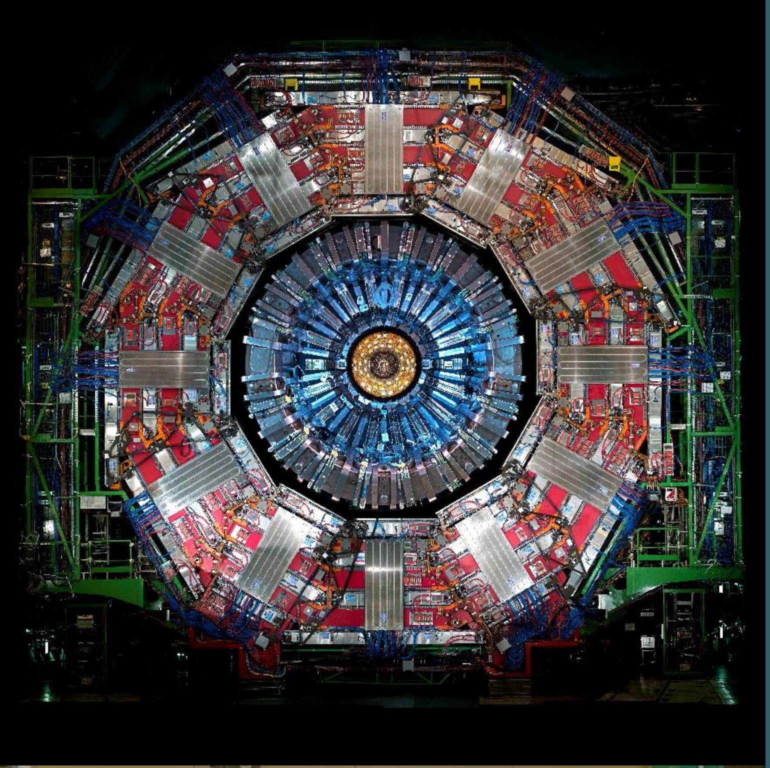

Longevity studies for the CMS Drift Tubes towards HL-LHC

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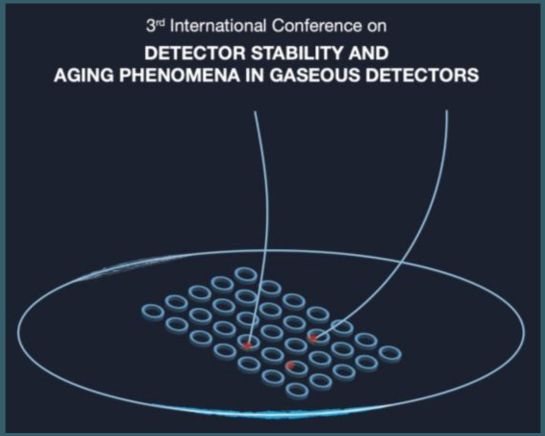
on behalf of the CMS Muon Group

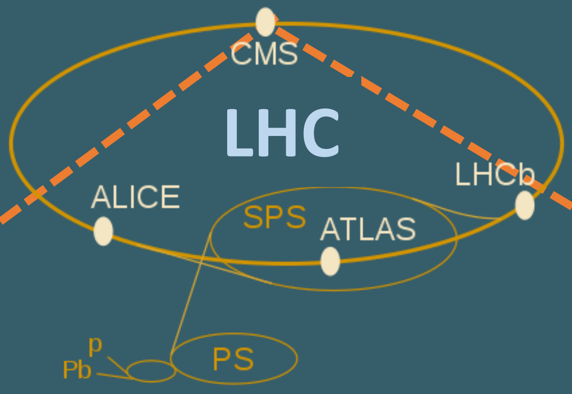
3rd International Conference on Detector Stability and Aging Phenomena in Gaseous Detectors

2023 – CERN

November 7th, 2023

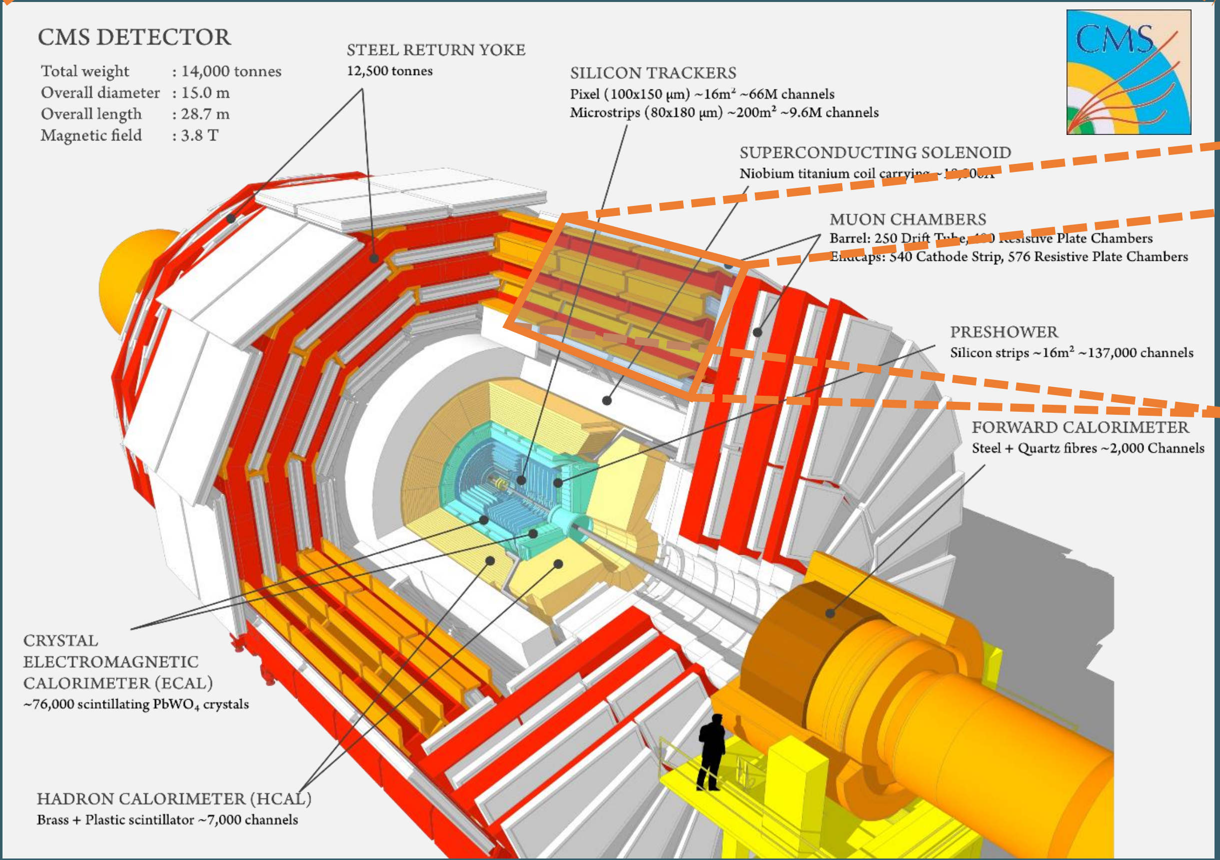


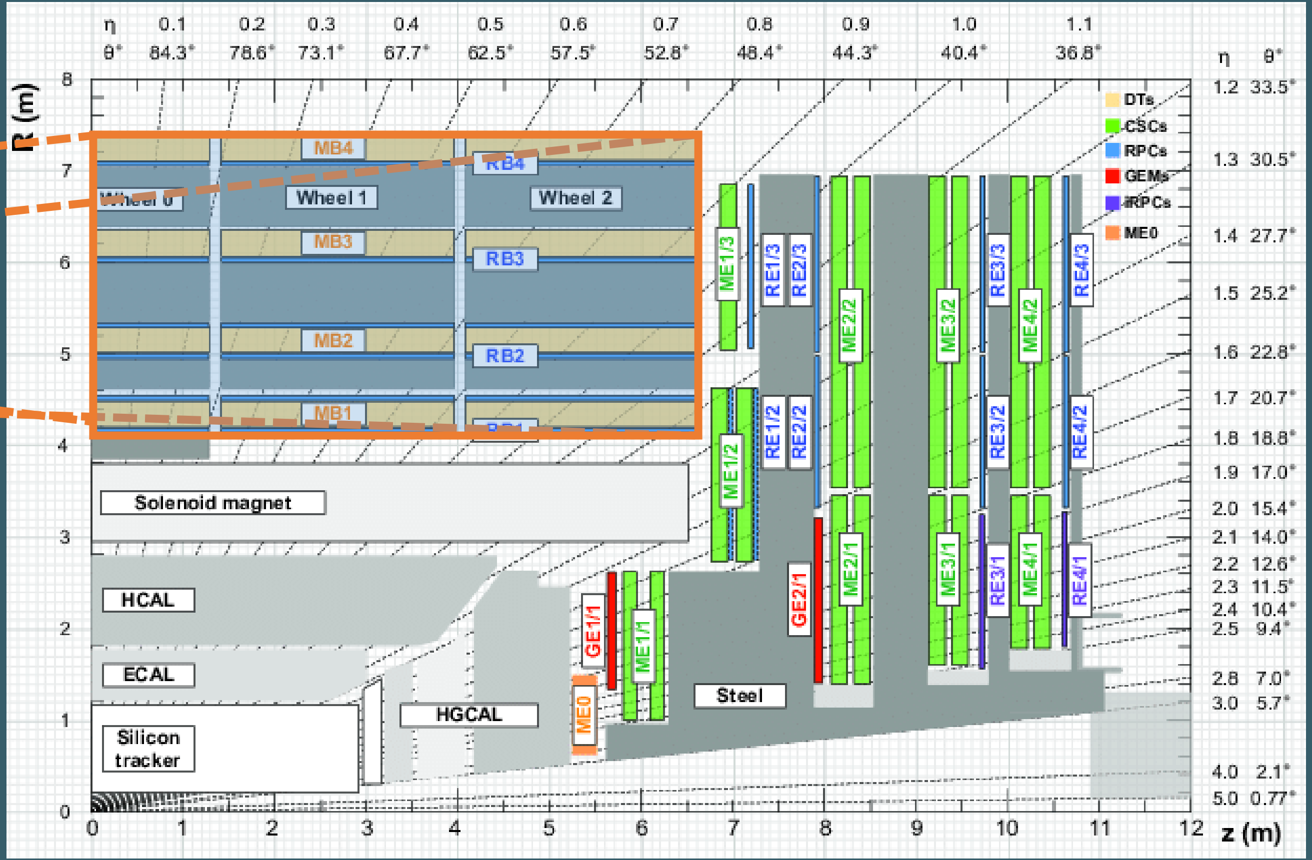
250 Muon DT Chambers @ CMS @ LHC



Located In the barrel region:

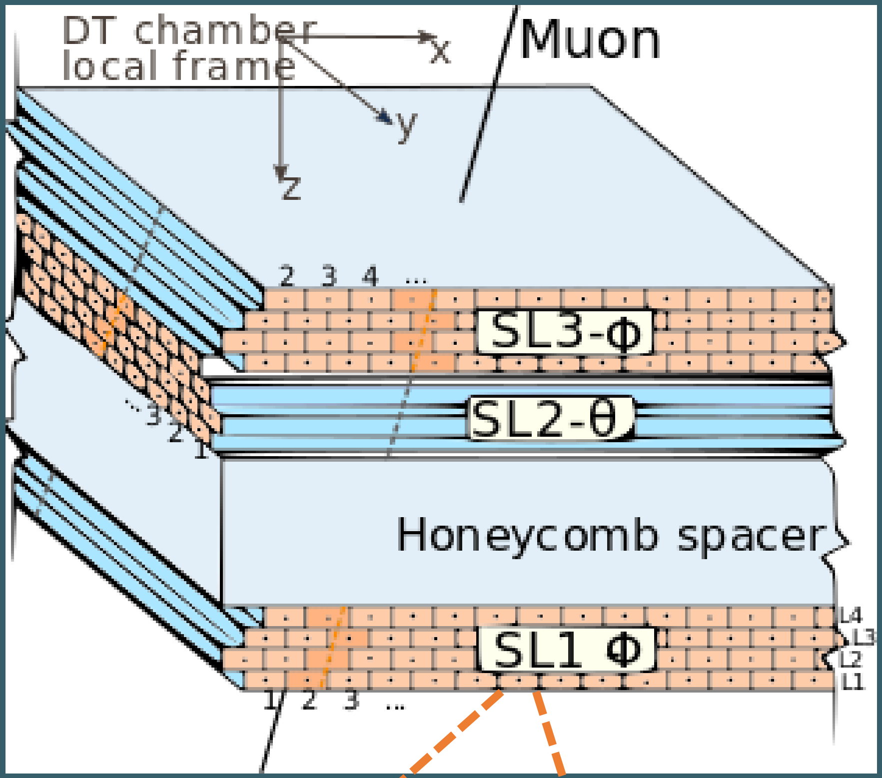
- 5 wheels: YB-2, YB-1, YB0, YB+1, YB+2
- 12 sectors: S1-S12
- 4 stations: MB1 (in), MB2, MB3, MB4 (out)

