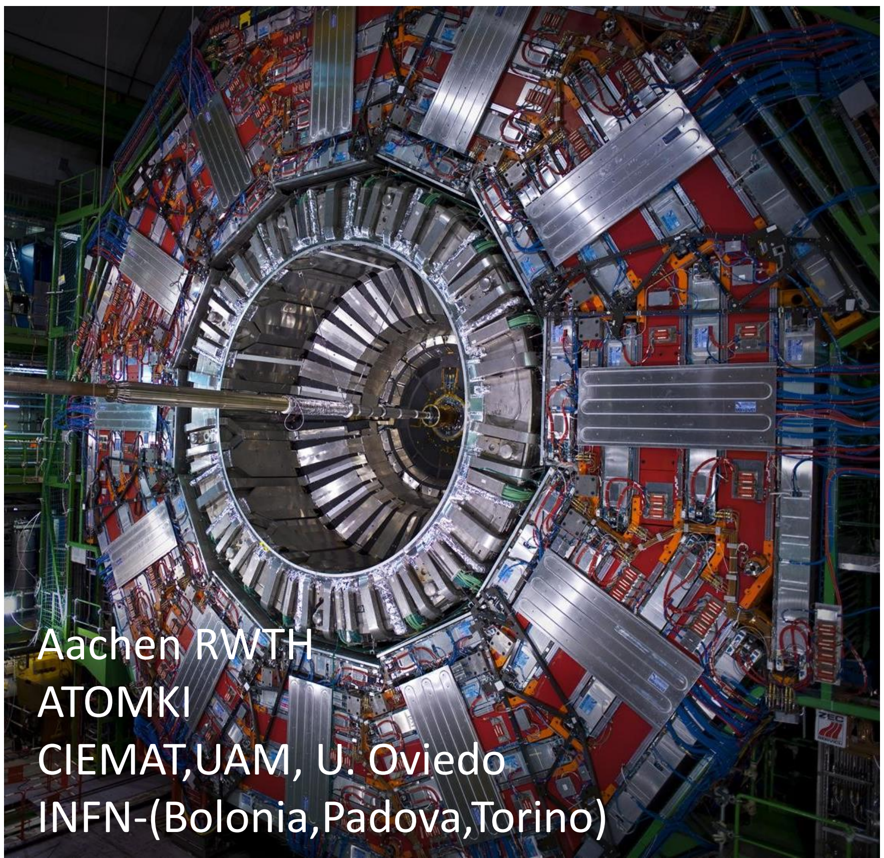
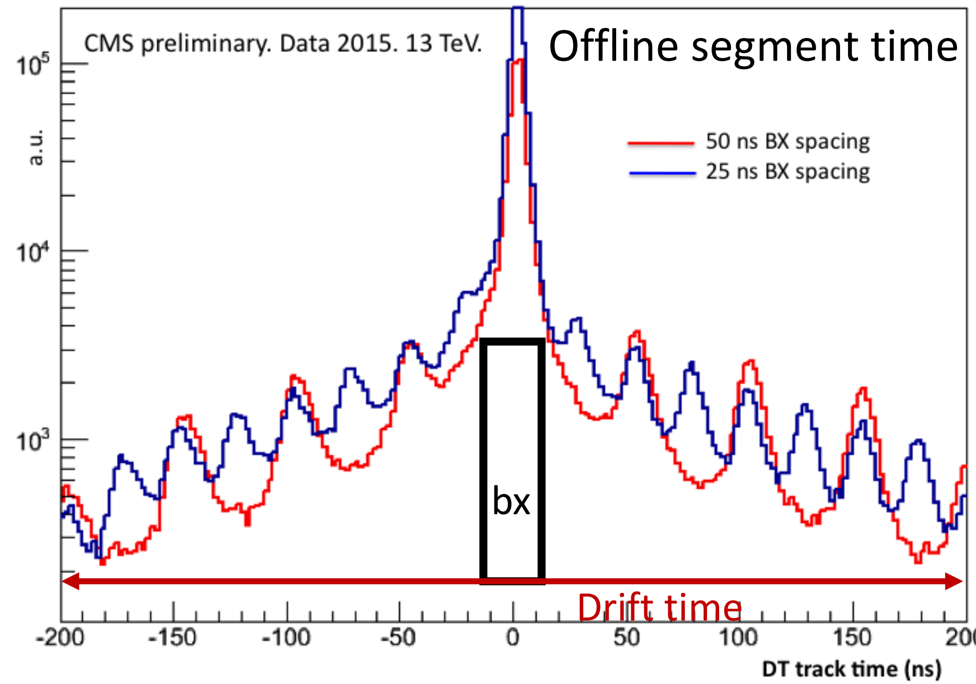
DT Phase-2 Slice Test Performance in Early Run 3 Collisions

Ignacio Redondo on behalf of the CMS Collaboration

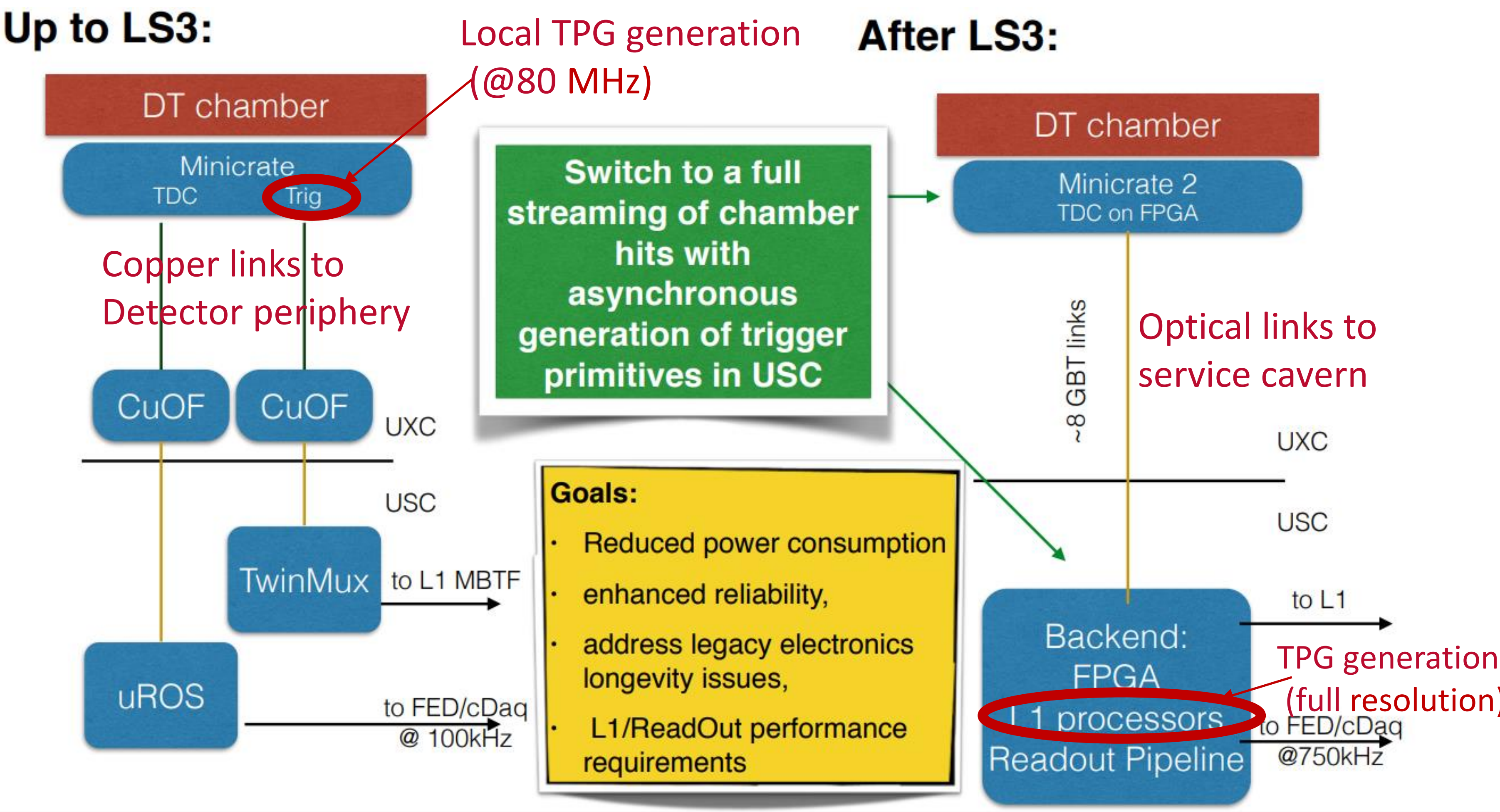
250 DT chambers instrument the return yoke of CMS arranged in 4 radial stations, identifying, measuring, and triggering muons in the barrel acceptance |η|<1.1.





Signals drift in each cell for ~16 bunch crossings (bx) at constant speed. This characteristic is what allows to cover this huge volume with only 170kchannels 4.2 cm wide cells achieving superb spatial (~250 μm) and time resolution (~2 ns) offline, reconstructing segments from ~1 ns HTDC digitized hits of the 12(8) sensing layers in each of the stations.

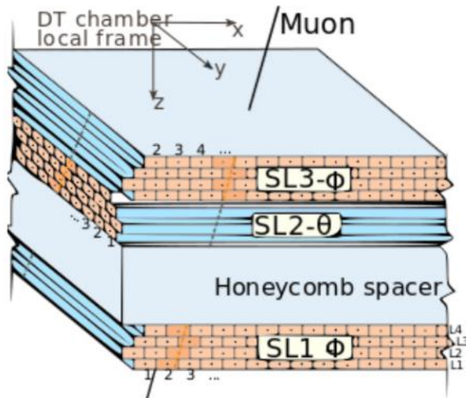
The CMS Muon DT Phase-2 Upgrade



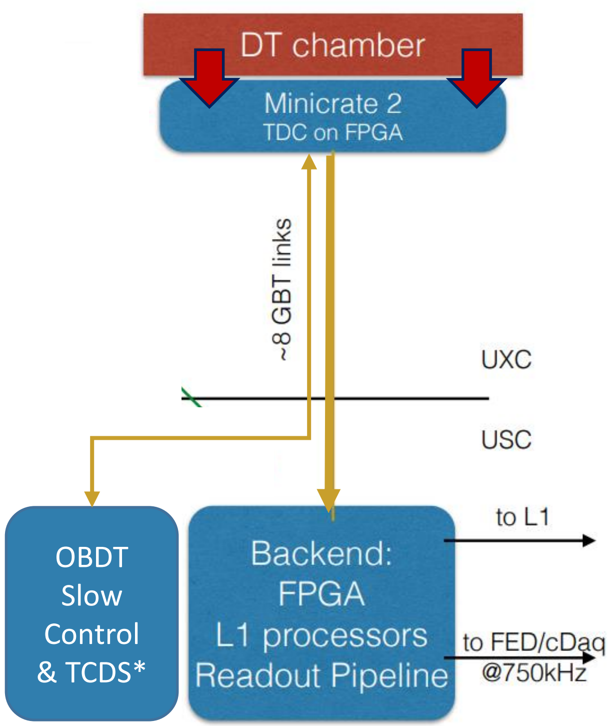
+ Potential for improving trigger : a priori the same segment reconstruction algorithms now offline can be deployed in the hardware to generate trigger primitives (TPG) provided enough bandwidth and processing capabilities are allocated.

+Resilience to aging effects as a larger fraction of the detector can participate in the TPG

DT Phase 2 Upgrade Challenges



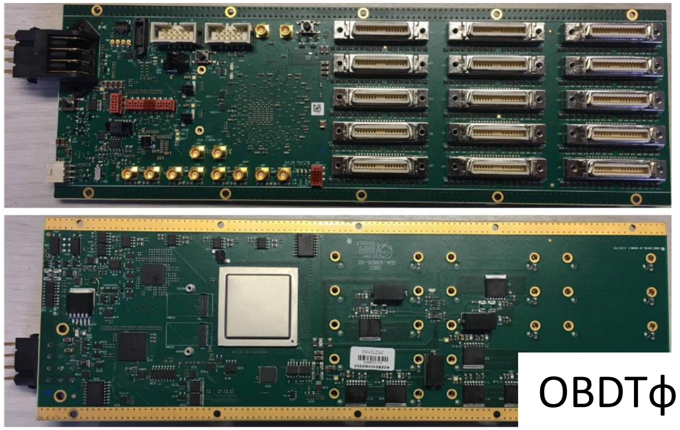
After LS3:



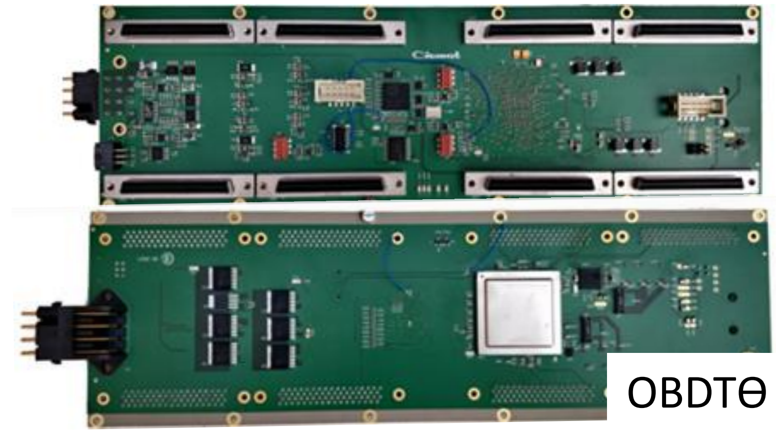
- Many integration constraints related to installation in an already operational detector.
  - Keeping CAEN power system and most of copper power distribution
  - Stay in cooling envelope
  - Keeping USC-UXC optical fibers installed in LS1
  - Access time and service availability for commissioning in LS3 constraints to be considered
  - During LS2 several mechanical aspects were investigated aiming to streamline installation& commissioning
  - FE copper cables to theta layers cannot be replaced, motivating two flavors of front end board.
  - Using different FE cable lengths, in contrast with legacy system, to speed installation.
- Moderate radiation hardness requirements (<0.5 Gy)
  - Frontend boards irradiated with final FW
- Clock distribution/Time scale stability
- Demonstration that offline algorithms can be ported to a state of the art FPGA within CMS L1 trigger constraints.
  - HL-LHC background levels x5, also expect some aging ineffiencies.
- Synchronization of all channels
  - Pre-setting of logical delays such that all digitized signals can be aligned based on TDC at the trigger processors to perform segment and bx matching, even if signal arrival time vary.

