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

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Readout and trigger for Run 3 and HL-LHC in Spain – COMCHA

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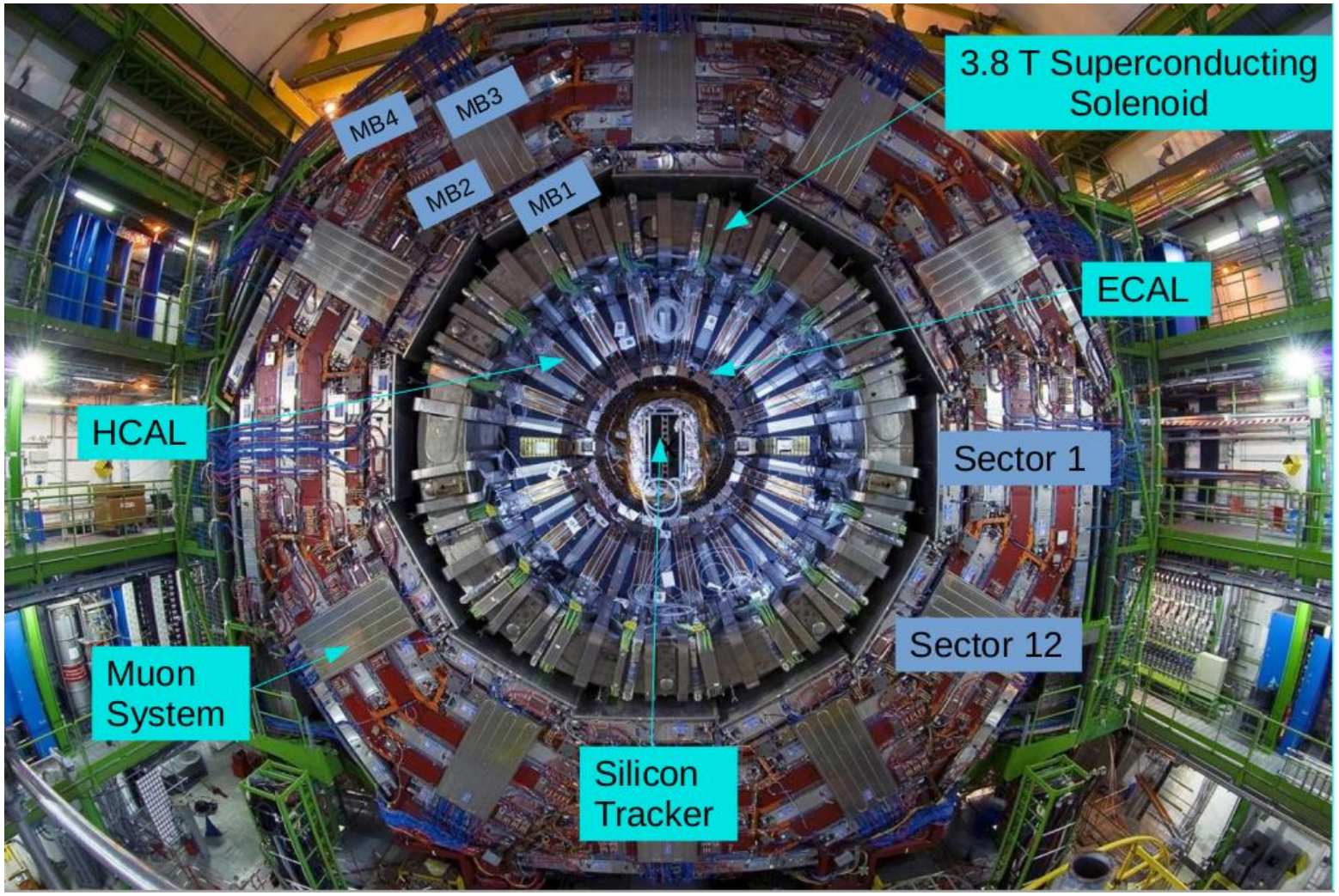
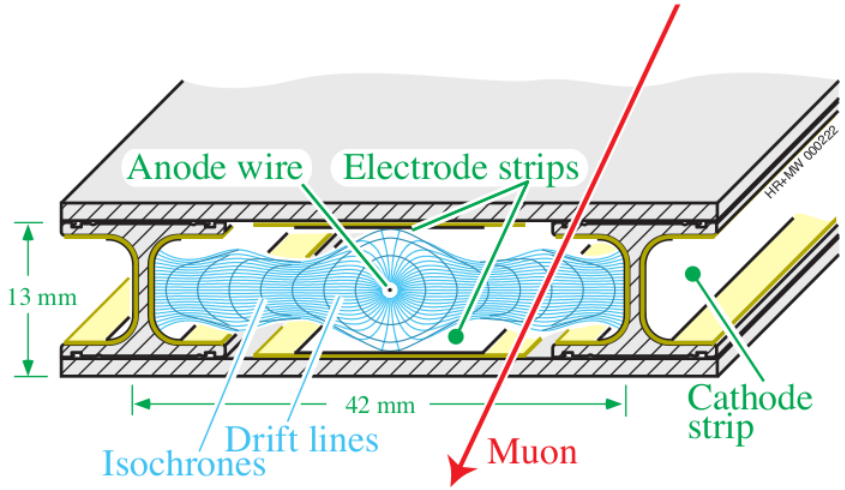
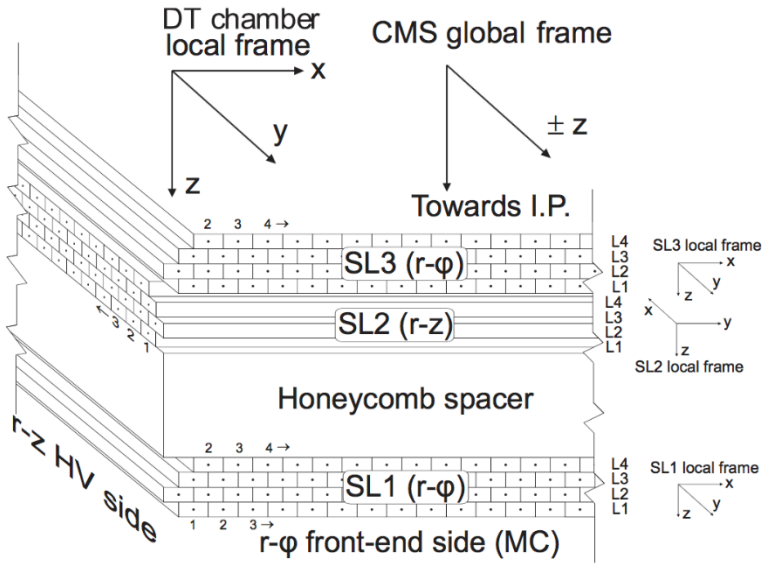
The CMS experiment



