RAM-based Coincidence Window Optimization for Real-Time Muon Reconstruction in HL-LHC ATLAS L0 Muon Trigger

Kyoto University

Tetsuro Nakagawa on behalf of the ATLAS Collaboration

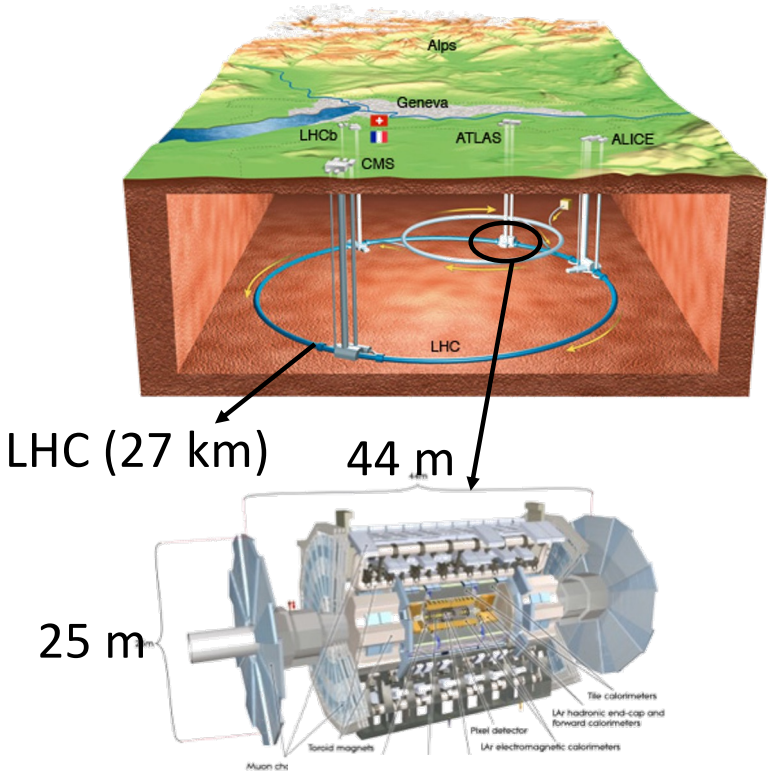
ATLAS experiment

Large Hadron Collider (LHC)

- Proton–proton collider
- Center of mass energy: 13.6 TeV (Run-3)
- Proton bunch crossings: 40 MHz
- Run-3: In operation since 2022
- The High-Luminosity LHC (from 2030): instantaneous luminosity ×3

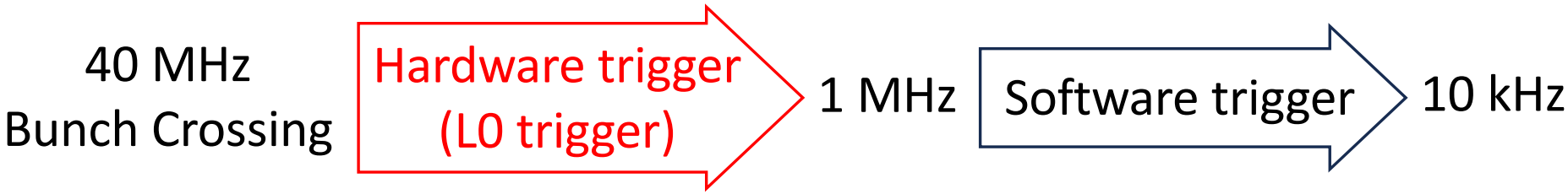
ATLAS detector and ATLAS experiment

- Standard Model precision measurement, new physics searches etc.



ATLAS detector

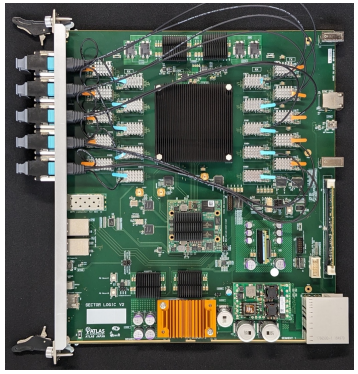
Hardware trigger of ATLAS at HL-LHC (L0 trigger)



- Trigger select events of interest, reducing event rate down to 10 kHz with two-stage triggers
- Hardware trigger (L0 trigger): Event selection in 10 μs, typically with FPGAs
- Without upgrading trigger and DAQ specifications, the trigger threshold would need to be raised, reducing the physics acceptance
- Improvements to the trigger and readout electronics will enhance the trigger-level selectivity

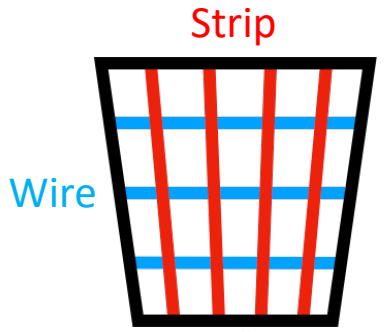
L0 muon trigger at the endcap region with TGC

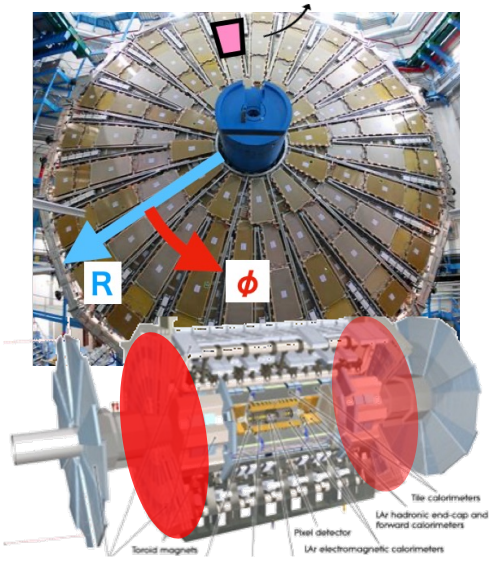
- Thin Gap Chamber (TGC):
  - Endcap detector for hardware (L0) muon trigger
  - Multi-wire proportional chambers:
    Anode wire (R/η), Cathode strip (ϕ)
- In HL-LHC, hit bitmaps from all channels will be sent to the backend electronics (Sector Logic)



Sector Logic

- Reconstruct tracks using large-scale LUTs implemented in FPGA RAM to achieve low-latency trigger processing
- Estimate transverse momentum (pT) of muon candidate with application of pT threshold

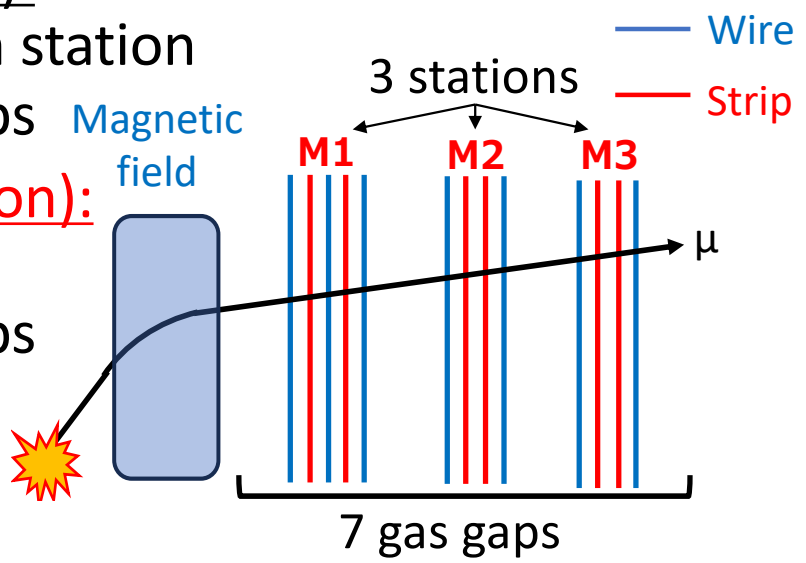




Reconstruction algorithm - Overview

- TGC is located outside the toroidal magnetic field and consists of 7 gas gaps, grouped into 3 stations
- The steps for trigger logic:

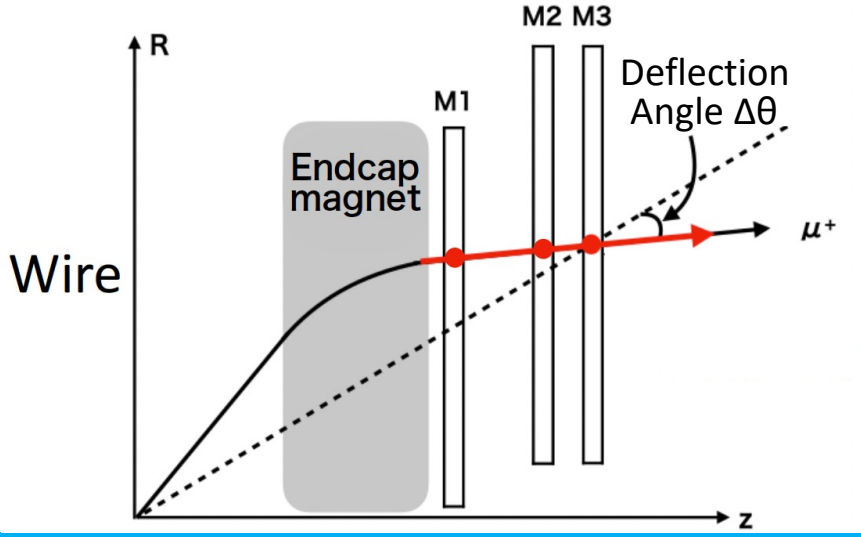
1. Intra-station coincidence (noise suppression):
   Hit coincidences between layers within each station performed independently for wires and strips
2. Inter-station coincidence (track reconstruction):
   Combining information across stations performed independently for wires and strips
3. Wire/Strip coincidence (pT estimation):
   Combining information of wire and strip to determine pT



Reconstruction algorithm - Detail

Inter-station coincidence (track reconstruction)

- Coincidence windows that output the track deflection angles for all the station channel combinations is used to reconstruct straight tracks
- The windows are implemented as LUTs, and in order to derive the alignment corrections, collision data are used



Coincidence Window

M1	M2	M3	Δθ
A	B	C	x

Input Output

Reconstruction algorithm - Detail

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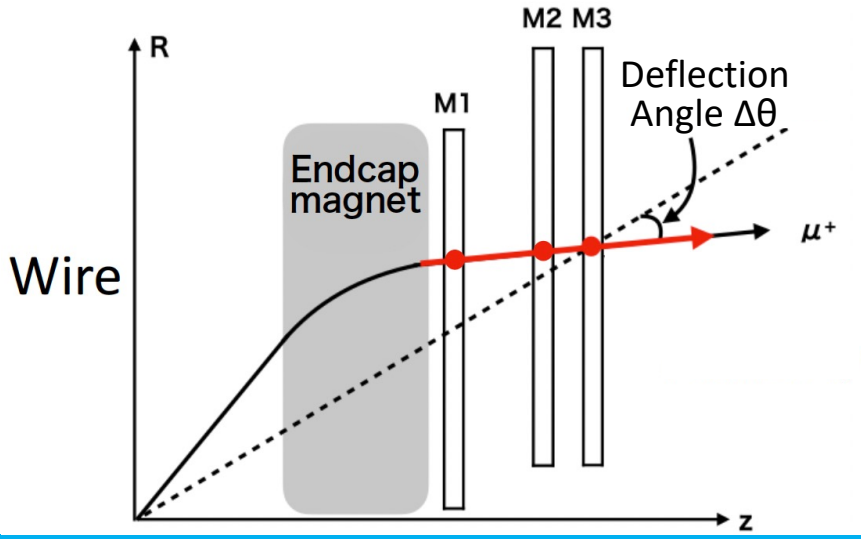


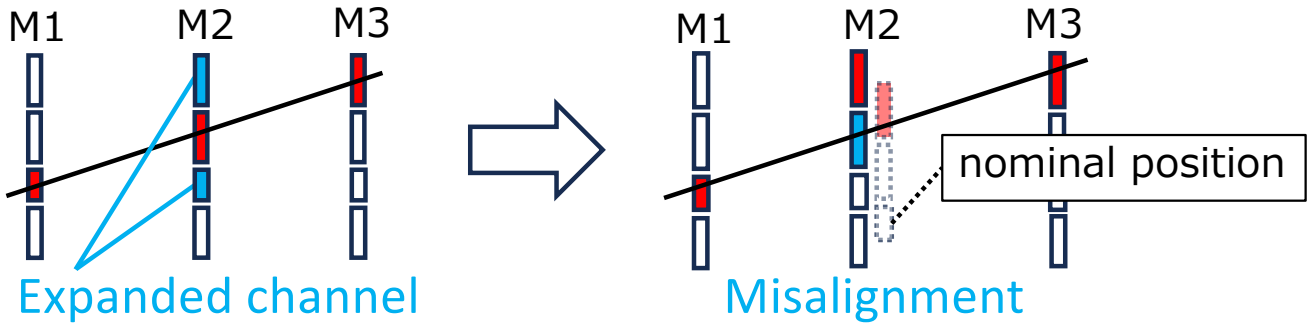
The role of each station is as follows:

- M3: Serve as the pivot
- M1: Provide the most extended lever arm with respect to M3 for point-angle measurement
- M2: Act as a confirmation layer to suppress accidental coincidence

Improvement idea

Relaxed LUTs

- In the early HL-LHC phase, a lack of reference data for alignment correction of LUTs will lead to efficiency losses
- The acceptance at the M2 station is relaxed by allowing channel combinations that deviate by up to ±1 channel from a linear pattern
- The relaxed LUTs are designed to improve robustness against detector misalignment without increasing the LUTs size

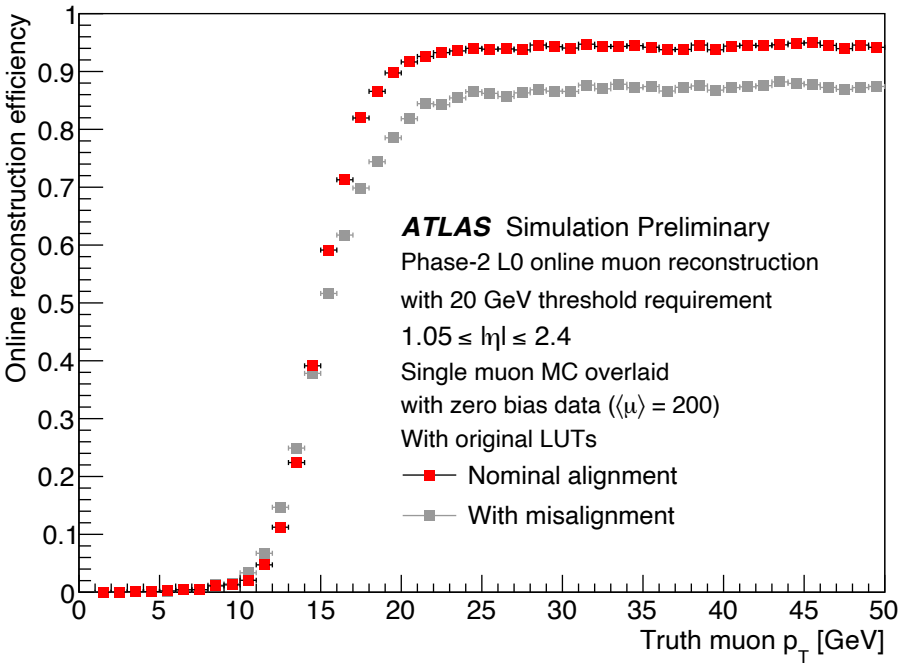


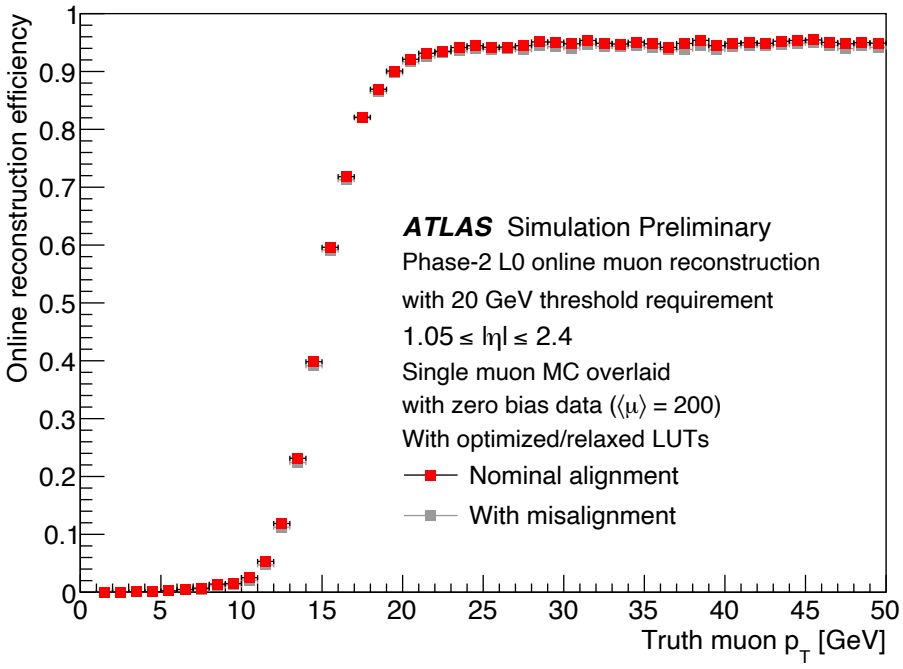
Simulation for performance evaluation

The sample which is used in the simulation

- Sample: Single-muon Monte Carlo simulation samples with the overlap of multiple proton-proton interactions (pileup)
  - Uniform distribution in η, ϕ, and pT
- Pileup conditions: Corresponding to an average of 200 interactions per bunch crossing are emulated by overlaying Run-2 random triggered (zero-bias) data
- The range of η: $1.05 < |\eta| < 2.4$

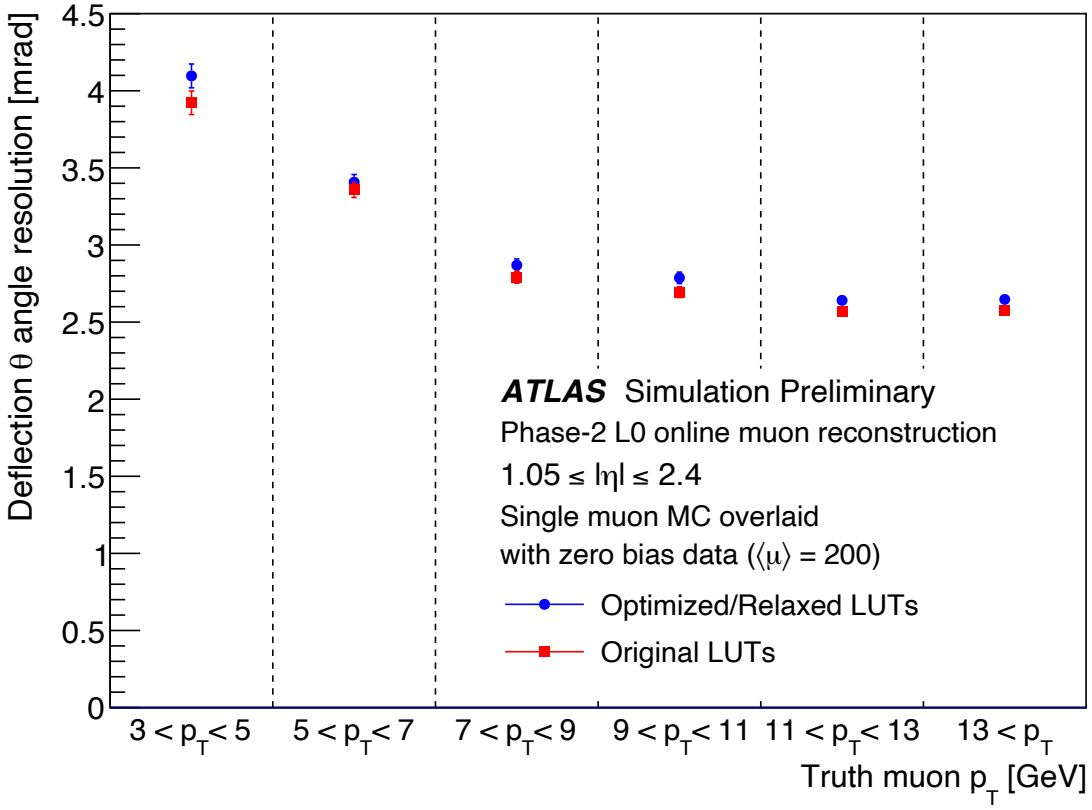
Results - Reconstruction efficiency [reference]





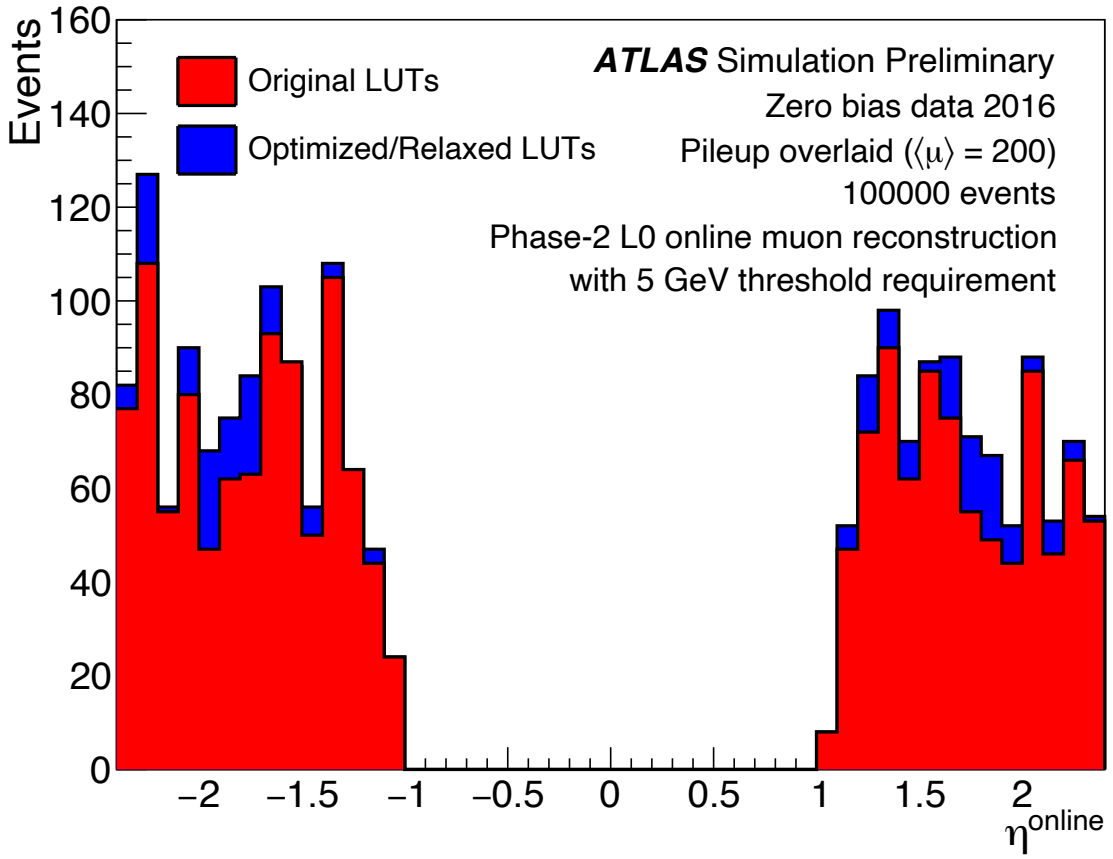
- As a proxy for evaluating the impact of detector misalignment, the Run-1 aligned LUTs were applied to samples generated with the nominal alignment
- The robustness against misalignment is increased

Results - Deflection angle resolution [reference]



- The limited impact of the relaxing the M2 acceptance on angular resolution

Results - Reconstruction rate [reference]



- 12% rate increase
- The events selected only by the relaxed LUTs originate mostly from charged-particle, with possible multiple scattering in M2 station
- The optimization does not increase accidental coincidences but instead increases the acceptance for genuine charged tracks

Conclusion

- In HL-LHC, the high luminosity will increase the trigger threshold and degrade physics acceptance without upgrading specifications.
- TGC electronics, which play a major role in the endcap L0 muon trigger, will be upgraded.
- The TGC reconstructs muon tracks from hit bitmaps from all channels.
- With the LUTs relaxation, the trigger algorithm becomes more robust against misalignment without degrading the deflection angle resolution and increasing the LUTs size.
- Although the reconstruction rate increases, this indicates that the optimization increases the acceptance for genuine charged tracks.