Fine synchronization of the CMS muon drift tubes local trigger

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Abstract

The drift tubes based CMS barrel muon trigger, which uses self-triggering arrays of drift tubes, is able to perform the identification of the muon parent bunch crossing using a rather sophisticated algorithm. The identification is unique only if the trigger chain is correctly synchronized. Some beam test time was devoted to take data useful to investigate the synchronization of the trigger electronics with the machine clock. Possible alternatives were verified and the dependence on muon track properties was studied.

1 Introduction

A major problem to solve for a trigger of a detector in the LHC[1] environment is its synchronization with the machine clock. The synchronization is required in order to reconstruct the same event in different parts of the detector. There are two main sources for a phase difference between the LHC clock and the trigger sampling clock in the muon barrel detector of CMS[2] : the muon time of flight and the delays due to signal and clock distribution. The trigger electronics will start the signal processing with a variable delay since the muon time of flight in CMS varies from 12 ns for the closest muon measurement station to 35 ns in the farthest one. Each muon station is therefore in an unknown phase relation with the absolute time given by the machine. On the other hand the signals from the wires are sampled with a 80 MHz clock derived from the LHC one, which is distributed with very long cables of different lengths to the trigger electronics within each station. The LHC bunch crossing 40.08 MHz frequency is high enough that, due to these delays, different chambers could be processing at the same time events belonging to different bunch crossings.

In the muon barrel detector another unusual synchronization issue comes from peculiarities of the bunch crossing assignment algorithm. In order to provide the correct bunch crossing assignment and maximize trigger efficiency the sampling clock needs to be adjusted. This clock is derived from the machine clock using a 0-25 ns delay programmable in 104 ps steps. Finding the best delay settings for each chamber is indeed a fine synchronization of the detector electronics.

The availability of the bunched beam, i.e. with muons synchronous with a 40 MHz clock, at CERN SPS in 2003 and 2004 was useful to test and understand possible algorithms to set up a fine synchronization procedure.

2 Synchronization of the Trigger Chain

The muon detector is described in [3]. We recall that each muon station in the CMS barrel is composed by three SuperLayers (SL) of drift tubes each one consisting of 4 layers of drift tubes staggered by half a cell. Two SLs measure the track in the transverse plane (φ plane) and are also used for the trigger, while one SL measures the track in the longitudinal plane (θ plane). Muon stations are organized in 5 wheels divided in 12 sectors. Each sector is instrumented with 4 stations named MB1, MB2, MB3 and MB4 starting from the interaction vertex.

The tool available for synchronization is the Trigger and Timing Control system (TTC)[4] which provides the machine clock distribution and broadcasts the general level-1 trigger strobe called L1A. The TTC provides also a 32-bits word carrying the bunch crossing number. The bunch crossing counter is reset at every LHC orbit at a time called BC0. In such a way any local trigger signal can be associated to a unique bunch crossing number. Alignment in time of triggers coming from different chambers requires a coarse synchronization in steps of 25 ns delaying earlier triggers in order to assign them to the same absolute bunch crossing number.

The synchronization procedure assumes that each muon station is hardware timed-in. This means that signal distribution within each muon station is done in such a way that the TTC signals are received simultaneously by each trigger board. The time equalization is hardware achieved with electrical connections between the components of the trigger chain using cables of adequate length. The maximum skew of the clock distribution within the trigger boards of a chamber was recently measured around 1 ns. Hence in the following description each muon station will be considered one intrinsically synchronous block, equipped with one Trigger Timing and Control Receiver (TTCrx).

The trigger system is described in full details elsewhere[5]. Trigger board electronics samples the signals coming from the wires and processes them in order to provide trigger signals. The front-end trigger device is the Bunch and Track Identifier (BTI) which is required to uniquely assign any issued trigger to a bunch crossing number distributed by the TTC system. This assignment is achieved by means of a sophisticated algorithm called generalized mean-timer method. Abstracting from the actual implementation, which can be found in [6], this method can be interpreted as a line fit through the muon chamber planes using the measured drift times. Therefore its result depends on the values that are assigned to two relevant parameters: the drift velocity v_d and the time pedestal t_0 corresponding to the time of a signal generated by a muon passing exactly on the anode wire. A wrong assignment of these parameters causes efficiency losses and wrong parent bunch crossing assignment of a triggering muon. The drift velocity is in fact input to the BTI as a configuration parameter, while there are no means of setting a t_0 value, since the device does not actually uses the drift times as measured by the TDC, but it continuously monitors the input connection of each wire in order to detect a signal and to sample it using the time after detection in its calculations. The sampling frequency is 80 MHz and therefore signals are latched every 12.5 ns, value which corresponds to the actual time precision used in the algorithm. The time of signal sampling de-facto implies a t_0 value inclusion in the BTI equations in a non-trivial way and so a wrong sampling of the signal can cause a large error in the BTI calculations. The BTI sampling time can be changed by setting a fine delay (104 ps step) provided inside the TTCrx device. Changing the sampling time of the signals is equivalent to a modification of the t_0 used in the track fit and therefore it is evident that the trigger efficiency and the bunch crossing assignment capability of the algorithm must depend on the actual value assigned to this delay. Therefore the best timing relation between the sampling clock and the machine clock (i.e. the best TTCrx delay setting) must be determined, in order to have correct time measurement and correct parent interaction identification.

The trigger synchronization must be done in several steps. The first step is the determination of the delay optimizing the trigger bunch crossing identification efficiency by setting the fine delay provided by the TTCrx device (sampling clock synchronization). The following step will align, using coarse 25 ns steps delays, the output trigger bunch crossing numbers in order to assure the simultaneity of triggers originated from the same muon in different chambers at any level of the trigger chain. Finally, an absolute synchronization is needed to define the absolute time with respect to the BC0 signal.

The most challenging step is the sampling clock synchronization: the tests done in 2003 and 2004 with bunched beam dealt with it.

These tests were performed using one MB3 type chamber in 2003 and a set-up of two chambers (one MB1 and one MB3) in 2004. Each chamber was equipped with its final front-end, trigger and readout electronics, while prototype modules were used for the off-chambers electronics. The SPS radio-frequency structure was similar to the one foreseen for the LHC. A proton beam delivered by the SPS hit a primary target in narrow bunches (about 2 ns long, separated by 25 ns) generating muons. The 40 MHz signal, synchronous with the accelerator RF signal, was distributed in the experimental area via a TTC system through optical links. It was used as clock signal for the readout and trigger electronics of the test set-up. Results about the local trigger performance in 2003 test were reported in [5] together with details about the test set-up, while the analysis of the higher level trigger devices tested in 2004 is ongoing.

3 Sampling Clock Synchronization

The wire signals from the drift chambers are sampled by the BTI which is therefore the actual device needing fine synchronization. After a trigger is issued by the BTI, its path is synchronous and needs to be adjusted with a coarse delay (25 ns steps)[3].

