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Monte Carlo Simulation of Inclusive Single- and Di-Muon Samples

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Abstract

This note describes the Monte Carlo generation and detector simulation of the datasets used for the study of the CMS Level-1 and High Level Trigger performance in muon topologies. A special event weighting procedure has been developed for efficient generation of minimum bias events with muons in the final state. The resulting inclusive single and di-muon rates within the kinematic acceptance of the CMS detector are reported.

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1 Introduction

At the LHC many interesting processes can be triggered because of the presence of one or more muons with high transverse momentum (p_T) in the final state. The trigger selection is therefore based on the request of a threshold on the p_T of reconstructed muons, and has to deal with a copious background of real muons – both *prompt* muons from heavy quarks and W/Z decays and *non-prompt* muons from pion and kaon decays.

A critical constraint on the muon selection is the maximum acceptable rate at each trigger level. The determination of the total rate as a function of the p_T threshold requires the simulation of an inclusive background sample large enough to allow good precision for rejection factors up to the order of 10^5. Since any K, π, b and c can decay into a muon, each LHC event can potentially cause a muon trigger, and the entire inelastic LHC cross section must be simulated. Moreover, the muon p_T spectrum must be simulated down to very low p_T values to take into account the triggers caused by mismeasured muons, which are relevant especially for the Level-1 trigger [1]. The full simulation of such a sample is very demanding, both in terms of the data volume to be stored and the CPU time needed to produce and process it. A special procedure has therefore been developed in order to get the maximum precision with an affordable number of simulated events.

This note reports the details of the event generation and detector simulation of the samples produced in the year 2002 for the study of the CMS muon trigger. In particular, the procedure adopted to optimise the production of inclusive muon samples is described. This procedure differs significantly from that used in a previous Monte Carlo simulation [2], specifically in the treatment of the heavy quark component and in the choice of a pseudorapidity-dependent cut on the minimum accepted p_T of the muons.

The simulation of the event samples was organised in several steps, details of which are discussed further in the note:

- the event generation, based on the PYTHIA [3] Monte Carlo generator, where the kinematic properties of the event and its stable particle content are determined;
- the detailed simulation of the CMS detector using CMSIM [4], which produces the particle *hits* in the detectors;
- the reformatting of the hits, *i.e.* the conversion from the CMSIM format to the one used by ORCA [5], the CMS object-oriented reconstruction package;
- the digitisation, where the response of the detectors to the particle hits is simulated with ORCA, taking into account the pile-up of events in the same and contiguous bunch crossings. The final product is given by the digitised hits (*digis*), which can be used as input for the trigger simulation and reconstruction programs.

The resulting inclusive single and di-muon rates within the kinematic acceptance of the CMS detector are reported.

2 Event Generation

The data generated for the muon Level-1 trigger and High Level Trigger (HLT) studies consist of a sample of about 10^6 fully simulated Monte Carlo events, split into several datasets corresponding to different physics processes, as listed in Table 1.

The bulk of the Monte Carlo production consisted in the simulation of the main source of background, *i.e.* minimum bias events having at least one final state muon with transverse momentum high enough to reach the muon trigger system. Since the full simulation of such a sample is very demanding, a special weighting procedure was developed, as described in Section 2.2. In addition to the minimum bias background, other physics processes which are sources of high p_T muons were simulated: the production of both W and Z/γ^* bosons and of top quark pairs. The generation of these samples is described in Section 2.3, together with a number of signal channels which have been used as benchmarks for the trigger signal efficiency.

After the generation, at least one muon above a given p_T threshold within the muon system acceptance was required for all generated samples, before the CMSIM full detector simulation step. Such acceptance requirements are responsible for the reduction from the number of generated events (N_{GEN}) to the number of events selected (N_{SEL}) and tracked through the CMS apparatus, as reported in Table 1.

Table 1: Generated Monte Carlo datasets. "MB" stands for the weighted minimum bias samples. Muons with $p_T > p_T^{\min}$ are selected within $|\eta| < 2.5$. N_{GEN} and N_{SEL} are the number of generated and selected events. f_{LL} and f_{HL} are the factors accounting for random failures in the production chain for low and high luminosity respectively, as described in Section 3. Their values are relative to the number of events analysed for the production of the ROOT trees for the muon PRS group, see Appendix A. Several samples were produced for each of the Higgs signals, as described in Section 2.3. For these signals (last four rows) only the total statistics is reported in the table.

Physics process	$p_T^{\min}$ (GeV/c)	N_{GEN}	N_{SEL}	f_{LL}	f_{HL}	σ (mb)
MB, Low-p_T	see text	1357640	278884	0.968	0.964	55.22
MB, Intermediate-p_T	4	54709859	404992	0.954	0.808	55.22
MB, High-p_T ($\hat{p}_T > 10$)	10	30375111	110513	0.924	0.892	2.66
W + jets $\to \mu + X$	3	569618	50000	0.910	0.979	$1.85 \cdot 10^{-4}$
Z + jets $\to \mu + X$	3	20000	20000	1.000	0.943	$1.74 \cdot 10^{-6}$
Z/γ^* + jets $\to \mu + X$	3	2268510	50000	0.990	0.960	$1.00 \cdot 10^{-3}$
$t\bar{t} \to \mu + X$	3	46229	20000	0.850	0.999	$6.24 \cdot 10^{-7}$
$H \to WW \to 2\mu 2\nu$ (5 samples)	3	64492	50000	see [6]		$3.0 - 18.0 \cdot 10^{-11}$
$H \to ZZ \to 4\mu$ (5 samples)	3	74653	50000	see [6]		$0.9 - 3.4 \cdot 10^{-12}$
$H \to 2\tau \to \mu + X$ (3 samples)	3	125818	40000	see [6]		$0.04 - 2.1 \cdot 10^{-9}$
$H \to 2\tau \to \mu + e + X$ (2 samples)	3	321731	20000	see [6]		$0.04 - 2.1 \cdot 10^{-9}$

2.1 Generation Parameters

The event generation was performed using the PYTHIA 6.158 [3] Monte Carlo generator. The values of the relevant parameters used in the simulation are given in Table 2. All other parameters were set to the PYTHIA 6.158 default value.

