Performance of the ATLAS RPC detector and Level-1 muon barrel trigger at $\sqrt{s} = 13$ TeV

ICNFP 2019 – Crete

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on behalf of the ATLAS collaboration

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26th August 2019
Outline

- The ATLAS Level-1 muon barrel trigger
- The ATLAS Resistive Plate Chambers
- Performance studies based on Run-2 data-taking
- Summary and conclusions
The ATLAS muon barrel trigger

- The Level-1 Muon Barrel Trigger is one of the main elements of the online event selection of the ATLAS experiment at the Large Hadron Collider (ATLAS trigger latency ~ 2.5 μs)
- It exploits the Resistive Plate Chambers (RPC) detectors to generate the trigger signal → **Intrinsic time resolution ~ 1 ns** (for 2 mm gas-gap)
- The RPCs are placed in the barrel region of the ATLAS experiment: they are arranged in three concentric double layers at radius 7 m and 10 m, operating in a toroidal magnetic field of about 0.5 T
- The Level-1 muon barrel trigger allows to select muon candidates according to their transverse momentum and associates them with the correct bunch-crossing
The ATLAS Resistive Plate Chambers

- Each RPC detector consists of two gas gaps (2 mm width), read out by two orthogonal planes of strips, in $\eta$ and $\phi$ views, with a width of 25-35 mm.

- Gas mixture of $\text{C}_2\text{H}_2\text{F}_4 : \text{C}_4\text{H}_{10} : \text{SF}_6$ (94.7 : 5.0 : 0.3)% operated in saturated avalanche mode at 9.6 kV nominal.

- RPC detectors cover the pseudo-rapidity range $|\eta| < 1.05$ ($\theta < 38^\circ$) for a total surface of about 4000 m$^2$ and ~3600 gas volumes (with 380k readout channels).

- Besides to provide trigger, RPC is the only system in the barrel Muon Spectrometer that provides the $\phi$ coordinate of the muon tracks.

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The Level-1 muon barrel trigger logic

- The RPC trigger system consists of 432 projective trigger towers. It is able to construct and provide to the HLT a Region of Interest (RoI) with a granularity of $\Delta \eta \times \Delta \varphi = 0.1 \times 0.1$ (~3600 RoIs).

- The Level-1 muon barrel trigger logic is based on the coincidence of hits from different RPC layers (both in $\eta$ and $\varphi$ projections).

- Two different $p_T$-regimes exist:
  - the **low-$p_T$ trigger** requires a coincidence between the two innermost RPC stations (RPC1 and RPC2). It is used to select muons with $p_T$ above 4 GeV (MU4), 6 GeV (MU6) and 10 GeV (MU10). They are used mainly for multi-object triggers and B-physics.
  - the **high-$p_T$ trigger** requires an additional confirmation on the third external station (RPC3) and selects muons with $p_T$ above 10 GeV (MU11) and 20 GeV (MU20 and MU21). MU20 is the lowest unprescaled single-muon trigger threshold.
RPC detector efficiency

- RPC detector efficiency is computed as the fraction of hits matched with the extrapolated position of the muon track within a distance of 30 mm from the centre of the strip and within 12.5 ns from the triggered bunch crossing (BCO)

Detector efficiency for $\eta$ and $\phi$ side views for each ATLAS run recorded in 2018 → stable performance during the year

**ATLAS** Preliminary

$\sqrt{s}=13$ TeV, Run 358395, 0.72 fb$^{-1}$

- Inclusive muons
- One RPC detector, $\eta$ side view

\[ \epsilon_{\text{all}} = 0.970 \pm 0.002 \]
\[ \epsilon_{\text{inTime}} = 0.967 \pm 0.002 \]
\[ \epsilon_{\text{signal}} = 0.965 \pm 0.002 \]

**ATLAS** Preliminary

Data 2018, $\sqrt{s}=13$ TeV, 60.8 fb$^{-1}$

- One RPC detector
- $|T| < 12.5$ ns, $|d| < 30$ mm

- $\eta$ view
- $\phi$ view

**Strip hit multiplicity and detector efficiency for $\eta$ and $\phi$ side views**
RPC detector efficiency

- RPC detector efficiency is computed as the fraction of hits matched with the extrapolated position of the muon track within a distance of 30 mm from the centre of the strip and within 12.5 ns from the triggered bunch crossing (BCO).

Distribution of the panel efficiencies of all live RPC panels in 2018

High efficiency for most of the panels

Mean detector efficiency as a function of time of all live RPC panels in 2018

Each point corresponds to a different run recorded in 2018 → stable performance during the full data-taking period

**ATLAS** Preliminary

$t_s = 13$ TeV, Run 358395

0.72 fb$^{-1}$, Inclusive muons

$|T| < 12.5$ ns, $|d| < 30$ mm

- detector $\eta$ side view  Mean 0.897
- detector $\phi$ side view  Mean 0.901
- gap efficiency  Mean 0.942

**ATLAS** Preliminary

Data 2018, $\sqrt{s} = 13$ TeV, 60.8 fb$^{-1}$

All live RPC detectors

$|T| < 12.5$ ns, $|d| < 30$ mm

- $\eta$ view
- $\phi$ view

FE threshold adjustment

day/month in 2018

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Hit position reconstruction

- Detector alignment and correct cabling are investigated using the correlation between the expected and measured muon positions
- Most of the panels perform properly, with most of the entries in the diagonal
- Actions are taken depending on the specific case

One representative RPC gas volume: η panel

One representative RPC gas volume: φ panel
Trigger efficiency

• Trigger efficiency investigated using unbiased muons from Z boson decays (Z→μμ Tag&Probe)
• Efficiency limited in the barrel region by toroid support structures and ATLAS “feet” supports
• Further reduction due to gas-gaps disconnected from HV (gas leaks) → mostly located on the external layer (BO chambers)

**Trigger efficiency x Acceptance** as a function of η and φ

- Efficiency drop at η = 0 due to the ATLAS services
- Efficiency drops due to the toroid ribs in the small sectors
Trigger efficiency

- Trigger efficiency investigated using unbiased muons from Z boson decays (Z→μμ Tag&Probe)
- Efficiency limited in the barrel region by toroid support structures and ATLAS “feet” supports
- Further reduction due to gas-gaps disconnected from HV (gas leaks) → mostly located on the external layer (BO chambers)

Trigger efficiency x Acceptance as a function of muon transverse momentum

**Plateau values:**
- MU10 → 76.5%
- MU20 → 70.0%
Trigger efficiency stability

- Trigger efficiency is one of the key parameters of the Level-1 muon barrel trigger monitored in each single run.
- Plateau values of the trigger efficiency as a function of time for six different Level-1 thresholds.
- Each point corresponds to a different ATLAS run recorded in 2018 during pp collisions at centre-of-mass energy $\sqrt{s} = 13$ TeV.
- Very good stability during the year has been achieved.

ATLAS Preliminary
Data 2018, $\sqrt{s} = 13$ TeV, 60.8 fb$^{-1}$
$Z \rightarrow \mu\mu$
$p_T^\mu > 27$ GeV, $0.1 < |\eta^\mu| < 1.05$
Timing performance

- Correct bunch crossing (BC) association is one of the main requirements of the Level-1 muon barrel trigger.
- Hits from various RPC detectors are calibrated in order to provide the correct timing.
- The “online” calibration is performed using programmable delays in steps of 1/8 BC (3.125 ns).
- 99.6% of the Level-1 muon barrel triggers are associated to the correct BC.

Each point corresponds to a different ATLAS run recorded in 2018.

Stable performance during the full year.
Studies for HL-LHC

- Study the response of few RPC chambers with lower HV and thresholds
- At HL-LHC (5 - 7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}) the integrated charge collected in the avalanche will be enough high to limit the detector lifetime
- In order to keep the performance of current system stable during years, it is needed to lower the HV in the RPC gas-gaps (9.6 kV → 9.2 kV). At the same time, new RPCs will be installed in the innermost layer of the Muon Barrel Spectrometer to increase the redundancy of the trigger system and the trigger efficiency
- This study demonstrates that part of the efficiency lost by reducing the RPC HV can be recovered by lowering the thresholds of the Front-End discriminator (10% on average)
Studies for HL-LHC

- Gas-gap currents (normalized to the gap area) as a function of instantaneous luminosity with 2018 data
- Aim to predict safe operating HV settings for each gas gap for HL-LHC
- Current proportional to the luminosity → this shows that the present RPC system is in a very good status
Summary and conclusions

• Muon triggers are of crucial importance for fulfilling the physics program of the ATLAS experiment

• L1 muon barrel trigger is the largest RPC system in a collider experiment

• ATLAS RPCs worked for long time with stable performance (both detector and trigger efficiencies) and operations for ~10 years, even with a factor of 2 larger than the design instantaneous luminosity → no signs of ageing observed

• Very large effort to monitor the RPC performance continuously during the year

• No major upgrades are foreseen for Run-3, but for Phase-II a completely new trigger system is expected (RPC in the BI layer + new trigger electronics) → See talk from Luca Pizzimento
Back-up slides
ATLAS data-taking performance during 2018

ATLAS Online Luminosity

- LHC Stable Beams

Peak Lumi: $21.4 \times 10^{33} \text{ cm}^2 \text{ s}^{-1}$

Total Delivered: 65.0 fb$^{-1}$
Total Recorded: 62.2 fb$^{-1}$

96% recorded
Muon barrel acceptance limits

- Acceptance holes of the Level-1 muon barrel trigger ~22%
- Holes due to toroid ribs (Small Sectors) and $Z=0$ crack (Large Sectors) + holes in feet region and bottom sector (elevator)

![Muon barrel acceptance limits graph](image-url)
Level-1 muon barrel trigger: feet region

Upgrade project to cover acceptance holes in the “feet” sectors (12-14) 4th RPC layer
2.8% increase of barrel acceptance

20 RPC chambers installed before 2008, equipped with services and electronics
during long shutdown 2013-2014

Special trigger “towers” implementing simple two-station coincidences (4 layers)
Level-1 muon barrel trigger: feet region

The overlap is between contiguous pads, like:

pad2-pad3 ; pad3-pad4; pad5-pad6; pad6-pad7
The MU10 trigger requires that a candidate passed the 10 GeV threshold requirement of the Level 1 muon trigger system, using medium trigger chambers.

The MU11 trigger requires that a candidate passed the 10 GeV threshold requirement of the Low-$p_T$ Level 1 muon trigger system, with a coincidence with a High-$p_T$ RPC chamber.

The efficiency is measured on an inclusive sample selected using all non-muon Level 1 ATLAS triggers, in 13 TeV data from 2017 with 25 ns LHC bunch spacing.
Level-1 muon barrel trigger: sector 13

R versus Z (side A)

Low-to-high connections:
- BML3 → BOL3
- BME → BOL4 (new)

Chamber digits:
- 1: BML3-η0
- 2: BML3-η1
- 3: BME-η0
- 4: BME-η1
- 5: BML5-η0
- 6: BML5-η1
Trigger efficiency vs pile-up

**ATLAS Preliminary** \( \sqrt{s}=13 \text{ TeV}, \text{ Data 2017, 15 fb}^{-1} \)

\[ Z \rightarrow \mu\mu \]
\[ p_T^{\mu} > 27 \text{ GeV}, |\eta^{\mu}| < 1.05 \]

**Efficiency**

**Number of reconstructed vertices**
Trigger performance expected for Run-3

Figure 3.5: Geometrical acceptance of the L0 barrel trigger with respect to reconstructed muons with $p_T = 25$ GeV in the $\eta$-$\phi$ plane. Figures (a), (b), and (c) show the acceptance for the different trigger coincidence logic schemes: 3/3 chambers, 3/4 chambers, and 3/4 chambers + BI-BO, respectively.

<table>
<thead>
<tr>
<th>BM and BO efficiency (%)</th>
<th>3/3 chambers</th>
<th>3/4 chambers</th>
<th>3/4 chambers + BI-BO</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>78</td>
<td>91</td>
<td>96</td>
</tr>
<tr>
<td>90</td>
<td>73</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>80</td>
<td>62</td>
<td>87</td>
<td>93</td>
</tr>
<tr>
<td>Worst case</td>
<td>63</td>
<td>85</td>
<td>92</td>
</tr>
</tbody>
</table>
Trigger performance expected for Run-3

Expected rates at $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for L1 MU20

(*) indicates the rate for a BI-BO trigger that is restricted to acceptance gaps

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Rate</th>
</tr>
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<tbody>
<tr>
<td>3/3 chambers</td>
<td>20 kHz</td>
</tr>
<tr>
<td>3/4 chambers</td>
<td>30 kHz</td>
</tr>
<tr>
<td>3/4 chambers + BI-BO</td>
<td>85 kHz</td>
</tr>
<tr>
<td>3/4 chambers + BI-BO (*)</td>
<td>45 kHz</td>
</tr>
</tbody>
</table>