Trigger and Reconstruction Studies with Beam Halo and Cosmic Muons

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**Abstract**

The efficient triggering and reconstruction of cosmic and beam halo muons is important for the commissioning phase of the Compact Muon Solenoid experiment (CMS), prior to operating with physics collisions. Since the standard trigger simulation and reconstruction algorithms have been designed to identify efficiently muons originating from the interaction point and in temporal coincidence with the beam crossing, a different optimization must be carried out in order to effectively reconstruct muons from other sources. Results of such an optimization for the muon system for simulated cosmic and beam halo muon events and rate estimates are presented.
1 Introduction and Motivation

Prior to recording proton-proton (pp) collisions, cosmic muons are the only freely available particle source for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). They may be used for detector commissioning and alignment. During the cosmic challenge/magnet test - a dedicated cosmic data taking period on the surface, where the CMS experiment is pre-assembled and its magnet coil tested - cosmic muons should be triggered, recorded, and reconstructed with a sufficiently high rate to achieve the goal of large statistics within a very short time. While underground, cosmic muons will be much reduced in rate by the rock overburden, but will still be the only major particle source before the LHC starts to operate. They may then be used for further detector commissioning and alignment. When running in pp-mode, cosmic muons constitute a background which must be suppressed. Similar arguments apply to beam halo muons, which may cross one or even both muon end-caps and thus allow detector studies before the start of collisions at the LHC, for instance during initial operation with one single beam.

One of the goals of this study is to estimate reliably the event rate for the cosmic ray muon data taking periods above and below ground. In the simulation muons were generated according to the known angular and energy distributions for cosmic muons. To achieve reasonable rates the trigger conditions had to be modified (Section 4). To verify the simulation at the hardware level, the simulated detector response is compared to real data from commissioning with cosmic muons (Section 5). Another component of this study focuses on how the trigger algorithms have to be modified in order to acquire and reconstruct muons traversing the detector but not originating from the nominal interaction point.

2 The CMS Muon System

The CMS muon system [1] consists of three detection subsystems: drift-tube chambers (DT) in the central or barrel part, cathode strip chambers (CSC) in the end-caps and resistive plate chambers (RPC) in both barrel and end-caps. The locations of these chambers in transverse and longitudinal views are shown in Fig. 1. There are two end-caps, named positive (+Z) and negative (-Z). Barrel chambers are labeled “MB” and end-cap chambers “ME”, both with the associated station number counted from the interaction point, for example “MB1” for the innermost barrel chamber and “ME4” for the outermost end-cap station. A muon originating at the nominal pp interaction point crosses four muon stations measuring its trajectory and the track bending in the magnetic field. The latter is the basis for determination of charge and momentum of the muons.

The basic detection element of a drift tube chamber in the barrel region is a $42 \times 13$ mm drift cell. Four layers of staggered drift cells form a group, called a superlayer, with three superlayers making up a chamber, in total 12 layers of drift cells. The bending of the muon trajectory in the $r, \phi$-plane of CMS is measured by two superlayers and the third determines the coordinate perpendicular to it. The only exception of this scheme are the outermost MB4 chambers containing only the two superlayers in the $r, \phi$-plane. The cathode strip chambers in both end-caps are multi-wire proportional chambers with six individual layers of anode wires and segmented cathodes. The strips inside the trapezoidal chambers are oriented radially with the wires perpendicular to them. Strips measure the muon position in the azimuthal $\phi$ direction and wires provide, less precisely but with faster response, the radial position. Since the cathode plane is divided into strips, the pulse heights on neighbouring strips can be combined by the center-of-gravity method such that the spatial resolution is better than the strip width. The fast wire information is primarily used for the trigger but supports also the coordinate reconstruction, although the high spatial precision is provided by the cathode information.

