Performance of the ATLAS Muon Spectrometer Detectors during Run3 data taking

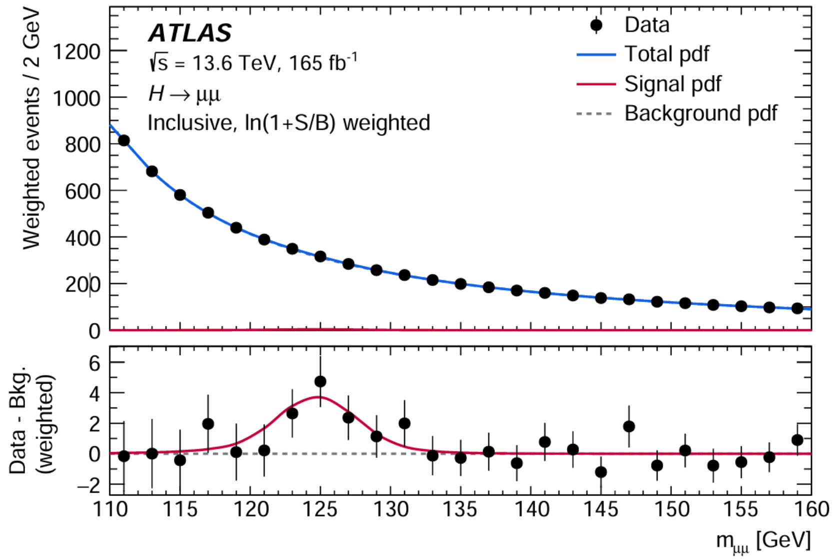
XIV International Conference on New Frontiers in Physics
Kolymbari, Crete, Greece, 24 July 2025

Arisa Wada (Nagoya Univ.)
on behalf of the ATLAS collaboration

Introduction and Motivation

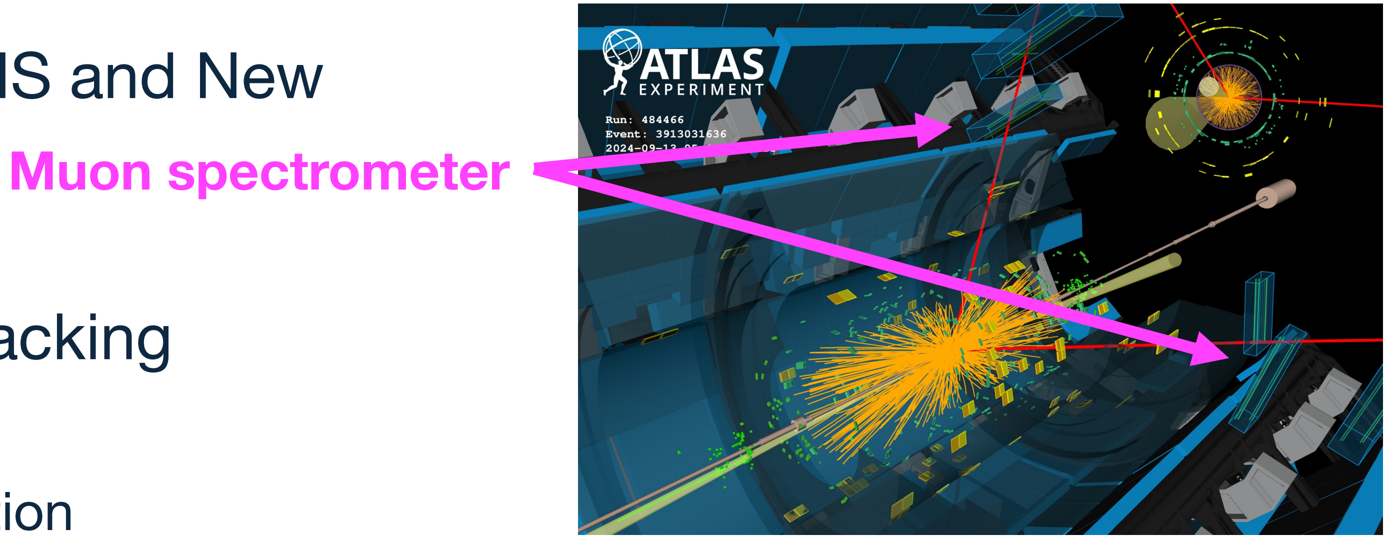
- Muon Spectrometer (MS) is essential in many physics analyses
- Used for both **trigger** and **precision tracking**
- Run 3 data taking under high pile-up conditions demands stable detector operation

example of recent analysis: $H \to \mu\mu$



<u>This talk covers:</u>

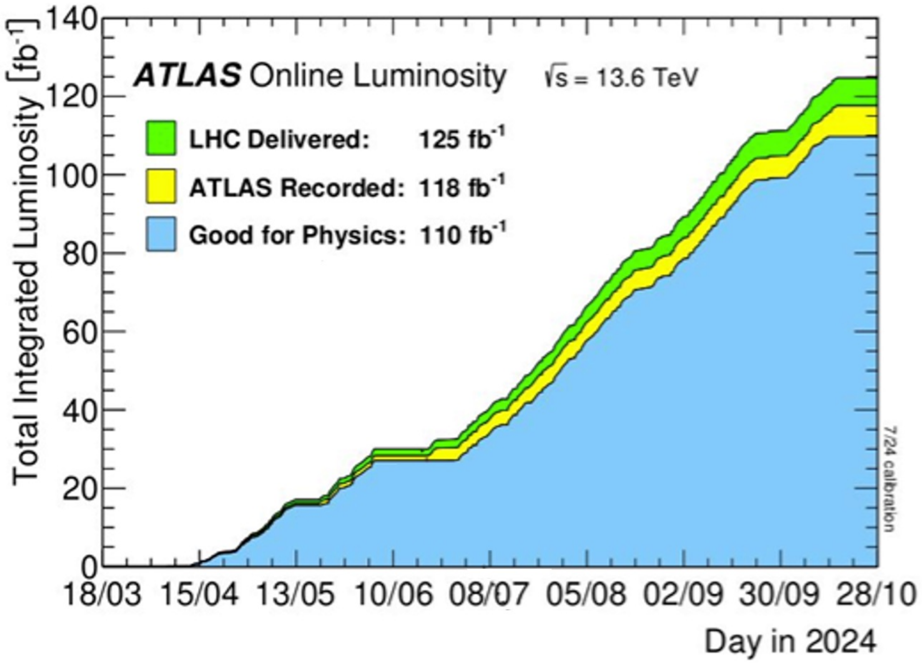
- Run 3 data taking overview
- Brief introduction of the legacy MS and New Small Wheel (NSW)
- Muon trigger system overview
- NSW impact on triggering and tracking
  - Trigger rate
  - Muon identification and reconstruction



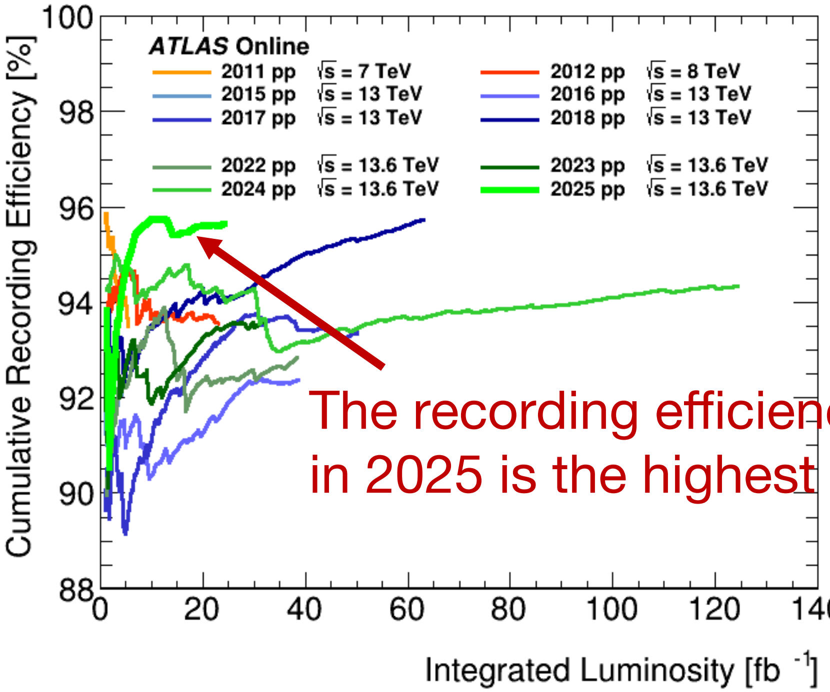
Run 3 data taking in ATLAS

- Run 3: from July 2022 to spring 2026
- Center-of-mass energy: 13.6 TeV

- LHC delivered a record amount of data in 2024



link



link

Fraction of data usable for physics analysis

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})														

