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RPC 2024

Performance of ATLAS RPC detectors and L1 Muon Barrel Trigger with a new CO_2-based gas mixture

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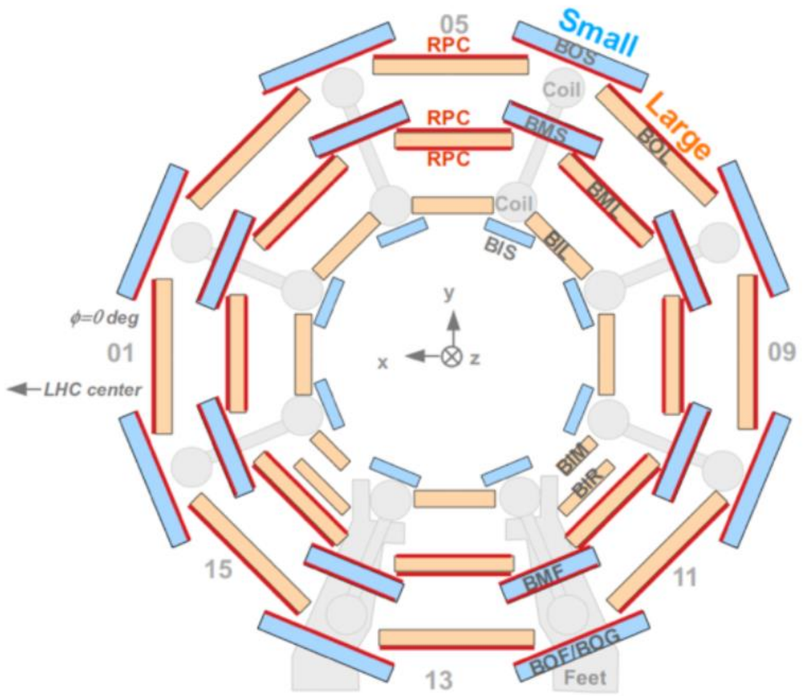
Outline

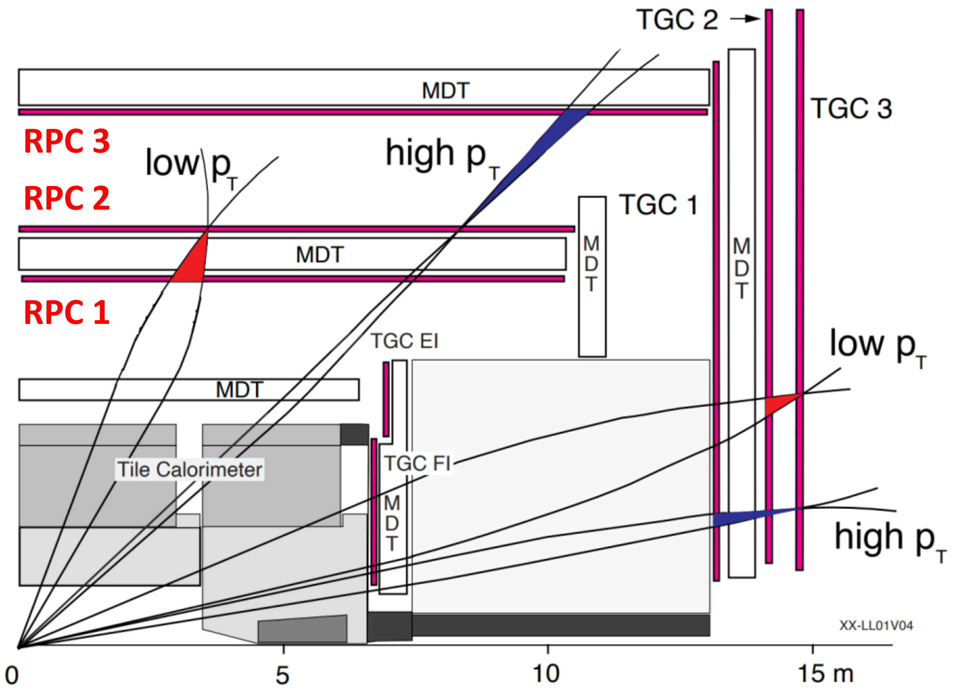
- ATLAS Level-1 Muon Barrel trigger
- The ATLAS RPC detector during Run3 (2022-2025)
  - The gas mixture change
  - The HV correction factor
- Detector performance
  - density of current of the gas gaps
  - cluster size at module level
- Trigger performance
  - Trigger efficiency across runs
  - Trigger efficiency p_T turn-on curves
  - η vs φ trigger efficiency maps
- Summary

ATLAS Level-1 Muon Barrel trigger



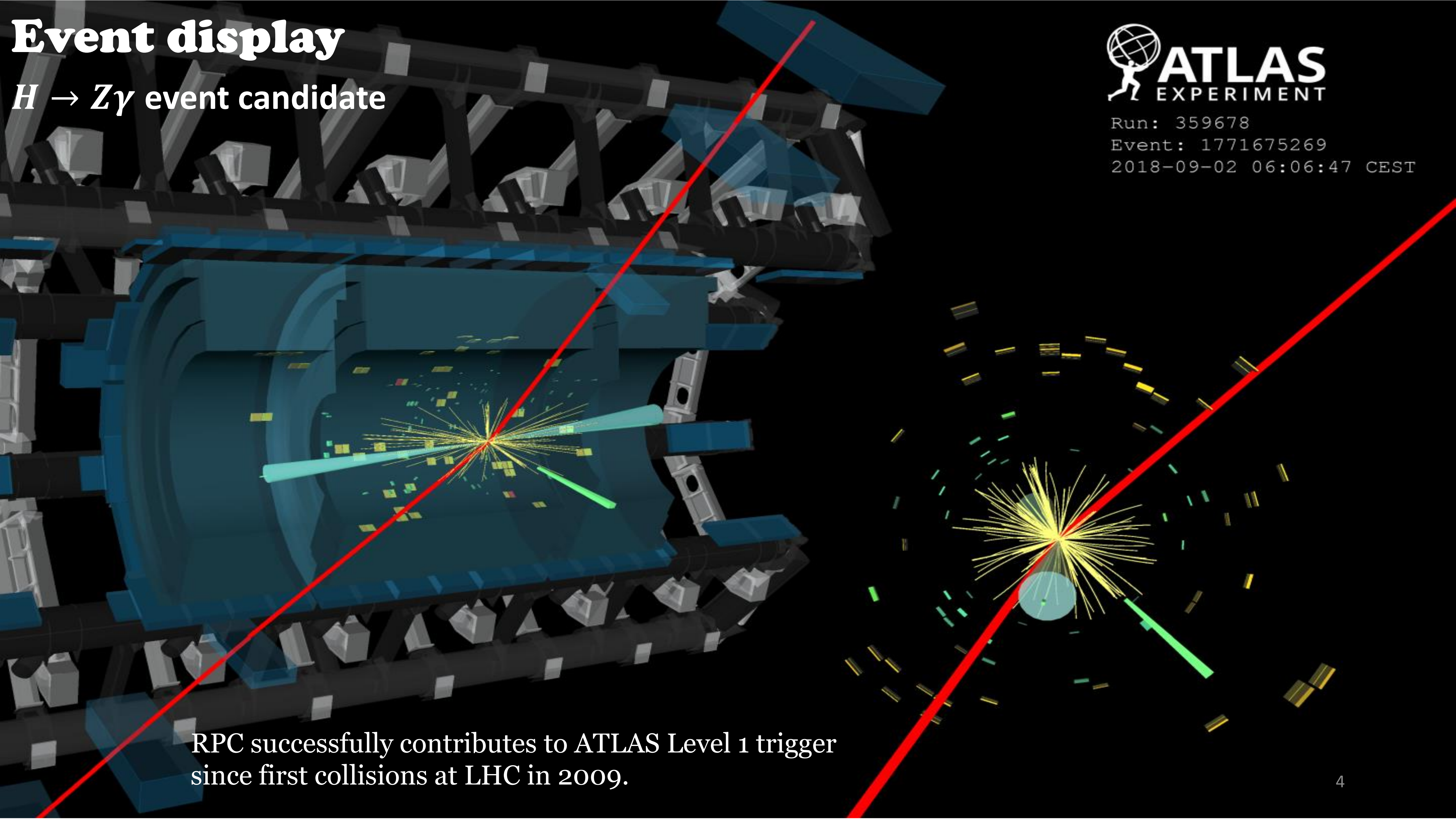
- ATLAS is a general-purpose particle detector observing collisions at Large Hadron Collider(LHC) at 40 MHz rate
- Efficient selection of muons is important for ATLAS physics programme
- Resistive Plate Chambers(RPCs) are used for triggering on muons, due to their **excellent timing performance** and **low-cost material**
- Three concentric doublet layers of RPCs
- 2 sensitive gas gaps, with read out on both surfaces with orthogonal strips to provide a measurement of the η and ϕ coordinates.

