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CMS experiment

Final Report

HEAVY STABLE CHARGED PARTICLES AT LHC WITH THE CMS DETECTOR: SEARCH AND RESULTS FOR A TRIGGER IMPLEMENTATION

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1 Introduction

During the 13 weeks of the Summer Student Programme, I worked with the CMS Muon Drift Tube group on the study and the implementation of a new 2BX algorithm for the L1 Muon Barrel Trigger to extend the acceptance for slow-moving particles. Initially, a study was done to understand the possible improvements in the trigger efficiency for an algorithm considering two consecutive bunch crossings (BX) at a time instead of one. The algorithm was then defined and tested for the final hardware implementation with a new concept of testbench. Finally it was implemented in the TwinMux, a data concentrator which combines the Drift Tubes and Resistive Plate Chambers primitives giving as output the so-called superprimitives, to take advantage of the different performances of the two CMS muon subdetectors.

The tasks I had to carry out during my stay at CERN were:

- The study of the performances of the L1 trigger chain with the present configuration, comparing them with the ones obtained with the new trigger algorithm
- The definition of the 2BX algorithm
- The testbench for the hardware simulation
- The final analysis of the data collected during the tests after the hardware implementation

2 The CMS experiment

The Compact Muon Solenoid experiment is one of the two multi-purpose detector at the Large Hadron Collider voted to the search for new physics mainly using $p-p$ collisions. Composed by several layers of high granularity synchronized detectors, each one specific for measuring the properties of the particles generated in the collisions, and a 4 T solenoidal magnetic field for bending the trajectories, it is designed to provide high precision measurements either for the stable particles crossing the detector and for the reconstruction of the decay vertexes. The performances of the CMS detectors make possible to identify the particles and to measure their trajectories, the energy and the momentum, including the missing energy.

2.1 CMS design and characteristics

The CMS detector has a cylindrical shape with total dimensions of 21.6 *m* in length and 15 *m* in diameter and a weight of 12500 *tons*. Due to the high symmetry of the collision topology, this particular shape grants to cover the largest variety of trajectory directions of the generated particles in the collisions or in the following decays. The entire structure is divided into three main blocks, the central Barrel, composed by 5 slices (wheels), and the two Endcaps. The natural coordinate system for CMS and for most of the multi-purpose detectors in high energy physics is a right-handed system with the center in the nominal collision point. The x-axis points radially to the center of LHC, the y-axis is normal to the ground plane directed upwards and the z-axis is along the beam pipe. The x-y plane is usually referred as the transverse plane and the projection of the particles energy and momentum in that plane are indicated as E_T and p_T . An alternative set of coordinates are the azimuthal angle ϕ in the x-y plane measured from the x-axis and the polar θ angle. A more common way to represent the polar angle is through the pseudorapidity $\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$.

2.2 The muon system

The outermost group of subdetectors of the CMS experiment is the muon system, constituted by four stations in the barrel and four disks in the endcaps, covering an angular range of $|\eta| < 2.4$. It is a robust and redundant muon spectrometer that can provide precise muon identification and high resolution p_T measurements.

The muon spectrometer consists in three different types of gaseous detectors; 250 Drift Tubes Chambers (DTs) are used in the barrel region ($|\eta| < 1.2$) where there are less occupancy and magnetic field, while faster and more radiation resistant 540 Cathode Strip Chambers (CSCs) have been chosen for the two endcaps ($0.8 < |\eta| < 2.4$) to cope with higher particle fluxes and non uniformities in the magnetic field. 610 Resistive Plate Chambers (RPCs) complement the DTs and the CSCs in both regions up to $|\eta| < 2.1$, because of their fast response and excellent time resolution, to improve the precision in the muon trigger on the determination of the bunch crossing (BX) in which the muon has been created.

2.3 Drift Tube Chambers

The muon barrel region outside the solenoid is characterized by a low intensity magnetic field, low occupancy and a large area to be covered. This requirements are satisfied in the CMS detector using the Drift Tube Chambers. The DTs are gaseous detectors fitting into the the iron yoke structure, which consists in 5 wheels, referred as Wheel−2 to Wheel+2, and 12 azimuthal sectors, labeled with numbers 1 ÷ 12 starting from the x-axis. For each wheel, 4 concentric rings (stations) of DT chambers are installed, named MB1, MB2, MB3, MB4 respectively from the inner to the outer part. Each station in a sector is constituted by one DT chamber, except the upper (4) and the lower (10) sectors where there are 2 MB4 side by side.

