ATLAS 4D Tracking for HL-LHC
VII Reunião Geral - Projeto Temático

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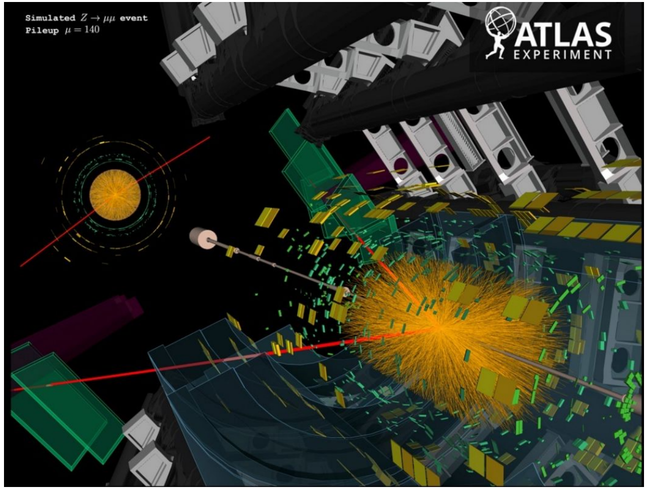
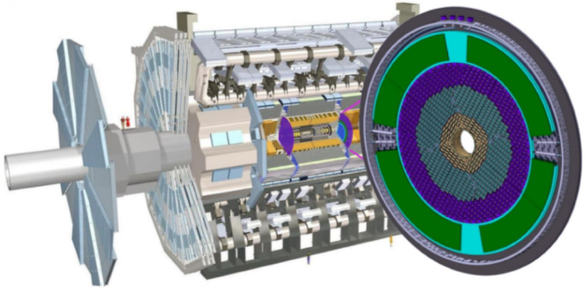
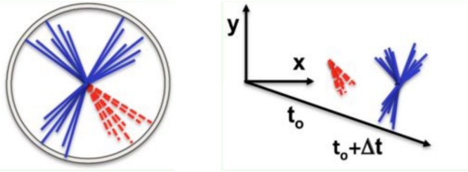
ATLAS preparations for HL operation: HGTD

- A High Granularity Timing Detector (HGTD) will be installed in the forward region of the ATLAS detector to provide track timing information that will complement the reconstruction



Simulation of Z →μμ with < μ > = 140, as seen by the ATLAS experiment



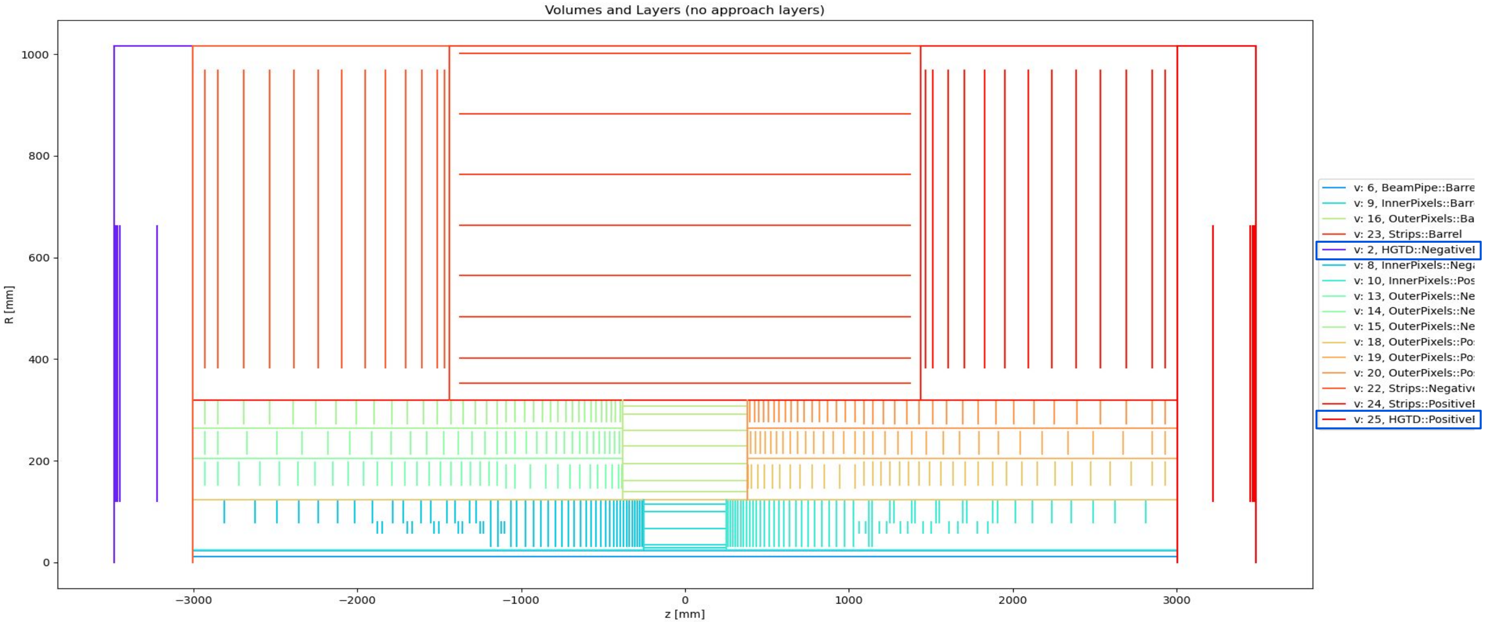


New reconstruction methods that are adapted to the new detector and meet performance requirements from the HL-LHC are necessary!

Image source: [2][4]

Simulating ATLAS with ACTS

- Using ACTS to simulate the track reconstruction with ITk and HGTD
  - More details on my previous presentation
- Managed to include ITk+ HGTD geometry
- Our first objective was to evaluate the performance of CKF after including HGTD time measurements



Including HGTD time smearing at geometry files

- At the digitization step, ACTS uses a geometry config file to simulate smearing of measurements
- We included the time parameter at volumes 2 and 25, which represent HGTD
    - Other volumes just measure l_0 and l_1

