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

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On behalf of the CMS Collaboration

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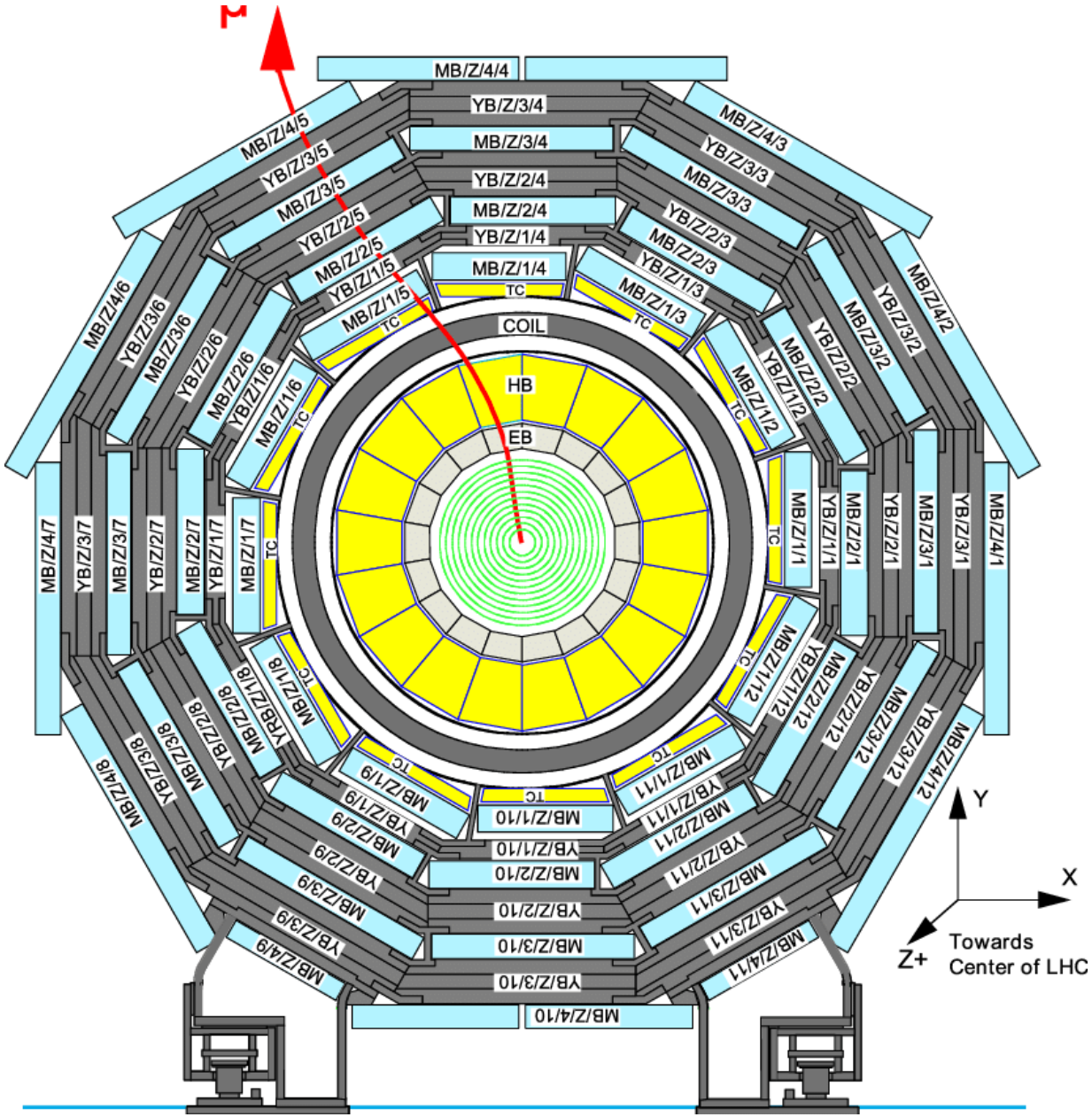
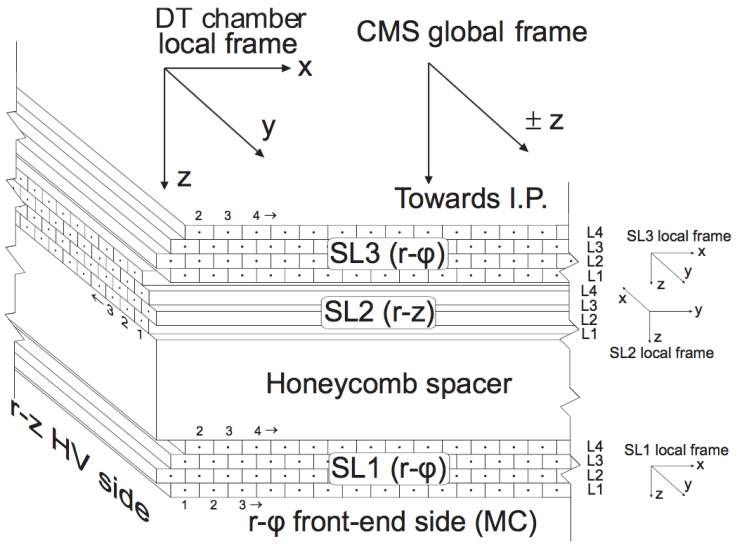
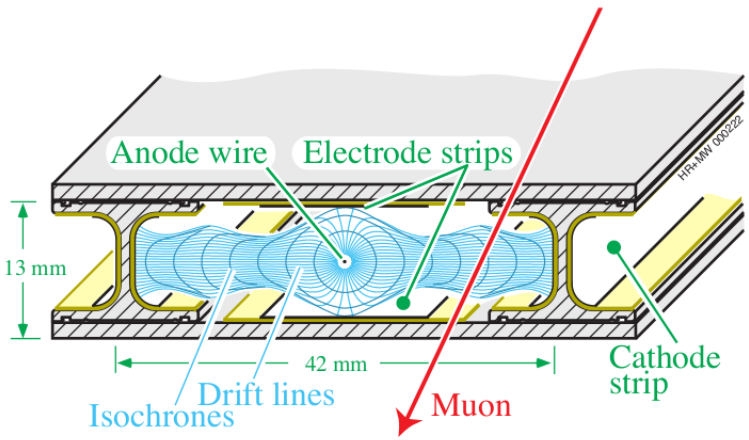
The CMS Experiment



