Triggers at ATLAS and CMS

Oleg Kuprash

TEL AVIV UNIVERSITY

On behalf of the ATLAS and CMS Collaborations

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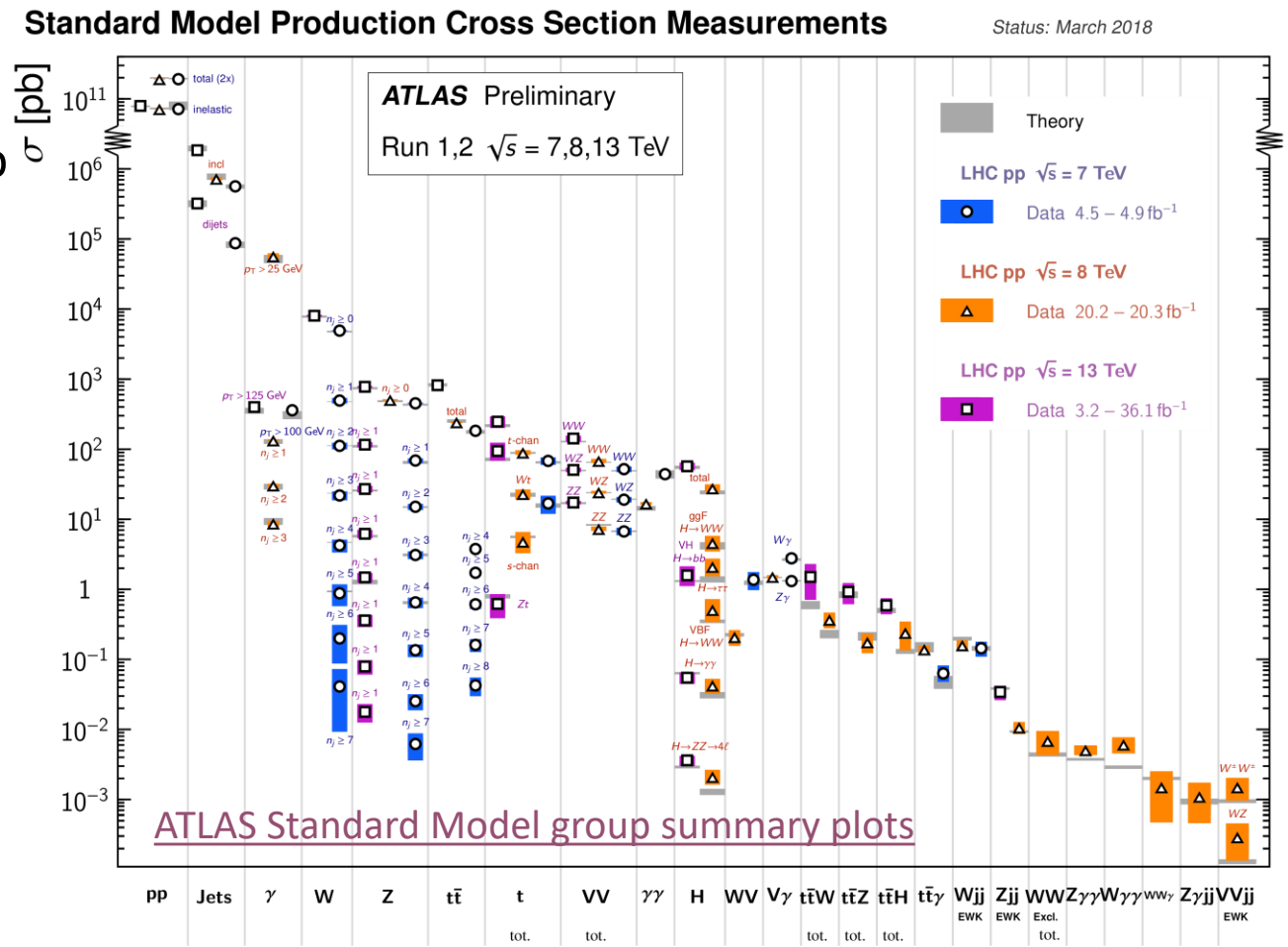
Why having a trigger?

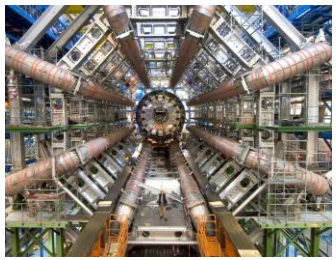
- Cross sections for many processes of interest are up to 13 orders of magnitude smaller than the total *pp* cross section
- LHC bunch spacing 25 ns, peak <μ> about 60 *pp* interactions per bunch crossing
  - ➢ Beyond capabilities of data readout & storage infrastructure (~1 MB/event)

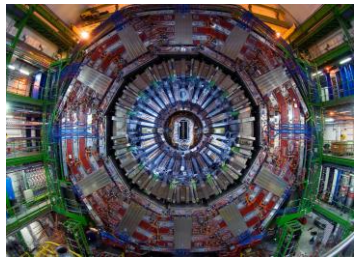


Trigger is the mechanism to promptly select the events to be recorded for offline analyses

ATLAS and CMS triggers

- ATLAS and CMS are both general-purpose detectors with similar physics programs
- Similar two-level trigger designs in Run-2:
  - Hardware Level-1 (L1) trigger gives a fast first guess if the event is interesting, using muon detectors and calorimeters
  - High Level Trigger (HLT): software-based (computer farm), with a much better energy and position resolution than at L1
- Differences between ATLAS & CMS triggers:
  - At L1 calorimeter trigger ATLAS uses sliding window (e/gamma, taus, jets) and simple cone (jets); CMS uses sliding window (jets) and dynamic clustering (e/γ, taus)
  - Muon trigger: ATLAS uses a subset of the Muon spectrometer for L1 trigger; whole muon system used for L1 in CMS
  - At L1 accept, ATLAS reads out Regions of Interest (RoI), while CMS reads out full detector





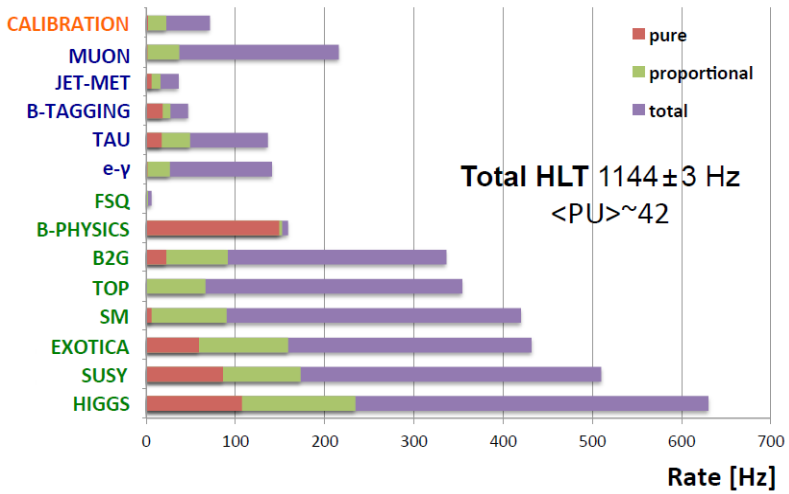
	ATLAS, CMS
L1 input rate	40 MHz
L1 output rate	100 kHz
L1 latency	2.5 μs, 3.8 μs
HLT output rate	O(1) kHz
HLT average processing time	About 200 ms*

*at $1.4 \cdot 10^{34}$ $cm^{-2}s^{-1}$, <μ>~40, highly sensitive to pileup, take with caution

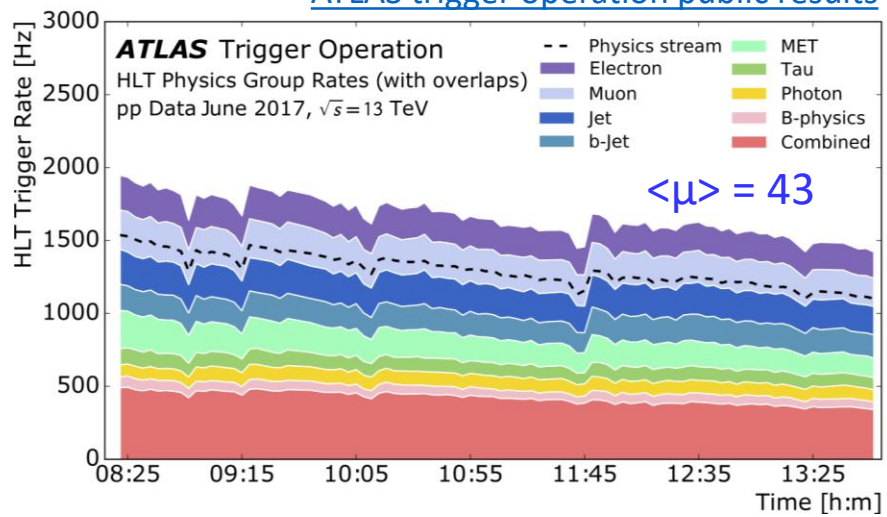
What about the physics content?

