The Muon Trigger of the ATLAS experiment: performance and improvements for Run 3

Andrea Ventura (University of Salento & INFN Lecce, Italy)
on behalf of the **ATLAS Collaboration**

Bologna - July 9th, 2022

UNIVERSITÀ DEL SALENTO

INFN Istituto Nazionale di Fisica Nucleare SEZIONE DI LECCE

ATLAS EXPERIMENT

CERN

ICHEP 2022 BOLOGNA

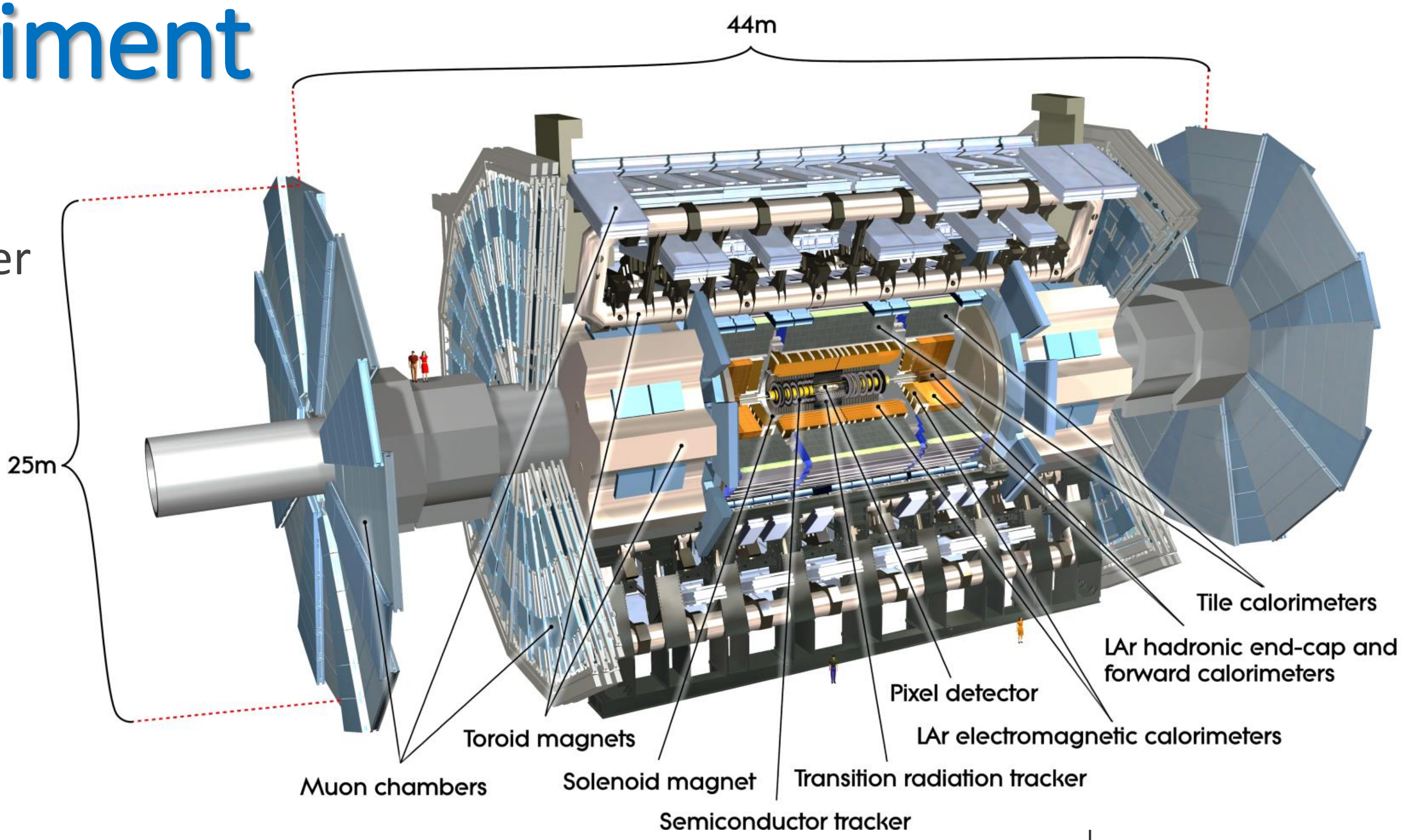
Outline

- The ATLAS Muon Spectrometer in Run 3
- The Trigger system and the Muon L1 & HLT design
- Run 2 performance
- Run 3 improvements
- Summary and outlook

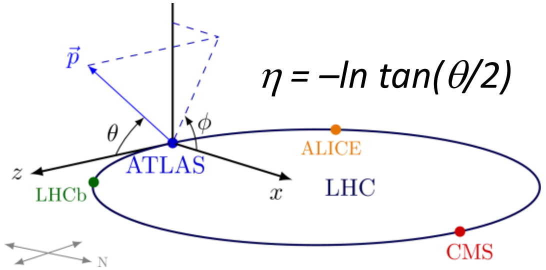
The ATLAS experiment

ATLAS is a **multi-purpose detector** running at the Large Hadron Collider (**LHC**) for high-precision Standard Model (SM) measurements and beyond SM searches.

- **Tracking system** in $|\eta| < 2.5$ with silicon pixels/strips and TR tracker.
- **Electromagnetic** (liquid Ar) and **hadronic** (scintillating tiles) **calorimeters** covering $|\eta| < 4.9$.



- **Muon spectrometer** (**MS**) for identifying muons with $\Delta p_T / p_T < 10\%$ up to 1 TeV.
- **Two magnet systems** (toroidal and solenoidal).



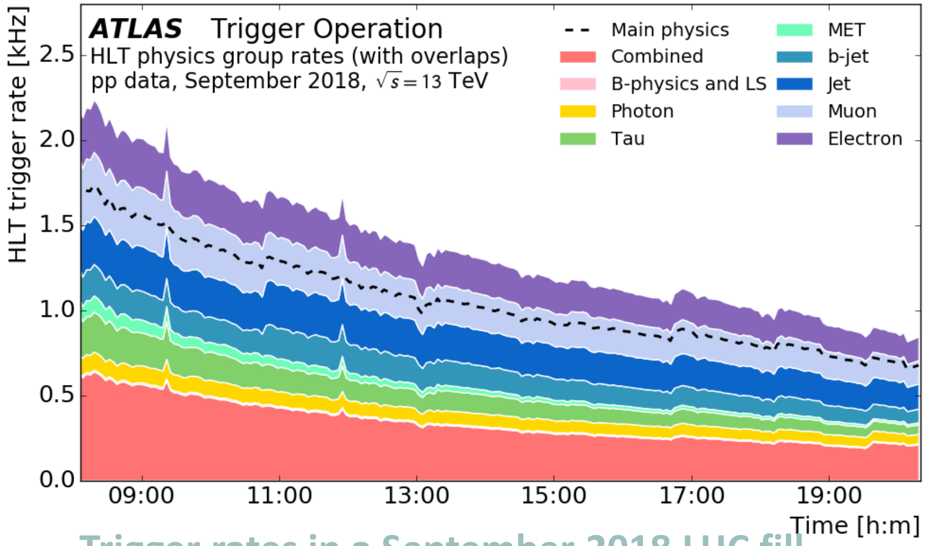
$\eta = -\ln \tan(\theta/2)$

Triggering on muons with ATLAS

Events with muons are a crucial signature for many analyses being carried out at the **LHC**.

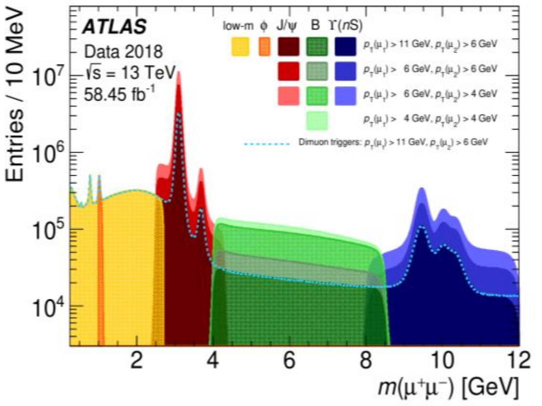
Muon triggers represent a significant fraction of the whole trigger rate at the **ATLAS** experiment.

