ATLAS EXPERIMENT

THE UNIVERSITY of EDINBURGH
School of Physics and Astronomy

ATLAS simulation at the (HL-)LHC

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CEPC Workshop, 5 July 2023

Three lessons for detector simulation

. . . for future colliders, based on my ATLAS experience:

1) The detector will be heavier than simulation predicts.

2) Use high-level physics metrics to guide detector design.

3) Harness machine learning in simulation.

(HL-)LHC timeline

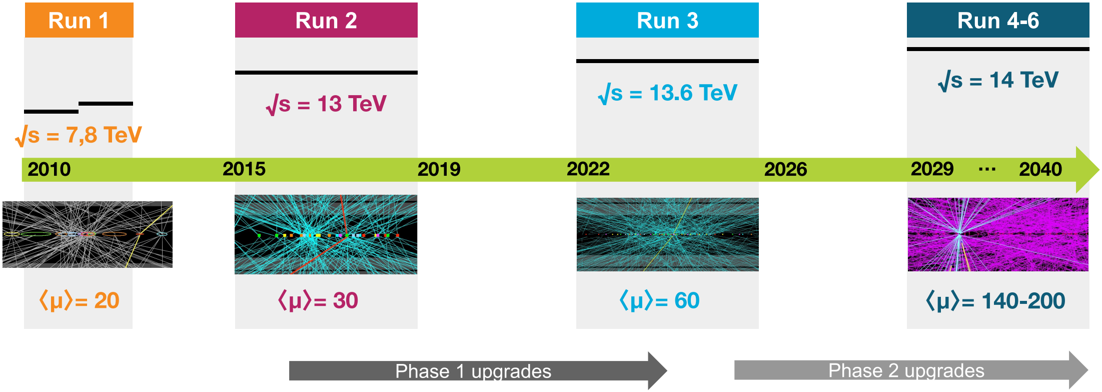
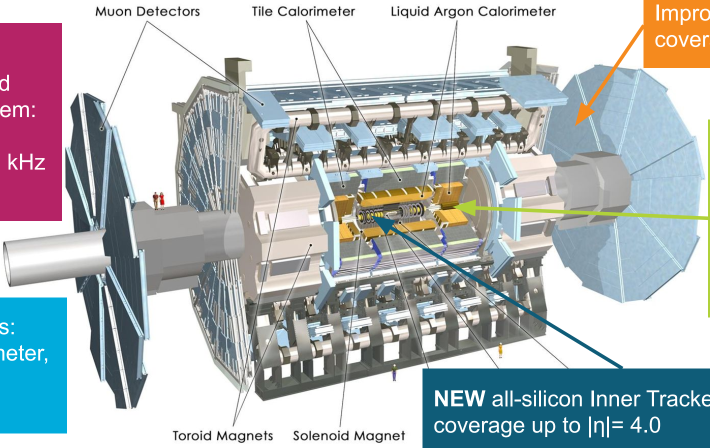


Image credit: L. Brost's talk @ Higgs2022

ATLAS Phase-II upgrade

Upgraded Trigger and Data Acquisition system:
- L0 rate: 1 MHz
- Event Filter: 10 kHz

