Jožef Stefan Institute
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ATLAS EXPERIMENT

HGTD Performance and Use of Timing Information in Run 4

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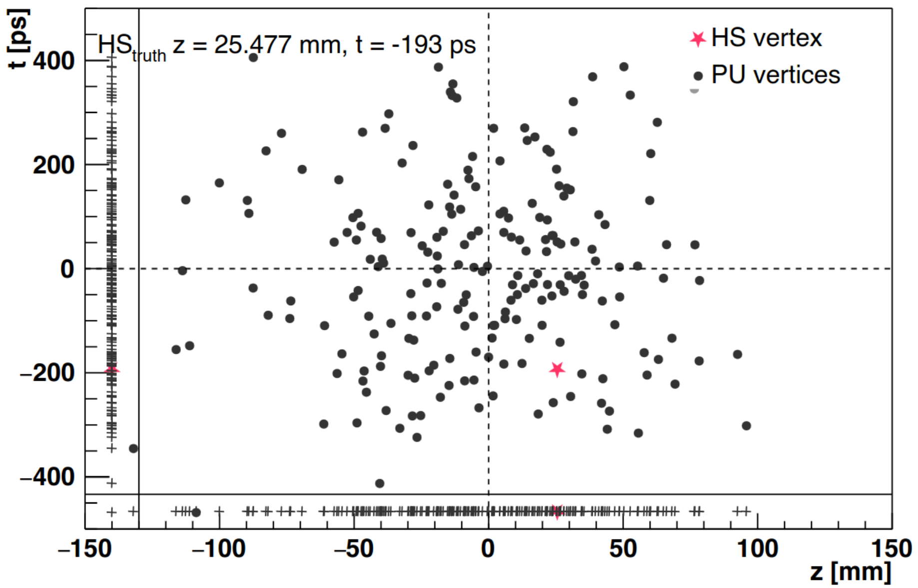
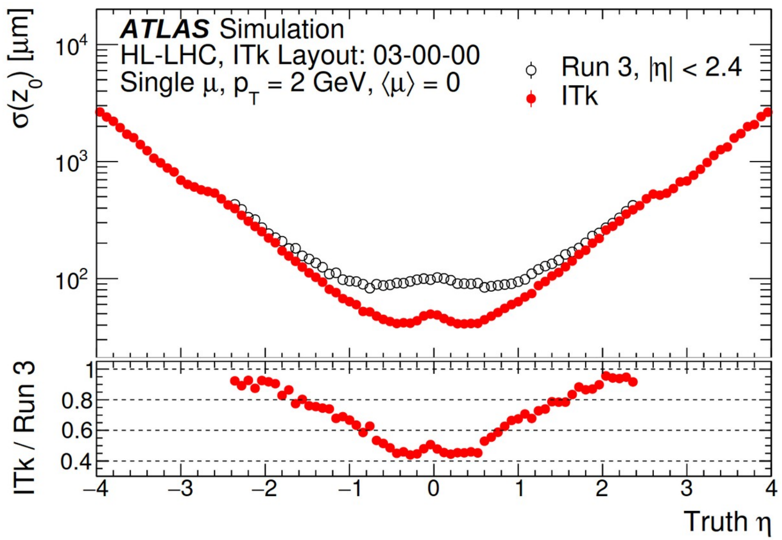
(on behalf of the *HGTD Simulation, Performance and Physics* group)

19 June 2025 – ATLAS Collaboration Week @ CERN

Benefit of HGTD timing information at HL-LHC

- High <μ>=200 pile-up environment will be a significant challenge at HL-LHC
- Spatial tracking information used to separate individual collisions generally degrades at high η
- Beam spot spread:
  - ~ 45 mm in z
  - ~ 180 ps in time
- $\mathcal{O}(10\ \mathrm{ps})$ timing measurement can exploit the temporal beam spot spread
- HGTD can improve the pile-up suppression performance in the forward region





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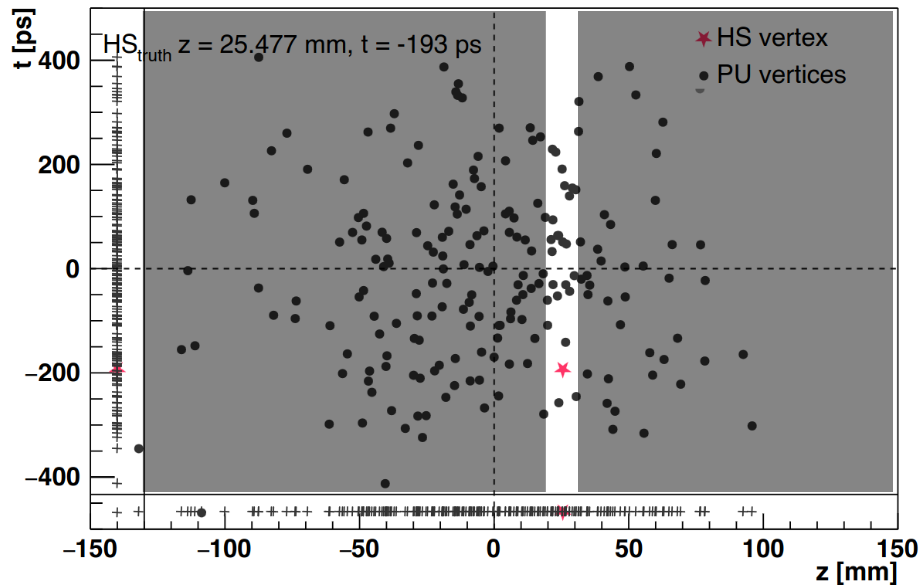