Examples of ATLAS physics results with analyses based on **muon triggers**:



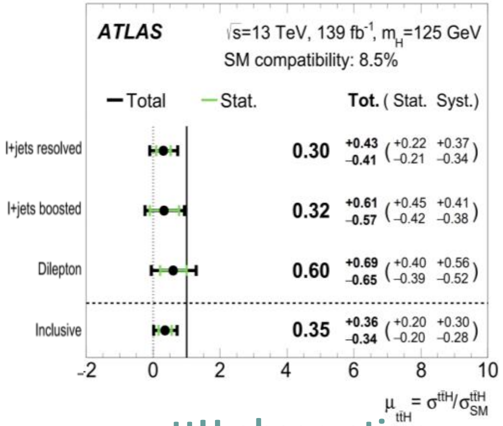
Trigger operation plots

Trigger rates in a September 2018 LHC fill



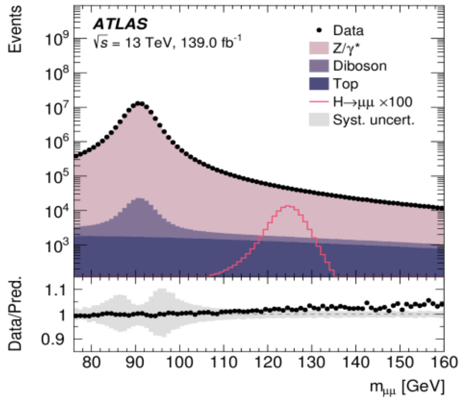
JINST 15 (2020) P09015

B-physics precise measurements



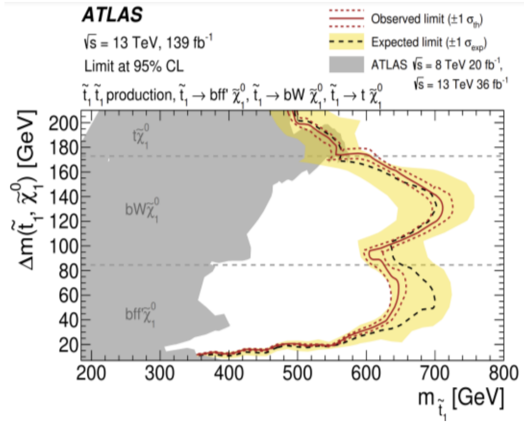
hep-ex arXiv:2111.06712

ttH observation



PLB 812 (2021) 135980

Higgs boson in μμ search



JHEP 04 (2021) 174

SUSY searches (1ℓ final state)

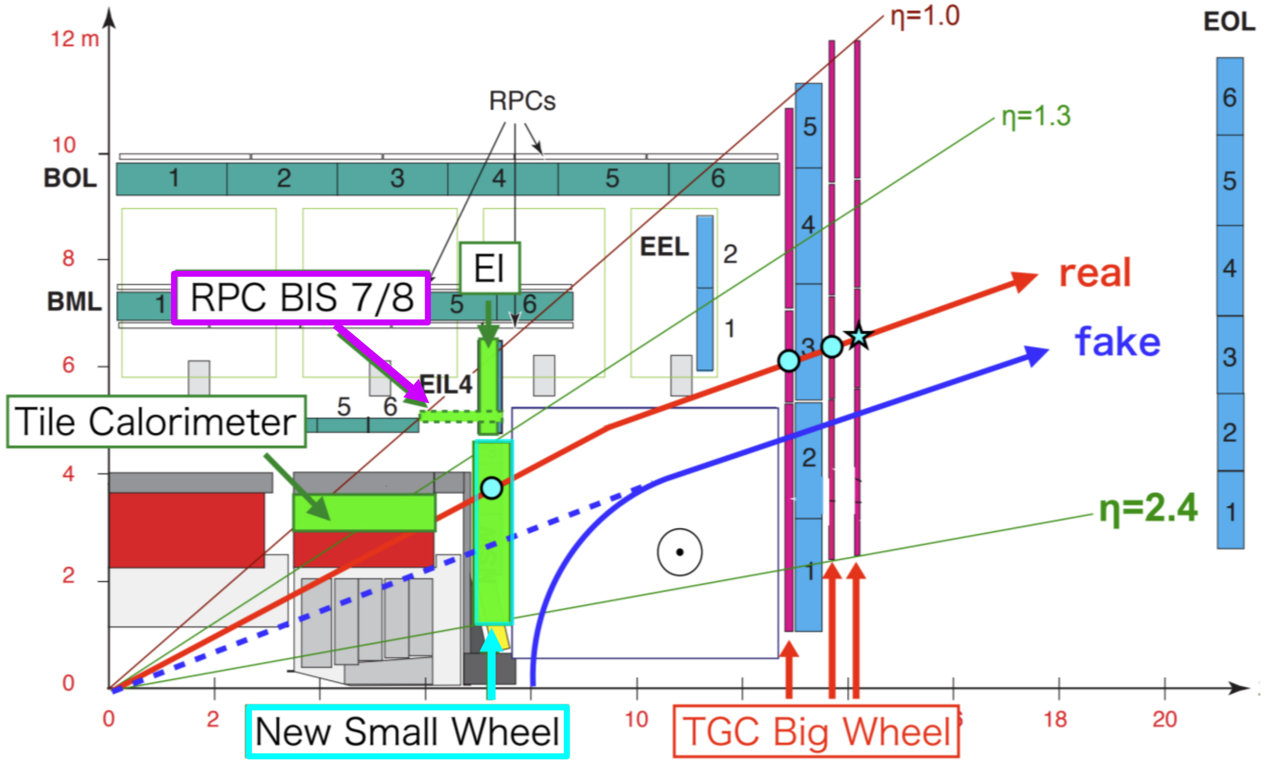
The ATLAS Muon Spectrometer in Run 3

MS based on four different sub-detectors since the beginning of ATLAS:

- **Resistive Plate Chambers** (RPC), **Thin Gap Chambers** (TGC) for trigger based on fast readout;
- **Monitored Drift Tubes** (MDT), **Cathode Strip Chambers** (CSC) for high resolution tracking.

Several upgrades to the MS completed for **Run 3** to handle higher luminosities:

- **sMDT** chambers and **thin-gap RPCs** in region $1.0 < |\eta| < 1.3$.
- Innermost muon chamber layers replaced with higher-granularity **sTGC**s and **MicroMegas** in New Small Wheels (**NSW**) in $1.3 < |\eta| < 2.7$.
- New sector logic implemented in TGC Big Wheel (**TGC-BW**).