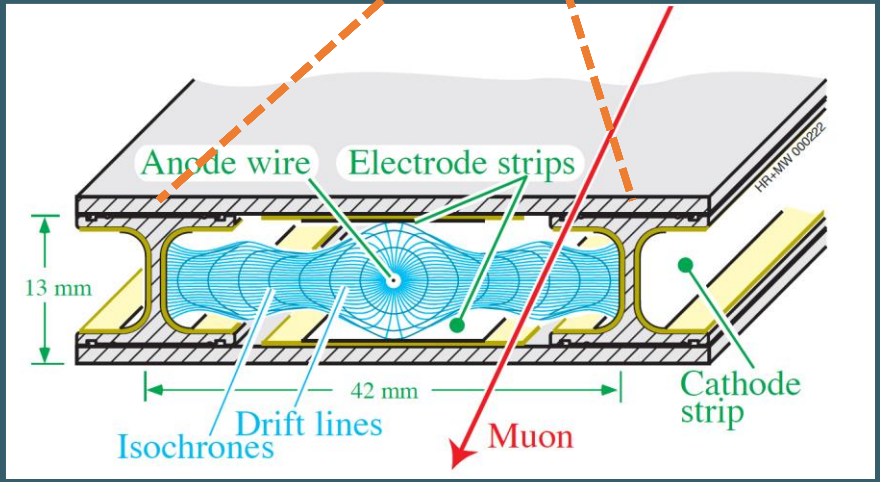




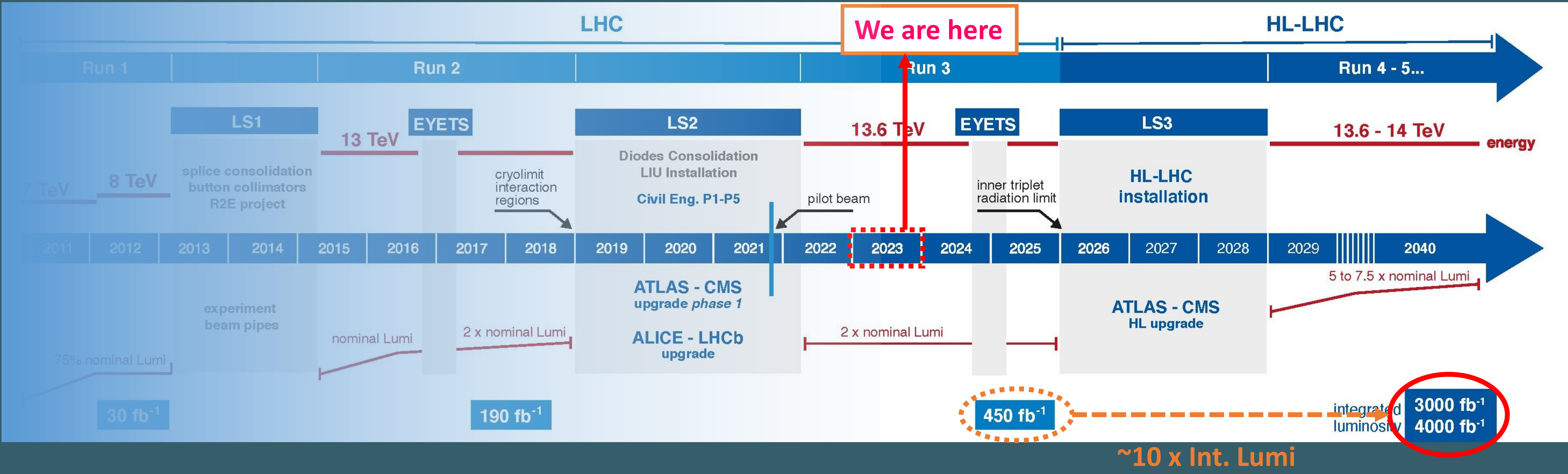
Drift Tubes @CMS

- A Drift Tube chamber (DT) is a 2m x 2.5m to 4m x 2.5m **gas detector** designed to measure with great precision the **position of muons** from the LHC collisions
- The basic detector element is a rectangular **drift cell**, filled with an Ar/CO_2 (85/15%) gas mixture, and a gold plated steel wire (50 microns) anode
- Particles passing through ionize the gas and the resulting electrons will drift towards the anode at approximately constant speed and generate an avalanche that results in an electric signal that can be processed by the electronics of the detector
- Timing information is related to position → 250 µm position resolution
- Some operational parameters:
  - **Anode HV**: 3600 V (nominal) → 3500-3500 V (now)
  - **Frontend Threshold** : 30 mV (nominal) – 20 mV (now)





Timeline towards HL-LHC

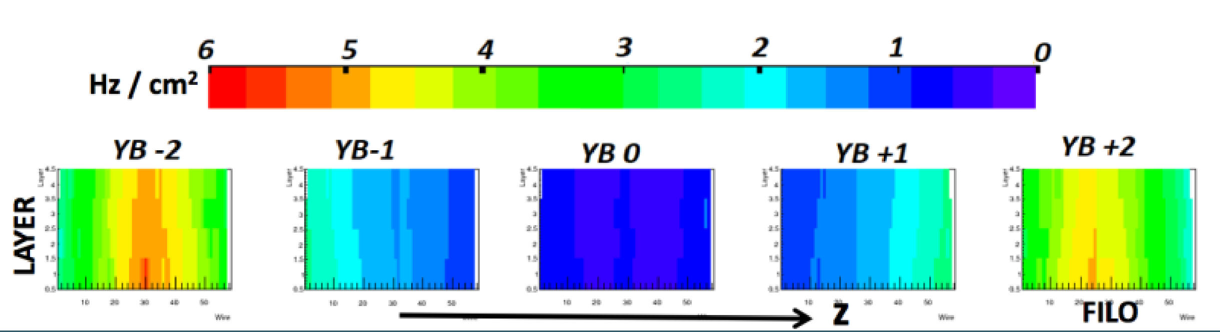


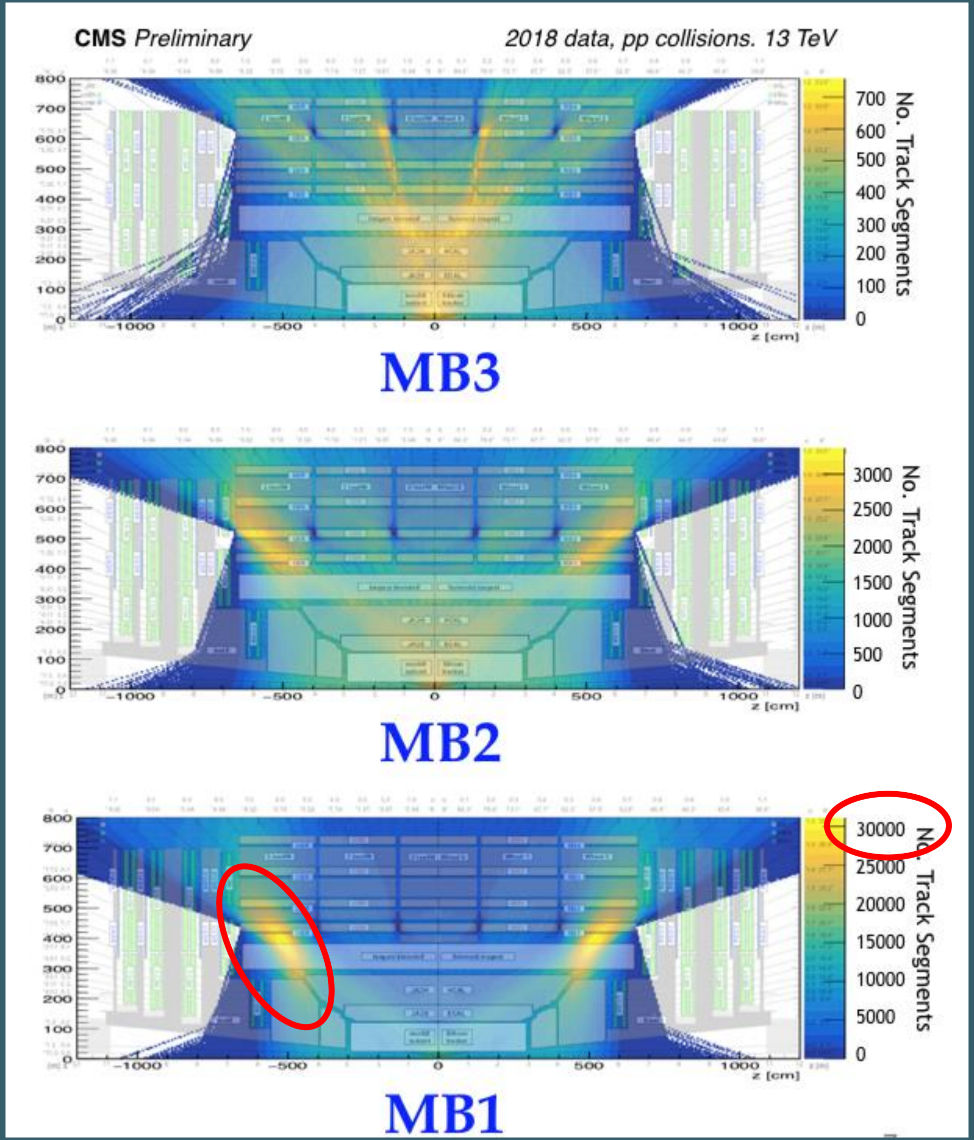
Can we withstand the expected accumulated charge?

5 × increase in instantaneous luminosity
10 × increase in integrated luminosity

Background distribution in the DTs

- Inhomogeneous background rate distribution
- **Most exposed** DT chambers located at high pseudorapidity, in the innermost part of the muon system
  → **MB1 YB±2**



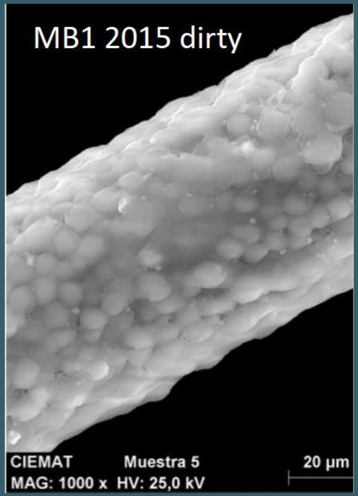


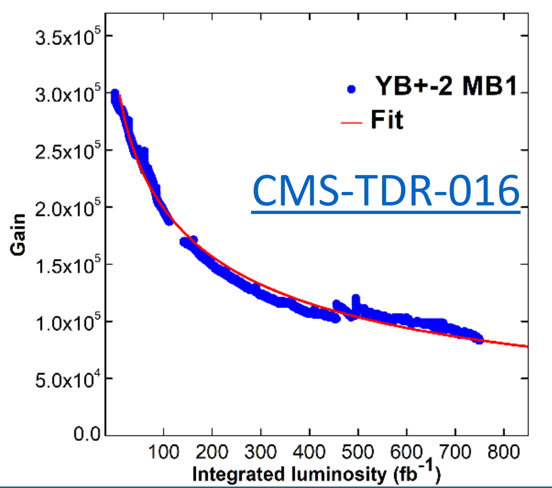
Background segments reconstructed in the MB1, MB2 & MB3 stations and propagated in the r-Z plane minimum bias events collected by CMS

A bit of history…

[2015 – 2016] Irradiation of a spare (MB1) chamber at high rate (× 100 HL-LHC):

- Results at *CMS TDR: The Phase-2 Upgrade Muon Detectors*
- First hints that exposure to radiation change the detector performance
- Fast gain drop observed. Direct investigation of irradiated wires in Legnaro and CIEMAT showed a Si an C coating with large resistivity
- Wire aging, main contribution of the hit efficiency loss: **acceptable** due to system redundancy



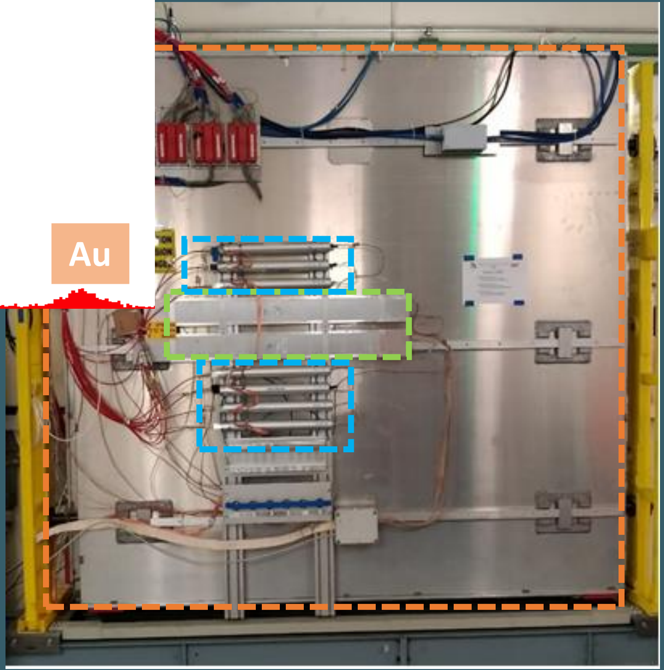


[2016 – 2019] Proportional counters (*simple detector mock-ups*): Bicells and Monotubes

- Installed at CMS Detector and GIF++: Allows for simple comparisons
- Well suited to investigate the poisoning material

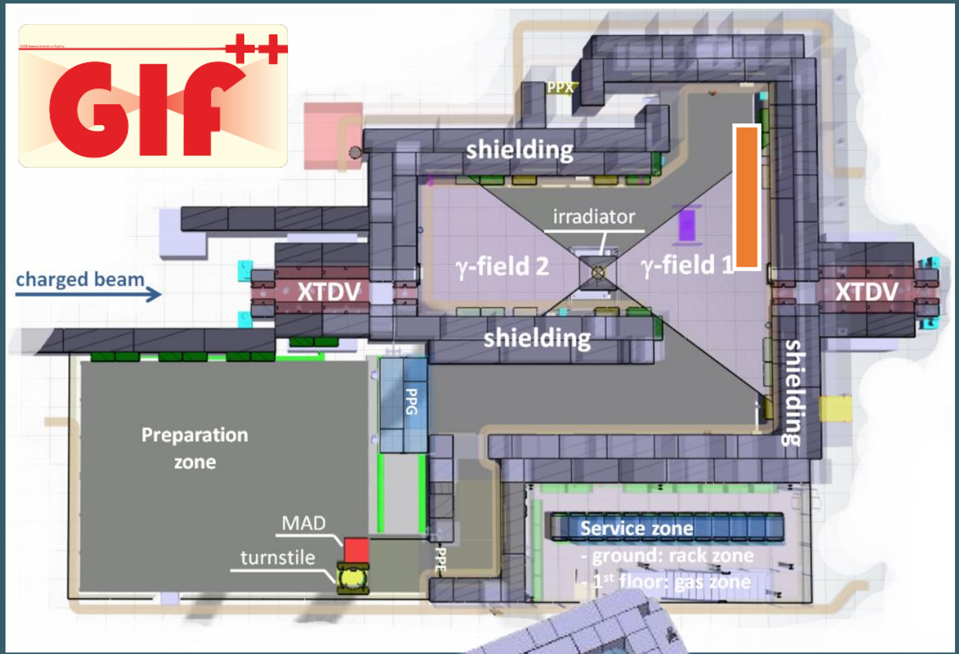
[2017 – 2023] Irradiation of new spare (MB2) at lower rate (× 10 HL-LHC):

- Longer and more systematic data taking complemented with muon test beams
- Irradiation up to 3 × HL-LHC expected dose



