ATLAS EXPERIMENT

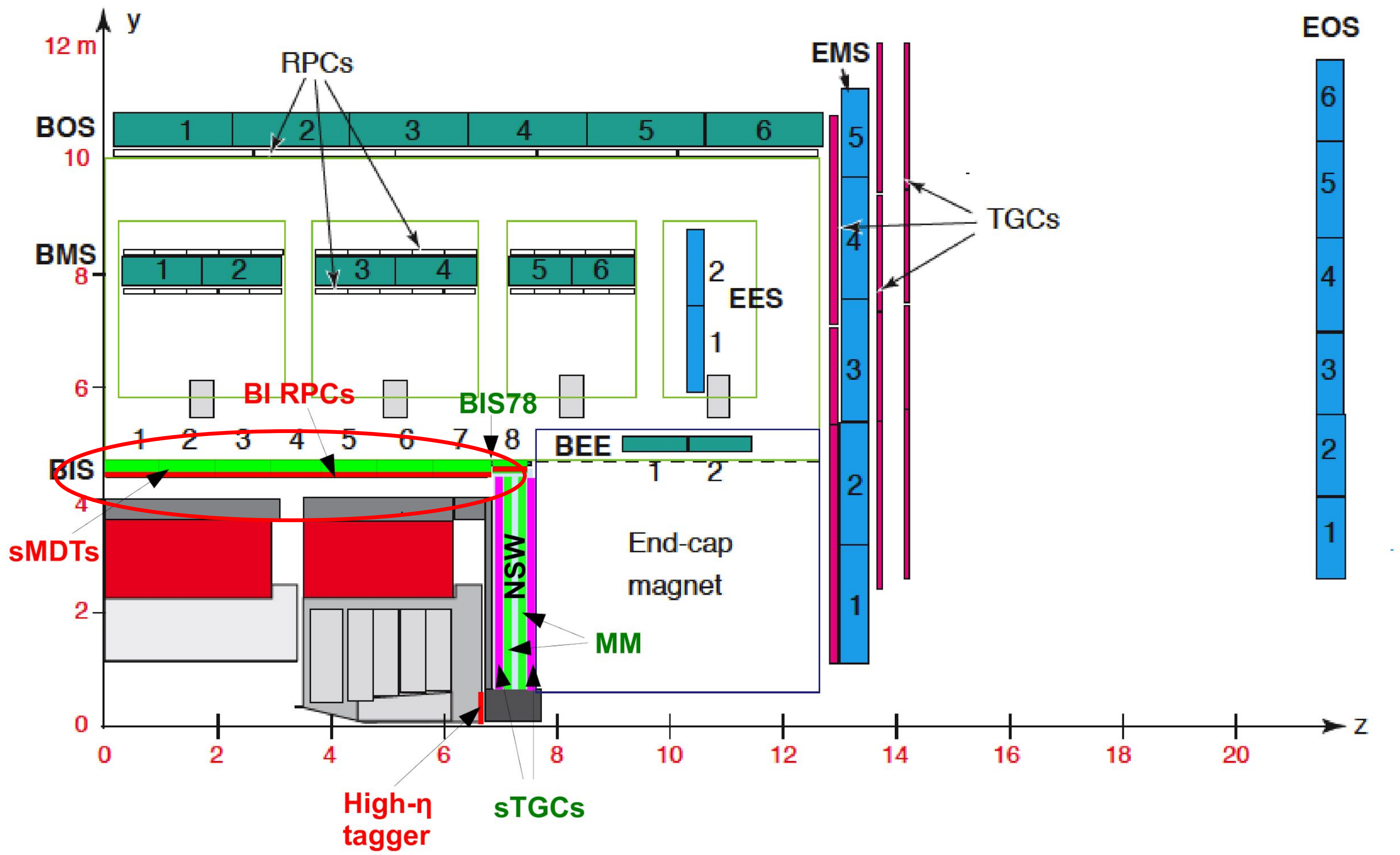
MAX-PLANCK-INSTITUT FÜR PHYSIK

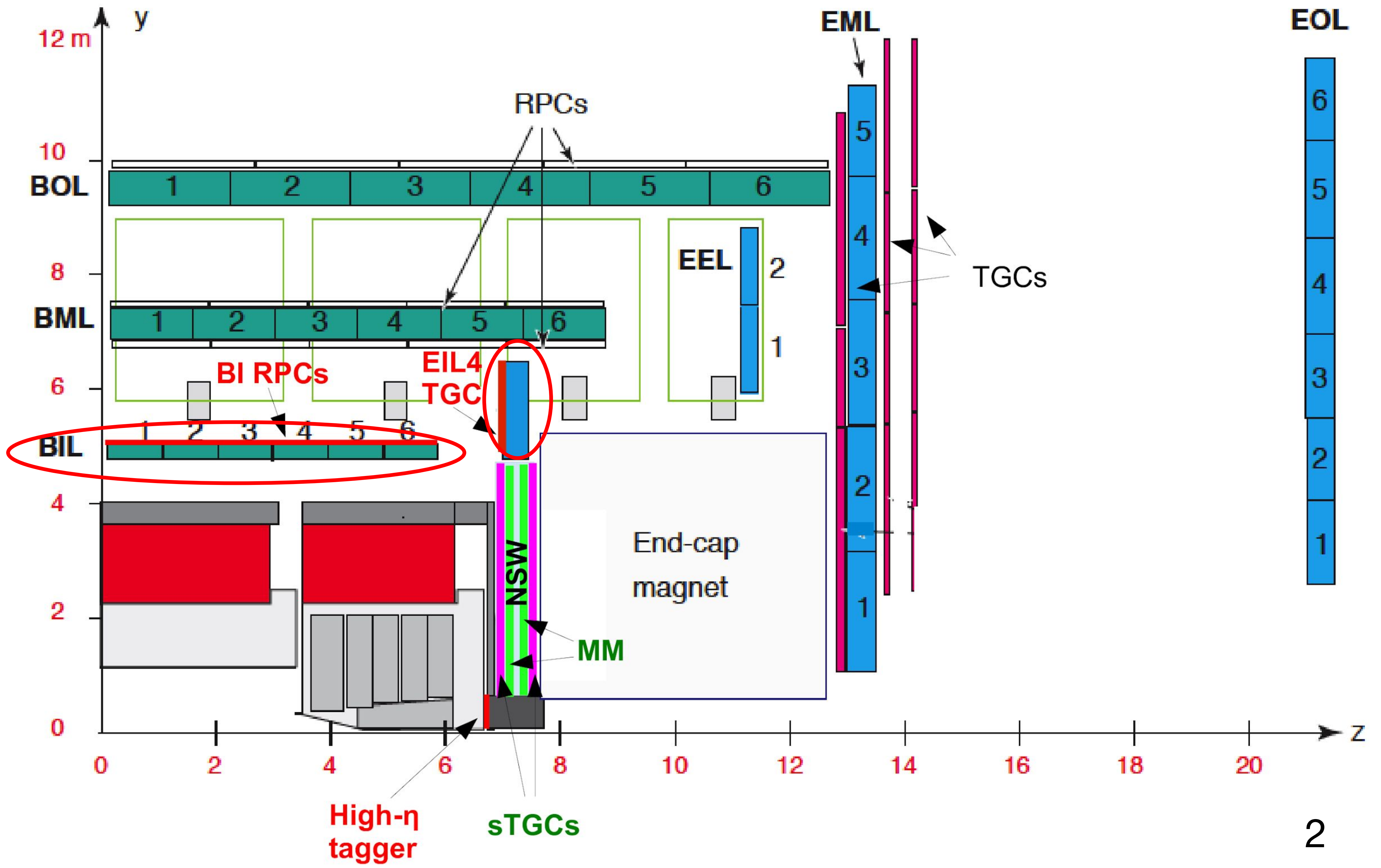
Upgrade of the ATLAS Muon Trigger for the HL-LHC

Davide Cieri (MPI) on behalf of the ATLAS collaboration - 28. July 2020

Introduction

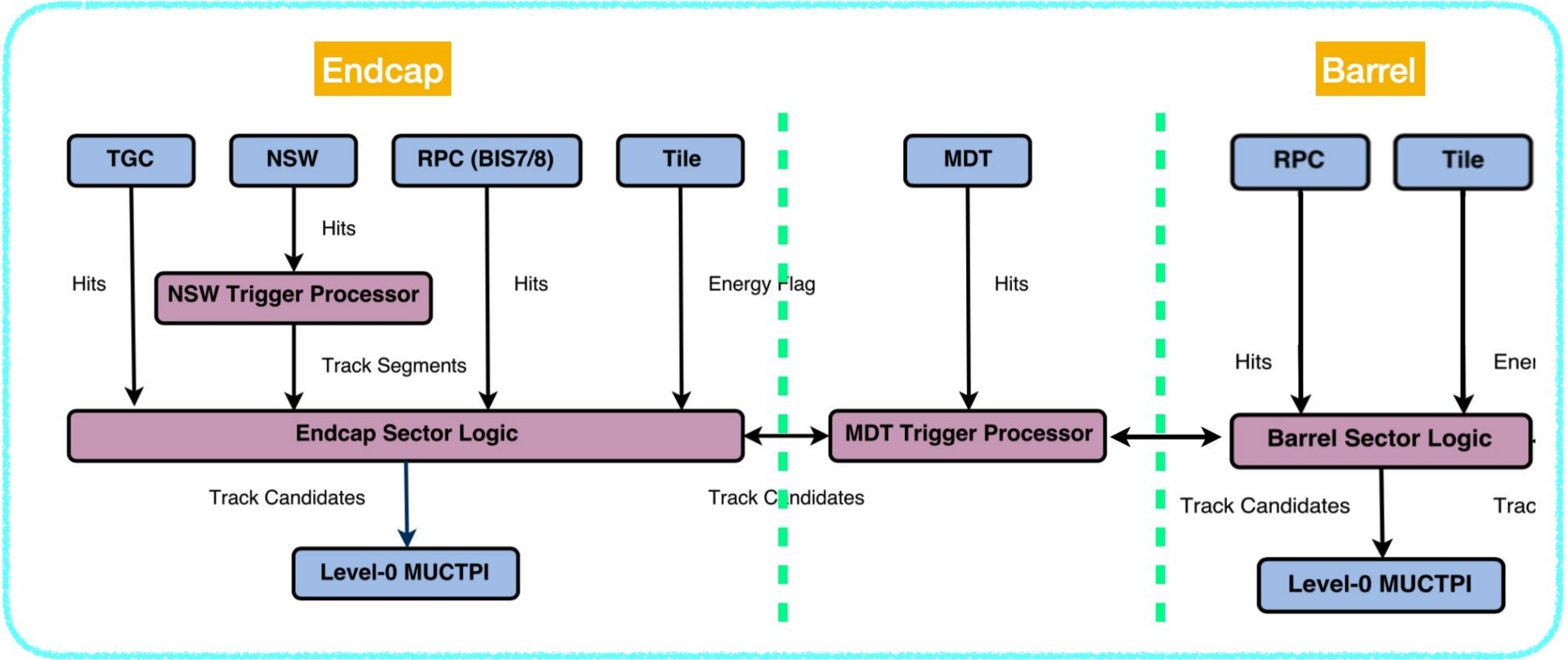
- **ATLAS Muon Spectrometer before Phase-II**
  - Three stations of Resistive Plate Chambers (RPCs) in the barrel
  - Three stations of Thin Gap Chambers (TGCs) in the end-cap
  - RPC/TGC used for hardware based Level-1 (L1) Trigger
  - Three stations of Monitored Drift Tubes (MDTs) in barrel/end-cap for tracking
  - New Small Wheel (Micro-Megas + sTGC) before magnet for tracking and trigger (Friday session)
- **Phase-II Upgrades**
  - New RPC chambers with increased rate capability in BI station
  - New sMDT in the BIS stations
  - New TGC triplets in the EIL4 station
  - Hardware-based trigger now called Level-0 (L0)





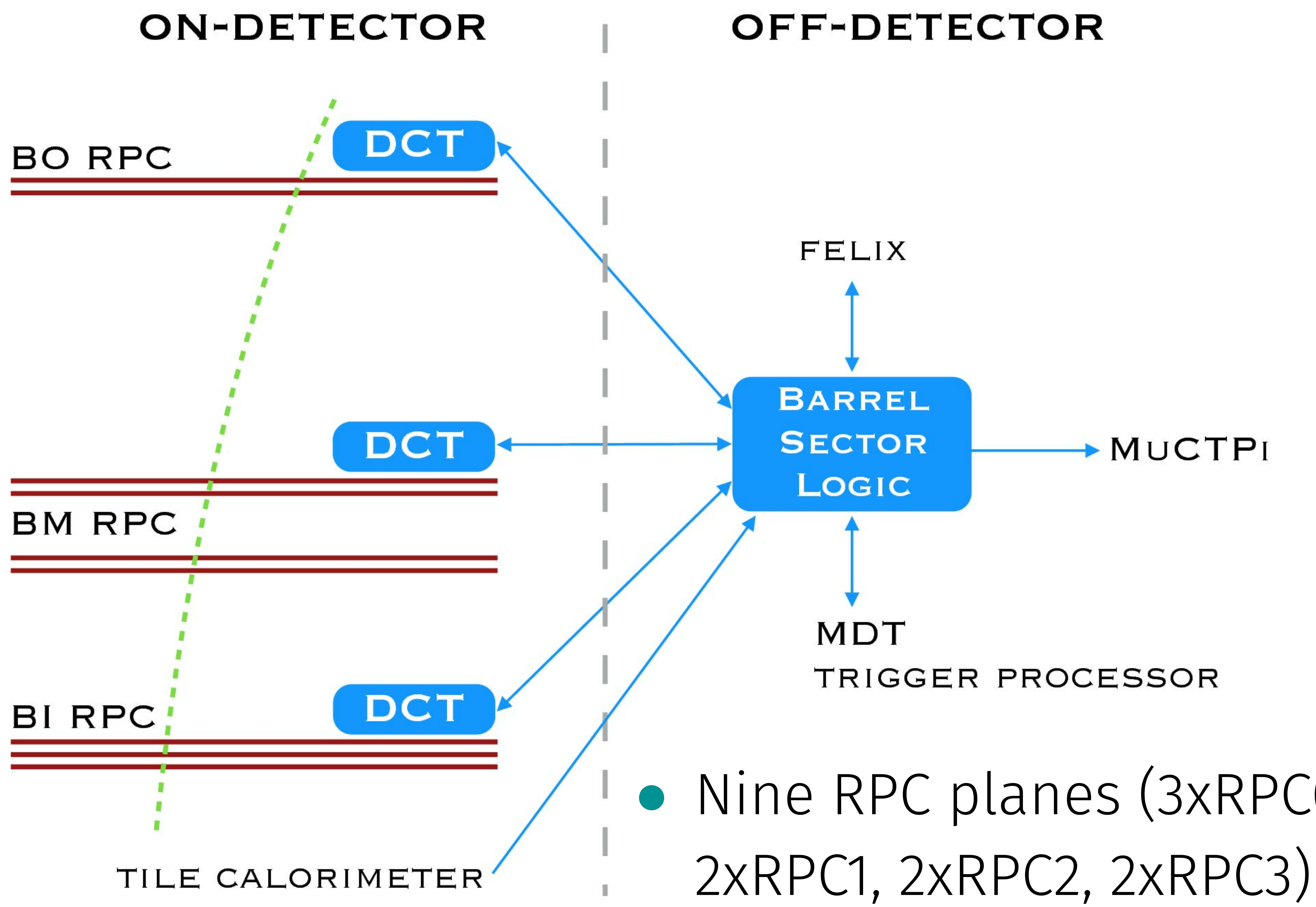
Upgrade of trigger and readout electronics

- **Readout:** The system must comply requirements of L0 Trigger
  - Higher readout L0 rate (1 MHz)
  - Longer latency (10 μs)
- **Trigger:**
  - Sharper efficiency turn-on-curves on thresholds
  - Suppress fake trigger rates



- **Trigger and readout** chain of RPC/TGC trigger chambers will be **replaced**
  - All the hit data sent off-detector for trigger processing
- MDT electronics chain completely redesigned
  - **MDT data** available at **L0** to improve quality of RPC/TGC/NSW trigger candidates
- Sector Logic boards and MDT Trigger processors hosts powerful FPGAs to perform track reconstruction

L0Muon Barrel Sector Logic



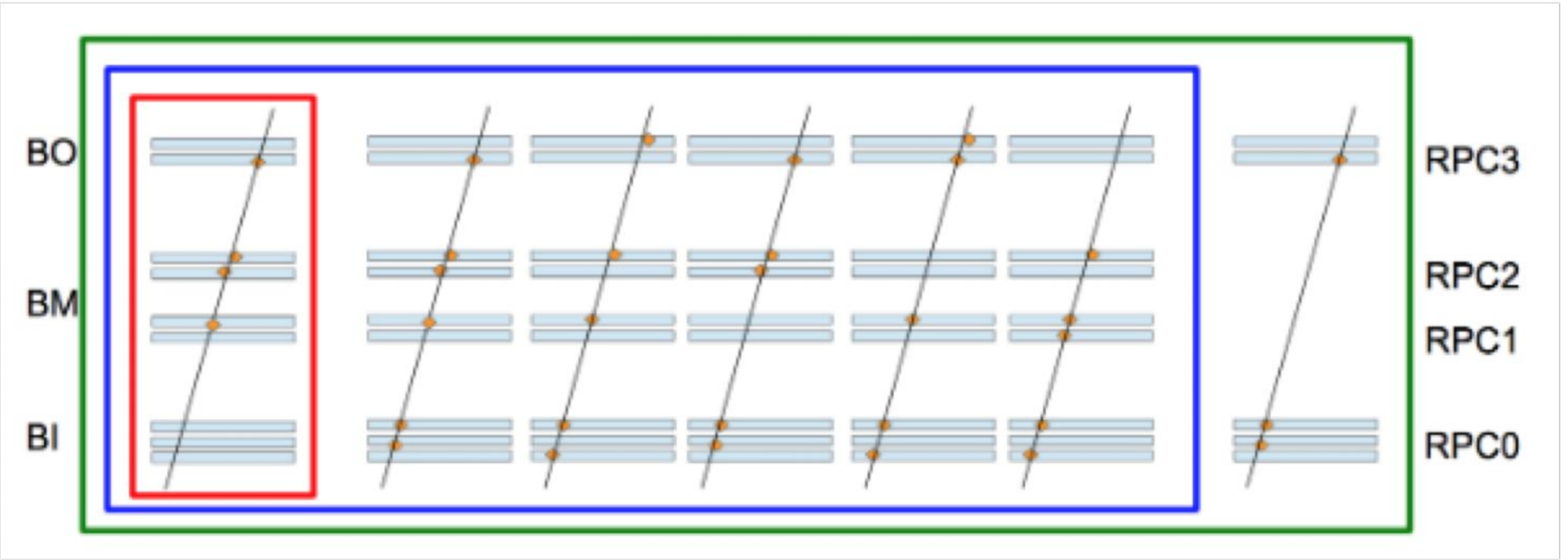
- Nine RPC planes (3xRPC0, 2xRPC1, 2xRPC2, 2xRPC3)
- 32 sectors along Φ

- **New BI RPC station**: trigger coverage increased by 20%
- **Data Collector Transmitter** (DCT) on-detector boards sends full RPC hit data to off-detector barrel Sector logic
- **Tile calorimeter** improves trigger coverage
- **Trigger algorithm**
  - Option 1. Coincidence algorithm
  - Option 2: Neural Networks based algorithm

LOMuon Barrel Track Reconstruction

ATLAS-TDR-029
ATL-DAQ-PROC-2020-008

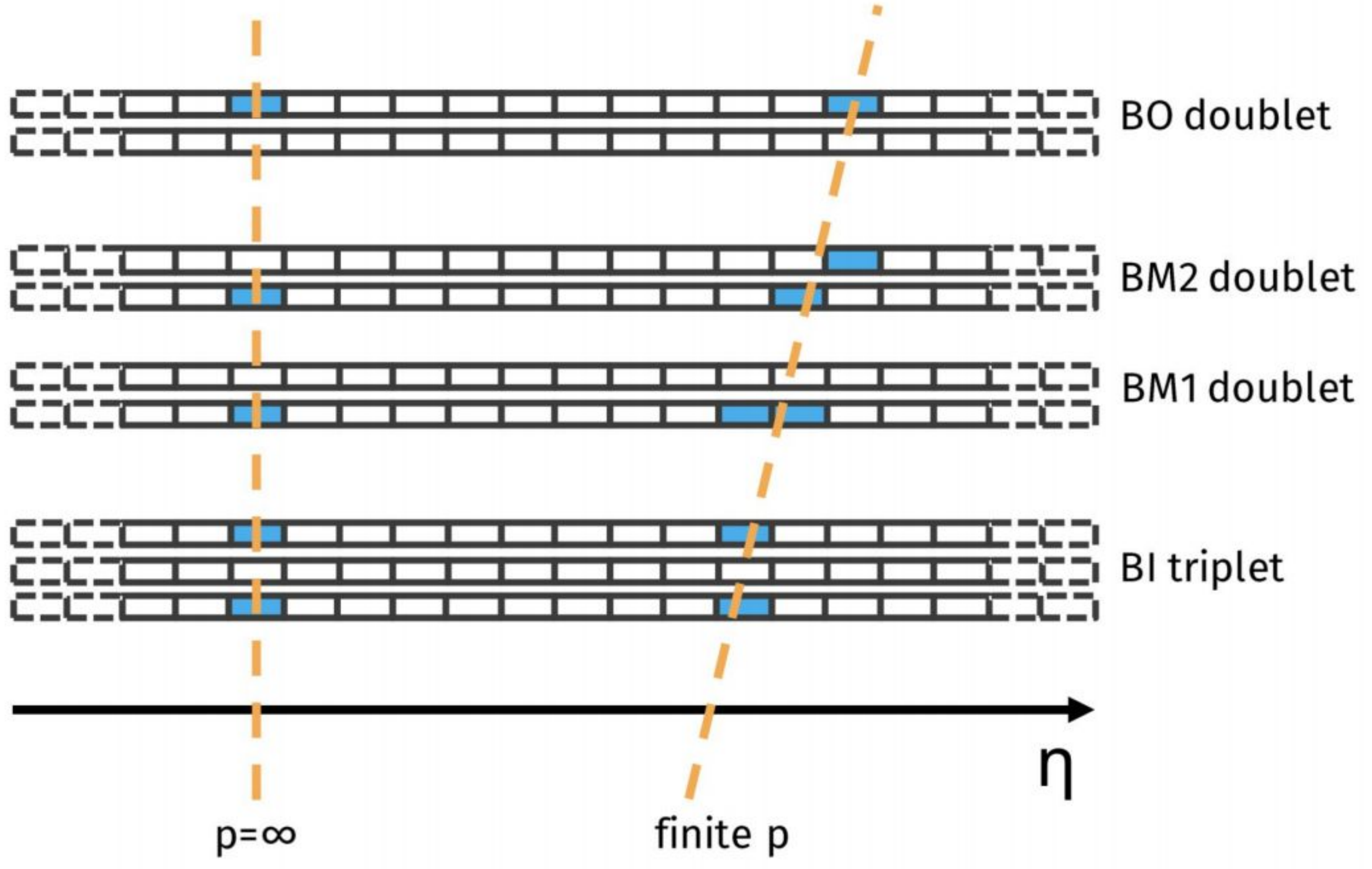
- **Option 1. Coincidence Algorithm**
  - **Baseline trigger scheme** evolution of current scheme (80% efficiency)
  - Check for **coincidences** in encapsulated windows
  - 3/4 chambers + BI-BO scheme for all p_T thresholds (96% efficiency)
  - Option to apply BI-BO only to regions with acceptance holes in BM (15% barrel)

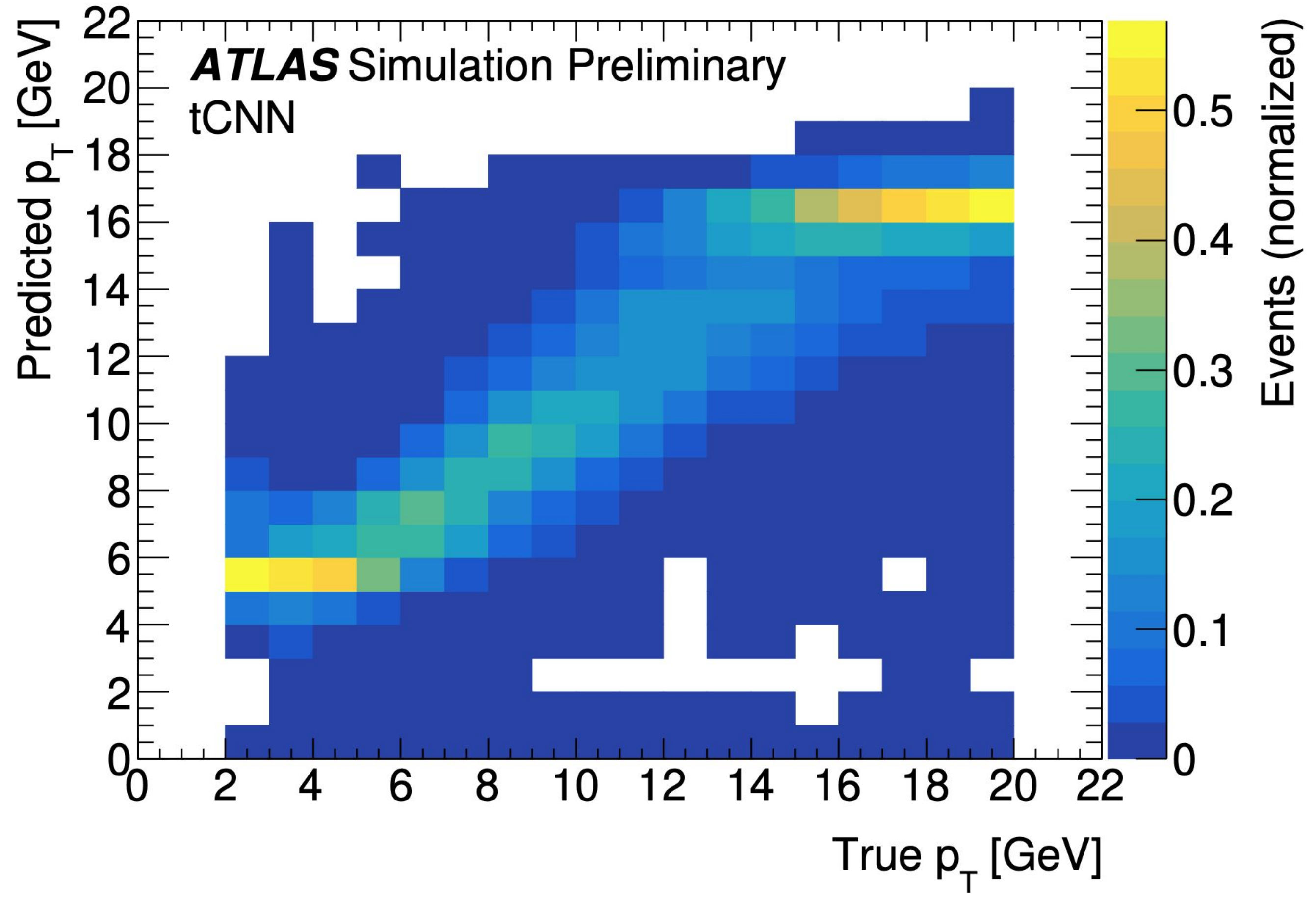


BM1-BM2-BO: current trigger
3 out of 4: including the new BI station
BI-BO: most inclusive (higher fake rate is expected)

- **Option 2. Deep Neural Networks**
  - ATLAS divided into two sides in η (η>0, η<0)
  - Mapping is η_{strip} vs. RPC layer
  - Infinite p_T muon represented by vertical lines
  - A **ternary convolutional neural network (tCNN)** is set up, outputting five parameters

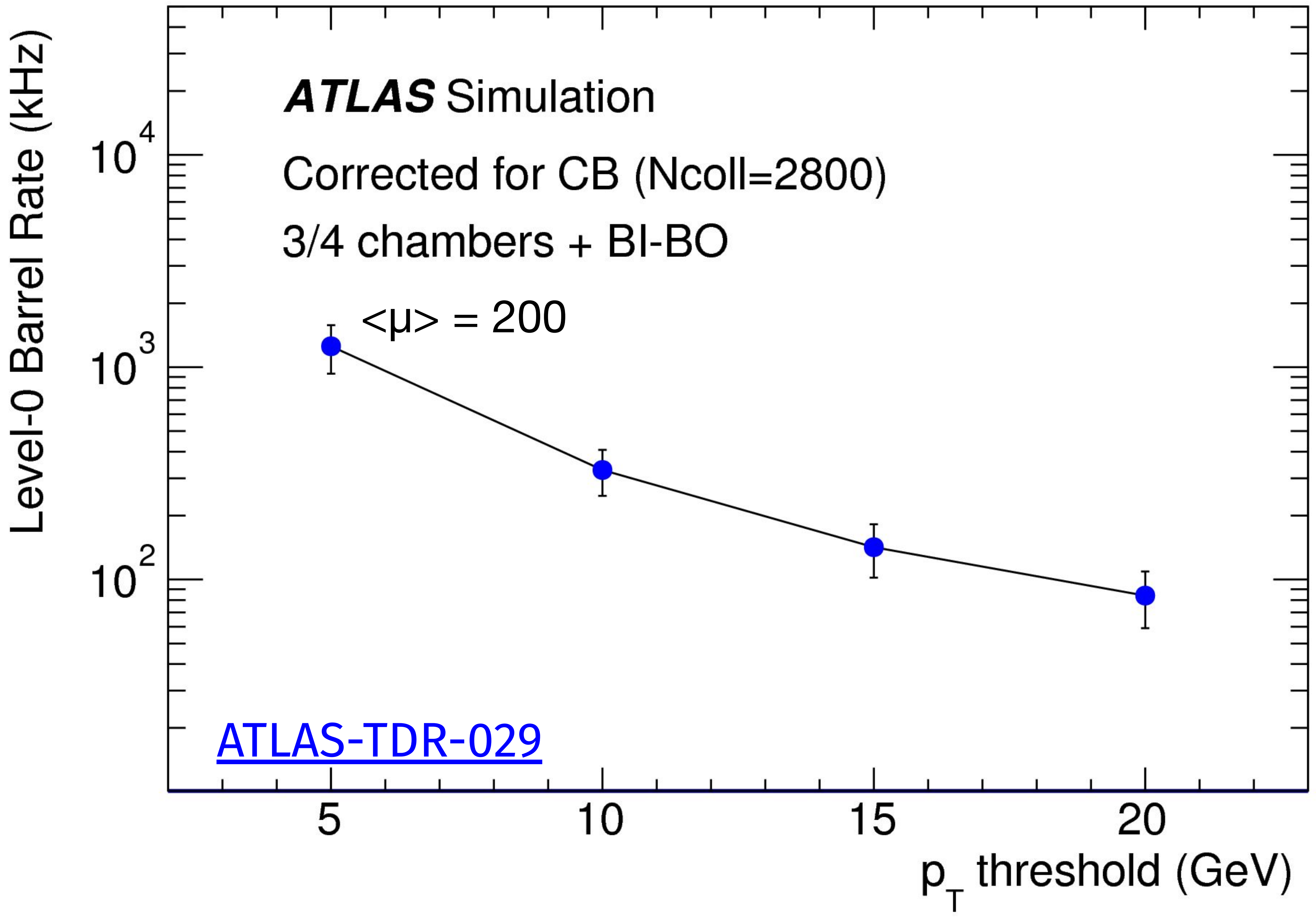
$$(p_T^{lead} \quad \eta^{lead} \quad p_T^{sublead} \quad \eta^{sublead} \quad n^{muons})$$

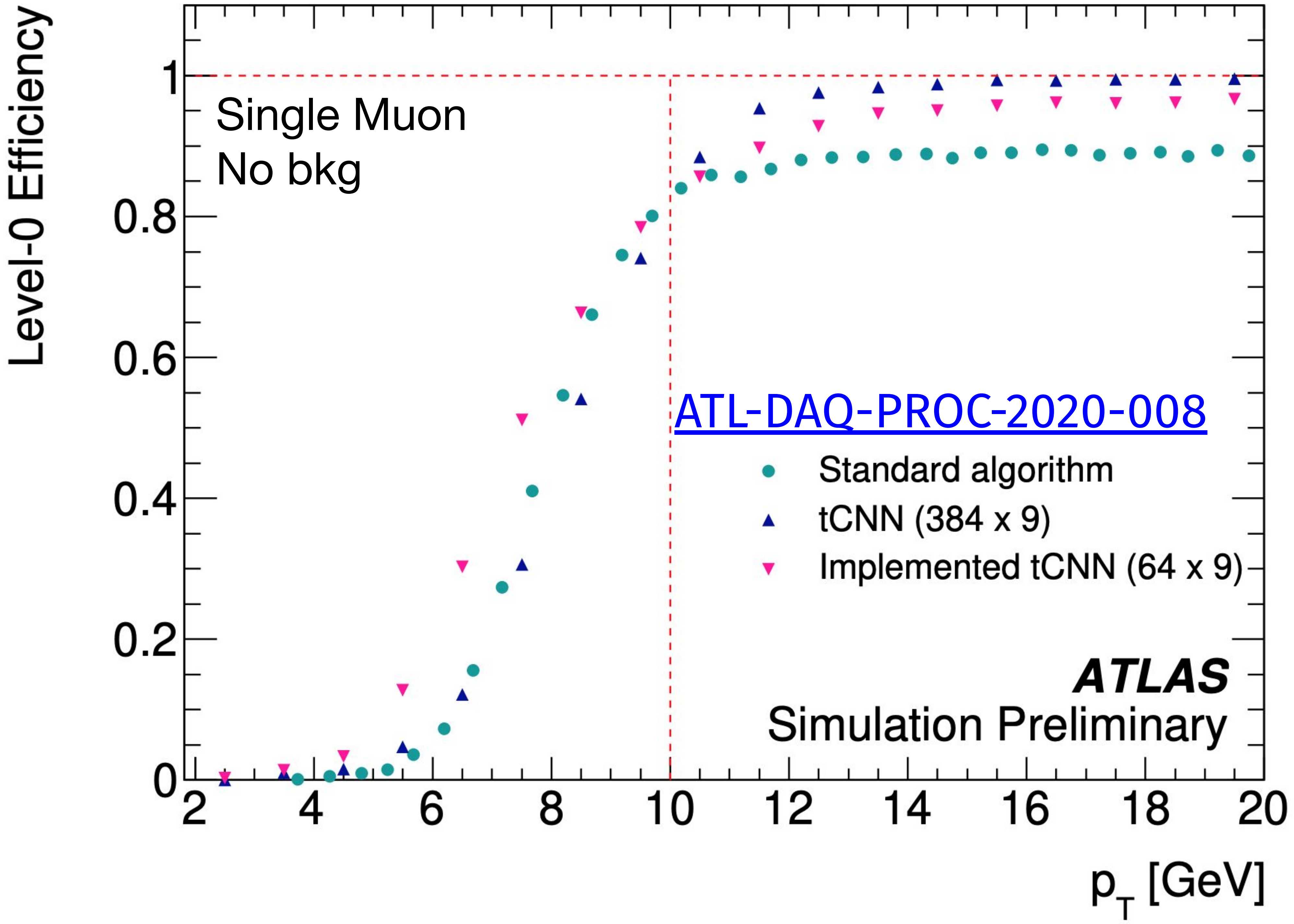




LOMuon Barrel Performance

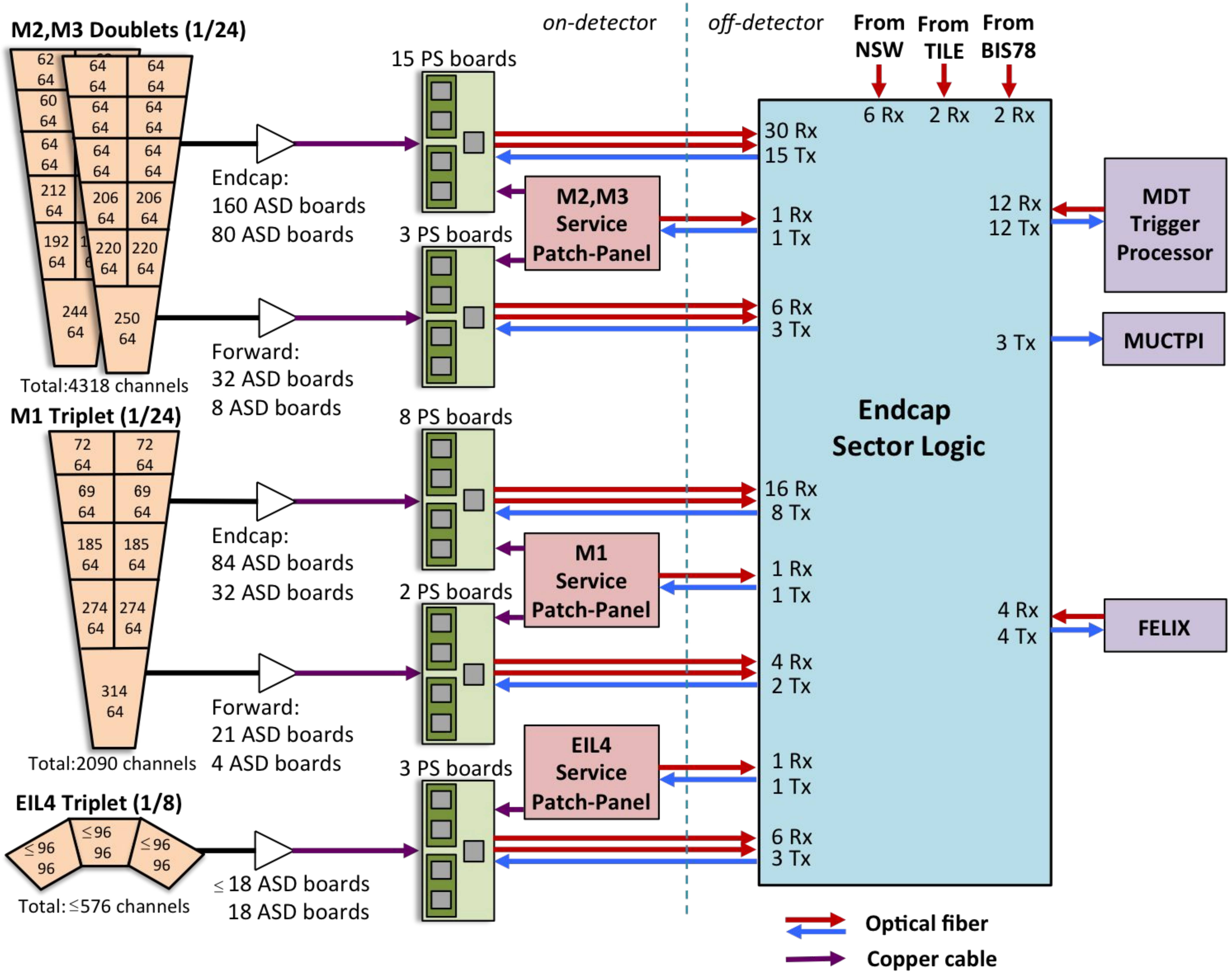
- Preliminary studies show that both algorithms are capable to **reconstruct muon candidates** with similar performance, within the latency requirement of 1µs
- The required logic fits in the chosen SL FPGA in both cases
- SL and DCT prototypes foreseen by end of 2020



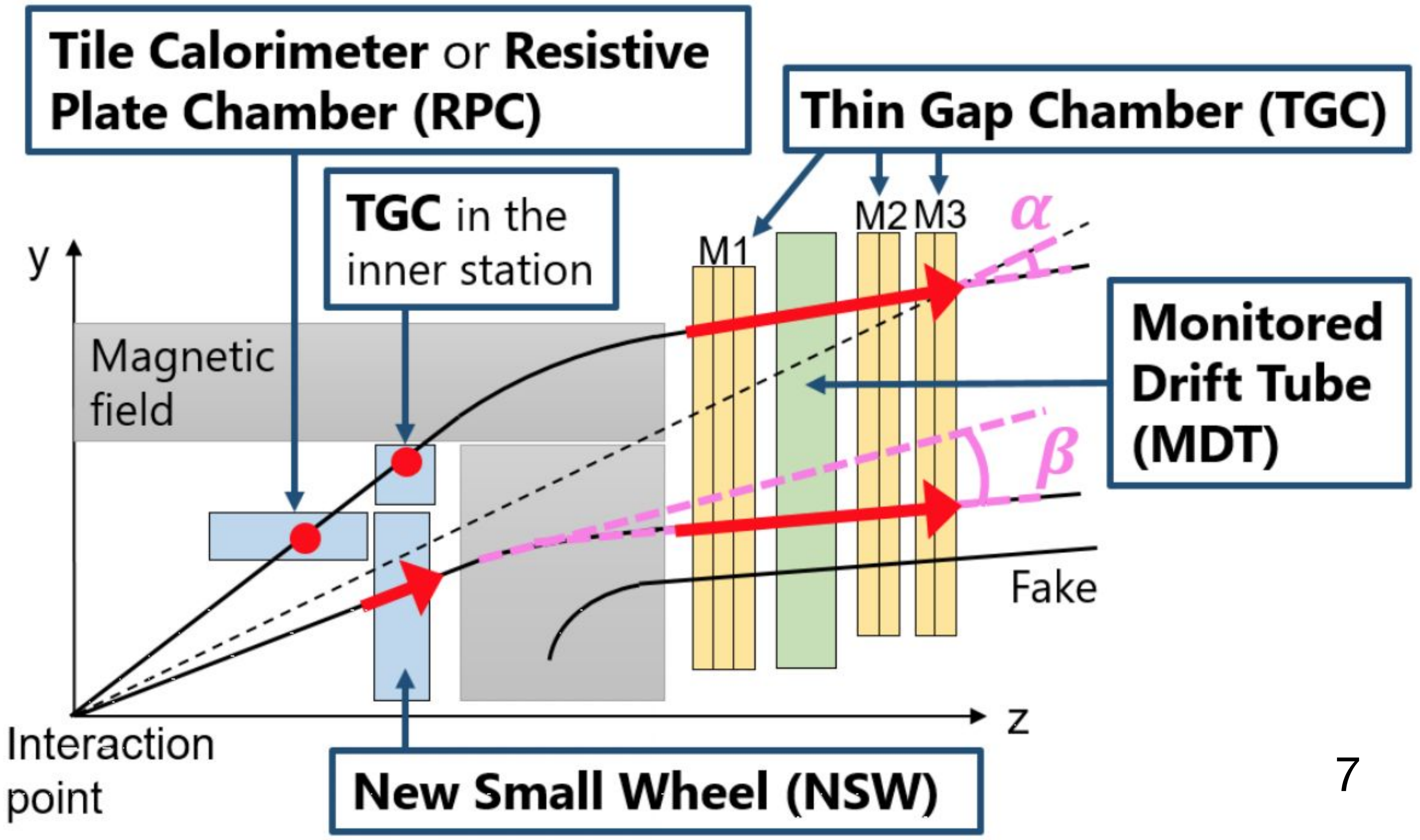


ATLAS-TDR-029 ATLAS-TDR-026

L0Muon Endcap system



- New **Front-end** electronics transmits all hits to Back-end (better performance)
- Data processed by **48 Sector-Logic** boards
- Full TGC hit precision available at L0
- TGC SL calculates muon p_T by measuring **α,β angles**
- Coincidence with detectors **before tororoid magnets** (less fake triggers)



ATL-DAQ-PROC-2019-027

L0Muon Endcap Track Reconstruction

#1: Take local coincidence within the station M1/M2/M3

M1 Coincidence
Hit ch: B B B → M1 Position ID: 3

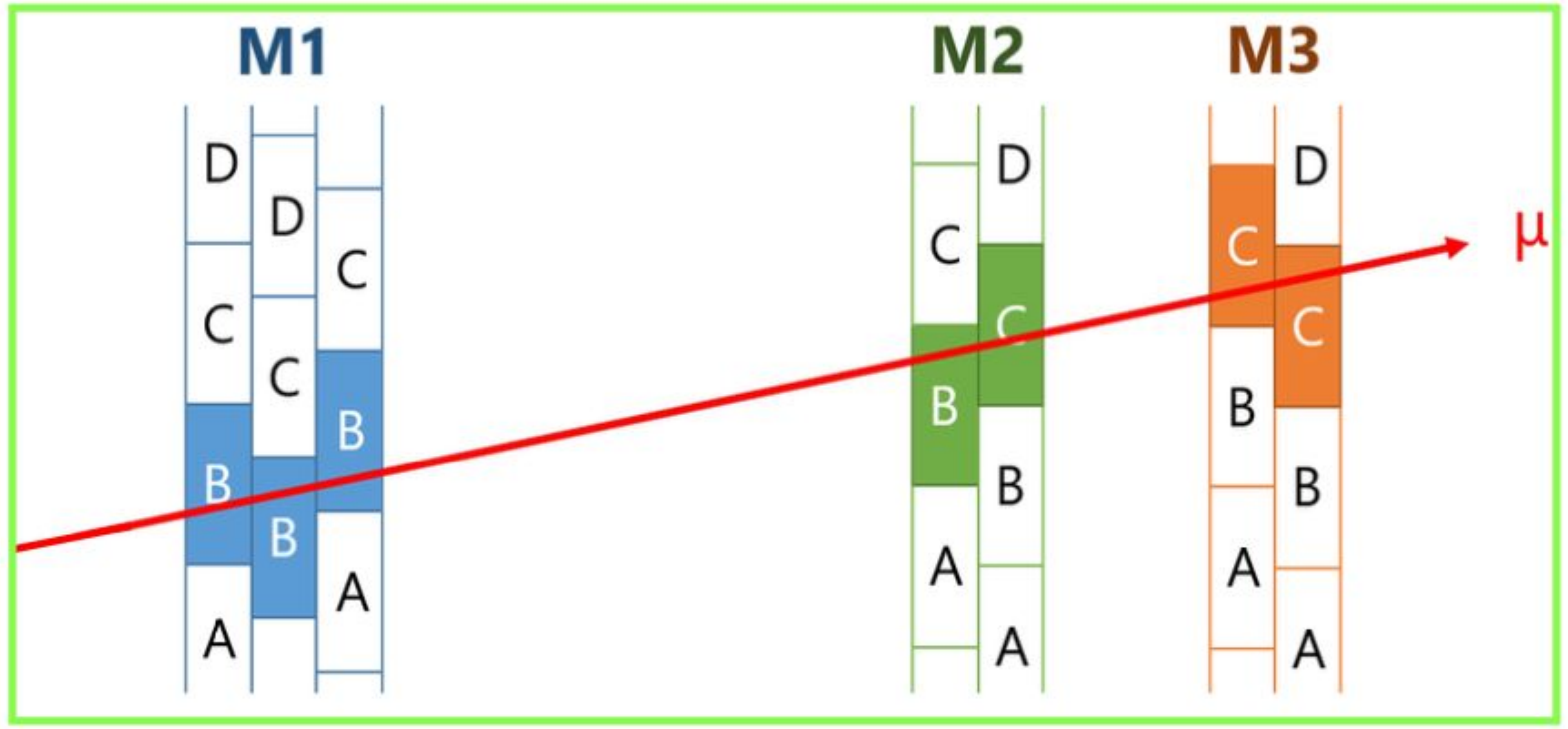
M2 Coincidence
Hit ch: B C → M2 Position ID: 4

M3 Coincidence
Hit ch: C C → M3 Positon ID: 5

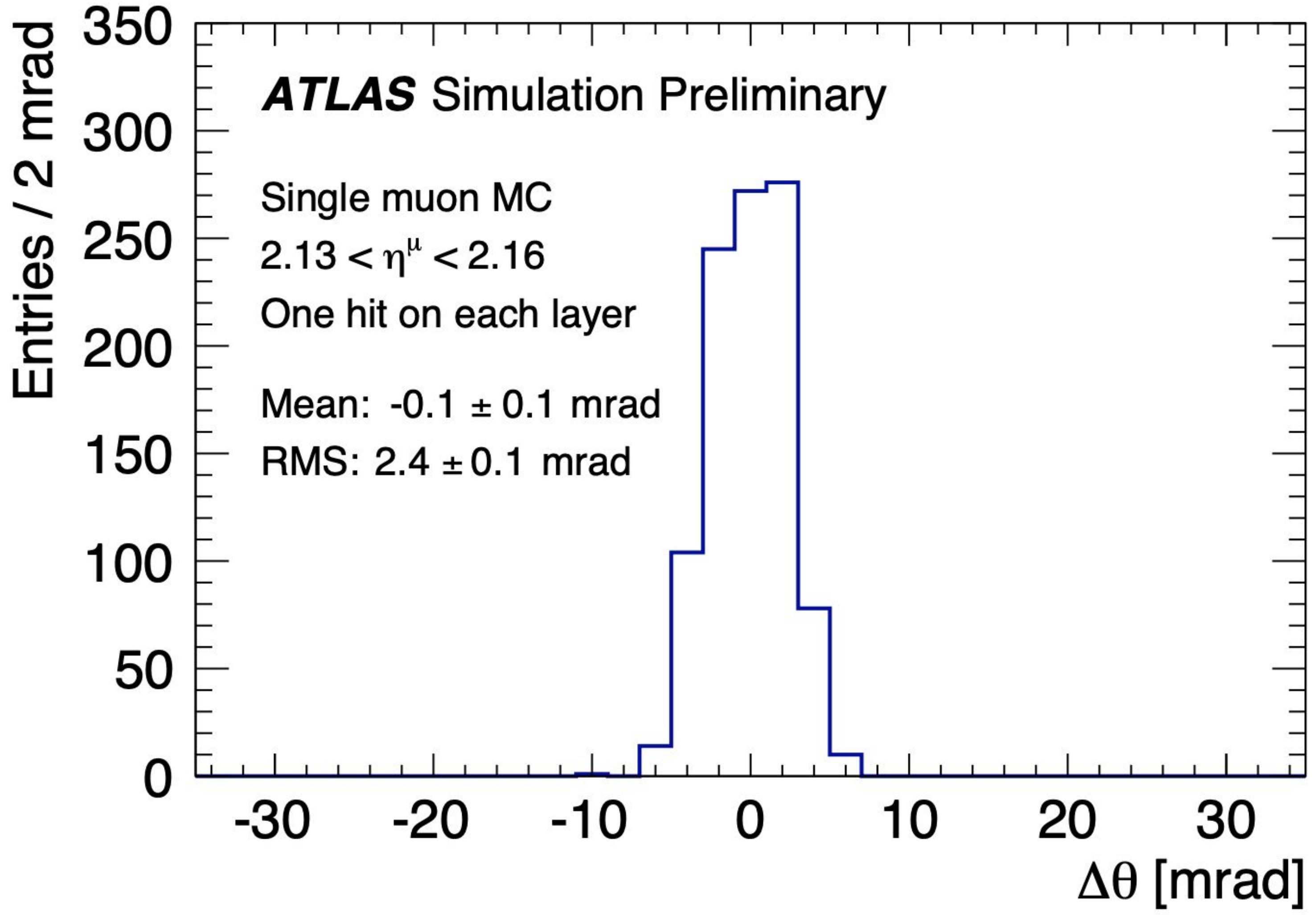
#2: Refer "predefined" Look-Up-Table (hit pattern) ⇒ define "Position" and "p_T"

Input (Position ID, 16 bit)			Output (Track segment, 18 bit)
3	4	4	Position$_a$, α_a, p_T threshold$_a$
3	4	5	Position$_b$, α_b, p_T threshold$_b$
3	5	5	Position$_c$, α_c, p_T threshold$_c$

~6 million patterns in total corresponds to **~30%** of the resource of XCVU9P



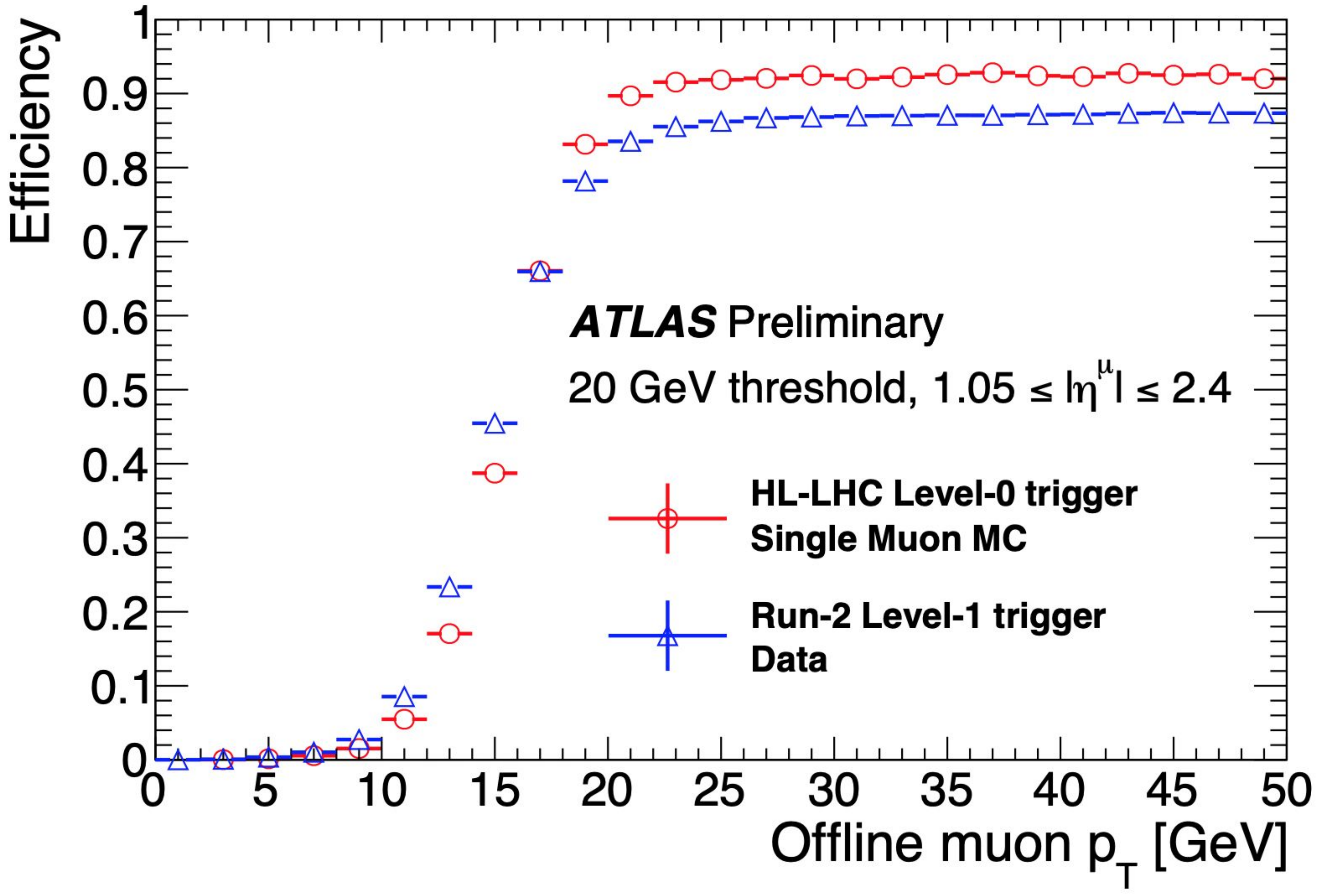
- Pattern matching algorithm divided into **two stages**
  1. Take a **coincidence** of TGC hits within each station, M1, M2 and M3.
  2. Extract track parameters from **LUT** indexed by coincidence pattern
- **Test firmware** under development, tested with a Xilinx XCVU9P FPGA

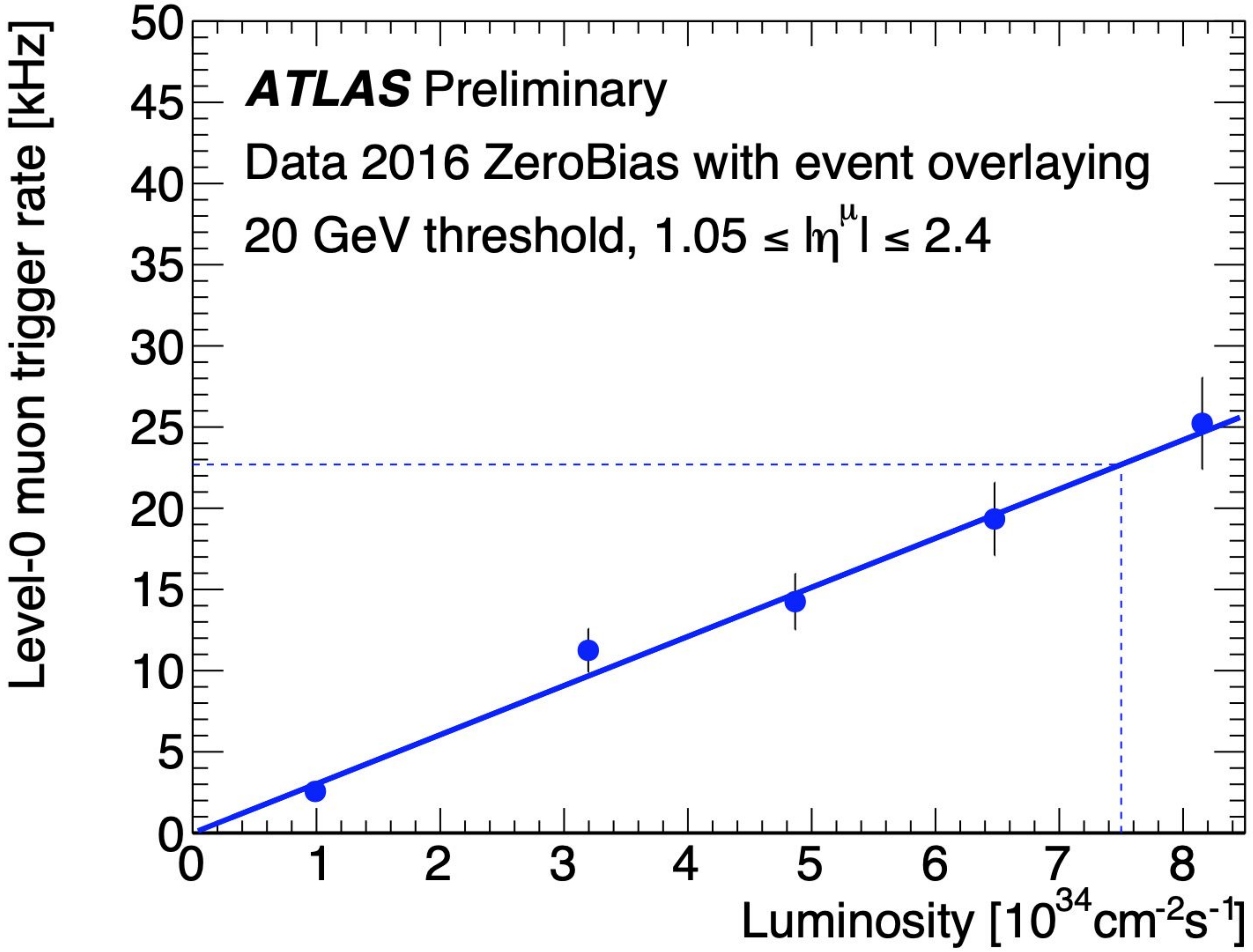


L0Muon Endcap Performance

ATL-DAQ-PROC-2019-027

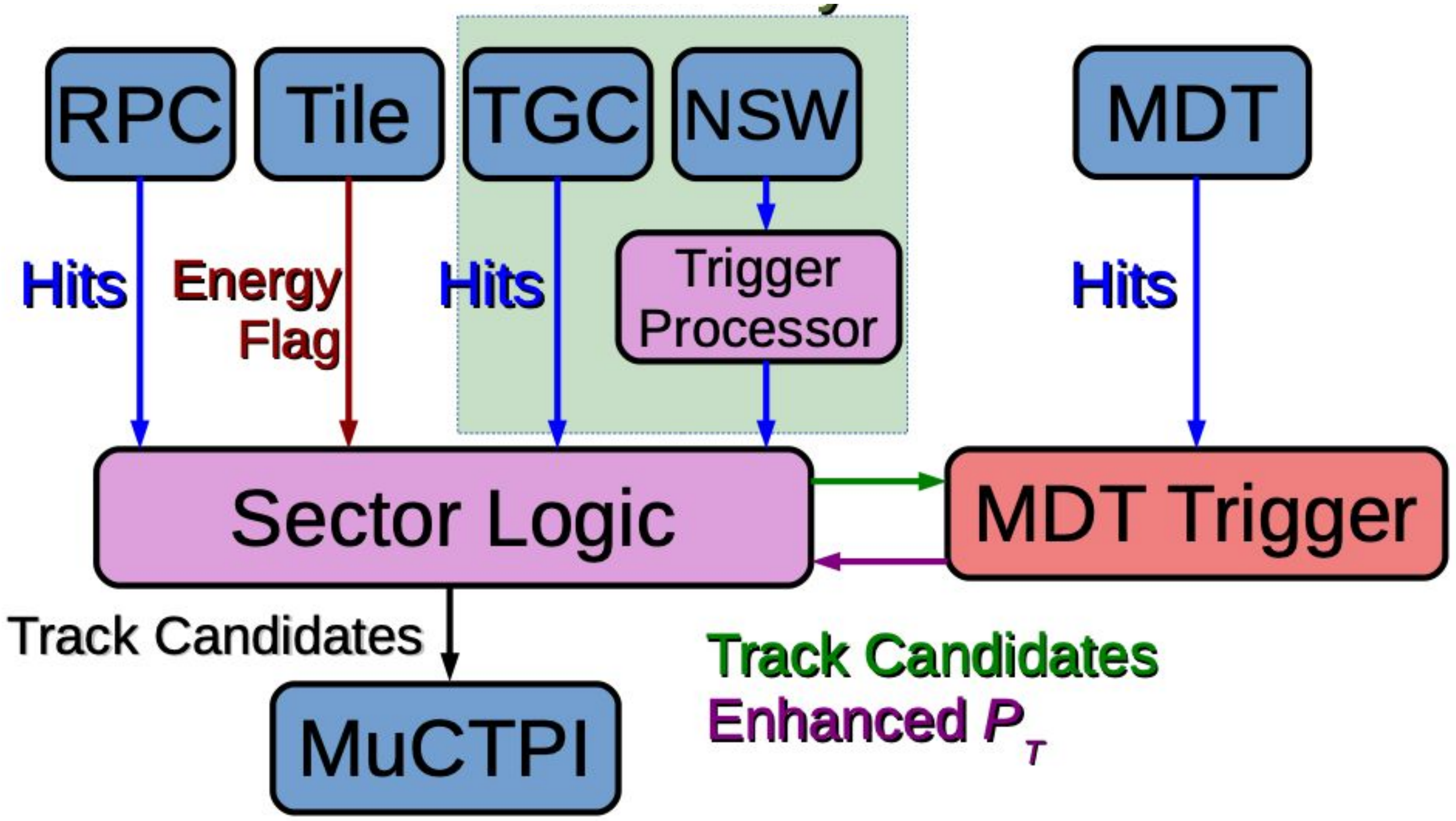
- New algorithm shows a **higher efficiency** than the current system.
- The **L0 rate** for the endcap single muon trigger, for a 20 GeV pT threshold, is less than **30 kHz**.





L0 MDT Trigger Concept

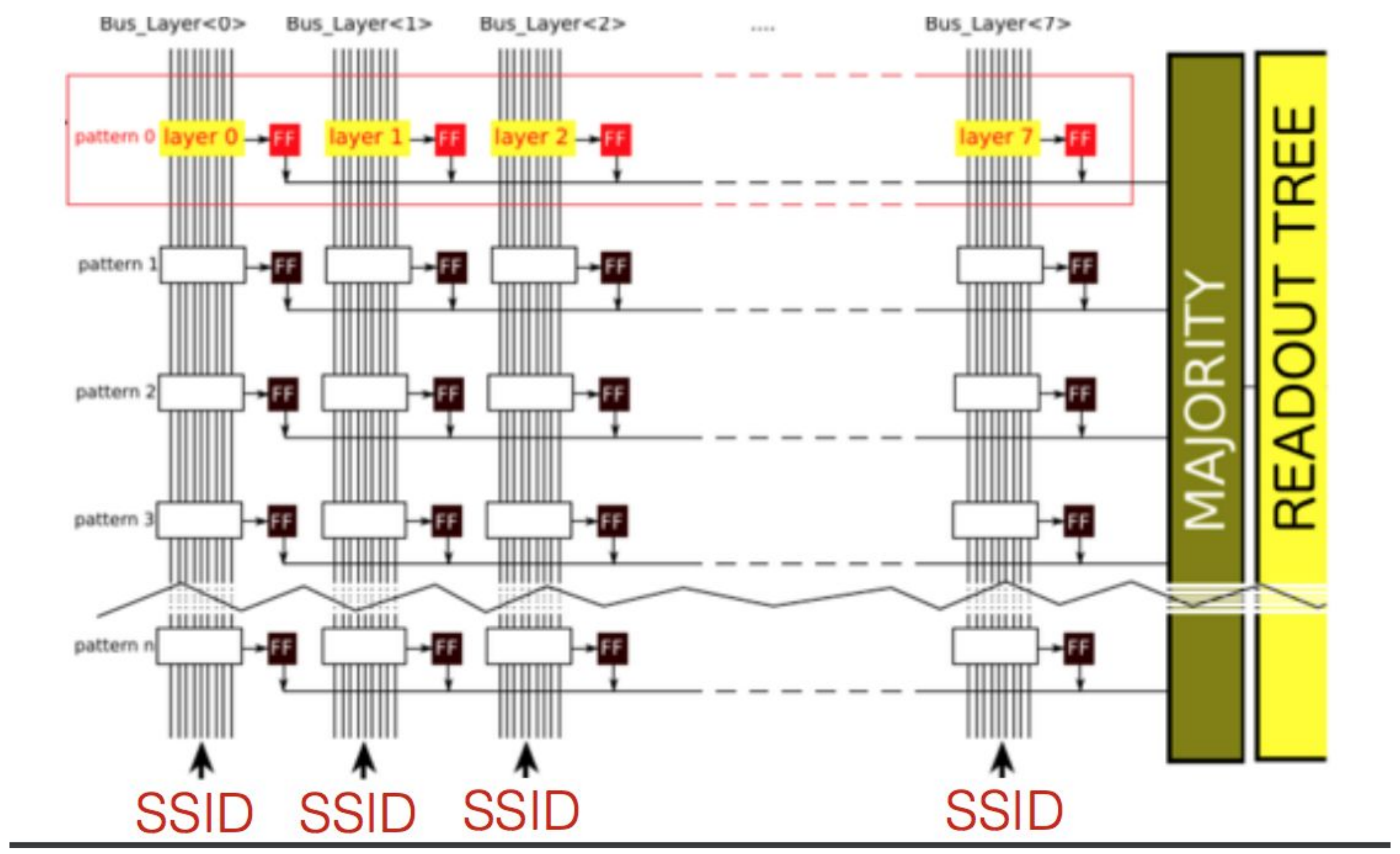
- MDT trigger consists of **64 sectors**, 32 in the barrel and 32 in the endcaps
- MDT Trigger receives up to three trigger candidates from **SL** (**seed** for finding muon track with MDT hits) per sector
- MDT hits compatible with SL candidates in time (**BCID**) and space (**RoI**) are used to reconstruct **muon track segments** in each MDT station



- MDT Segment information is combined to compute refined muon p_T and η
- MDT track candidates sent back to SL and then to MuCTPI
- If **L0 acceptance** arrives, the MDT Trigger Processor sends all MDT hits to **FELIX for readout**

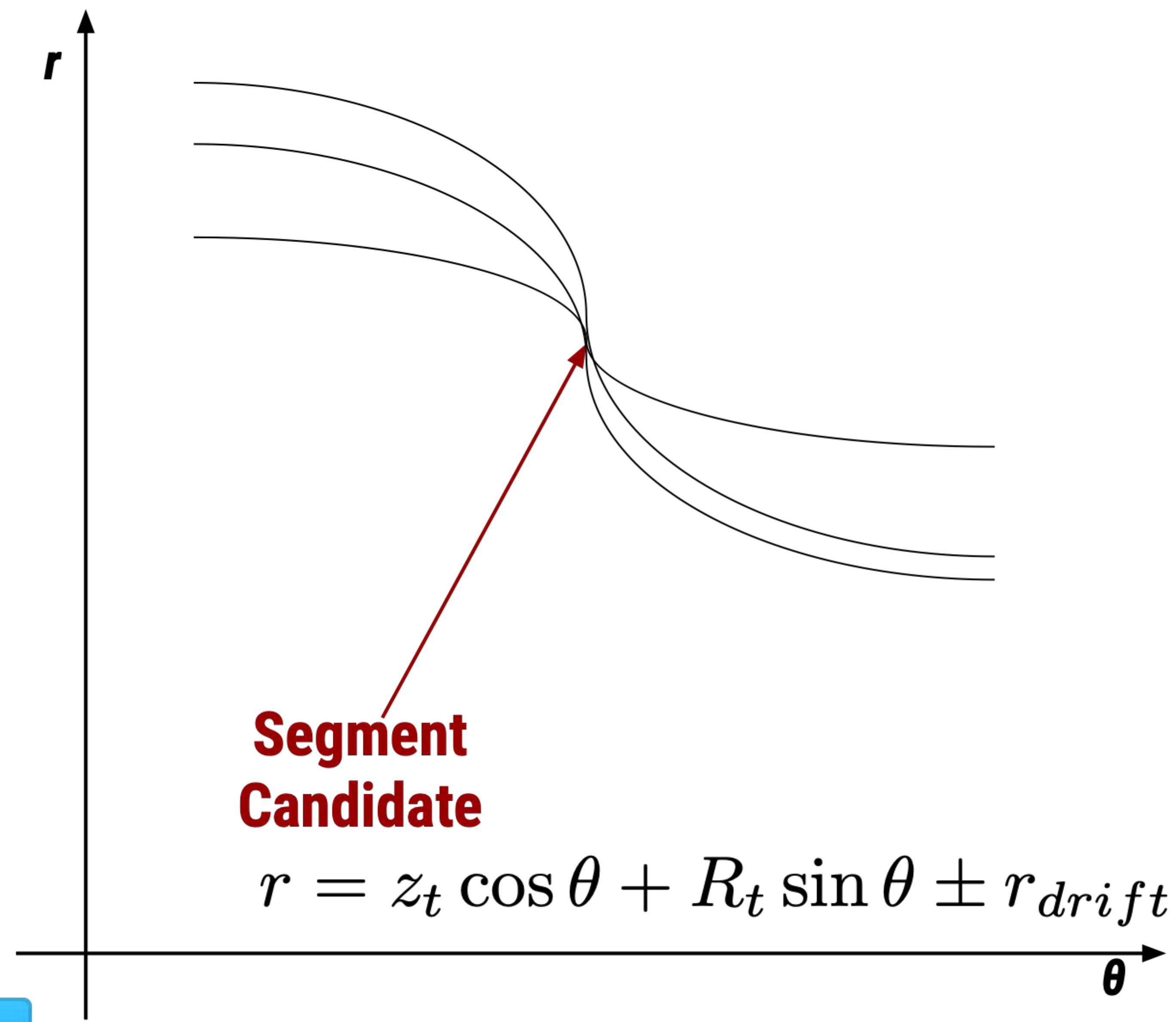
L0 MDT Segment Finder algorithms

Associative Memories (AM ASIC)



