JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Phase-1 Upgrade of the ATLAS Level-1 Calorimeter Trigger

EPS-HEP 2025

Marseille, 08.07.2025

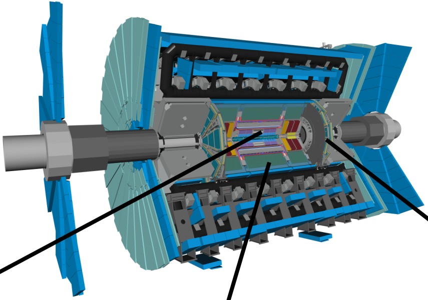
Ralf Gugel (JGU Mainz)
on behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

Gefördert durch:
Bundesministerium für Forschung, Technologie und Raumfahrt

ATLAS in Run 3

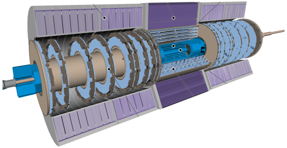
Spanning decades of evolving technology,



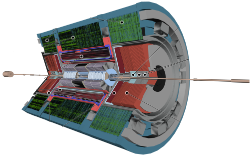
10 - 20 years old

partially upgraded

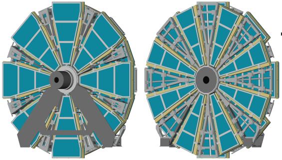
new



Inner Trackers



Calorimeters



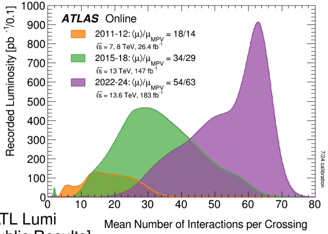
[JINST 19 P05063]

New Small Wheels

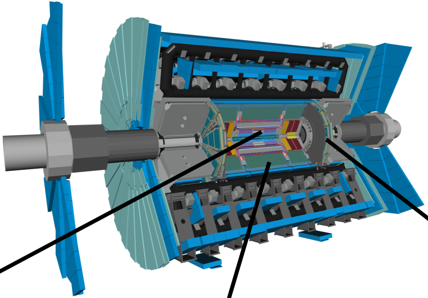
ATLAS in Run 3

Spanning decades of evolving technology,

experimental conditions,



[ATL Lumi Public Results]



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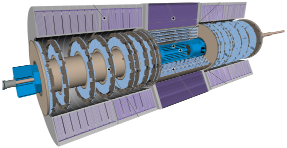

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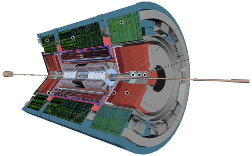
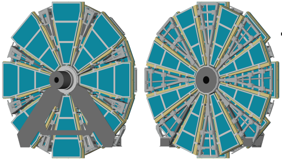


Calorimeters



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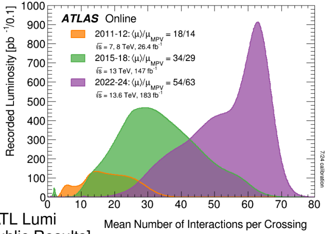

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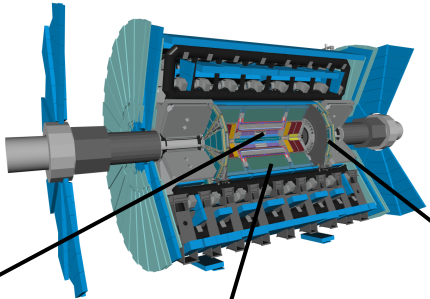


