

Commissioning of the CMS DT electronics under magnetic field

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Abstract

After several months of installation and commissioning of the CMS (Compact Muon Solenoid) DT (Drift Tube) electronics, the system has finally been operated under magnetic field during the so-called CRAFT (Cosmic Run at Four Tesla) exercise.

Over 4 weeks, the full detector has been running continuously under magnetic field and managed to acquire more than 300 million cosmic muons. The performance of the trigger and data acquisition systems during this period has been very satisfactory. The main results concerning stability and reliability of the detector are presented and discussed.

I. THE CMS BARREL DRIFT TUBE SYSTEM.

The Compact Muon Solenoid (CMS) [1] is a general purpose detector designed to run at the highest luminosity at the LHC collider. The central feature of the CMS apparatus is a superconducting solenoid of 6 m diameter that generates a magnetic field of up to 4 Tesla. Such a high field was chosen in order to allow the construction of a compact tracking system on its interior, and still performing good muon tracking on the exterior.

Muons are measured in CMS by means of three different technologies of gaseous detectors. In the barrel, where the magnitude of the residual magnetic field is of the order of 2 Tesla in the iron return yoke and the neutron background and muon rate are expected to be as low as a few Hz/cm², DTs (Drift Tubes) are used [2]. The drift tube chambers are responsible for muon detection and precise momentum measurement over a wide range of energies. The DT system also provides a reliable and robust trigger system with precise bunch crossing assignment, complemented by a set of Resistive Plate Chambers (RPC) which provides redundancy in the trigger.

The DT chambers are installed in the five wheels of the return yoke of the CMS magnet (named YB-2, YB-1, YB0, YB+1 and YB+2). Each wheel is divided in 12 sectors each covering $\sim 30^\circ$ around the interaction point and each sector is organized in four stations of DT chambers named MB1, MB2, MB3 and MB4 going from inside to outside, where MB stands for Muon Barrel. There are a total of 250 DT chambers in CMS. A schematic view of one CMS wheel is shown in figure 1.

A DT chamber is made of three (or two in MB4) Superlayers (SL), each made by four layers of rectangular

drift cells staggered by half a tube width. The wires in the two inner and outer SLs are parallel to the beam line and provide the track measurement in the magnetic bending plane (r, ϕ). In the central SL, the wires are orthogonal to the beam line and measure the θ position along the beam. The central θ -measuring SL is not present in the MB4 chambers, which therefore measure only the ϕ coordinate.

The basic element of the DT chamber is the drift tube, which has cross section dimensions of 13 by 42 mm. The total number of sensitive cells is around 172,000. Any charged particle going through a cell volume will generate a signal (hit) in its anodic wire that will be amplified and discriminated by the front-end electronics before being sent to the read-out boards in order to perform time digitalization. The position of the charged particle can be related to the time measurement since the drift velocity in the cell volume is constant. Each cell provides a resolution of 250 μm , and the 100 μm target chamber resolution is achieved by the 8 track points measured in the two (r - ϕ) SL.

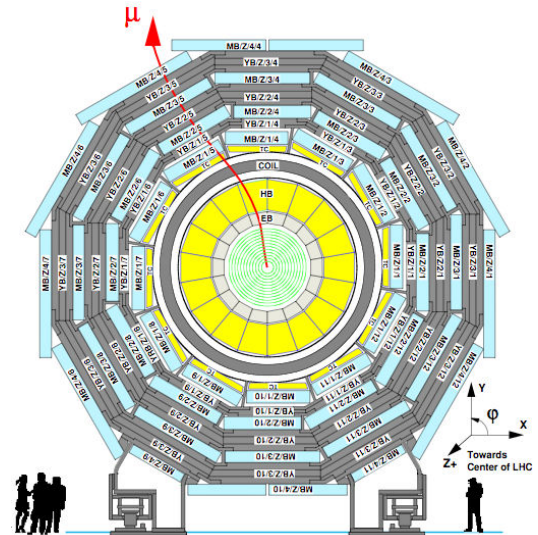


Figure 1: Transverse view of a CMS Barrel Yoke Wheel.

A. DT Read-out Electronics

DT read-out electronics is designed to perform time measurement of the chamber signals that will allow the reconstruction of charged particle tracks. There are several levels of data merging in order to achieve a read-out of the full detector at a Level-1 trigger rate of 100 kHz.