Table 2: Values of the PYTHIA parameters used for the generation. The values reported in italic are equal to the PYTHIA 6.158 defaults.

Parameter	Value	Sample	Description
`CKIN(3)`	10.0	"High-p_T" MB	$\hat{p}_T$ cut-off
	0.0	all other samples	$\hat{p}_T$ cut-off
`MSTP(51)`	*4*	All	Use GRV94 P.D.F.
`MSTP(81)`	*1*	All	Activate multiple interactions (M.I.)
`MSTP(82)`	*1*	b/c in MB events	Simple M.I. model
	4	All other events	Complex M.I. model
`MSTJ(11)`	3	All	Hybrid scheme for fragmentation function

The GRV94 [7] P.D.F., which is the default for PYTHIA 6.158, was used in the generation of all samples.

Evidence for multiple interactions within the same hadron-hadron scattering has been shown by collider data [8]. To simulate these multiple interactions, a model that assumes a double Gaussian distribution for the spatial distribution of the hadronic matter within the proton and a varying impact parameter between the two interacting partons was chosen (`MSTP(82)=4`, "complex" model in PYTHIA terminology) [1)]. However, since this complex model is very CPU-time expensive, the PYTHIA default model (`MSTP(82)=1`) was used in the dedicated generation phase where $b\bar{b}$ and $c\bar{c}$ events are produced (cf. Section 2.2), and where a large number of non-b, c events must be rejected in order to get a statistically enriched sample of heavy flavour events. In this "simple" model, the charged multiplicity of stable particles with $p_T > 1$ GeV/c is about 30% lower than in the complex model, which was conservatively adopted also for the minimum bias production of pile-up events (see Section 2.4).

Experimental data on fragmentation of jets containing c and b quarks indicate that the fragmentation function $f(z)$, where z is the fraction of the quark longitudinal momentum taken by the hadron at a given fragmentation step, is harder than in jets containing light quarks. For this reason, the hybrid model in PYTHIA (`MSTJ(11)=3`) based on the Lund fragmentation scheme for light quarks and the Peterson fragmentation function for c and b quarks was

1) Some indication in favour of multiple interactions models with varying impact parameter comes from the UA5 [9] and CDF [10] results on charged particle multiplicity.

used, with the PYTHIA default values of the Peterson parameters, $\epsilon_c = 0.05$ and $\epsilon_b = 0.005$, in fair agreement with the experimental data [11].

The PYTHIA code specific to the generation of these datasets and the full set of cards used are available on the on-line CMS production database [6] as described in Appendix A.

2.2 Generation of Minimum Bias Event Samples

Minimum bias events were generated by setting `MSEL=1` in PYTHIA, which includes both QCD 2→2 parton scattering and low-p_T production (where the protons are not resolved into the constituents partons, but interact as a whole). In order to efficiently generate a minimum bias sample with muons, one or more of the potential muon parents in each event was forced to decay, and the probability of the particular final state to occur was assigned as a weight. The details of this dedicated weighting procedure are described in Sections 2.2.1 and 2.2.2.

The event generation was performed in "runs", each one corresponding to one PYTHIA batch job generating few hundred events. During each run, the generation was performed according to the two-step procedure described below, and the events generated in the two steps were concatenated into a single output file for each run. The first production phase was devoted to the generation of minimum bias events with only light quarks in the final state. This was done by explicitly vetoing events with b/c quarks in the hard scattering or produced from gluon splitting into $b\bar{b}$ or $c\bar{c}$. In the second phase, a dedicated generation of b/c events from all possible production mechanisms (parton fusion, flavour excitation, gluon splitting) was performed, with an integrated luminosity a factor 10 higher with respect to the first production phase[2)]. This was meant to increase the statistical significance of b/c processes, which, albeit being characterised by smaller cross sections compared to light flavour processes, can contribute significantly to trigger rates at high p_T. In addition, the total $b\bar{b}$ cross section was normalised to $500\mu b$, following the recommendation of dedicated studies [12] and consistently with the approach [13] followed by the PRS b/τ[3)] group for the generation of $b\bar{b}$ minimum bias events.

The generation of minimum bias events was performed with inclusive kinematic requirements on the muons in the final state, in order to accurately estimate the background contribution to the accepted rate at the Level-1 and HLT trigger stages. Although single muon triggers will necessarily have rather high p_T thresholds (in the 20-40 GeV/c range), it is important to simulate low p_T muons to correctly account for feed-through effects [1] due to multiple scattering in the calorimeters and in the iron yoke. To obtain good statistical significance over a wide p_T spectrum, the generation was done in three different bins of transverse momentum. In each of these samples, events were required to have at least one muon within the acceptance of the detector, with a predefined momentum or transverse momentum cutoff:

- "Low-p_T" sample: a pseudorapidity-dependent cut was applied, in order to take into account the different minimum p_T values needed for a muon to reach the barrel, the endcaps and the overlap region of the muon system. The minimum generated p_T was 3 GeV/c in the barrel ($|\eta| < 1.2$) and 1.8 GeV/c in the overlap ($1.2 < |\eta| < 1.7$), while in the forward regions ($1.7 < |\eta| < 2.5$) a momentum of $p > 3.5$ GeV was required. To avoid overlap with the other two samples, events with muons having $p_T > 4$ GeV/c were rejected;
- "Intermediate-p_T" sample: a transverse momentum above 4 GeV/c was required within the full pseudorapidity range. In this case, the muon spectrum was simulated with no upper bound, to allow comparison with the "High-p_T" sample (see below). To avoid double counting, events with muons with $p_T > 10$ GeV/c must be excluded when analysing this sample;
- "High-p_T" sample: a transverse momentum above 10 GeV/c was required within the full pseudorapidity range. Since the fraction of minimum bias events with muons above this p_T threshold is small, the generation of this sample is more CPU-time expensive than that of the previous two samples. In order to enrich the sample with high-p_T muons and speed up the event generation, only events with a minimum transverse momentum of the parton level hard process ($\hat{p}_T$) above 10 GeV/c were generated. However, since it has been observed that the $\hat{p}_T > 10$ GeV/c cutoff introduces an unphysical dependence of the cross section when the multiple interaction complex model is used, a scaling factor was applied to the events with light flavour quarks, in order to normalise the event weights consistently with the other samples. Its value, 0.645, was

2) The weight of each event in the second production phase is scaled down by a factor 10, to preserve the correct normalisation of the rates.