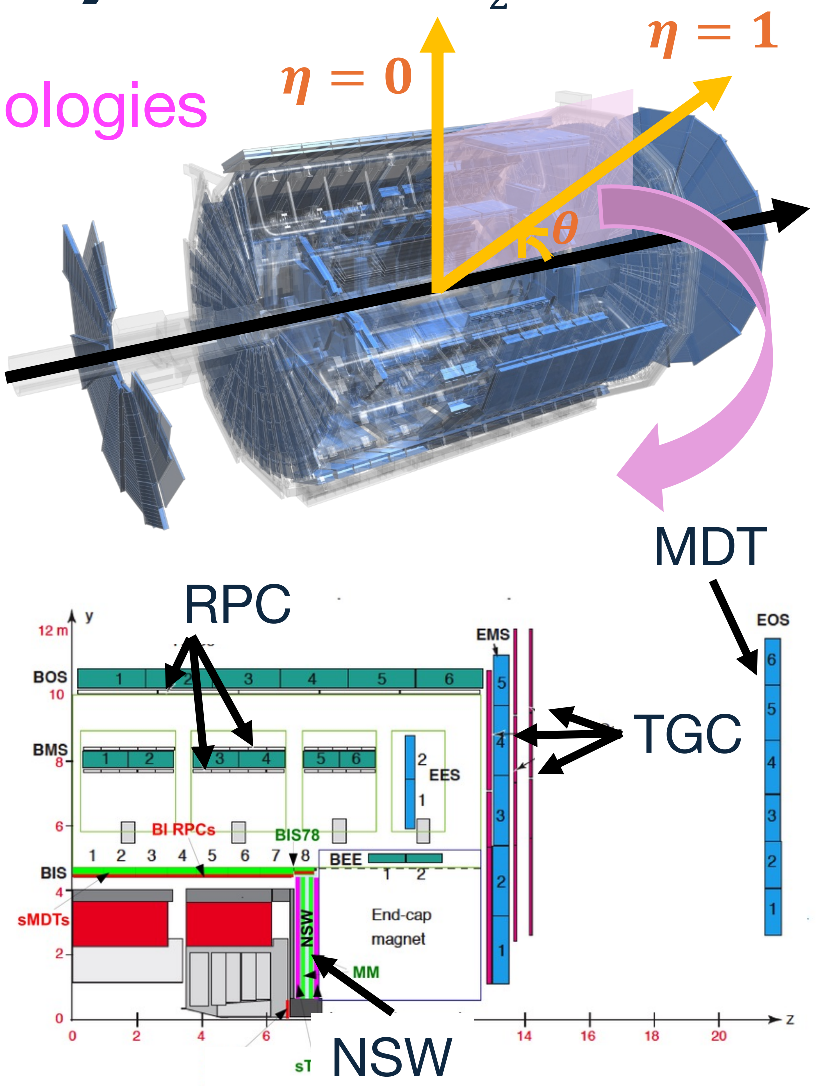
MS had >99% good data quality efficiency

ATLAS Muon Spectrometer (MS)

Pseudorapidity:
$\eta = -\ln \tan \frac{\theta}{2}$

◆ MS consists of three legacy and two new detector technologies

Chambers	Main Usage	Coverage
Monitored Drift Tubes (MDT)	Tracking	$\lvert\eta\rvert < 2.7$
Resistive Plate Chamber (RPC)	Trigger	$\lvert\eta\rvert < 1.05$
Thin Gap Chamber (TGC)	Trigger	$1.05 < \lvert\eta\rvert < 2.4$
New Small Wheel (NSW)		
├ Micromegas (MMG)	Tracking & Trigger	$1.3 < \lvert\eta\rvert < 2.7$
└ Small-strip TGC (sTGC)	Tracking & Trigger	$1.3 < \lvert\eta\rvert < 2.7$

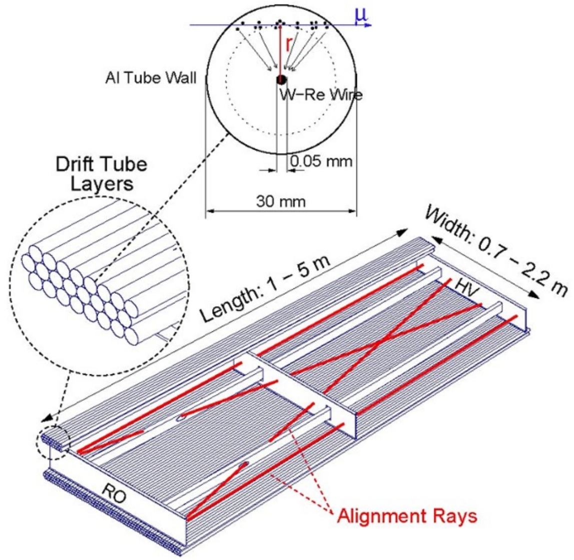


- The role of MS: Tracking and triggering for muon
- Legacy chambers are stable with no major issues
- Aging effects are managed through yearly maintenance and replacements

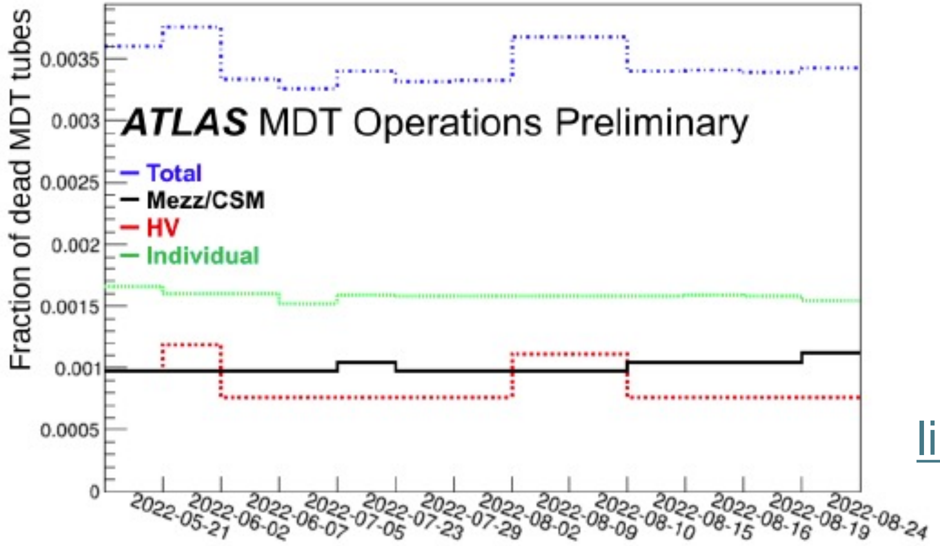
Performance of MDT

Precise tracking, single-tube resolution: 80 μm

- Two multi-layers (each with 3-4 tube layers) measure the η-direction
- Coverage: barrel and endcap
- Gas: Ar + CO_2 (93:7) with absolute pressure of 3 bar
- Nominal voltage: 3.08 kV



- The total fraction of dead tubes is at 0.35%
  - Due to highly reliable and robust system
- Ensure stable and long-term operation throughout Run 3



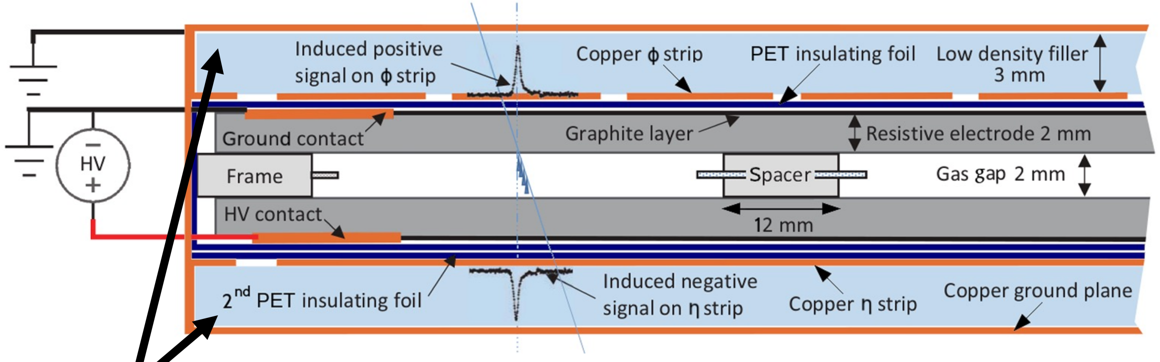
link

Performance of RPC

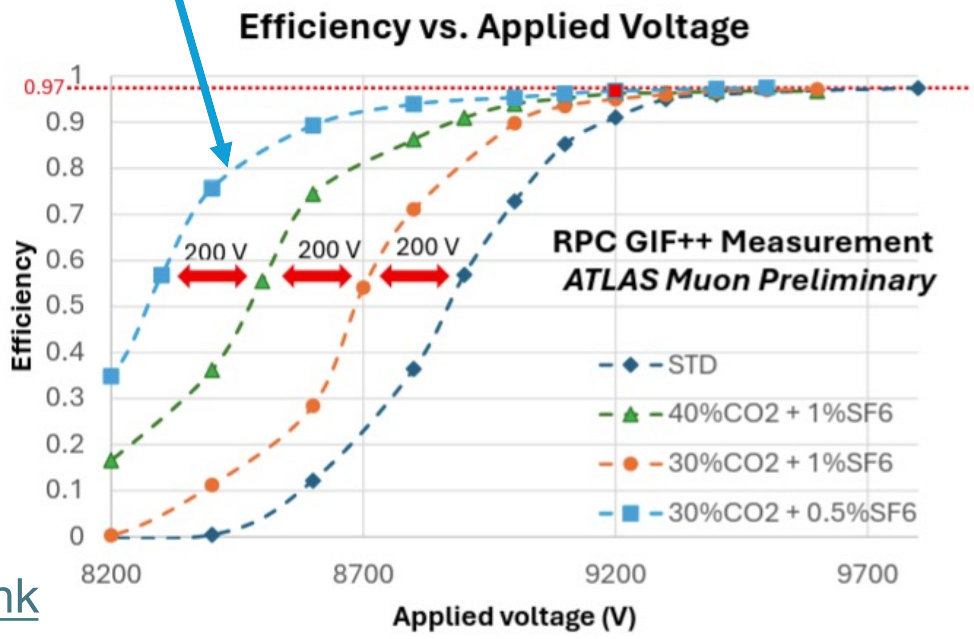
Trigger, Timing resolution: 1.5 ns

A gaseous detector built as a planar capacitor using two parallel high-resistivity plates (~10^{10} Ωcm) with a 2 mm gas gap

	$C_2H_2F_4$	CO_2	$i\text{-}C_4H_{10}$	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



Readout panels are made with η or φ-oriented strips on both sides of the gas gap



link

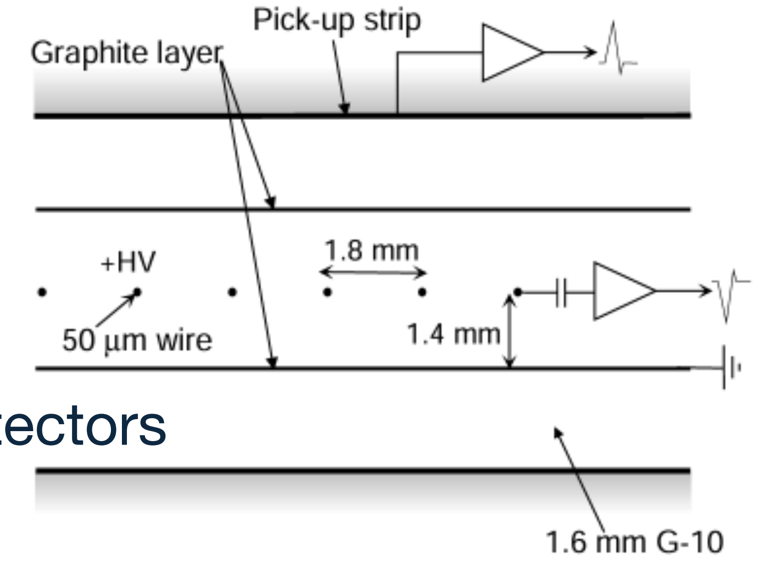
- **Main goal**: reduction of GWP by changing the gas mixture
- Mitigation of gas leaks during annual maintenance (Reduced gas leak rate ~1400 → ~1000 l/h during last year)
- Effective operation voltage is adjusted for temperature and pressure for each gas mixture
- **The maximum efficiency is about 97% for all mixtures**

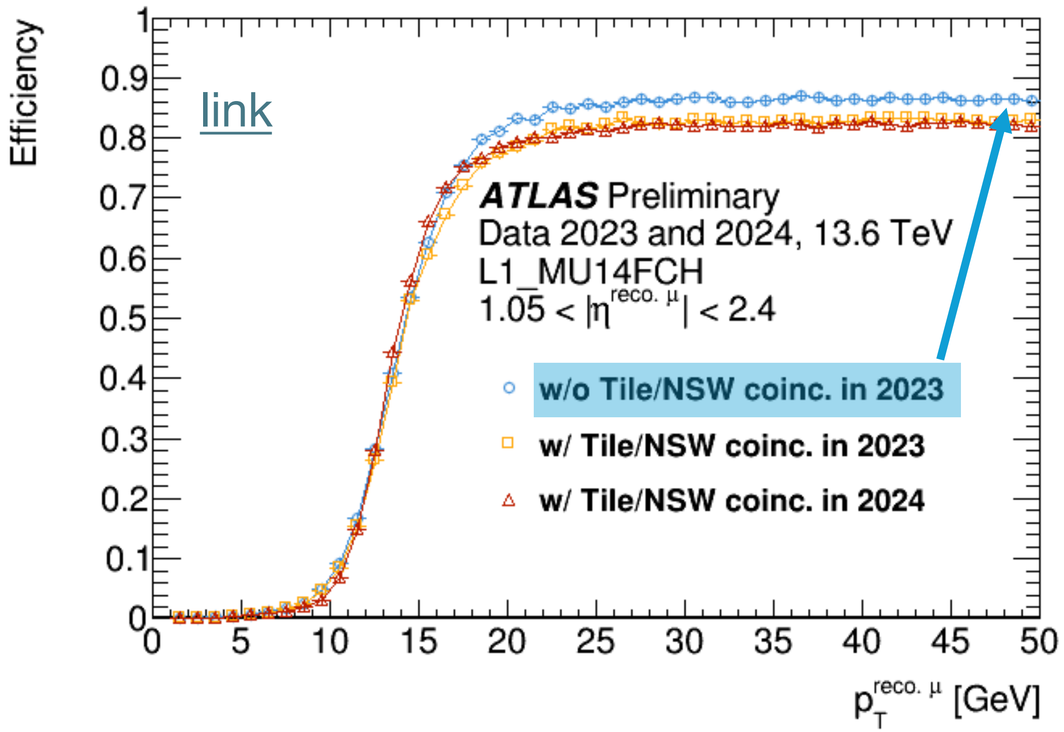
*Global Warming Potential: Impact on global warming (CO_2 = 1)

Performance of TGC

Trigger > 99% efficiency for 25 ns gate

- A kind of Multiwire proportional chambers
- Readout η from wires (anode) and φ from strips (cathode)
- Gas: CO_2 + n-pentane (55:45)
- Nominal voltage: 2.8 kV
- Triggering based on a coincidence between TGC and other detectors



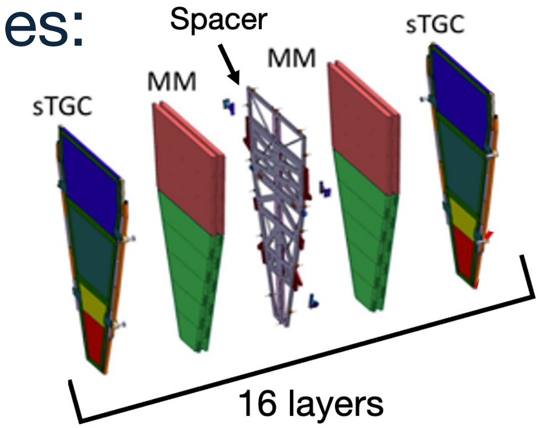


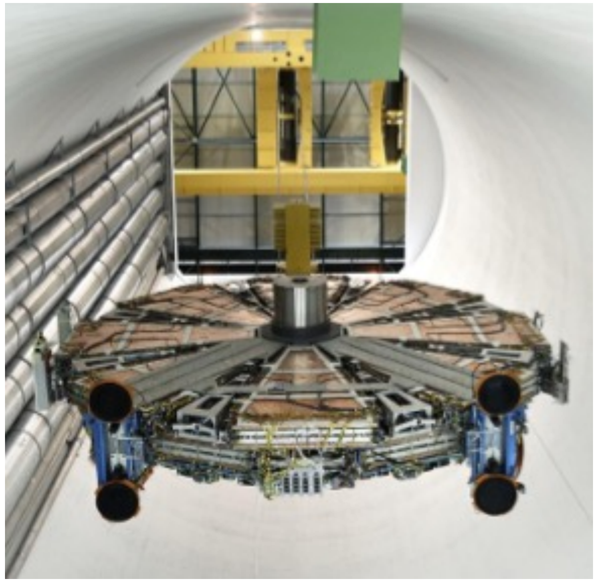
- The working fraction is kept above 99% by annual maintenance
- Level-1 muon trigger efficiency with 14 GeV threshold
- **Trigger efficiency using only TGCs is stable at around 86.3%**

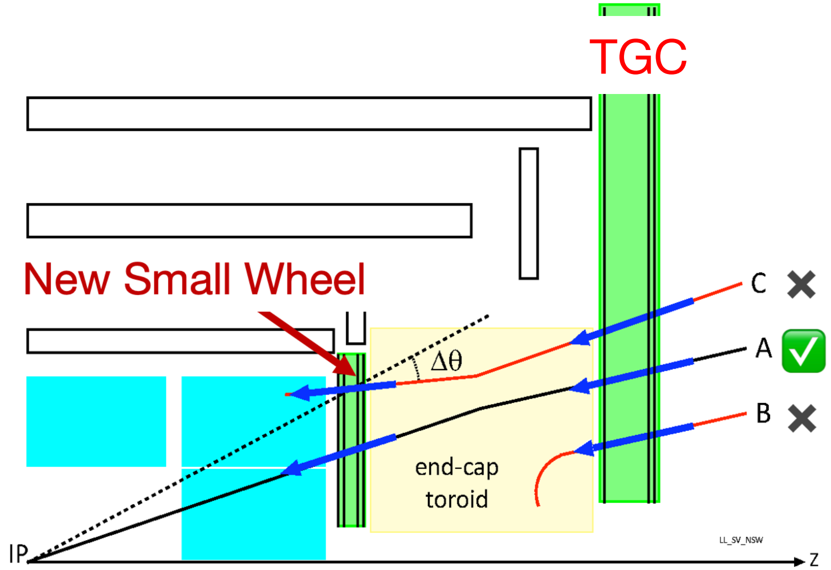
Phase I upgrade: New Small Wheel (NSW)

see also the talk by Michael

- Installed during LS2 (2019-2022)
- Motivation: **Improve both tracking and trigger performance**
- NSW comprises two detector technologies:
    - Micromegas and small-strip TGC (sTGC)
    - Each sector has 8+8 layers
    - Both tracking and triggering



