The ATLAS trigger in Run 2 at high luminosities

HEPMAD 2018

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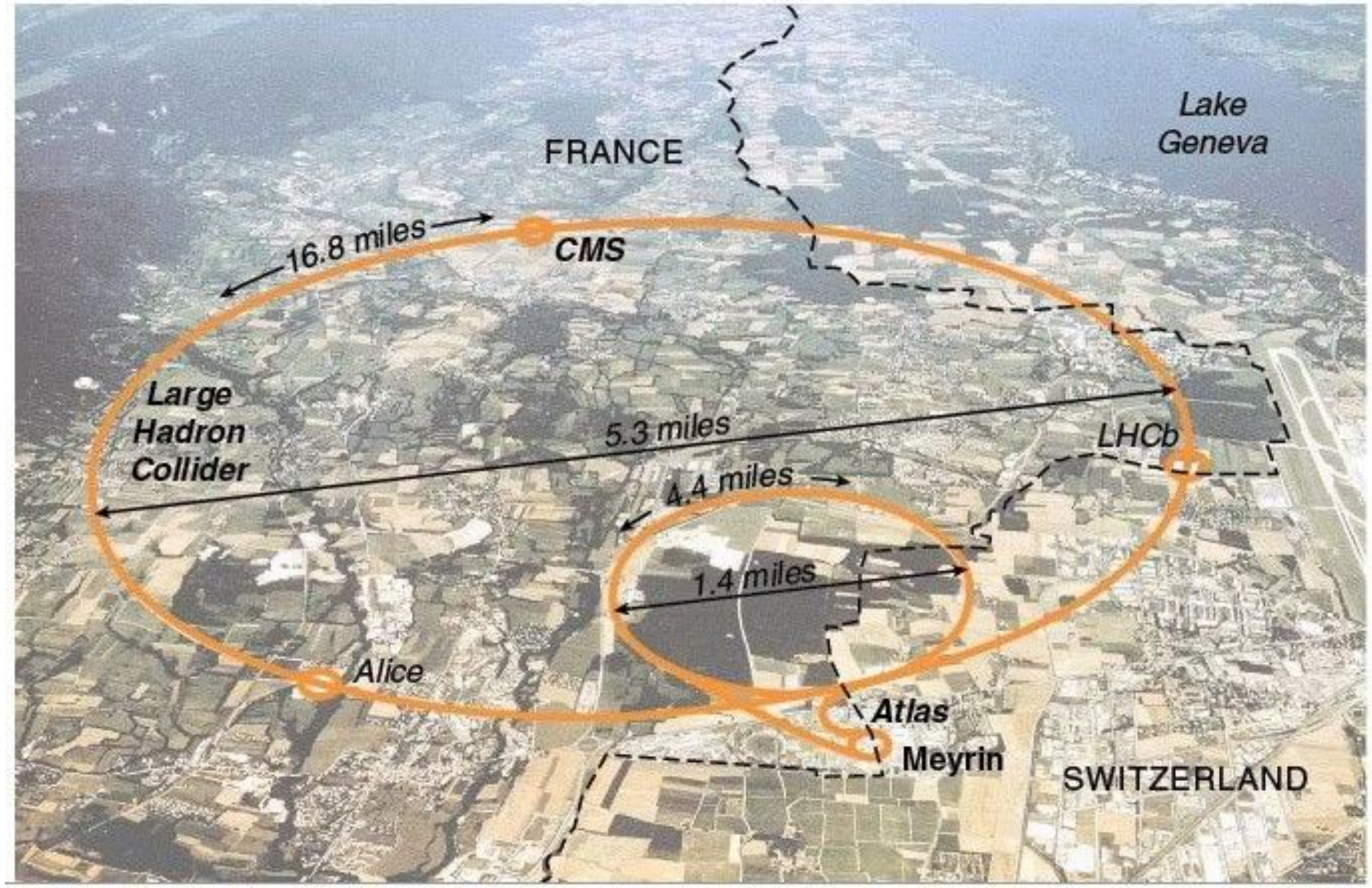
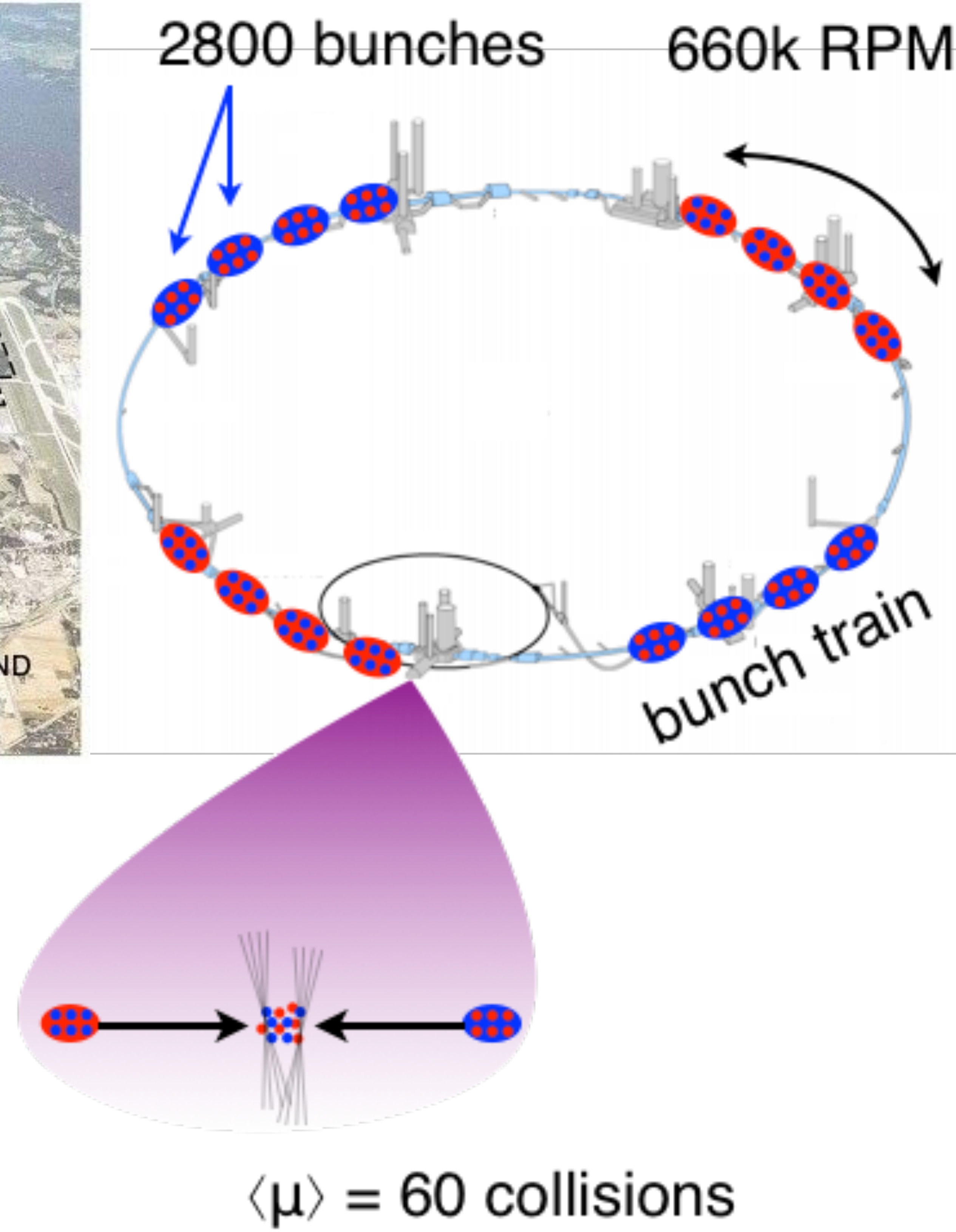
ATLAS Collaboration

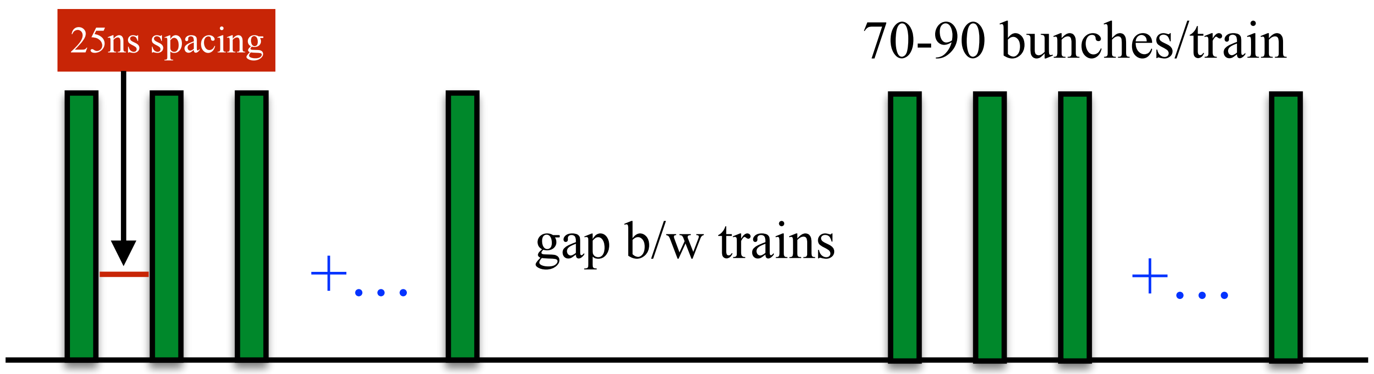
LHC

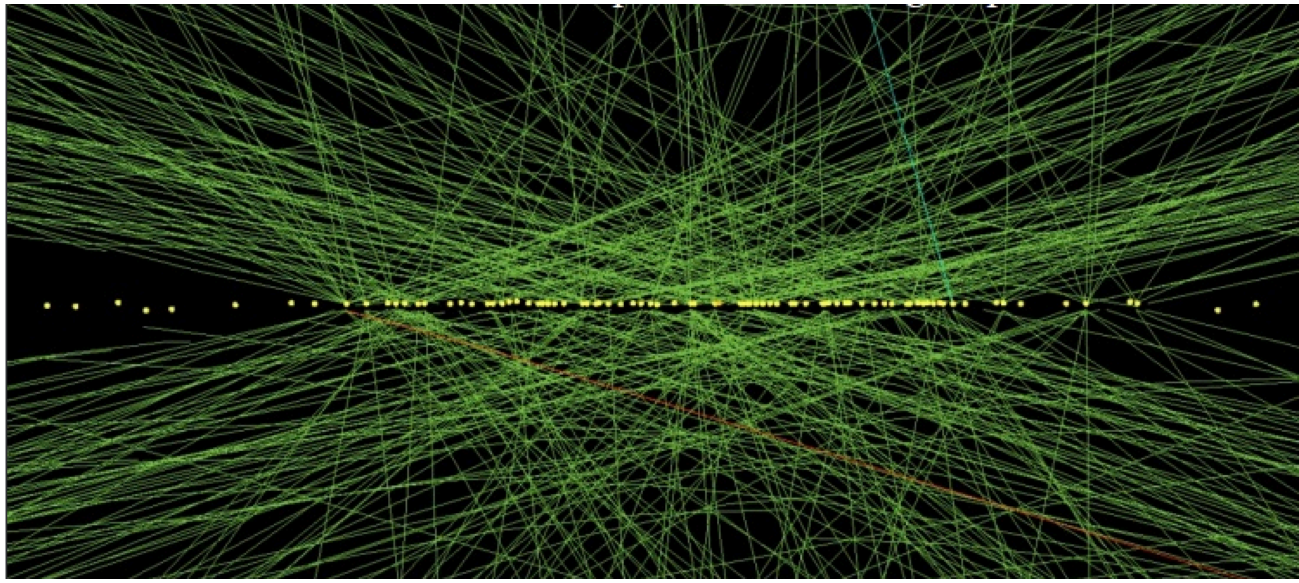




- Beam specifications
  - Number of bunches: 2800
  - Bunch spacing: 25ns
  - Crossing rate: 40 MHz

Pileup

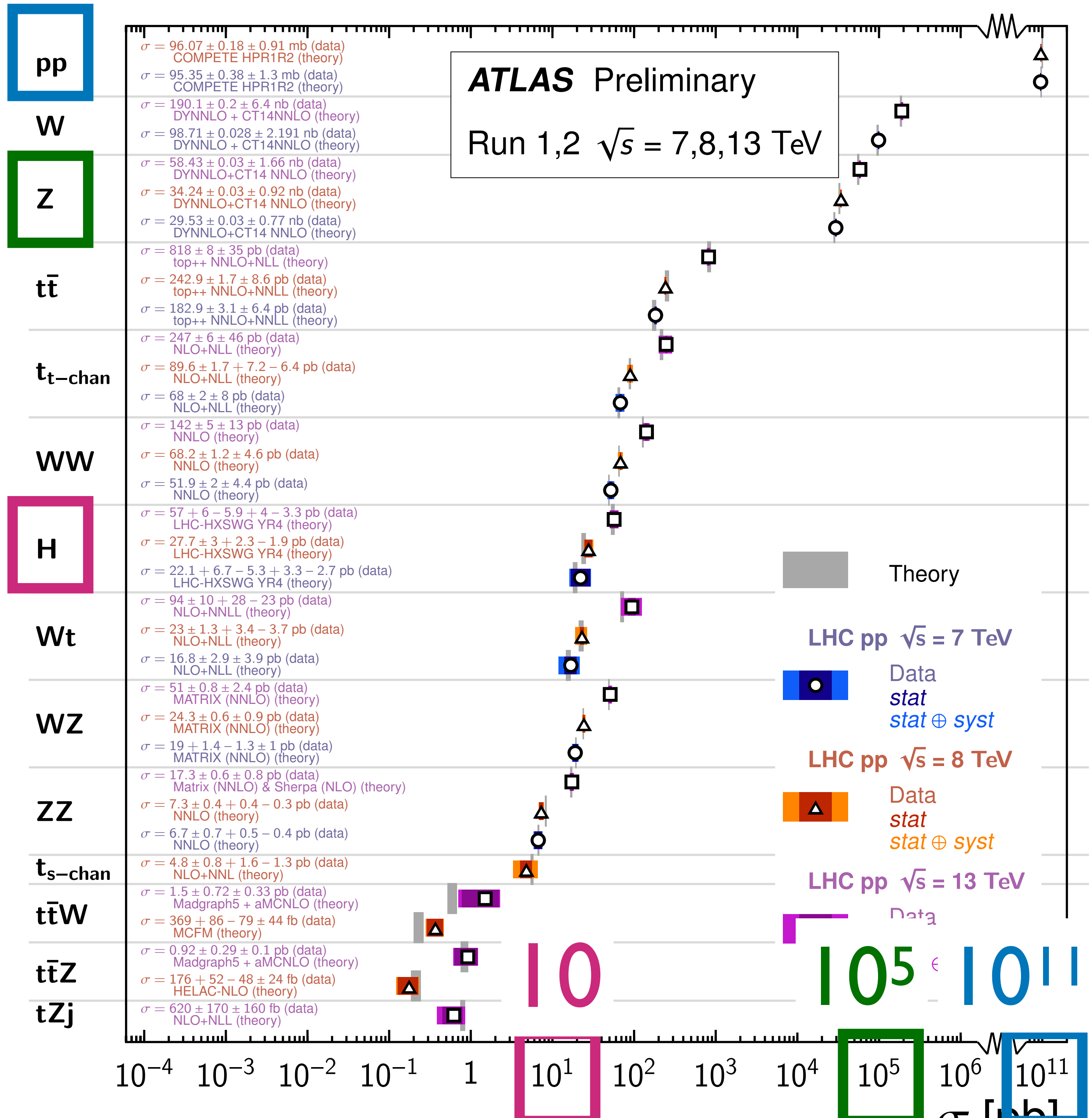




- Pileup: number of pp collisions per bunch crossing observed
- Two types of pileup:
  - *In-time pileup* :
    - due to additional pp collisions within a single bunch crossing
  - *Out-of-time pileup* :
    - due to signals from collisions in other bunch crossings

Why do we need triggers?