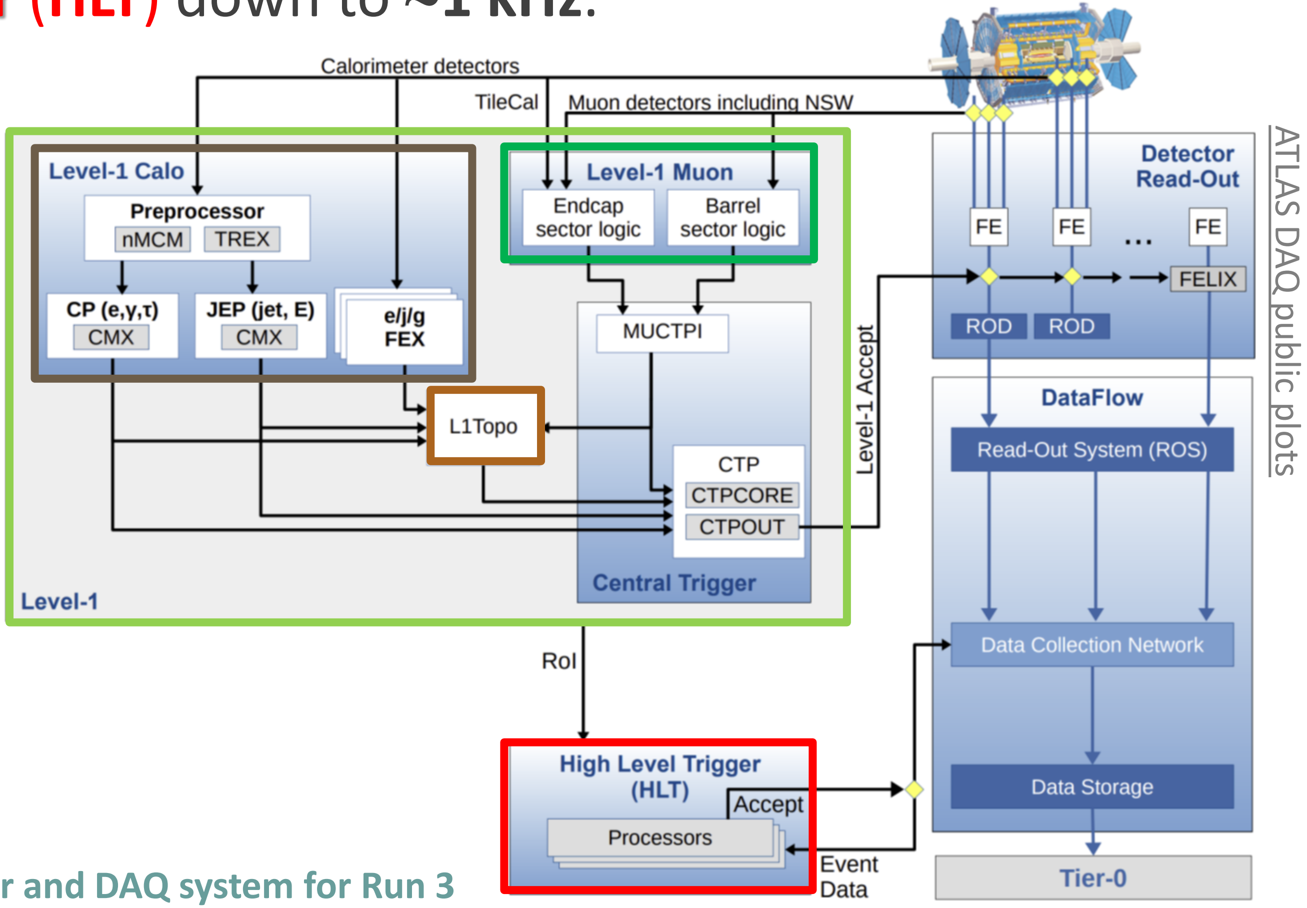
Side view of a quarter of MS

arXiv:1806.09234

The ATLAS Trigger system

- **40 MHz** of proton-proton collisions are reduced to up to **100 kHz** by the **Level-1** (L1).
- Rate reduced by the **High-Level Trigger** (HLT) down to **~1 kHz**.

- L1 Topological Processor (**L1Topo**) gets inputs from **L1 Calo**-rimeter Trigger and from **L1 Muon** Trigger with information on jets, e, γ, τ, μ and missing transverse energy.
- L1 trigger decision is passed to **HLT processors** for the final trigger decision and **data storage**.



Trigger and DAQ system for Run 3

The Muon Trigger system

Muon Level-1 Trigger

Fast and coarse, *hardware-based* trigger, producing transverse momentum (**p_T**) estimates of muons as degree of deviation from the hit pattern of infinite-p_T tracks with hits in RPCs and TGCs.

- Regions of Interest (**RoI**s) identified and passed to HLT.
- For Run 3, up to fifteen L1 p_T thresholds implemented.

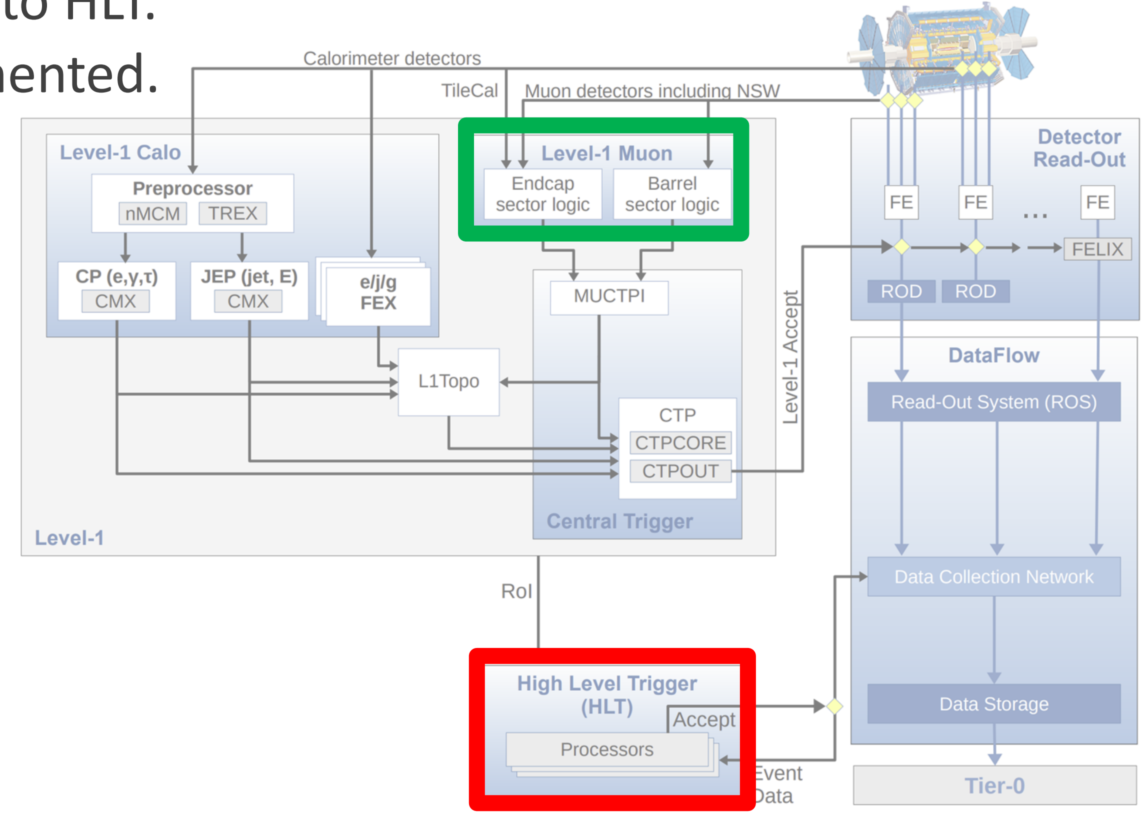
Muon High-Level Trigger

Software-based trigger using information from MS and inner tracking detector (**ID**).

HLT event selection performed in two stages:

- <u>fast reconstruction</u> inside muon RoIs,
- <u>precise measurements</u> of track parameters using full reconstruction tools.

For Run 3, HLT fully *migrated* to **multi-threaded** technology to reduce CPU memory usage.

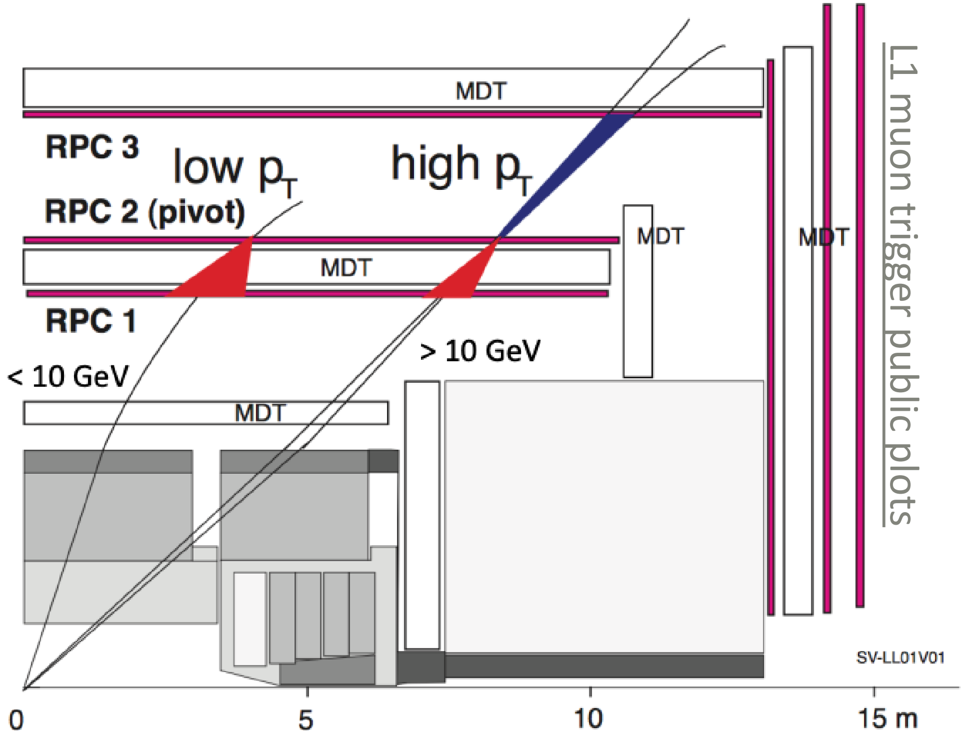


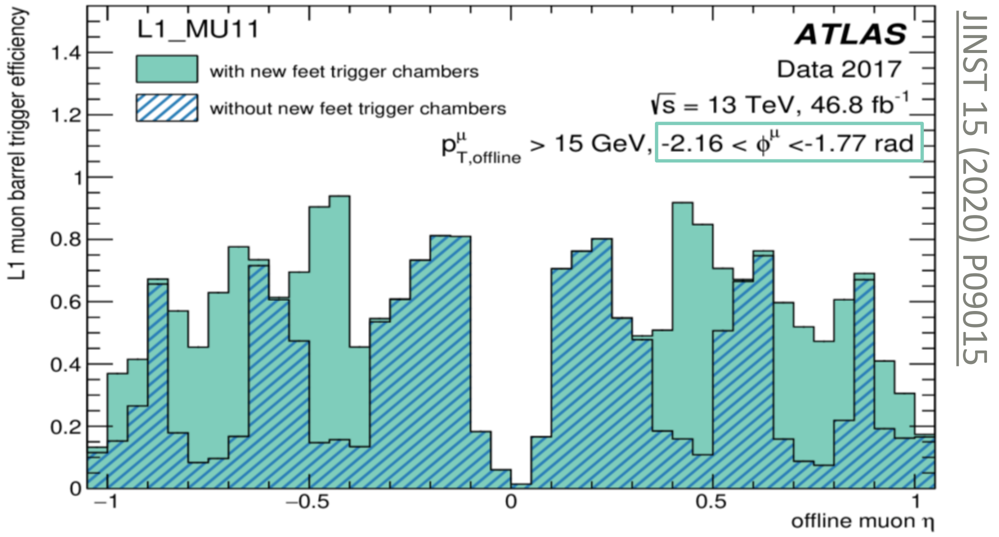
L1 Muon Barrel

RPCs arranged in the MS central detector region ("**barrel**"): **|η| < 1.05**, in three concentric doublet layers at radius 7 m, 8 m and 10 m, operating in a toroidal magnetic field (from 0.5 to 1.0 Tesla).

