The ATLAS Run-2 Trigger Menu for higher luminosities: Design, Performance and Operational Aspects

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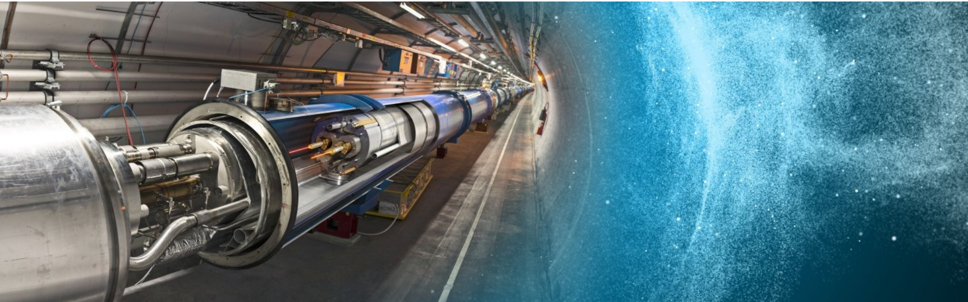
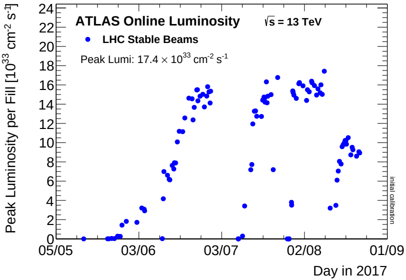
6th International Conference on New Frontiers in Physics

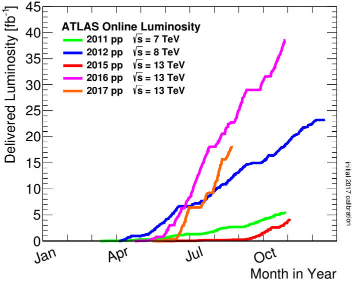
Kolymbari, Crete (Greece), 17-29 August 2017

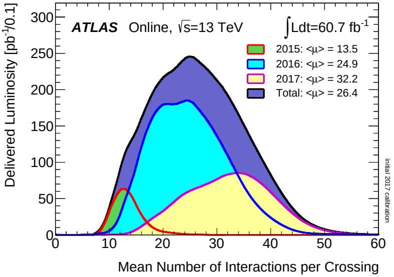


Introduction

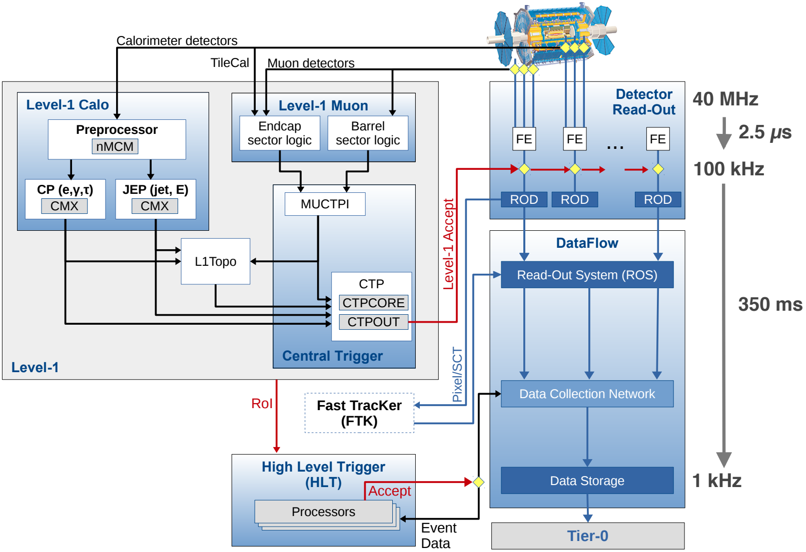
- LHC proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ in Run-2 (2015-2018)
- Record peak luminosity: $1.74 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - $\Rightarrow$ Design LHC luminosity: $10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - $\Rightarrow$ Peak lumi reached in 2016: $1.38 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - $\Rightarrow$ Trigger menu designed in 2017 for $2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- A total of $17.9\,\text{fb}^{-1}$ delivered so far (LHC goal for 2017 is $45\,\text{fb}^{-1}$)
- Increased number of interactions per bunch crossing (pileup): $\langle\mu\rangle = 32.2$ in 2017
- **Extremely challenging environment!**







