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The RPC System for the CMS Experiment at LHC

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Abstract

The CMS experiment designed for Large Hadron Collider is briefly described. An idea of a muon trigger based on RPC is presented. This talk focuses on the requirements on RPC as the trigger detectors for the CMS. We discuss the required chamber's parformance and segmentation. Current design of the system fulfilling these requirements is presented. Its expected trigger performances are given.

1 CMS Detector

The abbreviation "CMS" stands for Compact Muon Solenoid [1]. It is a general purpose particle detector to be operated at Large Hadron Collider at CERN in Geneva. Its main parts are an inner tracker, calorimeters and a muon system (Fig. 1).

The inner tracker consists of silicon pixel, silicon microstrips detectors and microstrip gas chambers (MSGC). The electromagnetic calorimeter is a matrix of $PbWO_4$ crystals. The hadronic calorimeter is a copper/scintillator sandwich up to $|\eta| = 3$. At higher $|\eta|$ it is completed with a very forward calorimeter made of iron with quartz fibers as sensitive elements. The characteristic feature of the CMS detector is that the inner tracker and both calorimeters are contained within the large superconductive solenoid, 6 m in diameter and 13 m long. The coil creates 4 T magnetic field. Outside the coil the magnetic flux is returned by an iron yoke. The yoke is interleaved with 4 muon stations. Each barrel muon station consists of drift tubes (DT) and RPC's. Endcap muon stations are equipped with cathode strip chambers (CSC) and RPC's as well.

2 CMS Muon Trigger

At the highest LHC luminosities about 20-30 pp interaction occure every 25 ns. Basic goal of the CMS first level muon trigger is to reduce this rate (1 GHz) down to a level acceptable for the second level trigger. CMS have chosen a solution where the second and the third level trigger algorithms are performed by a farm of commercial processors. The farm is designed to accept 100 kHz input rate. The output rate of the first level is, however, assumed to be only ~20–30 kHz, leaving a large safety margin. After distributing this bandwidth among various calorimeter and muon triggers, about 6 kHz is left for a first level single muon trigger. In order to achieve this huge rejection factor (1 GHz $\rightarrow$ 6 kHz) it is not enough to recognize a muon. The trigger system should measure the muon momentum quite precisely in order to enable relatively sharp p_t cut.

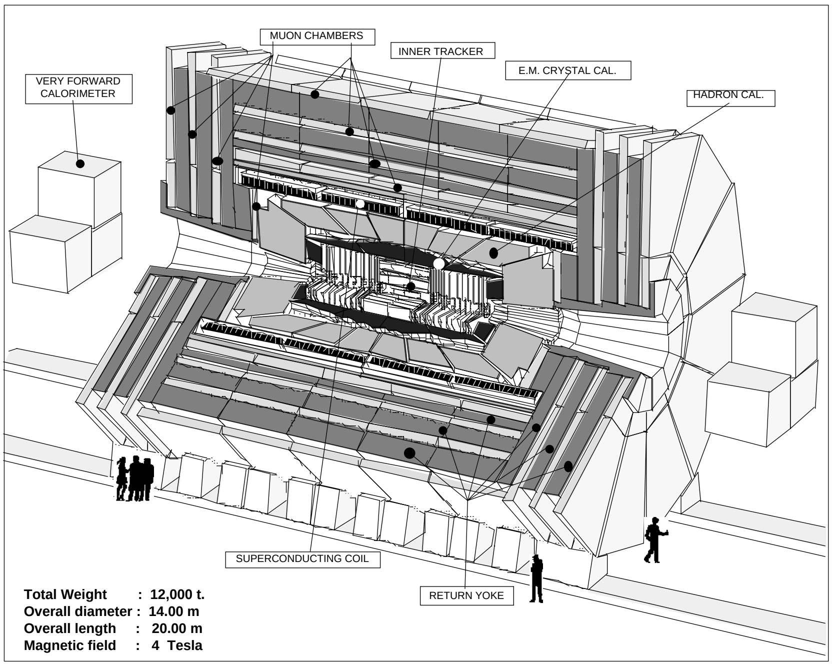

Figure 1: Layout of the CMS detector.

Another severe requirement is a bunch crossing identification. The recognised muon must be assigned to a given bunch crossing with accuracy better than 25 ns. This must include all possible jitters and time missalignments due to time of flight, detector response, signal propagation, clock distribution, etc.