[3]This second part of the synchronization procedure still needs some fine tuning, since signals are serialized on LVDS cables or optical fibers using parallel ports. The signals can reach the link receiver at different times and some hard work is needed to assure correct reconstruction of the serialized information. This part is supposed to be hardware achievable as

A BTI issues a trigger when at least 3 out of 4 signals sampled in any SL (inner or outer) are fitting in a line. It assigns to any trigger an intrinsic quality flag identifying alignments of 4 hits (HTRG) or 3 hits (LTRG[4]): in other terms it flags if the trigger is given by a 3 or 4 points fit. Then a second device (TRACO) correlates the trigger in the two SLs upgrading the quality flag. Finally the triggers are classified using seven quality flags (in decreasing quality order they are HH, HL, LL for correlated triggers and H_o, H_i, L_o, L_i for uncorrelated triggers inside the inner SL or the outer SL with obvious symbol meaning). Ideally only HTRG should be issued, but, due to inefficiencies or δ-rays emission masking the muon hit, the trigger may be of lower quality. The fraction of LTRGs increases in case of a wrong synchronization, since the BTI cannot anymore find precise alignments among hits. Another effect of a wrong synchronization is a reduction of the correlated triggers since the track parameters will be wrongly measured.

The algorithm produces a large number of low quality ghost triggers since a precise 4 hit fit at the correct bunch crossing generates lower quality triggers at different bunch crossing. These triggers must be rejected, but a single station trigger is highly inefficient in the discrimination of correct and ghost LTRGs. Therefore all the LTRG triggers must be rejected in spite of a much lower trigger efficiency in order to have the cleanest time spectrum of the events. Then the trigger devices must be configured in a way that maximizes the trigger efficiency as a function of the TTCrx delay.

The highest possible sensitivity and cleanliness is obtained by the requirement of the presence of a very high quality correlated trigger (HH or HL or LH). The rejection of lower quality triggers is expected to have dramatic effects on the trigger efficiency.

Figure 1 shows the effects on bunch crossing assignment of wrong settings of the sampling clock timing using such a configuration. Data were collected using a scintillator trigger to define uniquely muon crossing time in such a way that the BTI should always assign the same bunch crossing number to good triggers. The histograms show the progressive degradation of bunch crossing assignment quality since the bunch crossing is wrongly assigned for a fraction of events which depends on the actual delay set. The best delay is clearly set when there is no ambiguity in bunch crossing assignment, while setting the worst one the triggers are assigned to two close by bunch crossings. Both situations are visible in the plots of Figure 1. The chamber trigger configuration was set up in order to reject uncorrelated triggers, therefore we expected a big effect on efficiency figures as a function of the TTCrx delay. In fact we have

standard electronics set-up operation, although it is demanding.

[4]HTRG for High quality Trigger and LTRG for Low quality Trigger

already reckoned that the fraction of HTRGs and the correlation probability should vary depending on the TTCrx delay value. Using the same data plotted in Figure 1, we see in Figure 2 that the fraction of HH triggers is smaller in correspondence of the delays where the bunch crossing assignment is worst. When the fraction of HH triggers decreases, the HL triggers are instead growing and partially compensating the efficiency drop. This kind of behaviour fully meets our predictions. We also observe that there is a rather flat region of TTCrx delay values (about 8 ns wide) where the fraction of HH triggers is almost constant. Each station must be synchronized setting the fine delay that maximizes the trigger efficiency and from Figure 2 we understand that there is almost no de-synchronization effect in a ± 4 ns wide region around the best value. The effect is enhanced by the high quality requirements and we expect the efficiency drop to be negligible using the default configuration which includes uncorrelated triggers.

Therefore in principle a measurement of the trigger rate when modifying the sampling clock phase is the required procedure and the required precision is not really high. But this naive procedure is complicated by a few facts.

The first problem is the fact that the efficiency also depends on the actual drift velocity parameter used in the BTI calculations which could be different from station to station and even not constant inside the same station due to local environmental conditions like magnetic field strength. This implies that the search should be performed in a two parameters space. There is also a contribution expected from the drift velocity dependence on the angle of incidence. The final choice must therefore be some kind of average for different drift velocities and incident angles determined on a chamber by chamber basis.

Another problem is connected to the trigger rate stability. While scanning the clock phase the luminosity can significantly change, biasing the result of the procedure. This procedure can be executed in parallel for all the chambers on the monitor CPUs in the control room or locally for each half wheel on the Detector Control CPUs. In the first case a technical trigger (i.e. a special purpose single station L1A) is generated by the drift tubes trigger system every time there is a trigger inside any station. In principle data could be collected at the maximum allowed rate for muons (12.5 kHz). Every muon will produce a single chamber trigger in all the crossed chambers. The presence of more than one trigger at the same time will be confusing for data selection: only data from the triggering chamber should be used for the analysis. The procedure must therefore be repeated (at least four times since the chambers in the same sector will certainly give more than one simultaneous trigger) disabling the chambers already aligned until they are all synchronized. In the second case each station is set in autotrigger mode, i.e. the L1A signal is generated by each chamber Control Board. Therefore each station is independently sending to the Sector Collector crates (one for every half wheel) the data related to any L1A and all stations can in principle be read in parallel. The foreseen dead time to avoid conflicts between successive triggers is 3.2 μs and therefore a trigger rate up to 300 kHz could be possible. This readout rate will not be allowed by the bandwidth of the Detector Control System, but a reasonable readout rate of few kHz (therefore comparable to the one available making use of the global CMS readout) could be foreseen. In these conditions the procedure could take about a hour.

Hence an algorithm alternative to efficiency maximization, strictly connected to the efficiency measurement and luminosity independent, must be developed.

During the 2003 and 2004 beam tests the data were collected both in autotrigger mode (single chamber self-trigger) and with an external trigger (a scintillator setup). The two sets of data allow the verification of the possible scenarios at LHC. The external trigger data are also useful to develop the algorithm which needs to be used to synchronize Monte Carlo events in a proper way, since they will suffer from the same problems of the hardware trigger devices if the simulation is correctly done. Data were taken at different incidence angles with respect to the normal to the chamber and for different settings for the drift velocity parameters in the BTI.

4 Algorithms for Fine Synchronization

It is desirable that the algorithm that provides the fine delay value for each muon barrel station could be luminosity independent. The algorithm must use the autotrigger mode since obviously no external timing detector will be available. Finally the algorithm must be fully automatic and should be fast enough.

This means that we have to develop an algorithm that uniquely identifies the best delay without any external intervention and that it must use a small number of events.

The data available to the local DAQ for each accepted trigger are the trigger quality and the measured drift times. Both kinds of data can be used to find the best delay. The trigger quality was not available in the autotrigger setup we used in the beam test and we had to study the use of the trigger information analyzing the data collected with the external trigger. The drift times were instead available both in external trigger mode and autotrigger mode. The analyzed data were collected for different chambers and in different set-up conditions and therefore no direct comparison among different plots and quoted values can be done unless otherwise stated (e.g. in 4.3).

4.1 Algorithm Using Trigger Data

The trigger data are: the trigger quality, the impact position and the bending angle of the muon. The only sensible quantity that can be used is the quality. In fact the alignment of all the four hits is less probable when the phase is wrong and therefore the fraction of events of HL type will increase as soon as the phase will be worse. The best indicator we found is the ratio of HL trigger type to HH trigger type. This ratio is certainly luminosity independent and should have a maximum at the worst phase and a minimum at the best phase. The measured plot is shown in Figure 3.

We see a well defined maximum that identifies the position of the worst phase value. A displacement backward or forward by 12.5 ns provides the best phase value. The choice between adding or subtracting 12.5 ns is determined by the requirement that the delay to set is a value between 0 ns and 24 ns. The HL to HH trigger type ratio shows the same behaviour for all data samples.

