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SIMULATION STUDY OF THE RPC BASED, SINGLE MUON TRIGGER FOR CMS

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Abstract

We present a simulation study of the single muon trigger based on the Resistive Plate Chambers. The note contains a brief description of the proposed setup and algorithm, discussion of the particle rates at the vertex, efficiency curves for muons and the discussion of the background – punchtrough hadrons and muons from the hadron decays.

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Contents

1 Introduction

The purpose of this note is twofold:

1. To propose and discuss the preliminary version of the trigger setup based on the Resistive Plate Chambers (Sec. 2). The trigger decision algorithm based on the RPC's is described and critically discussed (Sec. 2.2)

2. To calculate muon trigger efficiences (Sec. 4) and trigger rates (Sec. 6) for the setup and algorithm described before. These calculations are based on the realistic simulation of the prompt muon signal (Sec. 3) and background from punchtrough hadrons and decay muons (Sec. 5).

2 Trigger setup based on the RPC

2.1 The RPC chambers

The Resistive Plate Chamber (RPC) [1] is a good candidate for the muon trigger detector.

It consists of two parallel plates, made out from the resistive plastic (with resistivity $10^{10} - 10^{12}$ $\Omega\times$cm) separated by a gas gap of few mm thickness. The outer surfaces of the resistive material are coated with conductive graphite paint to form HV and ground electrodes. The readout is done by the metal cathode strips, placed on outside of the separate plastic foil glued over the conducting surface of the cathode. The whole structure is made gas tight and encased in the Faraday cage of thin metal foil. The RPC detectors form a rugged, thin plates.

The RPC of 1×2 m^2 were well tested in several experiments [2].

The main properties of the RPC, which make them very good candidates for large surface muon trigger chambers, are

- Good intrinsic time resolution (≤ 5 ns), limited by the signal propagation time along the R/O strips.

- Large signals from m.i.p., allowing simple and cheap analog R/O electronics.

- Construction adapted to the mass production.

The muon trigger scheme based on the RPC's is being tested in the RD5 experiment in the conditions closely resembling these in the CMS detector [3].

The efficiency of the RPC is good for rates up to 100 Hz/cm^2. This is far in excess of what we expect in the barrel region, but may not be sufficient in the forward cones, where we consider the Parallel Plate Chambers (PPC's) as an alternative solution.

2.2 Simulated trigger setup

In order to propose a viable trigger setup and trigger algorithm one has to address three problems:

1. **The geometrical inefficiency.**

   In the present design of the CMS geometry (version 07b) the muon stations are staggered in φ in such a way that in 100 % of the cases a muon goes through at least three stations. In 70 % of the cases the track goes through 4 muon stations. The trigger setup in the standard CMS design consists of 1 station with the 100 % azimuthal coverage and 3 stations with 90 % coverage each.

   In order to increase the azimuthal coverage, and additionally increase the lever arm and make the trigger more redundant, we considered adding an extra trigger plane before the cryostat (MS0) in the barrel or inside the hadron calorimeter in the forward direction (MF0). In this option there are 2 trigger detectors with the 100 % azimuthal coverage, and 3 with the 90 % coverage each. The gains of this option in terms of efficiency have to be balanced against the increased cost and technical difficulties.

2. **The internal RPC inefficiency.**

   The single gap Resistive Plate Chambers are not 100 % efficient, but the problem can be solved by doubling the gas gap. In this note we assumed that the double gap RPC will be used up to $|\eta| = 2.0$ in all four stations. For larger pseudorapidities, the high rates preclude the use of RPC, at least in the first two stations. Some alternative technique e.g. the PPC's have to be used there.

3. **Problem of the low momentum muons.**

   The muon production rates are steeply falling functions of the muon transverse momentum. Because of that, the trigger rates will be dominated by the low momentum muons creeping in through the inefficient trigger. The highly efficient rejection of the low (few GeV) muons is, therefore, of primary importance.

   This rejection could be achieved by placing two trigger detectors in one station (e.g. MS1 or MS2 in the barrel, similarly in the forward regions). The distance between two detectors in one station will be of order of 30 cm.

The setup used in the simulation is shown in Fig. 1.

The size of the RPC chamber is defined by two requirements. In the barrel the strip length should not exceed $1 - 1.5$ m, in order not to spoil the time resolution (bunch crossing determination). In the forward region, the strip width has to matched to the azimuthal deflection of a track, which in turn depends on η.

The trigger detectors are grouped together in larger sectors. At the moment we envisage a projective geometry in η and φ. The trigger chambers from all stations in a given η sector will be connected to one trigger processor.

