The Drift Tube Track Finder Trigger at the CMS Experiment

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Abstract

The Compact Muon Solenoid (CMS) is a general purpose experiment designed to study proton-proton collisions at the Large Hadron Collider (LHC). The CMS L1 Trigger must select interesting collisions at a rate smaller than 100 kHz. The CMS Drift Tube Track Finder (DTTF) Trigger performs a full muon tracking analysis in real time for the CMS L1 Trigger. The DTTF trigger motivation, electronic implementation, and expected performance are presented.

I. Introduction

At the Large Hadron Collider (LHC) muons of large transverse momenta are expected to play a crucial role in the physics under study. The Compact Muon Solenoid (CMS) is a general purpose experiment designed to study proton-proton collisions at the LHC. There, proton beams will cross each other at a rate of 40 MHz, producing in average 20 p-p interactions. The CMS L1 Trigger must select interesting collisions at a rate smaller than 100 kHz. In this report we describe the Drift Tube Track Finder (DTTF) Muon Trigger. More information about the CMS L1 Trigger in general, and the other trigger subsystems in particular, can be found in [1].

CMS will combine three different technologies for precise muon detection and efficient triggering [2]: drift tube (DT) chambers in the barrel region ($|\eta| < 1.2$), cathode strip chambers (CSC) in the forward region ($0.8 < |\eta| < 2.4$), and resistive plate chambers (RPC) in both regions ($|\eta| < 2.1$). Fig. 1 shows a longitudinal view of the CMS muon detectors. The DT muon chambers are located in the gaps of the barrel iron yoke. The yoke is organized in five wheels along the detector axis. Each wheel is divided in twelve 30^o wedges in azimuth, and four concentric stations in the radial direction: MB1, MB2, MB3, MB4. In every station in a wedge, one DT muon chamber contains twelve layers of drift cells organized in two $r-\phi$ superlayers and one $r-z$ superlayer (except the MB4 chambers that do not contain $r-z$ superlayer).

The information delivered by the DT muon chambers is processed by the DT L1 Muon Trigger, which is divided into a DT Local Trigger and a DT Regional Trigger. Hits in the DT muon chambers are first organized in segments and assigned a beam crossing (BX) by the DT Local Trigger (BTI, Traco and Trigger Server subsystems). The Sector Collector gathers the segments in the four stations of a sector, synchronizes them, and sends them, via optical links, to the DTTF crates in the Counting Room. The performance of the DT Local Trigger was measured at the 2003 and 2004 Beam Tests [3, 4]. Beam test results relevant for the present report are the measured DT Local Trigger efficiency of 99% for DT fiducial muons and the Traco position resolution of about 0.5 mm.

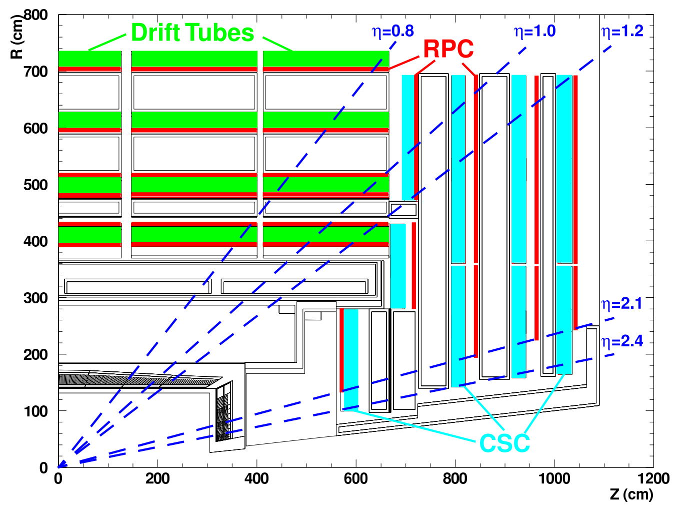

Figure 1: *Longitudinal view of the CMS muon system.*

The DTTF system implements the DT Regional Trigger. Taking advantage of the large (order 2 T) CMS return magnetic field, it is possible to go beyond the conventional coincidence analysis. The DTTF performs a full muon tracking analysis in real time for the CMS L1 Trigger.

II. The Drift Tube Track Finder Trigger

The task of the Drift Tube Track Finder Trigger is to reconstruct tracks consistent with the trajectory of a muon, to assign them physical parameters, to select the best four muons in the barrel detector, and to output them to the Global Muon Trigger for further processing [1].

