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Procedure for the fine delay adjustment of the CMS tracker

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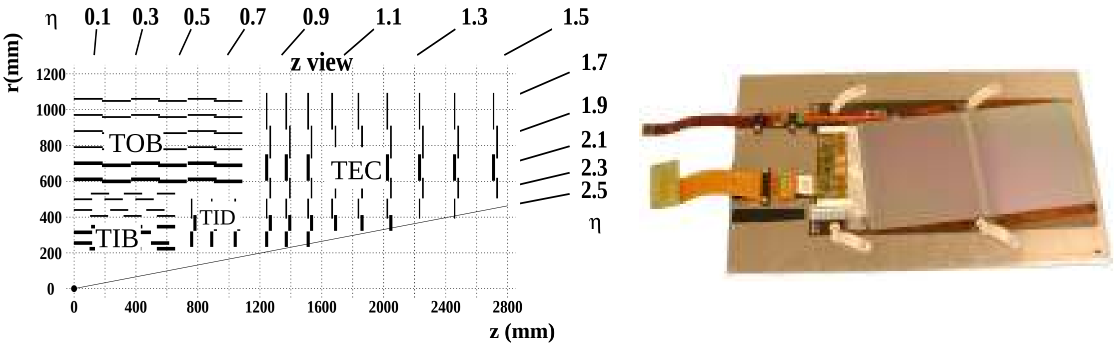
Abstract

One of the crucial aspects of the commissioning of the CMS silicon tracker will be the absolute timing adjustment of each module, to accommodate both delays introduced by the hardware configuration and effects due to the time of flight of particles. The objective is to be optimally synchronized with the bunch-crossing to maximize the efficiency while minimizing the number of remnant hits from the adjacent bunch-crossings.

In the present note, a procedure to reach that goal is studied. Monte Carlo studies as well as the analysis of data from the commissioning of the detector are used to assess the time needed and the resolution that can be achieved. Critical aspects are discussed, and results from the first implementation are presented.



(a) (b)

Figure 1: (a) Sketch of the tracker layout (1/4 of the r-z view); (b) a TOB module on its aluminum transport plate.

1 Introduction

The CMS silicon strip tracker is the largest device of its type ever built. It is divided into four main subsystems: the Inner Barrel (TIB), the Outer Barrel (TOB), the Inner Disks (TID) and the Endcaps (TEC) (Figure 1). There are 24244 single-sided micro-strip sensors covering an active area of $198 m^2$. Throughout the tracker, the strip pitch varies from the inner to the outer layers (from $80 \mu m$ to $205 \mu m$) in order to accommodate the anticipated occupancy and to ensure a resonably uniform $R - \phi$ resolution [1].

The size of the device has led to a design where the basic unit, called a module, houses the silicon sensors and the readout electronics. Signals are collected via a CR-RC shaper, sampled and stored in an analog pipeline by the APV25 front-end chip [2]. The APV25 chip also contains a deconvolution circuit to reduce the signal width [3]. The read-out can be performed either with or without the deconvolution, depending on the pile-up conditions. The two modes of operation are respectively called deconvolution mode and peak mode.

One aspect of the commissioning of the CMS silicon tracker will be the absolute synchronization of each module from data, to accommodate both the delays introduced by the hardware configuration and the effects due to the time of flight of particles. The objective is to be optimally synchronized with the bunch crossing to maximize the efficiency while minimizing the number of fake hits from adjacent bunch crossings. This aspect is critical due to the high frequency of interactions at the LHC (nearly 40MHz) and the width of the signal pulse (> 25ns).

The CMS tracker is not able to produce a trigger signal by its own. An external (Level-1) trigger generated from the information collected by other subdetectors, mainly calorimeters and muon chambers, is fed by dedicated optical control links from the front-end controllers to the APV25 chips. Upon reception of a trigger signal, data of the corresponding bunch crossing are read from the pipeline and sent to the front-end drivers (FED) via analog optical links. This is where the analog-to-digital conversion is done.