For practical solution we used projective geometry with 5.4 mrad strip width, both in central and forward region. This gives 1152 channels of readout in φ.

2.3 The trigger algorithm

The solenoidal magnetic field of the CMS detector causes track bending in a plane perpendicular to the beam direction. In the central part of the detector the magnetic field is almost independent on z coordinate (along the beam direction). In the forward region, bending power of solenoidal magnetic field decreases with pseudorapidity η. However the bending is still big enough to distinguish transverse momenta in wide range of values. Thus, the azimuthal angle φ can be used to measure bending and to determine the particle transverse momenta. We propose to measure angle φ using long strips. In the barrel region strips are positioned along beam direction, in the forward region - radially, perpendicular to the beam. For the triggering purposes it is enough to determinate the angle φ with accuracy of order of a few milliradians, which matches well with the typical width of RPC strips (few centimeters).

A particle passing the detector crosses muon stations, hitting strips on its way. In the absence of the energy loss and multiple scattering there will be one to one correspondence between the pattern of hits and the muon transverse momentum. In the real world with energy loss and multiple scattering there is a set of hit patterns (masks) for each value of the muon transverse momentum. The mask sets for two different transverse momenta are ordered i.e. the set for the higher p_T is a subset for the lower p_T. This property allowed us to establish the mask set for a given value of the threshold ${p_T}^{cut}$.

The sets of valid mask change with pseudorapidity η. They are practically η independent in the barrel region, but vary in the forward region.

Once calculated, the mask set for a given ${p_T}^{cut}$ and η can be used to calculate trigger efficiency for this cut in the given pseudorapidity range. The hit patterns of all generated muons are compared with the masks from the particular set.

The standard setup defined in the Sec. 2.2 has dead spaces in azimuth. The trigger algorithm has to take this fact into account. The actually tested algorithm was as follows:

1. **Case four – out of – four**. First we tried to base the decision on the information from all four stations[1].

   This is good solution in wide range of angle φ, when muon passes all four stations. It fails near the edges of the φ sectors.

[1] The set of curves obtained using this method we have inserted to the Letter of Intent for CMS detector.

2. **Case three – out of – four**. Failing a four station solutions, we tried taking a decision based on information from only three (out of four) stations.

   For each 4–strip combination of hits we checked if in the mask set there is a combination containing hit strip numbers in stations 1, 2, 3 or 1, 3, 4 or 2, 3, 4.

   This is preferred algorithm in the neighborhood of sector edges. Furthermore it is universal and can be used in any part of the detector.

To improve the results one can make the measuring arm longer. This can be achieved by adding additional trigger station in the inner part of the detector (before the coil) as mentioned in Sec. 2.2. The place before the coil gives the possibility to make it fully efficient in φ.

In such a setup we have used the following algorithm:

1. **Case five – out of – five** . The decision based on all five stations, if possible (i.e. in the middle part of the φ sectors).

2. **Case four – out of – five**. The decision based on four stations out of five (at the edges of the φ sectors). The positive decision is taken if in the mask register there is a combination for stations 0, 1, 2, 4 or 0, 1, 3, 4 or 0, 2, 3, 4.

The measuring arm is longer because we always require hits in stations MF0/MS0 and MF4/MS4.

3 Particle rates in the vertex

In order to estimate rates of particles produced at the vertex results of simulation with PYTHIA and ISAJET generators have been compared. The 80 mb cross section, 15 ns bunch spacing and 10^{34} cm^{-2}s^{-1} luminosity have been assumed. This gives 15 events per bunch crossing.

PYTHIA parameters have been tuned to reproduce UA1 minimum bias data [4]

```
MSEL      = 1     ! "min-bias"
MSTP (82) = 4
MSTP ( 2) = 2
MSTP (33) = 3
PARP (85) = 0.81
PARP (86) = 0.9
PARP (82) = 1.6
```

In total 10^6 events has been simulated. The p_T and η distribution of produced hadrons and prompt muons is shown in Fig. 2. It is seen that the rapidity spectrum in the interesting region is flat, thus the p_T spectrum can be regarded as rapidity independent.

The integrated (but not yet normalized) p_T spectrum of hadrons is drawn as full circles in Fig. 3a. It is seen that statistics above 20 GeV is not enough to enable accurate parametrization. In order to reduce fluctuations at the tail, 300 000 "hard" events with ${p_T}^{jet} > 40$ GeV have been simulated in addition. Then p_T spectrum of these events has been normalized to provide proper continuation of the minimum bias tail (Fig. 3b). Finally, a distribution to be parametrized, consist of minimum bias spectrum below 20 GeV and hard spectrum above.

