

# Improvements to ATLAS Inner Detector Track reconstruction for LHC Run-3

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# Track reconstruction in the ATLAS experiment



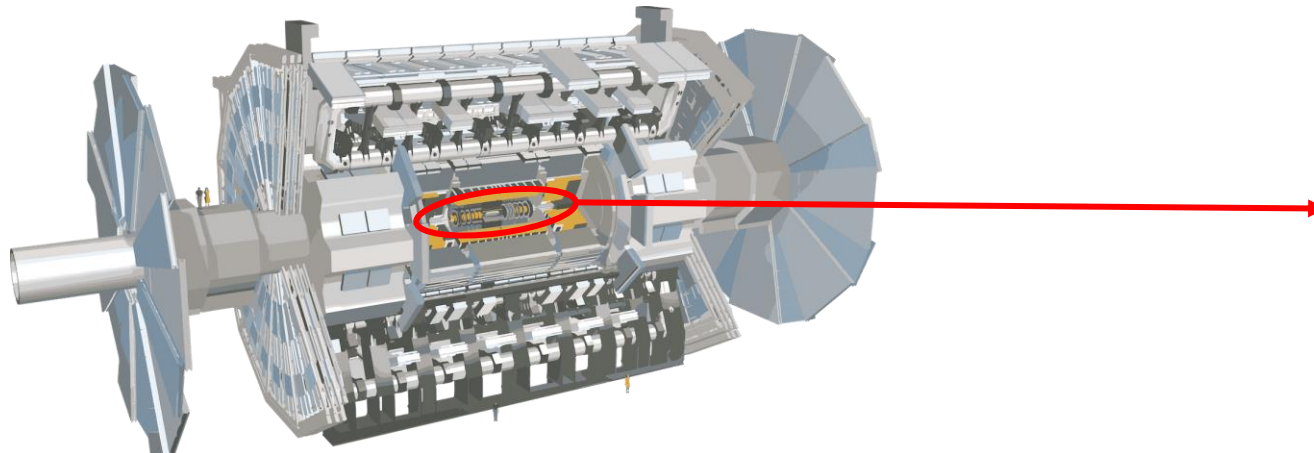
**Charged particle trajectories (tracks)** are essential ingredient to most collider signatures

- Muons, electrons, jets, semi-hadronic tau decays, photon conversions, Missing momentum, interaction vertices, ...

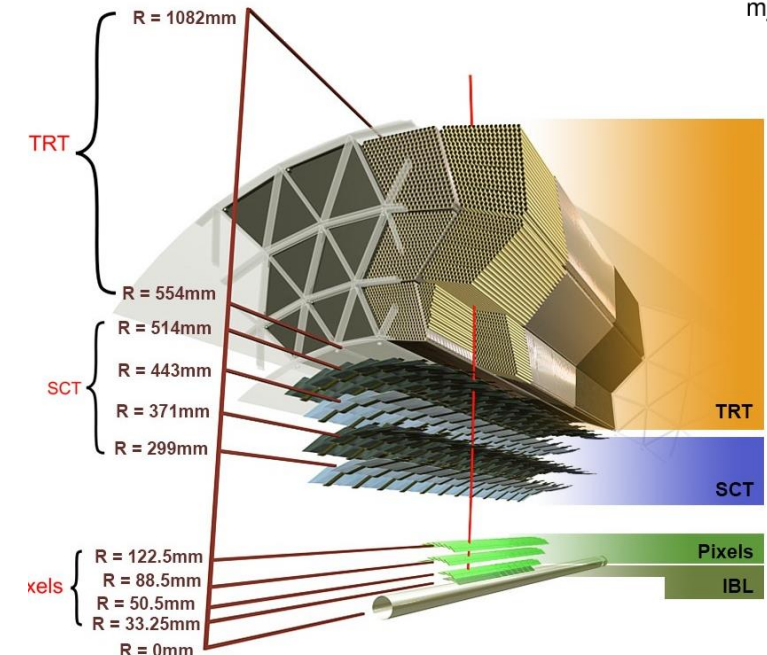
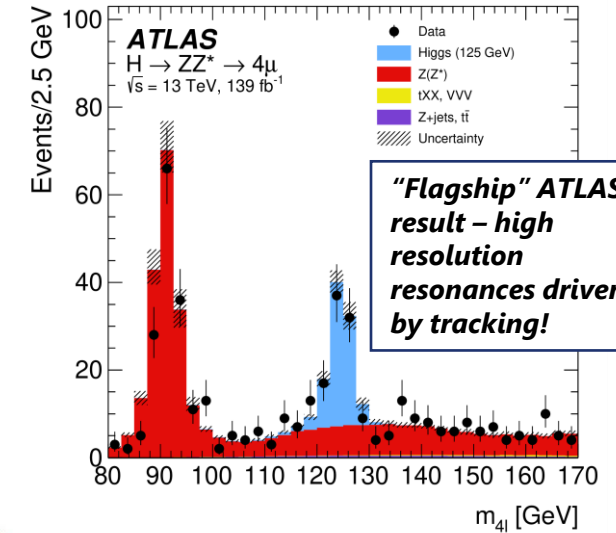
→ Track reconstruction is one of the **first steps** in ATLAS event reconstruction

## How do we reconstruct tracks in ATLAS?

- **Our tool:** the ATLAS Inner Detector
  - 4 **silicon Pixel** layers (2D measurements)
  - 4(x2) **silicon microstrip (SCT)** layers (stereo 1D measurements)
  - **Transition radiation detector (TRT):** Drift tubes at high radii
  - **2-Tesla solenoidal magnetic field** → momentum measurement



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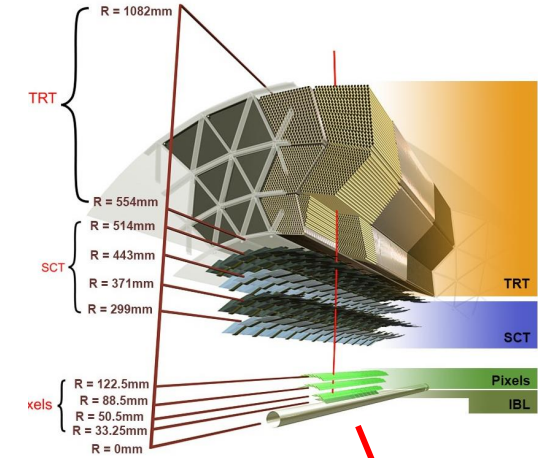
# Track reconstruction in the ATLAS experiment



## How do we reconstruct tracks in ATLAS?

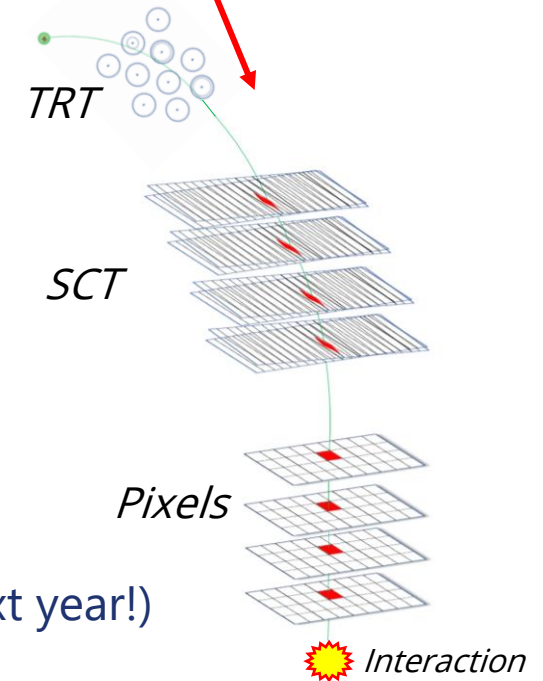
Traversing charged particles deposit charge in our sensitive elements

- each deposit is a separate signal – for this talk, also called a “hit”
  - *Disclaimer: Slight simplification. “Clustering” of adjacent deposits in Si sensors!*
- Per p-p collision in ATLAS: Tens of thousands of hits!



→ **Task of track reconstruction:** “Connect the dots” to find **tracks** among the hits!

- “Which hits belong to the same particle?” – *track finding*
  - “What are the properties of the particle?” – *track fitting*
- } Can be solved together



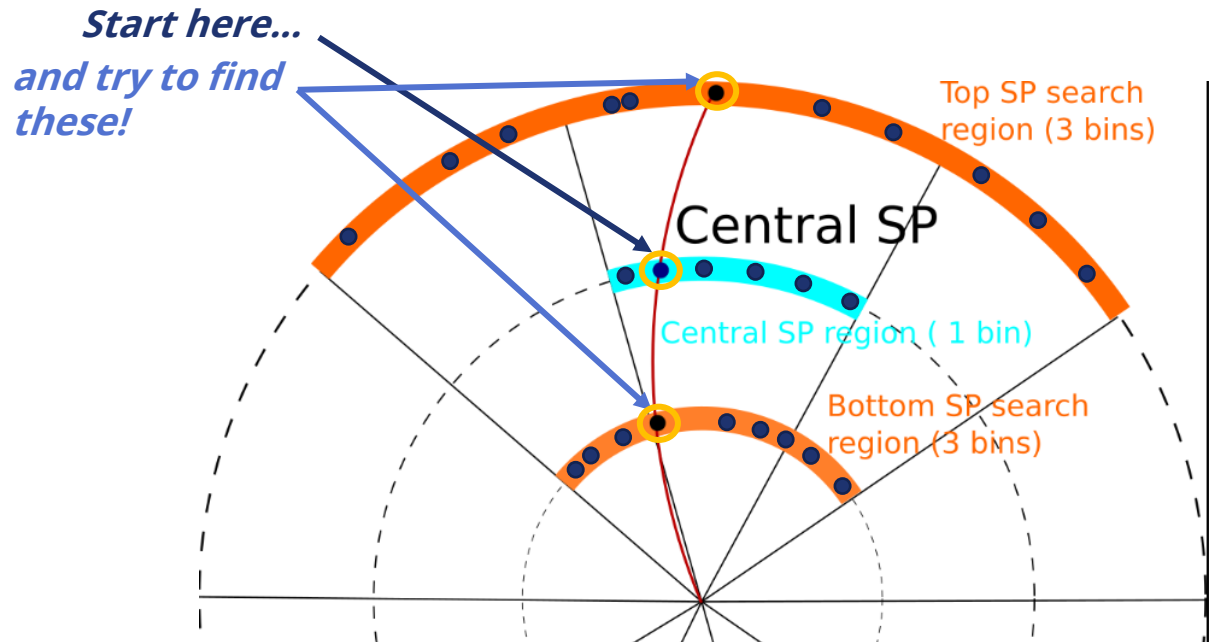
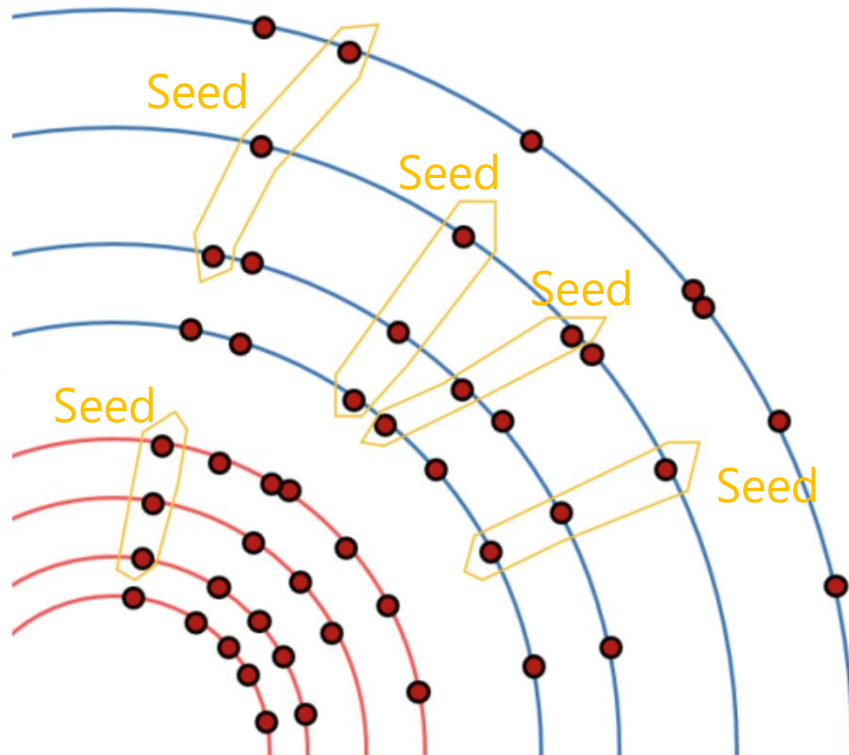
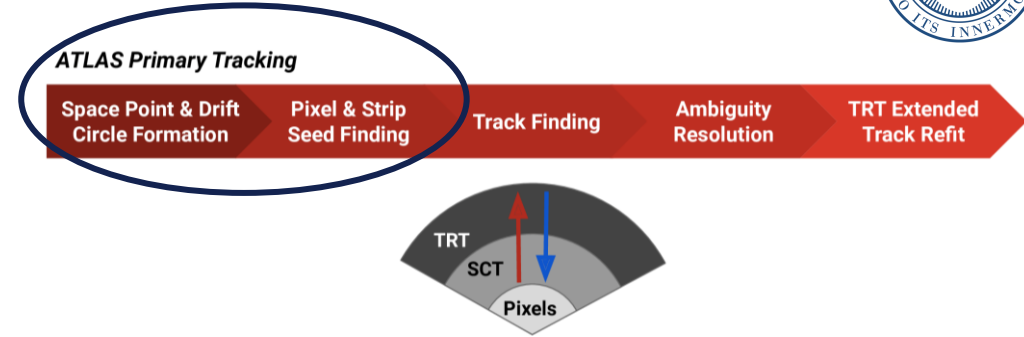
**This talk:** Summary of the procedure, challenges and improvements for **LHC Run-3** (→ next year!)

# ATLAS Track reconstruction procedure



## First step: Seeding

- Find **triplets** of compatible hits in subsequent layers of Pixels or SCT
- These are the **starting point** for potential tracks
  - Also called **seeds**
- Performed within angular regions in the detector
  - in each region, try all possible combinations

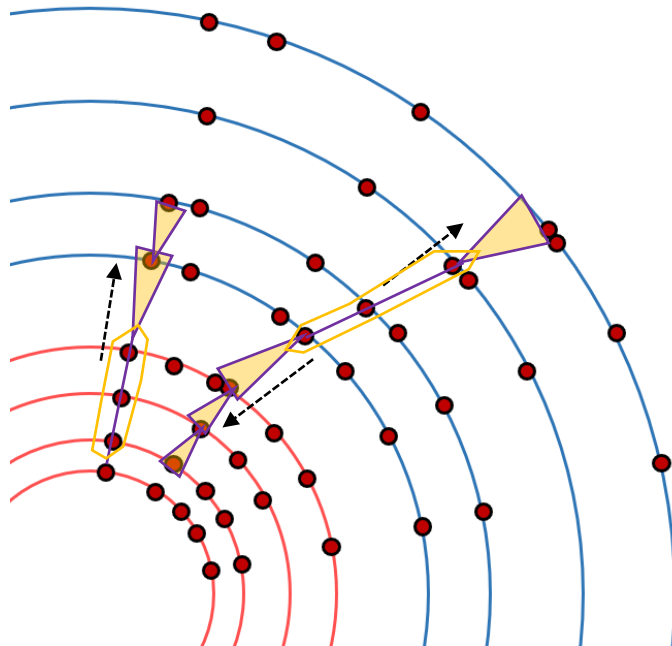


# ATLAS Track reconstruction procedure

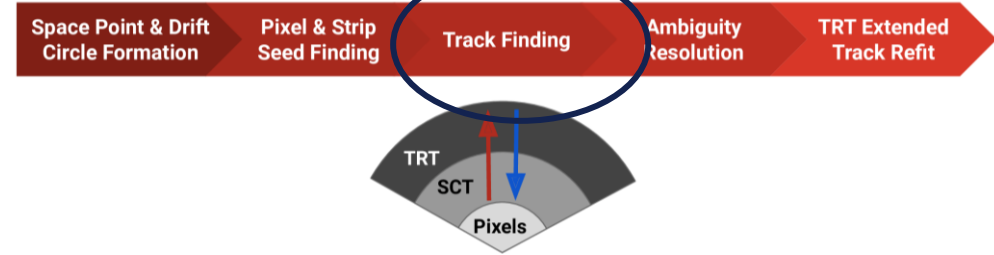


## Step 2: Extend seeds through the entire tracker

- Search for more hits along the projected trajectory of the seed
- Use a **combinatorial Kalman filter** to update our trajectory as we add hits to the track
- Do not (yet) try to avoid using the same hit on multiple tracks



### ATLAS Primary Tracking



### Bonus reading:

#### Sharing of hits

- Two separate tracks “use” the same hit
- can be a sign of **fake tracks** – incorrect sequence of hits falsely combined into a track candidate
- can be a **genuine effect** – collimated topologies e.g. in high- $p_T$  jets or conversions

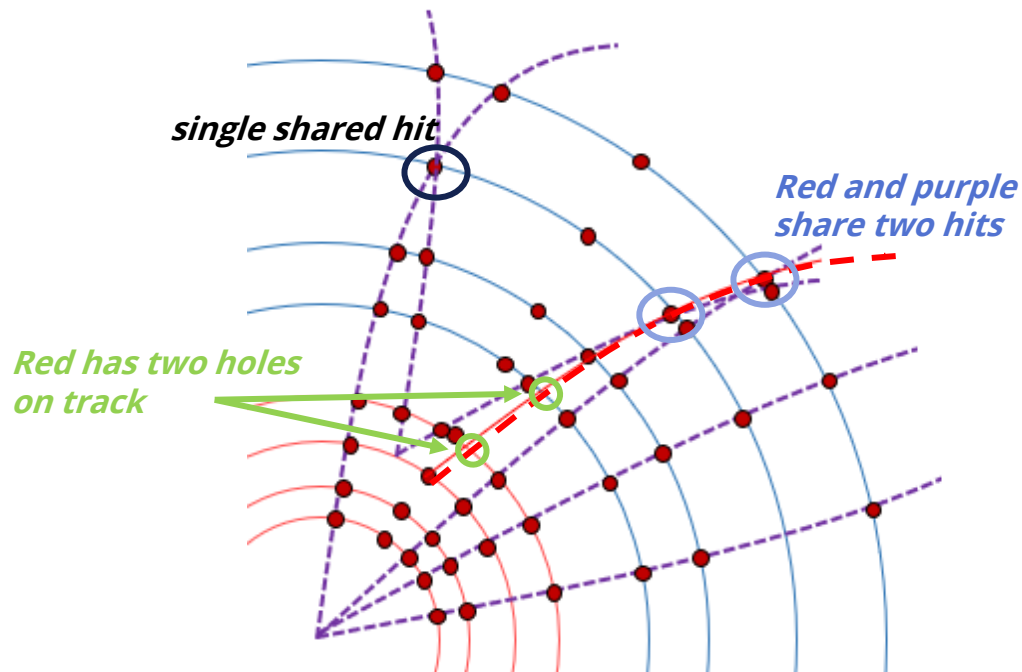
# ATLAS Track reconstruction procedure



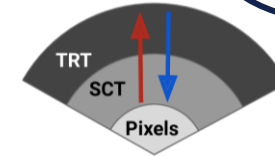
## Step 3: Ambiguity resolution

Remove overlaps between track candidates from the previous step

- Tracks compete for hits - limited sharing permitted
- Reject candidates with too many shared hits or holes, or too few total silicon hits
  - Likely incorrect combinations of hits (“fakes”)



### ATLAS Primary Tracking



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#### Holes on track

- A track is predicted to cross an active sensor, but we don't find a hit there
  - can be indicative of **fake tracks**
  - can occur on **genuine tracks** in an ageing detector

# ATLAS Track reconstruction procedure



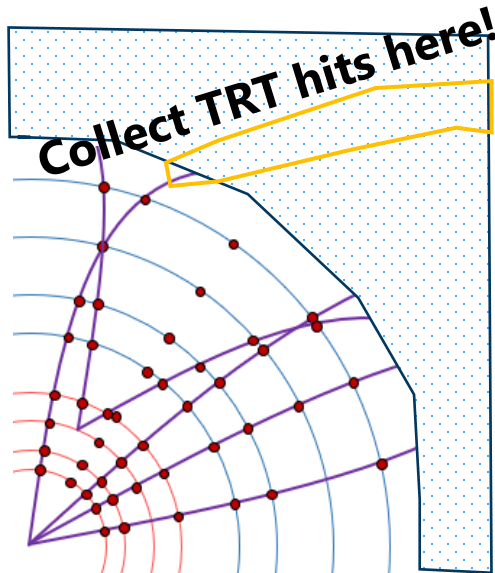
## Final steps: TRT Extension and final track fit

- Try to extend silicon candidates by adding **compatible TRT drift circles**
- TRT hits mainly improve momentum resolution (and particle ID)

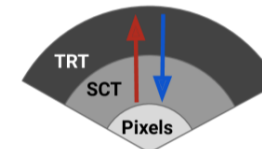
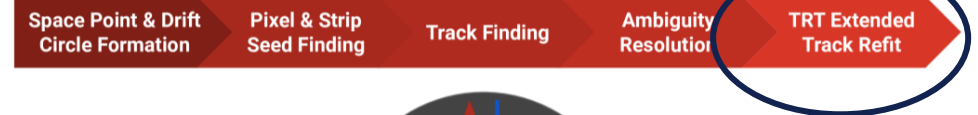
Finally, **precise parameter measurement by global  $\chi^2$  fit** of all hits on the track

→ Determine momentum, origin, charge with maximum precision

*Disclaimer: A few further, specialized tracking passes are run subsequently. Not covered in this talk*



### ATLAS Primary Tracking



# Challenges to ATLAS tracking at high luminosity

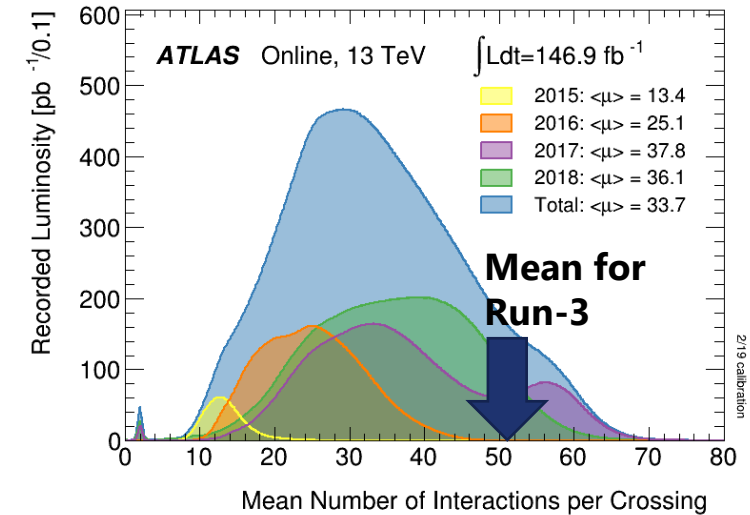


**LHC Run-3 (2022-24):** Will run at **increased luminosity** (2x LHC design)

- Necessarily also increases **pileup** - target  $\langle\mu\rangle\sim 50$  (slightly above)
  - 50% increase compared to Run-2 mean value

Increased pileup presents **severe challenge** for ATLAS track reconstruction:

- Increased number of **genuine** tracks – scales linearly with  $\langle\mu\rangle$
- Same for the number of **total hits** per event



*Tracks in an event with 65 vertices*



**But:** We just learned that **tracking is a combinatorial problem!**

- Number of **seed and track candidates** scales **more rapidly!**
- More potential for **incorrect combinations** (fake tracks)
- More processing time needed to find the genuine combinations



# Challenges to ATLAS tracking at high luminosity

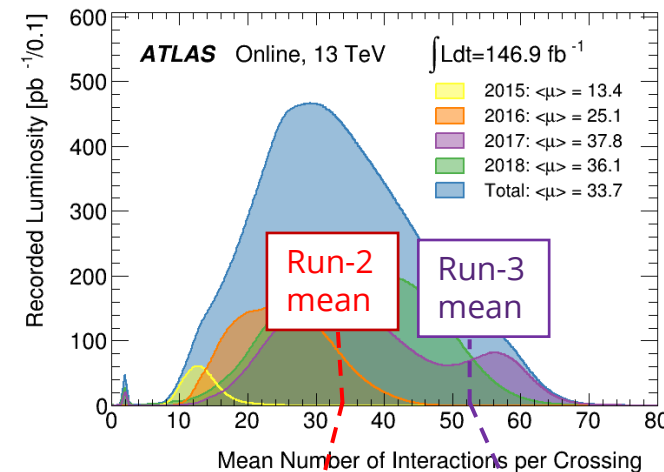


Existing ATLAS tracking was tuned for  $\langle \mu \rangle \sim 20$

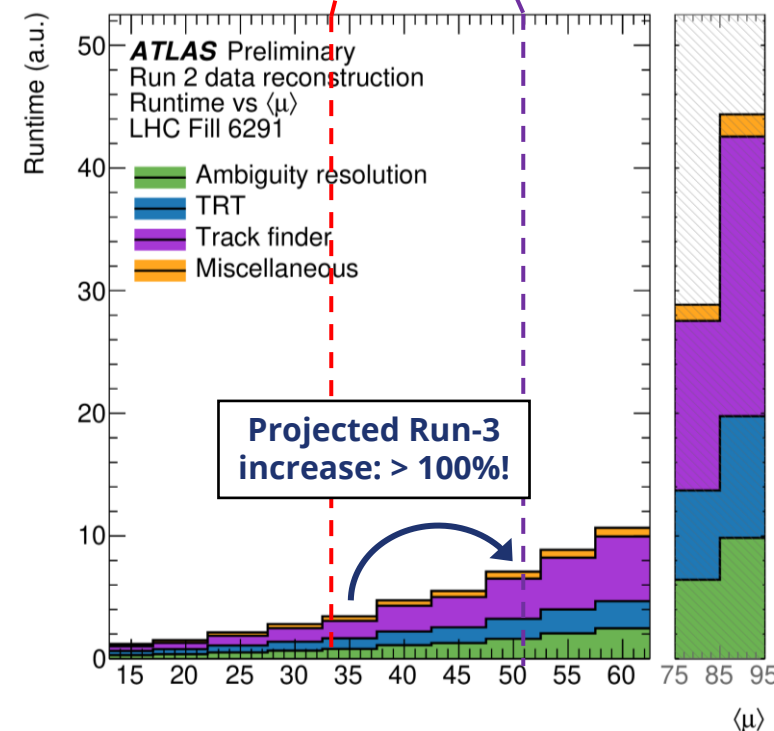
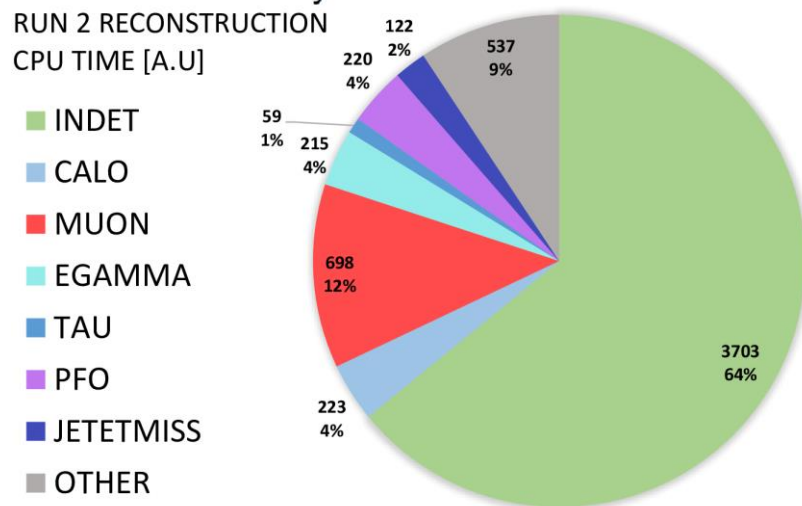
**Not feasible** to operate as-is in Run 3:

- **Processing time** more than doubled
  - Tracking is  $>60\%$  of **total reconstruction time!**
- Increased number of **fake tracks** (incorrect hit combinations)
  - occupy disk storage (bottleneck!)
  - “noise” for measurements using tracks

→ **Major effort** performed in 2020 to improve tracking for Run-3



**ATLAS Preliminary**  
RUN 2 RECONSTRUCTION  
CPU TIME [A.U]



# Improving track reconstruction for Run-3

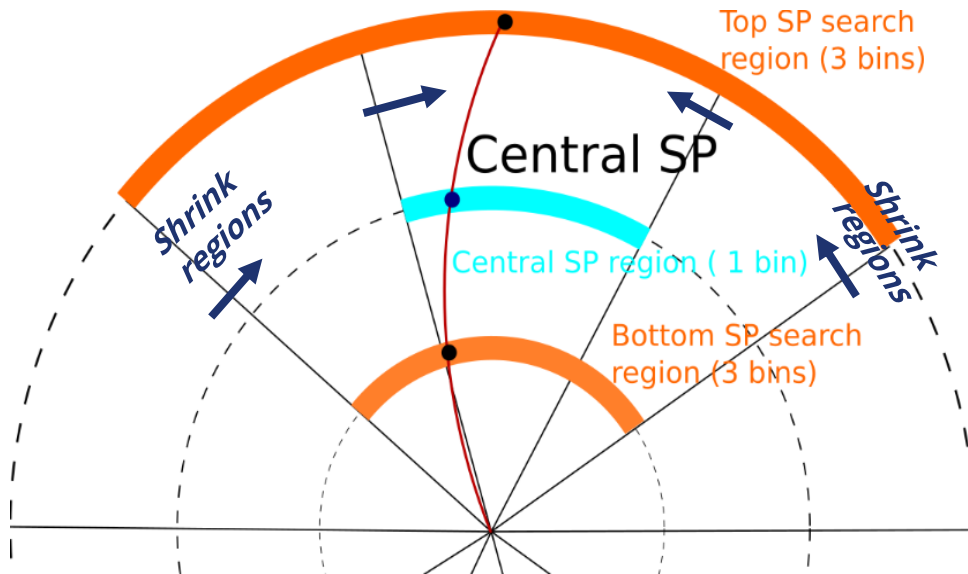
**Strategy:** Abort track reconstruction **as soon as possible** for non-promising candidates

➤ **Minimize** combinatorial pressure by arriving at “final” set of candidates as soon as possible

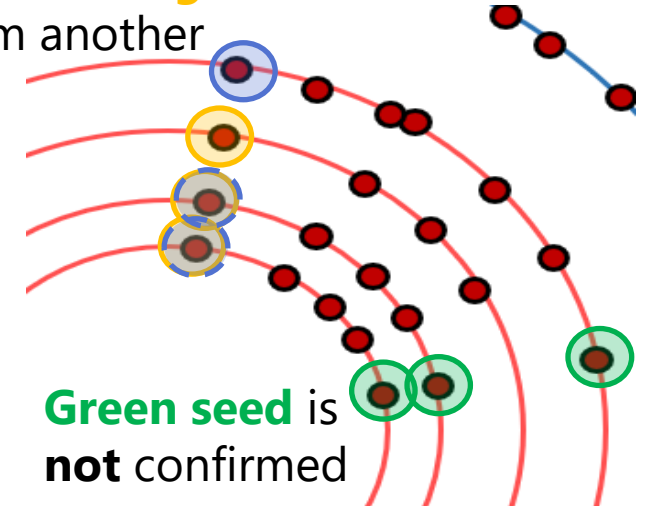
**Examples** (not exhaustive):

Limit size of **search regions** for hits to combine into **seeds**

- Guided by minimum target  $p_T$  for reconstruction– determines maximum expected curvature
- Use concept of **seed confirmation** to identify promising seeds and treat preferentially
  - Confirmation: Two mutually compatible seeds overlapping in two lower hits, but with different top hit



**Blue** and **orange** seeds confirm another

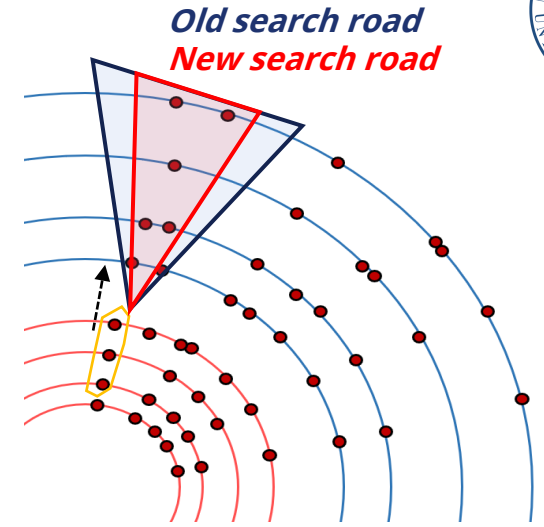


**Green seed** is **not confirmed**

# Improving track reconstruction for Run-3



- Reduce the **search region size** when looking for hits to add to the track candidate
  - Avoids extension attempts unlikely to succeed
- Require **more silicon hits** in order to keep track candidates – 8 instead of 7
  - strongly reduces tracks from accidental, combinatorial hit combinations
- Run **secondary passes** more selectively
  - Use calorimeter deposits to detect interesting regions
- Many further **algorithmic improvements** and **fine-tuning**



**Added physics potential:** Added an all-new **large- $d_0$  tracking pass** at the end, using leftover hits

- Cover  $|d_0|$  (closest. approach to beam line) of up to **30cm**, compared to 5mm in standard tracking!
- Reconstruct non-pointing tracks from long-lived particle decays.
- Not computationally feasible in old reconstruction (too slow)
  - In the past, required dedicated reprocessing (with inefficient data pre-filtering)

# Impact of improvements on performance

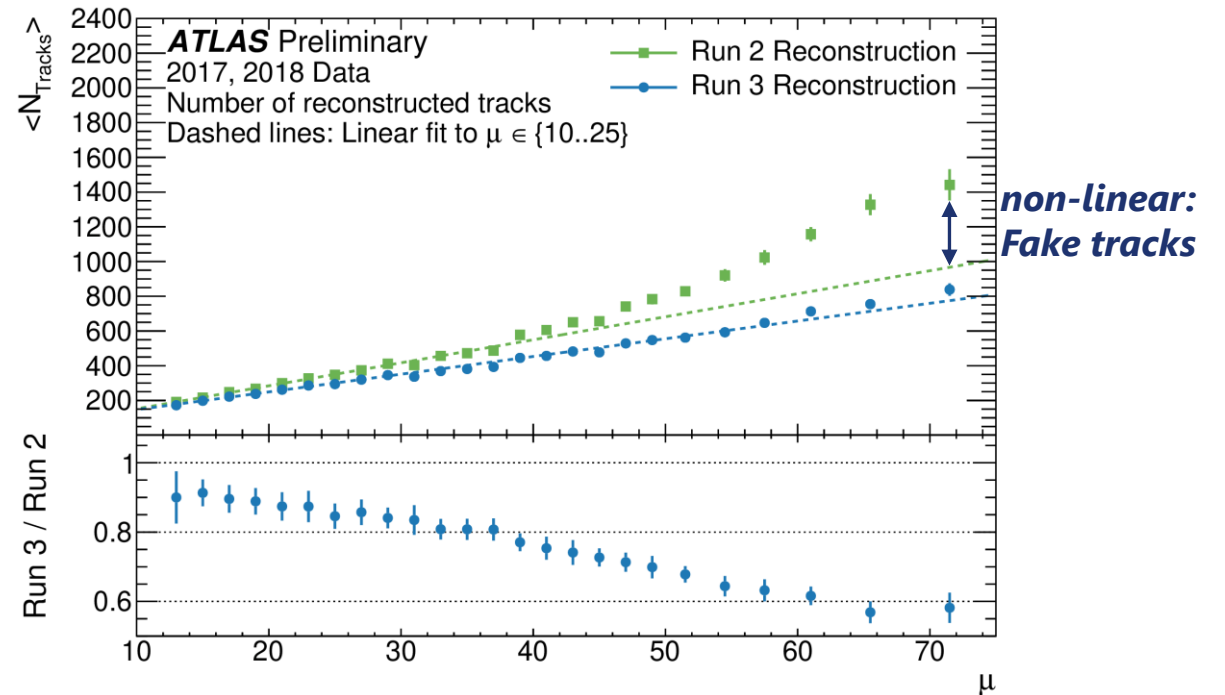
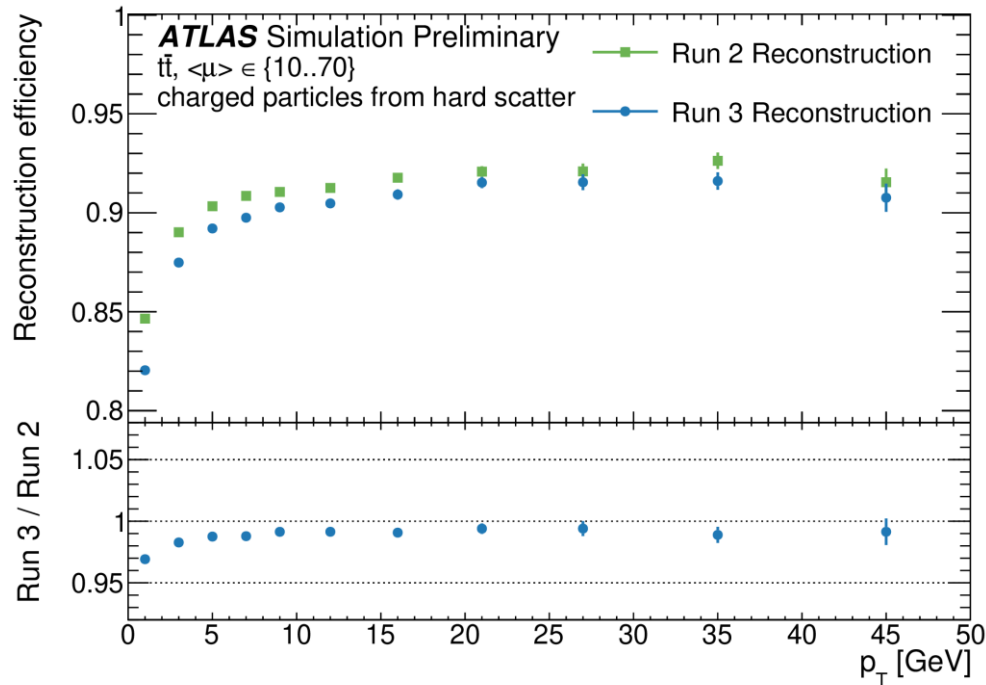
**Physics performance:** Only minimally affected

**Efficiency** reduced by 1-4% for pions, mainly at very low  $p_T$ , and unchanged for muons

**Linearity** of track yield versus pileup vastly improved

- Non-linear component indicative of combinatorial fakes
- Implies: Vastly improved **purity** of reconstructed track sample

Stable performance tested in both simulation and Run-2 data reconstruction



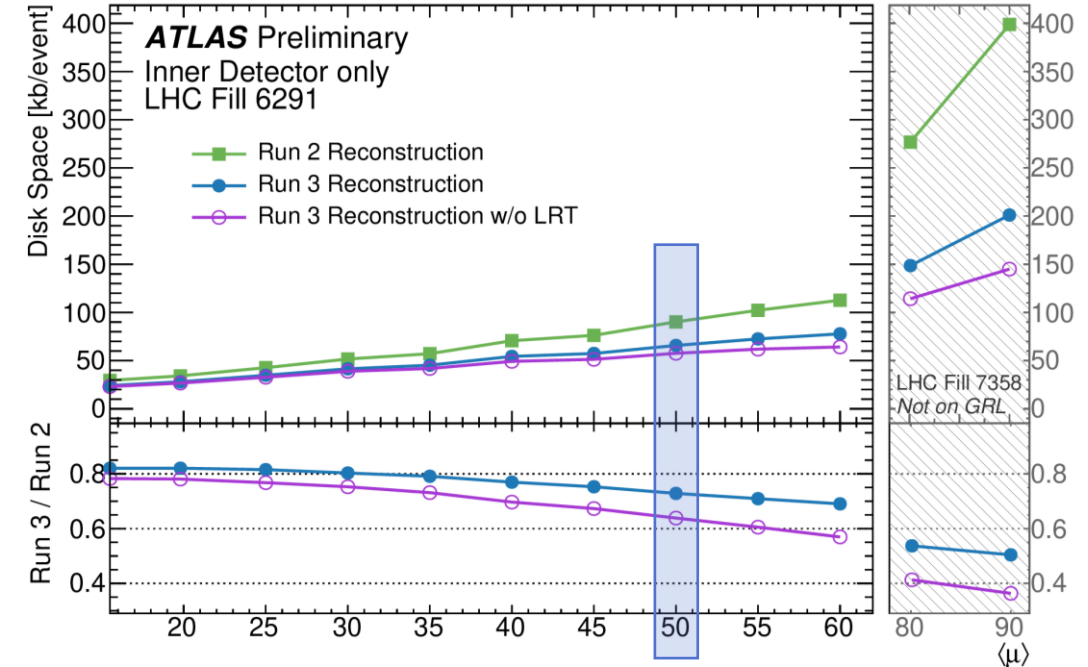
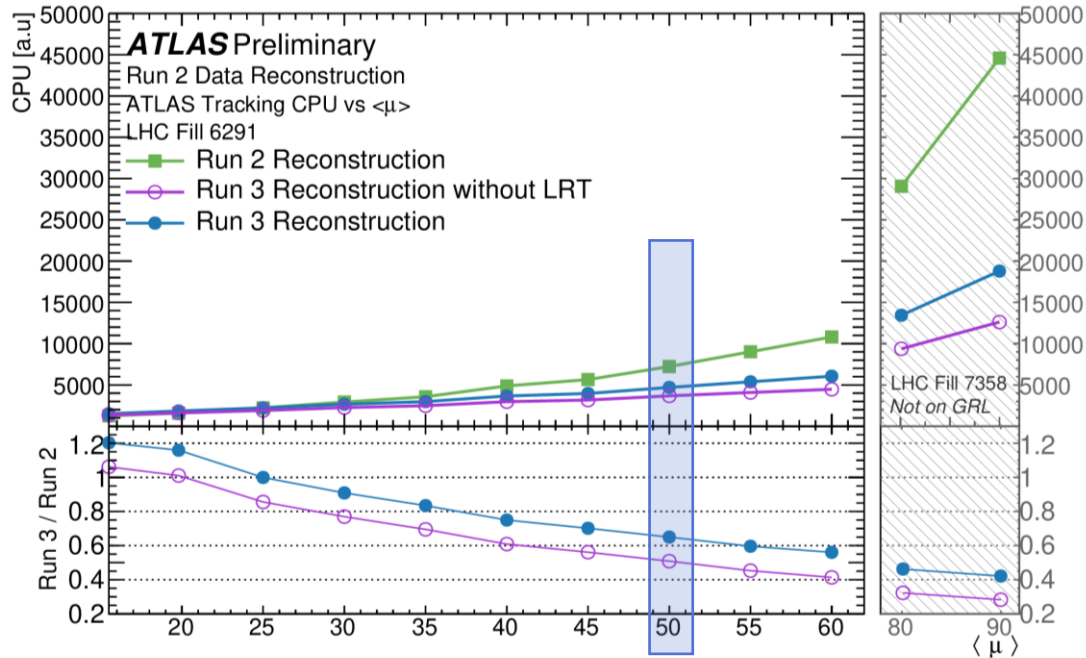
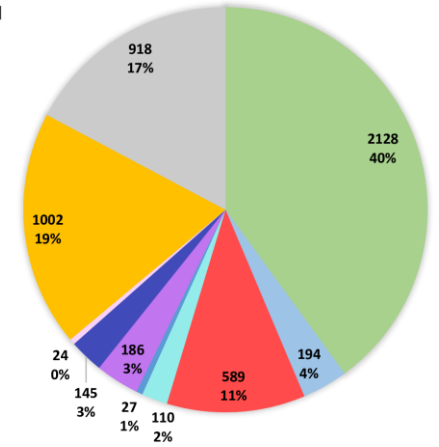


# Impact of improvements on performance

- **Software** performance: **Dramatically improved**
- Track reconstruction **factor 2** faster than before at  $\langle\mu\rangle=50$ 
  - as fast as old reconstruction at  $\langle\mu\rangle=35$
  - Reduce tracking from 64% to 40% of total reconstruction time
- Output **disk space usage** per event reduced by 30% at  $\langle\mu\rangle=50$ 
  - again, no increase compared to  $\langle\mu\rangle=35$  with old track reconstruction
- New Large- $d_0$  pass with small impact – retain significant net improvement

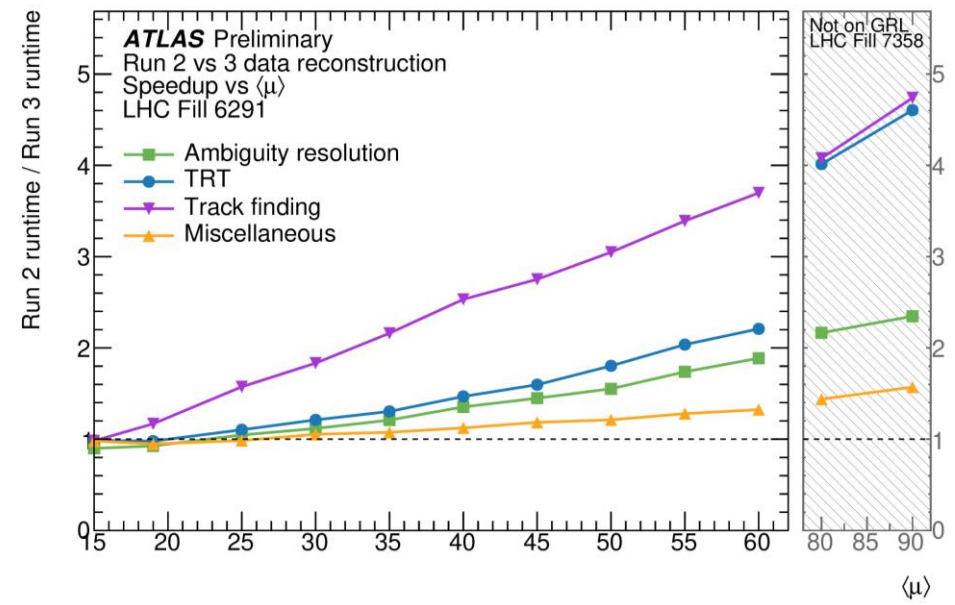
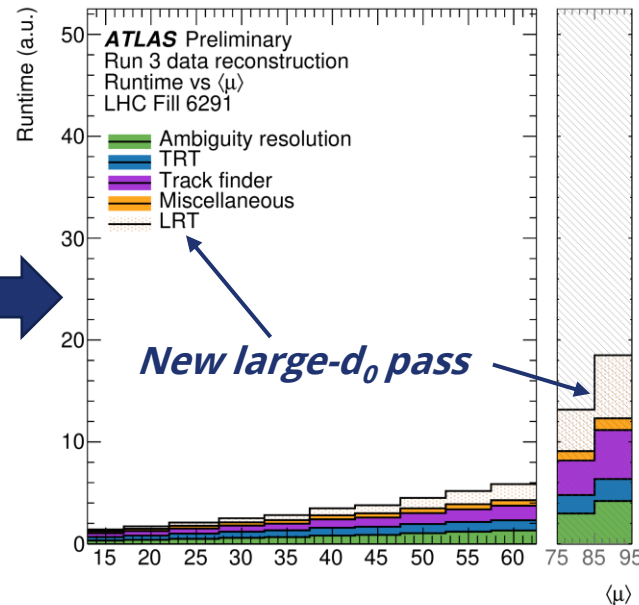
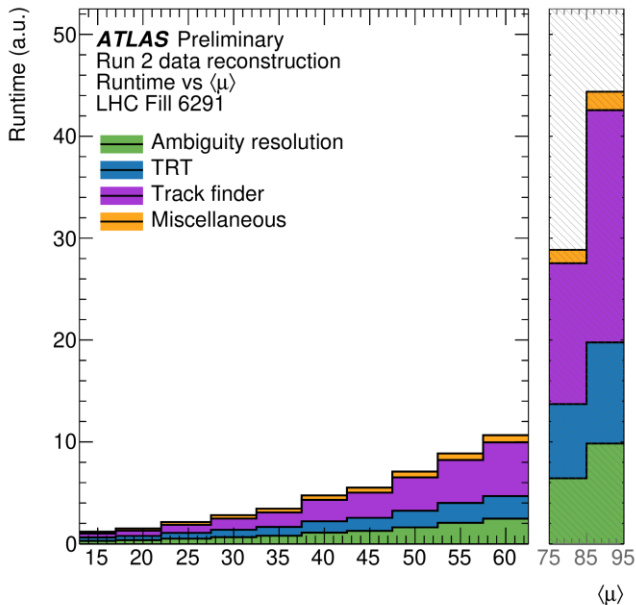
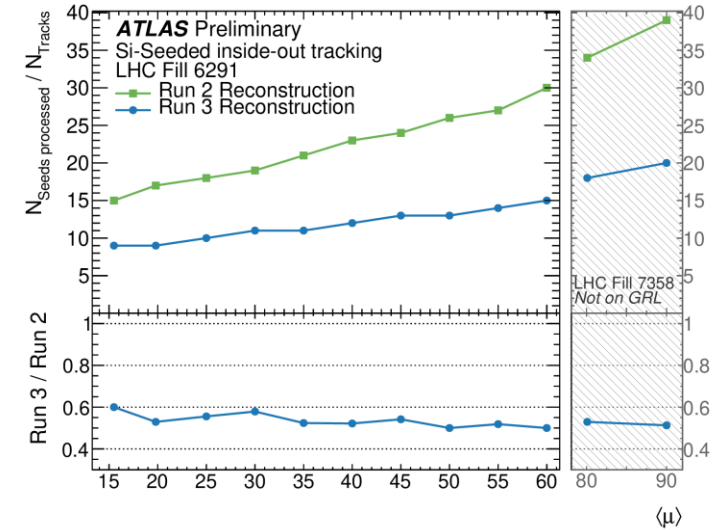
ATLAS Preliminary  
RUN 3 RECONSTRUCTION  
CPU TIME [A.U]

- INDET
- CALO
- MUON
- EGAMMA
- TAU
- PFO
- JETETMISS
- BTAG
- LRT
- OTHER



# Impact of improvements on performance

- Each step faster than before
- In particular: **Track finding** (largest CPU consumer) **factor 3 faster at  $\langle\mu\rangle=50!$** 
  - “Early abort” strategy visible in mean number of seeds processed per output track – reduced by ~half
- Much better scaling with pileup  $\rightarrow$  Reserves for luminosity tails!
- Further highlight: Improved vertex reconstruction – see [next talk by Ke Li!](#)



# Summary and Outlook



Upcoming LHC Run-3 represents new physics opportunities, but also **challenge to reconstruction**

- ATLAS track reconstruction: Major improvement campaign to mitigate impact of new run conditions

Results **exceed original aims:**

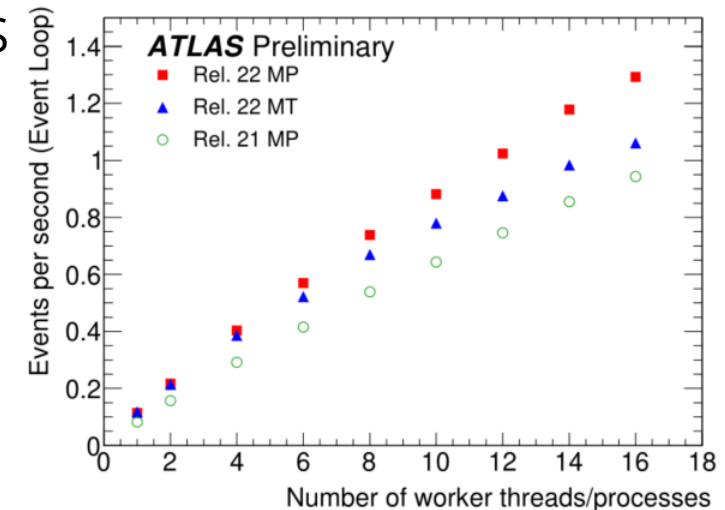
- Reconstruction **efficiency** close to **invariant**
- Drastic **reduction** of **fake tracks** – improved purity of resulting track sample
- **Factor 2 speed-up** of track reconstruction at Run-3 target pileup
- **Output size** reduced by 30% - mainly from reduction in fakes
- Improvements **scale** with increasing **pileup** – reserves for harsh run conditions
- Complements the **move to multi-threaded event reconstruction** in ATLAS

In addition: Able to add **new features**

- Dedicated Large- $d_0$  tracking pass – for **all** events, no filters/pre-scales!
- Improvements to vertex reconstruction – next talk!

ATLAS tracking ready to take Run-3 data (and reprocess existing Run-2)!

More reading:  
[ATL-PHYS-PUB-2021-012](#)





# Backup



# ATLAS Track reconstruction procedure

## Second pass: Backtracking

### Recover late appearing tracks (e.g. conversions)

- Triggered by un-used hit segments in the TRT
- Perform more permissive seeding step in silicon using **leftover hits**
- Extend seeds to tracks using same procedure as primary pass