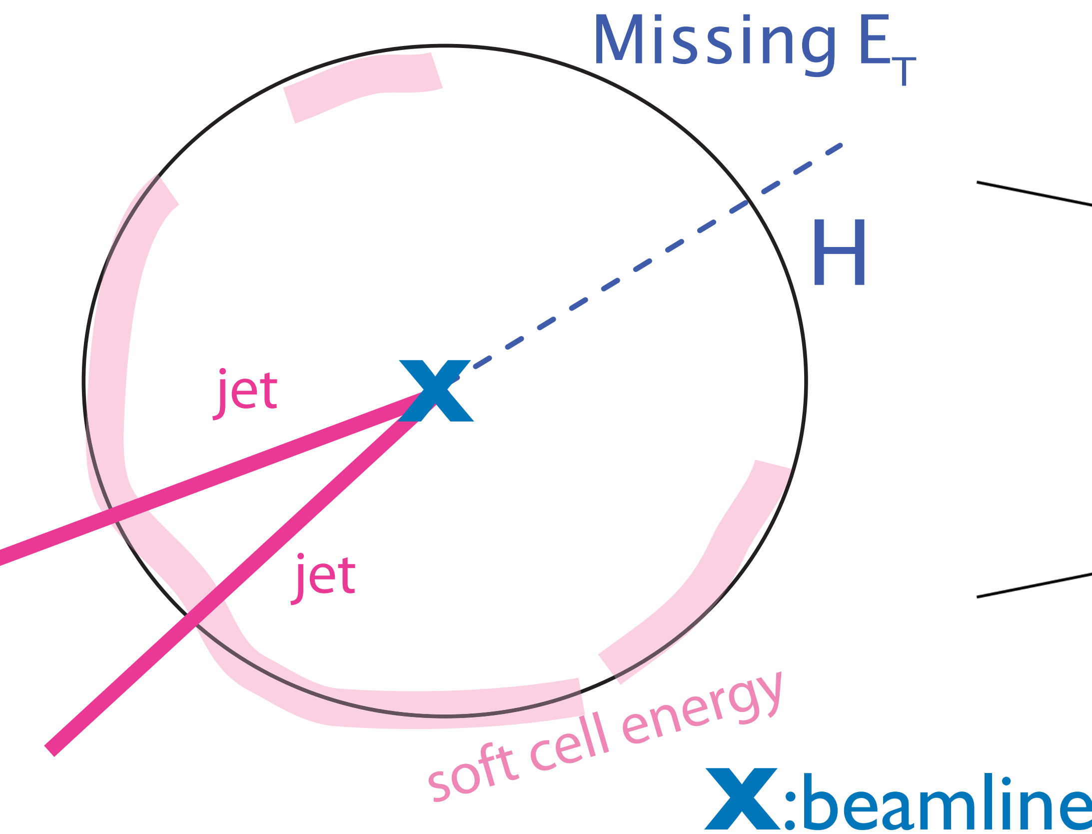
- Limitations:
  - Event size: ~1.5 MB
  - 40M crossings(events)/s
  - Can store: 1000 events/s
- The job of the trigger is to maximize physics outputs
  - Efficiency
  - Output rate

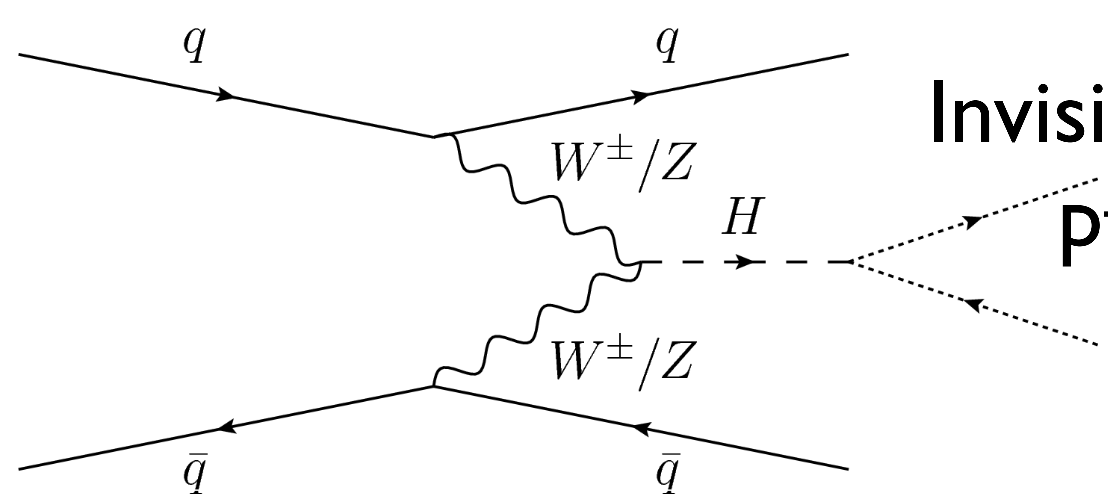


Summary Plots Standard Model

Physics to trigger example

- Physics Example: Vector Boson Fusion (VBF) H→ Invisible search is one of the high priority analyses





Invisible Dark Matter
p_T ~ 150 GeV

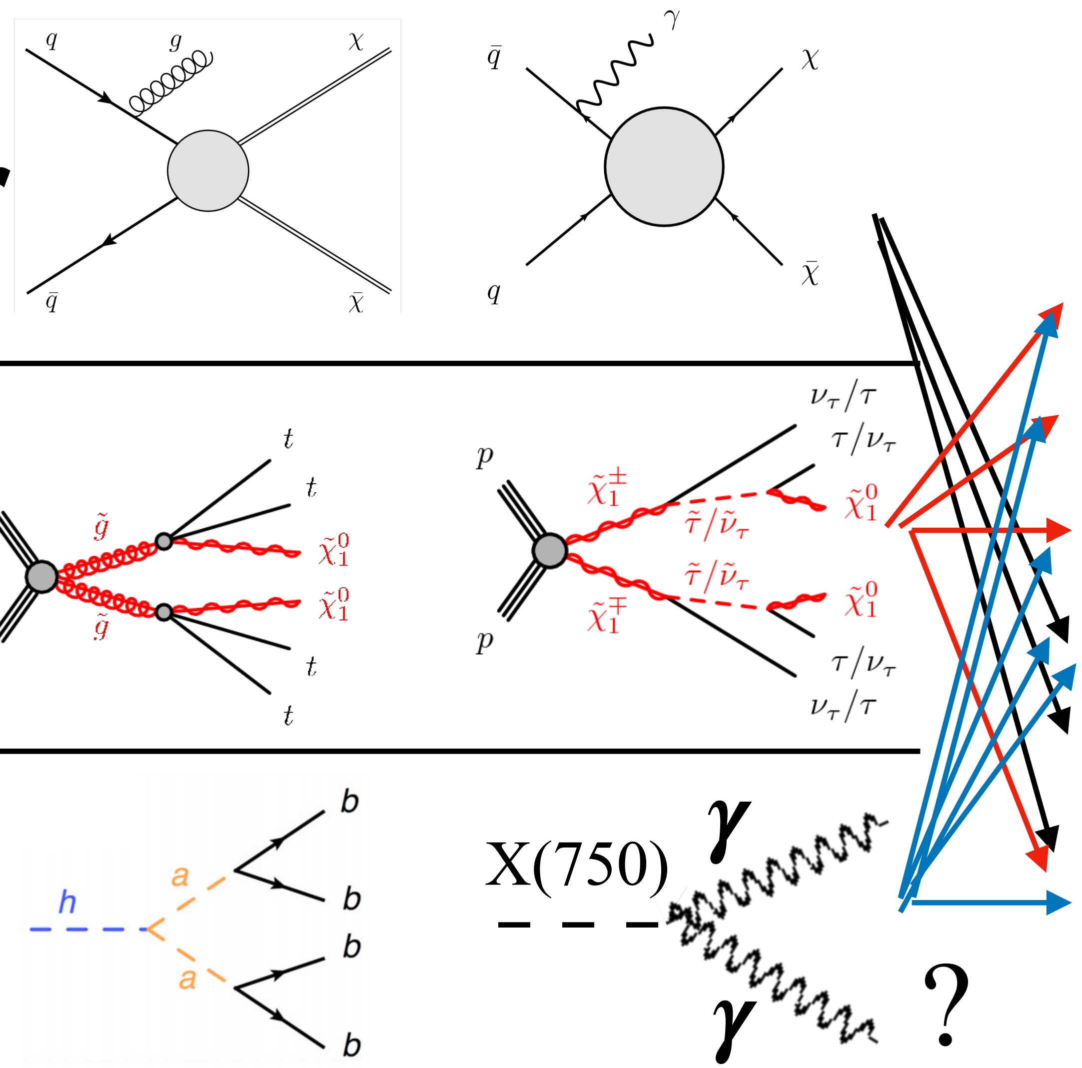
- Trigger for signal: Missing energy (“invisible”) Missing E_T > 150 GeV
- Trigger for “control” samples (to estimate background Z→νν/W→lν):
  - Leptons: Z→ ee, μμ, W→ eν,μν

Design a trigger system

Dark Matter

SUSY

Exotic Higgs
(+ production modes)



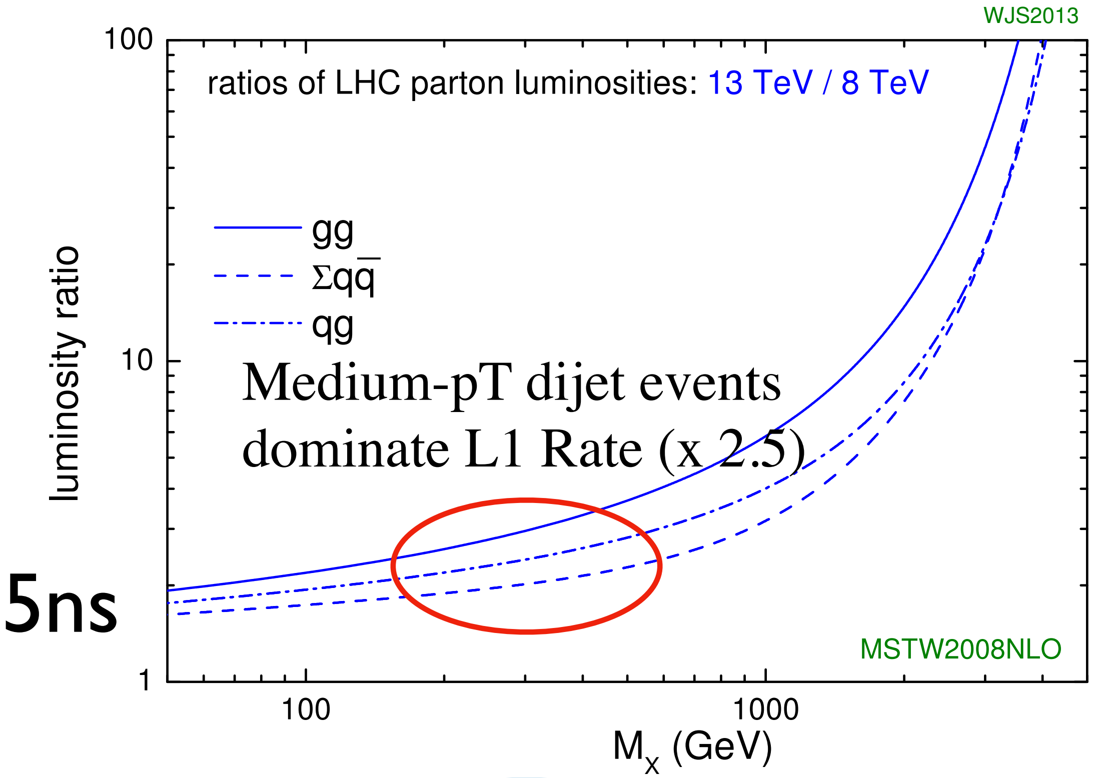
Triggers signatures

- Electrons
- Muons
- Taus
- Photons
- Jets (p_T, multijets, H_T, b-jets)
- Missing E_T

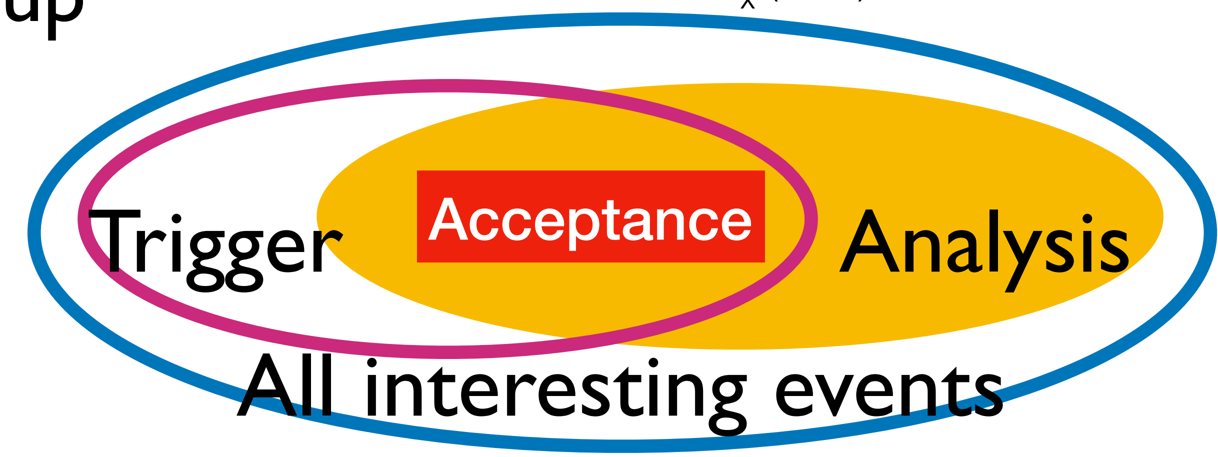
- Broad coverage of interesting physics
  - Optimize trigger menu (set of selection criteria running at the each stage)
  - Allocate resources (rate, memory/timing)
  - Balance between inclusive trigger used by many analysis and dedicated triggers maximizing the efficiency for a single analysis

From Run 1 (2011-2013) to Run 2 (2015-2018)

- LHC conditions brought new challenges:
- Higher energy: 8 TeV→13 TeV
- Higher luminosity:
  - More frequent bunch crossing: 50ns→25ns
  - Higher bunch intensity: 20 → 40 pileup



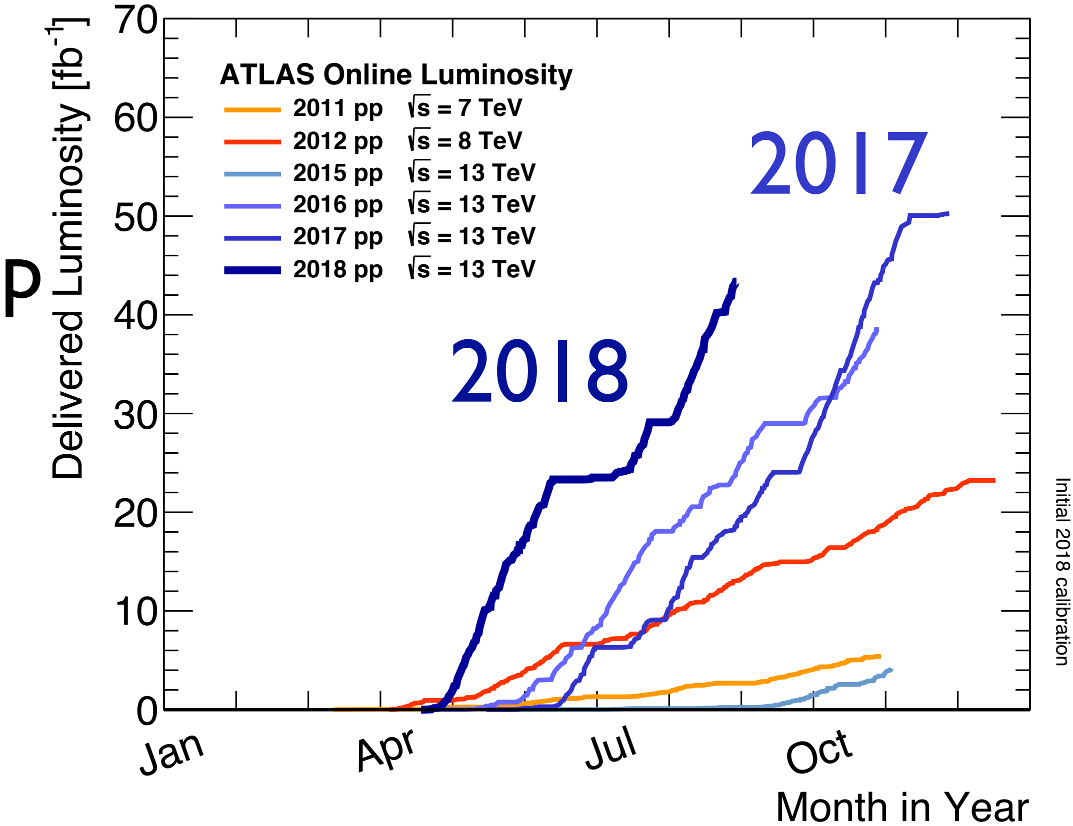
- ATLAS upgraded the trigger system:
  - Unified software part of the system
  - Adapted to reconstruction tools and data structures used in analysis
    - Improved acceptance for analysis
  - Optimized algorithms for different trigger signatures

