Muon trigger primitive generation with the Drift Tubes detector at CMS for the HL-LHC

2nd COMCHA Workshop - A Coruña

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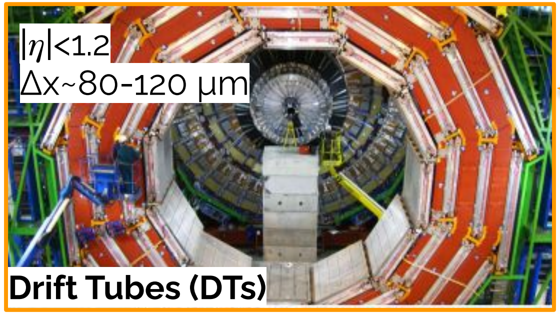
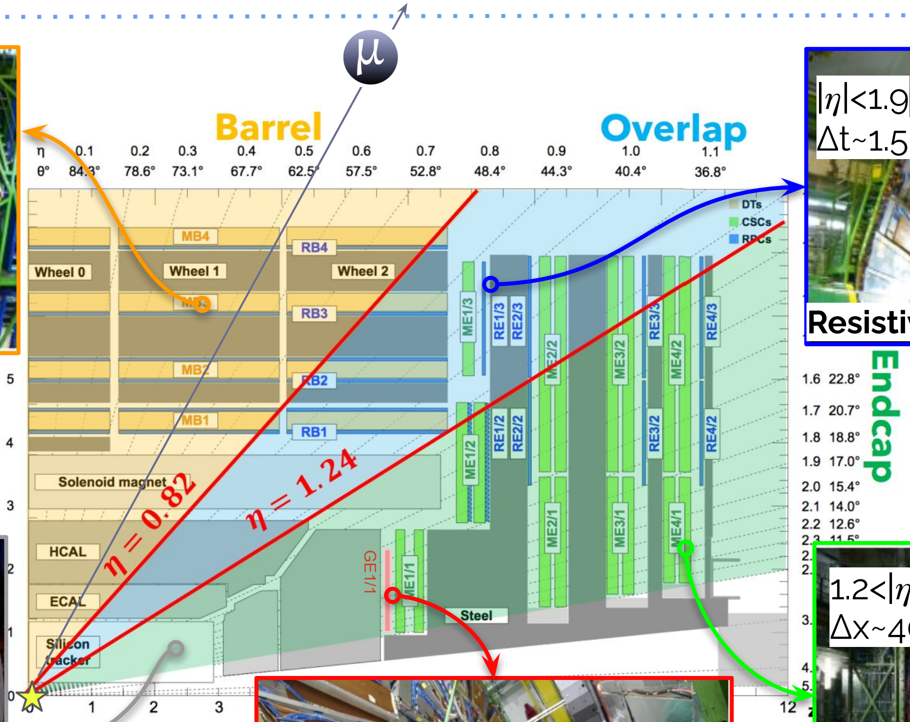
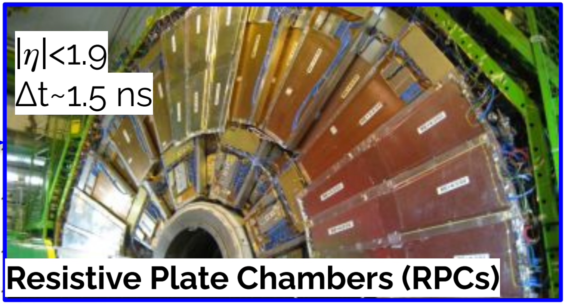
Overview

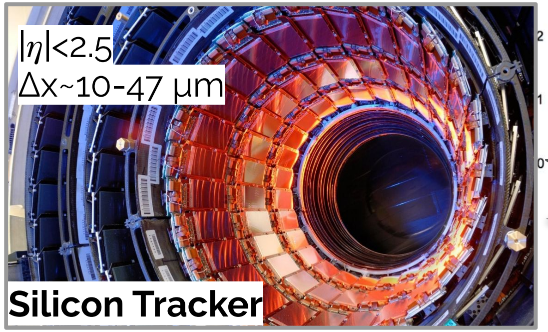
1. **Muon** detection in CMS
2. **Drift Tubes** and triggering system
3. **Analytical Method** algorithm for Trigger Primitive generation
4. **Performance** in simulation, firmware and real data
5. Ongoing and future **improvements**

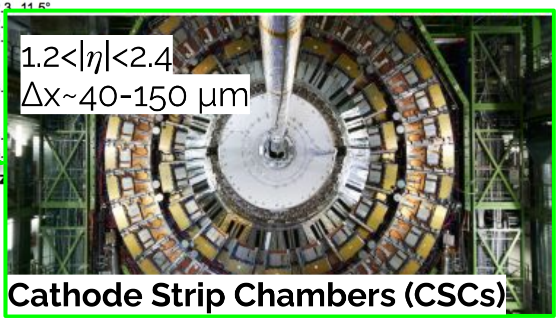
Muon detection with CMS





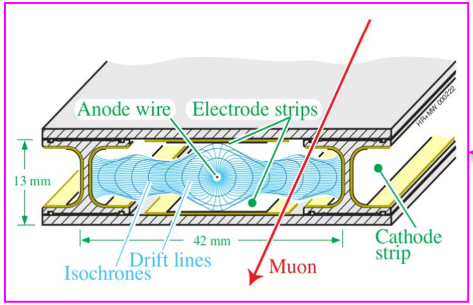




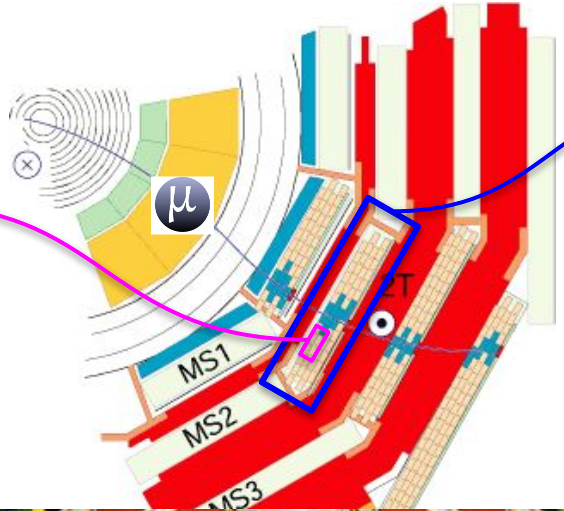


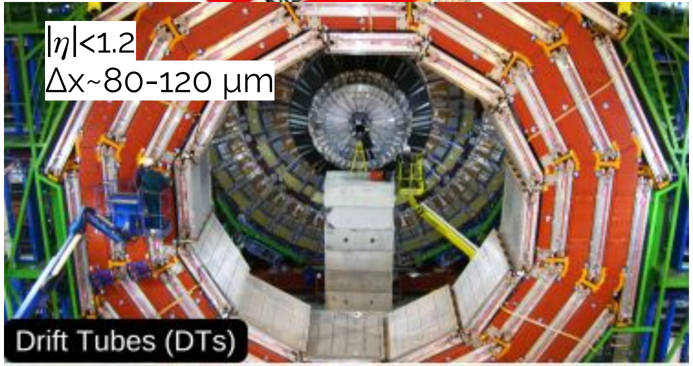
Muon detection with **Drift Tubes** (DTs)

Cells (172.000)

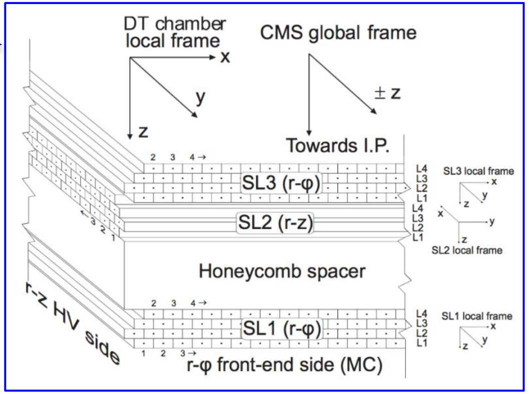


- **42 x 13 mm²**, Ar/CO_2
- Muons ionize the gas, electrons drift towards anode wire at **54 µm/ns**
- Measurement of drift time with a ***laterality*** ambiguity on the hit position





Chambers (250)



- **Superlayer** (SL):
  - 4 layers staggered half a cell
- **Chamber** (250)**:**
  - 2 superlayers measuring the **r-ϕ** coordinates (**SL1**, **SL3**)
  - 1 superlayer measuring the **r-z** coordinates (**SL2**)

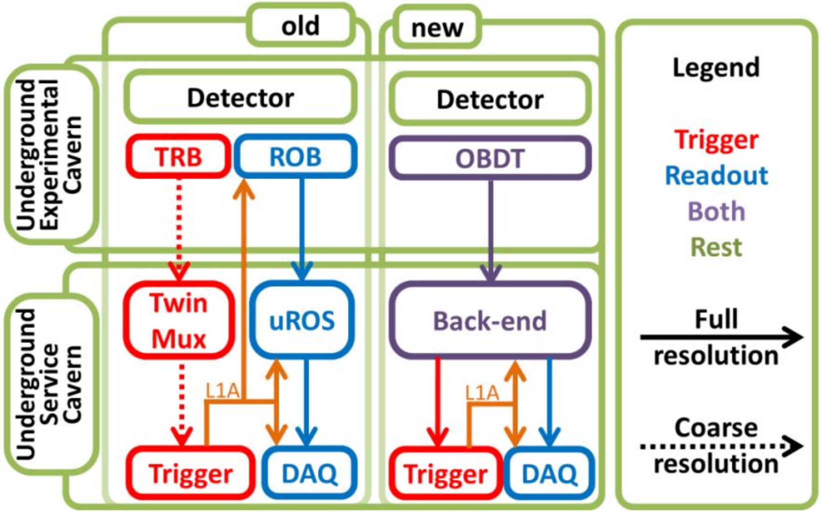
DTs **upgrade** for Phase 2

- **HL-LHC** operations (5–7.5 × 10^{34} cm^{-2} s^{-1}, 750 kHz) require an upgraded DT system:
  - **Current detectors** remain with minimal loss of performance
  - **Current electronics** cannot cope with increased radiation level and expected rates

Upgraded electronics

- On-detector electronics forward all detector information at **full TDC resolution** via **high-speed** serial links

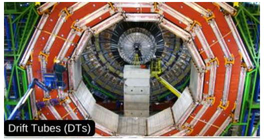
- High-performance **FPGAs** run sophisticated trigger algorithms to reconstruct the muon **trajectory** and identify the **bunch crossing**



DTs **upgrade** for Phase 2

On-board DT **(OBDT)**:
Time digitization **(~1ns)** and sorting of hits per chamber in radiation-tolerant **FPGAs**

DT cells:
Single wire hit signals

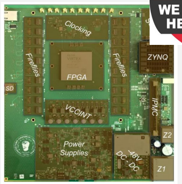


high-speed optical links

WE ARE HERE

this talk

Barrel Muon Trigger Layer-1 **(BMTL1)**:
Full chamber info at full time resolution to generate **trigger primitives** (TPs) in commercial **FPGAs**



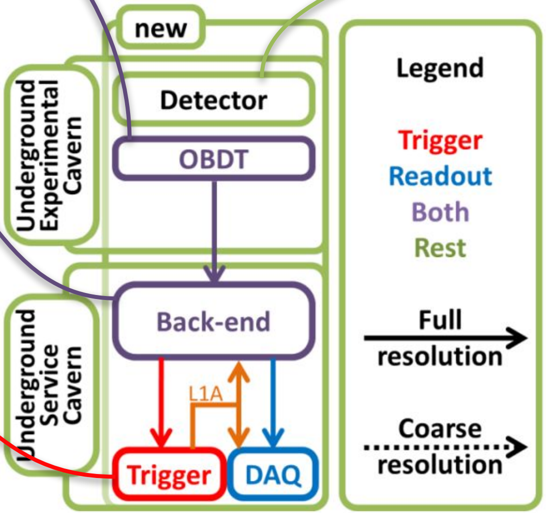
Barrel / Overlap Muon Track Finder **(BMTF/OMTF)**:
Muon pattern recognition to build L1 muons

EMTF

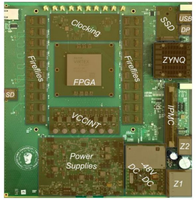
Global Muon Trigger (GMT)

L1

Tracker



Analytical Method algorithm



- Generation of **DT trigger primitives** in **BMTL1**

- **Challenges**:
  - **Harsh** experimental conditions (PU, rates, ageing)
  - Unknown hit arrival **time** (400 ns spread / BX)
  - Ambiguity in the hit **laterality** (left-right)
  - **Offline** reconstruction capabilities in **real time**
  - Easily portable to **FPGA** architecture

- **Analytical Method** (AM) algorithm:
  - Based on **analytical** solutions
  - Implemented for SL(r-ϕ) in **firmware** and C++ **emulator**
  - Tested in **simulation** and Run 3 collision **data**

Hits: [**time**, **cell**]

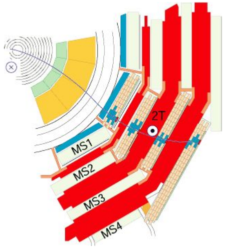
Grouping

Laterality prediction

Fitting

Correlation

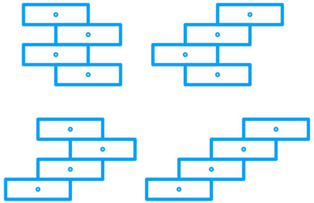
TPs: [**crossing time**, **position**, **direction**]

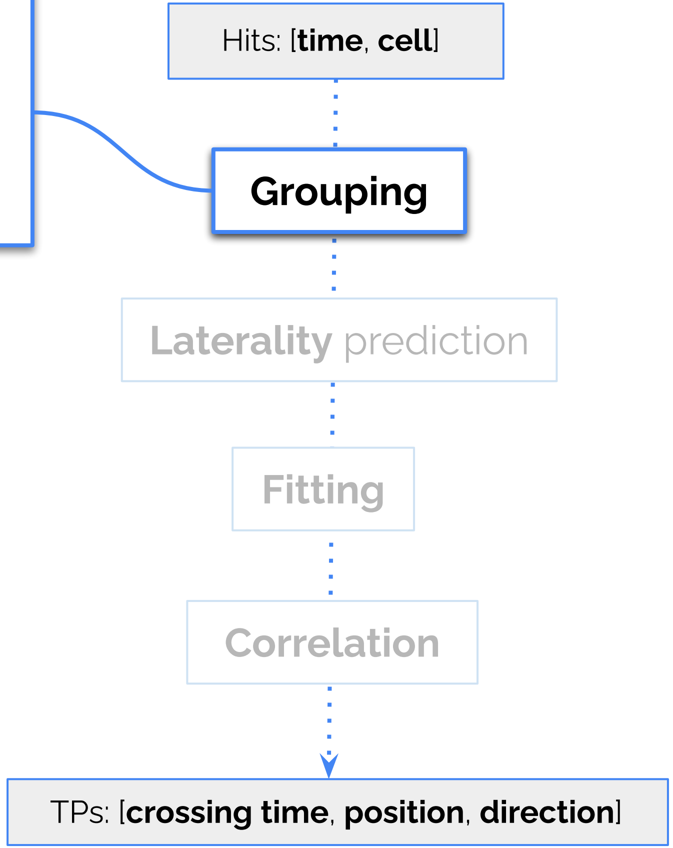


Universidad de Oviedo

Analytical Method algorithm: steps

- Groups of **3 or 4 hits** in 10 nearby cells of a SL compatible with a straight line (400 ns)





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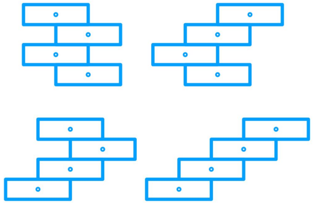
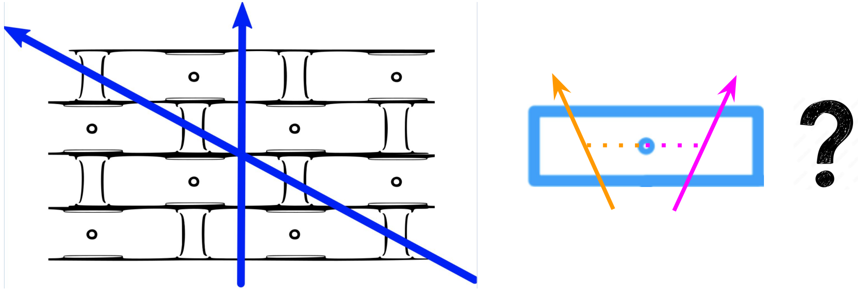


- Provide all possible **laterality combinations** for each hit group (≤ 4 combinations / group)
- Reduce to 3 combinations / group by applying **timing constraints** for firmware optimization



Hits: [**time**, **cell**]

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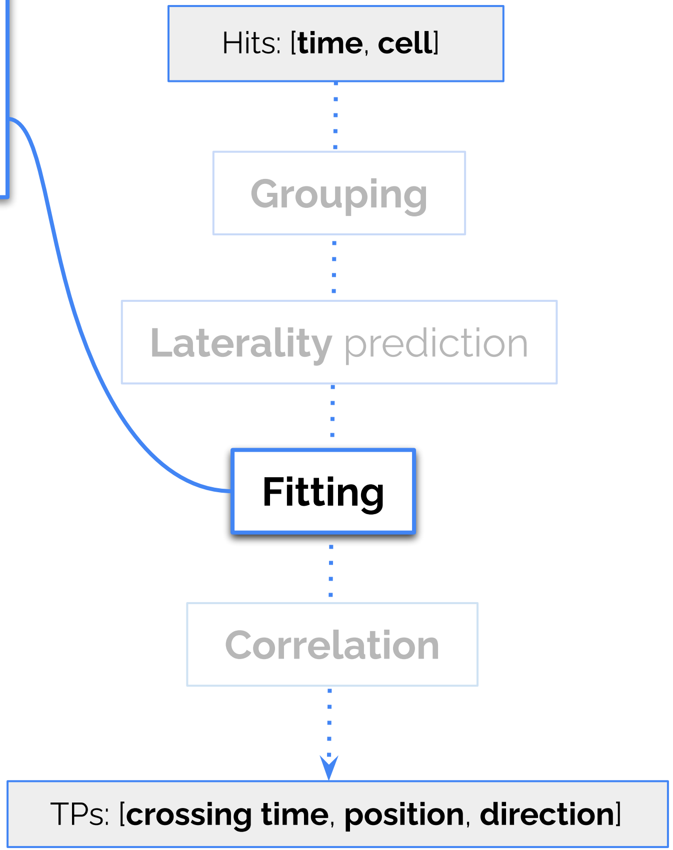
TPs: [**crossing time**, **position**, **direction**]

Analytical Method algorithm: steps

- Fit each hit **group** for each **laterality** combination
- Extract $\mathbf{t_0}$ (in ns and BX), **position** and **slope** of the TP, as well as the $\boldsymbol{\chi}^2$ of the fit



Analytical Method algorithm: steps

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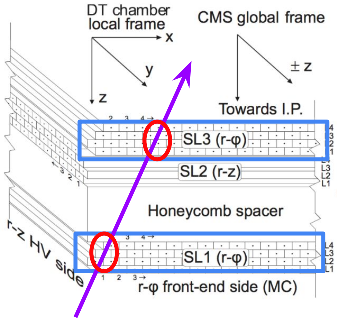
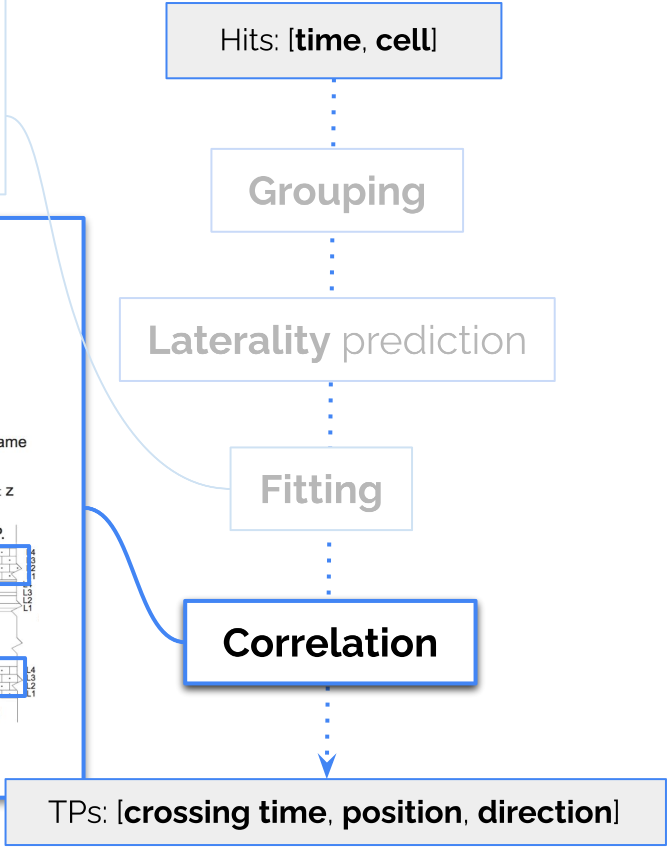
- Extract $\mathbf{t_0}$ (in ns and BX), **position** and **slope** of the TP, as well as the $\boldsymbol{\chi^2}$ of the fit

- Match TPs from **SL1** and **SL3** within $|\Delta t_0| < 25$ ns and re-compute the **combined track** parameters
- Assign a **quality** to the TP:

Quality	Description
1	3 hits (uncorrelated)
3	4 hits (uncorrelated)
6	3+3 hits (correlated)
7	3+4 hits (correlated)
8	4+4 hits (correlated)





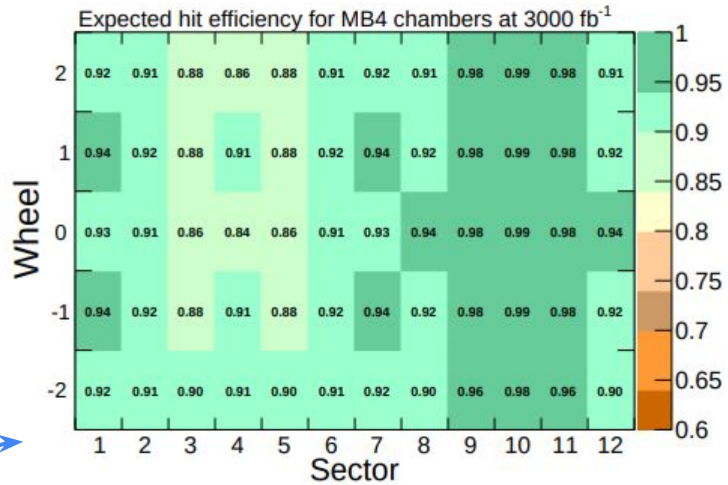
Performance on **simulation**: hit efficiency

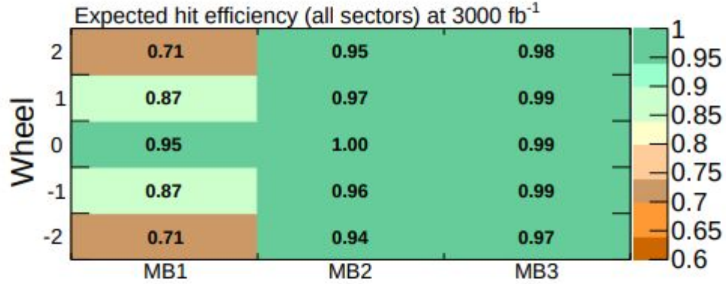
>90% except in most exposed regions

- **Performance** of the algorithm extensively evaluated in simulation, data and firmware [arXiv:2302.01666]

- **Simulation**: flat muon sample of p_T [20,200] GeV, in Phase-2 detector, with an average **pileup** of **200** collisions/BX
- Assume the most extreme **ageing** scenario (equivalent to 3000 fb^{-1}) to evaluate longevity and failures
- Expected **hit efficiencies** at the end of Phase-2 are **>90%** except for the most forward detector regions (~70%)

Hit efficiency with ageing

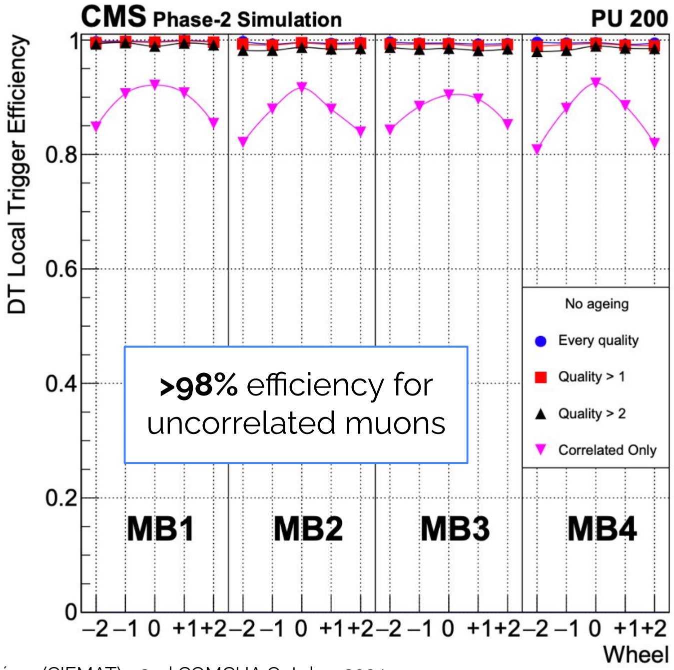




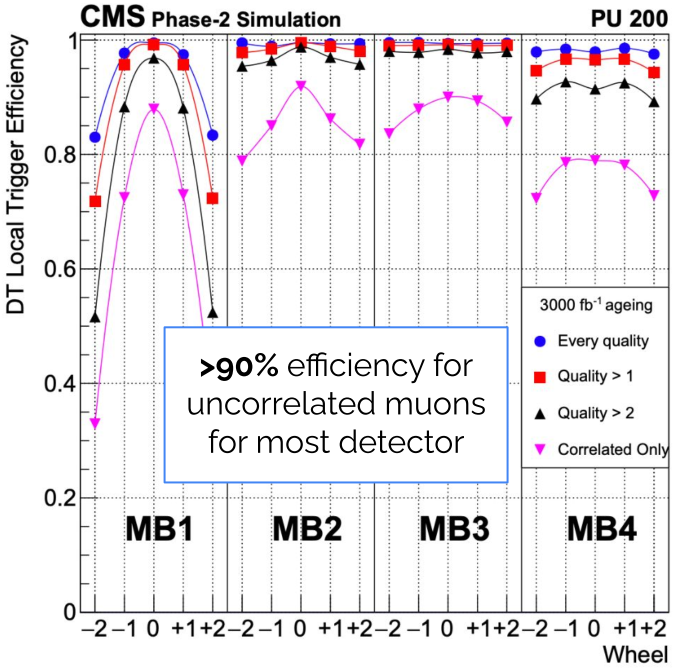
Performance on **simulation**: trigger efficiency

- Efficiency w.r.t. offline-reconstructed segments for different **qualities** and **ageing**
- **High efficiency** in the whole detector, degraded for regions more affected by ageing

Hit efficiency without ageing



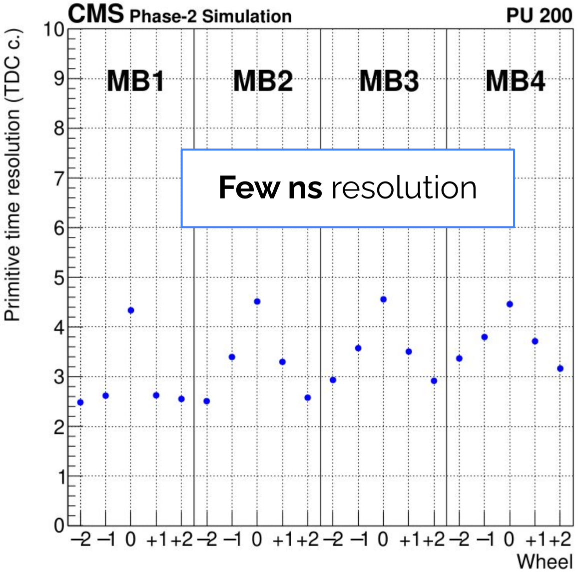
Hit efficiency with ageing



Performance on **simulation**: resolutions

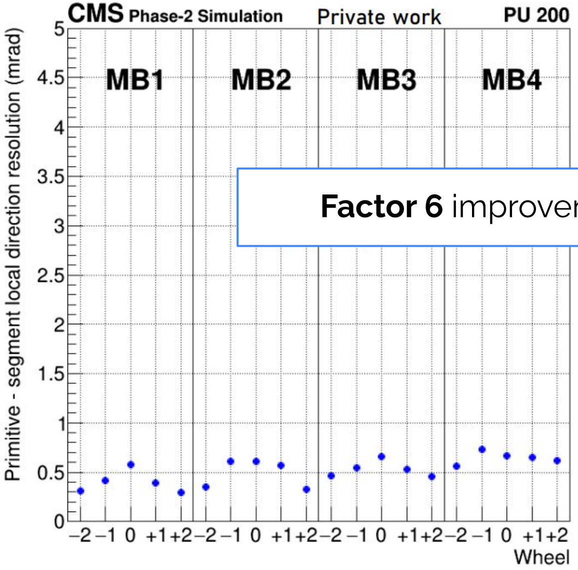
- **Time**, **direction** and **position** resolutions w.r.t. offline-reconstructed segments
- Performance comparable to the current Phase 1 **offline** reconstruction

Time resolution

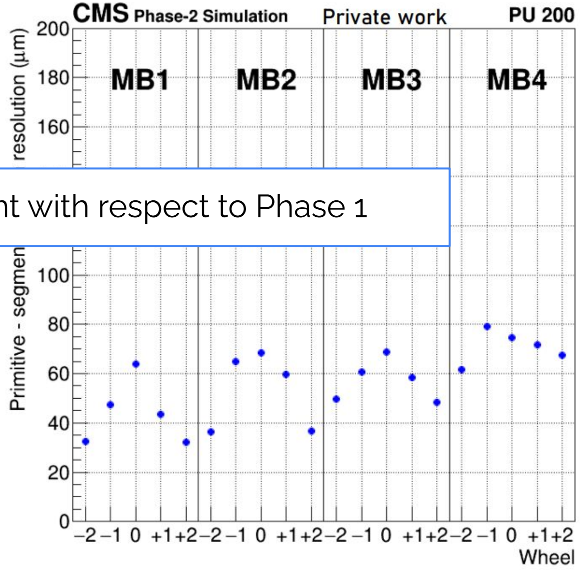


Few ns resolution

Local direction resolution



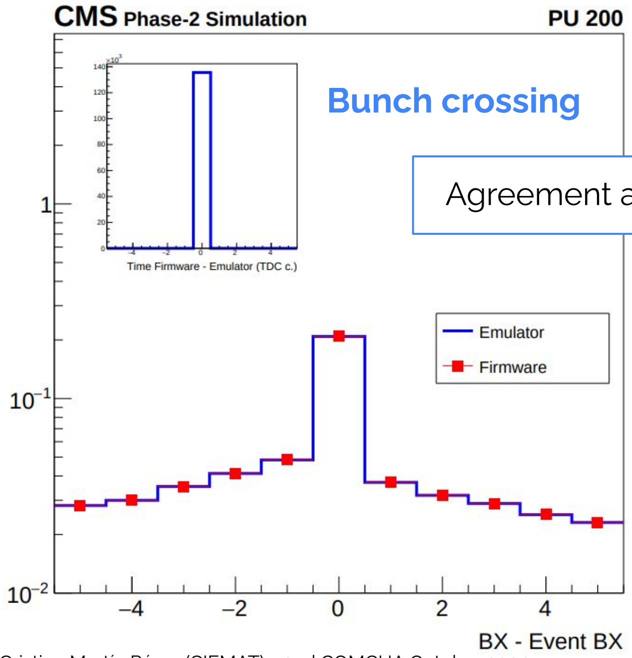
Local position resolution



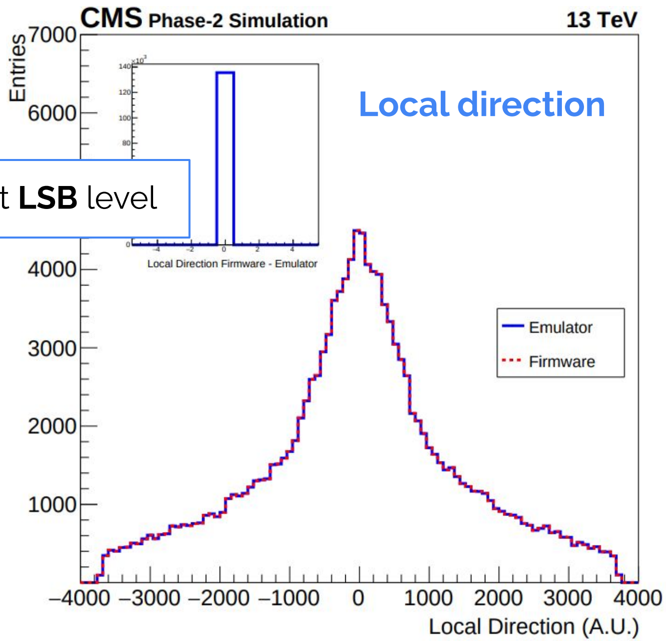
Factor 6 improvement with respect to Phase 1

Firmware implementation

- AM implemented in a **Xilinx Virtex Ultrascale Plus FPGA** test stand at CIEMAT, alongside several functionalities for **control** and **operation** of the system
- Extensive firmware-emulator comparisons show excellent agreement:



Agreement at **LSB** level



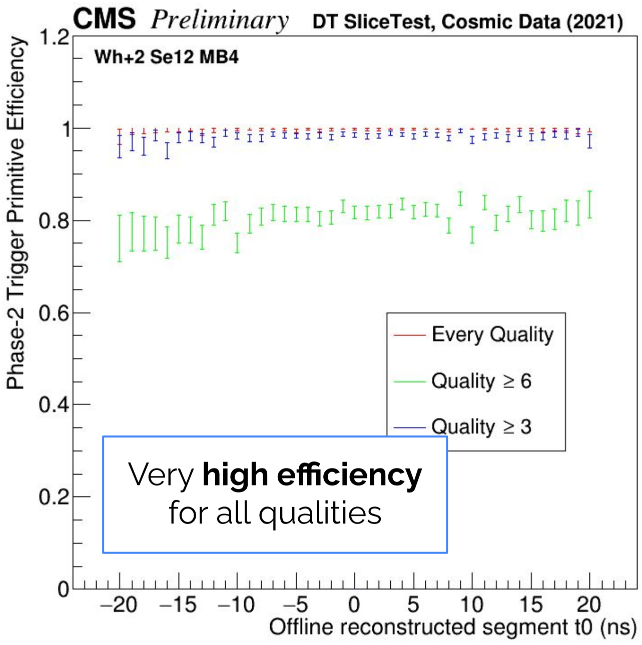
Matching efficiency

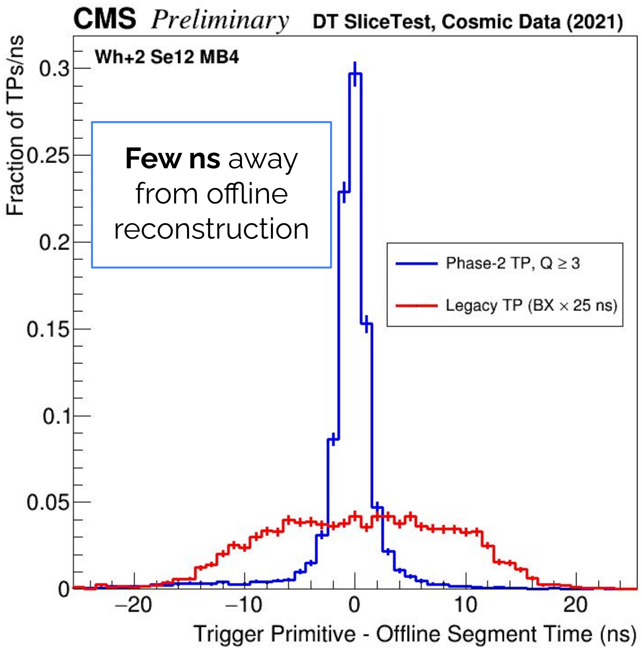
Quality	Matching w.r.t. emulator (%)
1	98.17 ± 0.05
3	99.70 ± 0.03
6	94.22 ± 1.19
7	97.63 ± 0.21
8	99.99 ± 0.01
Average	98.76 ± 0.03

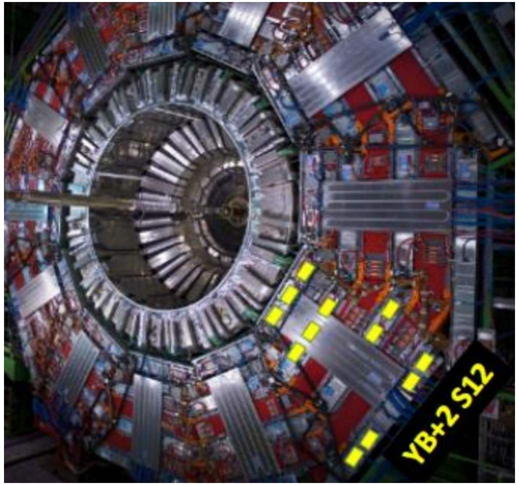
Quality	Matching w.r.t. firmware (%)
1	99.46 ± 0.03
3	99.93 ± 0.02
6	93.52 ± 1.24
7	97.61 ± 0.21
8	99.99 ± 0.01
Average	99.56 ± 0.02

Operation in a **DT Slice Test**

- During LS2, one CMS sector (Wh+2 S12) was instrumented with the **Phase-2** frontend and back-end **electronics**, in parallel to the current Phase 1 readout
- Validation with **cosmic** muons (LS2) and **collision** data (Run 3)

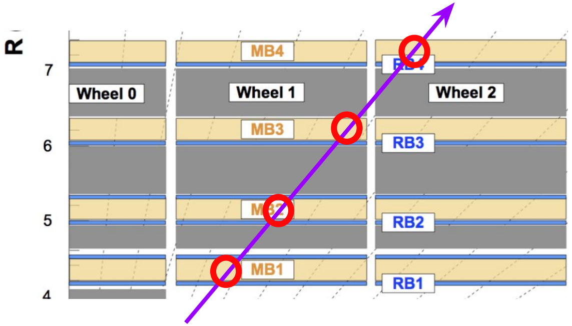


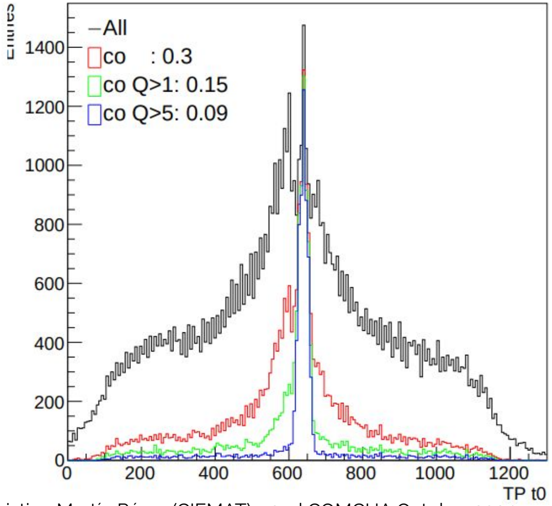


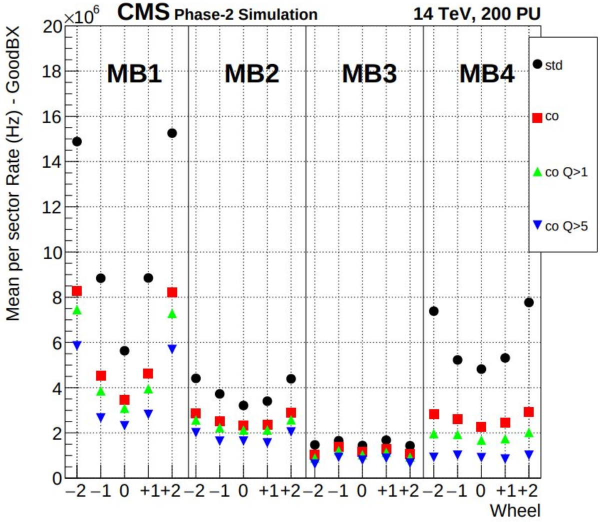


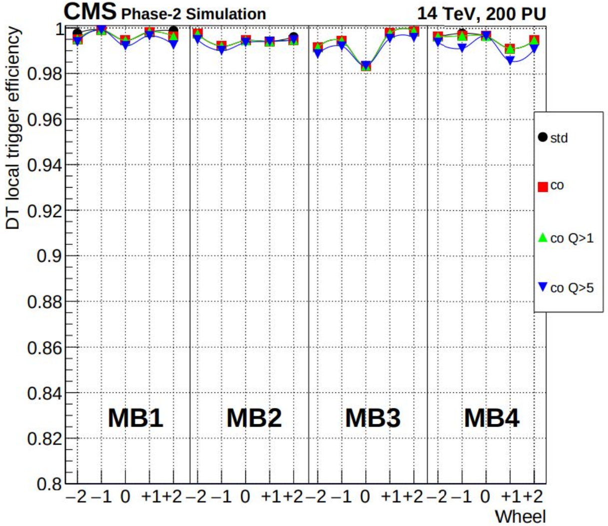
Coincidence filter NEW!

- Coincidences between **neighbouring chambers** within a chamber-dependent **$|\Delta t_0|$** window (extracted from FWHM)
- Handle to reduce the **rate** and remove "***ghosts***"
- Tested in simulation and data for different working points
- Significant **rate reduction** with little effect on efficiency



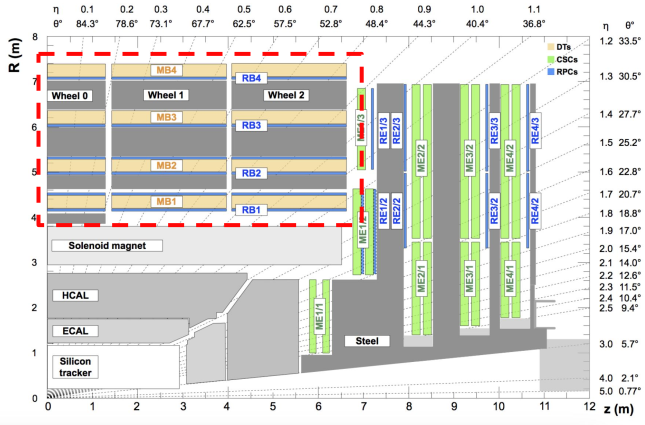


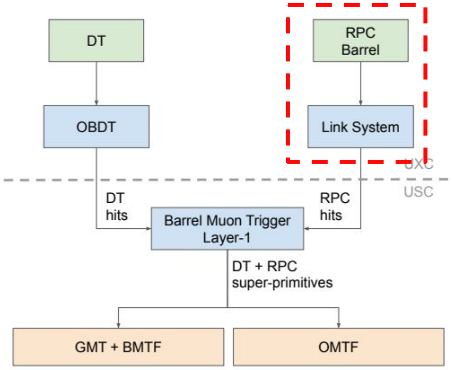


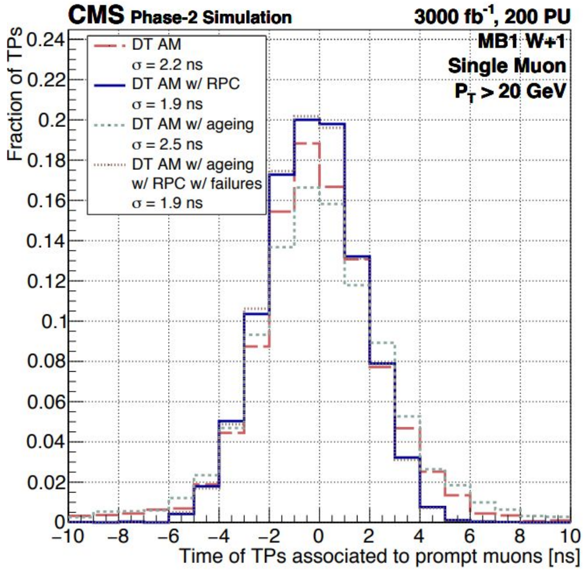


Future plans

- Ongoing work to extend the Analytical Method to include the **RPCs** in the **barrel**
- Combined "***superprimitives***" exploiting DT space resolution and RPC time resolution
- Exploring the use of **neural networks** profiting from the increased flexibility and computational power of the **FPGAs**:
  - pattern recognition in different detector regions
  - non-track objects (showers, displaced / slow muons…)
  - background ("ghost") cleaning







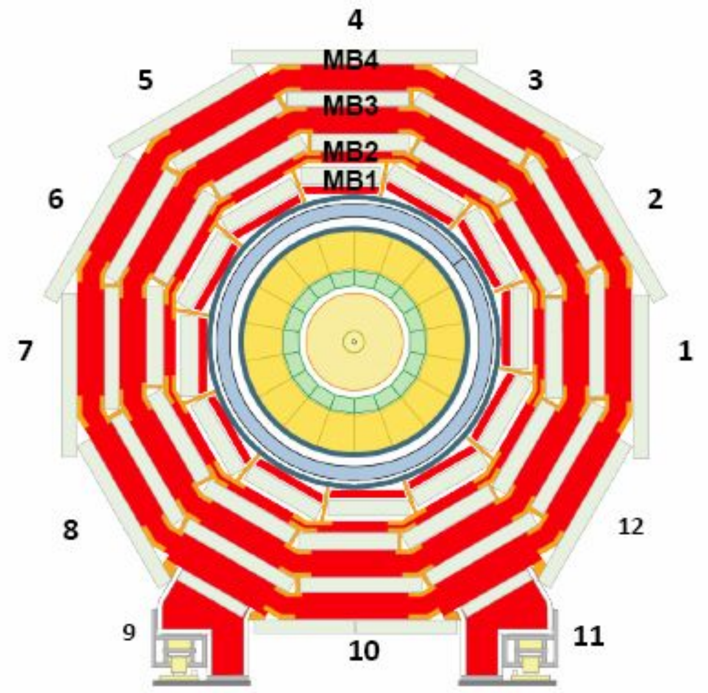
Summary

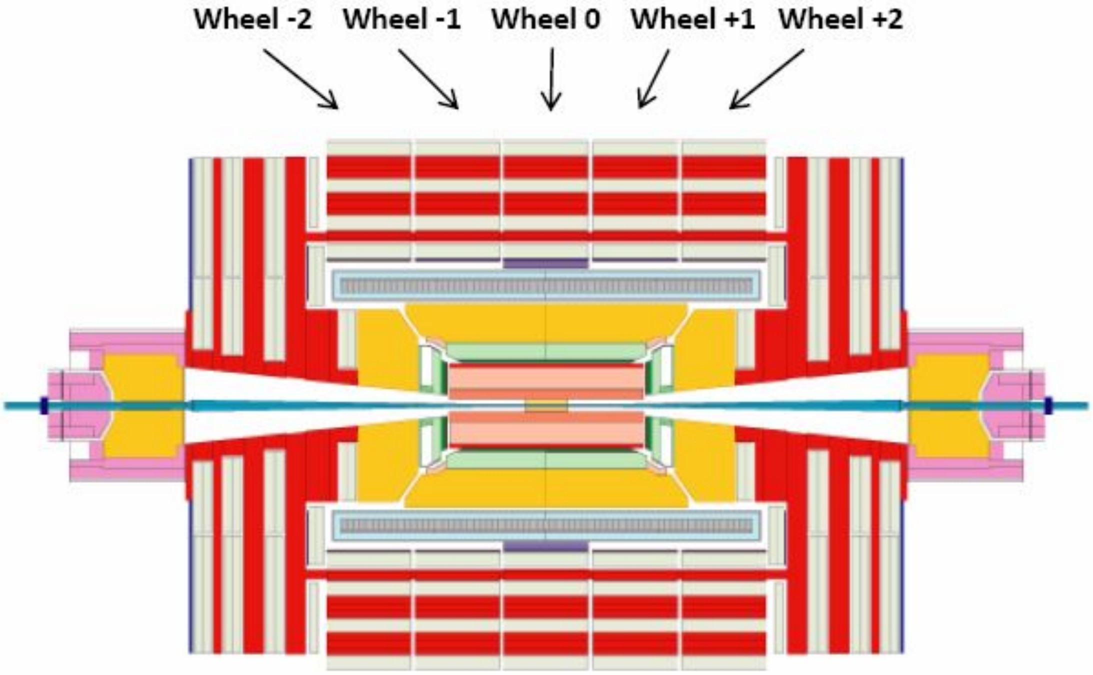
- In view of the upcoming **HL-LHC**, the **electronics** of the CMS **Drift Tubes** (DT) subdetector will be upgraded to cope with the increased rates and radiation levels
- The **Analytical Method** (AM) algorithm is responsible for reconstructing **trigger primitives** (TP) in the barrel before sending them to the muon trigger system
- It is a solid algorithm with excellent agreement between firmware and emulator, and a **performance close to offline** reconstruction for both simulation and data
- Currently exploring the use of **neural networks** running in **FPGAs** for RPC+DT combined TP generation towards an improved time resolution and efficiency

Thank You...

Backup

Drift Tubes detector





Laterality combinations