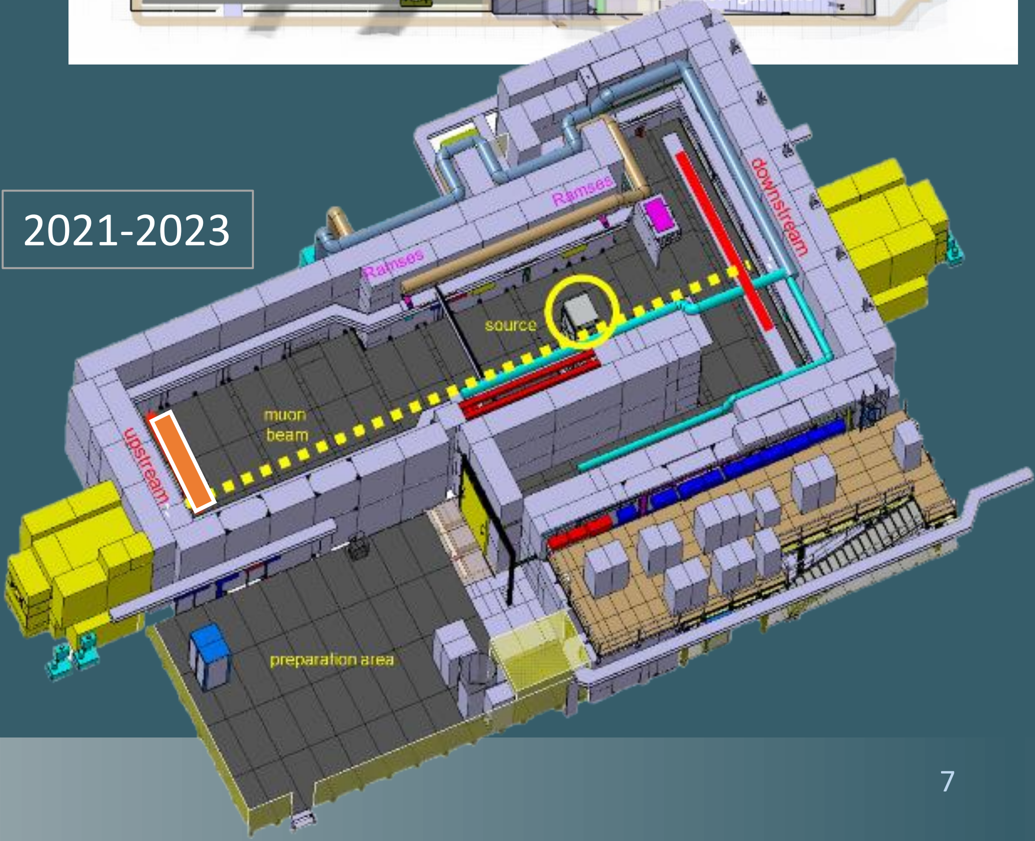
Experimental facilities

2017-2019



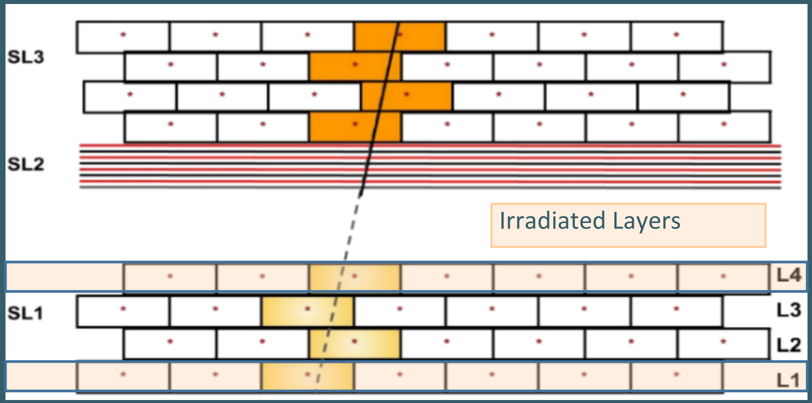
- **Irradiation & Muon test beams**: The **G**amma **I**rradiation **F**acility (**GIF++**) combines:
  - A ***high energy*** charged particle muon beam (from pions and kaons) → "Real" muon measurements
  - And a 14 TBq ^{137}***Cs source*** that produces a background gamma field ($E_\gamma = 662\ KeV$) → Irradiation & background studies
- Accumulate doses equivalent to HL-LHC experimental conditions in a reasonable time
  - **Instant dose** can be configured combining a set of attenuation filters
- Changes in **position**, **GIF++ geometry** and material in front of the chamber during the irradiation period

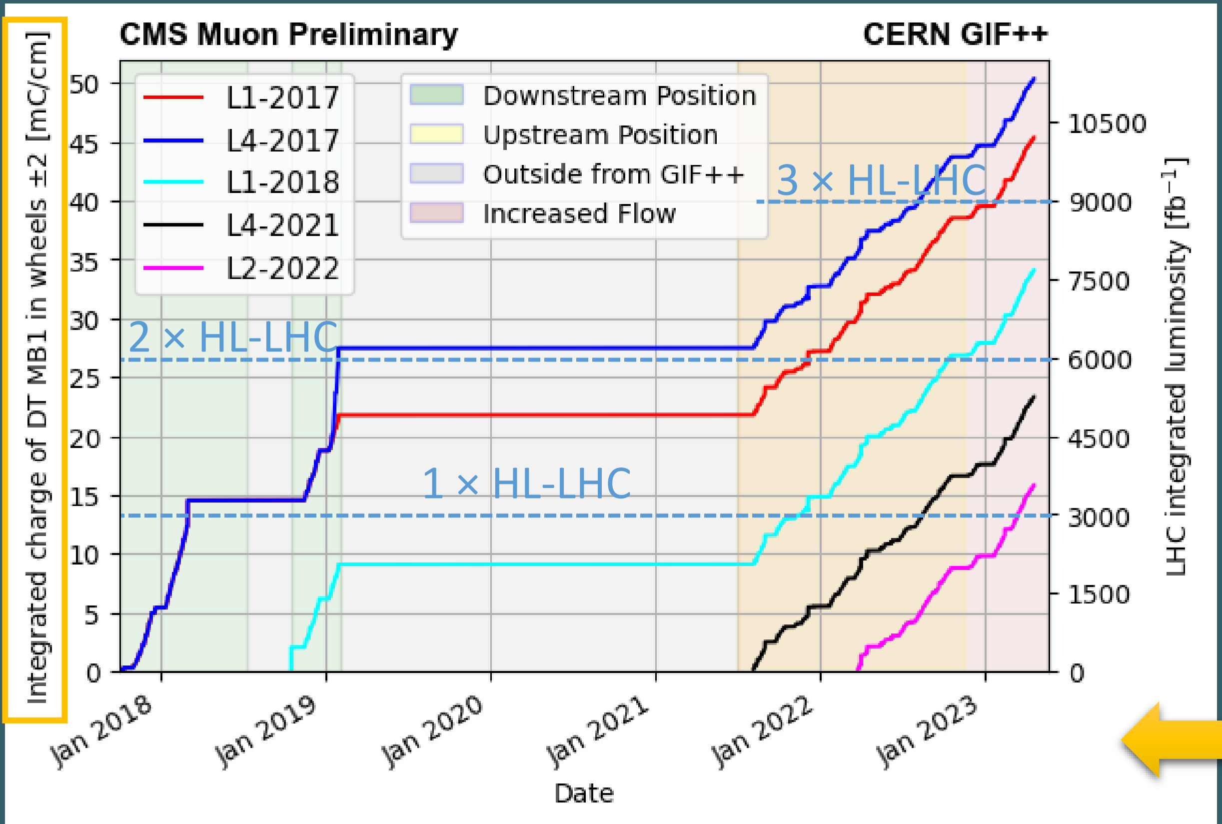
2021-2023



- ... and, of course, the DT chambers at CMS (P5) provide additional information

MB2 irradiation at GIF++

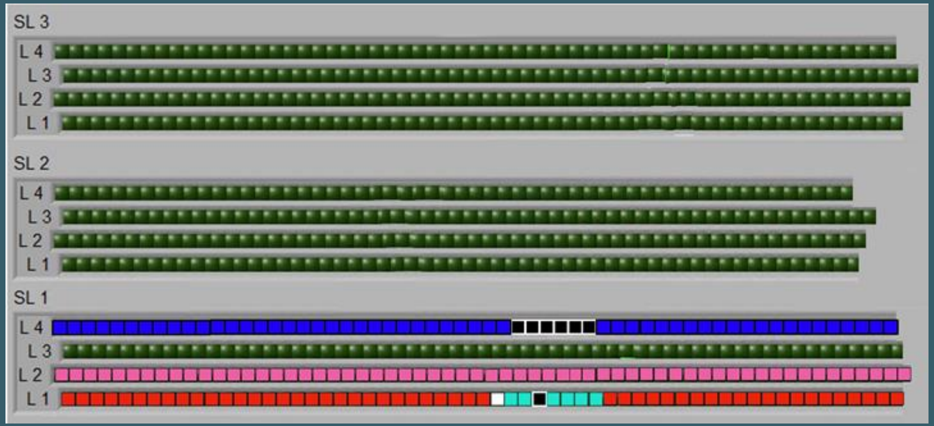


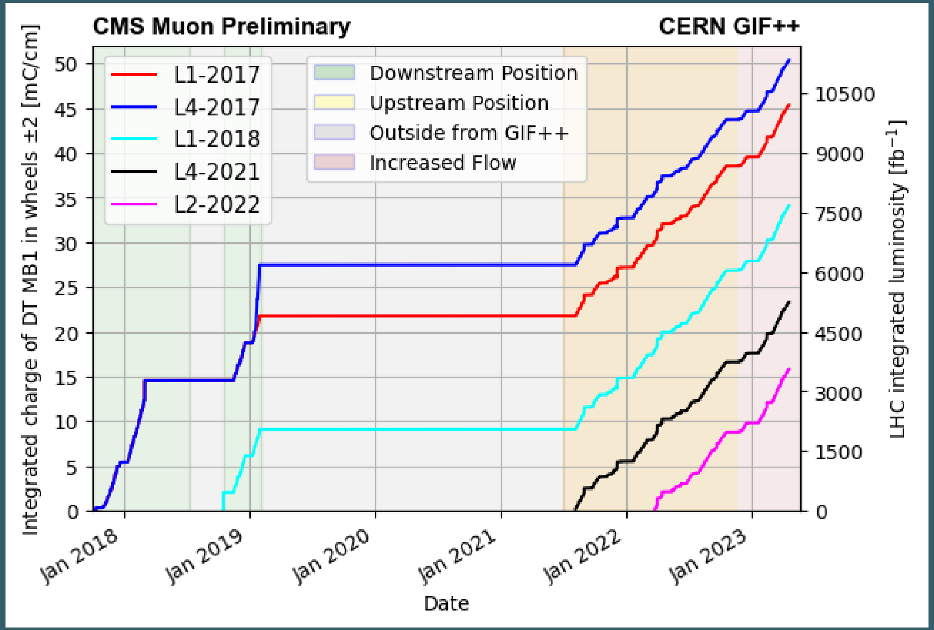


- Data taken in several campaigns (eras) during 2017-2023
- Use a spare MB2 chamber with 2 layers (L), organized in 3 superlayers (SL)
- The chamber was irradiated full time at ~10 times the expected dose at HL-LHC:
- Reference measurements taken periodically
  - Cosmic data recorded at different operation conditions (HV, FE Thresholds, …)
  - Measurements at different source rates were also performed
  - Muon beam data when available (1-2 times a year)
- **Integrated charge** is the equivalent charge that would have been integrated by a not aged wire
- **Gas test**: increased gas flow from Nov 2022 to April 2023

MB2 irradiation and data taking

- **Superlayer SL1 used for irradiation studies**, while
  - **Layers L1 & L4 in SL1** were always irradiated while HV was on
  - **L2** in the same SL1 was included at the end (2022)
  - **L3** in SL1 was kept off to be used as a reference
- **SL2 & SL3** were used for internal trigger with HV in *standby* (1900 V) to be used as reference
- Different irradiation patterns:
  - [2017] – Start irradiation of **L1-2017** and **L4-2017** wires collecting the same dose up to Jan 2019
  - [Summer 2018] – Replace 8 wires in L1 **L1-2018** → Analyse aged wires
  - [Jan 2019] – Keep **L4-2017** at very high HV → Collect more charge
  - [2021] – 5 wires in L4 replaced with the **L4-2021** wires
  - [2022] – **L2-2022** wires started the irradiation with the goal of checking the aging effects on a further (pristine) full layer

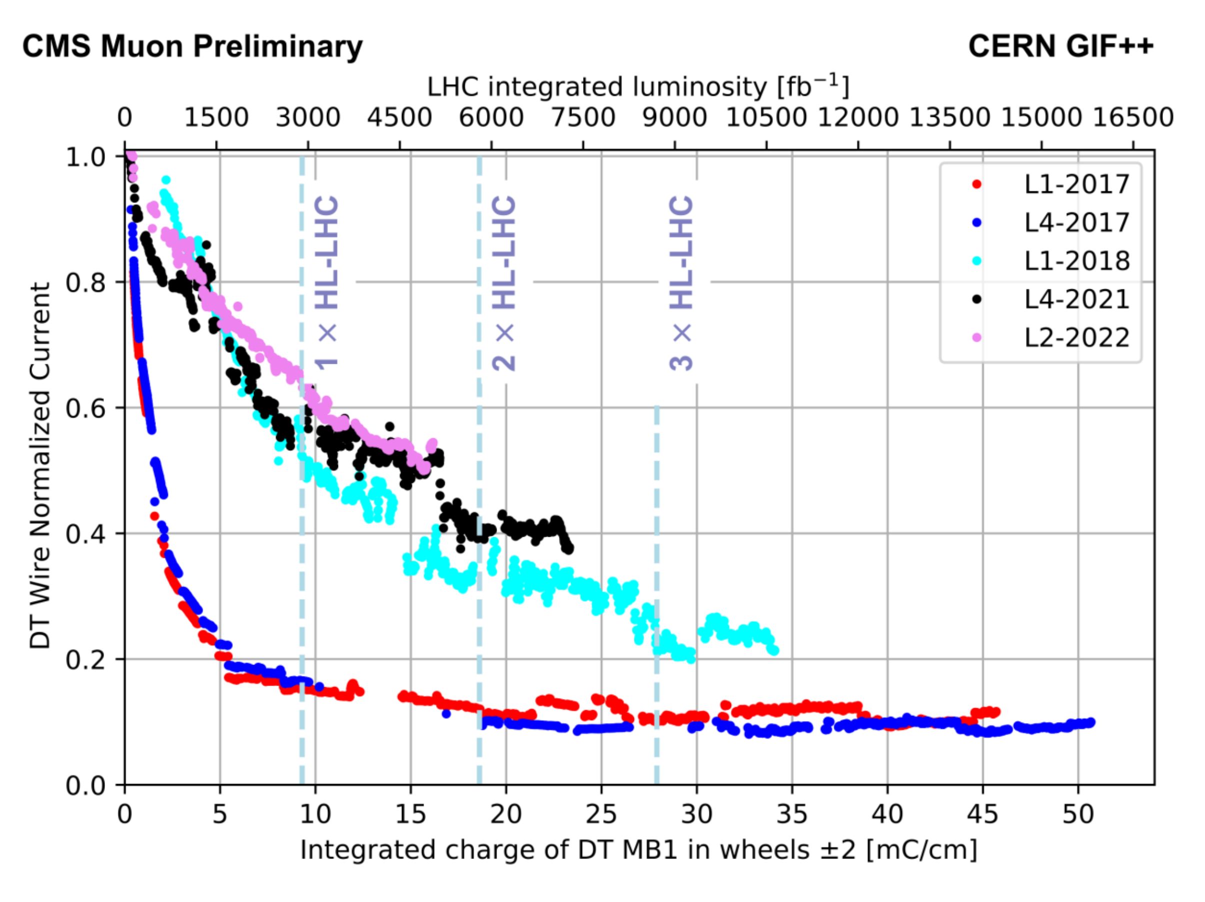




Current evolution

- **Normalized current**: Ratio between the instantaneous current and the instantaneous current in the reference SL1 L3
  - Currents are corrected for the measured pressure in the bunker
- **Integrated charge**: Time each wire is on multiplied by the wire current in reference SL1 **L3**
- **Luminosity** corresponding to expected integrated charge for the more exposed DT chambers during HL-LHC (MB1 YB±2)
- Gaps are caused by the loss of monitoring
- Original wires (**L1-2017** & **L4-2017**) show a big drop at the beginning that seems to stabilize at high integrated dose
- New wires show an almost linear behavior

Normalized current for different sets of irradiated wires as function of the integrated charge (dose)