The DTTF Trigger is physically realized using a sophisticated electronic system. Its segmentation replicates the CMS barrel detector geometrical structure (Fig. 2). The system is organized in twelve modules stored in six 9U crates. Each module processes the information that originated in a 30^o wedge of the barrel detector. One module is formed by eight boards : six Phi Track Finder (PHTF) sector processors (one PHTF for wheels ±1 and ±2, and two PHTF boards for wheel 0), one Eta Track Finder (ETTF), and one Wedge Sorter (WS). Two modules share the same crate and the same VME Controller, Timing, and Data Link Interface (DLI) boards. In addition, a seventh crate contains the Barrel Sorter (BS), Data Concentrator Card (DCC), VME Controller, and Timing boards.

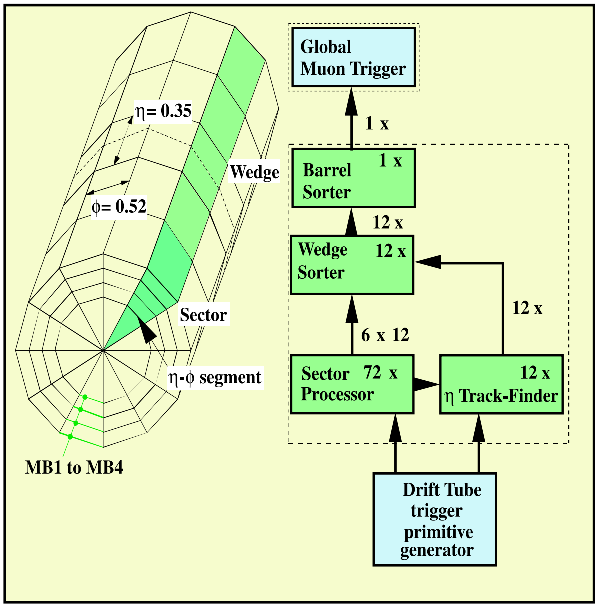

Figure 2: *Logical segmentation and block diagram of the DTTF Trigger.*

A. The Phi Track Finder

The Phi Track Finder (PHTF) processors reconstruct muon tracks in the $r - \phi$ plane. The PHTF track finding algorithm is implemented in three logical steps (Fig. 3):

- **Extrapolation:** In the first step the sector processor tries to match pairs of track segments (delivered by the DT Local Trigger) according to an extrapolation principle, i.e. the correlation between the change in the azimuthal coordinate ($\Delta\phi$) and the bending angle (ϕ_B). Using the spatial position, ϕ, and the angular measurement, ϕ_B, of a track segment in a Muon Barrel (MB) station, the extrapolated coordinate in an outer MB station can be calculated. Attending to this principle, an extrapolation is considered successful when the spatial position in the target MB is found to be inside a 99%-efficient extrapolation window. Windows are downloaded to the hardware in the form of Look-Up-Tables (LUTs).
- **Track Assembling:** The results of the extrapolation process are used in the track assembling step, where all consistent extrapolations are assembled together to form tracks. Depending on how many track segments and from which MB they come from, the PHTF will assign them a quality code.
- **Parameter Assignment:** Finally, the two reconstructed tracks with best quality codes are assigned muon physical parameters: 5 bits of transverse momentum (p_T), 8 bits of ϕ position, 1 bit of electric charge, and 3 bits of quality.

  The two inner muon stations with a valid extrapolation are used as a magnetic spectrometer for transverse momentum assignment: the value of p_T is estimated from the measured value of $\Delta\phi$ using a relation stored in hardware LUTs.

  The muon azimuthal coordinate (ϕ) is assigned attending to the local ϕ value measured at MB2. If no actual track segment was found at MB2, extrapolation from MB1 or MB4 is used to predict the ϕ position of the muon track at MB2. Again, this is implemented using LUTs which are downloaded into the hardware.