ATLAS Run-2 Trigger and Data Acquisition



ATLAS Run-2 Trigger and Data Acquisition

In Run-2, ATLAS uses a two level trigger system to efficiently select interesting events and reduce the interaction rate of 40 MHz to 1 kHz:

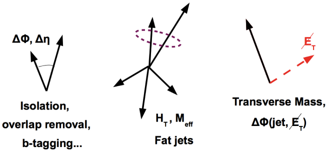
- Hardware-based **Level-1 (L1)** trigger:
  - **Level-1 Calo**: new Multi-Chip Module (nMCM) allows more flexible signal processing, more thresholds
  - **Level-1 Muon**: coincidences with inner detector, additional chambers in the feet of the barrel region and from Tile extended barrel region
  - **Central Trigger**: support multi-partition running
- Software-based **High Level Trigger (HLT)**:
  - Single farm (merged Level-2 and Event Filter farms used in Run-1) for better resource sharing
  - Fast offline-like sophisticated algorithms running mostly in L1 Regions-of-Interest
  - Full upgrade of readout and data storage systems
  - Events accepted at HLT are stored for offline event reconstruction at Tier-0 to be used in physics analyses

New systems installed in Run-2:

- **Level-1 Topological Trigger (L1Topo)**: topological cuts to reduce the rate and keep the thresholds low
- **Fast TracKer (FTK)**: hardware-based tracking which provides full track information to HLT after every Level-1 accept, currently under commissioning

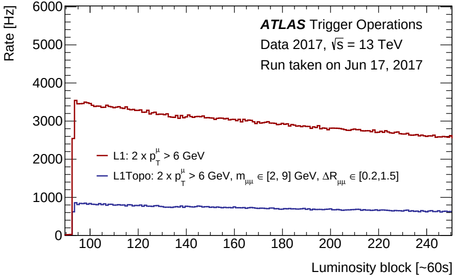
Level-1 Topological Trigger

- Level-1 Topological Trigger module combines calorimeter and muon information at Level-1 and applies topological selections to reduce the rate (e.g., angular distances, di-object invariant mass, transverse mass)



- FPGA-based algorithms used to analyse geometrical information on trigger objects
- L1Topo activated and commissioned in 2016 and used in several primary triggers in 2017

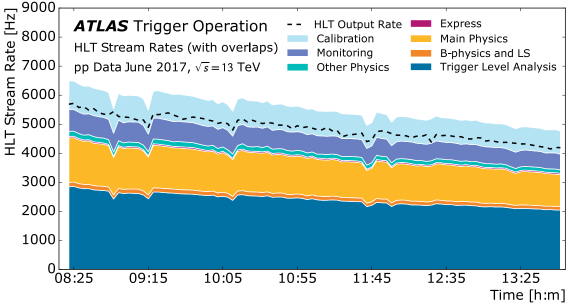
B-physics topological trigger

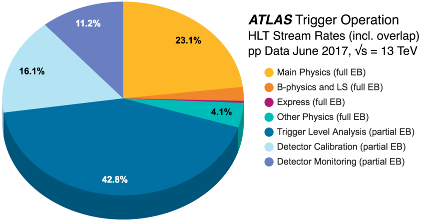


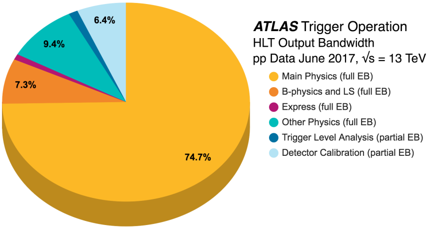
ATLAS Trigger Menu strategy

- Trigger menu:
  - **L1 menu** consists of **512 single items and combinations**
  - **HLT menu** consists of **O(1000) chains**
  - Rates are adjusted vias prescale sets, where each prescale set corresponds to a fixed value of instantaneous luminosity
- Chains are grouped into signatures: electrons, photons, muons, taus, jets, etc.
- Chains require either full event building (EB) or partial EB with only subdetector information for recording into data streams
- Different streams defined such as:
  - Main Physics: including majority of the events
  - Express: stream for fast offline monitoring and detector calibration
  - Trigger Level Analysis: using partial EB for di-jet resonance searches
- Trigger menu strategy based on:
  - Primary triggers: used for physics analyses, typically running unprescaled
  - Support triggers: used for efficiency and performance measurements or monitoring
  - Alternative triggers: running alternative online reconstruction algorithms
  - Backup triggers: tighter selections and lower expected rate
  - Calibration triggers: used for detector calibrations