After proper normalization the spectrum has been fitted with a following formula:

$$\frac{dN}{d|\eta|dp_T} = (1 + a_3x + a_4x^2)\mathrm{e}^{(a_1+a_2x)}$$

where

$$x = \log_{10}\ p_T\ [\mathrm{GeV}], \qquad a_1 = 21.66,\ a_2 = -12,\ a_3 = 3.6,\ a_4 = 32.4$$

and the distributions are given in [$\mathrm{GeV}^{-1}\cdot\mathrm{s}^{-1}$].

Result of the fit is plotted in Fig. 3c. Comparison of this parametrization with ISAJET results is shown in Fig. 3d. The procedure to obtain the ISAJET curve is described elsewhere [6].

Similar procedure has been done to parametrize prompt muon spectrum. However in this case it was necessary to simulate additional "intermediate" data set of $p_t^{jet} > 20$ GeV. It is illustrated in Fig. 4 a-d. In this case, the p_T spectrum is a lognormal distribution:

$$\frac{dN}{d|\eta|dp_T} = a\mathrm{e}^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

where

$$x = \log_{10}\ p_T\ [\mathrm{GeV}], \qquad a = 0.2434 \cdot 10^8,\ \mu = 1.565,\ \sigma = 0.5883$$

Agreement between ISAJET and PYTHIA is of the order of 50% which give us a feeling for the systematic precision of the Moncte Carlo hadron generators.

4 Single muon trigger efficiencies

4.1 Description of the simulation

The simulation was done using GEANT version 3.15 with CMS geometry (version 7b), including magnetic field map. Fluctuation of energy losses and multiple scattering were taken into account. To update the geometrical setup to current version of geometry (9a) we introduced small changes making stations MF2, MF3 and MF4 longer and MS4 shorter (see Fig. 1 for details).

4.2 Simulation and results

We generated muons with transverse momenta 3–99 GeV/c every GeV (97 values). For every value of the $\mathrm{p_T}$ we tracked 2500 charged muons (both signs) distributed flat in pseudorapidity interval $\mid \eta \mid < 1.0$ and 5000 (to increase statistics in forward regions) in the interval $1.0 < \mid \eta \mid < 2.6$. The detector was divided in ten parts in $\mid \eta \mid$, in each we found appropriate hit masks. Table 1 shows the pseudorapidity intervals and the set of station on which the decision is based.

Table 1: Pseudorapidity intervals and the set of stations on which the decision is based. There is a hole between MS1 and MF1 which we cover by MS0 even if only 4 stations are needed. The efficiency curves for a given interval are on indicated figures.

No.	pseudorapidity interval	Fig.	stations used
1	$\mid \eta \mid < 1.0$	5	(MS0), MS1, MS2, MS3, MS4
2	$1.0 < \mid \eta \mid < 1.1$	6	(MS0), MS1, MS2, MS3, MF3
3	$1.1 < \mid \eta \mid < 1.26$	7	(MS0), MS1, MS2, MF3, MF4
4	$1.26 < \mid \eta \mid < 1.39$	8	(MS0), MS1, MF2, MF3, MF4
5	$1.39 < \mid \eta \mid < 1.5$	9	MS0, MF2, MF3, MF4
6	$1.5 < \mid \eta \mid < 1.7$	10	(MF0), MF1, MF2, MF3, MF4
7	$1.7 < \mid \eta \mid < 1.9$	11	(MF0), MF1, MF2, MF3, MF4
8	$1.9 < \mid \eta \mid < 2.1$	12	(MF0), MF1, MF2, MF3, MF4
9	$2.1 < \mid \eta \mid < 2.3$	13	(MF0), MF1, MF2, MF3, MF4
10	$2.3 < \mid \eta \mid < 2.5$	14	(MF0), MF1, MF2, MF3, MF4

For each generated track we recorded hit strip numbers in every station. For each generated $\mathrm{p_T}$ and η interval we found the percentage of tracks with a particular hit pattern (one mask). In principle a set of valid masks for a given p_T^{cut} should contain all patterns created by tracks with $p_T > p_T^{cut}$. In reality, however, we accept only those with the total number of tracks larger than 2% of all with $p_T > p_T^{cut}$. This condition removes rare patterns created accidentally due to large fluctuations. By definition such set of masks provides a cut which is 98% efficient at $p_T = p_T^{cut}$.

