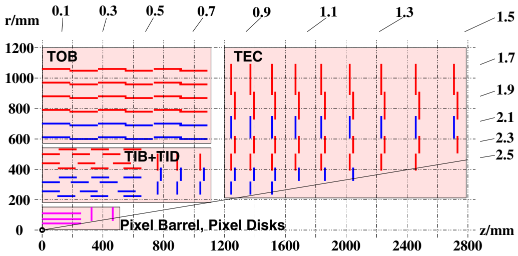

Figure 1. rz cut through one quarter of the CMS tracker.

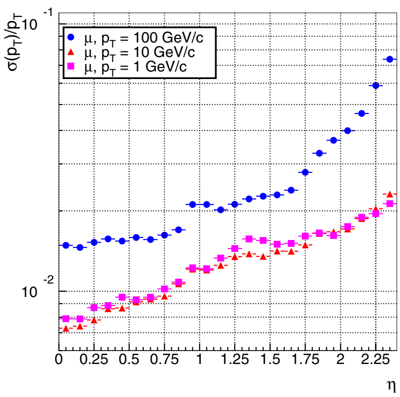

Figure 2. p_T resolution of the CMS tracker for single muons.

detector component used is the tracker, we will in the following highlight a few relevant features of the CMS tracker and track reconstruction.

2.1. The CMS Tracker

The CMS tracker (see Fig. 1) is an all-silicon detector, which is divided into four strip subdetectors TIB, TOB (inner and outer barrel), TID (inner discs) and TEC (endcaps), and two pixel subdetectors (barrel and endcaps), all housed within a tube of 2.4 m diameter and 5.4 m length.

The pixel tracker consists of $66 * 10^6$ pixels of 100μm(rϕ)$\times 150\mu$m(z) in 1440 modules, arranged into three barrel layers at $r = 4.4, 7.3$ and 10.2 cm and two endcap discs. The hit resolution is $10 \ldots 20$ μm and the efficiency to find 3 pixel hits per track is $> 90\%$ for $|\eta| < 2.2$.

The strip tracker consists of $>$ 15.000 strip modules with a pitch $80 \ldots 205$ μm, distributed over 10 barrel layers (4 TIB, 6 TOB), and 3+9 TID+TEC discs per side. The modules of the two innermost layers of TIB and TOB, as well as TID rings 1,2 and TEC rings 1,2,5 comprise two back-to-back mounted sensors each, providing a stereo coordinate measurement in both $r\phi$ and z.

The track reconstruction efficiency is $> 98\%$ for $|\eta| < 2.4$, and the transverse momentum resolution for single muons with $p_T = 1 \ldots 100$ GeV is in the range $0.7 \ldots 3\%$ for $|\eta| < 1.8$ (see Fig. 2).

2.2. CMS Alignment Strategy

In order to fully exploit the potential of the CMS tracker for track and vertex reconstruction (e.g. for b tagging), the intrinsic resolution of the silicon strip and pixel sensors of $10 \ldots 20$ μm should not be compromised due to imperfect knowledge of their exact positions and rotations both within the tracker as well as relative to other parts of the CMS detector, for example the muon system. Any large misalignments originating from the initial mechanical construction as well as due to temperature and dry-out effects during operation must be corrected for. While the mounting precision of an individual sensor on a module is of $\mathcal{O}(10 \ldots 30$ μm), it is only $\mathcal{O}(50 \ldots 500$ μm) for modules within higher level mechanical structures (layers, discs). To correct for these initial misalignments, two complementary approaches will be implemented: A laser alignment system (LAS) and several software alignment algorithms using tracks.

The LAS consists of several IR laser beams, which together with custom alignment position Si sensors are used to continuously monitor the relative positions of the larger structures of the strip tracker internally, as well as with respect to the muon system with a precision of 10 μm. However, the LAS does not cover the pixel detector.

The alignment of the pixel tracker, as well as of the individual sensors of the strip tracker, can only be achieved by running track based alignment algorithms, using cosmics and beam-halo muons at the LHC start-up, and muons from Z^0 and $W^{\pm}$ decays during physics data taking. Due to the large number of more than 16000 Si sensors, for which at least six degrees of freedom (3 translations, 3 rotations, tilts and sags for composed structures) have to be determined, this requires solving a problem with $\mathcal{O}(100k)$ unknowns. In CMS, several innovative algorithms are under study at the moment, which try to overcome the numerically challenging task of inverting very large matrices, for example using techniques based on the Kalman filter approach.

