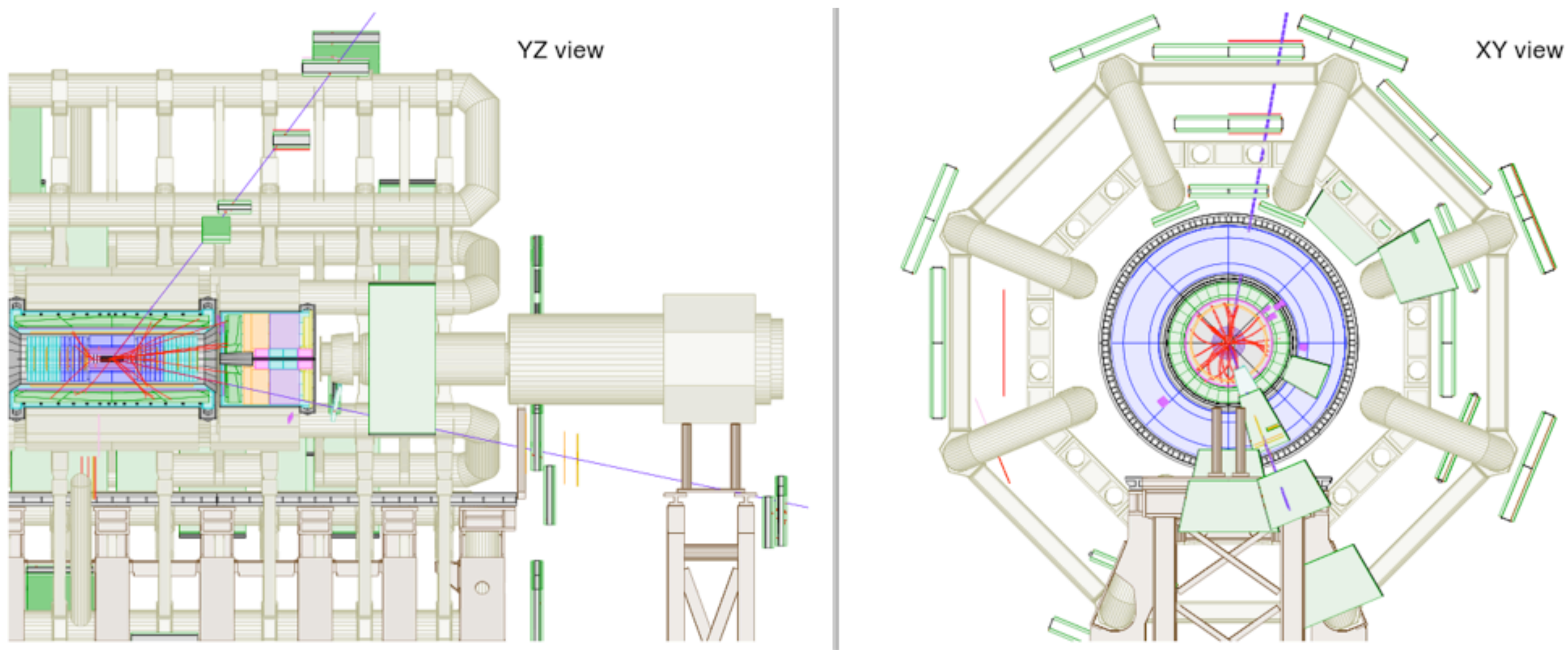
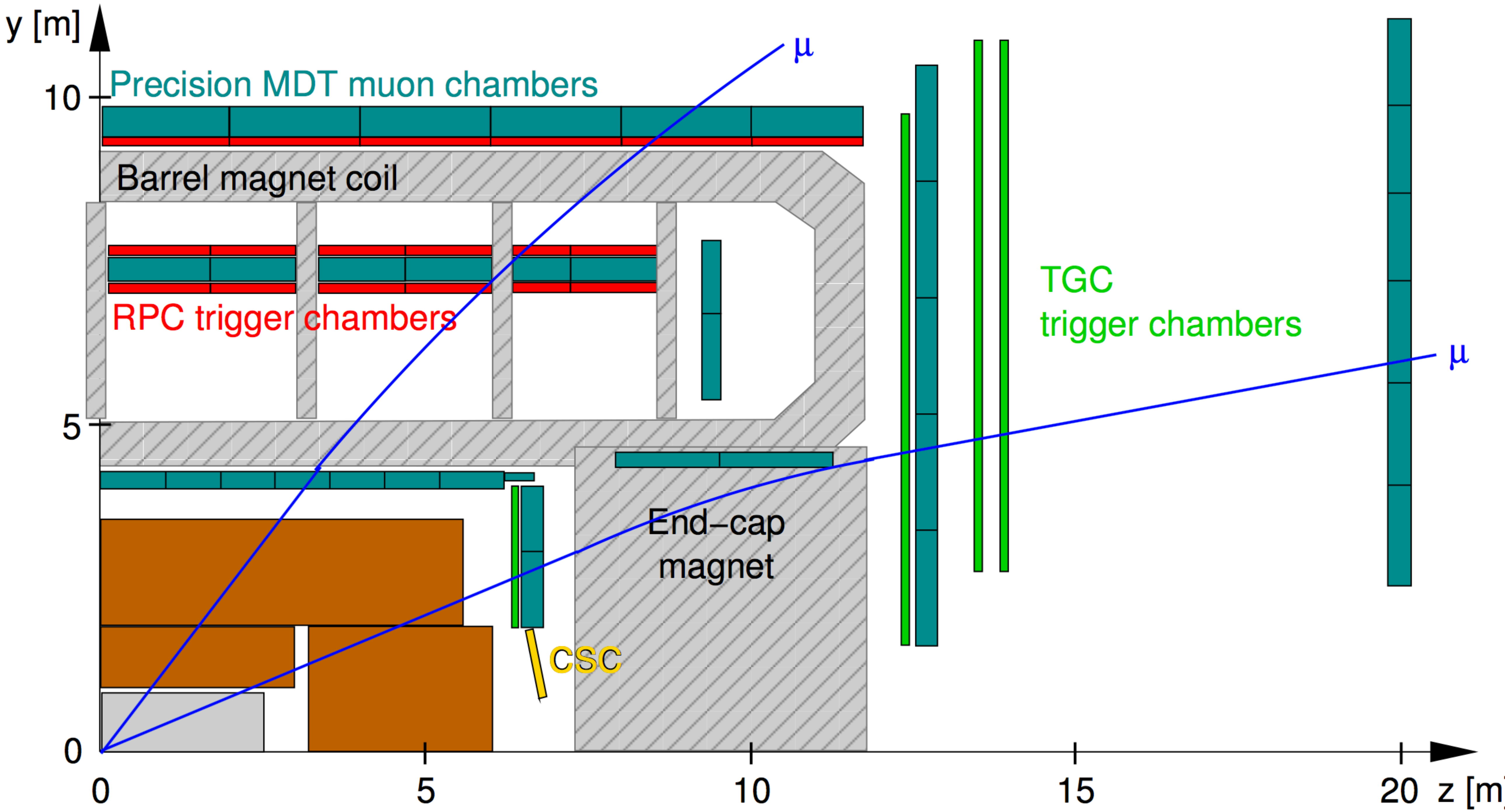


Muon Trigger Upgrades in ATLAS

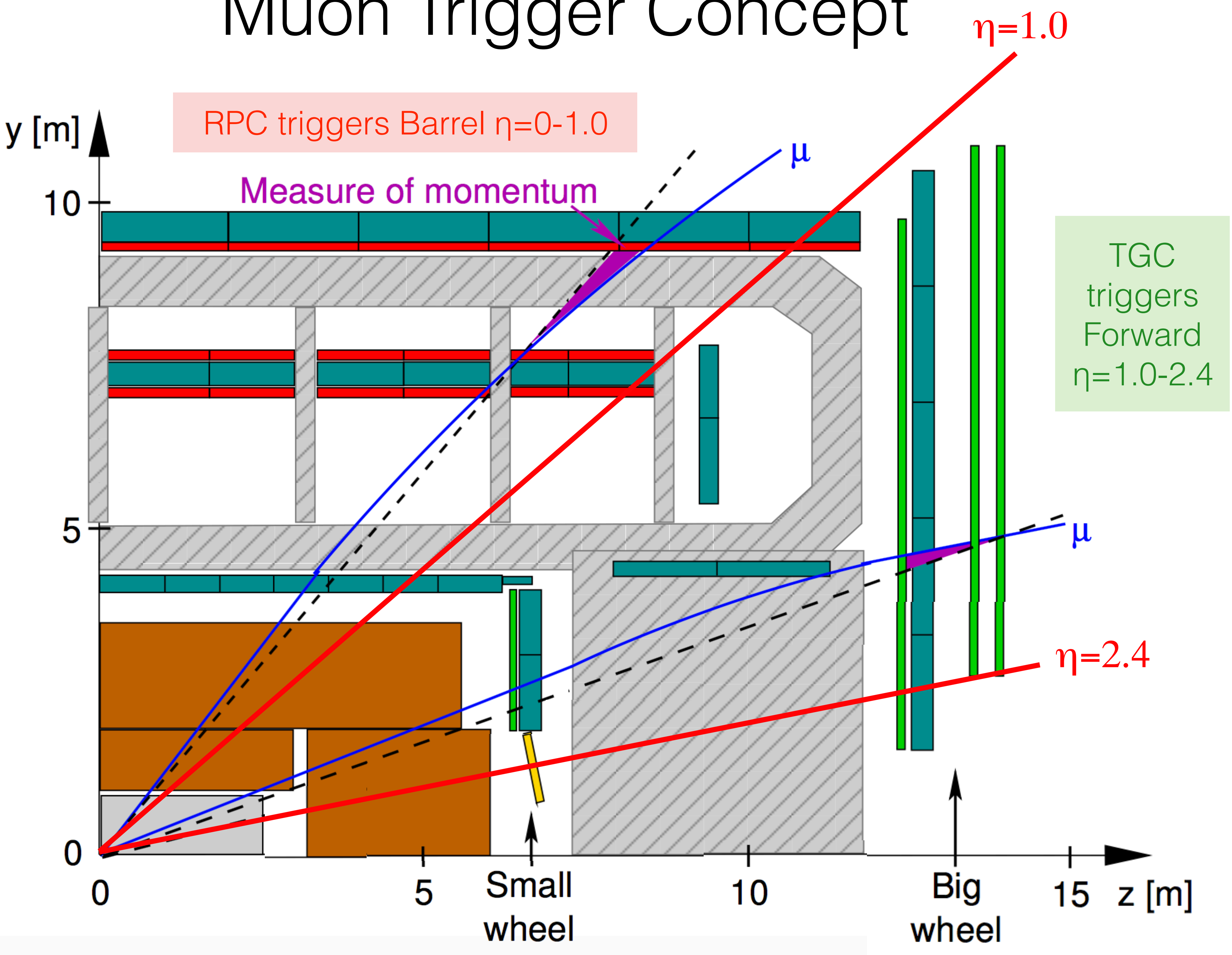
Verena Martínez Outschoorn
UMass Amherst

Reconstruction, Trigger and Machine Learning for the HL-LHC
April 26-27th 2018

The ATLAS Muon Spectrometer

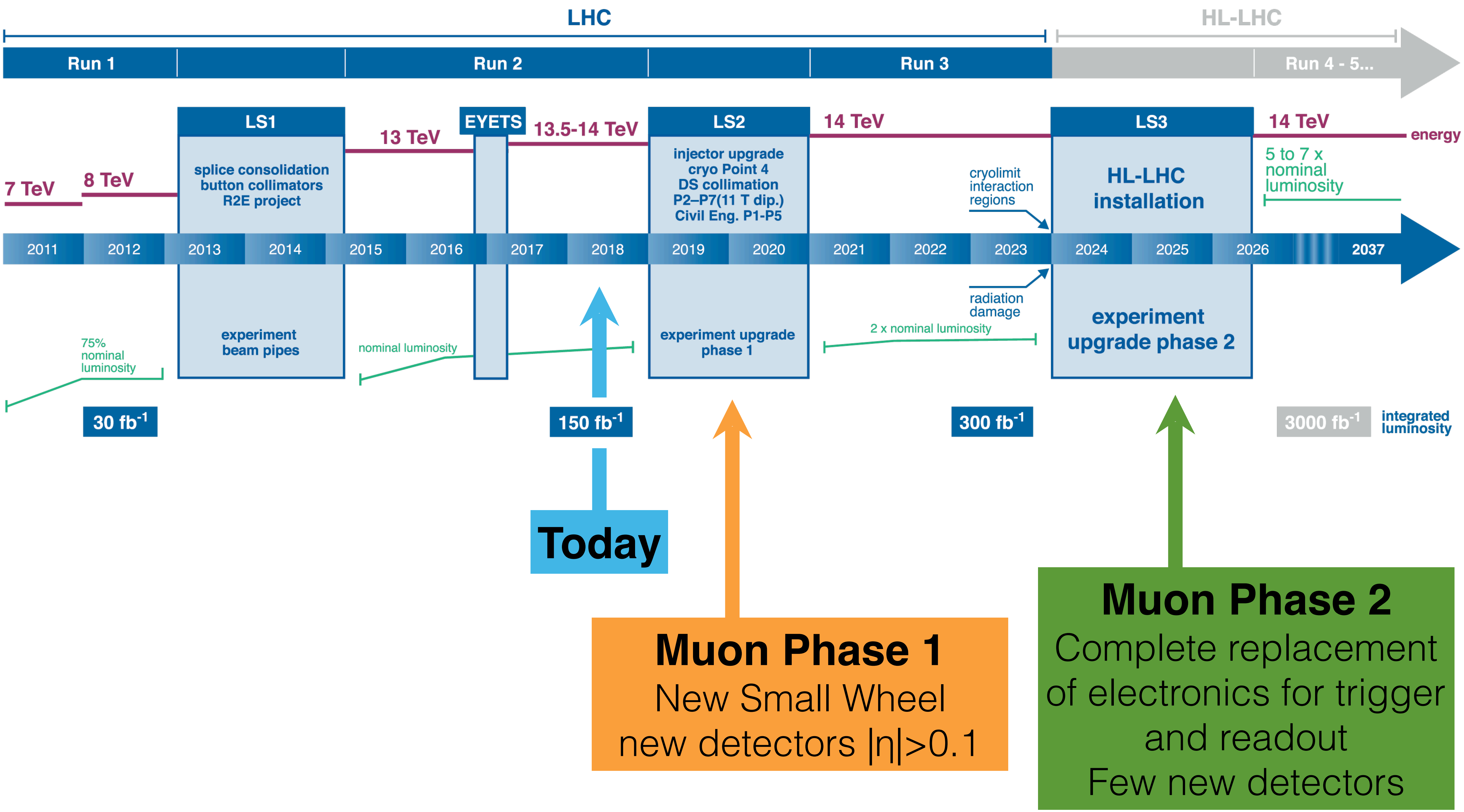


Muon Trigger Concept



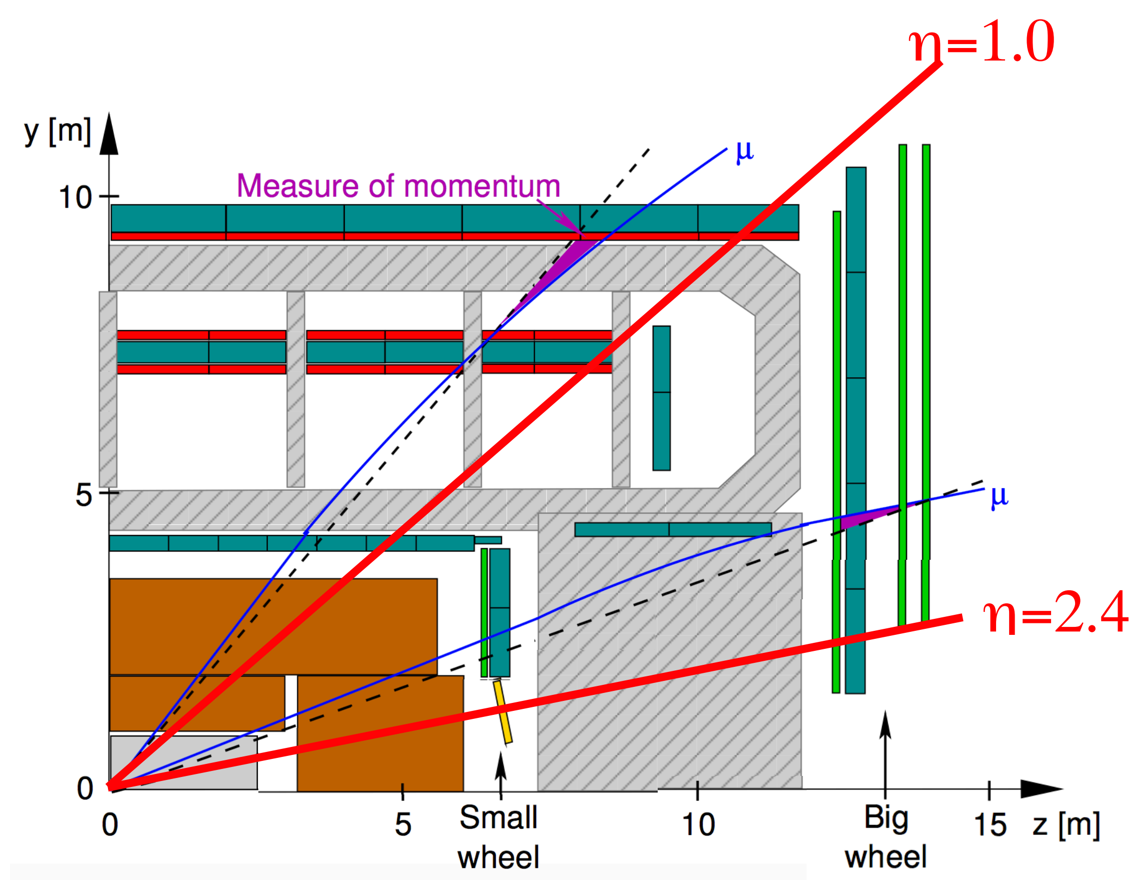
- Muon triggers use hit data from RPCs and TGCs
- Track candidates are identified by simple coincidence logic in the on-detector boards
- The transverse momentum is evaluated by look-up tables in off-detector boards

Upgrades Planned for the Muon System

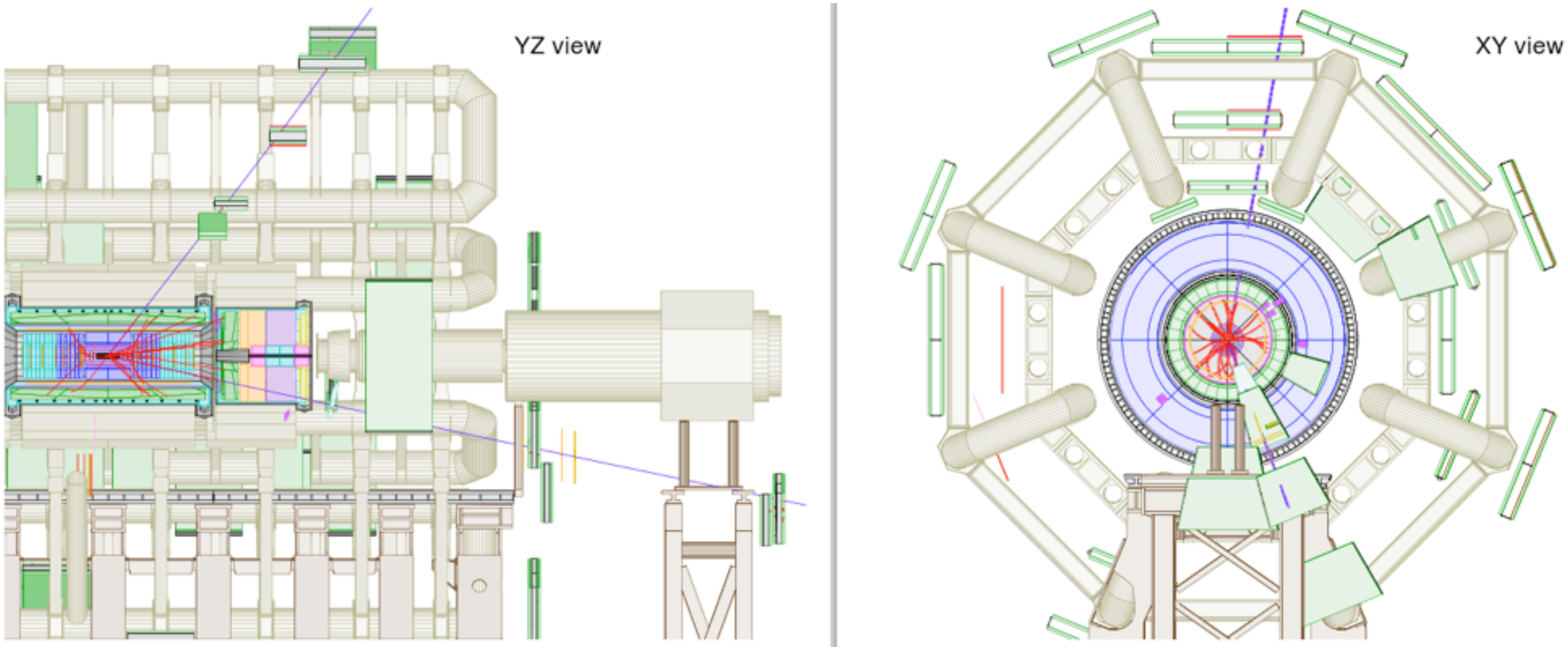


Muon Trigger Constraints and Goals

Parameter	LHC	HL-LHC
1st-level trigger latency	~1.9 μs	~6.7 μs
Max. 1st-level readout latency	2.5 μs	10 μs
Max. Trigger rate	100 kHz	1 MHz
Max Lumi	$3\ 10^{34}$ cm^{-2} s^{-1}	$7.5\ 10^{34}$ cm^{-2} s^{-1}
Max Pileup	80	200



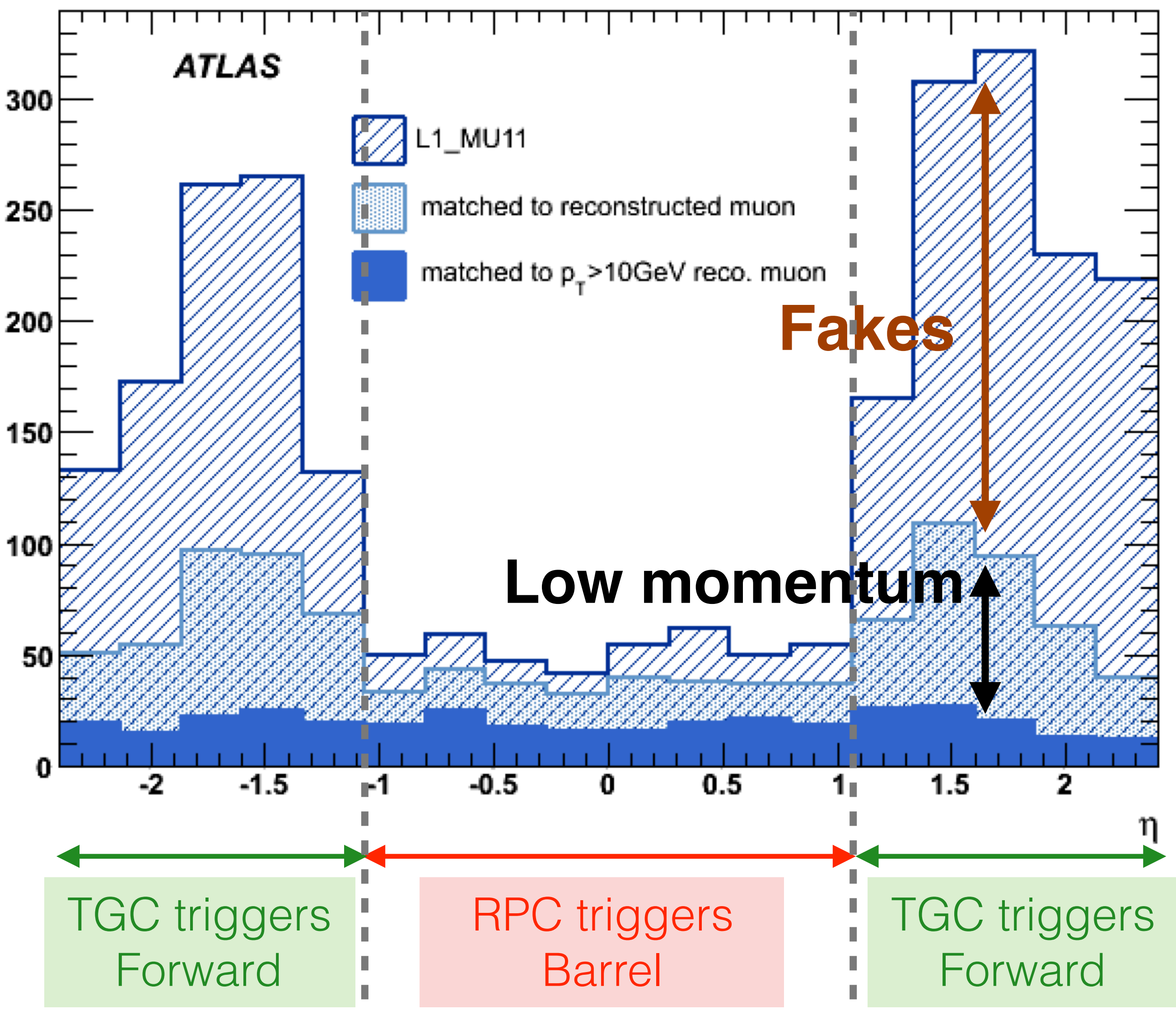
- Main information provided is the muon position and highest momentum threshold
- Performance limitations to address in upgrades
  1. Reduce 'fake triggers' - rate caused by the particles not directly from the IP
  2. Increase the efficiency
  3. Improve the momentum resolution - reduces trigger rates
- Describe current proposals and speculate on possible proposals where machine learning algorithms could improve performance further

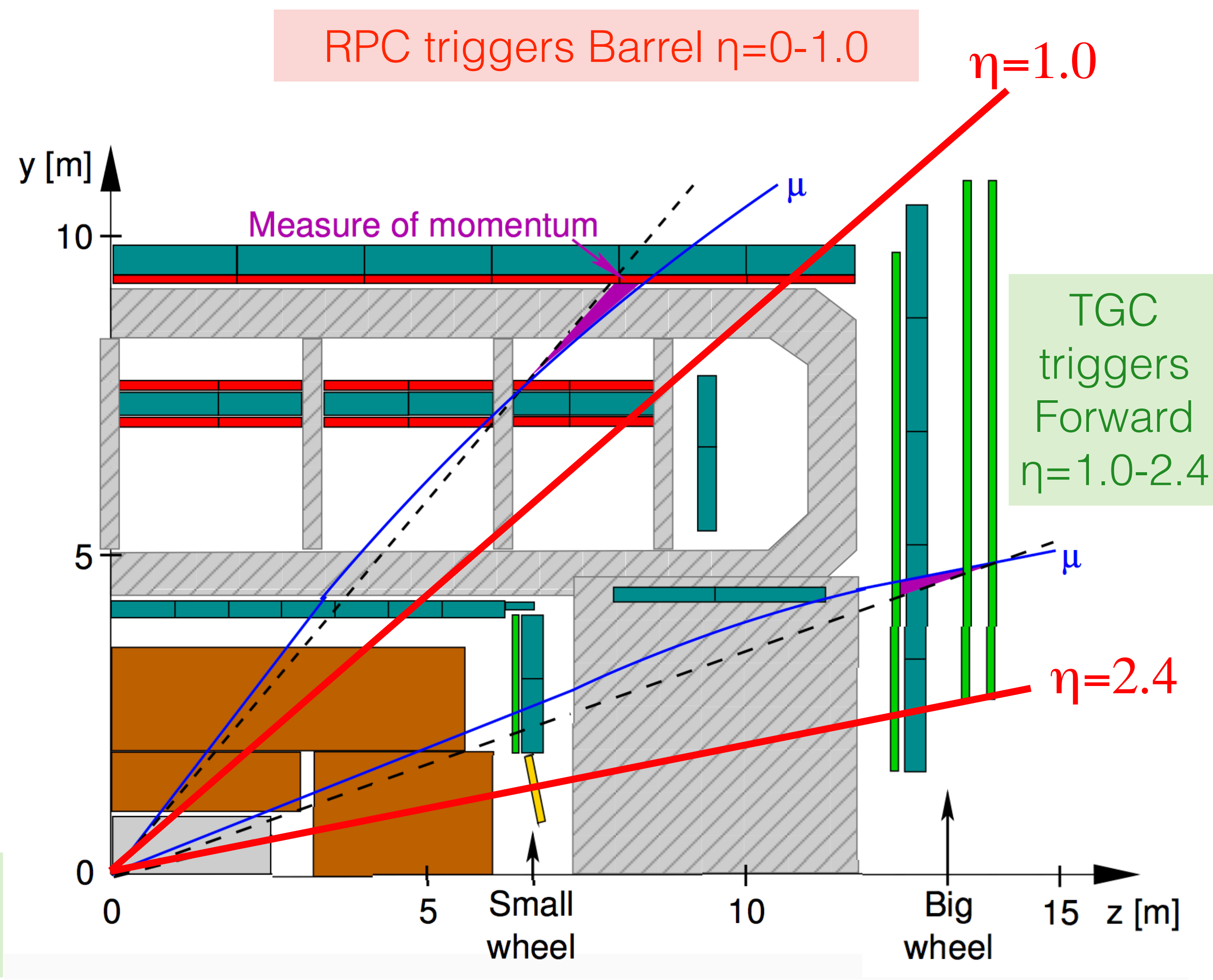


1. Reduce ‘fake triggers’

Challenges of the Muon System → Phase 1

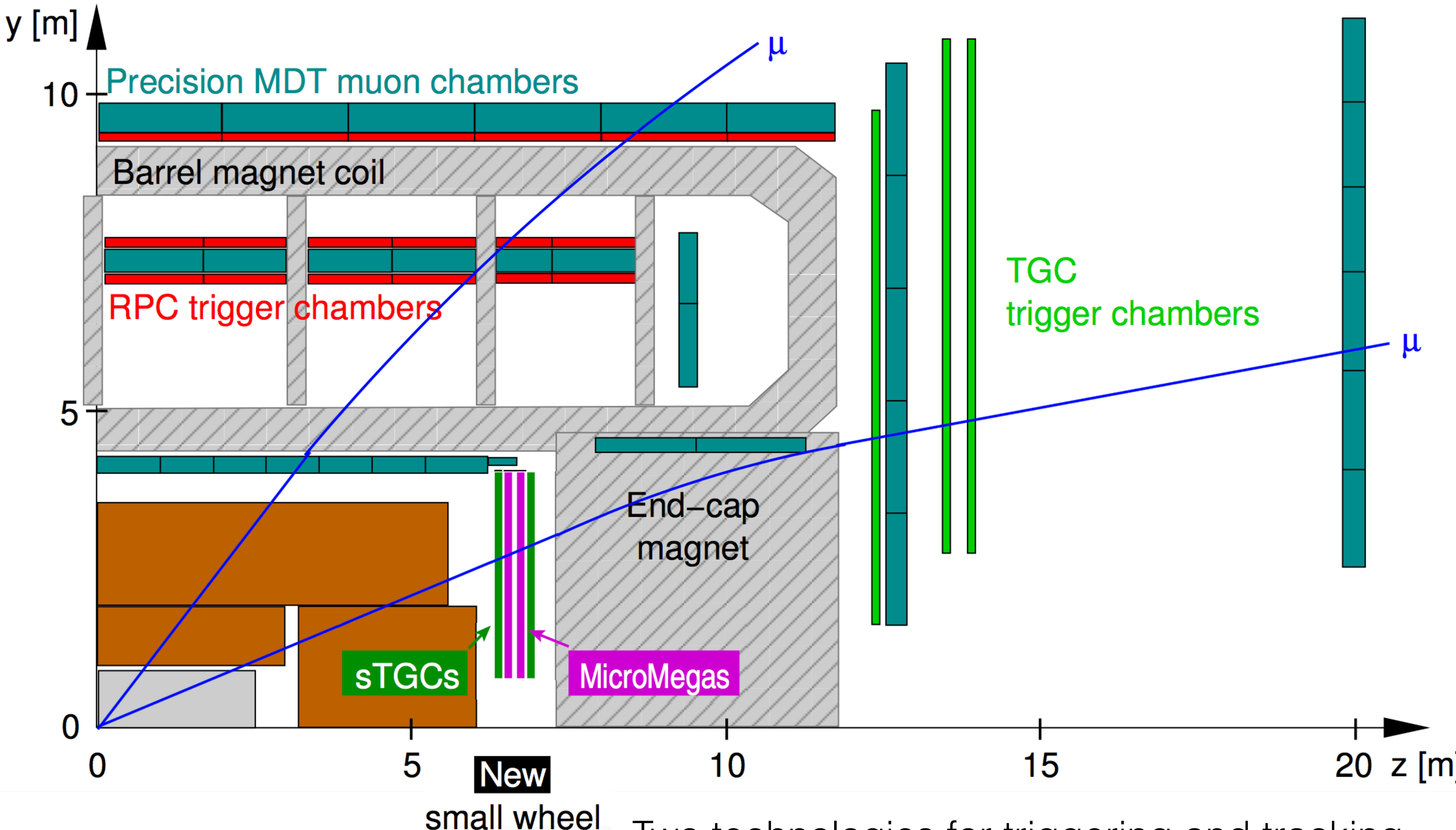
Muon triggers p_T>10 GeV





Majority of muon triggers are from backgrounds!

Muon Spectrometer Upgrades Phase-1

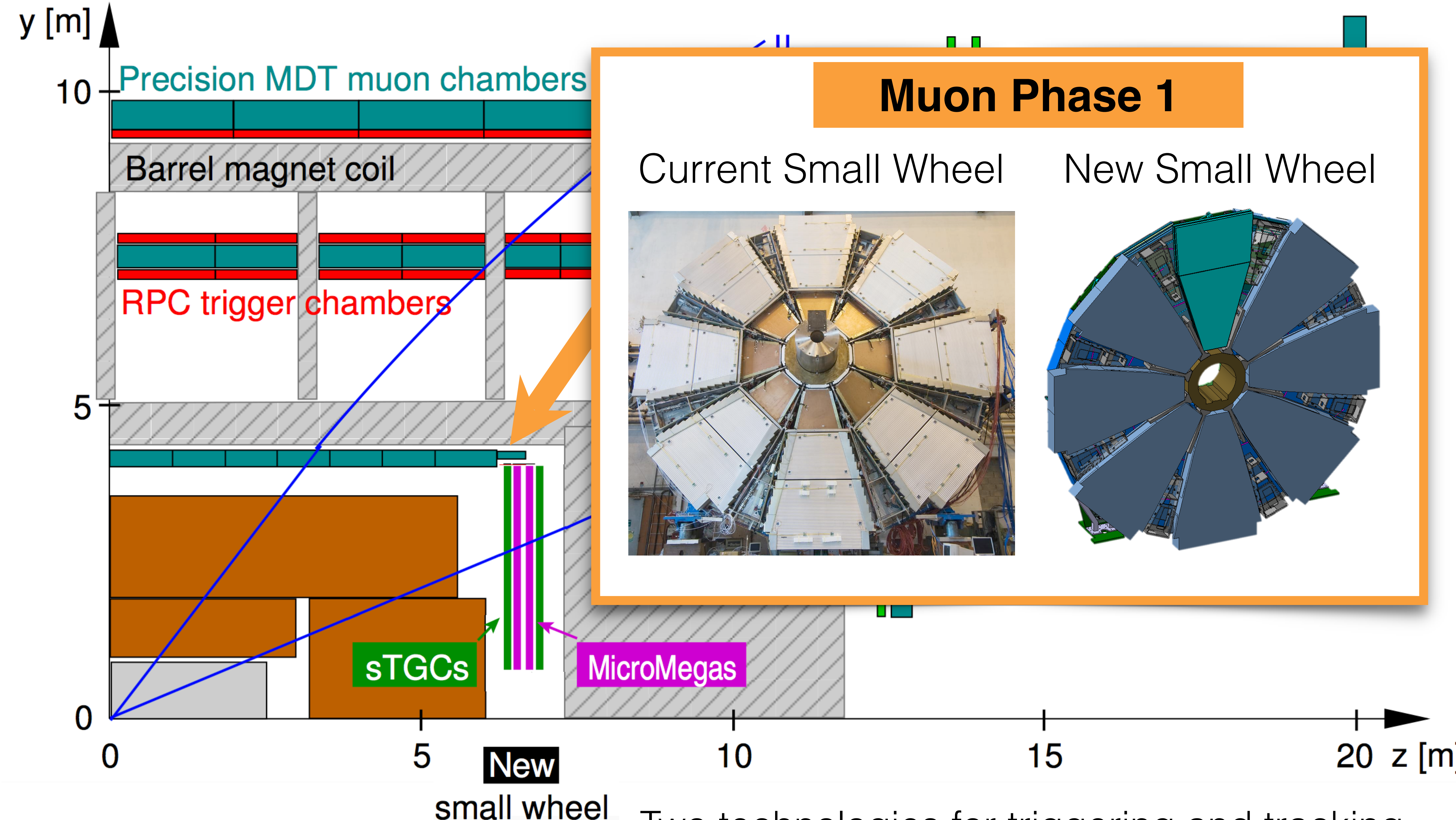


Two technologies for triggering and tracking

Small-strip Thin Gap Chambers (sTGCs)

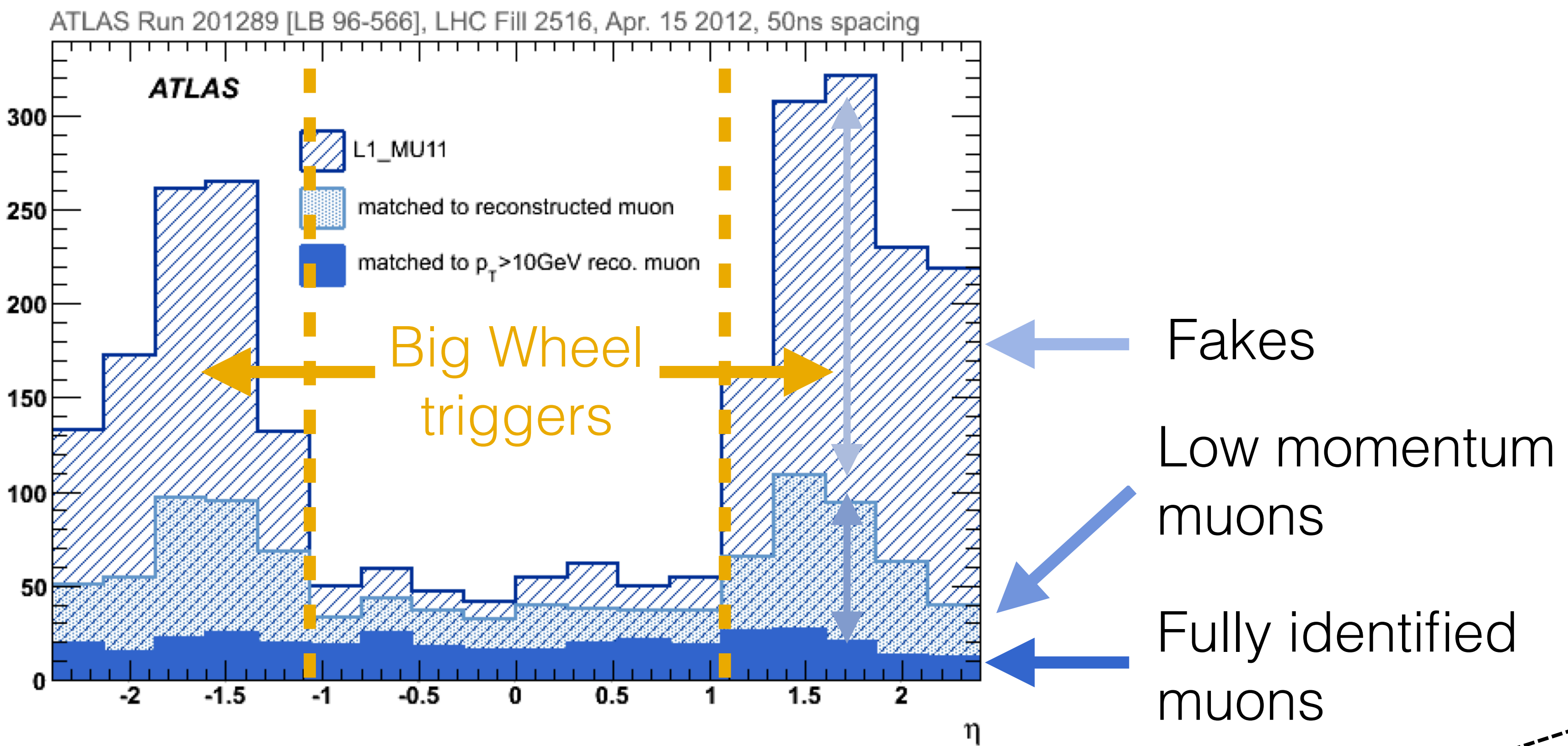
Resistive strip Micromegas (MM)

