CMS Drift Tubes at High-Luminosity LHC:
chamber longevity and upgrade of the detector electronics

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on behalf of the CMS collaboration

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The CMS muon Drift Tubes (DTs)

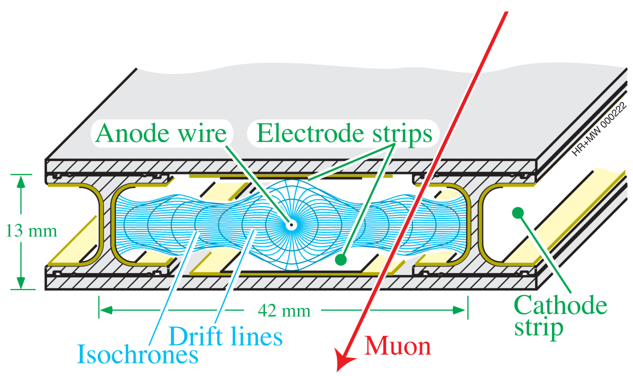
DT drift cell:

- size: 4.2 x 1.3 mm

- gas mixture: 85% Ar - 15% CO_2

- ~ const v_{drift} : ~54 μm/ns (t_{MAX} ~ 400 ns)

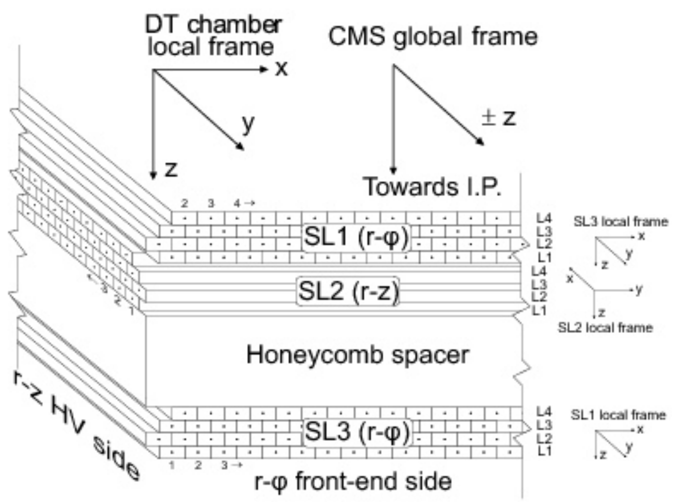
- ~ 172 000 DT cells in total



DT chamber:

- group of 4 detection layers form a super-layer (SL)

- 2 SLs in r-φ + 1 SL r-z (for 3 innermost stations)

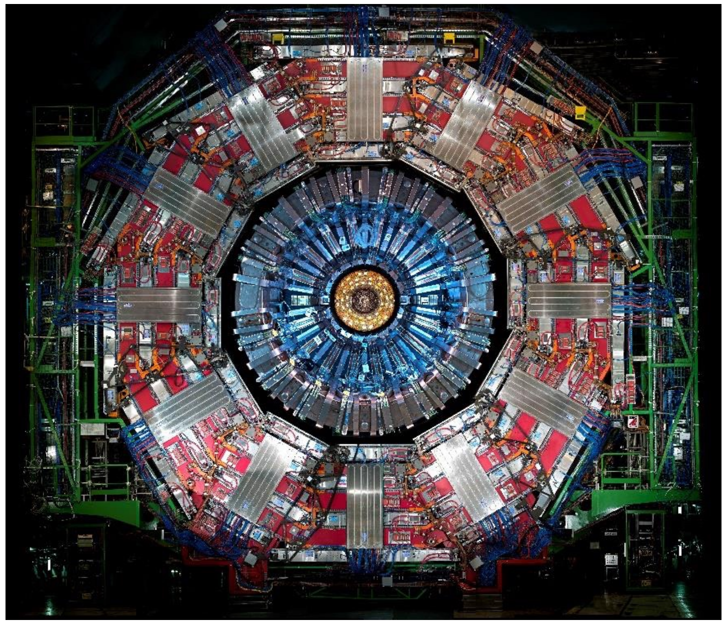


250 DT chambers in total:

- 4 concentric rings of stations (MB1-4)

-12 sector slices (S1-12)

- 5 wheels in the whole barrel (YB-2-+2)

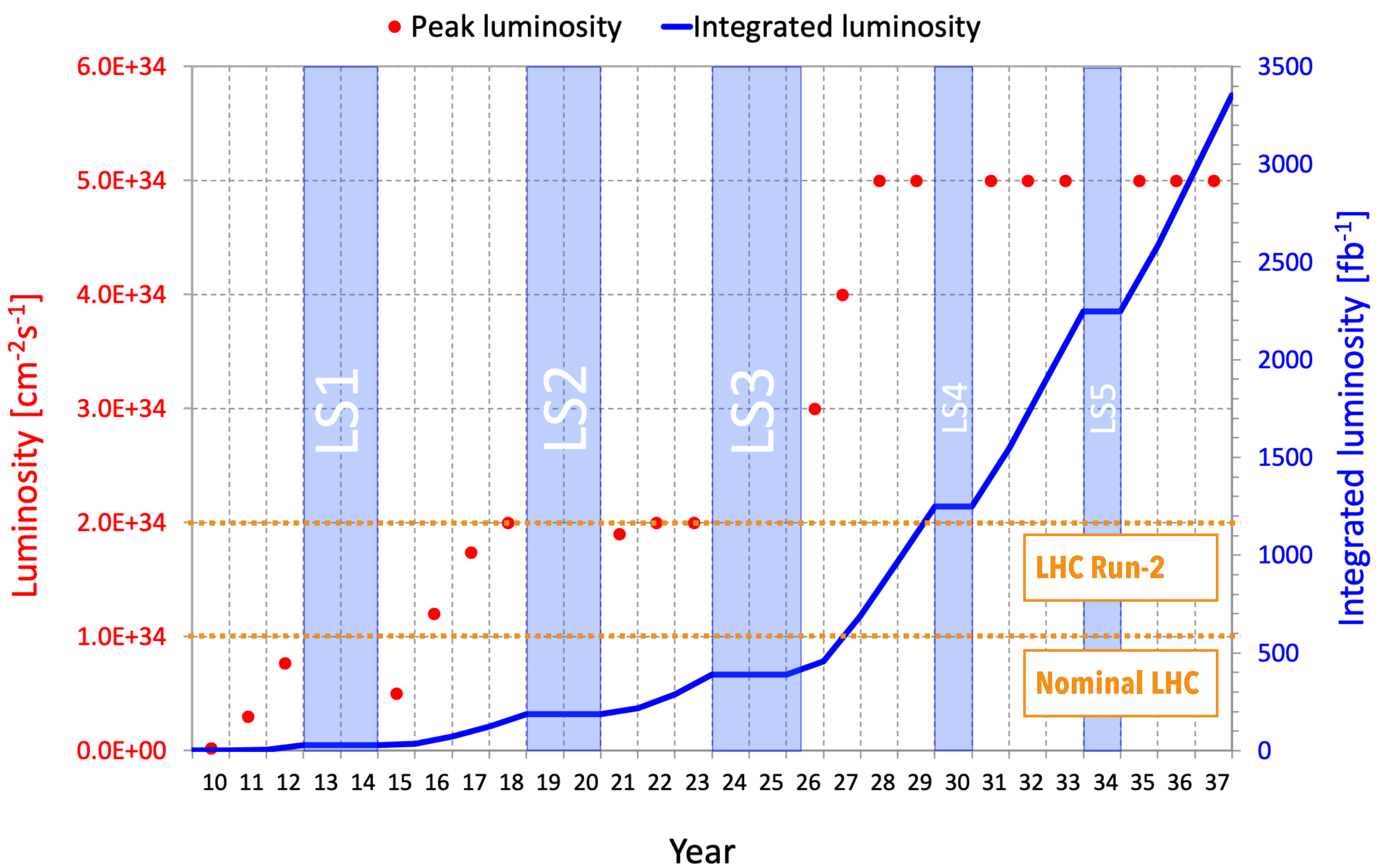


- Equip the barrel of the CMS muon spectrometer
- Are a tracking detector with standalone trigger capabilities

- Present offline reconstruction performance:
  - ~ 100% efficiency to build track segments in *r-φ*
  - segment spatial resolution ~ 100 *μm*
  - segment time resolution ~ 2 *ns*

- Present trigger performance:
  - performs parent bunch-crossing identification (BX-ID)
  - ~ 95% efficiency to build a trigger segment and identify BX
  - spatial resolution (position): ~ 1 *mm*
  - spatial resolution (direction): up to ~ 5 *mrad*

DTs in the CMS Phase-2 upgrade (1)



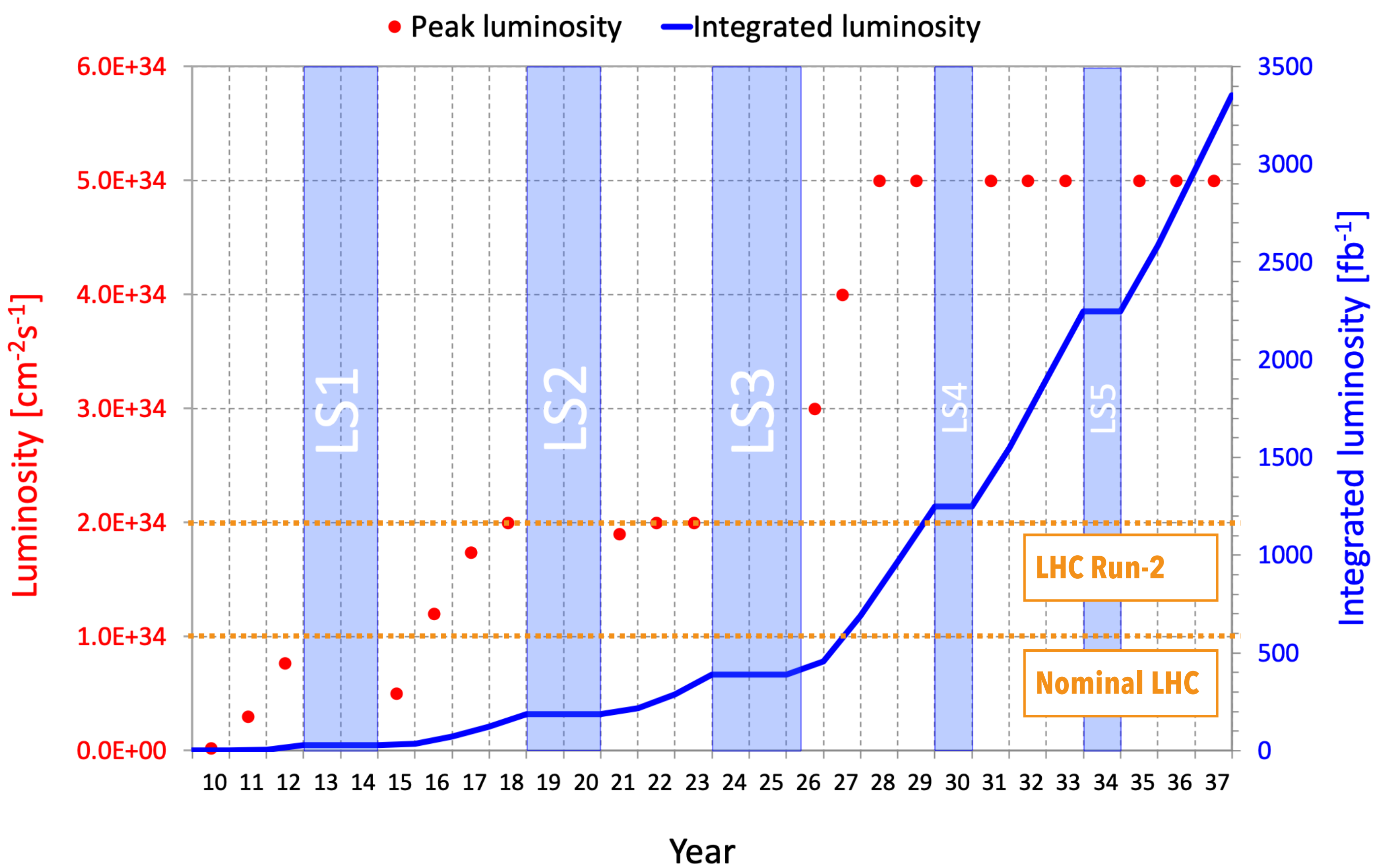
$\|\eta\|$ range	DT 0-1.2
neutron fluence (10^{12} n/cm^2)	0.4
total ionization dose (kRad)	0.12
hit rate (Hz/cm^2)	50
charge per wire (mC/cm)	20

Neutron fluence, integrated dose, BKGrate and integrated charge for the most exposed DT chamber @ HL-LHC

- Nominal HL-LHC scenario:
  - foresees inst. luminosities up to $5 \cdot 10^{34}$ cm$^{-2} \cdot$s^{-1} (x5 w.r.t. LHC design specifications, <pile up> up to ~150)
  - aims at collecting ~ 3000 fb^{-1}
  - all scales up to $7.5 \cdot 10^{34}$ cm$^{-2} \cdot$s^{-1} (<pile up> up to ~200) and ~ 4000 fb^{-1} for ultimate HL-LHC scenario

1. Chambers/electronics will operate at BKG/integrated-charges well beyond design specifications
2. The CMS maximal Level-1 Trigger (L1T) rate expected to scale from 100 kHz to 750 kHz
3. Furthermore, the CMS Level-1 Trigger latency is expected to increase from 3.6 μs to 12.5 μs

DTs in the CMS Phase-2 upgrade (2)



