Operation of the ATLAS Trigger System in Run 2 – Summary of Paper

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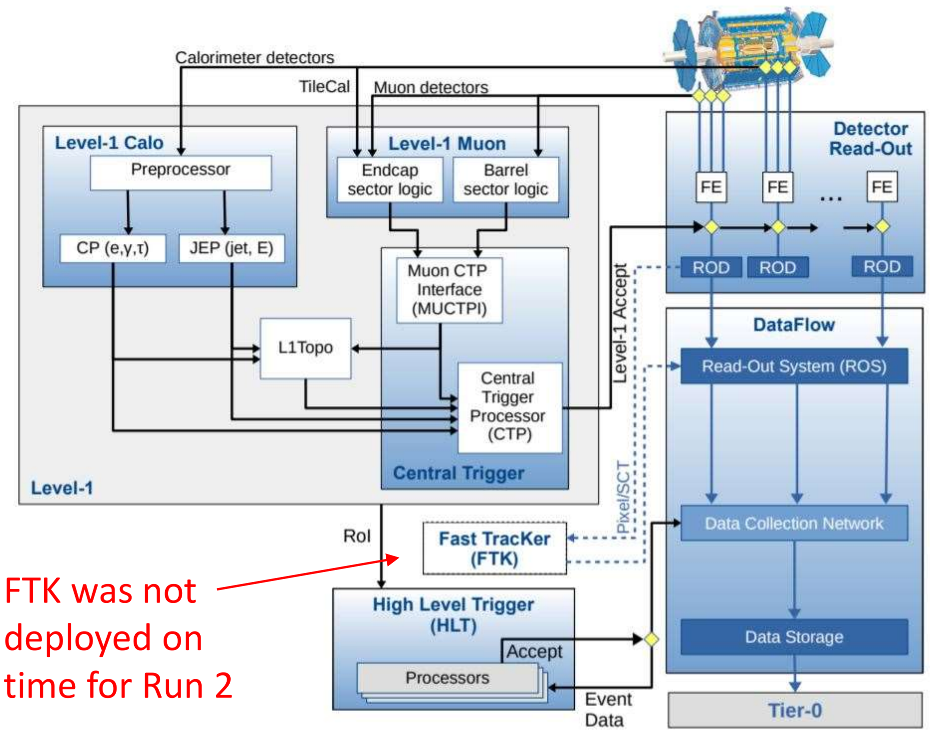
Ch.1: Introduction

- Overview of ATLAS Trigger and Data Acquisition System (TDAQ)
- LHC Run 2 (2015-2018)
- *“ATLAS trigger system operated successfully with excellent performance and flexibility”*
- Two-level trigger system
  - Level-1 Trigger (L1) and High-Level Trigger (HLT)
- Records data from collisions at an average rate of 1kHz
  - Initial proton-proton bunch crossing 40MHz
- ~ 1500 event selections in a trigger menu

Ch.3: TDAQ System during Run-2



FTK was not deployed on time for Run 2

- **Preprocessor:** Digitizes and calibrates the analogue detector signals
- **Cluster Processor (CP):** Identifies electron, photon, and tau candidates
- **Jet / Energy-Sum Processor (JEP):** Identifies jets as well as sums global scalar and missing pT
- **L1Topo:** topological requirements based on geometric and kinematic combinations
- **Central Trigger Processor (CTP):** Makes final L1 Trigger decision
- **Front-End (FE) :** Reads-out data from detector if L1 accepted
- **ReadOut Drivers (ROD):** Performs initial processing and formatting
- **High Level Trigger (HLT):** Software-based trigger algorithms
- **Tier-0:** Data storage at CERN's computing centre

Ch.3: Central Trigger Processor (CTP)

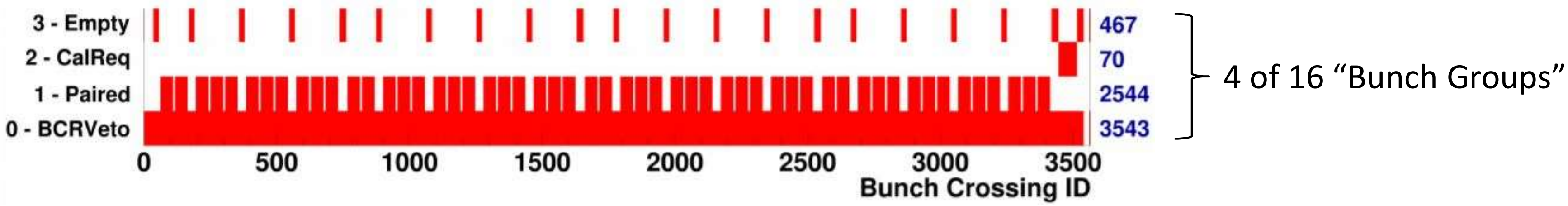
- Receives inputs to make final L1 trigger decision
- Responsible for applying *dead-time:*
  - ***Simple Dead-time***: Limits the minimum time between two consecutive L1 accepts to avoid overlapping readout windows
  - ***Complex Dead-time***: Restricts the number of L1 accepts allowed in a given number of bunch crossings to prevent front-end buffers from overflowing (“Leaky Bucket” Model – See p.5 Line 139)
- Accepts events up to the max detector read-out rate of 100kHz within a latency of 2.5μs

Ch.3: High-Level Trigger (HLT)

- 2nd Stage of Trigger (Software-based)
- Dedicated fast trigger algorithms to provide early rejection
- More precise and CPU intensive algorithms used for final selection
- Executed on a computing farm with ~40,000 Processing Units (PUs)
  - PUs make decisions within ~100ms
- Based on Athena, which is based on Gaudi
- Physics output rate is on average 1.2kHz with an average physics throughput to permanent storage of 1.2GB/s
- Once accepted by the HLT, data is sent to Tier-0

Ch.4: Beam Pick-up Based Timing System (BPTX)

- Electro-static detectors 175m away on either side of ATLAS along the beam pipe
- Discriminator for when a proton bunch passes through ATLAS
- Used both for the Level-1 trigger system and for LHC beam monitoring and redefining bunch groups
- Precision better than 100ps
- The CTP pairs each L1 trigger with a specific bunch group

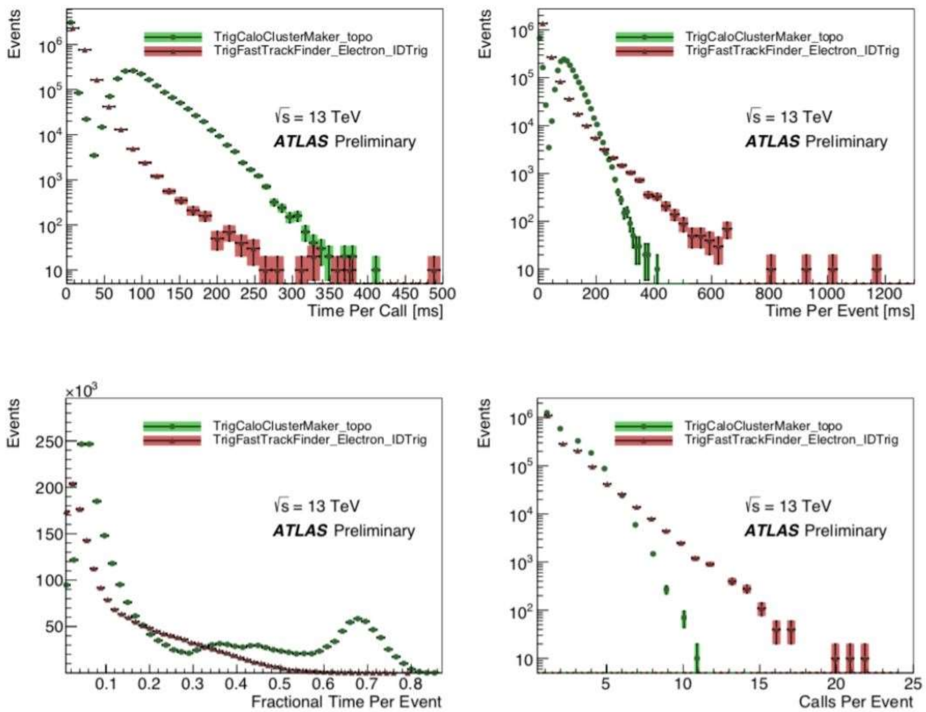


Ch.6: Run-2 Trigger Menu and Streaming Model

- Events are selected by trigger chains
  - A trigger chain consist of an L1 trigger item and a series of HLT algorithms
- Each chain is designed to select a particular physics signature
  - eg. presence of leptons, photons, jets, missing transverse energy, total energy, or *B*-meson candidates
- Trigger Menu is a list of multiple trigger chains
  - Includes prescale value for each trigger chain
  - For a prescale value of *n*, an event has a probability of 1/*n* to be kept
- Set of trigger selections must share resources (eg. readout rate, processing resources, storage)
- Main goal of Run-2 trigger was to maintain unprescaled single-electron and single-muon trigger pT thresholds around 25GeV
  - Ensures the collection of the majority of events with leptonic W and Z boson decays

Ch.6: Cost Monitoring Framework

- Collects data on CPU usage and data-flow during the trigger execution
- Used on sample events processed by HLT (both pass & fail events)
- Monitored data include:
  - algorithm execution time
  - data request size, and
  - the logical flow of the trigger execution for all L1-accepted events.
- Can estimate the number of PUs required to run a given trigger chain or menu
- See section 6.2 for Run-2 Streaming Models



Ch.8: Condition Updates in the HLT

- HLT event selection is driven by reconstruction and selection algorithms
- *Conditions* provide settings, such as calibration and alignment constants, to the algorithms
- *Conditions* are valid from the time of their deployment until their next update
- Most *conditions* are updated only between runs, but some require updates during ongoing data-taking
- *Conditions* data are stored in databases in a library called *COOL*

Ch.8: Condition Updates within a run

Online Beam Spot:

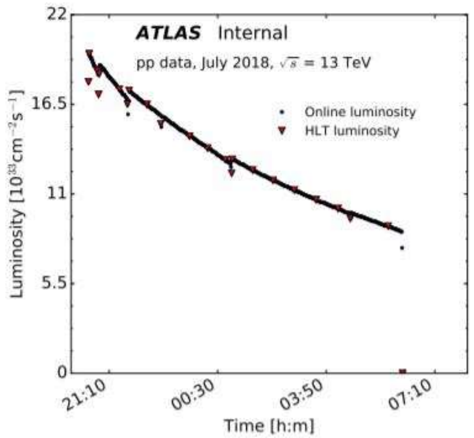
- position and width of LHC beam
- not constant within a run
- continuously monitored
- updated during data-taking if there are large enough deviations from the currently used value

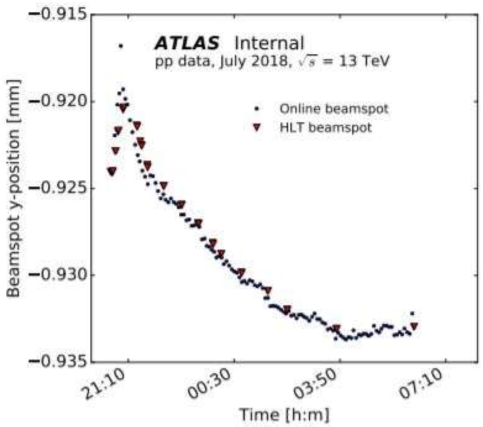
Update of trigger prescales:

- Being able to change trigger prescales during an ongoing run is extremely valuable
- Provides luminosity-dependent trigger configurations during data-taking to make optimal use of the available resources

Online Luminosity:

- LUCID detector monitors the overall and per-bunch luminosity
- Updates the conditions if average luminosity deviates by 5%





Ch.9: Trigger Configuration

- The trigger system's hardware and software configuration settings must be accurately recorded for future analysis
- Stored in a database called TriggerDB via a GUI called TriggerTool
- Used by the on-call trigger experts to prepare the configuration for the upcoming runs or adjust during an ongoing run
- See Chapter 9 for more info/screenshots of the GUI

Ch.11: Debug Stream Processing

- Sometimes the HLT is unable to make a decision on whether to accept an event due to processing failures
- Groups events by failure type and records them in a debug stream to further study offline
- Typically a small number of events, but an attempt to recover them is still made

Stream	Number of Events			
	2015	2016	2017	2018
Physics	1 694 555 330	538 7420 813	5 649 311 254	6 400 342 575
HLT Timeout	258 938	23468	212	16
PU Timeout	103 436	54460	5 759	710
HLT Error	21 302	46 614	897	82
PU Crash	16 830	6 024	2 125	147
Missing Data	1	2219	0	0
Possible Duplicate	1	42	4 161	129
Truncated HLT Result	0	101	1	16
Force Accept	11 110	55 450	4 838	397
Late Events	260	482	204	10
Total Debug	411 878	188 860	18 197	1 507
Total Debug w.r.t. Physics	0.0243%	0.0035%	0.00032%	0.00002%
Recovered Events	402 671	187 944	18001	1455
Recovered Events w.r.t. Total Debug	97.8%	99.5%	98.9%	96.5%

Ch. 12: Online Monitoring

Rate Monitoring

- Trigger rates are valuable indicators of the trigger performance
  - highly sensitive to detector malfunctions, LHC beam issues, and instantaneous luminosity variations
- Monitored and archived using the *Trigger Rate Presenter (TRP)*
  - Can monitor all individual L1 and HLT trigger chains in trigger menu
- The input/output rates can be compared before and after prescaling
- Cross-section / trigger rate *MONitoring tool (Xmon)* was used to compare trigger rates from the ongoing run with rate predictions

Ch. 12: Online Monitoring

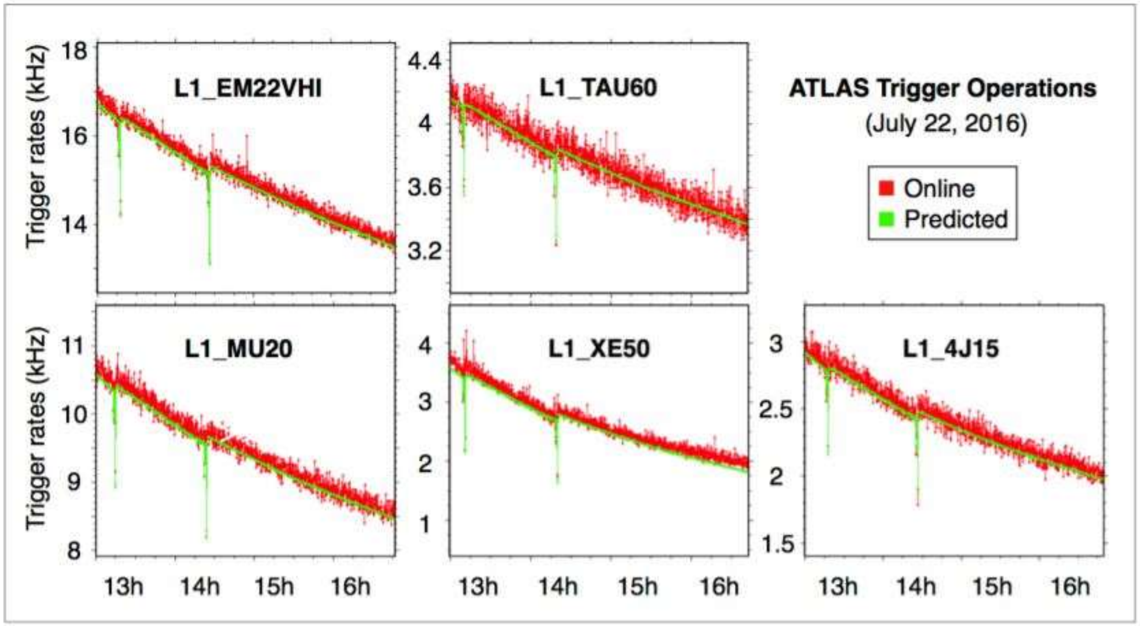


Figure 16: Live rates of several L1 trigger items (red) overlaid with the predicted rates (green) as a function of time for one run taken in July 2016. The downward spikes correspond to the luminosity optimization done by the LHC.

Ch. 12: Online Monitoring

Data-Taking Anomalies

- Deviation in trigger rate is one of the most common problems (too high or too low)
  - If rates are too high, prevents data being recorded
- Previously shown tools are used to identify the source of the deviation
- See Section 12.4 for examples of debugging

- *Additional online & offline monitoring processes in bonus slides*

Ch.13: DQ Efficiency

- Includes any data being rejected on grounds of data quality (not detector-related problems)
- Defects are mainly due to:
  - hardware problems in the L1 system, and
  - incorrect trigger configuration being loaded
- For L1 it was mostly detector coverage and problems with the CTP cables
- Defects due to TDAQ system are very rare

Year	Dataset	Trigger DQ Eff.		ATLAS DQ Eff.	Integrated Luminosity
		L1 [%]	HLT [%]	[%]	of good quality data
2015	*pp* @ 13 TeV (50 ns)	100.00	99.94	88.77	84 pb^{-1}
	pp @ 13 TeV	99.97	99.76	88.79	3.2 fb^{-1}
2016	*pp* @ 13 TeV	98.33	100.00	93.07	33 fb^{-1}
2017	*pp* @ 13 TeV	99.95	99.96	95.67	44 fb^{-1}
2018	*pp* @ 13 TeV	99.99	99.99	97.46	59 fb^{-1}
2015-2018	*pp* @ 13 TeV	99.57	99.94	95.60	139 fb^{-1}

Table 3: Luminosity-weighted relative detector uptime and good DQ efficiencies (in %) during stable beams *pp* collision physics runs at $\sqrt{s}$ = 13 TeV for 2015 (July to November), 2016 (April to October), 2017 (June to November) and 2018 (April to October) for the trigger system (L1 and HLT) and overall for the ATLAS detector. Numbers have been extracted from Ref. [73].

Ch. 14: Conclusion

The operation of the ATLAS trigger system during the LHC Run 2 was highly successful for both *pp* and heavy ion data-taking as well as for a variety of special runs. The recorded data are of a high quality with only minimal losses due to operational problems. The trigger's excellent performance and flexibility allowed collection of 139 fb^{-1} of high-quality *pp* collision data at $\sqrt{s}$ = 13 TeV over a wide range of running conditions, with peak instantaneous luminosities ranging from $0.5 \times 10^{34}\ cm^{-2}\ s^{-1}$ up to $2.1 \times 10^{34}\ cm^{-2}\ s^{-1}$ and pileup collisions from 28 to 60. A variety of tools and procedures, as detailed in this paper, have been used both in the offline and in the online environments to efficiently validate, monitor and assess the operation and the performance of the trigger system. They allowed maximal exploitation of the collisions delivered by the LHC in Run 2 for physics analyses, while fulfilling the limitations of the trigger system in terms of maximum readout rates, available HLT computing resources and sustainable storage output bandwidth.

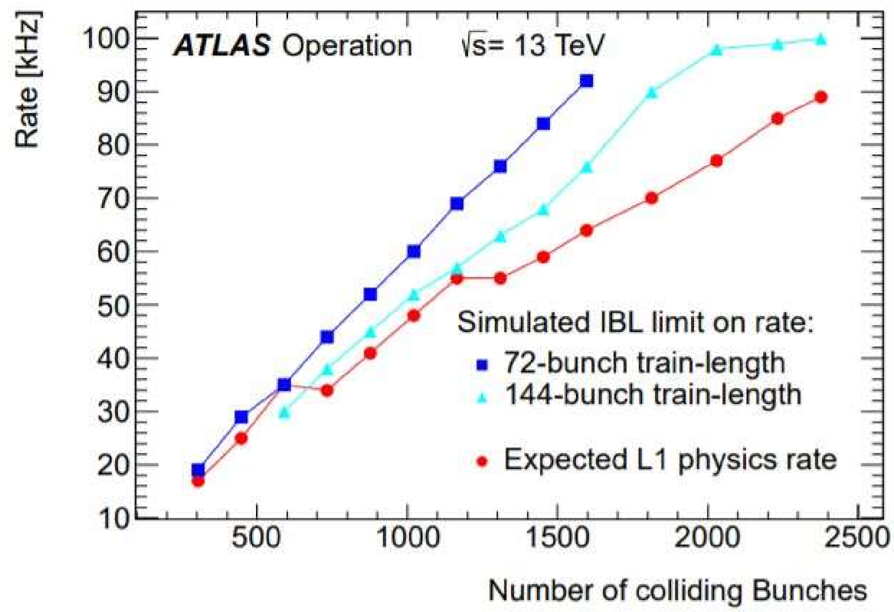
- *"The operation of the ATLAS trigger system during the LHC Run 2 was highly successful"*
- *"The recorded data are of a high quality with only minimal losses due to operational problems"*

https://cds.cern.ch/record/2720238/files/TRIG-2019-04-002.pdf?

Bonus Slides

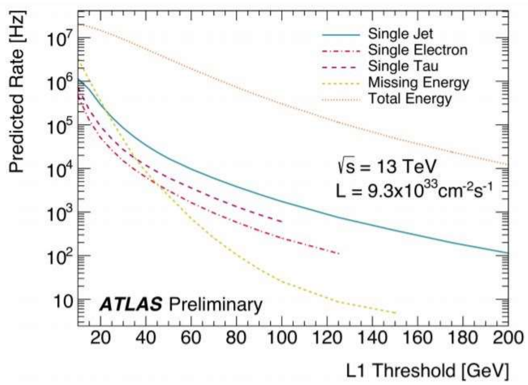
Ch.7: Special Data-Taking Configurations

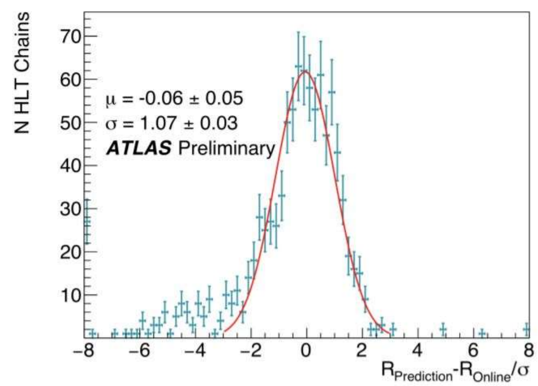
- Require a special trigger menu to comply with the usually tightened limits
- eg. Runs with few bunches (eg. 3, 12, 70, 300)
  - usually during LHC ramp-up or shutdown
  - still desired to collect data for calibration or low-luminosity searches
  - data passing L1 can be at mechanical resonance frequency of wire bonds of the Insertable B-Layer (IBL) of the pixel detector, causing physical damage
  - to protect the detector, a fixed-frequency IBL veto is implemented



Ch.10: Online Release Validation

- Validation of the HLT is crucial to ensure the reliability and predictability of its performance
- Kept separate from the offline reconstruction release
- Final validation of the trigger release is done using a suitable *Enhanced Bias (EB)* dataset
  - Minimally biased by the triggers used to select it
- Software development is driven mainly by the improvement of algorithms, the addition of new trigger chains, and addressing occasional problems in the software
- Throughout Run-2, around 80 software releases were deployed





Two examples of the EB rate predictions

Ch. 12: Online Monitoring

Online Data Quality Monitoring

- Histograms of other quantities from the trigger system are monitored:
  - Kinematic properties reconstructed by the trigger, and
  - more general infrastructure-related information (e.g. number of processing slots available in the HLT farm, the status of the magnets, etc)
- Displayed using the *Data Quality Monitoring Display (DQMD)*
- Compared with a reference histogram
  - flagged with different colours depending on the outcome of Kolmogorov-Smirnov

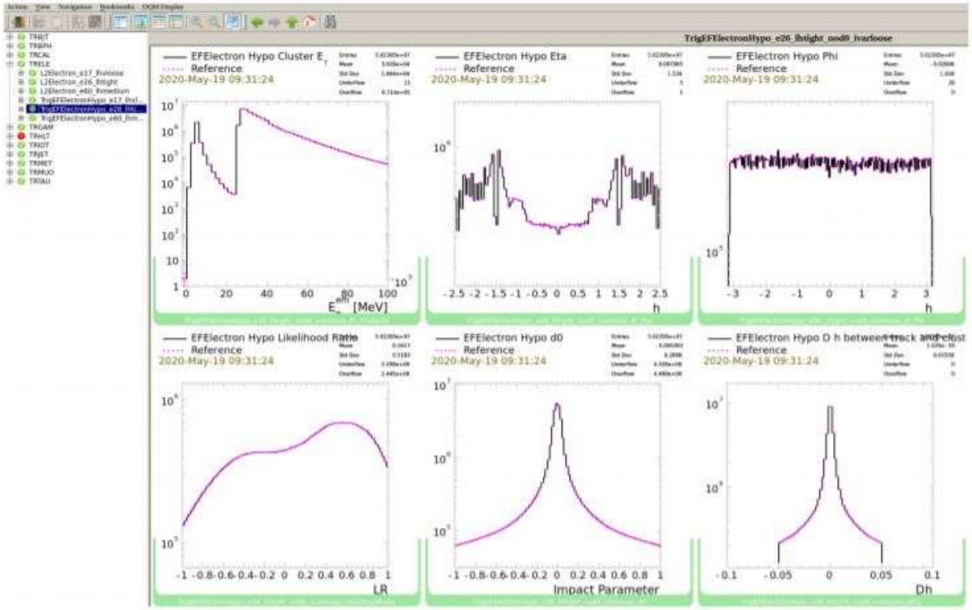


Figure 17: The Data Quality Monitoring (DQM) Display used for the HLT. The data (black) are compared to the reference (purple) using a Kolmogorov-Smirnov test to compare the shapes of the distributions. Based on the output of the comparison test, the histograms are flagged either green (good agreement with the reference), yellow (tolerable disagreement with the reference), or red (major disagreement with the reference).

Ch. 12: Online Monitoring

P-BEAST

- Web-based monitoring tool to monitor the system and debug problems
- Useful for displaying:
  - number of free processing slots in the HLT farm
  - memory usage
  - read-out request rates
  - luminosity
  - dead-times from detectors, etc.
- ***Shifter Assistant*** gives pop-up notification alerts of possible issues

Figure 18: An example of a P-BEAST dashboard as used by the shifters during 2017 operation. The HLT farm availability (top left), the luminosity and the pileup,"mu" (top right), the total L1 accept rate (bottom left), and the total HLT output bandwidth (bottom right) are shown.

Ch. 13: Offline Monitoring and Data Quality Assessment

- Additional data quality (DQ) assessment is carried out offline after the data is fully reconstructed
- Express stream is the main data stream used for the offline DQ assessment
  - fully reconstructed within a day after data is recorded
- Trigger chain performance is assessed by looking at a series of histograms
  - chosen to sample all relevant aspects of the particular trigger signature
- *Good Runs List (GRL):* list of all runs collected by ATLAS which are deemed good for physics analysis

Ch. 13: Offline Monitoring and Data Quality Assessment

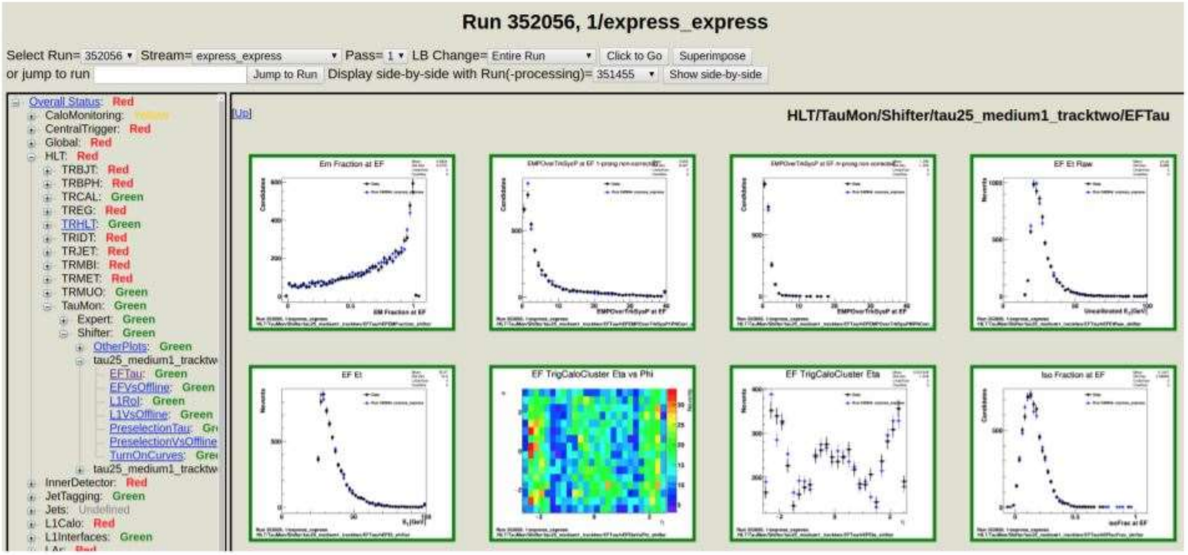


Figure 19: An example of the web-display for the offline DQ assessment. Shown here are various plots for hadronically decaying tau lepton candidates as reconstructed in the HLT. The data (black points) are compared with a reference (blue points), and flagged as green, yellow, or red depending on how well they agree, according to pre-defined algorithms. The reference run is updated periodically to reflect significant condition changes, such as updated trigger menus. This example shows run 352056 which was recorded in June 2018.