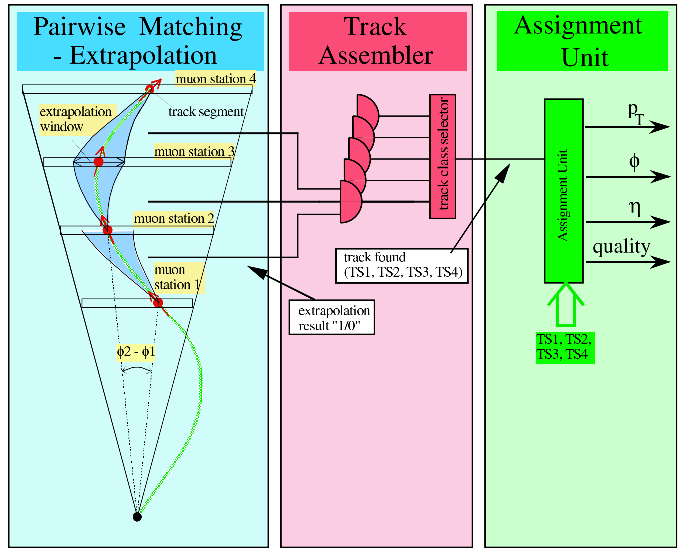

Figure 3: *Schematic representation of the PHTF three-step algorithm.*

The PHTF processors are 9U VME boards (Fig. 4). The complete implementation is based on synthesizable behavioral VHDL code. In the final design, one big Altera Stratix EP1S40 FPGA (1020 pins) mounted on a mezzanine board, accommodates the full track-finding algorithm and LUTs. This solution is referred to as System-on-Chip (SOC). For practical reasons, only the Input Receiver block is implemented in a different Altera Stratix EP1S10 FPGA (780 pins). Every PHTF finds up to two transverse tracks after 475 ns.

The number of PHTF inputs/outputs is considerable. One PHTF receives 506 bits/BX: 110 bits/BX via optical inputs from the Sector Collector, and the rest from PHTF interconnections. In addition, the outer wheel PHTF boards interchange segment information with the CSC. The outputs are 48 bits/BX to the WS, and 10 bits/BX for PHTF-ETTF interconnections.

The PHTF (and ETTF) boards contain a programmed Spy system, implemented as a synchronous, triggerable 512 BX-long ring memory accessible via a 2nd JTAG chain. At the board level, the Spy Master Trigger can be programmed with all possible situations at every step of the track-finding process. At the DTTF level, all Spies can be triggered simultaneously by an external L1 Accept condition. The Spy system allows to follow all the internal data flow in the board and, especially, to validate the trigger decision. The DTTF Local DAQ software system has been developed on top of the Spy hardware: Spy-DAQ. The DTTF Local software has been organized in maintenance, set-up, operation, monitoring and emulation modules. Spy-DAQ has been used intensively at the prototyping, test, quality control, and commissioning phases of DTTF development.

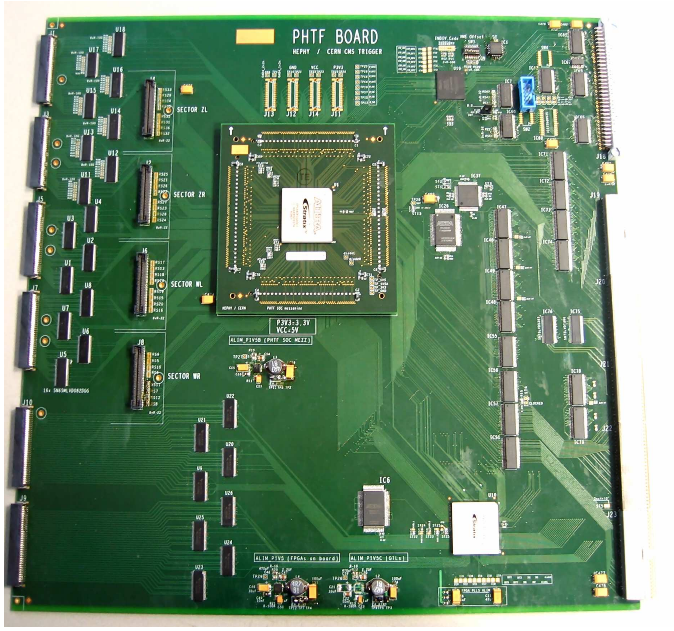

Figure 4: *Phi Track Finder production board.*

Production and quality control of the 72 PHTF boards needed for the final system, and 8 spare boards, finished in March 2006.