- RPC detectors cover the pseudo-rapidity range $|\eta| < 1.05$
- The Level-1 Muon Barrel trigger allows to select muon candidates according to their transverse momentum
  - 3 low-p_T thresholds and 3 high-p_T thresholds
  - **low-p_T**: RPC2 & RPC1
  - **high-p_T**: low-p_T & RPC3
- Coincidences are performed in coincidence matrices (CM) hosted inside PAD boxes placed on detector
- L1 reduction factor of 400 (40 MHz -> 100 kHz)



Event display

$H \rightarrow Z\gamma$ event candidate

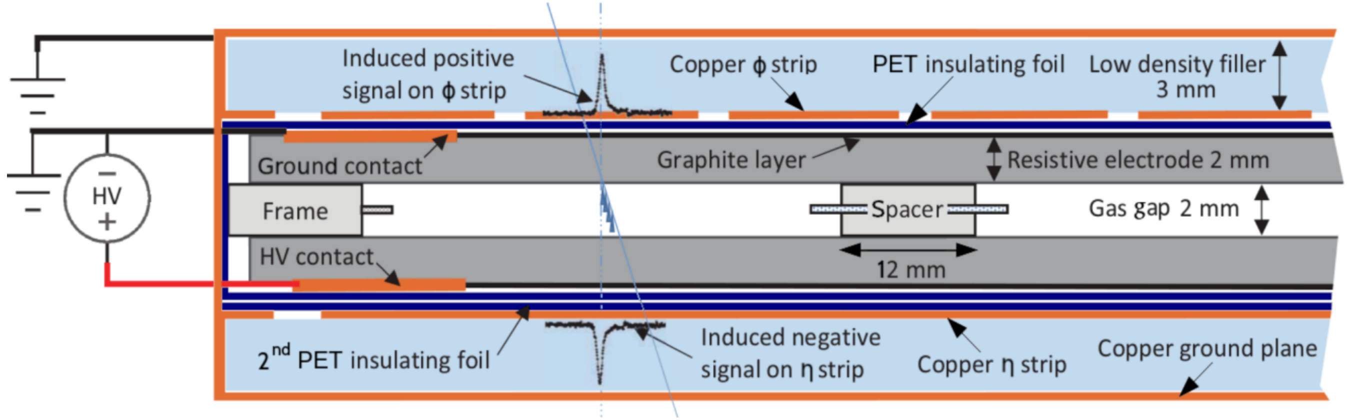


RPC successfully contributes to ATLAS Level 1 trigger since first collisions at LHC in 2009.

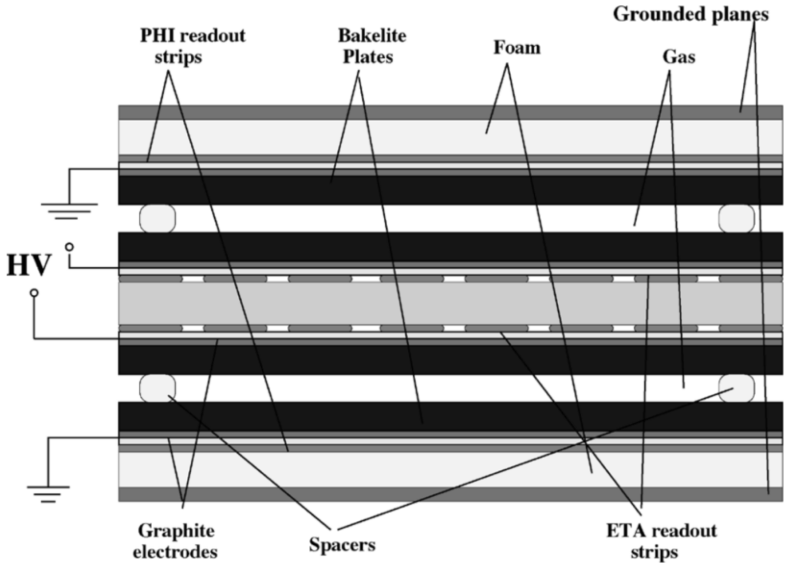
ATLAS Resistive Plate Chambers

- The RPCs are arranged in three concentric double layers with **~ 3700 gas volumes** and **~ 380k readout strips**, cover **total area of ~ 4000 m^2**
- All gas volumes have individual readout, measurements are available through ATLAS Detector Data Control System (DCS).
- Each RPC detector is made of 2 bakelite gas volumes with a 2 mm gas gap

RPC detector single layer



RPC detector doublet layer



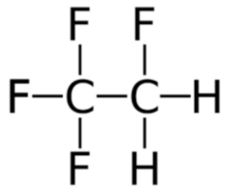
- Detector operates in **saturated avalanche mode** with automatic high voltage(HV) correction for temperature and pressure variations with respect to the reference values
- The intrinsic time resolution is **~ 1 ns** while the time to digital converter have sampling bin of **3.125 ns**

The RPC detector in Run3

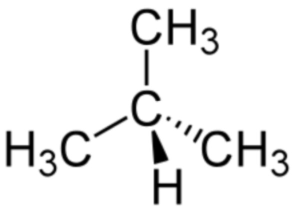
- After a successful data taking period in Run 2, the detector has undergone an **intense maintenance** to ensure an efficient data taking during Run 3.
- Several interventions have been carried out on the detector, mainly covering the **gas distribution** with the aim of
  - stabilizing the system
  - reducing the amount of gas released in the atmosphere
- The main interventions were:
  - New gas distribution racks have been added to increase the vertical segmentation and in view of the installation of new Phase-II chambers;
  - Non-return valves have been installed on the chamber outputs to avoid reverse flow with large leaks;
  - A massive gas leak repair campaign has been done for fixing the continuously developing leaks;
  - A new technique to repair and prevent new leaks has been tested;
  - **The segmentation of the HV channels has been doubled in a third of the spectrometer to mitigate the effect of detector failures;**
  - **Change of gas mixture adding a 30% CO_2 gas fraction**.

The RPC gas mixture

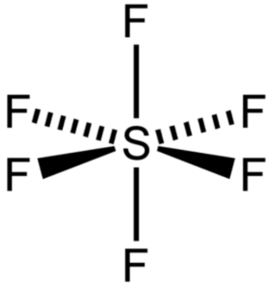
- ATLAS RPCs are operated with a gas mixture made of
  - $C_2H_2F_4$(also known as R-134a), active target providing a high number of ion–electron pairs
  - $i\text{-}C_4H_{10}$, photon quencher that helps to avoid propagation of the discharge
  - SF_6, electronegative gas used to limit the growth of avalanches
- The $C_2H_2F_4$ and SF_6 are greenhouse gases with Global Warming Potential(GWP) over 100 year
  - They are being phased down in the European Union, thereby also leading to rising cost
- The gas mixture was changed at the **end of pp collision in 2023**
  from $C_2H_2F_4$ 94.7%, $i\text{-}C_4H_{10}$ 5%, SF_6 0.3%
  to $C_2H_2F_4$ 64%, CO_2 30%, $i\text{-}C_4H_{10}$ 5%, SF_6 1%
  - The GWP of gas mixture is decreased by **14%**, from **1450** to **1150**
- The average applied voltage across all detector chambers is changed from **9.6 kV** to **9.35 kV**
- The effective operational voltage is corrected for local changes in environmental temperature and pressure with respect to the standard conditions



$C_2H_2F_4$
GWP: 1430



$i\text{-}C_4H_{10}$
GWP: 3.3



SF_6
GWP: 22800

The effective operational voltage correction

- The effective operational voltage V_{eff} is corrected for local changes in **environmental pressure** $\boldsymbol{p}$ and **temperature** $\boldsymbol{T}$ at the **chamber** level by the HV correction factor $\rho(p,T)$
- The applied operational voltage V_{app} is therefore given by

$$V_{app} = V_{eff}\rho(p,T)$$

where

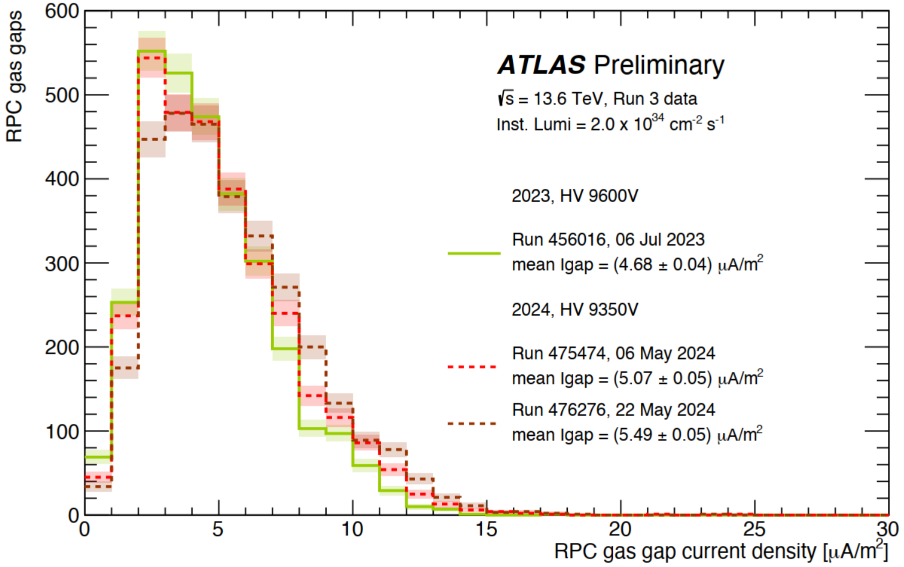
$$\rho(p,T) = \left[1 + \alpha_p\left(\frac{p}{p_0} - 1\right)\right][1 + \alpha_T\left(\frac{T_0 - 273.15}{T - 273.15} - 1\right)]$$