A schematic view of the read-out chain is shown in figure 2. First elements are the ROBs (Read Out Boards), based on the ASIC HPTDC (High Performance Time to Digital Converter), that perform the time digitalization of the hits coming from the chambers and assign them to the Level 1 trigger. They transmit their data through a ~30 meter copper link to the 60 ROS (Read Out Server) boards located in the tower racks in the cavern. ROS boards are in charge of merging the information from one sector and perform several tasks of data reduction and data quality monitoring. Each sector event is retransmitted through an optical link to the DDU (Device Dependent Unit) boards located in the counting room. The DDU boards merge data from up to 12 ROS to build an event fragment and send it to the global CMS DAQ through an S-LINK64 output at 320 MBps. These boards also perform errors detection on data and send a fast feedback to the TTS (Trigger Throttling System).

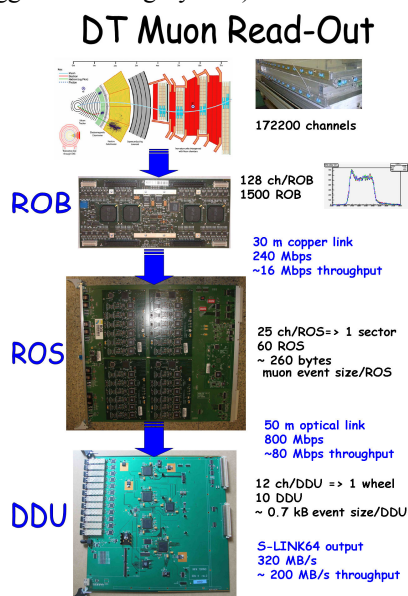


Figure 2: Schematic view of the DT Read-Out chain.

B. DT Trigger Electronics

The purpose of the DT trigger system is to provide muon identification and precise momentum measurement, as well as bunch crossing identification. It provides an independent Level-1 muon trigger to the experiment, selecting the four best muon candidates on each event.

The first level of the DT trigger chain is located inside the so-called Minicrates, an aluminium structure attached to the DT chambers that houses the ROBs, the Chamber Control Board (CCB) and the first level of the trigger electronics: the Trigger Boards (TRB) and the Server Boards (SB).

TRBs contain the Bunch Crossing and Track Identifier (BTI), which provides independent segments from each chamber SL, and the Track Correlator (TRACO), which correlates ϕ segments in the same chamber by requiring a spatial matching between segments occurring at the same bunch crossing. TRB output signals are fed to the SB which selects the best two tracks from all TRACO candidates.

Track segments are sent to the Sector collector boards in the tower racks, that perform trigger synchronization and send the encoded information of position, transverse momentum

and track quality through high-speed optical links to the DT Track Finder (DTTF) in the counting room. DTTF is divided in ϕ and η track finders that build full muon tracks and forward the data to the wedge and muon sorters that provide the best four muon candidates to the global muon trigger. There are different spy modes all over the chain in order to verify correctness of the data.

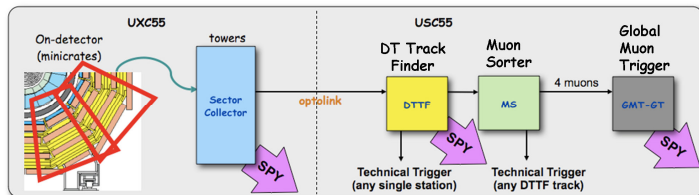


Figure 3: Schematic view of the DT Trigger chain.

II. DETECTOR INSTALLATION AND COMMISSIONING

The 250 chambers which form the complete CMS Barrel DT System were assembled in four production laboratories (RWTH Aachen, CIEMAT Madrid, INFN Padova and INFN Torino) which shared the work following the four different typology of chambers. In parallel to chamber assembly, parts assembly and electronics design was carried out in other laboratories (INFN Bologna – IHEP Protvino, INFN Torino – JINR Dubna, RWTH Aachen, IHEP Beijing, CIEMAT Madrid and INFN Padova). All parts of DT readout and trigger electronics were extensively tested before and after installation. Construction of the chambers started in January 2002 and was completed in June 2006. Installation in the five Yoke wheels of the CMS detector started on surface in July 2004 and was completed in the cavern in October 2007.

The commissioning of the DT Barrel System has been a long lasting process running at various stages in parallel to chamber production and installation. Beside dedicated test beam runs taken on prototypes and on final detectors prior and during chamber construction [3][4][5][6][7], system commissioning was performed through the following phases:

1. Test of constructed chambers with large cosmic data samples at production sites before shipment to CERN, with final front-end electronics and temporary trigger and readout electronics. The tests included gas tightness, efficiency, dead, noisy channels, and resolution;
2. Full dressing of the chambers with final onboard trigger and readout electronics (Minicrates). Test again as in point 1 prior installation, pairing to Resistive Plate Chambers (RPC) and survey on a dedicated alignment bench in order to determine wire positions with respect to the external reference marks of the general CMS barrel alignment system (built by the groups of Universidad de Cantabria, Santander and KFKI Budapest);
3. Installation and full test of each installed chamber through a cosmic test stand, with temporary cabling and local data acquisition system;
4. Since April 2006, and as soon as the integration progressed and final cabling for powering and data transfer where becoming available, the chamber

commissioning turned into sector commissioning, where four stations could be operated and read-out together, thus allowing also the tracking of cosmic muons between different chambers.

5. The subsequent step of the detector commissioning was the so-called wheel commissioning, where all sectors in a whole wheel were tested and commissioned together. In November 2007 the read-out and trigger of one full wheel was achieved and by May 2008 the five wheels were finally operating together.
6. These commissioning periods were spread with different global runs in which larger parts of the CMS detector were integrated and operated together. Those global data taking were done both with and without the magnetic field.

Measurements performed in the DT chambers during the commissioning phase included the identification of local tracks generated by cosmic muons, calibration patterns, as well as the measurement of the drift velocity and of the time pedestal, for synchronization purposes. It is worth noting that only 0.2% of all the DT channels was found dead after the final detector installation and commissioning.

The DT Detector Control System (DCS) has been evolving together with the integration of the electronics. At present, all basic parts can be configured and monitored in an easy and flexible way and further work is being done in order to obtain all the status information in a synthetic and comprehensible way. The same has happened with the online monitoring software that at present allows subsystem shifters to check the quality of the data as being produced by the detector and provide fast feedback. Many plots are present to study detector efficiency, data integrity and trigger performance; but more important, the summary of the status of the detector has been distilled in a limited number of concise plots.

III. OPERATION UNDER MAGNETIC FIELD DURING THE CRAFT EXERCISES

The first data taking exercise with the CMS magnetic field was the Magnet Test and Cosmic Challenge (MTCC) during summer-autumn 2006 [8]. This challenge was the very first global exercise for CMS in which 5% of the full system was installed and operated together on the surface hall and was the predecessor to the CRAFT (Cosmic Run at Four Tesla) exercises described here.

CRAFT exercises were two extended global data taking periods conducted in the experimental cavern with the magnetic field of the CMS detector on and with all the final systems in place: CRAFT08 ended on November 11th 2008 and CRAFT09 ended on September 1st 2009. These month-long data-taking challenges had the following goals:

- Test the solenoid magnet at nominal field (3.8 T) in-situ with the CMS experiment in its final installed configuration underground.
- Gain experience operating CMS continuously for one month.

- Collect more than 300 million cosmic triggers for performance studies of the CMS detectors.

These goals were successfully met and the cosmic muon dataset collected has proven invaluable for understanding the performance of the CMS experiment as a whole. During these campaigns, the 100% of the DT system was operational and due to its favourable location for cosmic detection, the contribution of the DT system to the global campaign was extremely relevant. During CRAFT08 370 million cosmics were collected, and 83% of these events were triggered and read-out by the DT system. In CRAFT09 the collection increased to 523 million cosmics, 92% of them acquired by the DT system.

As cosmics cross the detector from top to bottom a dedicated muon configuration and synchronization was set up in the DT trigger chain. It required the coincidence of at least two chambers in the same or nearby sector without requiring that the muon tracks point to the nominal interaction point. Also the upper sectors were delayed with respect to the bottom ones to take into account the time of flight and trigger at the same bunch crossing cosmic muons crossing both top and bottom sectors.

