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**The Compact Muon Solenoid Experiment**

# CMS Performance Note

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# Analytical Method (AM) for DT Trigger Primitive Generation in Phase 2. Slice Test Results with 2021 cosmics data

CMS Collaboration

**Abstract**

A full replacement of the muon trigger system in the CMS (Compact Muon Solenoid) detector is envisaged for operating at the maximum instantaneous luminosities expected in HL-LHC (High Luminosity Large Hadron Collider) of about 5-7.5x$10^{34}$cm$^{-2}$s$^{-1}$. Under this scenario, the new on detector electronics that is being designed for the DT (Drift Tubes) detector will forward all the chamber information at its maximum time resolution. A new trigger system based on the highest performing FPGAs is being designed and will be capable of providing precise muon reconstruction and Bunch Crossing identification. An algorithm easily portable to FPGA architecture has been designed to implement the trigger primitive generation from the DT detector. This algorithm has to reconstruct muon segments from single wire DT hits which, for a given BX, come with a spread of 400 ns due to the drift time in the cell. This algorithm provides the maximum resolution achievable by the DT chambers, bringing the hardware system closer to the offline performance capabilities

Results from 2021 cosmics data taking in the Slice Test, where a CMS DT sector has been instrumented with HL-LHC DT electronics prototypes running the AM firmware for trigger primitive generation, are presented.

# Analytical Method (AM) for DT Trigger Primitive Generation in Phase2

CMS Collaboration

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# INTRODUCTION

- A full replacement of the muon trigger system in the CMS (Compact Muon Solenoid) detector is envisaged for operating at the maximum instantaneous luminosities expected in HL-LHC (High Luminosity Large Hadron Collider) of about $5\text{-}7.5 \times 10^{34} cm^{-2} s^{-1}$.
- Under this scenario, the new on detector electronics that is being designed for the DT (Drift Tubes) detector will forward all the chamber information at its maximum time resolution.
- A new trigger system based on high performing FPGAs is being designed and will be capable of providing precise muon reconstruction and Bunch Crossing identification.
- An algorithm easily portable to FPGA architecture has been designed to implement the trigger primitive generation from the DT detector. This algorithm has to reconstruct muon segments from single wire DT hits which, for a given BX, come with a spread of 400 ns due to the drift time in the cell. This algorithm provides the maximum resolution achievable by the DT chambers, bringing the hardware system closer to the offline performance capabilities.

# Description of the algorithm: Analytical Method

- The input information is the wire position of the hit cell and the hit time from the start of the LHC orbit. From this, and assuming a given laterality, the hit position can be reconstructed.
- For a given hypothesis of muon trajectory within a superlayer, which is a straight line, using information from 3 cells allows to solve for the collision time, as the dependence on track slope is factored out. In this way one can identify the bunch crossing (BX) of the corresponding proton-proton interaction where the muon was produced.
- In practice a selection is made of patterns of 4 tubes and their sub-patterns of 3 tubes over 10 cells at a time, containing all physical trajectories in the given super layer. For cases with 4 hits (one per layer), time and track parameters are computed using exact formulas from least squares method (chi2-minimisation).
- For 3 hits all hit laterality assumptions providing physical solutions are considered as candidates. For 4 hits select a unique final candidate, the one with minimum chi2.
- For muons with fits of 4 hits or 3 hits both in superlayer 1 (SL1) and and superlayer 3 (SL3), the information from both fits can be correlated if the corresponding segment times are within a window of +/- 25 ns. If a match is found the candidate trigger primitive parameters are re-defined as follows: the new time is the mean of the per superlayer fits times, the new position is the mean of the superlayer fits positions, and the new slope is computed from the difference in fit positions in SL3 and SL1 divided by distance between the two r-phi superlayers. If no match found, all per-superlayer candidates are kept.
- In a final step information from RPCs (Resistive Plate Chambers) can be added to define 'super-primitives', with corrected time measurement. Note that results presented here **do not use RPC information**.
- This algorithm has been implemented in CMS software (CMSSW) as an emulator for the firmware implementation in FPGA.

# Description of the algorithm: Analytical Method

- A quality flag is defined for the trigger primitives as follows:

| Quality | Description |
|---|---|
| 1 | 3 hit track |
| 2 | 3+2 hits track |
| 3 | 4 hit track |
| 4 | 4+2 hits track |
| 6 | 3+3 hits track |
| 7 | 4+3 hits track |
| 8 | 4+4 hits track |

- Quality 1 refers to trigger primitives (TP) made of a fit of 3 hits in a single SL.
- Quality 2 to TPs made of a fit of 3 hits in a single SL and confirmed by 2 hits in the other SL.
- Quality 3 to TPs made of a fit of 4 hits in a single SL.
- Quality 4 to TPs made of a fit of 4 hits in a single SL and confirmed by 2 hits in the other SL.
- Qualities 6, 7 and 8 refer to correlated primitives, made respectively of fits of 3 hits in one SL and fits of 3 hits in the other, of fits of 3 hits in one SL and fits of 4 hits in the other and of fits of 4 hits in both SLs.

