

# ATLAS Muon Detectors Upgrades for High Luminosity LHC

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on behalf of the ATLAS collaboration

# HL-LHC

- The LHC will enter long shutdown 3 mid-2026 and undergoes an upgrade
- The High Luminosity LHC (HL-LHC) is planned for mid-2030 to 2041
- Increased (instantaneous) luminosity of up-to 7.5 times the nominal LHC design
- Up to 200 interaction per bunch crossing (pileup) on average
- Integrated luminosity up to 4000 fb<sup>-1</sup>



# ATLAS Phase-II Upgrade

- The ATLAS detectors will be upgraded to handle the increased pileup and integrated luminosity

## Muon Spectrometer (MS)

- New precision chambers with higher rate capability
- New inner layer
- Improved trigger performance
- Major upgrade for most electronics

## Trigger and Data Acquisition (TDAQ)

- New single level trigger (L0) with 1 MHz readout
- Permanent storage at 10 kHz

## High-Granularity Timing Detector ([Luca's talk](#))

- 30-50 ps resolution for tracks
- Improved pile-up rejection
- Per-bunch luminosity measurement

## Inner Tracker (ITk) ([Tony's talk](#))

- Brand new, all silicon detector
- Up to  $|\eta| = 4$  coverage

## Calorimeter (talk [Georges](#), [Mattia](#))

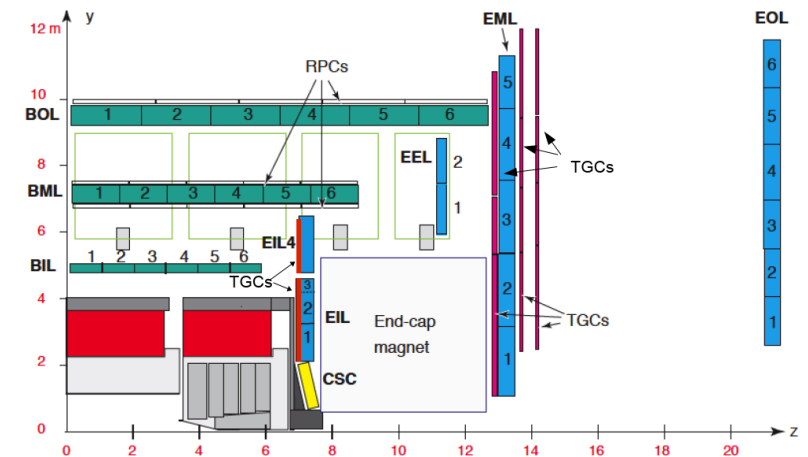
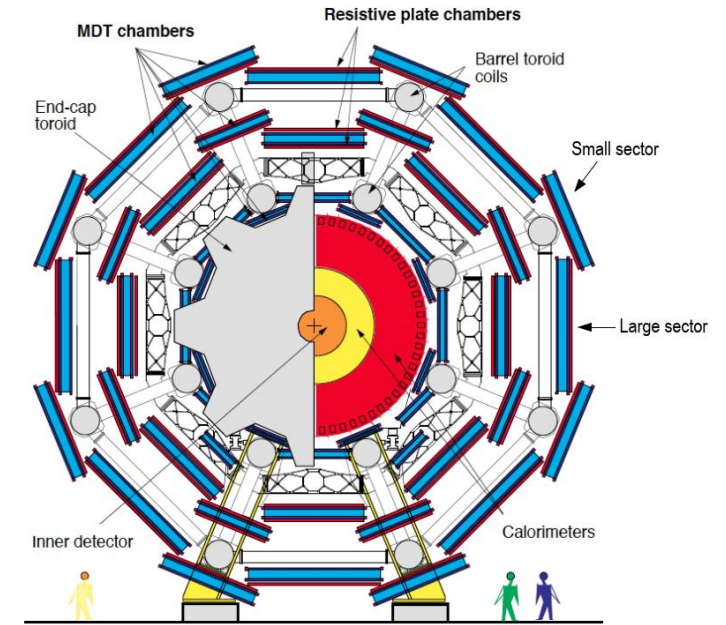
- Upgraded electronics
- 40 MHz readout
- Improved segmentation for trigger



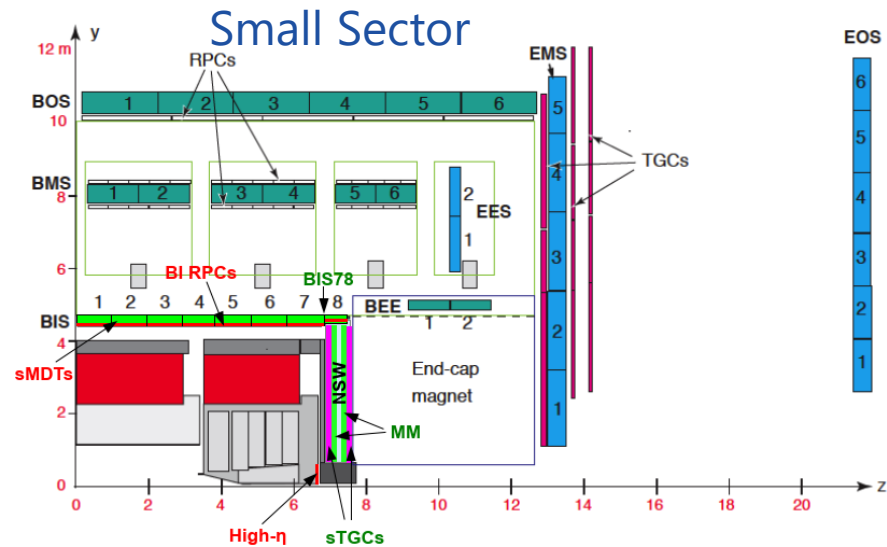
# ATLAS Muon Spectrometer

Current system:

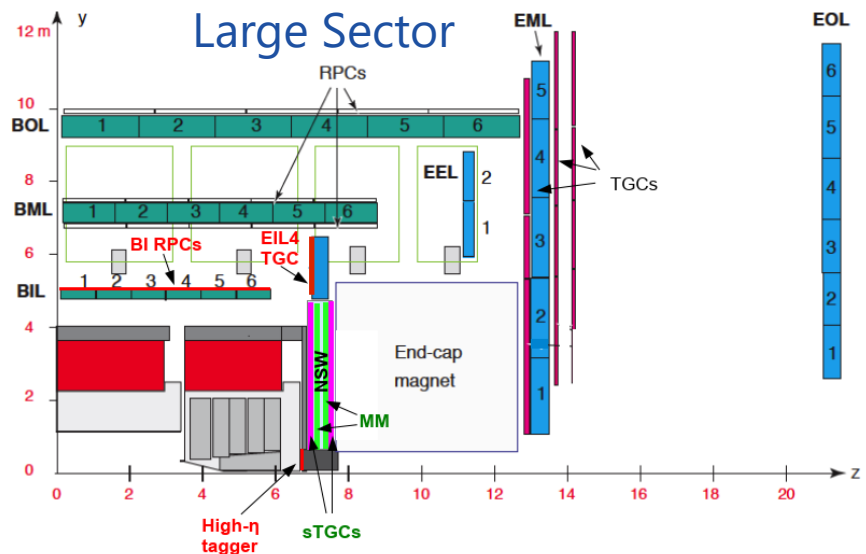
- Three layers of Monitored Drift Tubes (MDT) chambers for precision tracking
- Muon trigger provided by:
  - Barrel: 3 layers of Resistive Plate Chambers (RPC)
  - Endcap: 3-4 layers of Thin Gap Chambers (TGC) and NSW
- New Small Wheels (NSW) were installed during Phase-I upgrade
  - Using small-strip TGC and Micromegas chambers
  - Provide both triggering and precision tracking
  - Replacing the old small wheel MDT and Cathode Strip Chambers
- Originally designed for 10 years operation at luminosity of  $1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ 
  - Already exceeded in Run 3
  - Still works well thanks to the conservative safety factors at the time of design



# MS Phase-II Upgrade

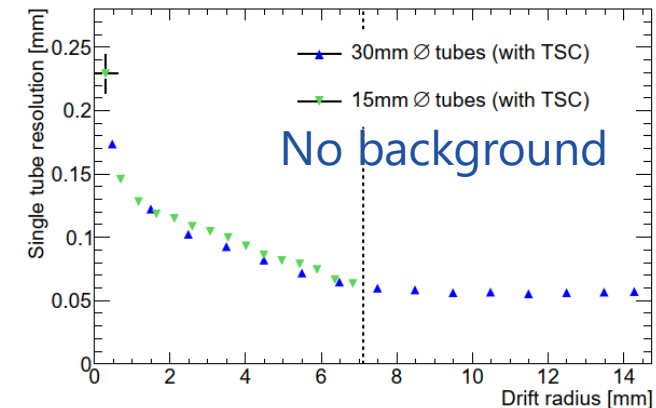
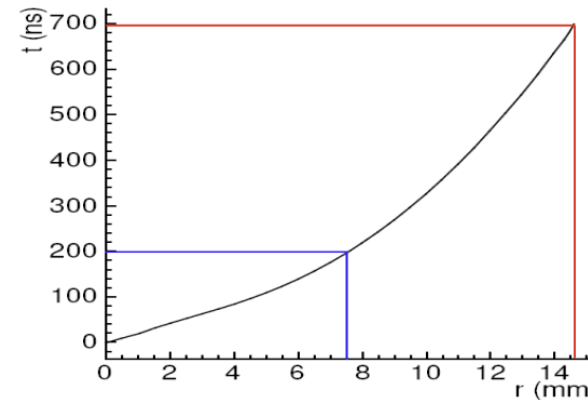
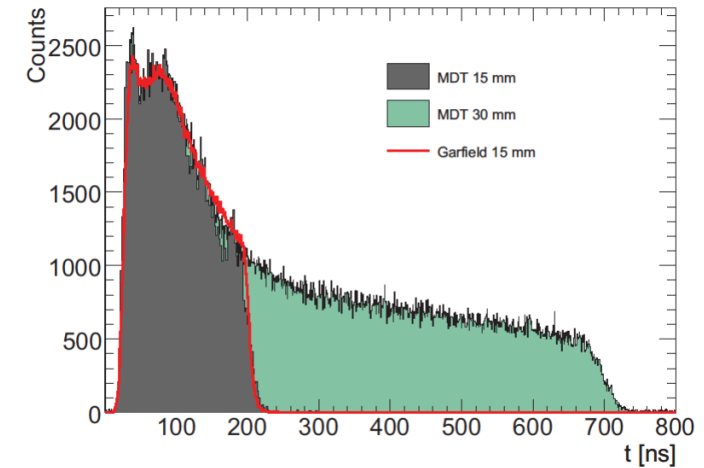


- In the small sector (overlaps with toroid magnet), the inner barrel layer will be replaced with small-MDT (sMDT)
- New, improved RPC on the innermost barrel layer
- The inner layer of endcap TGC 2  $\rightarrow$  3 layers
- New trigger and readout schemes require new on- and off-detector electronics
- Power system upgrade



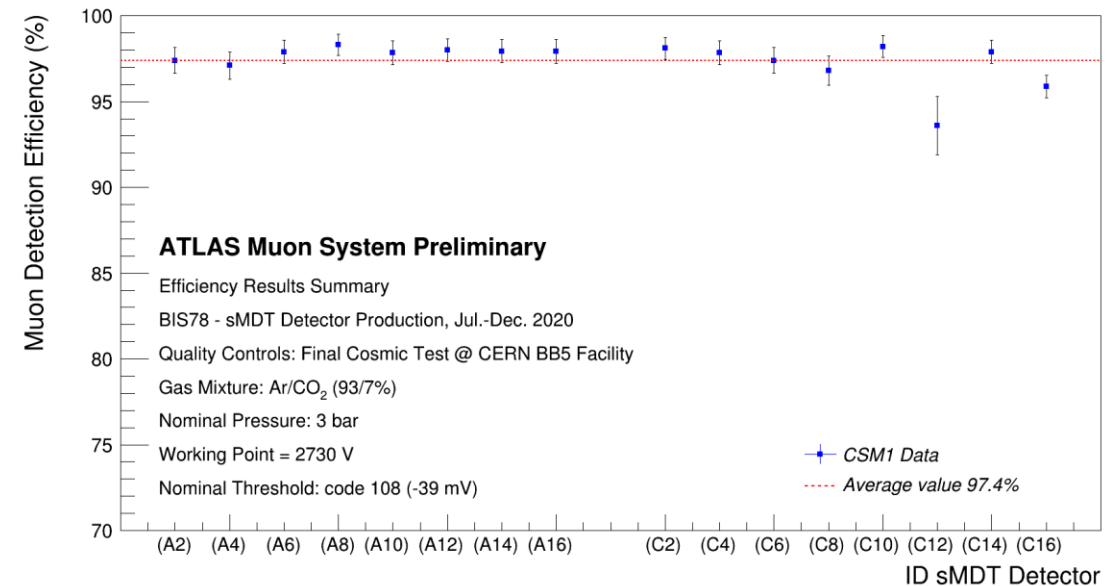
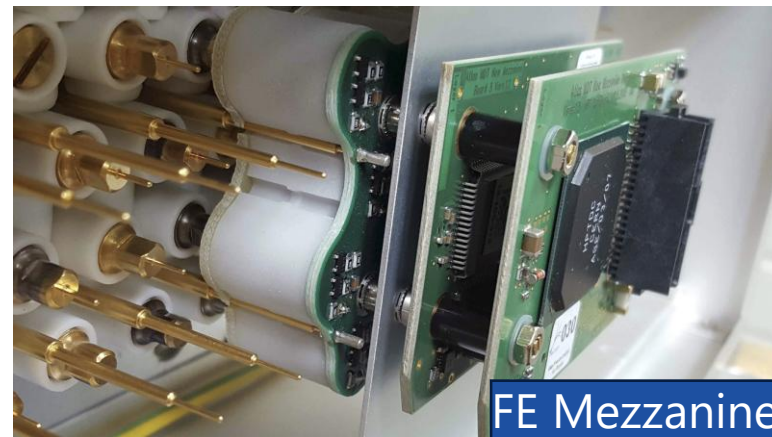
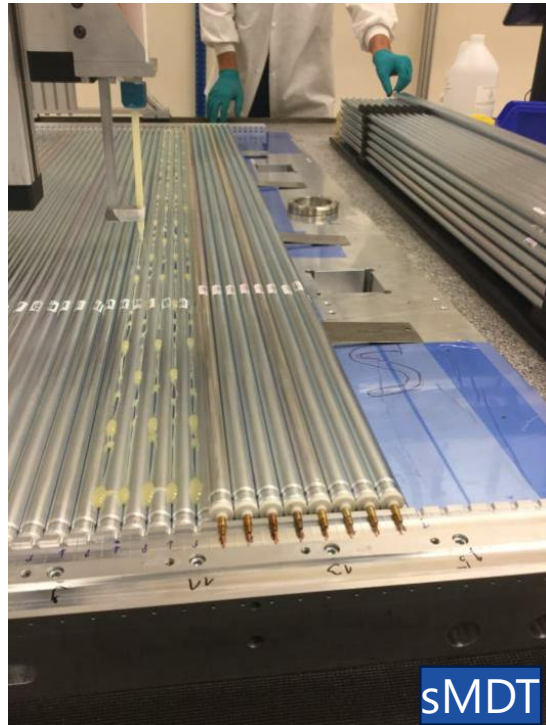
# sMDT chamber

- sMDT will replace the old MDT in the small sector to make space for new RPC
  - Half the diameter: 30 mm  $\rightarrow$  15 mm
    - The maximum drift time is reduced from  $\sim 700$  ns to  $\sim 200$  ns
  - Lower High Voltage: 3080 V  $\rightarrow$  2730 V
  - Same gas mixture, gas pressure, and gain
- Nearly linear space-to-drift time
- Mean resolution ( $\sim 110$   $\mu\text{m}$ ) is slightly better than MDT ( $130$   $\mu\text{m}$ ) at the 500 Hz/cm<sup>2</sup> background rate
  - At the lower background, MDT is comparable or better
- Capable of  $\sim 10$  times the rate of legacy MDT

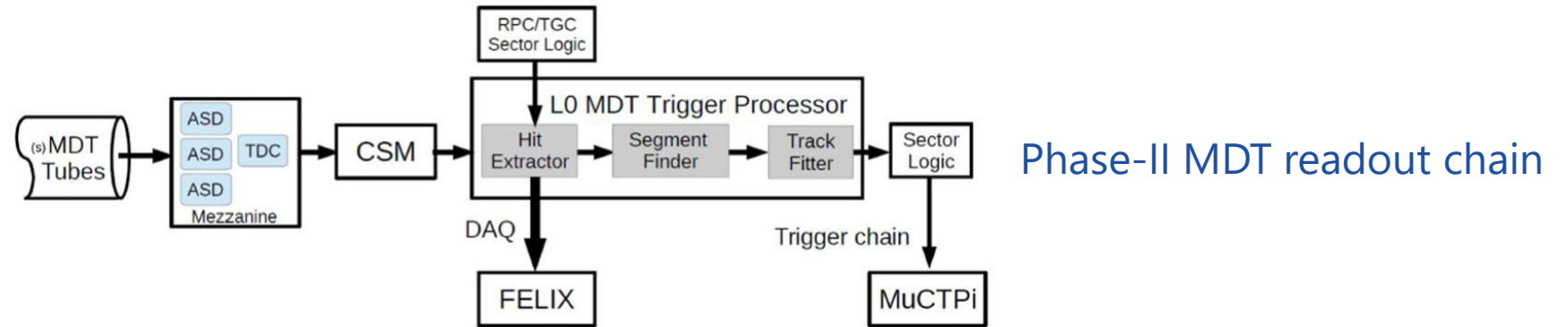


# sMDT Production

- sMDT chamber fully produced (96+6 spares) and delivered to CERN
- Passed the gas leak, dark current, and high voltage tests
- sMDT frontend mezzanine board production completed
- Chambers+FE board commission finished in 2025
- Ready for integration with new RPC



# MDT electronics

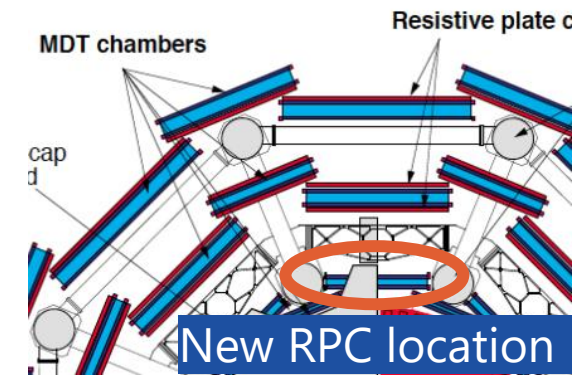


Several components are new or getting a redesigned

- Amplifier-Shaper-Discriminator (ASD) and Time-to-Digital Converter (TDC) ASICs
  - Produced and tested in 2024
- Mezzanine cards
  - ~67% (13800) produced and tested, enough for all needs in 2026
- Chamber Service Module (CSM) and CSM motherboard
  - First batch produced and tested in 2025, the rest will follow
- Mezz-to-CSM cables and CSM-to-MDT Trigger Processor optical fibers
  - In pre-production phase. 10% of Mezz-to-CSM cables are ordered and expected to be at CERN this month
- More on MDT Trigger Processor in [Panagiotis' talk](#)

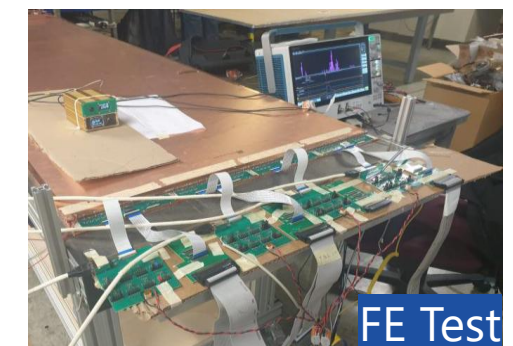
# RPC and FE

- Legacy RPC@HL-LHC: To reduce possible aging effect, plan to work at reduced gas gain  $\rightarrow$  15-35% efficiency loss
- To improve trigger performance, new RPC triplets will be added and installed in the innermost layer and in two sectors of the outer layers
  - Also increase barrel trigger acceptance from  $\sim 78\%$  to  $\sim 96\%$
- New-generation RPCs:
  - 1mm gas gap (old: 2 mm). Improved intrinsic time resolution 1.1 ns  $\rightarrow$  0.4 ns
  - New frontend electronics with better signal amplification capability
  - Compatible with usage of lower Global Warming Potential gas mixture



## Production status:

- $\sim 46\%$  of gas volume produced
  - Gas leak, current leak, and Volt-Amperometric characteristics test performed
- Read-out strip panel production completed
- $\sim 11\%$  of singlets produced. Module 0 triplets prepared for tests
- All FE ASICs produced. 500 pre-production FE board done

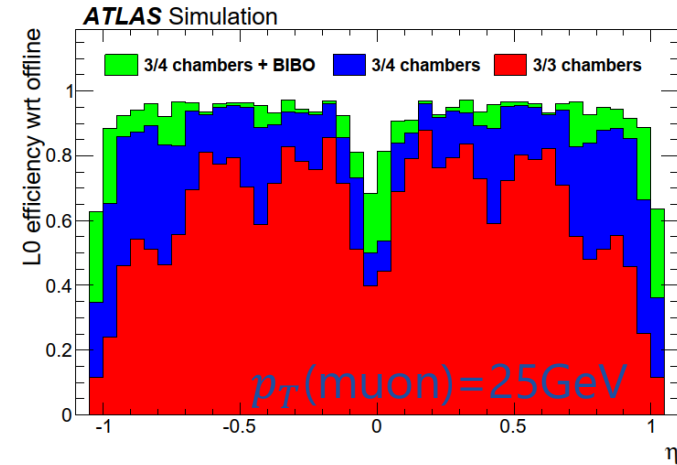
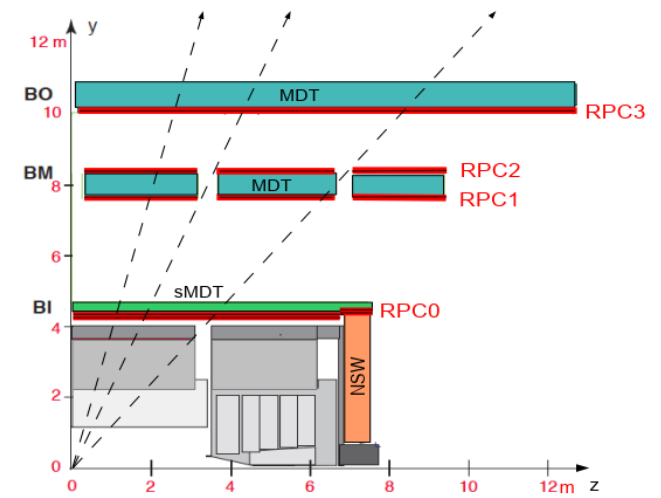


# RPC Electronics

- The addition of new triplets enables **new schemes** for the barrel trigger

Trigger	Requirements
3/3 chambers	3[RPC1+2] AND 1[RPC3]
3/4 chambers	3/3 chambers OR (2[RPC0] AND 3[RPC1+2+3])
3/4 ch.+BI-BO	3/4 chambers OR (2[RPC0] AND 1[RPC3])

- 92% trigger efficiency possible with worst-case scenario for legacy RPC
- Replaced with New Data Collector and Transmitter (DCT) boards:
  - Receives hit analog pulses from FE, measures arrival time with a FPGA-TDC and sends data to the off-detector
  - Two flavors: for legacy and for new-gen RPC
  - Only for new-gen, thanks to improved time resolution,  $\phi$  coordinate is estimated from the measurement of the  $\eta$  coordinate from both sides of the RPC
- Both flavors have passed the final design review and started preproduction. Estimate completion by the end of 2026
- A DCT prototype for legacy-RPC was installed in ATLAS cavern for testing



DCT Prototypes



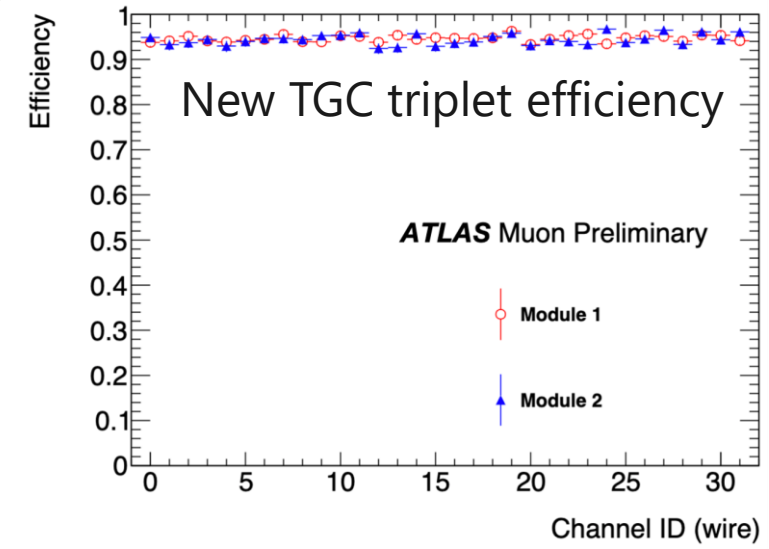
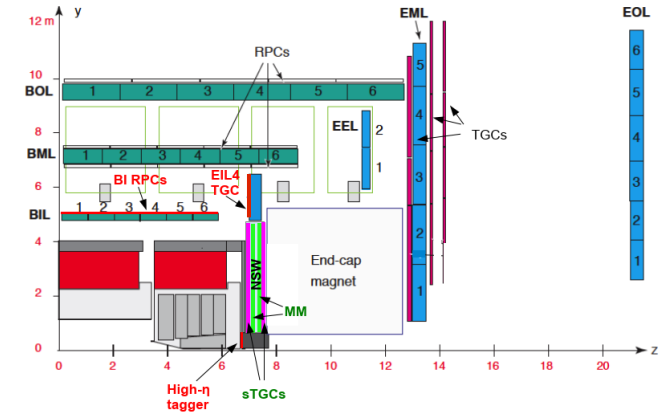
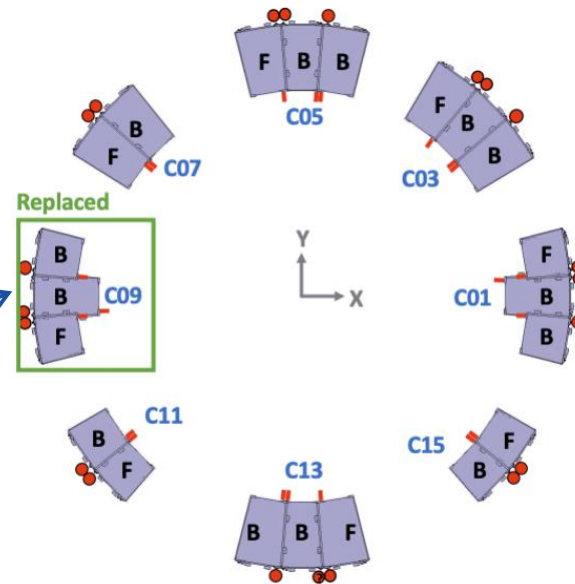
Legacy-RPC



New-gen-RPC

# TGC triplet chambers

- EIL4 TGC chambers are TGC doublets located in the transition region between barrel and endcap
  - Trigger logic is limited to logical OR of the two layers due to the single-layer efficiency
- New EIL4 TGC triplets with higher granularity offers better efficiency and reduced fake rate
  - Built-in redundancy against single-layer failure
- Productions are on schedule
  - ~2/3 singlets and ~1/2 triplets produced
  - Electronics production completed

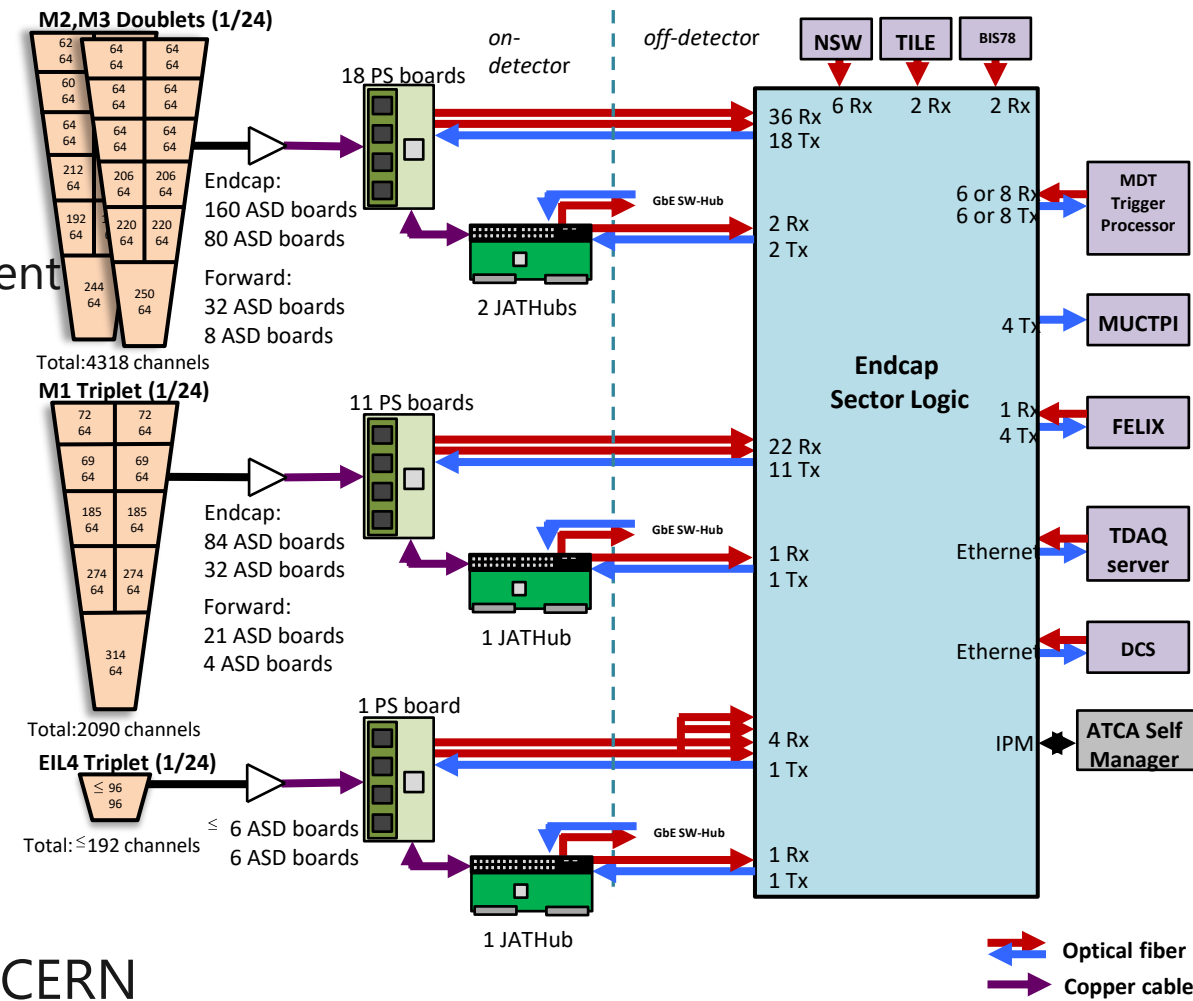


- Pilot sector C09 (3 chambers) has been successfully replaced with the new triplets during 2024-2025 YETS

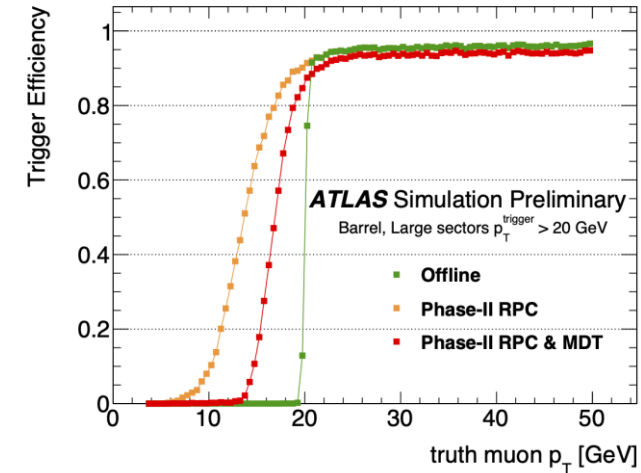
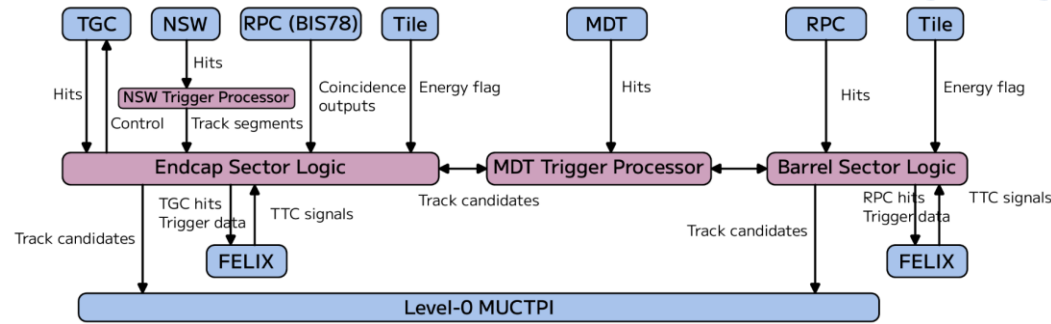
# TGC Electronics

To meet Phase-II TDAQ requirements, the whole TGC trigger/readout electronics will be upgraded

- Patch-Panel ASIC
  - Bunch crossing (BC) ID delay compensation and assignment
- PS board
- JATHub
  - PS board firmware programming
  - PS board clock phase calibration
- Timing Adjustment Master (TAM)
  - Clock skew measurement and phase adjustment
- All four productions are completed and shipped to CERN
  - Integration tests ongoing. Demonstrators installed in the cavern



# Level-0 Muon Trigger



- Muon Phase-II 1<sup>st</sup> stage trigger “Level-0” will use all muon subdetectors
- Sector Logic (SL) and MDT Trigger Processor (MDTTP) handle the readout and control of the FE
- SL reconstructs track candidates using hits data from RPC (barrel) and TGC (endcap), as well as:
  - Processed data from inner detectors (e.g., NSW track segments)
  - Transverse momenta from MDTTP to improve resolution
- Barrel and Endcap SLs share the same hardware design
- SL and MDTTP’s Final Design Review (FDR) are completed successfully
  - Hardware pre-production is ongoing
  - Majority of firmware and software are ready
- Combined tests of hardware are ongoing



Prototype-2 SL board

# Power System

- ATLAS Muon detectors are equipped with low-(LV) and high-voltage (HV) power system and associated monitoring and control modules
- The current components are certified for  $\sim 1500 \text{ fb}^{-1}$ , less than half of HL-LHC lifetime expectation
- Upgrade timeline are organized into short, medium, and long timeline
  - Status: prototype **accepted**, under test, *delivered*
  - Almost all short-timeline prototypes that are needed for the new detector, are accepted
- The new controller is capable of at least 10x rate increases, confirmed by our tests
  - Very useful for handling the several ten thousands of channels

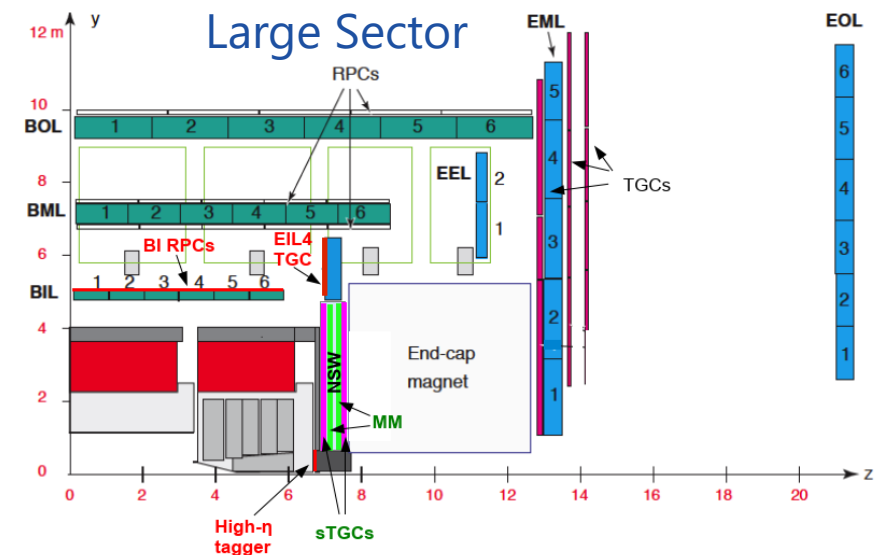
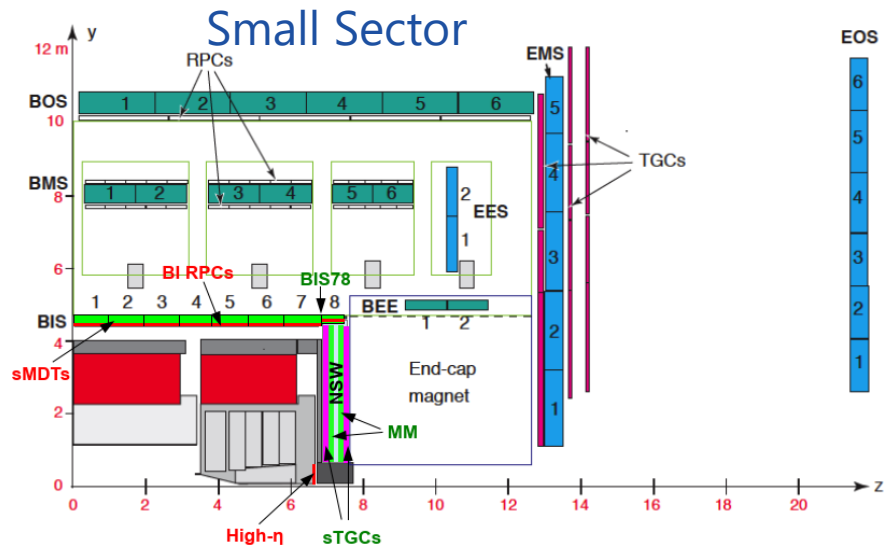
Short	Medium	Long
<ul style="list-style-type: none"><li>• <b>MDT, sTGC, RPC &amp; TGC controller (R6060)</b></li><li>• <i>19" crates MDT, RPC &amp; TGC</i></li><li>• <b>BI RPC HV (A1592)</b></li><li>• <b>BI RPC LV dig FE DCT (A5009)</b></li><li>• <u>BI RPC LV ana FE Thr (A5001)</u></li><li>• <b>BI RPC ADC (A5801)</b></li><li>• <i>MDT Ser/Pow generators</i></li></ul>	<ul style="list-style-type: none"><li>• MDT &amp; TGC LV (A5016)</li><li>• TGC LV (A5100)</li><li>• MDT, sTGC &amp; TGC HV (A5540)</li><li>• TGC 8" crates</li><li>• MDT DC/DC converter</li><li>• RPC &amp; TGC Serv generators</li></ul>	<ul style="list-style-type: none"><li>• RPC legacy HV (A5512)</li><li>• RPC legacy DAC (A5802)</li><li>• RPC &amp; TGC Pow generators</li></ul>

# Summary

- HL-LHC will provide an unprecedented amount of data
- ATLAS muon system will undergo a major upgrade to ensure the highest physics potential can be reached
  - Additional and/or improved layers for both trigger and precision measurements
  - New TDAQ design that includes more data from various subsystems to improve the trigger performance
  - New electronics to satisfy the new and faster Phase-II TDAQ
    - Also enable improved algorithm. See [Tetsuro's talk](#) and [Ryugo's poster](#) for example
- Good overall progress and in general on schedule

# Backup

# MS Phase-II Upgrade

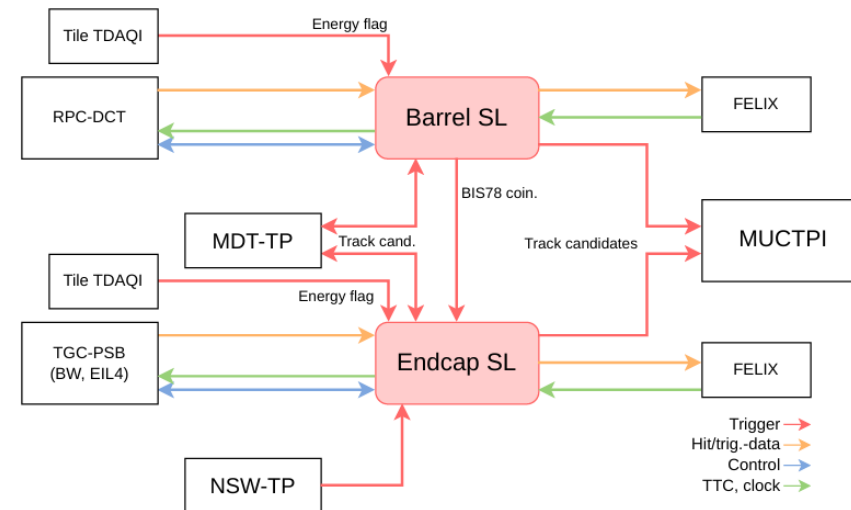


- The innermost layer of endcap TGC 2  $\rightarrow$  3 layers
  - Allowing a more robust 2/3 majority logic
  - Higher granularity to reduce fake rate
- New, improved RPC on the innermost barrel MDT layer
  - Helps maintain trigger efficiency and purity
  - Increases acceptance coverage
- In the small sector (overlaps with toroid magnet), the inner barrel layer will be replaced with small-MDT (sMDT)
  - Drift tubes with smaller diameter
  - To make space for the new RPC
- New trigger and readout schemes require new on- and off-detector electronics
  - Sending all RPC/TGC data to counter room
  - Combine with info from MDT to perform trigger logic on FPGAs
- Power system upgrade

# Integrations

- Status:

System	status (link)	status(protocol)
RPC-DCT	planned	planned
TGC-PSB	done	demonstrated
Tile TDAQi	done	planned
NSW-TP	planned	planned
FELIX	verified	demonstrated
MUCTPI	verified	demonstrated
MDT-TP	done	planned
SL	done	planned

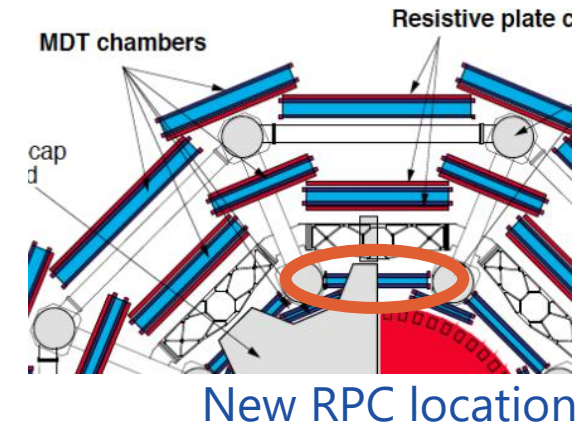


Links Diagram for Barrel and Endcap SL

- SL <-> MUCTPI system test has been done
  - ALTI/LTI acting as FELIX for TTC distribution, but with the new protocol
  - BER checked out ( $<10^{-15}$ )

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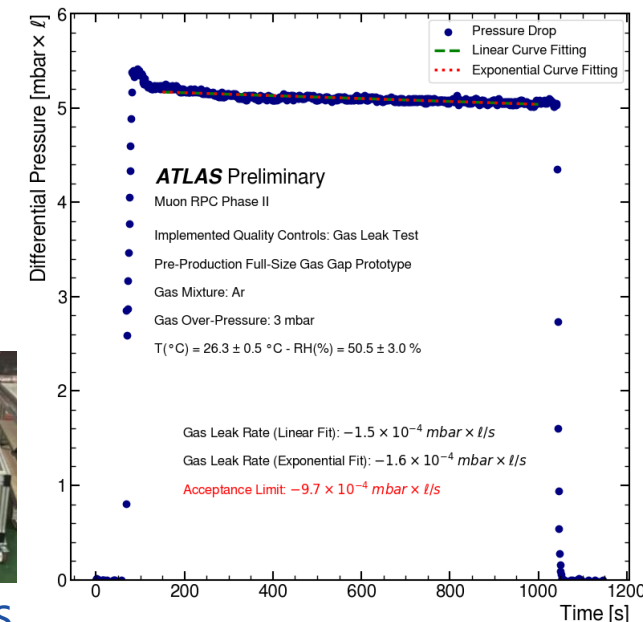


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RPC singlets



# Power System

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  - EASY (Embedded Assembly SYstem) 3000 family by CAEN
- The current components are certified for  $\sim 1500 \text{ fb}^{-1}$ , less than half of HL-LHC lifetime expectation
- Key components' electronics are becoming obsolete and maintenance up until 2040 is practically impossible
- CAEN is once again chosen as the producer
- Upgrade timeline are organized into short, medium, and long timeline
  - Most short-timeline prototyping are done
  - Status: prototype **accepted**, under test, *delivered*

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