opportunities & challenges

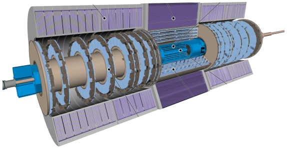
+ signal events

! background events

! event complexity

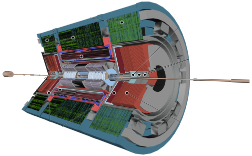
! legacy systems

10 - 20 years old



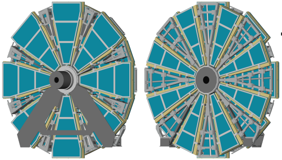
Inner Trackers

partially upgraded



Calorimeters

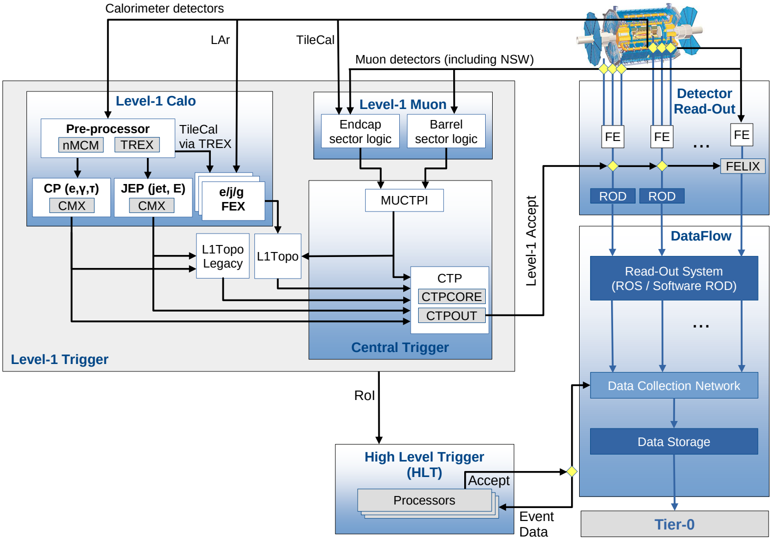
new



New Small Wheels

[JINST 19 P05063]

ATLAS TDAQ in Run 3



[JINST 19 P06029]

collisions @ 40 MHz

Level-1

limiting: FE buffers
→ hard real-time
latency: $\lesssim 2.5\,\mu s$

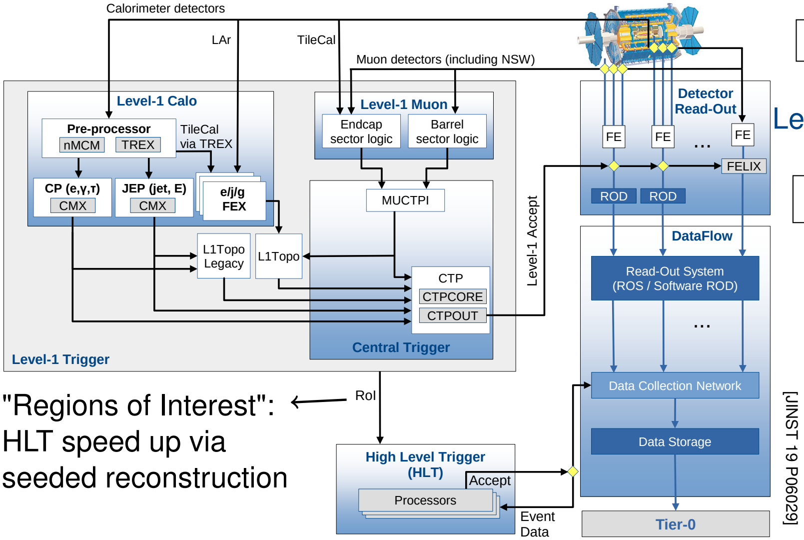
L1Accept @ 100 kHz

HLT

limiting: CPU cores & readout buffers
→ soft real-time
avg. latency: $\mathcal{O}(1\,\mathrm{s})$

recording ~ 3 kHz

ATLAS TDAQ in Run 3



"Regions of Interest": ← RoI
HLT speed up via
seeded reconstruction

collisions @ 40 MHz

Level-1

limiting: FE buffers
→ hard real-time
latency: $\lesssim 2.5\,\mu s$

L1Accept @ 100 kHz

HLT

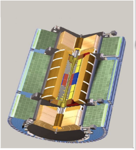
limiting: CPU cores & readout buffers
→ soft real-time
avg. latency: $\mathcal{O}(1\,\mathrm{s})$

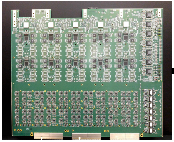
recording $\sim 3\,\mathrm{kHz}$

Calorimeter-side Upgrades

Liquid **Ar**gon calorimeter:

- EM calorimetry ($|\eta| \lesssim 1.6$)
  EM+had ($|\eta| \gtrsim 1.6$)
- Legacy: analog electrical
  → L1Calo trigger (off detector)
- Phase 1: on-detector digitization
  → off-detector processing (energy, timing)
- Simultaneous operation during commissioning

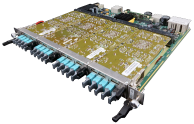




LAr trig. digitizer board (on detector)

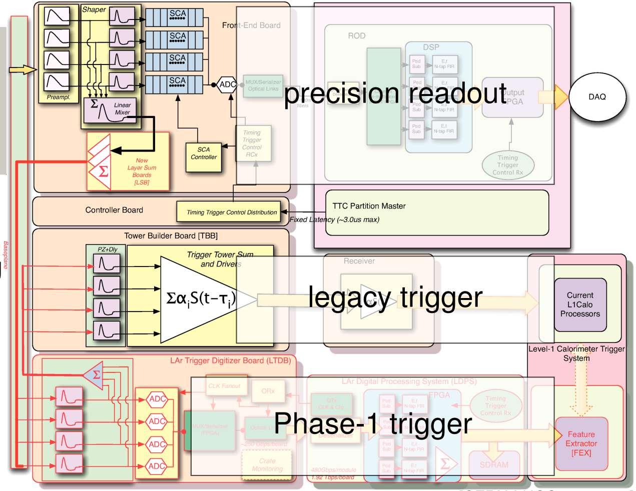
optical fibers

~ 25 Tbps



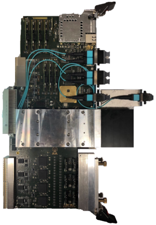
LAr trig. processing board (off detector)

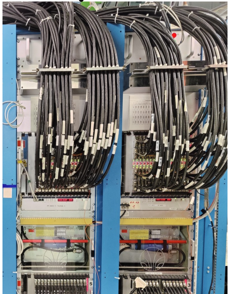
[photos courtesy of LAr team]



[CERN-LHCC-2013-017]

Level-1 Calorimeter Trigger: Inputs

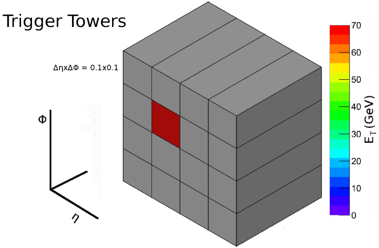




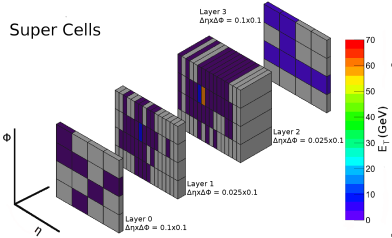
- **T**ile **R**ear **EX**tension for legacy pre-processors $\rightarrow$ fiber-optical inputs for Ph-1 **F**eature **EX**tractors

- Digital inputs from LAr $\rightarrow 10\times$ increased granularity

Tile / legacy LAr granularity
$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ *Trigger Towers*



Phase-1 LAr (EM) granularity
10 *Super Cells* per Trigger Tower



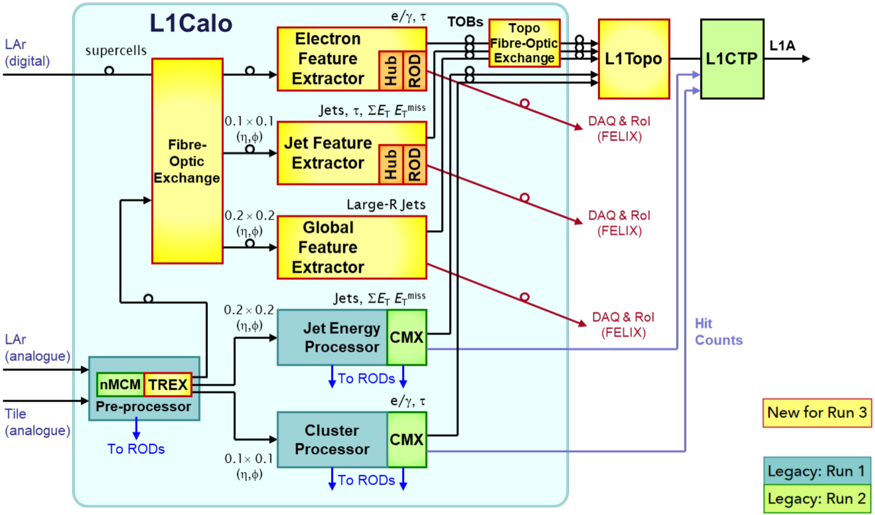
[CERN-LHCC-2013-017]

L1Calo Phase-1 Upgrade

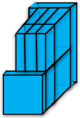
Feature **EX**tractors (FEXes)

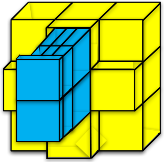
replacing

Jet & Cluster Processors

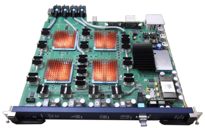
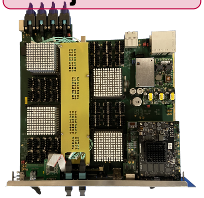
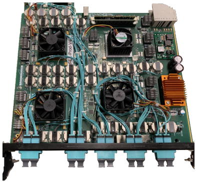


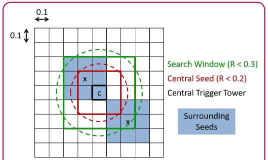
L1Calo Feature EXtractors



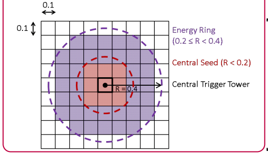


eEM E_T & hadronic isolation

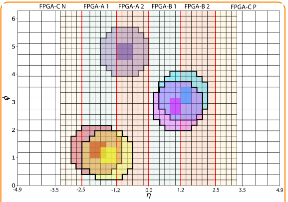
	electromagnetic **e**FEX	*jet* **j**FEX	*global* **g**FEX
			
	higher granularity ⟷		larger coverage & algorithmic windows
$\Delta\eta \times \Delta\phi$ (EM cal.)	0.025×0.1	0.1×0.1	0.2×0.2
max. $\|\eta\|$ (core)	≤ 2.5	≤ 4.9	≤ 4.9
trigger objects (TOB)	e/γ, τ_{had}	jets, τ_{had}, E_T^{miss}, $\sum E_T$, $e/\gamma_{\|\eta\|>2.5}$	large jets, E_T^{miss}, $\sum E_T$
main FPGAs	XC7VX550T ×96	XCVU9P ×24	XCVU9P ×3
#LUT/FPGA	346k	1 182k	1 182k
input bw/board	$\sim$ 1.4 Tbps (×24)	$\sim$ 2.2 Tbps (×6)	$\sim$ 3.4 Tbps (×1)



jJet seeding & shape ($R \sim 0.4$)

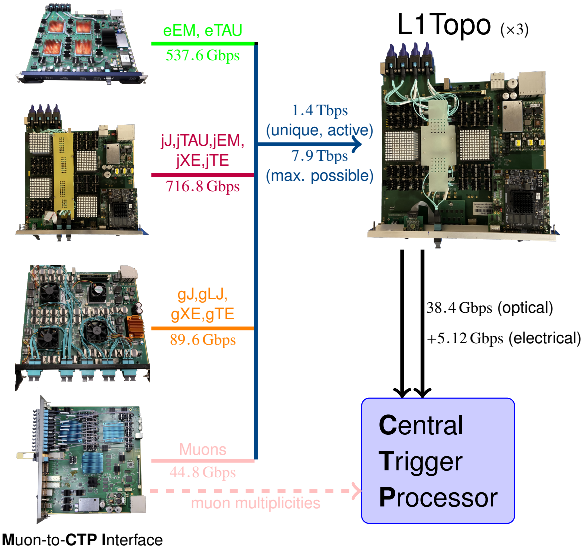


[JINST 19 P05063]

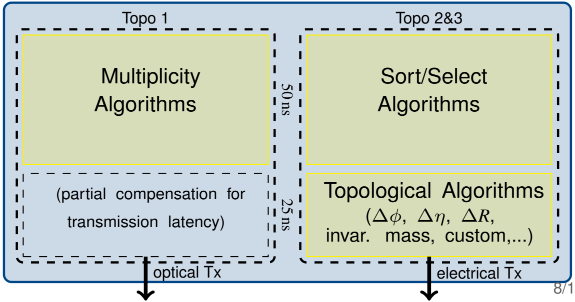


gLargeJet examples ($R \sim 0.8$)

L1Topo



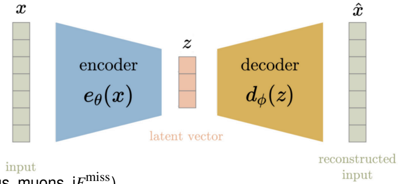
- jFEX-derived HW design, 3×2 FPGAs
- Different input composition per FPGA
  → maximize possible combinations
- Algorithmic firmware composition derived from (L1) Trigger Menu
  "Topo Converter": JSON → VHDL
- ~ 200 results/event



Algorithmic Examples: ML/AI

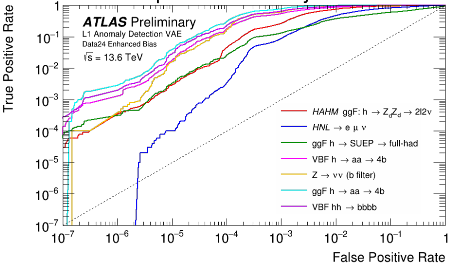
Real-time ML inference in ultra-low latency systems

- L1Topo: Anomaly detection w/ variational auto encoder
- [HLS4ML] + Vitis™ HLS
- Latent space based discriminant → inference w/o decoder part
- Inputs: $(E_T, \eta, \phi) \times 15$ TOBs (jJets, eTaus, muons, jE_T^{miss}) → 3 layer MLP & $\sum \mu^2_{\text{latent}}$ in $\leq 25\,\text{ns}$

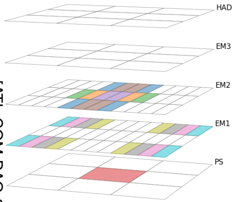


- eFEX: hadronic τ ID using BDT
- FW implementation via [Conifer] + Vitis™ HLS
- Resources & latency $\lesssim$ heuristic alternative

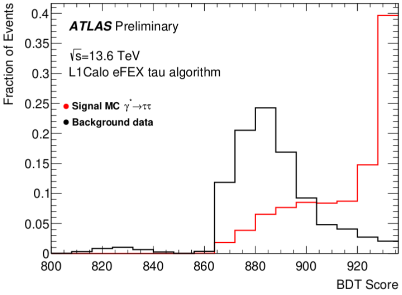
ROC examples for Anomaly Detection



[ATL-COM-DAQ-2025-039]



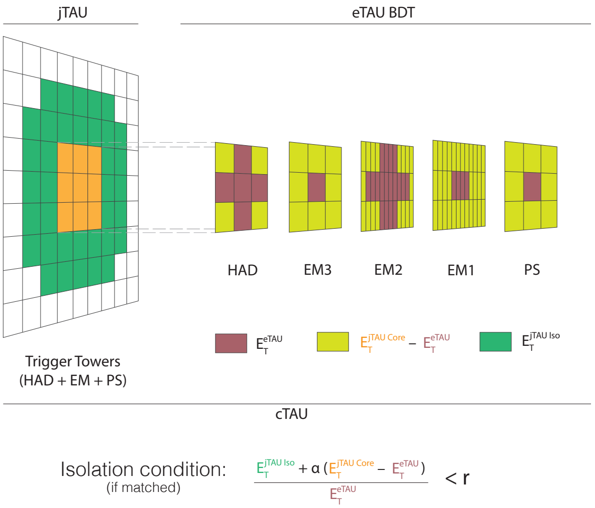
Cells summed for eTAU BDT inputs



[L1CaloPublicPlots]

Algorithmic Examples: "combined" TAU

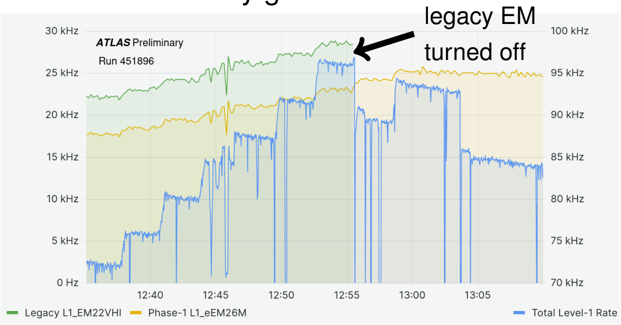
- eFEX:
  high granularity, small windows
  → E_T & BDT working point (0/L/M/T)
- jFEX:
  moderate granularity, large windows
  → E_T & E_T^{iso}
- L1Topo: combine eTAU + jTAU = cTAU
  → coordinate-based matching
- wide-area isolation & eTAU BDT
  for cTAU multiplicities

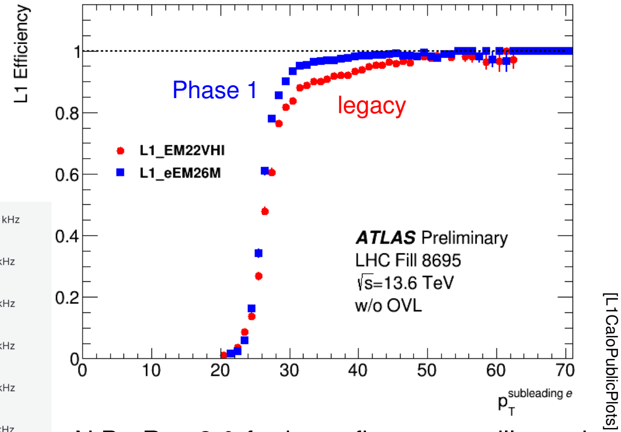


[courtesy of J.-Y. Beaucamp]

Performance: eFEX

- June'23: LHC intensity ramp-up, ATLAS nearing 100 kHz L1 rate
- eEM (Ph-1) replacing EM (legacy)
- ~ 5 kHz saving at L1
- Sizable efficiency gains!

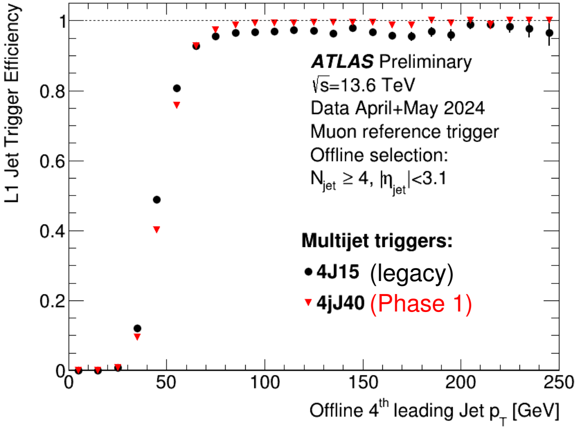




N.B.: Run 3 & further refinements still ongoing, results here = snapshots

Performance: jFEX

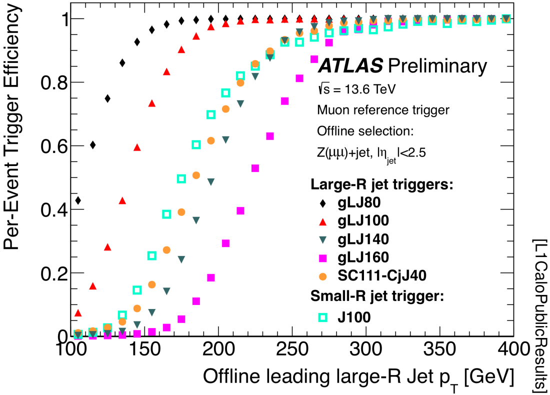
- jets: η-dependent calibration
  → sharpened turn-ons
- Multijet: resolving nearby jets
  → same rate, better pleateau efficiency
- E_T^{miss}: per-event pile-up density estimate & correction



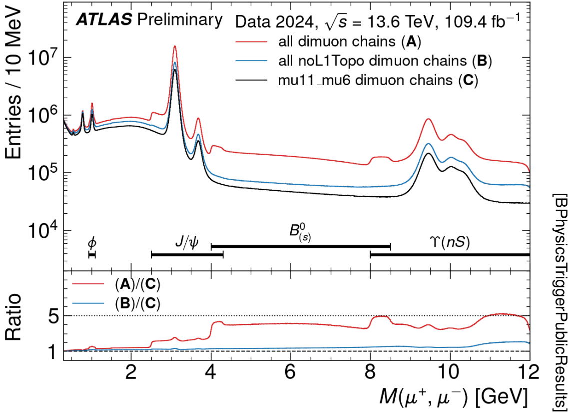
[JetTriggerPublicResults]

Performance: gFEX, jFEX, L1Topo

- HLT large radius jet chains seeded from
  - J100, jJ160 (leg./Ph-1 single jet)
  - gLJ140 (gFEX large-R jets)
  - SC111 (jJets reclustered @ L1Topo)
- Dedicated large-R triggers → earlier plateau, small additional rate
- Performance depends on topology (e.g. N_{subjets})



- Lowering (di)muon thresholds → rapidly increasing trigger rate
- Mitigation: L1Topo based selections using $M_{\mu\mu}, \Delta R_{\mu\mu}$
- Greatly enhanced dataset!

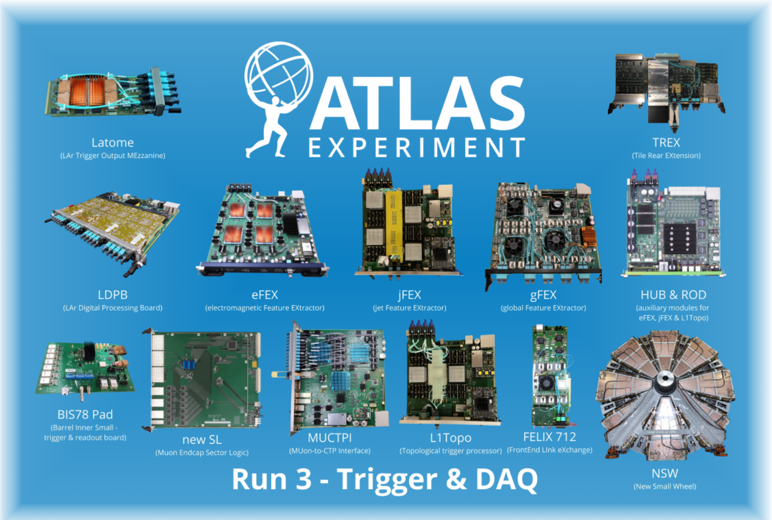


Conclusions

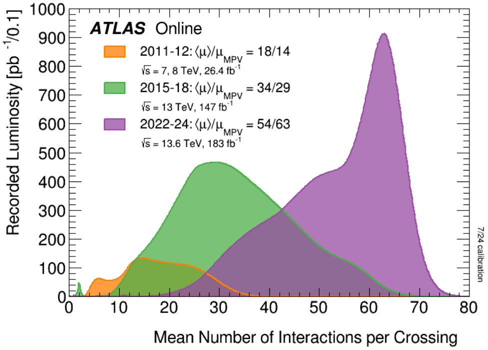
- Overview of ATLAS Phase-1 L1 Calorimeter trigger system & preliminary performance
- Crucial improvements to fully exploit LHC Run 3
- Important milestone towards Phase-2 / HL-LHC

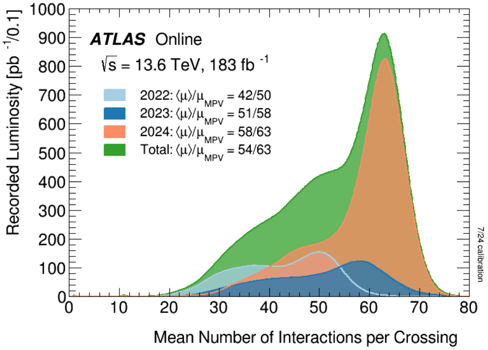
Thanks for your Attention!

Part of a larger Phase-1 Upgrade family



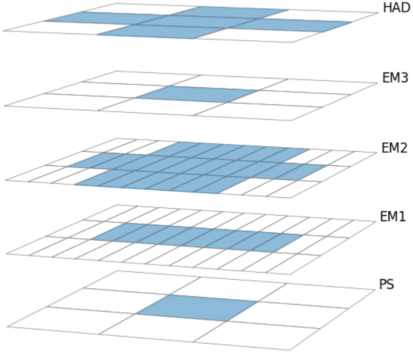
Pileup Evolution Runs 1-3

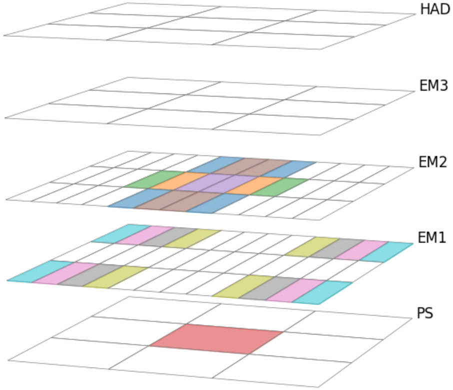




[ATL Lumi Public Results]

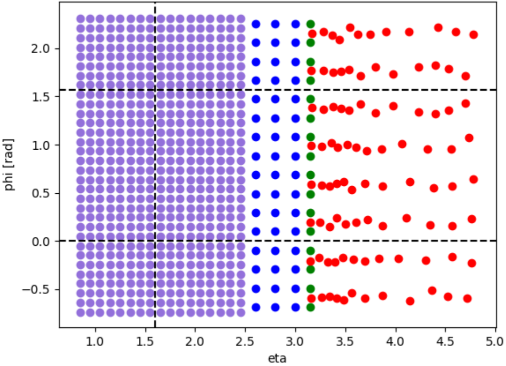
eFEX eTAU E_T and BDT Input Sums





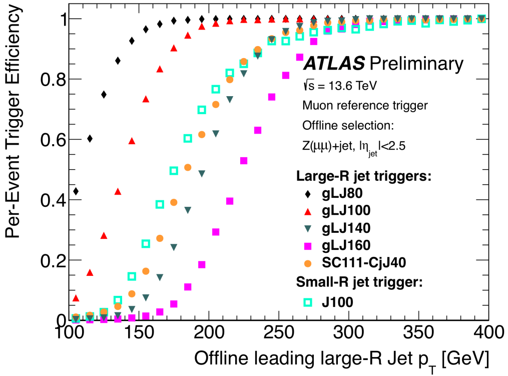
[L1CaloPublicPlots]

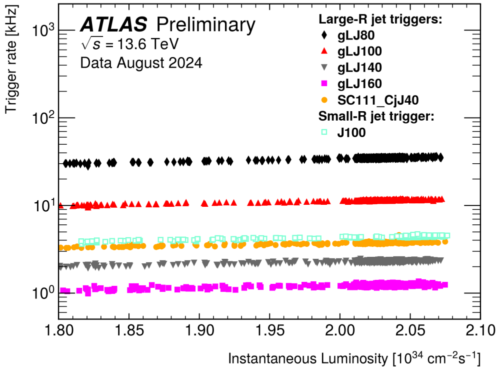
jFEX Input Granularity



[JINST 19 P05063]

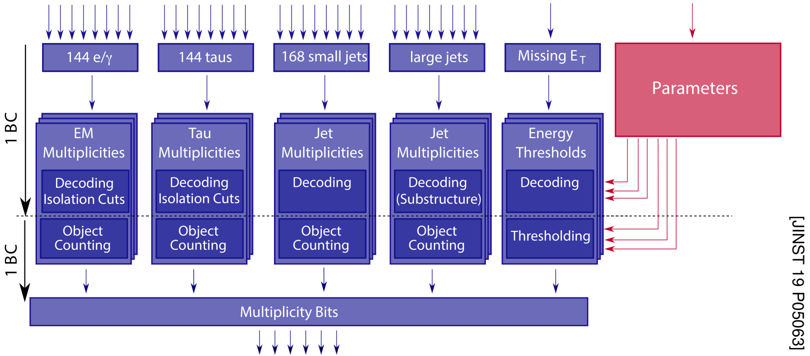
Large-R Jet Efficiency & Rate vs Luminosity



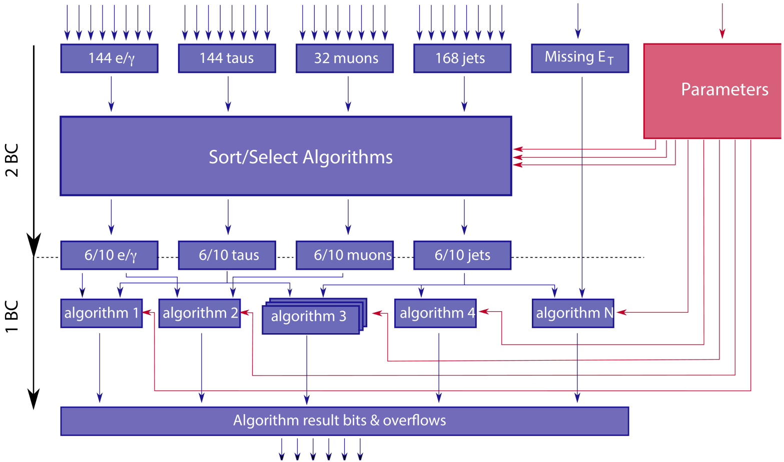


[L1CaloPublicPlots]

L1Topo Multiplicity FW Structure



L1Topo Topological FW Structure



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