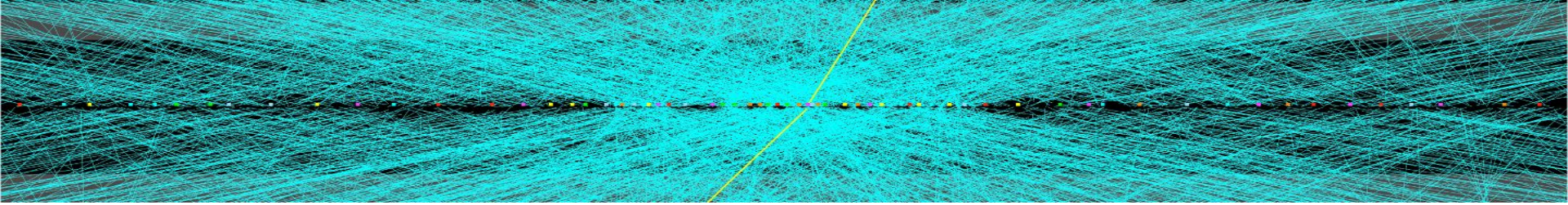


# Investigating the impact of 4D Tracking in ATLAS beyond Run 4

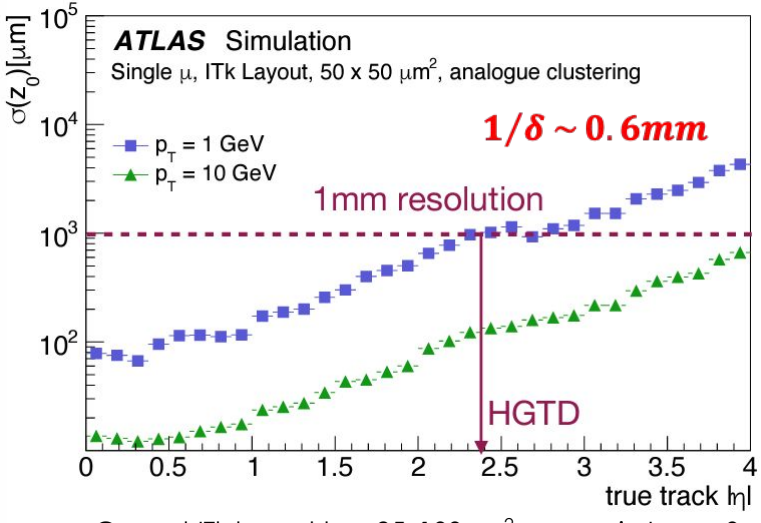
https://cds.cern.ch/record/2870326/files/ATL-PHYS-PUB-2023-023.pdf

**Ariel Schwartzman,**
**on behalf of the ATLAS Collaboration**
SLAC National Accelerator Laboratory

CPAD Workshop 2023
9-Nov-2023

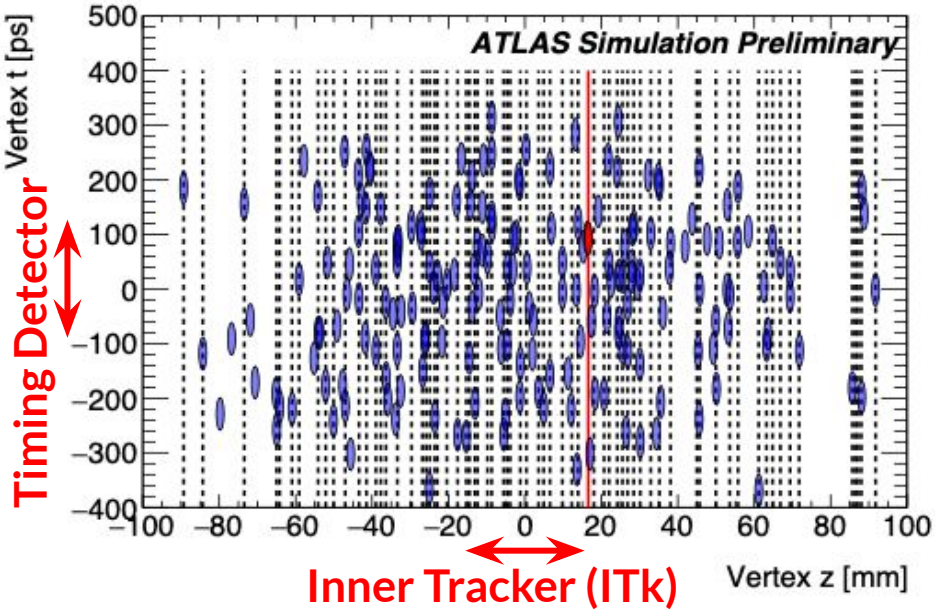
# Fast Timing in ATLAS

Under HL-LHC pileup conditions, the typical distance between vertices is comparable or smaller than the track longitudinal impact parameter at low $p_T$: **the association of tracks to vertices becomes ambiguous!**




Current ITk layout has 25x100um$^2$ sensors in Layer 0

**Exploit the time spread of collisions to reduce pileup (track) contamination**

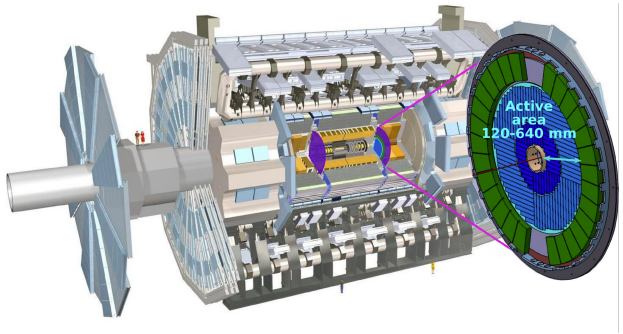


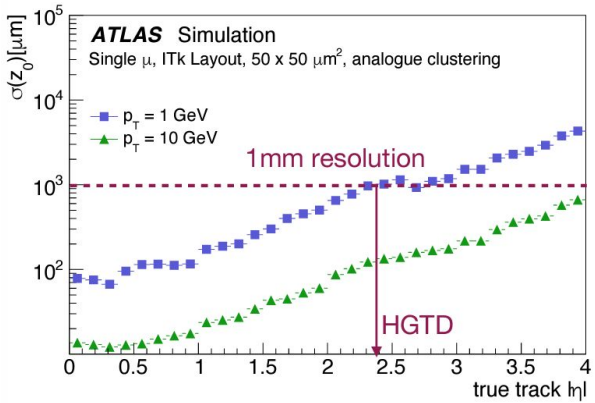

**Nominal HL-LHC Luminous region $\sigma_t$ = 180ps**

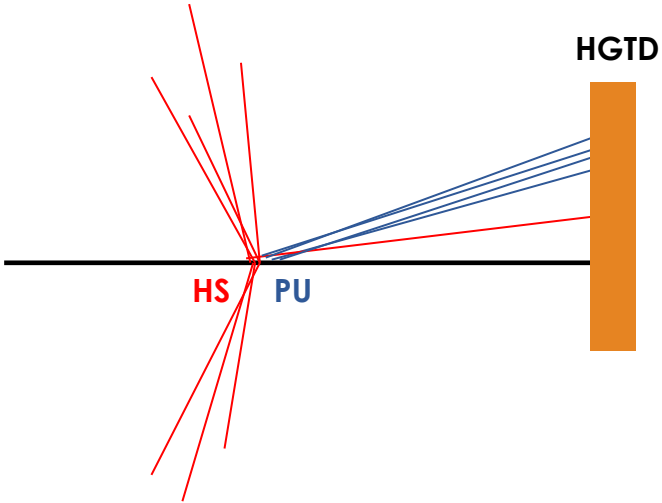
**HGTD(30ps)** → 30/180 = **6x pile-up rejection**

# Impact of HGTD Eta Coverage

**HGTD: silicon pixel detector with coarse spatial resolution and picosecond timing**




While the large ITk z0 resolution is mainly forward, HGTD requires a precise knowledge of the **vertex time** ($t_0$) to be able to relate a track time to a reference vertex time

**The reconstruction of $t_0$ becomes challenging when only forward tracks are available**

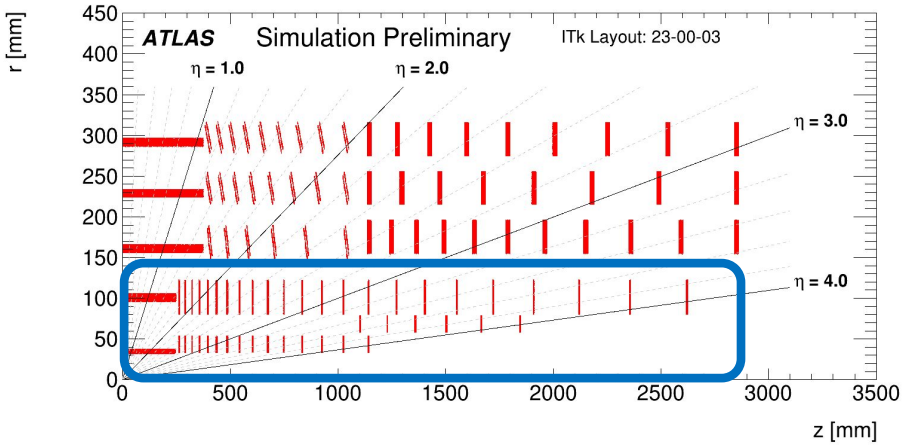
# Motivations to extend timing capabilities in the central region beyond Run 4

- The inner pixel replacement presents an opportunity to investigate the physics case of 4D tracking beyond Run 4
- Establish the merits of timing information in the central eta region using full simulated Monte Carlo samples, but with a simplified, and idealistic, model for track-time resolution

**Precise determination of vertex $t_0$:**
forward jets and leptons, and large $c\tau$ LLPs

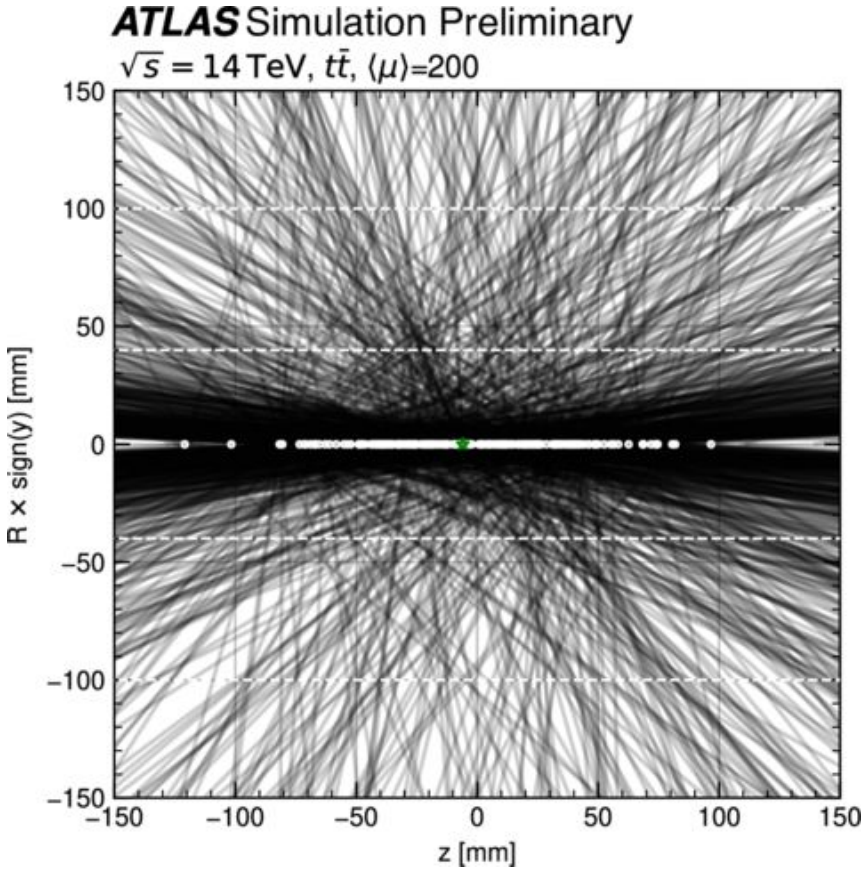
**Improve physics objects in the central region:**
b-tagging, small $c\tau$ LLPs

**Improve track and vertex reconstruction:**
CPU time, efficiency, purity, resolution, lower the minimum track $p_T$ threshold

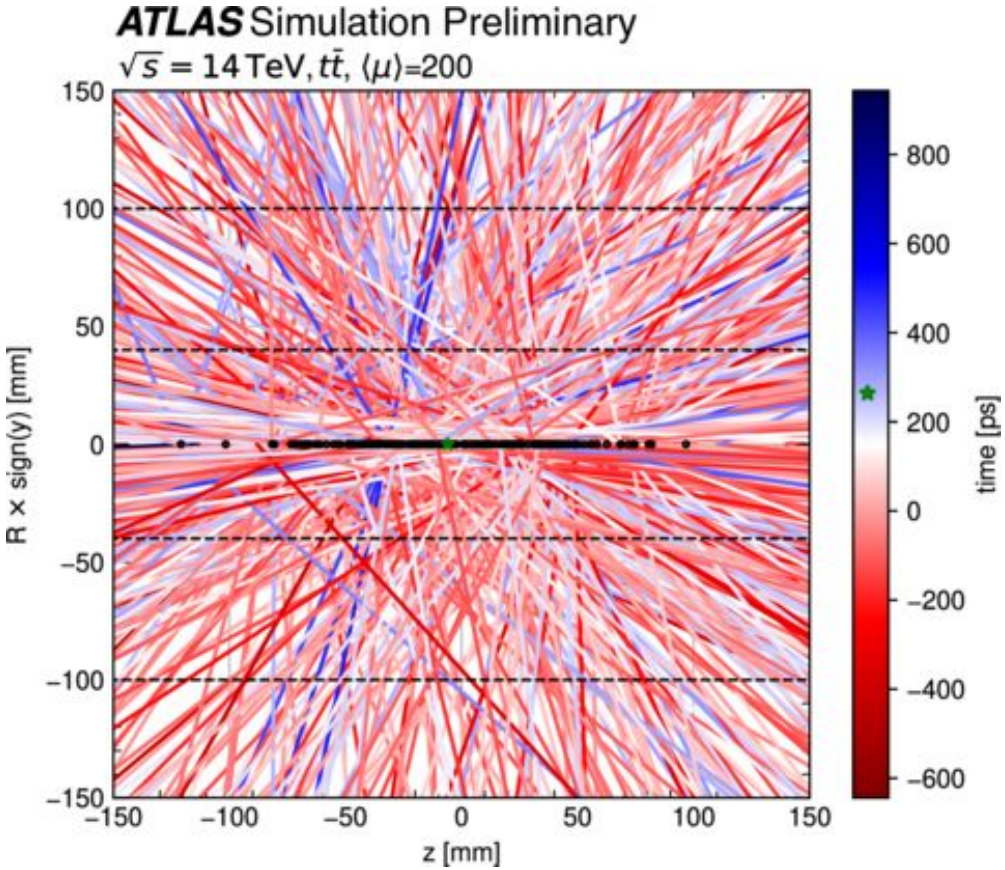



Inner Pixel is designed to to be replaced mid-way through HL-LHC

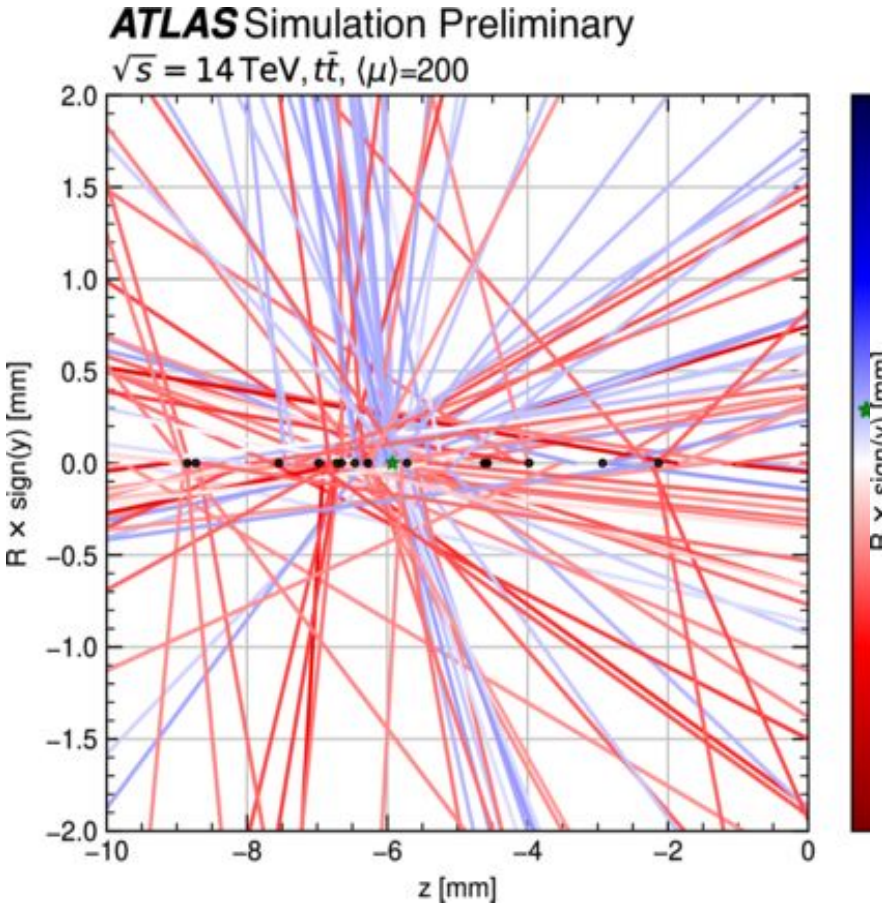
# ITk



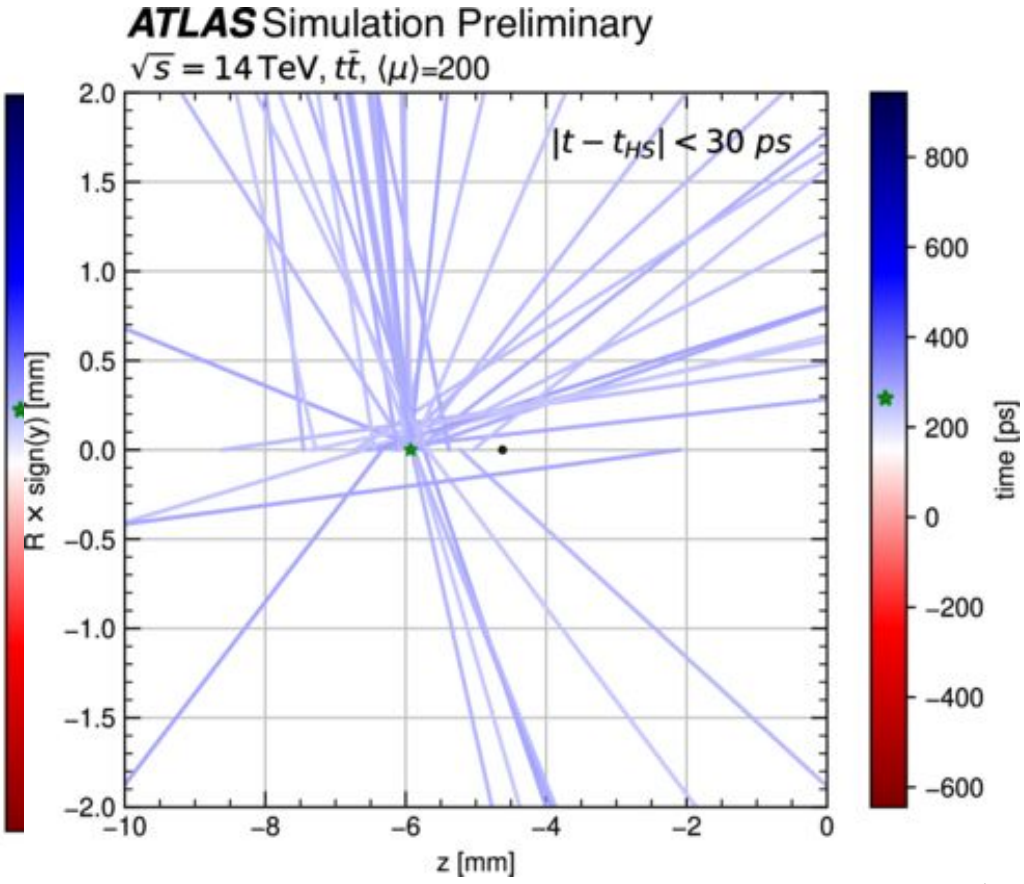

# 4D Tracker



# zoom



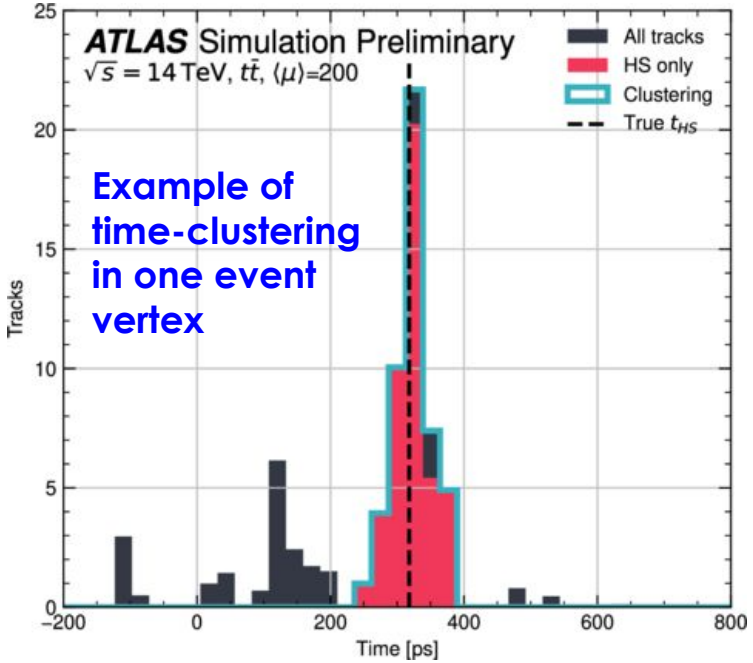

# pixel timing cut



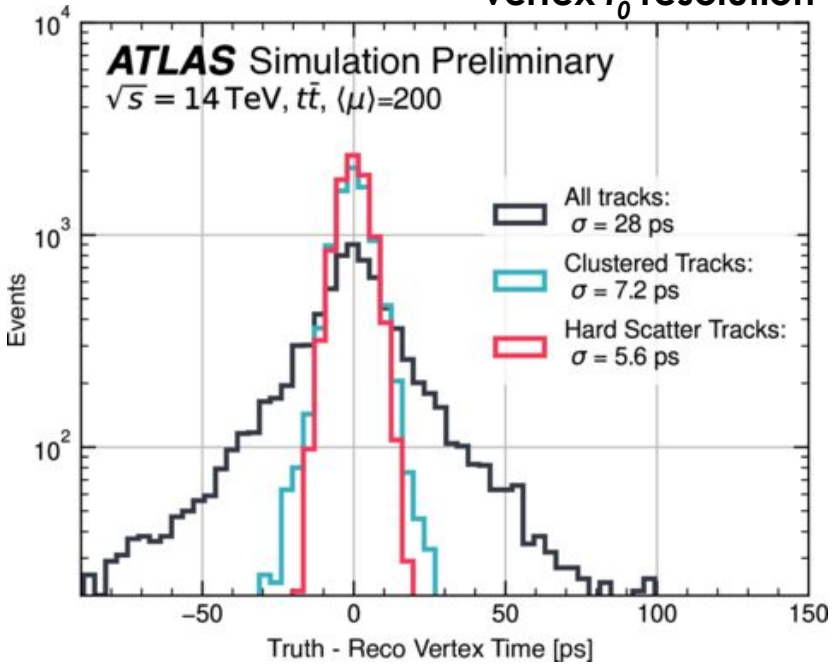
# Vertex $t_0$ reconstruction

DBSCAN clustering + average of track times

**Assumed time resolution: 30ps/track**

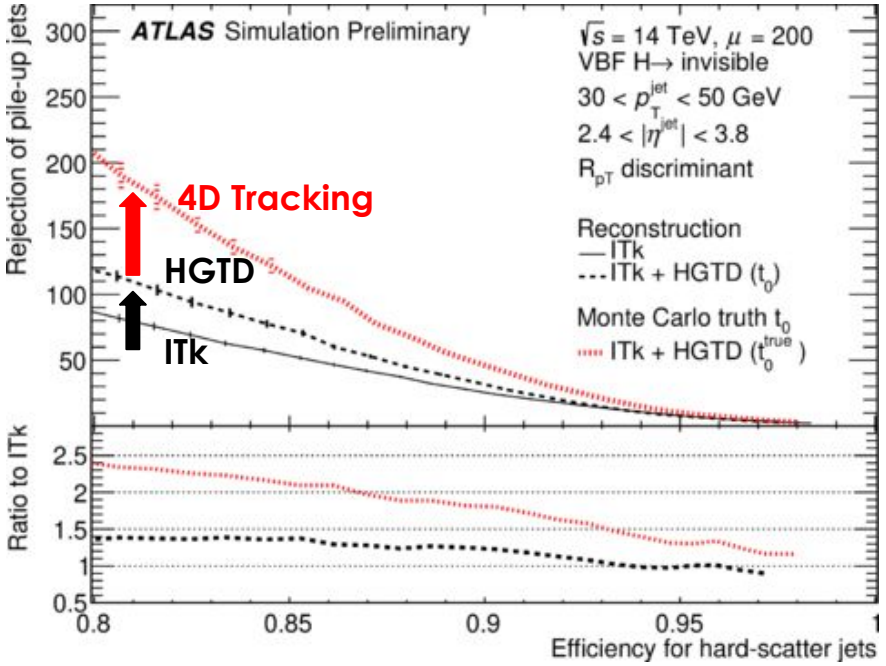


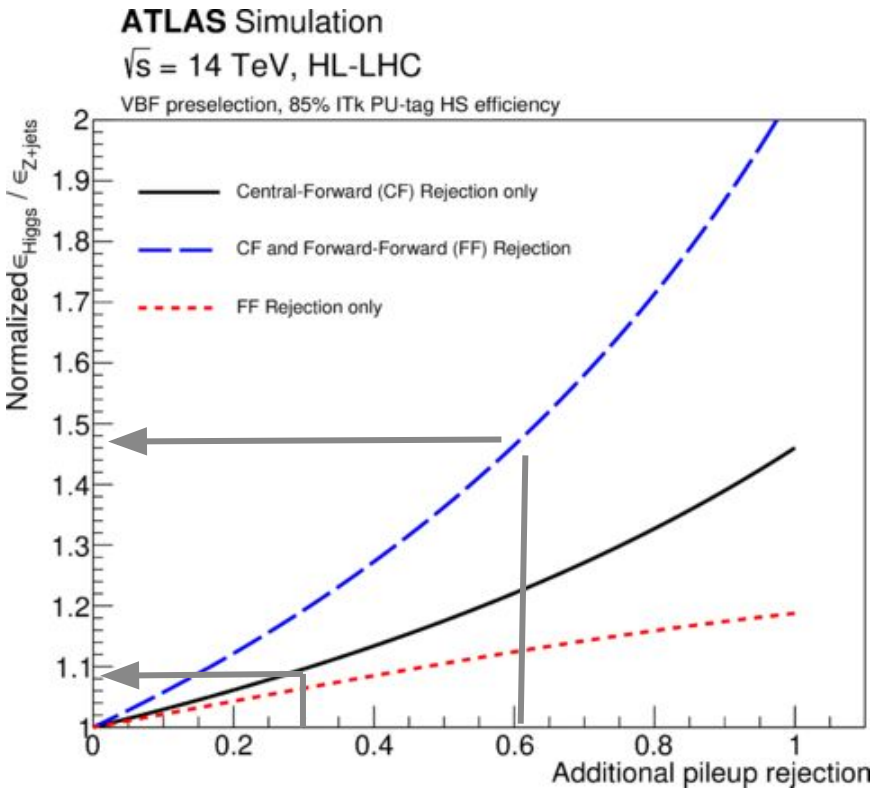

**vertex $t_0$ resolution**




Excellent (<<30ps) vertex $t_0$ resolution for **all events**!

# Pileup jet suppression



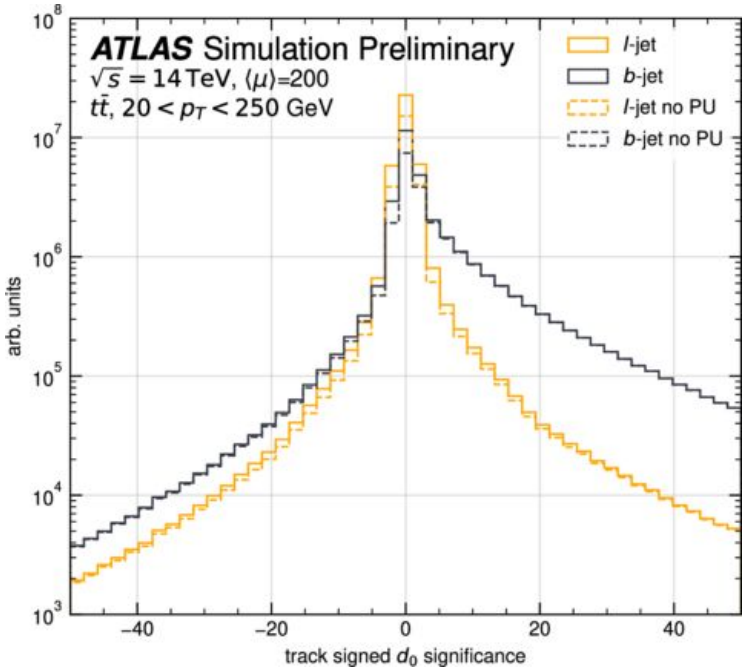

**50% Improvement in VBF H→invisible**

- improved PU jet suppression
- access to the full acceptance of central-forward jets

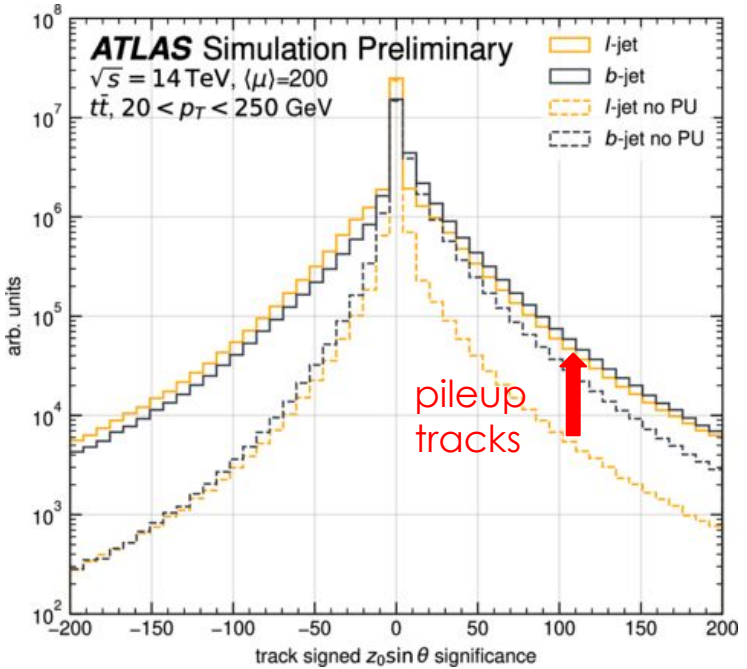
# b-tagging

Large impact in z0 significance from nearby pileup-vertices

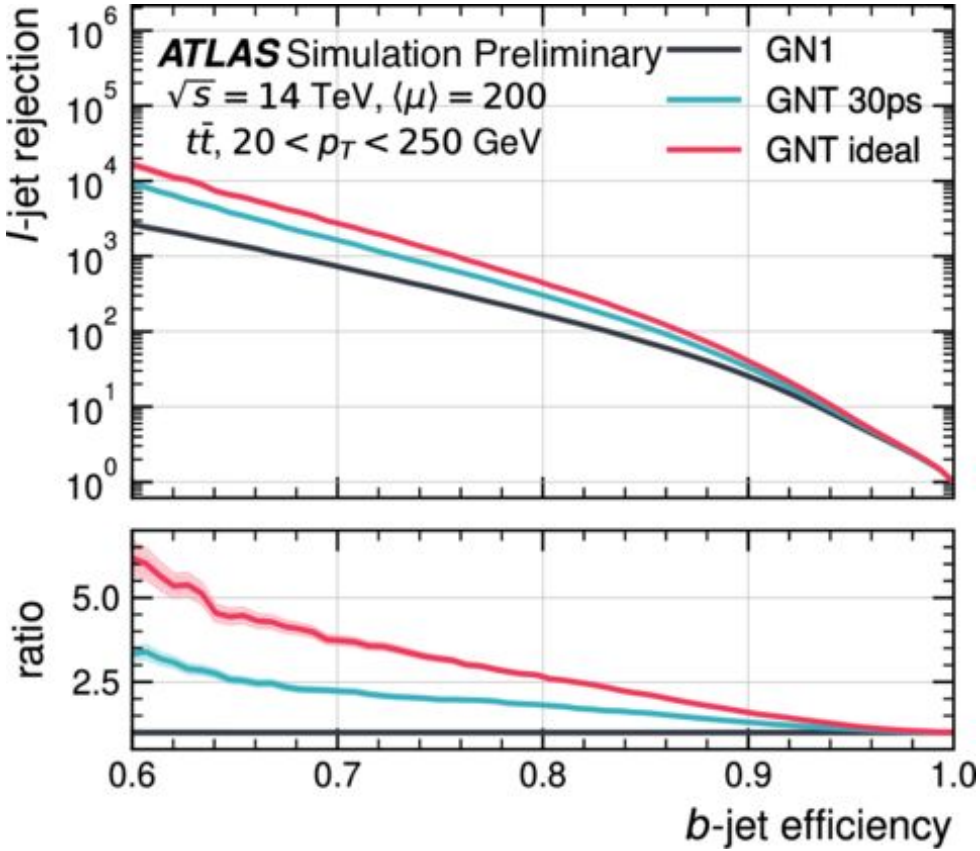
## d0




## z0

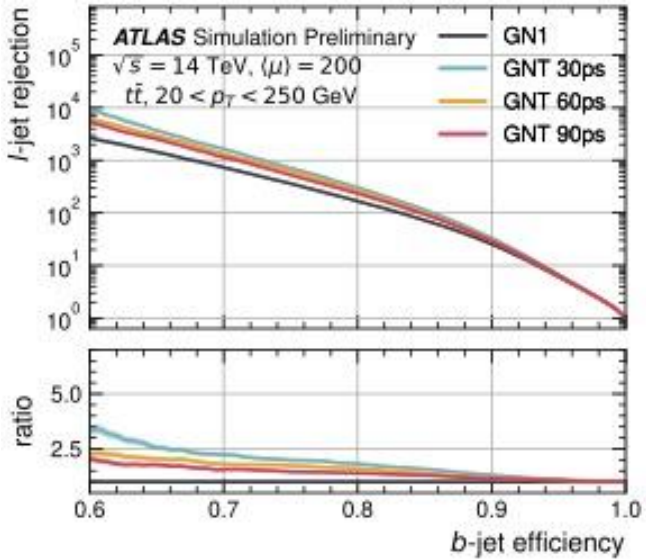


# 4D Tracking b-tagging improvement



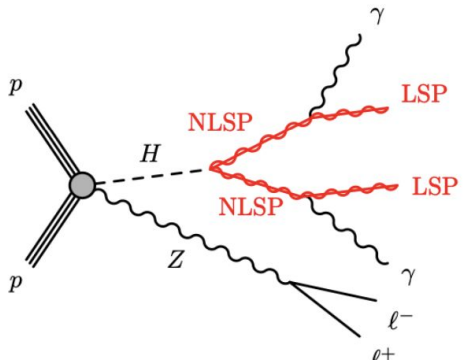

## Graph NN (GN1) b-tagging using track timing information

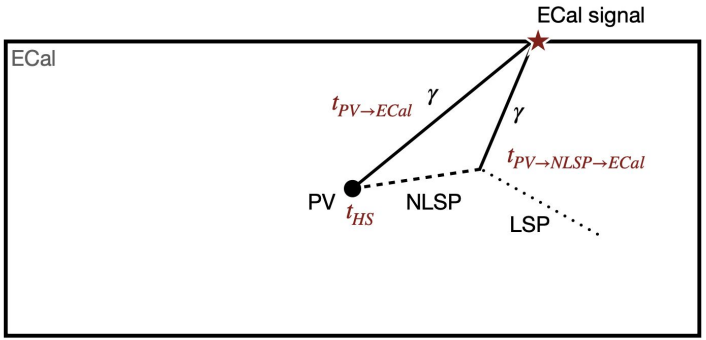
2x improvement in rejection at 70% efficiency and 30ps track time resolution

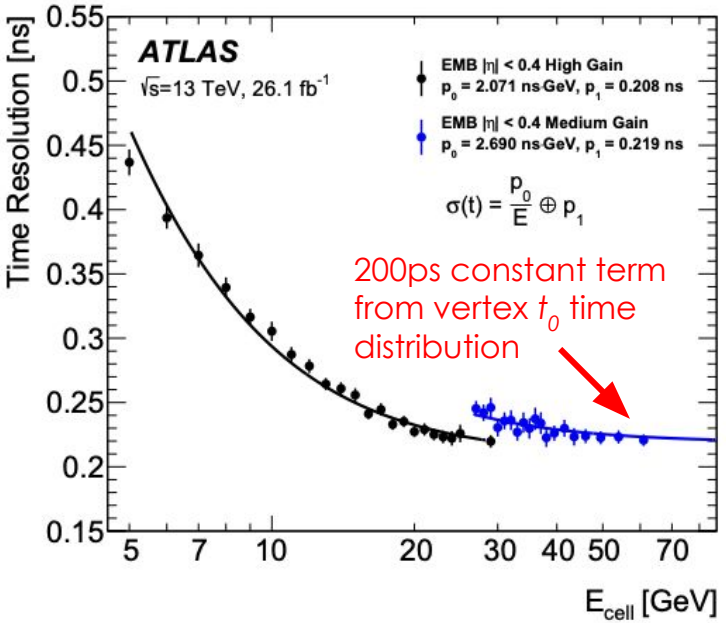


# Impact on LLP searches

**Displaced photons from exotic Higgs decays:** https://arxiv.org/pdf/2209.01029.pdf




**Lack of knowledge of vertex $t_0$ dominates timing uncertainty**

# Impact on LLP searches

$$\Delta t_{signal}^{4DTracking} = t_{HS} + t_{PV\to NLSP\to ECal}^{Measured} - t_{PV\to ECal} - t_{HS}^{4DTracking}$$

$\mathcal{N} \sim (0, 180\ \text{ps})$

Hard scattering time

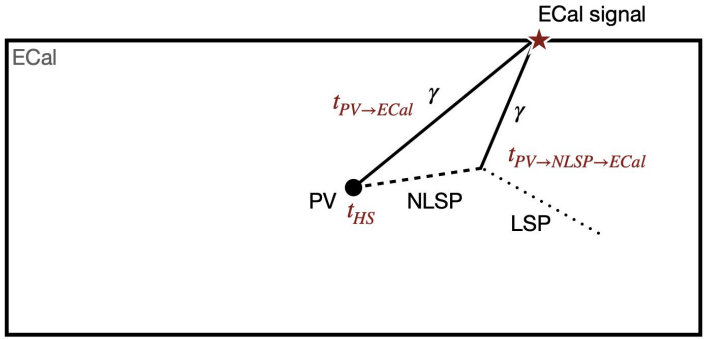
$\mathcal{N} \sim (t_{PV\to NLSP\to ECal}, 100\ \text{ps})$

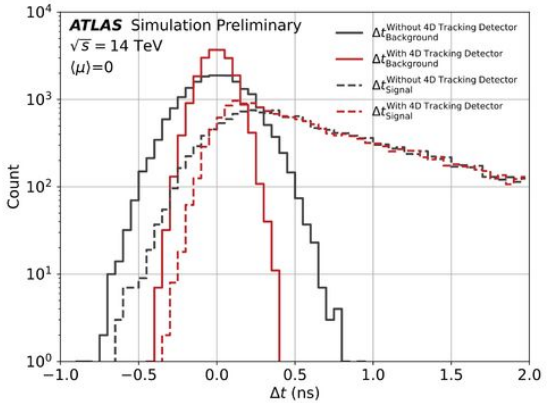
Timing information of signal process

SM background process (correction term)

$\mathcal{N} \sim (t_{HS}, < 30\ \text{ps})$

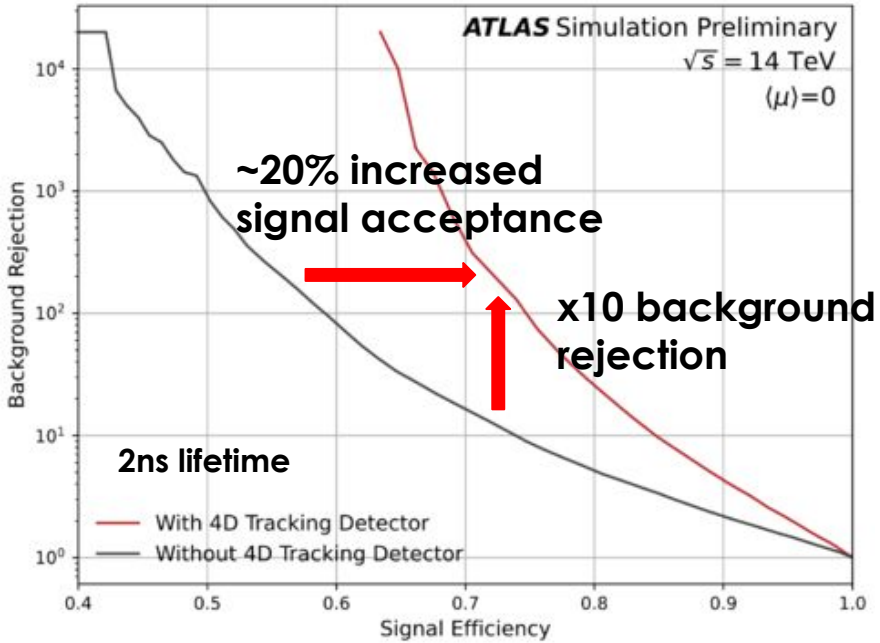
Reconstruction of hard scattering time using HGTD as a benchmark

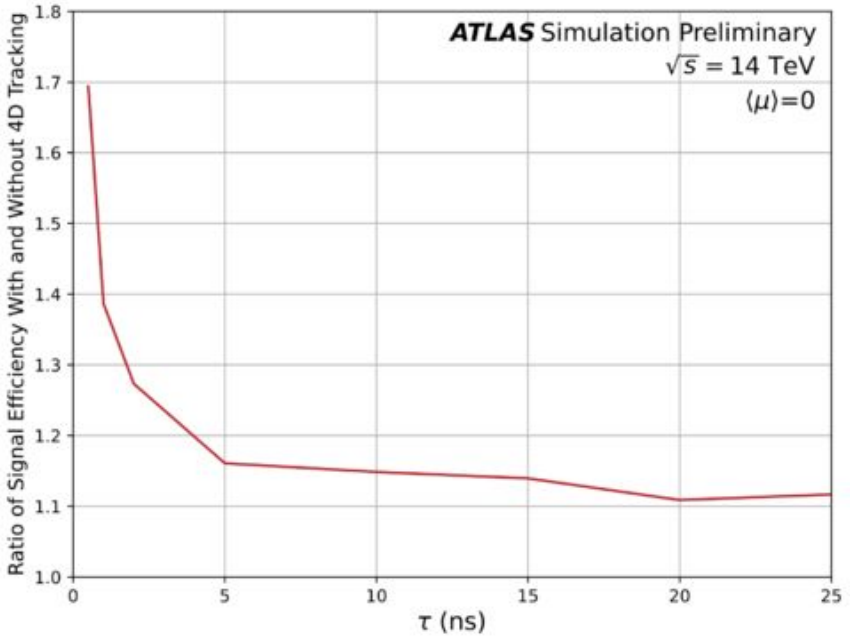


# Impact on LLP searches

**Significant gains in sensitivity for shorter lifetimes**
**Noticeable improvements at longer lifetimes as well**



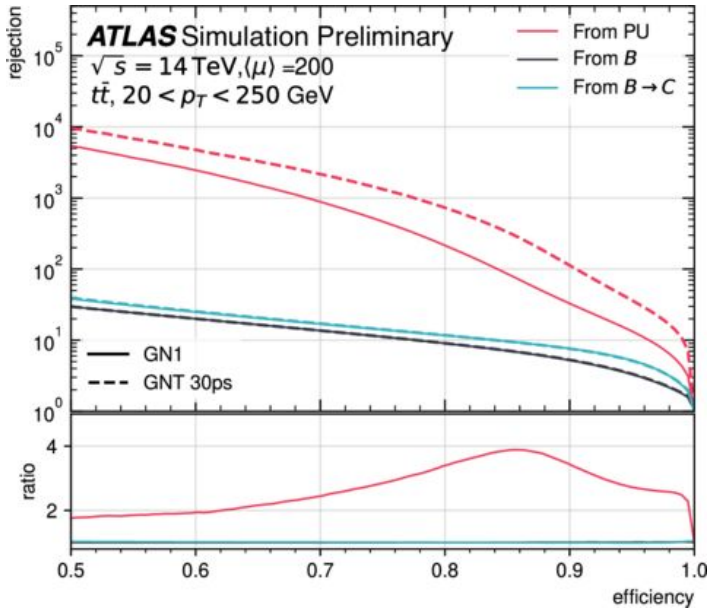
# Summary

- **The ATLAS ITk inner pixel replacement** presents a unique opportunity to bring technological innovations to address the complexity of pileup at the HL-LHC
- **The physics case of a 4D tracking upgrade in ATLAS, extending HGTD capabilities, can be broad and compelling:**
  - Provide precision vertex time O(5ps) for ALL events (assuming 30ps/track time resolution)
    - **Improve forward pileup jet suppression**
    - **Improve searches for delayed photons or jets** at shorter lifetimes compared to those accessible now or at the start of Run 4
  - **Improve b-tagging light-jet rejection by more than a factor of 2 → increase the $HH \rightarrow bbbb$ discovery significance by up to 0.3$\sigma$**, with similar improvements expected in other physics searches with b-quarks in the final state
- **These results, based on a simplified Gaussian model for track-time resolution, motivate future in-depth studies to incorporate a preliminary layout with more realistic detector assumptions, as well as more sophisticated reconstruction algorithms covering the full range of physics capabilities**

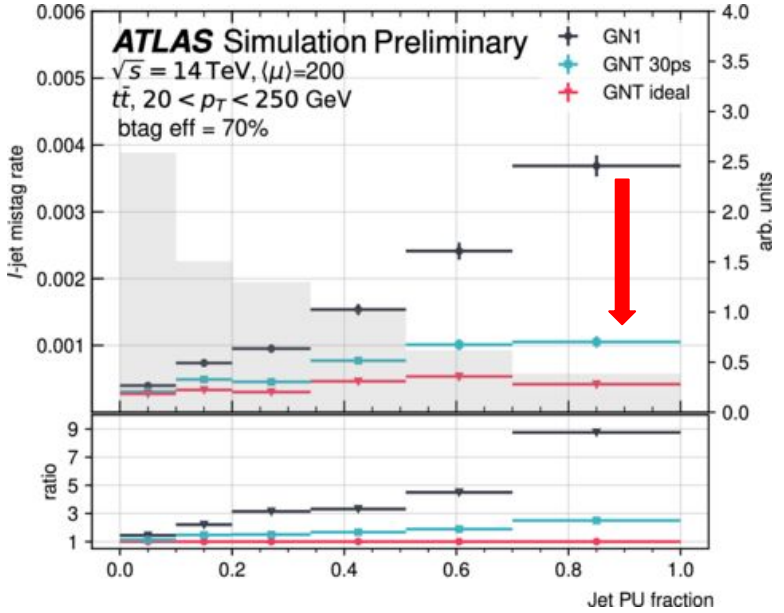
# Backup

# Where does the improvement come from?

**Pileup track rejection, as expected ✓**

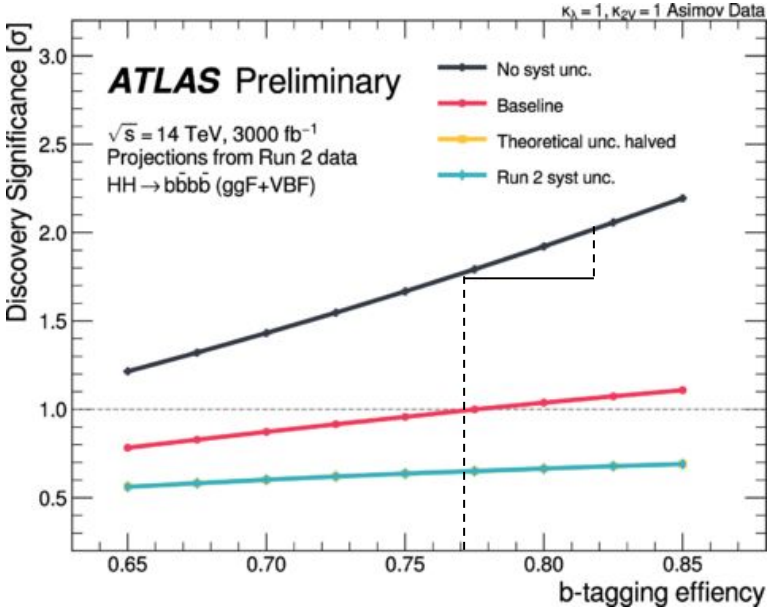



**Track-by-track classification improves <u>ONLY</u> for the PU track category**

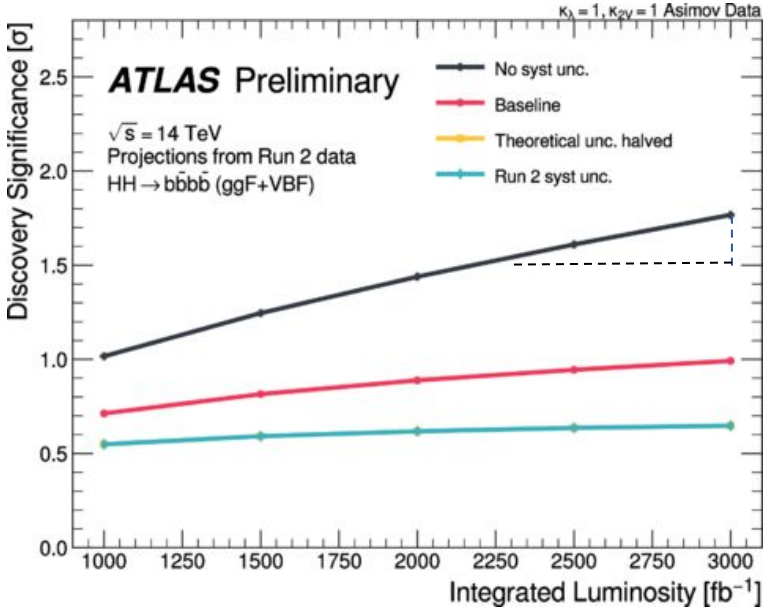



**light-quark and gluon jet rejection improves as a function of PU jet contamination**

# Impact on HH→4b



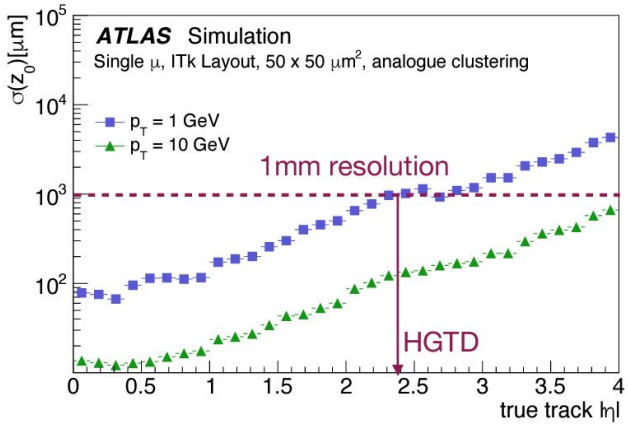

**5% efficiency improvement ⇒ 0.3 discovery significance**



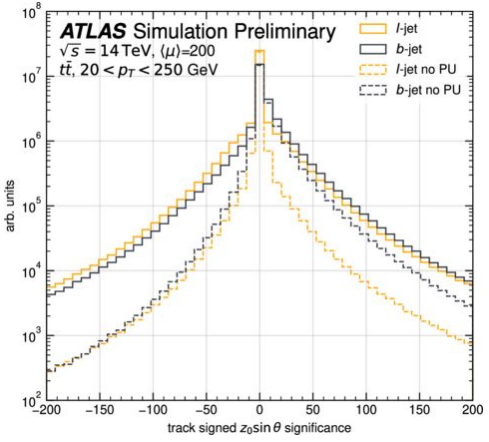

**Sensitivity enhancement of 500fb$^{-1}$ of data**

Actual improvement will depend on when upgrade happens: Run5 or Run 6

# Motivations to extend timing capabilities in the central region beyond Run 4




HGTD

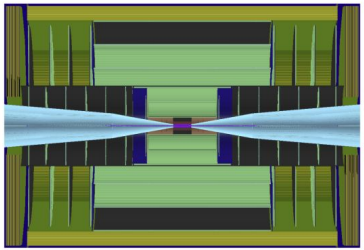



4D Tracker

- **Forward PU jet suppression:**
  - *z0 resolution (forward) > PU vertex separation* → track-vertex association ambiguity
  - **Detector resolution effect**

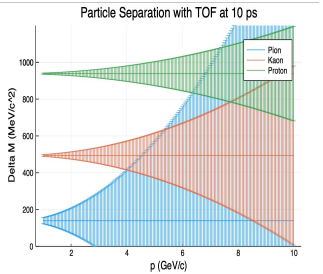
- **b-tagging:**
  - z0 *resolution* << PU vertex separation
  - Physics of B hadron decays → large displaced z0 tracks → *large z0 window to select tracks > PU vertex separation*
  - **Physics effect**

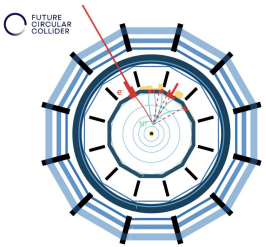
# Fast timing in Higgs Factories



Suppression of beam induced backgrounds at muon colliders

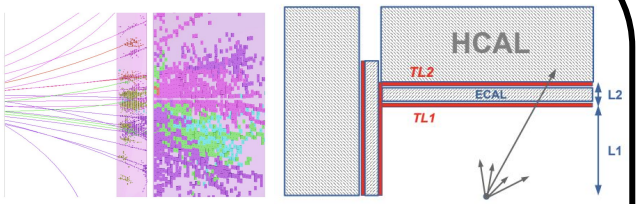
**Full 4D tracking**




Time of Flight for Particle ID at low momentum and Long Lived particles

**Timing layers**




Exploit the time structure of hadronic showers to enhance PFA and improve jet energy resolution

**5D Calorimetry**

Timing layers or volumetric timing