The CMS trigger system has two physical levels, where the first (L1) is implemented in custom-built hardware while the second level is based on software. The first level global trigger has to decide every 25 ns whether to accept or reject the event based on coarse information from the calorimeters the muon system. It runs dead-time free, achieved by a synchronous pipeline whose depth is limited to 128 bunch crossings. The total L1 latency is therefore fixed to $3.2 \mu$s which includes the drift time of up to 380 ns for cells in a DT chamber and the transmission time between detector and trigger electronics. The Global Muon Trigger combines information from all three complementary muon subsystems - the fast RPC timing information, the regional CSC and regional DT triggers [2, 3] - with the goal of reconstructing position and momentum of high momentum muons and assigning a bunch crossing with high efficiency. The latter is rather straightforward for CSC and RPC detectors, since both have readout times consistent with the 40 MHz interaction frequency. The drift-tube chambers, although integrating over up to 16 bunch crossing intervals, also have bunch crossing identification capability exploiting a dedicated implementation of the momentimer method [4, 5].
The L1 muon trigger for DT and CSC works in several consecutive steps, as illustrated in Fig. 2. First, the information of each chamber is processed independently by a local trigger to reconstruct track segments. The trigger front-end for DT chambers, called Bunch and Track Identifier (BTI), performs a straight line fit within a superlayer using at least three out of four hits. If available, the track segments from both phi superlayers are matched by the Track Correlator (TRACO). The segments are matched by the Drift Tube Track Finder (DTTF) into a single muon candidate, assigning the track parameters \( p_T, \eta, \phi \) and quality. The CSC L1 trigger works in a similar way. The first step is also a local reconstruction, independently for strips and wires. Strip hits are obtained by interpolation of the analysed charge of adjacent strips. Strip hits are combined to patterns when being compatible with a high \( p_T \) muon trajectory. Among the wire information, hit patterns consistent with a track originating at the nominal interaction point are searched for with a coincidence technique. A coincidence of two hits in two layers is needed for bunch crossing assignment. The CSC Track Finder combines the segments to a single muon. The Global Muon Trigger matches the muon candidates from the DT and CSC Track Finder and the RPC information in order to choose the best four muon candidates.

For this study, the effort of simulating a realistic First Level Trigger for muons not originating from the nominal interaction point has been made for the CSC and DT only.

3 The Beam Halo and Cosmic Muon Generators

Cosmic muons have been simulated for the scenario with the CMS detector being underground, and for the scenario with the CMS detector on the surface - relevant for the cosmic challenge/magnet test. The beam halo and cosmic muon generators are described in Ref. [6]. Here, a brief summary of the key parameters is given. For both scenarios all muons are generated with \( E(\mu^\pm) \geq 10 \text{ GeV} \) and with the CMS event generator software CMKIN [7]. The simulation of the CMS detector is performed with OSCAR [8], which is based on GEANT4 [9], and the reconstruction code ORCA [10] is used. For the CMS detector situated on the surface, cosmic muons are generated at a cylindrical surface around the detector with a radius of \( R = 8 \text{ m} \) and a length \( Z = \pm 15 \text{ m} \). For the scenario with the CMS detector in the underground cavern, cosmic and beam halo muons are generated, where the latter start at two planes at \( Z = \pm 23 \text{ m} \). The energy loss in both, material and detector is simulated, including consideration of the position and material of the access shaft. Beam halo muons are almost parallel to the beam axis and thus exhibit more hits in the forward than in the barrel detectors. Hits from cosmic muons, which traverse the detector from top to bottom, are distributed more homogeneously.

The various event samples of beam halo muons and cosmic muons used are summarized in Table 1. Samples with and without magnetic field are simulated. Despite the bending of muon tracks when the magnetic field is switched on, most muons still pass the detector and the rates remain almost unchanged.

Table 1: Detailed information about the generated data samples used in this analysis. The last column indicates the absolute rate normalization at a surface surrounding the detector. The rates for beam halo muons, presented in this table, are valid only for one specific set of LHC parameters (see Ref. [6]), which is obsolete by now. Therefore, the absolute rates have to be understood as rough estimates.