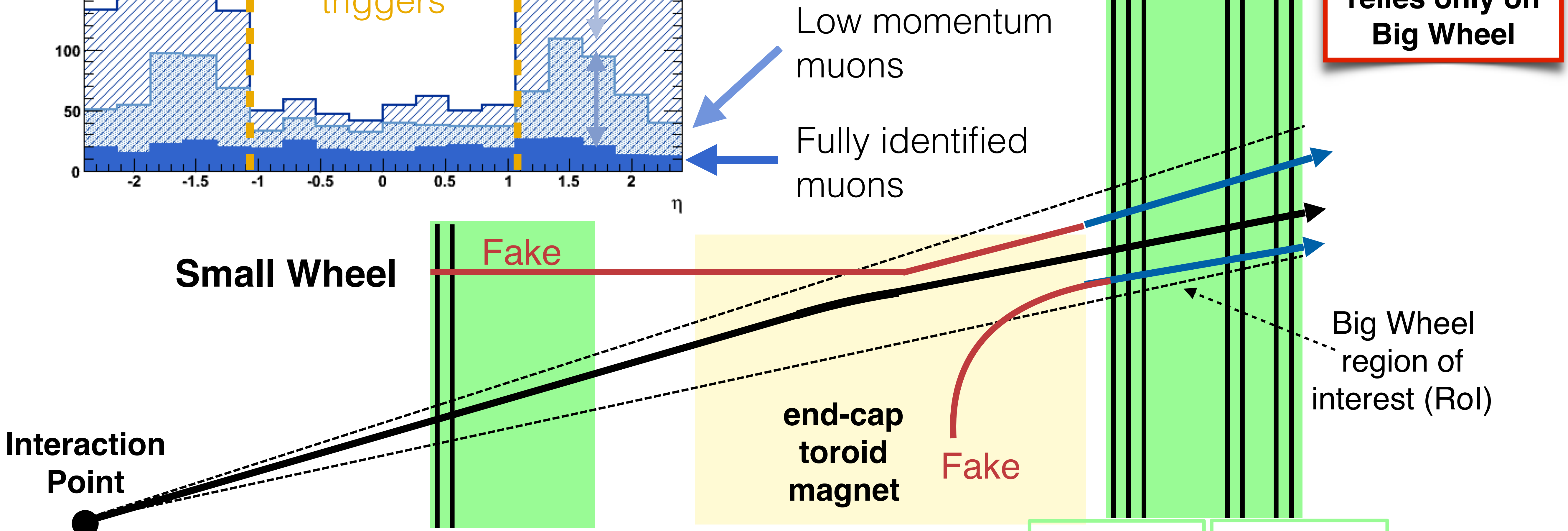
Muon Spectrometer Phase 1 Upgrade

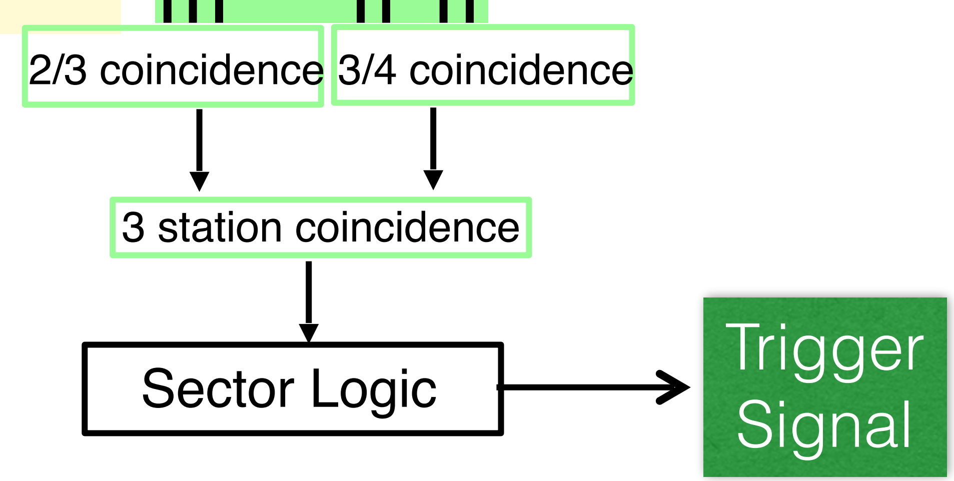


Two technologies for triggering and tracking
Small-strip Thin Gap Chambers (sTGCs)
Resistive strip Micromegas (MM)

Forward Muon Trigger



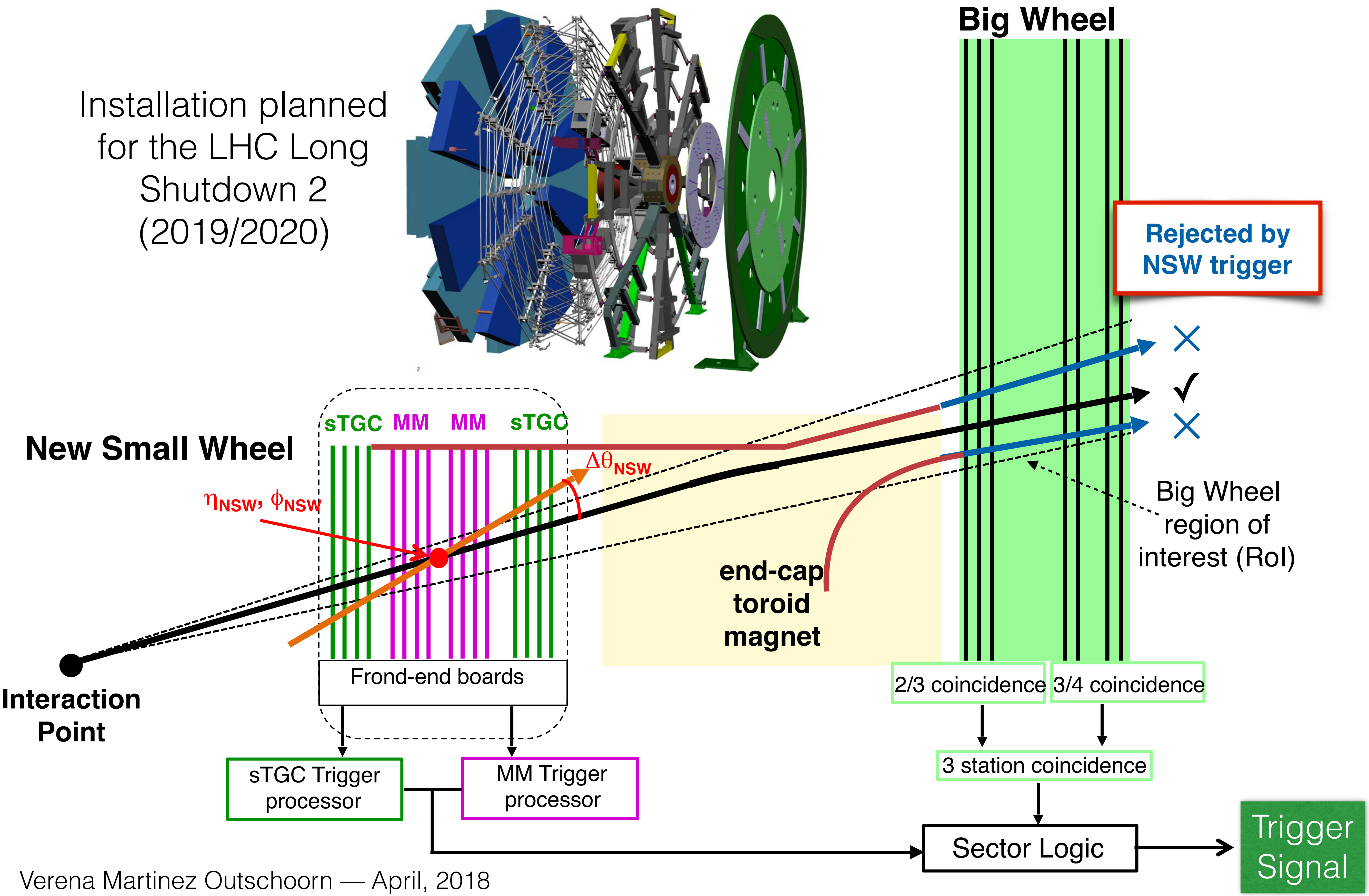




Main goal of the New Small Wheel upgrade is to reduce fake triggers from background hits

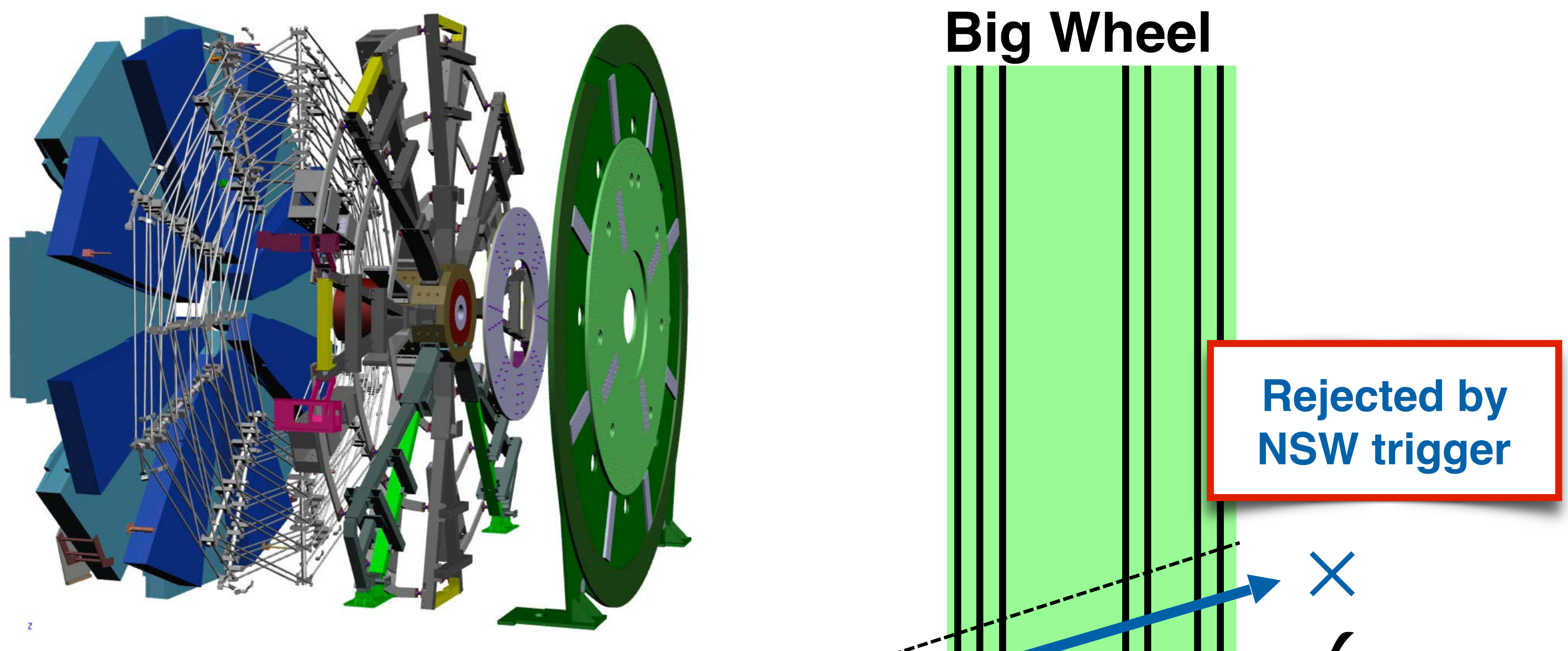
New Small Wheel Upgrade

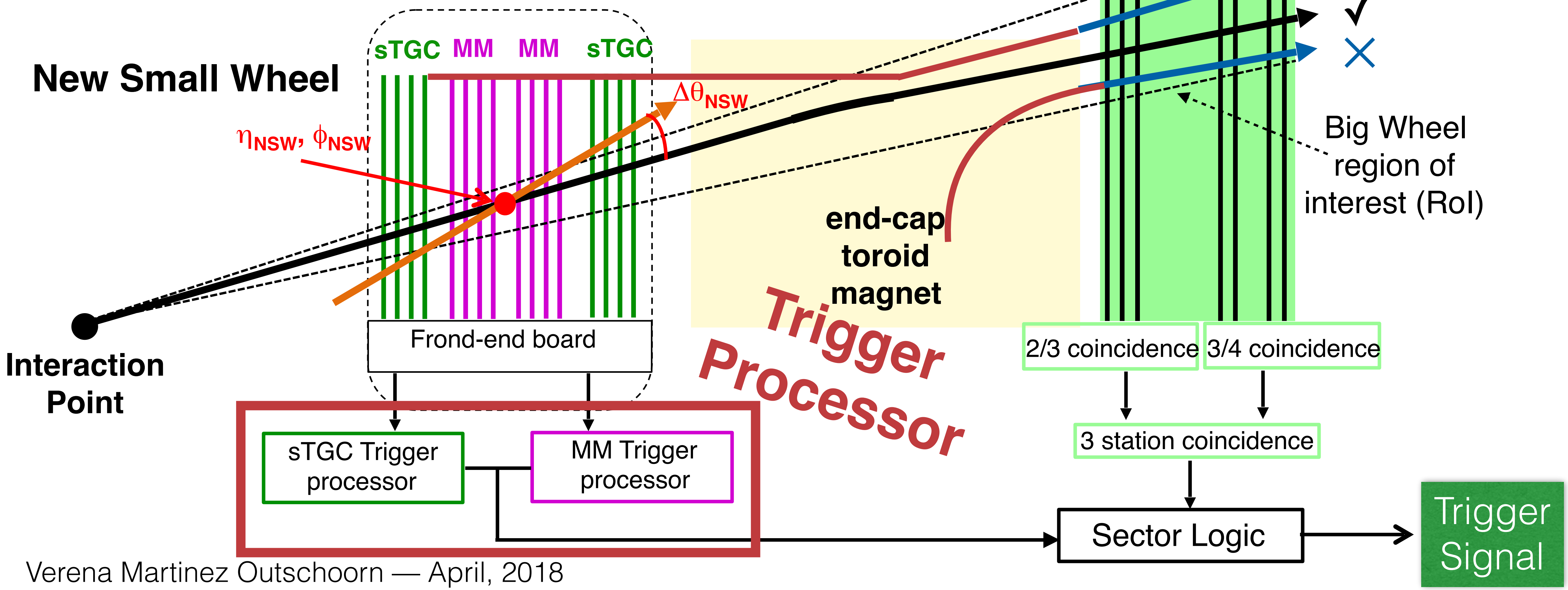
Installation planned for the LHC Long Shutdown 2 (2019/2020)



New Small Wheel Upgrade

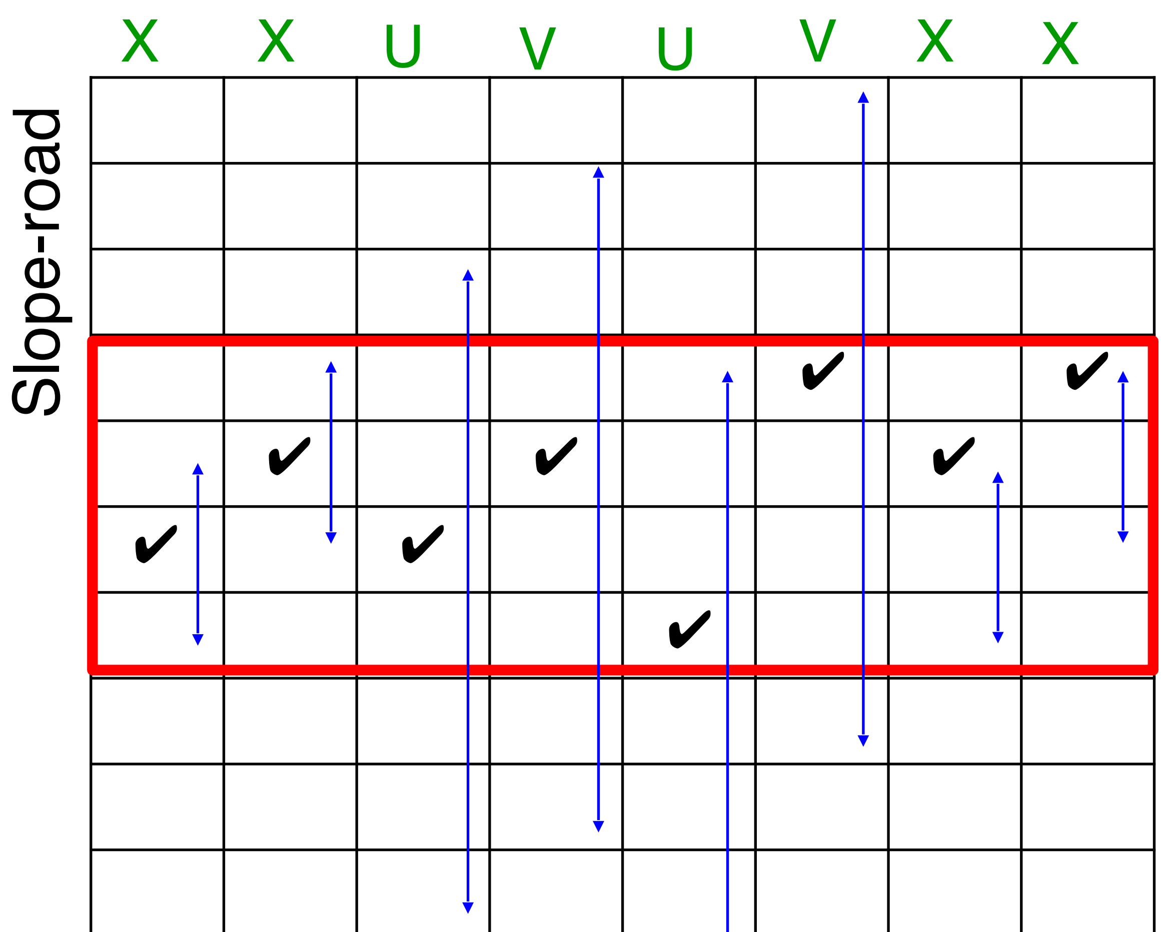
Installation planned for the LHC Long Shutdown 2 (2019/2020)





MM Trigger Algorithm

- Convert strip hits into projective slopes → translate hardware addresses encoding strip channel to global slope fixed at the IP

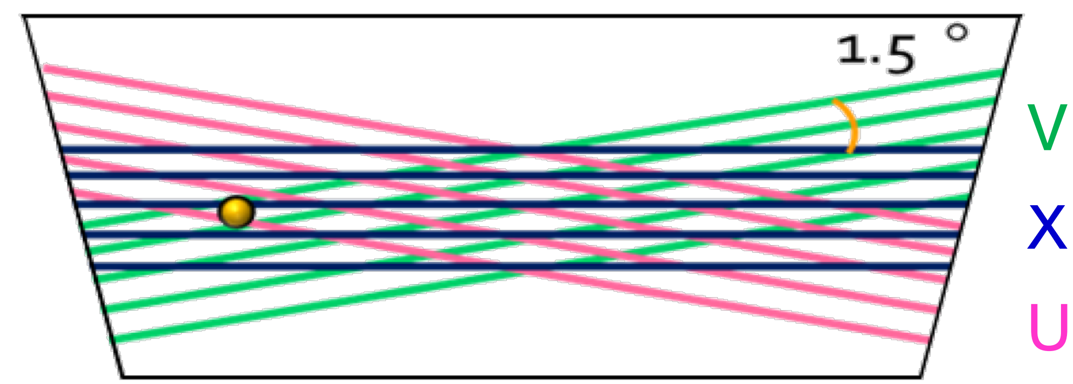


Track candidate (4X4UV)

✔: Slope-road with hit

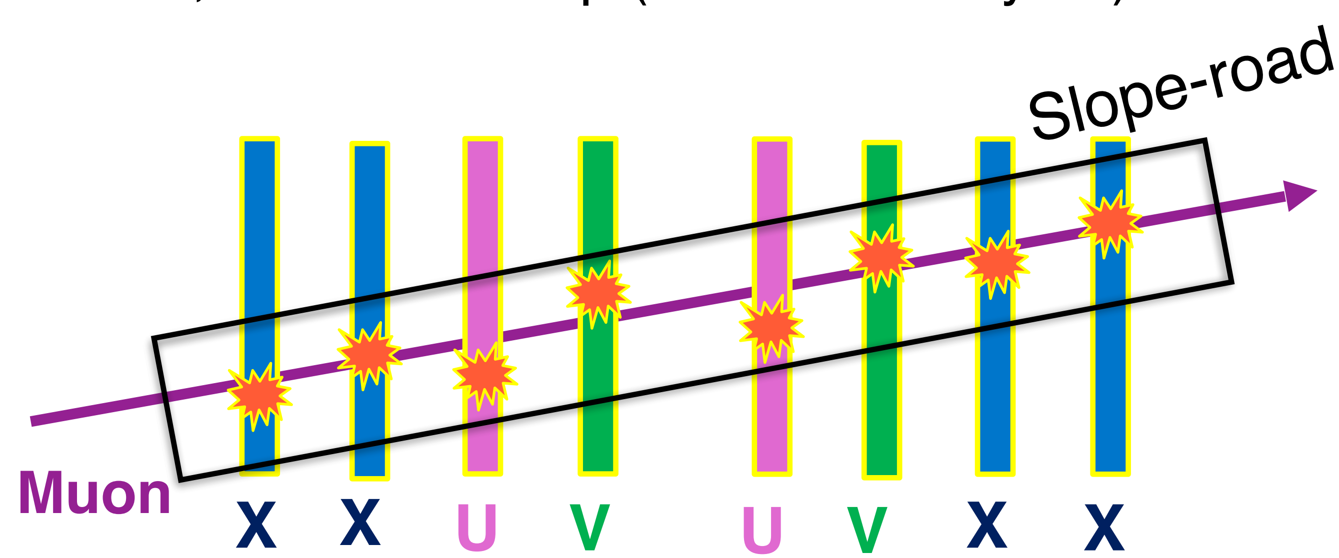
↕: Slope-road width for hit coincidence

- Find coincidences using projective roads → coincidences in roads reject background from the start



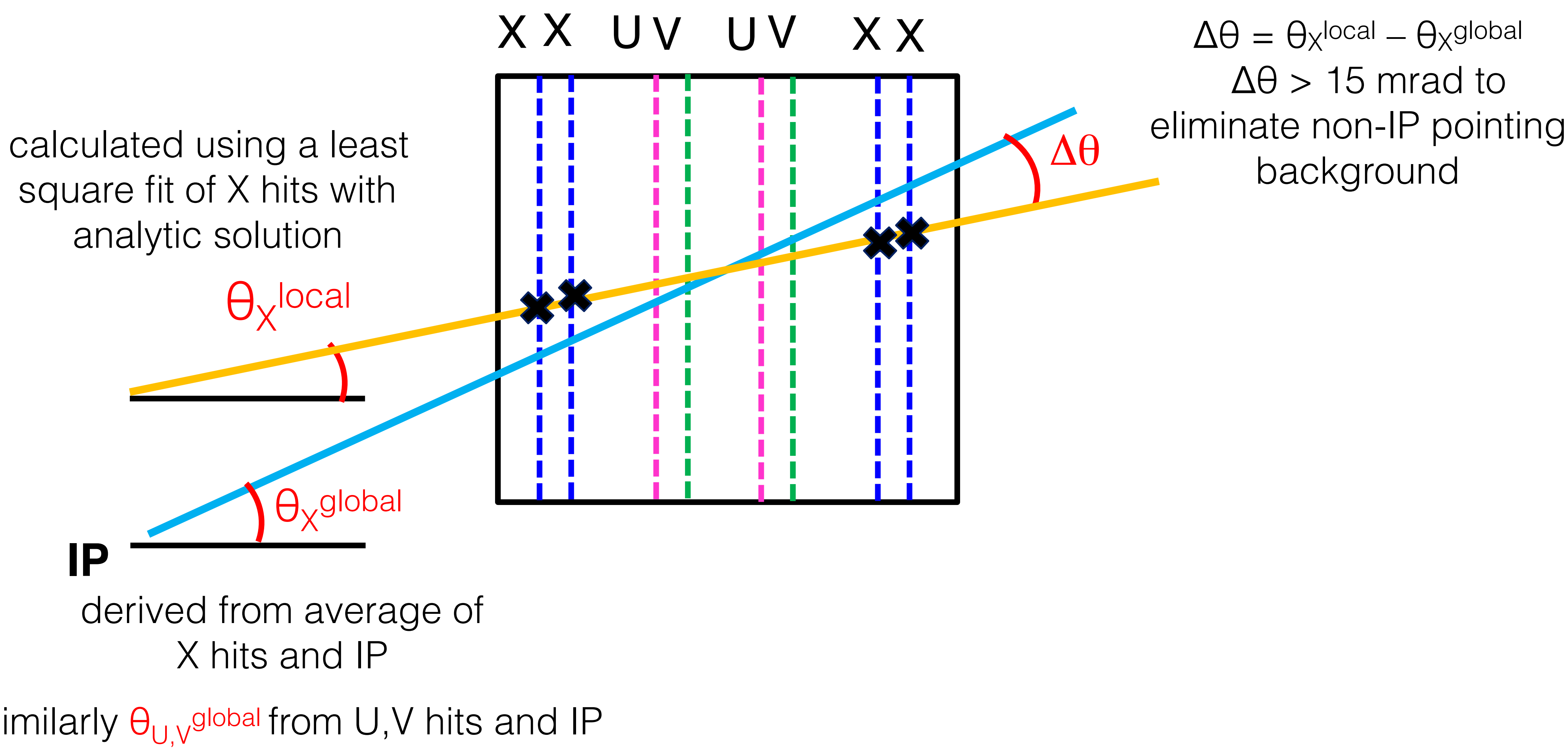
X : Horizontal strip (4 of 8 layers)

U, V : Stereo strip (each 2 of 8 layers)



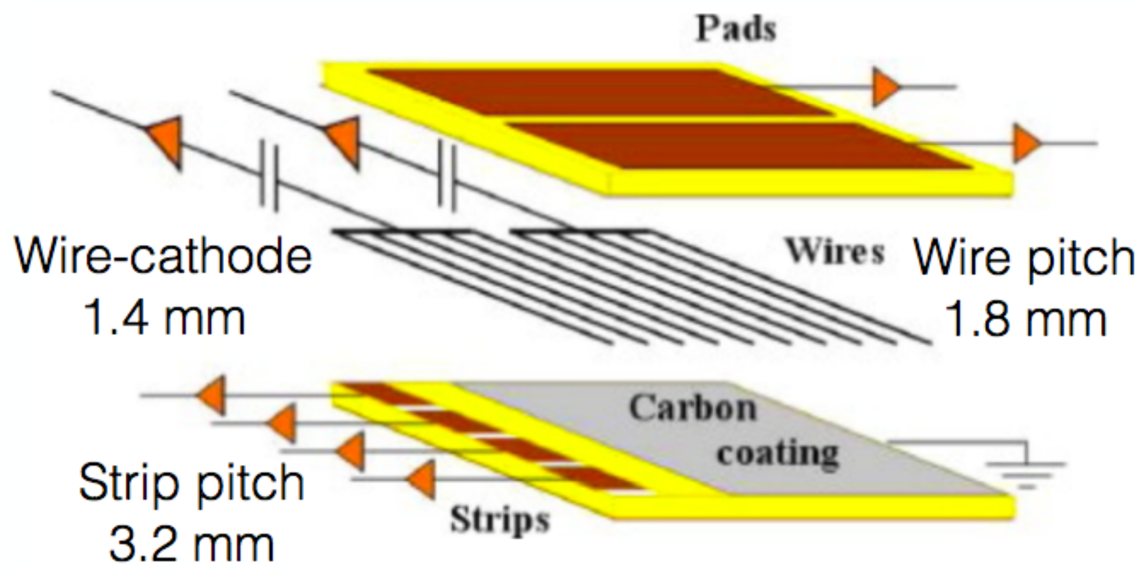
MM Trigger Algorithm

- Fit slopes to determine parameters
  - Δθ: Angular deviation of the MM segment with respect to an infinite momentum track from the IP → use "global" and "local" fits using horizontal hits (X) only
  - θ and ϕ: from average of horizontal and stereo hits and IP - determine RoI

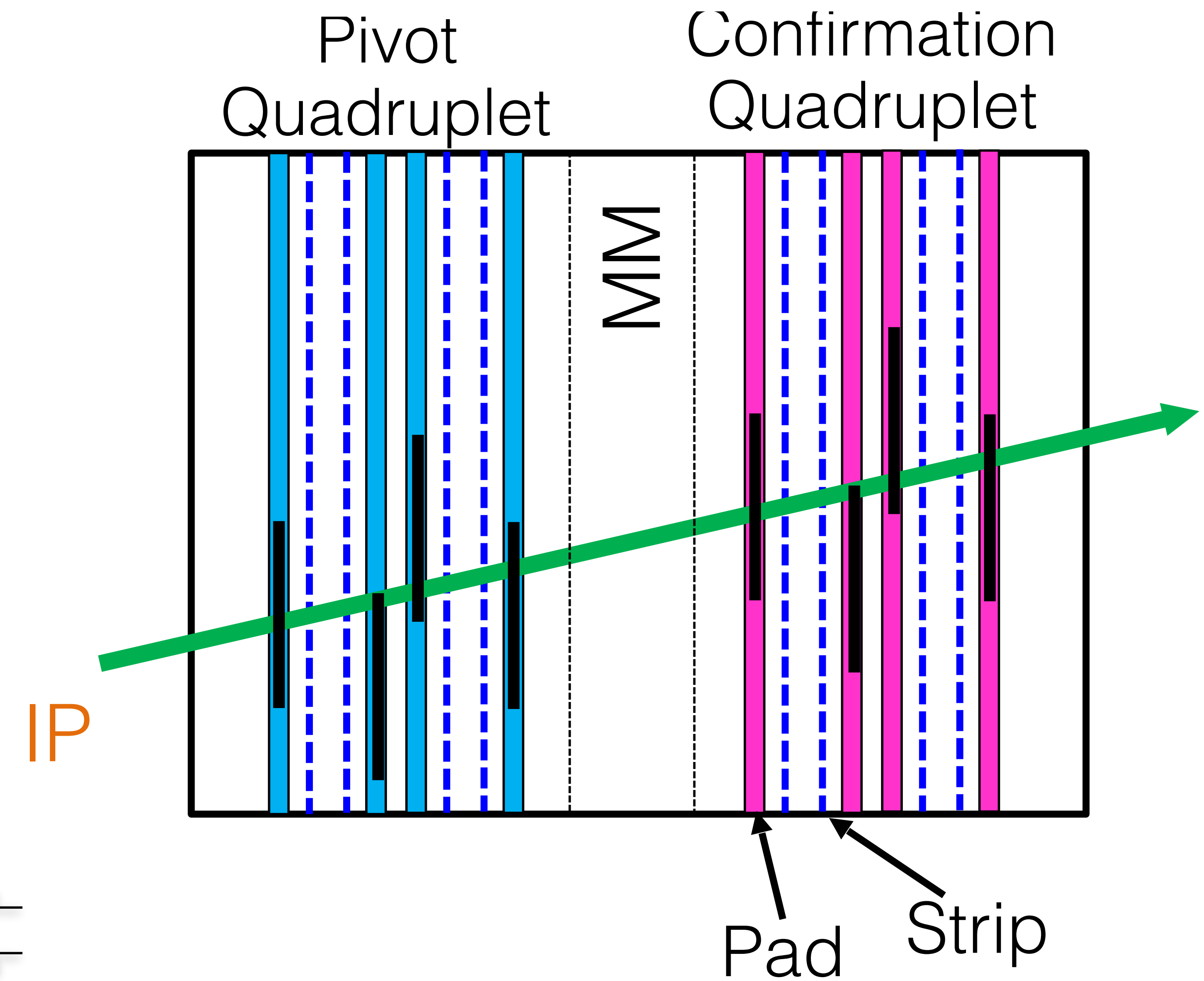


sTGC Trigger Concept

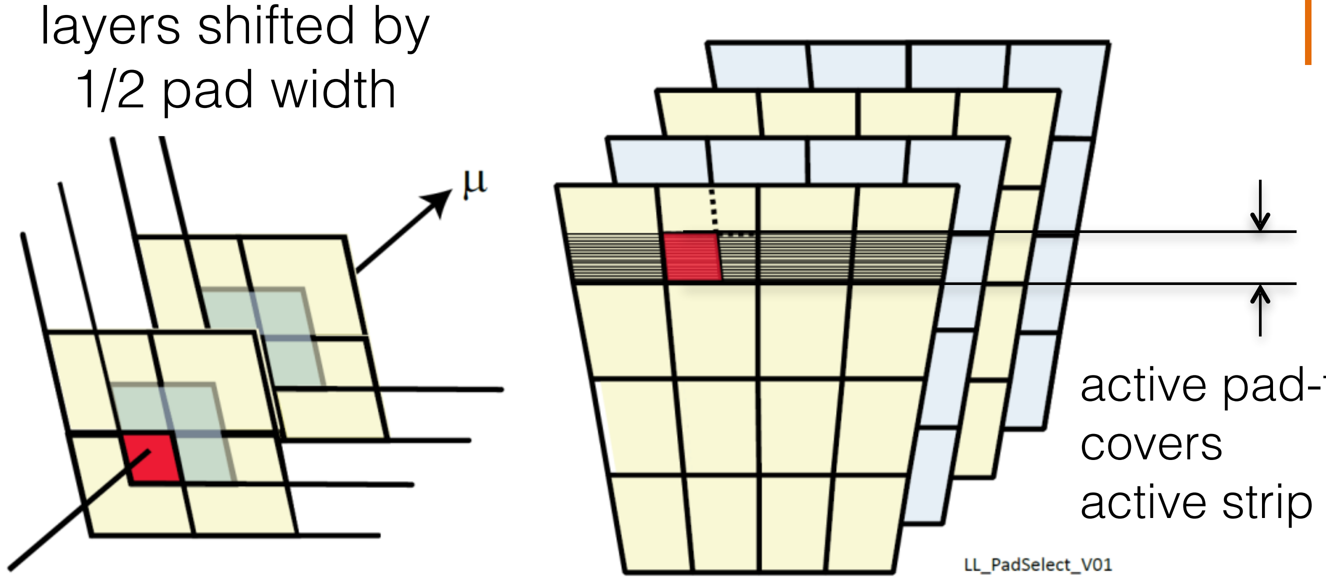
- Use strip data corresponding to pad coincidence



280k strips



pads in different layers shifted by 1/2 pad width

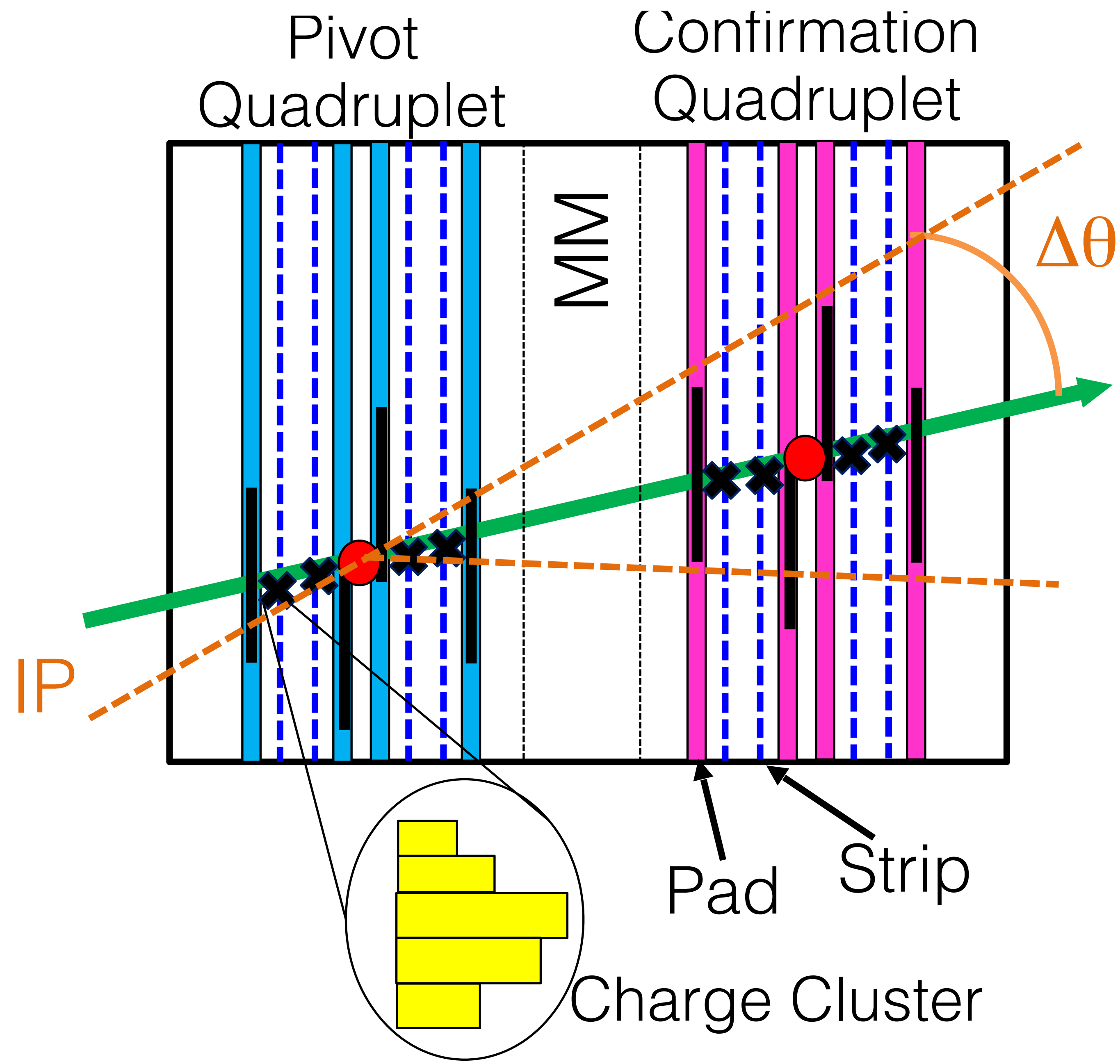


active pad-tower covers active strip band

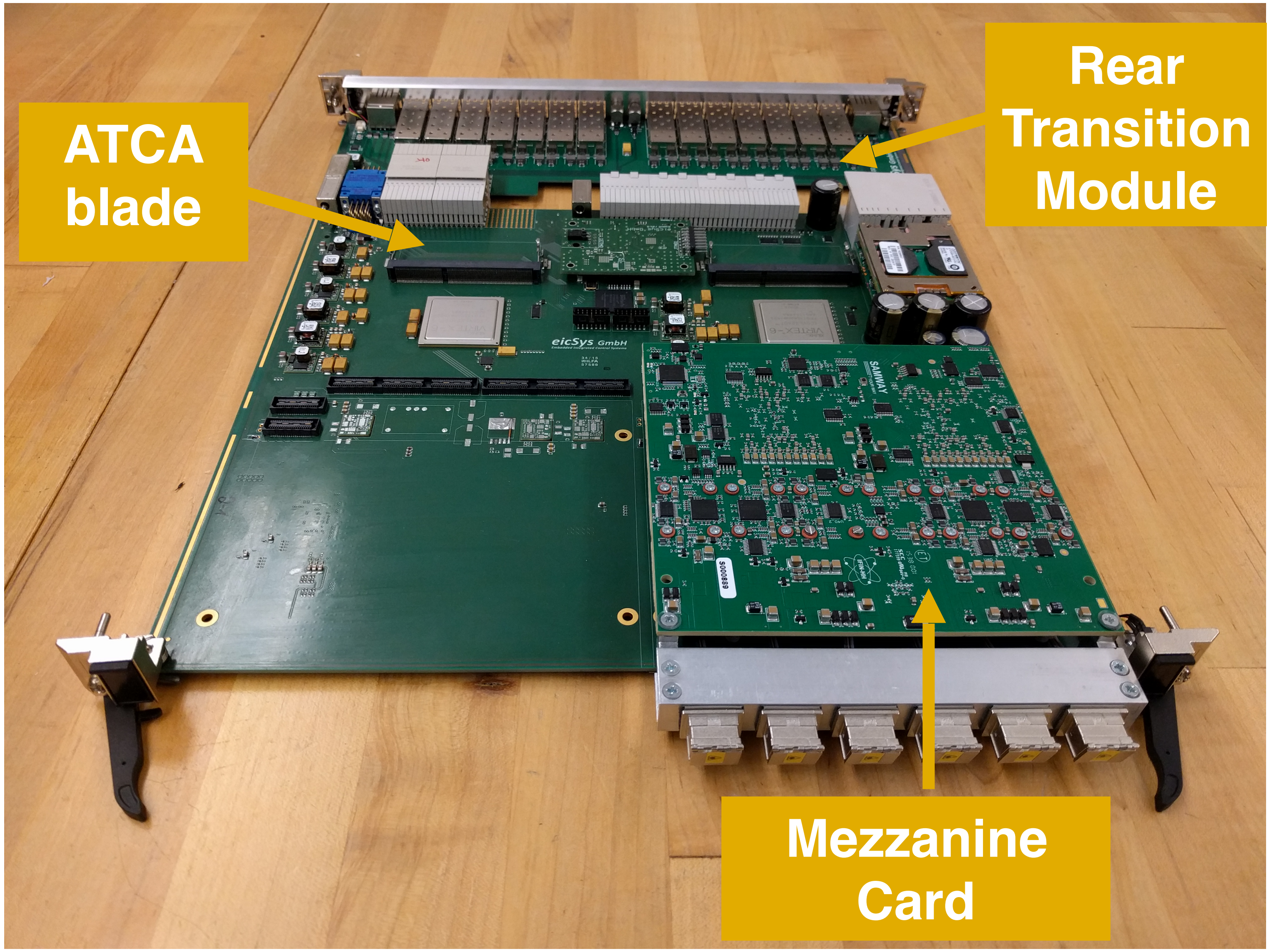
require 3/4 + 3/4 coincidence of pads

sTGC Trigger Algorithm

- Algorithm implemented in the trigger processor FPGA
  - Calculate charge centroid per layer
    - 0.1 mm
  - Average centroids in each quadruplet
  - Compute Δθ from LUT
    - Δθ = 'θ from confirmation/pivot centroids' – 'infinite momentum track angle of the pivot quadruplet centroid'
  - R-index is the centroid average of pivot and confirmation quadruplets
  - ϕ-index determined from the pad trigger tower ϕ-ID

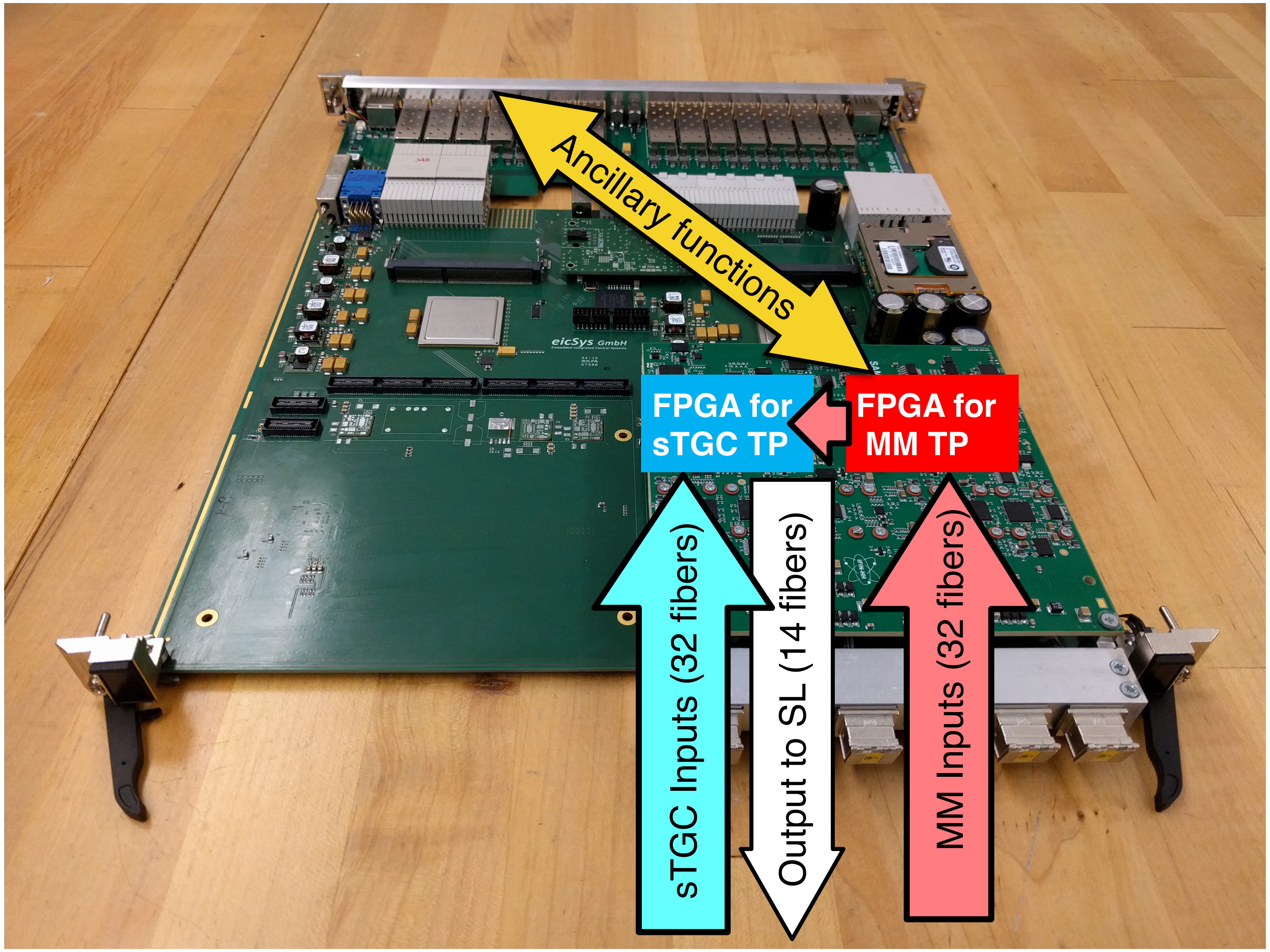


Trigger Processor Hardware



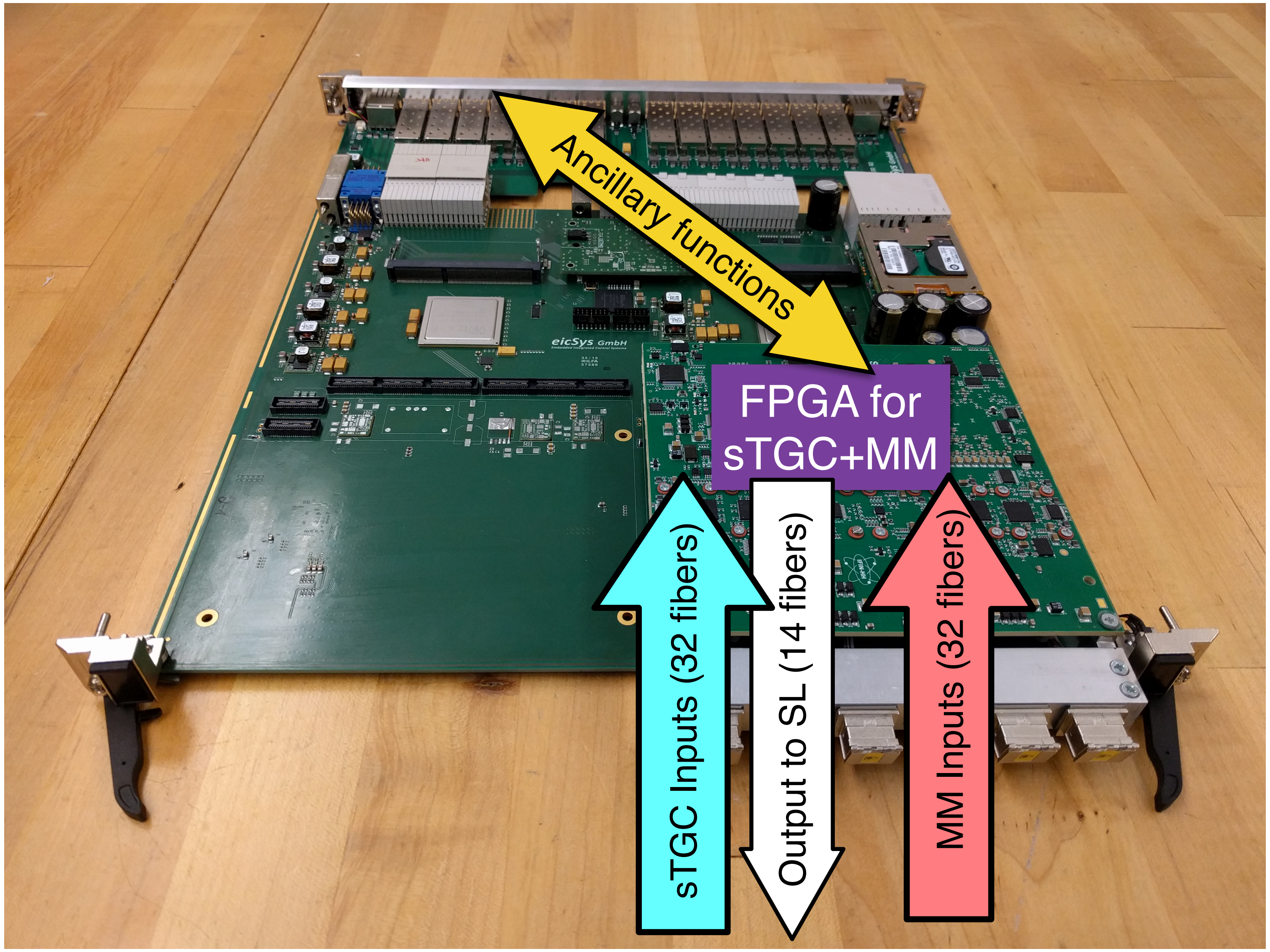
- Handles large number of readout channels and large volume of data
  - MM: ~2M strips (0.4mm)
  - sTGC: 280k strips (3.2mm), 45k pads, 28k wires

Trigger Processor Hardware

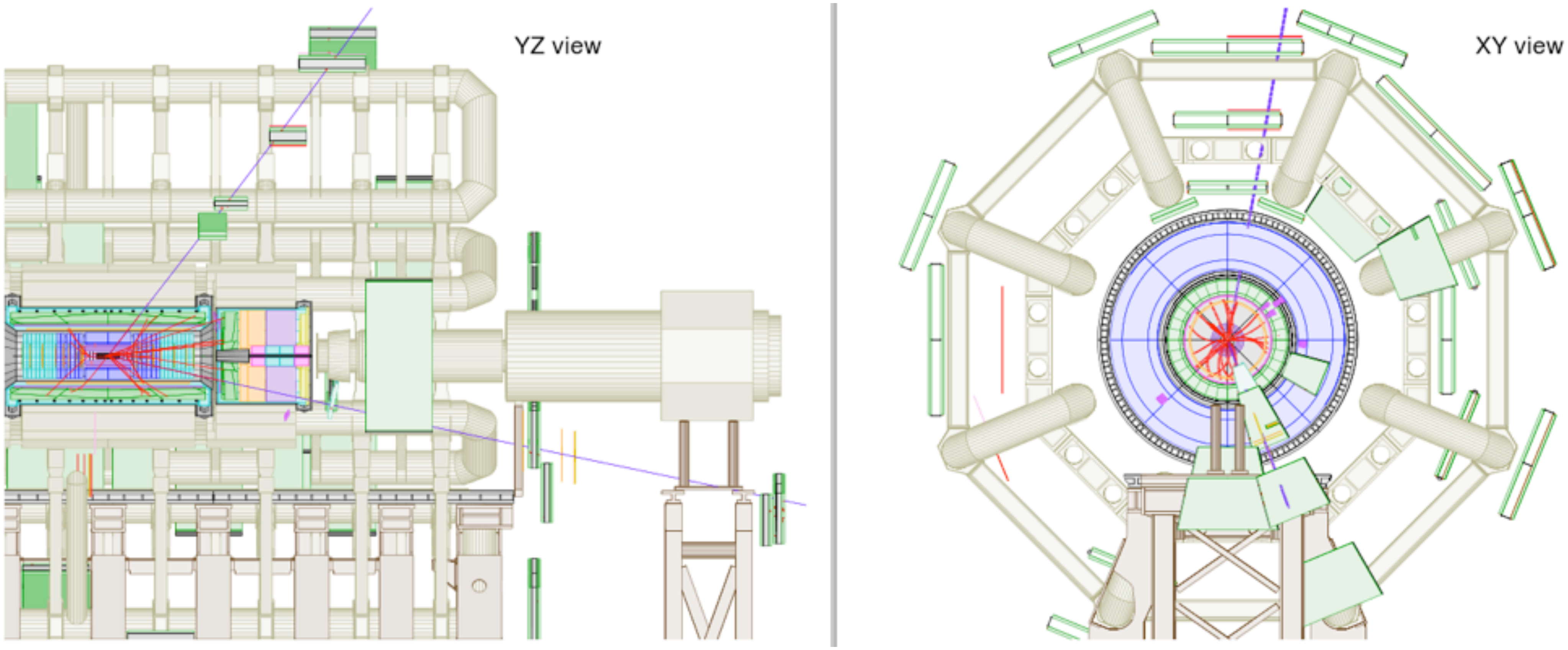


- sTGC and MM segment finding implemented on separate FPGAs for each sector in mezzanine card
- sTGC and MM candidates merged and sent to Sector Logic
- short time available to prepare and transmit trigger data: 500 ns electronics+ 500 ns fiber length
  - Trigger algorithms implemented in ~100ns

Trigger Processor Hardware for Phase 2



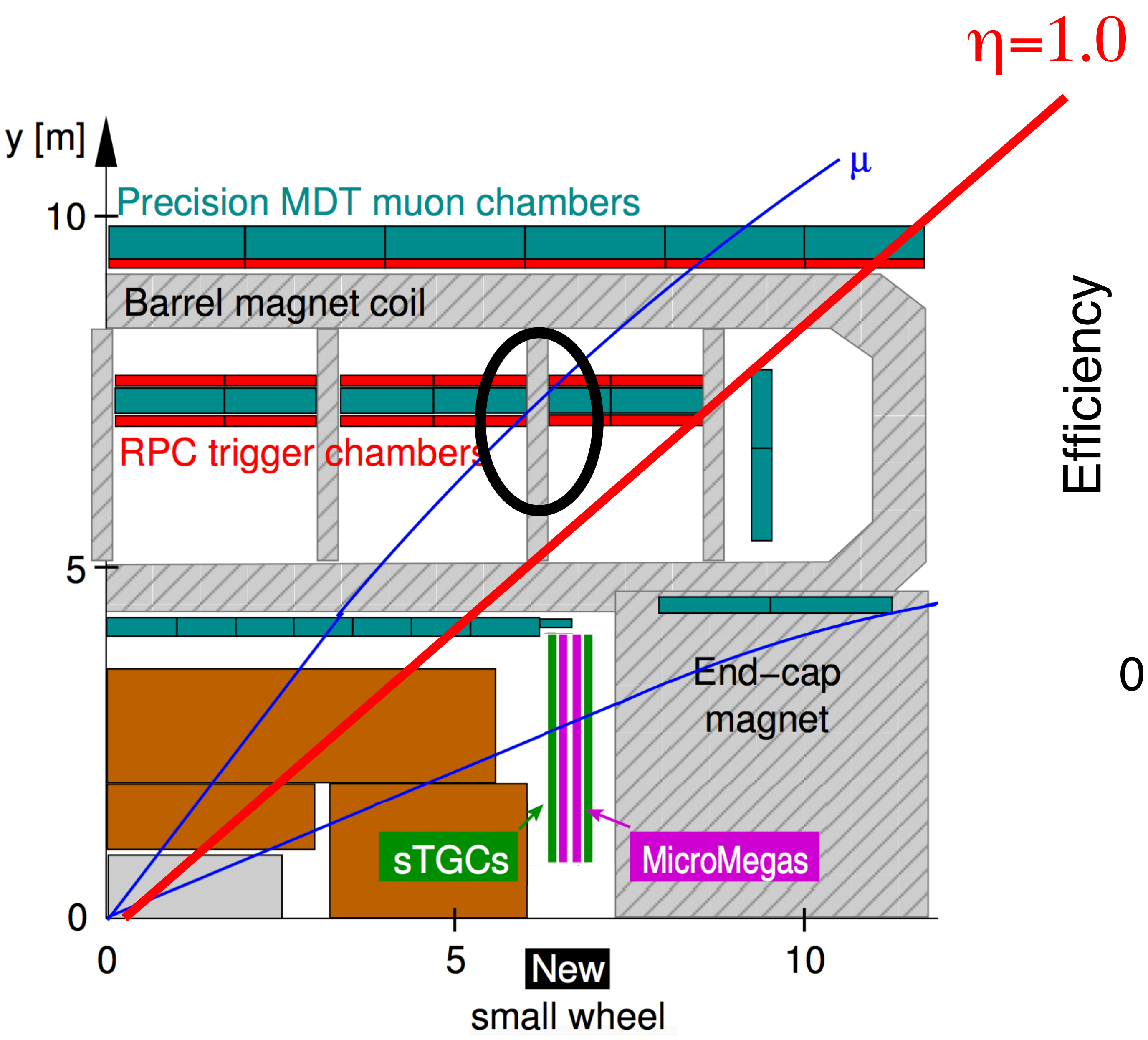
- Phase 2 upgrade proposal to use new FPGA with more resources to combine sTGC and MM information and perform single fit of both
- Increased latency in Phase 2 allows for more refined algorithm → more robust against backgrounds

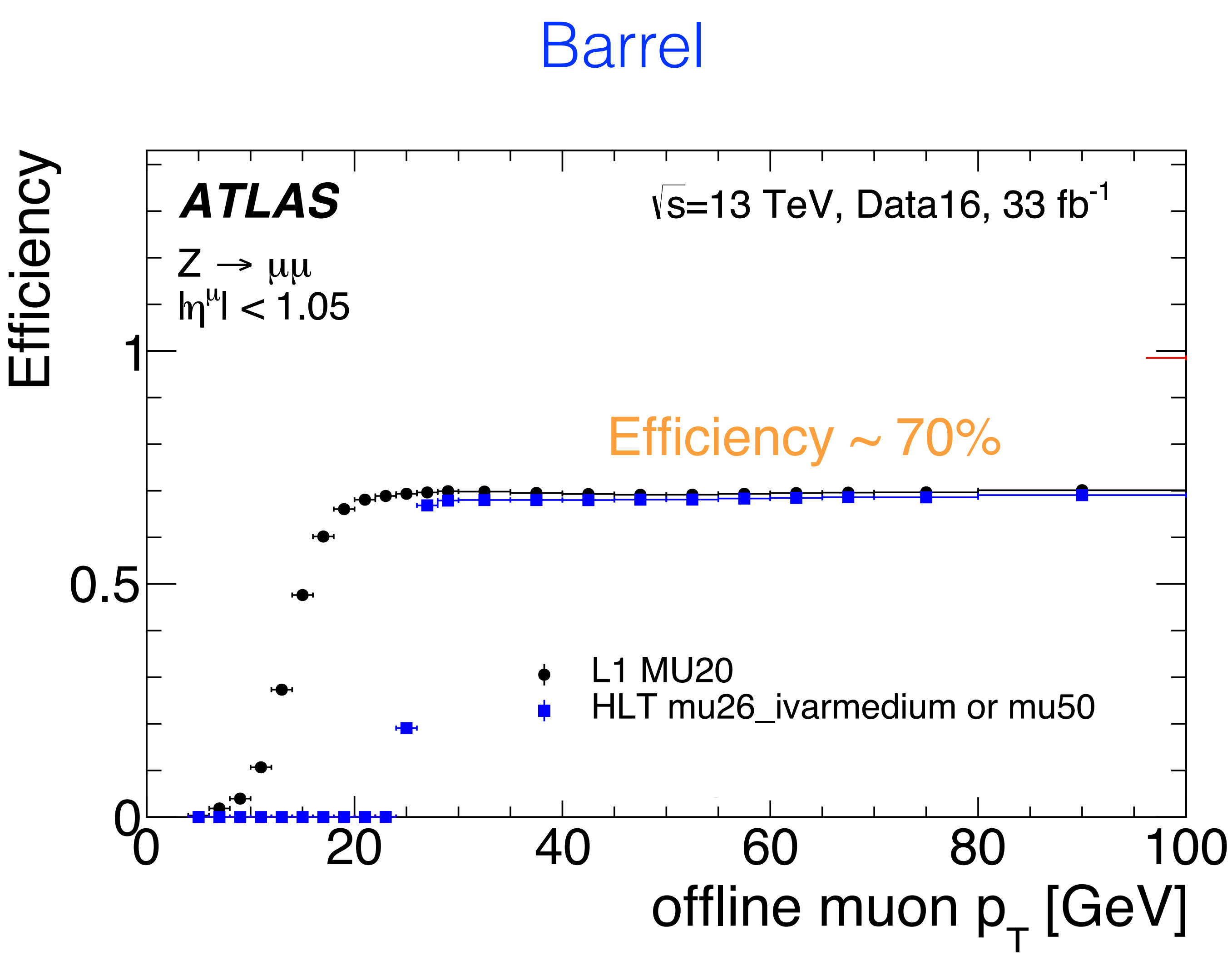


2. Increase Efficiency

Challenges of the Muon System → Phase 2

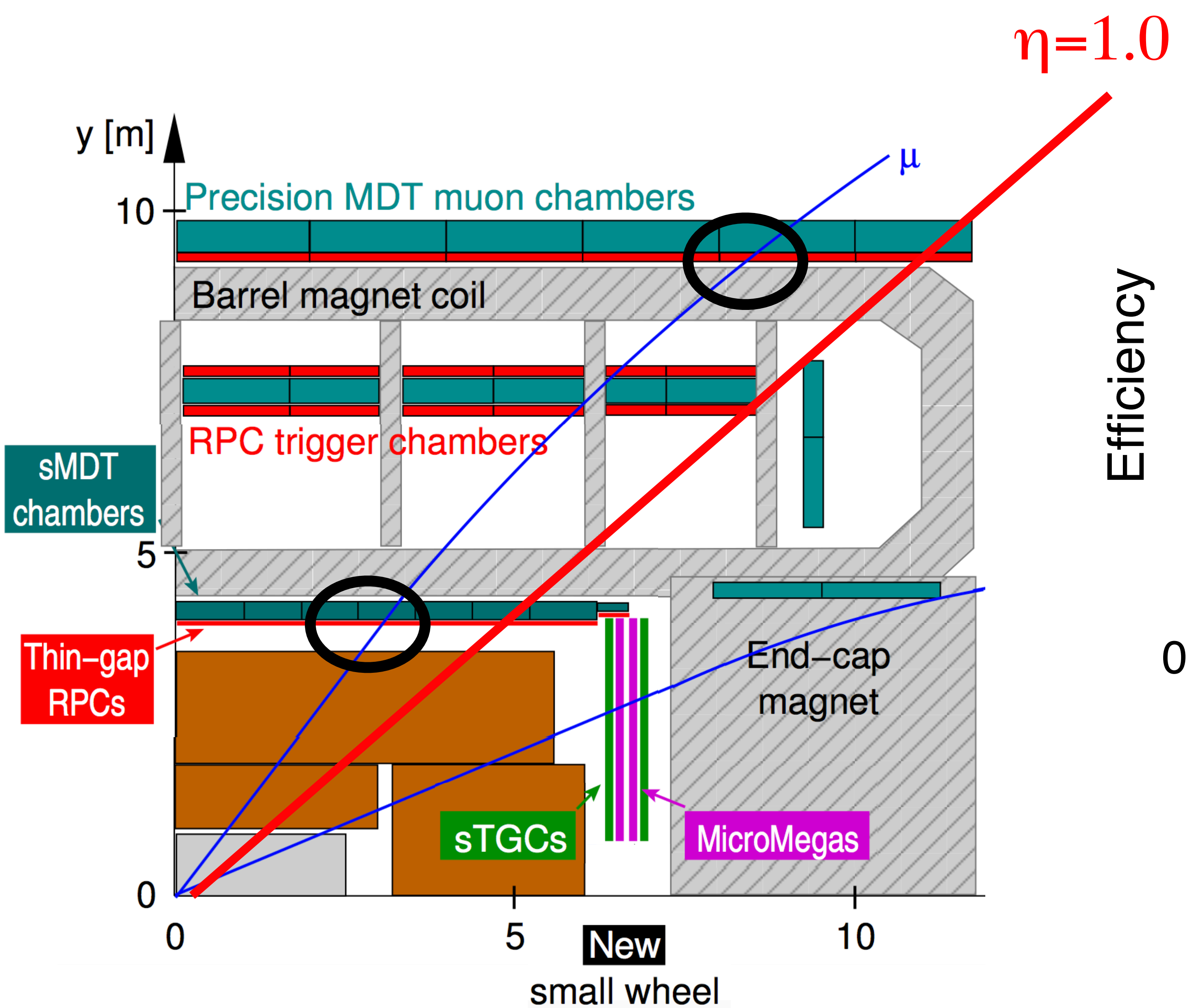
Low muon trigger efficiency in the barrel due to geometrical acceptance of the RPC chambers

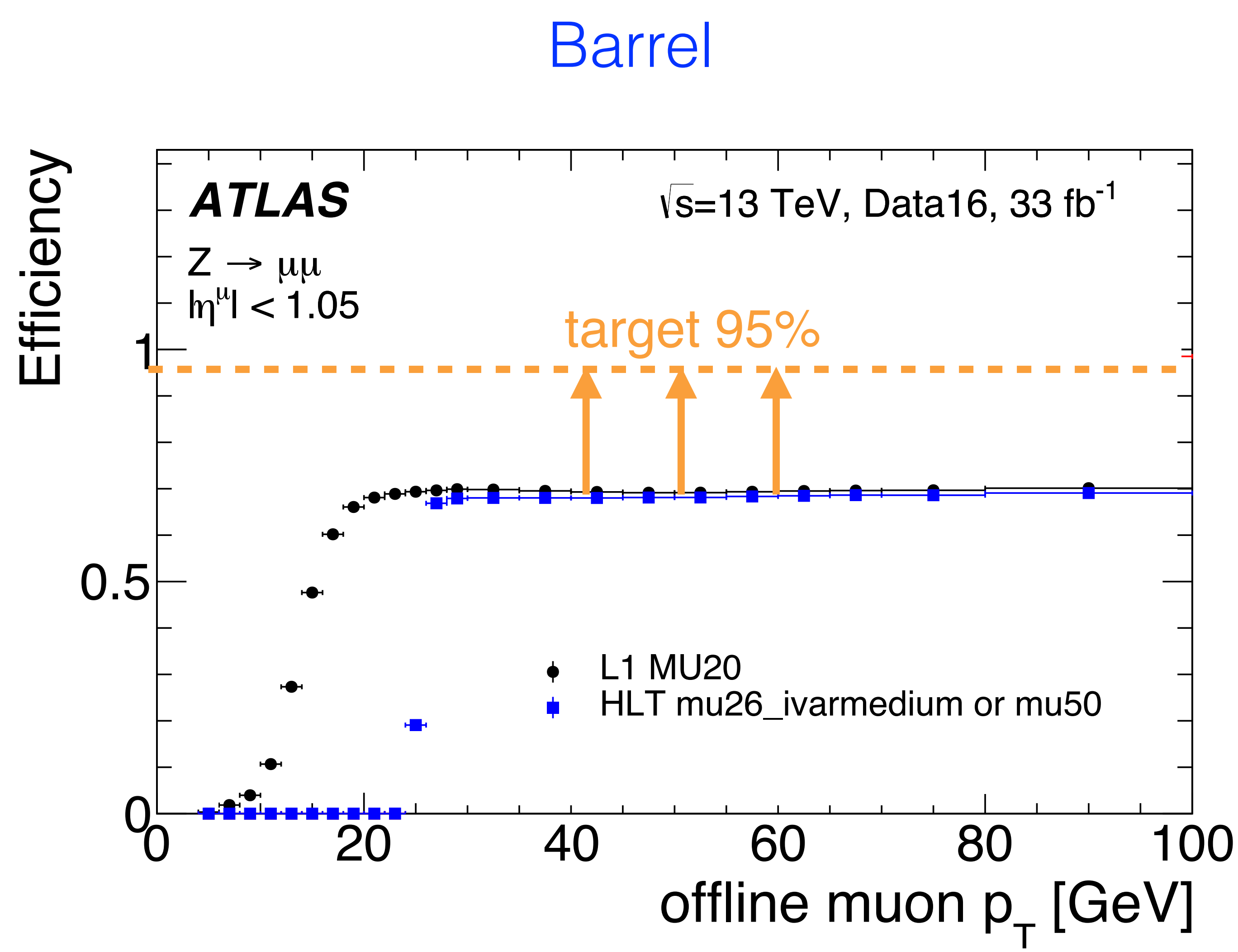




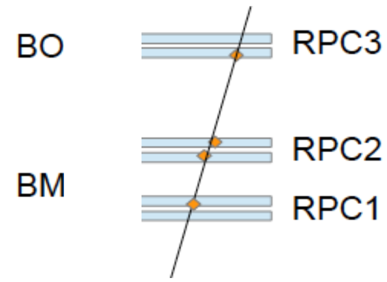
Phase 2 RPC Upgrade

Increase trigger efficiency in barrel region with an additional layer of RPCs

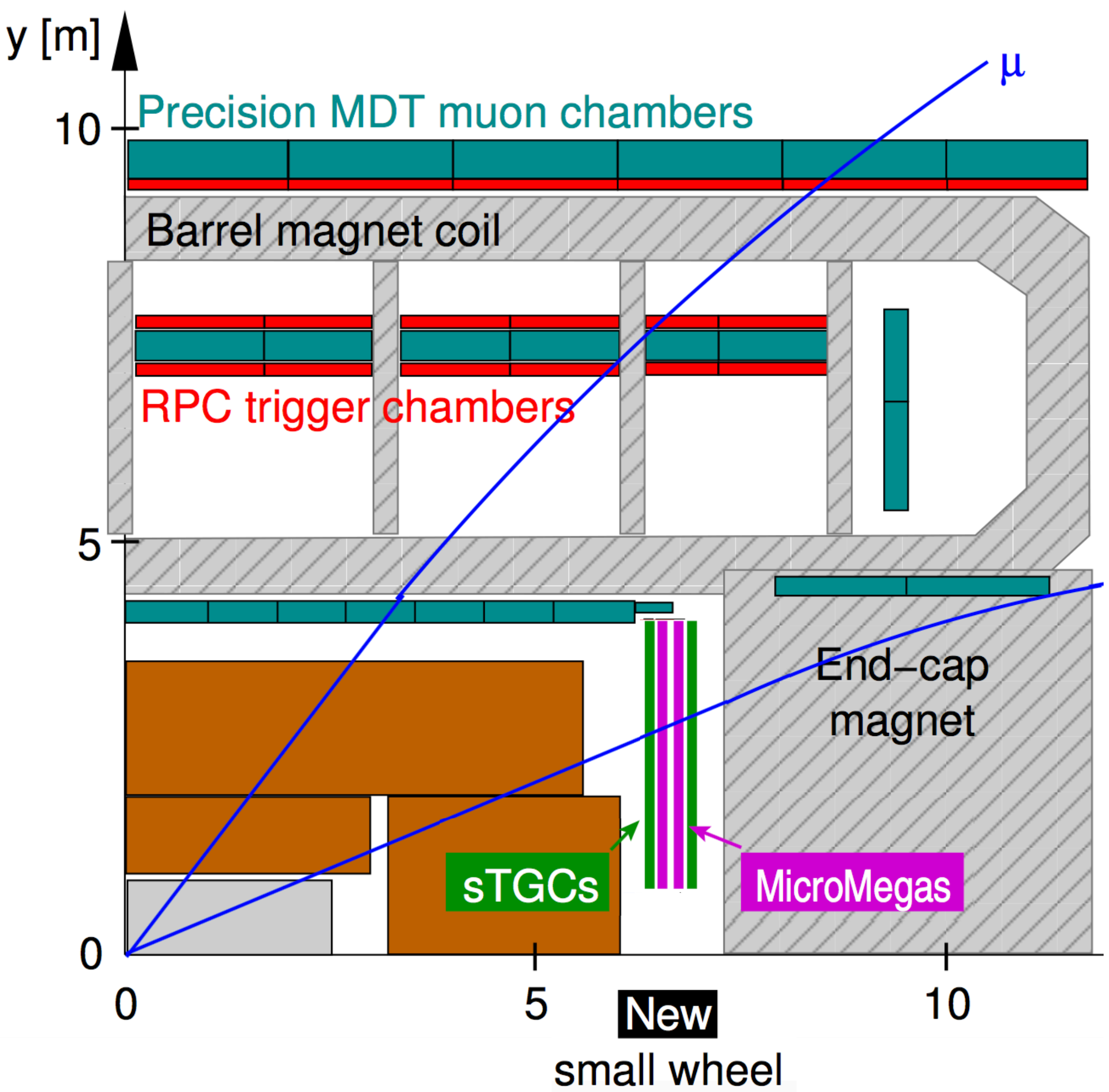


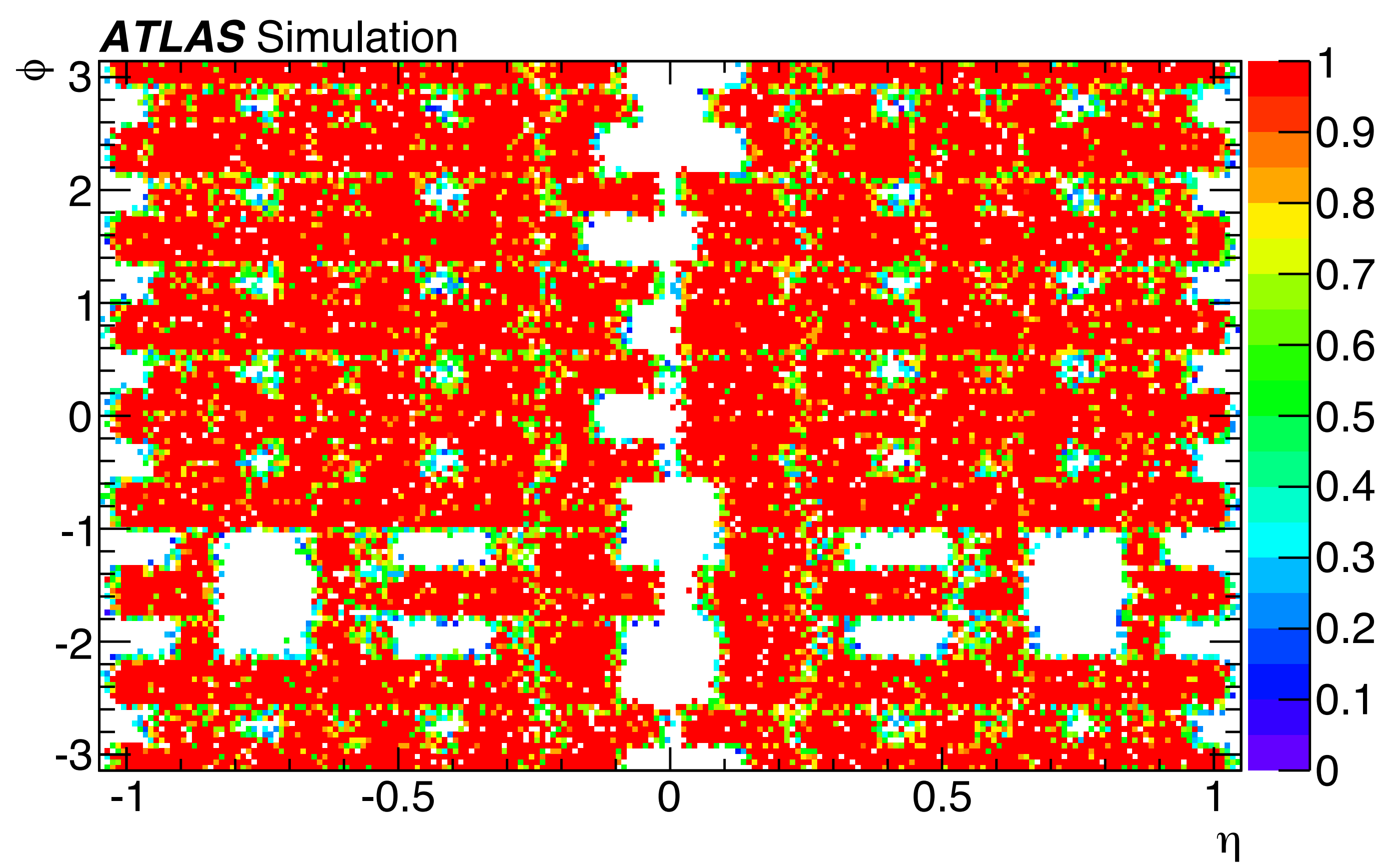


RPC Trigger Geometrical Acceptance

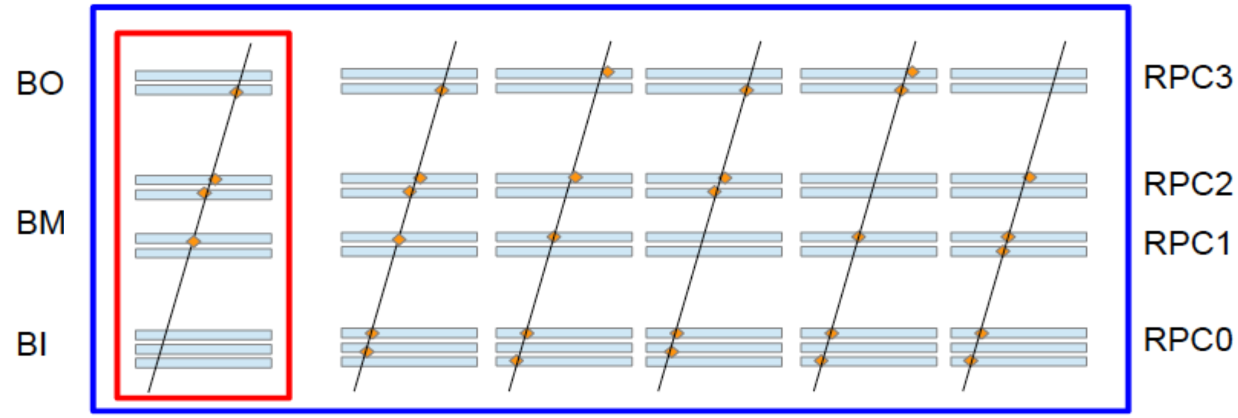


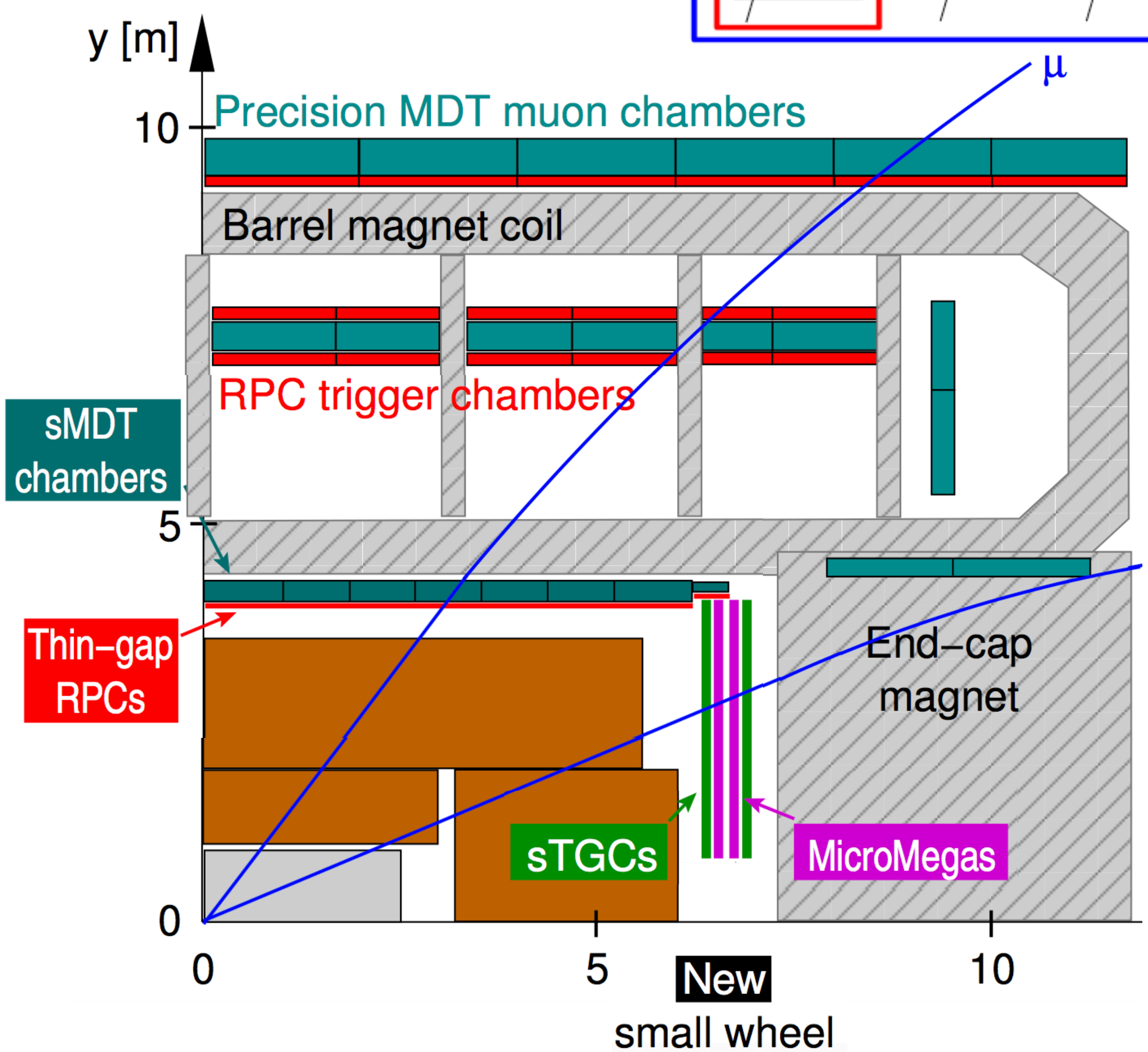
Limited to combinations of RPC hits that include middle chamber with low geometrical acceptance