To achieve the synchronization of the electronics a dedicated programmable delay is available in the Phase-Locked Loop (PLL) that is embedded in the front-end electronic of each module. It allows to shift the clock and trigger signals by steps of 1.04 ns. The global latency with respect to the central trigger is compensated by the "latency" parameter of each APV25 chip. That parameter defines an offset in the APV25 analog pipeline by steps of 25ns. Finally, the differences in length of the analog lines are compensated by programmable delays at the input of the FEDs. FED delays are set according to the fiber length information that will be optically measured from the front-end to the FED after the final detector cabling and stored in the construction database.

With the level-1 trigger rate 400 times lower than the bunch crossing rate, the front-end chip may not output data for a considerable time. The chip therefore outputs a synchronization pulse called "tick mark" every 35 clock cycles when there is no data to read out. The tick mark can be used to first synchronize all modules with each other to compensate for the length of optical and electrical control links, who propagate the clock and the trigger to the front-end, as well as the electronics latency. This is done adjusting the PLL delays such that, at the end of the procedure, the trigger arrival is synchronous on all tracker modules and, because of the delay settings in the FEDs, also the analog signal arrival time is synchronous on all FED channels. The module PLL and FED delay settings determined in this way have to be corrected to take into account the time of flight from the interaction point to each module as well as the latency with respect to the trigger and to still ensure the synchronous arrival of the analog signal to all FED inputs. If the first is known from the geometry, the second can only be determined by performing a latency scan. To guarantee optimal synchronization in a minimal amount of time, the latency scan is performed in two steps. In a first round, a rough global scan is performed in steps of 25ns using the APV25 internal latency register. This allows the correct bunch crossing to be located. A finer scan is then performed to achieve a precision of 1ns by using hits from selected tracks and readjusting the PLL delays. The commissioning sequence can therefore be sketched as follows.

1. Tune the PLL delays to synchronize all the tracker modules using the tick marks, i.e. guarantee that the clock is arriving synchronously on all tracker modules. This is done in one go for all the tracker.
2. Perform a rough global latency scan with respect to the central trigger, i.e. find the global shift between the tracker trigger and the central one. This is done tuning the APV25 latency parameter, in one go for all the tracker.
3. Perform a fine latency scan by retuning the PLL delays. This is done per detector layer to ensure that each reconstructed track crosses the considered subset once, being almost unaffected by the commissioning procedure.
4. Correct that tuning to take into account the theoretical time-of-flight. For that purpose, particles are assumed to propagate straight from the nominal interaction point to the center of the module.

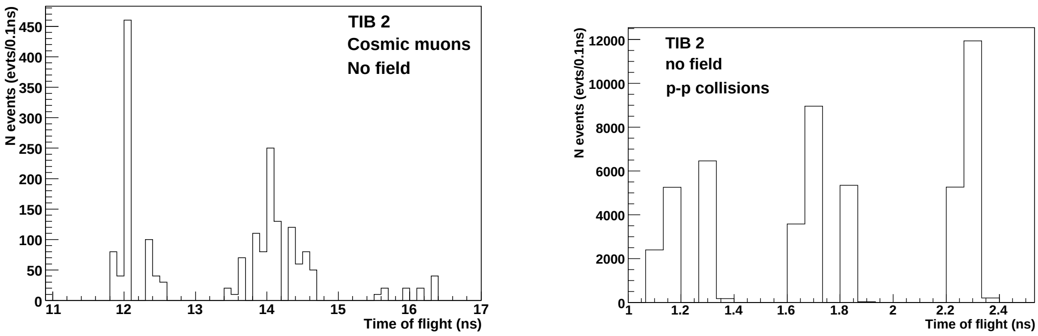
The aim of the present note is to establish the performance of the proposed method and to optimize the various parameters and cuts. Questions like the number of layers to study, the statistics and the needed commissioning time will be addressed.

This note is organized as follows. In Section 2, the procedure will be described and the key elements will be discussed. In Section 3, results of a toy Monte Carlo study will be presented. This provides an estimate of the statistics required to reach a given resolution. The commissioning time is then estimated in different scenarios using full simulation of the CMS tracker in Section 4. The method is finally confronted to real data obtained during the commissioning of tracker subdetectors in Section 5.

2 Description of the procedure

The overall synchronization procedure has been sketched in the introduction. The critical step that the present work is concerned with is the "fine delay scan per detector layer" that results in the final synchronization of each module with the central trigger. That delay scan proceeds as follows:

1. With a 50ns rising time, the CR-RC pulse spreads over several bunch crossings and its absolute position is less precise than the one of the 25ns width pulse in deconvolution mode. This is why one layer is set in deconvolution mode. Other layers are left in peak (RC-CR) mode to guarantee high efficiency out of time and serve as a telescope.
2. Events are accumulated and tracks are reconstructed.
3. The charge deposited on the leading strip in the vicinity of the crossing point between each reconstructed track and the studied layer is recorded.
4. Steps 2 and 3 are iterated while scanning the PLL delay by steps of a few nanoseconds on the targeted layer.
5. The recorded deposited charged is distributed as a function of delay, subtracting the *estimated* time-of-flight of individual particles. The distribution obtained that way is fitted using a deconvoluted RC-CR function as described in [3]. That eliminates biases due to the skewness of the APV response.
6. The delay is set to match the maximum of the fitted function, adding back the *mean* time of flight of high-Pt particles individually for each module.



(a) (b)

Figure 2: Time of flight for particles crossing the second TIB layer in the case of (a) cosmic muons and (b) p-p collisions. Both simulations were performed without magnetic field.

2.1 Use of tracking

Reconstructing tracks and considering hits belonging to these tracks has several advantages and reduces uncertainties. The time of flight can be computed independently for each track, potentially taking into account things like the reconstructed primary vertex and the track curvature, when there is a magnetic field. That time of flight can be subtracted from the delay between the central trigger and the module clock. Statistics is therefore accumulated merging hits on all sensors of the layer of interest. Since the time of flight is subtracted, the resulting tuning is equivalent to considering only high Pt tracks, even if relatively low Pt tracks are used.

The amplitude of the expected time of flight correction can be seen in Figure 2 for muons triggered by the CMS muon chambers. Simulation shows that differences are small for p-p collisions, but are significant for cosmic muons, where the time-of-flight is computed with respect to the upper muon chambers. In the case of cosmic muons, the distribution of time of flight shows two peaks corresponding to the upper and lower halves of the studied layer. In the case of p-p collisions, the spread is much more reduced, and one sees peaks corresponding to the eta position of modules within the layer. Since hits from stereo and phi modules are not matched, the hit position always corresponds to the center of the hit strip, which explains that discrete behavior.

Another advantage of that correction is that it allows the use of cosmic muons for an early tuning of the detector. As it will be shown in Section 4, the remaining jitter from the cosmic muon trigger has little impact on the delay scan. Also, the signal correction for to the crossing angle on each module can be applied.

2.2 Use of the leading signal

The main conclusion of [3] is that tuning the module on the maximum of the leading strip or on the maximum of the cluster gives significantly different results. It appears that tuning the modules on the leading strip gives the best performances by minimizing the cross-contamination from one bunch-crossing to the other (Figure 3).

During the delay scan, charge deposit on the leading strip is stored and the mean is considered for each step in delay. A pulse shape curve is reconstructed, and a fit around the maximum can be performed to extract the best delay.

2.3 Free parameters

There are several free parameters in the approach. These are either variants in the commissioning scenario or cuts applied to select the best data.