<table>
<thead>
<tr>
<th>Type</th>
<th>Location</th>
<th>B-field</th>
<th>Total rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic ray muons</td>
<td>Underground</td>
<td>ON</td>
<td>3 kHz</td>
</tr>
<tr>
<td>Cosmic ray muons</td>
<td>Surface</td>
<td>ON</td>
<td>47 kHz</td>
</tr>
<tr>
<td>Cosmic ray muons</td>
<td>Surface</td>
<td>OFF</td>
<td>47 kHz</td>
</tr>
<tr>
<td>Beam halo muons</td>
<td>Underground</td>
<td>ON</td>
<td>32 kHz</td>
</tr>
</tbody>
</table>

4 Optimization of the First Level Trigger and Stand-Alone muon reconstruction

A set of modifications is necessary in order to allow reconstruction and triggering of muon tracks which are not coming from the interaction vertex and which are not in temporal coincidence with the beam crossing. They are described in the following and the impact of such modifications on the number of muon tracks reconstructed
by the first level trigger simulation and by the reconstruction of muon tracks by the muon chambers alone (i.e. Stand-Alone muon reconstruction) is shown.

4.1 Level-1 Trigger

The principle of the L1 trigger was briefly reviewed in Section 2, for details references [2, 3, 4] may be used. The trigger code, expecting muons coming from the interaction point, had partly to be modified to account for the different angular distribution of cosmic muons. The modifications concentrated so far on the tracking detectors, CSCs and DTs, respectively. Changes in the RPC system will be implemented at a later stage. Changes to the CSC and DT Level-1 (L1) trigger code fall under the following categories:

4.1.1 Trigger Roads

As described in Section 2, the track finder tries to combine the track segments from several stations to a common muon track (right-most image of Fig. 2). This process should converge quickly and hence the extrapolation region, so-called trigger road, is restricted in space based on the expected track pattern for high momentum muons. One road unit, defining the road width in which the algorithm searches to extrapolate the track segment, corresponds to an interval of 0.0125 in pseudorapidity, such that the road width decreases in the forward regions where the particle flux of high momentum muons is larger. For the L1 CSC code, the pseudorapidity window of the trigger roads has been expanded from a road of two units as used for proton-proton events (very restricted) to its maximum range of 255 road units (wide open). In this configuration, all possible matches in pseudorapidity are accepted. Given that the rates of cosmics and beam halo muons are low, no problem in the trigger rates are expected.

4.1.2 Look-Up Tables

Part of the track extrapolation is the use of Look-Up Tables (LUT) which store expected pattern for high momentum muons. When acquiring data from proton-proton collisions they are optimized for muons originating at the nominal interaction point, that is the center of the detector. For this study special Look-Up Tables optimized for triggering on muons not originating from the interaction point have been used both for the CSC and for the DT. These tables allow for the coincidence of any two hits from different chambers and are currently used by the CSC and DT detector groups commissioning the chambers at the CMS surface hall.

4.1.3 Synchronization and Time of Flight Corrections

For the trigger and reconstruction it is necessary to synchronize the detector such that the muon’s arrival time at a certain detector is common for all stations. In order to synchronize the muon chambers, an average time of flight has to be taken into account in the \( t_0 \) calibration for each type of event. In case of pp collisions it is assumed that the muons come from the interaction point and move with speed of light \( c \) such that their approximate travel time \( \delta t \) to a muon chamber is:

\[
\delta t = \sqrt{X^2 + Y^2 + Z^2} / c.
\]  

(1)

The coordinates \( X, Y \) and \( Z \) indicate the center of each muon chamber, and the origin is given by the coordinates \((0,0,0)\), shown in Fig. 3. Since beam halo muons are expected to be in time with and parallel to the beam in most of the cases, the synchronization is even simpler:

\[
\delta t = \frac{Z}{c} \quad \text{(or} \quad \delta t = \frac{-Z}{c})
\]  

(2)

but it is valid only for one beam at a time, because \( \delta t \) is either positive or negative.

