ATLAS Muon Trigger performance

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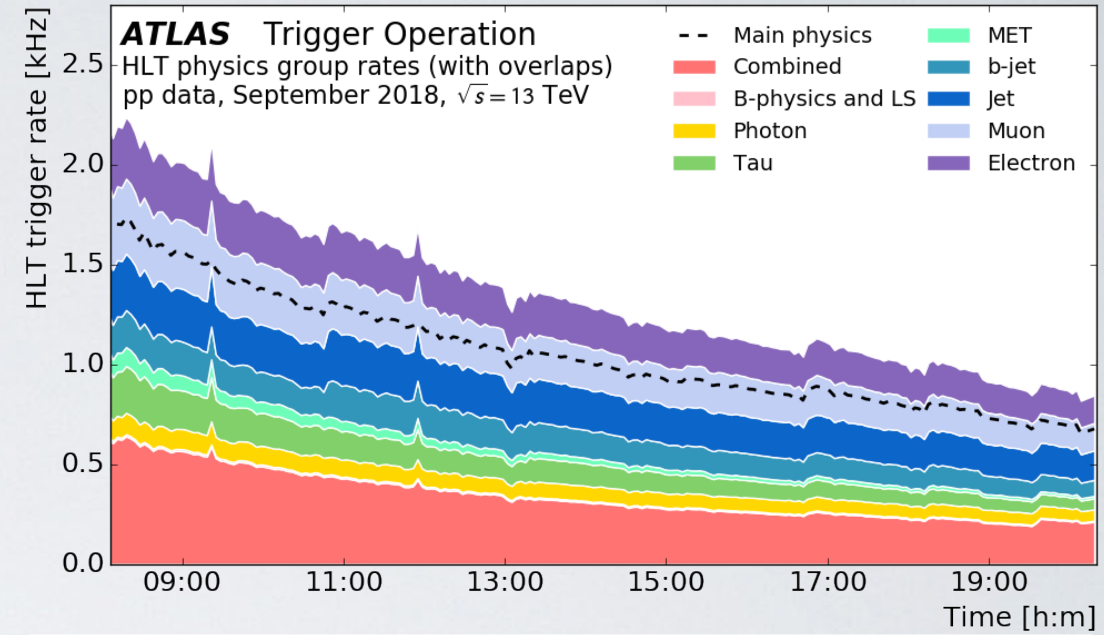
on behalf of the ATLAS Collaboration

TRIGGERING ON MUONS AT ATLAS

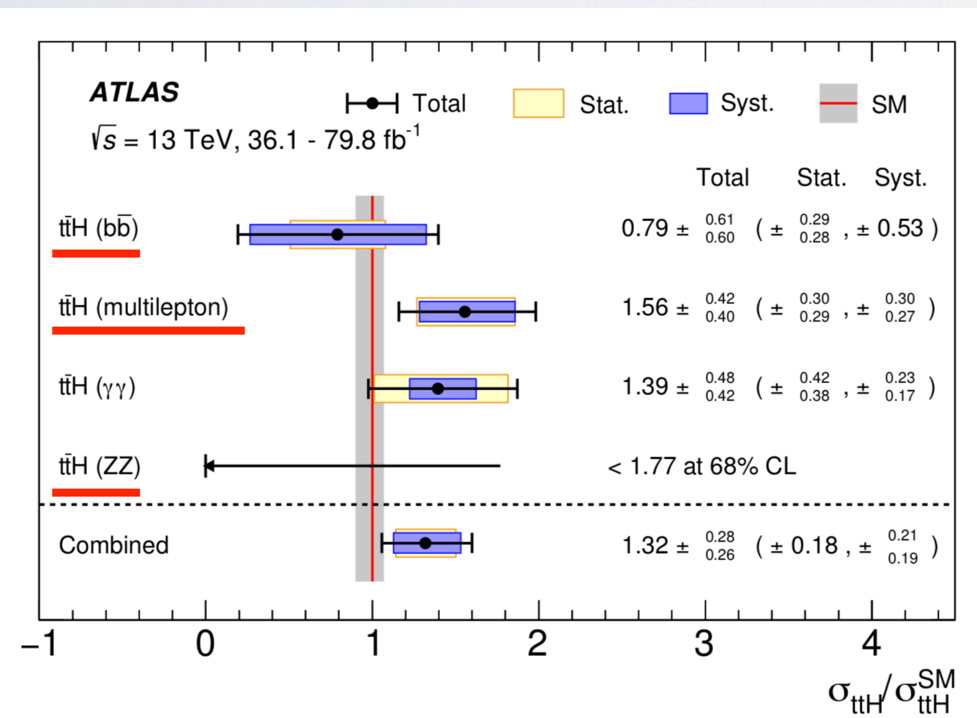
- The **muon trigger** is one of the ATLAS trigger systems
- Complex design and continuous improvements
  - Handle high luminosity and pile-up conditions to
    - Balance trigger rate and efficiencies
    - Provide high quality muon events over a large p_T spectrum



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults#Trigger_rates_and_bandwidth

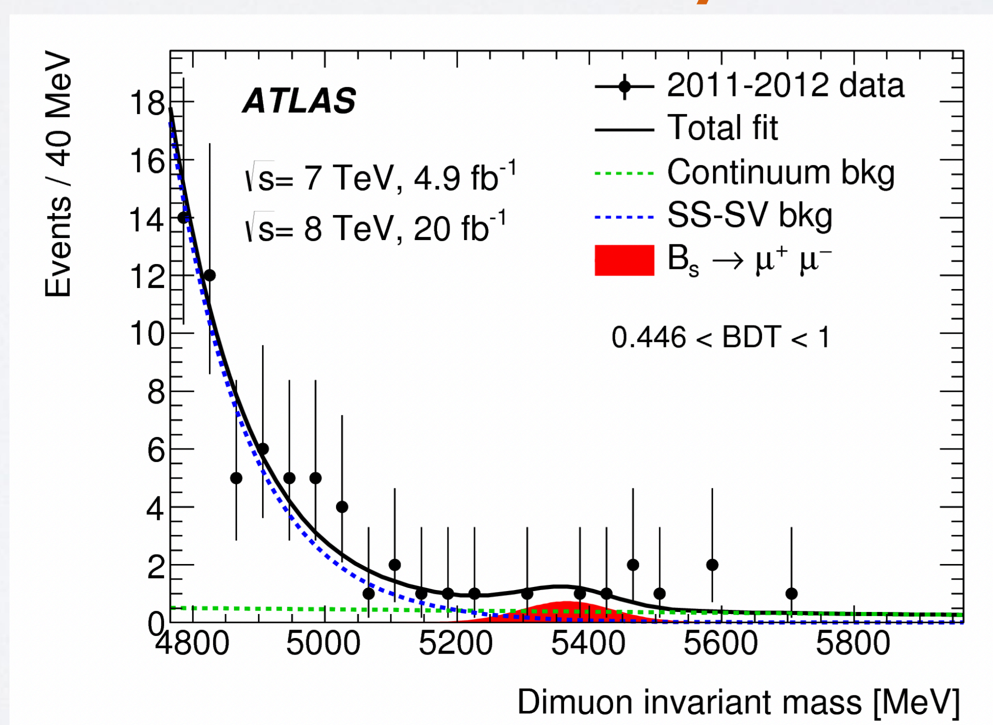
- Events containing muons in the final state are an important signature for many analyses being carried out at the Large Hadron Collider (LHC), including both standard model measurements and new physics searches
- Muon trigger system is a crucial ingredient to the ATLAS physics program; some examples:

ttH observation



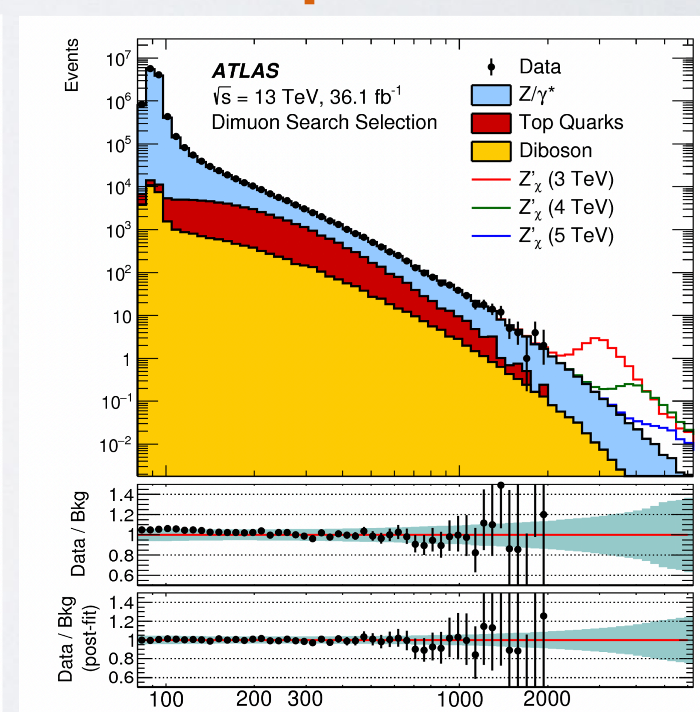
arXiv:1806.00425

Rare B decays



arXiv:1604.04263

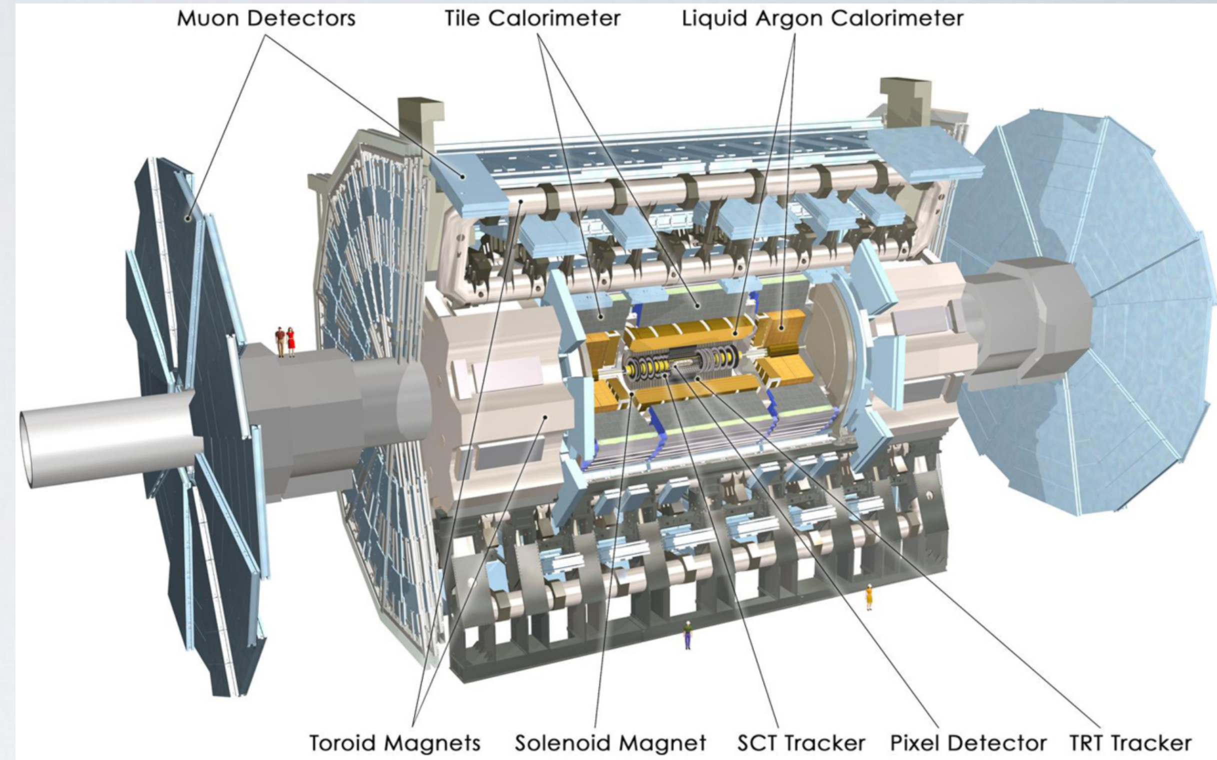
New phenomena

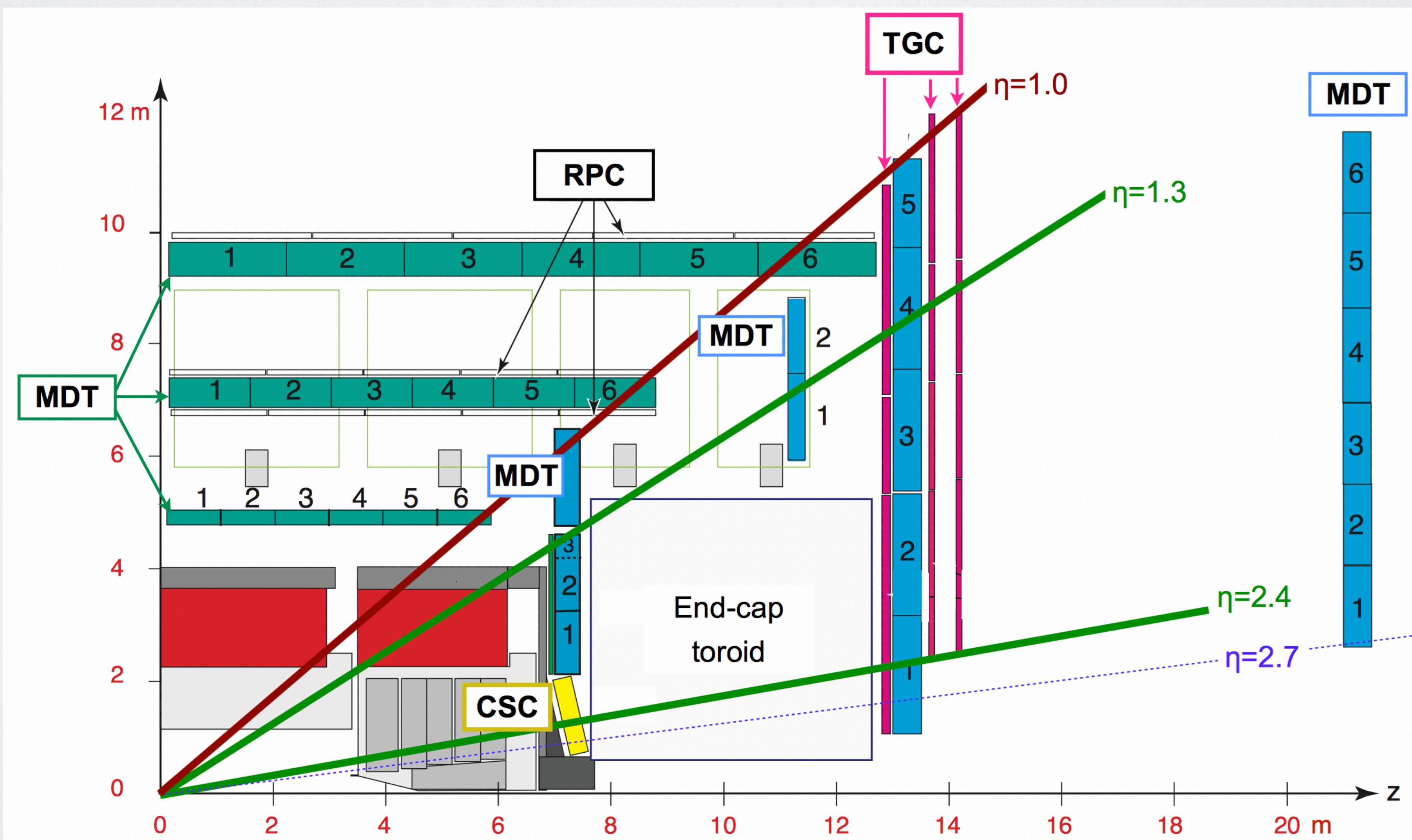


arxiv:1707.02424

ATLAS MUON SPECTROMETER

- Four different sub-detectors in ATLAS muon spectrometer (MS)
  - **Fast read-out** for initial trigger decision
    - **RPC:** Resistive Plate Chamber
    - **TGC:** Thin Gap Chamber
  - **High resolution**, precise tracking:
    - **MDT:** Monitored Drift Tube
    - **CSC:** Cathode Strip Chamber
- **Toroidal magnets** provide average magnetic field of 0.5 T



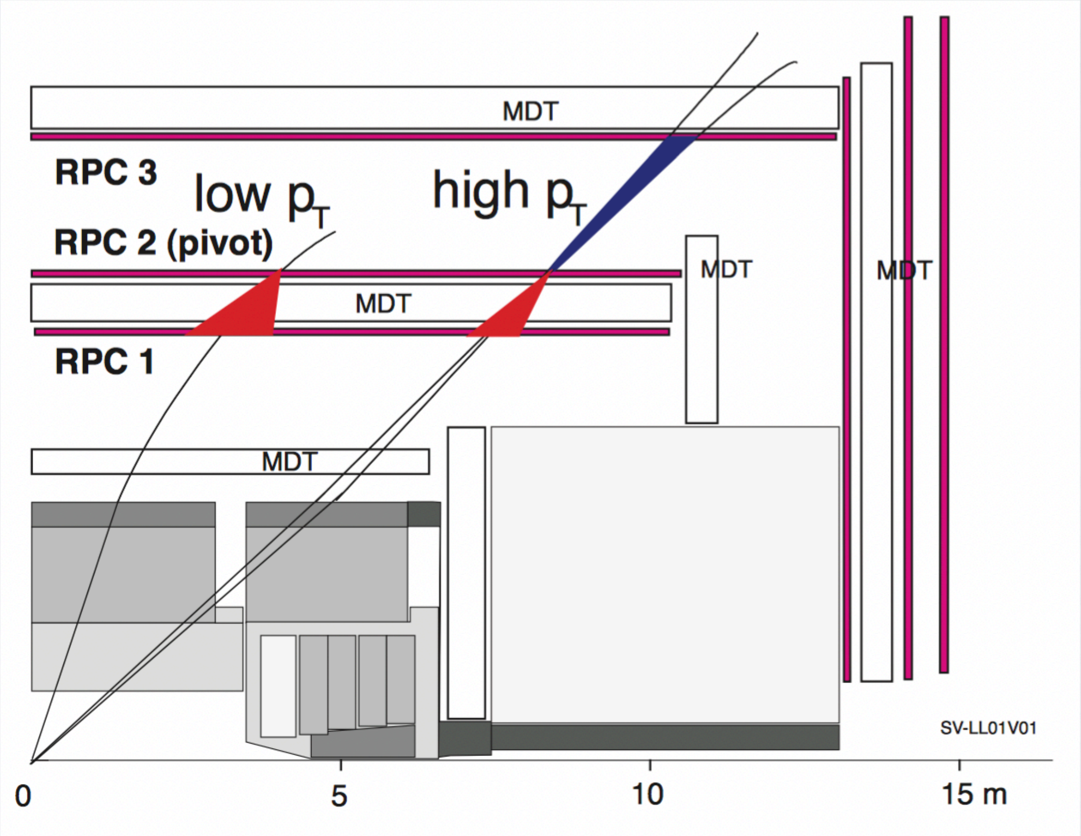


MUON TRIGGER SYSTEM

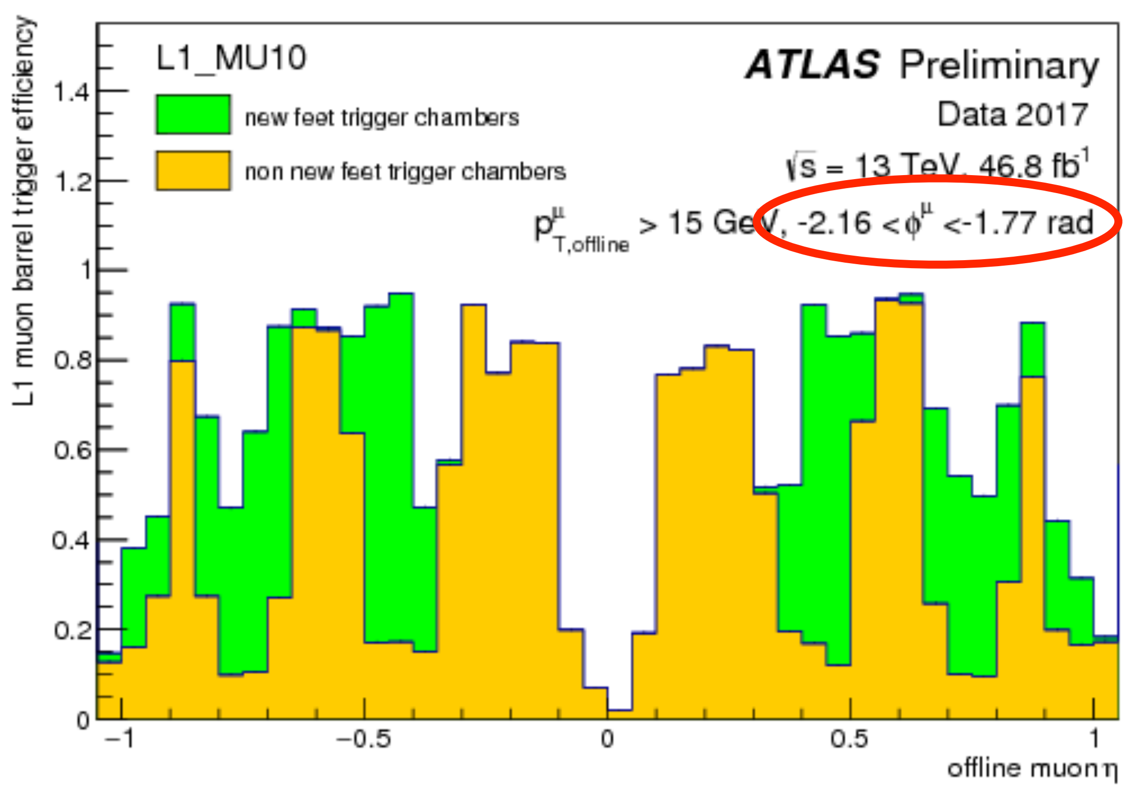
- Two stage approach
- **Level-1 muon trigger (L1)**
  - **Fast** and **coarse, hardware-based** system
  - Requiring coincidence of hits in **RPCs** or **TGCs**
  - p_T estimate by comparison to expected track of muon with infinite p_T
  - Finds **Regions of Interest (RoI)** for further processing
    - RoI size: $\eta \times \phi = 0.1 \times 0.1$ (0.03×0.03) in barrel (endcap)
  - Coverage: 99% in endcaps, 80% in barrel (limited by detector geometry)
  - Latency: 2.5 μs
- **High Level Trigger (HLT)**
  - **Software-based system**
    - Reduces data amount needing to be transferred and processed
  - Starts from RoI defined at L1
  - **Fast reconstruction** step, followed by **precision reconstruction** in $\eta \times \phi = 0.2 \times 0.2$ regions
  - Close to 100% trigger efficiency with respect to L1

L1 MUON BARREL TRIGGER

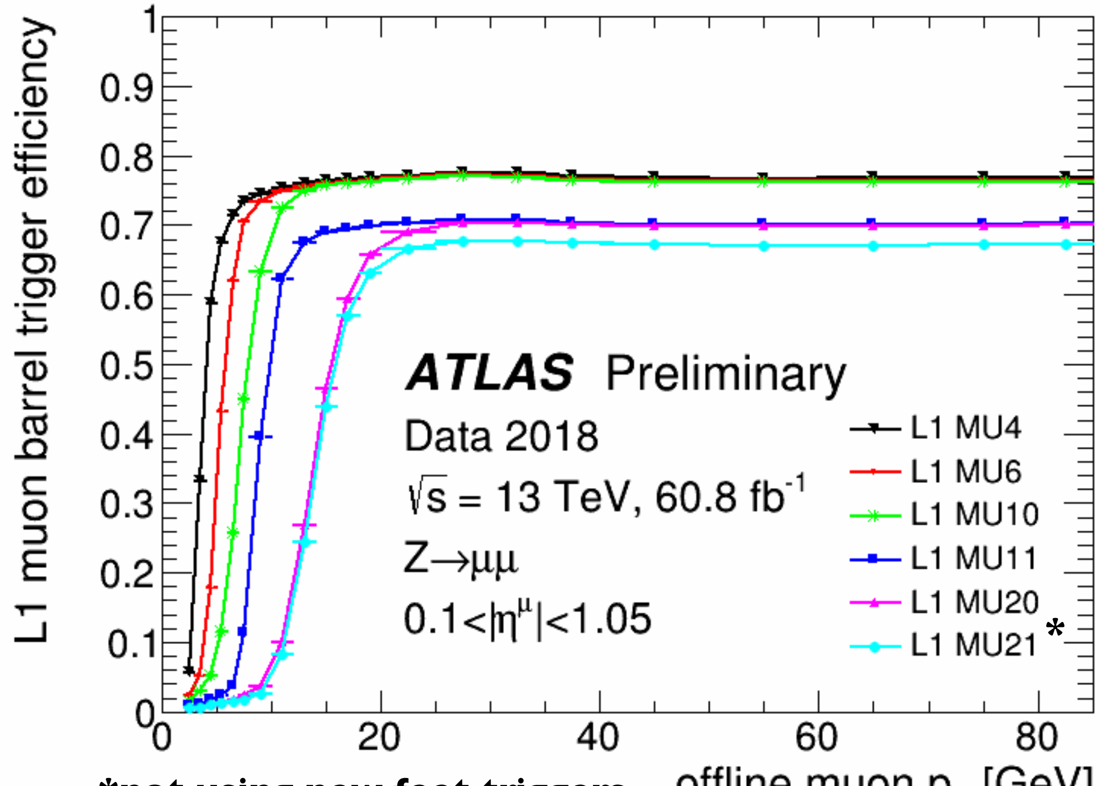
- RPC coincidence requirement depending on p_T
  - low-p_T thresholds between 4 and 10 GeV (multi-object signatures)
  - high-p_T thresholds between 11 and 20 GeV (single muon signatures)