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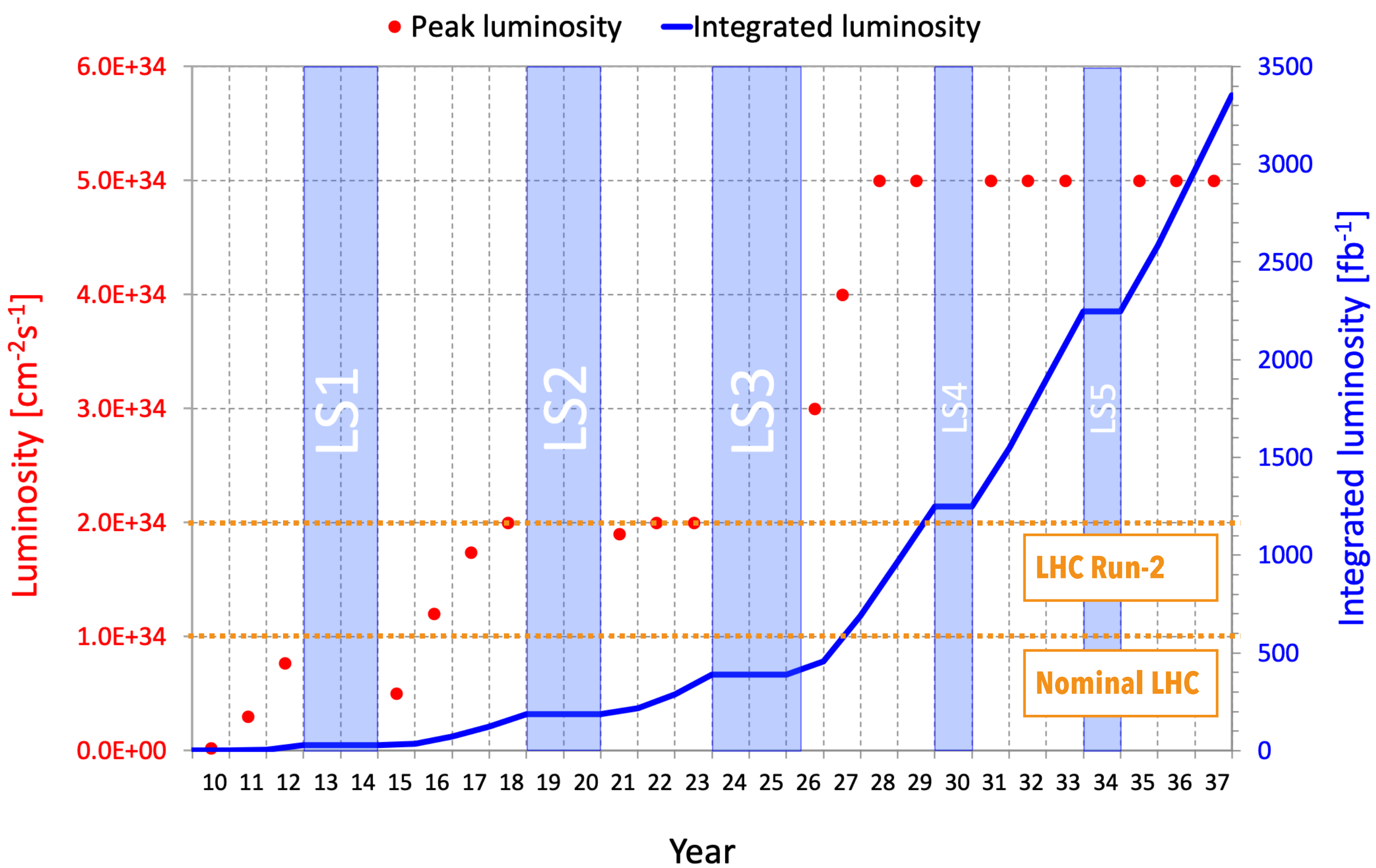
- Existing DT electronics is not expected to withstand 1. or handle 2./3.
- Chambers are instead expected to operate reasonably well throughout HL-LHC
- **DT upgrade in a nutshell:** install new (more powerful) electronics but keep existing chambers

In today's talk



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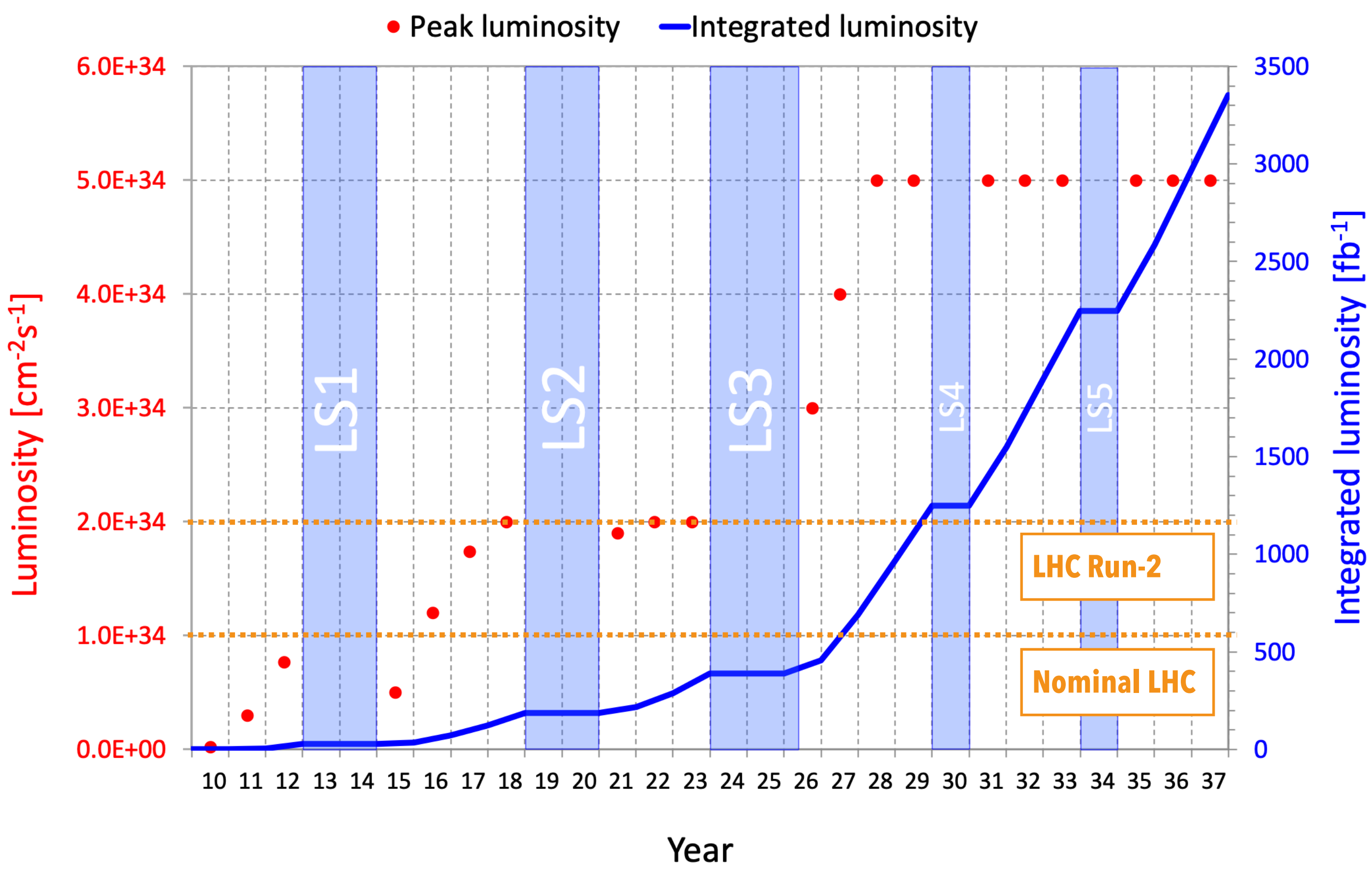

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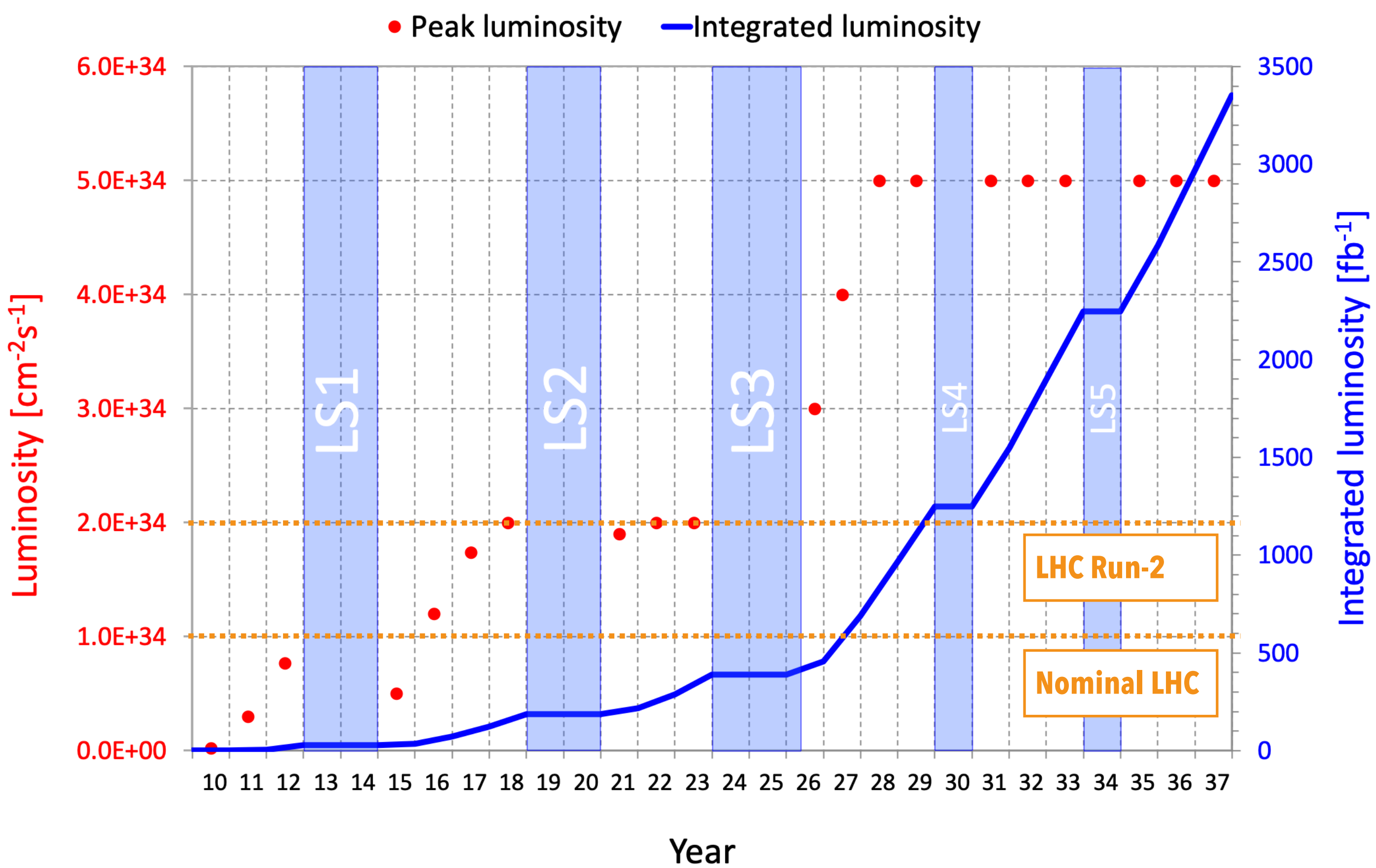

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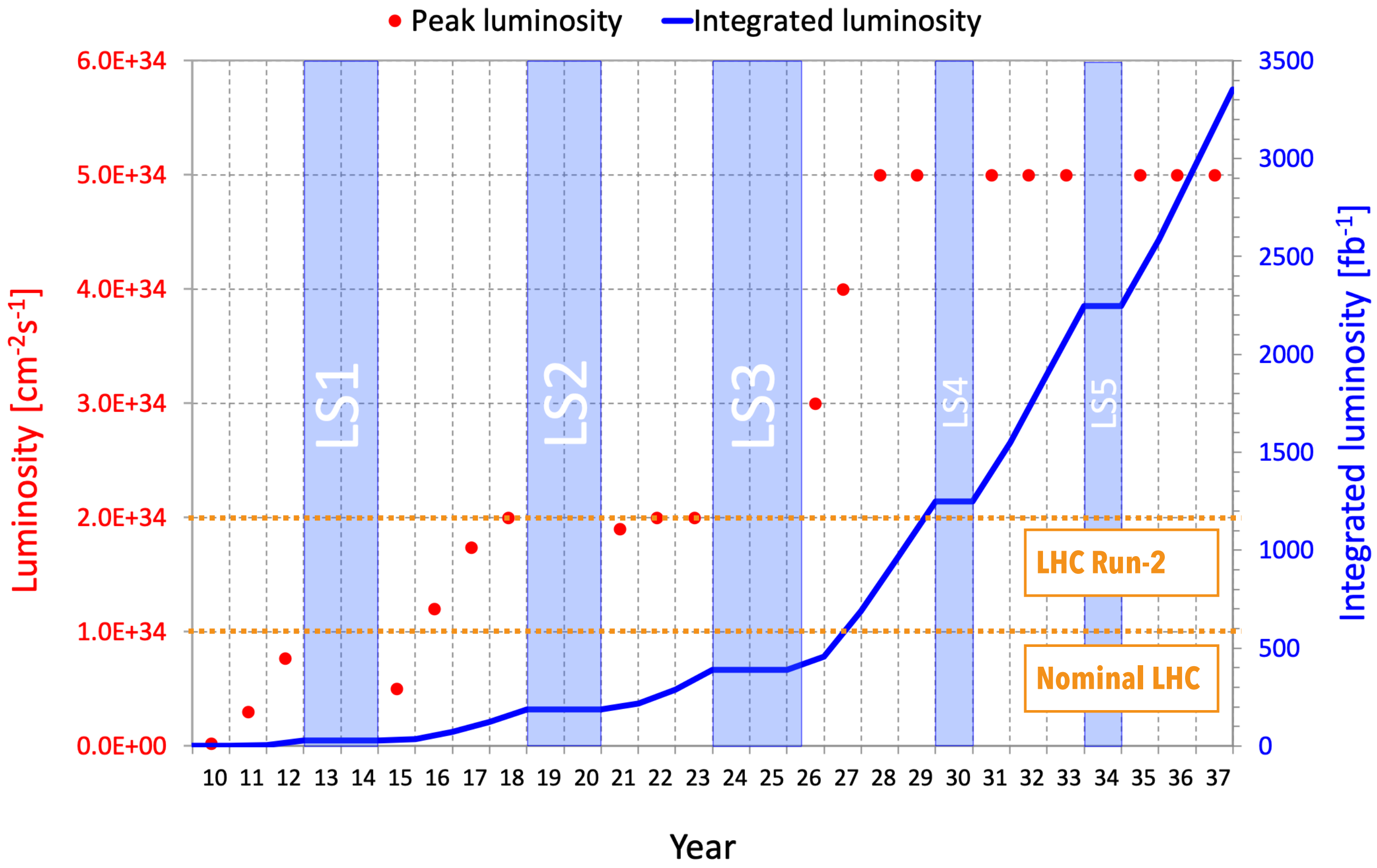

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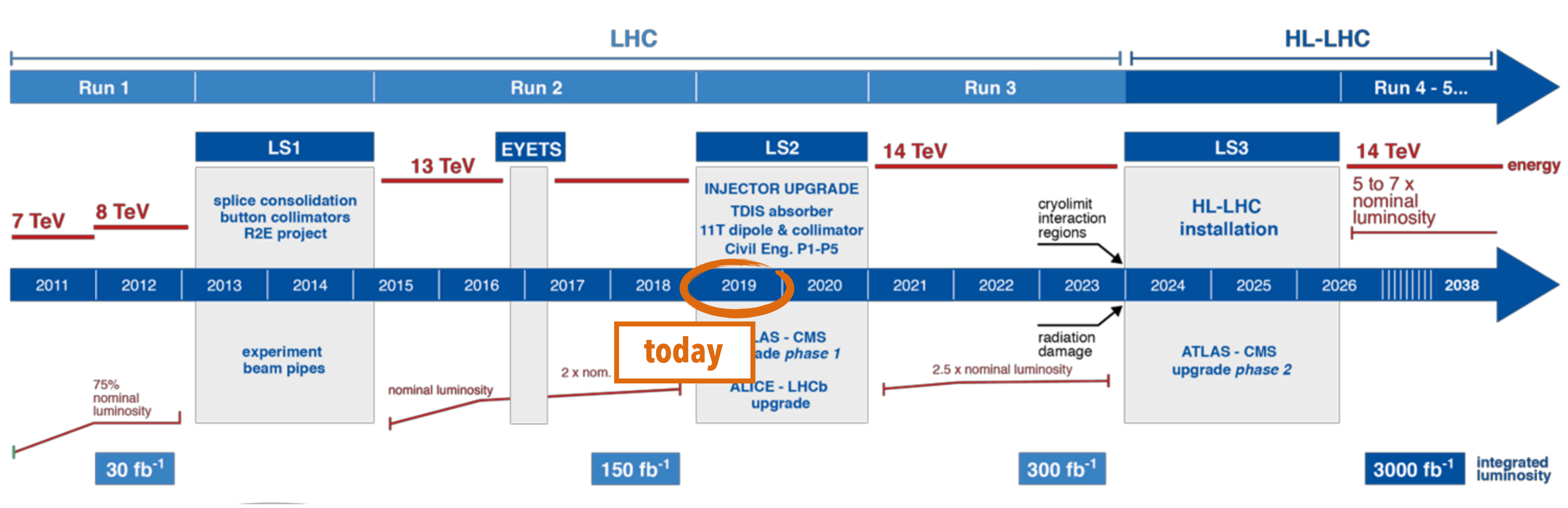
What can we do with this?

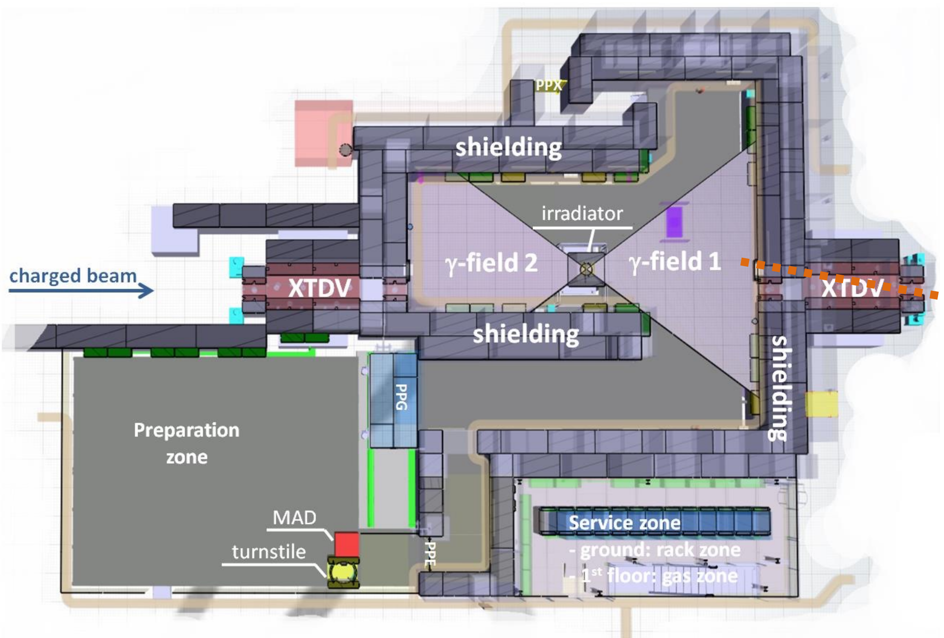
What have we done "in real life" until now

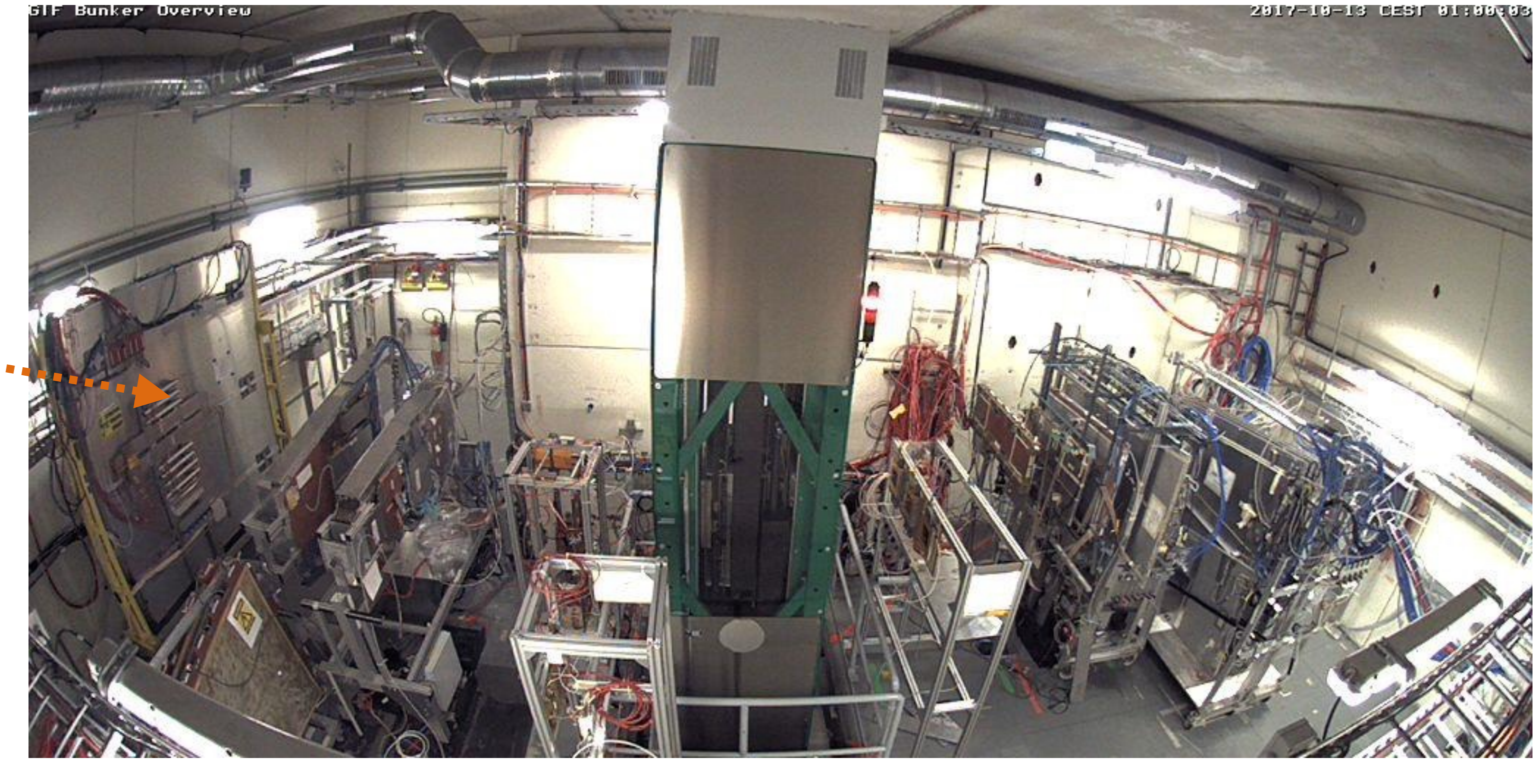
DT detector longevity

how will my chambers perform throughout HL-LHC?



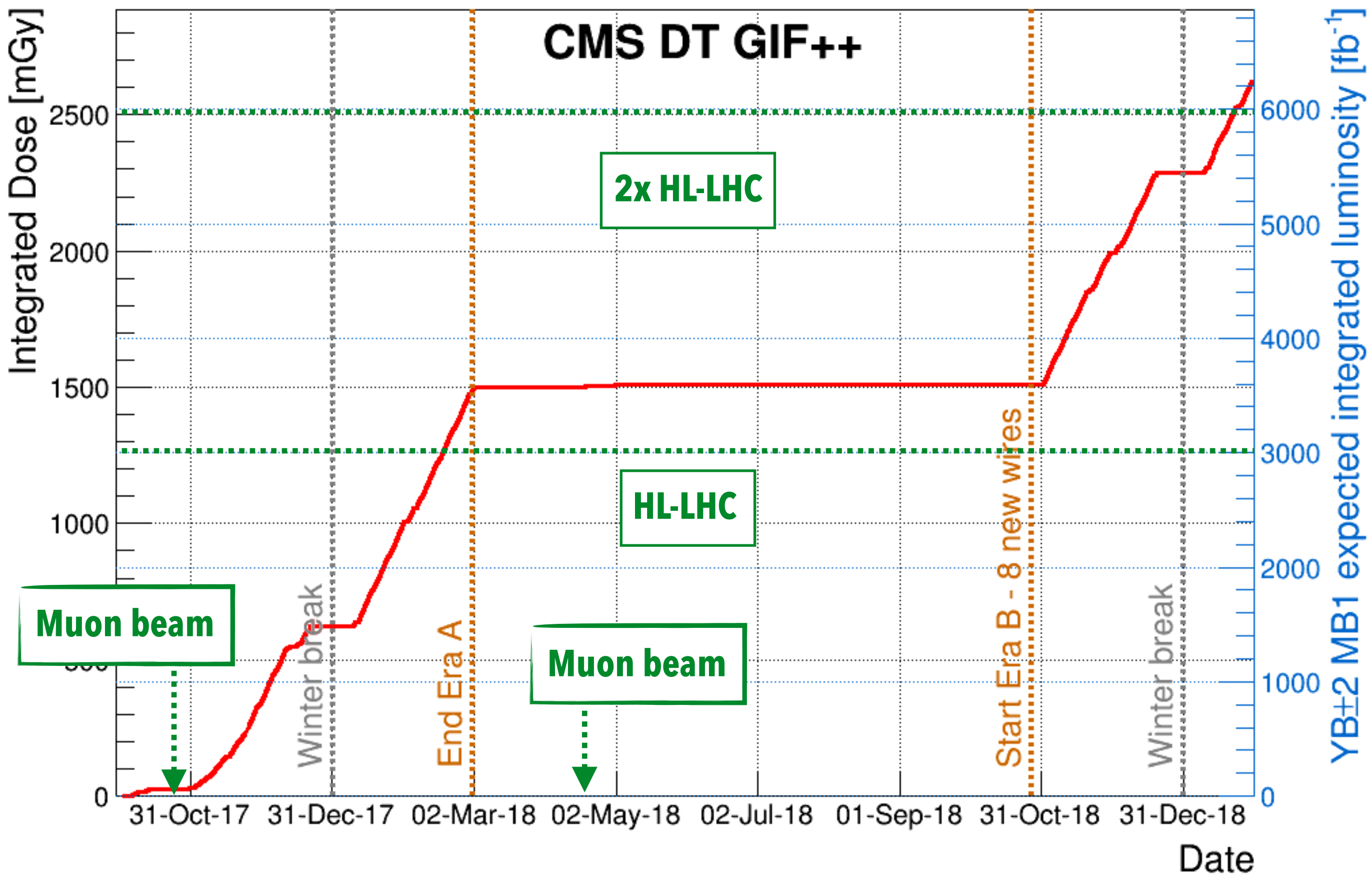
Where to asses detector longevity?





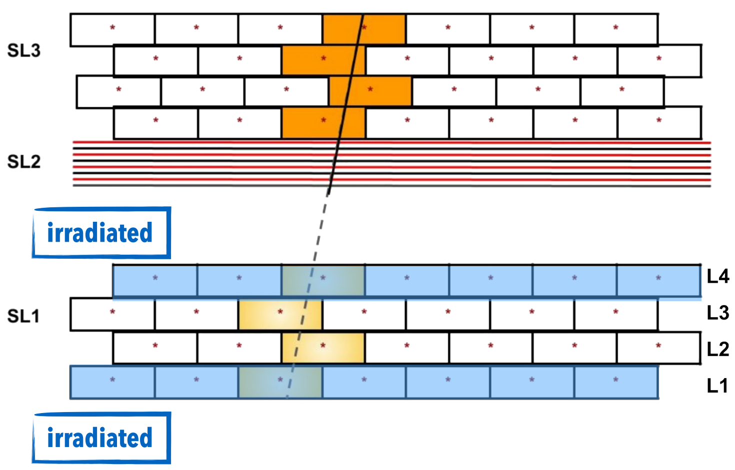
- Irradiation / test beam → the Gamma Irradiation Facility (GIF++) provides:
  - a high energy muon beam (from pions/kaons) to generate "signals" for muon chambers
  - a14 TBq ^{137}Cs source generating γ rays (E=662 *KeV*) used to:
    - perform irradiation campaigns
    - generate background (can be modulated using dedicated filters) for studies with muon beams and cosmic rays
- Allows to accumulate doses similar to HL-LHC ones in a "reasonable" time
- Of course CMS DT chambers are also regularly monitored to spot "on detector" ageing

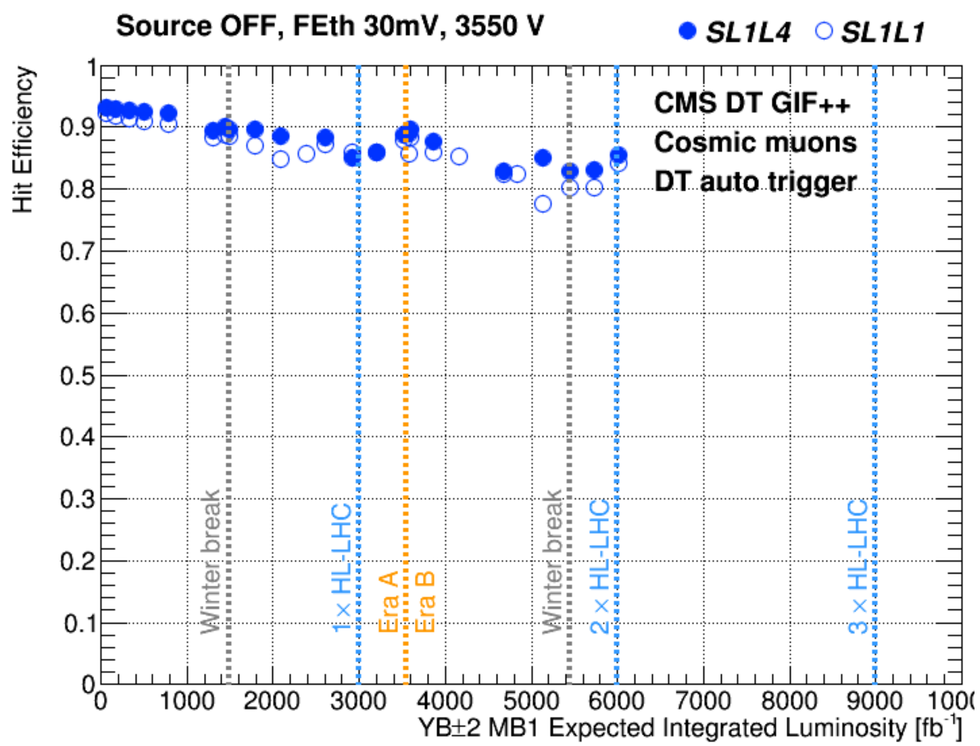
Irradiation data taking campaigns and definition of reference luminosity values