The synchronization is more difficult for cosmic muons, because they arrive at random times at the detector and their kinematic properties are less constrained. Since the reconstruction software assumes muons originating at the collision point in the center of CMS, it is sufficient to consider either the upper or the lower hemisphere of the barrel when calculating the time of flight. This is done by choosing the sign in the time of flight formula Equ. 4, taking into account that cosmic muons in the upper hemisphere pass in opposite direction than muons from pp
collisions. An average time of flight correction for typical cosmic muons is performed using the radius \( R = 8 \) m and the distribution in time of \( t' = 12.5 \) ns. For the lower half of the detector as:

\[
\delta t_{\text{lower hemisphere}} = \frac{\alpha \times (R + \sqrt{X^2 + Y^2})}{c} + t' \tag{3}
\]

and for the upper half of the detector as

\[
\delta t_{\text{upper hemisphere}} = \frac{\alpha \times (R - \sqrt{X^2 + Y^2})}{c} + t' \tag{4}
\]

Figure 3 illustrates the calculation. The parameter \( t' = 12.5 \) ns takes into account the generated starting time for cosmic muons which is a value chosen randomly in an 25 ns interval corresponding to the proton-proton bunch spacing at the LHC. The average angular spread of cosmic muons in three dimensions is taken into account by the parameter \( \alpha \), being a global parameter in the sense that we cannot assign different values of \( \alpha \) to individual cosmic muons. The parameter \( \alpha \) is inversely proportional to the cosine of the angular spread and has been observed with simulated cosmic muons with a hit in four muon stations. Its value has been determined to be \( \alpha = 1.04 \) in the barrel and \( \alpha = 1.1 \) for the end-caps.

Given that the drift time is the measured quantity on which track reconstruction is based, the synchronization of the 250 barrel DT chambers is essential for the study of any further tracking quantity. Fig. 4 compares the drift time spectra for the outer chambers, in a top and a bottom sector, in the case for which the synchronization is absent. The starting time of the spectrum and consequently the measured drift times are shifted in the lower sector, by about 50 ns in this particular case. This shift corresponds to the time-of-flight for the muon to reach the bottom chamber. In addition to this, the muons traversing the detector lose energy and are affected by the magnetic fields which leads to the difference in statistics between the top and the bottom chamber.

For DT chambers the simulation has also been compared with data measured with cosmic muons penetrating a single muon chamber during the chamber testing procedure. A single DT chamber has between 600 and 1000 individual drift cells, depending on the station where the chamber is located. While for chamber quality tests individual cell performances are studied, a comparison with the simulation can be done by averaging over all drift cells within a chamber. The observed spectrum of drift times ranges from almost 0 ns (for muons passing close to the wire) to 380 ns (or 486 TDC counts, one TDC count being the “hardware unit”). The drift time spectrum can be seen in Fig. 5 for simulated cosmic ray muons and for real data measured with a lower, horizontal chamber in the innermost station. In order to compare with the real data a generated sample without magnetic field is used, and the \( t_0 \)-determination used for real test data is applied.

### 4.1.4 Bunch Crossing Assignment

The assignment of a bunch crossing is somewhat meaningless for cosmic muons. In order to simulate the random arrival of cosmic rays, the generator distributes the arrival times uniformly in an interval of 0-25 ns. The standard Level-1 trigger code, more specifically the simulation of the Level-1 Global Muon Trigger in ORCA, accepts only one bunch crossing, and therefore never reports any time-shifted candidates. Since there are time-of-flight differences (which on average are corrected for during the synchronization procedure), some segments may appear late or early.

In ORCA, events accepted by Level-1 are assigned to “bunch crossing 0”. The chambers are synchronized to that bunch crossing with the procedure described in the previous section. “Bunch crossing 0” is therefore the bunch with the highest Level-1 rate. Neighboring bunches are labeled as “bunch 1” and “bunch -1” and so on. The minus sign of the bunch number indicates that the bunch is earlier in time than “bunch 0”. In some cases one muon can fire triggers in different bunches. For instance, “bunch -1” generates a trigger accept decision in the upper half of the CMS detector, and the same cosmic muon is triggered in “bunch 0” in the lower half. If a cosmic muon is triggered across two bunch crossings, the bunch closest to zero is designated the bunch crossing that triggered the event. This avoids double counting cosmic muons.