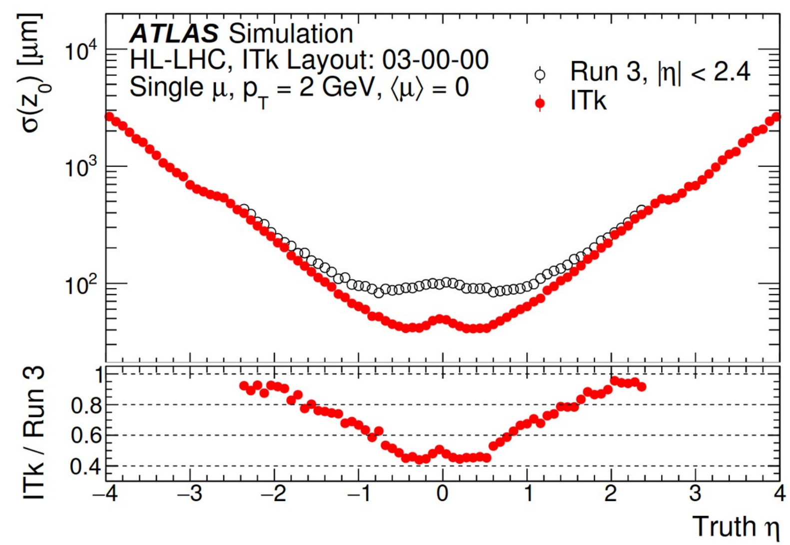

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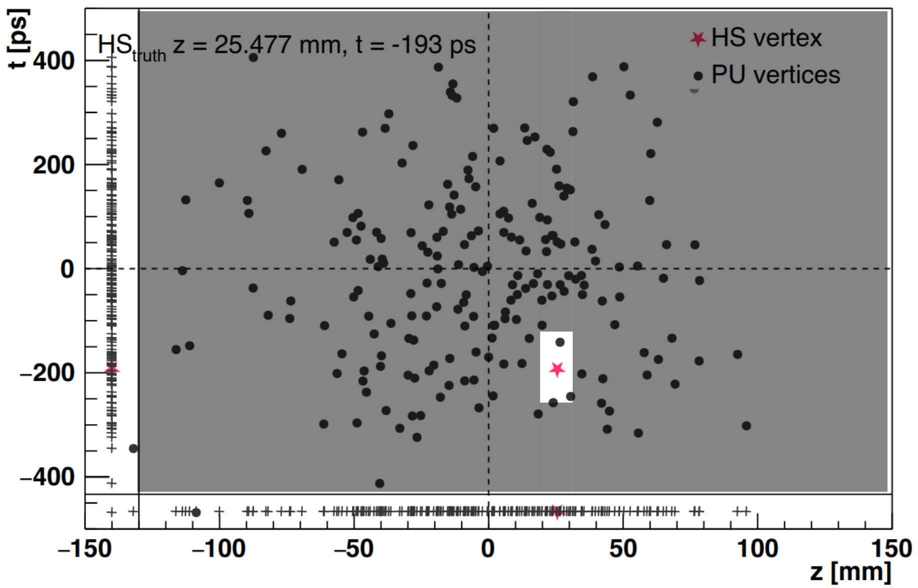
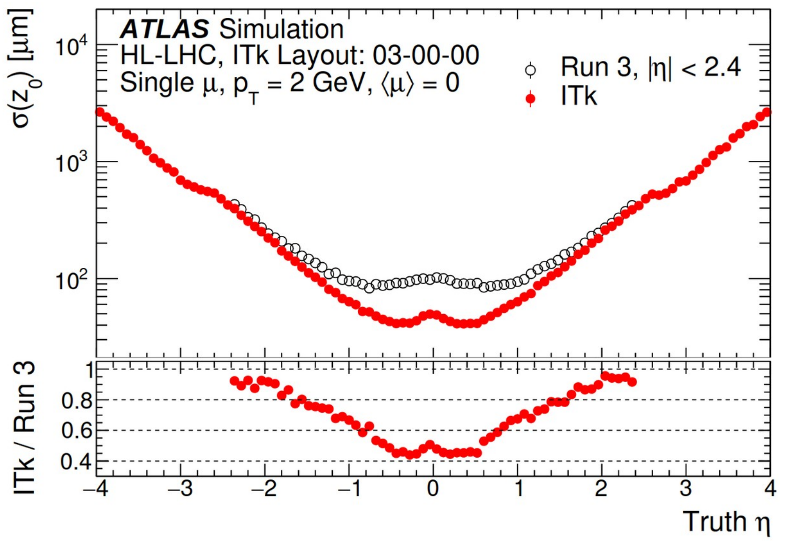
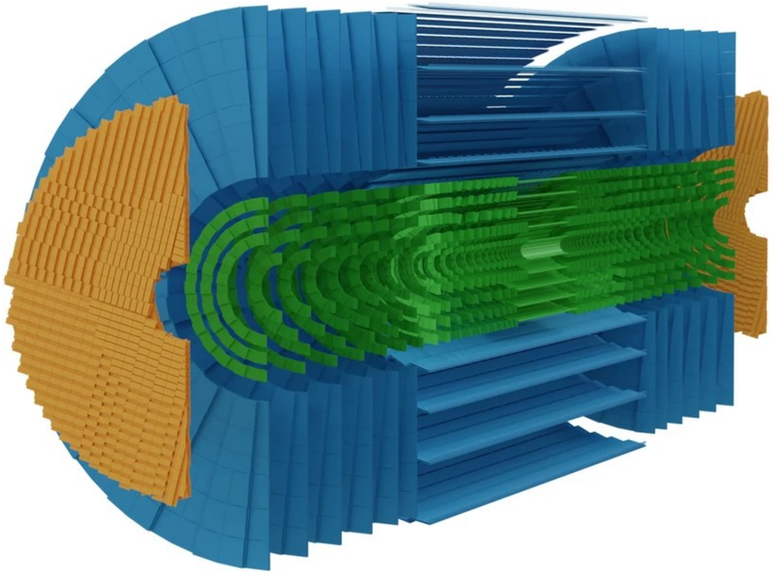


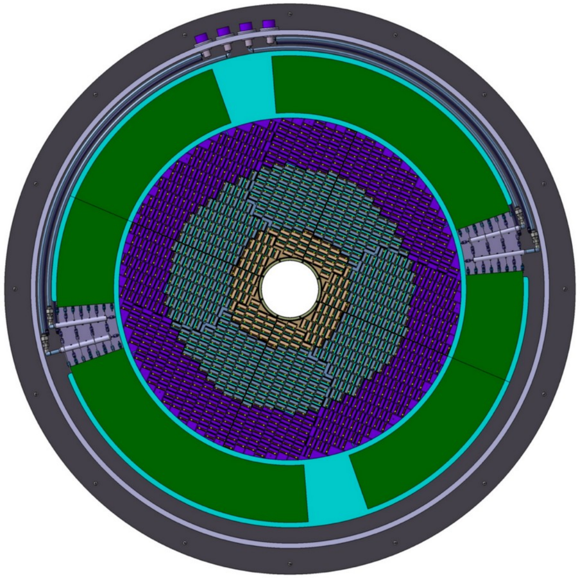


High Granularity Timing Detector - Overview

See Tuesday's slides for a general status overview here



- Coverage in the forward region: $2.4 < |\eta| < 4$
- ± 3.5 m from nominal interaction point – behind ITk
- Silicon LGADs 1.3 mm x 1.3 mm pad size
- < 10 % maximum occupancy
- 4 instrumented layers per end-cap
- 8032 modules, 3.6 M readout channels
- 3-ring geometry with varying module overlap
- Main objectives:
  - Provide timing information for tracks with resolution < 50 ps (< 70 ps per-hit resolution) – reconstruction efficiency inherently limited by acceptance
  - Per-bunch-crossing measurement of luminosity



Single-pad performance

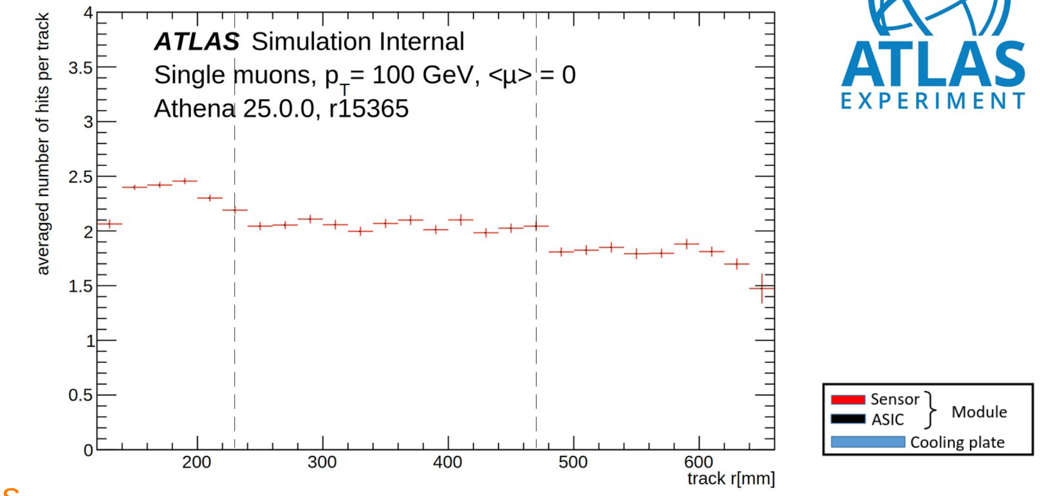
- **Timing resolution varies with radiation damage**
  - Inner and middle rings will require replacement
- Multiple contributions to timing resolution:

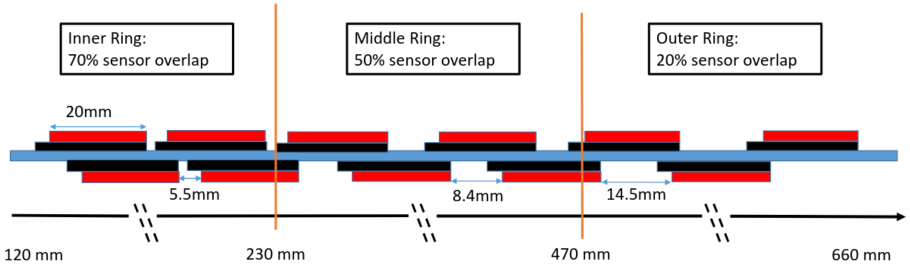
$$\sigma_t^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{timewalk}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{clock}}^2$$

- Currently, the per-hit resolution is expected to be 40-45 ps
- At most 4 hits per track, between 2 and 2.5 on average

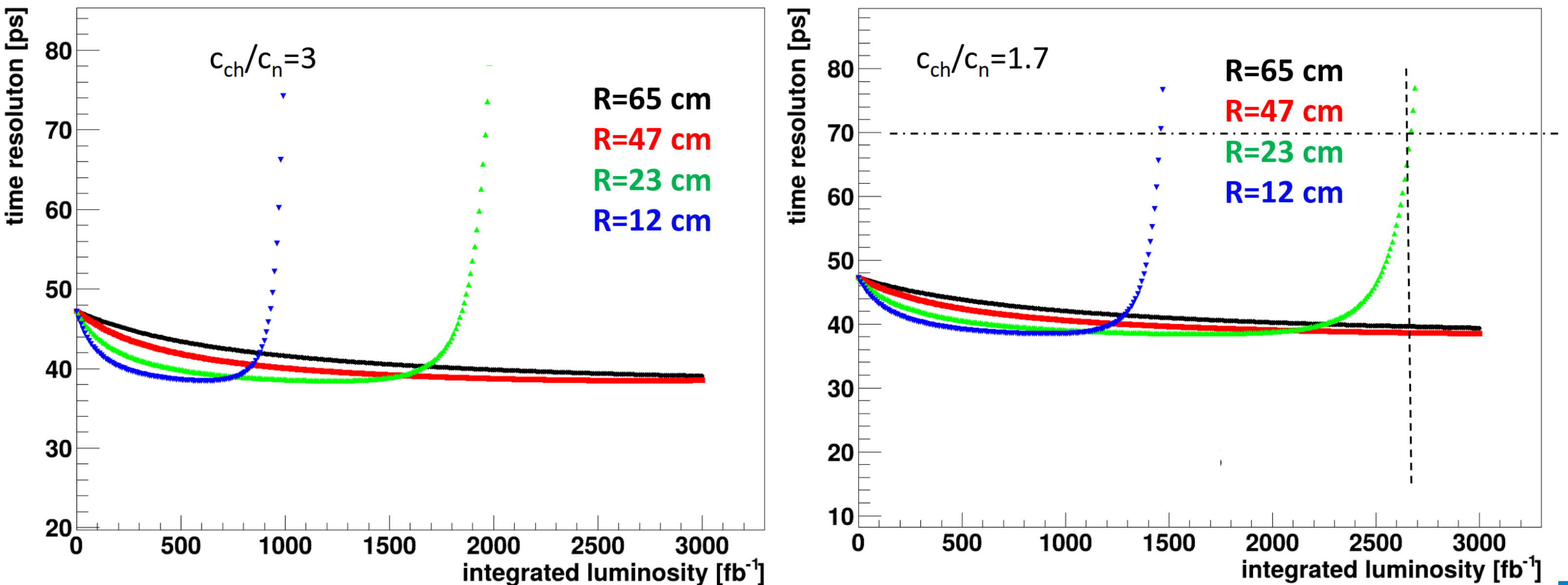
NB*: Simulation, reconstruction and performance studies currently assume a per-hit resolution of 35 ps

- Integration of more accurate timing resolution parametrization in Athena in progress



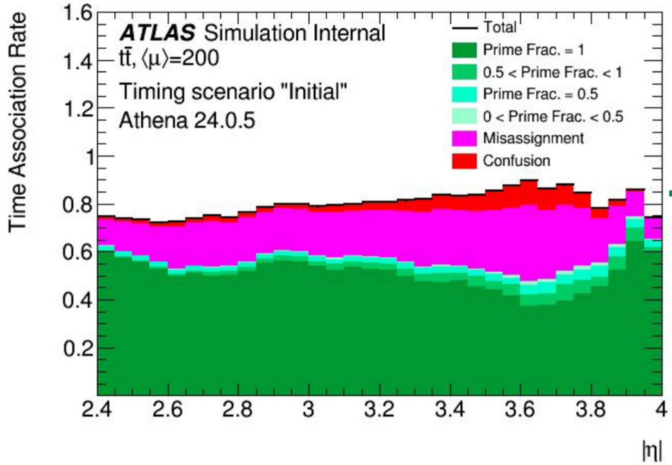


Overall per-hit timing resolution, no replacements

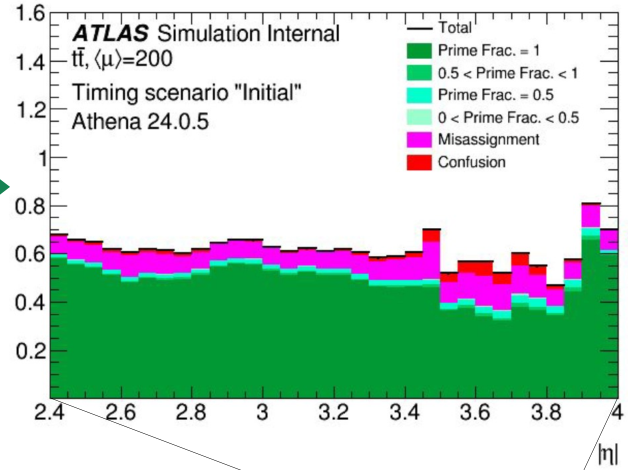


Track time reconstruction and performance

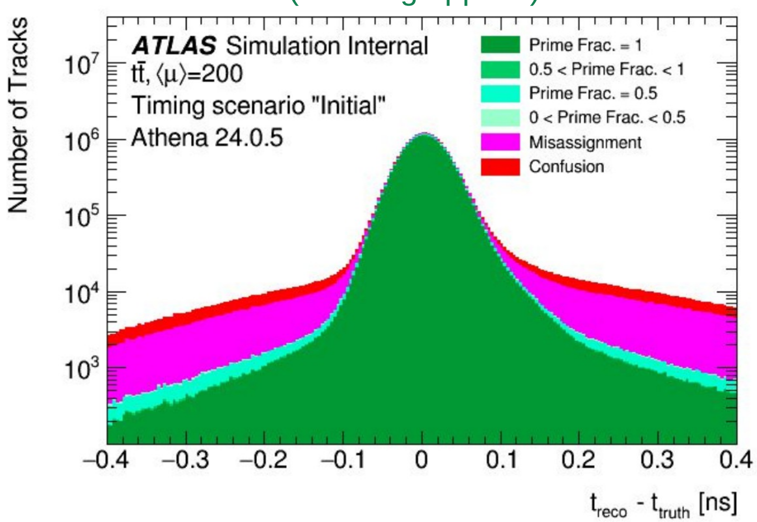
Extrapolation only

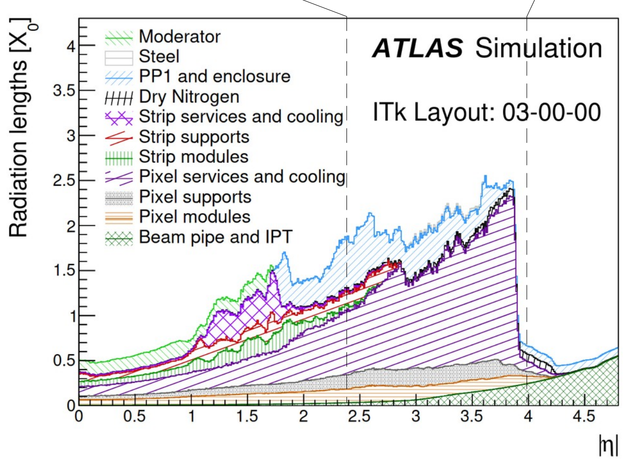


With cleaning applied



Reconstruction performance
(cleaning applied)





1) Tracks reconstructed in ITk extrapolated to HGTD surfaces to associate HGTD hits
2) Cleaning procedure applied: impose track quality requirements and hit time compatibility

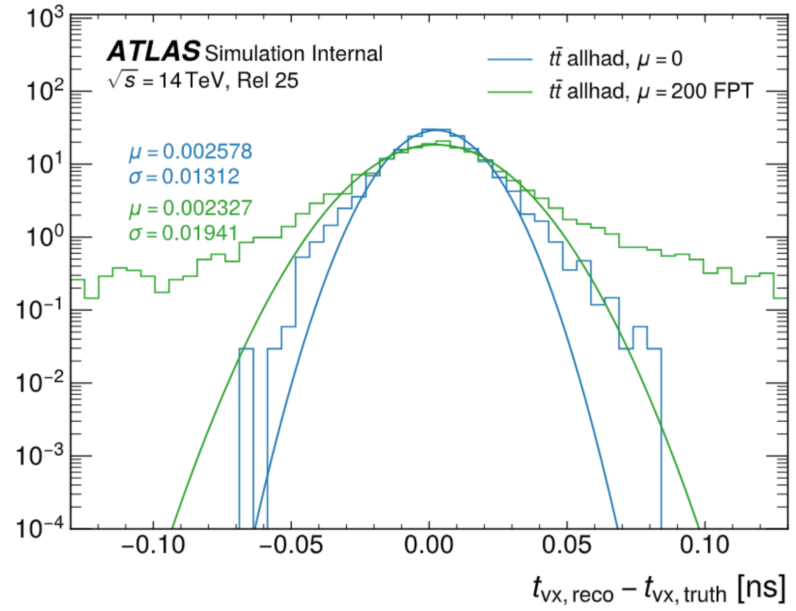
- Algorithm implemented both in standard reconstruction and with ACTS
- Reconstruction efficiency heavily impacted by upstream material budget – particles showering in ITk
- Overall time assignment rate ~62% (~ 13 % misasignments)
- Track time resolution is 30 ps*, distribution skewed due to under-compensating time-of-flight correction

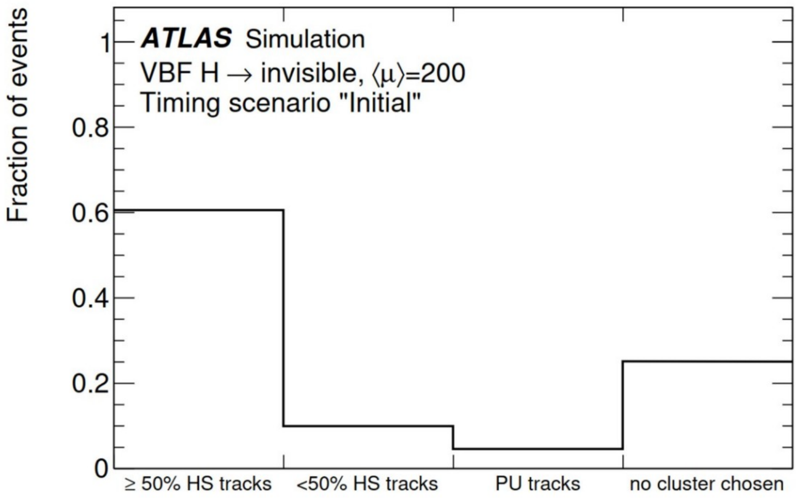
Vertex time reconstruction and performance

- Vertex time reconstructed for hard-scatter vertex only
- Track candidates clustered in temporal dimension
- Highest purity cluster chosen by BDT taking cluster properties as input
- Vertex time reconstructed as weighted average of track times in the highest-score cluster containing at least 3 tracks

$$t_{\mathrm{vx}} = \sum_{\mathrm{tr}\in\mathrm{cl}} w_i\, t_{\mathrm{tr},i} \qquad w_i = \frac{1}{\sigma^2_{t_{\mathrm{tr}},i}}$$

- Time assignment rate 75 % (~ 60 % correctly assigned)
- Overall time resolution is 19 ps*
- High purity is crucial – often used as reference time downstream
- Work in progress to move to more sophisticated cluster selection ML techniques and re-evaluate WP





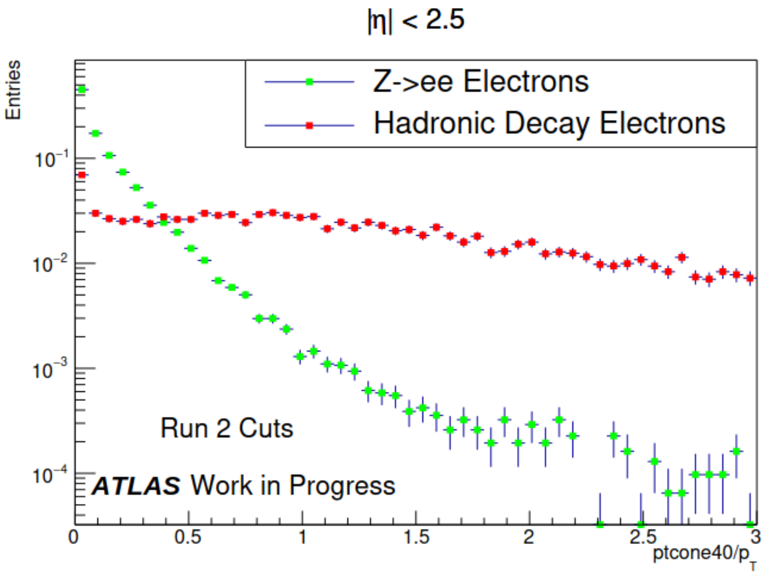
How can timing information be used?

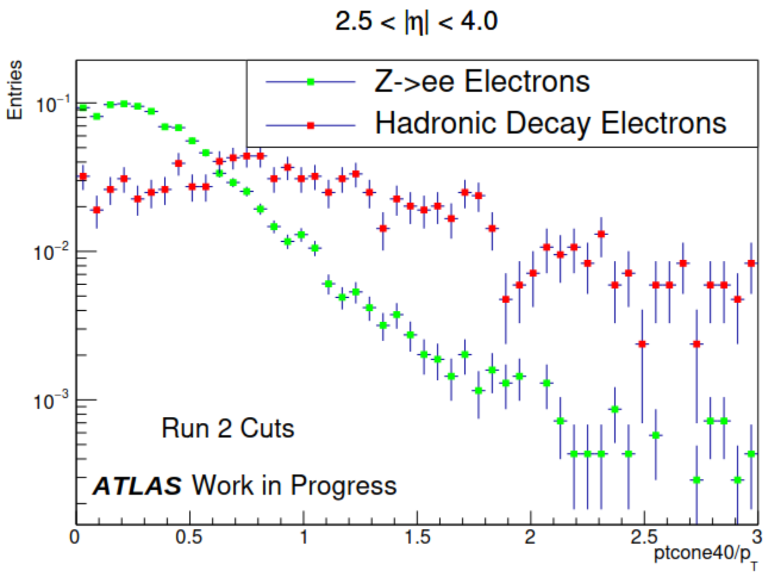
- Several completed Run 4 studies using HGTD timing information are presented in the rest of the talk:
  - Electron isolation
  - Suppression of pile-up jets
  - Jet energy resolution
  - Flavor tagging

Forward electron isolation (link to Note)

- Evaluating improvements of performance for pile-up suppression in the track isolation variable $p_{\mathrm{T}}^{\mathrm{cone40}}$
- Using Z → ee sample for prompt (signal) and ttbar events for non-prompt electrons
- Using same cuts on track variables as in Run 2
- Significant degradation of separation power seen in isolation variable in the forward region, notably due to degraded z_0 resolution

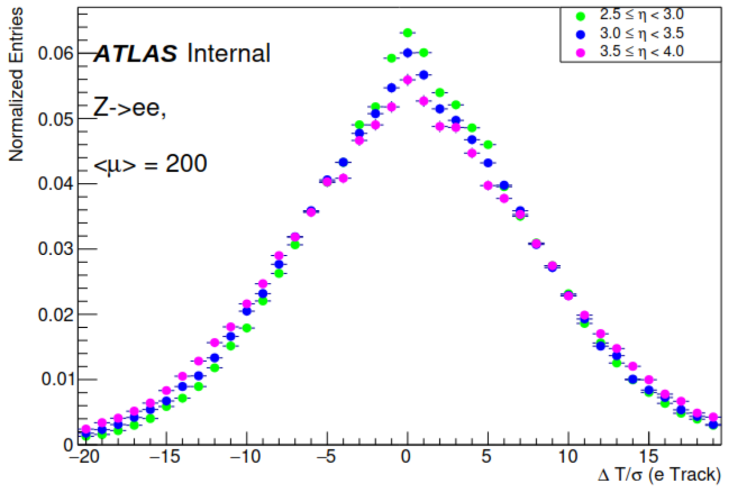
Variable	Cut Value
$\|\eta\|$	< 2.5
N_{si}	≥ 7
N^{sh}_{mod}	≤ 1
N^{si}_{hole}	≤ 2
N^{pix}_{hole}	≤ 1
p_T	≥ 1 GeV
$z_0 \sin\theta$	< 3 mm



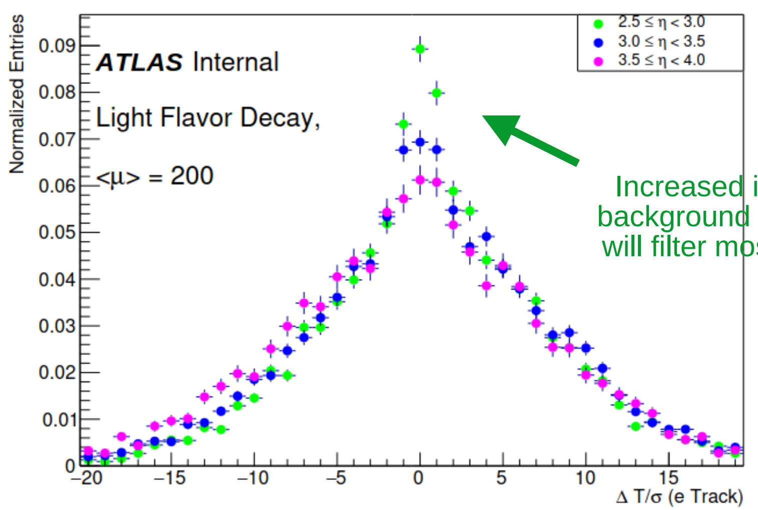


Forward electron isolation (*link to Note*)

$$\frac{\Delta T}{\sigma} \equiv \frac{t_{\text{electron track}} - t_{\text{cone track}}}{\sqrt{\sigma_e^2 + \sigma_t^2}}$$

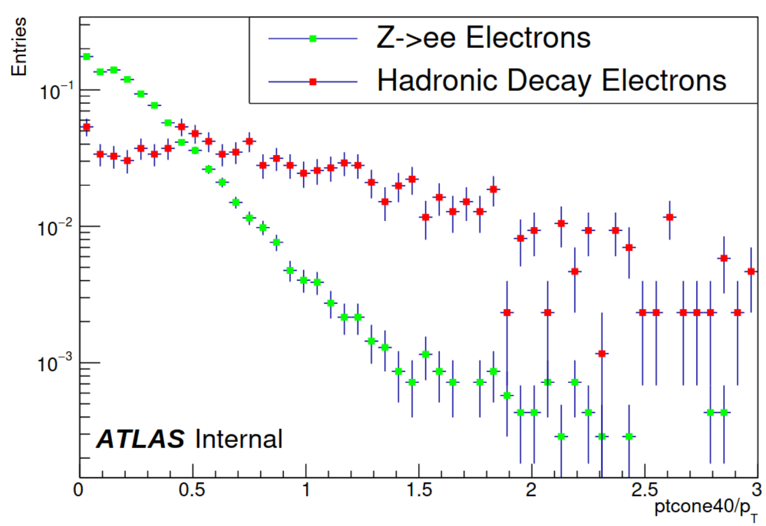


- Additional variable defined: time compatibility with the electron track (assigning correct track to the electron is crucial !)
    - Higher time association rate observed for electron tracks
    - Additionally using hard-scatter vertex time also considered, with similar performance
- Simultaneous optimization of z_0 and time cut: $z_0 \sin\theta < 3.25$ mm, $\Delta T/\sigma < 2.5$
- Background rejection improved by 10-14 % at same signal efficiency for different WPs



Increased in-time activity in background suggests time cut will filter mostly pile-up tracks

2.5 < |η| < 4.0



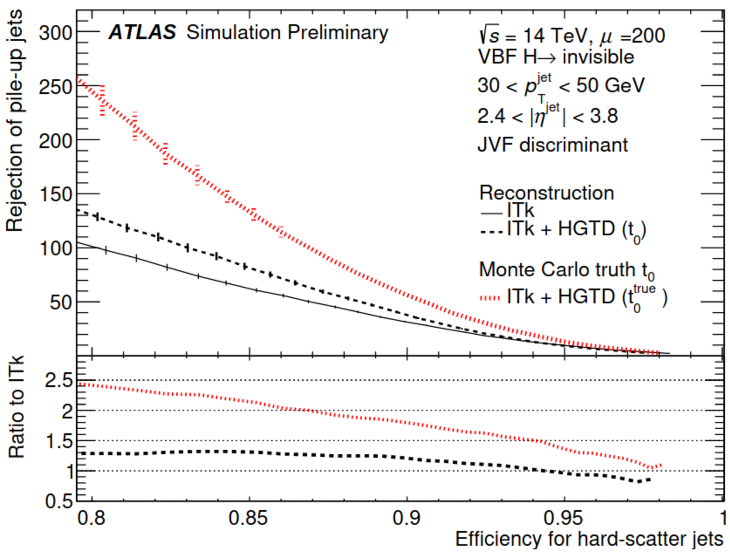
Suppression of forward pile-up jets (link to Note)

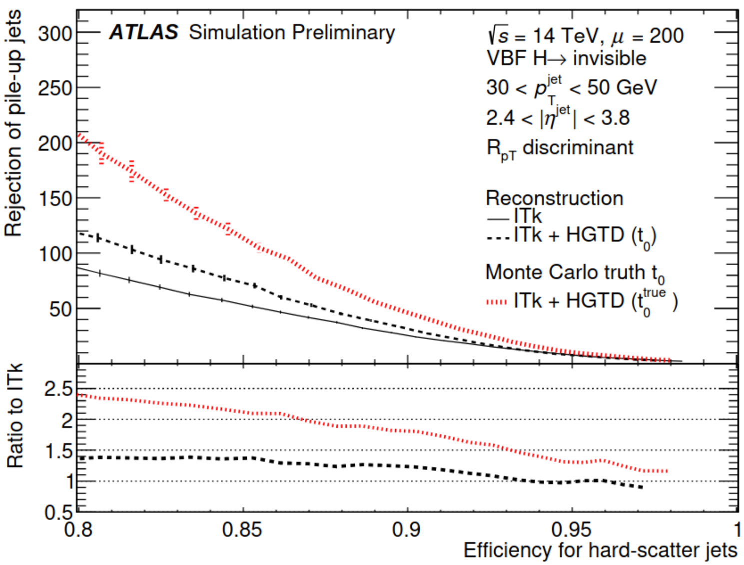
- Studying improvements by modifying the R_{pT} and JVF variables on VBF H → invisible sample
  - Direct use of track-to-vertex association and relative z position → inherently degraded performance in forward region
- Include an additional time compatibility requirement: Tracks with time have to be compatible with HS vertex
- 20-30 % improvement in rejection seen at 85 % efficiency

$$\mathrm{JVF} = \frac{\sum_k p_{\mathrm{T}}^{\mathrm{trk}_k}(\mathrm{PV}_0)}{\sum_l p_{\mathrm{T}}^{\mathrm{trk}_l}(\mathrm{PV}_0) + \sum_{n\geq 1}\sum_l p_{\mathrm{T}}^{\mathrm{trk}_l}(\mathrm{PV}_n)}$$

$$R_{\mathrm{pT}} = \frac{\sum_k p_{\mathrm{T}}^{\mathrm{trk}_k}(\mathrm{PV}_0)}{p_{\mathrm{T}}^{jet}}$$

Time-compatibility cut applied



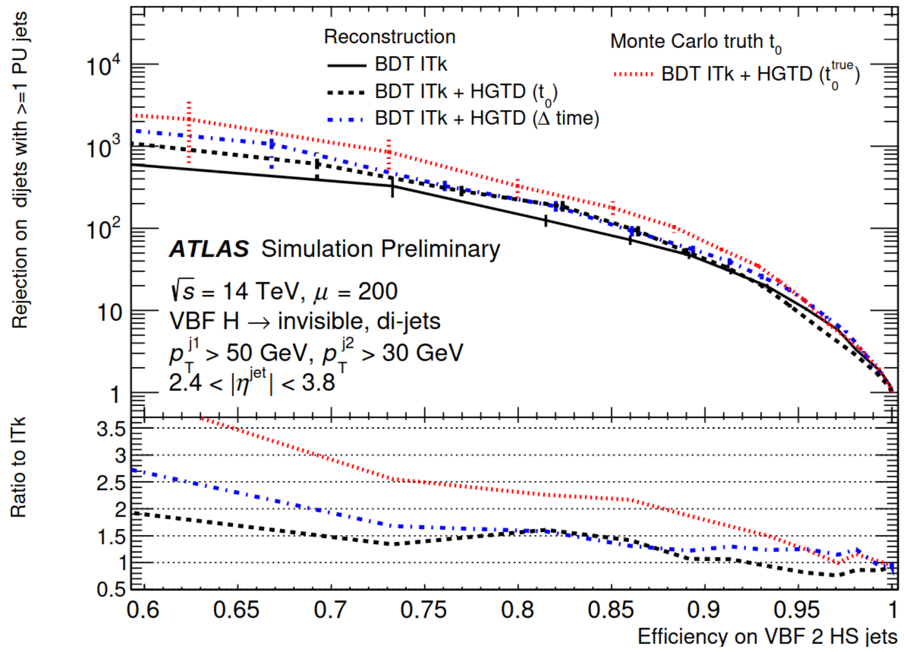


Suppression of forward pile-up jets *(link to Note)*

- Simple viability study performed for VBF signal event selection based on forward jet information
- BDTs trained on different inputs:
  - JVF of leading and sub-leading jet
  - JVF with time cut of leading and sub-leading jet (labeled "t_0" and "t_0^{true}")
  - $\mathrm{JVF(jet1), JVF(jet2)}$ (labeled "Δ time")

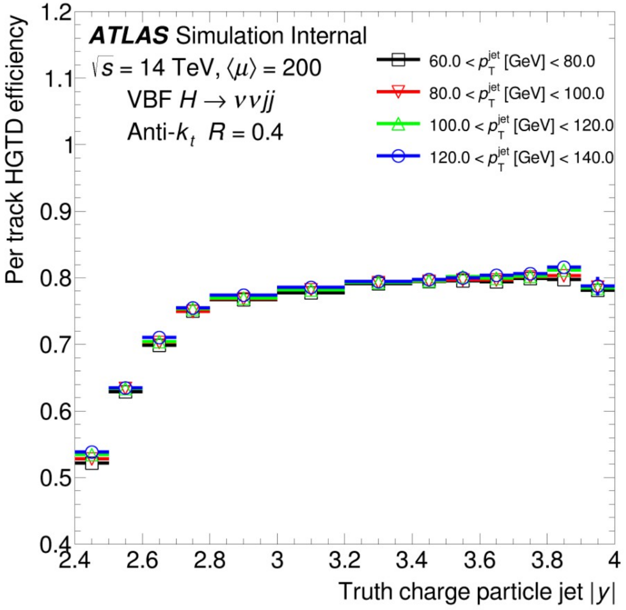
    $|t_{jet1} - t_{jet2}| / \sqrt{\sigma^2_{jet1} + \sigma^2_{jet2}}$

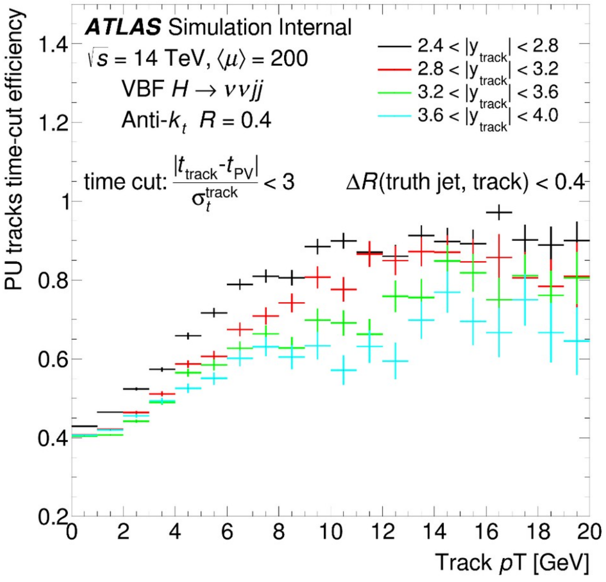
    $|t_{lead\,trk\,jet1} - t_{lead\,trk\,jet2}| / \sqrt{\sigma^2_{lead\,trk\,jet1} + \sigma^2_{lead\,trk\,jet2}}$

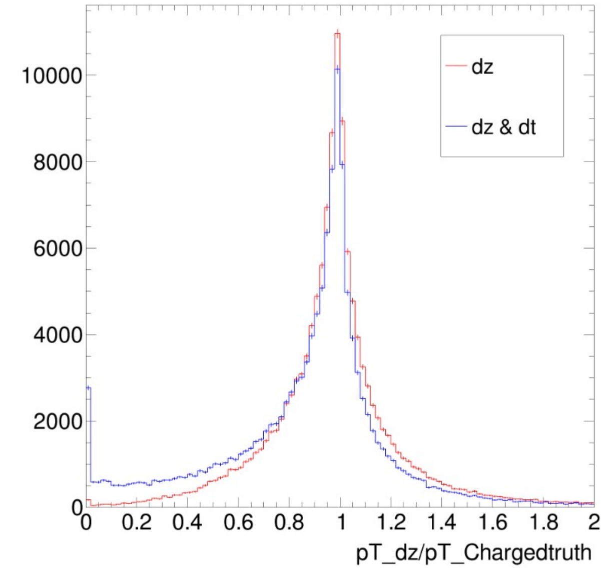


Timing information in jet energy resolution *(link to report)*

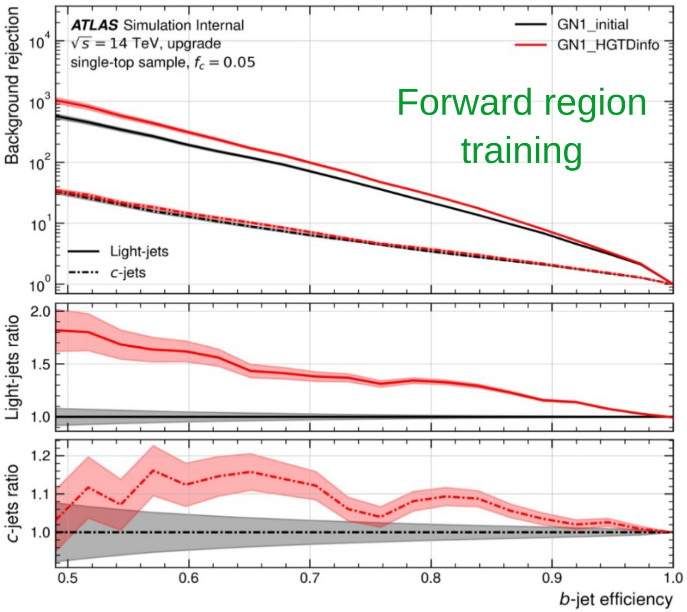
- Studying effectiveness of temporal cut on jet tracks in addition to Δz < 2 mm requirement
- VBF H → invisible sample to enhance forward jets
- Using truth vertex time – ideal case
- Temporal cut seen to further suppress pileup tracks in jets

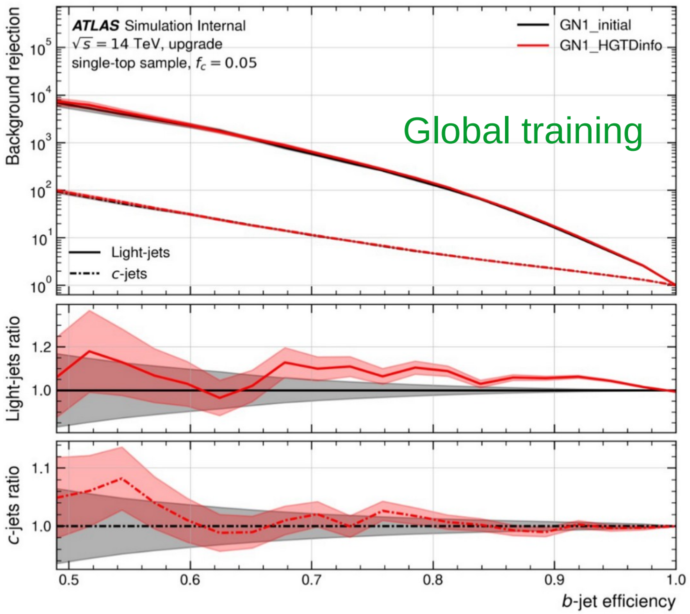




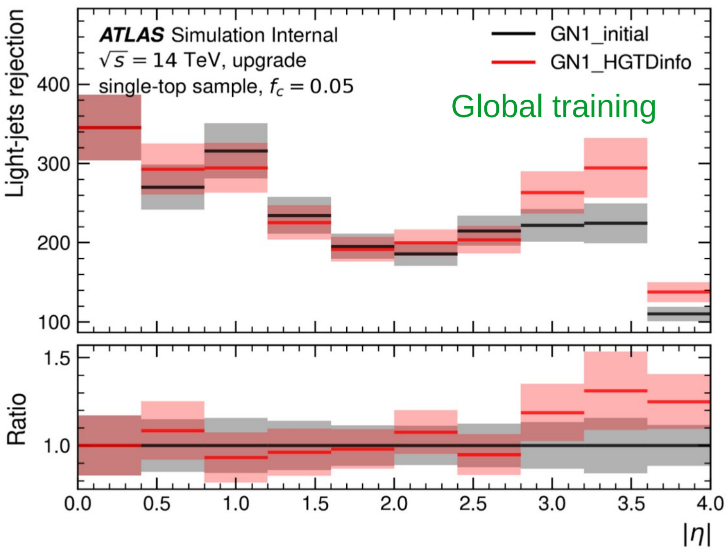


Timing information in flavor tagging *(link to report)*





- Single-top samples used for training – enriched in forward jets compared to ttbar (unavailability of other samples with sufficient stats)
- Training done using the GN1 network on |η| > 2.4 jets and inclusively
- Approach to include HGTD timing information in training features:
  $N_{\text{HGTD hits}}$, $t_{\text{track}} – t_{\text{vertex}}$ (+ boolean if time difference is valid)
  - Network without timing features re-trained on same sample for comparison
- Significant improvement seen in the background rejection in forward region, especially light jet rejection with improvement up to ~ 80% (~ 10 % when training inclusively)



Information for future studies in Rel 25

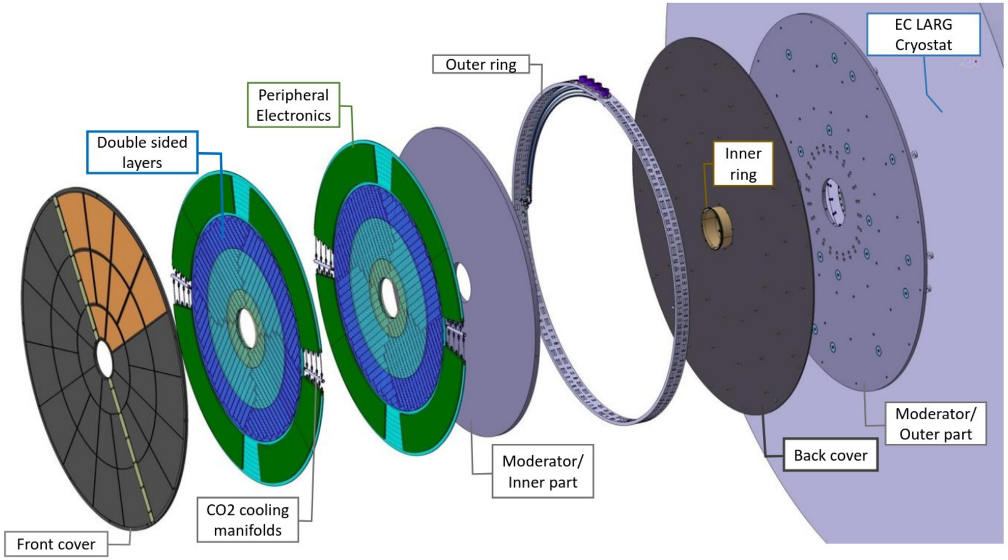
- Track and vertex time information already available in newer Run 4 AODs
- Example for `xAOD::Vertex` (equivalent functionality for `xAOD::TrackParticle`):

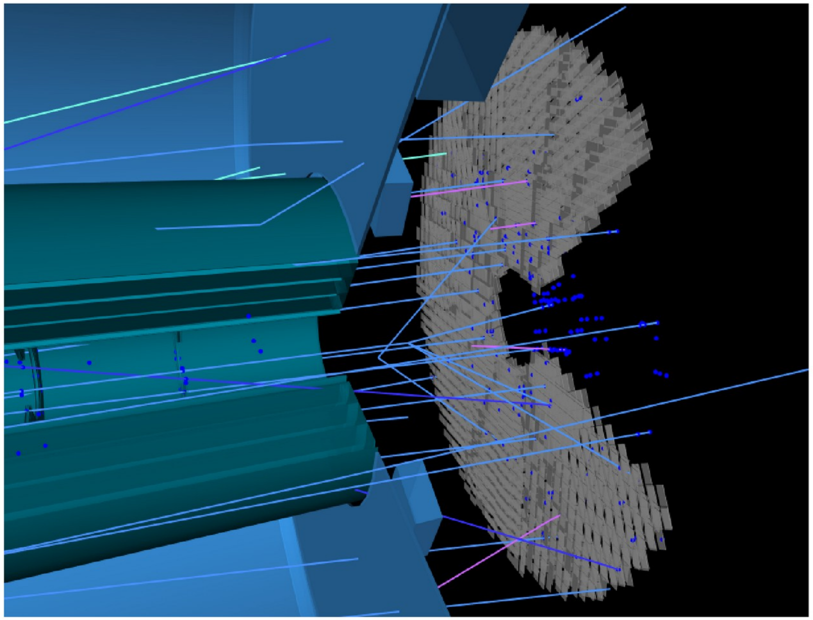
```
// Assuming we have a variable `const xAOD::Vertex* vertex`

// Always first check if a vertex has a time available
if (vertex->hasValidTime()) {
  float vertex_time { vertex->time() };
  float vertex_timeResolution { vertex->timeResolution() };
}
```

More information in the README

- Feel free to reach out on the HGTD Mattermost channel – if further information is needed; feedback from downstream highly appreciated

Thank you!


EC LARG Cryostat
Outer ring
Peripheral Electronics
Double sided layers
Inner ring
Front cover
CO2 cooling manifolds
Moderator/ Inner part
Back cover
Moderator/ Outer part



Backup

Track time reconstruction and performance

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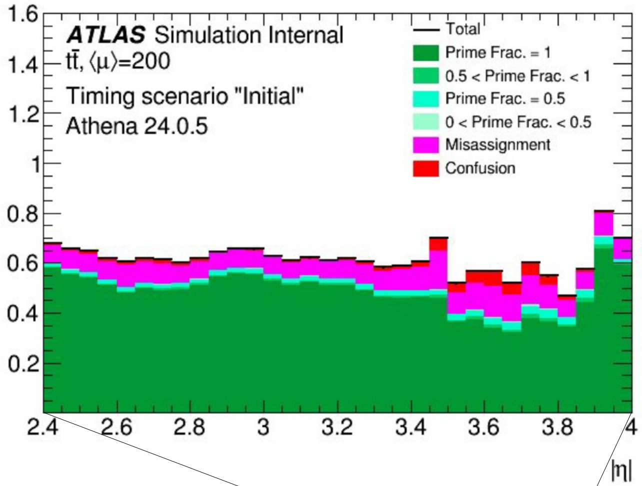

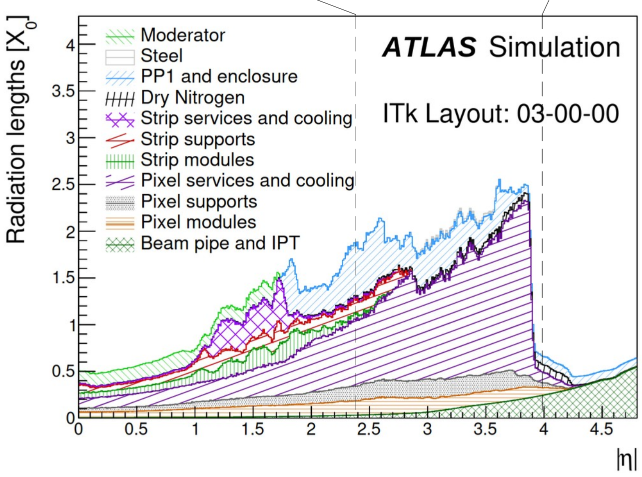

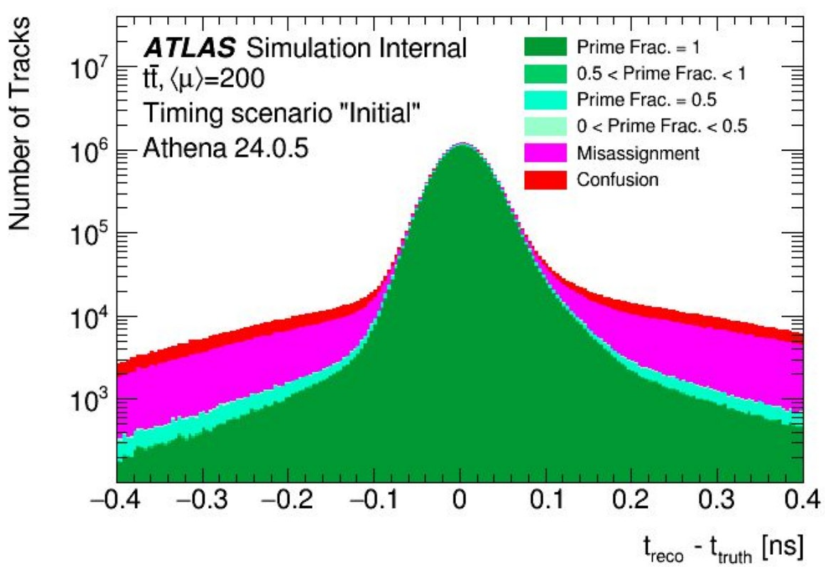

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