By construction, the method works on a given layer, using the rest of the tracker as a telescope in peak mode. The optimal delay is therefore obtained from the study of a single layer but can be applied to all layers - modulo the time of flight. This allows us to cross-check the result by computing the delay using

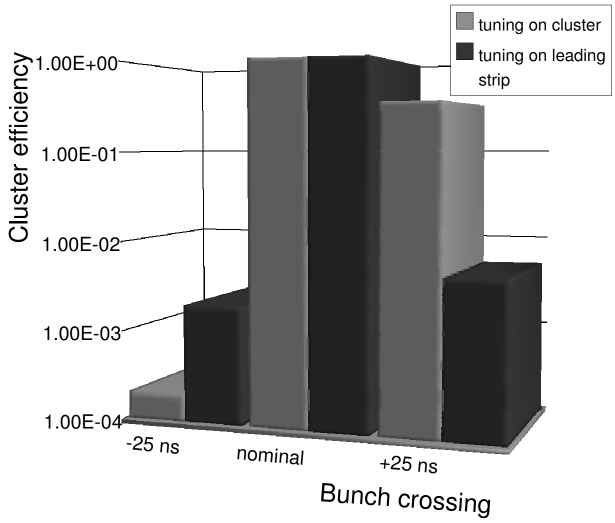


Figure 3: Typical cluster efficiency obtained using a synchronization on the cluster or on the leading strip. The efficiency is more symmetric when the leading strip is used as reference. From [3].

different target layers and by studying the compatibility of the obtained delay. The exact definition of the commissioning scenario therefore includes the choice (number and position) of layers to be studied

Then, the data quality is controlled by the cuts on the transverse momentum of the tracks used for the analysis, on the crossing angle of the track on the target layer and on the residual of the cluster with respect to the track. The Pt cut also suppresses the differences in energy deposit for the various particle types. The present study shows that results are not very sensitive to the cut used. The following conservative values are used when not stated otherwise.

- Maximum crossing angle of the track on the target layer: 45°
- Minimum track momentum: 3 GeV/c
- Maximum residual: 5mm

2.4 Choice of the working point

As already mentioned, the measured time-of-flight is subtracted when considering the signal profile (step 5 in the procedure) - that allows to combine the signal from different modules - and the mean time-of-flight of high-Pt tracks is added back when computing the optimal delays (step 6). The net effect is that the time-of-flight difference with respect to high-Pt tracks is compensated when computing the optimal delay. The probability to see hits in the next bunch-crossing is thus minimized for hits from high-Pt tracks, tracks more often used in physics analysis. That approach reduces the impact on physics objects used offline, but do not minimize the occupancy. Should the occupancy effect be critical, the outcome of the procedure could be corrected to reflect the time spent by low-Pt particles on their bent trajectories. This is not expected to be the case.

3 Toy Monte Carlo studies

A toy Monte Carlo simulation has been designed to evaluate the reach of the fine delay scan procedure. The main issue is the statistics required to reach the goal resolution of 1ns. Charge deposited in the tracker is simulated following a Landau distribution [4]. The effect of non-nominal delay between the trigger and the module clock is included by reducing the amplitude according to the nominal deconvoluted pulse shape obtained in [3], including drift-time effects. A pseudo experiment is then defined as a delay scan with a fixed stepping. The pulse shape obtained is fitted as planned in the commissioning procedure, and the maximum of the fitted function is recorded. A large number of such pseudo-experiments is performed to extract the intrinsic resolution as a function of the statistics accumulated in each step of the delay scan (Figure 4).

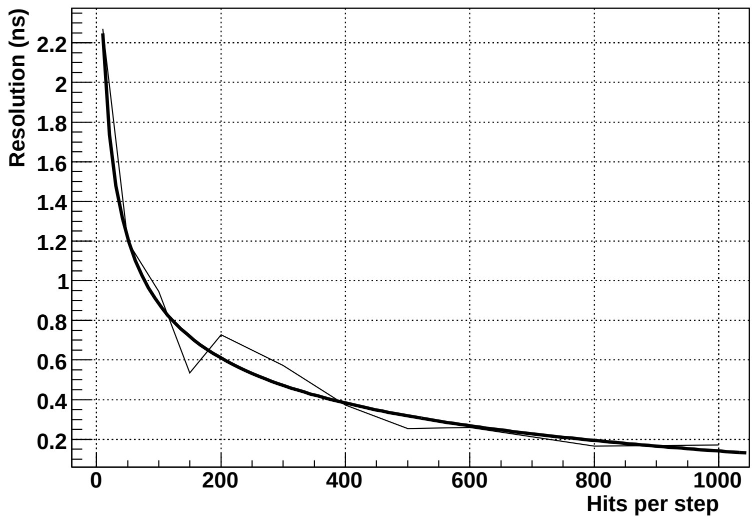


Figure 4: Resolution as a function of the statistics accumulated in each step of the delay scan.

