```
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

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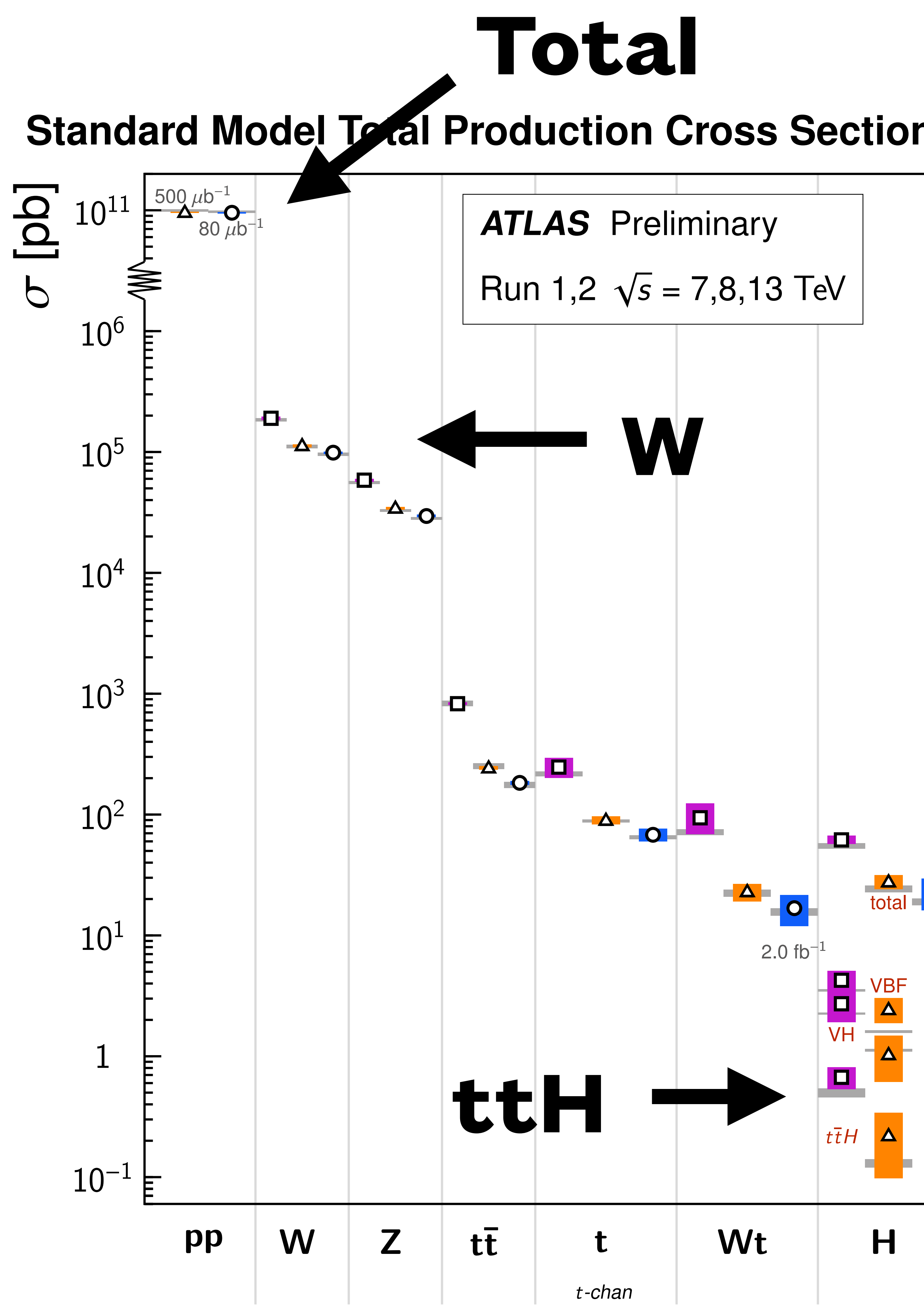
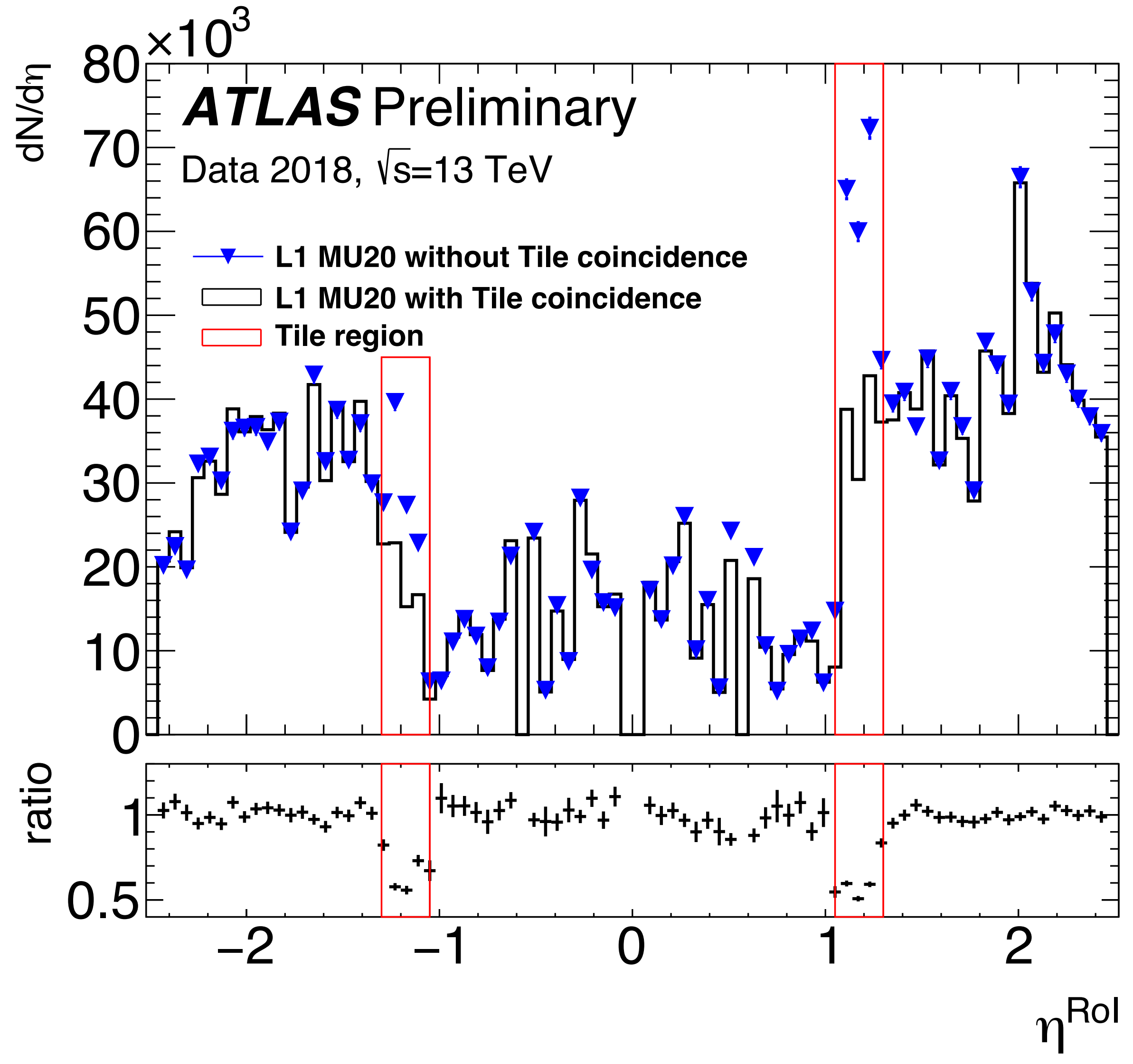
Introduction

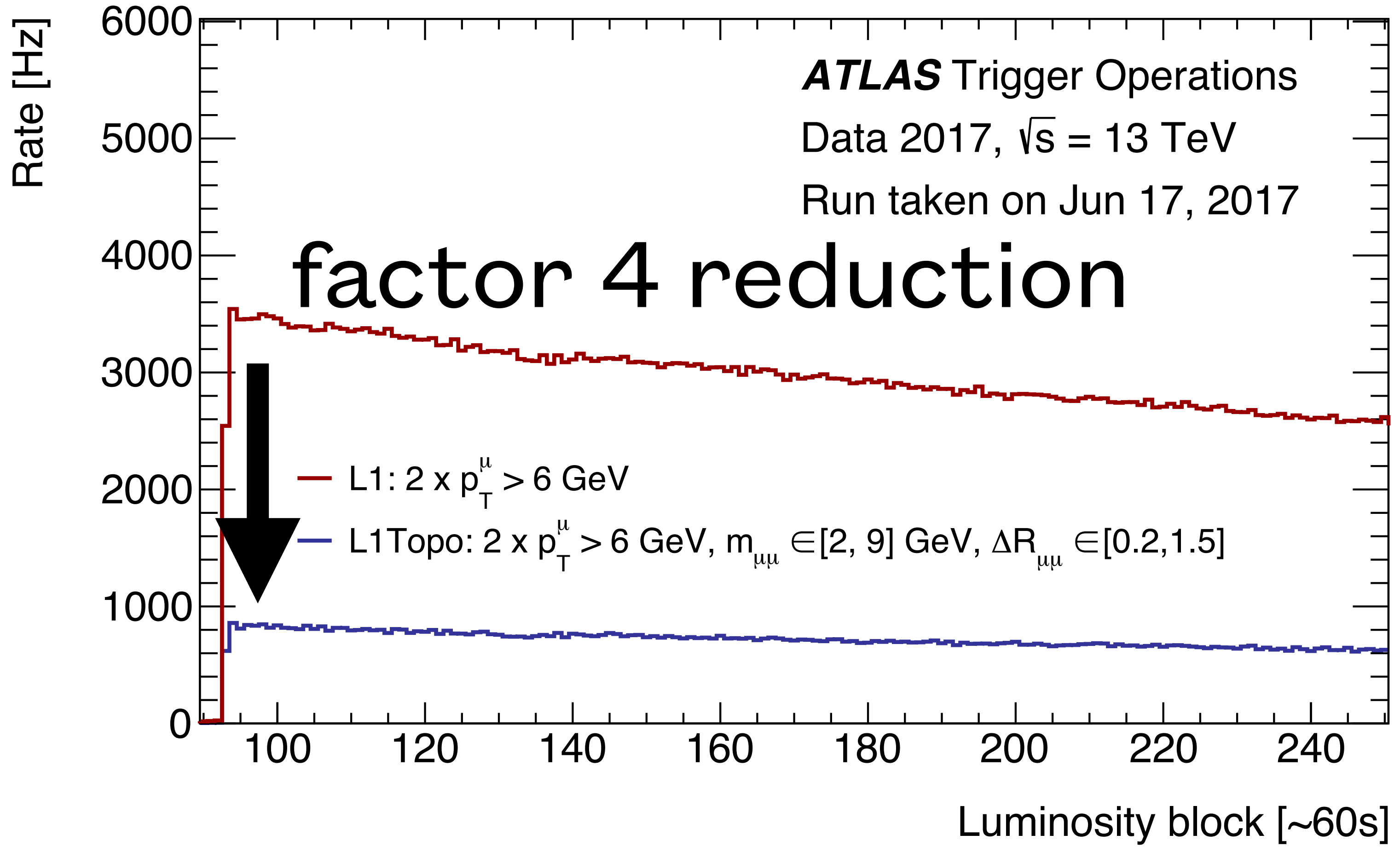
- The **Trigger** system of an experiment at a hadron collider has a critical role, unfeasible to reconstruct and/or store every collision
- Need to reject orders of magnitude of soft QCD before reaching the interesting electroweak / high-p_T / BSM regime
- Two-level system to reduce
  40 MHz collisions → 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



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 ($\eta \times \varphi$) 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