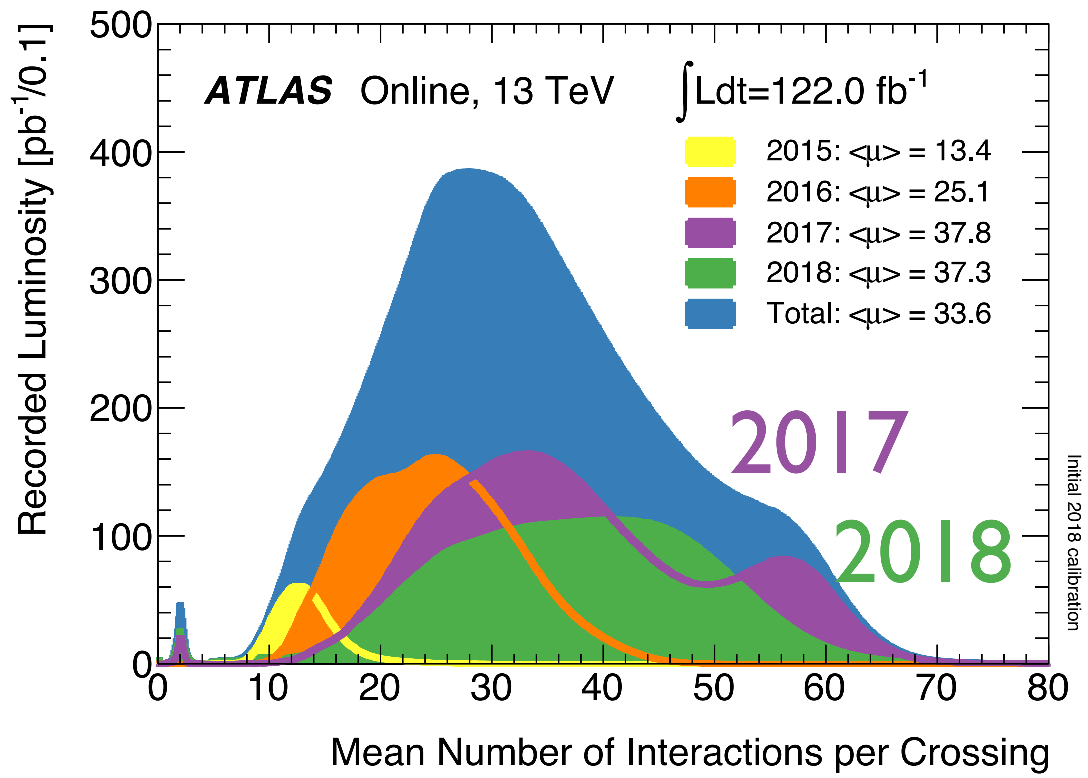


arXiv:0901.0002

More challenges during Run 2

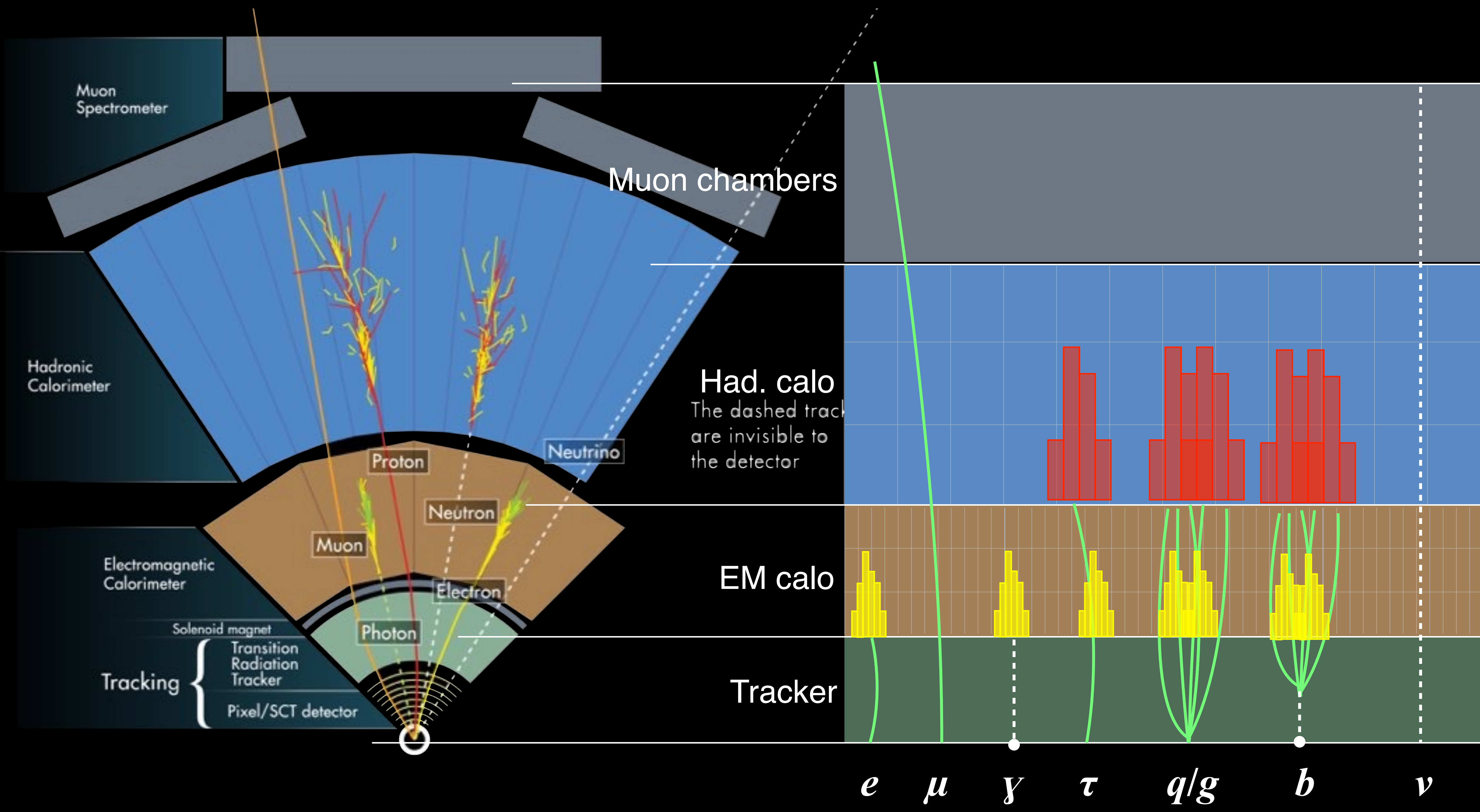
- In 2017/2018 LHC delivered record high instantaneous luminosity at record high pileup
- ATLAS trigger system adapted by
  - Optimizing menu
    - Prescaling triggers
    - Raising threshold
  - Reducing processing costs
  - More selective triggers (L1, L1Topo, HLT)





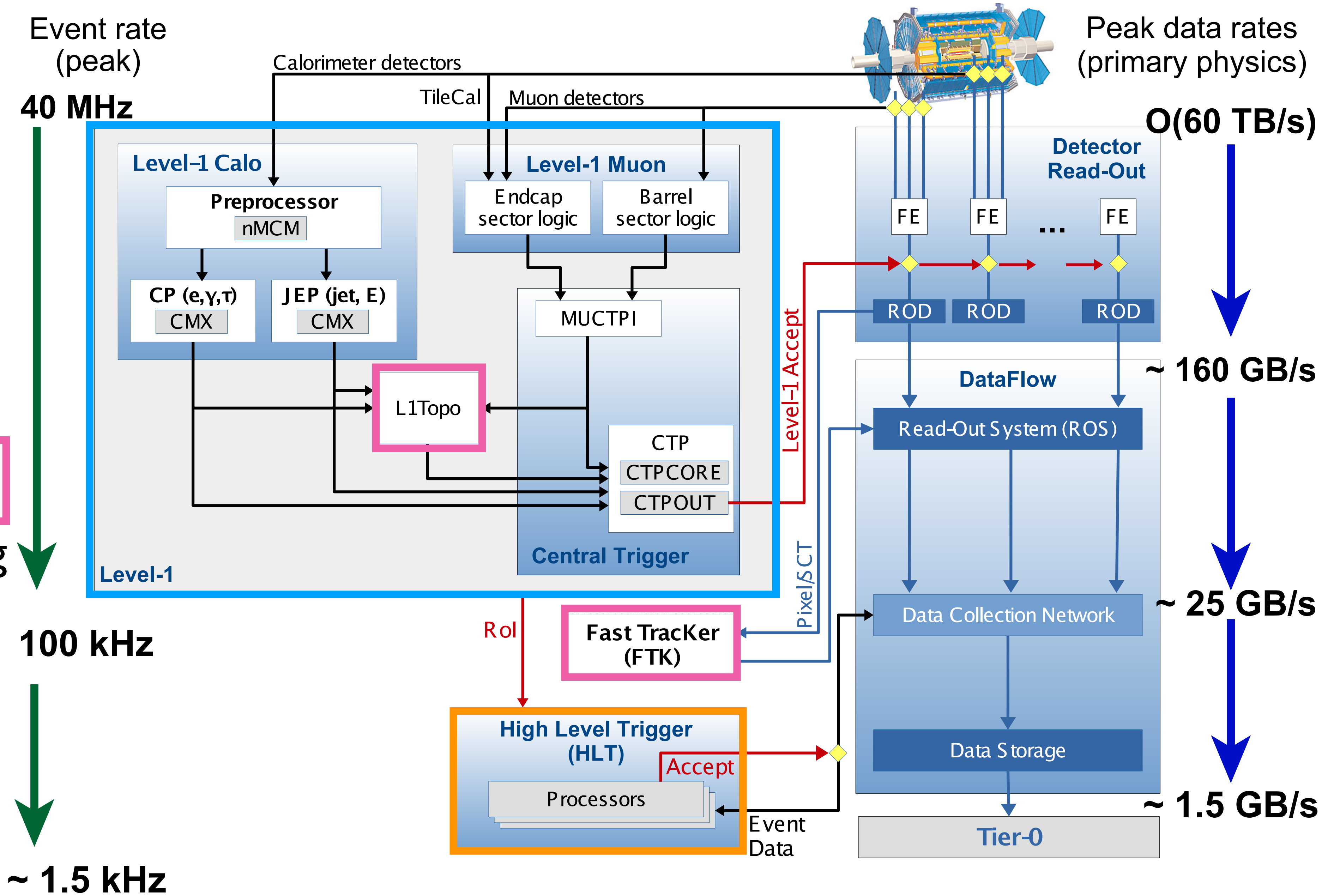
LuminosityPublicResultsRun2

ATLAS detector



Run 2 Trigger System Overview

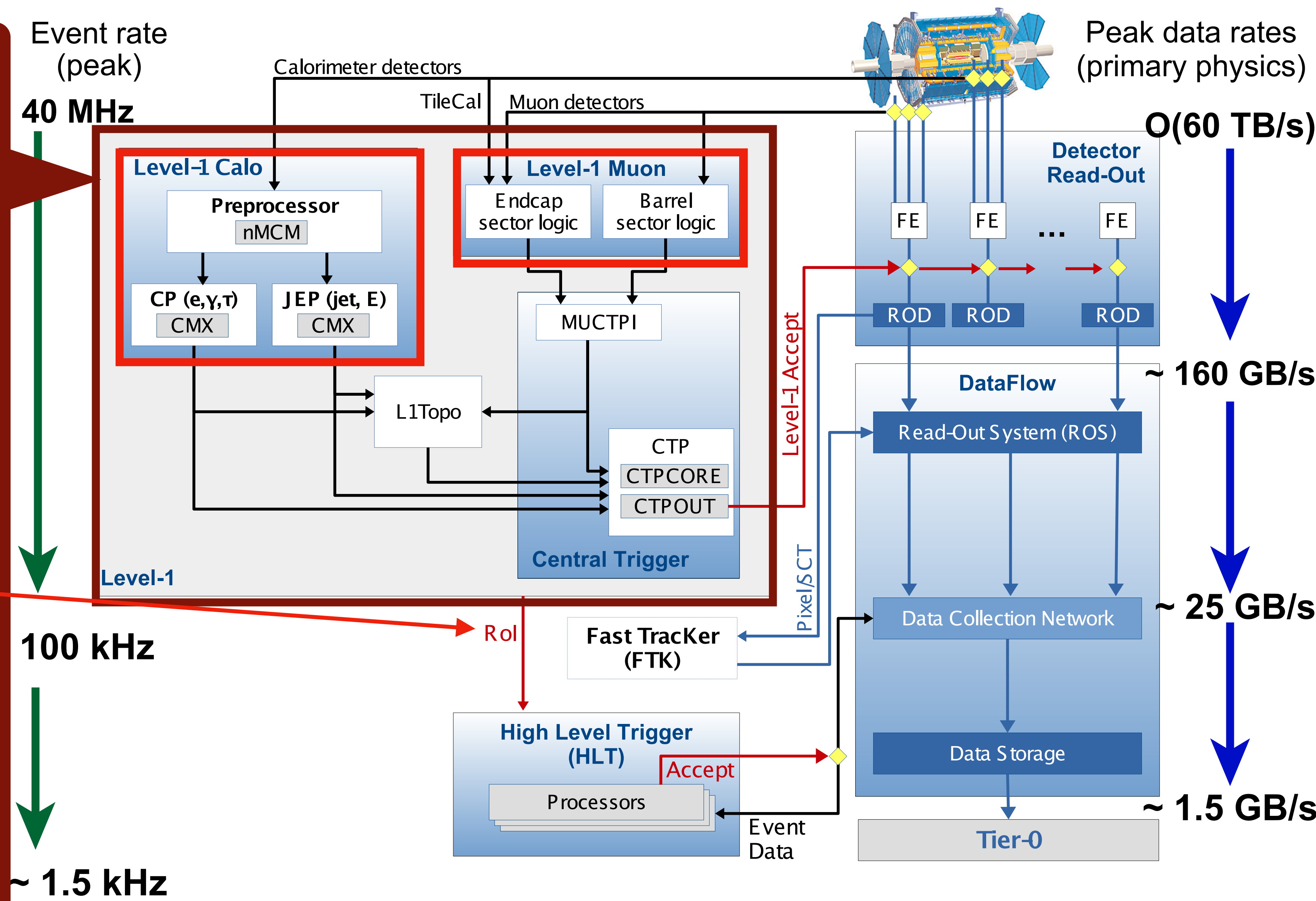
- Two-level trigger system:
  - Level 1 (L1): hardware
  - High Level Trigger (HLT): software
- New hardware components:
  - L1Topo: joined data taking since 2017
  - FTK: being commissioned



arXiv:1611.09661

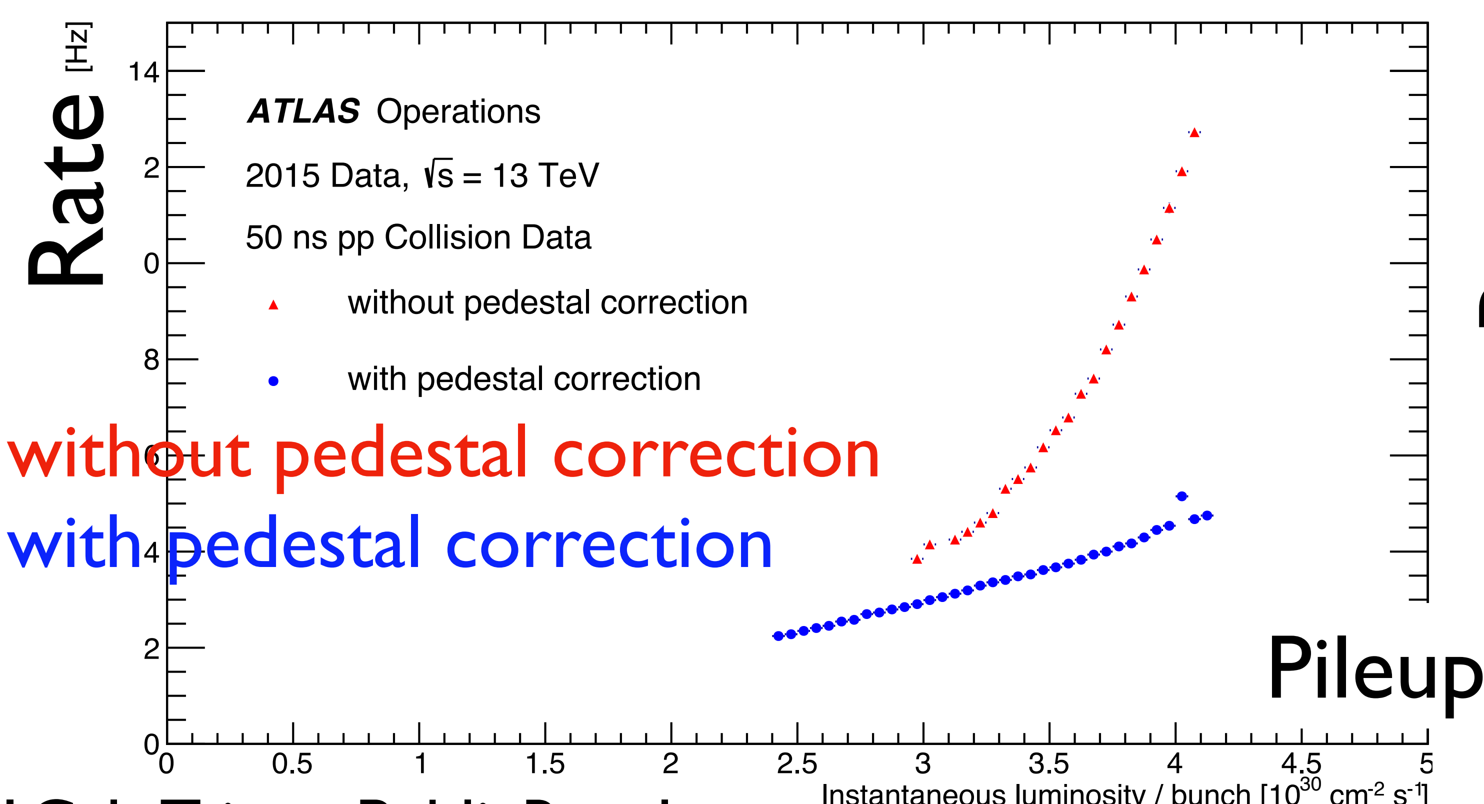
Run 2 Trigger System: L1

- Level-1 (L1) trigger:
  - Hardware-based
  - Takes in low granularity calorimeter/muon detector data
  - Fast decision to identify small regions restricted in angles for HLT (Regions of Interest: RoI)
  - L1 Calo: e/γ/τ/jet/MET/Total E
  - L1 Muon: μ
  - Fixed processing time 2.5 μs

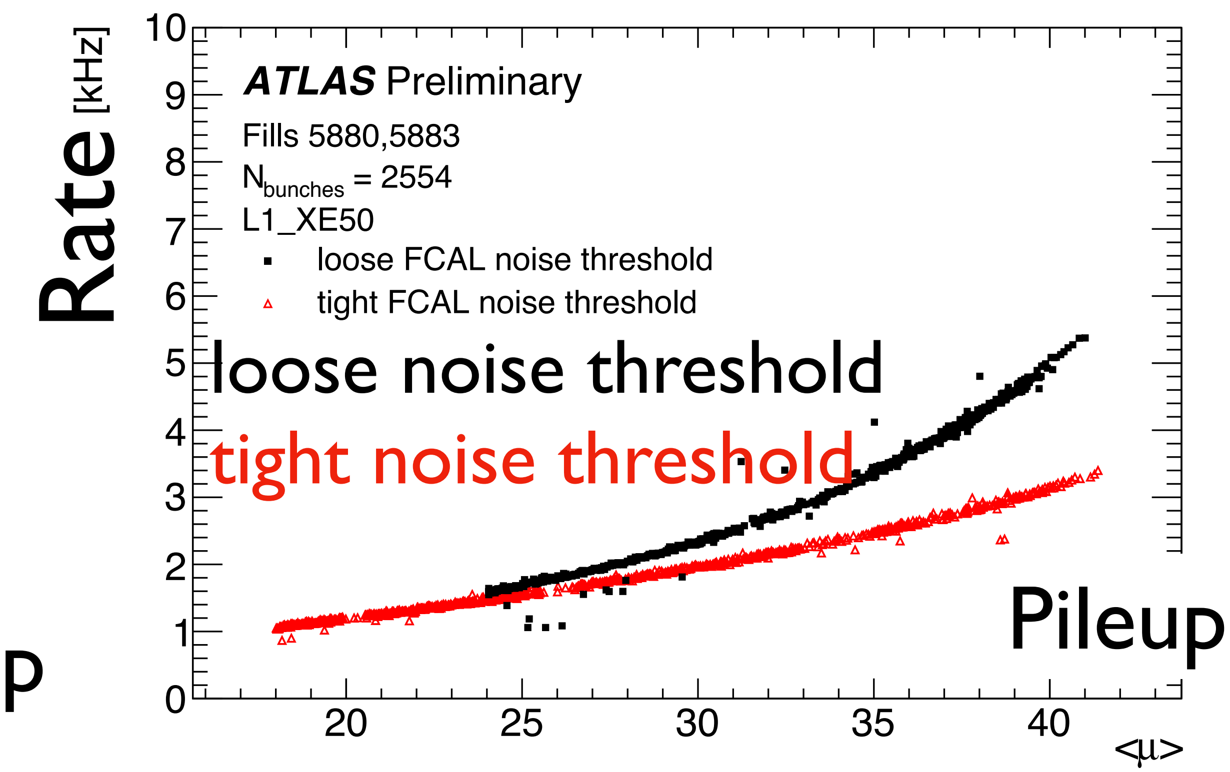


L1Calo

- Out-of-time pileup:
  - Pedestal correction: removes out-of-time pileup for start of bunch train
  - Autocorrelation filter: deweight previous bunches (wikipedia)
- In-time pileup:
  - Noise threshold raise: reduces rate with minimum resolution loss
- Significant improvement in rate for Missing E_T & jet triggers



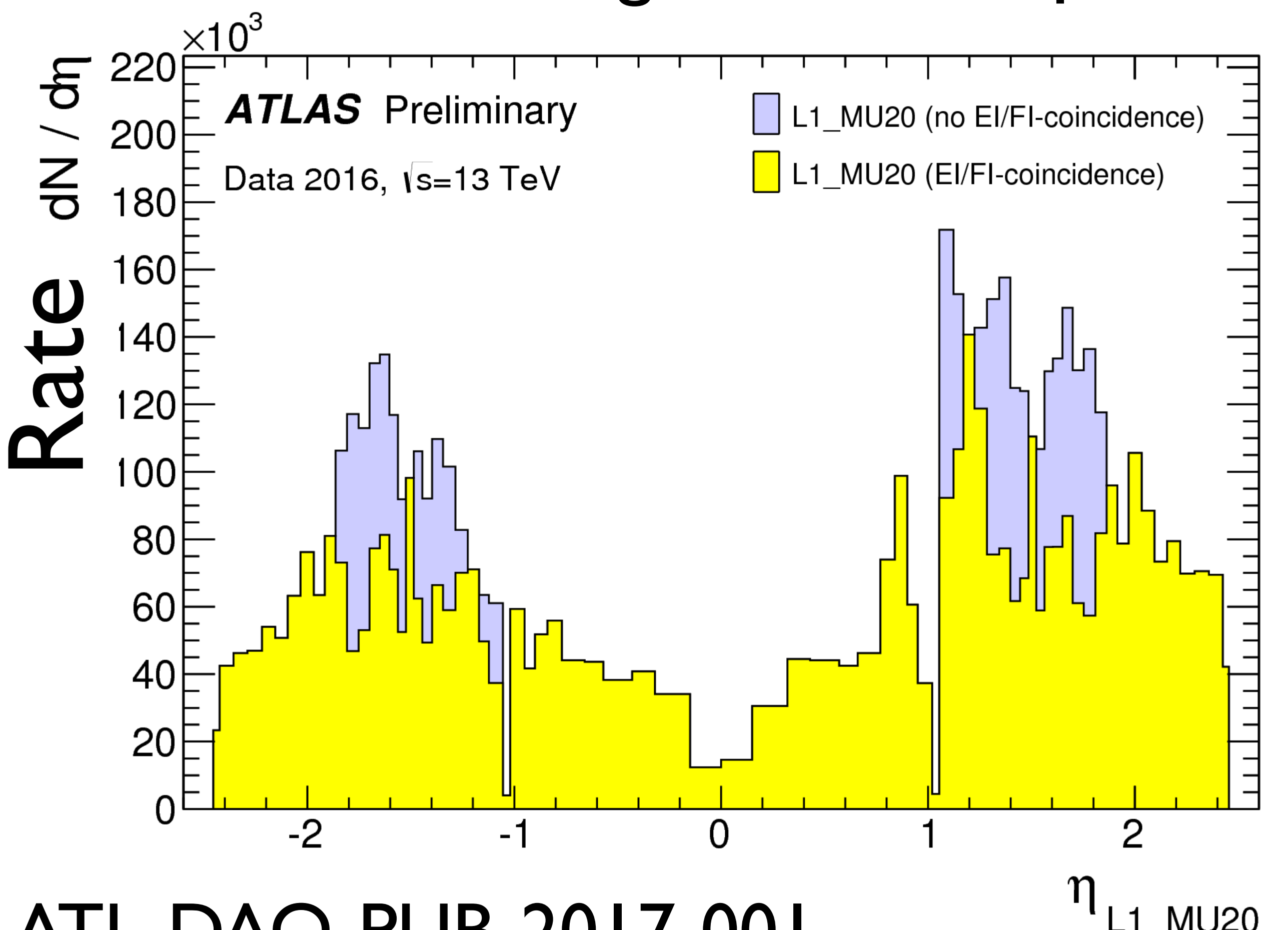
L1CaloTriggerPublicResults



MissingEtTriggerPublicResults

L1Muon

- Run 1: fake rate dominated by particles outside the interaction point
  - Worse at Run 2: +38%
- Run 2: requires coincidence of muon outer chamber with its inner station (2015)/ tile calorimeter (late 2017)
  - 28% rate reduction (1% efficiency loss)
  - Coincidence logic between η=1.0-1.3 (tile calorimeter) was enabled late 2017



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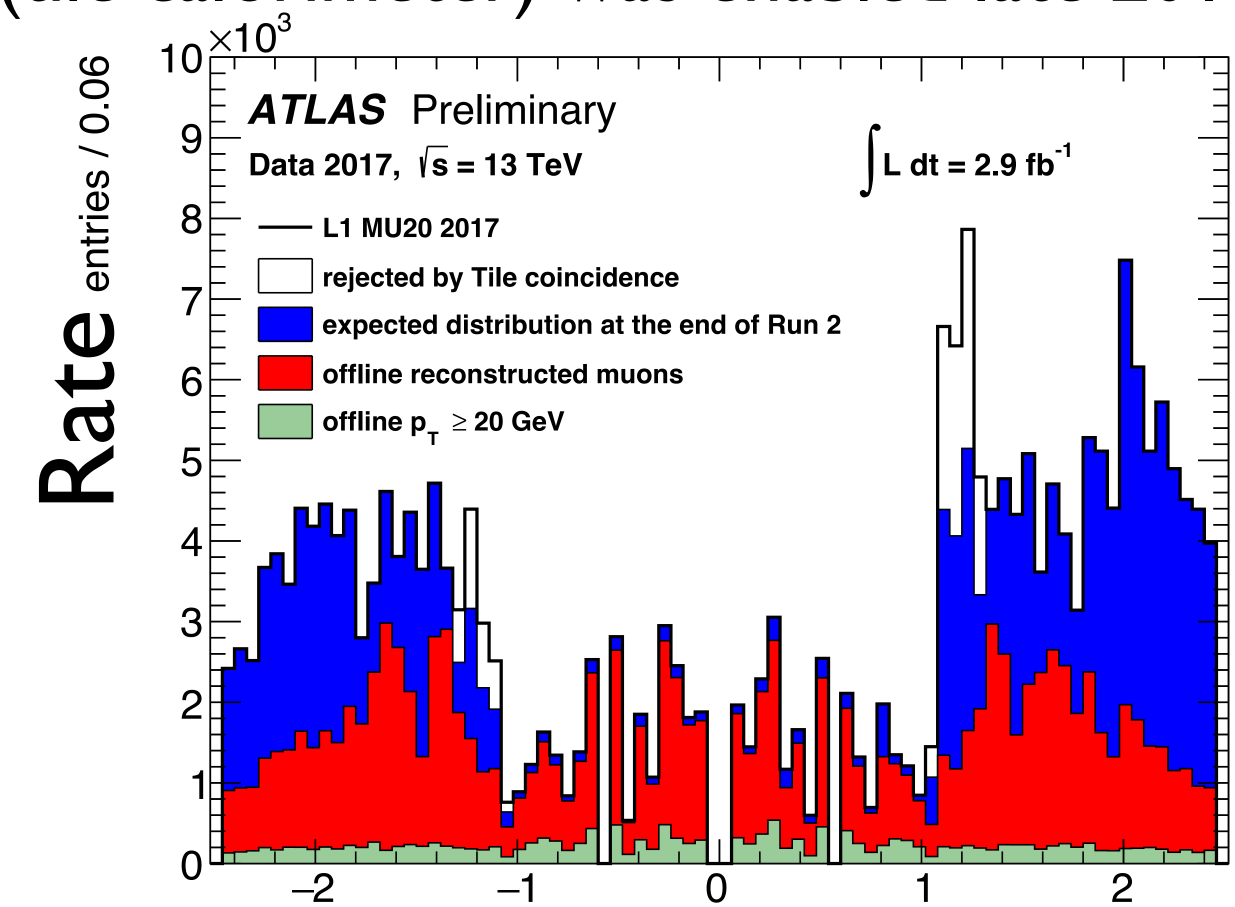
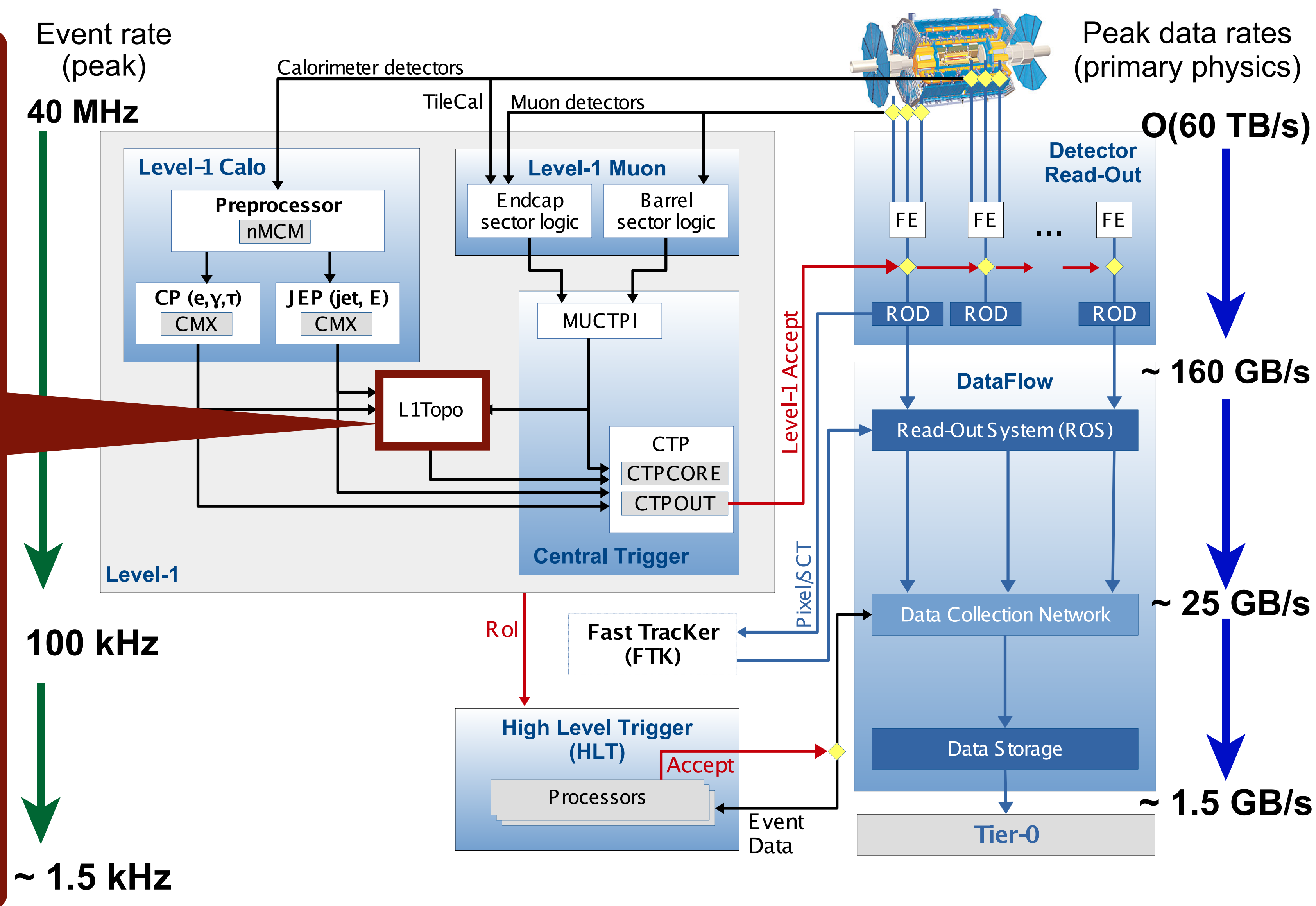


L1MuonTriggerPublicResults

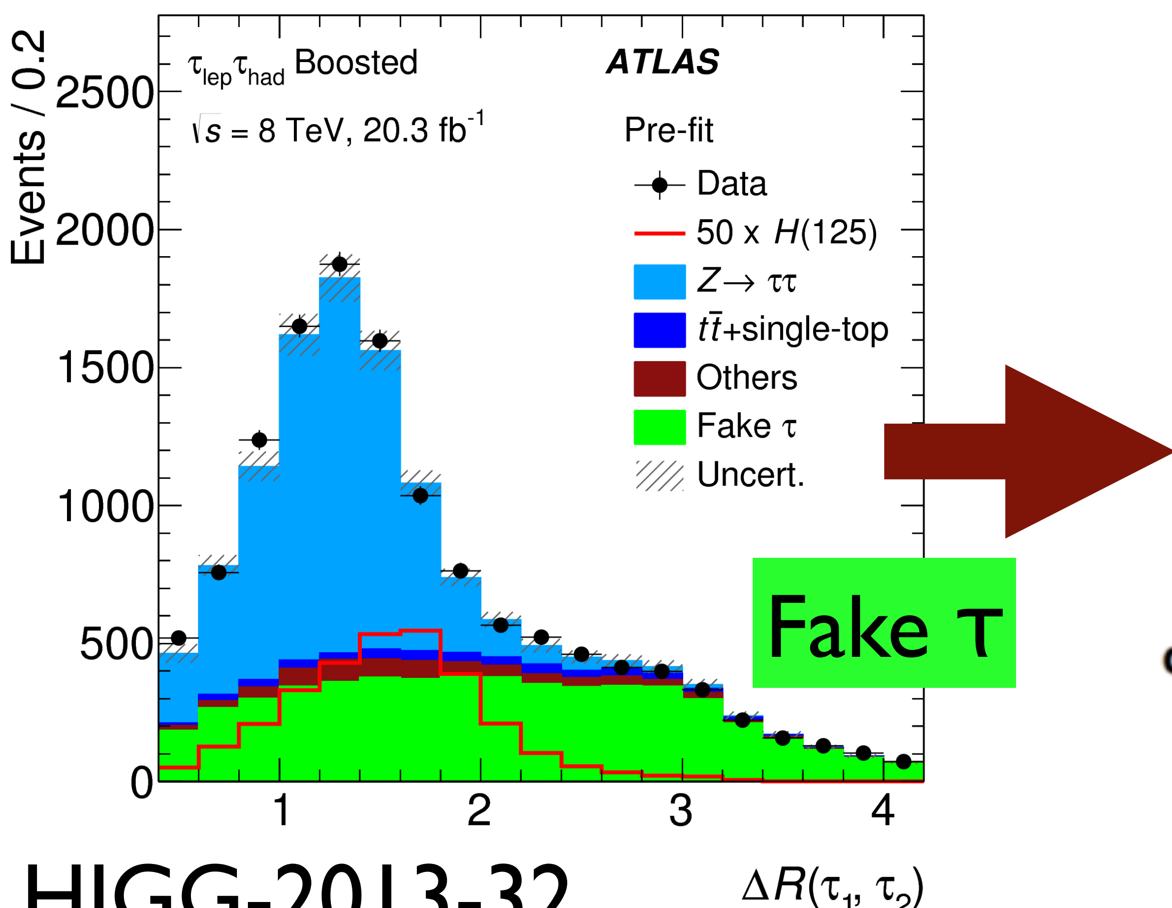
Run 2 Trigger System: L1Topo

- L1Topo: new hardware
  - Receive data from L1Calo, L1Muon
  - Execute topological algorithms in ~100 ns
- Used to collect physics data since 2017

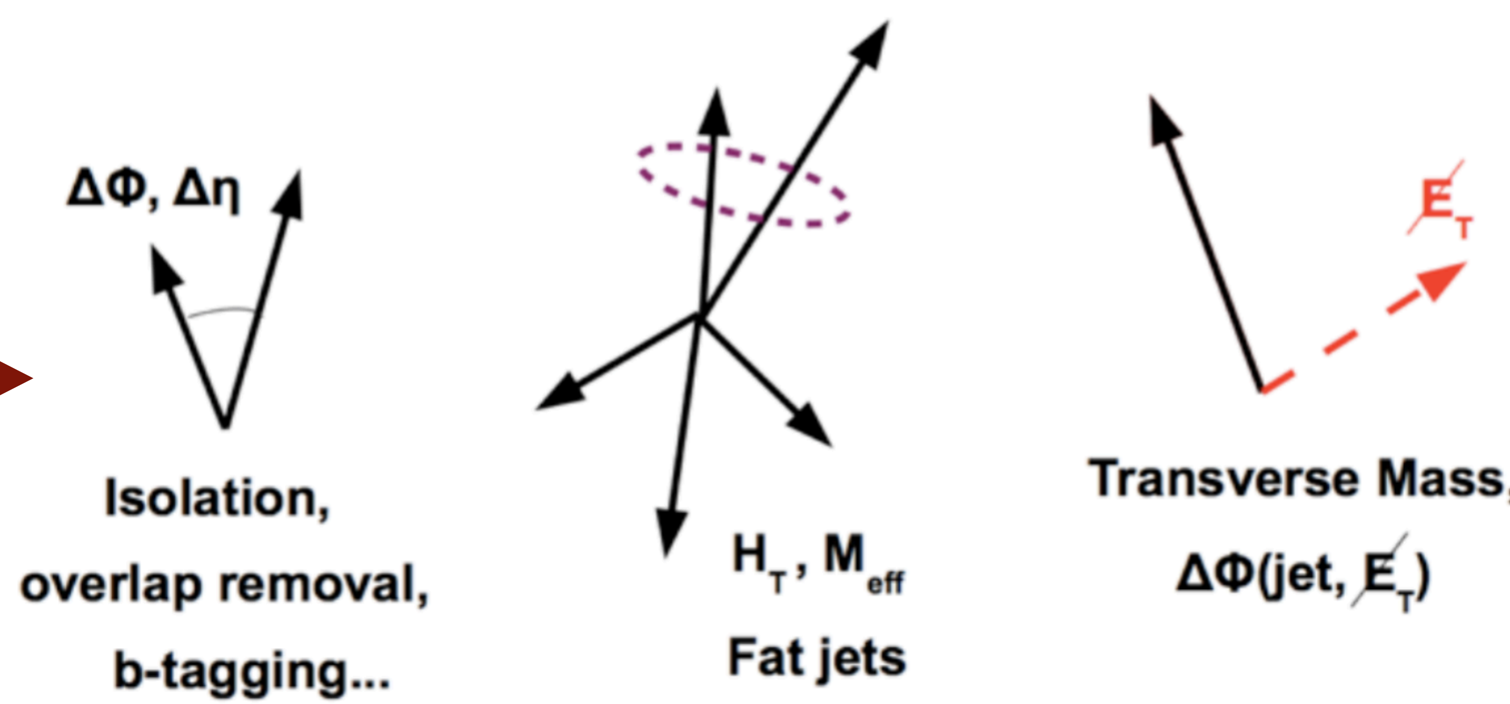


L1Topo

- Event-topology-based, uses geometrical and kinematic info of the regions of interests
- Employing real-time event kinematics and angular cut
- Allows dedicated decision makings before detector readout (100kHz)
- Up to 128 decision algorithm trigger bits
  - e.g. $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

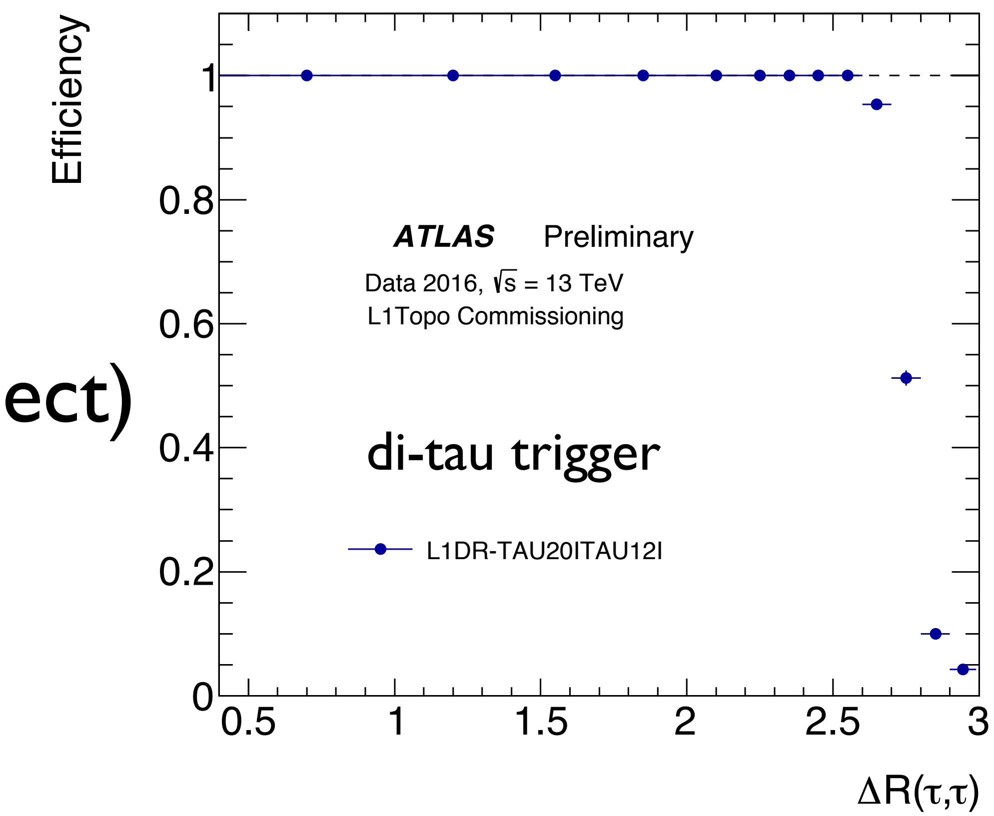


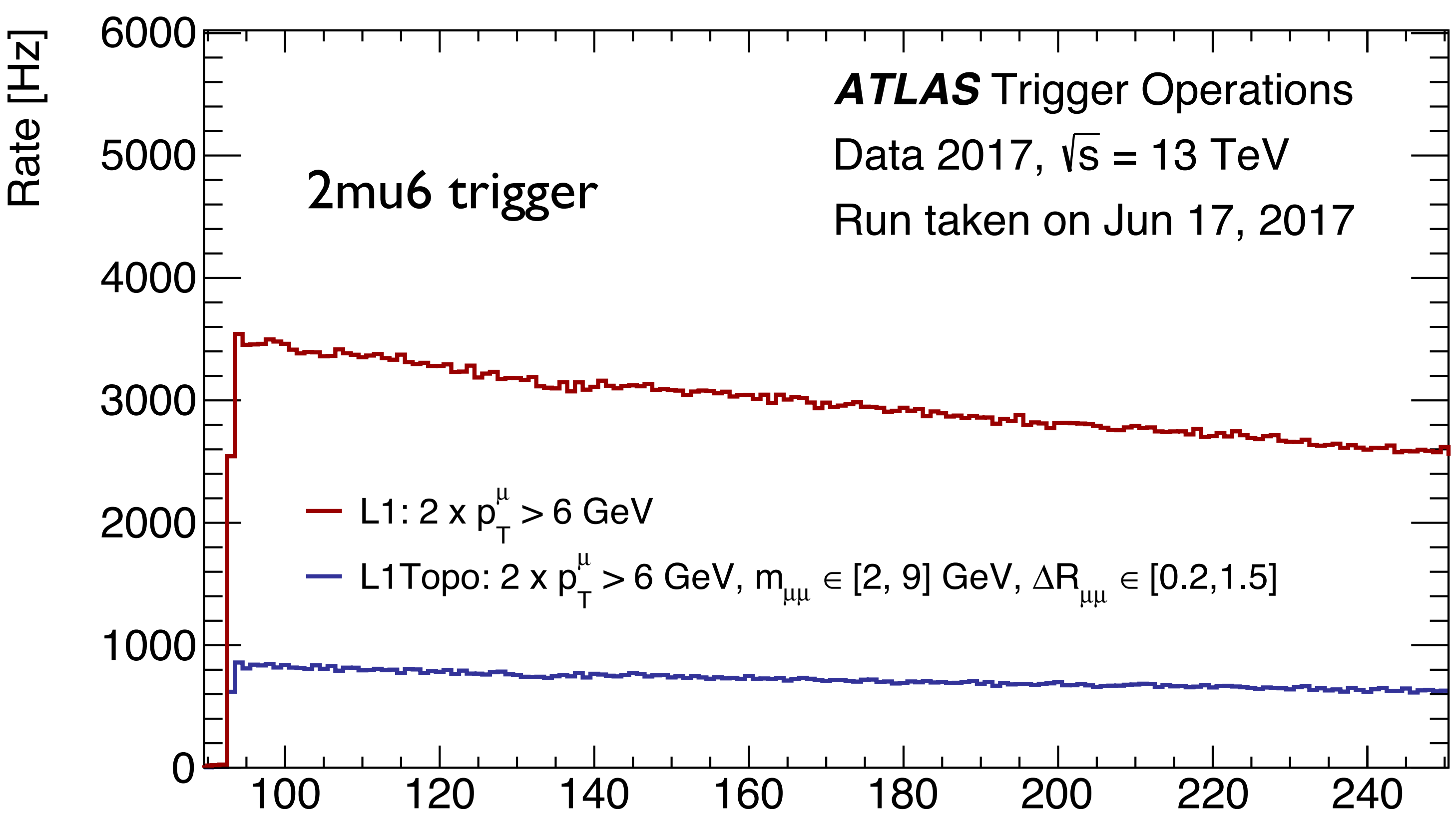
HIGG-2013-32

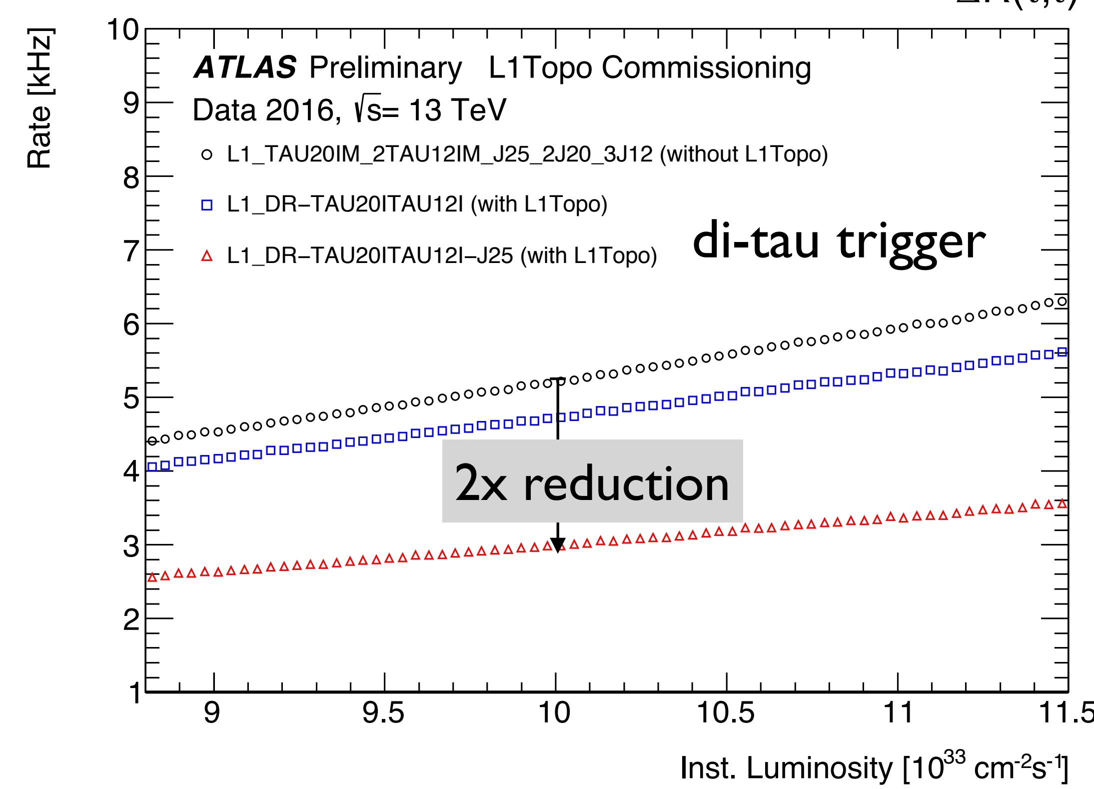


L1Topo

- Significant rate reductions achieved
  - Only small loss in efficiency
- Essential for rate-demanding signals
  - H→ττ, B physics… (typically low-pT di-object)
- Allows to trigger on difficult signatures
  - VBF H→bb, long-lived particles…



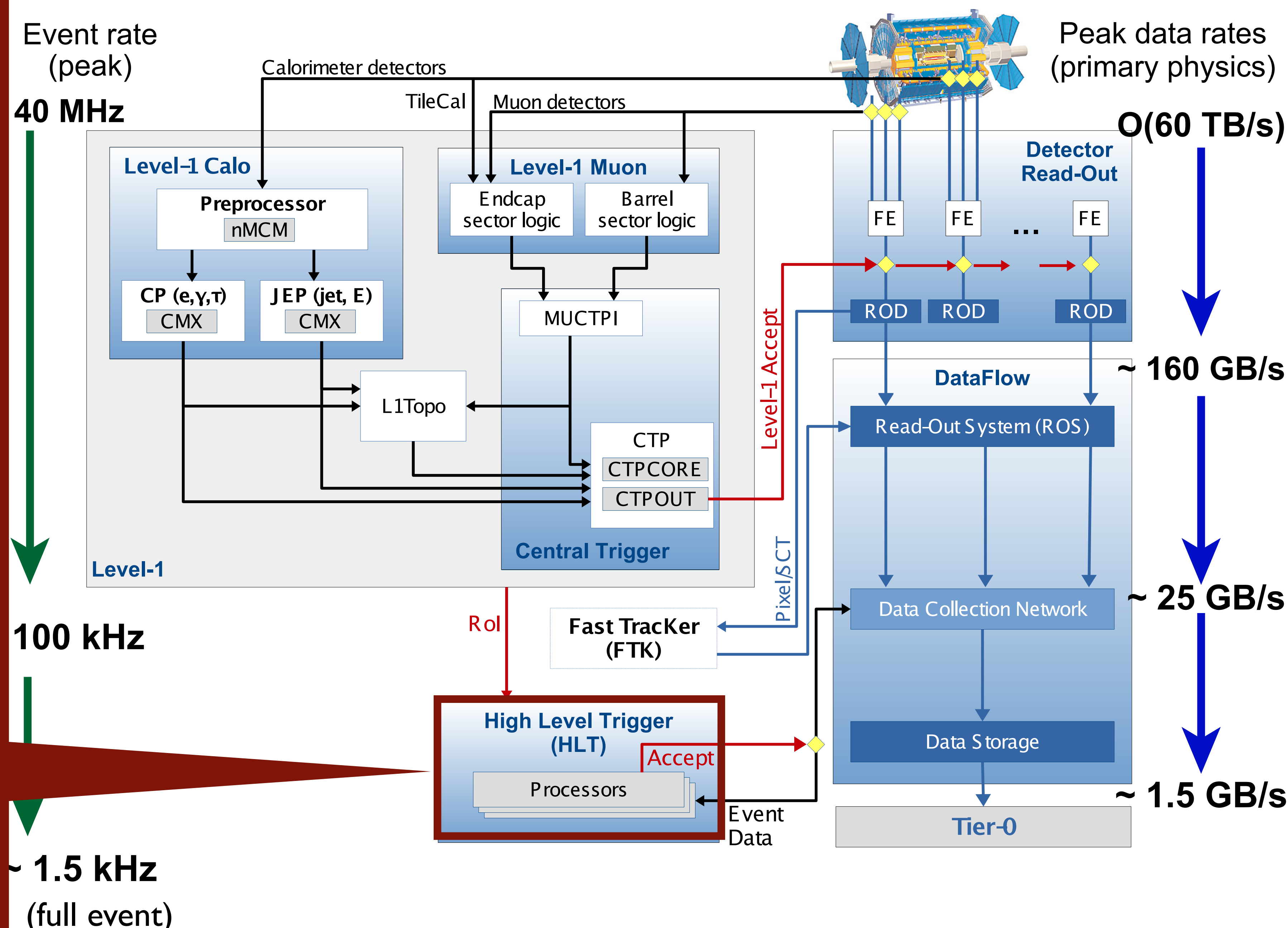




TriggerOperationPublicResults

Run-2 Trigger System: HLT

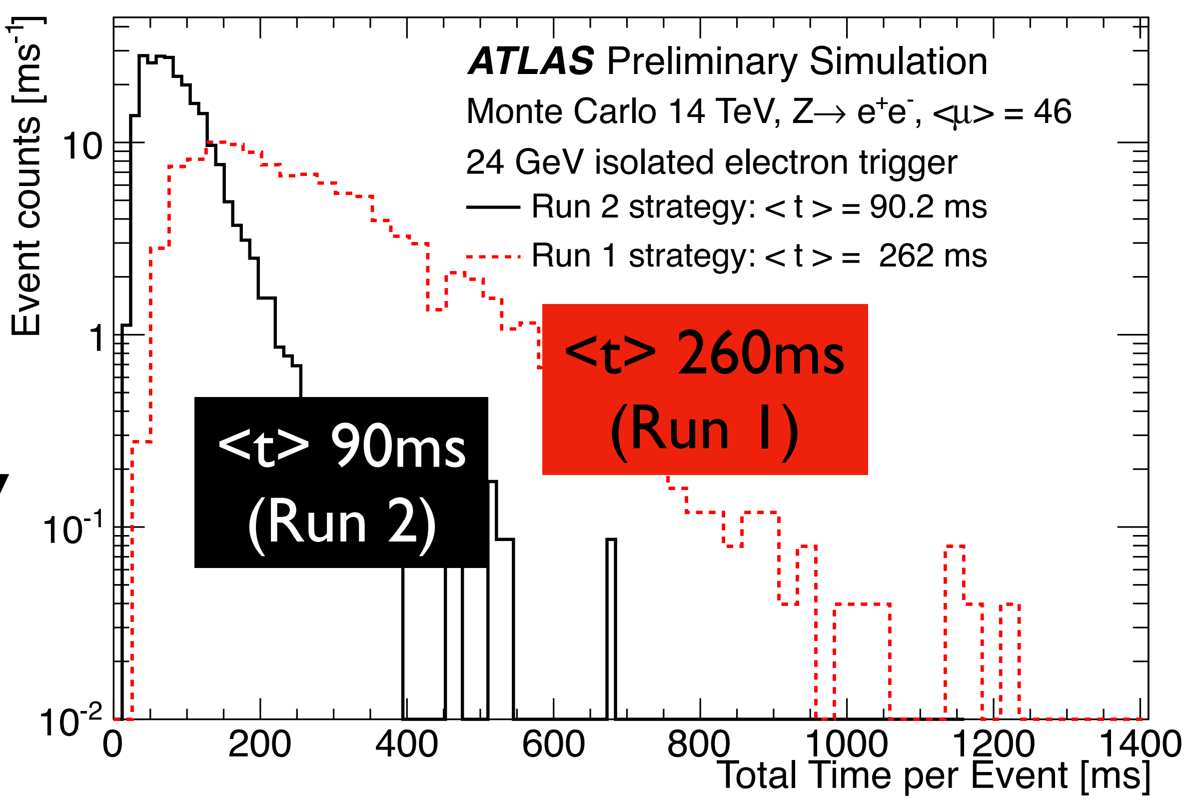
- High Level Trigger (HLT):
  - Software-based
  - ~40-50k processing units
  - Full-granularity data in
    - RoI
    - Full event
  - Analysis-like algorithms and selections
  - Latency : O(1s)
  - Max processing time: 500ms