3) CMS working group for Physics, Reconstruction and Selection (PRS) activities related to the CMS tracker.

determined by comparing the rate of muons from this sample with the rate of muons with $p_T > 10$ GeV/c in the intermediate-p_T sample, which was generated with no $\hat{p}_T$ cutoff. No scaling factor was necessary for the heavy flavour component, where the treatment of multiple interactions is done according to the simple model.

The distribution of the generated muon momentum as a function of η in the minimum bias samples is shown in Fig. 1.

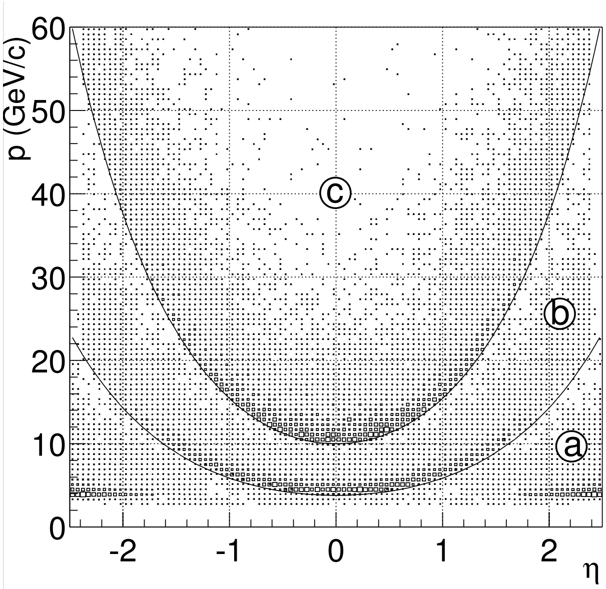

Figure 1: Momentum versus pseudorapidity distribution of muons in the minimum bias samples. The contributions of the events from (a) the low-p_T, (b) the intermediate-p_T, and (c) the high-p_T weighted minimum bias samples are shown.

2.2.1 Generation of Muons in the Final State and Event Weighting Procedure

An interface to the PYTHIA generator was written, which takes over the decay of particles that can potentially produce a muon. For this purpose, all potential muon parents, such as B- or D-mesons as well as pions and kaons, are declared stable for the PYTHIA event generation step. Then a probability for a decay containing a muon within the defined acceptance region in both η and p_T is evaluated for each of these particles. The PYTHIA decay routine `PYDECY` is called twice for each of the potential muon parents, once switching off all decay modes containing muons, and once switching off all the other decay modes, leaving only those with muons active. In both cases, possible muon parents might again be found among the decay products, so the procedure is recursively repeated for every particle until no muons can arise from further decays. When completed, this procedure produces an event record with several sets of decay products for the same hadron. In particular the event record contains all possible muons that could arise in the event.

For each particle that appears in the decay procedure described above, the probabilities $p_0, p_1, p_2, p_3, \ldots$ for it to yield exactly 0,1,2,3,... muons within the acceptance region are evaluated. Here are some examples:

- For a muon $p_1 = 1$ if it falls within the acceptance region, otherwise $p_0 = 1$. All other probabilities are zero;
- A charged pion has a 100% branching ratio into a muon and a neutrino. However, its lifetime is so long that it is most likely to be absorbed in the calorimeters before it decays. For these long-lived particles, a decay volume is defined. For the present study, we use a cylinder with a radius of 3 m, containing the CMS calorimeters. For a pion, a probability p_{decay} is evaluated for its decay to happen inside the given detector volume. For pions with transverse momenta of a few GeV, $p_{\mathrm{decay}} = \mathcal{O}(10^{-3})$ is typical. A decay vertex is chosen along its trajectory inside the volume, according to the expected exponential decay length distribution. The resulting probabilities are then $p_1 = p_{\mathrm{decay}}$ and $p_0 = 1 - p_{\mathrm{decay}}$, if the decay muon is within the acceptance, otherwise $p_0 = 1$ and all others are zero;

- The combined probabilities for a set of particles, like all decay products of one parent particle, or just a whole event, can be calculated from the corresponding probabilities of the individual particles. For a set of two particles (i and j) we obtain:

$$\begin{aligned} p_0 &= p_0^i p_0^j \\ p_1 &= p_1^i p_0^j + p_0^i p_1^j \\ p_2 &= p_2^i p_0^j + p_1^i p_1^j + p_0^i p_2^j \\ &\dots \end{aligned}$$

- For particles that decay via more than one possible channel, all probabilities are averaged over the decay channels, weighted with the corresponding branching ratios. Here is an example for a particle with two possible decays, *a* and *b*, with corresponding branching ratios B_a and B_b:

$$\begin{aligned} p_0 &= B_a p_0^a + B_b p_0^b \\ p_1 &= B_a p_1^a + B_b p_1^b \\ &\dots \end{aligned}$$

Complete evaluation of these probabilities for all particles in an event leads to a corresponding set of "muon probabilities" (i.e. probability to have 0,1,2,...muons in the final state) for the event as a whole.

The sum of all probabilities for multiplicities that would satisfy the selection criteria is assigned as a weight to the event. Then one of these accepted multiplicities is chosen at random, according to their relative contributions to the event weight.

Once the number of muons for the event has been chosen, a final state is selected for the event, by distributing the muons to be generated among the particles of the event, according to the probabilities evaluated during the procedure described above. As a simple example, assume that an event that contains two potential muon parents (i and j) is chosen to have two muons. The total two-muon probability p_2 of the whole event as given above can be split into the contributions from 3 possible final states, as a function of the number of muons originating from each of the possible parent particles:

$$p_2 = p_2^i p_0^j + p_1^i p_1^j + p_0^i p_2^j = p_2^{20} + p_2^{11} + p_2^{02}.$$

Here p_2^{20} is the probability for the event to have two muons, which both come from the first parent particle (i); the definitions of p_2^{11} and p_2^{02} are analogous. For the selection of a final state, one of these configurations is chosen at random, according to their relative probabilities.

