# Overview of ATLAS muon detectors: status and performance

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Abstract The ATLAS Muon Spectrometer, the largest muon system ever built at colliders, now comprises both legacy gaseous detectors—Monitored Drift Tubes (MDT), Thin Gap Chambers (TGC), and Resistive Plate Chambers (RPC)—which have been in operation for over 15 years, as well as newer technologies like Micromegas and small-strip TGCs in the NSW. These new systems are now in stable operation, following an extensive phase of construction and commissioning, which provides enhanced muon tracking and trigger capabilities. This presentation covers the status and performance of the Muon system.

## 1. ATLAS Muon Spectrometer (MS)

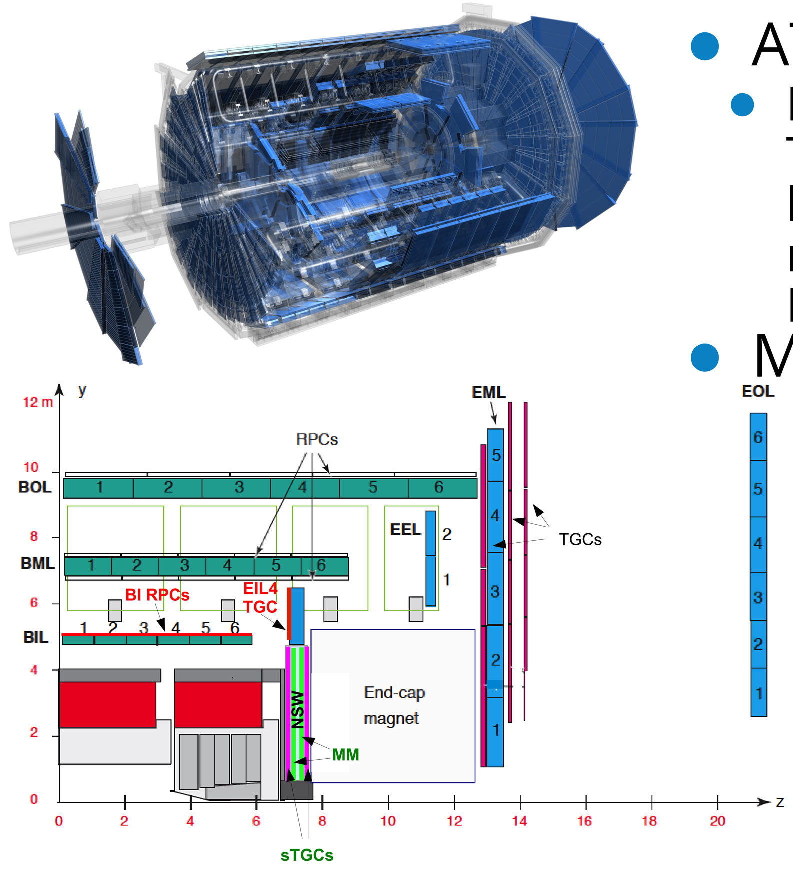
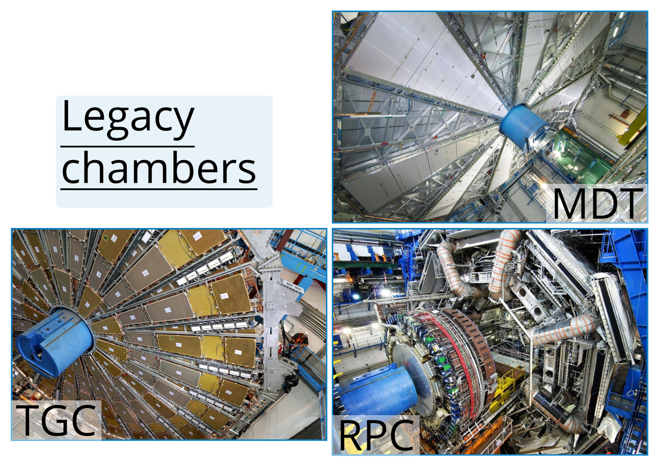


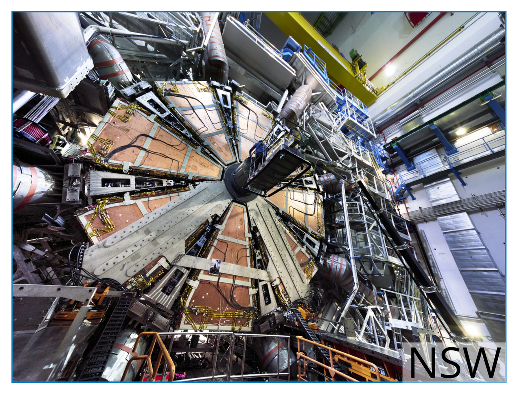
Fig. 1: Schematic view of ATLAS detector (top) and Muon Spectrometer (bottom).

- ATLAS detector: multi-purpose detector at LHC.
  - It consists of Inner Detector, Calorimeter, and Muon Spectrometer. Their designs were proposed around middle of 1990s. While the basic detector design has worked well for over ten years, the readout electronics were upgraded along with the upgrade of the LHC.
- MS: Track measurement and trigger for muon
  - Toroid magnet + complex of detectors

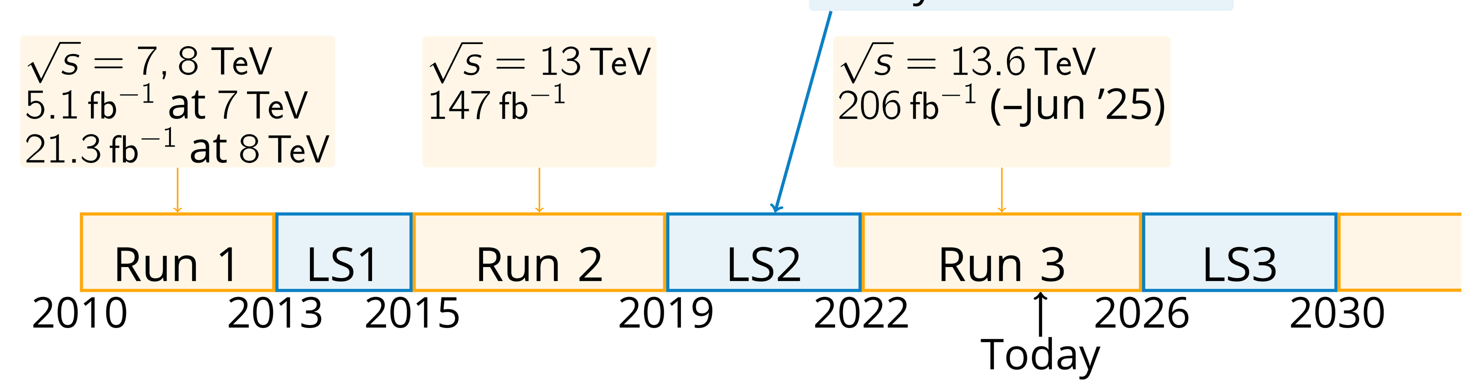
| Chamber | Main Usage | $N_{ch}$ |
|---|---|---|
| Legacy chambers | | |
| Resistive Plate Chamber | Trigger | $3.8\times10^5$ |
| Thin Gap Chamber | Trigger | $3.1\times10^5$ |
| Monitored Drift Tube | Tracking | $3.4\times10^5$ |
| New Small Wheel | | |
| small-strip TGC (sTGC) | Trigger & Tracking | $3.6\times10^5$ |
| Micromegas detector (MM) | Trigger & Tracking | $2.1\times10^6$ |









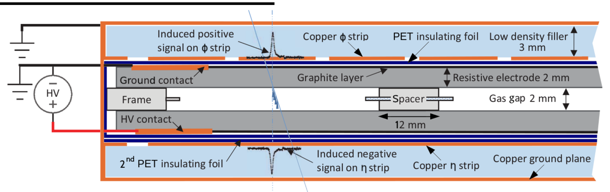




## 2. Legacy chambers since the beginning of ATLAS

Three types of chambers are working over 10 years. In addition, Cathode Strip Chamber was installed during Runs 1 and 2.

### Resistive Plate Chamber (RPC)



- Trigger detector
  - Timing resolution: $\sim 1.5$ ns
  - Coverage: $|\eta| < 1.05$
  - Double sided readout: $\phi$–$\eta$ orthogonal strips
- Gas mixture selection

| | $C_2H_2F_4$ | $CO_2$ | $C_4H_{10}$ | $SF_6$ | GWP |
|---|---|---|---|---|---|
| –2023 | 94.7 % | 0 % | 5 % | 0.3 % | 1450 |
| 2023–2024 | 64 % | 30 % | 5 % | 1 % | 1150 |
| 2025 | 64.5 % | 30 % | 5 % | 0.5 % | 1050 |

- Fluorine (F) has high Global Warming Potential (GWP). The gas leak is issue in operation. Gas mixture optimization and sealing are devoted to suppress environmental effect.