3 The TwinMux

The TwinMux is the data concentrator of the L1 barrel muon trigger chain and its main role is to compare, for the ϕ coordinate, the DT trigger primitives with the RPC ones correcting or confirming the BX assignment if they have corresponding coordinate and the BX difference between them is equal or less than 1. Another task the TwinMux performs is to add a RPConly candidate if there are no DT primitives in the MB1 and MB2 chambers, where 2 RPCs (inner and outer) are coupled with the DTs. From the hardware point-of-view, TwinMux is a μ TCA board, based around a XILINX Virtex-7 FPGA and equipped with optical connections for high speed data transmission (up to 13 Gbps). To cover the full barrel, 60 TwinMux are hosted in 5 TCA dual star crates with more than 3000 optical fibre cables for the input and output connections. Every BX, it receives up to 10 DT trigger primitives from the Front-End electronics (minicrates) installed in the muon DT chambers and up to 26 from the

RPCs and is connected in output to the Barrel Muon Track Finder. The main trigger primitive details contained in the input bitstream are:

- ϕ , corresponding to the azimuthal coordinate relative to the point where the segment connecting the center of CMS to the DT chamber is normal to the surface
- ϕ_B , representing the inclination of the reconstructed track segment in one DT chamber with relation to the particle trajectory
- ϕ quality, ranging from 0 to 6 corresponding to the codes $L_{i,o}, H_{i,o}, LL, HL, HH$, where $L = 3$ hits (number of layers with a signal) and $H = 4$ hits in the inner and outer ϕ superlayers

4 The 2BX L1 trigger for slow-moving particles

4.1 HSCP samples for the analysis

Heavy Stable Charged Particles (HSCP), theorized by Beyond Standard Models, have been selected as highly interesting candidates for slow-moving particles. They are supposed to have mass around 1 TeV and $0.2 < \beta < 0.8$. They are therefore arriving to the outer parts of CMS with delayed times with respect to ultra-relativistic muons traveling at the speed of light, for which the muon system is synchronized.

To study the improvements on the performances for HSCP with a dedicated trigger algorithm, it was essential to update emulated triggers in the CMSSW 8_0_21 software used for the sample productions, to the hardware configuration installed since 2016. The most important intervention was the substitution of the old simulator for the TwinMux with a new emulator, created by Giannis Flouris, and the implementation of a new logic for the RPCbit (recorded by DAQ) which turns to 1 when a DT primitive is confirmed or shifted by the RPC one. The same implementation has also been done in the TwinMux firmware.

Two simulated stau samples have been produced, with mass $M = 651 \text{ GeV}/c^2$ and $M = 1599 \text{ GeV}/c^2$, and the performances of the present L1 Muon Barrel trigger have been studied.

4.2 2BX trigger: working principles

While all the present L1 trigger chain considers only one BX at a time, the new 2BX trigger algorithm checks 2 consecutive BXs, looking for the BX-schemes which have the first valid superprimitive at the $BX = X$ and the other ones at the $BX = X+1$ as shown in figure 2. The condition required for the superprimitive in the first station is either to have a HH ϕ quality or the RPCbit = 1. This ensures with a large probability (99.5%) that the BX information is correct and not given by a possible pre-trigger¹.

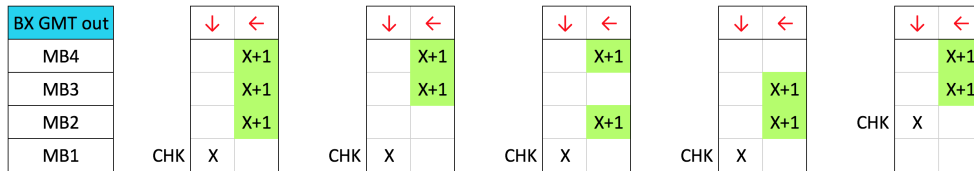


Figure 2: Special superprimitive BX schemes considered by the new 2BX trigger algorithm. The first station with a valid superprimitive has $BX = X$ and an HH quality or a RPCbit = 1 (CHK $\rightarrow$ conditions) and the others are at $BX = X+1$. The red arrows indicate the shift of all the superprimitives to $BX = X$.