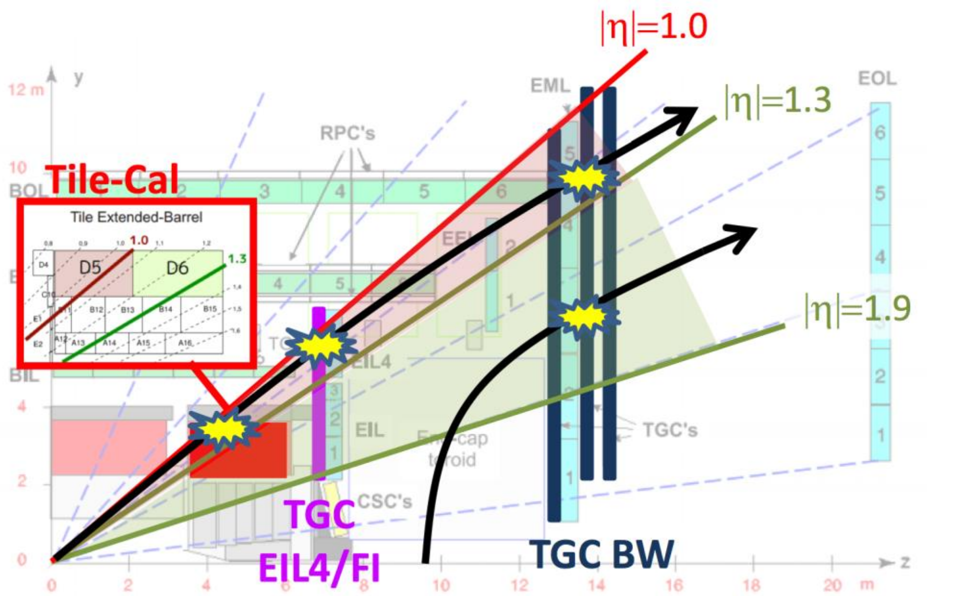
RPC coincidence requirements applied to define a total of 3 **low-p_T** and 3 **high-p_T** thresholds.

- Since Run 2, ~4% acceptance increase by installing additional chambers in support structures.
- For Run 3, improved sector logic and optimized thresholds to reinforce fake muon rejection.



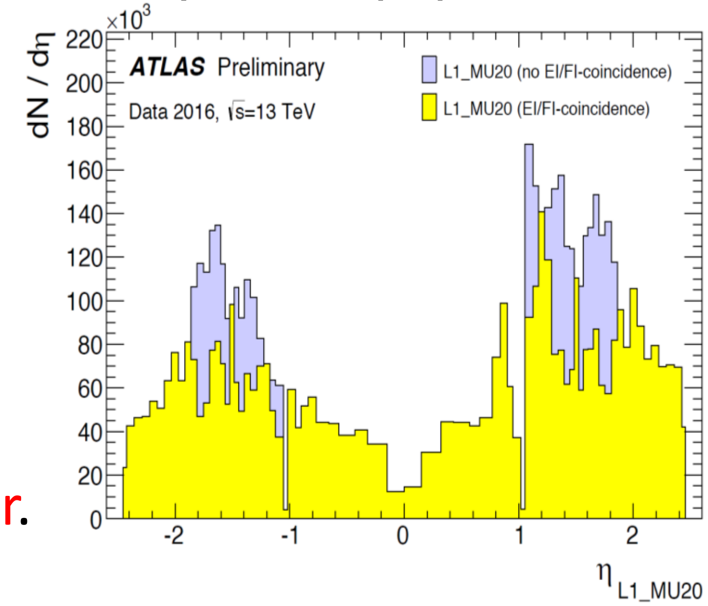


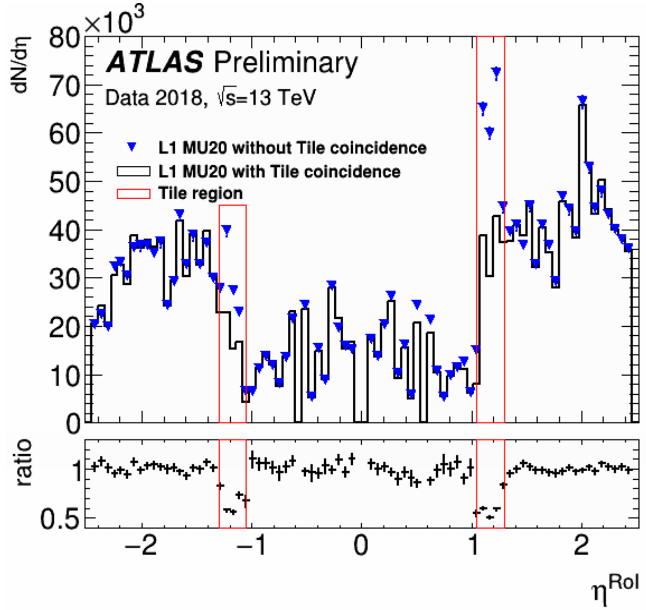
L1 Muon Endcap



TGCs produce triggers in the forward MS regions ("**endcap**"): **1.05 < |η| < 2.4**.

- Main background due to *low p_T protons* from IP. To reject such fake triggers, a coincidence was implemented during Run 2 between TGC BW and TGC Forward Inner (TGC FI) chambers or Endcap Inner (EI) chambers (EI/FI coincidence);
- ~20% reduction of fake tracks achieved for muon $p_T > 20$ GeV;
- further ~6% rate reduction obtained by an additional coincidence with the extended barrel region of the Tile Calorimeter.





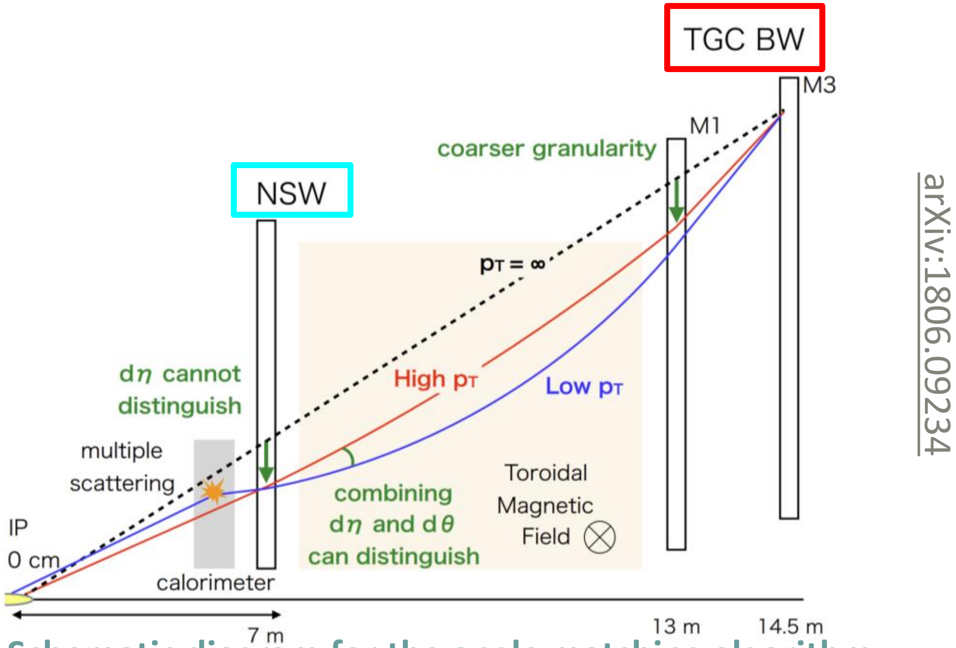
JINST 15 (2020) P09015

L1 Muon Endcap: Run 3 improvements

Usage of **position and angle matching** helps to **reject fake muons** (low p_T charged particles not originating at the IP).

Beam spot size in *z*-direction (O(10 cm)) considered, together with effects due to **multiple scattering** with the detector materials (especially the calorimeters).

Positions of **NSW** and **TGC-BW** hits can be very similar but significantly differ in dθ $\Rightarrow$ by **combining** the **dθ** and the **η** position information, low-p_T muons are removed.

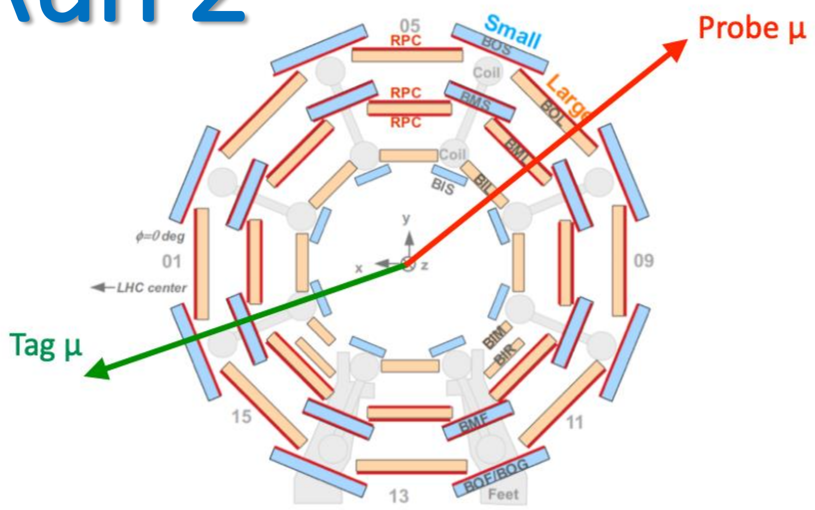


Schematic diagram for the angle matching algorithm

Muon L1: performance during Run 2

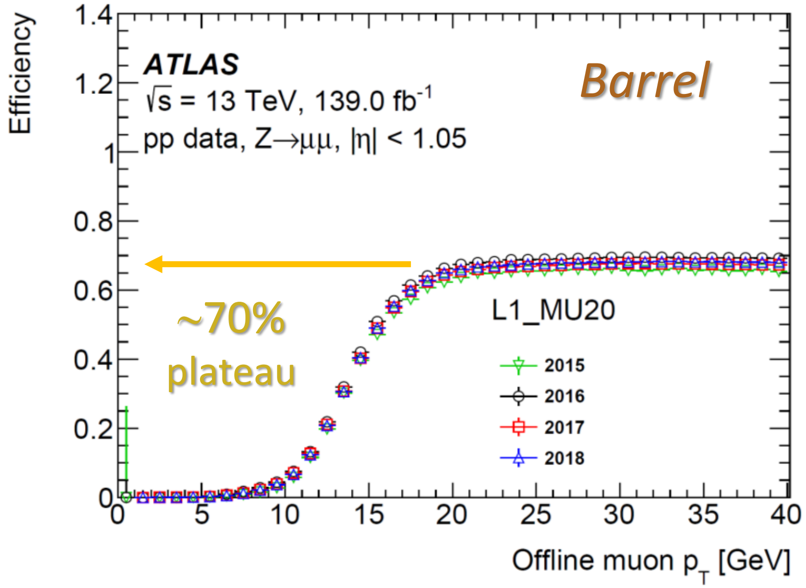
Muon trigger efficiencies measured by means of the «**Tag-and-Probe** method», based on di-muon events (such as $Z\rightarrow\mu\mu$ and $J/\Psi\rightarrow\mu\mu$), using the two muons as:

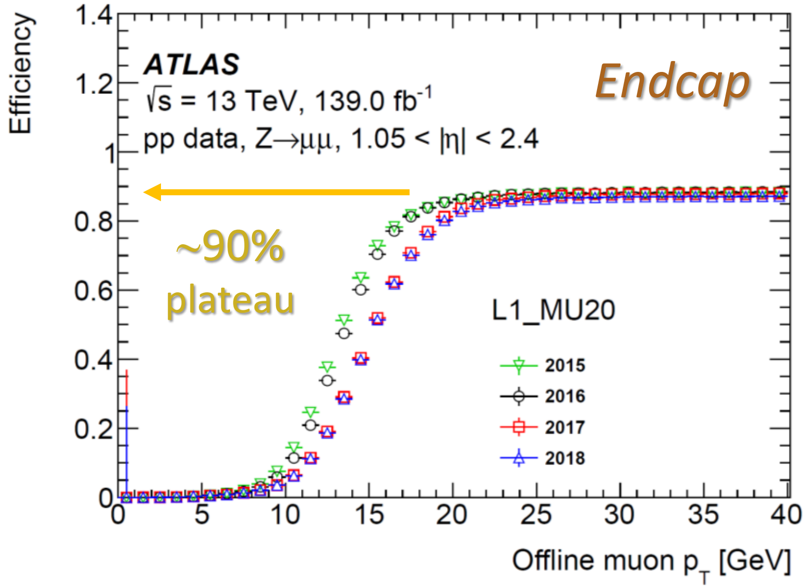
- Tag leg: select unbiased events;
- Probe leg: study trigger efficiency.



Muon L1 plateau efficiencies:
- barrel: ~**70%**
- endcap: ~**90%**.

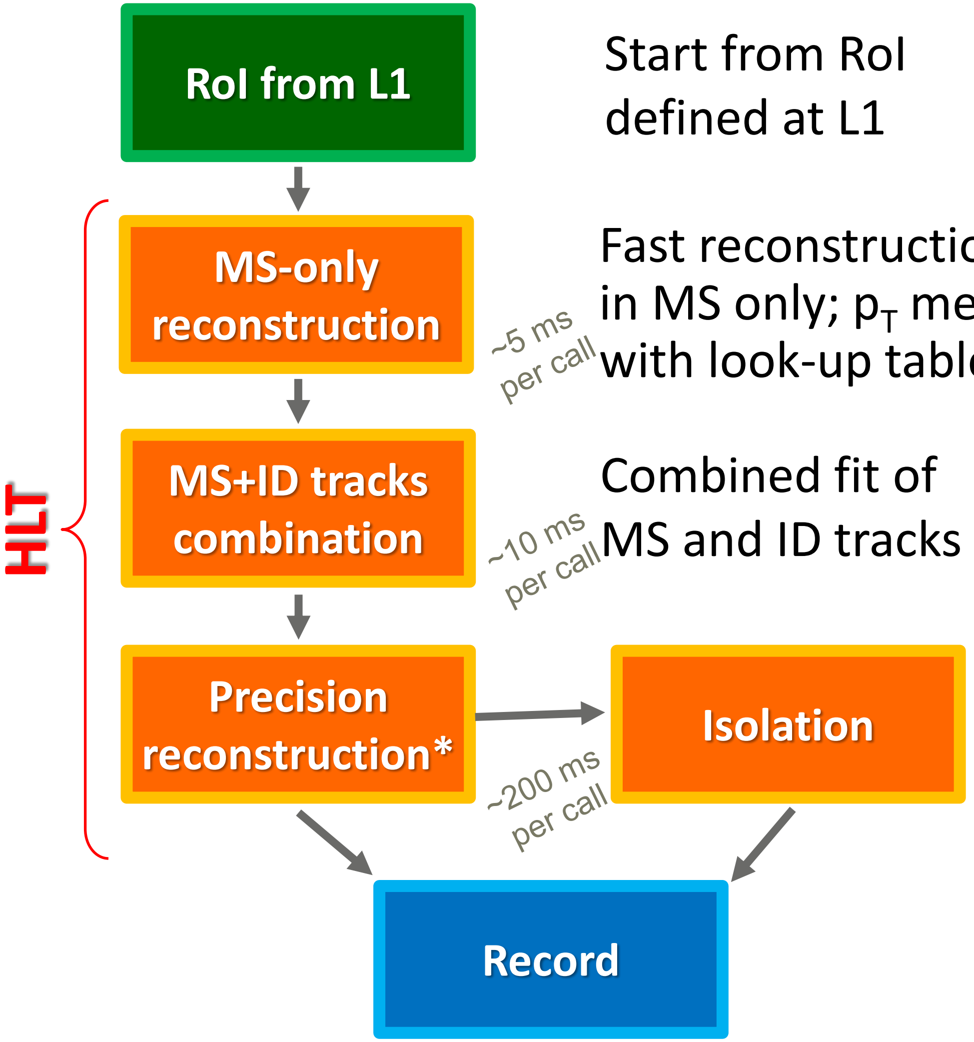
Performance vs. p_T stable over the entire Run 2.





