Performance of The ATLAS Trigger System

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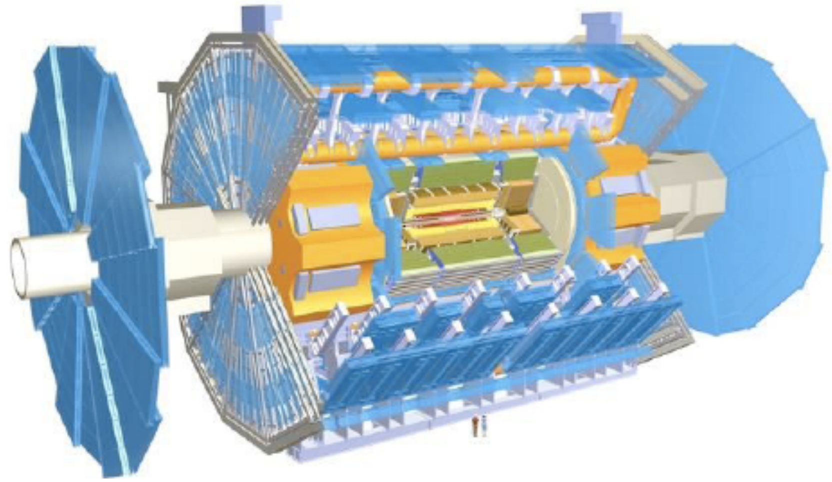
on behalf of The ATLAS Collaboration

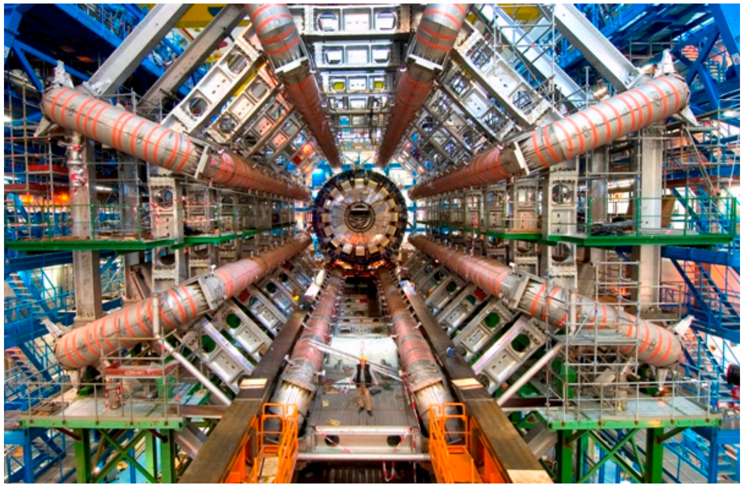
Other ATLAS Trigger/DAQ talks at TIPP

- ATLAS TDAQ system: current status and performance
  - Sergio Ballestrero
- The EDRO board connected to the Associative Memory: a "Baby" FastTracKer processor for the ATLAS experiment
  - Francesco Crescioli
- Resource utilization of the ATLAS High Level Trigger during 2010 LHC running
  - Rustem Ospanov
- Online Determination of the LHC Luminous Region with the ATLAS High Level Trigger
  - Rainer Bartoldus
- Calibration and performance of the ATLAS Level-1 Calorimeter Trigger with LHC collision data
  - Martin Wessels

The ATLAS Detector

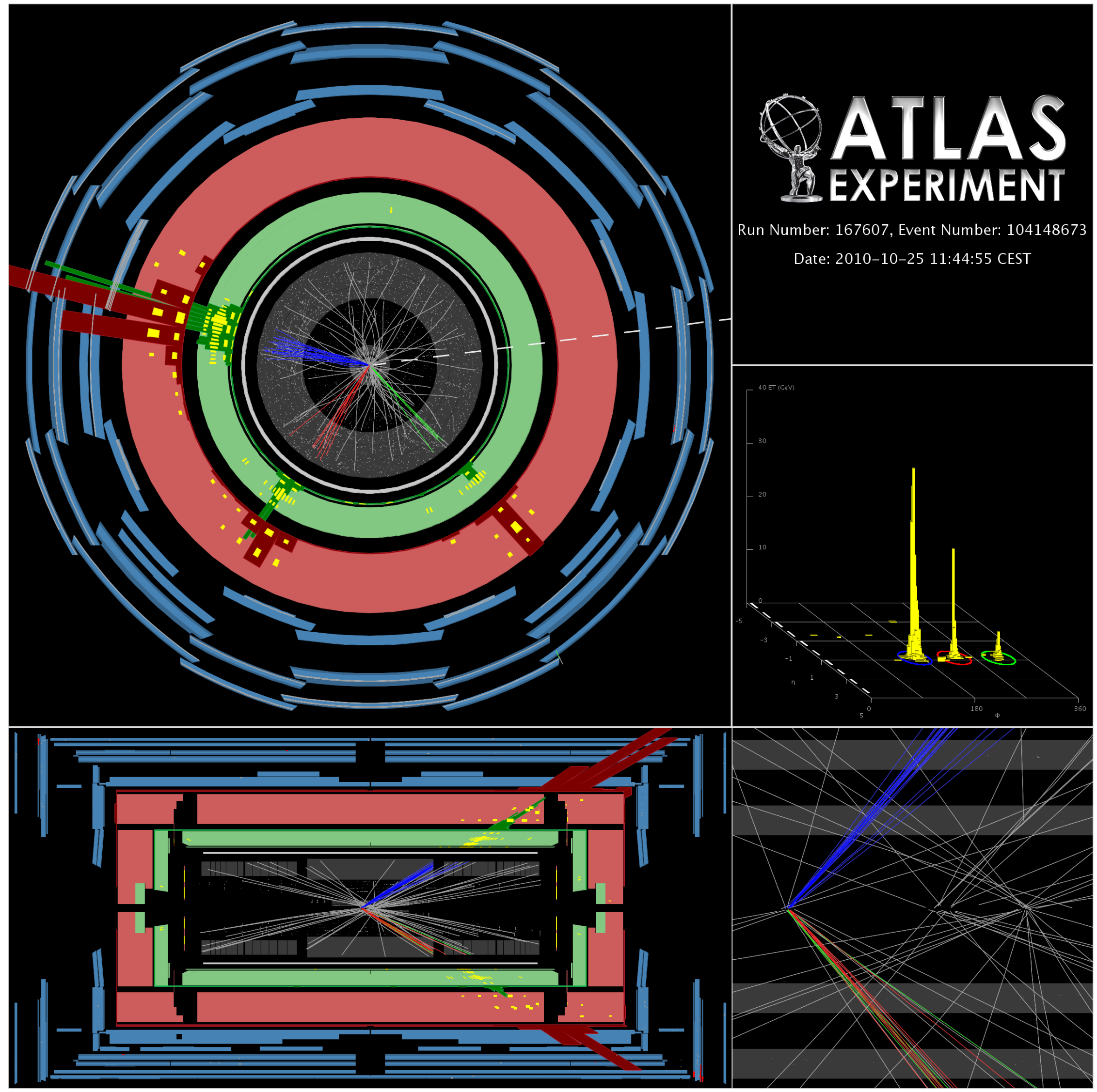
- Inner Detector: Precision Tracking & Vertexing
  - Silicon Pixels + Silicon Strips, Transition Radiation Tracker
  - 2T Central Solenoid, $|\eta| < 2.5$
- Calorimeter:
  - Electromagnetic:
    - Pb/LAr Calorimeter with
    - Accordion Geometry
  - Hadronic
    - Fe/Scintillator in barrel
    - Cu/LAr in endcap
- Muons:
  - Resistive Plate Chambers (RPC)
  - Thin Gap Chambers (TGC)
  - Muon Drift Tube Chambers (MDT)
    - providing precision tracking
  - Air Core Toroids



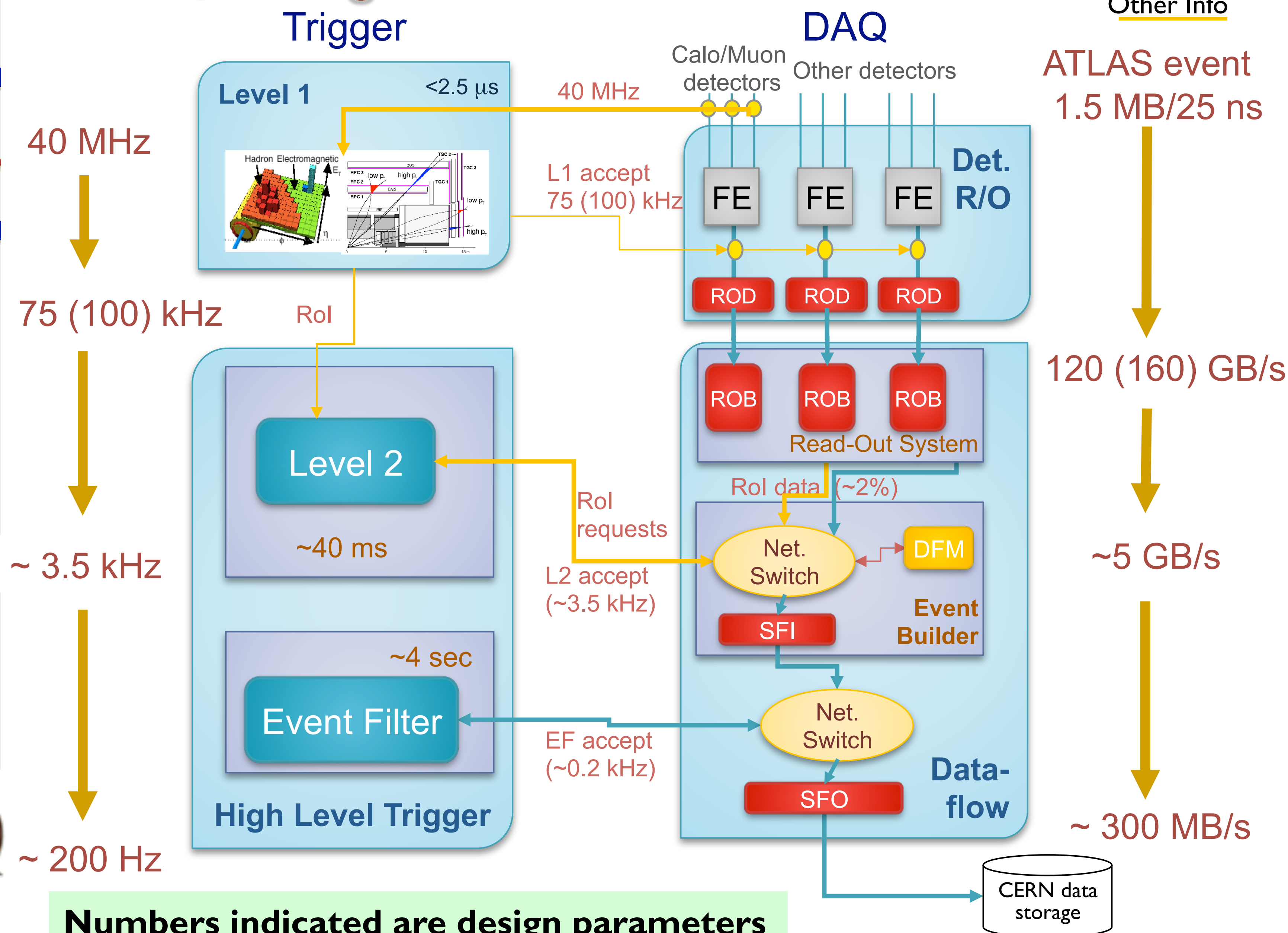


An ATLAS Event

- Three Jets:
  - 400, 120, 60 GeV
- Missing ET:
  - 420 GeV
- Multiple vertices reconstructed
- Trigger Satisfied:
  - Single Jet
  - Multi Jets
  - Missing ET
  - Jet + Missing ET



