Investigating the impact of 4D Tracking in ATLAS Beyond Run 4

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“Hiroshima” Symposium - Vancouver 2023
The Pile-Up Challenge

without time
The Pile-Up Challenge

without time

with time

ATLAS Simulation Preliminary

\( \sqrt{s} = 14 \text{ TeV}, t \tilde{f}, (\mu) = 200 \)
The Pile-Up Challenge

ATLAS Simulation Preliminary
\( \sqrt{s} = 14 \text{ TeV}, t, (\mu) = 200 \)

without time

with time

zoom in space
The Pile-Up Challenge

ATLAS Simulation Preliminary
\( \sqrt{s} = 14 \text{ TeV}, \, (p_T, \mu) = 200 \)

without time

zoom in space

with time

zoom in time

ATLAS Simulation Preliminary
\( \sqrt{s} = 14 \text{ TeV}, \, (p_T, \mu) = 200 \)

\(|t - t_{\text{ref}}| < 30 \text{ ps}\)
Motivations

Event display from **truth MC** $t\bar{t}$

PU: $\langle \mu \rangle = 200$
Motivations

Event display from **truth** MC $t\bar{t}$

PU: $\langle \mu \rangle = 200$
Motivations

Two innermost pixel layers [link] need to be replaced due to hard radiation after 2000 $fb^{-1}$ of data.

HGTD coverage: $2.4 < \eta < 4$
Resolution up to: $t_{\text{trk}} \sim 30\text{ps}$

Can we extend timing coverage to the barrel?

Can we determine precisely vertex $t_{\text{vtx}}$ on all events?
Motivations

HGTD:

PU removal in forward region

Timing in the barrel:

performance / physics improvements…
Determination of $t_{HS}$

reco vertex time is computed as:

$$t_{all}^{reco} = \sum_{trk} t_{trk} w_{trk}$$

$$t_{HS}^{reco} = \sum_{trk \in HS} t_{trk} w_{trk}$$

$$t_{clus}^{reco} = \sum_{trk \in clus} t_{trk} w_{trk}$$

Clustering is implemented with DBSCAN
Vertex time resolution

Inclusive resolution for 30ps smearing and three cases

The $t_{HS}$ resolution (std. dev.) can be improved up to the ideal one where only the HS tracks are considered

$28\text{ps} \rightarrow 7.2\text{ps} \ (\sim 4x)$

5.6ps ideal case where no PU is considered
Vertex PU contamination

New PU discriminating variable (per vtx):

\[ \text{PU fraction} = \frac{\#trk_{PU}}{\#trk} \]

Different track time resolutions are considered

Degrating the resolution the improvement on the \( t_{HS} \) resolution decreases

The improvement comes at larger PU fraction
Flavour Tagging: identification of the flavour of the parton originating the jet

Impact parameters are the most discriminant variables in FTAG

PU, primarily prompt with a low transverse impact parameter ($d_0$), significantly impacts the longitudinal dimension ($z_0$)
Graph Neural Networks for FTAG

GNT = GN1 + time significance

Time significance to discriminate between PU and HS:

\[ s(t) = \frac{|t_{trk} - t_{HS}|}{\sigma_t} \]
Performances: ROC

**ATLAS Simulation Preliminary**

\( \sqrt{s} = 14 \text{ TeV}, \langle \mu \rangle = 200 \)

\( t\bar{t}, 20 < p_T < 250 \text{ GeV} \)

- **GN1**
- **GNT 30ps**
- **GNT ideal**

**GN1** is the standard FTAG network

**GNT 30ps** is GN1+timing and 30ps smearing

**GNT ideal** is GN1+timing and no smearing

Up to a factor of 3 improvement in l-jet rejection with 30ps smearing on already great performances of GN1
Performances: \(1\)-jet mistag rate

**New PU discriminating variable (per jet):**

\[
\text{PU fraction} = \frac{\#\text{trk}_{PU}}{\#\text{trk}}
\]

Large improvement in highly PU contaminated jets

\(1\)-jets mistag rate gets flattened with time information
Impact of smearings

The improvement decreases with increasing the track time smearing

But an improvement remains also with lower resolution
b-tagging has a huge impact on di-higgs since one of the two H is required to decay to a couple of b quarks (BR~60%)  

\[ HH \rightarrow bbbb \] in the plot

Improving the b-tagging efficiency at fixed l-jet rejection will impact the significance of the analysis and the possibility to see the trilinier coupling during HL-LHC

This is potentially applyable to partial HL-LHC statistics
4D tracking can also improve the sensitivity to LLP:

- LLP with small $c\tau$

- displayed photons (in this note)

time resolution of delayed photons is $190\text{ps}$ due to the lack of knowledge about $t_{HS}$

$$\Delta t = t_0 + \text{Reconstructed } t_{\text{IP\rightarrow ECal}} - t_{\text{IP\rightarrow ECal}} - \text{Reconstructed } t_0$$

180ps 100ps 4D improves!
Conclusion

This study is the first study of potential impact of hermetic timing coverage in the tracker of ATLAS.

The work suggests that 4D tracking can potentially improve performances and physics cases.

These results motivate in-depth studies with more realistic detector assumptions and more sophisticated algorithms.
Backup
Track **time** is retrieved from **truth level** information

Different **smearings** (gaussian) are considered: 30, 60, 90ps

A relevant quantity is the **relative time** to the HS
New PU discriminating variable (per vtx):

\[ \text{PU fraction} = \frac{\#trk_{PU}}{\#trk} \]

Different track time resolutions are considered

Degrading the resolution the improvement on the \( t_{HS} \) resolution decreases

The improvement comes at larger PU fraction
Average spatial and temporal PU density

In both cases the distribution gets flattened

Lorenzo Santi

“Hiroshima” Symposium
FTAG studies: GNN

<table>
<thead>
<tr>
<th>Track</th>
<th>GN1 ITk</th>
<th>GNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_0$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$z_0 \sin \Theta$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$\sigma(\Theta)$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$q(\text{over} P)$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$\sigma(q(\text{over} P))$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$\phi$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$\sigma(\phi)$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>signed $d_0$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>signed $z_0$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$\Delta \eta(\text{trk, jet})$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$\Delta \phi(\text{trk, jet})$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$n \text{ pix hits}$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$n \text{ pix hits (11)}$</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$(t - t_{HS})/\sigma(t)$</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

GNT = GN1 + time

ideal → no smearing

Time significance to discriminate between PU and HS:

$$s(t) = \frac{|t_{trk} - t_{HS}|}{\sigma_t}$$
Track classification

The largest impact on the track classification happens on PU track as expected.

Tracks from HF are inclusively unchanged.
A complete simulation is needed for an accurate study.

We investigated independently the impact of **missing hits** and **mistag hits** showing that the performances get degraded mostly at low b-jet efficiencies.

**missing hit**: assuming time only in 2nd layer; if a track has no hit the significance of the track is randomly emulated as HS.

**mistag hit**: for tracks with Truth Match Probability < 80% the significance is randomly emulated as PU.
Impact on HH

caveat:
- possible only on partial HL-LHC stat

5% improvement in b-tagging eff. can lead to a $0.3\sigma$ improvement