For the special BX-schemes, the 2BX trigger algorithm acts shifting the BX of all the superprimitives belonging to a trigger candidate to $BX = X$. The result is the increasing of the number of HSCP accepted by the L1 trigger chain, modifying the BX assigned to the candidates by the Global Muon

¹A pre-trigger is defined as a time identification of the primitive at the previous BX than the correct one.

Trigger from '1' to '0', the correct one at which the particles are created in the collisions. Indeed, the GMT determines the BX of the track when it finds at least two superprimitives at the same BX. However, also the BX of the muon candidates with a pre-trigger in the first station can be modified, implying the loss of the muons if all the primitives are shifted to the $BX = -1$. To reduce this unwanted drawback of the algorithm, a selection on the ϕ_B of the superprimitives is done. Indeed, muons usually have a lower p_T than the HSCP particles, producing a larger ϕ_B in the muon station due to the fact that the radius of curvature of the trajectory is proportional to momentum of the particle, expressed by the formula $\rho = \frac{p}{qB}$. The maximum value for the ϕ_B angle of the superprimitive to be taken into account by the algorithm has been fixed to 3° , maximizing the benefits for HSCP and minimizing the interventions on muon candidates with pre-triggers.

4.3 Improvements for HSCP implementing the 2BX trigger in CMSSW

The following step, after the evaluation of the performances of the present L1 Muon Barrel trigger, was the implementation of the algorithm in a private version of the CMSSW 8_0_21 software. The code has been inserted into the TwinMux emulator considering as input the output of this component of the L1 barrel muon trigger chain. A brief scheme of the implemented algorithm in the simulation is depicted in figure 3.

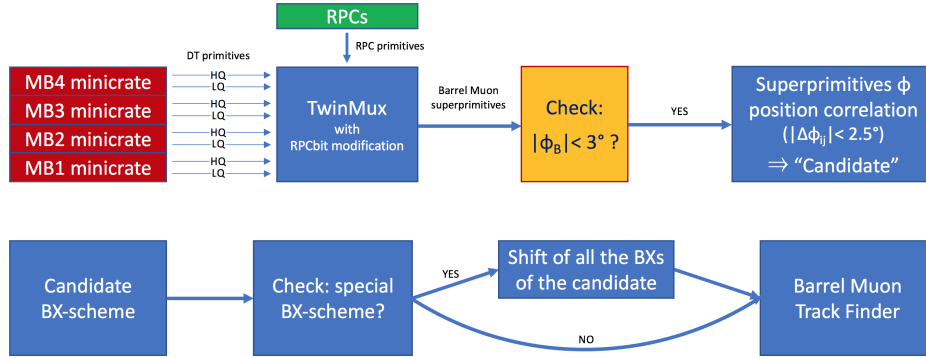


Figure 3: 2BX trigger algorithm implemented in the TwinMux emulator of a private version of CMSSW 8_0_21 software.

To check the results of such implementation, the two HSCP samples used for the initial production for the analysis have been simulated another time with the modification of the TwinMux algorithm. The results of the analysis considering the offline reconstructed tracks in the barrel with at least 3 segments are shown in figures 4. For staus with a mass of $651 \text{ GeV}/c^2$, the percentage of recovered muon tracks is $+2.5\%$; with $M = 1599 \text{ GeV}/c^2$ the improvement is $+4.8\%$.

4.4 2BX L1 Trigger: implementation on the TwinMux system

Once the study of the possible performances of the L1 muon barrel trigger with the 2BX algorithm and the test using the emulator software have been completed, the hardware implementation has been prepared and successfully executed during the Summer Student Programme at CERN. The most conservative and feasible operation to carry out in the L1 trigger chain is the implementation of the algorithm directly in the TwinMux board, adding the new instructions to the firmware of the FPGA. Even though this implementation has the disadvantages that the TwinMux works only with primitives received by one sector of one wheel and that it is impossible to have informations on the η position because the TwinMux operates separately for the ϕ and η coordinates, it is convenient to begin modifying the behavior of this component. The advantages are that it is relatively simple, fitting perfectly in the time of the stay at CERN, and also it can be conducted on a spare board having zero