The task of the muon trigger is especially difficult because of the presence of many kind of backgrounds. Punchthrough from hadronic showers, secondaries radiated by muons, backsplashes from very forward calorimeter and beam collimators, a beam halo and hits due to thermal neutrons may sum up to as much as 1 kHz/cm^2. Therefore the trigger system must be very robust.

In order to fullfill these requirements CMS has chosen to follow experiments running currently on hadronic beams (CDF, D0, H1, and Zeus) and use both precise moun chambers and fast dedicated detectors for the triggering purposes. Drift tubes in the barrel and cathode strip chambers in the endcaps provide track segments in each muon station with spacial and angular precision of 1–2 mm and 10–60 mrad respectively. However, having a long drift time ($\sim$160 ns for DT and $\sim$40 ns for CSC), they require rather complicated electronics to make correct bunch crossing assignment. Another drawback of CSC's and DT's is that the two spatial coordinates are given by long strips or wires. This may cause ambiguities in case of several tracks going throught a given chamber.

These drawbacks should be compensated by superior features of dedicated trigger detectors. They must be characterised by the excellent timing ($\sigma \sim 2$ ns) and high granularity. Current experiments, listed above, use scintillating counters for this purpose. The segmentation required at LHC (see the next section) makes this solution unpracticable because of technical and financial reasons. Therefore both LHC experiments ATLAS and CMS envisage RPC's in this place.

3 RPC Trigger Idea

The idea of the RPC based trigger for CMS is illustrated in Fig. 2. The solenoidal field bends tracks in the $r\phi$ plane. A pattern of hits recorded by RPC's carry the information about the bending, and can be used to determine p_t of the track. This is done by comparison with a predefined set of patterns corresponding to various p_t. Therefore we call this device Pattern Comparator Trigger (PACT) [4]. In this conference it is described in detail in a paper by A. Ranieri [2].

This idea has been practically tested in the RD5 experiment [3] especially designed to study various aspects of muon measurement and triggering at LHC detectors. Four RPC planes placed in the magnetic field simulating the CMS configuration (Fig. 4) have been connected to the PACT prototype build with programmable gate arrays ALTERA. Obtained efficiency curves are shown in Fig. 3. Details can be found in Ref. [4].

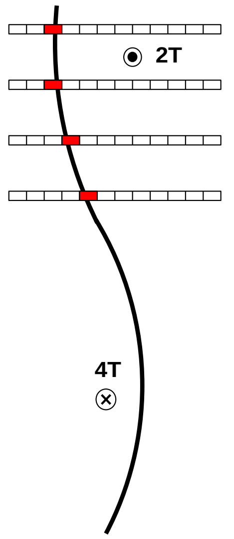

Figure 2: RPC trigger principle.

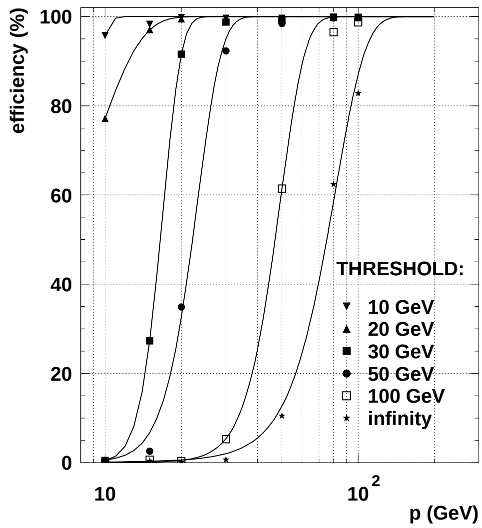

Figure 3: Results of PACT test in RD5.

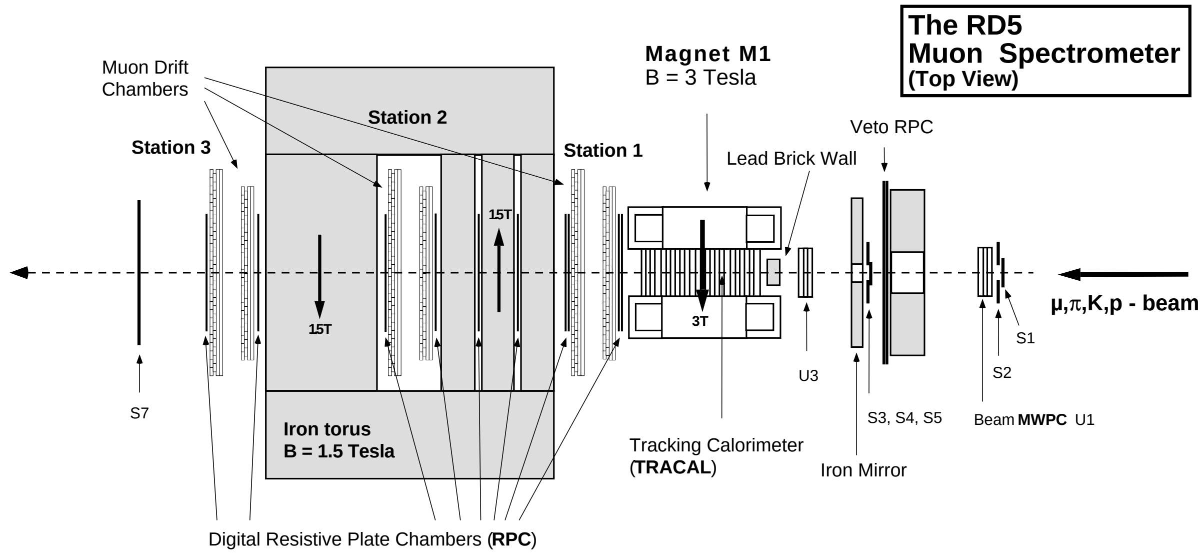

Figure 4: RPC trigger principle and its test in RD5.

4 Required Detector Granularity

Since the precision in ϕ determines momentum resolution, RPC are equipped with strips running parallel to the beam (along z) in the barrel and radially in the endcaps. The crucial point in the design of the RPC system is the choice of detector granularity. Possible factors to be considered are listed in Tab. 1. Dominant upper and lower limits are marked with $\Downarrow$ and $\Uparrow$ respectively.

Let us discuss the dominant factors one by one.

4.1 Track Bending and Strip Width

In order to maintain the single muon trigger rate at the level of a few kHz for luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ one should apply $p_t^{cut} \approx$ 20-30 GeV (see Sec. 7). Having in mind necessary safety margin one can require that the highest possible p_t^{cut} should be somewhere between 50 and 100 GeV. It has been found that this is possible with with strips $\Delta\phi \approx 1/3°$ which corresponds roughly to 2-3 cm in the inner muon stations (MB1 and MB2) of the barrel. This can be seen from the formulas collected in Fig. 5.

Table 1: Determination of the RPC granularity

Strip width ($\Delta\phi$)	
track bending (required momentum resolution)	$\Downarrow$
multiple scattering and energy losses	
cluster size	
Strip length ($\Delta\eta$)	
signal propagation time along the strip (bunch cross. assign.)	$\Downarrow$ *barrel*
change of the bending with η	$\Downarrow$ *endcaps*
change of η due to the non-$r\phi$ bending	
Strip area (number of strips)	
number of channels (cost)	
complexity of the trigger processor (feasibility)	$\Uparrow$
number of interconnections (feasibility)	$\Uparrow$
capacitance	
occupancy	
probability of random coincidences of background hits	$\Downarrow$ *endcaps*
mechanics of the chamber	

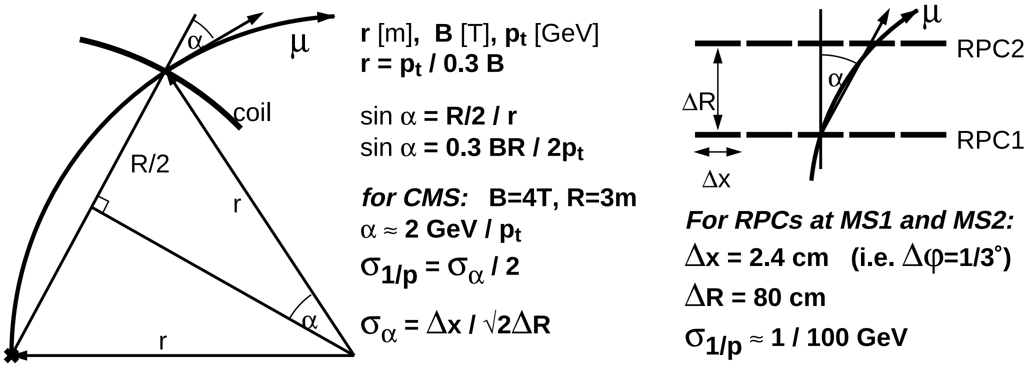

Figure 5: Momentum measurement in the solenoidal field of CMS.