The CMS Drift tube chambers

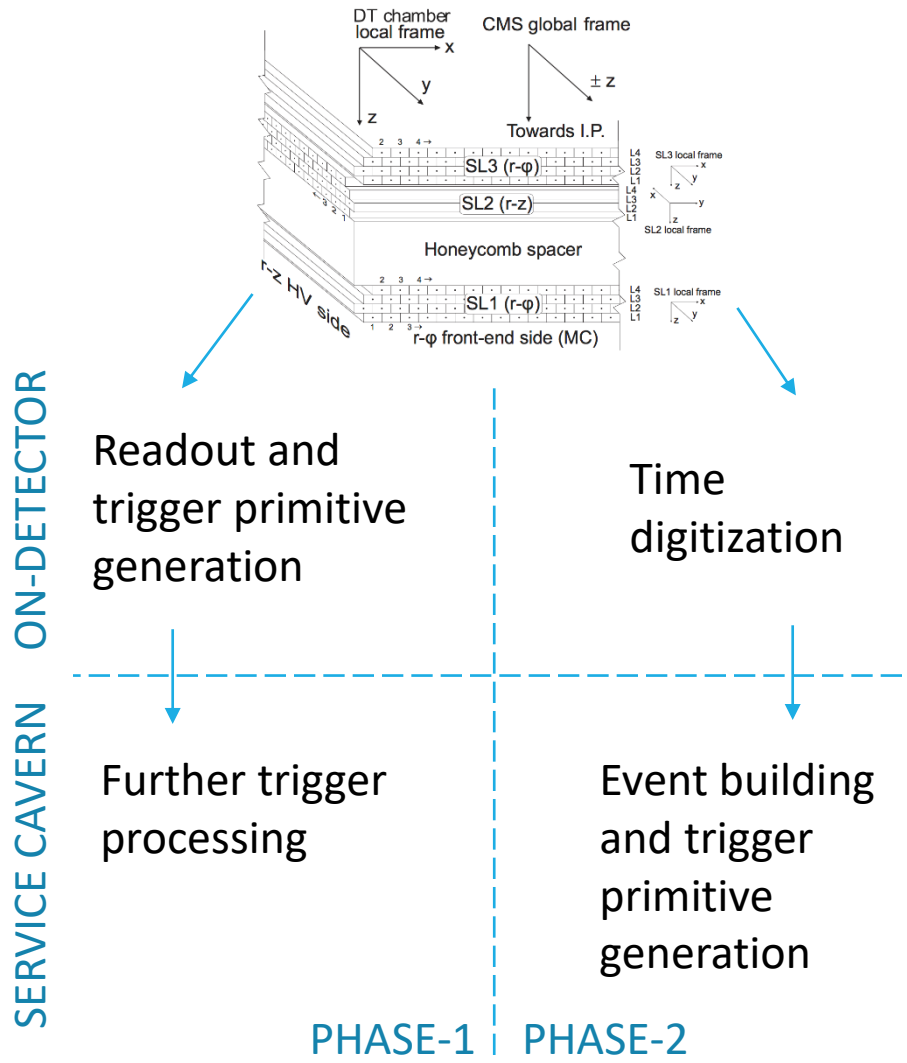




- The basic element of the drift tube chamber is the drift tube **cell**.
  - Transverse size of 42×13 mm^2 with an anode wire at the centre.
  - Filled with a mixture of Ar/CO_2 , providing a saturated drift velocity of about 54 μm/ns.
- Basic functioning:
  - A charged particle passing through the cell knocks electrons off the atoms of the gas, which drift towards the wire with constant velocity.
  - The drift time of the ionised electrons is measured. There is a left-right (**laterality**) ambiguity on the hit position.
- One **superlayer** (SL) groups four layers staggered half a cell.
- One chamber is formed by **two superlayers** measuring the r-φ coordinate (SL1, SL3) and **one superlayer** measuring the r-z coordinate (SL2).

DT Upgrade for Phase-2

- During LS3, a major upgrade will be performed to both the accelerator and the experiments, starting the HL-LHC.
- Increasing LHC instantaneous luminosity up to 5 – 7.5 × 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Present DT detectors will remain for HL-LHC operation. Expected loss of performance will be minimal after this period.
- New DT electronics architecture to cope with a higher L1 rate (100 kHz → 750 kHz).
  - Only the digitalization of all signals will be performed on-detector and then sent to the back-end system via optical links.
  - In the back-end, **trigger primitive generation** will be performed in powerful FPGAs profiting from a better time resolution on the signals.
  - See previous talk by Á. Navarro.