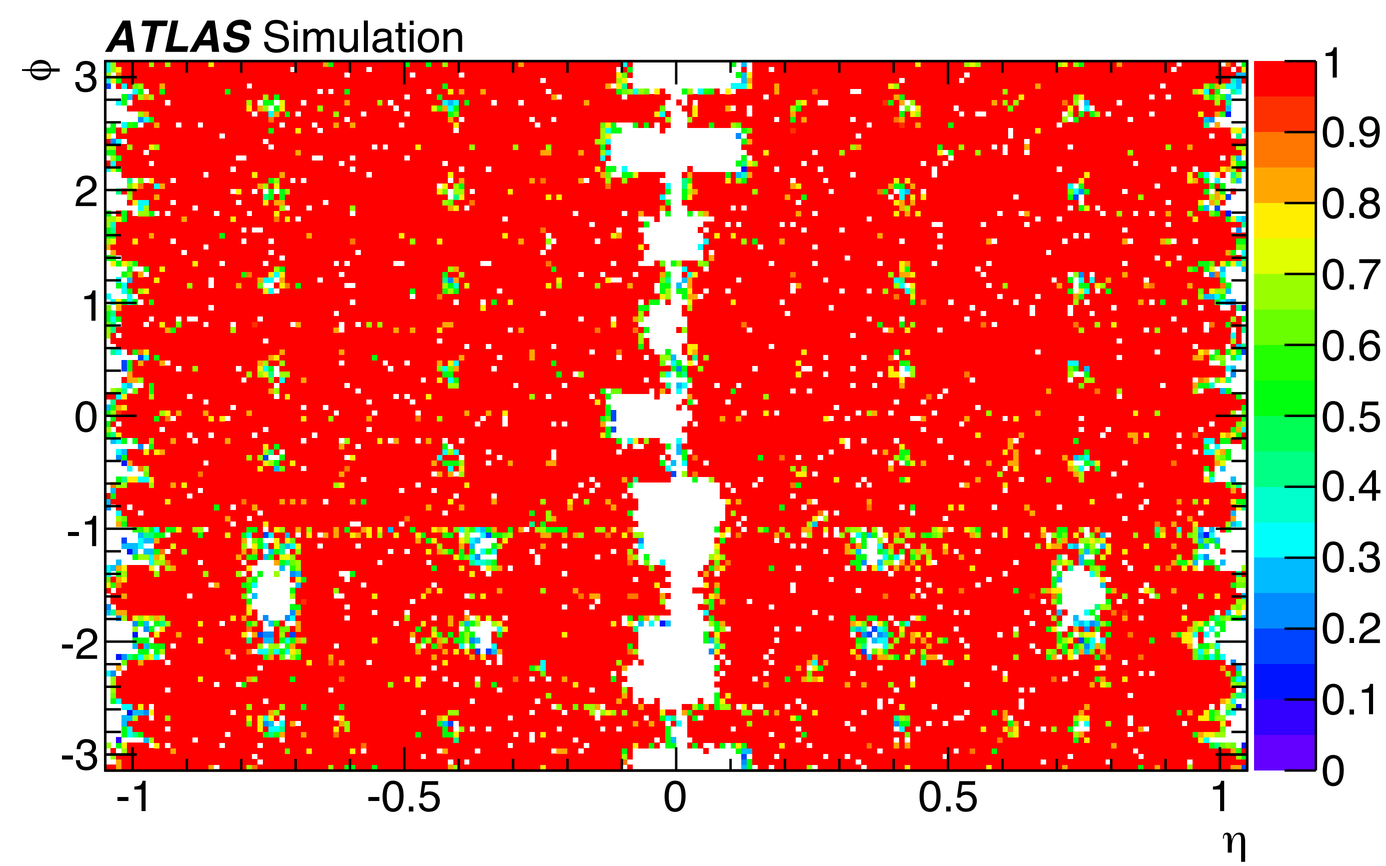




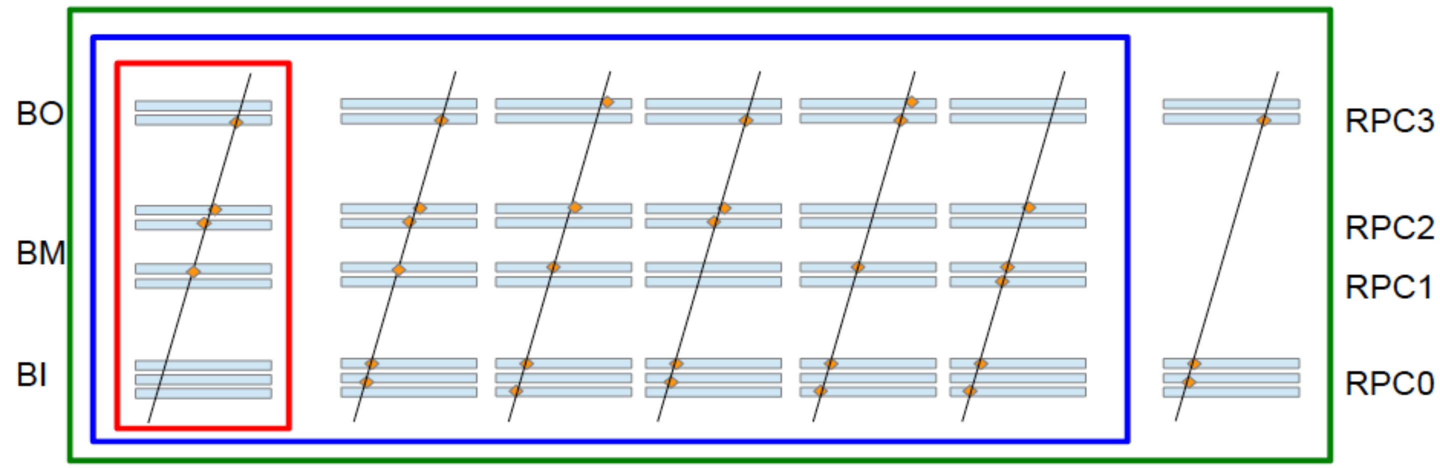
Phase 2 RPC Efficiency Recovery

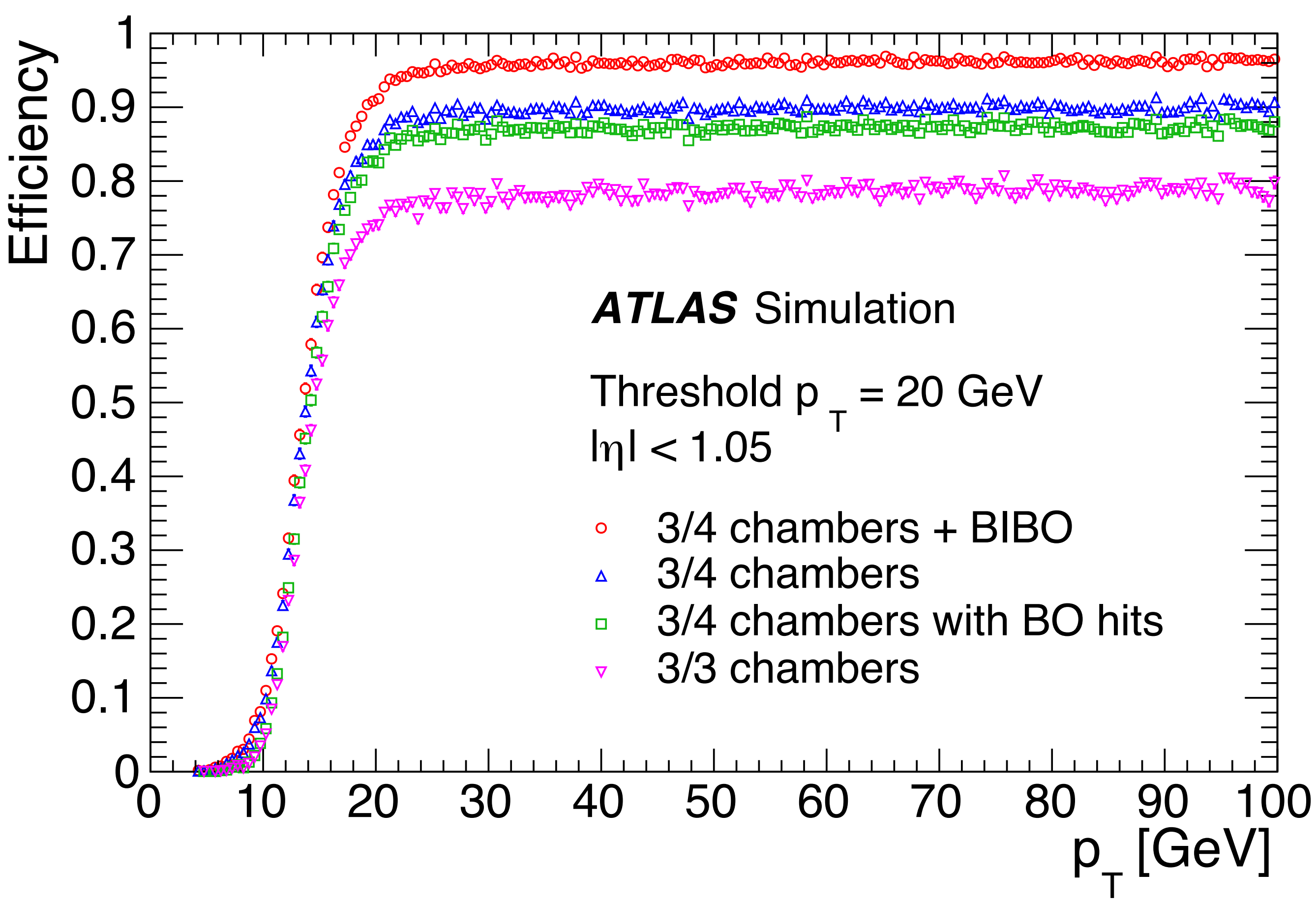


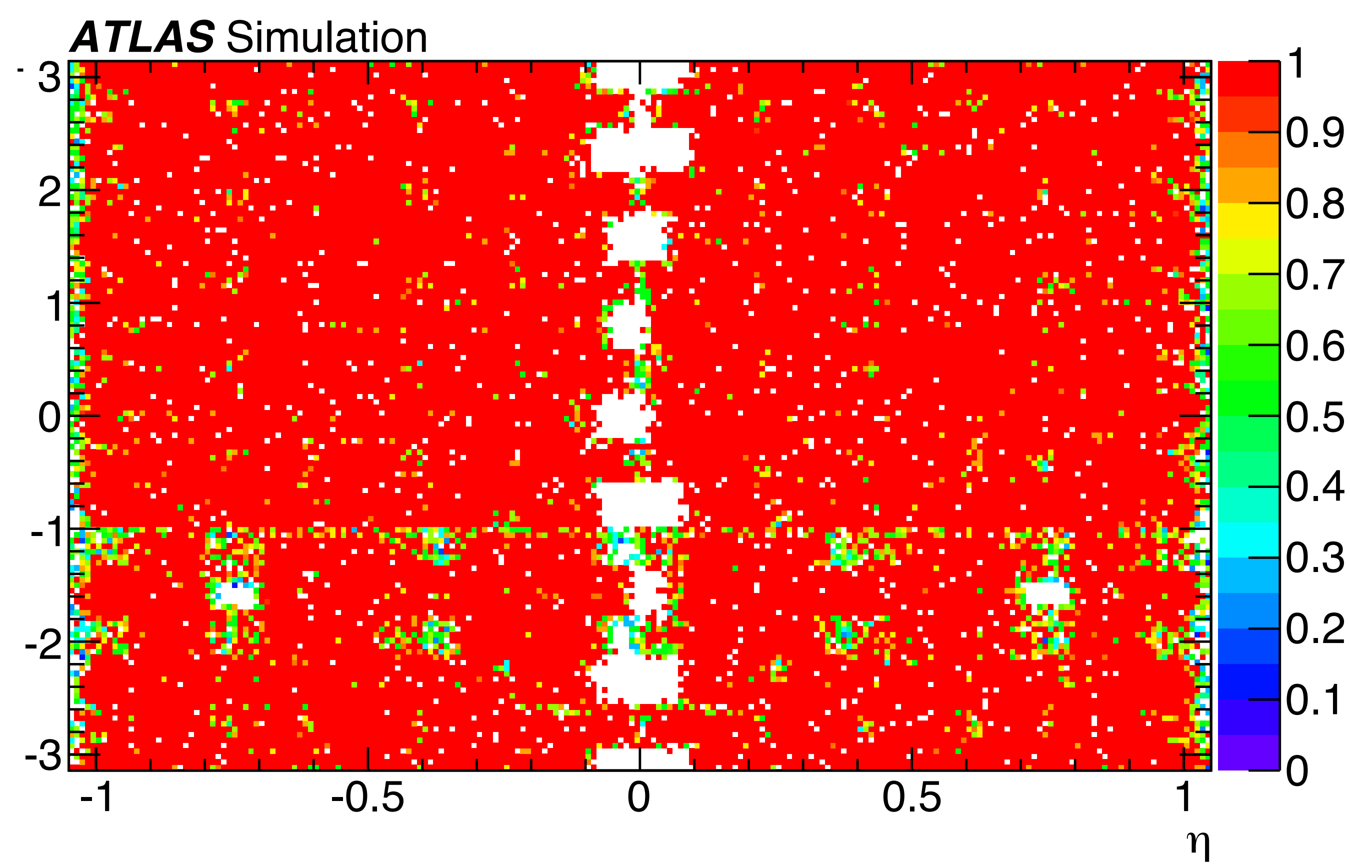




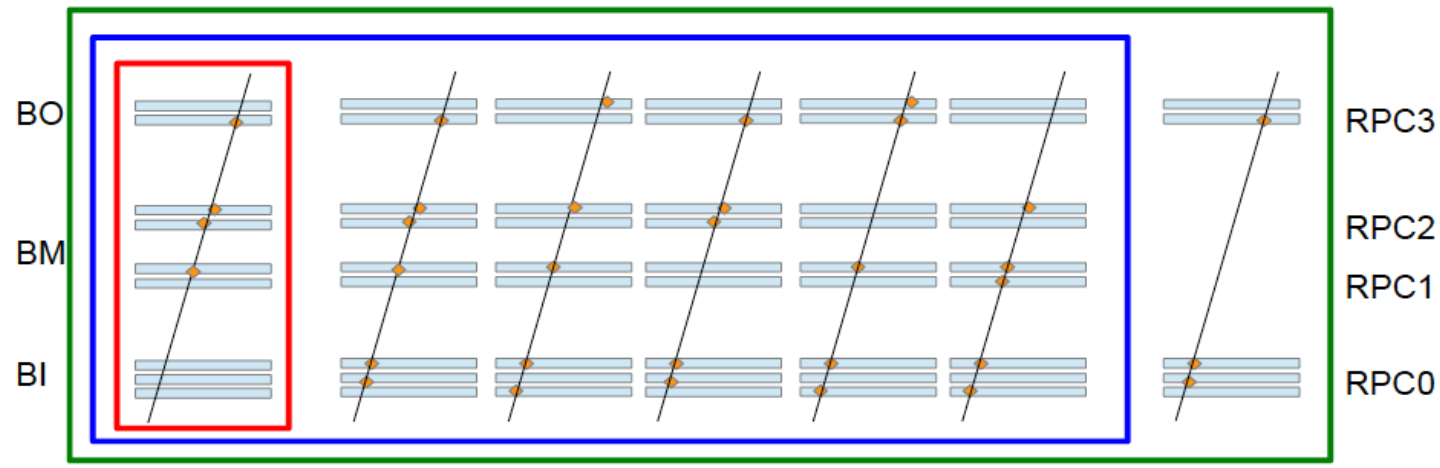
Phase 2 RPC Efficiency Recovery

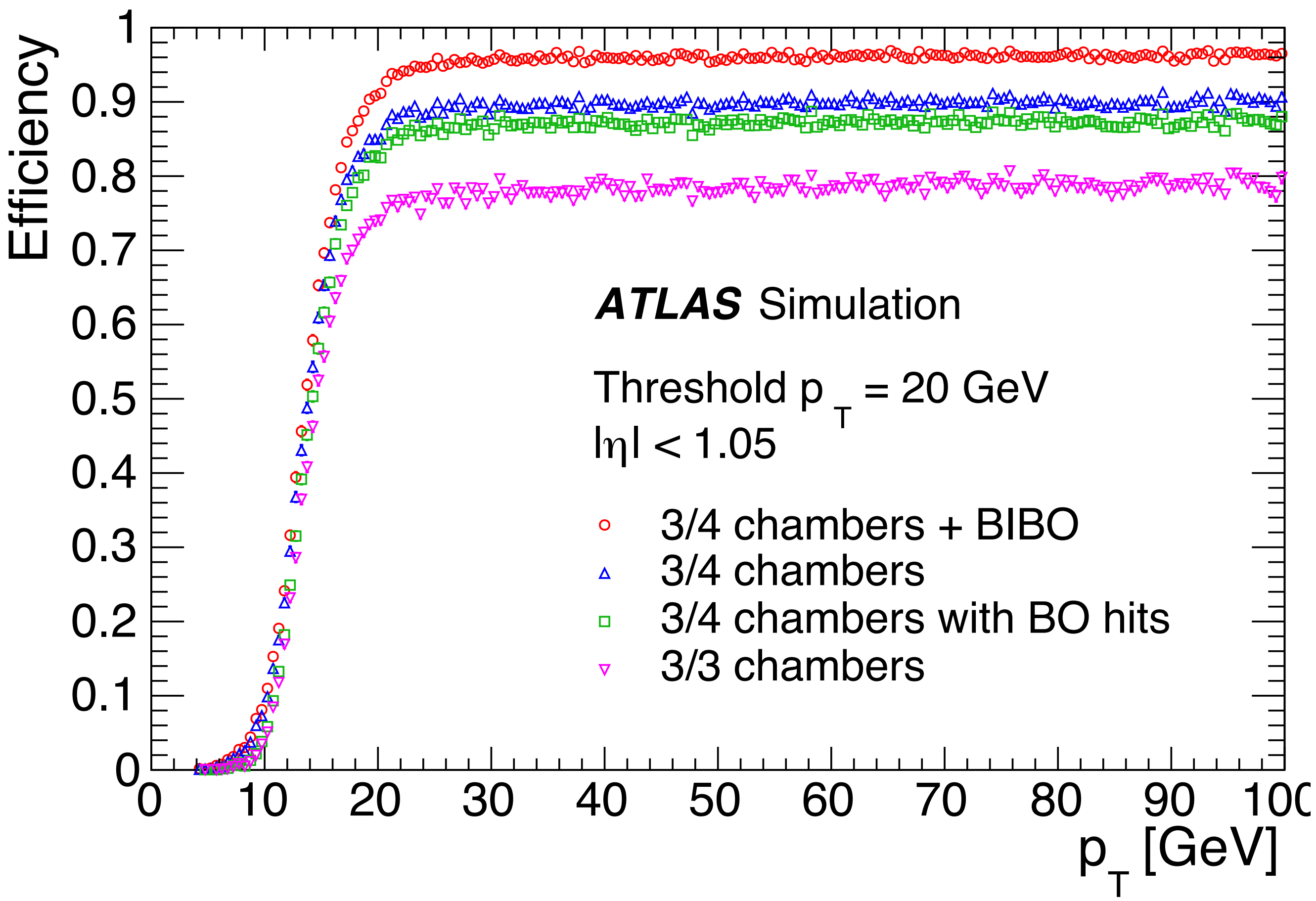


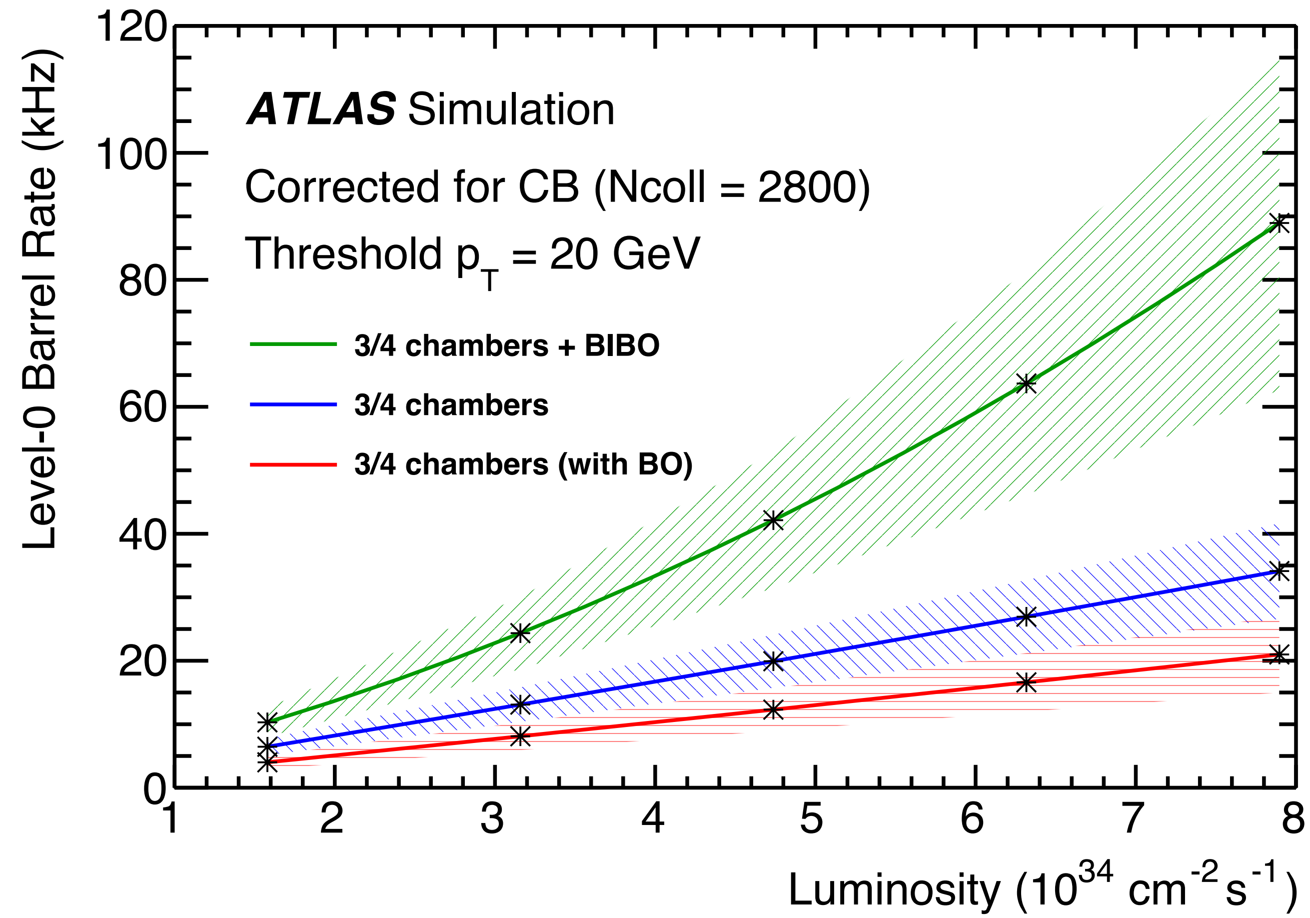




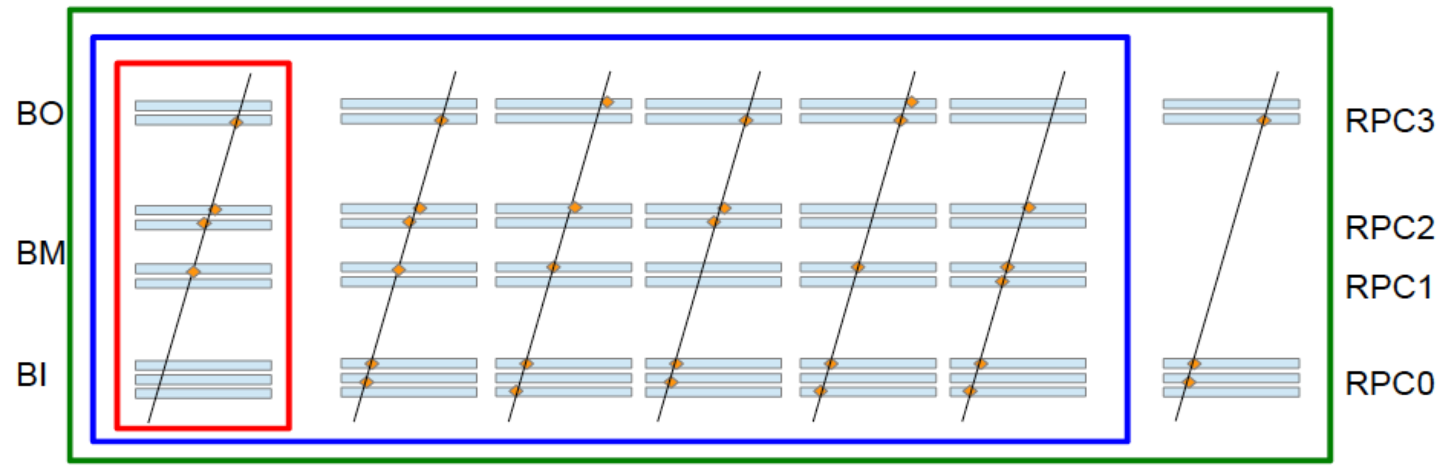
Phase 2 RPC Efficiency Recovery

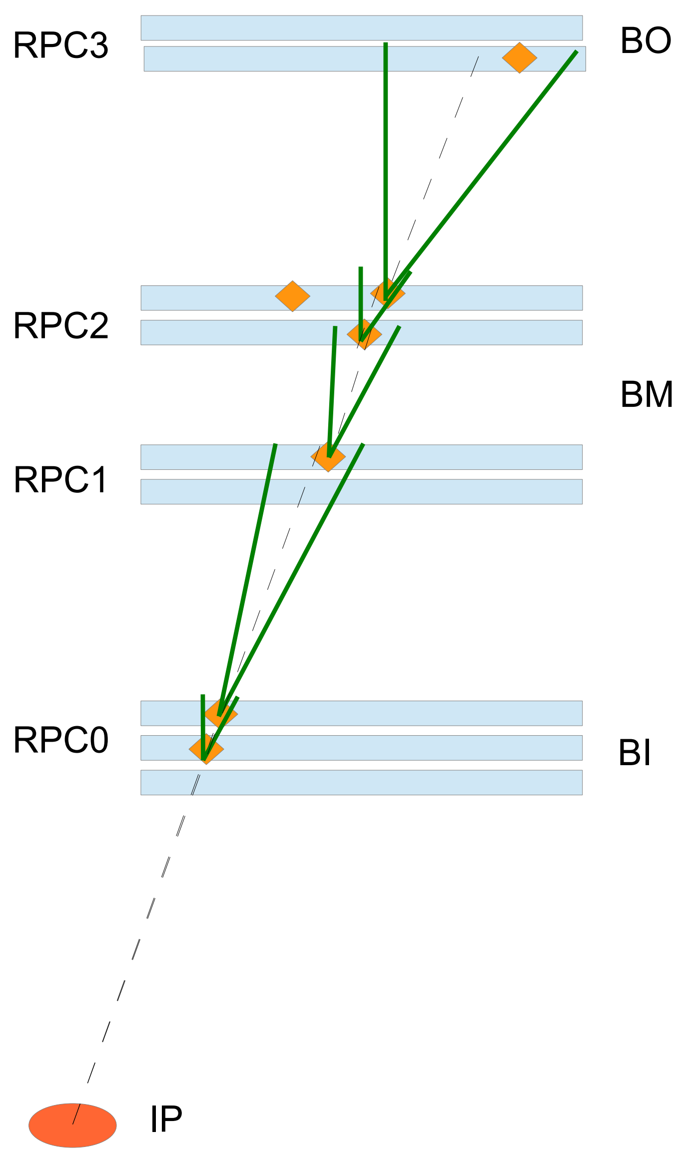






Phase 2 RPC Trigger Algorithm

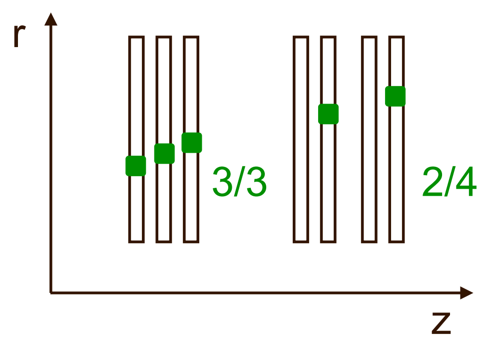




- Phase 2 proposed algorithm
  - Search for hits in innermost layer → define straight line between IP and innermost hit
  - Search for hits in coincidences in subsequent layers using distance in η and ϕ
- Performed in array of η towers simultaneously
- Algorithm effectively measures the momentum from the deflection of the trajectory

Phase 2 TGC Trigger Concept

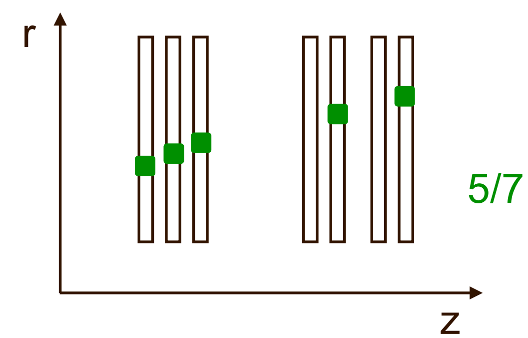
Current TGC trigger
≧2/3 & ≧3/4



This pattern is rejected.

Efficiency ~94%

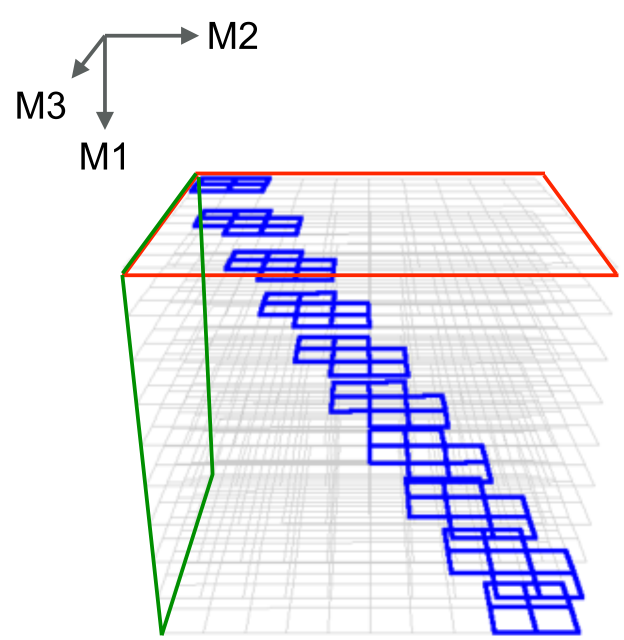
Phase 2 proposal
≧5/7

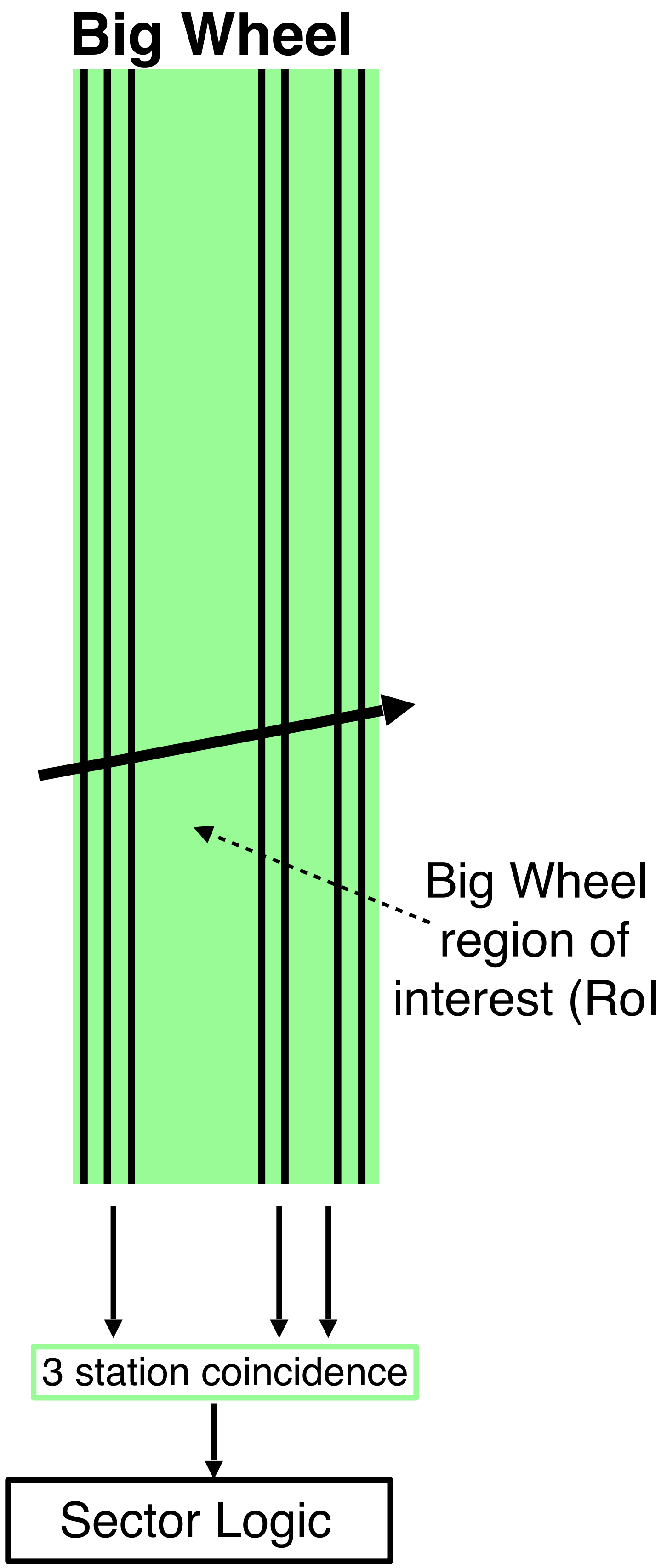


This pattern is accepted.

