

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

2nd COMCHA Workshop - A Coruña

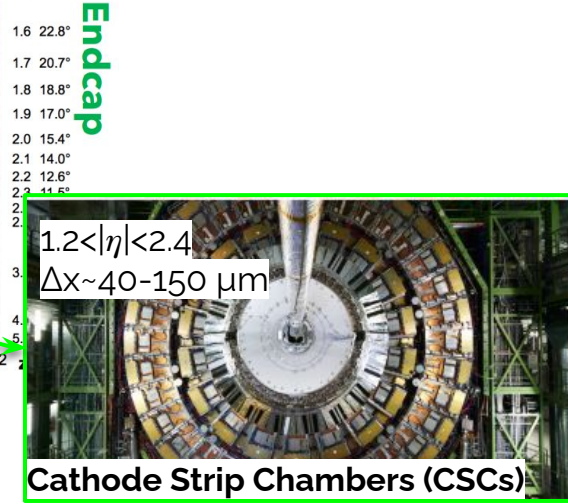
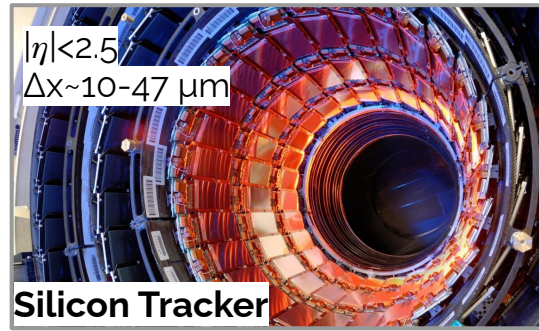
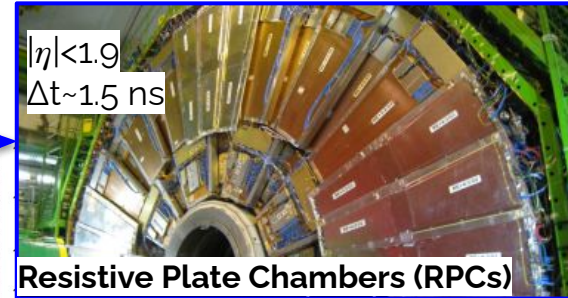
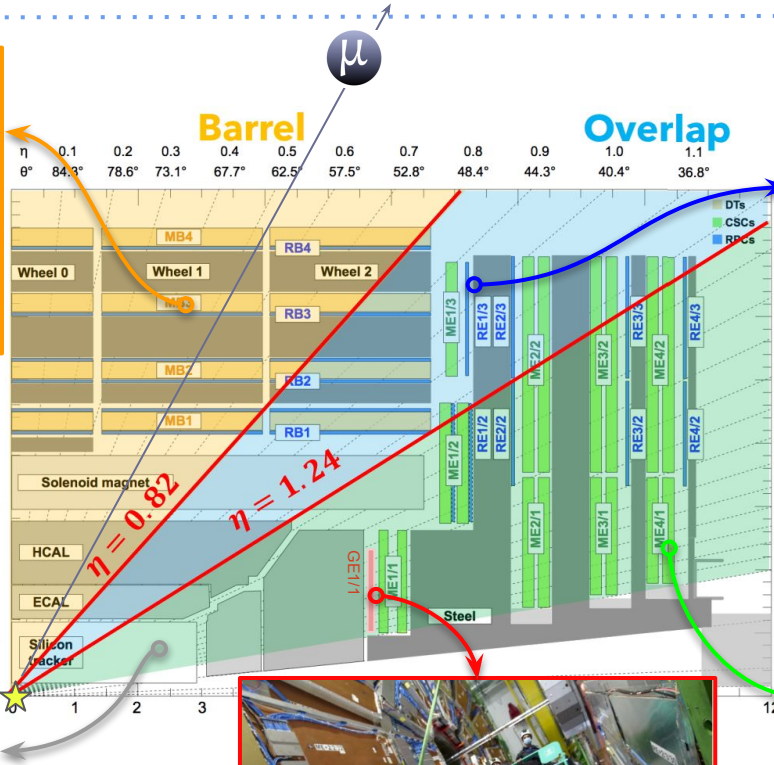
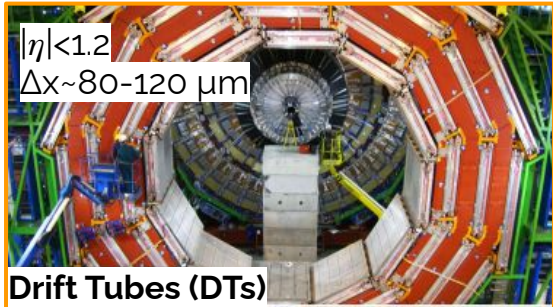
Cristina Martín Pérez - 03/10/2024

Proyecto PID2020-116262RB-C42 financiado por:



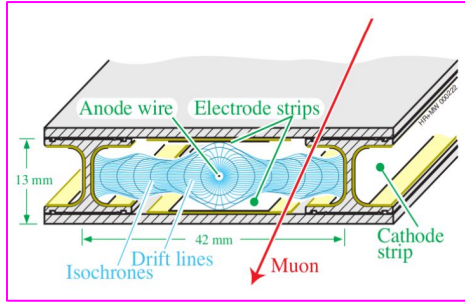
1. **Muon** detection in CMS
2. **Drift Tubes** and triggering system
3. **Analytical Method** algorithm for Trigger Primitive generation
4. **Performance** in simulation, firmware and real data
5. Ongoing and future **improvements**