The Analytical Method

- The **Analytical Method (AM)** is an algorithm for **Trigger Primitive (TP)** generation in HL-LHC. It profits from the better electronics time binning in Phase-2 (1 ns instead of the present 12.5 ns).
- The algorithm is capable of computing online the trigger primitive's **crossing time** (in ns and bunch crossing **BX** units), **position** and **direction** with an expected resolution close to the present offline system resolution.
- The algorithm has been implemented in **software as an emulator** and in **firmware**. The inputs to the algorithm are the time and cell numbers of all signals detected in each superlayer. It assumes muons follow a straight trajectory inside the chamber.
- For now, only considering the **two r-φ superlayers**. Presently studying how to profit from the information from the r-z superlayer.

The Analytical Method

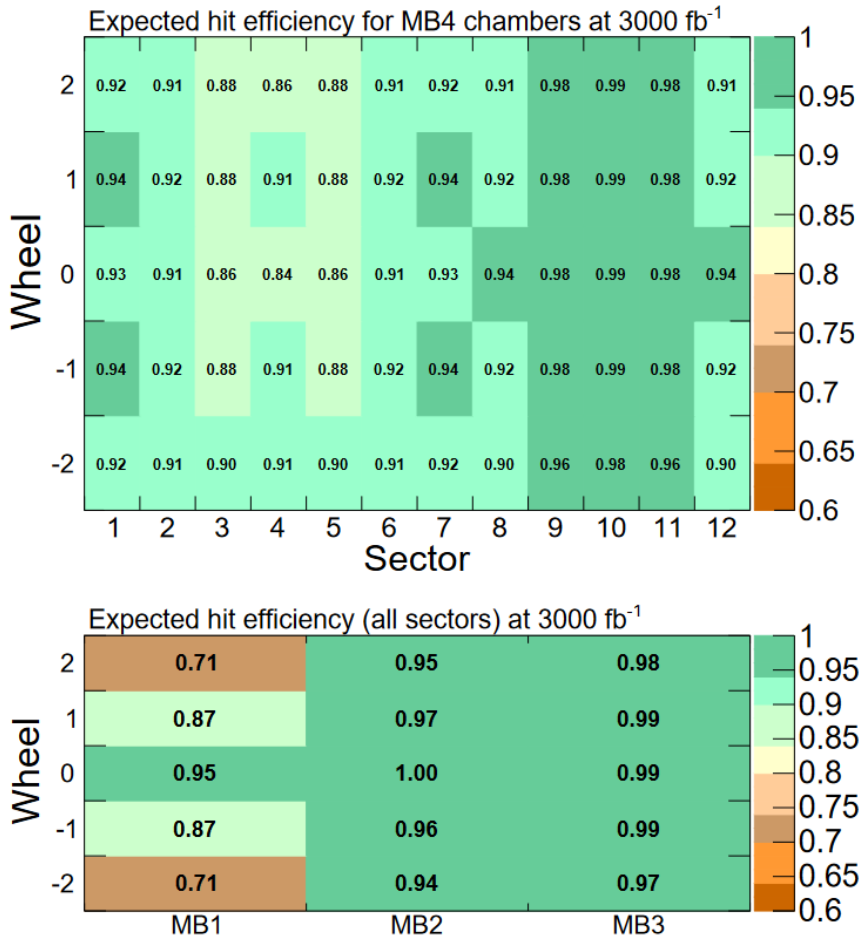
- Developed in four steps:
  1. **Grouping**: Builds all 3- and 4-hit groups by applying geometrical constraints on the cells of the hits.
  2. **Laterality prediction**: Reduces from 4 to 3 the possible laterality predictions for each hit group by applying timing constraints.
  3. **Fitting**: Computes the time (in ns and BX units), position, slope of the TP and the χ^2 of the fit.
  4. **Correlation**: If at least one fit per SL was obtained, they can be combined if their t_0's match within 25 ns. Another fitting is performed with the 6 to 8 hits obtaining new values for the TP parameters.

     A **confirmation** of a per-SL TP can also be done (only in the emulator) by matching at least 2 hits in the other SL with the extrapolation of the TP.
- Several filters are applied before and after the correlation step to reduce the combinatorial explosion.
- A further cleaning logic after the algorithm is being studied, see next talk by C. Vico.

Quality	Description	Type	
1	3-hit segment	uncorrelated	
2	3+2 hits segment	confirmed	→ Emu only
3	4 hit segment	uncorrelated	
4	4+2 hits segment	confirmed	→ Emu only
5	non-existing label		
6	3+3 hits segment	correlated	
7	4+3 hits segment	correlated	
8	4+4 hits segment	correlated	