# DT SliceTest Description

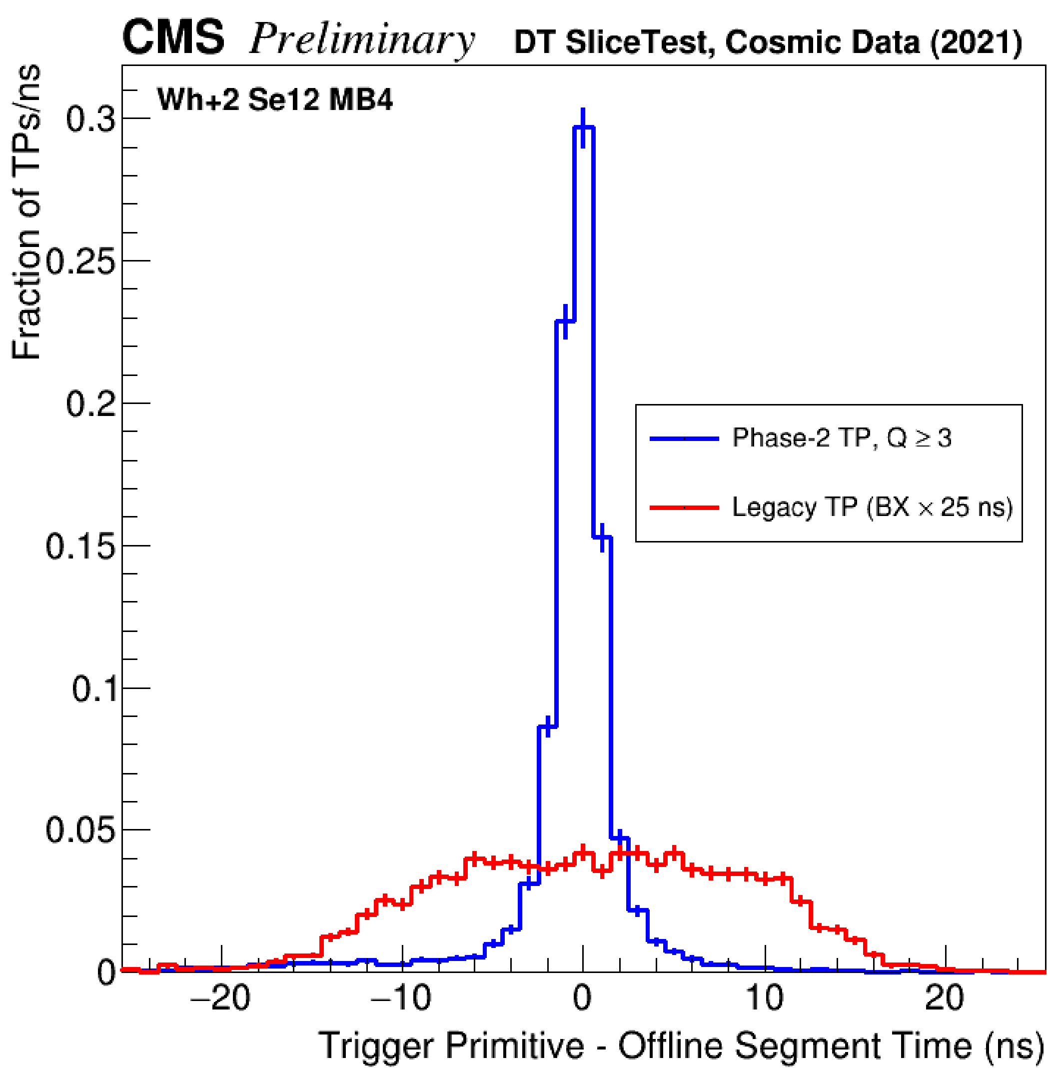
- During Long Shutdown 2 a complete exercise has been made to instrument one sector (wheel +2 sector 12) of the CMS detector with the HL-LHC DT electronics front-end and back-end prototypes. One of these backend boards (the so-called AB7) runs the AM firmware. This way, both Phase 1 and Phase 2 electronics can be run inside the CMS infrastructure, and the AM firmware can be validated using real cosmic muons.