4.2 Algorithm Using TDC Data

The TDC data are the measured TDC times (T) that are the sum of the true drift times (t) and the t_0. A L1A signal can be generated only at 40 MHz frequency and causes the TDC to send the drift times stored in a predefined window centered around the L1A signal time. The TDC time is determined by a bunch crossing counter (each count corresponding to 25 ns) and by a fine counter interpolating between successive bunch crossings. Hence in the case of a bad synchronization a certain fraction of events will be assigned to the bunch crossing close to the right one, causing the TDC time value to jump by 25 ns.

For every trigger the TDC data are assigned to a bunch crossing by the arrival of the L1A signal which defines the allowed time window for the data readout. Hence the TDC data will carry the offset introduced by the actual time slot assignment. If the bunch crossing assigned is too late or too early with respect to the correct one the TDC times will be shorter or longer by 25 ns. If the sampling clock is correctly synchronized almost all the events will have the same bunch crossing assignment, while in the case of maximum de-synchronization the events will be equally shared between two consecutive bunch crossings. Roughly, since all the times are relative to the trigger time, we have the superposition of two drift time distributions offset by 25 ns (i.e. with t_0s differing by 25 ns), instead of a single clean drift time distribution. This effect is evident using the measured times ($T = t + t_0$) of any three consecutive layers to compute the quantity.

$$MT_0 = \frac{T_1 + 2T_2 + T_3}{2} = \frac{t_1 + 2t_2 + t_3}{2} + 2t_0$$

The distribution of this quantity for some values of the time delay is shown in Figure 4. The t_0 does not need to be exactly determined since no track fit is required. Its evaluation can therefore be very rough causing an unimportant offset in the distribution. The variable MT_0 depends on the trigger latency, and indirectly, on the sampling clock phase: if the sampling clock is out of phase, the trigger output is distributed over two neighbouring cycles and as a consequence t_0 jumps by 25 ns and the distribution shows two distinct peaks separated by 50 ns.

We can have independent contributions from each SL, but the result is SL independent. Otherwise an average value should be found since both SLs signals are sampled by the same clock.

Within each SL MT_0 can be computed for the layers 1, 2 and 3 (MT_{01}) and the layers 2,3 and 4 (MT_{02}), if there is a four hit track, or only for one of them, if there is a 3 hits track. Since the two values are not independent we have to use arbitrarily only one of them. The best phase sensitive quantity is the r.m.s. of the MT_0 distribution. The delay associated with the smallest r.m.s. will be the best one.

The use of the r.m.s. needs some data selection to be really effective and give sensible and stable results, since events with wrongly measured drift times generate a roughly flat background weighing a lot in the r.m.s. calculation. The major effect comes from δ-rays that modify one or maybe two of the drift times we are using in the MT_0 calculation. This contribution artificially increases the r.m.s. value.

In order to solve the first problem we can define a fixed window centered around the maximum for the r.m.s. calculation. We have considered symmetric intervals around this value and, after comparison of the stability of the results, we have selected a ± 100 ns range around the highest peak as the best choice.

The only way to reject drift times affected by δ-rays is a comparison between MT_{01} and MT_{02}. This requirement immediately rules out the use of three hits tracks, since no comparison would be possible. The resolution of MT_0, computed by a gaussian fit using the external trigger data which are synchronous by default, is $\sigma \approx 5.7$ ns. The r.m.s. distribution for two cuts ($|MT_{01} - MT_{02}| \leq 3\sigma$ and ($|MT_{01} - MT_{02}| \leq 1\sigma$ is shown in Figure 5. It shows a broad minimum around the best phase and a well defined maximum at the worst phase. The figure shows that the 1σ cut provides a smoother and better defined curve, but does not influence the final choice. The result is quite stable even using a relatively small number of events (as small as 1000 events for each TTCrx delay value).

4.3 Qualification of the Algorithms

We have then identified at least two ways to perform fine synchronization. Both the algorithms easily identify the worst phase, being instead flat at the right phase consistently with the fact that the best phase can be set with some good safety margin. In order to be validated they must give the same delay value obtained by the maximum efficiency search.

We have therefore compared the methods for the same setup and the same chamber in Figure 6. The peak position of both quantities is compatible with the worst efficiency and the difference between best and worst phase is 12.5 ns as expected as effect of the 40 MHz clock frequency. Hence both methods are usable for fine synchronization.

5 Dependence on Drift Velocity and Incidence Angle

We have already anticipated that the synchronization procedure implies also the identification of the best configuration value for drift velocity. As a requirement the drift velocity must be know better the 2%. We have checked the behaviour of the synchronization sensitive variables in order to see if any of them could be used to help in the best drift velocity parameter choice.

The MT_0 r.m.s. of TDC data taken for different drift velocity settings as a function of the TTCrx delay is shown in Figure 7. There is a clear dependence of the best delay on the actual drift velocity chosen, but there is not a clear indication of a preferred value of drift velocity to set. An explanation of this result comes from autotrigger rate measurements with cosmics rays. We can in fact perform rate measurement since the cosmic flux is constant in time. On the other hand cosmics are asynchronous and therefore this measurement cannot depend on the TTCrx delay. The result of a drift velocity parameters scan is reported in Figure 8. The dependence is evident and we may conclude that for the values tried during beam test the trigger efficiency is roughly constant. Such a measurement can be done in CMS, but it works only for horizontal chamber. We may use the result obtained using horizontal chambers also for inclined chambers owing to approximate φ symmetry of the CMS barrel muon detector. This measurement could save a lot of time avoiding to repeat the fine synchronization procedure for several drift velocity parameters.

A drift velocity monitor chamber, measuring the drift time of electrons emitted by a radioactive source at known distance from a sense wire, is provided at input and output of each gas line. Although the actual value can be different from the one measured by these monitor chambers, due to local environmental conditions, this system could already provide the first guess for a drift velocity and above all it will provide direct information about modifications of the drift velocity which may affect the trigger performance.

We also expected a dependence of the best delay on the muon angle of incidence because of the angular dependence of the drift velocity. This effect was verified and results are reported in Figure 9. It is evident that the best choice is jittering by ± 2 ns. In CMS the delay will be automatically set to the average incident angle value just randomly collecting data in situ for any chamber.

6 Final remarks

The final algorithm must include an automatic delay finding method.

In both proposed methods, a maximum search provides the value of the worst delay. This value increased or diminished by 12.5 ns (the choice between the two cases is done by the constraint that this delay must be between 0 and 24 ns) gives the best fine TTCrx delay to set.

If a 1 ns step scan of the TTCrx delay will take too long, the easiest method for the best delay determination is the weighted average around the maximum. Then the formula to apply is

$$Bestdelay = \frac{\sum(rms \times delay)}{\sum rms} + 25ns \qquad (modulo 25)$$

The relevant checks are the comparison among the different methods and the verification of the stability of the results when modifying the number of events collected, the range for the weighted average calculation or the step used to scan the TTCrx delay. The results for an MB3 chamber during 2003 beam test are collected in Tables 1-2. The algorithms are essentially providing the same delay setting within 1 ns for all step sizes and windows.

Sampling clock synchronization is a key ingredient to good performance of the DT local trigger electronics. The data collected in the 2003 and 2004 beam tests show stable and coherent performance for the algorithms proposed for the sampling clock synchronization that is the most challenging step of the whole process. The analysis shows the existence of a 4 ns wide region available for delay setting without effects on trigger efficiency that is large enough to accommodate jitters observed in the data. Since the requirements of this analysis were quite stringent, we expect a negligible efficiency dependence on the delay when using the more relaxed default configuration foreseen for standard data taking at the LHC.

