Performance of the ATLAS Muon Spectrometer and Status for its Upgrade for High Luminosity LHC

Stefanie Götz on behalf of the ATLAS Muon Community
Ludwig-Maximilians-Universität München

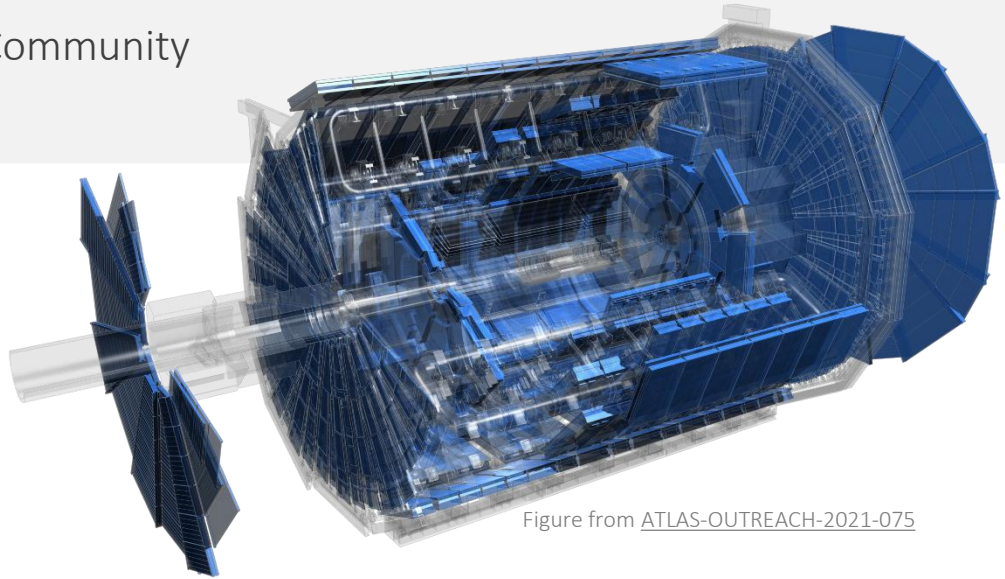


Figure from ATLAS-OUTREACH-2021-075

Corfu Workshop on Future Accelerators 2025
27 Apr – 4 May 2025, Corfu, Greece

Preparation for High Luminosity LHC (HL-LHC)

G. Aad et al 2024 JINST 19 P05063, ATLAS-TDR-026

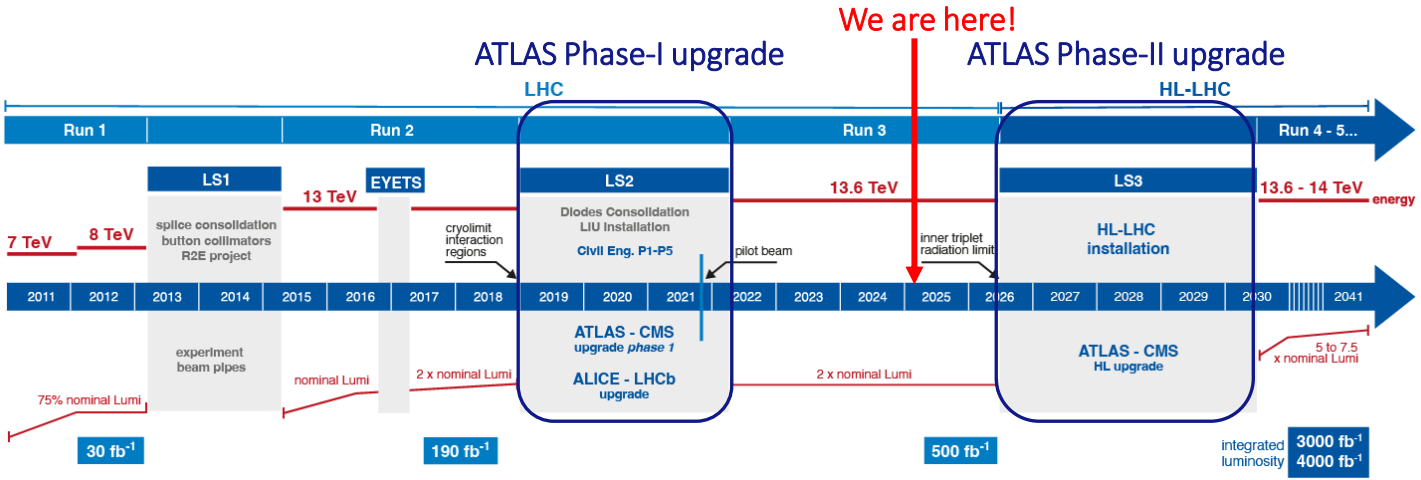
Aim for HL-LHC:

- Increase of instantaneous luminosity to up to $5 - 7.5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Final integrated luminosity of $3000\mathrm{fb}^{-1}$

Challenges:

- High background radiation environment
- High pile-up rates

⇒ **2 step ATLAS upgrade to cope with the new conditions and exploit physics potential of HL-LHC**



Project schedule from https://project-hl-lhc-industry.web.cern.ch/content/project-schedule, adapted

The ATLAS Muon Spectrometer in Run 3

⇒ **Determination of the muon momentum** from their deflection in a magnetic field ($\sim 0.5\mathrm{T}$); the sagitta is measured at 3 stations

Precision tracking:

- Monitored drift tubes (MDTs)
  $|\eta| < 2.7$, innermost layer $|\eta| < 1.3$

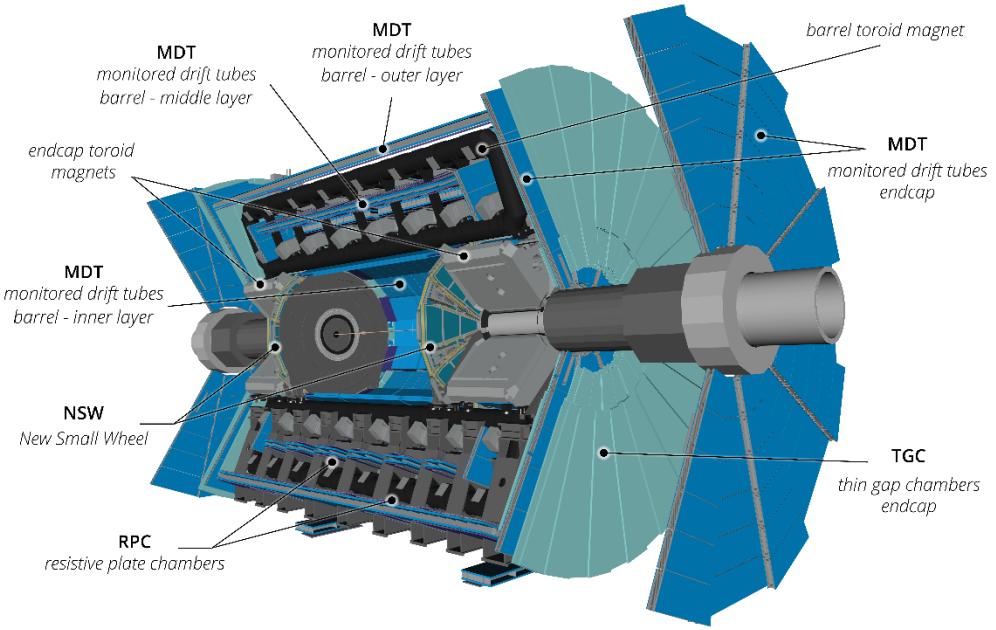
Precision tracking & trigger: **Phase-I upgrade!**

- New Small Wheel (NSW)
  $1.3 < |\eta| < 2.7$, trigger $1.3 < |\eta| < 2.4$
  - Micromesh gaseous structure (Micromegas)
  - Small-strip thin gap chambers (sTGCs)

Trigger:

- Resistive plate chambers (RPCs)
  $-1.05 < \eta < 1.3$
- Thin gap chambers (TGCs)
  $1.05 < |\eta| < 2.7$, trigger $1.05 < |\eta| < 2.4$

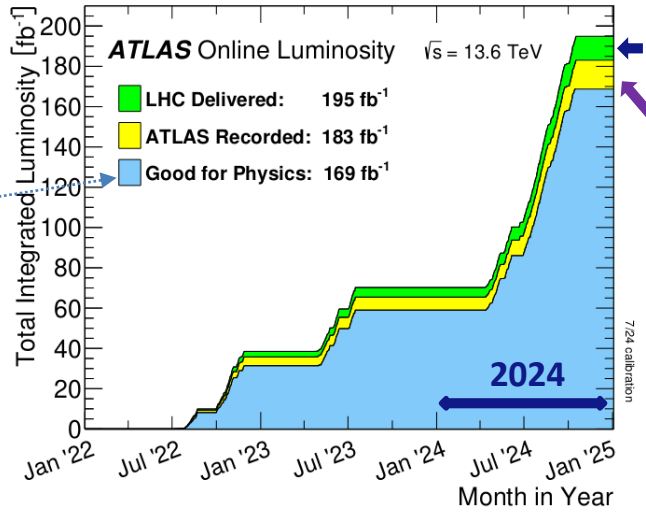
⇒ The BIS78 chambers ($1.0 < \eta < 1.3$) installed as part of the Phase-I upgrade contain a new technology of MDTs (sMDTs) and RPCs (thinner gas gap)



G. Aad et al 2024 JINST 19 P05063, ATLAS-TDR-026

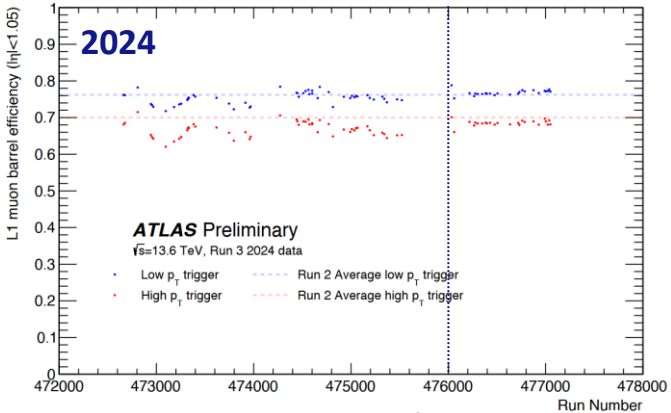
Performance of the Muon Spectrometer in Run 3

- Run 3 is scheduled from July 2022 to spring 2026
- $\sqrt{s} = 13.6\text{TeV}$
- The total recorded luminosity of Run 3 achieved 183fb^{-1} in 2024, overtaking the overall Run 2 dataset of 147fb^{-1}
- **Good for physics runs** are used by ATLAS analysis
- In general, **stable L1 muon barrel trigger efficiency**, comparable with Run 2



DAQ inefficiency, inefficiencies from the "warm start" (switch from standby to operation mode)

Non-standard run conditions



Update of HV corrections

Contribution of the muon spectrometer to the data taking efficiency

ATLAS pp Run-3: 2024														
Trigger	Inner Tracker			Calorimeters		Muon Spectrometer					Magnets		Global	
L1+HLT	Pixel	SCT	TRT	LAr	Tile	MDT	RPC	TGC	MM	sTGC	Solenoid	Toroid	Lumi. calib.	Other
99.7	99.7	99.8	99.9	99.8	99.3	100	99.8	99.8	100	100	98.3	96.6	99.6	99.9
Good for physics: 93.8% (110 fb^{-1})														

DIS2025 (ATLAS Muon Spectrometer Performance), https://twiki.cern.ch/twiki/bin/view/AtlasPublic/DataQualityResults

Phase-I Upgrade

- New Small Wheel project

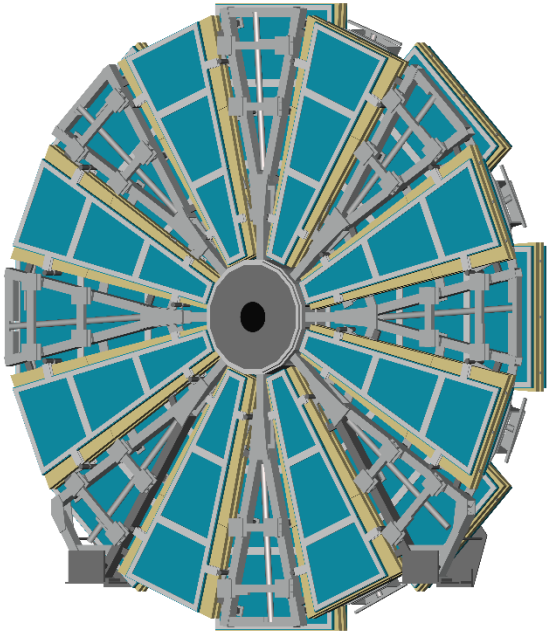
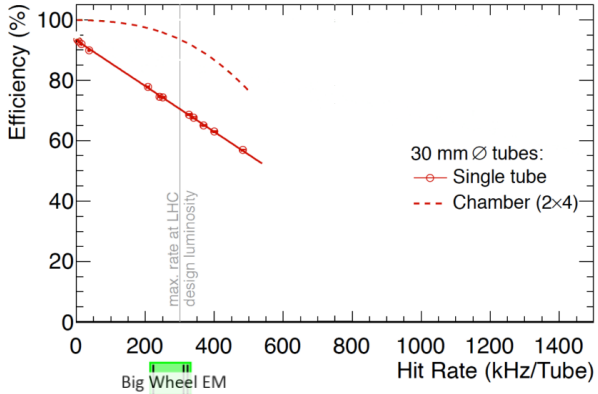


Figure from G. Aad et al 2024 JINST 19 P05063

Motivation for the New Small Wheels (NSW)

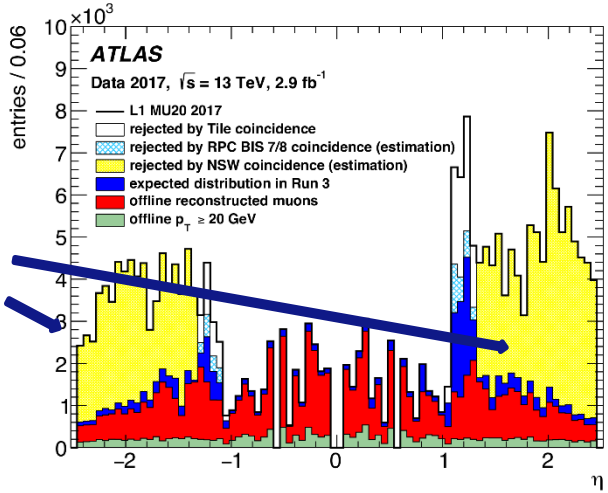
Decrease of the MDT efficiency expected for increased hit rates

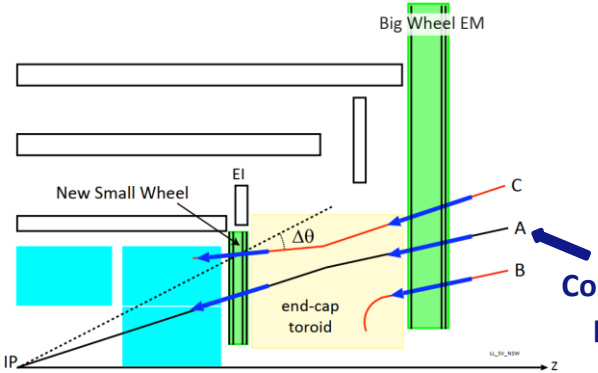
(Technology used in old Small Wheels)



- Maintain muon tracking performance in the muon spectrometer endcap
- Reduction of fake triggers by NSW coincidence with the Big Wheel

Expected muon trigger rate reduction from the NSW



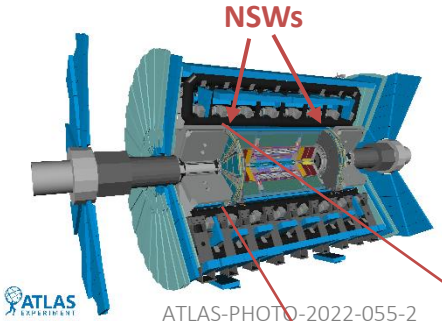


Correctly identified as pointing to the IP

G. Aad et al 2024 JINST 19 P05063, ATLAS-TDR-20

The New Small Wheels (NSW)

G. Aad et al 2024 JINST 19 P05063



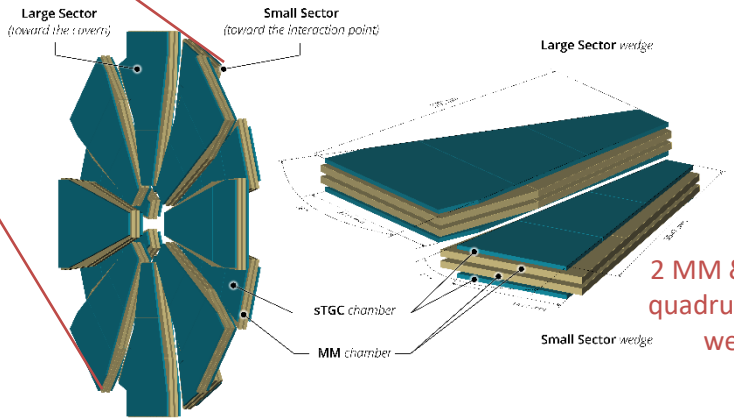
ATLAS-PHOTO-2022-055-2

- Precision tracking and triggering of muons in forward region ($1.3 < |\eta| <$ up to 2.7)
- Operation in high-background region (up to 20kHz/cm^2 expected for HL-LHC)

Performance requirements:

- p_T resolution better than 15% for ~1TeV muons ($\sim 150 - 175\mu$m resolution per plane)
- $> 97\%$ segment finding efficiency for muons with $p_T > 10\text{GeV}$
- ~1mrad angular resolution for L1 trigger track segment reconstruction (needed for HL-LHC)

- **16 sectors**
  8 large & 8 small ones
- **2 detector technologies**
  Micromegas (MM) & sTGCs
- **16 active layers**
  8 Micromegas & 8 sTGC layers



2 MM & 3 sTGC quadruplets per wedge

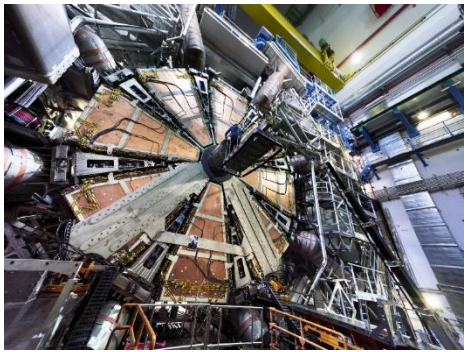


Figure from CERN-PHOTO-202107-094-112

NSW Detector Technologies

G. Aad et al 2024 JINST 19 P05063

Micromegas (MM):

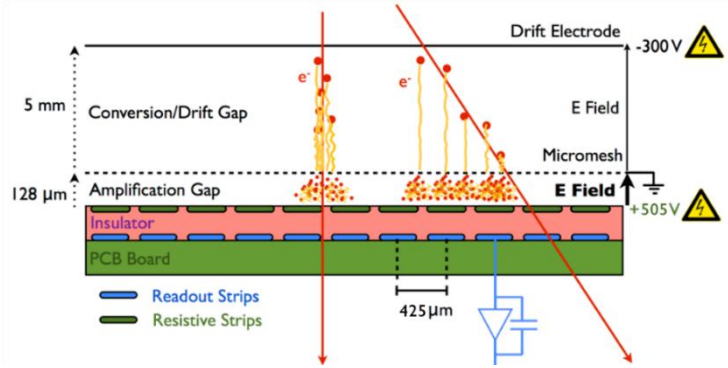
- $\mathrm{Ar}:\mathrm{CO_2}:\mathrm{i\text{-}butane}$ gas mixture $(93:5:2\%)$
- Gas gain close to 10000 by electron avalanche in amplification region

Small-strip thin gap chambers (sTGCs):

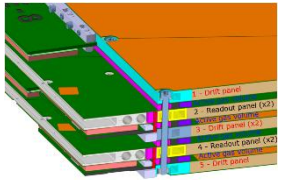
- $\mathrm{CO_2}:\mathrm{n\text{-}pentane}$ gas mixture $(55{:}45\%)$
- Improved ATLAS TGC technology

$\Rightarrow$ Both technologies exhibit trigger and precision tracking ($\sim 100\,\mu\mathrm{m}$) capabilities

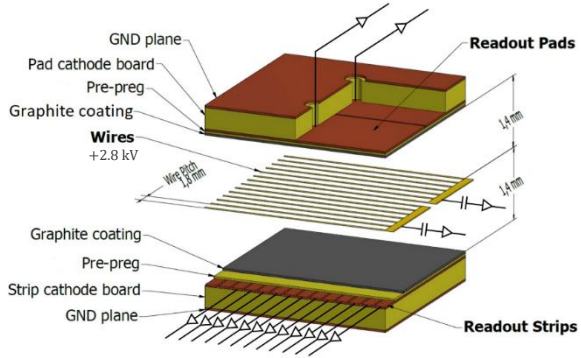
$\Rightarrow$ sTGCs used as primary trigger due to $> 95\%$ single bunch crossing identification capability



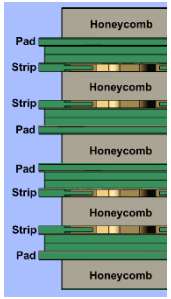
MM operating principle



MM quadruplet structure



sTGC operating principle



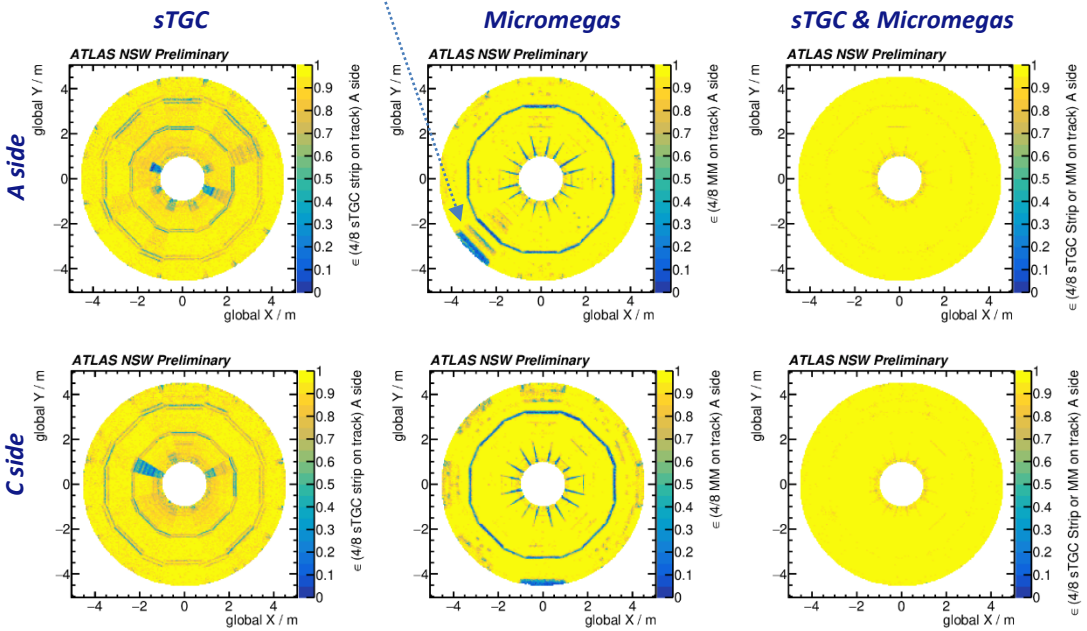
sTGC quadruplet structure

New Small Wheel Performance with Run 3 Data

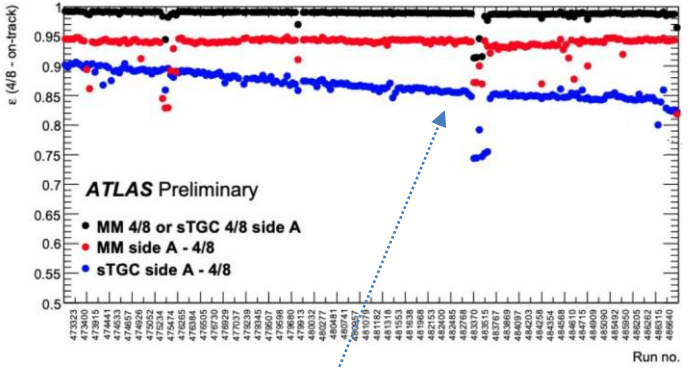
- Efficiency
- Spatial resolution
- Trigger performance
- Muon reconstruction and identification performance

NSW Efficiency

- The efficiency corresponds to having at least 4 out of 8 either sTGC or Micromegas layers associated to a muon track passing through the NSW
- Regions of **low efficiency** are due to detector and readout issues at the time of data taking



High efficiency performance of about 99% achieved in 2024



- **Efficiency decrease** due to sTGC HV failures mainly for the chambers at the centre of the wheel at side A
- A reduction of HV working points in 2024 resulted in a slow down of the effect

NSW Spatial Resolution

- The resolution is obtained from the residuals between the cluster position and the muon track
- Resolution is evaluated as the 68% confidence interval around the peak of a double gaussian fit
- The cluster position is reconstructed from the charge weighted mean value of the strip position

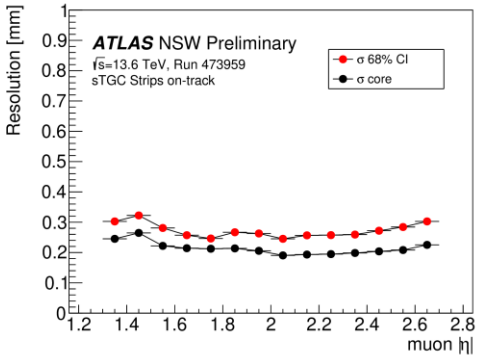
Current performance:

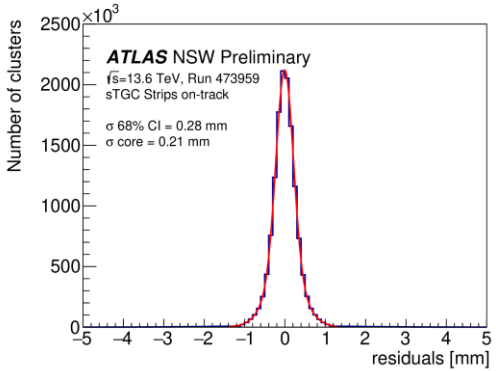
- ~280µm for sTGCs
- ~410µm for Micromegas

⇒ Evaluation of new reconstruction methods using timing information ongoing

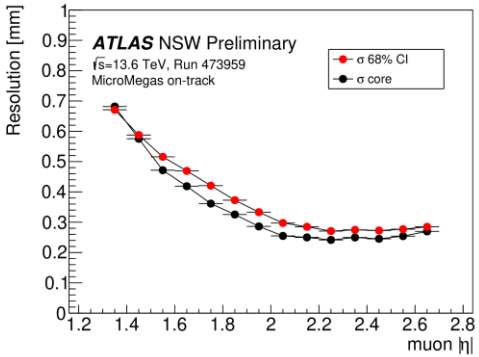
η dependence of the resolution | ***Average resolution***

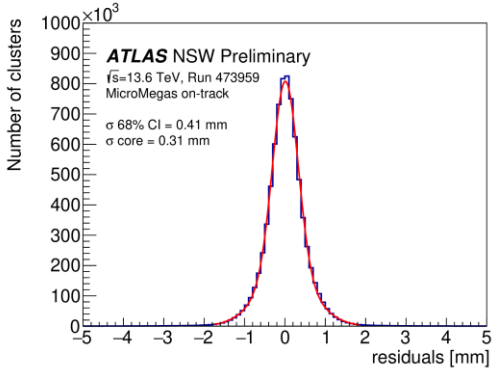
sTGC





Micromegas





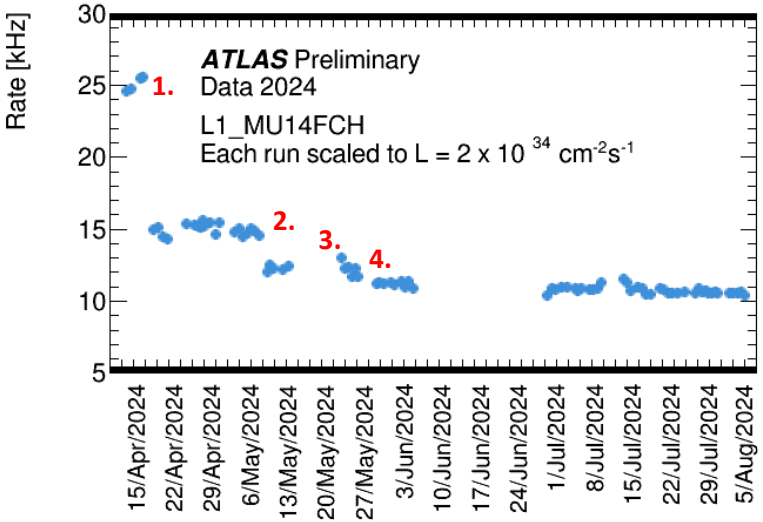
Trigger Performance with the NSW

ATL-COM-DAQ-2024-065

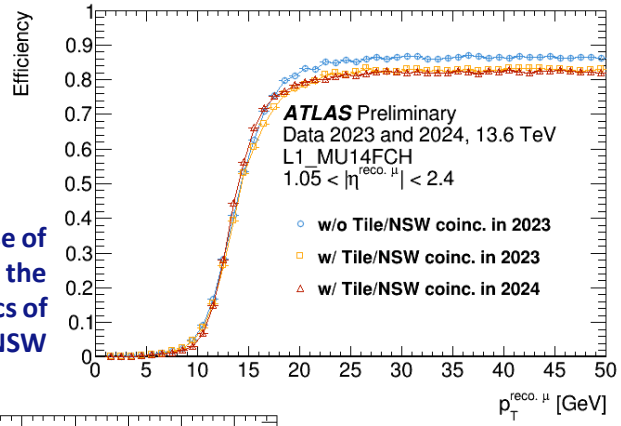
Integration of the NSW into the L1 muon trigger in 2024:

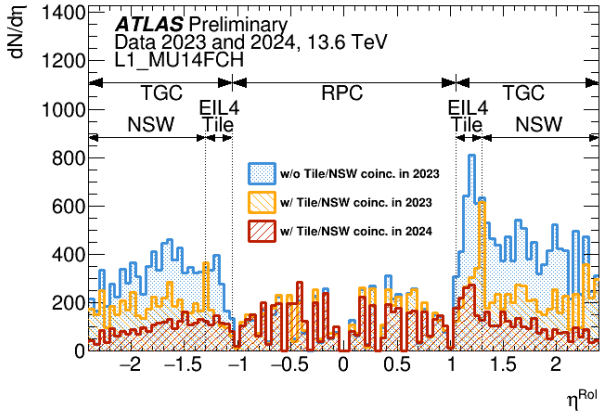
1. 65% of sTGC Pad triggers added ⇒ -10kHz rate
2. 85% of sTGC Pad triggers added ⇒ -3kHz
3. Migromegas triggers included ⇒ $+1\text{kHz}$ but efficiency improvement
4. All sTGC Pad and Micromegas triggers added ⇒ -2kHz

⇒ **Overall rate reduction of 14kHz**



Slight efficiency decrease of about 4%, aligning with the performance characteristics of the NSW





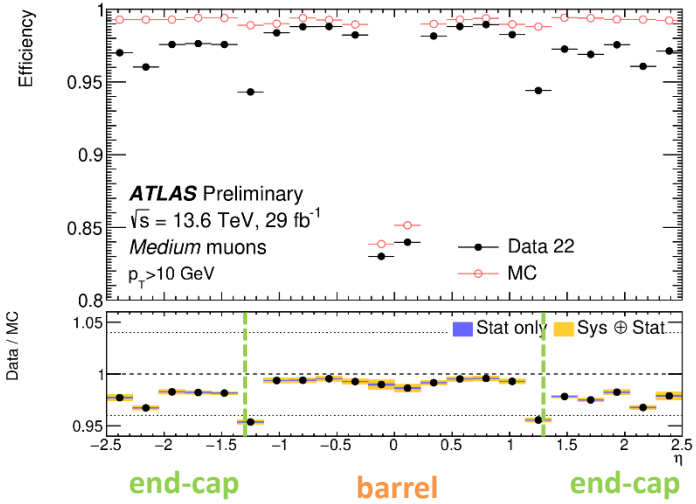
Fake trigger rate reduction in forward region

Muon Reconstruction and Identification Performance

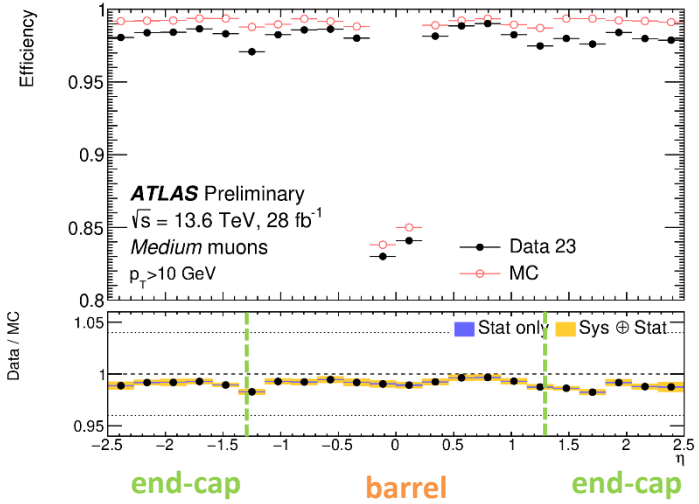
ATL-COM-PHYS-2024-158

- $Z \rightarrow \mu^+\mu^-$ events
- Medium working point

NSW only included in a small fraction of events



NSW fully included in data taking



⇒ Including the NSW in the data taking in 2023 lead to an increase of the efficiency in the end-caps region

⇒ Comparable barrel efficiency for 2022 and 2023

Phase-II Upgrade

- New resistive plate chamber (RPC) installations
- Replacement of monitored drift tubes (MDTs) by small-diameter MDTs (sMDTs)
- Replacement of the electronics of the MDTs, RPCs and thin-gap chambers (TGCs)
- Upgrade of the power system of the RPCs, TGCs and MDTs

Motivation for the Phase-II Upgrade

ATLAS-TDR-10, ATLAS-TDR-026

Aim:

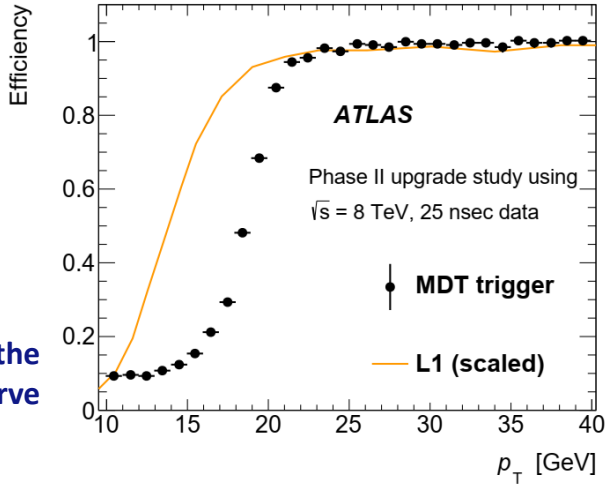
- Preserve excellent muon identification and tracking performance and standalone and combined momentum resolution
  - Harsher conditions with higher particle rates, integrated radiation and pile-up

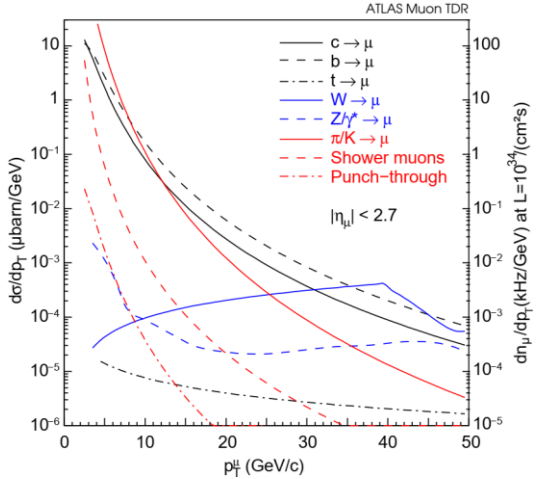
Phase-II:

- Improve selectivity and redundancy of the muon trigger
  - Low p_{T} thresholds required for many physics channels should remain affordable (acceptable trigger rate)

Upgrade study on the performance of an MDT 3-station trigger for a p_T threshold of $20GeV$ with respect to the Run 1 first level trigger; the MDT segments are used from the offline reconstruction

Sharpening of the trigger turn-on curve





Transverse momentum dependence of inclusive muon cross-sections

Too high trigger thresholds would result in losing interesting physics channels

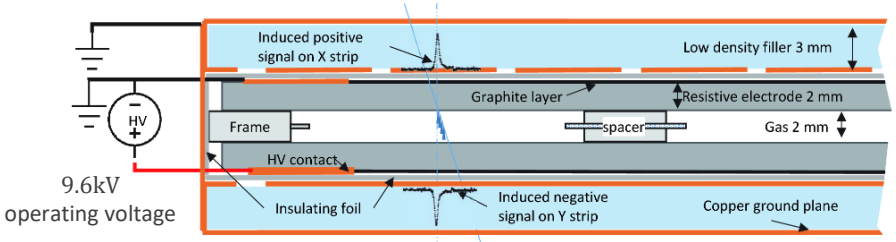
⇒ Main focus of the ATLAS Phase-II upgrade is the trigger and readout system, introducing a new first-level (L0) hardware trigger with a maximum rate increased from $100\mathrm{kHz}$ to $1\mathrm{MHz}$

Legacy Resistive Plate Chambers (RPCs)

- RPCs provide the first-level muon trigger in the barrel region at $|\eta| < 1.05$ and track reconstruction in the non-bending (ϕ) coordinate
- Intrinsic time resolution of 1.1ns achievable through immediate electron avalanche after primary ionisation in the gas gap
- Gas mixture: $C_2H_2F_4 : CO_2 : \text{i-}C_4H_{10} : SF_6$ $(64 : 30 : 5 : 1)$

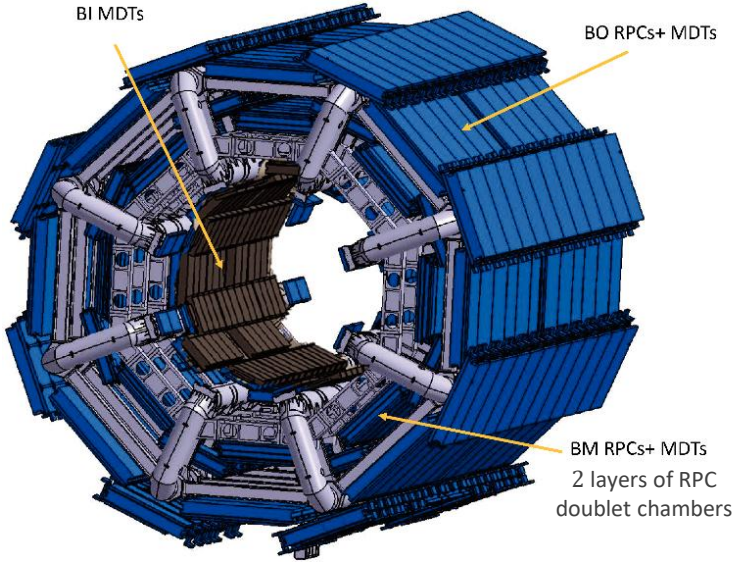
HL-LHC challenges:

- RPCs not designed for the higher luminosity and the extended operational time
- Procurement / use of current gas mixture due to its high global warming potential (GWP)



Cross-section of an ATLAS-like RPC

1094 RPC doublet chambers, arranged in 3 layers



RPC and MDT chambers of the muon spectrometer barrel

Resistive Plate Chamber (RPC) Upgrades

- To extend the lifetime of the legacy RPC chambers, the gas gain need to be reduced by lowering the operational voltage, resulting in efficiency losses between 15% and 35%

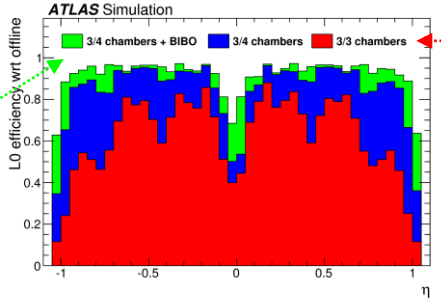
Phase-II upgrades:

- New inner layer of RPCs in the barrel to **recover efficiency** through a more robust trigger logic
- 96 BIS triplets and 130 BIL triplets will be installed
- 80 triplets will be installed in the barrel outer layer
  - no space at the inner layer of sector 11 & 15
- Acceptance increase of up to 96% expected in the barrel

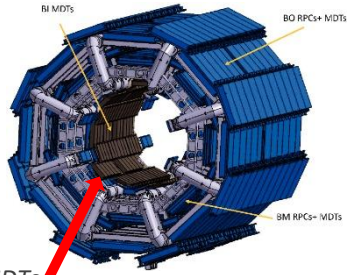
New-generation RPCs:

- Triplet chambers with 3 sensitive gas gaps
- More compact design, increased lifetime and improved performance due to a thinner gas gap
- Improved intrinsic time resolution (from 1.1ns to 0.4ns)
- Operation with low-GWP gas mixtures

Efficiency without/with the new BI RPC chambers

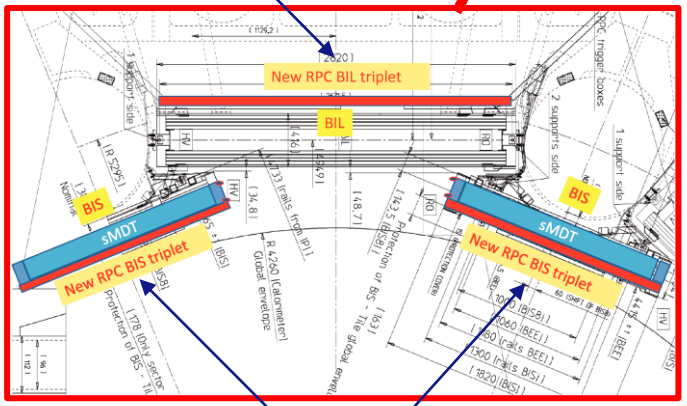


Performance of legacy RPCs



New RPCs will be attached to the existing MDT chambers in the barrel large sectors

Position of the new BI RPCs and BIS sMDTs



Existing MDT chambers will be replaced by sMDT chambers in the barrel small sectors to provide space for new RPCs

Monitored Drift Tubes (MDTs)

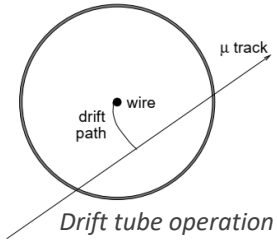
MDT chambers:

- MDT chambers are designed for high-precision tracking in the toroidal field of ATLAS
  - Gas mixture $\mathrm{Ar}:\mathrm{CO}_2$ $(93:7)$ with a pressure of $3\mathrm{bar}$
  - Gas gain: $2 \cdot 10^4$
- Reliable operation up to background counting rates of $500\mathrm{Hz/cm}^2$
  - MDT chambers for which this limits are expected to exceed were replaced during the Phase-I upgrade by the New Small Wheel

Phase-II upgrade:

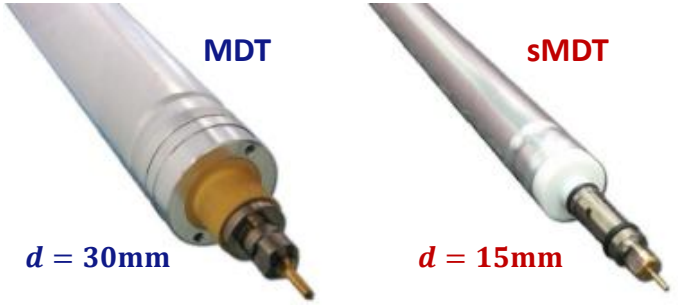
- The new layer of thin-gap RPC chambers at the barrel inner layer requires additional space

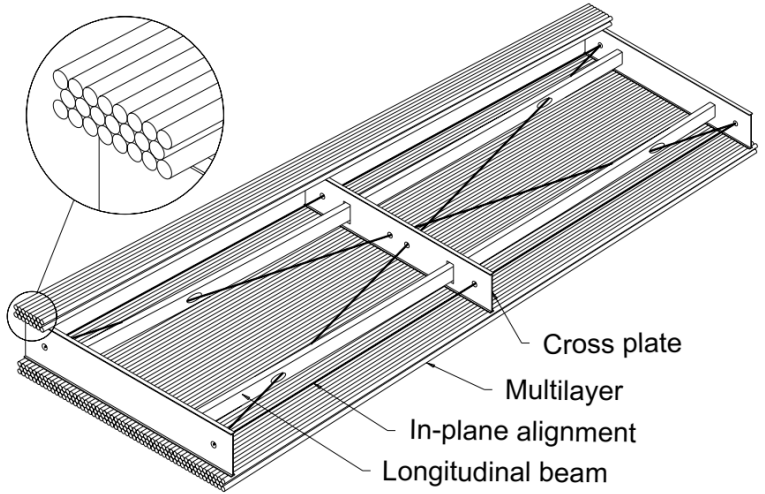
$\Rightarrow$ Installation of small-diameter MDT (sMDT) chambers to replace the larger MDT chambers



Drift tube operation

Comparison of the MDT and sMDT drift tubes





Schematic drawing of an MDT chamber

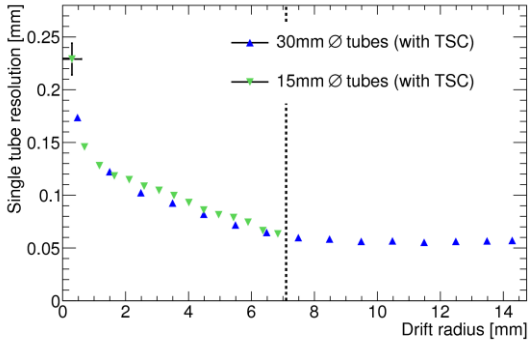
Small-Diameter Monitored Drift Tubes (sMDTs)

sMDT chamber characteristics:

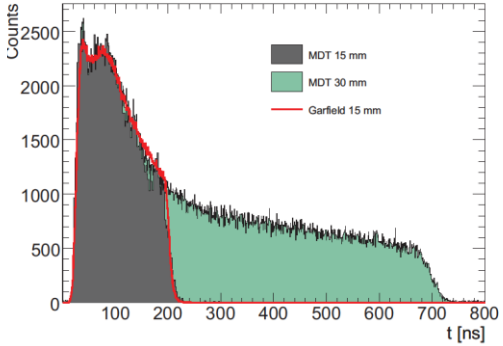
- Same gas mixture, gas pressure, gas gain as MDTs
- Operating voltage reduction from 3080V to 2730V
- Wire position accuracy better than $10\mu\text{m}$ ($20\mu\text{m}$ for MDTs)
- Rate capability ~ 10 higher
- No ageing observed up to an accumulated charge on the same wire of 9C/cm

$\Rightarrow$ Similar performance as MDTs with a reduced maximum drift time from 720ns to 175ns

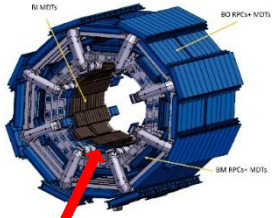
Single tube resolution

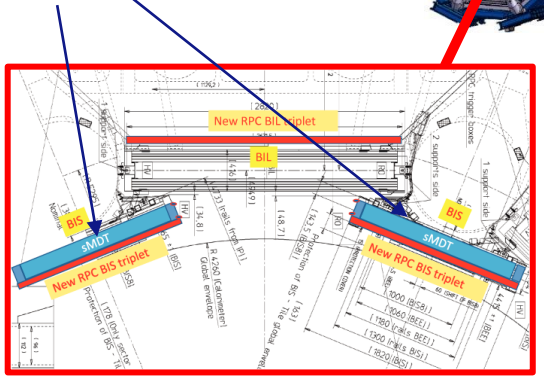


Drift time spectrum



96 MDT chambers will be replaced by sMDT chambers in the barrel small sector inner layer to provide space for the new additional RPCs





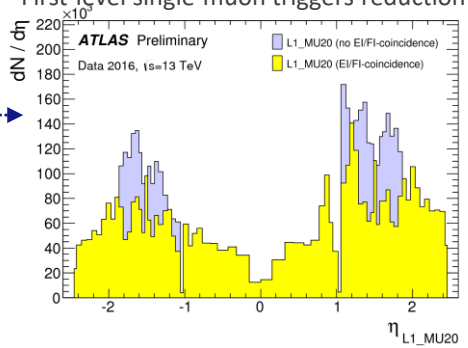
$\Rightarrow$ Two small sector MDT chambers at the A side, BIS7 and BIS8, were already replaced with 8 new unified sMDT chambers (BIS78) as part of the Phase-1 upgrade

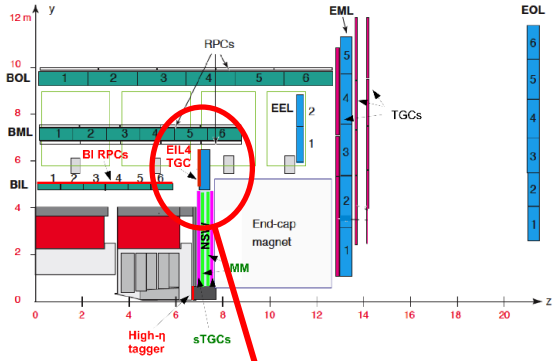
Thin Gap Chamber (TGC) EIL4 Upgrade

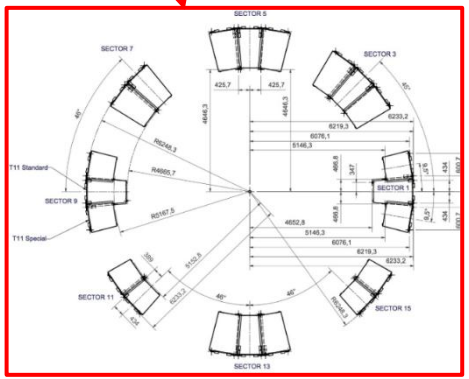
LHC-HL challenges:

- Original TGCs not designed for being part of the trigger system but allow for rejection of fake triggers and a uniform level of purity for triggered muons in the endcap
  - Important especially for high background regions of the EIL4 TGC chambers (expected hit rate $450\mathrm{Hz/cm^2}$)

First-level single-muon triggers reduction







TGC EIL4 system layout

Phase-II Upgrade:

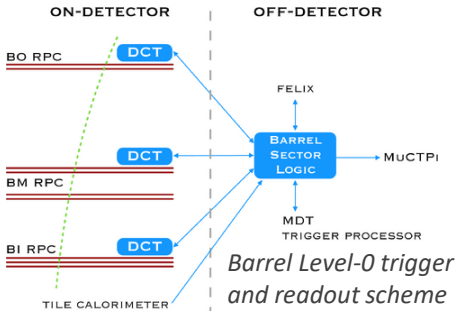
- Replacement of 2×21 EIL4 TGC chambers in the barrel-endcap transition region ($1.05 < |\eta| < 1.3$) of the large sectors

New chamber design:

- Finer readout granularity to reduce random coincidences with background hits
- New triplet TGC chamber design instead of doublets to allow for more robust 2/3 trigger logic in case one plane becomes inoperable

Replacement of the MDT, RPC & TGC Electronics

Trigger and readout electronics requires replacement for compatibility with the higher trigger rates and longer latencies of the new Level-0 trigger



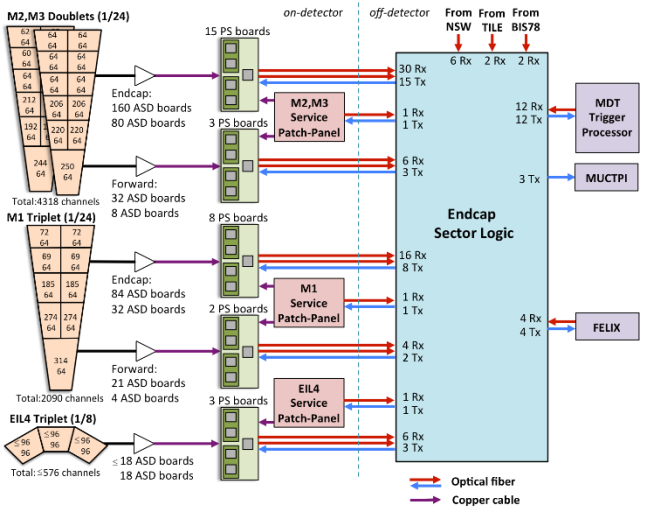
Barrel Level-0 trigger and readout scheme

- **TGC** upgrade motivated to exploit excellent track segment resolution of the NSW ($\sim$1mrad)

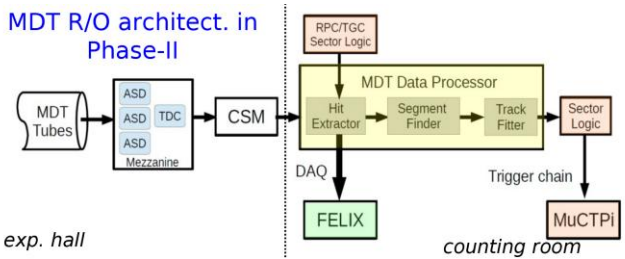
⇒ Replacement of coincidence-based trigger by a tracking-based one

- Replacement of all present trigger and readout electronics except for the ASD boards mounted directly on the chamber

⇒ Installation of new data collector and transmitter (DCT) boards for **RPCs** and retro-fitting of a selected set of chambers with new front-end electronics



Schematic diagram of the TGC electronics system for 1/24 of the Big Wheel TGC (one forward trigger sector and two endcap trigger sectors)



- To sharpen the p_{T} threshold of the muon trigger, **sMDTs & MDTs** will be included in the Level-0 trigger

⇒ New mezzanine cards and chamber service modules (CSMs) required

ATL-MUON-SLIDE-2020-072

ATLAS-TDR-026

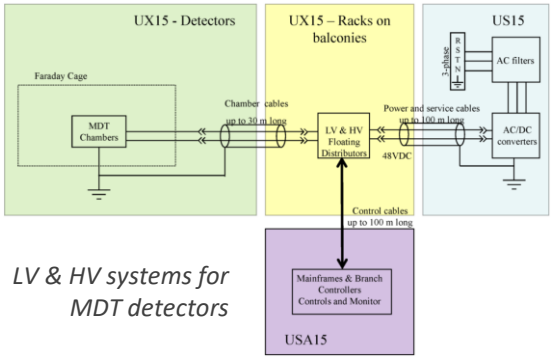
Power System Upgrade

- The muon spectrometer comprises an extensive powers system including HV & LV power supply modules as well as modules for monitoring and control
- **Main challenges for HL-LHC:**
  - Ageing and limited lifetime
  - Irradiation ⇒ components not designed/tested for HL-LHC
  - Component obsolescence and possibly maintenance difficulties until 2035-2040

⇒ Gradual replacement starting after Run 3 and until ~2030

⇒ Backwards-compatible devices required

⇒ Development and procurement together with other LHC experiments



LV & HV systems for MDT detectors

To be replaced in long-shutdown 3 and beyond

+ need for additional modules for the RPCs and the NSW

CAEN module	Function	MDT	RPC	TGC	CSC	Total
A3000NF	3-phase notch filter	11	2	2		15
A3009	12 ch. 8V/9A/45W		92			92
A3016B	6 ch. 8V/16A/90W	32				32
A3025A	4 ch. 8V/25A/150W		25			25
A3025B	4 ch. 8V/25A/150W	126	86			212
A3025D	4 ch. 8V/25A/150W			79		79
A3050D	2 ch. 25-80A/150-450W			30		30
A3100D	1 ch. 8V/100A/600W			84		84
A3485	2 ch. 3-phase 400V AC-48V DC	23	4	5	3	35
A3486	2 ch. 3-phase 400V AC-48V DC		28	30	2	60
A3512A	6 ch. 12kV/1mA		89			89
A3535A	32 ch. 3.5kV/0.5mA			134	22	156
A3540A	12 ch. 4kV/1mA	208			13	221
A3801	128 ch. ADC		58			58
A3802	128 ch. DAC		32			32
A1676A	EASY branch controller	18	23	16	2	59
EASY3000	RPC and TGC crate		88	24	4	116
EASY3000M	TGC special crate			26		26
EASY3000R	TGC special crate			12		12
EASY3000S	MDT crate	72				72
SY4527A	Mainframe	3	4	2	8	17
Total		**493**	**531**	**444**	**54**	**1522**

Inventory of the CAEN EASY 3000 power system components of the muon spectrometer without NSW

Status of the Phase-II upgrade

- **RPCs**
  - $\sim 40\%$ of the BI gas volumes produced, BI strip panels are fully produced
  - Front-end ASICS electronics fully produced, front-end boards to be produced in the coming months
  - Trigger board prototype currently under tests
- **sMDTs & MDT**
  - sMDT front-end board production completed
  - Production of the MDT front-end boards advanced
  - CSM production and validation planned for this year
  - All required sMDT chambers are built and shipped to CERN; the chamber commissioning and integration is ongoing
- **TGC EIL4 chamber upgrade**
  - EIL4 TGC chamber production ongoing ($\sim 2/3$ of singlets and $\sim 1/2$ of triplet chambers are produced)
  - Successful installation of pilot sector C09 in YETS
  - Electronics production completed
- **Power system**
  - Most urgent prototypes have been delivered and tested
  - Order for preproduction expected to be ready by spring 2026 (consistent with the present schedule)

Conclusion

Phase-I upgrade:

- The New Small Wheel is the main project of the ATLAS Phase-I upgrade, comprising 2 detector technologies with excellent trigger and tracking capabilities

Run-3 performance:

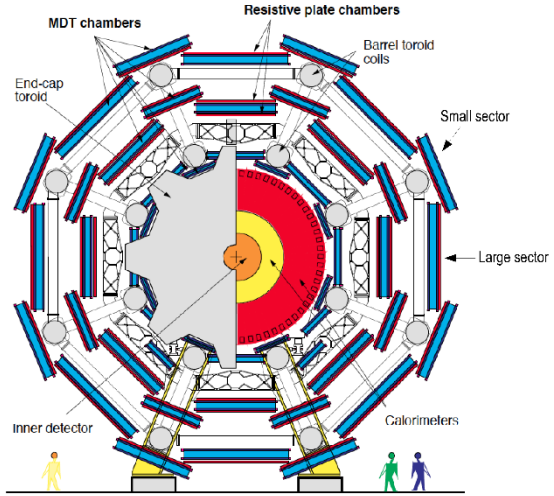
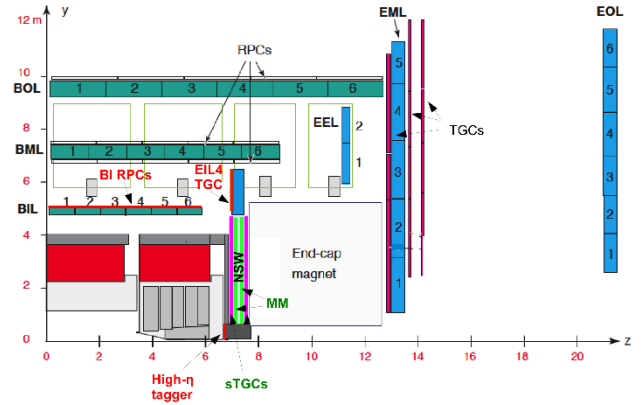
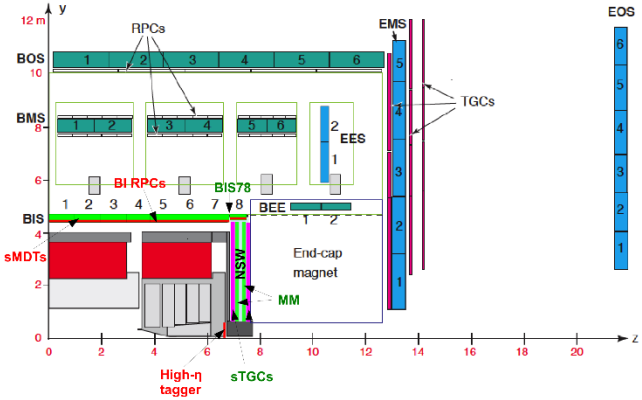
- Good muon spectrometer performance in the first years of Run 3 data taking
- The New Small Wheel indicates good efficiency and trigger performance; new reconstruction methods for the micromegas spatial resolution including timing information are studied
- The New Small Wheel improves the muon reconstruction and identification performance

Phase-II upgrade:

- To improve trigger performance, additional layers of RPCs and new TGCs will be installed; the MDTs will be included in the trigger
- The barrel inner MDTs of the small sector will be replaced by sMDTs to provide space for the additional RPC layer
- Electronic upgrades ensure compatibility with the new L0-trigger
- Ageing, radiation damage and component obsolescence requires upgrade of the power system
- Overall, the preparation for HL-LHC is progressing well

Thank you for your attention!

Backup

Muon detection

- Muon are usually detected in an inner, middle and outer layer of the muon spectrometer barrel or endcap
  - Barrel layers BI, BM, BO
  - Endcap layers EI, EM, EO
- In the transition region ($1.05 < |\eta| < 1.3$), muons are detected in the EIL4 or BIS7/8, EE (extra) and EM layers
- Around $|\eta| = 1.6$ where the magnetic field reverses sign, the BEE layer provides a fourth measurement layer