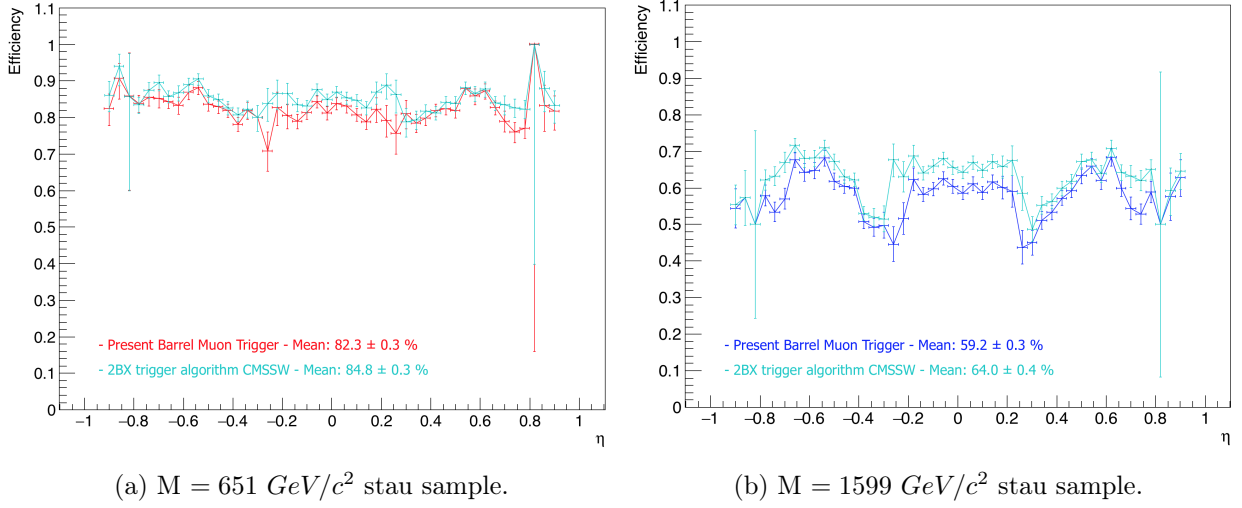


Figure 4: Trigger efficiency as a function of η for reconstructed tracks of simulated stau particles. Comparison between present L1 trigger efficiency and efficiency with the implementation in CMSSW of the new 2BX trigger algorithm for two different mass samples.

impact on the rest of the CMS system. After the initial evaluation tests, it could be implemented on the Barrel Muon Track Finder, which as input receives the TwinMux output of an entire wedge of the barrel (five aligned sectors of the different wheels), plus the two neighbor ones.

The first operation was to define the simplest algorithm to implement on the FPGA. Indeed, strict requirements in term of execution time and complexity of operations are fixed for a pipeline mode trigger; every calculation must be carried out in less than 25 ns to have the total latency of the algorithm limited to 2BX. To be considered by the 2BX trigger, the conditions that the i -th and j -th superprimitives, coming from the i and j muon stations, have to fulfill are:

- Highest quality (HQ) superprimitive for each station
- $|\phi_B| < 3^\circ$, corresponding to a value of $|\phi_B| < 27$ with a 10-bit precision on ϕ_B
- $|\Delta\phi_{i,j}| < 2.5^\circ$, corresponding to a value of $|\Delta\phi_{i,j}| < 140$ with a 12-bit precision on ϕ
- Special BX-scheme, depicted in figure 2
- Innermost superprimitive with HH quality or BX confirmed by RPCs (RPBbit = 1)
- No other HQ superprimitives in the outer station at the first of the two BXs

If the incoming superprimitives have the listed properties, all of them are sent to the output at the BX of the first valid superprimitive, so that the ones from the outer stations are anticipated of 25 ns. The entire trigger chain and especially the BMTF have to be informed about this temporal shift of superprimitives, possibly with a single bit set to 1 in case of activation of the algorithm.

TwinMux simulation and testbench

Once the suitable algorithm for the 2BX trigger was defined, it was written in the VHDL programming language and tested with the Vivado simulation software by XILINX, the manufacturer of the FPGA hosted by TwinMux. The setting selected for the simulation were 'Virtex-7' for the product family and the product specific name 'xc7vx330tffg1761-3'.

Usually the testbenches for the TwinMux are done with a very limited number of ad-hoc created BX-schemes given to the input of the simulation. To test the new algorithm, it has been decided to produce the testbench input VHDL file by a C++ program in the ROOT framework. Analyzing the stau sample with a mass of 1599 GeV/c², 100 events have been selected in order to be given as 'input stimulus' to the simulation, where events with a special BX patterns and events that, instead, should

have not been modified were alternated. The output of the simulation was written on a text file and analyzed with a different ROOT macro. A graphical example of a typical Vivado simulation input and output is given in figure 5.