- Plots show results using the information extracted from Phase-2 primitives (obtained by the AB7 board or the AM emulator) or Phase-1 primitives obtained by the TwinMux board, for a cosmic muon sample collected in YB+2/Se12 with the SliceTest set up and triggered by opposite sector (6) in a global run with the Barrel Muon Track Finder (BMTF).

- Phase-1 segments are reconstructed offline from legacy hits and selected to have a |local dir|< 30°, at least 4 hits, and |t0| < 50 ns. Time calibration correction has been implemented in the TDC data used to produce the Phase2 trigger primitives. The implementation of the calibration improves results substantially with respect to the L1 TDR.

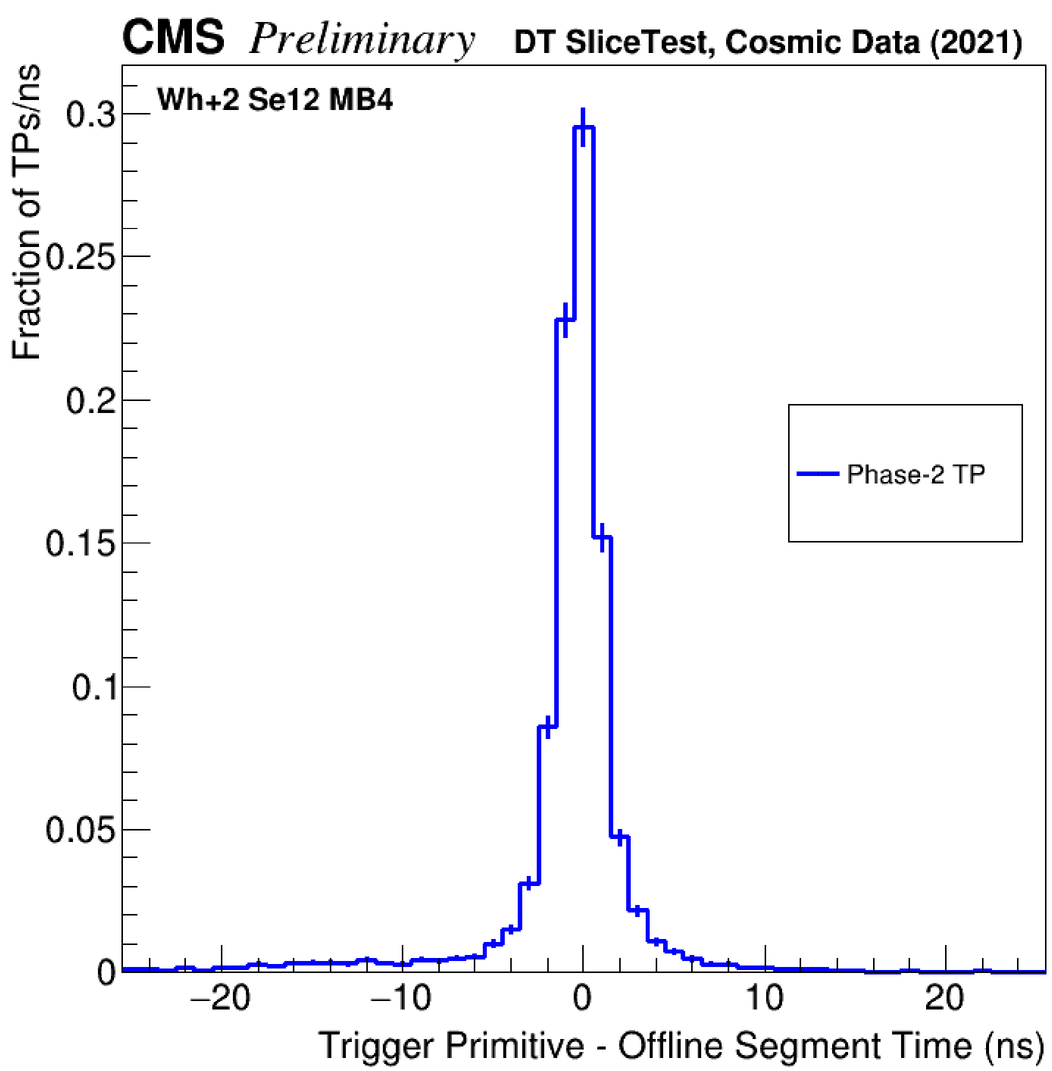
- **Note**: 'Confirmed' qualities 2 (3+2 hit tracks) and 4 (4+2 hit tracks) are not implemented in the AM Firmware at the moment. Therefore, primitives with those qualities will end up with qualities 1 (3 hit tracks) and 3 (4 hit tracks) respectively at the current firmware output. This happens in particular in the Slice Test set up.