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# EVENTS/DELAY	STEP(ns)	WINDOW (steps)	BESTDELAY (ns)
10000	1	±2	2.50
		±4	2.52
	2	±1	3.32
		±2	3.17
	3	±1	2.53
		±2	2.55
1000	1	±2	2.50
		±4	2.53
	2	±1	3.35
		±2	3.16
	3	±1	2.54
		±2	2.61

Table 1: Stability of the TTCrx best delay using the weighted average best delay determination applied to MT_0 r.m.s. for different choices of number of events collected for each TTCrx delay, frequency of variation of the TTCrx delay and number of bins around maximum used for the weighted average calculations. Data refer to $(|MT_{01} - MT_{02}| \leq 1\sigma$ and autotrigger mode for a MB3 in 2003 beam test.

	METHOD		
	HH/HL RATIO	RMS (φ SL)	RMS (θ SL)
BESTDELAY (ns)	2.55	2.46	2.41

Table 2: Result from different methods and SLs. Results refer to an MB3 type chamber during 2003 beam test at the drift velocity parameters equivalent to 54.2 μm/ns at $+15^o$. The actual number used in the beam test operation was 2 ns.

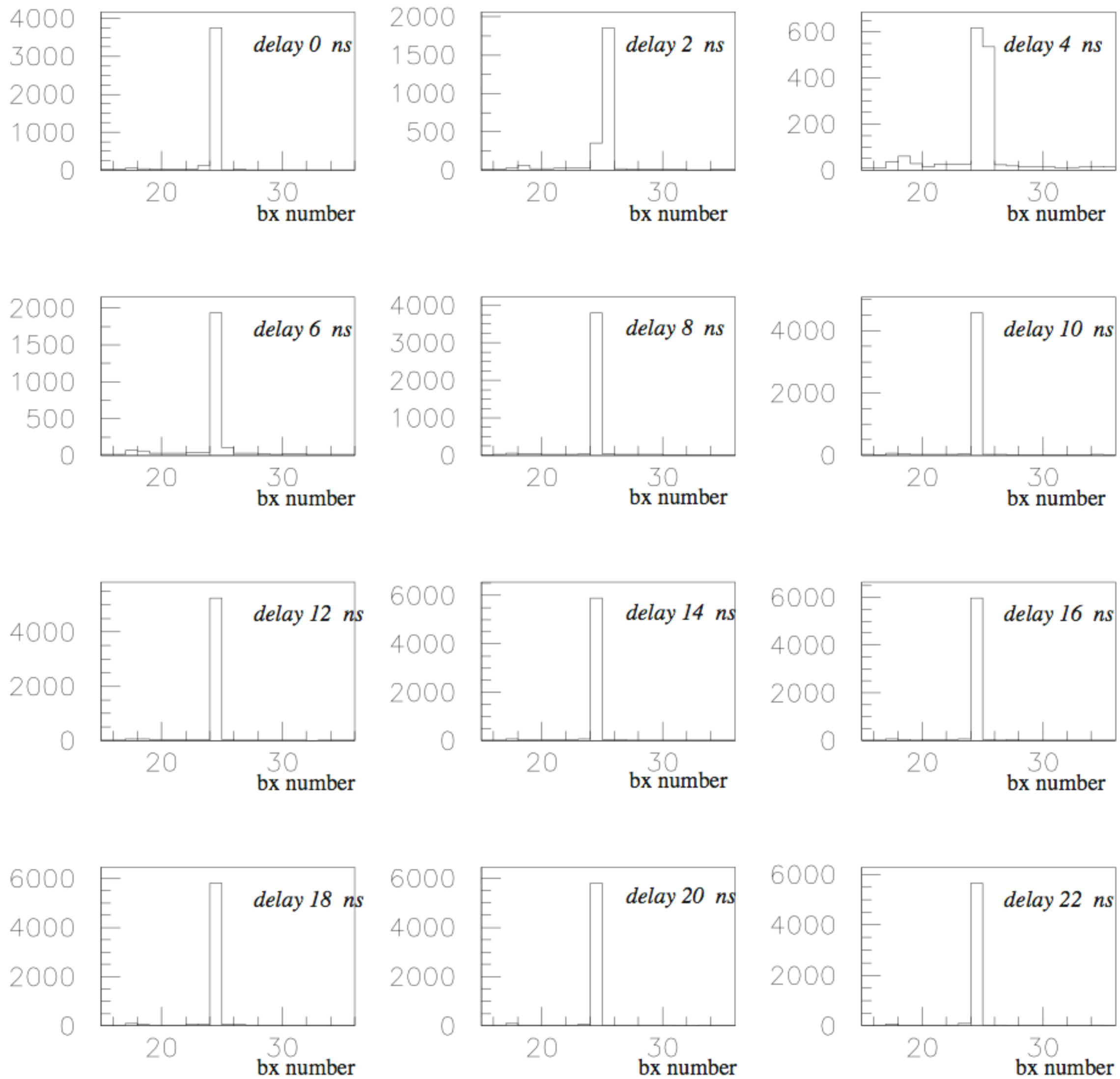

Figure 1: BTI bunch crossing number assignment for different delays set on the TTCrx clock distribution device. Data were collected in 2004 using a scintillator for 0^o incident muons on an MB1 type chamber. The number of scintillator trigger is the same for each plot.