Muon detection with CMS

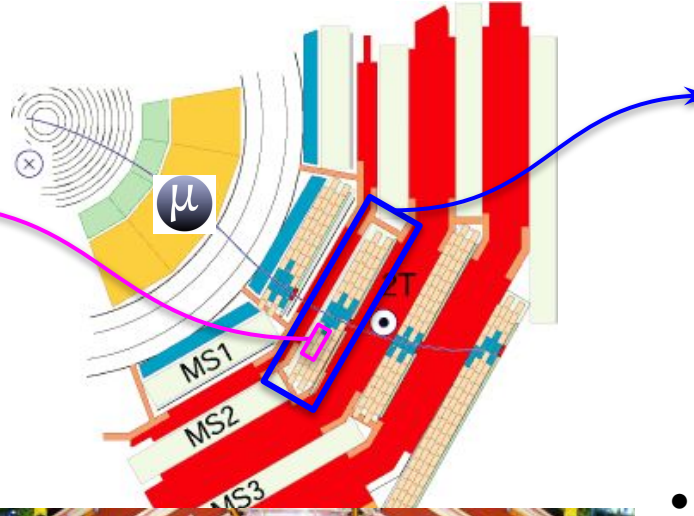


Muon detection with Drift Tubes (DTs)

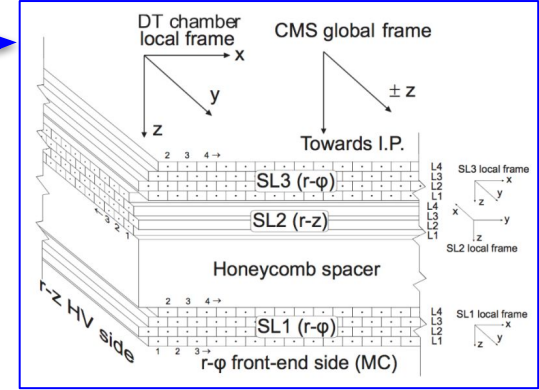
Cells (172.000)



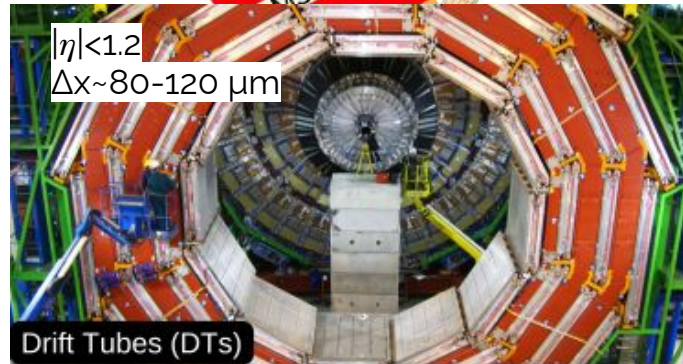
- **42 x 13 mm²**, Ar/CO₂
- Muons ionize the gas, electrons drift towards anode wire at **54 μm/ns**
- Measurement of drift time with a **laterality** ambiguity on the hit position



Chambers (250)



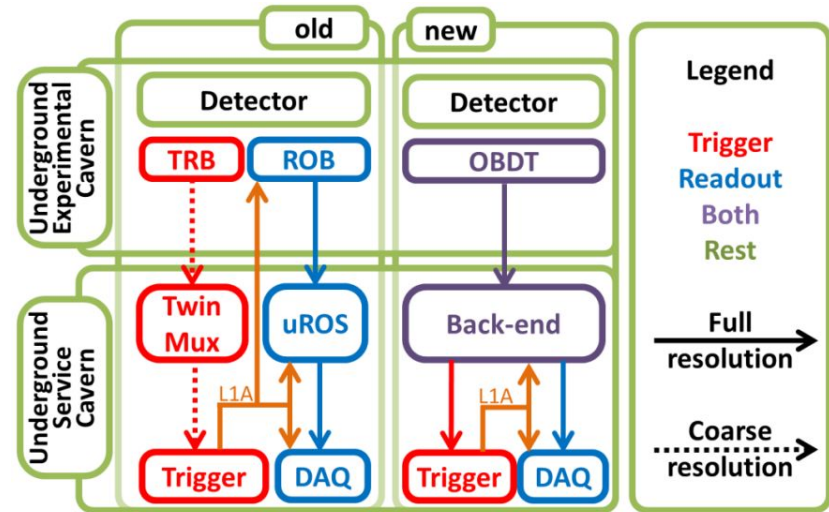
- **Superlayer (SL):**
 - 4 layers staggered half a cell
- **Chamber (250):**
 - 2 superlayers measuring the **r-φ** coordinates (**SL1, SL3**)
 - 1 superlayer measuring the **r-z** coordinates (**SL2**)



- **HL-LHC** operations ($5-7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, 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

high-speed optical links

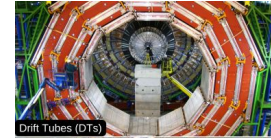
On-board DT (OBDT):

Time digitization ($\sim 1\text{ns}$) and sorting of hits per chamber in radiation-tolerant **FPGAs**



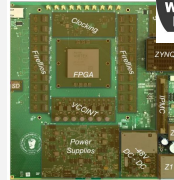
DT cells:

Single wire hit signals



Barrel Muon Trigger Layer-1 (BMTL1):

Full chamber info at full time resolution to generate **trigger primitives (TPs)** in commercial **FPGAs**



WE ARE HERE this talk

Barrel / Overlap Muon Track Finder (BMTF/OMTF):