# DT SliceTest time resolution



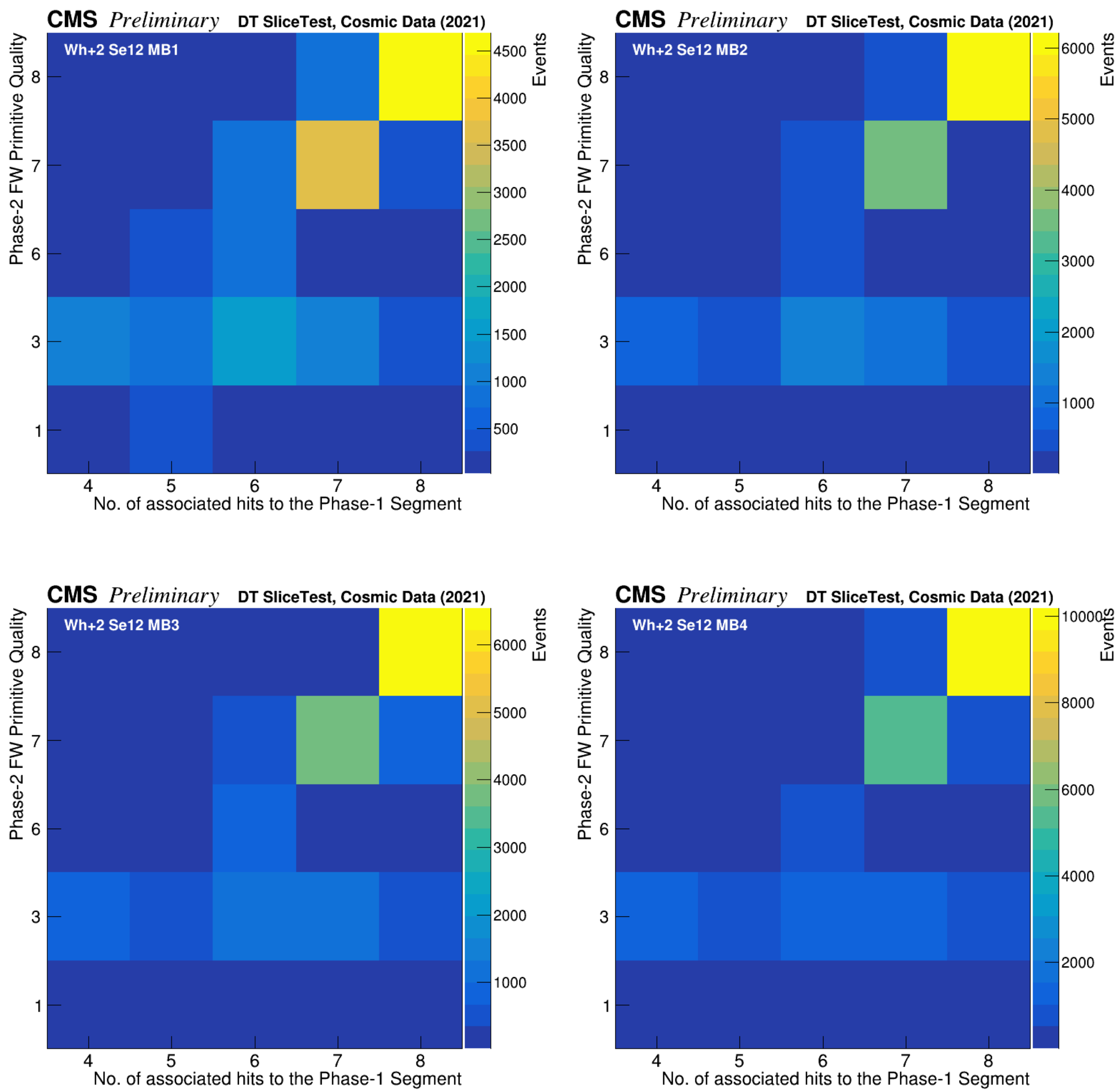

- Difference between trigger primitive's time and the offline reconstructed segment time, for Phase-2 in blue and for Legacy trigger (red) in a cosmic muon sample collected in the DT SliceTest set up.
- For Phase-2 only primitives fitting at least 4-hits are considered (denoted as Q≥3 in the legend), in order to be compared with the Legacy system (requesting minimal H quality).
- For the Legacy system the trigger output time is in BX units (25 ns step). The red line shows the convolution of a flat distribution within the BX time interval of 25 ns with a 3-4 ns time resolution of the reconstructed segment. For Phase-2, the inherent online time resolution is of ns.
- The improved online time resolution in Phase-2 reflects in this particular sample (unbunched cosmic muons) as a lower fraction of triggers at a wrong bx, i.e. 12.5 ns away from the time the muon crossed the chamber.

