The Run-2 ATLAS Trigger System

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on behalf of the ATLAS Collaboration

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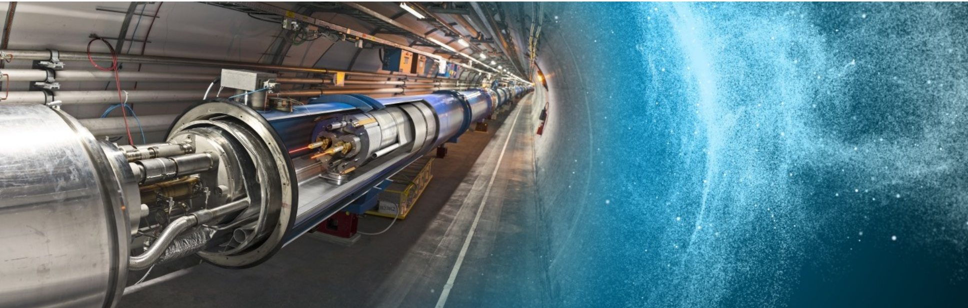
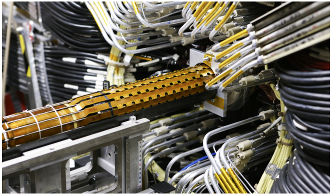


Introduction

- Very successful data taking at 7 and 8 TeV during Run-1 (2010-2012)
- Many improvements in the TDAQ system during the LHC shutdown (2013-2014):
    - Upgraded L1 Calorimeter trigger
    - Installation of additional L1 Muon trigger chambers in the feet region
    - New L1 Topological trigger
    - New Central Trigger Processor (CTP)
    - Unified High Level Trigger (HLT) architecture
    - Fast TracKer (FTK), hardware-based tracking
    - Data Scouting
    - Higher bandwidth:

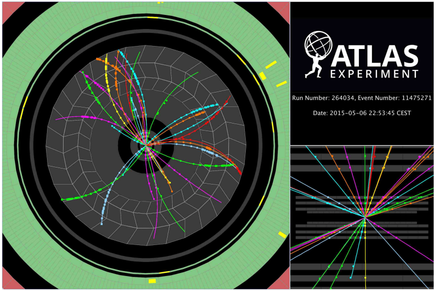
	L1	HLT
2012	75 kHz	400 Hz
2015	100 kHz	1000 Hz

- Trigger successfully recommissioned with the first 13 TeV data in 2015

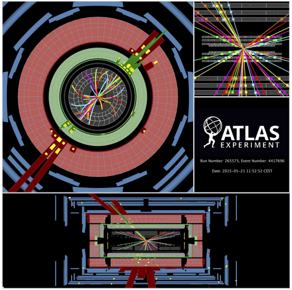


LHC is back!

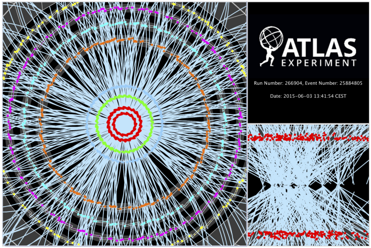
First collisions at $\sqrt{s} = 900$ GeV on May 6



