# TDAQ Phase-I Upgrade

*LHCC Meeting*

CERN
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***for the ATLAS Collaboration***

# Outline

- LHC assumptions, challenges, upgrade strategies
- Physics Motivation
- Level-1 Calorimeter trigger upgrade
- Level-1 Muon trigger upgrade
- Central Trigger
- Topological triggers
- High-Level Trigger and DAQ
- Update on FTK
- Summary and Conclusions

# LHC Assumptions

- Baseline for trigger resource planning, e.g. rates, is $L = 3 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- Pile-up of $\langle\mu\rangle = 81$
  - This is the readout limit for parts of the Inner Detector at 100 kHz
  - Subsystems must handle 100 kHz already during Run 2
- Energy of $\sqrt{s} = 14$ TeV
  - Cross sections for physics processes increase by factors of 2-3 (more for some jet rates)
- Assume similar duty cycle and fill profile to 2012, but have contingency plans (with loss of physics) for better machine performance

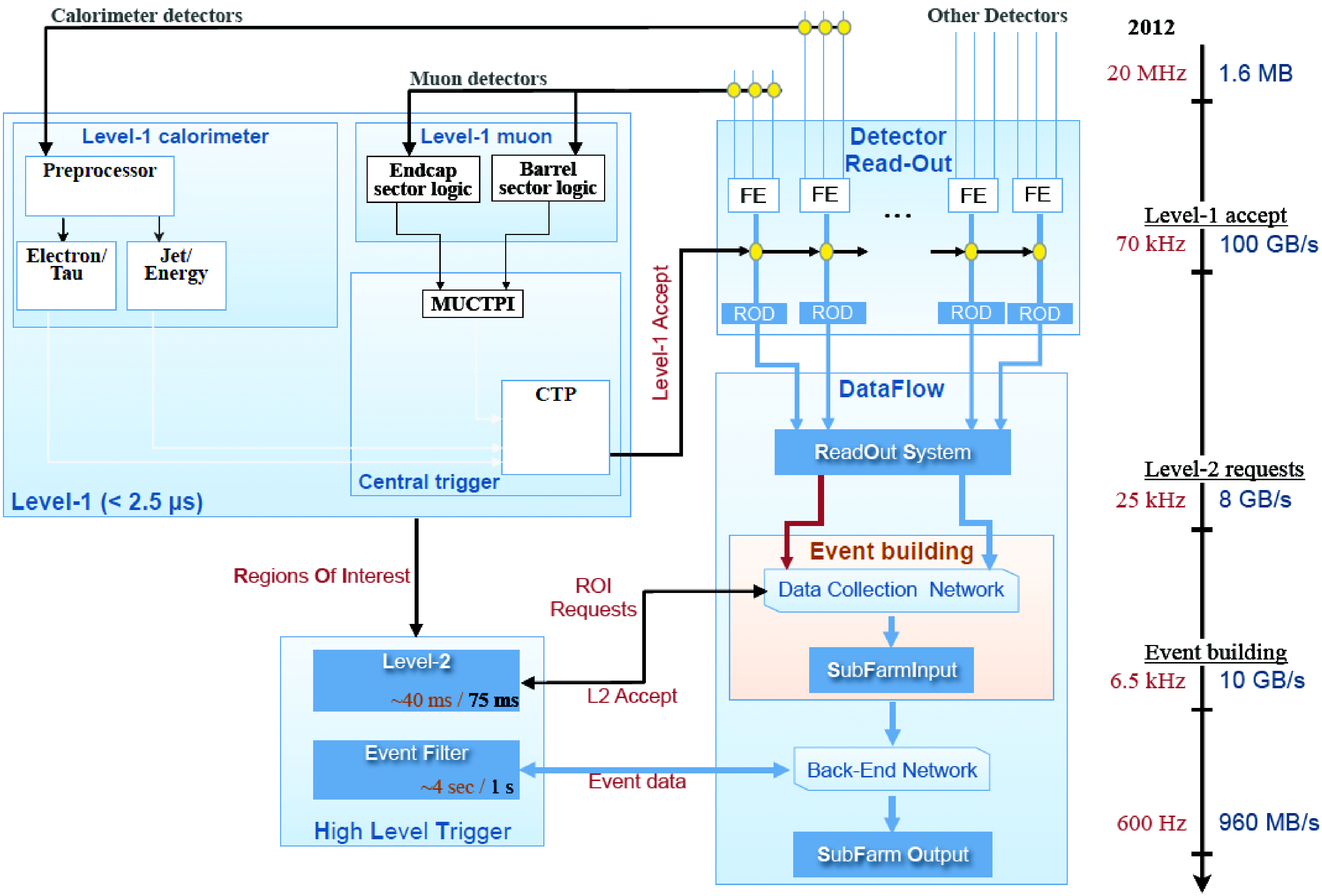
# Phase-I Challenges

- Higher pile-up (20~35 → 81) degrades calorimeter performance, softens turn-on curves, compromises isolation, resulting in higher trigger rates and lower efficiencies; increases HLT processing time
- Shorter bunch spacing (50ns → 25ns) increases out-of-time pile-up and fake beam-induced particle rates, e.g. in the muon detector
- As luminosity and cross-sections increase, (~10x) higher physics rates need to be handled by a much more selective Level 1 Trigger, and a High-Level Trigger (HLT) with significantly improved rejection power
- The current TDAQ system was conceived in the late 1990s, and operated until 2013 with only limited evolution in commercial hardware and no changes to custom electronics

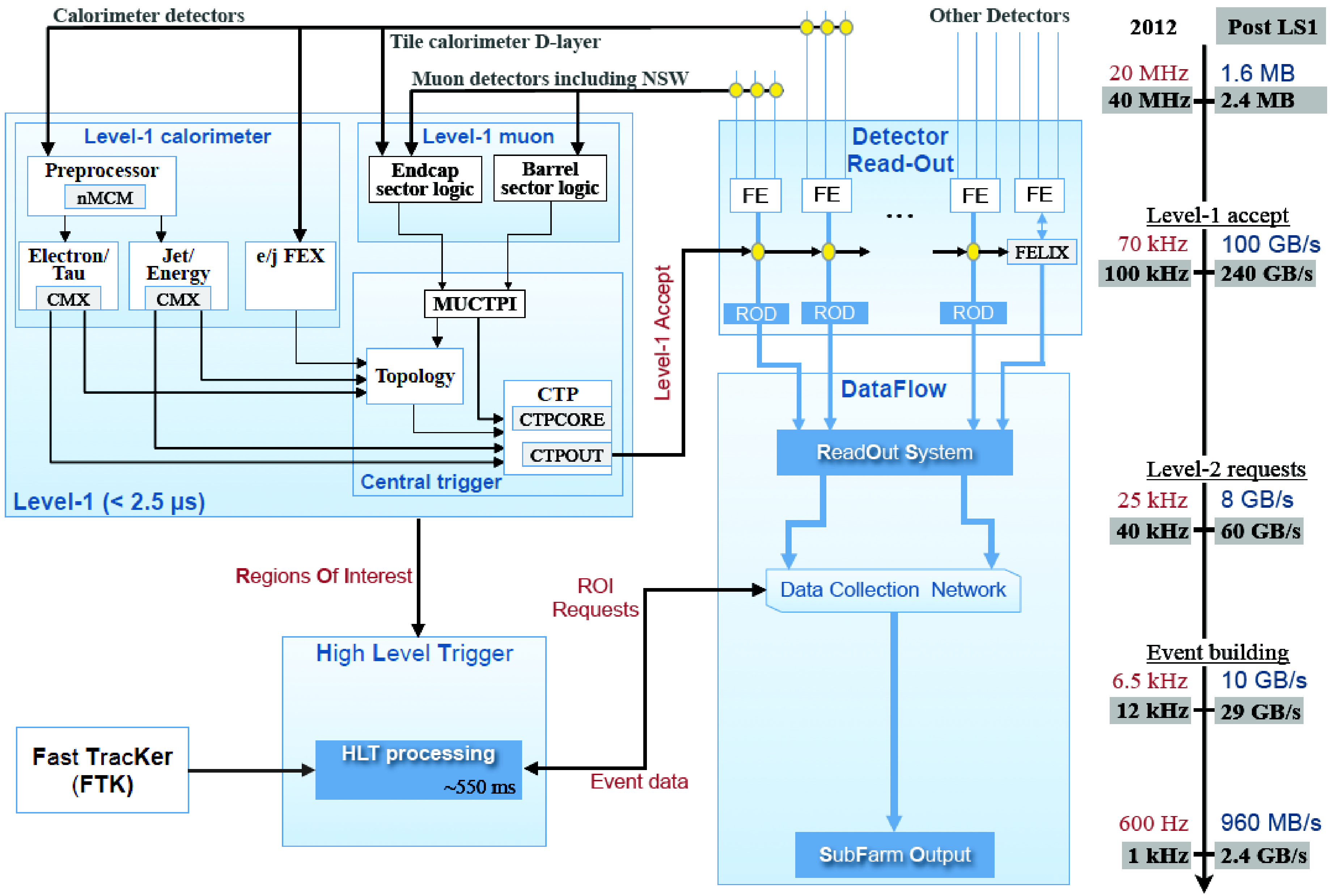
# Upgrade Strategies

- Make use of increased granularity of the LAr calorimeter data, going from 0.1 x 0.1 trigger towers to SuperCells, with new electromagnetic and jet processors (eFEX, jFEX)
- Integrate New Small Wheel in L1Muon trigger electronics, form coincidences between Big Wheel and muon inner stations and Tile calorimeter to suppress fake, beam-induced particle rates
- Improve physics coverage by complementing inclusive selections with more exclusive ones, e.g. topological trigger processor applying cuts on angles and invariant masses (that are now done offline)
- Apply more sophisticated algorithms and corrections in the HLT using fast (full event) hardware tracking (FTK) and full calorimeter read-out for a large fraction of events; use more offline algorithms
- Leverage technology advances of the past 15 years

# Run 1 TDAQ System



# Run 3 TDAQ System



# Upgraded Trigger Menus

- Staying efficient for single electrons and single muons at Level-1 covers
  - $H \rightarrow ZZ \rightarrow l\,l\,l\,l$
  - $H \rightarrow WW \rightarrow e\nu\ \mu\nu$
  - $WH \rightarrow e/\mu\ \nu\ b\ \bar{b}$
  - …
- Use di-object triggers for
  - $H \rightarrow \gamma\gamma$
  - $H$ + jet $\rightarrow \tau\ \tau$ + jet (VBF, ISR jet or associated production)
- With these modes covered, will be efficient for most exotic processes with leptons
- Use multi-object triggers and topological triggers to correlate objects and maintain a reasonably low $E_T^{miss}$ threshold

A principal goal for Run 2 and Run 3 is to measure the properties of the 125 GeV Higgs

# Example Level-1 Trigger Menus

*All rates calculated at 3 x$10^{34}$ cm$^{-2}$ s$^{-1}$*

| | Run 1 | Offline $p_T$ Threshold [GeV] | Rate [kHz] | Run 2 | Offline $p_T$ Threshold [GeV] | Rate [kHz] | Run 3 | Offline $p_T$ Threshold [GeV] | Rate [kHz] |
|---|---|---|---|---|---|---|---|---|---|
| e | EM18VH | 25 | 130 | EM30VHI | 38 | 14 | EM25VHR | 32 | 14 |
| | EM30 | 37 | 61 | EM80 | 100 | 2.5 | EM80 | 100 | 2.5 |
| | 2EM10 | 2x17 | 168 | 2EM15VH I | 2x22 | 2.9 | 2EM12VHR | 2x19 | 5.0 |
| | **EM total** | | **270** | | | **18** | | | **20** |
| μ | MU15 | 25 | 150 | MU20 | 25 | 28 | MU20 | 25 | 15 |
| | 2MU10 | 2x12 | 14 | 2MU11 | 2x12 | 4.0 | 2MU11 | 2x12 | 4.0 |
| | **Muon total** | | **164** | | | **32** | | | **19** |
| e,μ | EM10VH_MU6 | 17,6 | 22 | EM15VH_MU10 | 22,12 | 3.0 | EM10VHR_MU10 | 17,12 | 3.0 |
| | | | | EM10H_2MU6 | 17,2x6 | 2.5 | EM10HR_2MU6 | 17,2x6 | 1.0 |
| tau | TAU40 | 100 | 52 | TAU80V | 180 | 4.7 | TAU80VR | 180 | 3.2 |
| | | | | 2TAU50V | 2x110 | 3.8 | 2TAU40VR | 2x100 | 3.9 |
| | 2TAU11I_TAU15 | 30,40 | 147 | 2TAU20VI_3J20 | 2x50,60 | 5.2 | 2TAU15VR_3J15 | 2x40,50 | 8.1 |
| | 2TAU11I_EM14VH | 30,21 | 60 | 2TAU20VI_ EM18VHI_3J18 | 50,25,60 | 2.8 | 2TAU15VR_ EM13HR_3J13 | 40,20,50 | 3.3 |
| | | | | TAU15VI_MU15 | 40,20 | 3.8 | TAU11VR_MU11 | 35,12 | 6.4 |
| | TAU15_XE35 | 40,80 | 63 | TAU20VI_ XE40_3J20 | 50,90,60 | 4.4 | TAU15VR_ XE40_3J15 | 40,90,50 | 5.0 |
| | **Tau total** | | **238** | | | **20** | | | **25** |
| jet | J75 | 200 | 34 | J100 | 200 | 7.0 | J100 | 200 | 7.0 |
| | 4J15 | 4x55 | 87 | 4J25 | 4x60 | 3.3 | 4J25 | 4x60 | 3.3 |
| | | | | J75_XE40 | 150,150 | 8.3 | J75_XE40 | 150,150 | 8.3 |
| $E_T^{miss}$ | XE40 | 120 | 157 | XE90 | 250 | 10 | XE70 | 200 | 13 |
| | **Jet/$E_T^{miss}$ total**[a] | | **306** | | | **25** | | | **25** |
| | **Topological triggers** | | - | | | ~5 | | | ~20 |
| | **Total** | | ~800 | | | ~100 | | | ~100 |

**Phase-I**

**Significantly improved thresholds**

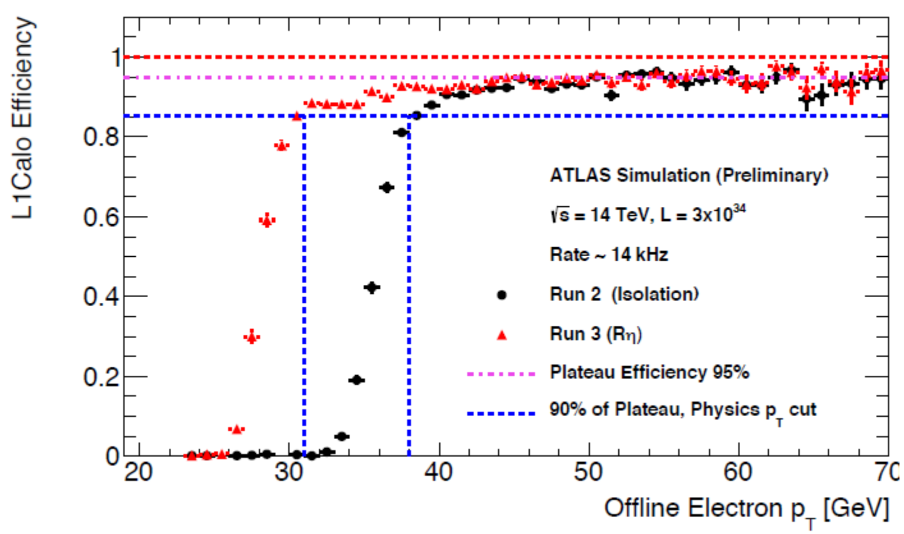
**~2x rate reduction from NSW in trigger**

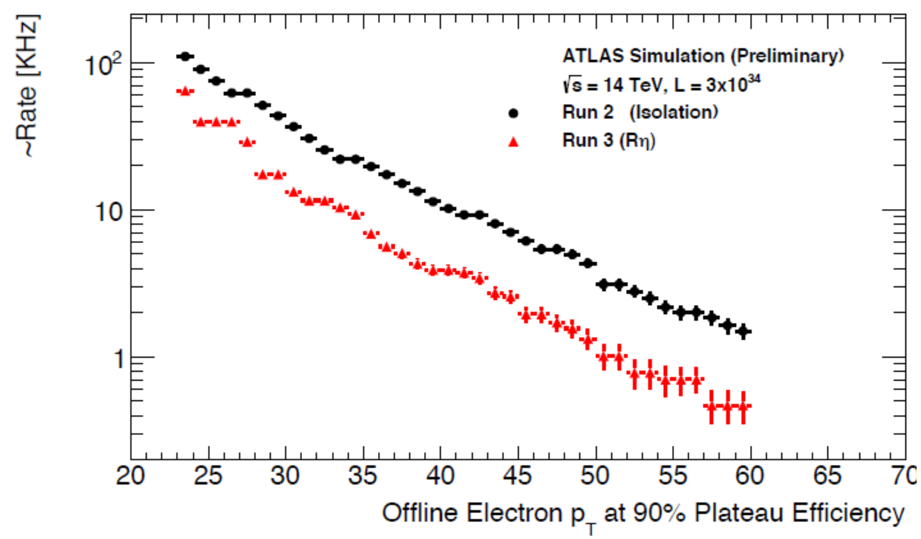
**Multiple lower thresholds**

**More room for topological triggers**

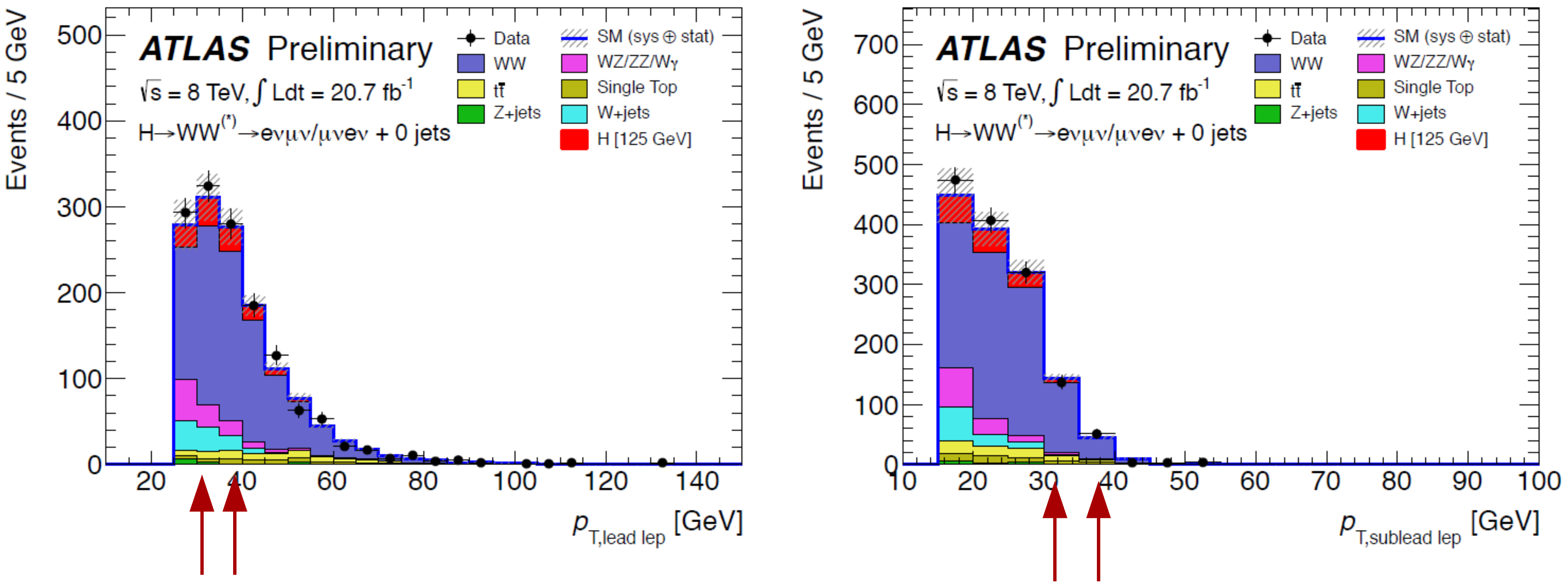
# Electron/Photon Rates

- With 0.1 x 0.1 trigger towers, EM isolation against energy deposits in the 12 towers surrounding a 0.2 x 0.2 core allows a 38 GeV threshold at 14 kHz, with 3% efficiency loss
- After Phase-I, can use $R_\eta$ (0.075 x 0.2 over 0.175 x 0.2) isolation:
  - At same rate: sharper turn-on curve and lower threshold of 32 GeV
  - At same efficiency: factor 2-3 lower rates
- More sophisticated shower shape requirements and energy weighting under study (*see Francesco's presentation of LAr TDR*)



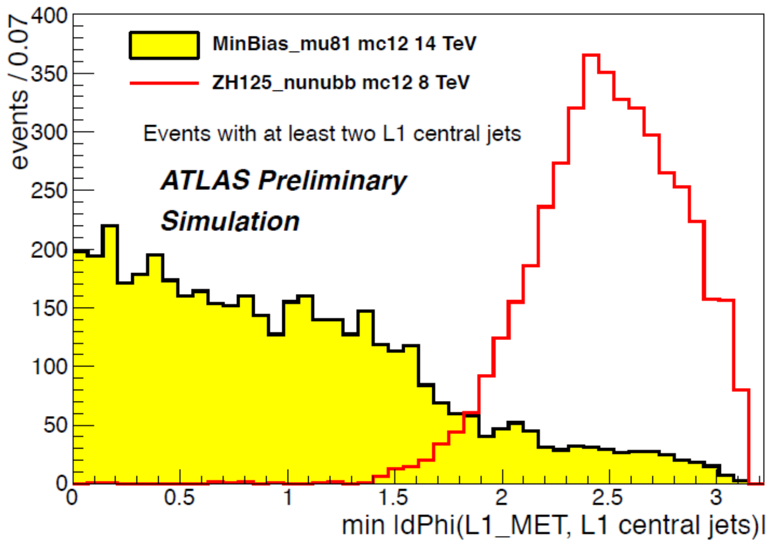



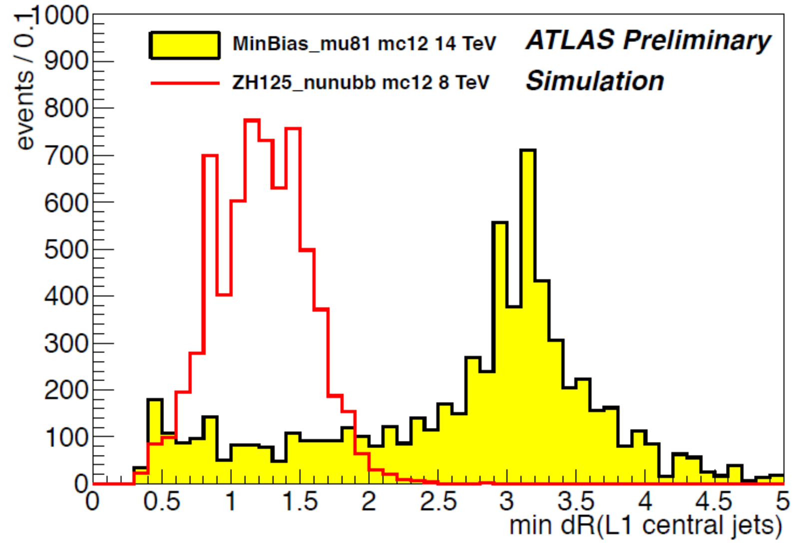
# Electron Thresholds Matter




- Without Phase-I upgrade, di-object triggers involving muons suffer from limited muon acceptance (72% in barrel)
- For example, in ***H → WW → eν μν*** , if leading lepton is electron, efficiency loss from lost muon is 25% if EM threshold is 38 GeV rather than 32 GeV
- 5 GeV shifts in EM thresholds occur close to peaks of the distribution
- Similar gains in many other channels

# Topological Triggering



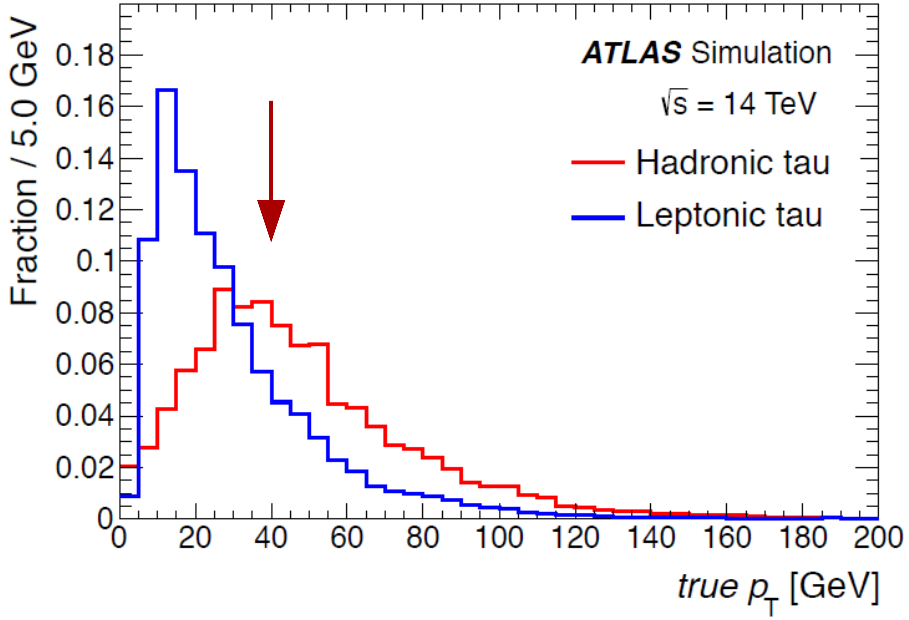



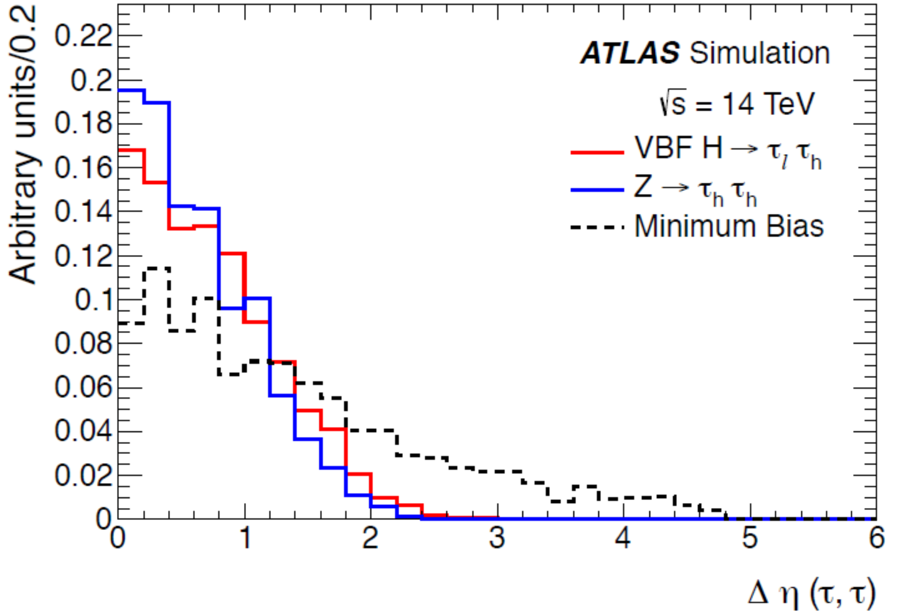

Example: exploit characteristic location of pile-up jets wrt $E_t^{miss}$ vector

- In Phase-I, ***ZH*** **→** $\boldsymbol{\nu\bar{\nu}b\bar{b}}$ with 160 GeV $E_T^{miss}$ trigger (XE40) would alone exceed total L1 rate due to pile-up jets faking missing energy
  - Increasing threshold rapidly costs signal efficiency
- Combination with inclusive jet trigger brings rate down to ~10 kHz (still too high)
- With L1Topo, a cut on azimuthal distance between jet and $E_T^{miss}$ ($\Delta\varphi > 1$) reduces rate by ~45% with negligible loss in signal efficiency
  - radial distance ($\Delta R$) cut could be used to further reduce rate

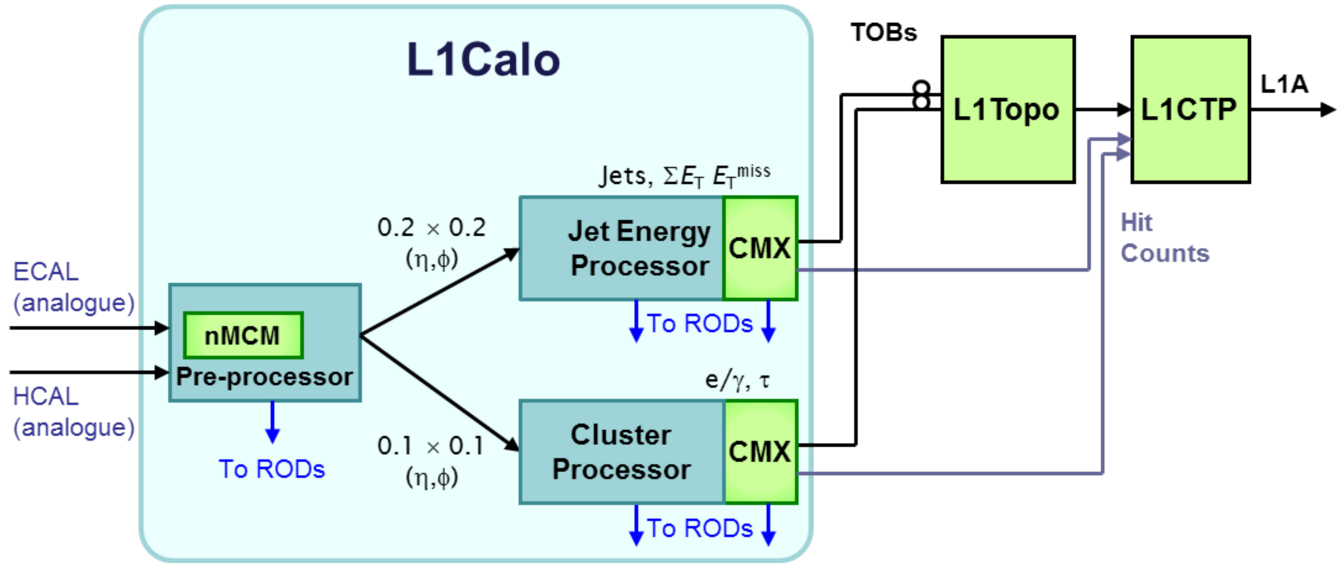
# Triggering on Taus

- Low-momentum thresholds also important for taus
- Phase-I upgrade allows hadronic tau thresholds to be reduced, e.g. from 50 to 40 GeV
- Near the peak of the true $p_T$ spectrum for example in VBF $H \rightarrow \tau\,\tau$
- Without Phase-I upgrade, efficiency loss for $e - \tau_{had}$ ($\mu - \tau_{had}$) final state is 37% (32%)
- Also, topological cut on $\Delta\eta < 2.0$ reduces rate by 25% with almost no signal loss



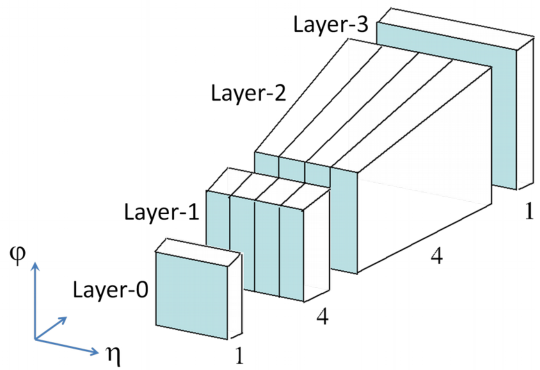



# L1Calo for Run2

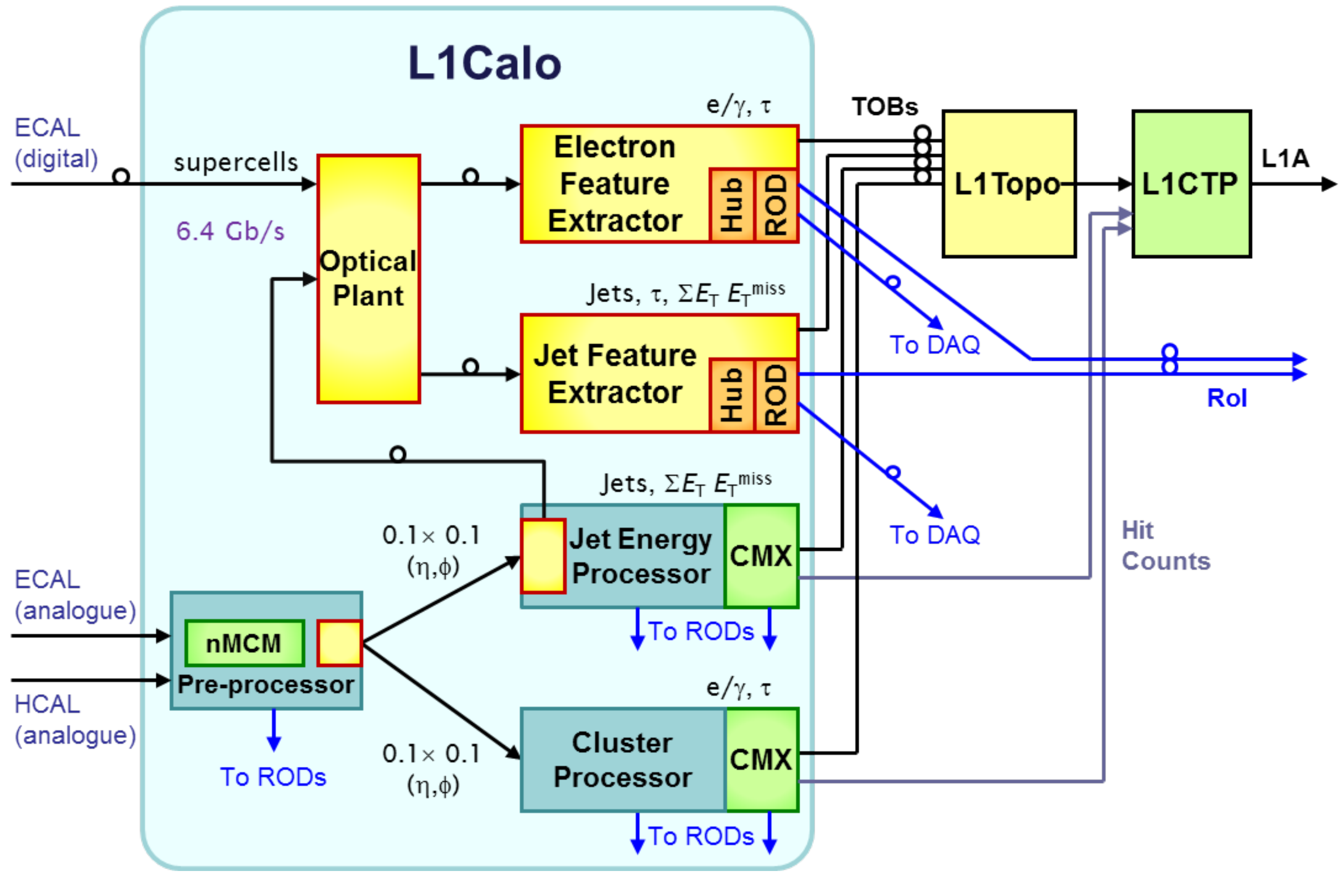



- Over this shutdown, L1Calo electronics is being upgraded for Run 2 and will make first use of Topological Trigger (L1Topo)
- Input signal digitization, calibration and filtering with new modules (nMCM) at 80 MHz, with lower noise and greater flexibility to handle pile-up; and separate *E* scales for *e/γ* and jets
- Output modules replaced with extended merger modules (CMX) that feed location, energy, object type and sums of $E_T$, $E_T^{miss}$ to L1Topo

# L1Calo Phase-I Upgrade




Each trigger tower segmented into 10 supercells, with 4 depth layers and 4 η strips in middle two

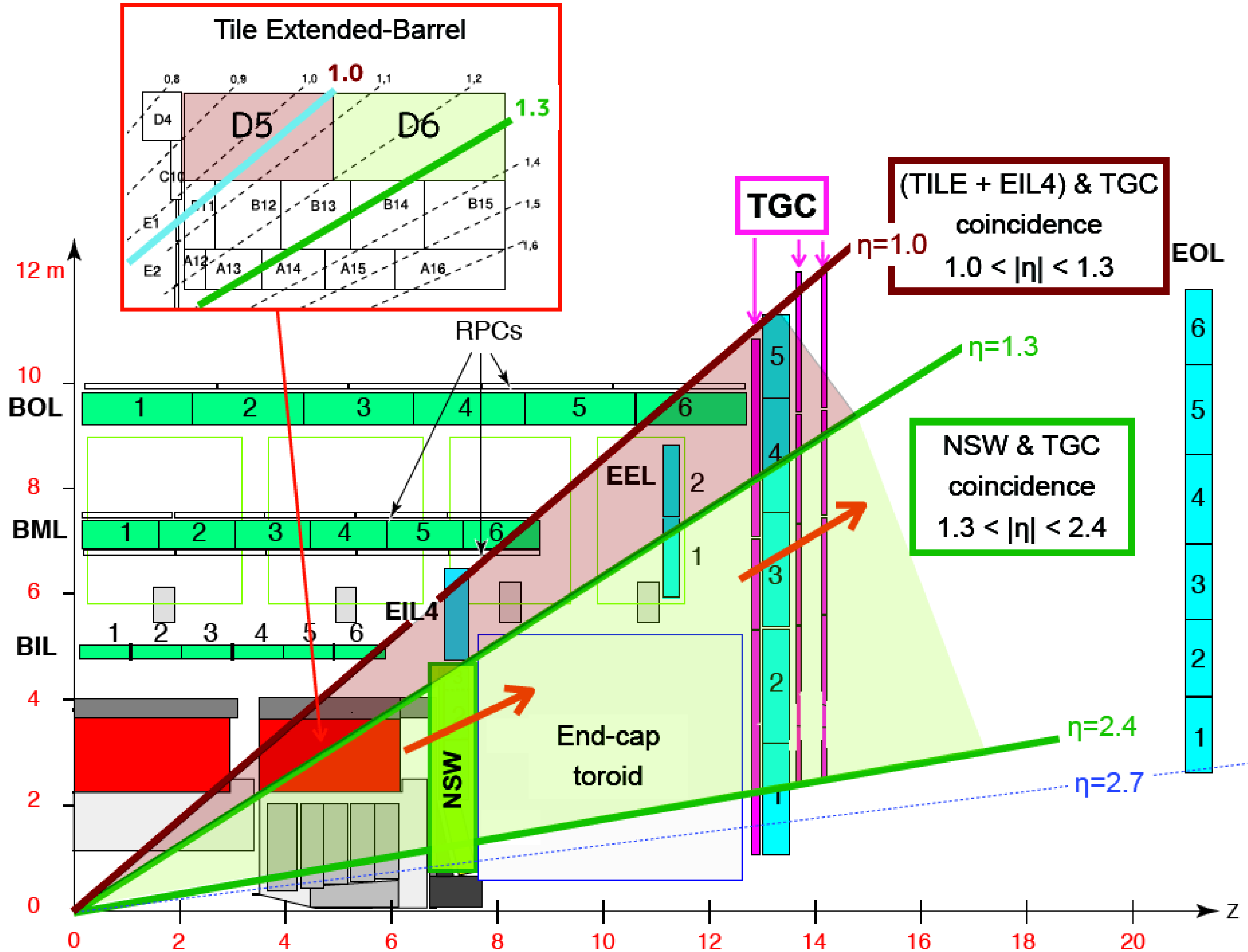



- New electron and jet feature extractor modules process digital SuperCell data, output to DAQ and L1Topo (directly)
- Analogue hadronic TileCal data are digitized in upgraded preprocessor -- with increased tower granularity (0.1 x 0.1) – and copied into the new system

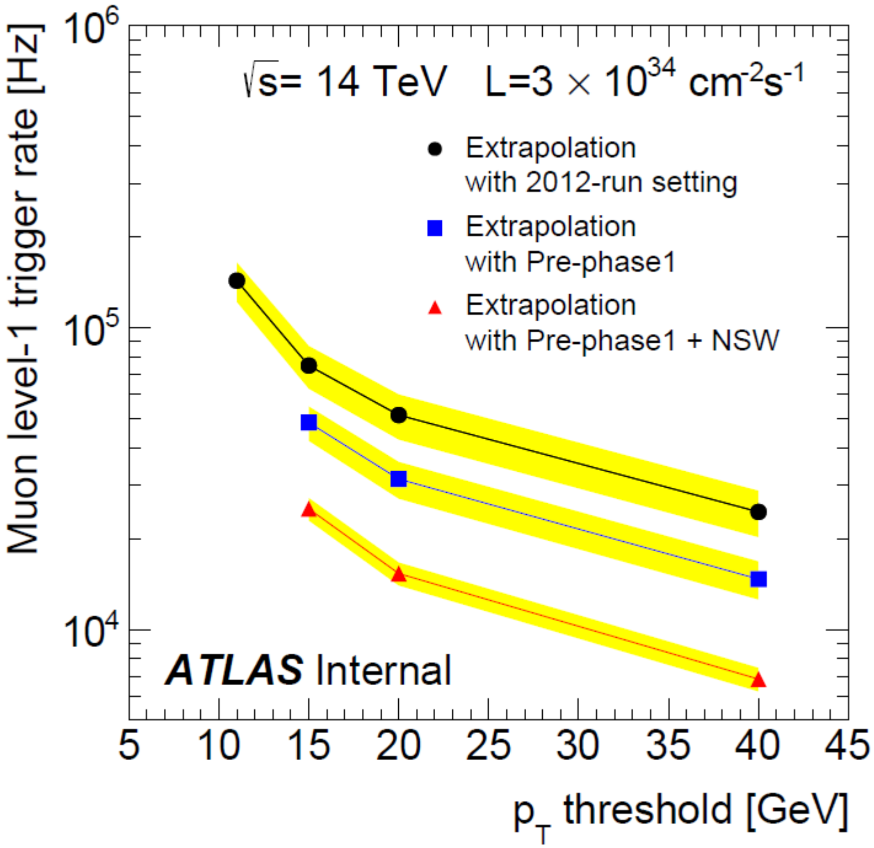
# eFEX and jFEX Processors

- eFEX feature extractor module for electrons/photons, taus
  - Processes SuperCells at full granularity, optimized for energy and spatial resolution, and improved isolation capability
- jFEX feature extractor for jets, taus, $\Sigma E_{\mathrm{T}}$, $E_{\mathrm{t}}^{\mathrm{miss}}$
  - Processes trigger towers, but at higher granularity than the current system (0.1 x 0.1 within $|\eta| < 2.5$, 0.2 x 0.2 outside, coarser again in FCAL)
  - Adds $|\eta|$ segmentation in the FCAL
  - Like eFEX, four times finer digital scale (250 MeV/count) allows to resolve small signals (~2 GeV) from noise
- gFEX ("global") is an optional additional processor for large area jets with an even wider range of up to 1.8 x 1.8 which would allow event-by-event local pile-up corrections

# Muon Trigger Coincidences



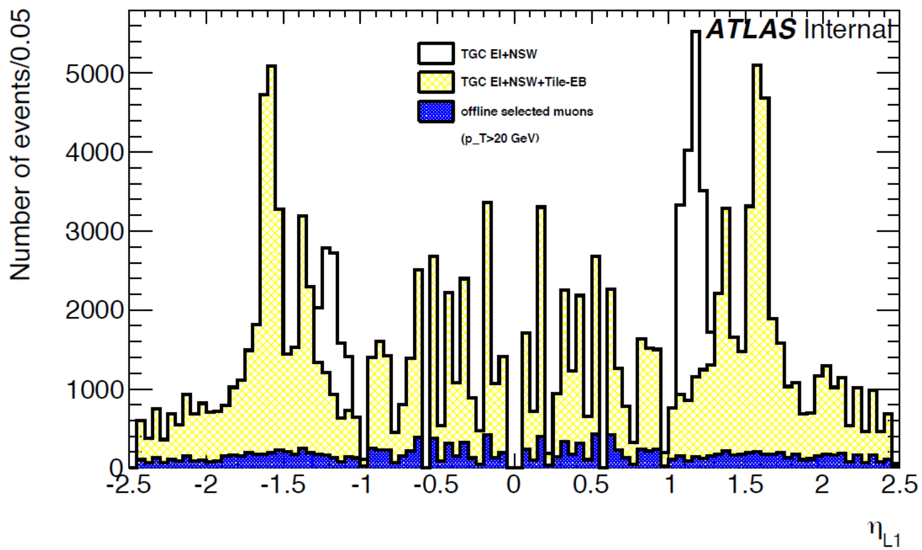
# Muon Trigger Rates

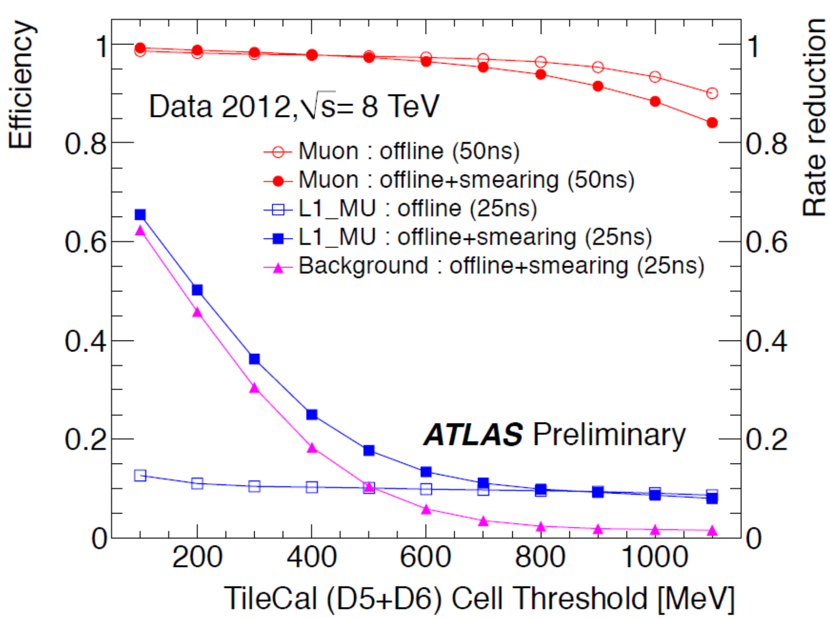



- Backgrounds 40% worse at 25 ns
- Raising threshold cannot help due to limited $p_T$ resolution
- NSW has a dramatic effect in cutting overall fake rates in half
- 13 kHz gain in bandwidth for other triggers

| Online $p_T > 20$ GeV $3\times10^{34}$ cm$^{-2}$s$^{-1}$ | No Change Rate [kHz] | TGC EIL4 + (TGC FI or NSW) Rate [kHz] | TGC EIL4 + (TGC FI or NSW) + Tile Cal. Rate [kHz] | TGC EIL4 + ( TGC FI or NSW) + Tile Cal. + low field mask Rate [kHz] |
|---|---|---|---|---|
| Run 2 (pre NSW) | 51 | 34 | 31 | 28 |
| Run 3 (post NSW) | | 17 | 15 | 13 |

# Tile Muon Trigger




- Main source of fake triggers are low-momentum protons emanating from endcap toroid and shielding
- $1.0 < |\eta| < 1.3$ region of Big Wheel TGC not covered by the NSW
- Use hadronic TileCal extended barrel (D-layer) for trigger coincidence
- Energy resolution smeared by electronics noise in Level-1 read-out path lowers efficiency above 500 MeV
- Tile Muon coincidence reduces rate by 82% at that threshold

# Muon Sector Logic and CTP Interface

- New Sector Logic boards are being built that receive all old and new inputs, wire and strip ($R$,$\varphi$) data from the BW-TGC as well as track information from the NSW ($R$,$\varphi$,$\delta\theta$)
- Current system does not have enough inputs to receive the NSW signals
- A new MUCTPI with more inputs will use optical links to receive the muon sector logic data and send detailed ROI information to L1Topo at 40 MHz
- The Sector Logic of the muon barrel will also be rebuilt to be able to fit the optical inputs of the new MUCTPI
- The core of the Central Trigger Processor will be upgraded to double the available inputs to up to 512 distinct triggers, generating more flexibility, e.g. making room for more topological triggers

# Online and HLT Software

- Improved HLT algorithms are crucial to maintain rejection in spite of much more selective Level-1
- Much work ongoing to incorporate FTK; optimize steering and menus; adopt more CPU intensive offline techniques
- Adapt to new software framework jointly developed with offline for future many-core CPUs and co-processors; exploit growing parallelism
- Evaluate new technologies, review online software infrastructure

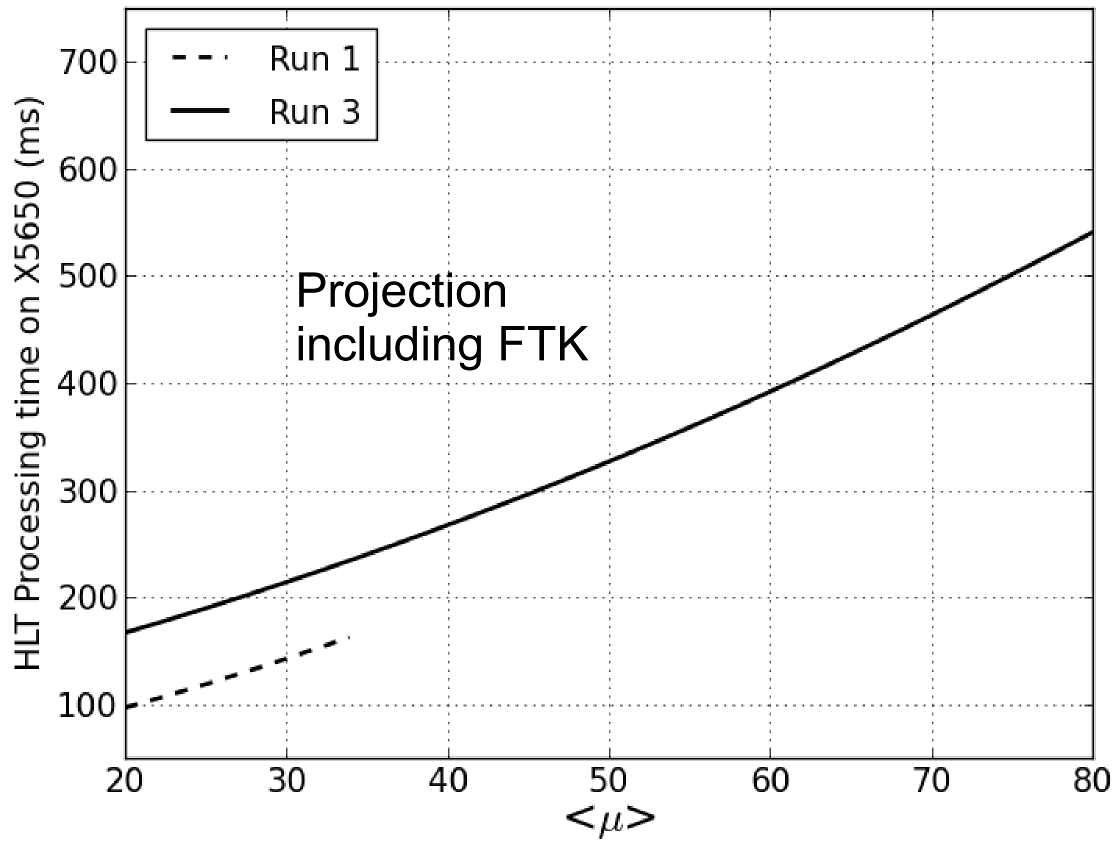
- A major effort: 50% of the total ~300 FTE years through 2018
  - Total breaks down to 0.5-1.0 FTE per institute over 5 years
- Tight connection with needed HLT compute power

| **Work package** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **Total** |
|---|---|---|---|---|---|---|---|
| Trigger | | | | | | | |
| Core software | 2.1 | 3.9 | 6.5 | 9.3 | 8.5 | 4.3 | 34.6 |
| Evaluate and exploit new technologies | 1.6 | 1.1 | 2.0 | 3.0 | 3.0 | 1.5 | 12.2 |
| Menus & algorithms | 3.0 | 3.0 | 7.5 | 9.5 | 13.0 | 12.0 | 48.0 |
| Simulation | 1.5 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 7.8 |
| Online | | | | | | | |
| HLT Processing Unit | 0.0 | 0.0 | 1.0 | 0.5 | 0.4 | 0.4 | 2.3 |
| Core Software, Infrastructure | 0.0 | 1.0 | 1.0 | 3.0 | 4.0 | 1.0 | 10.0 |
| Configuration, Control, Monitoring | 0.0 | 1.0 | 2.5 | 7.3 | 6.0 | 0.3 | 17.0 |
| Dataflow, Event Format | 0.0 | 0.0 | 1.2 | 2.4 | 3.4 | 1.2 | 8.2 |
| Detector Software and Tools | 0.0 | 0.0 | 0.5 | 1.0 | 3.0 | 1.5 | 6.0 |
| Evaluate and exploit new technologies | 0.0 | 0.5 | 1.0 | 1.0 | 1.0 | 0.5 | 4.0 |
| Totals | 8.2 | 9.8 | 24.4 | 38.3 | 43.6 | 24.0 | 150.1 |

# HLT Processing Time

- CPU usage is dominated by software tracking (pattern recognition)
- Higher in Phase-I with enriched physics sample after Level-1
- Non-linear increase with pile-up
- Estimate a factor of ~5 overall (c.f. today's CPU)
- Need 30,000 cores with compute power anticipated to be available in LS2

| | Tracking | Calorimetry | Muon | Other |
|---|---|---|---|---|
| Level-2 | 73 | 17 | 7 | 3 |
| Event Filter | 52 | 24 | 16 | 8 |

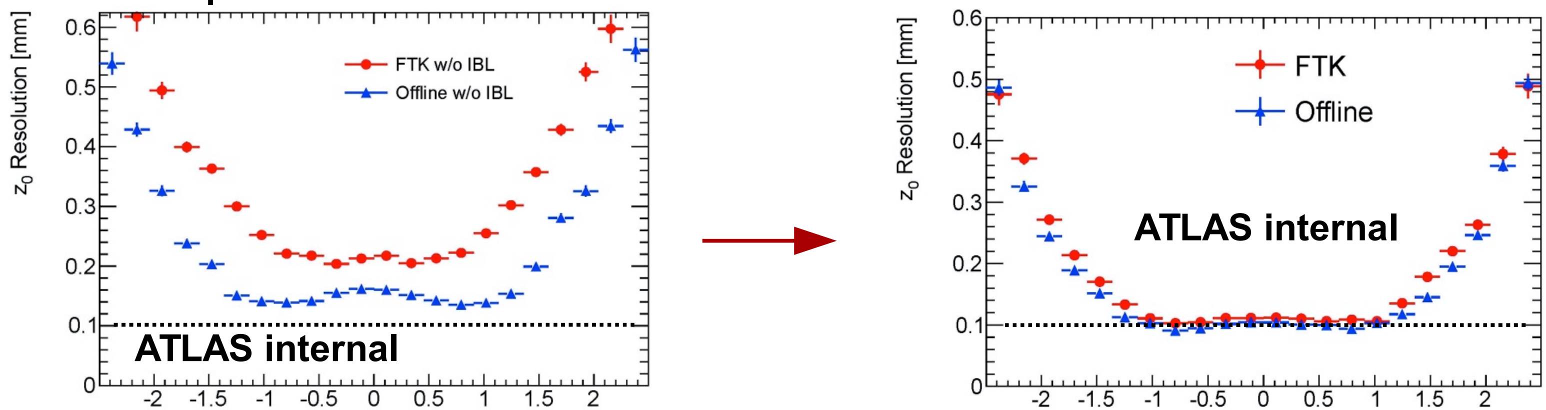


# Update on FTK

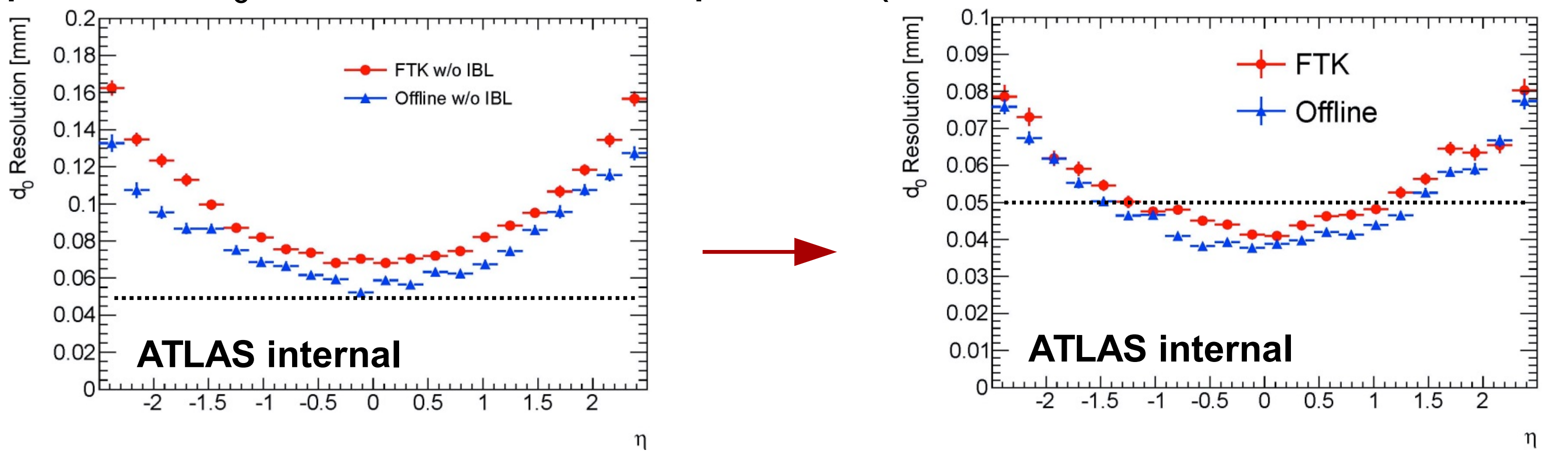
- At the June LHCC meeting there were a few outstanding issues:
  - FTK $z_0$ resolution was considerably worse than offline
    - Thought to be a problem with the pixel clustering
    - Expected to find the problem and solve it
  - Samples with the Insertable B-Layer (IBL) implemented weren't available
    - Still had to show that FTK works with IBL
    - Expected the performance to improve, especially when impact parameter is important

# $z_0$ Resolution

- Improvements:
  - Correct handling of pixels of different lengths
  - Implemented simple time-over-threshold weighting of hits in cluster
  - Now samples are with IBL



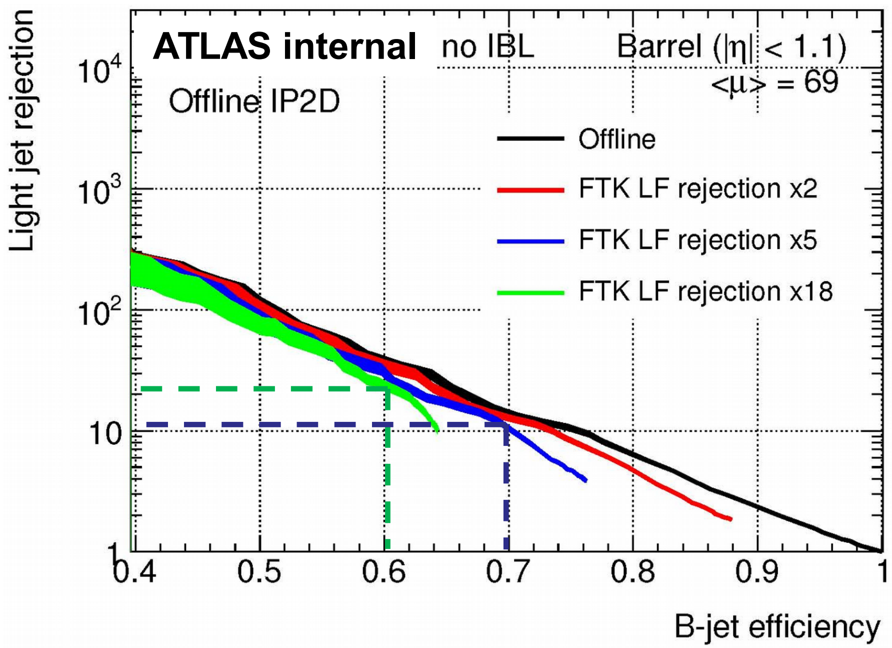

- As expected, $d_0$ resolution also improves (vertical scales are different)



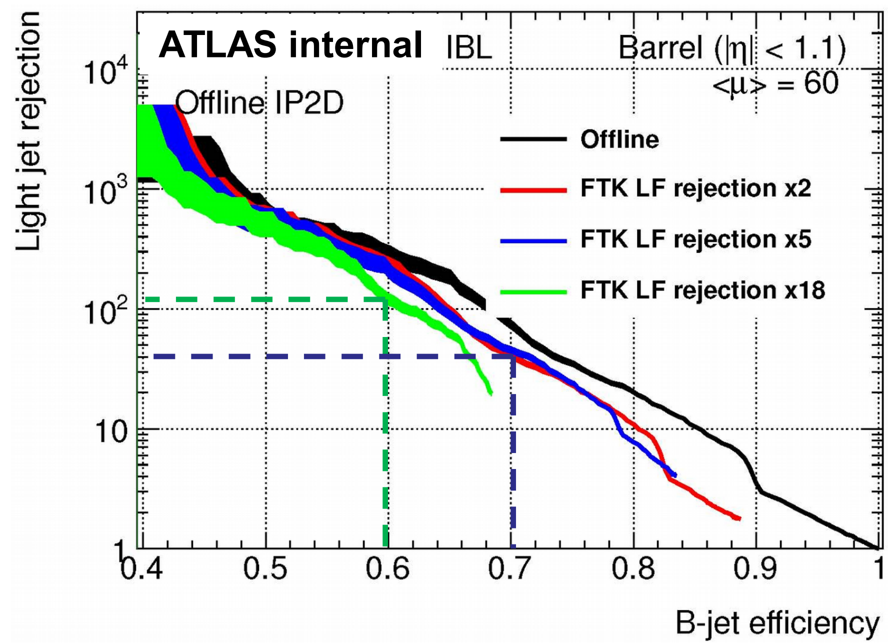
# *b*-Tagging with FTK

- Better performance with better impact parameter resolution (FTK and offline)

*Without IBL*




*With IBL*



# Summary

- The Phase-I Upgrade of the TDAQ system will allow ATLAS to efficiently trigger and record data at up to 3 times design luminosity
- New calorimeter feature extraction modules will be built to process finer granularity LAr data
  - Improved lepton and jet selections, and pile-up corrections for missing energy triggers
- The NSW will be included in the muon endcap trigger and dramatically reduce rates by eliminating fake triggers
  - Adding TileCal signals will improve the barrel/endcap overlap region
- A new muon-to-CTP interface allows for muon and calorimeter objects to be combined in new topological trigger processor
- The HLT farm will be upgraded to handle full calorimeter read-out on a large fraction of the 100 kHz rate and make full use of the Fast Tracker
- Improved Dataflow software and HLT algorithms will allow the logging rate to be controlled to stay below 1 kHz

# Conclusion

- The design presented in the TDR provides ATLAS with a robust configuration for high-luminosity running up to $3 \times 10^{34}\ cm^{-2}\ s^{-1}$, enabling the experiment to take full advantage of the accelerator upgrades

# Backup

# Core Cost of the TDAQ Upgrade

| WBS | System | CORE (kCHF) | Possible addition | Common items | CORE Cost per year (kCHF) 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Central Trigger** | | | | | | | | | |
| 1.1 | Central Trigger Processor | 90.0 | | | 90.0 | | | | | |
| 1.2 | Topology | 503.1 | | | 63.6 | 219.4 | | | 220.1 | |
| 1.3 | MUCTPI | 342.0 | | | | | | | 342.0 | |
| 2 | **Level-1 Calo** | | | | | | | | | |
| 2.1 | eFEX system | 1,370.0 | | | 147.3 | 147.3 | 294.6 | 339.0 | 294.6 | 147.3 |
| 2.2 | jFEX system | 786.5 | | | | | | 371.1 | 415.5 | |
| 2.3 | optional gFEX system | | 389.3 | | | | | | | |
| 2.4 | Hub, ROD & optical plant | 700.5 | 53.7 | | | | 18.0 | 270.5 | 412.0 | |
| 2.5 | Tile Input | 139.5 | | | 3.1 | 3.1 | 6.1 | 118.1 | 6.1 | 3.1 |
| 2.6 | PreProcessor (nMCM) | 500.0 | | | 400.0 | 100.0 | | | | |
| 2.7 | Extended Merger Module (CMX) | 153.6 | | | 75.1 | 120.2 | | | | |
| 3 | **Level-1 Muon** | | | | | | | | | |
| 3.1 | Endcap Sector Logic | 500.0 | | | | | 30.0 | 325.0 | 135.0 | 10.0 |
| 3.2 | Tile D-layer muon interface | 264.8 | | | | 264.8 | | | | |
| 3.3 | NSW Trigger Processor | 679.7 | | | | | | 214.2 | 444.1 | |
| 3.4 | Barrel MUCTPI interface | 72.8 | | | | | | | 72.8 | |
| 4 | **DAQ/HLT** | | | | | | | | | |
| 4.1 | Dataflow (see note 1) | 1,219.4 | | | | | | 853.6 | 365.8 | |
| 4.3 | HLT compute power | | | 3,208.3 | | | | | | |
| | **Total** | 7,321.9 | 443.0 | 3,2083 | 779.1 | 845.8 | 348.7 | 2,675.0 | 2,913.6 | 160.4 |