# DT SliceTest time resolution



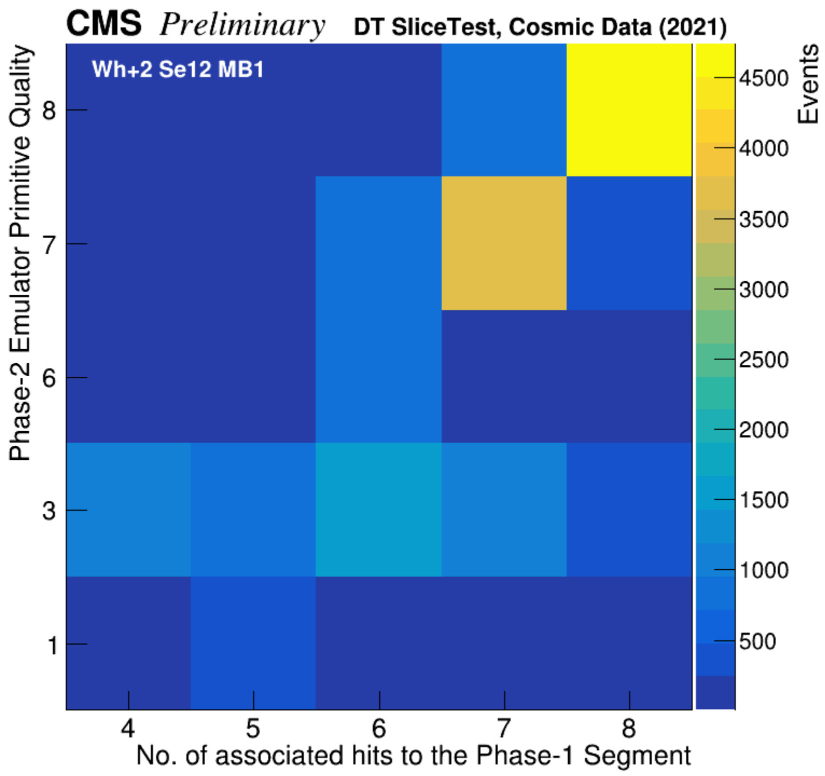

- Difference between Phase-2 trigger primitive's time and the offline reconstructed segment time, for a cosmic muon sample collected in the DT SliceTest set up.
- Considering every quality (3-hit primitives included).
- Showing only Phase-2 trigger primitives, as 3-hit trigger primitives are not included in the Phase-1 system.
- The inherent online time resolution is of the order of ns.

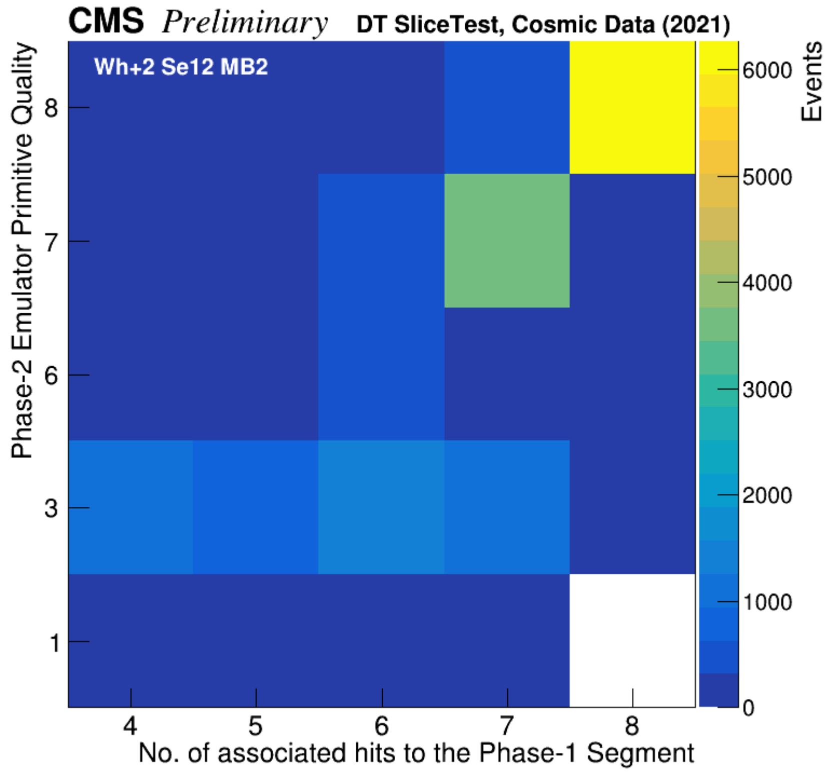
# TP Quality vs Num. of Hits in segment: AB7