TDAQ Design



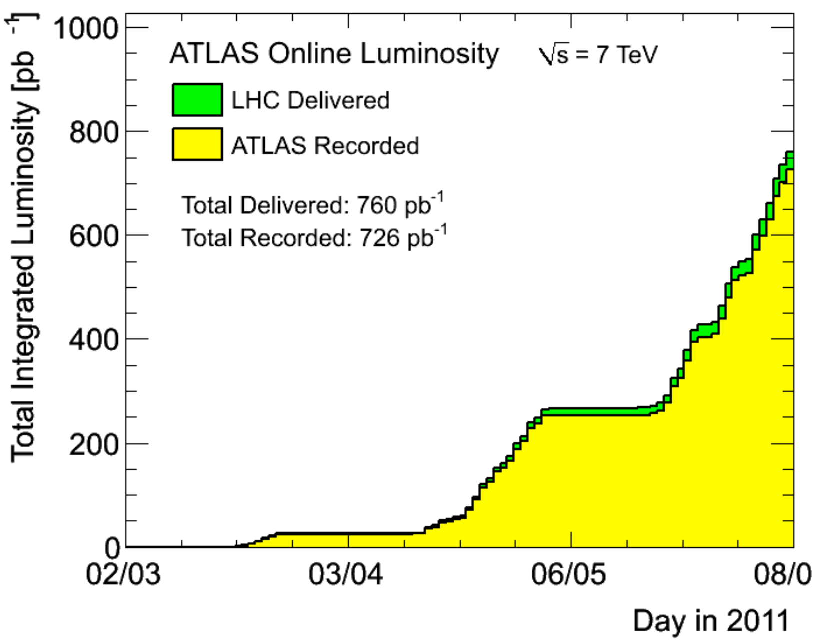
Numbers indicated are design parameters

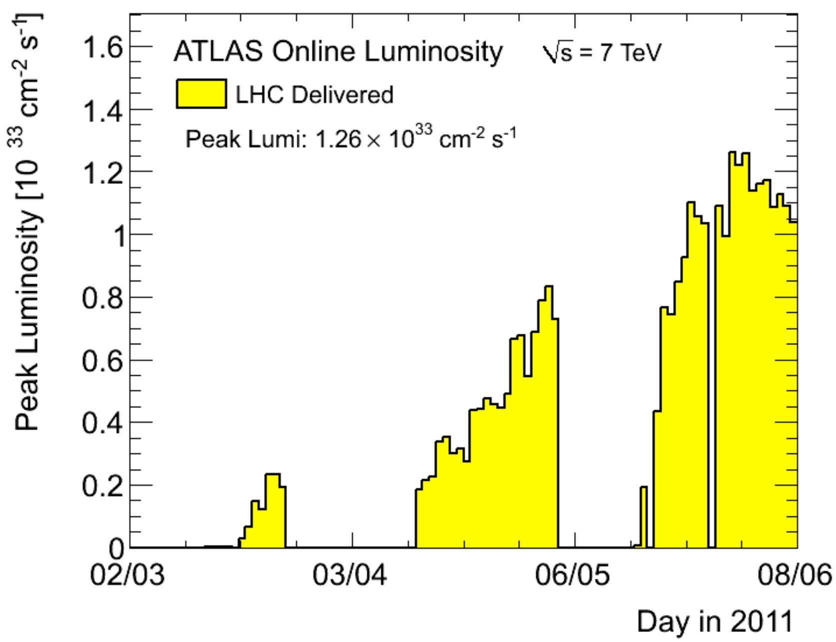
The ATLAS Trigger System

- Three Level Architecture
  - Hardware (L1) & Software based system (L2 & EF)
  - Designed to operate in:
    - High Luminosity ~ 10^{34} cm^{-2} s^{-1}
    - High pile-up (~ 25 interactions/crossing) environment
    - 25 ns proton bunch spacing.
- The system has been commissioned & deployed successfully
  - Now has been operated in a wide range of beam conditions:
    - 10^{27} to over a record luminosity of over 10^{33} cm^{-2} s^{-1}
    - Mean number of interactions/crossing (μ) ~ 8, peak $\langle\mu\rangle$ = 10-12
  - Typical physics data taking rates thus far:
    - L1: up to 50 kHz
    - L2: up to 5 kHz, exceeding design parameters
    - EF: 300 – 400 Hz physics output rate to storage at ~1.2 MB/event
      - Limited by offline computing constraints.

Luminosity Profile

- Integrated Luminosity collected to date: > 0.7 fb^{-1}
- Peak Luminosity delivered: 1.26 x 10^{33} cm^{-2} s^{-1}
- Number of bunches: 1092 (and going up)
  - 50 ns bunch spacing
- Expectations for the rest of the year: 2 up to 5x10^{33} cm^{-2} s^{-1}
  - A challenging environment for the trigger.





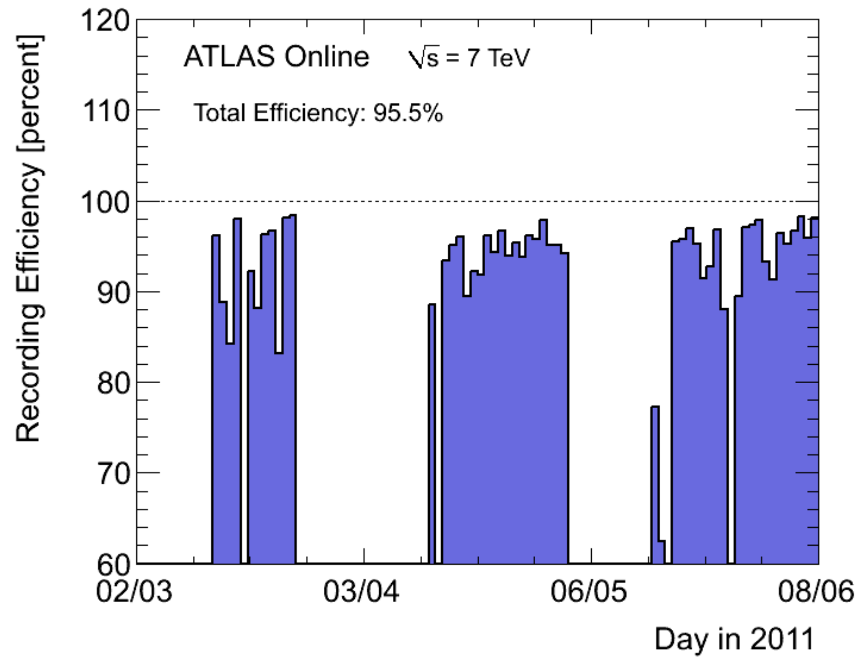
Efficient Performance

- High Data Taking Efficiency: ~ 95%
  - Fraction of time recording physics data during stable LHC beams.
- Dead Time during stable physics run ~ 2-3% @ 50 kHz L1 rate
- Features that allow us to run with high efficiency include:

• Dynamic changes to trigger settings during a run without stop/start

• Allows us to enable/disable or set rates for individual triggers during the run.

• Can not only change physics priorities during run, but also control misbehaved triggers.

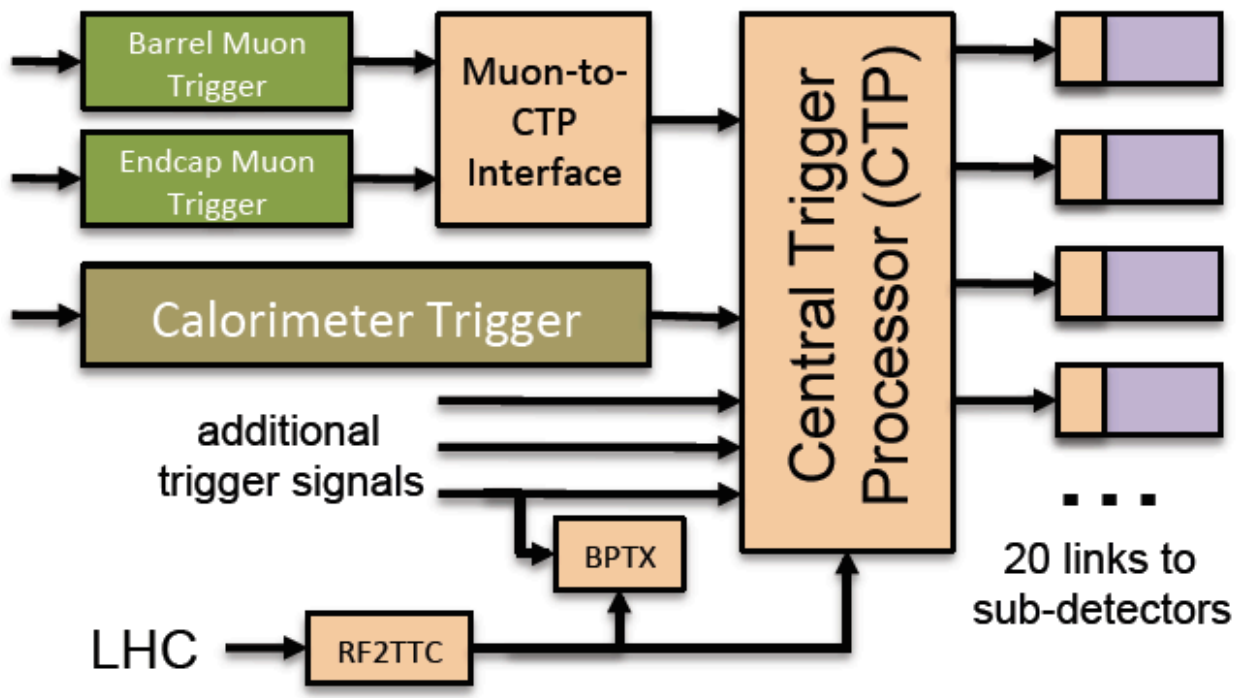


• Stopless removal/recovery of detector readout components.

• Dynamic resynchronization with LHC clock

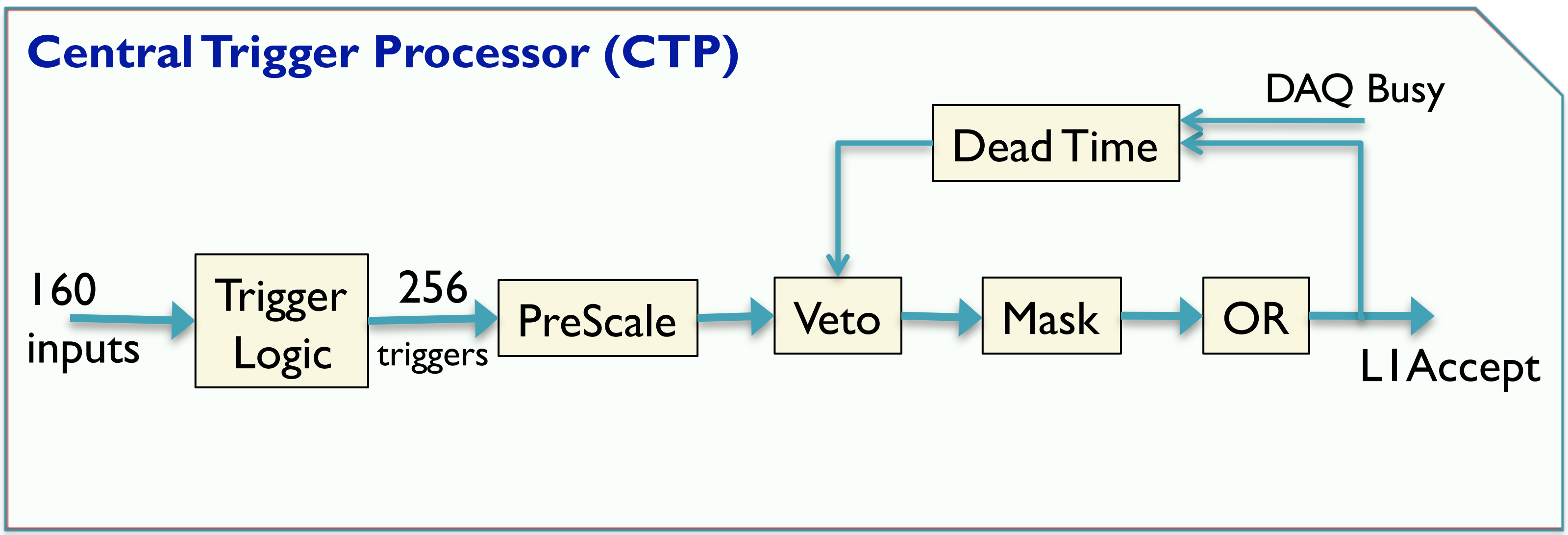
The ATLAS Level 1 (L1) System

- The Central Trigger Processor reduces the L1 trigger information to a single bit: The Level 1 Accept (L1A) Signal.
  - Using inputs from Calorimeter, Muon and additional signals.
  - Receives 40 MHz clock signal from LHC
  - Distributes clock, L1A to sub-system front end electronics.