For the case of a particle where more than one decay channel is used, one of the channels has to be chosen. This is again done according to the probabilities for the desired muon multiplicity in each decay channel. In our example, if a particle with two decay channels (a and b) has been selected to produce 2 muons, its total 2-muon probability

$$p_2 = B_a p_2^a + B_b p_2^b$$

consists of two contributions from the two possible decays, and one of them is again chosen randomly according to their relative probabilities.

This whole procedure is repeated recursively for any daughter particle that can produce muons during decay. Once all muons have been assigned, the decay products of all remaining particles are deleted, and these particles are allowed to decay as usual, with all decay channels switched on. Each of these decays is checked for possible muons within the acceptance. In case a muon is found, the decay products are deleted and the decay is repeated until no accepted muons are found.

The final result is an event satisfying the selection criteria in which all unstable particles have decayed, with no double-counting of energy. These events recover all properties and all distributions of the original unbiased sample, except that they come with event weights.

2.2.2 Optimisation of Event Weights

When an event sample with a non uniform distribution of weights is used, there is a loss of statistical significance compared to a sample which contains the same number of events with uniform weights.

A figure of merit is the *equivalent number of unweighted events*, defined as the number of events in a hypothetical sample of unweighted events that would yield the same statistical uncertainty on the event rate as a given weighted sample. For a sample of N weighted events with weights $w_i, i = 1 \ldots N$, the equivalent number of unweighted events $N_{\rm eq}$ can be calculated as

$$N_{\rm eq} = \frac{(\sum_{i=1}^{N} w_i)^2}{\sum_{i=1}^{N} w_i^2}.$$

In order not to use too many additional computing resources for detector simulation and further processing of the events, $N_{\rm eq}$ should not be much smaller than the actual number of events in the sample, which implies that the spread of weights in the sample should be kept small. Most minimum bias events without heavy flavours have a very small weight when forced to have one muon in the final state. Once heavy quarks (b, c or t) are produced, however, the typical event weights become considerably larger, because of the large branching fraction of B and D mesons into decay channels with muons. Events containing heavy quarks are rare and statistical fluctuations of their weight can have a big impact on the significance of the sample. In order to reduce this effect, b/c events have been generated separately, as already mentioned in Section 2.2, with an integrated luminosity a factor 10 higher than the rest of the events, and then combined to the light flavour sample with a weight scaled down by the same factor. The $b\bar{b}$ event weights are further scaled by a factor which sets the total $b\bar{b}$ cross section in minimum bias processes to 500 μb as described in Section 2.2.

The weights of the events forced to contain muons with a minimum transverse momentum typically increase with the hard scale $\hat{p}_T$ of the parton scattering. The reason is that for such events the probability to produce b and c quarks is higher and the average momentum of the potential muon parents is larger. For the "High-p_T" sample, which is produced with $\hat{p}_T > 10$ GeV/c, the differential cross section $d\sigma/d\hat{p}_T$ used by PYTHIA to generate the events was artificially modified using the function

$$w_1 = 1 + 0.0003(\hat{p}_T/\text{GeV}/c)^2$$

so that the sample is enriched in the high-$\hat{p}_T$ component. The event weight was then divided by w_1 to get the correct normalisation and cross section. In this way, the final distribution of the weights is uniform in the $\hat{p}_T$ range of interest.

Finally, to further reduce the spread of event weights and improve the statistical significance of the sample, the abundance of events with very small weights was reduced with a procedure applied to all events with a weight w below a cutoff value $w_{min} = 0.1$. Each of these events was either selected with a probability w/w_{min} and assigned the weight w_{min}, or rejected from the sample. As a result, no event with weight below w_{min} is left and the overall composition and rate of the sample is unchanged.

The integral minimum bias rate as a function of the threshold on the muon transverse momentum obtained for a luminosity of $10^{34}\text{cm}^{-1}\text{s}^{-1}$ with this weighting procedure is compared in Fig. 2 with the one obtained from an unweighted sample of eight million minimum bias events generated with PYTHIA with `MSEL=1` and no $\hat{p}_T$ cutoff[4].

This comparison shows that the weighting procedure does not significantly bias the muon rate and produces a sample that, despite containing only a fraction of the events of an unweighted sample, is statistically significant up to much higher p_T thresholds.

2.2.3 Multi-Muon Events from Pile-Up

An important source for background events with more than one muon in the final state is the random overlap of two (or more) collisions with muons within the same bunch crossing. If detector occupancies are low, then the trigger objects caused by muons from different collisions in the same crossing may be considered independent and the resulting trigger rates may be calculated using combinatorics [14]. This was done for the low LHC luminosity scenario. In order to simulate multi-muon trigger rates under realistic conditions, for the high-luminosity scenario, a sample of bunch crossings was constructed by overlaying multiple minimum bias collisions from the three samples generated in bins of muon-p_T according to the procedure described in [14]. Pile-up events without muons were added as discussed in Section 2.4. Crossing configurations with up to four collisions with muons were found to contribute significantly to the expected trigger rates and were therefore included in the sample.

4) For the purpose of this comparison, in the weighted sample the normalisation of the b component to 500 μb total $b\bar{b}$ cross section was removed, to be consistent with the generation of the unweighted sample.