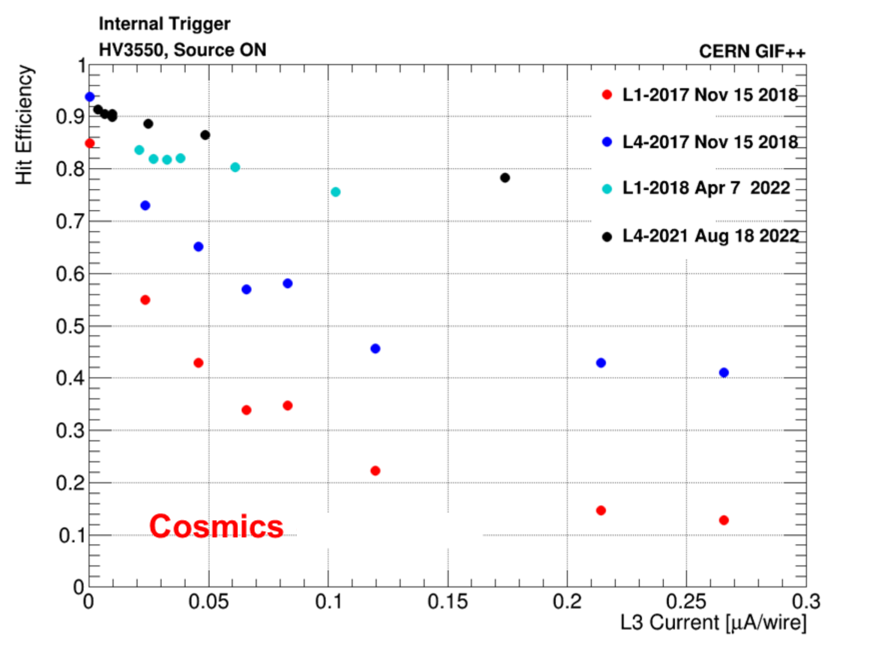


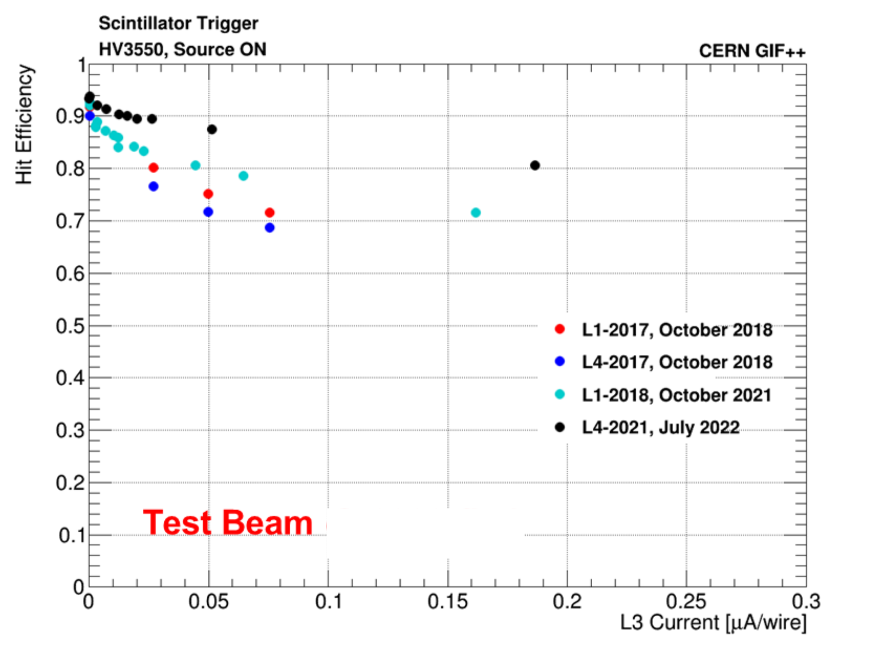
Performance checks @ GIF++

$$\varepsilon_{hit} = \frac{\sum hit_{detected}}{\sum hit_{expected}}$$

The position of expected hits is determined using as probes sets of well reconstructed track segments with associated hits in at least 4 layers in SL3 and at least 1 layer in SL1

- Irradiation not homogeneous in position or time
  - The position of the chamber changed during time
  - The position and the intensity of the gamma-ray source changed
  - Movement of other detectors in the facility
- **Hit efficiency** for Cosmic vs Test Beam muons **at different background rates**:
  - Homogeneous vs inhomogeneous intensity and distribution
  - Internal trigger vs scintillator trigger
  - DT controlled vs GIF++ controlled source attenuators
- Good agreement for **L1-2018** & **L4-2021** wires
- A factor 2 difference for the **L1-2017** and **L4-2017** wires (in cosmics)

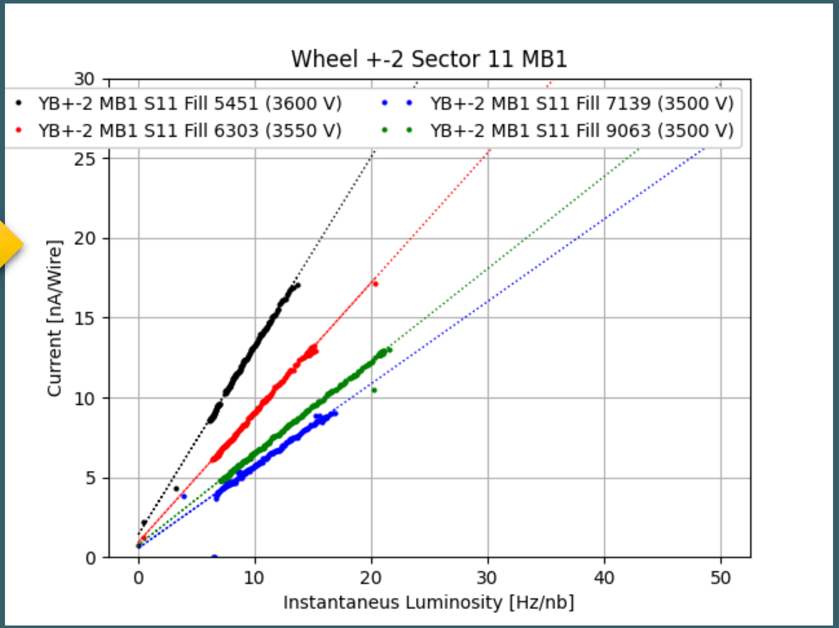


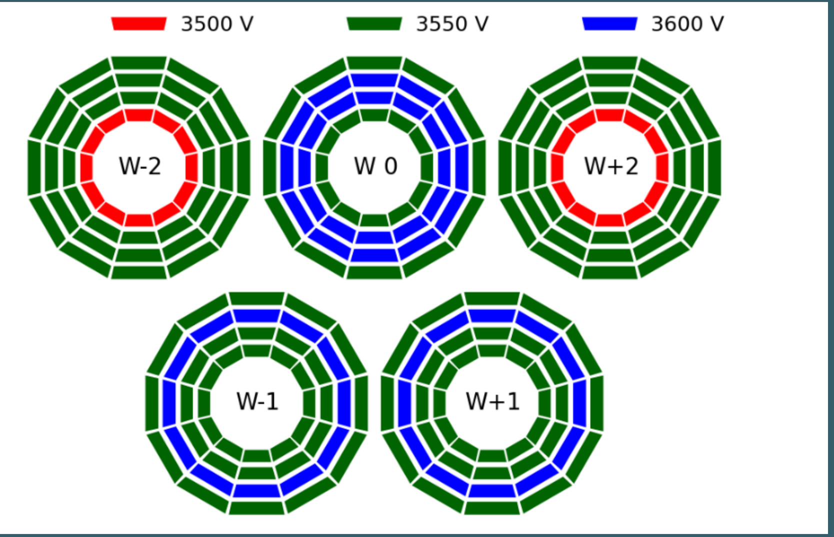


Extrapolating hit efficiency to CMS

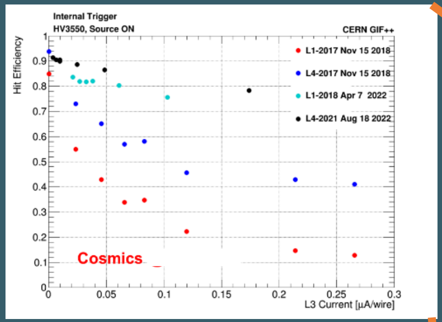
- Measurements of the currents at P5, generated mainly from background, are the starting point to describe HL-LHC conditions
- Current vs Inst. Luminosity behaves linearly and can be extrapolated to HL-LHC instantaneous luminosity
  - Provides a measure of the expected background & the expected integrated charge at HL-LHC
- A simulation of CMS using FLUKA with upgrades in geometry (HGCAL, new beampipe,...) provide a more accurate estimation of the dose expected
- We can estimate the expected integrated charge and background current at HL-LHC conditions using P5 extrapolations corrected with FLUKA predictions
  - Most exposed chambers (MB1 in YB±2, 10% of the detector) will integrate less charge that computed in the past because they are operated at 3500 V

Chamber	Expected integrated charge at 1 HL-LHC mC/cm	Expected background at HL-LHC (current at 3550 V) μA/wire
MB1 YB± 2	**9.4**	**0.06**
MB1 YB±1 and MB4 S4 YB0	**4.6**	**0.02**
MB2 YB± 2 MB4 Upper Sectors	≃2.5	≃0.01
Rest of the detector	≲1.0	≲0.005





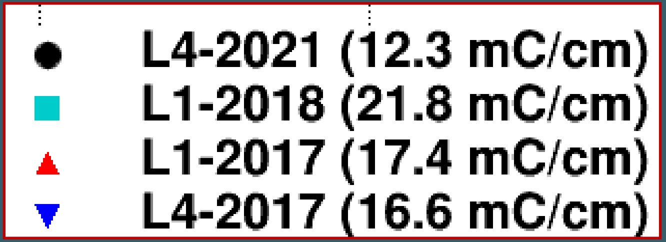
Extrapolating hit efficiency to CMS (P5)



- Use individual hit efficiency as a function of instantaneous dose (background)
  - Efficiency has a strong background dependence in aged wires
- Integrated charge at GIF++ known → Convert to P5 using expected integrated charge for each group of chambers

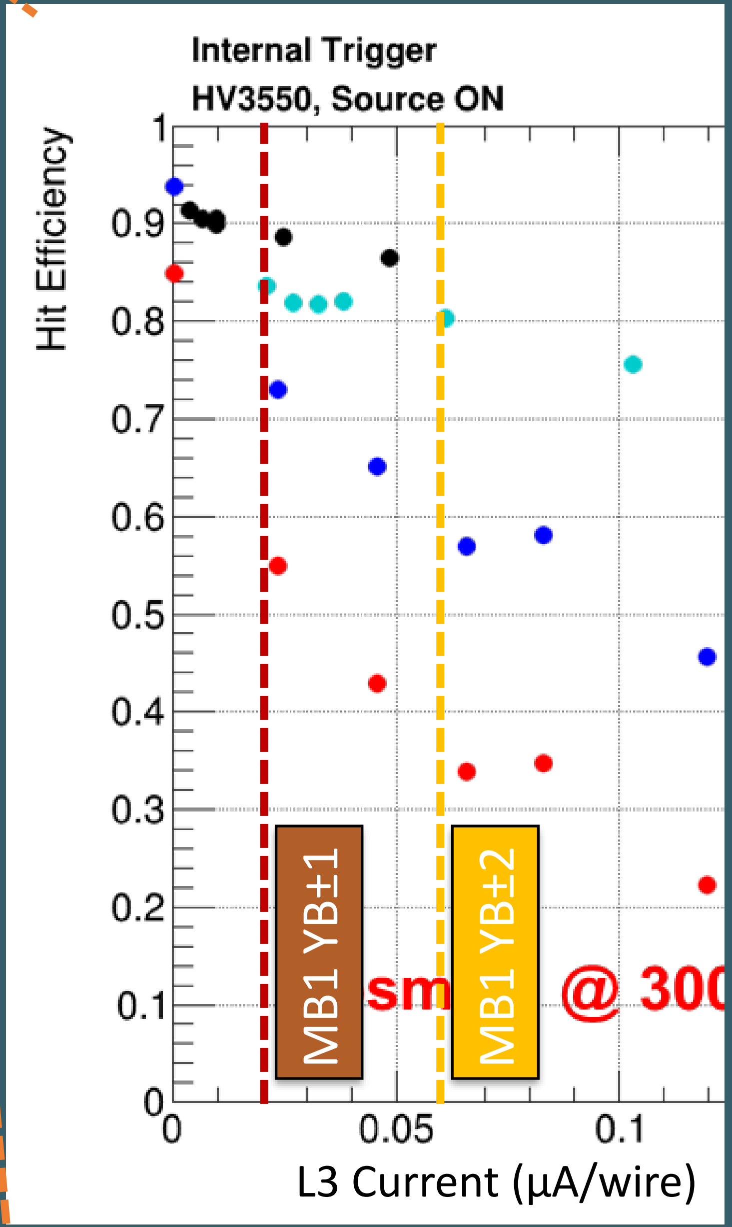
Chamber	Expected integrated charge at 1 HL-LHC mC/cm	Expected background at HL-LHC (current at 3550 V) μA/wire
MB1 YB± 2	9.4	0.06
MB1 YB±1 and MB4 S4 YB0	4.6	0.02

- Same procedure for cosmic and test beam data



From **L1-2018**:

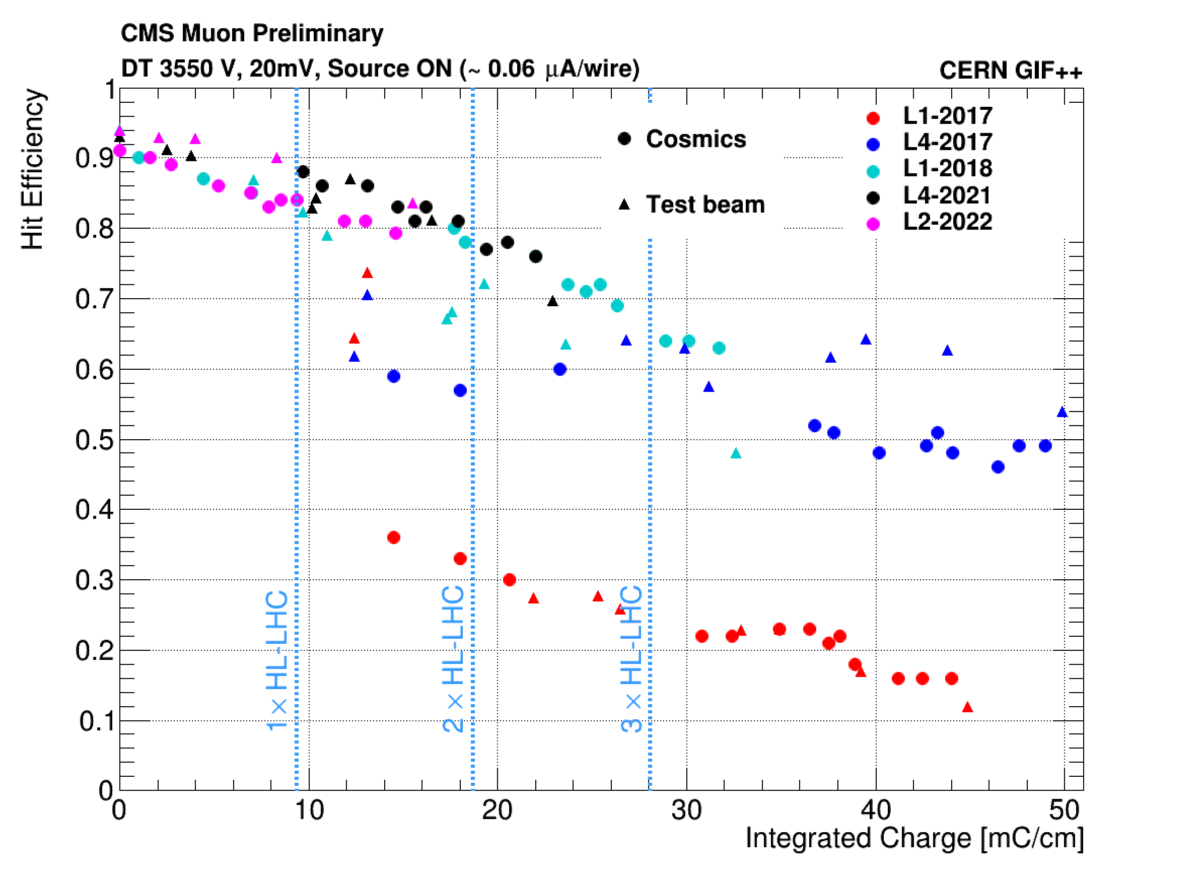
- 2.3 × HL-LHC for MB1 YB±2
- 4.7 × HL-LHC for MB1 YB±1



Evolution of the hit efficiency in HL-LHC background conditions

- Hit efficiency with a background similar to that expected in the most exposed chambers: MB1 YB±2 (24 out of 250 chambers)
- Different efficiency between cosmic and TB muons → expected due to the intrinsic difference of the two sources
- Newer wires (**L1-2018** & **L4-2021**) show compatible trend
  - Even **L2-2022** which is a full layer

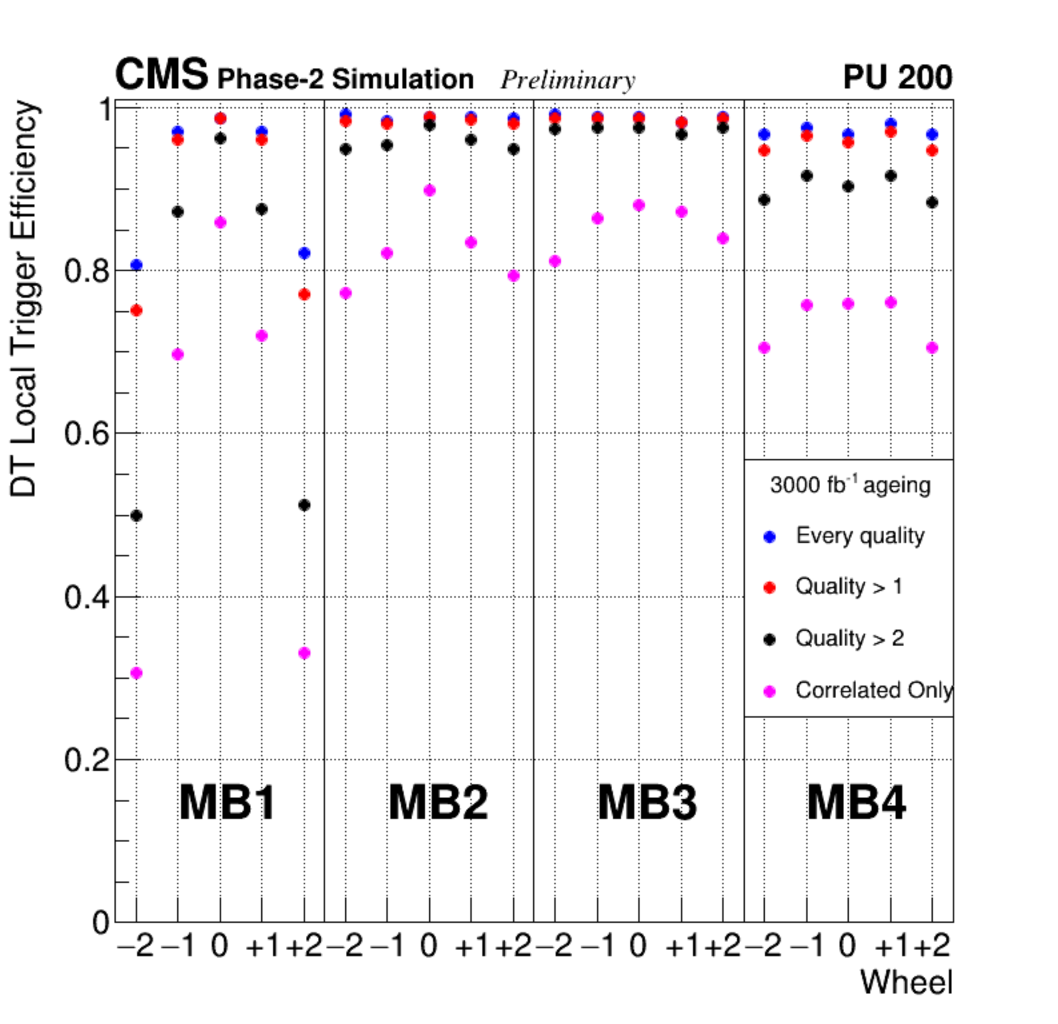
(Absolute value of efficiency at P5 is not directly comparable to the one at GIF++)



Physics performance (trigger)

- In 2019 we used the data from **SL1L1** & **SL1L4** to build an aging scenario and derive expected hit efficiencies at each of the CMS DT chambers at the end of the HL-LHC
  - Very **pessimistic** scenario that uses **safety factor 2**, both on expected background and integrated dose on the chambers
  - From MC samples we computed the DT Local Trigger Efficiencies assuming Phase I (current) trigger algorithms
- The aging would have a **negligible impact** on **DT Local Trigger Efficiency** for most of the chambers
- Major effect seen in the **MB1 chambers in the external wheels** will be effectively mitigated by:
  - Improved trigger algorithms being developed that use the full power of the new backend electronics in Phase2
  - Redundancy of the DT muon system with 3 more (barely affected) stations as the muon travels out of CMS
  - Having multiple layers per chamber (3 out of 8 are needed)

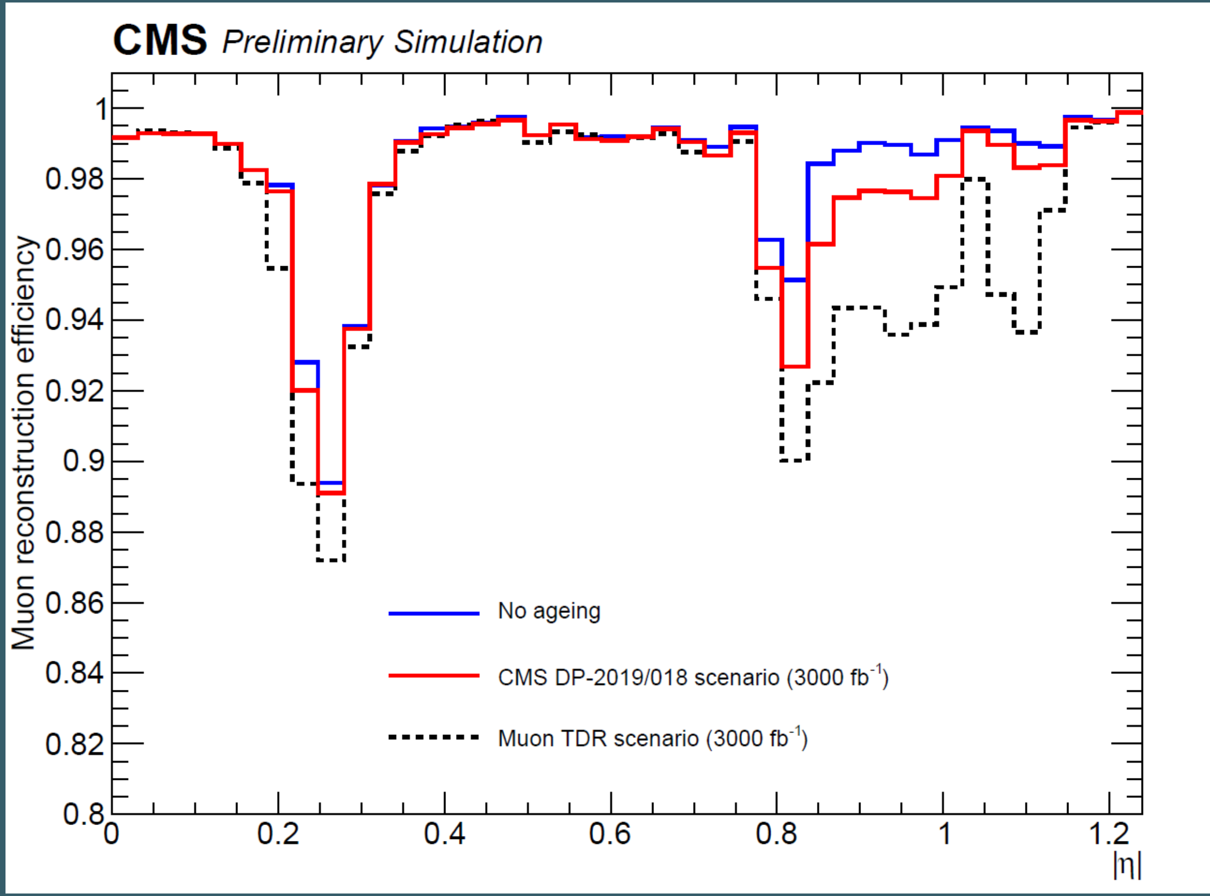
DT Local Trigger Efficiency built using only data collected up to 2019 from SL1L1 and SL1L4
Pessimistic aging scenario (safety factor 2)



Physics Performance (reconstruction)

- The previous (pessimistic) aging scenario was used to compute the **standalone muon reconstruction efficiency** using MC samples
- The standalone muon reconstruction efficiency shows a minor impact on most of the region covered by the DTs
  - A mild reconstruction efficiency drop is seen for muons located in the overlap region (high pseudorapidity)
- The most aged DT region is also covered by 3 CSC stations and 4-5 RPC layers along a prompt muon trajectory

Standalone muon reconstruction efficiency built using only data collected up to 2019 from SL1L1 and SL1L4
Pessimistic aging scenario (safety factor 2)

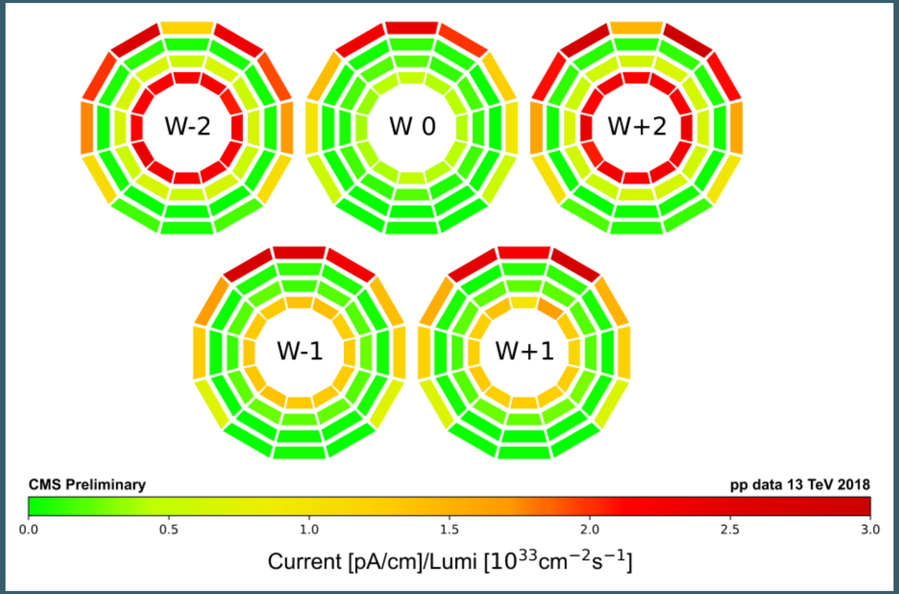


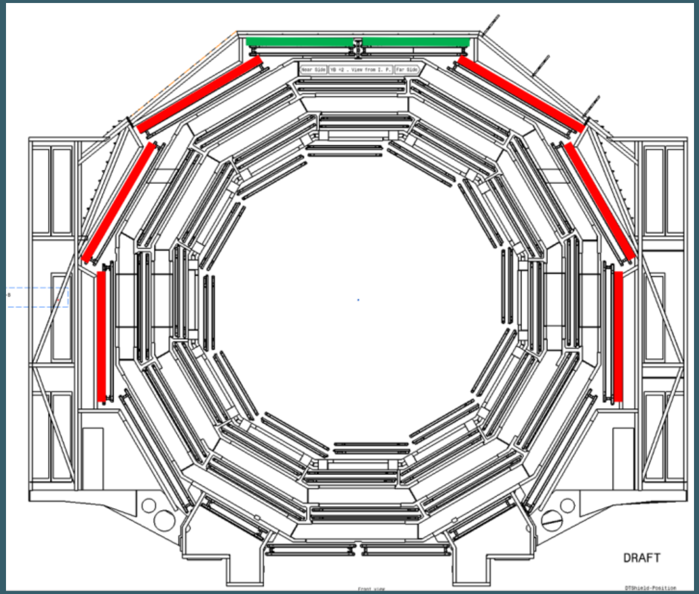
Mitigation strategies: shielding

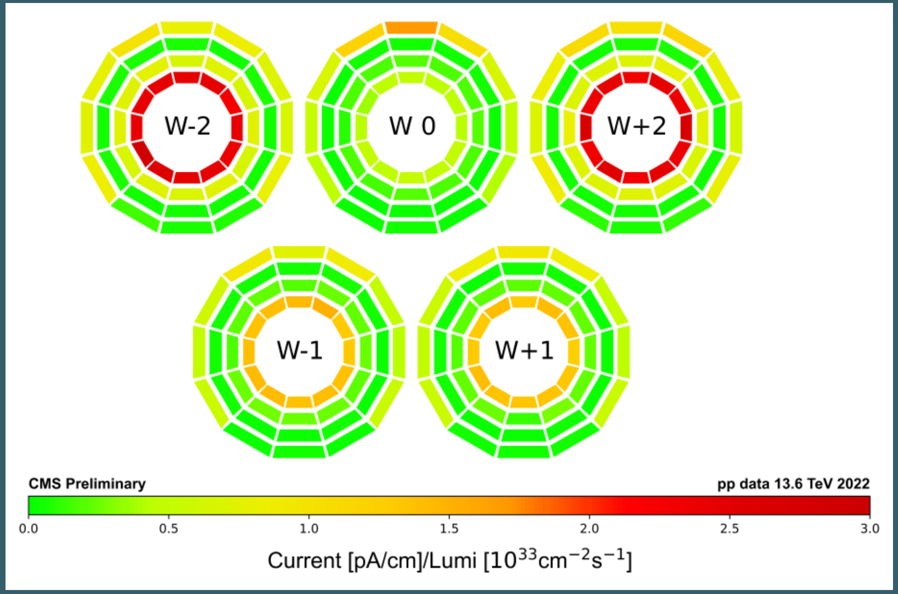
- A big part of the radiation that affects the chambers comes from the scattering on the walls and the activated materials in the CMS cavern
  - 3 cm layer of Borated Polyethylene + 1 cm layer of lead for gamma absorption

➔ 25% less background in the experimental cavern (top)