Dead Time (DT)

- The Central Trigger Processor introduces:
  - Preventive DT: protect front-end electronic buffers from overflowing.
    - Simple DT: Veto 5 Bunch Crossings (BC) after a L1 Accept
    - Complex DT: Allow not more than 8 triggers in 80 μs
      - (Leaky Bucket Algorithm)
- Busy from DAQ:
  - Fed back from the detector readout electronics to L1 CTP.



L1 CTP Input Allocation

- 160 bus lines as input to CTP
  - Inputs from Calorimeter, Muons
  - + Forward Detectors
  - + Direct Inputs
- Nomenclature:
  - EM: 8 x 3
  - Implies 8 Energy threshold settings for Electromagnetic (EM)
    - e.g. EM3, EM7, EM10, EM14, EM14I, EM16, EM20, EM50.
  - Each with a 3 bit multiplicity count.
  - Hence uses up 8 x 3 = 24 of the 160 available input bus lines.

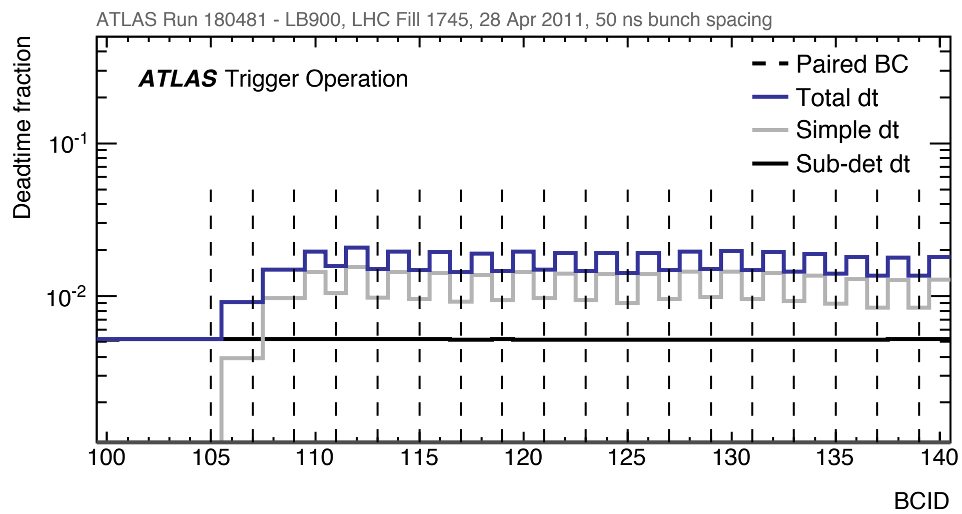
EM	8 x 3
MUONS	6 x 3
TAU	8 x 3
JETS	8 x 3
FORWARD JETS	8 x 2
$\not{E}_T$, $\not{E}_T$(sig)	8 + 8
ΣE_T, ΣE_T(jets)	4 + 7
MBTS	2 x 3
ZDC	3 x 1
BPTX	2 x 1
BCM	6
LUCID	3 x 1
Others	7

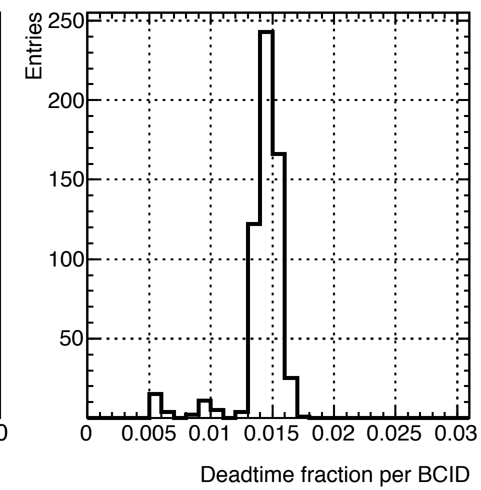
Forward Detectors

L1 Items

- The 160 L1 inputs are combined to form up to 256 possible L1 items.
  - e.g. an input EM10 (An EM cluster above 10 GeV) can be used to form multiple L1 items:
    - L1_EM10: At least one EM cluster above 10 GeV
    - L1_2EM10: At least two EM clusters, each above 10 GeV
    - L1_EM10_MU6: An EM cluster above 10 and a Muon above 6 GeV.
- Each of the L1 items can individually be pre-scaled (allowing only 1 in N triggers to be accepted) or masked.
- A L1 Accept is generated and sent to the detector readout electronics only if at least one L1 item survives.
- A Dead Time is generated and fed back to prevent subsequent triggers for a short time thereafter.

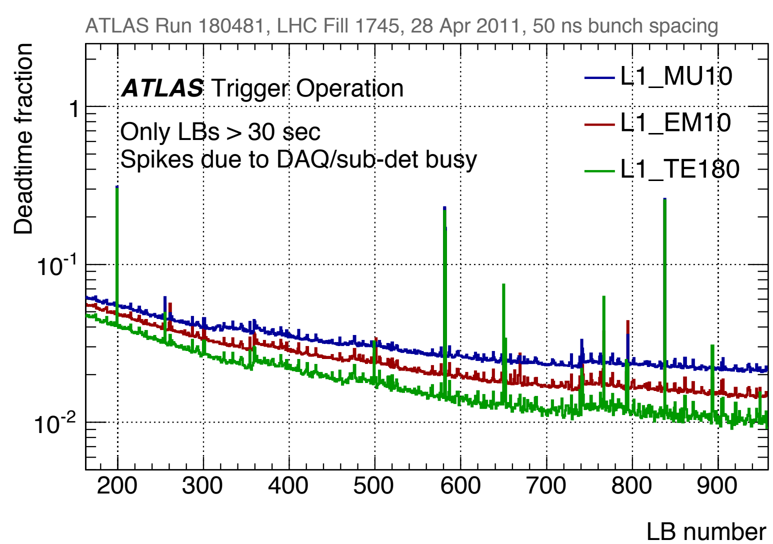
Dead Time Observations





Dominated by simple DT ~ 1-2% at 50 kHz L1 rate

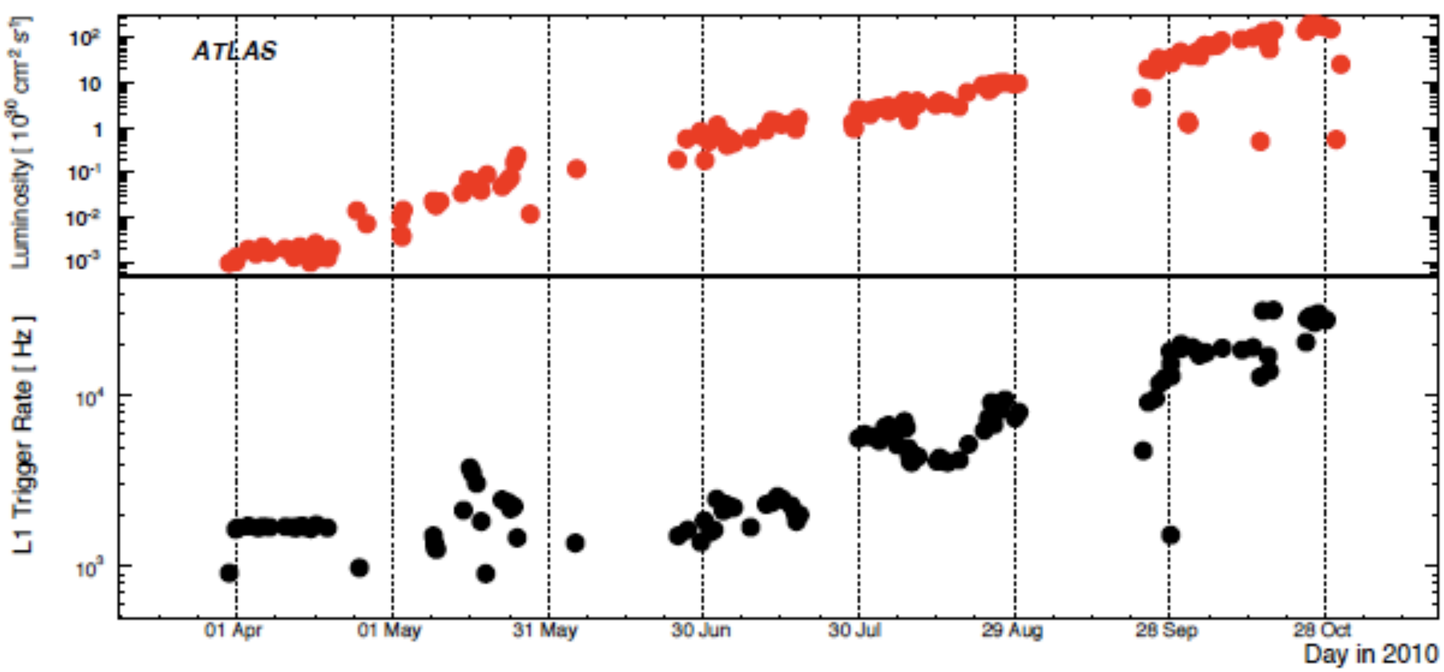
- Complex DT negligible
- Detector busy < 1%
    - with recent optimizations
- Total DT dropping during the fill as the input L1 rate decreases
- Small dependence on trigger type



LB = Luminosity Block ~ 1 min
where data taking configuration is guaranteed to be unchanged

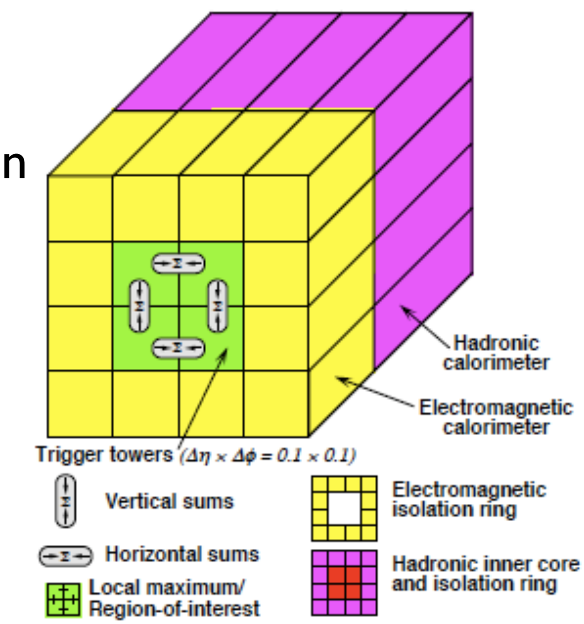
Evolution of output L1 rates (2010)

- 2010 witnessed five orders rise in Luminosity
  - 10^{27} cm^{-2} s^{-1} to 10^{32} cm^{-2} s^{-1}
- Rely on forward Minimum Bias Trigger Scintillators and low threshold L1 triggers for commissioning during the early phase.
- With increasing Luminosity, move to higher L1 thresholds.
- Total L1 rate gradually increased to about 30 kHz by end of 2010.
- In 2011, L1 rate typically has been over 50 kHz at 10^{33} cm^{-2} s^{-1}



L1 Calorimeter Triggers

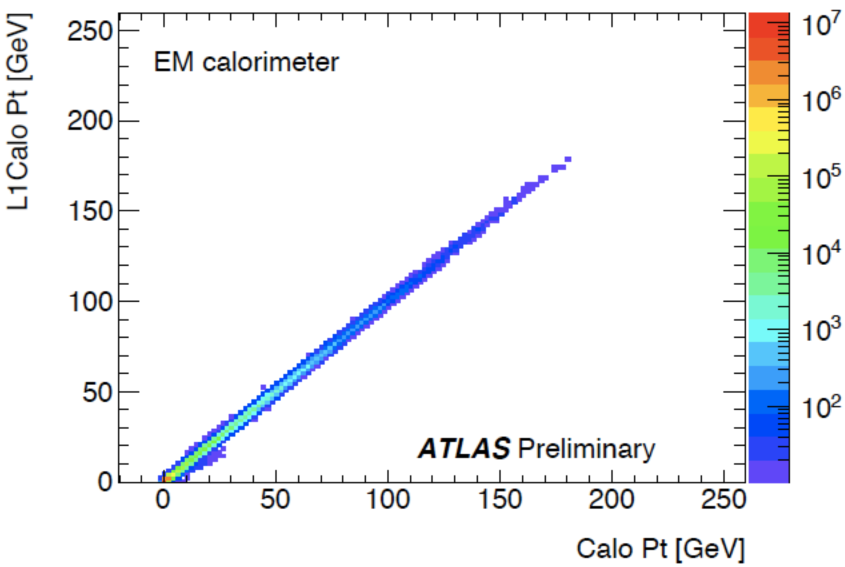
- Inputs from the EM and Hadronic Calorimeters
  - 7168 analog trigger towers ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$)
  - Digitized, Summed and Compared to programmable thresholds
- Formation of a Region of Interest (RoI)
  - Identify geometrical regions for further consideration by HLT
- Electron/photon RoI:
  - 2x2 EM Trigger Towers (TT)
  - Possibility of lateral/longitudinal Isolation
- Tau RoI: 2x2 Hadronic TT
- Jet RoI: 4x4, 6x6 or 8x8 TT
- Scalar Sums:
  - Missing ET (XE), Total Energy (TE)
  - Missing ET Significance (XS)

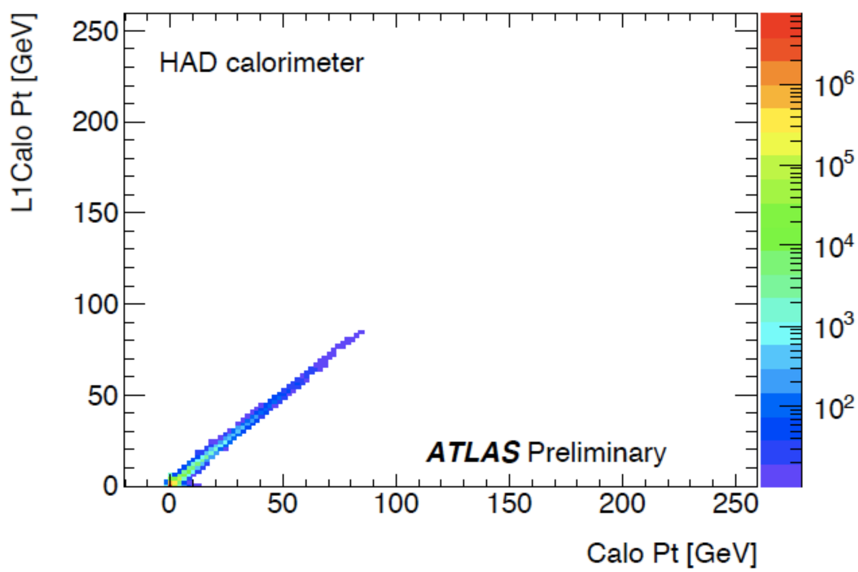


L1 Calorimeter Trigger Performance

- L1 calorimeter trigger (EM and Hadronic) operates at the Electromagnetic scale.
- Timing calibration achieved initially with pulser & cosmic and later fine tuned with data to a precision of $\pm$ 2 ns.
- A noise cut ~ 1.2 GeV applied to remove fakes.
- Good linearity observed with calibrated offline clusters.

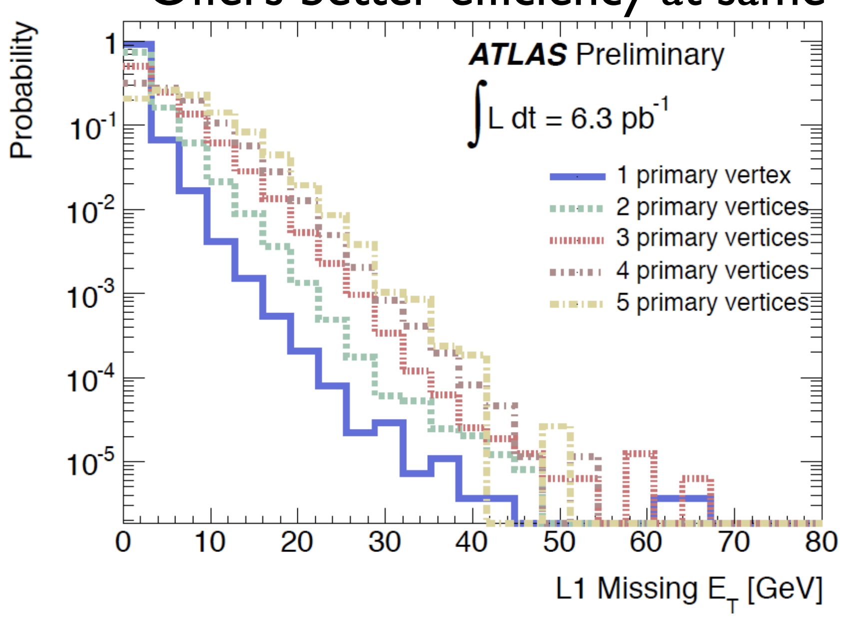
Details in talk by M.Wessels in Level-1 Session:
"Calibration and performance of the ATLAS Level-1 Calorimeter Trigger"

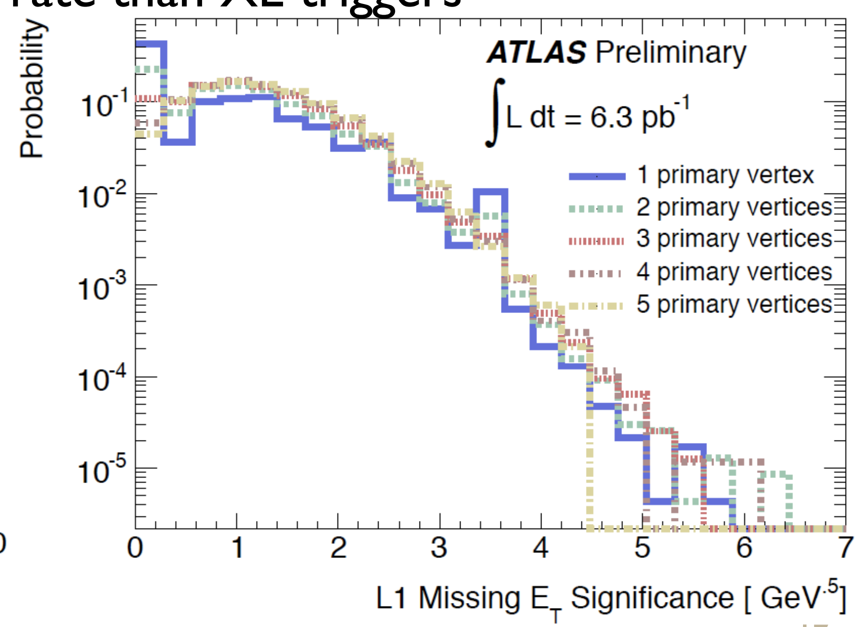




L1 Scalar Sums:

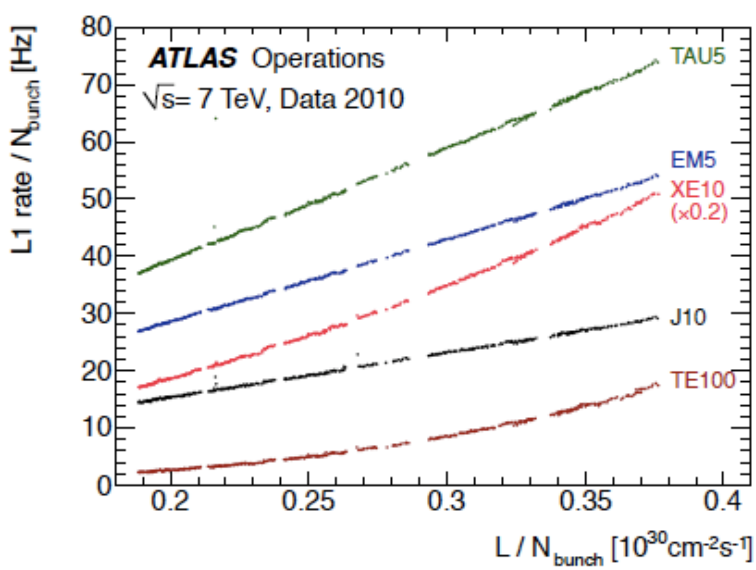
- Missing ET (XE) and Total Scalar Sum ET (TE)
  - Computed using Trigger Towers with 0.2 x 0.2 granularity
  - High inclusive rates, sensitive to pile-up.
- Missing ET Significance (XS)
  - XS = XE / a*(√TE + b)
  - Insensitive to pile-up
  - Offers better efficiency at same rate than XE triggers

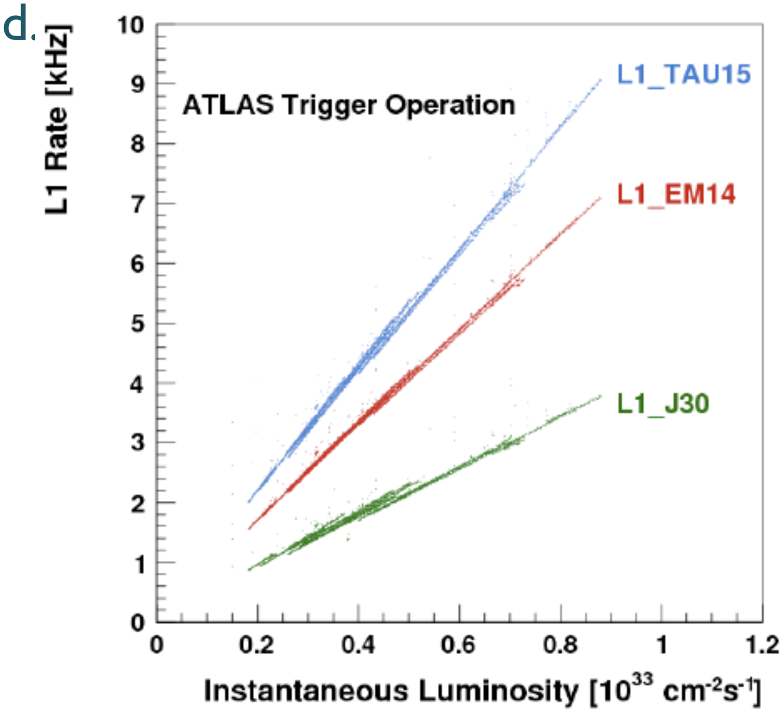




L1 Calorimeter Trigger Rates

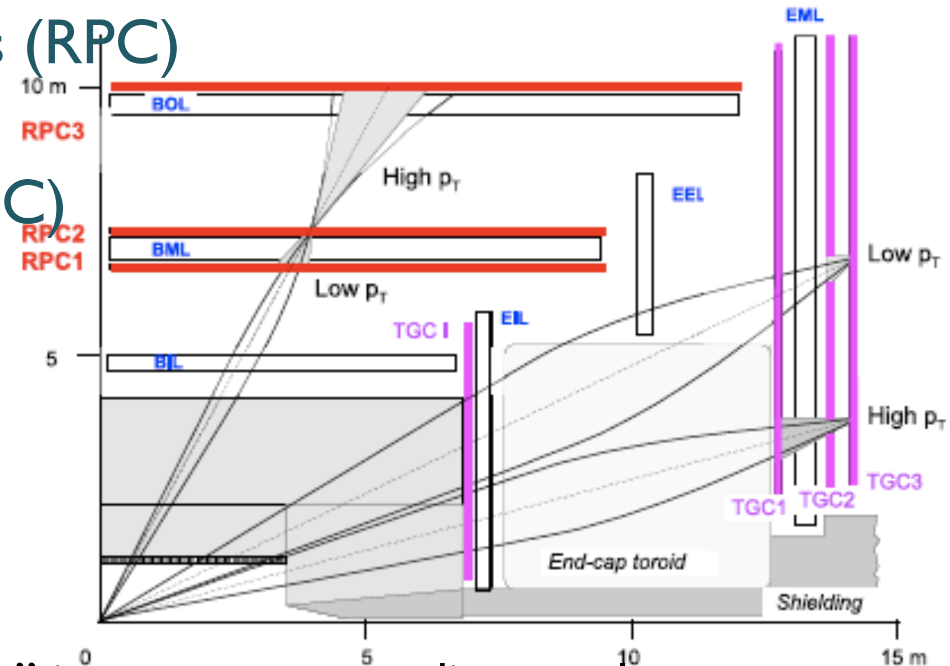
- Linear increase observed for EM, TAU and JET trigger rates
  - No visible impact so far with increasing pile-up.
- Scalar quantities (Missing ET and Total ET) have a pronounced impact with pile-up.
- Lowest un-prescaled L1 EM trigger at 10^{33}= EM14 with a rate of 9 kHz. An EM16 will get us to about 3 x 10^{33} above which isolation and/or higher thresholds need to be considered.