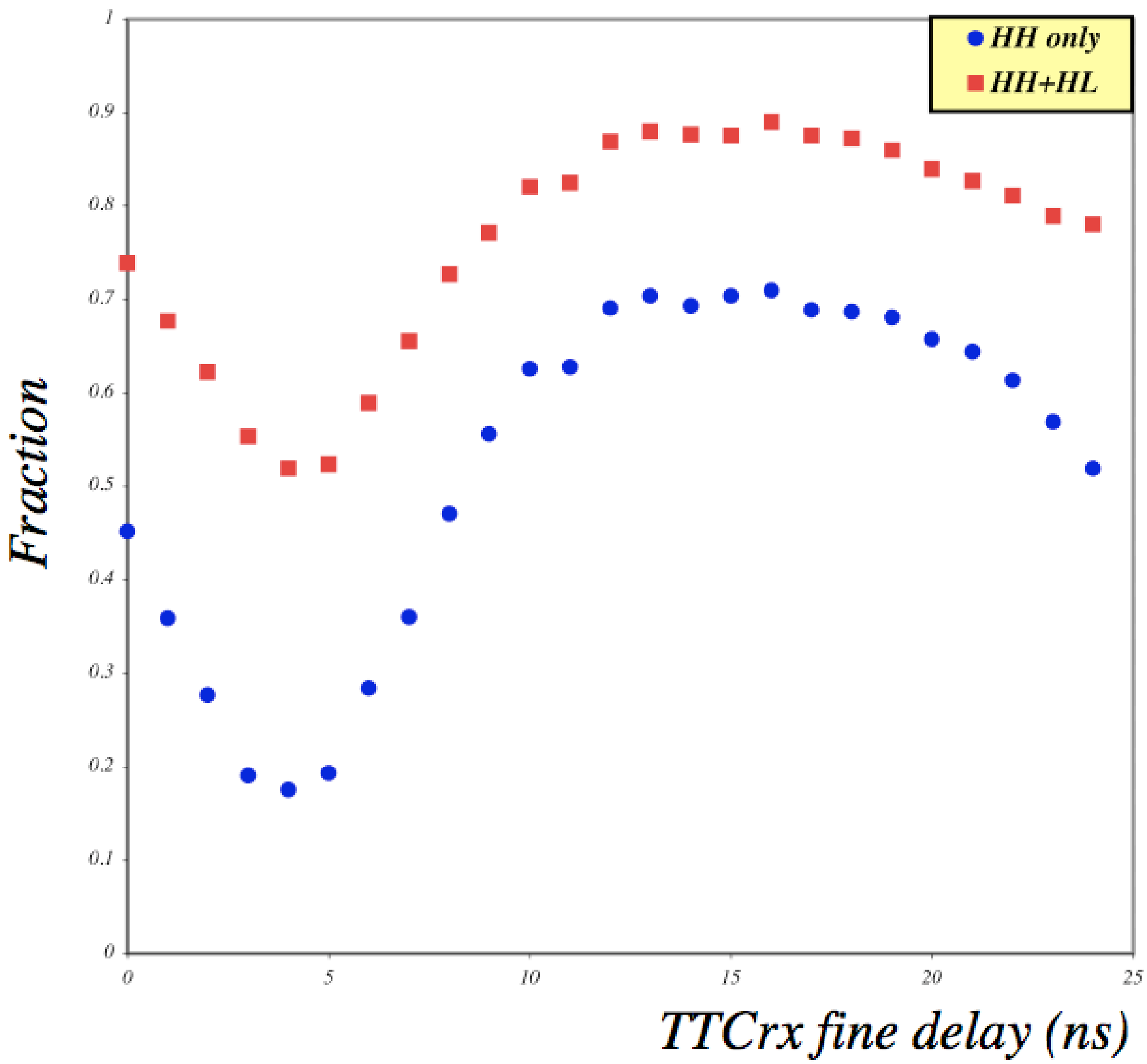

Figure 2: Fraction of correlated triggers as a function of TTCrx delay set. Data were taken in 2004 beam test using a scintillator setup for a MB1 type chamber at 0^o incident angle.

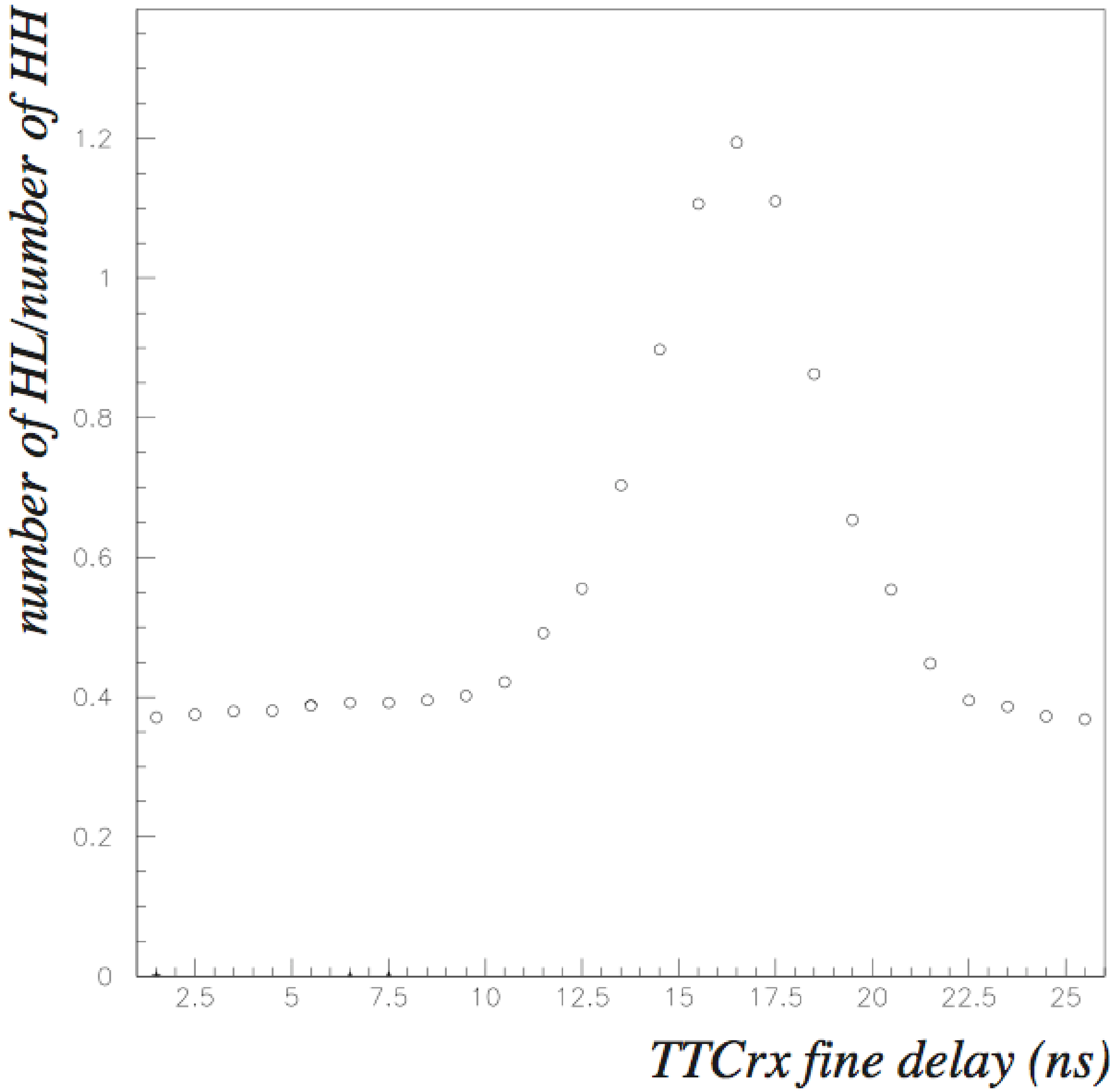

Figure 3: Ratio of HL to HH trigger type from external trigger data for a MB3 type chamber in 2003 beam test.

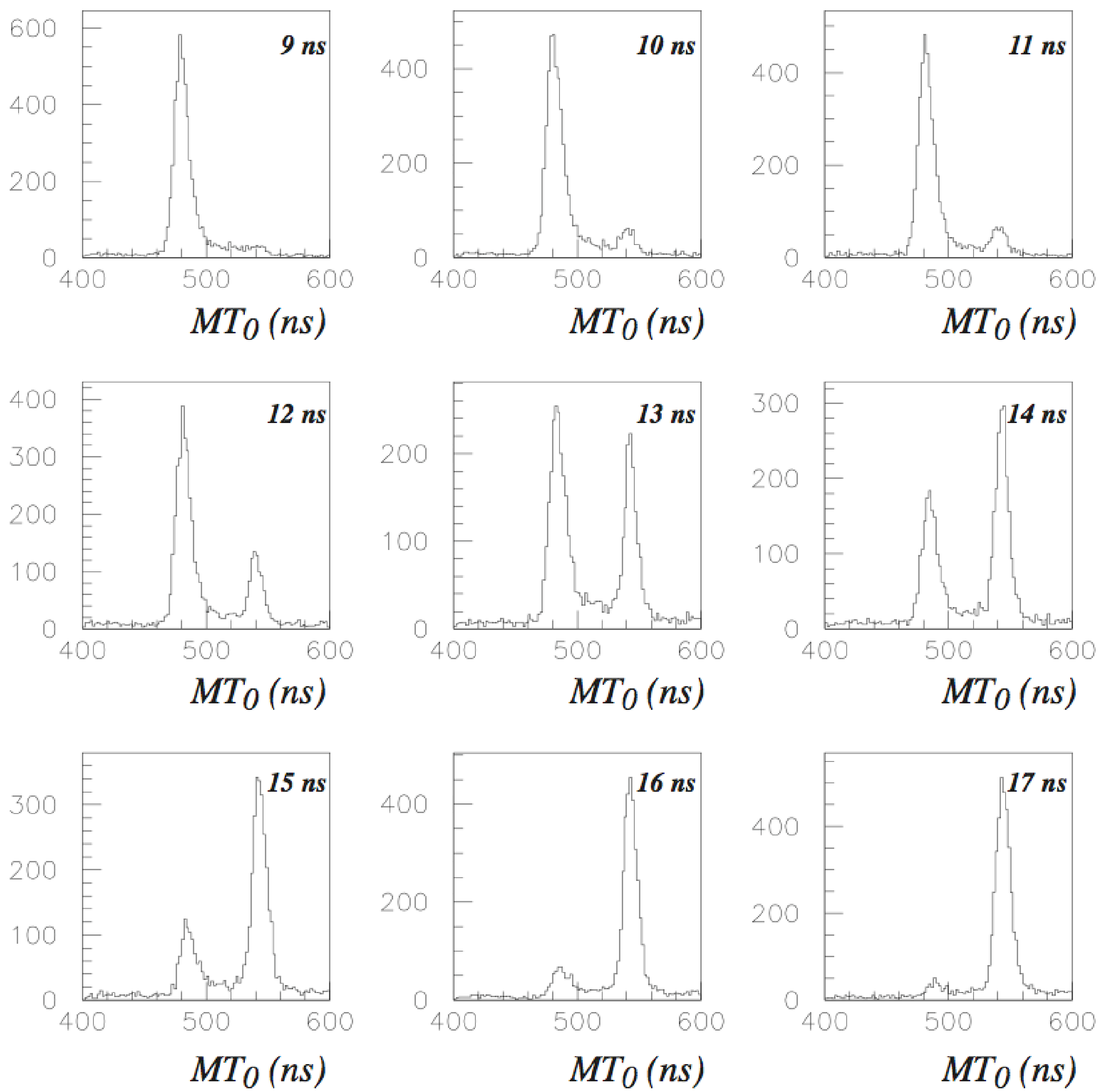

Figure 4: Evolution of the quantity MT_0 while increasing the fine delay of TTCrx. Plots are obtained for an MB3 type chamber during 2003 beam test.

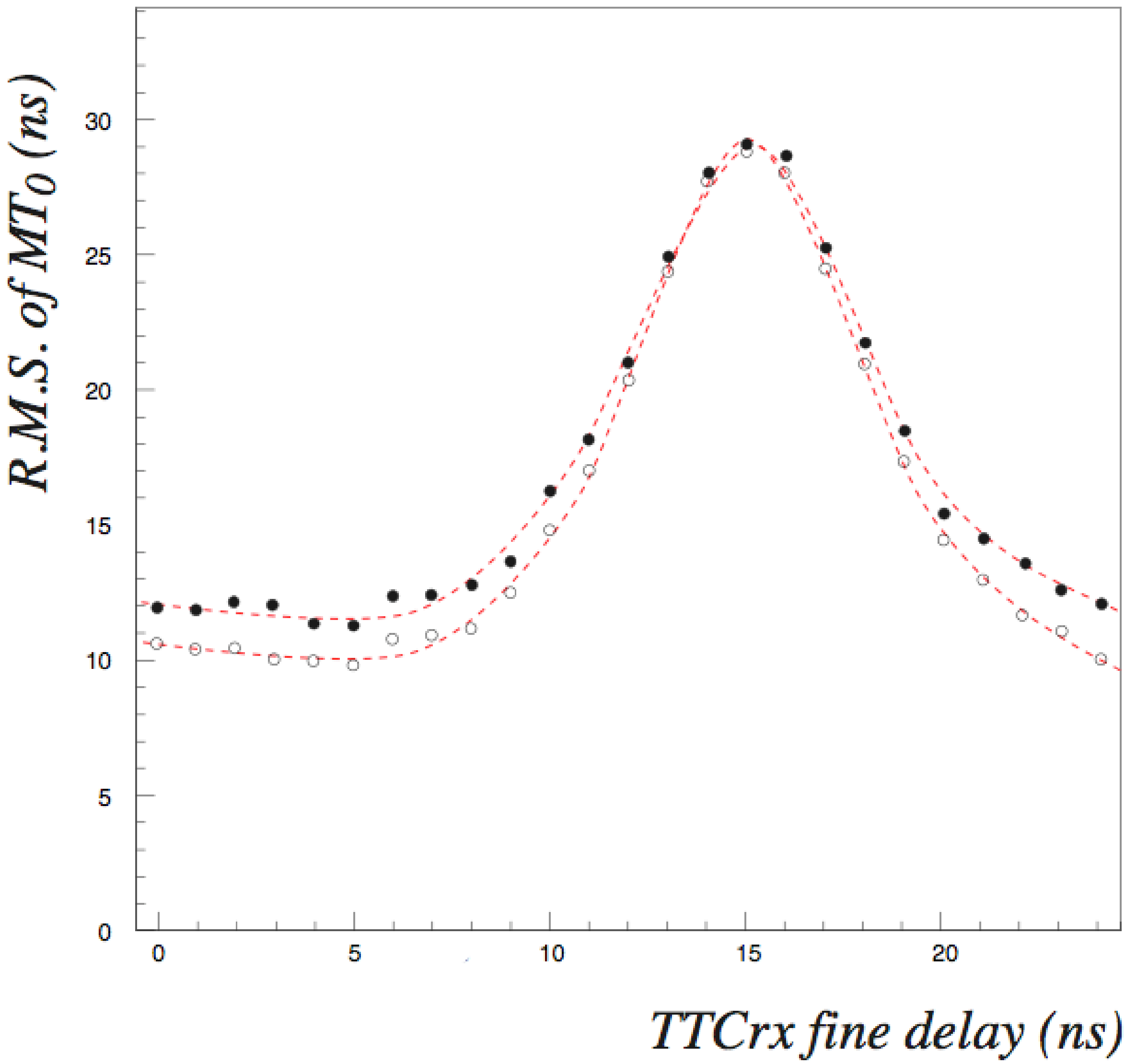

Figure 5: R.m.s. of MT0 distribution for ($|MT_{01} - MT_{02}| \leq 1\sigma$ (open circles) and (b) ($|MT_{01} - MT_{02}| \leq 3\sigma$ (full circles). Data are for an MB3 chamber in 2003 beam test. Lines are drawn just to guide the eye.