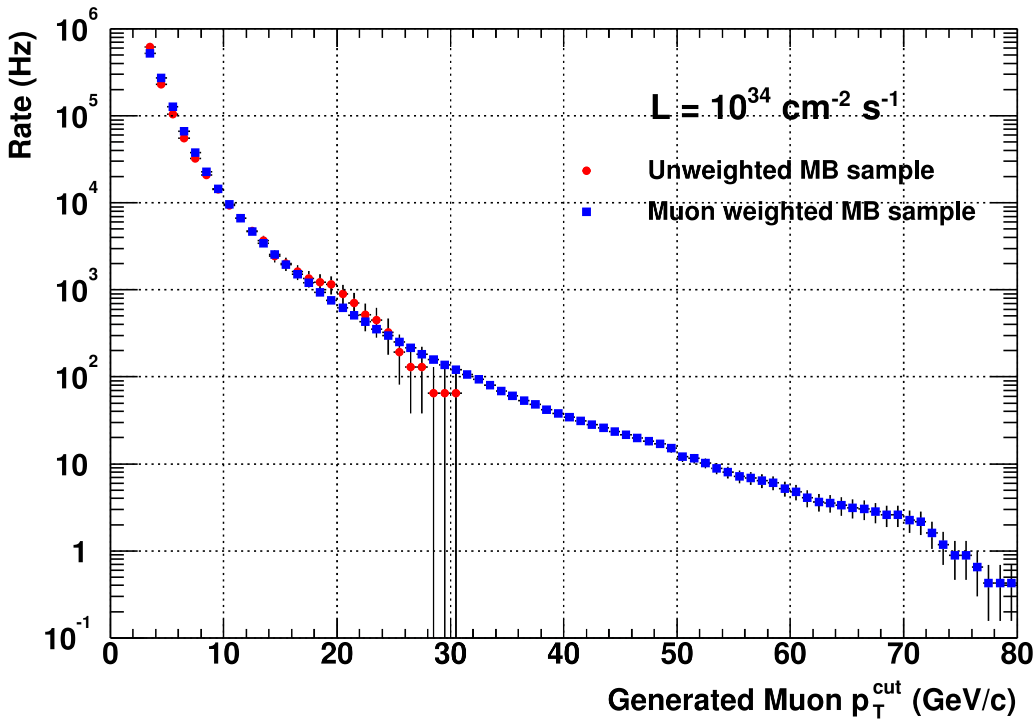

Figure 2: Integral minimum bias rate for $|\eta| < 2.1$ at $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ as a function of the muon transverse momentum cutoff p_T^{cut}, from an unweighted sample of $\approx$ eight million minimum bias events (circles) and from the weighted muon minimum bias sample (squares). Note that, since these are integral distributions, the errors on consecutive bins are correlated.

Event weights were taken into account by defining a crossing weight proportional to the product of the weights of contributing collisions. In order to compensate for the rapidly dropping muon p_T spectra, the sample was enriched with muons of high transverse momenta by increasing the number of crossings for configurations with collisions from the intermediate- and high-p_T samples. The loss of statistical significance due to the spread of crossing weights (see Section 2.2.2) was individually compensated for in each configuration by increasing the respective number of crossings.

Computing resources were saved by constructing the crossings from the available simulated minimum bias collisions at the level of ORCA digitisation. In order to obtain a full sample of crossings as they will occur at the LHC, 1.10×10^5 crossings with two or more collisions with a muon were constructed from part of the available simulated minimum bias collisions, while the remaining 2.22×10^5 minimum bias collisions were used to represent crossings with only one collision with a muon.

An important advantage of this method over the analytic calculation of the rate of overlapping collisions with muons is that the resulting sample of crossings can be used to study any trigger condition. In particular, topological multi-object triggers and conditions based on the relative positions of the vertices of reconstructed muons or on their invariant masses can be studied.

2.3 High-p_T Muon Backgrounds and Signal Samples

The production of W and Z/γ^* bosons, as well as of top quarks pairs, represents an additional source of background muons. These processes were simulated without any dedicated weighting procedure.

The generation of single W and Z/γ^* was performed via the lowest order $2 \rightarrow 1$ resonant processes (`MSEL=11,12`), with initial state QCD radiation switched on to simulate additional jets through parton showering (PYTHIA default value `MSTJ(41)=2`). In PYTHIA, this is considered the best option to simulate inclusive single-boson production with moderate transverse momentum $P_T \ll M_{W,Z}$, which is relevant for HLT muon background studies. The generation of $t\bar{t}$ events was performed via `MSEL=6`, which simulates top quark pair production via quark or gluon fusion.

To optimise the generation, a routine was implemented in PYTHIA to directly reject events without a predefined number of muons within the acceptance of the detector. Direct muonic decays of W and Z/γ^* bosons were not forced, so that muons selected with this procedure could originate either from direct boson decays or from the τ, b and c decay chains.

The same procedure was used to generate some benchmark signal samples of Standard Model Higgs boson decaying to $ZZ^* \rightarrow 4\mu$ (for $m_H = 130$, 150, 200, 300 and 500 GeV/c^2) and to $WW^* \rightarrow 2\mu 2\nu$ (for $m_H = 120$, 140, 160, 180 and 200 GeV/c^2). For these signal samples, the decay of W and Z bosons to muons was forced in PYTHIA to obtain the desired topology.

Additionally, some samples needed for specific studies were generated. In particular, samples of MSSM Higgs bosons decaying to $\tau\tau \rightarrow \mu\tau_{jet} + X$ and $\tau\tau \rightarrow \mu e + X$ (for $\tan\beta = 20$ and $M_A = 200$ and 500 GeV/c^2) were produced using a dedicated selection code. Two additional samples of Z bosons with direct muon decay were also generated: a sample of Z^* bosons (with $m_{Z^*} > 110$ GeV/c^2) and a sample of on-shell Z bosons (with $81 < m_Z < 101$ GeV/c^2).

Details of the generation of all the samples quoted above are reported in Table 1.

2.4 Minimum Bias Sample for Pile-Up

The LHC will operate at a bunch crossing rate of 40 MHz. The bunch structure is such that only about 80% of the bunches will have collisions [15]; therefore the total inelastic pp cross section, predicted by PYTHIA to be 55 mb, results on average in 17.3 minimum bias events per bunch crossing at the LHC design luminosity of 10 nb^{-1}s^{-1}, and 3.5 events per bunch crossing at the initial luminosity of 2 nb^{-1}s^{-1}.