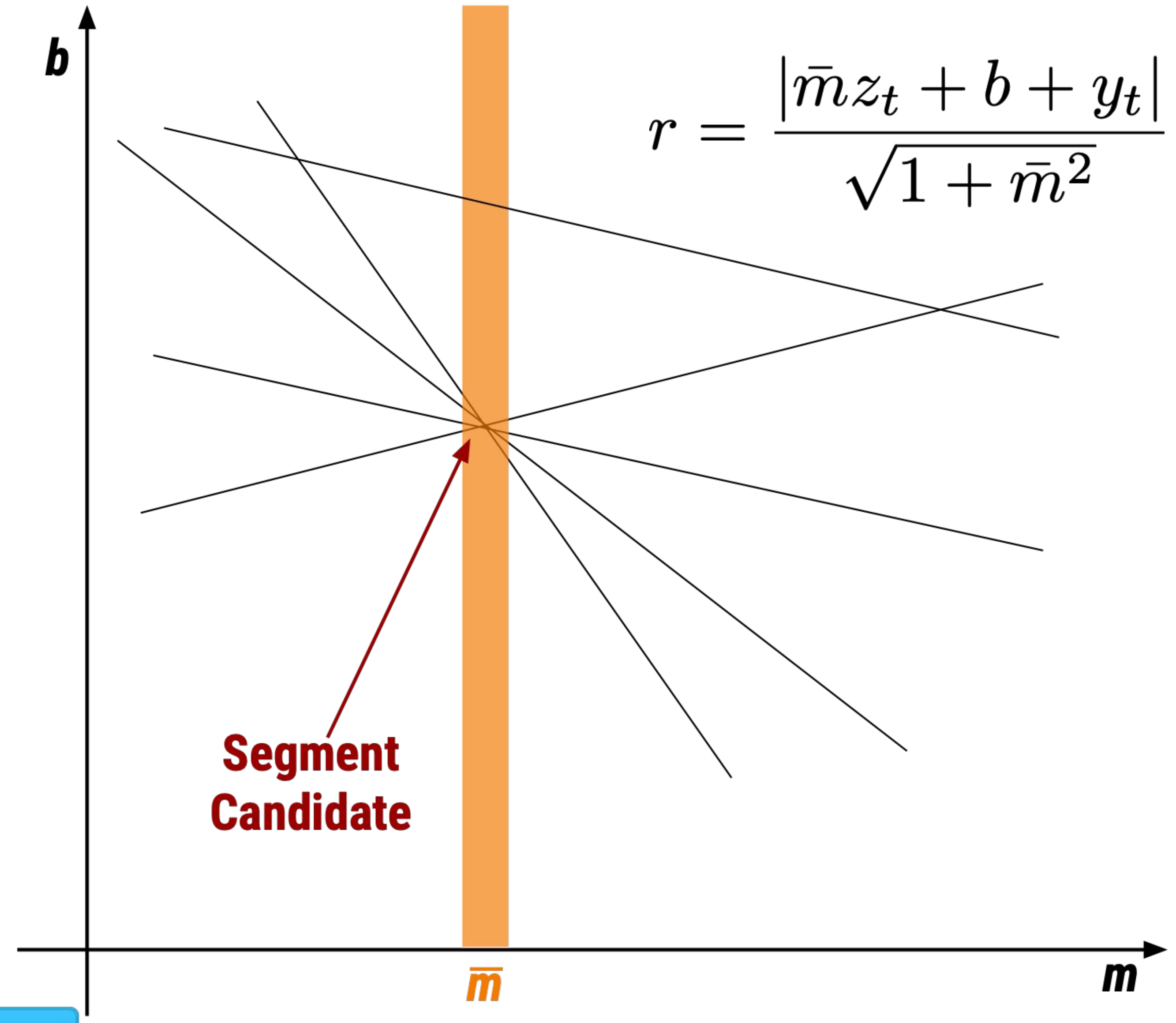
- Pattern recognition using precomputed pattern banks
- Require different hw architecture (AM ASICs)

Legendre Transform (FPGA)



- 2D scan over position and direction around SL seed
- Candidate *r*, *θ* given by most populated bin

Compact Segment Finder (FPGA)



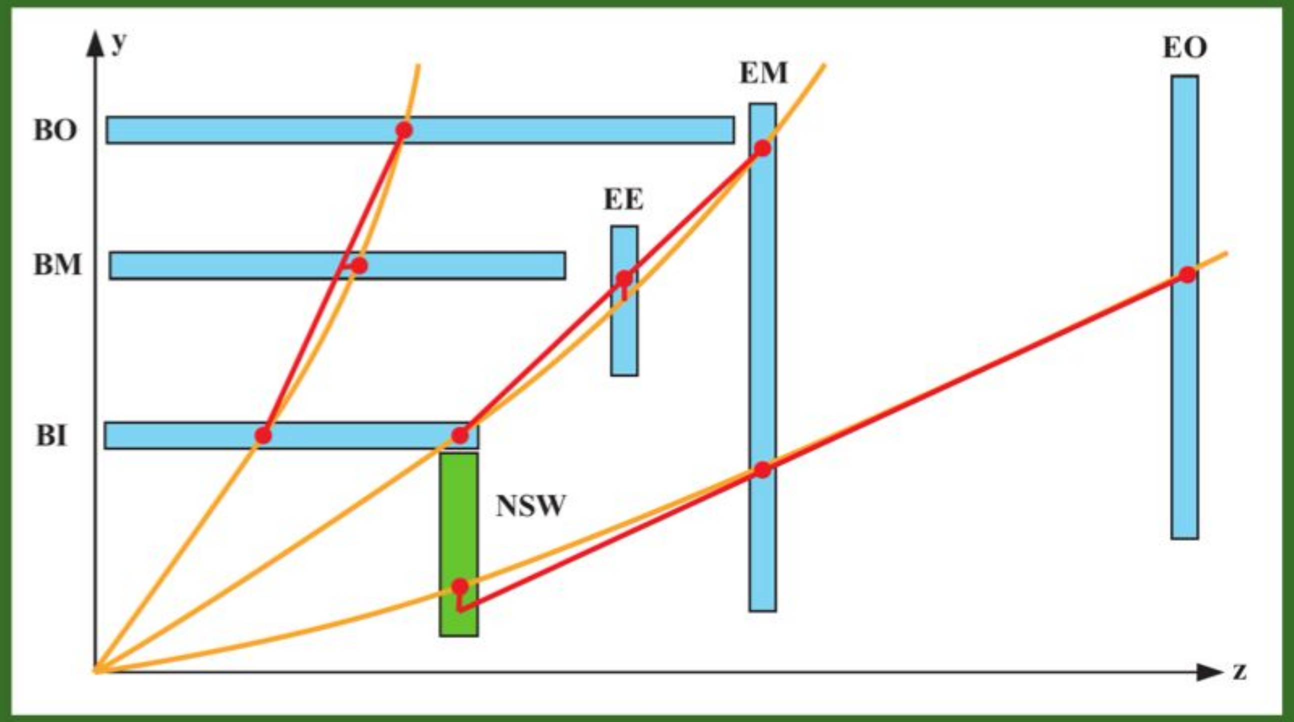
- 1D scan only over position by using SL seed for direction
- χ^2 fit for final segment parameters and quality

L0 MDT Track Fitter

- Muon **p_T** is calculated using the reconstructed **MDT segment** coordinates
- Depending on the number of stations with valid MDT segments, muon p_T can be estimated as a function of the **sagitta *s*** or the **deflection angle *Δβ***
  - 3/3 stations - Sagitta. Defined in the barrel (endcaps) as the distance in the bending plane of the segment in the middle (inner) chamber from the straight line connecting the other two
  - 2/3 stations - Deflection Angle. Defined as the polar angle difference of the two segments
- **Φ, η corrections** take into account distorsions in the magnetic field

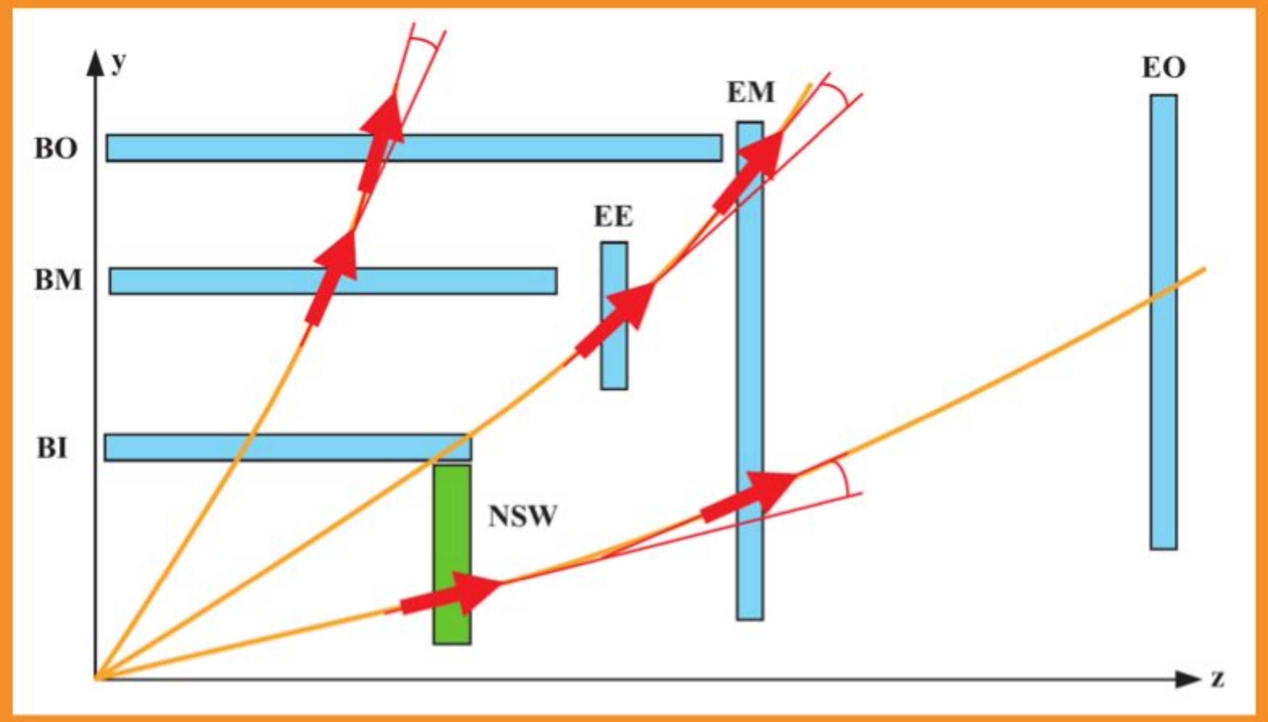
Sagitta Method

$$p_T = \Sigma_{i=0}^{2} \frac{a^i}{s^i} + \Sigma_{i=0}^{2} b_i \cdot \phi^i + \Sigma_{i=0}^{1} c_i \cdot \eta^i$$



Δβ Method

$$p_T = \Sigma_{i=0}^{2} \frac{a^i}{\Delta\beta^i} + \Sigma_{i=0}^{2} b_i \cdot \phi^i + \Sigma_{i=0}^{1} c_i \cdot \eta^i$$



LO MDT Performance

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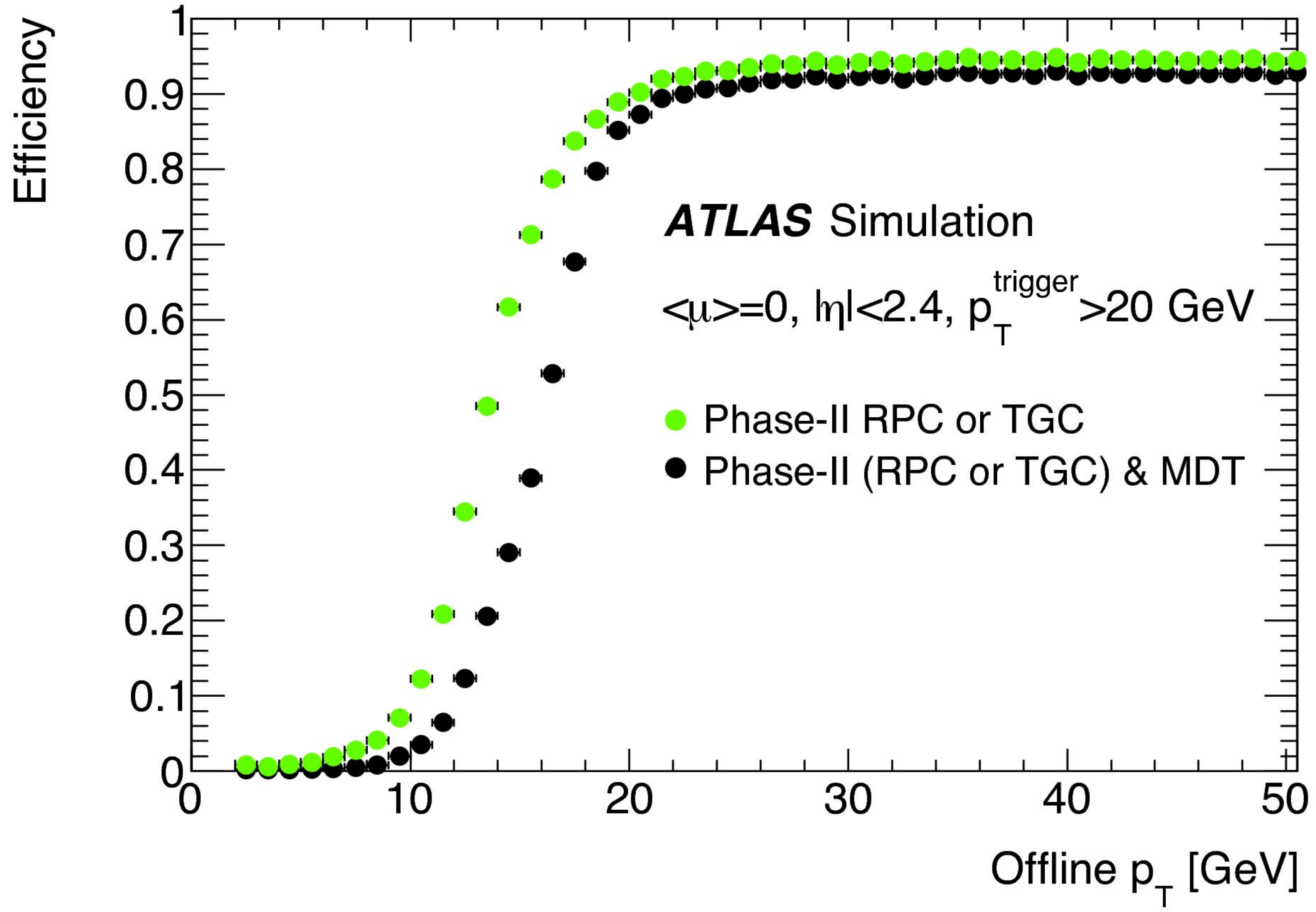

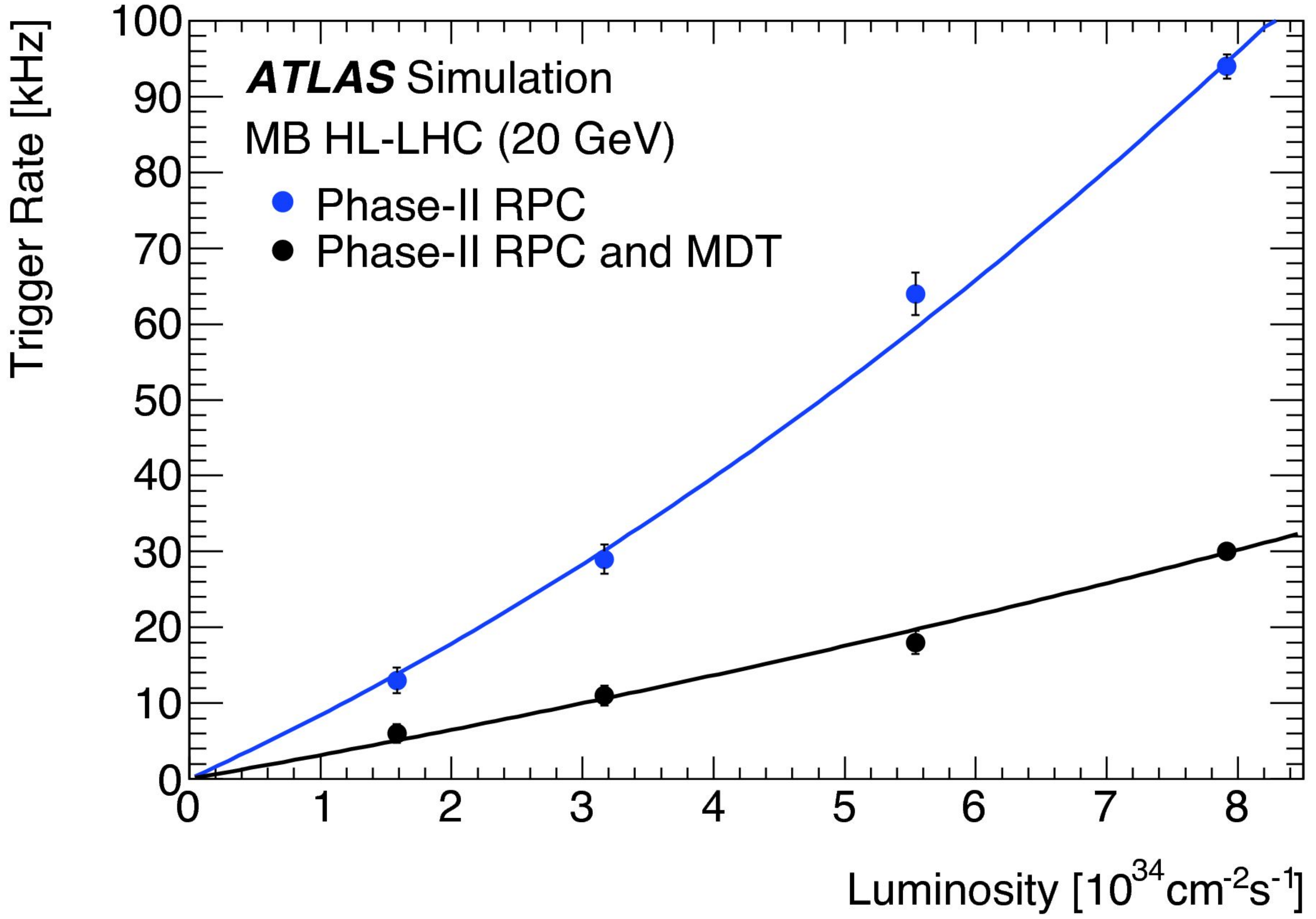

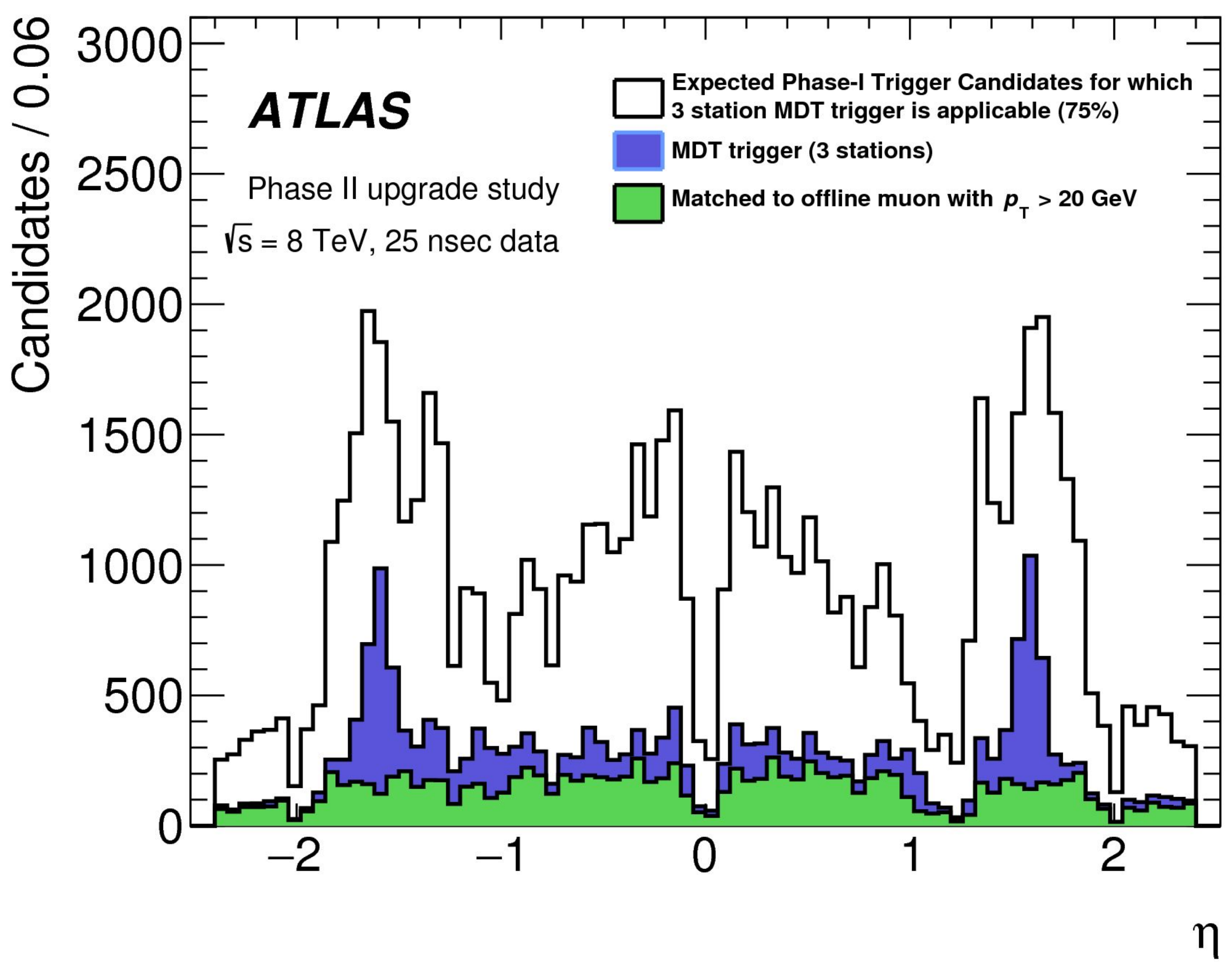

- MDT Trigger provides improved selectivity for muon p_T around the threshold, keeping a **high efficiency plateau**
- **Rate reduction** is between 50-70%, depending on the detector region and considered threshold
- Firmware under development, preliminary results show feasible resource usage and latency

Conclusions

- The upgrade of the **ATLAS muon spectrometer readout and trigger electronics** constitutes a great challenge
  - Majority of **front- and back-end electronics** will be **replaced**
  - All **data** will be transmitted **off-detector** for trigger processing with full hit precision
  - Increasing in latency and output rate
- Three main components of L0Muon system
  - **Barrel Sector Logic**: constructs muon track candidates out of RPC and Tile calorimeter hits.
  - **Endcap Sector Logic**: constructs MTC using TGC hits combined with data from NSW, Inner RPC Small sector and Tile calorimeter
  - **MDT Trigger Processor**: refines SL candidates measurements using hits from MDT detectors
- **Several algorithms** under study to perform trigger decision
- Preliminary studies show **good performance** and feasible **resource requirements**

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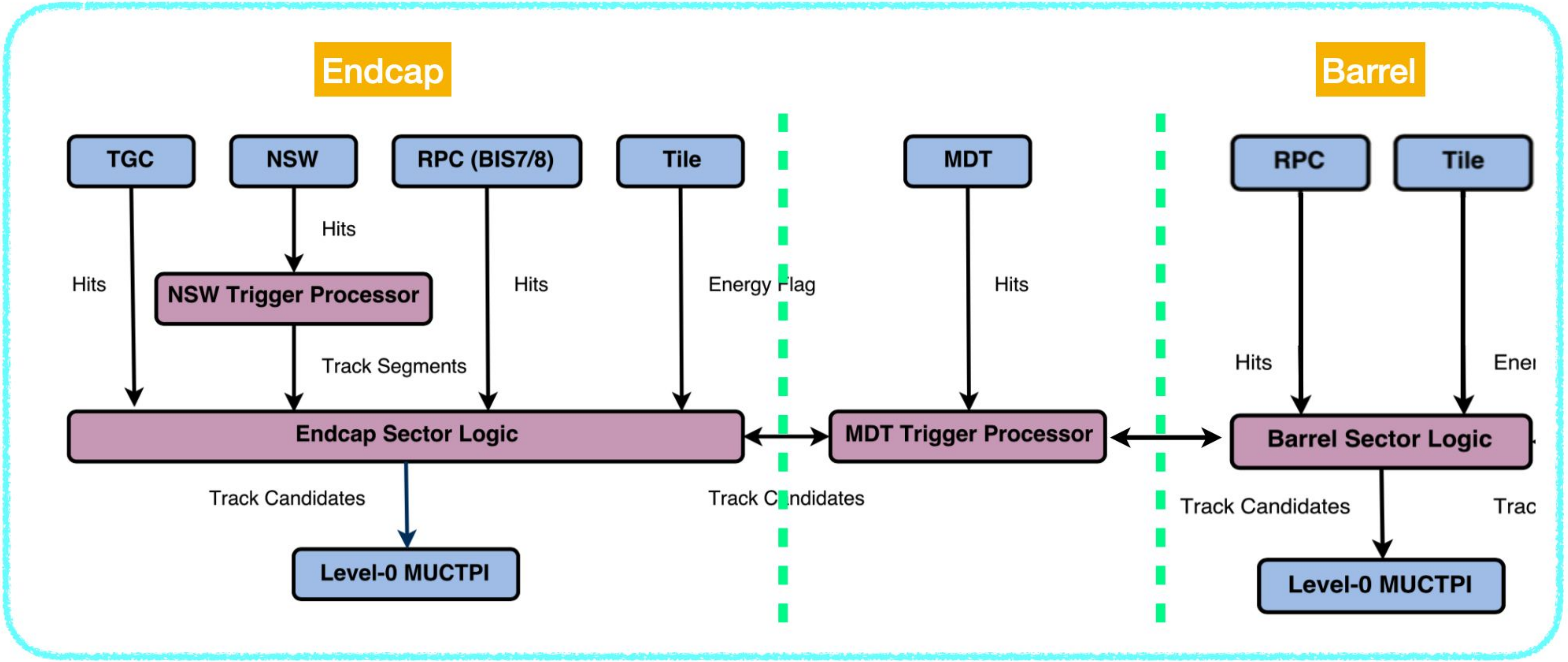
Thanks for listening!
Any questions?

L0Muon Trigger System

- Three main components:
  - **Barrel Sector Logic**: constructs muon track candidates (MTCs) out of RPC and Tile calorimeter hits
  - **Endcap Sector Logic**: constructs MTC using TGC hits combined with data from NSW, Inner RPC Small sector and Tile calorimeter
  - **MDT Trigger Processor (MDTTP)**: refines Sector Logic (SL) candidates measurements using hits from MDT detectors

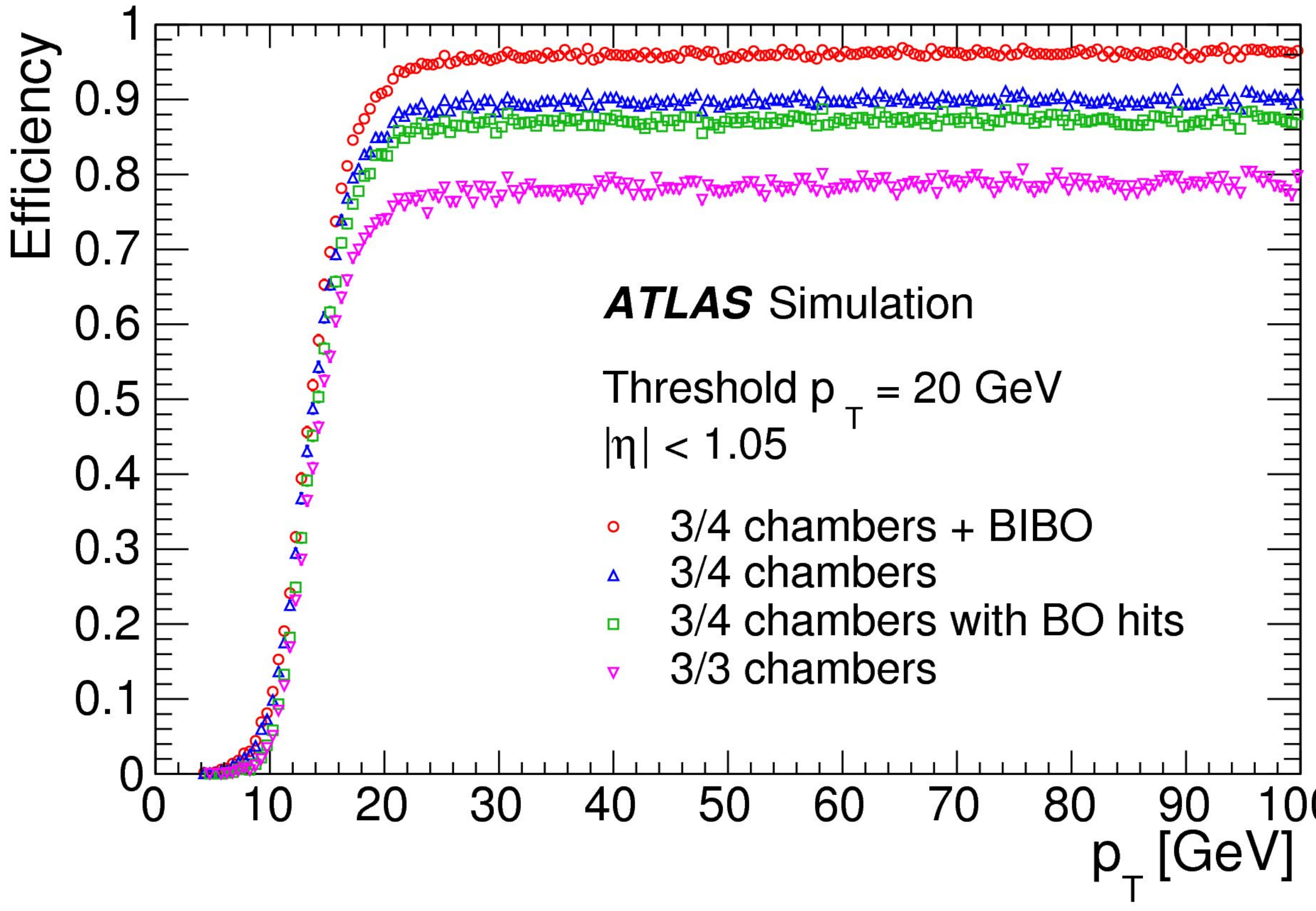


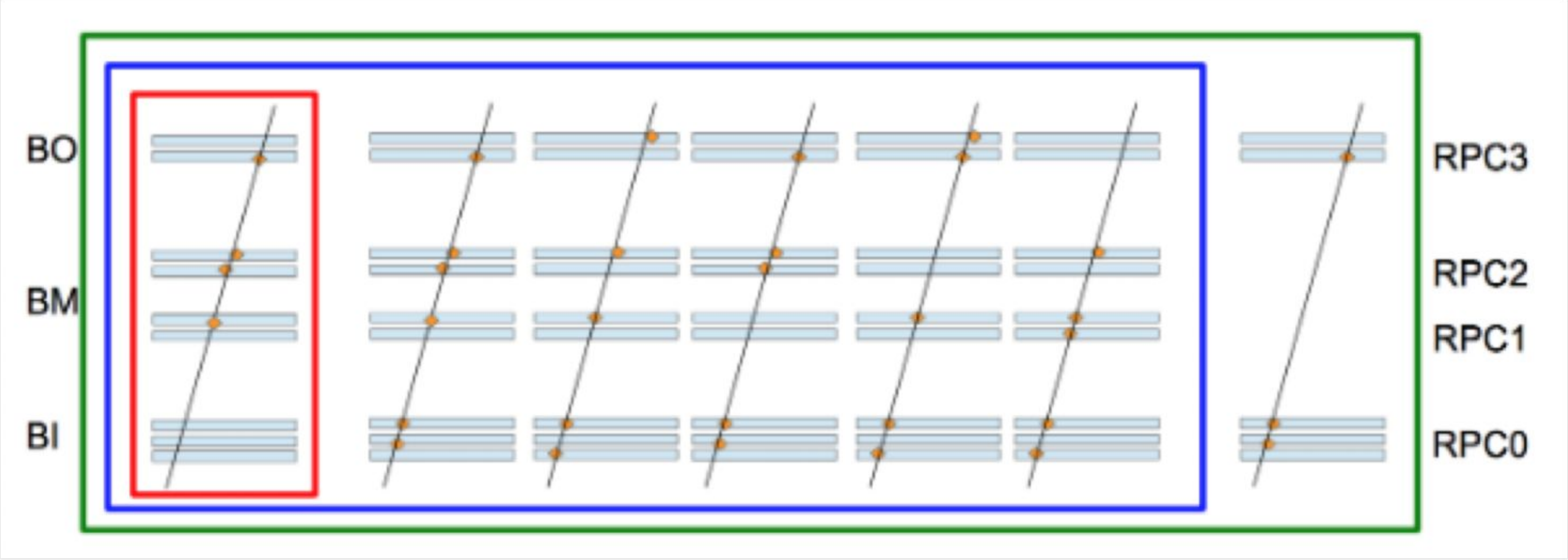
- Barrel/Endcap Sector Logic will share the same hardware
  - ATCA board with a Xilinx Virtex UltraScale+ XCVU13P
- MDT Trigger Processor implemented in another ATCA dedicated board