Physics content

CMS HLT rates in 2016 Mia Tosi @ EPS17



ATLAS trigger operation public results

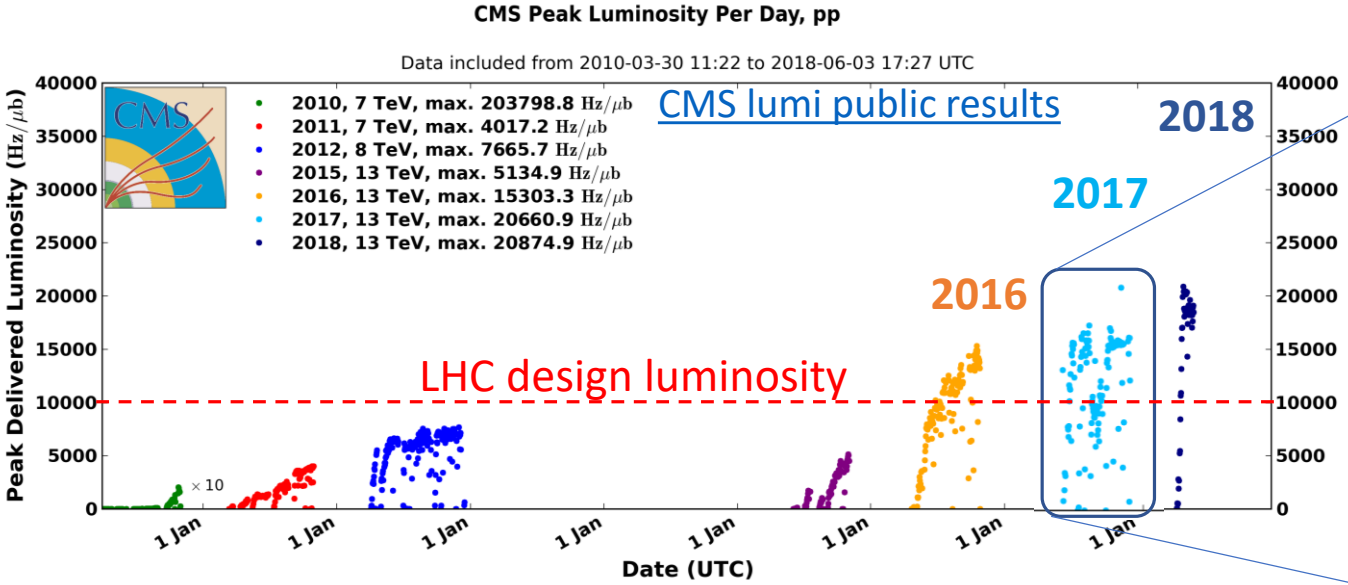


- Bandwidth allocated for various trigger objects follows the experiment priorities
- Combined triggers (based on multiple signatures) allow maintaining low energy thresholds
- Similar p_T thresholds for lowest unprescaled triggers for ATLAS and CMS
- Rich trigger menu provided by both experiments

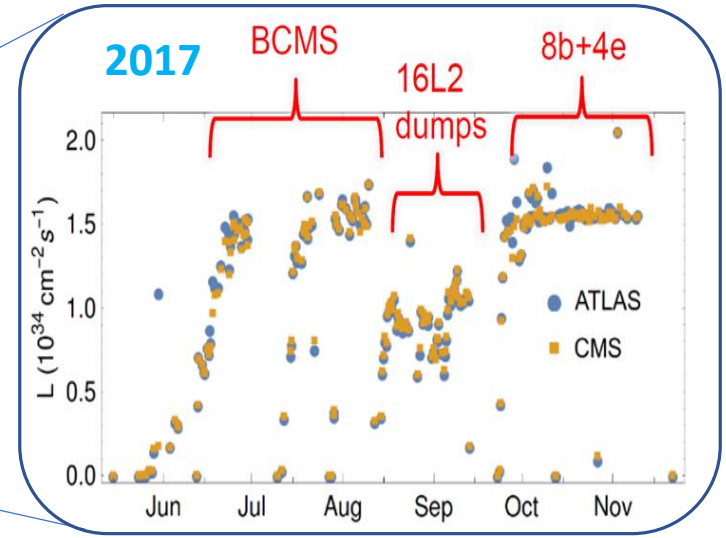
ATLAS trigger menu table

	ATLAS HLT (GeV)	CMS HLT (GeV)
Single electron	26 (i)	32
Single muon	26 (i)	24 (i)
Dimuon	22, 8	17, 8
e + μ	26, 8 (7, 24)	23, 8
Single gamma	140	110 (i)
Two photons	2x20	30, 18
Two taus	35, 25	35, 35
Single jet	460	500
Two b-jets (e=60%)	175, 60	-
Missing E_T	110	120
Total H_T	-	1050
Number of HLT items	~1500	~650

LHC luminosity evolution



M. Zerlauth @ 133d LHCC

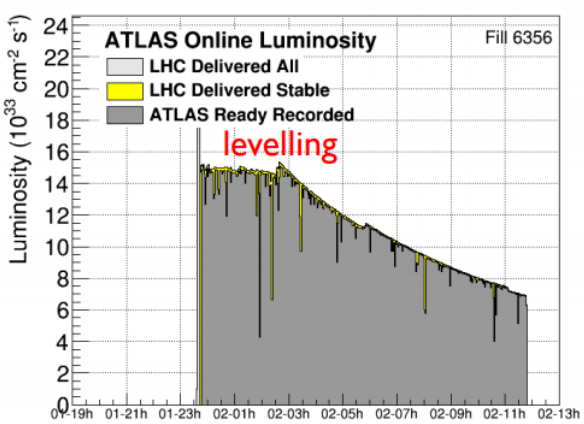


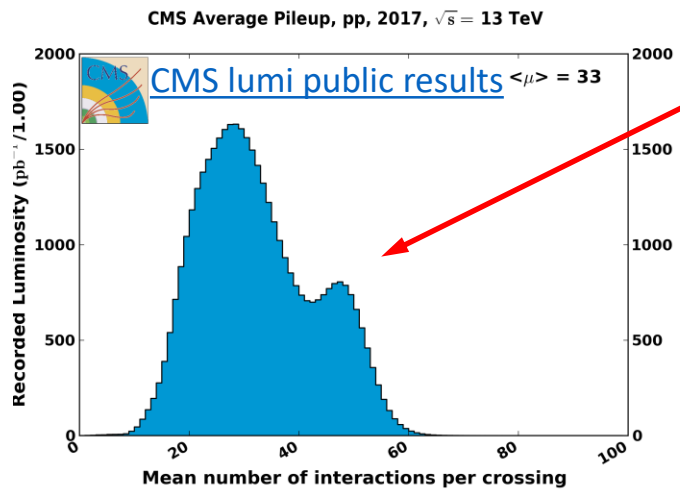
- In 2016 LHC went above the design luminosity. Experiments triggers needed to accommodate:
  - Raise energy thresholds (loosing data)
  - Prescale triggers (loosing data)
  - Use more robust methods (topological L1 trigger, combined triggers, optimize HLT software)
- 2017: "Gruffalo" problem: beam dumps due to fast beam losses in sector 16L2 (gas leakage)
  - As a remedy, LHC changed the injection pattern: 8 filled bunches followed by 4 empty bunches
  - **8b4e** has 20% less bunches than nominal scheme -> lower instantaneous luminosity
  - To keep the same luminosity, LHC increased number of protons/bunch and squeezed the beams
  - Number of pileup interactions <μ> increased to ~80; ATLAS & CMS requested luminosity leveling