The realistic simulation of a triggering event in this conditions requires the simulation of the *in-time pile-up* occurring in the same bunch crossing and, for detectors with a long time window, of the *out-of-time pile-up* occurring in the contiguous bunch crossings.

Out-of-time pile-up is particularly relevant for the calorimeters, where dedicated studies [16] have shown that it is necessary to simulate the bunch crossings in a window of [-5,+3] with respect to the triggering event. At high luminosity this implies the superposition of an average of 156 minimum bias events, which, in the present study, were randomly chosen from a dedicated sample of about 2×10^5 minimum bias events.

The minimum bias pile-up sample was produced with the parameters reported in Table 2, without any weighting procedure. However, since the events in the minimum bias samples used for the determination of the trigger rates are forced to contain muons (cfr. Section 2.2), no muon should be present in the the pile-up sample to avoid an artificial increase of the di-muon rate and a bias due to the multiple occurrence of few triggering pile-up events. The pile-up sample was therefore filtered to remove all events containing potentially triggering muons (*i.e.* with $p_T > 1.0$ GeV/c in $|\eta| < 2.0$ and $p > 3.0$ GeV for $2.0 < |\eta| < 2.5$).

Muon detectors are also sensitive to thermalised neutrons (produced in collisions up to millions of bunch crossings earlier), which, when captured by a nucleus, may yield a gamma-ray that converts into an electron-positron pair close enough to an active gas layer to produce a signal. Although parameterisations of this long-time pile-up exist, they were not enabled in this simulation, mainly due to the excessive CPU time spent on digitising a large number of random hits. A dedicated Level-1 trigger study showed negligible impact of this background on the performance of the Level-1 Track-Finder for the CSC system [17]. The neutron background effect is also expected to be negligible on the performance of the Level-1 Track-Finder for the Drift Tube system, where the neutron flux is expected to be 10–100 times smaller [18]. On the other hand, the output of the Level-1 Pattern Comparator Trigger of the RPC system is sensitive to the neutron background in a way that is dependent on the intrinsic detector noise assumed [19], and further dedicated Level-1 trigger studies are underway.

The details of the digitisation procedure, where the pile-up is added to triggering events, are described in Section 3.

3 Detector Simulation

Particles were tracked through the CMS detector using CMSIM 125 [4], a simulation program based on GEANT3 [20] which includes the detailed geometry of the CMS detector. During this step, the collision point was displaced with respect to the detector centre, according to a Gaussian with $\sigma = 5.3$ cm along the beam line and $\sigma = 1.5$ mm in each of the transverse coordinates.

A description of the CMS Muon system can be found in [21]. The most relevant change from what described therein is that the trigger electronics will not be installed in the forward CSC station ME1/1a, thus limiting the Level-1 trigger acceptance to $|\eta| < 2.1$.

Multiple scattering, bremsstrahlung, Compton scattering and pair-production processes were activated in the GEANT simulation with low energy cutoffs in the last 4 cm of iron layers before the muon chambers, in order to have a realistic simulation of the delta-rays and shower processes in the chambers. Hadronic interactions at energies as low as 1 MeV were simulated with the GCALOR hadronic package [22]. The values of the energy cuts set in GEANT for tracking particles in the apparatus are summarised in Table 3.

Table 3: Energy cut-off values set in GEANT for tracking particles in the apparatus. "Special" cut values were applied in the Tracker region and in the 4 cm thick material regions before muon detector active volumes. "Normal" values were adopted elsewhere in the apparatus.

GEANT parameter	cut value *normal*	cut value *special*	GEANT parameter	cut value *normal*	cut value *special*
CUTGAM	1 MeV	10 keV	CUTELE	1 MeV	10 keV
CUTNEU	10 MeV	10 MeV	CUTHAD	10 MeV	100 keV
CUTMUO	10 MeV	100 keV			
BCUTE	1 MeV	10 keV	BCUTM	1 MeV	10 keV
DCUTE	10 TeV	10 keV	DCUTM	10 TeV	10 keV

A special treatment was necessary for the weighted minimum bias samples, due to the presence of the non-prompt muons generated by PYTHIA with the procedure described in Section 2.2. A routine was therefore implemented in CMSIM[5)], where the pions and kaons that were forced to decay at the generation step were tracked through the detector and their decay point was chosen according to the lifetime assigned in the generation stage. The direction of the decay products was assigned according to the generated kinematics, taking into account the bending of the parent particle in the magnetic field. However, during the tracking pions and kaons were allowed to undergo hadronic interactions before the predicted decay point; in this a case no muon was generated.

After the processing with CMSIM, the simulated hits were read by ORCA and stored in an object database. Weighted minimum bias events containing no muons due to hadronic interaction of pions and kaons before the predicted decay point were skipped to save CPU time and disk space in the following steps.

The final step in the production chain was the *digitisation*, where the response of the detector to the hits of the triggering event and of the pile-up was simulated with ORCA. The results are the *digis*, which are equivalent to the raw data collected by the detector for real events. Events were independently digitised for two LHC luminosity scenarios: $\mathcal{L} = 2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ("Low luminosity") and $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ("High luminosity"). Pile-up events were added to the triggering event via a random selection from the sample described in Section 2.4. The number of events added per bunch crossing was determined according to the Poisson distribution, with averages of 17.3 and 3.5 at high and low luminosity, respectively. Out-of-time pile-up in a window of [-5,+3] bunch crossings was included in the digitisation of calorimeters and of the CSC detectors. However, out-of-time pile-up does not affect significantly the CMS tracker, the Drift Tubes and the RPC detectors and was not taken into account for these systems.

The effect of the superposition of 2 triggering interactions in the same bunch crossing was studied using the "mixed" sample described in Section 2.2.3. On the other hand, the effect of events with real muons occurring in off-time bunch crossings with respect to the triggering event was neglected in this study, since the probability for a muon to give a trigger at the wrong bunch crossing has been shown to be only 2% in the case of the L1 drift tube track-finder [21], and is expected to be smaller in the cathode strip chamber system.