It appears that a resolution better than 1ns is quickly obtained (after less than 100 hits per step). Accumulating 500 hits per step even pushes the 1ns bias at more than three standard deviations which also corresponds to the intrinsic jitter expected from the initial synchronization using tick marks. That value will be used in the following.

4 Full-detector simulation

In order to go from statistics requirement obtained in Section 3 to an expected commissioning time one needs an estimate of the hit rate in the different tracker layers, for different types of trigger conditions. A full simulation of the CMS detector has been used for that purpose, using version 1.2.0 of the CMS simulation and reconstruction software [5]. During the simulation, the actual commissioning procedure has been used to select suited hits.

4.1 Data samples

The tracker commissioning can be performed using any event providing energetic transverse tracks. The two main classes of such events are cosmic rays, where muons coming from above are crossing the tracker volume, and p-p interactions where tracks are coming from the center of the detector.

Cosmic muons can be used during the start-up phase of the accelerator, when no or few collisions are occurring. The advantage is that such events are occurring continuously, so it can be used as soon as the tracker is operational. The main drawbacks are the additional jitter with respect to the central clock and trigger, and the verticality of such tracks that reduces the statistics in endcaps. Cosmic muons were generated in the tracker volume for a detector underground in the CMS cavern without magnetic field.

In order to evaluate the potential of p-p events, a few key samples corresponding to the dominating signals after High Level Trigger (HLT)[6] have been considered. The aim is to study the behavior of the algorithm for some key representative signals, not to reproduce the actual event mix after trigger. Therefore, QCD events generated with $\hat{P}t \in [50, 80]$ GeV/c, $W \to e\nu$ and $Z \to \mu\mu$ samples have been studied. Events considered are simulated with magnetic field and low-luminosity ($2\,10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) pile-up at a center of mass energy of 14 TeV. The samples used and the statistics considered are presented Table 1.

4.2 Estimated commissioning time

Using the full simulation of the CMS tracker, and applying the actual commissioning procedure on the simulated data, the rate of interesting hits on each subdetector is obtained. Combining this information with the required statistics from the toy Monte Carlo study, the commissioning time in various scenarios can be estimated.

Table 1: Samples used and the statistics considered in the study of suited hits occupancy.

Sample description	Cuts	Number of events	HLT rate (Hz)
QCD di-jets	$\hat{Pt} \in [50, 80]$GeV/c	10000	55.3 ± 6.9 (without $\hat{Pt}$ cut)
$W \rightarrow e\nu$	$\|\eta\| < 2.7, Pt > 7$GeV	10000	9.7 ± 0.2
$Z \rightarrow \mu\mu$	$\|\eta\| < 2.5, Pt > 10$GeV	10000	1.5 ± 0.0
cosmics	$E > 2$GeV$, \|\theta\| < 80°$	10000	~ 10

Table 2: Hit occupancy (number of hits per layer) per trigger obtained on various detector layers after filtering for the various samples considered.

	TIB2	TOB4	TEC3	TID1
QCD di-jets	13.4	3.6	10.9	17.9
$W \rightarrow e\nu$	13.0	1.9	13.5	24.1
$Z \rightarrow \mu\mu$	14.6	2.7	14.2	25.6
cosmics	0.1	0.3	0.0001	0.002

Table 2 shows the hit occupancy per trigger after filtering for the various samples considered. In the case of cosmic runs, it appears clearly that both the TID and the TEC are unusable for any measurement. One could nevertheless use information from these layers with a low statistics to cross-check results from the barrel layers. Considering a scenario where TIB2 and TOB4 are successively used, the commissioning procedure would take 100 minutes.

To illustrate the procedure on cosmic events, the result of a delay scan emulated on Monte Carlo Cosmic events is depicted in Figure 5. In that scenario, the delay scan was performed taking 500 triggers for each step. Given the occupancy results above, about 50 hits are available for each value of delay. This corresponds to an expected resolution of 1.3ns, and to 15 minutes of data taking. The result of the fit is an offset of 1.1ns with respect to the correct value, which is fully compatible with these assumptions.

In the case of p-p runs, hits are more uniformly distributed among the tracker. Forward disks can therefore be used efficiently. It is interesting to note that the occupancy of interesting hits does only marginally depend on the event type. Commissioning time estimates therefore only relies on the trigger rate that can be obtained, as well as on the fraction of events sent online to the commissioning process. We will here use a value of 1Hz for the net event rate to the commissioning process. It is a reasonable estimate of what can be achieved in the early days [7]. It is trivial to adapt the results to other rates. Con-

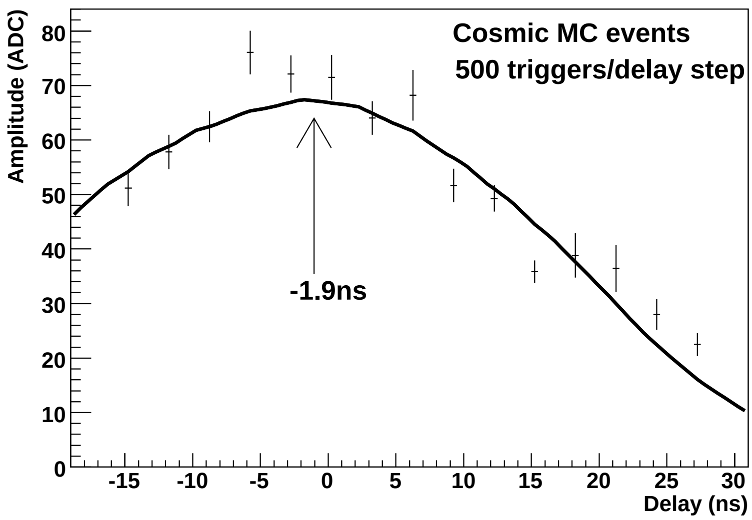
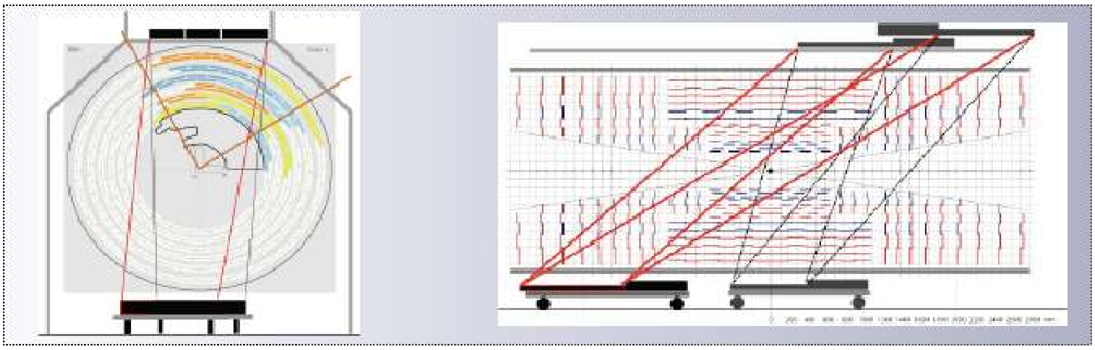


Figure 5: Result of a delay scan emulated on Monte Carlo Cosmic events corresponding to 15 minutes of data taking. The commissioning procedure is applied and the pulse shape is localized at t=-1.9ns while it was simulated at t=-3ns.



(a) (b)

Figure 6: Test configuration at the tracker integration facility. (a) Transverse view of the tracker barrel, with the active TIB and TOB modules highlighted. (b) Position of the plastic scintillators around the tracker tube.

sidering a scenario where TIB2, TOB4, TID1 and TEC3 are used, the commissioning procedure would take 50 minutes. Using a more complex data-taking scheme where more than one layer would be in deconvolution mode would allow to reduce that time to about 30 minutes, which is not significant. The simple scheme where a single layer is studied per run is therefore preferred.

5 Analysis of commissioning data

Data obtained at different level during the detector integration are now available. In particular, several "slice tests" were performed at the Tracker Integration Facility (TIF), from January to July 2007. After integration, a cosmic trigger system has been installed in order to record events containing cosmic muons. As part of that trigger system, plastic scintillators were installed above and behind the tracker tube, as depicted in Figure 6 [8].

Results were obtained for the fine delay scan in July 2007 using a configuration where about 12.5% of TIB and TOB are powered and read out together. The run was done using TOB layer 4 as studied layer. The scan was done starting from 25ns before the latency indicated by the coarse latency scan, and going on by steps of 2ns. 200 triggers were accumulated for each delay step. In order to accommodate the special operating condition with the cosmic trigger at the tracker integration facility, notably the absence of magnetic field, no cut on the track angle or on the track momentum have been applied. The result of that scan is presented in Figure 7.

From the analysis, the optimal latency is determined with a precision of 0.5ns at 6.4 ns from the working point chosen by the coarse latency scan.

That test validated the online commissioning procedure. Compared to previous results, this shows also that effects like charge sharing, Lorentz angle or cross-talks between adjacent channels do not impact the performances of the procedure.

6 Conclusions

A method to tune the delay between the central trigger and the CMS tracker clock has been presented. Performance of the method have been established by the use of toy Monte Carlo and full detector simulation. Questions like the number of layers to study, the statistics, the resolution and the commissioning time have been addressed. It turns out that the proposed method can optimize the delay with a precision below 1ns in a reasonable amount of time.

Such a precision results in a gain in performances for physics by reducing the fake rate in the detector due to remnant hits from previous bunch crossings. The method is implemented as a standard commissioning procedure for the CMS silicon tracker and has been validated during the Tracker Integration Facility tests.

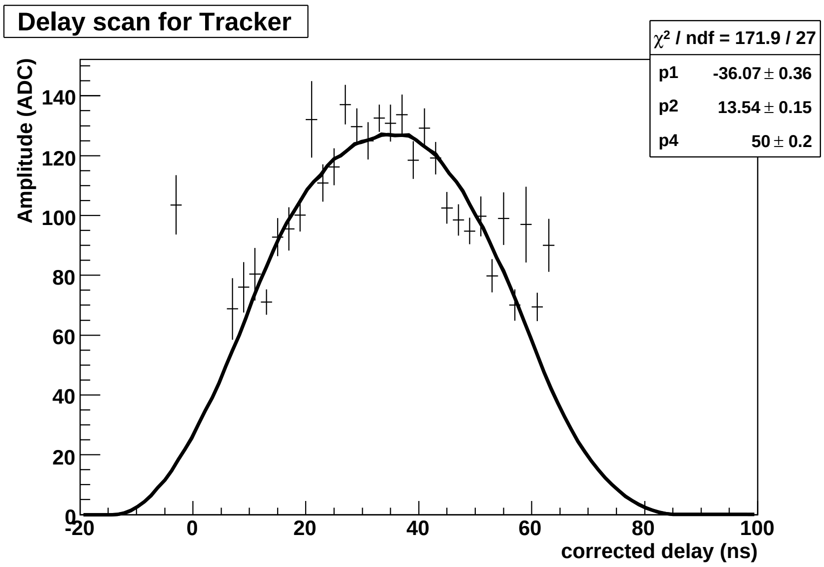


Figure 7: Result of a fine delay scan on the TIB+TOB slice test configuration. The mean amplitude is plotted as a function of the delay, after correction for the time of flight. The commissioning procedure is applied and the pulse shape is localized at t=33.7 ns

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