CMS Drift Tube chambers (DT)

- 1 **chamber** $\rightarrow$ 3 **Superlayers** (1 in θ view and 2 in φ view).
- 1 Superlayer (SL) $\rightarrow$ 4 **layers** displaced **half a cell**.
- 1 Layer $\rightarrow\sim 50 - 100$ **cells**.

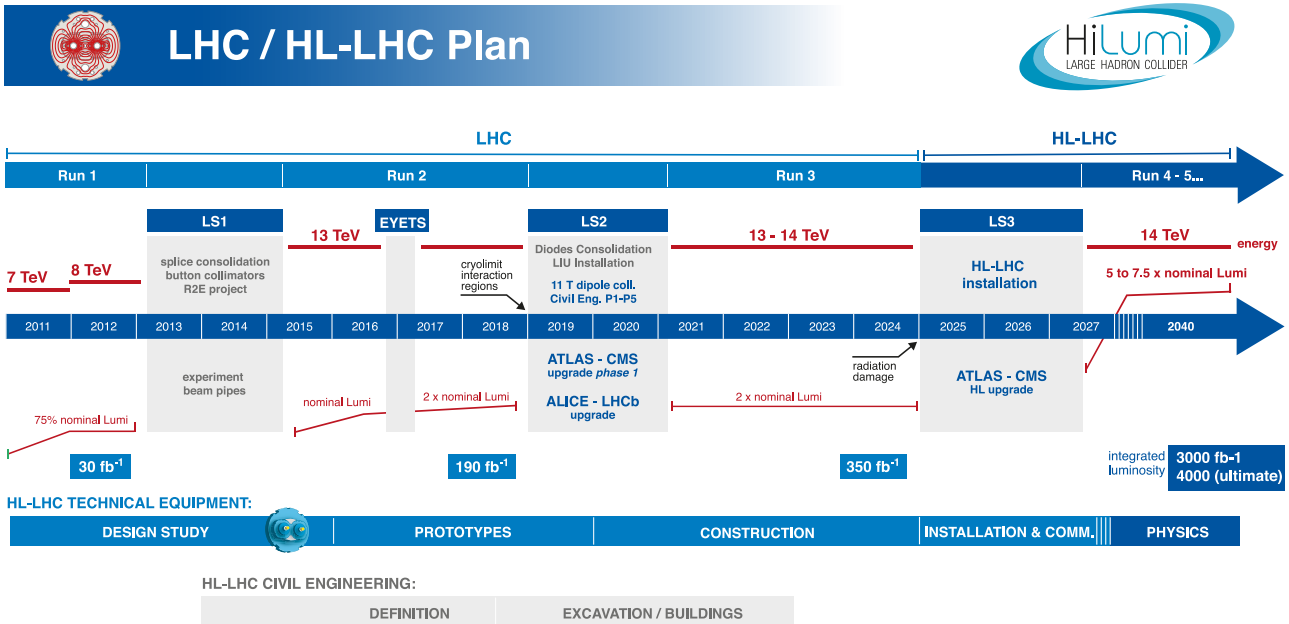




- Basic functioning: The ionization of a charged particle passing through the cell drifts towards the wire with constant drift velocity (54 μm/ns). The time of the avalanche upon reaching the wire is measured by associated electronics, being able to extract precise coordinates by pattern reconstruction.
- There is **left-right (laterality) ambiguity** on the hit position.

High Luminosity-LHC

- LHC upgrade during 2025-2027 shutdown.
- **Increasing** LHC instantaneous luminosity up to 7.5×10^{34} from the present 2×10^{34}.
- It becomes necessary to upgrade certain subdetectors due to the expected radiation doses, the increasing background and CMS readout rate.
- **DT Chambers**: present on-detector electronics (limiting trigger rate to 100 kHz instead of the 750 kHz needed) is going to be substituted for a new Phase 2 system that digitalizes all detector signals and sends them to a new electronic backend system in the service cavern in charge of the trigger primitive generation and event matching.



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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 present 12.5 ns).
- The algorithm is capable of computing trigger primitive's **crossing time** (in ns and bunch crossing **BX** units), **position** and **local direction** with an expected resolution close to the present offline resolution.
- The AM has been implemented in software as an emulator and in firmware. The inputs of this algorithm are the time and cell number of all signals detected in a superlayer. It assumes the muons follow straight lines inside a chamber.

The Analytical Method

The algorithm is developed in three steps:

- **Grouping**: selects patterns of 3 or 4 DT fired cells compatible with a straight line in a single SL and their sub-patterns of 3 cells.
- **Fitting**: for each group of cells identified, computes unambiguously the BX using the mean-timer property and the track parameters using exact formulas from χ^2 minimization.
- **Correlation**: attempts a combination of compatible tracks from single SLs, re-computing SL track parameters and profiting from the larger lever arm.

