ATLAS MUON TRIGGER PERFORMANCE

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ON BEHALF OF THE **ATLAS COLLABORATION**

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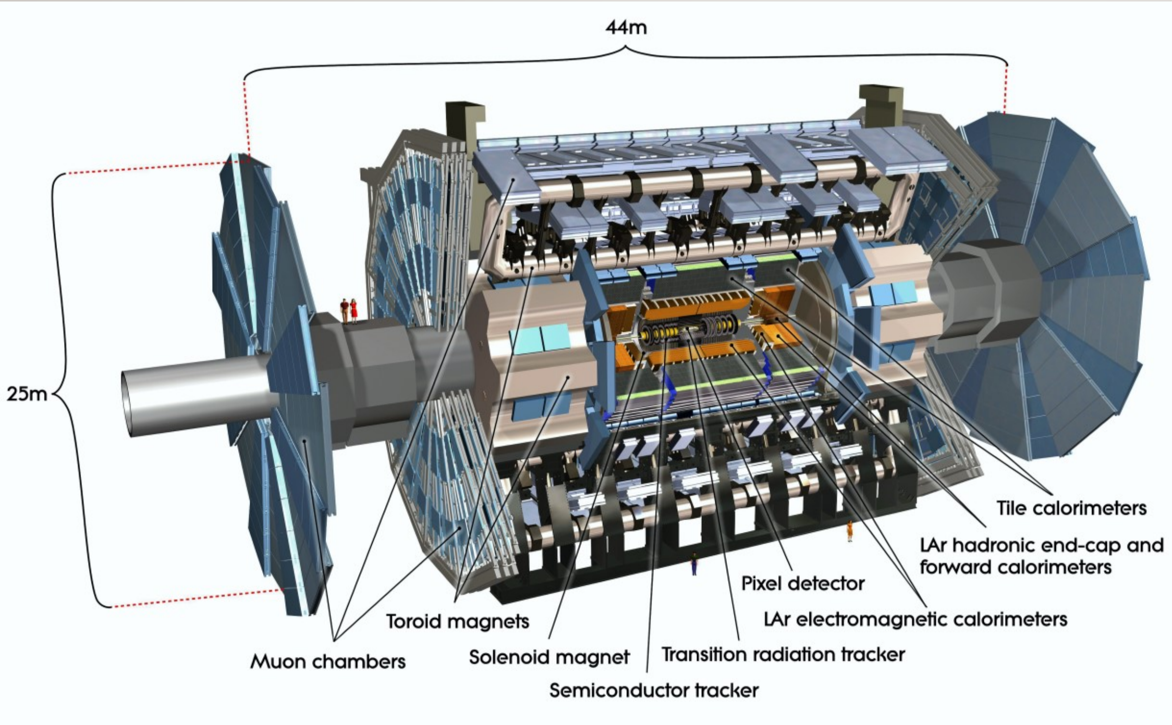
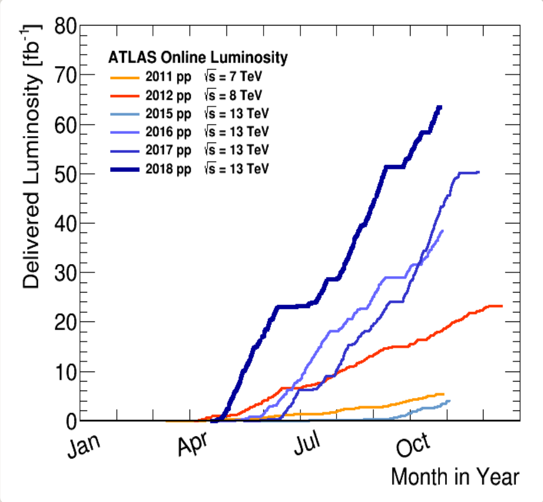
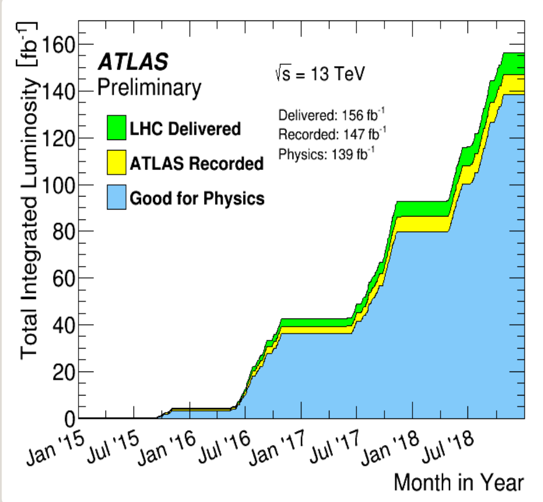
OVERVIEW OF THE TALK

- The ATLAS detector and the Muon Spectrometer
- The Muon L1 & HLT System
- Improvements & optimizations of performance during Run 2
  - Trigger efficiency
  - Fake rates reduction
  - Muon isolation
  - Muon charge identification
  - p_T and spatial resolution
- Outlook for Run 3
- Summary and conclusions

THE ATLAS EXPERIMENT







ATLAS TriggerOperationPublicResults

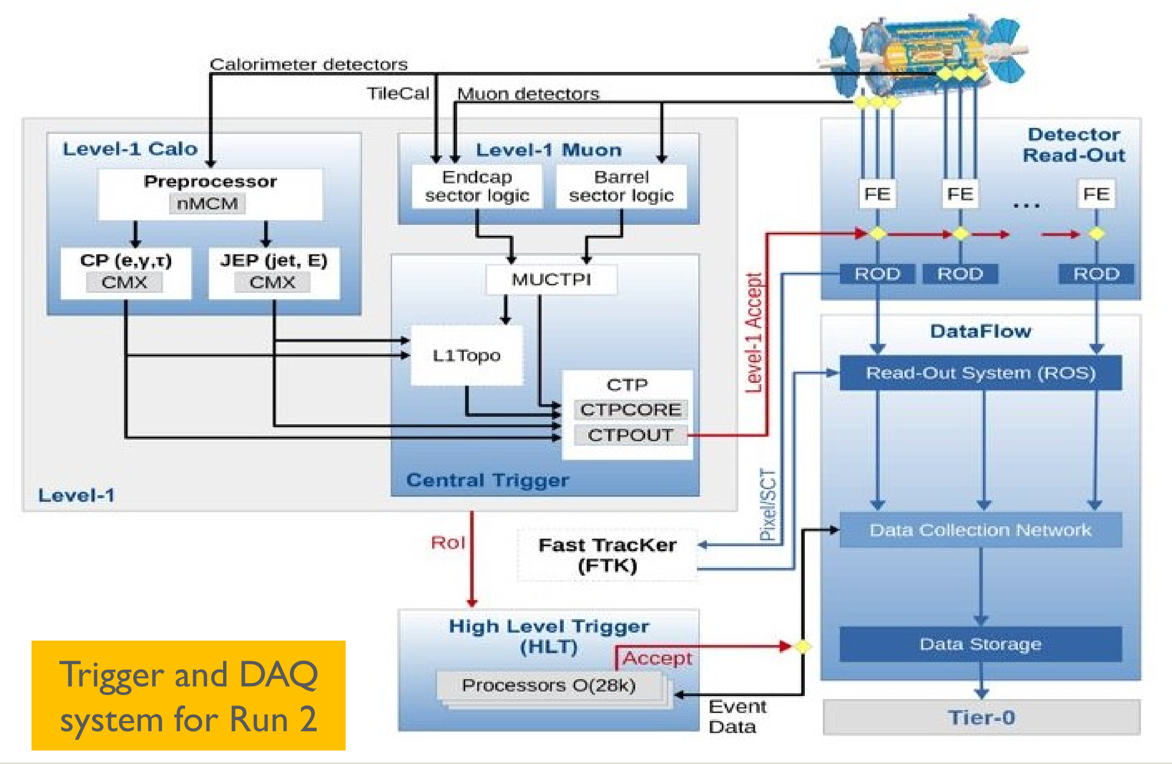
Multi-purpose detector for high-precision SM measurements and beyond SM searches

- Tracking system in $|\eta|< 2.5$ (silicon pixels/strips and TR tracker)+insertable b-layer
- EM (liquid Ar) and hadronic (scintillating tiles) calorimeters covering $|\eta|< 4.9$
- **Muon spectrometer** for muon identification with $\Delta p_T/p_T < 10\%$ up to 1 TeV
- Two magnet systems (toroidal and solenoidal)

THE ATLAS TRIGGER SYSTEM

- 40 MHz of proton-proton collisions are reduced to a rate of up to 100 kHz by the Level-1 (**L1**) Trigger and further processed by the High-Level Trigger (**HLT**) with software-based approach results in a final event recording rate of ~1 kHz on average.