Inner Detector tracking in the HLT

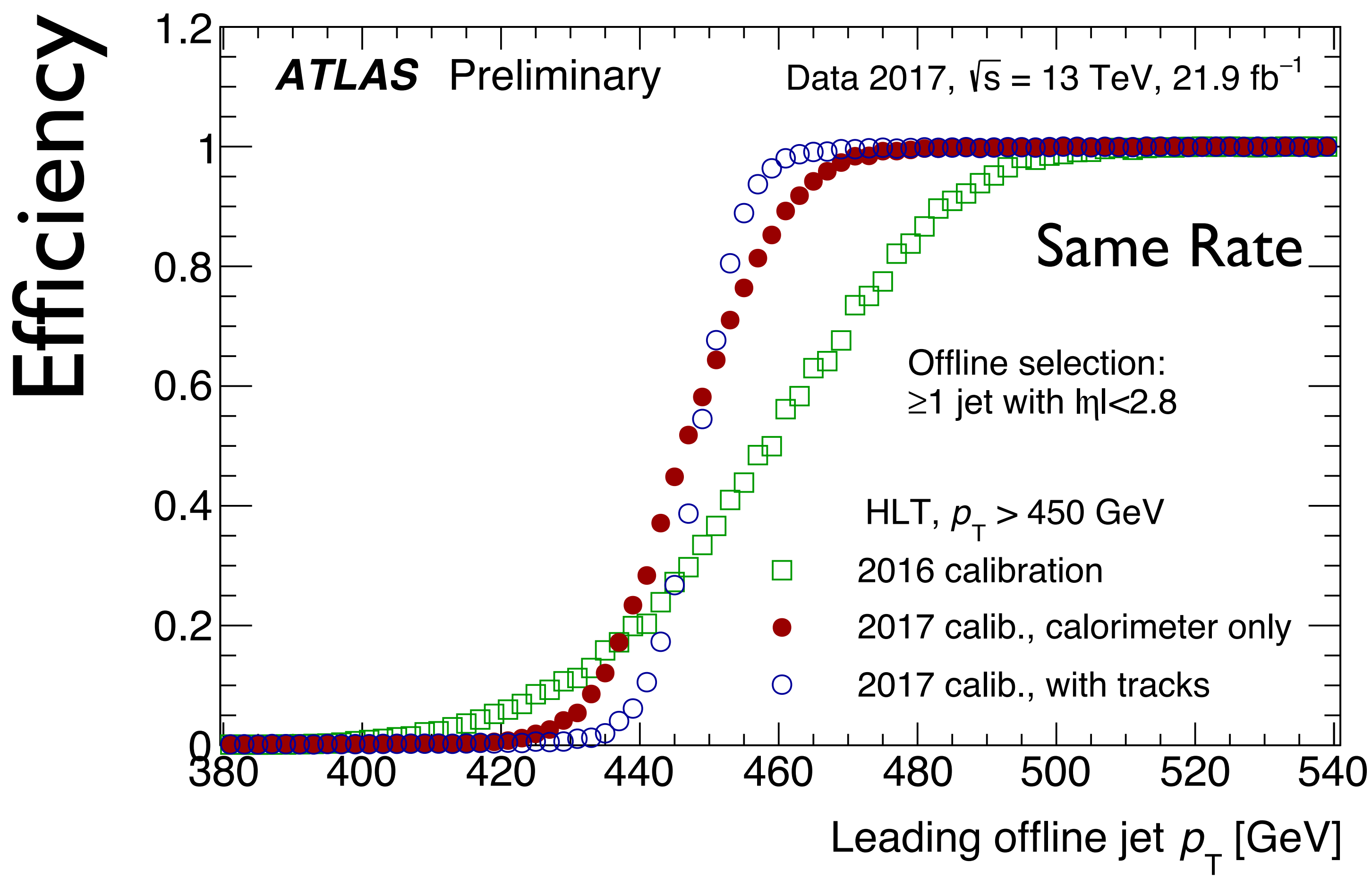
- Tracking: Needed by most triggers
  - Very CPU intensive in HLT
  - Can mostly only afford to do tracking within RoI
- Strategy change from Run 1 to Run 2:
  - Fast Track Finder (FTF): tracking in narrower regions
  - Precision Tracking: more detailed tracking
  - Do precision tracking using seeded information from FTF

Approximately 2x speedup between run 1 and run 2 strategy



Jet Trigger

- Efforts to move to analysis-like jet calibration throughout Run-2
- Started with parts of analysis-like jet calibrations in 2015:
  - Pileup subtraction+jet energy scale correction
- Improved the jet calibrations to be more complete in 2017
  - Using both inputs from calorimeter and inner detector
  - Only use tracks cached from b-jet triggers to avoid additional CPU cost



Significant improvement!

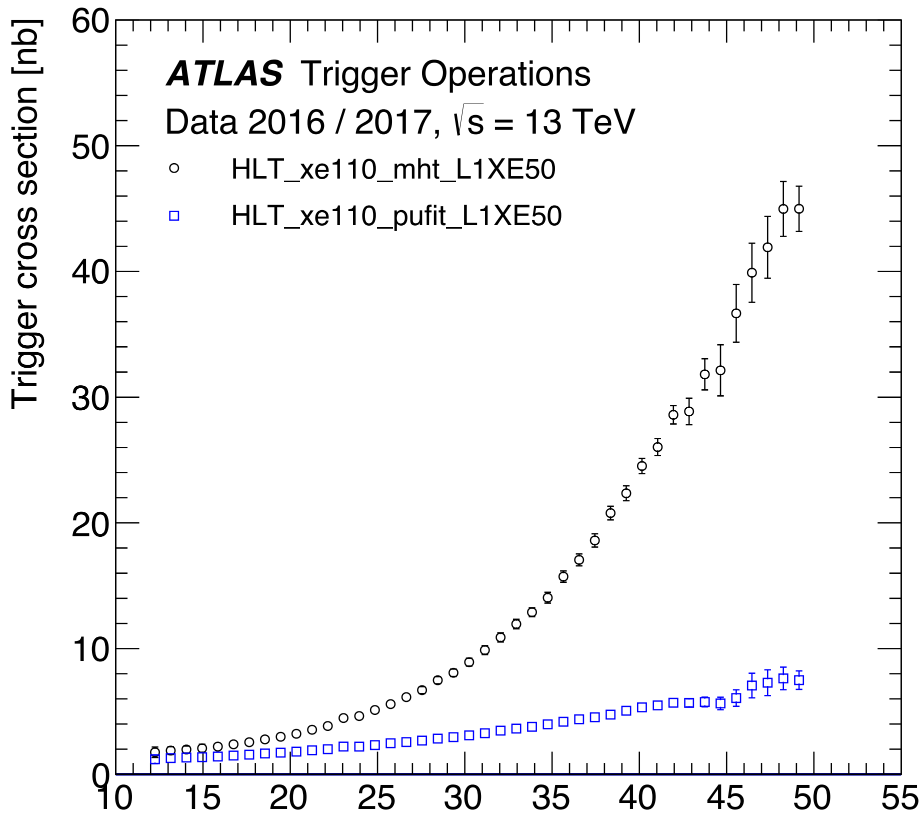
- Steep turn on curves
  - Lots of analyses only work on the plateau
  - Rate in turn on region is wasted

Important for DM mediator searches!

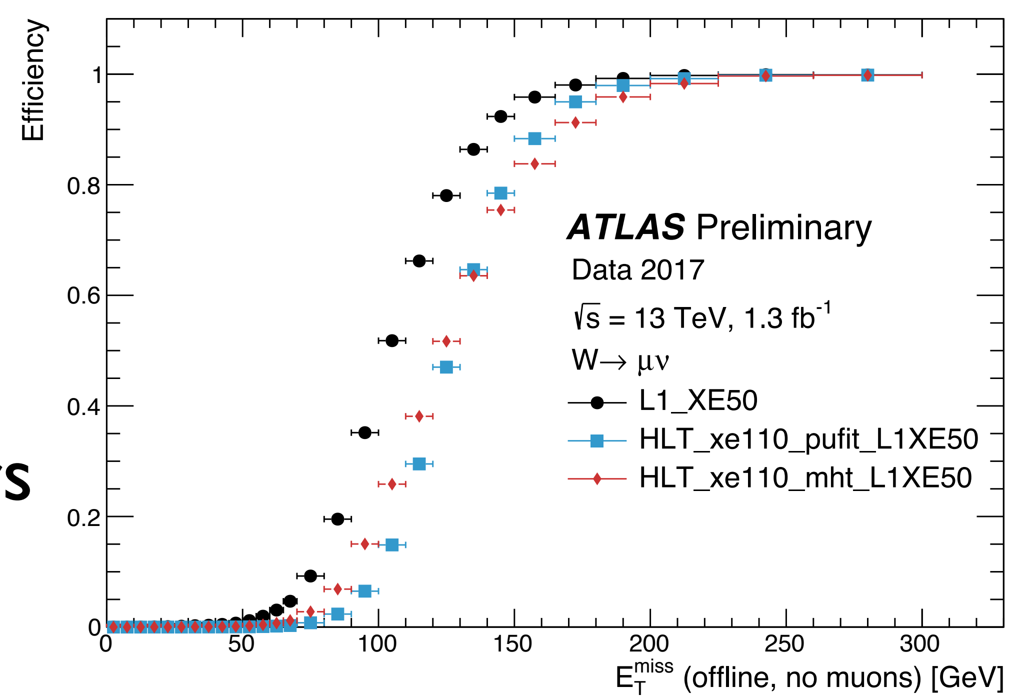
JetTriggerPublicResults

MET Trigger

- Original Run 2 MET algorithm MHT
  - Missing E_T = vector sum of p_T of jets
  - Rate blows up as pileup increases
- New algorithm Pufit: rate reduced at high pileup with no efficiency loss
  - Divide calorimeter into towers
  - Look at the energy deposits inside each tower
  - Dynamically categorize towers into hard scattering and pileup, based on their energy
  - Fit both sets of towers, estimate the pileup contribution inside hard scattering towers
  - Missing E_T = sum of p_T of corrected HS towers

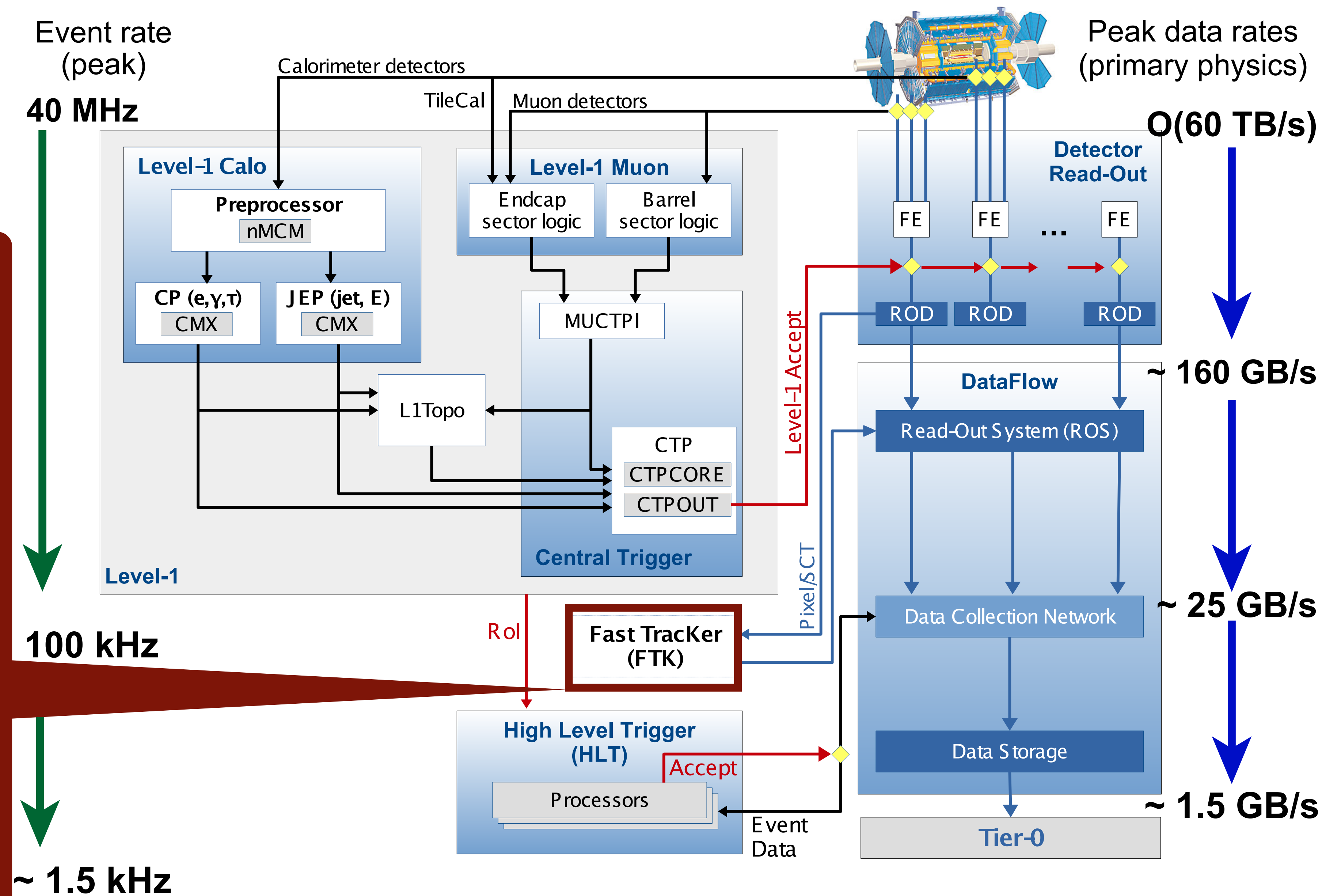


MissingEtTriggerPublicResults



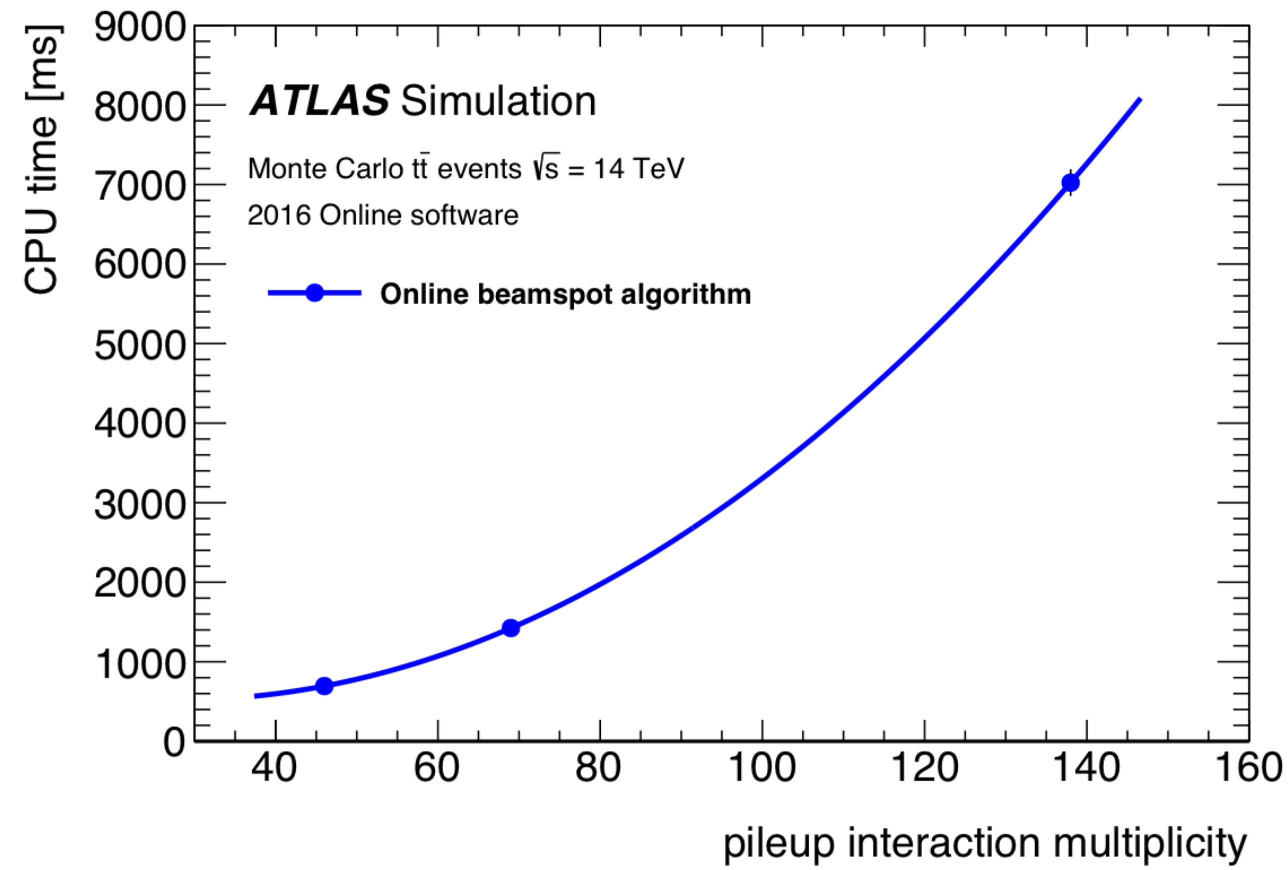
Run-2 Trigger System: FTK

- Fast TracKer: new hardware
- Currently being commissioned
- Sits between L1 and HLT
- Track reconstruction of full detector (track p_T > 1 GeV)
- Latency: ~100 μs



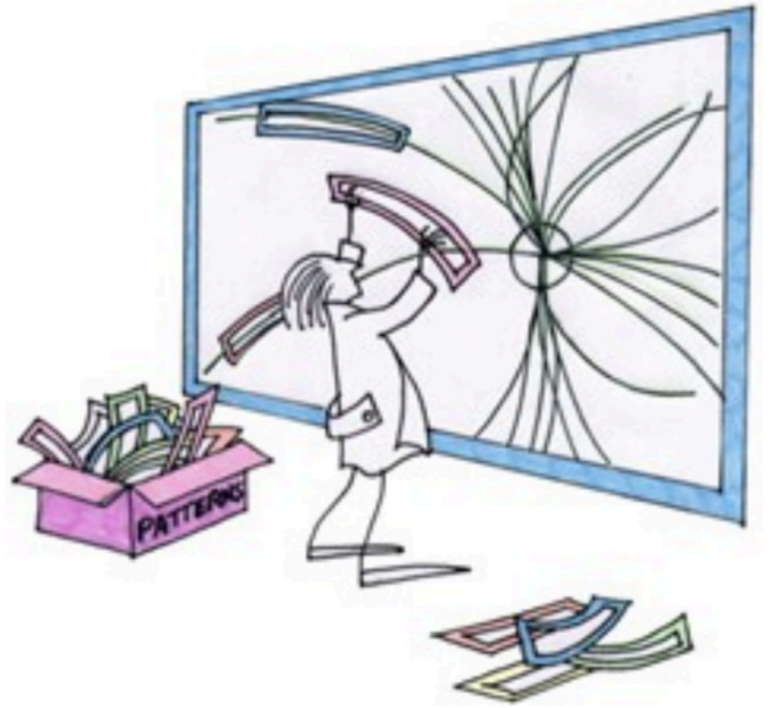
Why do we need FTK?