Upgraded electronics: Liquid Argon Calorimeter, Tile Calorimeter, Muon system



Improved muon coverage and trigger

NEW endcap high - granularity timing detector

NEW all-silicon Inner Tracker, coverage up to $|\eta| = 4.0$

Annotation credits: L. Brost's talk @ Higgs2022

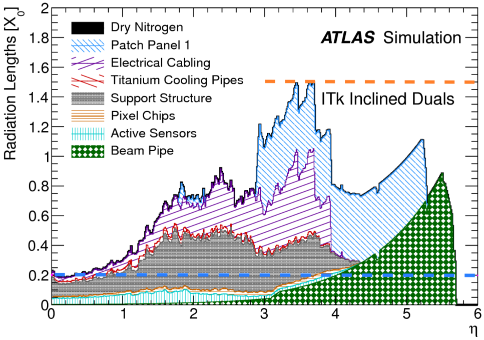
1) The detector will be heavier

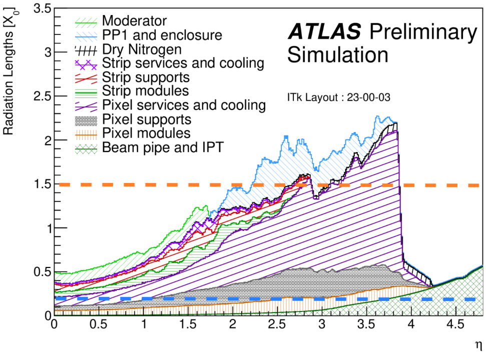
Inner Tracker (ITk) material evolution

Radiation length X_0: parameterises energy of electrons:

$$E = E_0 e^{-x/X_0}$$

ITk Technical Design Report, 2017 | **Revised material budget, 2021**

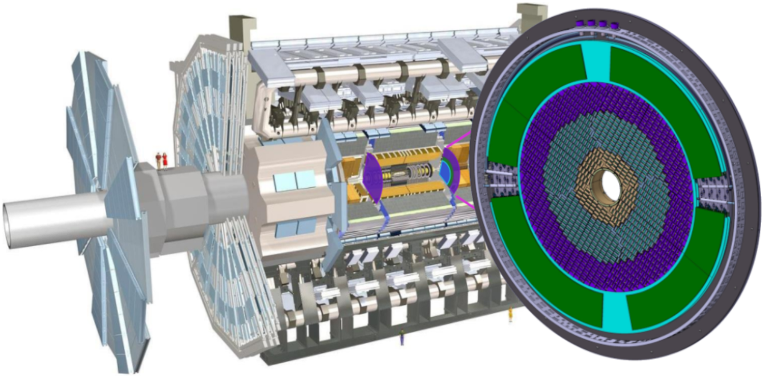




Factor of ~ 2 increase in material since TDR!

High Granularity Timing Detector

Example adverse effect of underestimated tracker material:



- z $\pm$ 3.5 m,
  $2.4 < |\eta| < 4.0$,
  just after the ITk.
- LGAD sensors.
- $\Delta t \sim 30$ ps,
  reject pile-up!
- But: Δt sensitive to radiation damage.

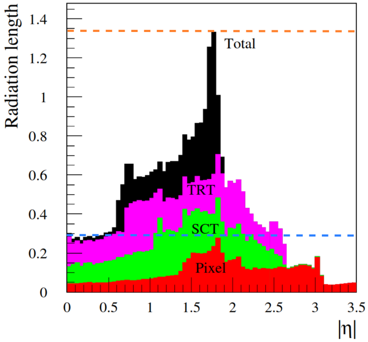
Extra material⇒3-ring design: 12-23 cm ($1000\ \mathrm{fb}^{-1}$), 23-47 cm ($2000\ \mathrm{fb}^{-1}$), 47-64 cm.

Image: High Granularity Timing Detector technical design report.

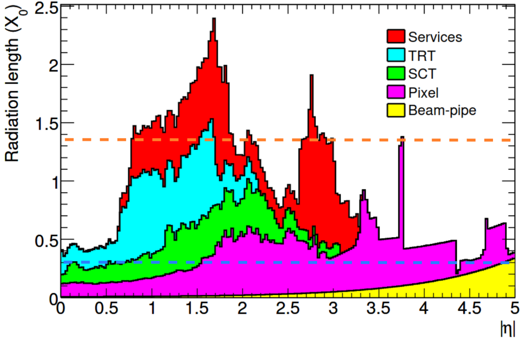
Why is ITk material underestimate relevant beyond ITk?

1) (Most of) missing ITk material was not due to simple bugs/omissions.
2) Legacy (Run1-Run3) ATLAS inner tracker material evolution (figures).

Tracker Technical Design Report, 1997



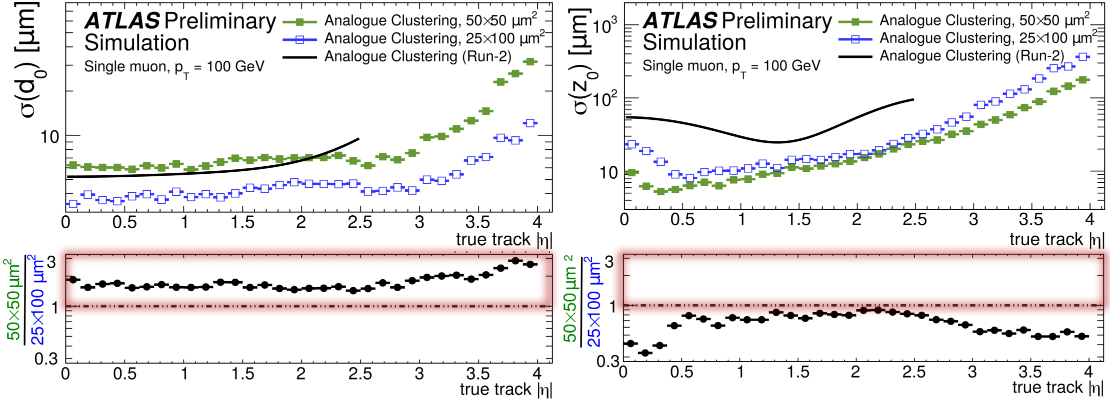
Revised material budget, 2008



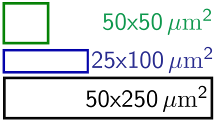
2) Use high-level physics metrics

Inner Tracker Pixel Pitch

Why is 25x100 μm^2 better than 50x50 μm^2?



Current detector: 50x250 μm^2



Source: Studies led by LM

Inner Tracker Pixel Pitch

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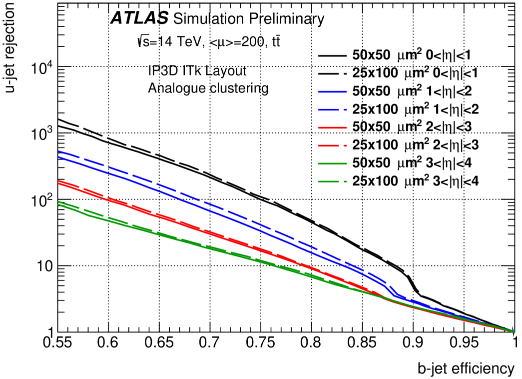

Flavor tagging notably improved with 25x100 μm^2.

Source: Studies led by LM

Inner Tracker Pixel Pitch

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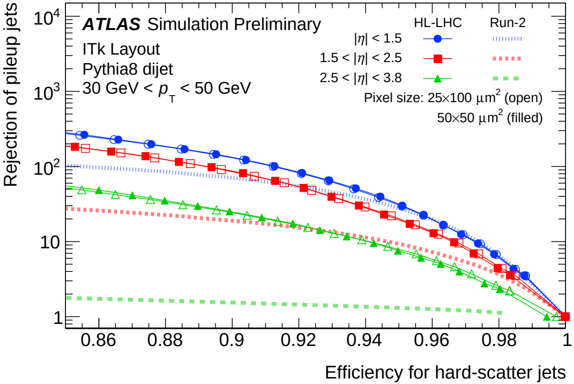


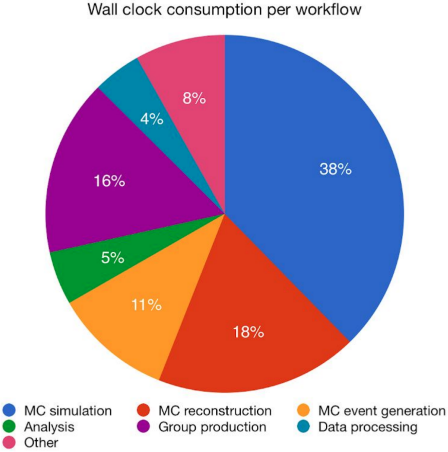
Pile-up rejection not notably degraded with 25x100 μm^2 (and flavour tagging notably improved) $\Rightarrow$ prefer 25x100 μm^2 .

Source: Studies led by LM

3) Harness machine learning in simulation.

ATLAS Detector Simulation: CPU

ATLAS CPU consumption, 2018

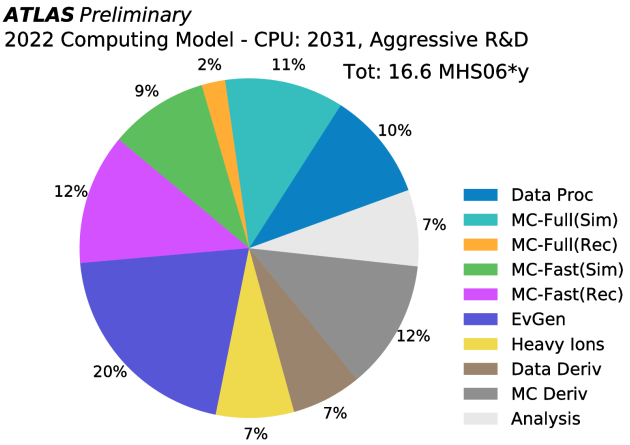


- **Detector simulation** is time consuming.
- When **evaluating the detector performance** (new layout idea, adding forgotten material etc.), the **simulation is a CPU bottle-neck**.
- Esp. when using high level physics metrics.

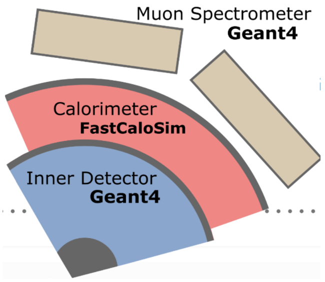
Source: CERN-LHCC-2020-015

ATLAS Detector Simulation, HL-LHC

ATLAS CPU consumption, HL-LHC



- **Fast simulation: resolve the bottle-neck.**
- **90%** of ATLAS simulation time is spent in the calorimeter.

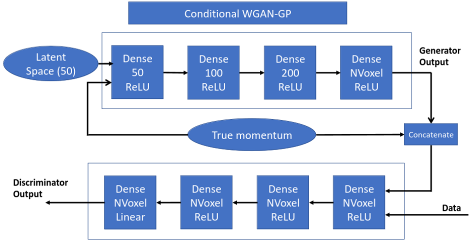


Sources: CERN-LHCC-2022-005 & H. Ahmed's talk

Machine Learning for Simulation

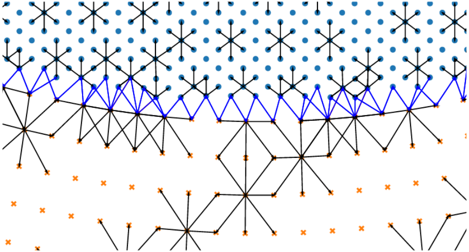
ATLAS

- **Run3 calorimeter simulation:** a blend incl. ML, for large fraction of samples.
- ML Algorithm: Generative Adversarial Network (**GAN**)



CMS

- **Phase II HGCal Calorimeter simulation**: ML prototype.
- HGCal: **H**igh **G**ranularity **Cal**orimeter; 1cm^2 cells, 6M channels.
- Generative graph neural net (**GNN**).



Sources: arXiv:2109.02551 & CMS LPCC WS talk

Summary

Lessons from ATLAS simulation, I'll keep in mind in work on future colliders:

1) **The detector will be heavier than simulation predicts**
   because of complex design. Extra material affects upstream components.

2) **Use high-level physics metrics to guide detector design,**
   because no gain in physics performance may allow for a safer hardware choice (and vice-versa).

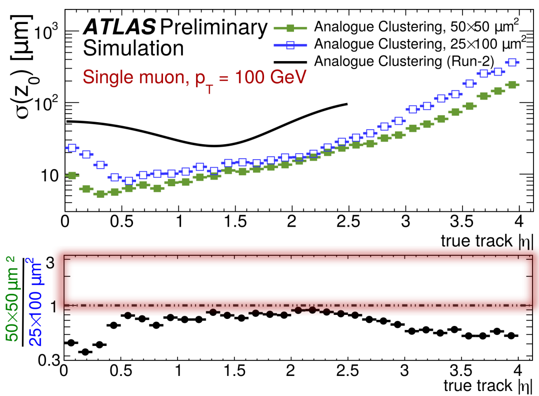
3) **Harness machine learning in simulation,**
   because simulation is likely to be a bottleneck when evaluating your detector design, and ML can provide a fast, high-fidelity solution.

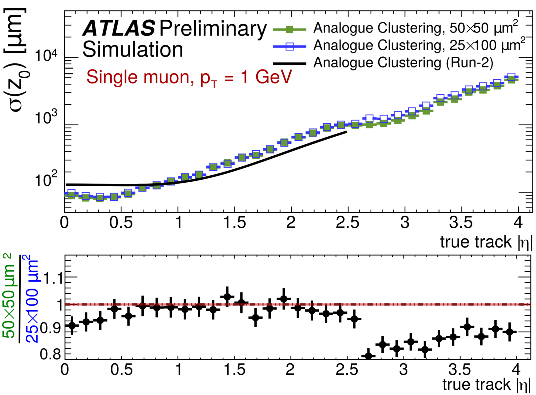
Working on ATLAS simulation has been challenging and fun, best of luck with simulation for CEPC!

Extra

ITk: pixel pitch

50x50μm^2 vs 25x100μm^2: why is pile-up rejection comparable?

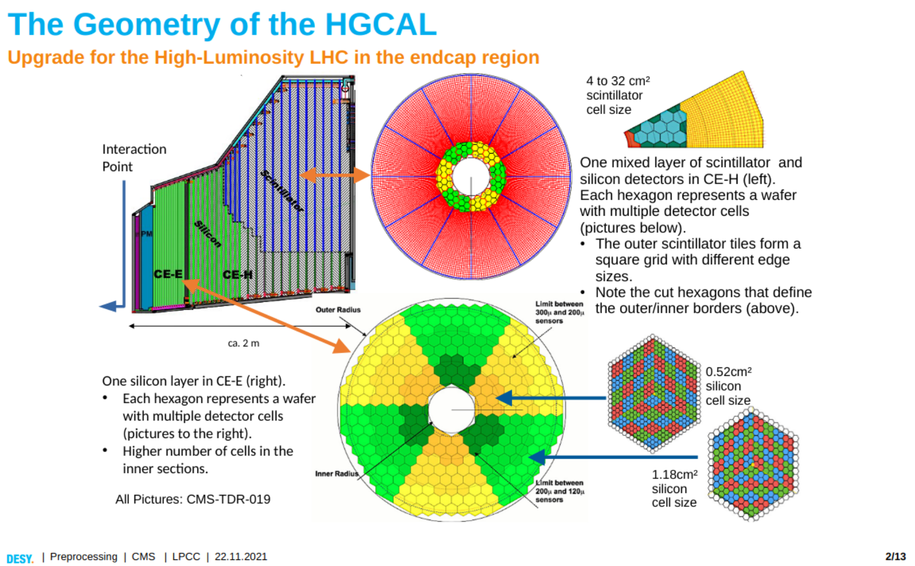




A: Rejection relies on low-pt tracks, where material interactions rather than pitch dominate the tracker resolution (right figure).

Source: cds:2669540

CMS HGCAL



Source: CMS LPCC WS talk