The sets of valid masks were established for six arbitrarily chosen values of the $\mathrm{p_T}^{\mathrm{cut}}$ (10, 20, 30, 40, 60 and 90 GeV/c).

For each value of the $p_T{}^{cut}$ we computed a set of efficiency curves in all η intervals.

These curves are shown in Figs 5–14 a–d. The Figures a and b contain the curves for 'four–out of–five' and 'three–out of–four' cases. The Figures c and d contain the curves for the 'five–out of–five' and 'four–out of–four' cases.

The inspection of the efficiency curves shows that in some cases the mask sets for different values of the $p_T{}^{cut}$ are not very much different – the curves lie close together. This is especially visible in the pseudorapidity region around 1.2 – 1.5, (detector's corner) where we have to combine information from the barrel and forward chambers. It seems that an extra RPC plane in the forward region is needed in this area.

The efficiency curves in the barrel region (Fig. 5) for different values of $p_T{}^{cut}$ are reasonably steep and well separated in all four cases a – d.

In the forward region the steepness is less pronounced and the sensitivity to the cut is small. More studies are needed there.

4.3 Parameterization.

We found that efficiency curve $\varepsilon(p_T)$ can be well parametrized by the gaussian integral (Fig. 15):

$$\varepsilon = \frac{1 + erf(x)}{2}$$

where

$$erf(x) = \int_{-\infty}^{x} e^{-\frac{x^2}{2}} \text{ , } and \quad x = \frac{p_T - \mu}{\sigma}$$

.

We fitted this formula to each efficiency curve separately with two free parameters μ and σ.

The value of $p_T = \mu + \sigma$ corresponds to $\varepsilon \approx 92\%$. Thus we redefined the p_T^{cut} to be equal to $\mu + \sigma$ which is closer to the usual definition at 90% than 98% used in the previous chapter. Correspondence between the old definition and the new one is shown in Table 2.

Table 2: The old and new definitions of the $p_T{}^{cut}$ values.

p_T^{cut} for ε=98%	10	20	30	40	60	90	GeV
p_T^{cut} for ε=92%	10	17	26	35	45	70	GeV

The obtained curves are shown in Fig. 16 and their parameters in Fig. 17. We found that, for each rapidity region, σ depends linearly on the p_T^{cut}. This enables further simple parametrization:

$$\sigma = ap_T + b \ , \quad \mu = p_T - \sigma \ .$$

Values of fitted a and b are given in Fig. 17. The final parametrization of the efficiency curves is presented in Fig. 18.

5 Hadronic background

5.1 Simulation

To study background coming from initial hadrons we tracked them, taking into account produced secondary particles. We used program GEISHA, implemented into GEANT framework. Generated hadrons were distributed flat in pseudo-rapidity interval $|\ \eta\ | < 2.6$. To be close to reality we have generated mixture: 51.7% $\pi^{\pm}$; 28.1% $K_L^0, K_S^0, K^{\pm}$; 12.3% $p, \overline{p}, n, \overline{n}$; 3.2% $\Lambda, \overline{\Lambda}$; 3.4% $\Sigma^{\pm}, \overline{\Sigma}^{\pm}$; 1.3% $\Xi^-, \overline{\Xi}^+, \Xi^0, \overline{\Xi}^0$. Table 3 shows number of generated hadrons and initial hadron momenta.

Table 3: Initial hadron momenta and number of generated particles

Initial transverse momenta (GeV)	number of generated events
3, 3.5, 4, 4.5, 5, 5.5	60000
6, 7, 8, 9	75000
10, 12, 14, 16, 18	75000
20, 25, 30, 35	50000
40, 45, 50	40000
60, 70, 80, 90, 99.9	15000

5.2 Punchthrough and decay probability

The generated data were used to calculate the punchtrough and decay probability. Obtained results on punchtrough agrees quite well with the parametrization of the RD5 results [5]. The muons from the pion and kaon decay in the central cavity of the CMS were also taken into account.

In the Fig. 19 we show the combined punchtrough and decay probability as a function of the parent's hadron momentum. The two columns correspond to two rapidity regions: barrel on the left, forward on the right. The rows correspond to the different muon stations: MS0 (MF0) on the top, MS4 (MF4) at the bottom.

5.3 Muon contamination

We have calculated probability of finding a muon coming from hadron leptonic or semileptonic decay. There are two possibilities:

- Muons can come directly from the decay of generated hadrons. It may happen if initial hadron is a pion or a kaon. Such decays will generally occur before particle reaches electromagnetic calorimeter. They are called primary decays.
- It is possible, that initial hadron will interact strongly in the detector producing secondary pions or kaons which in turn decay to muons. Such decays are called secondary decays and they will generally occur after particle reaches hadronic or electromagnetic calorimeter.