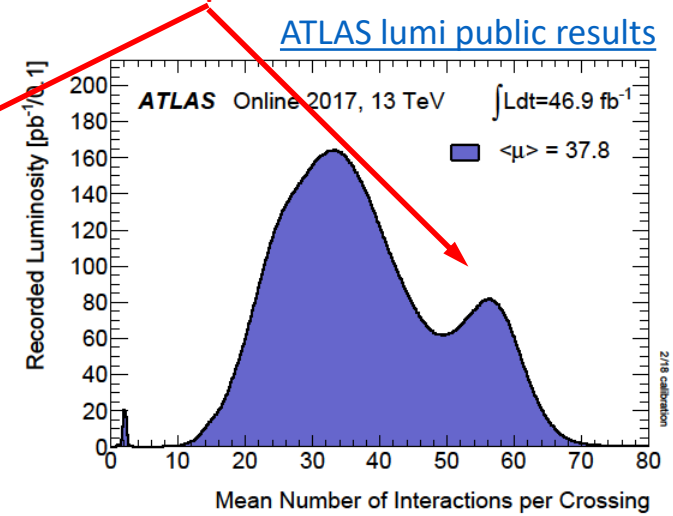
Luminosity leveling

- For both experiments, in September 2017 the limit of trigger systems was reached at average <μ> = 60
  - ➢ CMS: L1 rate limit (L1 output rate too high)
  - ➢ ATLAS: HLT farm limit (limited by number of CPU cores)
- Solution: ATLAS and CMS requested to level the instantaneous luminosity at $1.5 \cdot 10^{34}$ $cm^{-2}s^{-1}$ and <μ> = 55…59
  - ➢ Number of options to level: not head-on beam collisions, change beams crossing angle, change β*

Leveling at a ~constant <μ> below 60





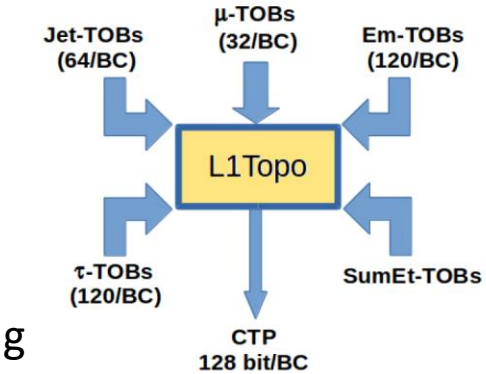


Leveling proved to be a successful approach to preserve physics reach of the experiments!

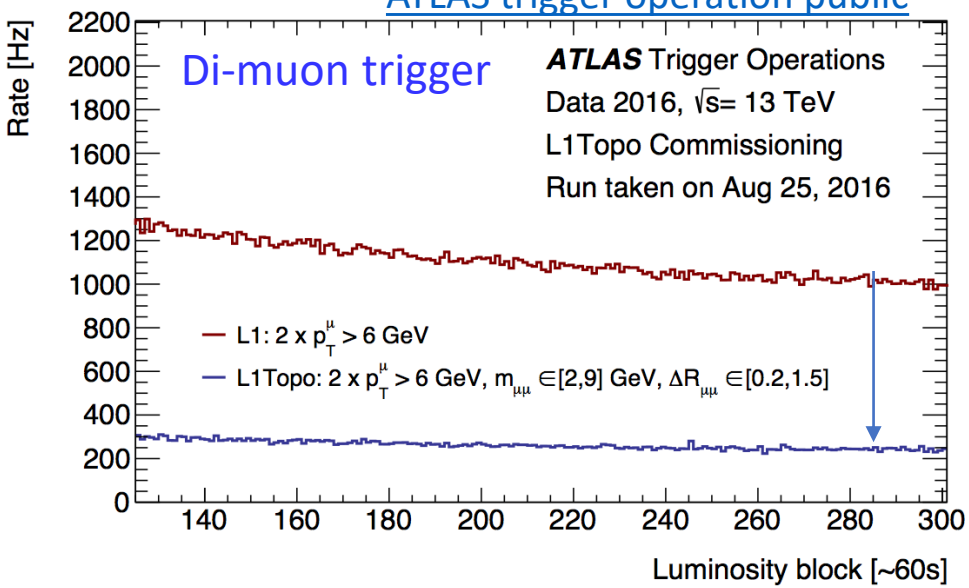
> 50% of the 2017 data taken in runs with luminosity leveling

ATLAS: topological L1 trigger

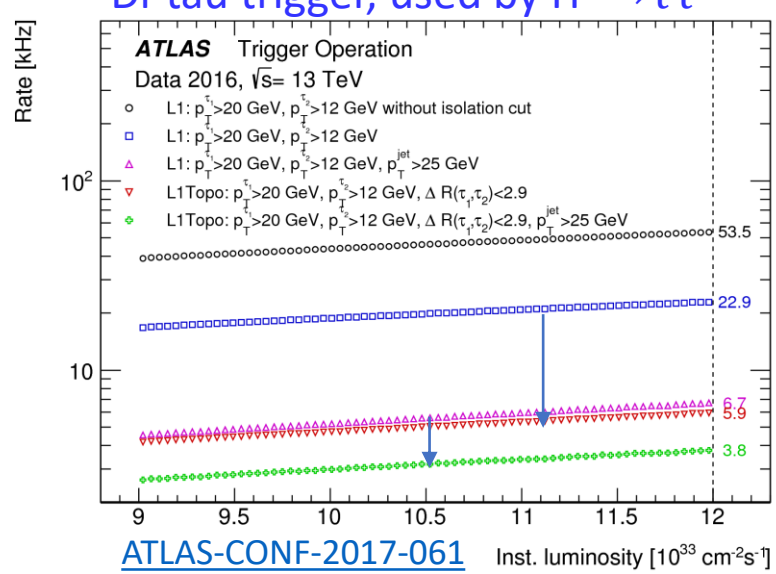
- New component in Run-2
- Better selection at L1 by using geometrical and kinematic information (e.g. invariant masses) in addition to energy thresholds to reduce the rate and remain efficient for physics signals
  - ➢ Input: L1Calo and L1Muon Trigger Objects (TOBs)
  - ➢ Outputs up to 128 result bits to the central trigger (equivalent to having 128 cut-based analyses running online at L1)
- Example impact: significant reduction of rate by applying DeltaR requirements



ATLAS trigger operation public



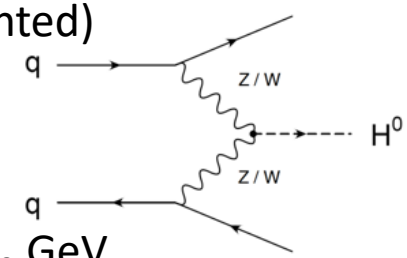
Di-tau trigger, used by H ⟶ττ



ATLAS-CONF-2017-061

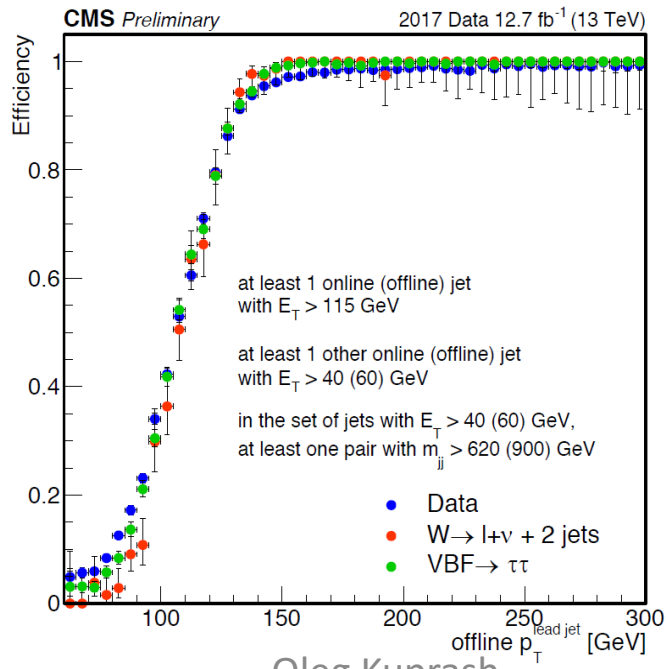
CMS: upgraded L1 trigger

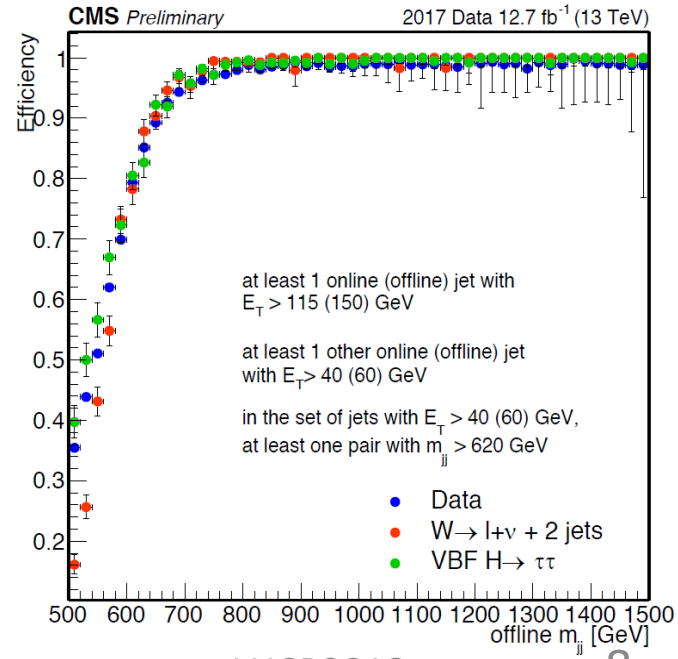
- Since 2016: increased trigger tower granularity at L1 (4x finer granularity in both eta and phi than in Run-1); dynamic clustering at L1
- L1 global trigger: allows triggering on complex object correlations (e.g. invariant masses) for muons, electrons, taus, jets and $E_{T,miss}$ (2017: 486 algorithms implemented)
  - ➢ Example L1 algorithm: VBF trigger
    - ✓ At least one L1 jet with $E_T > X_1$ GeV
    - ✓ At least one L1 other jet with $E_T > X_2$ GeV ($X_1 > X_2$)
    - ✓ Among L1 jets with $E_T > X_2$ GeV, at least one pair with $m_{jj} > X_3$ GeV



CMS-DP-2018-005

- L1 VBF trigger efficiency vs offline is measured in data and MC. L1 selection:
  - ➢ X_1 = 115 GeV
  - ➢ X_2 = 40 GeV
  - ➢ X_3 = 620 GeV

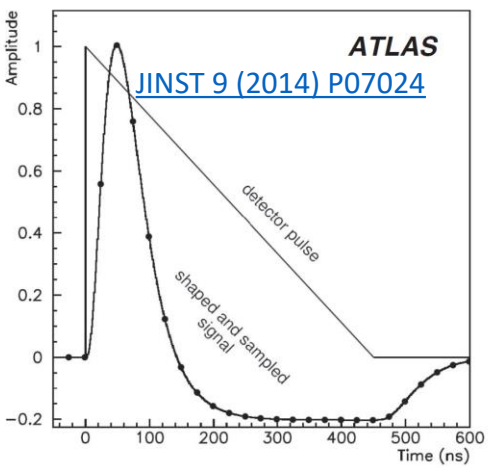


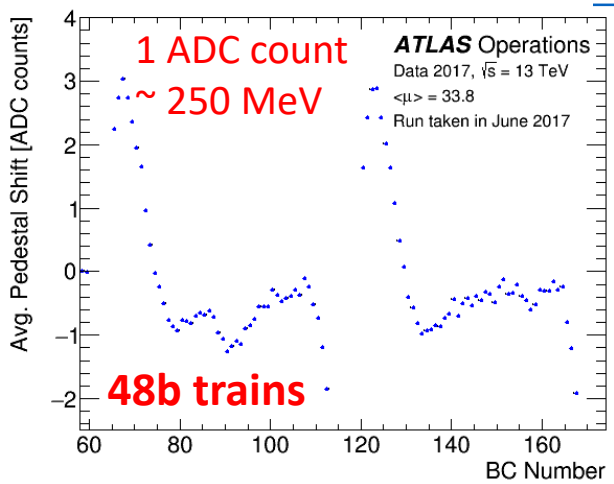


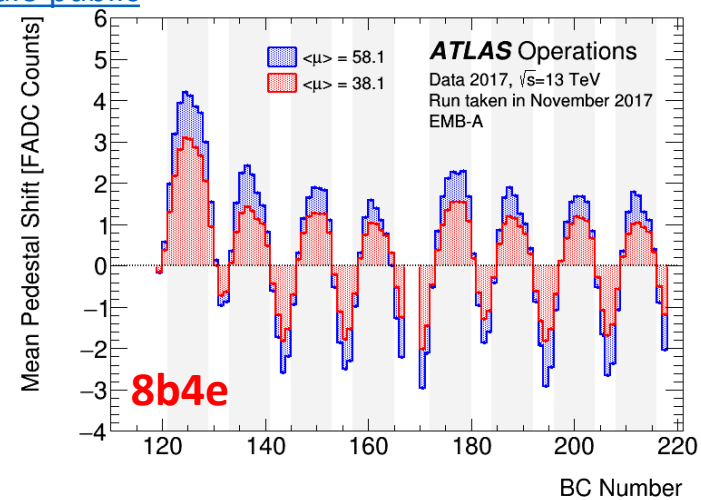
ATLAS: L1Calo bunch-by-bunch pedestal correction

- LAr calorimeter pulses are longer than time between bunch crossings ⟶ increase of the L1Calo rate at the beginning of the bunch train due to interplay of in-time and out-of-time pileup
- Apply the dynamic correction by subtracting the average input (averaging over O(1000) orbits, for each bunch position individually): significantly reduced the rates of jet and missing E_T triggers
  - ➢ Helped to adapt fast to the 8b4e filling scheme, for which the LAr calorimeter pileup correction was not optimized initially

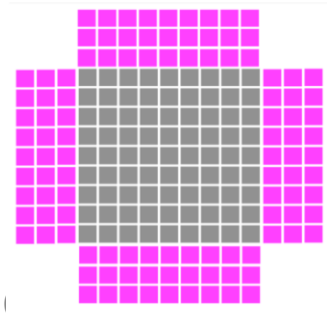
L1Calo public

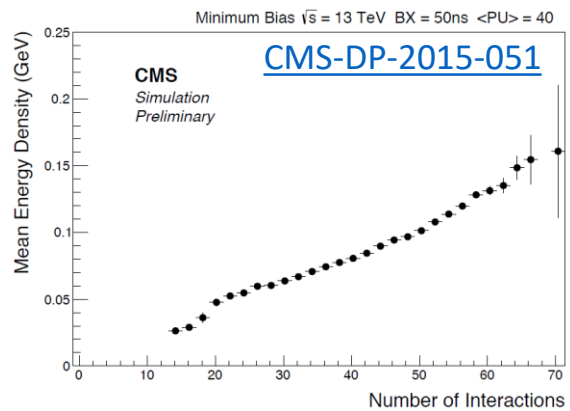






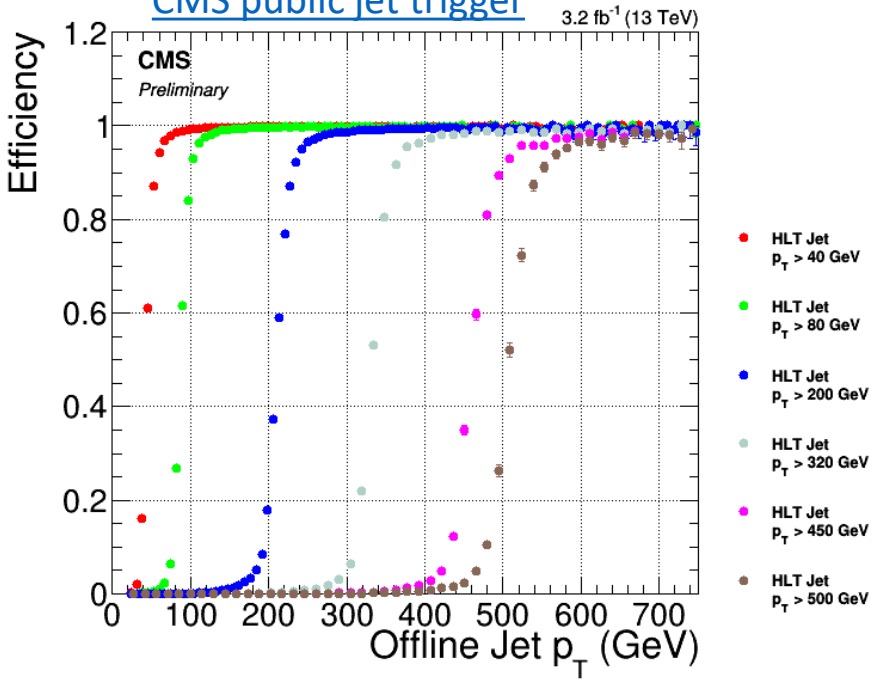
- CMS applies "donut" pile-up correction: subtract average activity in calorimeter trigger towers around jet
  - ➢ Activity around jet scales linearly with the pileup



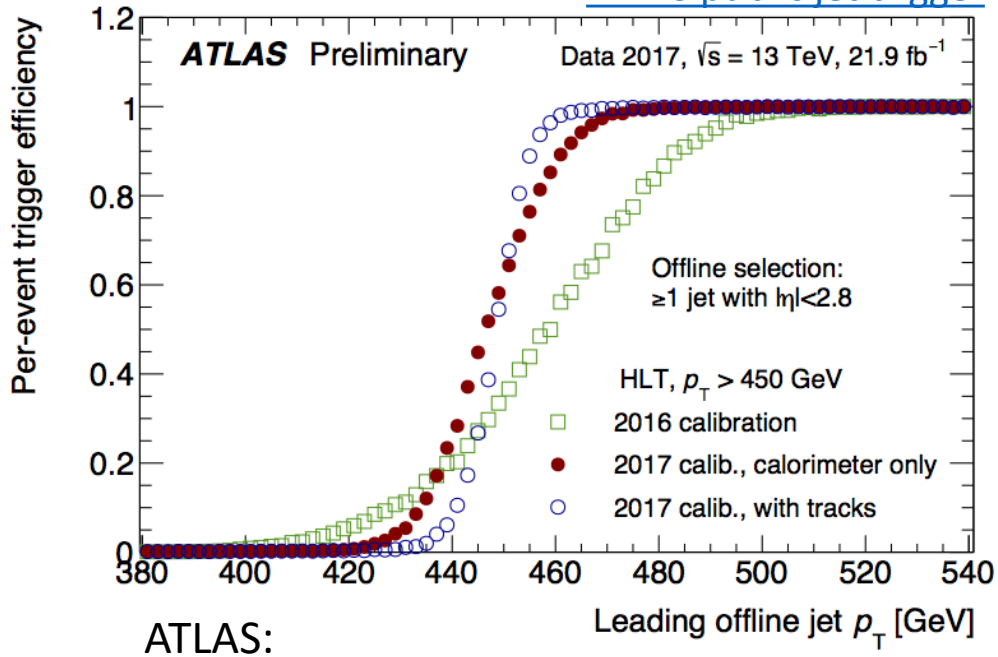


Performance: jet triggers

CMS public jet trigger



ATLAS public jet trigger



CMS:

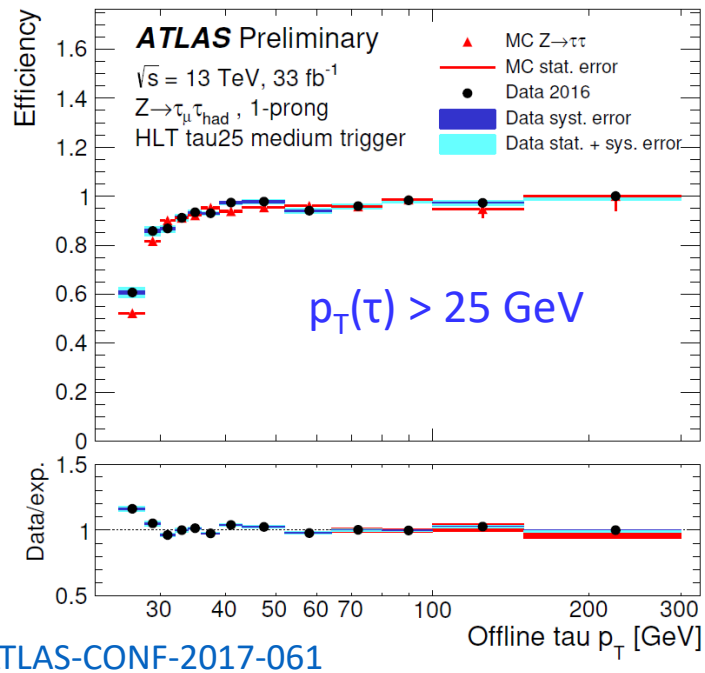
- Efficiency vs offline jet p_T for jets matched to HLT, $|\eta| < 3.0$
- HLT (and offline) jets reconstructed with particle flow algorithm, clustering with anti-k_T algorithm R=0.4

ATLAS:

- Efficiency vs leading offline jet p_T
- Jet clustering algorithm over calorimeter cells
- Updated calibration in 2017:
  - Global sequential calibration (GSC): improves jet energy resolution by taking into account shower shape
  - In situ corrections using tracking information (eta-intercalibration)

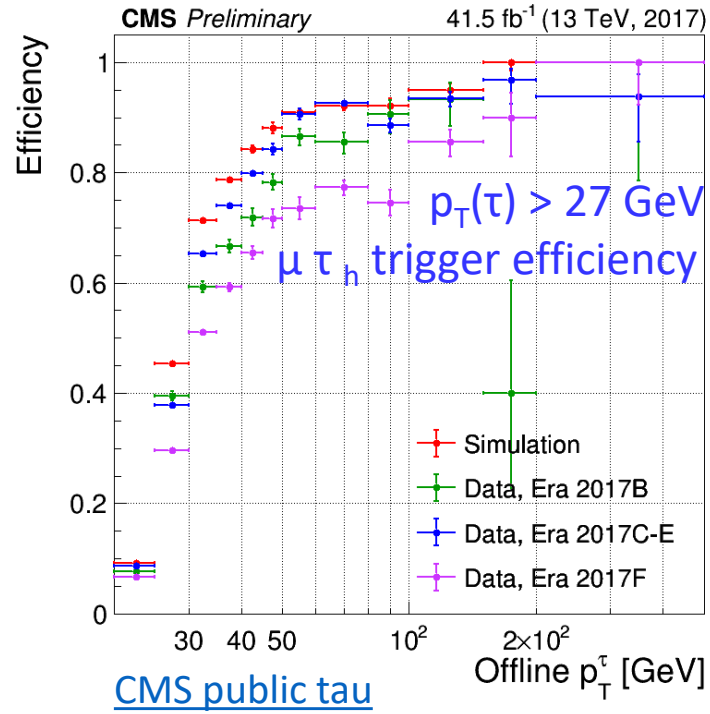
Performance: tau triggers

- HLT efficiency vs offline $p_T(\tau)$ for $Z \longrightarrow \tau^+\tau^- \longrightarrow \mu\,\tau_h$ events with the tag (μ) and probe (τ) method



ATLAS-CONF-2017-061

Both experiments were able to observe $H \longrightarrow \tau\,\tau$ signal with optimized τ triggers



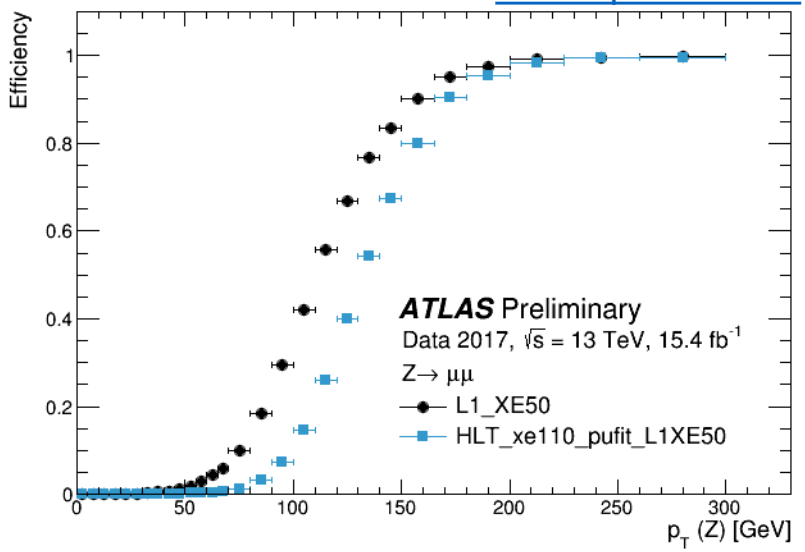
CMS public tau

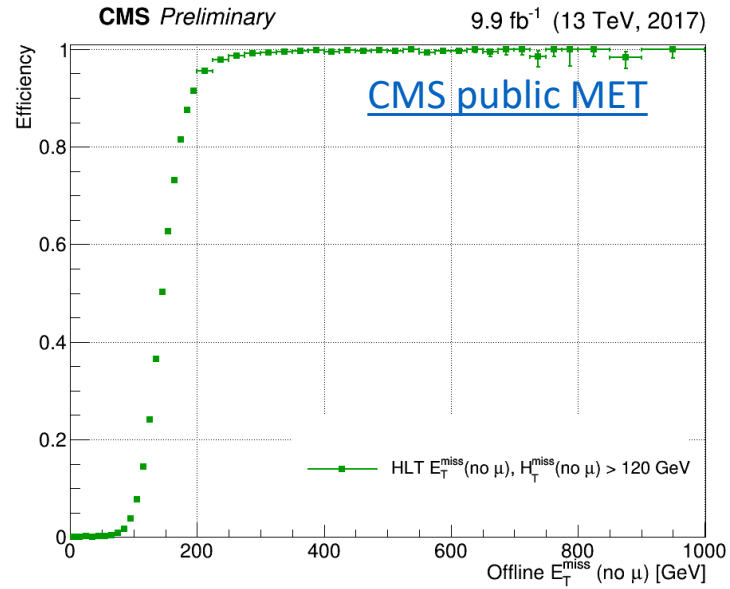
- ATLAS: seeded by L1 tau RoI
- Two-stage fast tracking at HLT
- Particle identification provided by a boosted decision tree

- CMS: seeded by $\mu + \tau$ at L1
- Efficiency in data affected by changing conditions of the pixel detector
- Higher performance of the updated CMS L1 trigger brings additional improvement

Performance: missing E_T trigger

ATLAS public MET

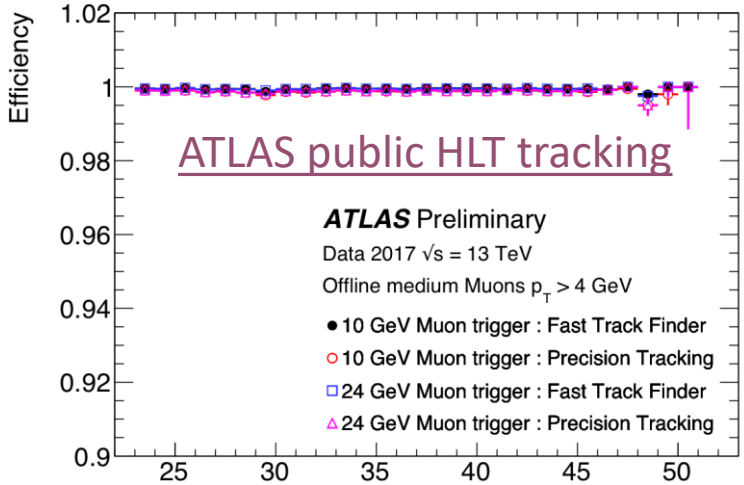


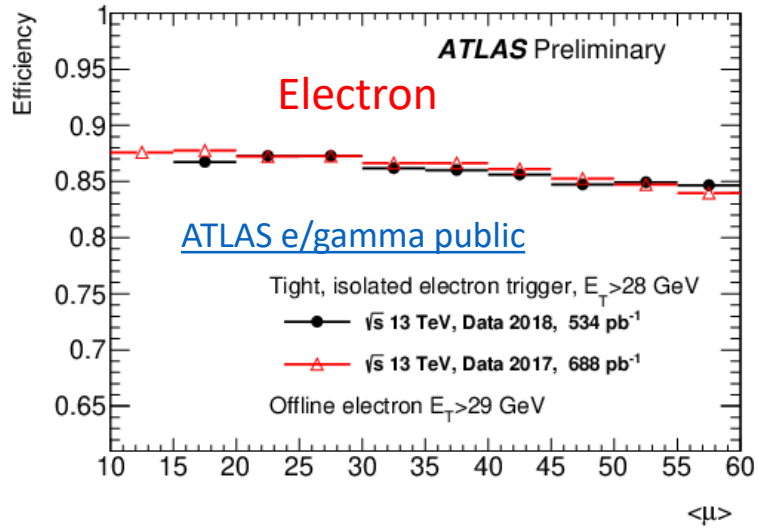


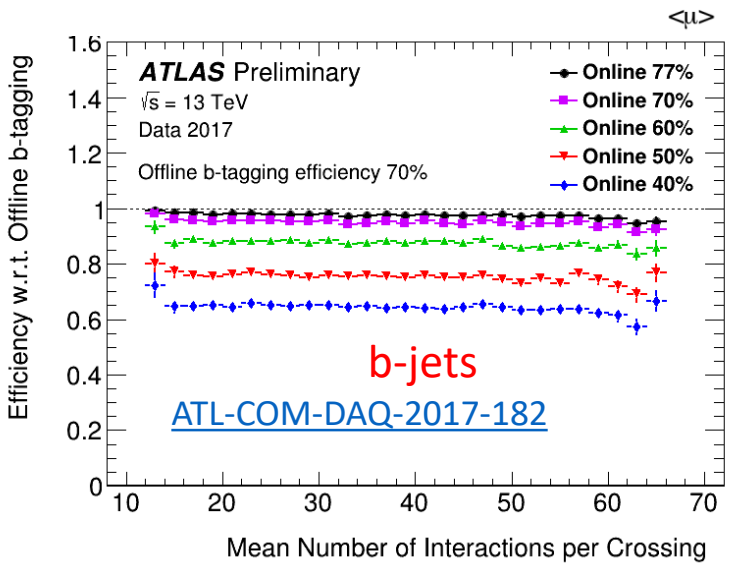
- ATLAS: HLT efficiency for E_T^{miss} > 110 GeV as calculated for Z ⟶ μ μ data selected events
- Dependence on $p_T(Z)$ is given
  - ➢ Muons are treated as invisible objects by the trigger concerned
- "Pufit" algorithm calculates the negative of the transverse momentum vector sum of calorimeter topological clusters corrected for pileup

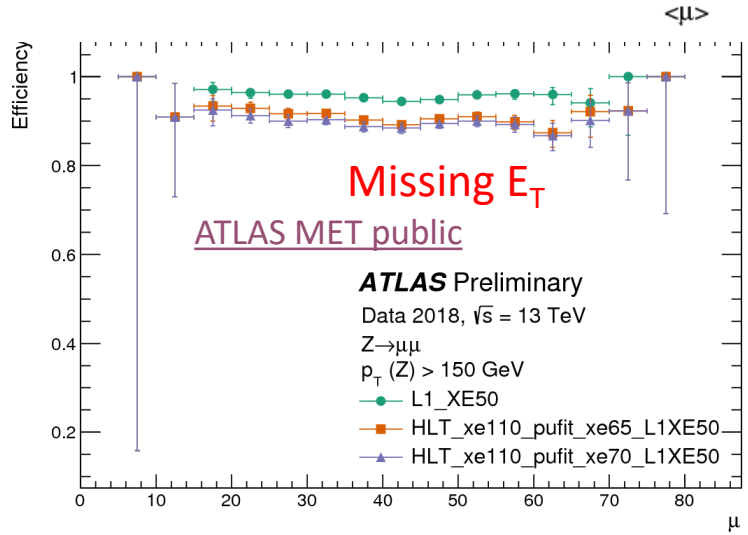
- CMS: HLT efficiency for H_T^{miss} > 120 GeV for a single muon dataset
- H_T^{miss} obtained from the vector sum of transverse momenta of jets reconstructed with the particle flow algorithm, after removing muons (i.e. hadronic contribution only)

Performance: dependence on pileup (ATLAS)









- Good stability of the efficiency vs pileup

ATLAS & CMS Trigger Upgrades

- 2018 is the final year of LHC Run-2, followed by two years Long Shutdown 2 (LS2):
  - ATLAS working on redesigning HLT software to use multithreading and on L1 hardware improvements (e.g. superclusters for L1Calo)
  - CMS L1 trigger is Phase-I upgraded since 2016
- Upgrades for LS3 (2023-2025):
  - Major improvement is the inclusion of silicon trackers at L1
    - L1 latency will increase (2.5 ⟶ 40 μs ATLAS, 4 ⟶ 12.5 μs CMS)
  - Use full calorimeter granularity
  - ATLAS: include MDT into trigger
  - L1 output rates: ATLAS 400 kHz, CMS 750 kHz

Summary

- ATLAS and CMS triggers demonstrate excellent performance and flexibility
  - Continuously developed following the evolution of the LHC instantaneous luminosity above the design value
  - Very good coordination between LHC and experiments
- High pileup environment in 2017 posed a difficulty for triggers of both experiments; helps for better understanding of bottlenecks towards Run-3 (even higher pileup)
- Work on upgrades towards Run-3 and HL-LHC ongoing in both experiments

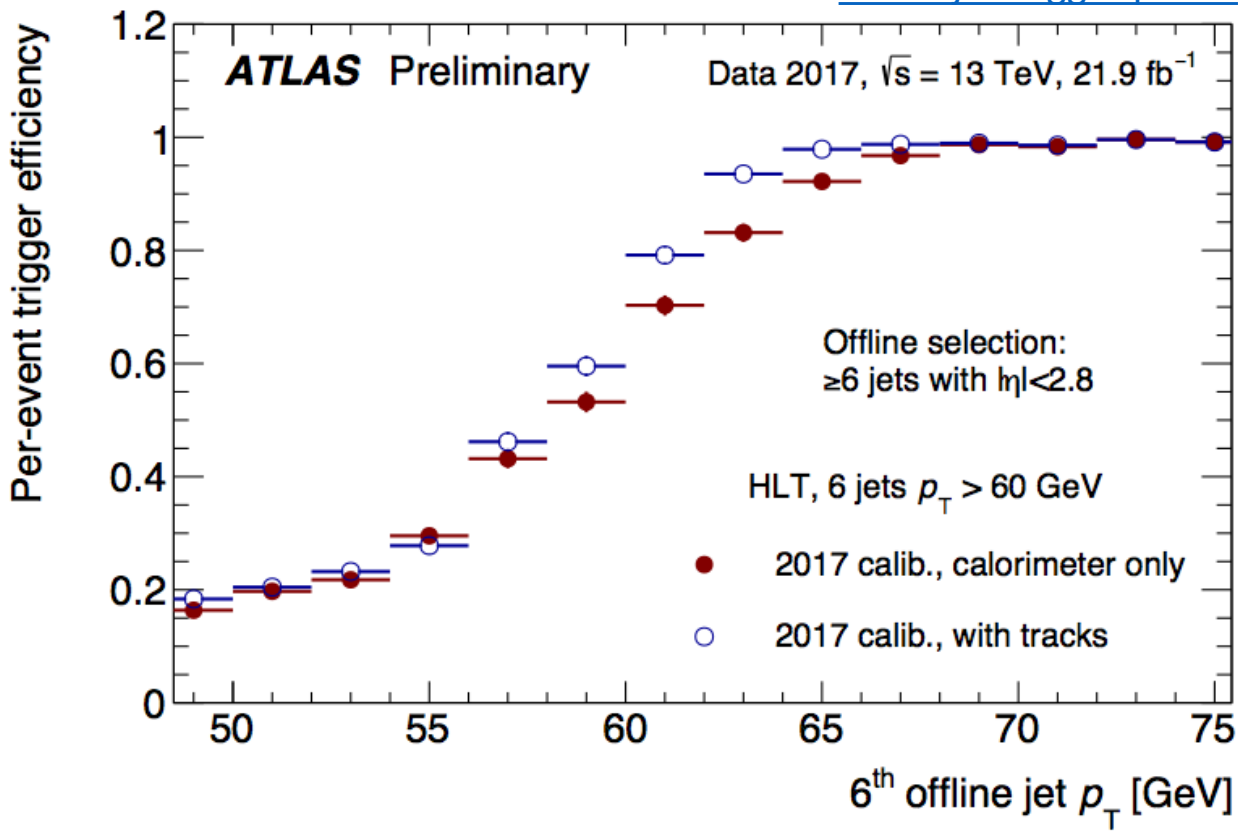
Backup

References

- The CMS trigger system, JINST 12 (2017) P01020, arXiv:1609.02366
- CMS trigger public results, https://twiki.cern.ch/twiki/bin/view/CMSPublic/HighLevelTriggerRunIIResults , https://twiki.cern.ch/twiki/bin/view/CMSPublic/L1TriggerDPGResults
- CMS trigger performance, 6th international Conference on New Frontiers in Physics – Kolymbary – August 2017
- The Phase-2 Upgrade of the CMS DAQ Interim TDR, CMS-TDR-018
- Performance of the ATLAS Trigger System in 2015, Eur. Phys. J. C 77 (2017) 317, arXiv:1611.09661
- ATLAS trigger public results, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerPublicResults , https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults
- ATLAS TDR for the Phase-II upgrade of the TDAQ system, ATLAS-TDR-029

ATLAS: Multi-jet trigger

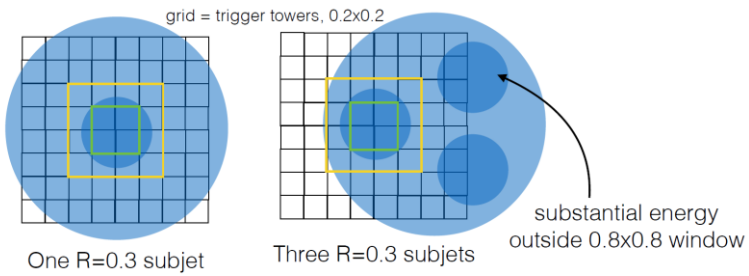
ATLAS jet trigger public



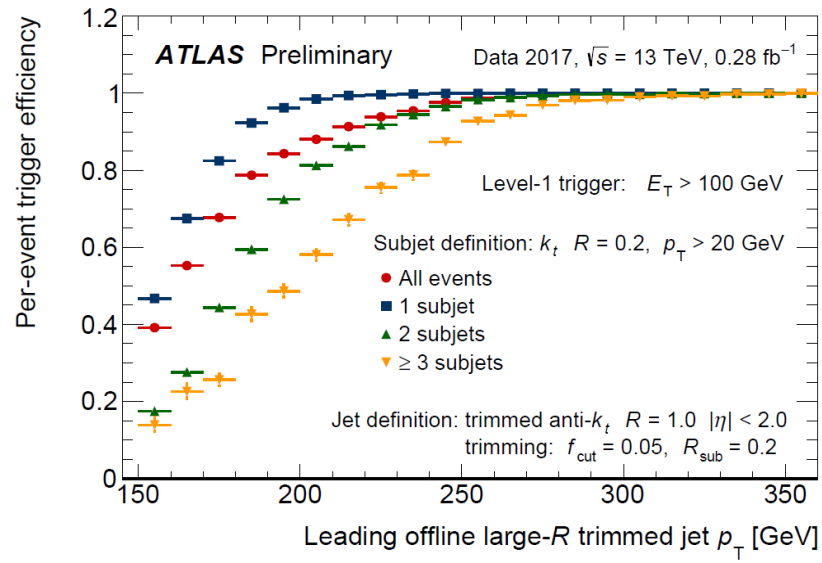
- Efficiency of the unprescaled 6-jet trigger
- Using data driven eta-intercalibration correction improves the efficiency in the turn-on region

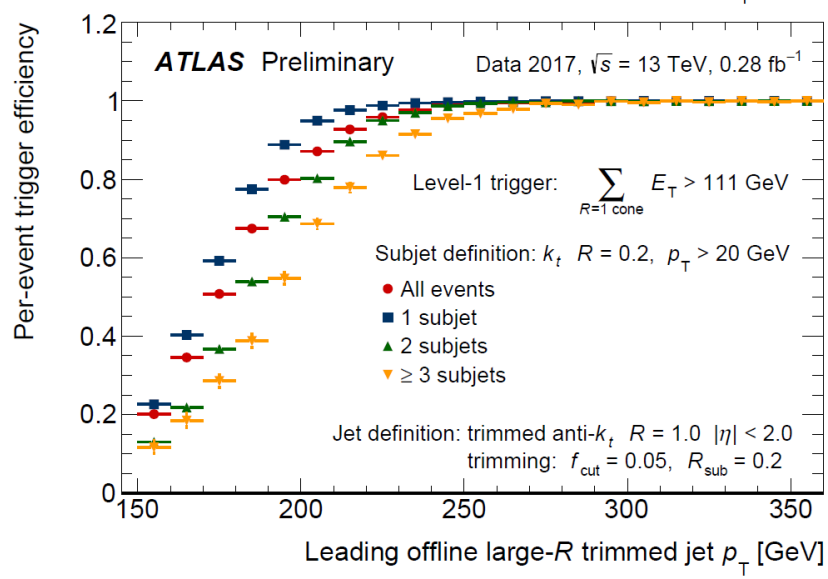
ATLAS: L1Topo trigger for large-R jets

- L1J100 trigger requires E_T > 100 GeV in a Δη x Δϕ window of 0.8 x 0.8 (RoI) within a sliding-window algorithm
  - ➢ Misses large-R jets with substructure



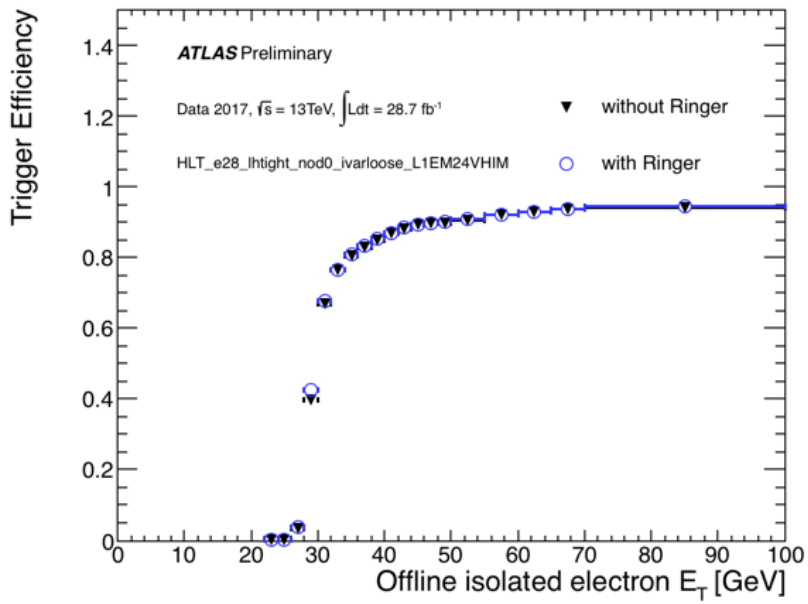
- SimpleCone L1Topo item L1_SC111 avoids this problem by summing E_T RoIs with E_T > 15 GeV within a cone of radius 1.0
- The threshold of 111 GeV gives equal rate to L1J100 trigger
  - ➢ Trigger efficiency is improved for jets with ≥3 subjets

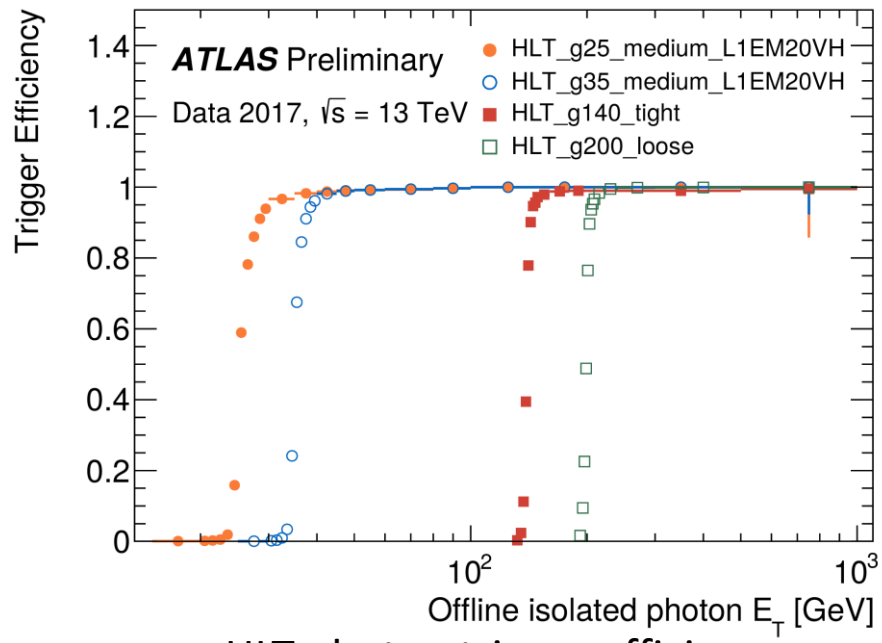




Performance: ATLAS e/gamma triggers

ATLAS public e/gamma





- HLT electron trigger efficiency vs offline electron E_T
- New in 2017: HLT uses Ringer algorithm, based on ensemble of neural networks fed by ring-shaped energy description

- HLT photon trigger efficiency vs offline photon E_T
- Selection of triggers with loose, medium and tight identification requirements