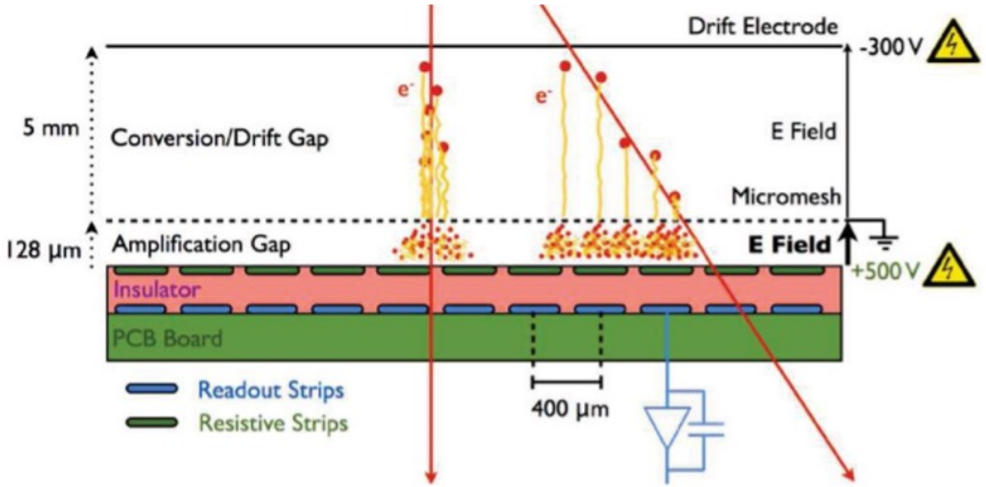




- To suppress fake muons
    - fake muons**:** Charged particles not originating from the interaction point
- Fake muons increase the muon trigger rate and are suppressed by requiring coincidence with TGC

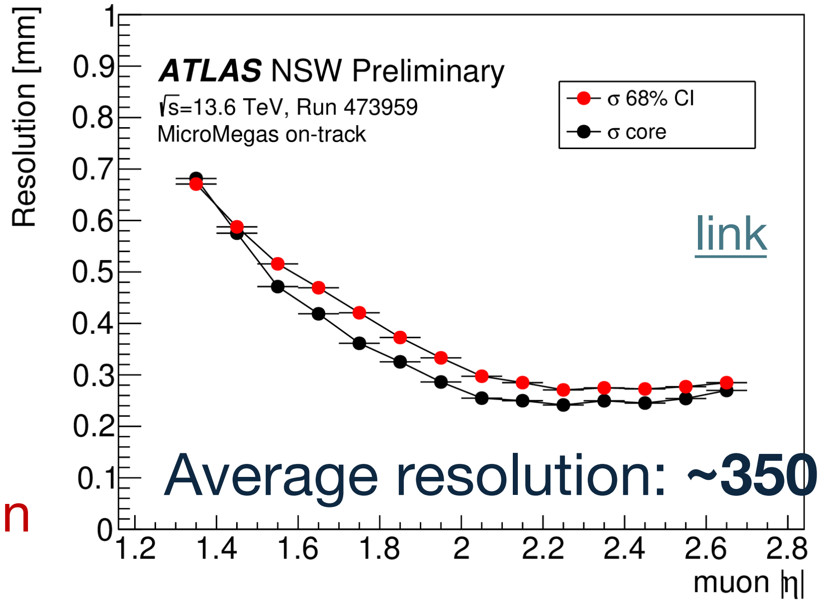
Micromegas details and spatial resolution

- Micromesh gaseous structure
- Spatial resolution: ~100 μm
- Gas: Ar + CO_2 + isobutane (93:5:2)
- Primarily for **precise tracking**, also contributes to trigger using earliest strip above threshold per group of 64 strips



Hit resolution as a function of $|\eta|$

- Resolution derived from cluster-track residuals (μ with $p_T > 15$ GeV)
- Using centroid cluster position with charge weighted mean value of the strip position
- Resolution degrades at low η due to signal spread over multiple strips
- New reconstruction under development using time information and cluster shape will significantly improve the resolution

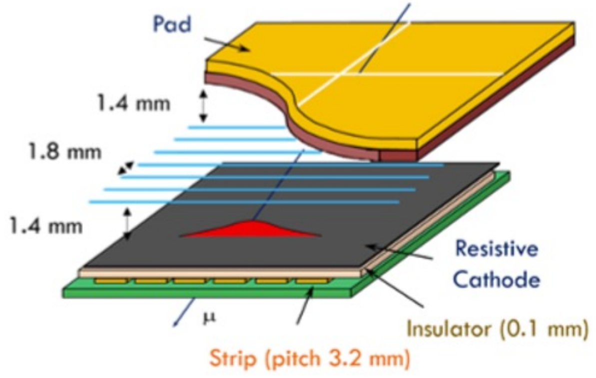


Average resolution: **~350 μm**

sTGC details and spatial resolution

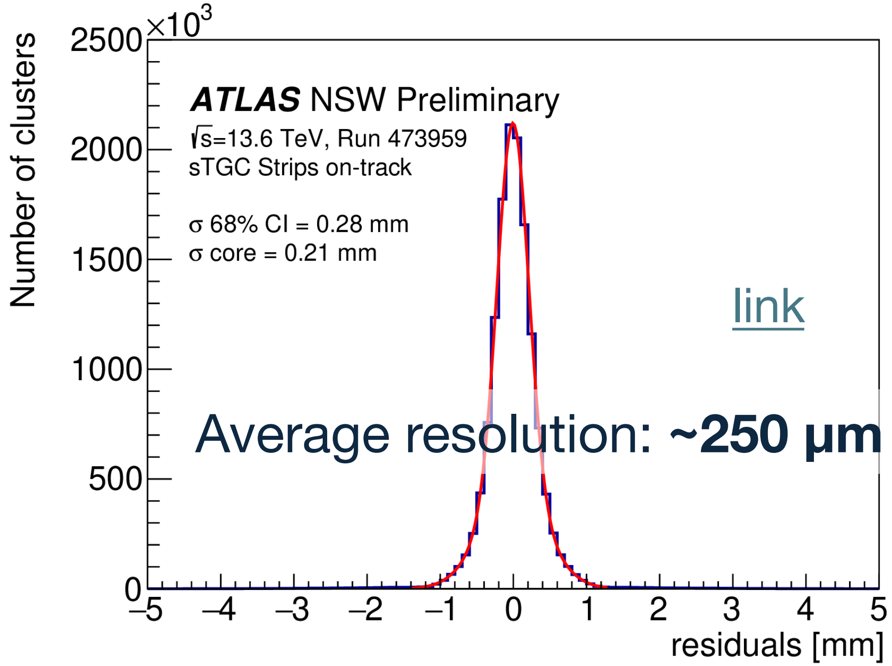
- High granularity multiwire proportional chamber
- Strip pitch: 3.2 mm then “small” strip
- Pad is coarse but fast identify the hit region
  - Triggering
  - Selecting appropriate strip readout region
- Primarily for triggering, also contributes to precision tracking

	direction	pitch
wire	$\emptyset$	1.8 mm
strip	η	3.2 mm
Pad	$\eta\times\emptyset$	



<u>Hit resolution</u>

- Resolution from cluster-track residuals (μ with $p_T > 15$ GeV)
- Using centroid cluster position with charge weighted mean value of the strip position
- Improve strips resolution 10% in 2024 vs 2023
  - due to alignment
- New reconstruction under development using cluster shape will significantly improve the resolution

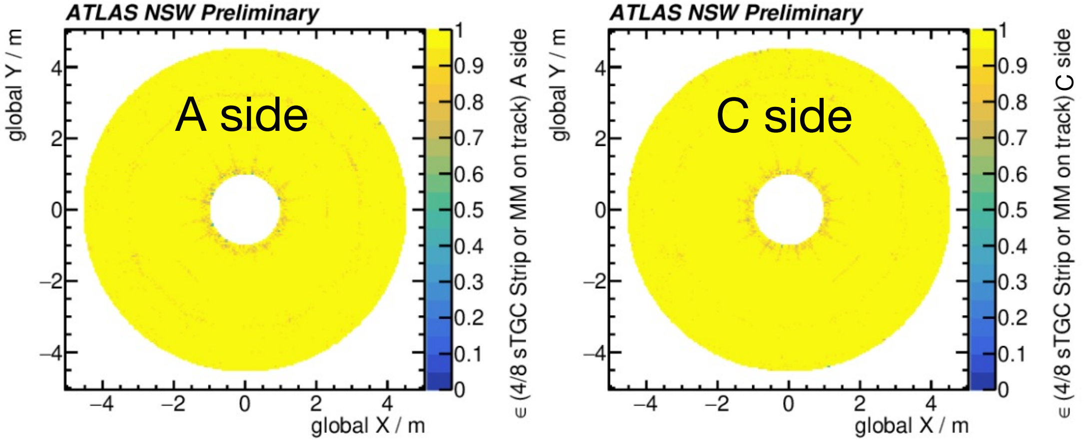


link

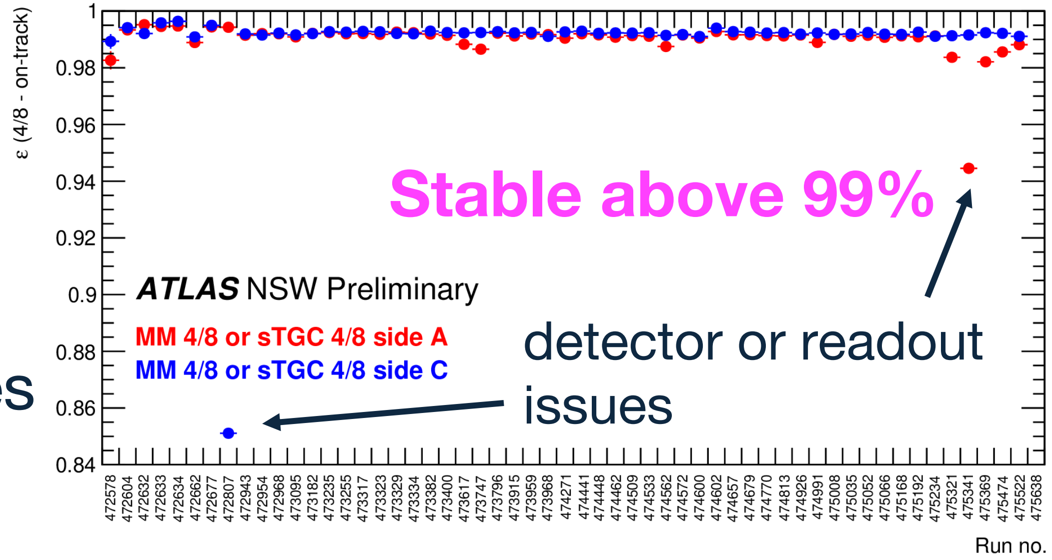
Average resolution: **~250 μm**

NSW tracking efficiency

- Shows efficiency with at least 4 out of 8 layers associated with outer MS tracks
    - muons $p_T > 15\,\mathrm{GeV}$
    - $|\eta| > 2.5$: MS only tracks
    - $|\eta| \leq 2.5$: Combined tracks (ID+MS)
    - Used as OR of Micromegas and sTGC

