Upgrade of the CMS muon detector Trigger timing: from Run3 to HL-LHC

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CMS
Compact Muon Solenoid

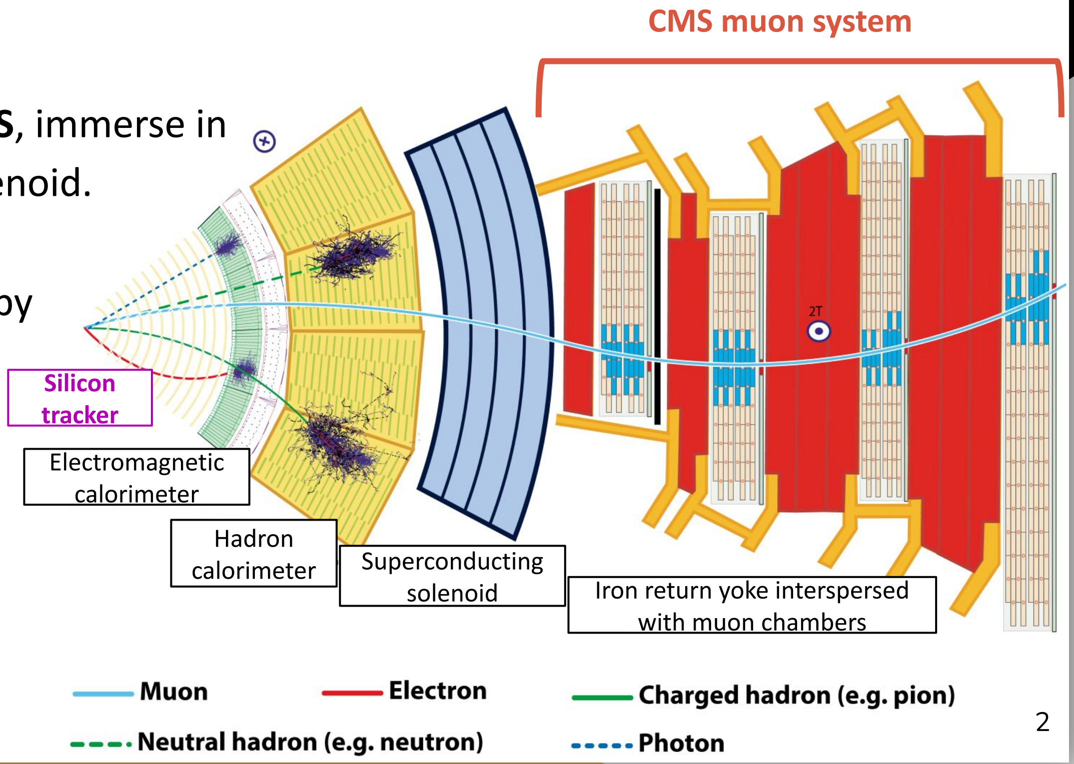
CMS muon system

The **CMS muon system** is built to identify muons and measure their momenta and contribute to the CMS trigger system.

It is located in the **outermost region of CMS**, immerse in the external **magnetic field** of the CMS solenoid.

In the barrel, each muon station is formed by two separate muon detection systems:

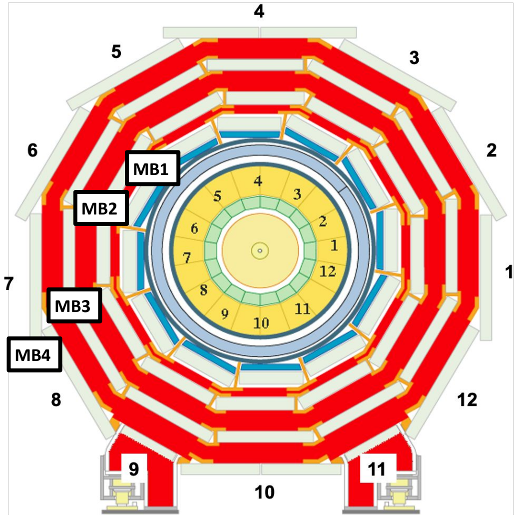
- The **drift tube (DT) system**.
- The **resistive plate chambers (RPC) system**.

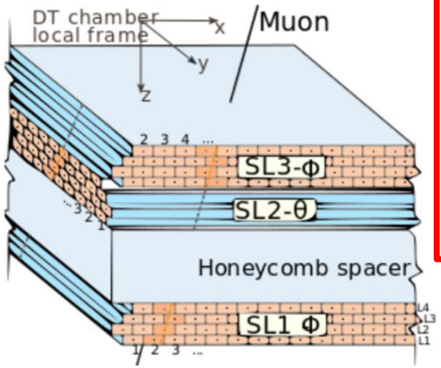


The CMS drift tube system

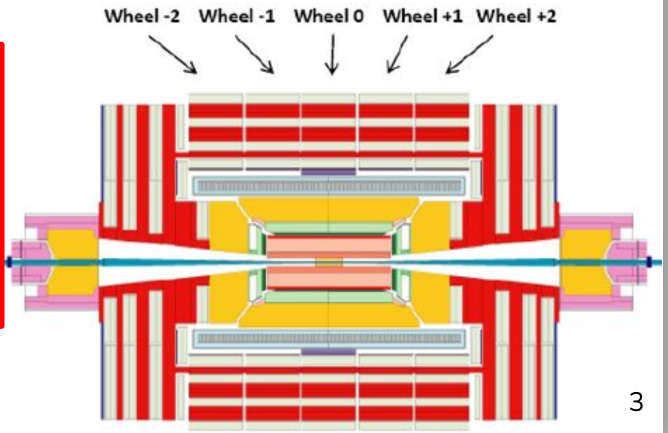
The **drift tube (DT) system** measures and identifies muon tracks.

- ➢ **250 DT chambers** arranged in 5 wheels and 12 sectors each, having 4 radial stations per sector: MB1, MB2, MB3 and MB4.
- ➢ Chambers are divided into **3 superlayers** (MB4 only 2), with 4 layers each, containing the drift cells which allows to measure the passage of muons with **superb spatial (~100 µm)** and **time (~2 ns) resolution** in high quality offline reconstruction [*JINST* **19** P05064].





It also provides an **independent and efficient barrel muon trigger**, with a performance limited by Phase 1 on-detector electronics rough **time digitization 12.5 ns**.

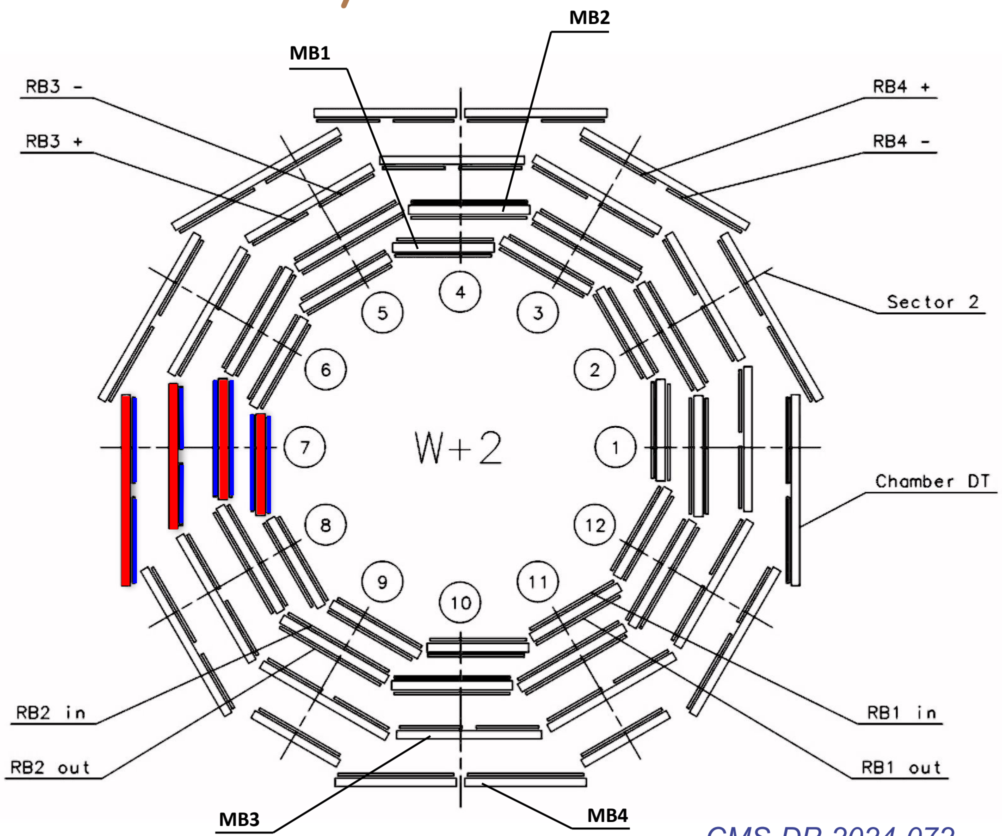


The CMS resistive plate chamber system

The **resistive plate chamber (RPC) system** are fast gaseous detectors:

- **Excellent intrinsic online time resolution (~1.5 ns)**[*JINST* **19** P05064].
  - **Hits are sampled every 25 ns**, matching the LHC bunch spacing.
- Complements DTs information during trigger.

➢ **480 RPCs (blue)** distributed among DTs **(red)** in 5 wheels and 12 sectors each, having 4 radial stations per sector: RB1, RB2, RB3 and RB4.



CMS-DP-2024-072

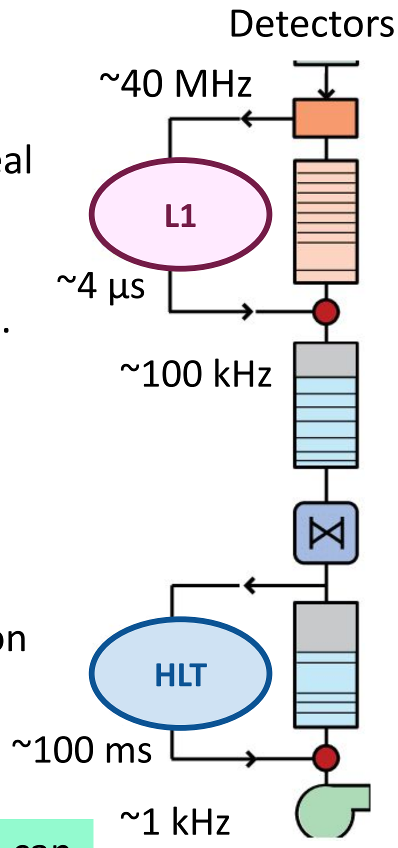
The CMS trigger system

CMS has a two-level trigger system to select the most interesting collisions in real time [CMS-TRG-12-001]:

- **Level 1 (L1) trigger**
  - based on information provided by the **muon system** and **calorimeters**.
    - **Trigger Primitives (TP).**
  - deliver its decision **~4 μs after the particle collision**.
  - input rate ~40 MHz → output rate ~100 kHz.

The complete detector is read upon receiving a Level-1 Accept (L1A) signal.

- **High Level Trigger (HLT)**
  - use information from the **full detector**: tracker+calorimeters+muon system.
  - **stricter identification and quality criteria**.
  - input rate ~100 kHz → output rate ~1 kHz.



Protons beams collide **every 25 ns (bunch-crossing, BX)** + Trigger operation rules **inhibit firing two next consecutive BX** = **Trigger on an earlier BX** can lead to the **loss of potentially interesting collisions**.

JINST 15 (2020) P10017

CMS Level-1 Barrel Muon Trigger in Phase 1

1. The **DT local trigger** builds trigger segments → **position and direction** + identify the **collision bunch-crossing** (BX)

2. The **TwinMux** tests the geometrical matching of RPC hit clusters with DT trigger segments

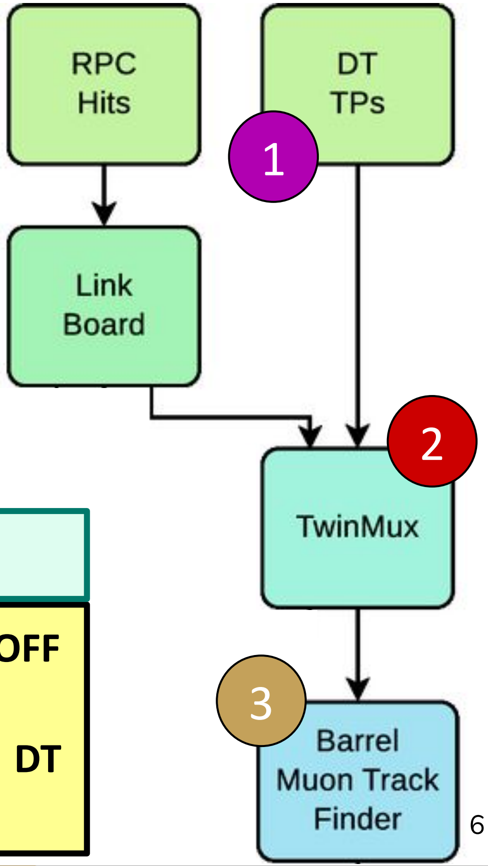
- **improve BX identification** in each chamber → RPC excellent time resolution.

3. **Barrel Muon Track Finder** (BMTF): requires **at least two TPs** in two different stations with the **same BX** to build a trigger track.

It is important a correct identification of the collision BX at TP level.

Over the CMS Run 3, **~30% of the CMS barrel RPCs are kept OFF** [*CMS-DP-2024-072*].

In regions where RPCs are OFF (or not properly working) → **the DT trigger timing is re-optimized to minimise prefiring.**



TP BX mis-ID

The **Trigger Primitive Bunch Crossing misidentification (TP BX mis-ID)** is defined to quantify both the performance of DTs and the role of RPCs in identifying BX:

$$\text{TP BX mis} - \text{ID}^{(1)} = \frac{\text{TP }(\text{BX} = -1)}{\text{TP }(\text{BX} = 0)} \qquad \text{TP BX mis} - \text{ID}^{(2)} = \frac{\text{TP }(\text{BX} = -2)}{\text{TP }(\text{BX} = 0)}$$

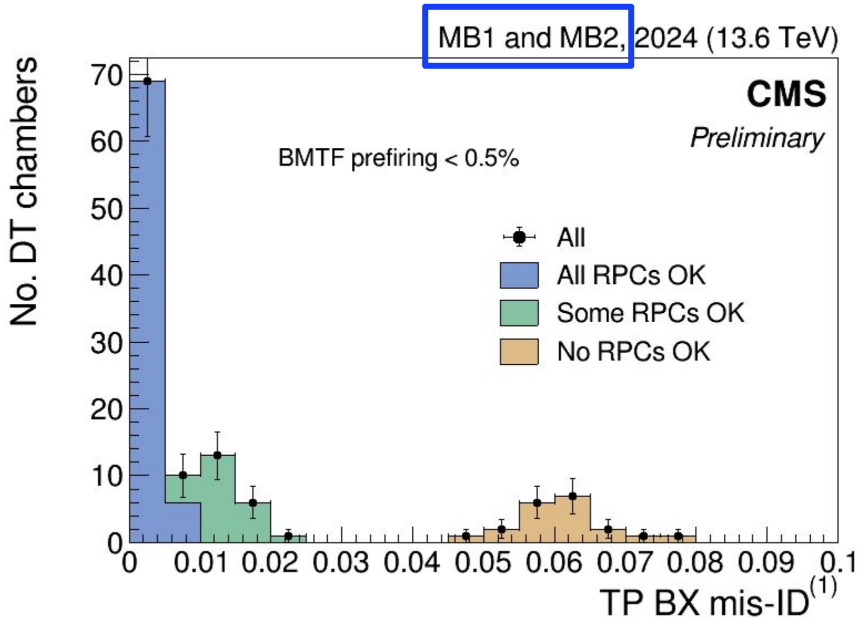
where TP(BX=0,-1,-2) are the number of TPs assigned to BX=0,-1,-2 respectively, BX=0 being the correct event bunch crossing.

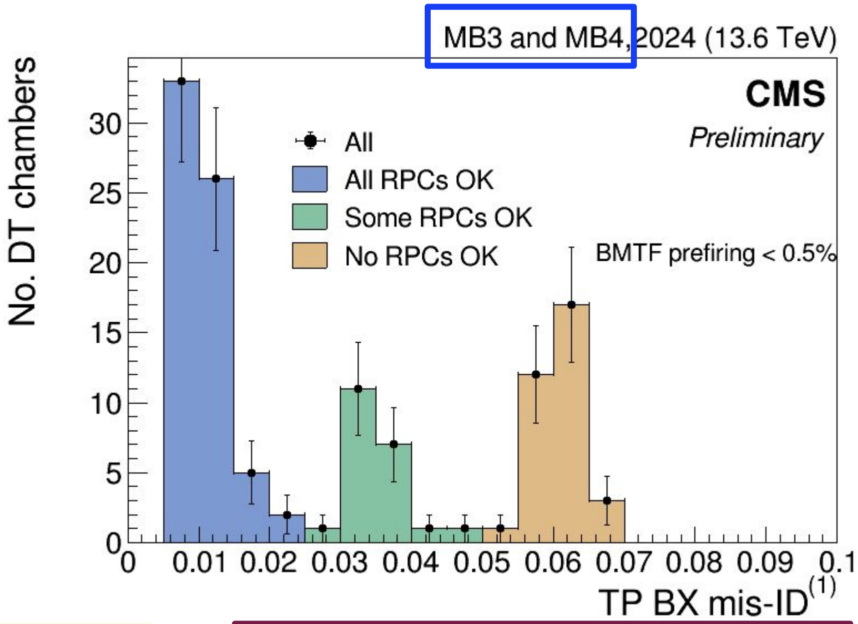
- It is computed applying the *tag and probe* method [CMS-DP-2025-008].
    - Muons from Z boson decays.
    - The “Tag” muon: a well identified, high quality, triggered muon.
    - The “Probe” track: an unbiased track selected with loose criteria.
- With real data of Run3 and simulations for Phase 2.

TP BX mis-ID for 2024 data

CMS-DP-2025-008

Distribution of **TP BX mis-ID for BX = -1** for all 5 wheels and 12 sectors having 1 entry per DT chamber





DT-only performance shows TP **BX mis-ID ≅ 0.06** for BX=-1.
Operational RPCs significantly **reduce** TP BX mis-ID.

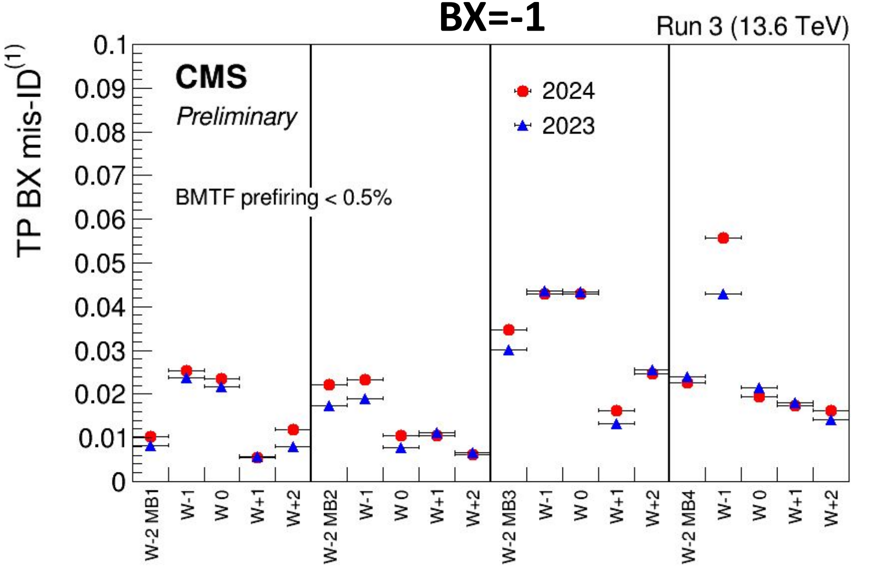
Based on TP BX mis-ID for BX=-1, it is **estimated BMTF prefiring < 0.5%**

CMS-DP-2025-008

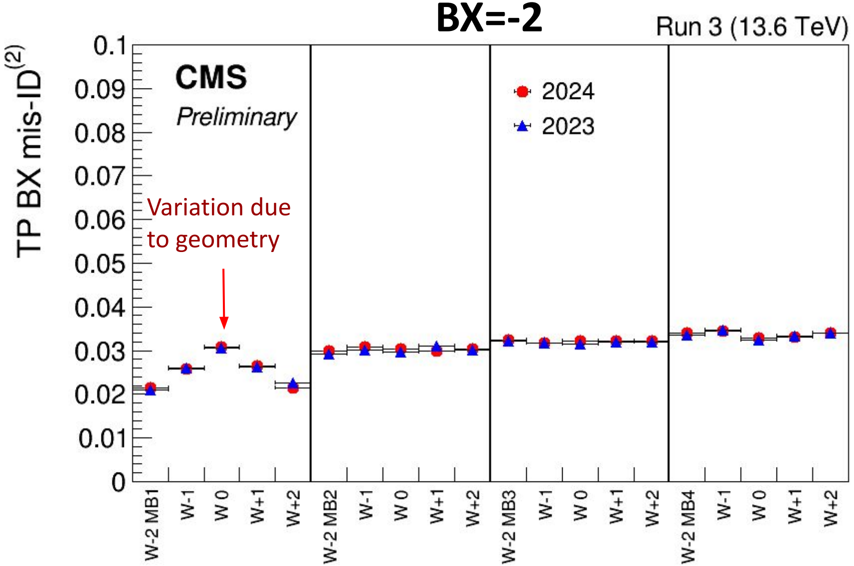
Comparing 2023 and 2024 performance

Distribution of **TP BX mis-ID** per DT wheel/station ring, integrating over the 12 DT sectors.

BX=-1



BX=-2



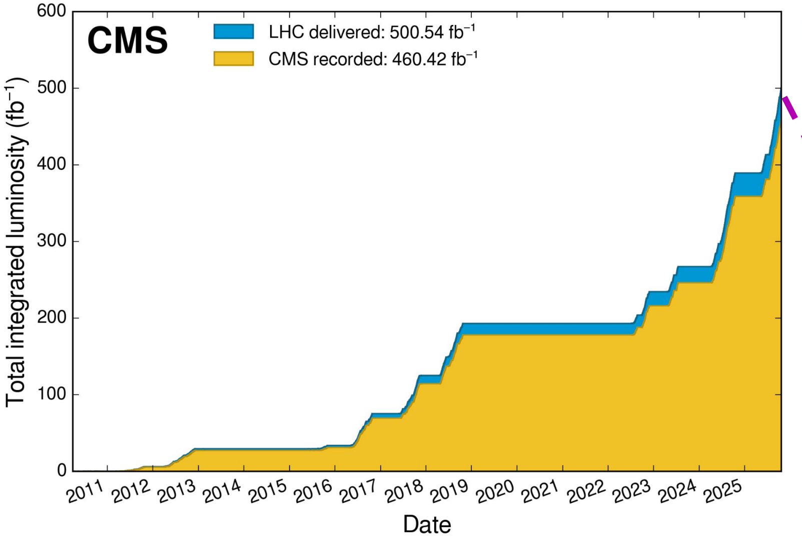
- The year-on-year **differences** and differences within each data set are due to the **number of operational RPCs**.
- **BMTF prefiring <0.5%**

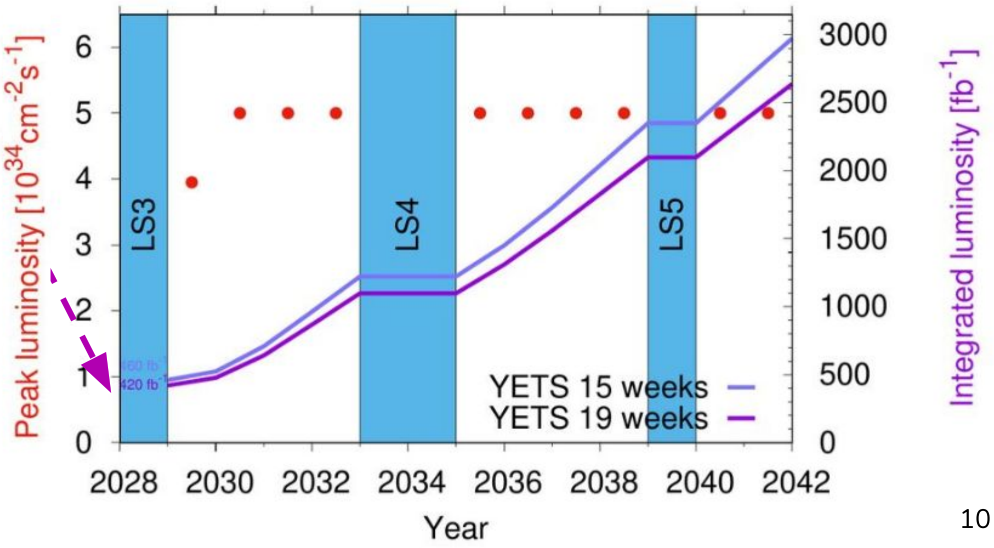
- **Independent of RPCs.**
- **Negligible contribution to prefiring**