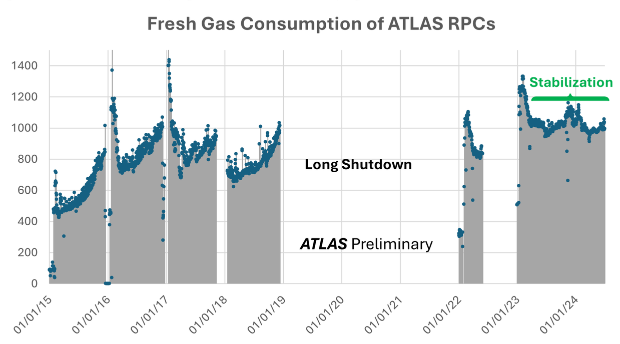
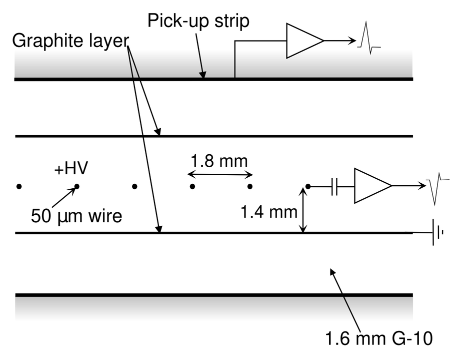




Fig. 2: time developmen of RPS gas leak.

### Thin Gap Chamber (TGC)



- Trigger detector
  - Timing resolution: $\mathcal{O}(1)$ ns $> 99$ % eff. for 25 ns gate
  - Coverage: $1.05 < |\eta| < 2.4$
  - Wire + strip readouts for $\eta$ and $\phi$ direction
  - Gas: $CO_2$(55 %)–n-$C_5H_{12}$(45 %)
- Working stably over time
  - Failure rate is 0.5 %/year. The working fraction is kept above $\sim 99$ % by annual maintena

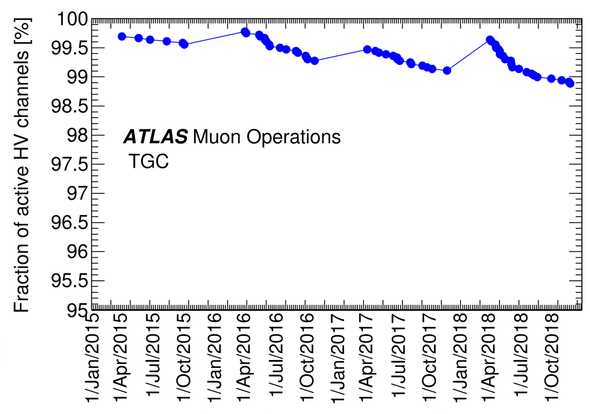
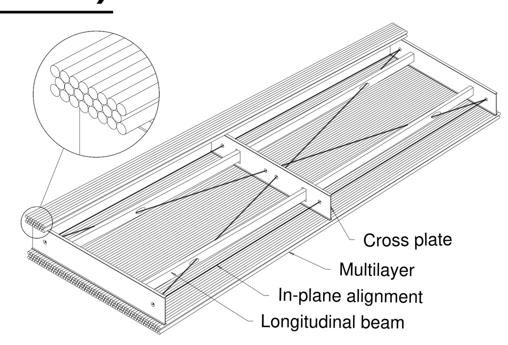




Fig. 3: time development of TGC dead channel fraction.

### Monitored Drift Tube (MDT)



- Precise tracking
  - Spatial resolution by drift-time on $\eta$-direction
  - Tube radius: 15 mm (720 ns max)
  - Coverage: barrel & endcap ($|\eta| < 2.7$)
  - Gas: Ar(93 %)–$CO_2$(7 %) with 3 bar
- Low dead channel fraction
  - The fraction is kept minimal, $\sim 0.5$ %, by extensive maintenance.

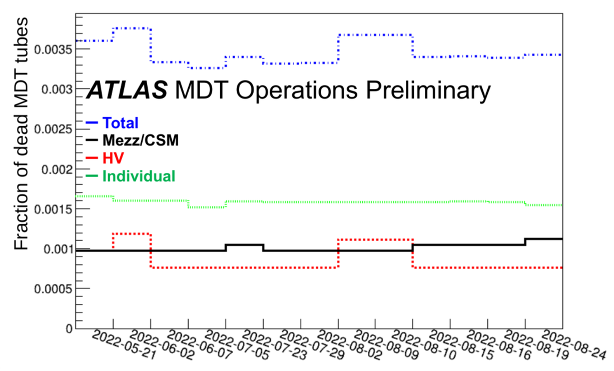


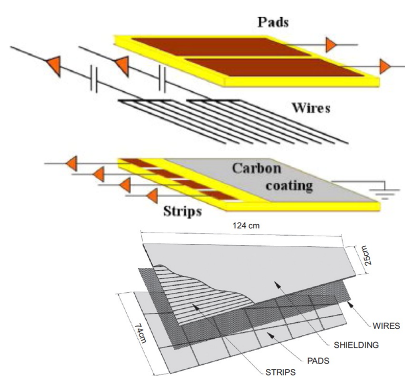


Fig. 4: time development of fraction of MDT dead tubes.

## 3. Phase-I Upgrade: New Small Wheel (NSW)

- Endcap system upgrade: inner stations
  - Precision tracking & trigger: fine channels and fast response
  - Motivation: to improve high-luminosity performance in Phase-I upgraded LHC (Run 3–) and High-Luminosity LHC upgrade (Run 4–). High background radiation region $\lesssim 20$ kHzcm$^{-2}$.
- Two technologies: small strip TGC (sTGC) and Micromegas (MM)
  - Four wedges consisting of sTGC quadruplets or MM quadruplets: sTGC–MM–MM–sTGC. In total, 16 sensible layers.

### Small strip TGC (sTGC)



- Channel geometry

| | Direction | Pitch |
|---|---|---|
| Wire | $\phi$ | 1.8 mm |
| Strip | $\eta$ | 3.2 mm |
| Pad | $\eta\times\phi$ | |

- Performance in 2024 runs
  - $\sigma \sim 200$ µm and uniform in $\eta$

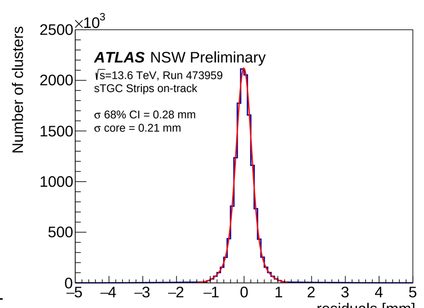
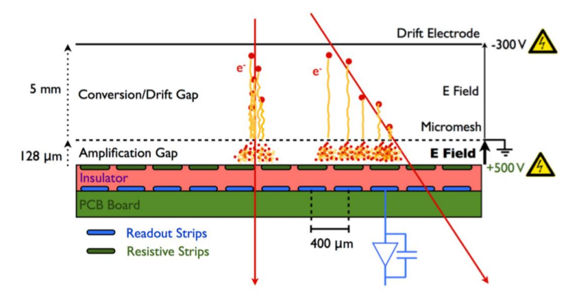




Fig. 5: sTGC's hit residual.

### Micromegas (MM)



- Ch. geometry:
  - 0.4 mm pitch strips
  - One-quadruplet: two $\eta$-layers + two inclined stereo layers with $\pm1.5°$
- Performance in 2024 runs
  - $\sigma \sim 300$ µm with $\eta$-dependency.

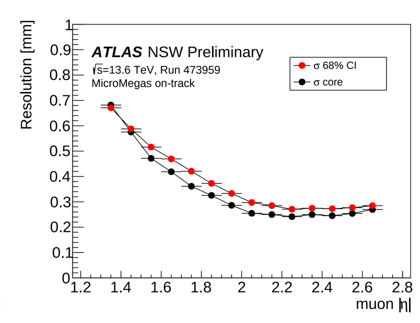


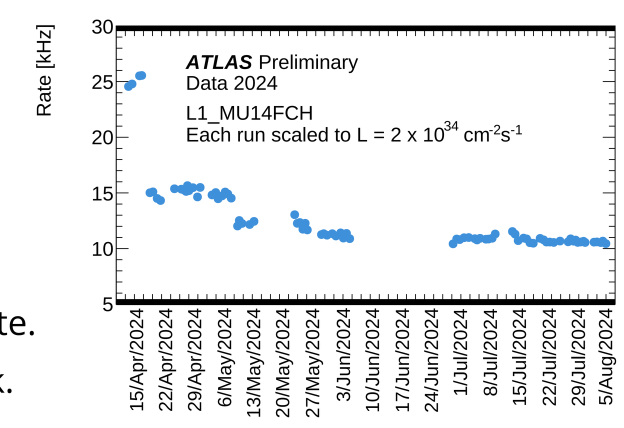


Fig. 6: MM's hit resolution as a function of $|\eta|$.

### Trigger Improvement

Requiring coincidence between NSW and TGC helps in suppression of fake tracks. In 2024, the trigger processors are activated in operation in almost all sectors. After the full activation:

$\Rightarrow$ Significant L1 rate reduction: 25 kHz $\to$ 10.5 kHz.





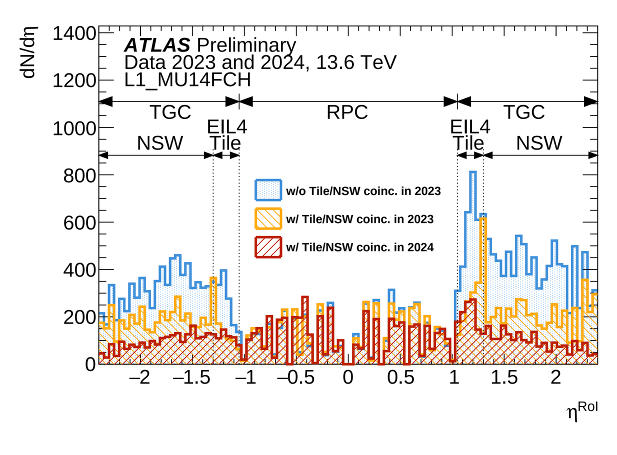




Fig. 7 (left): Muon level-1 trigger rate.

Fig. 8 (right): $\eta$ distribution of level-1 muon track.

## 4. Combined performance of muon tracking

- Tasks
  - Reconstruction and identification: determined by combination of Inner Tracker, Calorimeter, and MS.
  - Isolation: identifying the muon is originating from the heavy particles, such as $W, Z$, or Higgs bosons, or produced in semileptonic decays of $t, b$ etc.
  - Momentum calibration: geometric correction factor and charge effects for MC and data differences.
    - ▶ Detector alignment and understanding of magnetic fields are essential. Left and right figures of Fig. 9 show the correction factor, which reflects poor alignment and deformation, for 2022 and 2023. In 2023, the NSW information newly included and suppress the correction scale in the endcap region.
- $m_{\mu\mu}$ resolution: The performances were evaluated via $J/\Psi$ and $Z$ events. Fig. 10 shows the resolution in Run 3, which shows similar performance to Run 2.
  - Further improvement is expected and under study with timing information.

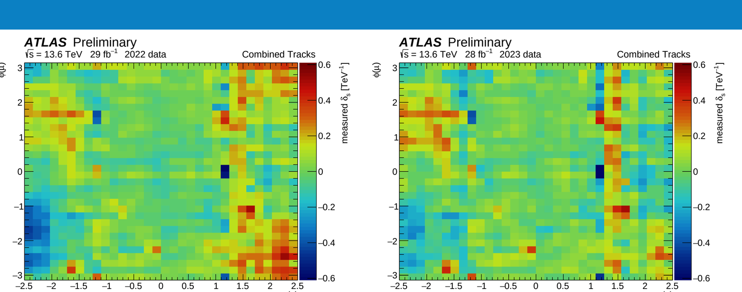




Fig. 9: $p_T$ correction factor for 2022 (left) and 2023 (right).

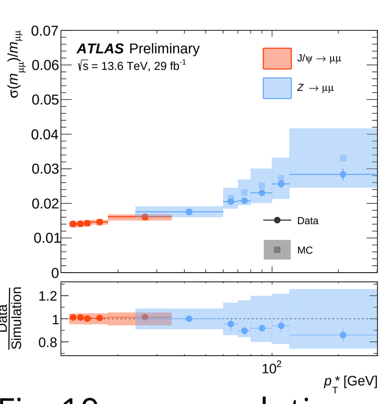




Fig. 10: $m_{\mu\mu}$ resolution.

## 5. Summary and prospects

The current ATLAS muon spectrometer consists of three legacy types of chambers and two new types of chambers. Even the legacy chambers are working for more than ten years, the failure rate is minimized thanks to daily maintenance. To keep aligned with the recent social requirement of environmental effect, gas mixtures are under optimization. The new technology, NSW, plays a significant role in the fake trigger rate suppression. The precise structure of the NSW helps to keep the reconstruction performance. Those legacy and new chambers will be running in HL-LHC era, which plans additional ten years.

Reference: [1] ATLAS Collaboration, "ATLAS muon spectrometer: Technical Design Report," CERN-LHCC-97-022, [2] T. Kawamoto, *et al.*, "New Small Wheel Technical Design Report," CERN-LHCC-2013-006.

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