The distribution of bunch crossing numbers is shown in Fig. 6 for cosmic muons underground, in Fig. 7 for cosmic muons on the surface, and in Fig. 8 for cosmic muons on the surface, triggered and reconstructed in a \( 255^\circ < \varphi < 315^\circ \) slice, approximately corresponding to the region instrumented for the magnet test. The differences are explained in the following: there are more bunches outside “bunch 0” for cosmic muons at the surface than for cosmic muons underground, because the angular spread is larger for cosmic muons at the surface, which leads to a wider bunch crossing distribution. If only a portion of the detector is considered (in this case, a \( \varphi \)-slice at the bottom of the detector), the cosmic muons are less likely to produce trigger accept decisions in different
bunches. In this case the chance of having two trigger accepts in different bunches is small, which decreases the probability of assigning “bunch 0" as the bunch crossing that triggered the event.

In order to estimate the rate of cosmic muons, it is necessary to sum over all bunch crossings. When summing over all the bins of Fig. 6, of Fig. 7, and of Fig. 8 the rate of all bunches is 16% higher than the rate for “bunch 0” only for underground cosmic muons, 20% higher for surface cosmic muons, and 30% higher for surface cosmic muons in the magnet test $\varphi$-slice. This effect is corrected for when estimating rates.

4.2 Stand-Alone Muon Reconstruction

The Stand-Alone muon reconstruction uses only information from the muon system, without the inner tracker. Both combined are so-called global muons. To reconstruct Stand-Alone (S.A.) muon tracks we use the existing algorithm [10, 11]. Unless otherwise noted, the Stand-Alone muon tracks are required to have at least three two-dimensional reconstructed track segments. For barrel muon chambers a two-dimensional segment is provided by the theta or the phi projection (see Fig. 3 for the geometry), with the phi segment being either a combination of both (if available) or just one phi superlayer in a chamber. Since each projection contains wires in only one direction, it provides only two-dimensional information. Similarly for the forward cathode strip chambers, two-dimensional segments derive from either anode wires or cathodes. In other words, at least two muon stations have to contribute to the tracking. Another requirement is that the track parameters – track position, momentum and direction – are calculated at the innermost muon chamber which has a two-dimensional track segment. To be able to reconstruct Stand-Alone muons for very forward beam halo muons, the pseudorapidity coverage of the reconstruction has been relaxed.

As a common feature to both cosmic and beam halo muon reconstruction, for high energy muons two Stand-Alone muon tracks may be reconstructed if the geometrical acceptance permits. For a beam halo muon, the two tracks will typically correspond to the segments reconstructed in the forward and backward muon chambers, on opposite sides of the interaction point. For a cosmic muon crossing the barrel region, the two tracks correspond to the segments reconstructed in the top and in the bottom part of the detector, respectively, including the inner tracker in cases where the muons are central enough. The majority of the tracks are reconstructed in the barrel region.

Throughout this analysis, the parameterized time-to-drift relation [12] is used for the determination of the hit position in barrel drift chambers. An improvement to the track residual distribution for cosmic muons are expected when using an event-by-event $t^4$ corrections.

5 Results

In this section the results on tracking, resolutions and rate estimates for cosmic muons at the surface and underground and for beam halo muons are presented. Table 2 illustrates the impact of the described modifications of the first level trigger simulation and the Stand-Alone muon reconstruction. The results achieved with trigger and reconstruction algorithms optimized for cosmic and beam halo muons show the necessity to tune the standard algorithms for this purpose. The improvement is most pronounced for beam halo muons which are most unlikely to accidently point to the interaction region. The table should be understood as indicative since further improvements are possible with upcoming timing, calibration and reconstruction algorithms.