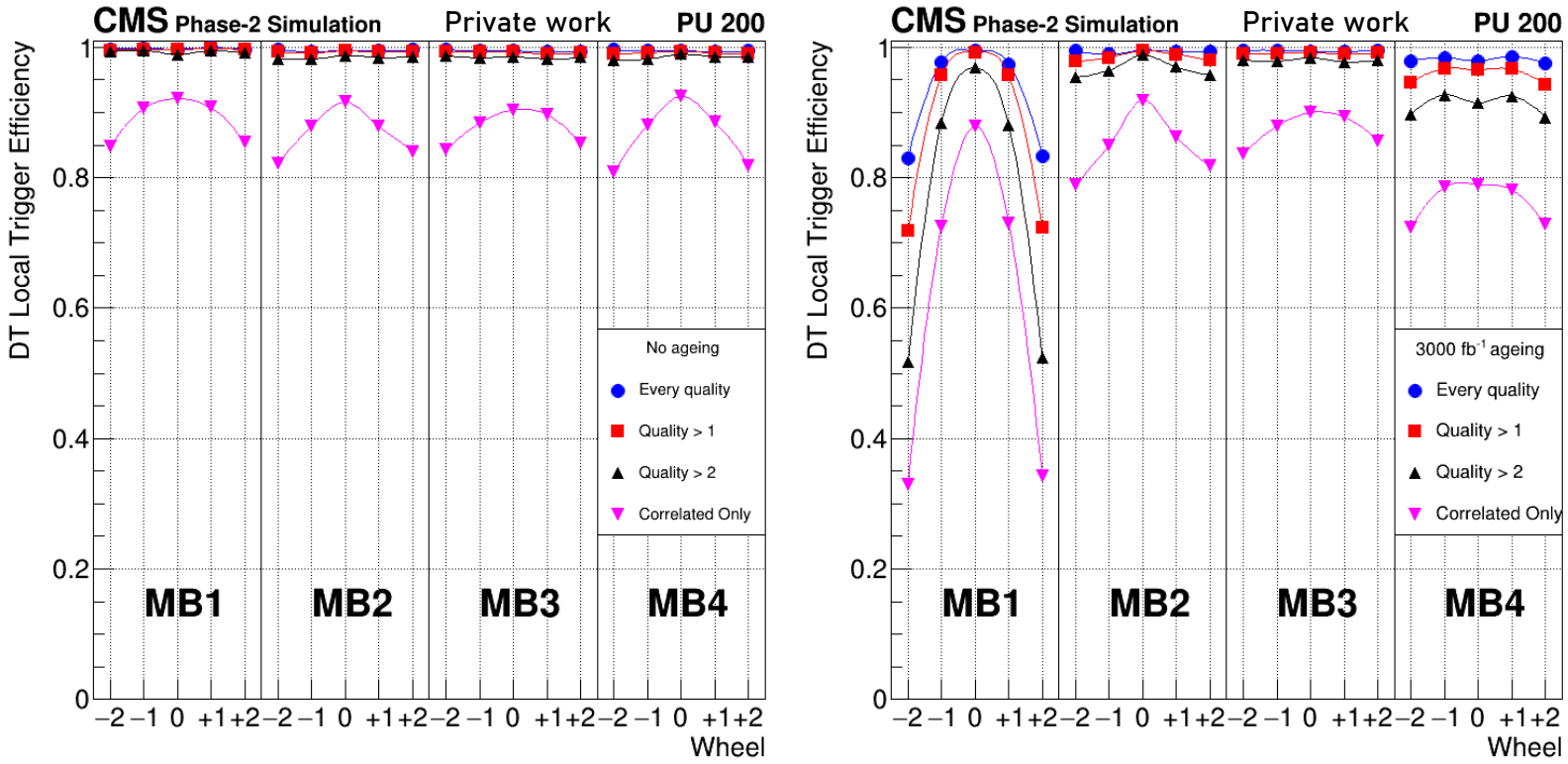
Performance using simulated samples

- The Analytical Method has been evaluated in several samples, including Run 2 data, Phase-2 Simulation and cosmic and collision data obtained with the DT Slice Test.
- Latest results are obtained using a privately simulated sample of 3700 events using Phase-2 conditions.
- The <pile-up> is of 200 collisions/BX, including the most up-to-date recipe for neutron simulation, which is superimposed in a [-16,+16] BX range to the signal of 4 muon pairs per event with flat pt in the range [20,200] GeV and within $|\eta|$<1.2.
- The sample is processed with and without assuming the “end of Phase-2 (3000 fb^{-1})” ageing/failure scenario.



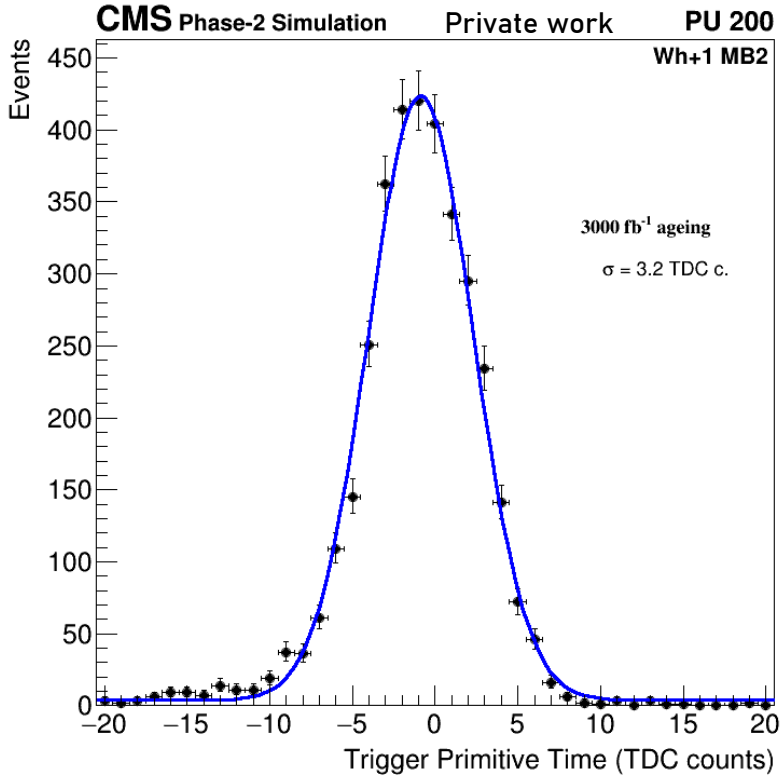
Efficiencies using simulated events

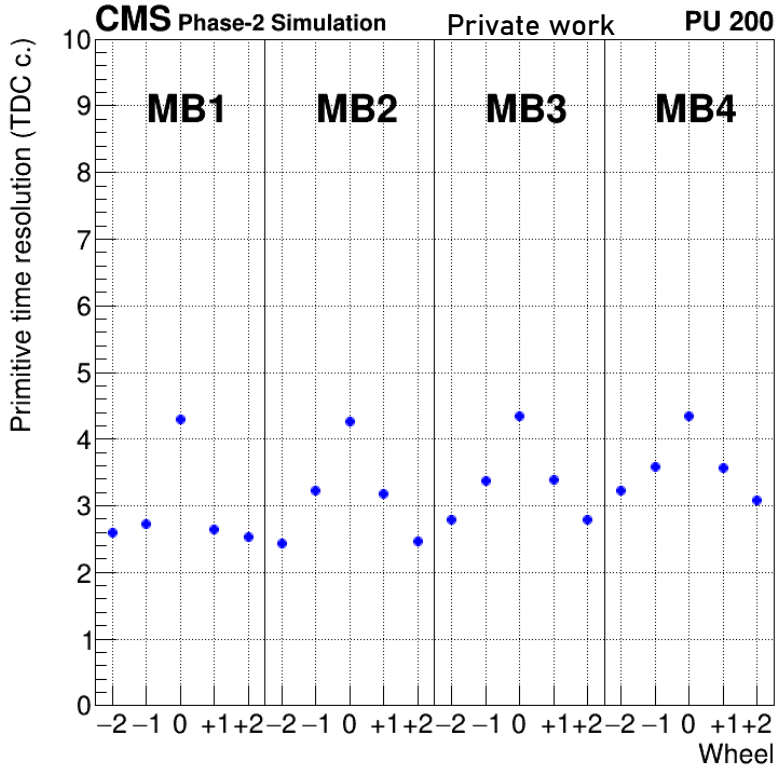
- Efficiencies are calculated with respect to offline segments with quality cuts and geometrically matched to the generated muons. Only trigger primitives in the right BX are considered efficient.
- High efficiency achieved in the whole detector. As expected, the drop in efficiency is higher for the chamber more affected by ageing.



Time distributions

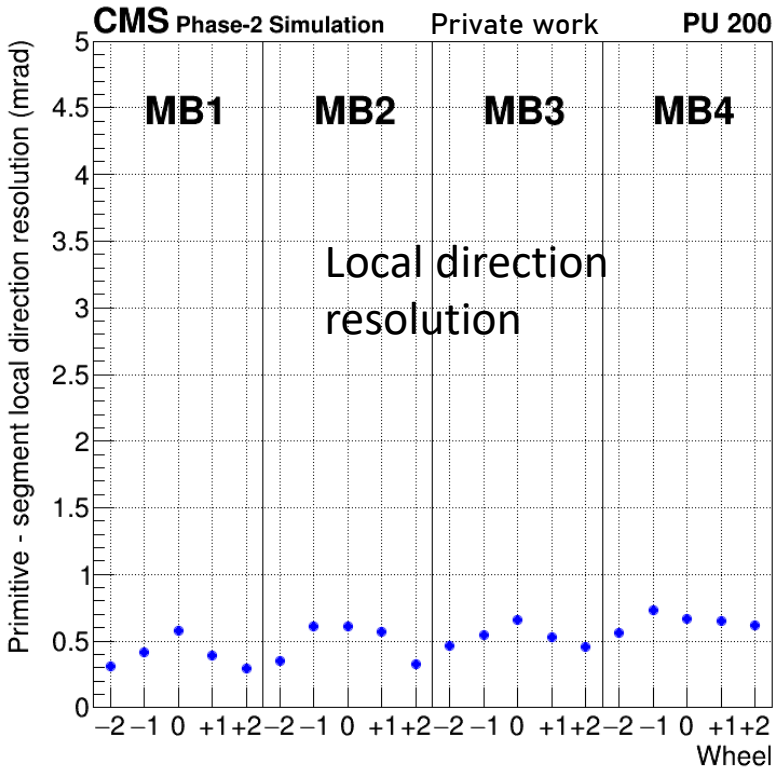
- Fitting the TP time distributions to a gaussian plus a flat contribution.
- Including only correlated TP, as are the ones that populate the core gaussian.
- Time expressed in TDC count units (1 TDC c. = 25/32 ns), minimal precision unit used throughout the algorithm.
- Timing distributions with gaussian widths of few ns, while in Phase-1 time was given in BX units (25 ns step).

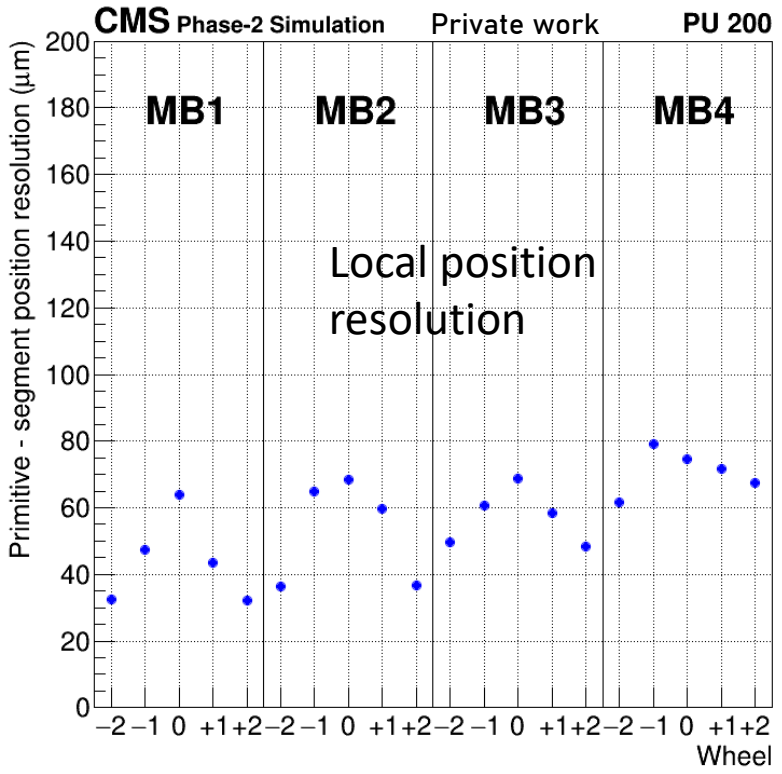




Resolutions w.r.t offline segments

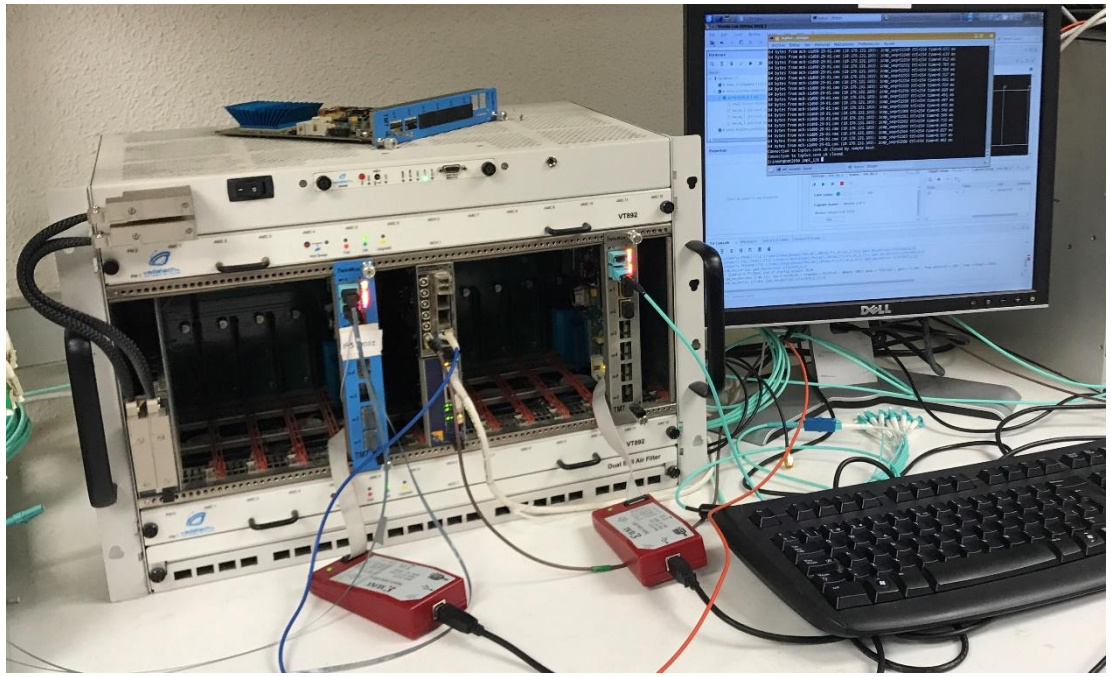
- Resolutions are computed with respect to offline segments with quality cuts and geometrically matched to the generated muons. Only trigger primitives in the right BX are included.
- Fitting distributions to a gaussian plus a flat contribution.





Firmware implementation

- The AM firmware is implemented in a Xilinx Virtex Ultrascale Plus FPGA and written in VHDL.
- The present implementation includes the AM algorithm w/o confirmation + readout, slow control, tcds,…
- A test stand at CIEMAT allows to perform dedicated tests of this firmware, injecting hits from all chambers from the CMS detector, generating and reading the trigger primitives and then comparing to the ones obtained by the software emulator.



Firmware-emulator comparison

- Comparing firmware and emulator implementation using hits from the previous simulated sample.
- Efficiency w.r.t emulator is defined as the number of TPs in the emulator output that can be *matched* to a TP in the firmware output.
- Efficiency w.r.t firmware is defined as the number of TPs in the firmware output that can be *matched* to a TP in the emulator output.

Matching: Two TPs share the same hits with the same laterality assumption or match in quality, time, position, and slope within very stringent ranges.

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        Efficiencies w.r.t emu

3 hits      :  98.17 (75310 / 76716)
4 hits      :  99.70 (29511 / 29601)
6 hits      :  94.22 (  375 /   398)
7 hits      :  97.63 ( 4986 /  5107)
8 hits      :  99.99 (20995 / 20998)
Average     :  98.76 (131177 / 132820)

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        Efficiencies w.r.t fw

3 hits      :  99.46 (75311 / 75718)
4 hits      :  99.93 (29511 / 29533)
6 hits      :  93.52 (  375 /   401)
7 hits      :  97.61 ( 4986 /  5108)
8 hits      :  99.99 (20995 / 20997)
Average     :  99.56 (131178 / 131757)

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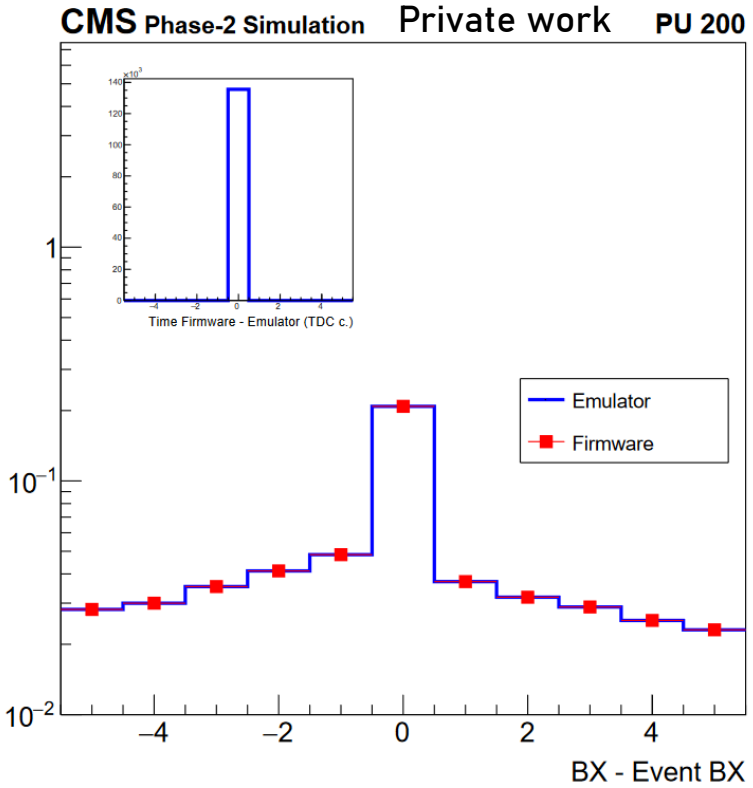
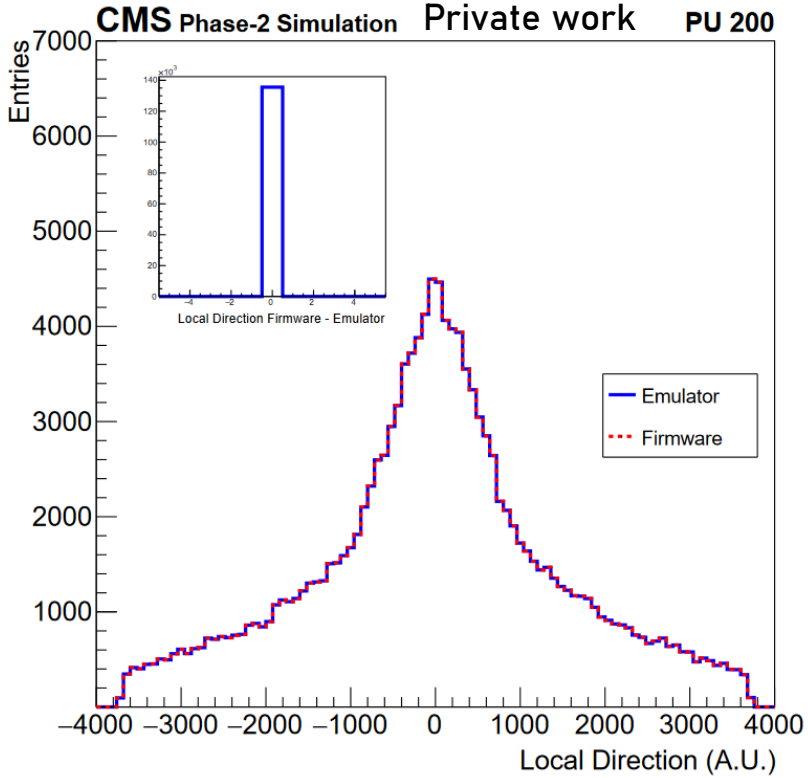
Firmware-emulator tests

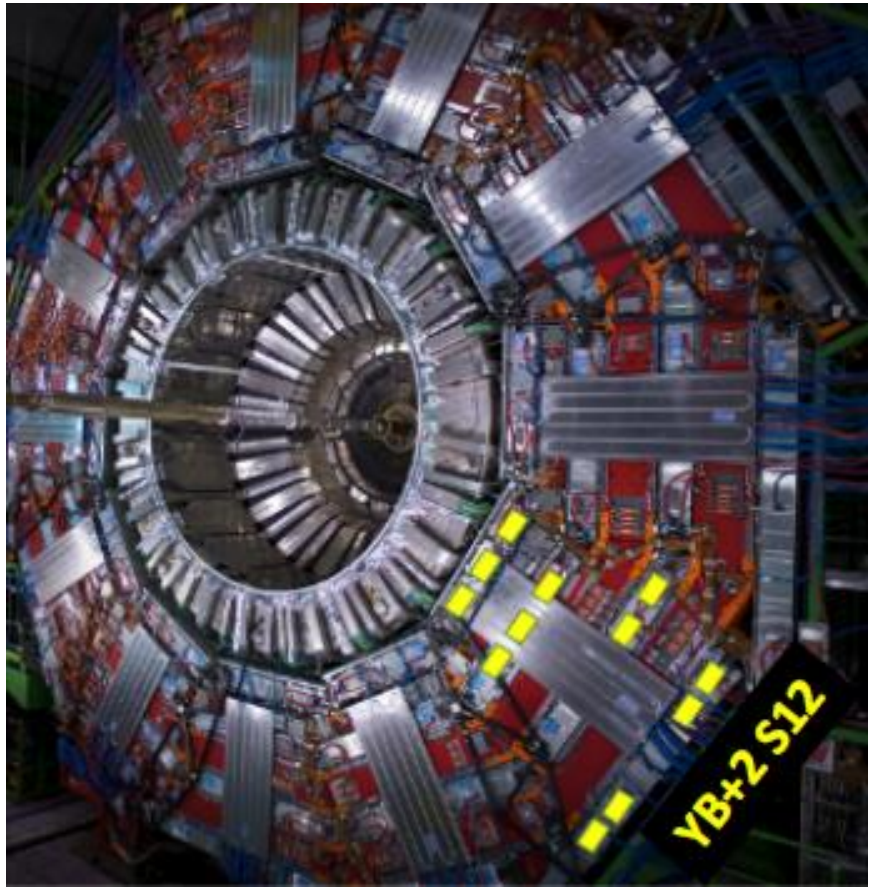
- Comparing the parameter values obtained by both firmware and emulator the TPs fitting the same hits with the same laterality assumptions.
- Agreement to the LSB in all quantities.