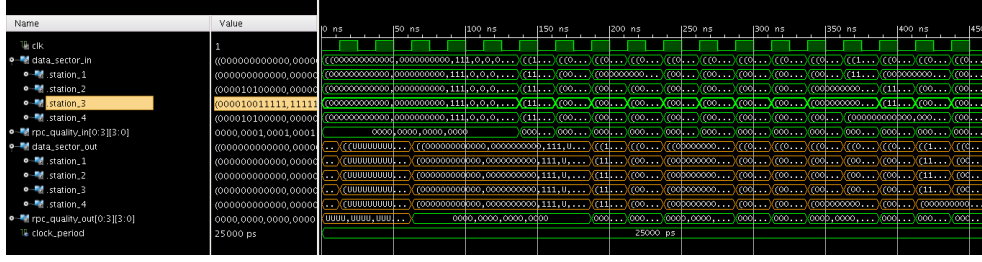


Figure 5: Typical Vivado simulation input and output graphical picture (waveform view).

The correctness of the implemented code has been proven and the results are shown in figure 6, where the alternate value of the distribution demonstrates that one out of two BX-schemes have been modified by the 2BX trigger, as it was given as input of the testbench.

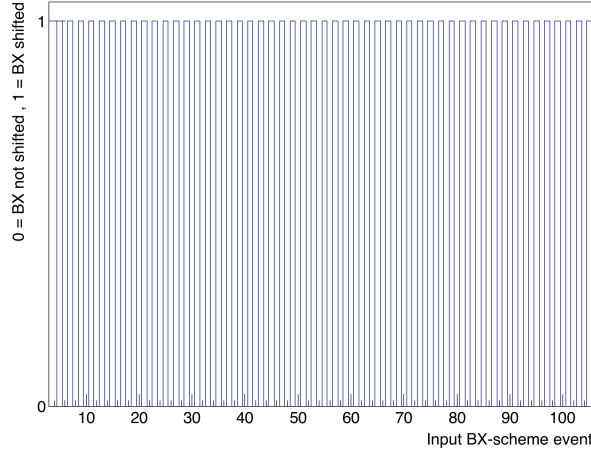


Figure 6: Results of the Vivado testbench for the new algorithm. The alternated values of the curve show that, as it was given to the input, one out of two superprimitive BX-schemes has been shifted to the BX of the innermost superprimitive by the 2BX trigger.

If some characteristics are intentionally modified in the superprimitives of the special BX schemes in order not to respect the requirements, for example increasing the ϕ_B angle to be greater than 3° in the BX schemes with all 4 superprimitives, the algorithm behaves as expected, not changing the BX of the superprimitives with wrong properties. An example is give in the figure 7, where are also shown the details of some superprimitives that were not satisfying the 2BX trigger conditions.

TwinMux hardware implementation and preliminary results

Finally, the new firmware in which the 2BX trigger algorithm was included has been implemented into the spare TwinMux board. Due to the fact that it is used for tests mainly with cosmic rays, the 61-st TwinMux can be connected to one of the sectors that have been splitted: 9, 10 or 11 of the wheels -1 and -2 . Those sectors are the ones with the highest rates because they are almost parallel to the ground and the cosmics have a $\cos^2(\theta)$ angular distribution with respect to the vertical direction and the two wheels are under the pit of the CMS cavern so that the rate of muons is not reduced by the 100 meters of ground. Up to the end of August 2017, only DT primitives were received by the spare TwinMux, thus only the HH quality condition on the first valid DT primitive of the BX-schemes could activate the algorithm shift. Once also the RPC signals are available, the DT primitives will be

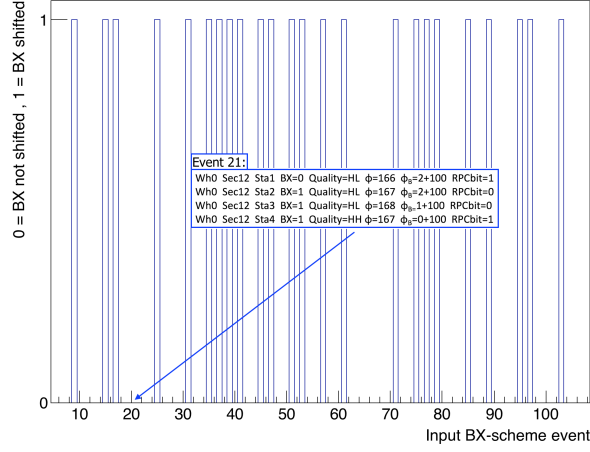


Figure 7: Results of the Vivado testbench for the new algorithm. The missing superprimitives BX modification is due to an intentional increase of the ϕ_B in order not to fulfill the requirements of the 2BX algorithm. An example of BX scheme with modified properties is given.

corrected in case of RPC confirmation and the requirement on the $\text{RPCbit} = 1$ will become effective. Initially, data have been collected during the proton-proton interactions and in cosmic runs, while the LHC was stopped, monitoring the number of times the algorithm was activated when the spare TwinMux was connected to the sector 9 of wheel -2 . In both 301142 and 301161 pp LHC runs, which lasted for almost 6 and 5 hours respectively, 9 events were registered. In figure 8, the distribution of the events as a function of the time is presented. For these runs, the data files of the reconstructed tracks for the muon system have been produced and analyzed, founding *zero* events corresponding to particles generated in the collision region. To explain the origin of the algorithm activations, the 7.5 hours long 301062 cosmic run has been analyzed. 5 special BX-schemes were found, confirming that the cause is mainly due to the cosmic muons crossing the detector during both proton-proton collisions and cosmic runs. Owing to the fact that offline analysis are affected by all the trigger and reconstruction selections, a number less or equal to the one registered during the online data taking is expected.

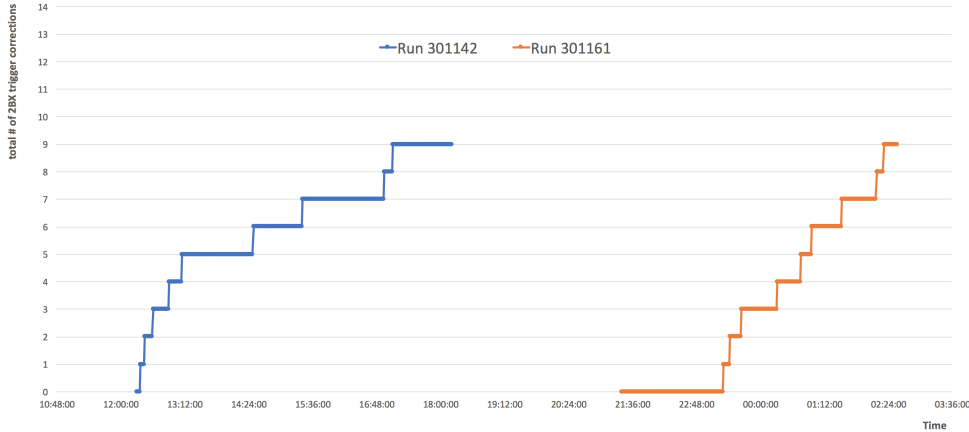


Figure 8: TwinMux spare board connected to the sector 9 of wheel -2 . Total number of 2BX algorithm activation as a function of the time during the LHC pp collisions in runs 301142 and 301161. For both the runs, lasted for 6 and 5 hours respectively, 9 events were registered.

To check the difference in the rate of the algorithm activation when considering different sectors, the 61st TwinMux has been connected to the wheel -1 and -2 using the sector 10. The rate for both the lowest sectors was 1 – 2 events per hour during pp and cosmic runs, as registered for the initial

considered sector.

5 Conclusions

The Summer Student Programme at CERN was one of the most interesting and enriching experiences of my entire career as a physics student. Several results were obtained during these 13 weeks and the most important are the confirmation that the 2BX trigger algorithm will improve the statistics for detecting particles that can open a new era for the high energy physics and the successful test demonstrating that it works properly when implemented on a real TwinMux board. For the future, I hope it will be possible to implement this specific algorithm to all the 60 TwinMux boards of the entire CMS detector and, as a final step, to modify directly the BMTF firmware to have the possibility of considering tracks crossing different sectors and wheels.

6 Acknowledgement

First of all, I want to express my gratitude to my supervisor, Dr. Andrea Triossi, for the patient teaching, the fundamental advices and the encouragements he gave to me during the project. Besides, I would like to thank my master thesis supervisor Prof. Anna Teresa Meneguzzo, my co-supervisor Dr. Luigi Guiducci and Dr. Carlo Battilana for helping me to learn how to behave and to use all the necessary tools to take part actively to the research. Last but not least, many thanks to all the people that made possible this experience as a Summer Student in CERN.