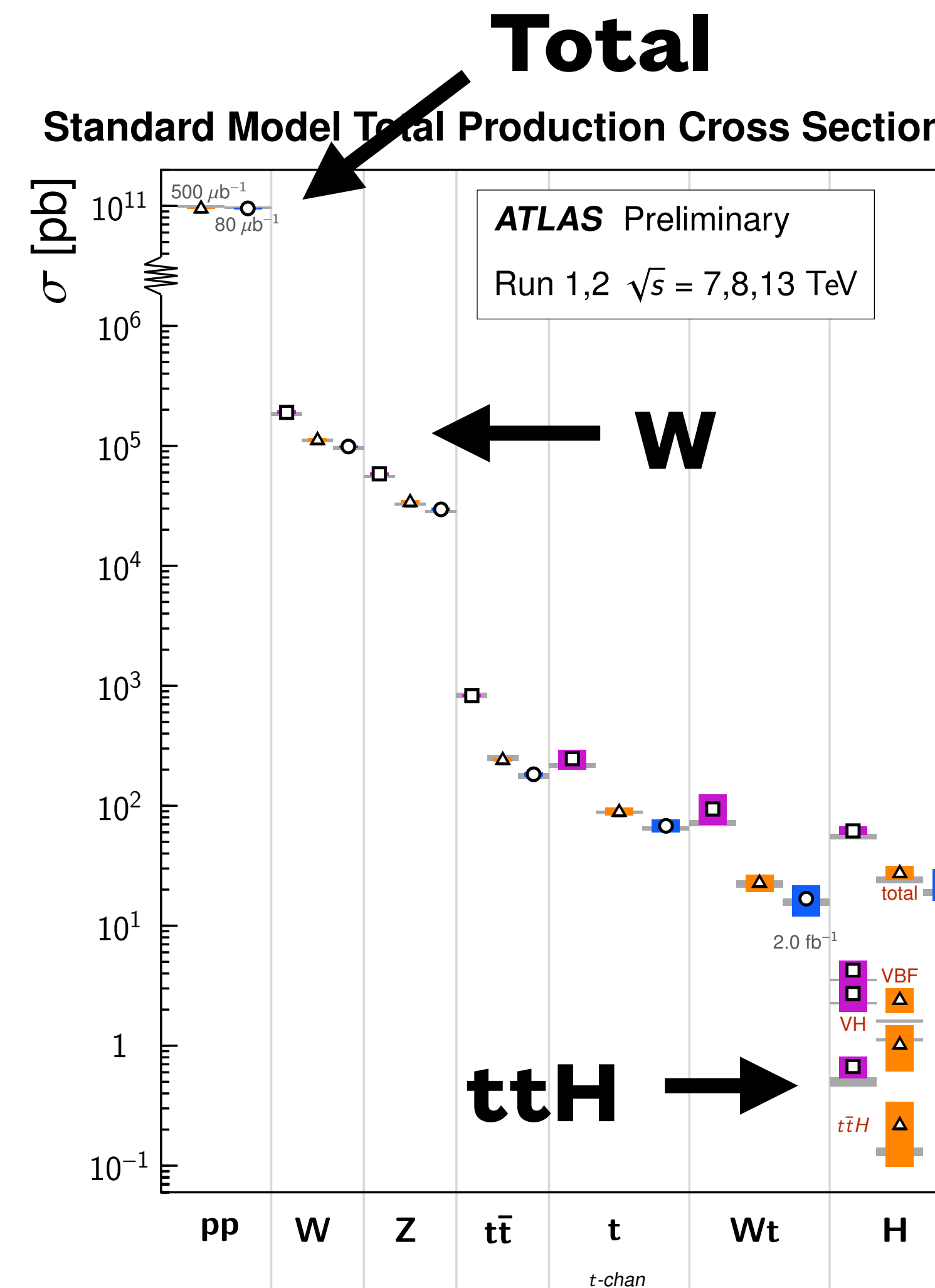```python
from ATLAS import trigger

if coolPhysics == True:

    trigger.doStoreEvent()

else:

    pass
```

# Triggering in the ATLAS Experiment

*making sure the needle ends up in the haystack*

JAVIER MONTEJO BERLINGEN (CERN) ICHEP 2020

# Introduction

- The **Trigger** system of an experiment at a hadron collider has a critical role, unfeasible to reconstruct and/or store every collision

- Need to reject orders of magnitude of soft QCD before reaching the interesting electroweak / high-$p_T$ / BSM regime

- Two-level system to reduce
  40 MHz collisions → 100 kHz L1 → 1 kHz HLT → storage

- To put rates in context @13 TeV and 2e34 cm$^{-2}$s$^{-1}$ we expect ~600 Hz of **W**(→lep), and ~0.01 Hz of **ttH**

- The trigger needs to decide in < 2.5μs (at L1) and < 500 ms average (at HLT) which events to store and which to reject.
  Compared with up to 30 sec for full offline reconstruction

**Total**

Standard Model Total Production Cross Section

$\sigma$ [pb]

**ATLAS** Preliminary
Run 1,2 $\sqrt{s}$ = 7,8,13 TeV

$10^{11}$  $500\ \mu b^{-1}$  $80\ \mu b^{-1}$

**W**

$10^6$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

total

2.0 fb$^{-1}$

VBF

VH

**ttH**

$t\bar{t}H$

$10^{-1}$

pp    W    Z    $t\bar{t}$    t    Wt    H

*t-chan*

# Level-1 trigger

- **L1** hardware-based trigger (40 MHz → **100 kHz**)

  - Output rate limited by detector readout

  - Use coarse information from calorimeter (L1Calo) and muon (L1Muon) systems to define (η × φ) Region-of-interest (RoI) for feature extraction

  - Simple selection on different signatures: muon, (isolated) calorimeter energy deposits consistent with electron/photon, tau, jet, MET

  - Several improvements in Run 2
    - Muon endcap - calorimeter coincidence
    - Updated filters and noise cuts of L1Calo hardware logic

- **L1Topo** provides more sophisticated selections (angle, mass, …)

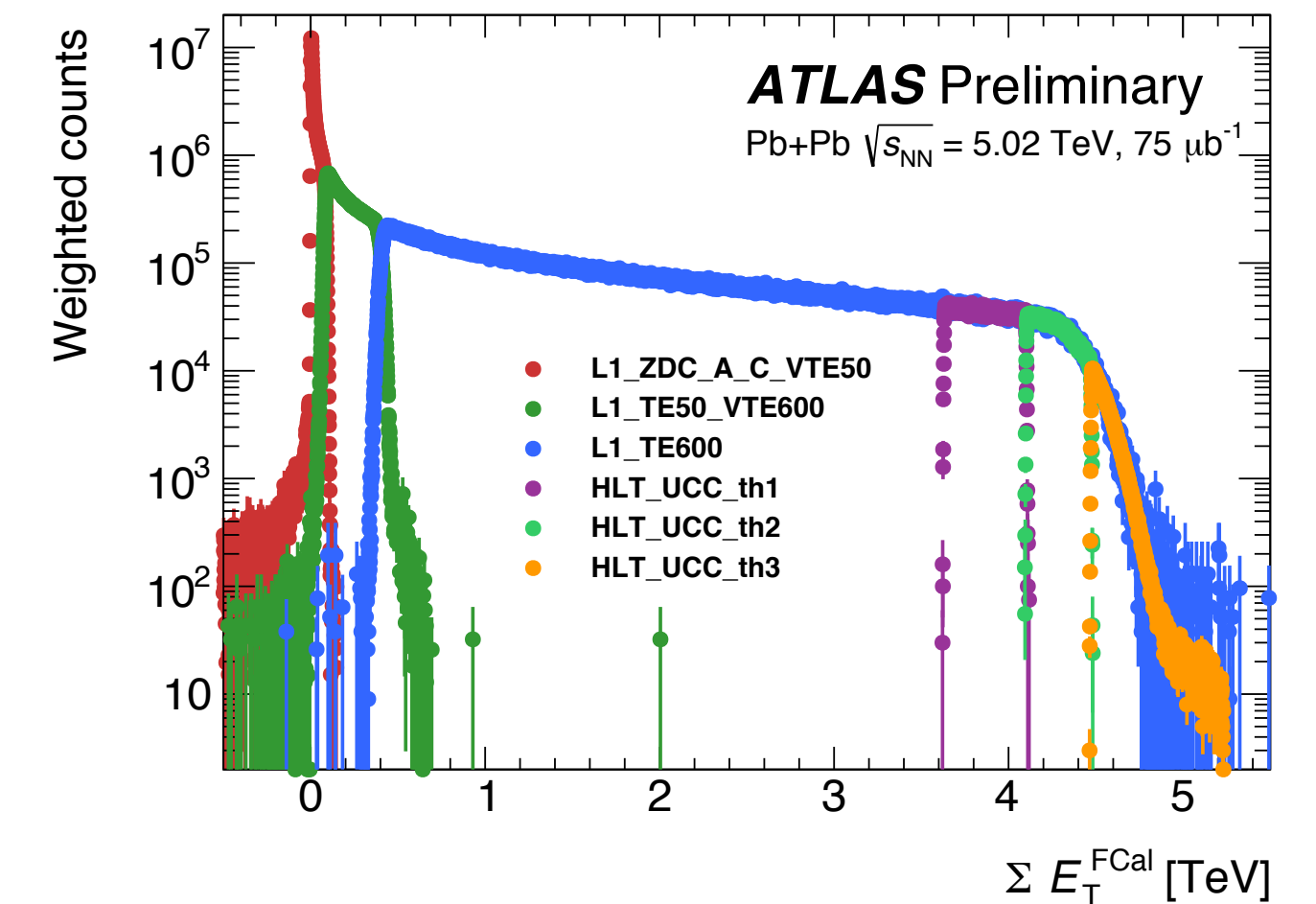  - Critical for triggers such as di-tau and b-physics
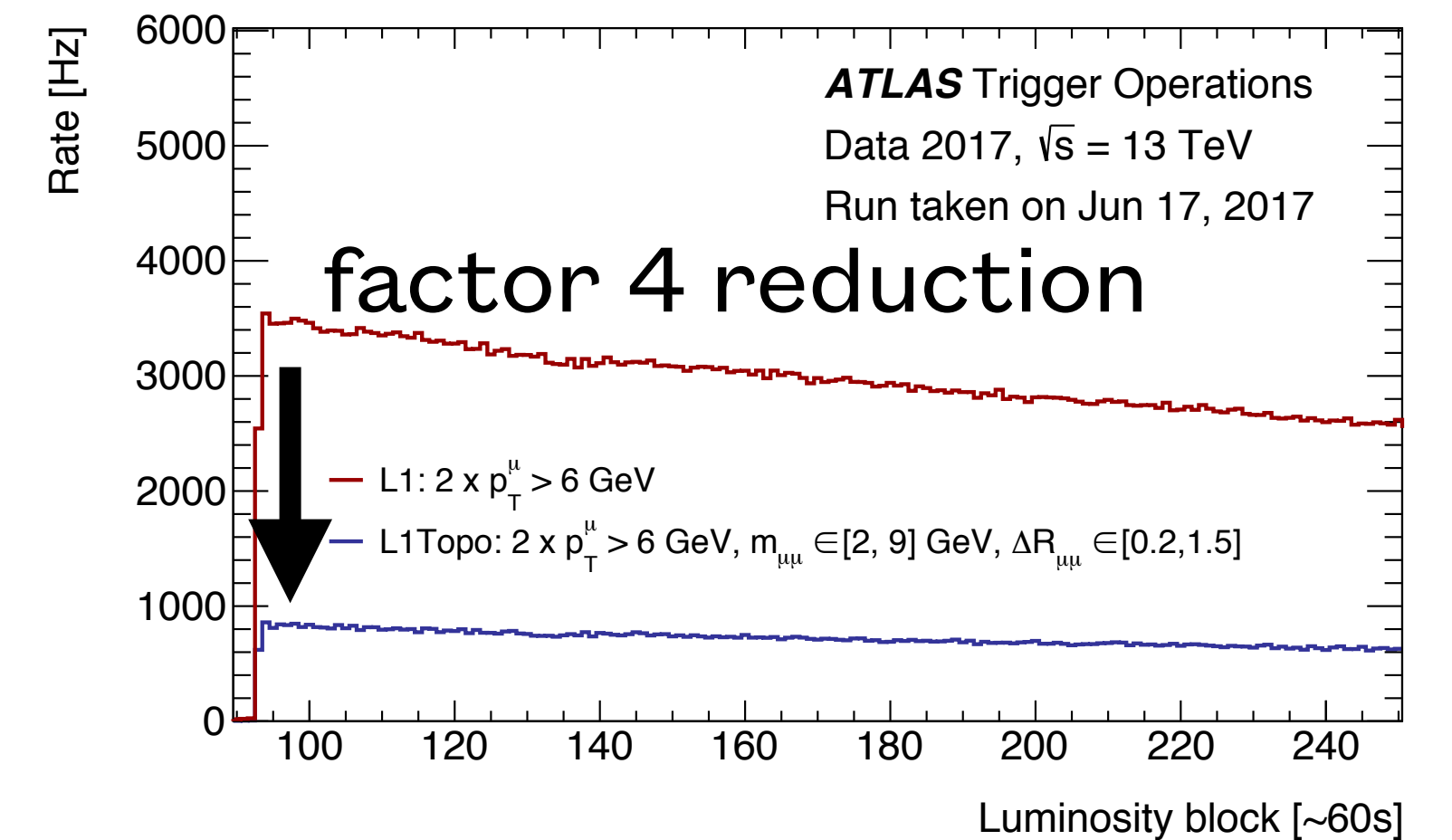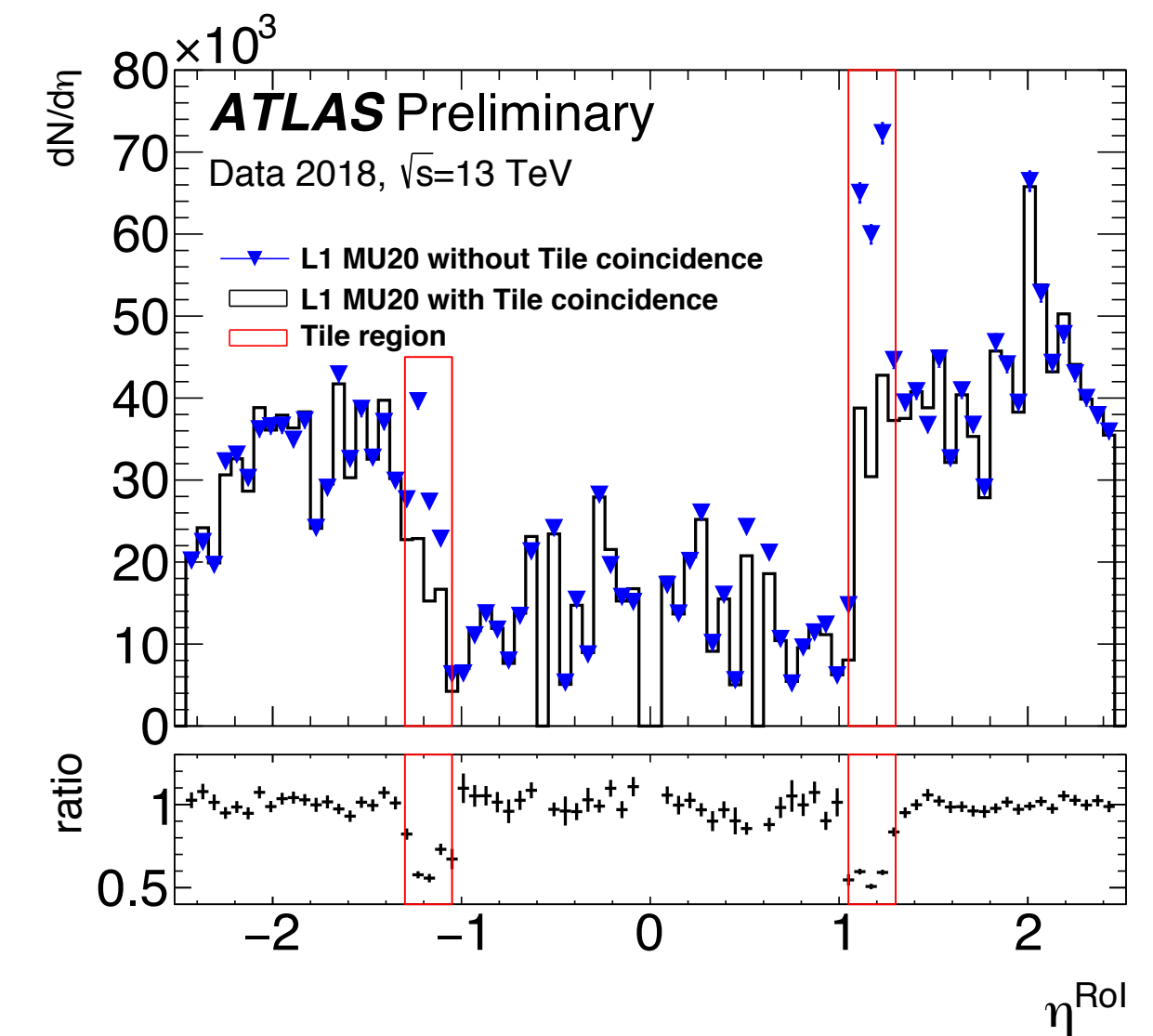
# High-level trigger

- **HLT** software-based trigger (100 kHz → **1 kHz** average)
  - Full-granularity data available in a region-of-intereset (RoI) or full event
  - Selection very close to offline, including also multivariate selections, e.g. for b-tagging and tau identification
  - Latency O(s), max average processing time ~500 ms

- Up to ~1500 HLT selection chains defined, out of which 300 physics primaries

- Managed to keep the same kinematic selection on trigger particle candidates throughout Run 2 with help of improved identification, pile-up rejection methods, etc

# ATLAS Trigger menu @2e34

- Trigger decision is based on a set of conditions (object $p_T$, identification, isolation, multiplicity), that define the **Trigger menu**

  - documented in ATL-DAQ-PUB-2019-001
  - Highest rates at HLT for single muon/electron, ditau, MET
  - Same $p_T$ threshold for electron/muon at HLT

- Also documented dedicated menus for heavy-ion, low-μ dataset (μ≈2), special runs



| Trigger | Typical offline selection | Trigger Selection | | L1 Peak Rate [kHz] | HLT Peak Rate [Hz] |
| | | L1 [GeV] | HLT [GeV] | $L=2.0\times10^{34}$ cm$^{-2}$s$^{-1}$ | |
|---|---|---|---|---|---|
| Single leptons | Single isolated $\mu$, $p_T > 27$ GeV | 20 | 26 (i) | 16 | 218 |
| | Single isolated tight $e$, $p_T > 27$ GeV | 22 (i) | 26 (i) | 31 | 195 |
| | Single $\mu$, $p_T > 52$ GeV | 20 | 50 | 16 | 70 |
| | Single $e$, $p_T > 61$ GeV | 22 (i) | 60 | 28 | 20 |
| | Single $\tau$, $p_T > 170$ GeV | 100 | 160 | 1.4 | 42 |
| | Two $\mu$, each $p_T > 15$ GeV | 2 × 10 | 2 × 14 | 2.2 | 30 |
| | Two $\mu$, $p_T > 23, 9$ GeV | 20 | 22, 8 | 16 | 47 |

# Trigger menu design

- Designing the menu is a **balance** between analysis requests (store all the physics!) and system constraints
  - Peak L1 rate below 100 kHz (detector readout)
  - Average HLT rate ~1 kHz (storage and prompt reconstruction constraints)
  - Decide within 500 ms in average (available CPU in the HLT farm)

- Want to store only events that are actually going to be used, want online and offline reconstruction algorithms to be as close as possible

- Main **limitation** for:

- Ditau, multijet, b-physics
- Single jet, single photon

- Multi-bjet, low-$p_T$ electrons

- MET, multijets

# Predicting trigger rates and CPU

- Rate and CPU can be predicted for triggers in development making use of <u>Enhanced Bias</u> (EB) data
  - EB data: a dataset with O(1M) events, enhanced in high-$p_T$ objects, selected using only L1 triggers
  - By knowing the L1 prescales the selection bias can be removed with **event weights**
  - Provides an **unbiased** sample with sufficient statistical precision in the high-$p_T$/high-multiplicity regime

- Reprocessing enhanced bias data with a new trigger menu allows to predict rates and CPU for triggers in development



$\sqrt{s}$ = 13 TeV
L = 9.3x$10^{33}$cm$^{-2}$s$^{-1}$

**ATLAS** Preliminary
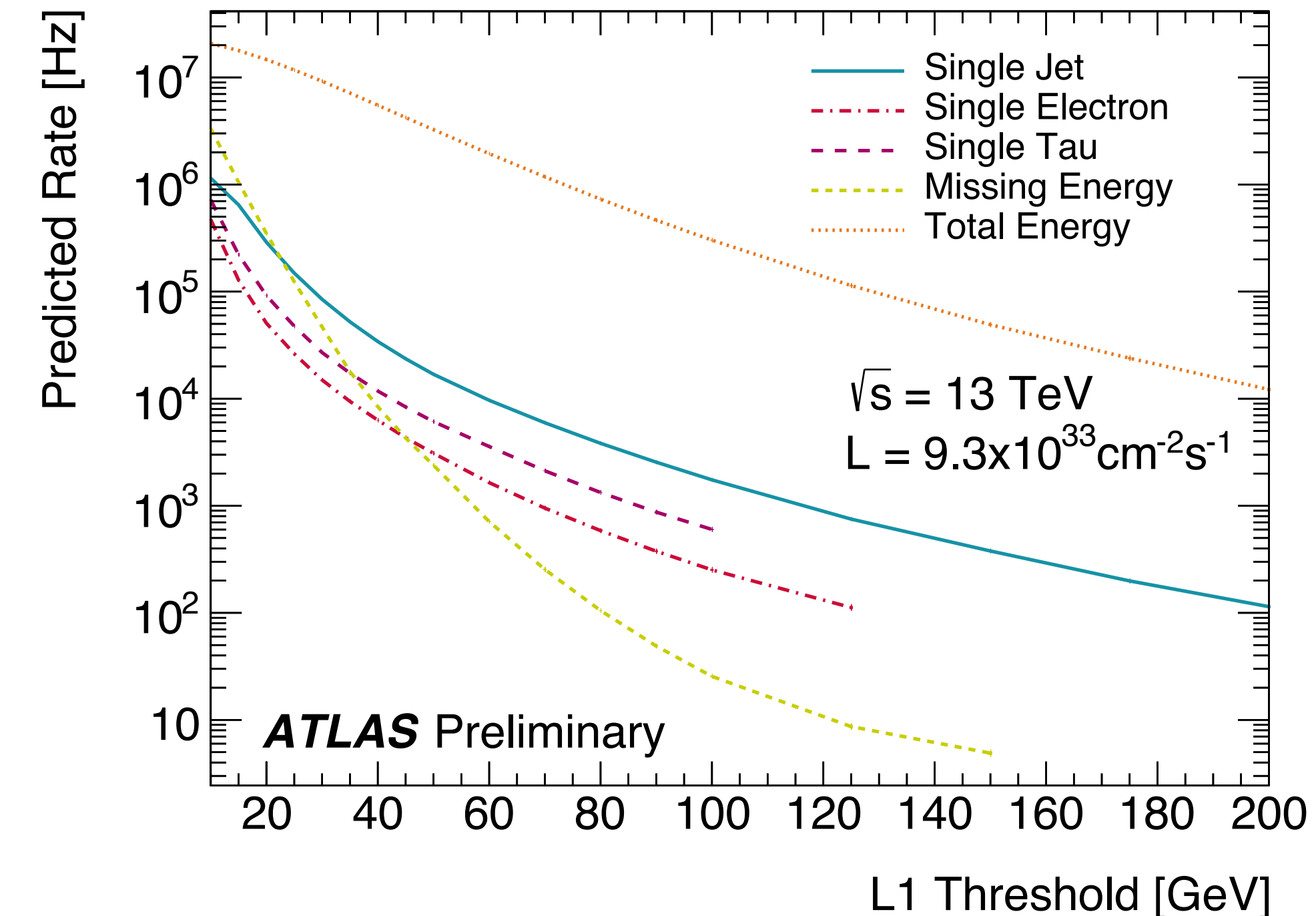
ATL-DAQ-PUB-2016-002

# Performance highlights

- Offline **MET** threshold kept at ~200 GeV across all Run 2 thanks to constant improvements to MET reconstruction
  - 2015 cell: $E_T^{miss}$ from calorimeter cells above noise threshold
  - 2016 mht: $E_T^{miss}$ from calibrated jets
  - 2017 pufit: $E_T^{miss}$ from hard-scatter clusters, sorted out from pileup based on a threshold based on total event energy
  - 2018 pufit+cell

- Improved **tau identification**
  - Feed tracks to a recurrent neural network (**RNN**)
  - Includes a 0-track mode to recover inefficiencies from track finding in the first pass of HLT tracking
  - Better performance allowed to improve the efficiency while keeping the same rate
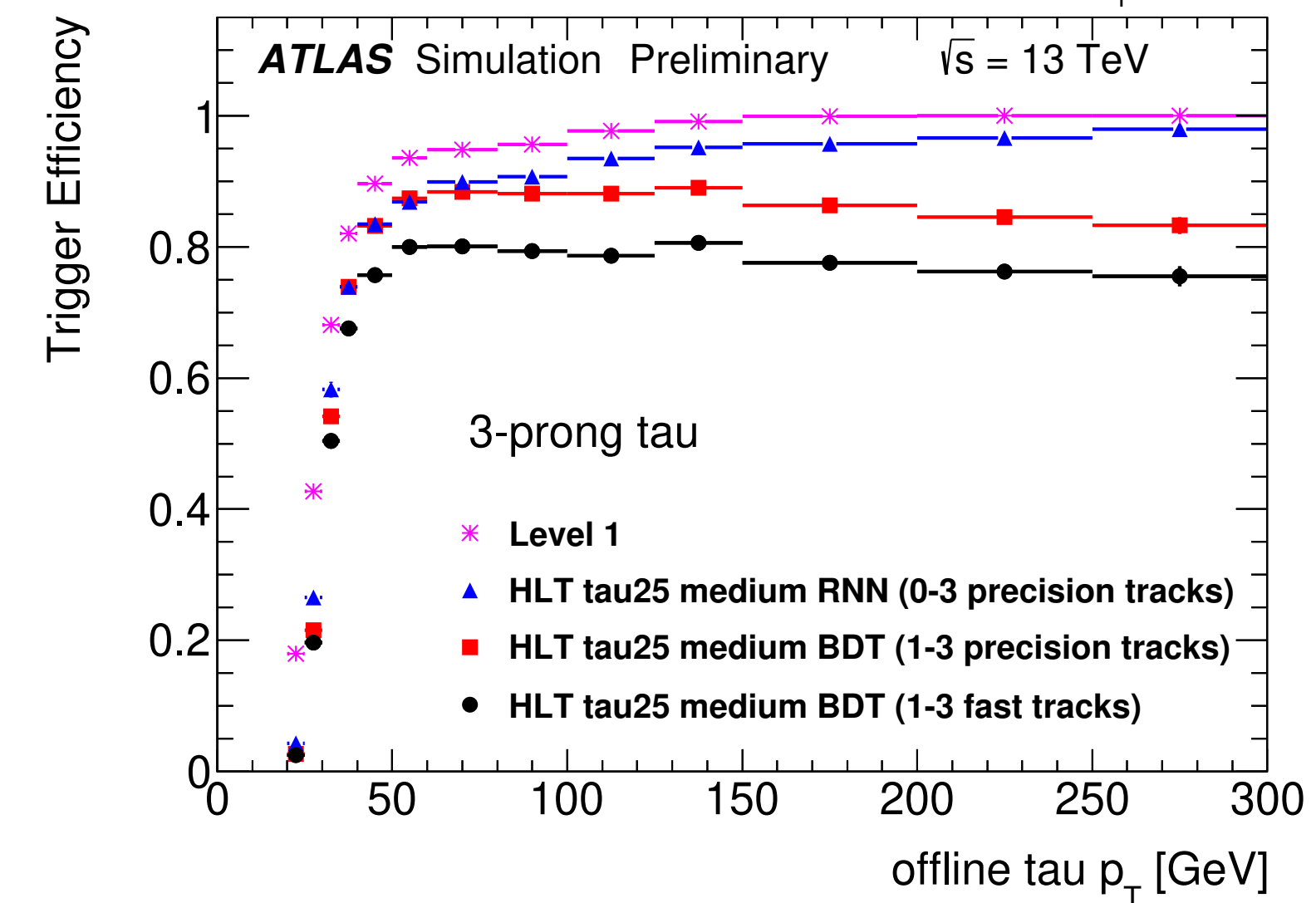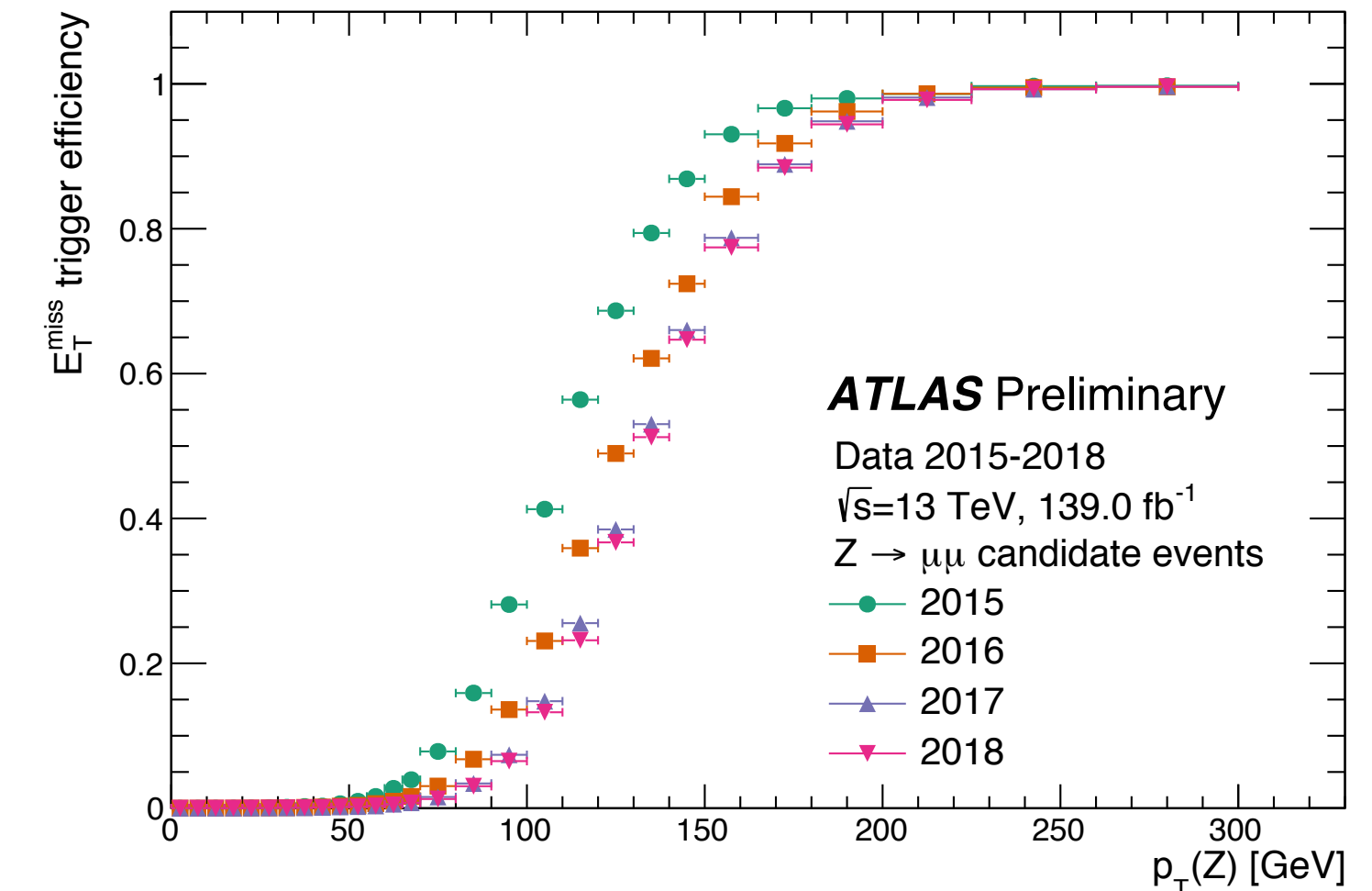
# Performance highlights

- Dedicated **B→K\*ee triggers**, targeting resolved and also merged dielectron final states

- **L1**
  - Resolved: require two separated electrons with $E_T > 7/5$ GeV and $m(e,e) < 9$ GeV
  - Merged: require one electron with $E_T > 7$ GeV close to a jet with $E_T > 15$ GeV
  - Both would have too high rate, and require additionally 1 muon with $p_T > 6$ GeV or 2 muons with $p_T > 4$ GeV
  - **Unseeded**, run HLT algorithm on every L1-accepted event

- **HLT**
  - select two 5 GeV electrons, originating from a common vertex and $0.1 < m(e,e) < 6$ GeV
    - additional muons at HLT if the L1 seed requires muons
  - extremely CPU-demanding, requires to run low-$p_T$ electron reconstruction on every EM RoI
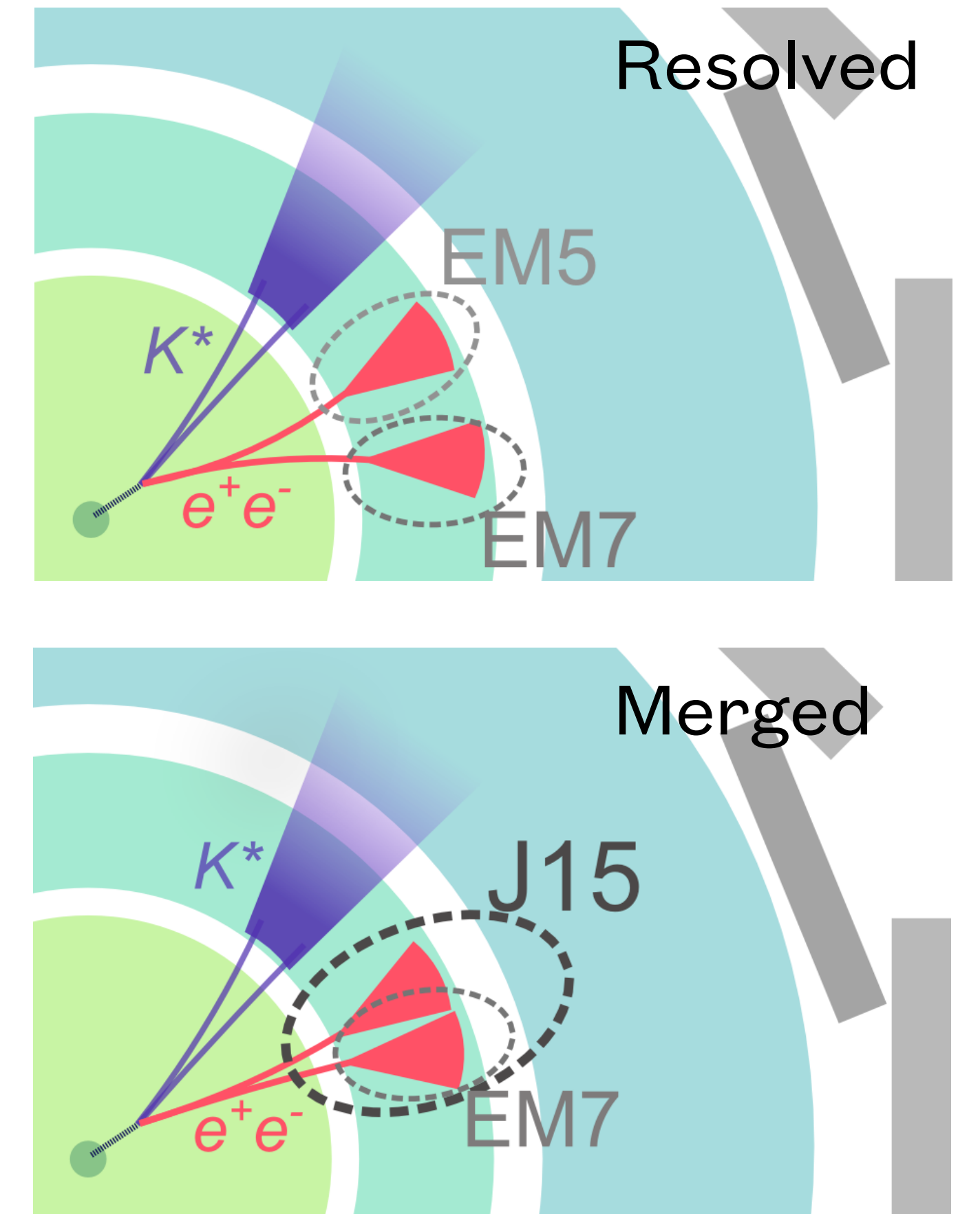
# Run 3, trigger phase-I upgrades

- Several upgrades will improve the trigger performance towards Run 3

- The two upgrades with most impact on the trigger:

- **L1Calo** upgrade: new readout allows for improved granularity in the trigger: 1 old tower = 10 new super cells
  - Largest gain from reduction in isolated electron rates, and improved turn-on

- **L1Muon**: upgraded endcap can reduce by ~40% the muon rate. Allows for spatial and angular coincidence with the muon BW
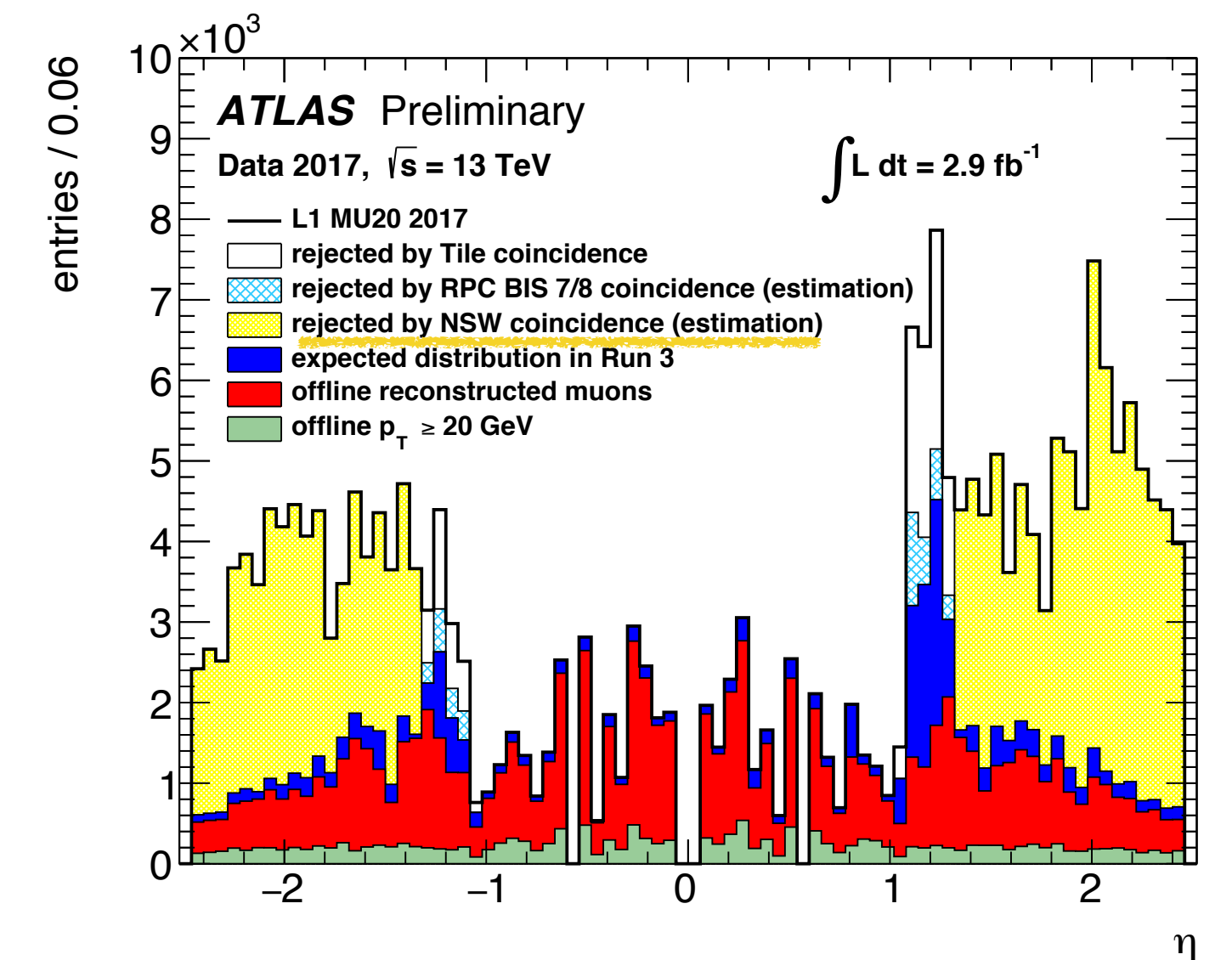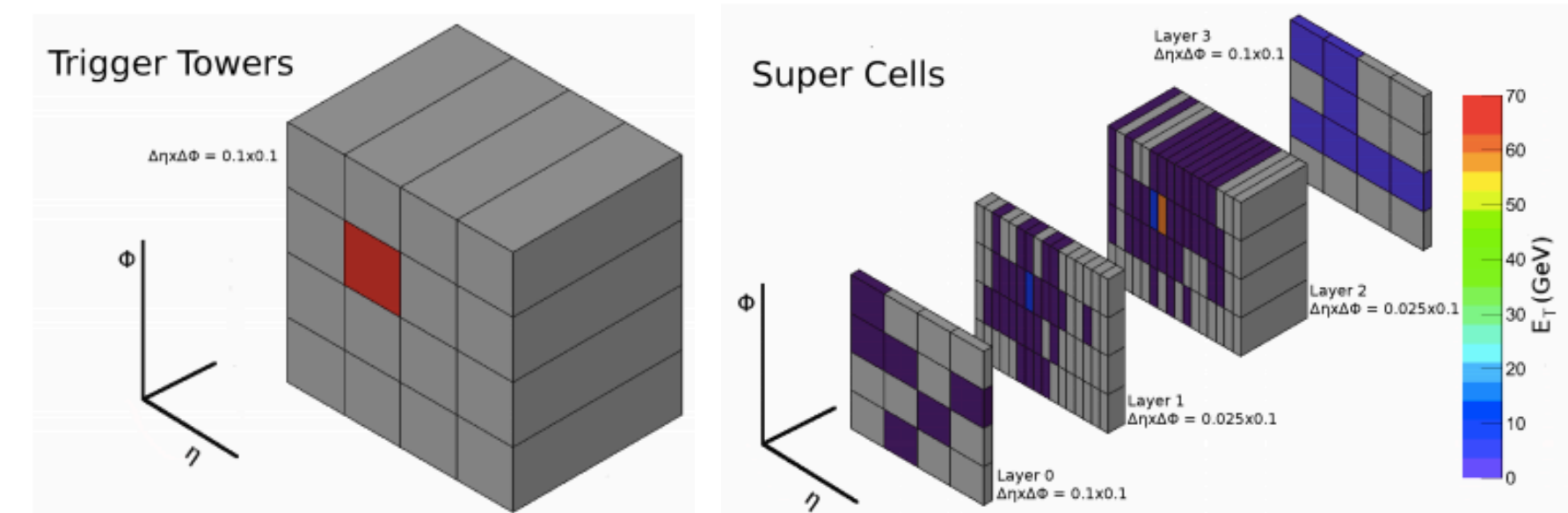
# Conclusions

- Excellent performance of the trigger system allowed very stable data-taking by the ATLAS detector during Run 2

- Constant evolution and improvements of triggers ensured a nearly-constant offline threshold despite the large increase in instantaneous luminosity and pileup

- The triggers system (both hardware and software) is being upgraded to improve its capabilities towards Run 3

- Many great physics results made possible thanks to creative and custom triggers!
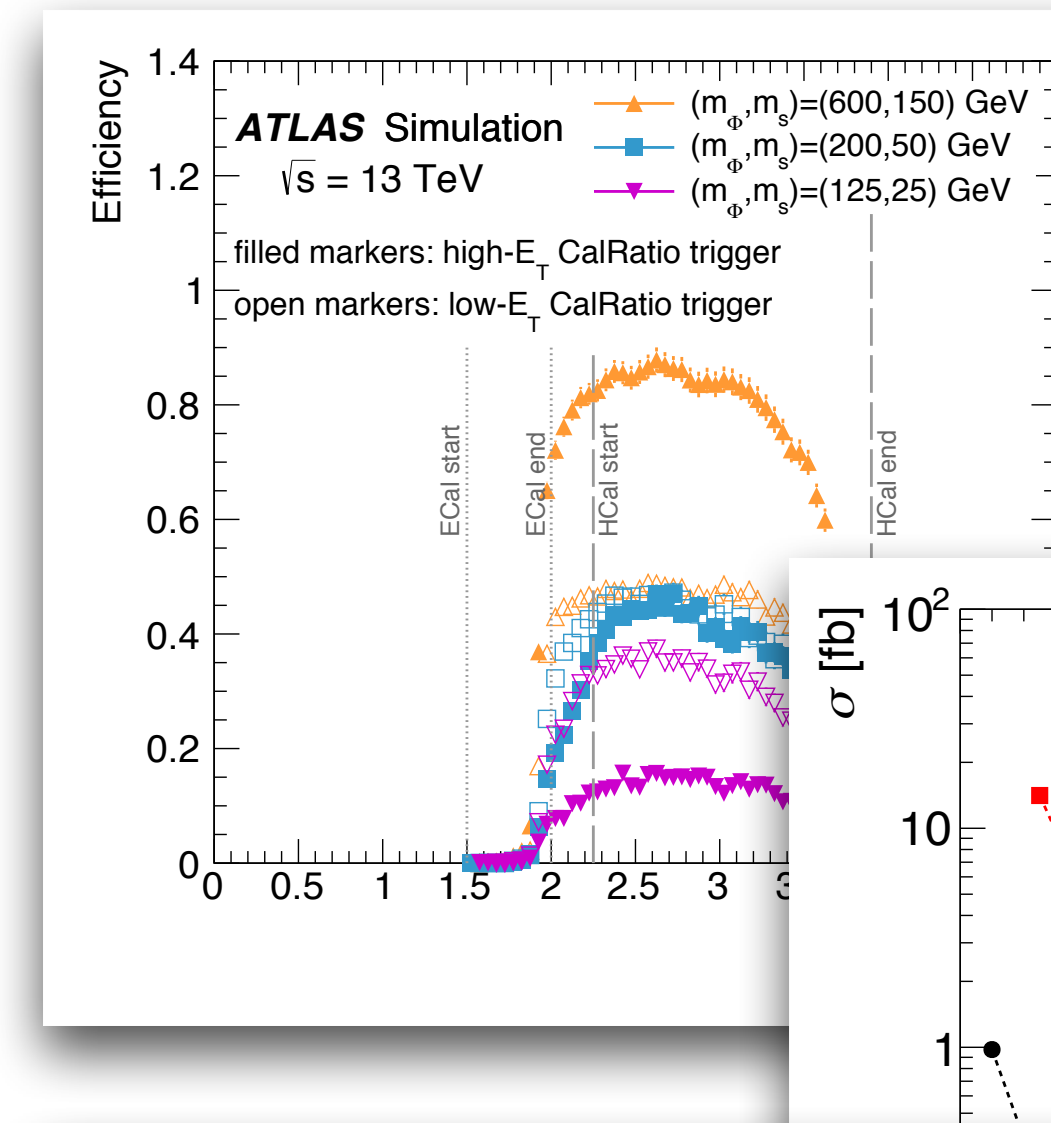
Displaced hadronic jets
EXOT-2017-25
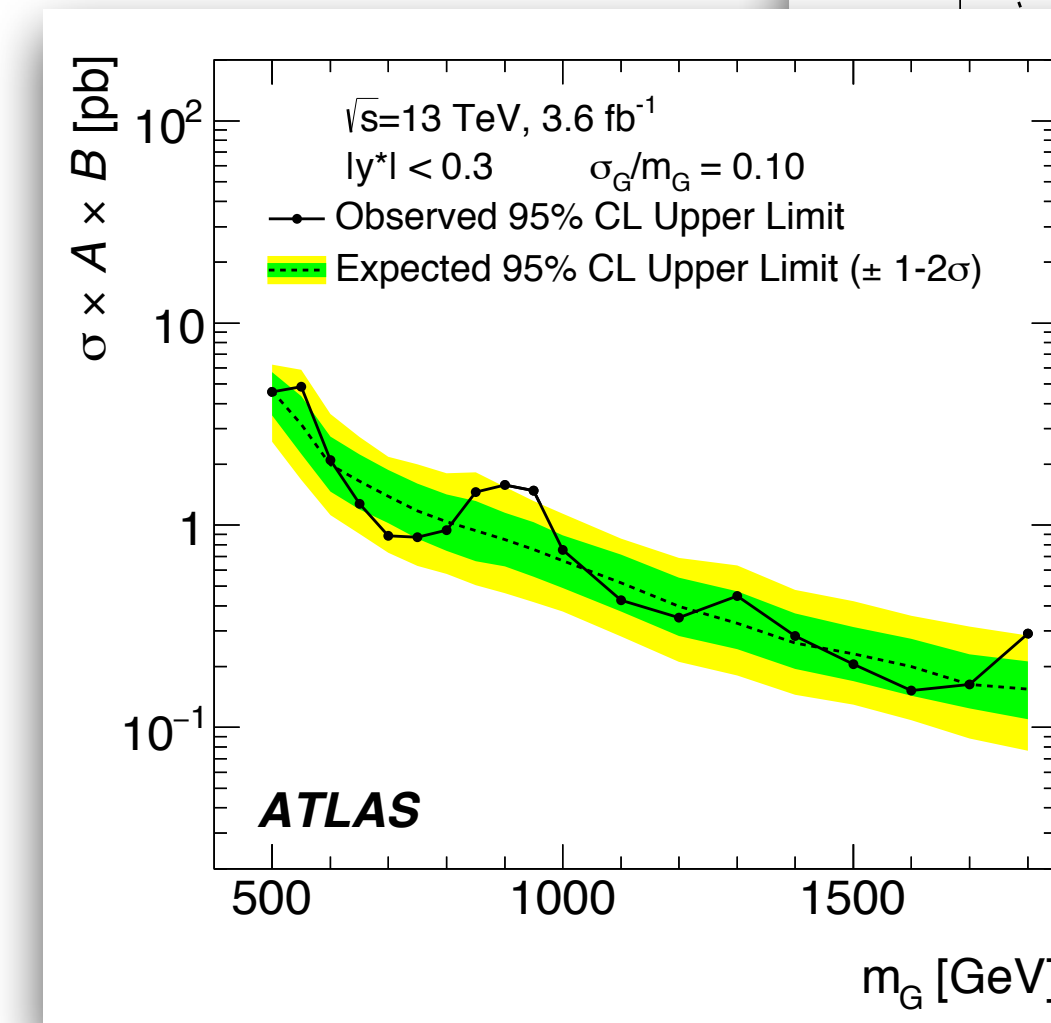
Monopoles
EXOT-2017-20

TLA EXOT-2016-20

# Backup

# Run 3 electron turn-on

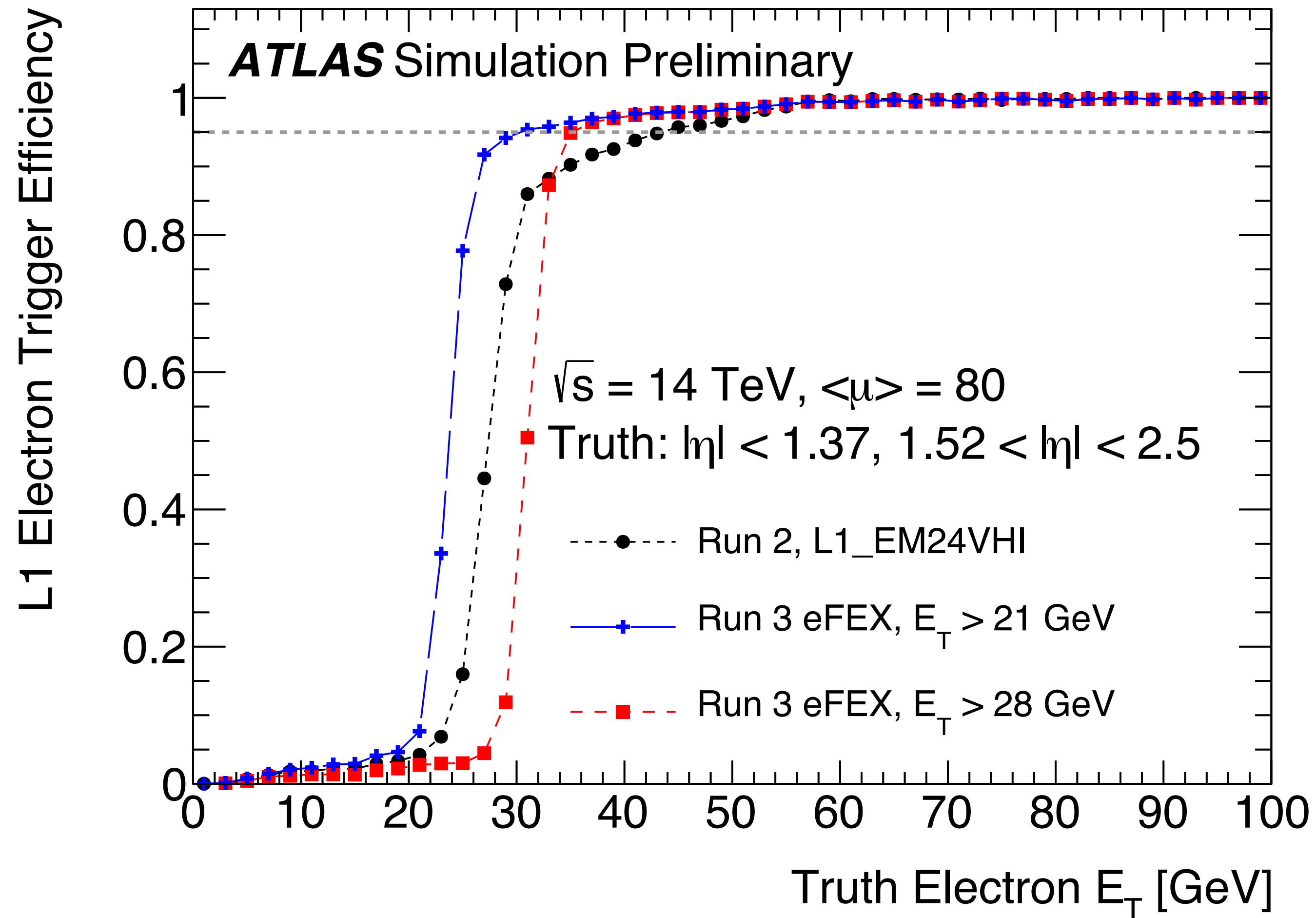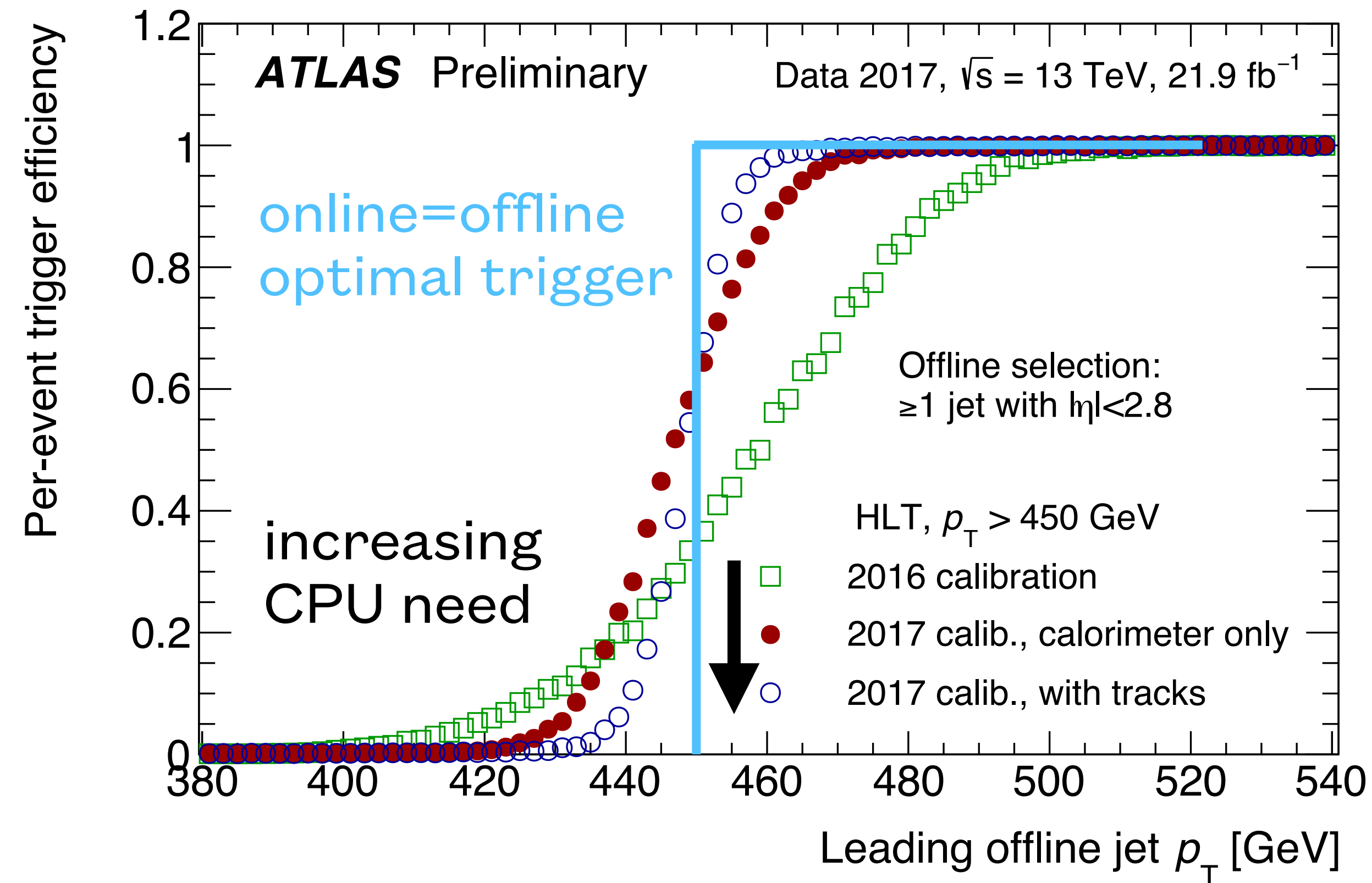| Trigger | Typical offline selection | Trigger Selection | | L1 Peak Rate [kHz] | HLT Peak Rate [Hz] |
| | | L1 [GeV] | HLT [GeV] | $L=2.0\times10^{34}$ cm$^{-2}$s$^{-1}$ | |
| --- | --- | --- | --- | --- | --- |
| Single leptons | Single isolated $\mu$, $p_T > 27$ GeV | 20 | 26 (i) | 16 | 218 |
| | Single isolated tight $e$, $p_T > 27$ GeV | 22 (i) | 26 (i) | 31 | 195 |
| | Single $\mu$, $p_T > 52$ GeV | 20 | 50 | 16 | 70 |
| | Single $e$, $p_T > 61$ GeV | 22 (i) | 60 | 28 | 20 |
| | Single $\tau$, $p_T > 170$ GeV | 100 | 160 | 1.4 | 42 |
| Two leptons | Two $\mu$, each $p_T > 15$ GeV | 2×10 | 2×14 | 2.2 | 30 |
| | Two $\mu$, $p_T > 23, 9$ GeV | 20 | 22, 8 | 16 | 47 |
| | Two very loose $e$, each $p_T > 18$ GeV | 2×15 (i) | 2×17 | 2.0 | 13 |
| | One $e$ & one $\mu$, $p_T > 8, 25$ GeV | 20 ($\mu$) | 7, 24 | 16 | 6 |
| | One loose $e$ & one $\mu$, $p_T > 18, 15$ GeV | 15, 10 | 17, 14 | 2.6 | 5 |
| | One $e$ & one $\mu$, $p_T > 27, 9$ GeV | 22 (e, i) | 26, 8 | 21 | 4 |
| | Two $\tau$, $p_T > 40, 30$ GeV | 20 (i), 12 (i) (+jets, topo) | 35, 25 | 5.7 | 93 |
| | One $\tau$ & one isolated $\mu$, $p_T > 30, 15$ GeV | 12 (i), 10 (+jets) | 25, 14 (i) | 2.4 | 17 |
| | One $\tau$ & one isolated $e$, $p_T > 30, 18$ GeV | 12 (i), 15 (i) (+jets) | 25, 17 (i) | 4.6 | 19 |
| Three leptons | Three very loose $e$, $p_T > 25, 13, 13$ GeV | 20, 2×10 | 24, 2×12 | 1.6 | 0.1 |
| | Three $\mu$, each $p_T > 7$ GeV | 3×6 | 3×6 | 0.2 | 7 |
| | Three $\mu$, $p_T > 21, 2×5$ GeV | 20 | 20, 2×4 | 16 | 9 |
| | Two $\mu$ & one loose $e$, $p_T > 2×11, 13$ GeV | 2×10 ($\mu$) | 2×10, 12 | 2.2 | 0.5 |
| | Two loose $e$ & one $\mu$, $p_T > 2×13, 11$ GeV | 2×8, 10 | 2×12, 10 | 2.3 | 0.1 |
| Signle photon | One loose $\gamma$, $p_T > 145$ GeV | 24 (i) | 140 | 24 | 47 |
| Two photons | Two loose $\gamma$, each $p_T > 55$ GeV | 2×20 | 2×50 | 3.0 | 7 |
| | Two $\gamma$, $p_T > 40, 30$ GeV | 2×20 | 35, 25 | 3.0 | 21 |
| | Two isolated tight $\gamma$, each $p_T > 25$ GeV | 2×15 (i) | 2×20 (i) | 2.0 | 15 |
| Single jet | Jet ($R = 0.4$), $p_T > 435$ GeV | 100 | 420 | 3.7 | 35 |
| | Jet ($R = 1.0$), $p_T > 480$ GeV | 111 (topo: $R = 1.0$) | 460 | 2.6 | 42 |
| | Jet ($R = 1.0$), $p_T > 450$ GeV, $m_{jet} > 45$ GeV | 111 (topo: $R = 1.0$) | 420, $m_{jet} > 35$ | 2.6 | 36 |
| $b$−jets | One $b$ ($\epsilon = 60\%$), $p_T > 285$ GeV | 100 | 275 | 3.6 | 15 |
| | Two $b$ ($\epsilon = 60\%$), $p_T > 185, 70$ GeV | 100 | 175, 60 | 3.6 | 11 |
| | One $b$ ($\epsilon = 40\%$) & three jets, each $p_T > 85$ GeV | 4×15 | 4×75 | 1.5 | 14 |
| | Two $b$ ($\epsilon = 70\%$) & one jet, $p_T > 65, 65, 160$ GeV | 2×30, 85 | 2×55, 150 | 1.3 | 17 |
| | Two $b$ ($\epsilon = 60\%$) & two jets, each $p_T > 65$ GeV | 4×15, $|\eta| < 2.5$ | 4×55 | 3.2 | 15 |
| Multijets | Four jets, each $p_T > 125$ GeV | 3×50 | 4×115 | 0.5 | 16 |
| | Five jets, each $p_T > 95$ GeV | 4×15 | 5×85 | 4.8 | 10 |
| | Six jets, each $p_T > 80$ GeV | 4×15 | 6×70 | 4.8 | 4 |
| | Six jets, each $p_T > 60$ GeV, $|\eta| < 2.0$ | 4×15 | 6×55, $|\eta| < 2.4$ | 4.8 | 15 |
| $E_T^{miss}$ | $E_T^{miss} > 200$ GeV | 50 | 110 | 5.1 | 94 |
| $B$-physics | Two $\mu$, $p_T > 11, 6$ GeV, $0.1 < m(\mu, \mu) < 14$ GeV | 11, 6 | 11, 6 (di-$\mu$) | 2.9 | 55 |
| | Two $\mu$, $p_T > 6, 6$ GeV, $2.5 < m(\mu, \mu) < 4.0$ GeV | 2×6 ($J/\psi$, topo) | 2×6 ($J/\psi$) | 1.4 | 55 |
| | Two $\mu$, $p_T > 6, 6$ GeV, $4.7 < m(\mu, \mu) < 5.9$ GeV | 2×6 ($B$, topo) | 2×6 ($B$) | 1.4 | 6 |
| | Two $\mu$, $p_T > 6, 6$ GeV, $7 < m(\mu, \mu) < 12$ GeV | 2×6 ($\Upsilon$, topo) | 2×6 ($\Upsilon$) | 1.2 | 12 |
| Main Rate | | | | 86 | 1750 |
| B-physics and Light States Rate | | | | | 200 |

| Trigger | Signature | Trigger Selection | | L1 Rate [kHz] | HLT Rate [Hz] | L1 Rate [kHz] | HLT Rate [Hz] |
| | | L1 [GeV] | HLT [GeV] | $L=5.0\times10^{27}$ cm$^{-2}$s$^{-1}$ | | $L=2.0\times10^{27}$ cm$^{-2}$s$^{-1}$ | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Leptons | Single $\mu$ | 6 | 8 | 0.47 | 54 | 0.21 | 23 |
| | Two $\mu$ | 2×4 | 2×3 | 0.16 | 38 | 0.071 | 15 |
| | Two $\mu^\dagger$ | 4 | 2×4 | 1.5 | 28 | 0.93 | 15 |
| | Single $e$ (lhloose) | 12 | 15 | 2.5 | 11 | 0.97 | 4.4 |
| | Single $e$ (loose) | 16 | 20 | 0.93 | 35 | 0.36 | 14 |
| | Two $e$ (loose) | 2×16 | 2×20 | 0.29 | 0.2 | 0.11 | 0.13 |
| Photons | Single $\gamma$ | 12 | 20 | 2.5 | 61 | 0.97 | 25 |
| Jets | Single jet ($R = 0.4$) | 30 | 85 | 17.1 | 120 | 6.6 | 47 |
| | Single jet ($R = 0.4$)$^\dagger$ | 12 | 60 | 0.24 | 13 | 1.3 | 69 |
| | Single jet ($R = 1.0$) | 50 | 180 | 14.4 | 66 | 5.6 | 26 |
| | Single jet ($R = 0.4$, $|\eta| > 3.2$) | 15 | 55 | 12.5 | 25 | 9.7 | 19 |
| $b$-jets | Jet ($R = 0.4$) & $\mu$ | 4 ($\mu$), 15 (jet) | 4 ($\mu$), 60 (jet) | 1.8 | 7 | 0.7 | 3 |
| | Jet ($R = 0.4$) & $\mu^\dagger$ | 4 ($\mu$) | 4 ($\mu$), 50 (jet) | - | - | 0.93 | 6 |
| | Jet ($R = 0.3$) & $\mu^\dagger$ | 4 ($\mu$) | 4 ($\mu$), 40 (jet) | - | - | 0.93 | 6 |
| | Jet ($R = 0.2$) & $\mu^\dagger$ | 4 ($\mu$) | 4 ($\mu$), 30 (jet) | - | - | 0.93 | 6 |
| MB | Very peripheral coll. | TE < 50, ZDC A & C | 1 (#tracks) | 1.4 | 95 | 1.2 | 261 |
| | Peripheral coll.$^\dagger$ | 50 < TE < 600 | none | 0.034 | 34 | 0.12 | 116 |
| | Central coll.$^\dagger$ | TE > 600 | none | 0.029 | 29 | 1.2 | 120 |
| MB PEB | Very peripheral coll. | TE < 50, ZDC A & C | 1 (#tracks) | 5.4 | 786 | 9.6 | 2048 |
| | Peripheral coll.$^\dagger$ | 50 < TE < 600 | none | 0.3 | 298 | 0.9 | 920 |
| | Central coll.$^\dagger$ | TE > 600 | none | 0.8 | 822 | 0.23 | 2251 |
| Global | Ultra central coll. | 12000 < TE | 4450 ($\Sigma E_T^{FCal}$) | 2.3 | 81 | 0.89 | 32 |
| | Event shape$^\dagger$ | 600 < TE | top 0.1% $v_2$ in A/C side | - | - | 1.2 | 0.6 |
| | Event shape$^\dagger$ | 600 < TE | top 0.1% $v_3$ in A/C side | - | - | 1.3 | 0.6 |
| UPC | $\gamma + \gamma \to \gamma + \gamma$ | 4 < TE < 200 & 1 ($\gamma$) | FgapAC & < 15 (PH) | 7.7 | 34 | 3.1 | 34 |
| | $\gamma + \gamma \to \gamma + \gamma$ | TE < 50 & 2×1 ($\gamma$) | FgapAC & < 15 (PH) | 1.8 | 3 | 0.66 | 2.7 |
| | $\gamma + \gamma \to \mu + \mu$ | TE < 50 & 4 ($\mu$) | 4 ($\mu$) | 0.27 | 5 | 0.19 | 2.1 |
| | $\gamma + \gamma$(A) $\to$ HF | TE< 200 & 4 ($\mu$) & (!ZDC A or !ZDC C) | 4 ($\mu$) | 0.25 | 1.5 | 0.19 | 0.6 |
| | $\gamma + \gamma \to e + e$ | TE < 200 & 7 ($e$) | 12 ($e$) | 0.09 | 1 | 0.03 | 0.5 |
| | $\gamma + \gamma \to \gamma + $jet | TE < 200 & 7 ($\gamma$) | 12 ($\gamma$) | 0.09 | 6 | 0.03 | 2.4 |
| | $\gamma + A \to $jets | 5 < TE < 200 & ((ZDC A & !ZDC C) or (ZDC C & !ZDC A)) | 20 (jet) | 0.93 | 69 | 0.40 | 24 |
| | $\gamma + \gamma \to $jets | 4 < TE < 200 & (!ZDC A & !ZDC C) | 15 (jet, $R = 0.4$) | 0.65 | 22 | 0.74 | 11 |
| | $\gamma + \gamma \to $jets | 4 < TE < 200 & (!ZDC A & !ZDC C) | 15 (jet, $R = 1.0$) | 0.65 | 36 | 0.74 | 20 |
| | high multiplicity | 4 < TE < 200 & ZDC A & !ZDC C | FgapC & 35 (#tracks) | 0.48 | 2.4 | 0.20 | 0.7 |
| | high multiplicity | 4 < TE < 200 & ZDC C & !ZDC A | FgapA & 35 (#tracks) | 0.47 | 2.4 | 0.20 | 0.9 |
| | $\gamma + A \to $X$^\dagger$ | TE< 200 & ((ZDC A & !ZDC C) or (ZDC C & !ZDC A)) | 1 (#tracks) | 0.56 | 15 | 0.50 | 12 |
| | $\gamma + A \to $VM$^\dagger$ | TE < 20 | 1-15 (#tracks) | - | - | 16.5 | 60 |

# Trigger menu design

- Continuous effort to port offline improvements to the trigger

- Need to find a compromise between performance and CPU requirements

- Maximize synergy between different trigger signatures

  - E.g. jet calibration uses tracks if available from b-tagging, but has also a calorimeter-only version if tracking has not run



**ATLAS** Preliminary   Data 2017, $\sqrt{s}$ = 13 TeV, 21.9 fb$^{-1}$

online=offline
optimal trigger

Offline selection:
$\geq$1 jet with $|\eta|$<2.8

increasing
CPU need

HLT, $p_T$ > 450 GeV
□ 2016 calibration
● 2017 calib., calorimeter only
○ 2017 calib., with tracks

Per-event trigger efficiency

Leading offline jet $p_T$ [GeV]

# Streams and prescales

- Most of the **bandwidth** is devoted to the main physics stream (>80%) and a dedicated b-physics stream (~15%)

- Most of the **rate** goes to <u>trigger-level analysis</u> (stores only jet 4-vectors reconstructed by HLT) and calibration streams, which store only a subset of the detector/objects

- Support and lower priority physics triggers are prescaled, and their prescale can be reduced towards the end of the LHC fill, once the limiting resources (L1 rate, CPU) are available
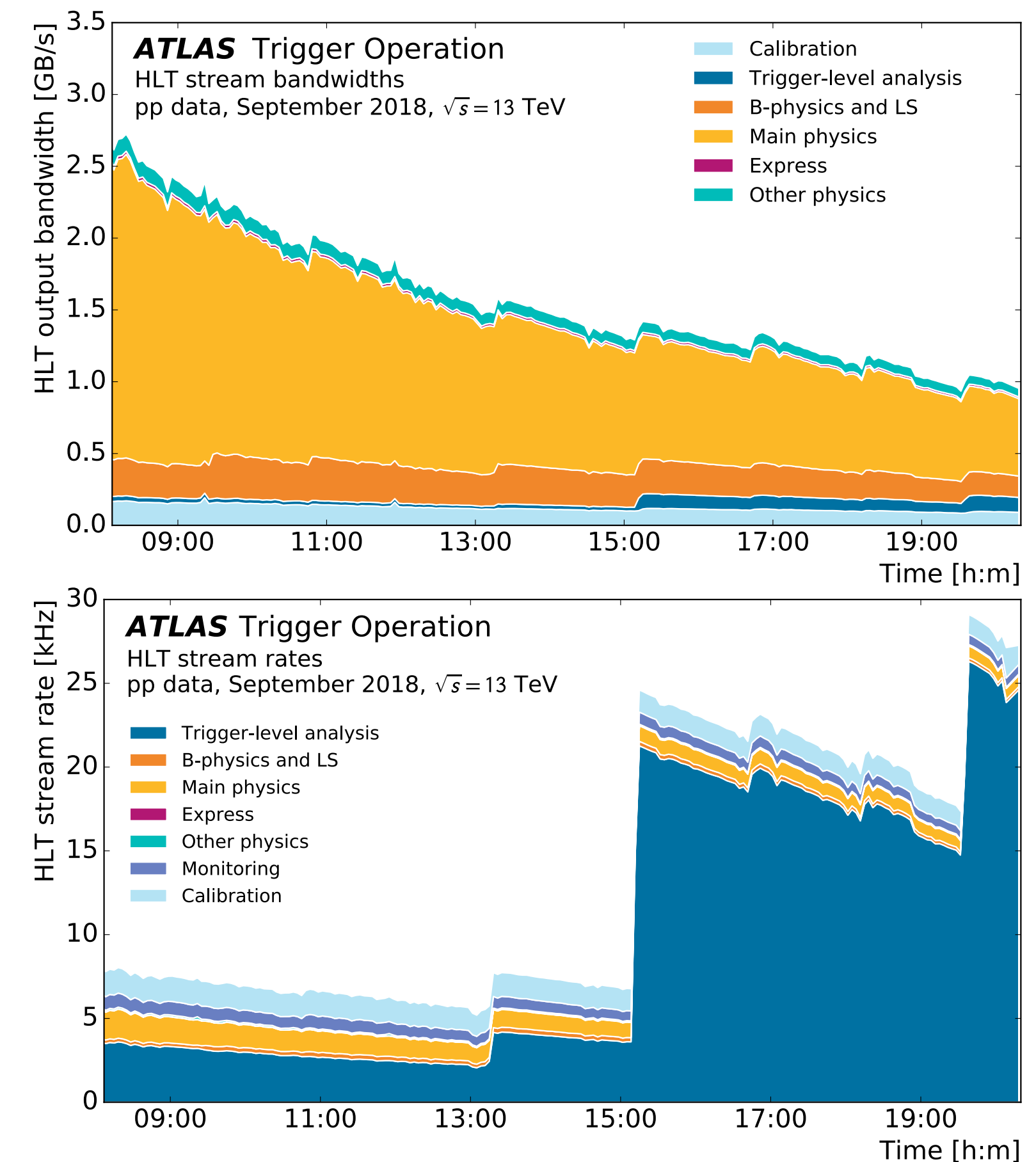
# Run 3, multi-thread

- ATLAS is redesigning its core framework for native, efficient and user-friendly multi-threading support → AthenaMT

- HLT trigger is not limited by memory, but will profit from the redesign in order to integrate more tightly with offline reconstruction

- HLT requirements (partial event reconstruction in Regions of Interest and early rejection) considered during design of AthenaMT from the beginning

- Replacing own scheduling and caching by native Gaudi Scheduler, which is also used for offline reconstruction

- AthenaMT offers three kinds of parallelism
  - Inter-event: multiple events are processed in parallel
  - Intra-event: multiple algorithms can run in parallel for an event
  - In-algorithm: algorithms can utilize multi-threading and vectorisation