A sizeable fraction of minimum bias events containing very low p_T muons does not actually lead to a trigger. To save resources, the digitisation of the low-p_T and intermediate-p_T minimum bias samples was done in two steps. Initially only the muon detectors and the calorimeters were digitised. The digitisation of the tracker was performed separately for events with at least one muon reconstructed by the Level-1 trigger.

5) This routine has been included in the special CMSIM release 125.1 and can be activated with the card `STRD`.

The multiple-step event selection procedure described above affects the final event weight to be applied for normalisation at the analysis stage. Let N_{GEN} be the number of generated events, N_{HIT} those written to the hit database, N_{DIGI} the events after muon and calorimeter digitisation, N_{FILTER} those passing L1 filtering (if any) and N_{ANA} those after tracker digitisation and event reconstruction. The case of a non negligible event loss due to random failures (e.g. crashes due to data access problems) in the processing is reflected by $N_{HIT} \neq N_{DIGI}$ and $N_{FILTER} \neq N_{ANA}$. The rate contribution r_i corresponding to an event with the weight w_i is then given by:

$$r_i = w_i \frac{\sigma \mathcal{L}}{f N_{GEN}} ,$$

where $f = (N_{DIGI}/N_{HIT}) \cdot (N_{ANA}/N_{FILTER})$ is the fraction of processed events, σ is the cross section of the data sample and $\mathcal{L}$ is the LHC luminosity. The values of N_{GEN}, σ and f for high and low luminosity are reported in Table 1 for all datasets. The formula is also valid for signal events where weights are equal to 1 and no Level-1 filtering step was applied ($N_{FILTER} = N_{DIGI}$).

4 Rates

In Fig. 3 the single-muon differential cross sections of the three minimum bias datasets are shown as a function of the muon p_T along with those of the W, Z and $t\bar{t}$ samples. The three minimum bias samples are combined together with an event weight as described in Section 3.

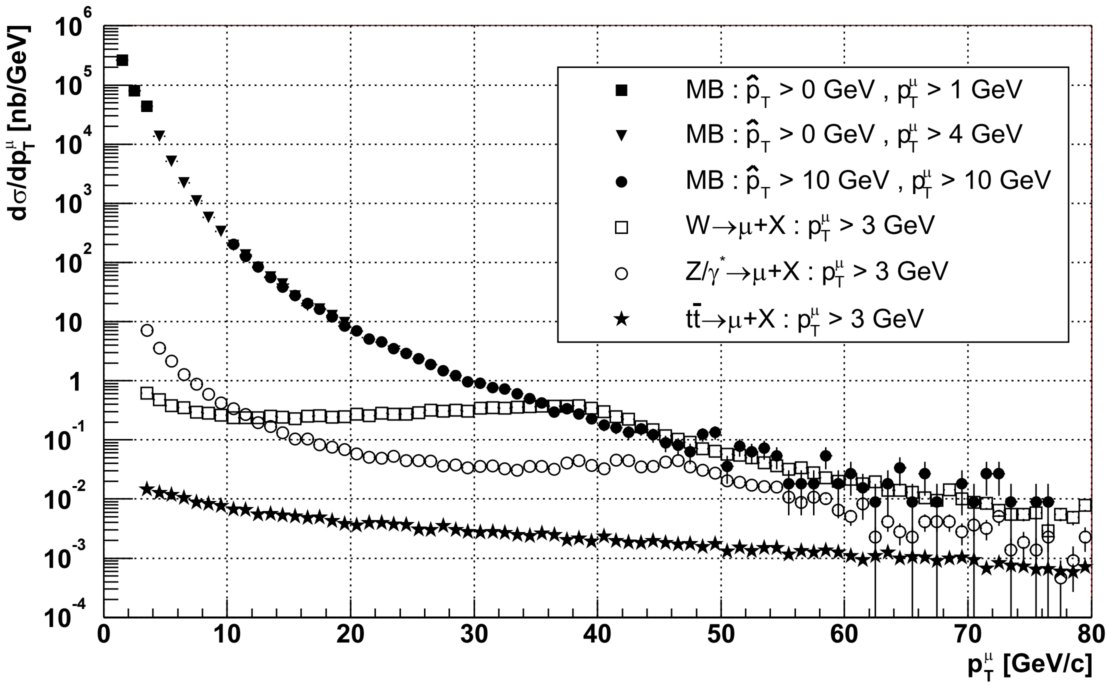

Figure 3: Differential cross section for events with at least one muon within the trigger acceptance of $|\eta| < 2.1$ for the various datasets.

The resulting integrated rate of single muons obtained from PYTHIA as a function of the p_T threshold is shown in Fig. 4. Rates are computed for a luminosity of $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (1 nb $\equiv$ 10 Hz). The muons are restricted to the detector acceptance of $|\eta| < 2.1$. The breakdown in terms of the muon parent particles is also shown.

From Fig. 4 it can be seen that the inclusive single muon rates for p_T thresholds up to 5 GeV/c are completely dominated by non-prompt muons from charged K and π decays; for p_T thresholds between 5 and 25 GeV/c the dominant contribution is bottom and charm quark decays, and only above $p_T > 25$ GeV/c does the contribution from W and Z decays become important.

Fig. 5 shows the integrated rate of di-muons at the generator level, for a luminosity of $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$. For low p_T thresholds the inclusive di-muon rate is dominated by minimum bias events, while for p_T thresholds above 13 GeV/c decays of Z bosons dominate over the minimum bias background.