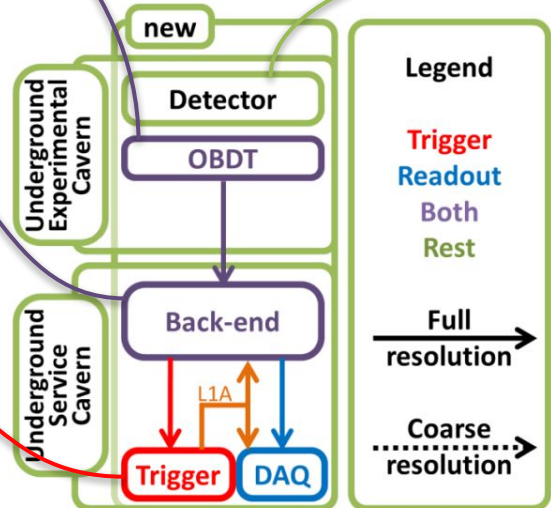
Muon pattern recognition to build L1 muons

EMTF

Global Muon Trigger (GMT)

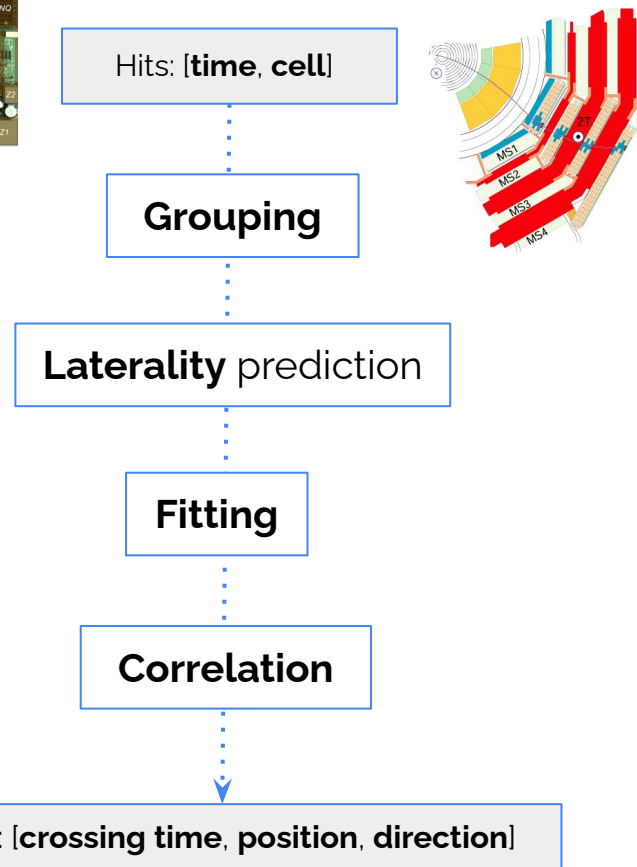
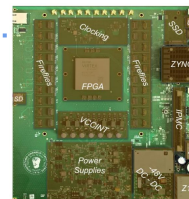
L1

Tracker



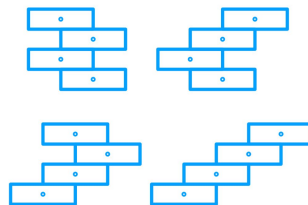
Analytical Method algorithm

- 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**



Analytical Method algorithm: steps

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



Hits: [time, cell]

Grouping

Laterality prediction

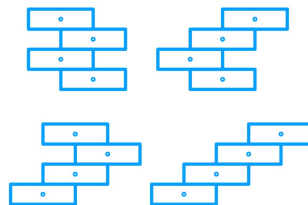
Fitting

Correlation

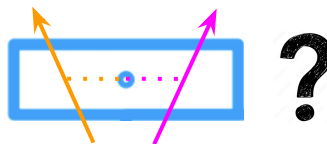
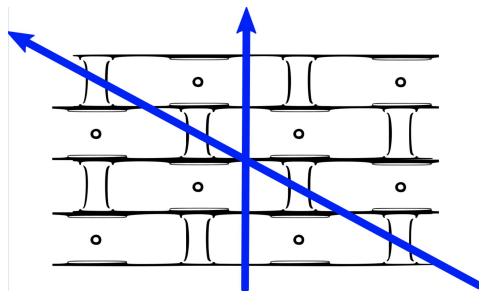
TPs: [crossing time, position, direction]

Analytical Method algorithm: steps

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



- 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]

Grouping

Laterality prediction

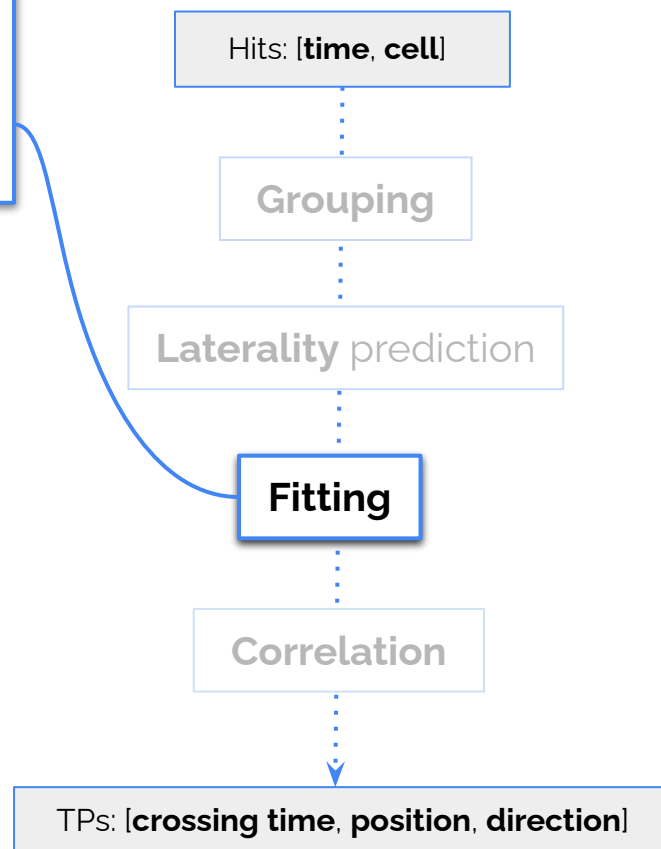
Fitting

Correlation

TPs: [crossing time, position, direction]

Analytical Method algorithm: steps

- Fit each hit **group** for each **laterality** combination
- Extract t_0 (in ns and BX), **position** and **slope** of the TP, as well as the χ^2 of the fit

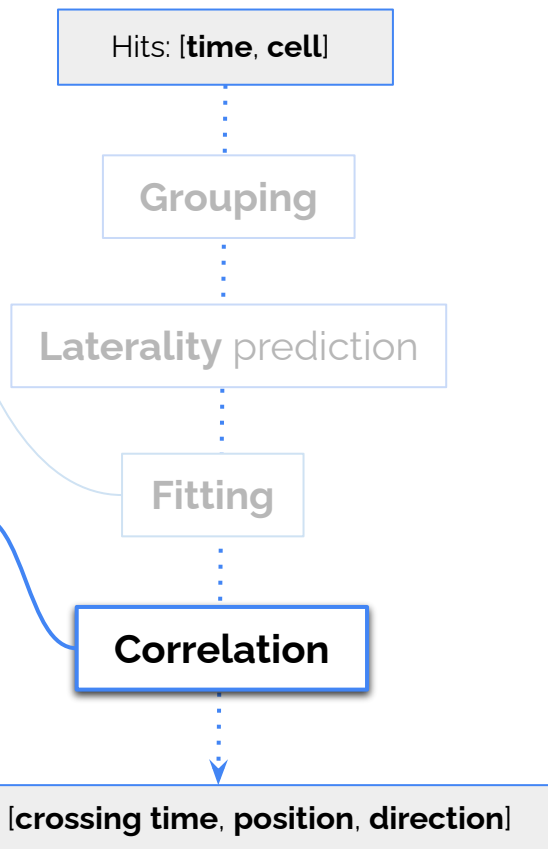
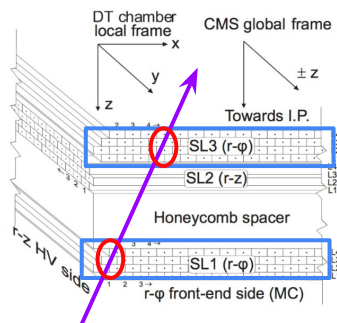


Analytical Method algorithm: steps

- Fit each hit **group** for each **laterality** combination
- Extract t_0 (in ns and BX), **position** and **slope** of the TP, as well as the χ^2 of the fit

- Match TPs from **SL1** and **SL3** within $|\Delta t_0| < 25$ ns and re-compute the

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)

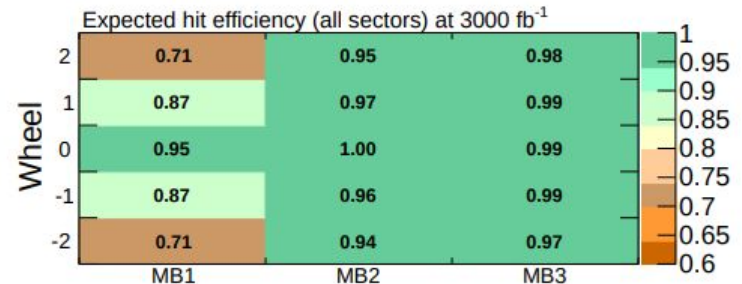
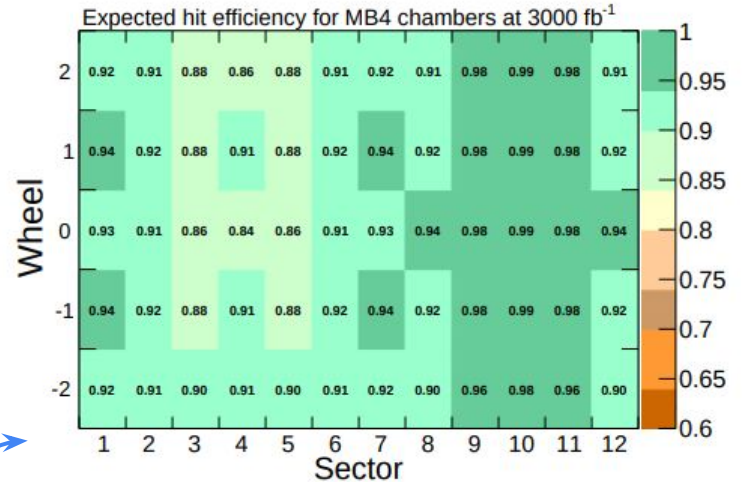


Performance on **simulation**: hit efficiency

>90% except in most exposed regions

- **Performance** of the algorithm extensively evaluated in simulation, data and firmware [[arXiv:2302.01666](https://arxiv.org/abs/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%)

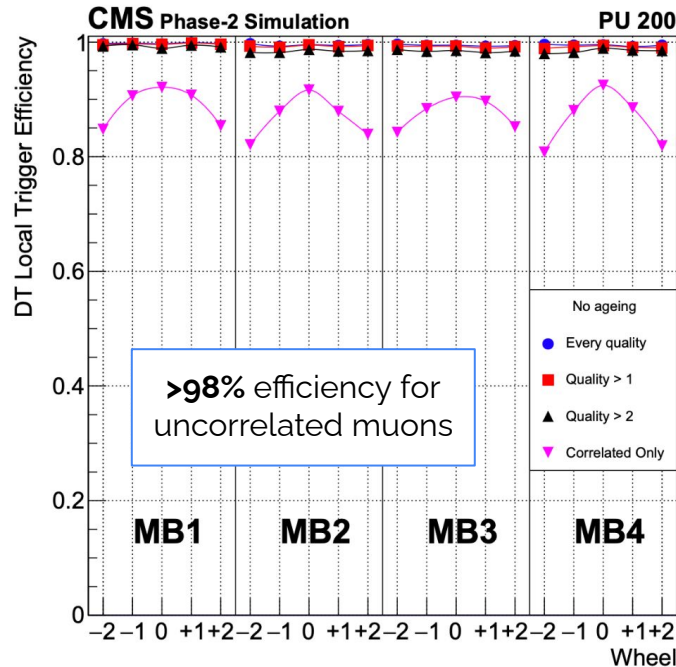
Hit efficiency with ageing



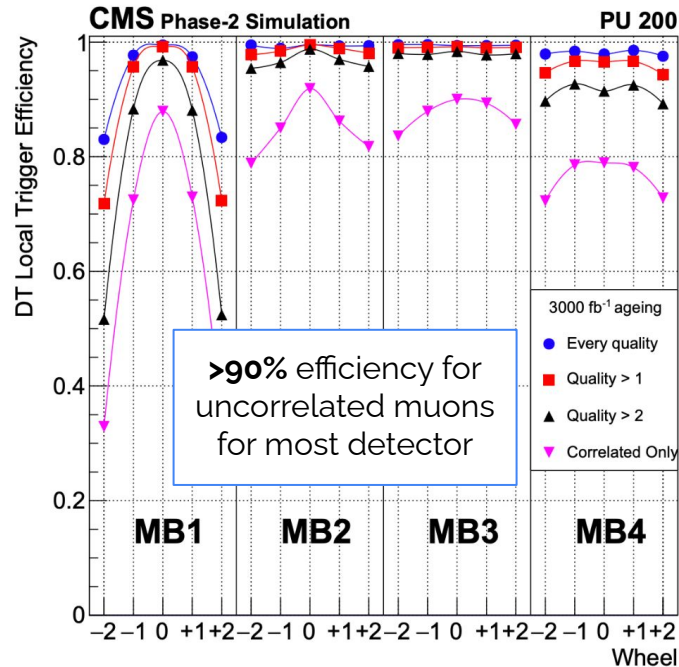
Performance on **simulation**: trigger efficiency

- 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



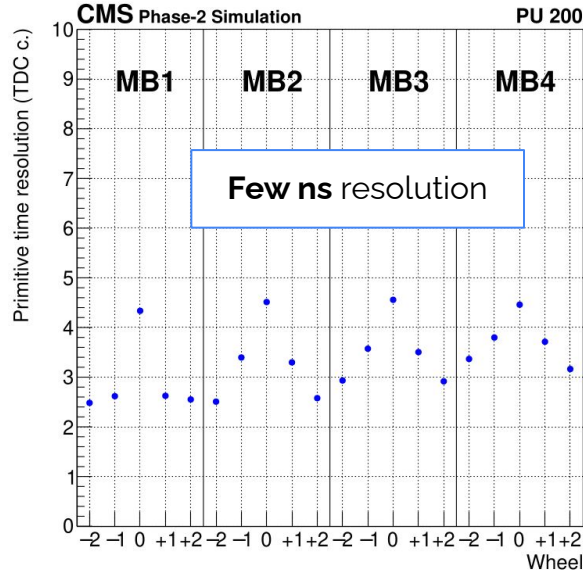
Hit efficiency with ageing



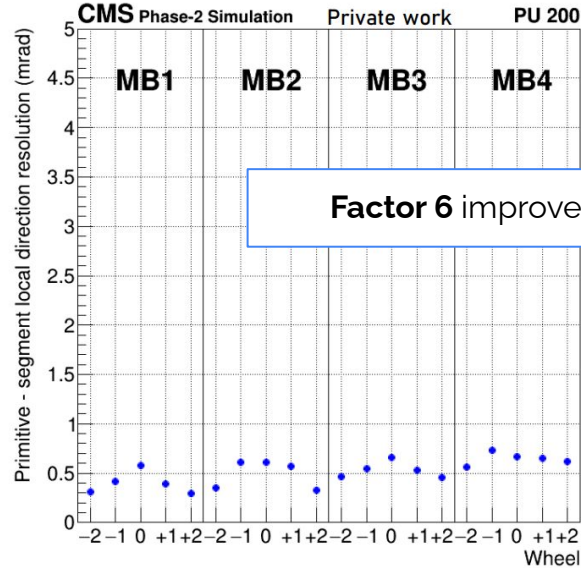
Performance on **simulation**: resolutions

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

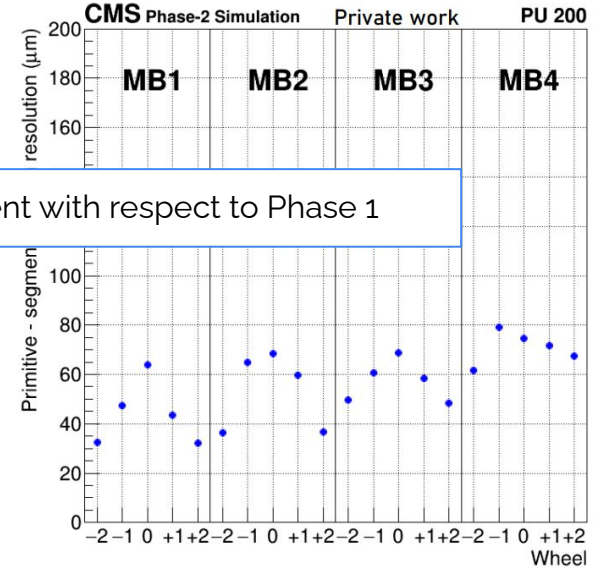
Time resolution



Local direction resolution

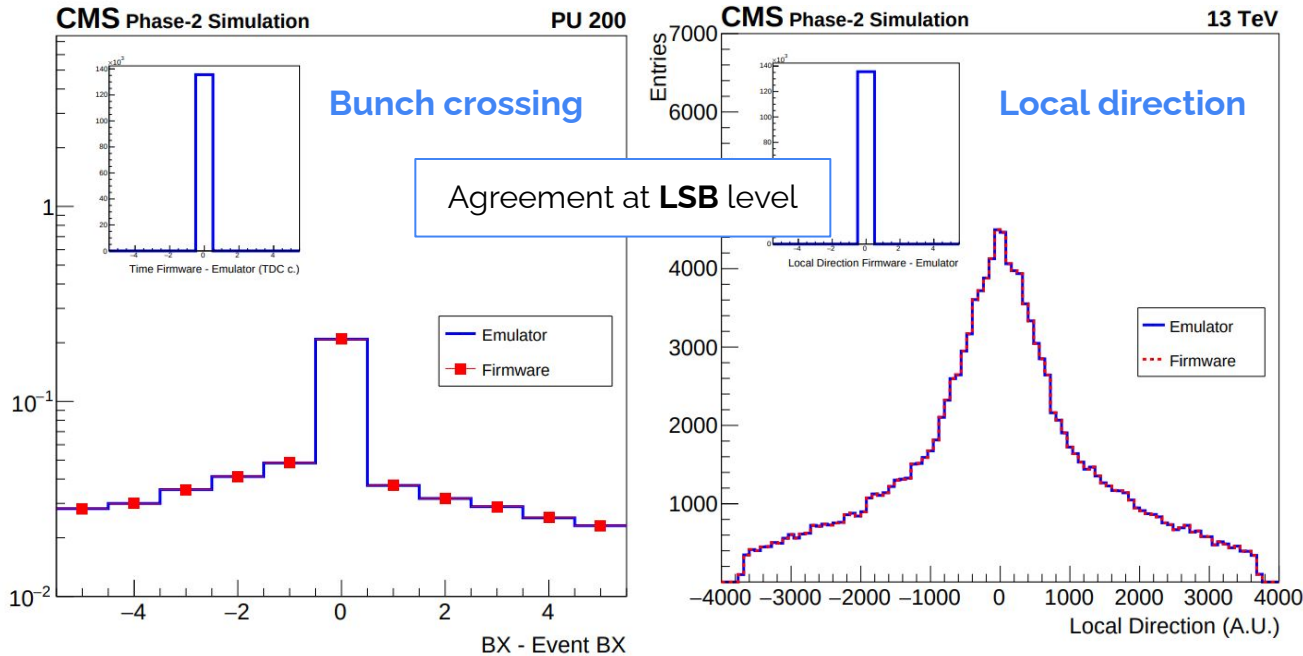


Local position resolution



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:



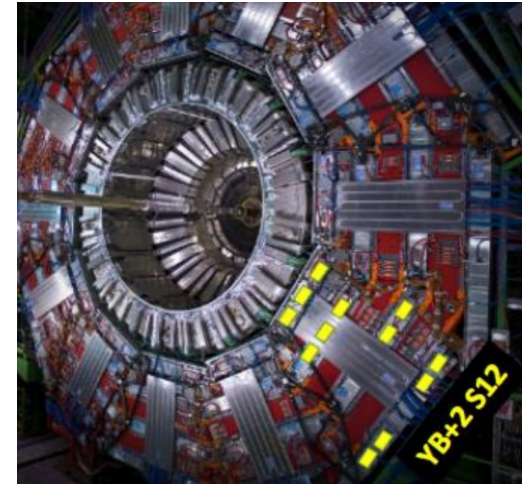
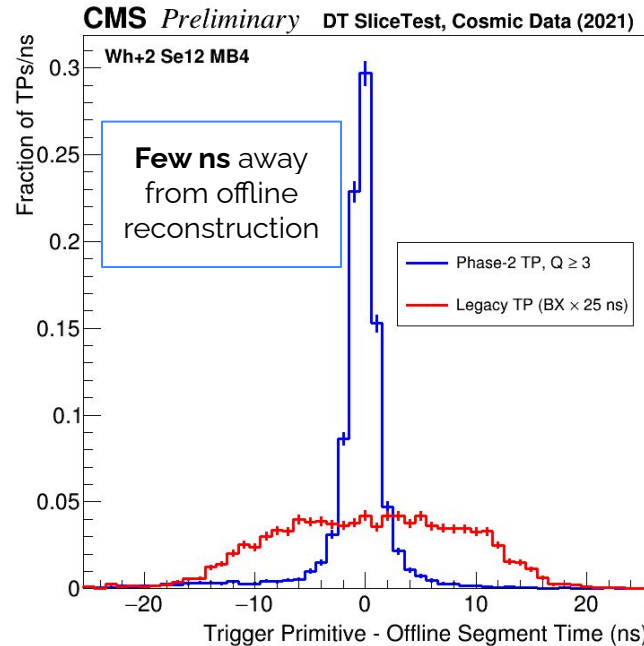
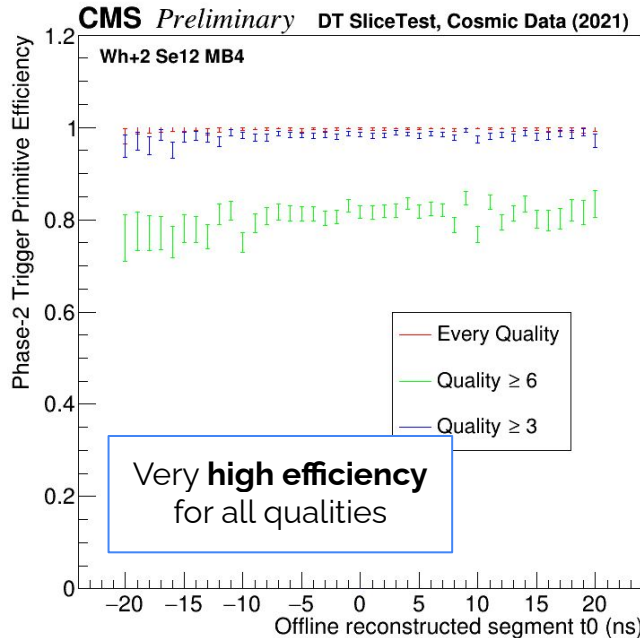
Matching efficiency

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

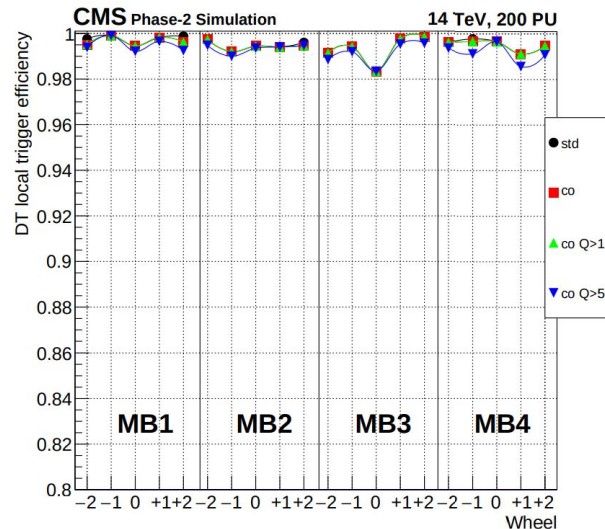
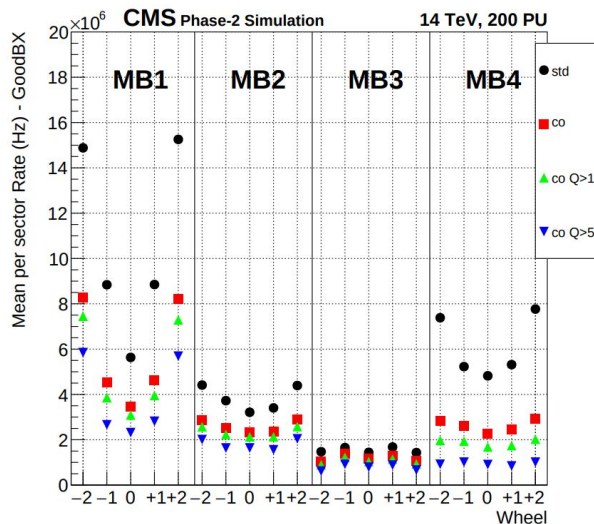
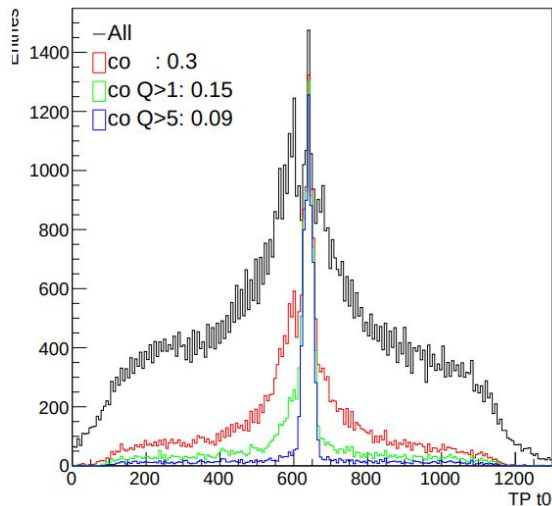
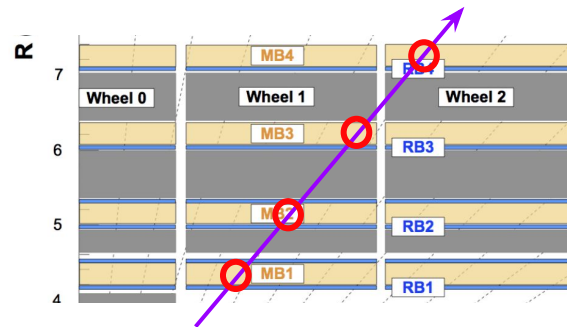
- During LS2, one CMS sector (Wh+2 S12) was instrumented with the **Phase-2** frontend and back-end **electronics**, in parallel to the current Phase 1 readout
- Validation with **cosmic** muons (LS2) and **collision** data (Run 3)