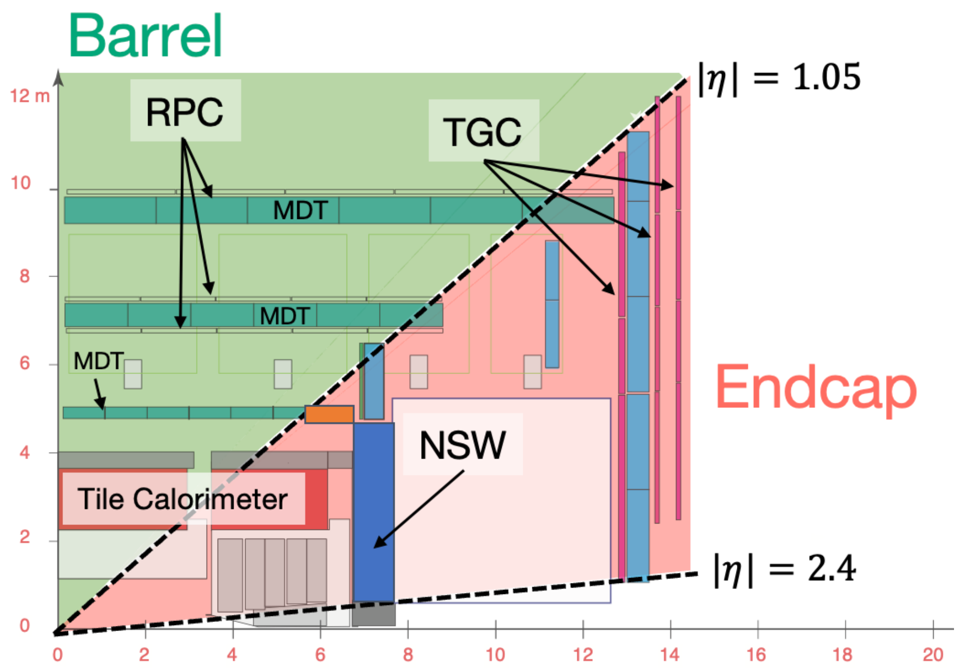


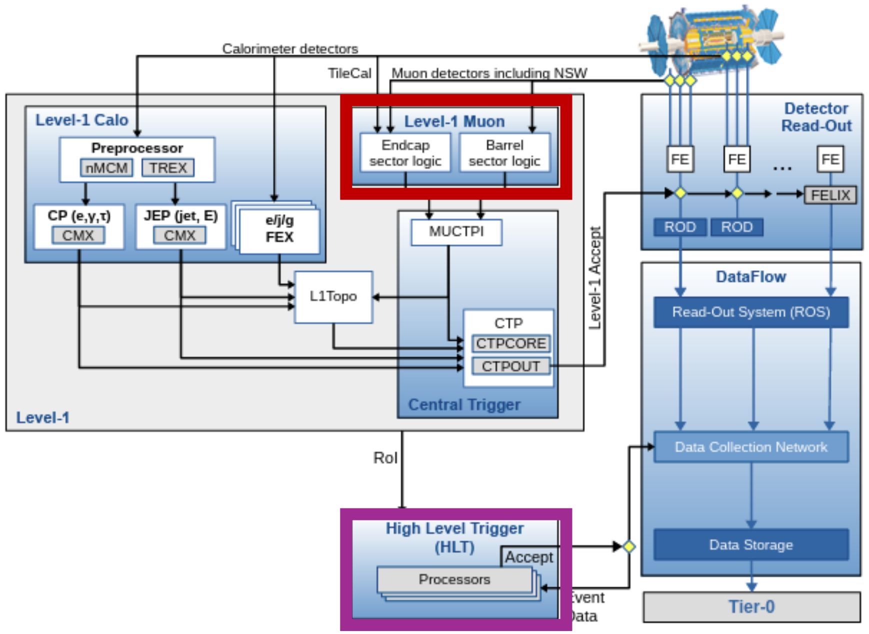
- Each detector (MMG and sTGC) has 8 layers
    - at least 4 active layers
      → muon track can be reconstructed independently
- Plot shows how efficiently the NSW contributes to muon track reconstruction in the endcap
- Significant contribution to track reconstruction



The muon trigger system

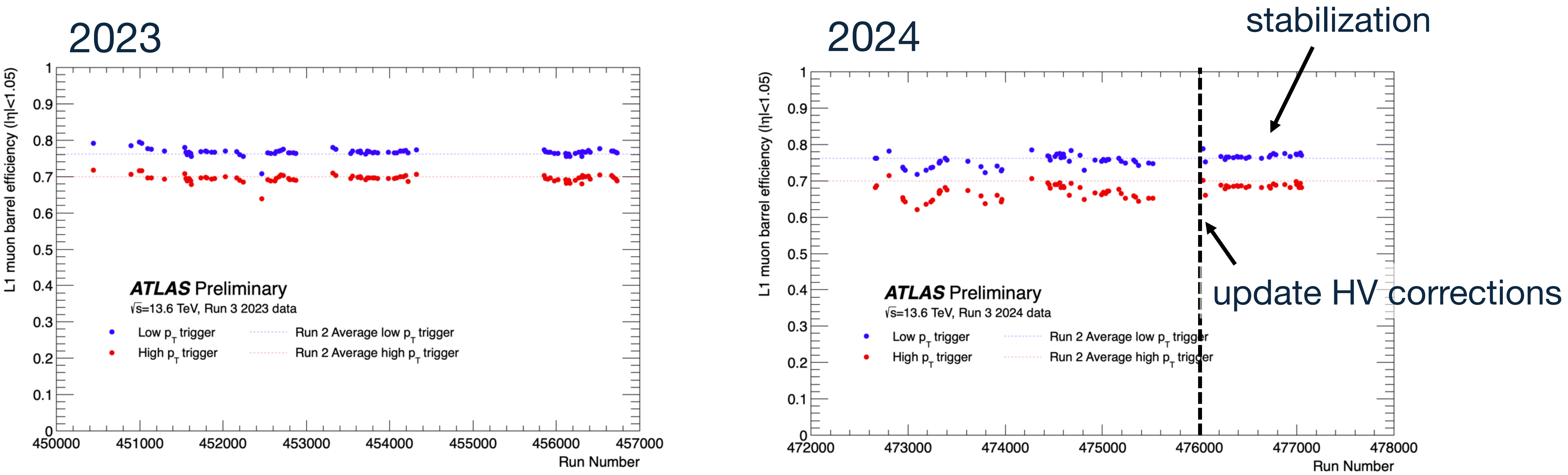
- **Level-1 trigger:**
  a fast hardware based trigger, latency ~2.5 μs
  - RPC for the barrel ($|\eta| < 1.05$), TGC for the Endcap ($1.05 < |\eta| < 2.4$)
  - p_T estimated from deviation from infinite-p_T track pattern in RPC/TGC
  - To suppress background, an additional coincidence with the Tile Calorimeter and NSW is required with respect to the TGC signal
  - Identifies Regions of Interest (RoI) and sends them to the Central Trigger and HLT
- **High Level Trigger (HLT):**
  refined selections using software based algorithms
  - Select data within the muon RoI using information from the inner tracking detector





Level-1 muon barrel trigger performance

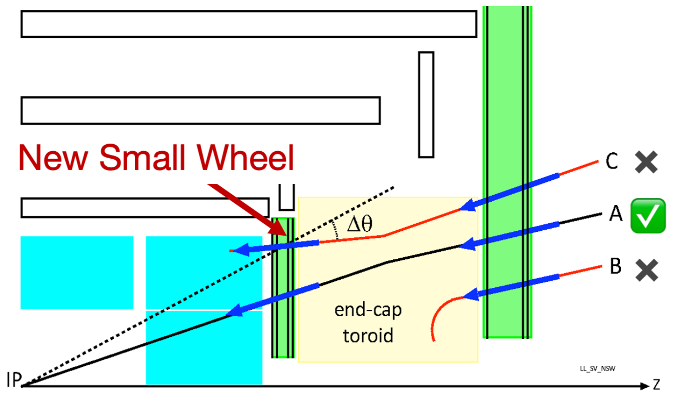
link



- The efficiency includes also the acceptance for both plots, obtained with non-muon triggers
- Trigger efficiency fairly constant during 2023 and 2024, fluctuation from run to run
- Instabilities in 2024 were fixed by an improved version for the handling of the HV correction factor