First collisions at $\sqrt{s} = 13$ TeV on May 21

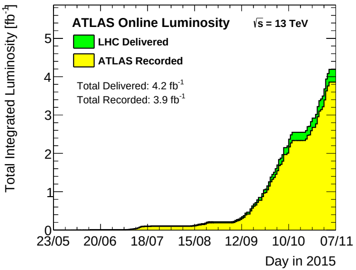


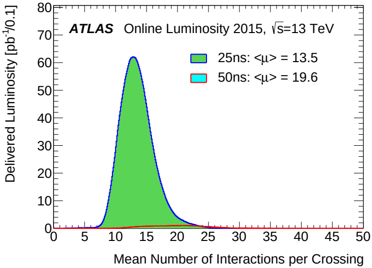
Stable beams since June 3

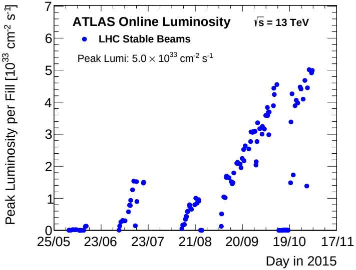


Run-2 data taking

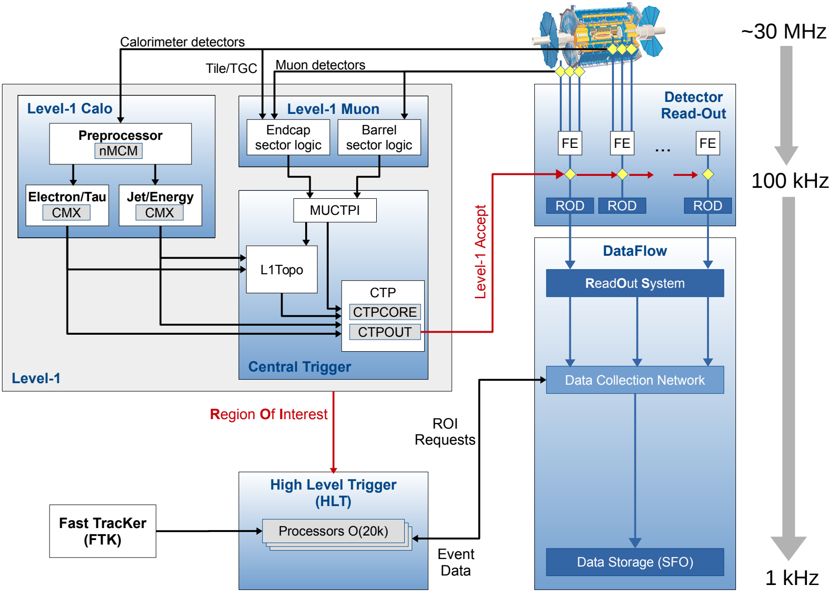
- Data taking in 2015:
  - 50 ns pp data (July)
  - 25 ns pp data (August-November)
  - PbPb data (November-December)
- Peak luminosity: 5.0×10^{33} $cm^{-2}s^{-1}$
- Recorded luminosity: 3.9 fb^{-1}
- Average of 13.5 collisions per bunch crossing





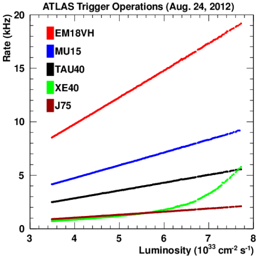


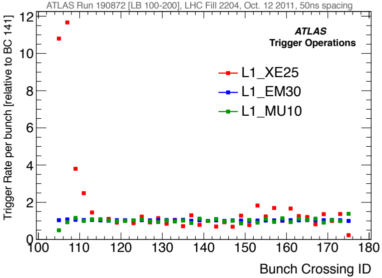
Run-2 ATLAS Trigger/DAQ system



L1 Calorimeter Trigger

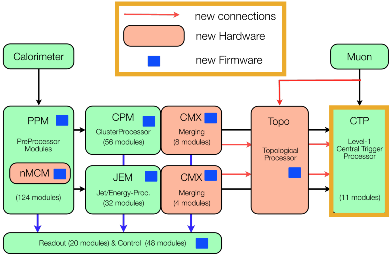
In Run-1, significant rate effects from out-of-time pileup observed at the highest luminosities (low threshold E_T^{miss}, forward jet and multijet triggers), dominated by early bunches in train → Critical to have pileup suppression at all trigger levels in Run-2





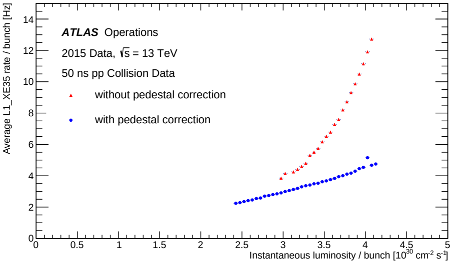
HW improvements:

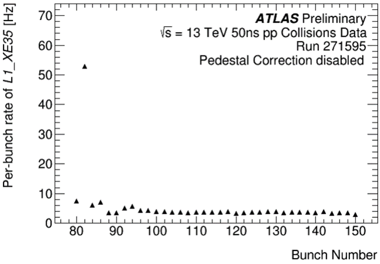
- The pulse/energy extraction ASIC was replaced by FPGA → A dynamic pedestal subtraction applied before the energy calculation
- Number of EM/TAU and J thresholds increased
- Possibility to have user-defined η regions for J/XE and TE thresholds
- E_T dependent isolation definitions

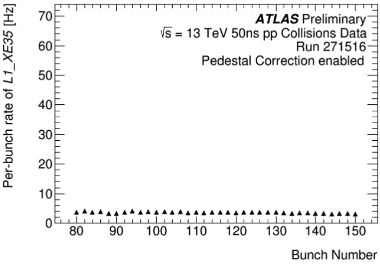


L1 Calorimeter Trigger

In Run-2, a linear behaviour for all items is observed as well as a good agreement for the different bunch spacing schemes

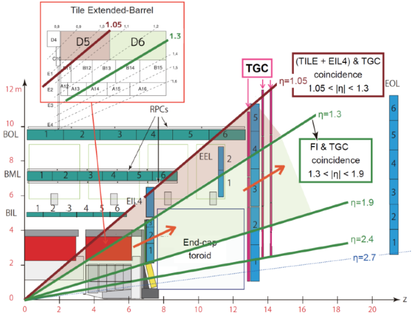




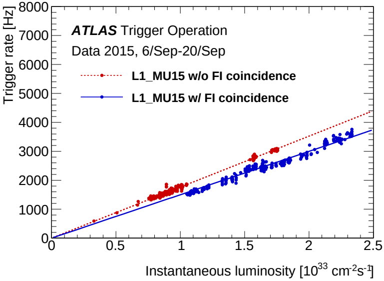


L1 Muon Trigger

- New trigger chambers:
  - Installed in the feet of the barrel region (4% larger acceptance for L1 muons)
- New coincidence logic:
  - In Run-1, L1 muon rates in the forward region were polluted by low-p_T charged particles (protons) from out of interaction point
  - The muon endcap trigger ($1.05 < |\eta| < 2.4$) requires coincidence with the new Forward Inner (FI) station (ready) as well as with the extended barrel of the Tile Calorimeter (ongoing)

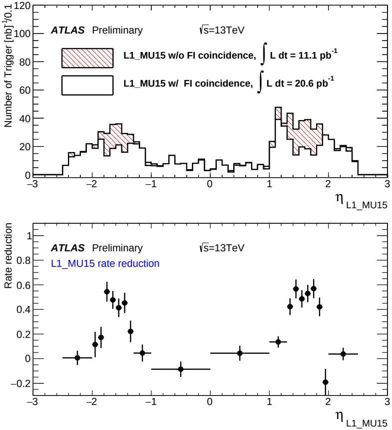


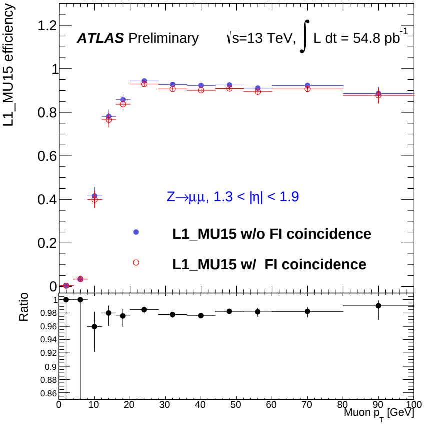
L1_MU15 rate reduction of 15%



L1 Muon Trigger

- FI coincidence reduces the L1_MU15 rate $\sim$50% in $1.3 < |\eta| < 1.9$
- Very small signal efficiency loss $\sim$2% in $1.3 < |\eta| < 1.9$





New L1 Topological Trigger Module

- New piece of Level-1 hardware which receives input from L1Calo and L1Muon and applies trigger decisions based on the event topology to reduce the rate

Angular Requirements

$\Delta\eta, \Delta\varphi, \Delta R^2, \Delta\eta + \Delta\varphi$

Mass Requirements

$M^2 = 2 E_T^1 E_T^2 (\cosh\Delta\eta - \cos\Delta\varphi)$

$M_T^2 = 2 E_T^1 E_T^{miss} (1 - \cos\Delta\varphi)$

Event Requirements

$H_T = \sum p_T(jets)$

$H_{CT} = \sum p_T(central\ jets)$

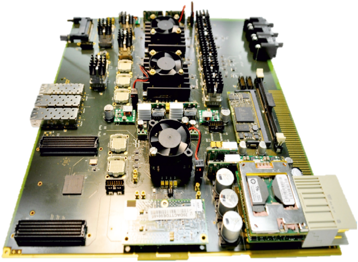
L1Topo MET

Dedicated Algorithms

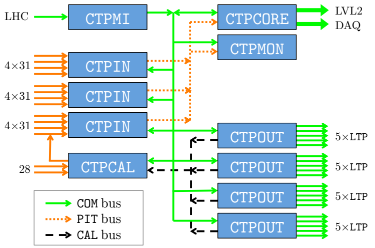
Calorimeter Ratio

Delayed Particles

- Constraints:
  - 128 L1Topo trigger items
  - Latency (algorithm) $\leq$ 3 BC (75 ns)
  - FPGA resources
  - Combinatorial constraints (most algorithms limited to work with *N* leading p_T objects)
- 2 custom modules in ATCA crate $\rightarrow$
  2 FPGAs per module $\rightarrow$
  32 trigger decisions / FPGA $\rightarrow$
  128 trigger decisions to the CTP
- System still being commissioned



New Central Trigger Processor



Feature	2012	2015
CTPIN input cables	12	12
PIT bus lines	160	320
CTPCORE trigger items	256	512
CTPCORE bunch groups	8	16
CTPCORE front inputs	0	192
Max # bits inOR	12	15
Per-bunch item counters	12	256
Output cables to TTC	20	25

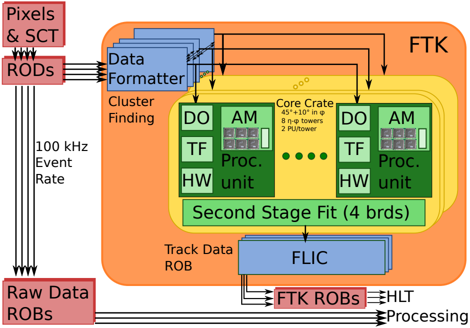
- CTPMI (machine interface)
  - receives timing signals from LHC
- CTPIN (input modules) → NEW FW
  - trigger inputs from sub-detectors
  - synchronization / alignment / monitoring
- CTPCAL (calibration module)
- CTPCORE → NEW HW
  - decision taking → L1 accepts (L1A)
  - dead time generation
  - generation of timing signals
  - summary information to HLT / DAQ
- CTPMON (monitoring module)
  - per bunch monitoring of trigger rates
- CTPOUT (output modules) → NEW HW
  - distribute trigger & timing signals to sub-detectors
  - receives calibration requests

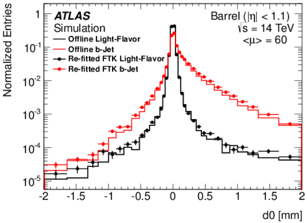
Fast Tracker (FTK)

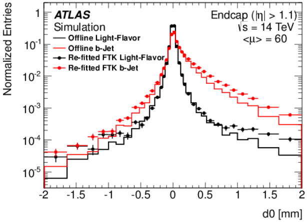
FTK performs a global track reconstruction (tracks with $p_T > 1\,\text{GeV}$) receiving input from the IBL, Pixels and SCT after each Level-1 trigger and provides full-event track information to the HLT at full Level-1 rate (100 kHz)

- Hardware-based track finder
- Using associate memory for pattern matching
- Installation ongoing, expected to be operational for barrel by mid 2016

See talk by Naoki Kimura on Tuesday

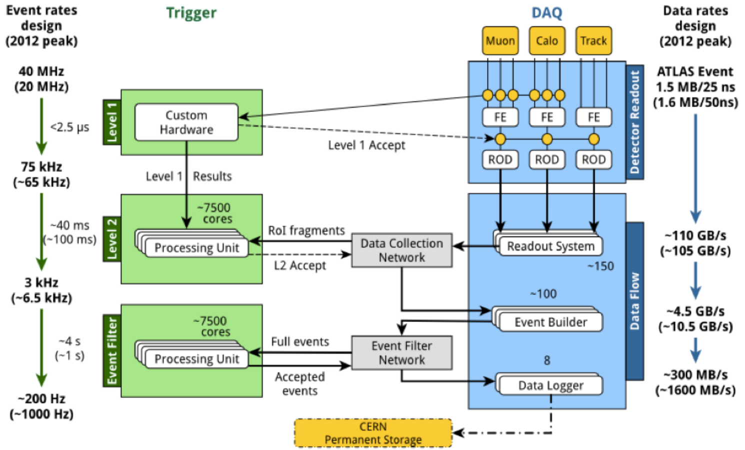






New HLT architecture

- New merged High Level Trigger:
  - Reduces complexity and increases flexibility
  - More efficient resource-wise and reduces duplicated data-fetching
  - Average processing time $< 200\,\text{ms}$



New HLT architecture

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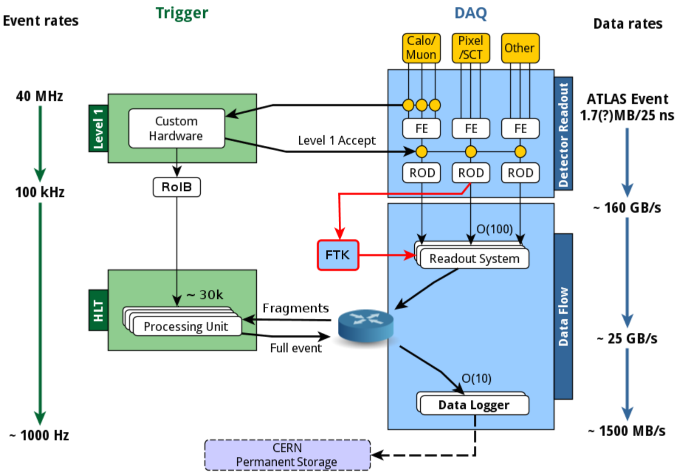
  - Average processing time < 200 ms



Trigger menu strategy in 2015

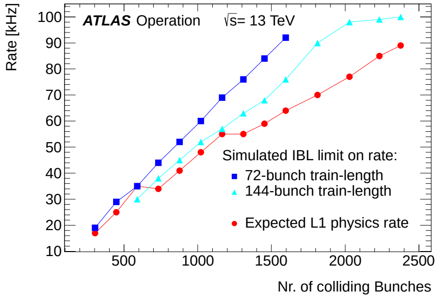
Trigger menu with ~400 L1 triggers and ~1500 HLT triggers used in 2015, the thresholds are basically the same as at the end of 2012

Trigger	Typical offline selection	Trigger Selection		Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
		Level-1 (GeV)	HLT (GeV)	$L = 5 \times 10^{33}$ cm^{-2}s^{-1}	
Single leptons	Single iso μ, $p_T > 21$ GeV	15	20	7	130
	Single e, $p_T > 25$ GeV	20	24	18	139
	Single μ, $p_T > 42$ GeV	20	40	5	33
	Single τ, $p_T > 90$ GeV	60	80	2	41
Two leptons	Two μ's, each $p_T > 11$ GeV	2×10	2×10	0.8	19
	Two μ's, $p_T > 19, 10$ GeV	15	18, 8	7	18
	Two loose e's, each $p_T > 15$ GeV	2×10	2×12	10	5
	One e & one μ, $p_T > 10, 26$ GeV	20 (μ)	7, 24	5	1
	One loose e & one μ, $p_T > 19, 15$ GeV	15, 10	17, 14	0.4	2
	Two τ's, $p_T > 40, 30$ GeV	20, 12	35, 25	2	22
	One τ, one μ, $p_T > 30, 15$ GeV	12, 10 (+jets)	25, 14	0.5	10
	One τ, one e, $p_T > 30, 19$ GeV	12, 15 (+jets)	25, 17	1	3.9
Three leptons	Three loose e's, $p_T > 19, 11, 11$ GeV	15, 2×7	17, 2×9	3	< 0.1
	Three μ's, each $p_T > 8$ GeV	3×6	3×6	< 0.1	4
	Three μ's, $p_T > 19, 2 \times 6$ GeV	15	18, 2×4	7	2
	Two μ's & one e, $p_T > 2 \times 11, 14$ GeV	2×10 (μ's)	2×10, 12	0.8	0.2
	Two loose e's & one μ, $p_T > 2 \times 11, 11$ GeV	2×8, 10	2×12, 10	0.3	< 0.1
One photon	one γ, $p_T > 125$ GeV	22	120	8	20
Two photons	Two loose γ's, $p_T > 40, 30$ GeV	2×15	35, 25	1.5	12
	Two tight γ's, $p_T > 25, 25$ GeV	2×15	2×20	1.5	7
Single jet	Jet ($R = 0.4$), $p_T > 400$ GeV	100	360	0.9	18
	Jet ($R = 1.0$), $p_T > 400$ GeV	100	360	0.9	23
E_T^{miss}	$E_T^{miss} > 180$ GeV	50	70	0.7	55
Multi-jets	Four jets, each $p_T > 95$ GeV	3×40	4×85	0.3	20
	Five jets, each $p_T > 70$ GeV	4×20	5×60	0.4	15
	Six jets, each $p_T > 55$ GeV	4×15	6×45	1.0	12
b−jets	One loose b, $p_T > 235$ GeV	100	225	0.9	35
	Two medium b's, $p_T > 160, 60$ GeV	100	150, 50	0.9	9
	One b & three jets, each $p_T > 75$ GeV	3×25	4×65	0.9	11
	Two b & two jets, each $p_T > 45$ GeV	3×25	4×35	0.9	9
b−physics	Two μ's, $p_T > 6, 4$ GeV plus dedicated b-physics selections	6, 4	6, 4	8	52
Total				70	1400

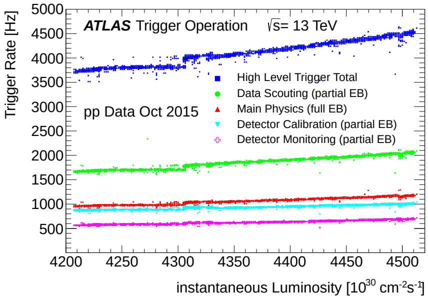
Trigger operations

- Peak L1 rate of 80 kHz @ 5.2e33
- ATLAS can run at 100 kHz (but at low number of bunches, dangerous resonance frequencies could damage the IBL wire-bonds → automatic fixed frequency veto protects IBL)
- Average HLT output rate of 1.2 kHz with full Event Building (EB) → 25% drop in luminosity and rates at the middle of the run
- HLT output rate composed of:
  - Main physics stream (full EB)
  - Data scouting, calibration and monitoring streams (partial EB)

Level-1 trigger rate



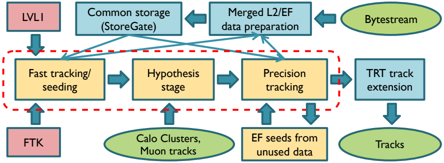
HLT trigger rate

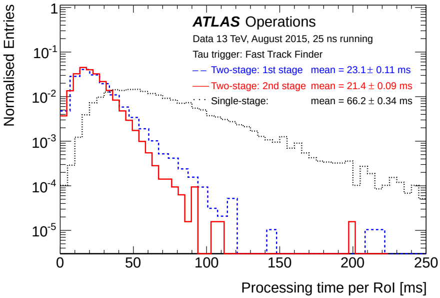


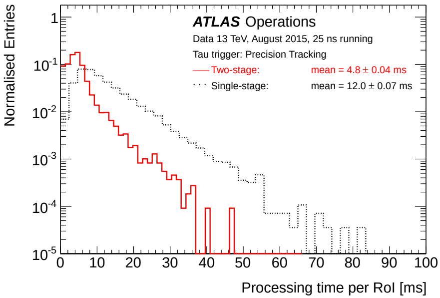
First trigger results at 13 TeV

HLT tracking performance

- Fast and precision tracking combined in the same machines in steps
- Pattern recognition and data preparation run only once (fast tracking) and later refined tracking (precision tracking)
- Speed up by a factor 3
- See poster by Callum Kilby on Friday



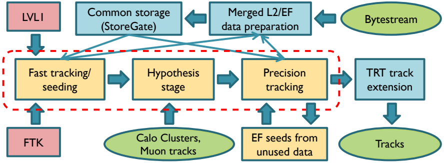


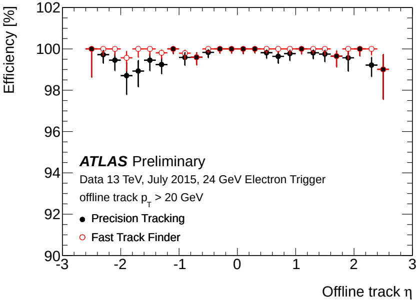


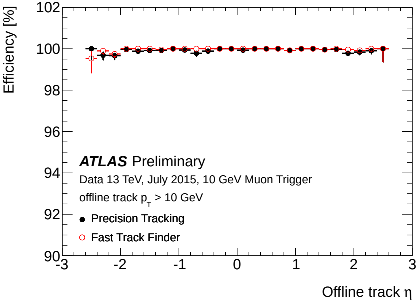
First trigger results at 13 TeV

HLT tracking performance

- Fast and precision tracking combined in the same machines in steps
- Pattern recognition and data preparation run only once (fast tracking) and later refined tracking (precision tracking)
- Tracking efficiency larger than 99%
- See poster by Callum Kilby on Friday





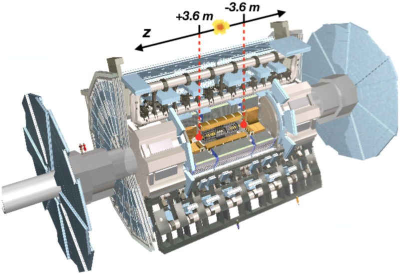


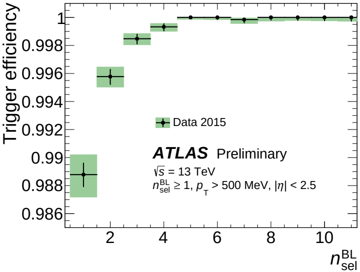
First trigger results at 13 TeV

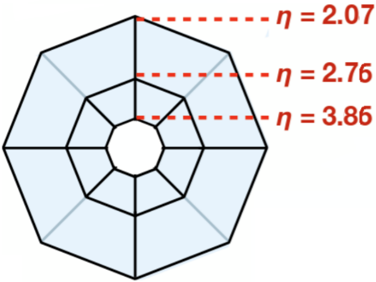
Minimum bias trigger efficiencies and performance

Used in very low-pileup data taking (pp and HI)

- Scintillator tiles located in front of the endcap calorimeters
- Two disks, each one with 12 counters (8 inner and 4 outer)
- Acceptance: $2.07 < |\eta| < 3.86$
- Completely replaced between 7 TeV and 13 TeV measurements
- Trigger efficiency with respect to the event selection, as a function of the number of reconstructed tracks



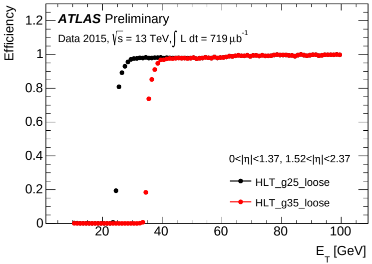


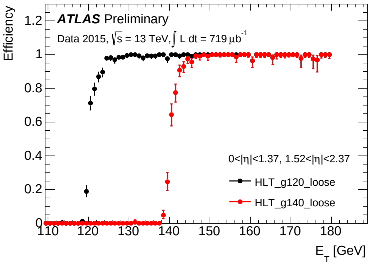


First trigger results at 13 TeV

Photon trigger efficiencies and performance

- At L1, E_T dependent veto against energy deposited in the hadronic calorimeter behind the candidate's electromagnetic cluster
- At HLT, a **cut-based identification criteria** is used with different selections available (loose, medium and tight)
- Lowest unprescaled single-photon trigger: HLT_g120_loose
- Main di-photon $H \to \gamma\gamma$ trigger: HLT_g35_loose_g25_loose
- HLT trigger efficiency measured as a function of the E_T of the offline tight photon candidates using events recorded with a L1 trigger requiring an electromagnetic cluster with $E_T > 7$ GeV with no background subtraction applied

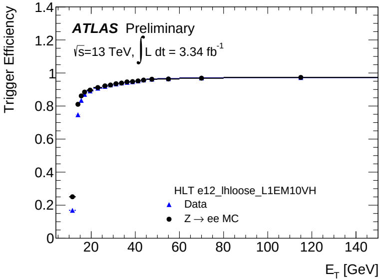


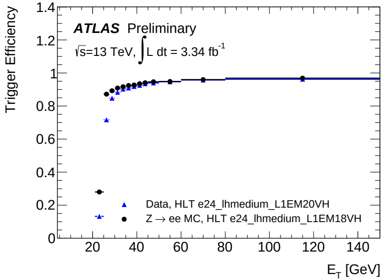


First trigger results at 13 TeV

Electron trigger efficiencies and performance

- At L1, E_T dependent veto against energy deposited in the hadronic calorimeter behind the electron candidate's electromagnetic cluster
- At HLT, a **likelihood-based identification criteria** is used taking as input electromagnetic shower shape and tracking information with different selections available (lhloose, lhmedium and lhtight)
- Single-electron primary trigger: HLT_e24_lhmedium_L1EM20VH
- Di-electron primary trigger: HLT_2e12_lhloose_L12EM10VH
- Combined L1 and HLT trigger efficiency measured as a function of the E_T of the offline lhloose (left) and lhmedium (right) electron candidates using $Z \to ee$ T&P





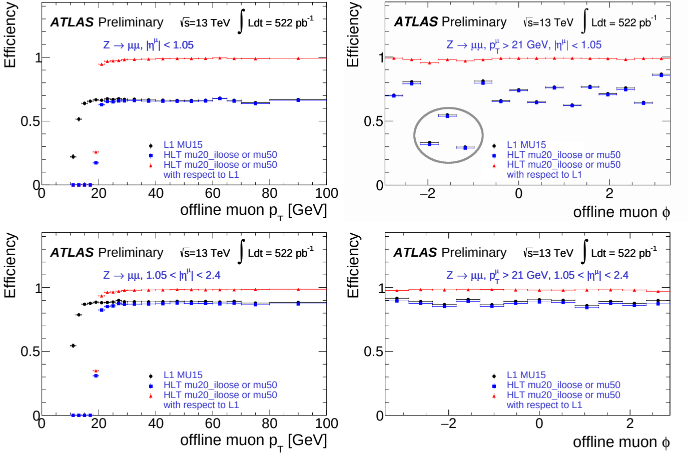
First trigger results at 13 TeV

Muon trigger efficiencies and performance

- At HLT, muons reconstructed by combining the inner detector and muon spectrometer tracks
- L1 and HLT trigger efficiency measured as a function of the p_{T} and ϕ of the offline medium muon candidates using $Z \to \mu\mu$ T&P with no background subtraction applied
- HLT_mu20_iloose and HLT_mu50 triggers ORed to recover the efficiency loss at high p_{T} due to the loose muon track isolation "iloose" ($\sum p_{\mathrm{T}}^{\mathrm{trk}}/p_{\mathrm{T}} < 0.12$ in $\Delta R < 0.2$) applied at HLT

Muon Barrel

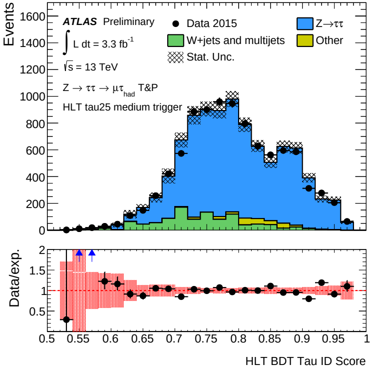
Muon Endcap

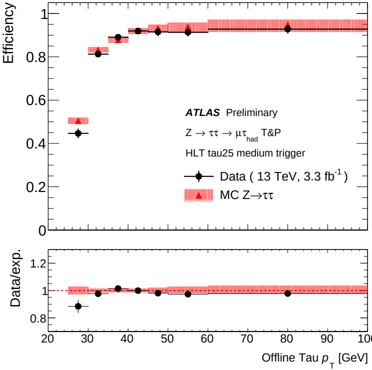


First trigger results at 13 TeV

Tau trigger efficiencies and performance

- At L1, an isolation cut on the transverse energy in an annulus of calorimeter towers around the tau candidate relative to the tau transverse energy is applied
- At HLT, a **boosted decision tree** built from calorimeter and track quantities is used to identify the tau candidates using different working points (loose, medium and tight)
- Combined L1 and HLT trigger efficiency measured as a function of the p_{T} of the offline reconstructed tau candidates passing the offline medium identification using $Z \to \tau\tau \to \mu\tau_{\mathrm{had}}$ T&P (events collected using a single muon trigger)

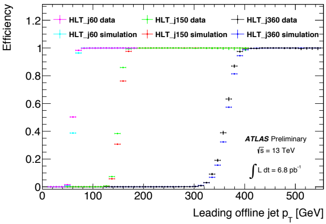


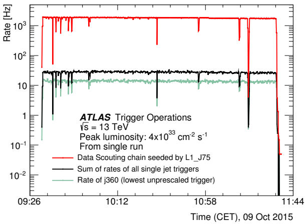


First trigger results at 13 TeV

Jet trigger efficiencies and performance

- Different jet trigger configurations available:
  - Pseudorapidity range: [0, 3.2] (default), [0, 2.4], [2.4, 3.2], [0, 4.9] or [3.2, 4.9]
  - Jet algorithm: anti-k_t with $R = 0.4$ (default) or $R = 1.0$
  - Constituent type: topo-clusters (default) or L1 trigger towers
  - Constituent energy scale: no weights applied (default) or local cluster weighting
  - Jet energy scale: calibration factors and pileup subtraction (default), calibration factors only, pileup subtraction only or no corrections at all
  - Calorimeter readout: full scan (default) or partial scan
- Excellent performance due to porting much offline code to the HLT
- Now apply jet-area-dependent ambient energy correction
- Per-event HLT trigger efficiency turn-on curves compared between data and MC simulation for three typical thresholds
- Data scouting allows us to write out data at much higher rate to increase the sensitivity in low dijet mass resonance searches

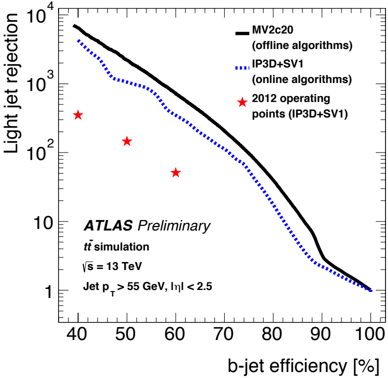


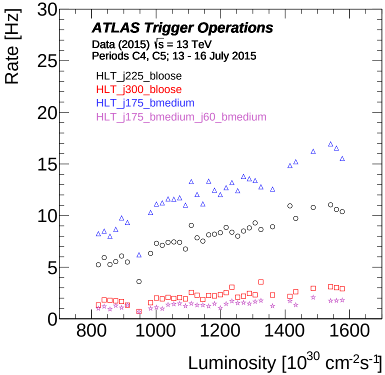


First trigger results at 13 TeV

b-jet trigger efficiencies and performance

- *b*-tagging performance is much improved over 2012 due to a better algorithm tuning and the addition of a 4th innermost pixel layer (Insertable B-Layer, IBL)
- The operating points bloose and bmedium are optimized such that the efficiency for selecting *b*-jets is 79% and 72%, respectively



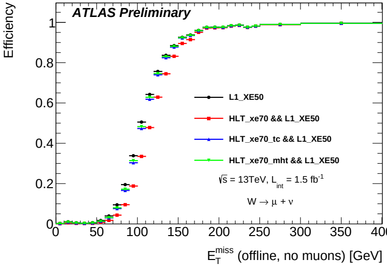


First trigger results at 13 TeV

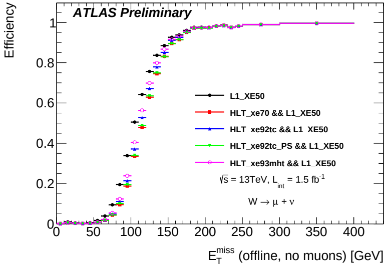
E_T^{miss} trigger efficiencies and performance

- Pileup mitigation as main challenge of the E_T^{miss} trigger
- Different algorithms studied:
  - default: cell-based algorithm
  - tc: topocluster-based algorithm
  - tc_PS: topocluster-based algorithm with a pileup subtraction scheme
  - mht: jet-based algorithm
- Trigger efficiency measured on events selected using the lowest unprescaled single muon trigger and applying a $W \to \mu\nu$ selection

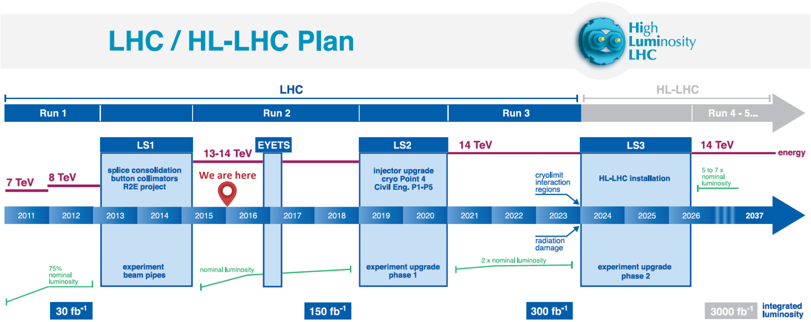
Lowest unprescaled triggers activated during the 25 ns runs



Thresholds for the different algorithms corresponding to equal trigger rate



LHC schedule



Run-1 (2010-2012)

- $\sqrt{s} = 7\,(8)$ TeV
- 50 ns bunch spacing
- $L_{int} \sim 30$ fb^{-1}
- $L_{peak} \sim 7.5 \times 10^{33}$ cm^{-2}s^{-1}
- $\langle\mu\rangle \sim 30$

Run-2 (2015-2018)

- $\sqrt{s} = 13\,(14)$ TeV
- 25 ns bunch spacing
- $L_{int} \sim 100 - 150$ fb^{-1}
- $L_{peak} \sim 1.3\text{-}1.5 \times 10^{34}$ cm^{-2}s^{-1}
- $\langle\mu\rangle \sim 40$

Run-3 (2021-2023)

- $\sqrt{s} = 14$ TeV
- 25 ns bunch spacing
- $L_{int} \sim 300$ fb^{-1}
- $L_{peak} \sim 2 \times 10^{34}$ cm^{-2}s^{-1}
- $\langle\mu\rangle \sim 60$

Conclusions

- Many improvements in the ATLAS trigger system during the LHC shutdown (2013-2014) to keep trigger thresholds as low as possible and selections offline-like:
  - L1 Calorimeter and Muon trigger upgraded
  - New L1 Topological trigger
  - New Central Trigger Processor
  - New HLT architecture
  - Higher L1 and HLT bandwidth
  - Large speed-up in the HLT software (tracking and clustering)
- Trigger successfully commissioned with 50 and 25 ns data in 2015
- First performance studies of the different trigger signatures have been presented using 13 TeV data (minimum bias, e/γ, muons, taus, jets, b-jets and E_T^{miss})
- Prospects for data taking in 2016:
  - Trigger menu prepared for 2×10^{34} cm^{-2}s^{-1}
  - Tile D-layer and TGC coincidence ongoing
  - L1 Topological trigger to be commissioned
  - FTK to be installed and commissioned during this year
- More information in: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerPublicResults