Improvements to ATLAS Inner Detector Track Reconstruction for LHC Run 3

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ATLAS Track Reconstruction

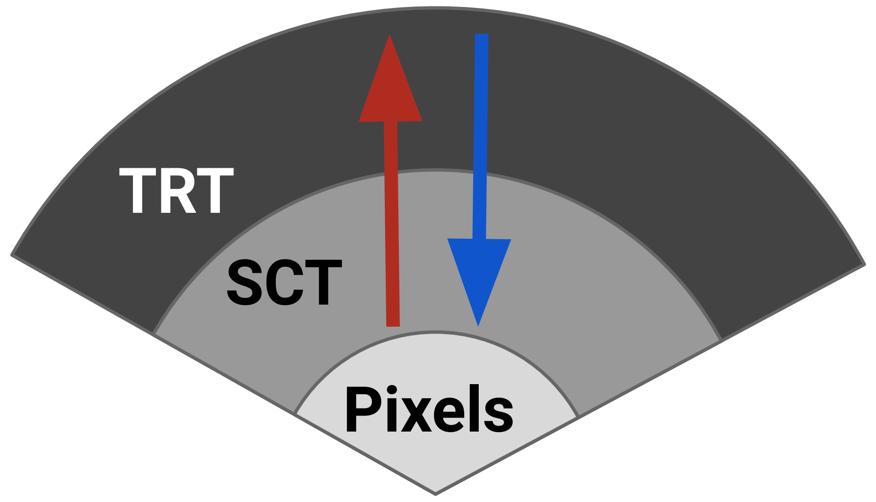
- Track reconstruction is a multistep process: **clusters → space-points → seeds → tracks**
- **Primary tracking chain** runs **inside-out** starting from hits recorded in the **pixel** and **strip** subdetectors
- **Back-tracking chain** runs **outside-in**, seeded from drift circles in the **TRT** to recover photon conversions
- Additional tunes exist based on various physics needs → **Large Radius Tracking (LRT)** for displaced vertices

Useful Definitions

- **Drift circles:** hits recorded by TRT straw tubes
- **Clusters:** aggregate of nearby silicon hits
- **Space-points:** clusters with 3D space information
- **Seeds:** triplets of curvature-compatible space-points
- **Tracks:** refit extension of seeds into outer layers

ATLAS Primary Tracking

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

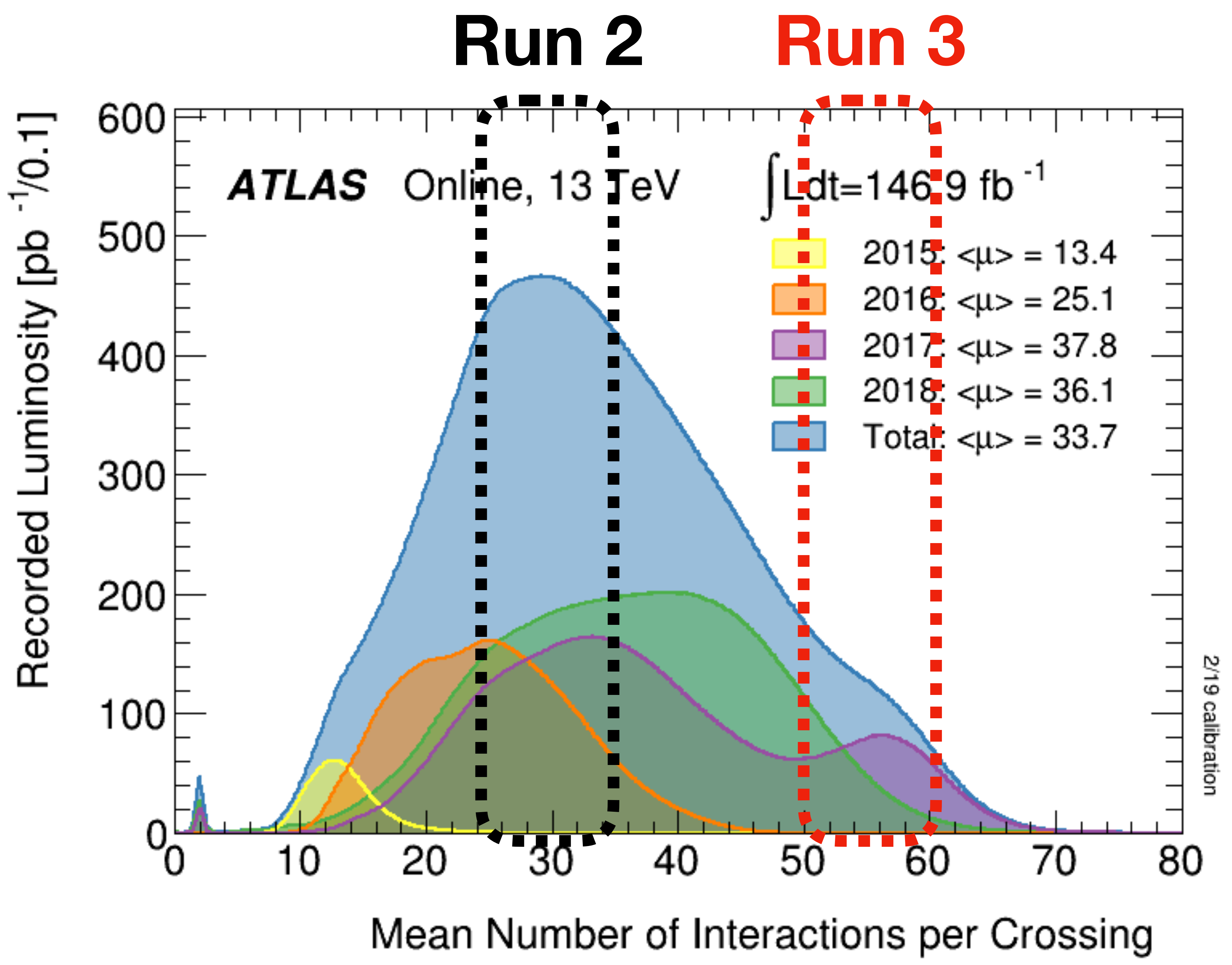


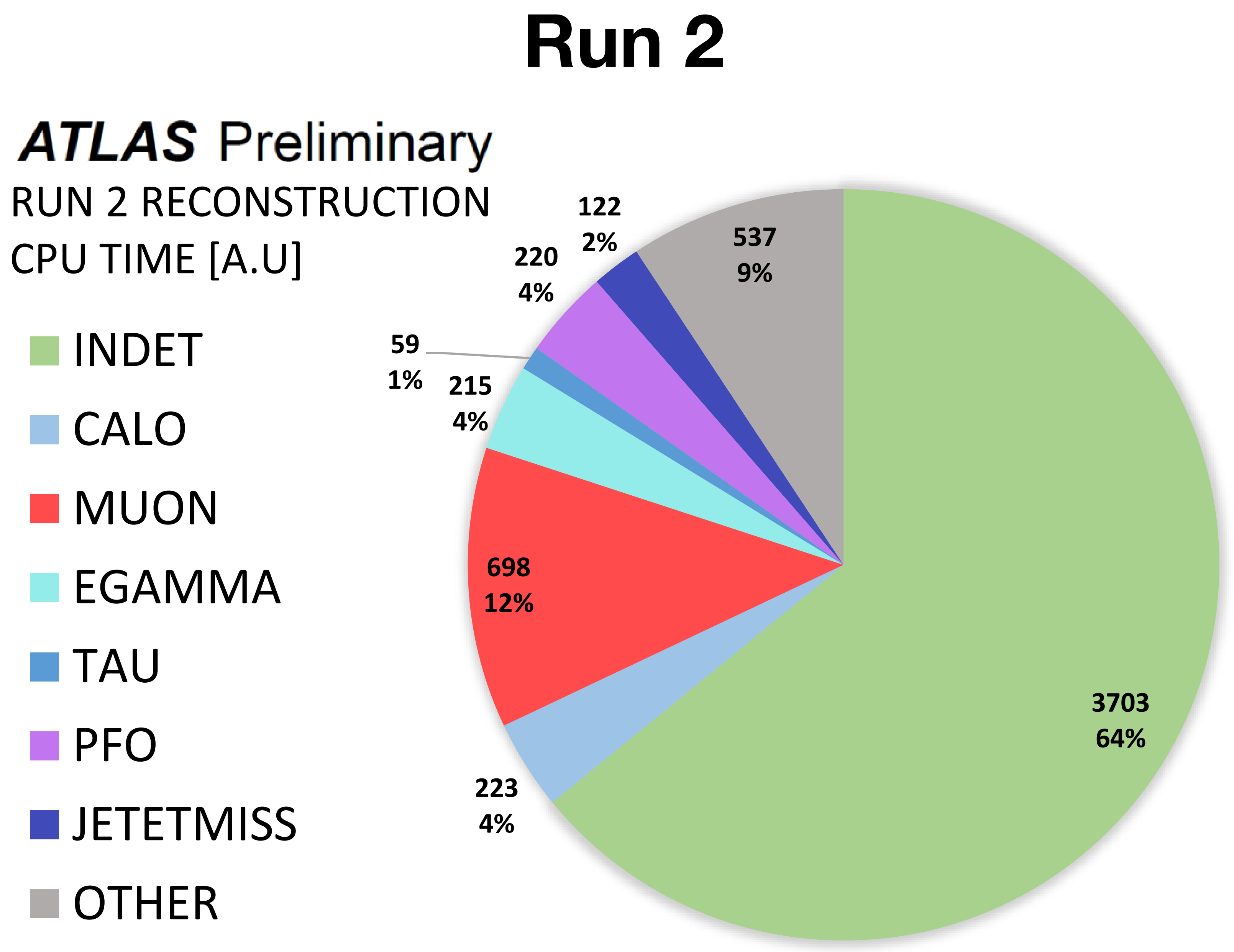
ATLAS Back-Tracking

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

The Challenge of Tracking in LHC Run 3

- **Pile-up** $\langle \mu \rangle$ has already posed **serious challenges** to ATLAS, particularly to the ID reconstruction
- Expect **average collision multiplicity** of $\langle \mu \rangle = 50 - 60$ in Run 3, up from Run 2 average of $\langle \mu \rangle = 34$
  - Given its fine granularity and proximity to the beam-line, each collision produces up to 1500 hits in the ID
- **Tracking** is fundamentally a problem of **combinatorics** → need to address **scaling with pile-up**
- In Run 2, **ID tracking** alone accounted for nearly $65\ \%$ of the total ATLAS reconstruction time



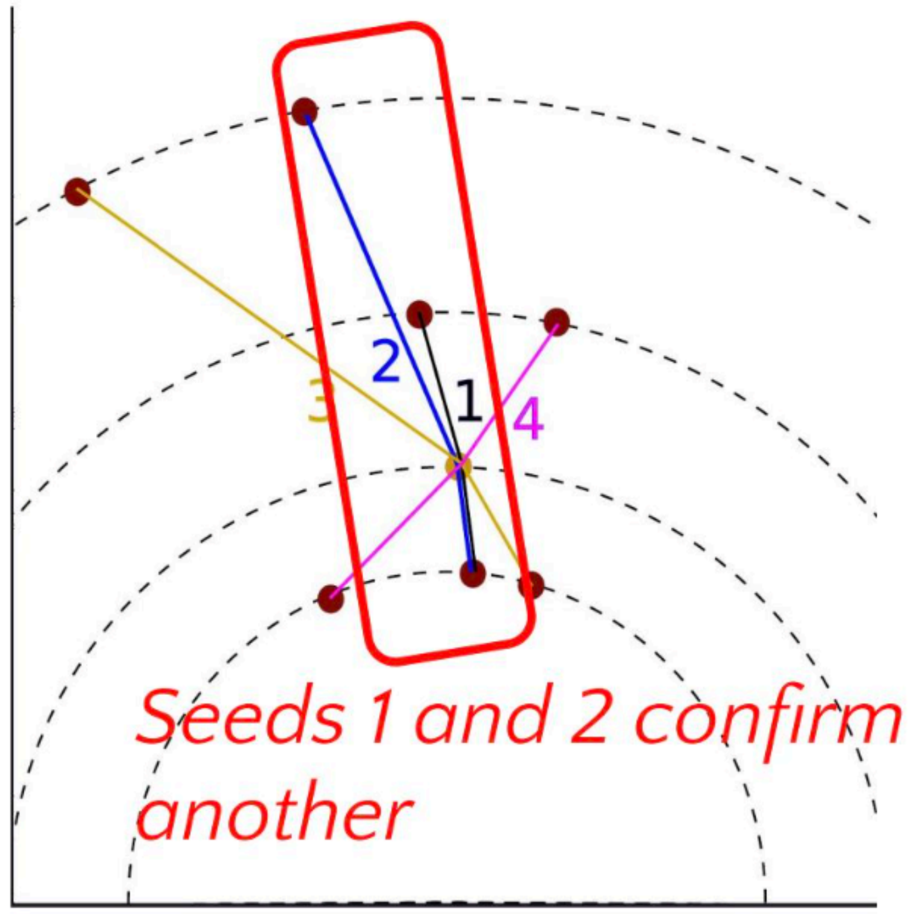


Overhaul of Tracking for Run 3

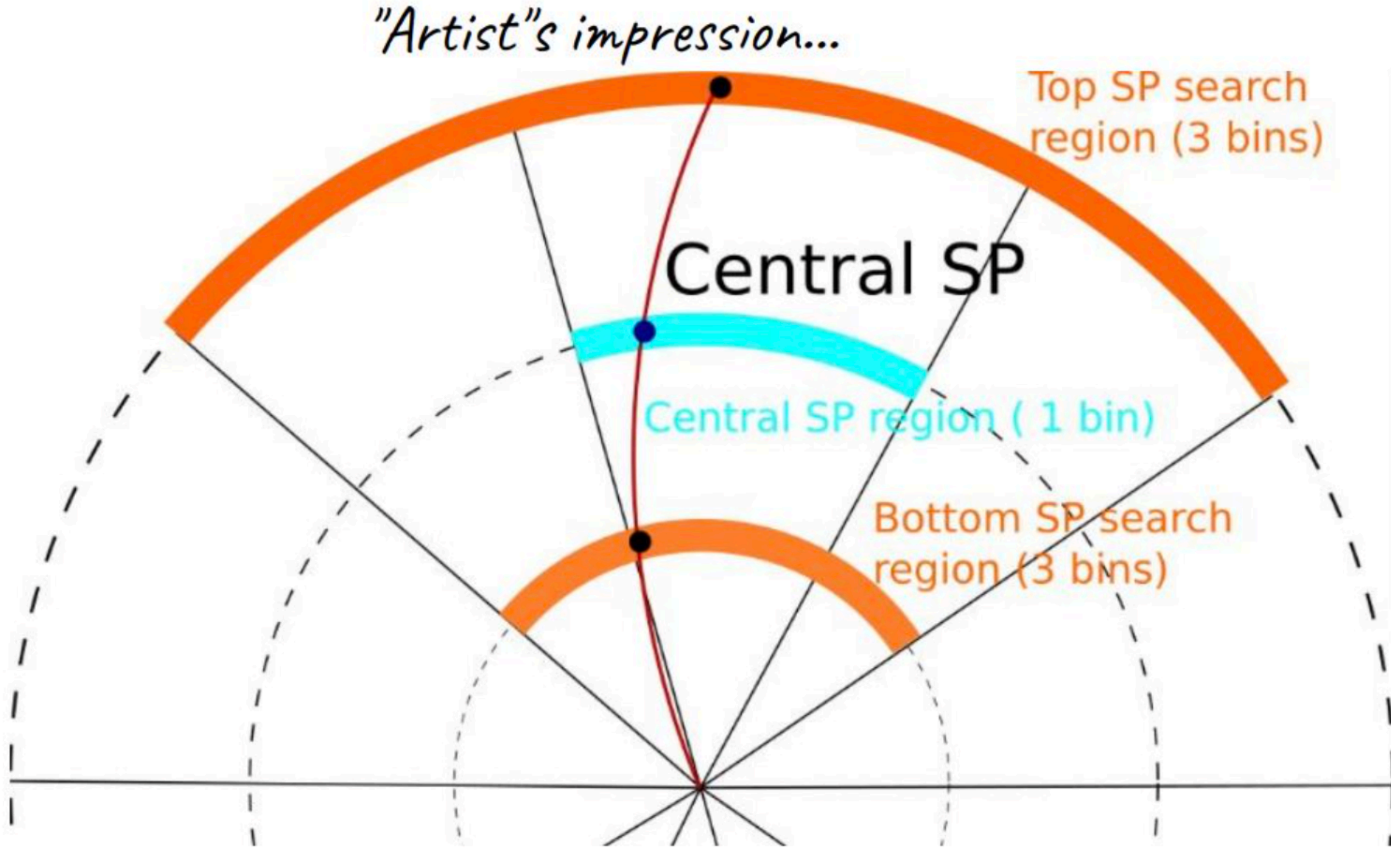
- **Goal:** Speedup track reconstruction by $\times 2$ over Run 2 **and** significantly reduce disk space usage
  - Retune track reconstruction from $\langle \mu \rangle = 20 \rightarrow 60$
  - Physics motivation to improve stability against increasing pile-up
  - Prevent catastrophic slowdowns when running at high pile-up
- Best handle is **reducing** the number of **low quality seeds** → cascading downstream speedups
  - In particular, **tighten seed requirements** to **align** with **track cuts** further down the chain
- Thanks to a coordinated effort by many, **several changes** have been made to the **software** for Run 3:
  - Stricter tracking cuts
  - Back-tracking and TRT optimization
  - Seed and pattern recognition tuning
  - Reduction in seed formation regions
  - Migration of hole search
  - Inclusion of ACTS-based vertexing

→ **Now let's see where we stand versus Run 2 …**

Seed Confirmation



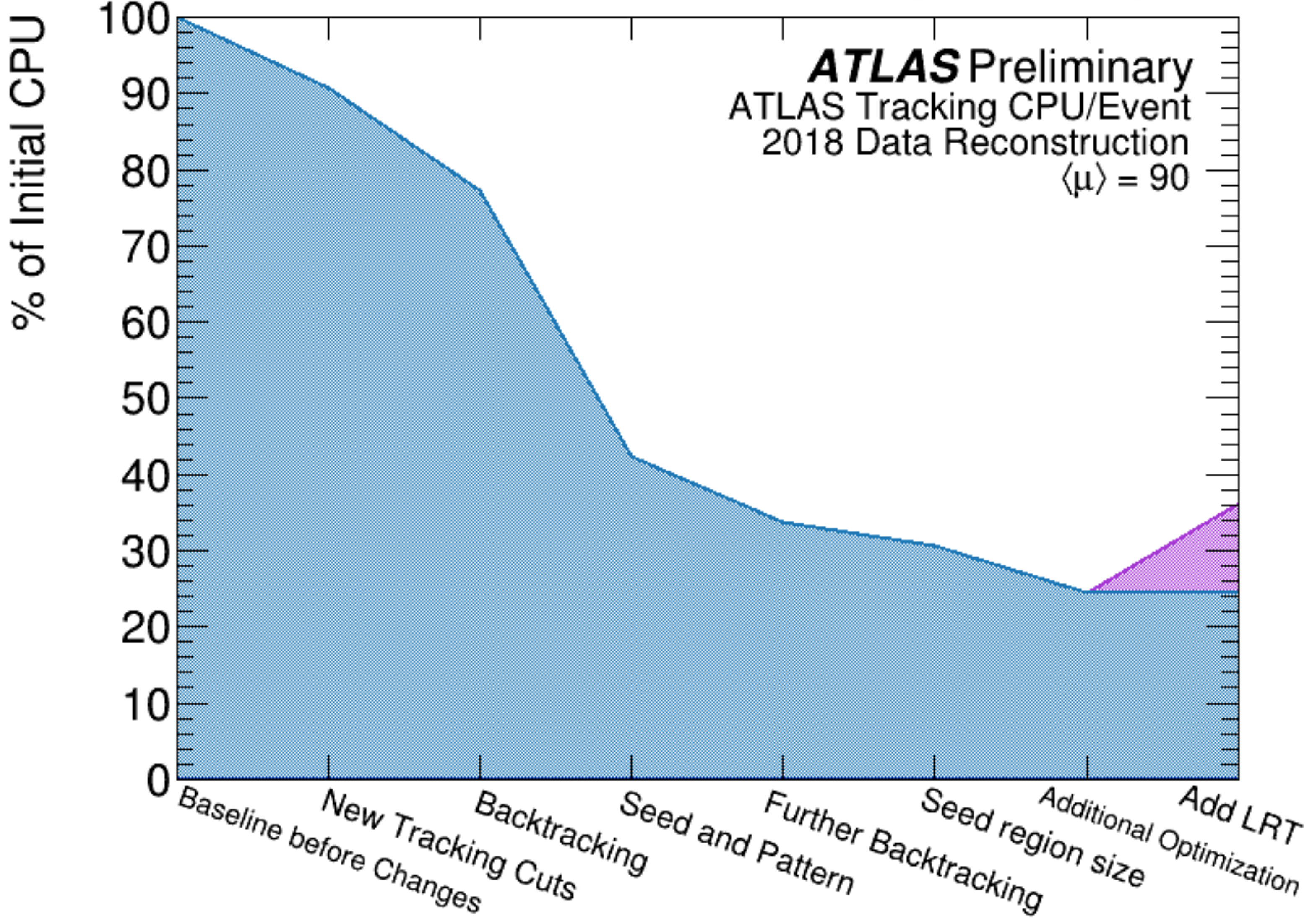
Seed Formation Regions



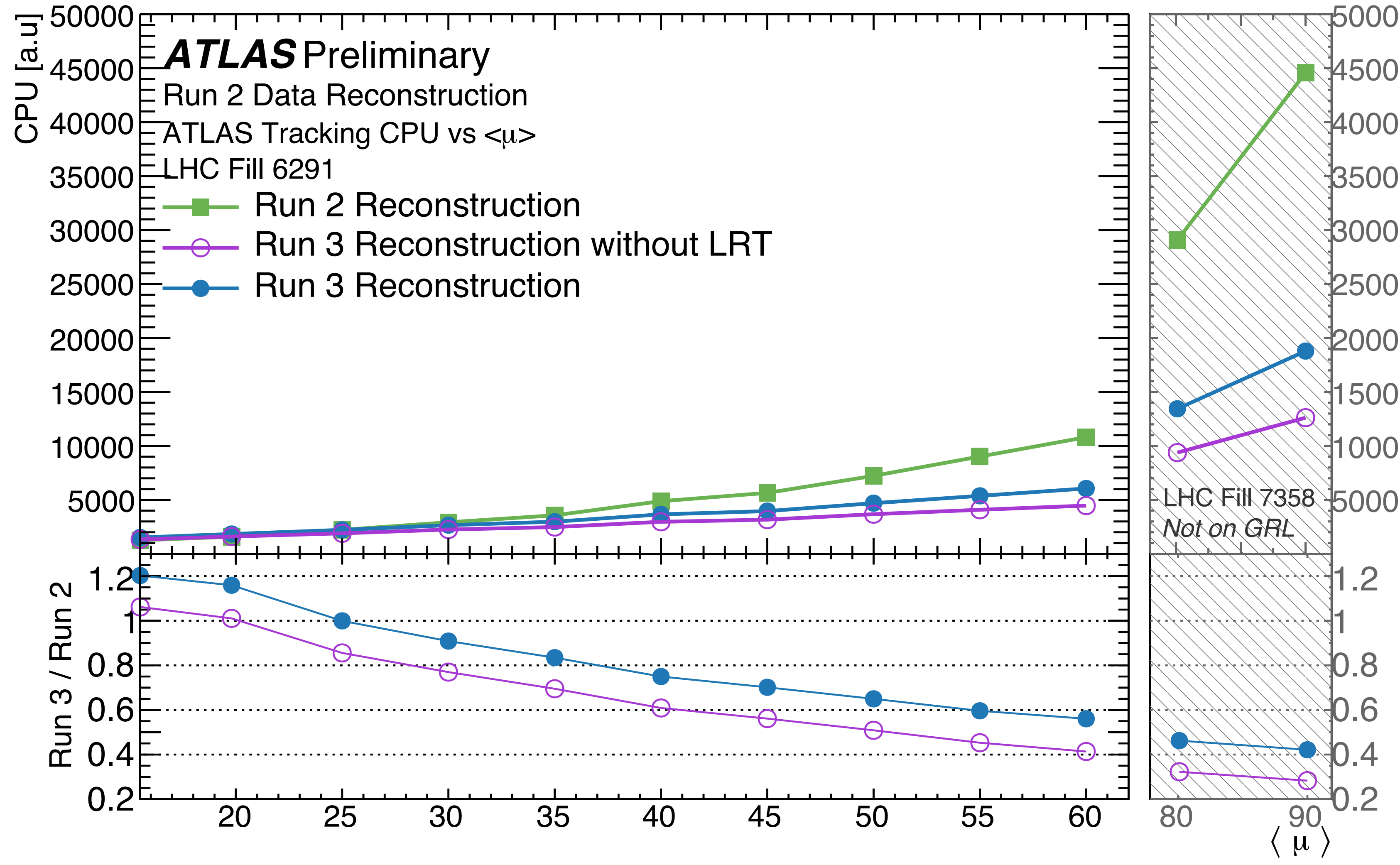
Summary of Performance Improvements

- **Headline:** Run 3 reconstruction is over $2\times$ faster with a $25\,\%$ reduction in the disk space
  - Significantly improved scaling with pile-up → capable of running up to $\langle\mu\rangle = 90$ 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**
  - No longer wasting processing time and disk storage on poor quality tracks

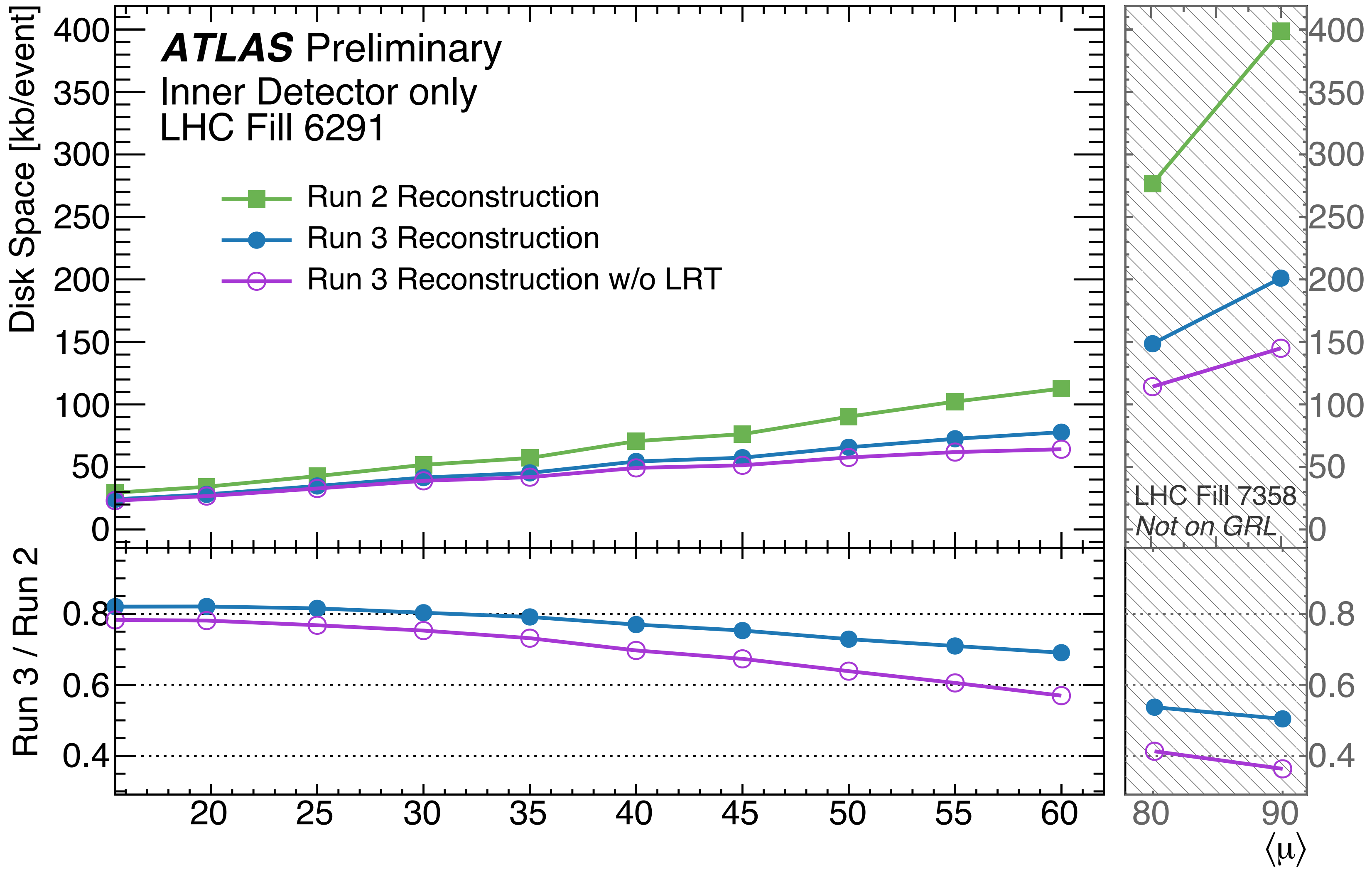
Incremental CPU Speedup



Run 2 and Run 3 CPU vs. $\langle\mu\rangle$



Run 2 and Run 3 Disk vs. $\langle\mu\rangle$

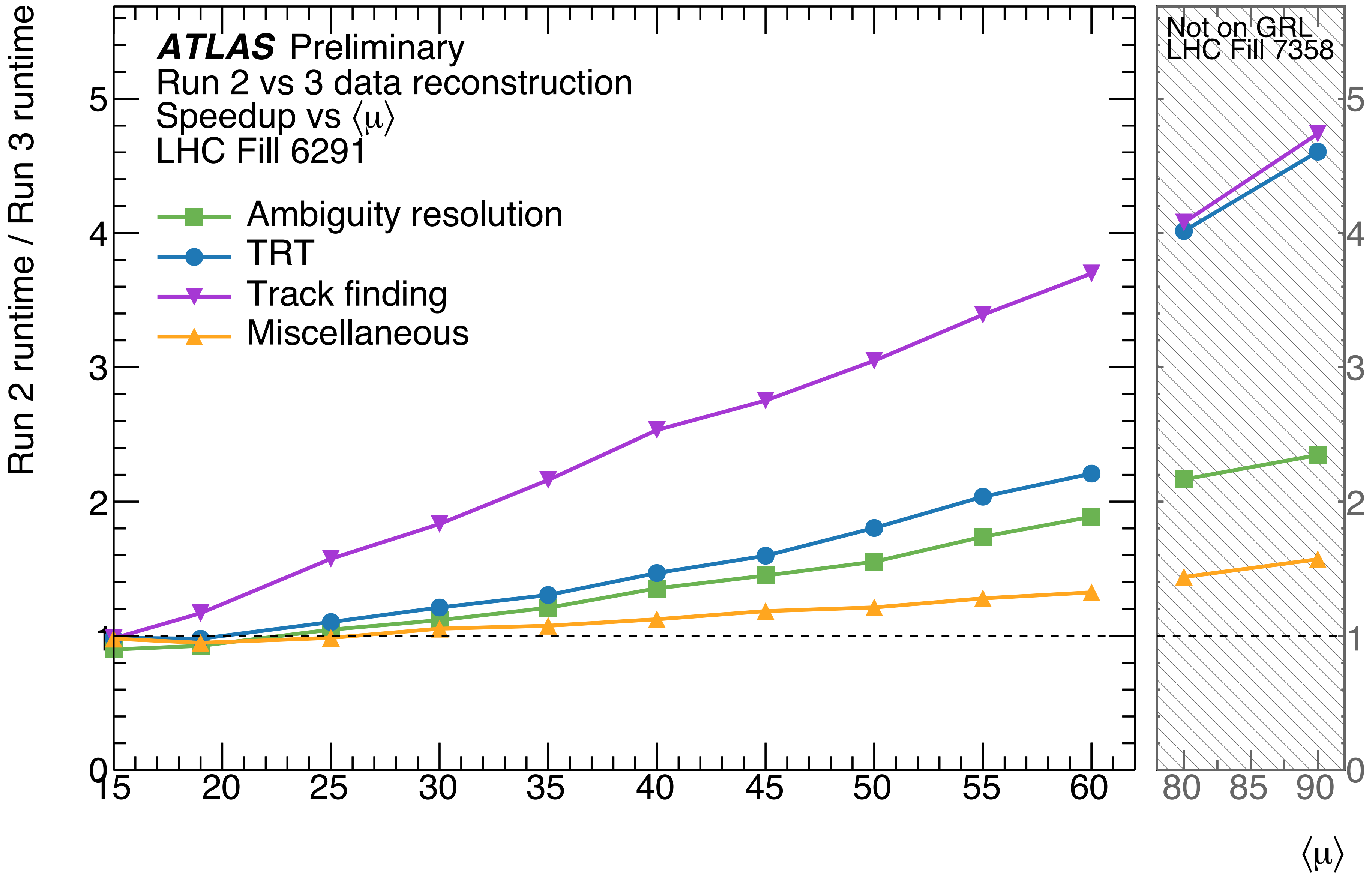


Note: All tests run in **single-thread** mode

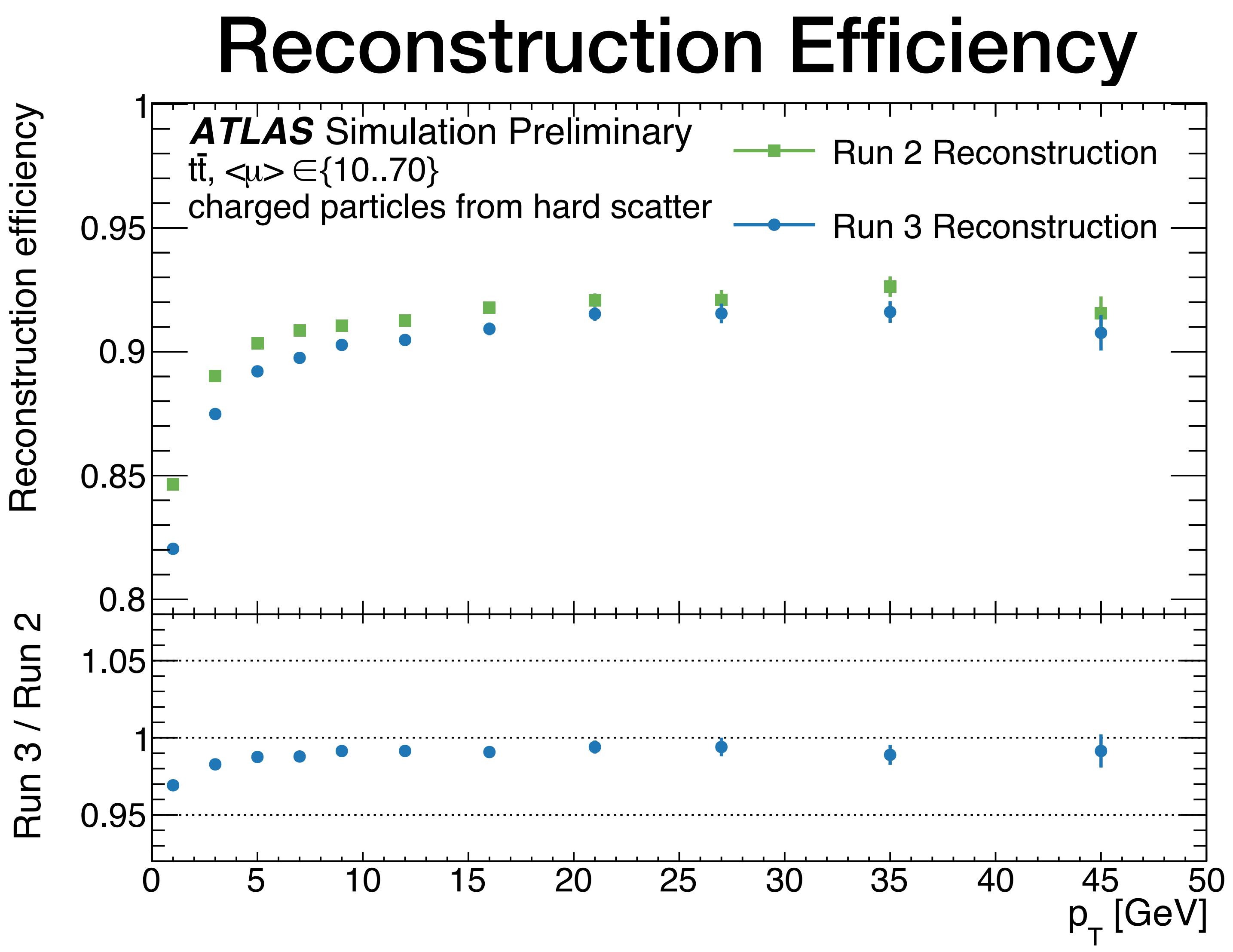
Breakdown of Performance Improvements

- Major speedups come from improvements to **track finding** and the **TRT reconstruction**
  - **Track finding** is the largest CPU consumer → now over $4\times$ faster
- Importantly, the changes do not result in any significant impact on the reconstruction efficiency
  - While the fake rate is significantly reduced → key to performance improvements
- Improvements in **vertexing** driven by the adoption of the **Adaptive Multi Vertex Finder** algorithm
  - First production use of **ACTS** common tracking framework in an LHC experiment!

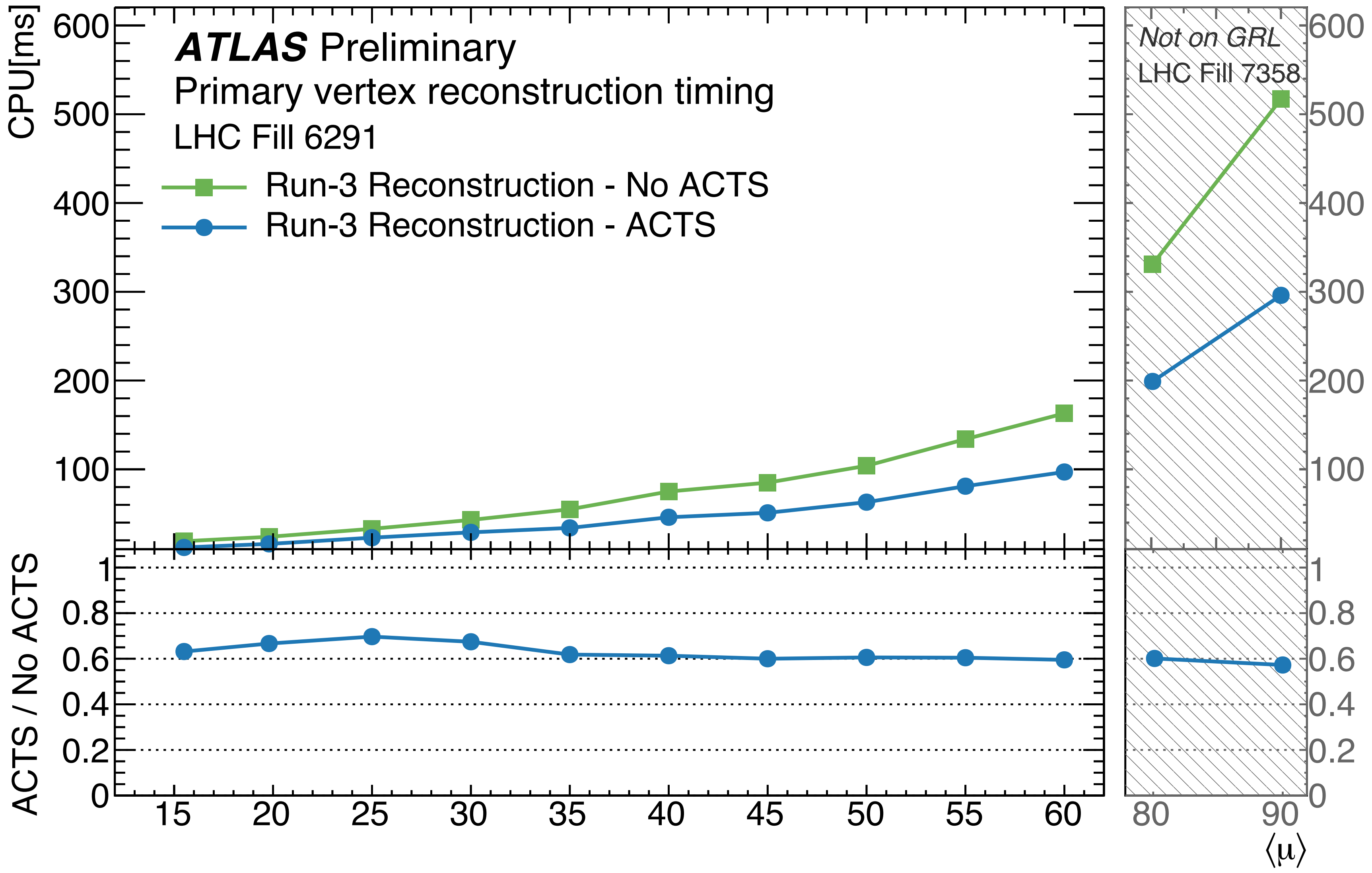
Detailed CPU Speedup vs. $\langle\mu\rangle$



Reconstruction Efficiency



Vertexing CPU vs. $\langle\mu\rangle$



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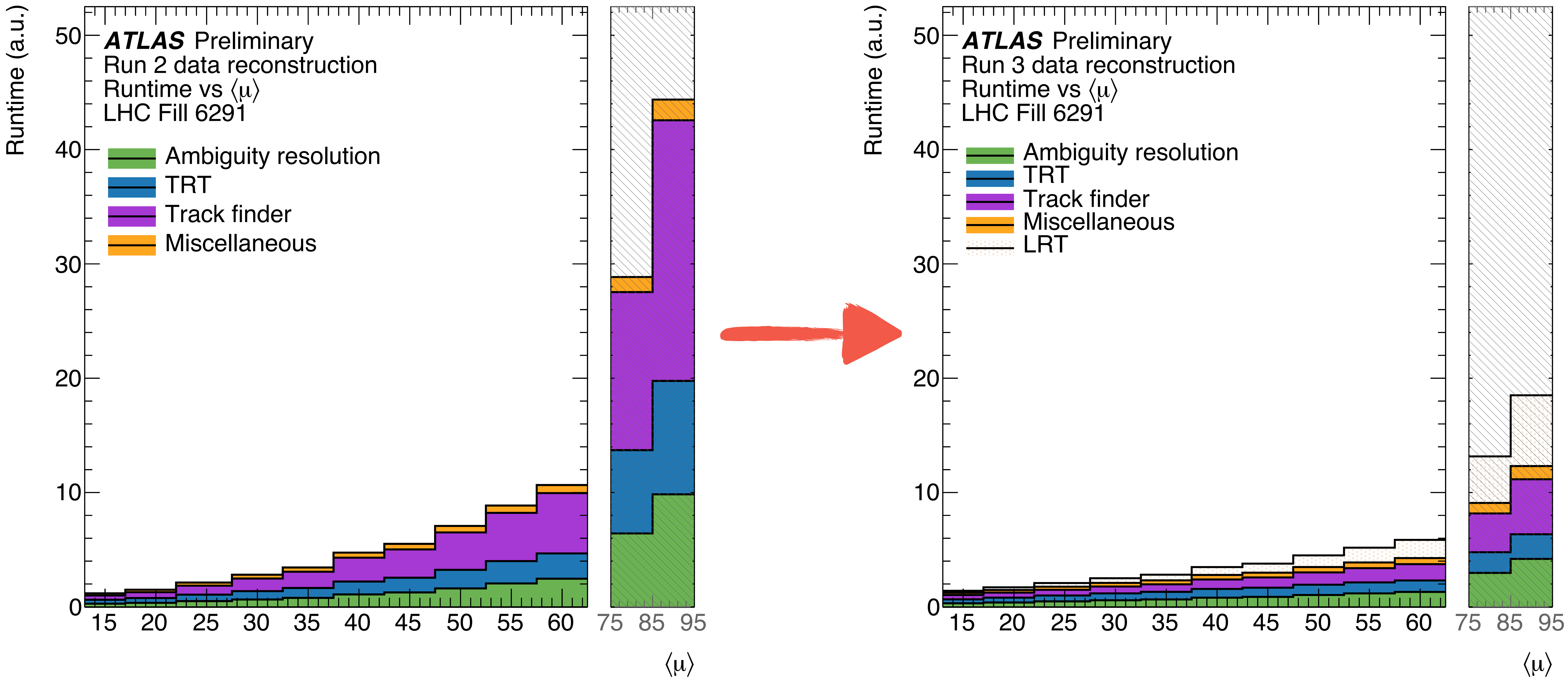
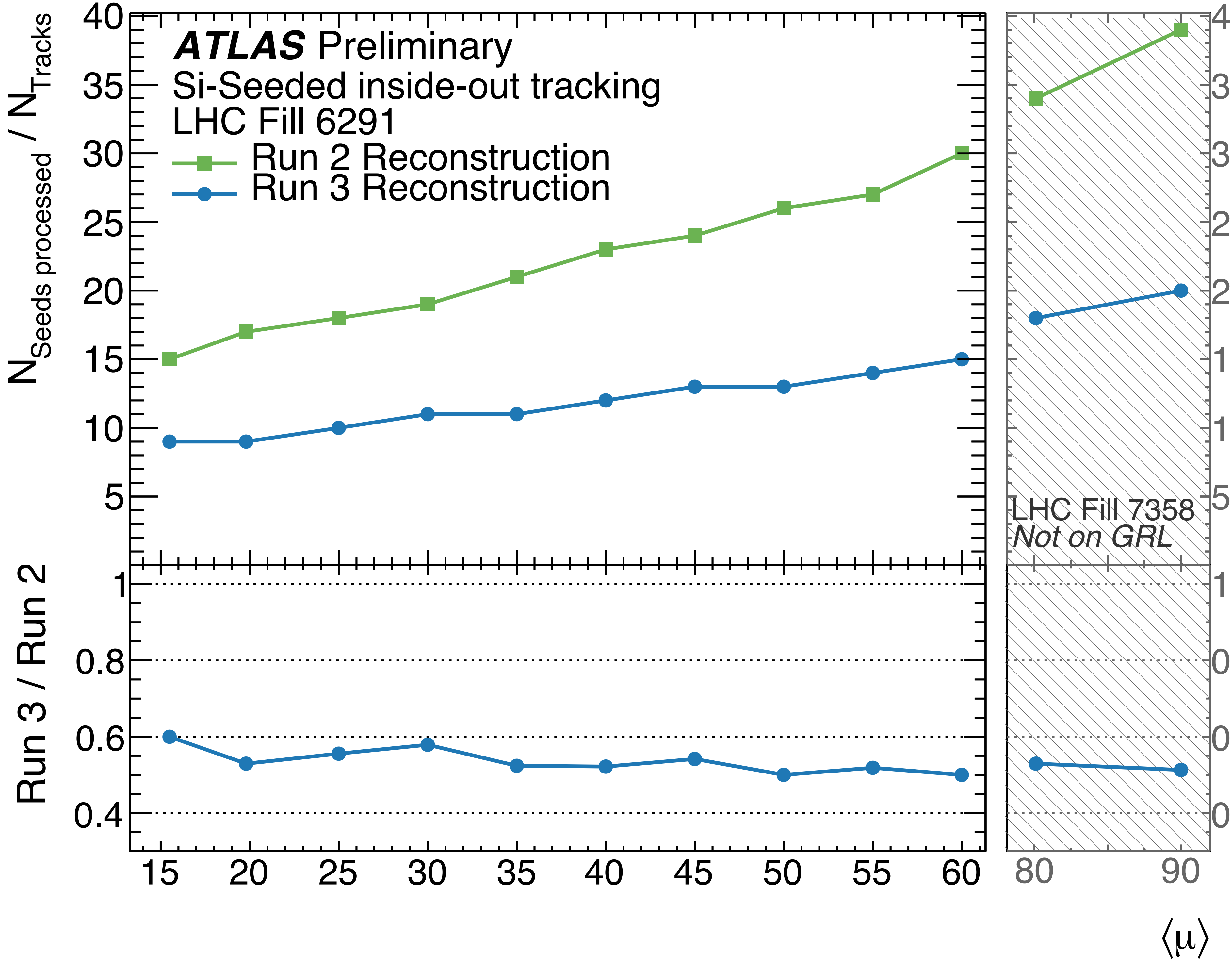


Absolute CPU Usage vs. $\langle\mu\rangle$

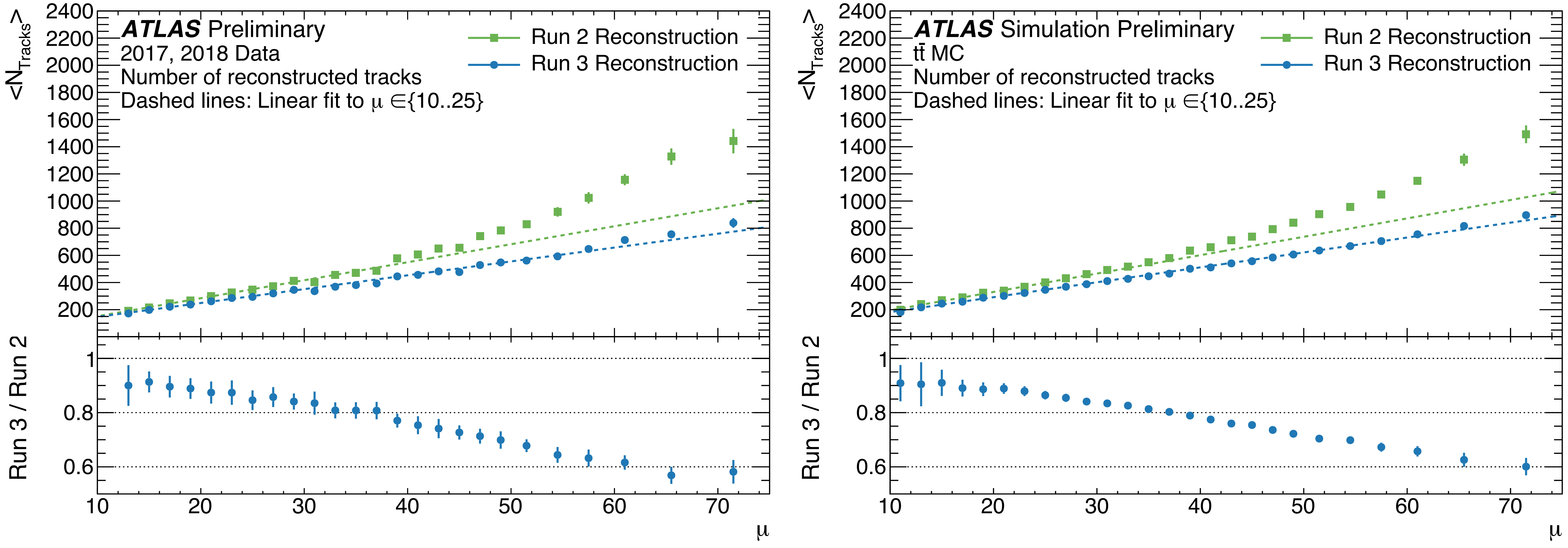
Breakdown of Performance Improvements

- We now process **less than half** the **number of seeds per reconstructed track**
  - Implying the costly seed-extension algorithms are being called half as frequently!
- Additionally, the **number of reconstructed tracks** in **data** and **MC** is now approximately **linear in μ**
  - Expect **real component** to scale **linearly**, and **fakes** to scale with a **higher power**

Ratio of Seeds-to-Tracks vs. $\langle\mu\rangle$



Number of Reconstructed Tracks vs. μ

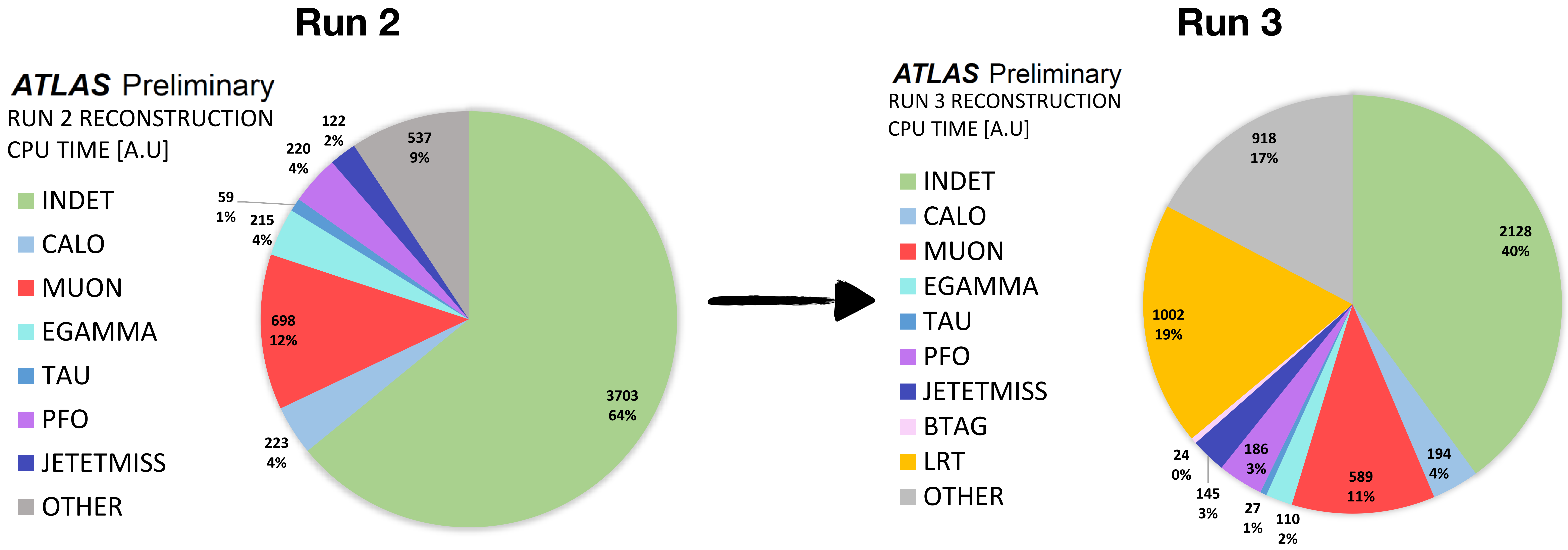


Data

$t\bar{t}$ MC

Summary of Tracking for Run 3

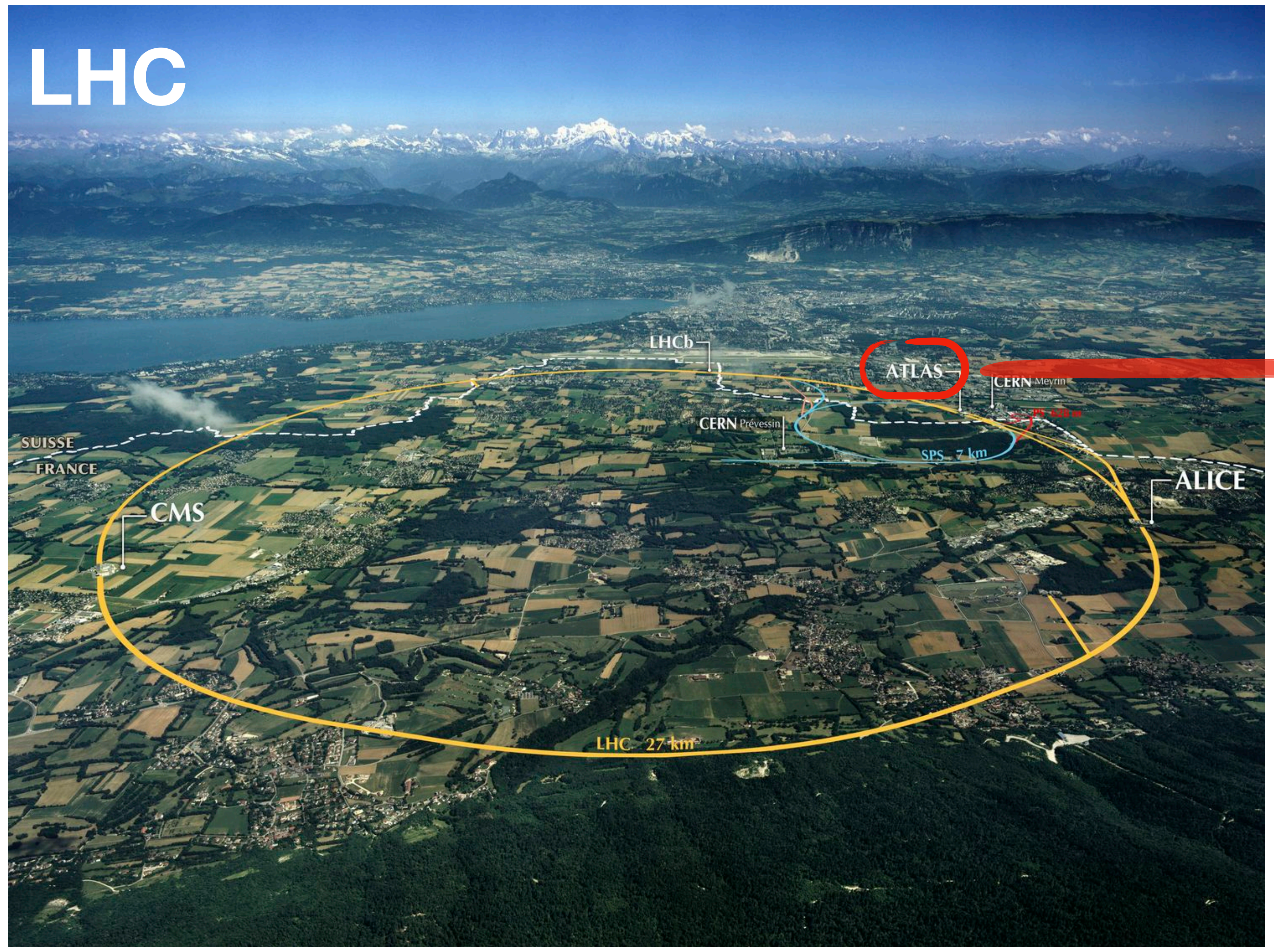
- We are now in a much better position for track reconstruction in Run 3
- **Surpassing $\times 2$ CPU speedup** and $25\,\%$ **disk reduction**, even with the added **inclusion** of **LRT** by default
- **Total ID reconstruction** time reduced from $65\,\%$ in Run 2 to $40\,\%$ in Run 3 at $\langle\mu\rangle = 50$ (excl. LRT)
- Looking ahead, there are still many interesting challenges to overcome for tracking in the high-luminosity LHC
  - Will use Run 3 as a learning opportunity to optimize tracking for $\langle\mu\rangle = 200$

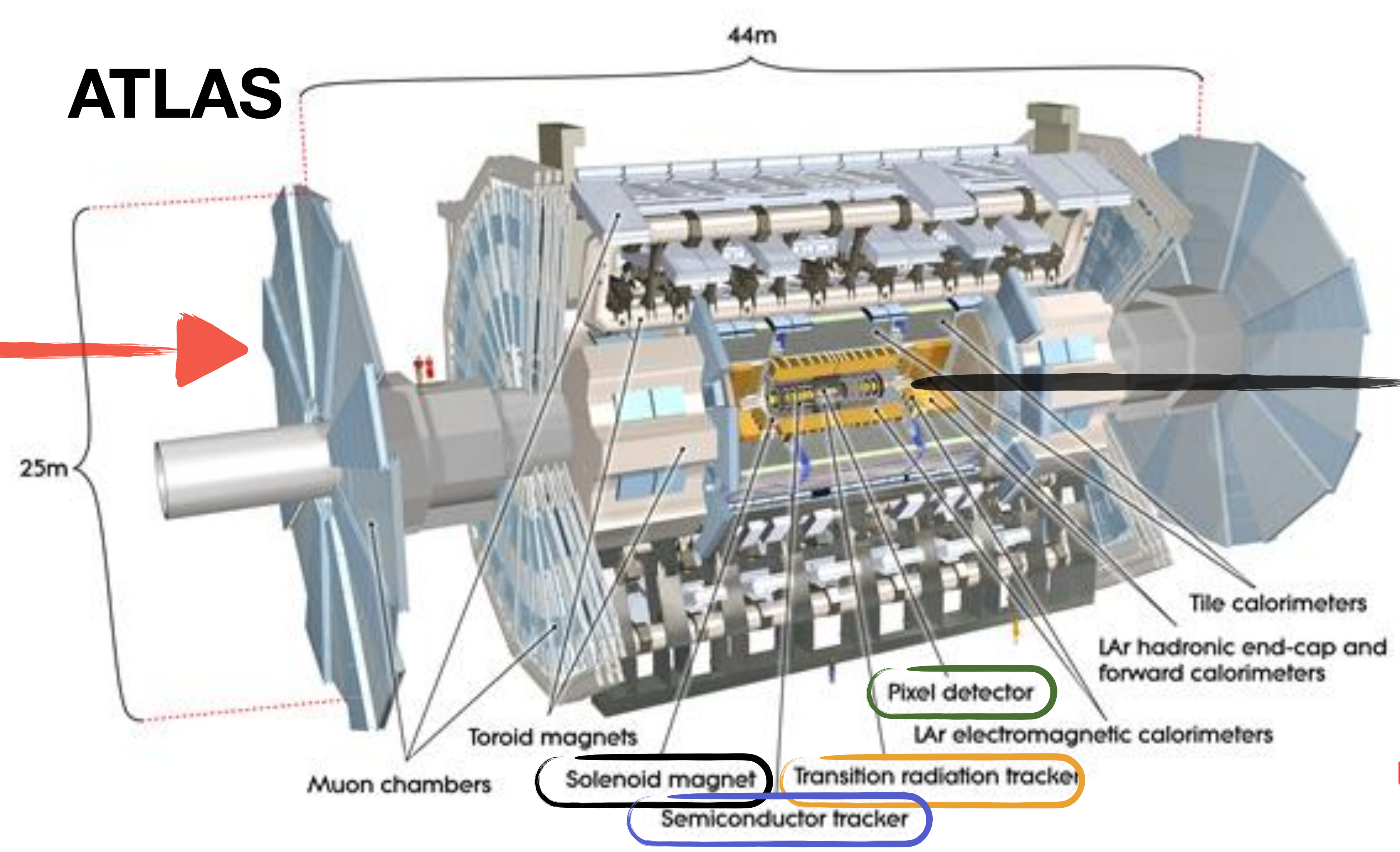


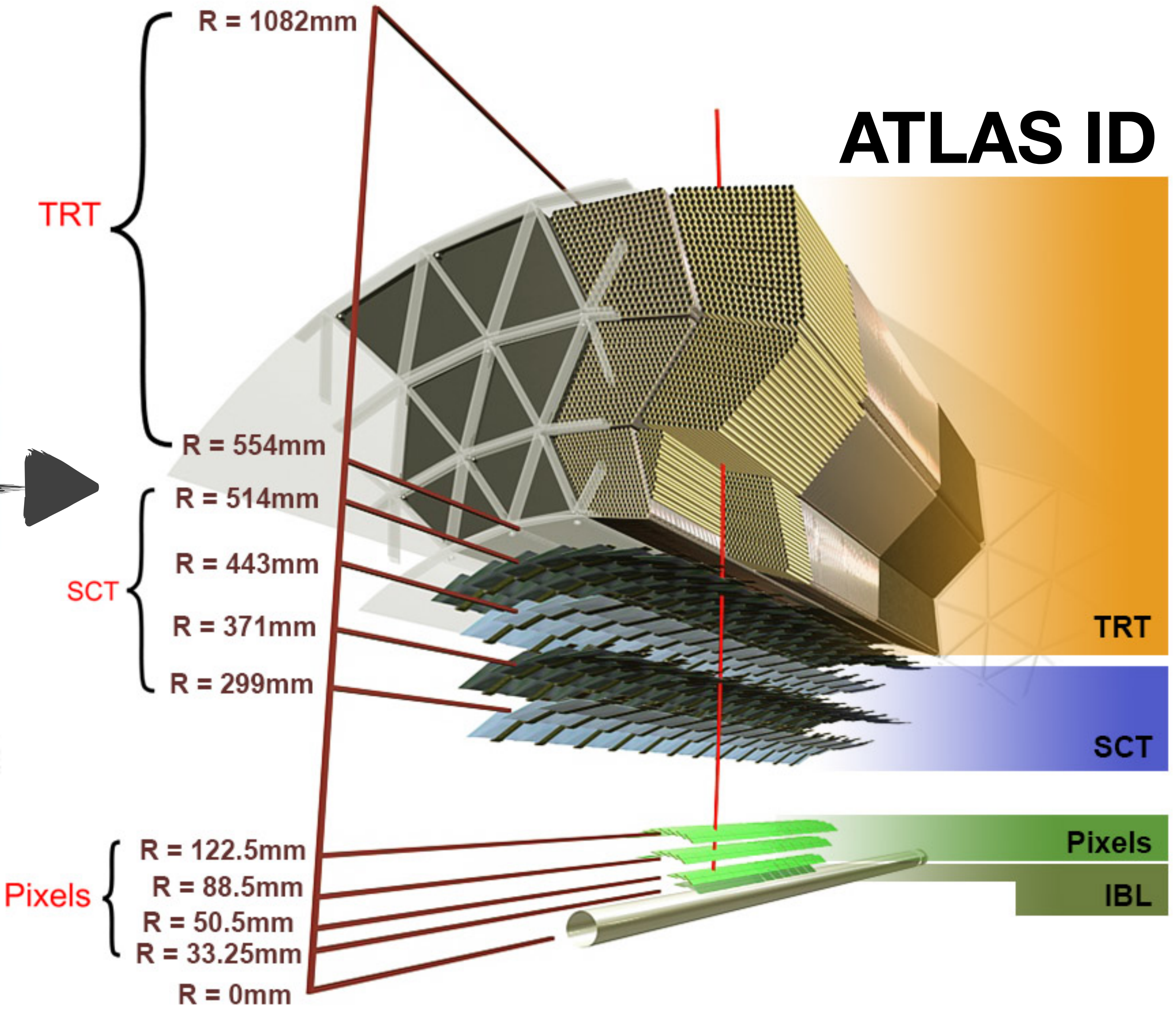
Backup

Tracking in ATLAS at the Large Hadron Collider

- ATLAS is a multipurpose detector situated on LHC Point 1 built from several concentric subdetectors
- The **Inner Detector (ID)** is the **centermost** system responsible for **charged particle tracking**
  - **Three layers:** Pixel, Semiconductor Tracker (SCT), Transition Radiation Tracker (TRT)
  - Crucial for **many aspects** of object **reconstruction** → transverse momentum, vertexing, *b*-tagging, …
- Reconstruction describes the transformation from **raw detector signals** → **analysis-ready physics objects**





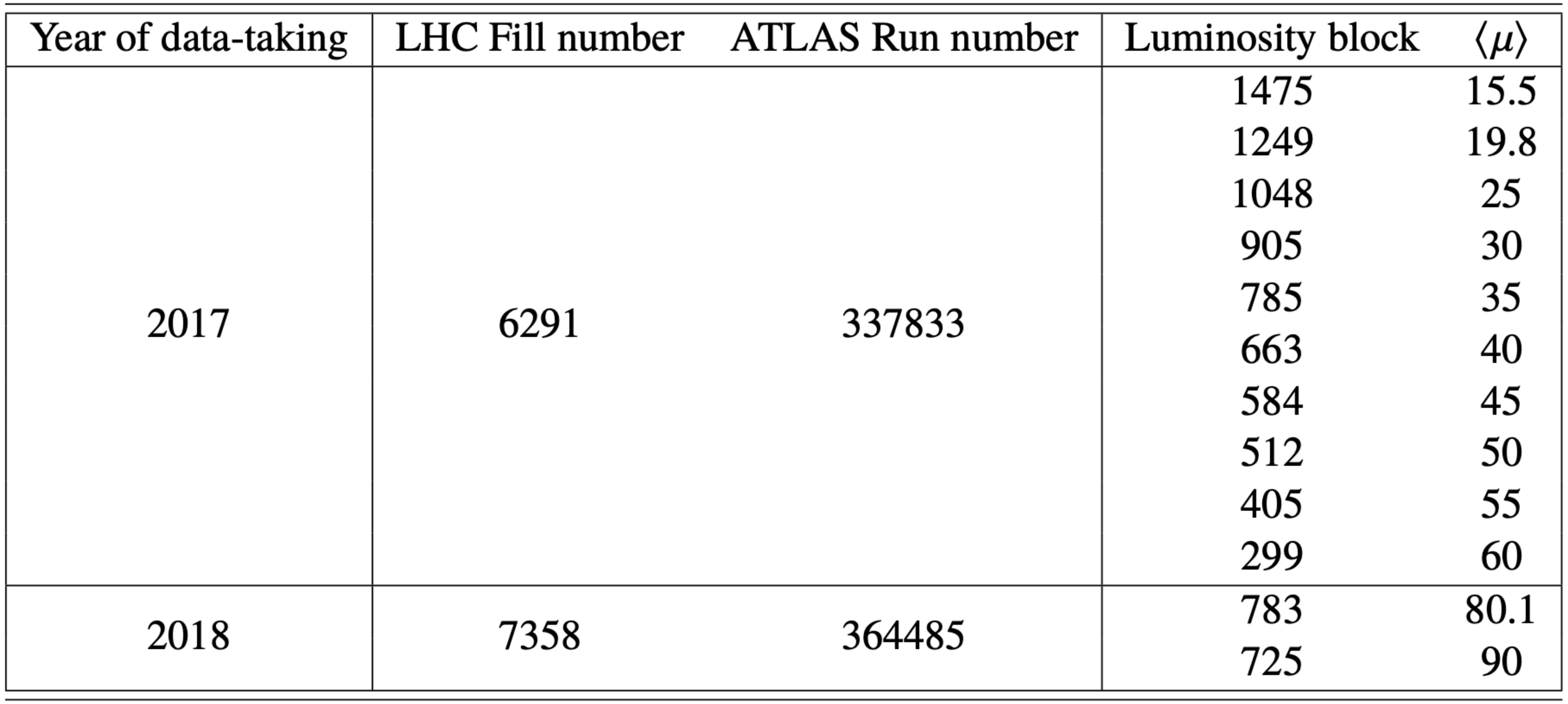


Detailed Summary of Changes

- **Clustering and Space Point Formation**
    - Internal logic improvements
- **Seeding and Track Finding**
    - Store fewer pixel seeds (only one) sharing the same central space point and all confirmed seeds
    - Reduce combinatorics by tightening $\phi - z$ regions in which seeds are formed, adapted based on p_T cut
    - Restrict size of search road
- **Ambiguity Resolution**
    - Tighten track selections from $7 \rightarrow 8$ silicon hits and $d_0 < 10 \rightarrow 5$ mm
    - Streamline of hole search procedure
- **TRT Extension**
    - Update definition (tighten quality) of precision hits
    - Require more precision hits on track (PHF $30\,\% \rightarrow 40\,\%$) for successful extrapolation
- **Back-tracking**
    - Tighten electromagnetic calorimeter region of interest threshold used for seeding
- **Vertexing**
    - Move from Iterative Vertex Finder to Adaptive Multi Vertex Finder (based on ACTS)

Details on Benchmarking

- **Dataset:** twelve luminosity blocks corresponding to two LHC fills **6291** (2017) and **7358** (2018)
  - Average over 300 consecutive collision events
- **Setup:** machine with two Intel(R) Xeon(R) E5-2630 v3 8-core, 2.4 GHz processors and 128GB of RAM
  - CERN CENTOS 7 operating system
  - CPU scaling set to performance mode and hyper-threading disabled
  - Resulting HS06 score of 278
- All tests run in **single-thread** mode



Year of data-taking	LHC Fill number	ATLAS Run number	Luminosity block	$\langle\mu\rangle$
2017	6291	337833	1475	15.5
			1249	19.8
			1048	25
			905	30
			785	35
			663	40
			584	45
			512	50
			405	55
			299	60
2018	7358	364485	783	80.1
			725	90

Breakdown of Performance Improvements

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  - **Track finding** is the largest CPU consumer → now over $4\times$ faster

Fractional CPU Usage vs. $\langle\mu\rangle$