$$\vec{x} = (l_0, l_1, \phi, \theta, q/p, t)^T$$


```json
{
    "acts-geometry-hierarchy-map": {
        "format-version": 0,
        "value-identifier": "digitization-configuration"
    },
    "entries": [
        {
            "volume": 2,
            "value": {
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                    {
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                        "mean": 0.0,
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                        "type": "Gauss"
                    },
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                        "index": 1,
                        "mean": 0.0,
                        "stddev": 0.37527767,
                        "type": "Gauss"
                    },
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                        "index": 5,
                        "mean": 0.0,
                        "stddev": 0.37527767,
                        "type": "Gauss"
                    }
                ]
            }
        },
    ...
}
```
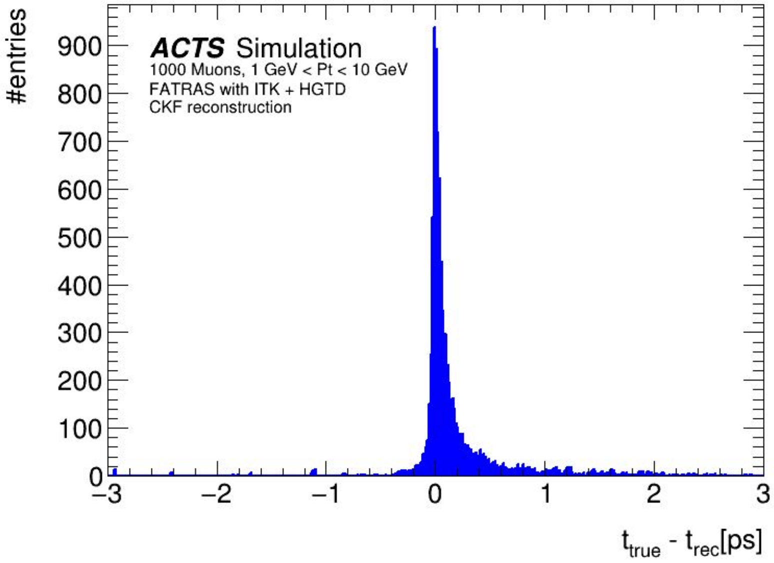
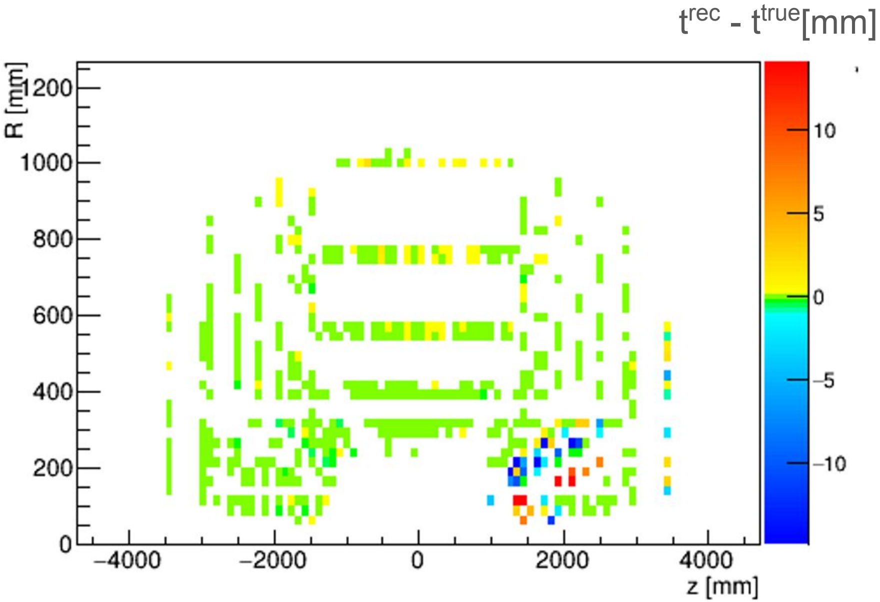

CKF performance evaluation on Particle guns

- Incorporated HGTD time measurements on the CKF reconstruction method
- Below are the results for the simple scenario of a particle gun
  - Muons are generated at the coordinate (0,0,0,0) and shot at the detector with a variable angle η ~ U(-4,4)

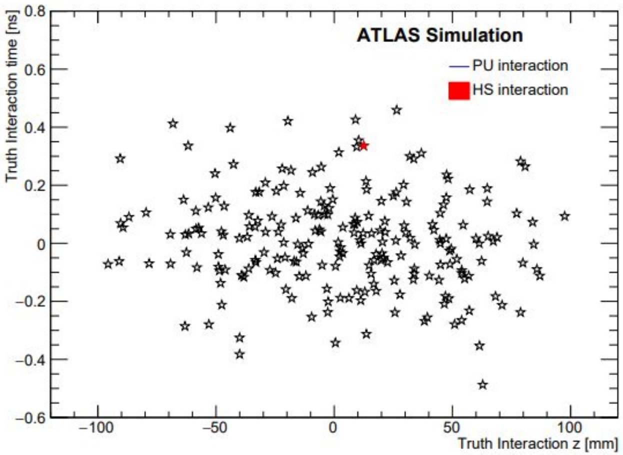


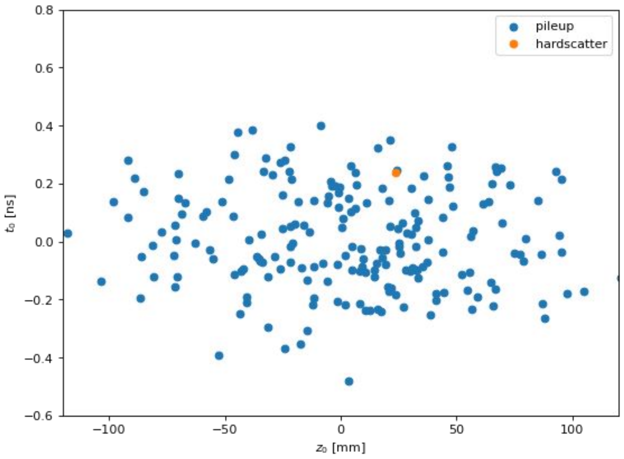


Simulating HL-LHC beam with ACTS Pythia8

- Managed to simulate the same scenario as the TDR
  - z0 ~ N(0,50 mm), t0 ~ N(0,175ps)
- Simulated ttbar events with 1000 events

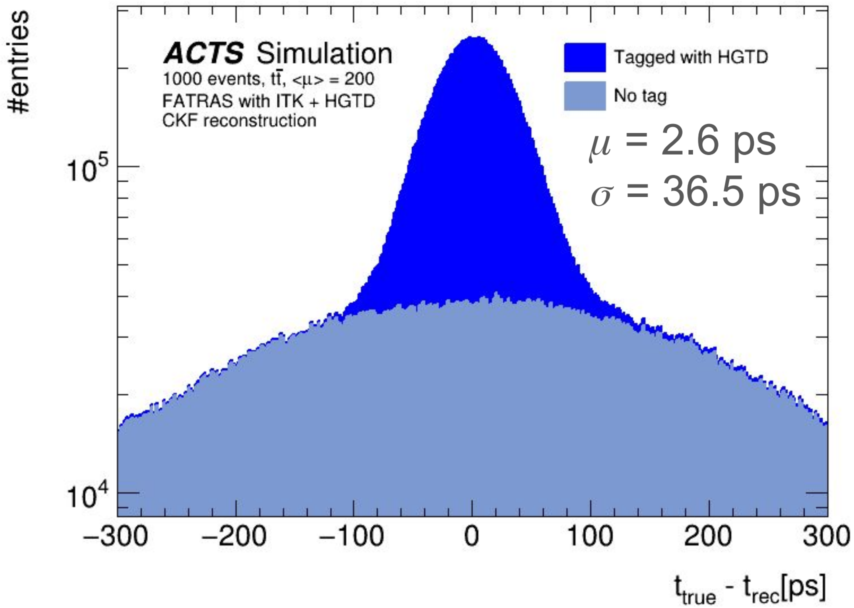
```
addPythia8(
    s,
    hardProcess=["Top:qqbar2ttbar=on"],
    npileup=200,
    vtxGen=acts.examples.GaussianVertexGenerator(
        stddev=acts.Vector4(0.0125 * u.mm,
                            0.0125 * u.mm,
                            50 * u.mm,
                            0.175 * u.ns),
        mean=acts.Vector4(0, 0, 0, 0),
    ),
    rnd=rnd,
    outputDirRoot=outputDir,
)
```





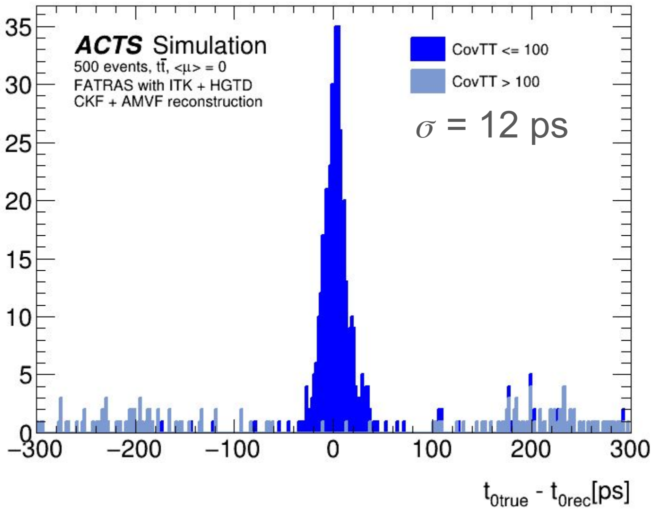
CKF Performance evaluation: Residue plot

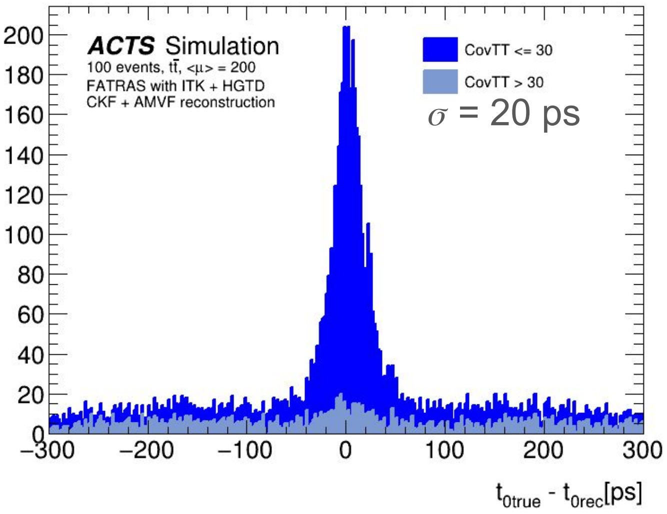
- It is possible to isolate tracks tagged by HGTD with the reconstruction covariance matrix
- Tracks without HGTD tagging rely on first estimate for time reconstruct, which has a high error associated with.
- When a track reaches HGTD, the error drops significantly because of the low error attributed to the measure
  - In the plot aside, the covariance threshold to separate the tracks (err_eT) was set to 1000



AMVF Vertex time reconstruction

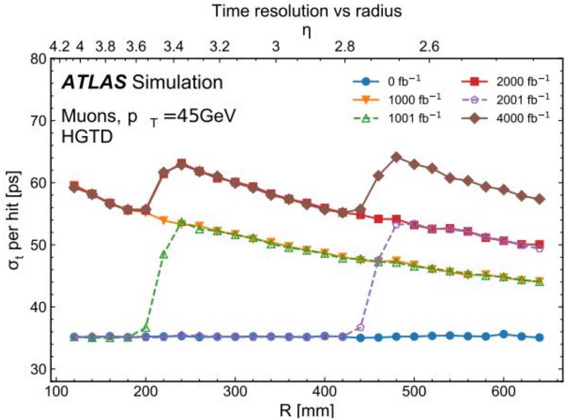
- To understand the impact of CKF on the global t_0 reconstruction we added a step to estimate primary vertex positions using AMVF
  - Detailed explanation of AMVF on backup
- Estimates with high residual can mostly be filtered by the time error parameter on the covariance matrix (internal parameter of AMVF)
  - Work point choice of purity x sensibility
- After filtering out high error estimates, a Gaussian fit was made to get t_{0rec} resolution

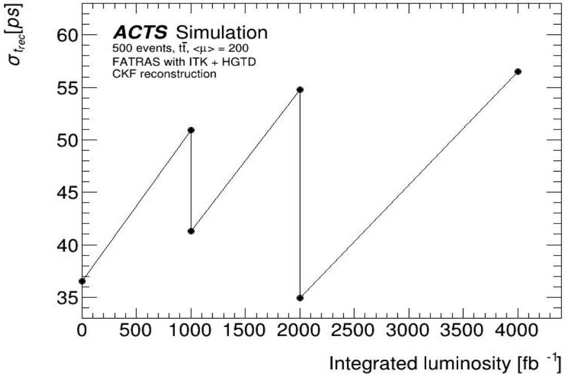




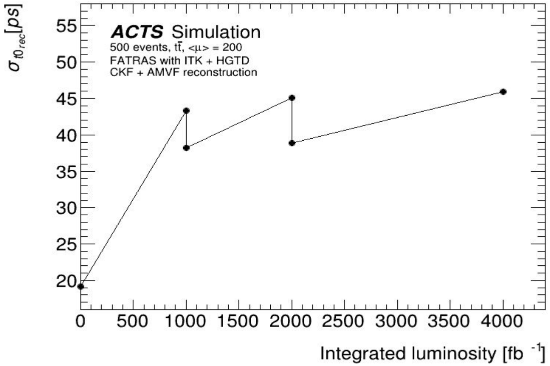
Simulation of sensor deterioration

- We simulated the sensor deterioration with increasing integrated luminosity
- ACTS could be used as a quick test bench before a full implementation in ATHENA
  - Way faster to implement and to test the full reconstruction chain with the changes
- We can use this to evaluate the impact of degradation on the track reconstruction





hit time resolution



t0 resolution

Presentation at the ACTS Developers Workshop

- Will present these results at the ACTS Developers Workshop
- The presentation will focus on the performance of CKF time reconstruction using a timing layer detector and the impact of sensor degradation on that vertex reconstruction

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ATLAS Qualification Project

- Started an Authorship Qualification Project together with HGTD Simulation and Performance team
- The first goal is to include the simulation of HGTD front end electronics response in the ATHENA framework
  - Simulation of digitization of Time to Digital Converters (TDCs) and calculation of Time of Arival (TOA)
  - Allows for more accurate Monte Carlo simulation of the detector
- Implementation is done, just need to discuss some code organization and changes to downstream components (cluster building)

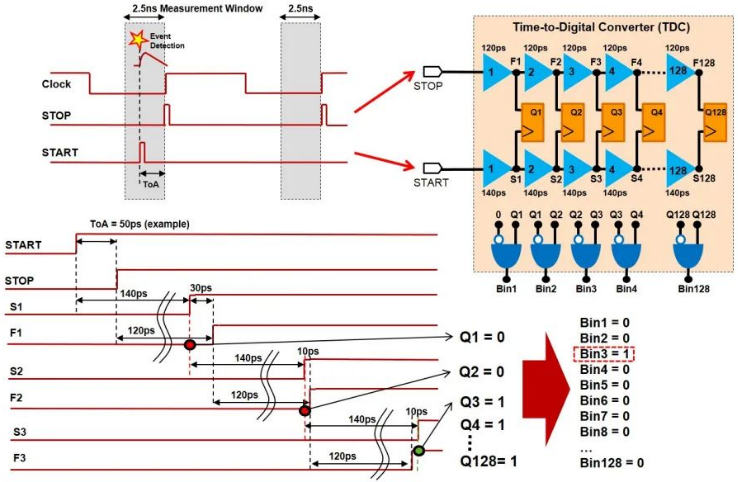


Image source: [4]

Next steps

- Now that we have a good understanding of CKF and its performance, we can start the research of new reconstruction methods
- For now, ATLAS has been supporting the GNN tracking method for its, but the chose has yet to be made

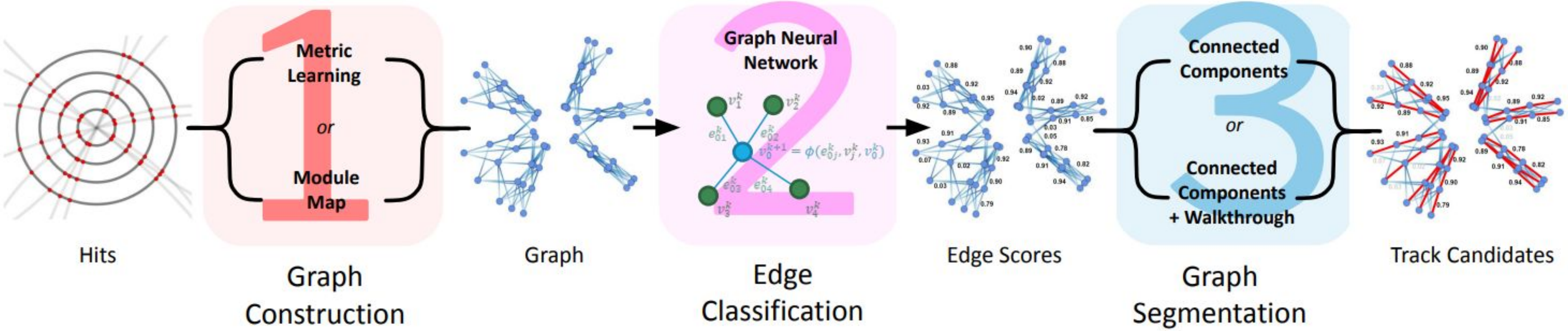


Image source: [3]

We're on the right track 😉

OPEN PROBLEMS

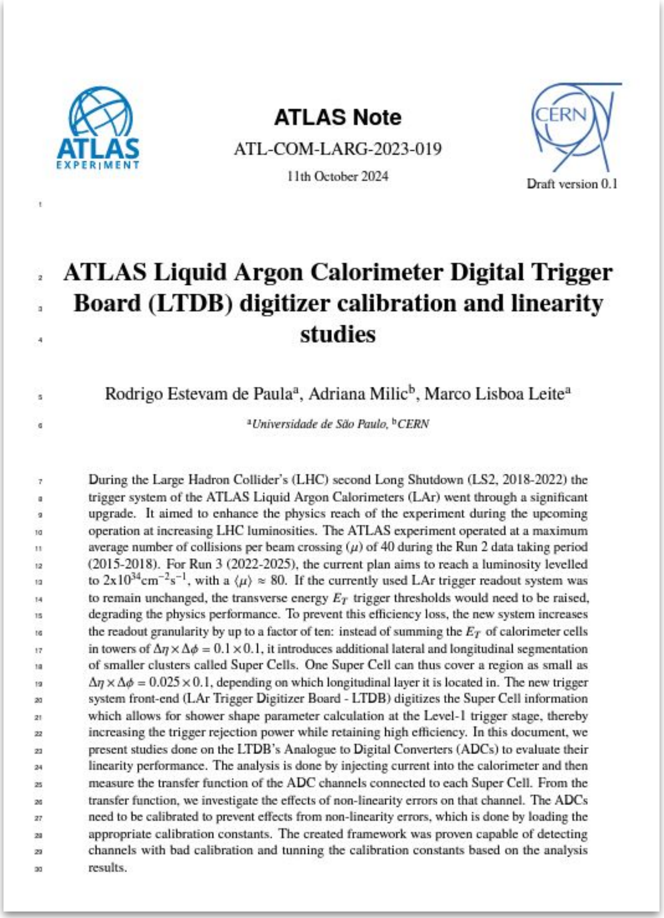
- Extending Tra TrackML nference timing and scaling studies to ATLAS ITk
- Investigating training and inference performance on lower p_T tracks (i.e. < 1 GeV) and high p_T tracks (i.e. > 10 GeV)
- Investigating performance on large radius tracks and dense track environments
- Direct comparison with combinatorial Kalman filter (current algorithm) efficiency and track parameter resolution

ExaTrkX BERKELEY LAB HighRR Lecture Week - Heidelberg University - **September 13, 2023** 87

Taken from Daniel Murnane lecture [3]

Bonus: Finally finished interal note 😀

- The note can be found in CDS: https://cds.cern.ch/record/2863410
- Documents (some of) our contributions to the commissionament of Phase-I LAr upgrade



ATLAS Note
ATL-COM-LARG-2023-019
11th October 2024
Draft version 0.1

ATLAS Liquid Argon Calorimeter Digital Trigger Board (LTDB) digitizer calibration and linearity studies

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During the Large Hadron Collider's (LHC) second Long Shutdown (LS2, 2018-2022) the trigger system of the ATLAS Liquid Argon Calorimeters (LAr) went through a significant upgrade. It aimed to enhance the physics reach of the experiment during the upcoming operation at increasing LHC luminosities. The ATLAS experiment operated at a maximum average number of collisions per beam crossing $\langle\mu\rangle$ of 40 during the Run 2 data taking period (2015-2018). For Run 3 (2022-2025), the current plan aims to reach a luminosity levelled to $2\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$, with a $\langle\mu\rangle \approx 80$. If the currently used LAr trigger readout system was to remain unchanged, the transverse energy E_T trigger thresholds would need to be raised, degrading the physics performance. To prevent this efficiency loss, the new system increases the readout granularity by up to a factor of ten: instead of summing the E_T of calorimeter cells in towers of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, it introduces additional lateral and longitudinal segmentation of smaller clusters called Super Cells. One Super Cell can thus cover a region as small as $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$, depending on which longitudinal layer it is located in. The new trigger system front-end (LAr Trigger Digitizer Board - LTDB) digitizes the Super Cell information which allows for shower shape parameter calculation at the Level-1 trigger stage, thereby increasing the trigger rejection power while retaining high efficiency. In this document, we present studies done on the LTDB's Analogue to Digital Converters (ADCs) to evaluate their linearity performance. The analysis is done by injecting current into the calorimeter and then measure the transfer function of the ADC channels connected to each Super Cell. From the transfer function, we investigate the effects of non-linearity errors on that channel. The ADCs need to be calibrated to prevent effects from non-linearity errors, which is done by loading the appropriate calibration constants. The created framework was proven capable of detecting channels with bad calibration and tunning the calibration constants based on the analysis results.

Thank you for your attention!

Questions?

Referencias

[1] ATLAS Collaboration. *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC.* Physics Letters B,2021. https://doi.org/10.1016/j.physletb.2012.08.020.

[2] M. Gullstrand, and S.Maraš. “Using Graph Neural Networks for Track Classification and Time Determination of Primary Vertices in the ATLAS Experiment” (Dissertation). Disponível em http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-288505

[3] Daniel Murnane. Full-length tutorial on Tracking with Graph Neural Networks (Sep 2023, Heidelberg). Available at: https://exatrkx.github.io/

[4] ATLAS Collaboration, “Technical Design Report for the ATLAS ITk Pixel Detector”,Tech. Rep. ATL-COM-ITk-2018-019, CERN, Geneva, 2018.Disponível em: https://cds.cern.ch/record/2310230

[5] ATLAS Collaboration, “Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade”. Technical report, CERN, Geneva, 2020. Disponível em: https://cds.cern.ch/record/2719855/files/ATLAS-TDR-031.pdf

[6] Paul Gessinger-Befurt. *Development and improvement of track reconstruction software and search for disappearing tracks with the ATLAS experiment*, 2021. Presented 30 Apr 2021.

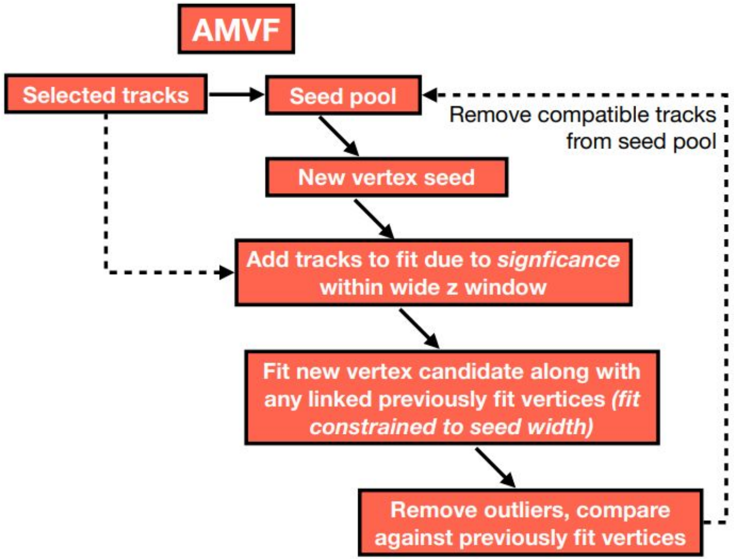
[7] ATLAS Collaboration. *ACTS documentation.*
Disponivel em: https://acts.readthedocs.io/en/latest/index.html

Backup

AMVF Time reconstruction

AMVF overview

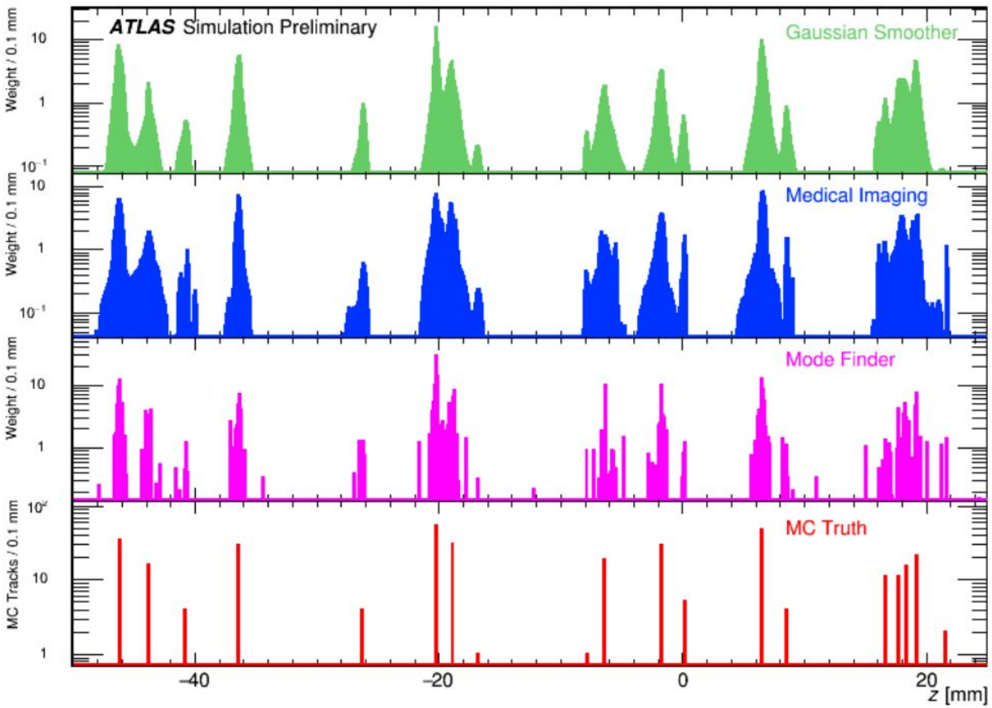
- I managed to include time information in the AMVF reconstruction
- The following slides will be an overview of the method in order to understand its performance
- The process can be divided into three steps:
  - Vertex seeding: Gaussian Track Density
  - Vertex finding: AMVF
  - Vertex fitting: Kalman Filter updater
- The steps are looped until all (valid) tracks are assigned to a vertex



- Reference for this section:
  - ATLAS Collaboration (2019). Development of ATLAS Primary Vertex Reconstruction for LHC Run 3 [White paper]. CERN.

Vertex seeder

- The seeding step establishes first estimates for primary vertices positions



- Most of the vertex seeders project tracks to origin and evaluate density distribution
  - The peaks of the distribution will be the seeds for vertices
-

Gaussian Track Density

- The density of track origin can be represented by a multi-variate Gaussian distribution:

$$P(r,z) = \frac{1}{2\pi\sqrt{|\Sigma|}} e^{-\frac{1}{2}((r-d_0),(z-z_0))^T \Sigma^{-1} ((r-d_0),(z-z_0))}.$$

$$\Sigma = \begin{pmatrix} \sigma^2(d_0) & \sigma(d_0, z_0) \\ \sigma(d_0, z_0) & \sigma^2(z_0) \end{pmatrix}.$$

- If we project it to the z-axis, we have the density at that axis. Furthermore, If we consider the distribution to be locally Gaussian, it's possible to do a peak search with steps of size:

$$W(z) = \sum_{i \in \text{tracks}} P_i(0, z).$$

$$\Delta z = \frac{W(z)W'(z)}{W'^2(z) - W''(z)W(z)}.$$

- The output will be the position of the peak and the width of the distribution around it

$$z_{max} = \max_z W(z)$$

$$\sigma(z) = \sqrt{-\frac{W(z_{\max})}{W''(z_{\max})}}$$

Adaptive Multi Vertex Finding (AMVF)

- Given a collection of reconstructed tracks and estimates of vertexes, establishes a “compatibility” value for each track-vertex
- The algorithm is adaptive in a sense that vertexes compete for the same track (multiple vertex-tracks weights)
- Iterate over association weights until convergence
- Short paper explaining

Fitting procedure

- Fit all vertexes using the assignment probability as track weights
- Recompute the assignment probabilities using the most recent vertex positions

Weight function

- Having n tracks to be fitted to m vertexes

The weight of vertex j to track i is:

$$w_{ij} = \frac{\exp(-\chi^2_{ij}/2\,T)}{\exp(-\chi^2_{\text{cut}}/2\,T) + \sum_{k=1}^{m} \exp(-\chi^2_{ik}/2\,T)}$$

T is a temperature parameter
X^2cut is a cut-off to suppress not assigned tracks
X^2ij is the chi2 distance between track and vertex

Kalman Filter Updater

- From the collection of tracks assigned to a vertex originated from the previous step, a Kalman Filter is used to fit the vertex position
- The position of the first deposition (measurement) is used to evaluate the vertex position and momentum of the track (vector state)
- The measurement equation would be:

$$q_i = h_i(v, p_i), \ i = 1 \dots, n.$$

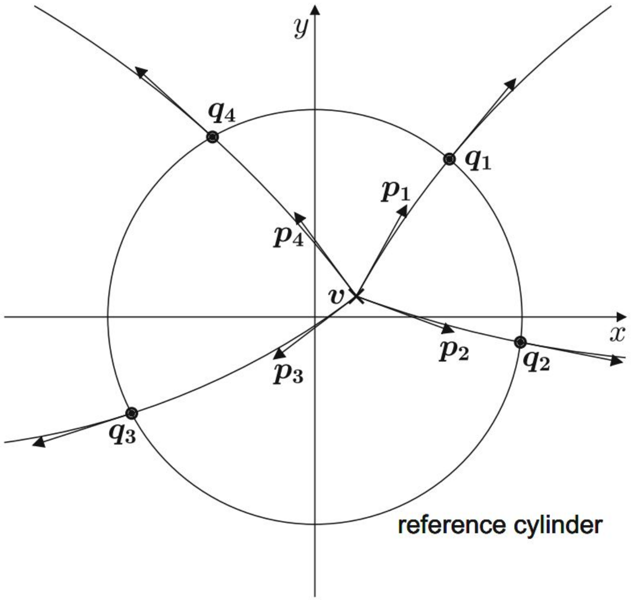


Fig. 8.1 A vertex fit with four tracks. The parameters of the fit are the vertex $\boldsymbol{v}$ and the momentum vectors $\boldsymbol{p}_i$; the observations are the estimated track parameters $\boldsymbol{q}_i$

Kalman Filter updater equations

- The measurement equation is linearized so the Kalman Filter can be used
- Check on the book for detailed explanation
- The AMVF weights multiply the inverse of the covariance matrix as to imitate a “significance” of the measurement

$$\boldsymbol{v}_i = \boldsymbol{C}_i \left[\boldsymbol{C}_{i-1}^{-1} \boldsymbol{v}_{i-1} + \boldsymbol{A}_i^{\mathsf{T}} \boldsymbol{G}_i^{\mathrm{B}} (\boldsymbol{q}_i - \boldsymbol{c}_i) \right],$$

$$\boldsymbol{p}_i = \boldsymbol{W}_i \boldsymbol{B}_i^{\mathsf{T}} \boldsymbol{G}_i (\boldsymbol{q}_i - \boldsymbol{c}_i - \boldsymbol{A}_i \boldsymbol{v}_i),$$

update equation for both vertex position and particle momentum

$$\mathrm{Var}[\boldsymbol{v}_i] = \boldsymbol{C}_i = \left(\boldsymbol{C}_{i-1}^{-1} + \boldsymbol{A}_i^{\mathsf{T}} \boldsymbol{G}_i^{\mathrm{B}} \boldsymbol{A}_i \right)^{-1},$$

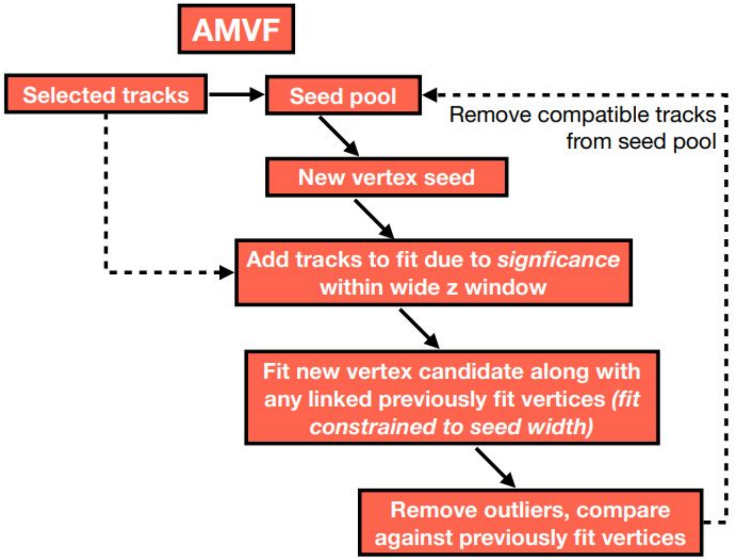
$$\mathrm{Var}[\boldsymbol{p}_i] = \boldsymbol{W}_i + \boldsymbol{W}_i \boldsymbol{B}_i^{\mathsf{T}} \boldsymbol{G}_i \boldsymbol{A}_i \boldsymbol{C}_i \boldsymbol{A}_i^{\mathsf{T}} \boldsymbol{G}_i \boldsymbol{B}_i \boldsymbol{W}_i,$$

$$\mathrm{Cov}[\boldsymbol{v}_i, \boldsymbol{p}_i] = -\boldsymbol{C}_i \boldsymbol{A}_i^{\mathsf{T}} \boldsymbol{G}_i \boldsymbol{B}_i \boldsymbol{W}_i.$$

update equation for both vertex position and particle momentum

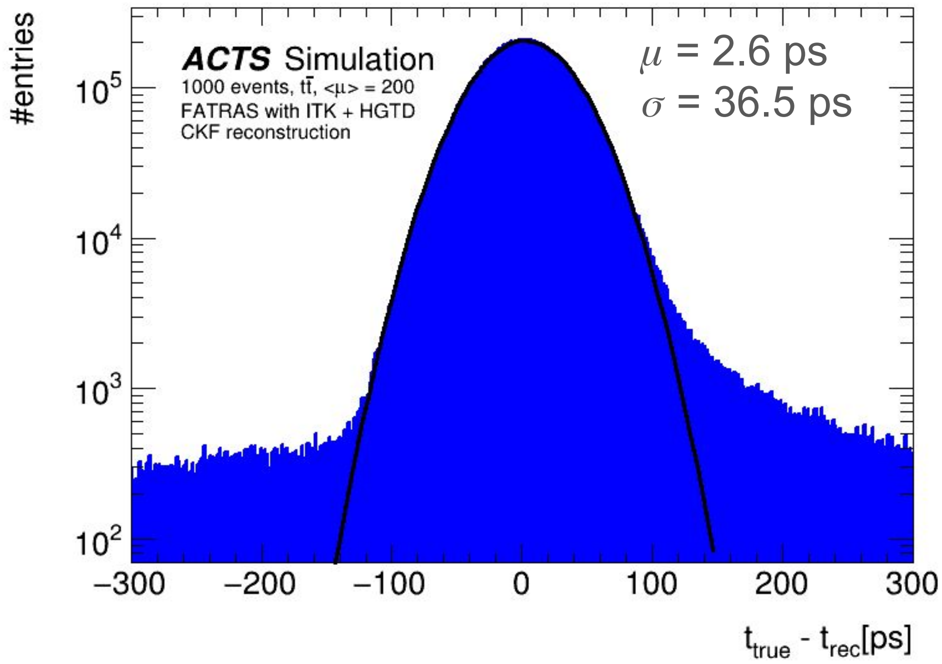
AMVF overview (again)

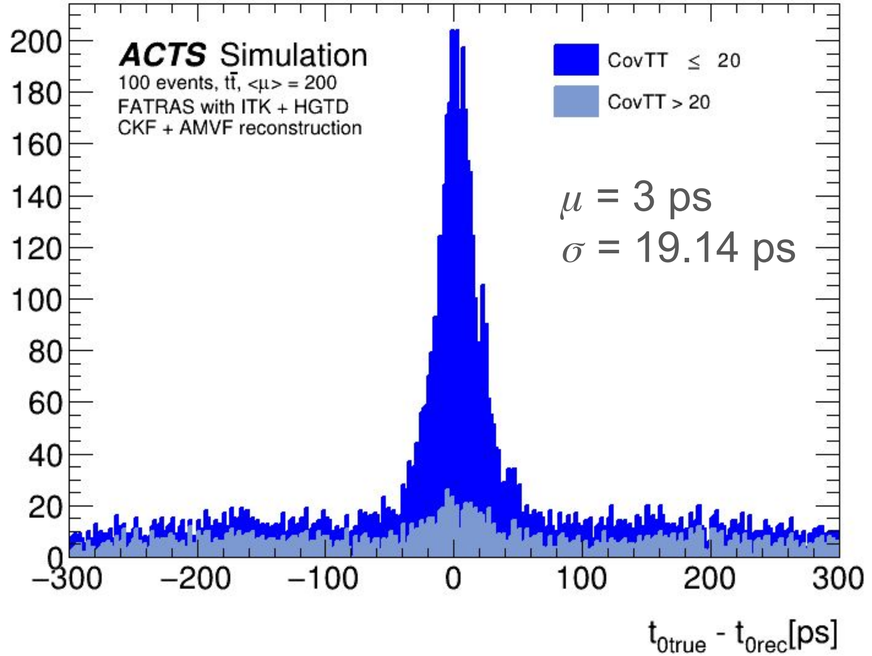
- The process can be divided into three steps:
  - Vertex seeding: Gaussian Track Density
  - Vertex finding: AMVF
  - Vertex fitting: Kalman Filter updater
- The steps are looped until all (valid) tracks are assigned to a vertex



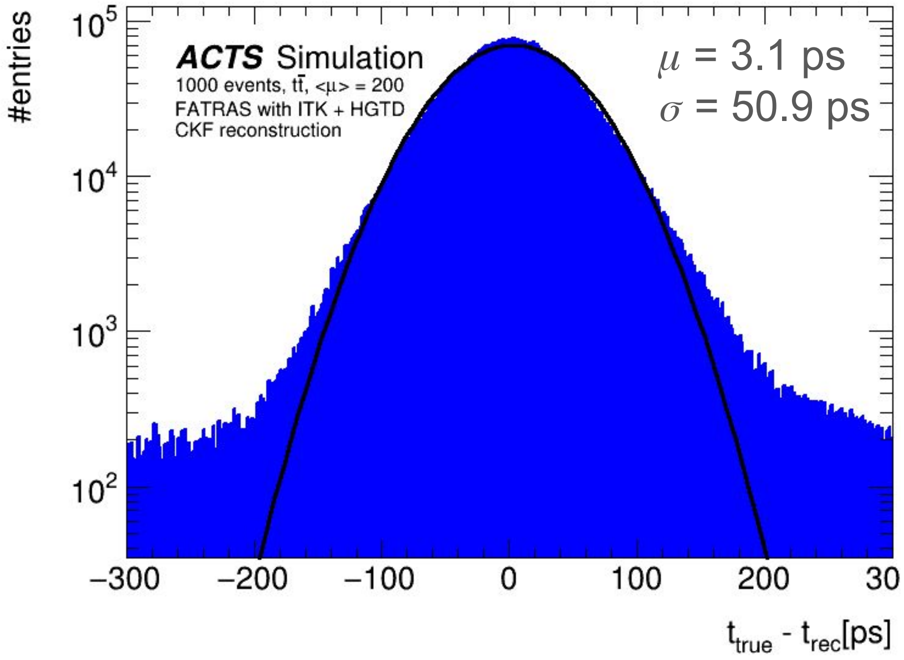
Evaluating impact of sensor degradation

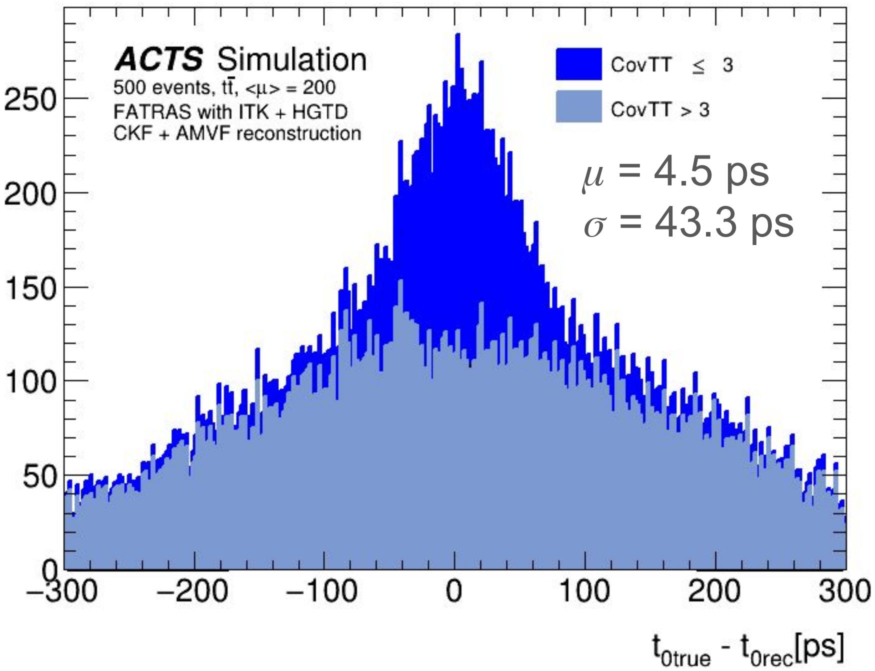
Reconstruction performance at 0 fb^{-1}



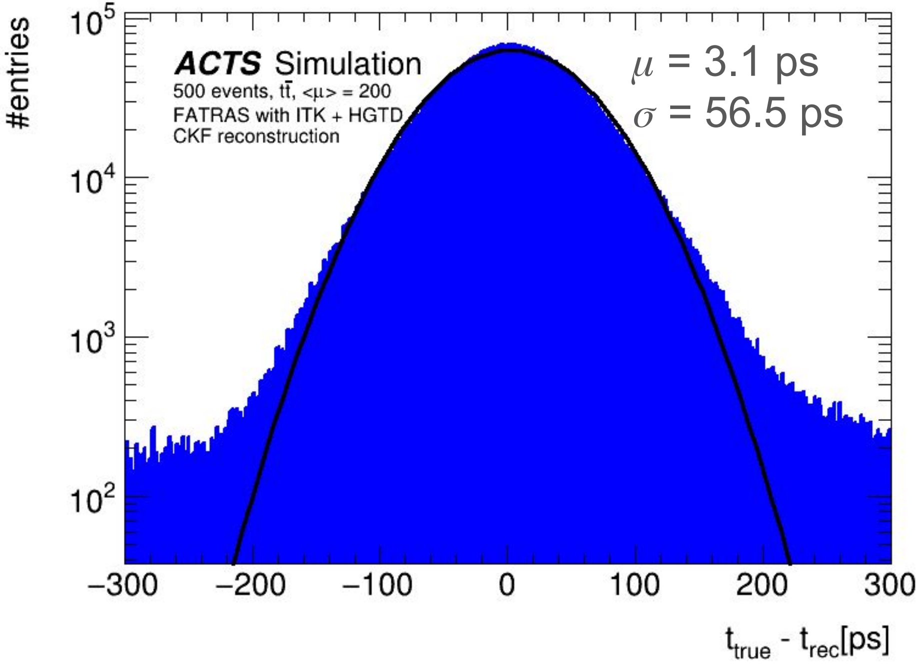


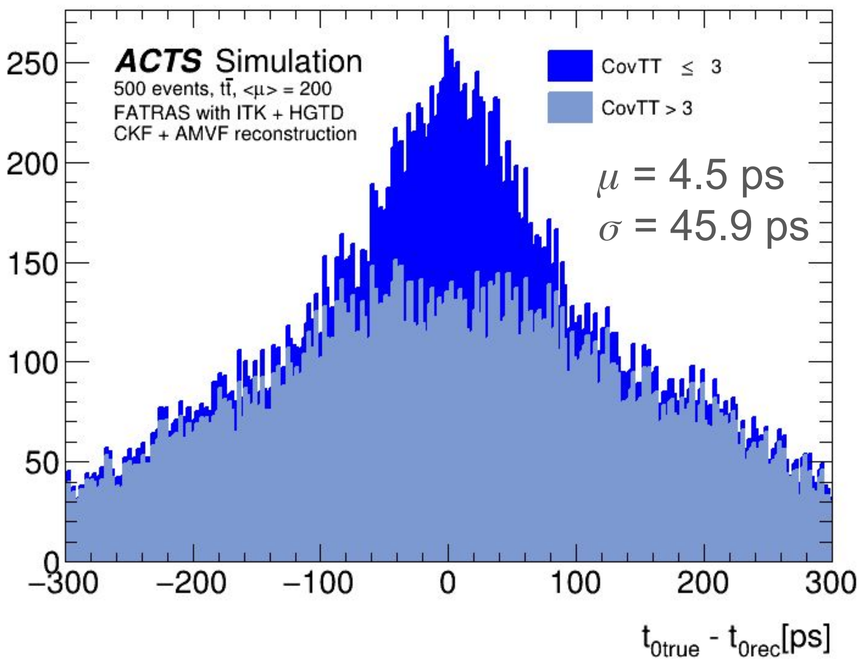
Reconstruction performance at 1000 fb^{-1}





Reconstruction performance at 4000 fb^{-1}



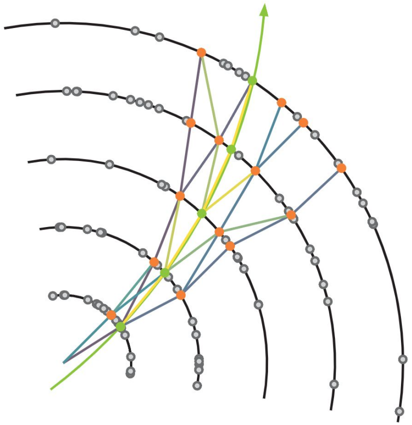


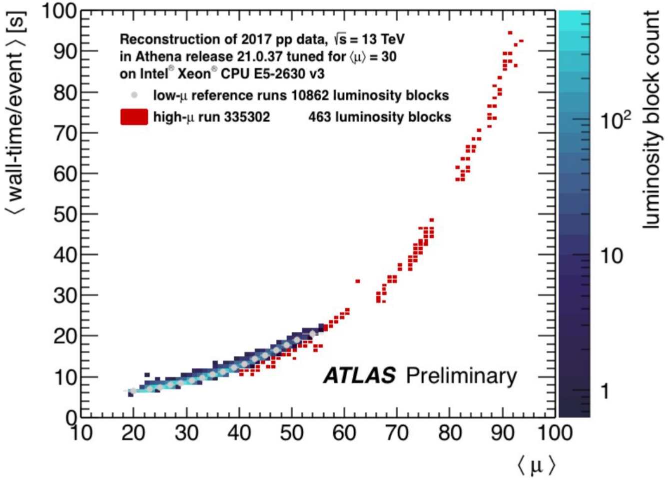
Outlook

- We managed to include HGTD time information in the CKF track reconstruction
  - Still need to evaluate (and improve) track efficiency (second part of AQP)
- This reconstruction chain can be used to assert sensor performance in different phases of its lifetime
  - Need to get more accurate degradation info with sensor group

Tracking challenges on HL-LHC

- Today's track reconstruction (*tracking*) process will not be fast enough to operate in a high luminosity scenario
- For Run 3, ATLAS utilizes Combinatorial Kalman Filter (CKF) for tracking
  - $O(N^2)$ processing time, N being the number of vertices (depositions)

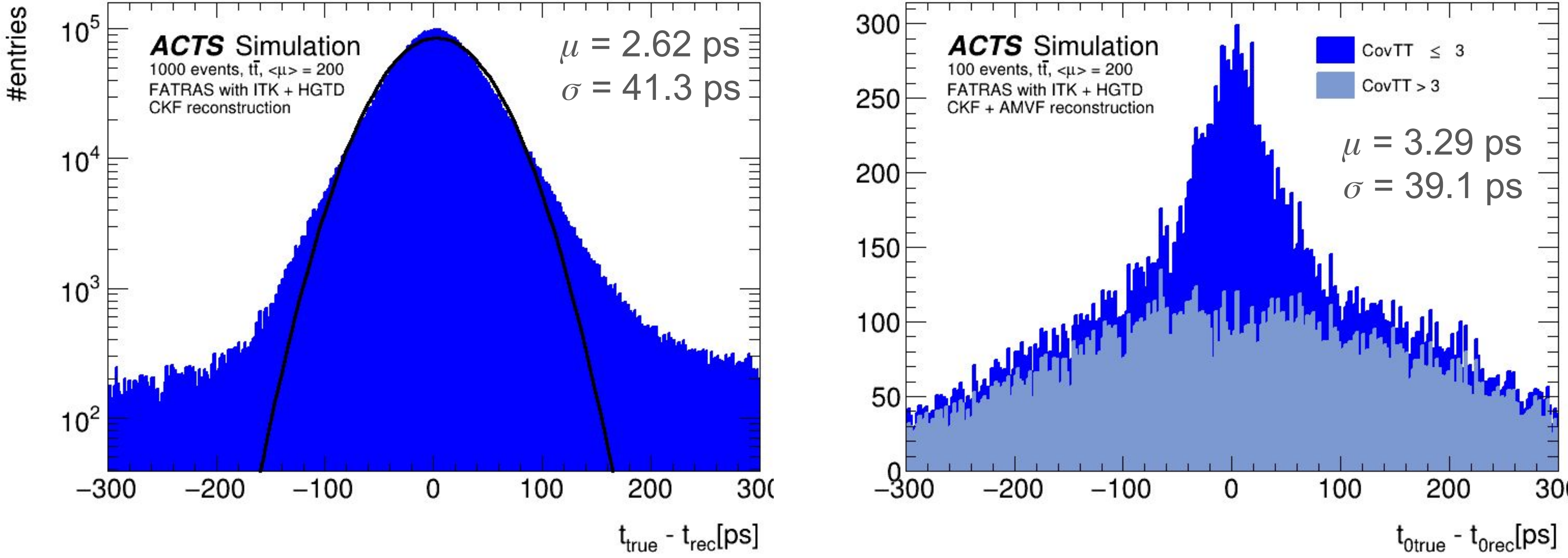




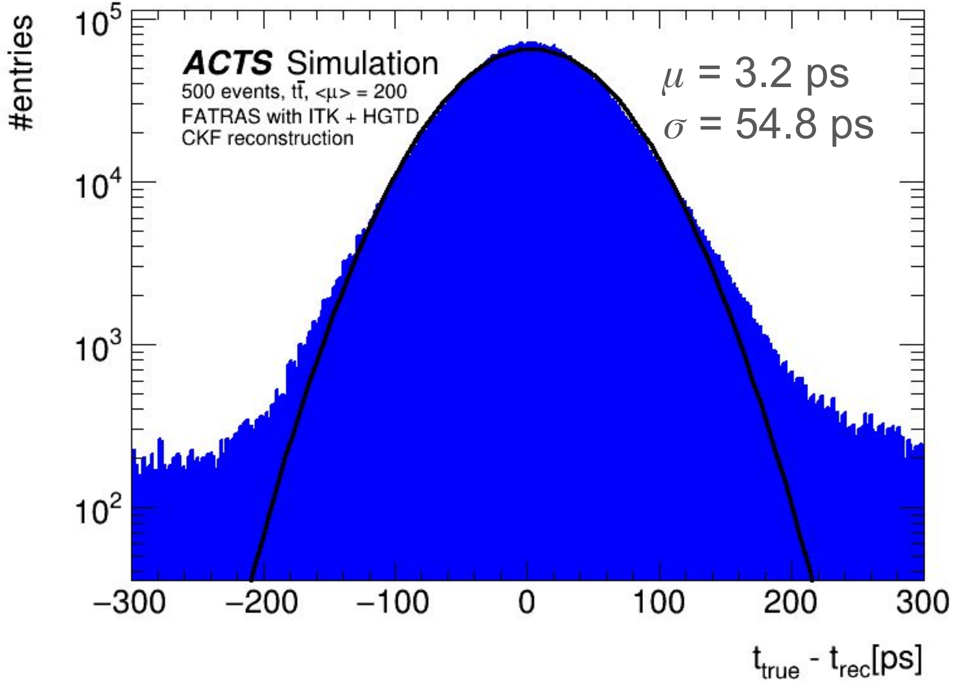
Créditos da imagem: [3][7]

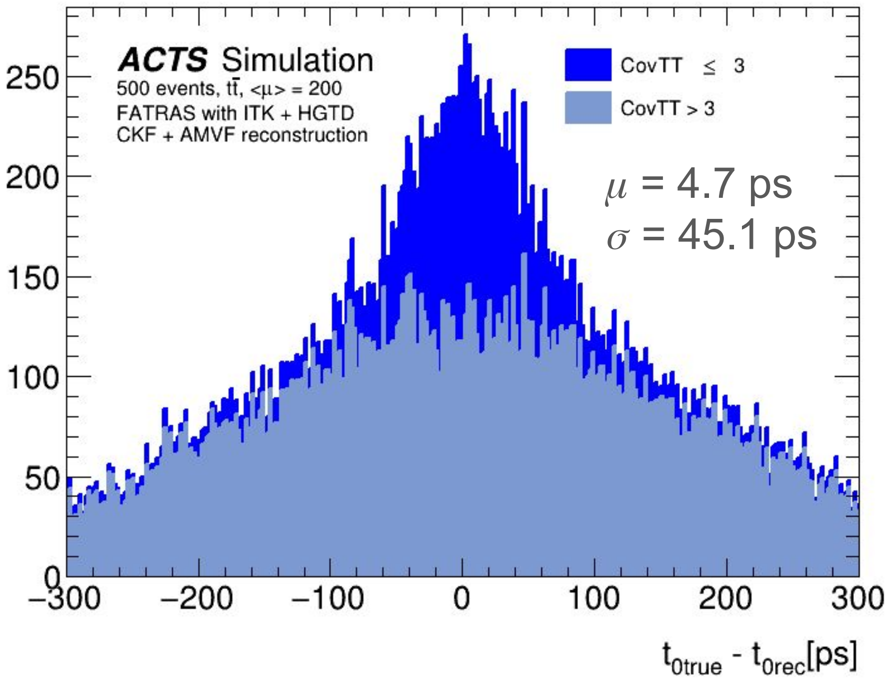
Additional plots on sensor degradation

Reconstruction performance at 1001 fb^{-1}



Reconstruction performance at 2000 fb^{-1}





Reconstruction performance at 2001 fb^{-1}