*TCDS=Timing &Control Distribution System

DT Phase 2 Upgrade Frontend Status



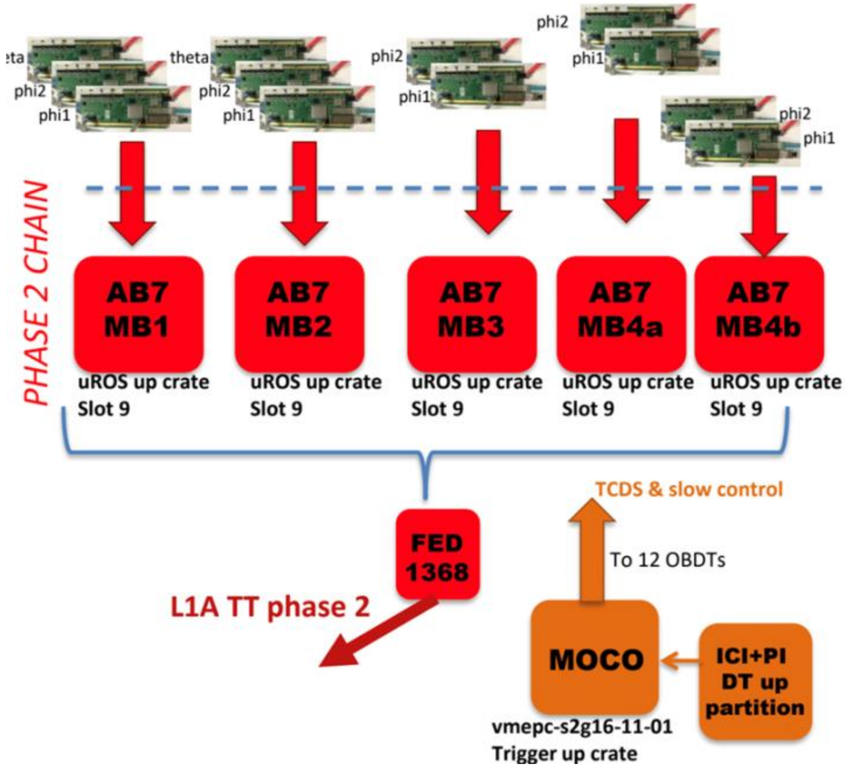
OBDTϕ x 650



OBDTΘ x 180

- The time signals coming from the chambers will be digitized by 830 On detector Board for the Drift Tube chambers (OBDT), which are built around a Microsemi PolarFire FPGA and will use CERN's lpGBT and VTRX+ optics.
- 2 OBDTv2 boards (lpGBT&VTRX) flavours: OBDT phi has been irradiated in Legnaro INFN lab, OBDT thetha will be irradiated at CERN's CHARM.
- Early prototypes, OBDTv1 [TWEPP19], porting the same FPGA but GBT and commercial optics have been already irradiated at CERN's CHARM and installed in 1 CMS sector (out of 60) during LS2: **DT phase 2 Slice Test**
- Project have reached the production stage after CMS inner review last June (ESR), procurement ongoing.

DT Phase 2 Slice Test Installation in LS2

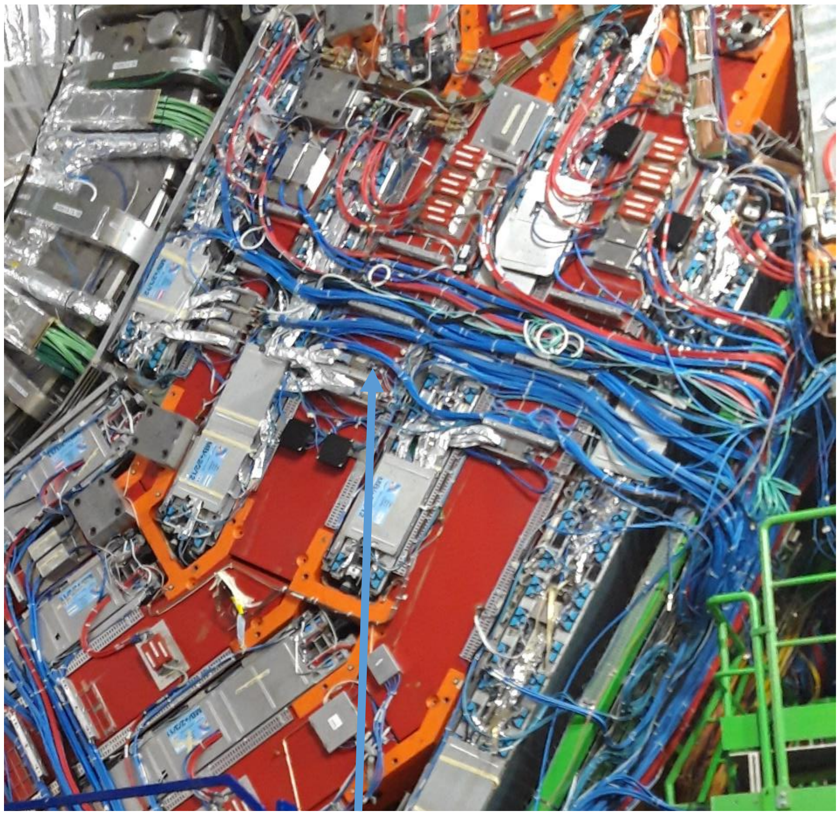


- FE: **OBDTV1 (GBT,VTRX)**
- Backend: Phase-2 FW (AM algorithm) on **Phase-1 uTCA HW , TM7**
- Integrated in CMS (power, TCDS,DAQ,CMSSW)
- Extensively operated in CMS Global Runs
- Operating regularly during LS2, including cosmics at 3.8 T and now during Run 3 collisions [TWEPP21]

It is a dense area with tight integration constraints in Z

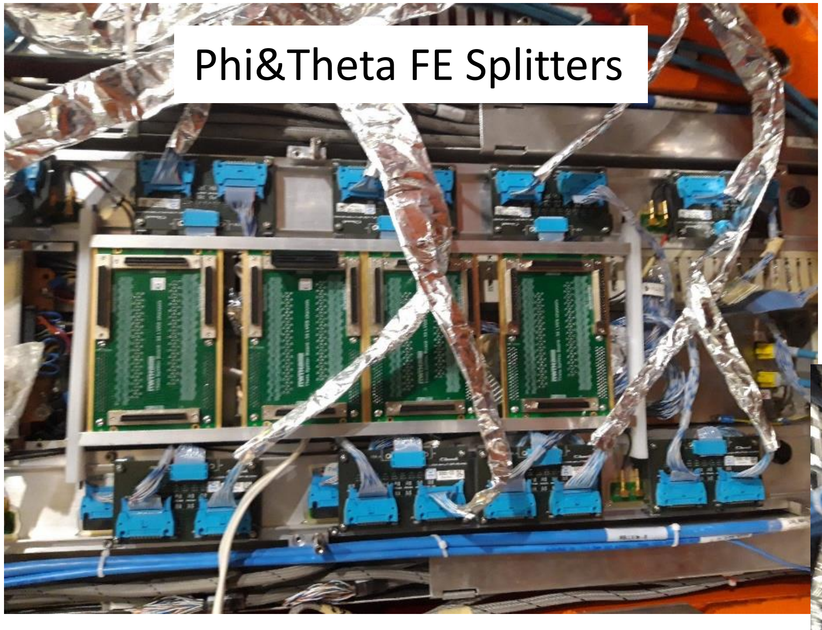
Recable after installing alignment MAD

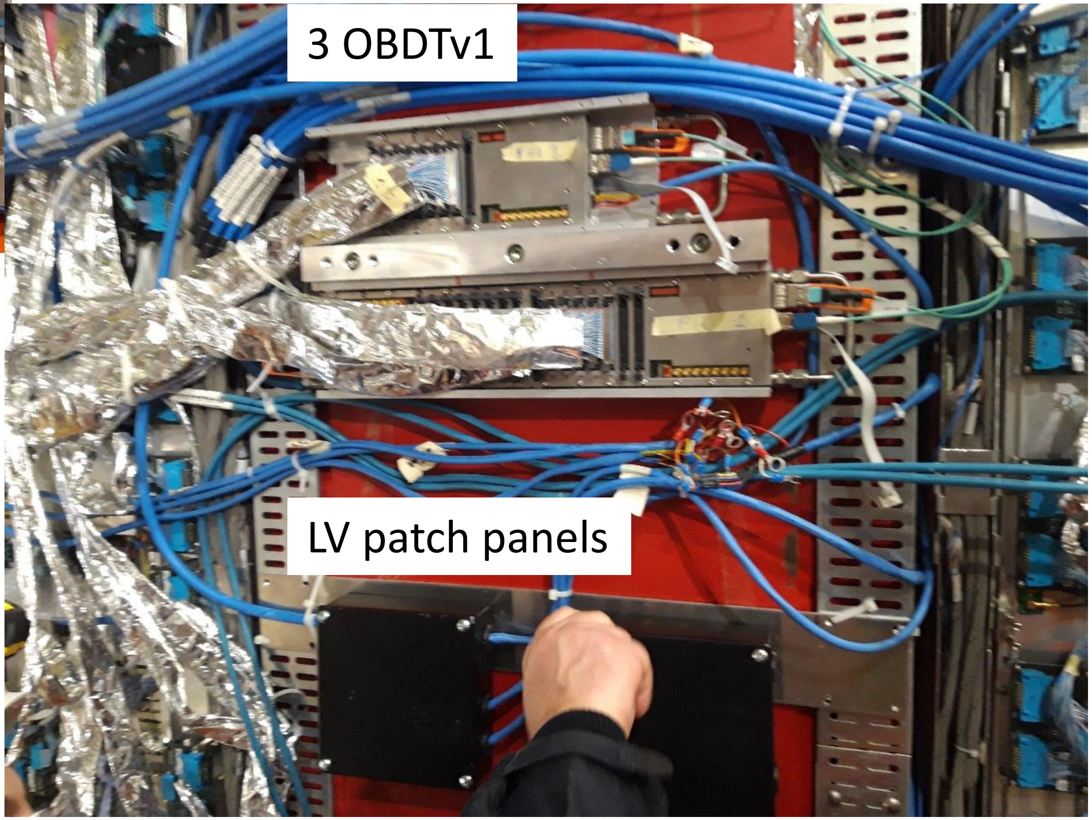
Before installing alignment MAD



Blue cables are legacy copper links to periphery (DT&RPC) and LV power distribution
Red HV cables

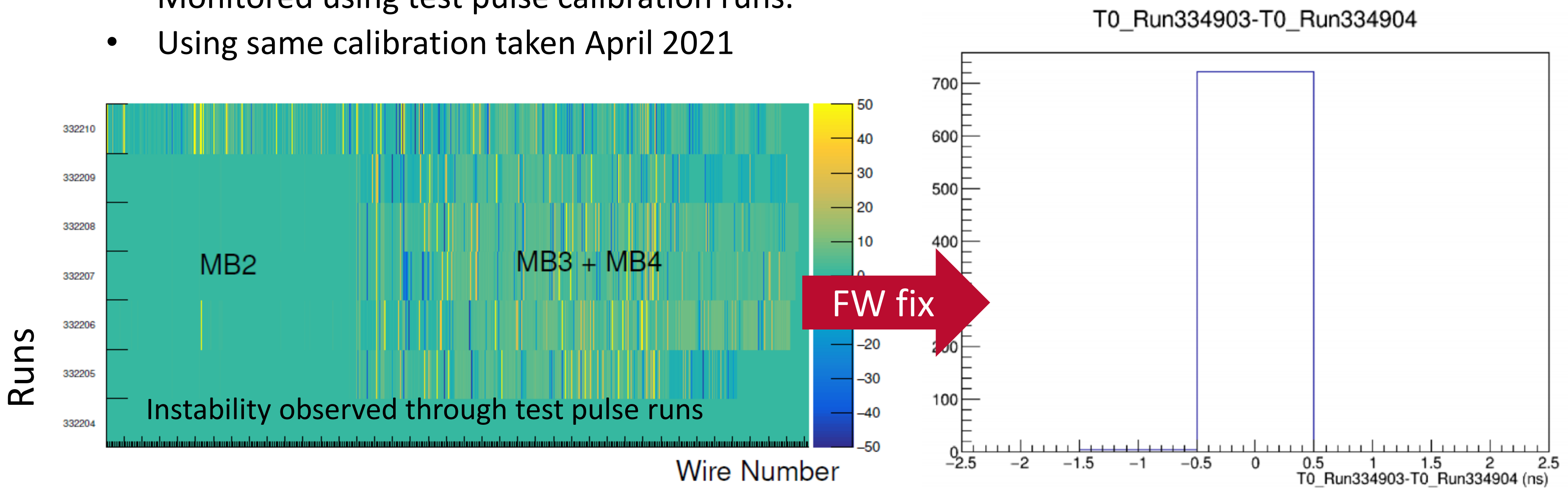
…aggravated by keeping the 2 chains in parallel





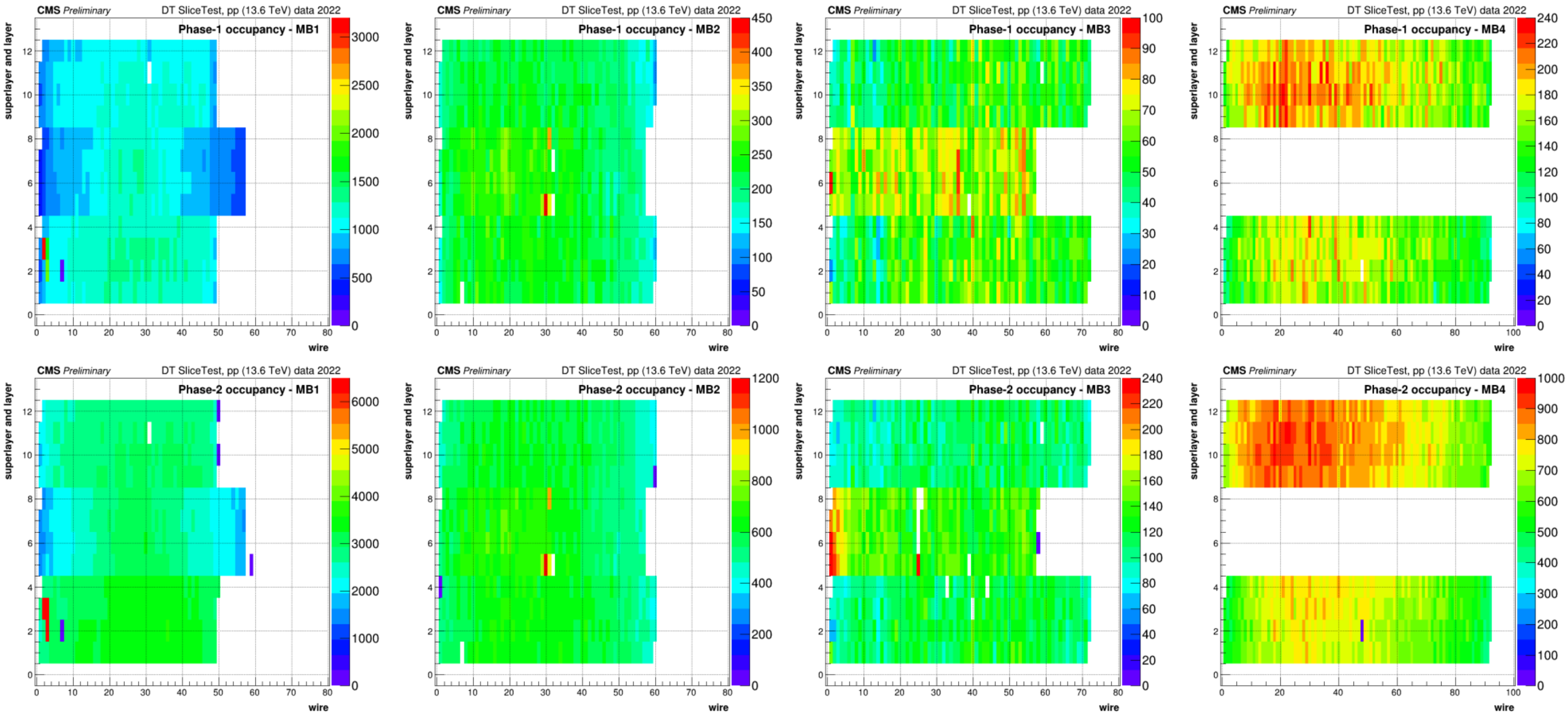
Commissioning: DT Slice Test Time Stability

- Time scale stability. Found that the time offset between Phase 1 and Phase 2 was not stable after power cycles or reconfigurations.
  - Traced back to issues with the phases of the resets of the internal PLLs of the Polarfire and fixed in FW.
  - Monitored using test pulse calibration runs.
  - Using same calibration taken April 2021



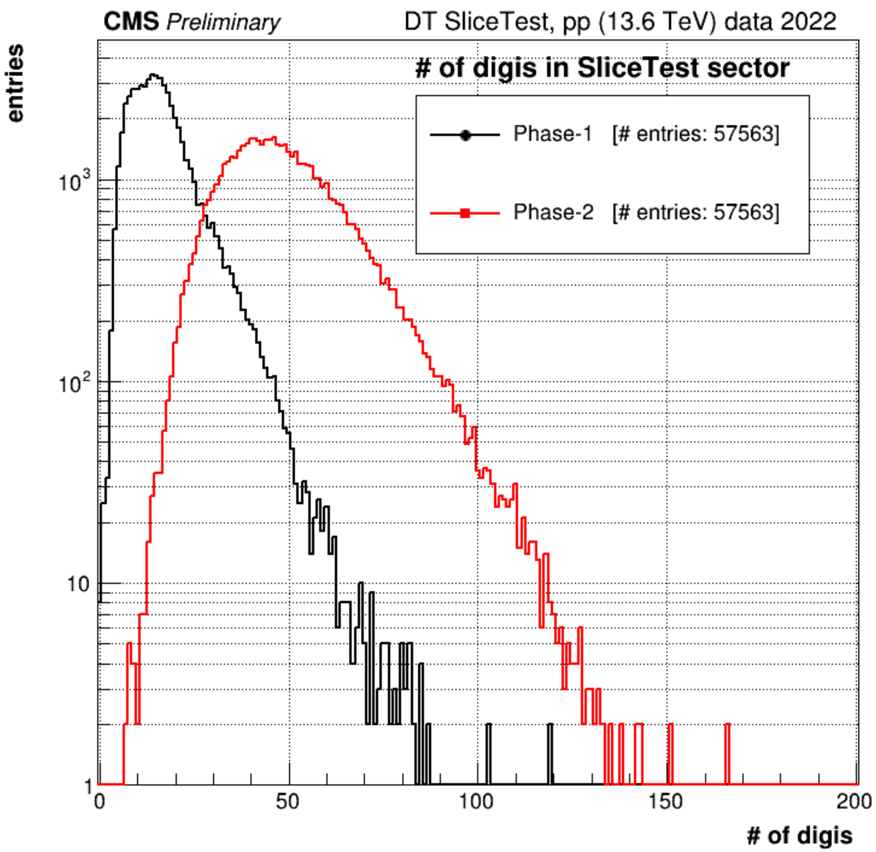
- Main cause of data ineffiency has been loss of lock of GBT optical links.
  - Failure typically triggered by TCDS clock reset (happens regularly during CMS running) & clock ramps.
  - Improved when slice test trigger backend (AB7) and frontend clock source moved to the same crate (common clock source).
  - To smooth operation mitigated via automatic sw recovery mechanism via slow control backend. Final system uses lpGBT.

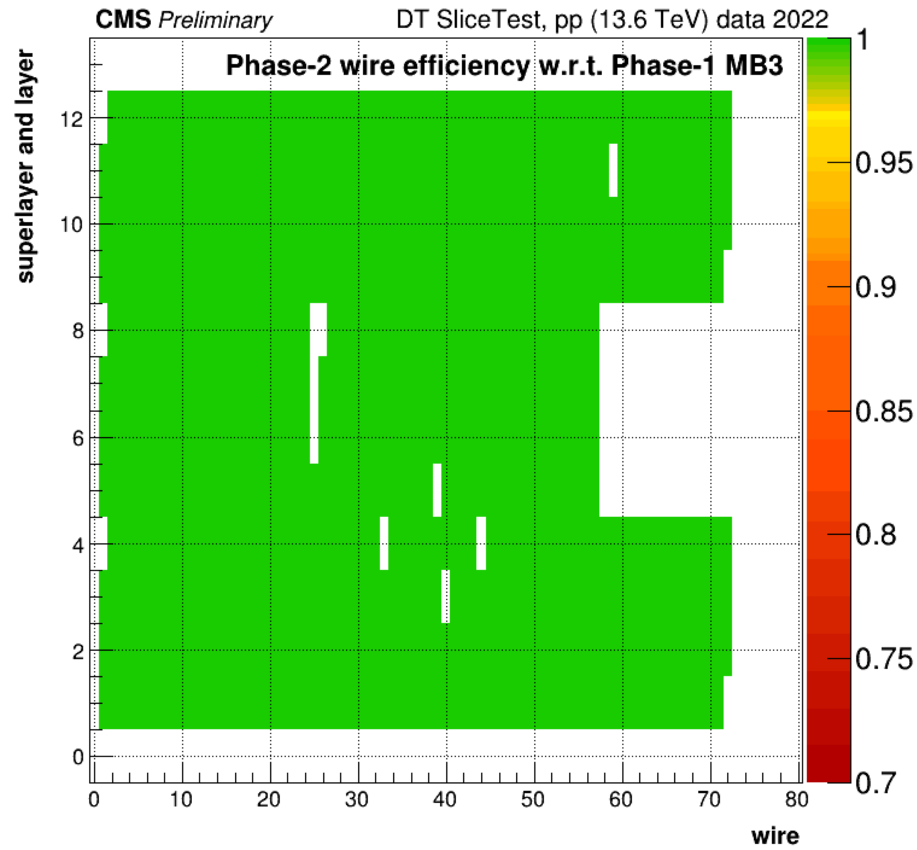
Occupancy Distribution for the 4 Chambers in the ST



- Hit occupancy for the different DT cells of the Slice Test stations as measured by the Phase-1 (top row) and Phase-2 (bottom row) electronics in a typical collision run.
- The non uniform occupancy within the chamber results from the background environment.
- Modulo few masked wires, one very prominent in MB3 masked in Phase-1 and not in Phase-2 , good agreement between the Phase-1 and Phase-2 occupancies is observed.

TDC Readout Performance in Early Collisions





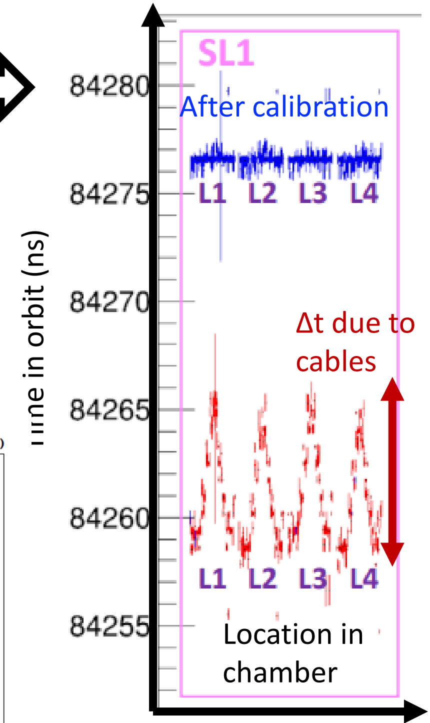
As Phase 2 chain has more bandwidth capability, readout window in early data was kept ~5 times wider than in the legacy (50 bx), which is clearly visible in the distribution of number of hits per event .

Relative efficiency to detect a hit with the Phase-2 readout, when a hit is recorded by the Phase-1.

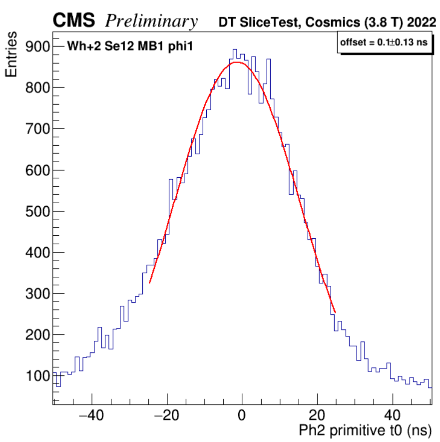
➔ When a hit is detected by Phase-1, it is detected also by Phase-2.

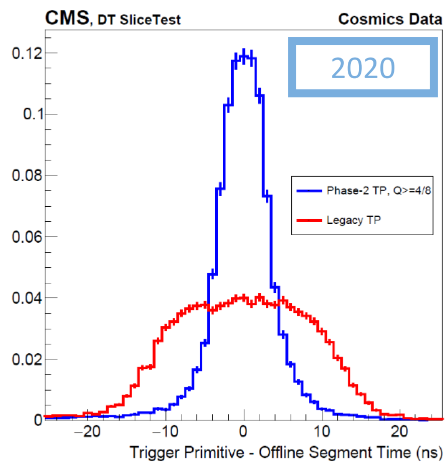
DT Slice Test Synchronization

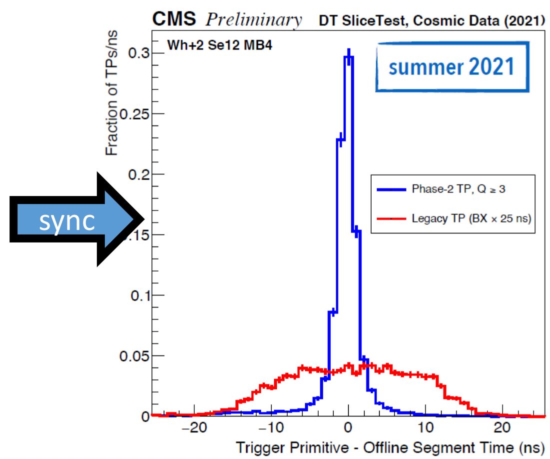
1. First step of calibration of the inter-channel equalisation to homogenize channels in each OBDT removing cable length effect



2. At a second stage, each superlayer delay is calculated from the average time of passage of the 4 –hit primitives in each ϕ superlayer.
   - Optimal delays between superlayers depend on track direction and timing, which with cosmic rays, can be selected to a certain extent using trigger and offline cuts.
   - Delays were measured and applied for different configurations throughout LS2.