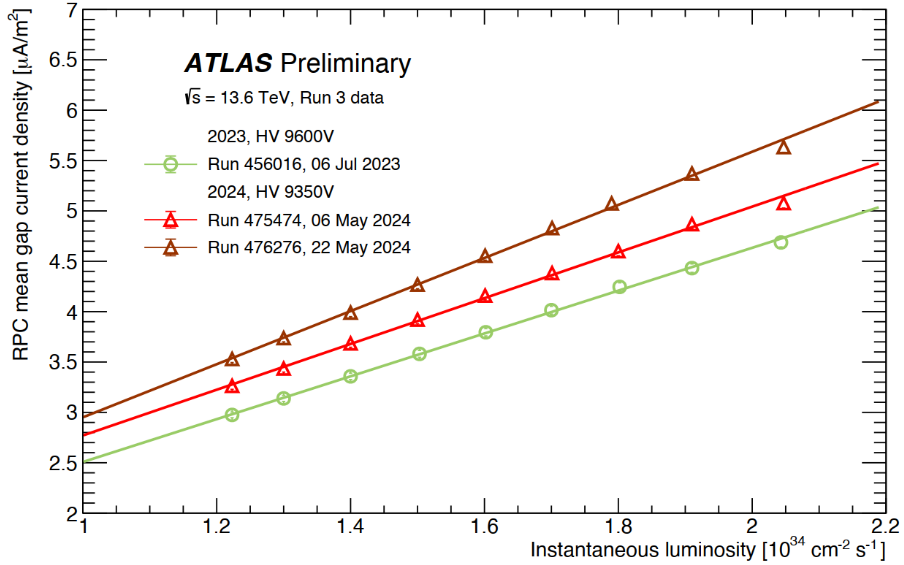
In the formula,

- $\alpha_p = 0.8, \alpha_T = 0.5, p_0 = 9.6 \cdot 10^4$ Pa$, T_0 = 294.15$ K$, V_{eff} = 9350$ V
- p is the atmospheric pressure from a probe in ATLAS experimental cavern (UX15)
- T is the temperature from sensors installed onto every chamber
- $0.98 \leq \rho(p,T) \leq 1.02$

- The final HV correction factor $\rho(p,T)$ was updated to take into account a **new pressure probe** and **local changes of pressure and temperature for the BO chambers** whose segmentation for the HV channels has been doubled
- The updated HV correction factor led to an **increase between ~30 V and ~150 V** for some of the RPC chambers, resulting in an **increase of the mean gas gap current density** and **improving the stability of the RPC trigger efficiency**

Density of gas gap current



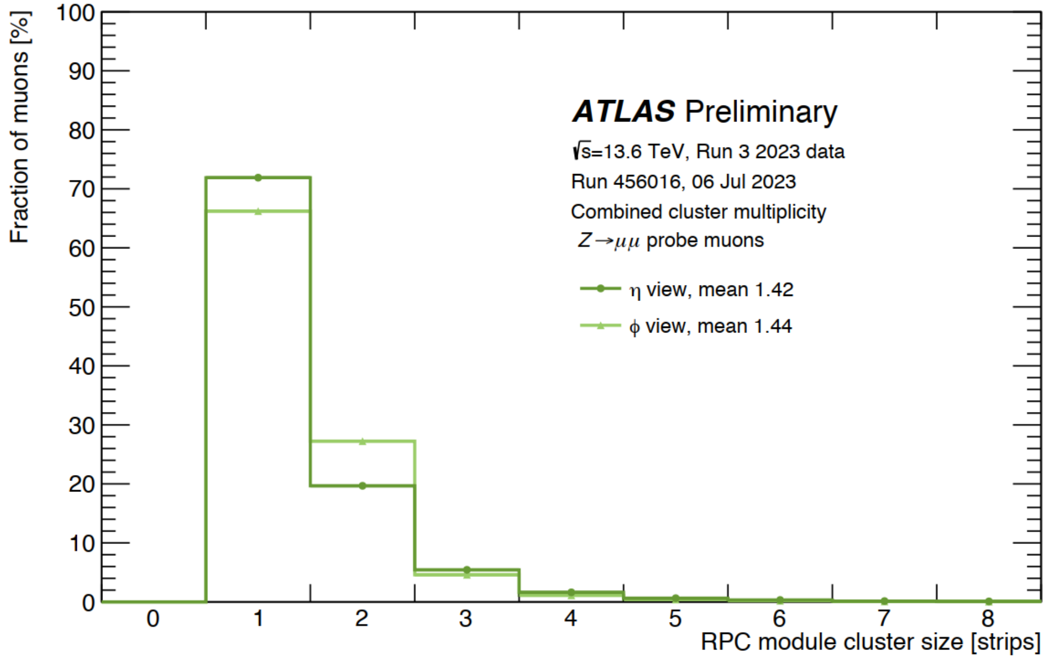


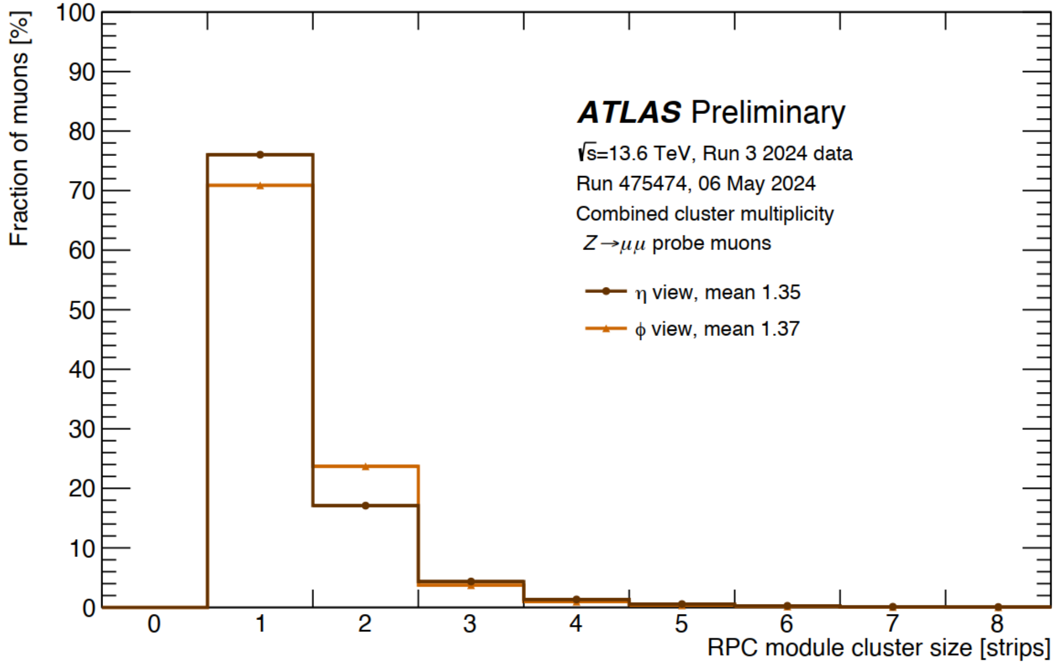
- **Up**: distributions of the measured current density for all the RPC gas gaps at the instantaneous luminosity of $2.0 \times 10^{34}\ cm^{-2}s^{-1}$
- **Bottom**: measured current density for all the RPC gas gaps as a function of the instantaneous luminosity
  - **Linear** increase of the RPC mean gap current density as a function of the instantaneous luminosity
- Three runs
  - Run 45016 (2023)
  - Run 475474 (2024 before the updated HV correction factor)
  - Run 476276 (2024 after the updated HV correction factor)

- The addition of the CO_2 leads to an increase of the current density of the gas gaps of around **~17%** in agreement with prototype results, even if the operational voltage has been lowered with the new gas mixture, **without decreasing the muon detection performance**

Cluster size at module level

Cluster size distributions for **Run 456016 (2023, left)** and for **Run 475474 (2024, right)**

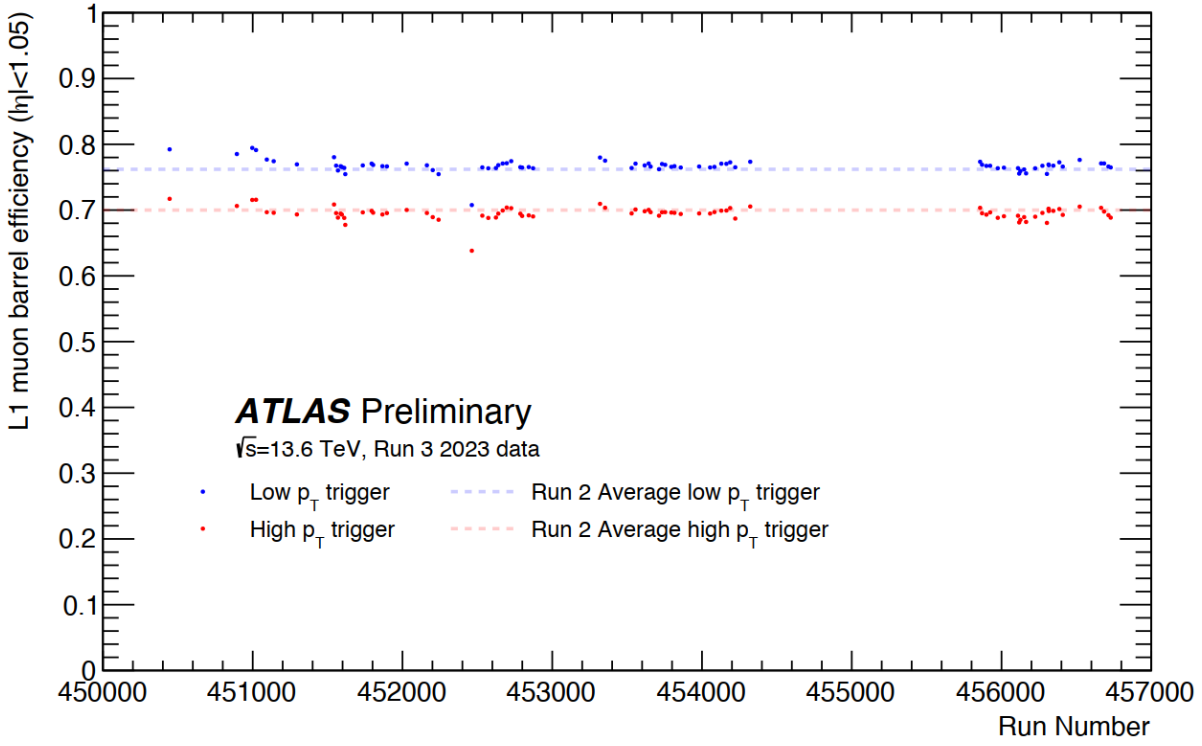


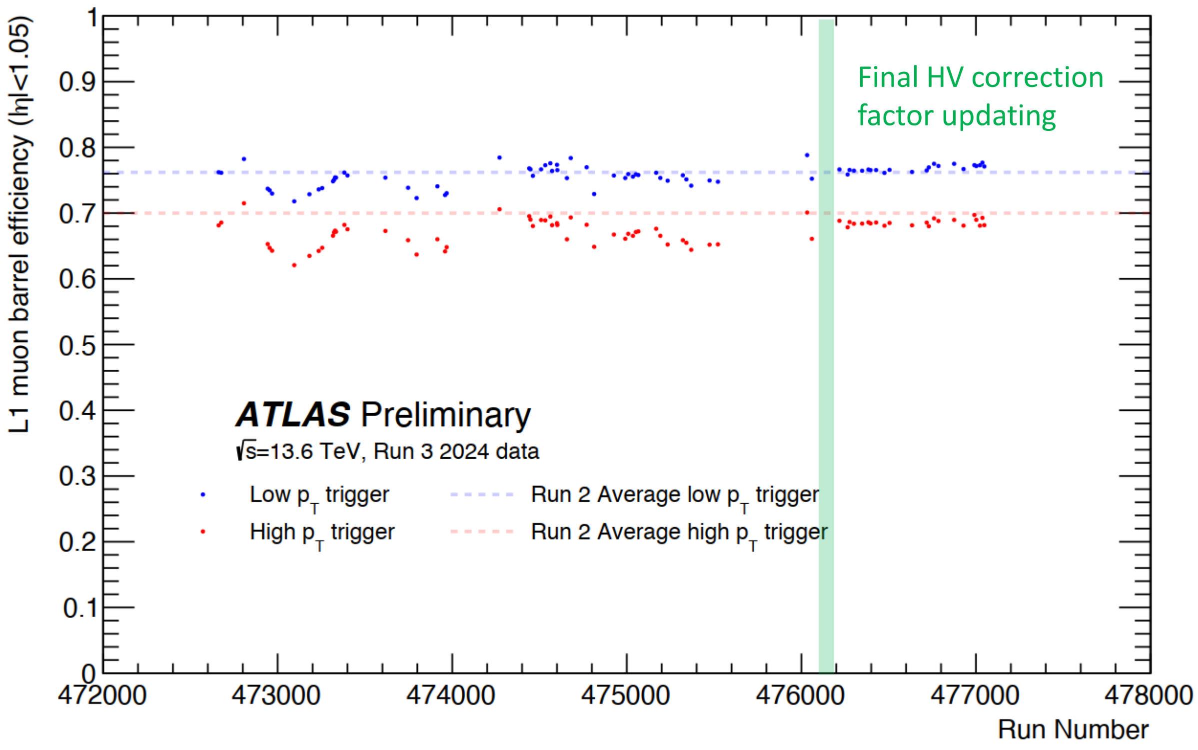


- The addition of CO_2 would increase the cluster size but the increased SF_6 component in the gas mixture limits the dimension of the avalanche
- The combined effect yields a similar cluster size between 2023 and 2024, smaller in 2024 than in 2023.
- No signs of detector ageing effects yet

Trigger performance

L1 muon barrel trigger efficiency (efficiency including acceptance) for **2023 (left)** and **2024 (right)** as a function of the Run Number, obtained with non-muon triggers on the physics main-stream

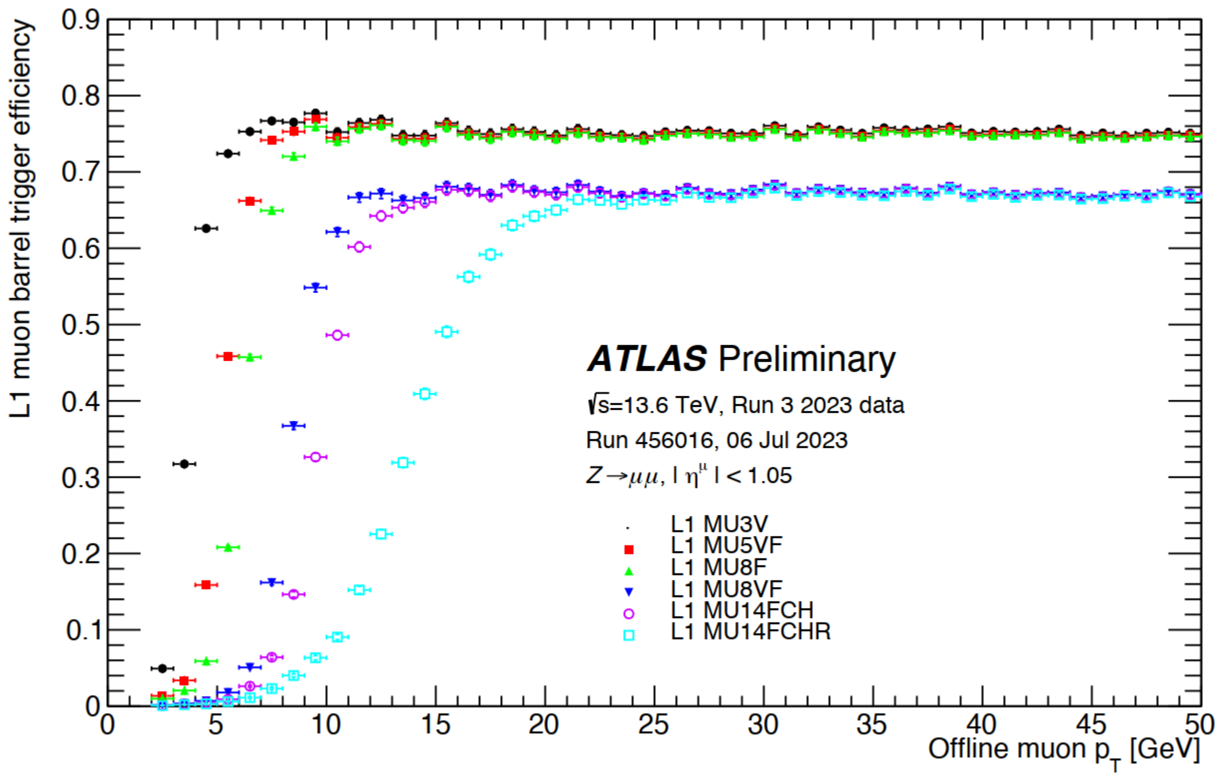


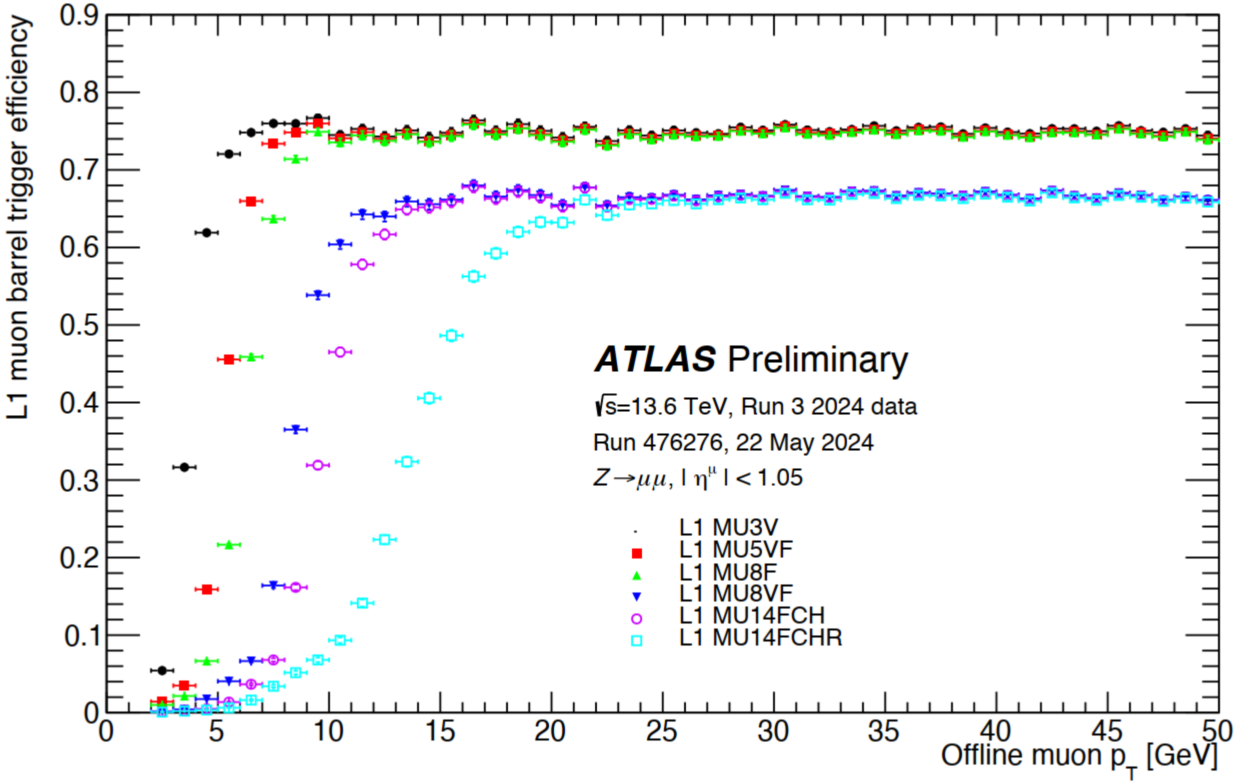


- ❑ RPC trigger efficiency is fairly constant during 2023 and 2024, fluctuating from run to run
- ❑ Initial instabilities in 2024 were fixed by an improved version for the handling of the HV correction factor ρ

Trigger performance--p_T turn-on curves

L1 muon barrel trigger efficiency as a function of the offline muon p_T for **Run 456016 (2023, left)** and for **Run 476276 (2024, right)** for different L1 triggers used in Run 3

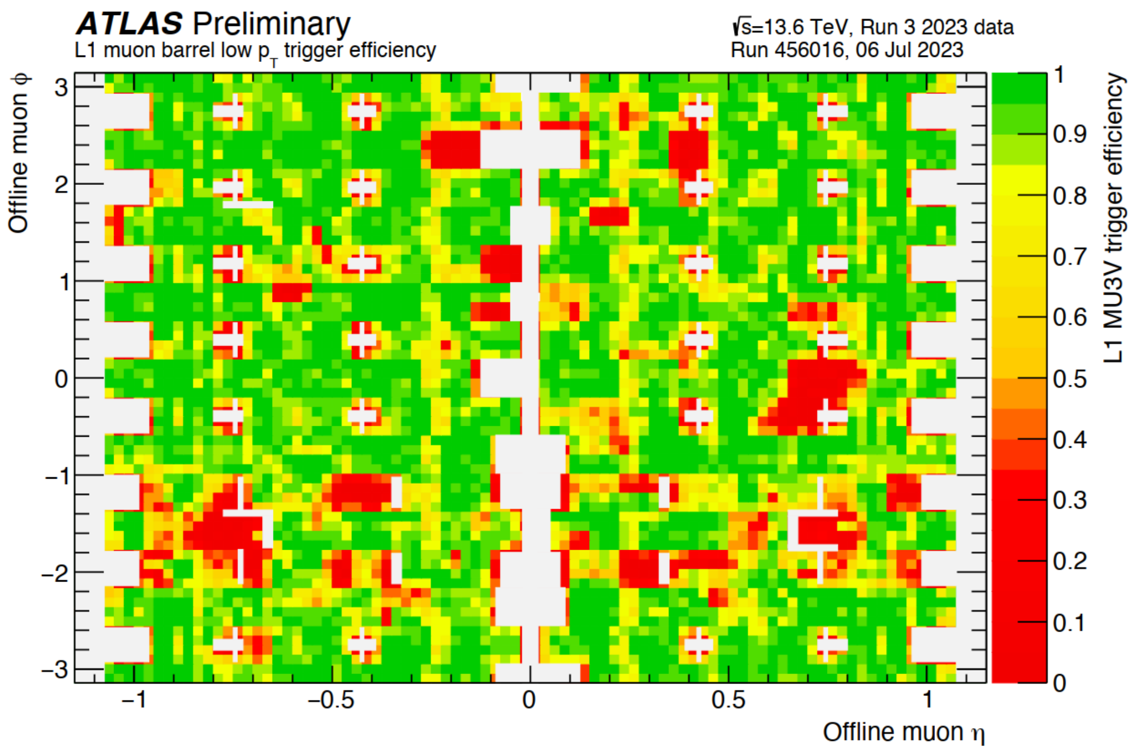


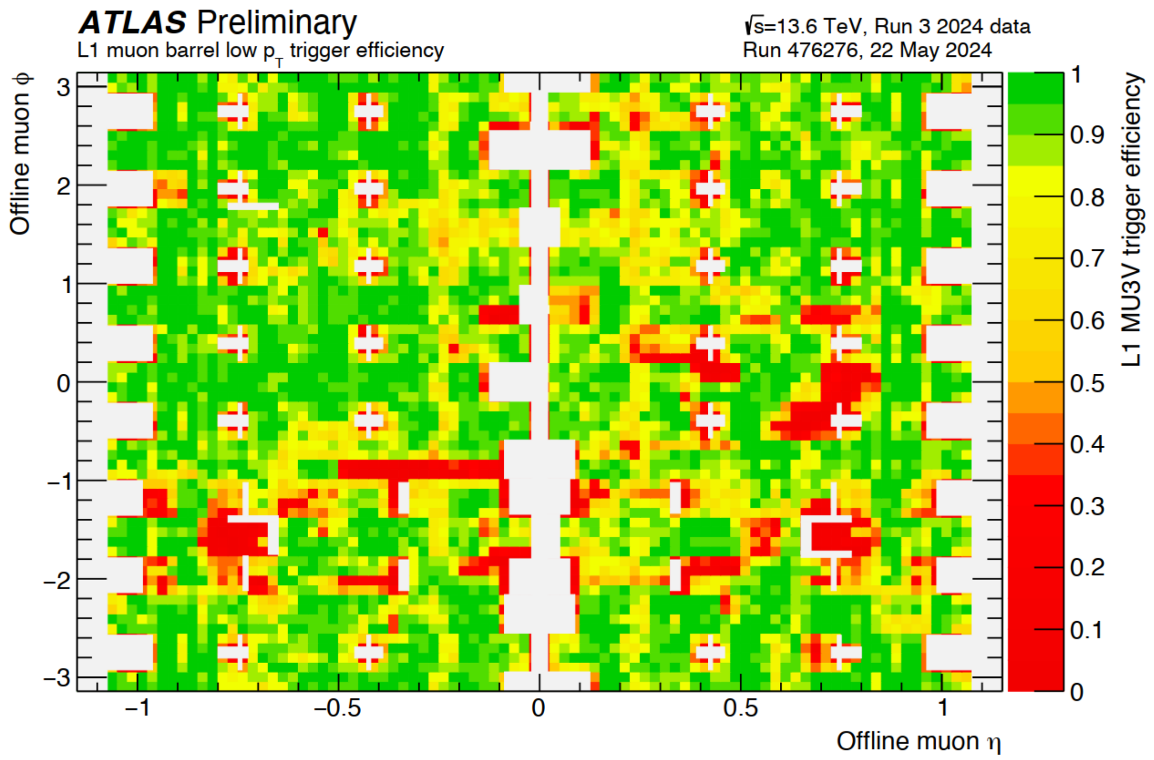


Constant trigger performance between 2023 and 2024 for the different Run3 L1 trigger thresholds

Trigger performance--low p_T η - φ efficiency maps

Low p_T L1 muon barrel trigger efficiency as a function of the offline muon η and φ for
Run 456016 (2023, left) and for **Run 476276 (2024, right)**

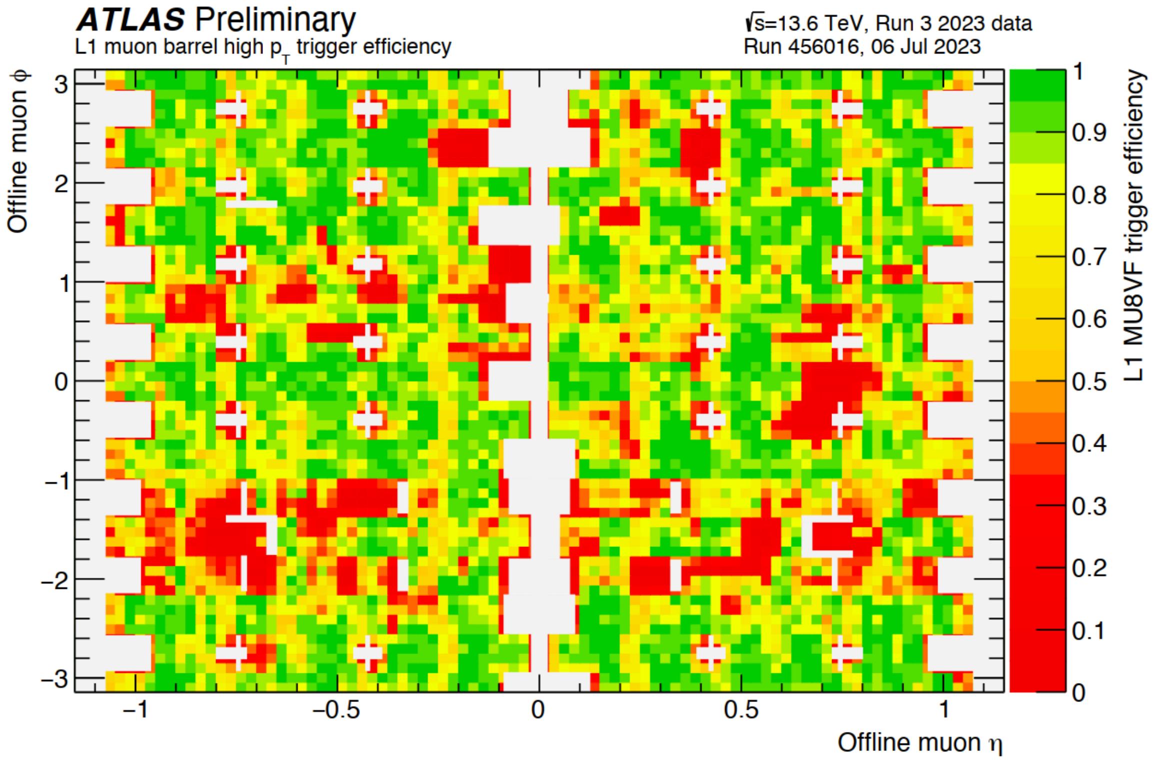


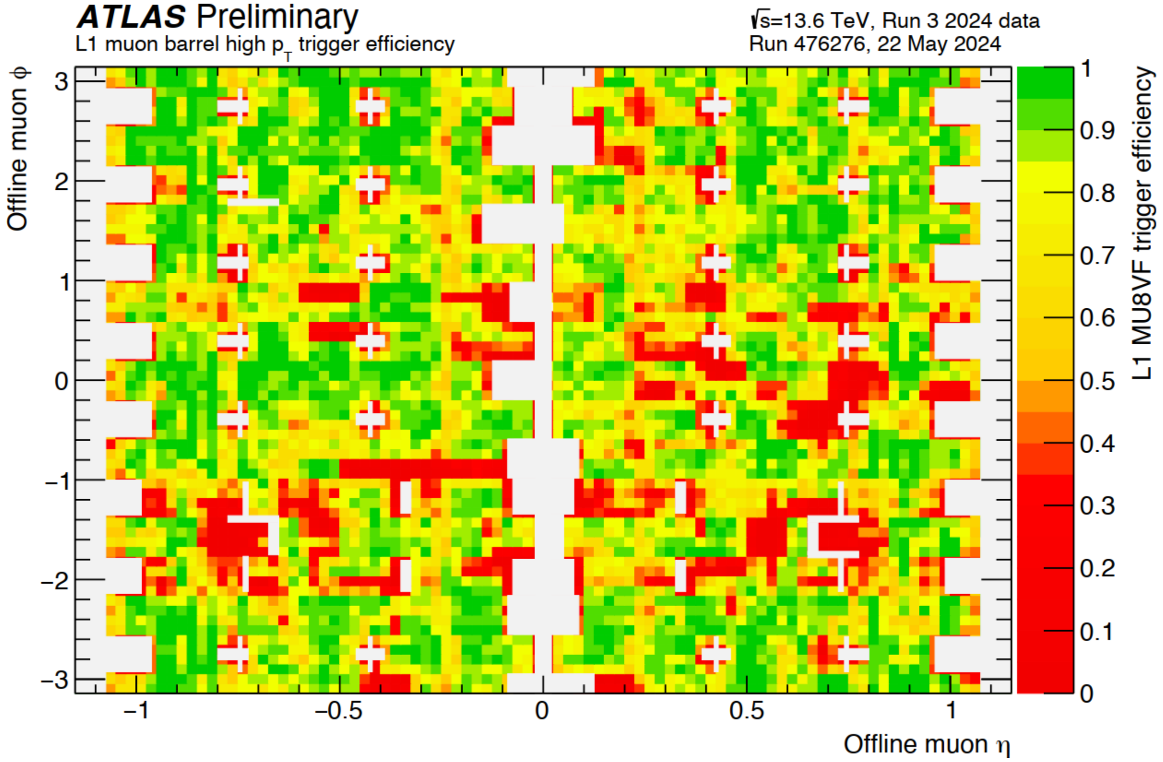


- **Constant trigger performance** between 2023 and 2024 for low p_T Triggers
- Improvement in trigger coverage due to the interventions in the year-end technical stop (YETS)
  - The number of gas gaps disconnected in **July 2024** are 310 over a total of 3716 (**8.3%**), while the number of gaps disconnected at the **end of 2023** data taking was 362 (**9.7%**)

Trigger performance--high p_T η - φ efficiency maps

High p_T L1 muon barrel trigger efficiency as a function of the offline muon η and φ for **Run 456016 (2023, left)** and for **Run 476276 (2024, right)**





- **Constant trigger performance** between 2023 and 2024 for high p_T Triggers
- Improvement in trigger coverage due to interventions in the YETS
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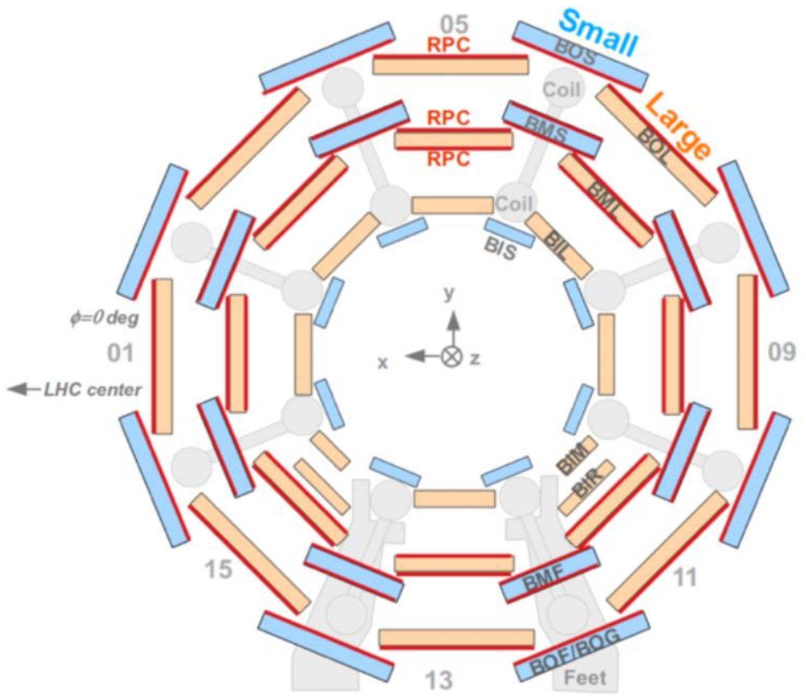
Summary

- RPC detector operating with a new gas mixture **adding 30% CO_2** at the end of pp collision in **2023**
- Detector status and performance with the new gas mixture are being monitored/studied.
- The new gas mixture is behaving as expected at detector level, yielding a **~17% increase of the gas gap current and a similar cluster size**.
- The measured trigger efficiency during 2024 is at a similar level to 2023.
- The measured trigger efficiency during Run 3 is at a similar level to Run 2.
- 2024 operations are progressing well with focus on reducing gas leaks and increasing as much as possible the trigger coverage.

backup

ATLAS Level-1 Muon Barrel trigger



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  - **low-p_T**: RPC2 & RPC1
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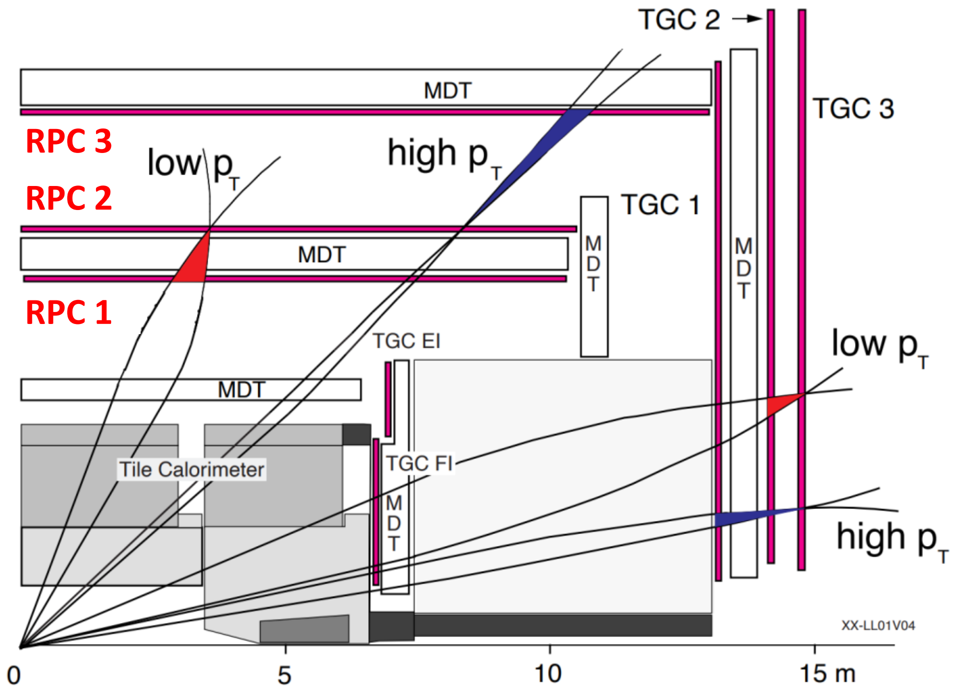
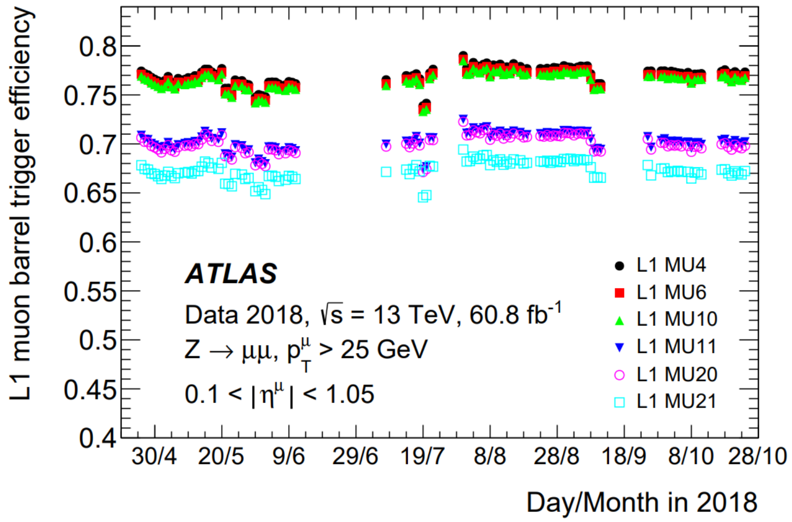
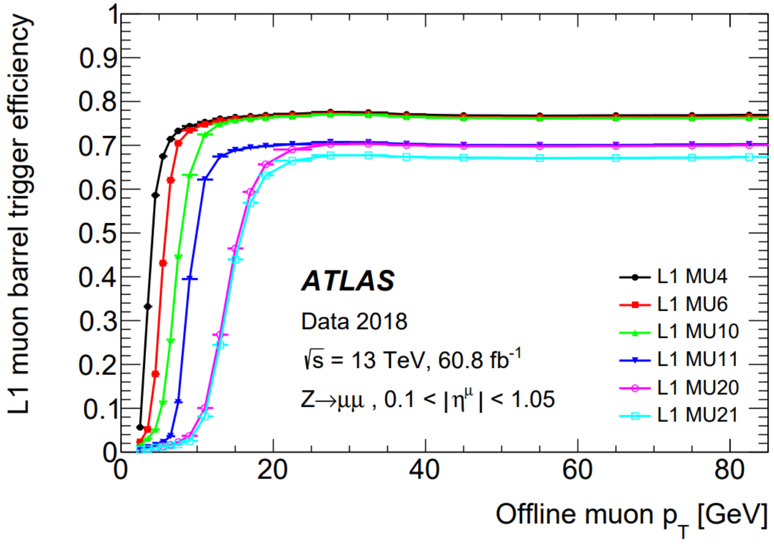
- L1 reduction factor of 400 (40 MHz -> 100 kHz)

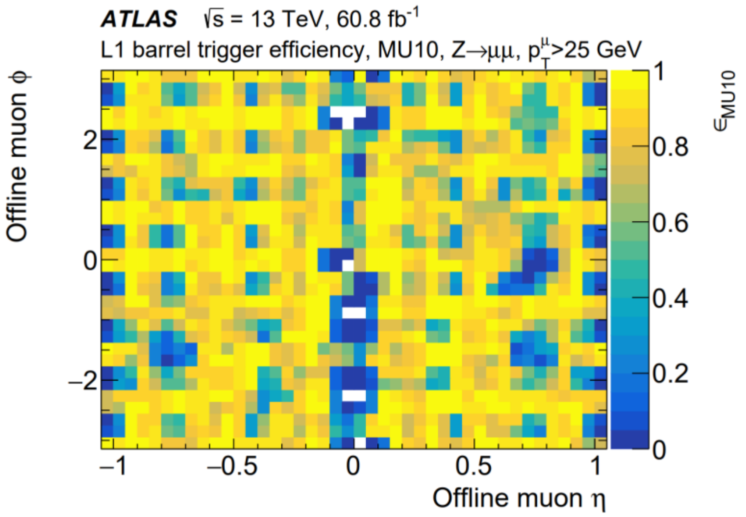


RPC trigger performance during Run2

- Measured L1 muon barrel efficiency in 2018 during Run 2[1].







The overall measured L1 muon barrel trigger efficiency as a function of time.

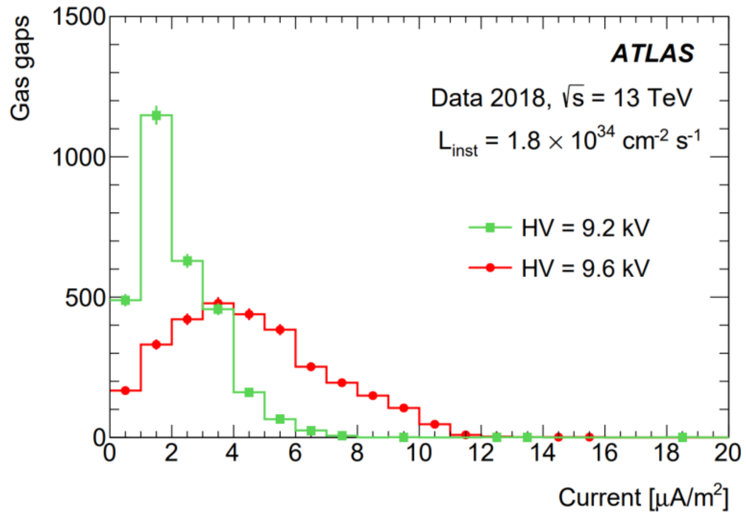
L1 muon barrel trigger efficiency plotted as a function of the probe muon p! .

L1 muon barrel trigger efficiency as a function of the muon pseudorapidity and azimuthal angle for the MU10 L1 trigger.