JINST 15 (2020) P09015

Muon HLT design and rates



Start from RoI defined at L1

Fast reconstruction of tracks in MS only; p_T measurement with look-up tables

Combined fit of MS and ID tracks

Muon trigger category	Run 2 ($L=1.7\times10^{34}$ $cm^{-2}s^{-1}$)			Run 3 ($L=2.0\times10^{34}$ $cm^{-2}s^{-1}$)		
	HLT p_T threshold [GeV]	L1 rate [kHz]	HLT rate [Hz]	HLT p_T threshold [GeV]	L1 rate [kHz]	HLT rate [Hz]
1 isolated μ	26	15	180	24	16	220
1 μ	50	15	60	50	16	40
2 μ	14, 14	1.8	26	14, 14	2.2	25

ATL-DAQ-PUB-2018-002

Rates of un-prescaled muon triggers in Run 2 (measured) and Run 3 (expected)

Threshold of lowest isolated single muon decreased by 2 GeV.

* **High resolution reconstruction** (using offline software)

- *outside-in*: MS $\rightarrow$ ID:
- *inside-out*: recovers low-p_T inefficiencies;
- *full-scan*: runs over the whole detector (with heavy CPU usage), for one leg of multi-muon triggers, to recover L1 inefficiencies.

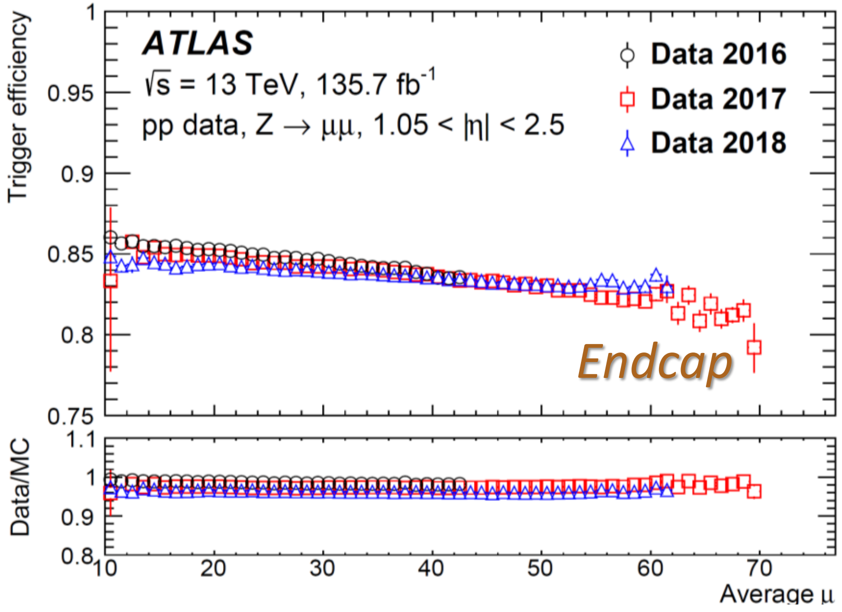
Isolation (optional)

- Allows to lower muon p_T thresholds, keeping reasonable rate.

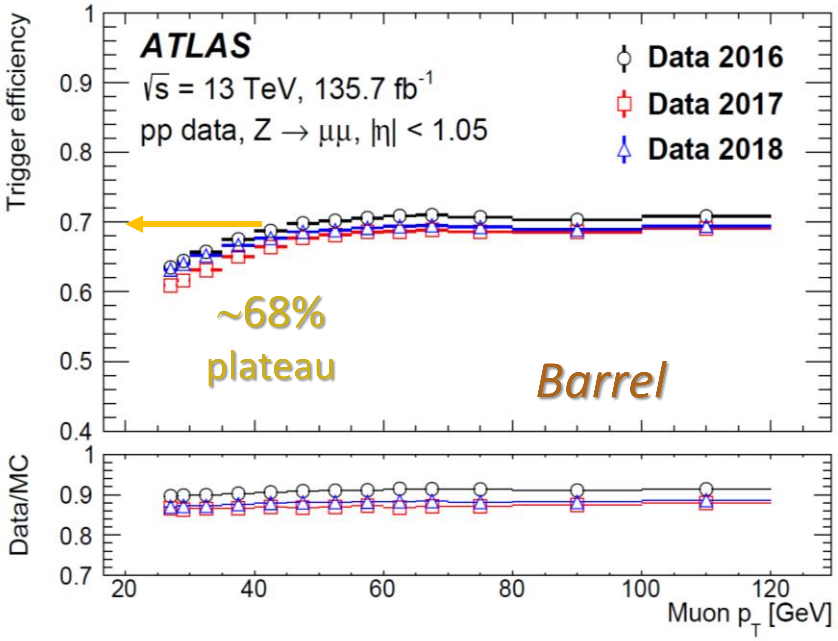
Muon HLT efficiencies - Run 2

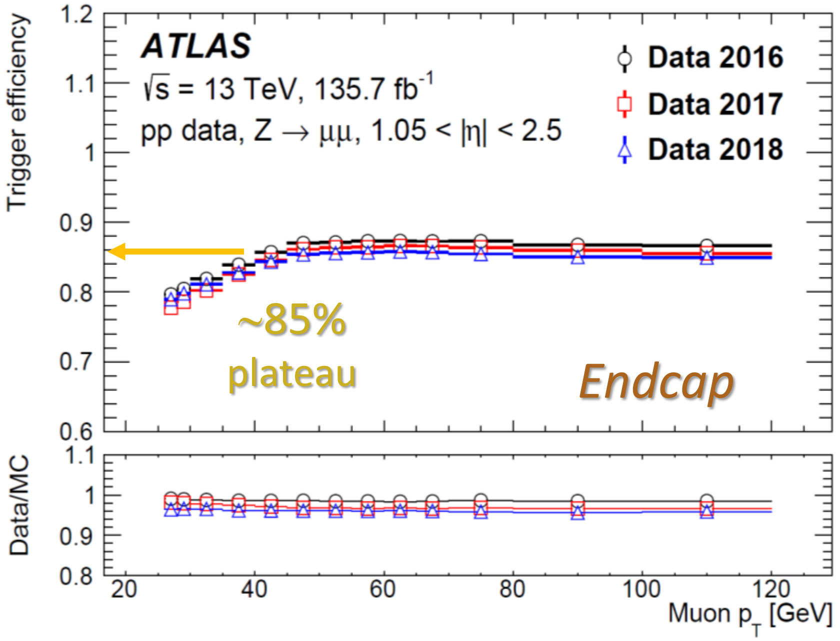
Excellent **Muon HLT** performance:

- Stable performance versus pile-up conditions (as a function of number of reconstructed vertices).



- Most of efficiency losses from L1, limited by geometric coverage.
- HLT efficiency relative to L1 close to 100%.

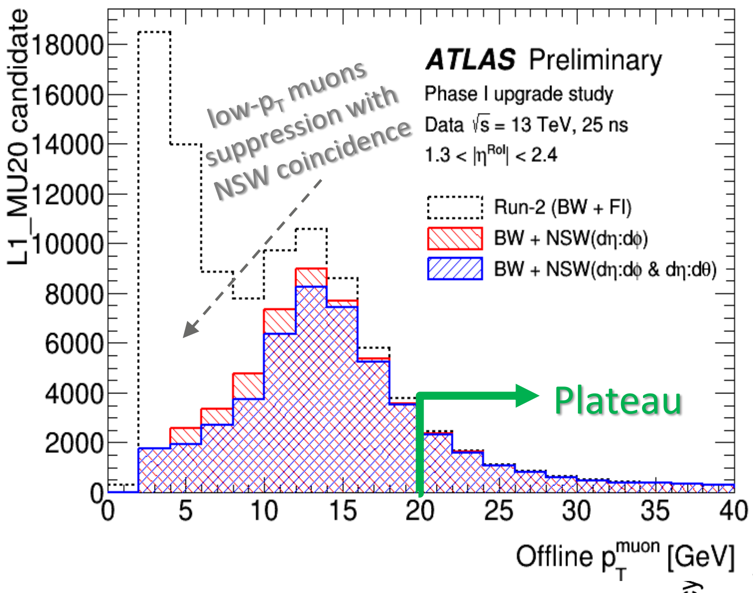


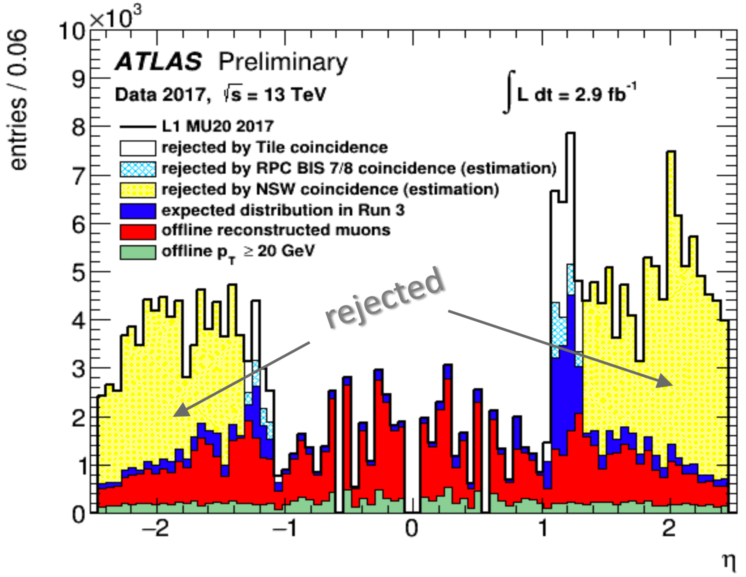


JINST 15 (2020) P09015

Expected performance in Run 3

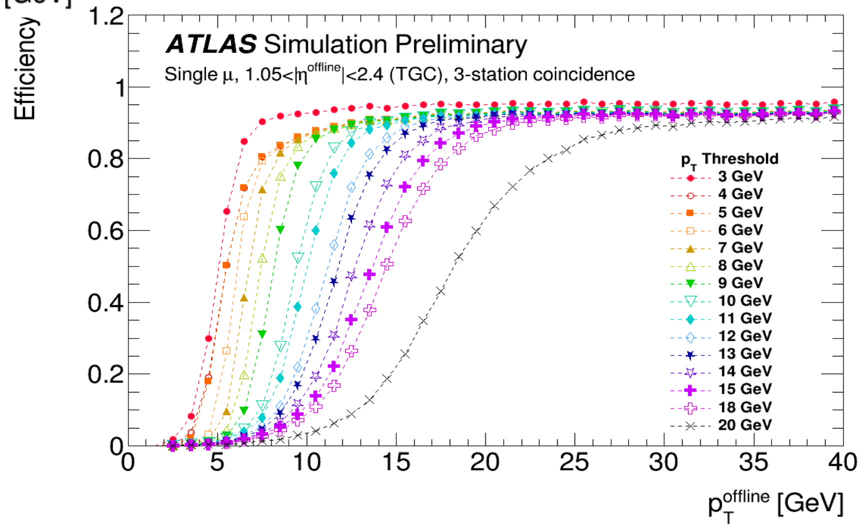
- Rejection of low-p_T muon candidates by using the **NSW + TGC-BW coincidence** allows a **~45%** rate reduction below the 20 GeV threshold in Run 3 with respect to Run 2, with a negligible efficiency loss.





L1 muon trigger public plots

- L1 Muon Endcap Trigger efficiencies estimated for a total of 15 p_T thresholds.
- Trigger logic can require 2- or 3- layer coincidence of **TGC-BW** for 6 GeV threshold or lower.
- The use of **NSW** hits will strongly reduce L1 rates due to fake muons.

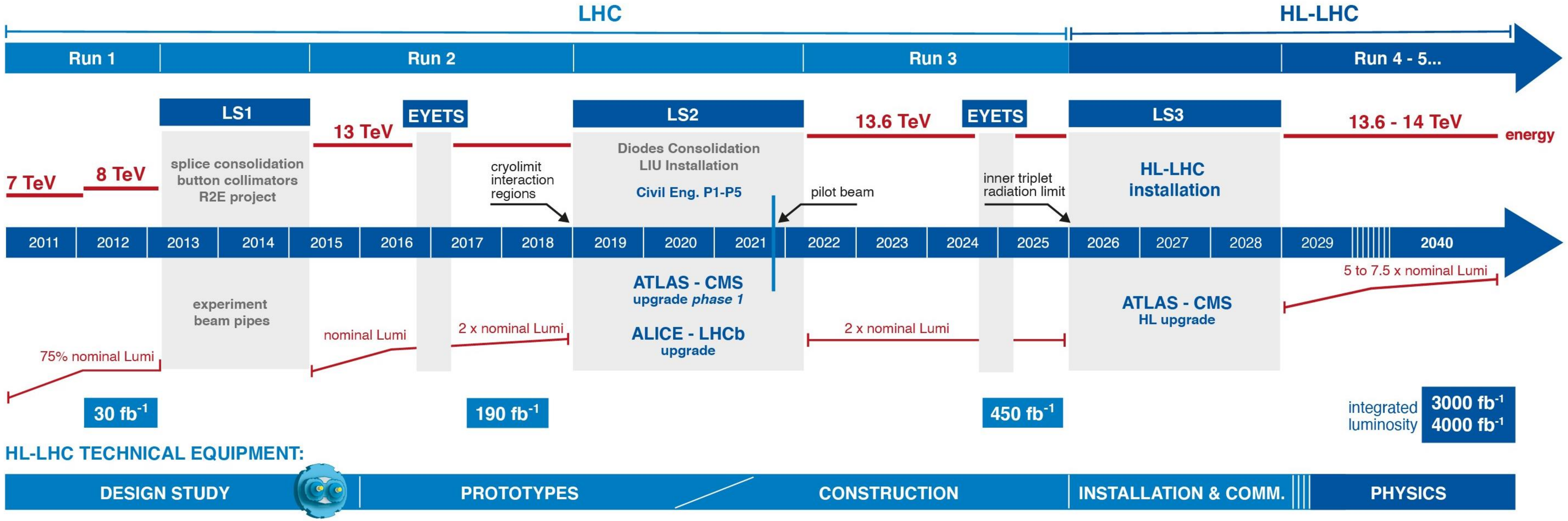


Summary and outlook

- The ATLAS Muon Trigger system has shown an **excellent performance** during LHC **Run 2** (2015-18), successfully fulfilling all physics program requirements.
- Stable performance and high efficiencies achieved both at Muon L1 and at Muon HLT.
- Various ***Phase 1 upgrades*** toward **Run 3** (2022-24) to handle higher luminosity, while ensuring no efficiency losses with respect to Run 2.

Backup slides

LHC & HL-LHC plan



https://hilumilhc.web.cern.ch/content/hl-lhc-project

- **Muon system** receives major upgrades in forward small wheel region
- **TDAQ system** is upgraded to allow for a 1 MHz hardware trigger rate

