Track and Vertex reconstruction in ATLAS for LHC Run-3 and High-Luminosity phases

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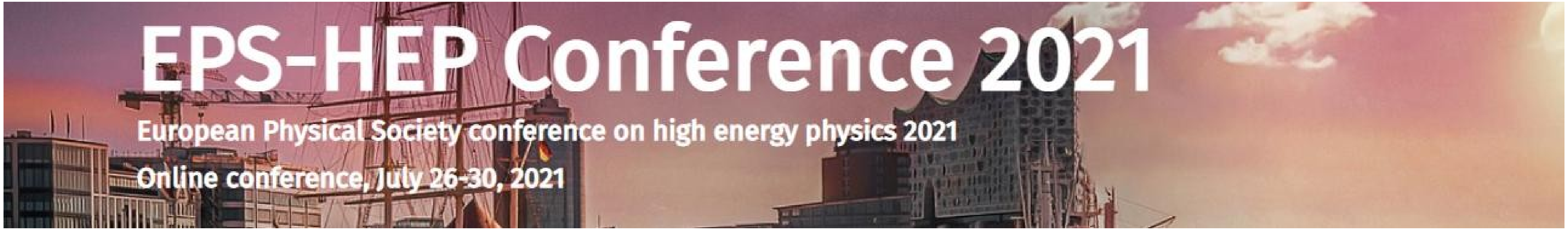
On behalf of the ATLAS Collaboration

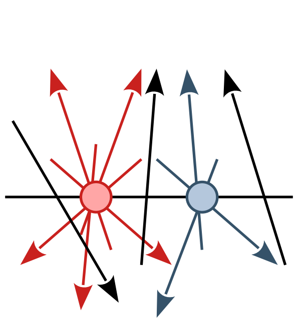


Tracking challenges at LHC

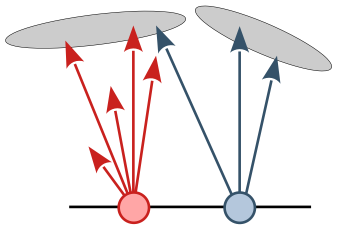
- Tracking is a **key ingredient** of reconstructing the full event
  → Used in **almost every element of reconstruction**
- Tracks need to be reconstructed
  - With very **high** efficiency, with **precise** track parameters, at very **low** fake rate, **quickly**
- **Increase in number of interactions** per bunch crossing implies an **increase in number of charged particles** per event
  - In Run-3 each collision is expected to produce **up to O(10^4) hits**

→ **Complex combinatorial problem** for tracking whose difficulties increase with pile-up

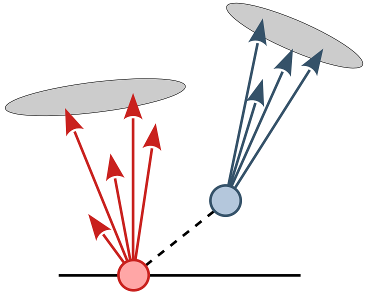
- It is challenging to **maintain high quality** of reconstructed tracks **under high pile-up**
  - High cluster density → incorrect cluster-to-track association → incorrect estimation of track parameters
  - Increase of clusters → increase in fake contribution
  - CPU for tracking rapidly increases with pile-up



Primary vertex reconstruction

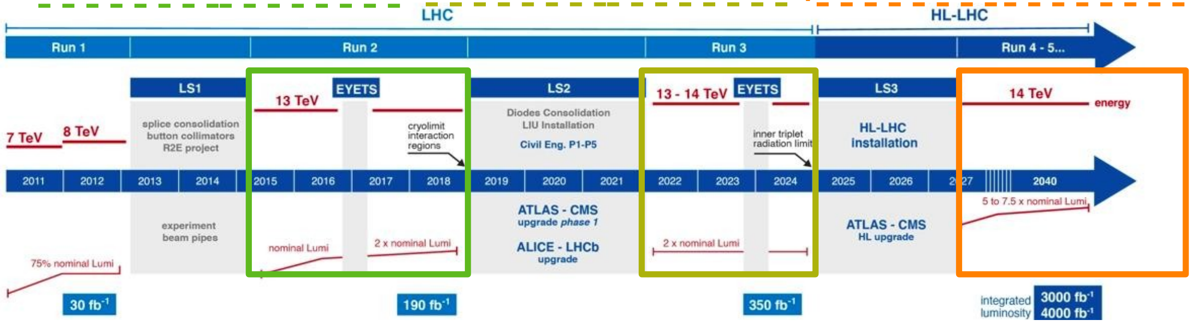


Pile-up removal



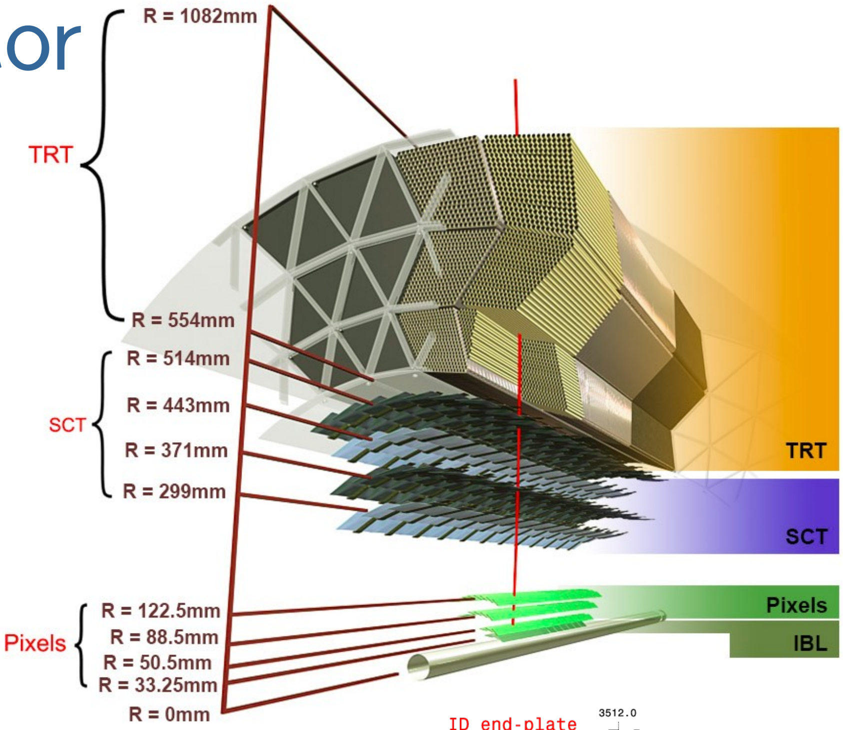
Jet flavour tagging

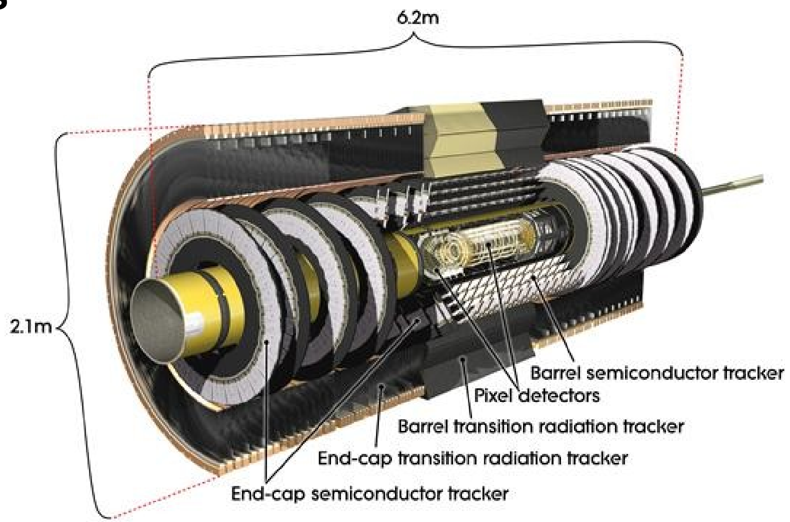
RUN-2 design	RUN-3 design	HL-LHC design
$\mathcal{L}=1\times10^{34}$ cm^{-2} s^{-1}	$\mathcal{L}=2\times10^{34}$ cm^{-2} s^{-1}	$\mathcal{L}=7{,}5\times10^{34}$ cm^{-2} s^{-1}
$\langle\mu\rangle\approx25$, for 150 fb^{-1}	$\langle\mu\rangle\approx50$, for 300 fb^{-1}	$\langle\mu\rangle\approx200$, for 4000 fb^{-1}

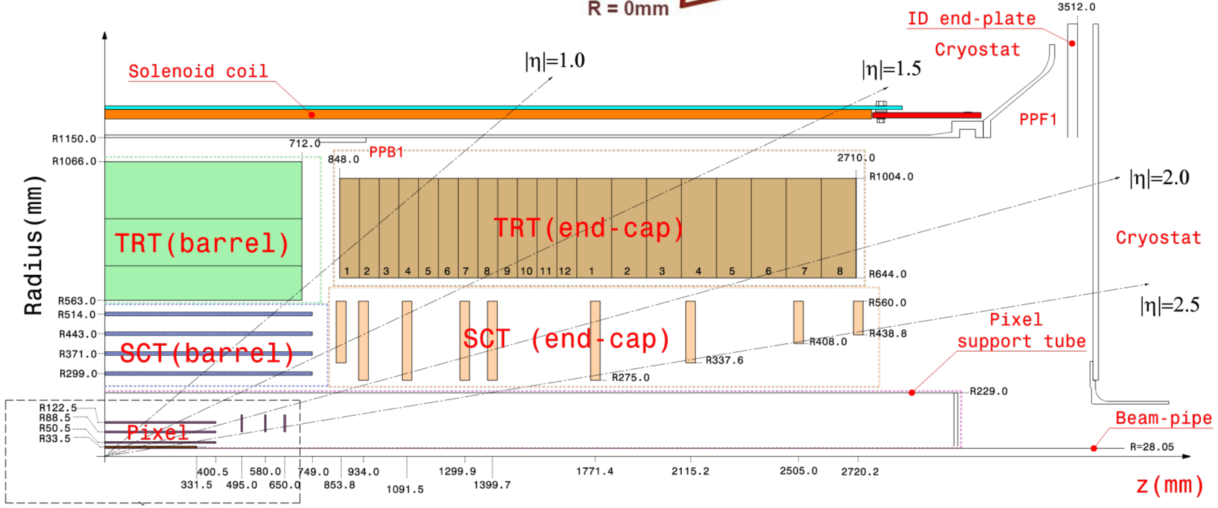


ATLAS Inner Detector

- Designed to **reconstruct** charged particles **up to $|\eta|<2.5$**
  - Three different detector technologies:
    - **Silicon pixel detectors**
      - Insertable B-layer (IBL) added before Run-2 and designed to improve precision and robustness
    - **Semiconductor Tracker (SCT)**: silicon strip detectors
    - **Transition Radiation Tracker (TRT)**: gas-filled straw tubes
- Surrounded by a thin superconducting solenoid providing **2 T axial magnetic field**







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Track Reconstruction in ATLAS

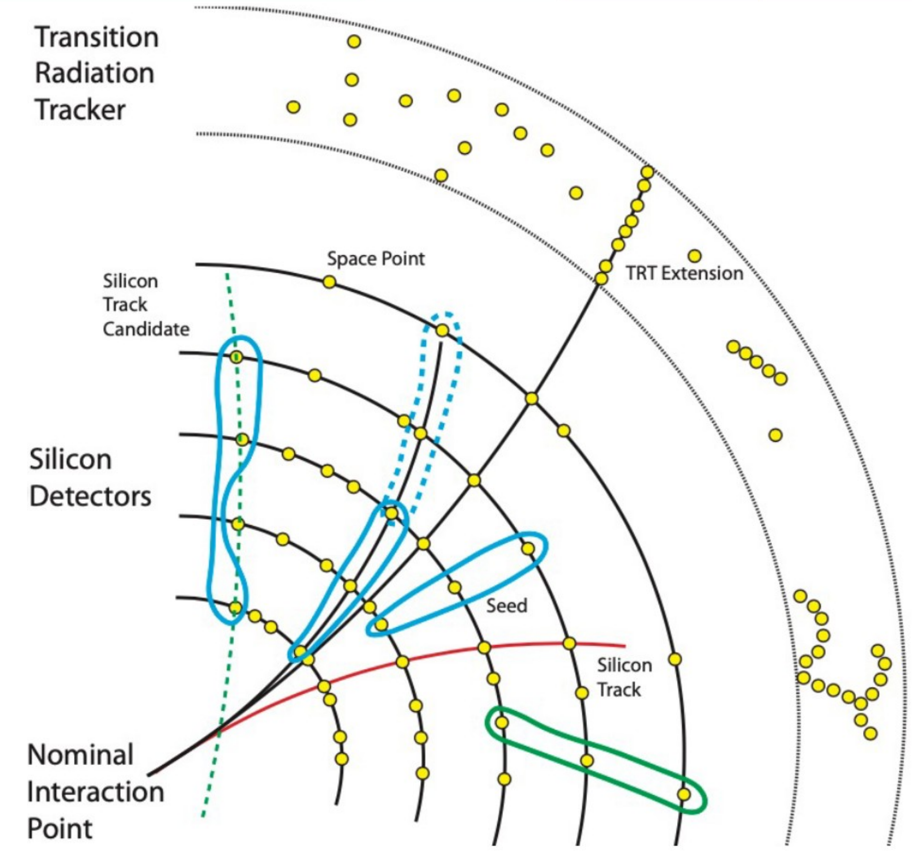
ATLAS Primary Tracking

Space Point & Drift Circle Formation → Pixel & Strip Seed Finding → Track Finding → Ambiguity Resolution → TRT Extended Track Refit

ATLAS Back-Tracking

TRT Segment Finding in Calorimeter Regions of Interest → Track Finding → Ambiguity Resolution → TRT Extended Track Refit

- **Primary Tracking (INSIDE-OUT) → prompt tracks**
  - Formation of seeds from 3 silicon hits
  - Combinatorial Kalman filter extends seeds in search roads and builds track candidates
  - Assignment of clusters to competing tracks based on scoring algorithm
    - NN based algorithm to judge if a cluster has to be split among track candidates
  - Final fit using a global-$\chi 2$
  - Extension to TRT and re-fit to improve momentum resolution and particle identification
- **Back-Tracking (OUTSIDE-IN) → particles produced at larger distance from beamline (mainly electrons from photon conversion)**
  - Track reconstruction in regions of interest seeded by deposits in EM using only left-over hits from prior passes
  - Segments of TRT hits extended towards the interaction point using same procedure as primary tracking to build track candidates
  - Dedicated ambiguity resolution and final track fit
- **Additional tracking passes use left over hits from prior passes**
  - Tracklet from muons at $|\eta|>2.5$ and short tracks
  - Non-pointing tracks from displaced decays, aka large-radius tracking (LRT) (not in standard reconstruction in Run-2)



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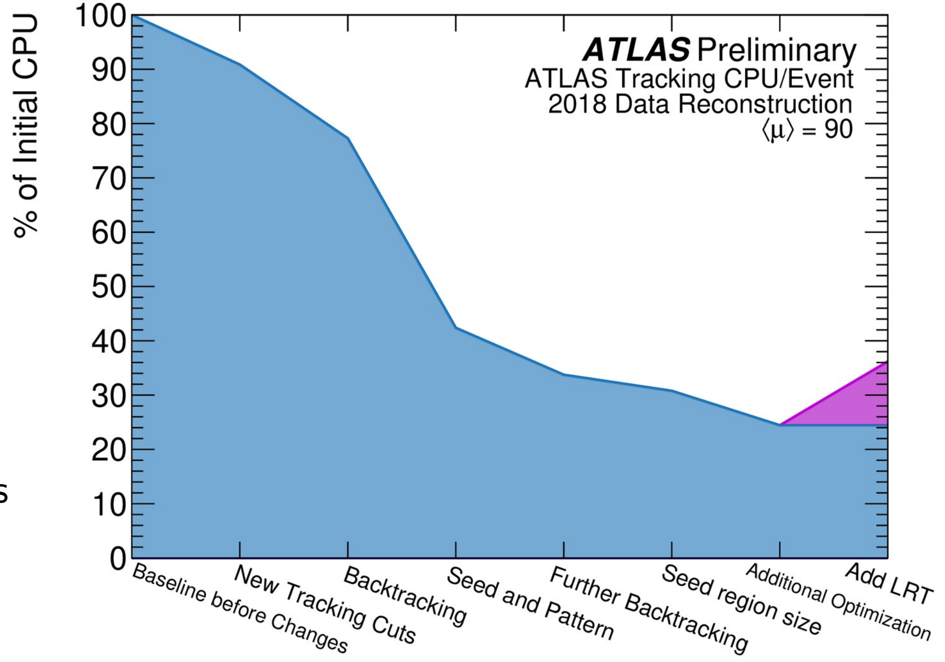
Software optimisation for Run-3

- Number of changes to the tracking software to **ensure** that **computational performance** and **size of the output remain sustainable** during LHC Run-3 data-taking

  → Best handle is to **abort track reconstruction as early as possible** for low quality candidates to reduce time and resources of down-stream algorithms

  - **Stricter tracking cuts**
    - At least 8 hits and $|d_0| < 5$ mm
  - **Back-tracking and TRT optimization**
    - Using RoIs seeded by EM deposits with E_T>6 GeV
  - **Seed and pattern recognition tuning**
    - Stricter requirements on seeds, narrower search roads, restriction of number of overlapping seeds
    - Seed confirmation from 4th layer and smaller seed formation regions
  - **General optimisation of software implementation**
    - Inclusion of ACTS-based vertexing



x4 improvement (at ⟨μ⟩=90) in speed is achieved since the beginning of the optimisation process!

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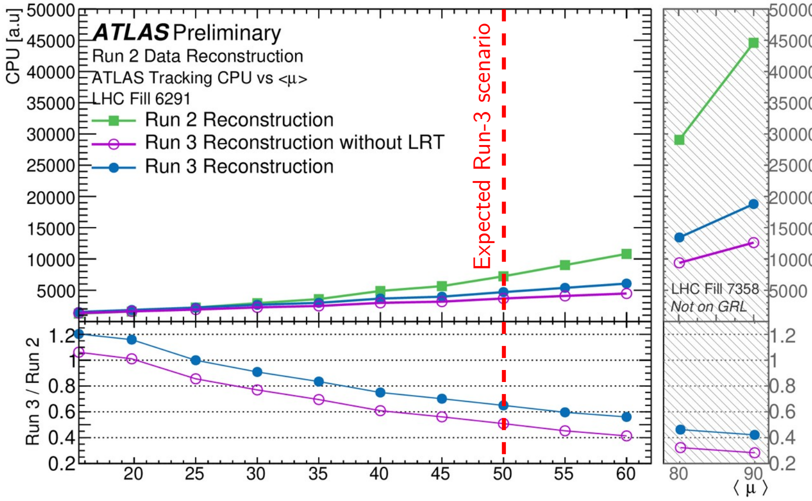
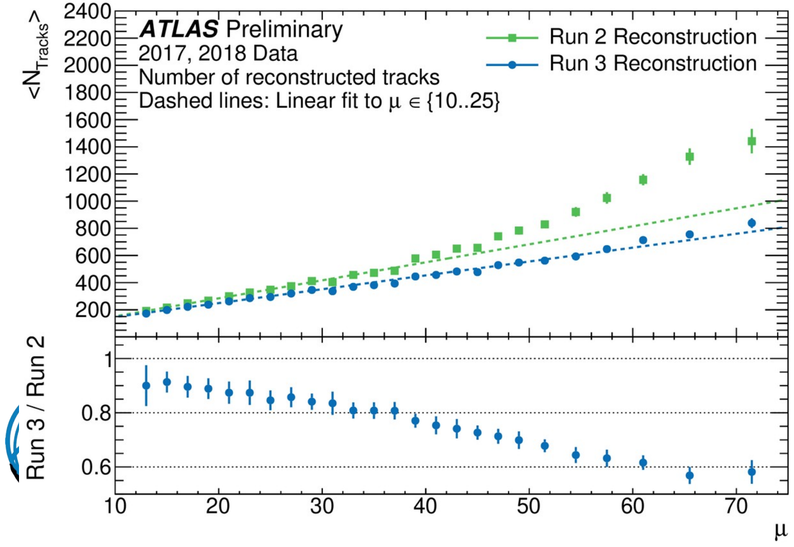
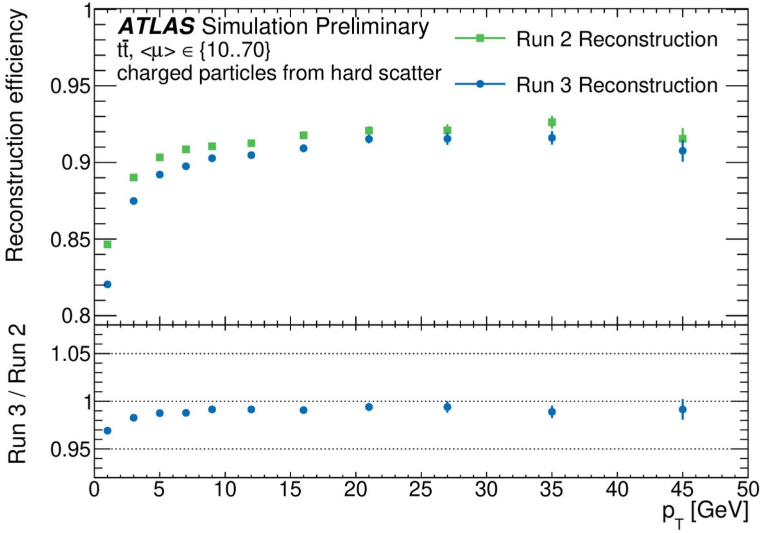
Summary of Performance Improvements

- Run-3 reconstruction is over **x2 faster** with a **25% reduction** in the disk space
  - Timing of the pattern recognition reduced by a **x4** (!)
  - Significantly **improved scaling with pile-up** → capable of running up to high ⟨μ⟩ without major slowdowns
- Allows for the **inclusion of LRT by default**, while still meeting the targeted CPU and disk goals
  - Previously run separately on only a subset of data → exciting prospects ahead for long-lived particle searches!







- Performance improvements are largely thanks to a **reduction in the fake rate**
  - Number of real tracks expected to scale linearly with μ, while random combinations expected to scale with a higher power
- **No significant impact on the reconstruction efficiency**
  - <4% (1%) at low (high) p_T

Vertex Reconstruction for Run-3

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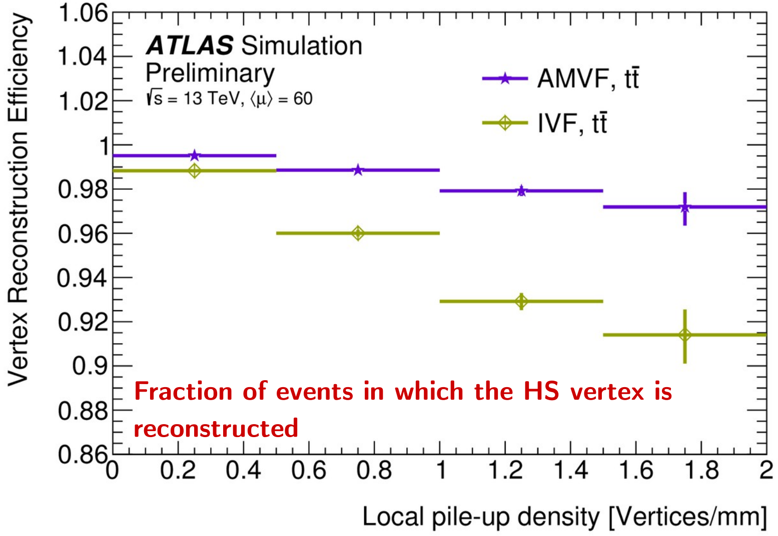
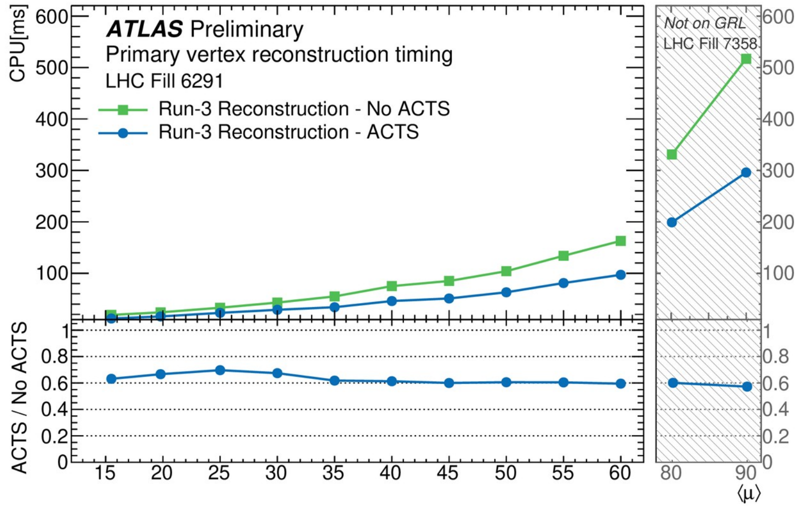
- ATLAS developed **new vertex reconstruction strategy** for Run-3 to **improve efficiency and pile-up robustness**
  - Recommissioning of **Adaptive Multi-Vertex Finder and Fitter (AMVF)** instead of Iterative Vertex Finder (IVF)
    - Use of Gaussian Track Density Seed Finder
    - Tracks for vertex fitting are associated to seed according to impact parameter significance and constrained to the seed position in z
    - **Tracks** share weights with multiple vertices, which **are fit simultaneously**
  - **Better overall vertex reconstruction efficiency**
    - **Improves** the already-high **efficiency** for $t\bar{t}$ and recovers half the inefficiency for VBF $H\rightarrow 4\nu$
    - **Less dependence** of reconstruction efficiency **on pile-up**
    - **Improved longitudinal separation**
      - 20% (10%) better resolution for $t\bar{t}$ (VBF $H\rightarrow 4\nu$)
  - In addition, **ACTS-provided implementation of AMVF**
    - Brings a **40% reduction** in the **CPU** timing

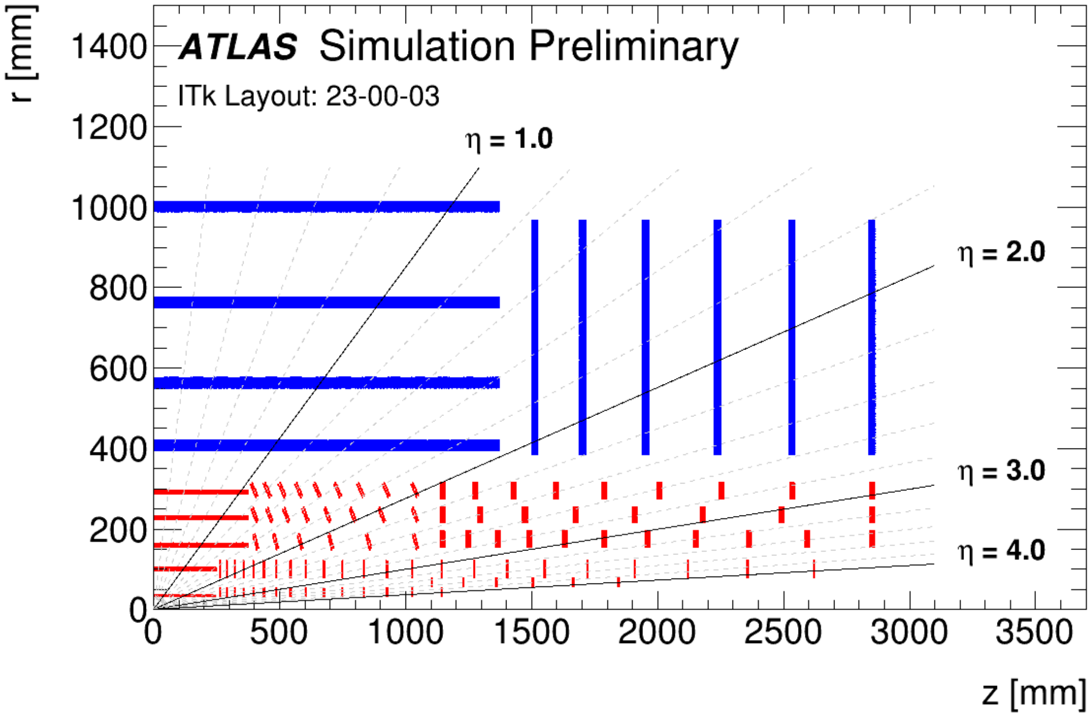


→ number of vertices per unit length within a ±2 mm longitudinal window



Upgrade of the ID for HL-LHC: ITk

- More challenging data-taking conditions at HL-LHC: **$\mathcal{L}$=7,5×10^{34} cm^{-2} s^{-1}, ⟨μ⟩≈200, for 4000 fb^{-1}**
- **ITk** (Inner Tracker) is a **full replacement of the ATLAS ID**
  - "all-silicon" detector, new pixel and strip detectors
- Extended tracking acceptance: **up to |η|~4**
  - **Improved sensitivity and acceptance** in VBS, VBF Higgs studies, bbH, H → 4l, etc.
  - **Pile-up jet suppression** → Improved MET resolution
  - **Better identification** of the **hard scatter vertex**
  - **Improved identification or suppression of b-jets**
  - **Increased range for lepton reconstruction**



→ 4 strip **barrel layers** and 6 **end-cap** discs

→ 5 pixel **barrel layers** and inclined and vertical **rings**

- **reduced innermost radius**: flat layer (inner radius of rings) at 34 (33.2) mm [IBL: 33.25 mm]
- **25x100 μm^2** pixels for flat **innermost layer** and **50x50 μm^2 elsewhere** [IBL: 50x250 μm^2]

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Tracking Performance with ITk

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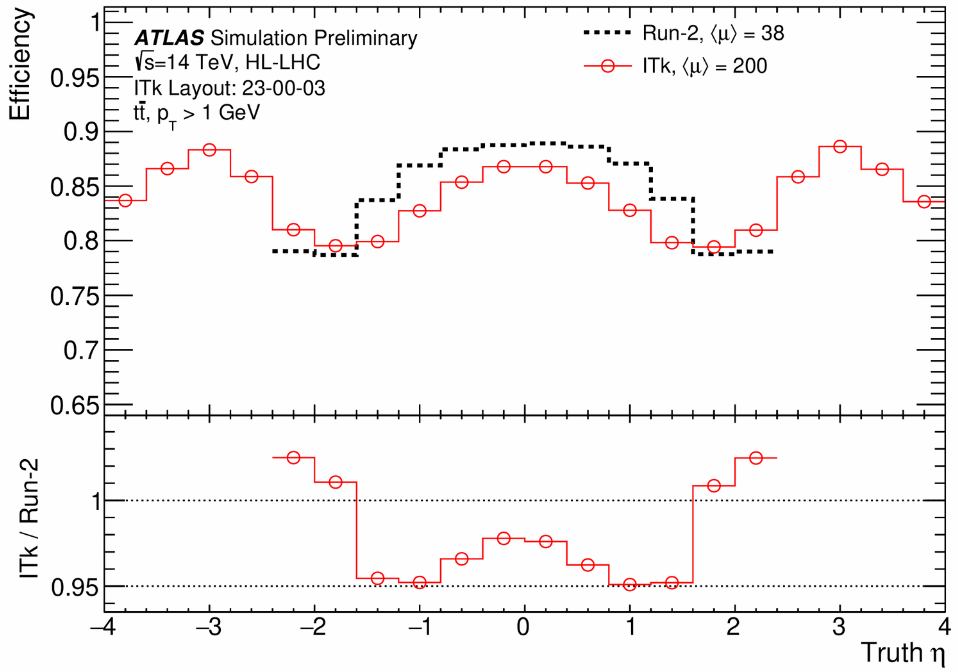
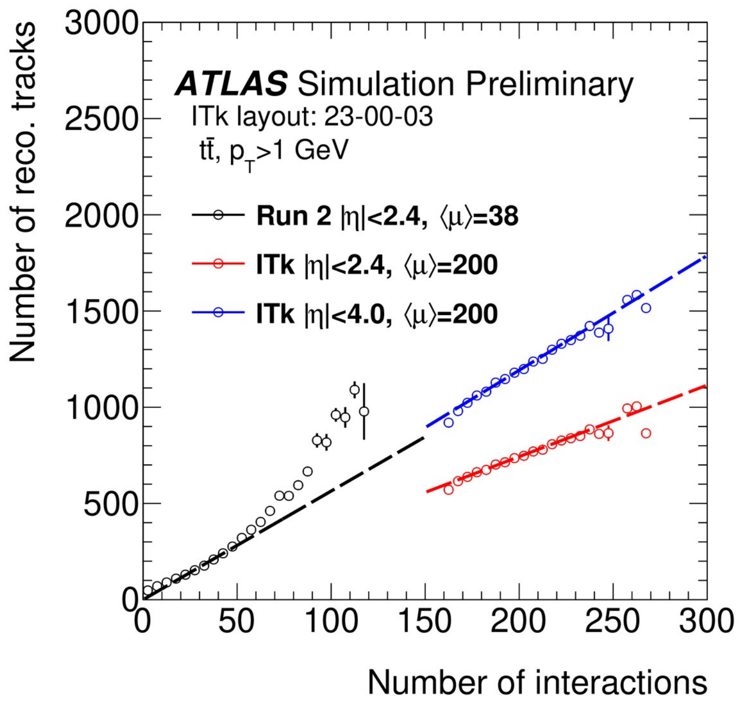
- **Excellent** tracking **performance** despite the **increased** level of **pile-up**
  - Tracking efficiency for tracks with p_T>1 GeV within the detector acceptance for $t\bar{t}$ with pile-up
    - **$|\eta|$<1.4**: ITk detector (‹μ›=200) is **within 5%** to the one of the Run 2 detector (‹μ›=38)
  - **Very high purity** tracks shown by linearity of number of reconstructed tracks as a function of number of interactions: **negligible tracking fake rate ($O(10^{-4})$)** in spite of the ‹μ› = 200





→ **Previously seen this has been improved already in view of Run-3 data-taking!**

Track Parameter Resolutions

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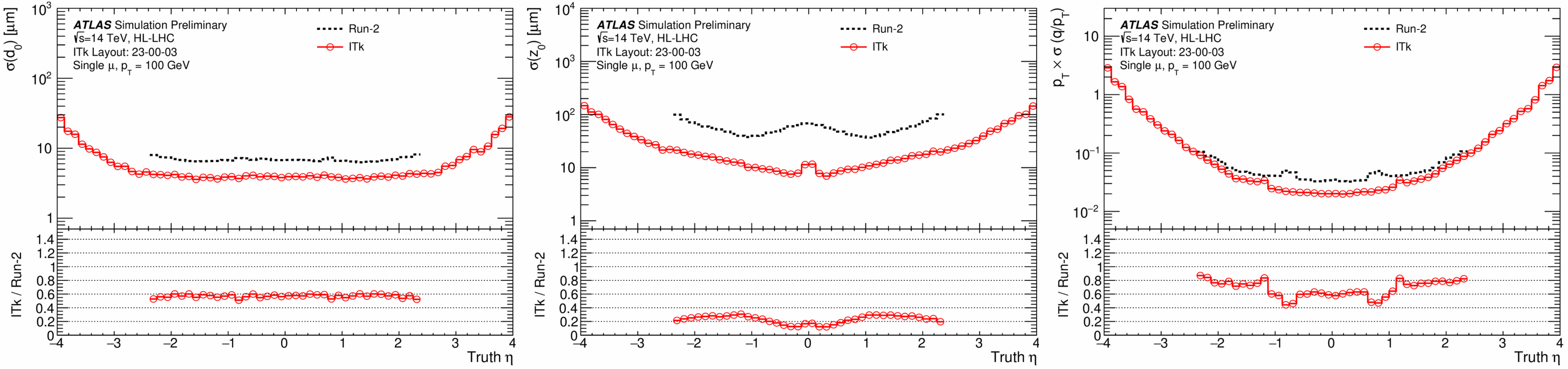

- Track parameter resolutions **improved** wrt current detector, thanks to the **comparable radius of the innermost pixel layers** and **reduced pixel pitch** (25x100 or 50x50 μm^2 for ITk, 50x250 μm^2 for the IBL)
  - **d_0 and z_0 resolutions** improved by a **x2** and **x4**, respectively
  - **transverse momentum resolution outperforms** Run-2
    - better resolution in the bending direction for silicon strip sensors, compared to TRT

Vertex Reconstruction with ITk

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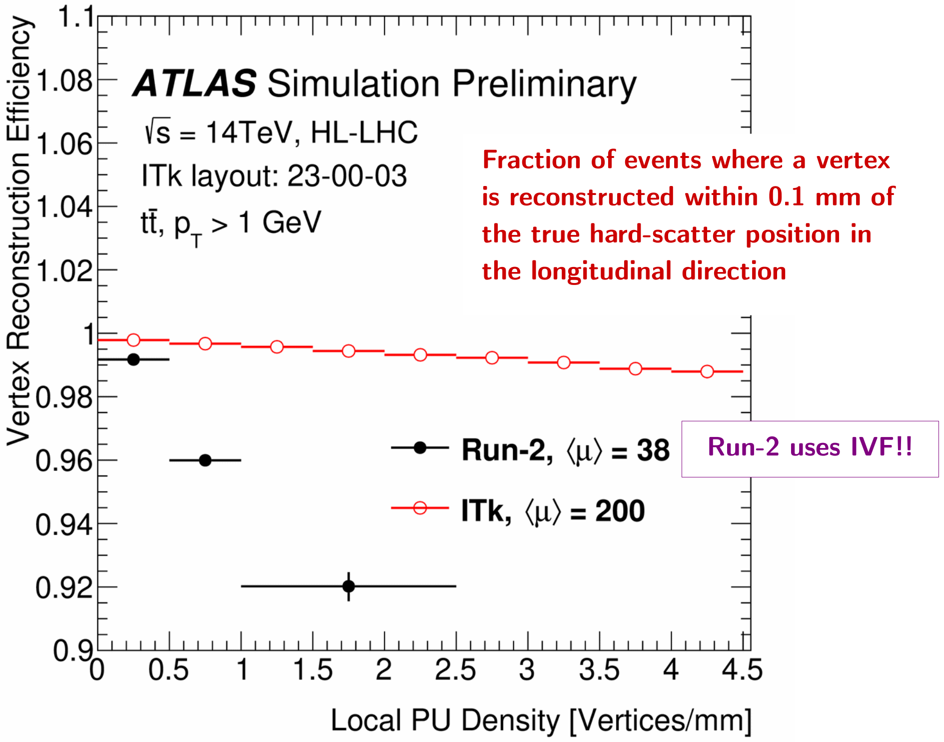
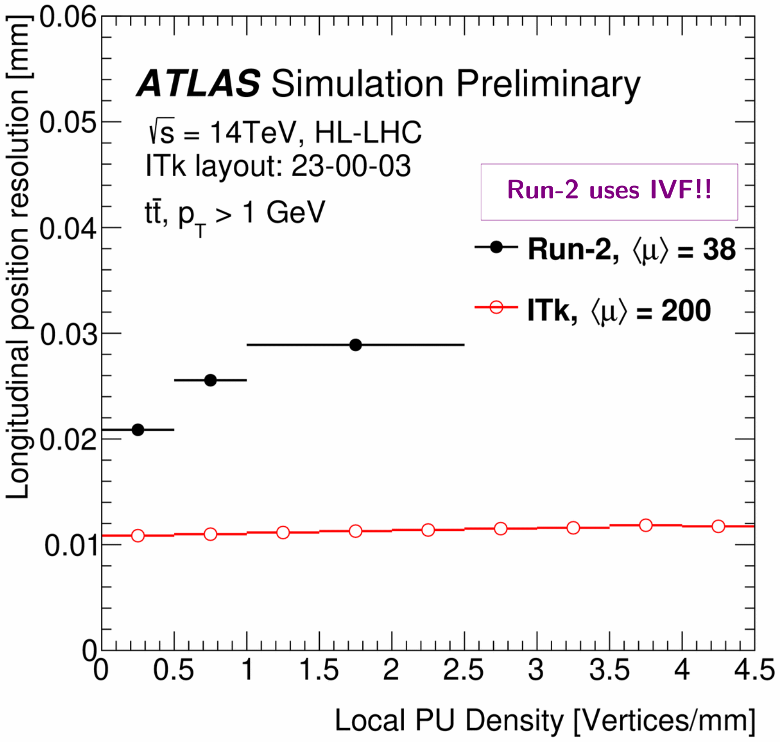
- Vertex reconstruction relies on **AMVF**, fitting all vertices simultaneously
  - **Excellent vertexing performance and robustness against pile-up**
    - **High** vertex reconstruction efficiency and **improved** longitudinal position resolution wrt ID





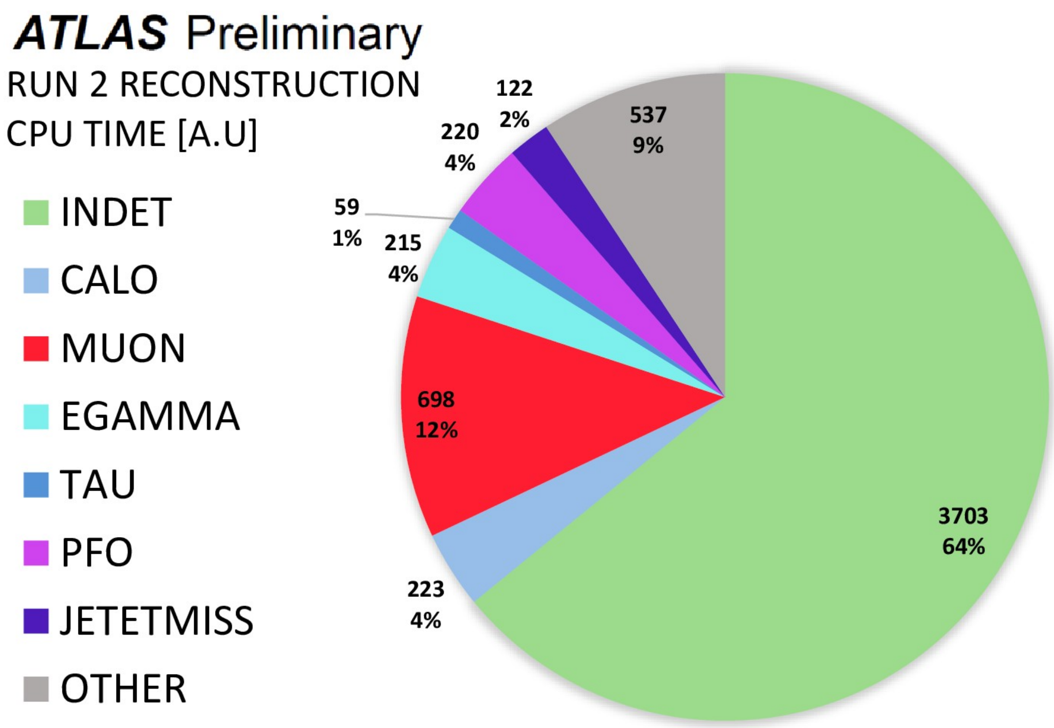
→ number of vertices per unit length within a ±2 mm longitudinal window

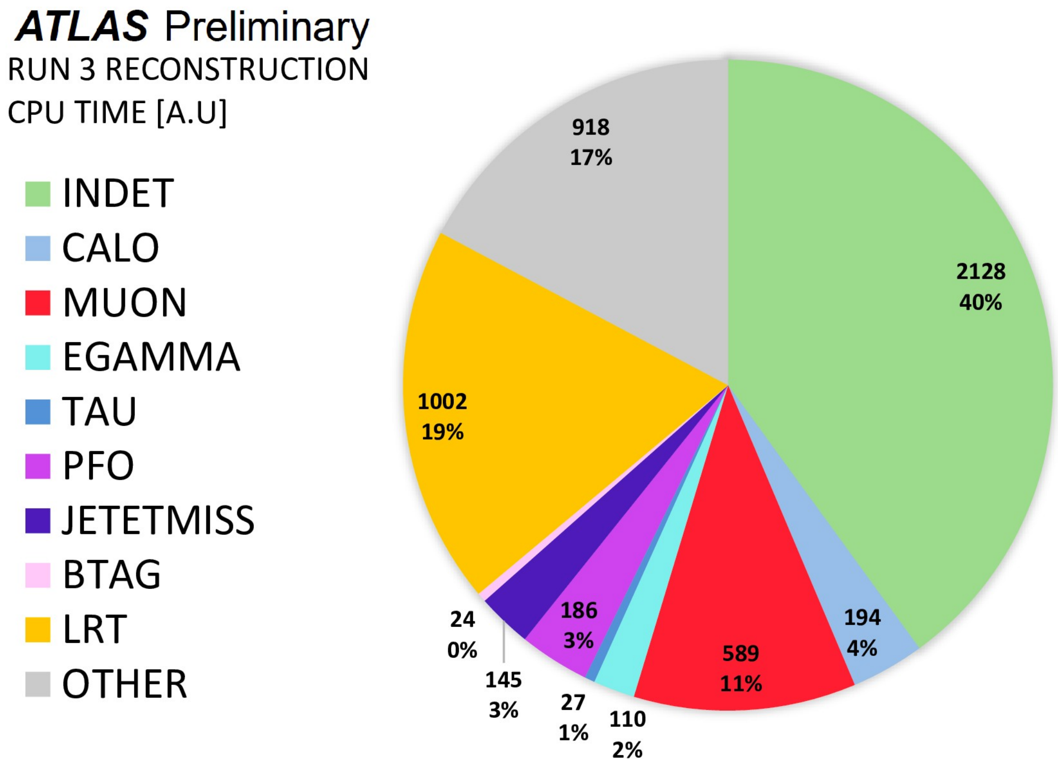
Conclusion

- Tracking algorithms need to provide **high-quality tracks efficiently with an efficient use of resources**
  - **ATLAS** provided **excellent tracking** and **vertexing performance in Run-2**
- Many **improvements** to get ready for the **challenging Run-3 data-taking**
  - Surpassing **x2 CPU speedup and 25% disk reduction**, even with the added **inclusion of LRT by default**
- **HL-LHC will provide unprecedented challenges** in terms of track and vertex reconstruction
  - **Excellent performance** for tracking and vertex reconstruction for the **ITk** wrt the current detector despite the **increase in pile-up**
- Opens up a **rich playground for future developments**, using what we have learned so far as well as investigating new strategies

Additional Slides

Run-2 vs Run-3 fraction of total CPU requirement





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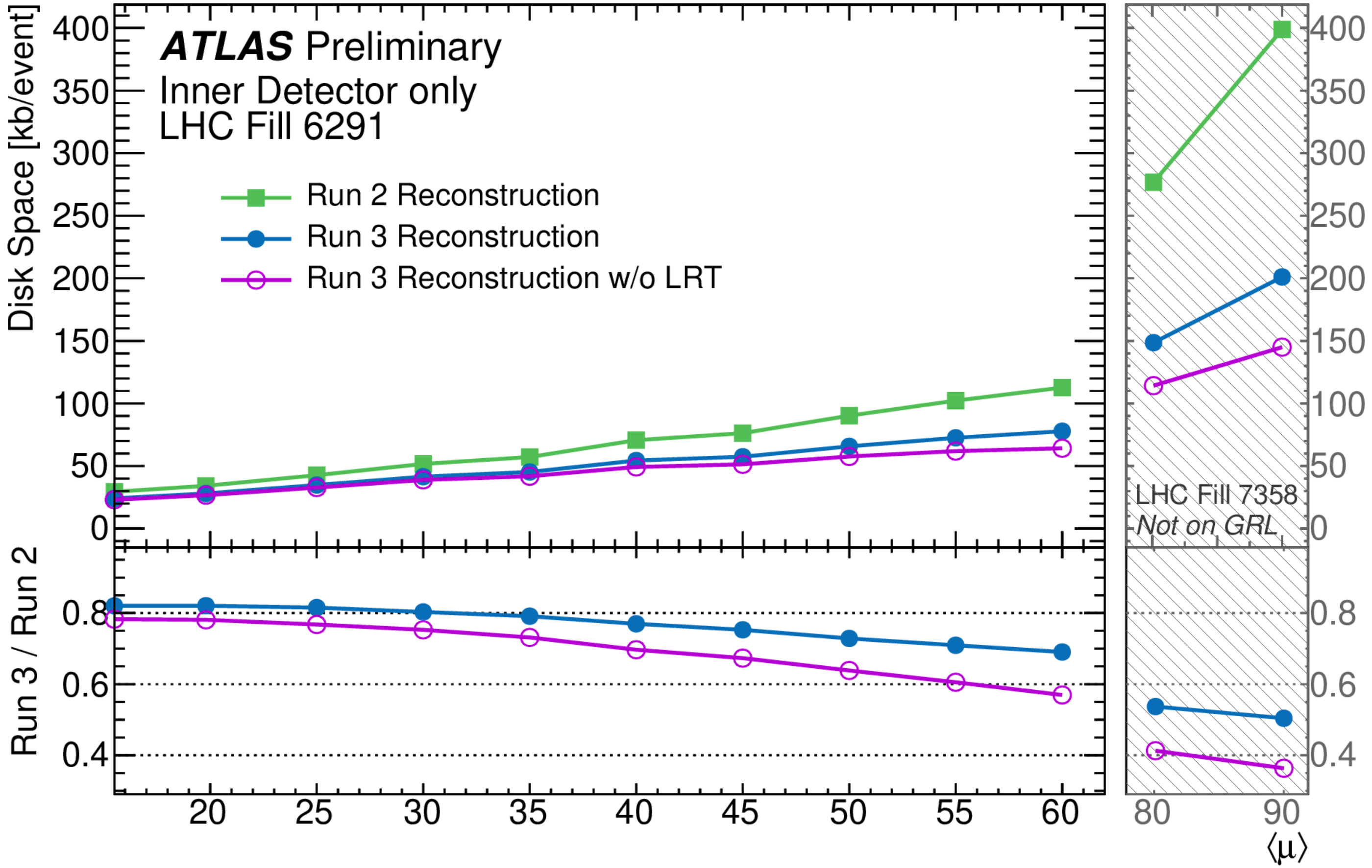
Disk space: Run 2 vs Run 3 track reconstruction



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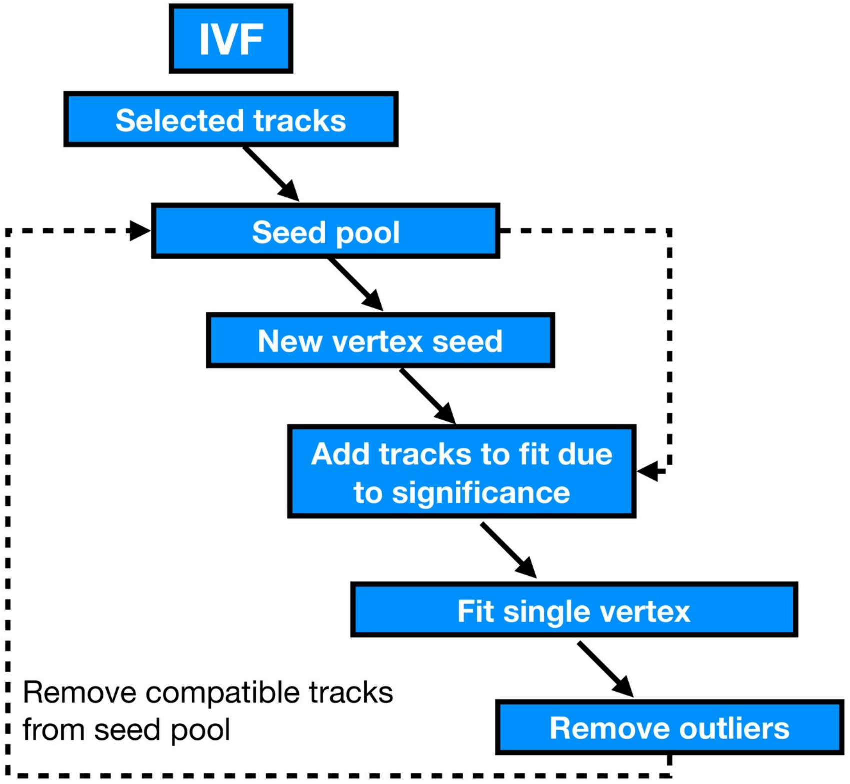
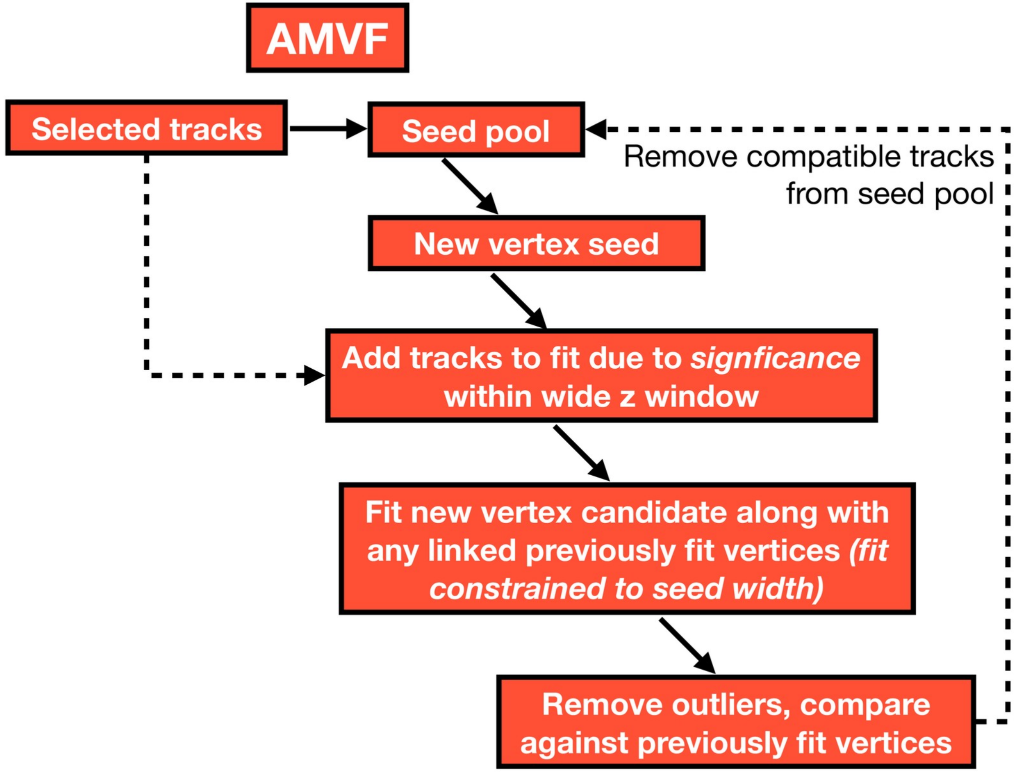
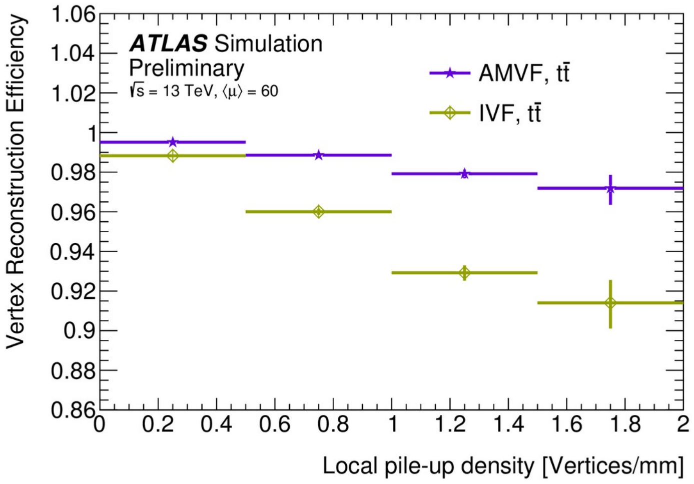
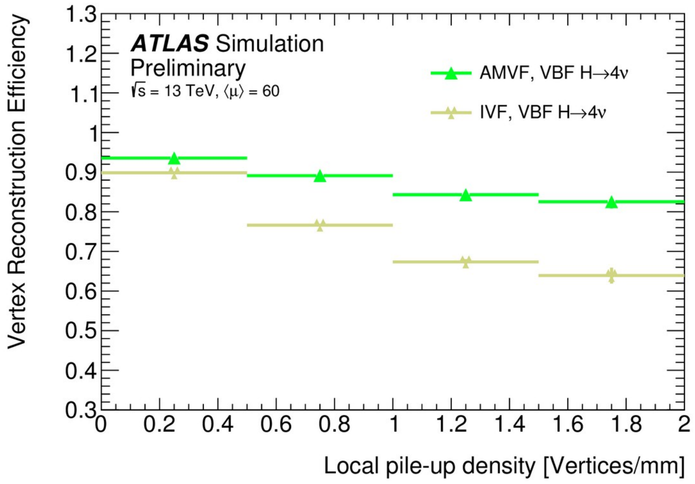
IVF vs AMVF

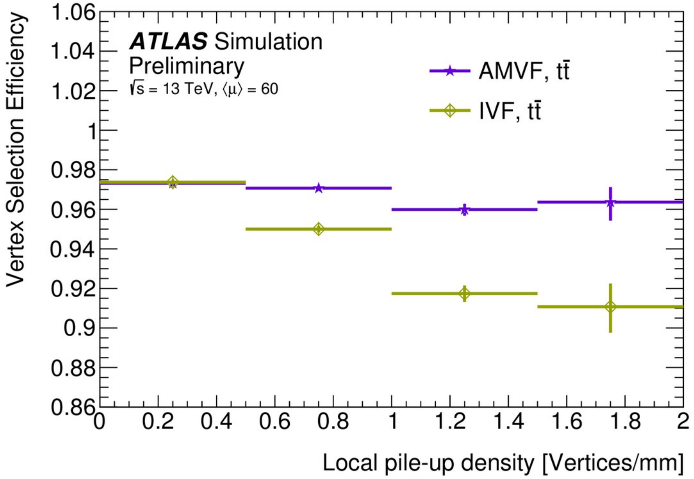


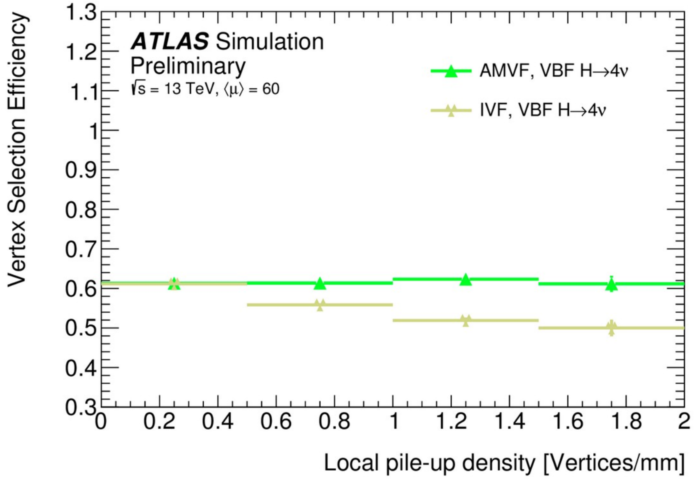


Vertex Reconstruction and Selection Efficiency









Local pile-up density
→ number of vertices per unit length within a ±2 mm longitudinal window

Vertex reconstruction efficiency
→ Fraction of events in which the HS vertex is reconstructed

Vertex selection efficiency
→ Fraction of events in which the highest Σp_T^2 vertex contains the largest weight of true HS tracks

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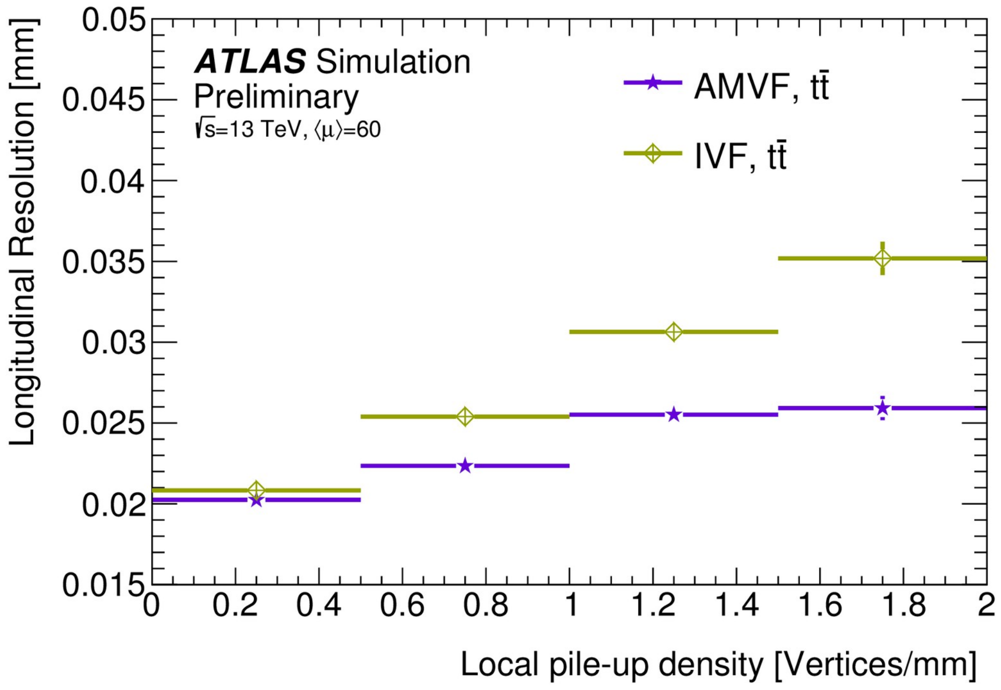
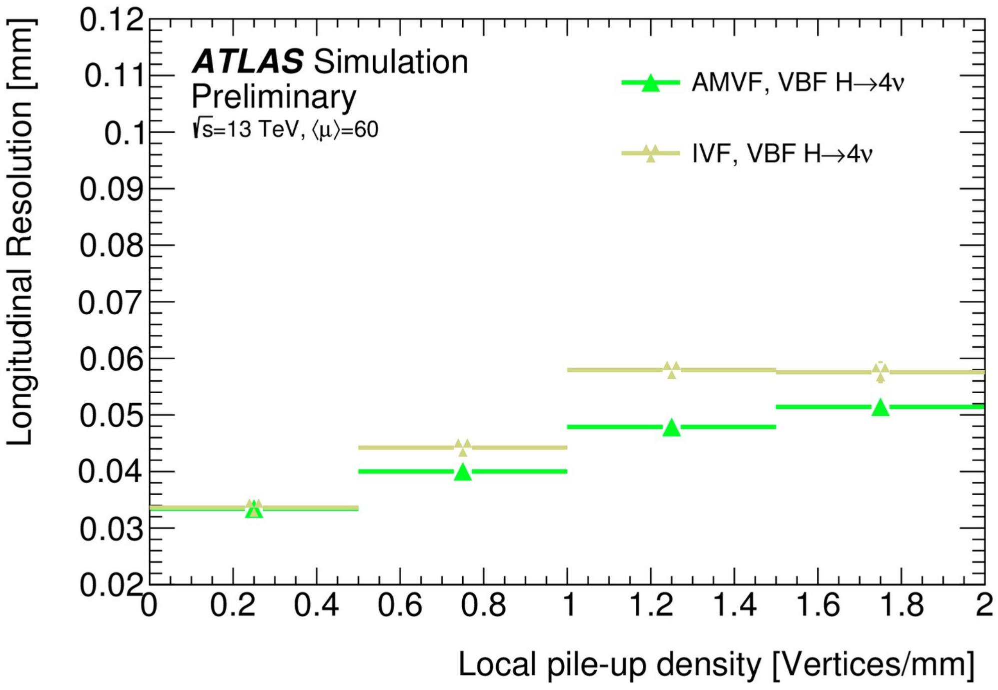
Vertex Longitudinal Resolution





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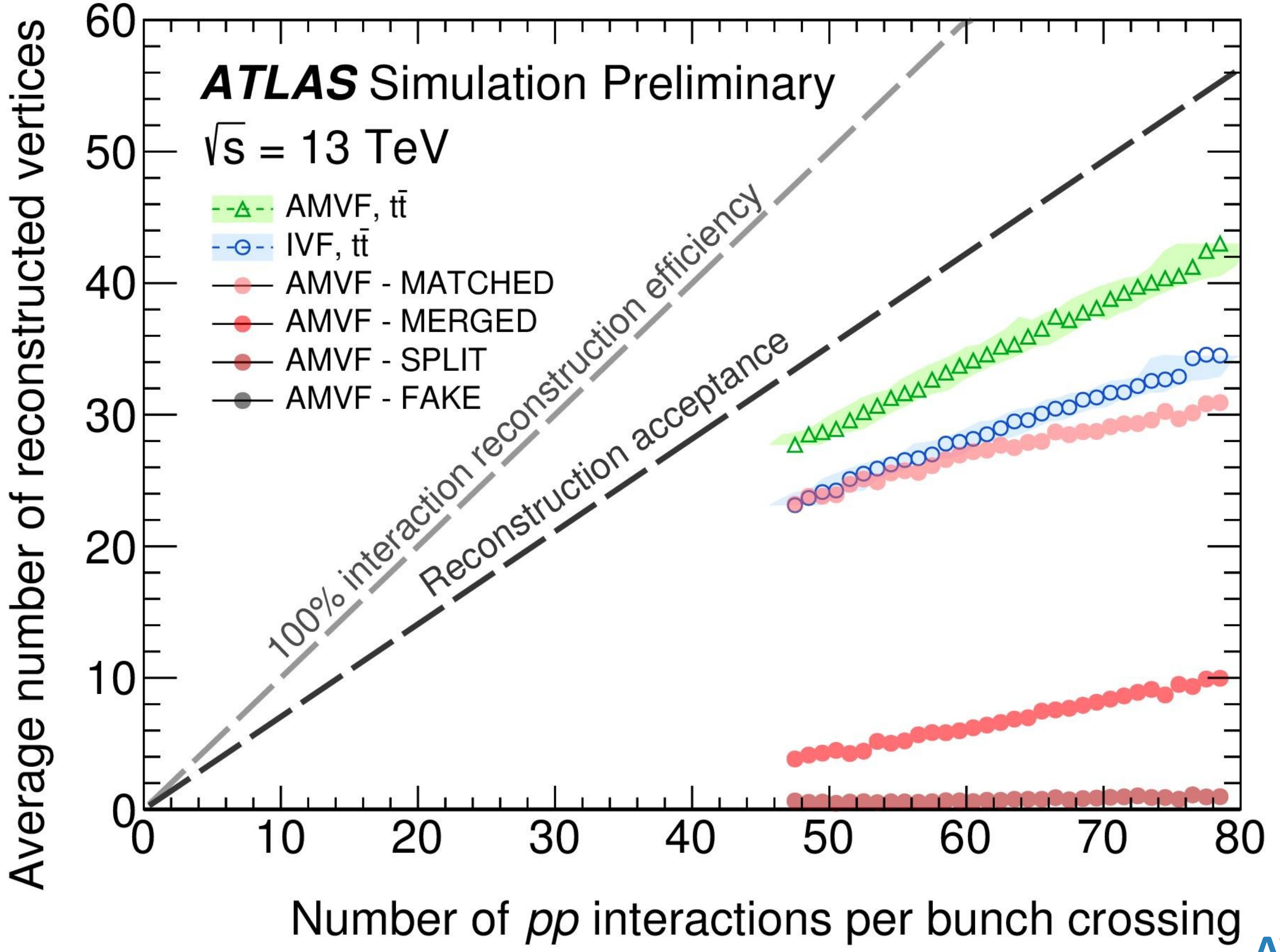
Reconstructed Vertices



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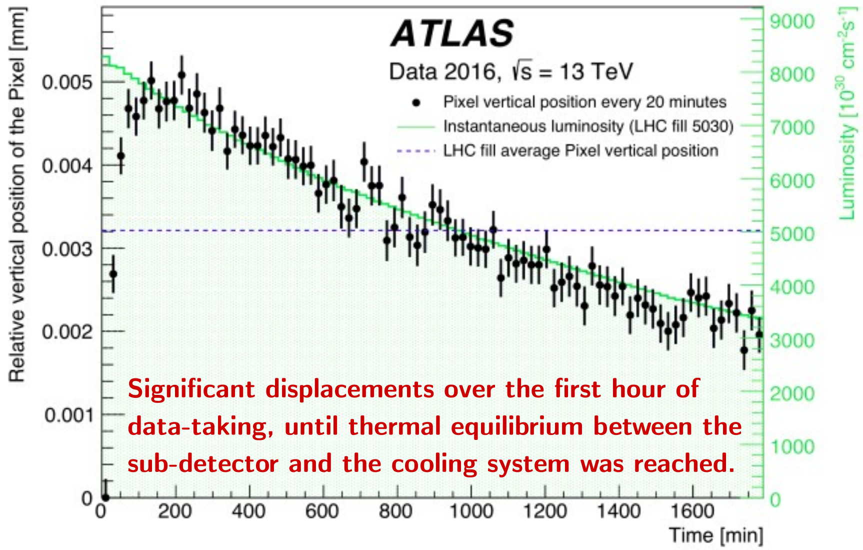
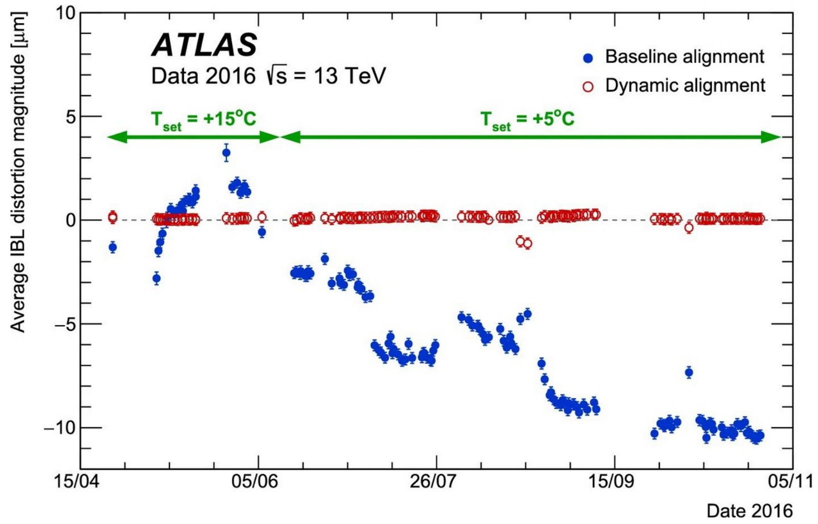
Alignment of the Inner Detector

- Determination of detector geometry as accurately as possible and correction for time-dependent movements
  - Based on the minimization of track-hit residuals in a sequence of hierarchical levels
    - from global mechanical assembly structures to local sensors, with increasing numbers of degrees of freedom
  - Operational conditions affect the positions of ID elements
    - pixel detector moves upwards every time the data acquisition is activated, staves of the IBL bow depending on the temperature, while remaining structures are quite stable during LHC fill

→ Automated alignment scheme for the ID
  - Dynamic alignment update throughout each LHC fill calibrating the recorded data
    - every 20 minutes during the first hour of data-taking; every 100 minutes for the rest of the fill





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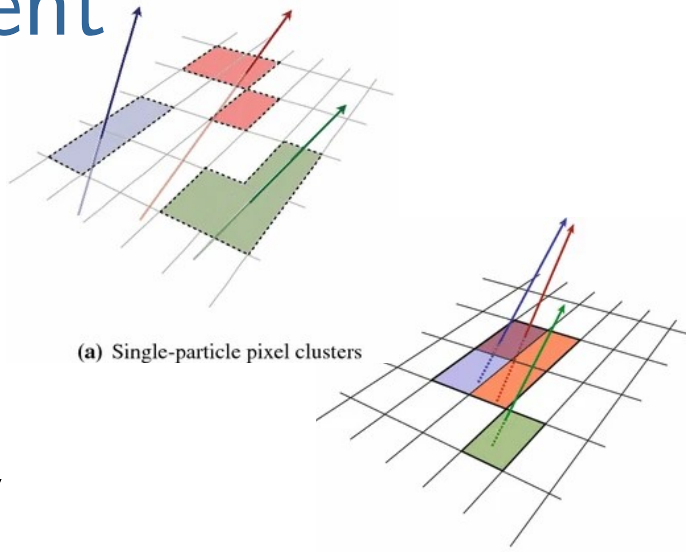
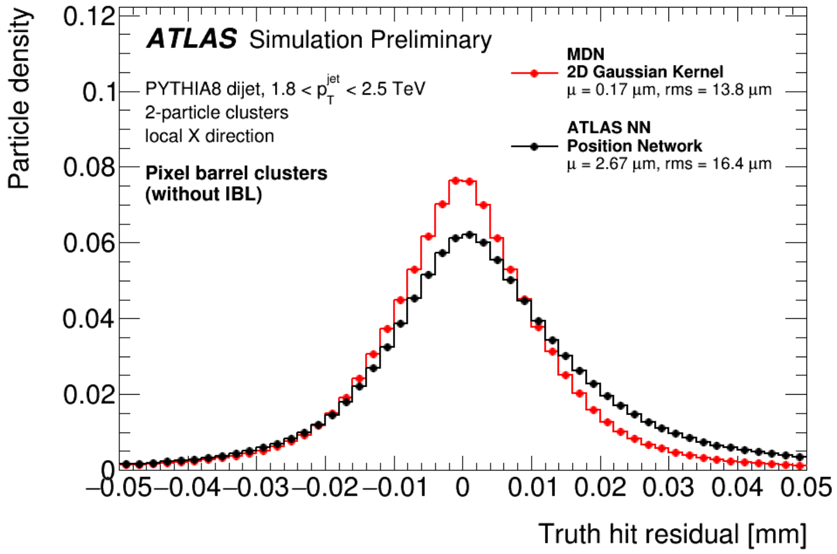
Tracking in Dense Environment

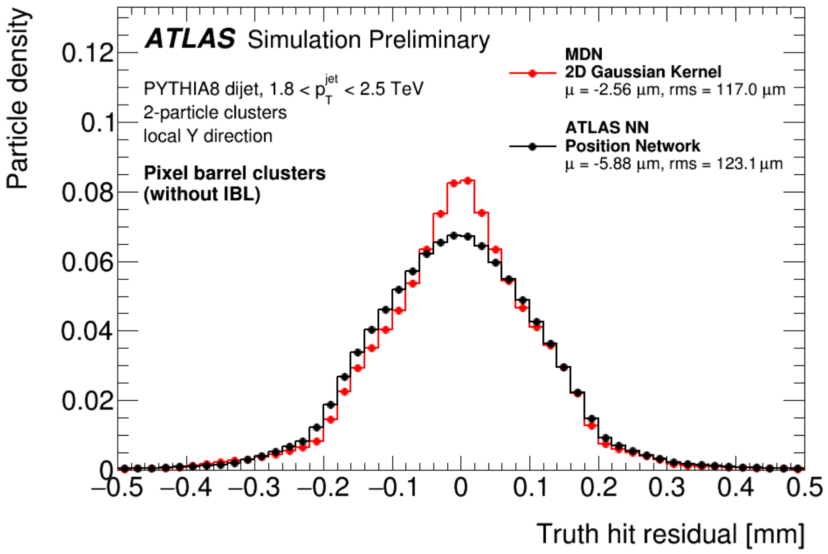
- In dense environment, multiple tracks get associated with one cluster
  - High-p T signatures (taus, jets)
- In ATLAS, Neural networks have been implemented to resolve those ambiguities
  - 3 NNs for (x,y) position (1,2 and ≥3 particle hits) + 2x3 for (σ_x,σ_y) uncertainties NNs
- Previous approach improved using algorithm based on Mixture Density Networks (MDN)
  - 9 NNs replaced with 3 MDNs: can estimate both hit position and associated uncertainty simultaneously



(a) Single-particle pixel clusters

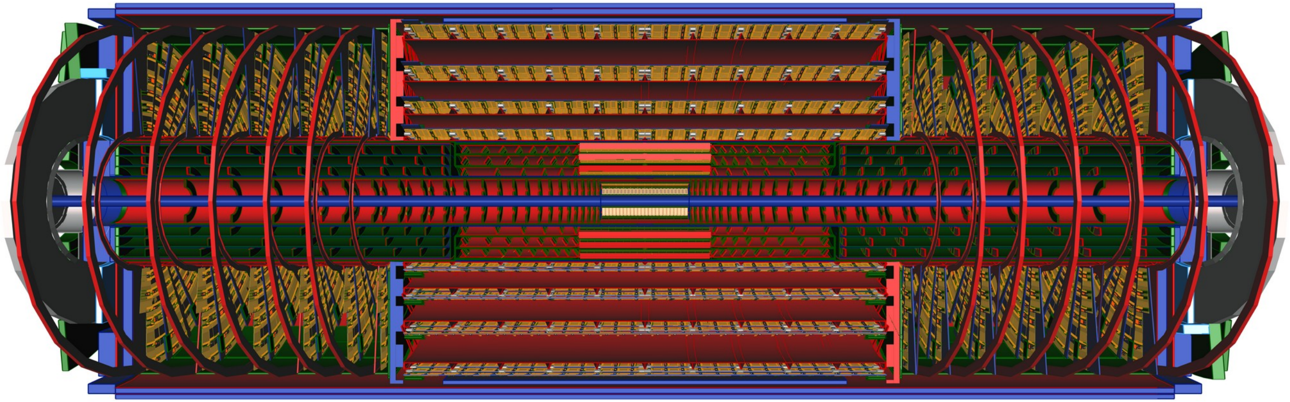
(b) Merged pixel cluster

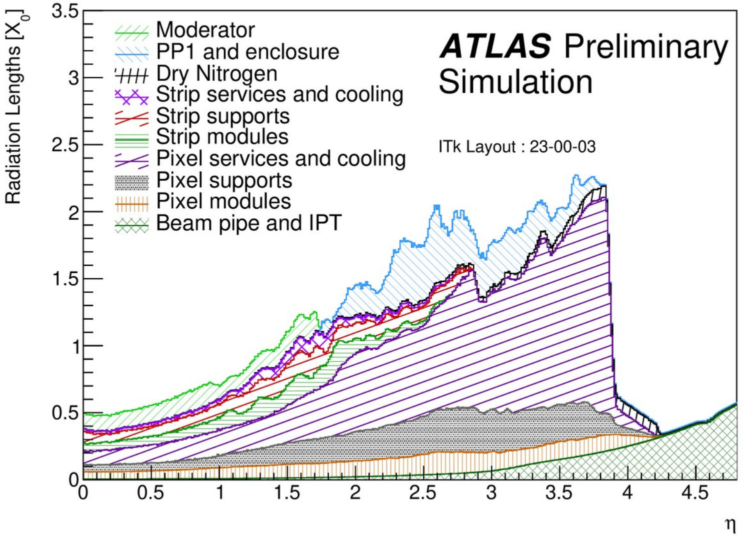




Simulation and Track Reconstruction for ITk

- **Updated and improved modeling** of the Pixel and Strip Detectors in simulation
  - Support structures, services, patch panels in forward region, ...
- Updated description of modules and **improved accuracy** of digitization model





- Track reconstruction based on Run-2 ID software with requirements updated to ITk characteristics

Requirements	Pseudorapidity interval		
	$\|\eta\| < 2.0$	$2.0 < \|\eta\| < 2.6$	$2.6 < \|\eta\| < 4.0$
pixel + strip hits	≥ 9	≥ 8	≥ 7
pixel hits	≥ 1	≥ 1	≥ 1
holes	≤ 2	≤ 2	≤ 2
p_T [MeV]	> 900	> 400	> 400
$\|d_0\|$ [mm]	≤ 2.0	≤ 2.0	≤ 10.0
$\|z_0\|$ [cm]	≤ 20.0	≤ 20.0	≤ 20.0

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Hermeticity check for ITk

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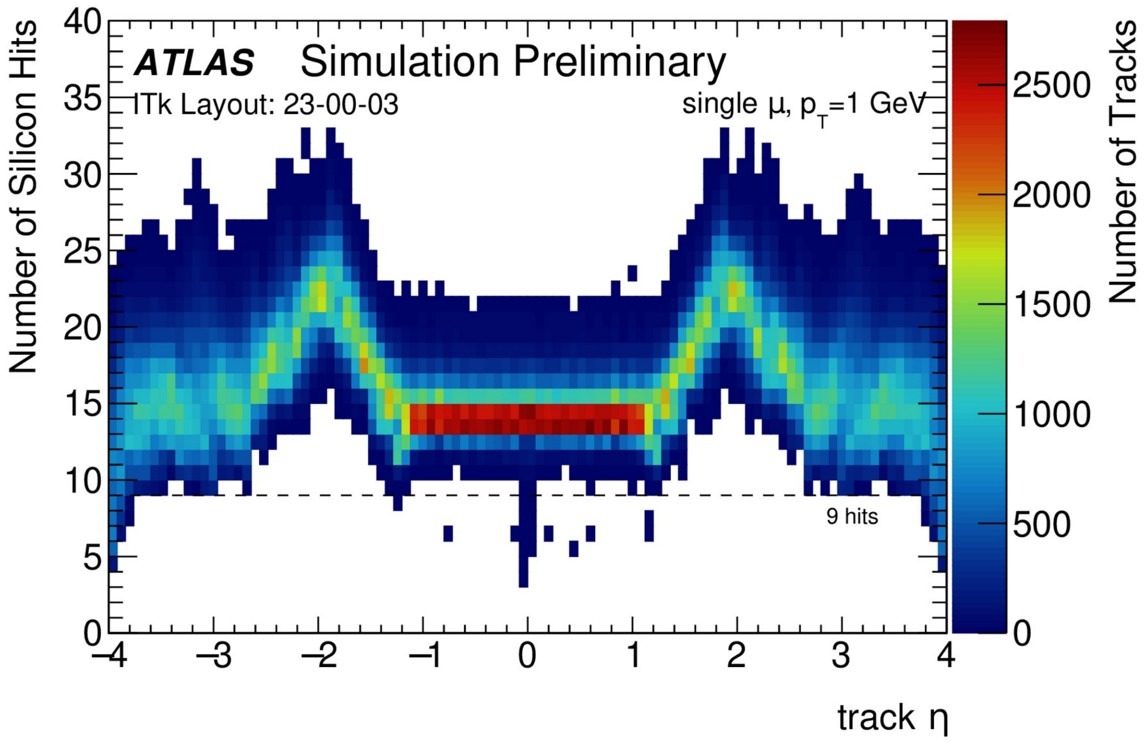
- Provide **hermetic coverage** with a **minimum of 9 hits** for primaries with **p_T> 1 GeV** and **z_{vertex}= [-150, 150] mm**

  → Strip+Pixel provide a total of **13 hits for |η| <2.6**
  - **11 hits** in the strip barrel/end-cap transition (|η|~1.2)

  → The **pixel end-cap system** is designed for of at least **9 hits from |η|>2.7** (except very close to |η|~4)



Tracking Performance with ITk

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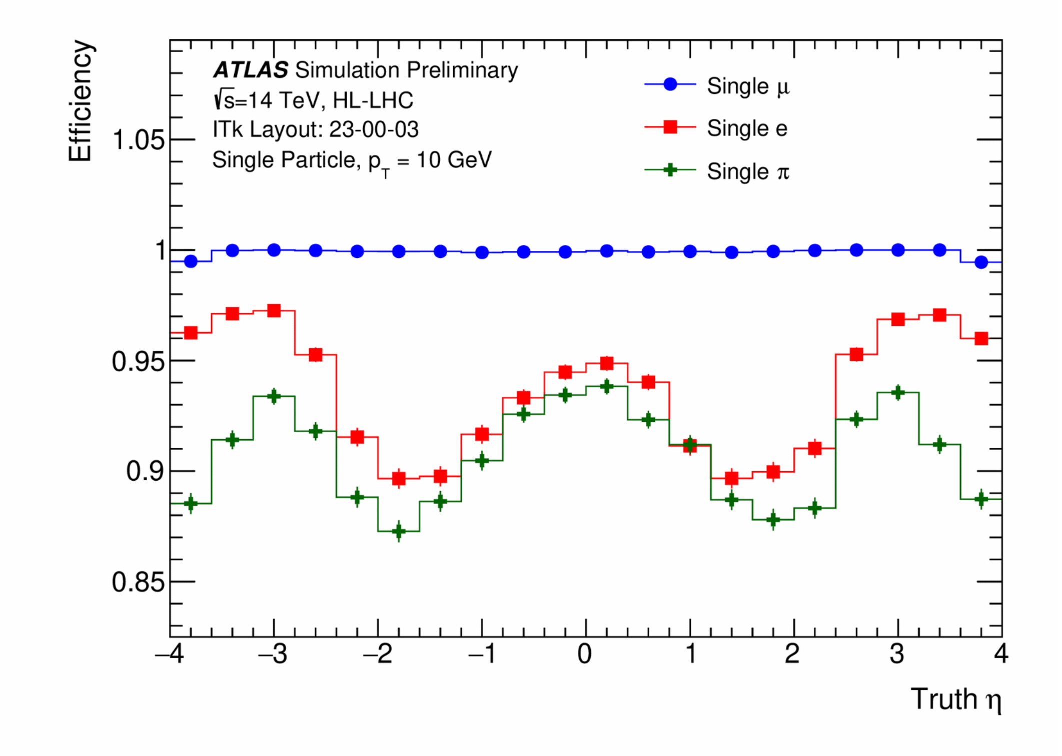

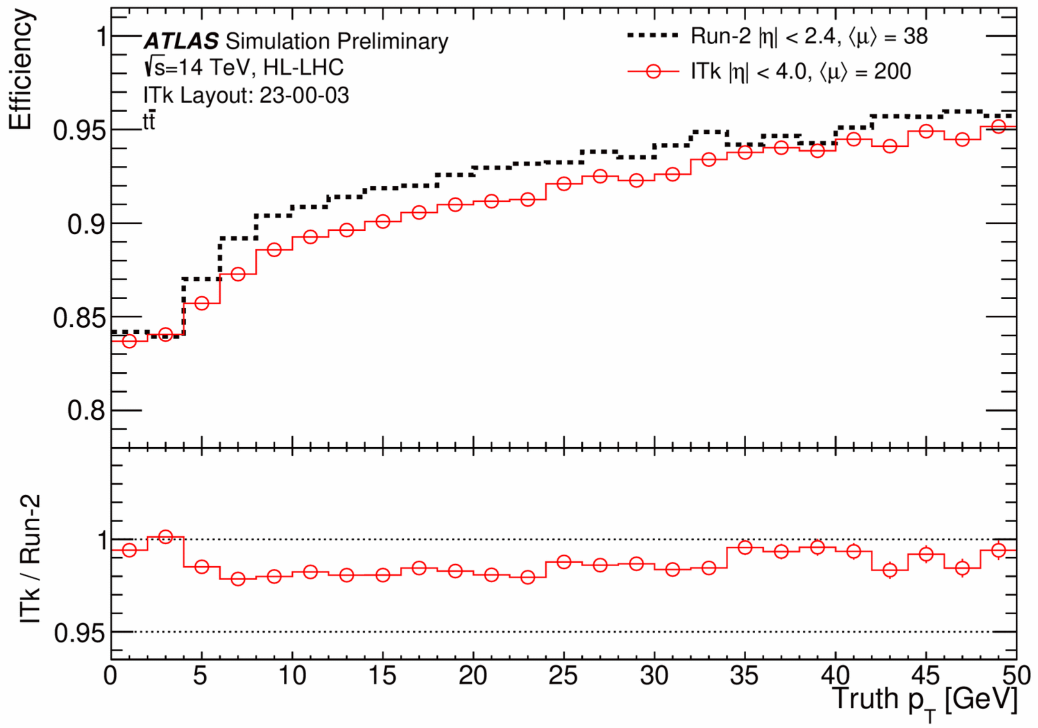

- Tracking efficiency for different particle types with p_T=10 GeV
  - >85% for any kind of prompt and stable charged particles
- Tracking efficiency as a function of pT for $t\bar{t}$ events with pile-up
  -

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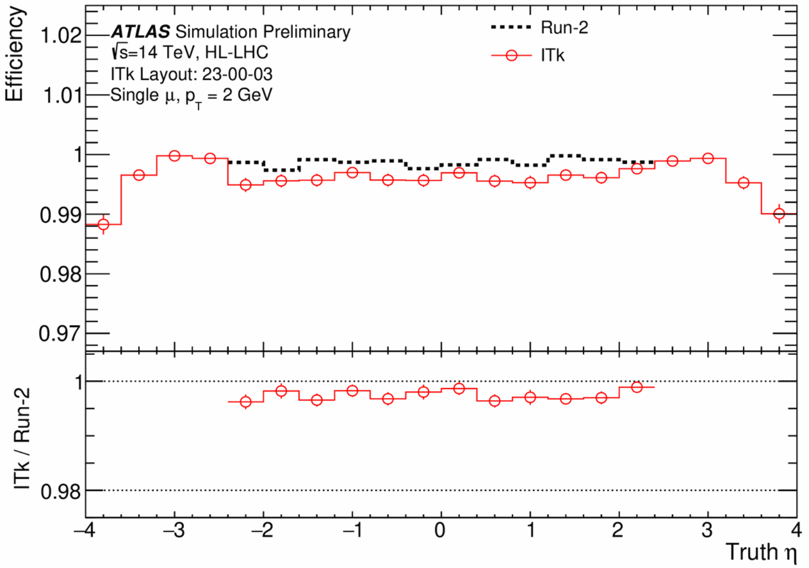
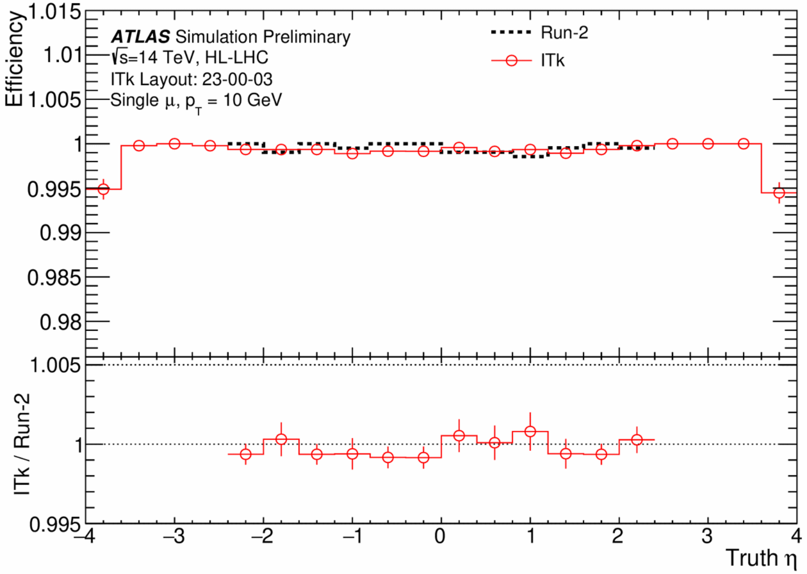
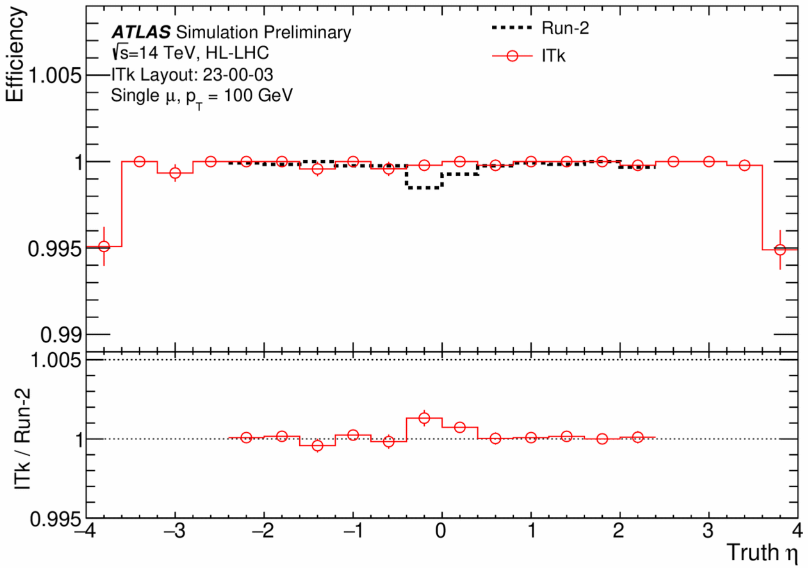
ATL-PHYS-PUB-2021-024







- Tracking efficiency shown for 2, 10 and 100 GeV muons
  - very compatible with the one obtained with the Run 2 detector for $|\eta|<2.4$
  - 0.5% reduction observed in the barrel for 2 GeV muons
    - expected to be recovered in future optimisations

Track Parameter Resolutions

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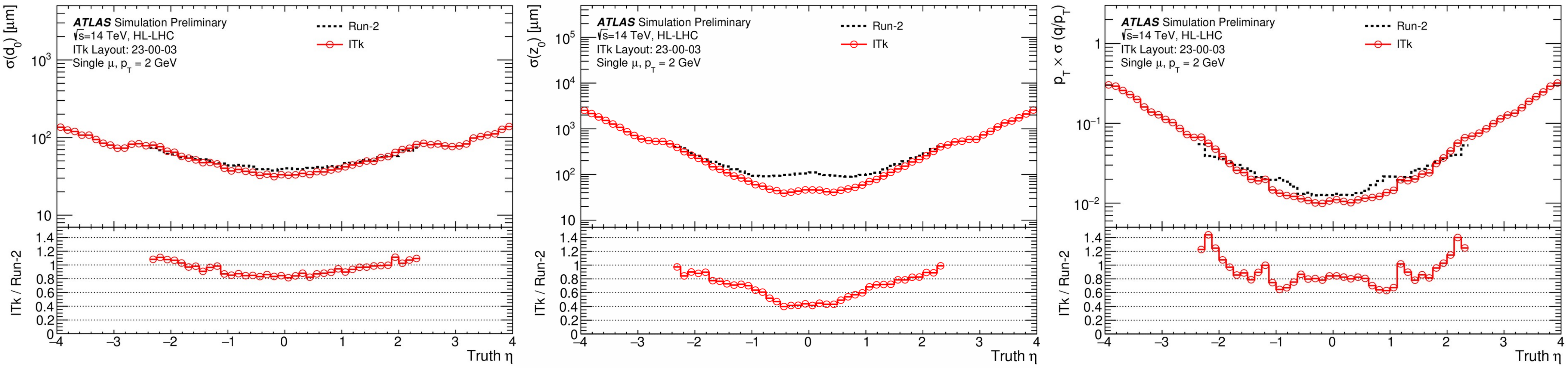

- At low p_T dominated by multiple scattering effects
  - Similar d_0 resolution is achieved between the ITk and the Run-2 detector, thanks to similar innermost radius
  - z_0 resolution improved by up to a x2, thanks to the smaller pixel pitch used in the ITk pixel detector
  - Similar q/p_T resolution, improved thanks to the better precision of strip measurements wrt TRT

Vertex Reconstruction with ITk

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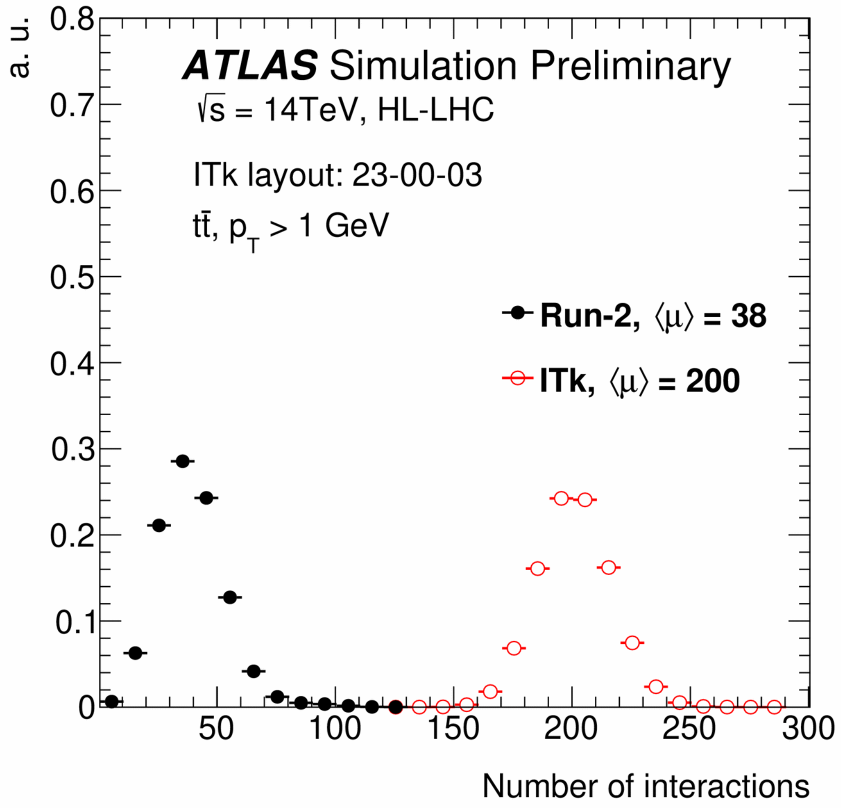
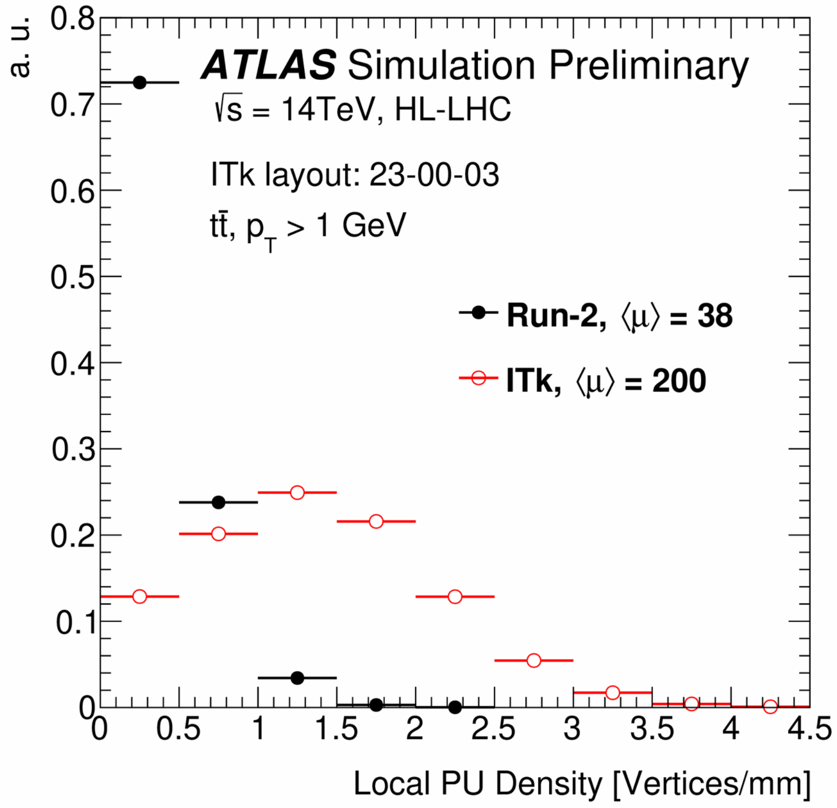
ATL-PHYS-PUB-2021-024

- Number of interactions and local pile-up density distribution
  - The local pile-up density takes into account event-by-event fluctuations, by computing the number of pile-up vertices in a small window (=+/-2 mm) around the hard-scatter vertex / the size of the window.





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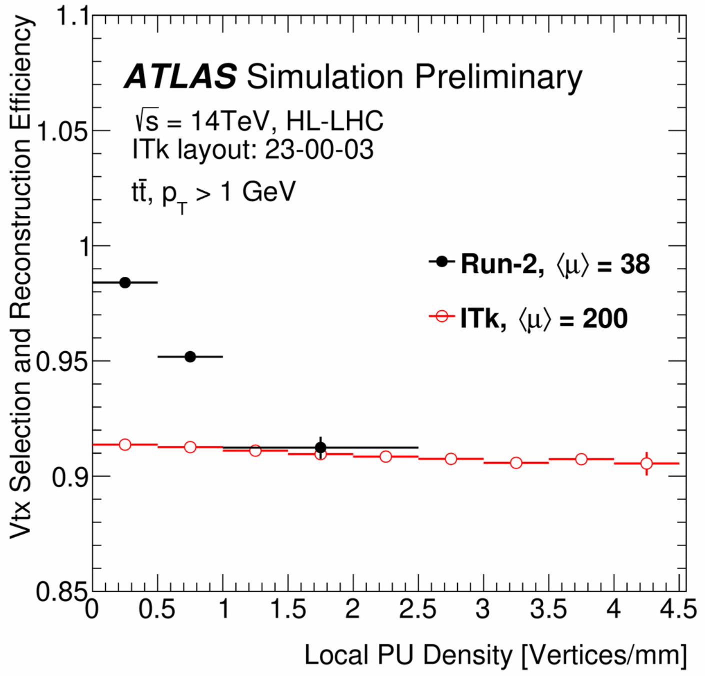
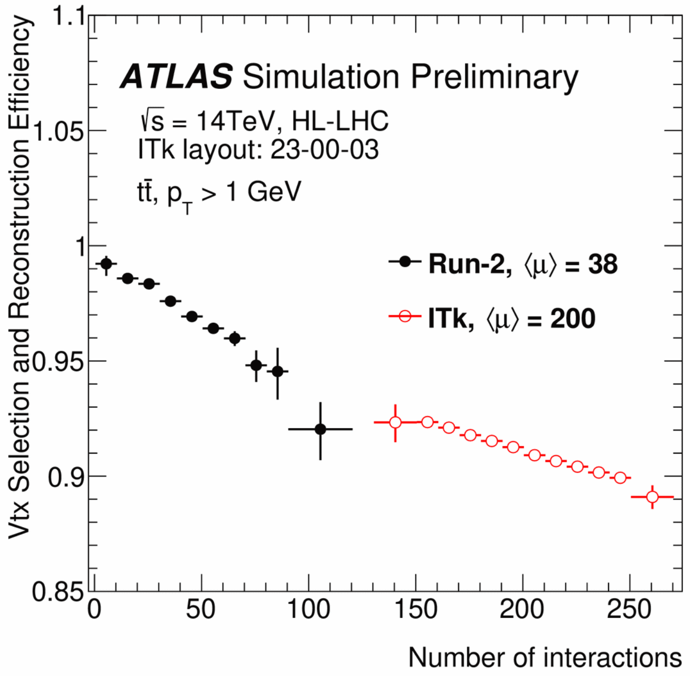
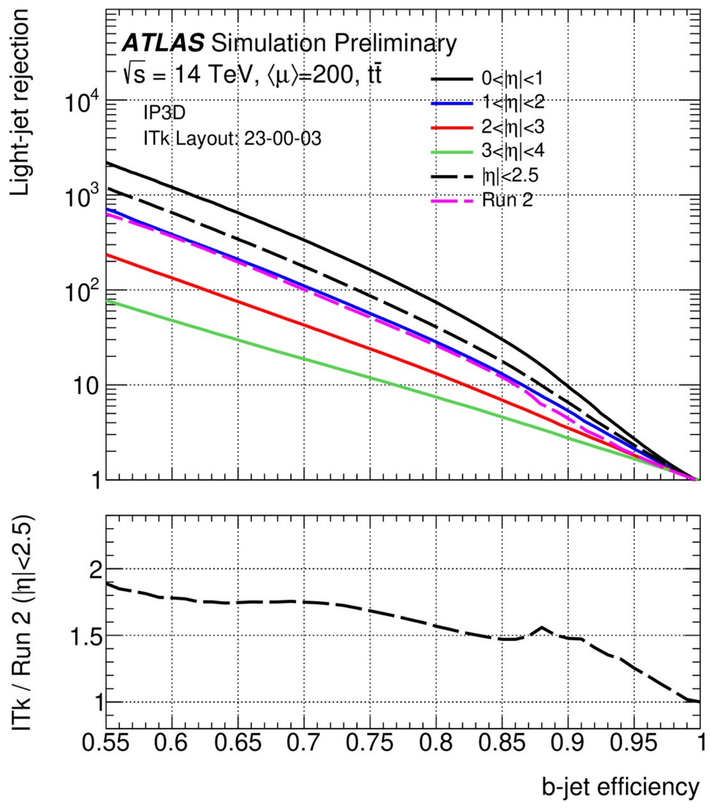
Vertex selection and reconstruction efficiency

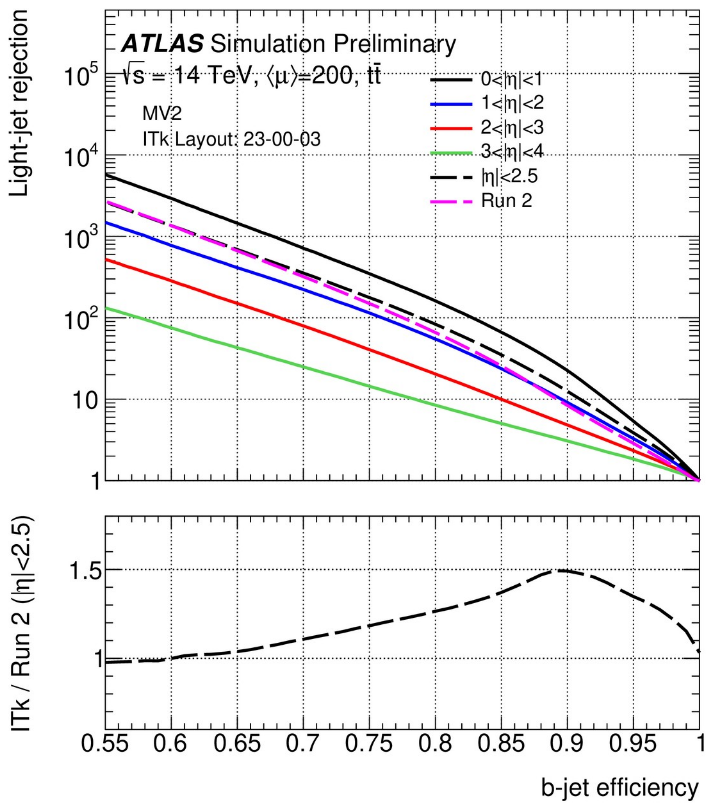




- Combined vertex selection and reconstruction efficiency is impacted by many effects:
  - Splitting of HS vertex into several reco vertices or merging of pile-up vertices reduced probability of selecting the HS vertex as the one with highest Σp_T^2; pileup interactions can genuinely produce a vertex with Σp_T^2 larger than simulated HS process
    - All effects correlated with number of interactions per bunch crossing → reduced selection and reconstruction efficiency with increasing pile-up

Jet Flavour tagging performance with ITk





- Improvement in low-level algorithms:
  - improved IP3D track categorisation exploiting p_T-dependance of IP resolution in central region + hit-content in forward region
  - material rejection for secondary vertices for SV1 + JetFitter
- Improved IP3D performance both from improved IP + track categorisation
- 40% improvement for MV2, driven by IP3D improvement
  - 20% higher light-jet rejection wrt Run-2 at 77% b-jet efficiency working poiny

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Fast Track Reconstruction For ITk

- We have seen CPU reduction thanks to **layout optimisation** and **harder selection cuts** for ITk wrt Run2 (based on Run2 tracking software): ATL-PHYS-PUB-2019-014

  → Proven a fully functional software prototypes for fast reconstruction demonstrate that nearly offline quality track reconstruction performance can be reached within much reduced CPU resource requirements