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



Trigger and DAQ system for Run 2

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THE ATLAS MUON SPECTROMETER

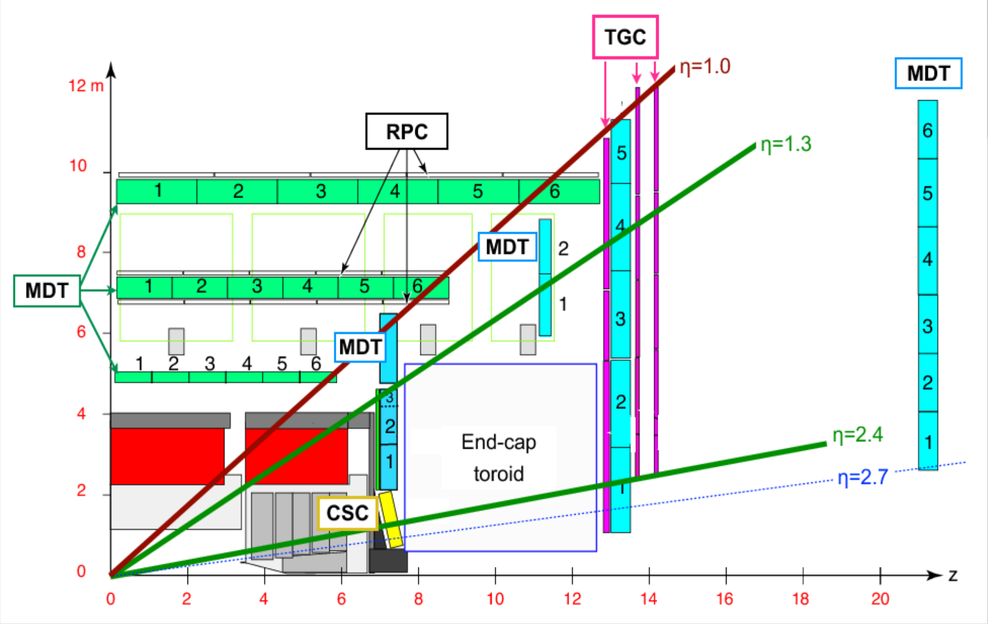
Muon Spectrometer (MS) **acceptance**: |η|<2. 7 (muon trigger system: |η|<2.4).

Muon L1 based on:

- Resistive Plate Chambers (RPC) used in the barrel (|η|<1.05),
- Thin Gap Chambers (TGC) in the endcap regions (1.05<|η|<2.7).

Precision measurements of the track coordinates in the main bending direction of the magnetic field provided by:

- Monitored Drift Tubes (MDT) over most of the range (|η|<2.7)
- Cathode Strip Chambers (CSC) with higher granularity in the innermost station (2<|η|< 2.7).



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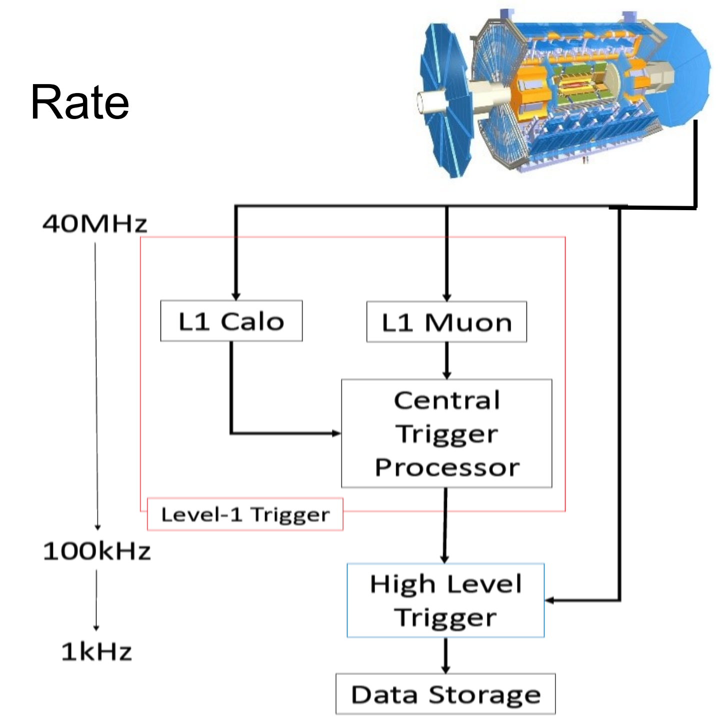
Barrel and endcap **toroids** provide the bending power of:

- about 1.5-5.5 Tm for 0<|η|<1.4 ,
- roughly 1.0-7.5 Tm for 1.6<|η|<2.7 .

MUON L1 AND HLT

- **Muon Level-1 Trigger**
  Hardware-based trigger. The transverse momentum (p_T) of muons is estimated as the degree of deviation from the hit pattern of infinite-p_T tracks by means of 6 possible thresholds and the identification of Regions of Interest (**RoI**s).
- **Muon High Level Trigger**
  Software-based trigger using information from both the MS and inner tracking detectors (ID). It selects events in two stages executing fast muon reconstruction inside given RoIs, and precise measurements parameters of muon tracks using full reconstruction tools.

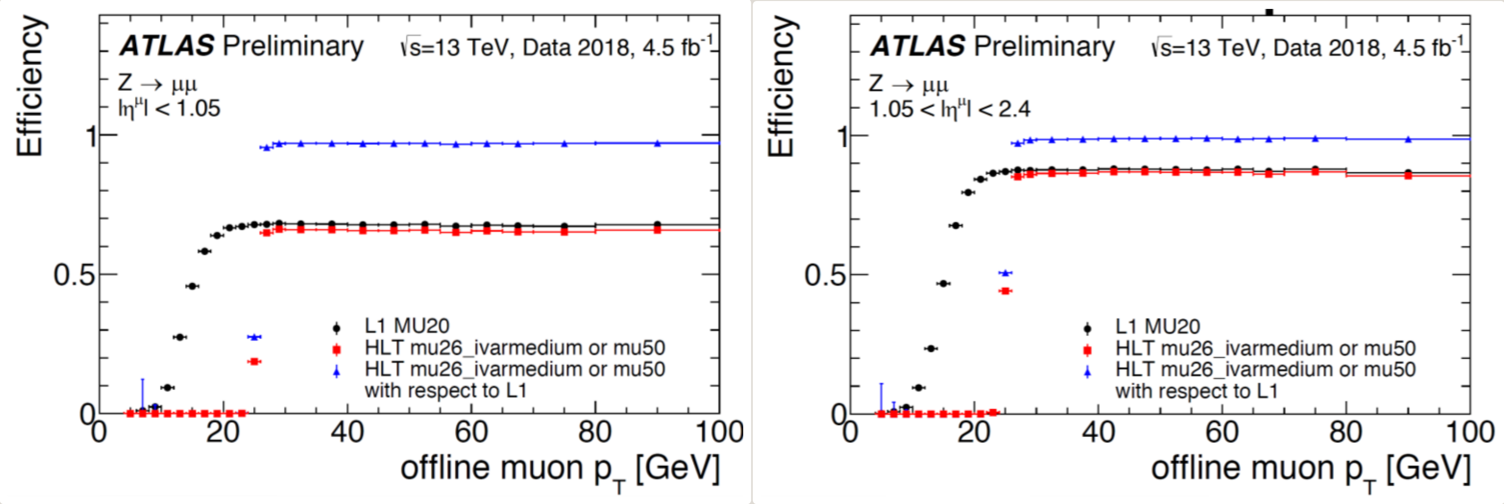


Typical peak luminosity: $\sim 2 \times 10^{34}$ $cm^{-2}s^{-1}$

Representative muon trigger	p_T threshold (GeV)		Peak rate	
	L1	HLT	L1	HLT
One isolated μ	20	26	15 kHz	180 Hz
Two μ	2 x 10	2 x 14	1.8 kHz	25 Hz

TRIGGER EFFICIENCY MEASUREMENT

- The performance of the muon trigger is evaluated exploiting the **“tag-and-probe”** method using $Z \rightarrow \mu\mu$ events (or $J/\psi \rightarrow \mu\mu$ at lower p_T).
  One leg of the decay (tag) is used to unbias events with respect to the trigger and the second leg (probe) is used to study trigger efficiency.



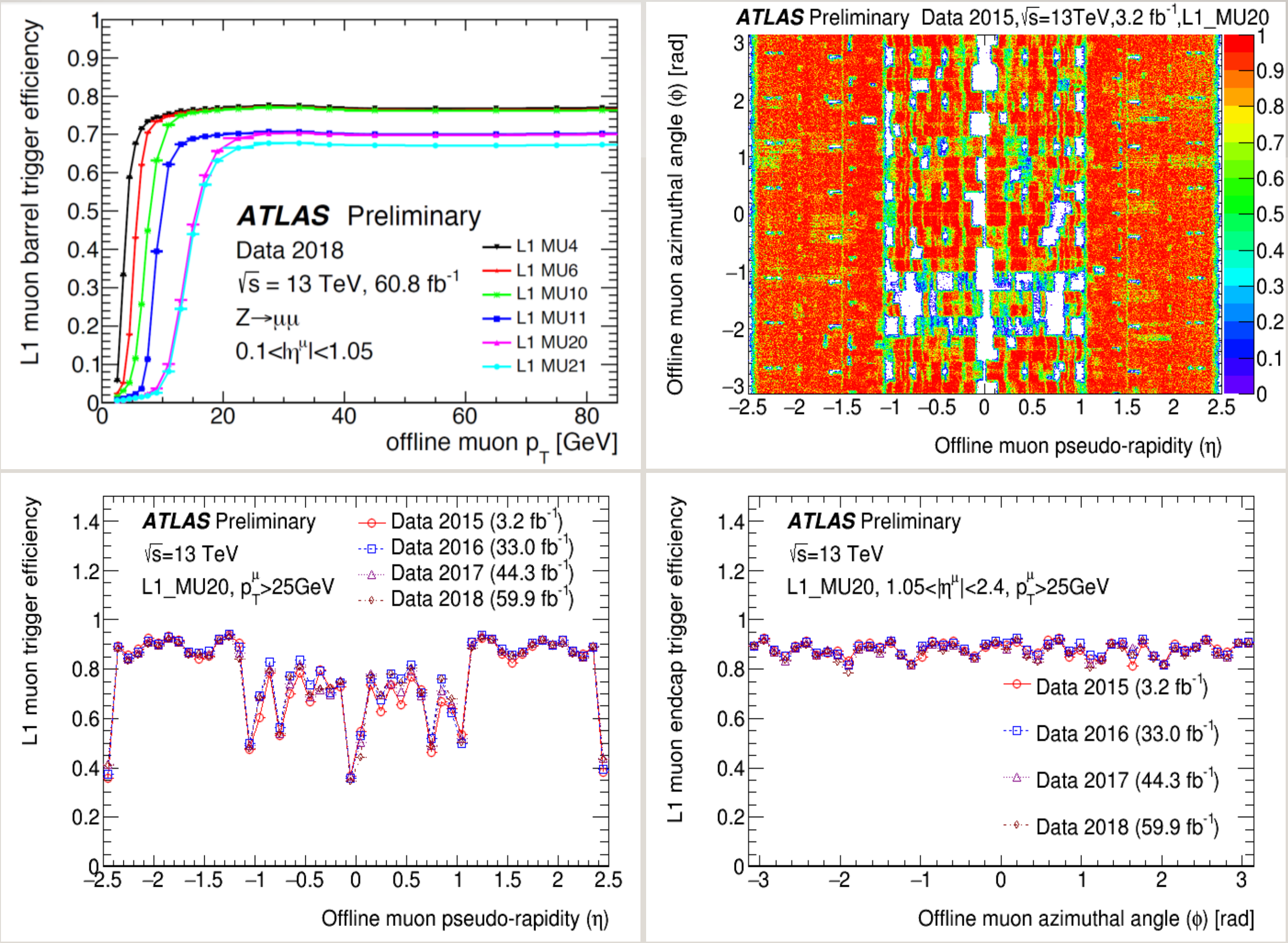
ATLAS MuonTriggerPublicResults

L1 trigger: Efficiency is about 90% in the endcaps and nearly 70% in the barrel. The efficiency loss in the barrel is essentially due to uncovered detector regions.
HLT: About 100% efficiency relative to L1 is found and sharper turn-on curves are obtained as a function of p_T .

L1 MUON TRIGGER EFFICIENCY

- Muon Trigger efficiencies are computed with respect to offline muon parameters.

- Performance of **muon L1** is stable with time (no big changes since 2015 data).



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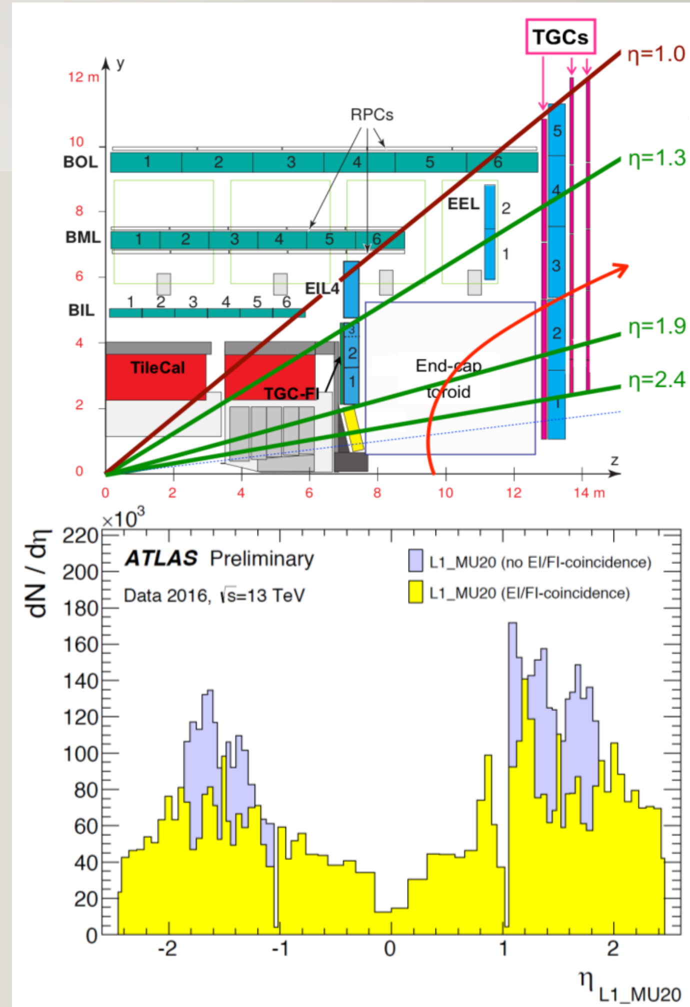
FAKE RATE REDUCTION WITH TGC

- The main source of background in the L1 muon endcap system is low-p_T protons that emerge from the endcap toroid magnets (*fake muons*).
- In order to reject such background, a **coincidence** between TGC Big Wheel (TGC-BW) and TGC Forward Inner (TGC-FI) chambers or Endcap Inner (EI) chambers (EI/FI coincidence) has been implemented.
- The introduction of EI/FI coincidence in 2016 has caused a ~20% reduction of fake tracks passing L1 muon triggers for p_T passing the 20 GeV threshold (L1_MU20) while losing only a 1% efficiency.



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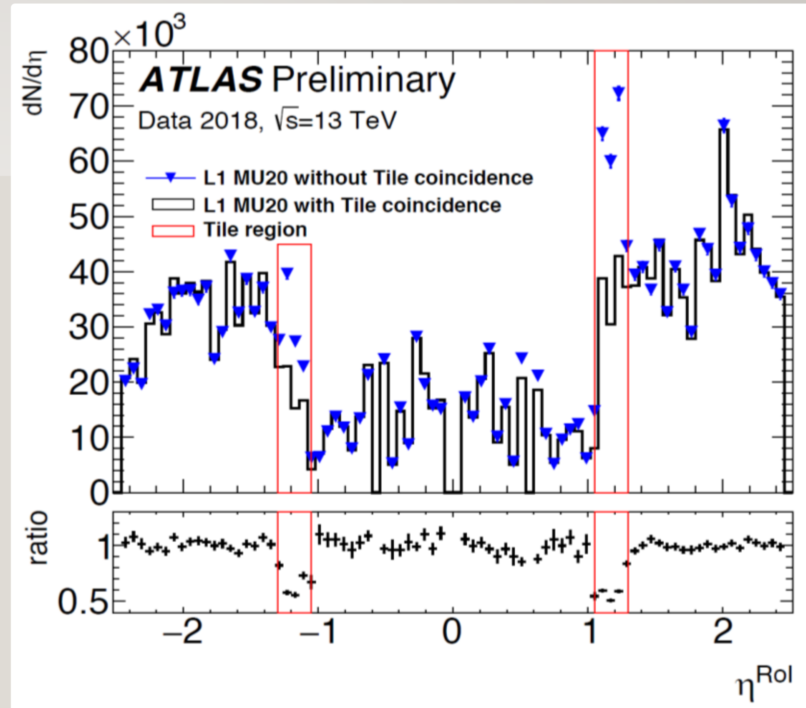
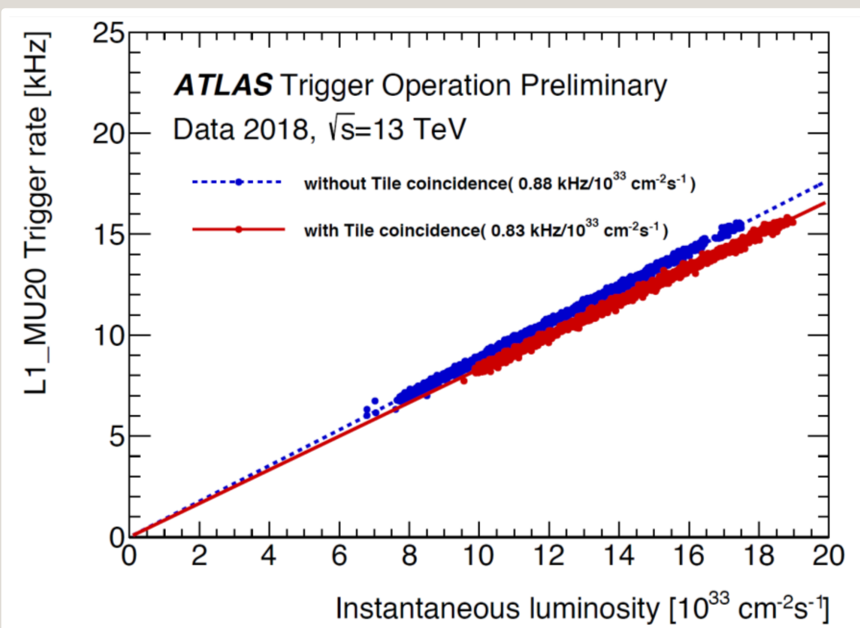
FAKE RATE REDUCTION WITH TILE-MUON

- Tile-Muon coincidence introduced in 2018.
- Its introduction has brought to a ~45% trigger rate reduction in the Tile-Muon coincidence region ($1.05 < |\eta^{RoI}| < 1.3$) for L1_MU20.





- In terms of the full muon trigger coverage, the rate reduction for L1_MU20 due to the Tile-Muon coincidence was about 6%.

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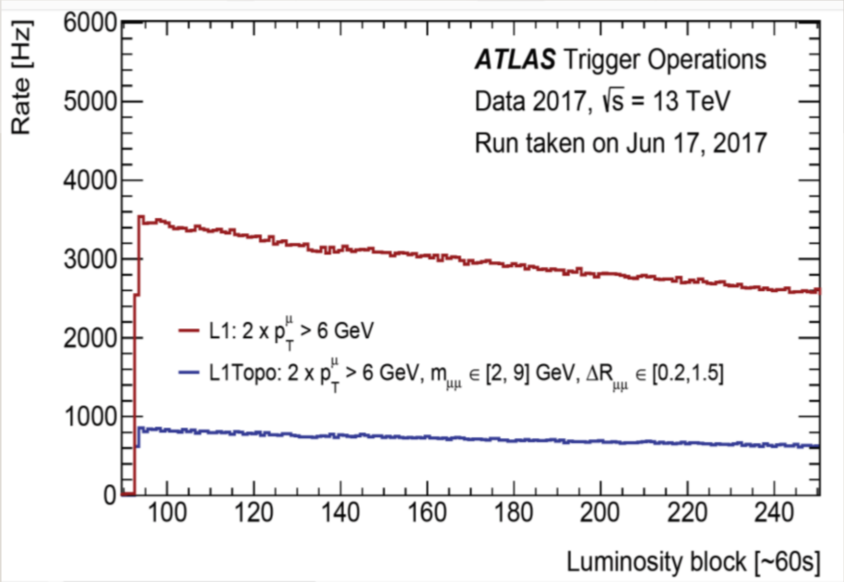
MUON L1: DI-MUONS

- Thanks to the L1 Topological Processor trigger, the L1 Muon system can take advantage of elaborated information, including also L1Calo.
- The **L1 di-muon rate** is compared with (blue) and without (red) L1Topo requirements. The baseline trigger selects muon pairs having p_T larger than 6 GeV, while the topological trigger acts on invariant masses of the di-muon and selects values between 2 and 9 GeV, combined with an angular separation $\Delta R \in [0.2, 1.5]$.



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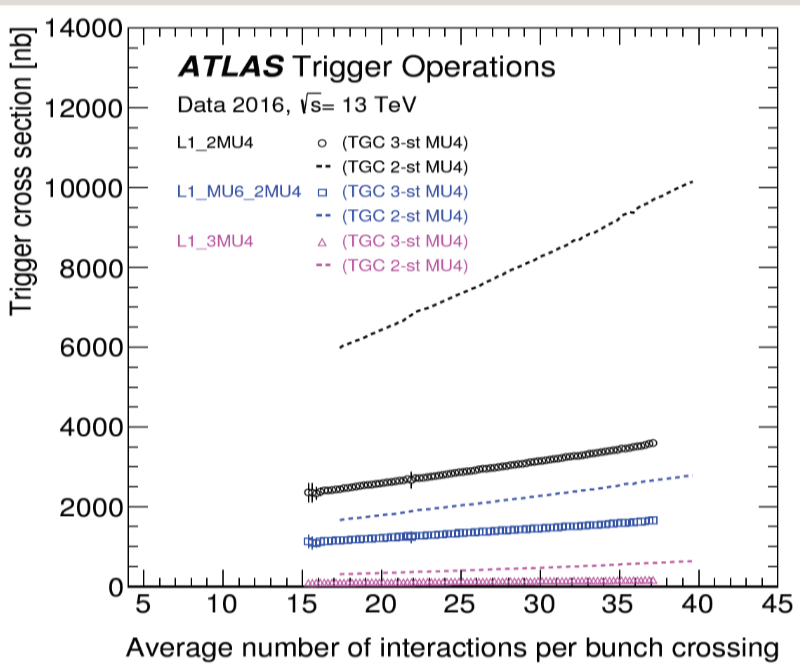
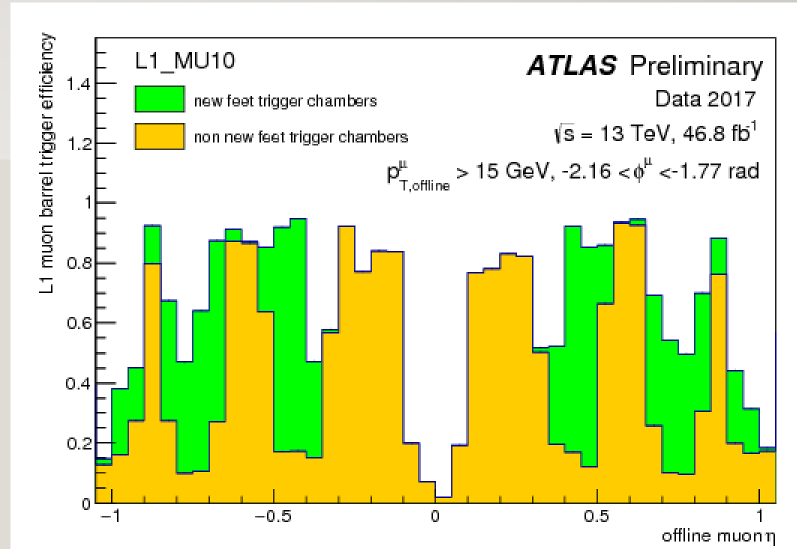
A very large rate reduction (up to a factor of 5) is obtained, without significant losses in terms of efficiency, keeping wide possibilities for multi-muon physics studies (from B-physics to exotics).

IMPROVEMENTS TO LEVEL-1

Barrel Trigger Efficiency

- Introduction of RPCs in barrel support structures (operational since 2016) has increased trigger acceptance by ~4% in barrel.





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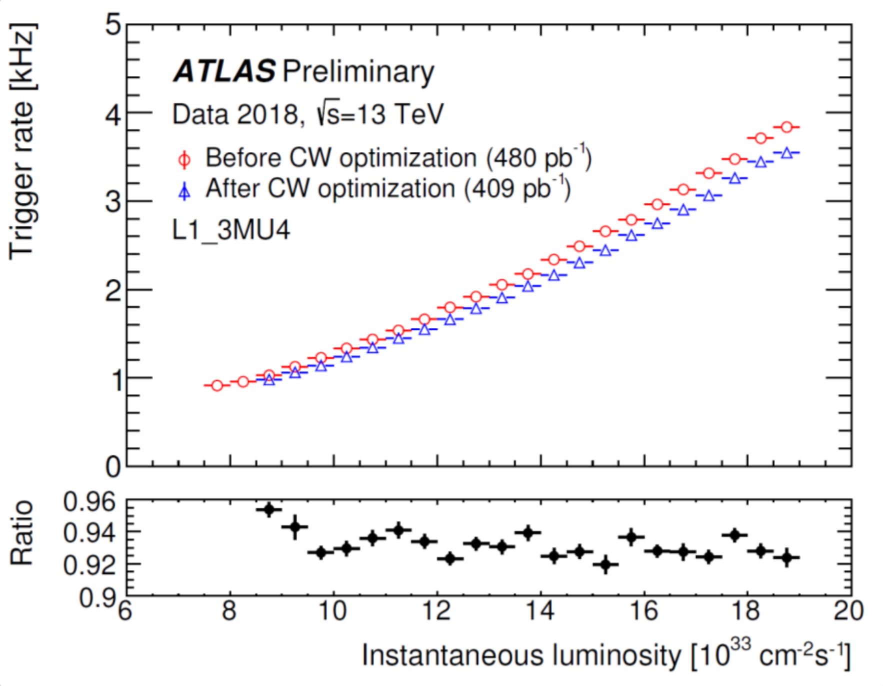
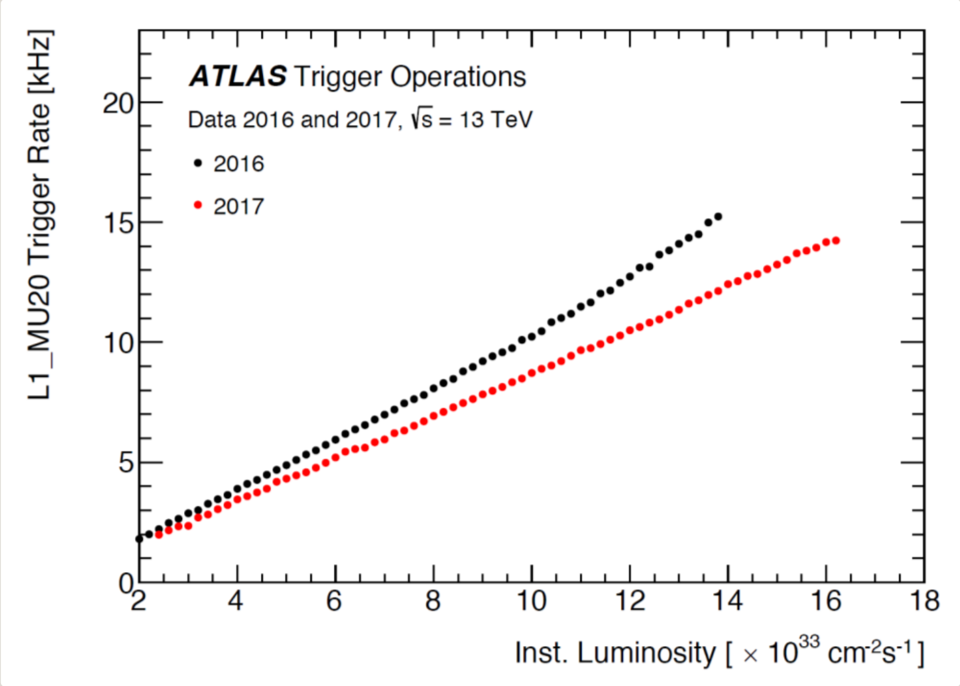
Low-p_T coincidence requirement

- The new **3-station requirement** for L1_MU4 in the endcaps (like for higher thresholds) reduces rates and dependence from pileup, while keeping efficiency almost unchanged.

OPTIMIZATIONS IN ENDCAPS

- Reduction of **L1 trigger rates** in the endcap regions has been obtained by means of dedicated optimizations.





- Coincidence Window optimization reduces trigger rates implementing a dedicated *look-up table* (L1_3MU4 and L1_MU20 shown above)

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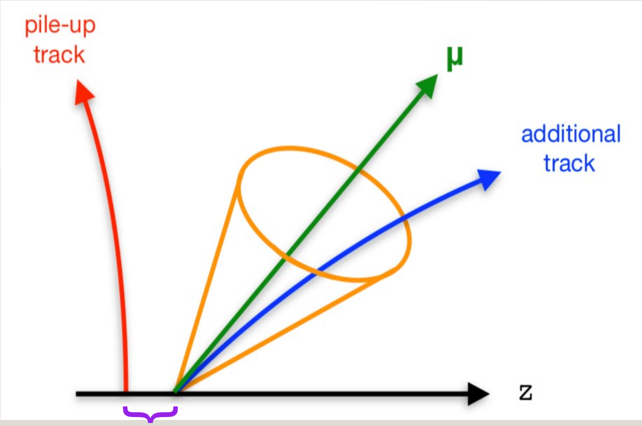
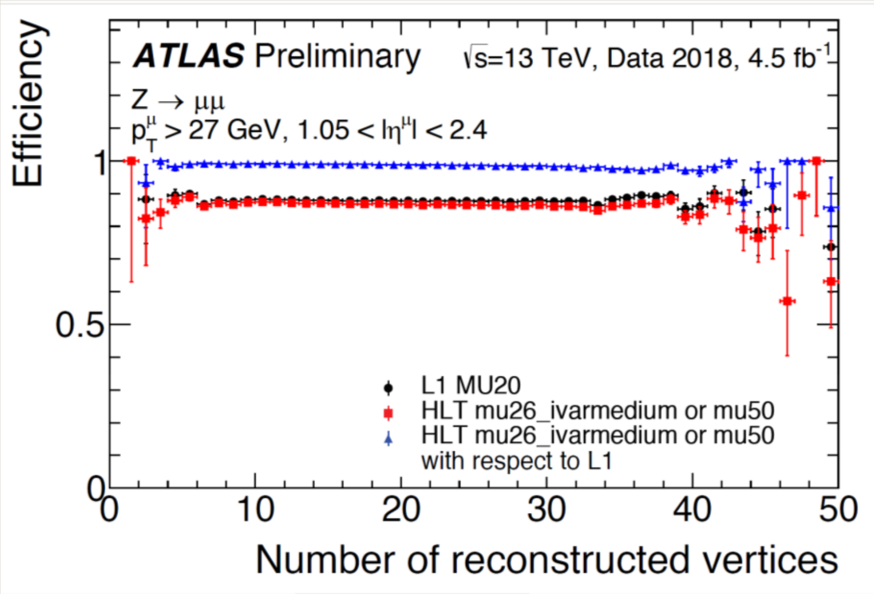
IMPROVEMENT ON HLT MUON ISOLATION

- Isolation for combined muons is quantified by summing the p_T of ID tracks having $p_T^{trk} > 1$ GeV within an optimized cone size.
- In 2018 dz cut moved from 6 mm to 2 mm in order to reduce the efficiency loss observed in 2017 due to the high pileup conditions



dz = *distance between muon track and other track*



- Muon HLT efficiency is found to be extremely stable with respect to the number of vertices in the event: performance of muon isolation does not depend on the pileup conditions.

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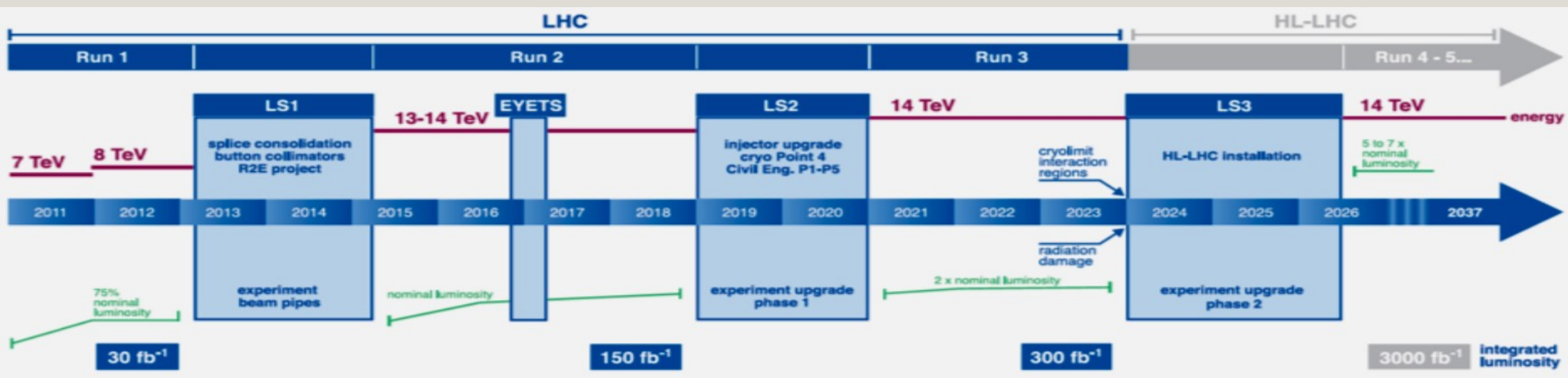
TOWARD HIGH-LUMINOSITY LHC

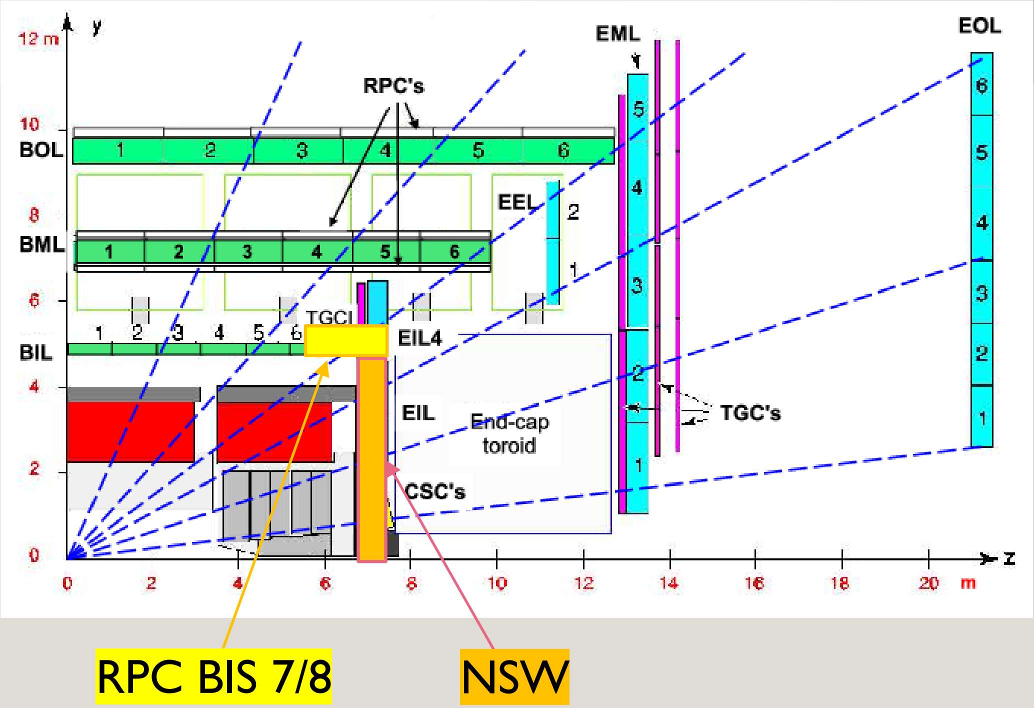
- During **Run 3** (from 2021 for three years) instant luminosity will be $\mathcal{L} = 2\times10^{34}\ cm^{-2}s^{-1}$.
- New conditions at **HL-LHC**: $\sqrt{s} = 14$ TeV, $\mathcal{L} = 7.5\times10^{34}\ cm^{-2}s^{-1}$, $\langle\mu\rangle = 200$ for a total integrated luminosity 3000 fb^{-1} .
- Significant **detector upgrades** for stringent requirements on radiation hardness, bandwidth, granularity and η coverage: new all-silicon Inner Tracker, upgraded read-out electronics for calorimeters, new innermost layer in muon system barrel.