Efficiency ~98%

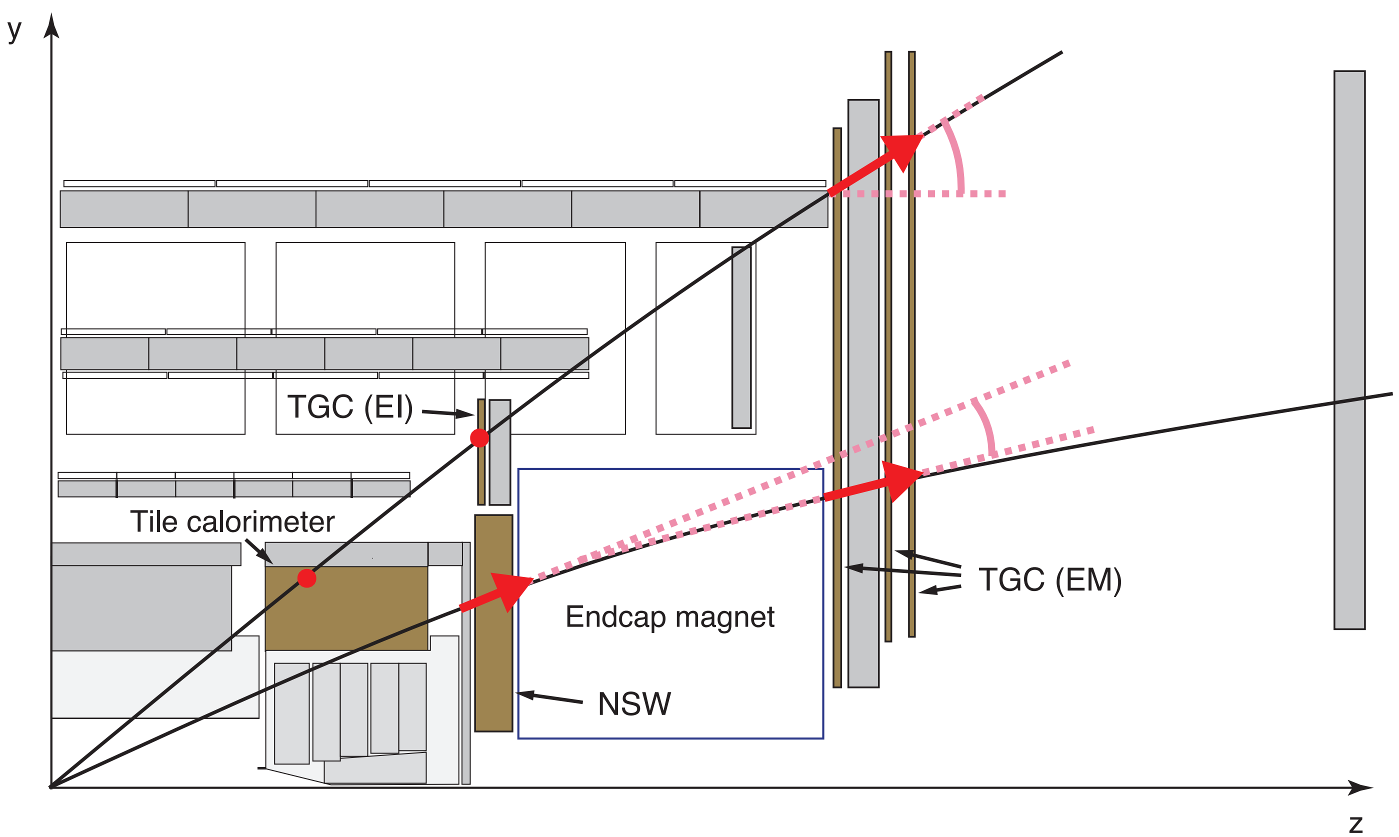
Phase 2 plan is to use a more sophisticated coincidence matrix including all layers

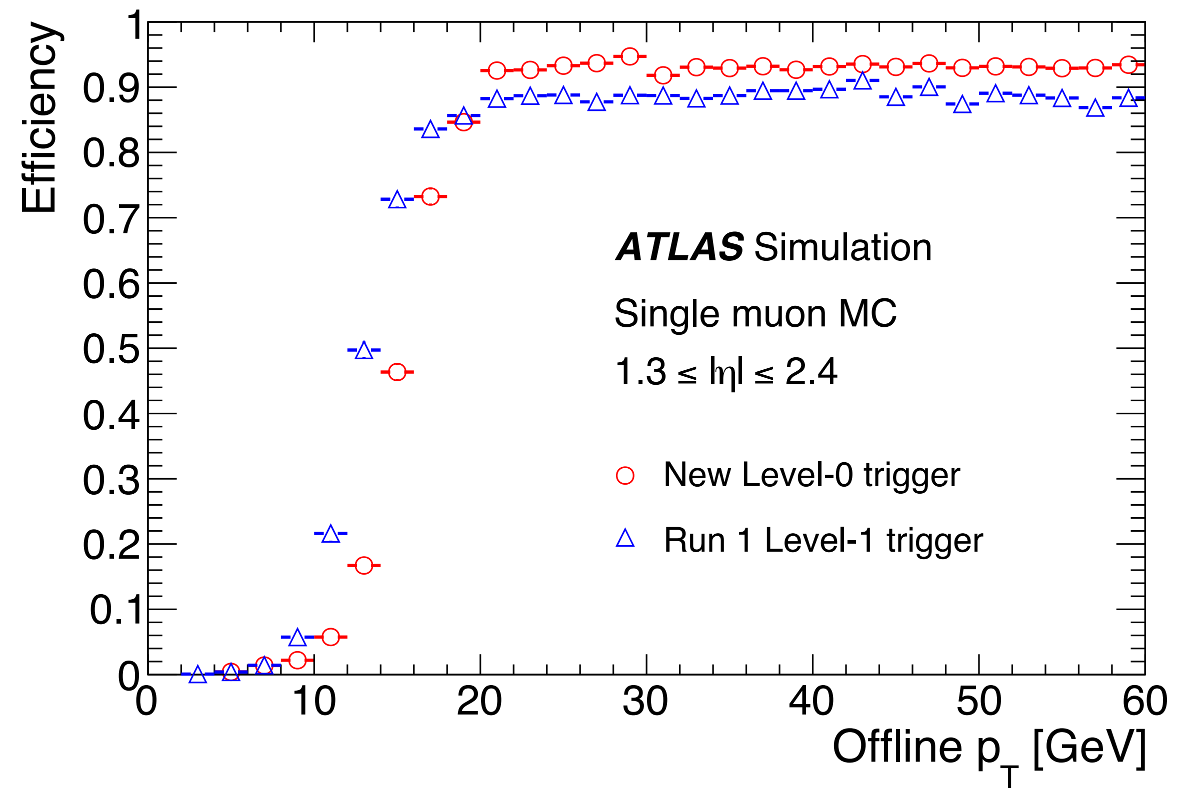


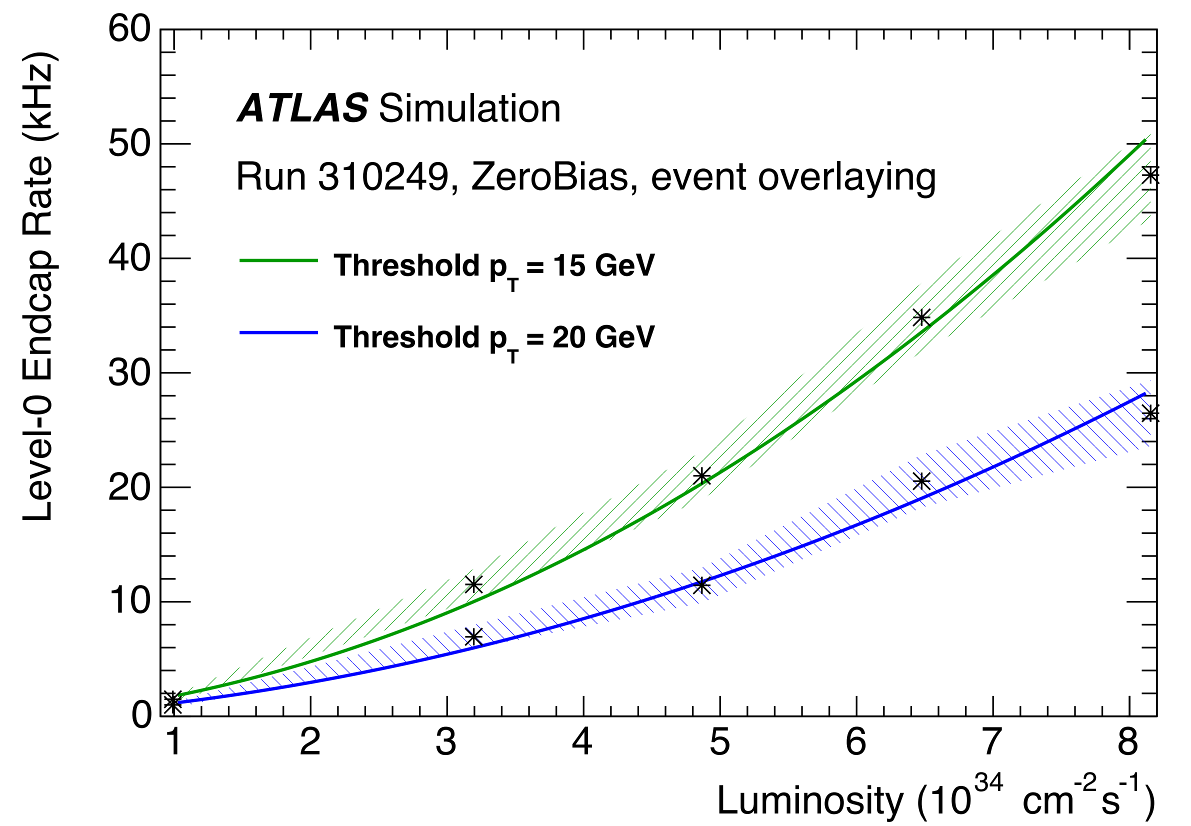


Phase 2 TGC Trigger

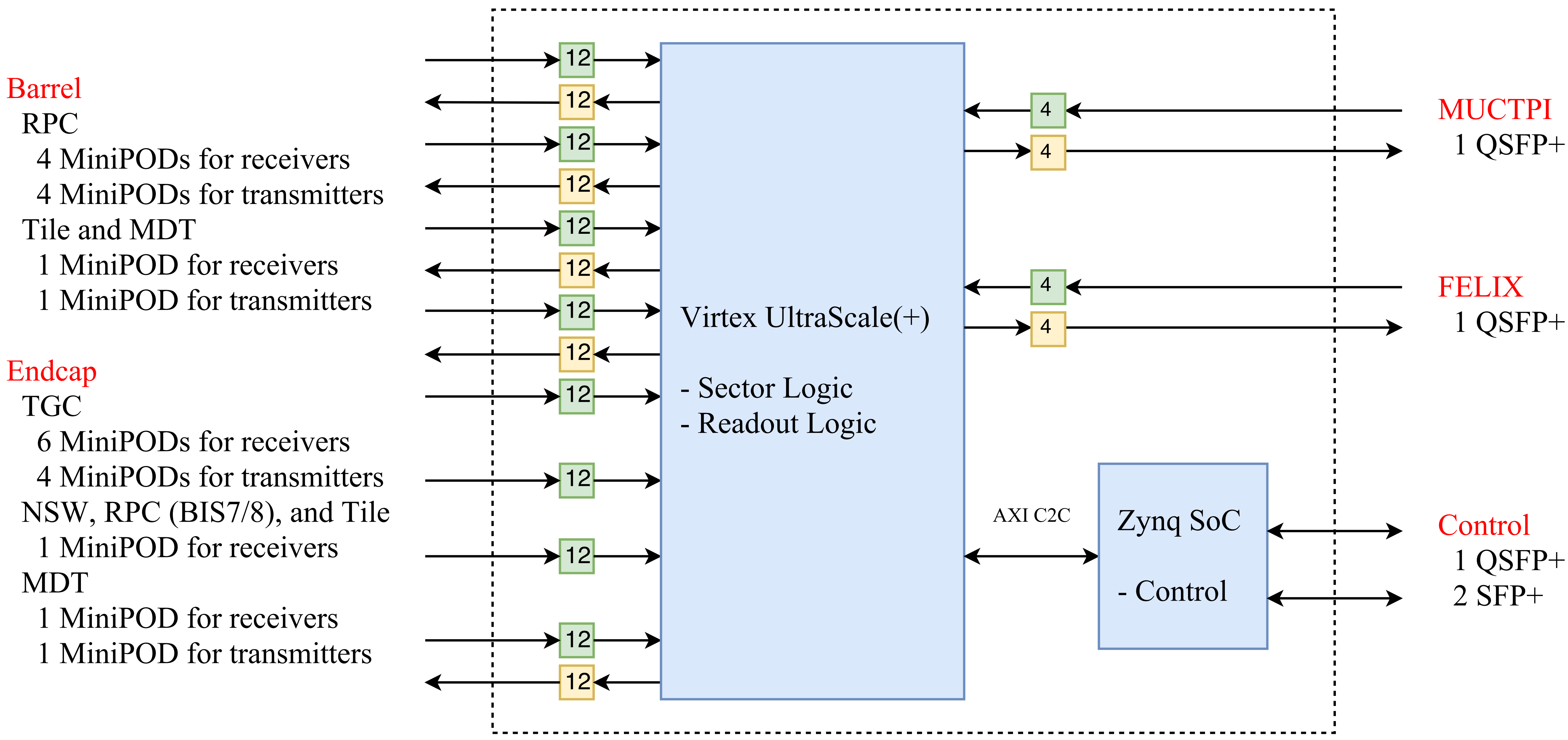
- A track segment is reconstructed by a minimum χ^2 fit to the TGC hits which satisfy the coincidence requirement
- Apply requirements on the polar angle of the segment direction depending on the p_T thresholds

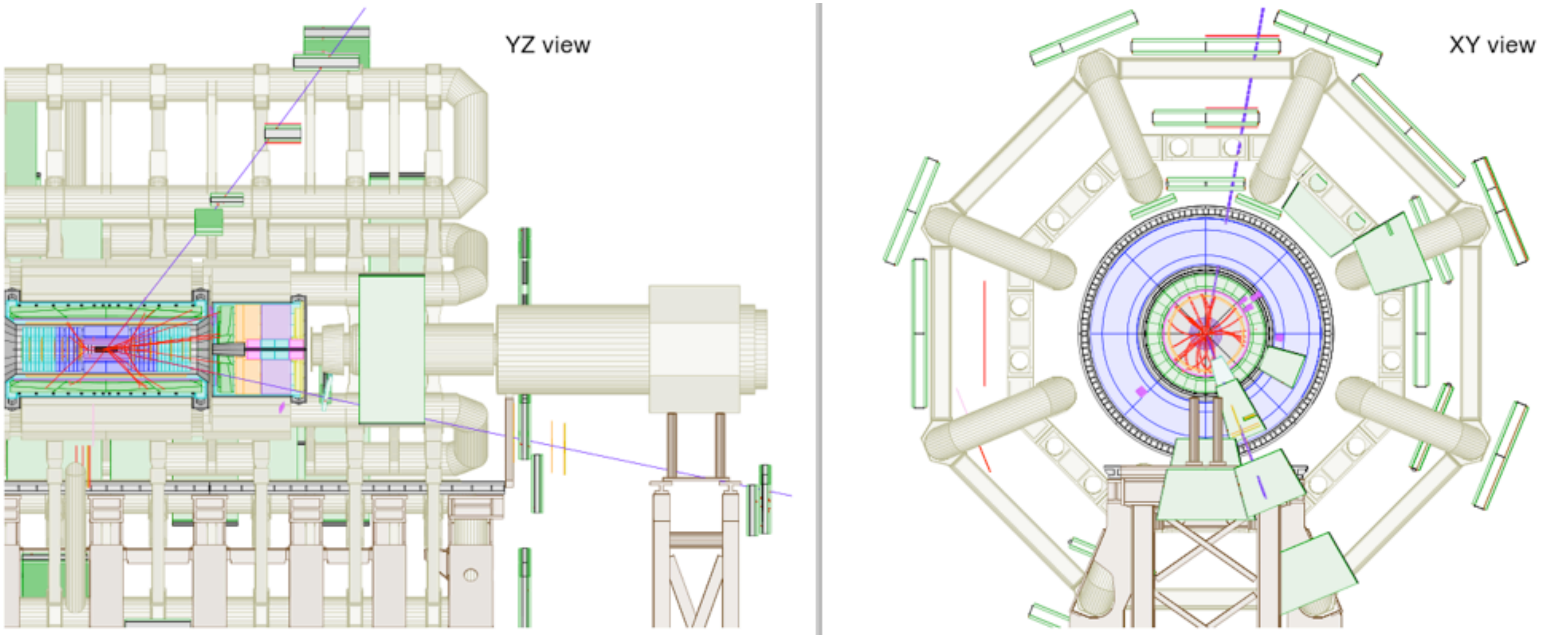






RPC and TGC Trigger Hardware



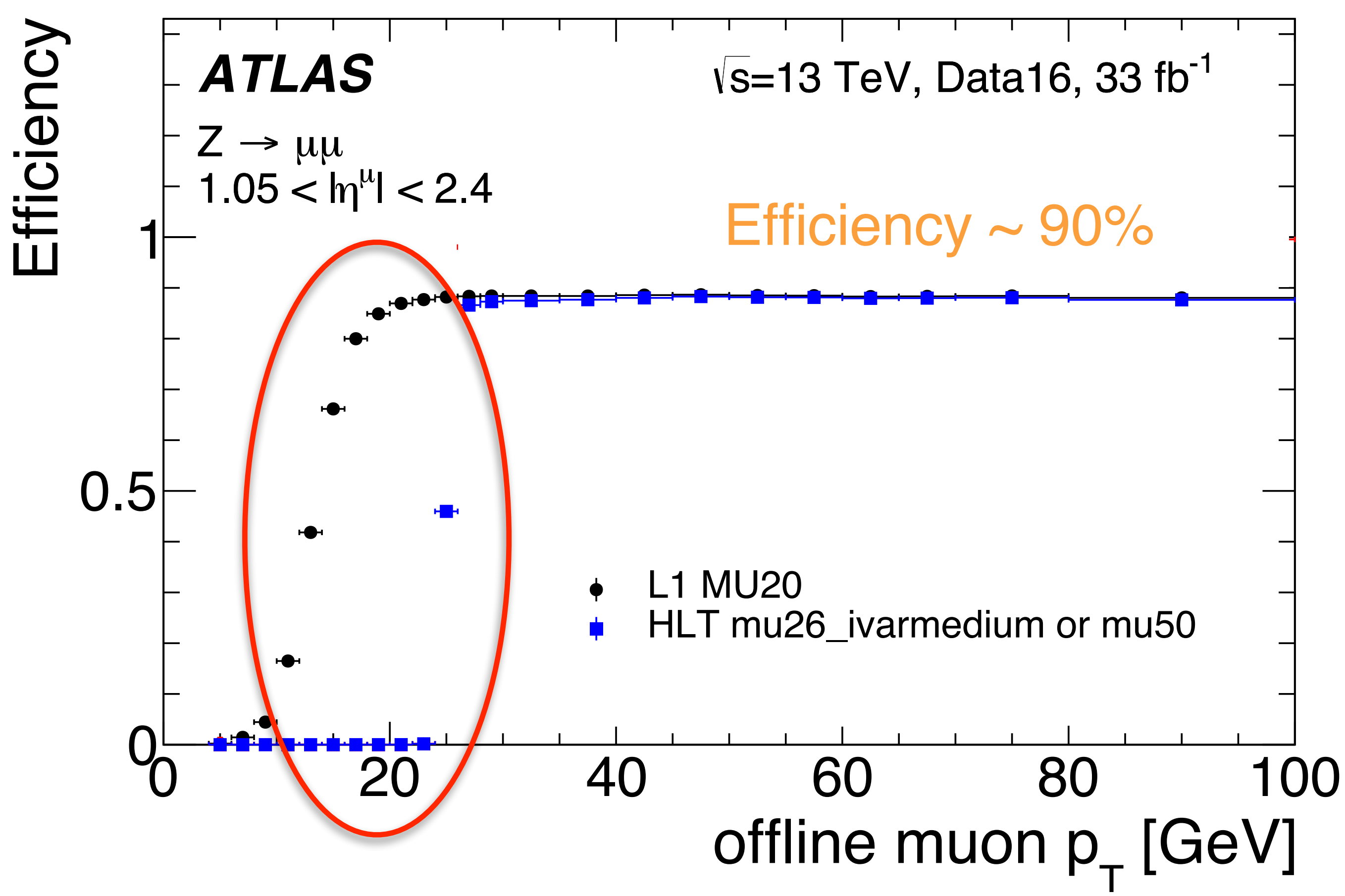


3. Improve Momentum Resolution

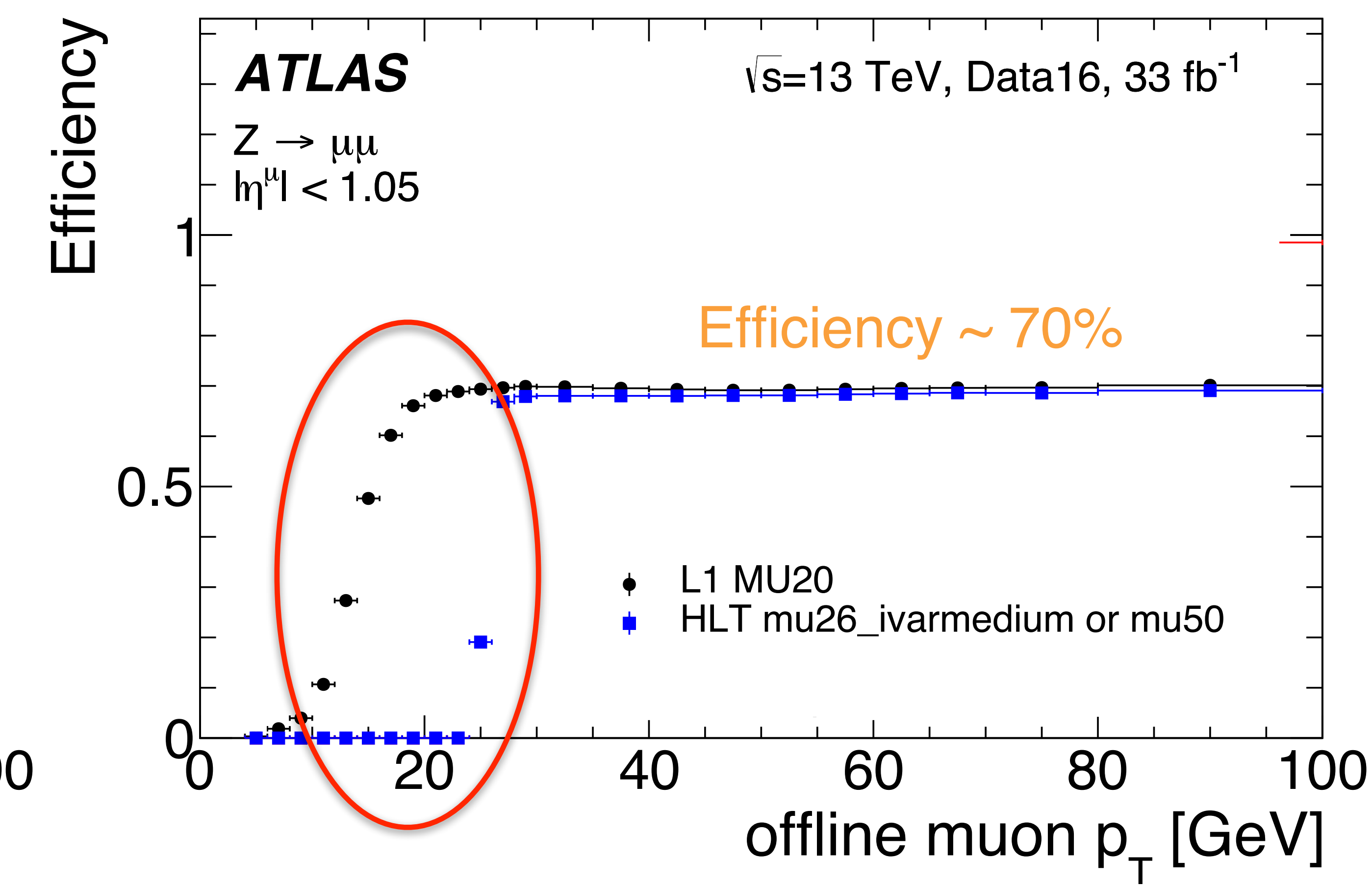
Challenges of the Muon System → Phase 2

Moderate p_T resolution of RPC and TGC chambers - limited spatial resolution

Endcap

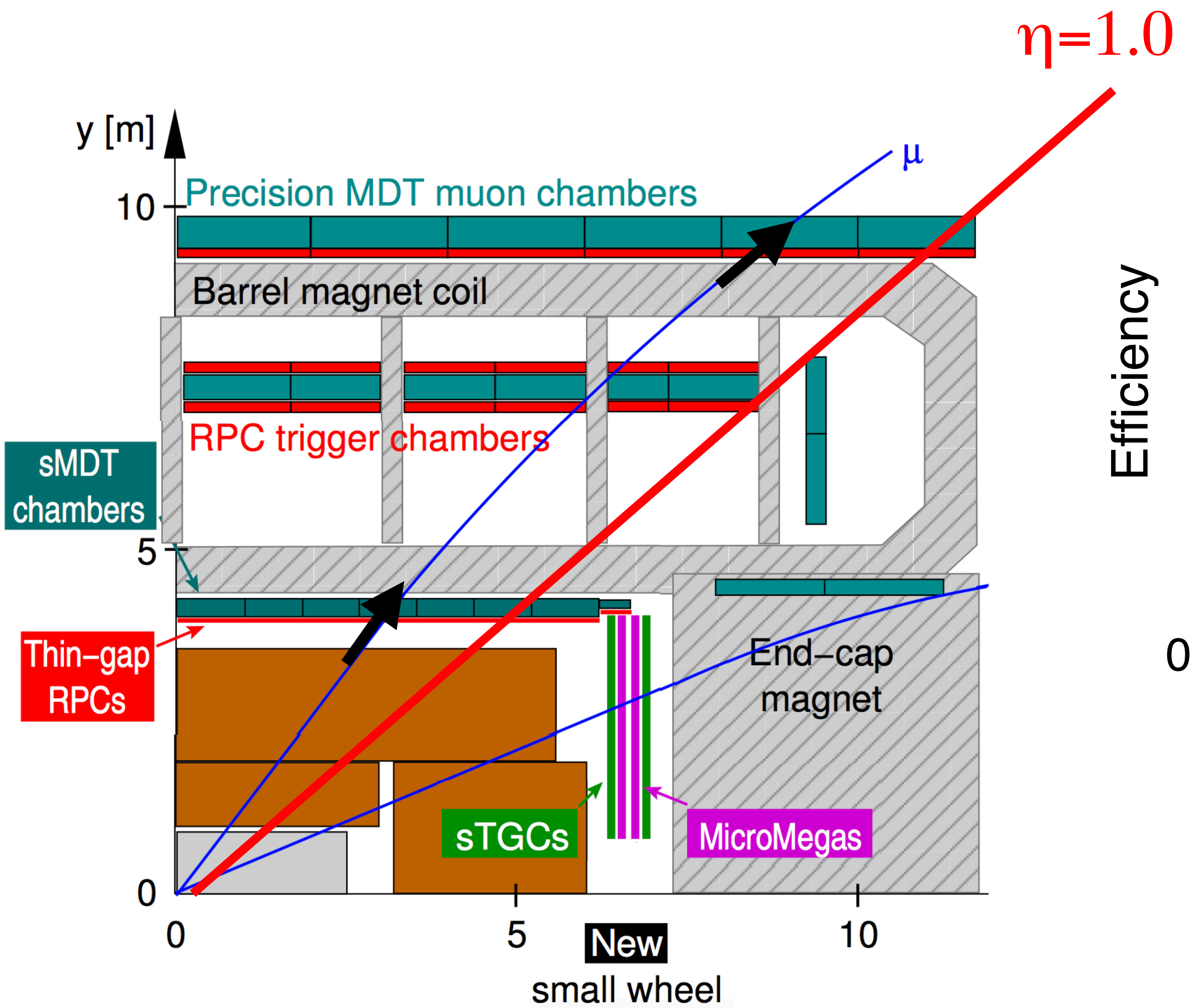


Barrel

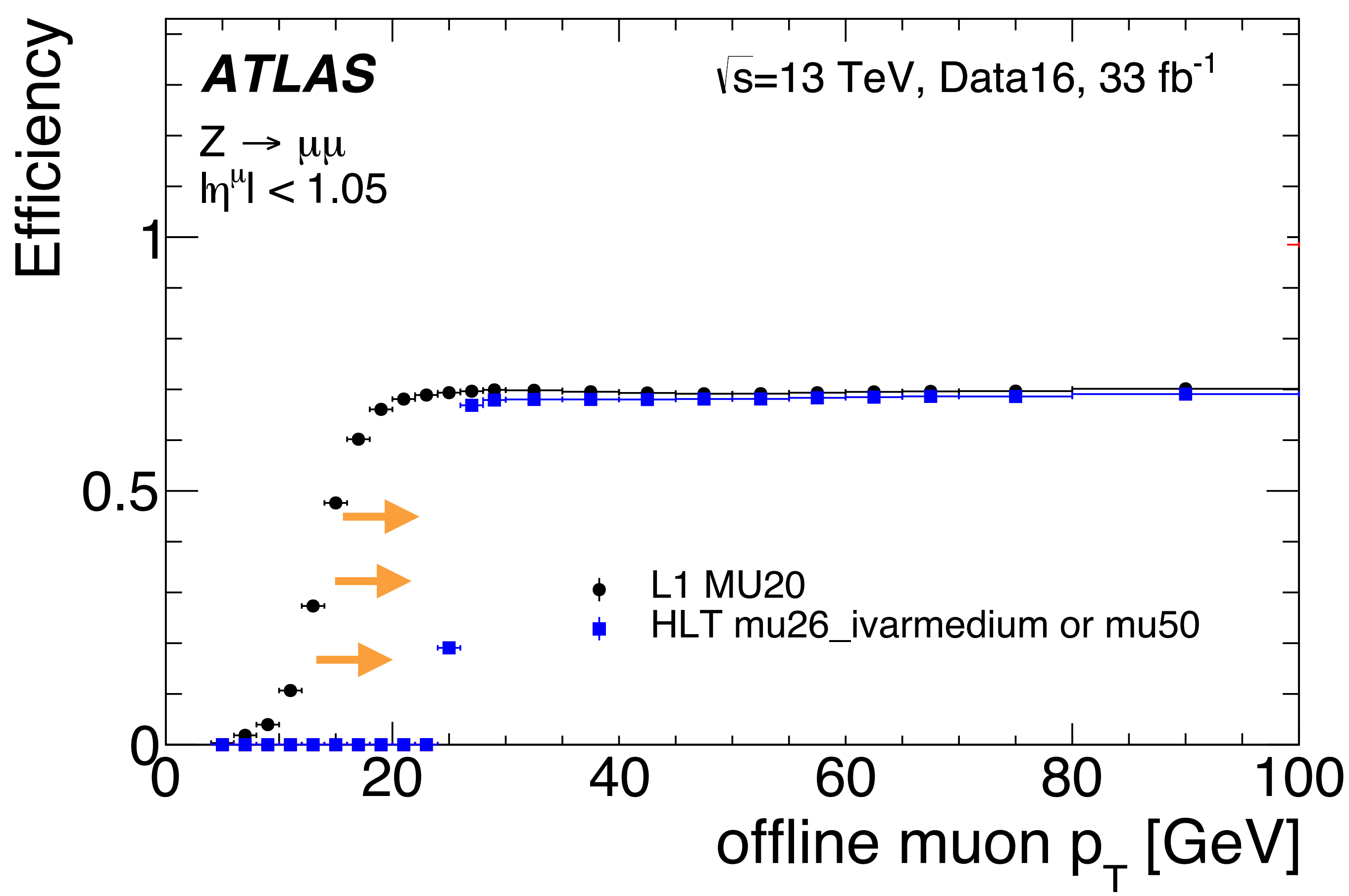


Phase 2 MDT Trigger

Improve the momentum resolution and maintain low rates



Barrel



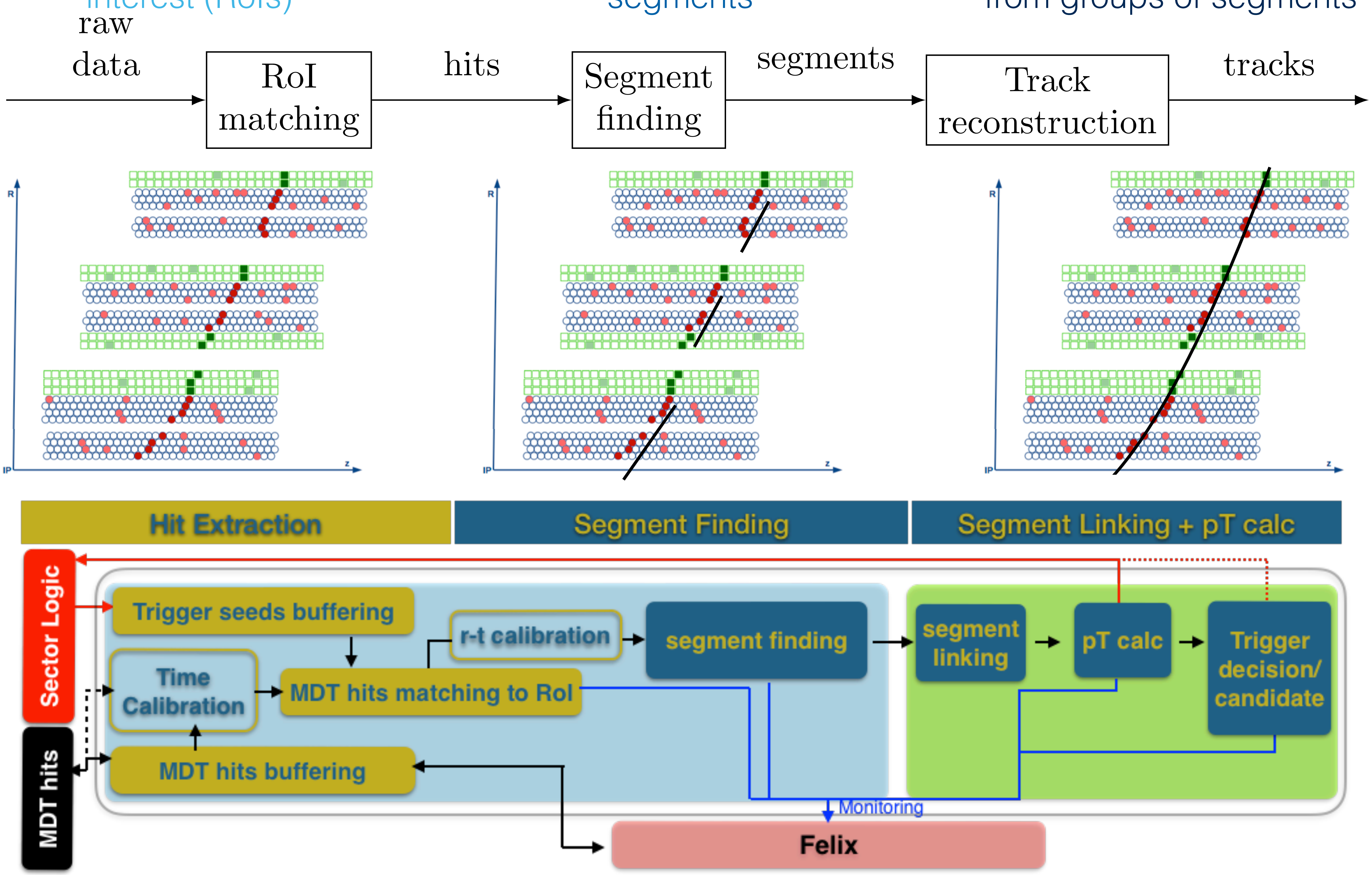
Similar for the endcap

MDT Trigger Concept

1. Hit extraction: matching MDT hits with regions of interest (RoIs)

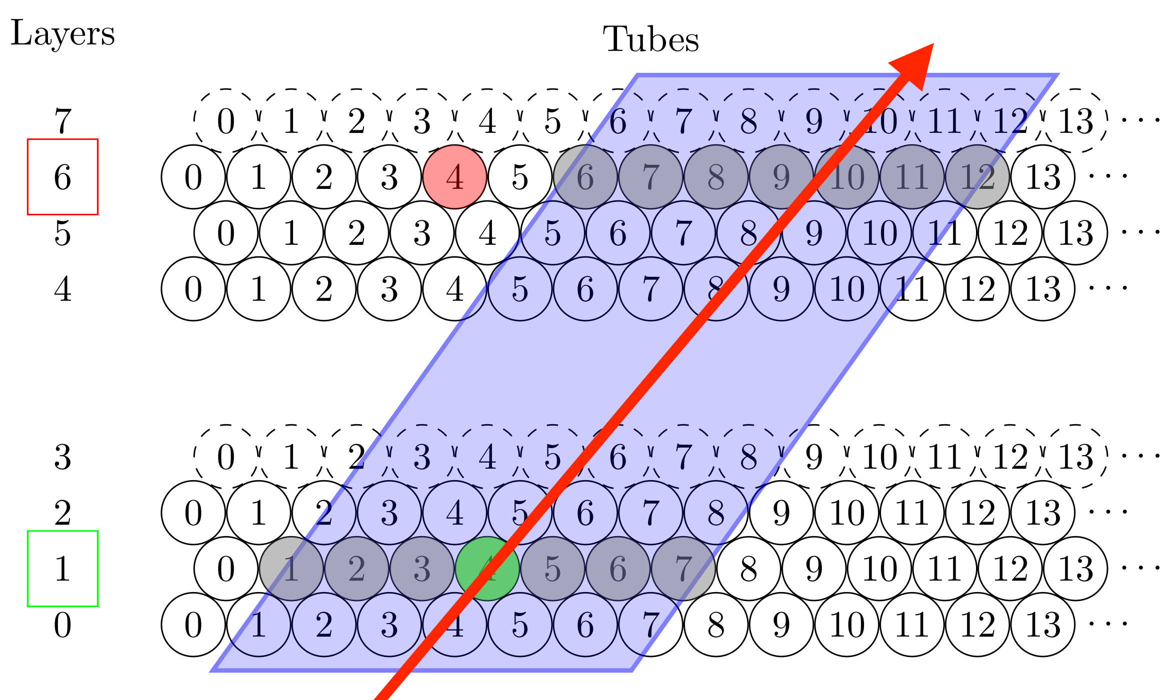
2. Segment finding: grouping of hits into track segments

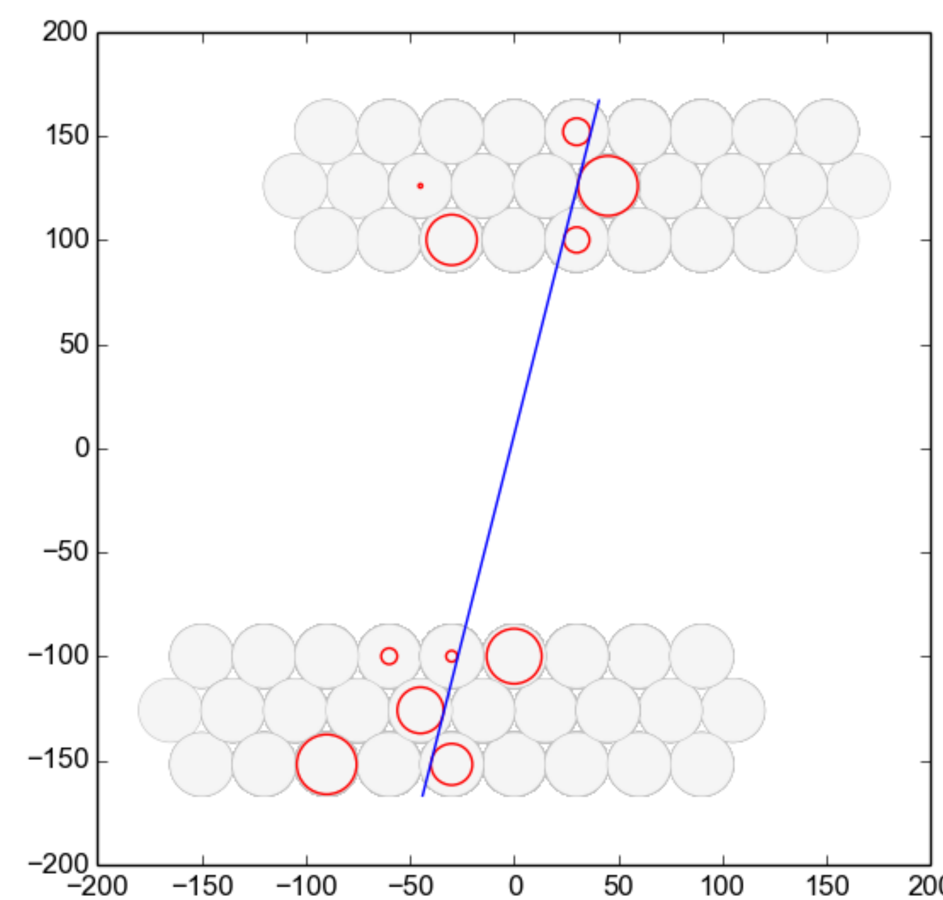
3. Track reconstruction: momentum measurement from groups of segments



MDT Hit Extraction & Segment Finding

- RPC and TGC provide pre-trigger candidates for MDT trigger
  - Reference time and position vector for matching the MDT hits in space and time
  - 2nd coordinate measurement (along non-bending plane)
- MDTs are slow detectors (max drift time ≈800ns) so tracks span many BCs and information from RPC and TGC can be processed before all MDT hits arrive
- Matched hits are calibrated and fit to a line
  - segment is defined is the common tangent line to drift circles
    - Legendre algorithm
    - Tangent method
    - Associative memory



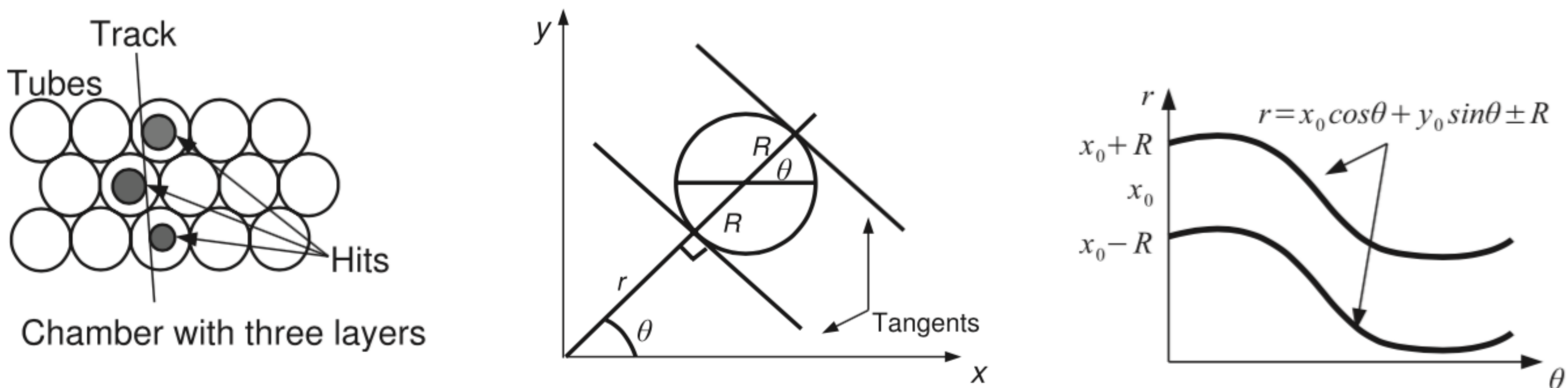


Legendre Transform Segment Finder

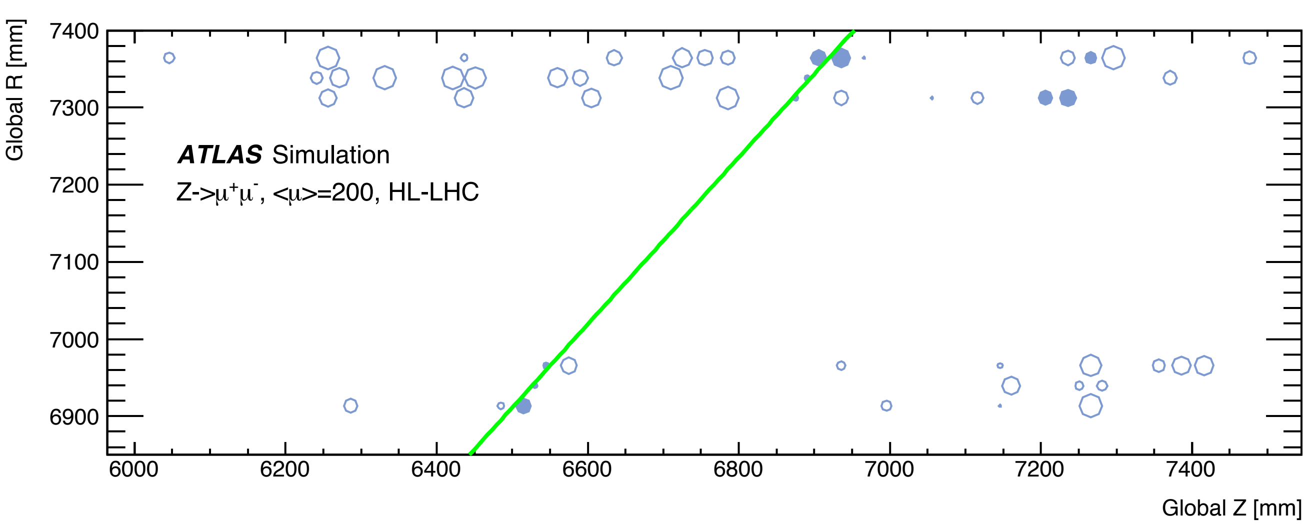
- Use a Hough transform to convert (x,y,r) coordinates to consistent segments parametrized by (R, θ)

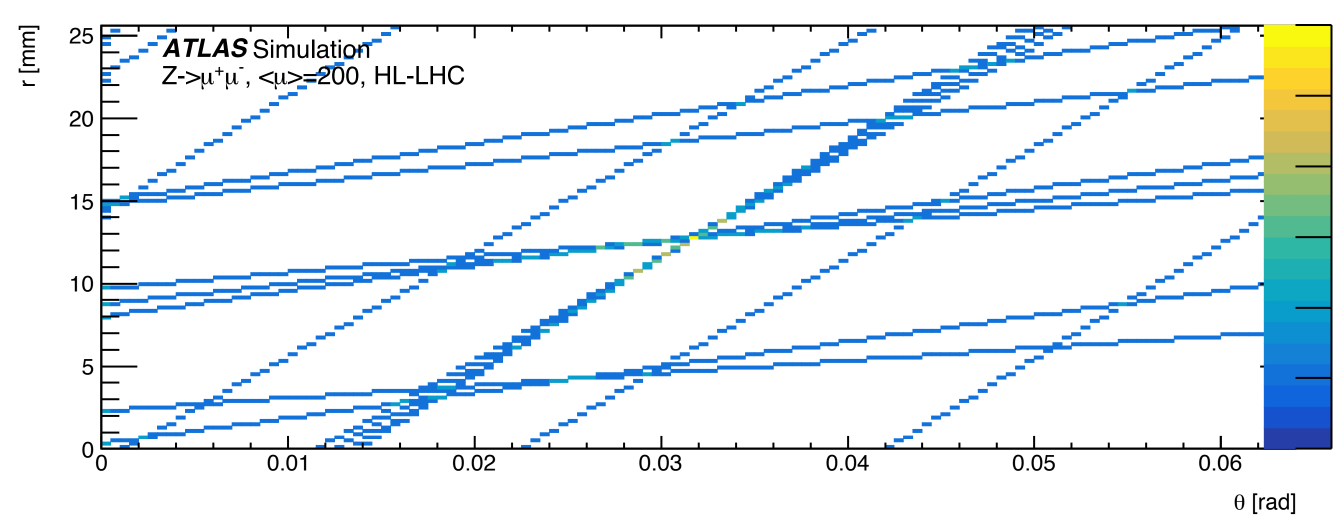
$$R = x \times \cos\theta + y \times \sin\theta \pm r$$

- Segment parameters correspond to maximum in (R, θ)



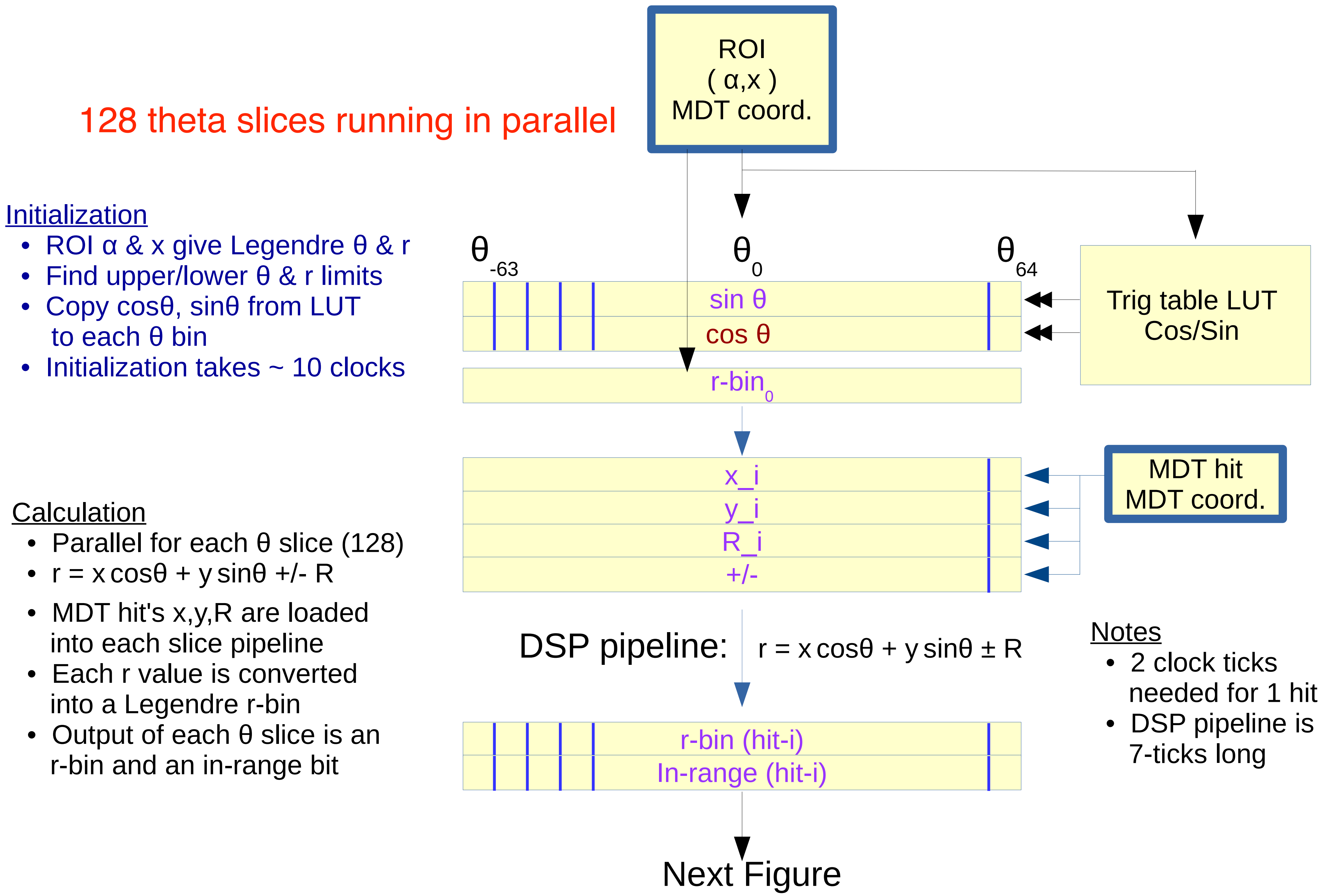
Diagrams from NIM A **592** (2008) 456





Legendre Segment Finder - FPGA Implementation

- R values for O(100) values of θ in the two arcs (for ±r) are calculated in parallel using a LUT and stored in registers in the the FPGA
- The various values of (R, θ) for a hit, as well as all the hits are calculated in parallel → Very fast operation in O(2) clock cycles



Legendre Segment Finder - FPGA Implementation

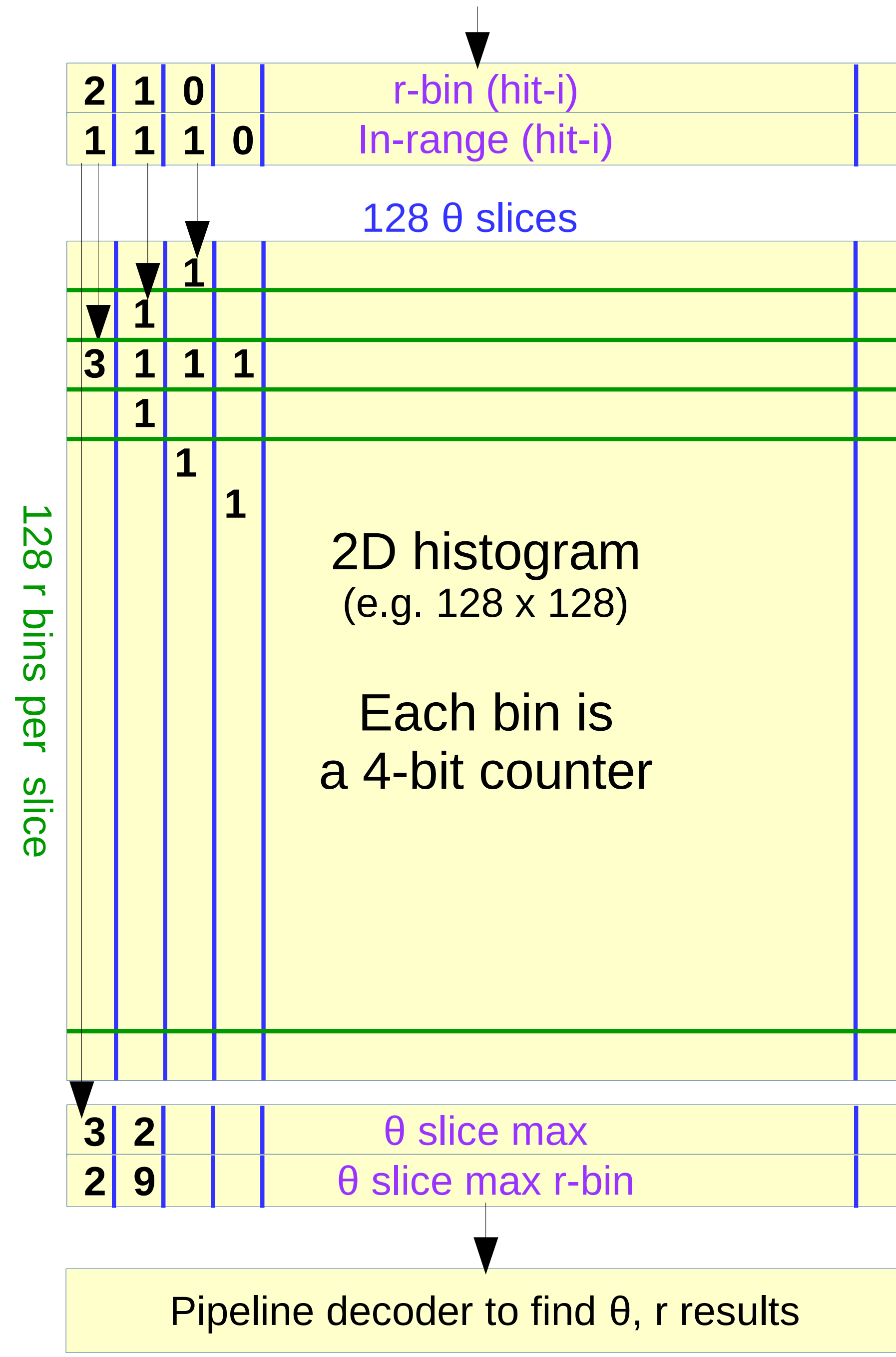
- Local maxima in the register histogram correspond to segments. The segment finding can be done in O(200ns)

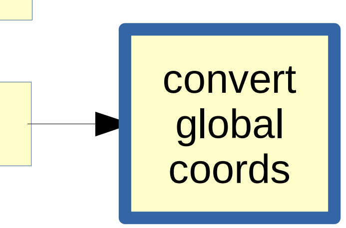
Histogram Building

- Each clock gives a new r-bin for each θ.
- Each θ-slice increments its counter-bin in parallel
- Each θ-slice caches its max-bin/value
- Ideally processes all hits in $7+2*N_{hits}$

Finalization

- Search θ-slice max values to find Legendre max r,θ.
- Decode and convert resulting (r,θ) to global coords
- Finalization takes ~ 10 clocks



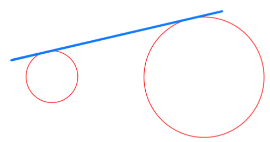


Notes:

- Current design handles one track per ROI but can expand to multiple tracks
- Total latency is about: 25 clocks (70ns) plus 2 clocks (5.6ns)/hit (at 360 Mhz)
- Each bin requires two LUTs plus 4 registers, so a 128x128 histogram requires 32k LUTs and 64k registers

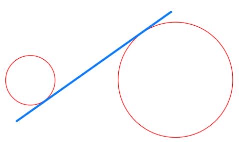
Tangent Method Segment Finder

a)



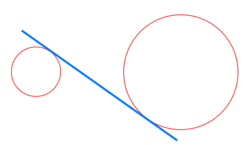
$$m' = \frac{r_2 - r_1}{\sqrt{L^2 - (r_1 - r_2)^2}} \qquad b' = r_1 \cdot \sqrt{1 + m'^2}$$

b)



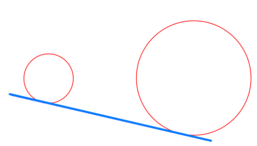
$$m' = \frac{r_1 - r_2}{\sqrt{L^2 - (r_1 - r_2)^2}} \qquad b' = -r_1 \cdot \sqrt{1 + m'^2}$$

c)



$$m' = -\frac{r_1 + r_2}{\sqrt{L^2 - (r_1 + r_2)^2}} \qquad b' = r_1 \cdot \sqrt{1 + m'^2}$$

d)



$$m' = \frac{r_1 + r_2}{\sqrt{L^2 - (r_1 + r_2)^2}} \qquad b' = -r_1 \cdot \sqrt{1 + m'^2}$$

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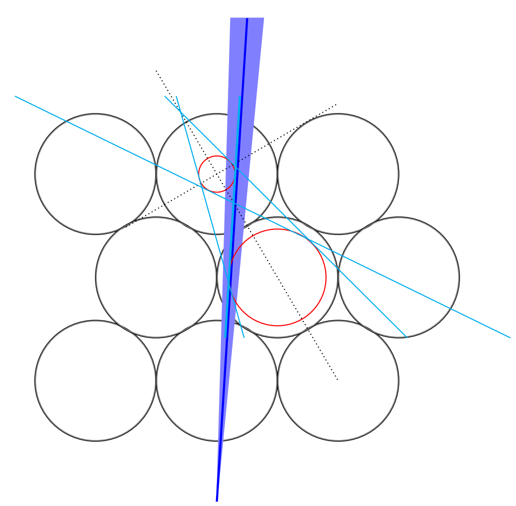
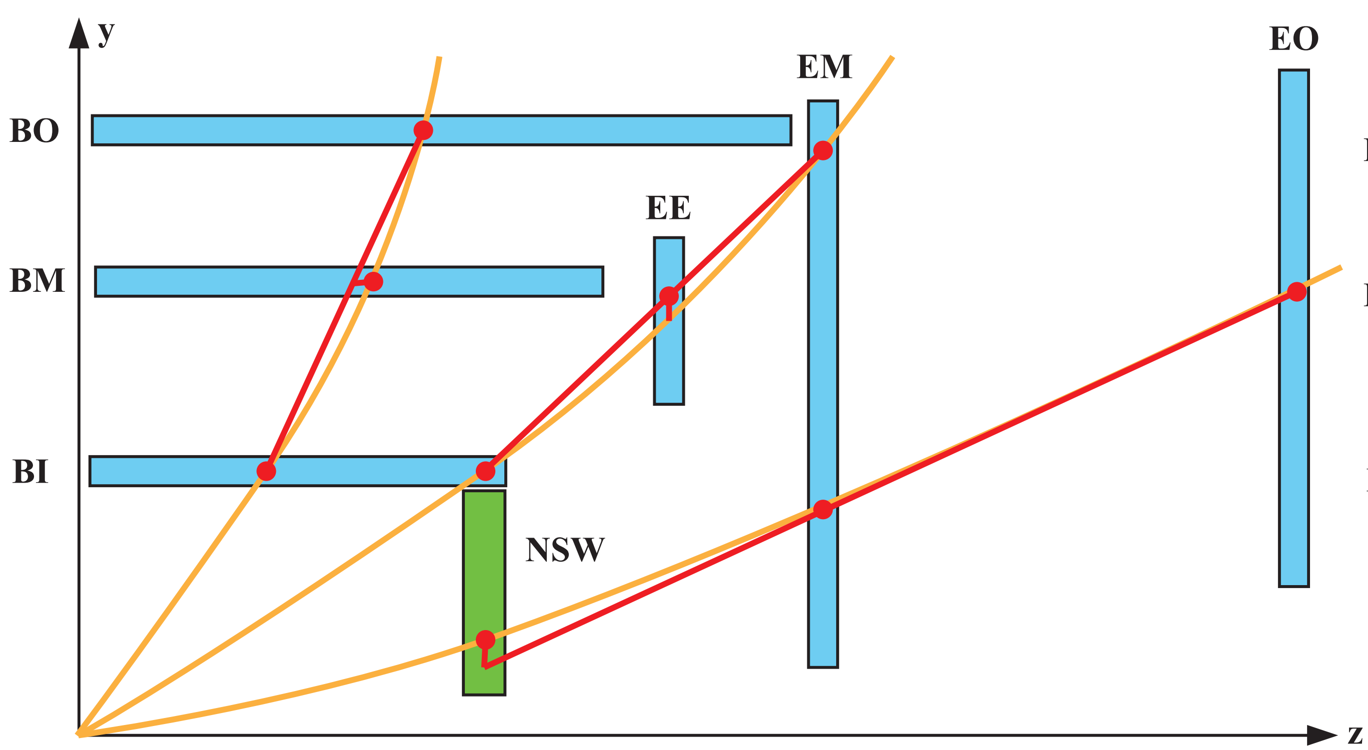


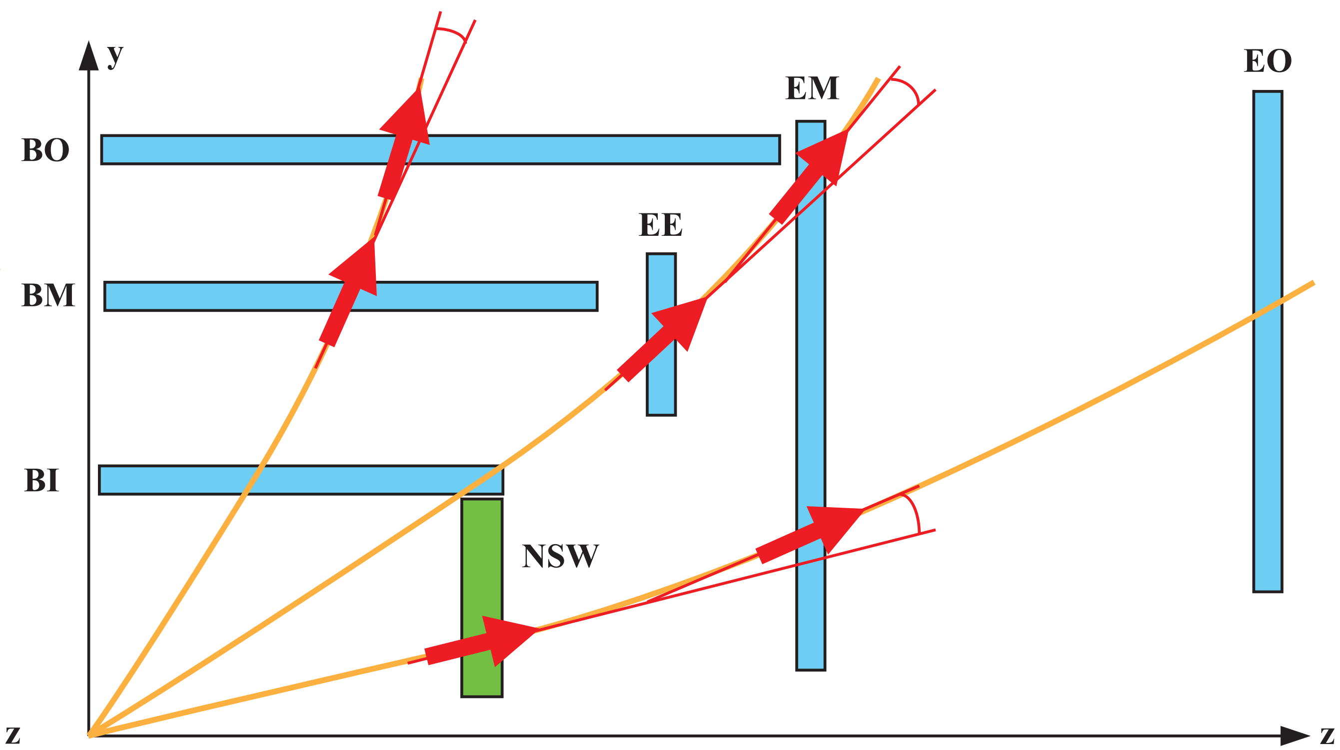
- Method based on the idea that two drift circles have 4 possible tangents → analytic form for the tangent lines
- Observe that only one of the 4 tangents agree with the seed angle from the trigger chamber, the other are way off.

- Simplified tangent algorithm
    - Determine the tangents to all the matched pairs of MDT hits
    - Keep the tangent which is closest in slope to the seed segment
    - Check if the selected segments agree within errors
    - Use the straight line through the positions of the selected segments in their multilayers as reconstructed segment

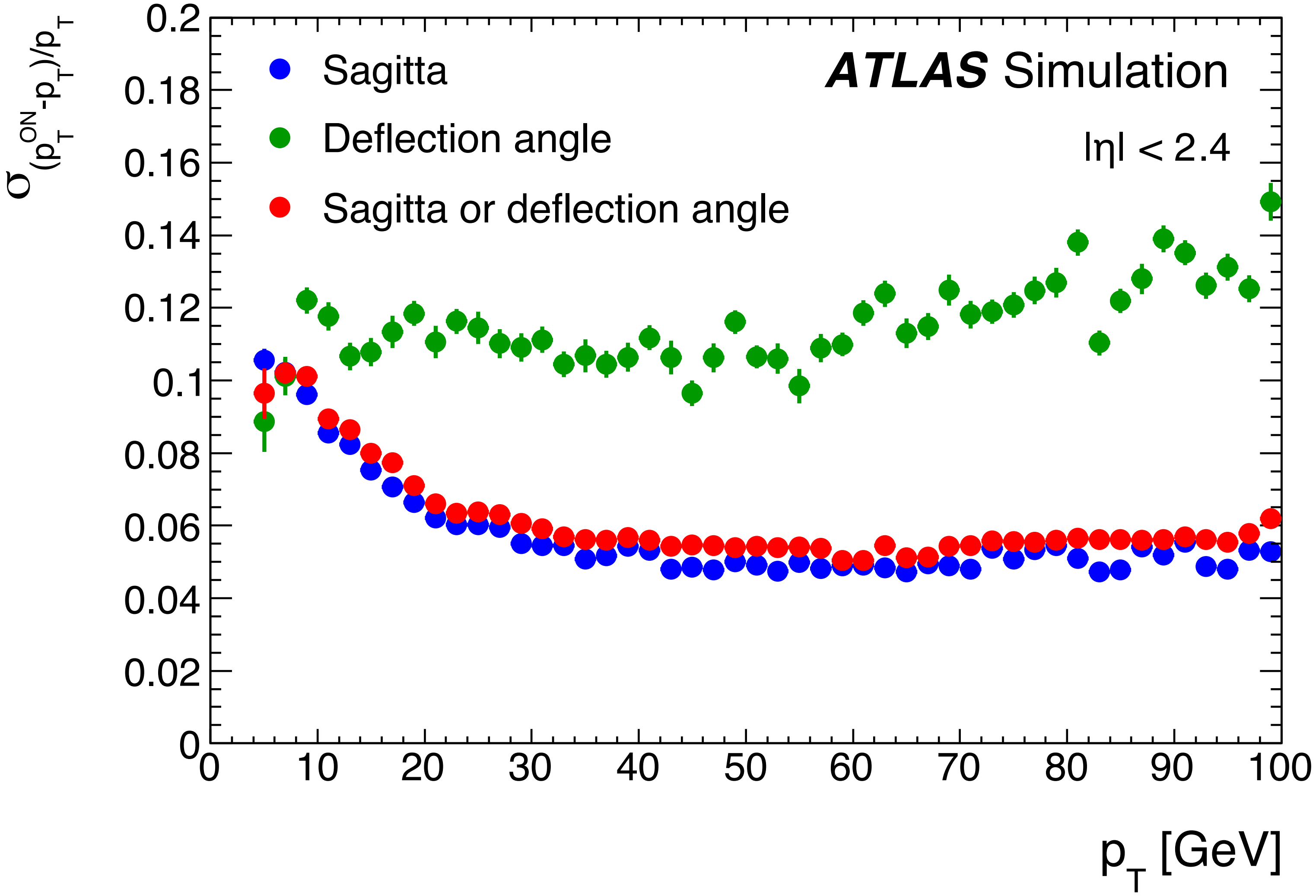
Momentum Determination

- Algorithms proposed to determine muon momentum based on number of segments considered
  - Sagitta: uses segments in 3-stations (73% of muons)
    - measure the sagitta using the position of the segments
  - Deflection angle: uses segments in 2-stations (94% of muons)
    - measure the segment deflection angle
- Precision in both angle and segment position necessary for precise p_T determination





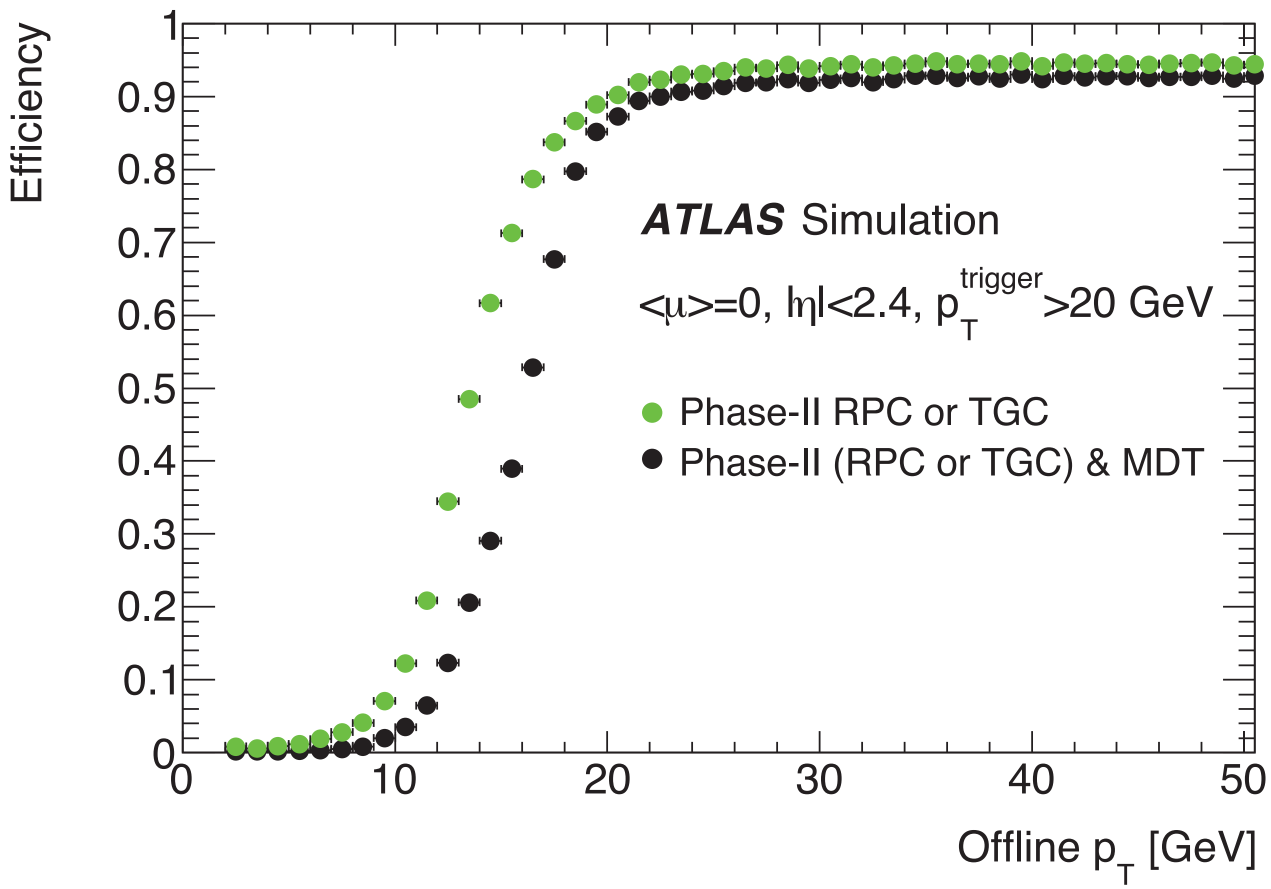
Momentum Determination Performance

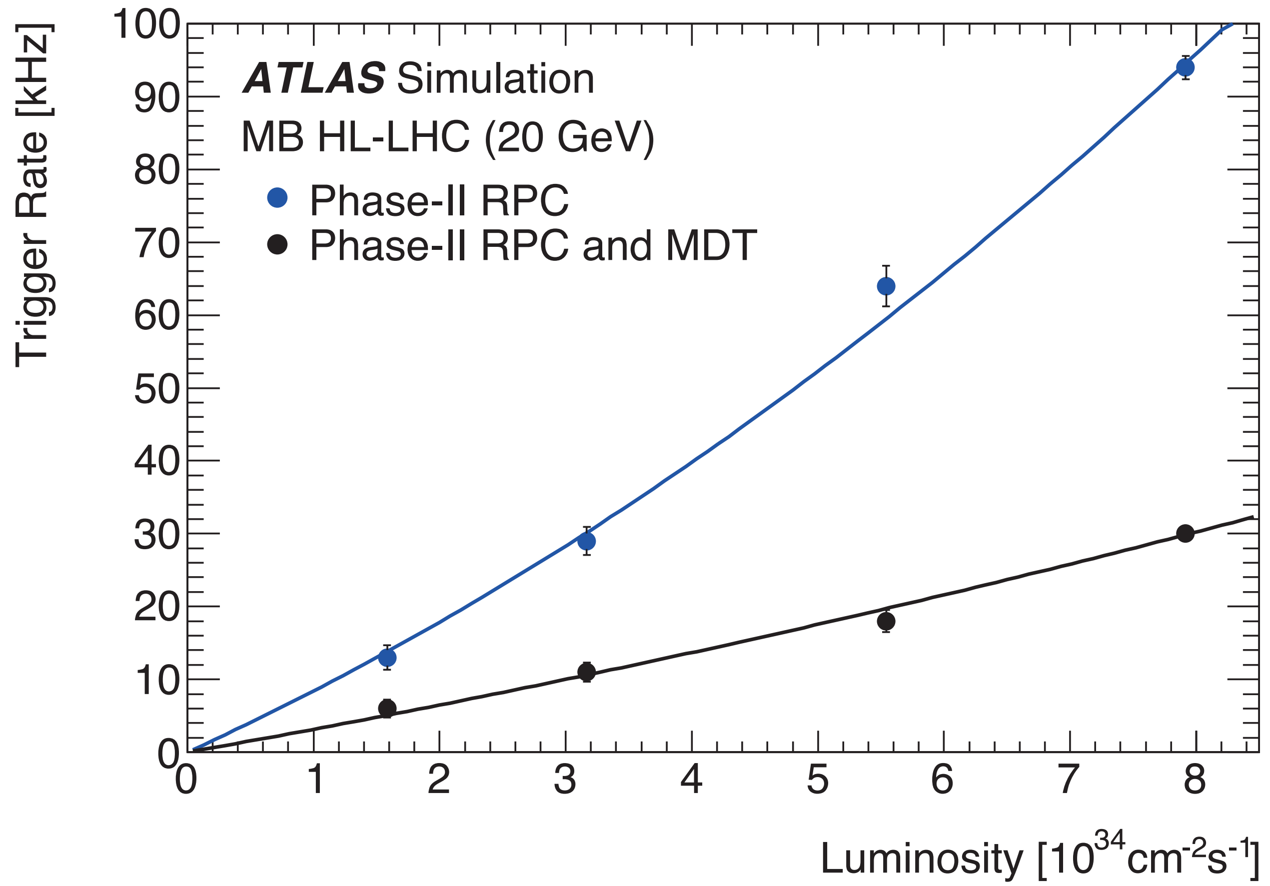


- Use a parametrization to implement algorithm and estimate performance
- Sagitta method has better resolution than deflection angle → combine two methods for maximum efficiency
- Can achieve momentum resolution ~5% above ~20 GeV
- Segment reconstruction precision is with $\sigma_r \leq$1mm and $\sigma_\theta \leq$1 mrad

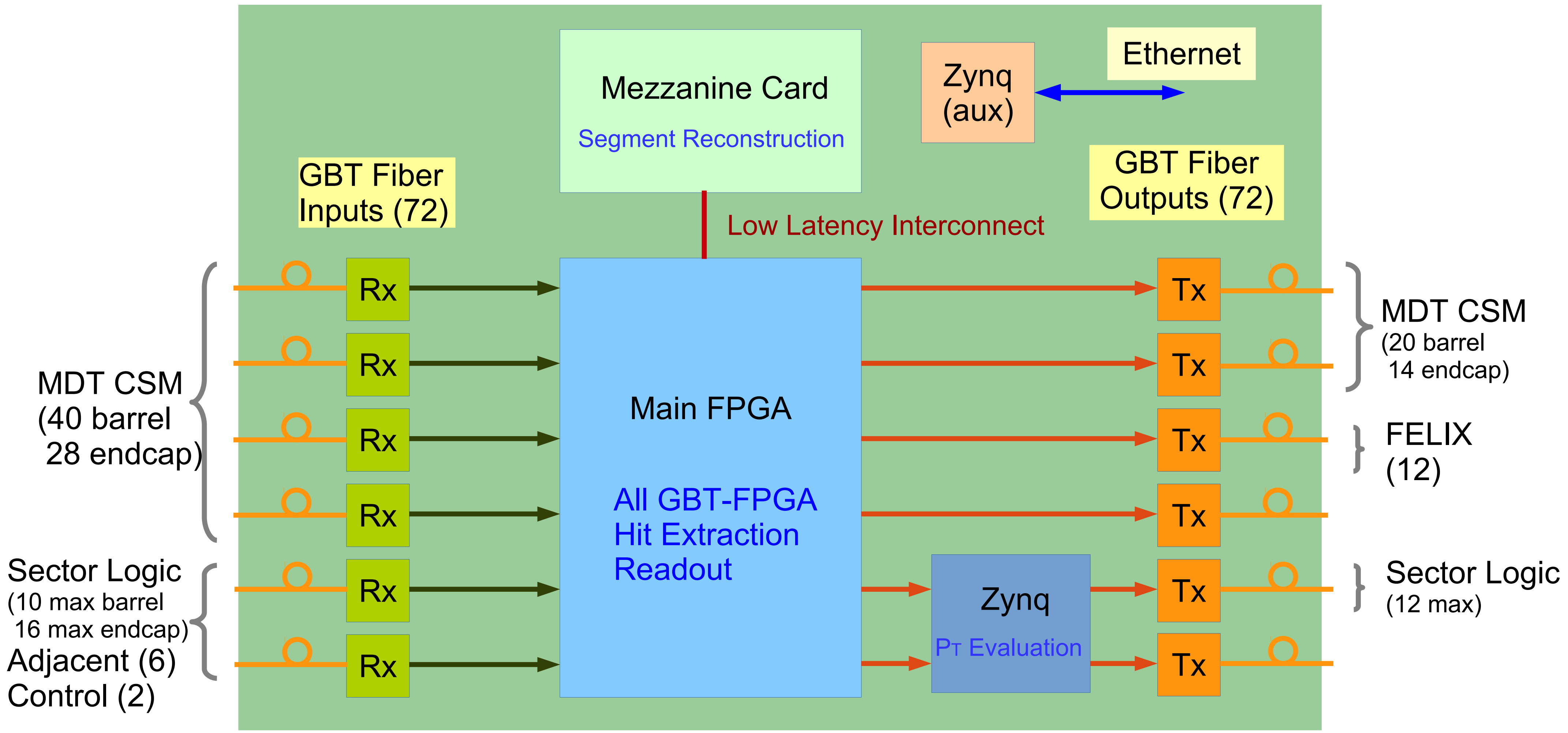
MDT Trigger Performance

- Increased momentum resolution sharpens the turn-on curve and reduces rates
- Rate reduction mainly from low quality RPC coincidences (e.g. BIBO) which are suppressed with the MDT requirement





MDT Trigger Processor - Conceptual Hardware Design

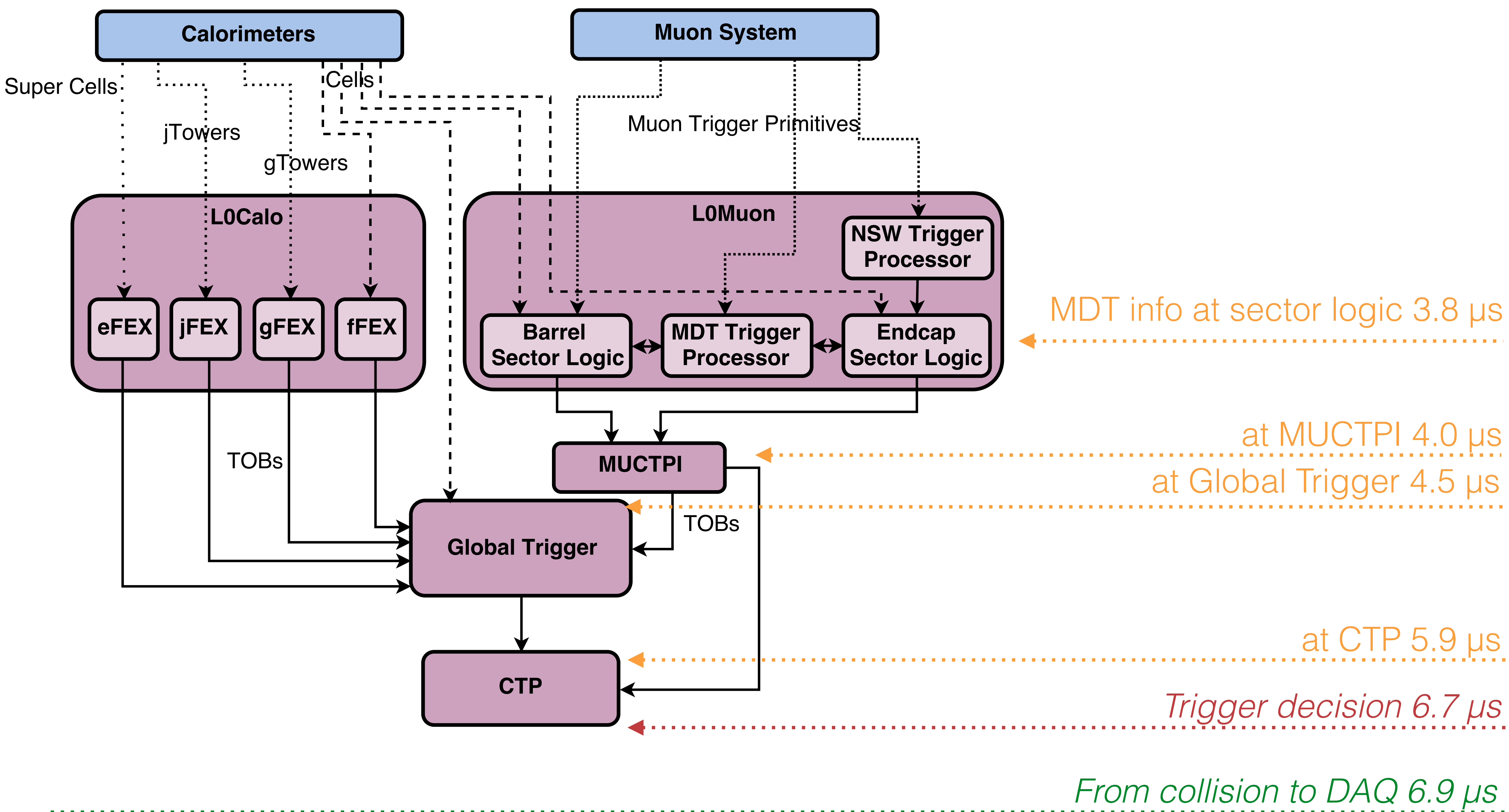


- ATCA blade with GBT (or lpGBT) with 4.8Gb/s (or 9.6Gb/s) links
- Following ATLAS MDT segmentation one MDT trigger processor handles 1/16 ϕ sectors
  Separate also in Barrel/Endcap regions and A/C side
    - 64 trigger processors in total for the full MDT system
    - Max 18 MDT chambers per trigger processor

Trigger Latency Summary

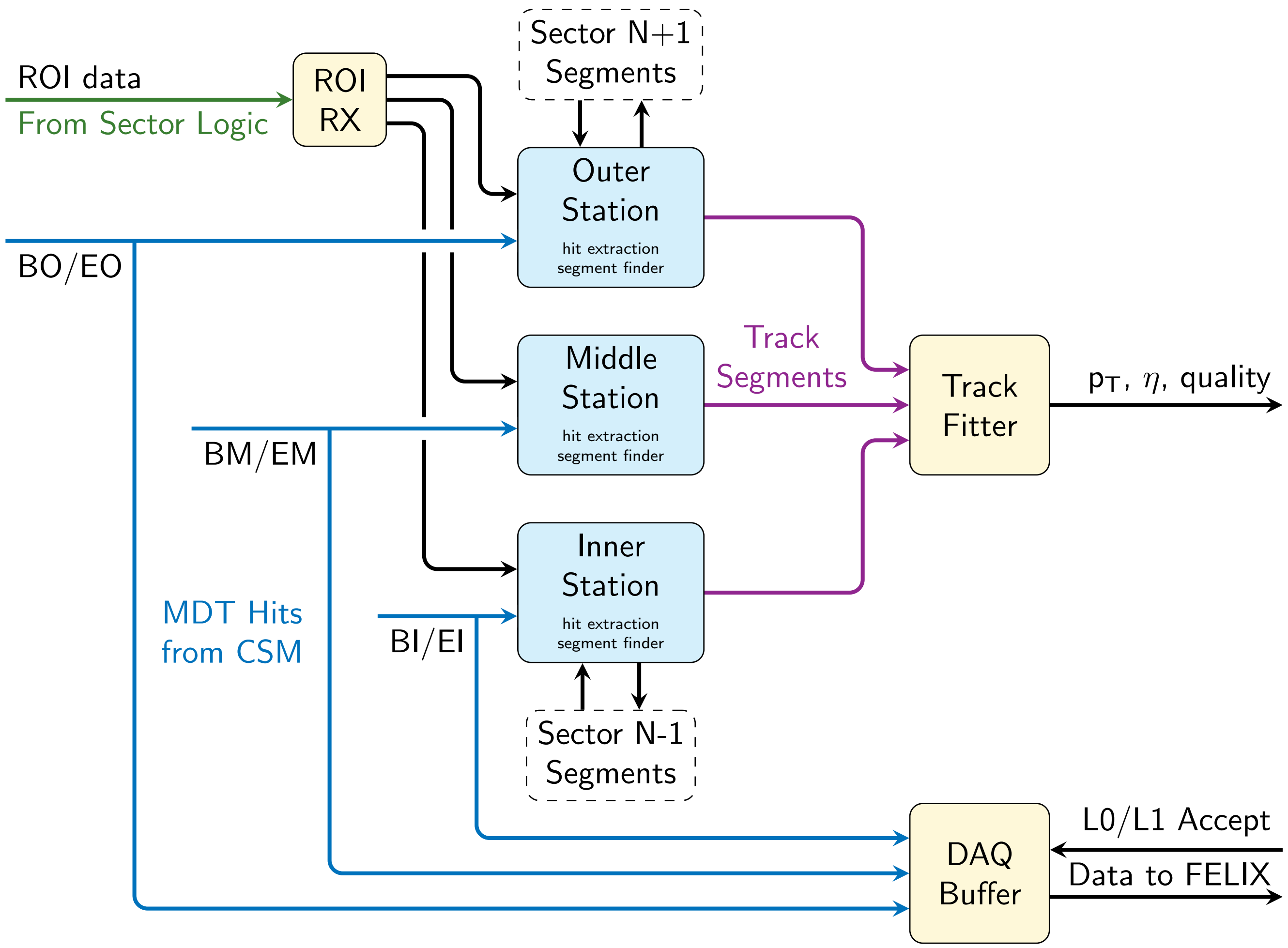
Overall latency comes from muons

→ MDTs are the slowest detectors and drive the latency envelope



Phase 2 Muon Trigger Latency Estimate

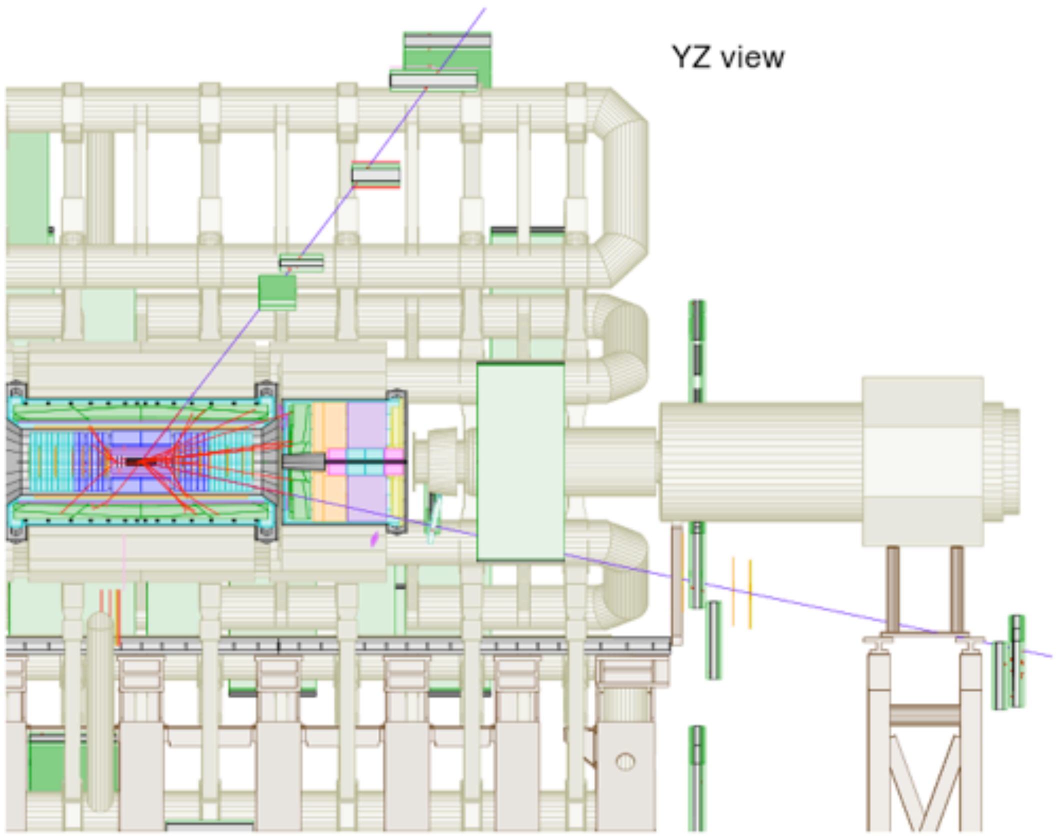
- Performed detailed latency estimate of full MDT electronics chain in HDL
  - Implemented full logic and count clock-ticks
- Estimate includes front-end electronics, segment finding, transfer of data, etc

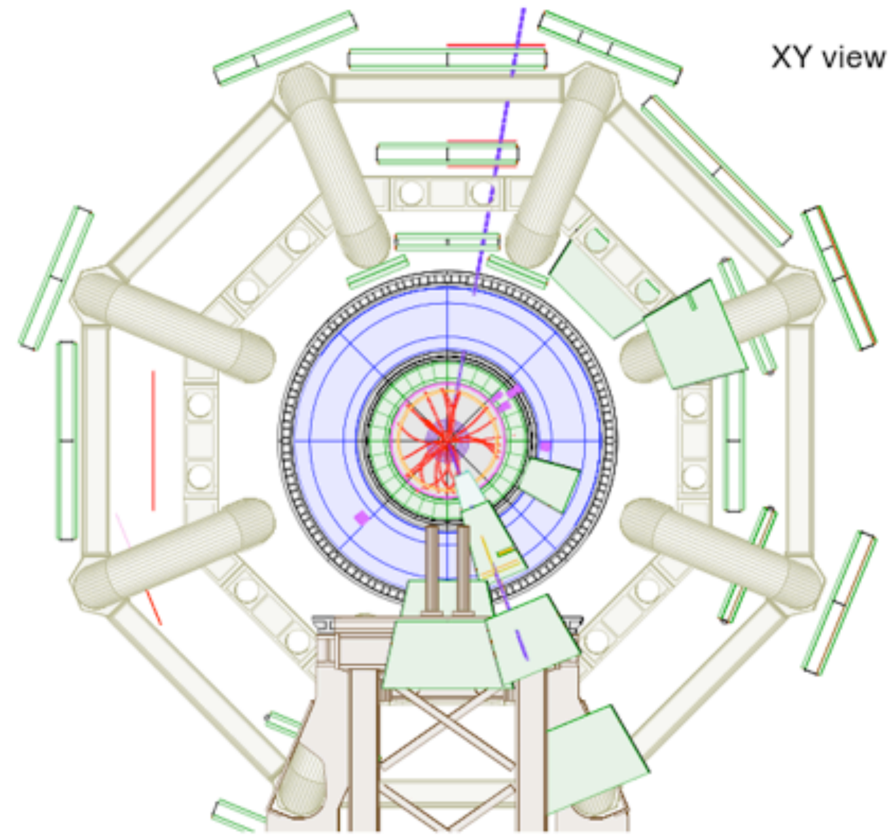


Description	latency [ns]	total latency [ns]
Earliest MDT hit signal arrival		609
Sector Logic track candidate arrival		1785
Latest MDT hit signal arrival		2357
Decoding and domain crossing	100	2458
Buffering	967	3424
Hit extraction	8	3432
Segment finding	128	3560
Transverse momentum evaluation and selection	75	3635
Optical link to sector logic (10m)	175	3810

total 3.8 μs

There is a delay in the processing of MDT hits because first hits arrive around 609 ns, but the sector logic candidate arrives only about 1785 ns

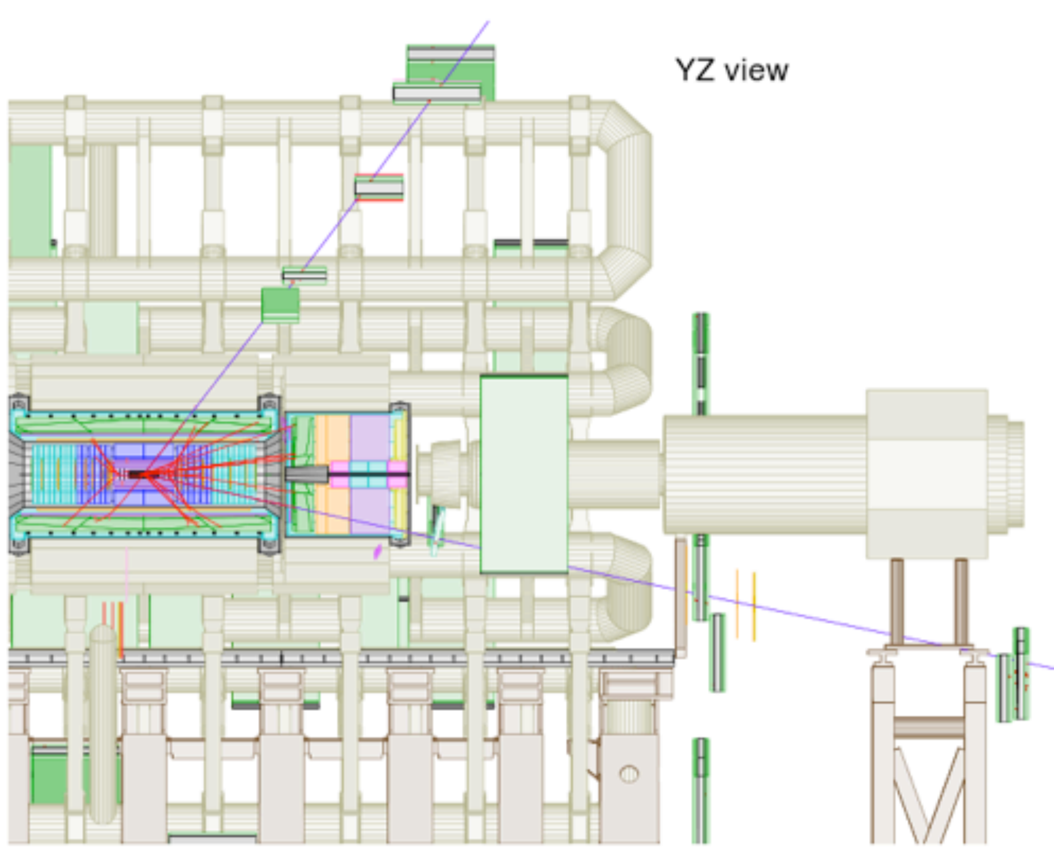


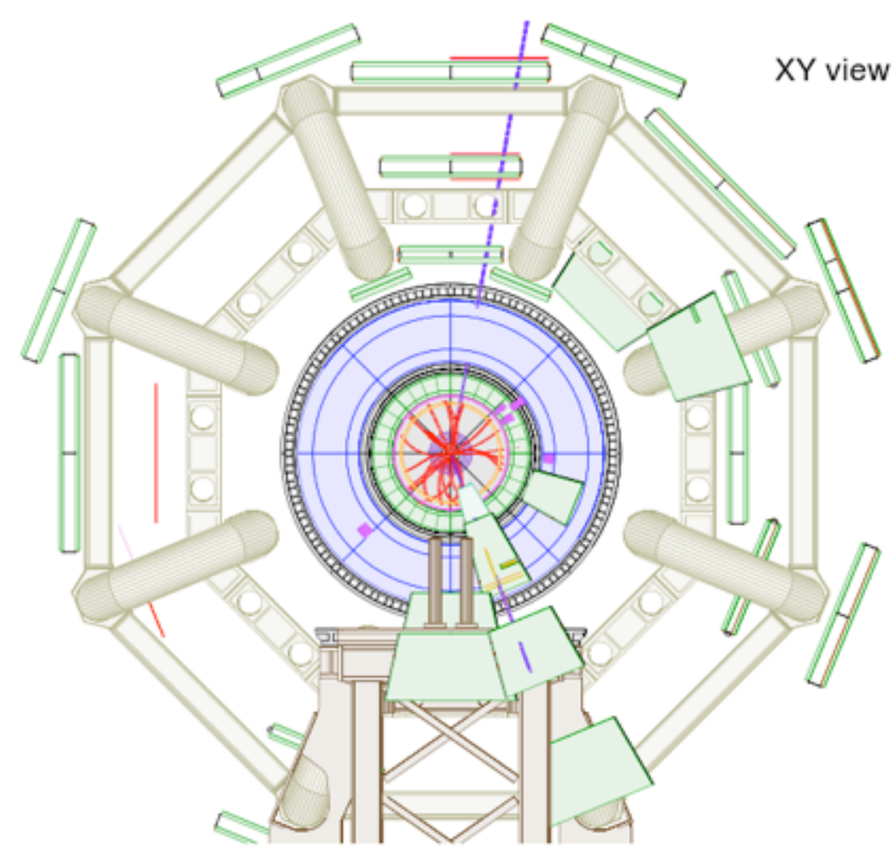


Future Possibilities

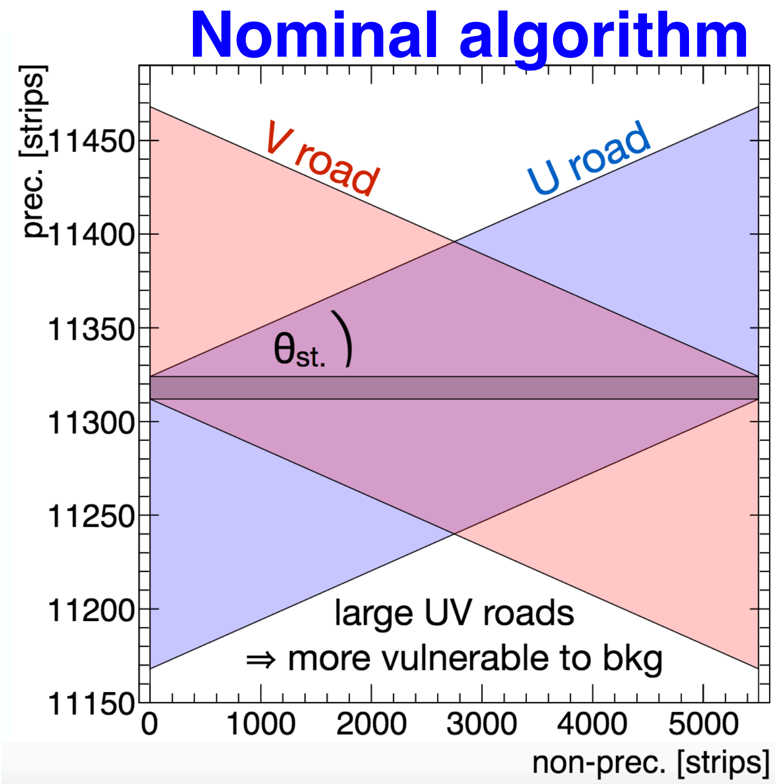
Machine Learning Approaches

- In the muon triggers because of the complexity of ATLAS detector (e.g. magnetic field) or the complexity of the process, some problems depend on many variables and are hard to parametrize
- These are prime candidates for machine learning methods
- Examples of two problems that may be approached in this way
    - Momentum determination
    - Rejection of background hits

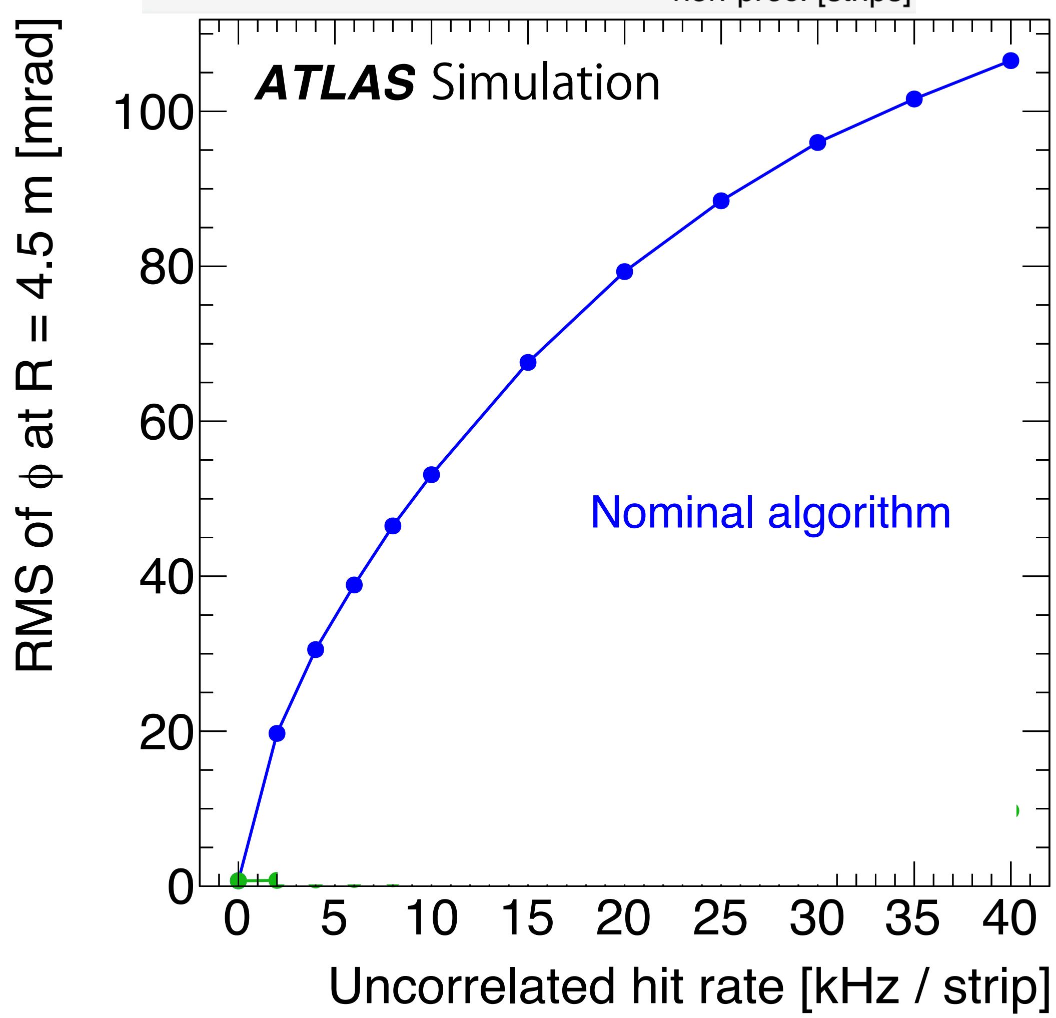


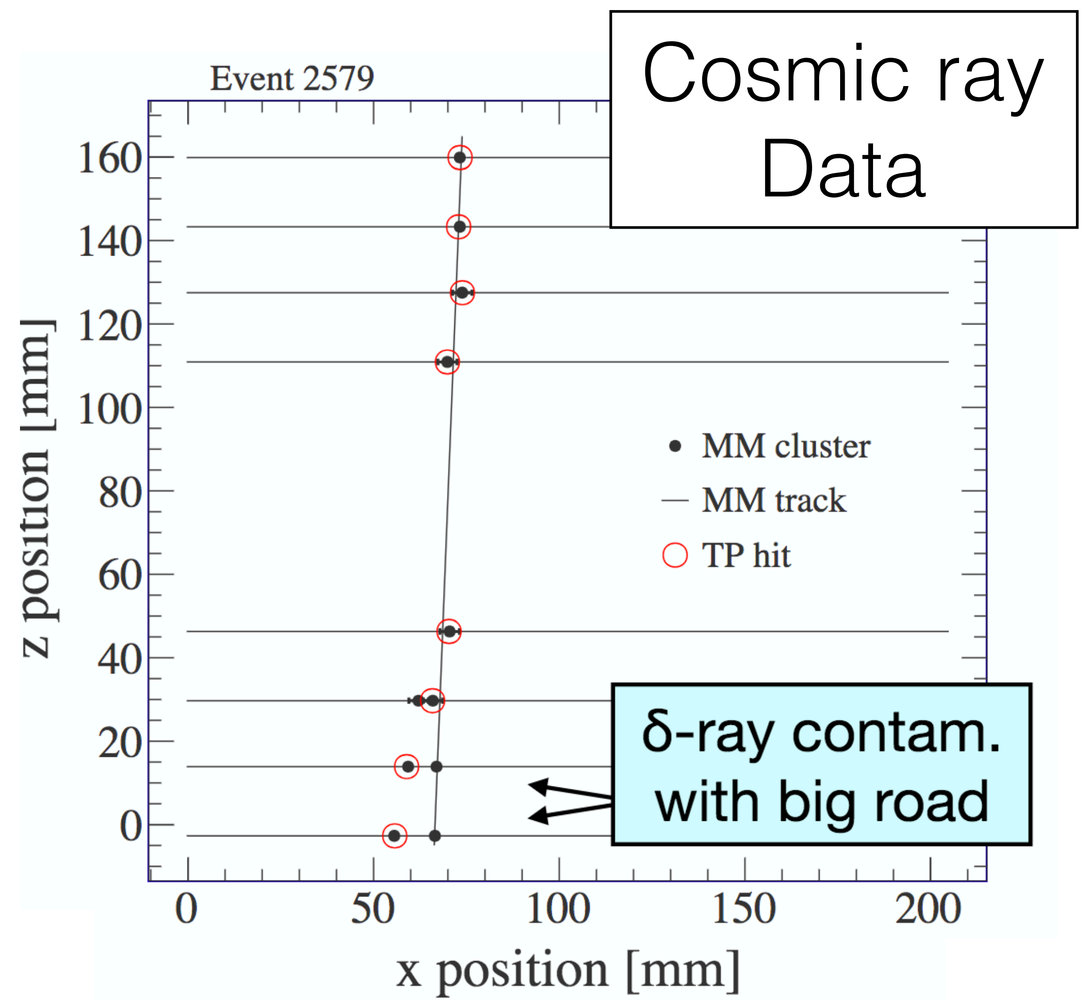


Rejection of Background Hits



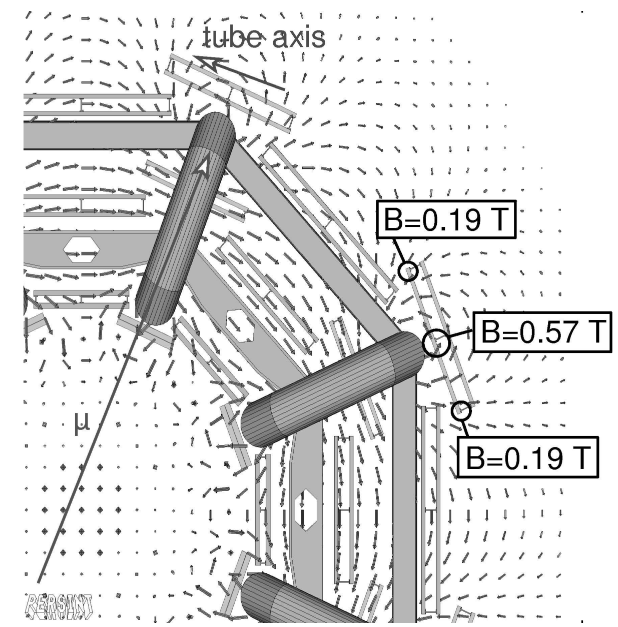
- Example from MM trigger
- Large impact of backgrounds on performance for current algorithm
  - Affects precision, efficiency and rates
- An algorithm trained using machine learning techniques could determine if hits look like signal or background

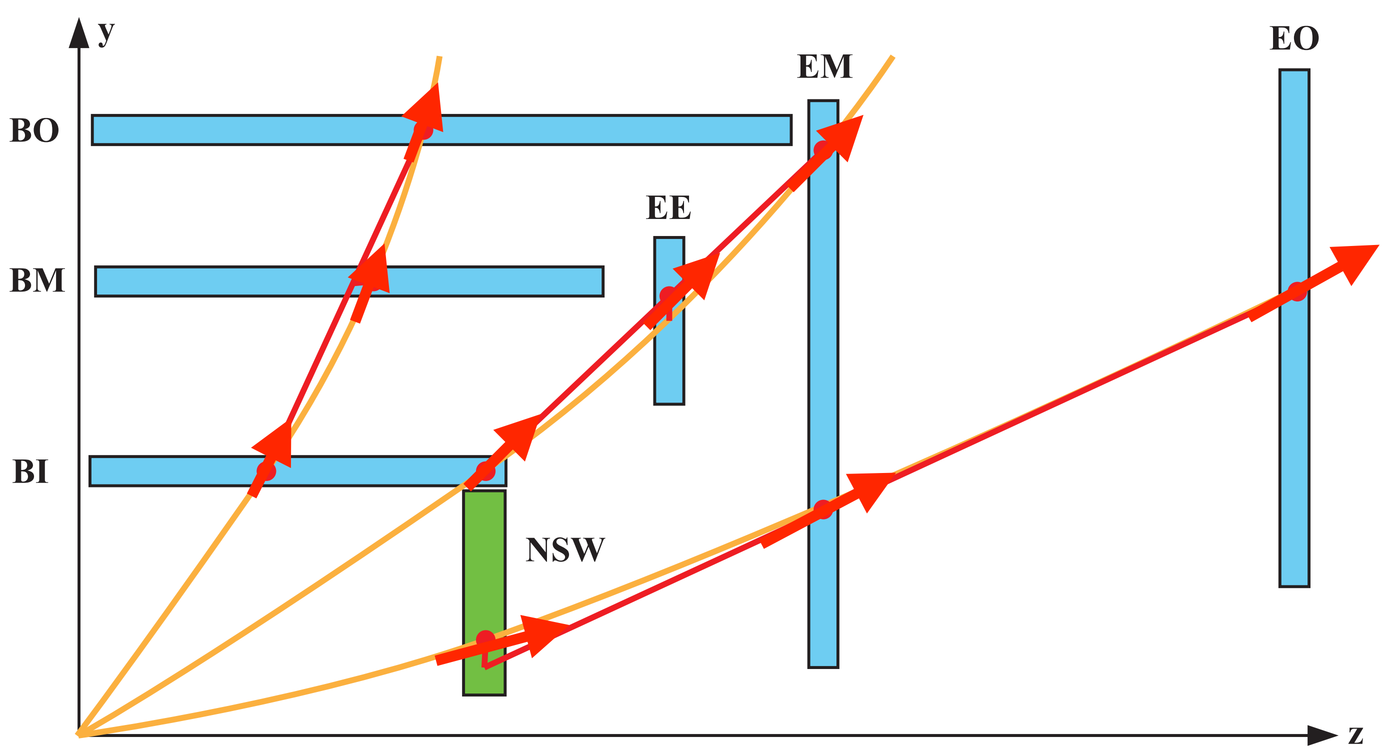


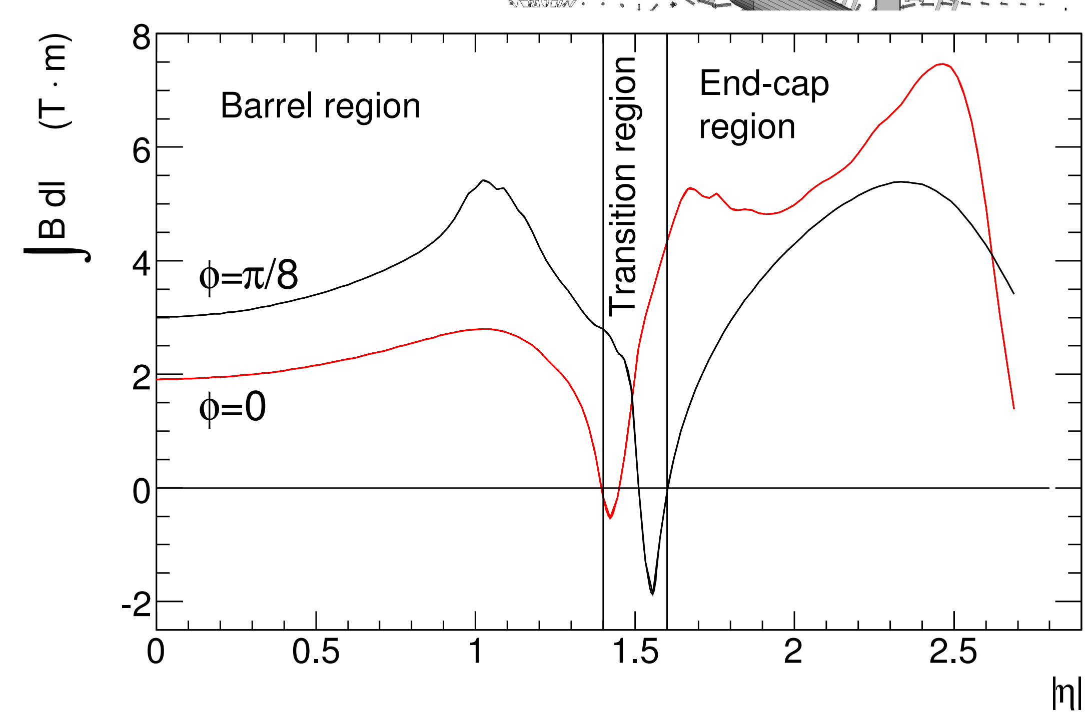


Momentum Determination

- Parametrization of the momentum is complex due to several effects
  - Inhomogeneous magnetic field
  - Material
- A machine learning regression could be used for a better estimation of the momentum
- CMS has an example of an implementation of such a method for the muon momentum determination in the endcap (CR -2017/357)

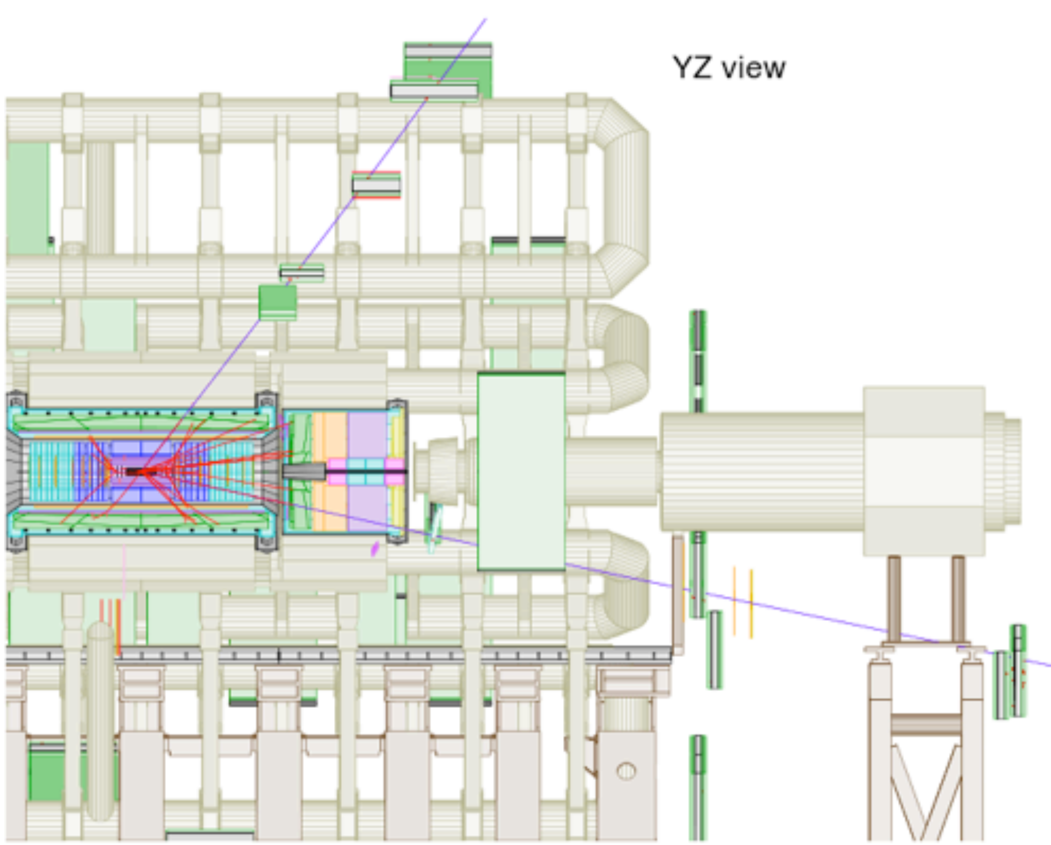


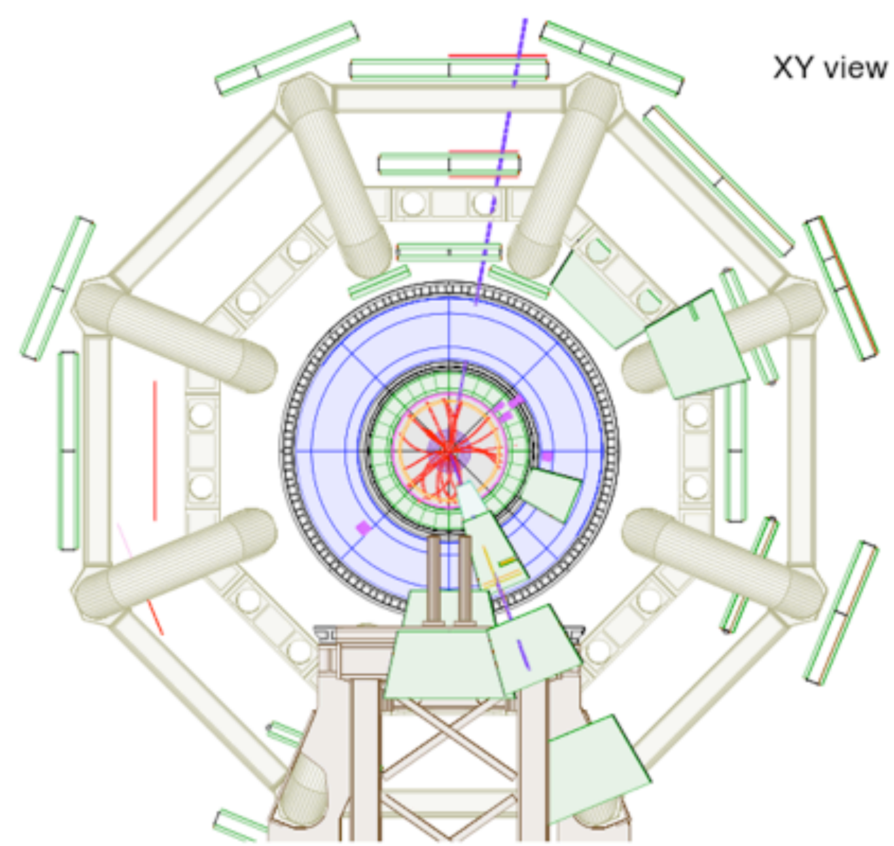




Conclusions & Outlook

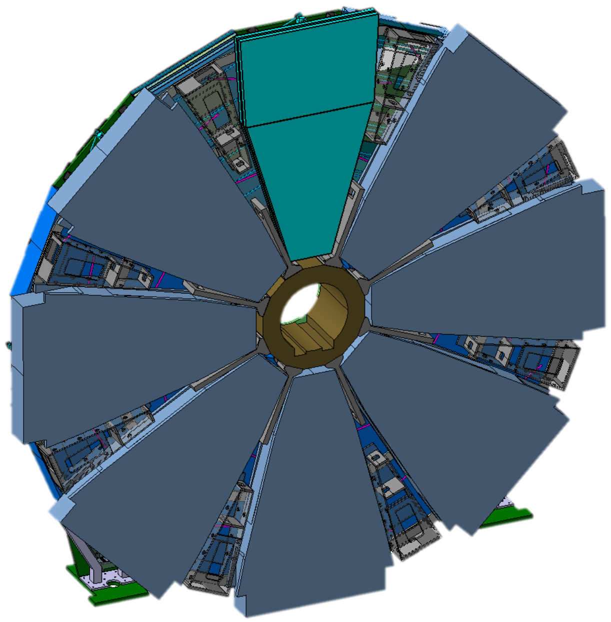
- Several upgrades are planned for the ATLAS muon triggers in the next shutdowns
- Goals are to reduce fake triggers, increase efficiency and improve the momentum resolution
- Several algorithms and possible hardware implementations are being investigated for all muon technologies → plan to include the MDTs in the trigger
- Machine learning techniques could have an impact on the performance
    - Considering some possible applications (e.g. momentum determination)
    - More ambitious possibilities for RPC/TGC seed or even full muon reconstruction

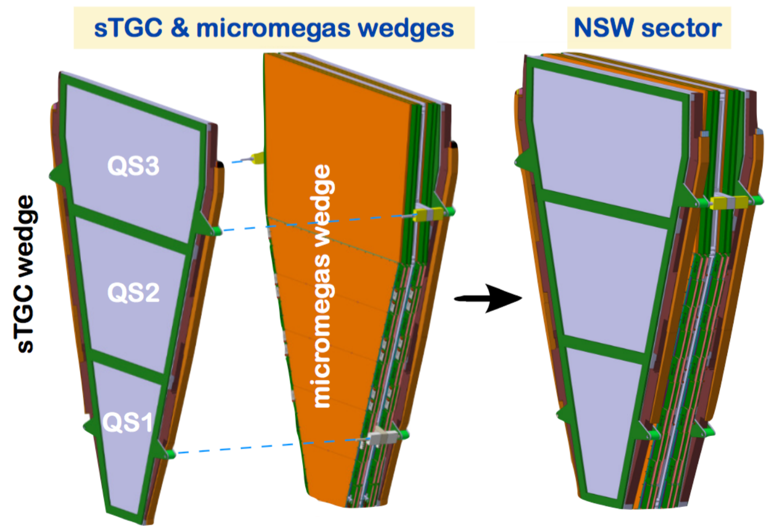




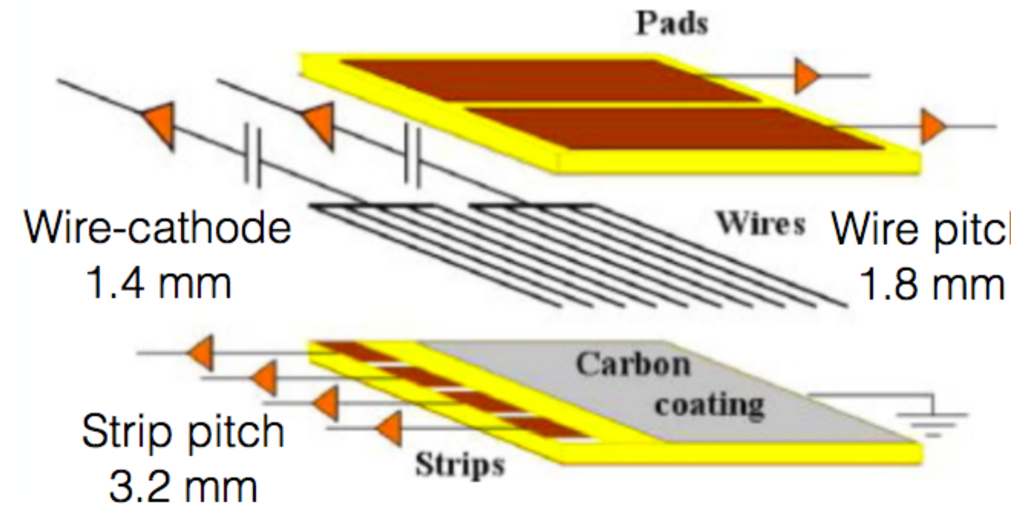
Backup

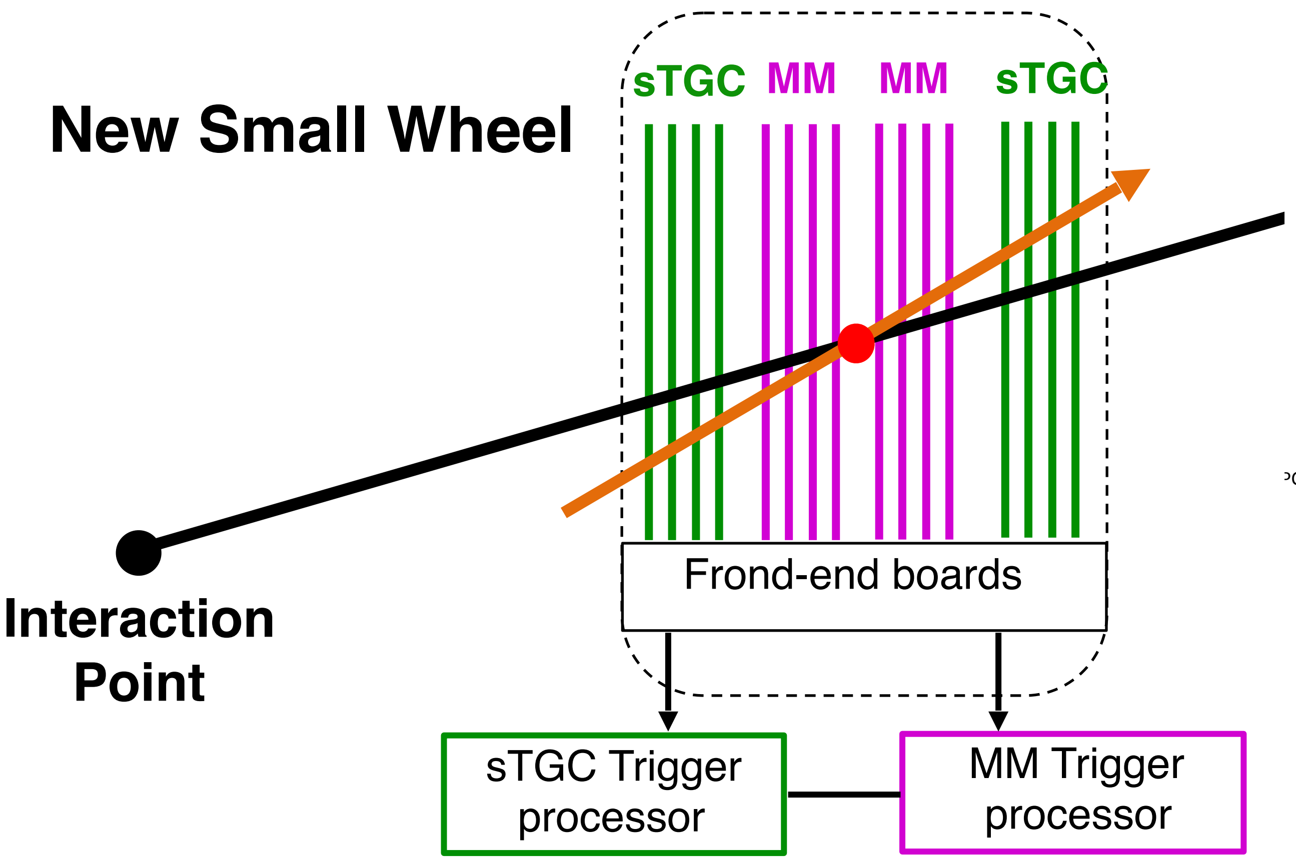
NSW Detector



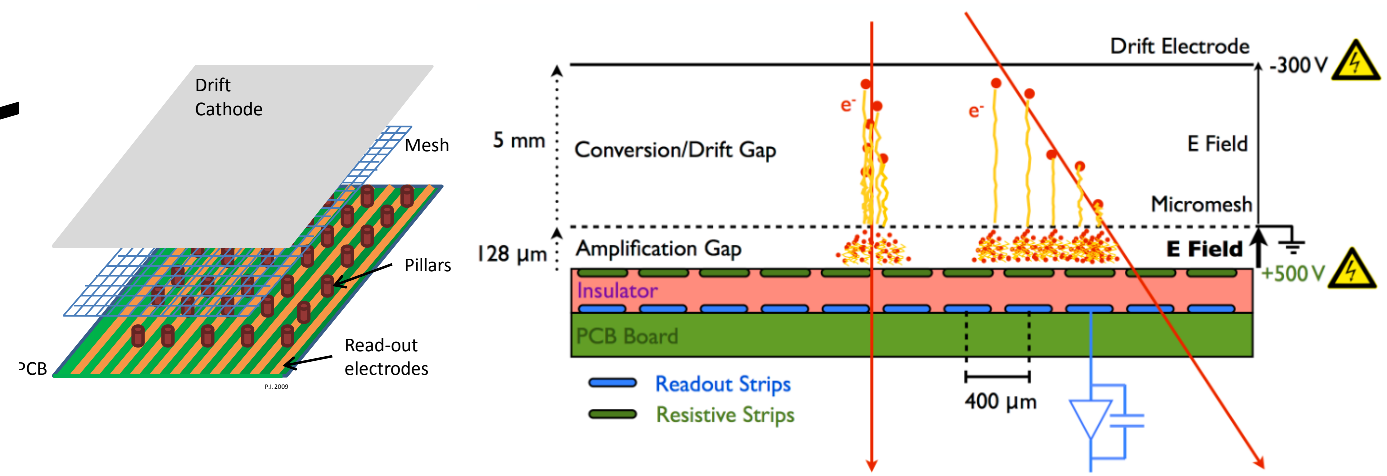


sTGC Detector





MM Detector



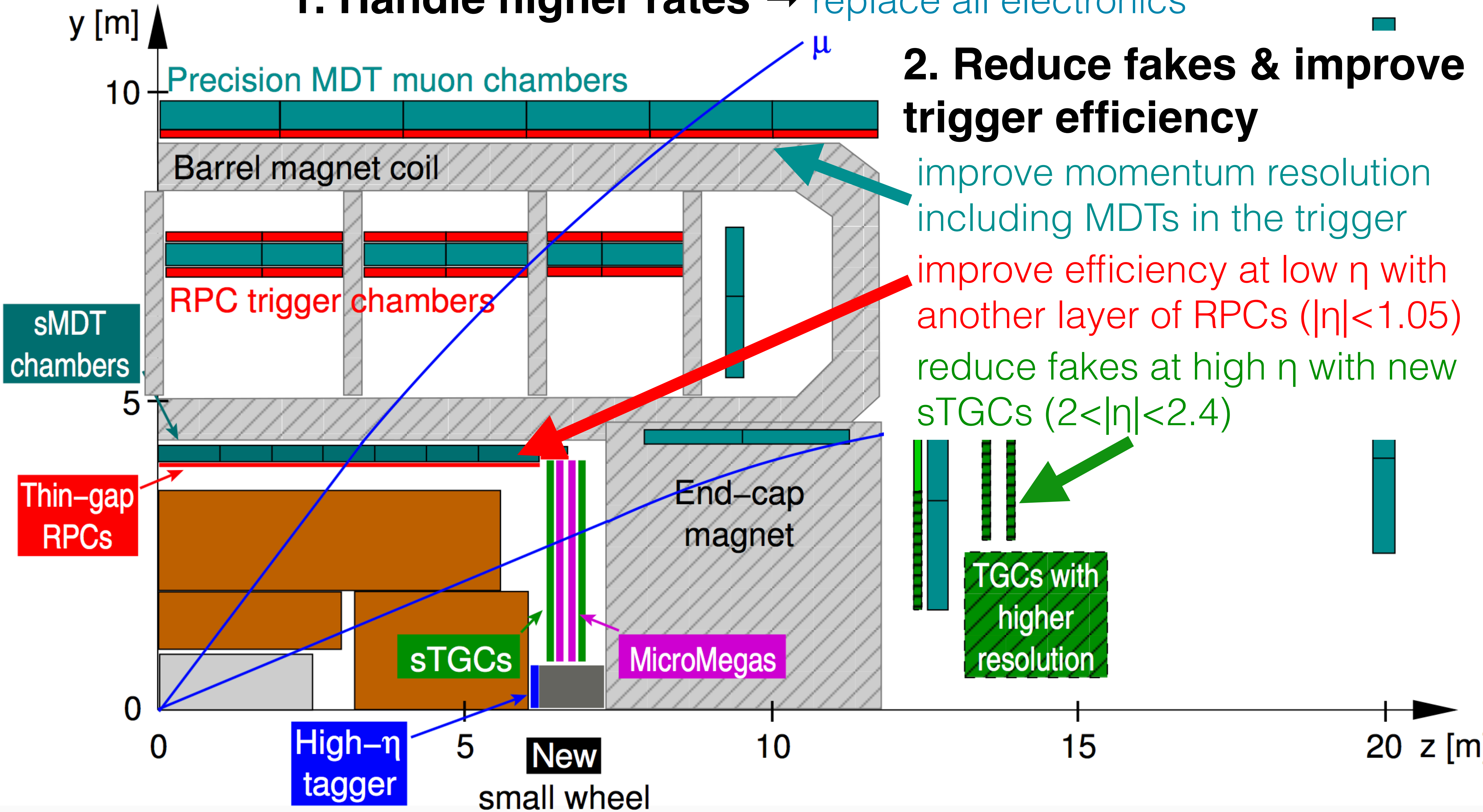
- Large channel number
  - MM: ~2M strips (0.4mm)
  - sTGC: 280k strips (3.2mm), 45k pads, 28k wires

Goals of the Phase 2 Muon Upgrades

1. Handle higher rates → replace all electronics

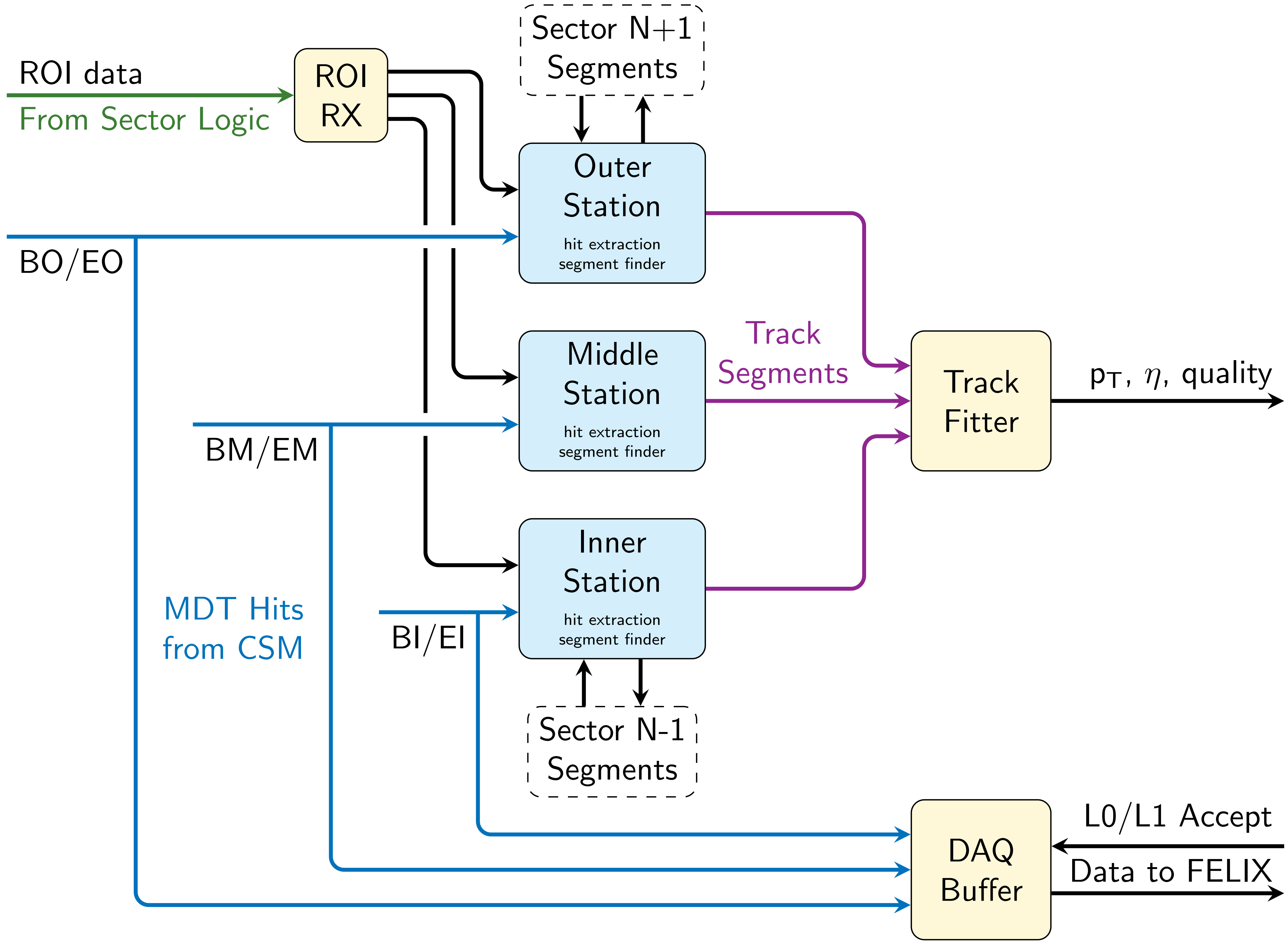
2. Reduce fakes & improve trigger efficiency

- improve momentum resolution including MDTs in the trigger
- improve efficiency at low η with another layer of RPCs (|η|<1.05)
- reduce fakes at high η with new sTGCs (2<|η|<2.4)



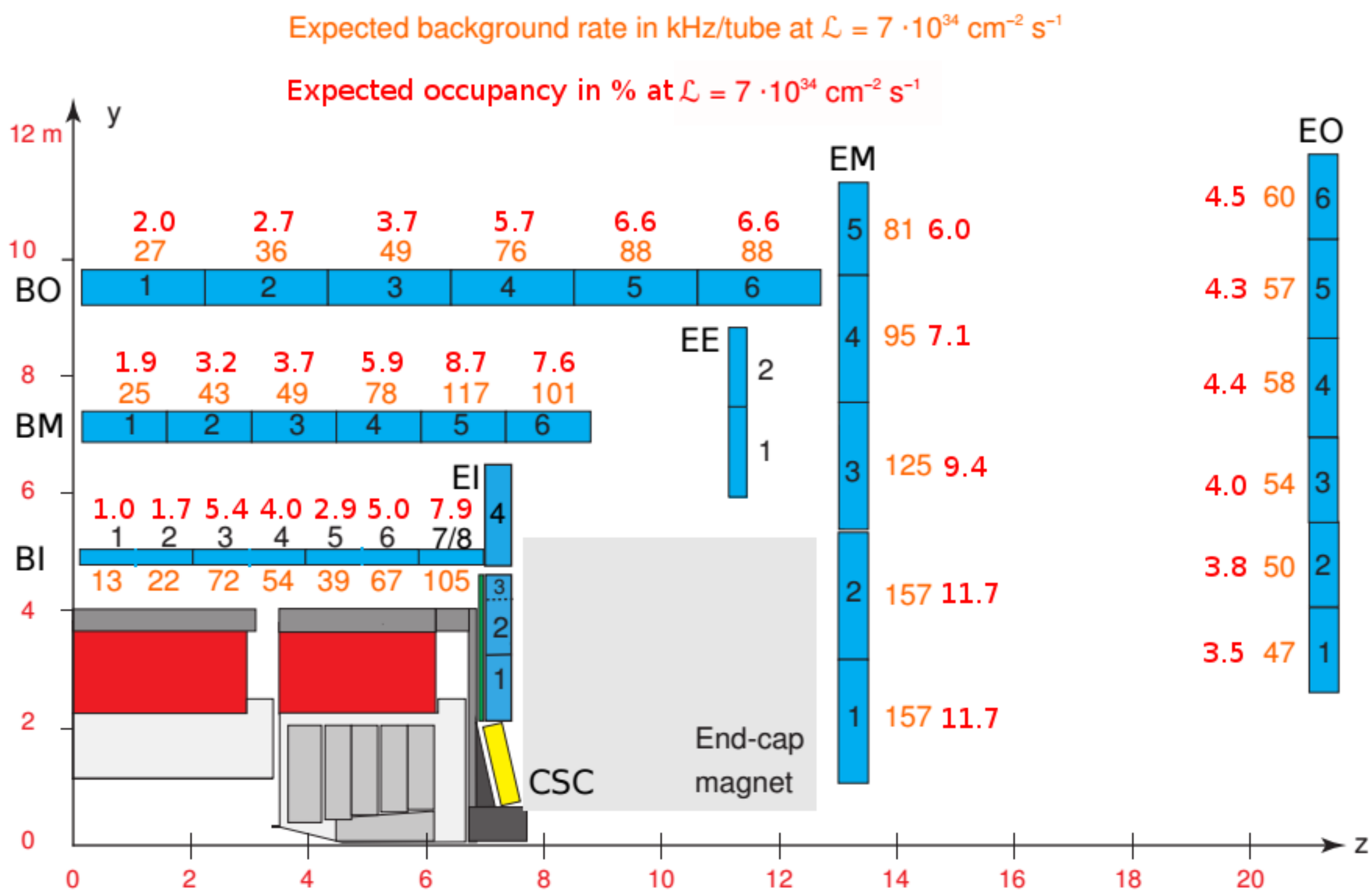
MDT Electronics Upgrade — readout & trigger

MDT Trigger Processor Block Diagram

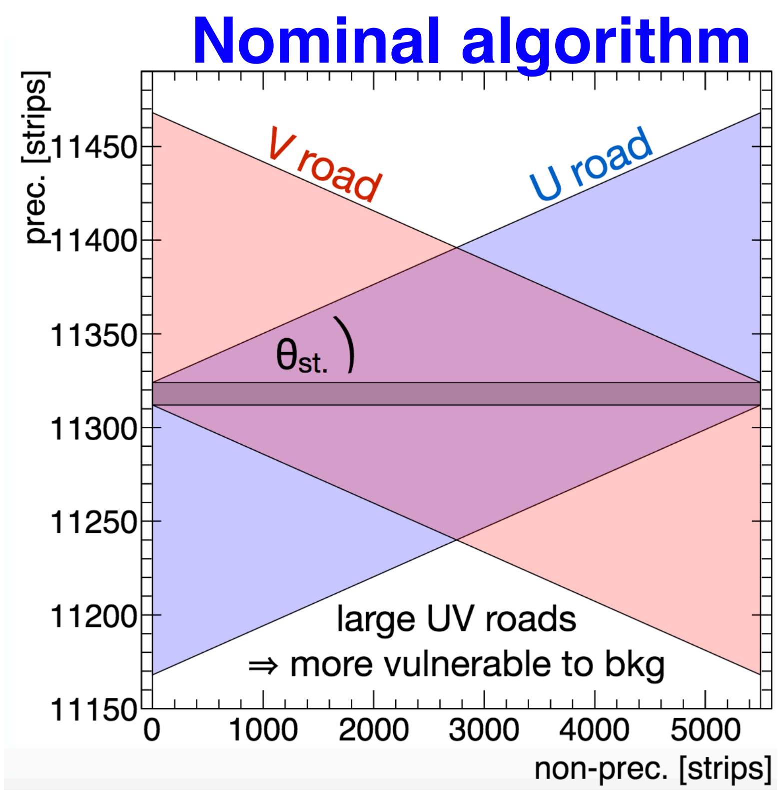


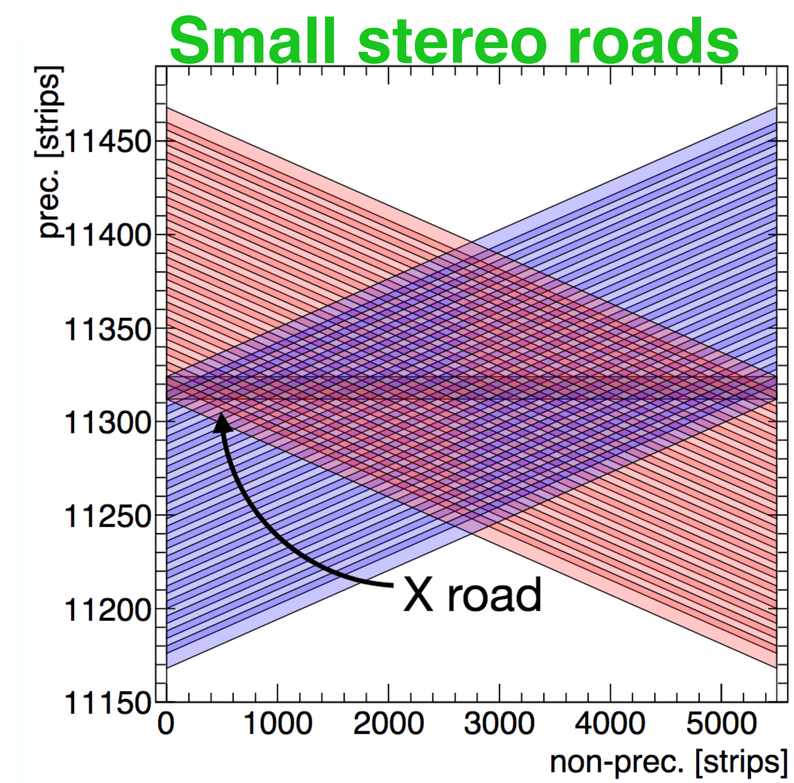
- Reconstructed segments are shared between neighboring sectors to handle sector overlap and barrel-endcap transition region

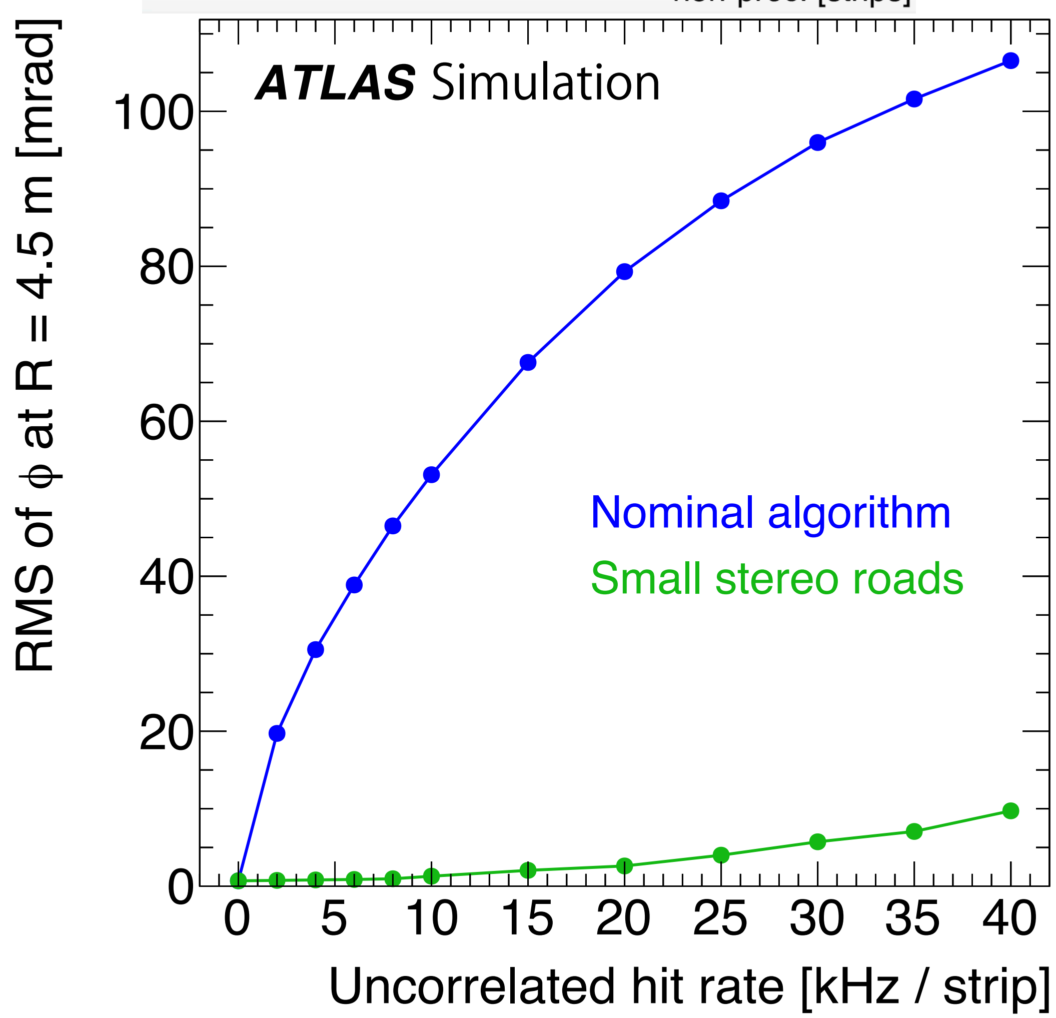
Hit Rates and Occupancy

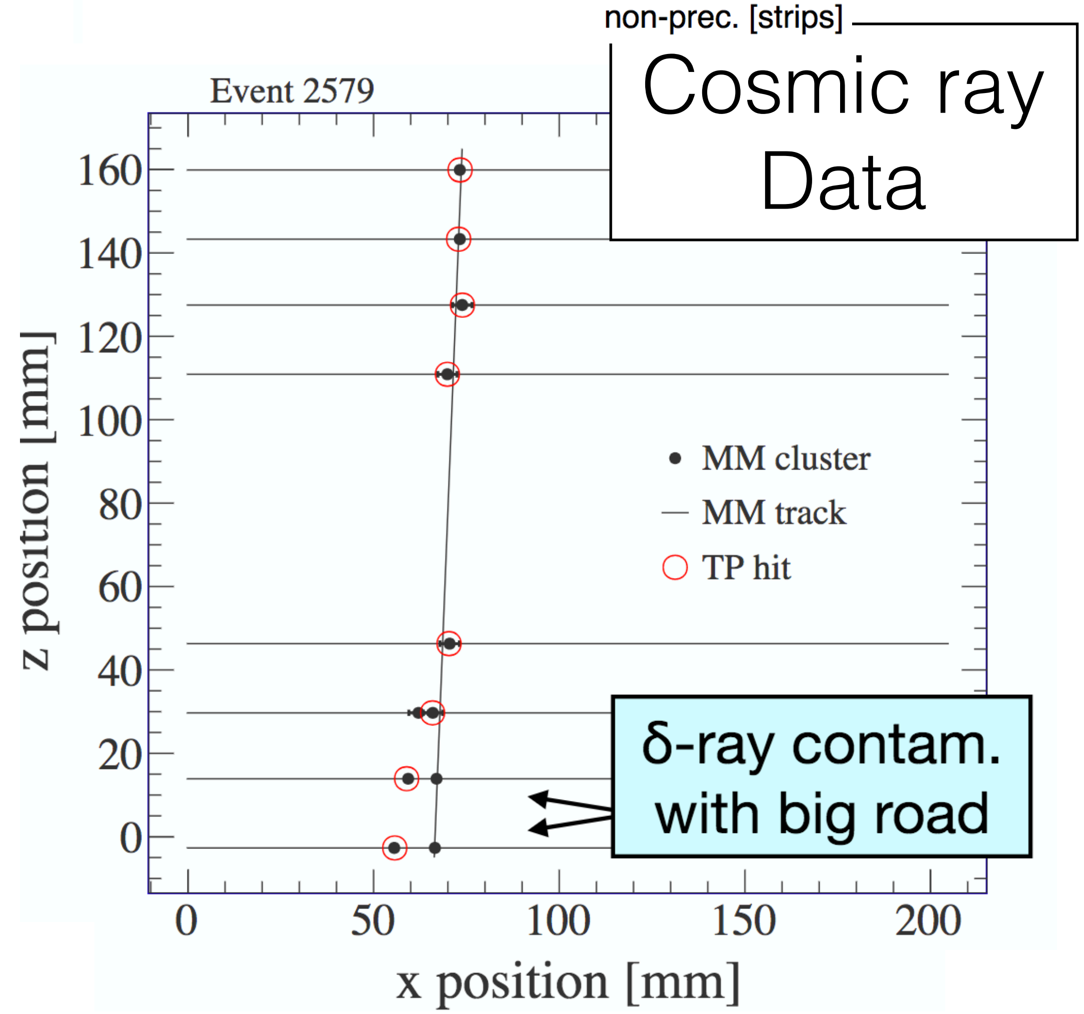


Rejection of Background Hits

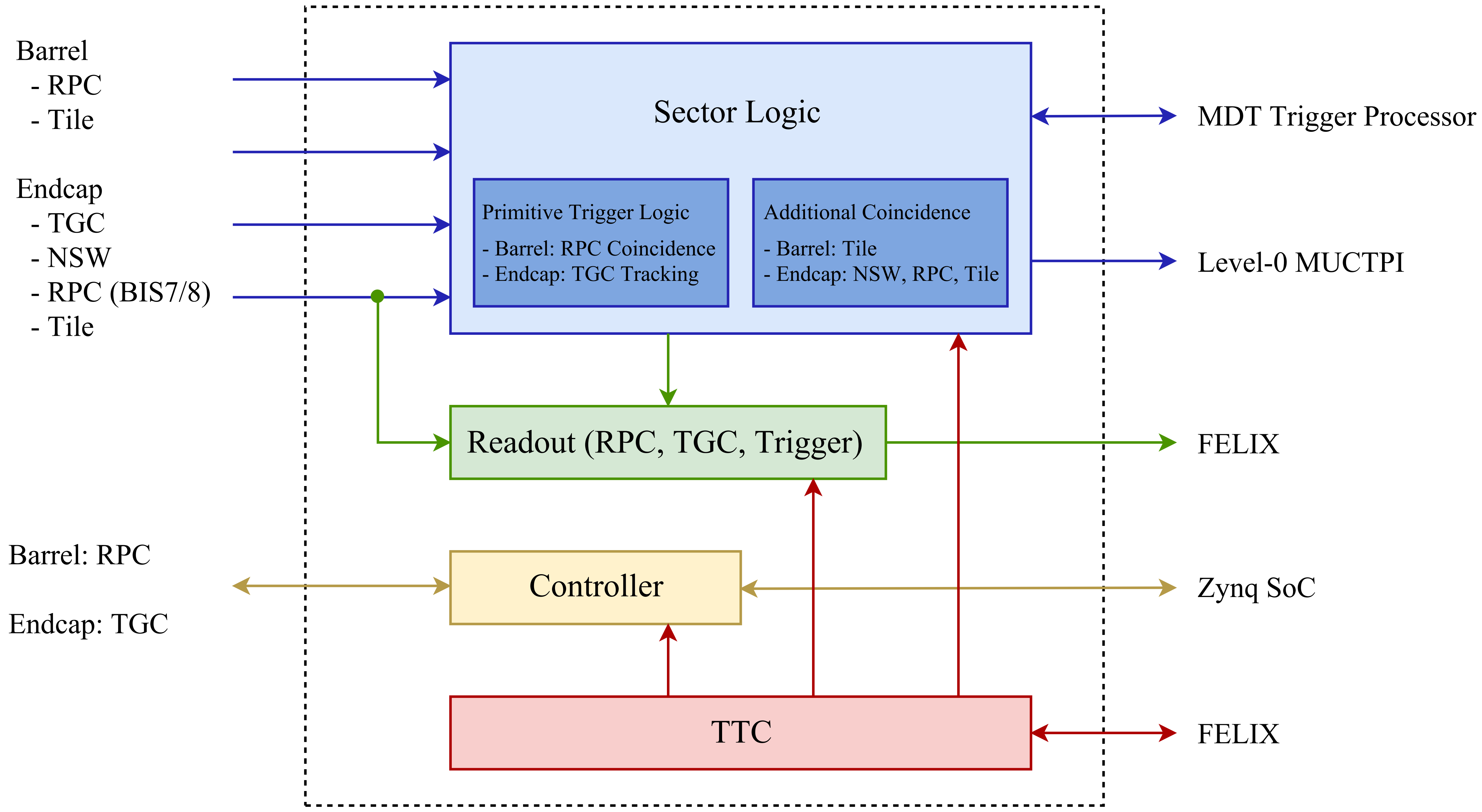




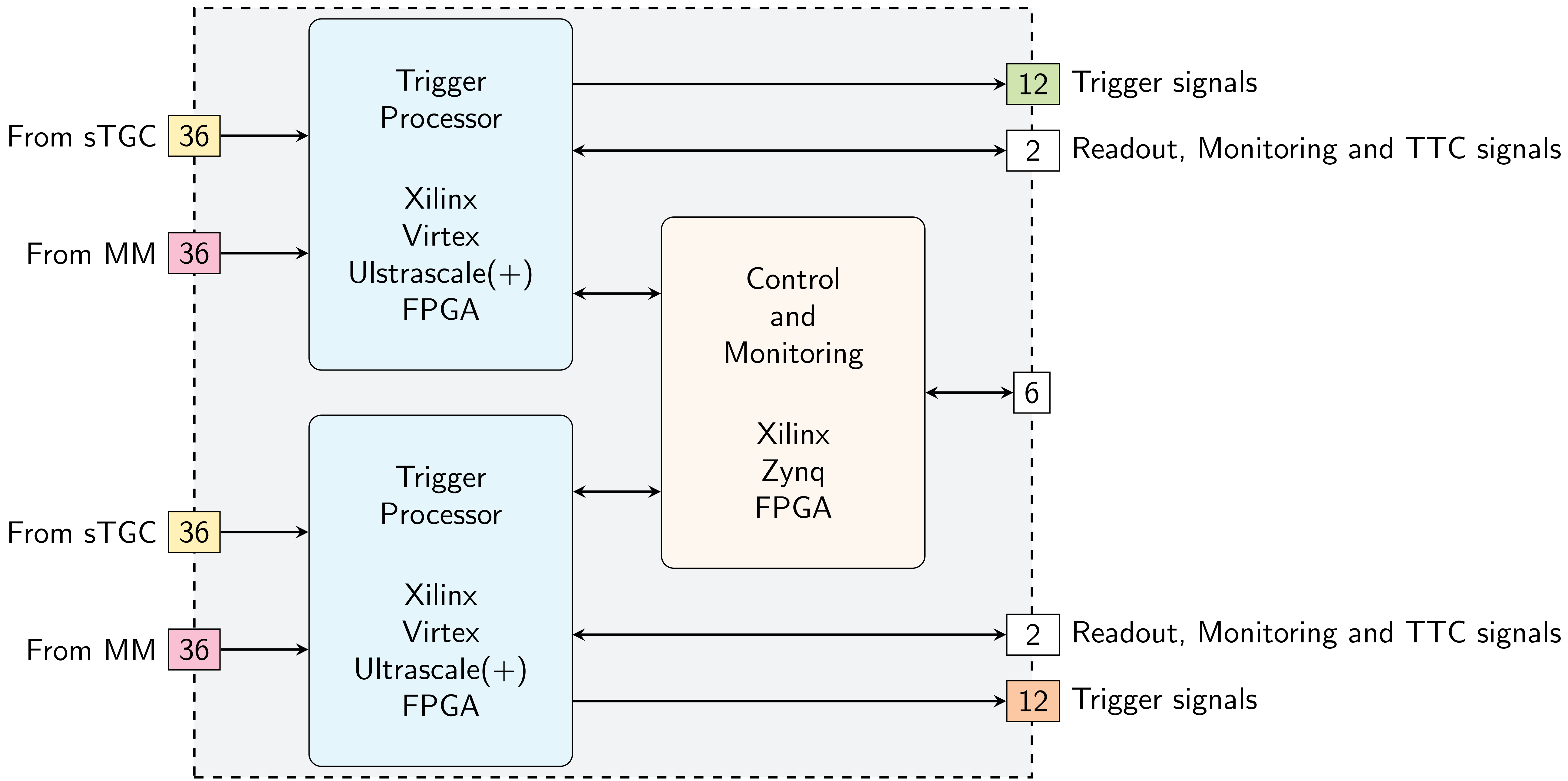




RPC and TGC Trigger Firmware



NSW Trigger Hardware



NSW Trigger Firmware