- **Upgrade in Run-2**
  - RPCs in barrel support structures increased trigger acceptance by ~4%



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1MuonTriggerPublicResults#Performance_plots_for_Level1_Bar

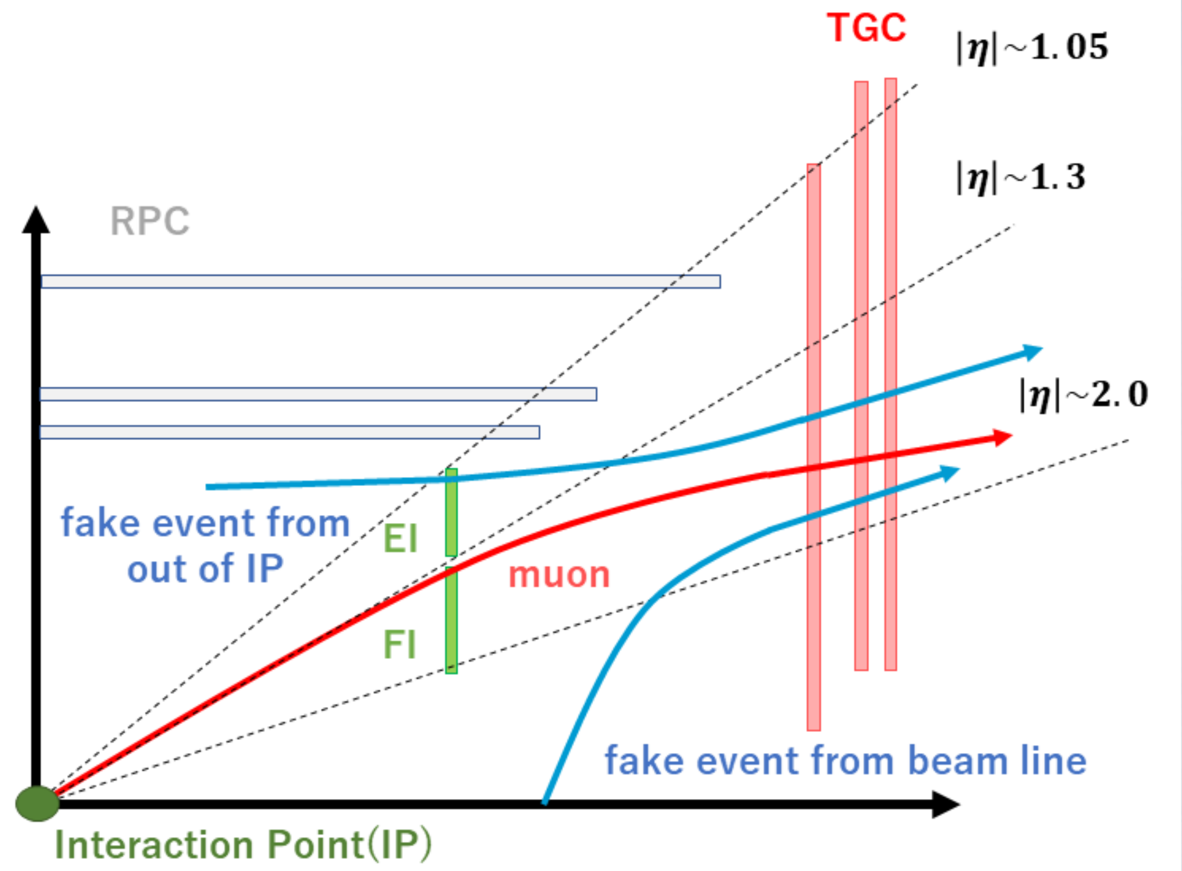


*not using new feet triggers

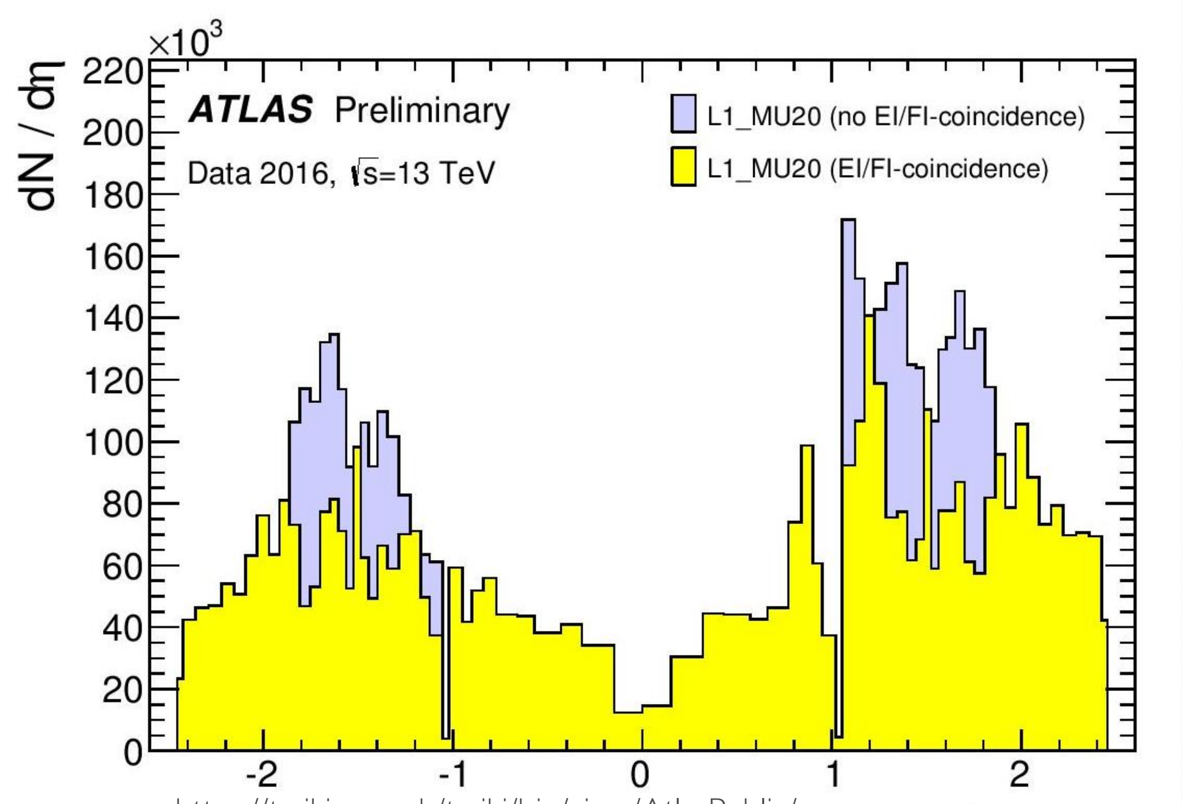
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1MuonTriggerPublicResults#Level_1_muon_barrel_trigger_perf

L1 MUON ENDCAP TRIGGER

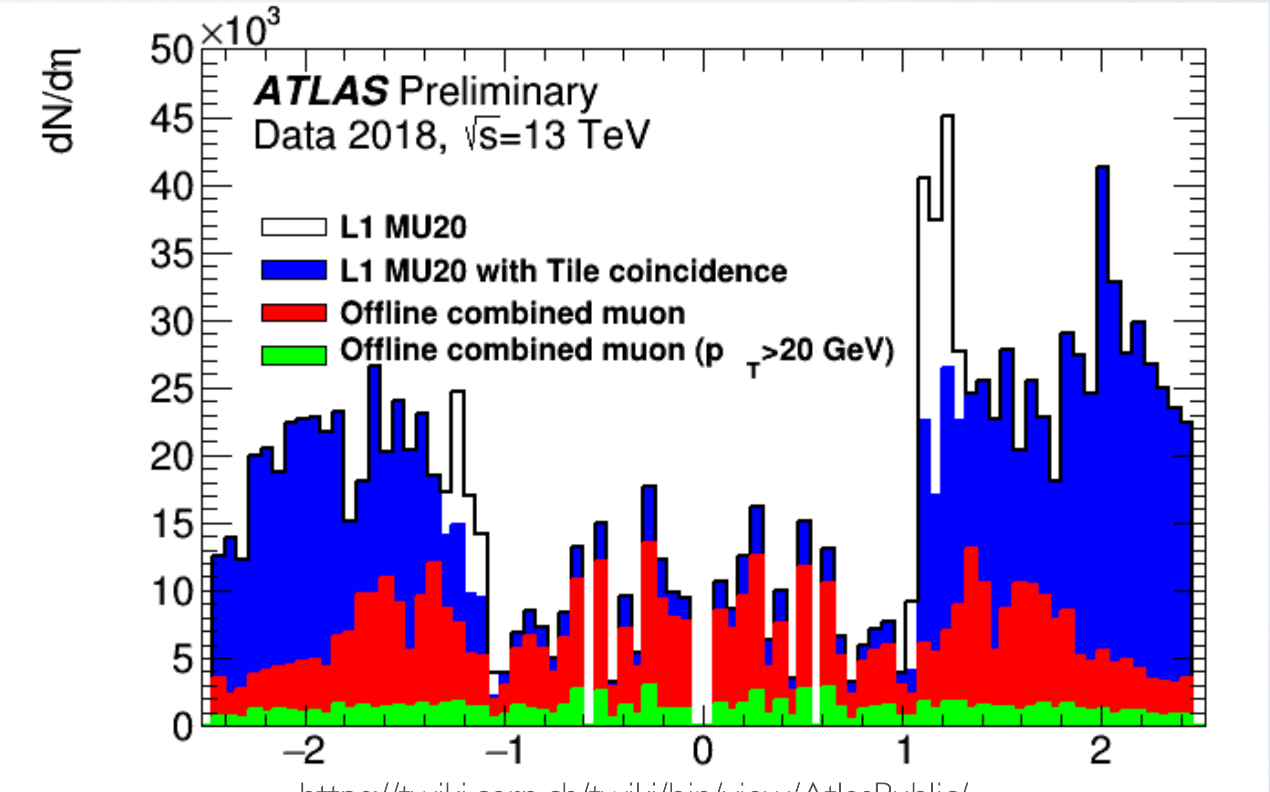
- TGC coincidence requirement depending on p_T
- L1 trigger rates in forward region dominated by low-p_T background protons



- **Upgrades in Run-2**
  - Coincidences with FI and EI TGC inner muon chambers placed before the toroid magnet are used to discard muon fake candidates
    - ~20% rate reduction for L1 muon candidates with $p_T > 20\text{GeV}$, $1.05 < |\eta| < 2.0$ and efficiency loss below 1%
  - Further reduction enabling the new TGC coincidence with extended barrel region of the Tile Calorimeter
    - ~6% rate reduction for L1 muon candidates with $p_T > 20\text{GeV}$