ATLAS-TDR-025 ATL-PHYS-PUB-2016-026

UPGRADES FOR RUN 3: MUON SPECTROMETER

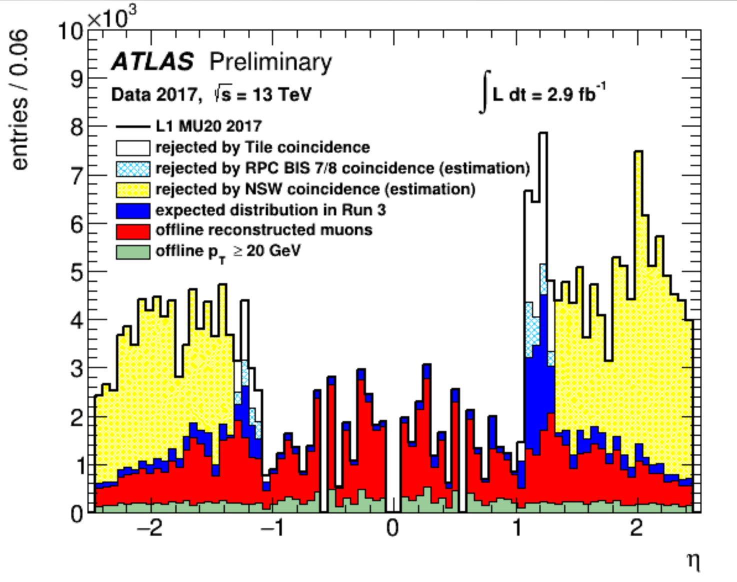
- To deal with the higher luminosity expected during Run 3 ($L=2.0\times10^{34}\ cm^{-2}s^{-1}$) and to increase acceptance, the chambers of the **muon innermost layer** will be replaced with higher granularity detectors, called New Small Wheels (NSW) and consisting of sTGCs + MicroMegas, and a new set of RPCs, called RPC BIS 7/8.



- NSW will also provide precise tracking information

UPGRADES FOR RUN 3: PERFORMANCE

- In order to optimize the muon trigger performance, additional upgrades will be realized for Run 3:
  - a new trigger hardware for L1,
  - multithreading techniques for HLT.



Expected η distribution of Run 3 Muon Trigger

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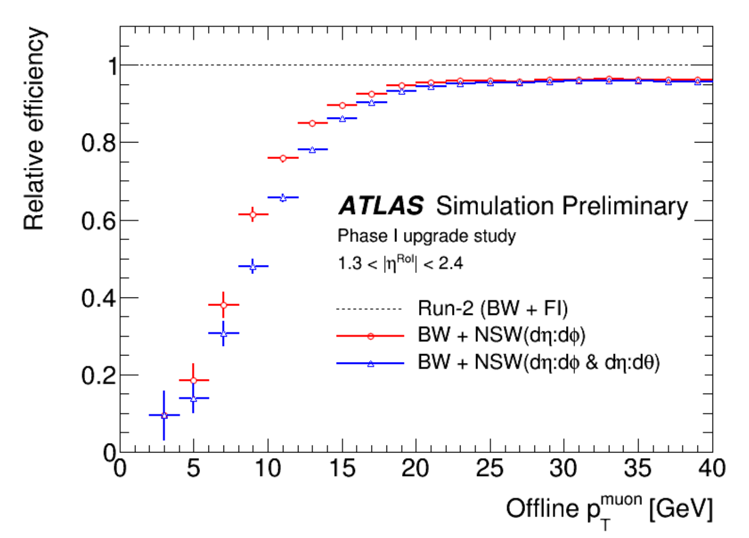
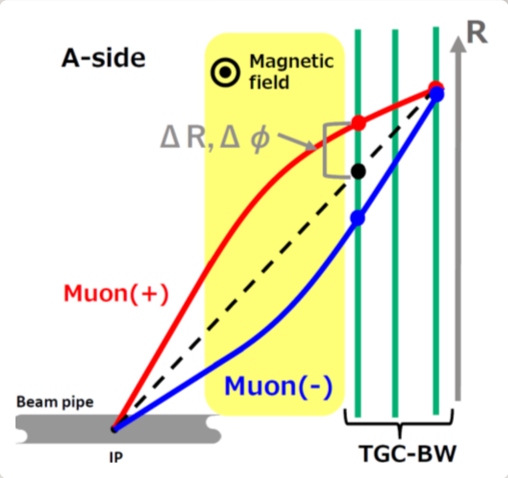
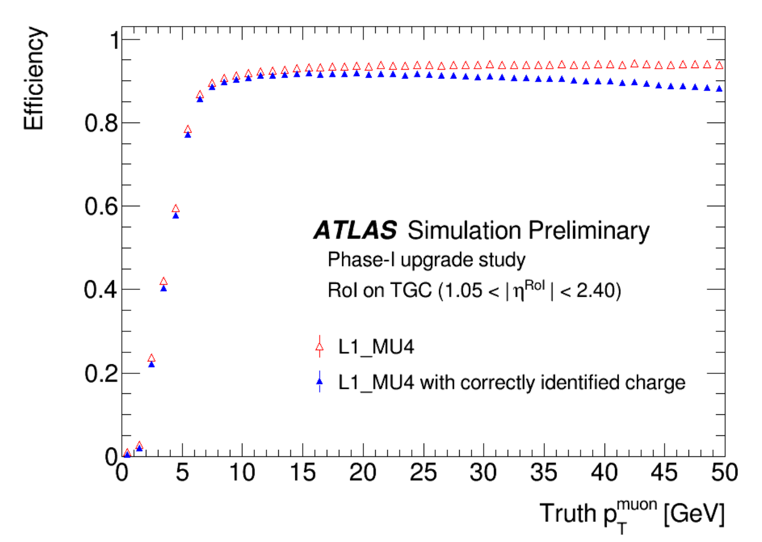


- Low-p_T candidates are effectively rejected by TGC-BW + NSW coincidence with only a few % of efficiency loss and ~50% rate reduction expected for L1_MU20 with respect to Run 2.

MUON CHARGE IDENTIFICATION

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

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SUMMARY AND CONCLUSIONS

- Many measurements have been carried out to study the **performance** of the **ATLAS Muon Trigger** System using muons selected in LHC collisions.
- Results reported here concern **Run 2** and include:
  - trigger efficiencies, fake rate reduction, resolution improvements and optimizations on isolation and charge identification.
- All measurements show **stable** performance and **efficient** triggering of muons.
- Significant **detector upgrades** are moving from design to production and commissioning to improve trigger performance toward **Run 3**.
- Even more performing features are expected for the **High-Luminosity LHC** to cope with higher luminosity/energy and harder pileup conditions.
- Final goal is to maximixize the impact on New Physics searches and high-precision Standard Model physics, improving signal acceptance and reducing background rate.