➔ 50-70% of background reduction in the MB4 chambers

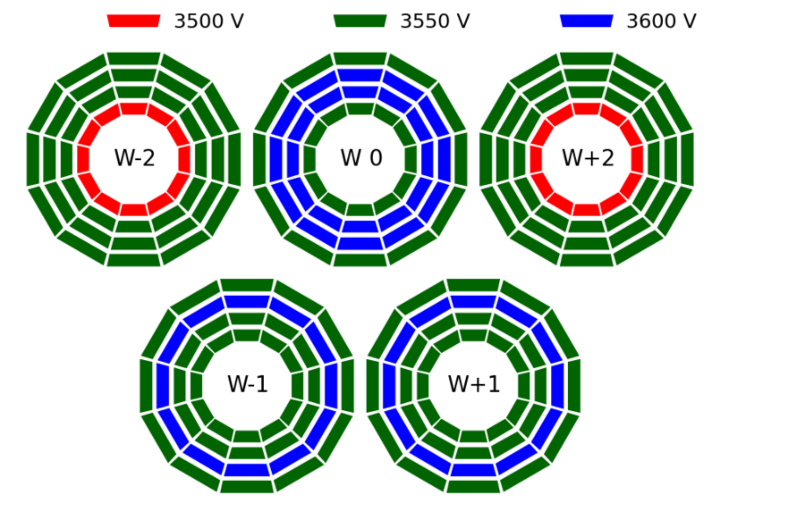


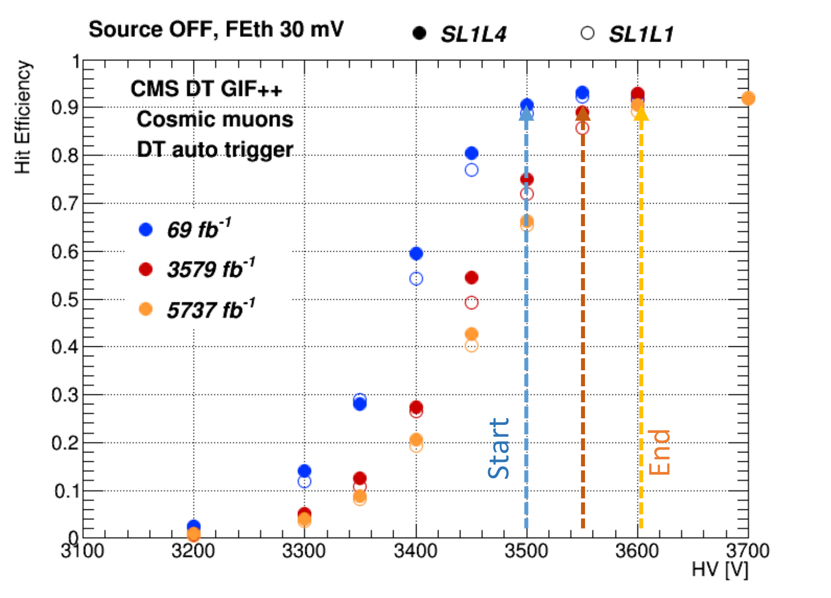


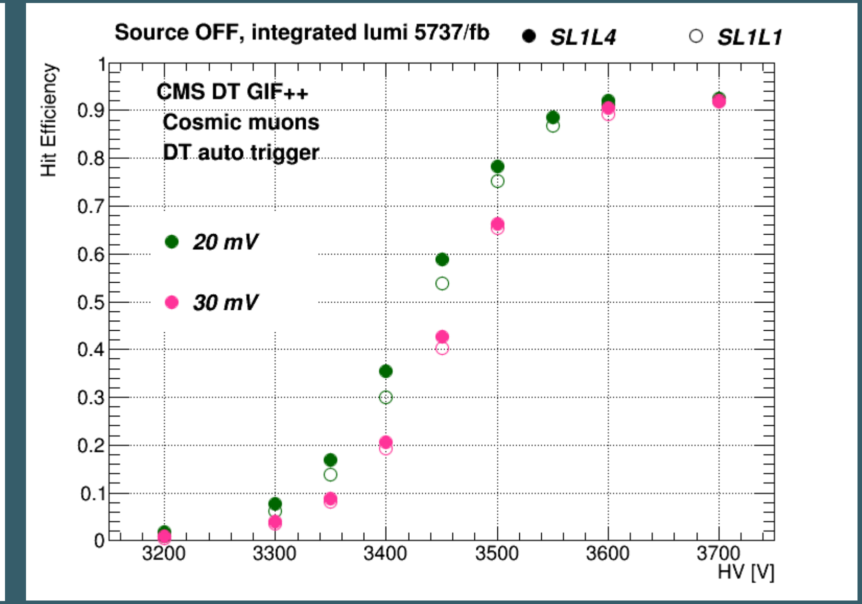


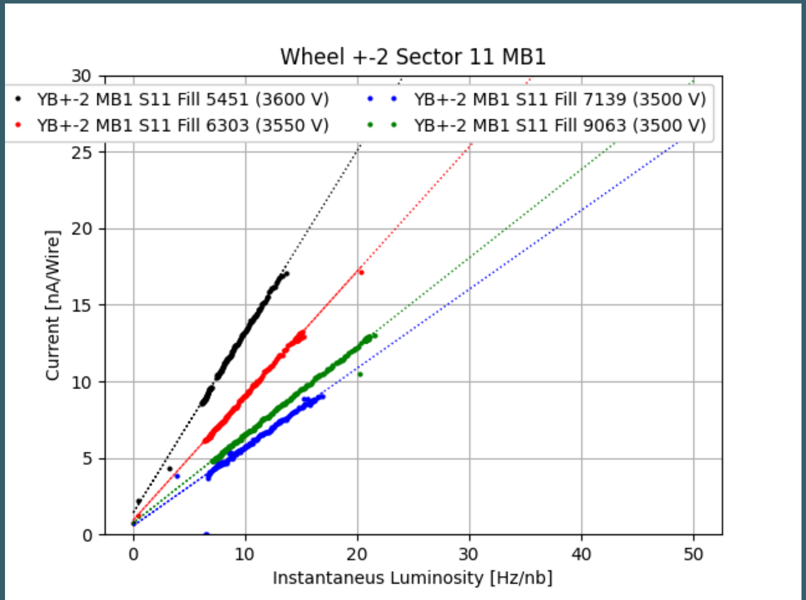
Mitigation Strategies: Operational parameters

- Since 2016 **voltage** of the wires in the most exposed chambers has been **reduced**:
    - Each step of 50 V decreases the integrated charge by about 30%
- Readout thresholds also reduced from 30 to 20 mV
- During HL-LHC, manage operational conditions (HV, FE Threshold) dynamically:
    - Lower HV (& higher FE Thr.) values at the beginning to reduce ageing
    - As signs of ageing appear, go to higher HV & lower FE Thr. to move again into the plateau









Mitigation Strategies: Gas and electronics

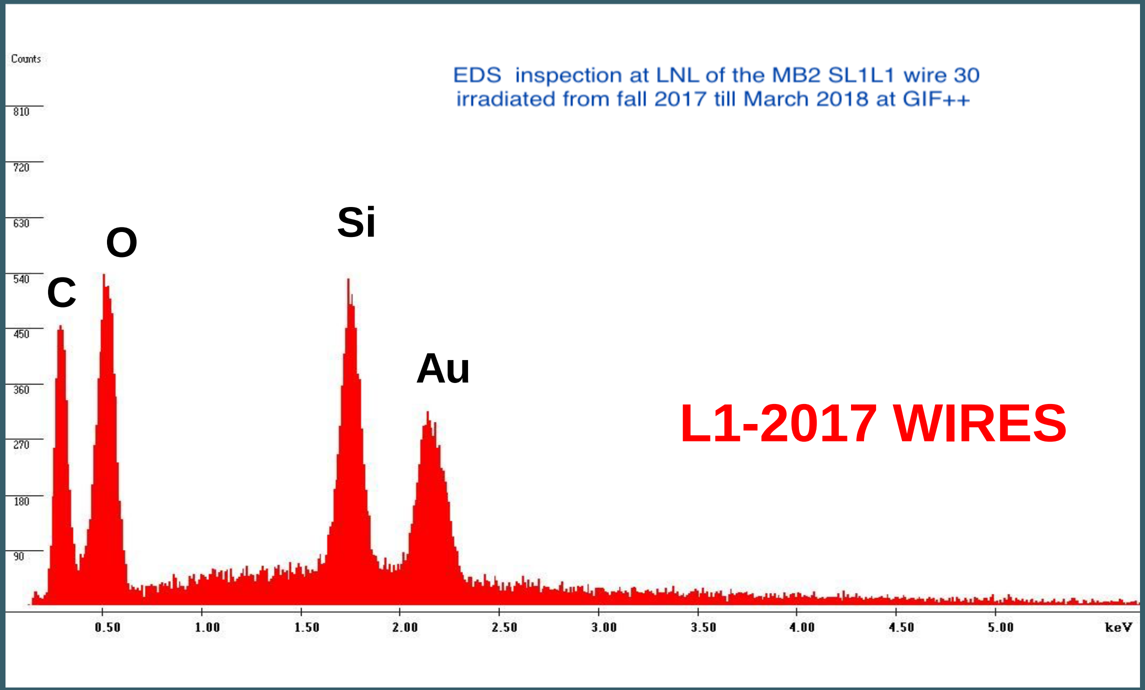
- In 2017 the **gas system** at CMS was modified to operate in **open loop** to minimize the recirculation of the possible pollutants in the DTs
- Test with an **increased** (~ 2 ×) **gas flow** (same pressure) at GIF++ → No significant difference observed in chamber performance
- For HL-LHC a new readout is foreseen (already under test in a couple of sectors at P5). New L1 trigger algorithms under study and development should mitigate the aging effects

Conclusions

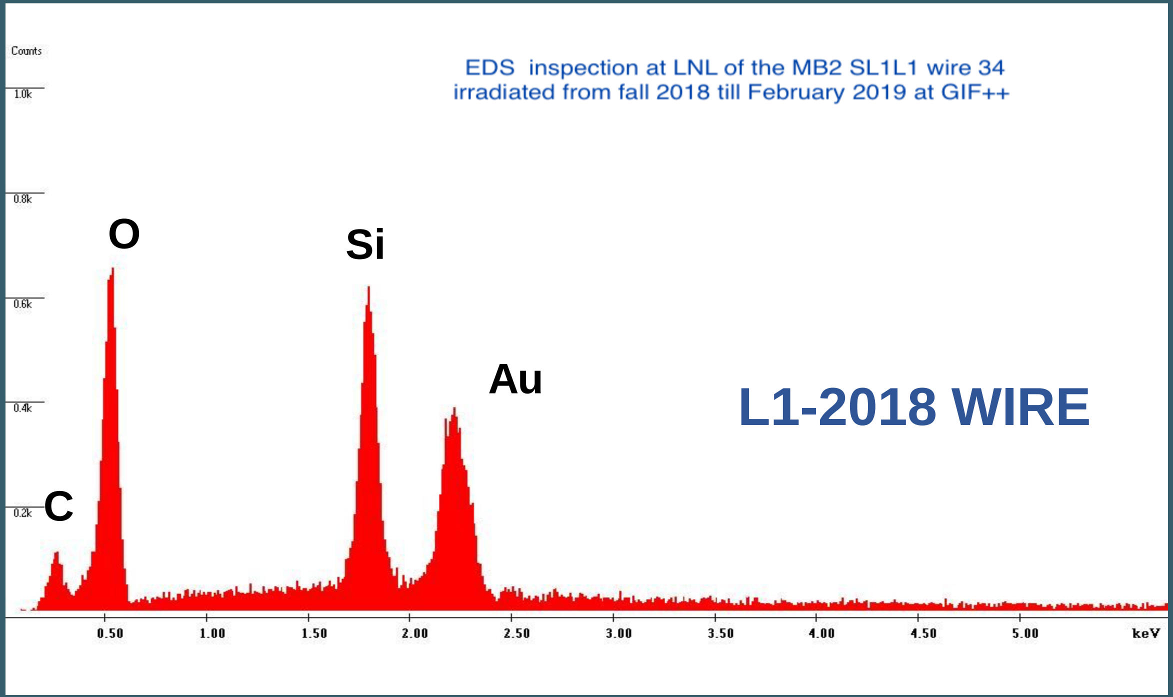
- HL-LHC will create a **difficult environment** for CMS subdetectors, and in particular for the Drift Tubes Muon detector that may degrade the performance on some of the chambers
- A **big effort** has been done **to characterize the radiation effects** and to develop strategies to guarantee the muon reconstruction and identification stays at an optimal level in CMS throughout the HL-LHC operation
- A pessimistic extrapolation based on the data collected at the CERN GIF++ facility shows a drop in the single hit efficiency. The hit efficiency does not go below 80% at the end of the HL-LHC for the most exposed chambers, while for the big majority of the system the hit efficiency stays well above 90%. Very preliminary muon trigger and reconstruction studies show a mild localized effect in the overlap region
- We believe that with a combination of different strategies including dynamic operation and improved algorithms for muon trigger and reconstruction the Drift Tubes at CMS will have a great impact on the physics during the HL-LHC

Backup

DT Spectroscopy analysis



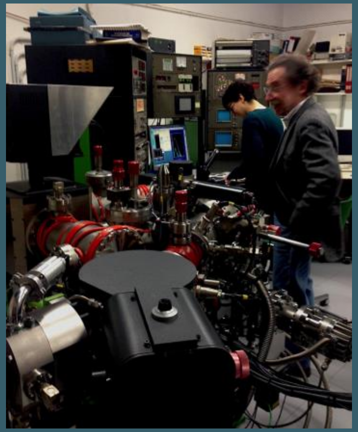
Energy dispersive X-ray spectroscopy (EDS) of a wire of SL1L1 of the MB2 chamber exposed at GIF++ on the first irradiation, 2017-2018 , and extracted after ~1 Hl-LHC integrated charge (as expected on the most exposed DT chamber, MB1 of wheels +2 and -2).In the x axis the energy of the absorbed gammas of different material are reported. From the left the peaks correspond to carbon (C), oxigen (O), silicon (Si) and aurum (Au).



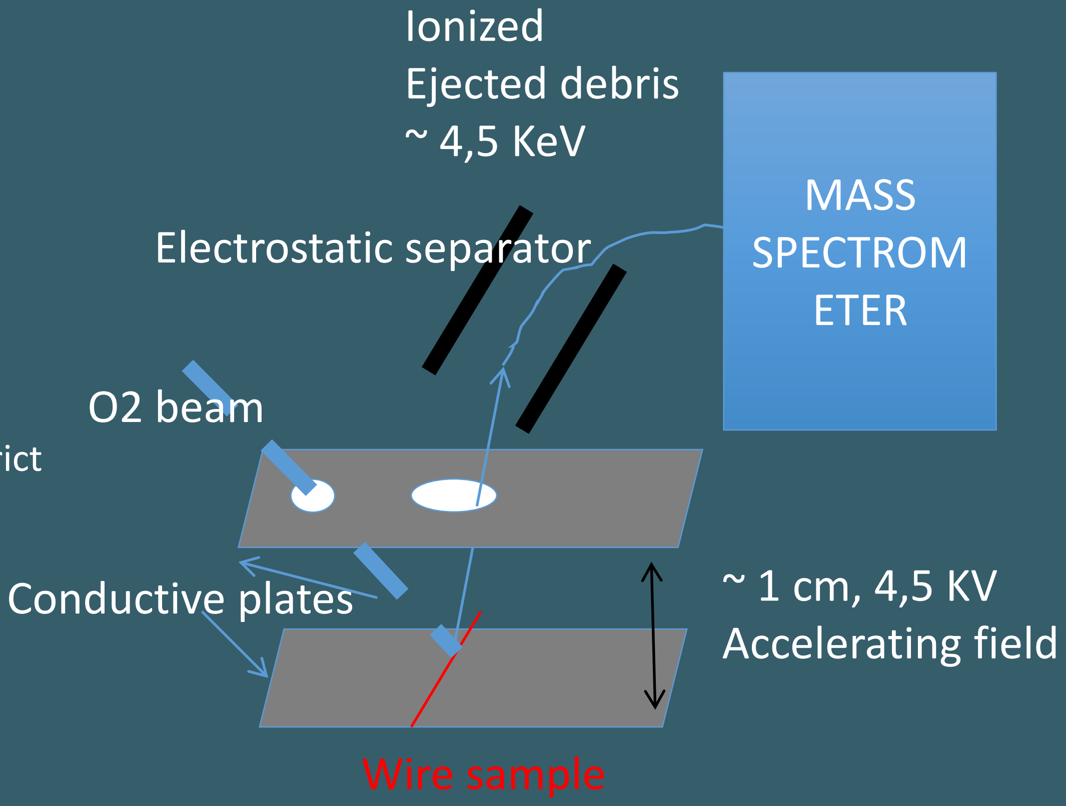
Energy dispersive X-ray spectroscopy (EDS) of a wire of SL1L1 of the MB1 chamber exposed at GIF++ on 2018-2019 after ~0.7 HL-LHC integrated charge (charge expected on the most exposed DT chamber, MB1 of wheels +2 and -2). In the x axis the energy of the absorbed gammas of different material are reported. From the left the peaks correspond to carbon (C), oxigen (O), silicon (Si) and aurum (Au).

Further analysis at DFA on the DT irradiated wires extracted with SIMS

- SIMS (Secondary Ions Mass Spectrometer) is a powerful instrument used by the solid state scientists (in DFA, Padova) to analyze the composition of thin flat layers of material
  - It allows to find the presence of different elements going deeper into the sample by excavating it with an energetic ion beam.
  - The ion beam extracts atoms or molecules from the sample that are than injected into a Mass Spectrometer
  - Beam formed by O_2 at 8KeV of O2 that splits into two O at 4KeV . Beam diameter 10~15 micron
  - The beam sweeps a region of 250X250 micron but an optical system can restrict the accepted region of origin of the ions to an area of ~ 20 micron
  - Usually the samples to be analyzed are flat and thin and do not introduce distortions in the accelerating field.
  - Extracted ions are accelerated to a kinetic energy of 4,5 KeV , bent by the electrostatic separator into the Mass Spectrometer that measures the momentum and so the mass.

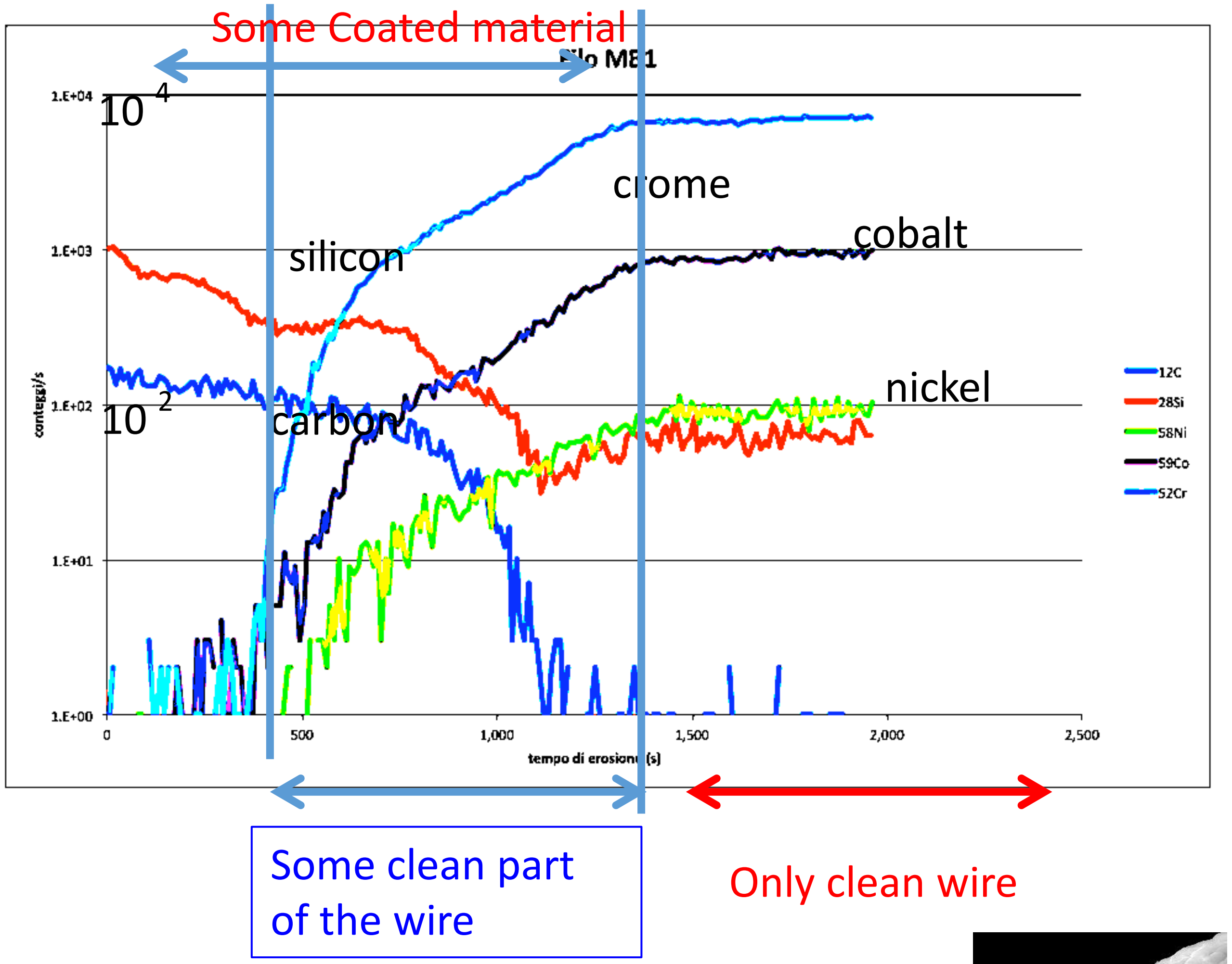


Measurements taken by the Prof. Alberto Carnera

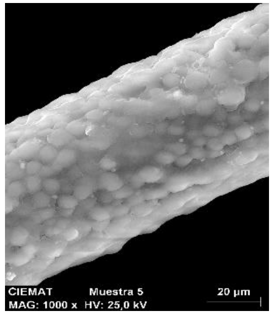


Results from SIMS

- At the beginning only C and Si are visible , after a while the coating start to be thin enough to allow the beam to reach the wire extracting heavy ions from it.
- When the coating has been completely erased, Si and C drop by order of magnitude.
- A fraction of silicon remains probably extracted from the supporting plate.
- What did we learned of the aged wires:
  - The coating material is very highly resistive
  - The coating material is constant along the depth in radius



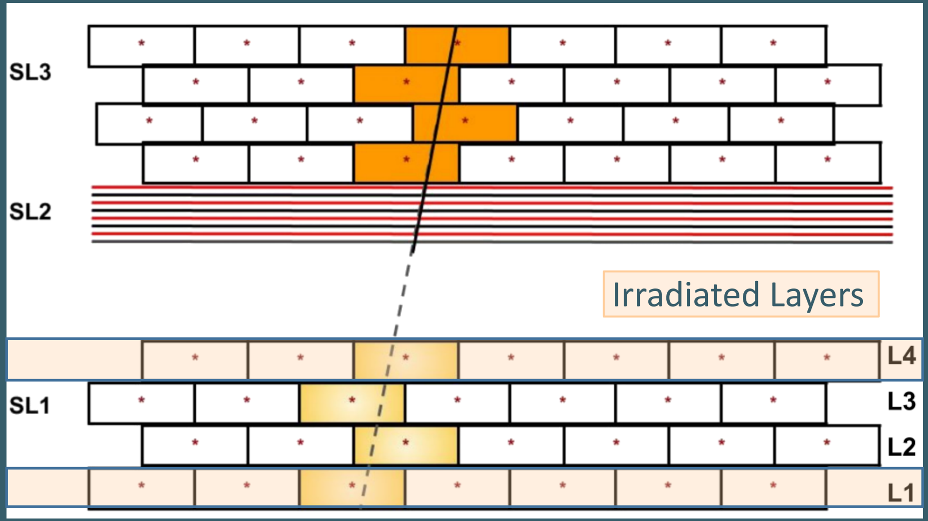
Coated material not uniform in depth , ~8 micron



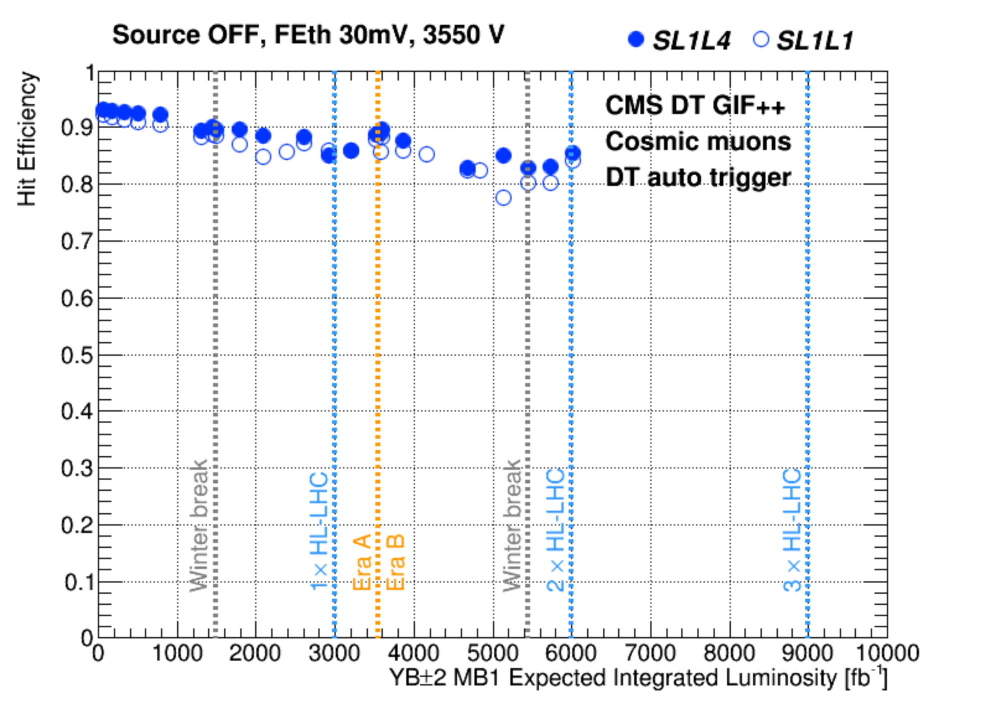
MB2 hit efficiency (Cosmics)

$$\varepsilon_{hit} = \frac{\sum hit_{detected}}{\sum hit_{expected}}$$

The position of expected hits is determined using as probes sets of well reconstructed track segments with associated hits in at least 4 layers in SL3 and at least 1 layer in SL1



Hit efficiency for cosmic muons as a function of integrated luminosity for the aged layers at 3550 V (2017-2019)



- Each point corresponds to data taken with High Voltage variation scans that were collected every week
- The DT trigger was used for cosmic muon tracks, avoiding any bias on the layers irradiated with HV ON
- The loss of efficiency without background radiation is around 10% for the expected integrated luminosity equivalent to 2 × HL-LHC

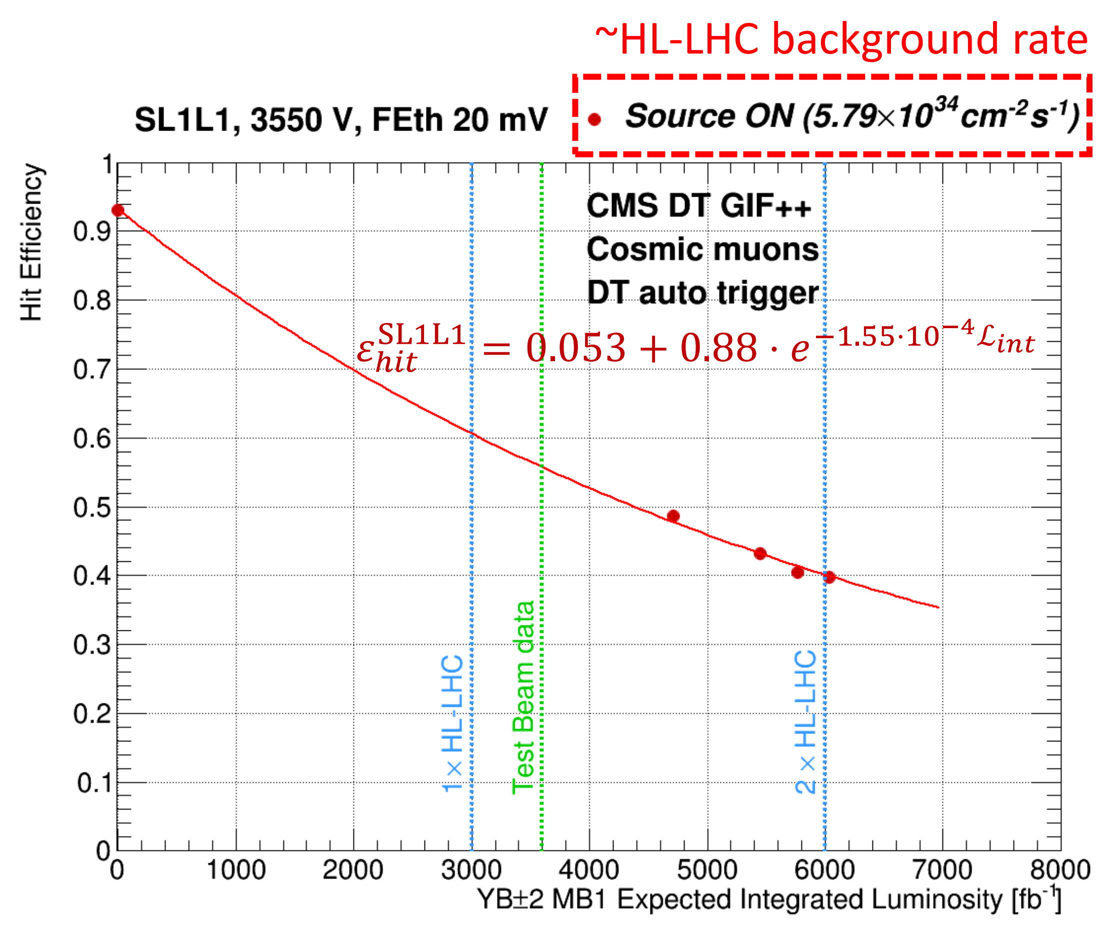
Building an ageing scenario

[Use safety factor 2 on instantaneous and integrated luminosity]

Hit efficiency for cosmic muons as a function of integrated luminosity for the aged layer SL1L1 and with a background rate ~HL-LHC

- Unfortunately, we could not collect test beam data at the end of the irradiation…
- … but we have data from cosmic muons in conditions close to the HL-LHC background rate

→ We can use this data to propagate the dependency to 2 × HL-LHC (safety factor)

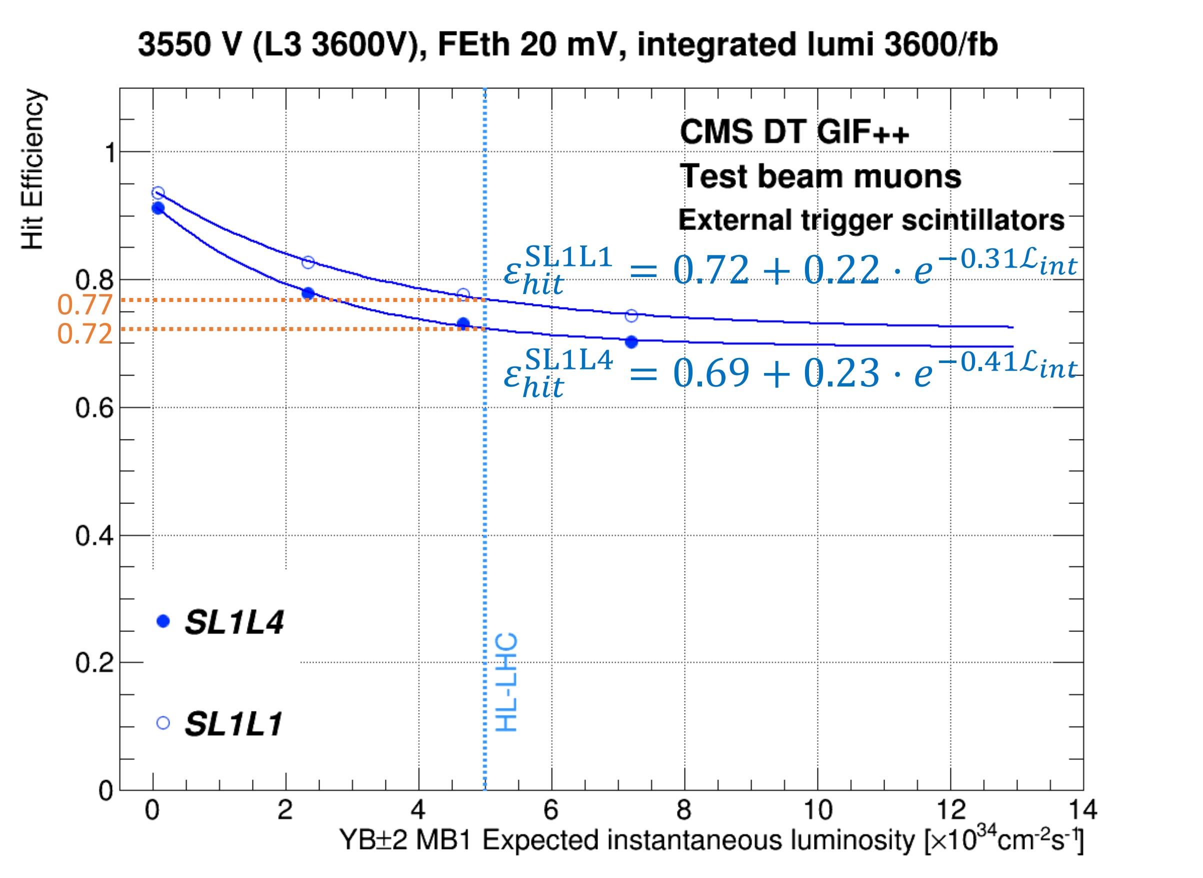


Towards an aging scenario MB2 hit efficiency (Muons)

- Muon beam data taken after an integrated dose equivalent to an HL-LHC integrated luminosity of 3600 fb^{-1}
- External trigger scintillators used for muon tracks, identifying a track in both projections on SL2 and SL3 of the DT chamber in coincidence with the scintillators, avoiding any bias on the layers irradiated with HV on
- The hit efficiency degrades ~20% when in presence of background radiation equivalent to HL-LHC.
- Around **75% hit efficiency** for the most exposed chambers at **HL-LHC background rate** after HL-LHC integrated luminosity
  - Please note that test beam muons are perpendicular to the test chamber: No track length correction applied
- If we double the background rate efficiency stays around 71%

Using data collected in 2017-2019 irradiating only SL1L1 and SL1L4. To be updated with full data soon.

Hit efficiency for beam muons as a function of instantaneous luminosity for the aged layers at 3550V



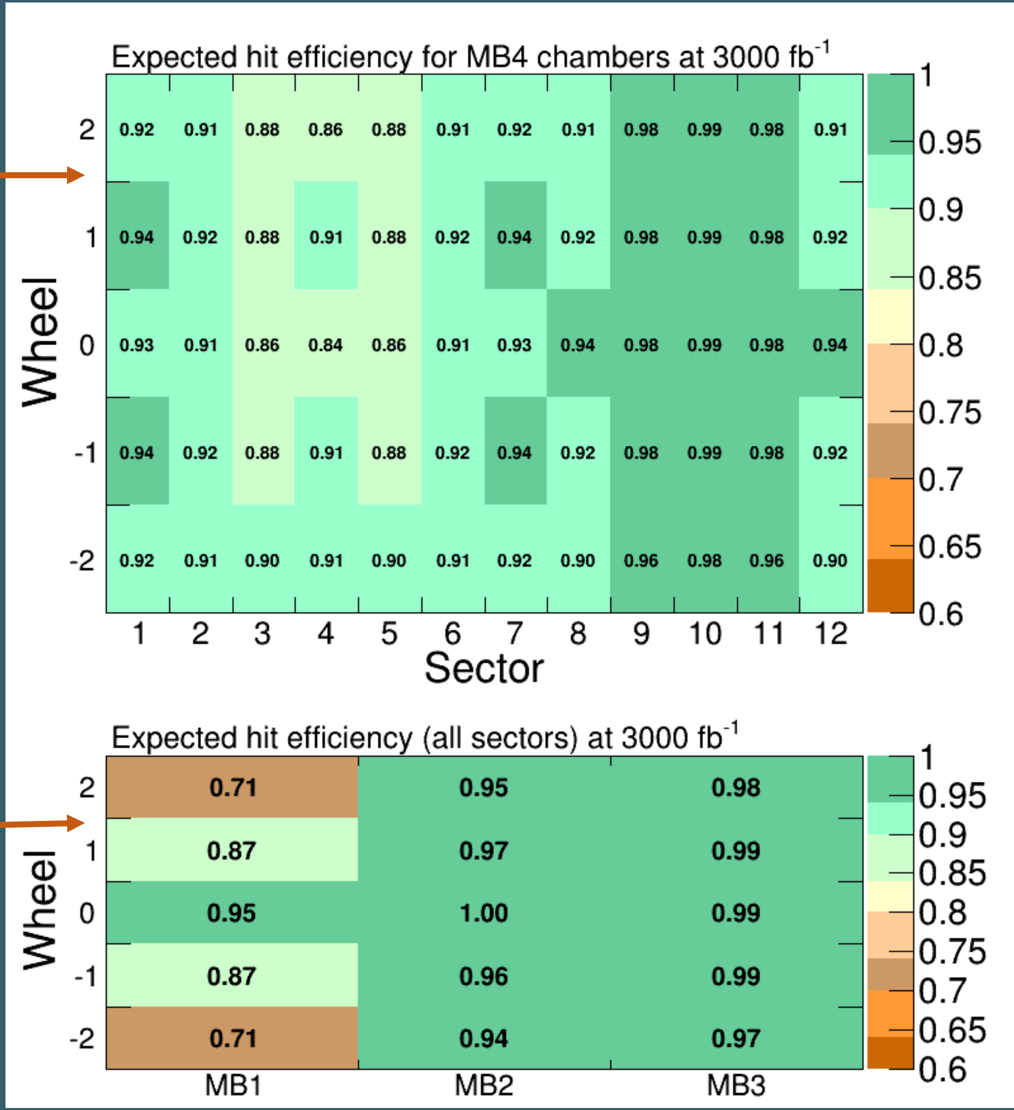
Building an ageing scenario

[Use safety factor 2 on instantaneous and integrated luminosity]

Expected hit efficiencies at the end of the (2 ×) HL-LHC for all the DT chambers of the CMS muon system:

- **MB4 chambers: top plot**
- **MB1, MB2 and MB3: bottom plot, all sectors together**

Results estimated using a more accurate CMS geometry simulated with FLUKA

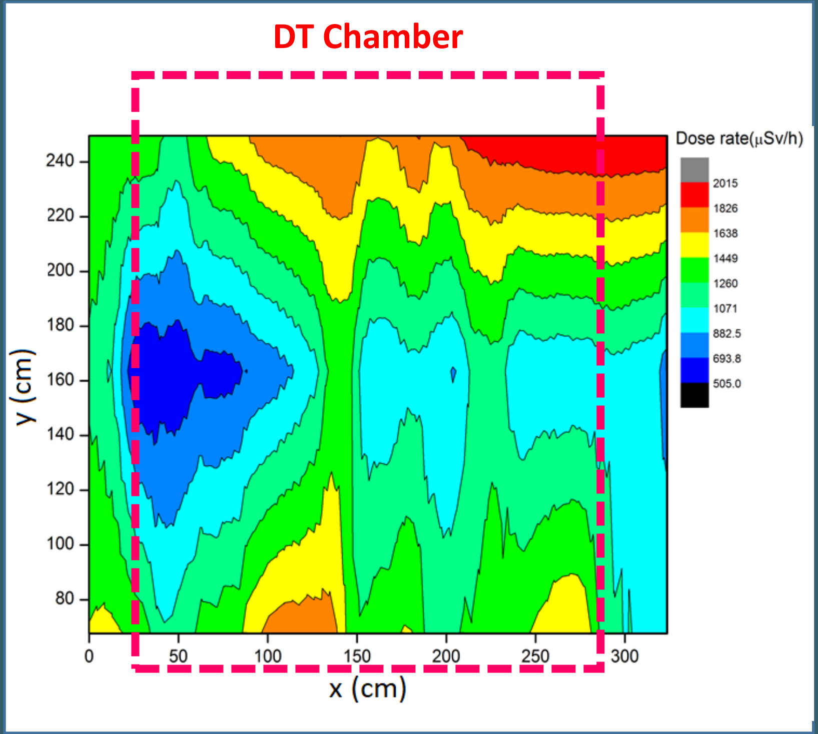


- Efficiencies estimated considering a safety factor of 2 for the expected HL-LHC background rate **(10×10^{34} cm^{-2}s^{-1})** and a safety factor of 2 for the expected integrated luminosity **(6000 fb^{-1})** to obtain the expected hit efficiency for the MB1 chambers in wheels ±2 and extrapolating to the rest of the CMS muon system using the expected integrated charge at the end of HL-LHC

Dose and equivalent luminosity

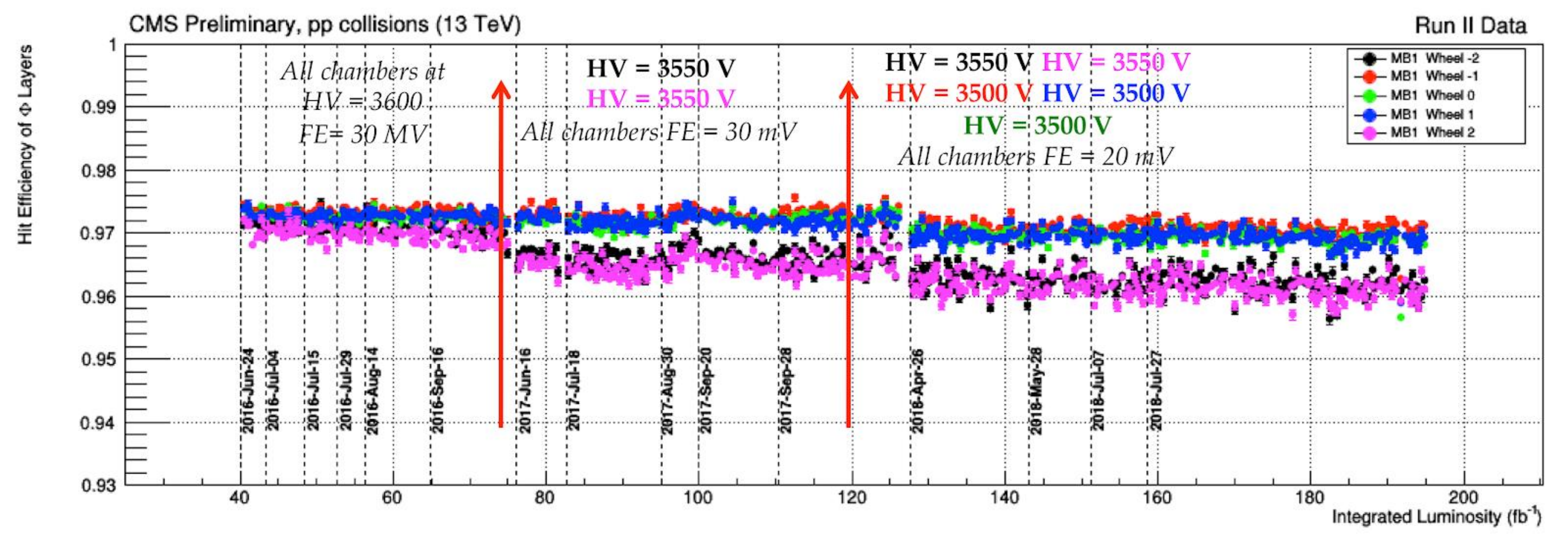
- At GIF++ the dose rate is measured with a REMUS dosimeter inside GIF++
  - Several measurements were done with a portable dosimeter in different positions of the MB2 chamber to extrapolate the REMUS measurement to the surface of the MB2 chamber
- Conversion factors from dose to luminosity were computed comparing currents in the MB2 chamber at GIF++ and DT chambers at CMS
  - Dose rate to instantaneous luminosity conversion was calculated at HL-LHC background rate:
    1 fb^{-1}/s = 0.304 mGy/s
  - Integrated dose to integrated luminosity was calculated at GIF++ aging rate (~10 × HL-LHC):
    1 fb^{-1} = 0.42 mGy

The integrated luminosity quoted in our studies corresponds to the integrated dose expected for the most exposed chambers during the HL-LHC



Inhomogeneous dose rate over the chamber was averaged to compute the integrated dose

No efficiency drop seen at P5 so far. Changing the HV and FE has a very small effect on hit efficiencies, but will delay ageing.



Study of the coating on wires from MB2

- Wires studied in Legnaro and CIEMAT using SEM (Scanning Electron Microscope) and SIMS (Secondary Ion Mass Spectrometer)

→ Coating material clearly visible
→ Very resistive

HV Scans performed with cosmic data

- DT hit efficiency as a function of High Voltage in the detector regions most exposed to background, i.e. the MB4 and MB1 stations
- While well visible is the effect of the reduced FE threshold on the measured efficiency, within each pair of results the two curves overlap each other well so that no effects of ageing were observed so far.