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

CLHCP 2020

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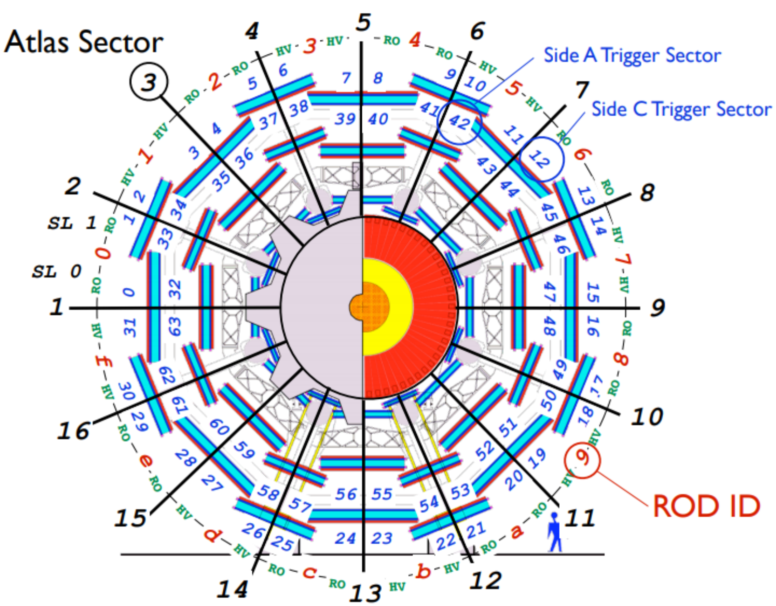
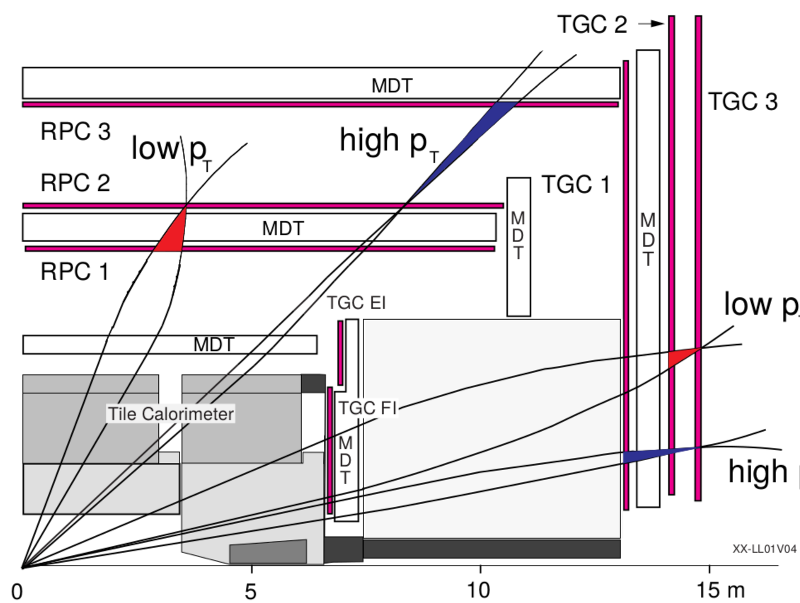
The ATLAS muon barrel trigger

- 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 → <u>Intrinsic time resolution ~ 1 ns (for 2 mm gas-gap)</u>
- 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 selects the muon candidates according to their transverse momentum and associates them to the correct bunch-crossing

X-Y view

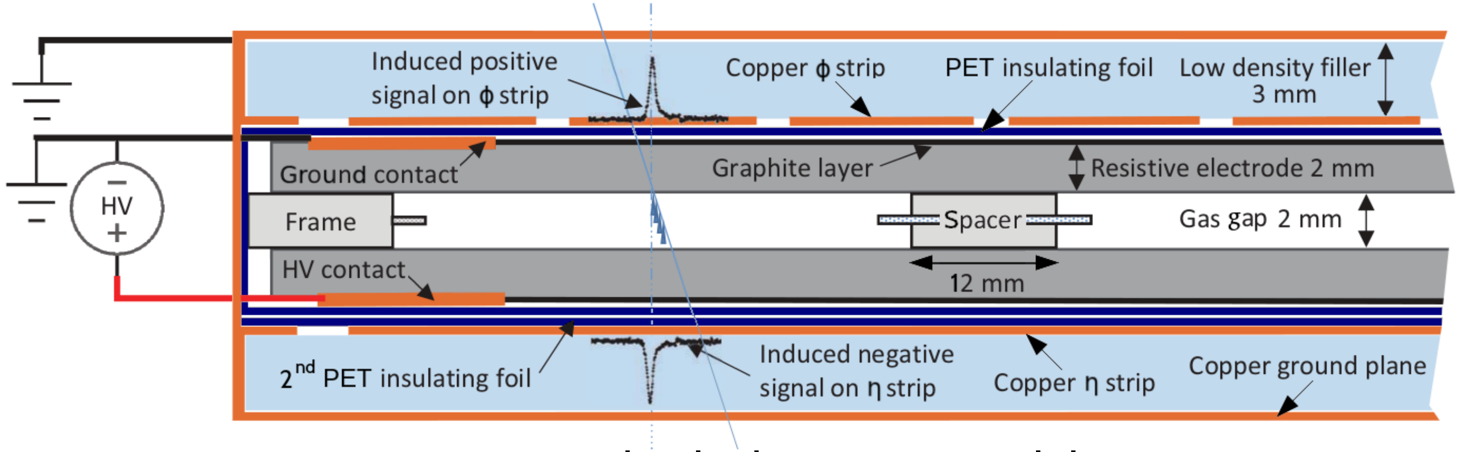


Y-Z view



The ATLAS Resistive Plate Chambers

- Each RPC chamber consists of two RPC layers with 2 mm width gas gaps. Each module is read out by two planes of orthogonal strips, in η and φ views, with a width of 25-35 mm
- Gas mixture of $C_2H_2F_4 : C_4H_{10} : SF_6$ (94.7 : 5.0 : 0.3)% operated in saturated avalanche mode at 9.6 kV
- RPC detectors cover the pseudo-rapidity range $|\eta| < 1.05$ ($\vartheta < 38^\circ$) for a total surface of about 4000 m^2 and ~3700 gas volumes (with 380k readout channels)
- RPC is the only system in the barrel Muon Spectrometer that provides the φ coordinate of the muon tracks



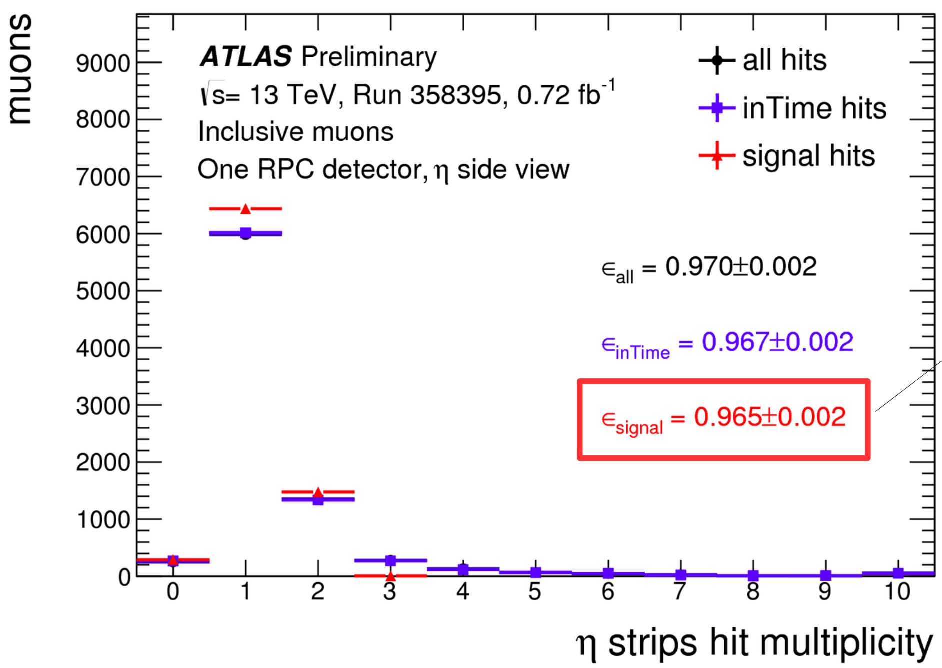
One individual RPC gas module

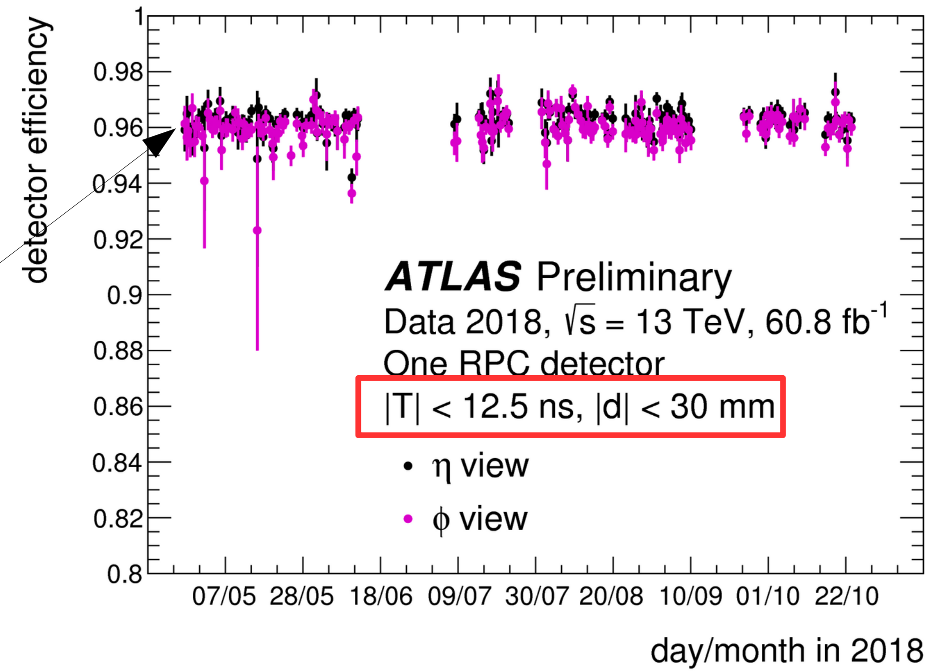
RPC detector efficiency

- 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)

Strip hit multiplicity and detector efficiency **for one RPC module** in η view

Detector efficiency for η and φ side views for each ATLAS run recorded in 2018
→ stable performance during the year





RPC detector efficiency

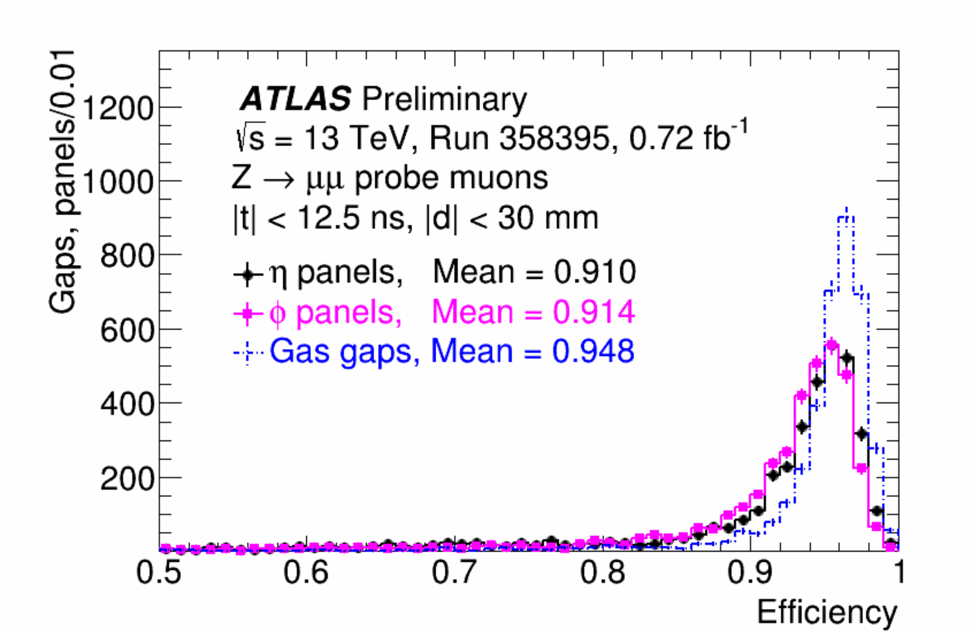
- RPC detector efficiency is computed as the fraction of hits matched with the extrapolated position of the muon track within a distance of 30 mm from the centre of the strip and within 12.5 ns from the triggered bunch crossing (BCO)

Distribution of the panel efficiencies of **all RPC modules** in 2018

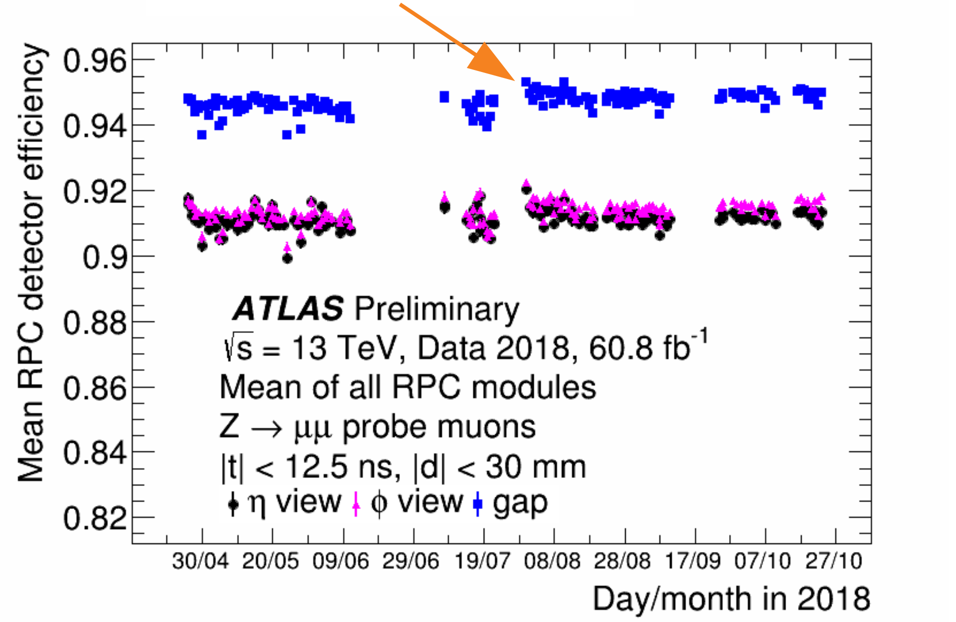
High efficiency for most of the panels

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



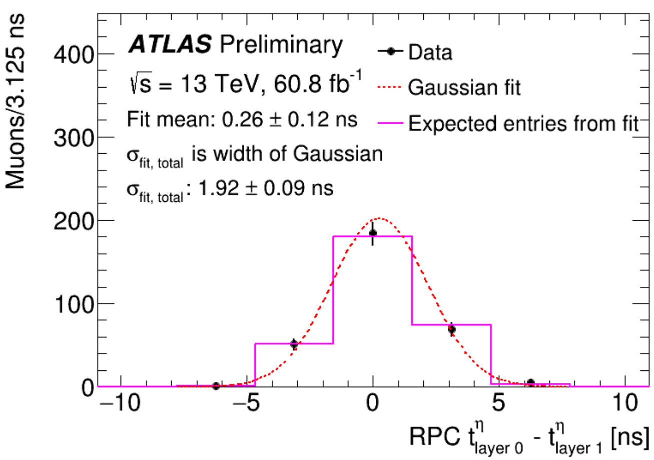
Front-end discriminator threshold adjustment