HL-LHC and Phase-2

The increase in luminosity for the HL-LHC supposes a challenge to the current (*Phase 1*) DT trigger system:

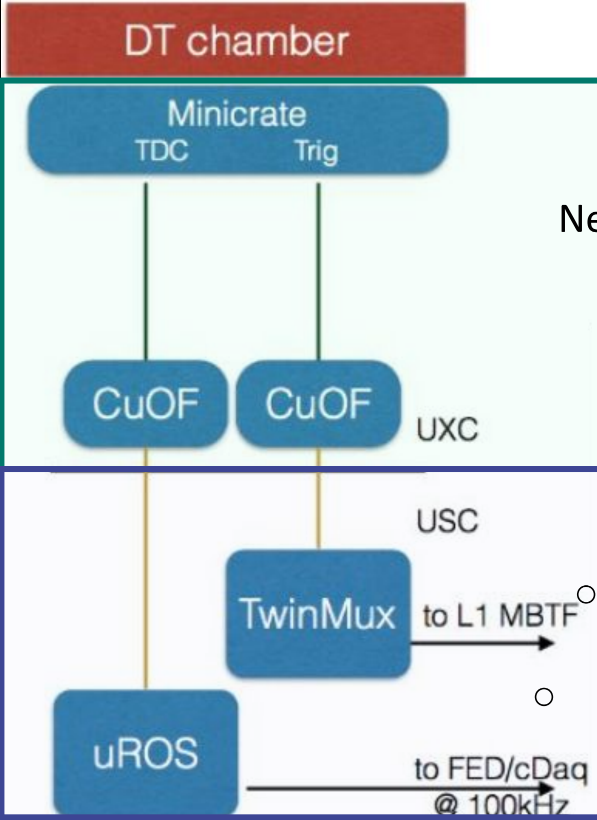
- **Radiation effects** can damage the electronics.
- Phase 1 system allows a maximum trigger rate of ~300 kHz, while for the **HL-LHC a 750 kHz rate is expected**.





The CMS DT Phase 2 Upgrade

Phase 1



Replace **readout** and **trigger electronics**:

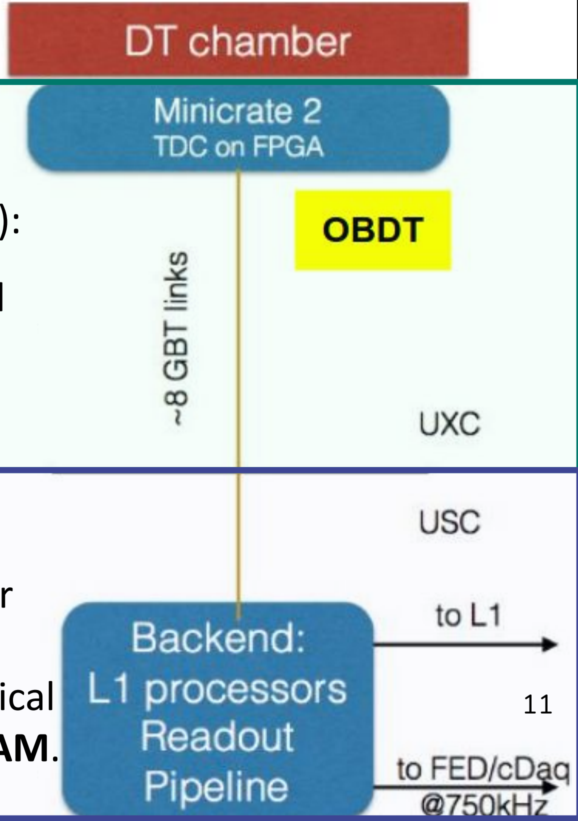
New **On-Board electronics for DT** (OBDT):

- Time measurements implemented in FPGA.

New **Trigger logic system**:

- Sends all chamber hits to the trigger backend.
- Trigger primitive generation by Analytical Method (AM) designed by **CIEMAT+UAM**.

Phase 2



Trigger Primitives in Phase 2

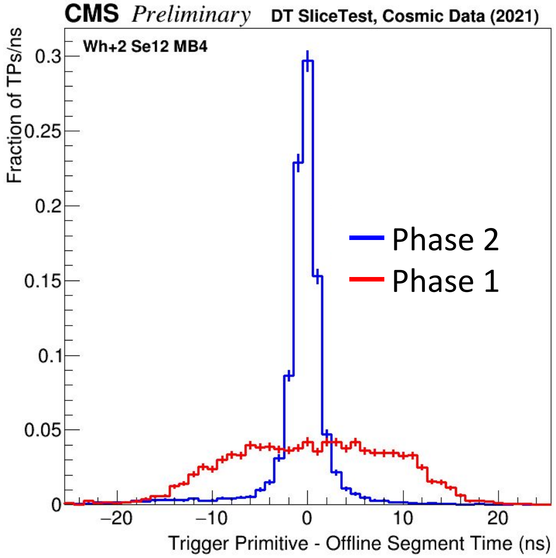
Analytical Method (AM) is the new DT Trigger Primitives Generation (TPG) algorithm implemented for Phase 2:

- It provides **excellent DT TPGs position and time resolution**, achieving ultimate performance (~20 urad and **~2.7 ns or even better** for high-quality TPs) [NIM A 1049, 2023, 168103]
  - ➢ Significant improvement compared to the **12.5 ns online** time granularity of **Phase 1 DT TPGs**.
  - ➢ Incorporating **RPC** in Phase 2 **improves up to 1.9 ns**, less relevant improvement than in Phase 1.

Online performance will be similar to **current offline performance**.

The new trigger logic allows to trigger at any BX! → **Pre-trigger in Phase 2 should not be a concern!**

Performance verified with cosmics and pp collision data!



Phase-2 Slice Test Demonstrator: Prototypes Phase2 on-board electronics (OBDTs) operating in parallel with present system

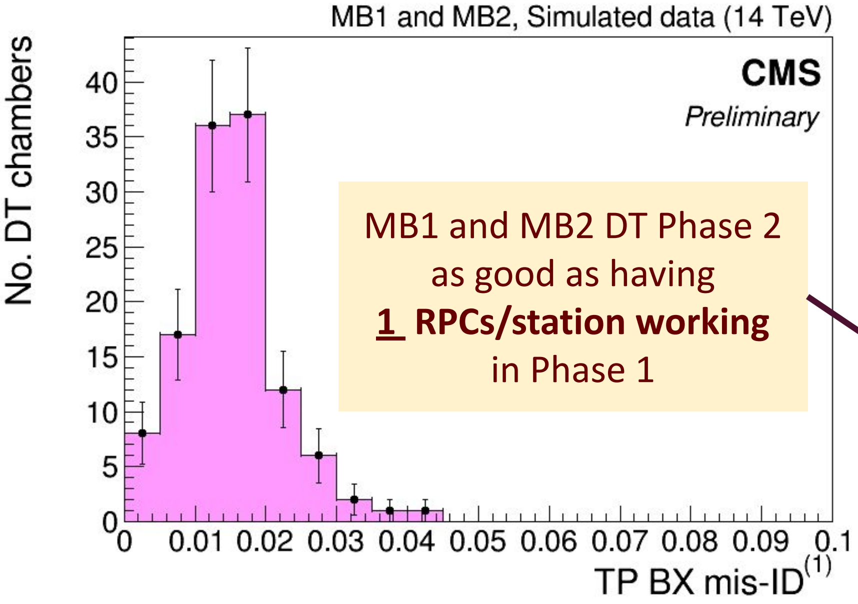
- Installed in the DT sectors 1 and 12 at Wh+2.

[*JINST* **17** C10007]

Phase 2 simulation vs Run 3 data: **BX=-1, MB1, MB2**

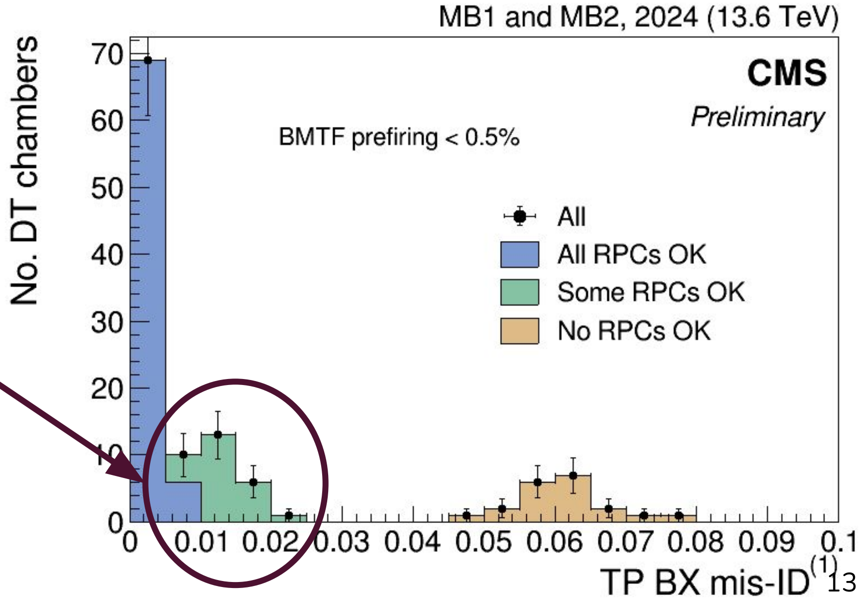
Distribution of **TP BX mis-ID for BX = -1** for all 5 wheels and 12 sectors having 1 entry per DT chamber for stations **MB1 and MB2**

DT-only, No RPCs! **Phase 2**



MB1 and MB2 DT Phase 2 as good as having **1 RPCs/station working** in Phase 1

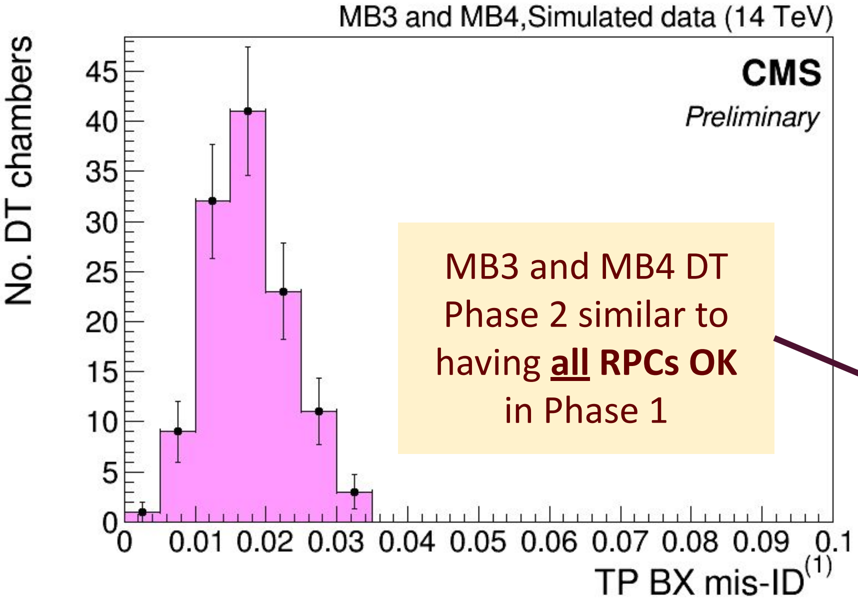
Run 3 data **with RPCs!**



Phase 2 simulation vs Run 3 data: **BX=-1, MB3, MB4**

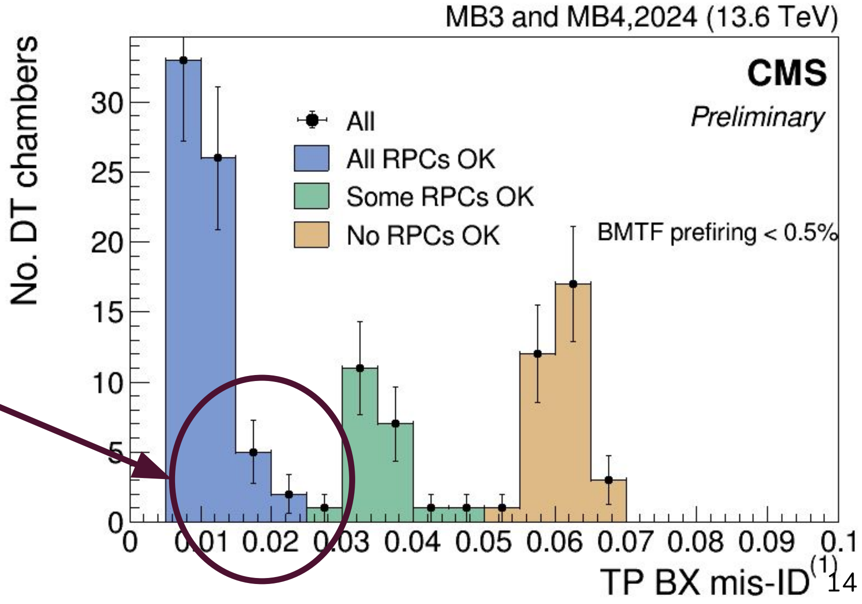
Distribution of **TP BX mis-ID for BX = -1** for all 5 wheels and 12 sectors having 1 entry per DT chamber for stations **MB3 and MB4**

DT-only, No RPCs! **Phase 2**



MB3 and MB4 DT Phase 2 similar to having **<u>all</u> RPCs OK** in Phase 1

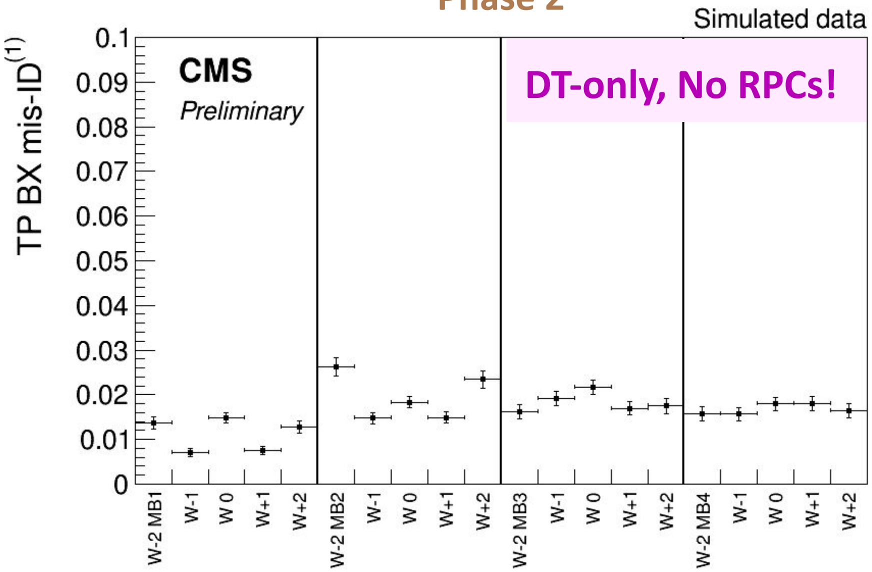
Run 3 data **with RPCs!**



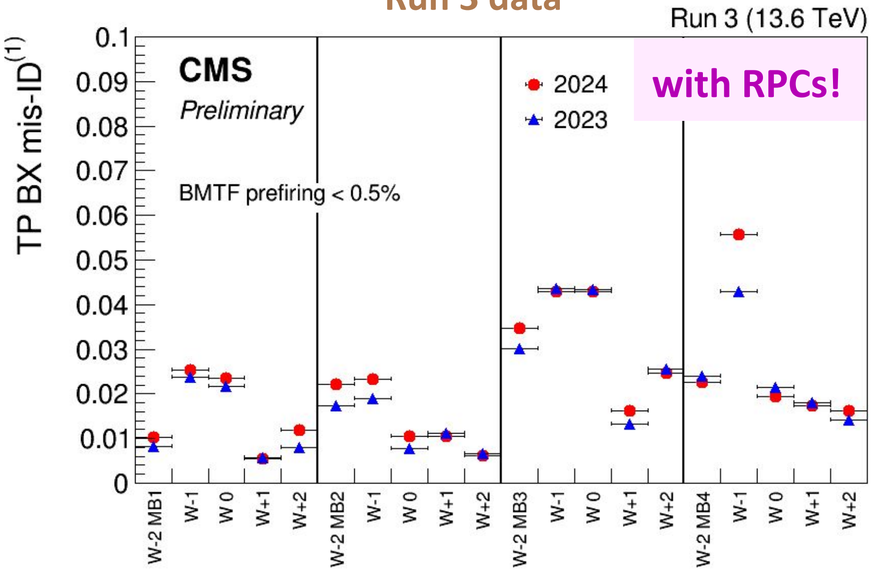
Phase 2 simulation vs Run 3 data: **BX=-1, ALL**

Distribution of **TP BX mis-ID for BX=-1** per DT wheel/station ring, integrating over the 12 DT sectors.

Phase 2



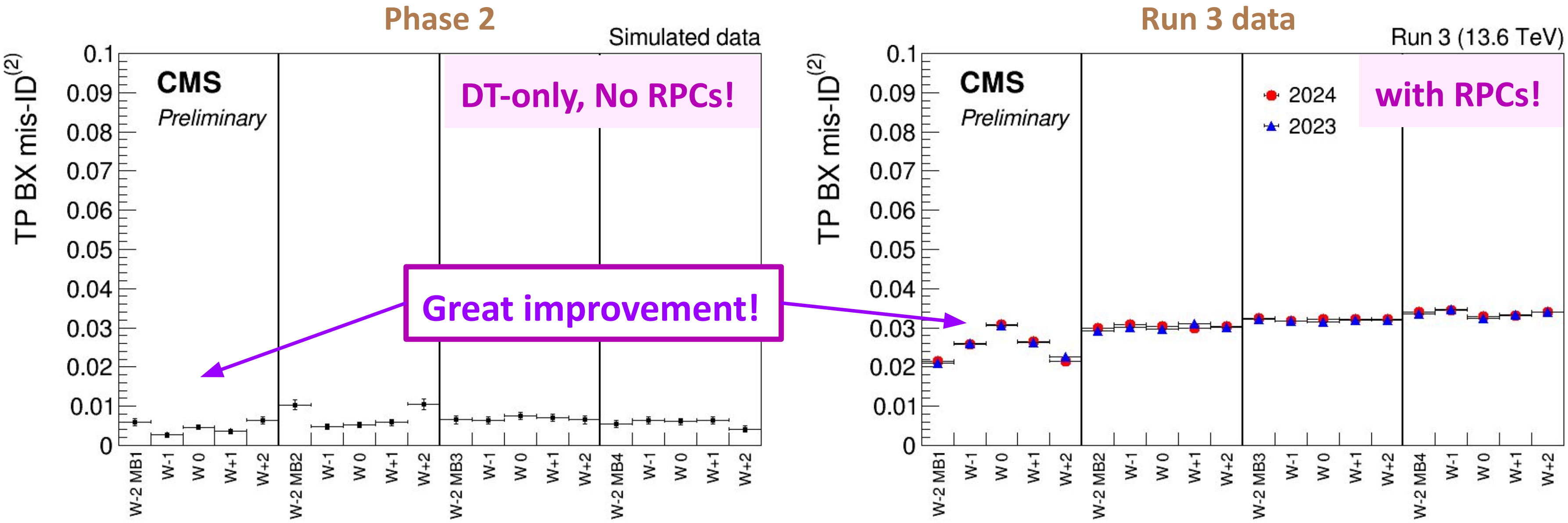
Run 3 data



The average improvement in TP BX mis-ID in Phase 2 suggest a lower pretrigger at the BMTF level in **Phase2 without RPCs** than currently in **Run 3 with RPCs!**

Phase 2 simulation vs Run 3 data: **BX=-2, ALL**

Distribution of **TP BX mis-ID for BX=-2** per DT wheel/station ring, integrating over the 12 DT sectors.



TP BX mis-ID at BX-2 has greatly reduced with the **new DT Trigger Primitive Generator algorithm!**

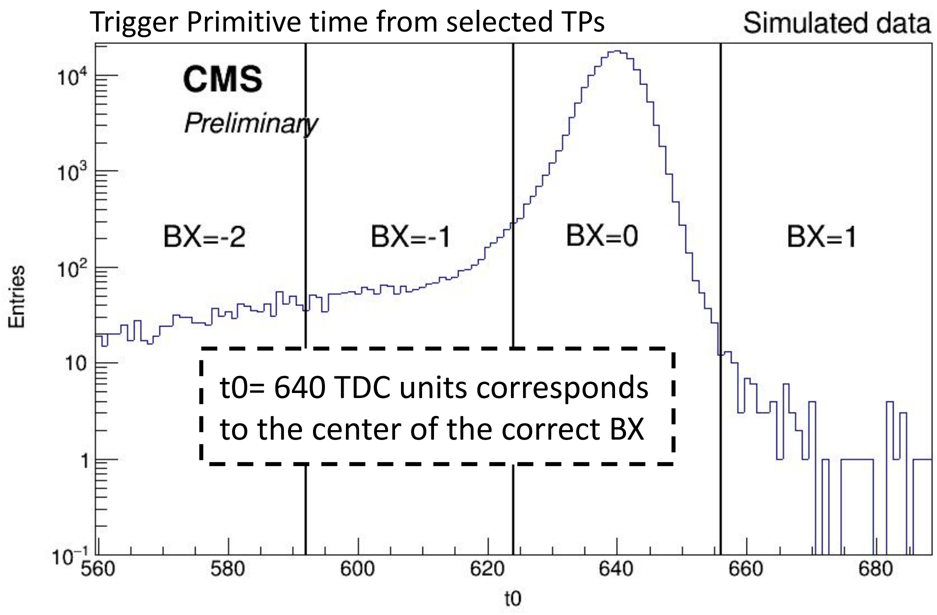
Trigger Synchronization: t0 distribution

- **Phase 2** system allows to adjust the mean of the TP time (t0) at will for each region of the acceptance (even wire by wire)
- An electronics calibration system based on charge injection allows to **control the electronics delays better than 1 ns**.
- Cosmics and Collision data allows to **adjust the position of this mean** from other instrumental effects (TOF, angle) **better than 1 ns** (demonstrated in the slice test)

Time offset can be finely synchronized up to ~1 ns

Trigger Primitive time is measured in **TDC** (Time-to-Digital Converter) units

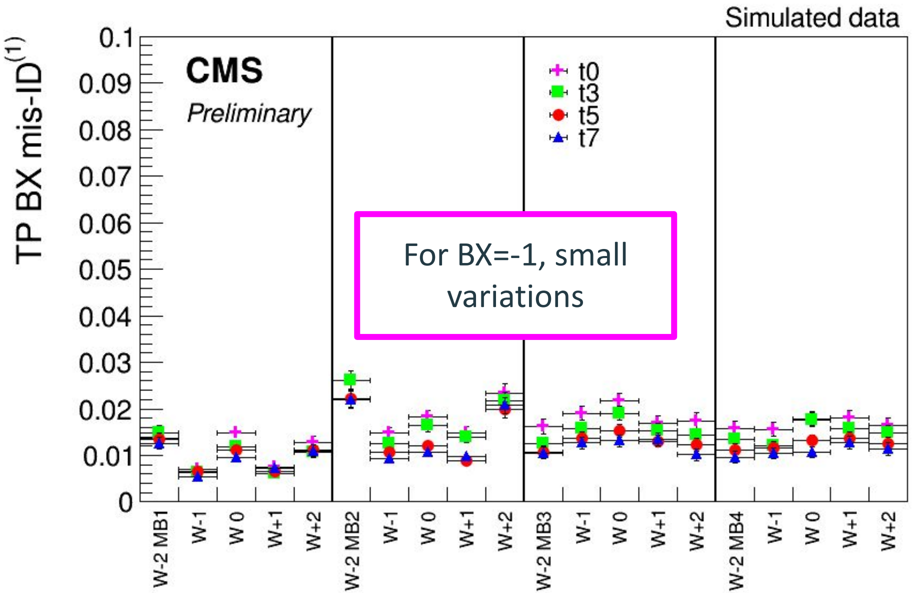
t(ns) = t(TDC) * 25/32

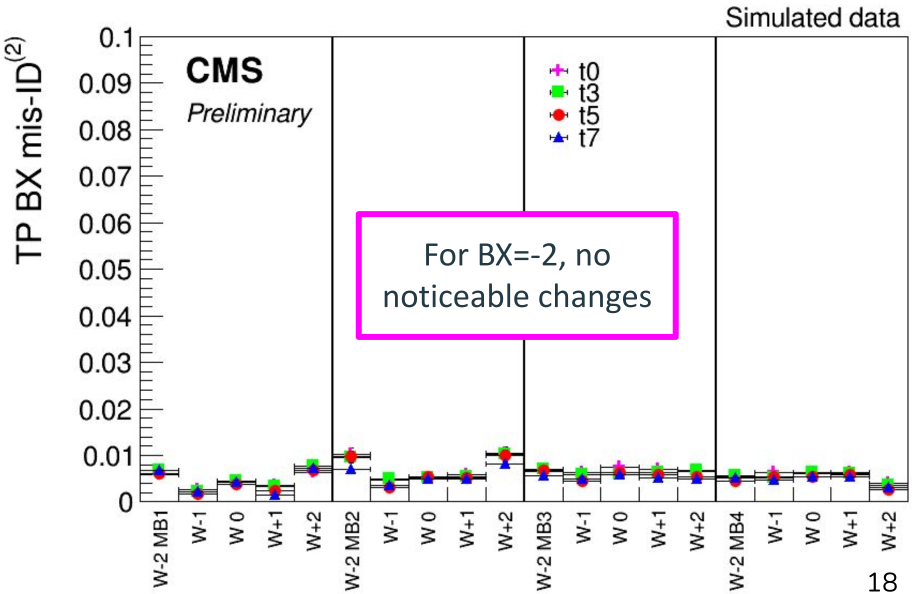


TP BX mis-ID dependence on t0 synchronization

Adding **global** time offset **delays** up to 7 TDC units ≃ **5.5 ns** we find:

- A comfortable range of some ns <u>does not substantially affect TP BX mis-ID.</u>
- The synchronization can be optimized to minimize TP BX mis-ID (as it is done now).



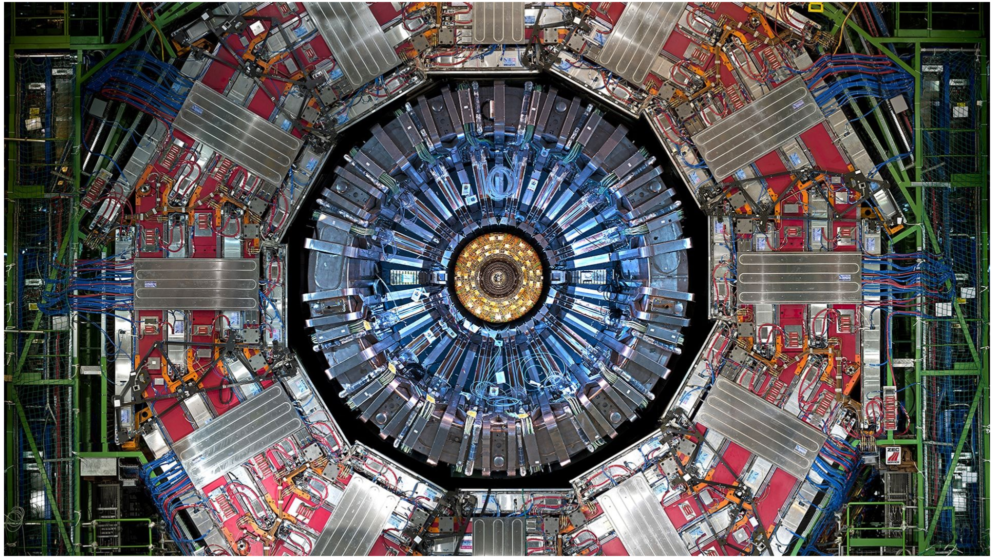


Summary

The upgrade of the CMS Drift Tube system will significantly improve the bunch crossing identification, making the barrel muon trigger more efficient.

- The new Analytical Method (AM) algorithm and Phase 2 readout electronics provide an excellent time resolution of ~2.7 ns or even better for high-quality TPs.
  - Online performance will be similar to current offline performance as demonstrated in the slice test with collisions and cosmic data.
- Phase 2 simulation results of TP BX mis-ID show DT-only performance comparable to or better than Run 3 performance with RPCs.
- It will be possible to optimize up to ~1 ns the DT trigger time synchronization for each readout channel to minimize TP BX mis-ID.

Backup



Computing TP BX mis-ID

Following CMS DP -2025/008

We compute the **Trigger Primitive Bunch Crossing misidentification (TP BX mis-ID) per DT chambers.**

The study is performed applying the *tag and probe* method.

Tag and probe method: all possible pairs of "good" muons (common vertex, a large-enough p_T to fire the trigger and opposite charge) with an invariant mass in the 80 - 100 GeV range.

Tag muon: good quality (Tight Muon ID working point) and matched to an isolated trigger [*].

HLT not simulated in the MC sample!

Probe track:

- Probe in DT acceptance: $|eta| < 1.2$
- Distance to the primary vertex: $|d_{xy}| < 0.2$ cm and $|d_z| < 0.5$ cm
- Number of valid pixel hits > 0
- Number of valid tracker layers > 5
- Relative track isolation (0.3 cone) [*] < 0.1

Requirements on the Tracker track as in the Tight Muon ID [*]

[*] *JINST* 13 (2018) P06015

Computing TP BX mis-ID → Following [CMS DP -2025/008]

To compute the TP BX mis-ID probability we consider the probes that have **at least one segment in two muon stations** consistent with the track projection from the Tracker to the Muon System (these are called *matched segments*).

- Within each DT chamber crossed by the probe extrapolation, we select the *matched segment* as the segment closest to the probe using $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$
- Next, within the same chamber, we find all possible TPs with Quality>2 (Phase 2 equivalent of NoSingleL) compatible with the matched segment, requiring $|\Delta x| < 10$ cm, $|\Delta x| = |x_{TP} - x_{seg}|$.
- Finally, we get the bunch crossing of the TP with lowest BX

We compute the **TP BX mis-ID** as:

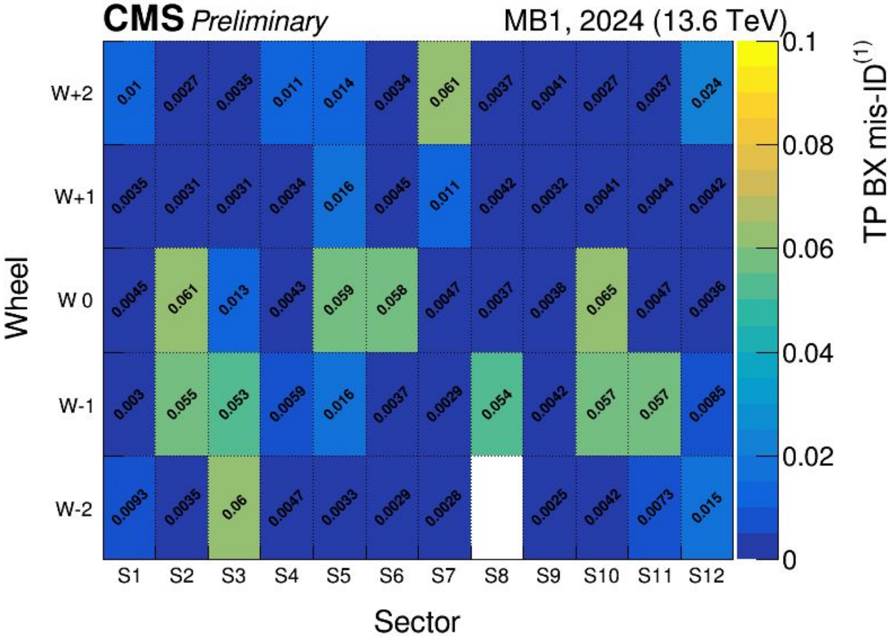
$$\mathrm{TP\ BX\ mis-ID}^{(1)} = \frac{\mathrm{TP\ (BX = -1)}}{\mathrm{TP\ (BX = 0)}} \qquad \mathrm{TP\ BX\ mis-ID}^{(2)} = \frac{\mathrm{TP\ (BX = -2)}}{\mathrm{TP\ (BX = 0)}}$$

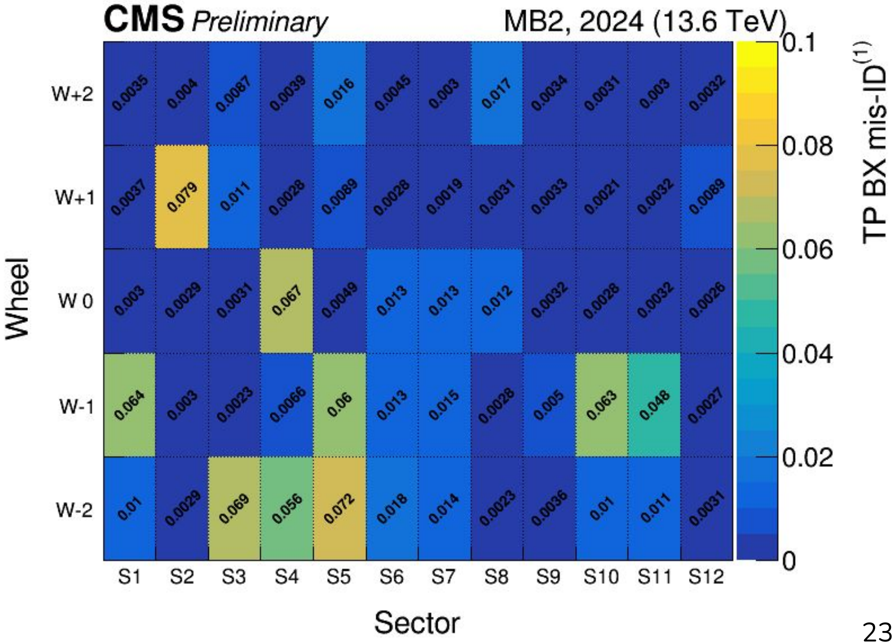
where TP(BX=0,-1,-2) are the number of TPs assigned to BX=0,-1,-2 respectively, BX=0 being the correct event bunch crossing.

2024: TP BX mis-ID map (BX -1): **MB1 and MB2**

CMS-DP-2025-008

Bidimensional map of the **TP BX mis-ID for BX = -1** per DT muon chamber for all 5 wheels and 12 sectors in station **MB1 and MB2**.

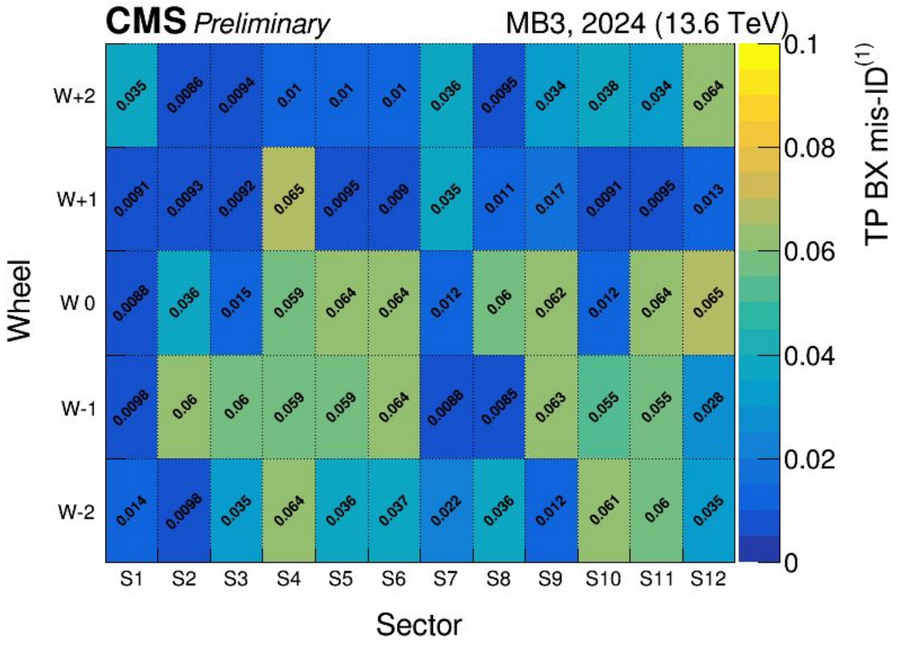


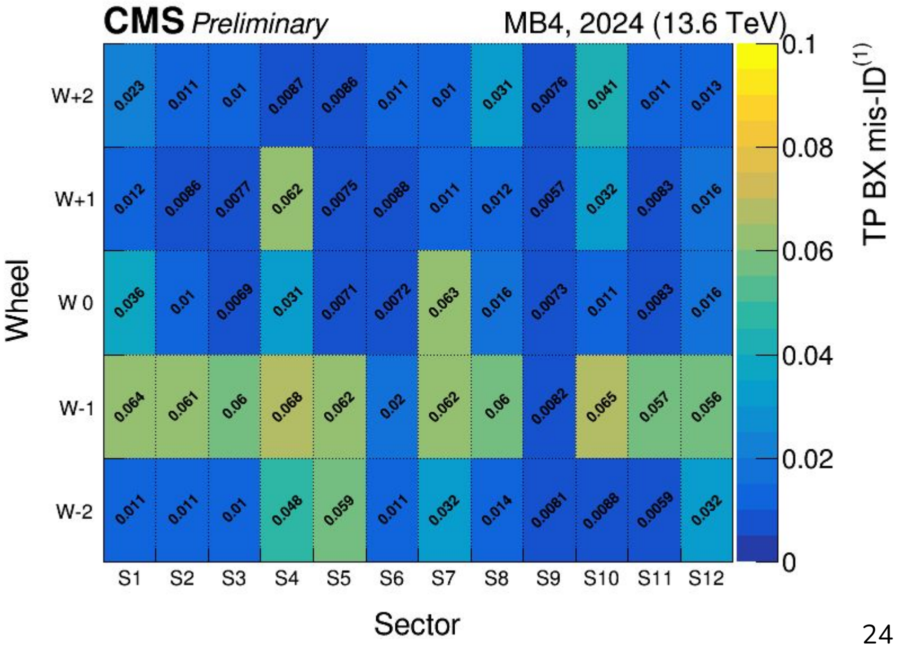


2024: TP BX mis-ID map (BX -1): **MB3 and MB4**

CMS-DP-2025-008

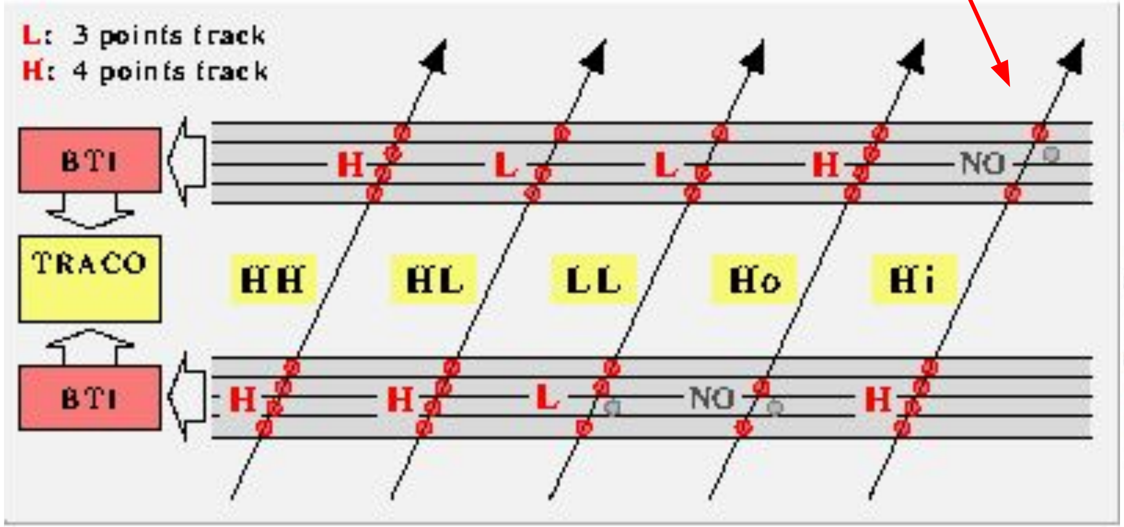
Bidimensional map of the **TP BX mis-ID for BX = -1** per DT muon chamber for all 5 wheels and 12 sectors in station **MB3 and MB4**.

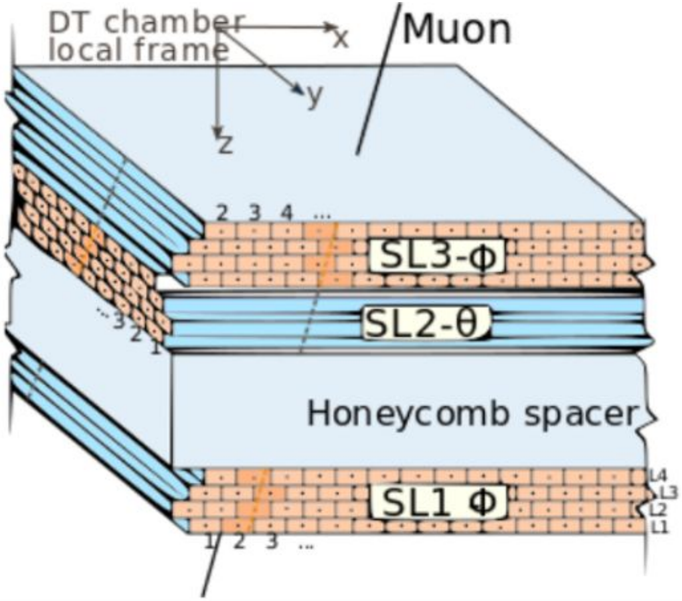




Trigger Primitive quality in Phase 1

At least 3 hits in a SL needed in Phase 1!





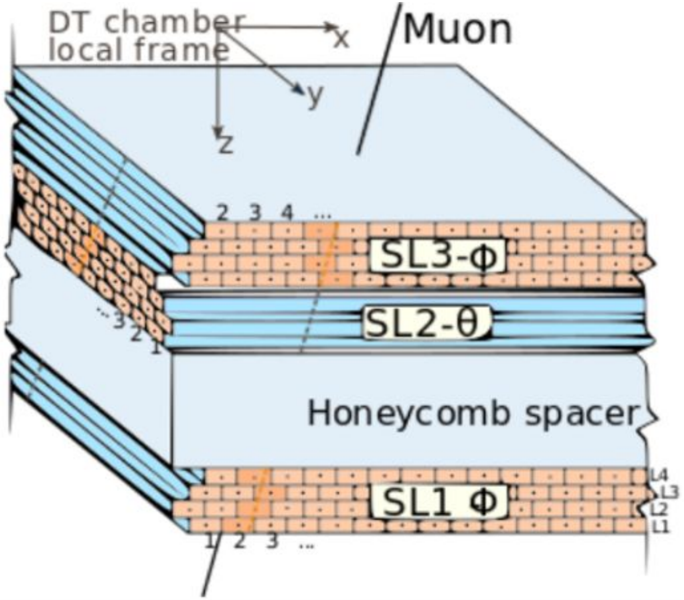
Phase 2 equivalent:	**8**	**7**	**6**	**3**

Trigger Primitive quality in Phase 2

Analytical Method (AM, the new TPG algorithm) produce a quality flag depending on the number and type of hits found in the SLs

Quality	Description	Type
1	3 hit segment	uncorrelated
2	3+2 hit segment	confirmed
3	4 hit segment	uncorrelated
4	4+2 hit segment	confirmed
6	3+3 hit segment	correlated
7	4+3 hit segment	correlated
8	4+4 hit segment	correlated

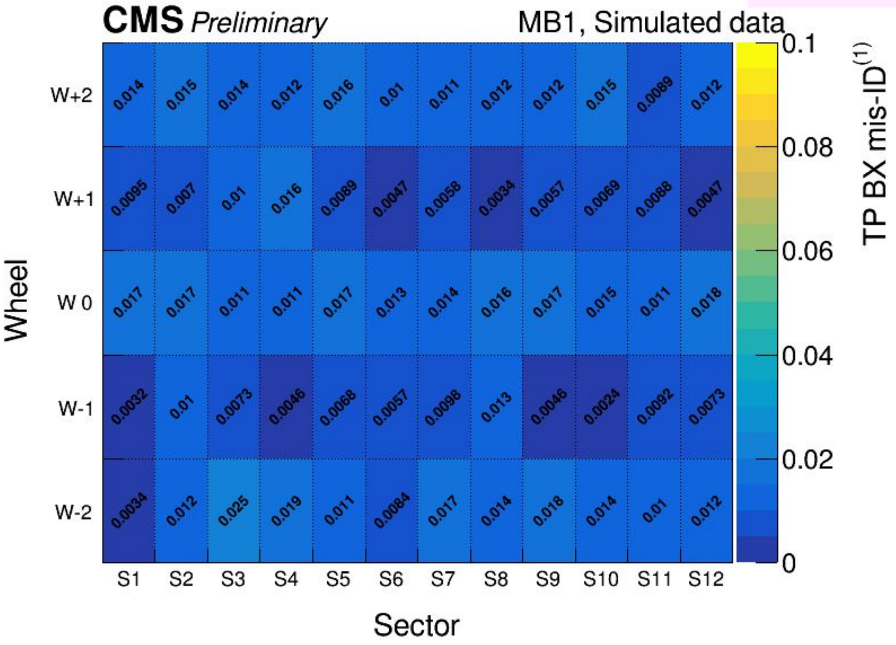
Used now in Run3

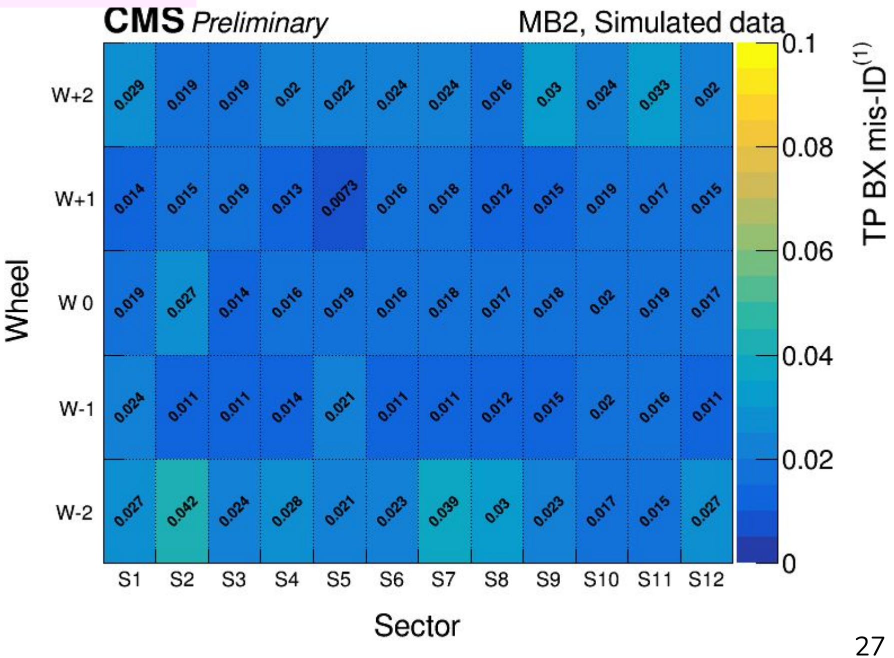


Phase 2: TP BX mis-ID map (BX -1): **MB1 and MB2**

Bidimensional map of the **TP BX mis-ID for BX = -1** per DT muon chamber for all 5 wheels and 12 sectors in station **MB1 and MB2**.

DT-only, No RPCs!

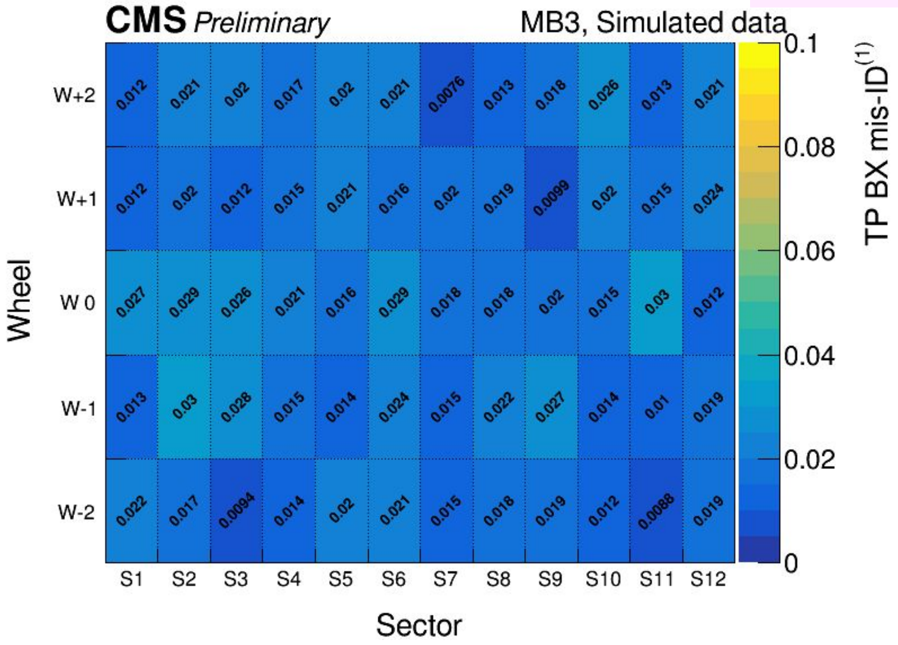


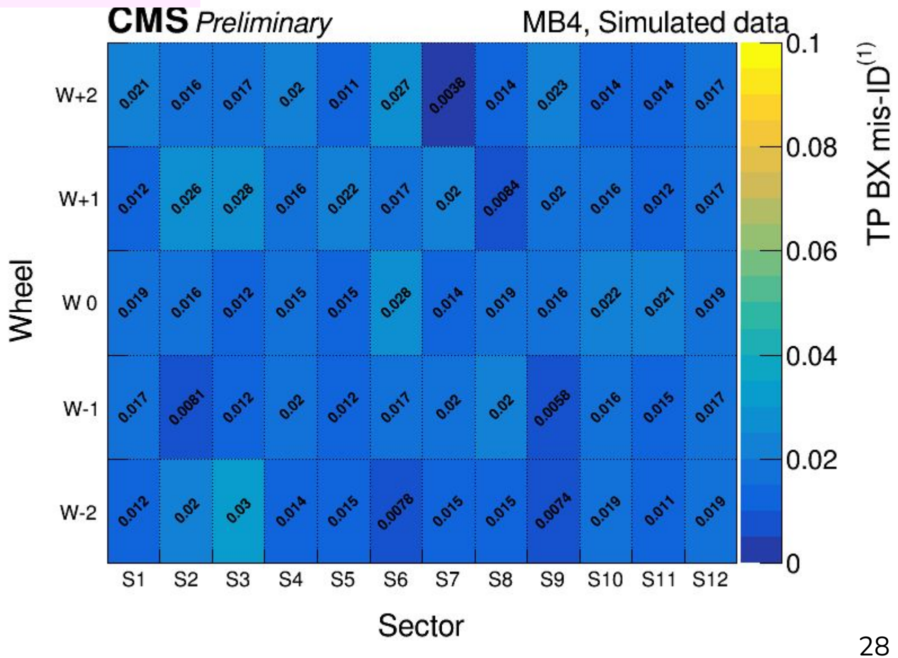


Phase 2: TP BX mis-ID map (BX -1): **MB3 and MB4**

Bidimensional map of the **TP BX mis-ID for BX = -1** per DT muon chamber for all 5 wheels and 12 sectors in station **MB3 and MB4**.

DT-only, No RPCs!

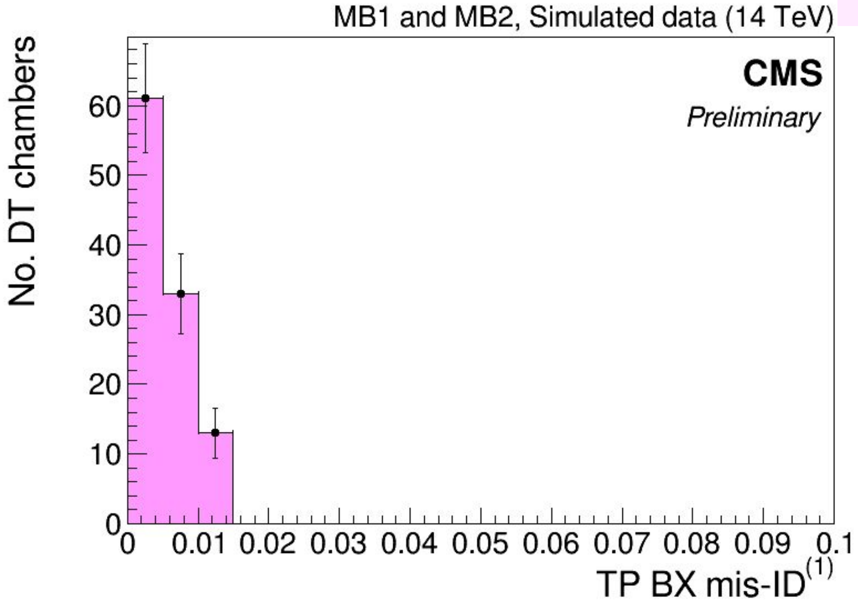




Phase 2 correlated TPs TP BX mis-ID: MB1 and MB2

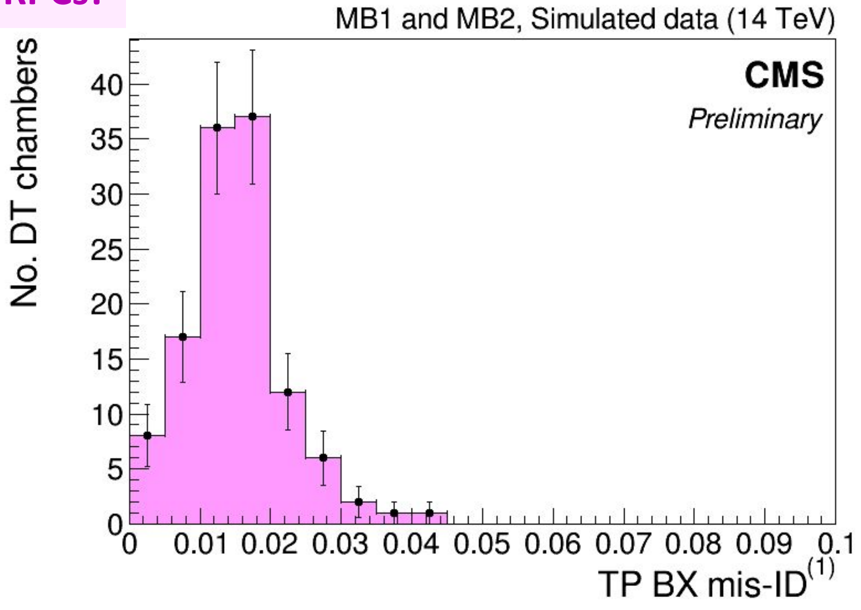
Distribution of **TP BX mis-ID for BX = -1** for all 5 wheels and 12 sectors having 1 entry per DT chamber for stations MB1 and MB2

DT phase 2 correlated TPs



No RPCs!

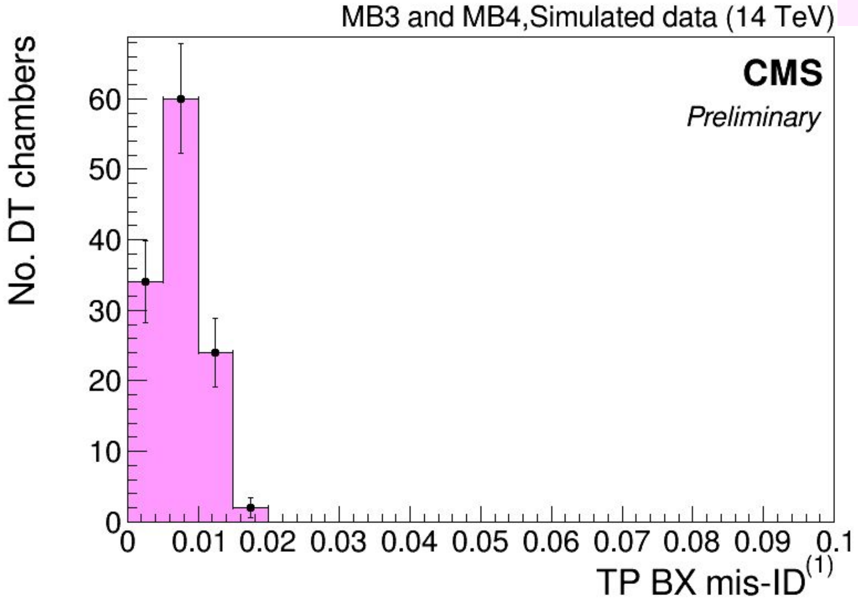
DT phase 2 TPs



Phase 2 correlated TPs TP BX mis-ID: MB3 and MB4

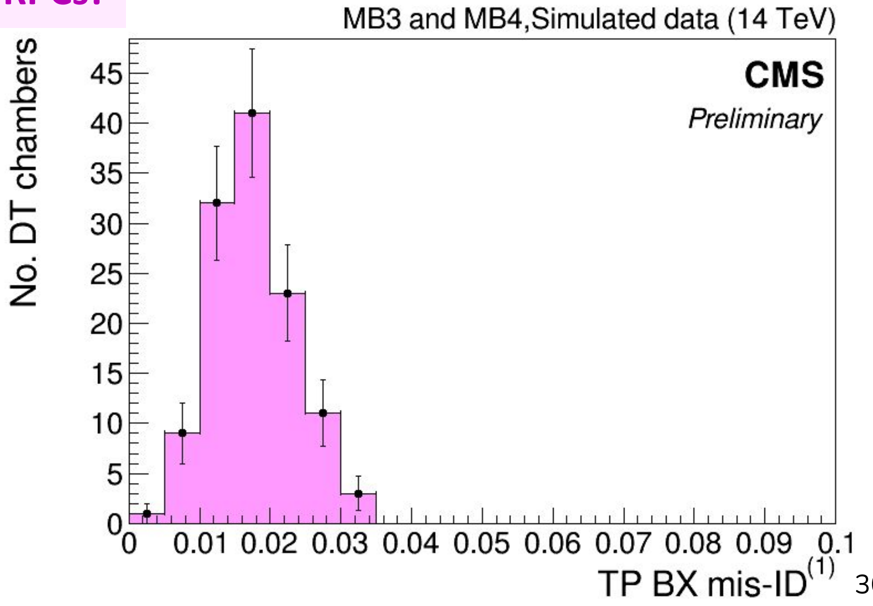
Distribution of **TP BX mis-ID for BX = -1** for all 5 wheels and 12 sectors having 1 entry per DT chamber for stations MB3 and MB4

DT phase 2 correlated TPs



No RPCs!

DT phase 2 TPs



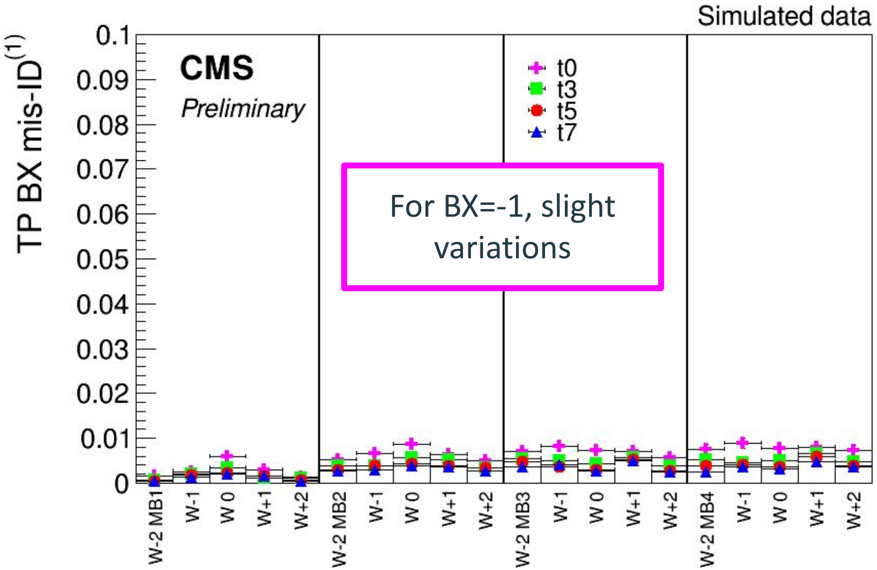
Phase 2 correlated TPs TP BX mis-ID

Adding **global** time offset **delays** up to 7 TDCs ≃ **5.5 ns** we find:

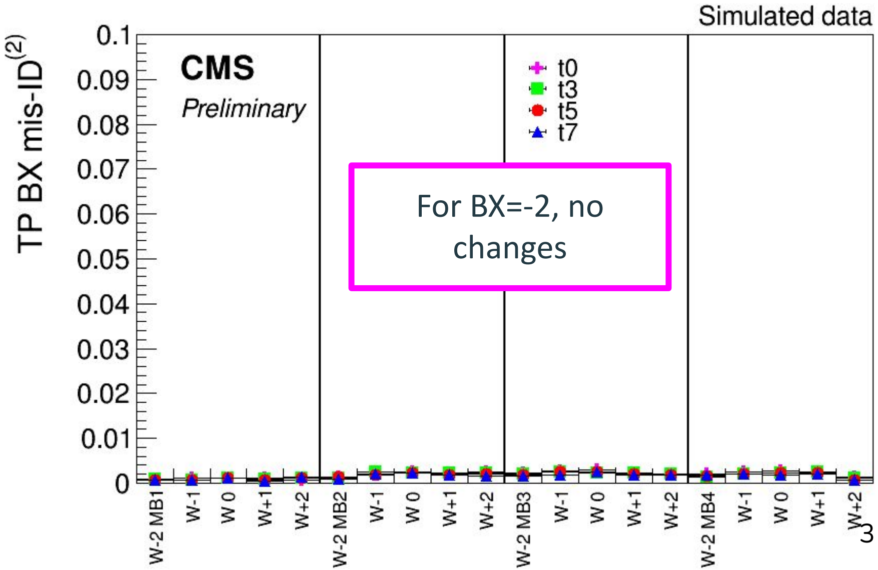
- Correlated TPs are less sensitive to time offset delays.
- For BX=-2 there is no effect!

No RPCs!

For BX=-1



For BX=-2



Slice Test

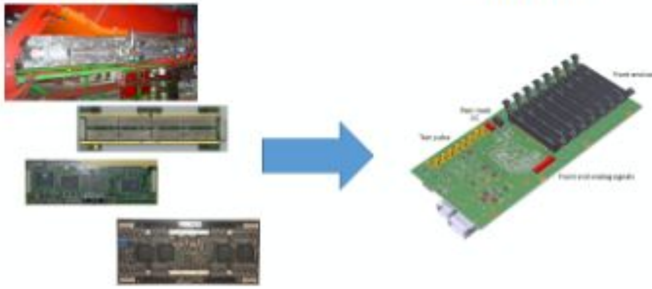
HL-LHC DT electronics front-end and back-end prototypes operating **in parallel with present system** [CMS-DP-2024-090]:

- Installed in the DT sectors 1 and 12 at Wh+2.
- Front-end signal fed both to the Phase 1 and Phase 2 electronics.
- One of the backend boards (the AB7) runs the Analytical Method (AM) firmware.
  - Generates the trigger primitives

Operating regularly during Long Shutdown 2, including cosmics at 3.8 T and now during Run 3 collisions [CMS DP -2022/059].

Phase 1 front-end: Minicrate

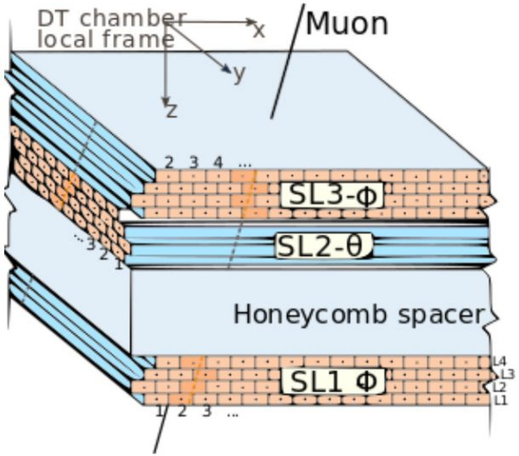
Phase 2 front-end: OBDTs

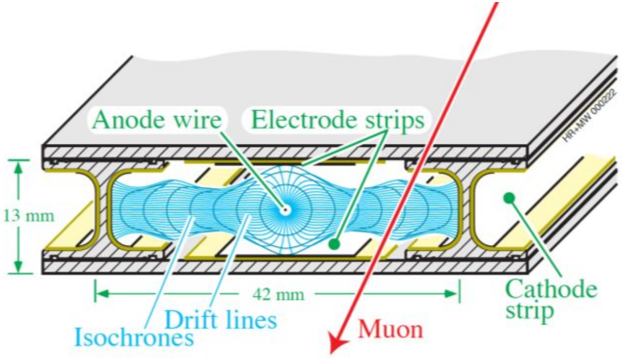


DTs

Tubes are gas-filled cells with a thin central wire (anode). When a **muon** passes through a drift cell:

1. It ionizes the gas, creating electrons and ions.
2. Electrons drift slowly toward the central wire due to the electric field.
3. The **drift time** is measured → gives the distance of the muon from the wire.
4. Multiple layers allow reconstruction of the muon's **position** and **track angle** with high precision.

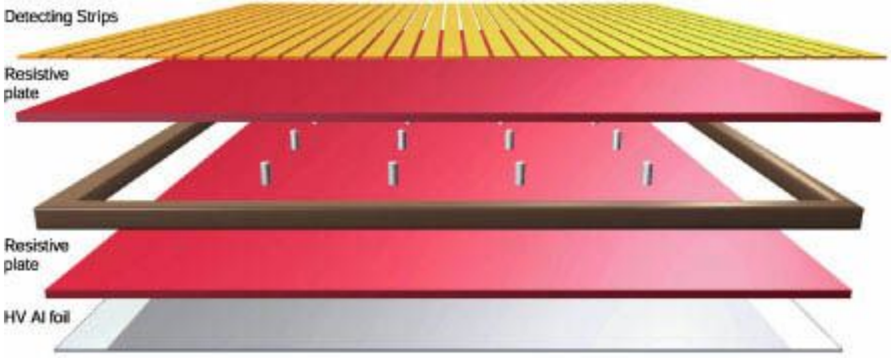


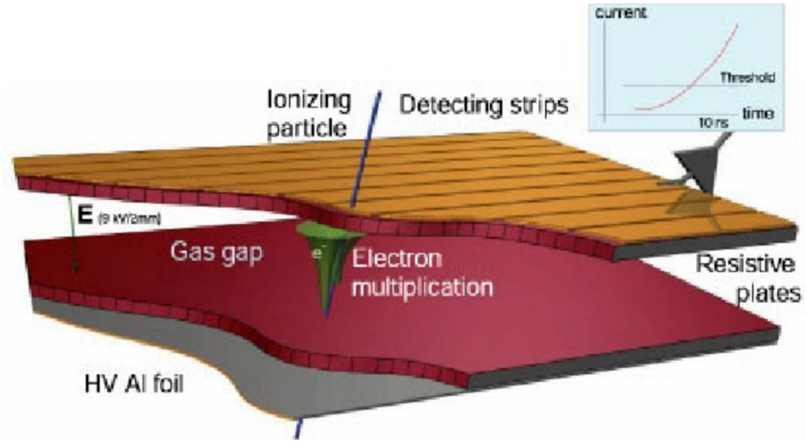


RPCs

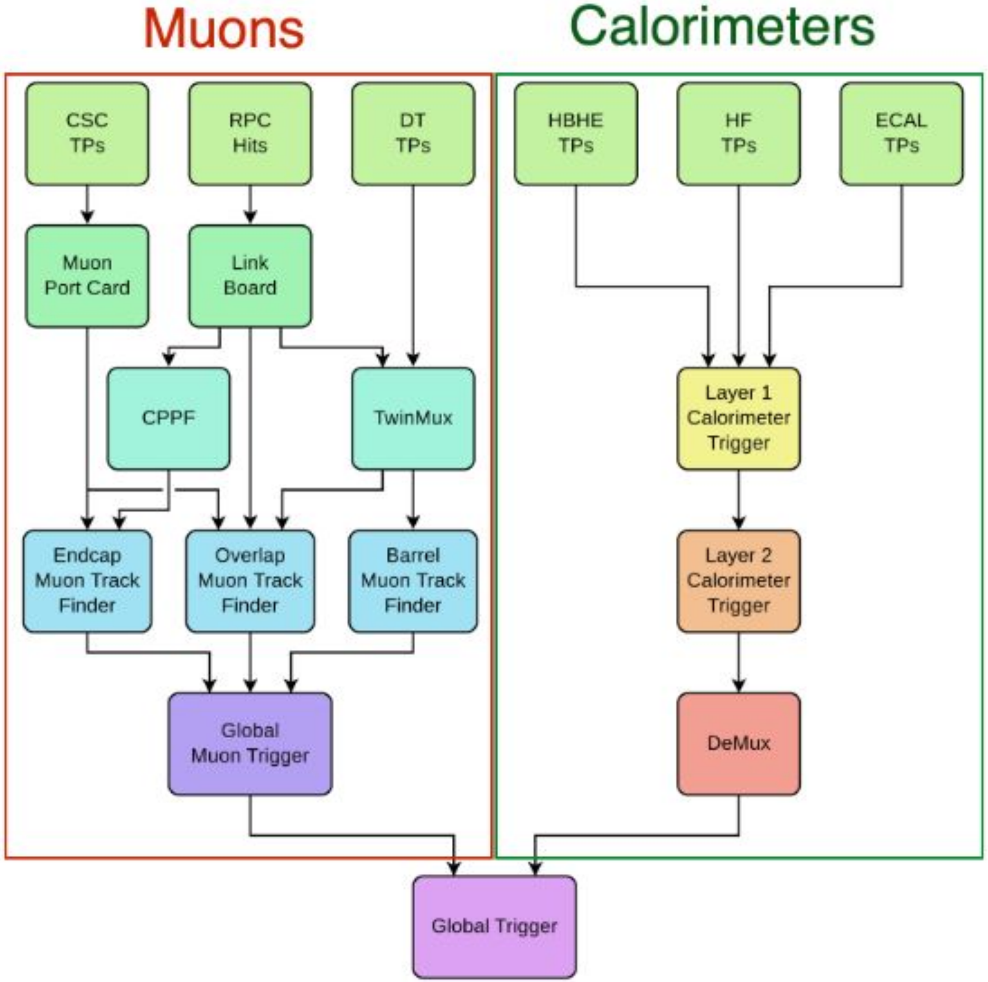
RPCs consist of two resistive plates separated by a thin gas gap under a strong electric field.
When a muon passes through the chamber,:

1. The gas gets ionized.
2. causing a cascade of electron.
3. The cascade is collected by external metallic strips, delivering a fast electrical signal.





L1T scheme


Muons
Calorimeters
CSC TPs
RPC Hits
DT TPs
HBHE TPs
HF TPs
ECAL TPs
Muon Port Card
Link Board
CPPF
TwinMux
Layer 1 Calorimeter Trigger
Endcap Muon Track Finder
Overlap Muon Track Finder
Barrel Muon Track Finder
Layer 2 Calorimeter Trigger
Global Muon Trigger
DeMux
Global Trigger