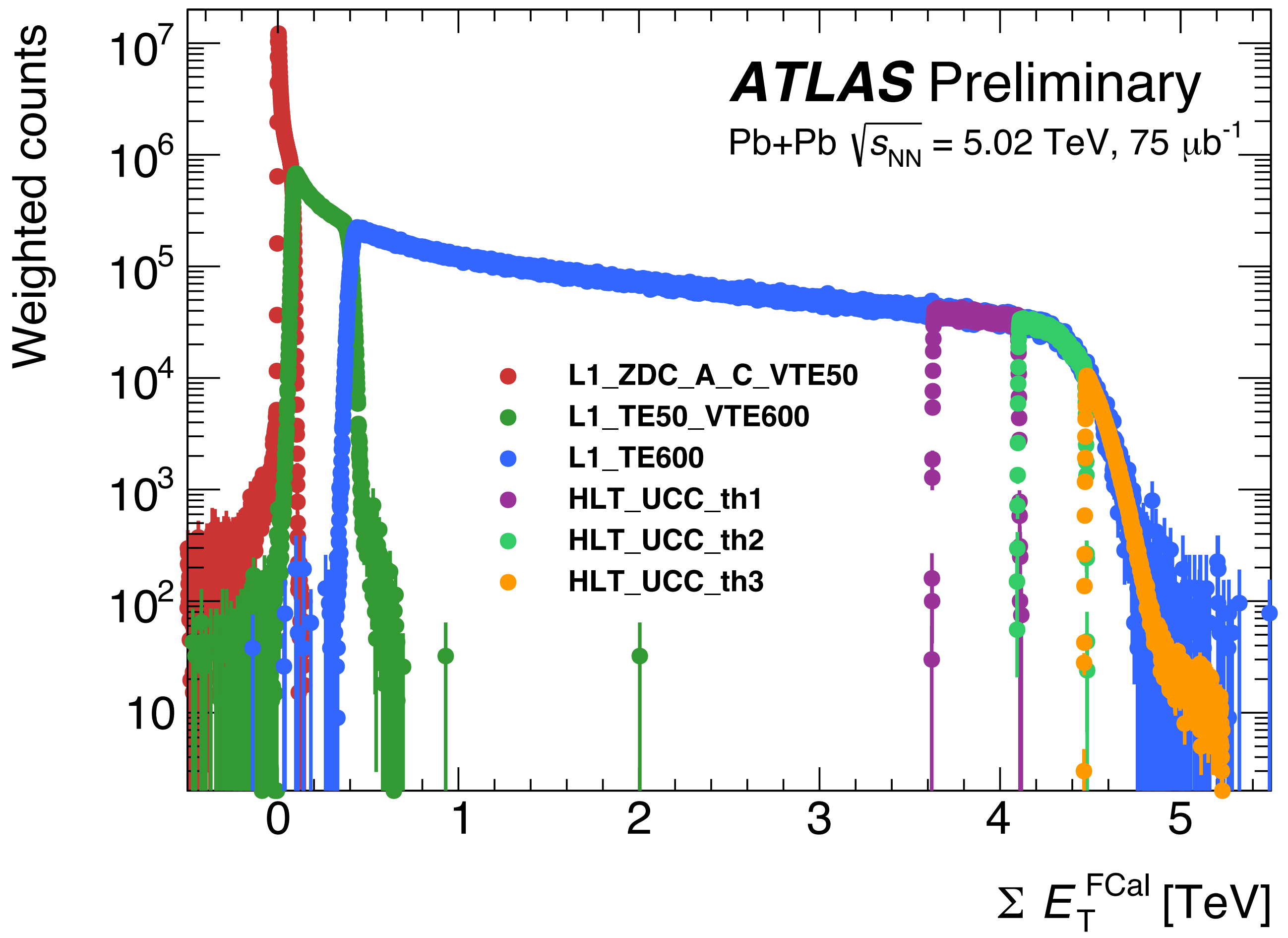


High-level trigger

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

Trigger menu design

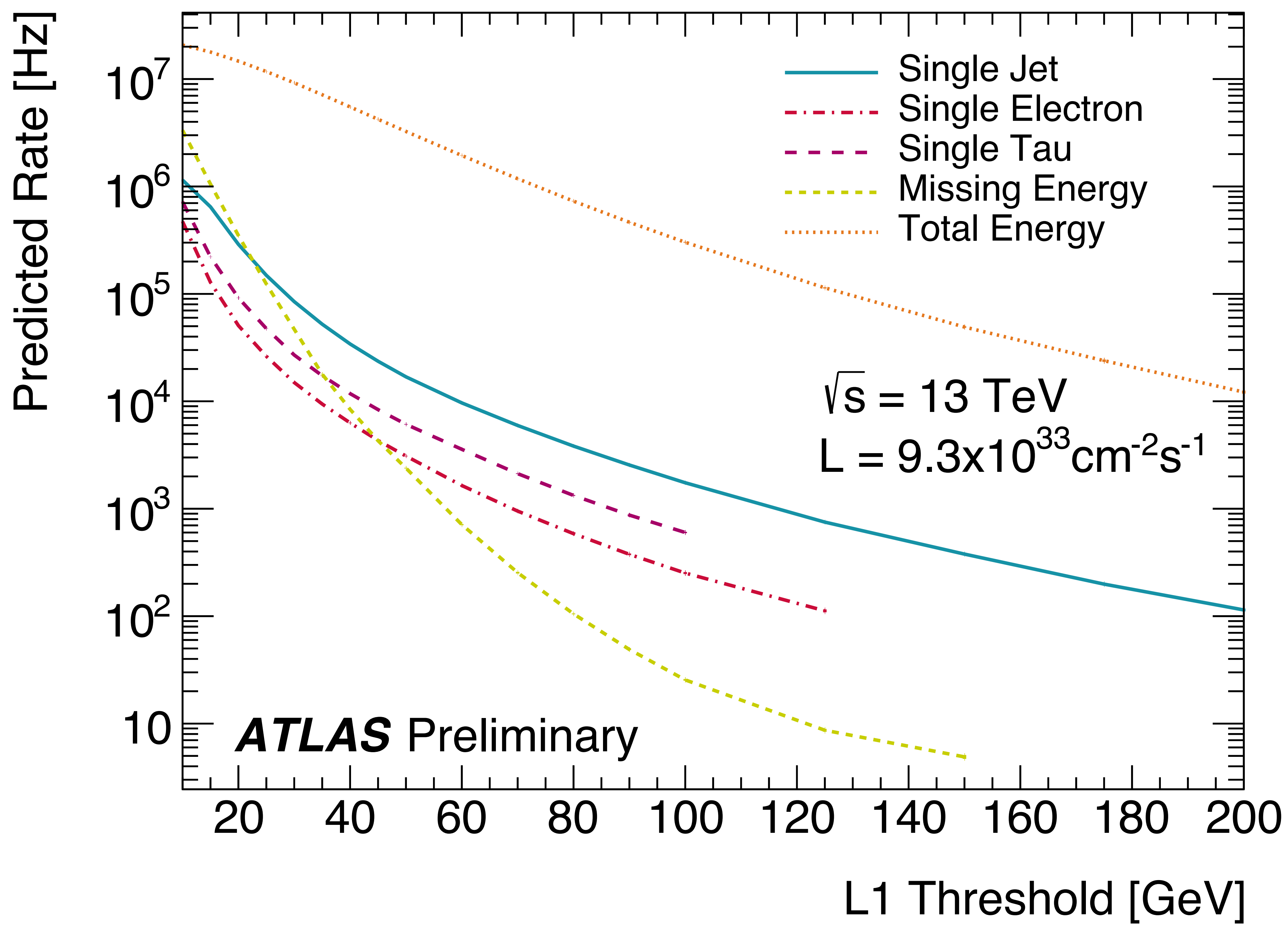
- Designing the menu is a **balance** between analysis requests (store all the physics!) and system constraints
  - Peak L1 rate below 100 kHz (detector readout)
  - Average HLT rate ~1 kHz (storage and prompt reconstruction constraints)
  - Decide within 500 ms in average (available CPU in the HLT farm)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

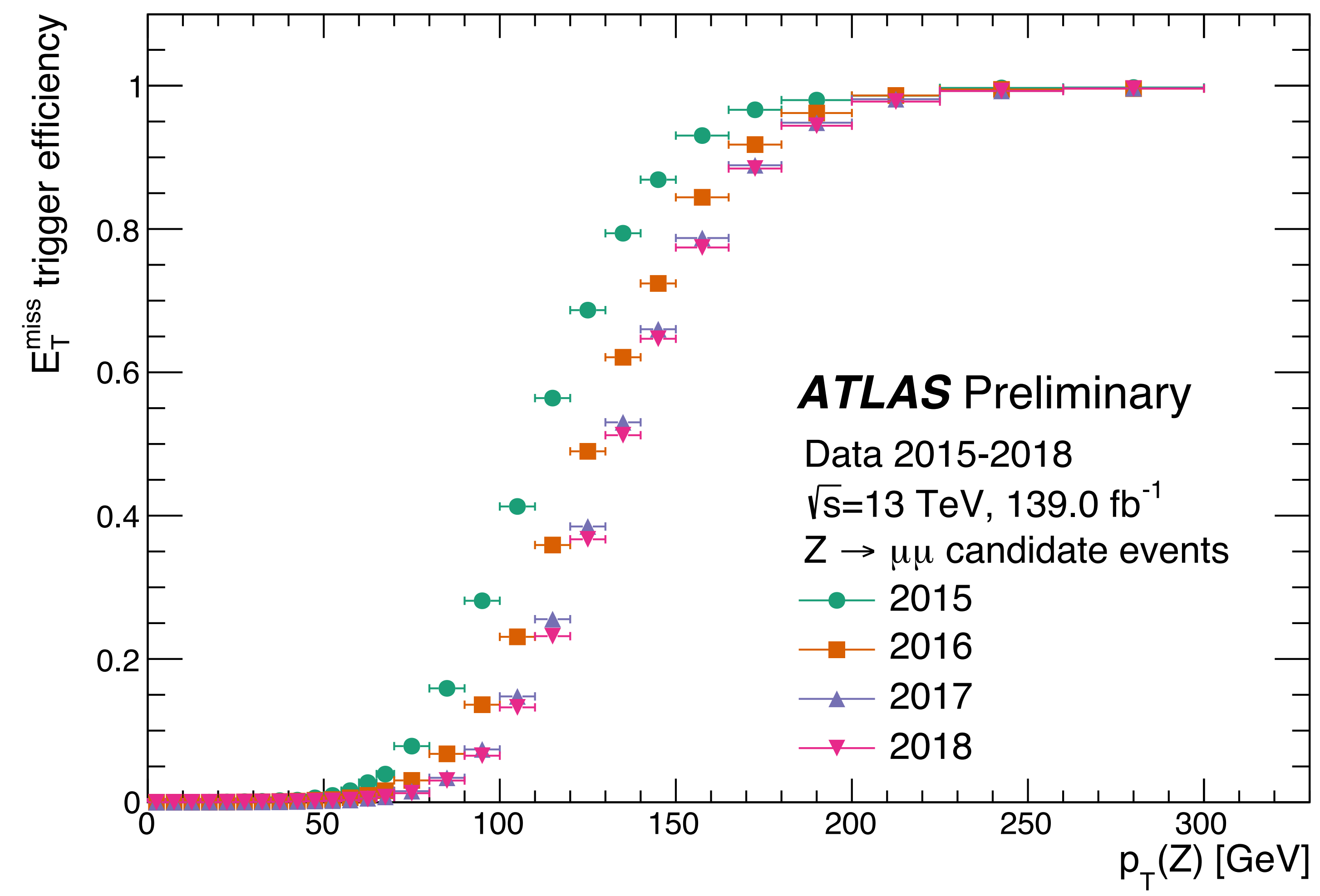
- Reprocessing enhanced bias data with a new trigger menu allows to predict rates and CPU for triggers in development