The obtained $\sigma_{1/p_t} \approx 1/100$ GeV means that a 50 GeV track is measured by two stations with precision $-17/+50$ GeV and a 100 GeV one with $-50/+\infty$. This is confirmed by a detailed GEANT simulation as shown in Fig. 6. It shows the track bending measured by $\Delta\phi$ expressed in one strip units. It is seen that the 50 GeV track can be easily distinguished from the straight (infinite p_t) tracks, whereas the 100 GeV one can be distinguished neither form 50 GeV nor from infinite p_t tracks.

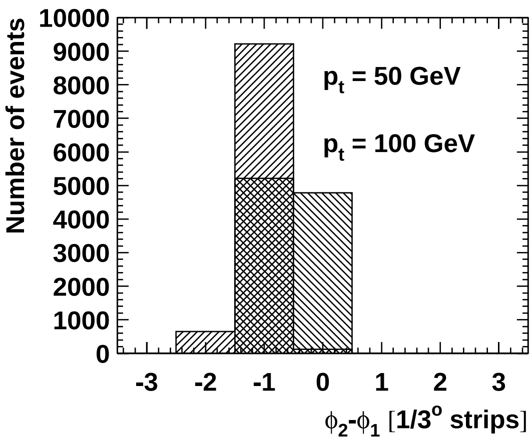

Figure 6: a) Bending angle measured by the first two muon stations.

This can be still improved by using more muon stations. One can use the overlap of 50 and 100 GeV distributions as a measure of this improvements. It is plotted in Fig. 7a which shows that it saturates above 5 planes. On the other hand one should watch the complication of the trigger logic. It can be expressed in terms of the number of possible patterns associated with one strip, which is shown in Fig. 7b. This number grows exponentially with the number of measuring planes. The two figures justify the actual choice of 4 RPC planes used for the CMS trigger.

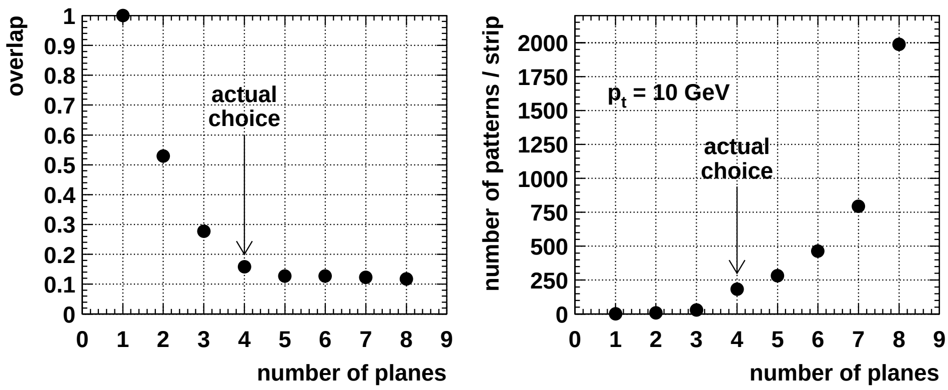

Figure 7: a) p_t resolution expressed as an overlap of 50 and 100 GeV distributions. b) Complication of trigger logic presented as a number of patterns per strip.

Another reason for having 4 muon stations is a need for some redundancy. One station can be lost from the measurement because of dead areas, electromagnetic showers caused by radiating muons or punchthrough from hadronic showers. These phenomena have been extensively studied in the RD5 experiment [3]. Two example events are shown in Fig. 8.