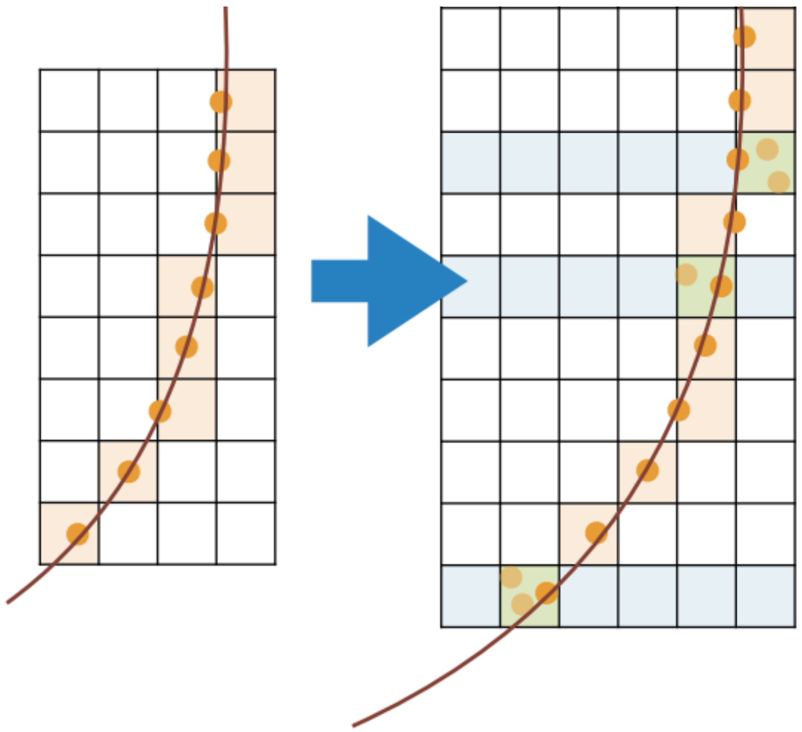
- Full detector tracking is essential to:
  - Keeping low trigger thresholds
  - Primary vertex identification
  - Pileup suppression
- Full detector tracking in HLT:
  - Expensive. Takes a lot of resources that scale non-linearly with pileup
- Target: run full detector tracking at the input rate of HLT 100kHz
  - ~0.1 ms / event



How to make tracking fast?

- Parallelization
  - Divide the detector into 64 overlapping towers
  - Parallel process each tower
- Multi staging
  - Pattern recognition of coarse data
  - First stage linearized fit of 8 out of 12 layers
  - Second stage linearized fit of full 12 layers

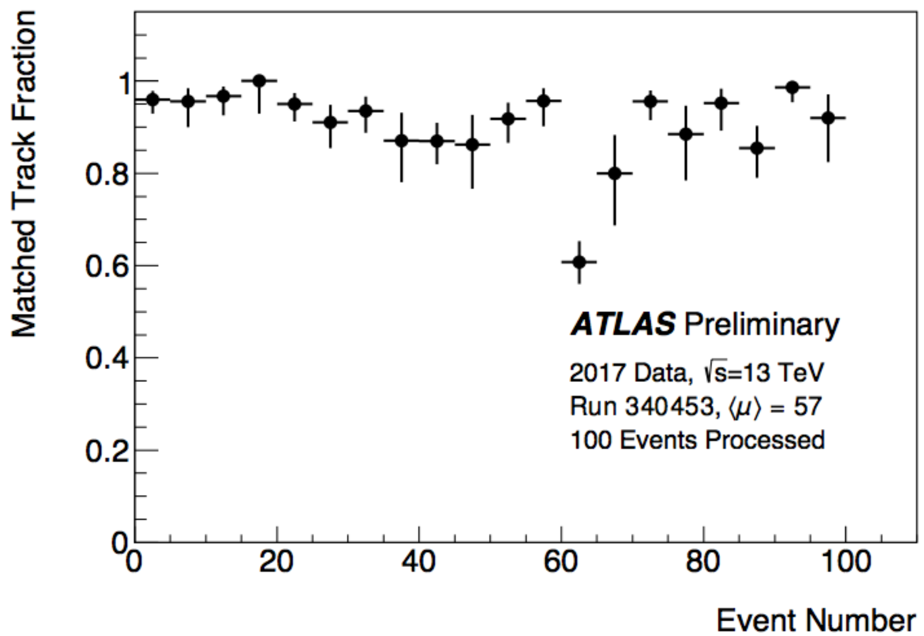




Commissioning Status

FTKPublicResults

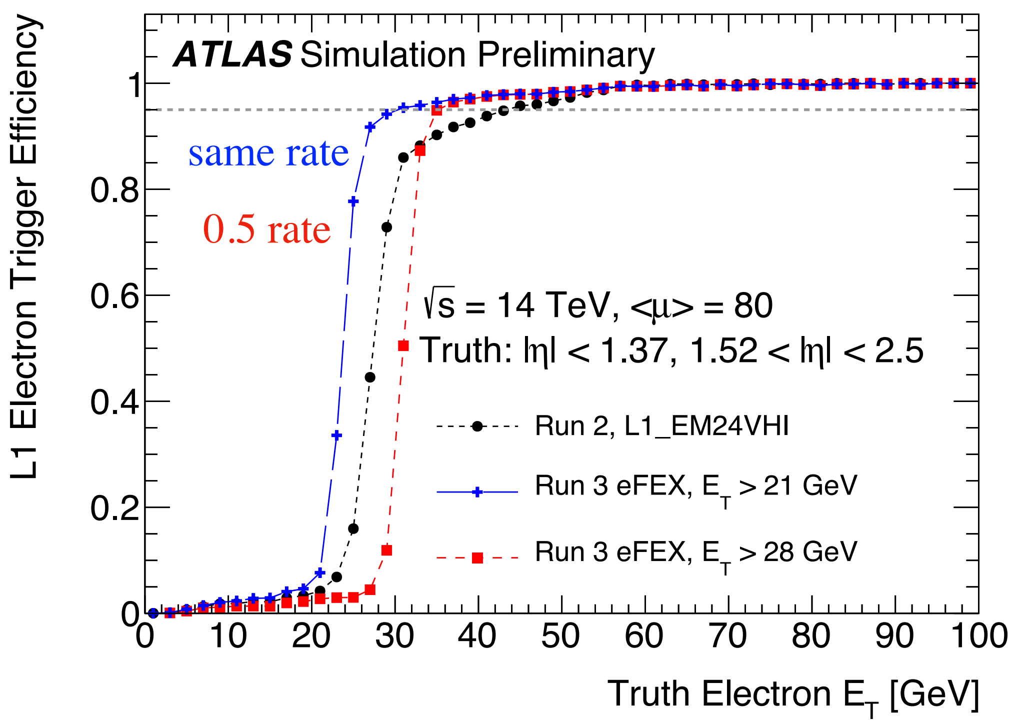
- Status: End of 2017, one Processing Unit with 8-layer tracks joined ATLAS
  - Matched output tracks to simulation (~90%!)



- In 2018, two Processing Units join ATLAS run regularly and output 8-layer and 12-layer tracks
- Goal:
  - Run stably with partial detector coverage 2018
  - Full coverage of detector for physics in Run 3 (2021-2023)

Run-3 ideas

- Continuation of Run-2 challenges
- L1 hardware upgrades & improved architecture
  - Exploit more info from the calorimeter
  - Improve resolution, efficiency for e/γ, jets, Missing E_T
  - Allow largest jet rejection, crucial for e identification
- Upgrades in muon detector



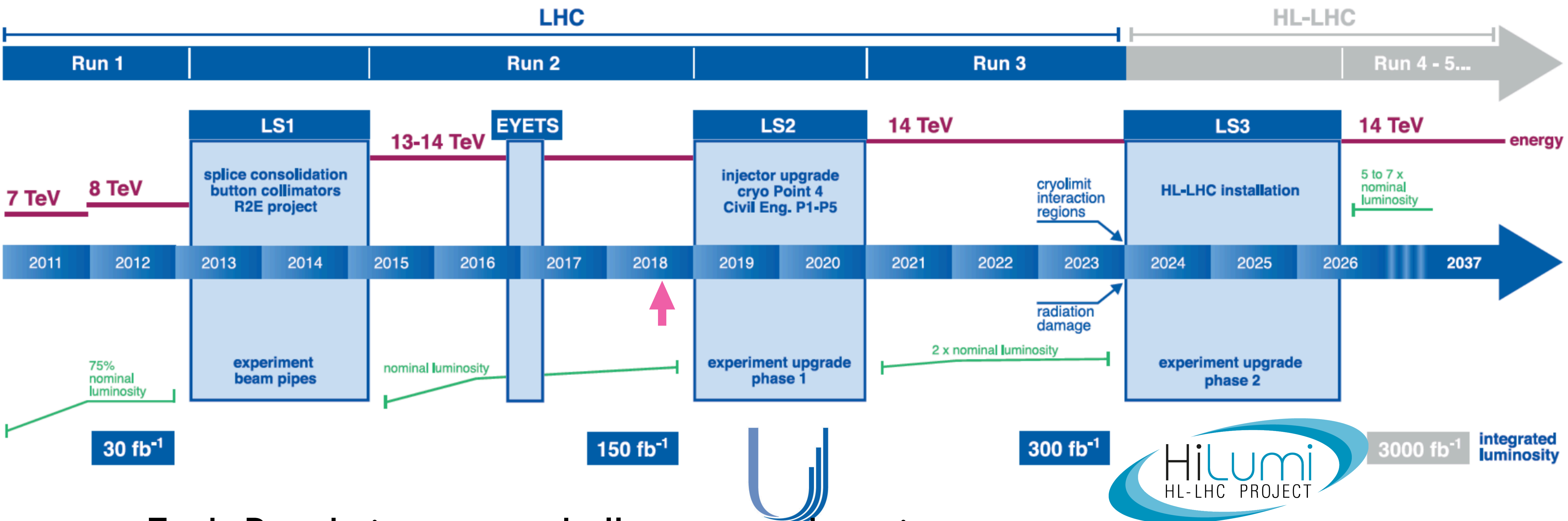
- Full FTK installation: full detector tracking
  - Tracking in Missing E_T trigger
    - MHT with tracking to reduce pileup dependence
    - Pufit with tracking: use tracks to identify hard scattering towers
    - Need full detector tracking to reconstruct good vertex
- Continuing improvements on HLT algorithms

Summary

- ATLAS trigger system adapted well to exceptionally challenging conditions in Run 2
  - L1Calo dynamic pedestal correction for pileup suppression
  - L1Muon TGC-Tile coincidence to suppress fake muons
  - L1Topo to improve selection at L1 (low-p_T di-object triggers)
  - HLT CPU and performance improvements
- New challenges and exciting upgrades for Run 3 and HL-LHC!
  - Running at high pileup in 2018 is precious opportunity to test upgrade ideas

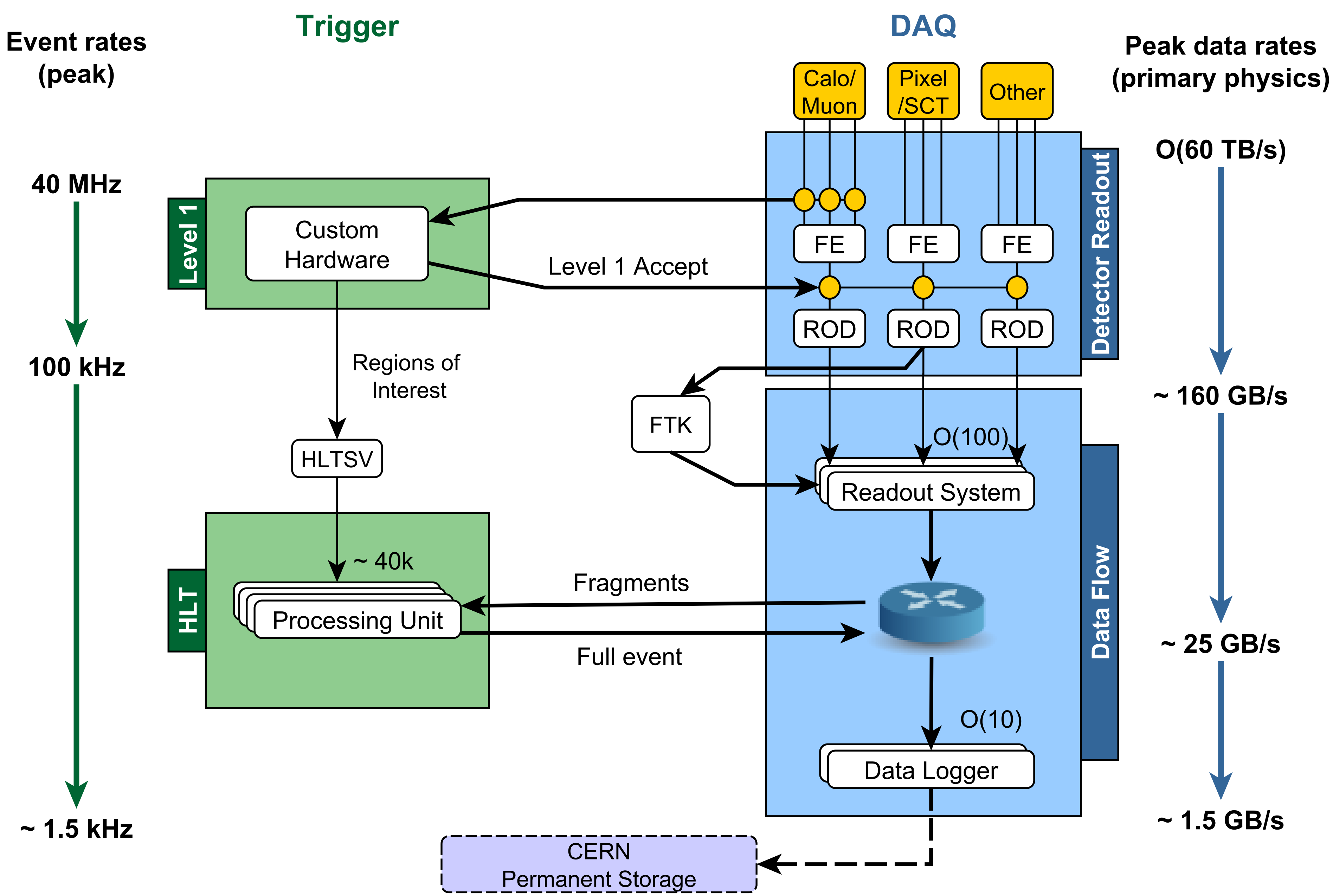
Backup

LHC Run plan

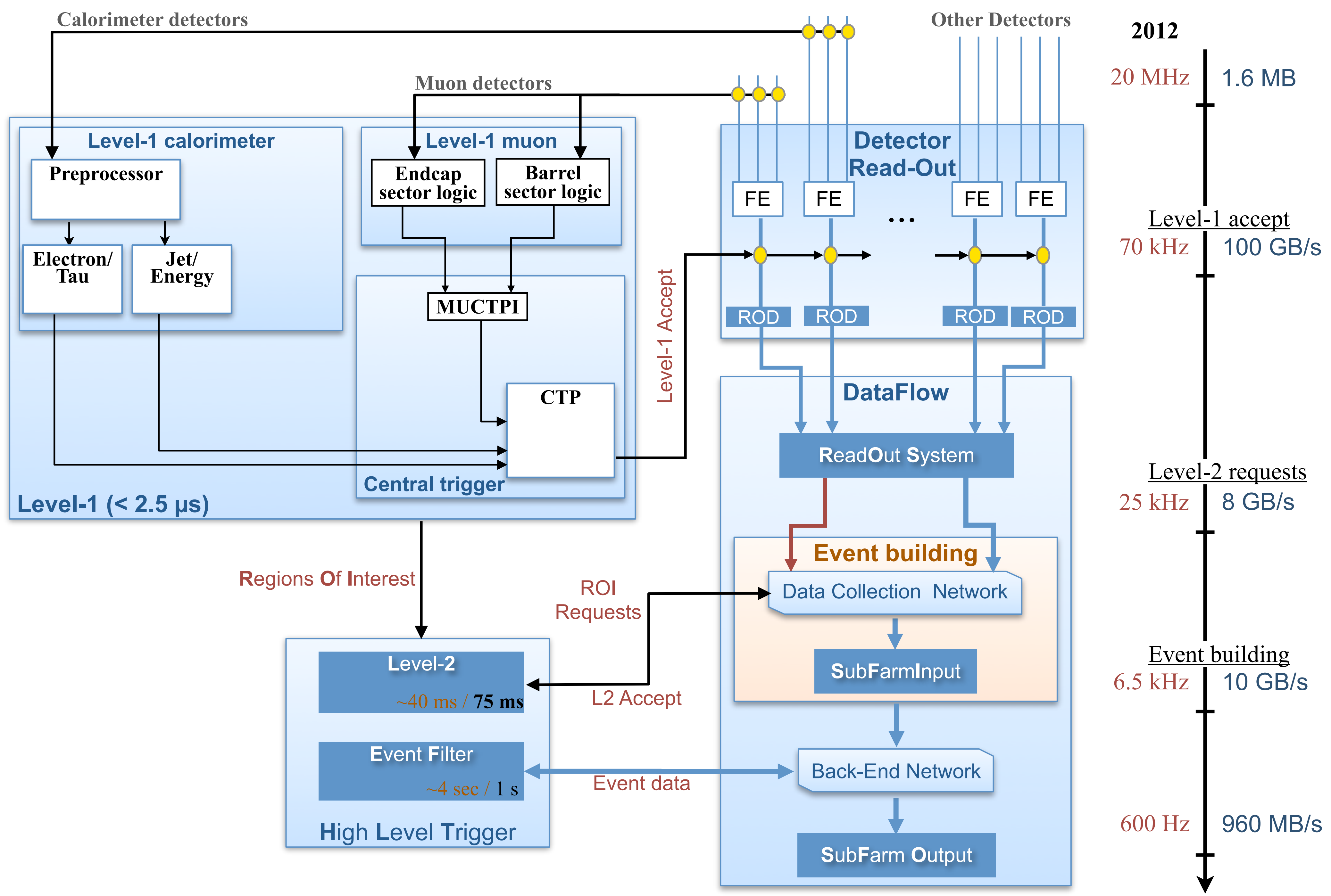


- Each Run brings new challenges to the trigger system
- Major LHC upgrades during each Long Shutdown (LS)
  - LS1: energy upgrade 8TeV-13TeV
  - LS2: injector upgrade (LIU) to improve beam intensity and emittance (for HL-LHC)
  - LS3: HL-LHC installation