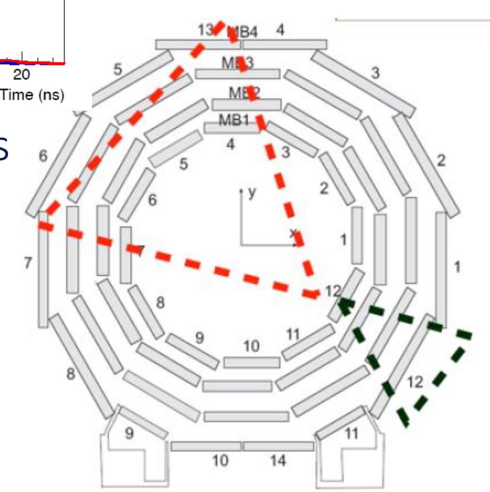


3. To prepare collision synchronization startup, the trigger was configured to select signals from sectors opposite to the ST one to :

   1- enhance collisions pointing geometry,

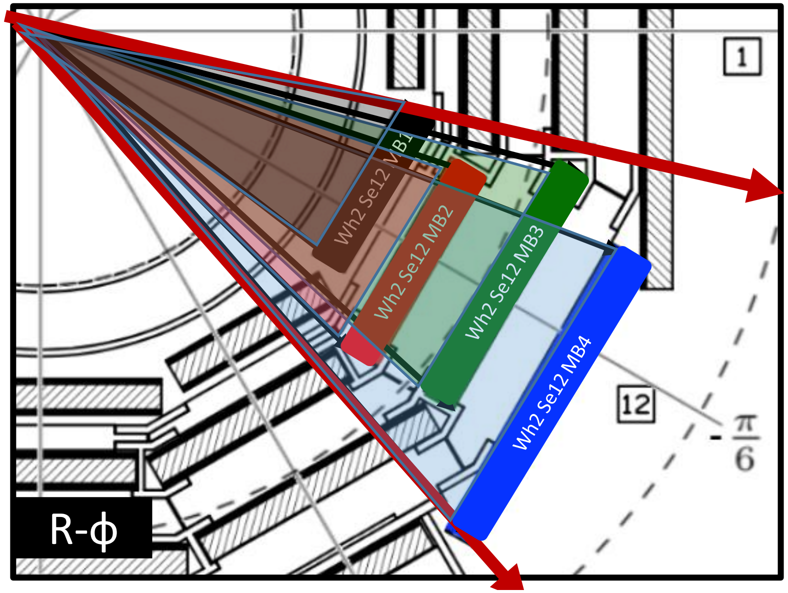
   2- have similar time of flight among superlayers and latency as in collisions, and

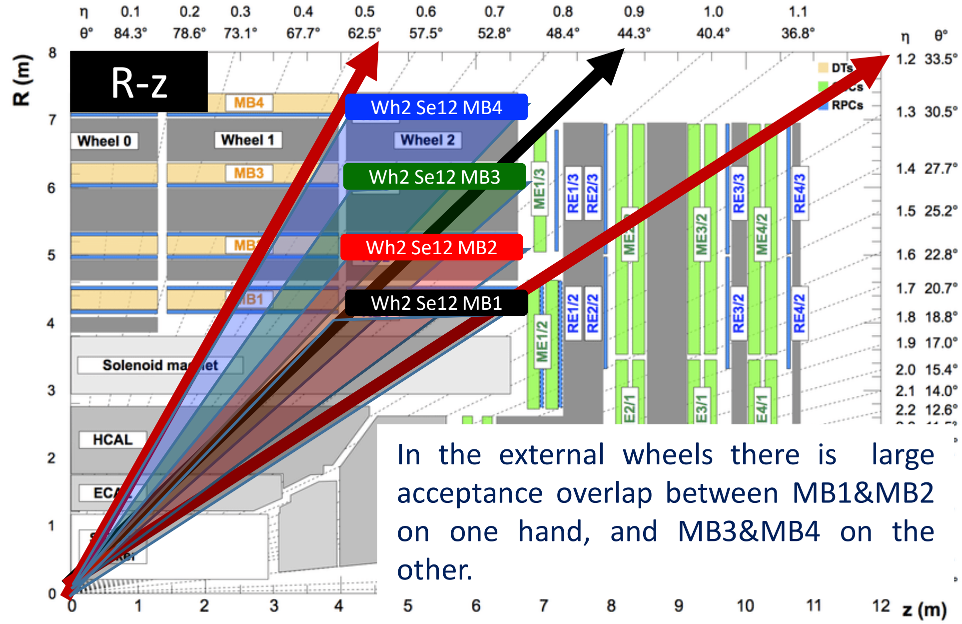
   3- avoid trigger bias, as the Slice Test chambers do not participate in the trigger.



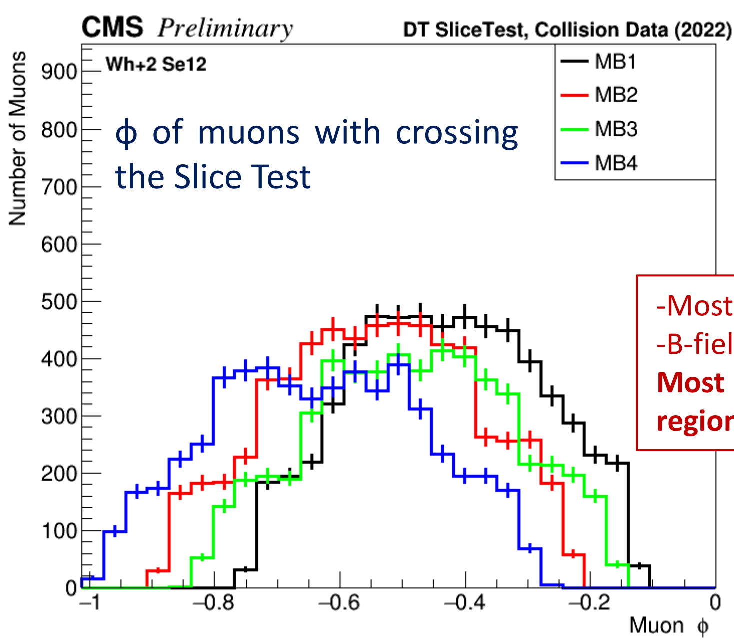
4. In Collisions, muons have to be filtered to avoid background bias

DT Slice Test Acceptance for Collision Muons, Run 3

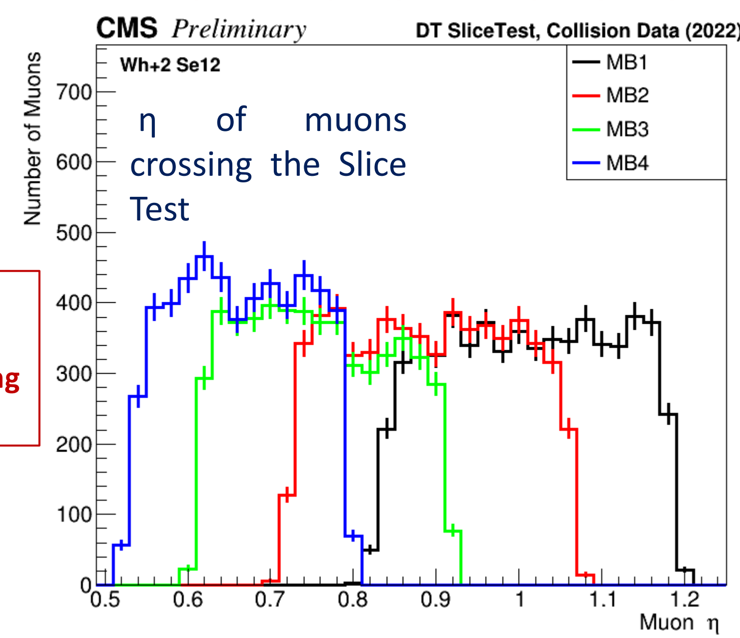




In the external wheels there is large acceptance overlap between MB1&MB2 on one hand, and MB3&MB4 on the other.

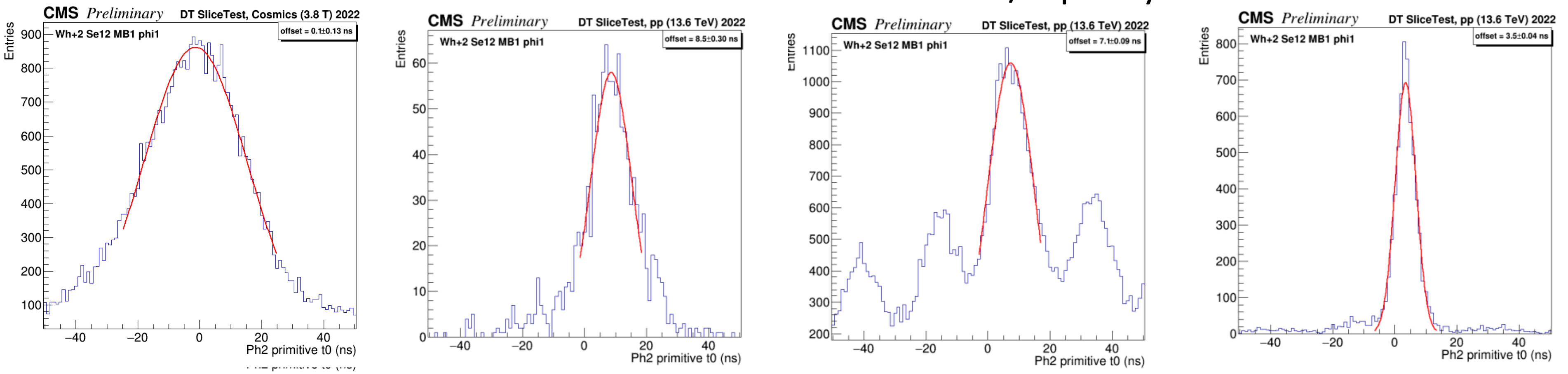


-Most irradiated,
-B-field effects…
Most challenging region in the barel



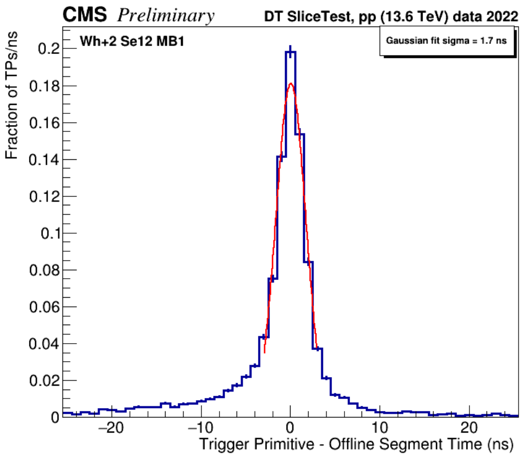
DT ST Synchronization : From Cosmics to Final Collision Delays

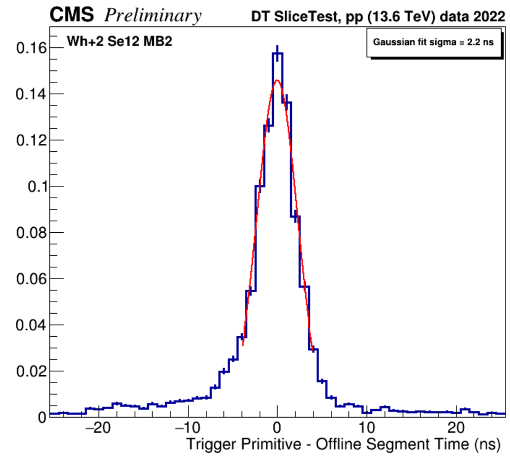
Time of the 4-h TPGs for one OBDT/superlayer:



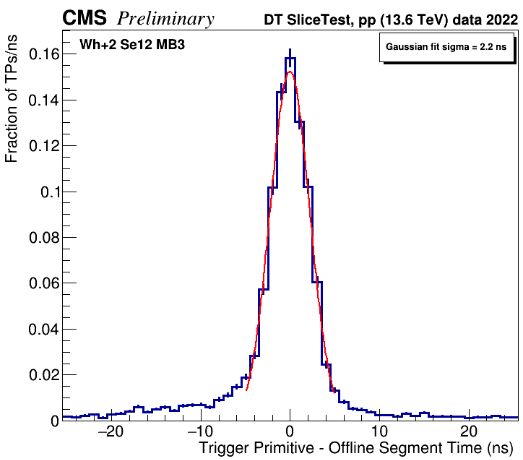
1. Cosmic run at 3.8 T sample used to extract startup delays
2. A 0.6 pb^{-1} collisions run, with 8 isolated colliding bunch crossings in CMS.
   - The distribution is dominated by background from collision products. Significant delay shifts (<10 ns) with respect to cosmics synchronization in MB1&MB2.
3. Unfiltered full synchronization sample, dominated by filling schemes with several neighboring collision bx by “train”.
   - Train data also shows significant delay shifts (<10 ns) in MB1&MB2.
   - Contributions of other bunches in the train, spaced by 25 ns are visible, demonstrating the sub-bx resolution even for single SL TPGs.
4. Subsample of previous point 3. obtained selecting events with collision muons
   - The Gaussian fits to the distribution core have sigma of 3 ns

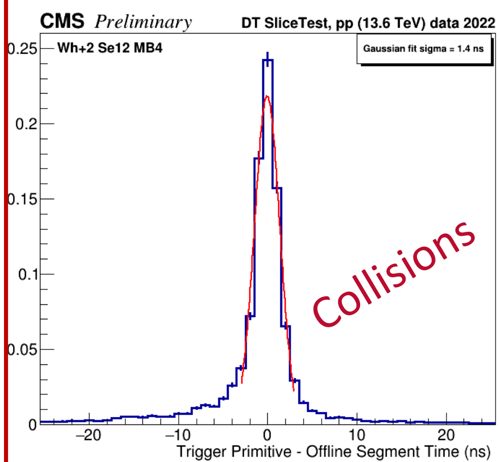
TPG Time Resolution versus Offline Segments for Collision Muons

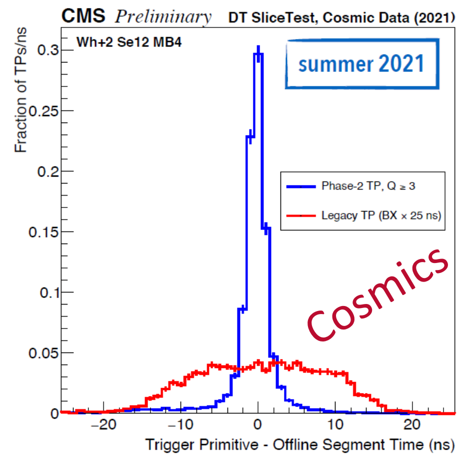




- Difference between Phase-2 trigger primitive's time and the offline reconstructed segment time for a collision muon sample collected in the DT Slice Test set up. This distribution is a metric of how well the AM trigger algorithm delivers online the performance now only available offline.