The CMS alignment strategy currently estimates that at the LHC start-up the module positions will be known to $\mathcal{O}(100\ \mu\text{m})$ from the initial placement measurements plus the laser alignment, which will already make efficient pattern recognition possible. While the LAS will continuously monitor the composite structures (except pixel) to 10 μm, a fast quasi-online track based alignment will be implemented to monitor in particular the pixel detector layers and discs, which is crucial with respect to the performance of the secondary vertex reconstruction at the High Level Trigger. Offline, a full track based alignment at the level of individual sensors using large samples of tracks will be performed on a regular basis.

2.3. Tracking at the High Level Trigger

The CMS high level trigger (HLT) consists of a PC farm and reduces the event rate from 100 kHz to 100 Hz by running selection algorithms on the full event. Due to the limited amount of CPU time available for the trigger decision, several concepts are foreseen to speed up the track reconstruction by reducing the number of track seeds as well as the number of operations per seed.

Firstly, in *regional seed generation* track seeding is limited to regions of interest (ROI) defined by Level-1 objects, e.g. a cone around the direction of a muon candidate.

Secondly, in *partial* or *conditional tracking* track reconstruction is stopped if certain criteria are met, such as the number of reconstructed hits, the transverse momentum or its resolution have reached given thresholds. It has been shown [7] that even when limiting the number of reconstructed hits to 5 or 6, both efficiency and fake rate are already similar to the full offline reconstruction performance. The impact parameter resolution as a function of the number of required hits is shown in Fig. 3.

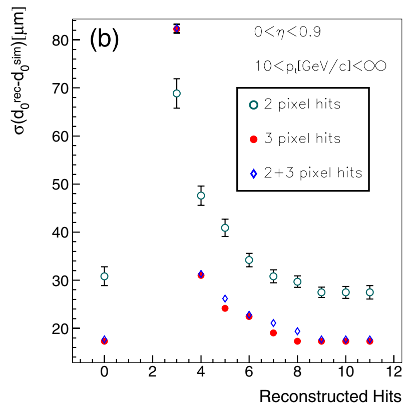

Figure 3. Impact parameter resolution of the CMS tracker for partial and full (shown as "0 hits") reconstruction.

3. $B_s^0 \to \mu^+\mu^-$ OFFLINE ANALYSIS

The offline analysis of the decay $B_s^0 \to \mu^+\mu^-$ using the CMS detector has been studied in [8]. Fully simulated samples of signal and background Monte Carlo events have been used, the background arising dominantly from gluon splitting. The basic kinematic selection cuts applied to the two muon candidates are transverse momentum $p_T^{\mu} > 4.3$ GeV, rapidity $|\eta^{\mu}| < 2.4$, distance in $\eta\phi$ between the muons $0.4 < \Delta R_{\mu\mu} < 1.2$ and for the dimuon pair $p_T^{\mu\mu} > 12$ GeV. For this kinematic selection, the estimated event numbers for a luminosity of 10 fb^{-1} are $N_{signal} = 66$ and $N_{bkg} = 3 * 10^7$.

A series of further selection cuts are then applied to improve the signal to background ratio:

- Dimuon mass window: A cut of ± 80 MeV around the nominal B_s^0 mass of 5.369 GeV results in a background rejection of 98.9%.
- Secondary vertex selection: Several cuts are

applied on variables provided by the vertex reconstruction algorithm, such as the minimal transverse distance between the two muons, the impact parameter and its error in the transverse plane, and the angle between the secondary vertex direction and the dimuon momentum in the transverse plane. The resulting background rejection power is better than $2.3 * 10^{-4}$ at the 90% confidence level. At the same time 30% of the signal are kept.

- Isolation: To further reduce the background, the two muons are required to be isolated in $r\phi$ in both the tracker as well as the calorimeter. In the tracker, no charged track with $p_T > 0.9$ GeV is required within $\Delta R = 0.5\Delta R_{\mu\mu} + 0.4$. In the electromagnetic and hadronic calorimeters the total E_T within the same cone ΔR must not exceed 4 (6) GeV in the case of low (high) lumi. This selection leads to a further background rejection power of around 0.01 whilst keeping 45% (30%) of the signal for low (high) lumi.

In summary, these selection cuts reduce the background from $3 * 10^7$ to < 1 (< 6.4) events for a luminosity of 10 (100) fb^{-1}, whereas the number of signal events amounts to 7 (26). From these numbers it follows that a 4σ observation should be possible after three years of running at 10 fb^{-1} per year, even if the background would be underestimated by a factor two. However, this does not yet take into account the first and high level trigger selections, which are discussed in the next section.

4. $B_s^0 \to \mu^+\mu^-$ ONLINE SELECTION

4.1. First Level Trigger

Purely leptonic B decays in CMS can principally only be triggered using the single or dimuon trigger at level one, since the electron trigger thresholds are too high. The currently foreseen L1 trigger thresholds for the inclusive isolated muon trigger is 14 GeV, whereas for the dimuon trigger it is 3 GeV. With these thresholds, the expected trigger rates are 2.7 and 0.9 kHz, respectively. Due to the relatively low threshold of 3 GeV, the dimuon trigger can be used for the selection of $B_s^0 \to \mu^+\mu^-$ candidates, and it does not cut further into the basic offline selection as defined in section 3.

4.2. High Level Trigger

It is currently foreseen that out of the 100 Hz HLT output rate, approximately 30 Hz are allocated to the inclusive single and dimuon trigger channels, resulting in trigger thresholds of 19 (7) GeV for the single (di) muon trigger, respectively (see Fig. 4) [7]. The contribution of processes involving charm and beauty quarks to the single

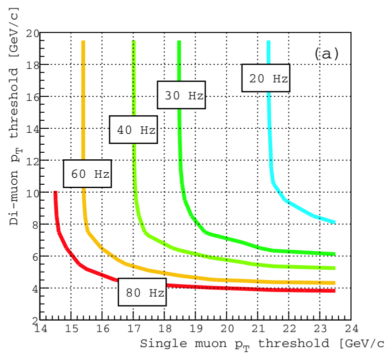

Figure 4. Single and dimuon high level trigger rates for low luminosity.

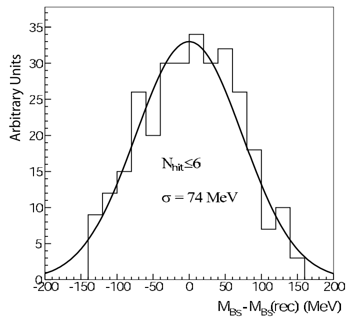

Figure 5. Dimuon invariant mass of the $B_s^0 \to \mu^+\mu^-$ candidate for HLT reconstruction.

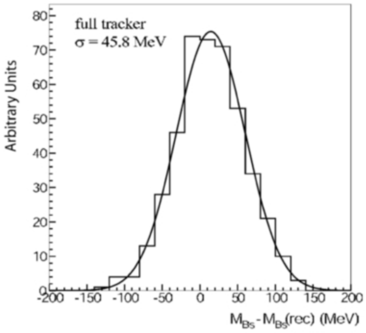

Figure 6. Dimuon invariant mass of the $B_s^0 \to \mu^+\mu^-$ candidate for full reconstruction.

muon rate is only $\sim$ 25%. Hence, it is very inefficent to use inclusive muon triggers for rare B decays, and efficient HLT selection algorithms are mandatory.

The HLT selection algorithm for the $B_s^0 \to \mu^+\mu^-$ channel [7] makes use of both regional and conditional tracking (see section 2.3). Pixel seeds are only considered within cones around the L1 muon candidates with $p_T > 4$ GeV and impact parameter < 1 mm, compatible with the primary vertex. Track reconstruction is stopped if the transverse momentum is < 4 GeV with 5σ significance. Only tracks with at least six hits and $\sigma(p_T)/p_T < 2\%$ are kept. If exactly two opposite sign tracks are found, their invariant mass is calculated and only pairs with a mass within ± 150 MeV around the B_s^0 mass are retained. They must be compatible with a secondary vertex with an impact parameter $d_0 > 150$ μm and $\chi^2 < 20$. The dimuon invariant mass resolution is found to be 74 MeV$attheHLT(Fig.5), comparedwith46MeV$ using the full offline reconstruction (Fig. 6).

4.3. $B_s^0 \to \mu^+\mu^-$ Efficiency and Rates

For the trigger selection described above, the signal efficiencies are 15.2% and 33.5% at the first and high level trigger, respectively, which amounts to a global efficiency of 5.1% [7]. This corresponds to 47 $B_s^0 \to \mu^+\mu^-$ events for a luminosity of 10 fb^{-1}. The trigger rate (dominated by background) is below 2 Hz.

5. CONCLUSIONS

CMS is well suited for b physics in general and rare B decays in particular, due to the high luminosity, the precise all-silicon tracker and the powerful muon system, which also provides a first level trigger. Crucial ingredients for the selection of the rare decay $B_s^0 \to \mu^+\mu^-$ are a low transverse momentum muon threshold at L1 and a very efficient online reconstruction at the high level trigger. Both secondary vertex and invariant mass reconstruction require that the very good intrinsic resolution of the CMS silicon tracker is not significantly compromised due to misalignment.

An observation of the decay $B_s^0 \to \mu^+\mu^-$ can place severe constraints on extensions of the standard model, such as super-symmetry. It has been shown that an observation in the CMS detector within the first few years of data taking is possible, even with moderate luminosity. Hence, the $B_s^0 \to \mu^+\mu^-$ channel represents a very promising topic on the early physics agenda of CMS.

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