NSW integration into Level-1 muon trigger

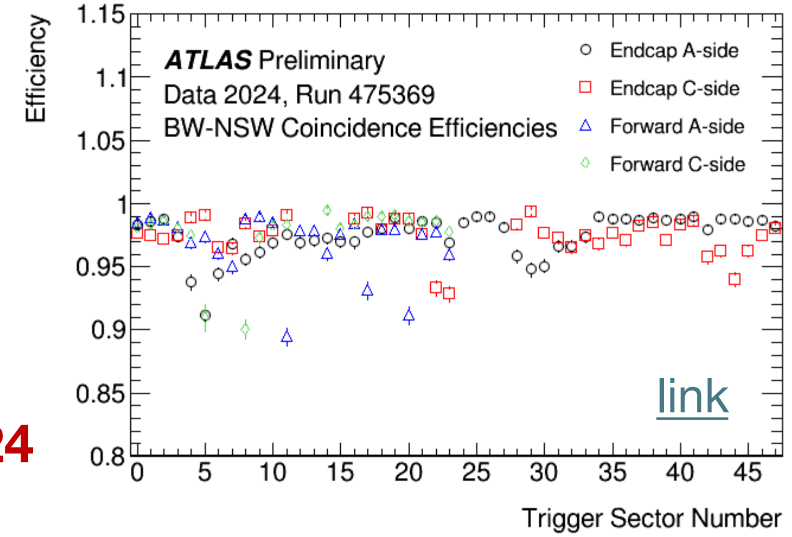
To suppress the increase in the Level-1 trigger rate due to higher pile-up and luminosity, the NSW was integrated into the trigger system



The trigger algorithm:

1. Identified based on TGC wire/strip (TGC only trigger)
   - 7-layers coincidence for TGC wire and strip, determined p_T
2. Reject fake muons by combining NSW with TGC trigger (TGC + NSW trigger)

TGC + NSW coincidence efficiency



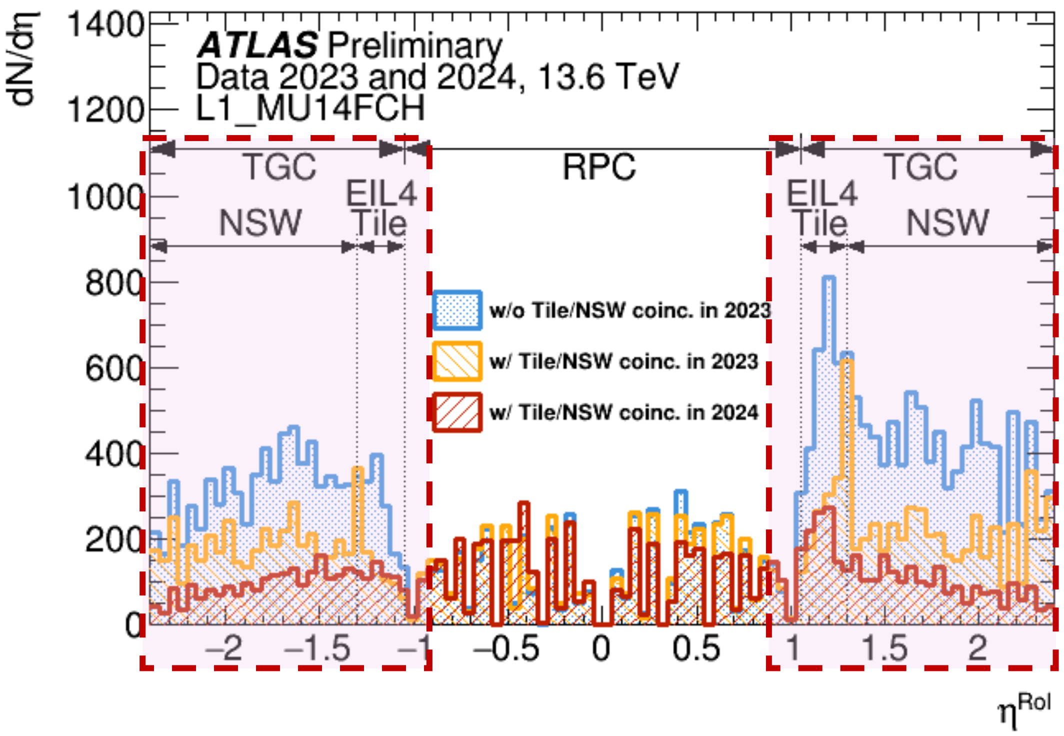
- Coincidence can be enabled individually for each small unit
- Efficiency optimization in each NSW region
  - Masking of low-efficiency areas
  - Signal timing fine-tuning to further improve the efficiency

The full integration of all the NSW sectors completed in May 2024

Level-1 muon endcap trigger performance

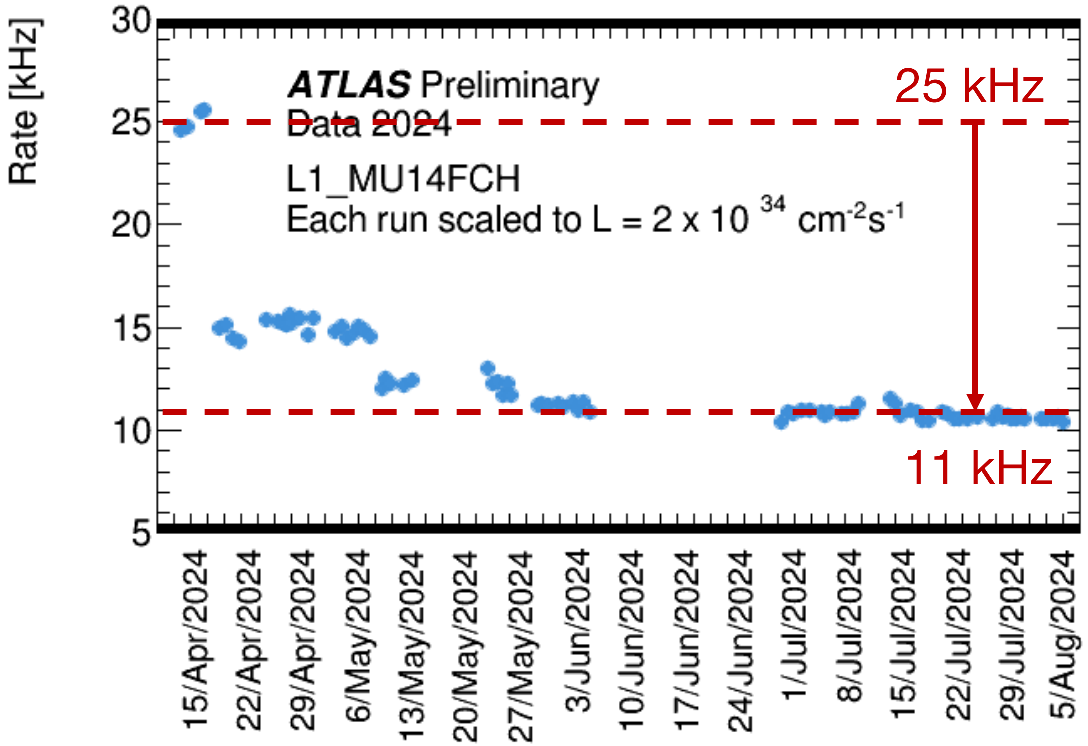
link

trigger rate reduction for each η region



- Blue: 2023 rate with TGC only trigger
- Red: 2024 rate after TGC-Tile-NSW trigger
- **Visible fake reduction in the Endcap regions**

Level-1 muon trigger rate transition



- Rate reduction through the gradual integration of the NSW
- **Total reduction of the Level-1 trigger rate by 56%**

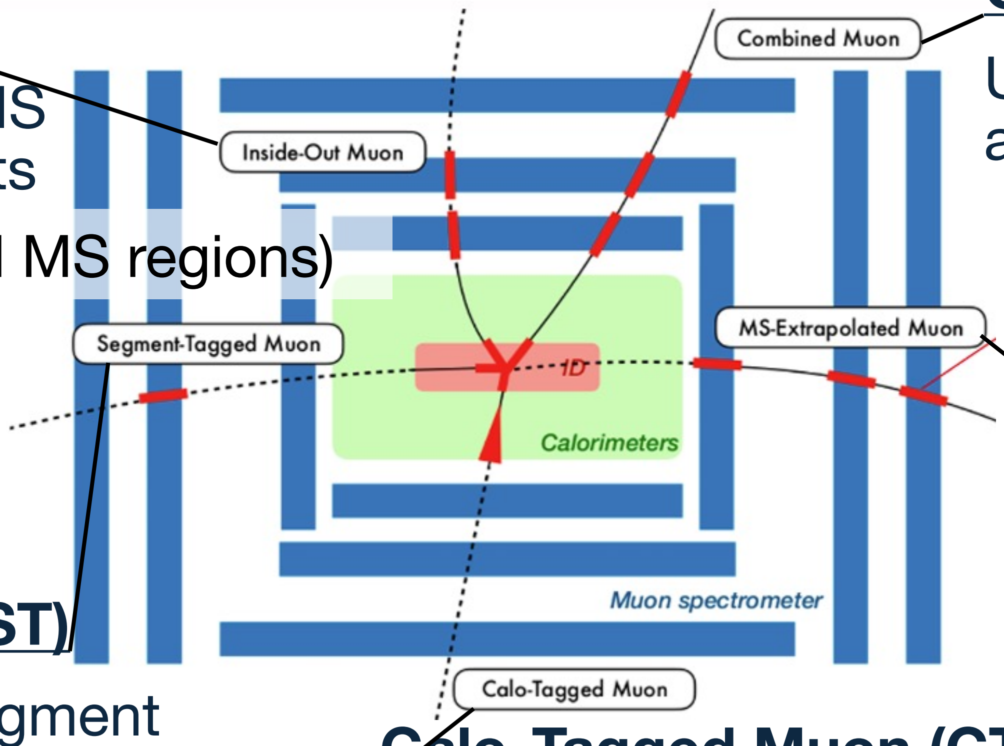
Muon reconstruction

Muons are reconstructed using information from the **Muon Spectrometer (MS)**, the **Inner Detector (ID)** and the **Calorimeter**.

Inside-Out Muon (IO)

ID track extrapolated to MS and matched to ≥3 MS hits

(useful in low-p_T or limited MS regions)



Combined Muon (CB)

Uses matched tracks from MS and ID for highest precision

MS-Extrapolated Muon (ME)

Identified using a track reconstructed only from MS

Segment-Tagged Muon (ST)

ID track matched to MS segment

(helps in low- p_T or partial coverage)

Calo-Tagged Muon (CT)

ID track tagged by calorimeter energy deposit

(improves acceptance in regions with limited MS coverage)

Muon identification

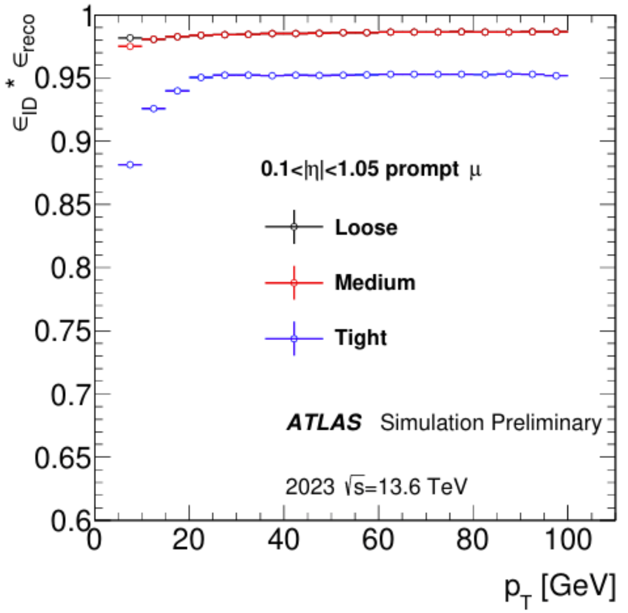
- Working Points (WP) are defined as quality criteria applied to reconstructed muon candidates for physics analyses

WP name	Description	Used muon
Loose	Maximize the acceptance. Best for multi-leptons analysis.	Medium + CT, ST
Medium	Good acceptance, low fake rate, small systematics. Used by most analyses.	CB, IO, ME
Tight	Maximize purity. Strong rejection of fakes.	CB, IO at least 2 station

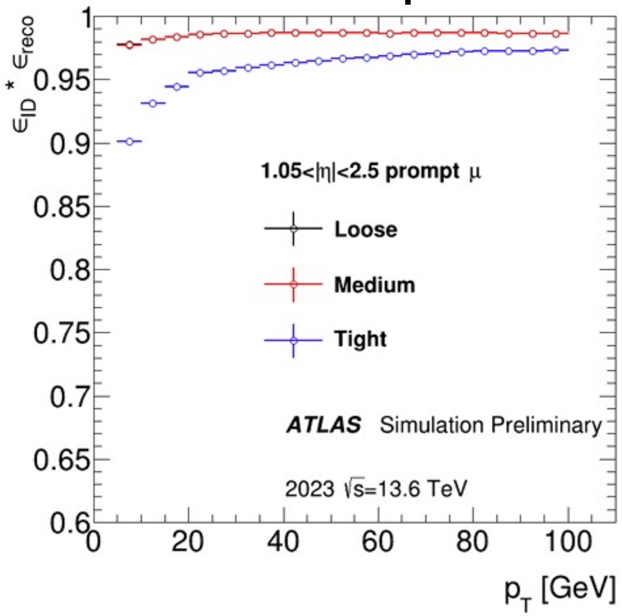
$$\text{Efficiency} = \text{reconstruction eff.} \times \text{identification eff.}$$

Both barrel and endcap show over 90%

Barrel

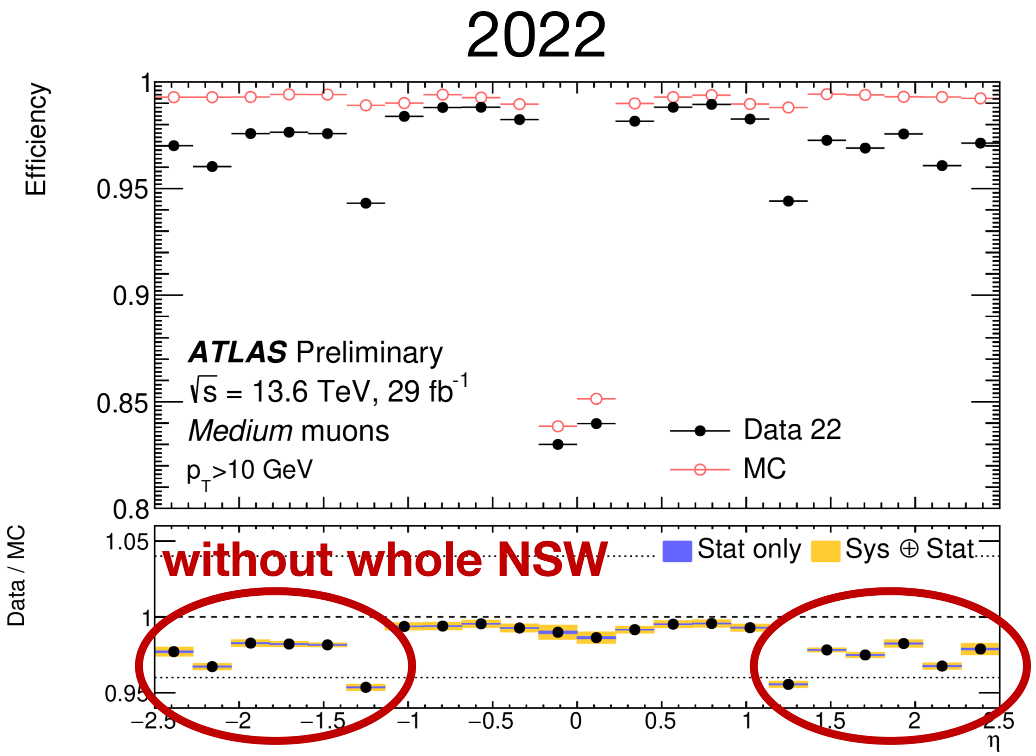


Endcap link

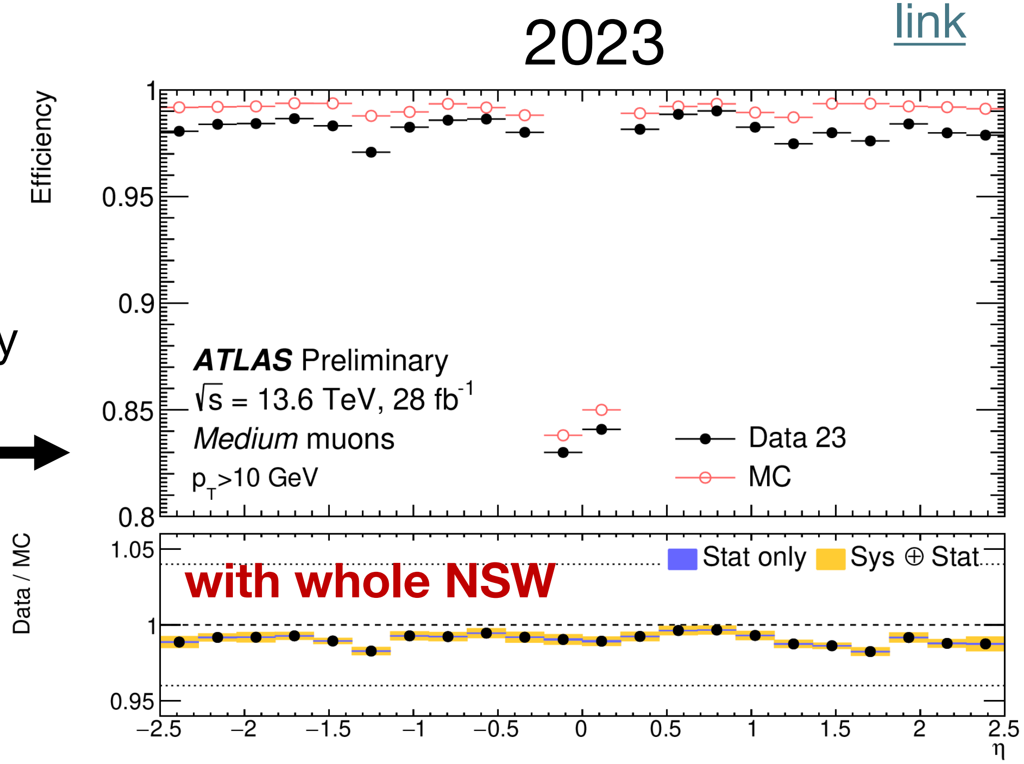


Muon efficiency

link



NSW completely commissioned

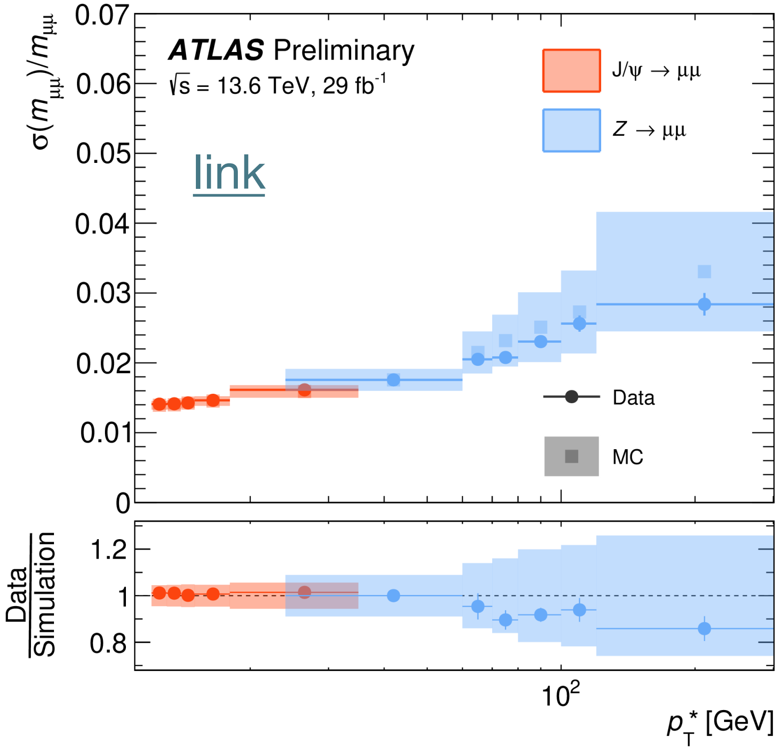


- Reconstruction and identification efficiency of muons with $p_T > 10$ GeV
- Measured using $Z \to \mu\mu$ events from data
- **Efficiency improvement in the endcap region due to the NSW included**
  - Acceptance hole at $\eta \sim 0$ due to space for services

Muon spectrometer alignment in Run 3

link

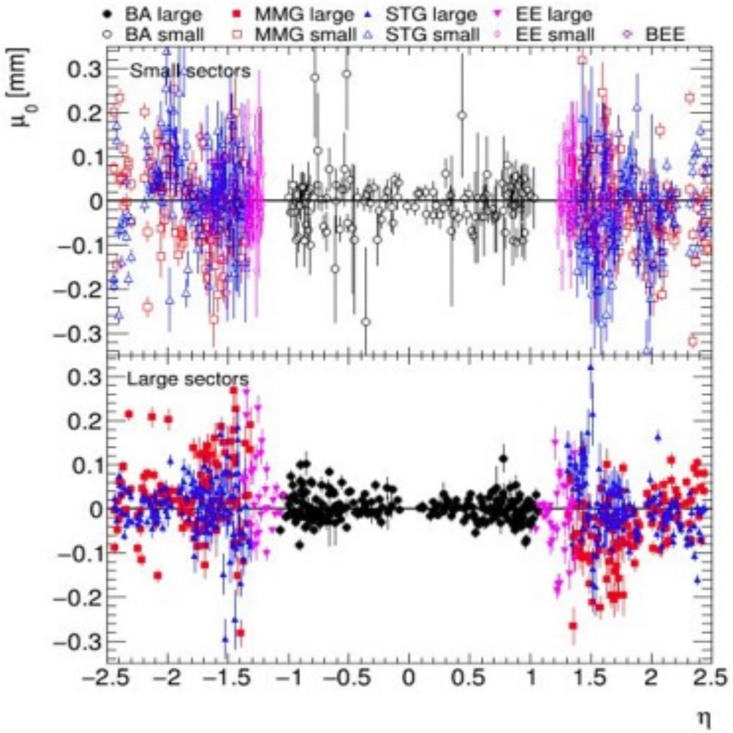
- New MS alignment for Run 3 data
  - based on 2022-2023 cosmic and collision data without magnetic field
- The initial Run 3 alignment was improved
  - To a precision in the 30–100 μm range



link

[μm]	σ_{ali}(total)
BA large	29 ± 2
BA small	38 ± 4
EC large	77 ± 2
EC small	103 ± 3
EE large	121 ± 9
EE small	94 ± 9
BEE	84 ± 7

New Run 3 alignment



- Accurate alignment contributes to improving the momentum resolution
  - evaluated using $Z \to \mu\mu$ and $J/\psi \to \mu\mu$ events
- The relative dimuon mass resolution ranges from ~1.2% to ~4.0% in the considered p_T range

Conclusions

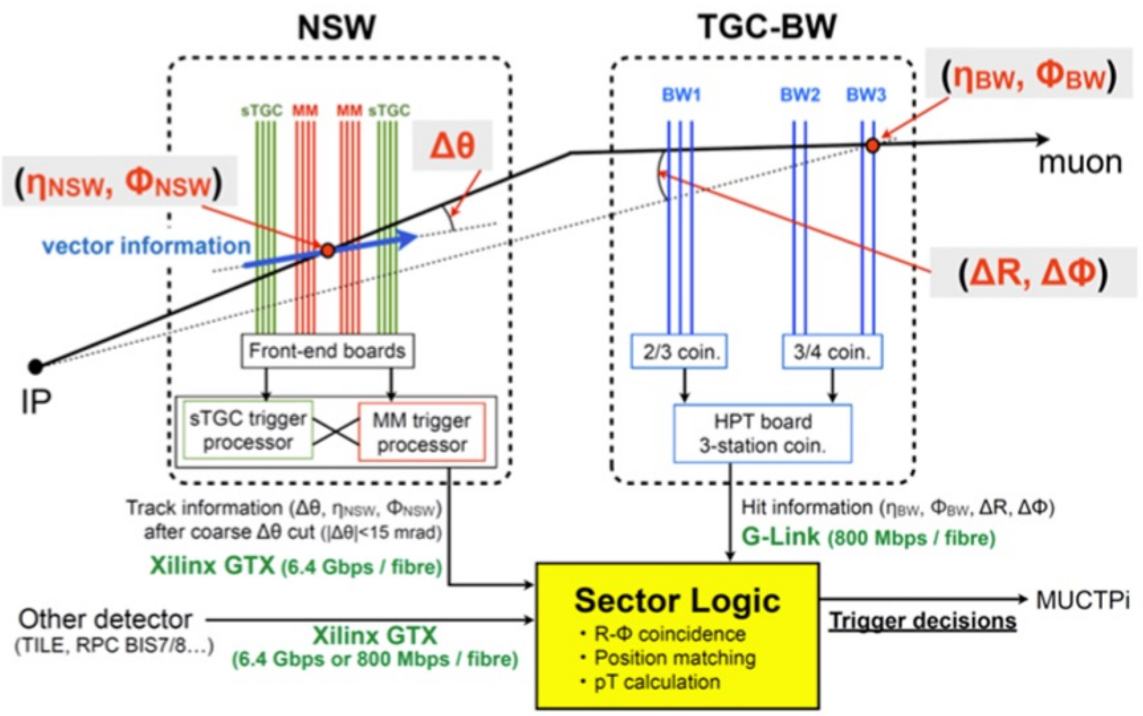
- Throughout Run 3, **ATLAS has collected unprecedented luminosity**, with **2024 setting a new record within the experiment**
- The current ATLAS **muon spectrometer consists of three legacy types of chambers and two new types of chambers**
  - The legacy systems (MDT, RPC, TGC) are stable during Run 3
  - NSW(MMG and sTGC) has been installed in the last Long Shutdown, before Run 3
- In 2024, both the **trigger and detector performance have improved**
  - The NSW detectors were fully integrated into the Level-1 muon trigger
  - Also contributed to track reconstruction performance
  - Efficiency improved in the Muon Combined Performance analysis
  - Accurate alignment ensures good momentum resolution
- **In 2025, the LHC and the ATLAS detector are performing well**, recording a high integrated luminosity

Backup

Muon identification algorithm

NSW Trigger Logic Overview

- NSW uses two technologies: small-strip TGC (sTGC) and Micromegas (MM), each in two quadruplet chambers
- Track segments are reconstructed independently in each technology
- Up to 8 segments per sector are sent to the Level-1 Endcap Muon Sector Logic
- Sector Logic applies a coincidence between TGC-BW muon candidates and NSW segments



Muon spectrometer alignment in Run 3

NSW and MDT are equipped with optical sensors for alignment

- The measured **sagitta** s_i indicates the deviation from the ideal straight trajectory
- Due to alignment imperfections or magnetic field distortions, a **bias** can appear in the sagitta measurement
- **Sagitta bias**

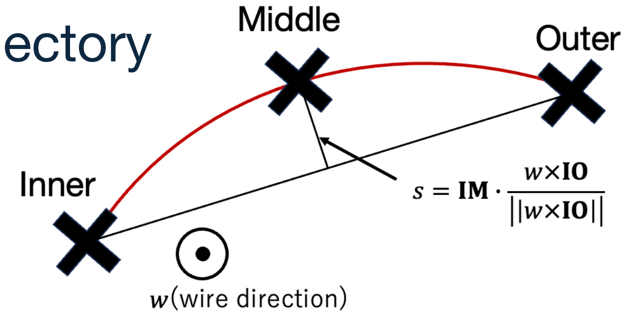
$$\mu = \mu_0 + \mu_\theta \frac{\theta_i - \langle\theta\rangle}{rms(\theta)} + \mu_\phi \frac{\phi_i - \langle\phi\rangle}{rms(\phi)}$$

  - μ_0 : average sagitta bias in the tower (fixed offset)
  - μ_θ : dependence on the polar angle θ
  - μ_ϕ: dependence on the azimuthal angle ϕ

- **Sagitta resolution (uncertainty)** σ

$$\sigma = SF \times \sigma_{sag}(s_i)$$

  - Ideally, all sagitta values s_i follow a Gaussian distribution centered around the bias μ
  - The spread of this distribution represents the **alignment precision**
  - SF: scale factor to account for multiple scattering in the detector material



Initial Run 3 alignment

[μm]	σ_{ali}(total)
BA large	59 ± 3
BA small	146 ± 10
EC large	167 ± 5
EC small	193 ± 5
EE large	469 ± 42
EE small	612 ± 54
BEE	1793 ± 175

New Run 3 alignment

[μm]	σ_{ali}(total)
BA large	29 ± 2
BA small	38 ± 4
EC large	77 ± 2
EC small	103 ± 3
EE large	121 ± 9
EE small	94 ± 9
BEE	84 ± 7

target: 30-100 μm