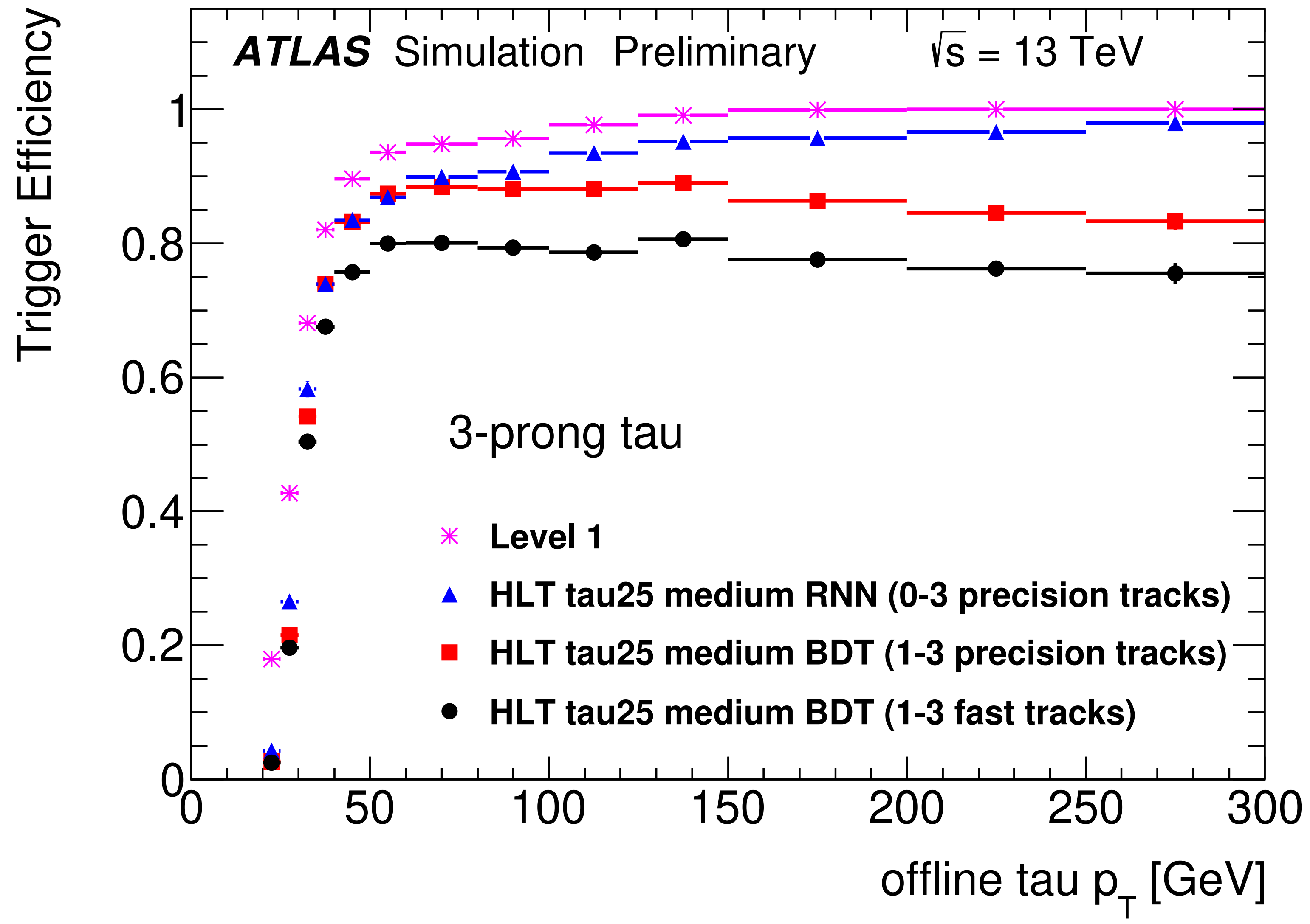


ATL-DAQ-PUB-2016-002

Performance highlights

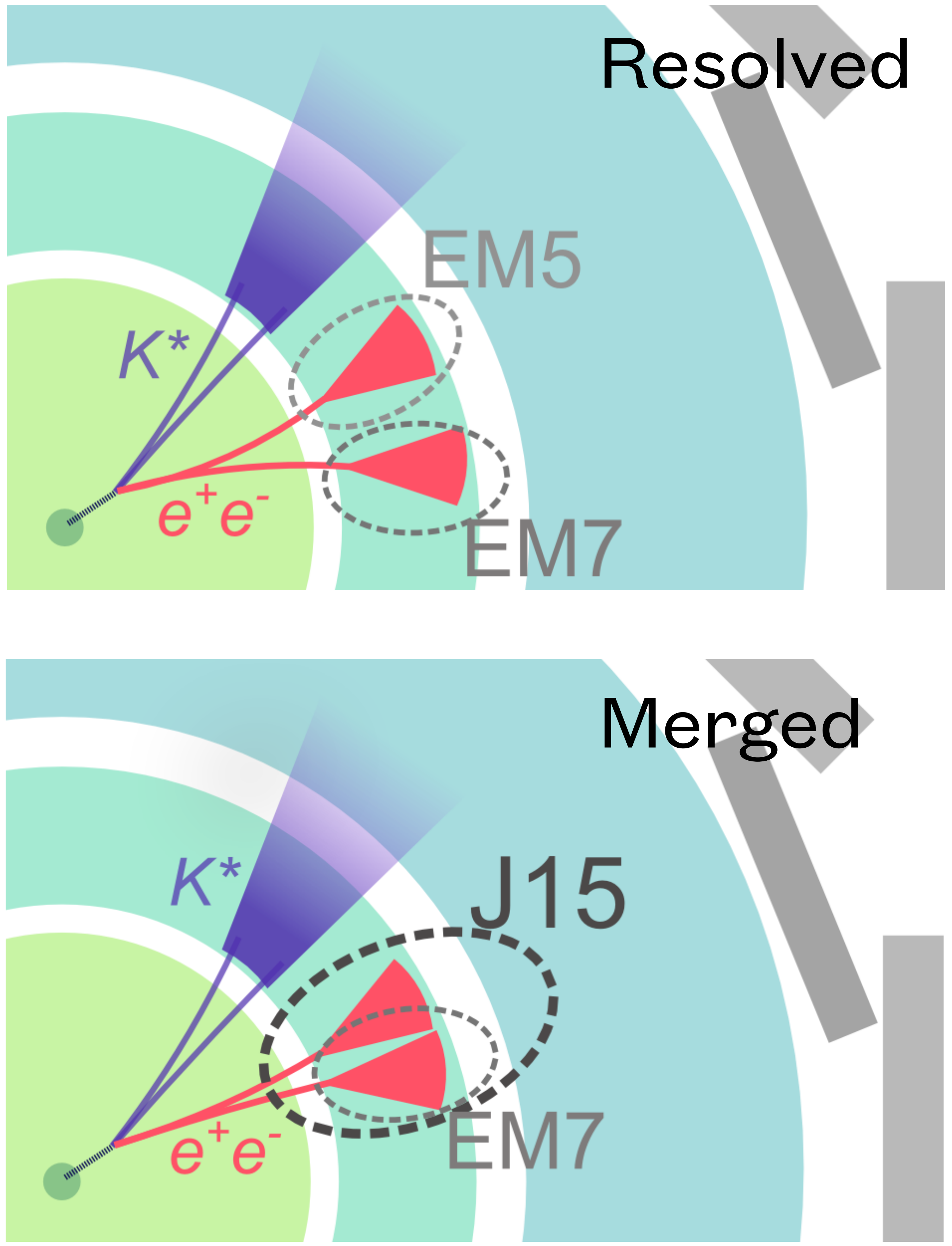
- Offline **MET** threshold kept at ~200 GeV across all Run 2 thanks to constant improvements to MET reconstruction
  - 2015 cell: E_T^{miss} from calorimeter cells above noise threshold
  - 2016 mht: E_T^{miss} from calibrated jets
  - 2017 pufit: E_T^{miss} from hard-scatter clusters, sorted out from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





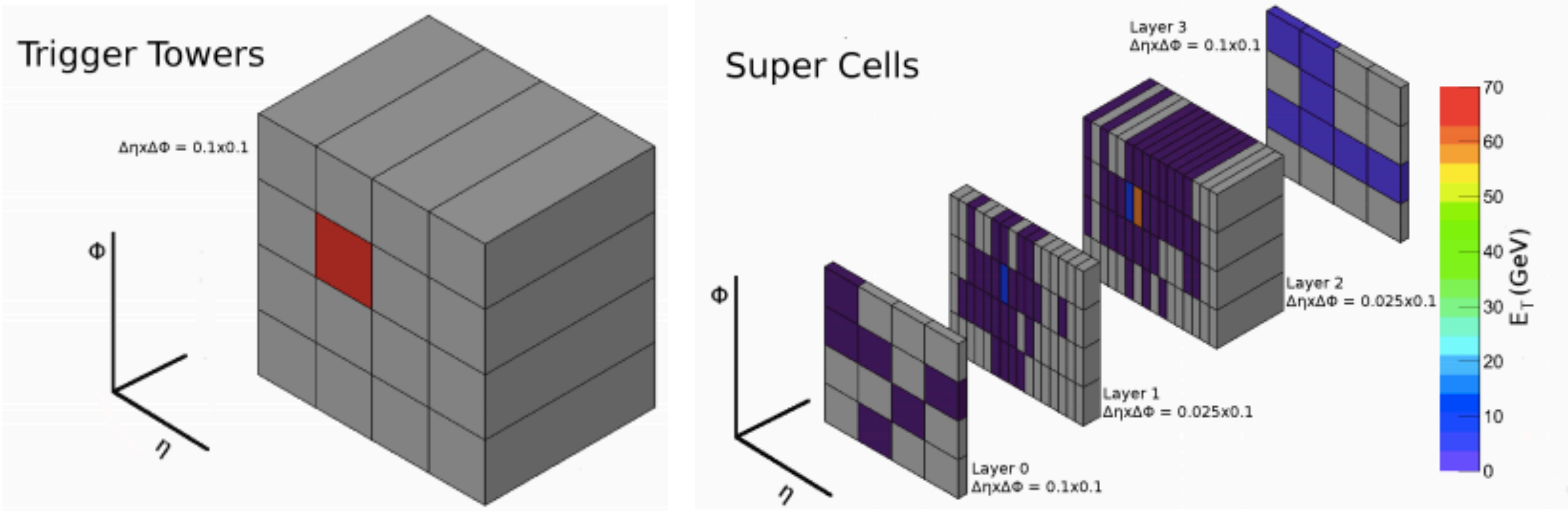
Performance highlights

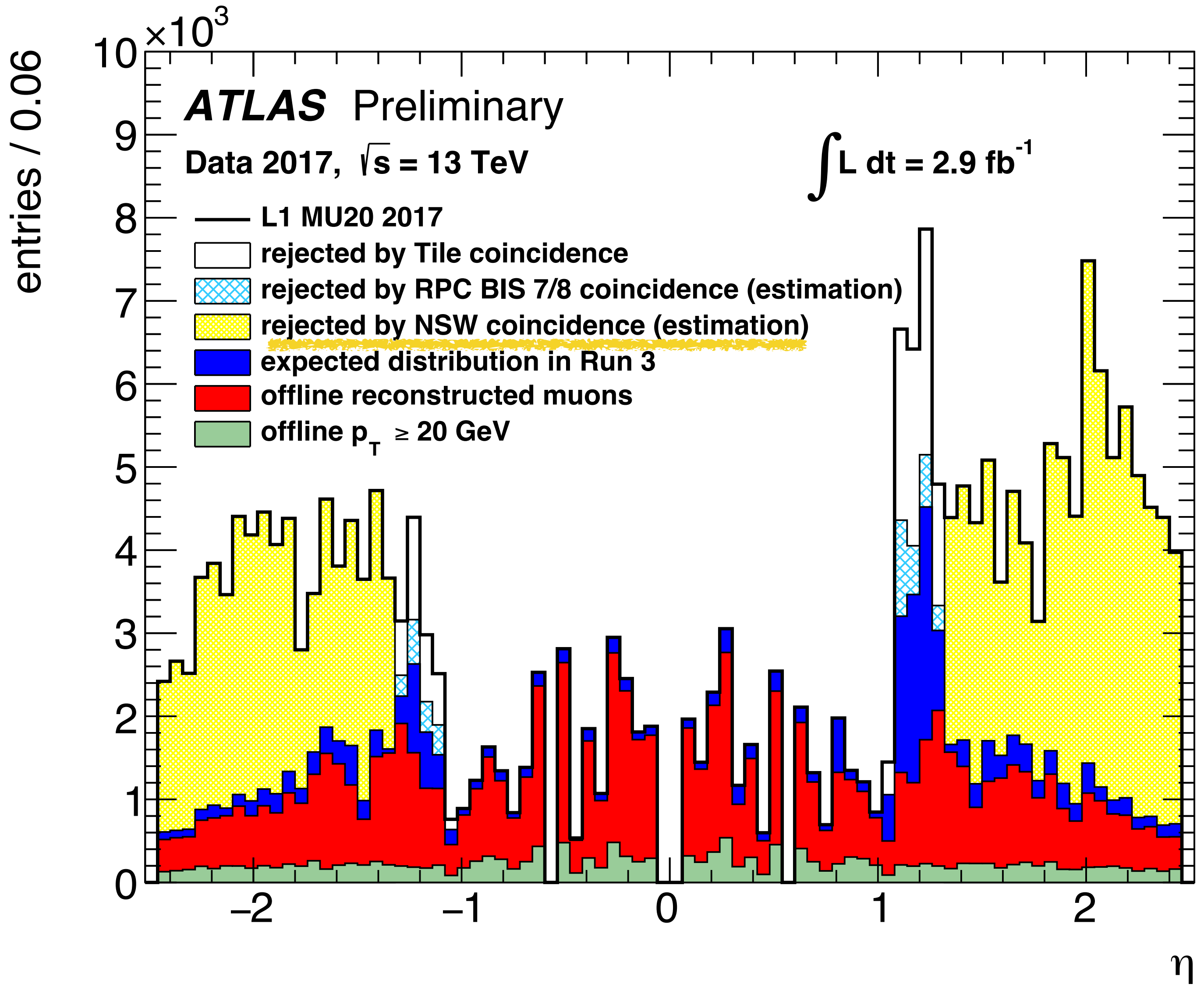
- Dedicated **B→K*ee triggers**, targeting resolved and also merged dielectron final states
- **L1**
  - Resolved: require two separated electrons with $E_T > 7/5$ GeV and $m(e,e) < 9$ GeV
  - Merged: require one electron with $E_T > 7$ GeV close to a jet with $E_T > 15$ GeV
  - Both would have too high 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

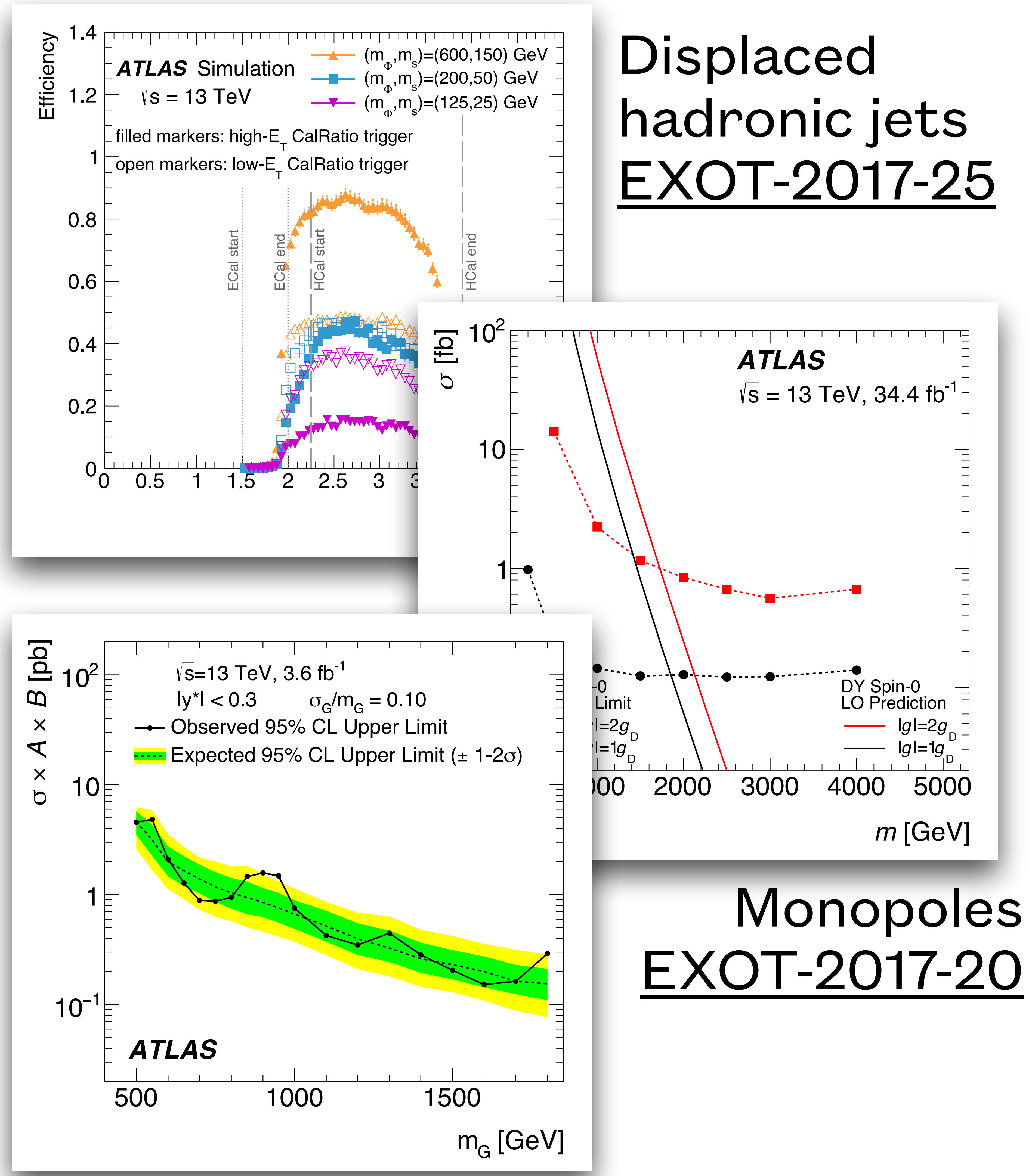
- Several upgrades will improve the trigger performance towards Run 3
- The two upgrades with most impact on the trigger:
- **L1Calo** upgrade: new readout allows for improved granularity in the trigger: 1 old tower = 10 new super cells
  - Largest gain from reduction in isolated electron rates, and improved turn-on
- **L1Muon**: upgraded endcap can reduce by ~40% the muon rate. Allows for spatial and angular coincidence





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!



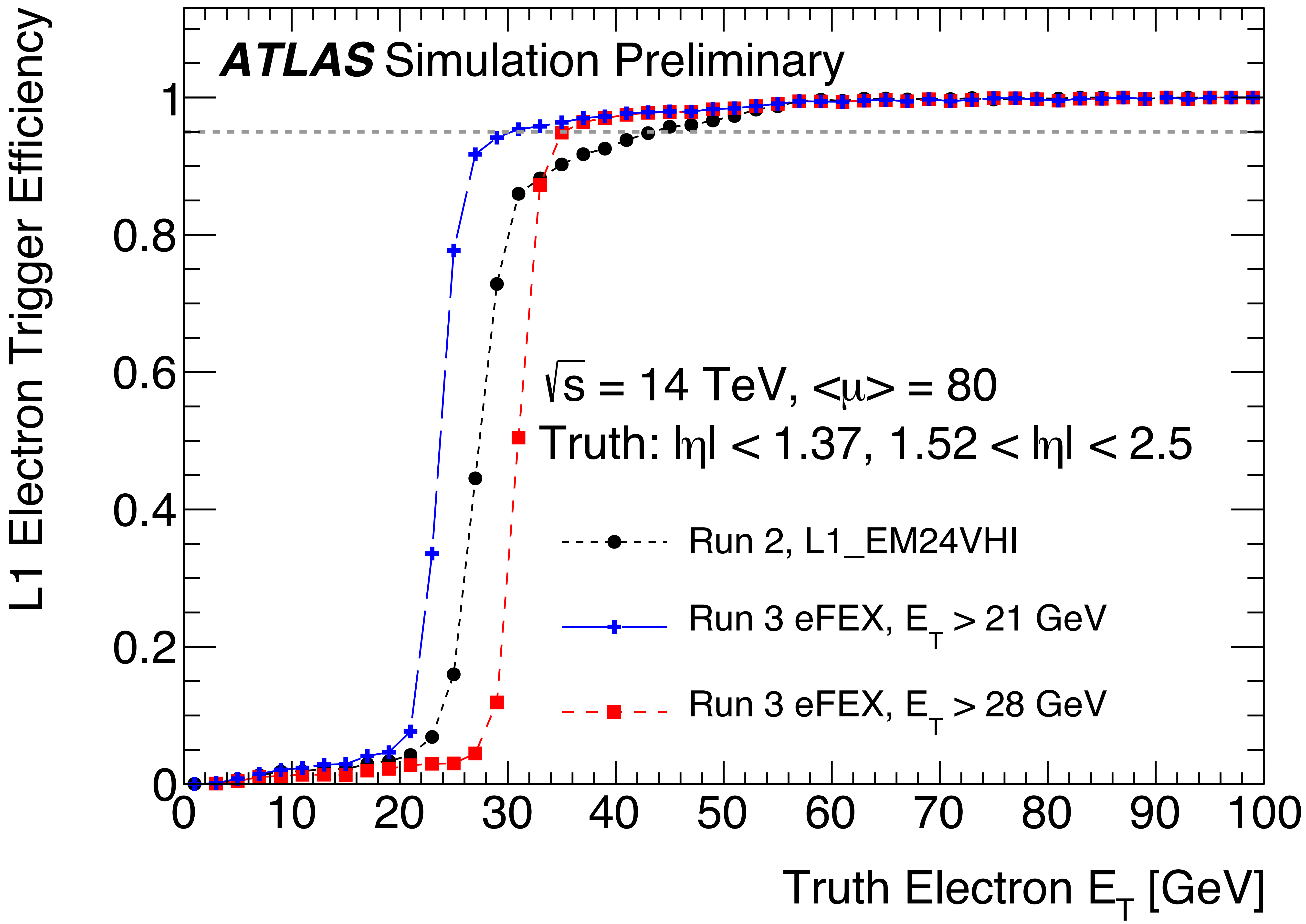
Displaced hadronic jets
EXOT-2017-25

Monopoles
EXOT-2017-20

TLA EXOT-2016-20

Backup

Run 3 electron turn-on



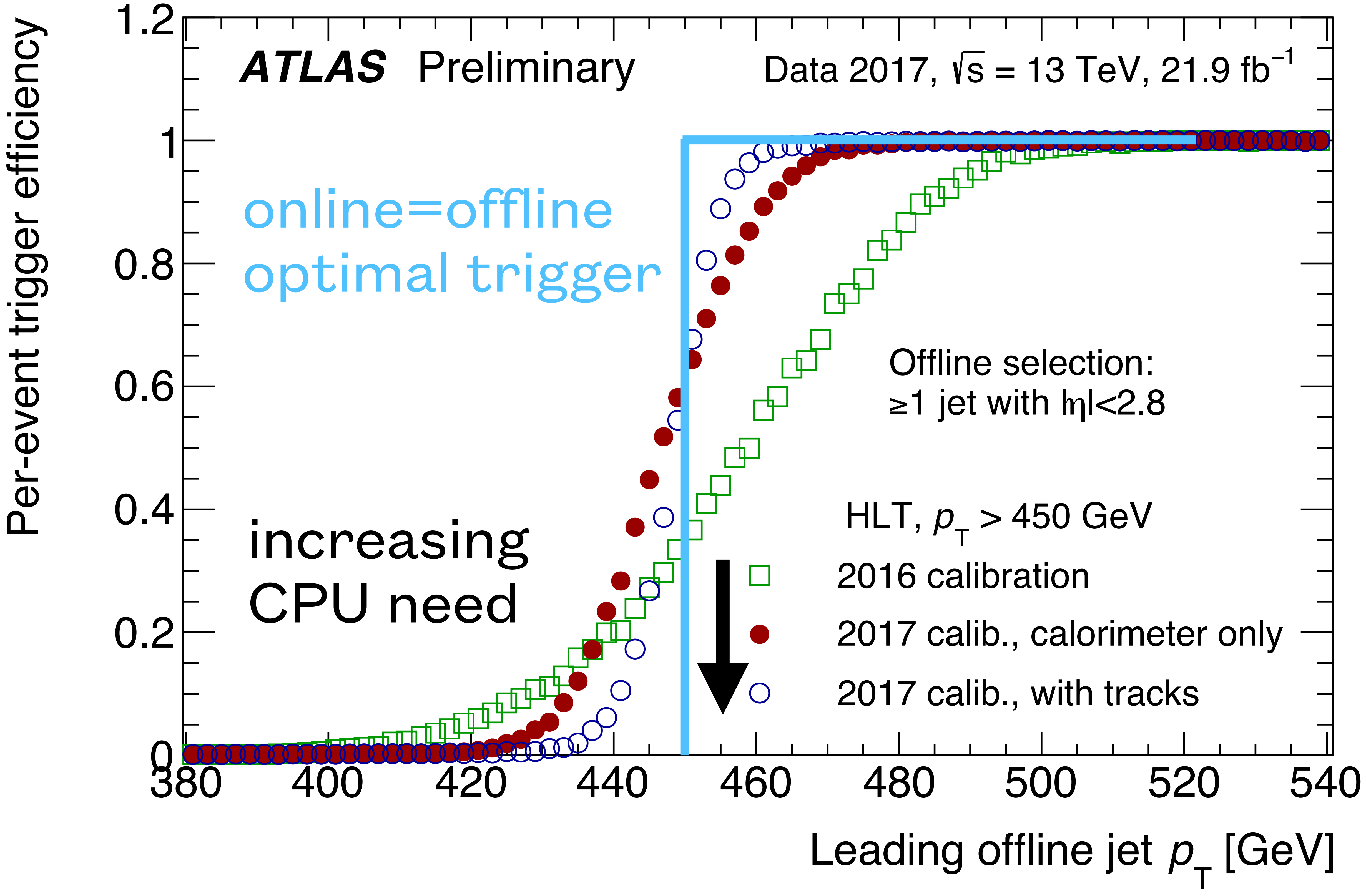
ATLAS Trigger menus (pp, HI)

Trigger	Typical offline selection	Trigger Selection L1 [GeV]	Trigger Selection HLT [GeV]	L1 Peak Rate [kHz] ($L=2.0\times10^{34}$ cm^{-2}s^{-1})	HLT Peak Rate [Hz] ($L=2.0\times10^{34}$ cm^{-2}s^{-1})
Single leptons	Single isolated μ, $p_T > 27$ GeV	20	26 (i)	16	218
	Single isolated tight e, $p_T > 27$ GeV	22 (i)	26 (i)	31	195
	Single μ, $p_T > 52$ GeV	20	50	16	70
	Single e, $p_T > 61$ GeV	22 (i)	60	28	20
	Single τ, $p_T > 170$ GeV	100	160	1.4	42
Two leptons	Two μ, each $p_T > 15$ GeV	2×10	2×14	2.2	30
	Two μ, $p_T > 23, 9$ 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 μ, $p_T > 8, 25$ GeV	20 (μ)	7, 24	16	6
	One loose e & one μ, $p_T > 18, 15$ GeV	15, 10	17, 14	2.6	5
	One e & one μ, $p_T > 27, 9$ GeV	22 (e, i)	26, 8	21	4
	Two τ, $p_T > 40, 30$ GeV	20 (i), 12 (i) (+jets, topo)	35, 25	5.7	93
	One τ & one isolated μ, $p_T > 30, 15$ GeV	12 (i), 10 (+jets)	25, 14 (i)	2.4	17
	One τ & 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 μ, each $p_T > 7$ GeV	3×6	3×6	0.2	7
	Three μ, $p_T > 21, 2\times5$ GeV	20	20, 2×4	16	9
	Two μ & one loose e, $p_T > 2\times11, 13$ GeV	2×10 (μ)	2×10, 12	2.2	0.5
	Two loose e & one μ, $p_T > 2\times13, 11$ GeV	2×8, 10	2×12, 10	2.3	0.1
Signle photon	One loose γ, $p_T > 145$ GeV	24 (i)	140	24	47
Two photons	Two loose γ, each $p_T > 55$ GeV	2×20	2×50	3.0	7
	Two γ, $p_T > 40, 30$ GeV	2×20	35, 25	3.0	21
	Two isolated tight γ, 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, $\lvert\eta\rvert < 2.5$	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, $\lvert\eta\rvert < 2.0$	4×15	6×55, $\lvert\eta\rvert < 2.4$	4.8	15
E_T^{miss}	$E_T^{miss} > 200$ GeV	50	110	5.1	94
B-physics	Two μ, $p_T > 11, 6$ GeV, $0.1 < m(\mu,\mu) < 14$ GeV	11, 6	11, 6 (di-μ)	2.9	55
	Two μ, $p_T > 6, 6$ GeV, $2.5 < m(\mu,\mu) < 4.0$ GeV	2×6 (J/ψ, topo)	2×6 (J/ψ)	1.4	55
	Two μ, $p_T > 6, 6$ GeV, $4.7 < m(\mu,\mu) < 5.9$ GeV	2×6 (B, topo)	2×6 (B)	1.4	6
	Two μ, $p_T > 6, 6$ GeV, $7 < m(\mu,\mu) < 12$ GeV	2×6 (Υ, topo)	2×6 (Υ)	1.2	12
Main Rate B-physics and Light States Rate				86	1750 200

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

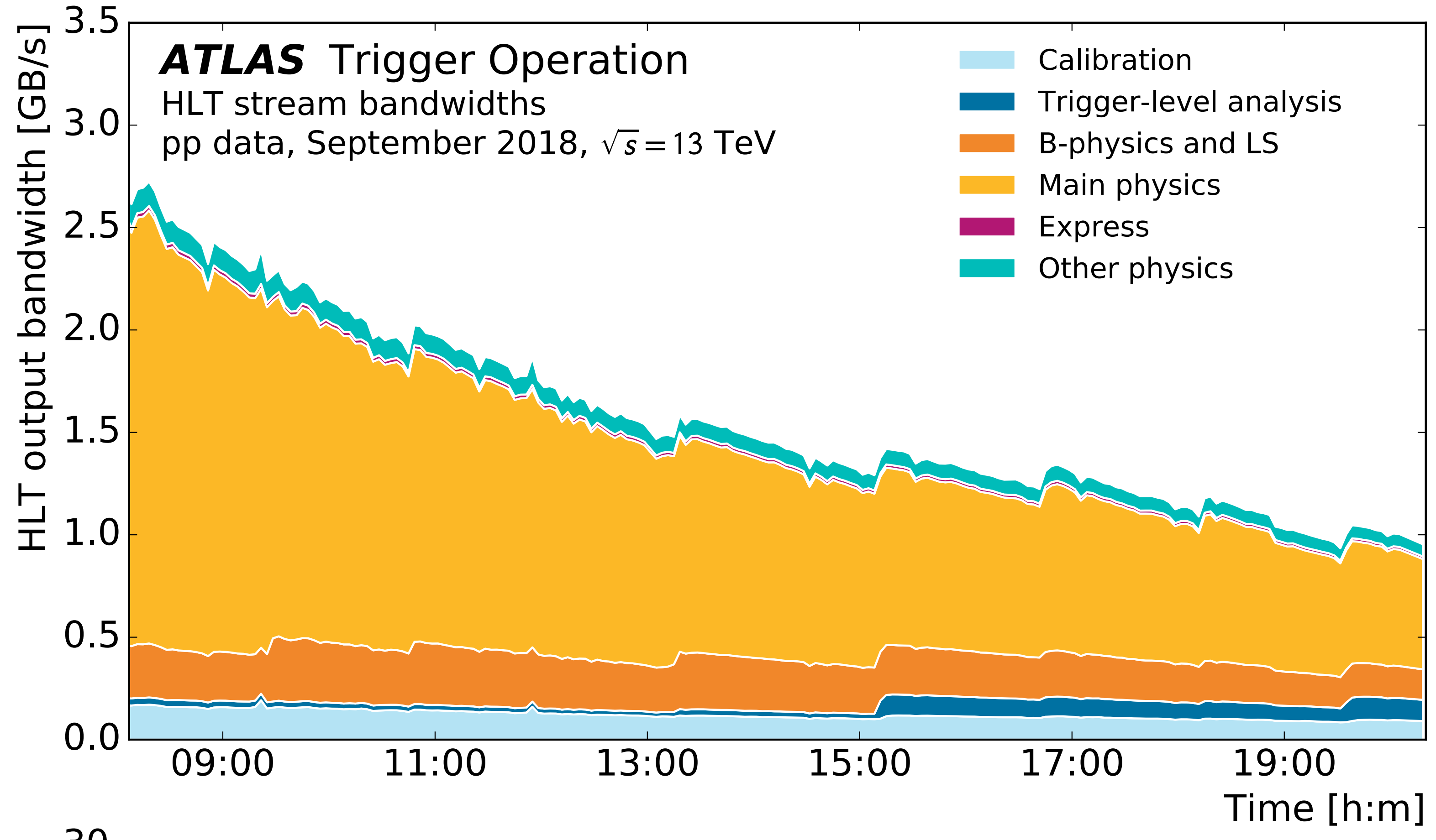
Trigger menu design

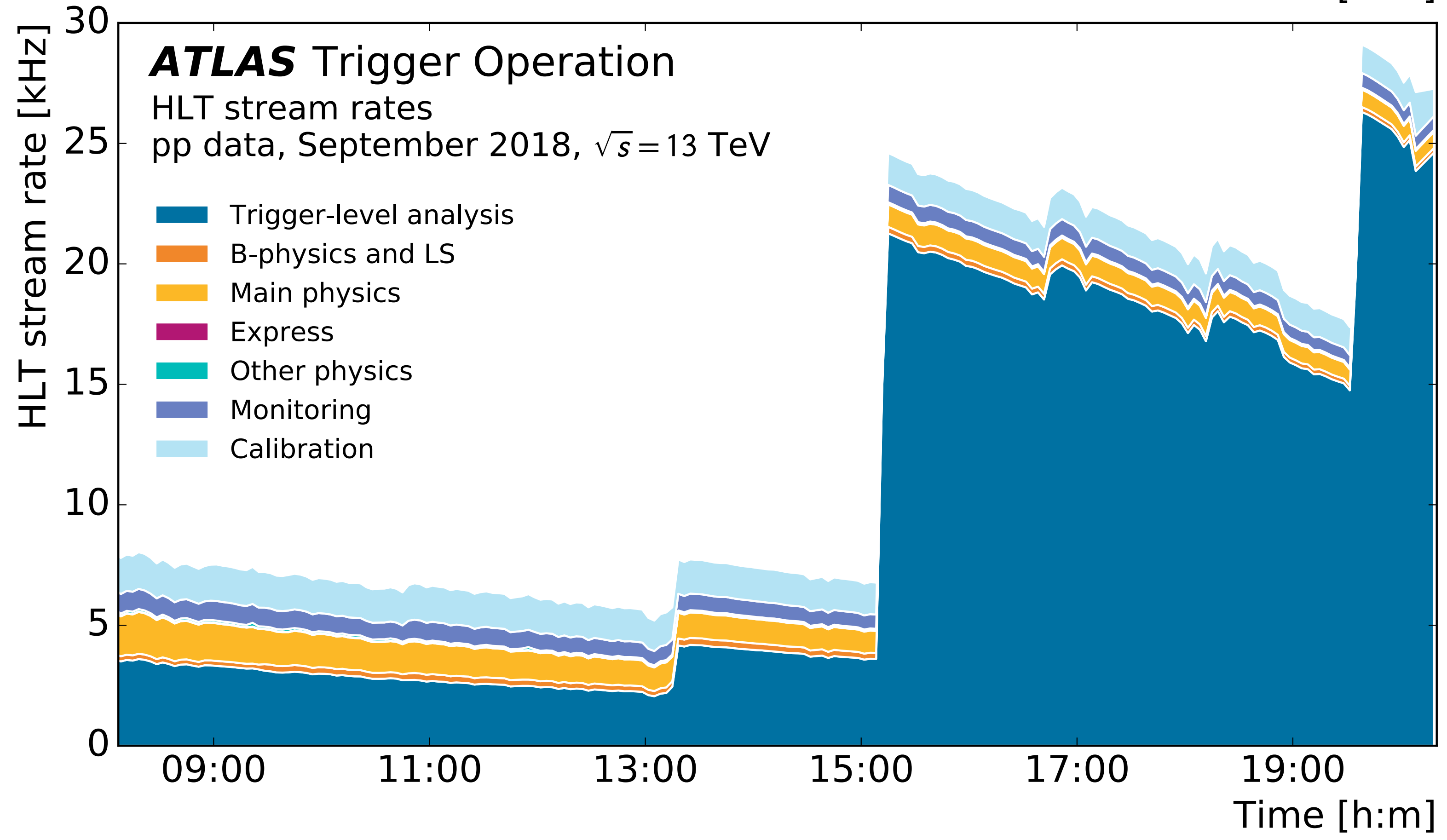
- Continuous effort to port offline improvements to the trigger
- Need to find a compromise between performance and CPU requirements
- Maximize synergy between different trigger signatures
  - E.g. jet calibration uses tracks if available from b-tagging, but has also a calorimeter-only version if tracking has not run



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 trigger-level analysis (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