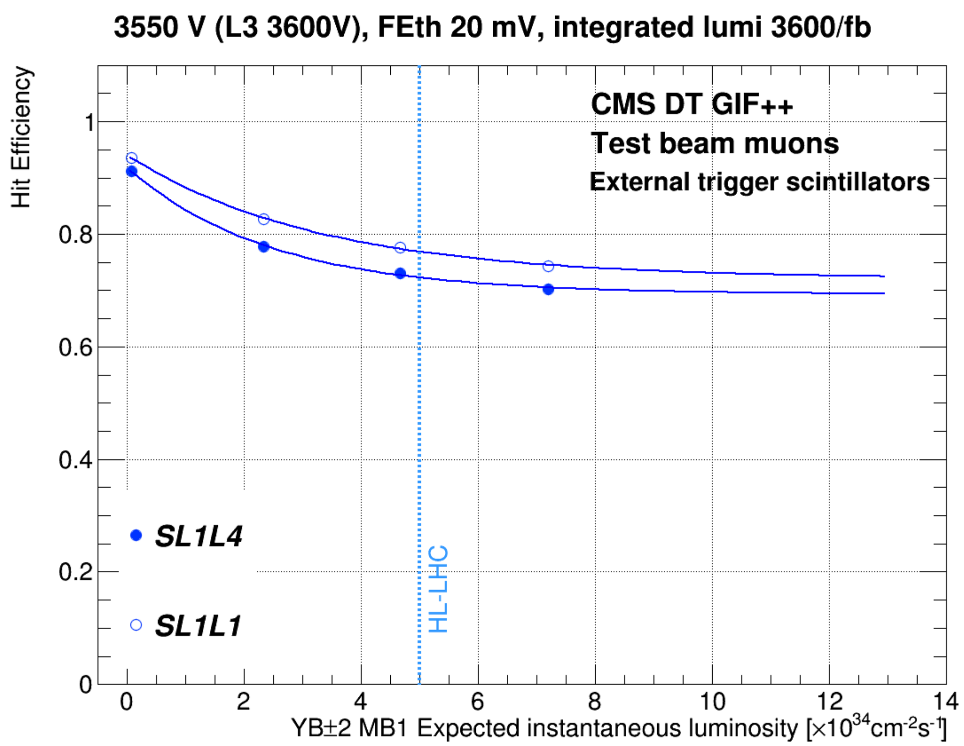


- Today's results are based on two specific irradiation campaigns on a DT station 2 chamber (MB2)
  - longest and most systematic ones, covering an int. luminosity up to 2 x HL-LHC
  - include measurements with muon beams (twice) and cosmic rays
- GIF++ dose rates (integrated doses) converted to HL-LHC inst. (int.) luminosity values by comparing wire currents (integrated charges) @ GIF++ and in CMS
  - GIF++ dose measurement from one REMUS dosimeter → several measurements made in front of MB2 to extrapolate REMUS to DT
    - dose rate → inst. luminosity conversion calculated at HL-LHC background rate: 1 fb^{-1}/s = 0.304 mGy/s
    - int. dose → int. luminosity calculated at GIF++ ageing rate (~10 x HL-LHC): 1 fb^{-1}= 0.42 mGy
  - quoted (int./inst.) luminosities corresponds to the dose (integrated/rate) expected for the most exposed DT chambers

Efficiency measurement with muon beams and cosmic rays



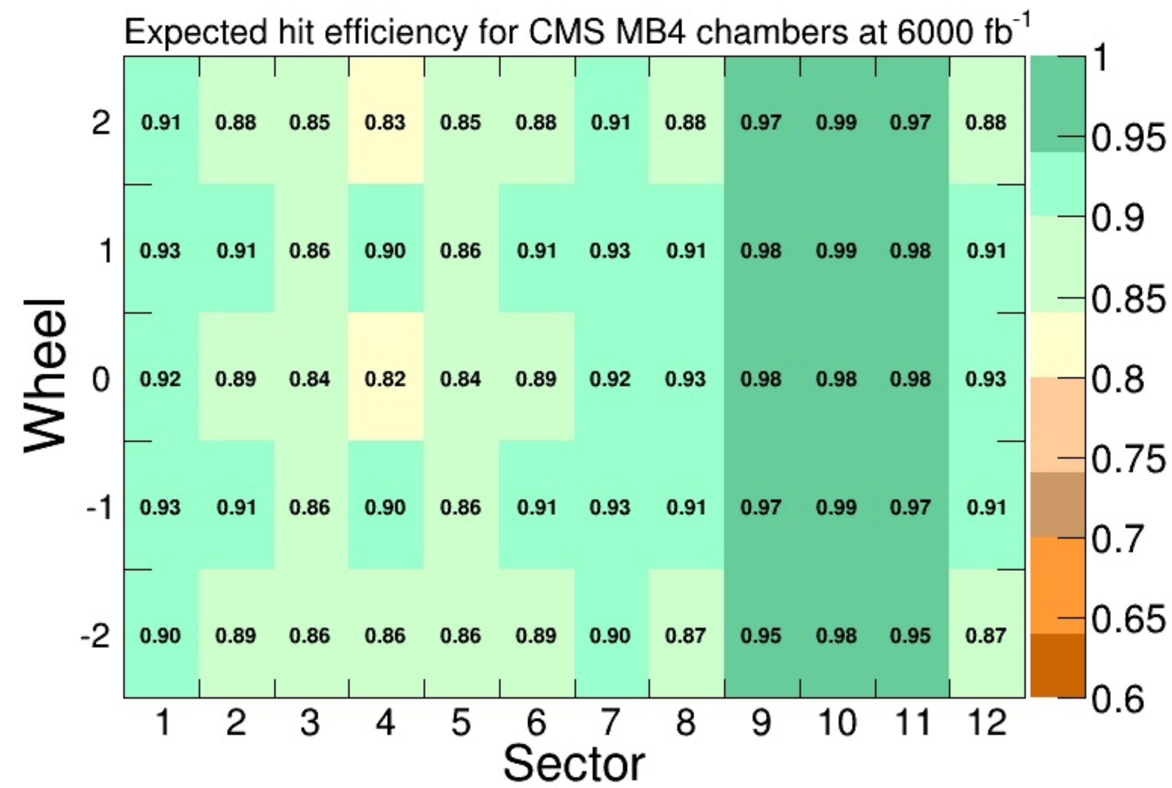


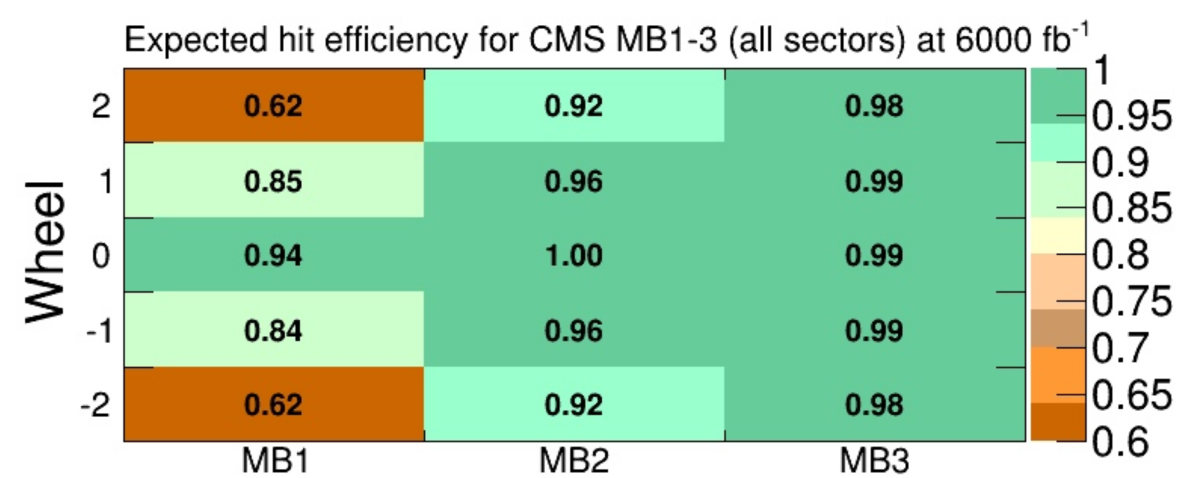


- Only 2 DT layers (SL1 L1/4) kept ON during irradiation campaigns
  - all other layers kept with HV in stand-by (1900 V) to be used as reference
- Efficiency computed as following:
  - offline segments reconstructed in SLs 2 and 3 propagated to layers of SL1 to identify cells where hits are expected
  - a cell is efficient if a hit is found where expected
  - triggers: for muon beam studies are provided by external scintillators, for cosmics non aged SLs are used
- Efficiency in muon beam studies, at approx HL-LHC int. / inst. lumi (3600 fb^{-1} - $5 \cdot 10^{34}$ cm^{-2}s^{-1}) around 75%

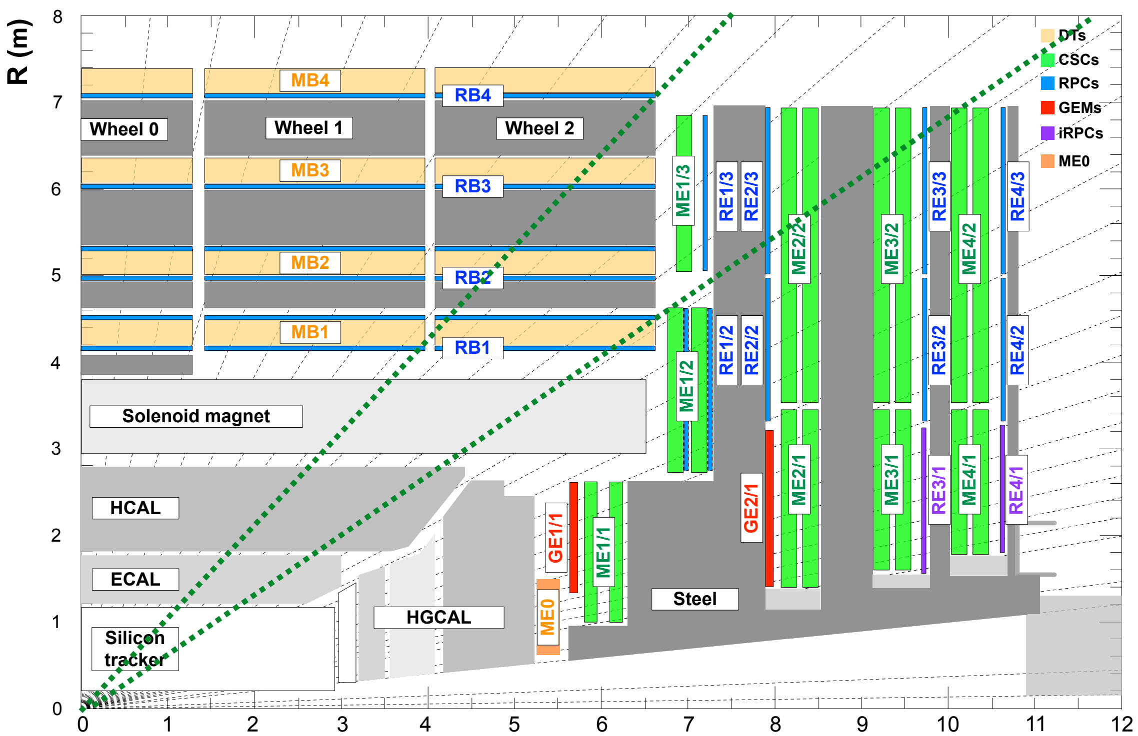
Towards the definition of ageing scenarios

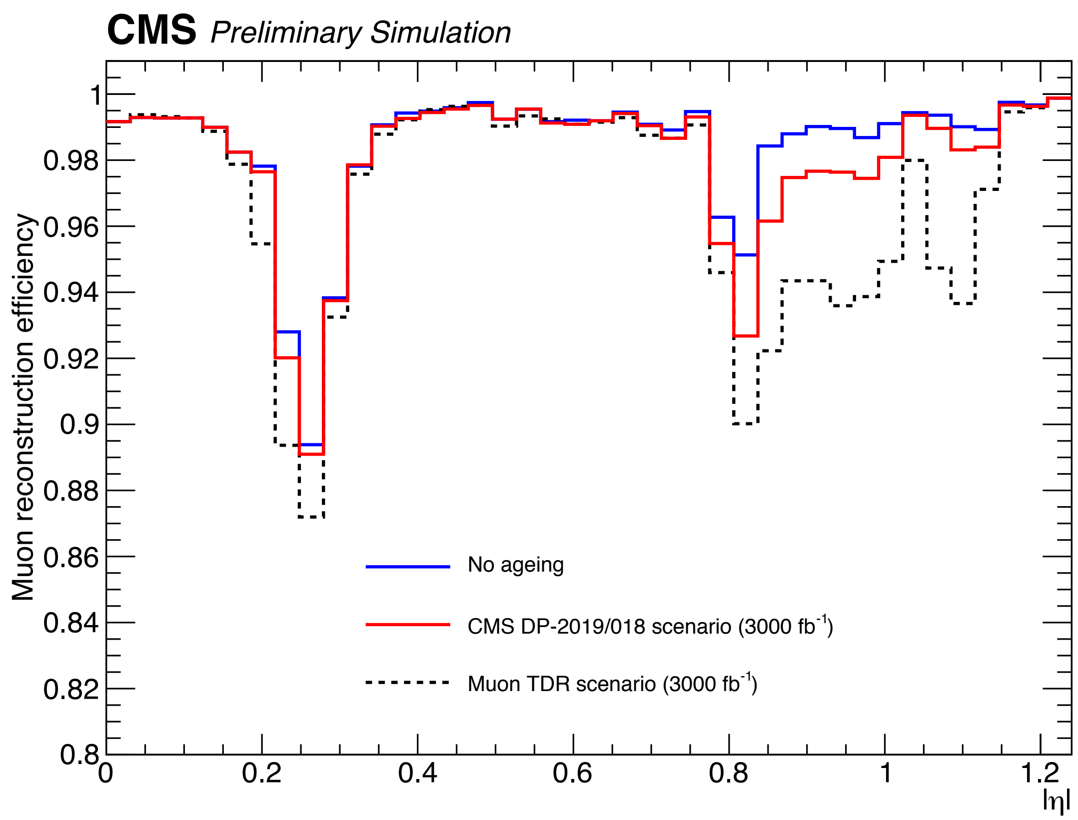
1. From parametrised dependence of efficiency w.r.t. inst. lumi (test beam data - prev. slide) **we get the expected efficiency @ $10 \cdot 10^{34}$ cm^{-2}s^{-1}** (at 3600 fb^{-1})
2. We have no test beam data to parametrise efficiency vs int. lumi, but we have measurements with cosmics → **we use cosmics to scale to an int. lumi of 6000 fb^{-1}**
3. All this **refers to the most irradiated chambers**, we **extrapolate to the test of the system based on the expected integrated charge in each camber**
4. We obtain **a "conservative" scenario** modelling ageing at **3000 fb^{-1} and $5 \cdot 10^{34}$ cm^{-2}s^{-1} with x2 safety factors both on integrated and instantaneous luminosities**
5. These data is further **injected in simulations** to asses the impact of ageing on CMS muon **reconstruction and trigger**





Offline muon reconstruction with ageing scenarios

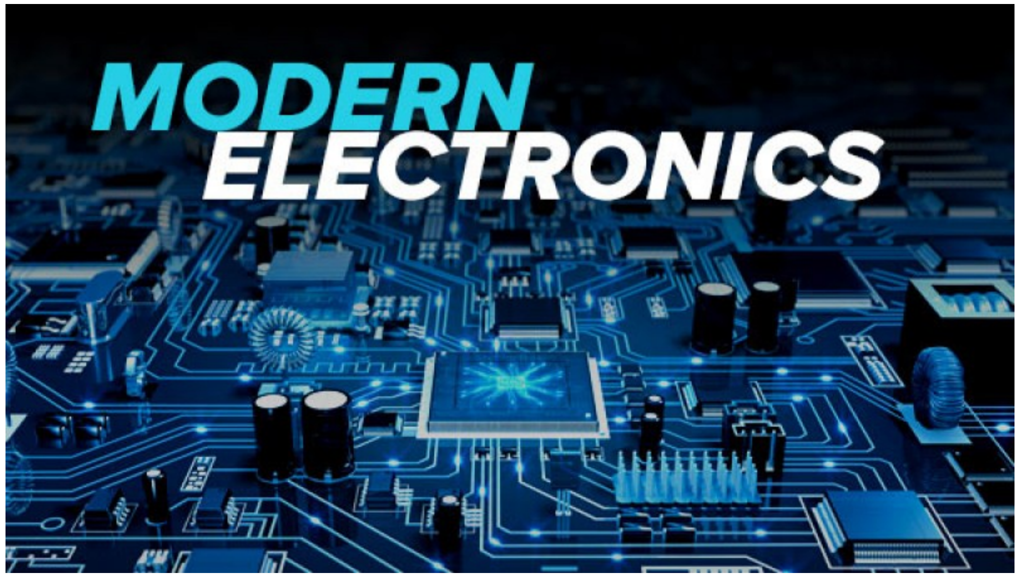




- **A DT chamber has multiple layers:** out of 8 r-φ layers, ≥ 3 are needed to build an offline segment
- **The muon system is redundant:** in the region of the DTs most affected by ageing, there is a coverage of 3 DT/CSC stations + 4-5 RPC layers along the trajectory of a prompt muon
- The single hit inefficiency of the YB+/-2 MB1s has hence "just" a marginal impact on overall standalone muon reconstruction efficiency

DT Phase-2 local trigger algorithms

what can we do @ HL-LHC with a more powerful electronics?



Paradigm and benefits of the DT electronics upgrade

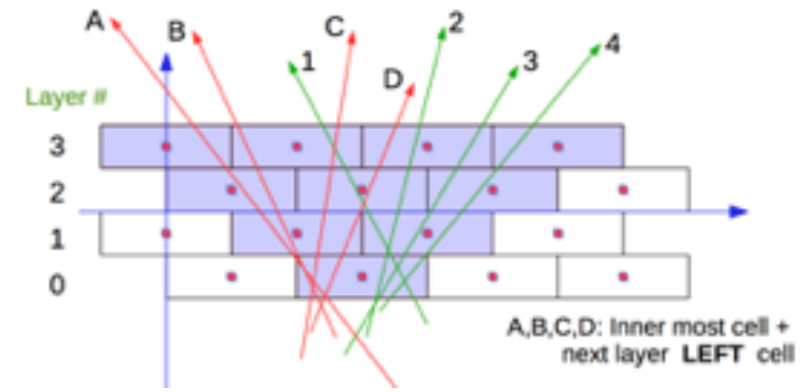
- At present, the burden of RO and trigger segment generation is (in part) on the on-detector electronics
- In the upgraded DT architecture:
  - TDC data is streamed directly to the new back-end electronics in the service cavern
  - event building / trigger segment generation to happen there, using status-of-art commercial FPGAs
- This brings few advantages:
  1. on-board electronics energy consumption is reduced → cooling requirements are lowered
  2. electronics building trigger segments accessible in service cavern also when the detector is closed / operating
  3. can reconstruct trigger segments exploiting ultimate DT time resolution (*few ns* w.r.t. 12.5 *ns* for present electronics)
- Two different algorithmic approaches to reconstruct trigger segments are being investigated
  d. one relies the mean-timer property (BX-ID) and does fitting using exact formulas (least squares) **[Analytical-method - AM]**
  e. the other is based on Majority Mean-Timer (BX-ID) and Compact Hugh Transform (track building) methods **[MMT-CHT]**
- Both:
  - assume straight line tracks within a chamber
  - require at least a triplet of fired layers within a SL to build a trigger segment

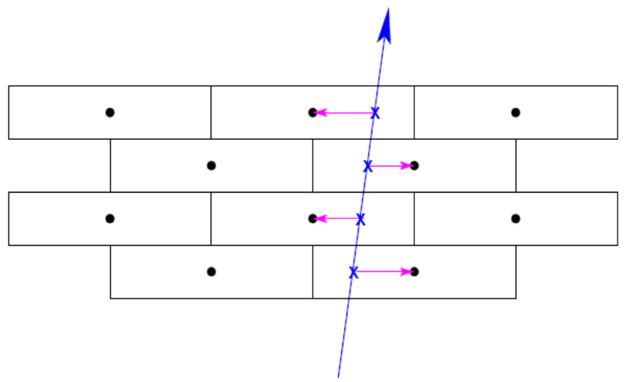
Analytical method algorithm brief description

- **Grouping:** select patterns of 3 or 4 DT fired cells compatible with a straight line in a single SL and their sub-patterns of 3 over 10 cells at a time in order to reduce combinatorics (all patterns / laterality combinations considered).

- **Fitting:** from group of cells is identified, compute unambiguously the BX using the mean-timer property, for 4 hits group, the BX is the mean of the BX of all triplets. Then track parameters are computed using exact formulas from χ^2 minimisation.

- **Correlation:** attempt a combination of geometrically compatible tracks from single SLs in a window of $\pm$ 25 *ns* using the 2 r-φ SLs. If successful single SL track parameters are re-computed (and improved profiting of the ~20 *cm* level arm between r-φ SLs).





mean-timer property:

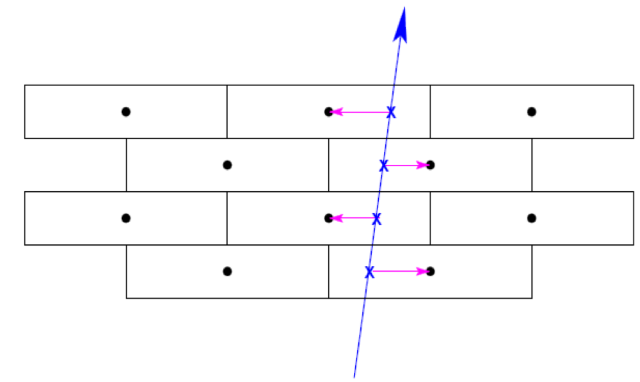
$t_{HALF\_CELL} = (t_1 + t_3)/2 + t_2$

For a valid 4-hits group

$$\begin{cases} X_{chamber} = \dfrac{x_3+x_2+x_1+x_0}{4} \\ \tan(\varphi) = \dfrac{3\cdot x_3+x_2-x_1-3\cdot x_0}{10\cdot h} \\ \chi^2 = \sum_{i=0}^{3}(x_i-\tan(\varphi)\cdot y_{wire_i}-b) \\ b = \dfrac{1}{4}\sum_{i=0}^{3} x_i \end{cases}$$

MTT-CHT algorithm description

- **Majority Mean-Timer:** meaningful triplets in a set of pre-clustered channels (*macrocell*) used to compute BX using the mean-timer technique. Within a macrocell consider BX estimation from all triplets / quadruplets and select most voted one as candidate BX.
- **Compact Hough Transform:** all pair permutation of TDC counts from the 2 r-φ SLs identified at the previous step are used to compute (for all lateralities) track slope hypotheses. 3 histos: 2 with pairs from each r-φ SL,1 with pairs from both SLs are filled with such hypotheses. A discrimination threshold is applied, after that, the most voted hypothesis is used to define the trigger segment slope.
- **Intercept estimation:** additional histograms in SL1 and SL3 are used to find track intercept, on the basis of the already computed candidate track slope and crossing time.



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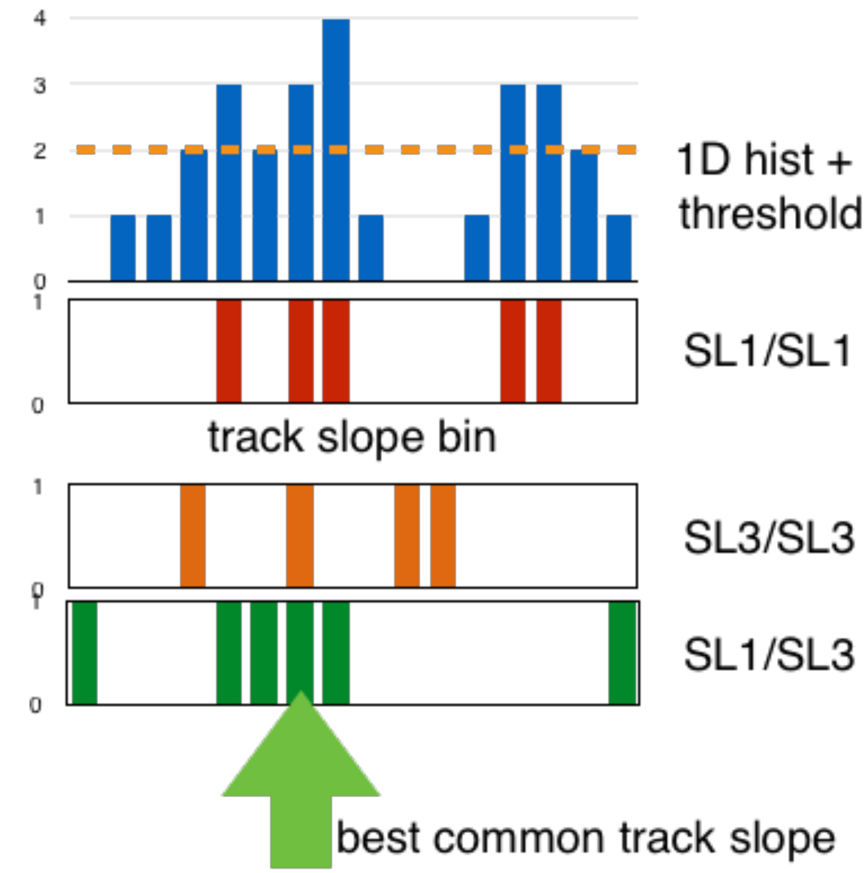
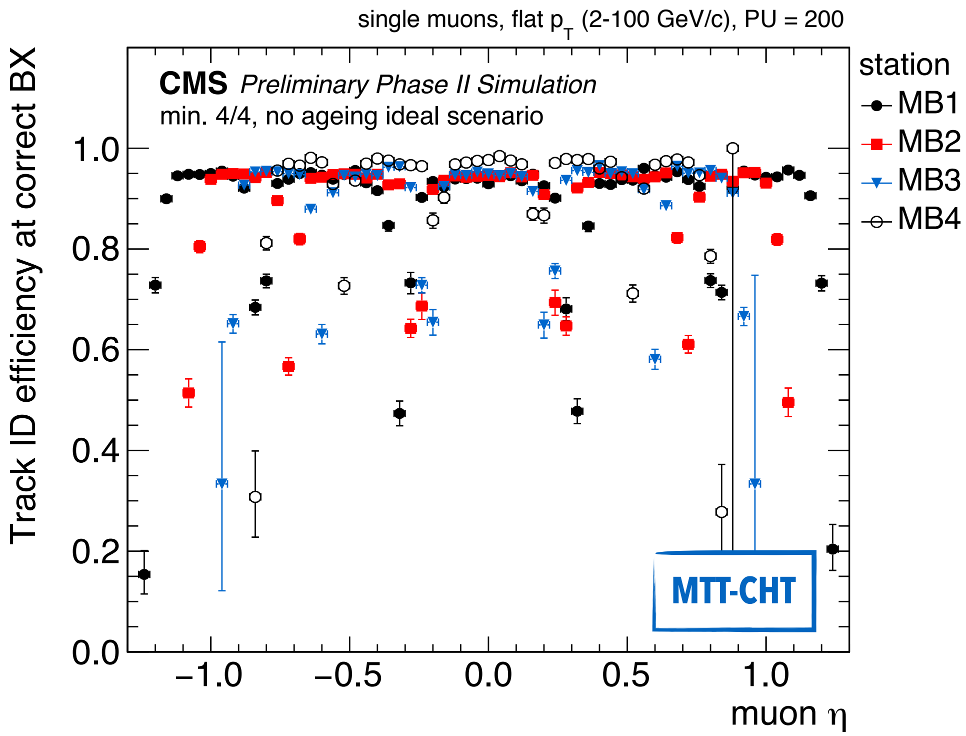
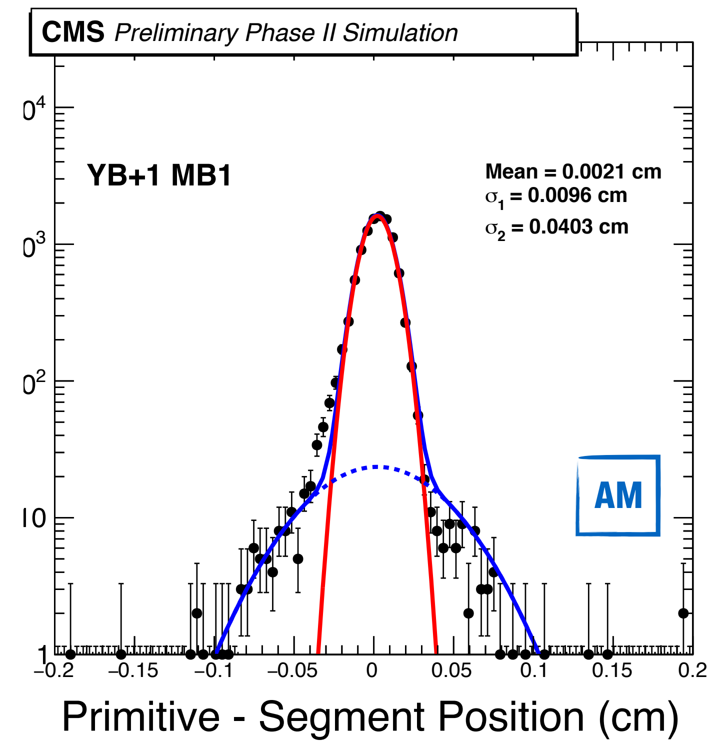
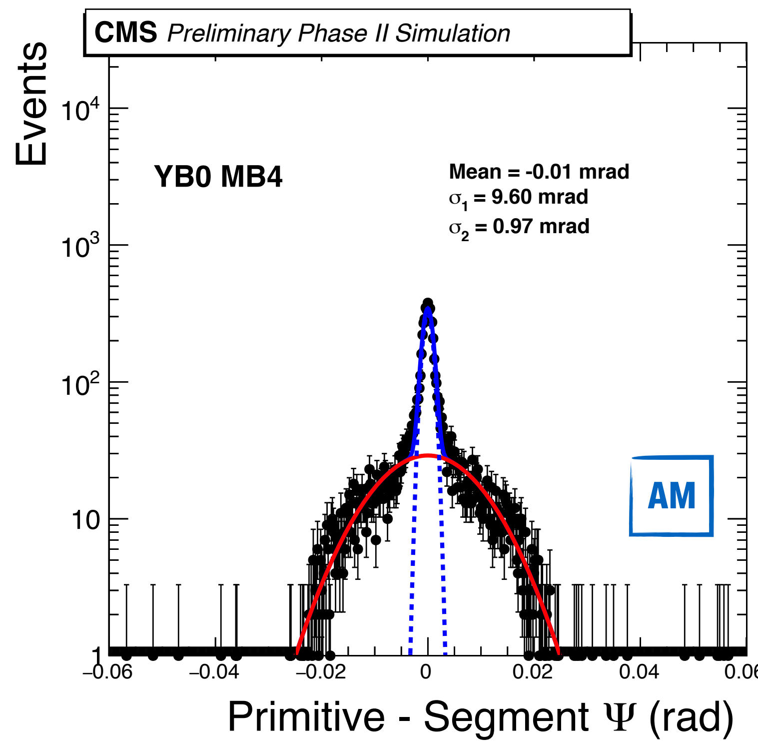


Phase-2 DT local trigger performance

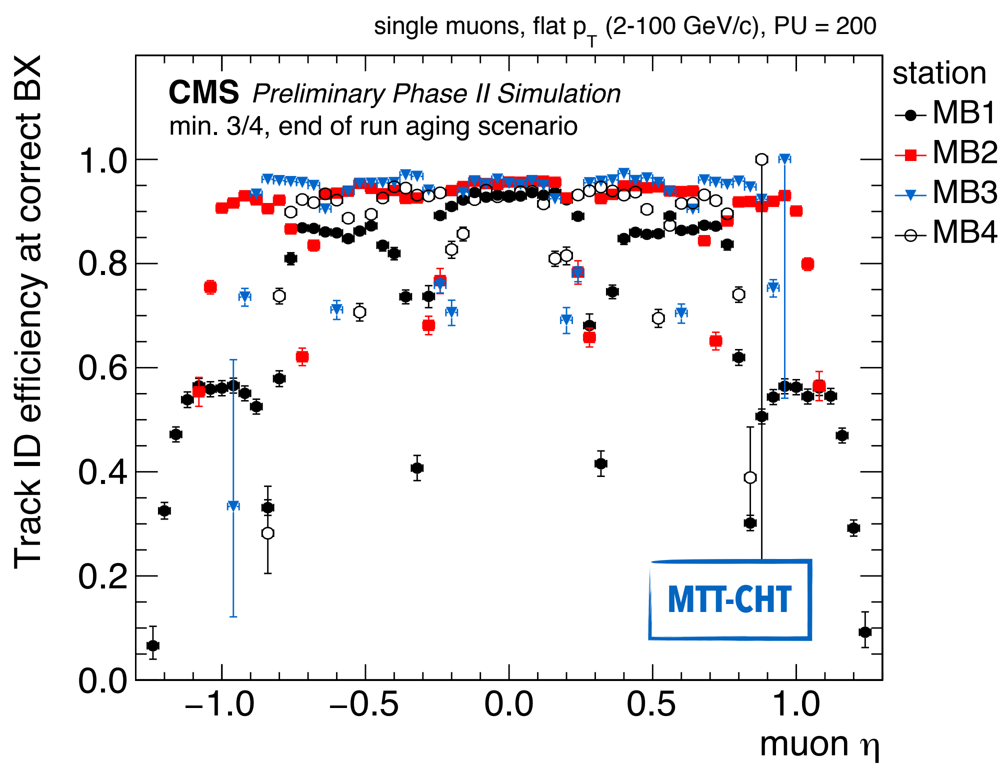


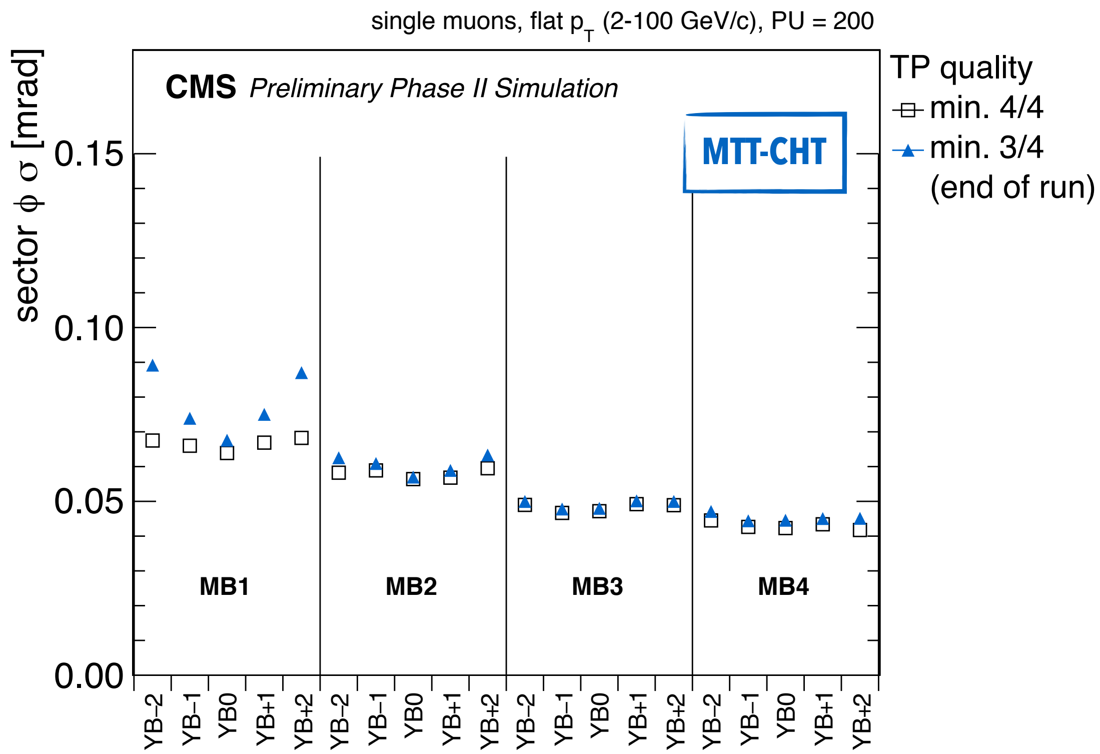




- Performance of AM and MTT-CHT algorithms measured with simulations and Run-2 data
  - assessed with respect to both, simulated information (when available) and offline reconstruction
  - studied in simulated samples up to stress-test scenarios with 300 <pile-up> collisions per BX
- Results are overall very good
  - as efficient as present system: 95% (when similar permutations of hits are considered to build trigger segments)
  - spatial resolution (pos. / dir.) improves according to scaling in single hit time resolution (12.5 *ns* → ~ few *ns*)
- Also add new features: e.g. sub-BX timing, fundamental for some exotic particles triggers as HSCP

Performance with "conservative" ageing scenario



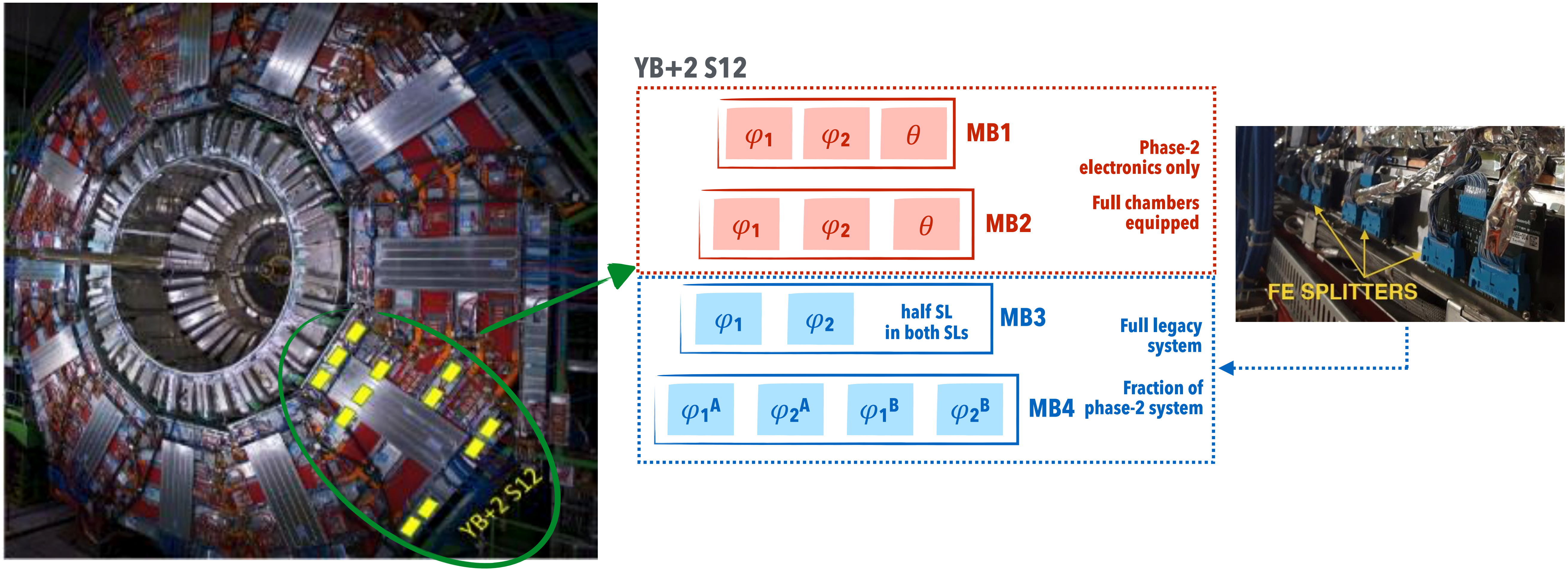


- Studies being performed also using "conservative" ageing scenario
  (3000 1 fb^{-1} and $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$ with x 2 safety margin on both quantities)
- Performance remains very good in most of the system, sizeable degradation only in YB+/-2 MB1s
  - ~55% efficiency w.r.t. simulated hits for "most inclusive" trigger configuration
  - position resolution also degrades, but keeps being better than in present system
- Impact on final L1T objects being evaluated **(as part of a Level-1 Trigger upgrade TDR, in preparation)**
  - **mind muon system redundancy:** the impact of the lowered performance in YB+/-2 MB1s is expected to be mitigated by the presence of multiple detector laters along the muon trajectory

The DT slice test

building tomorrow's system already today

The DT Slice Test in a nutshell

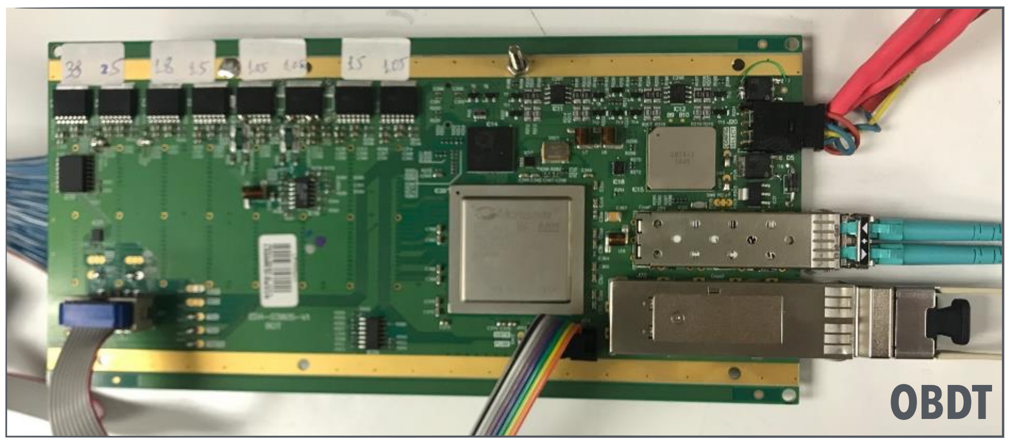


- One DT sector instrumented with prototypes of phase-2 electronics
- Different goals for different stations:
  - **MB1/MB2:** perform integration as close as possible to final system → assess replacement routine in view of LS3
  - **MB3/MB4:** run legacy and phase-2 chains in parallel → validate phase-2 data quality using legacy information
- Being integrated in steps, operated on regular basis (cosmics / calibration runs) since summer 2019

DT Slice Test HW components and layout

Not being exhaustive, more details in Dmitry Eliseev's talk

OBDT: prototype board performing <1 *ns* time digitization in FPGA of chamber signals. Core of the new on-detector electronics.



(Virtex 7 XLXXC7VX330T-3FFG1761E)

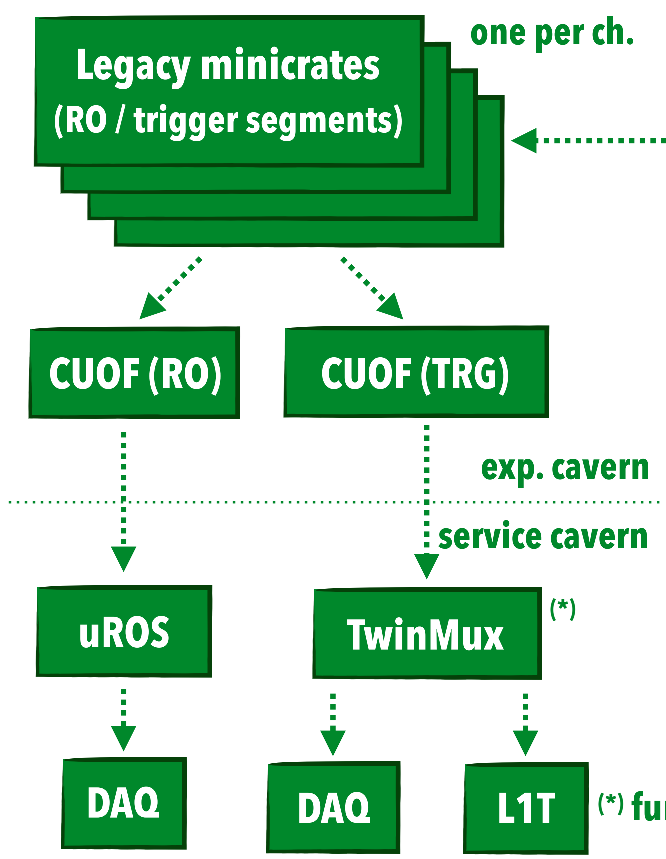
Selection of final back-end boards ongoing (most of the ones used for L1T upgrade could work).

Presently using phase-1 board (TM7) also for phase-2, for two purposes: slow control (**MOCO**) and trigger segment generation (**AM algorithm**) / event building (**AB7**)

AB7 functionalities:

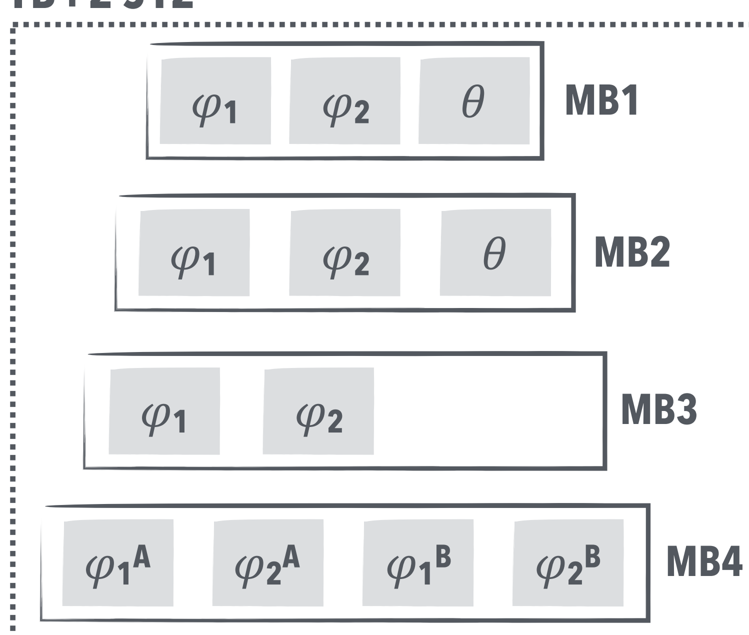
- process data from up to 3 OBDTs
- generates trigger primitives
- performs event matching and

Legacy RO/trigger chain

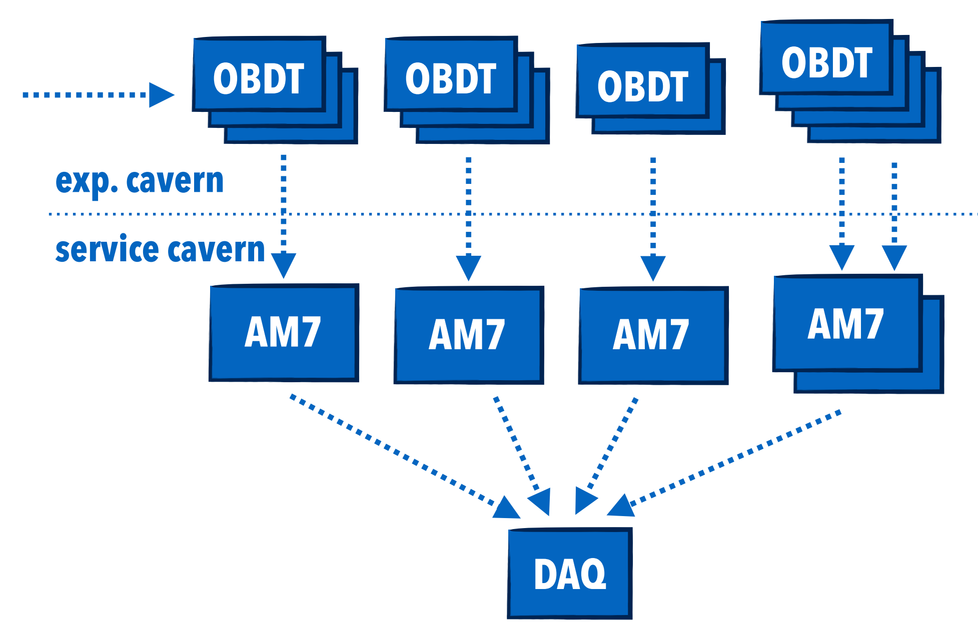


(*) further trigger segment processing

YB+2 S12

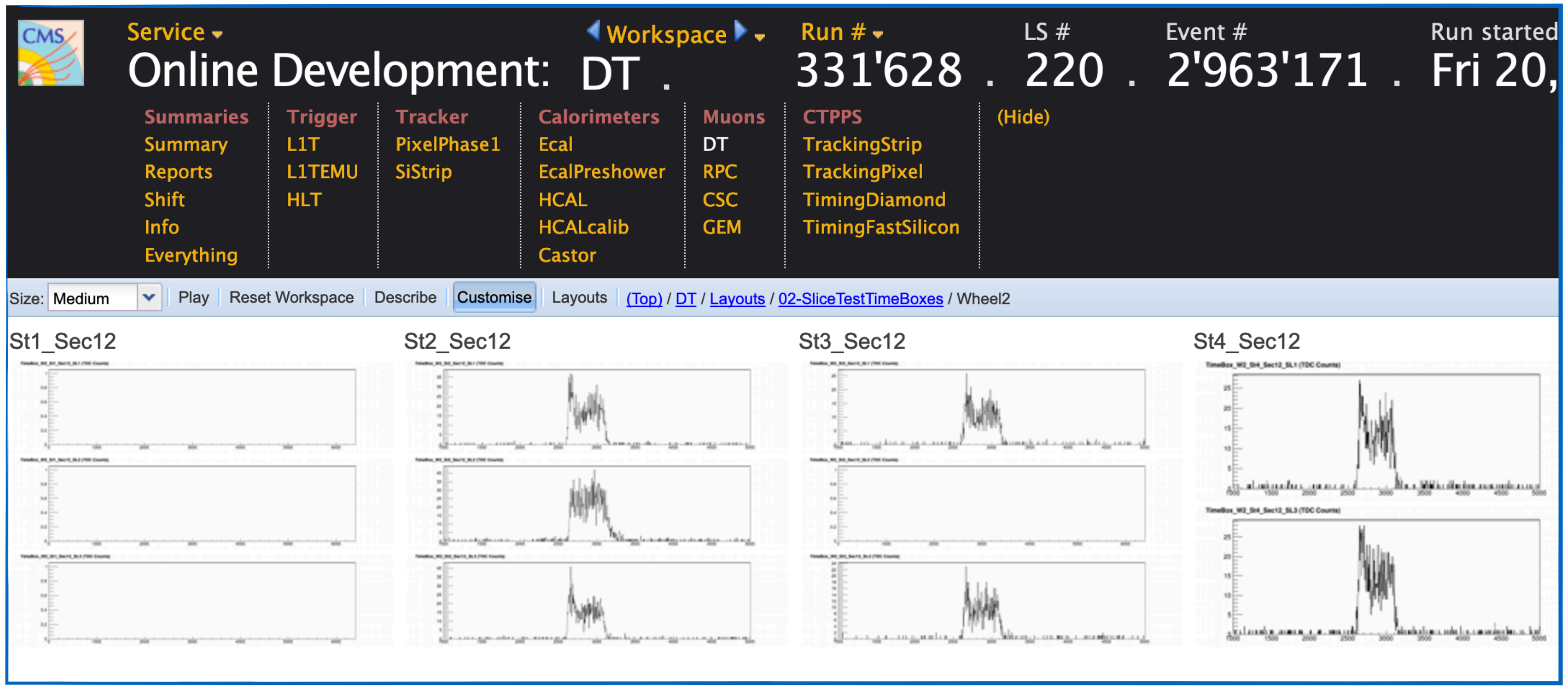


Slice Test RO/trigger chain

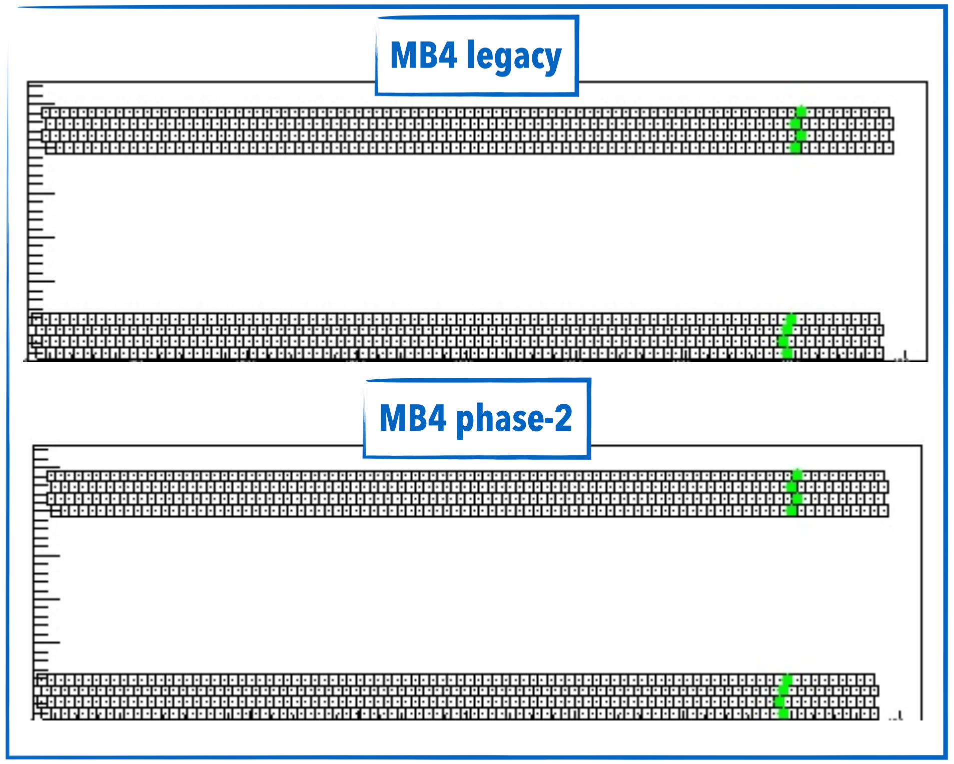


DT Slice Test software and analysis: low latency feedback tools

Slice Test TDC hits Monitoring in DT Online DQM

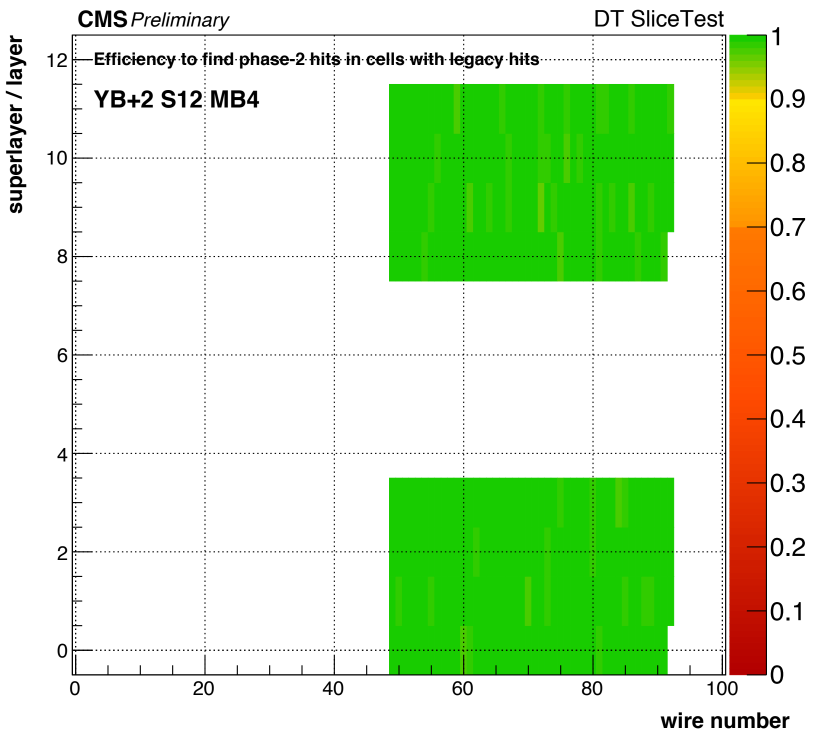


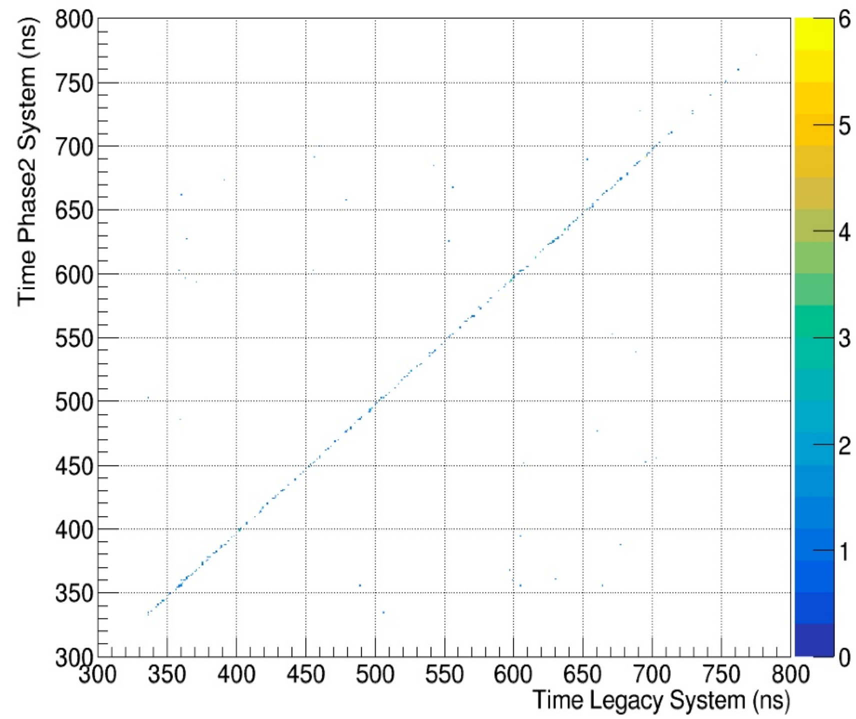
Event display comparing phase-2 and legacy RO chains

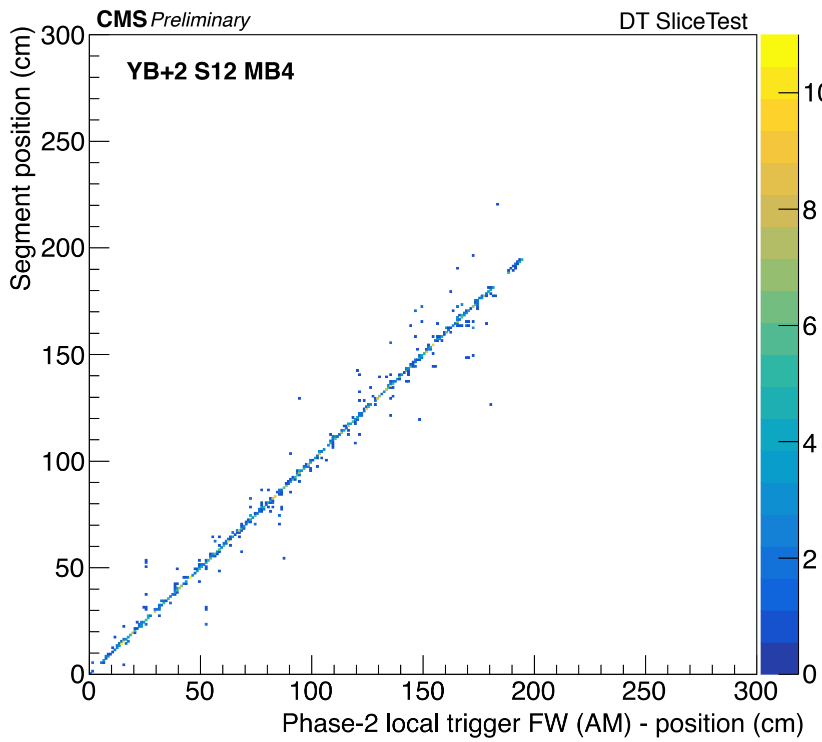


- Fundamental to provide tools to asses basic data quality *in real time*
  - SliceTest DT TDC hits monitoring (occupancy/TDC time) part of DT Online DQM since the beginning of operation
  - Here showing status of slice test integration at a glance, as of Sep. 20 phase-2 electronics for MB2/3/4 has been integrated
- Also important to provide rather early programs for basic offline checks
  - E.g. event display can be used to validate consistency of mapping of cells between phase-2 and phase-1 RO chains

DT Slice Test software and analysis: highlights on commissioning and present performance







- Offline analysis and software development progressing, at present in many fronts:
  - **TDC hits performance:**
    - validate correspondence (TDC hits presence and time) of phase-2 and legacy information
  - **calibration/reconstruction:**
    - develop phase-2 calibration workflows, allow reconstruction to run with 2 calibration sets
  - **local trigger:**
    - use offline segment reconstruction and legacy triggers as metrics for comparison
    - use trigger emulators to validate firmware
    - measure: efficiency, spatial resolution (position, direction) and BX-ID capability
- An activity in full swing, with many fresh results, but even more milestones yet to be achieved!

Summary

- Over Run-2 CMS Drift Tubes performed remarkably well as trigger and tracking detectors
- For HL-LHC an upgrade of the DT system electronics is foreseen, but chambers won't be replaced
- Studies have been performed to measure the DT chamber performance in accelerated longevity studies carried out at the GIF++ facility
  - a sizeable decrease in hit efficiency (@ 3000 fb^{-1} and 5·1034 cm^{-2}s^{-1} with x 2 safety margin on both) is observed only for a subset of chambers (10% of the total) which are the ones most exposed to background
- The replacement of the DT electronics will bring critical components of the system into the service cavern, making them more easily accessible
- Moreover, in the new layout, it will be possible to exploit the ultimate chamber resolution (few *ns*) in L1 trigger, improving the performance of DT trigger segments and adding new features (e.g. sub-BX timing)
- Prototypes of the phase-2 DT electronics are being integrated on-site in CMS and are being commissioned with cosmic rays

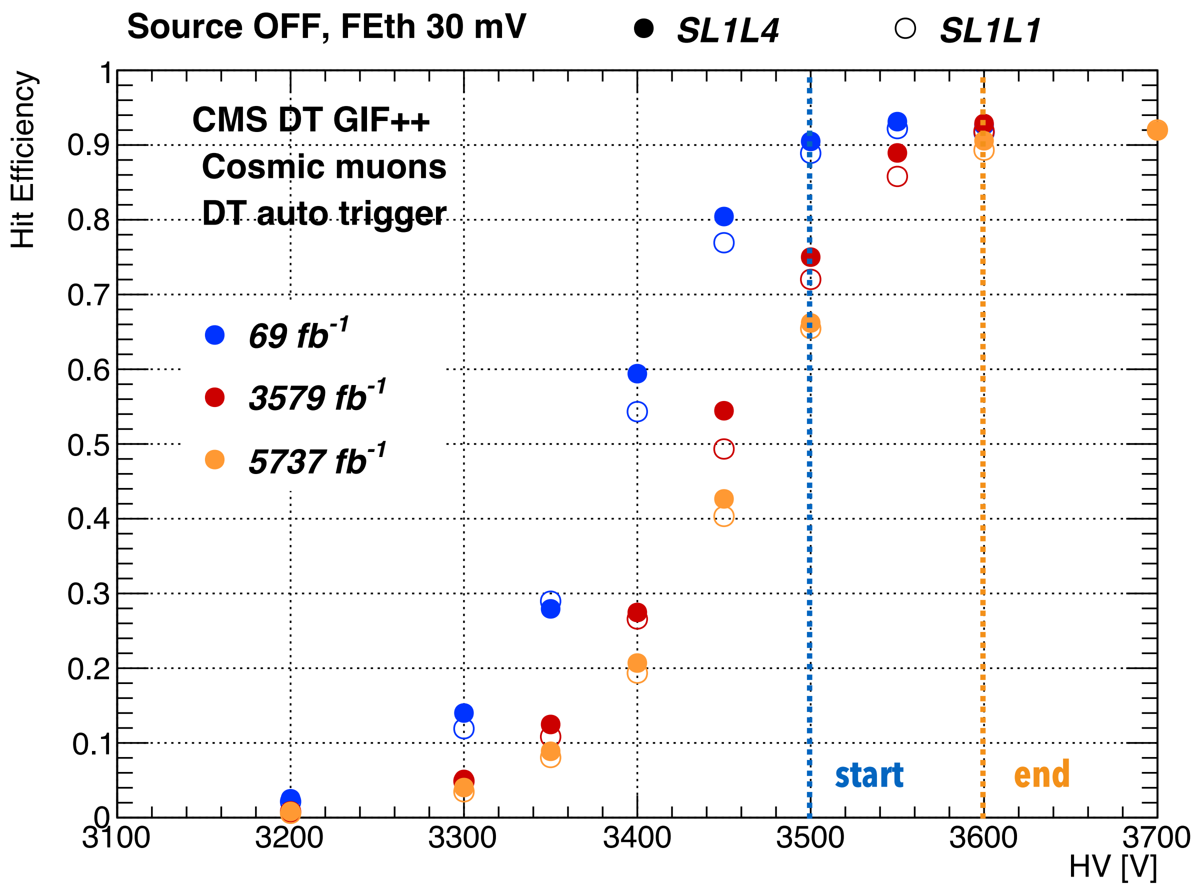
The effort to preserve the crucial role of the DT system in CMS @ HL-LHC is ongoing, many valuable people are contributing to it, exciting times are ahead of us!

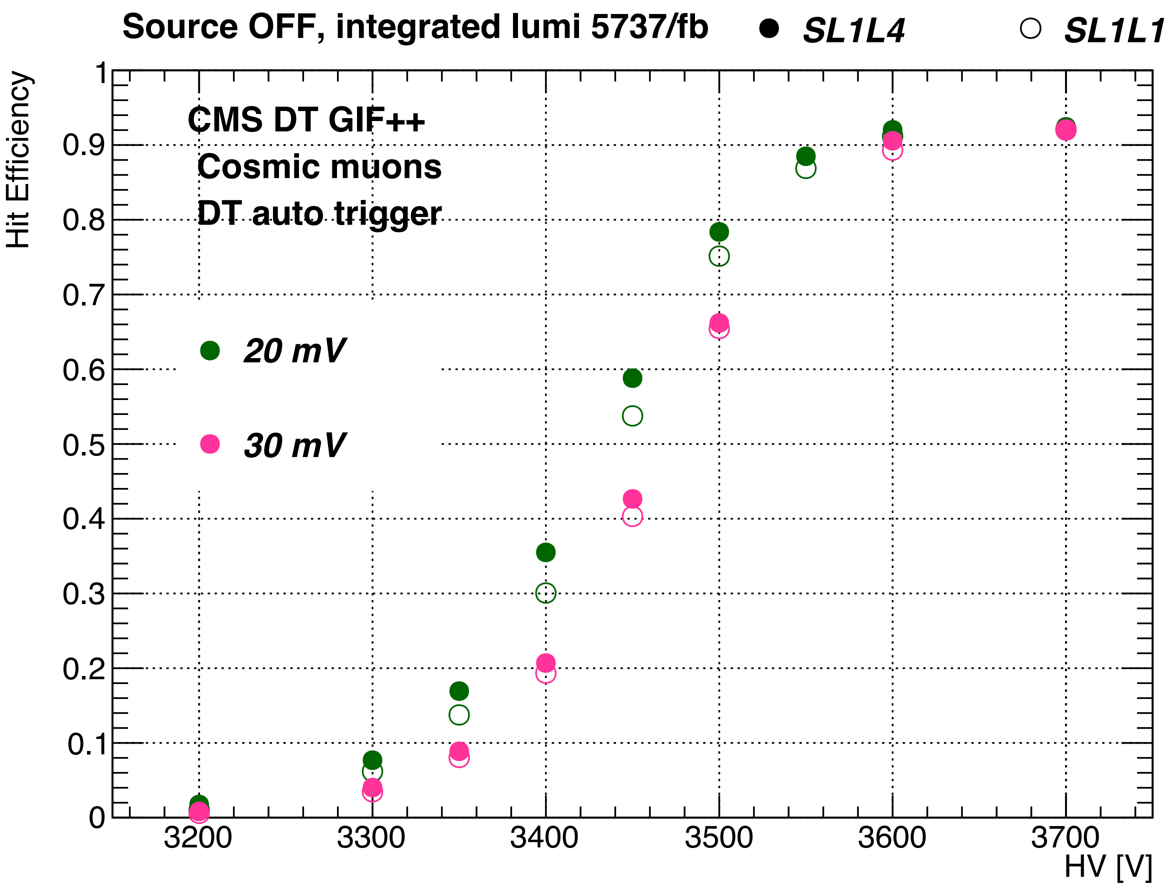
Thank you for your attention!

Questions?

Backup

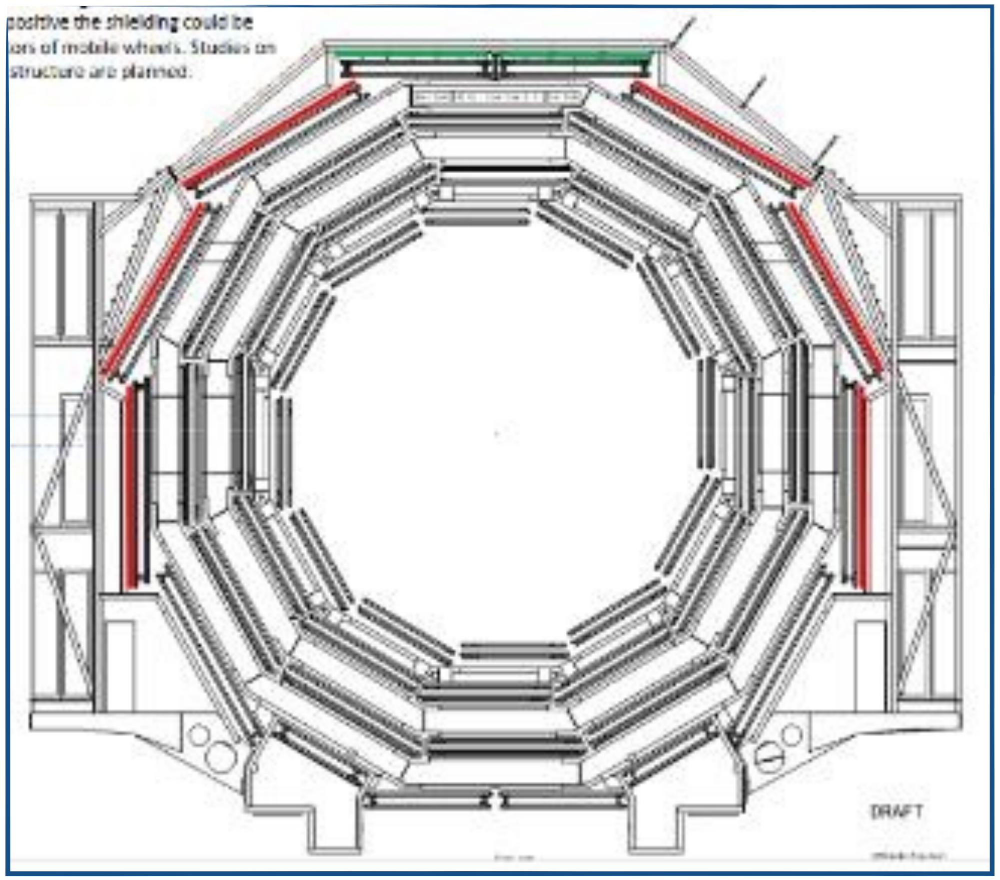
Strategies to mitigate detector ageing (1)





- Detector operational conditions can be managed dynamically
  - along Run-2 the HV of the chambers more affected to ageing was lowered to maximise longevity
  - to mitigate small inefficiencies due to HV lowering the front-end discrimination thresholds were lowered accordingly
  - as/if sign of ageing appear, can revert back to higher HV to maintain high efficiency

Strategies to mitigate detector ageing (2)



- The most significant source of background affecting external chambers (MB4) comes from radiation being scattered from the cavern walls and activated material in the cavers
  - therefore shields (7 *mm* lead + 30 - 90 *mm* borated polyethylene) are being installed on the TOP sectors of the CMS muon barrel to protect such chambers
- Over Run-2, DT chambers started being operated flushing fully with fresh gas instead of recycling 75% of it
  - this avoids that potential material from outgassing keeps circulating within the detector and form coating on DT wires

Irradiation data taking campaigns and definition of reference luminosity values (2)

- Here focusing on two specific irradiation campaigns on a DT station 2 chamber (MB2)
  - longest and most systematic ones, covering an int. luminosity up to 2 x HL-LHC
  - include measurements with muon beams (twice) and cosmic rays
  - more details and studies (e.g. performed @ different rates on other chambers or on simple detector mock-ups) discussed here
- Dose (integrated/rate) converted to luminosity (int./inst.) comparing wire currents @ GIF++ and in CMS
  - GIF++ dose measurement from one REMUS dosimeter → several measurements made in front of MB2 to extrapolate REMUS to DT
    - dose rate → inst. luminosity conversion calculated at HL-LHC background rate: 1 fb^{-1}/s = 0.304 mGy/s
    - int. dose → int. luminosity calculated at GIF++ ageing rate (~10 x HL-LHC): 1 fb^{-1}= 0.42 mGy
  - quoted (int./inst.) luminosities corresponds to the dose (integrated/rate) expected for the most exposed DT chambers