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TRIGGERING ON DELAYED PARTICLES IN THE CMS DETECTOR*

Michał Olszewski

on behalf of the CMS Collaboration

Faculty of Physics, University of Warsaw
Hoża 69, 00-681 Warszawa, Poland

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Many of the BSM theories predict existence of massive charged particles with masses greater than $\gtrsim 100$ GeV/c^2 and with a decay path greater than a radius of the typical collider detector. The detection of such particles requires dedicated techniques in the trigger system and data analysis algorithms. In the particular case of PAttern Comparator Trigger of the CMS detector (PACT, part of the Level 1 Muon Trigger), one of the important issue is related to massive charged particles which are moving slowly and are delayed in the muon system. The assumption taken throughout the development of PACT about the close to the speed-of-light velocity of particles is irrelevant for massive particles and leads to the signal registration on improper (late) synchronization window of muon chambers electronics. In this note, we present an upgrade proposition for PACT which could allow to detect efficiently delayed particles during Run 2 of the LHC.

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1. Introduction

Apart of SM particles detection, the CMS detector is used for searches for particles with specific set of exotic features. Amongst them, there are particles with large masses, fractional or multiple charges or such that can change their charge during travel through the matter. Predicted by many supersymmetric [1] and extra-dimensional unified [2] theories those particles became an object of extensive studies, in which transverse momentum, energy losses via ionization and Time-Of-Flight (TOF) measurements were used as discriminants.

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The 2013 results of massive stable charged particles searches with full data set of 2011 and the 2012 LHC runs were published by the CMS Collaboration [3]. Depending on a type of the searched particles, the requirement of tracks: (1) only in the silicon tracker; (2) only in the muon system; (3) in the silicon tracker and the muon system was adopted. No signal of new particles was found and it was possible to set up exclusion bounds on minimal masses for various stable charged particles at 95% confidence level. Gluino masses below 1322 and 1233 GeV/c^2 were excluded for hadronization fraction $f = 0.1$ in the cloud interaction model and the charge-suppressed model, respectively (Fig. 1). For direct $\bar{\tau}_1$ production masses below 339 GeV/c^2 were excluded.

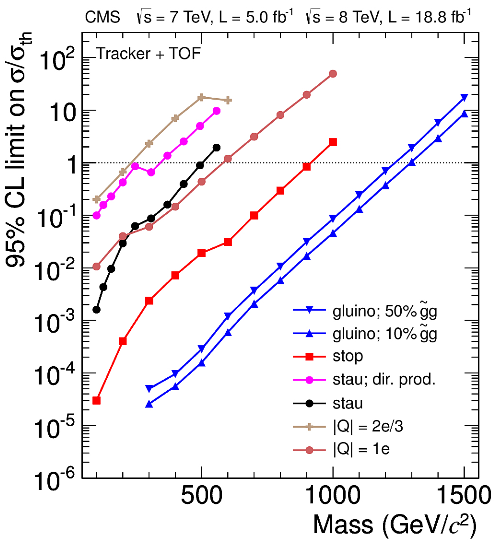
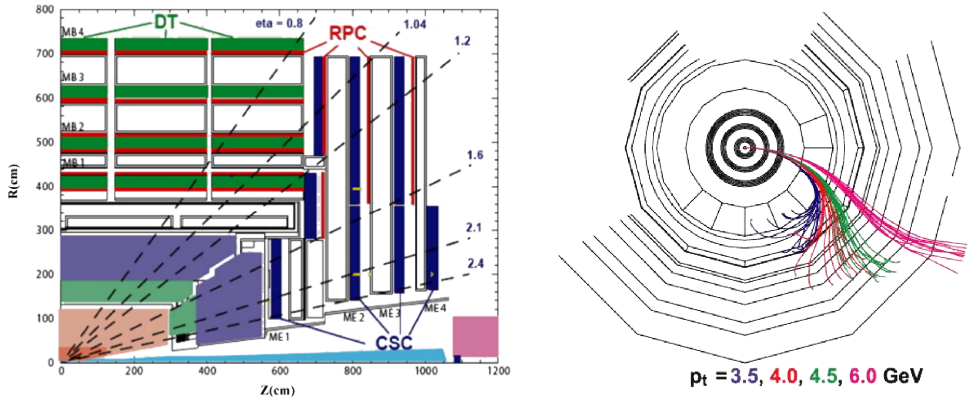


Fig. 1. Ratio of the cross section upper limits at 95% C.L. to the theoretical value for combined 2011 and 2012 dataset and for tracker+TOF analysis for various signal models [3].