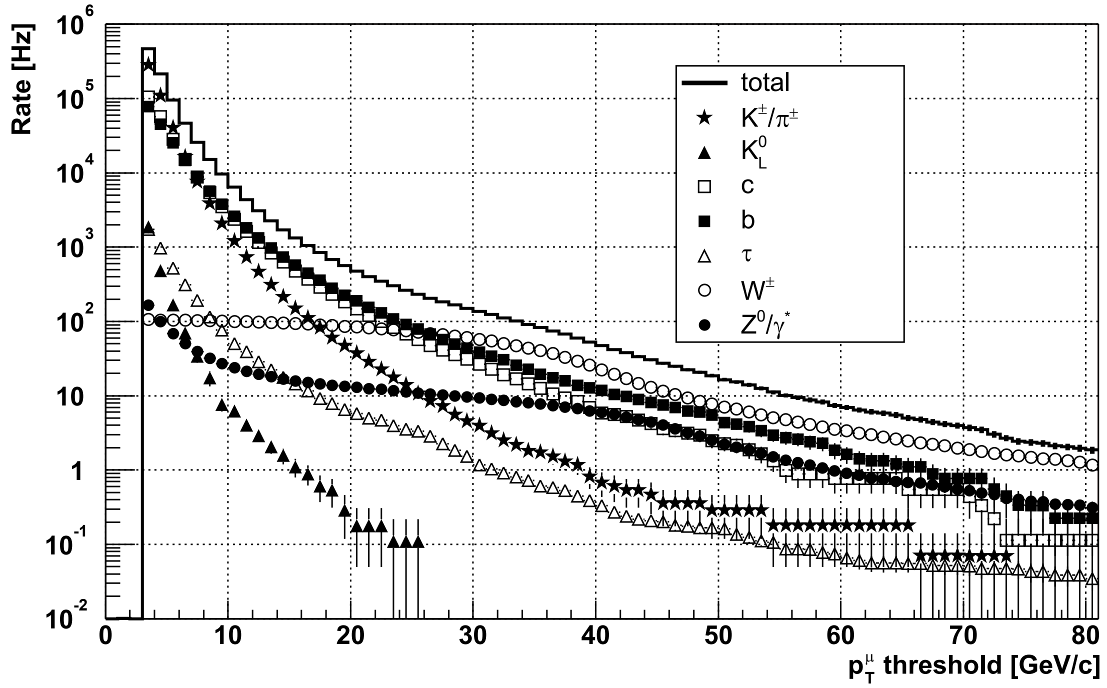

Figure 4: Inclusive integral rate of single muons from PYTHIA as a function of the muon p_T threshold for a luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The breakdown of the rate on each source of muons is shown.

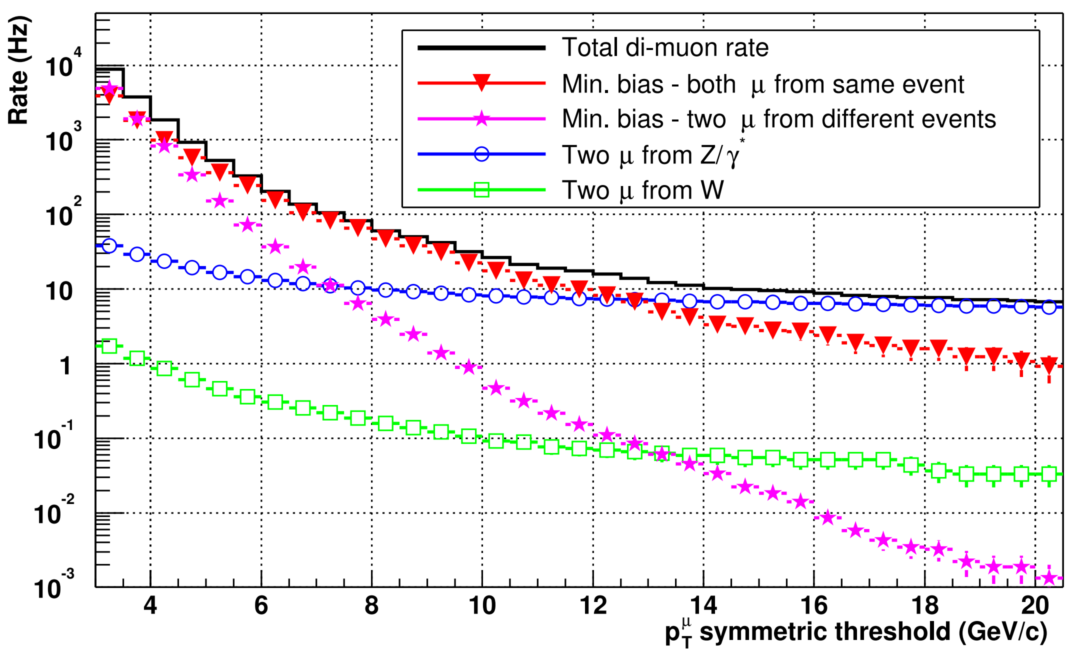

Figure 5: Inclusive integral rate of di-muons from PYTHIA as a function of the (symmetric) muon p_T threshold for a luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The breakdown of the rate on each source of muons is shown.

5 Conclusions

This note reports the details of the event generation and full detector simulation of the signal and background samples produced in the year 2002 for the study of the CMS muon High Level Trigger performance. Particular emphasis was given to the description of the procedure adopted for the production of inclusive muon samples in order to get the maximum significance with an affordable number of simulated events. This procedure has been used to generate and simulate about 8×10^5 weighted minimum bias events that cover the p_T spectrum in the range 3–70 GeV/c. It is shown that the resulting muon rate is compatible with that obtained with an inclusive unweighted production. However, obtaining the same statistical significance from such a production using similar p_T bins and selection requirements would have required the generation of about 850 millions of events, and would not have been affordable with the existing computing resources.

Acknowledgements

We would like to thank the Production Team for the effort in producing the simulated data used for this study.

A Dataset location and software documentation

All the details of the generation and simulation steps for the samples described in this note are available in the online CMS production database [6]. In particular, following the link "List Datasets" it is possible to get the full list of the samples produced by the muon PRS group, together with the PYTHIA, CMSIM and ORCA cards and versions used, the statistics after each processing steps, and the location of the Objectivity/DB database with the output data. Following the link "List applications" it is possible to get details on the additional PYTHIA code used for the generation of weighted minimum bias events and for the selection of final states with muons in signal samples. This code is also available on AFS on `/afs/cern.ch/cms/Physics/muon/CMSIM/cms125.1/`.

The datasets described in this note were processed with the reconstruction application of the muon PRS group [23]; the output ROOT trees are available via RFIO on
`shift19:/shift/shift19/data3/zh/cmsmuon/mu02/2002_08_Trees622/`.

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