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Synchronization of the CMS Muon Detector

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Abstract

Precise synchronization is crucial for the functioning of the CMS Muon Detector. In this paper we first discuss the possible sources of data misalignment, like variations in particle time of flight, signal formation and propagation within a detector (e.g. drift time), connections between various elements, set-up times and jitters of digital electronics. Then we review several methods which can be used to synchronize the system for the first time and to maintain the synchronization over a long period of time. Finally we discuss in detail a possible application of those methods to the Resistive Plate Chambers. We also briefly discuss the cases of Drift Tubes and Cathode Strip Chambers.

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1 Trigger synchronization

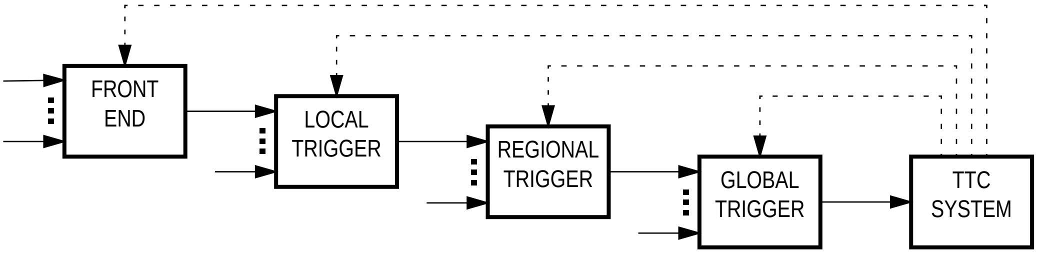

Figure 1: Generic trigger structure.

The CMS Trigger System has a tree-like structure which is schematically shown in Fig. 1. The data flow through the entire chain should be synchronous, driven by the 40.08 MHz clock. Let us consider simplified signal flow diagram of the CMS Trigger shown in Fig. 2 with only one trigger device (e.g. Local Trigger) indicated.

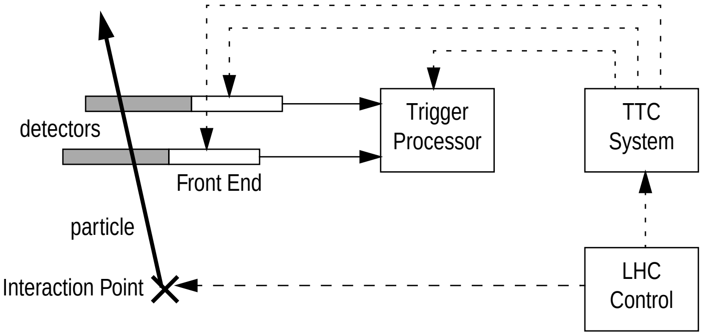

Figure 2: synchronization with real data and test data.

The LHC Control system determines the interaction moment by driving RF and magnet currents (dashed line). Its clock is distributed by the TTC system [1] to Front End and Trigger electronics (dotted line). Particles created at the Interaction Point are flying towards detectors (thick solid line). Generated detector signals are sent from the Front End boards to the Trigger Processors (thin solid line). The following requirements have to be fulfilled:

- incoming data should be in phase with the local clock — **clock phase adjustment**
- data from different sources should correspond to the same bunch crossing (b.x.) — **relative b.x. synchronization**
- the data should correspond to the b.x. given by the local TTCrx — **absolute b.x. synchronization**

Phase adjustment at digitisation

Analog signals from the detectors have to be in a right phase with respect to the clock in order to be correctly digitized and processed. The signals often have a jitter due to time of flight, detector response and the signal propagation.

Phase adjustment of digitized signals

Once the signals are digitized they have no jitter, except for the electronics jitter which is usually below 1ns. However, when the signals are sent to another board they might have a constant shift in phase in respect to the local clock at the destination. The rule to be followed is

synchronize the phase of the signal
at the <u>destination</u> to the <u>local</u> clock.

In order to synchronize the system one can use **real data** or **test data**. The first iteration, however, should be done **without data**, by measuring and calculating all the delays in the system. Test data provide an efficient way for partial synchronization of the system. However, final synchronization can only be done with real data, because there is no other way to measure precisely the path

LHC Control → Interaction Point → particle flight → detector → Front End.