Table 2: Yields ratios of the modified Stand-Alone muon reconstruction (S.A.) and the Level-1 trigger (L1) with respect to the standard version.

<table>
<thead>
<tr>
<th></th>
<th>$r(N_{L1})$</th>
<th>$r(N_{S,A.})$</th>
<th>$r(N_{S,A.})$ with L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Halo muons</td>
<td>60</td>
<td>16</td>
<td>80</td>
</tr>
<tr>
<td>Underground cosmic ray muons</td>
<td>2.4</td>
<td>1.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

5.1 Cosmic Muons at the Surface and Underground

Before studying muons reconstructed in the whole CMS detector, one basic unit of track finding, a DT chamber, is investigated in detail. Each of these chambers can determine a three-dimensional track segment and the combination of up to four such track segments from the four muon stations is transferred to the global fitting algorithm.
The track residual distribution is a measure for the quality of a track segment $t$, based on the distance between each of the original hits $x_{hit}$ compared to the its corresponding position $x_{track}$ after the segment fit. For individual chambers a maximum of 12 hits is required, corresponding to the number of individual layers in a DT chamber. Such a distribution is shown in Fig. 9 for cosmic muons and for muons originating in pp interactions reconstructed in a MB3 chamber in the top sector 10. Since the latter are bunched in time, their resolution is about three times better (sigma of 130 $\mu$m). The timing uncertainty of cosmic muons, which are uniformly distributed in time, is reflected by a worse resolution (sigma of 360 $\mu$m). It should be noted that these residual widths do not directly translate into spatial resolutions as all layers are added without further correction factors.

Another study performed with cosmic muons concerns the angular distribution measured within a single chamber. Shown in Fig. 10 is the distribution of the track angle with respect to the chamber vertical for cosmic muons on the surface, measured with the same chamber as in the track residual distributions studies described above. The comparison with Fig. 12, where the corresponding generated angle is displayed, shows that the reconstruction at the chamber level is well understood.

The next level of muon reconstruction is the combination of several chamber-segments to form a proper track within the muon system only. The Stand-Alone muon reconstruction algorithm appears flexible enough to perform well on cosmic muon reconstruction. Fig. 12 and Fig. 13, where the rate for all events accepted by L1 can be compared with the rate for the events, accepted by L1, which contain at least one Stand-Alone muon track, show that the efficiency for reconstructing one or more Stand-Alone muon tracks is high for events which have been accepted by L1. Fig. 11 shows the azimuthal distribution of Stand-Alone muon tracks reconstructed from simulated cosmic muons at the surface. Highlighted is the azimuthal region corresponding to the slice of the detector which will be instrumented during the magnet test. The rate of reconstructed (and triggered) cosmic muons, shown in Figs. 14 to 17, is larger in the top half of the detector, due to energy loss effects in the detector material. This can also be seen for the case where the CMS detector is placed underground. The energy spectrum is less steep in case of cosmic muons underground, which is due to the fact that only energetic muons reach the CMS detector through the rock.

5.2 Beam Halo Muons

Beam halo muons move almost parallel to the beam axis and lead to tracks in the forward muon detectors. In case of two Stand-Alone muon tracks per beam halo muon, there is one track reconstructed on each side of the detector, which is useful to inter-align the two halves of the forward muon chambers.

If there is only one Stand-Alone muon track found, it is usually on the same side where the beam enters the CMS detector, as can be seen in Fig. 18. The opposite side is much less populated, because many muons are stopped in the detector material, mainly calorimeter, magnet, and iron yoke, on their way through the detector. The effect of the energy loss in the CMS detector is also illustrated in Figure 19, where the rate of muons with two Stand-Alone muon tracks starts to catch up with the rate of one Stand-Alone muon track above a generated muon energy of about 40 GeV.