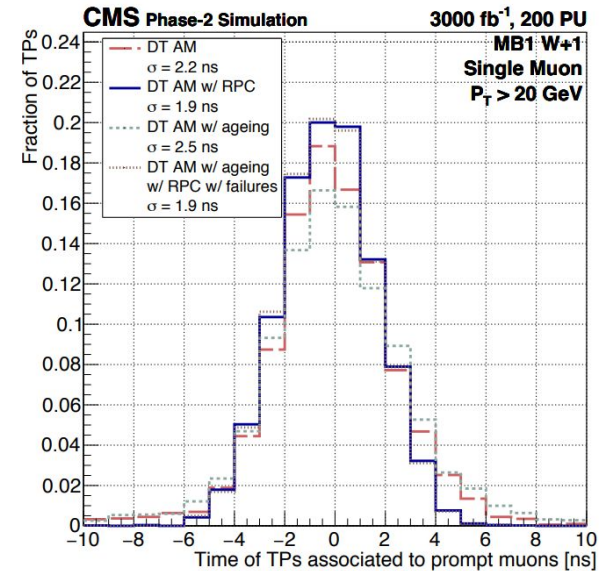
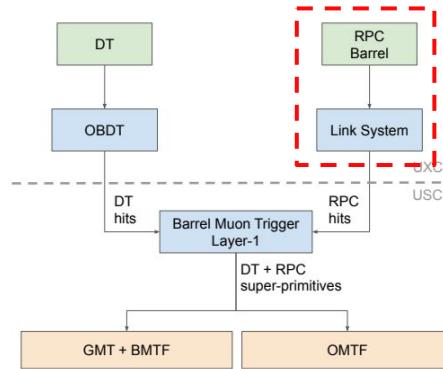
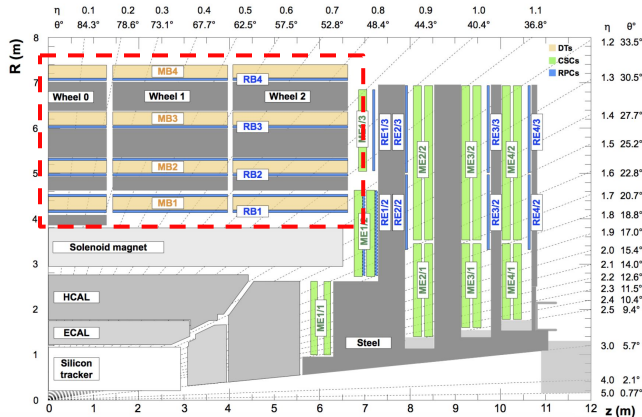
Coincidence filter



- 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



- 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

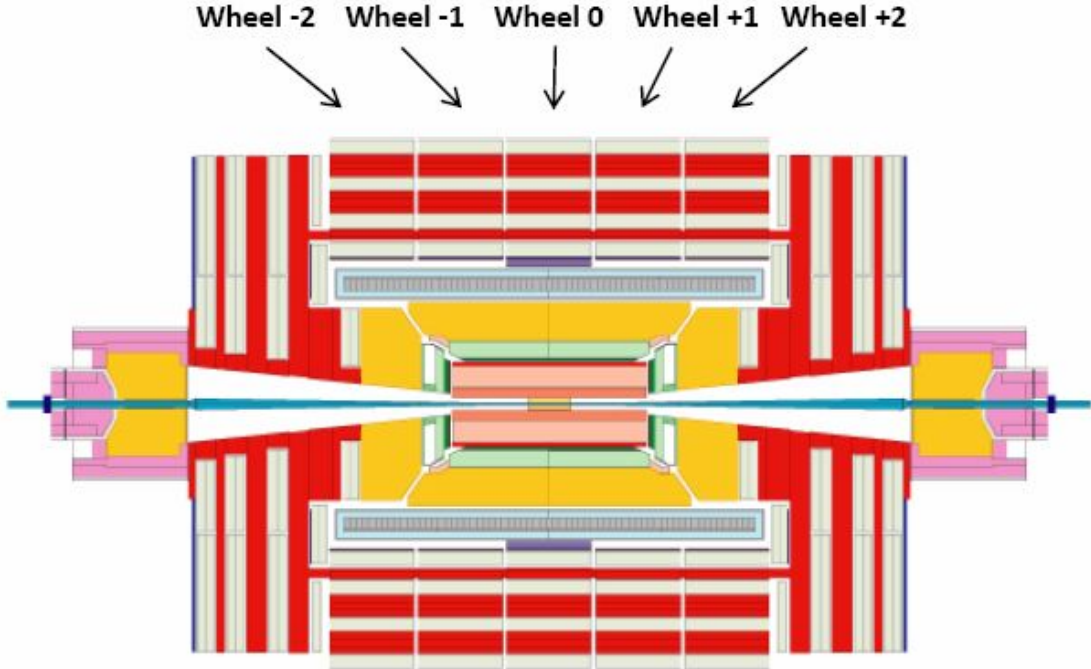
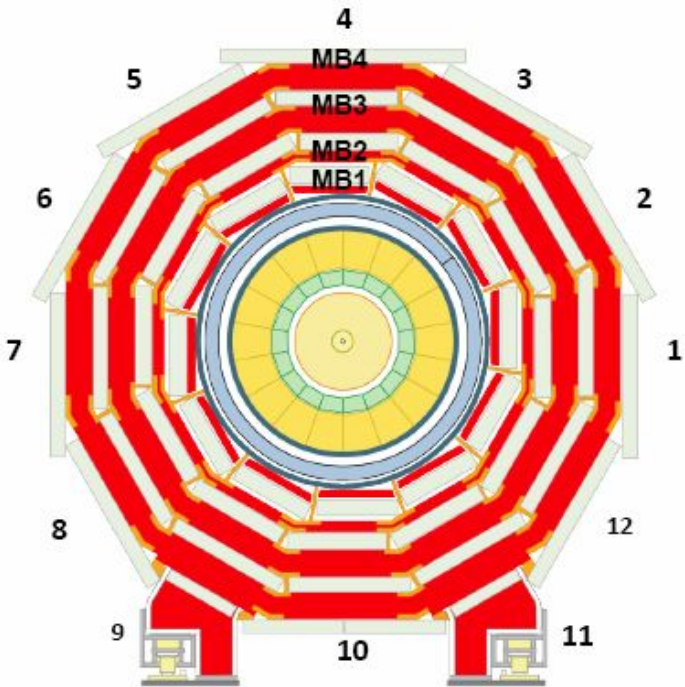


- In view of the upcoming **HL-LHC**, the **electronics** of the CMS **Drift Tubes** (DT) subdetector will be upgraded to cope with the increased rates and radiation levels
- The **Analytical Method** (AM) algorithm is responsible for reconstructing **trigger primitives** (TP) in the barrel before sending 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