During these data taking periods we could confirm that the DT trigger rates were very stable with time. Since the cosmic rate in the cavern underground is low, random triggers were also injected in order to stress the system to the 100 kHz maximum expected during LHC running. No problems were seen in the DT read-out system when running at high trigger rate; data integrity was not affected and no backpressure or bottlenecks were detected in the read-out path.

Calibration events (around 100 Hz) were also injected during data taking. In the DT system the calibration mechanism works through the so-called Test Pulses, in which signals are injected at front-end level simulating vertical tracks orthogonal to the chamber. This procedure allows performing inter-channel synchronization and it is also a useful tool to scan for dead channels in all the electronics chain. One of the goals in these campaigns was to verify that the calibration mechanism can be implemented in the around 2.5 μ s of the LHC orbit abort gap, so that no dedicated running period would be needed. After a few corrections in the timing configuration to avoid leaks outside the orbit gap, the calibration stream was operated very satisfactorily in both CRAFT exercises.

The DT system demonstrated high reliability and stability during this long data taking periods in which it has been operated continuously. Chambers and electronics were always powered on except during magnet ramps when the high voltage of the chambers was lowered for safety reasons.

Very few problems were seen during these data taking exercises. By CRAFT08, after one year of operation of the detector in many local and global data taking campaigns, only 1,2 % of the detector was lost due to various types of problems, which were fixed during the 2008-2009 shutdown. Main activities during this shutdown included improvement of the secondary back-up copper connection to the Minicrate and reinforcement of the DT safety system in order to move toward a centrally supervised operation scheme.

No issues have been found in the DT electronics for running with the magnetic field on. The only unexpected effect observed were some problems while reading the 1-wire temperature sensors in a few ROS boards while ramping up the magnet, which was easily solved with a power cycle of the crate.

The data integrity provided by the DT read-out system during these campaigns has been excellent. The number of events in which some inconsistency has been found is very low: 15 events out of 460 million. The configuration time of the DT DAQ system is below 1 minute, and very rarely (twice in CRAFT08 and twice in CRAFT09) any error in the DT read-out forced to stop the data acquisition. During these campaigns it was also possible to verify that the TTS mechanism worked satisfactorily and that the DT system recovers smoothly from sporadic errors.

Figure 4 shows the percentage of errors versus run number in CRAFT09 as detected in the ROB/ROS system. These errors can be due to parts being off, lack of communication with Minicrates, transmission problems, etc. It can be seen that the number of errors is very low and that there is no dependency with the magnetic field.

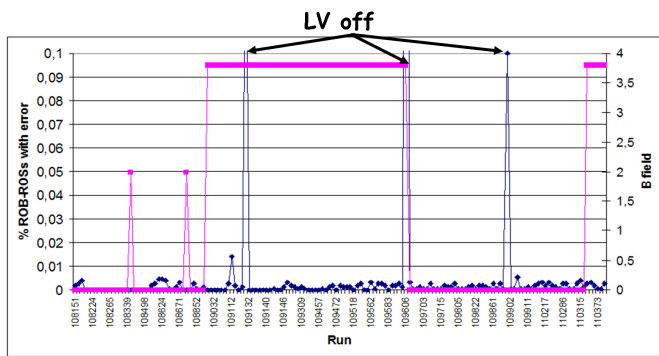


Figure 4: Percentage of errors versus run number in CRAFT09 as seen in the DT read-out chain. The continuous pink like shows the value of the magnetic field.

The hit reconstruction efficiency in the chambers is measured using the extrapolation to the considered cell computed from the track segments built in the chamber, fitted excluding the hits in the relevant layer, and looking for the presence of a reconstructed hit in the cell.

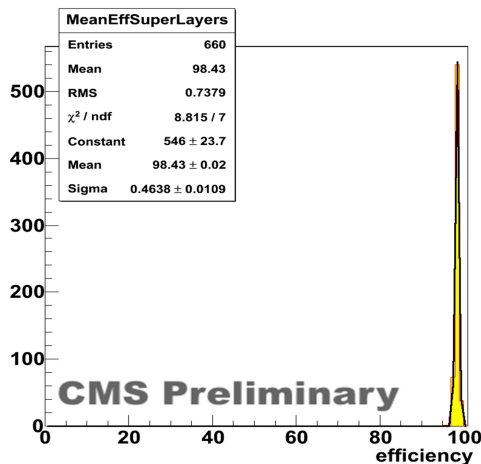


Figure 5: Mean efficiency of cell hit detection within a SL computed with respect to the offline reconstructed segment (CRAFT09).

Cell efficiency is flat both with respect to channel number and for the different typology and dimensions of chambers. Figure 5 shows the mean cell efficiency averaged on all the cells of each SL and it can be seen that the efficiency is higher than 98%, being the inefficiency due partly to the effect of the I-beams that separate the drift tubes. This efficiency was also very similar in both campaigns and no significant differences have been seen with and without magnetic field.

The DT local trigger has also shown a very good performance. Trigger primitives have quality bits assigned, according to the number of drift cells in which hits were found aligned. In each SL an alignment of 3 out of 4, or 4 out of 4 hits is called Low (L) or High (H) quality respectively. If such alignments are correlated together between the two SLs, the quality of the trigger primitive then becomes HH, HL or LL.

As can be seen in figure 6 the measured trigger efficiency is 95% for any trigger quality and 73% for high quality correlated triggers. The efficiency in the position and direction determination by the DT local trigger is not at all affected by the presence of the magnetic field. This efficiency is what expected for cosmic muons and will be higher for LHC running, since the DT trigger system has been designed to trigger muons synchronized with the beam clock and the efficiency drops with cosmic muons that have a random time of arrival with respect to the clock.

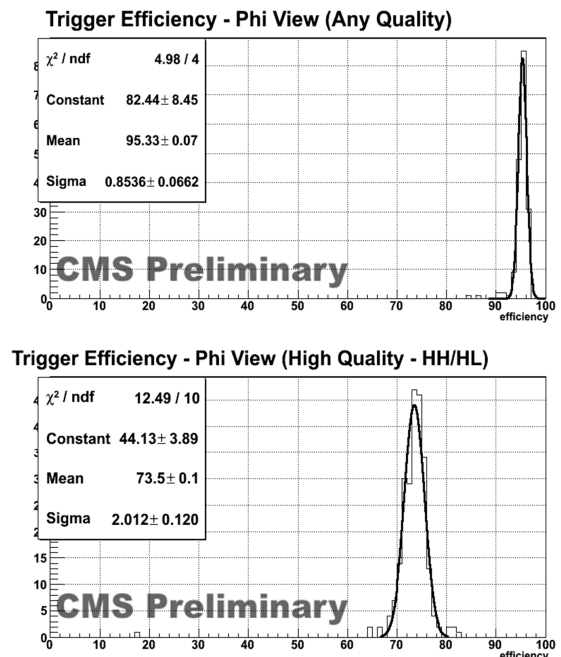


Figure 6: DT Local Trigger efficiency with respect to local reconstruction in the phi view for triggers of “any quality” (top) and “high quality (i.e. HH/HL ones - bottom) (CRAFT09).

The distribution of the quality of the trigger primitives also remains unaffected by the magnetic field, as can be seen in figure 7 for all the chambers in YB-2.

Finally, no significant differences were observed in the DT system synchronization due to the magnetic field. A variation of the maximum drift time, which corresponds to an apparent change of the drift velocity which may happen due to the presence of magnetic field, can degrade the trigger

performance, since BTIs are configured to work with the same drift velocity everywhere within the same chamber. Figure 8 shows the difference between the mean of the bunch crossing distribution obtained with and without magnetic field. The largest effect is observed in MB1 at the external wheels YB+2 and YB-2, in agreement with the expectations and in any case, too small to affect trigger capability.

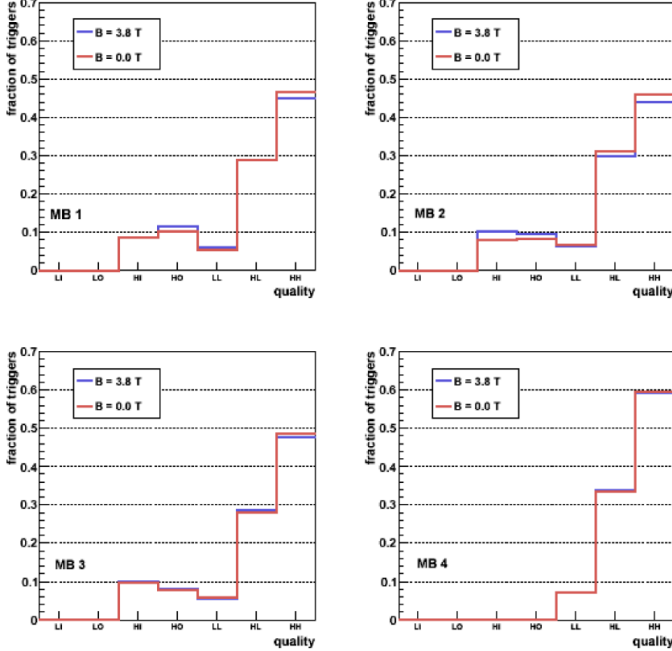


Figure 7: Distribution of the quality of the trigger primitives for data taken with and without magnetic field in YB-2 (CRAFT08).

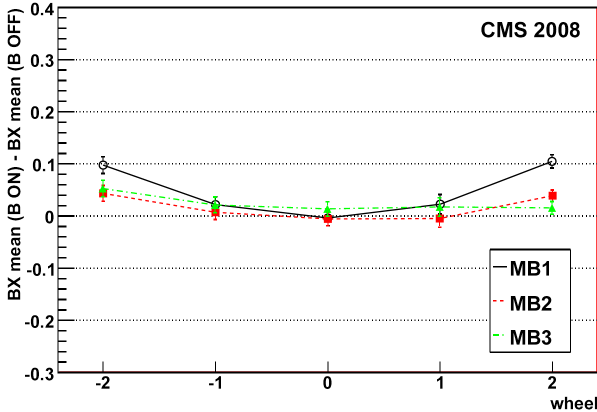


Figure 8: Difference between the mean of the bunch crossing distribution with and without magnetic field, as a function of the wheel number, for the four types of muon station (CRAFT08).

Every hit registered by the front-end electronics with a signal higher than a common threshold of 30 mV (that corresponds to 9-10 fC) and not associated to the passage of a particle, is considered a noise hit. A cell is defined as noisy if its hit rate is higher than 500 Hz. The number of noisy channels within the DT system has been analysed for different run conditions of data taking, with different subdetectors participating and for runs with magnetic field switched off and on. In figure 9 it is shown the distribution of cell noise rate in the system, which has an average value of 4 Hz. There are around 20 to 30 noisy cells out of the 172,200 cells and the distribution is stable for different run conditions and in

both CRAFT campaigns. The noisy cells are usually located in the edges of the chambers, where the high voltage cables pass through.

Even though the noise in the system is usually very low, some big noisy events have been seen sporadically during both campaigns that affect large regions in the detector. These events are independent of the magnetic field and their period is extremely low, in the order of days. They do not affect chamber performance nor the electronics chain, but deeper studies are on going in order to understand their source.

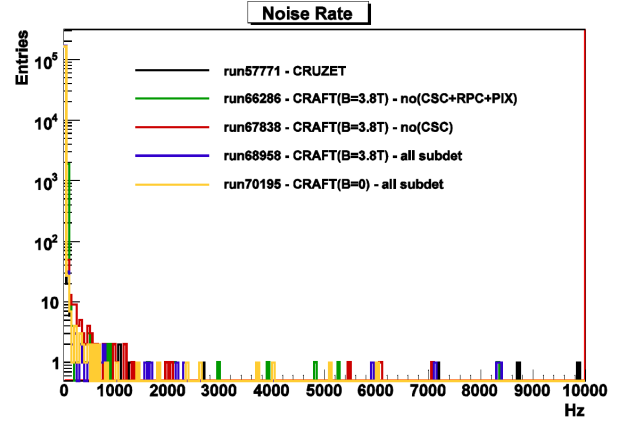


Figure 9: Distribution of the cell noise rate for different conditions of data taking (CRAFT08).

IV. CONCLUSION

The Drift Tubes system is an example of a very large and complex system that is working at present in a very efficient and stable way through long periods of data taking. The quality of the data acquired during the CRAFT campaigns is very good, and the data integrity problems are extremely low. During the whole period the chambers and the local trigger have shown a high and stable performance, as expected for cosmic muons detection.

The cosmic data collected through this period have been very valuable to the study the performance of the detector and also for the first studies of physics which are being carried out [9]. The presented system has proven to be ready for the exciting periods ahead and the whole DT muon barrel community is eagerly waiting for the first LHC collisions.

V. REFERENCES

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