Primary decays will occur most often for low energy pions and kaons. Muons from the primary decays have momenta comparable with those of initial hadrons. On the other hand, muons from the secondary decays have much smaller energies than generated hadrons, but they will occur for hadrons with the higher p_T.

In the Fig. 20 we show a probability of finding a muon. There are five pictures (MS/MF 0 at the top to MS/MF 4 at the bottom) in two columns - for barrel and forward case. On the vertical axes we marked the ratio of hadrons producing muons (with the range long enough to come to a given station) to number of hadrons producing any type of detectable (charged) particles in the station. The ratio is plotted versus transversal momentum of initial hadron. The muon finding probability decreases with increasing p_T of an initial hadron, except for very small transversal momenta. Our interpretation of that feature is that, for small momenta, the ratio of pions to neutrons decreases (due to ionization energy losses) and consequently the ratio of muons to charged particles is smaller. It is easily seen that in MS/MF 3–4, up to p_T = 100 GeV/c, the signal is dominated by muons coming, from primary and secondary decays. This is not true for the regions near the coil, where we mostly expect hadrons from punchthrough.

5.4 Hadron rejection efficiency

The final point of this section is to present hadron rejection efficiency of the trigger ie. the probability that an initial hadron will not give a trigger signal. The four – out of – four algorithm is used. We applied the same sets of masks for different p_T^{cut} values described in the section 4.2. Plots obtained are presented in the Fig. 21. The probability of trigger due to hadron is plotted for six p_T^{cut} values (top to bottom), for barrel and forward region (left and right column). The initial hadron transvers momenta are marked on abscissae.

6 Trigger rates

With the particle production rates in the vertex and trigger efficiencies for various pseudorapidity intervals one can calculate trigger rates. Figures 22 to 25 show differential and integrated muon rates in various η intervals. All plots in the left column present differential rates for six cuts discussed previously (Sec 4.2 and 4.3). The fout – out of – four algorithm discussed above is applied. The curve showing muon rates at the vertex is superimposed on each figure.

In the right column of each figure, we show integrated rates in each pseudorapidity interval. A histogram filled with dots shows integrated rates in one unit of pseudorapidity versus a cut number. The cut number (1 – 6) is a number of the curve from the differential plot. Each cut number corresponds to one curve. The hatched histogram presents rate of "false" triggers, ie. the rate of triggers produced by particles with p_T lower than p_T^{cut}. One can see that the region $1.26 < |\eta| < 1.5$ is critical and therefore station MS0 was in addition used here for the total trigger rates calculations.

Comparison of generated and triggered rates from various processes is presented in Fig. 26. Generated differential muon rates are shown in Fig. 26 a,b, and integrated ones in Fig. 26 c,d. Integrates trigger rates are shown in Fig. 26 e,f. Single muon rates are grouped in the left column whereas double muon rates are on the right.

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Figure captions

Fig. 1. Simulated detector setup.

Fig. 2. Generated $|\eta|$ and p_t distributions of hadrons and prompt muons.

Fig. 3. Parametrization of the p_t spectrum of hadrons (see text).

Fig. 4. Parametrization of the p_t spectrum of prompt muons (see text).

Fig. 5–14. Efficiency curves for muons, obtained using information from:

- **(a)** four stations out of five,
- **(b)** three station out of four,
- **(c)** all five stations,
- **(d)** four stations out of four.

Various figures corresponds to various η ranges.

Fig. 15. Function used to parametrized efficiency curves.

Fig. 16. Obtained trigger efficiency (points) and the parametrization of individual cuts (curve).

Fig. 17. Parameters of curves from Fig. 16.

Fig. 18. Final trigger efficiency parametrization.

Fig. 19. Punchthrough and decay probability in each station for pseudorapidity intervals $|\eta| < 1.0$ and $1.0 < |\eta| < 2.1$.

Fig. 20. Muon contamination in each station. Left column presents curves for barrel region, right one – for forward region.

Fig. 21. Trigger signal probability in case of initial hadron.

Fig. 22–25. Differential (left) and integrated (right) muon rates in various $|\eta|$ intervals.

Fig. 26. Muon trigger rates due to various processes:

- **(a)** differential single muon rates at vertex,
- **(b)** differential double muon rates at vertex,
- **(c)** integrated single muon rates at vertex,
- **(d)** integrated double muon rates at vertex,
- **(e)** integrated single muon trigger rates,
- **(f)** integrated double muon trigger rates.