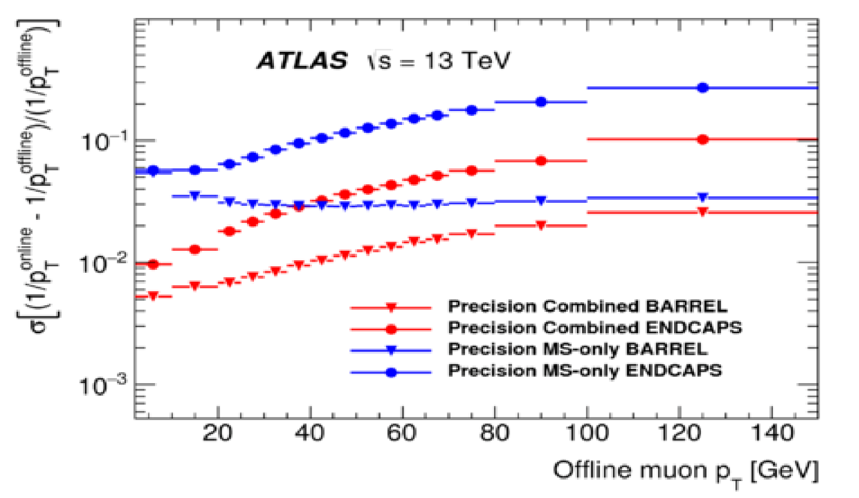
BACKUP SLIDES

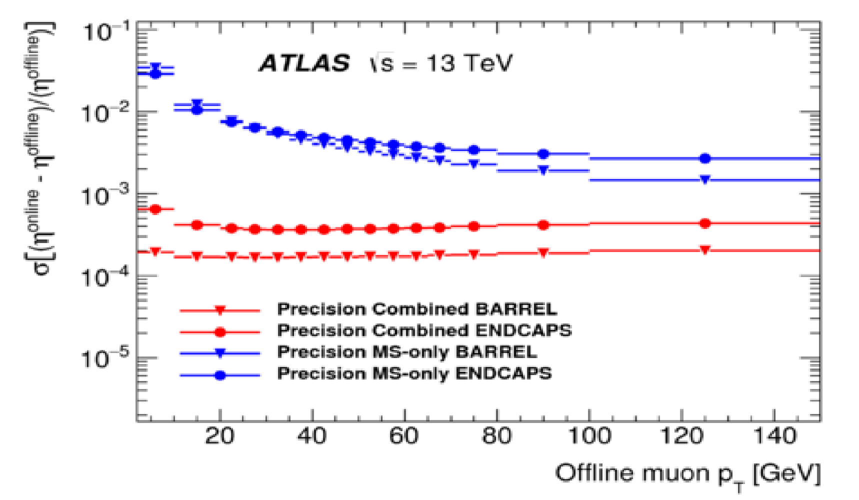
Some web references

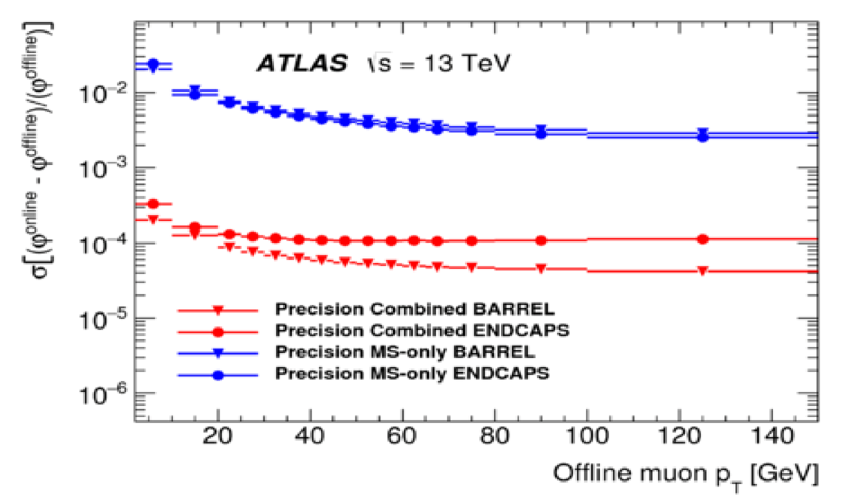
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerPublicResults
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1MuonTriggerPublicResults
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MuonTriggerPublicResults
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsDAQ

RESOLUTION STUDIES

- Width of the residuals for inverse-p_T , η, ϕ as a function of offline muon p_T for the precision MS-only and combined algorithms in the barrel ($|\eta|<1.05$) and end-caps ($1.0<|\eta|<2.4$).







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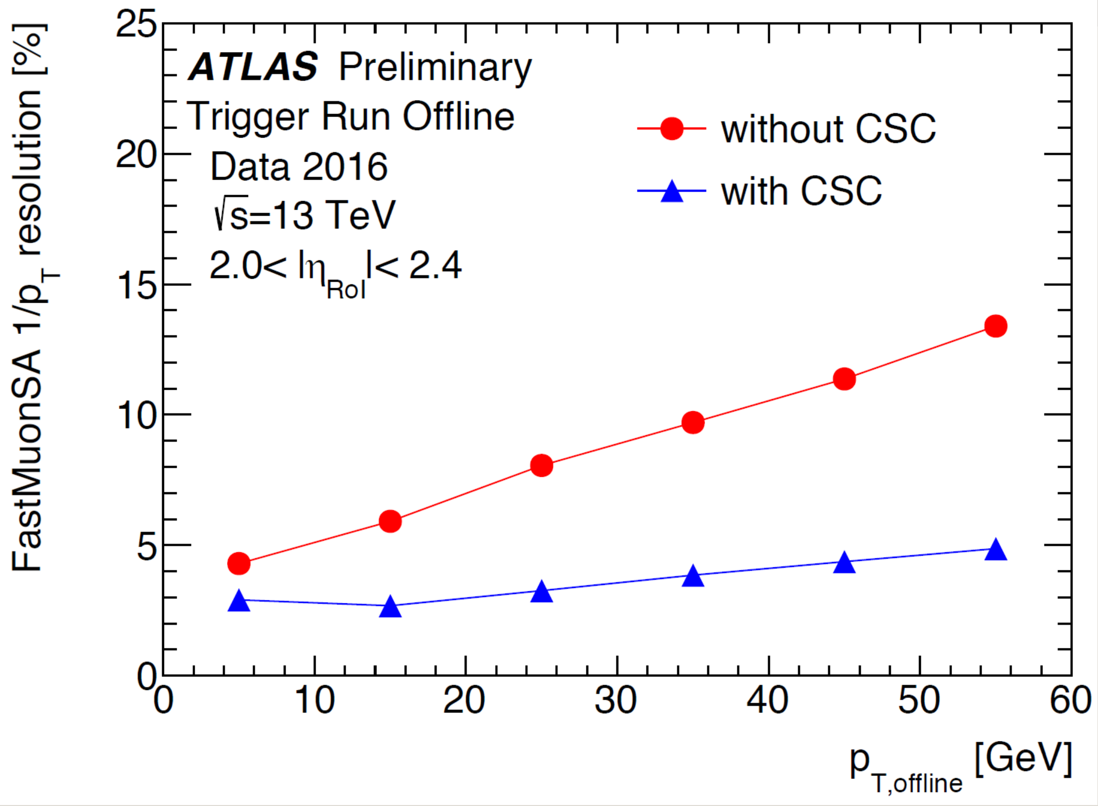
IMPROVED RESOLUTION WITH CSC

- CSCs are included in the fast p_T determination algorithm of HLT to improve measurement in the forward region ($|\eta|>2.0$).



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ABSTRACT

- Events containing muons in the final state are an important signature for many analyses being carried out at the Large Hadron Collider (LHC), including both standard model measurements and searches for new physics. To be able to study such events, it is required to have an efficient and well-understood muon trigger. The ATLAS muon trigger consists of a hardware based system (Level 1), as well as a software based reconstruction (High Level Trigger). Due to the high luminosity in Run-2, several improvements have been implemented to keep the trigger rate low, while still maintaining a high efficiency. Some examples of recent improvements include requiring coincidence of hits in the muon spectrometer and the calorimeter and optimised muon isolation. We will present an overview of how we trigger on muons, recent improvements, the performance of the muon trigger in Run-2 data and an outlook for the improvements planned for Run-3.