2. TOF and Pattern Comparator Trigger

The TOF measurements used in this analysis were done outside of the magnet's coil in the muon system of the CMS detector. The muon system is built as a set of detecting layers consisted of Drift Tubes, Cathode Strip Chambers and Plate Chambers (RPC) (Fig. 2 (a)). A particle coming from the interaction vertex traverses the distance between layers, thus the moment of detection differs for every one of them. To properly identify signals from layers with the particle synchronization system have been introduced. The synchronization indicates the proper BX[1] identification. For RPCs, this system is optimized for speed-of-light particles, in a way that muons are detected in the middle of 25 ns synchronization window.



(a) (b)

Fig. 2. (a) The segmentation of muon chambers in the longitudinal profile of the CMS detector; (b) The transverse profile of CMS with simulated tracks of muons with different transversal momentum [4].

The massive charged particles can travel with a speed much smaller than speed of light. We make an assumption that the muon and the stable massive charged particle are produced at the same time and have the same transverse momentum (Fig. 3). Both particles have the same track, but muon is faster and it is detected before the massive charged particle in the muon system. The delay δ_t of the detection for particle with velocity β is given by the formula

$$\delta_t = \frac{L}{c}\left(\beta^{-1} - 1\right) . \qquad (1)$$

The delay increase with the distance from vertex L. Because of the size of the CMS detector, a small shift in the time at the first layer of the muon chambers is significantly larger at last layer as it is schematically shown in Fig. 3.

The identification of the signal and the bunch crossing performed by the synchronization system works properly as long as the delay is smaller then half of the synchronization window[2]. When the delay exceeds 12.5 ns at a

[1] A bunch-crossing (BX) is a time-stamp corresponding to a possible LHC collision event (*i.e.*, proton–proton collision) and is related to the machine clock. Since collisions may occur every 25 ns, the bunch-crossing is also used to mark the 25 ns time interval between beam–beam collisions.

[2] Gaussian blur, jitter, boundary effects *etc.* are neglected here to simplify the description but these effects are taken into account in the simulation.

given layer, the massive particle misses appropriate synchronization window and is detected as particle coming from the next consecutive proton–proton bunch crossing. For the 25 ns time window, we compute that a particle with velocity less than half of speed of light misses the synchronization window in all layers. Such particles are not detectable at the 25 ns mode of LHC.

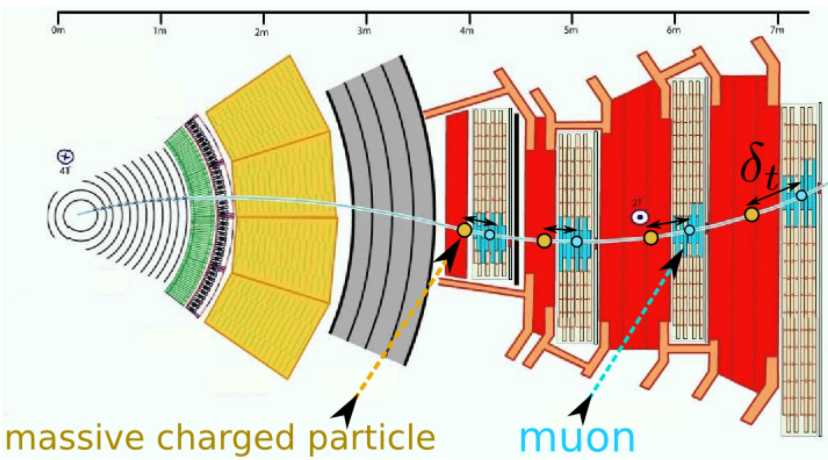


Fig. 3. Transverse cross section of the CMS detector. The increasing delays δ_t of massive particle with respect to muon.

2.1. *Default PACT algorithm*

Muons crossing the muon chamber generate a signal in the readout strip called hit. Information about hits from every strip (spacial coordinate of PACT system) in given BX (temporal coordinate of PACT system) is sent via custom hardware to FPGA chips, where the sequence of hits from consecutive layers is compared to the set of predefined patterns (Fig. 4). The pattern contains information about addresses of strips and has the assigned transverse momenta and charge of muon candidate. Patterns are prepared in a way to account for the expected bending of the muon tracks (Fig. 2 (b)) allowing for a measurement of muons transverse momenta.

If sufficient number of hits matches a given pattern, a muon candidate is produced as a 9 bit information about momentum, quality[3] and charge sign. The whole procedure is repeated every 25 ns, regardless if LHC is working in the 50 ns or the 25 ns mode. Owing to hardware used inside the trigger system, it is possible to process signals from up to eight consecutive bunch crossings, what is crucial for triggering on delayed particles.

[3] The quality indicates "how good" muon candidate is *i.e.* how many hits match a pattern. The quality is an important quantity in the High Level Trigger.

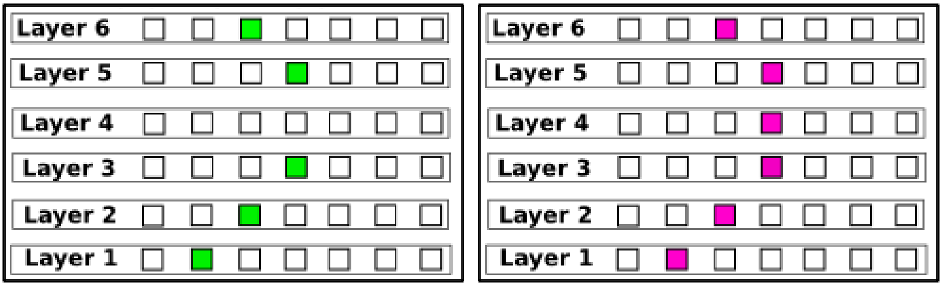


Fig. 4. Illustration of particle signal in RPC (left) and matching pattern (right). The logic units of PACT system are BX (temporal coordinate) and strip (spacial coordinate). The logical strips are shown schematically as squares. The logical strips are ranged from bottom to top into logical layers with first layers being the closest to beam and the sixth layer being the furthest [4].

The temporal coordinate of PACT system is not involved during a comparison of signal and patterns in the default algorithm. This means that the track perfectly matches the pattern only if the particle leaves hits in every layer within synchronization windows belonging to one BX.

Hits left by a massive charged particle can belong to two[4] consecutive BXs. If there are one or two hits from last layer(s) assigned to additional (next consecutive) BX then the muon candidate will be generated with reduced quality. For a very slow particle, which has three or more missing hits in the proper BX, the default algorithm fails and generates no muon candidate. This case is illustrated in Fig. 5.

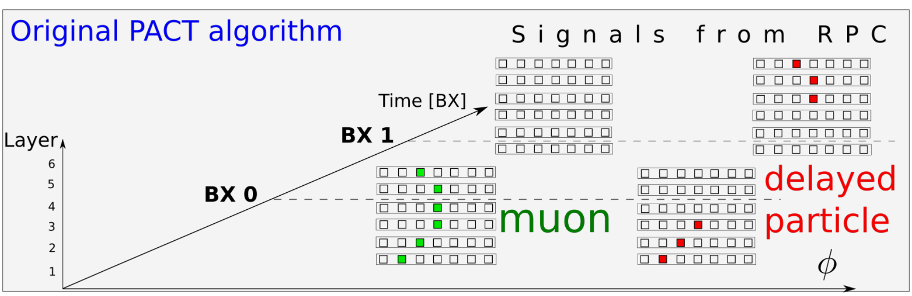


Fig. 5. Default PACT. The muon left the signal in every layer within synchronization window assigned to BX0. The track matches the pattern and a muon candidate is generated. In contrast to the muon case, no candidate for the delayed particle is generated because there are only three hits in a single BX.

[4] Very slow particles can leave signals in even more than two BXs, but it is impossible to trigger on such objects without compromising efficiency of trigger system for muons.

2.2. BX-extended PACT algorithm

To make triggering on delayed particles possible during LHC Run 1, working in 50 ns mode, the changes to the original algorithm have been made. All RPCs hits from every bunch crossing were artificially duplicated onto subsequent BX, and the original PACT algorithm was used for such data. As a consequence of the changes, delayed particles could be triggered, but also every muon was generated twice. To remove additional candidates and ensure a proper time qualification, algorithm uses an additional coincidence of the signal from beam monitoring devices.

In Fig. 6, for BX-extended algorithm, all six muon hits were duplicated and the muon candidate was generated twice. An additional veto signal has chosen only one of candidates. In the case of the delayed particle, three hits from first three layers were duplicated into the next BX and in BX1 the muon candidate can be created for the set of six hits in one BX.

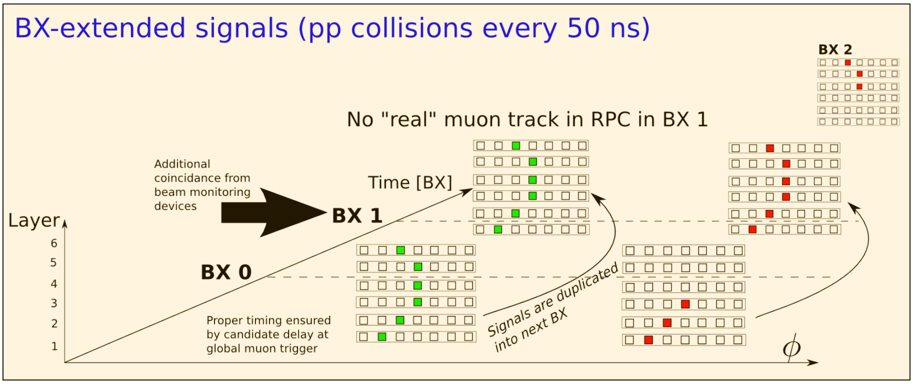


Fig. 6. The BX-extended PACT. The triggering was possible only because a trigger in the BX1 could be attributed to the right BX0 due to the use of beam monitors. It is not the case at 25 ns LHC mode of operation.

2.3. Delayed patterns PACT algorithm

The inability to use the BX-extended algorithm after LHC long shutdown was the motivation to design a modified PACT algorithm. In a new implementation, instead of duplication of hits from RPCs, patterns were extended by an additional time coordinate. In practice, every pattern was multiplied into six patterns[5], where every one of them had a distinctive combination of BX numbers assigned to all layers of the detectors.

[5] To be precise, multiplication factor is equal to the number of layers in a given region of CMS *i.e.* six in the barrel, five in the overlap region and four in endcups.

The delayed patterns were formed using the following procedure [5]:

- all original patterns have BX0 assigned in all layers;
- then all patterns with BX0 are copied, but the last (the sixth) layer time coordinate is replaced by BX1;
- we iterate the above successively for all layers without the first one.

The patterns only with BX0 refers to non-delayed particles. The correct operation of delayed patterns involves delivering signals from two consecutive bunch crossing onto FPGA chips.

We illustrate the case in Fig. 7. For a speed-of-light particle, the best muon candidate is created thanks to a pattern with BX0 in every layer, where all hits match the pattern. For the delayed particle, the fourth pattern, with three last layers in BX1, makes the perfect match and causes the particle candidate creation. The usage of separate patterns for delayed particles can be used to distinguish the muons and the massive particles at the trigger level.

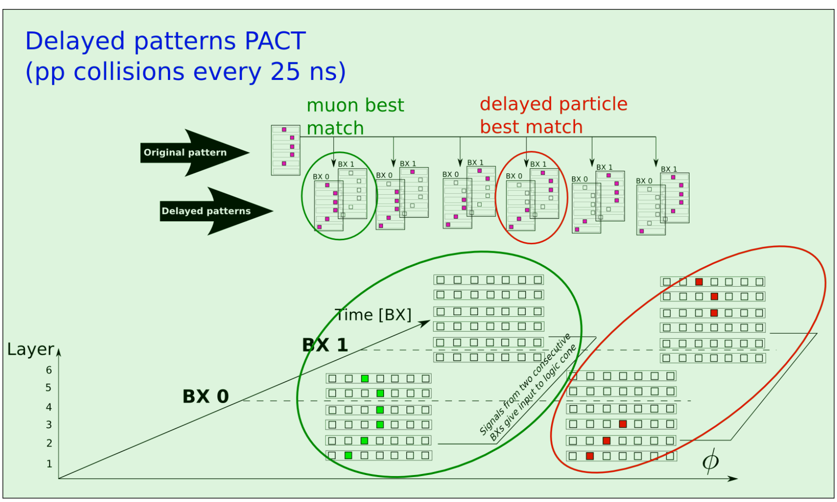


Fig. 7. Delayed patterns the PACT. The particle candidate for delayed particle is created properly thanks to the dedicated set of patterns.

3. Conclusions

Since the year 2015, the LHC will work at the 25 ns frequency and BX-extended mode of operation of PACT system is no longer possible. Delayed patterns algorithm has been proposed. It allows for significant increase of the trigger efficiency (with respect to the original trigger) in the range of $0.5 < \beta < 0.75$, which is crucial from the point of view of the offline signal discrimination. Currently, the firmware implementation into FPGA is ongoing. The study of the performance and possible optimization of this algorithm is continued. The proposed modifications should be implemented into level one (L1) muon trigger system after an approval by the CMS Collaboration.

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