Different cleaning filters applied at several stages.

- After building the AM DT primitives and clustering the RPC hits, the information from both subdetectors can be combined into a **superprimitive** (SP), exploiting the redundancy and complementarity of the two subsystems and combining DT spatial resolution and RPC time resolution.

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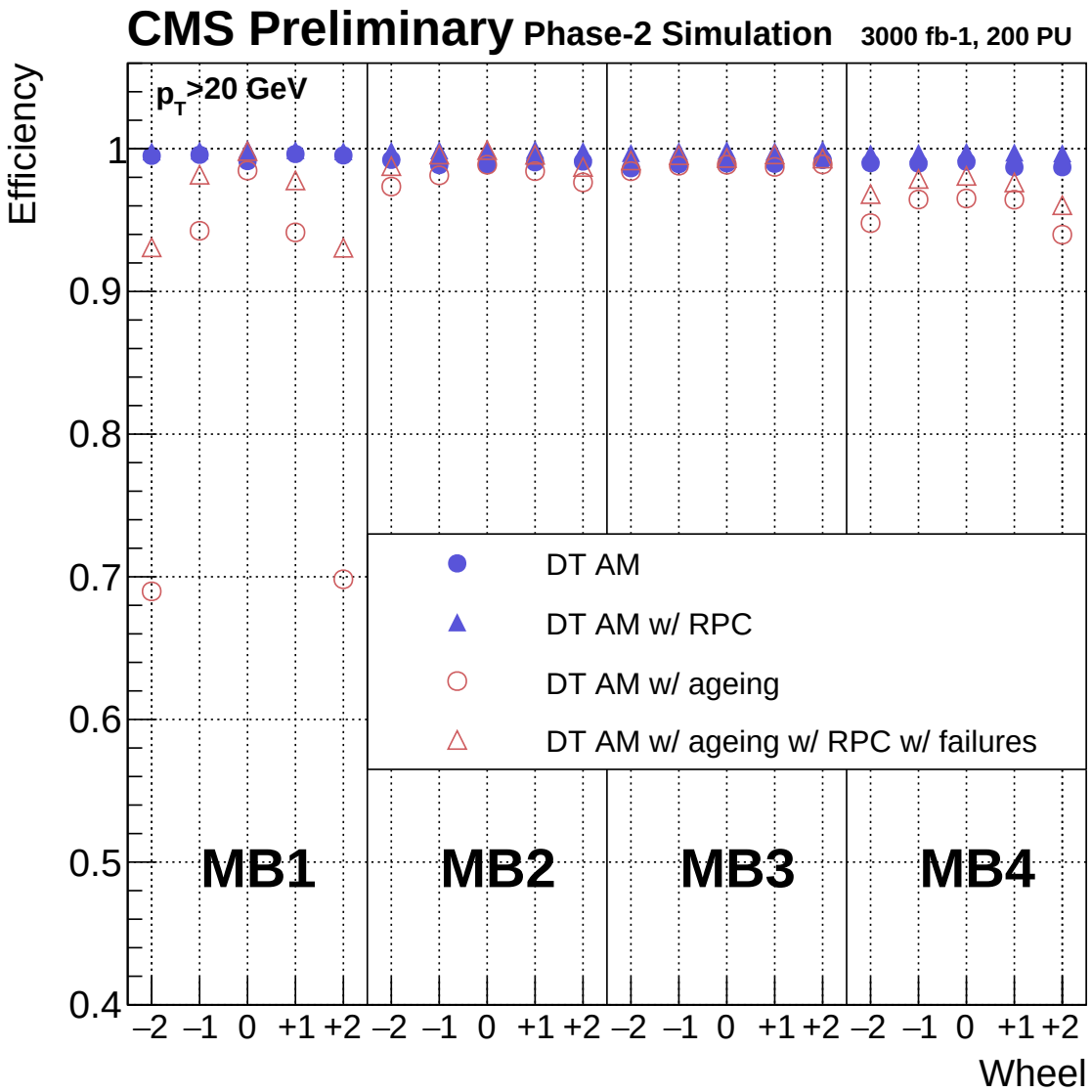
Performance evaluation in simulation

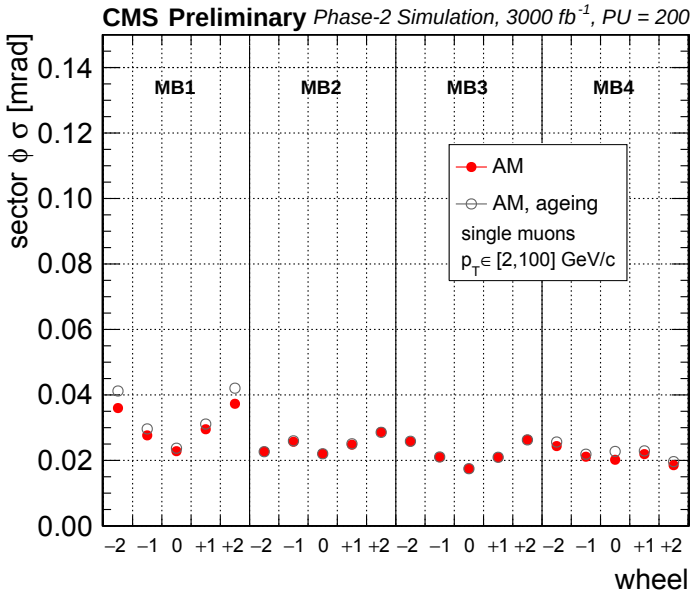
- The algorithm's performance has been evaluated in a sample of simulated single-muons with an average pile-up of 200 collisions/BX.
- **Efficiencies** are calculated with respect to offline segments with quality cuts and geometrically matched to the generated muons. Only trigger primitives in the right BX are considered efficient.
- *Sector* ϕ and *bending* ϕ **resolutions** (position and direction in global coordinates) are computed with respect to the simulated hits in the muon chambers.
- In the following plots we will show results with and without using the RPC system and considering the DT and RPC aging scenario predicted at the end of HL-LHC (see backup).

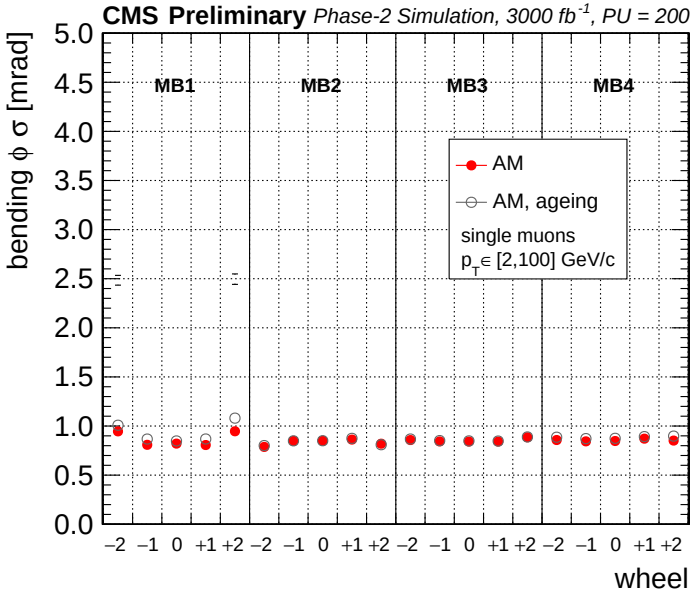
Performance evaluation in simulation: Efficiencies



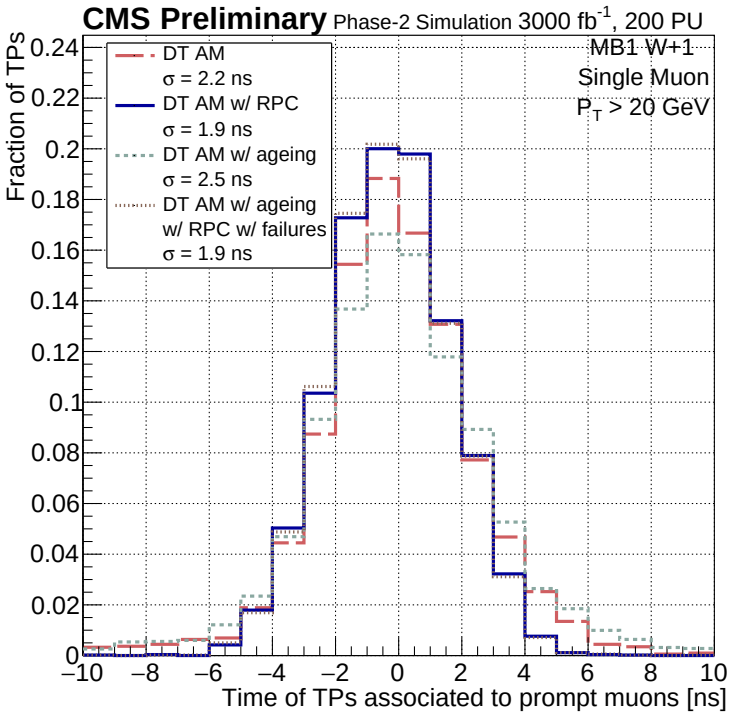
- Trigger primitive efficiency w.r.t reconstructed segments.
- With aging, DT-only efficiency decreases in MB1 external wheels, where ageing effects are larger.
- RPC helps recovering efficiency.

Performance evaluation in simulation: Resolutions



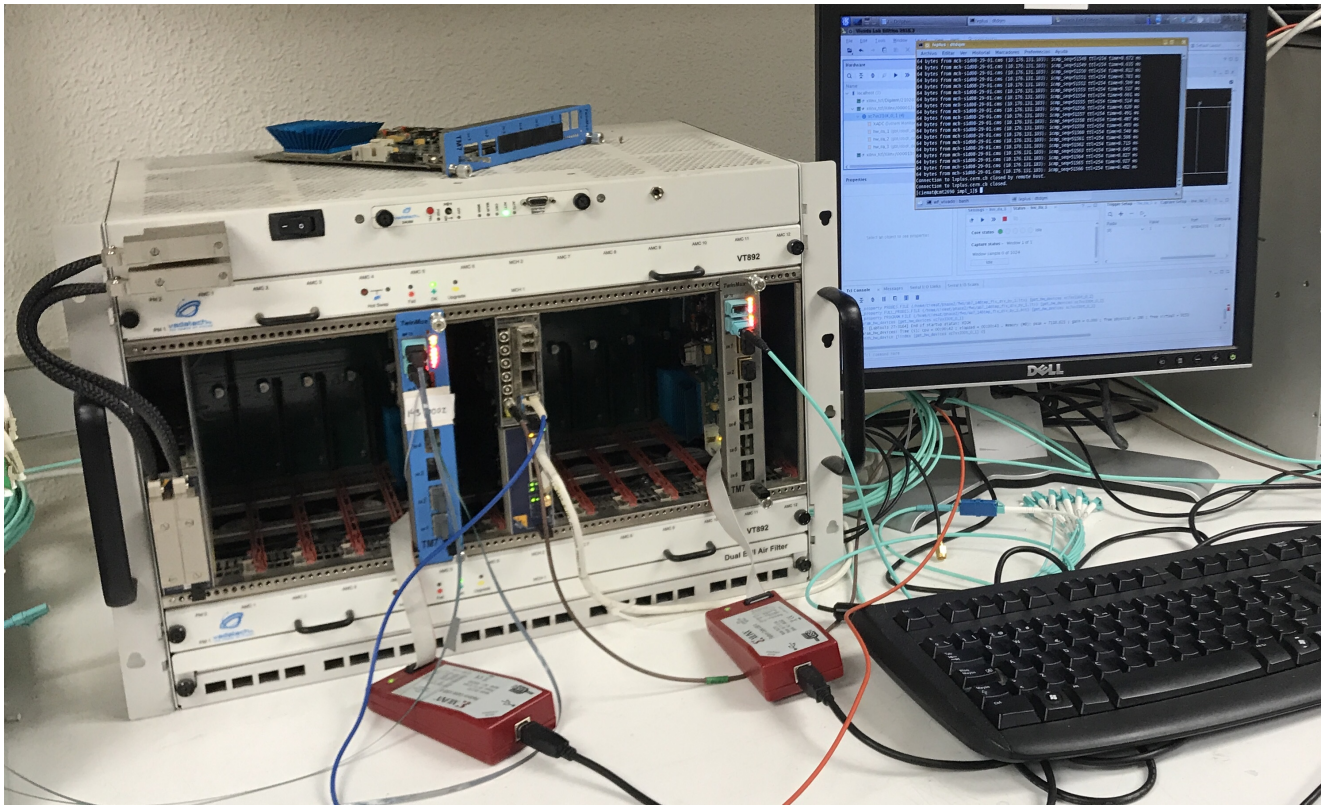


- Trigger time core resolution < 2.5 ns.
- As and example, MB2 stations show a sector phi resolution of ~ 0.03 mrad for the AM, which reflects an improvement of a factor of ~ 6 with respect to the legacy TPs.
- A similar improvement is observed for the direction resolution, which is 1 mrad.



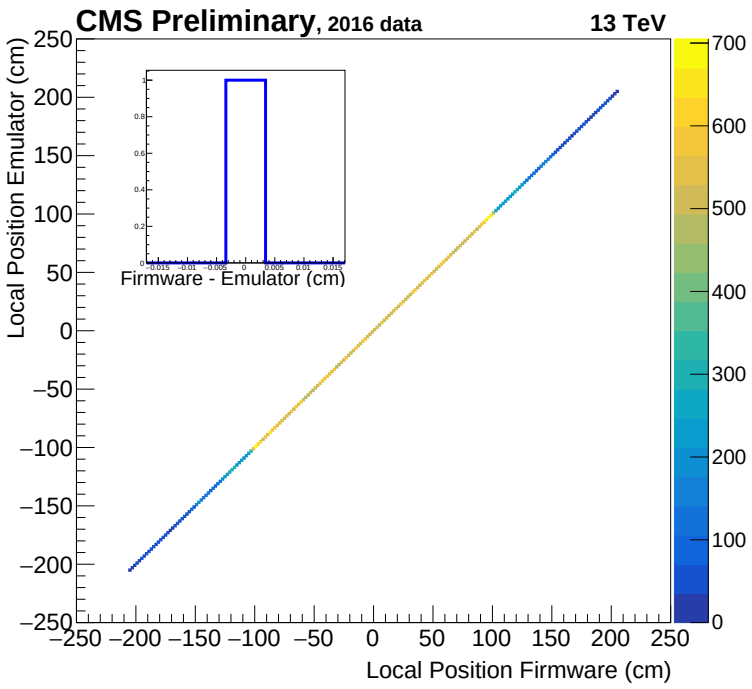
Firmware status

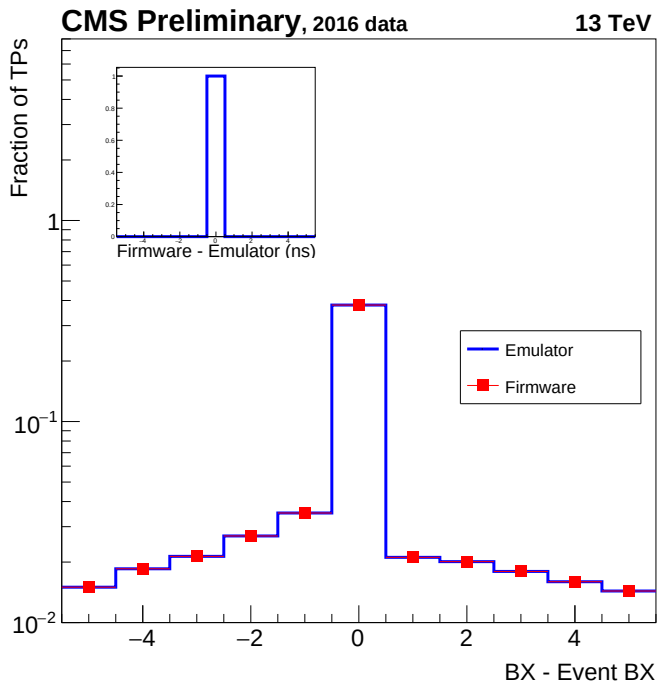
- The AM firmware is implemented in a Xilinx Virtex 7 XLXXC7VX330T FPGA and written in VHDL.
- Present implementation: AM algorithm w/o RPC + readout, slow control, tcds,...
- A test stand at CIEMAT allows to perform dedicated tests of this firmware, injecting hits from all chambers of the CMS detector, generating and reading the trigger primitives and then comparing to the ones obtained by the software emulator.