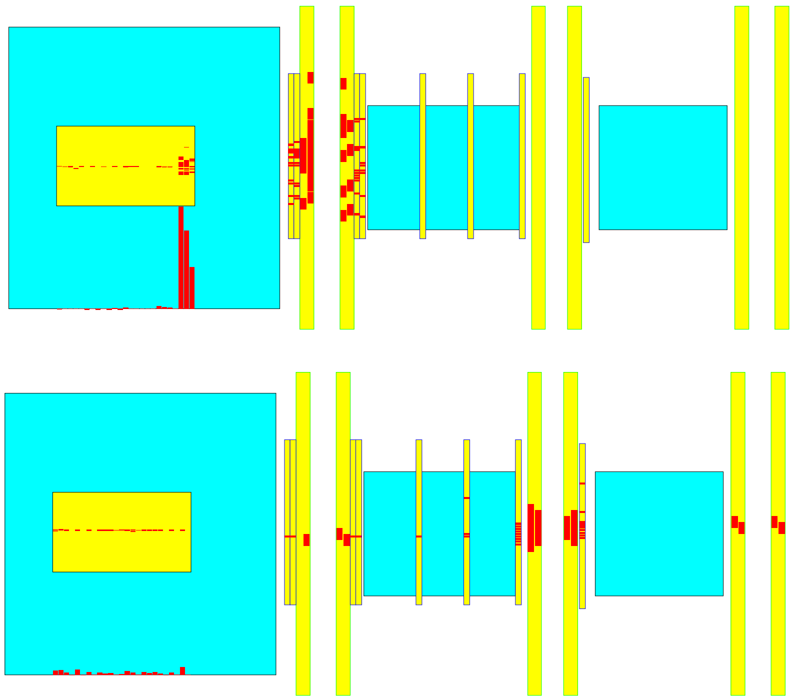

Figure 8: Events observed in RD5. One station is useless for momentum determination because of large number of hits due to a) punchthrough from a 20 GeV π b) electromagnetic shower from 300 GeV μ.

Experience gained in RD5 is widely used in the design of the CMS trigger. It will be based on 4 RPC planes requiring a coincidence of 3 out of 4 planes. It has been shown [5] that trigger performance is not afected by dead spaces if the "3 out of 4" acceptance approaches 100% and the "4 out of 4" one is not smaller than 80%.

4.2 Track Bending and Strip Length

The bending power $\int |B \times dl|$ of the CMS magnet in the barrel is constant and equal 17 Tm. In the endcap however it decrease down to 8 Tm at $|\eta|$=2.0 and to 6 Tm at $|\eta|$=2.4 . Therefore particles of a given p_t are bent differently at different $|\eta|$. This is shown in Fig. 9 where the bending measured by $\Delta\phi$ between the first two stations is expressed in one strip units. The bending angle $\Delta\phi$ significantly depends on $|\eta|$. Thus one has to know $|\eta|$ in order to determine p_t from the $\Delta\phi$ measurement. From Fig. 9 one can see that precision of the order of 0.1 η-unit is needed, which determines the maximal length of the strips.

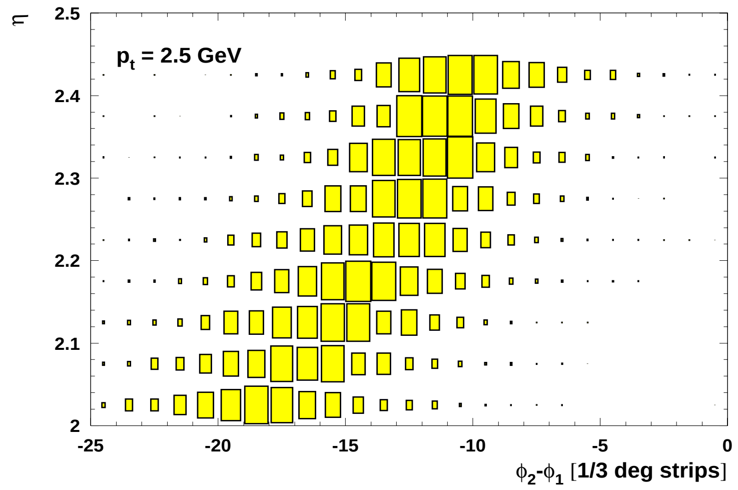

Figure 9: In the endcaps the track bending $\Delta\phi$ depends on $|\eta|$.

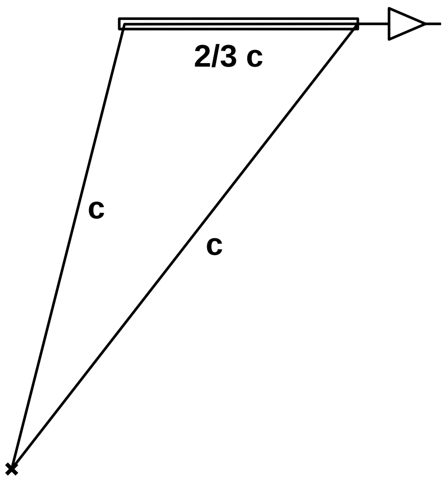

Figure 10: Uncertainty due to the time of flight and the signal propagation along the strip.

4.3 Time of Flight and Signal Propagation

Muons emitted at different η cross a given RPC strip at different positions. Therefore they have different time of flight and different time is needed for signals to propagate along the strip to an amplifier. Fig. 10 shows two extreme cases. If we require this time spread not to dominate the bunch crossing assignment precision it should not be much longer than 5 ns. This means, that the strip length should be of the order of 1 m or shorter (assuming $\frac{2}{3}c$ for the signal propagation speed).

4.4 Random Coincidences of Background Hits

The single hit rate of RPC in CMS is dominated by random hits due to soft neutrons and photons [6]. In the barrel it stays at the level of 1-10 Hz/cm^2 and it should not cause any problems. In the endcaps it is quite uniformly distributed if expressed in $\eta\phi$ coordinates [7]. Therefore projective geometry has an advantage that the rate per one RPC strip is roughly constant. For strips of $\Delta\phi = 1/3^\circ$ and $\Delta\eta = 0.1$ it is about 6000 Hz per strip[8]. This corresponds to $\sim$ 30 hits per bunch crossing in the whole detector at high luminosity.

Those hits can affect the trigger rates in two ways. Random coincidence of three such hits in different stations can cause false trigger if they are by chance aligned along a possible muon track. A coincidence of a single background hit with hits of low p_t, curved muon track can look like more straight track and thus increase the apparent muon momentum. These two contributions (denoted as "n" and "μ/n" respectively) are compared with prompt muon rates in Fig. 13c. The "n" rate is proportional to the third power of the number of background hits per strip because the trigger is based on "3 out of 4" coincidences. Therefore increasing the size of the strips by factor e.g. 2 would increase the trigger rate by factor 8 and damage seriously the safety margin.

5 Requirements on the RPC Performance

5.1 Chamber Efficiency

Since the trigger relay on coincidence of several RPC planes, each of them must be very efficient. We set our target at 98%. This can be ensured by use of double gap chambers with staggered spacers.

5.2 Timing

Unambiguous bunch crossing identification requires trigger gates to be open for less then 25 ns. Leaving some margin for electronics set up time etc. one can assume 20 ns for this length. Another 5 ns should be subtracted for the signal propagation discussed above. Thus only 15 ns is left for the intrinsic RPC jitter. The precise requirement may be that: 98% of events should stay within 15 ns wide window. In practice it corresponds roughly to $\sigma \sim 2$ ns, but the tails are important.

5.3 Clusters

A sigle minimum ionising particle often causes signals from several adjacent strips to pass a discriminator threshold. This leads to deterioration of the momentum measurement. Therefore, one should require that the average cluster size is not bigger than 2 strips and that the fraction of events with clusters having more than 4 strips do not exceed 1%.

5.4 Rate Capability

Hit rates expected in CMS have been estimated using three different Monte Carlo programs: Fluka [9], Mars [10], and Gcalor [11]. A sample of results is shown in Tab. 2. One cannot say which program is the best one because they have different advantages and drawbacks. One can only expect that the systematic errors are of the same order as differences between the programs. In order to stay on the safe side we took the most pessimistic estimate and we applied a safety factor of 2. The derived requirements on the rate capability are summarized in Tab. 2.

Table 2: Expected and required RPC hit rates

muon station		expected rate (Hz/cm^2) Fluka	Mars	Gcalor	required rate (Hz/cm^2)
MB1-3		1	–	–	100
MB4		10	20	–	
MF1	$\|\eta\| = 2.1$	200	600	700	1500
MF2-4	$\|\eta\| = 2.1$	20	60	300	
MF1	$\|\eta\| = 2.4$	800	1300	1800	3000
MF2-4	$\|\eta\| = 2.4$	100	300	900	

Assuming uniform technology for the entire endcap one should aim for the most demanding conditions, i.e. those at MF1. However, it should be investigated whether using different technology for MF1/1 and relaxing requirements (by factor 2) for other MF chambers, may result in significant cost savings and/or a more robust design. The limit for $|\eta| <2.4$ is to remind us that the eventual upgrade requires more performing detectors.

6 Geometrical Layout of the RPC System

As a result of the optimisation process described in Sec. 4 we have chosen approximately projective geometry with strips of width $\Delta\phi \approx 1/3^\circ$ and length $\Delta\eta \approx 0.1$. Precise dimensions of the chambers as well as single strips are given in Fig. 11. The strip width of $\Delta\phi = 1/3^\circ$ would result in having 90 strips per chamber. We have decided to have 96 strip, i.e. $\Delta\phi = 5/16^\circ$ instead, in order to facilitate the design of digital electronics.

Each muon station will be equipped with one double gap RPC except two innermost barrel stations MB1 and MB2 which will contain two RPC planes. This is because low momentum muons (p_t <6-8 GeV) cannot reach the outer stations, for which a special low p_t trigger is foreseen. This trigger will be again based on 4 planes: 2 in MB1 and 2 in MB2. This is not necessary in the endcaps where the same

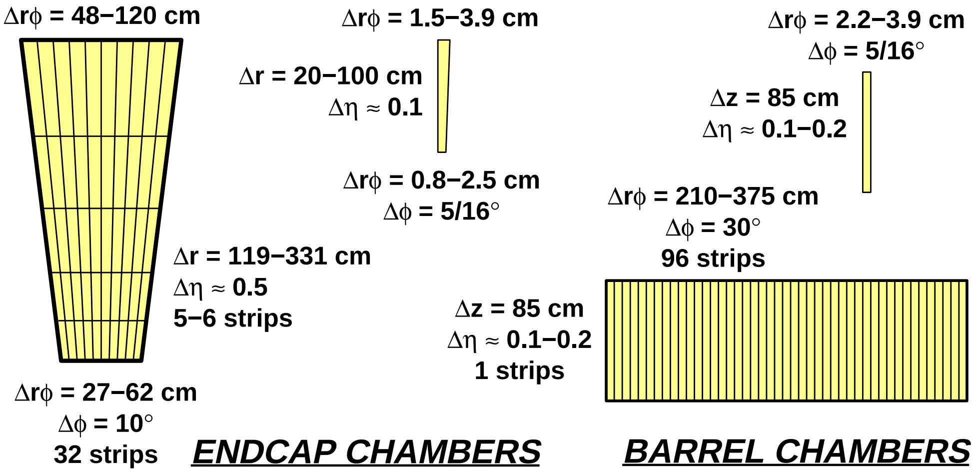

Figure 11: Dimensions of RPC chambers and strips.

p_t corresponds to much higher total momentum. Finally, the low p_t reach of the CMS muon trigger will be about 4 GeV in the barrel and 2.5-3.5 GeV in the endcaps.

In total there will be 1656 RPC' in CMS covering the area of 3400 m^2. They will be read out by about 200 000 electronics channels.

7 Summary

The RPC system of the CMS detector is designed to provide an efficient and robust muon trigger. The main advantage of the RPC detector is that all the coordinates ϕ, η and t are given by the same signal so no ambiguities can arise. The superior time resolution of RPC allows us to use adjustable trigger gates shorter than 25 ns, which enables straightforward bunch crossing identification and can largely reduce an "out of time" or random background. Muon momentum measurement is done by a programmable algorithm which can be easily adopted to actual running conditions. In addition, the RPC information can be used offline for solving pattern recognition ambiguities especially in the endcaps, where the CSC strips are 6 times longer than the RPC ones.

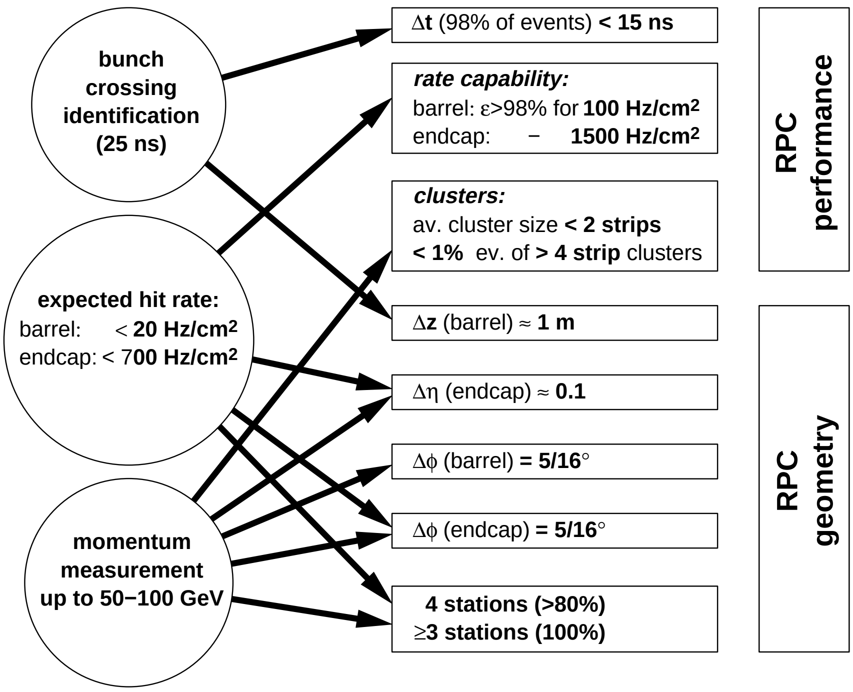

Figure 12: Driving requirements on the RPC system for CMS.