1.1. Synchronization without data

All particle and signal paths should be measured or calculated. Corresponding time differences should be compensated either by cutting the cables or by adjusting programmable electronics delays. It should not be too difficult to achieve precision better than 5ns, which corresponds to ~1m of cable. Special care should be taken with TTC fibres. Good knowledge of their length will facilitate synchronization with test data.

1.2. Synchronization with test data

Relative synchronization

Test patterns should be generated at the source (e.g. Front End board) and transmitted on request broadcasted by the TTC. At the destination (e.g. Trigger Processor board) they should be compared to the generated ones. Let us consider a simple example — a sequence (00100) sent through all channels. The same sequence should be observed at the destination, namely the “1” should come at the same time, defined by the bunch crossing number provided by TTC. If in one of the channels, the “1” was observed e.g. one bunch crossing later, it means that this channel is delayed by one b.x. in respect to others.

Absolute synchronization

Test data can be used for absolute synchronization of data to the LHC clock at the destination if the absolute synchronization was already done at the source. Before using real data this can be done only approximately, taking the LHC clock and bunch crossing number provided by TTC at Front End as a reference. Precision of this method is limited by the knowledge of all delays in the TTC network. The main purpose of this procedure is to setup the system, so it can fully operate with test data. In this way trigger hardware and algorithms can be tested before the LHC beam is available.

Generated test pattern should unambiguously mark one b.x. Let us denote by N its number given by the TTC at the source. Again one can use the sequence (00100) as an example. The “1” should be sent in bunch crossing N. The delay of the signal or the TTC clock at the destination should be adjusted in such a way, that the “1” is received in b.x. N, according to the local TTC.

1.3. Synchronization with real data

The LHC frequency of 40.08 MHz corresponds to a 25ns period. One LHC orbit consists of 3564 periods. They are often call “bunches” although some of them do not contain protons. The proton bunches are grouped in 35 trains, 81 bunches each. The structure of gaps between them can be used for the absolute synchronization [2],[3]. Events containing data in a given detector region (e.g. a muon hit in a given RPC) are histogrammed according to the b.x. number (mod 3564). Accumulated histogram can be compared to the expected bunch structure. The same method can be used for relative synchronization of two channels by comparing their histograms.

Special synchronization run

A special run dedicated to the synchronization might be very useful. It may differ from a normal physics run:

- special LHC bunch structure (e.g single, separated bunches) can be set up
- different trigger and DAS partitions can be run independently in order to facilitate internal synchronization of each one
- trigger algorithms may run in a “loose” mode to collect needed statistics in a shorter time
- DAS partitions may run in special modes, e.g. without zero suppression, reading out several consecutive b.x.

Normal physics run

During a normal physics run one can perform synchronization with both test data and real data. The gaps in the LHC bunch structure, especially the *Abort Gap* of 3.17 µs at the end of the orbit, can be used for sending test data. Real data can be used to accumulate timing histograms, as described above. They can also be used to monitor the synchronization by observing efficiency maps of the trigger, because desynchronization of a certain part of a system will very probably result in efficiency loss in corresponding region.

2 DAQ synchronization

Two places are crucial for synchronization in the DAQ chain

- phase adjustment at Front End
- trigger - data matching at the end of DAQ pipelines

The first item was discussed in the previous section, so we concentrate here on the second one. Data in a given DAQ channel are waiting for the LV1 decision in the pipeline. They are read out from the end of the pipeline if there was a positive LV1 response. The “LV1 Accept“ corresponding to a given b.x. has to match the data from the same b.x. This can be achieved by delaying the “LV1 Accept“ or adjusting the length of the pipeline. The value of the delay can be established using one of the following methods.

Multi-crossing readout of real data

This method is especially suitable for low occupancy detectors participating in the trigger, e.g. RPC, CSC and Drift Tubes. A given detector region is read out if there was a “LV1 Accept“ caused by the data from this region. Several consecutive b.x. are read out in order to discover a possible misalignment of data with respect to “LV1 Accept“. High occupancy may disturb this method if probability of having data in consecutive b.x. is high.

Multi-crossing readout of test data

This method is suitable for any detectors participating in the trigger, i.e. muon detectors and calorimeters. A test pattern causing a trigger is generated in a certain detector region. The data from this region, covering several consecutive b.x. are read out in order to discover a possible misalignment of data with respect to “LV1 Accept“.

Histogramming real data

This method is similar to the trigger b.x. synchronization with real data (Sec. 1.3). Whenever there was a trigger, the data are stored in a histogram according to the b.x. number given by the trigger. Possible misalignment can be detected comparing obtained histograms to the LHC bunch structure. This method can be used by any detector, not necessarily participating in the trigger, e.g. by the tracker. High occupancy is of advantage in this method, because needed statistics can be collected faster.

3 Optical links

Special attention should be given to 1 GHz optical links connecting the detector with the counting room. In addition to the problems discussed above an internal synchronization of each link should be maintained. The first symptom of any synchronization problem will probably be higher bit error rate. Therefore, the data must be accompanied by an error detection code. Every time an error is detected the resynchronization procedure should be invoked. More detailed discussion of this problem can be found in [2] and [3].

4 Muon rates

Proton-proton interactions provide the only way to make the absolute synchronization. Unfortunately the rate of muons, especially in the barrel, is very low. On average less than 1 muon per 1000 pp interactions enters the first barrel station MB1 and a few times less enter the last one MB4. At luminosity $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ the muon rate at MB4 of about 6 $\mathrm{Hz/m}^2$ is expected. The area of MB4 RPC is $1.28{\times}3.75\mathrm{m}^2 \approx 5\mathrm{m}^2$. Similarly, the area of the smallest Drift Tube chamber at MB4 (the one in the CMS leg) is $2.52{\times}2.0\mathrm{m}^2 \approx 5\mathrm{m}^2$. This gives ~30Hz per chamber, i.e. ~1800 muons / minute / chamber.

In the endcap the rate expressed in $\mathrm{Hz/m}^2$ varies rather fast with rapidity. Therefore, it is more useful to quote the rate per η-unit. The lowest rate will be seen by the CSC ME1/3, which is 10° wide and covers η=0.88-1.14. In this region the muon rate is about $4{\cdot}10^4$Hz/η-unit, which results in 300Hz/chamber. This is 10 times higher than in the case of RPC and Drift Tubes, therefore later in this paper we consider only the RPC/DT rate, as the worst case.

4.1. Relative synchronization

In order to make the relative station-to-station synchronization one can use all muons traversing a given detector region. It can be assumed that all channels of one chamber are aligned in time by construction with a precision better than 1ns. In such a case one needs to collect ~1000 μ per chamber. This can be done in 1 minute.

4.2. Absolute synchronization

Absolute synchronization can be done only with muons from isolated (at least from one side) bunches. Running with only one bunch in the machine would reduce the lu-minosity by factor ~5000 to the level of $2{\cdot}10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In such a case only 20 μ / hour / chamber are expected, i.e. 50 hours are needed to collect 1000 μ / chamber.

Much better solution is to run with the full available luminosity, e.g. $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and make use of the LHC bunch structure. For the absolute synchronization only the first or last bunch in each train can be used. Hence ~1% of muons is useful. This gives an effective rate of 0.3Hz / chamber, i.e. 1000 μ / hour / chamber. It does not sound unreasonable.

The most effective configuration should have single bunches of protons separated by several “empty bunches”. For example 1 bunch of protons followed by 4 “empty bunches” would give the muon rate of ~6Hz per chamber, i.e. ~360 μ / min / chamber. In such a case 3-5 minutes would be enough to collect reasonable statistics.

4.3. Background

Synchronization with muons can be disturbed by the presence of background. There are two major kinds of background to be considered

- electrons — mainly from thermal neutron capture followed by γ emission and conversion,
- charged hadrons — mainly due to punchthrough from hadronic showers and backsplashes from the forward calorimeter (HF).

The single hit rate due to neutrons ($n\to\gamma\to e$) is 1-3 orders of magnitude higher than that of muons. CSC and Drift Tubes are able to eliminate this background by local coincidence of several layers in one chamber. The relative timing of those layers is ensured by construction, so the synchronization is not affected. The case of RPC is more difficult, because there is no local coincidence within one muon station. The only place when the neutron background can be suppressed is the Patter Comparator processor, looking for coincidence of at least 3 RPC planes. This implies that the RPC synchronization with real data (Sec. 1.3) must involve the trigger. That, in turn, means that the first iteration, done without the beam (Sec. 1.1 and Sec. 1.2), should be precise enough to enable trigger to work with at least 10% efficiency and thus to make the relative synchronization (Sec. 4.1) in <10 min.

The rate of charged hadrons is of the same order as the rate of muons. Charge hadrons can traverse several CSC or DT layers and satisfy the local trigger coincidence. However they often come in time, so their presence helps, rather than disturbs the synchronization process. Those created in HF can come 1 bunch crossing later. Their number, however, is too small to cause any synchronization problems.

5 RPC PACT synchronization

5.1. PACT block diagram

Block diagram of the RPC PACT is shown in Fig. 3. Each chamber is equipped with *Front End Boards* (FEB) containing *Front End Chips* (FEC) with preamplifiers and discriminators. The signals are shaped and aligned with the clock by the *Synchronization Unit* (SU). Signals from several Front End Boards are collected by a *Link Board* (LB) through twisted pair cables, up to 3 m long. Then, the data are compressed (LMUX) and transmitted (TX) through optical fibers to the Counting Room. Here the data are split into two streams. The trigger stream data are decompressed (DEMUX) and processed by *Pattern Comparator* (PAC) processors. Recognized muon candidates are sorted according to their transverse momentum p_t and sent to the *Global Muon Trigger*. The DAQ stream data are stored, event by event, in pipeline memories (PIPE). Events selected by *Level 1 Trigger* (LV1) are derandomized (DRND) and sent by *Front End Driver* (FED) to the DAQ system.

Main elements important for synchronization are also marked on the diagram. Synchronization Unit (SU) consists of WINDOW electronics for phase adjustment and *Synchronization Buffer* (SBUF) for b.x. synchronization. Synchronization with test data is done by test data generator (TEST DATA) and error detection circuit (CHECK). The TTC network is also shown. There is one TTCrx per Link Board and one per each crate in the Counting Room.

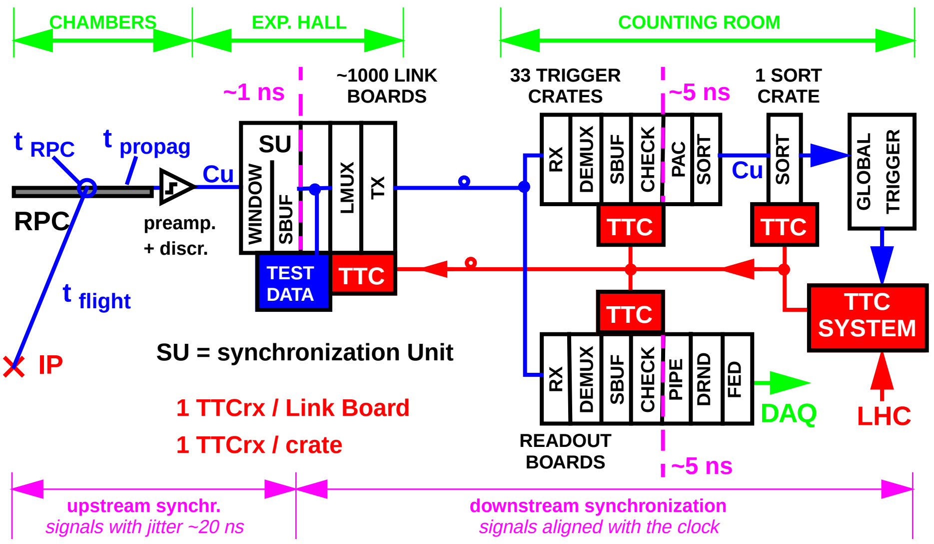

Figure 3: Block diagram of the RPC PACT.

5.2. PACT timing

From the timing point of view the RPC PACT system consists of two distinct parts:

- *upstream* — before Synchronization Unit — signals are randomly spread in time with a jitter of ~20 ns,
- *downstream* — after Synchronization Unit — signals are aligned with the clock.

Since the downstream part is very similar for all detectors we discuss in this section only the upstream one.