Run 2 Trigger System Overview



Trigger System in Run 1



Trigger Menu 2017

Trigger	Typical offline selection	Trigger Selection		Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
		Level-1 (GeV)	HLT (GeV)	$L = 1.7 \times 10^{34}$ cm^{-2}s^{-1}	
Single leptons	Single isolated μ, $p_T > 27$ GeV	20	26 (i)	15	180
	Single isolated tight e, $p_T > 27$ GeV	22 (i)	26 (i)	28	180
	Single μ, $p_T > 52$ GeV	20	50	15	61
	Single e, $p_T > 61$ GeV	22 (i)	60	28	18
	Single τ, $p_T > 170$ GeV	100	160	1.2	47
Two leptons	Two μ, each $p_T > 15$ GeV	2×10	2×14	1.8	26
	Two μ, $p_T > 23, 9$ GeV	20	22, 8	15	42
	Two very loose e, each $p_T > 18$ GeV	2×15 (i)	2×17	1.7	12
	One e & one μ, $p_T > 8, 25$ GeV	20 (μ)	7, 24	15	5
	One e & one μ, $p_T > 18, 15$ GeV	15, 10	17, 14	2.0	4
	One e & one μ, $p_T > 27, 9$ GeV	22 (e, i)	26, 8	28	3
	Two τ, $p_T > 40, 30$ GeV	20 (i), 12 (i) (+jets, topo)	35, 25	5	61
	One τ & one isolated μ, $p_T > 30, 15$ GeV	12 (i), 10 (+jets)	25, 14 (i)	2.1	10
	One τ & one isolated e, $p_T > 30, 18$ GeV	12 (i), 15 (i) (+jets)	25, 17 (i)	4	15
Three leptons	Three loose e, $p_T > 25, 13, 13$ GeV	$20, 2 \times 10$	$24, 2 \times 12$	1.3	< 0.1
	Three μ, each $p_T > 7$ GeV	3×6	3×6	0.2	6
	Three μ, $p_T > 21, 2 \times 5$ GeV	20	$20, 2 \times 4$	15	8
	Two μ & one loose e, $p_T > 2 \times 11, 13$ GeV	2×10 (μ)	$2 \times 10, 12$	1.8	0.3
	Two loose e & one μ, $p_T > 2 \times 13, 11$ GeV	$2 \times 8, 10$	$2 \times 12, 10$	1.7	0.1
One photon	One loose γ, $p_T > 145$ GeV	22 (i)	140	28	43
Two photons	Two loose γ, $p_T > 55, 55$ GeV	2×20	50, 50	2.6	6
	Two medium γ, $p_T > 40, 30$ GeV	2×20	35, 25	2.6	17
	Two tight γ, $p_T > 25, 25$ GeV	2×15 (i)	2×20 (i)	1.7	14
Single jet	Jet ($R = 0.4$), $p_T > 435$ GeV	100	420	3.3	33
	Jet ($R = 1.0$), $p_T > 480$ GeV	100	460	3.3	24
	Jet ($R = 1.0$), $p_T > 450$ GeV, $m_{jet} > 50$ GeV	100	420, $m_{jet} > 40$	3.3	29
E_T^{miss}	$E_T^{miss} > 200$ GeV	50	110	5	110
Multi-jets	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	5	10
	Six jets, each $p_T > 80$ GeV	4×15	6×70	5	4
	Six jets, each $p_T > 60$ GeV, $\lvert\eta\rvert < 2.0$	4×15	6×55, $\lvert\eta\rvert < 2.4$	5	15
b−jets	One b ($\epsilon = 40\%$), $p_T > 235$ GeV	100	225	3.3	15
	Two b ($\epsilon = 60\%$), $p_T > 185, 70$ GeV	100	175, 60	3.3	12
	One b ($\epsilon = 40\%$) & three jets, each $p_T > 85$ GeV	4×15	4×75	5	15
	Two b ($\epsilon = 70\%$) & one jet, $p_T > 65, 65, 160$ GeV	$2 \times 30, 85$	$2 \times 55, 150$	1.2	15
	Two b ($\epsilon = 60\%$) & two jets, each $p_T > 65$ GeV	4×15, $\lvert\eta\rvert < 2.5$	4×55	3.2	13
B-Physics	Two μ, $p_T > 11, 6$ GeV	11, 6	11, 6 (di-μ)	2.5	47
	Two μ, $p_T > 6, 6$ GeV, $2.5 < m(\mu,\mu) < 4.0$ GeV	2×6 (J/ψ, topo)	2×6 (J/ψ)	1.6	48
	Two μ, $p_T > 6, 6$ GeV, $4.7 < m(\mu,\mu) < 5.9$ GeV	2×6 (B, topo)	2×6 (B)	1.6	5
	Two μ, $p_T > 6, 6$ GeV, $7 < m(\mu,\mu) < 12$ GeV	2×6 (Υ, topo)	2×6 (Υ)	1.4	10
Total Rate				85	1550

ATL-DAQ-PUB-2018-002

Trigger Menu 2016

Trigger	Typical offline selection	Trigger Selection		Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
		Level-1 (GeV)	HLT (GeV)	$L = 1.2 \times 10^{34}$ cm^{-2}s^{-1}	
Single leptons	Single isolated μ, $p_T > 27$ GeV	20	26 (i)	13	133
	Single isolated tight e, $p_T > 27$ GeV	22 (i)	26 (i)	20	133
	Single μ, $p_T > 52$ GeV	20	50	13	48
	Single e, $p_T > 61$ GeV	22 (i)	60	20	13
	Single τ, $p_T > 170$ GeV	60	160	5	15
Two leptons	Two μ's, each $p_T > 15$ GeV	2×10	2×14	1.5	21
	Two μ's, $p_T > 23, 9$ GeV	20	22, 8	13	30
	Two loose e's, each $p_T > 18$ GeV	2×15	2×17	8	7
	One e & one μ, $p_T > 8, 25$ GeV	20 (μ)	7, 24	13	2
	One loose e & one μ, $p_T > 18, 15$ GeV	15, 10	17, 14	1.5	2.6
	Two τ's, $p_T > 40, 30$ GeV	20 (i), 12 (i) (+jets)	35, 25	6	35
	One τ & one isolated μ, $p_T > 30, 15$ GeV	12 (i), 10 (+jets)	25, 14 (i)	1.5	7
	One τ & one isolated e, $p_T > 30, 18$ GeV	12 (i), 15 (i) (+jets)	25, 17 (i)	3	9
Three leptons	Three loose e's, $p_T > 18, 11, 11$ GeV	$15, 2 \times 8$	$17, 2 \times 10$	15	< 0.1
	Three μ's, each $p_T > 7$ GeV	3×6	3×6	0.1	3
	Three μ's, $p_T > 21, 2 \times 5$ GeV	20	$20, 2 \times 4$	13	4
	Two μ's & one loose e, $p_T > 2 \times 11, 13$ GeV	2×10 (μ's)	$2 \times 10, 12$	1.5	0.2
	Two loose e's & one μ, $p_T > 2 \times 13, 11$ GeV	$2 \times 8, 10$	$2 \times 12, 10$	1.1	0.1
One photon	One loose γ, $p_T > 145$ GeV	22 (i)	140	20	30
Two photons	Two loose γ's, $p_T > 40, 30$ GeV	2×15	35, 25	8	40
	Two tight γ's, $p_T > 27, 27$ GeV	2×15	2×22	8	16
Single jet	Jet ($R = 0.4$), $p_T > 420$ GeV	100	380	3	38
	Jet ($R = 1.0$), $p_T > 460$ GeV	100	420	3	35
E_T^{miss}	$E_T^{miss} > 200$ GeV	50	110	6	230
Multi-jets	Four jets, each $p_T > 110$ GeV	3×50	4×100	0.4	18
	Five jets, each $p_T > 80$ GeV	4×15	5×70	3.5	14
	Six jets, each $p_T > 70$ GeV	4×15	6×60	3.5	5
	Six jets, each $p_T > 55$ GeV, $\lvert\eta\rvert < 2.4$	4×15	6×45	3.5	18
b−jets	One b ($\epsilon = 60\%$), $p_T > 235$ GeV	100	225	3	24
	Two b's ($\epsilon = 60\%$), $p_T > 160, 60$ GeV	100	150, 50	3	20
	One b ($\epsilon = 70\%$) & three jets, each $p_T > 85$ GeV	4×15	4×75	3.5	19
	Two b ($\epsilon = 60\%$) & one jet, $p_T > 65, 65, 110$ GeV	$2 \times 20, 75$	$2 \times 55, 100$	2.7	25
	Two b ($\epsilon = 60\%$) & two jets, each $p_T > 45$ GeV	4×15	4×35	3.5	56
b−physics	Two μ's, $p_T > 6, 6$ GeV plus dedicated b-physics selections	6, 6	6, 6	4.7	20
Total				85	1500

ATL-DAQ-PUB-2017-001

Trigger Menu 2015

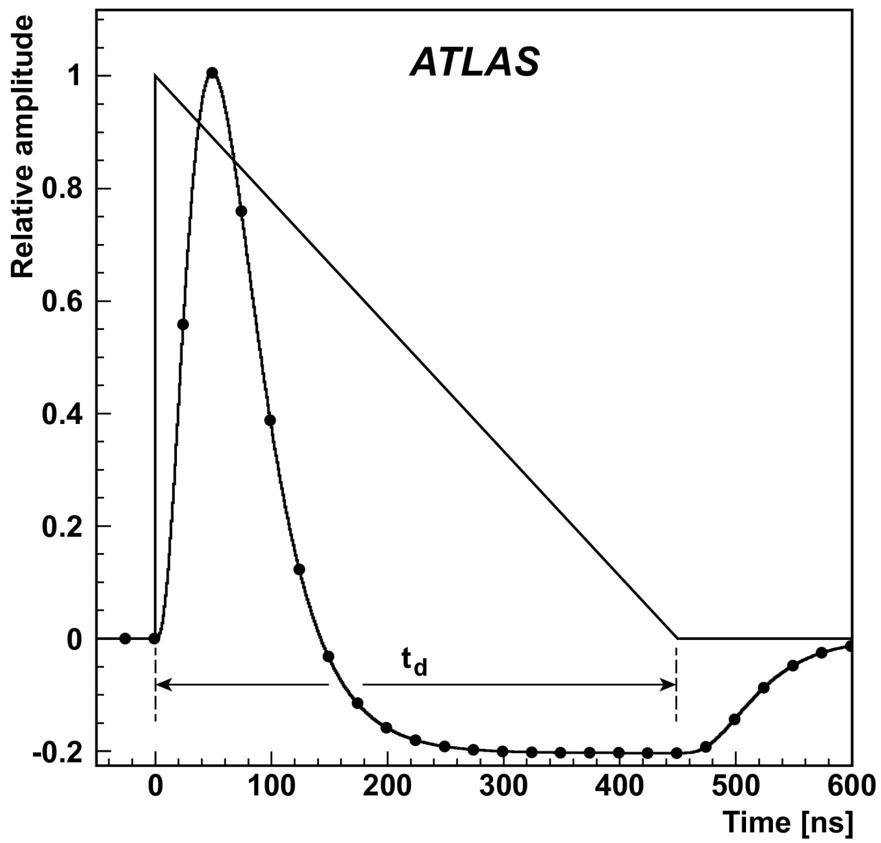
Trigger	Typical offline selection	Trigger Selection		Level-1 Rate [kHz]	HLT Rate [Hz]
		Level-1 [GeV]	HLT [GeV]	$L = 5 \times 10^{33}$ cm^{-2}s^{-1}	
Single leptons	Single iso μ, $p_T > 21$ GeV	15	20	7	130
	Single e, $p_T > 25$ GeV	20	24	18	139
	Single μ, $p_T > 42$ GeV	20	40	5	33
	Single τ, $p_T > 90$ 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	$15, 2 \times 7$	$17, 2 \times 9$	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	$18, 2 \times 4$	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 J/ψ-physics selection	6, 4	6, 4	8	52
				70	1400

ATL-DAQ-PUB-2016-00

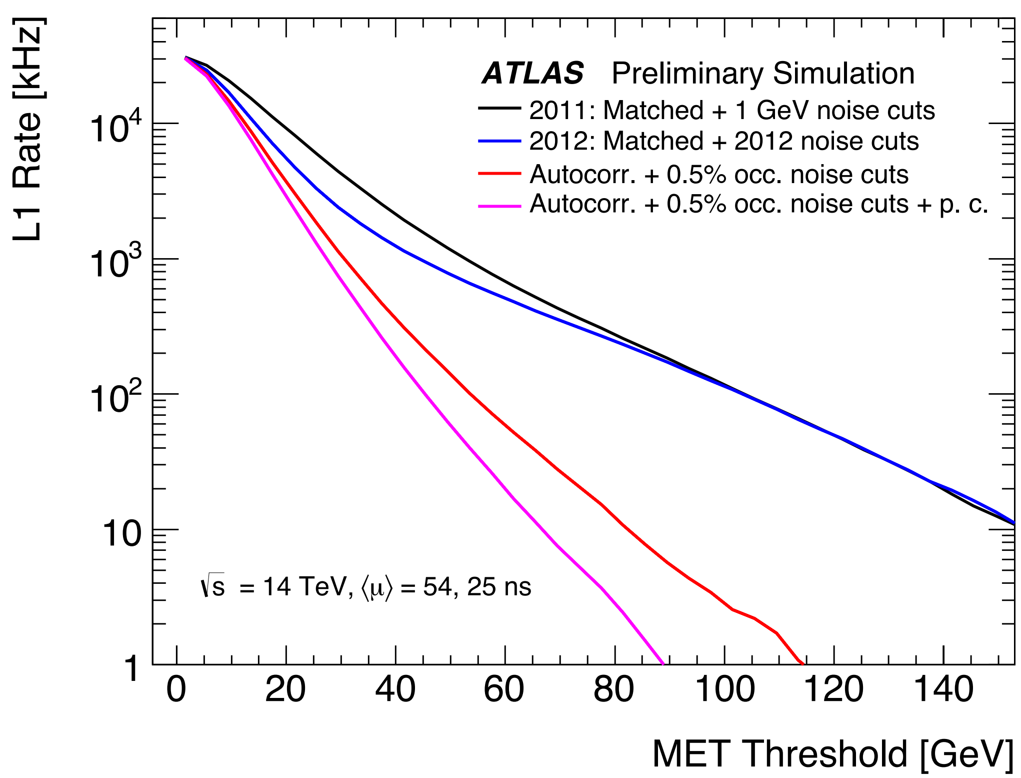
What if triggers can't stand the run condition?

- Lumi levelling
  - Ensures a highly efficient data taking when pileup reaches levels beyond the capabilities of the HLT farm
  - 2017
- End-of-fill Triggers
  - High-rate and CPU-intensive triggers can be enabled within the data storage output limitation
  - Used for Trigger-level Analysis and B-physics

L1Calo

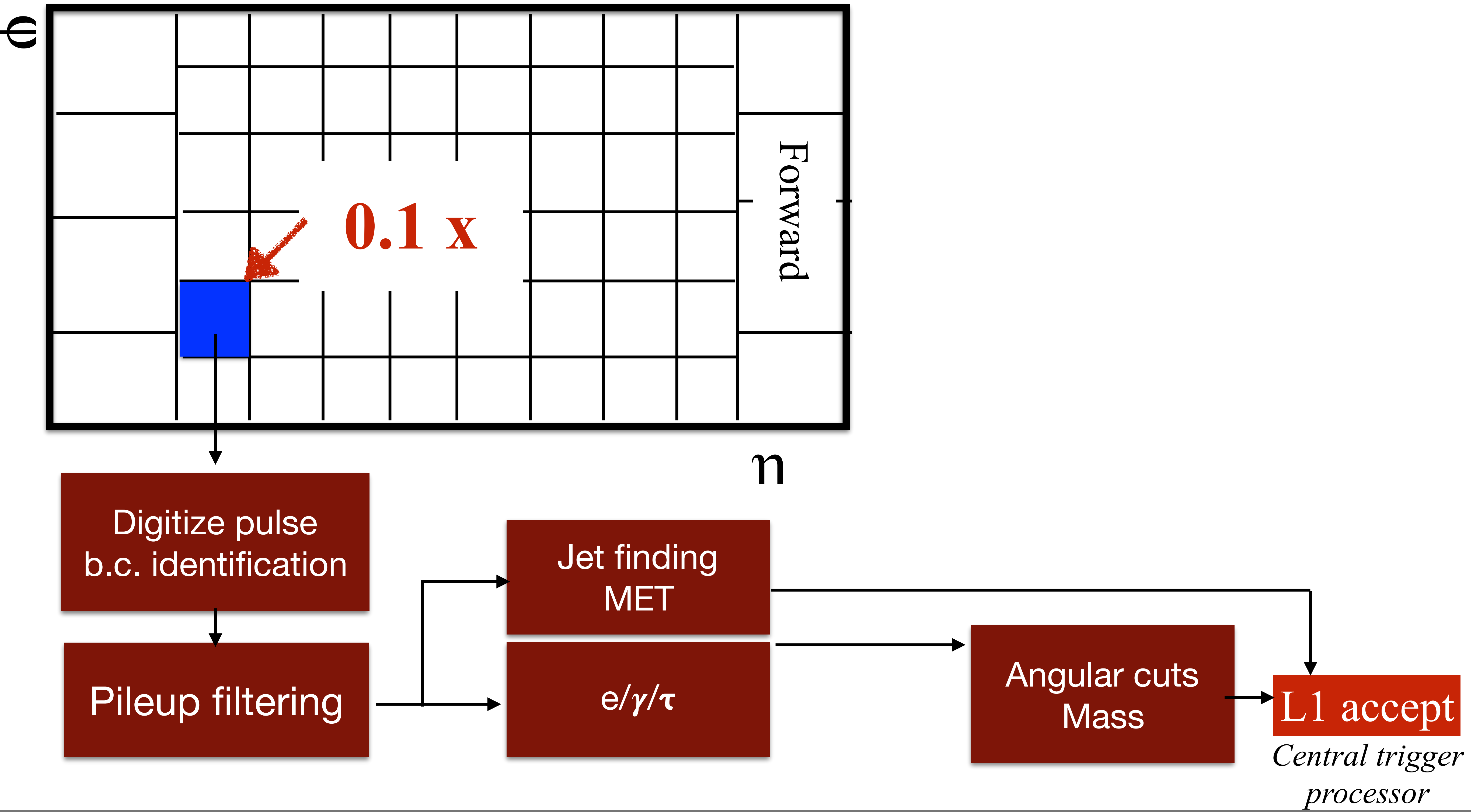


ATLAS
Relative amplitude
1
0.8
0.6
0.4
0.2
0
-0.2
t_d
0
100
200
300
400
500
600
Time [ns]



ATLAS Preliminary Simulation
2011: Matched + 1 GeV noise cuts
2012: Matched + 2012 noise cuts
Autocorr. + 0.5% occ. noise cuts
Autocorr. + 0.5% occ. noise cuts + p. c.
L1 Rate [kHz]
√s = 14 TeV, ⟨μ⟩ = 54, 25 ns
MET Threshold [GeV]
0
20
40
60
80
100
120
140

L1Calo



φ
0.1 x
Forward
η
Digitize pulse
b.c. identification
Pileup filtering
Jet finding
MET
e/γ/τ
Angular cuts
Mass
L1 accept
Central trigger
processor