Performance evaluation in data

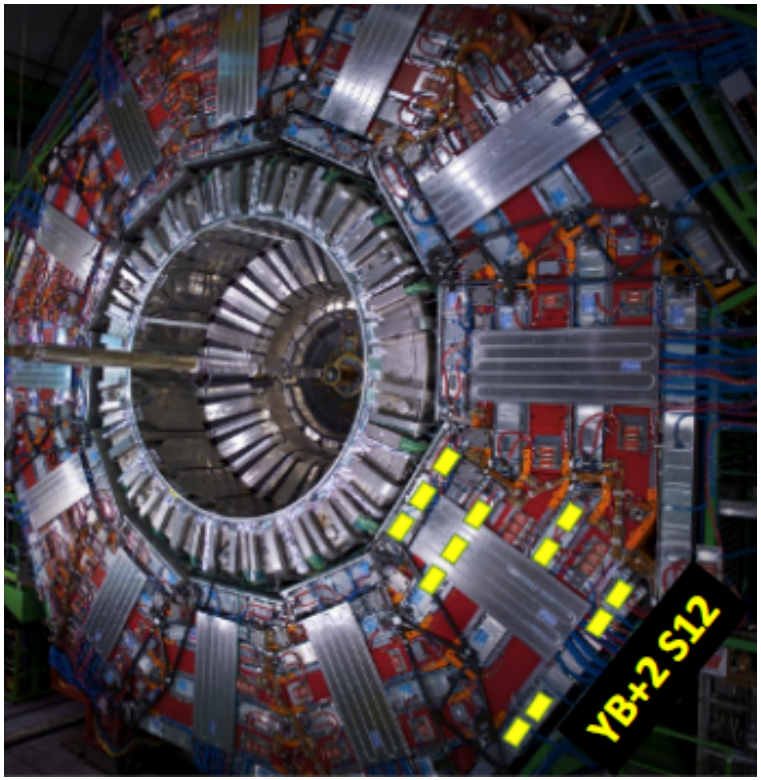
- Injecting hits from selected $Z \rightarrow \mu\mu$ events from 2016 real collision data.
- When comparing the primitives obtained with the same hits and lateralities in firmware and emulator, the agreement in fitted time, position and local direction reaches the Least Significant Bit.



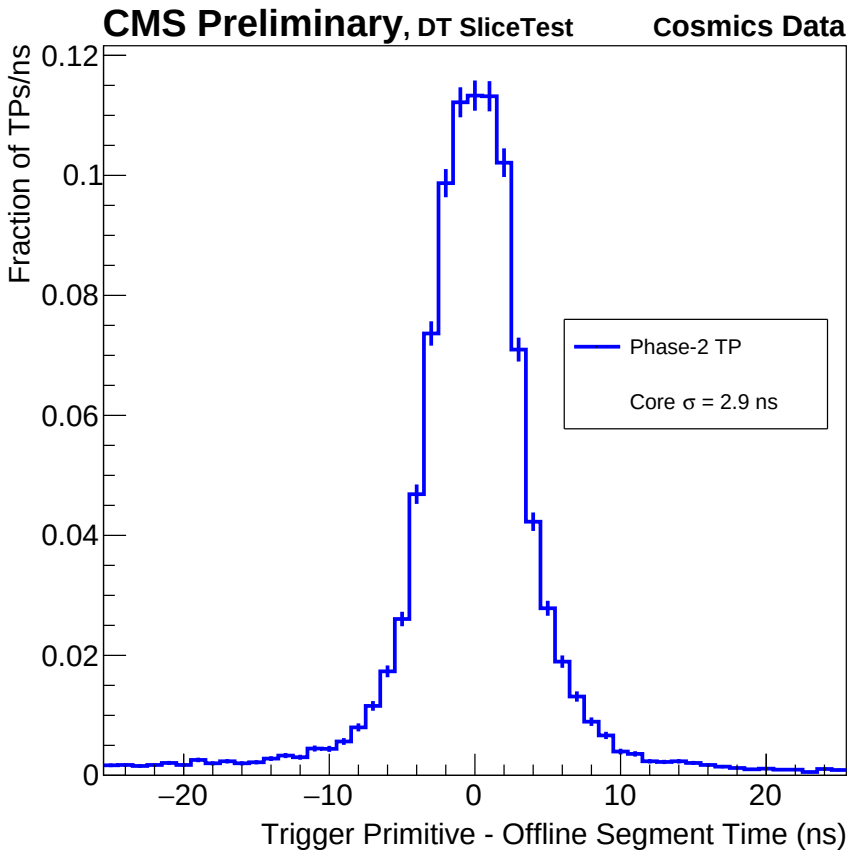


Performance evaluation in data: DT Slice Test

- One CMS sector is being instrumented with the new frontend and backend 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.



Performance evaluation in data: DT Slice Test



- Difference between trigger primitive's fitted time and the offline reconstructed segment time, for Phase 2 trigger primitives in a cosmic muons sample collected in the Slice Test setup (MB4/YB+2/Se12).
- Core sigma is around 3 ns.
- While for the Phase 1 system the trigger output time is in BX units (25 ns step), for Phase 2 the inherent online time resolution is of few ns.