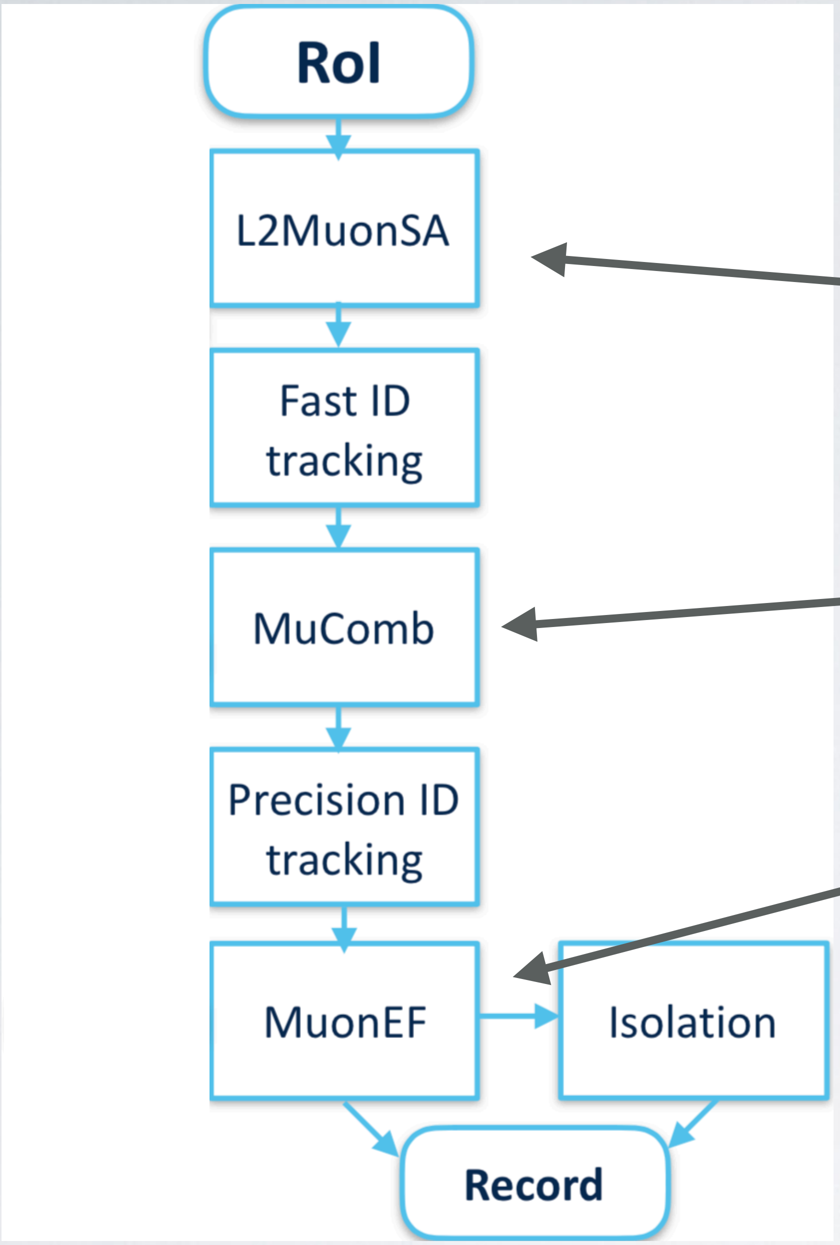


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MuonTriggerPublicResults#Rate_reduction_by_2016_EI_FI_coi



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1MuonTriggerPublicResults#Performance_plots_of_the_Tile_Mu

MUON HLT TRIGGER

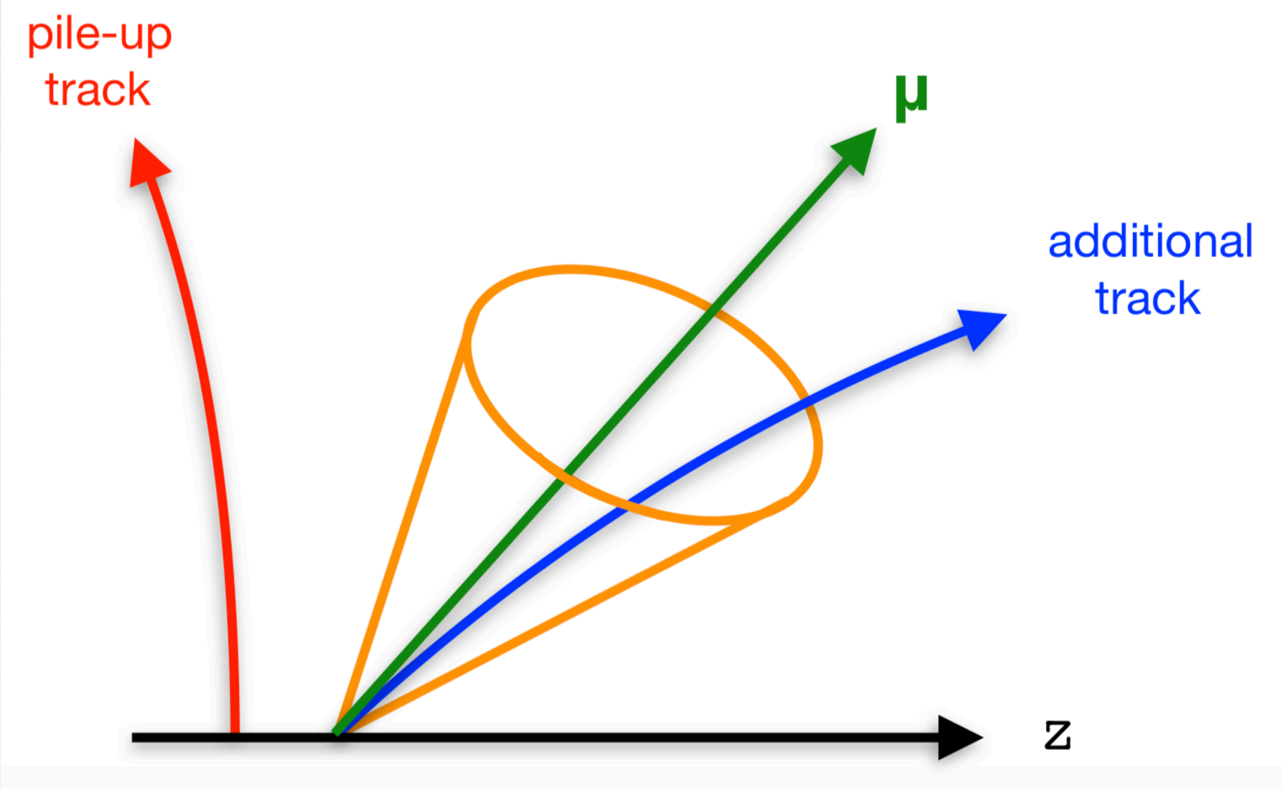


- **Start with RoI defined at L1**
- **Fast reconstruction** of tracks in MS only
  - p_T measurement with look-up tables
- **Combined fit of MS and inner detector (ID) tracks**
- **High resolution reconstruction**
  - Starting outside-in: MS → ID
  - Inside-out recovers low-p_T inefficiencies
- Optional: other requirements like **isolation**

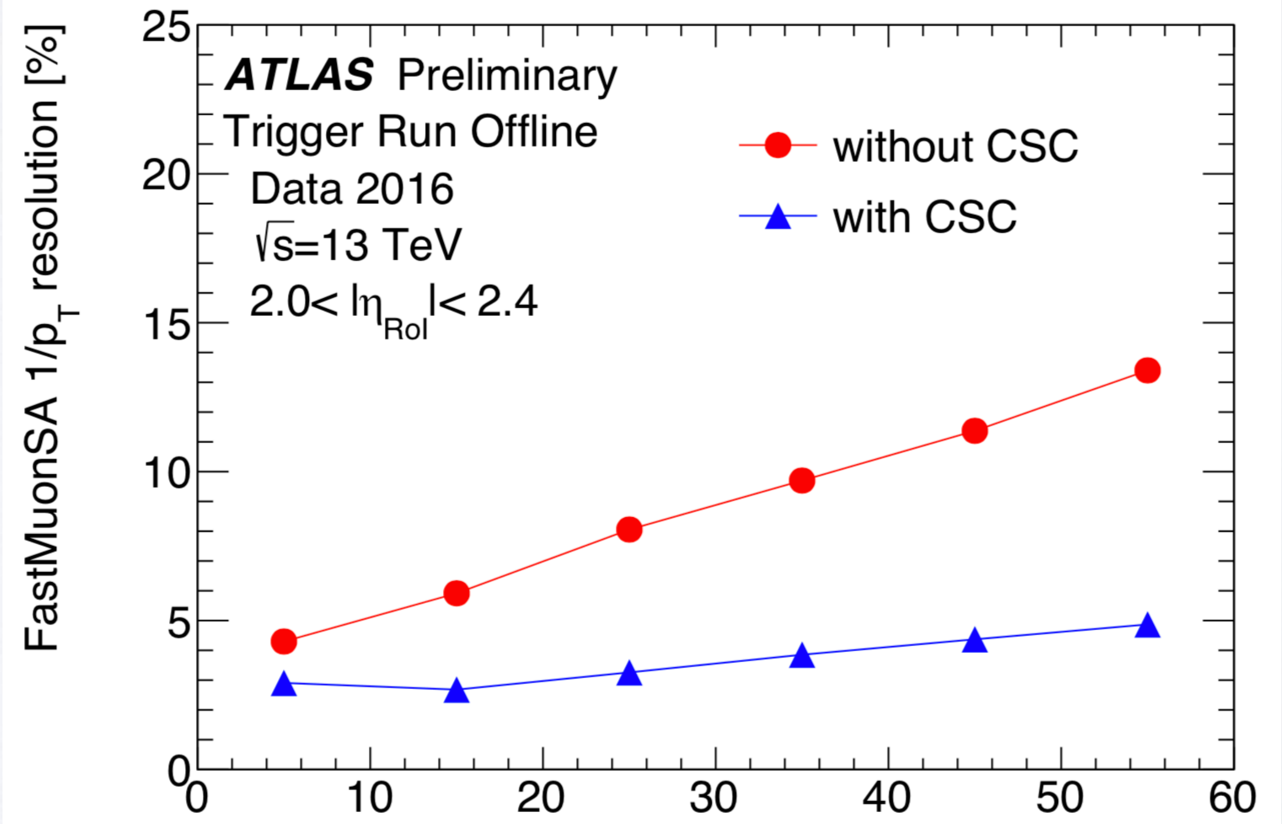
- **High resolution muon reconstruction can be also run over the whole detector in full scan mode (FS)**
  - RoI building around MS tracks
  - ID track reconstruction
  - Outside-in muon building
- **High trigger efficiency thanks to recovery of L1 inefficiency**
- **CPU expensive → multi-muons: one leg with a muon reconstructed in an ROI and the other leg in FS**

IMPROVEMENTS AT HLT DURING RUN-2

- **Isolation**
  - Isolation requirements at trigger level allow lower muon p_T threshold and reasonable trigger rate - crucial for many physics analyses
    - Define p_T-dependent isolation cone around muon candidate
    - Cut on scalar sum of track p_T in cone around muon candidate
  - dz (distance between muon track and other track) cut tightened from 6 mm to 2 mm in 2018 to deal with efficiency loss observed in 2017 high pileup conditions (small rate increase)



- **p_T resolution**
  - CSC hits included in fast algorithms to improve p_T resolution



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MuonTriggerPublicResults#L2MuonSA_Endcap_pT_Resolution_Im

MUON TRIGGERS IN RUN-2

- **Various combinations of muon triggers**
  - Single-μ, multi-μ
  - Muon + lepton (e, τ) or + jets
  - Muon + γ
  - B-physics selection (e.g. di-μ invariant mass)
  - Specialized triggers for specific analyses (e.g. long-lived particles)
- More in Ligang's talk