Muon Spectrometer upgrades

Upgrade of several types of muon chambers

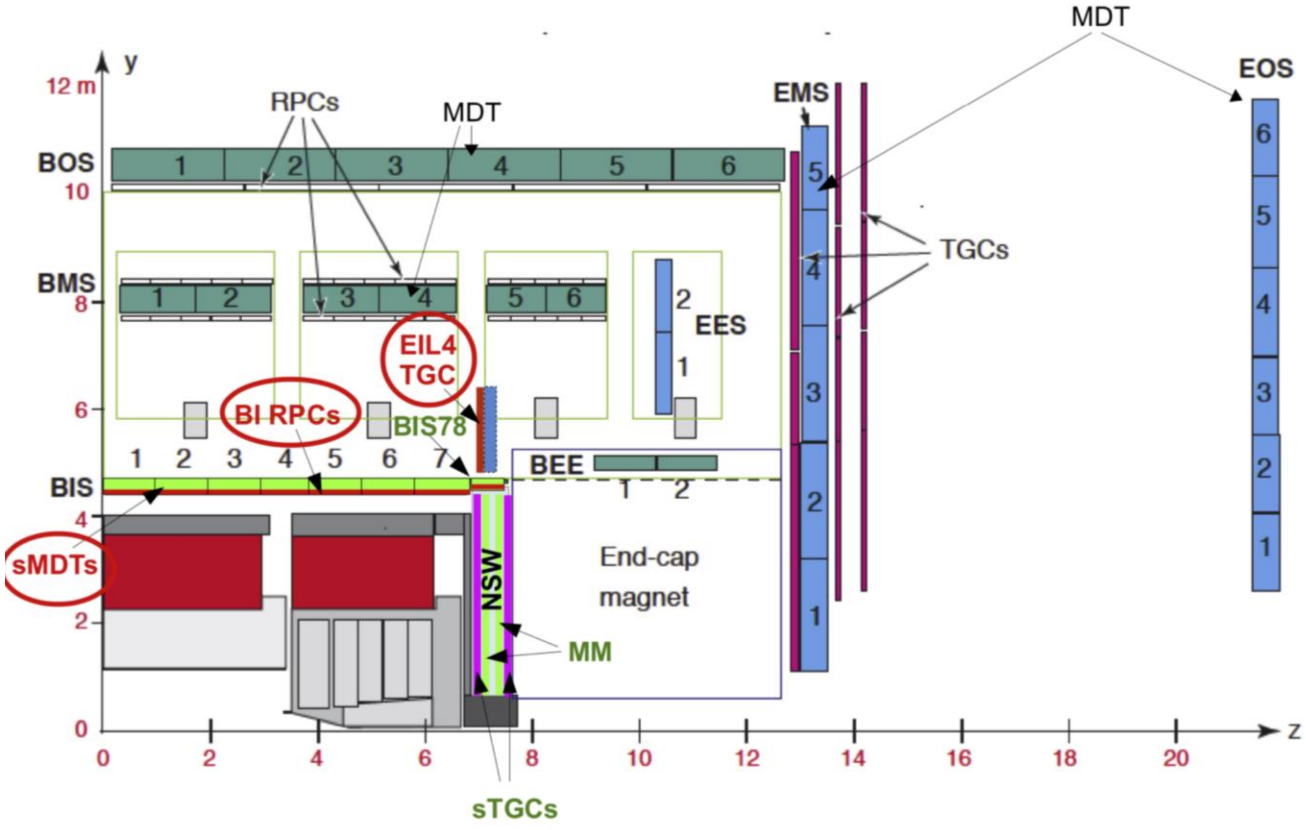
- BI RPC+sMDT
- EIL TGC
- NSW sTGC

Upgrade of readout electronics

Upgrade of power systems

Important progress despite the technological challenges and COVID-19

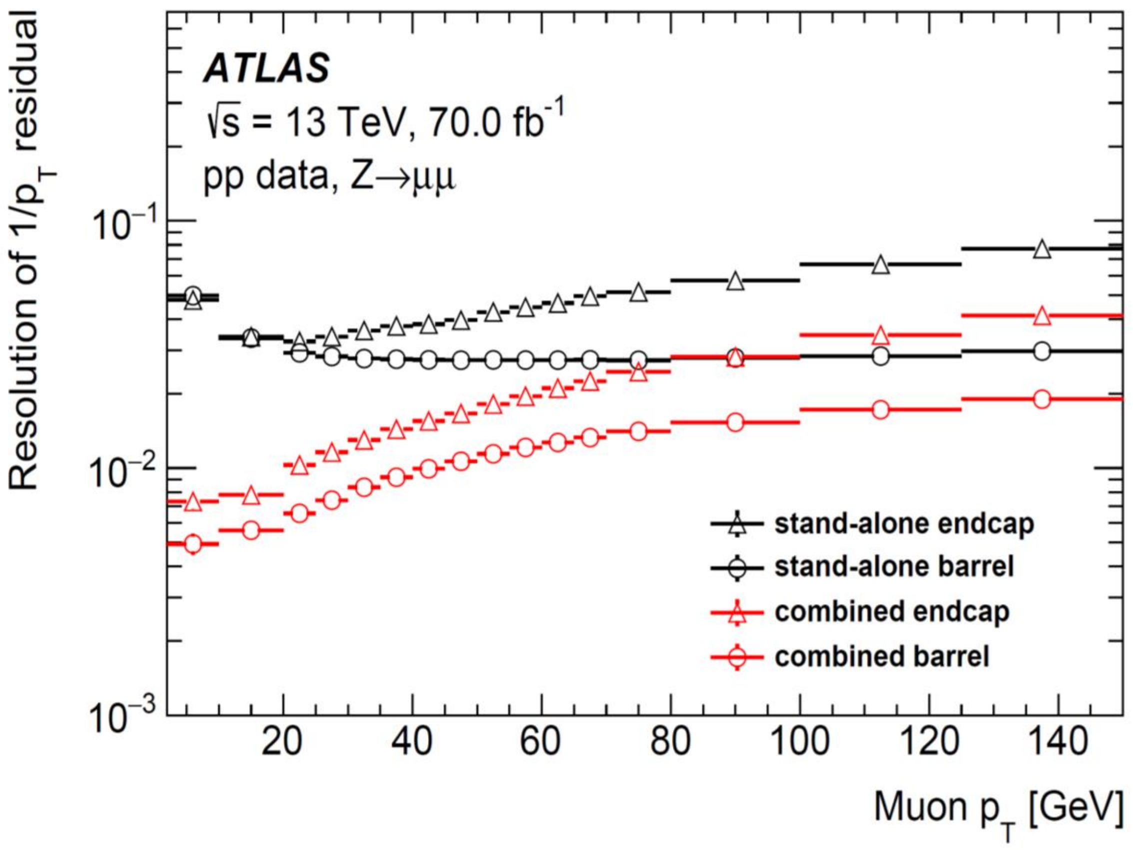
Most of the projects in prototyping phase



Muon trigger resolution studies

Resolution with respect to offline reconstruction of the inverse-p_T residual as a function of offline muon p_T .

- **Stand-alone** muon trigger reconstruction better than 10% resolution in endcap region, as good as 3% in the barrel.
- **Combined** muon trigger reconstruction with resolution below 1% for p_T < 20 GeV, moving to few percent at higher p_T .



JINST 15 (2020) P09015

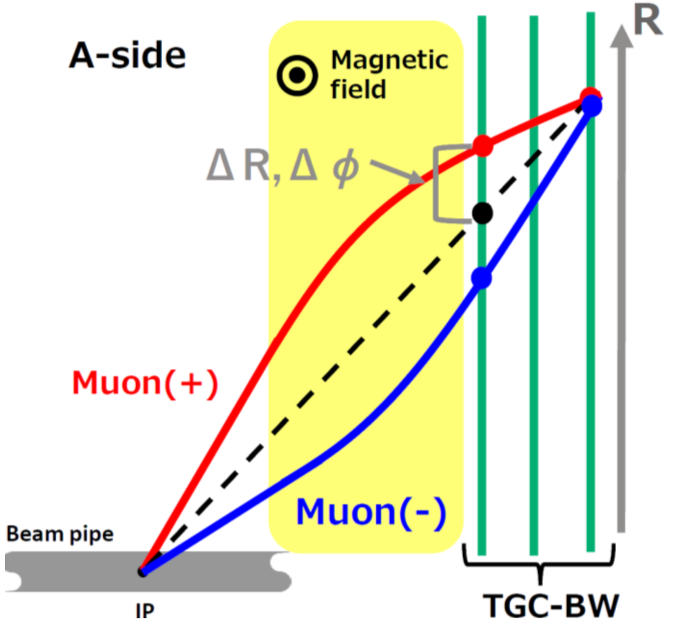
Muon charge identification

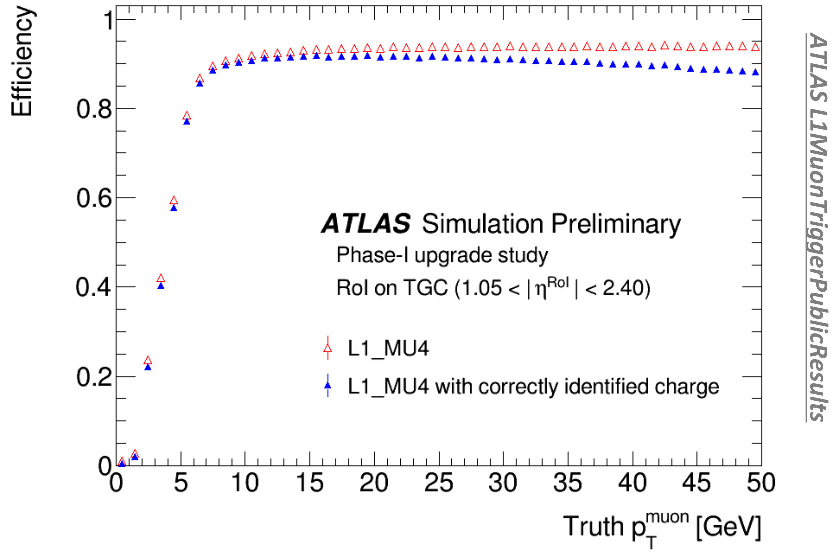
Information on **charge** is fundamental, e.g. in processes with opposite-sign muons (such as $B \to \mu^+\mu^-$).

Charge is identified from muon **bending direction** in the magnetic field by ΔR and $\Delta\phi$.

Instead of using the sign of ΔR only, a look-up table is implemented to use the full ΔR and $\Delta\phi$ information.

- Performance of charge identification is evaluated through a simulation study based on Phase-I upgrade.
- Accuracy of muon charge identification at $p_T < 30$ GeV is found to be larger than 98%.





Abstract

Events with muons in the final state are fundamental for detecting a large variety of physics processes in the ATLAS Experiment, including both high precision Standard Model measurements and new physics searches. For this purpose, the ATLAS Muon Trigger has been designed and developed into two levels: a hardware based system (Level-1) and a software based reconstruction (High Level Trigger). They have been optimized to keep the trigger rate as low as possible while maintaining a high efficiency, despite the increased particle rates and pile-up conditions at the LHC. An overview of the muon triggering strategies will be provided, showing the performance in Run 2 data of both Level 1 and High Level Trigger. The most recent improvements implemented for Run 3 will also be presented.