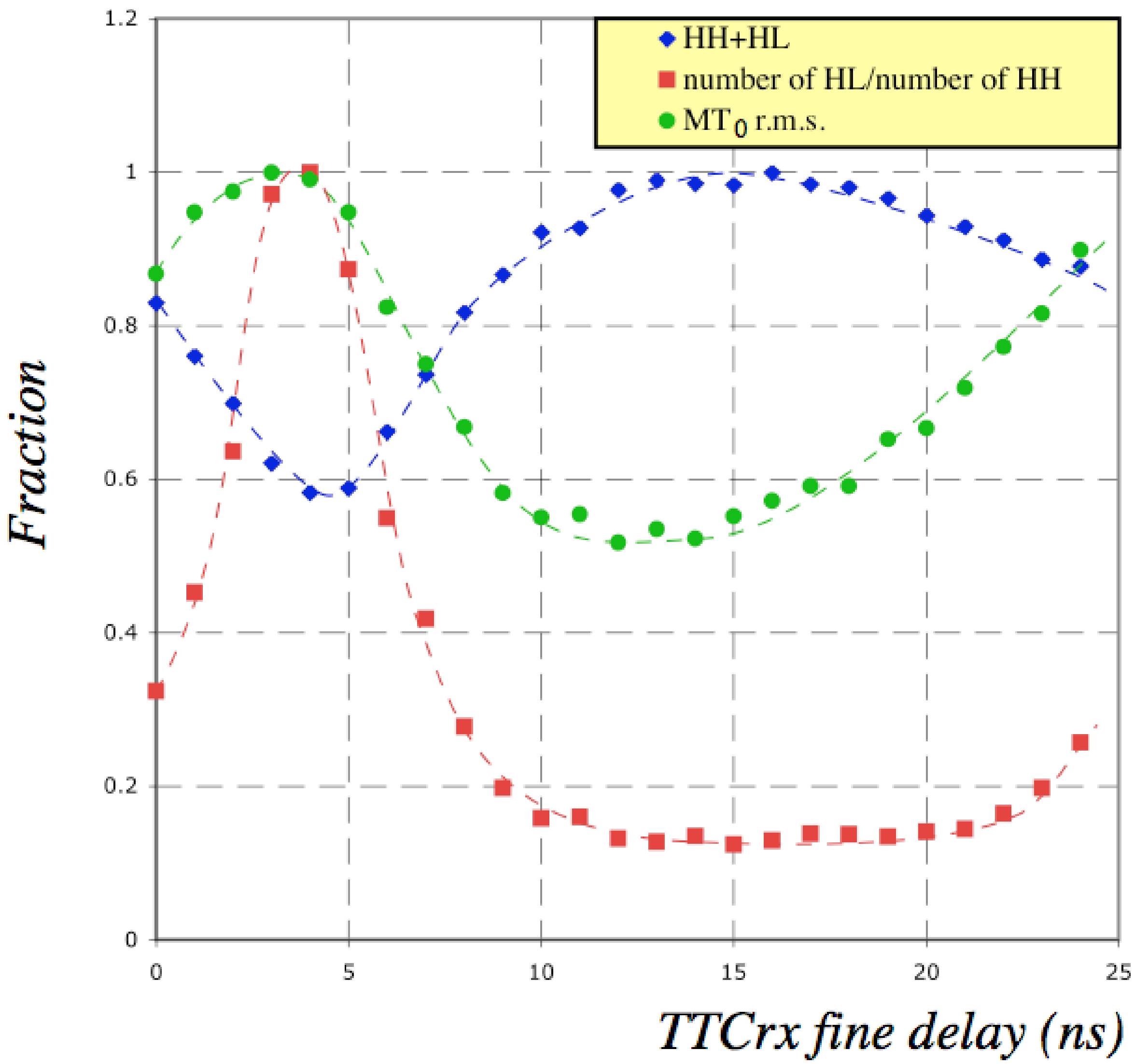

Figure 6: Behaviour as a function of the TTCrx delay of the trigger efficiency (HH+HL fraction), ratio of HL to HH and r.m.s. of MT_0 distribution. Data are for muons incident at 0^o on a MB1 type chamber during 2004 beam test. Due to the large difference in absolute values of the three quantities, they are shown normalized to their highest value in order to allow better comparison among them. Lines are drawn to guide the eye.

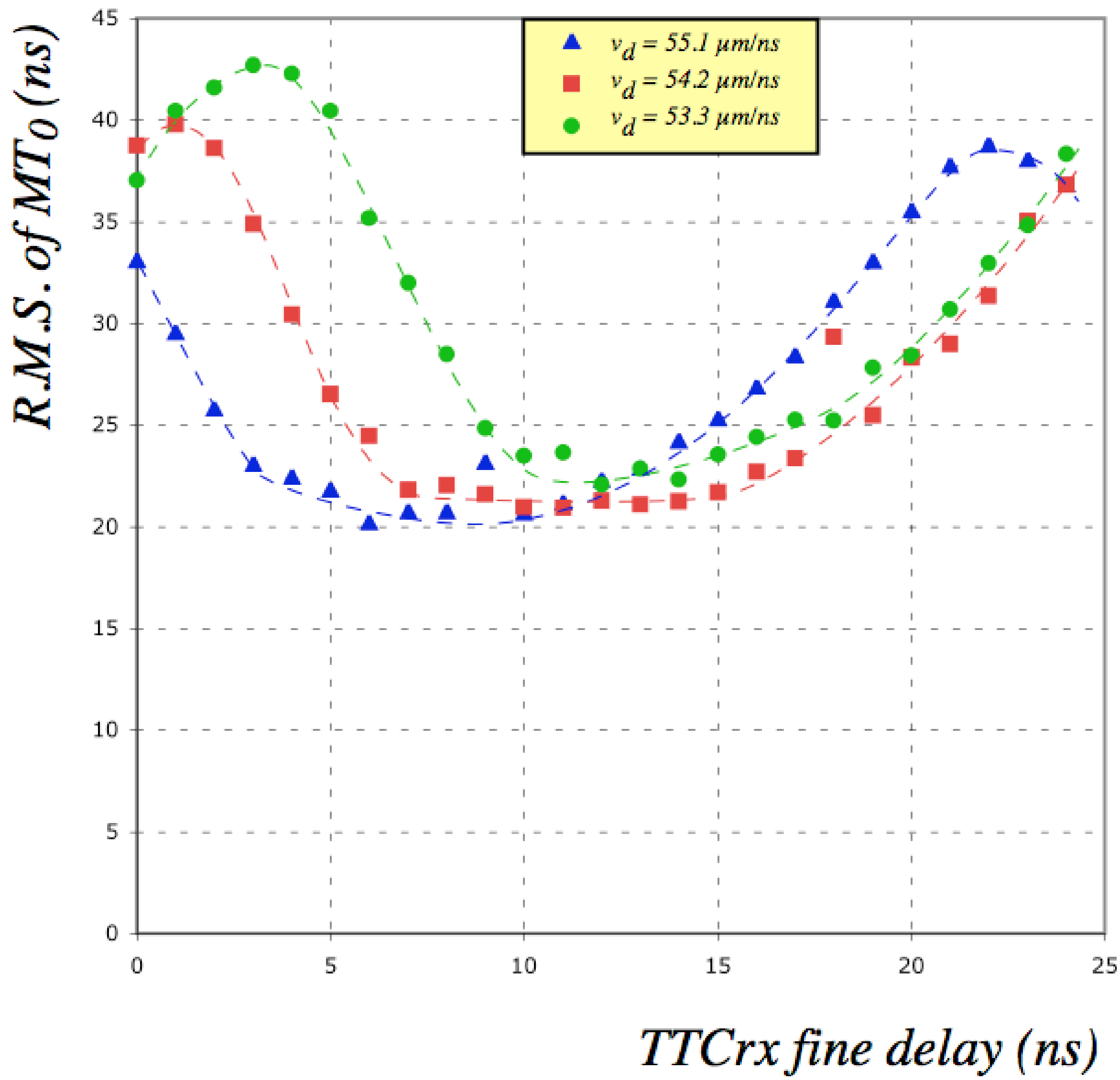

Figure 7: Behaviour of the r.m.s. of the MT_0 quantity for different drift velocity parameter settings. Data were collected in 2004 beam test for an MB1 type chamber in autotrigger mode at 0^o incident angle.

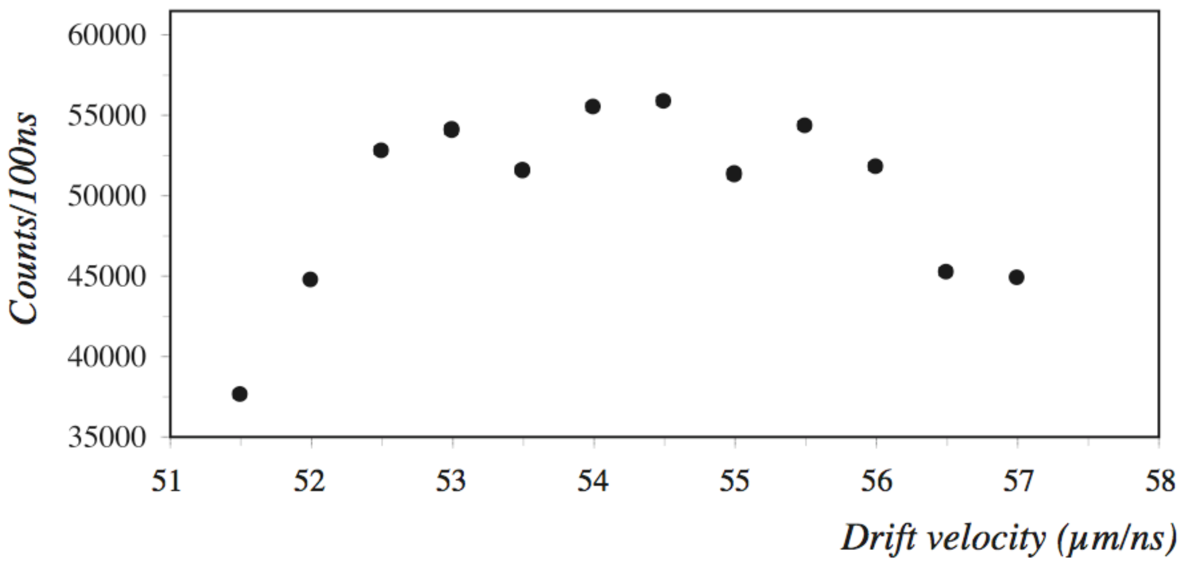

Figure 8: Autotrigger rate on a MB3 type chamber (HH and HL triggers only) for cosmics as a function of the drift velocity settings. The regular efficiency drop every three steps is due to an hardware bug in the BTI ASIC which cannot be corrected. The hole is filled when allowing uncorrelated triggers.

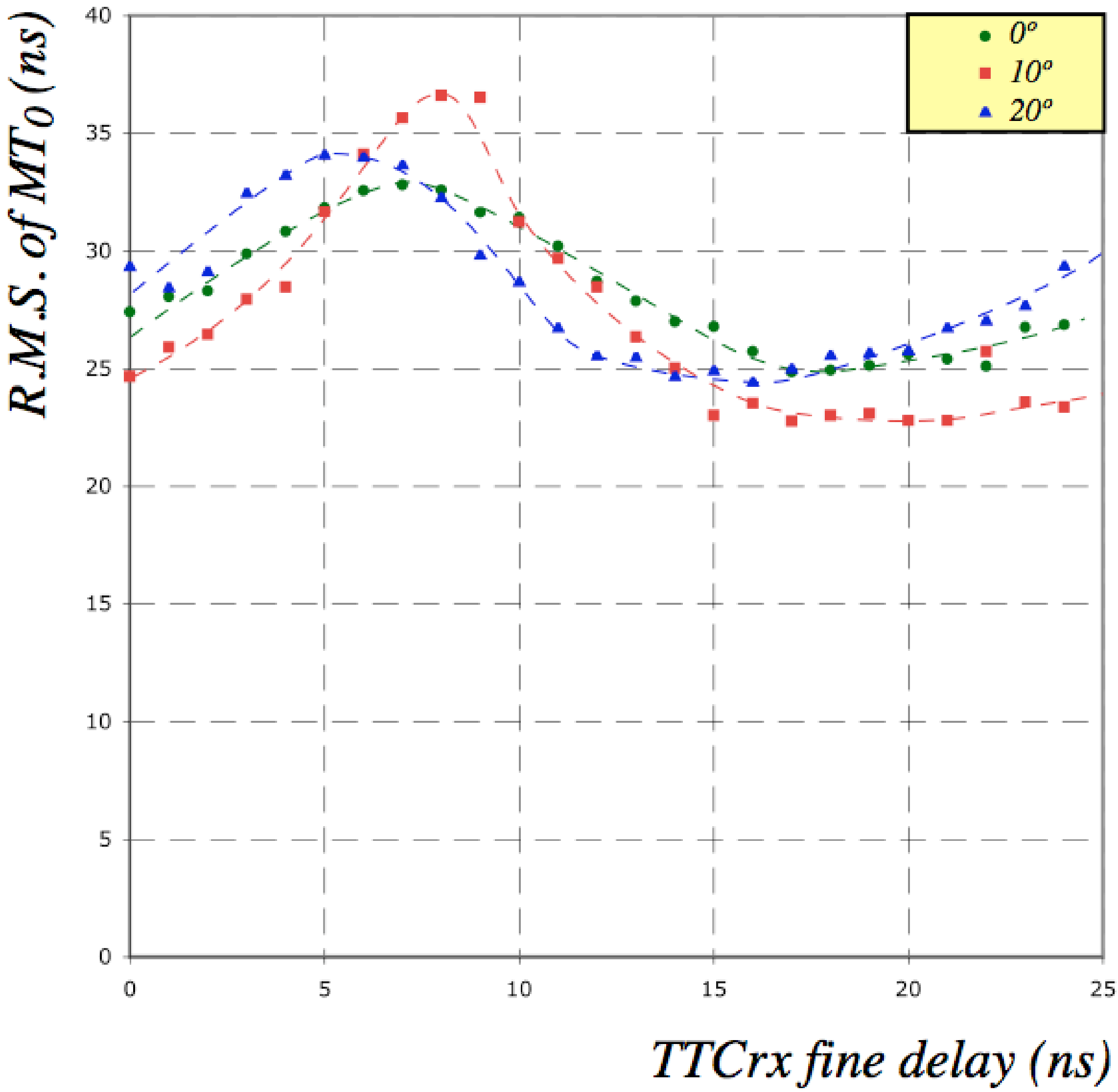

Figure 9: Dependence of the r.m.s. of MT_0 for few angles of incidence of the muons. The plots are for autotrigger data on an MB3 type chamber during 2004 beam test. Lines are drawn just to guide the eye.