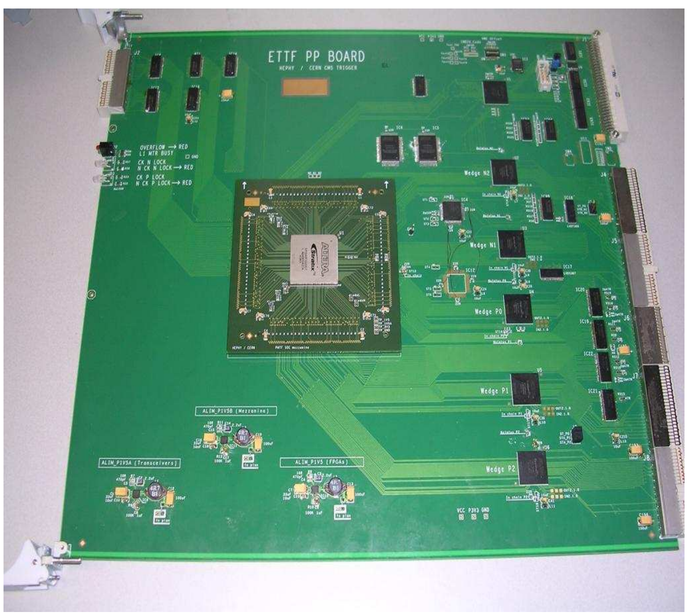

Figure 5: *Eta Track Finder production board.*

B. The Eta Track Finder

The Eta Track Finder (ETTF) processor task is to promote PHTF transverse tracks into full DTTF 3D muon candidates. In every wedge, the ETTF reconstructs the muon trajectory in the $r - z$ projection using data from the $r - z$ superlayers in the five MB1, MB2 and MB3 chambers.

The ETTF implements a pattern-matching algorithm, divided in three logical steps. First, patterns of $r - z$ segments are recognized among a predefined set (η-patterns). Second, η-patterns are matched to PHTF tracks. Finally, if the pattern matching step was successful, the PHTF track is assigned a fine value of the η coordinate. If no η-pattern could be matched, the ETTF can still assign a rough η value according to the place where the PHTF track crossed wheel boundaries.

The final ETTF 9U VME design (Fig. 5) adopted the SOC solution (Altera Stratix EP1S25, 1020 pins) for the pattern-matching algorithm. Five Altera Cyclone EP1C4 (324 pins), with independent timing, accommodate the five Wheel Input Receivers.

One ETTF receives 235 bits/BX from the DT Local Trigger, and 60 bits/BX from the PHTF processors in the same wedge. The outputs are 84 bits/BX to the WS.

Successful production and quality control of the 12 ETTF final boards, and 5 spare boards, was accomplished by April 2006.

C. The Drift Tube Sorters

The DT Sorters [5] select the four highest rank DTTF muons in the barrel detector, after a clean-up procedure (removal of PHTF duplicate tracks below the expected dimuon trigger rate), and forward them to the Global Muon Trigger. The highest rank muons are those with highest quality and highest transverse momentum. The sorting process is implemented in two steps:

- **Wedge Sorter:** In every wedge, one Wedge Sorter (WS) receives the addresses and muon physical parameter information from the six Phi Track Finder and Eta Track Finder processors. Using this information, it selects the two best muon tracks out of (at most) twelve candidates.

  Fig. 6 shows a WS 9U VME production board. See [5] for more information.

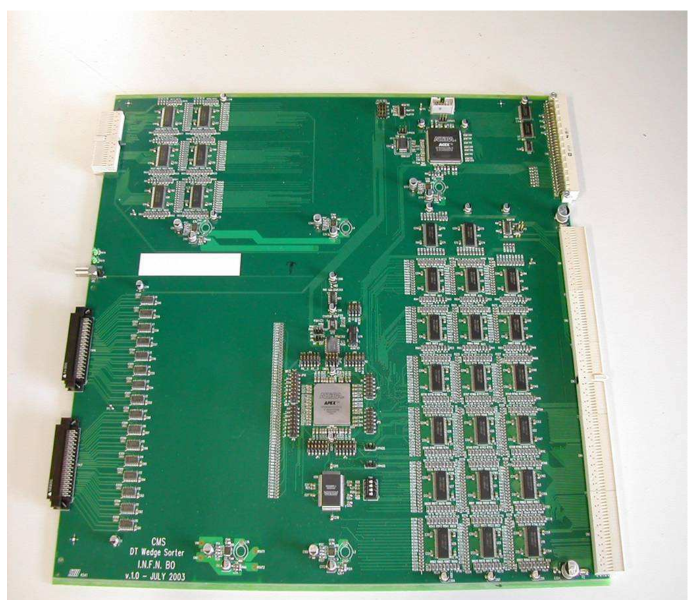

Figure 6: *Wedge Sorter production board.*

- **Barrel Sorter:** There is one DT Barrel Sorter (BS) for all the DTTF Trigger system. It selects the four highest rank muons among the (at most) 24 delivered by the 12 Wedge Sorters and forwards them to the Global Muon Trigger.

