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

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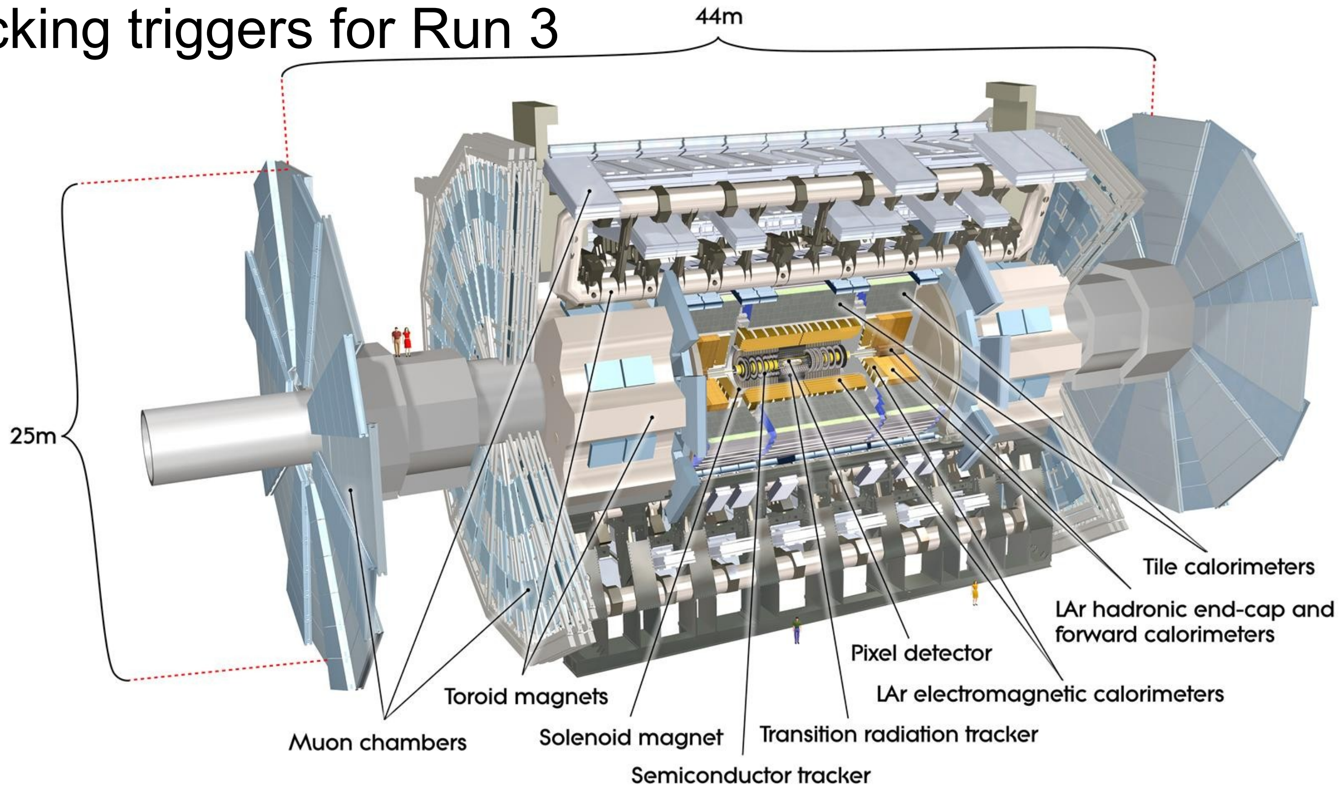
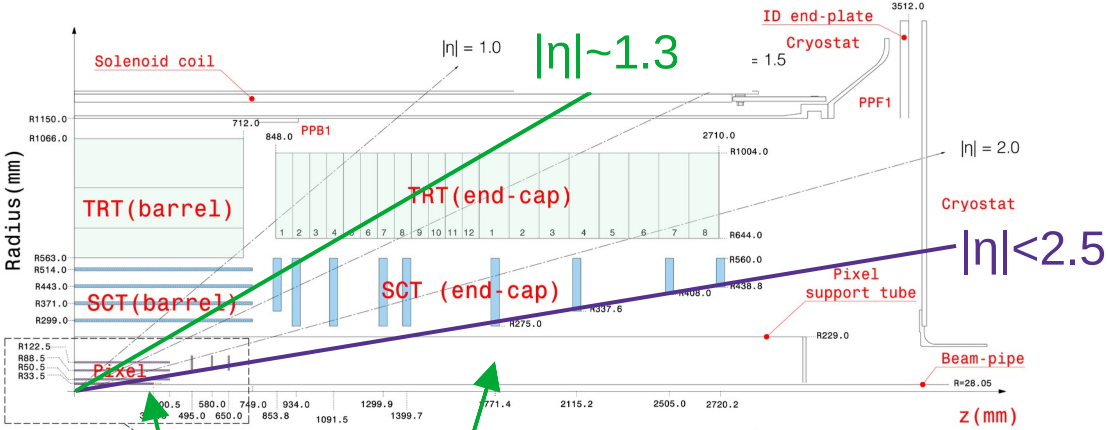
CTD 2023

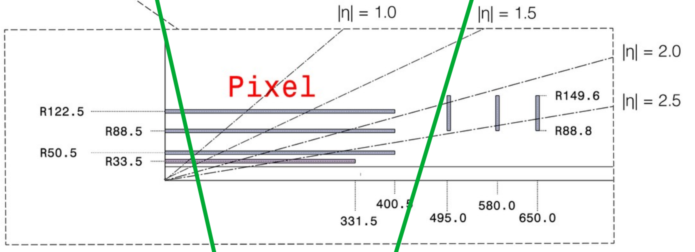
Introduction

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



ATLAS Inner Detector (ID)



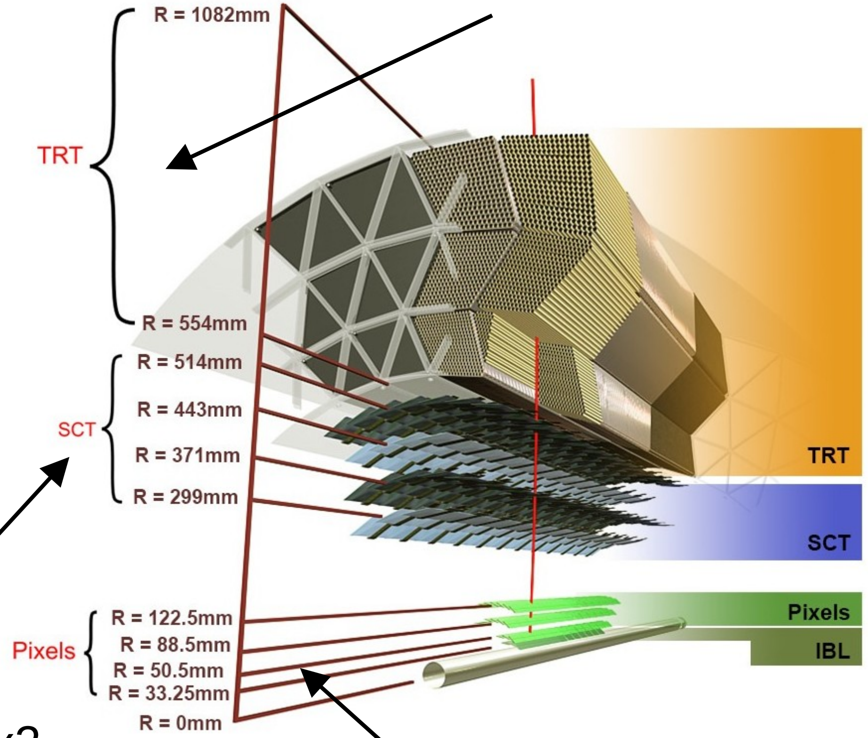


Envelopes

Pixel	31<R<242 (mm)
SCT barrel	255<R<549 (mm)
SCT end-cap	251<R<610 (mm)
TRT barrel	554<R<1082 (mm)
TRT end-cap	617<R<1106 (mm)

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

Transition Radiation Tracker: *O*(30) additional hits per track



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

4 pixel layers [8 coordinates]

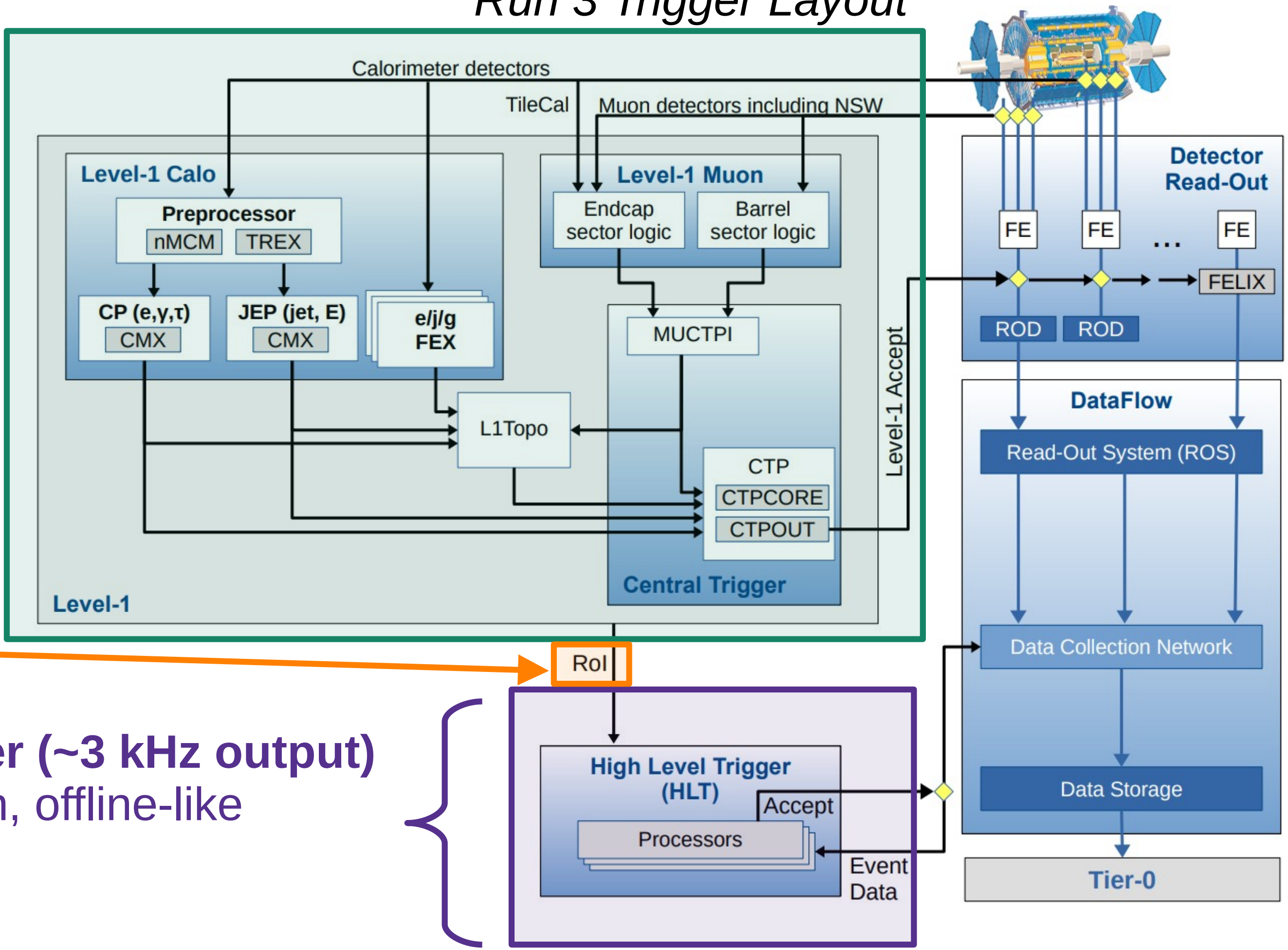
12 silicon layers

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

Run 3 Trigger Layout



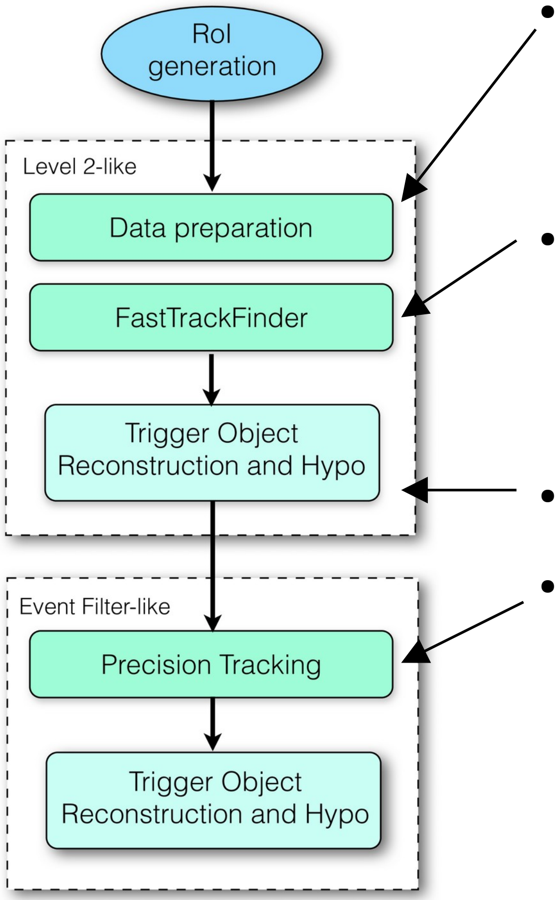
- **"HLT" Software Trigger (~3 kHz output)**
- Full detector information, offline-like reconstruction
  - Tracking runs here!

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

Eur. Phys. J. C 82 (2022) 206



- **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

ATL-COM-DAQ-2023-075

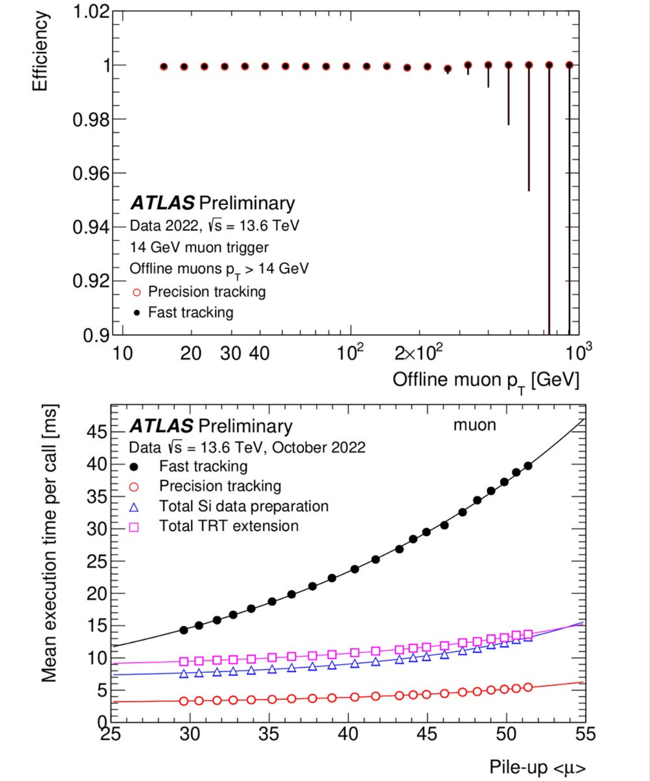
Efficiencies are with respect to offline tracks

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

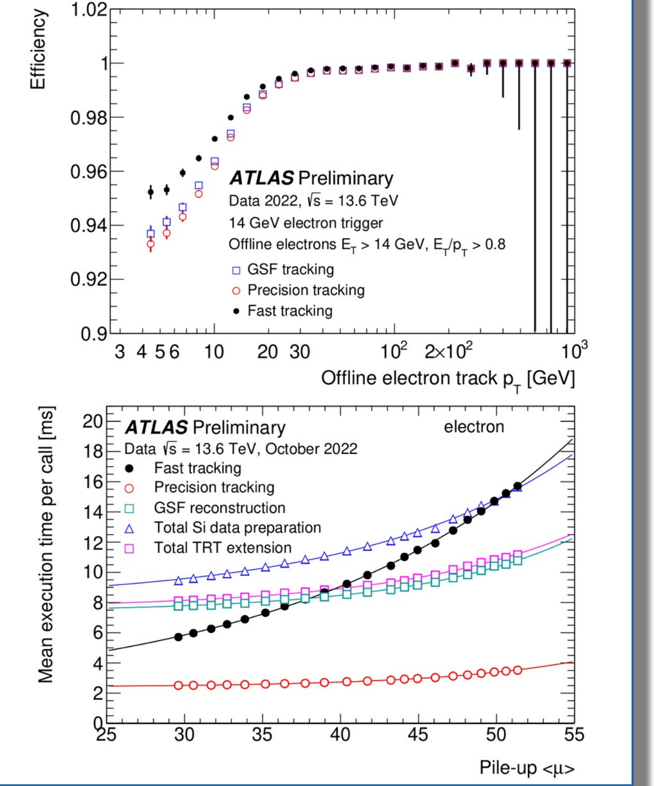
Efficiency

Timing

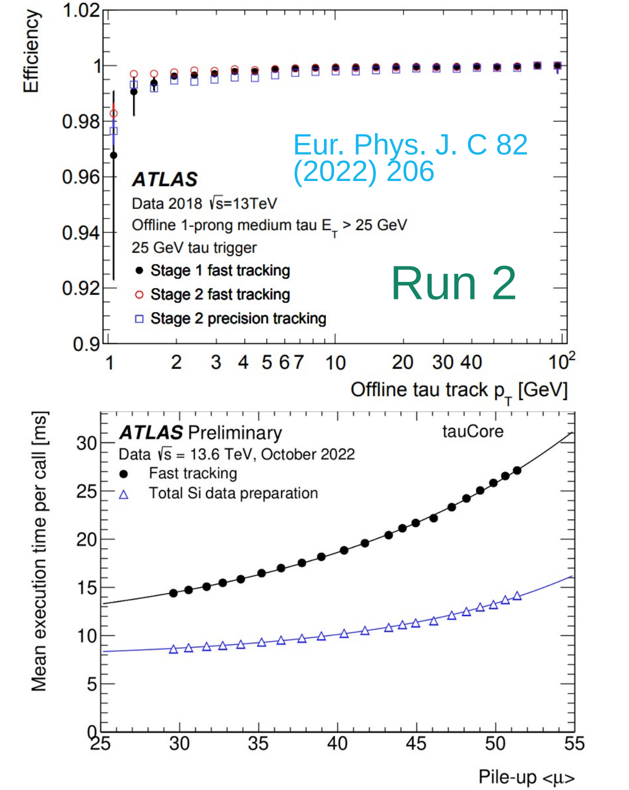
Muons



Electrons

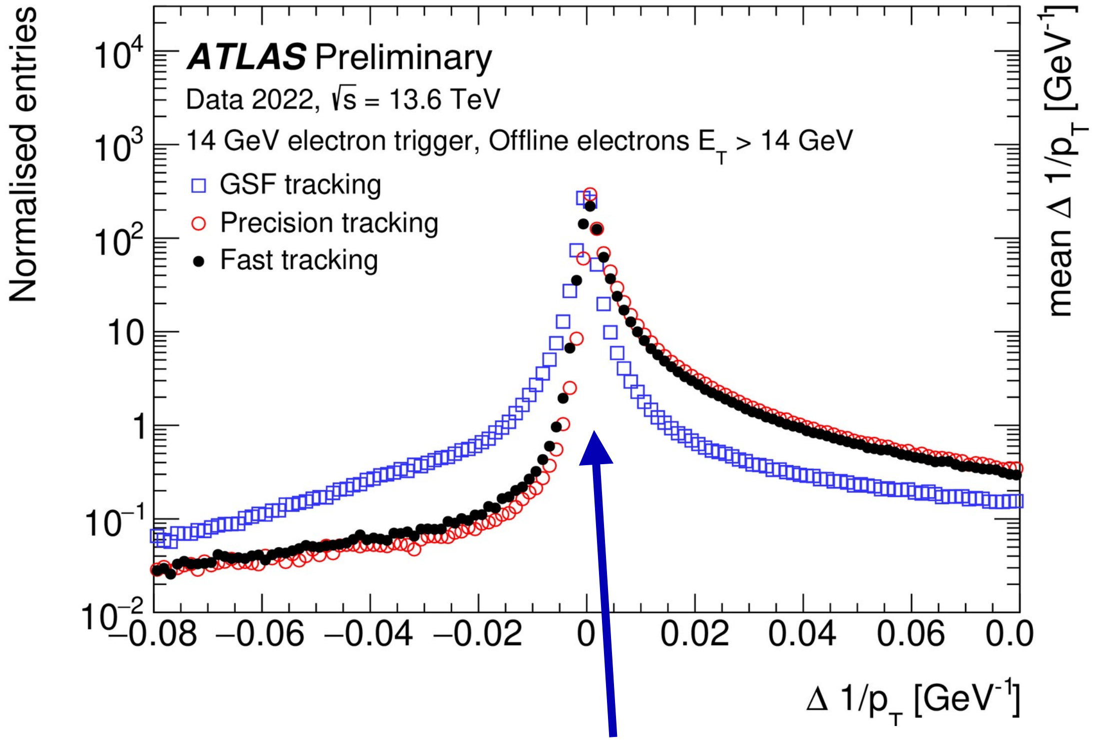


Taus

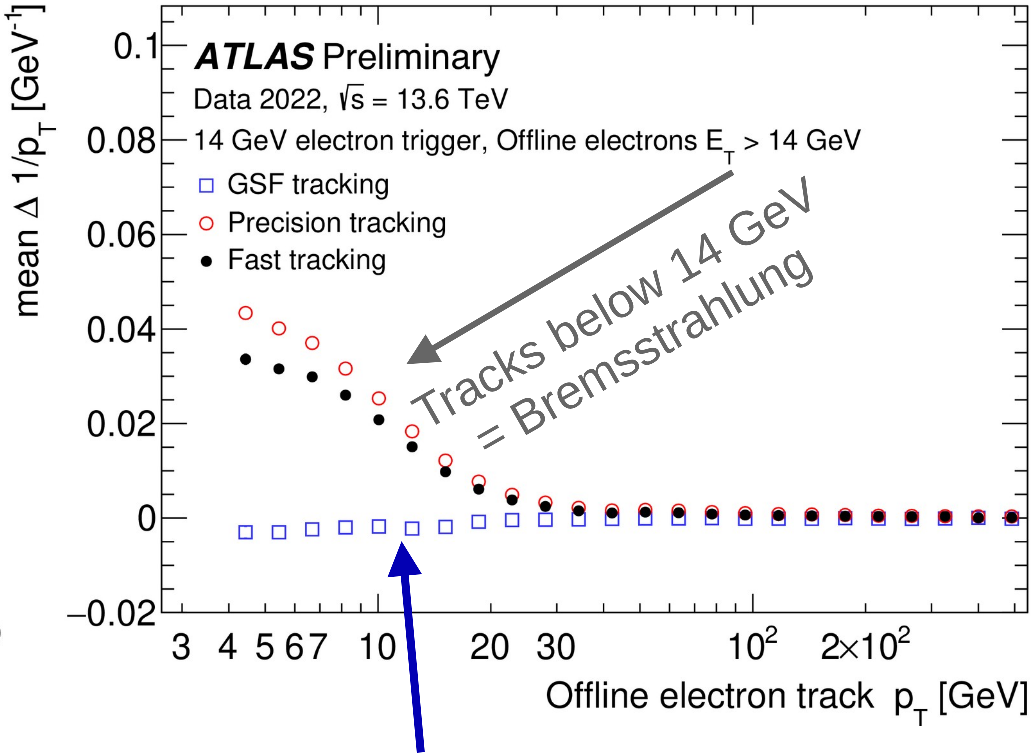


New for Run 3: Improved Electron p_T resolution with GSF

- p_T difference wrt offline tracks improved



More symmetric

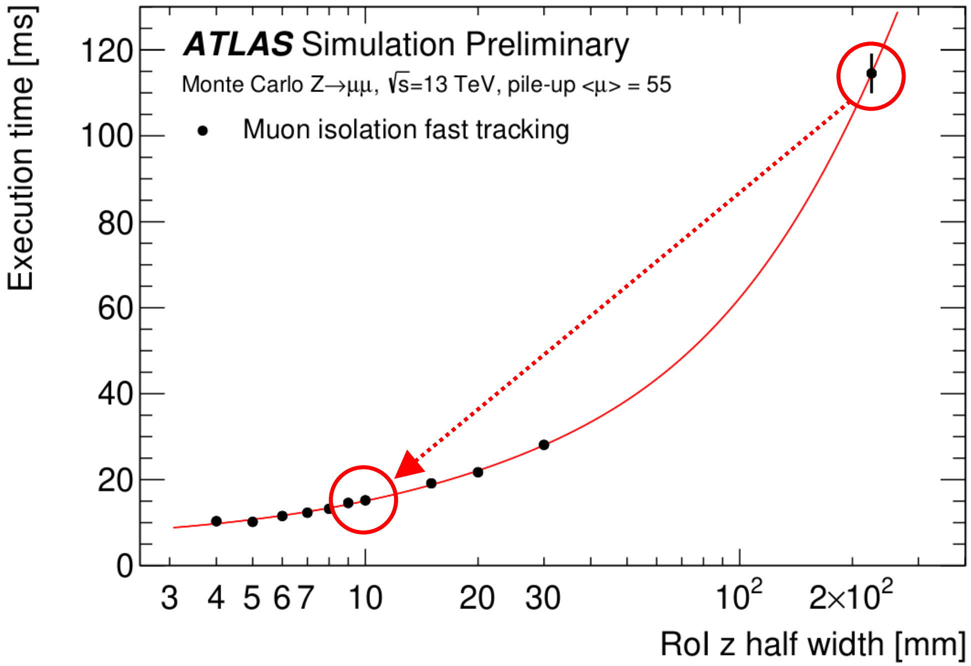


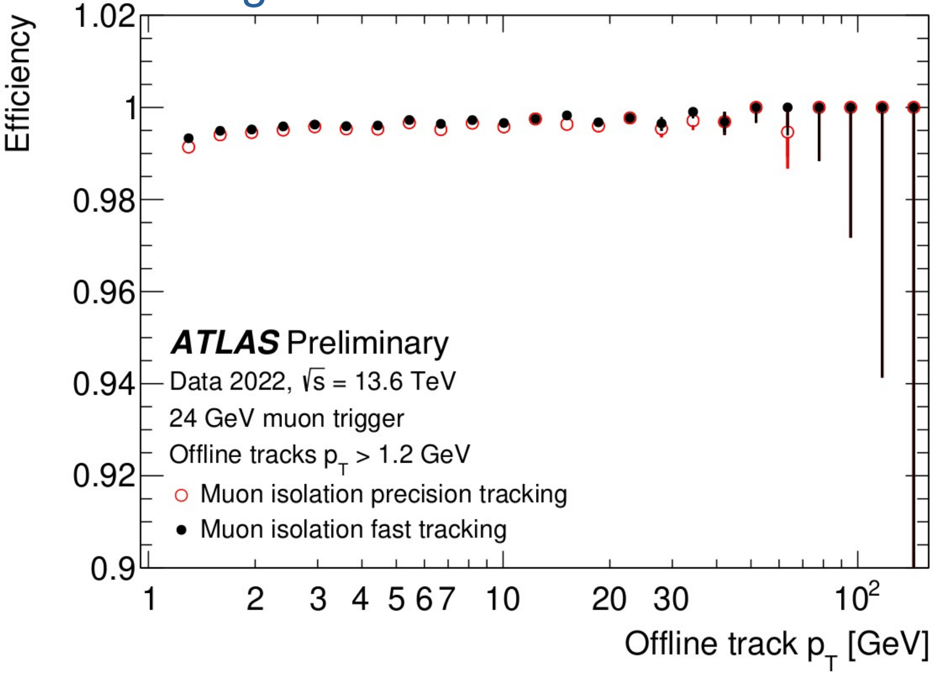
Mean closer to zero at low p_T

New For Run 3: Speeding up tracking for Muon Isolation

RoI η and Φ are wider for isolation tracking

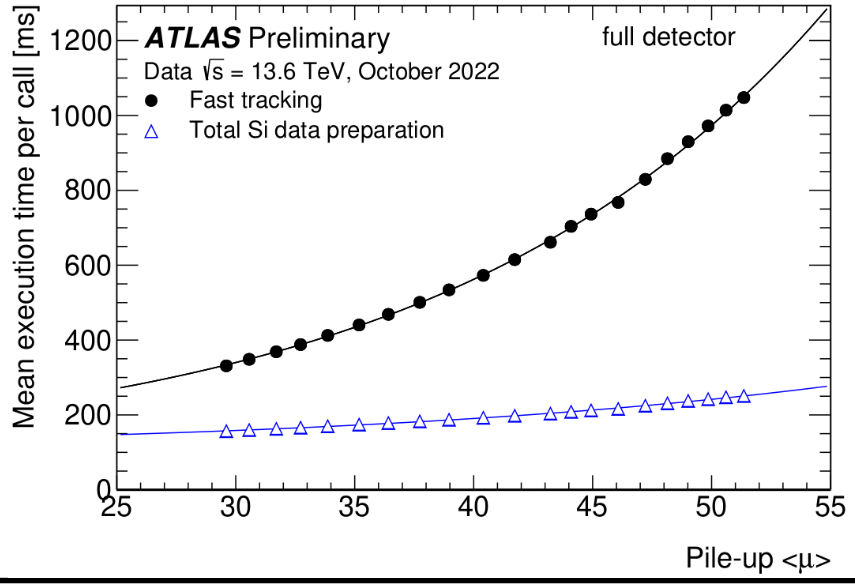
- Run in second step after finding muon
- Better use of muon candidate to refine isolation tracking RoI to z_0 position of muon candidate with a 10 mm half-width
  - For Run 2, the z_0 width was not restricted
- 5x reduction in execution time; efficiency remains high

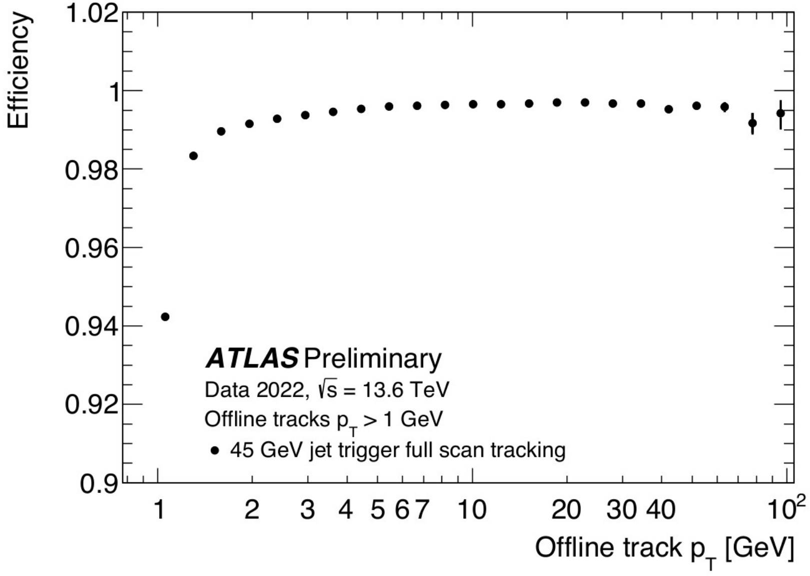




New For Run 3: Full detector tracking in HLT

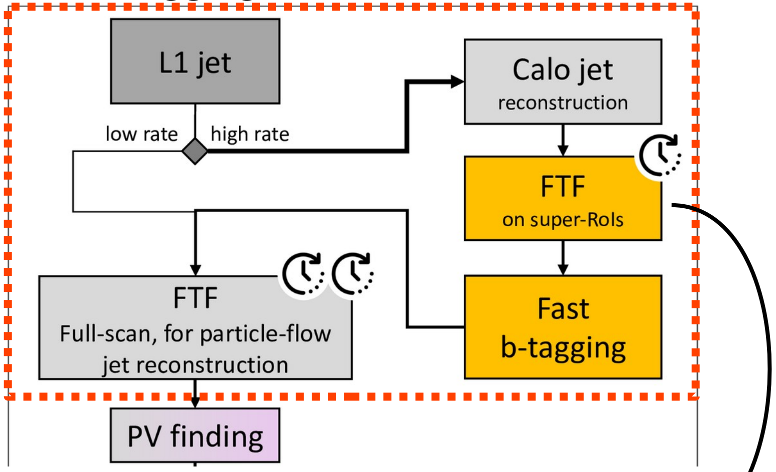
- Want full detector tracking to improve trigger performance of jets and E_T^{miss}
- No new FPGA/GPU-based solution for Run 3
- Full detector tracking is slow (~1.3 seconds / evt) and expensive
  - Increase CPU farm performance
  - Optimize tracking (filtering seeds [see backup], only FTF)
  - Run tracking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



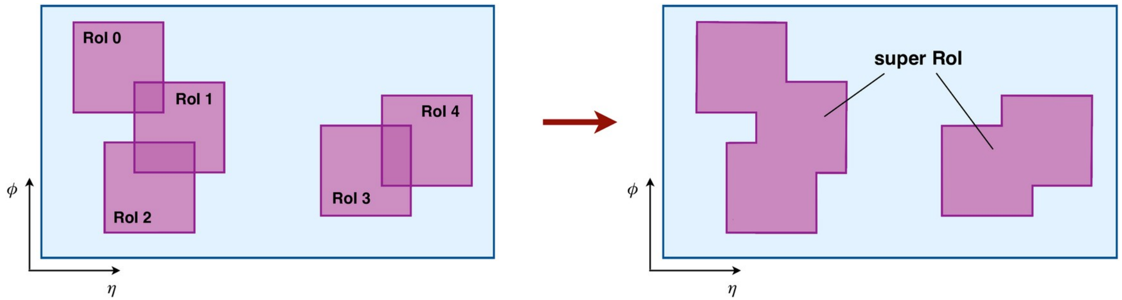


New For Run 3: RoI b-jet tracking + fast b-tagger for early rejection

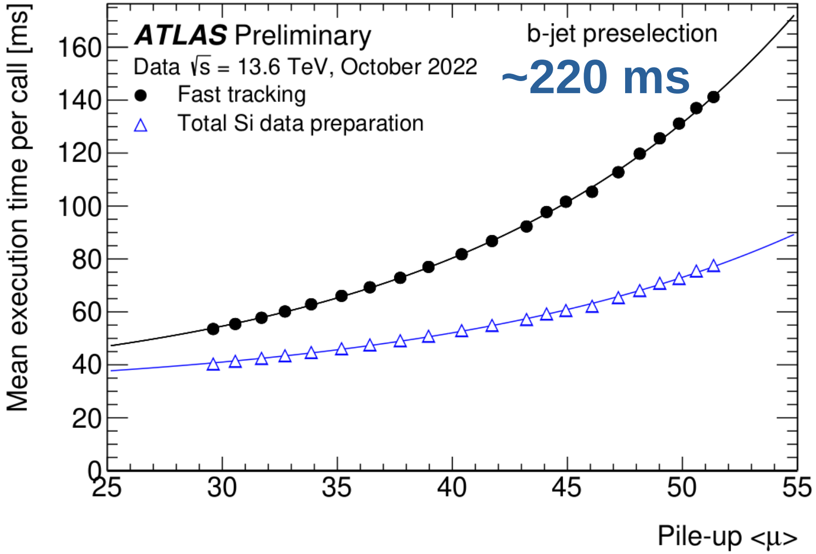
Fast b-tagging at HLT: 2306.09738



Merge RoIs to 'Super RoI'

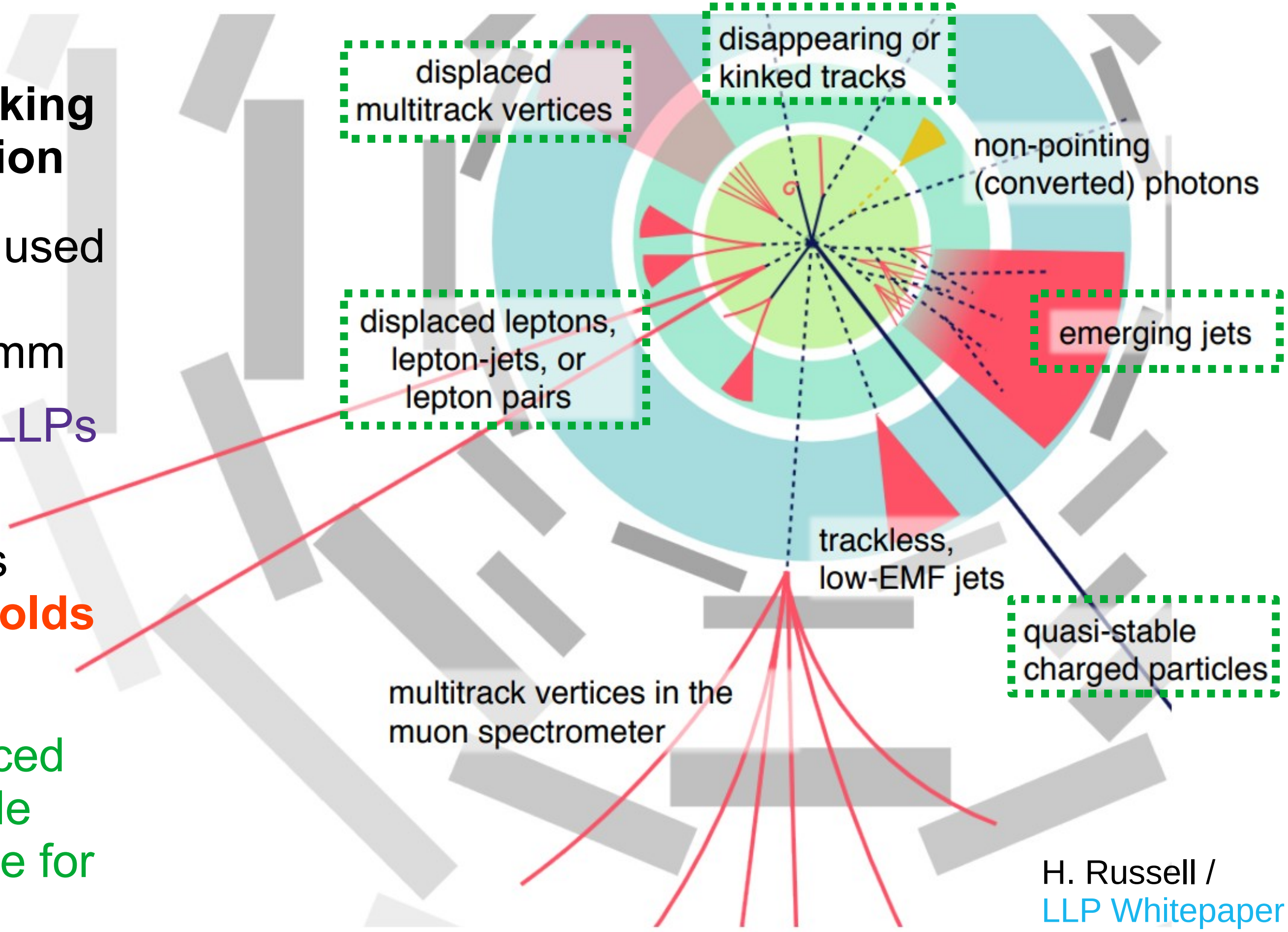


- Fast b-tagging run as a preselection before full detector tracking
  - 5 rejection factor for HH→*bbbb* signature (2% loss)
- Fast tracking in merged RoI around jets
  - Much faster than Full Scan



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 $|d_0| < 5\text{-}10$ 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



H. Russell / LLP Whitepaper

New LLP triggers for Run 3

ATL-COM-DAQ-2023-075

- 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:

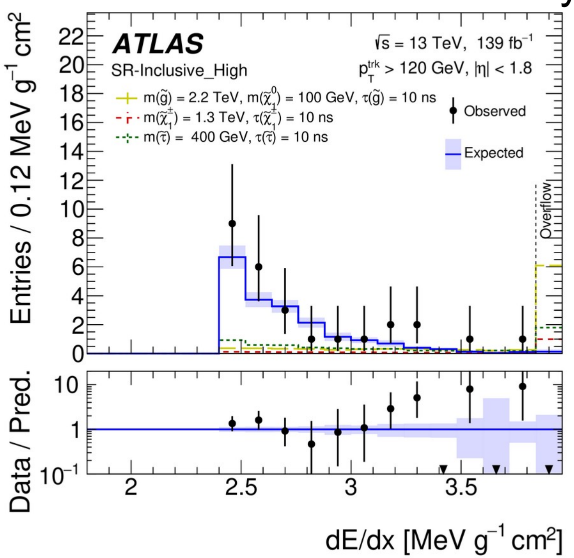
- *Make use of full scan tracking*
- *Apply additional requirements to reduce Jet or MET thresholds*
  - *Single jet threshold: 420 GeV*
  - *E_T^{miss} threshold: 90 GeV*
- *Run Large Radius Tracking (LRT)*

Most of the following slides are MC-based performance

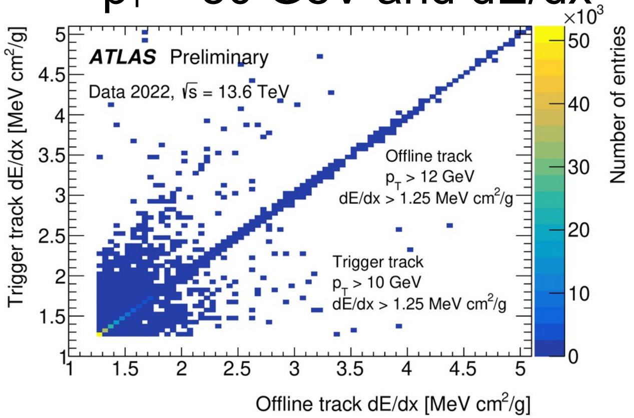
High dE/dx

dE/dx: JHEP 06 (2023) 158

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

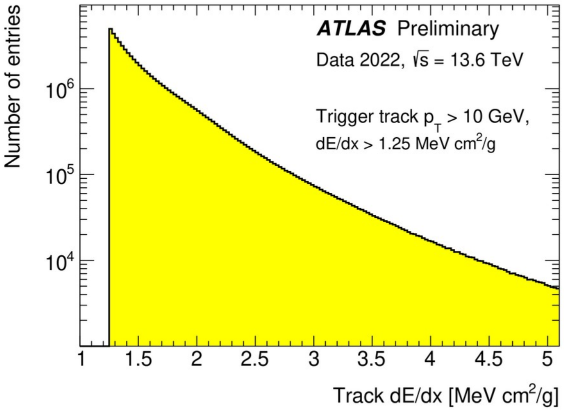


- Directly trigger on high dE/dx tracks
- Full detector tracking after **E_T^{miss} > 80 GeV**
- p_T > 50 GeV and dE/dx > 1.7 MeV/cm



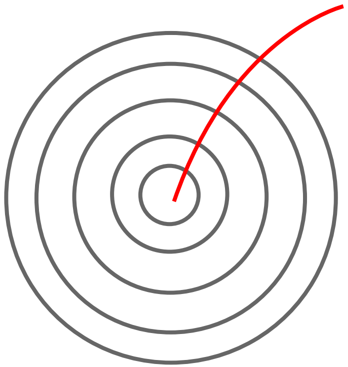
Offline v Trigger dE/dx

Trigger dE/dx from monitoring

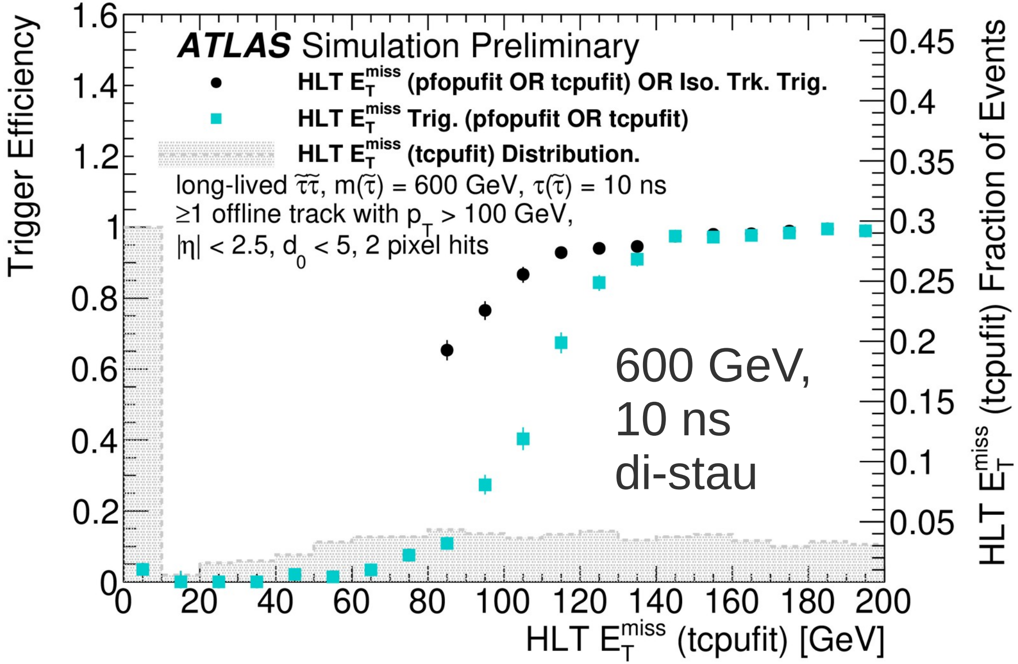


Isolated high p_T tracks

- 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^{miss} requirement for Run 3 searches

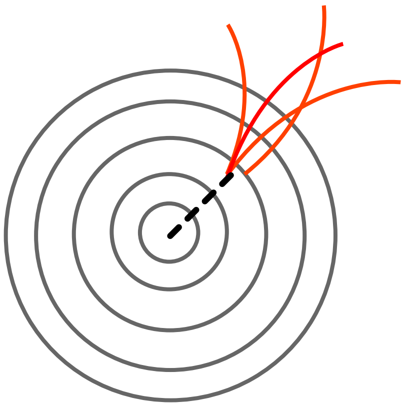


- Directly trigger on isolated high p_T tracks
- Use full scan tracking after **E_T^{miss} > 80 GeV**
- p_T > 120 GeV + track-based isolation

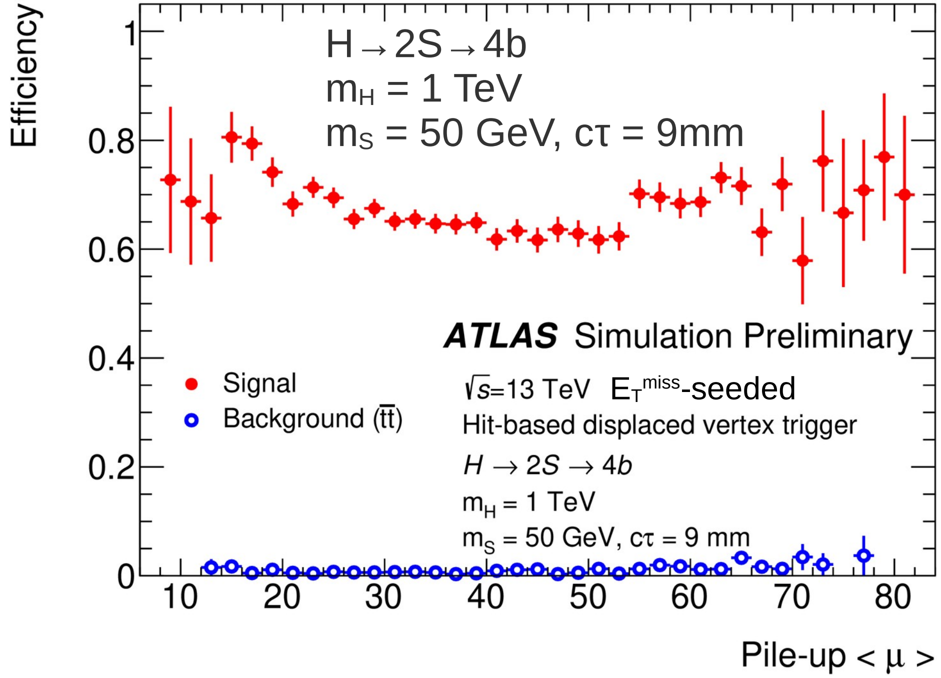


Hit-based Displaced Vertex

- 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

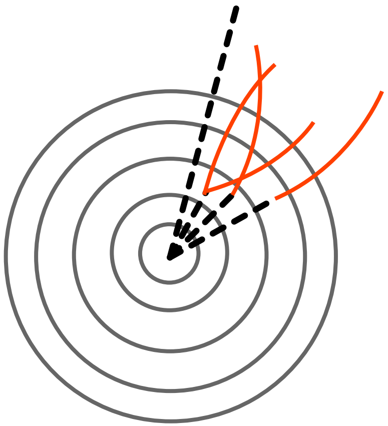


- 1) E_T^{miss} preselection and Jet with p_T > 200 GeV and |η| < 1 passing BDT
- 2) Jet with p_T > 260 GeV and |η| < 1 passing BDT

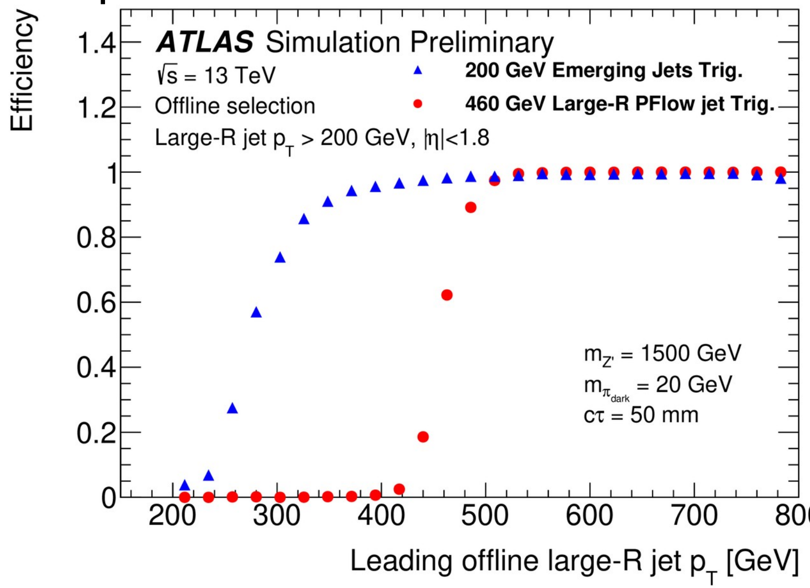


Emerging jets

- 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

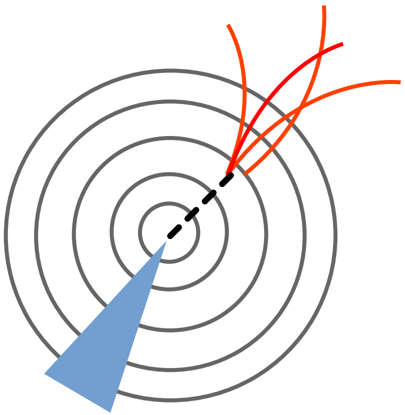


- 1) Central Large-R jets with p_T>200 GeV and PTF < 0.08
- 2) 45 GeV Photon seeded with 2 Large R jets with p_T > 55 GeV and PTF < 0.1
- Overall efficiency depends on PTF acceptance

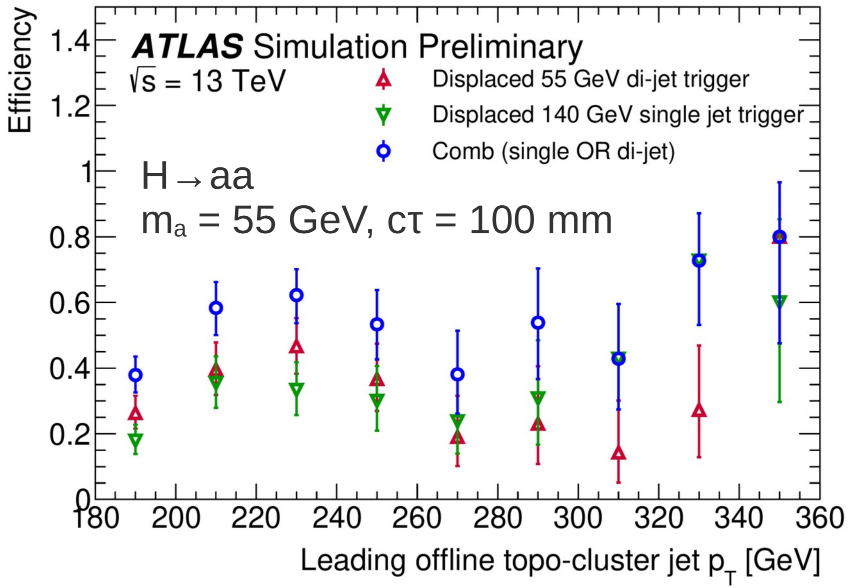


Displaced jets

- 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 $n_{prompt} \leq 2$

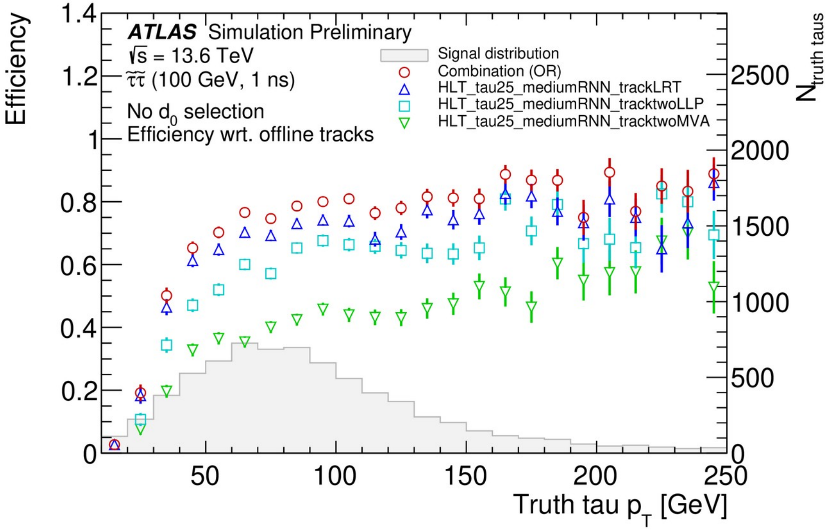


- Leading 180 GeV jet (ISR Jet) +
- 1) 140 GeV jet with $n_{promp} \leq 1$ and $n_{disp} \geq 3$
- 2) Two 50 GeV jets with $n_{promp} \leq 2$ and $n_{disp} \geq 3$
  - 2nd jet may have $n_{disp} \geq 0$ if $n_{promp} \leq 1$

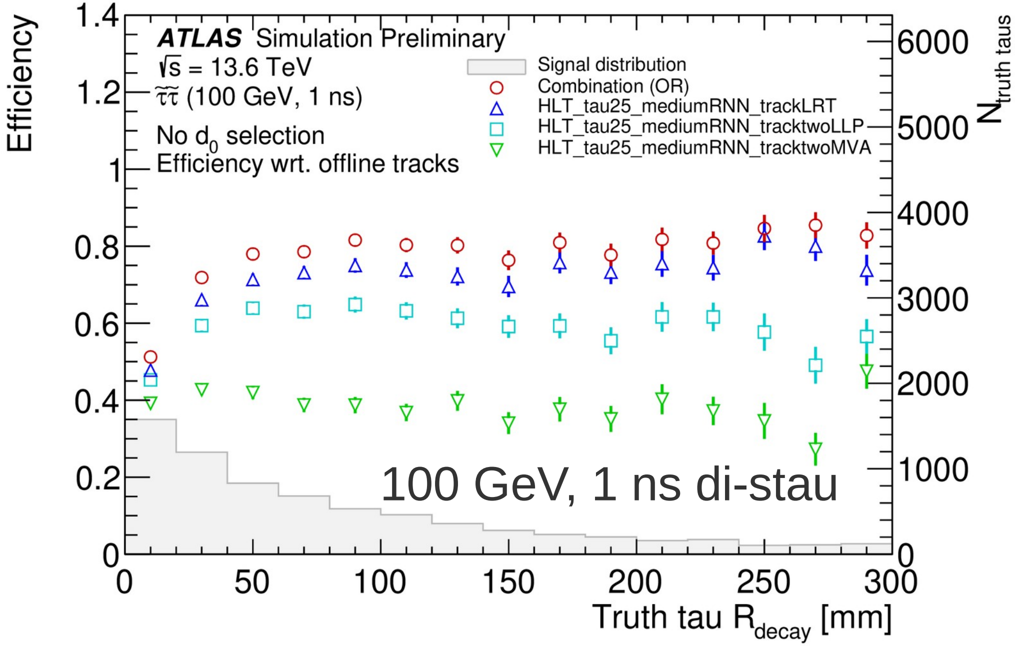


Displaced Taus

- 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

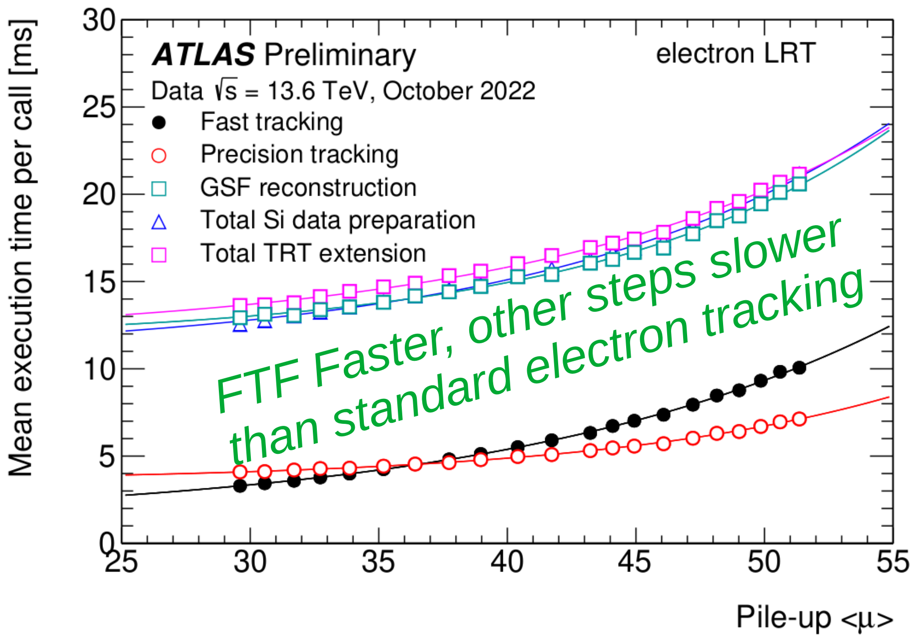


- Single tau: $p_T > 200$ GeV
- Di-Tau: $p_T > 80$ GeV and $p_T > 60$ GeV
- Tau+X, seeded by X, with lower thresholds

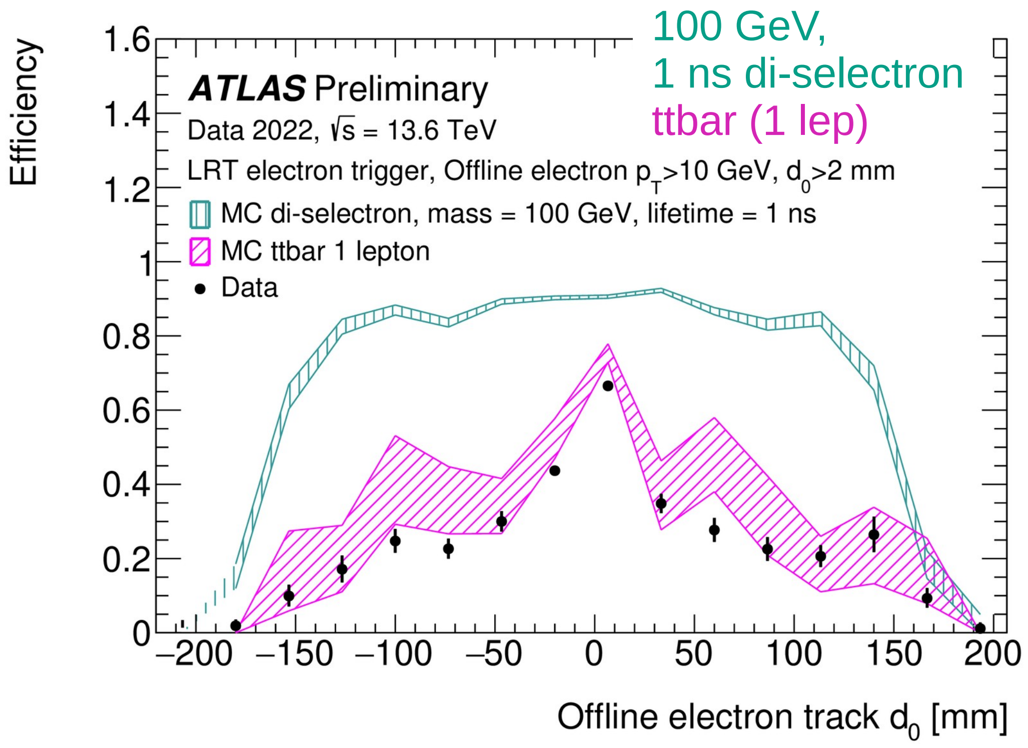


Displaced Electrons: Trigger Tracking Performance

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

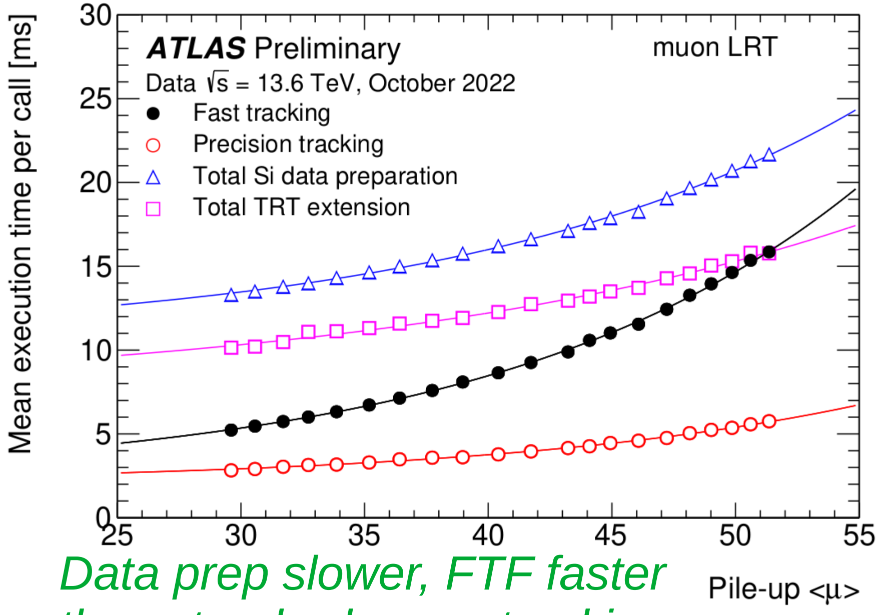


- p_T > 30 GeV and d_0 > 3 mm
- Modified electron ID that doesn't depend on d_0 or number of silicon hits



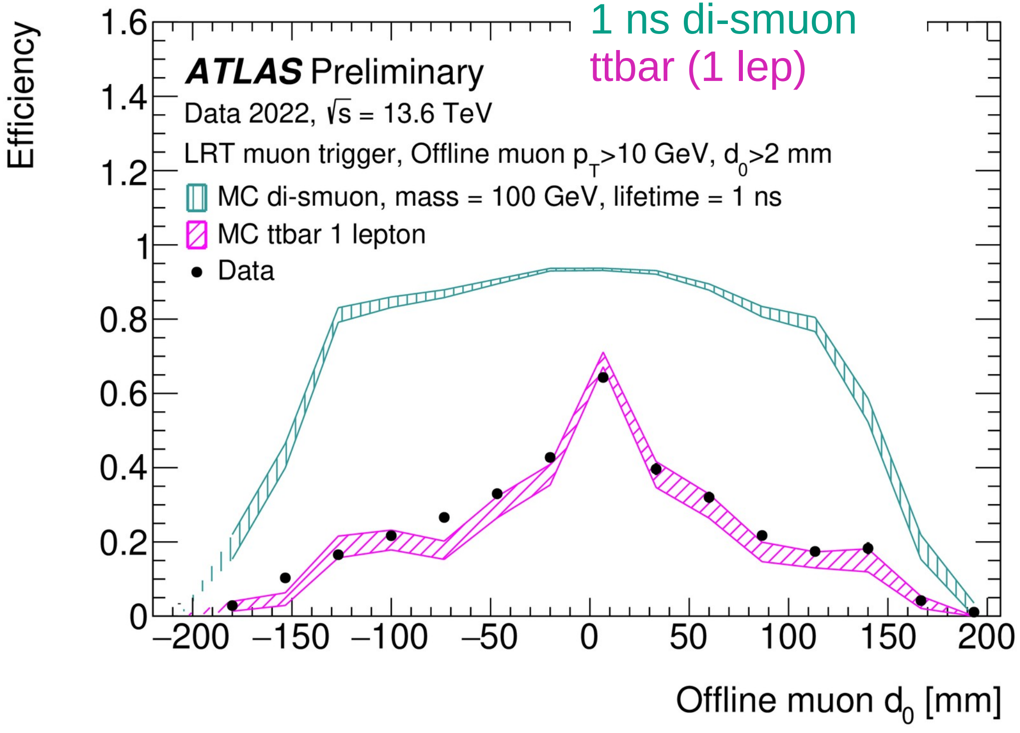
Displaced Muons: Trigger Tracking Performance

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



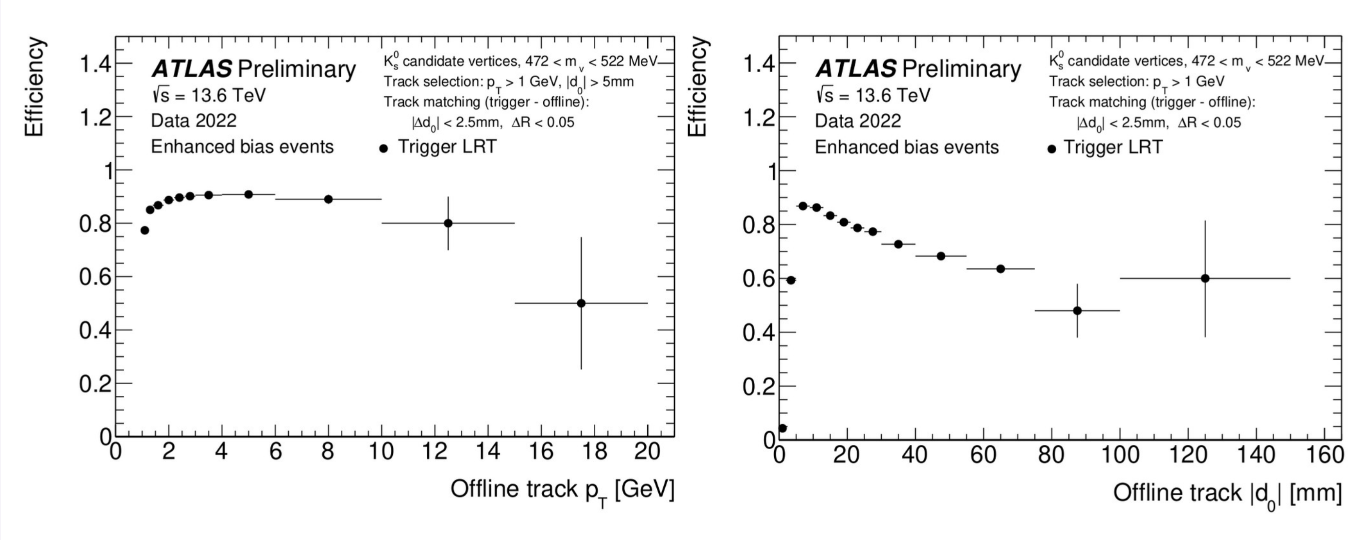
Data prep slower, FTF faster than standard muon tracking

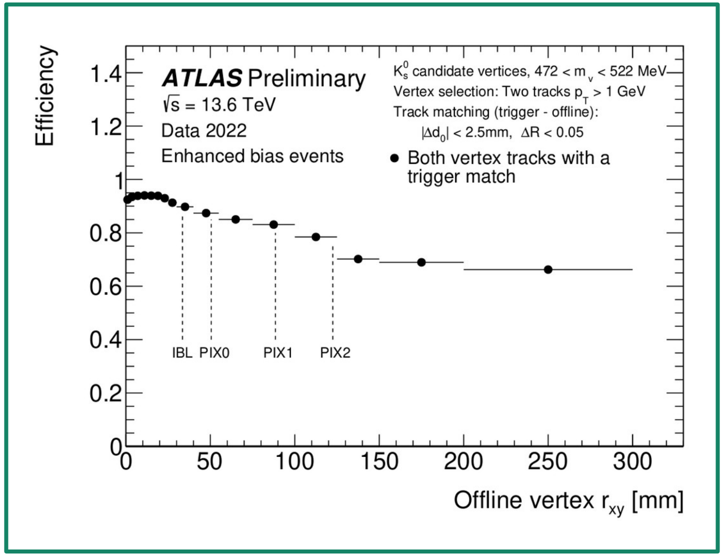
- p_T > 20 GeV and d_0 > 2 mm



Full Detector Trigger LRT Tracking Performance with K^0s

- Use offline K^0s 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^{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

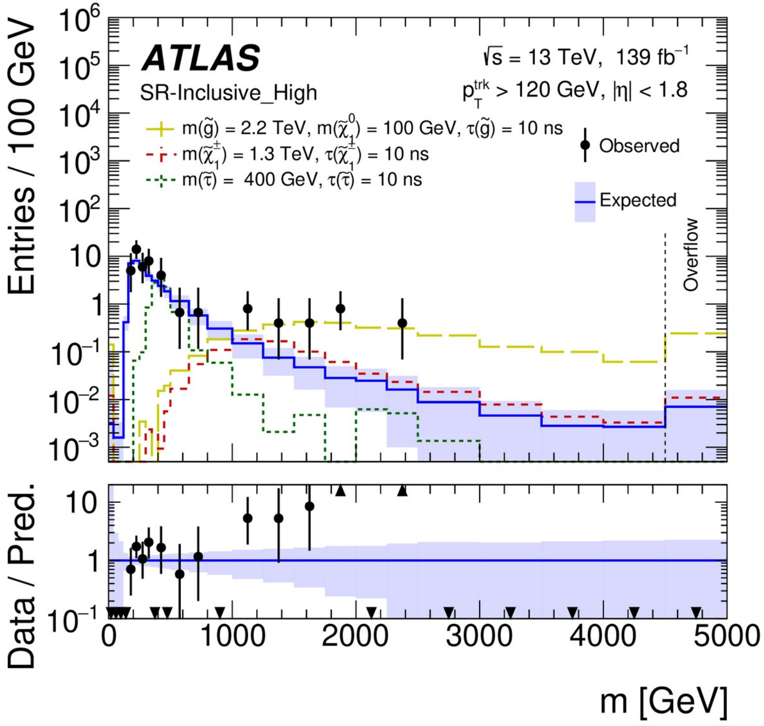
- Excellent performance in Run 3 so far and continues to improve

Backup

dE/dx Run 2 search

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

dE/dx+ToF: ATLAS-CONF-2023-044



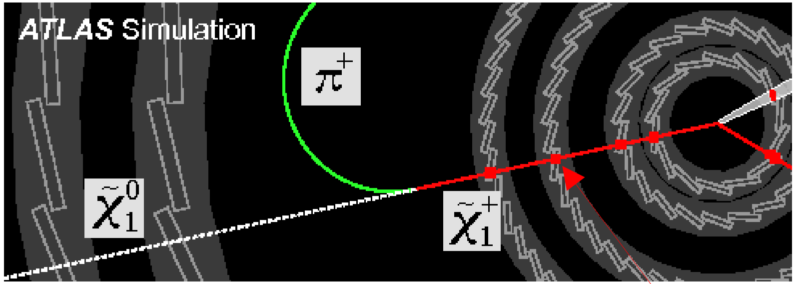
Improvements for Run 3

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

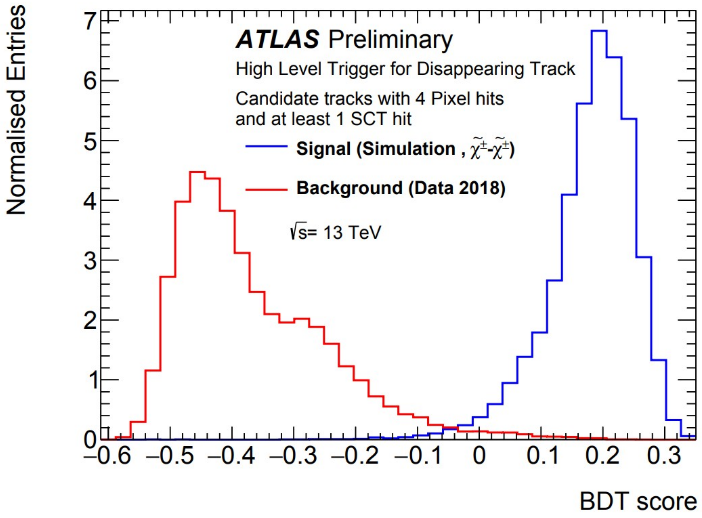
Disappearing Track Trigger

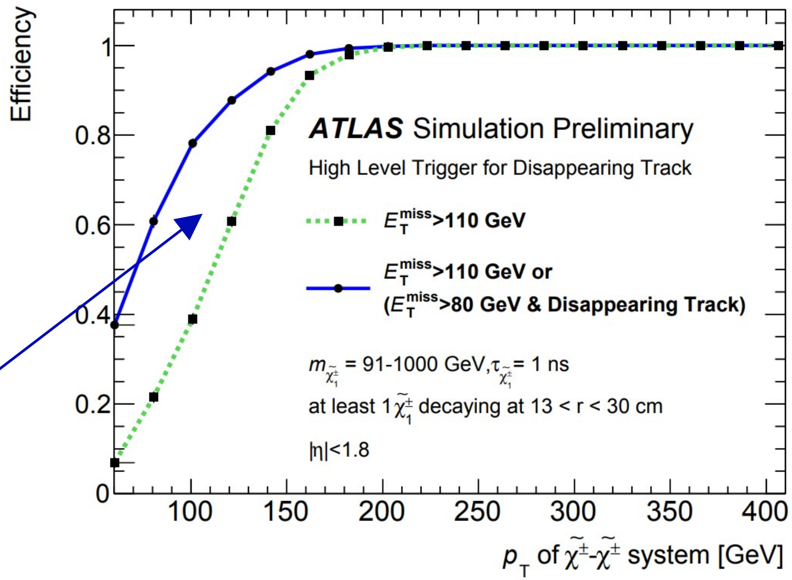
ATL-COM-DAQ-2022-011

- 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, χ^2,..)



Long-lived chargino



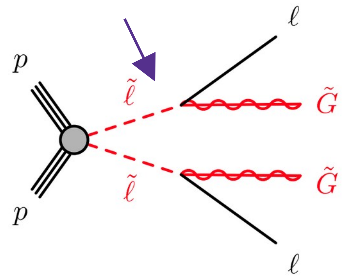


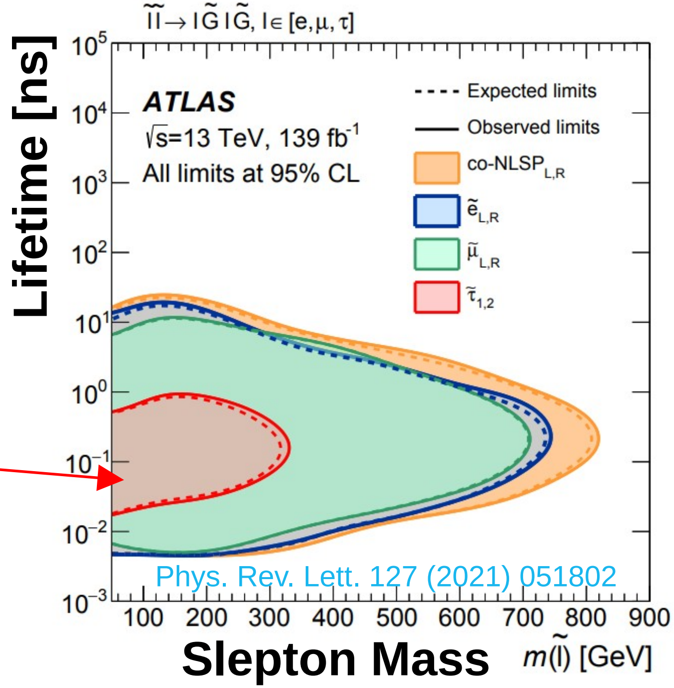
- Improves acceptance over pure MET trigger for lower momentum models!

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

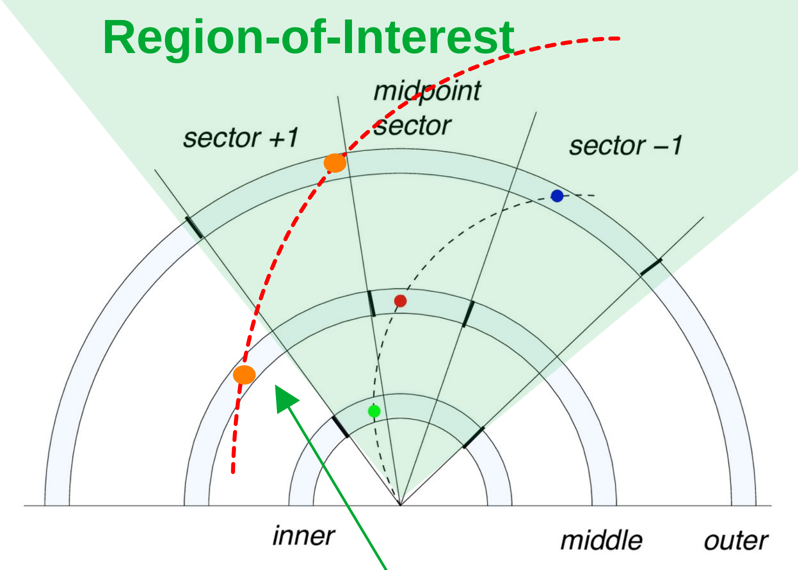
Displaced Decay





Large Radius Tracking for Leptons in RoIs

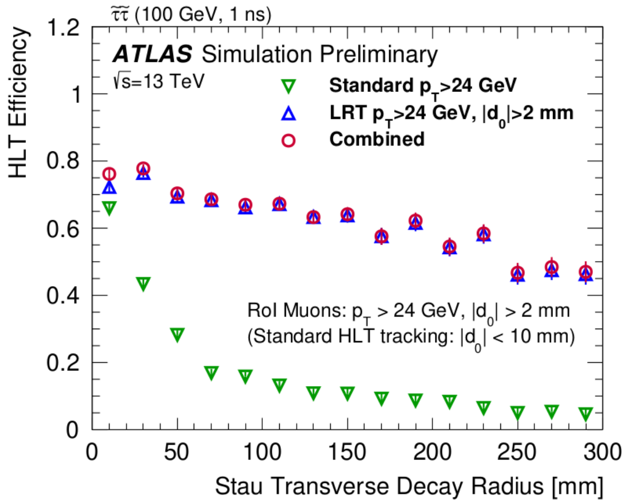
- **SCT only seeding**, without ordering by impact parameter; tighter track selection than for prompt
- **Single pass of tracking**, unlike offline tracking that runs on remaining hits after standard tracking
  - **Reconstructs p_T>1 GeV and $|d_0|$>2mm**
  - Timing and performance acceptable without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

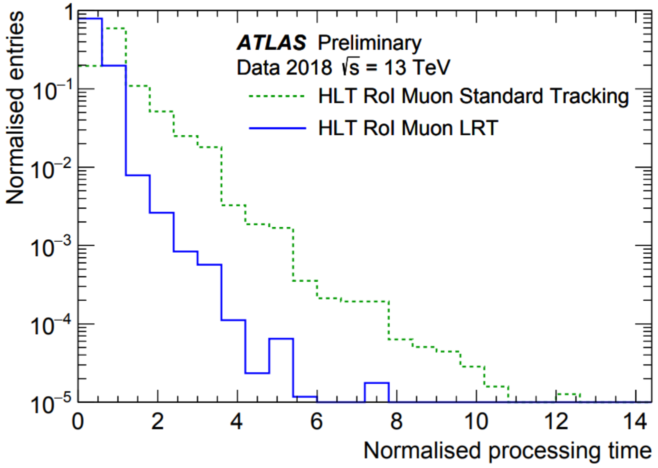


Number of layers required and size of RoI in ϕ limit reach to large displacements

ATL-COM-DAQ-2022-023

ATL-COM-DAQ-2022-026



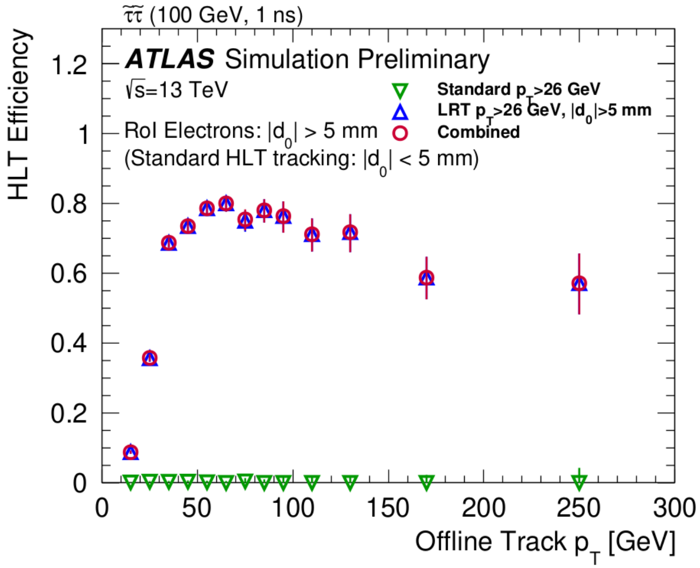


Expected LRT Lepton Trigger Performance

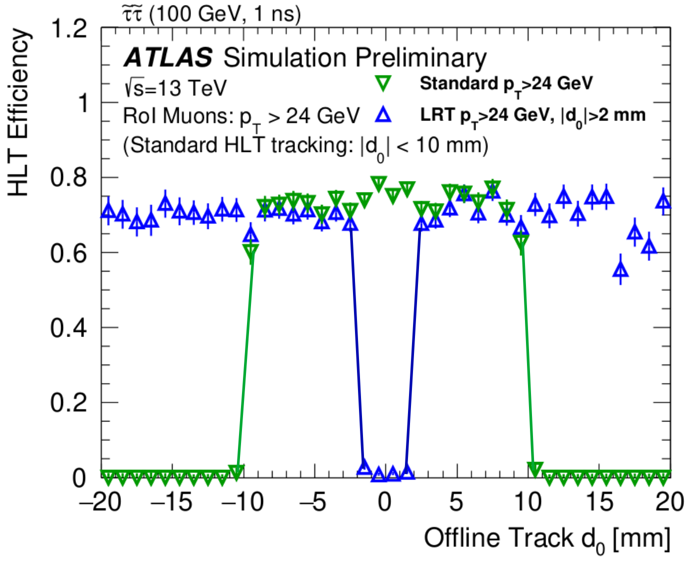
ATL-COM-DAQ-2022-023

- 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!



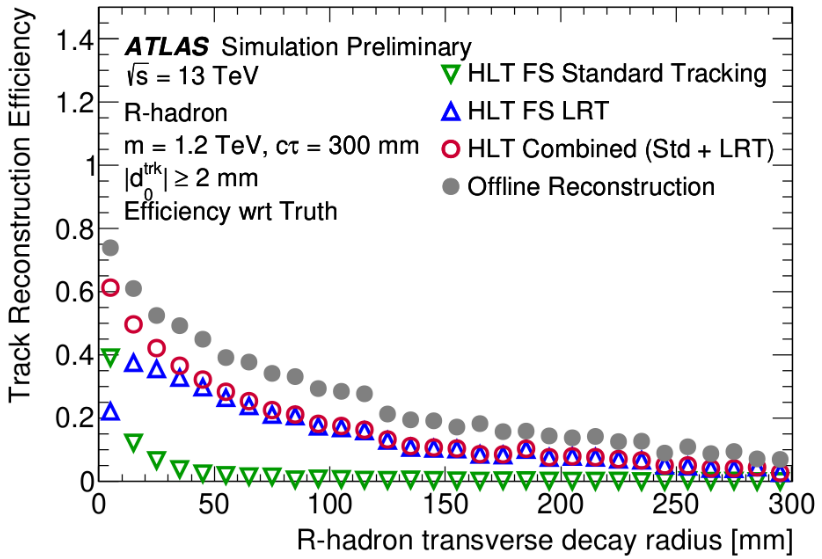
Complements coverage in d_0 from standard muon chain

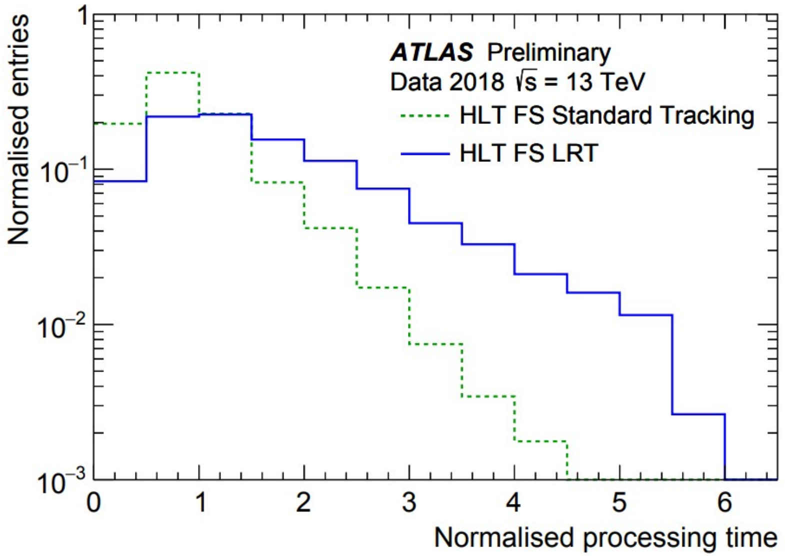


Full Scan Large Radius Tracking

- 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

ATL-COM-DAQ-2022-023

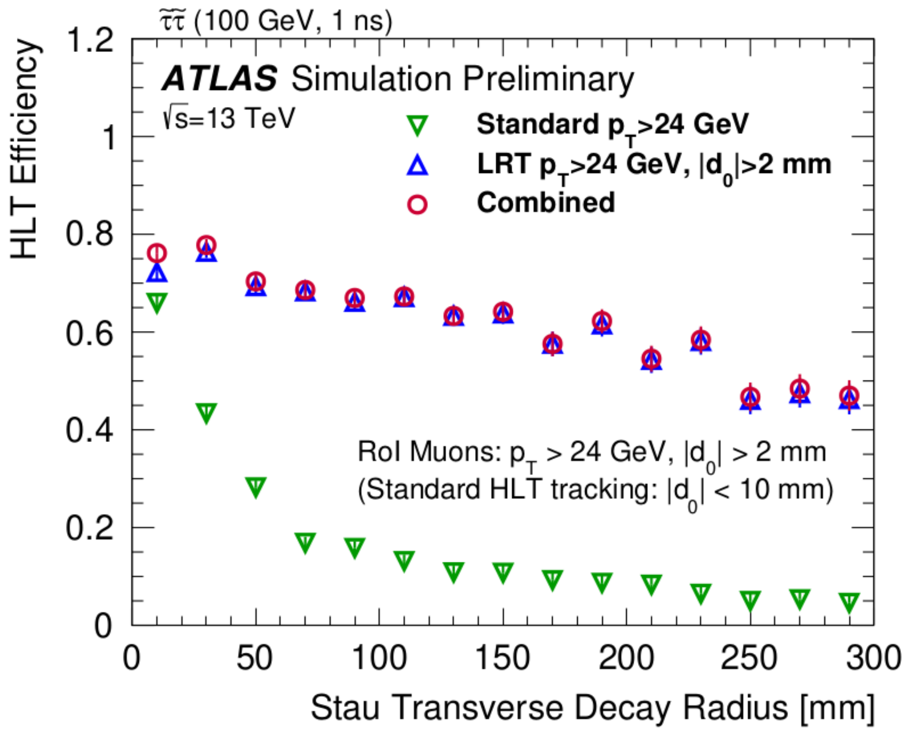


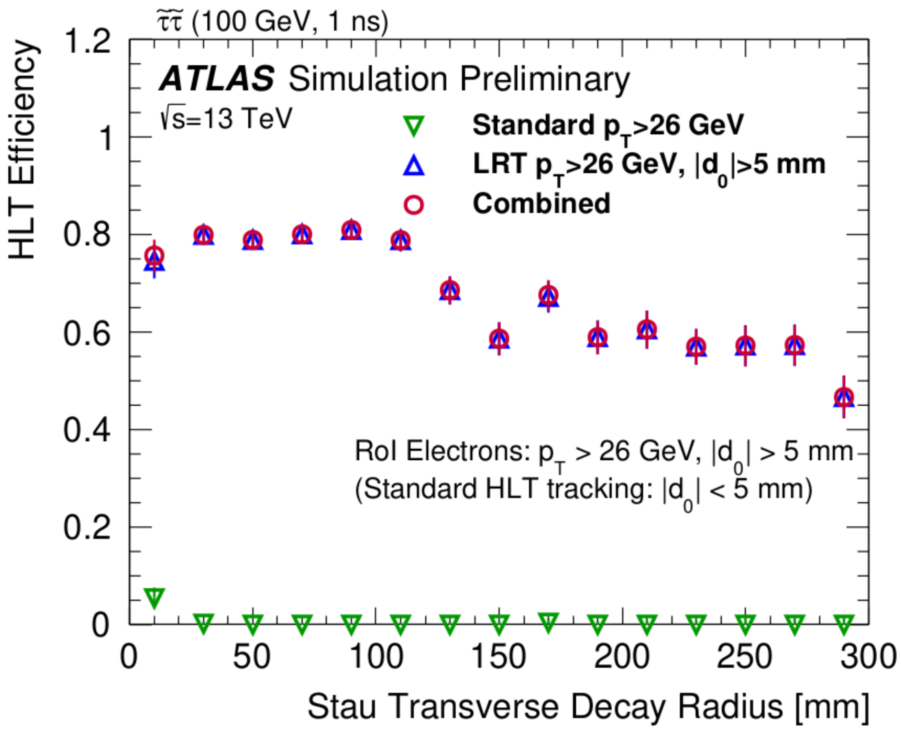


ATL-COM-DAQ-2022-026

LRT Lepton Eff vs Prod Radius

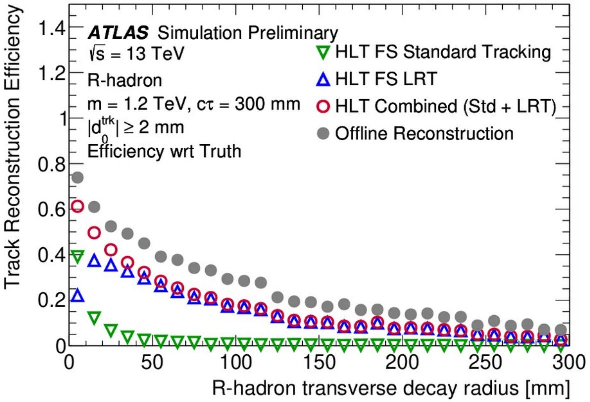
ATL-COM-DAQ-2022-023

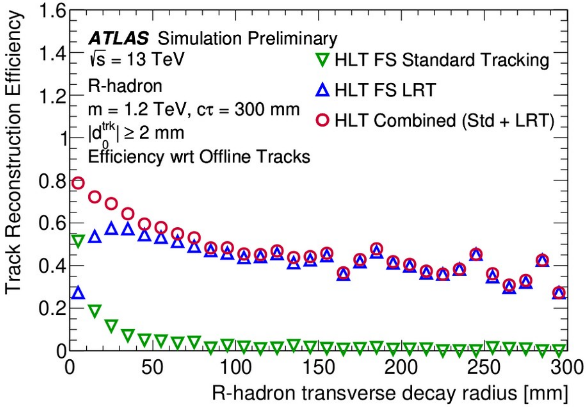


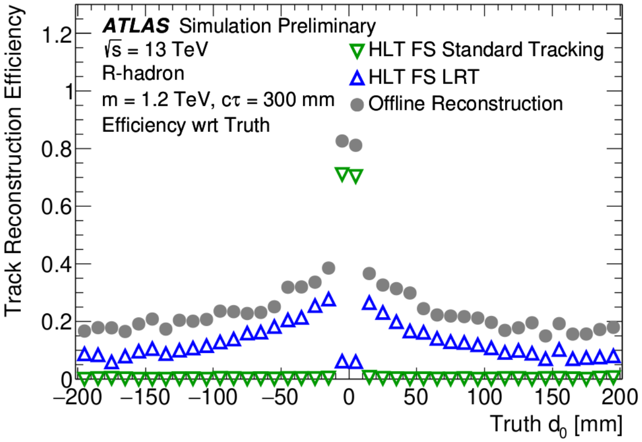


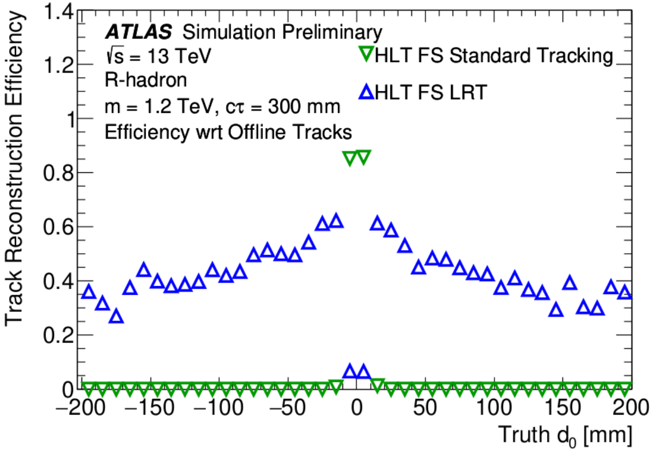
Additional LRT Full Scan Eff

ATL-COM-DAQ-2022-023







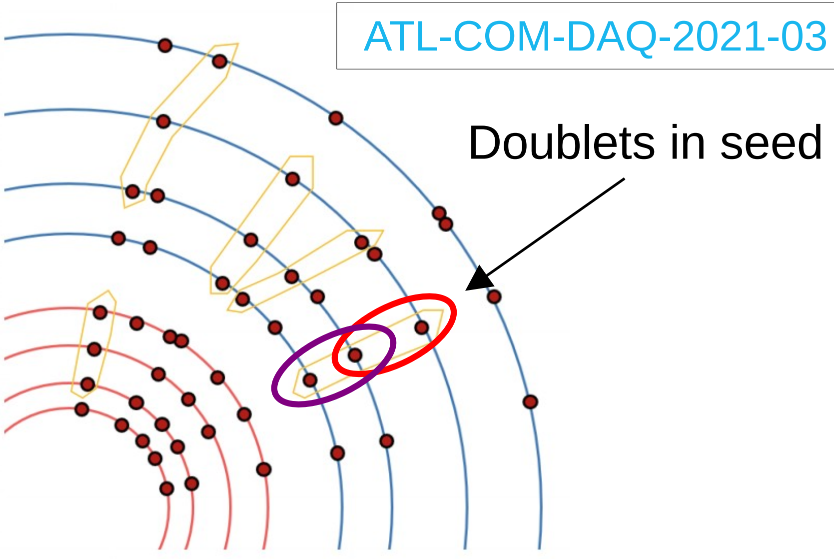


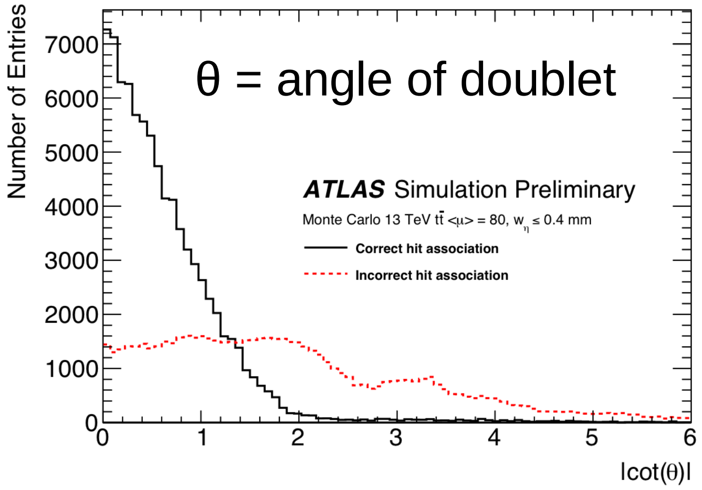
Speeding up Full Scan tracking

Speeding up Track Seeding

ATL-COM-DAQ-2021-03

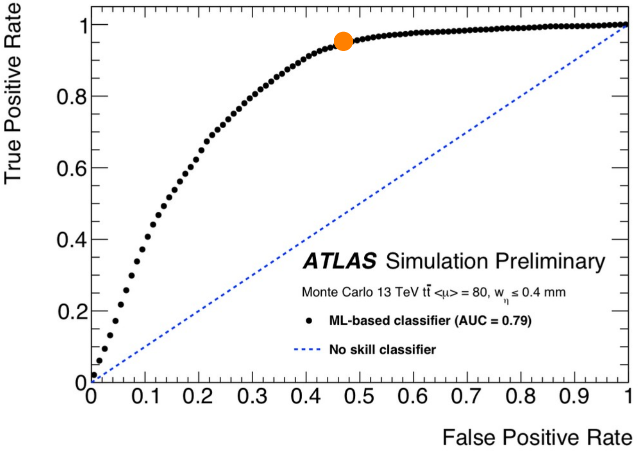
- Full scan tracking is time consuming
- Seeding, forming of triplets, first step in combining hits into tracks
- Number of seeds increases rapidly with number of hits (e.g. larger pileup)
- Number of seeds also impacts time needed for later steps of tracking
- **Speed up tracking by rejecting bad seeds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

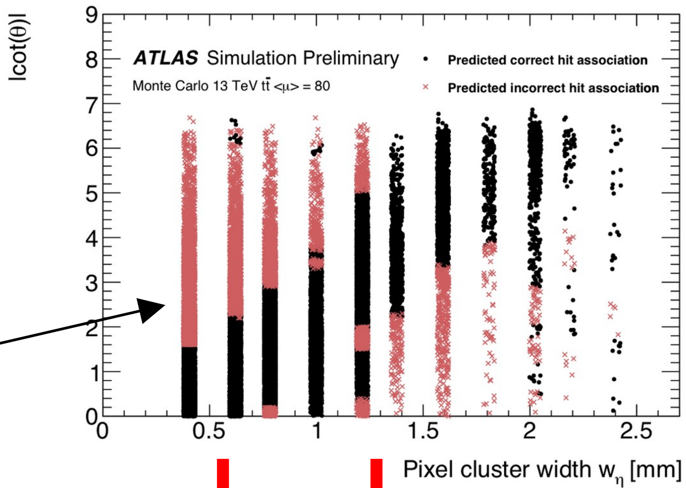


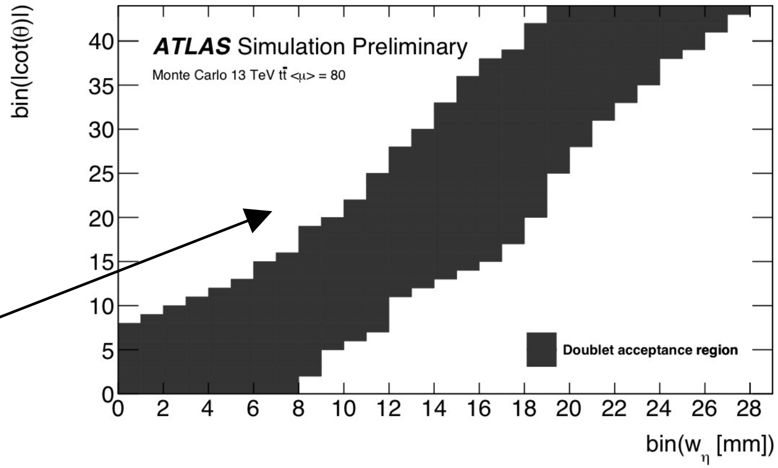


ML based filtering

- Train classifier on **cluster width in η** and **doublet inclination angle** with respect to the z-axis
- Train for pixel-barrel and pixel-endcap doublets and standard/long pixel combinations (banding)







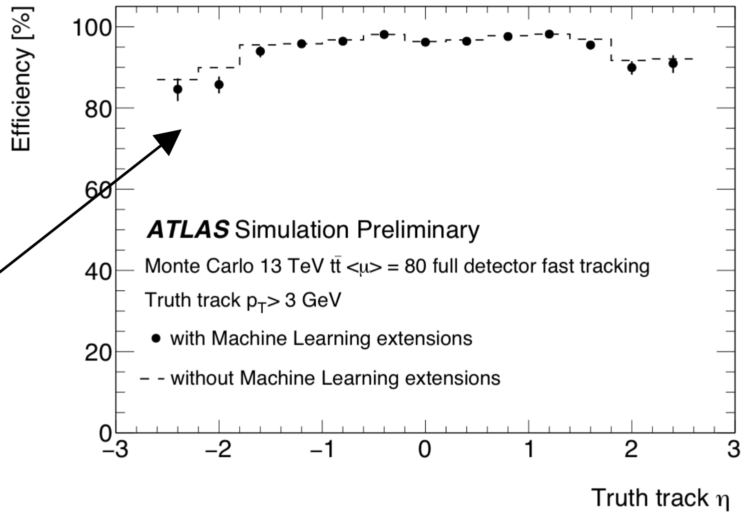
ATL-COM-DAQ-2021-03

- Turn acceptance region of doublets into **look up table**

Resulting Reduction in Processing Time

ATL-COM-DAQ-2021-03

Total Speed-up Factor	Seed Generation	Seed Processing	Track Fitting
2.3×	1.3×	3.3×	1.5×



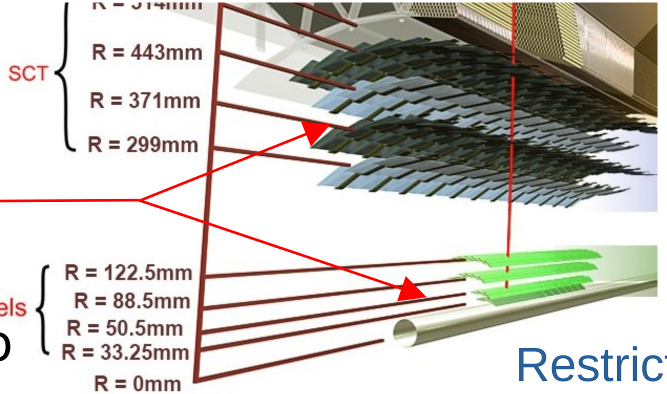
- Large reduction in seed processing time and total fast tracking time
- Minimal loss in efficiency
- Robust improvement with increasing pileup

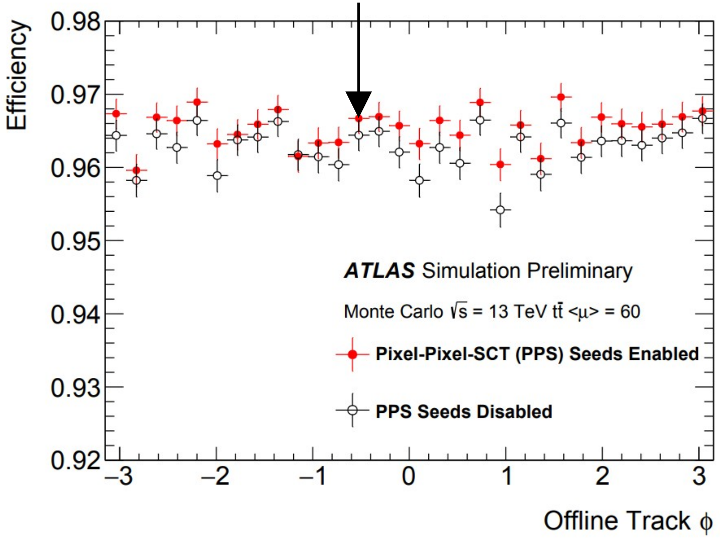
$< \mu >$	Efficiency Loss (%)	Total Speed-up Factor
40	0.7	1.6×
60	0.7	2.1×
80	1.1	2.3×

Optimizing Full Scan Tracking for Jet and MET Signatures

ATL-COM-DAQ-2022-022

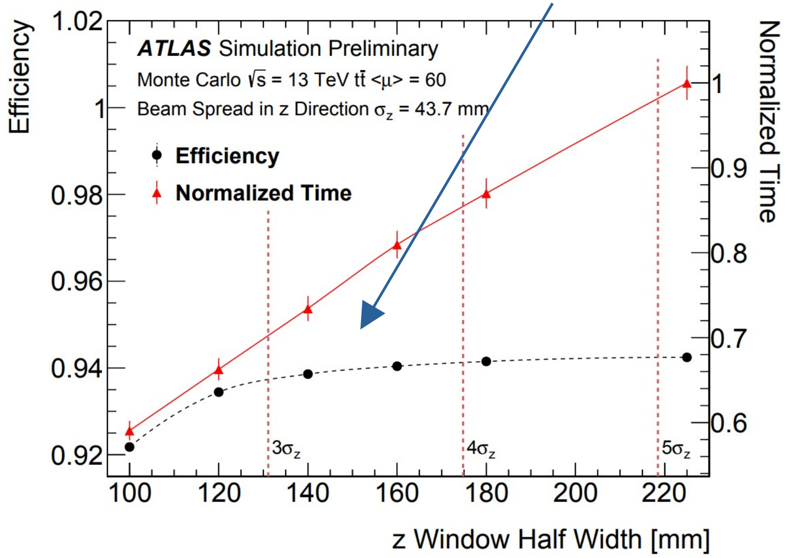
- No mixed Pixel+SCT triplet seeds
  - ‘PPP’ and ‘SSS’ only
- 1.9x mean event processing time speed up





Minimal loss in efficiency

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



Other backup material
Run 2 / RoI details

Timing for Muon Trigger

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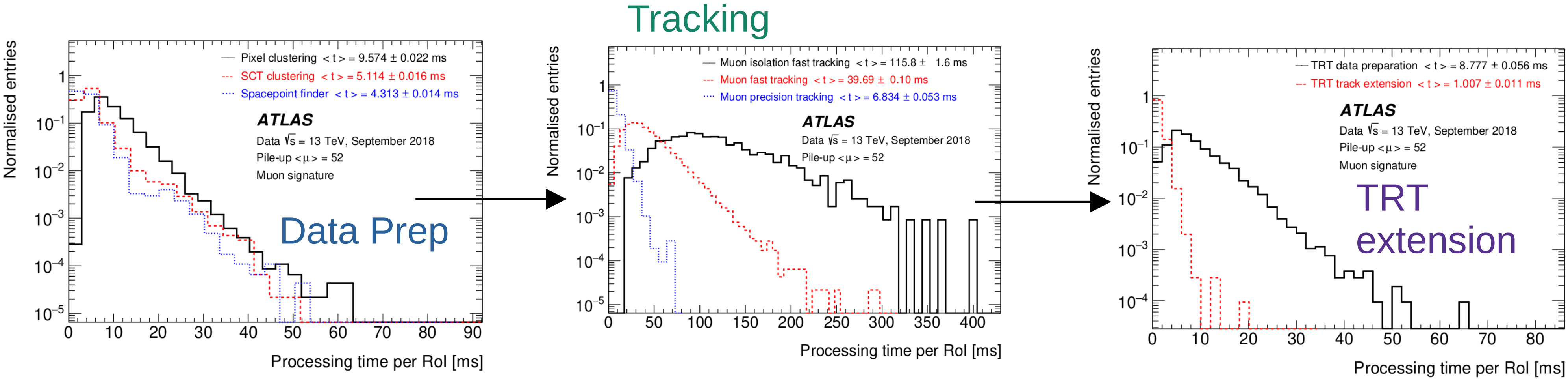

- Clustering and spacepoint formation is fast: 4-10 ms
- Fast Tracking mean of 40 ms (tail up to 300 ms), precision tracking 7 ms
- Tracking for isolation in wider RoI is slower around 116 ms
- Extension to TRT is also fast, under 10 ms
- Sum of mean times < 200 ms

Lepton Tracking Efficiency and Resolution vs Offline Tracks

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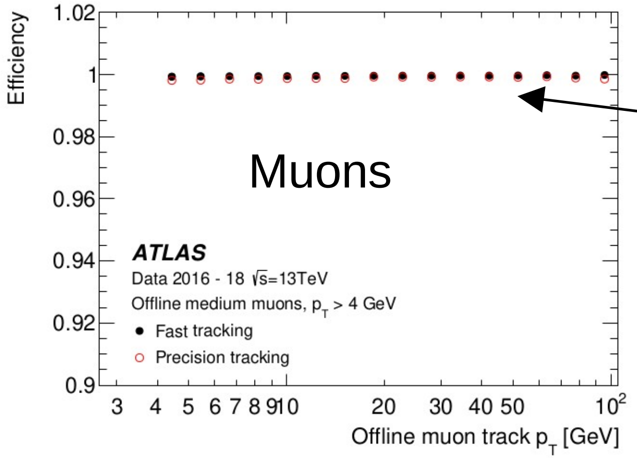
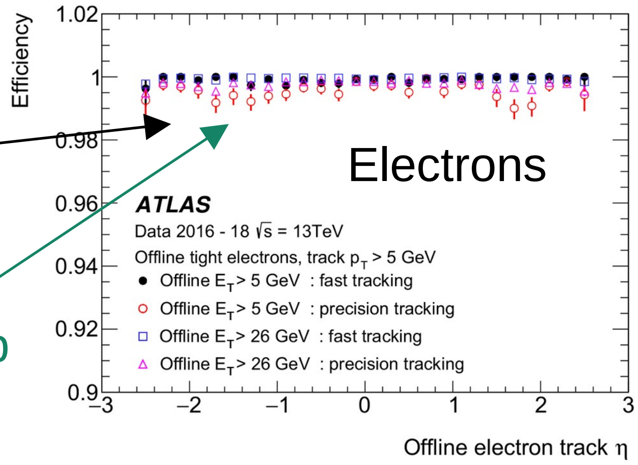
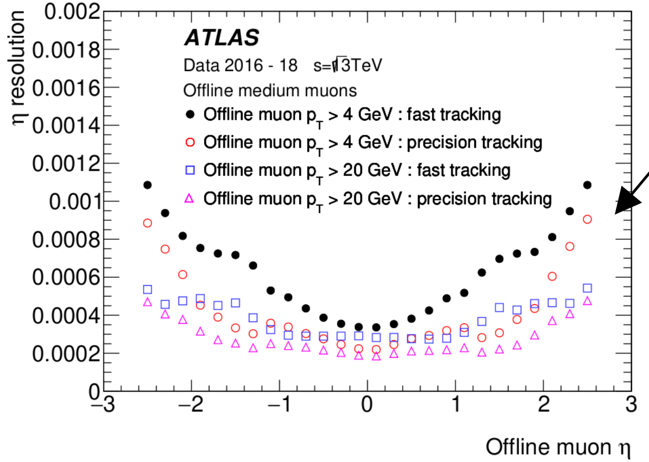


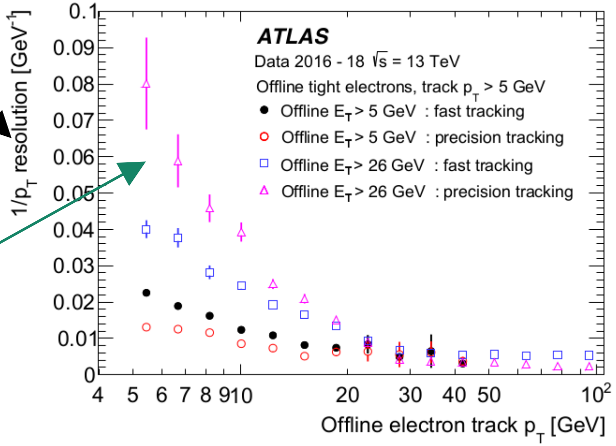
Nearly fully efficiency with respect to offline tracks



Small inefficiency for electrons near transition between barrel and endcap



Precision tracking improves object resolution



Track p_T << electron threshold allows for bremstralung

Two Stage Tracking

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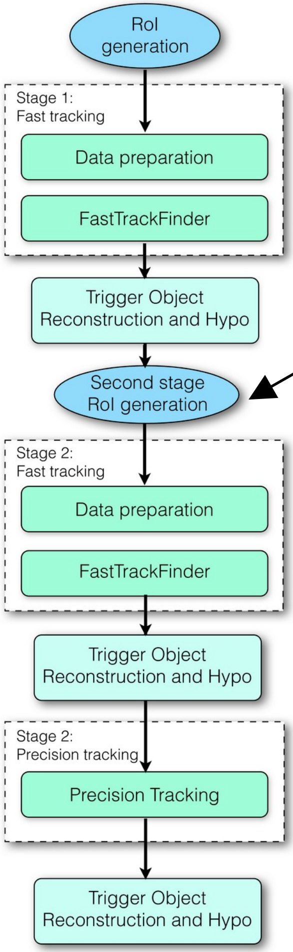
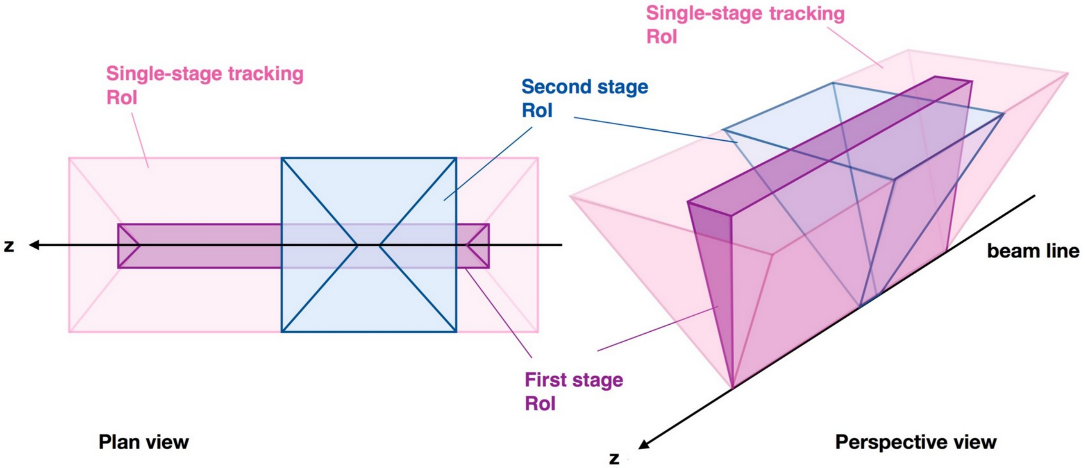
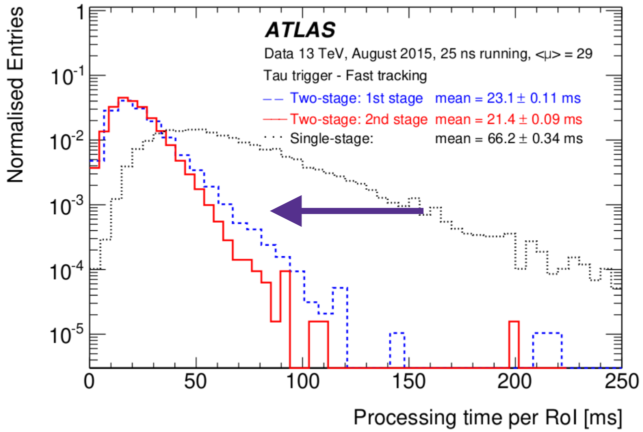


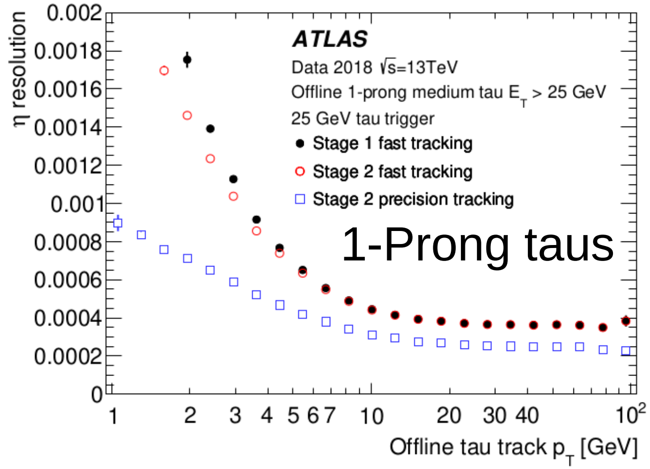
- Allows for updating RoI after first pass to optimize CPU performance and efficiency—**improvement** over single stage strategy
- Used for **tau** and **b-jet** triggers
  - Run first pass to find luminous / vertex region in Z with narrow eta and phi
  - Second pass with restricted Z region, but full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

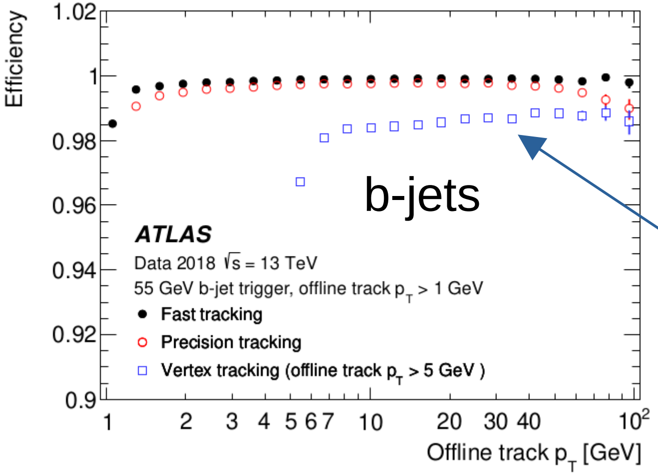


Two stage tracking for taus



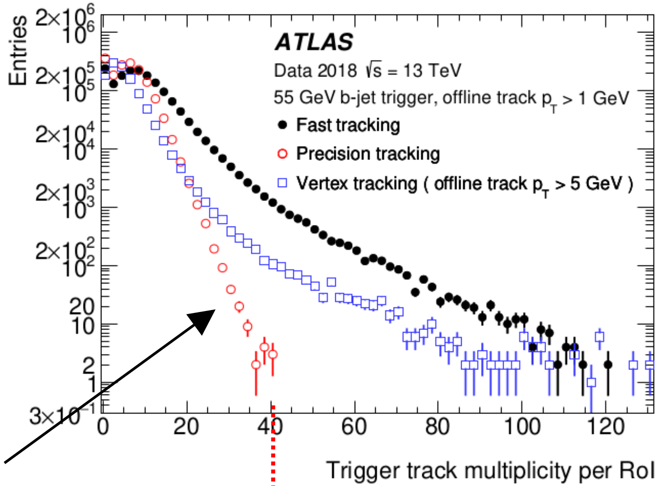
Two Stage Tracking (taus and b-jets)



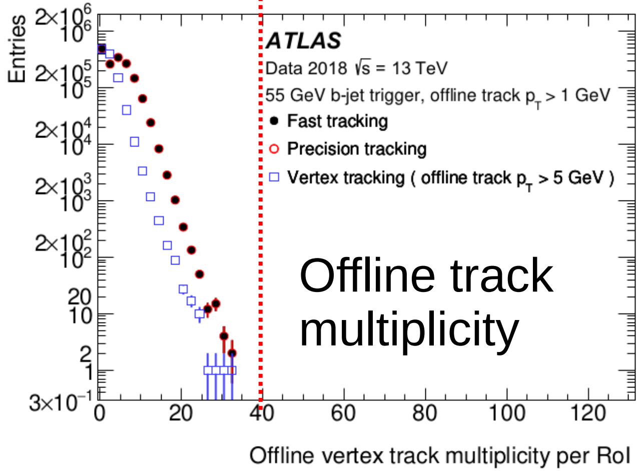


Vertex track pattern recognition only runs on track candidates with p_T>5 GeV

b-jet Trigger track multiplicity



Example of precision tracking increasing purity of tracks



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Merging Regions-of-Interest: ‘Super RoIs’

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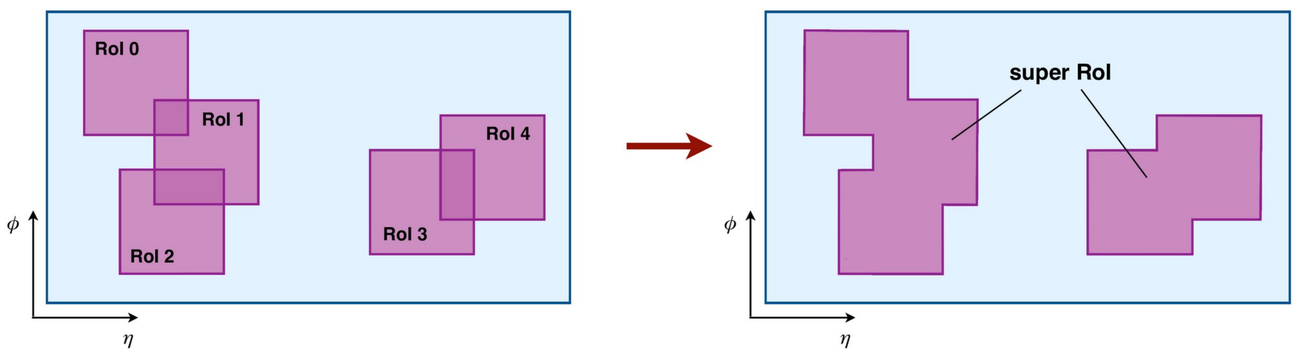
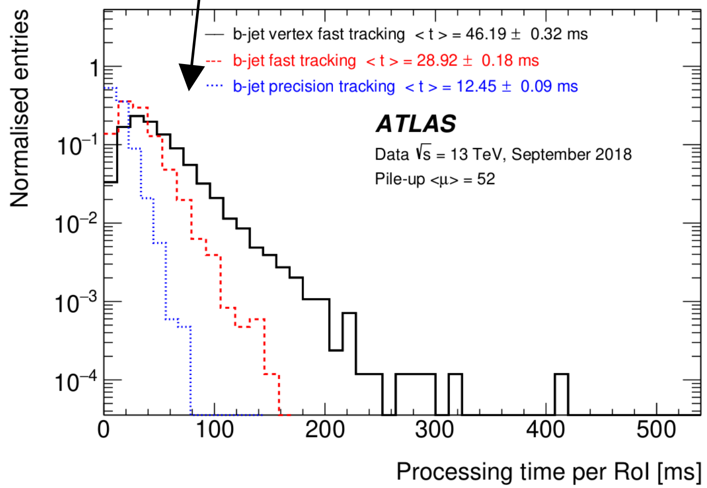
- B-Jet triggers are most costly in terms of CPU resources
- Jet triggers may have multiple RoIs per event used to seed b-jet trigger
  - **Merging the RoIs** into a single event wide RoI reduces the overhead from overlapping regions, e.g. data preparation
- Two stage tracking strategy to first find 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) ms for lepton RoIs]

Merge RoIs to ‘Super RoI’





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

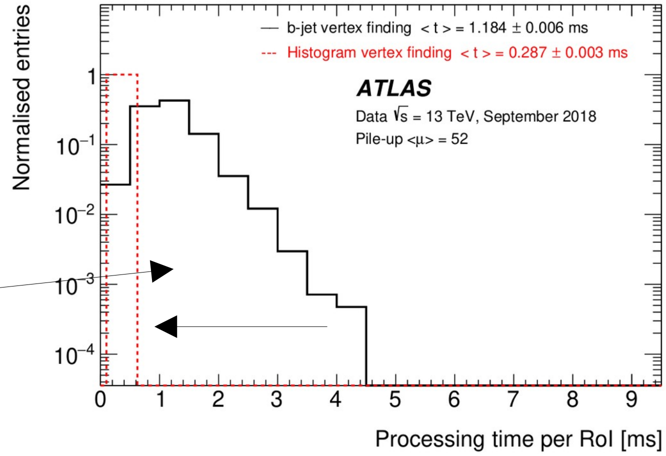


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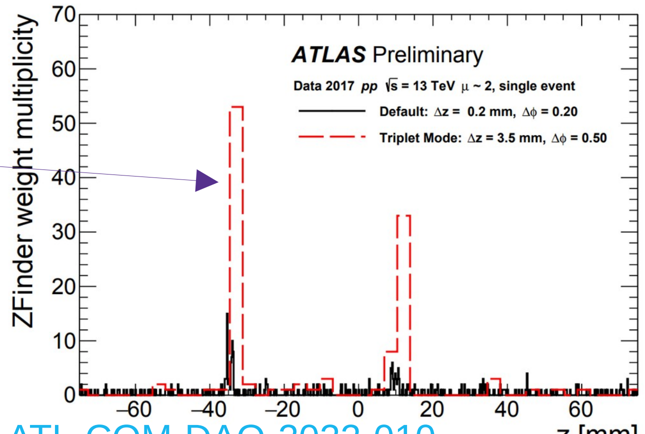
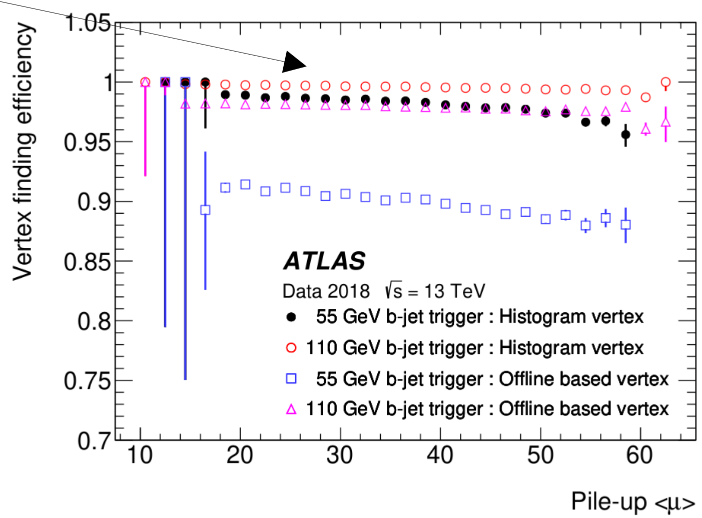
Illustration of concept using seeds

Peaks correspond to vertex candidates



ATL-COM-DAQ-2022-010



Electron and b-jet Timing

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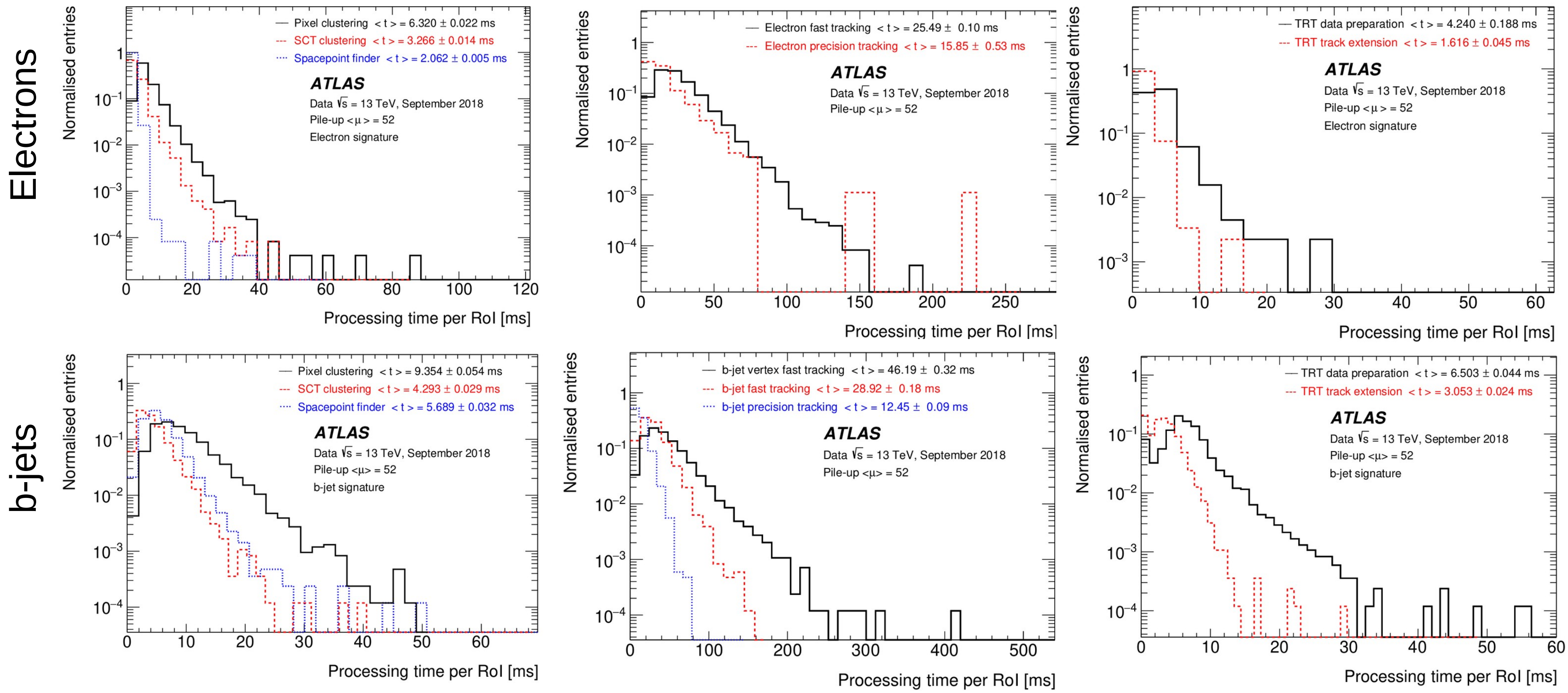
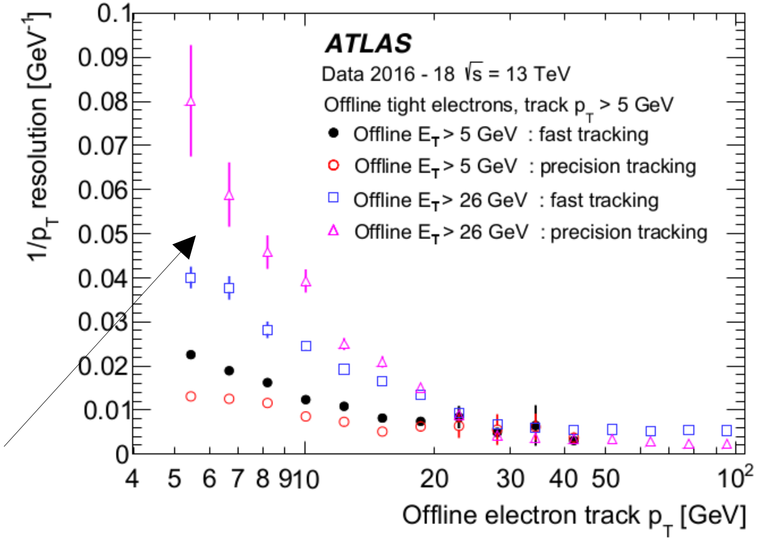


Electron precision tracking resolution worse than FTF at low pT



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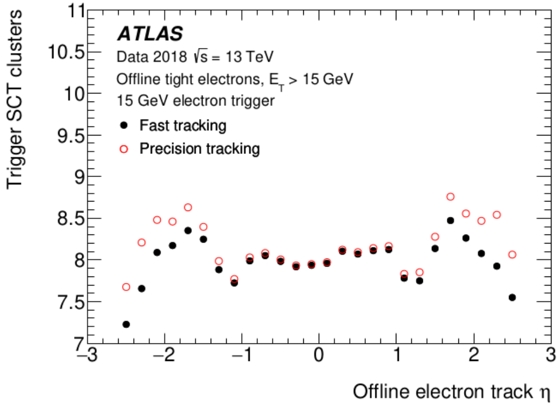
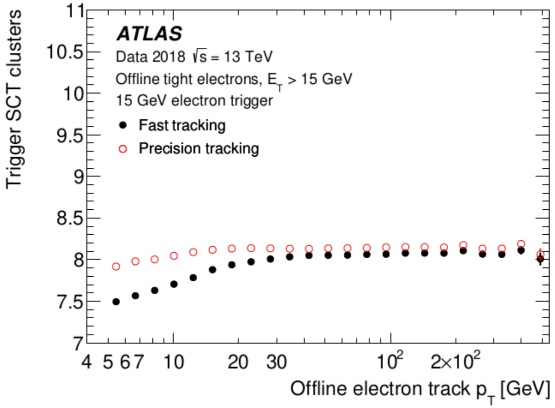
SCT Hit Multiplicity





- These are likely electrons that have radiated (track pT<<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

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