L1 Muons

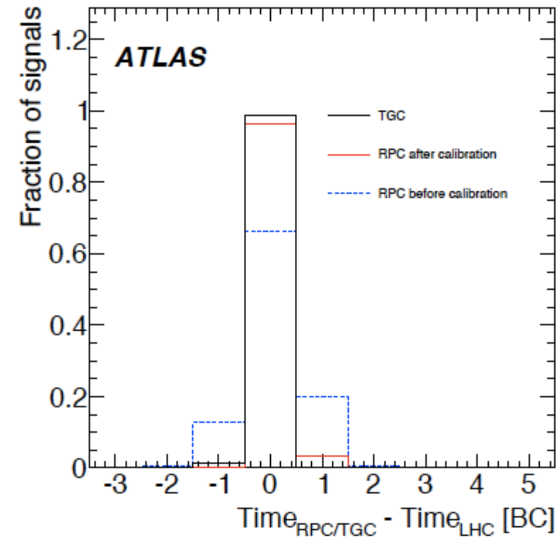
- Resistive Plate Chambers (RPC)
  - $|\eta| < 1.05$
- Thin Gap Chambers (TGC)
  - $1.05 < |\eta| < 2.4$



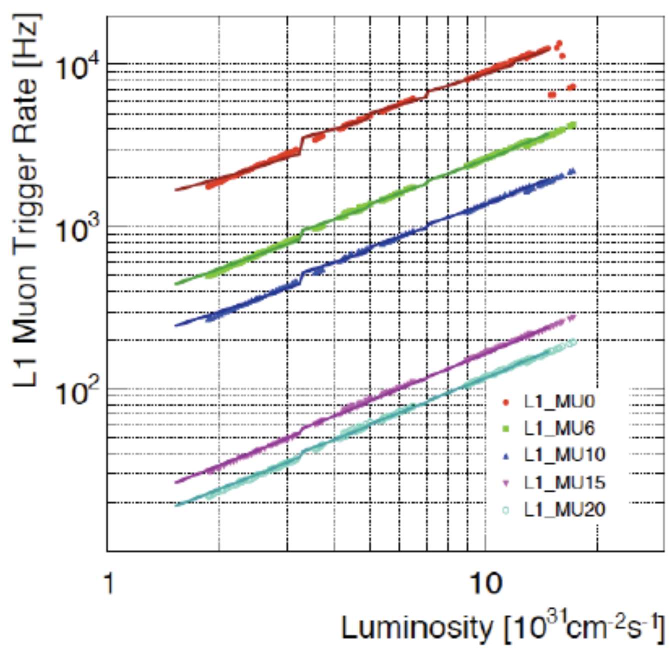
- Trigger Logic:
  - Hits in the pivot plane
  - Additional hits inside "roads" in one or more adjacent planes.
  - Width of these roads define the muon PT thresholds
  - RPC and TGC coincidences generated separately and combined later in programmable trigger logic as input to CTP.
  - Six programmable trigger thresholds:
    - Three low PT ($\leq$ 10 GeV) and three high PT.

L1 Muon Timing & Rates

- Contributions to signal delay
  - Time of flight ~ 200 ns
  - Signal Propagation ~ 1 – 10 ns
  - Timing calibration through combination of test pulses, cosmic, collisions



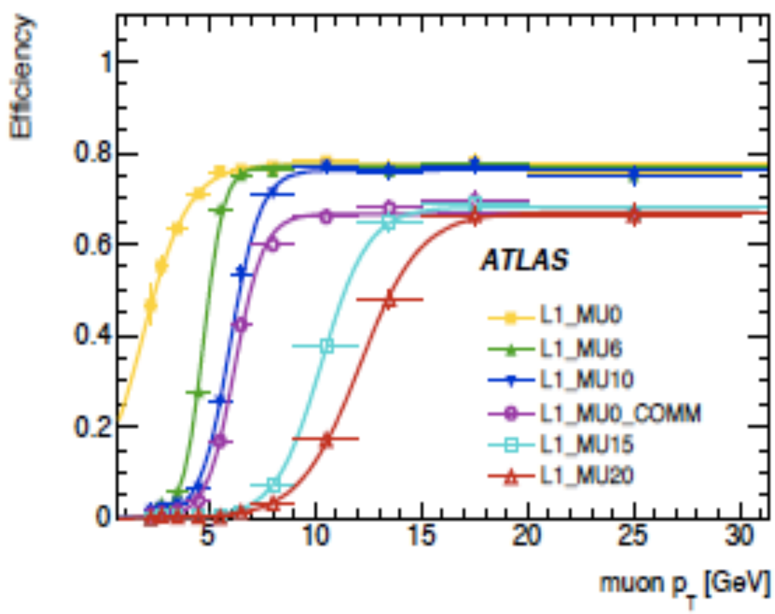
- Trigger Rates:

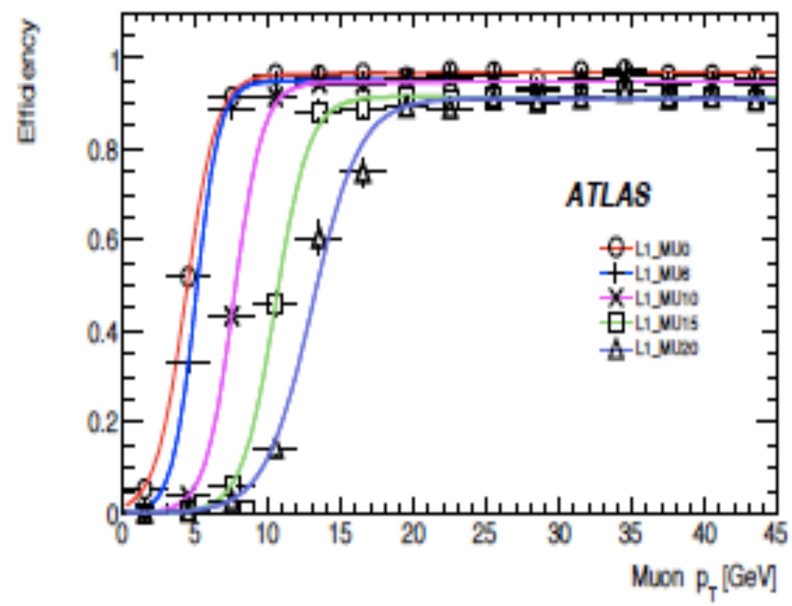


L1 Item	Rate @ 10^{33} (kHz)
L1_MU6	18
L1_MU10	11
L1_MU11	4
L1_2MU0	5

L1 Muon Trigger Performance

- RPC geometrical acceptance for low PT triggers (< 10 GeV) is ~ 80%
  - Further reduced for higher PT triggers that require a 3-station coincidence.
- High efficiency observed for both systems within detector acceptance.





Other L1 Triggers

- Triggers with different bunch configurations
  - All physics triggers require colliding paired bunches.
  - Unpaired bunches (one-sided proton bunch) and Empty bunches (unfilled bunches) are useful for various studies:
    - Beam backgrounds, Detector calibration and monitoring
- Random Triggers:
  - Triggered on Random LHC clock
    - Can demand random triggers during paired, unpaired or empty bunches.
  - Zero Bias Trigger
    - Luminosity weighted Random trigger
    - Trigger on a Physics, but generate L1 Accept one revolution later
- Forward Detectors
  - Minimum Bias Trigger Scintillator (MBTS), Luminosity Cerenkov Detector (LUCID), Zero Degree Calorimeter (ZDC), ALFA Detector (Roman Pots), Beam Counter Monitor (BCM).
  - Used for Forward Physics studies, Luminosity determination & Beam Monitoring.

L1 Trigger Thresholds at 10^{33} cm^{-2} s^{-1}

- Limited by total output rate of 75 kHz
- Important to keep low thresholds for lepton triggers to preserve physics.
  - Increasing rates at higher luminosity will require consideration of isolation, improved L1 calibration, and reliance on multiple objects at L1 to preserve the physics of interest.

Trigger Signature	Notation		Level 1 Threshold Settings at 10^{33} (prescaled triggers are shown shaded)							
	L1	HLT								
electron	EM	e	3	5	7	10	12	14	16	30
photon	EM	g	3	5	7	10	12	14	16	30
muon	MU	mu	0	6	10	11	15	20		
jet	J	j	10	15	20	30	50	75	175	250
forward jet	FJ	fj	10	30	50	75				
tau	TAU	tau	5	6	8	11	11I	20	30	50
Missing ET	XE	xe	10	20	25	30	35	40	50	60
ET miss Significance	XS	xs	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Sum Scalar ET	TE	te	20	180	300	400	500	600	700	
Total Jet Energy	JE	je	60	100	140	200				

High Level Trigger (= L2 + EF)

- **Level 1**
  - Defines Region of Interest (RoI)
  - Seeds L2 algorithms.
- **Level 2:**
  - PC farm, software based
  - Fast algorithms
  - Target <t> = 40 ms
  - Access to event data at full granularity in RoI only.
- **Event Filter:**
  - PC farm, software based
  - Offline Algorithms
  - Target <t> = 2 s with 5kHz input
  - Access to FULL event data.
  - Output Rate constrained by offline computing resources

Ramping up L1 output rate from an initial~20 kHz to 75 kHz

↓

Typical L2 output Rate ~4 - 5 kHz

↓

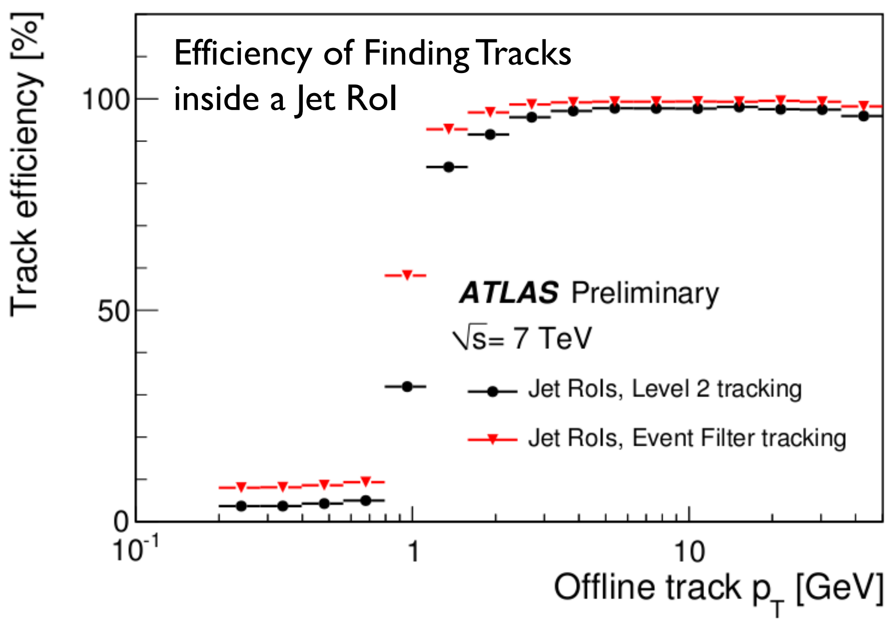
Typical output to Storage ~ 300 – 400 Hz

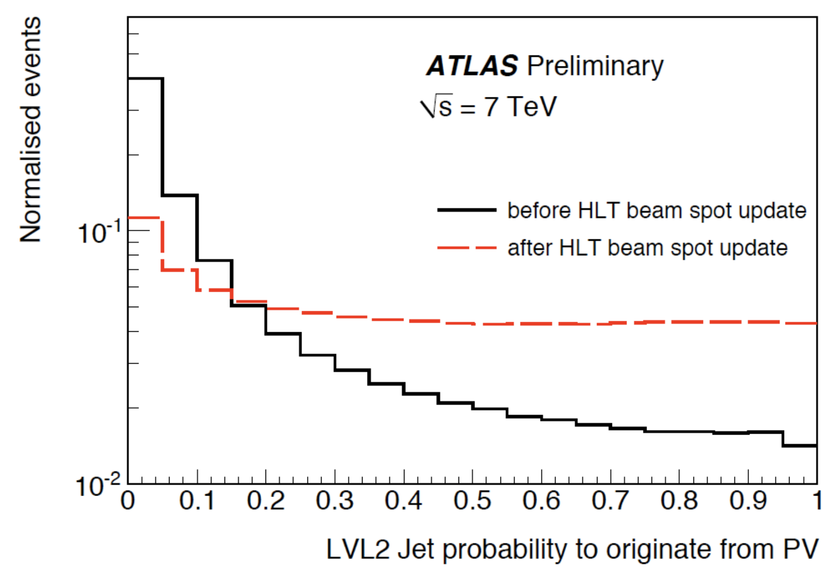
Typical L2 and EF rates in ongoing runs are beyond design parameters

Tracking at HLT

- Customized fast tracking algorithms implemented at L2.
- Offline tracking algorithms used at the Event Filter.
- Good efficiency observed for tracking at L2 and EF.
- Multiple clients, including:
  - Beam Spot determination
    - Used by online algorithms and monitoring/feedback to LHC.
  - Displaced vertex finding for heavy flavor tagging.

Details in talk by R. Bartoldus on "Online Determination of LHC Luminous Region"





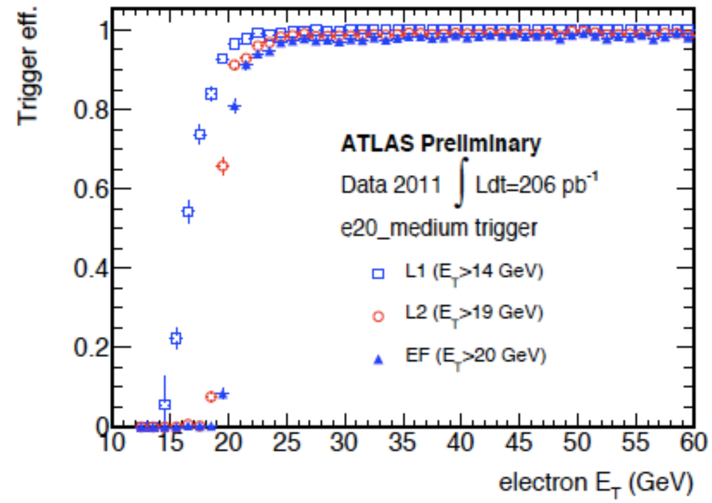
Electron & Photon Identification at HLT

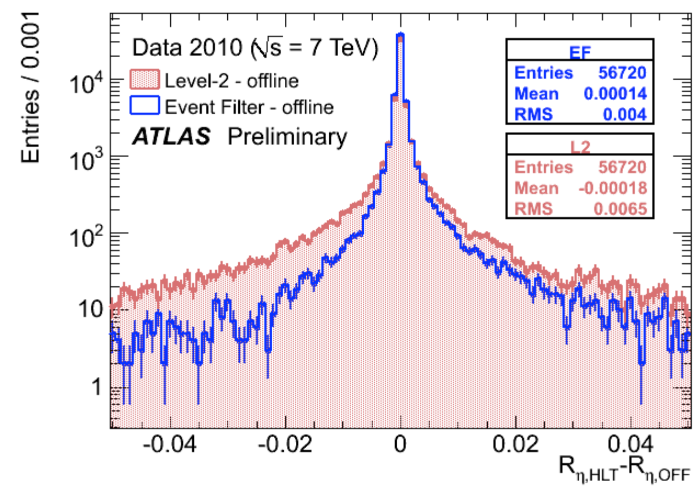
Level 1

- Requires ET of a local cluster ($\Delta\eta x \Delta\phi$ = 0.2x0.2) > threshold in $|\eta| < 2.5$

High Level Trigger

- Reconstruction of EM cluster using seed provided by Level 1.
- Electron id: Additional search for track in geometrical volumes defined by the cluster
- Three sets of selections cuts are defined: loose, medium, tight:
  - Include cuts on lateral shower shape, hadronic leakage, track quality and E/p.
  - HLT provides rejection ~ 150 for e20 with medium cuts keeping over 98% efficiency wrt offline.
  - Tighter cuts gain additional rejection of 2-3 with minimal loss in efficiency.





Jet Identification at HLT

Level 1

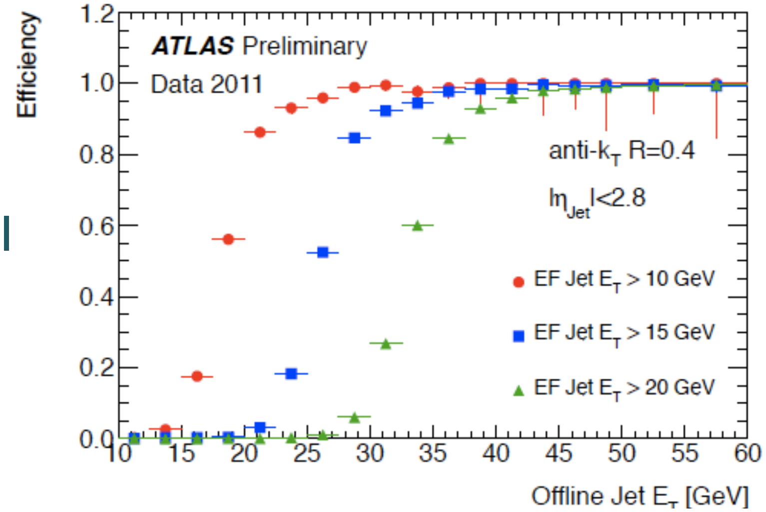
- Hadronic cluster in $\Delta\eta \times \Delta\phi = 0.8 \times 0.8$

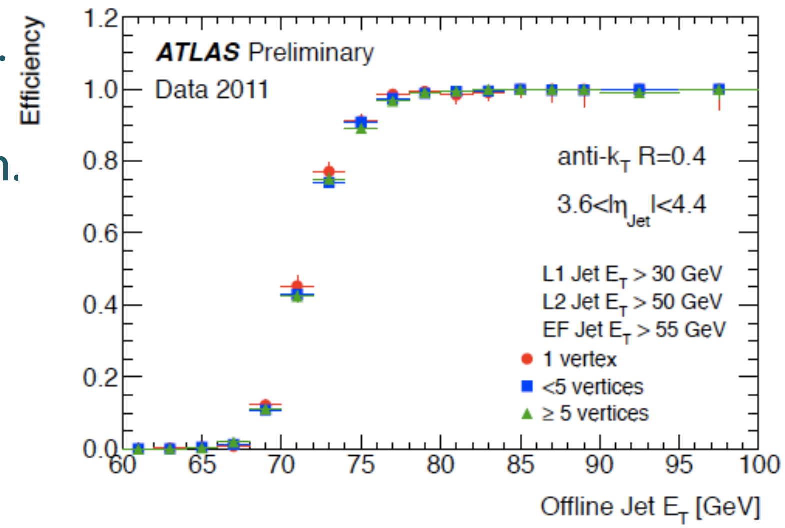
Level 2

- Seeded by L1 jets
- Cone Algorithm, R = 0.4
- Energy threshold typically 20 GeV over L1

Event Filter

- Anti-KT algorithm, R = 0.4
- Full reconstruction of all jets
  - Triggered by any L2 accepted trigger.
- Energy threshold typically 5 GeV over L2.
- No visible effects on turn-on with pile-up, some increase in forward rates seen.
- Both L2 & EF reconstruct jets at EM scale.
- Total rejection at L2/EF ~ 2 to 8 depending on ET of the jet.





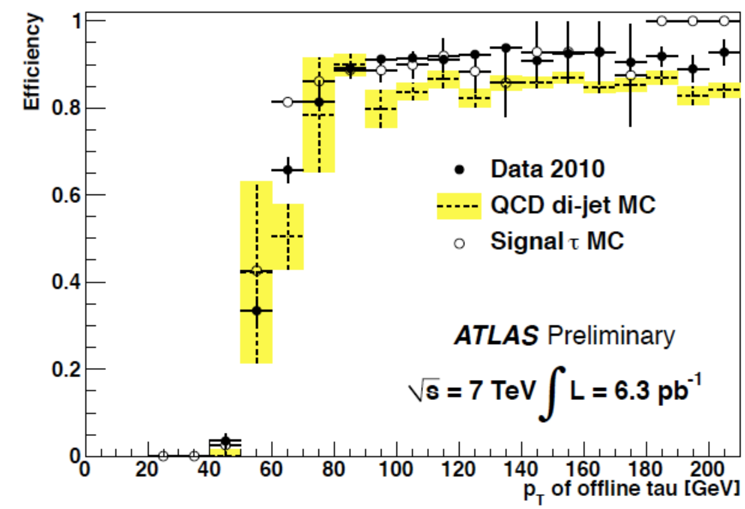
Tau Identification at HLT

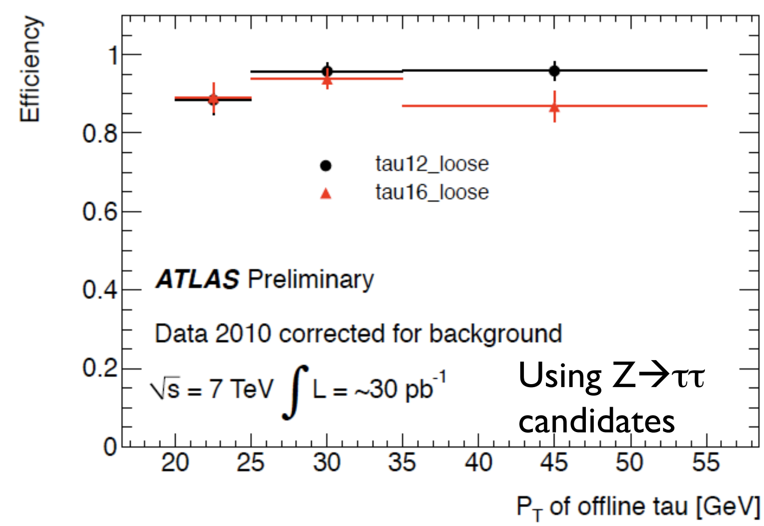
Level 1

- Hadronic cluster in $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$

High Level Trigger

- Reconstruction of a calorimeter cluster using seed provided by L1.
- Selection Cuts at HLT include:
  - A cut on the energy weighted radius and small number of associated tracks provide good rejection against QCD jets.
  - EF reconstruction applies different selections for 1-prong vs 3-prong.
- Typical HLT rejection obtained are 10 (low threshold, loose selection) to 40 (high threshold, tighter selection) against QCD jets [wrt L1].





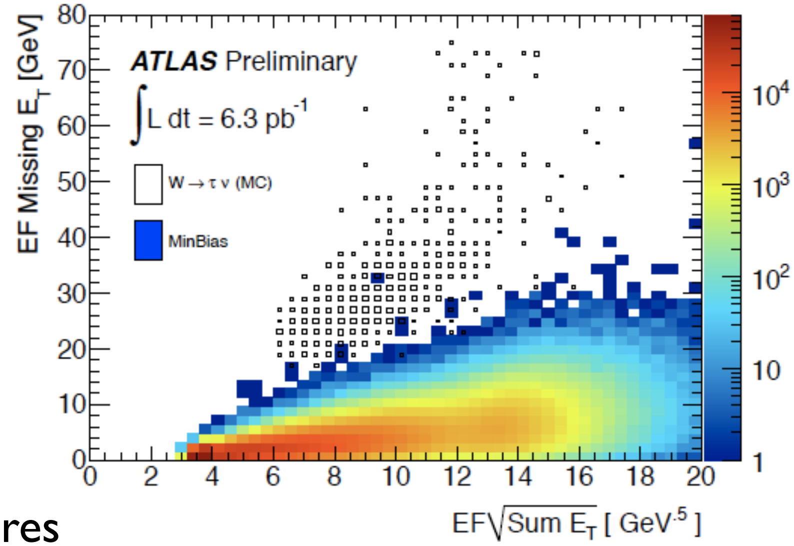
Missing ET at HLT

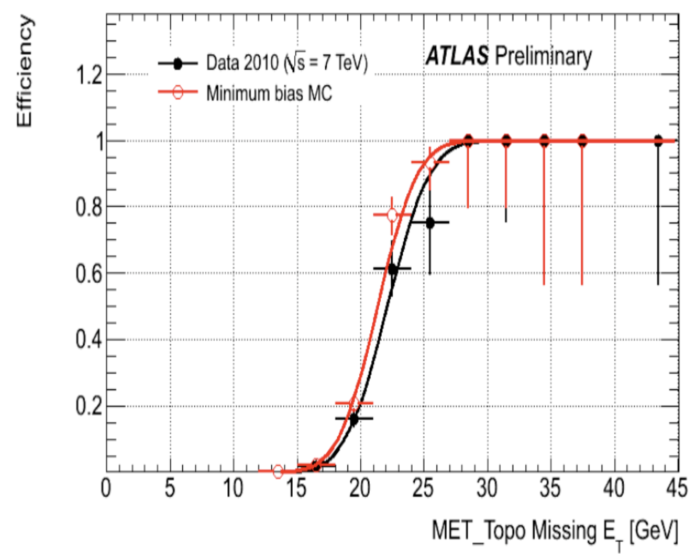
Level 1

- Missing ET computed using calorimeter Trigger Towers of $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$.
- Since 2011, Missing ET Significance also computed at L1.

High Level Trigger

- Possibility to apply only Muon corrections at L2.
  - Full Missing ET calculation at L2 requires access to full calorimeter data. To minimize this: Ex, Ey components calculated in Front-End Electronics and will be made available at L2.
- EF has access to full data.
  - Missing ET and significance calculated with cell level data and relevant calibration.
- Primarily used in combination with other triggers as inclusive rates are large.





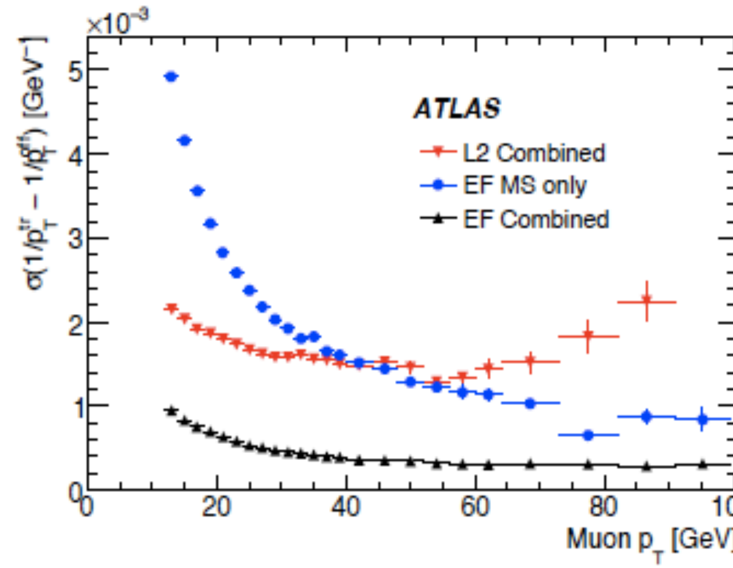
Muon Identification at HLT

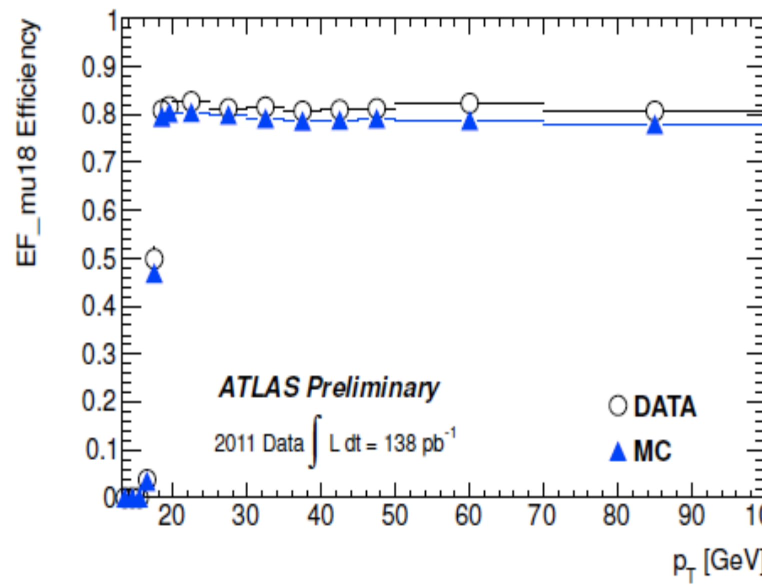
Level 1

- Hits in roads in RPC or TGC

High Level Trigger

- Level 2 uses hits in Muon Spectrometer (MS) in an RoI defined by L1.
  - Select MDT hits and fit based on MDT drift time and position information and assign pT using fast look up tables.
- Additional refinements:
  - Tracks extrapolated to IP correcting for material and alignment and associate track from Inner Detector in RoI
    - Referred to as "Combined"
  - Isolation in Calorimeter & Tracking
- Event Filter:
  - Same as L2, but fits performed on hits in MDT and Tracking instead of using LUT.

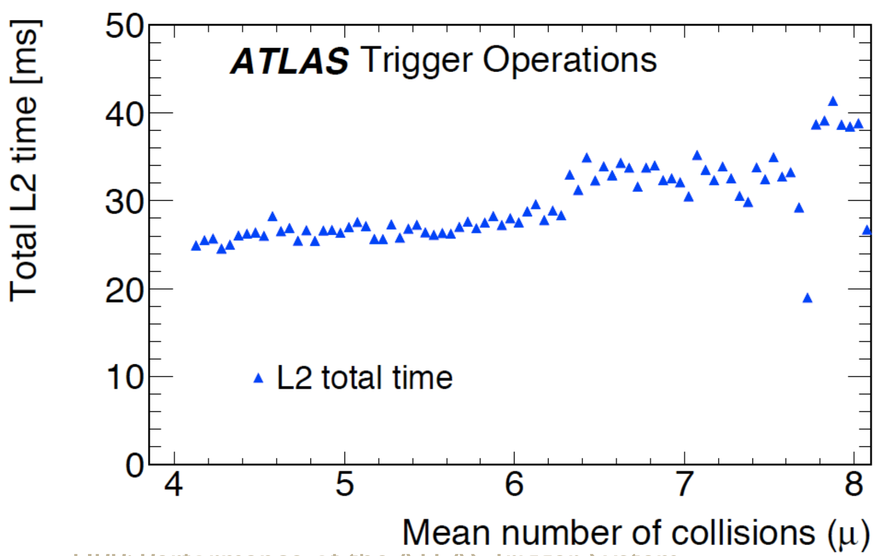


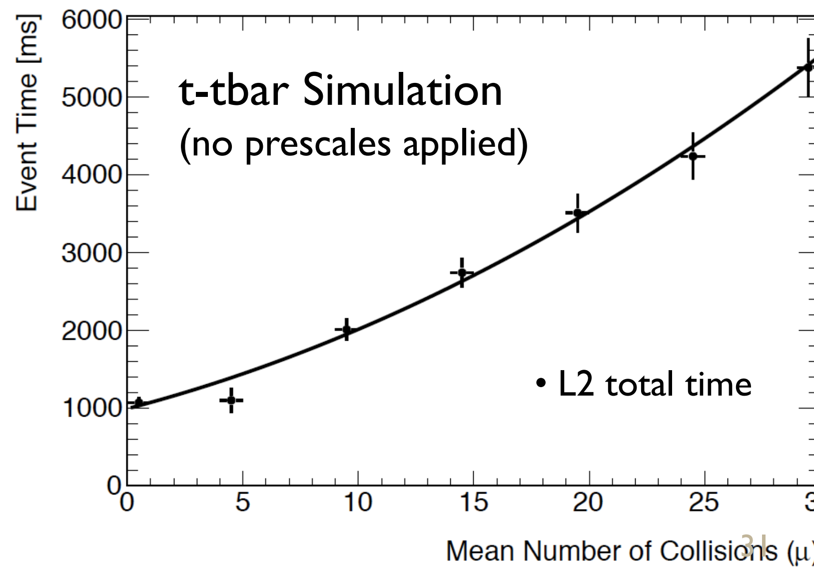


CPU resource needs with Pile-Up

Details in talk by R. Ospanov on "Resource Utilization" later this session

- Resource Usage heavily depends on the menu being used.
  - Some trigger scale linearly with pile-up, some quadratic, others constant.
    - Behavior of triggers studied extensively with simulation with pile-up up to 30.
  - Using a model which assumes a combination of constant, linear & quadratic behaviour: can predict resource needs with increasing pileup
  - These extrapolations suggest that the L2 and EF resources are well equipped to handle higher pile-up conditions and if necessary, menu optimizations and further deployment of compute power (only 50% of foreseen compute cycles deployed today) will allow us to operate smoothly.



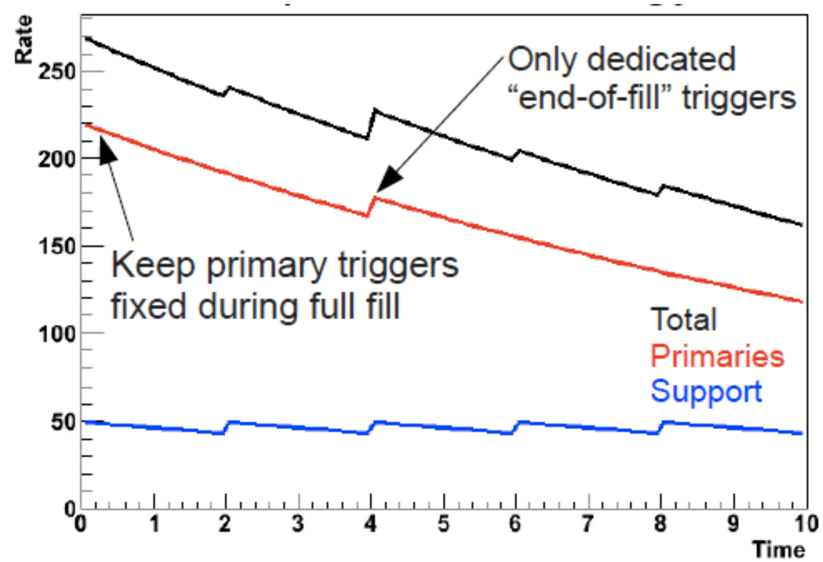


Triggers of different flavors

- Primary
  - Primary triggers for physics analysis normally running un-prescaled.
  - Must evolve to higher thresholds/tighter selections with Luminosity
- Supporting
  - Used for efficiency and other performance studies
  - Normally using some fixed output bandwidth.
- Calibration
  - Used explicitly for calibration, alignment studies
  - Normally writing out only partial events at fixed output bandwidth
- Commissioning & Monitoring
  - For monitoring the online performance or testing new triggers for future deployment. Running at low fixed output rate.
- A "Trigger Menu" is a collection of all these triggers:
  - Typically , few hundred triggers in a menu deployed at any time.