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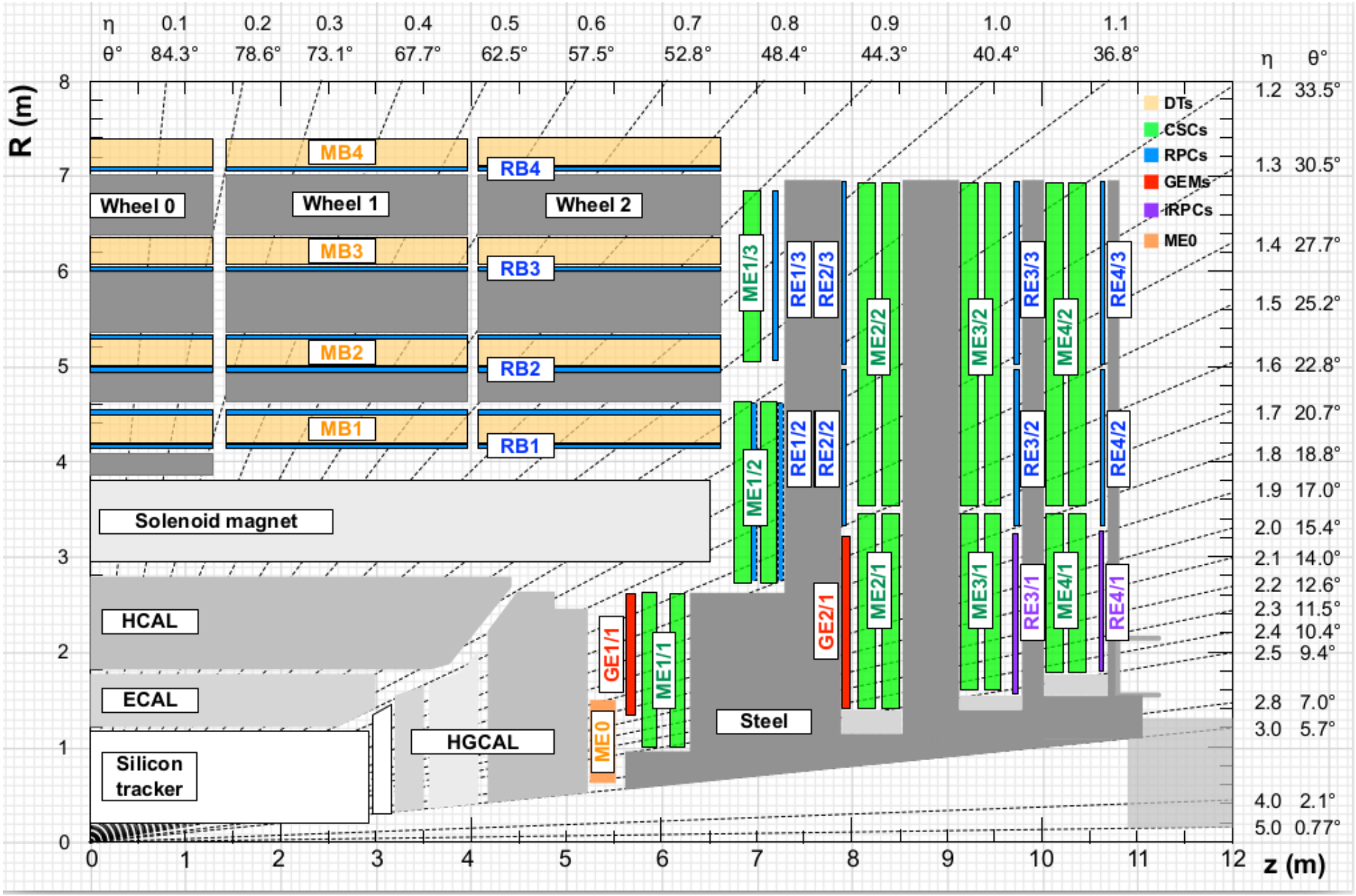
Conclusions and further steps

- We have proposed a new algorithm for Phase 2 DT electronics system.
- It obtains good efficiencies and resolutions.
- The algorithm is already implemented in firmware and being tested in a testbench with injected hits from real collision data samples and with real cosmics directly on the CMS detector.
- Further steps
  - Include the θ Superlayer in the algorithm and the RPC hits in the firmware implementation.
  - Integrate the system with the next trigger level.

More details about this talk can be found in the *L1 Trigger Phase 2 Upgrade TDR*.

Backup


η
θ°
0.1 84.3°
0.2 78.6°
0.3 73.1°
0.4 67.7°
0.5 62.5°
0.6 57.5°
0.7 52.8°
0.8 48.4°
0.9 44.3°
1.0 40.4°
1.1 36.8°
1.2 33.5°
1.3 30.5°
1.4 27.7°
1.5 25.2°
1.6 22.8°
1.7 20.7°
1.8 18.8°
1.9 17.0°
2.0 15.4°
2.1 14.0°
2.2 12.6°
2.3 11.5°
2.4 10.4°
2.5 9.4°
2.8 7.0°
3.0 5.7°
4.0 2.1°
5.0 0.77°
R (m)
z (m)
DTs
CSCs
RPCs
GEMs
iRPCs
ME0
Wheel 0
Wheel 1
Wheel 2
MB4
MB3
MB2
MB1
RB4
RB3
RB2
RB1
Solenoid magnet
HCAL
ECAL
Silicon tracker
HGCAL
Steel
ME1/3
ME1/2
ME1/1
ME0
GE1/1
GE2/1
RE1/3
RE1/2
RE2/3
RE2/2
ME2/2
ME2/1
ME3/2
ME3/1
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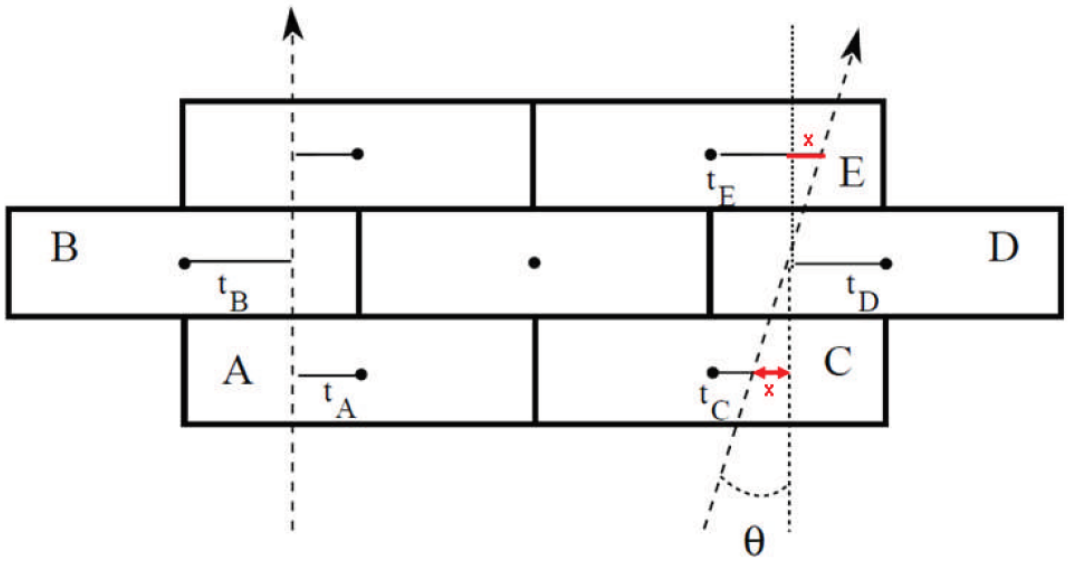
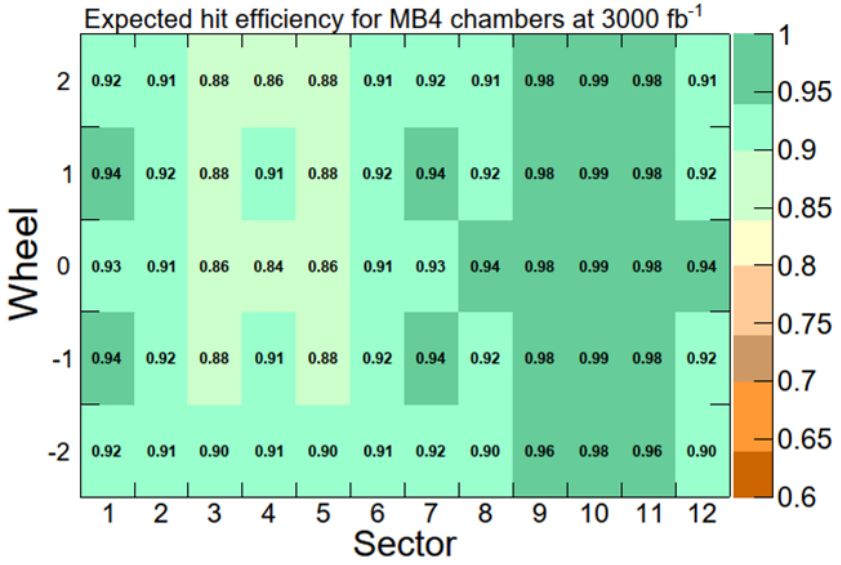
The meantimer method

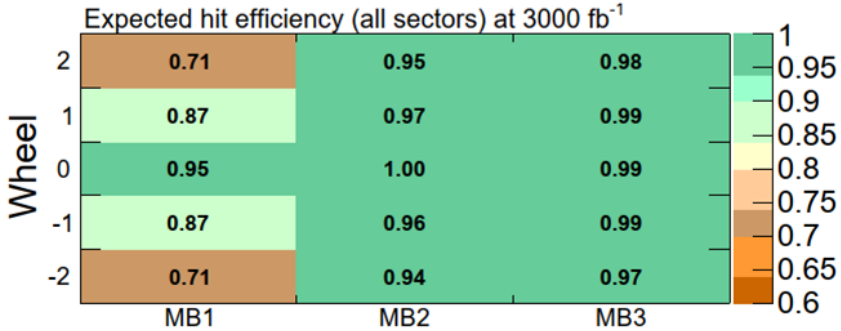


$$\left.\begin{aligned} t_E + t_D - x &= T_{\max} \\ t_C + t_D + x &= T_{\max} \end{aligned}\right\} \Rightarrow T_{\max} = t_D + \frac{t_E + t_C}{2}$$

Aging scenario

Expected hit efficiencies at the end of the HL-LHC for all the DT chambers of the CMS muon system, MB4 chambers (upper) and for MB1, MB2 and MB3 (lower). These efficiencies have been estimated considering a safety factor of 2 for the expected HL-LHC background rate ($10x10^{34}$ $cm^{-2}s^{-1}$) and a safety factor of 2 for the expected integrated luminosity (2×3000 fb^{-1}) and taking into account the angular effect of prompt muon tracks and the expected integrated charge at the end of HL-LHC in each chamber. For the MB1 chambers in wheels ± 2 the increase of 30% of the background rate, shown by the preliminary Fluka simulation comparing 2019 to 2018 geometry, has been included.





https://twiki.cern.ch/twiki/bin/view/CMSPublic/DTLongevitynewHGCal

The RPC failure scenario is described as switching off 158 detector rolls on top of the efficiency measured in Run-1.