The total signal propagation time in the upstream part t_{up} has four components

$$t_{up} = t_{flight} + t_{RPC} + t_{propag} + t_{preamp}$$

The time of flight t_{flight} is different for different chambers. It varies from 4m/c = 13ns for station MB1, to 12.6m/c = 42ns. More important is variation within one chamber. The worst case is MB/2/1. The strip length of 1.26m causes the flight path variation of 1m and the time of flight variation Δt_{flight} = 3.5ns. The differences between various chambers can be corrected by adjusting the length of cables or electronics delay. The variation within one chamber cannot be corrected and it should be considered as a random jitter.

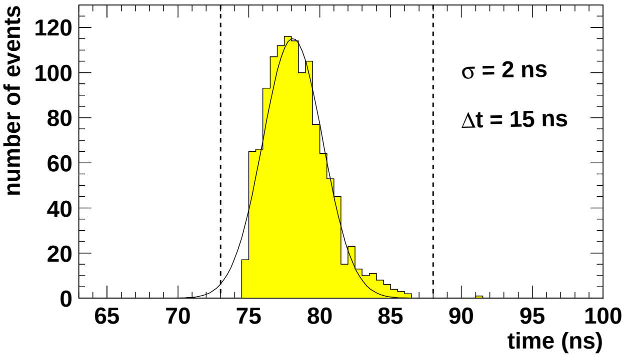

Figure 4: Typical distribution of the RPC response time t_{RPC}.

Second contribution is the time of intrinsic RPC phenomena: ionization, avalanche formation, drift to electrodes and pulse formation — denoted all together by t_{RPC}. It has quasi-gaussian distribution with σ = 1-5ns. An example is shown in Fig. 4.

The third contribution is signal propagation along the strip t_{propag}. The signal induced on the strip at the particle impact point propagates towards the preamplifier with velocity of about 2/3 of c, i.e. ~0.2m/ns. The propagation time varies from 0 to *max* t_{propag}, which for the longest strips of 1.26m is ~6.3ns. One cannot correct for it online and from the trigger point of view it should be considered as having approximately flat random distribution. However, one can achieve partial compensation of Δt_{flight} and Δt_{propag} by a proper placing of the amplifier (see Fig. 5), such that

$$\Delta(t_{flight} + t_{propag}) = (min\ t_{flight} + max\ t_{propag}) - max\ t_{flight} < \Delta t_{flight} + \Delta t_{propag}$$

In the worst case of MB/0/1 the combined variation $\Delta(t_{flight} + t_{propag})$ = 5.7ns.

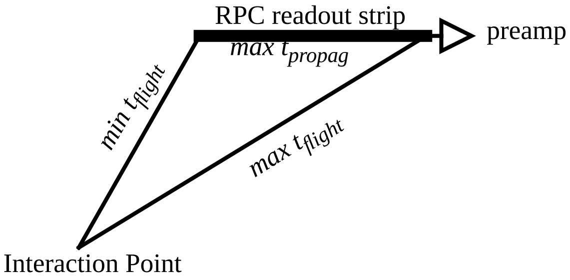

Figure 5: Partial compensation of time of flight Δt_{flight} and signal propagation along the strip Δt_{propag}.

The contribution from preamplifier and discriminator jitter Δt_{preamp} is usually much smaller than 1ns. Moreover, it is difficult to distinguish it experimentally from the intrinsic RPC jitter Δt_{RPC}. Therefore, the measured value of Δt_{RPC} often contains Δt_{preamp}, and we will follow that convention in this paper.

The total jitter of the upstream part Δt_{up} must be lower than 25ns in order to recognize the bunch crossing. We have seen that is has two major contributions: $\Delta(t_{flight} + t_{propag})$ and Δt_{RPC}. Assuming 1-3ns for the setup time of the synchronization electronics and taking the worst case of $\Delta(t_{flight} + t_{propag})$ = 5.7ns, one gets 15-18ns remaining for Δt_{RPC}. In the case of gaussian distribution this would correspond to $\sigma_{RPC} < 3.0$-3.5ns with 99% efficiency. This requirement is fulfilled by recently tested RPC prototypes (Sec.5.9 of [4]).

5.3. Synchronization Unit

The Synchronization Unit (SU) is an integrated circuit which shapes the detector signals and aligns them with the LHC clock. It is done in the following way (see Fig. 6). From the LHC clock (denoted as CLOCK) provided by the TTCrx, a WINDOW signal is derived. Its width and phase can be adjusted from 0 to 25ns with 1ns step. They should be adjusted in such a way, that the rising edge of INPUT from the detector is always within the high level of WINDOW. The WINDOW should be wide enough to contain the jitter Δt_{up}. The coincidence of the WINDOW signal and the rising edge of the INPUT generates the OUTPUT signal which is 25ns wide and is in phase with the CLOCK. The OUTPUT might be delayed by 0-3 clocks using Synchronization Buffer (SBUF).

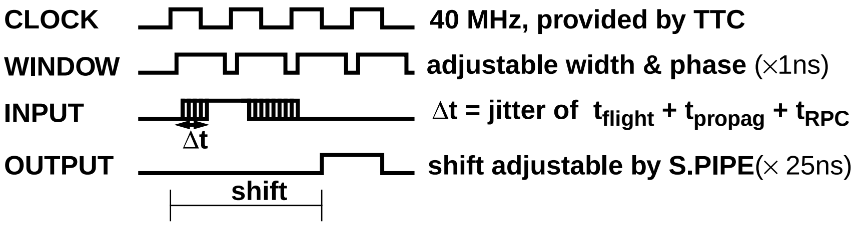

Figure 6: Timing in synchronization Unit.

5.4. PACT synchronization procedures

All the methods described in Sec. 1 will be used for setting and maintaining the synchronization of PACT. The full sequence of actions may look as follows.

Procedure without the beam — first iteration

- Calculate the time of flight and measure the cables as precisely as possible — expected precision: < 5 ns
- Adjust the WINDOW phase and the Synchronization Buffer shift accordingly
- Set the WINDOW width close to 25 ns to maximize the efficiency

Procedure with the beam — special run

- For each trigger collect data from several (e.g. ±2) consecutive b.x.'s
- Observe how the data are distributed among b.x.'s
- Correct the WINDOW position and the synchronization Pipeline shift accordingly
- Narrow the WINDOW width to the calculated jitter

Procedure with the beam — "physics" run

- Monitor efficiency map of the detector — inefficiency in certain regions may be caused by wrong timing

6 Synchronization of Cathode Strip Chambers

The timing structure of the CSC system has several components similar to those of RPC. The difference is that the chamber response time t_{CSC} includes drift time, which makes the t_{CSC} distribution as wide as 50-70ns at the base (Fig.4.4.13 of [4]). Because of that the bunch crossing identification is more difficult, but on the other hand, the synchronization requirement for the phase adjustment at the Front End can be slightly relaxed. Apart from that the synchronization procedures are similar to those of the RPC PACT.

The local trigger is based on a coincidence of at least 4 out of 6 layers within 75ns gate. The bunch crossing is identified by the second (in time) hit of those contributing to the coincidence. Prototype tests indicates that the distribution of the second hit arrival time is fully contained within 20ns (Fig.4.8.20 of [4]). Assuming 1-3ns for the setup time of the electronics, about 2-4 ns remains for the phase adjustment precision.

In the DAQ path the anode (wire) signals are discriminated, whereas the cathode (strip) signals are sampled 8 times with 50ns step. Because the signal can arrive at any clock phase due to the long drift time, there is no requirement on the phase adjustment precision.

7 Synchronization of Drift Tubes

Requirements for Drift Tubes are similar to those of CSC. Here the drift time is even longer — about 400ns. The bunch crossing recognition is performed by *Bunch and Track Identifier* (BTI) circuit, using generalized meantimer technique (Sec.3.4.2 of [4]). This method relays on the clock phase adjustment relative to the incoming data. The required precision is about 5ns. In order to determine the delay one has to find the maximum of the BTI efficiency for real muons.

There is no requirement on phase adjustment at the Front End in the DAQ path. The signals are digitized by TDC, so the exact time can be reconstructed off-line.

Conclusions

Synchronization of an LHC detector is a complex issue which requires advanced studies involving both engineers and physicists. Procedures for setting and maintaining the synchronizations must be developed and necessary hardware has to be build. This paper represents one of the first attempts to this problem with respect to the CMS Muon System. The author is very grateful to Maciek Kudla, Paul Padley, Wesley Smith, and Joao Varela for many useful discussions.

References

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[4] *The Muon Project — Technical Design Report*, **CERN/LHCC 97-32**.