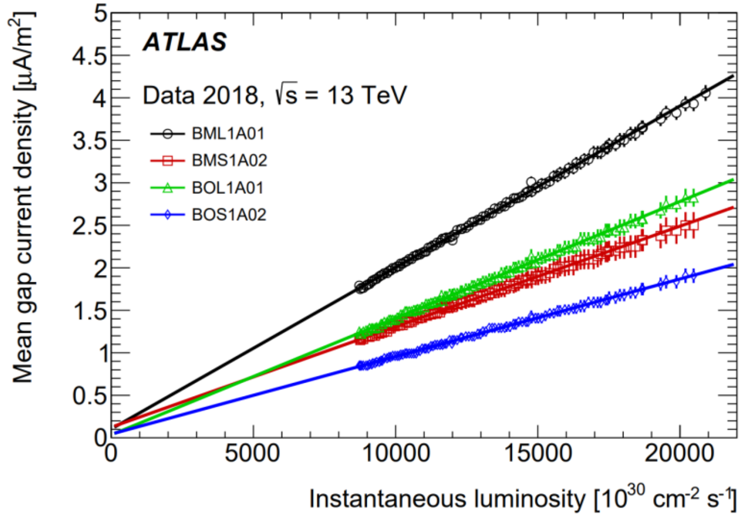
[1] ATLAS Collaboration, “*Performance of the ATLAS RPC detector and Level-1 muon barrel trigger at 13 TeV*”, JINST 16 P07029 (2021), https://doi.org/10.1088/1748-0221/16/07/P07029.

RPC detector performance during Run2

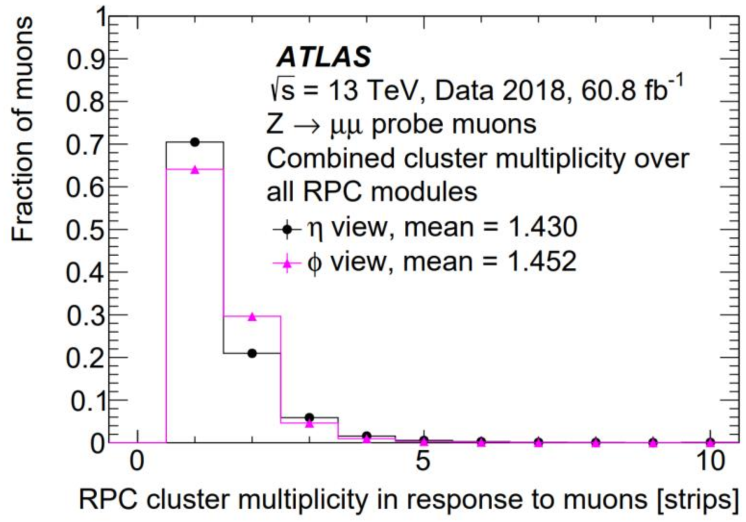
Measured gas gap current density, mean gas gap current densities and cluster size in 2018 during Run 2[1].



Distributions of the measured current density for the selected RPCs obtained at an instantaneous luminosity of $1.8 \times 10^{34}\ cm^{-2}s^{-1}$. The measurements were taken during one representative run in 2018.



RPC mean gap current density shown as a function of instantaneous luminosity for all the modules in some of the RPC stations.

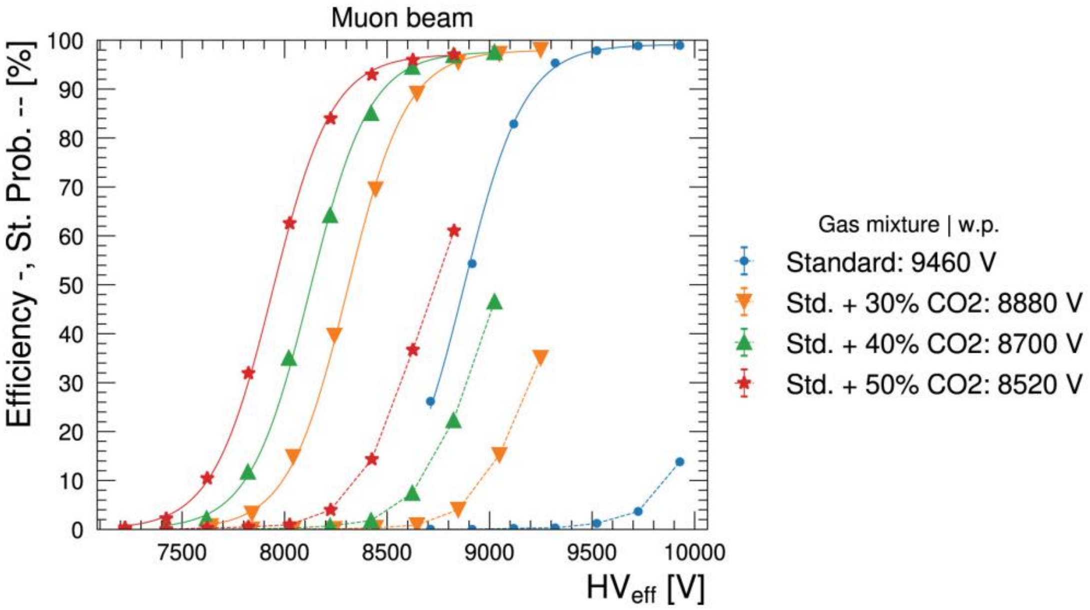


RPC cluster size distribution combined over all RPC modules with η and ϕ panels shown separately.

[1] ATLAS Collaboration, "*Performance of the ATLAS RPC detector and Level-1 muon barrel trigger at 13 TeV*", JINST 16 P07029 (2021), https://doi.org/10.1088/1748-0221/16/07/P07029.

Prototype results

The performance of RPC detectors operated with different levels of to $C_2H_2F_4$, CO_2, SF_6 was carefully evaluated using prototypes at the CERN Gamma Irradiation Facility in presence of muon beams[2].



Efficiency (full lines) and streamer probability (dashed lines) curves of the standard gas mixture and the gas mixture with the addition of 30%, 40%, 50% of CO_2.

Gas mixture	Currents	Time resolution
Std.	245 μA ± 1 μA	1.94 ns ± 0.05 ns
30% CO_2 + 0.3% SF_6	292 μA ± 1 μA	1.62 ns ± 0.05 ns
30% CO_2 + 0.9% SF_6	284 μA ± 1 μA	1.60 ns ± 0.05 ns
40% CO_2 + 0.9% SF_6	300 μA ± 1 μA	1.61 ns ± 0.05 ns

Currents and time resolution for different levels of CO_2 and SF_6 gas mixture.

[2] G. Rigoletti, R. Guida, B. Mandelli, "*Performance studies of RPC detectors operated with C2H2F4 and CO2 gas mixtures*", Nucl. Instrum. Methods Phys. Res. Section A, V1049 (2023), https://doi.org/10.1016/j.nima.2023.168088.

Alternative gas mixture[3]

Alternative gas mixtures with GWP ~ 200

$C_3H_2F_4/CO_2/$i-$C_4H_{10}/\ SF_6$

✓ **Pros :** Significant reduction of the GWP thanks to the full substitution of $C_2H_2F_4$ with $C_3H_2F_4/CO_2$ **(GWP ~1)**

✗ **Cons :** The double C-C bond of the $C_3H_2F_4$ increases its susceptibility to breakage, resulting in higher production of F^-radicals that can potentially accelerate aging

Gas mixtures studied

ECO3 : 25% $C_3H_2F_4$ /70% CO_2 /4% i-C_4H_{10} /1% SF_6

ECO2 : 35% $C_3H_2F_4$ /60% CO_2 /4% i-C_4H_{10} /1% SF_6

ECO55 : 55% $C_3H_2F_4$ /40% CO_2 /4% i-C_4H_{10} /1% SF_6

ECO65 : 65% $C_3H_2F_4$ /30% CO_2 /4% i-C_4H_{10} /1% SF_6

(V)

Alternative gas mixtures with GWP ~ 1100

$C_2H_2F_4/CO_2$i-C_4H_{10}/SF_6

✓ **Pros:** Minimal impact on the detector longevity is expected due to the similarity in composition to the standard gas

✗ **Cons:** not significant reduction of the GWP

Gas mixtures studied

65% $C_2H_2F_4$ /30% CO_2 /4% i-C_4H_{10} /1% SF_6
(Used in ATLAS since August 2023)

55% $C_2H_2F_4$ /40% CO_2 /4% i-C_4H_{10} /1% SF_6

65.5% $C_2H_2F_4$ /30% CO_2 /4% i-C_4H_{10} /0.5% SF_6

(VI)

- ❑ The gas mixtures 65% $C_3H_2F_4$ /30% CO_2 /4% i-C_4H_{10} /1% SF_6 and 65% $C_2H_2F_4$ /30% CO_2 /4% i-C_4H_{10}/1% SF_6 are the most promising in sight of the operation of the ATLAS phase-2 RPC.
- ❑ They show excellent performance in terms of efficiency, current under irradiation and time resolution.

[3] G.Proto, "*Study of environment-friendly gas mixtures for the Resistive Plate Chambers of the ATLAS phase-2 upgrade*"
https://agenda.infn.it/event/37033/contributions/227268/attachments/120065/174396/poster-Giorgia-Proto.pdf