ATLAS Trigger rates and bandwidth

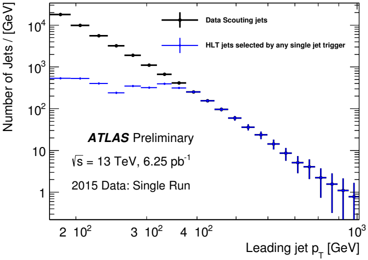






Trigger Level Analysis (TLA)

- **Novel idea to circumvent the bandwidth limitation using partial event building** (< 5% standard event size recorded)
- Prescale factors normally applied to the HLT jet triggers in the standard stream
- Large gain in statistics for the data scouting stream for $p_T < 400$ GeV
- Important for low mass dijet searches → **Increase sensitivity**



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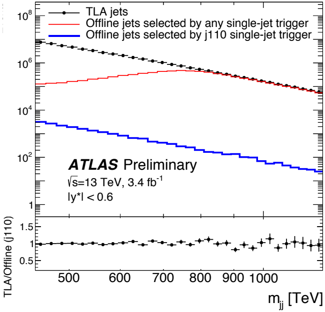
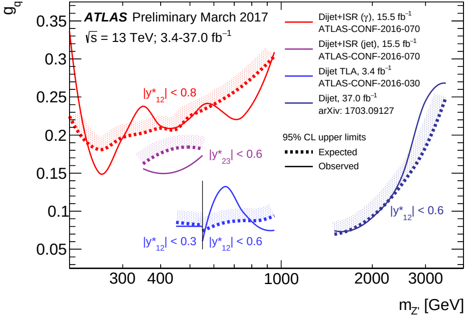




ATLAS Level-1 Trigger rates

- Representative Level-1 triggers running unprescaled in a fill taken in June 2017:
  - **EM**: electromagnetic clusters
  - **MU**: muon candidates
  - **J**: jet candidates
  - **XE**: missing energy
  - **TAU**: tau candidates

EM22VHI

22: Nominal trigger threshold in GeV

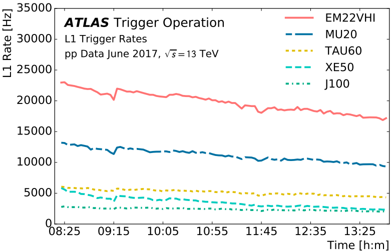
V: η-dependent trigger thresholds applied

H: Hadronic core isolation applied for $E_T < 50\,\text{GeV}$

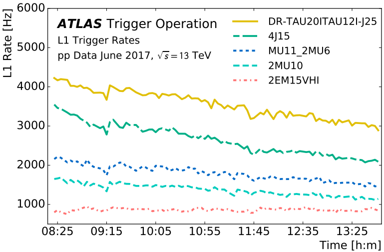
I: Electromagnetic isolation applied for $E_T < 50\,\text{GeV}$

- Exponential decay with decreasing luminosity during an LHC fill
- The rates periodically increase due to LHC luminosity re-optimisations, dips are due to deadtime and spikes are caused by detector noise