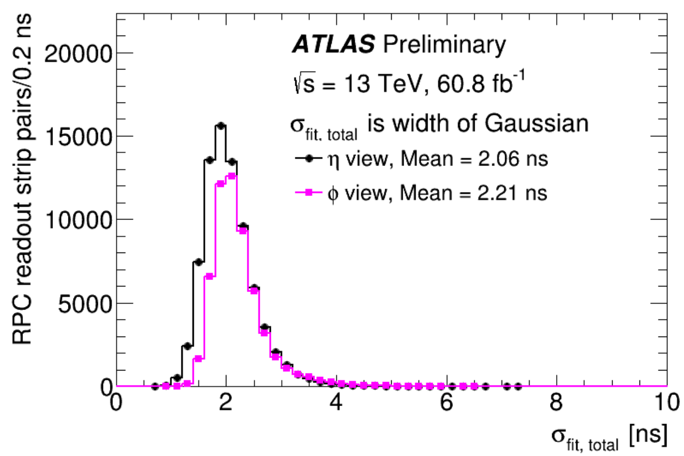
Time resolution

- Measure **total RPC time resolution** by measuring time differences between muon hits in 2 RPC layers
  - 2 layers are separated by ~20 mm → negligible muon time-of-flight
  - Fit time differences for every pair of RPC strips with Gaussian function
  - Includes both intrinsic RPC time resolution and front-end electronics effects (320 MHz sampling rate)
- Measure **electronics time resolution** by measuring time differences between muon η and φ hits in 1 layer
  - η and φ measurements for the same avalanche event
  - Fit time differences for every pair of η and φ strips with Gaussian function
- Intrinsic **RPC time resolution** estimated by subtracting electronics component from the total for every strip pair

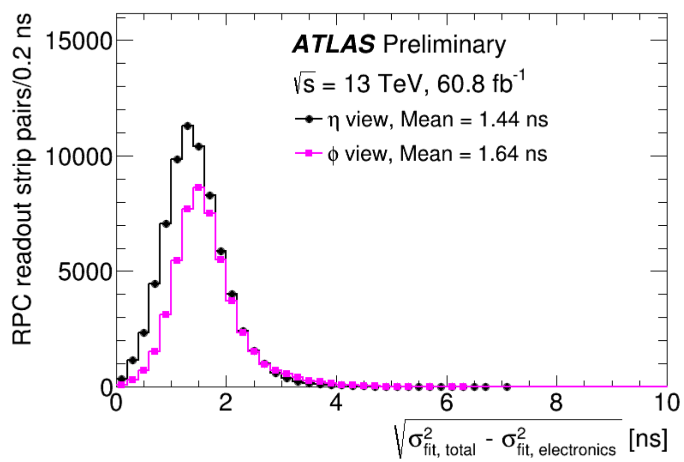
Time difference for one strip pair



Total time resolution

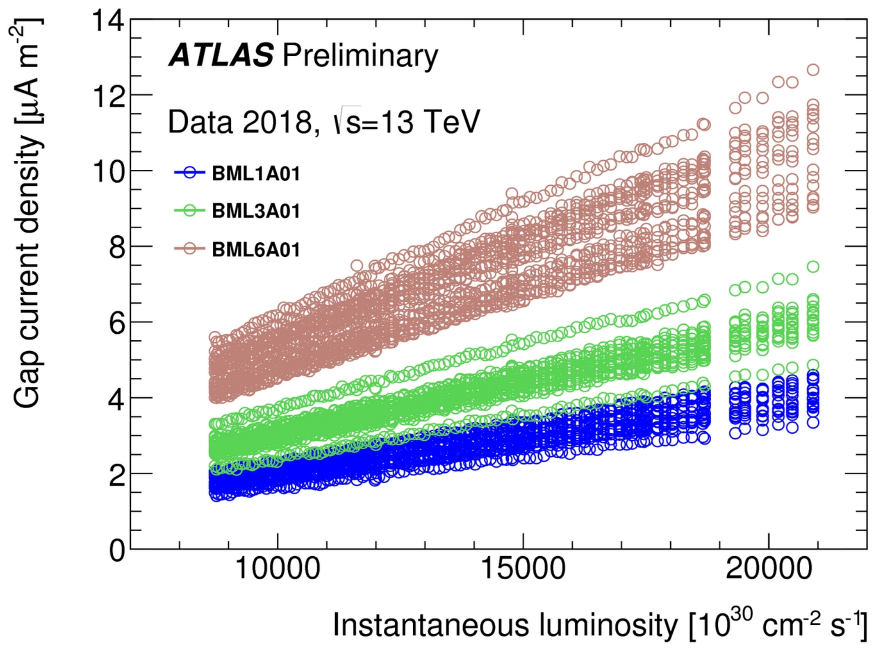


Intrinsic time resolution

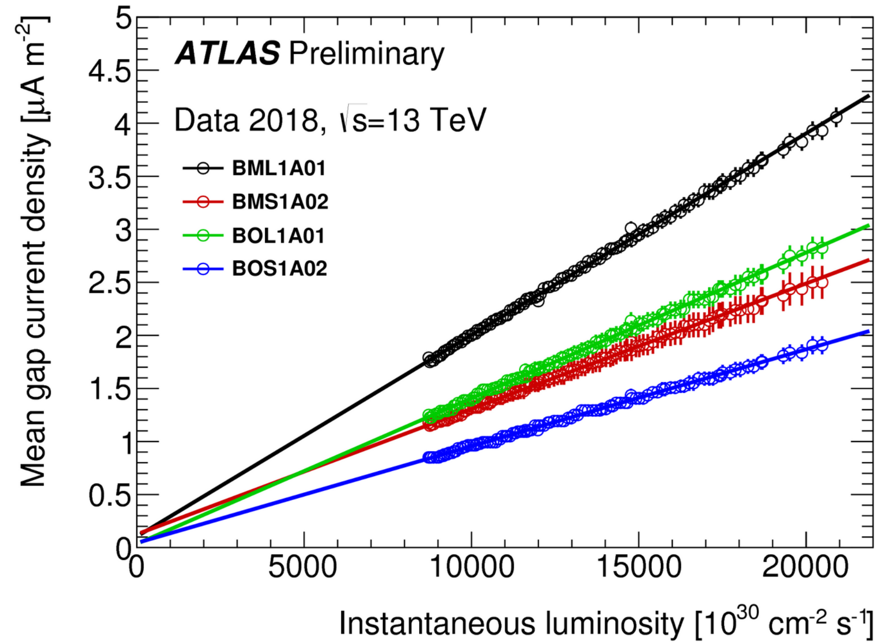


Current measurements

- RPC current and counting rate are dominated by secondary particles
  - Mostly photons and neutrons produced in interactions with the detector and beam pipe material
- Gas-gap currents (normalized to the gap area) are measured as a function of instantaneous luminosity
- Aim to predict safe operating voltage settings for each gas gap for HL-LHC
- Current is observed to be proportional to the luminosity → this shows that the present RPC system is in a very good status



Several gas volumes belonging to chambers at different z positions

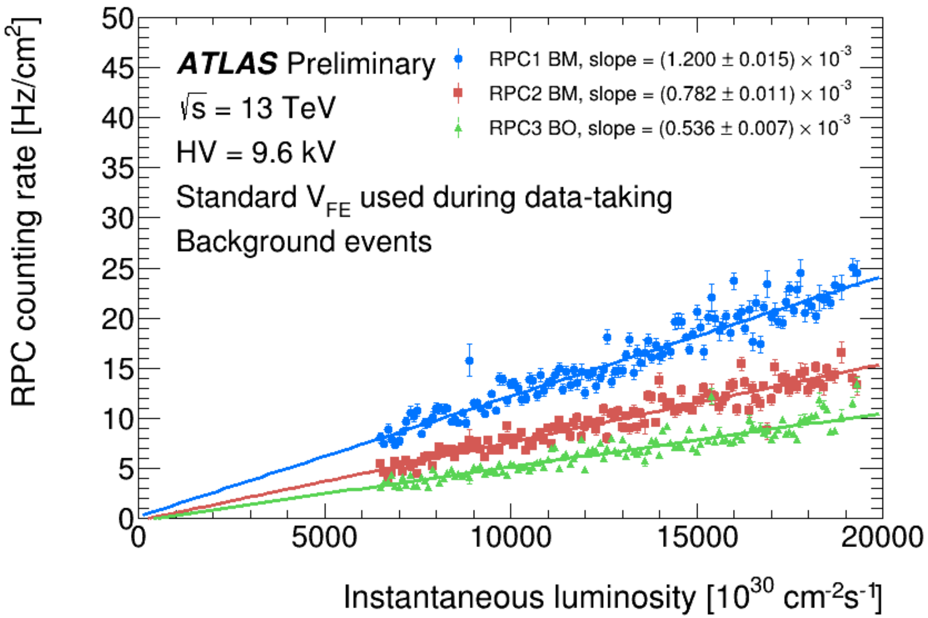


Averaged currents of several gas volumes belonging to chambers at different distance from IP

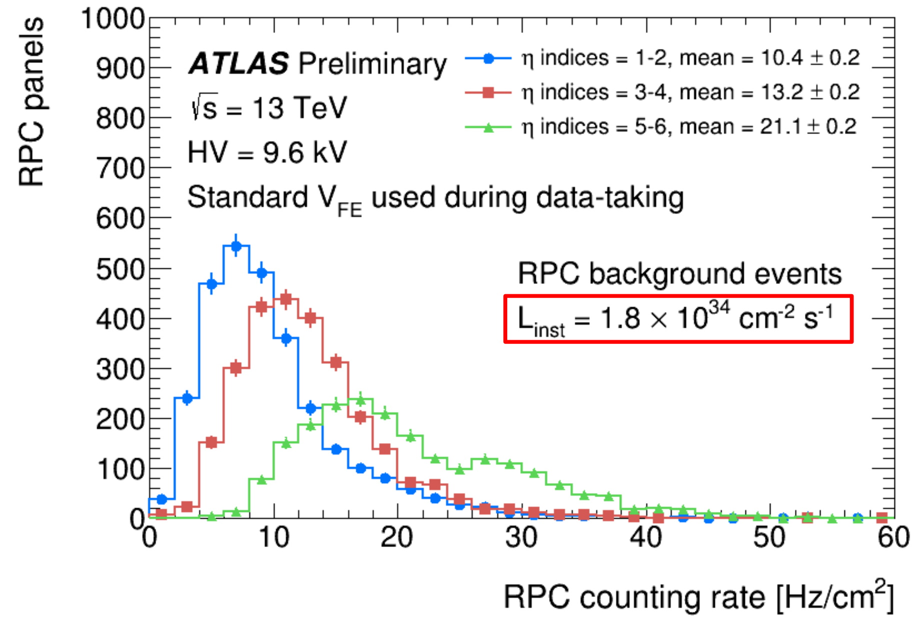
Counting rate

- RPC current and counting rate are dominated by secondary particles
  - Mostly photons and neutrons produced in interactions with the detector and beam pipe material
- Counting rates measured in the 3 bunch crossings (BC) immediately preceding the BC triggered by the single muon trigger (BC0)
- Rates normalised to surface area plotted as a function of the instantaneous luminosity or measured at the reference luminosity of $1.8{\times}10^{34}$ Hz/cm^2 for all modules

One RPC module

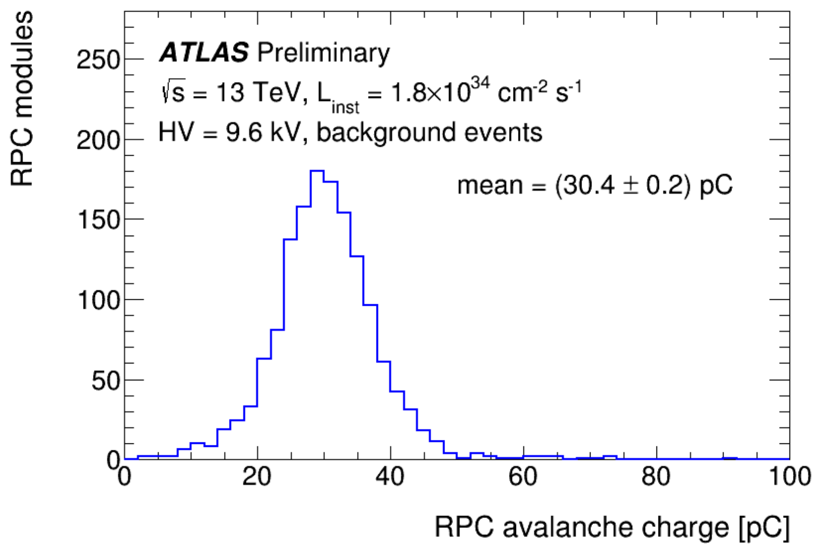


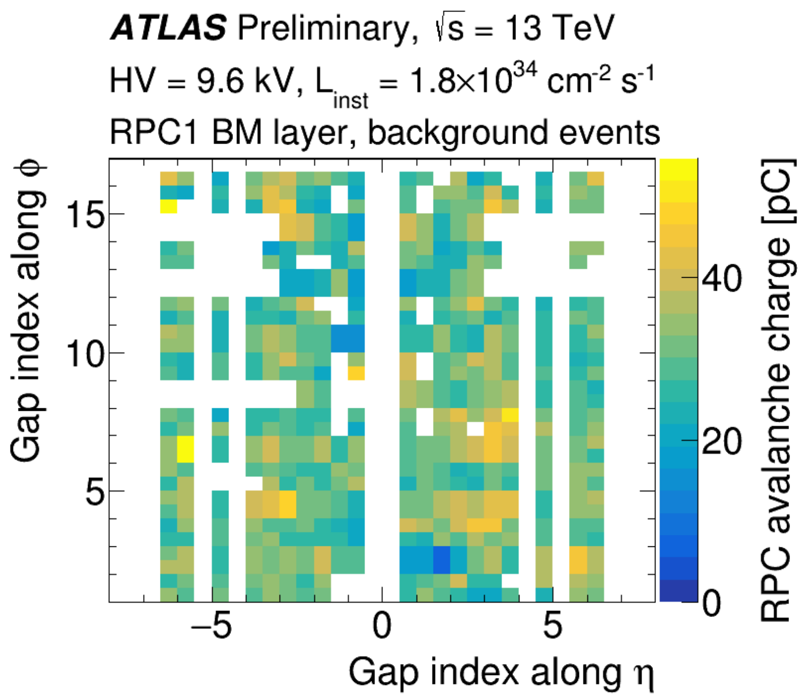
All RPC modules



Avalanche charge

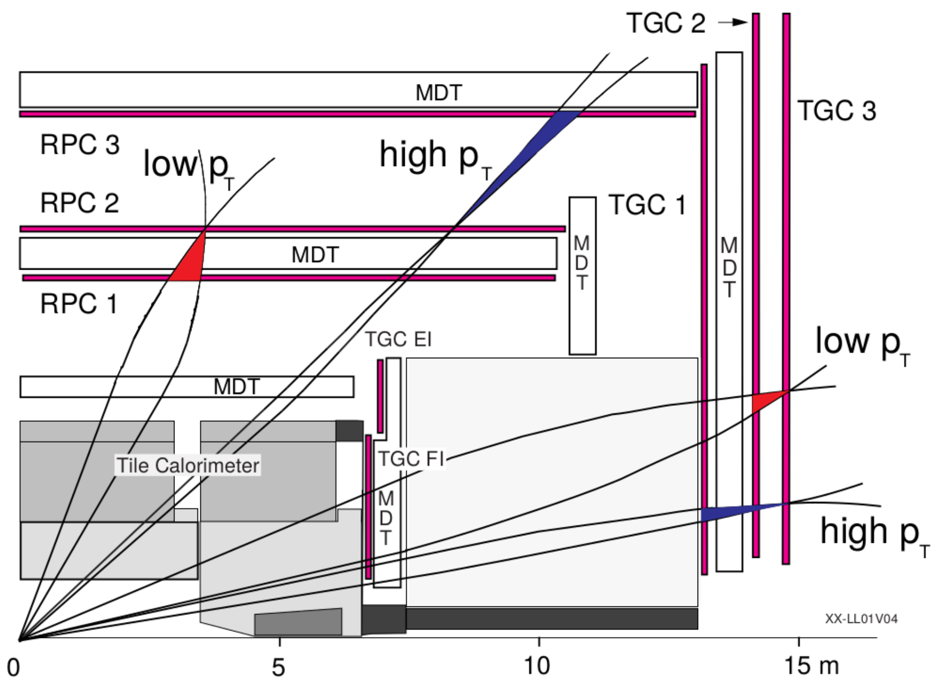
- The avalanche charge produced by the electron amplification process inside the gas depends mainly on the electric field across the gas-gap and the gas mixture
- The avalanche charge is measured using background events as $Q = \frac{Current}{Rate}$
  - Current measured as total charge per second, while counting rate measured using only signals above threshold
- Mean avalanche charge of about 30 pC is consistent with previous measurements, obtained using γ sources or at test beam facilities
- Avalanche charge is approximately uniform across the detector, with variations between modules due to differences in front-end discriminator thresholds, applied voltage and temperature





The Level-1 muon barrel trigger logic

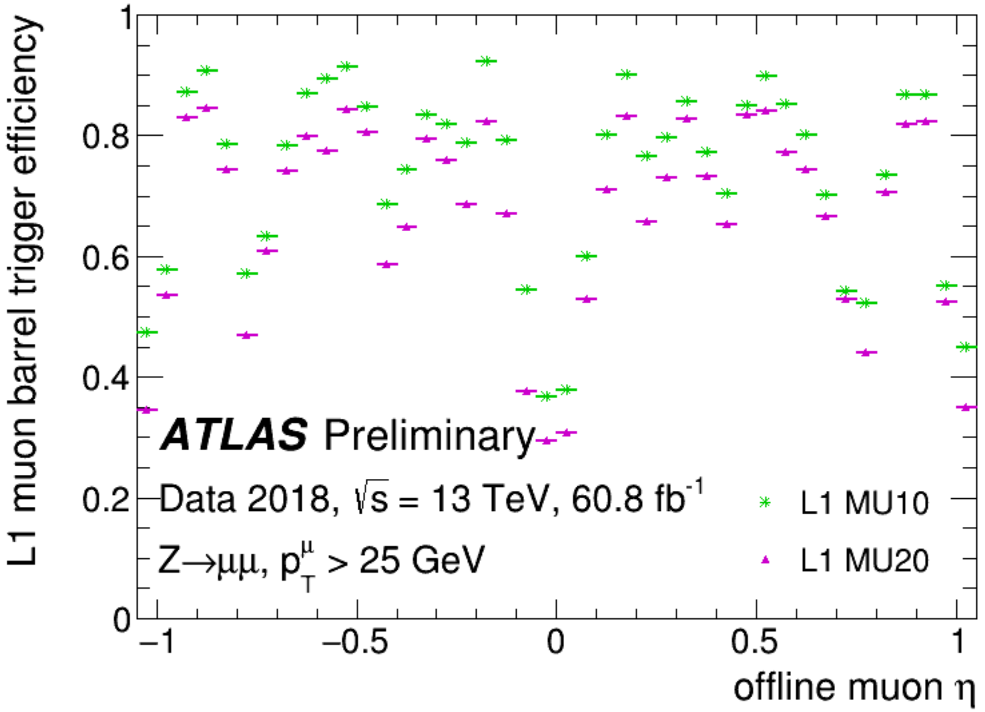
- The RPC trigger system consists of 432 projective trigger towers. It is able to construct and provide to the software-based High Level Trigger a Region of Interest (RoI) with a granularity of $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
- The Level-1 muon barrel trigger logic is based on the coincidence of hits in different RPC layers (both in η and φ projections)
- Two different p_T-regimes exist:
  - the **low-p_T trigger** requires a coincidence between the two innermost RPC layers (RPC1 and RPC2). It is used to select muons with p_T above 4 GeV (MU4), 6 GeV (MU6) and 10 GeV (MU10).
    <u>They are used mainly for multi-object triggers and B-physics</u>
  - the **high-p_T trigger** requires an additional confirmation on the third external layer (RPC3) and selects muons with p_T above 10 GeV (MU11) and 20 GeV (MU20 and MU21).
    <u>MU20 is the lowest unprescaled single-muon trigger threshold</u>



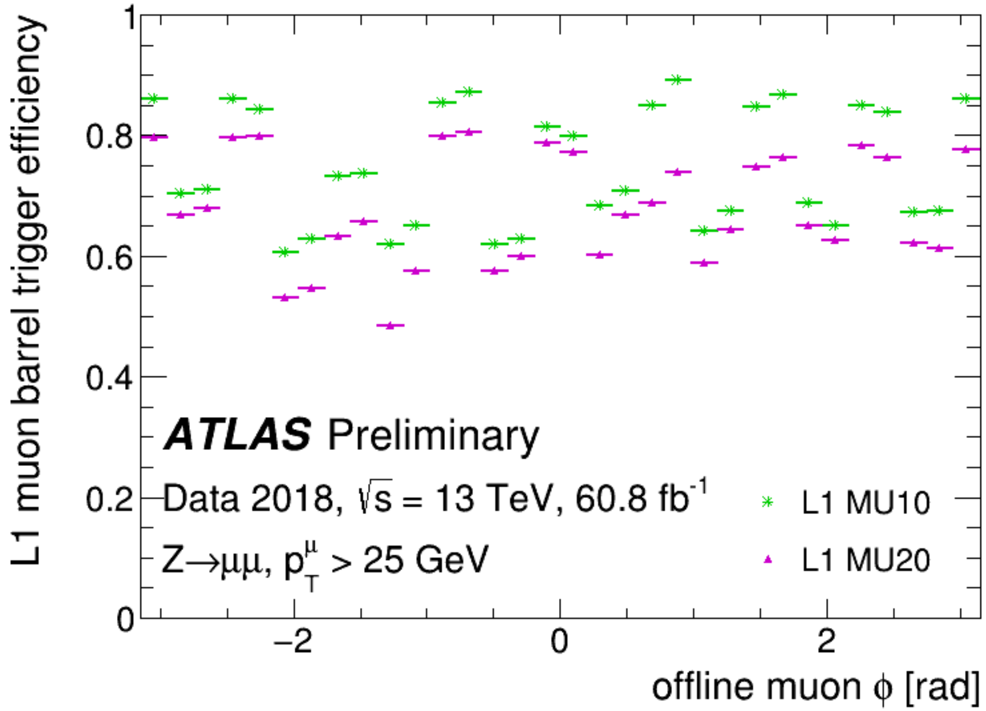
Level-1 muon barrel trigger efficiency

- Trigger efficiency investigated using unbiased muons from Z boson decays ($Z\rightarrow\mu\mu$ Tag&Probe)
- Efficiency limited in the barrel region by toroid support structures and ATLAS "feet" supports

Trigger efficiency x Acceptance as a function of η and φ



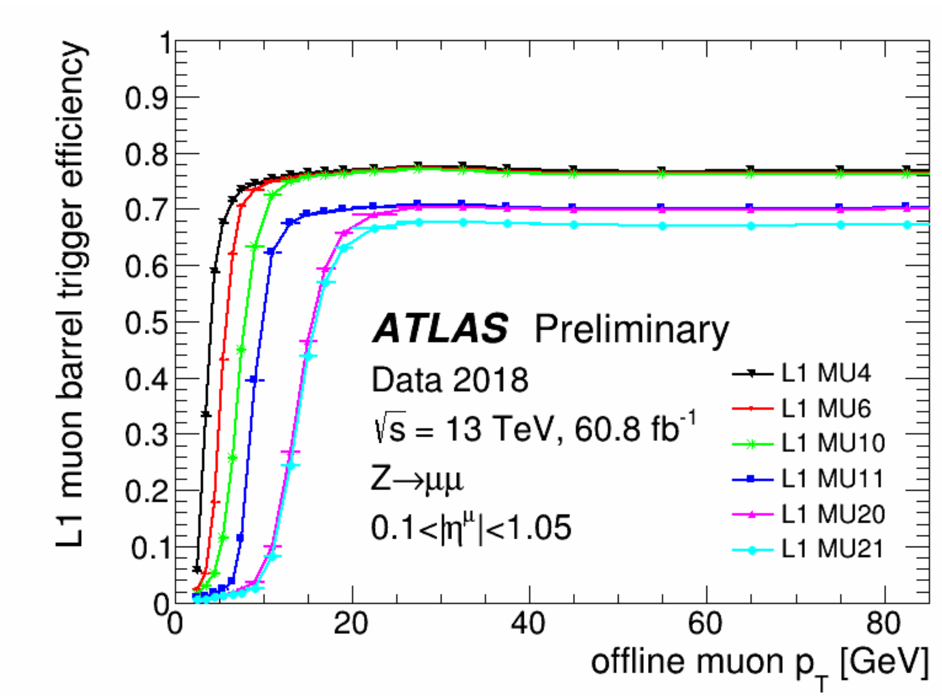
Efficiency drop at η = 0 due to the ATLAS services