The BS hardware implementation (Fig. 7) accommodates all the logic in a big Altera Stratix EP2S130 FPGA (1508 pins) mounted on a mezzanine card. The rest of the 9U VME board is essentially used for the 24 input (744 bits/BX) and 4 output (128 bits/BX) LVDS connectors.

All final 12(1) WS(BS) boards, and 6(2) spare boards, have been produced and tested.

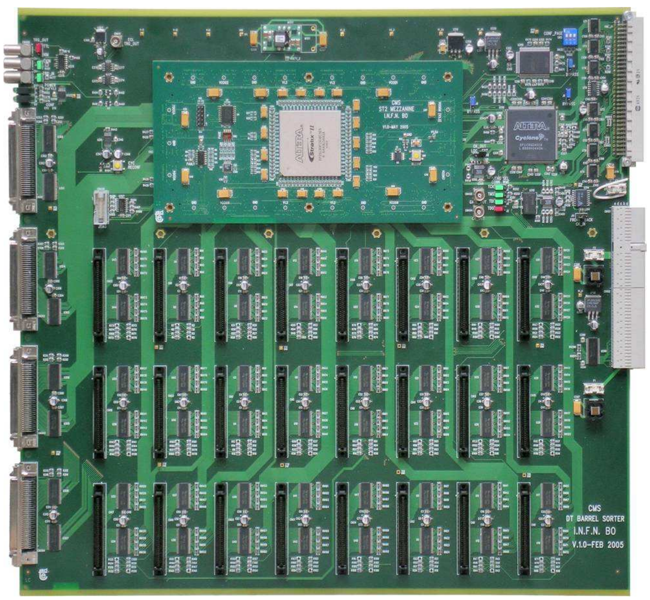

Figure 7: *Barrel Sorter production board.*

In addition, the Barrel Sorter can generate a trigger signal under programmable conditions. The BS input (i.e. the WS output) and output trigger data can then be validated using the 128 BX-long Spy memories. The BS trigger signal has been used at the MT/CC 2006 (see next Section), and will be the base of the DTTF Local Monitoring system at CMS.

D. DTTF Readout

The DTTF, as any other CMS subdetector, sends data to the CMS Central DAQ system at L1 Accept condition. The DTTF data record contains all the input and and output signals from the triggered BX, the previous one, and the next one. The total event size is 53.2 kbit, corresponding to a data rate of 635 MB/s at a maximal L1 trigger rate of 100 kHz. To comply with the maximal allowed average bandwidth of 200 MB/s, a zero-suppression algorithm has been worked out.

The hardware implementation starts with DAQ blocks in the PHTF and ETTF processors. The PHTF and ETTF boards in one crate send bit streams at L1 Accept to the DLI board. Information from the six DLIs is gathered by the DCC board at the seventh crate, and transmitted to the CMS DAQ using the CERN Slink-64 protocol.

III. DTTF TRIGGER PERFORMANCE

In this section, the DTTF Trigger performance highlights are presented.

In October 2004 the real DTTF Trigger behavior was studied using data at the CERN test beam [4, 6]. At this beam test all PHTF features, except Track Assembling, were validated.

In 2006, the DT Trigger (including the DTTF) has provided a 3-Sector Cosmic Trigger for CMS at the Magnet Test / Cosmic Challenge (MT/CC). The DTTF hardware setup included three PHTFs, one WS, and one BS. The software setup included Spy-DAQ, online monitoring, and a C++ bit level emulator program. In August, a total of 25 million DT events at 0 and 4 T, with the ECAL and Tracker in the readout, have been offered to the Collaboration. Just from the DTTF point of view, the MT/CC has been the first opportunity to validate triggers coming from long tracks, especially tracks changing wheels and/or sectors. Analysis of the data is underway.