Single Level-1 trigger items

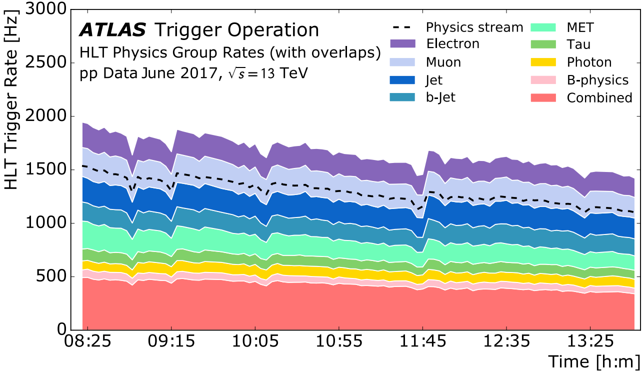


Multi Level-1 trigger items



ATLAS HLT Trigger rates

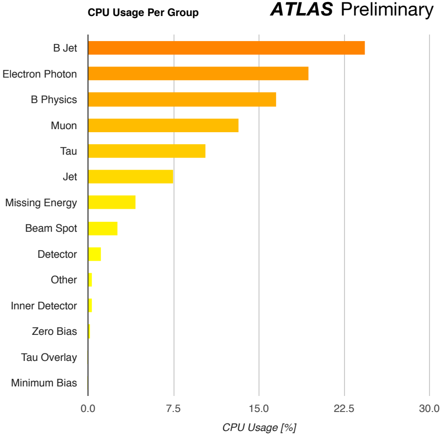
- Physics trigger group rates at the HLT as a function of time in a fill taken in June 2017
- Overlaps are only accounted for in the total Main Physics Stream rate
- Exponential decay with decreasing luminosity during an LHC fill
- The rates periodically increase due to LHC luminosity re-optimisations, dips are due to deadtime and spikes are caused by detector noise



ATLAS Trigger CPU usage

- HLT is computer farm of up to approximately 40,000 CPU cores
- Higher CPU-usage **partially scaling exponentially with pileup**
- Improved CPU usage of the trigger chains in 2017
- Summary of the CPU consumption for all chains as assigned to physics groups

ATL-DAQ-PUB-2016-002



Physics use cases:

- **B Jet:** $H \to b\bar{b}$, $t\bar{t}$, etc.
- **Electron:** Generic analyses (W, Z, dibosons, $t\bar{t}$, etc.)
- **Photon:** $H \to \gamma\gamma$, γ production, etc.
- **B Physics:** J/ψ, Υ, etc.
- **Muon:** Generic analyses (W, Z, dibosons, $t\bar{t}$, etc.)
- **Tau:** $H \to \tau\tau$, searches, etc.
- **Jet:** jet production, dijet resonances searches, etc.
- **Missing Energy:** SUSY searches, etc.

ATLAS Trigger software validation

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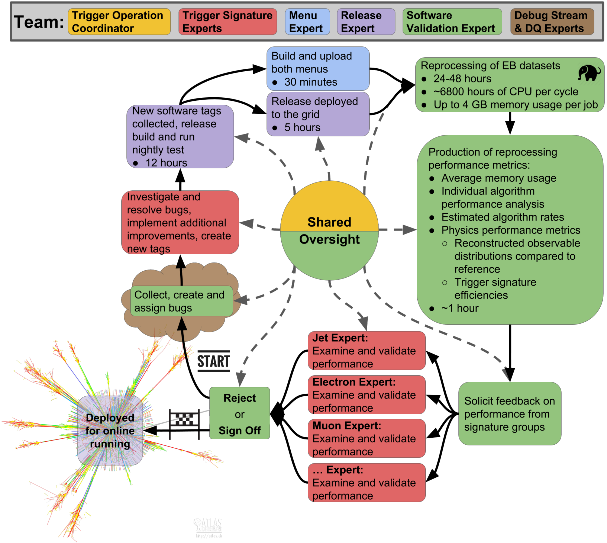
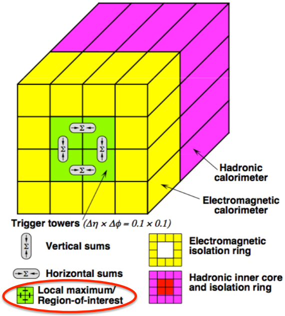


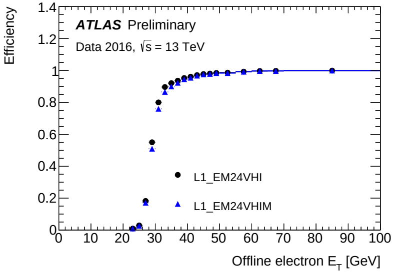
Level-1 EM isolation optimization for 2017