5.3 Rate Estimates

The numbers of triggered events of each type are summarized in Table 3. Most of the beam halo muon tracks are reconstructed in the forward muon detectors, while most of the cosmic muon tracks are reconstructed in the barrel region. Approximately 15% of the total L1 cosmic muon rate contains a L1 trigger in the CSC.

The total rates for L1 events with at least one S.A. track is less than the rate for L1 alone. It should be kept in mind that all rates depend on the trigger conditions, the track requirements, and the precise energy spectrum of the muons. If only two reconstructed hits are required per Stand-Alone muon track, the sum of the rates “one Stand-Alone muon track” and “two Stand-Alone muon tracks” is much closer to the trigger rate at L1.

The simulated L1 rates for the 60° $\varphi$-slice are comparable with the measured commissioning rates for the L1 CSC and the L1 DT. For DT bottom/top sector (maximum acceptance for cosmic ray muons) that is around 300-500 Hz surface muons. For the CSC, the matched coincidence rate between two chambers in a 20° sector is 60 Hz.

6 Summary

In summary, beam halo and cosmic ray muons can be triggered and reconstructed efficiently with the CMS muon system. Both sources of muons are useful to study and understand the performance of the detector, in particular the
Table 3: Rates of events accepted by the L1 trigger for beam halo and cosmic muons. Events with reconstructed Stand-Alone (S.A.) muon tracks are divided into two categories: with exactly one Stand-Alone and exactly two Stand-Alone muon tracks. Also shown is the rate for the \( \varphi \)-slice to be instrumented in the magnet test.

<table>
<thead>
<tr>
<th>Type of muon sample</th>
<th>L1 Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1 Rate</td>
</tr>
<tr>
<td></td>
<td>with 1 S.A. track</td>
</tr>
<tr>
<td>Surface cosmic ray ( \mu^\pm )</td>
<td>12 kHz</td>
</tr>
<tr>
<td>Underground cosmic ray ( \mu^\pm )</td>
<td>0.7 kHz</td>
</tr>
<tr>
<td>Beam halo ( \mu^\pm )</td>
<td>6.6 kHz</td>
</tr>
</tbody>
</table>

muon trigger system. Cosmic ray muons above ground provide a good opportunity to study detector performance or to work on synchronization etc. before the LHC is turned on. Below ground cosmic ray muons and beam halo muons are anticipated to be used for alignment and synchronization purposes.

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References
Figure 1: Longitudinal view of one quarter (left) and transverse view (right) of the CMS muon system. There are four muon stations, labeled MB and ME in the barrel and the end-caps, respectively.

Figure 2: Illustration for the DT and CSC trigger.
Figure 3: Illustration for the synchronization of cosmic muons and the coordinate systems for the barrel region. Muons from pp collisions (black lines) originate at the interaction point in the center of the CMS detector and cross the barrel detectors in upgoing or downgoing direction. Cosmic muons (red, dashed lines), generated at a cylindrical surface around the detector \((R = 8 \text{ m})\) may cross both the upper and lower hemisphere. Their arrival time is synchronized as explained in the text.
Figure 4: Two DT chamber drift time spectra for simulated cosmic muons for a top (Sector 4) and bottom (Sector 10) of a barrel wheel. If the starting time \( t_0 \) for each spectrum is not synchronized with the rest of the detector, the drift times of the lower sector appear shifted by the time corresponding to the TOF of the muon to travel from the top to the bottom sector (about 15 meters in the detector). Energy loss within the detector decreases the rate of the lower chamber with respect to the upper one.

Figure 5: In order to verify the signal creation in the cosmic muon simulation, a drift time spectrum from simulation (continuous line) is compared to drift times as measured with real cosmic ray muons taken with an horizontal muon DT chamber (triangles). For this study, the simulation is done with no magnetic field in order to match the conditions of the data.
Figure 6: Rate as a function of the bunch crossing number for cosmic muons underground. Events with multiple L1 accepted bunch crossings are filled into the bunch closest to the zero bunch.