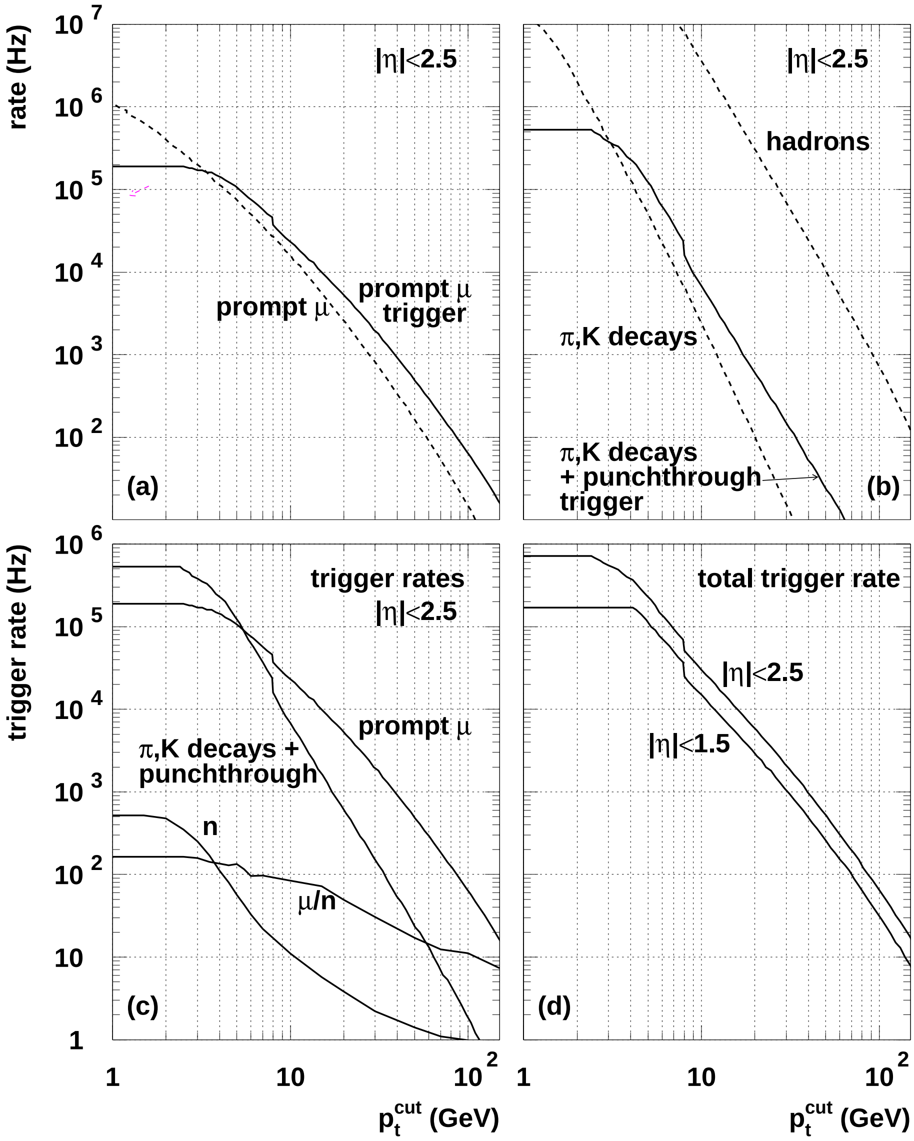

Figure 13: Single muon trigger rates in CMS.

Main requirements discussed above are summarised in Fig. 12. The final trigger performance in shown in Fig. 13 where various signal and background rates as the functions of the p_t threshold are compared. Fig. 13a shows the rate due to prompt muons. The trigger rate is higher at high p_t because of its limited momentum resolution. The very low p_t muons are absorbed by the calorimeters and the iron yoke. The top dashed curve at Fig. 13b shows the hadron rate at the vertex. Some of the hadrons decay into muons (lower dashed curve) some others may give punchthrough. Resulting trigger rate is again indicated as a solid line. These two contributions are compared in Fig. 13c with the random coincidences of single hits (denoted as "n" for "neutrons") and mixtures of muon and background hits (denoted as "μ/n"). Finally the total trigger rates at L=10^{33} and 10^{34}cm^{-2}s^{-1} are shown in Fig. 13d.

It should be stressed that the ultimate low p_t reach is determined only by the amount of the absorber, and is as low as 4 GeV in the barrel and 2.5-3.5 GeV in the endcaps. The actual threshold values will be chosen depending on current running conditions and physics priorities.

8 References

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