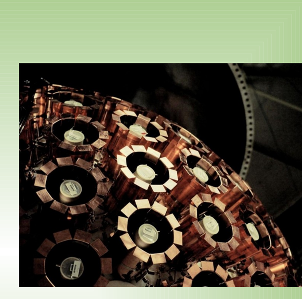
A muon tracking algorithm for the Level 1 trigger in the CMS barrel muon chambers during HL-LHC

José-Manuel Cela-Ruiz on behalf of the CMS collaboration

(JoseManuel.Cela@ciemat.es)

GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA E INNOVACIÓN · Ciemat, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

TIPP 2021 International Conference on Technology and Instrumentation in Particle Physics



The problem

To determine the trajectory of the muons, generated in the CMS hadrons interaction point, the barrel external region is covered with gaseous **Drift Tube Chambers** (‘**DT**’) capable to detect the ionization signals caused by the particles traveling through them. When those signals are received by the read-out electronics, they are digitized and a time tag is associated to the identifier of the cells that collected the ionization avalanches getting ‘**hits**’.

It is possible to reconstruct each muon trajectory, using these ‘hits’ information, by computing chamber segments defined in local coordinates (horizontal position and trajectory angle) and extrapolating them to detector global coordinates. Additionally, it can be identified the LHC bunch- crossing (‘**BX**’) where each muon was created. This is more challenging than expected due to a ‘DT’ drift time of ~16 ‘BXs’.

The **Analytical Method** (‘**AM**’) is an algorithm designed to identify the trajectory of muons by performing those calculations in hardware, at the same time that identifies and rejects any other spurious signals coming from different effects within the cells. It is implemented in **VHDL** and currently is executed in a **Xilinx’s FPGA [1]**. This method is an improvement of the original idea, evolved from the mean-timer algorithm, that was developed as a C++ software emulator and presented in TWEPP 2016 **[2]**.

The idea behind the algorithm

AM expands the processing method defined in **[2]** to two ‘**φ**’ angle super-layers (‘**SL-φ**’) **[3]**, adding new characteristics as well as a correlation mechanism between the two ‘SL-φ’ present in a chamber.

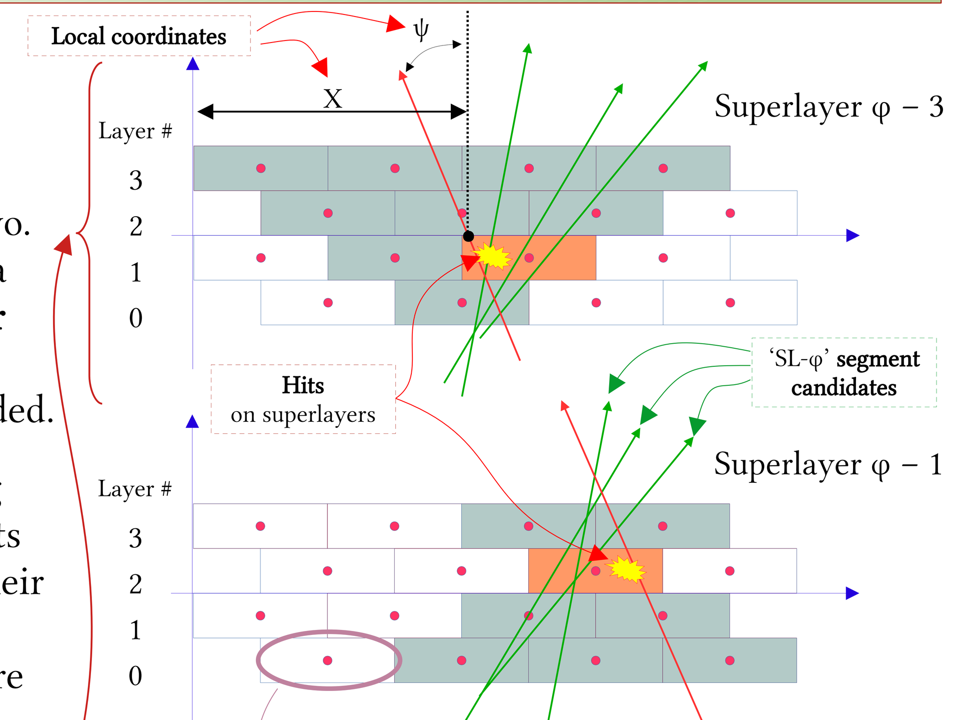
For each ‘SL-φ’, the received ‘hits’ are combined with the previous ones to form super-layer **segment candidates**. Every candidate is analyzed to determine if it is compatible with a muon trajectory, computing the horizontal position in the ‘SL-φ’, its local ‘**ψ**’ angle, the LHC bunch-crossing and a χ^2 error/quality estimator.

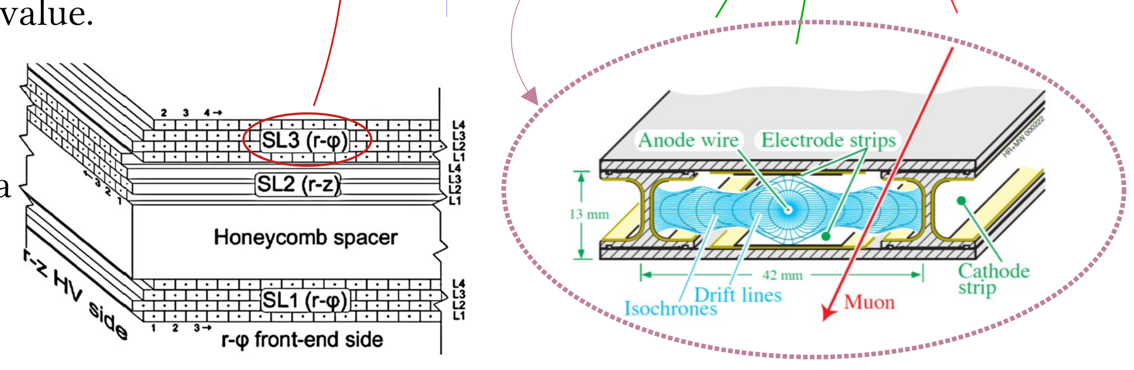
Several filtering criteria, applied along the processing pipe, allow to discard some candidates based on χ^2 and ‘ψ’ angle programmable limits.

Accepted candidates are sent to a segment matching module that tries to find colinear segments by comparing segment pairs two by two. They must share the same ‘BX’ value as well as a common ‘ψ’ angle to be considered as a **chamber muon segment** (‘**primitives**’). Candidates with a ‘BX’ value outside several logic limits are discarded.

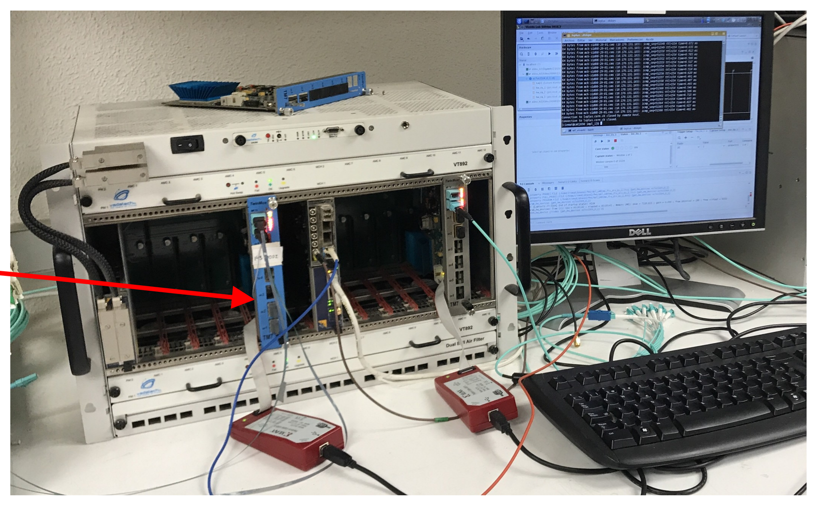
Segment pairs that accomplish with all matching criteria are grouped into chamber muon segments and labeled with a quality value depending on their number of valid ‘hits’.
Those that do not match, but were not filtered, are also labeled with a lower quality value.

Finally, for all of accepted primitives, along with the muon segment computed information, a ‘DT’ technical trigger signal is sent outside the **AM** algorithm core module.





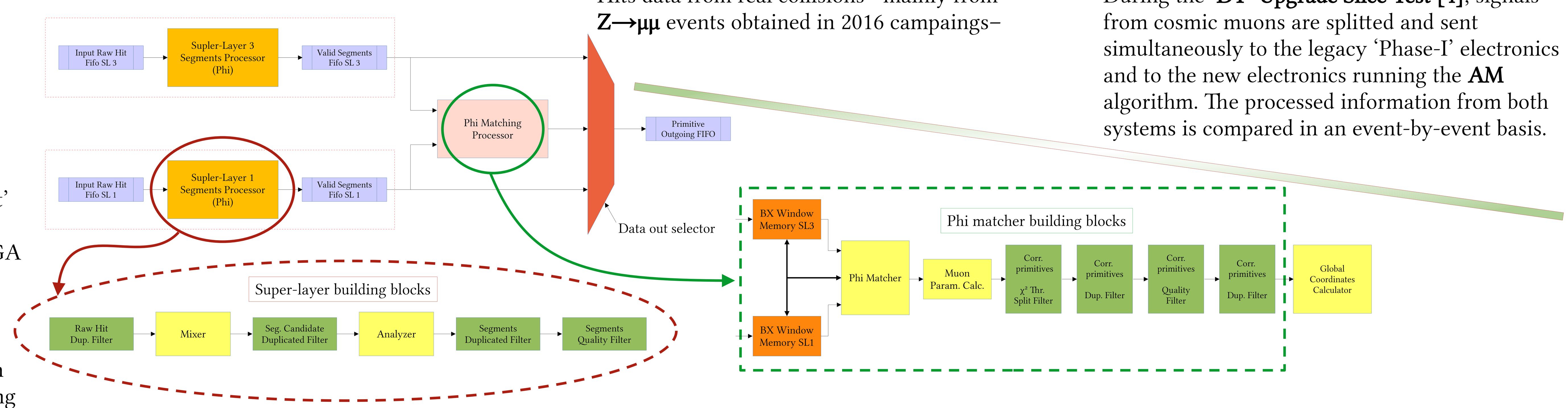
Phase-II trigger and read-out test stand at Ciemat



Algorithm architecture

AM core comprises two main types of building blocks: **Super-layer segment processor** and phi-segments **matching processor**. The core allows to select which block sends data to the outgoing collector FIFO.

Each block is built with **operational modules** and data **filters**, chained with ‘First-Input First-Output’ (‘FIFO’) buffers or FIFO-like ad-hoc components. The last ones have been designed to optimize FPGA resources usage and timing.



The Super-layer processor components

- The **Mixer** processor receives ‘hits’ and, for each one, prepares groups of segment candidates using previously stored items that were buffered in temporary memory blocks (‘**grouping**’). ‘Hits’ considered too old are periodically removed from those buffers.
- After the mixer, a filter removes duplicated segment candidates from the processing pipe that were generated by the own nature of the grouping procedure.
- The **Analyzer** module computes muons trajectory, valid lateralities **[2]** and quality parameters and, based on them, accepts or rejects each candidate.
- For a given event, the analysis procedure can also leave duplicated valid segments, requiring from another filter after it.
- Along the super-layer processing stages, a mix of similar segments with different qualities are being generated, but only the best one of each related group –according to certain criteria– has some interest, so a **segments quality** final **filter** compares parameters within each group discarding those with a relative lower quality.

Algorithm performance validation

Software validation tests

- An emulator of the **AM** algorithm has been written and integrated into the CMS Software Framework (‘**CMS-SW**’) to simulate its behaviour and performance.
- Hits data from real collisions –mainly from **Z⟶μμ** events obtained in 2016 campaings– are injected both in a hardware testing setup, running the firmware version, and into the ‘CMS-SW’ emulator. The results from both are compared.

Hardware validation tests

- During the **‘DT’ Upgrade Slice Test [4]**, signals from cosmic muons are splitted and sent simultaneously to the legacy ‘Phase-I’ electronics and to the new electronics running the **AM** algorithm. The processed information from both systems is compared in an event-by-event basis.

The Phi-Matcher processor components

- Segments from each super-layer processor are sorted by ‘BX’ value into a pair of memory blocks, one per ‘SL-φ’. All segments from a single event are processed in block.
- The **Phi-matcher core** module retrieves them trying to find pairs of segments –one per ‘SL-φ’– whose ‘BX’ differs as much as one unit and their Δ‘ψ’ is limited, discarding any other pair with larger differences. A pair per ‘BX’ is accepted as valid. In those ‘BX’ with no pair, a single ‘SL-φ’ segment –the best– is labeled as valid.
- For every item outgoing from the **Phi-matcher core**, new chamber-level trajectory parameters, χ^2, and a new quality tag are computed, resulting into a ‘primitive’.
- In a similar way to super-layer processing stage, a further chain of filters rejects ‘primitives’ based on no-duplicity, quality level and χ^2 criteria.
- A final module converts computed local muon trajectory coordinates into global sector coordinates.

Results

Figure 1 shows the AM reconstruction efficiency for the local chamber position, while **Figure 2** shows the efficiency for the identified muon creation bunch-crossing ‘BX’ (‘**t0**’), respect to the values obtained by the offline phase-I legacy system, by using cosmic muons.

Efficiencies for different primitive quality levels are depicted in different colors.

In red curves every primitive identified by the phase-I offline is considered, while in blue curves primitives are built with more than 4 ‘hits’ and in green curves the primitives have six or more ‘hits’ –3 or more per super-layer–.

All selected segments were built with more than 4 ‘hits’, which also have an inclination in the radial coordinate smaller than 30º with respect to the direction perpendicular to the chamber.

Figures 3 and **4** show a comparison for global ‘**φ**’ and for ‘**φ-bending**’ angles computed by the ‘CMS-SW’ emulation and by the AM hardware test setup, after injecting ‘hits’ data coming from a particle-gun sample (2 GeV ≤ p_T ≤ 100 GeV) with a pile-up level of 200 collisions per BX.

The compared primitive pairs –around 4000 items– have the same hits and the same lateralities.

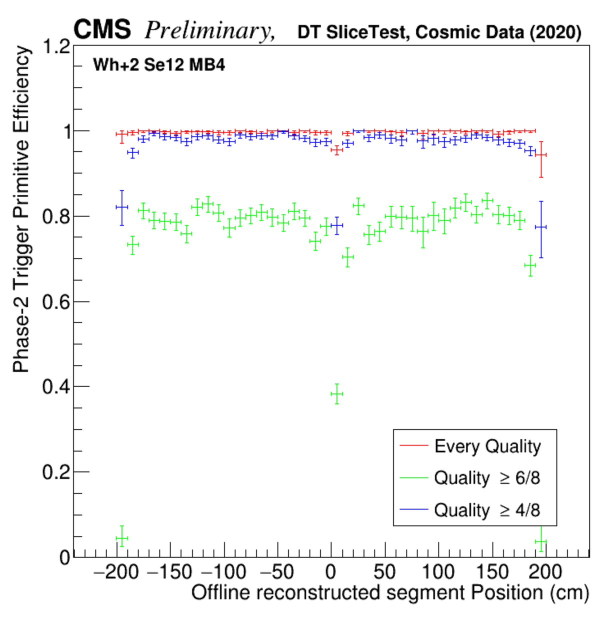


Figure: 1

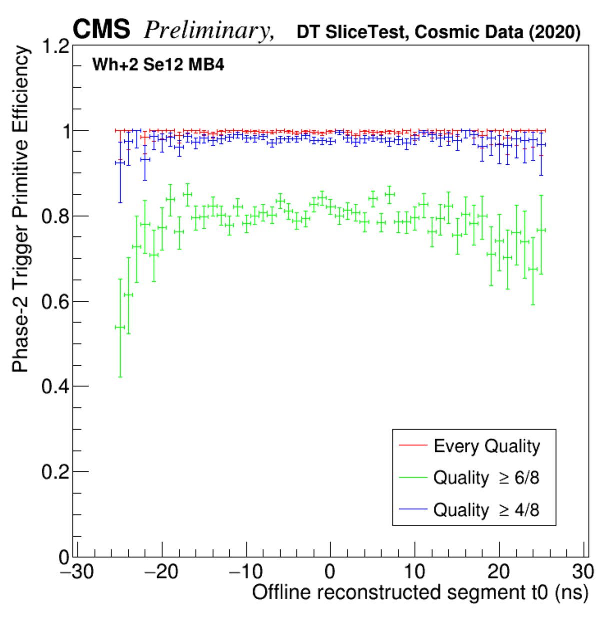


Figure: 2

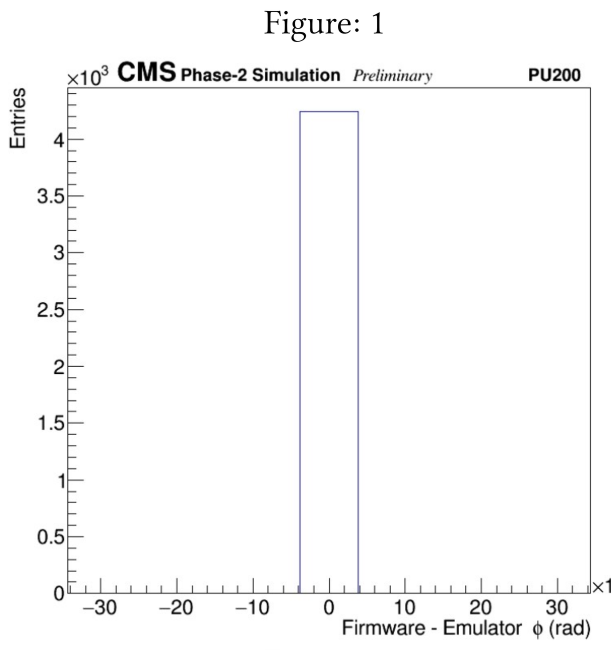


Figure: 3

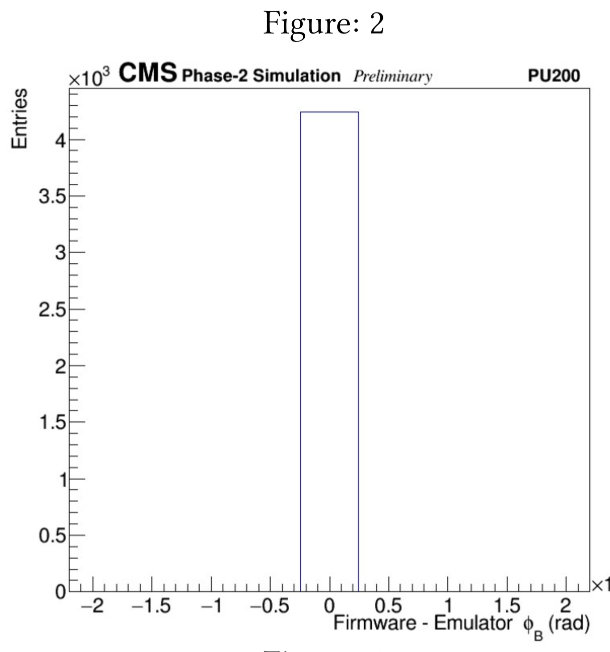


Figure: 4

Conclusions

- The AM proposed trigger algorithm **[2]** for the High Luminosity LHC (‘**HL-LHC**’) has been successfully migrated to a hardware implementation using VHDL, designed to be portable, as much as possible, to different FPGA devices by using only standard language structures and manufacturer macros –not core wizards–.
- It has been extended to two super-layers with a subsequent matching mechanism and a converter to global coordinates.
- The agreement between firmware and emulated versions is high, as well as the efficiency in segment reconstruction when tested with cosmic muons.
- At the present time, the AM algorithm is being expanded to cope not also with the two ‘SL-ψ’ but to include segments computed by a ‘**θ**’ angle **[3]** super-layer processor.
- Additionally, it is under study the replication of multiple AM algorithm processing instancies, by porting them to a new type of ATCA boards with bigger FPGAs, to reach an overall higher integration level.

References

[1] **The CMS Barrel Muon trigger upgrade**, Andrea Triossi on behalf CMS collaboration, JINST 12 (2017), no. 01, C01095, doi:10.1088/1748-0221/12/01/C01095

[2] **FPGA-based algorithms for the new trigger system for the phase 2 upgrade of the CMS drift tubes detector**, J.M.Cela Ruiz on behalf CMS collaboration, JINST 12 (2017), no. 01, C01033, doi:10.1088/1748-0221/12/01/C01033

[3] **The Drift Tube System of the CMS Experiment**, G.Cerminara, JINST Vol. 172 (2007), pages 71-74, doi:10.1016/j.nuclphysbps.2007.07.016

[4] **Implementation in a sector of the CMS Drift Tube chambers of a muon tracking algorithm for Level 1 trigger during HL-LHC**, C. F. Bedoya, IEEE-NSS 2020