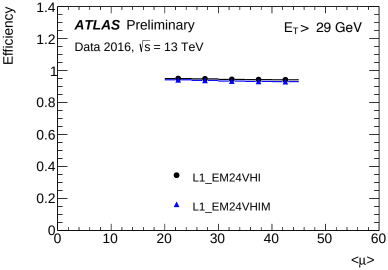
- The unprescaled single Level-1 EM trigger is the item with the highest rate in the Level-1 menu
- Level-1 EM isolation tightened to reduce the trigger rate and keep the single-electron trigger threshold low
- Default Level-1 EM isolation used in 2016: $\max\{2\ \text{GeV}, E_{\text{T,cluster}}/8 - 1.8\ \text{GeV}\}$ for $E_{\text{T,cluster}} < 50\ \text{GeV}$
- New Level-1 EM medium isolation implemented in 2017: $\max\{1\ \text{GeV}, E_{\text{T,cluster}}/8 - 2.0\ \text{GeV}\}$ for $E_{\text{T,cluster}} < 50\ \text{GeV}$

Medium isolation (IM) with respect to the default isolation (I)

Level-1 E_T	Efficiency loss	Rate reduction
22 GeV	1.3%	14.6%
24 GeV	1.0%	10.8%



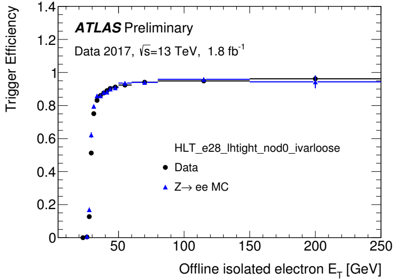


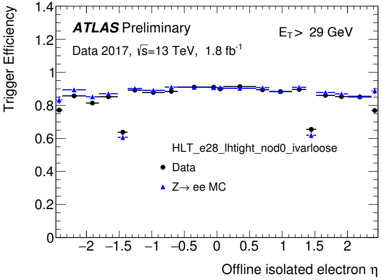


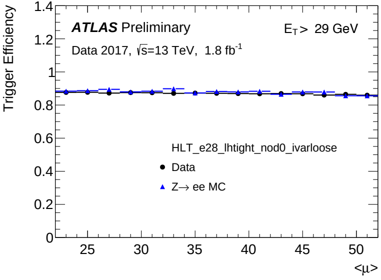
First 2017 performance

Electron trigger efficiencies

- Likelihood-based electron identification applied at HLT, different working points defined: tight, medium, loose, very loose
- Lowest unprescaled single-electron trigger HLT_e28_lhtight_nod0_ivarloose (trigger seeded by L1_EM24VHI)
- HLT track-based isolation applied (ivarloose: $\sum p_{\mathrm{T}}^{\mathrm{trk}}/p_{\mathrm{T}} < 0.1$ in $\Delta R < 0.2$)
- Efficiency with respect to offline isolated tight electrons using $Z \to ee$ Tag & Probe
- No background subtraction applied



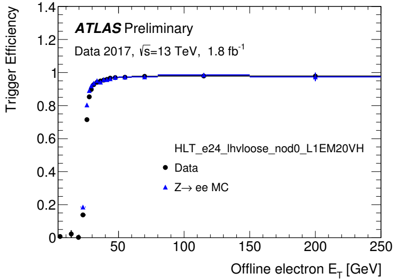


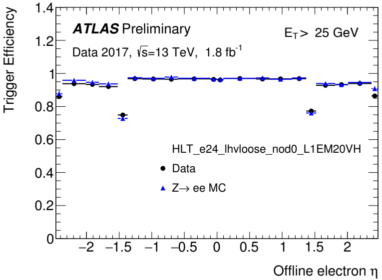


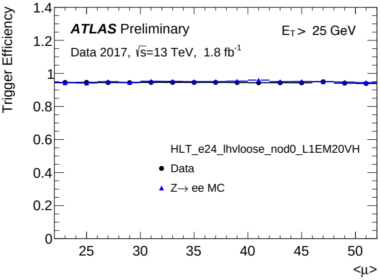
First 2017 performance

Electron trigger efficiencies

- Likelihood-based electron identification applied at HLT, different working points defined: tight, medium, loose, very loose
- Leg of the unprescaled di-electron trigger HLT_2e24_lhvloose_nod0 (trigger seeded by L1_2EM20VH)
- Efficiency with respect to offline loose electrons using $Z \to ee$ Tag & Probe
- No background subtraction applied



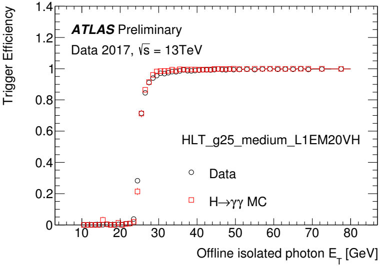


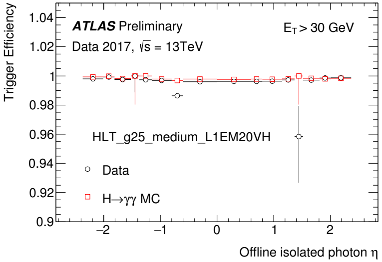


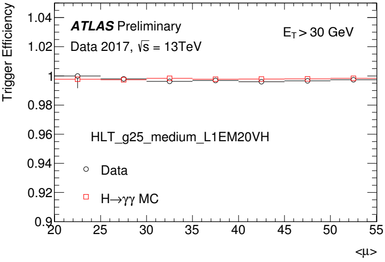
First 2017 performance

Photon trigger efficiencies

- Cut-based photon identification applied at HLT, different working points defined: tight, medium, loose
- Leg of the unprescaled di-photon trigger HLT_g35_medium_g25_medium_L12EM20VH (trigger seeded by L1_2EM20VH) → Main trigger used for $H \to \gamma\gamma$
- Efficiency with respect to offline isolated tight photons using the bootstrap method
- No background subtraction applied



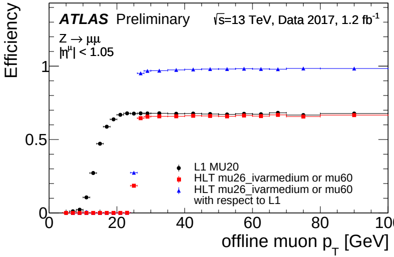


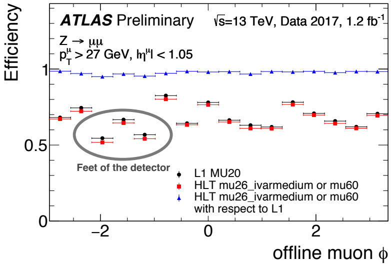


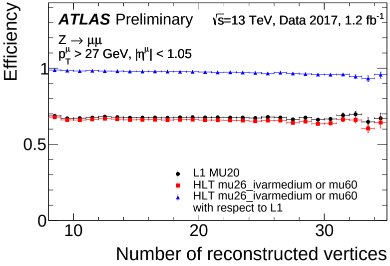
First 2017 performance

Barrel muon trigger efficiencies

- Muons reconstructed combining Inner Detector + Muon Spectrometer information (**reduced barrel geometrical acceptance**)
- Lowest unprescaled single-muon triggers HLT_mu26_ivarmedium || HLT_mu60 (triggers seeded by L1_MU20)
- HLT track-based isolation applied (ivarmedium: $\sum p_{\mathrm{T}}^{\mathrm{trk}}/p_{\mathrm{T}} < 0.07$ in $\Delta R < 0.3$)
- Efficiency with respect to offline isolated medium muons using $Z \to \mu\mu$ Tag & Probe
- No background subtraction applied



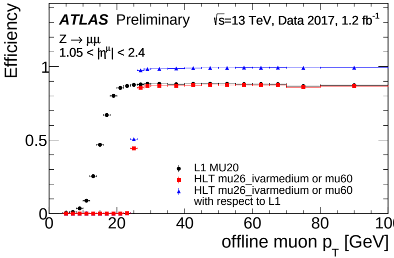


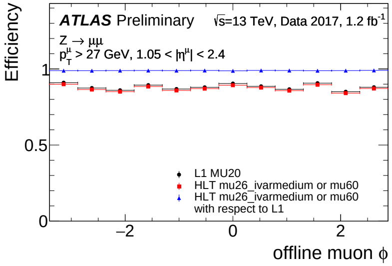


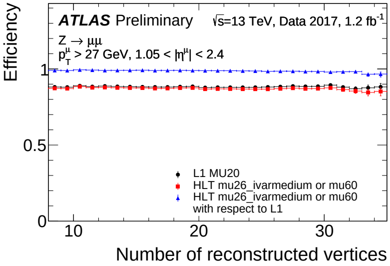
First 2017 performance

Endcap muon trigger efficiencies

- Muons reconstructed combining Inner Detector + Muon Spectrometer information
- Lowest unprescaled single-muon triggers HLT_mu26_ivarmedium || HLT_mu60 (triggers seeded by L1_MU20)
- HLT track-based isolation applied (ivarmedium: $\sum p_T^{trk}/p_T < 0.07$ in $\Delta R < 0.3$)
- Efficiency with respect to offline isolated medium muons using $Z \to \mu\mu$ Tag & Probe
- No background subtraction applied





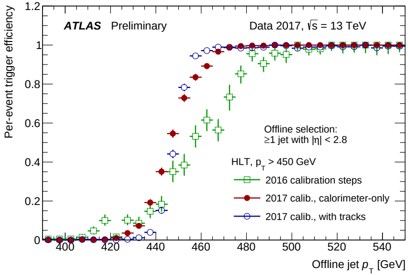


First 2017 performance

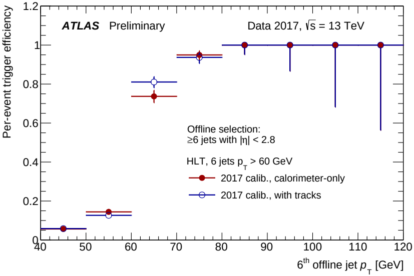
Jet trigger efficiencies

- Jets reconstructed using the **anti-k_t $R=0.4$ algorithm** and calibrated at HLT
- Comparison of **different calibrations**:
  - Updated calibration using only calorimeter information
  - Updated calibration including additional track information
- The Global Sequential Calibration (GSC) corrects jets according to their longitudinal shower shape and associated track characteristics without changing the overall energy scale
- Efficiencies computed using the **bootstrap method**

Unprescaled single-jet trigger



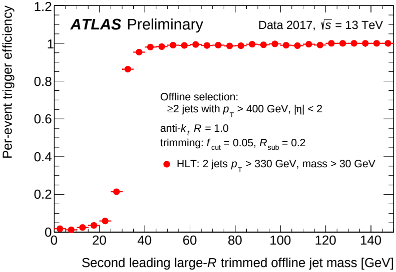
Unprescaled multi-jet trigger

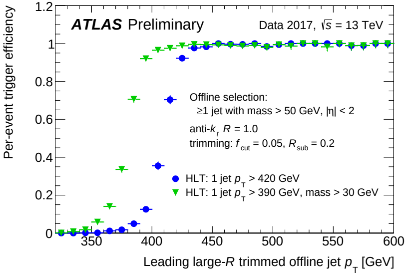


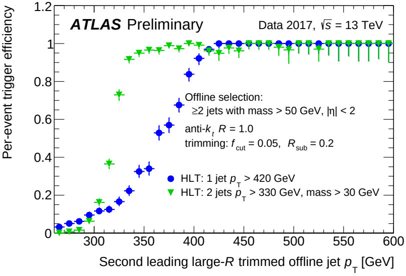
First 2017 performance

Large-*R* jet trigger efficiencies

- **Trimming** (JHEP 02 (2010) 084) applied to mitigate contamination from soft radiation (initial state radiation, multiple parton interactions, pileup)
- Jet trimming procedure:
  - **anti-k_t $R = 1.0$ algorithm** used for large-R jets
  - Within a jet, recluster the constituents into subjets with radius $R_{\text{sub}} = 0.2$
  - Discard subjets if $p_{\text{T},i} < f_{\text{cut}} \cdot \Lambda_{\text{hard}}$ ($f_{\text{cut}} = 0.05$ used)
  - Remaining subjets assembled into the trimmed jet
- Mass cut also applied



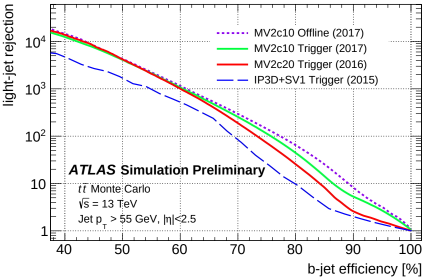


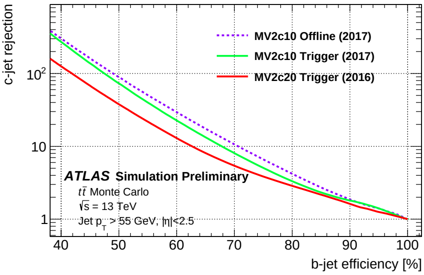


First 2017 performance

b-jet trigger efficiencies

- The *b*-jet trigger uses a **Boosted Decision Tree (BDT)** algorithm to separate *b*-jets from light and *c*-jet backgrounds
- BDT re-optimized to improve the *b*-tagging performance
- The performance of the *b*-tagging algorithms measured using $t\bar{t}$ Monte Carlo
- *b*-tagging algorithms used for *b*-jet triggers:
  - 2017 data: **MV2c10** (multivariate algorithm with a 10% *c*-jet fraction in the training)
  - 2016 data: **MV2c20** (multivariate algorithm with a 20% *c*-jet fraction in the training)
  - 2015 data: **IP3D+SV1** (impact parameter tagger, secondary vertex finding algorithm)

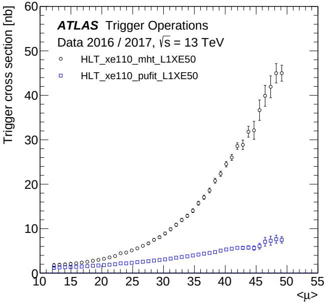


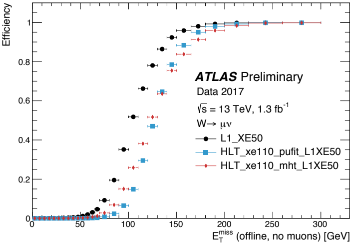


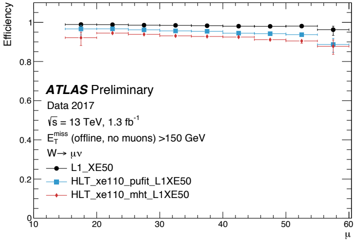
First 2017 performance

Missing E_T trigger efficiencies

- **Pileup mitigation is the main challenge** $\rightarrow$ significant effort to mitigate the impact on the trigger rates and deliver more efficient pileup suppression algorithms
- Efficiency of the lowest unprescaled E_T^{miss} triggers using events with reconstructed $E_T^{miss} > 150\,\text{GeV}$ and a $W \rightarrow \mu\nu$ selection
- **pufit:** baseline algorithm in 2017, E_T^{miss} calculated as the negative of the p_T sum of all calorimeter topological clusters corrected for pileup
- **mht:** default algorithm in 2016, E_T^{miss} calculated as the negative of the p_T sum of all jets reconstructed by the anti-k_t jet algorithm

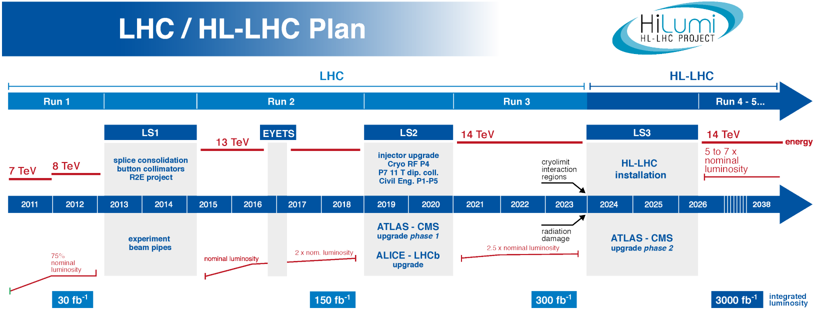






Prospects

- The upgrades of the detectors and trigger system will be essential in the coming years to take full advantage of the physics potential of the LHC
- LHC Run-3 (2021-2023) begins after the Phase-1 detector upgrades
- HL-LHC (High Luminosity LHC) starting in 2024 with the Phase-2 detector upgrades followed by Run-4
- The goal of the Phase-2 upgrades in ATLAS is to cope with an instantaneous luminosity of up to $7.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a pileup of 200 collisions per crossing



Conclusions

- **Significant improvements in many areas**, several hardware and software improvements during the LHC shutdown (2013-2014) to cope with the challenges to face in the LHC Run-2 (2015-2018)
- **Surpassed the initial design**, trigger menu prepared for twice the design luminosity (2×10^{34} cm^{-2}s^{-1}) and high pileup conditions ($\mu \sim 60$) expected in 2017 data taking
- **Rock-solid well-established validation procedures** to ensure a smooth trigger operation
- **First performance studies using 2017 data** of different trigger signatures (electrons, photons, muons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$) have been presented
- More results in:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerPublicResults