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Development of a Level 1 Track Trigger for the CMS experiment at the high-luminosity LHC

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ABSTRACT

Over the next decade, several upgrades in the LHC and its injector chain will eventually increase the luminosity by up to a factor of 10 compared to the original design figure of 10^{34} cm^{-2} s^{-1}. In order to cope with the large number of interactions per bunch crossing, a novel tracking system for the CMS experiment will be designed and built. The new tracker will also provide information to the Level 1 trigger decision, in order to improve the ability of selecting interesting physics channels in a higher density environment. The CMS collaboration is developing a novel module concept ("p_T-module"), where signals from two closely spaced sensors are correlated in the front-end electronics, to select pairs of hits compatible with particle p_T above a certain threshold. Selected pairs of hits, called "track stubs", represent between 5% and 10% of the overall data rate: such a reduction factor enables the data processing at Level 1. Two main types of p_T-modules are being developed, one based on strip sensors, and the other coupling a strip sensor with a pixelated sensor, which provides also precise information in the z coordinate. The main features of the p_T-module options under development are reviewed, as well as the benchmark results from simulation studies.

1. Introduction

By the end of 2012, the LHC experiments have not found any signal of physics beyond the Standard Model yet, in data collected at $\sqrt{s}=7$ and 8 TeV with proton–proton collisions. The results which will be obtained during the future runs at 13 and 14 TeV will eventually set the basis for the future of particle physics studies with colliders. The CMS collaboration is preparing to pursue the search for the most rare processes with a high-luminosity LHC (HL-LHC). Such a scenario will be characterized by an increasingly challenging pile-up environment (PU), in which the current detector performance can be retained only through major upgrades of the different CMS subsystems.

The number of minimum-bias events per bunch-crossing, with a luminosity leveled to about 5×10^{34} cm^{-2} s^{-1} at $\sqrt{s}=14$ TeV, is expected to be about 140, with several thousands of charged particles traveling the tracking volume. In such a scenario, the Level 1 trigger (L1) rate at CMS is expected to exceed its design limit, which is currently 100 kHz [1]. With the current L1 based on primitives from muon system and calorimeters, the thresholds required to cope with the maximum allowed bandwidth would be too high. A remarkably better resolution is needed to keep the thresholds low and collect a significant amount of events for the CMS physics program. The inclusion of tracker information, which is currently used only at the High-Level trigger, in the L1 decision, can provide the necessary resolution, as shown in Fig. 1, left. This would be possible only with the design and construction of a novel tracking system, capable of providing information for the L1 trigger. Such tracker should maintain high reconstruction efficiency and low fake rate, hence featuring high granularity to keep occupancy below a level ~0.01, and it should withstand a harsh radiation environment. In addition, its performance as part of L1 should include a precise measurement of muon p_T to allow for a sharp threshold at $p_T\sim O(10)$ GeV, the possibility to match track to calorimeter L1 candidates and isolate electrons, $\tau-$leptons and photons, and the possibility to associate objects to their corresponding primary vertex to reduce fakes from PU.

2. The concept of Level 1 Track Trigger

The Track Trigger can be seen as a two-steps process. The first step aims at reducing the data rate at the front-end, by using cluster width and local p_T information, rejecting up to 95% of tracks from minimum-bias events, as shown in Fig. 1, right. The second step employs a real-time tracking facility that reconstructs tracks at L1 from the non-rejected hits.

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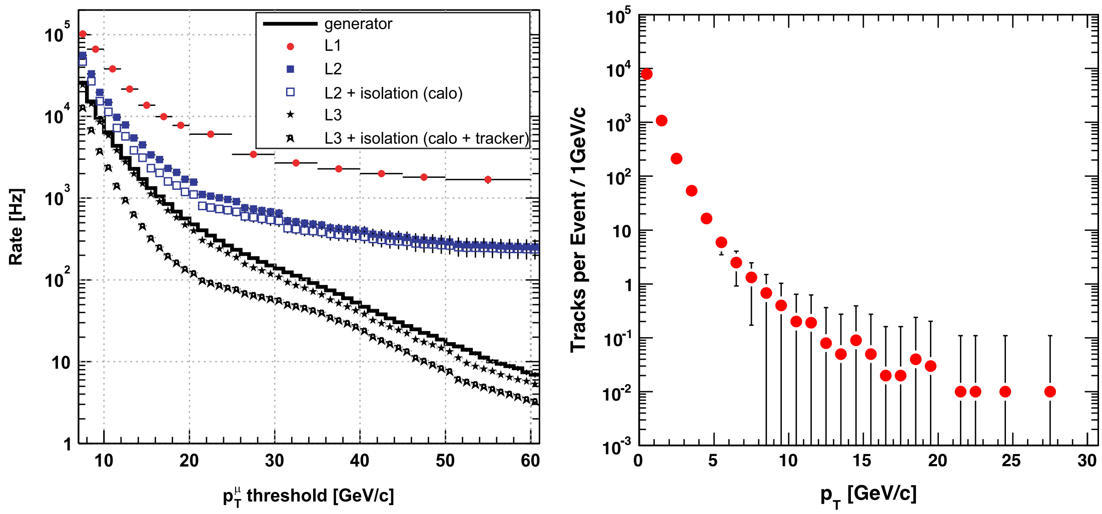

Fig. 1. Left: effect of the different p_T resolution in L1 and high-level muon triggers on the trigger rate as a function of the threshold applied. A rough estimate of the behavior at HL-LHC can be obtained by rescaling the expected L1 muon rate, at nominal 14 TeV LHC conditions, by a factor 10. In such a case, only a tracker-grade resolution, such as the one of the L2 and L3 in HLT, can keep the threshold low enough to accept events of physical interest and the rate low enough to cope with the data-acquisition limits [2]. Right: p_T spectrum of the average number of tracks per event reaching a layer 25 cm from the beam line in simulated minimum-bias events. Less than 10% of the tracks have a p_T greater than 2 GeV/c. Imposing such a threshold at the front-end could reduce by a factor 10 the data rate to be processed by the L1 trigger.

The p_T-module concept is at the roots of Track Trigger. Such a module features two closely spaced silicon strip or pixel sensors and a front-end that can perform local p_T reconstruction measuring the relative transverse displacement of narrow clusters in the two sensors. This result can be achieved, in the current field of the CMS solenoid, with sensors separated by few mm and strip or pixel pitch of about 100 μm. Accepted pairs of clusters are called *track stubs*. A graphical representation of the process is shown in Fig. 2, including the kind of correction needed to compensate for the misalignment of hits due to the flatness of the modules and their orientation.

There are three main types of p_T-modules under evaluation [3]. One type of module, called 2S (2-Strip-sensors), features two identical silicon microstrip sensors which share the same ROC (Read-Out Chip) array, which is designed to perform the stub-finding cluster correlation. The size of the strips in the current design of 2S modules is 90 μm × 50.2 mm. Two other types of modules, called respectively PS and VPS (Pixel-plus-Strip) couple a strip sensor to a pixelated sensor. The PS module features two separate ROC arrays for strips and pixels. The pixel ROC array is bump-bonded to the pixel sensor and designed to perform the stub finding cluster correlation. The size of the strips and pixels in the current design of PS modules are 100 μm × 23.1 mm and 100 μm × 1.446 mm, respectively. The VPS module is a particular version of the PS module, featuring vertically integrated electronics (Vertical-PS). The VPS modules are being developed specifically for one particular layout, called the "LongBarrel", which is dedicated to L1 track finding and which is composed of long interlocking rods (see Section 5 and Fig. 4). Fig. 3 shows three-dimensional representations of 2S and PS modules.

The 2S and PS/VPS modules are complementary in a HL-LHC tracker layout. While all of them can perform the local p_T reconstruction necessary to implement the Track Trigger, the PS and VPS modules will additionally measure the position of the stubs, in the direction of the beam line, with a resolution of $O(1)$ mm, at distances shorter than 60 cm from the beam line, where the track density is higher. This feature will help in identifying the primary vertex of the event and in isolating relevant trigger objects from the pile-up.

The development of 2S modules already established benchmarks in most of the critical aspects of the design, which will be summarized in this contribution; the design of PS and VPS modules is at an earlier stage, due to the exploration of new technologies to be used, such as CMOS 65 nm for the PS modules front-end and 3D vertical integration for VPS modules. For this reason, this contribution will mainly focus on the development of 2S modules.

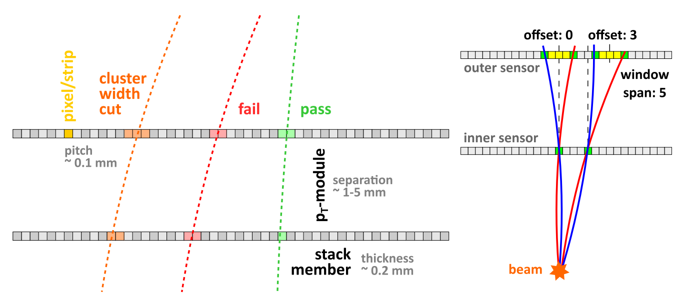

Fig. 2. Left: sketch of the Track Trigger basic idea. A track with p_T≈2 GeV/c, in the 3.8 T magnetic field of the CMS solenoid, produces hits in two closely spaced sensors, positioned at a distance of 30–100 cm from the beam line, which have a relative displacement in the transverse plane that can be measured with a pitch-to-separation ratio of about 1-to-10. Right: sketch of the position-dependent offset and matching window span in stub finding. The stub finder window is centered on the radial projection of the innermost hit onto the outermost sensor. In the areas which are far away from the center of the sensor, where the projection falls out from the channel corresponding to the innermost hit, an offset must be applied to preserve the stub finding efficiency.

3. Mechanics and cooling

One of the main challenges in the design of a novel tracker module is represented by its mechanical support, which must be lightweight to minimize the amount of passive material, and which must be also optimally coupled to the pipes in which the cooling fluid flows.

The support structure of the p_T-modules is based on two bridges which keep the sensors aligned and separated by the chosen distance. Different options have been explored for the design of support bridges. In particular, the possibility of using a support bridge made of carbon-fiber (CF) strips coupled to graphite sheets and a foam spacer, joined to the cooling pipe with aluminum feet, has been studied. Such a design turned out to be at risk of shear stress, which could cause delamination of the graphite sheets and loss of thermal contact between the module and the aluminum feet. For this reason, the option of a hollow