Triggering on Long-Lived Particles in the Upgraded ATLAS Detector

Anthony Carroll
University of Oregon
Brookhaven Forum 2025

Overview

Introduction to Long-Lived Particles

LHC/ATLAS Trigger system

LLP Detector Signals

Phase-I upgrades to the calorimeter trigger: gFEX

Emerging Jets Trigger

Phase-II Global Trigger Upgrade

What is a Long-Lived Particle?

The probability that a particle will decay at a time t is given by an exponential distribution

$$P(t) = e^{-t/\tau}$$

Where τ is the mean proper lifetime of the particle

Several factors can contribute to a particle having a large lifetime

- Decays via a heavy particle
- Limited decay phase space
- Small couplings

LLPs arise in many theoretical models

Detector "Long Lived"

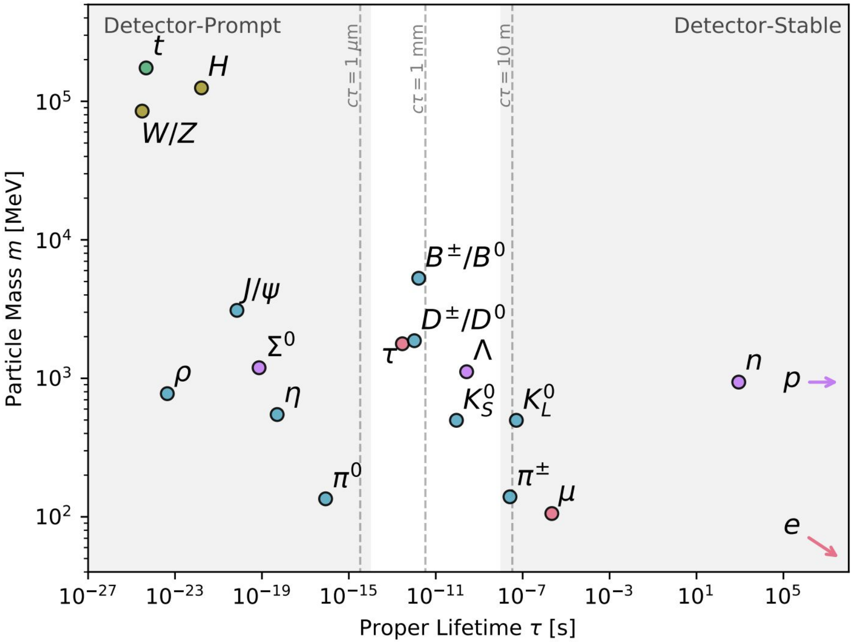


Figure from [1]

Some Canonical Standard Model LLP Examples

Decays via a heavy particle

- Muons decay primarily to an electron and two neutrinos via a W Boson

Limited decay phase space

- K short (long) commonly decays to two (three) pions
- $m_K - m_{2(3)\pi} \approx 220\ (80)$ MeV

Small couplings

- B quarks within a B meson decay via a W Boson and c quark, which is suppressed by an off diagonal CKM Matrix element

Detector "Long Lived"

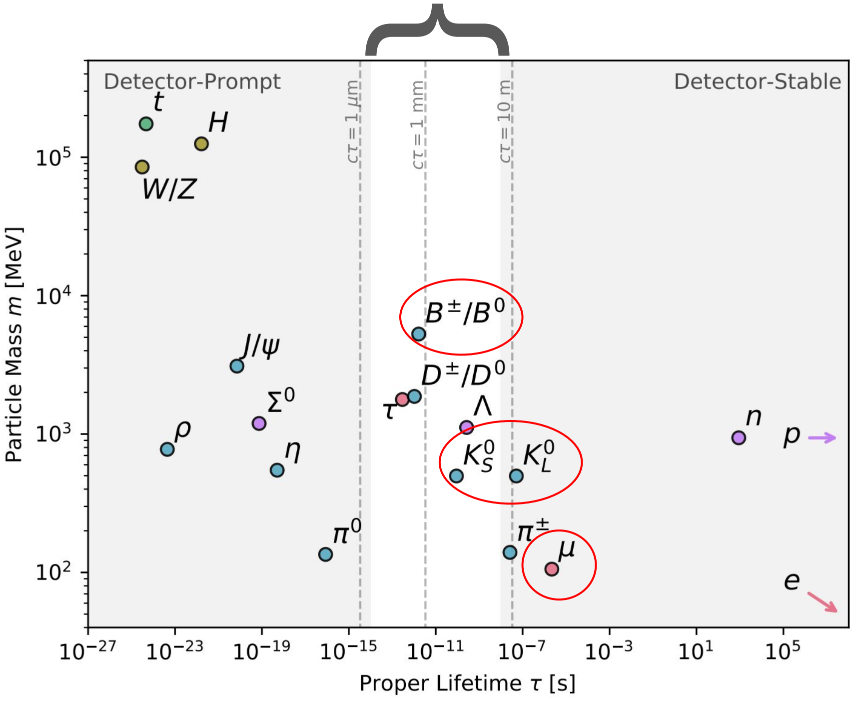


Figure from [1]

The ATLAS Detector at the LHC

ATLAS is a general purpose detector, one of the 4 main experiments at CERN's Large Hadron Collider (LHC)

Covers almost all of the solid angle around the LHC beam collision point

Comprised of

- Inner Detector
- Liquid Argon Electromagnetic Calorimeter
- Steel/Scintillator Tile Hadronic Calorimeter
- Muon Spectrometer

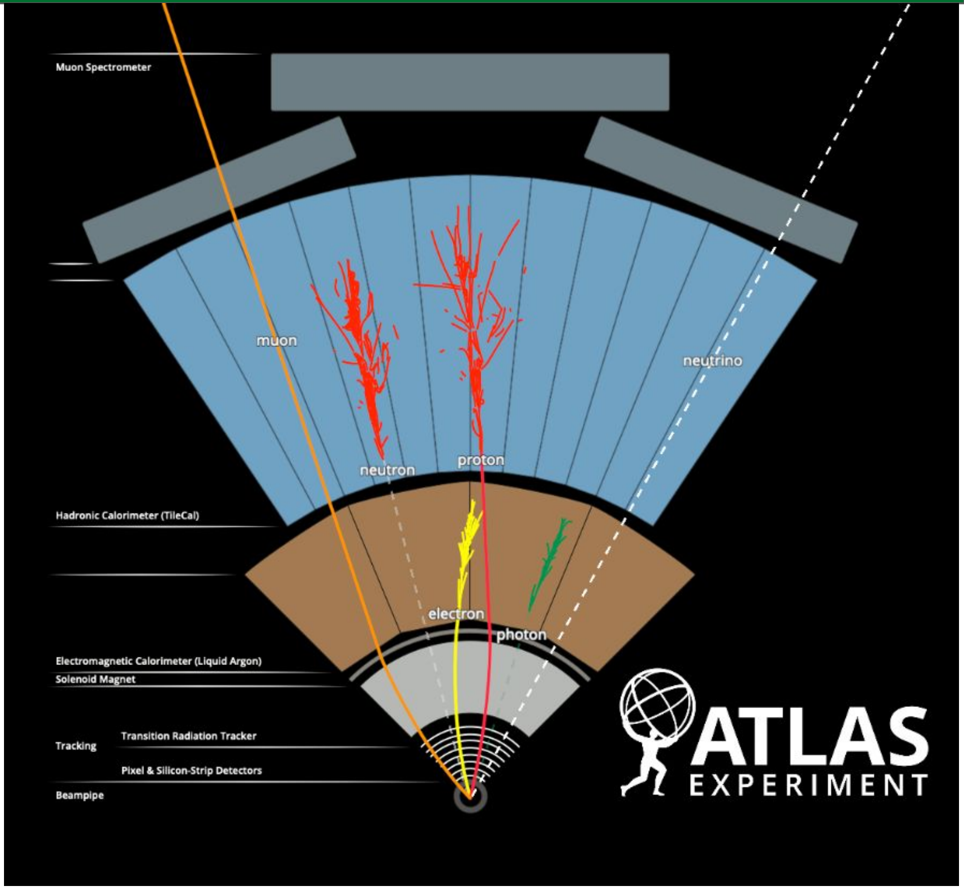


Figure from [2]

The ATLAS Trigger System

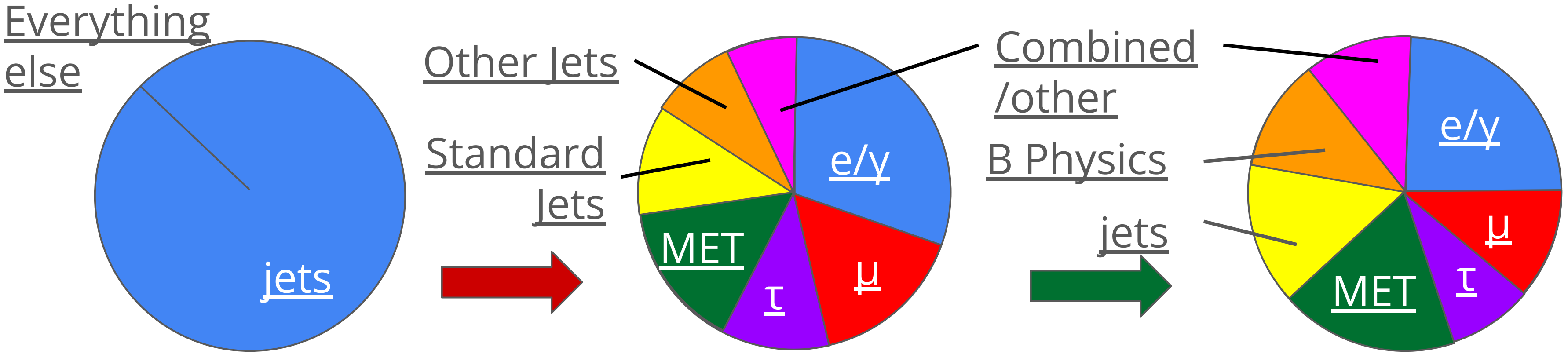
The LHC provides proton collisions at a rate of 40 MHz (40 Million Events/sec)

Impossible to save all these events (and in fact, most are “boring!”)

ATLAS trigger system is two-tiered:

- Level-1 Trigger - Hardware - reduces rate to ~100 kHz
- High Level Trigger - Software - reduces rate to ~ 3 kHz -> data we save!

(~64 Tb raw data/sec) (~160 Gb raw data/sec) (~4.8 Gb raw data/sec)



How do we find LLPs at detectors?

LLP Signatures at Colliders

- Anomalous Ionization
- Delayed Detector Signal
- Disappearing Tracks
- Displaced Tracks
- Displaced Vertices
- Emerging Jets

Old strategy: use standard triggers and look for these signatures offline

Can we utilize trigger upgrades to do better?

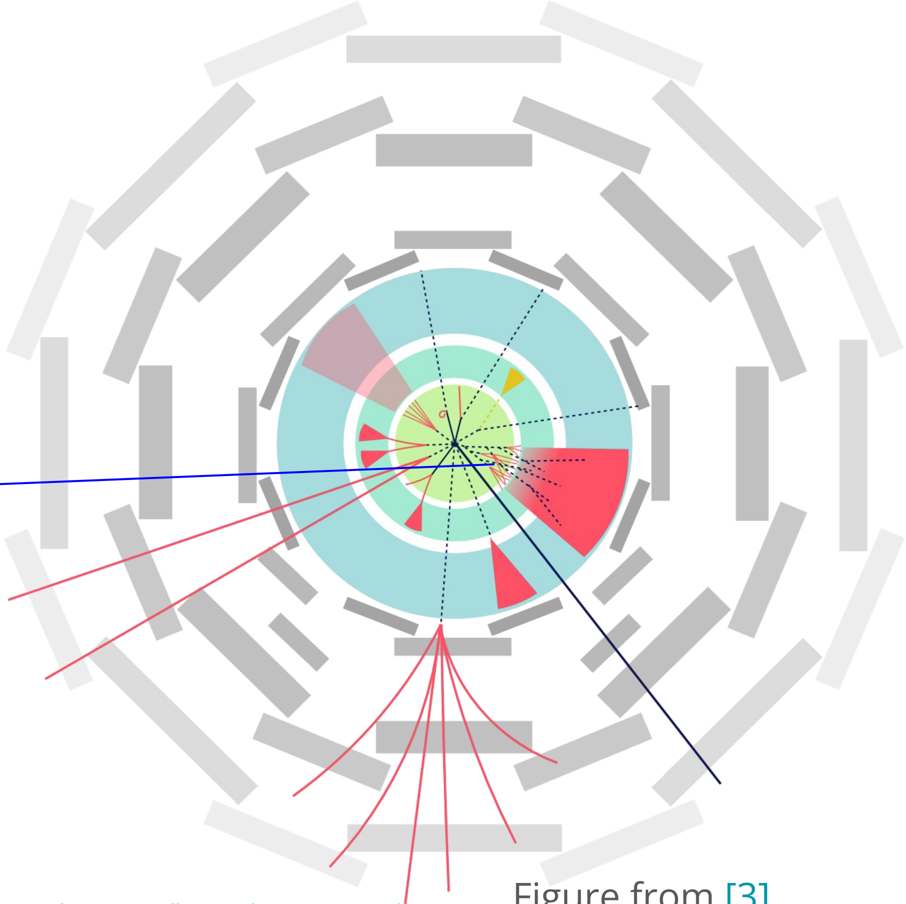
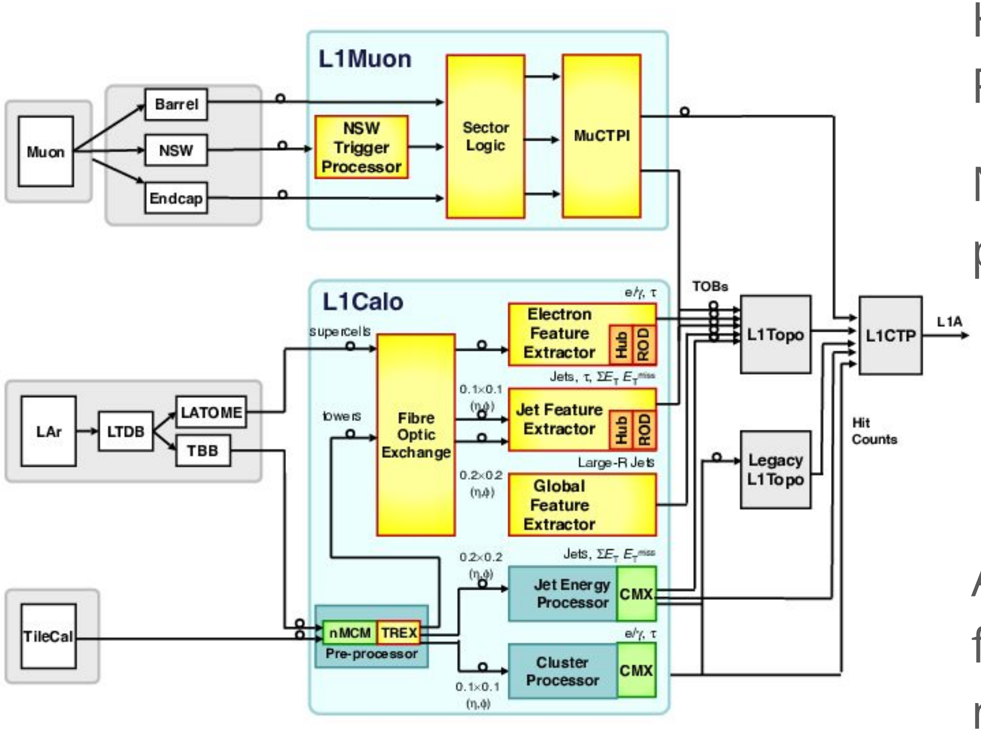


Figure from [3]

Upgrades to the ATLAS Trigger: L1Calo Architecture



Hardware trigger upgraded for LHC Run 3

New FEXes responsible for different physics signatures

- Electron Feature Extractor (eFEX)
- Jet Feature Extractor (jFEX)
- Global Feature Extractor (gFEX)

All FEXes utilize FPGAs to run custom firmware algorithms, allowing for more complex selections at the hardware level

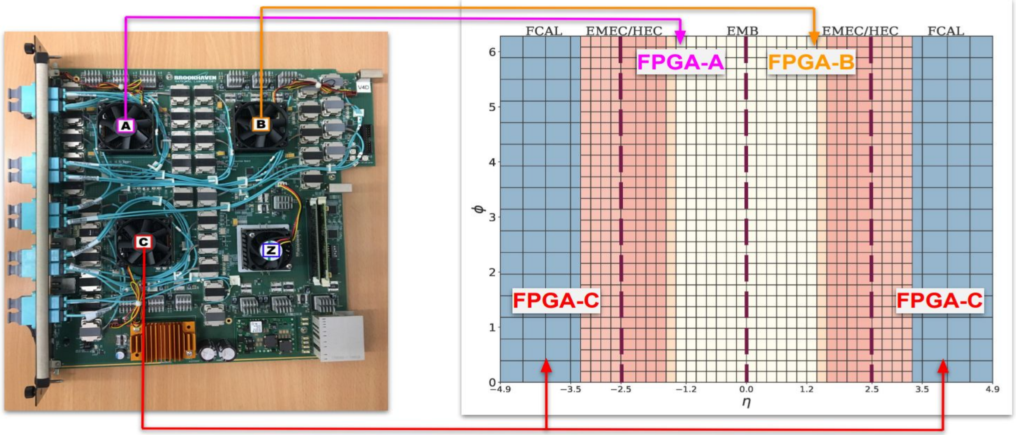
gFEX: Providing Global Event Triggers at Level 1

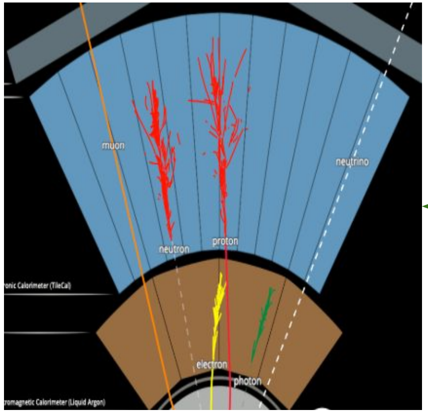
One ATCA board covers the entirety of the ATLAS detector (up to |η| 4.9)

Very coarse tower granularity: 0.2x0.2 in η/φ space compared to 0.1x0.1 in jFEX and 0.025x0.1in eFEX

3 FPGAs cover different regions of space

Allows for global event calculations quickly





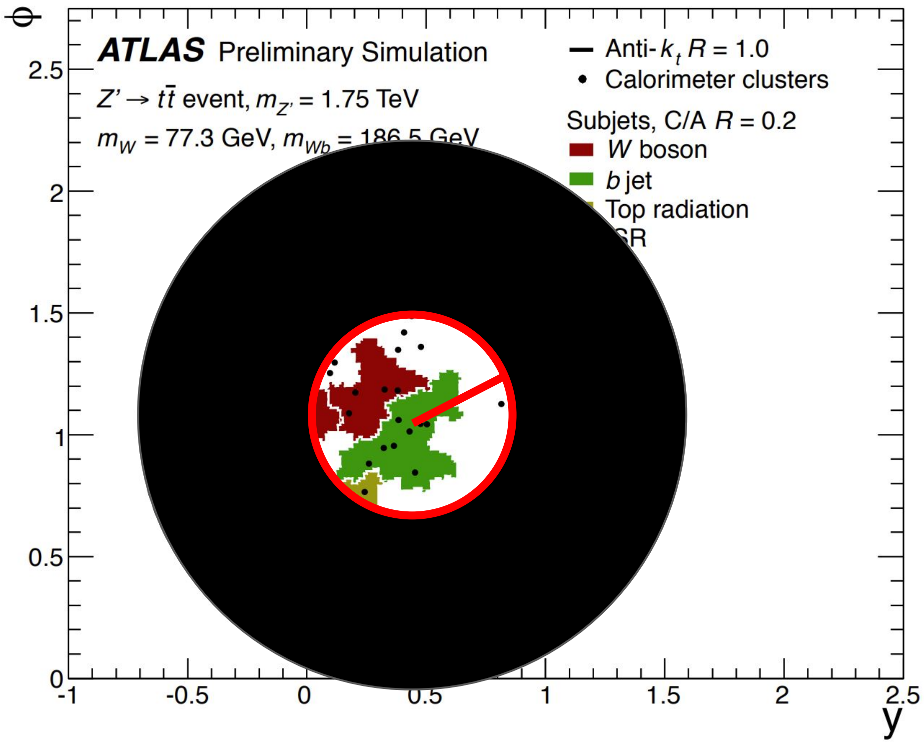
2D projection of calorimeters into an η/φ map

Physics Case for gFEX Large Radius Jets

Goal: Bring sensitivity to Lorentz boosted objects to L1

Standard Hardware Level Jet: 0.4 Radius (Small-R) in η/φ space

In Run 2: only chance to save this event is triggering on the high energy center



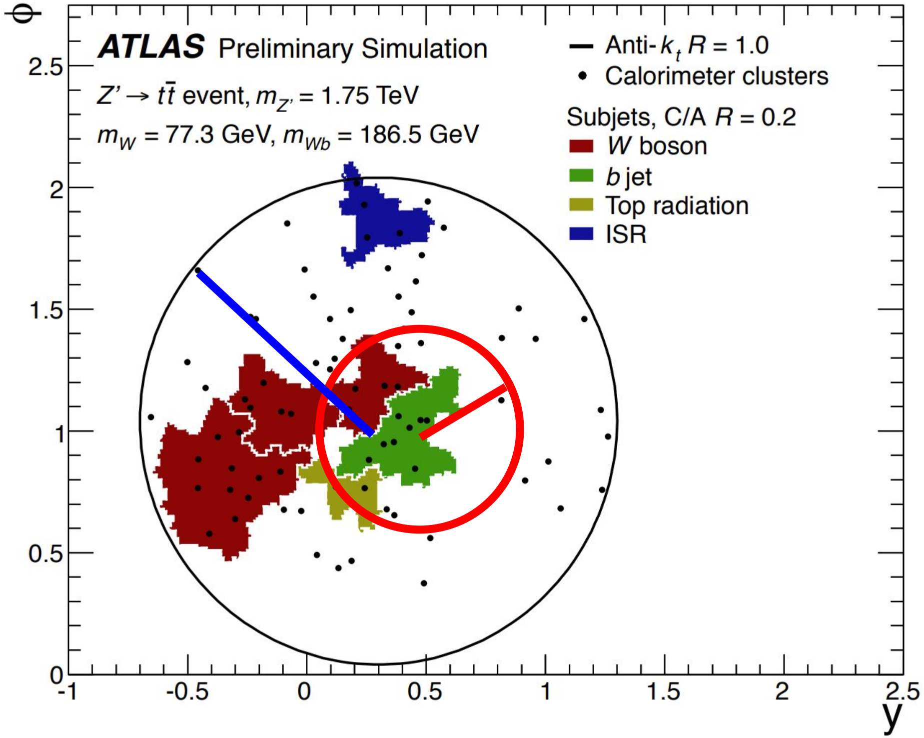
Physics Case for gFEX Large Radius Jets

Goal: Bring sensitivity to Lorentz boosted objects to L1

Standard Hardware Level Jet: 0.4 Radius (Small-R) in η/φ space

In Run 2: only chance to save this event is triggering on the high energy center

In Run 3: can trigger on an overall “softer” event by capturing all energy in a large η/φ radius: 1.0 (Large-R)

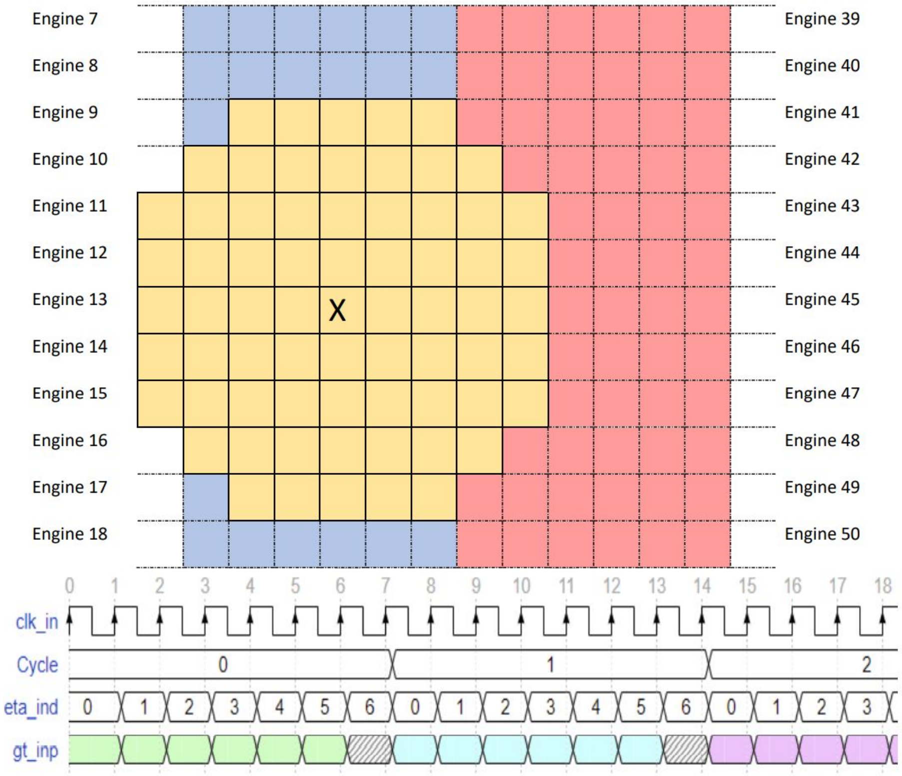


gFEX Large-R Jet Algorithm in a Nutshell

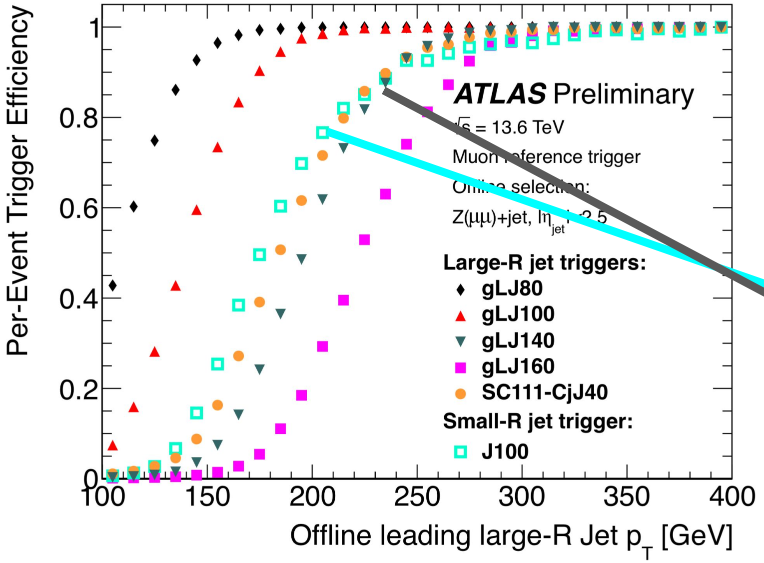
Offline Large-R Jets are “easy” - just anti kT algorithm with a radius of 1.0

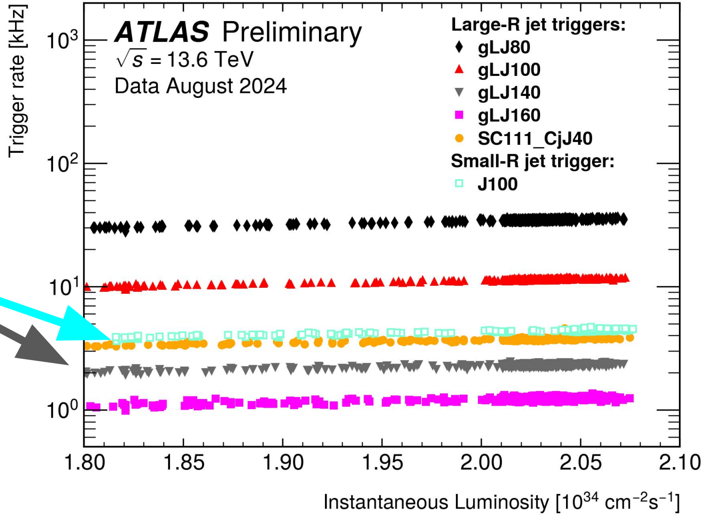
Hardware level is harder - need to be able to run jet finding algorithm on FPGA architecture

For an assumed Large-R Jet center, add all the towers around it and find the one in each region with highest energy



gFEX Performance in Run 3





Providing reliable Large R Jet triggers with a faster turn on and a lower rate than equivalent legacy Small R Jet triggers

The Emerging Jets Prompt Track Fraction Trigger

Software based HLT Trigger in Run 3

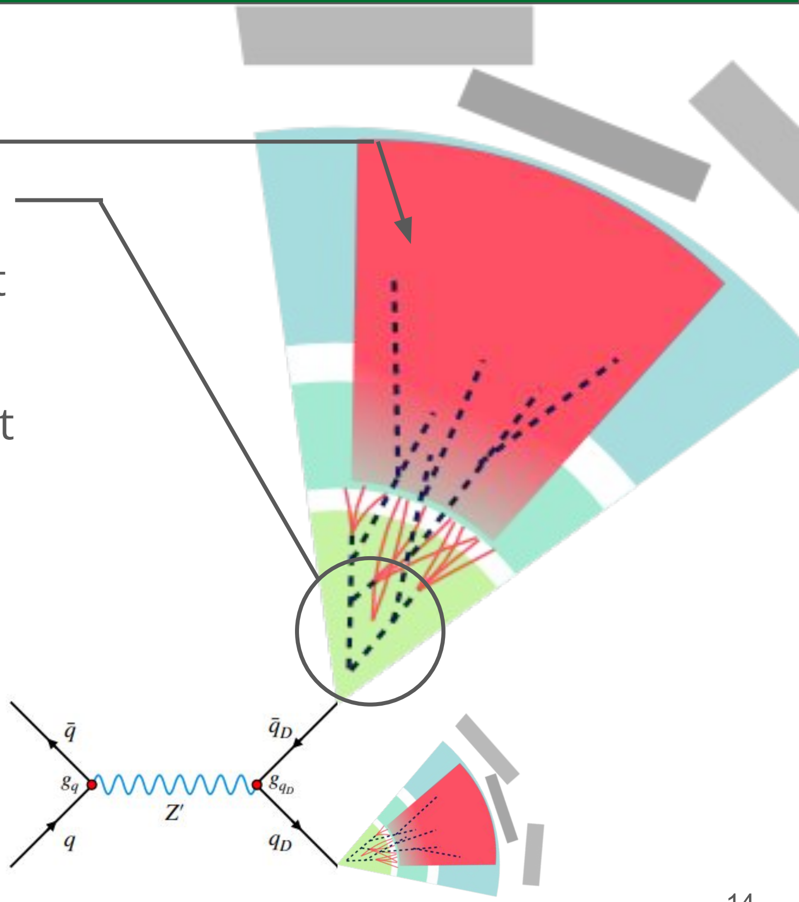
- Large-R Jet with pT > 200 GeV
- Fraction of track pT of prompt tracks in jet < 0.08

Level 1 seed decides which events this trigger looks at

- 2022-2023: Legacy Small-R Jet
- 2024: Several new seeds, such as gFEX Large-R Jet - can gain sensitivity to a wider range of LLP lifetimes

Studied in active ATLAS LLP analyses

- New trigger gives up to 50% more signal efficiency for simulated H->aa processes
- Largest Sensitivity increases for heavier LLPs



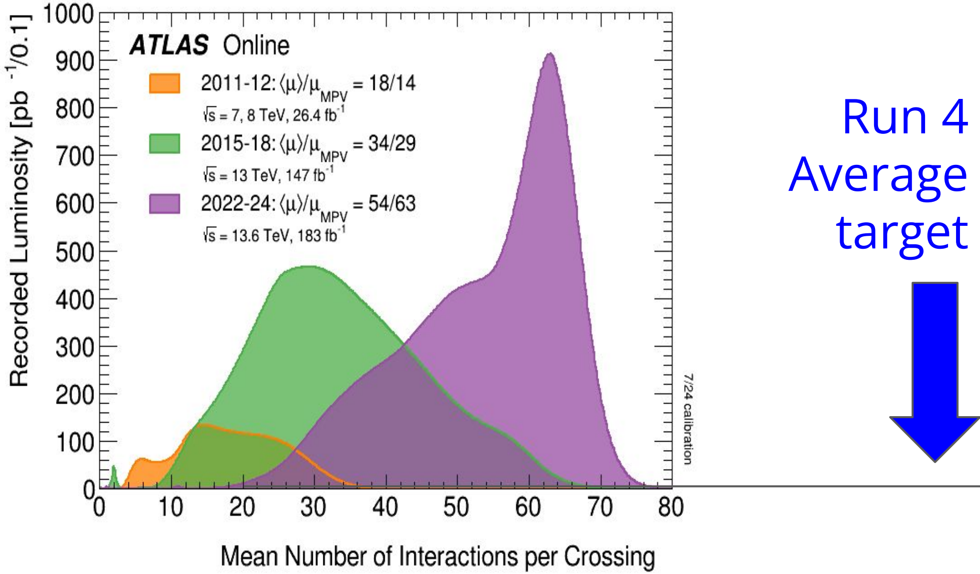
Looking Towards Run 4: High Luminosity LHC

Summer 2026: Run 3 ends and upgrades begin!

Increased Intensity: Average pileup (mean interactions per bunch crossing) target of 140 (~64 in Run 3)

Run 4 Hardware Trigger:

- Withstand new high intensity environment
- Lower trigger thresholds
- Maintain/decrease current trigger rates



Exciting Hardware Trigger Upgrade: Global Trigger (Developed here at BNL!)

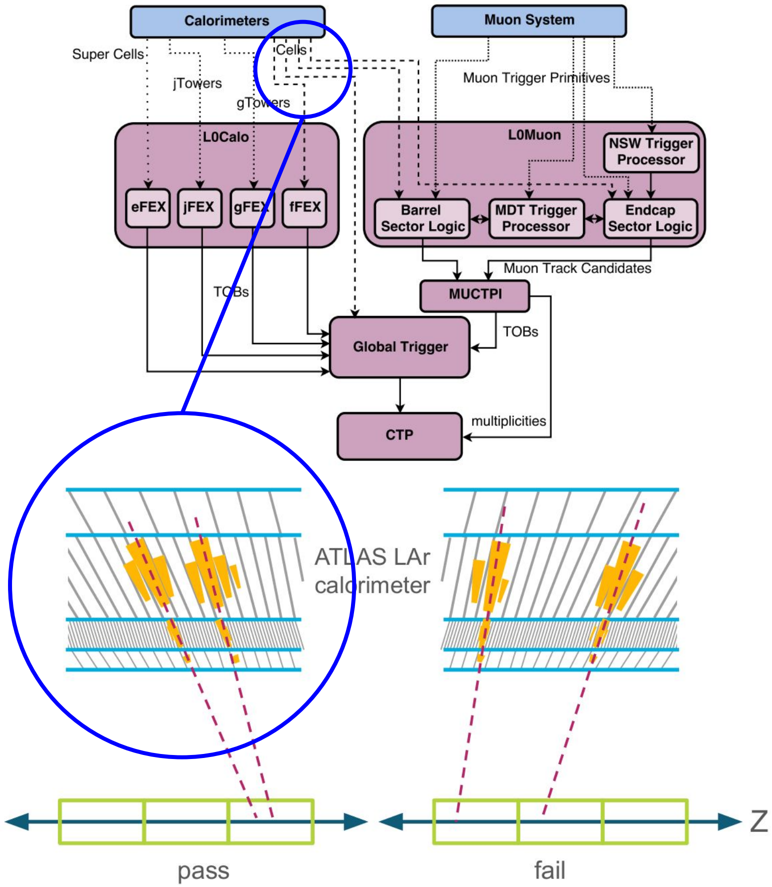
Global Trigger - Diphoton Algorithm

Take advantage of calorimeter cell information to do photon pointing at hardware level

Identify two photon candidates that come from the same vertex

Lower trigger threshold: Help in sensitivity to both SM (diHiggs) and BSM (LLPs)

Currently under development by the team here at BNL!



Conclusions

The search for Long-Lived Particles at colliders can be challenging

New upgrades to triggers are allowing us to gain sensitivity by saving events with LLP signatures

- Access to new signatures like boosted topologies at hardware level to help seed LLP signatures like emerging jets
- Allows greater sensitivity to new lifetimes of LLPs

There is much more data to collect and analyze with LLPs in mind!

Thank you for your attention!

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education for the DOE under contract number DE-SC0014664.

References

[1] L. Lee, C. Ohm, A. Soffer, and T.-T. Yu, Collider searches for long-lived particles beyond the Standard Model, [Prog. Part. Nucl. Phys. 106, 210 (2019)].

[2] S. Mehlhase, ATLAS Collaboration, ATLAS detector slice (and particle visualisations), 2021. https://cds.cern.ch/record/2770815

[3] H. Russel, Long-lived particle graphics, https://hrussell.web.cern.ch/hrussell/graphics.html

[4] ATLAS Collaboration, The ATLAS experiment at the CERN Large Hadron Collider: a description of the detector configuration for Run 3. 2024. *JINST* 19 P05063 10.1088/1748-0221/19/05/P05063

[5] ATLAS L1Calo Trigger Public Results https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1CaloTriggerPublicResults

[6] ATLAS Luminosity Public Results https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3

[7] ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS TDAQ System. 2017. https://cds.cern.ch/record/2285584

Backup