In addition, the expected DTTF performance at LHC has been computed using simulated events [6]:

- **Efficiency:** The combined effects of efficiency and transverse momentum resolution are summarized in the 'turn-on' curves in Fig. 8, where the DTTF single muon trigger efficiency is represented as a function of the muon transverse momentum, for different transverse momentum thresholds. The plateau efficiency is 95%, only limited by the DT detector geometrical acceptance.

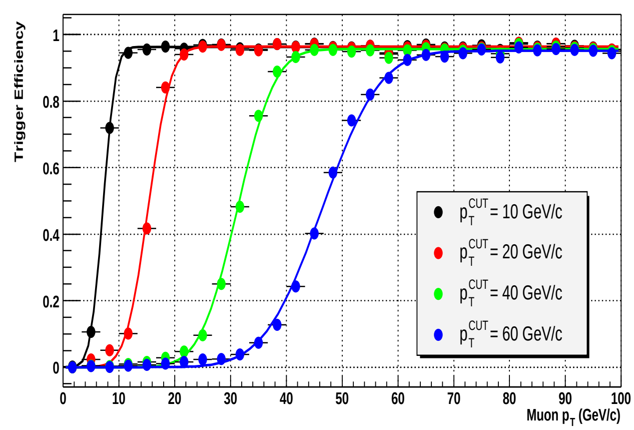

Figure 8: *The DTTF trigger efficiency as a function of the muon transverse momentum, for different p_T thresholds.*

- **Momentum resolution:** From the turn-on curves an overall transverse momentum resolution of 14% is obtained, dominated by dead material effects in the barrel iron yoke.
- **Position resolution in ϕ:** Resolution in phi is dominated by the PHTF output bin size (0.02 rad). The dimuon resolving power is limited by the DT Local Trigger segment position resolution.
- **Position resolution in η:** Resolution in the η coordinate is 0.03 (0.08) for fine (rough) assignment.

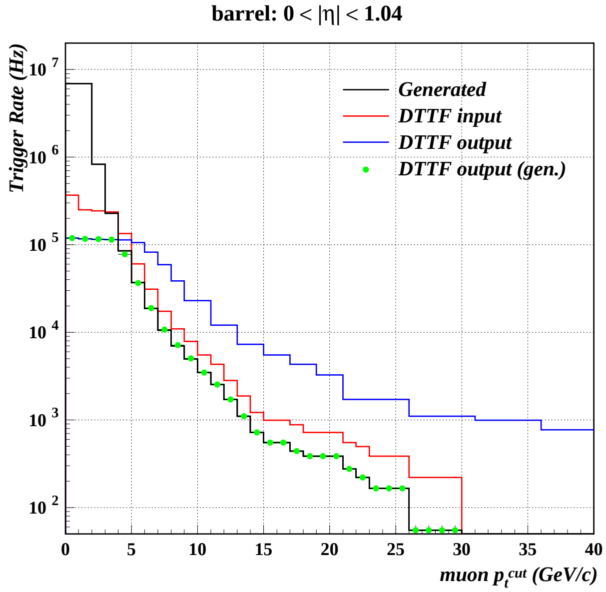

Figure 9: *Integrated inclusive muon DTTF trigger rates at nominal LHC luminosity, as a function of the muon p_T threshold.*

- **Trigger rate:** The accumulated inclusive muon DTTF trigger rate at nominal LHC luminosity, as a function of the transverse momentum threshold, is shown in Fig. 9. Output transverse momenta are assigned for 90% cut efficiency. At low-, intermediate-, and high-p_T the rate is dominated by real muons (decays-in-flight, heavy quarks, and vector bosons, respectively). For a transverse momentum threshold of 15(25) GeV the expected rate is about 6(2) kHz.

IV. Conclusions

In summary, the Drift Tube Track Finder Trigger has been presented. Its rationale, modus operandi, hardware implementation and software tools have been described. Finally, the system performance has been summarized; actual at beam tests and at the MT/CC, and expected at the LHC.

Production of the full DTTF system electronics is complete. Installation at the CMS underground Counting Room and integration with the rest of the CMS L1 Trigger will follow, to be ready for the 2007 LHC Pilot Run.

V. Acknowledgments

The results presented in this report are the result of the ingeniousness and diligent work of all the members of the CMS DTTF Collaboration.

The author acknowledges the financial support from the Spanish Ministry of Education and Science, under project number FPA2005-00780.

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