Figure 7: Rate as a function of the bunch crossing number for cosmic muons on the surface. Events with multiple L1 accepted bunch crossings are filled into the bunch closest to the zero bunch.
Figure 8: Rate as a function of the bunch crossing number for cosmic muons on the surface, triggered and reconstructed in a $255^\circ \leq \varphi \leq 315^\circ$ slice. Events with multiple L1 accepted bunch crossings are filled into the bunch closest to the zero bunch.
Figure 9: Residual distribution for a single DT chamber (here Wheel 0 Sector 4 Station 3) using the distance between the original hit $x_{\text{hit}}$ and its position $x_{\text{track}}$ after the segment fit. The track reconstruction required one hit in each of the 12 individual layers of a DT chamber. Upper plot: cosmic muons and B-field on, Lower plot: muons from $pp \rightarrow Z \rightarrow \mu^+ \mu^-$ at the LHC with a bunched beam.
Figure 10: Angular distribution in a single horizontal muon DT chamber (here Wheel 0 Sector 4 Station 3). The track angle $\theta_y$ is w.r.t. the vertical axis of the chambers.

Figure 11: Rate of Stand-Alone muon tracks accepted by L1, as a function of azimuthal angle, for surface cosmic muons. The box identifies the 60° region which will be instrumented in the Magnet Test. The rate inside the box does not reflect the fact that the L1 trigger rate is lower in case the top half of CMS detector is not instrumented.
Figure 12: L1 rates for all events, events with exactly one S.A. track, and events with at least one S.A. track as a function of the polar angle, in the X-Z plane, of the generated muon. No constraints on the number of reconstructed hits per Stand-Alone muon track is imposed here. This translates to an upper bound on the Stand-Alone muon track reconstruction efficiency of L1 triggered events.

Figure 13: L1 rates for all events, events with exactly one S.A. track, and events with at least one S.A. track as a function of the azimuthal angle, in the X-Z plane, of the generated muon. No constraints on the number of reconstructed hits per Stand-Alone muon track is imposed here. This translates to an upper bound on the Stand-Alone muon track reconstruction efficiency of L1 triggered events. The angles at $90^\circ$ and $270^\circ$ point in the directions of $-Z$ and $+Z$. 
Figure 14: Rates of Stand-Alone (S.A.) muon tracks as a function of $\varphi$ for cosmic muons at the surface, accepted by the L1 trigger. The maximal rate appears at the top of the detector, which corresponds to $\varphi = 90^\circ$. The bump around $\varphi = 270^\circ$ is at the bottom of the CMS detector.

Figure 15: Surface cosmic muon L1 rates for all events, events with at least one S.A. track, and events with at least two S.A. tracks as a function of the energy of the generated muon. In case of at least two S.A. muon tracks, the efficiency is low at low energies, which means that cosmic muons with low energy are stopped in the detector.
Figure 16: Rates of Stand-Alone (S.A.) muon tracks as a function of $\varphi$ for underground cosmic muons, accepted by the L1 trigger. The maximal rate appears at the top of the detector, which corresponds to $\varphi = 90^\circ$. The bump around $\varphi = 270^\circ$ is at the bottom of the CMS detector.

Figure 17: Underground cosmic muons L1 rates for all events, and events with at least one S.A. track or with at least two S.A. tracks as a function of the generated muon energy. In case of at least two S.A. muon tracks, the efficiency is low at low energies, which means that cosmic muons with low energy are stopped in the detector.
Figure 18: Rates of Stand-Alone (S.A.) muon tracks as a function of $\vartheta$ for beam halo muons, accepted by the L1 trigger. The beam halo muon is coming from the -$Z$ ($-\vartheta$) side and moving to the +$Z$ ($+\vartheta$) side.

Figure 19: Beam halo muon L1 rates for all events, events with at least one S.A. track, and events with at least two S.A. tracks as a function of the generated muon energy. In case of at least two S.A. muon tracks, the efficiency is low at low energies, which means that beam halo muons with low energy are stopped in the detector.