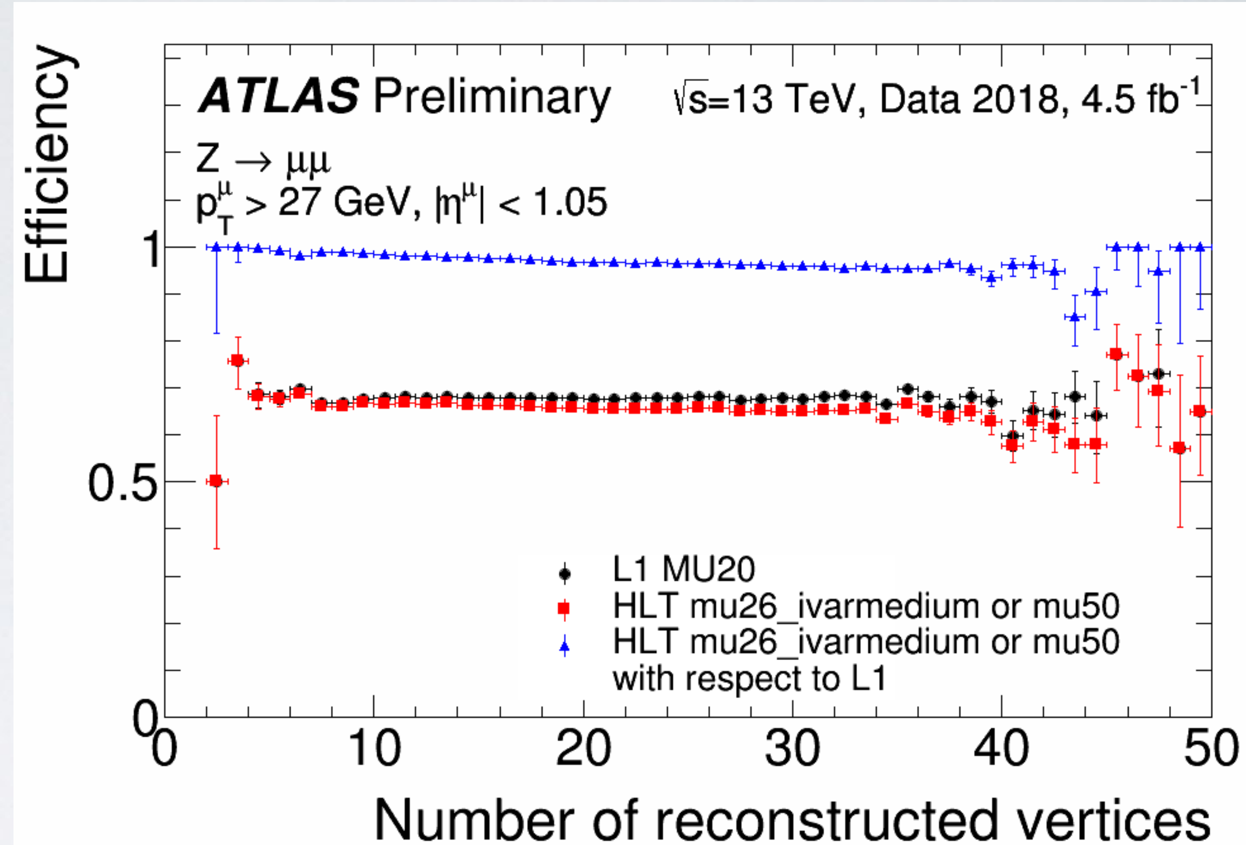
Trigger examples:	Level-1 p_T threshold [GeV]	HLT p_T threshold [GeV]	Level-1 rate [kHz]	HLT rate [Hz]
Single isolated muon	20	26	15	180
Single muon	20	50	15	61
Two muons	10, 10	14, 14	1.8	26
Two muons	20	22, 8 (FS)	15	42
Three muons	6, 6, 6	6, 6, 6	0.2	6

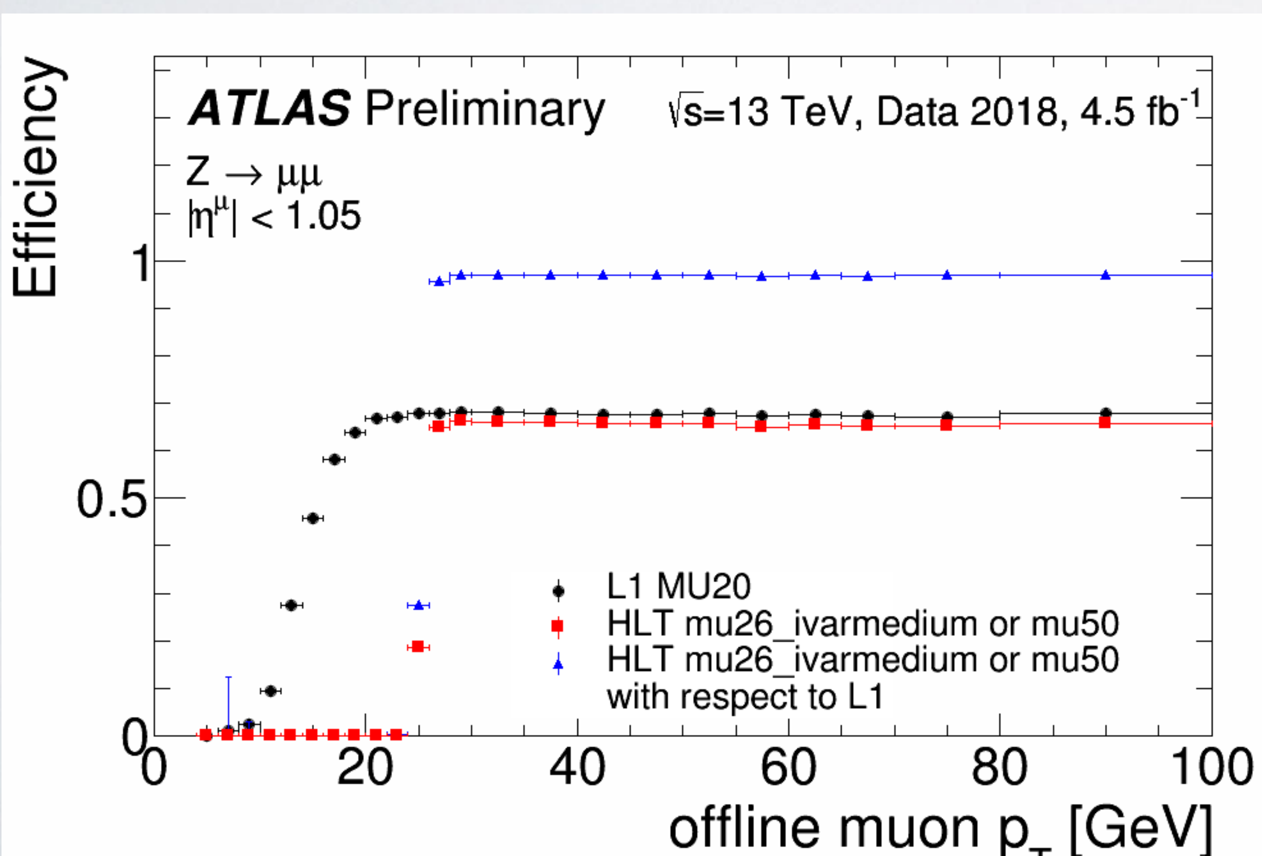
ATL-DAQ-PUB-2018-002

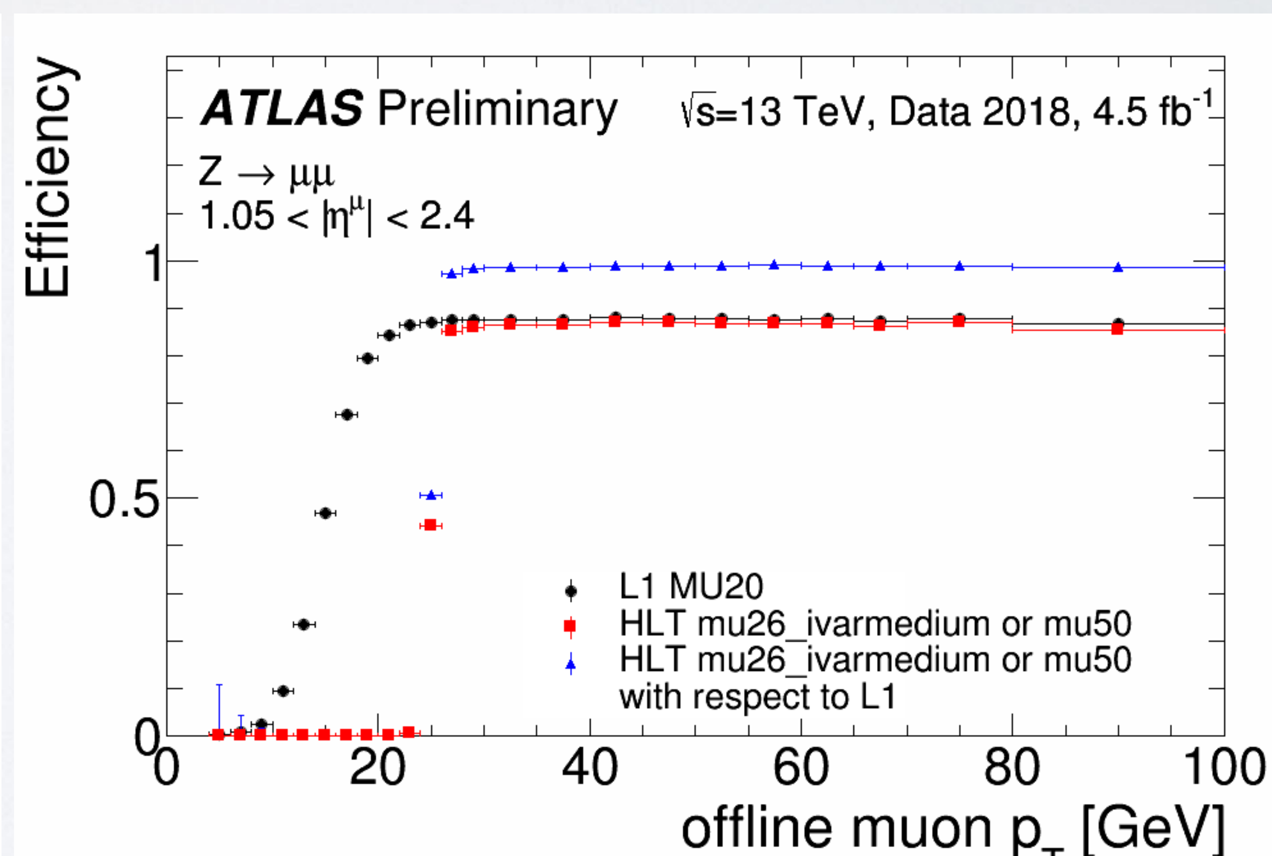
rates @ L=1.7 x 10^{34} cm^{-2} s^{-1}

TRIGGER EFFICIENCIES

- Trigger efficiency is measured exploiting di-muon $Z\rightarrow\mu\mu$ (J/Ψ for low p_T muons) events in a "**tag & probe**" method
- Efficiency losses mainly coming from L1
  - Limited by hit efficiency and geometric coverage
- HLT relative to Level-1 almost 100% efficient
  - reduces rate by factor 100
- Trigger efficiency is quite stable with respect to pile-up
- Sharp turn-on in p_T dependence for HLT
- Higher efficiencies in endcap (99% coverage) than in barrel (80% coverage)



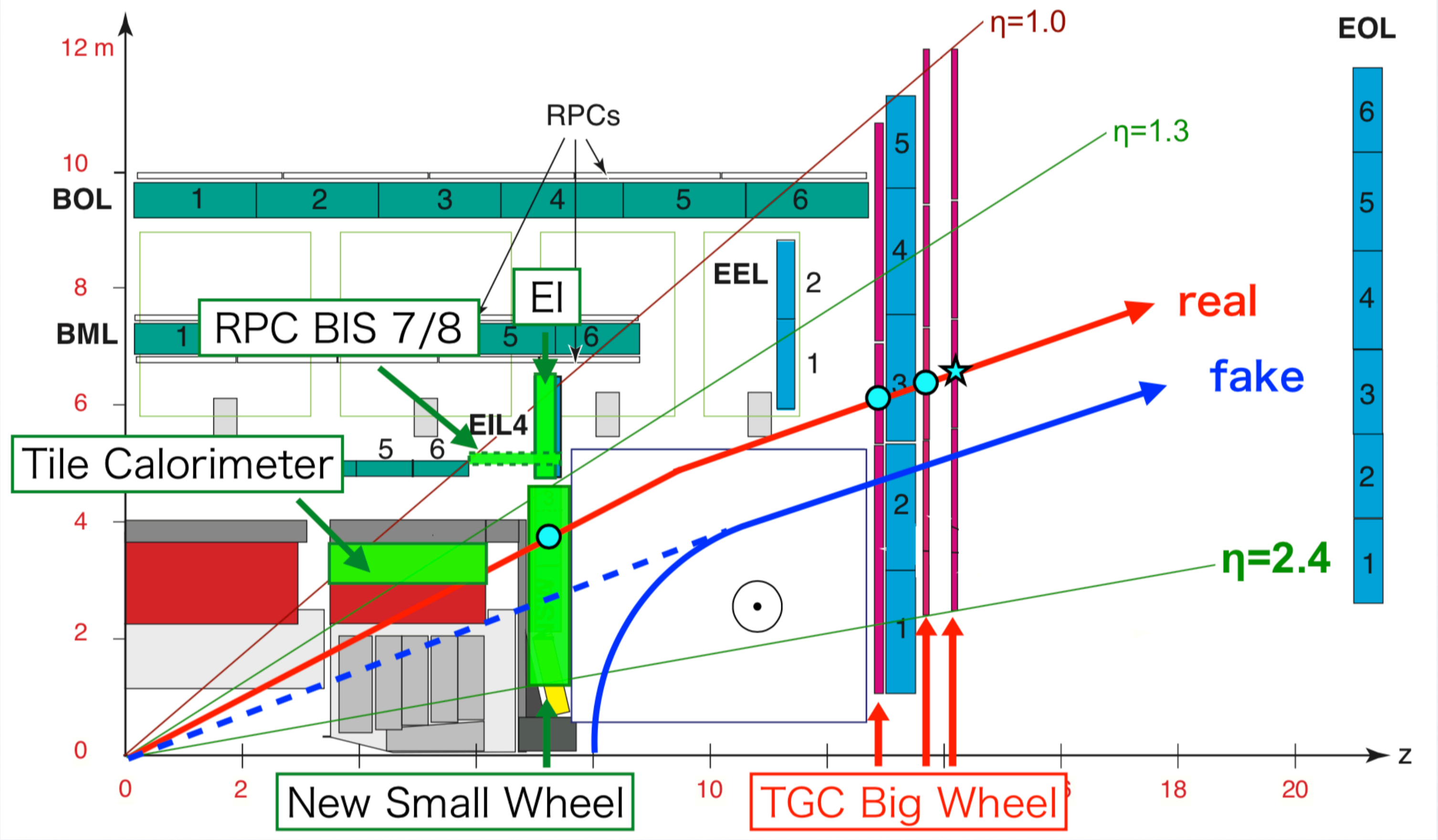




https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MuonTriggerPublicResults#Muon_trigger_performances_in_201

OUTLOOK FOR RUN-3

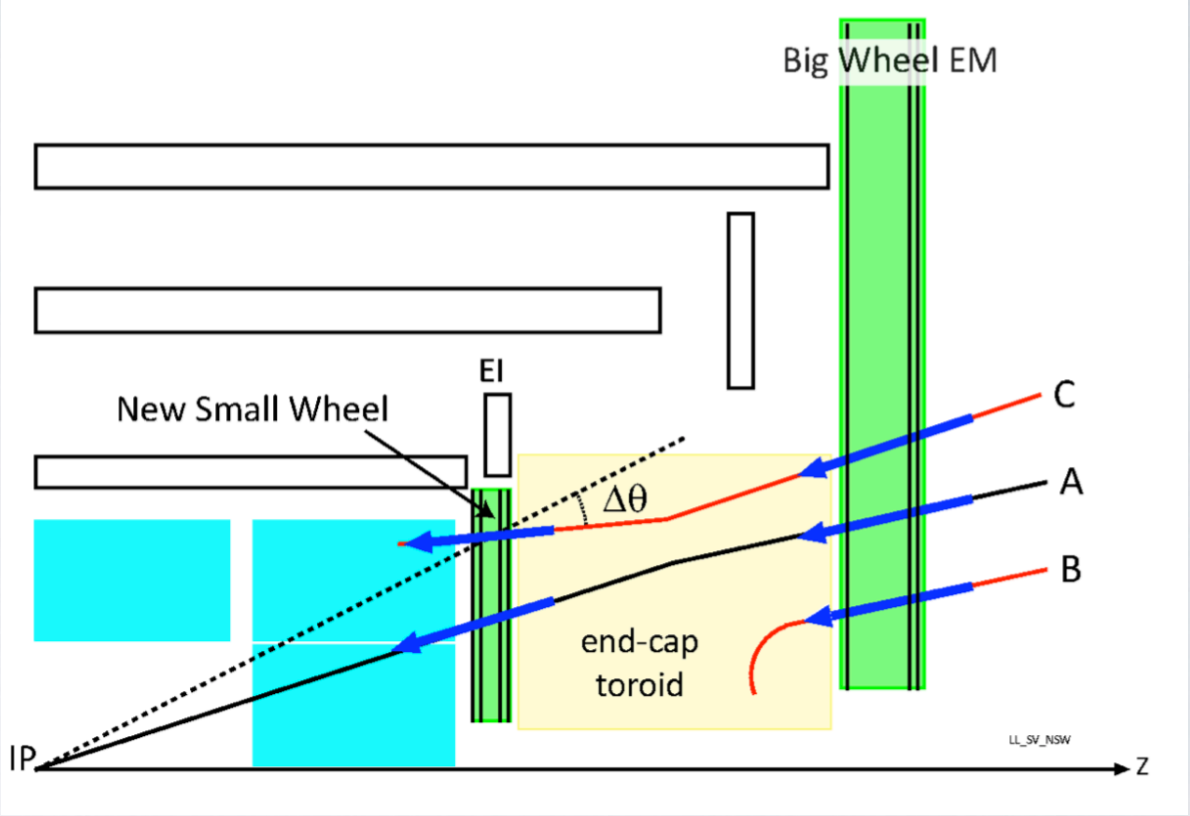
- LHC Run-3: 2021~ 2023
  - luminosity up to 3.0 × 10^{34} $cm^{-2}s^{-1}$; +50 % compared to Run-2 luminosity
- With current trigger algorithm, rate for muon trigger with p_T > 20 GeV would be 30 kHz @ 3.0 × 10^{34} $cm^{-2}s^{-1}$
  - Run-3 requirement at this luminosity is 15 kHz → **More powerful trigger strategy** is needed to reduce the trigger rate, while keeping same Run-2 trigger threshold and the efficiency
- **Exploit new detectors available for Run-3**
  - **sMDT chambers** and **thin-gap RPCs** cover gaps in barrel-endcap transition region to increase efficiency
  - **sTGCs** and **MicroMegas** provide the **New Small Wheel** ($1.3 < \eta < 2.4$)

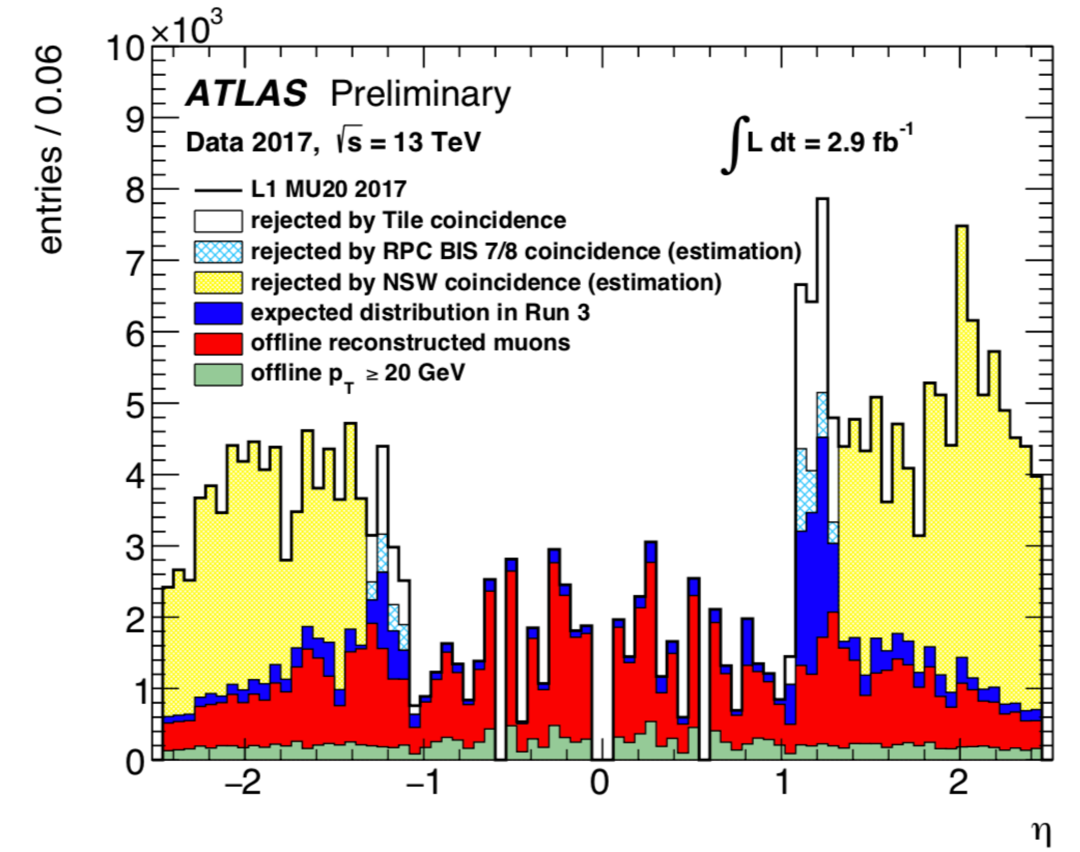


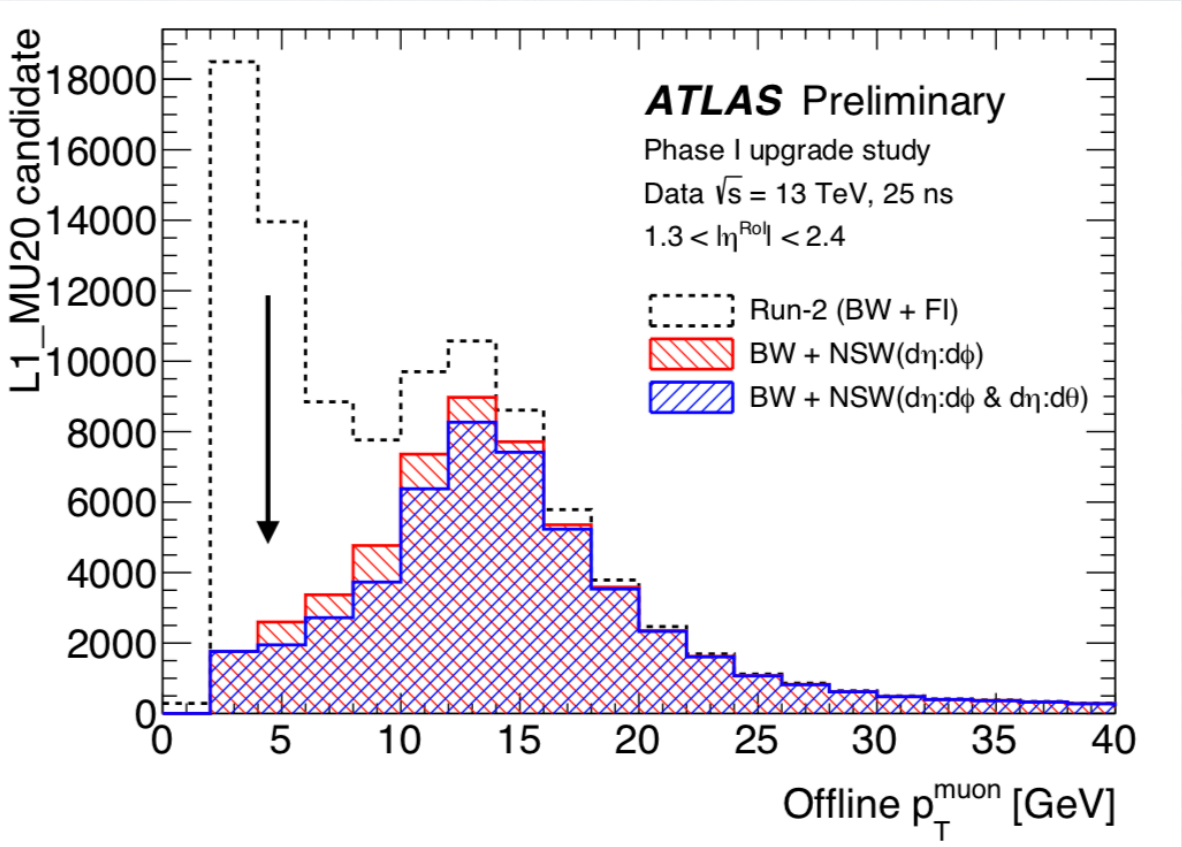
- Strategy: reduce fake muon triggers and low p_T triggers in the $|\eta|>1$ region by requiring **additional coincidence** of the big wheel with NSW

RUN-3 EXPECTED TRIGGER PERFORMANCE

- Muon NSW accepts track A, rejects tracks due to particles that don't originate from the IP (tracks B and C)
- At 3.0×10^{34} cm^{-2}s^{-1}, NSW reduces L1 muon trigger rate by ~50%, to <15 kHz
- Efficiency ~ 95% for muons with $p_T > 20$ GeV, relative to Run-2 trigger (assuming NSW segment finding efficiency 97%)







https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1MuonTriggerPublicResults#Performance_plots_for_Phase_I_up

SUMMARY

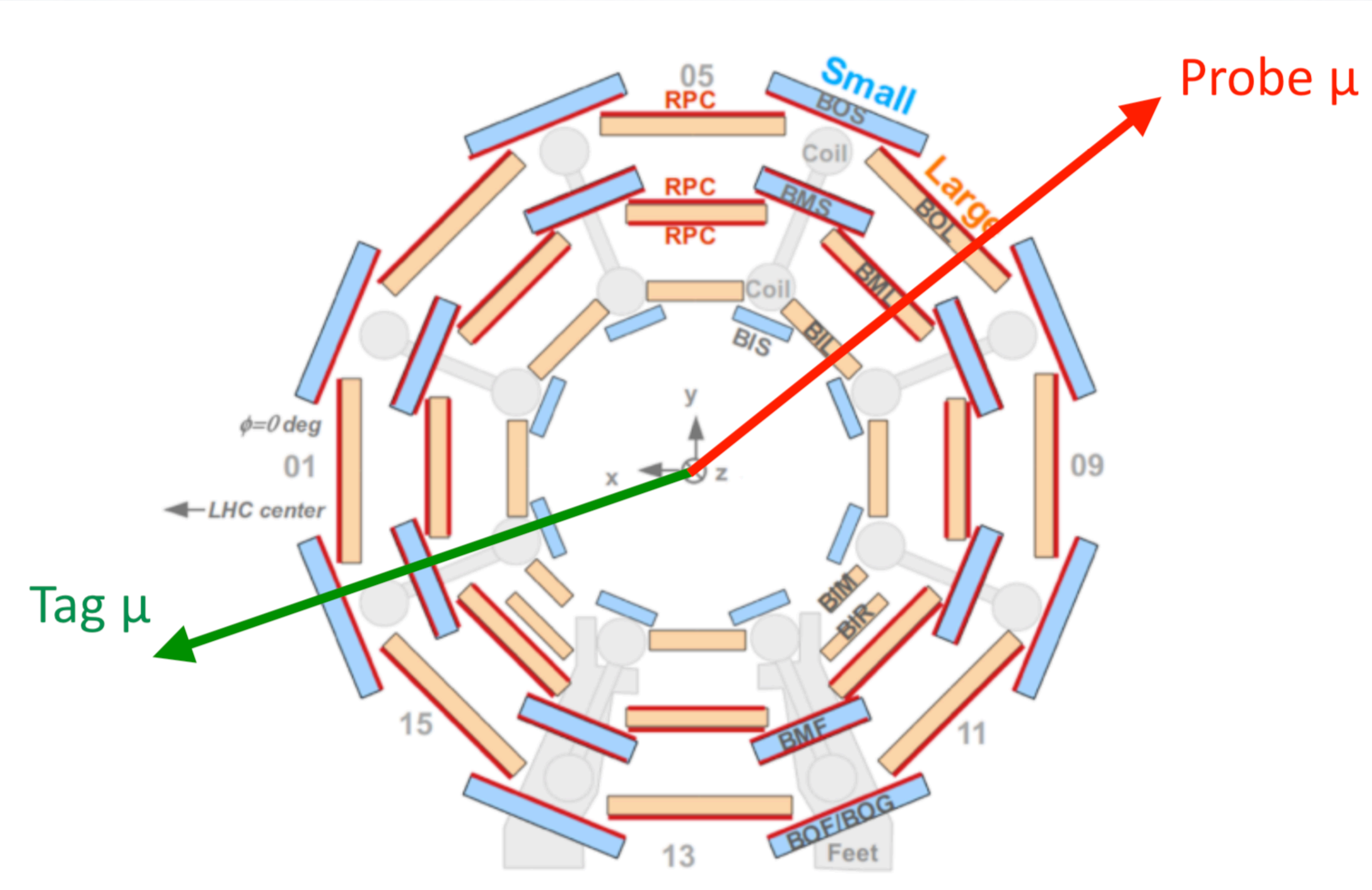
- Muon trigger important to fulfil ATLAS physics program
- Successful operations during Run-2
- Several upgrades/improvements to cope with Run-2 challenges
  - New RPC feet chambers
  - FI/EI coincidence for end-cap L1 trigger
  - Mitigation of pileup effects in muon isolation requirements
- Excellent performance of muon triggers during Run-2

- Upgrade of the muon trigger system is essential for Run-3
  - the main strategy is to take coincidence of the already existing detectors with New Small Wheel to reject fake and low p_T muons
  - migration of the HLT software to multi-threading (see Rafal's talk)

BACKUP

EFFICIENCY MEASUREMENT

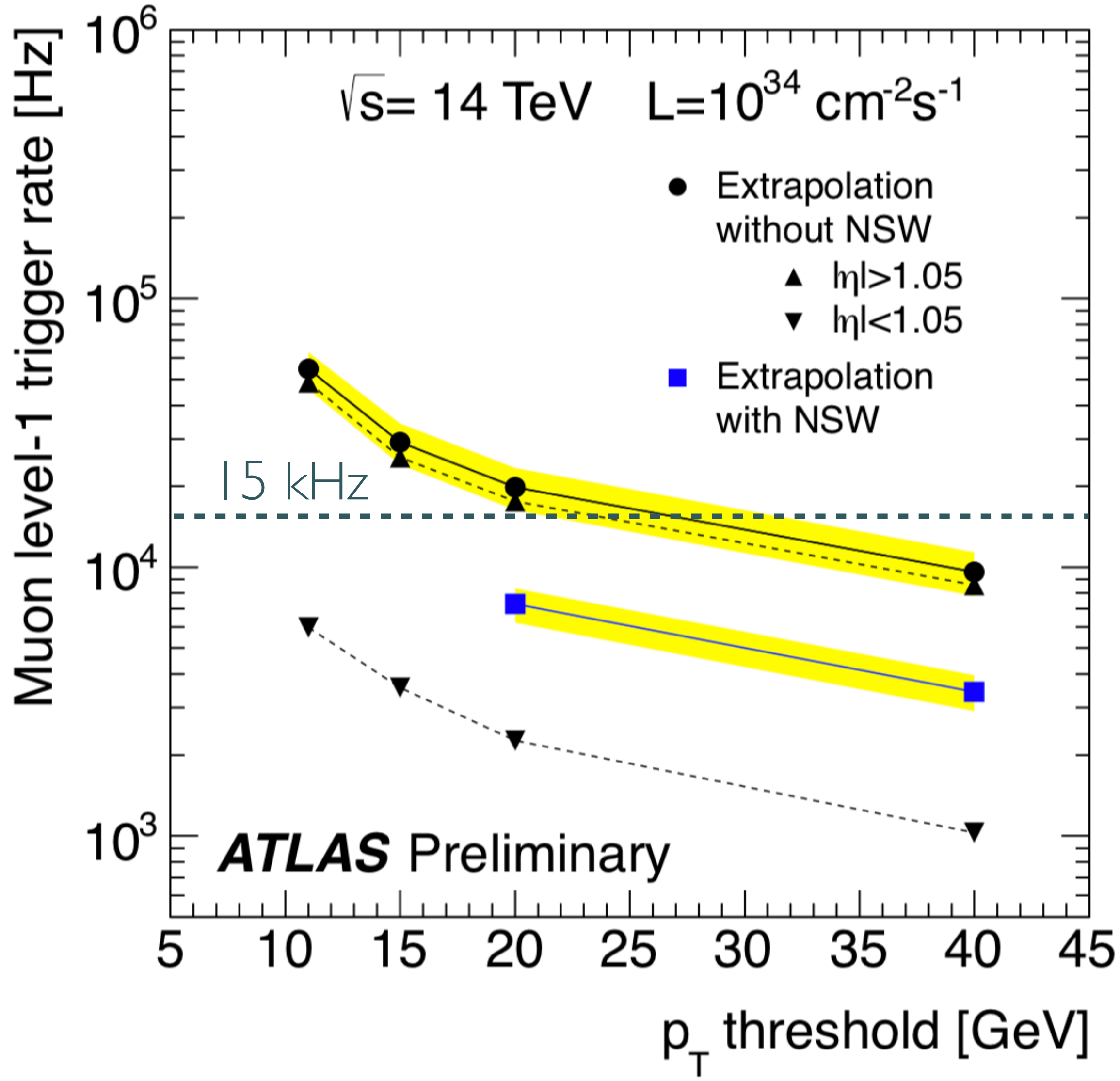
- Trigger efficiency is measured exploiting di-muon $Z\rightarrow\mu\mu$ (J/Ψ for low p_T muons) events in a "**tag & probe**" method
  - Select events by triggering on tag muon
  - Count how many probe muons are also triggered on
  - **Trigger efficiency**: fraction of probe muons identified by muon trigger
    - w.r.t several quantities(p_T, η, ϕ, pileup, …)



PHYSICS MOTIVATION FOR RUN-3 UPGRADE

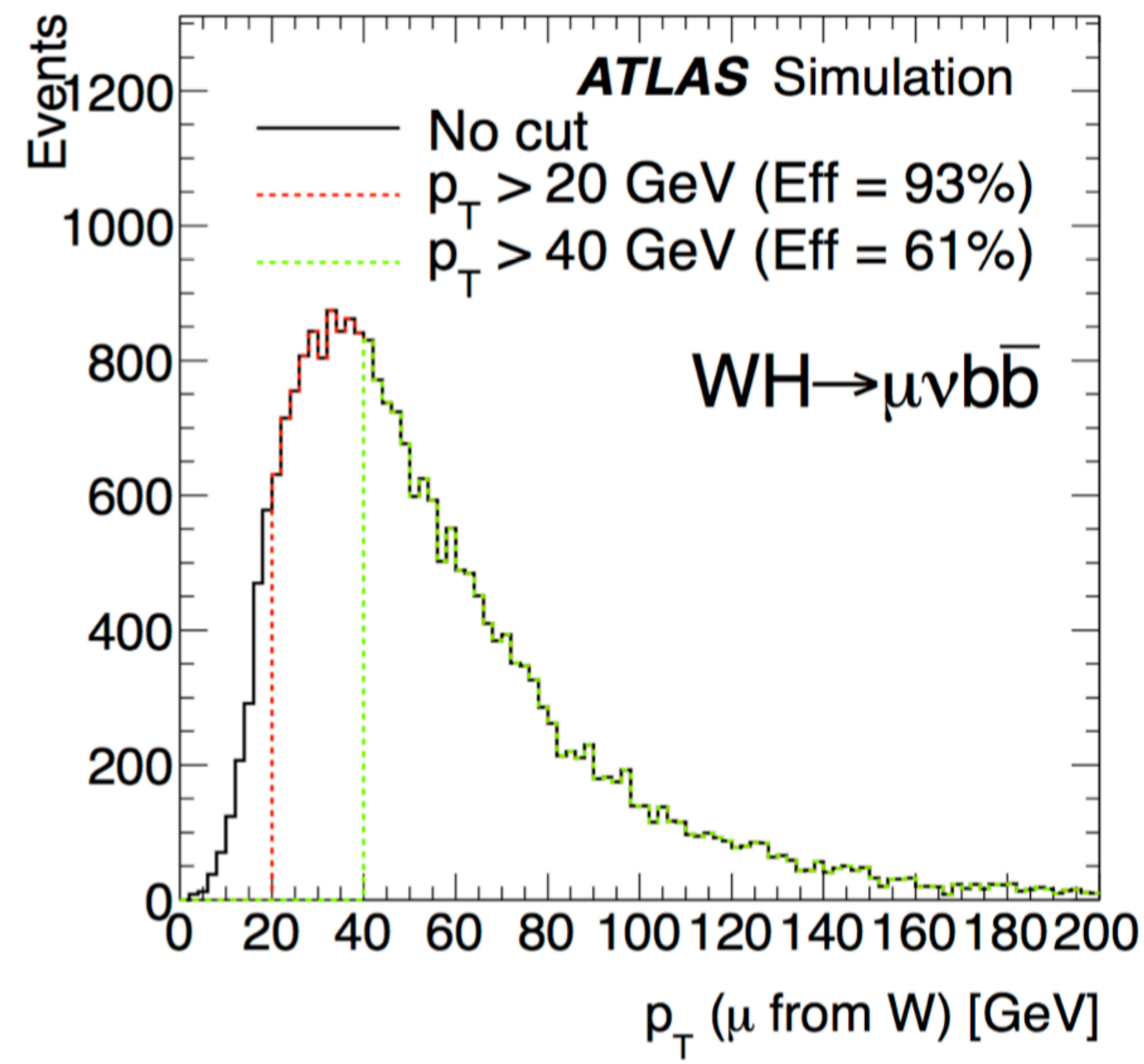
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MuonTriggerPublicResults#Plots_for_Upgrade_higher_luminos

- Run 3 trigger rate estimation



- Without the phase-1 upgrade, to keep the trigger rate to the require level, the p_T threshold will need to be raised to ~40 GeV.

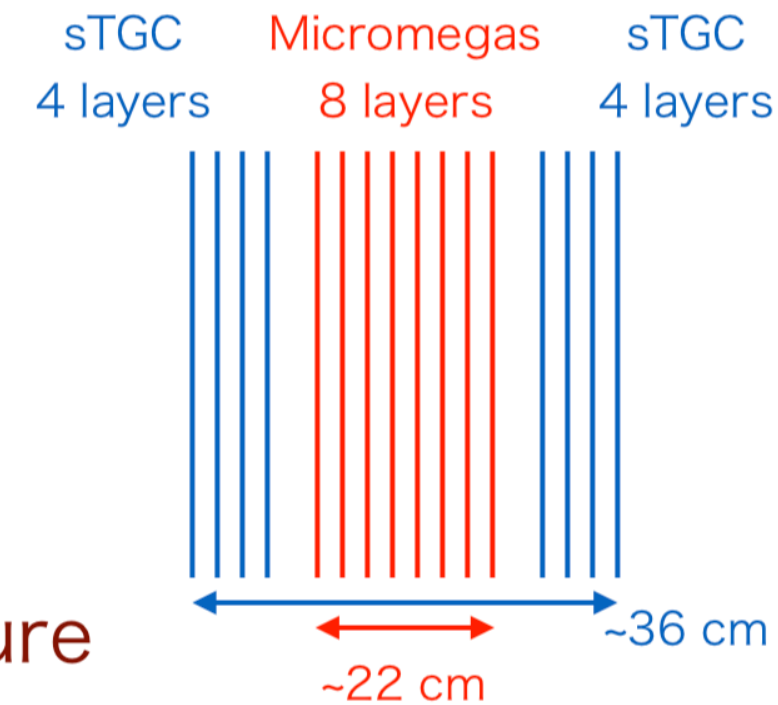
- Physics Acceptance



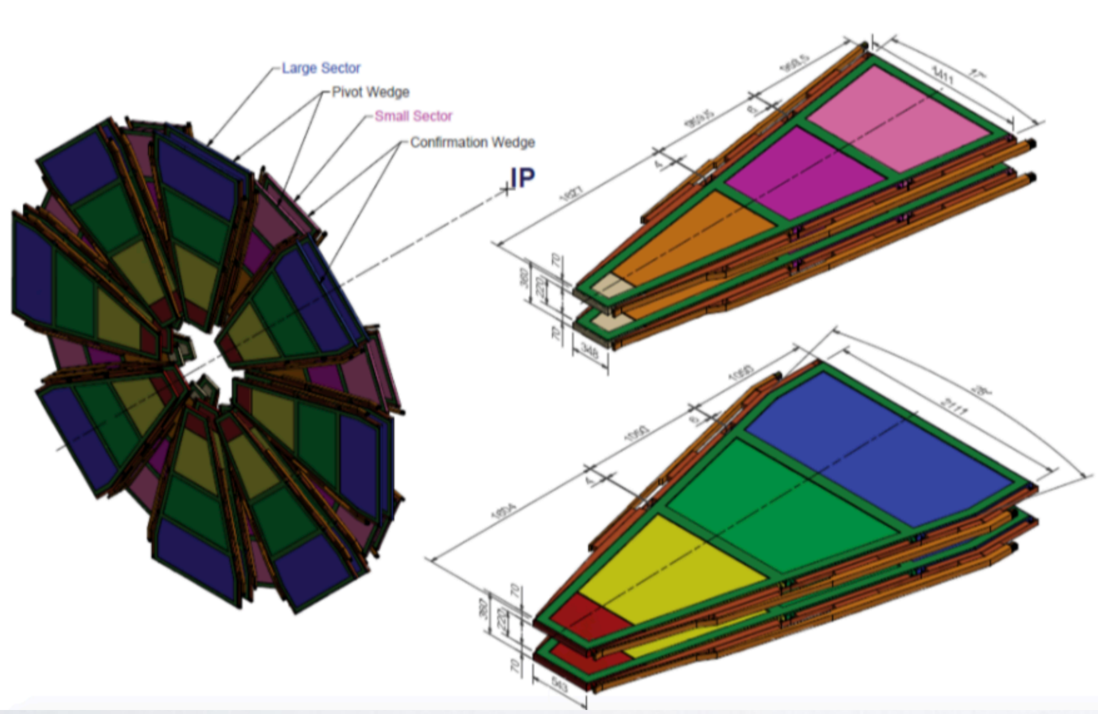
- If the threshold is raised to 40 GeV, the efficiency for muons from the decays of W boson produced in association with Higgs will be 61%.

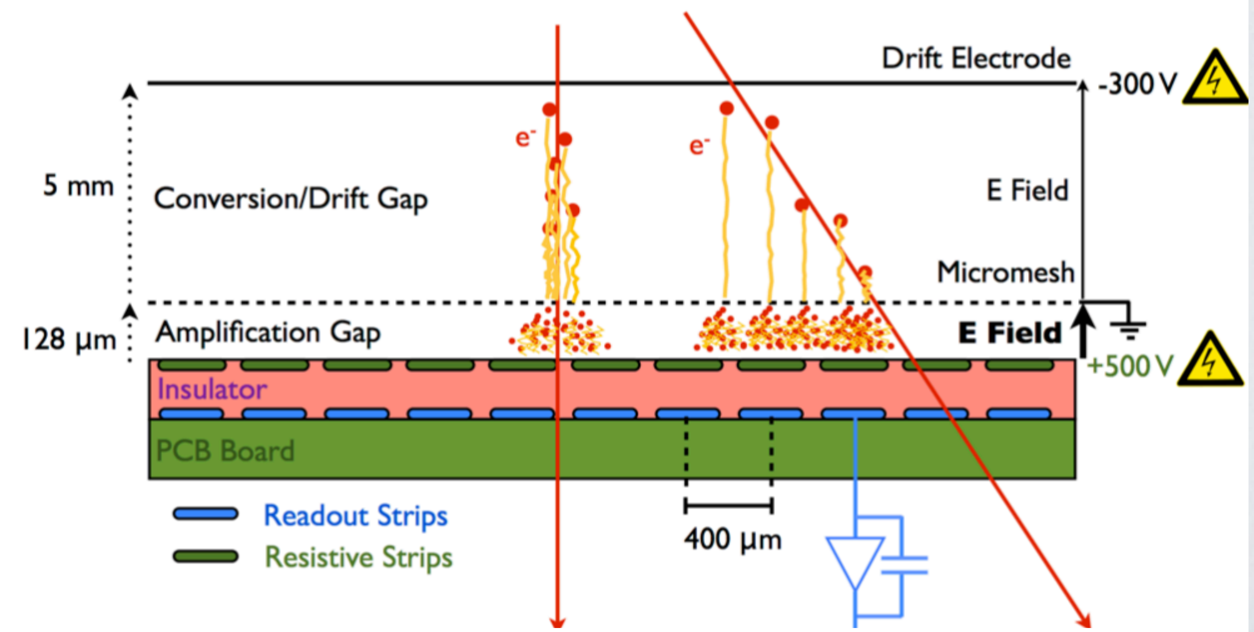
NEW SMALL WHEEL

- Consists of sTGC and Micromegas
  - sTGC: small strip TGC
    - TGC chamber with strip width of 3.2mm, smaller than the strip width of current TGC (> 15 mm)
    - 4 wire-strip pairs are combined to make 1 module.
    - position resolution 60~150 μm
  - Micromegas: micro mesh gaseous structure
    - position resolution ~90 μm
    - 8 layers are sandwiched by sTGC 4-layer modules, to compose the New Small Wheel



Resolution: position ~30 μm
angle ~0.3 mrad.





NSW Technical Design Report

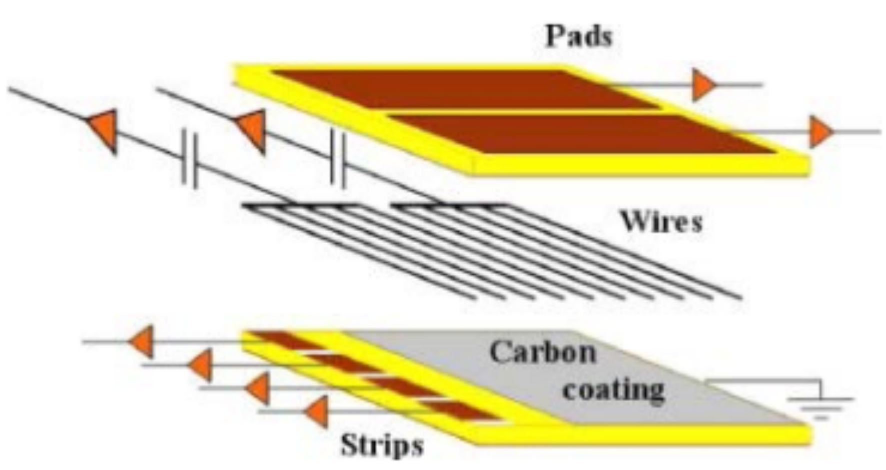
NEW SMALL WHEEL

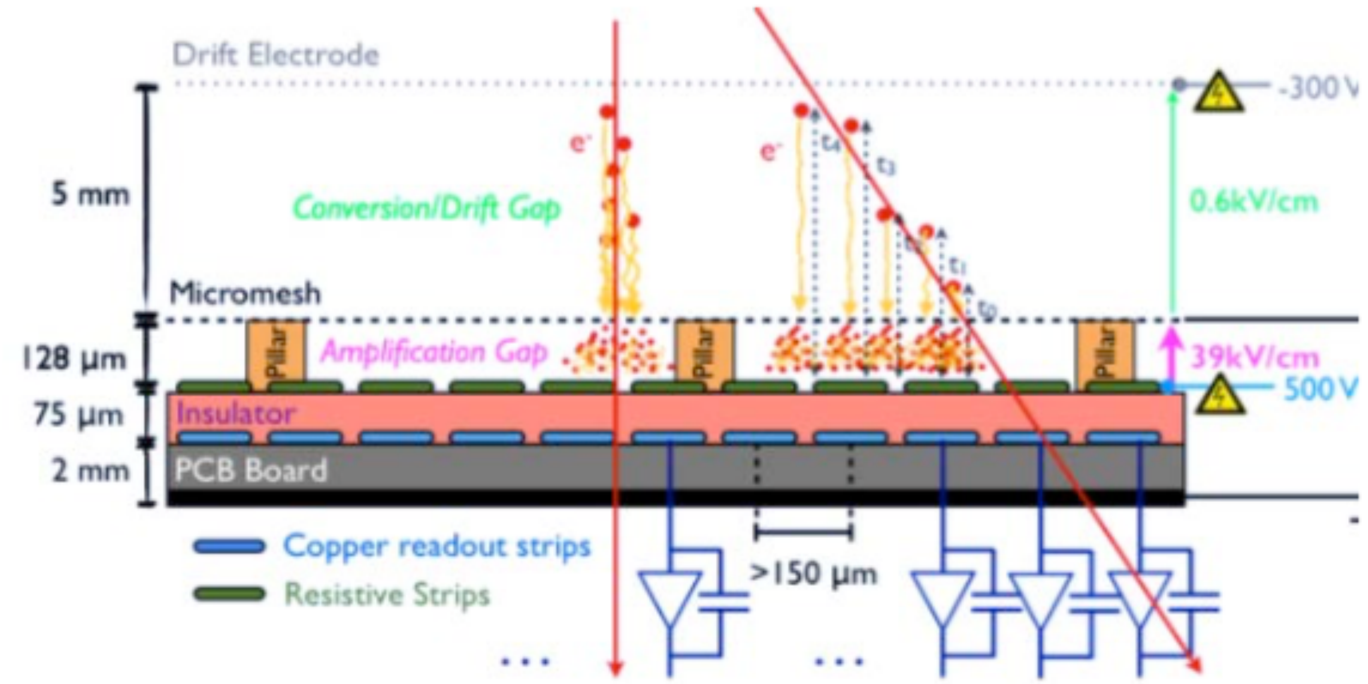
Small Strips TGC (sTGC)
primary trigger detector

- Bunch ID with good timing resolution
- Online track vector
  with <1 mrad angle resolution
- pads: region of interest
- strips: track info (strip pitch 3.2 mm)
- wire groups: coarse azimuthal coordinate

MicroMegas (MM)
primary precision tracker

- Good Spatial resolution < 100 μm
- Good track separation (0.4 mm readout granularity)
- Resistive anode strips → suppress discharge influence on efficiency
- Provide also online segments for trigger





NSW Technical Design Report

L1 MUON ENDCAP TRIGGER IN RUN-3

- Run-3 Trigger scheme overview
  - TGC Big Wheel hit position defines the RoI, which will be the trigger seed
  - TGC Big Wheel local coincidence logic calculates the p_T of the track
  - Require additional inner coincidence to reject fakes, and also to re-calculate the p_T