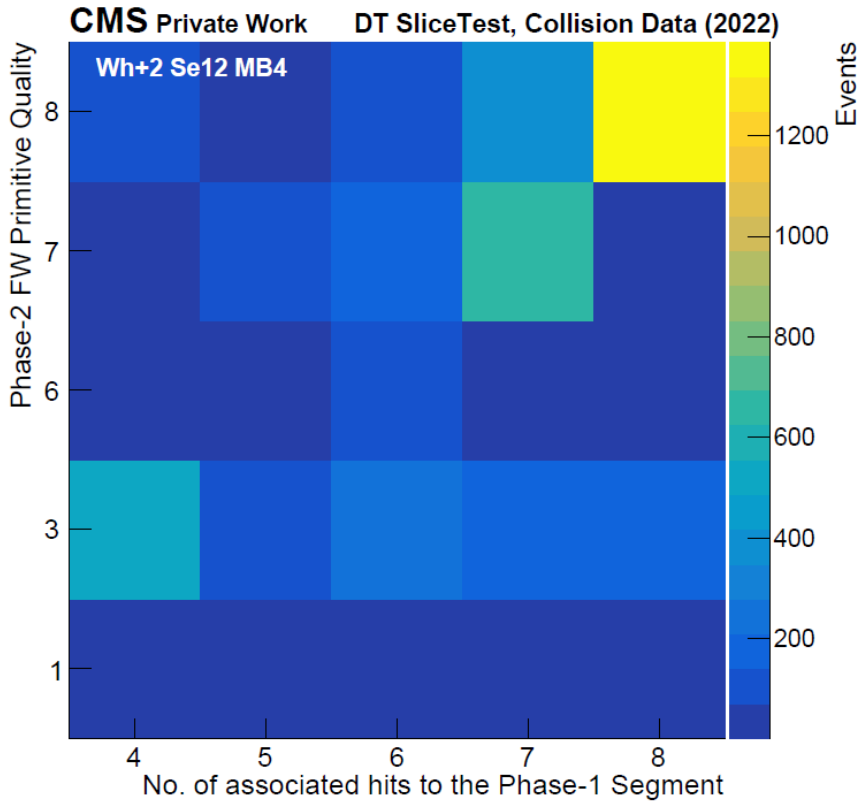
Performance evaluation in data: DT Slice Test

- During LS2, one CMS sector (Wh+2 Se12) has been instrumented with the new front-end and back-end electronic prototypes. This way, both Phase-1 and Phase-2 electronics can be run in real conditions inside the CMS infrastructure.
- One of these backend boards (the so-called AB7) runs the AM firmware, so it can be validated using real cosmic muons and collision data.

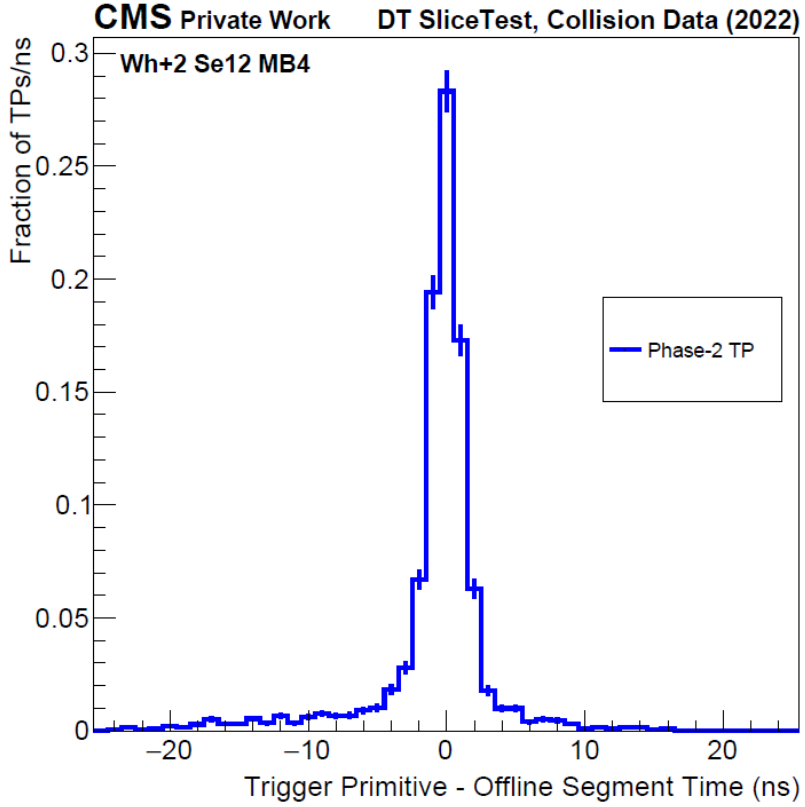


Performance evaluation in data: DT Slice Test

Good agreement between the number of hits used to build the TP and the segment



- 2D distribution of the Phase-2 TP quality obtained by the AM firmware versus the number of hits associated with the offline reconstructed segment in the MB4 station for the DT Slice Test collision data taken during the start of Run 3 in 2022.



Time resolution with respect to offline segments of few ns.

- Difference between the AM TP fitted time and the offline reconstructed segment time for DT Slice Test collision data in the MB4 station during the start of Run 3 in 2022.

Conclusions

- The **Analytical Method** is an algorithm implementing analytical solutions for reconstructing the DT trigger primitives for HL-LHC.
- Performance studies on a realistic Phase-2 simulated sample show very good results, both in efficiency and in resolution with and without the ageing scenario expected at the end of HL-LHC.
- The AM firmware is on a good shape, showing a very good agreement with the AM emulator and providing good results at the DT Slice Test (already with Run 3 collision data).