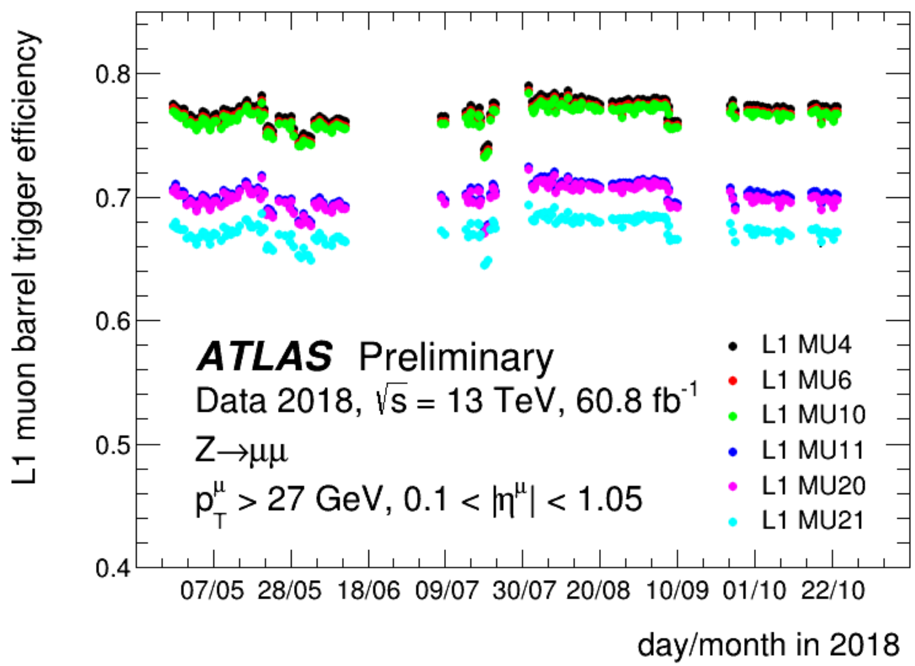


Efficiency drops due to the toroid ribs in the small sectors

Level-1 muon barrel trigger efficiency

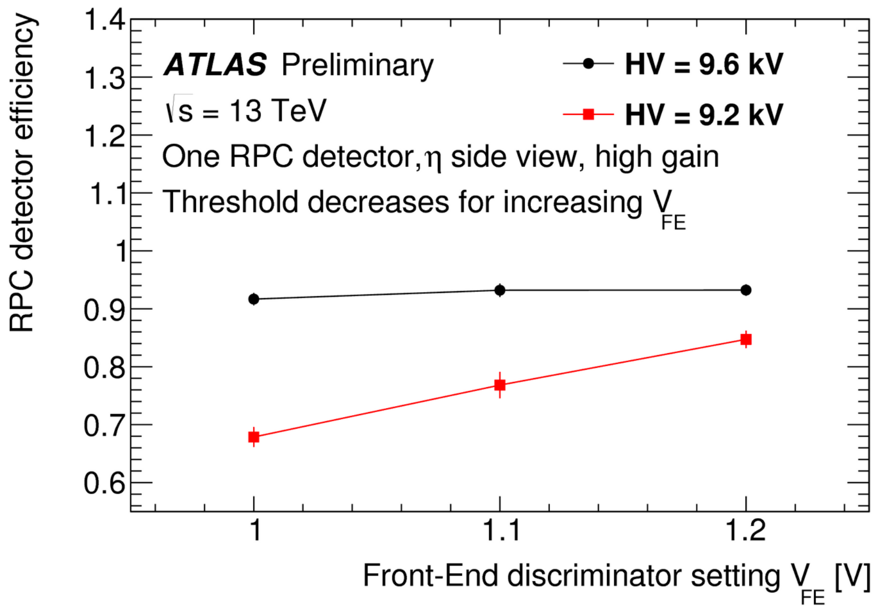
- Trigger efficiency (× geometrical acceptance) as a function of muon transverse momentum → 76.5% for MU10 and 70.0% for MU20 in the plateau region
  - Efficiency reduction due to gas-gaps disconnected from power supply (gas leaks) → mostly located on the external layer (BO chambers)
- Plateau values measured in each ATLAS run → Very good stability during the data taking has been achieved

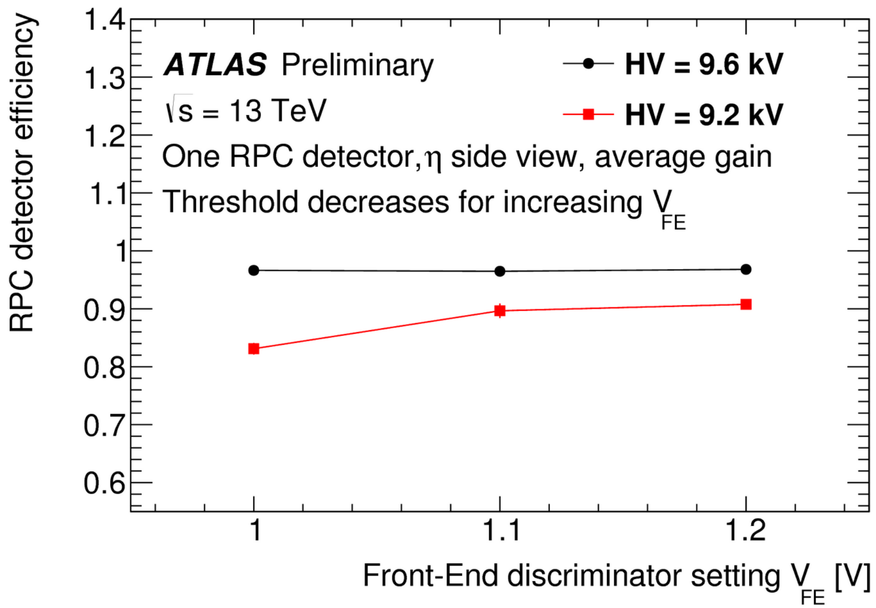




Detector response at different FE discriminator thresholds

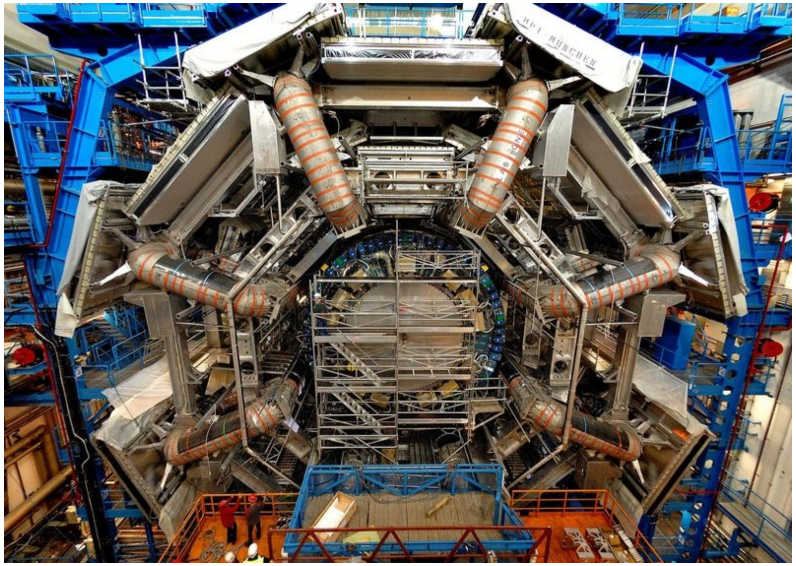
- Study the response of few RPC chambers with lower HV and thresholds
- At HL-LHC ($5 - 7.5 \cdot 10^{34}$ cm^{-2} s^{-1}) the integrated charge collected in the avalanche will be enough high to limit the detector lifetime
- In order to keep the performance of current system stable during years, it is 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)

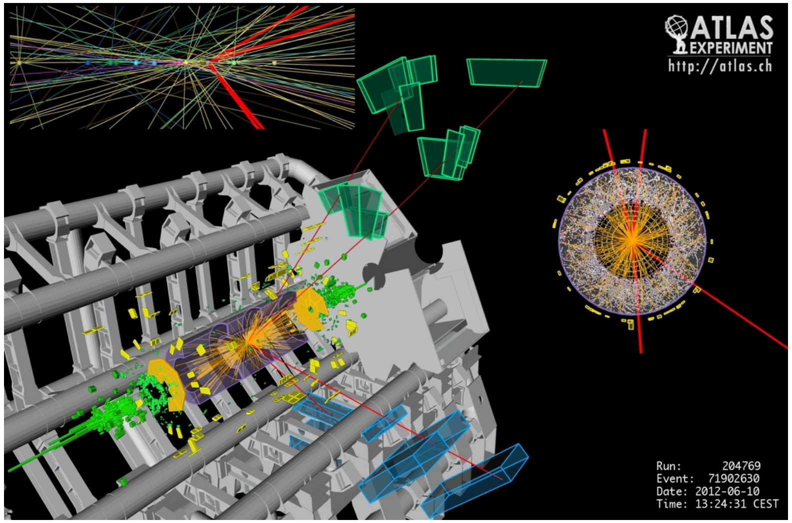




Summary and conclusions

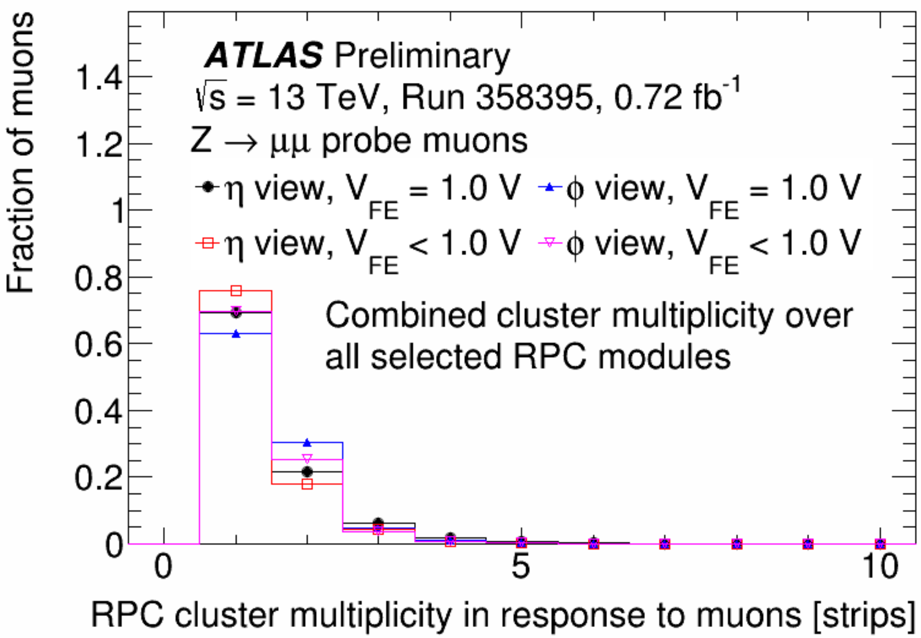
- Muon triggers are of crucial importance for fulfilling the physics program of the ATLAS experiment
- L1 muon barrel trigger is the largest RPC system in a collider experiment
- ATLAS RPCs worked for long time with stable performance (both detector and trigger efficiencies) and operations for ~10 years, 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 → major effort by USTC group
- No major upgrades are foreseen for Run-3, but for Phase-II a completely new trigger system is expected: 1 mm gas gap RPCs in the innermost muon spectrometer layer (BI) + new trigger electronics
- All ATLAS RPC public results available here:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1MuonTriggerPublicResults
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/MUON-2018-09/
  https://atlas.web.cern.ch/Atlas/GROUPS/MUON/PLOTS/MDET-2020-01/

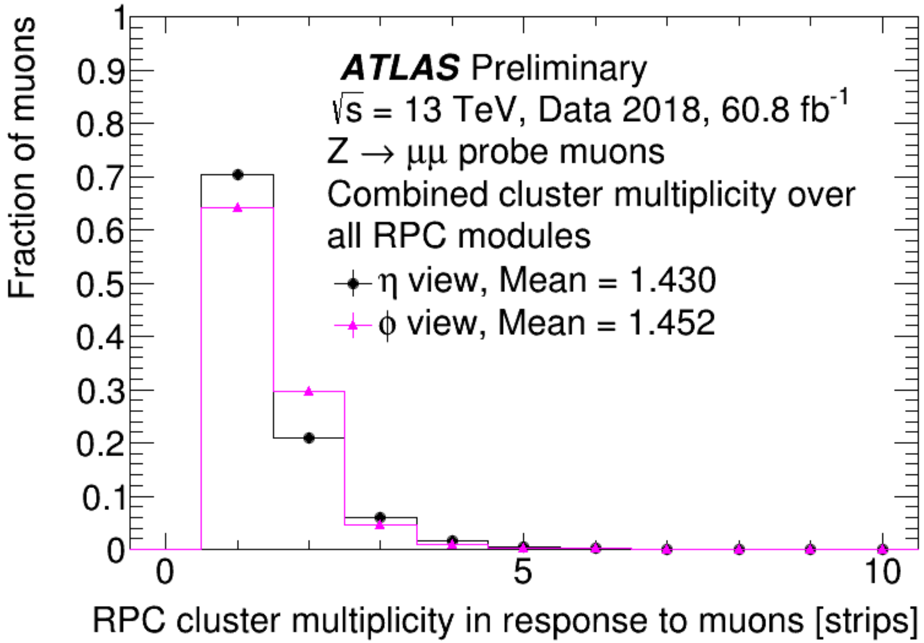




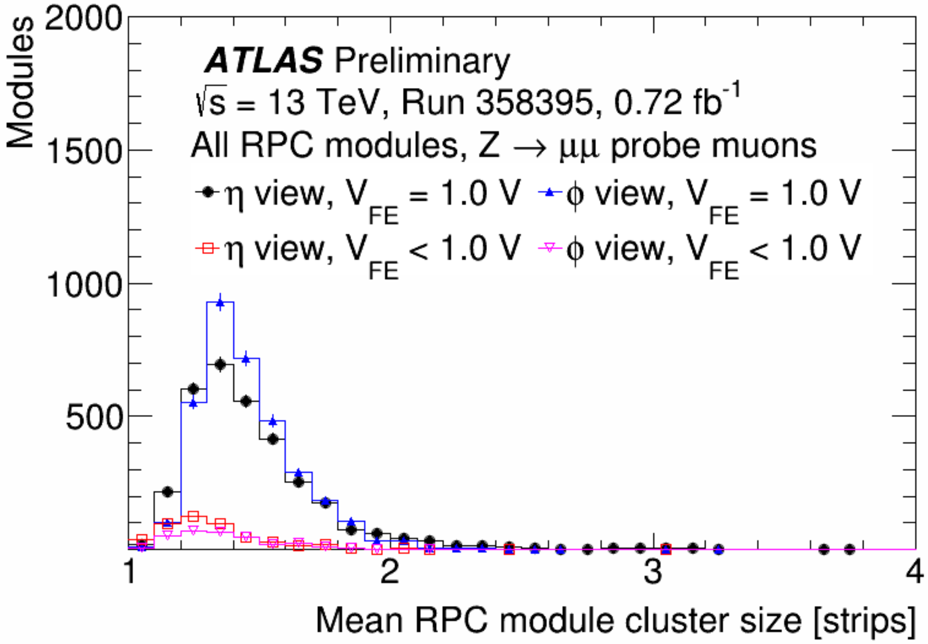
Back-up slides

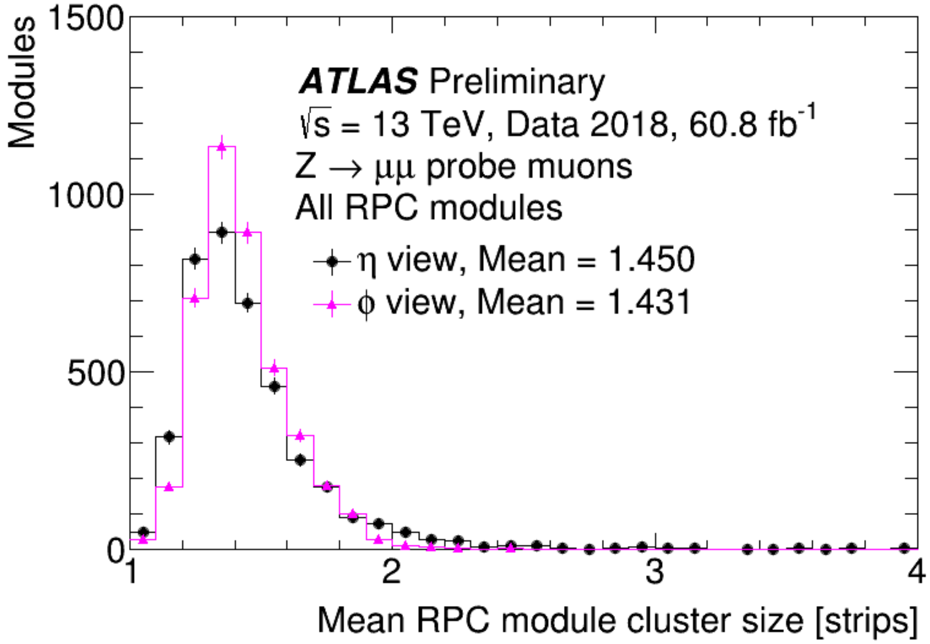
Cluster hit multiplicity



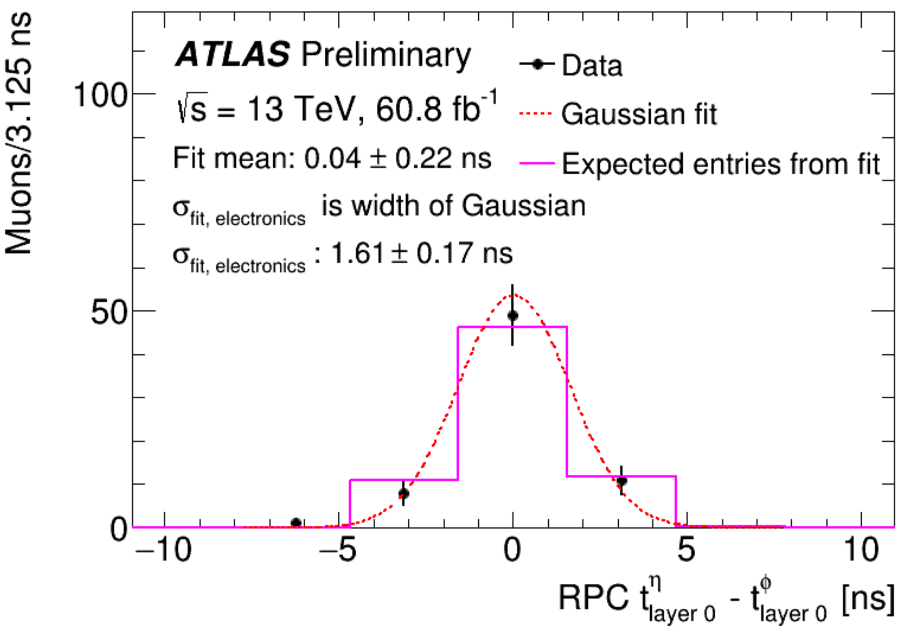


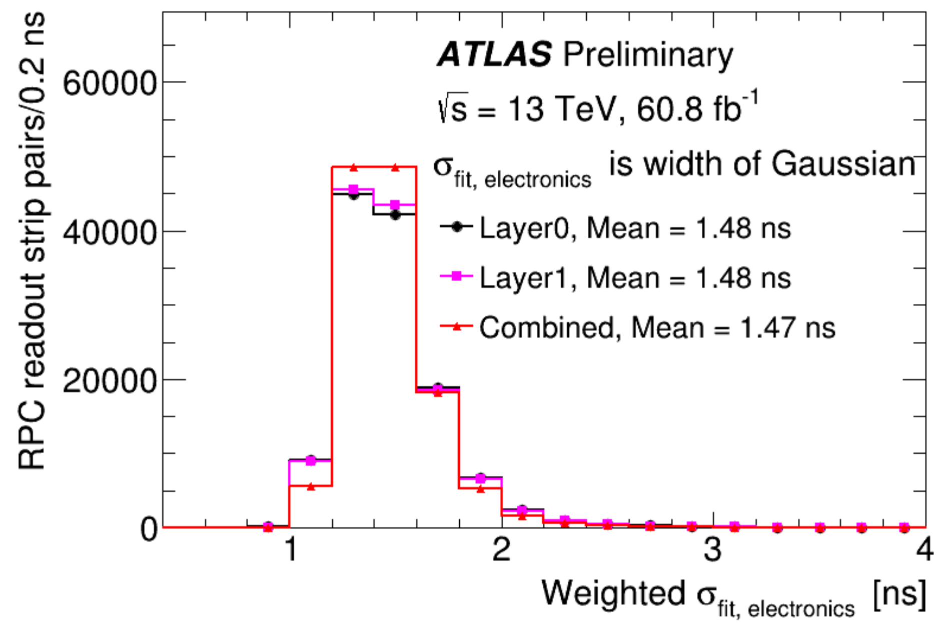
Cluster size



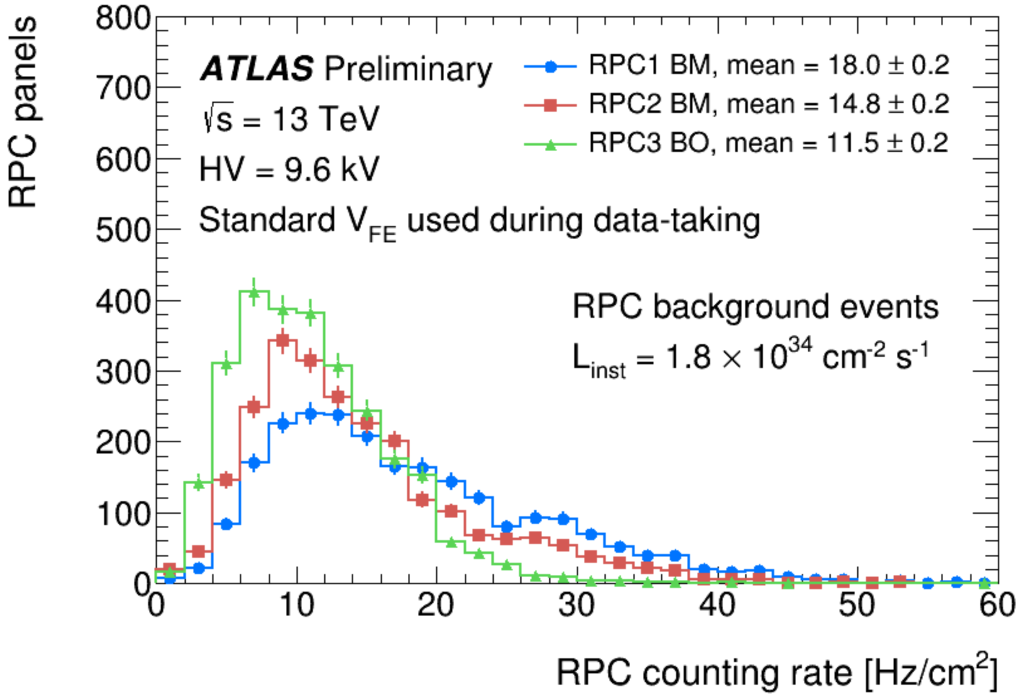


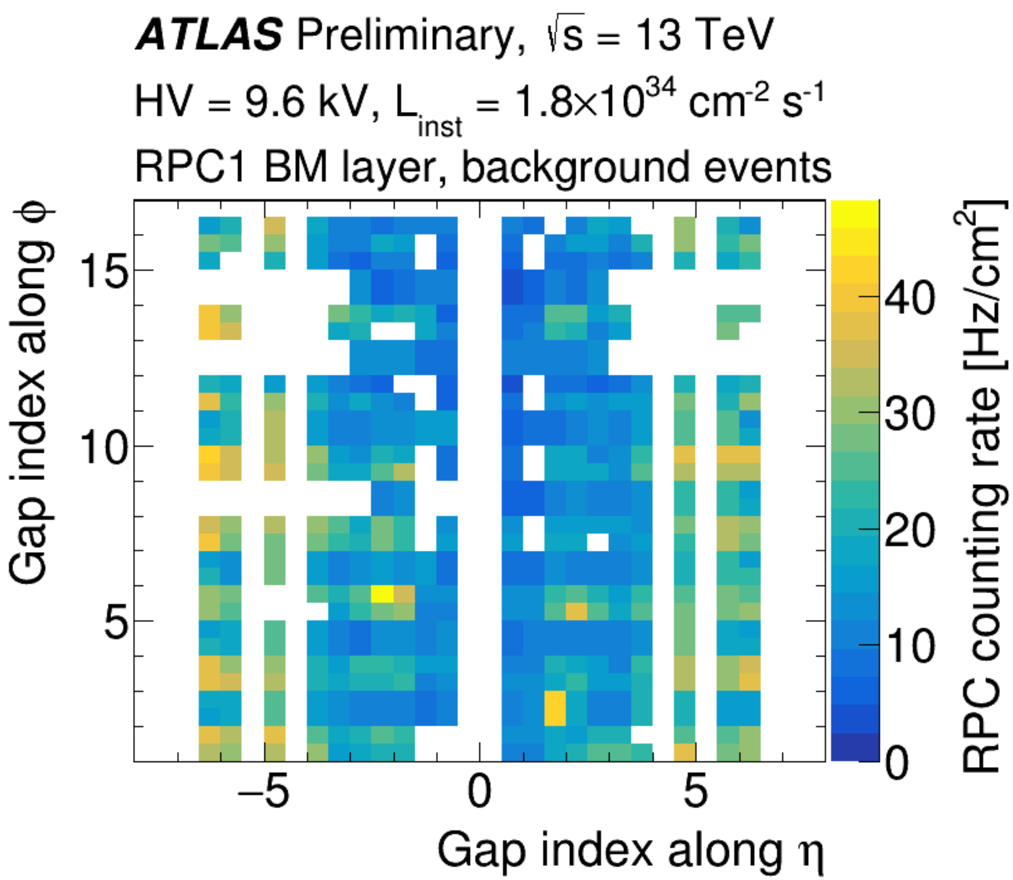
Time resolution: front-end electronics component





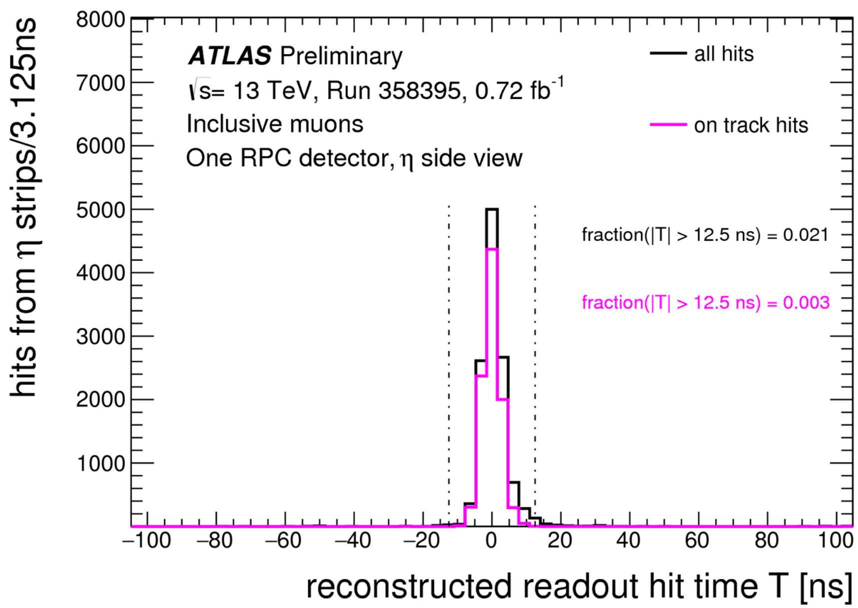
Counting rate: extra plots

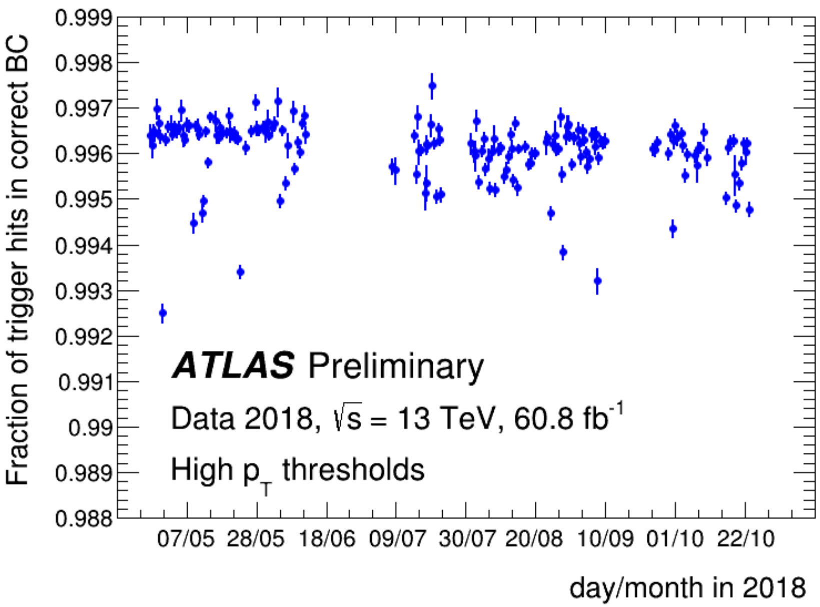




Timing performance

- 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



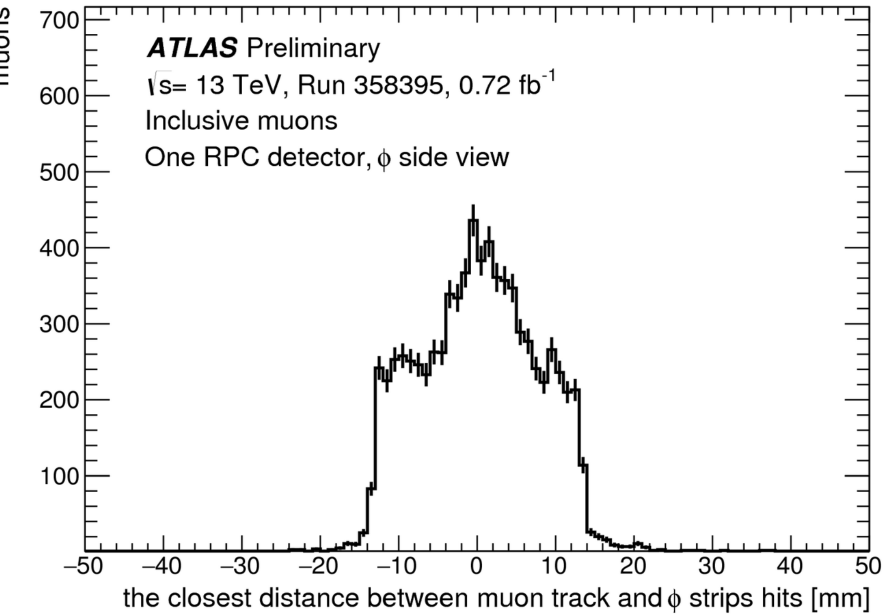


Each point corresponds to a different ATLAS run recorded in 2018

Stable performance during the full year

Closest distance between muon tracks and hits

ETA



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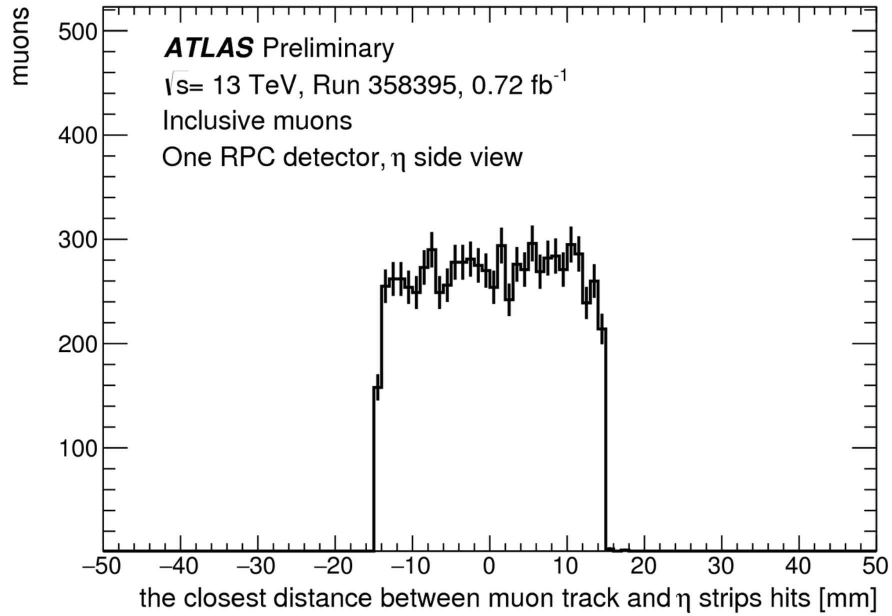
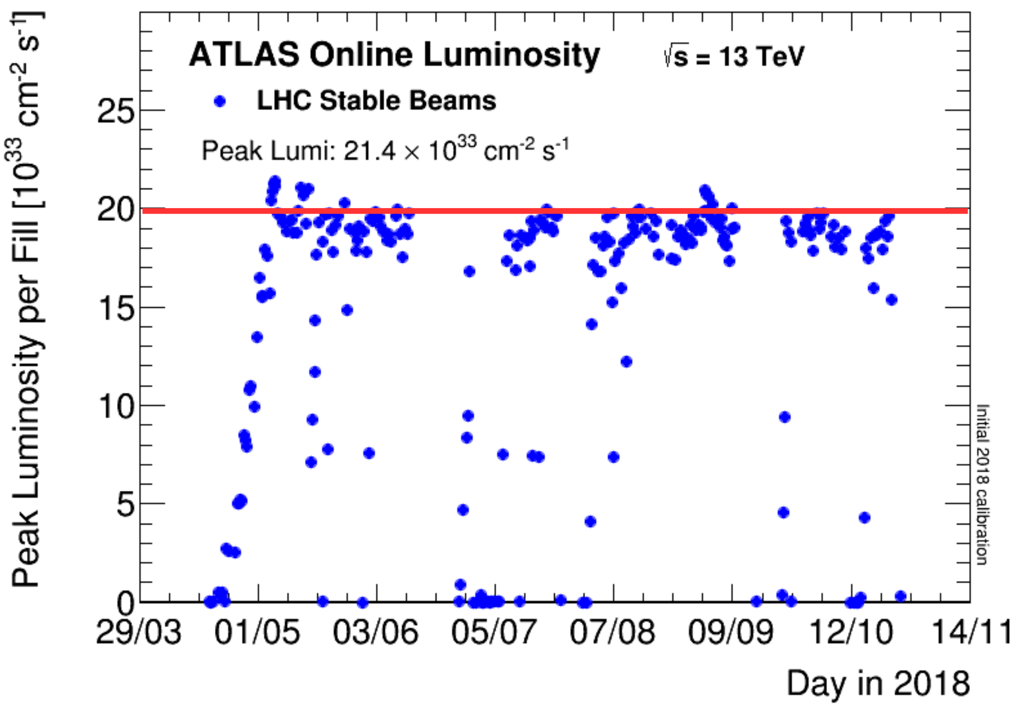
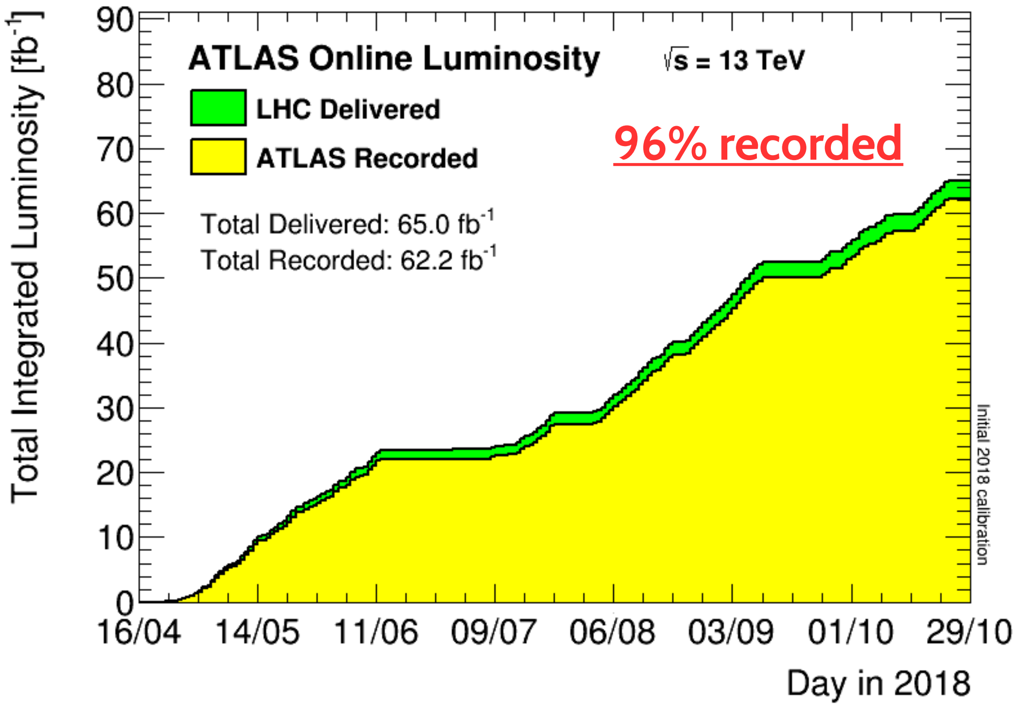
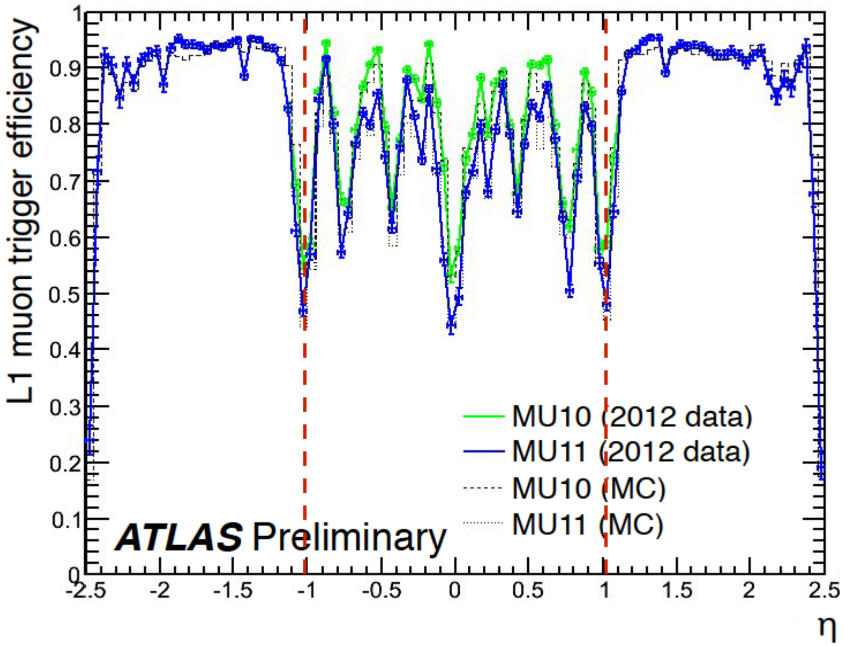


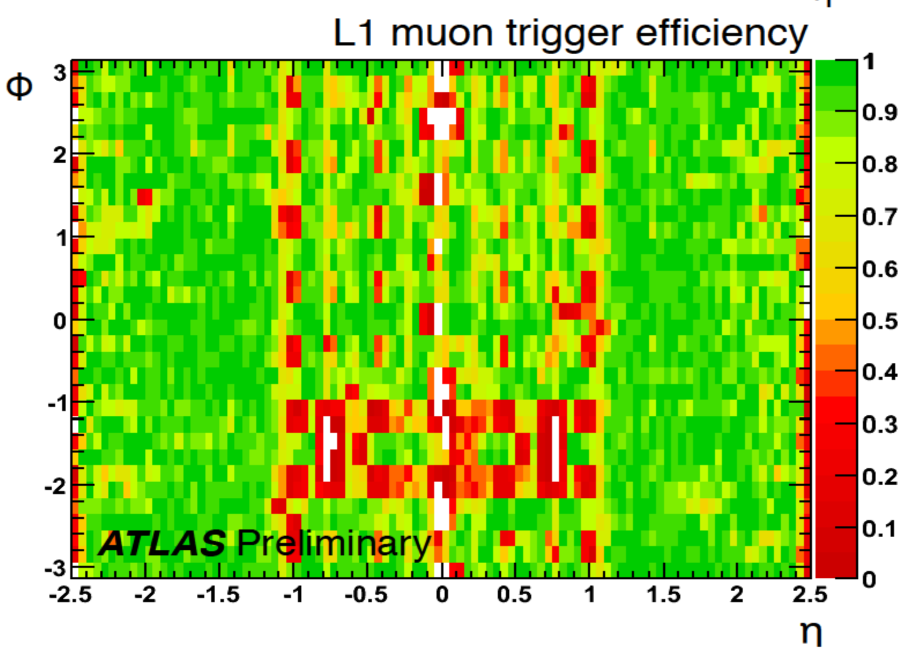
ATLAS data-taking performance during 2018



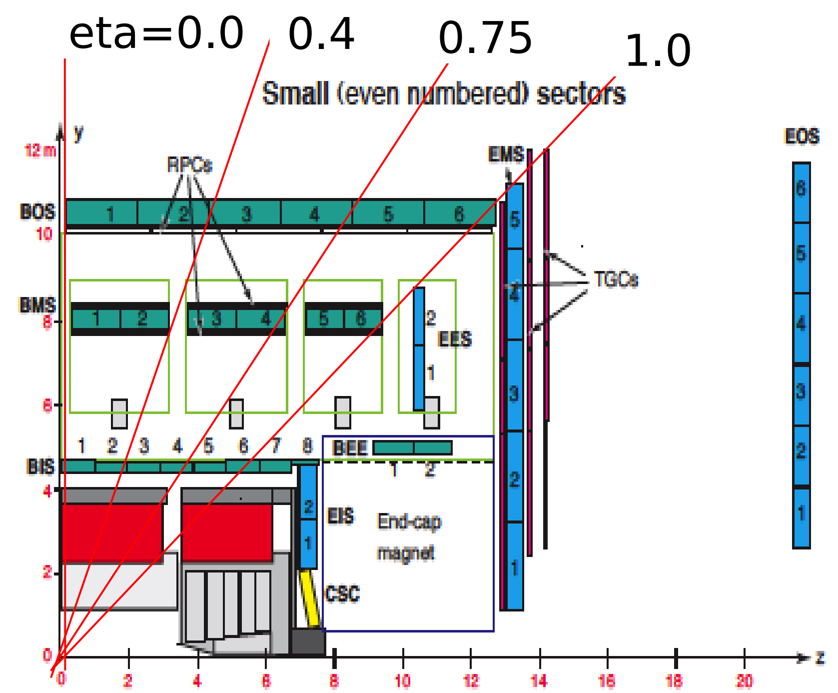


Muon barrel acceptance limits





- 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)



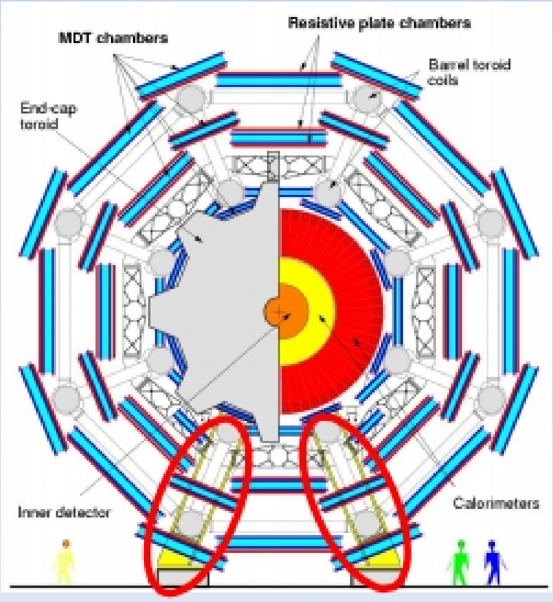
Level-1 muon barrel trigger: feet region

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)

Interaction



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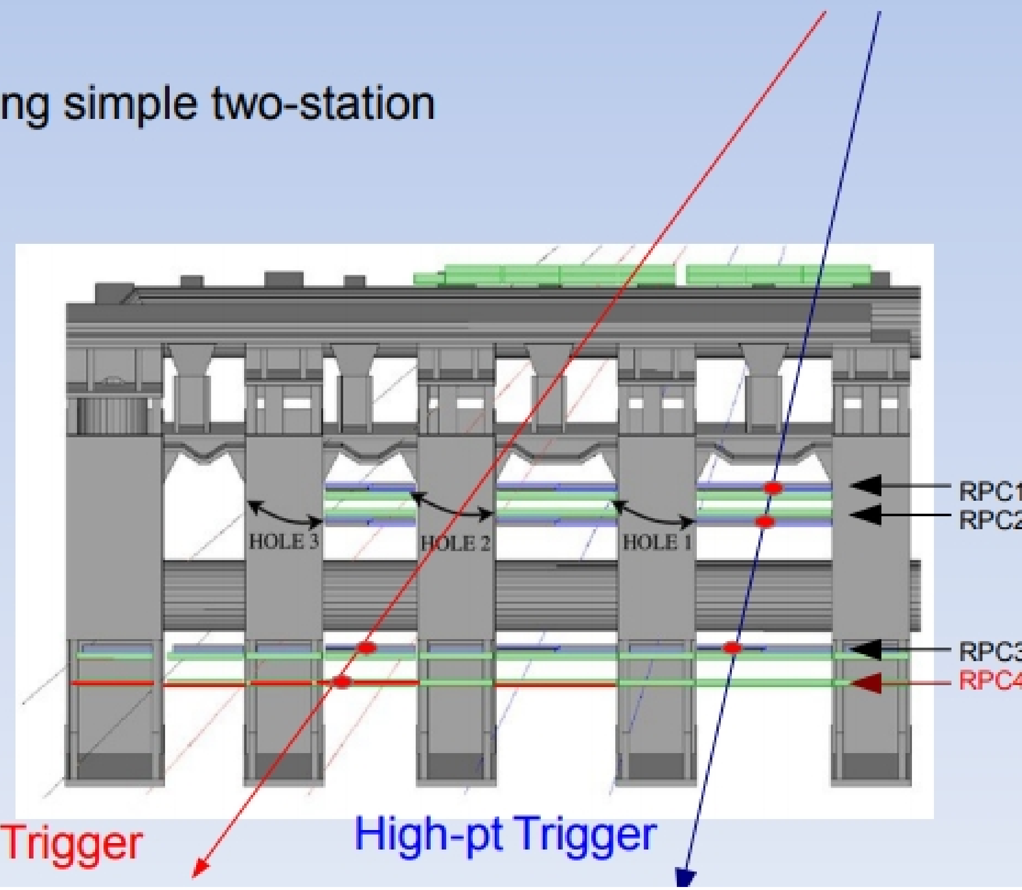
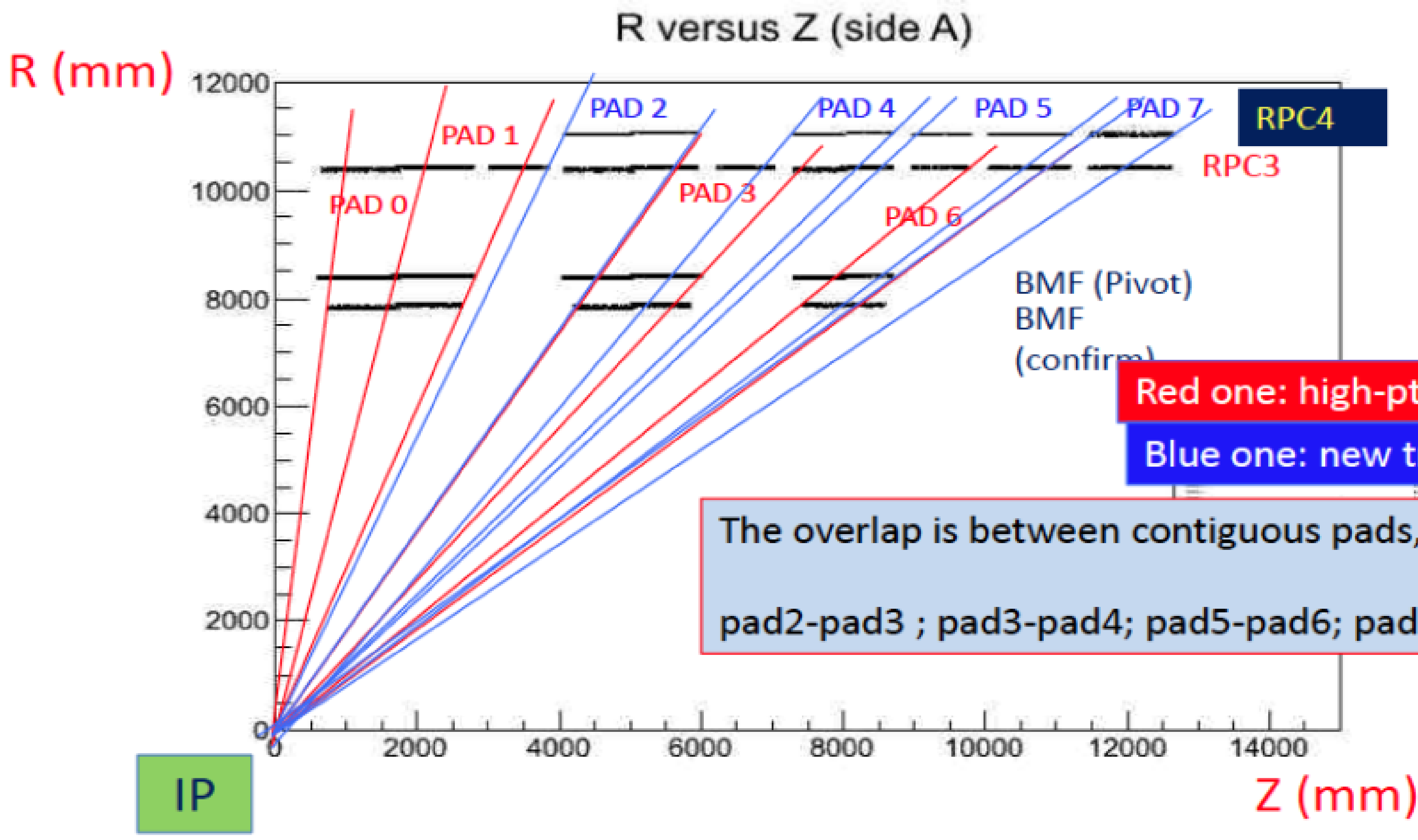


Feet Trigger High-pt Trigger

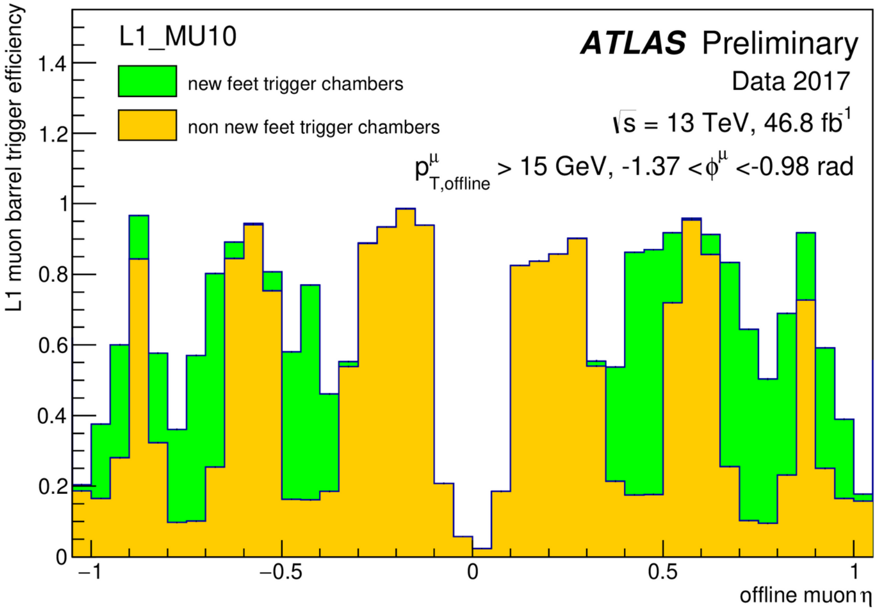
Level-1 muon barrel trigger: feet region

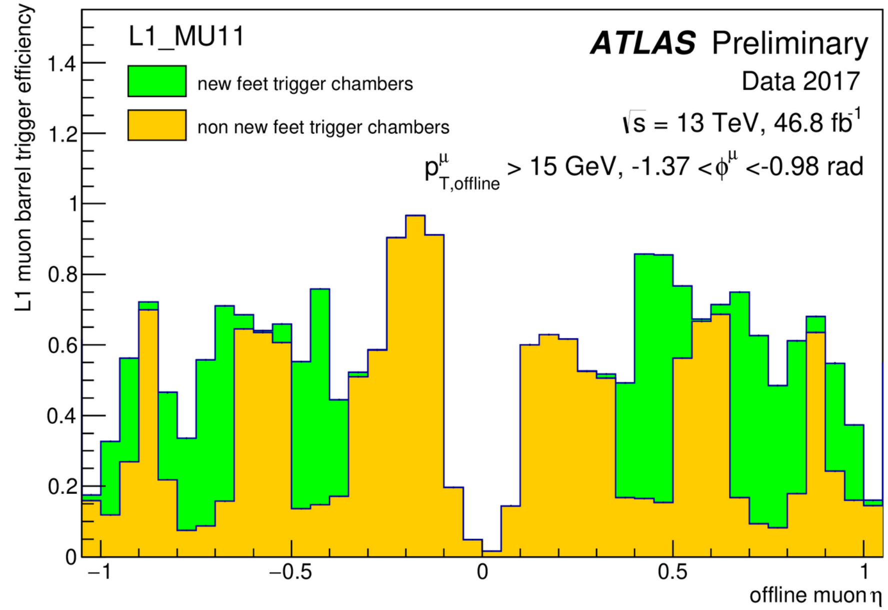


The overlap is between contiguous pads, like:

pad2-pad3 ; pad3-pad4; pad5-pad6; pad6-pad7

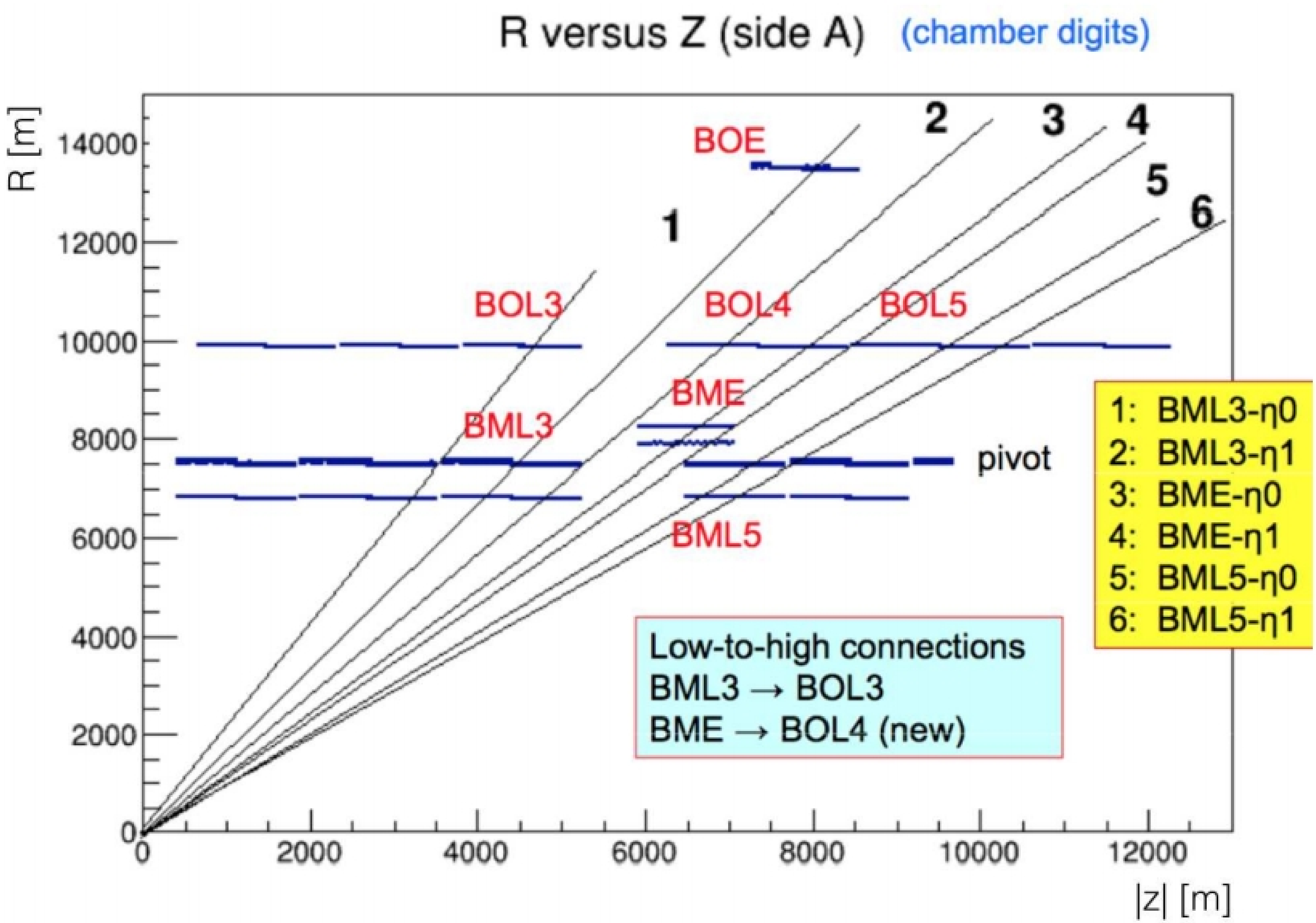
Trigger efficiency in one feet sector (2017)



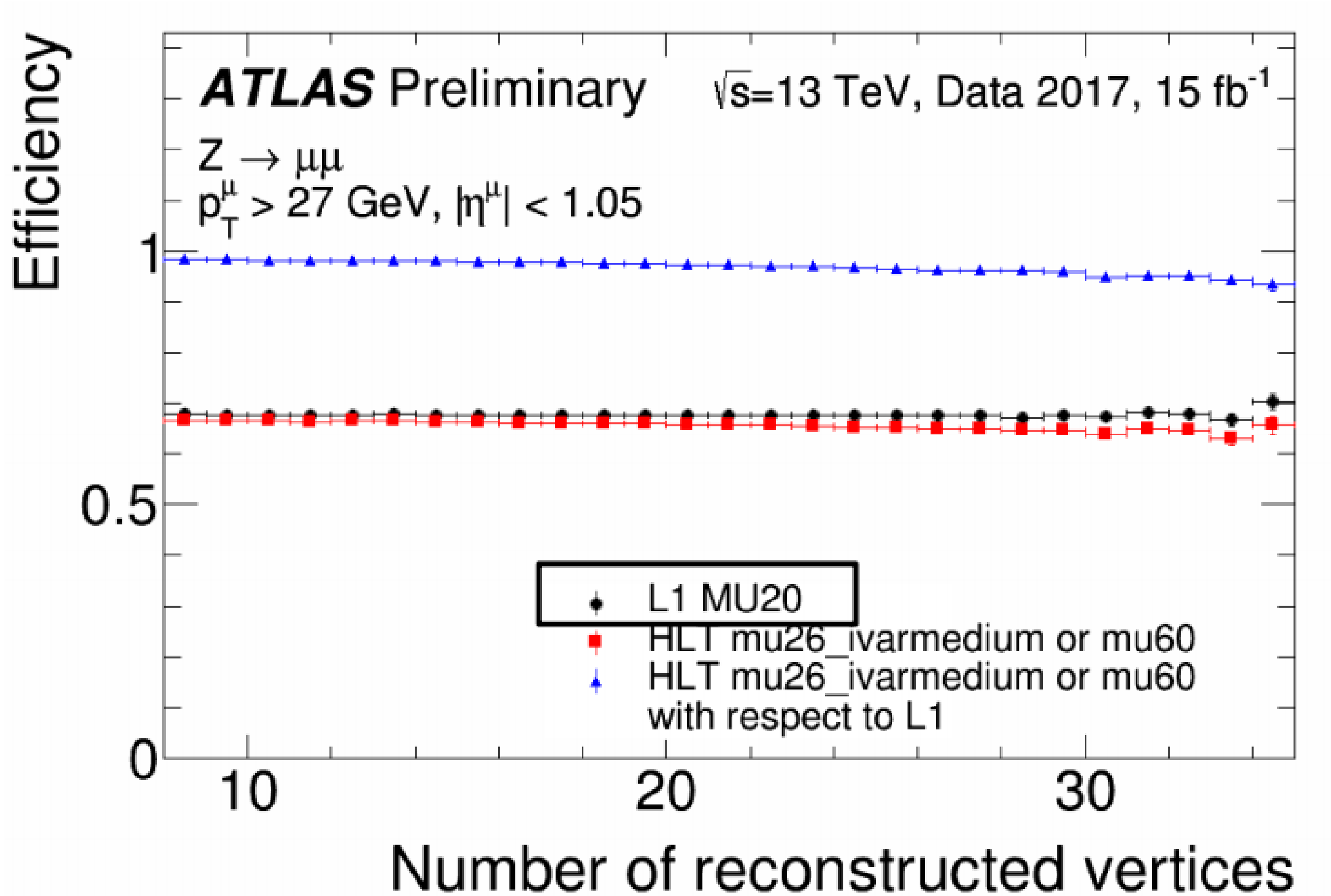


- The MU10 trigger requires that a candidate passed the 10 GeV threshold requirement of the Level 1 muon trigger system, using medium trigger chambers.
- The MU11 trigger requires that a candidate passed the 10 GeV threshold requirement of the Low-p_T Level 1 muon trigger system, with a coincidence with 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.

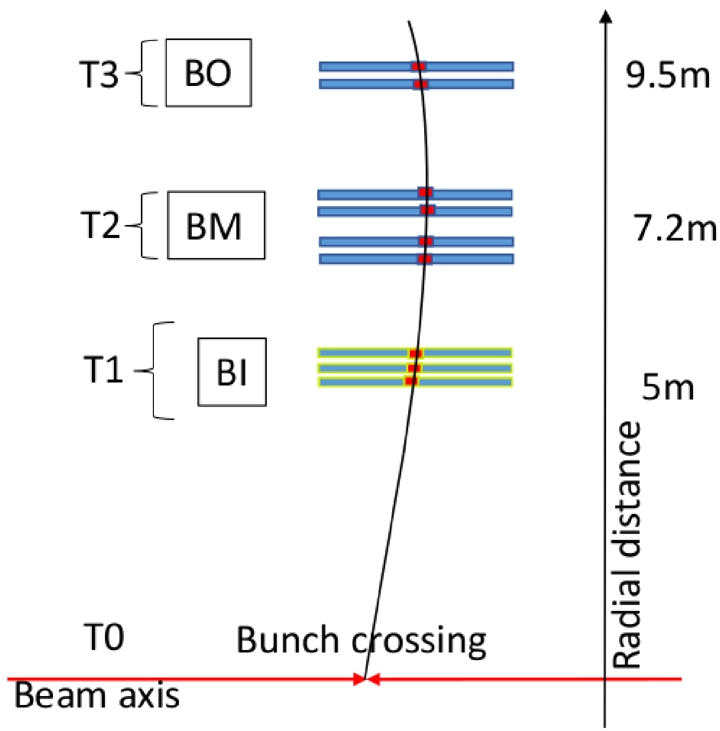
Level-1 muon barrel trigger: sector 13



Trigger efficiency vs pile-up



Trigger performance expected for Run-3



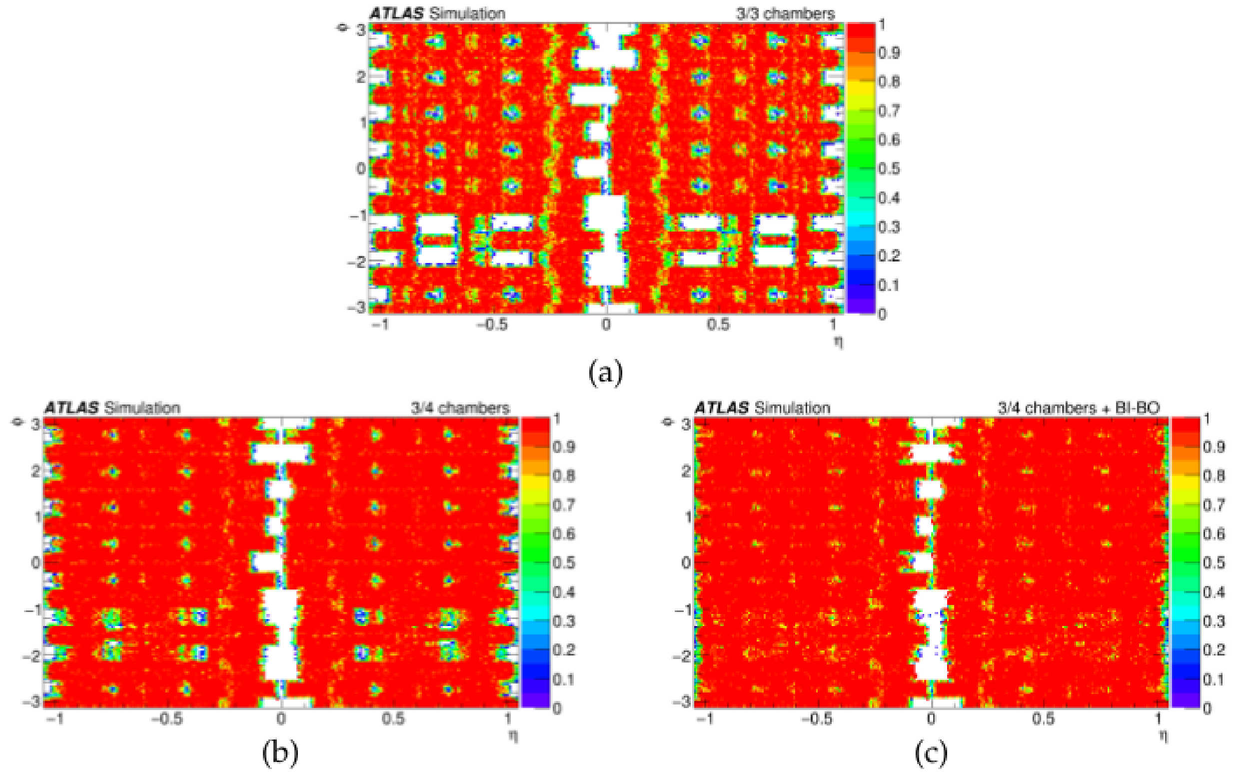
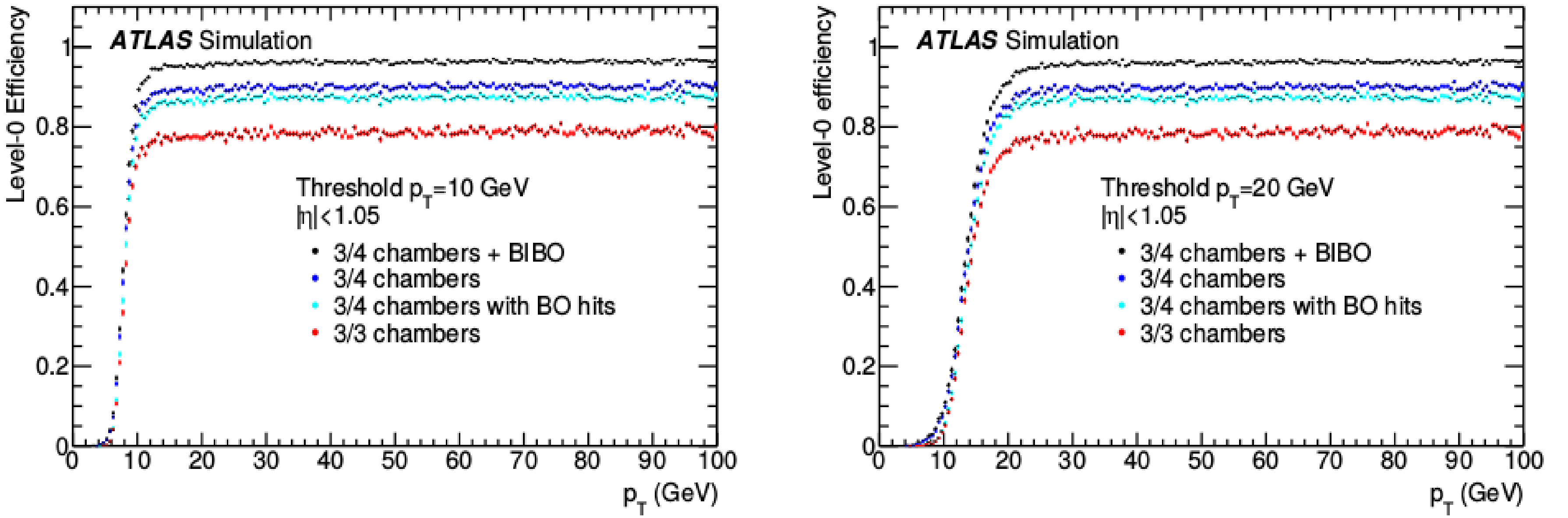


Figure 3.5: Geometrical acceptance of the L0 barrel trigger with respect to reconstructed muons with $p_T = 25$ GeV in the η-ϕ plane. Figures (a), (b), and (c) show the acceptance for the different trigger coincidence logic schemes: 3/3 chambers, 3/4 chambers, and 3/4 chambers + BI-BO, respectively

BM and BO efficiency (%)	Trigger efficiency × acceptance (%) 3/3 chambers	3/4 chambers	3/4 chambers + BI-BO
100	78	91	96
90	73	90	95
80	62	87	93
Worst case	63	85	92

Lowered HV in BM and BO

Trigger performance expected for Run-3



(a) (b)

Requirement	Rate
3/3 chambers	20 kHz
3/4 chambers	30 kHz
3/4 chambers + BI-BO	85 kHz
3/4 chambers + BI-BO (*)	45 kHz

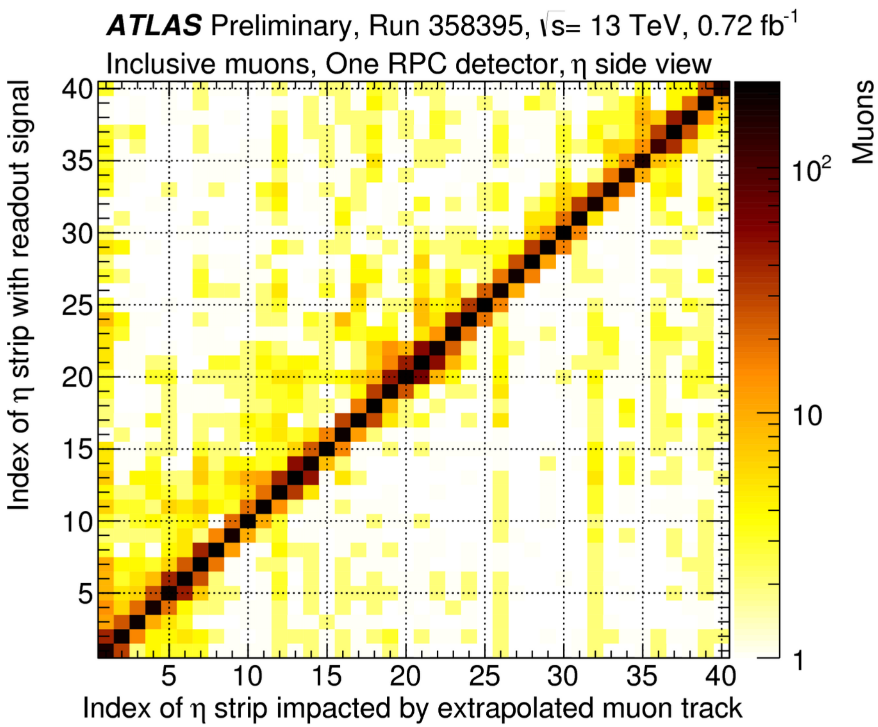
Expected rates at $7.5*10^{34}$ cm^{-2} s^{-1} for L1 MU20

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

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