Operational Strategy

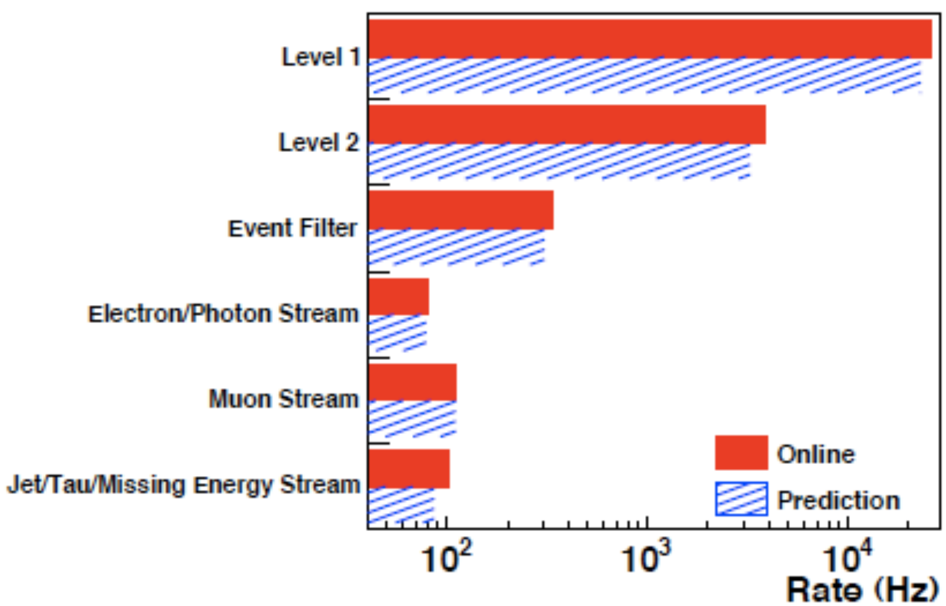
- Typical trigger menu provides several threshold points and designed to work over order of magnitude in Luminosity.
- Keep primary triggers as stable as possible, not just over the run but over long data periods
  - Highly desirable for Analyses.
- As Luminosity falls over fill:
  - Enable additional triggers
    - Requiring high L1 rate.
- Keep supporting and other monitoring triggers at fixed output rate.

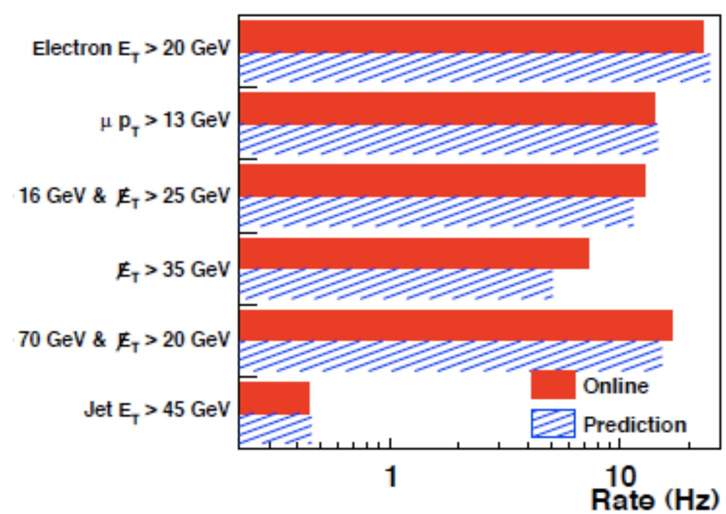


- Rates adjusted during the fill with "prescale sets", deployed during a run without the need for a stop/re-start.

Trigger Rate Predictions

- An "Enhanced Bias" data sample is collected at a specific luminosity point:
  - Consists of data streamed solely on a low threshold L1 decision
  - Higher L1 thresholds and HLT selections can be performed offline.
- This sample is then use to study the rates for different triggers and extrapolate the behavior to higher luminosity





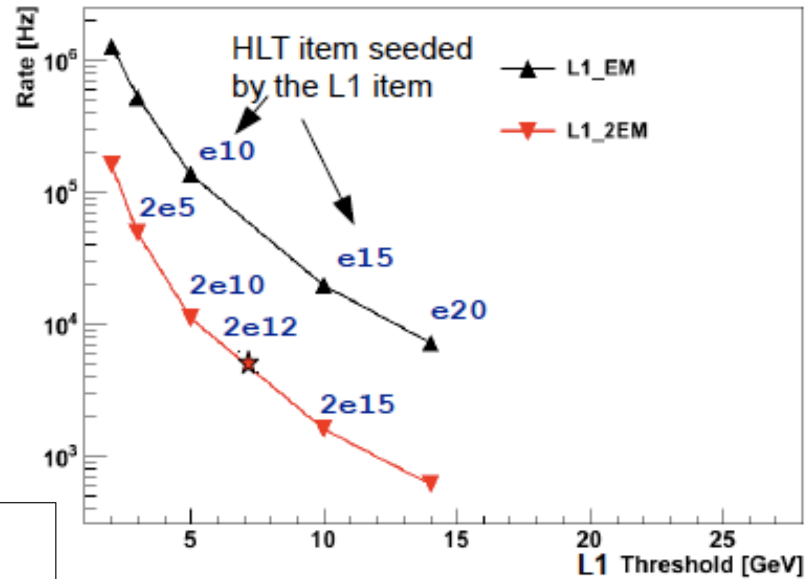
UnPrescaled Triggers & Rates @ 10^{33}

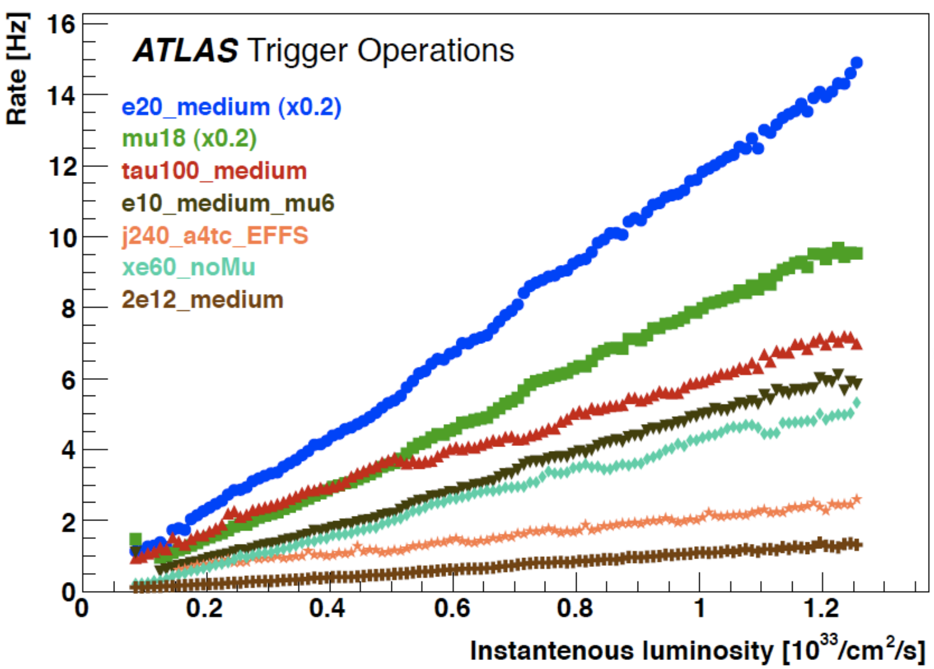
- Sample of primary single lepton, photon and jet triggers running un-prescaled at 10^{33} cm^{-2} s^{-1}.
    - Shown are the Triggers, the L1 Item and the rates for each.
  - At higher luminosity, raise thresholds, tighten selections incl. isolation and use of multi-object triggers to optimize physics acceptance

Trigger	L1 Item	L1 Rate (Hz)	EF Rate (Hz)
e20_medium	EM14	8500	50
2e12_medium	2EM7	5700	1
g40_tight	EM30	700	16
mu18	MU10	5300	40
2mu10	2MU10	100	1
xe60	XE40	300	4
J180	J75	200	6
tau29medium_xe35	TAU11_XE20	3800	6
tau16_e15	TAU6_EM10	7500	6
j75_xe45	J50_XE20	500	10

Evolution of Rates with Luminosity

L1 rate projections for several electron triggers at 10^{33} cm^{-2} s^{-1}





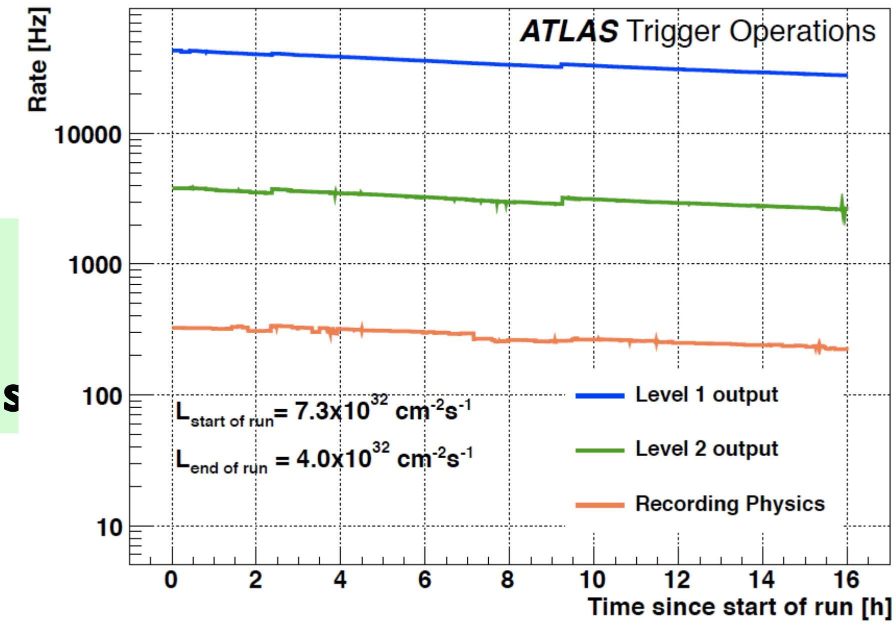
Observed rates for primary Physics triggers as a function of Luminosity

Raw Data Streaming

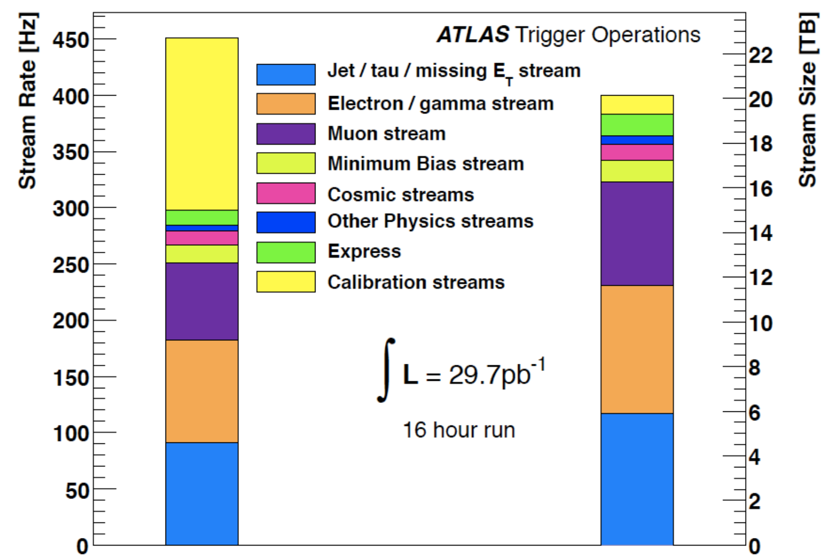
- Streaming helps prioritize re-processing at finer granularity.
- Data Streamed inclusively:
  - A given event may appear in more than one stream
  - Overlap across streams kept to less than 10%
- Primary Physics Streams:
  - MinimumBias, JetTauEtMiss, eGamma, Muons.
- Several additional output streams, including:
  - Calibration Streams: Some with partial event storage.
  - Debug Stream: Carrying events that failed processing at HLT, DAQ errors or data corruption errors.
    - Reconstructed offline and integrated with main streams.
  - Express Stream: Carrying a small fraction of events that are rapidly processed to ensure data quality.

Rates: Graphical View

L1, L2 and EF output rates
For a data taking run
At <Luminosity> of 1 x 10^{33} cm^{-2} s



Recorded Output in each stream for the above run.
Total Rate in Hz and Total Data Storage in TB are shown for the physics and additional calibration streams.



Conclusions

- The ATLAS Trigger System was successfully deployed and commissioned during the early data taking phase.
- It has successfully operated over a rise in luminosity of over six orders of magnitude during the past year.
  - Performing with > 95% data taking efficiency.
- The output rates from L2 and EF are operating successfully beyond design parameters.
- Several measures have been taken to address the weaker links during the past shutdowns.
  - Cabling Rerouted, Processor Upgrades
  - Timing, Calibration, Algorithms, Selections have been optimized.
- The ATLAS Trigger remains ready to face the expected further increase in LHC luminosities and pile-up.