Performance of the ATLAS Inner Detector tracking and new Long-Lived Particle triggers in the LHC Run 3

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Introduction

- Run 3 ATLAS Inner Detector Trigger
- Run 3 ID trigger performance
- Unconventional tracking triggers for Run 3
ATLAS Inner Detector (ID)

|η|<2.5

- Barrel-endcap structure
- Tracking out to |η|<2.5

4 strip layers x2 (w/ stereo angle) [8 coordinates]
12 silicon layers
4 pixel layers [8 coordinates]

Transition Radiation Tracker: \(O(30)\) additional hits per track
ATLAS Trigger Schematic

- Hardware Level-1 Trigger feeds HLT (40 MHz to 100 kHz in 2.5μs)
- Based on calorimeter and muon spectrometer
- New L1Calo and L1Muon hardware turning on in Run 3!

‘Region-of-Interest’ (RoI) passed to HLT

- “HLT” Software Trigger (~3 kHz output)
- Full detector information, offline-like reconstruction
- Tracking runs here!
Trigger Software Tracking Overview

• Signatures that use tracking:
  - Electrons, muons, b-jets, taus, B-physics, long-lived particles
  - Isolation for leptons
  - Full Detector tracking for Jet and Missing Transverse Momentum enables particle flow

• Closer to offline, better jet resolution, better pile-up rejection

• Crucial element of ATLAS trigger to find and save events needed for physics program

• Designed considering speed and efficiency with respect to offline tracking
  - Computationally challenging in high pile-up environment

• **Full Detector** (entire Inner Detector) and **Region-of-Interest** (small regions around calorimeter or muon spectrometer signature)
HLT Trigger Tracking Flow

- **Data Preparation**
  - Retrieve raw Pixel and SCT detector data within region of interest and cluster hits; space-point formation

- **Fast Track Finder (FTF) (unique to trigger)**
  - First pass of tracking optimized for speed and efficiency
  - *Seeding and track formation (slow)*

- **Optional ‘Hypo’, i.e. selection to reject event**

- **Precision Tracking**
  - Offline-like tracking seeded by Fast Track Finder to increase purity and resolution of tracks
  - Runs ambiguity removal between tracks
  - Extension into Transition Radiation Tracker
Run 3 Performance of Trigger Lepton Tracking

- Exceptional performance of inner detector trigger continues
- New for Run 3: Gaussian Sum filter (GSF) for electrons (better for Brem.)

Efficiencies are with respect to offline tracks

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Muons

- Exceptional performance of inner detector trigger continues

Electrons

New for Run 3:
- Gaussian Sum filter (GSF) for electrons (better for Brem.)

Taus

 Run 2

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New for Run 3: Improved Electron $p_T$ resolution with GSF

- $p_T$ difference wrt offline tracks improved

More symmetric

Mean closer to zero at low $p_T$
New For Run 3: Speeding up tracking for Muon Isolation

- Run in second step after finding muon
- Better use of muon candidate to refine isolation tracking RoI to $z_0$ position of muon candidate with a 10 mm half-width
  - For Run 2, the $z_0$ width was not restricted
- 5x reduction in execution time; efficiency remains high

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**ATLAS Simulation Preliminary**
Monte Carlo $Z \rightarrow \mu\mu$, $\sqrt{s}=13$ TeV, pile-up $<\mu> = 55$
- Muon isolation fast tracking

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**ATLAS Preliminary**
Data 2022, $\sqrt{s} = 13.6$ TeV
24 GeV muon trigger
Offline tracks $p_T > 1.2$ GeV
- Muon isolation precision tracking
- Muon isolation fast tracking
New For Run 3: Full detector tracking in HLT

- Want full detector tracking to improve trigger performance of jets and $E_T^{\text{miss}}$
- No new FPGA/GPU-based solution for Run 3
- Full detector tracking is slow (~1.3 seconds / evt) and expensive
  - Increase CPU farm performance
  - Optimize tracking (filtering seeds [see backup], only FTF)
  - Run tracking only when we really need it (~14 kHz, once per event)
- Calorimeter-based preselection (eg 1 jet $p_T > 225$ GeV or $E_T^{\text{miss}} > 65$ GeV)
New For Run 3: RoI b-jet tracking + fast b-tagger for early rejection

- Fast b-tagging run as a preselection before full detector tracking
  - 5 rejection factor for $HH \rightarrow bbbb$ signature (2% loss)
- Fast tracking in merged RoI around jets
  - Much faster than Full Scan

**Fast b-tagging at HLT:** 2306.09738

**Merge RoIs to ‘Super RoI’**

- Fast b-tagging run as a preselection before full detector tracking
  - 5 rejection factor for $HH \rightarrow bbbb$ signature (2% loss)
- Fast tracking in merged RoI around jets
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**Fast b-tagging run as a preselection before full detector tracking**

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**Fast b-tagging run as a preselection before full detector tracking**

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Unconventional Tracking for Long-Lived Particles (LLPs)

- Many unique, non-standard signatures that **rely on tracking information for identification**
- Only **standard tracking** was used in the Run 2 trigger, with coverage out to $|d_0| < 5-10$ mm
  - Not adequate for most LLPs
- Calorimeter and muon spectrometer based triggers generally have **high thresholds** to keep rates reasonable
- Directly triggering on displaced objects keeps rates low while improving trigger acceptance for LLP searches
New LLP triggers for Run 3

- Long-lived charged particles
  - Disappearing track triggers (see CTD2022/backup)
  - Large $dE/dx$
  - Isolated high $p_T$ track
- Long-lived particle decaying into jets
  - Hit-based Displaced Vertex
  - Emerging jets
  - Displaced jets
- LLPs decaying into SM leptons (see CTD2022/backup for more)

Generally:
- Make use of full scan tracking
- Apply additional requirements to reduce Jet or MET thresholds
  - Single jet threshold: 420 GeV
  - $E_T^{\text{miss}}$ threshold: 90 GeV
- Run Large Radius Tracking (LRT)

Most of the following slides are MC-based performance
High $dE/dx$

- Signature: long-lived massive charged particle
  - Relatively large energy deposits in silicon sensors on track
- Run 2 analysis:
  - Trigger $E_T^{\text{miss}} > 110$ GeV
  - Track $p_T > 120$ GeV
- 3.3σ excess in Run 2 $dE/dx$ analysis

- Directly trigger on high $dE/dx$ tracks
- Full detector tracking after $E_T^{\text{miss}} > 80$ GeV
- $p_T > 50$ GeV and $dE/dx > 1.7$ MeV/cm
Isolated high $p_T$ tracks

- Signature: long-lived massive charged particle with detector (ID) stable lifetime
  - Isolated track
- Also motivated by dE/dx search
  - Would like to lower $E_{T\text{miss}}$ requirement for Run 3 searches

- Directly trigger on isolated high $p_T$ tracks
- Use full scan tracking after $E_{T\text{miss}} > 80$ GeV
- $p_T > 120$ GeV + track-based isolation

**ATLAS Simulation Preliminary**

- HLT $E_{T\text{miss}}$ (pflowfit OR tcpufit) OR Iso. Trk. Trig.
- HLT $E_{T\text{miss}}$ Trig. (pflowfit OR tcpufit)

long-lived $\tilde{\tau}$, $m(\tilde{\tau}) = 600$ GeV, $\tau(\tilde{\tau}) = 10 \text{ ns}$

$\geq$1 offline track with $p_T > 100$ GeV,

$|\eta| < 2.5$, $d_0 < 5$, 2 pixel hits

600 GeV, 10 ns di-stau
Hit-based Displaced Vertex

- Signature: long-lived neutral particle decaying into jet/displaced vertex in the ID volume
- Run standard full-detector tracking and find left-over hits around jet
  - Large number of hits on outer layer compared to inner layer signature of displaced vertices that are not reconstructed
- BDT uses fraction of hits-per-layer to identify this signature

- 1) $E_T^{\text{miss}}$ preselection and Jet with $p_T > 200$ GeV and $|\eta| < 1$ passing BDT
- 2) Jet with $p_T > 260$ GeV and $|\eta| < 1$ passing BDT

$H \rightarrow 2S \rightarrow 4b$
$m_H = 1$ TeV
$m_S = 50$ GeV, $c\tau = 9$ mm
Emerging jets

- Signature: semi-visible jets often in models with dark sector
  - Displaced tracks and displaced vertices in semi-visible jets
- Use standard full-detector tracking to compute fraction of jet momentum associated with prompt tracks (PTF)
  - Expect low fraction for emerging jets

- 1) Central Large-R jets with \( p_T > 200 \text{ GeV} \) and PTF < 0.08
- 2) 45 GeV Photon seeded with 2 Large R jets with \( p_T > 55 \text{ GeV} \) and PTF < 0.1
- Overall efficiency depends on PTF acceptance
**Displaced jets**

- **Signature: displaced jet**
  - Jets without many prompt tracks
- Requires HLT jet with $p_T > 180$ GeV
  - Single jet threshold is 420 GeV
- **Count prompt and displaced tracks** with $p_T > 1$ GeV around $\Delta R < 0.4$ of jets
  - Threshold at $|d_0| = 3$ mm
- Run LRT on remaining hits in RoI around jets that pass preselection $n_{\text{prompt}} \leq 2$

**Analysis**

- **Leading 180 GeV jet (ISR Jet)** +
  - 1) **140 GeV jet** with $n_{\text{prompt}} \leq 1$ and $n_{\text{disp}} \geq 3$
  - 2) **Two 50 GeV jets** with $n_{\text{prompt}} \leq 2$ and $n_{\text{disp}} \geq 3$
    - 2nd jet may have $n_{\text{disp}} \geq 0$ if $n_{\text{prompt}} \leq 1$

**Graph**

- *ATLAS Simulation Preliminary*
- $\sqrt{s} = 13$ TeV
- $H \rightarrow aa$
- $m_a = 55$ GeV, $c\tau = 100$ mm
- Displaced 55 GeV di-jet trigger
- Displaced 140 GeV single jet trigger
- Comb (single OR di-jet)

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**Oct 11, 2023 (CTD 2023)  Jonathan D. Long (UIUC)**
Displaced Taus

- **Signature:** displaced tau
  - Hadronically decaying taus with large \( d_0 \)
- **Standard single tau threshold of 160 GeV**
- **Retrained tau RNN to select displaced taus based on standard tracking**
- **Additional trigger running LRT in RoI around tau under development**

### Single tau: \( p_T > 200 \text{ GeV} \)

### Di-Tau: \( p_T > 80 \text{ GeV} \) and \( p_T > 60 \text{ GeV} \)

### Tau+X, seeded by X, with lower thresholds

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**ATLAS** Simulation Preliminary

- \( \sqrt{s} = 13.6 \text{ TeV} \)
- \( \sqrt{s} (100 \text{ GeV}, 1 \text{ ns}) \)

No \( d_0 \) selection

Efficiency wrt. offline tracks

**Truth tau \( p_T \) [GeV]**

**Truth tau \( R_{\text{decay}} \) [mm]**

**100 GeV, 1 ns di-stau**
Displaced Electrons: Trigger Tracking Performance

- **Signature**: displaced electron
  - Electrons with large $d_0$
- **Run LRT in RoI around Calo candidate**
- **Performance measured with respect to offline electron tracks**

- $p_T > 30$ GeV and $d_0 > 3$ mm
- Modified electron ID that doesn’t depend on $d_0$ or number of silicon hits

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**ATLAS Preliminary**

Data $\sqrt{s} = 13.6$ TeV, October 2022

- Fast tracking
- Precision tracking
- GSF reconstruction
- Total Si data preparation
- Total TRT extension

**FTF Faster, other steps slower than standard electron tracking**

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**Efficiency**

100 GeV, 1 ns di-selectron ttbar (1 lep)

Data 2022, $\sqrt{s} = 13.6$ TeV

LRT electron trigger, Offline electron $p_T > 10$ GeV, $d_0 > 2$ mm

- MC di-selectron, mass = 100 GeV, lifetime = 1 ns
- MC ttbar 1 lepton
- Data
Displaced Muons: Trigger Tracking Performance

- **Signature**: displaced muon
  - Muons with large $d_0$
- **Run LRT in RoI around MS candidate**
- **Performance measured with respect to offline muons**

- $p_T > 20$ GeV and $d_0 > 2$ mm

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**Data prep slower, FTF faster than standard muon tracking**

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ATLAS Preliminary

Data, $\sqrt{s} = 13.6$ TeV, October 2022

- Fast tracking
- Precision tracking
- Total Si data preparation
- Total TRT extension

ATLAS Preliminary

Data 2022, $\sqrt{s} = 13.6$ TeV

LRT muon trigger, Offline muon $p_T > 10$ GeV, $d_0 > 2$ mm

- MC di-smuon, mass = 100 GeV, lifetime = 1 ns
- MC ttbar 1 lepton
- Data

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100 GeV, 1 ns di-smuon ttbar (1 lep)
Full Detector Trigger LRT Tracking Performance with $K^0_s$

- Use offline $K^0_s$ vertices to measure trigger LRT performance
  - $p_T > 1$ GeV, $d_0 > 5$ mm, opp. charge, 25 MeV mass window
  - Match offline (STD+LRT) tracks to *standard trigger tracks* (and remove)
  - Remaining offline tracks used as denominator
- Reprocessed special dataset to run trigger full detector LRT
- Per track efficiency and efficiency of matching both tracks in vertex
Conclusion

- Greatly expanded use of tracking in the HLT for Run 3
  - Running full detector tracking for all $E_T^{\text{miss}}$ and Jet signatures
  - New triggers targeting a wide variety of LLP signatures

- Tracking is the most CPU intensive part of the HLT, requiring selective use and clever optimization

- Tracking continues to be a key element of the ATLAS Trigger
  - Exciting prospects with new LLP triggers

- Excellent performance in Run 3 so far and continues to improve
Backup
dE/dx Run 2 search

- Follow-up using calorimeter timing. Events not compatible with slow moving particle

ATLAS
SR-Inclusive_High
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
\( p_T^h > 120 \text{ GeV}, |\eta| < 1.8 \)

- \( m(\tilde{q}) = 2.2 \text{ TeV}, m(\tilde{\chi}^0) = 100 \text{ GeV}, \tau(\tilde{q}) = 10 \text{ ns} \)
- \( m(\tilde{\chi}^0) = 1.3 \text{ TeV}, \tau(\tilde{\chi}^0) = 10 \text{ ns} \)
- \( m(\tilde{g}) = 400 \text{ GeV}, \tau(\tilde{g}) = 10 \text{ ns} \)

Observed
Expected

dE/dx+ToF: ATLAS-CONF-2023-044
Improvements for Run 3

- Unconventional tracking signatures
- Full detector tracking for Jet and Missing Transverse Momentum signatures
Disappearing Track Trigger

- Modify tracking algorithm to save failed tracklets
  - Run in full scan instances (MET)
- Categorize tracklets based on number of Pixel and SCT hits
- Train BDT based on various track-related quantities to reject fake tracklets (parameters, $\chi^2$,..)

- Improves acceptance over pure MET trigger for lower momentum models!

ATLAS Simulation

Long-lived chargino
Large Radius Tracking (LRT)

- See J. Burzynski’s talk from CTD2022 for information on improved ATLAS LRT for Run 3

- **Key improvements**
  - Reduced number of fake tracks
  - Improved processing time

- Run 2 LLP searches generally relied on calorimeter or muon-spectrometer based triggers with **high thresholds** (~60 GeV for two objects)
  - Impacted acceptance of interesting models such as **light displaced staus**, which have relatively low momentum decay products
Large Radius Tracking for Leptons in RoIs

- **SCT only seeding**, without ordering by impact parameter; tighter track selection than for prompt
- **Single pass of tracking**, unlike offline tracking that runs on remaining hits after standard tracking
  - Reconstructs $p_T > 1$ GeV and $|d_0| > 2$ mm
  - Timing and performance acceptable without extra complexity of two steps

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Number of layers required and size of RoI in $\phi$ limit reach to large displacements

ATL-COM-DAQ-2022-023

ATL-COM-DAQ-2022-026
Expected LRT Lepton Trigger Performance

- Target displaced electrons and muons from a few mm out to 300 mm
- Efficiency with respect to offline tracks truth-matched to signal leptons

**Lower thresholds** compared to Run 2 scheme and only a single object required!

Complements coverage in $d_0$ from standard muon chain

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[ATL-COM-DAQ-2022-023]
Full Scan Large Radius Tracking

- Useful for signatures without obvious RoI or adding LRT to jets
- Runs as second pass after standard tracking, otherwise similar to RoI LRT
  - 1.7x mean processing time compared to standard tracking
- Optimizations for processing time reduce efficiency compared to offline tracking
LRT Lepton Eff vs Prod Radius

ATLAS Simulation Preliminary

$\sqrt{s} = 13$ TeV

- Standard $p_T > 24$ GeV
- LRT $p_T > 24$ GeV, $|d_0| > 2$ mm
- Combined

Rol Muons: $p_T > 24$ GeV, $|d_0| > 2$ mm
(Standard HLT tracking: $|d_0| < 10$ mm)

Rol Electrons: $p_T > 26$ GeV, $|d_0| > 5$ mm
(Standard HLT tracking: $|d_0| < 5$ mm)
Additional LRT Full Scan Eff

ATLAS Simulation Preliminary

- HLT FS Standard Tracking
- HLT FS LRT
- HLT Combined (Std + LRT)
- Offline Reconstruction

Track Reconstruction Efficiency vs. R-hadron transverse decay radius [mm]

ATLAS Simulation Preliminary

- $\sqrt{s} = 13$ TeV
- R-hadron
- $m = 1.2$ TeV, $ct = 300$ mm

Efficiency wrt Truth

Track Reconstruction Efficiency vs. Truth $d_y$ [mm]

ATLAS Simulation Preliminary

- $\sqrt{s} = 13$ TeV
- R-hadron
- $m = 1.2$ TeV, $ct = 300$ mm

Efficiency wrt Offline Tracks
Speeding up Full Scan tracking
Speeding up Track Seeding

- Full scan tracking is time consuming
- Seeding, forming of triplets, first step in combining hits into tracks
- Number of seeds increases rapidly with number of hits (e.g. larger pileup)
- Number of seeds also impacts time needed for later steps of tracking

- Speed up tracking by rejecting bad seeds from the start
ML based filtering

- Train classifier on **cluster width in $\eta$** and **doublet inclination angle** with respect to the $z$-axis

- Train for pixel-barrel and pixel-endcap doublets and standard/long pixel combinations (banding)

- Turn acceptance region of doublets into **look up table**
Resulting Reduction in Processing Time

- Large reduction in seed processing time and total fast tracking time
- Minimal loss in efficiency
- Robust improvement with increasing pileup

<table>
<thead>
<tr>
<th>Total Speed-up Factor</th>
<th>Seed Generation</th>
<th>Seed Processing</th>
<th>Track Fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3×</td>
<td>1.3×</td>
<td>3.3×</td>
<td>1.5×</td>
</tr>
</tbody>
</table>

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ATLAS Simulation Preliminary
Monte Carlo 13 TeV tt <q> = 80 full detector fast tracking
Truth track p_t > 3 GeV
- with Machine Learning extensions
- without Machine Learning extensions

<table>
<thead>
<tr>
<th>µ</th>
<th>Efficiency Loss (%)</th>
<th>Total Speed-up Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.7</td>
<td>1.6×</td>
</tr>
<tr>
<td>60</td>
<td>0.7</td>
<td>2.1×</td>
</tr>
<tr>
<td>80</td>
<td>1.1</td>
<td>2.3×</td>
</tr>
</tbody>
</table>
Optimizing Full Scan Tracking for Jet and MET Signatures

- No mixed Pixel+SCT triplet seeds
  - ‘PPP’ and ‘SSS’ only
- 1.9x mean event processing time speed up

Restricting Z RoI width to decrease CPU time for small efficiency loss

Minimal loss in efficiency
Other backup material
Run 2 / RoI details
Timing for Muon Trigger

- Clustering and spacepoint formation is fast: 4-10 ms
- Fast Tracking mean of 40 ms (tail up to 300 ms), precision tracking 7 ms
- Tracking for isolation in wider RoI is slower around 116 ms
- Extension to TRT is also fast, under 10 ms
- Sum of mean times < 200 ms
Lepton Tracking Efficiency and Resolution vs Offline Tracks

Nearly fully efficiency with respect to offline tracks

Small inefficiency for electrons near transition between barrel and endcap

Precision tracking improves object resolution

Track $p_T \ll$ electron threshold allows for bremsstrahlung
Two Stage Tracking

- Allows for updating RoI after first pass to optimize CPU performance and efficiency—**improvement** over single stage strategy
- Used for **tau** and **b-jet** triggers
  - Run first pass to find luminous / vertex region in Z with narrow eta and phi
  - Second pass with restricted Z region, but full eta and phi

Two stage tracking for taus

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Two Stage Tracking (taus and b-jets)

Example of precision tracking increasing purity of tracks

Vertex track pattern recognition only runs on track candidates with $p_T > 5$ GeV
Merging Regions-of-Interest: ‘Super RoIs’

- B-Jet triggers are most costly in terms of CPU resources
- Jet triggers may have multiple RoIs per event used to seed b-jet trigger
  - **Merging the RoIs** into a single event wide RoI reduces the overhead from overlapping regions, e.g. data preparation
- Two stage tracking strategy to first find luminous region and then for b-jet vertexing
  - Primary vertex cached per event from most expensive step (vertex fast tracking)
  - Vertexing itself is fast <10ms \[ O(1) \text{ ms for lepton RoIs} \]

**Merging RoIs to ‘Super RoI’**

![Diagram of merging RoIs](image)

**Graph:**
- b-jet vertex fast tracking \( \langle t \rangle = 46.19 \pm 0.32 \text{ ms} \)
- b-jet fast tracking \( \langle t \rangle = 28.92 \pm 0.18 \text{ ms} \)
- b-jet precision tracking \( \langle t \rangle = 12.45 \pm 0.09 \text{ ms} \)

**ATLAS**
- Data \( p\bar{p} = 13 \text{ TeV}, \text{ September 2018} \)
- Pile-up \( \langle p \rangle = 52 \)
Fast Primary Vertex Finding

- Extrapolate tracks back to beamline
- Histogram count of tracks compatible with windows in Z
- High efficiency vs pile-up and faster

Illustration of concept using seeds

Peaks correspond to vertex candidates

ATL-COM-DAQ-2022-010
Electron and b-jet Timing

**Electrons**

**ATLAS**
- Data $\sqrt{s} = 13$ TeV, September 2018
- Pixel clustering $<t> = 9.354 \pm 0.654$ ms
- SCT clustering $<t> = 4.293 \pm 0.029$ ms
- Spacepoint finder $<t> = 5.689 \pm 0.032$ ms

**b-jets**

**ATLAS**
- Data $\sqrt{s} = 13$ TeV, September 2018
- Pixel clustering $<t> = 8.425 \pm 0.522$ ms
- SCT clustering $<t> = 4.293 \pm 0.029$ ms
- Spacepoint finder $<t> = 5.689 \pm 0.032$ ms

Electron precision tracking resolution worse than FTF at low pT

- These are likely electrons that have radiated (track $p_T <<$ threshold)
- FTF likely rejecting outermost SCT hit
  - Track not getting pulled by outer hit
  - Better resolution for $p_T$ based on inner hits
Vertexing Resolution

ATLAS
Data 2018 $\sqrt{s} = 13$ TeV
- 110 GeV b-jet trigger: Histogram vertex
- 420 GeV b-jet trigger: Histogram vertex
- 110 GeV b-jet trigger: Offline based vertex
- 420 GeV b-jet trigger: Offline based vertex

ATLAS
Data 2018 $\sqrt{s} = 13$ TeV
- 110 GeV b-jet trigger: Histogram vertex
- 420 GeV b-jet trigger: Histogram vertex
- 110 GeV b-jet trigger: Offline based vertex
- 420 GeV b-jet trigger: Offline based vertex

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