ATLAS-TDR-029

L0Muon Barrel Standard Trigger Scheme

- **Baseline trigger scheme** evolution of current scheme (80% efficiency)
  - Check for **coincidences** in encapsulated windows
  - 3/4 chambers + BI-BO scheme for all p_T thresholds (96% efficiency)
  - Option to apply BI-BO only to regions with acceptance holes in BM (15% barrel)





BM1-BM2-BO: current trigger
3 out of 4: including the new BI station
BI-BO: most inclusive (higher fake rate is expected)

- **Stable and reliable**, good performance
- Caveats:
  - Windows must be tuned by "hand"
  - Pointing to primary vertex (no displaced muon trigger)
  - Muon p_T determined from Look-Up Tables

L0Muon Barrel DNN Trigger

- Alternative algorithm based on **Deep Neural Networks**
- ATLAS divided into two sides in η (η>0, η<0)
- Mapping is η_{strip} vs. RPC layer
  - Infinite p_T muon represented by vertical lines
- A **ternary convolutional neural network (tCNN)** is set up, outputting five parameters

$$(p_T^{lead} \quad \eta^{lead} \quad p_T^{sublead} \quad \eta^{sublead} \quad n^{muons})$$

- tCNN implemented on an FPGA using the [HLS4ML](HLS4ML) tool

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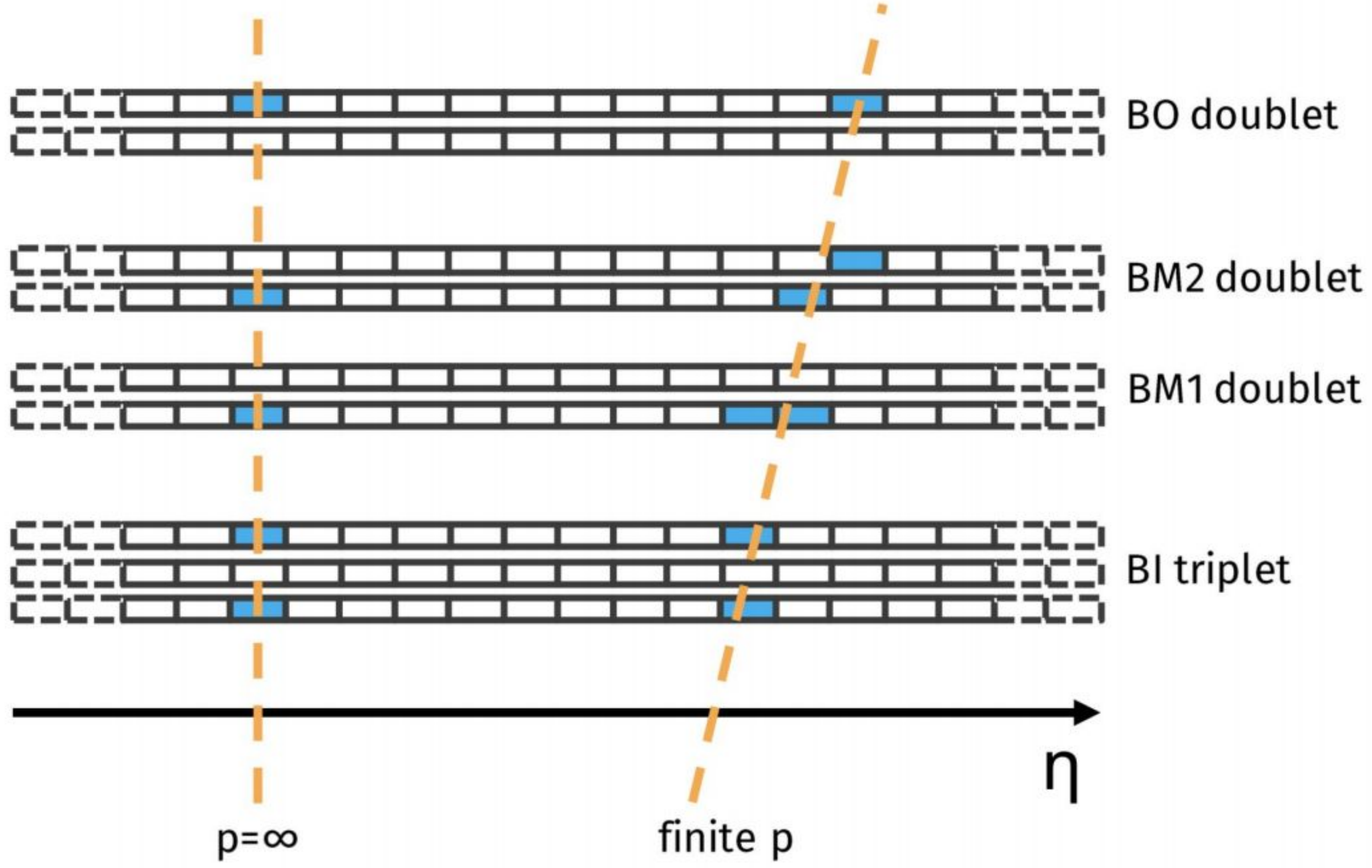
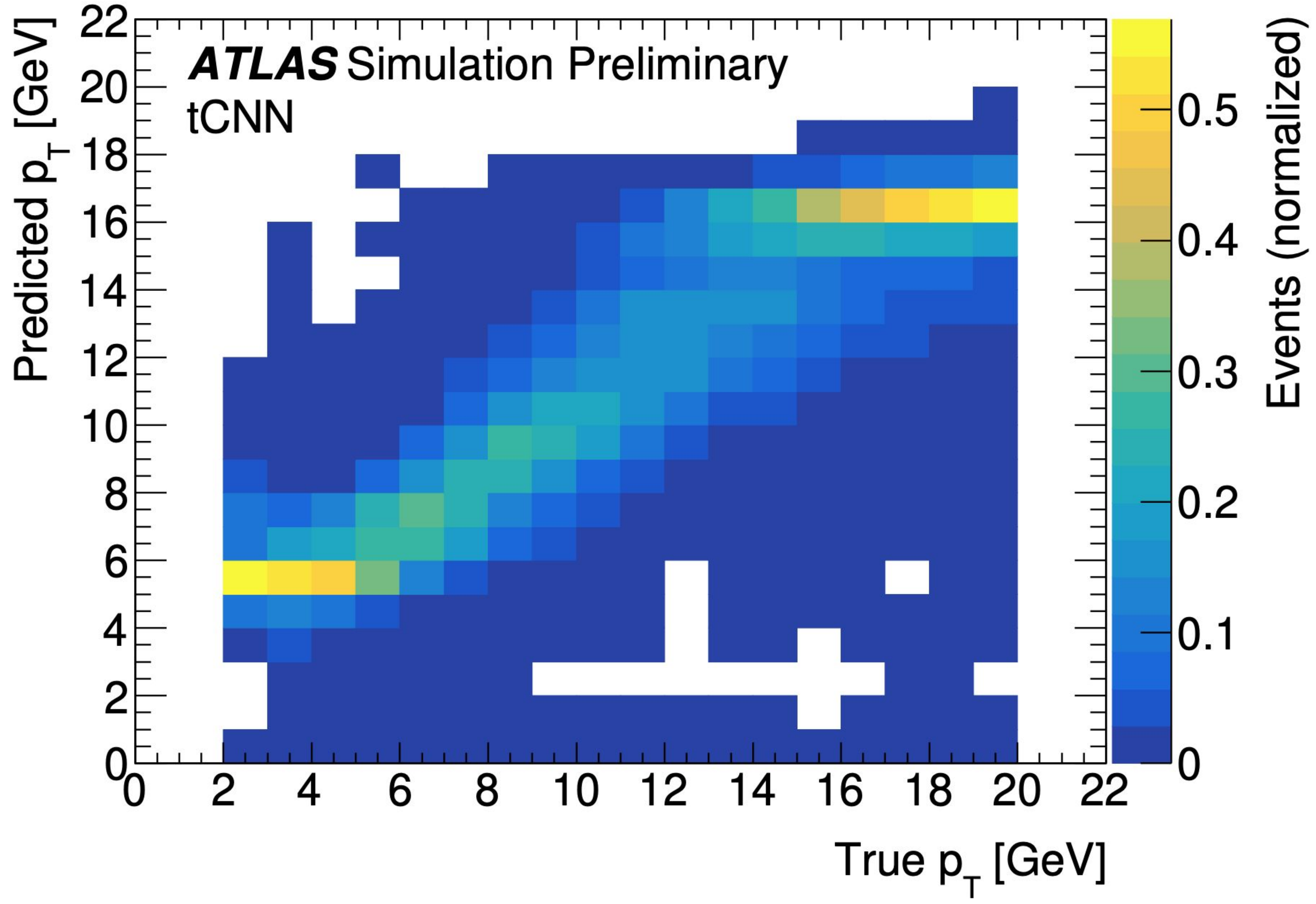
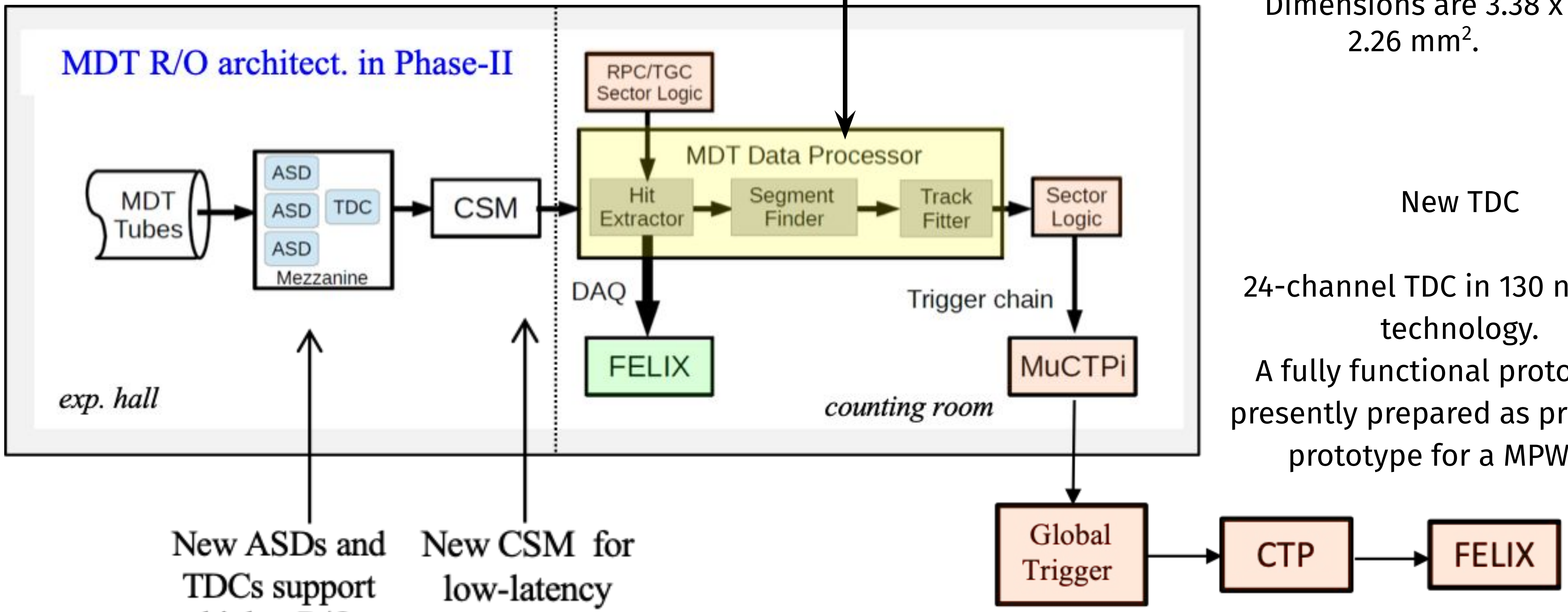




MDT Electronics Upgrade

MDT Trigger Processor refines p_T measurement

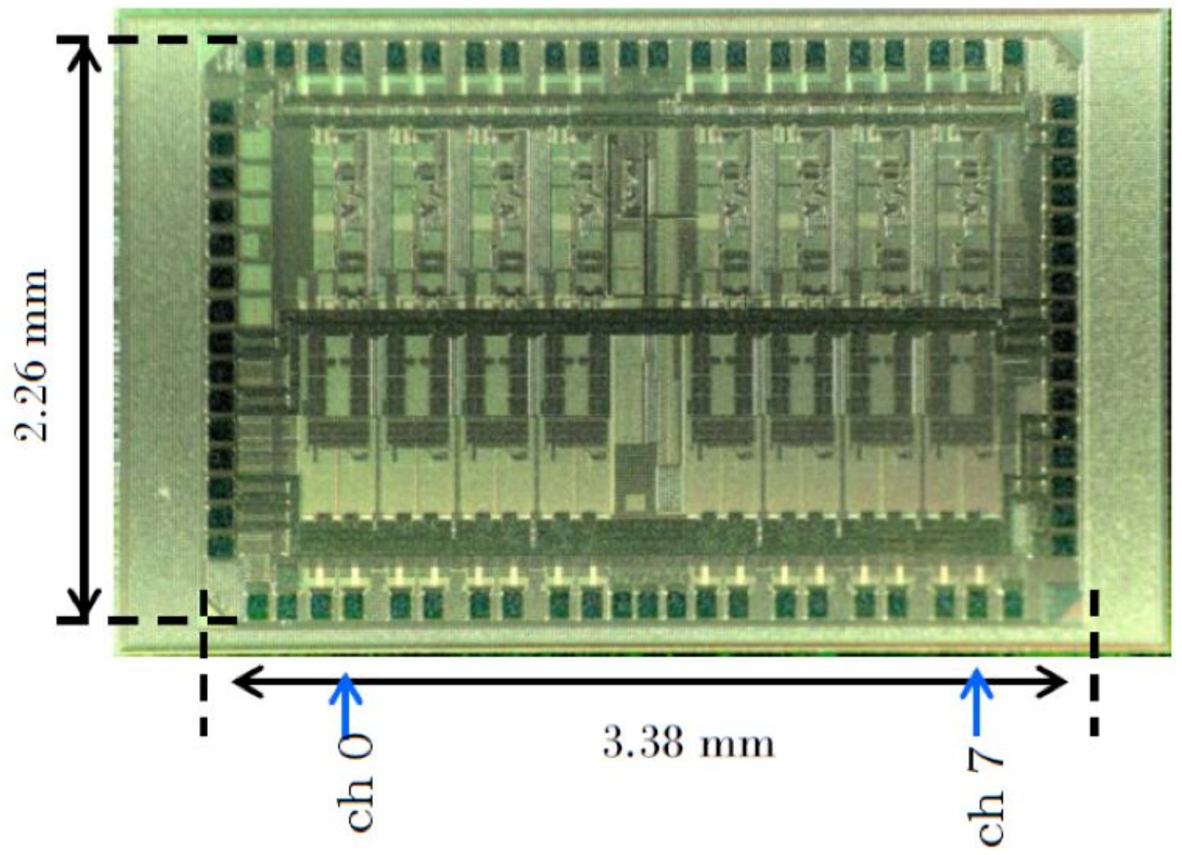


New ASDs and TDCs support higher R/O bandwidth

New CSM for low-latency R/O & high bandwidth

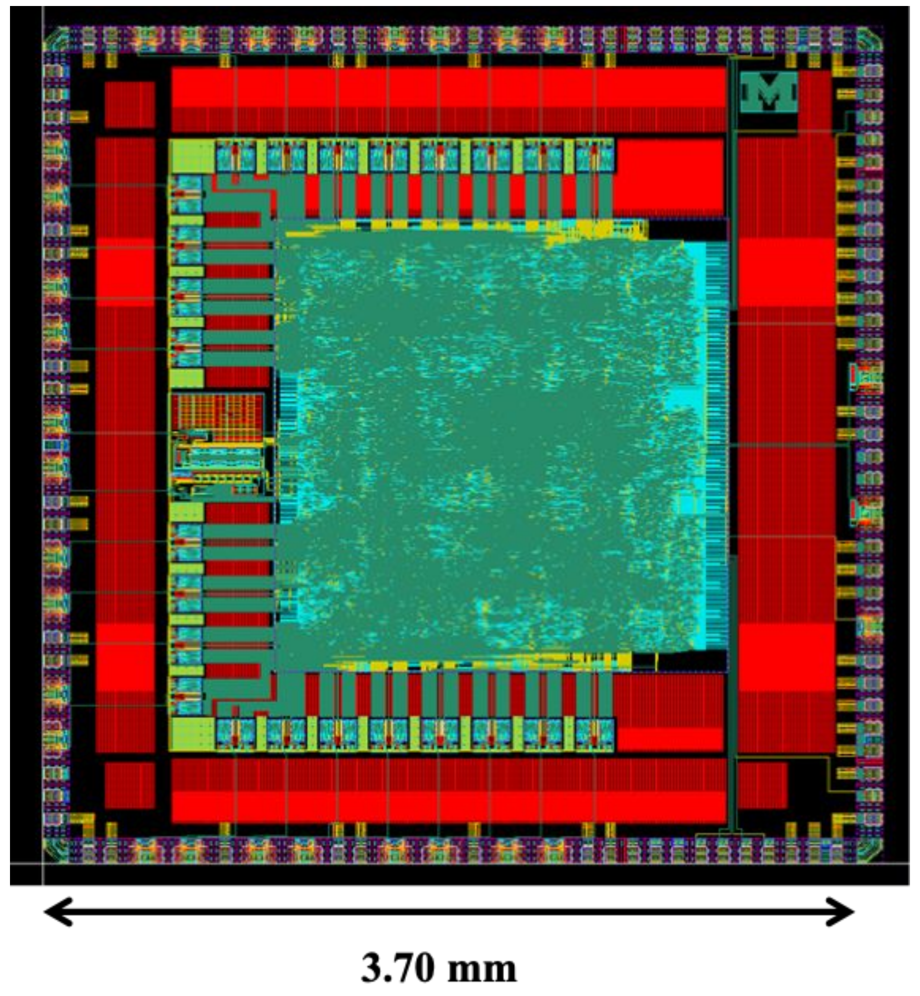
New ASD

8-channel ASD in 130 nm IBM/GF technology. 7k chips from the engineering run are presently under test. Dimensions are 3.38 x 2.26 mm^2.



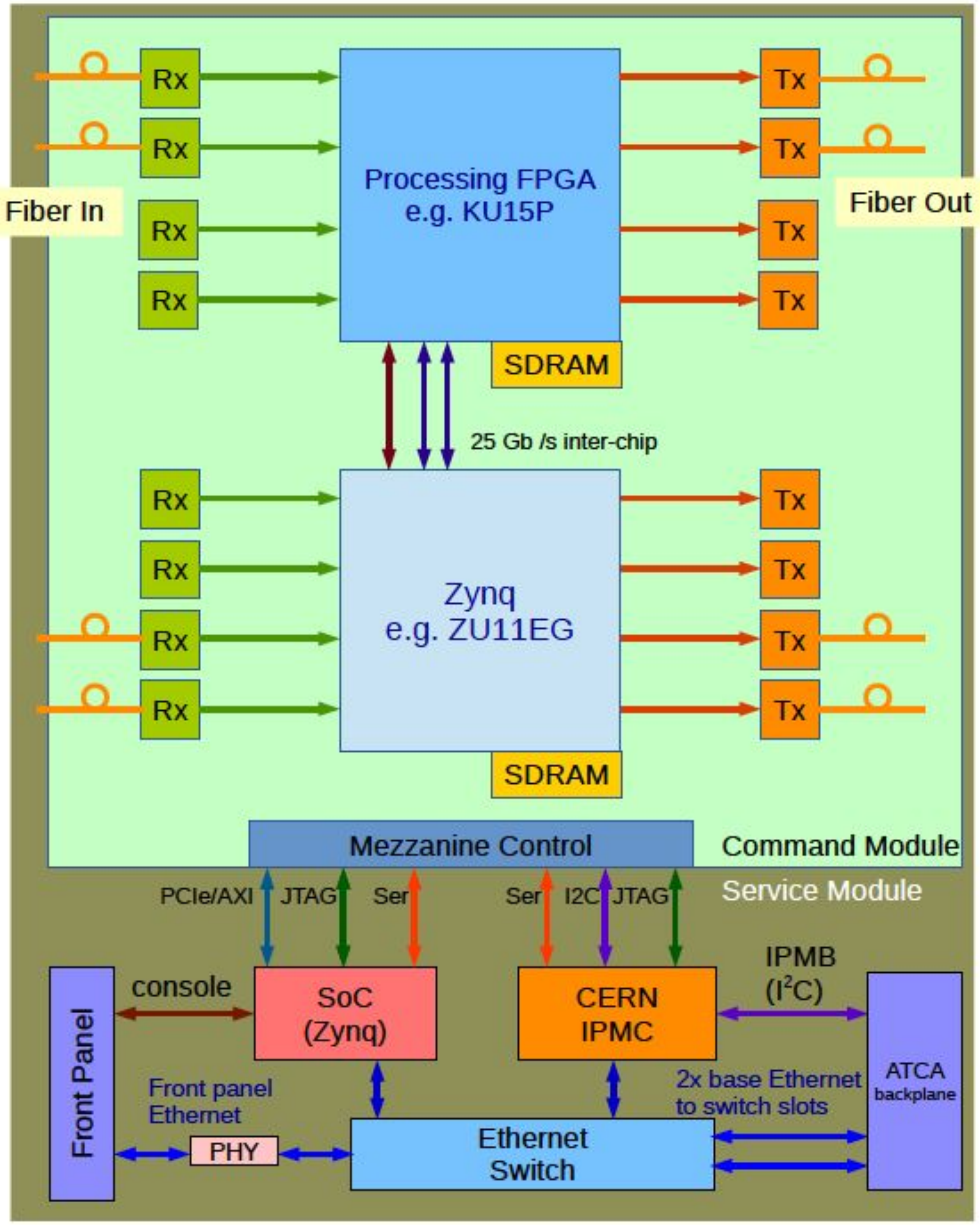
New TDC

24-channel TDC in 130 nm TSMC technology.
A fully functional prototype is presently prepared as production prototype for a MPW run.



R. Richter, TWEPP2019

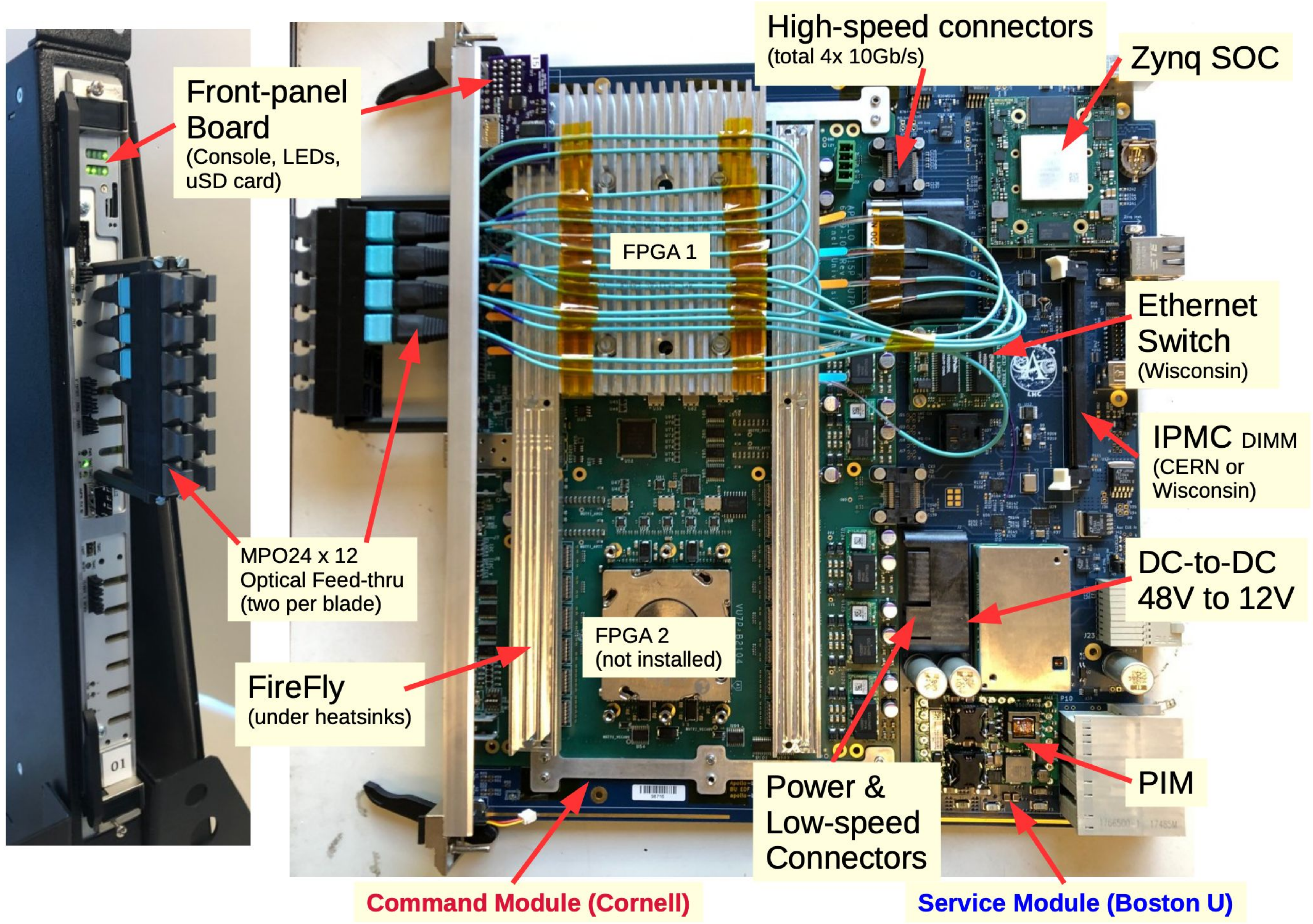
LO MDT Trigger Demonstrator

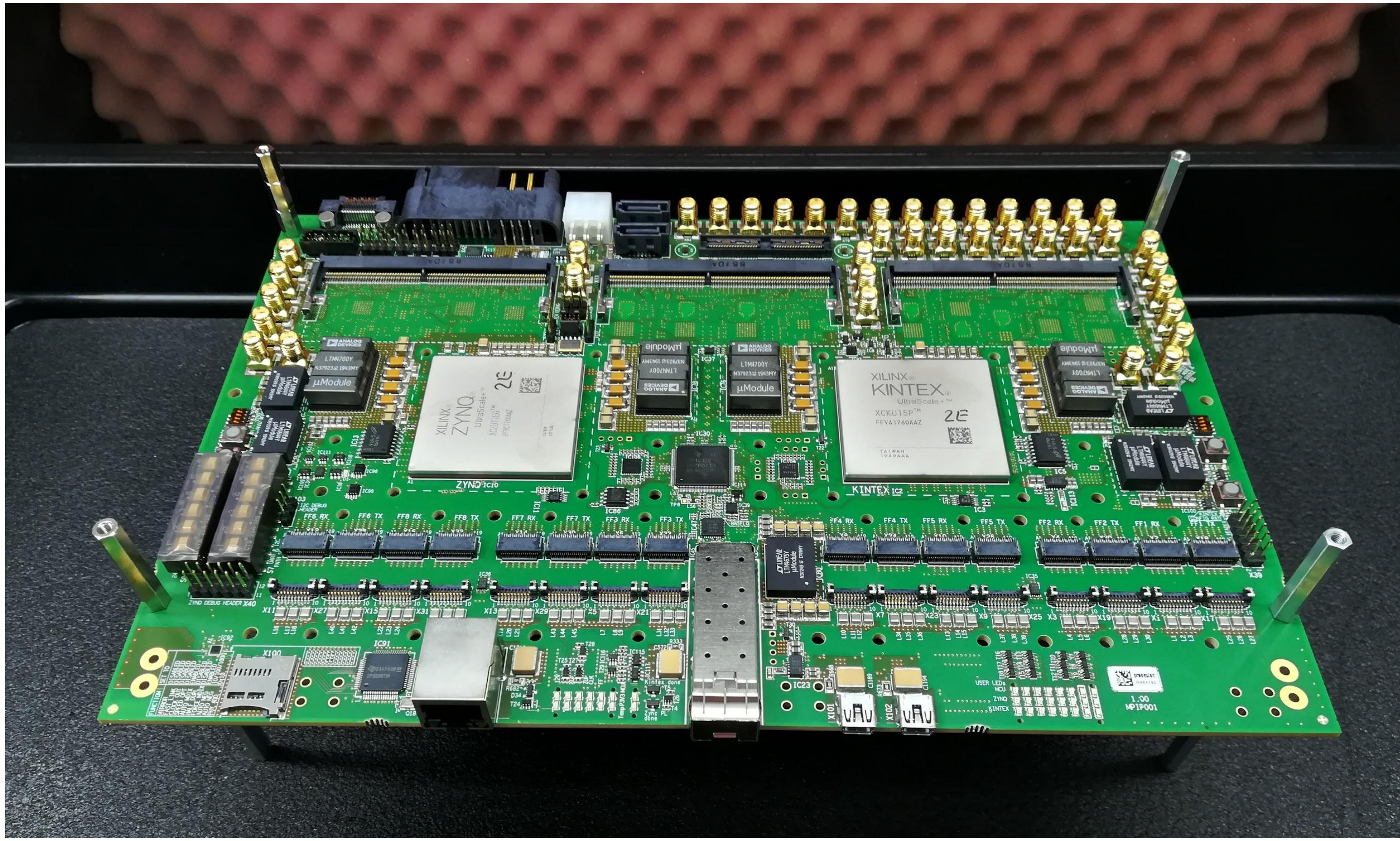


E. Hazen, APOLLO A Modular ATCA Platform, TWEPP2019

- A first **MDTTP demonstrator** board is currently under testing
- Modular ATCA design based on the **APOLLO framework**
  - **Service Module** (**SM**): infrastructure, control and powering
  - **Command Module** (**CM**): processing unit, FPGAs, Optics, application specific
- SM same for all applications, prototype already available
- CM specific for L0MDT developed, currently under test at industrial partner facility

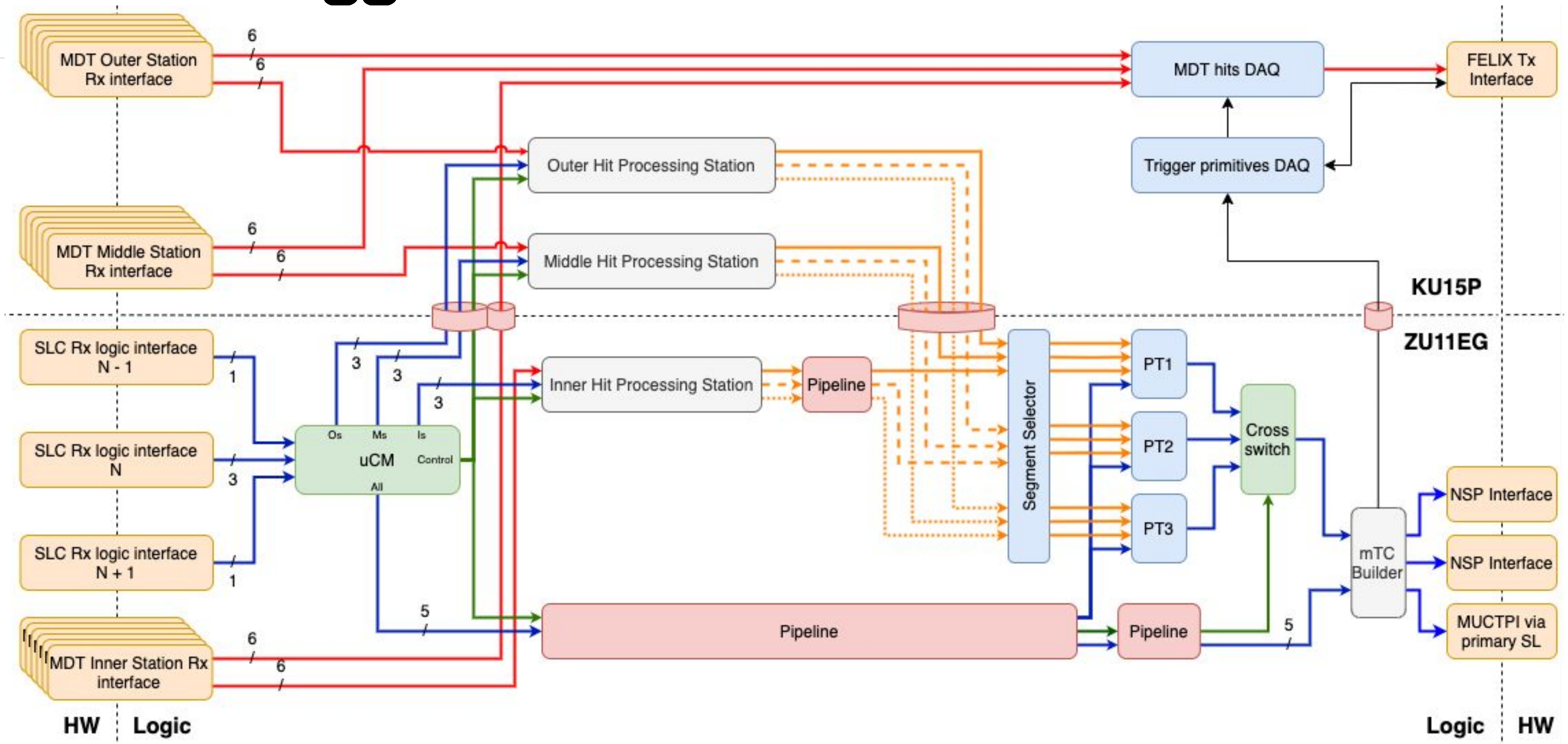
LO MDT Trigger Demonstrator





- SM boards already available since one year. Used and tested also in other projects (CMS tracker)
- First CM prototype currently being tested at proDesign (delivery July)

L0 MDT Trigger Dataflow



L0MDT

L0 MDT firmware design workflow

- MDTTP firmware requires a **complex design**, with inputs/outputs from/to several other system in the ATLAS system (Sector Logics, MDT CSM, FELIX)
- Workload divided between the participating institutes
  - Several developers and **three languages** (VHDL, Verilog, HLS)
  - Workflow eased by use of **Hog tool** to coordinate firmware development and guarantee results reproducibility and traceability
- **Main processing** parts already developed and under testing
  - Hit extraction, Segment Finders, Track Fitting
  - Preliminary results show relative **low resource usage**
  - Complying with the requirement of processing at least **three muon candidates** per sector, within the latency budget of 1μs