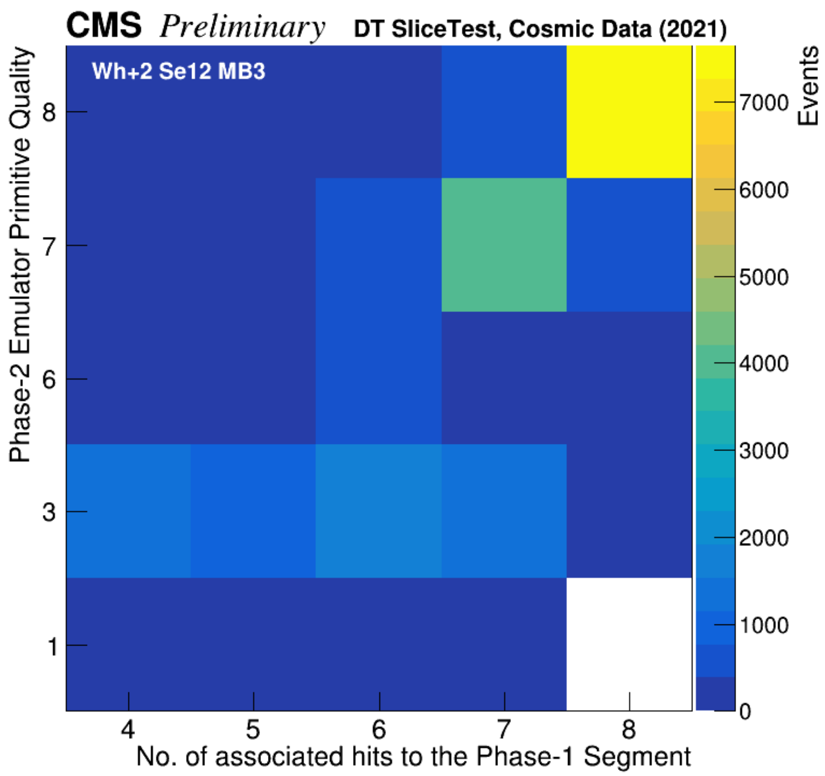


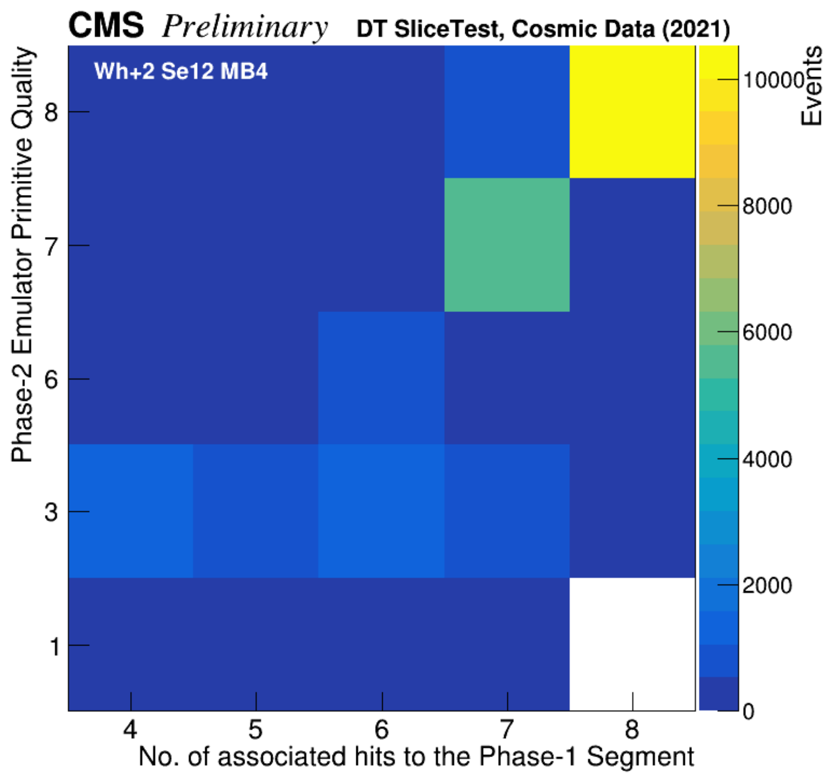

- 2D distribution of the Phase-2 Trigger Primitive Quality obtained by the AB7 board versus the number of hits associated to the offline reconstructed segment (phi view) for the DT SliceTest data in 2021 in all four chambers of Sector 12 Wh+2.

# TP Quality vs Num. of Hits in segment: Emulator



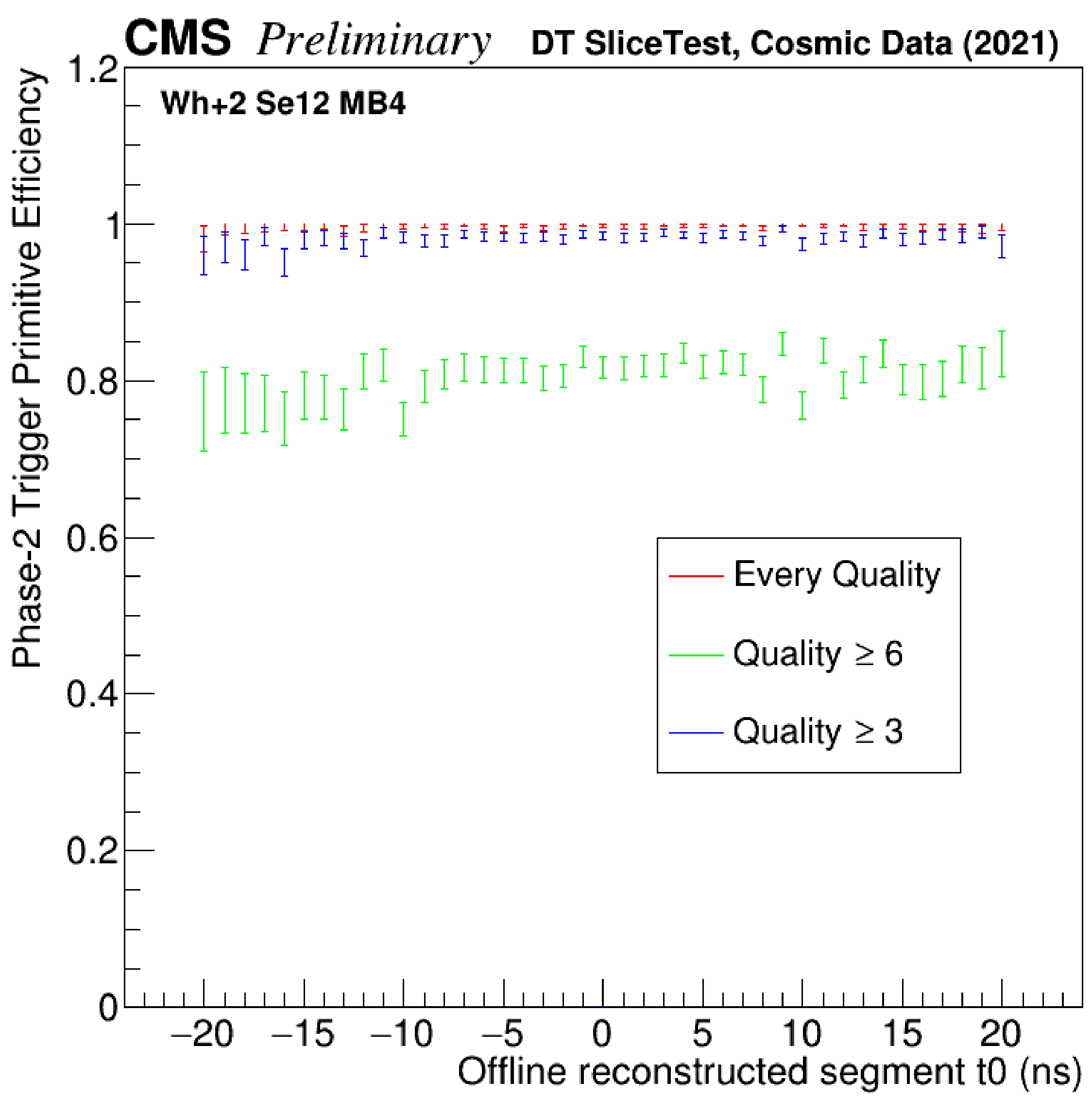



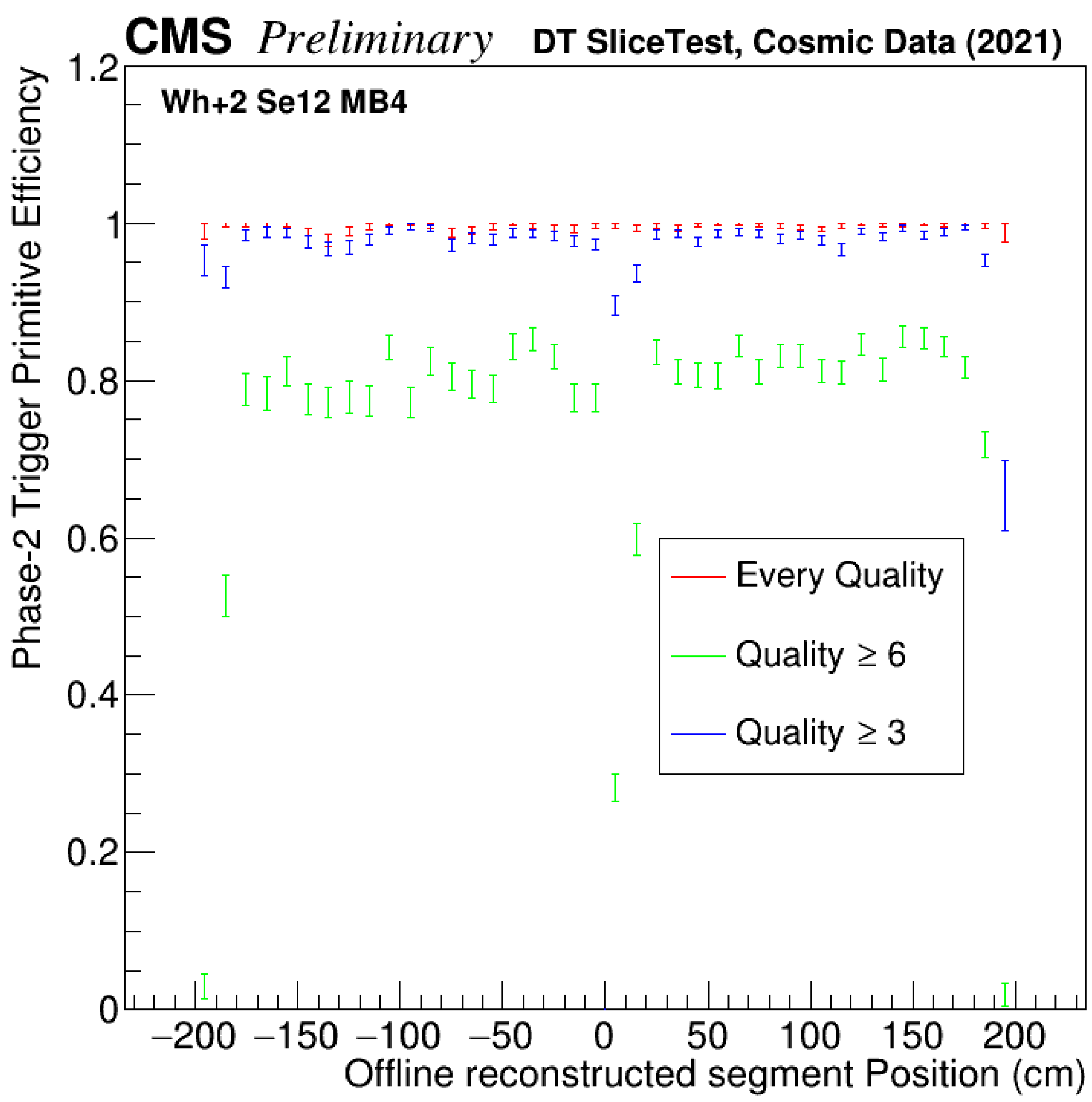

- 2D distribution of the Phase-2 Trigger Primitive Quality obtained by the AM Emulator versus the number of hits associated to the offline reconstructed segment (phi view) for the DT SliceTest data in 2021 in all four chambers of Sector 12 Wh+2.

# Trigger Primitive Efficiency vs Segment Time




- Efficiency of finding a Phase-2 Trigger Primitive in any BX with respect to the t0 of the offline segment reconstructed out of hits detected by the Phase-1 system considering every primitive (red), primitives built with more than 4 hits (blue) and primitives with more than 6 hits, i.e. 3 or more hits per Superlayer (green) for the DT SliceTest data in 2021 in MB4 Sector 12 Wh+2.
- Selected segments are built with more than 4 hits and have an inclination in the radial coordinate smaller than 30° with respect to the direction perpendicular to the chamber. No geometrical matching between the offline segment and the Trigger Primitive is required.

# Trigger Primitive Efficiency vs Segment Position




- Efficiency of finding a Phase-2 Trigger Primitive in any BX with respect to the local position of the offline segment reconstructed out of hits detected by the Phase-1 system considering every primitive (red), primitives built with more than 4 hits (blue) and primitives with more than 6 hits, i.e. 3 or more hits per Superlayer (green) for the DT SliceTest data in 2021 in MB4 Sector 12 Wh+2.
- Selected segments are built with more than 4 hits and have an inclination in the radial coordinate smaller than 30° with respect to the direction perpendicular to the chamber. No geometrical matching between the offline segment and the Trigger Primitive is required.
- Since one AB7 prototype board only generates primitives from one half of the MB4 chamber, an efficiency drop is visible at the boundary (x=0) between the two regions due to edge effects. The final system will use only one board for the full chamber, so this effect will disappear.