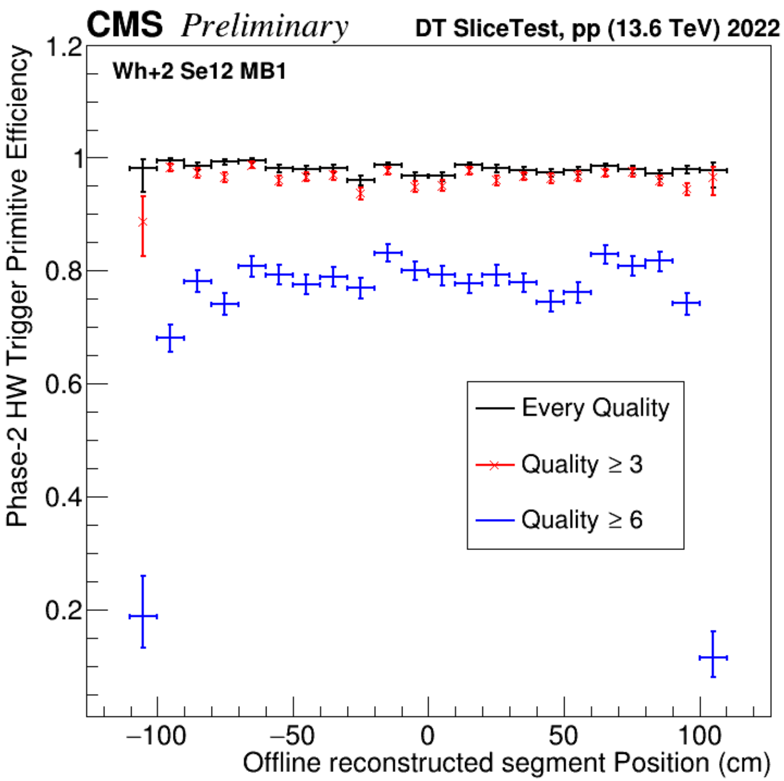


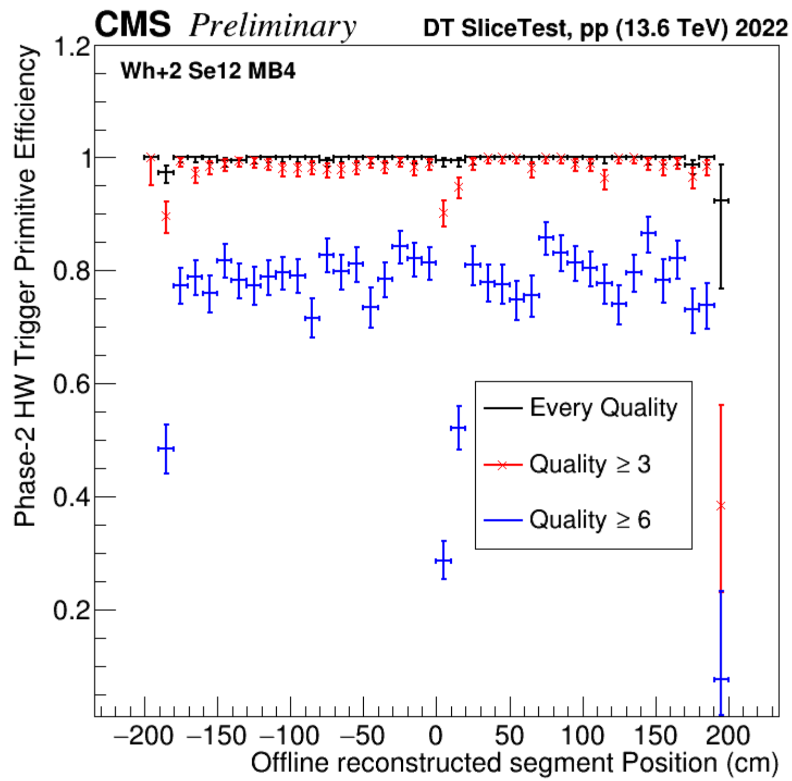




- A Gaussian fit to core of the distribution gives a sigma of ~2 ns. Apart from MB4, width is dominated by wire propagation effects, which are implemented offline, but not in the TPGs.
- Ultimate performance is not achieved, as data were taken before the Phase-2 fine synchronization and Phase-1 full-precision offline calibration of the DT system were deployed.

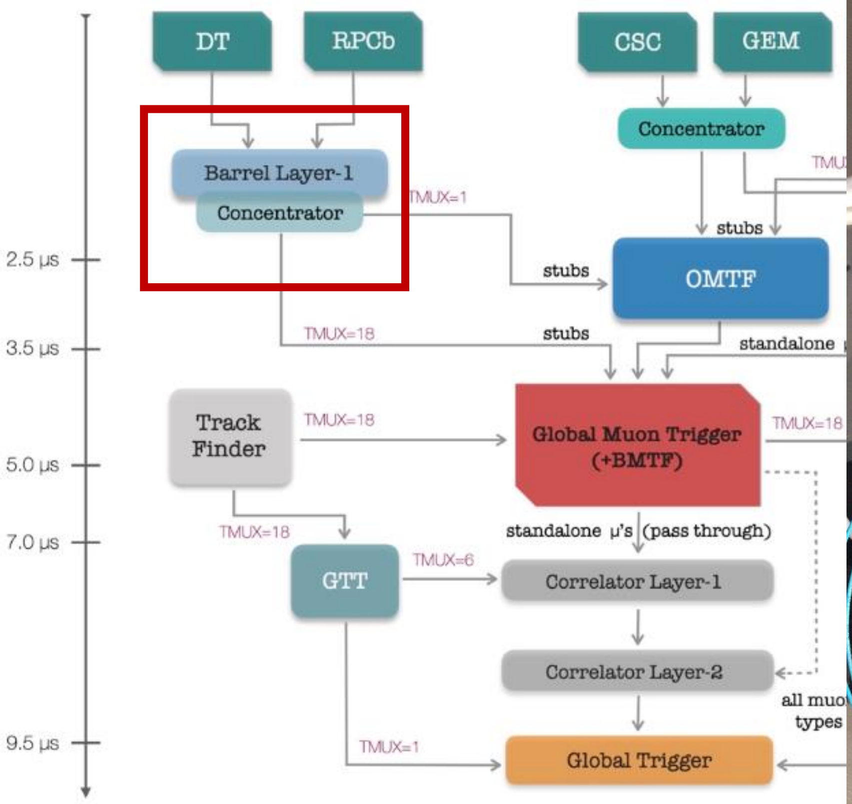
MB1 Trigger Efficiency vs Position in Collisions for Muons Crossing the ST

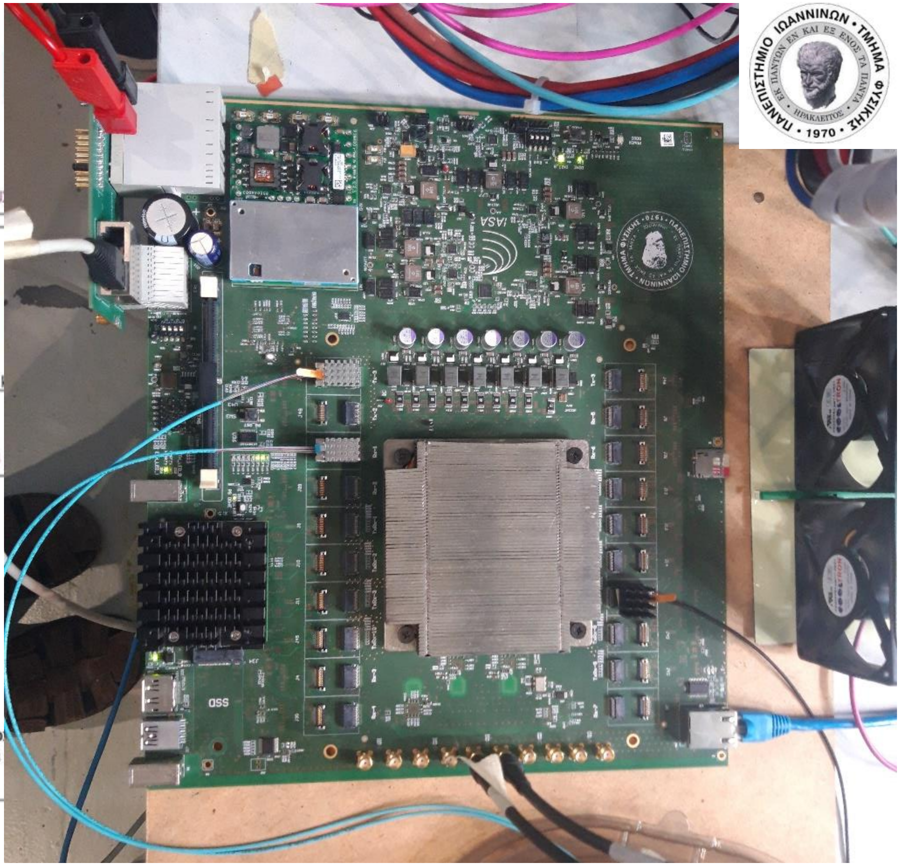




- Efficiency of finding a Phase-2 TPG in any BX with respect to the local position of the Phase-1 offline segment selecting events with a muon in the acceptance of the Slice Test for
  - every primitive (black)
  - primitives 4 hits in a superlayer (red)
  - 2 superlayer primitives with more than 6 hits (blue)
- Satisfactory performance

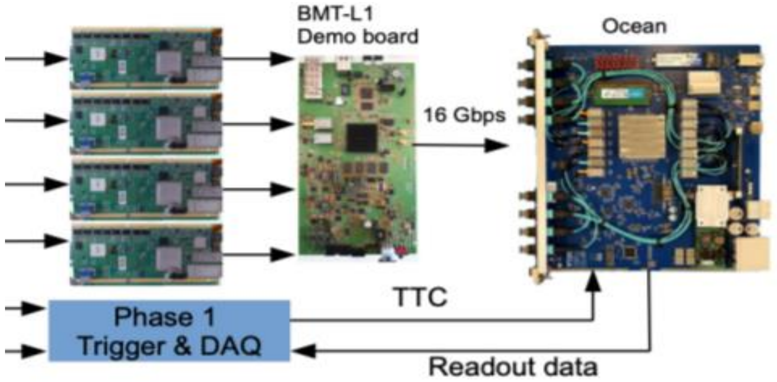
DT Phase 2 Slice Test Trigger Backend Status

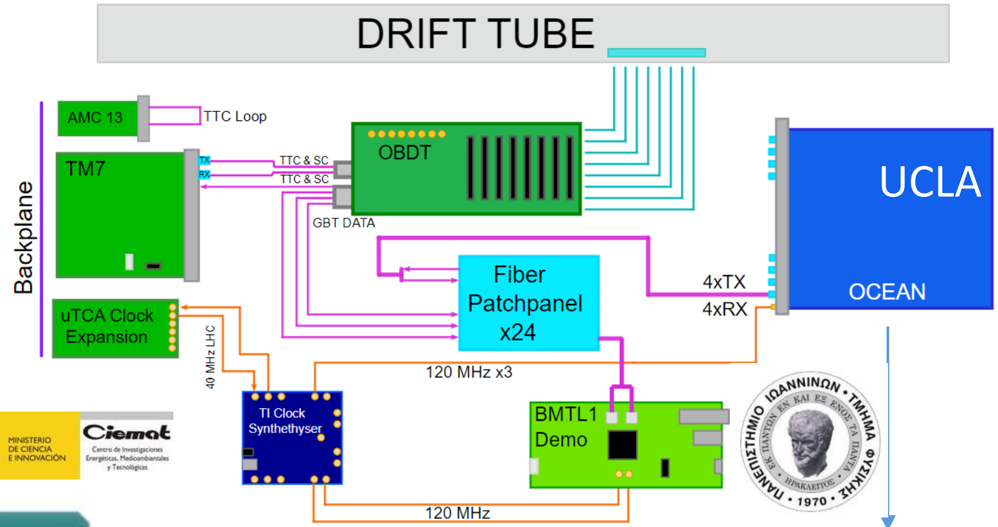


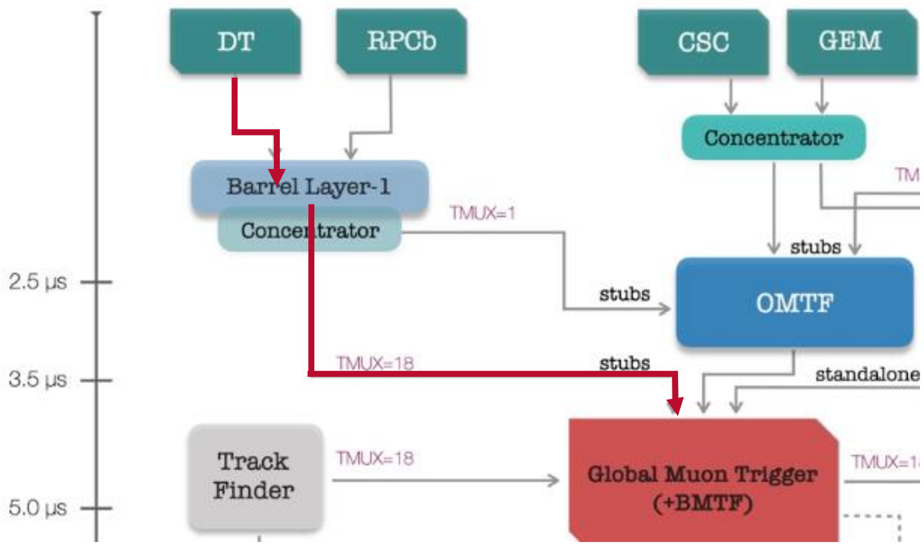


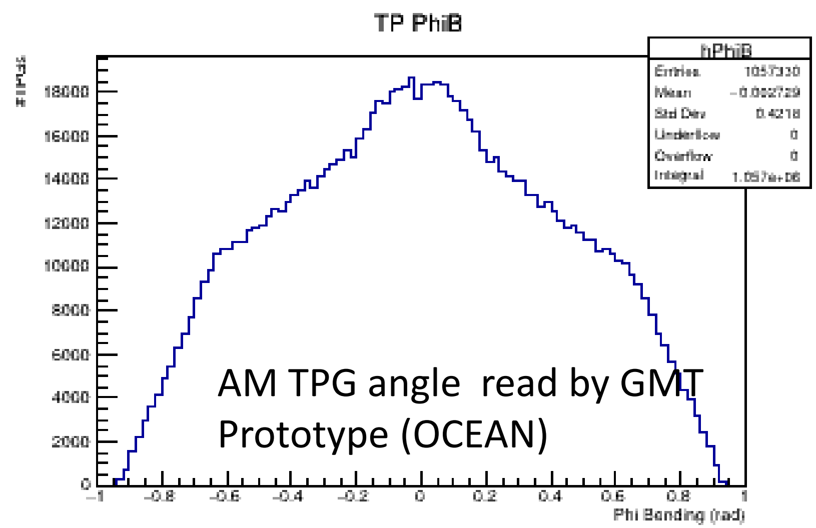
- Backend board (BMTL1) will port one VU13P and firefly optics, ATCA prototype board (see I. Bestinazos contribution ,this workshop).
  - Being integrated with OBDTthetha (lpGBT board), at P5 surface cosmics setup
- Resource requirements, being evaluated to define number of boards in the system by spring, driven by processing power.
  - Phase-2 Muon TDR system has 84 ATCA blades, including DT&BMTL1 DAQ functionality.

Surface DT Chamber Cosmics Test Stand





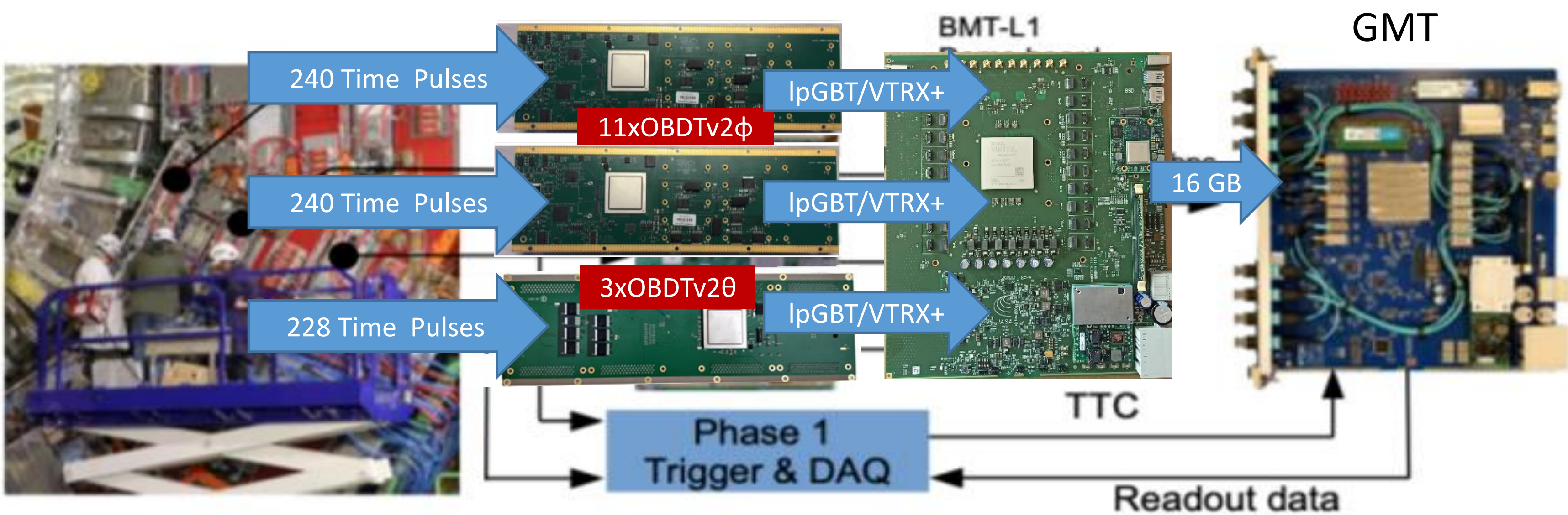




Achieved full vertical integration in FW from DT chamber to GMT with Phase-2 backend prototypes

Summary&Plans

- Demonstrated synchronization of the Phase-2 Slice Test chain, largely based on previous cosmics data taking.
- Rather satisfactory performance of OBDTv1-based Slice Test in collisions, proving feasibility of the chosen architecture.
    - Expect to be able to perform in the Phase-2 TPG system ~ now available only offline.
- Installing ATCA backend prototype in USC fed by DT Slice Test signals before the end of the year feasible, being integrated in surface setup.
- Preparing to install lpGBT-based OBDTv2 boards in one sector during YETS2223

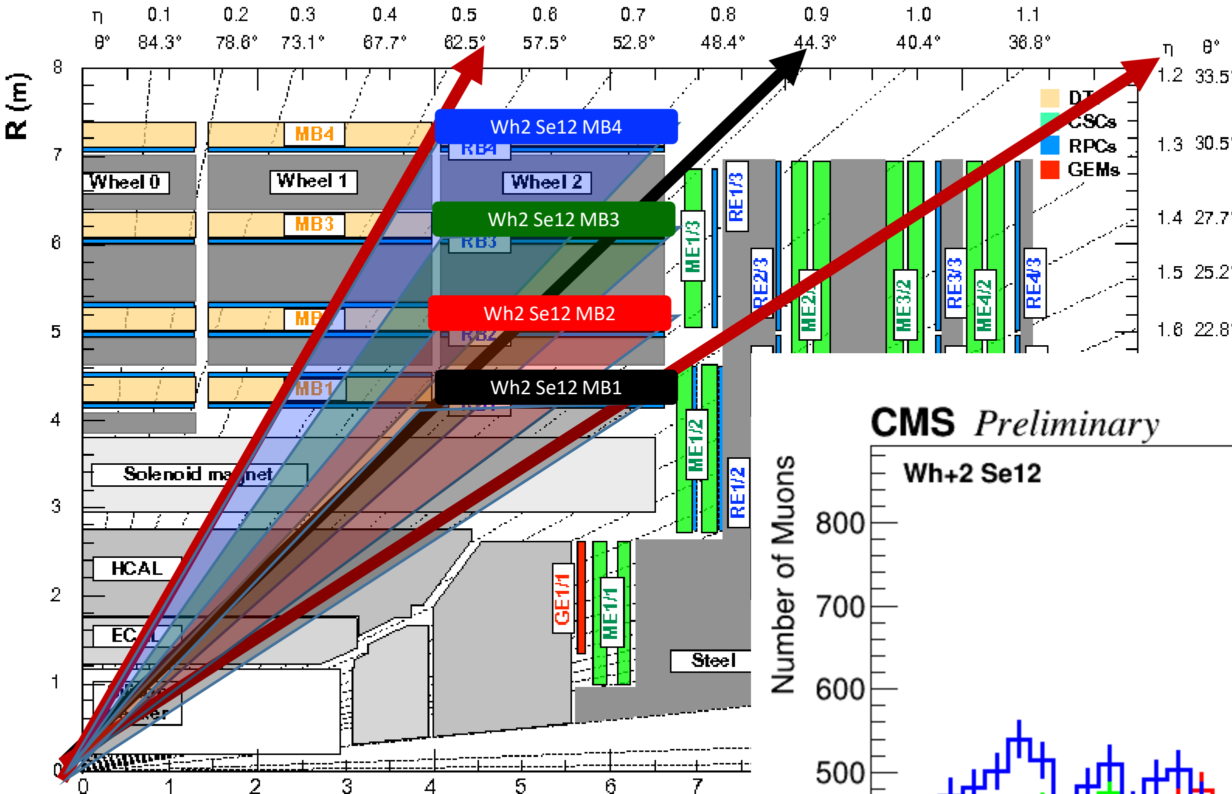


Additional Material

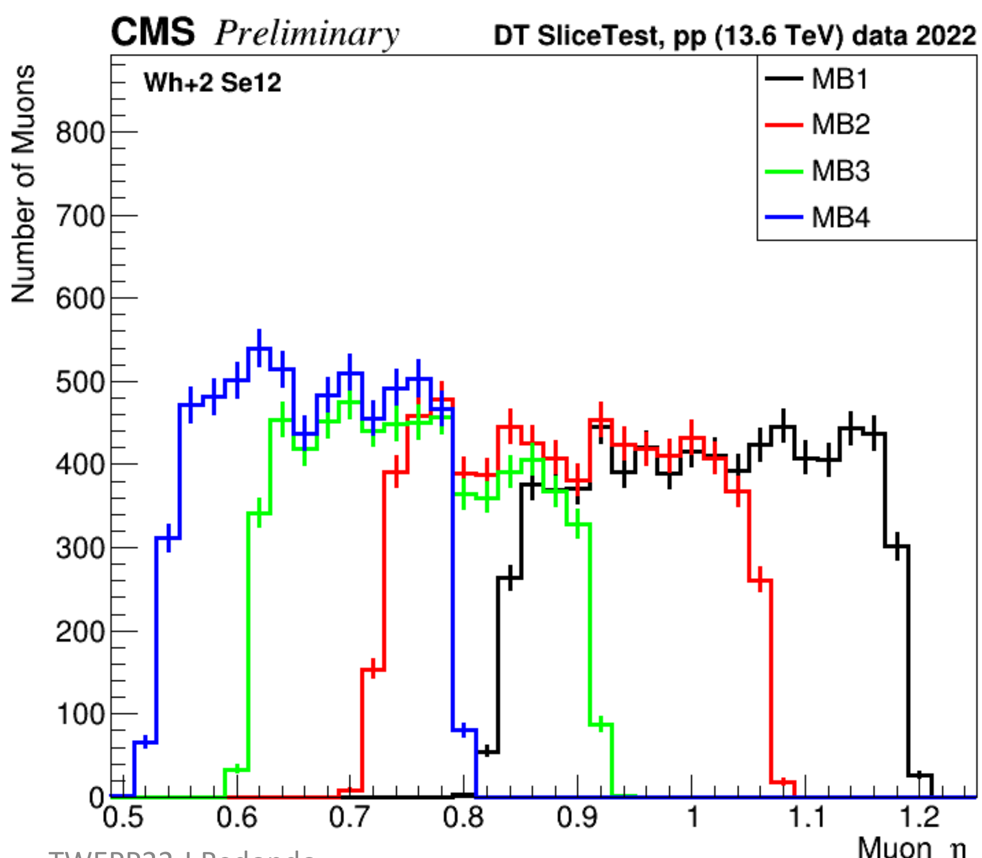
Previous DT Phase-2 Slice Test Public Results

- AM algorithm public results
  - CMS Note-2022/009 "A Firmware-oriented Analytical Algorithm for Trigger Primitive Generation in the CMS Drift Tubes detector for the High Luminosity LHC" , to be submitted to IEEE trans, including Slice Test demonstrator data
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/DTPhase2TriggerAnalyticalMethod200611
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/DTPhase2TriggerAnalyticalMethod190411
  - Performance results on simulation
    - http://cdsweb.cern.ch/record/2792319/files/DP2021_028.pdf
    - http://cds.cern.ch/record/2777924/files/DP2021_011.pdf
  - Recent Slice Test public results:
    - Stability of the Time Digitization time reference, aka TDC T0s:
      - http://cdsweb.cern.ch/record/2801640/files/DP2022_001.pdf
    - Slice Test Results with 2021 Cosmics data:
      - Trigger: http://cdsweb.cern.ch/record/2792318/files/DP2021_027.pdf
      - Readout: http://cdsweb.cern.ch/record/2799473/files/DP2021_036.pdf

DT Slice Test Acceptance: R-z



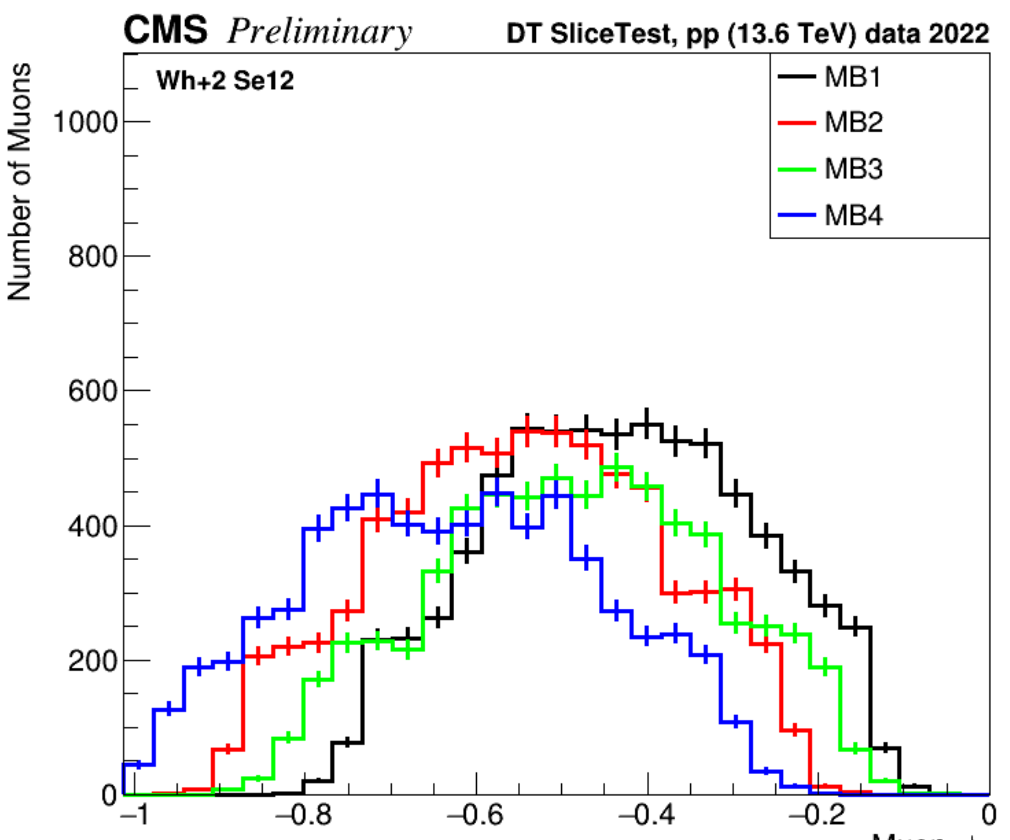
Distribution in η of tight muons with p_T > 25 GeV crossing any of the Slice Test chambers in Wh+2 Se12.

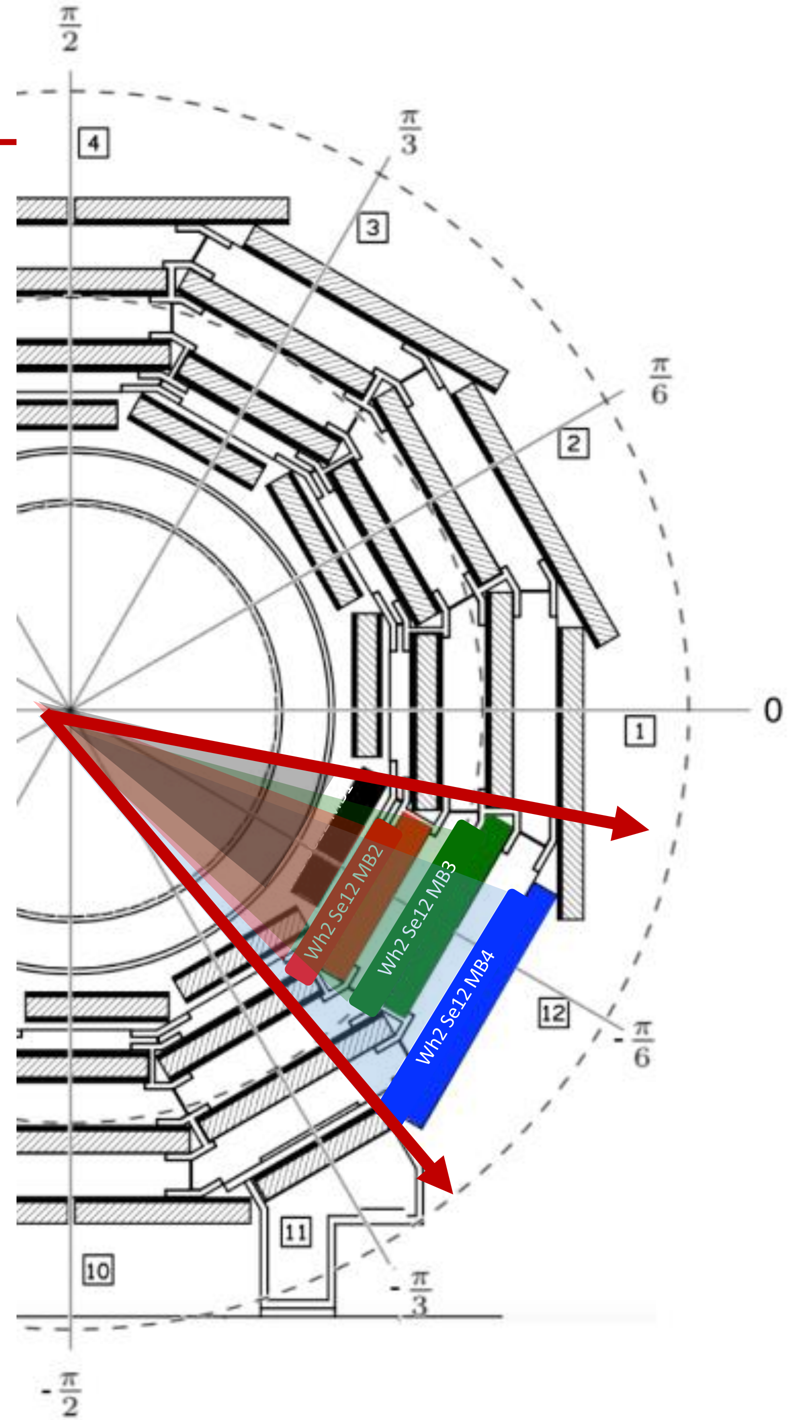


In the external barrel wheels there is large acceptance overlap between MB1&MB2 on one hand, and MB3&MB4 on the other.

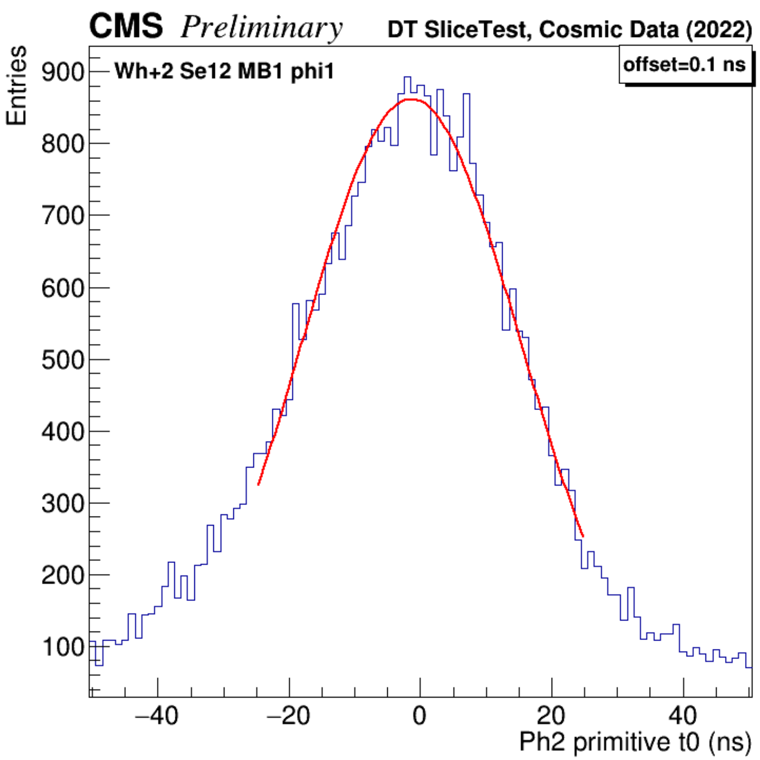
DT Slice Test Acceptance: R-ϕ

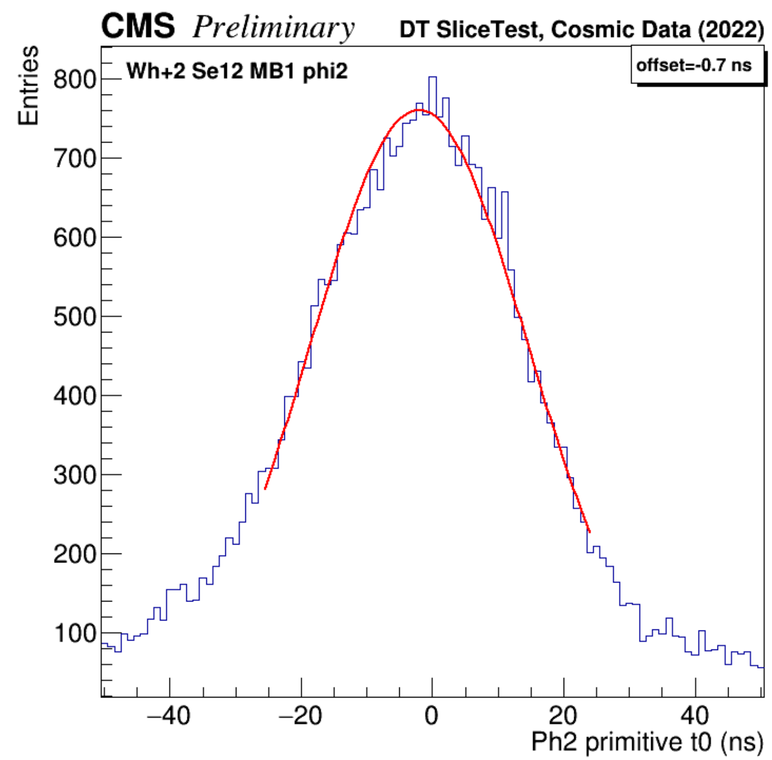
Distribution in ϕ of tight muons with p_T > 25 GeV crossing any of the Slice Test chambers in Wh+2 Se12.





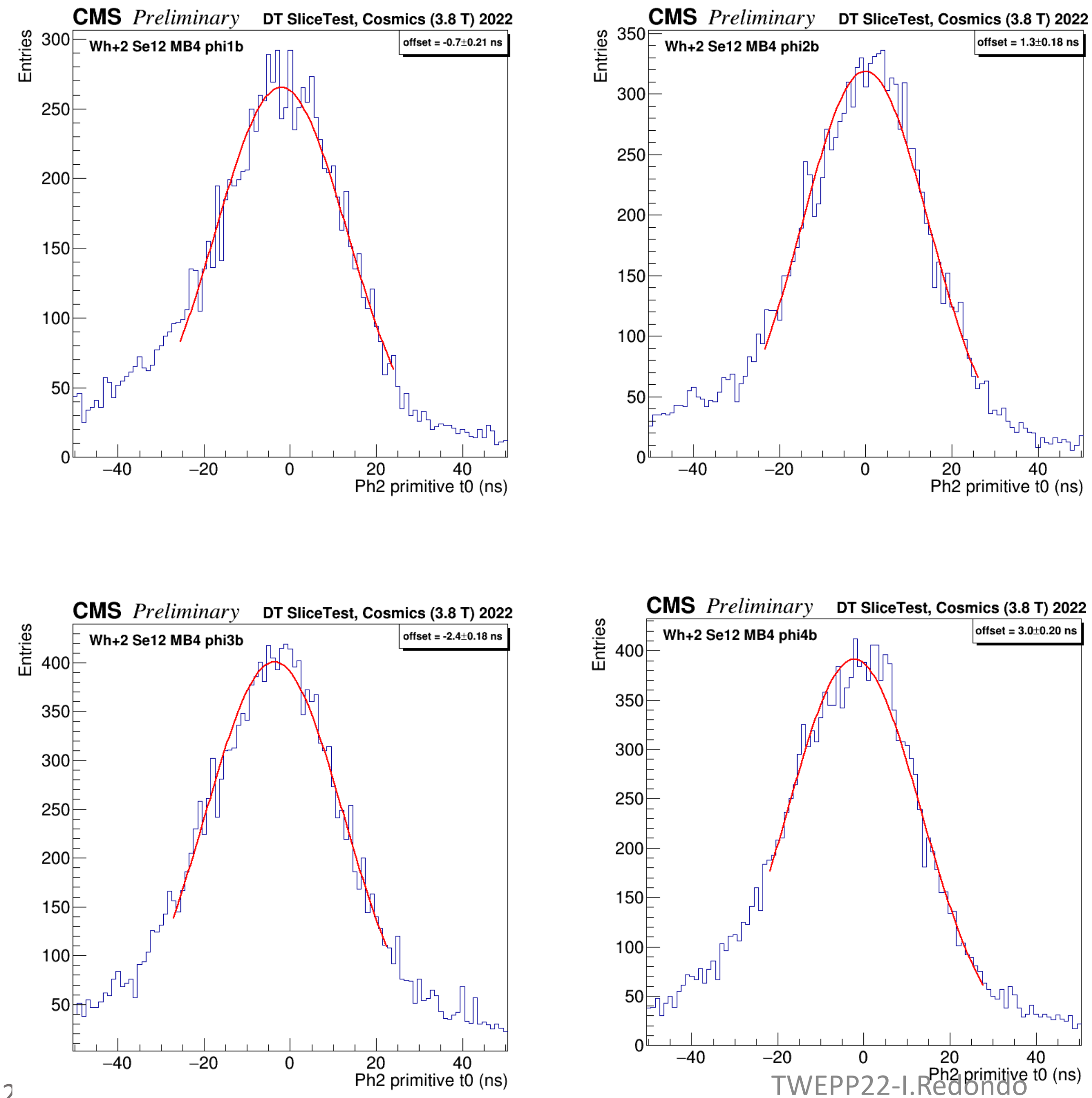
MB1 Synchronization in Cosmics Data (3.8 T)





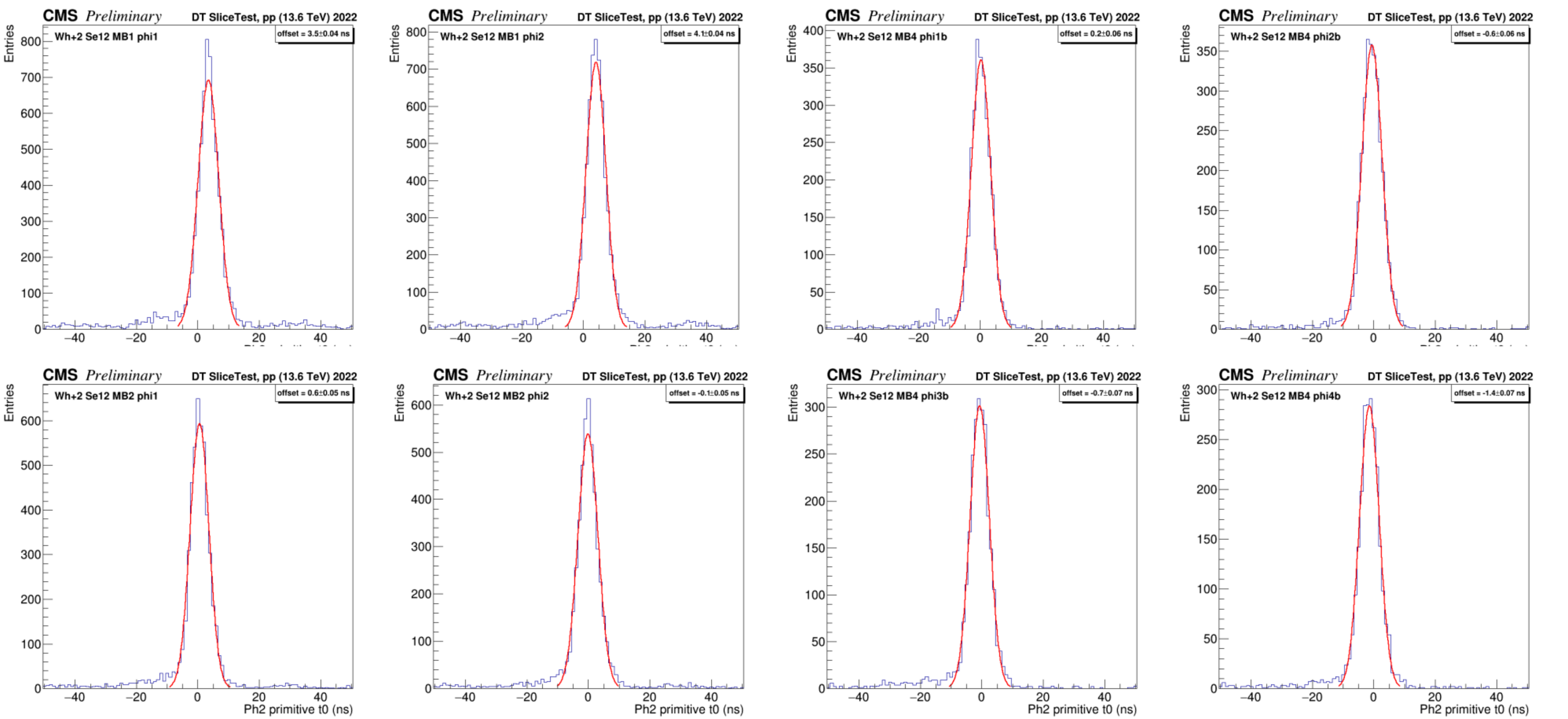
- Time of the 4-h primitive coming from hits digitized in each of the OBDT boards instrumenting the YB+2 MB1 S12 PHI superlayers for cosmic ray events with magnetic field triggered by the sectors opposing the Slice Test sector.
- The offsets had been set previously to zero using the same method in a sample of cosmics rays taken in absence of magnetic field.
- The Gaussian does not intend to model the underlying time spread processes, the fit not representing the 4-h primitive resolution. The initial cosmics time distribution flat over a 25 ns bx is polluted by small contributions from neighboring bx from out of time triggers by the CMS L1 Muon trigger and only then smeared by the 4-h primitive time resolution.

MB4 Synchronization in Cosmics Data (3.8 T)



- Time of the 4-h primitive coming from hits digitized in each of the four OBDT boards instrumenting the YB+2 MB4 S12 chamber for cosmic ray events with magnetic field triggered by the sectors opposing the Slice Test sector.
- The offsets had been set previously to zero using the same method in a sample of cosmic rays taken in absence of magnetic field.
- The Gaussian does not intend to model the distribution, the fit not representing the 4-h primitive resolution. The ideal initial cosmics time distribution flat over a 25 ns bx is polluted by small contributions from neighboring bx from out of time triggers by the CMS L1 Muon trigger and then smeared by the 4-h primitive time resolution.

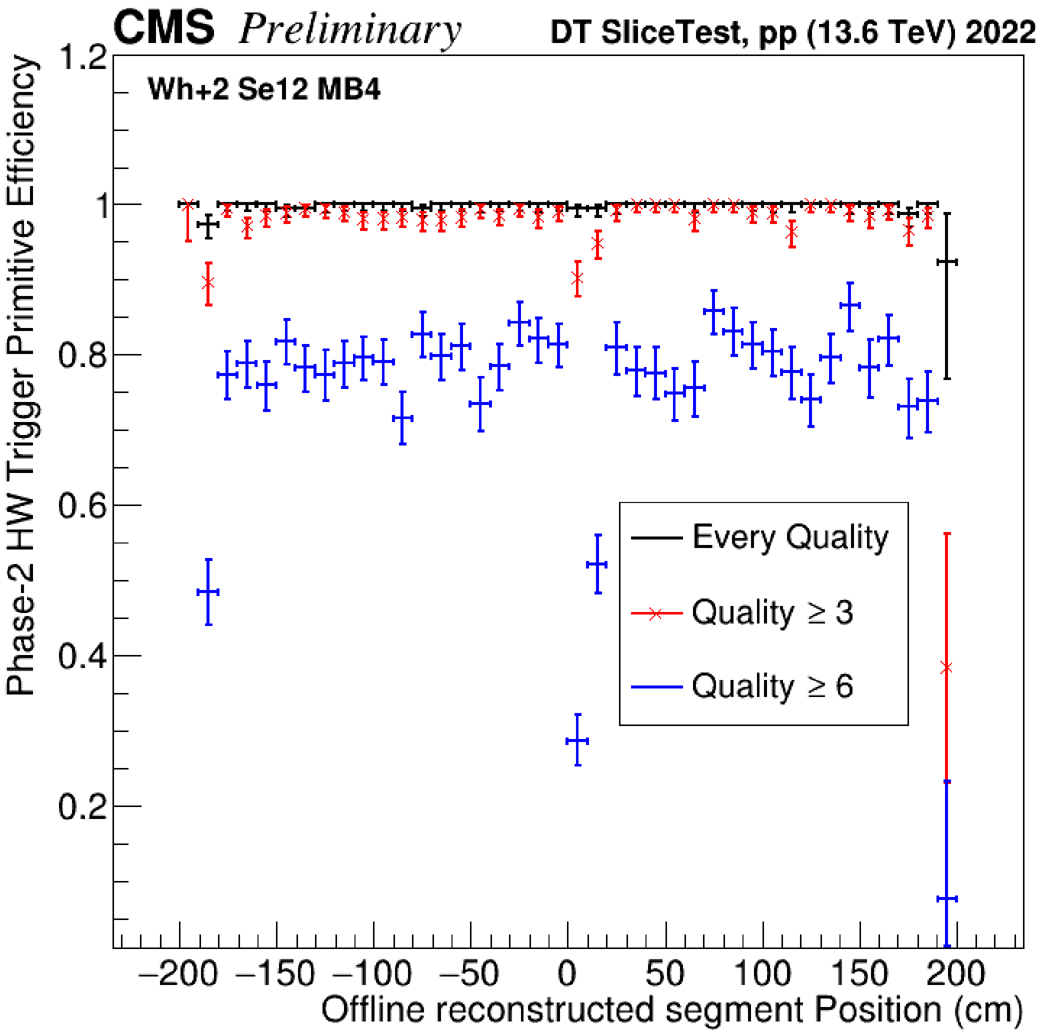
DT ST Synchronization in Collisions, Selecting Muon Tracks



- Time of the 4-h primitive coming from hits digitized in each of the OBDT boards instrumenting the MB1, MB2 and MB4 chamber in early Run 3. Delays were updated in subsequent running.

- Filtering events to select collision muons as described before reduces significantly the offsets to ≤ 4 ns, affecting specially MB1&MB2, which suffer larger background. MB3&MB4 OBDTs have delay updates ≤ 1 ns. The Gaussian fits to the distribution core have sigma of 3 ns, which is an upper limit to what is ultimately achievable given these are single-superlayer primitives and the system was not fully synchronized.

MB4 Trigger Efficiency vs Position in Collisions for Muons Crossing the ST



- 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 (black), primitives built with more than 4 hits in a superlayer(red) and primitives with more than 6 hits, i.e. 3 or more hits per superlayer (blue) for the DT Slice Test Wh+2 Se12 MB4 data in 2022 collisions. .
- Events are required to have tight muon with $p_T > 25$ GeV in the acceptance of the Slice Test.
- 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 prototype backend 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. In the final system all channels from a chamber will be processed by one backend board, so this effect will disappear.

DT Phase-2 Slice Test Description

• During Long Shutdown 2 (LS2) one sector (wheel +2 sector 12) of the CMS DT detector has been instrumented with the HL-LHC DT electronics front-end and back-end prototypes. The chamber FE signals are split and fed both to the legacy system and to these new electronics. One of the backend boards (the AB7) runs the so-called Analytical Method (AM) firmware, which generates the trigger primitives. This way, both Phase-1 and Phase-2 electronics can be run inside the CMS infrastructure, and the AM firmware can be validated under realistic conditions. Details of the AM can be found in CMS NOTE-2022/009.

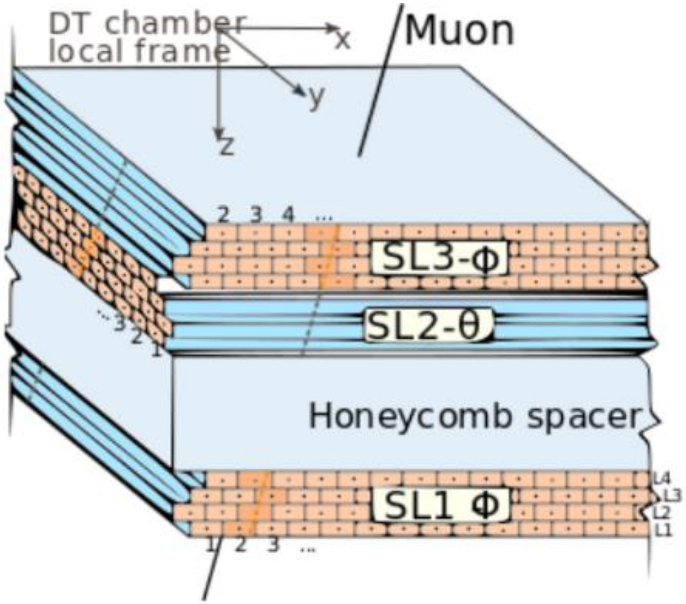
• Calibration of the optimal fully configurable delays used online has been extensively studied during LS2 with cosmic-ray muons and the obtained wire-by–wire delays used as starting calibration for early Run 3 collisions. Fully calibrated results from cosmics can be found in DP/2021-28 and DP/2021-36.

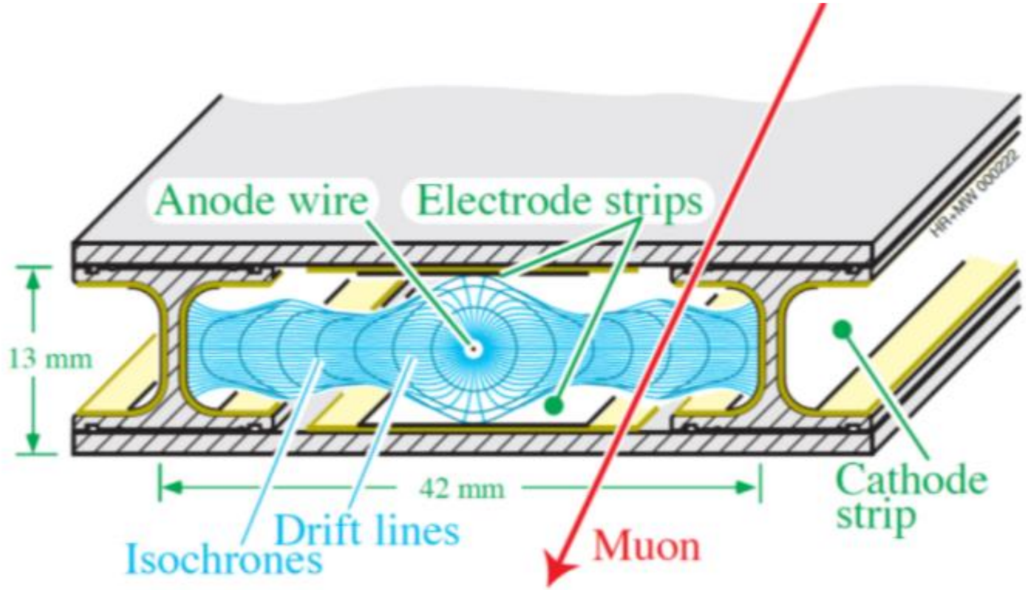
• The information extracted from Phase-2 primitives (generated by the AB7 board) is compared with Phase-1 segments. Phase-1 segments are reconstructed offline from legacy hits and selected to have i) an inclination with respect to the direction orthogonal to the chamber layer plane < 30°, ii) at least 4 hits, and iii) a |t0|< 50 ns, where t0 stands for the time associated to the segment as reconstructed by a 3-parameter fit. Results presented use:

- A cosmic muon sample with 3.8 T collected with the Slice Test set up and triggered by opposite sectors in a global run with the Barrel Muon Track Finder (BMTF) .

- A collision data sample of 1.9 fb^{-1} that was collected during LHC Run 3 startup in July and August 2022.

CMS DT chambers





Long Term LHC shceadule