A High-Granularity Timing Detector for the ATLAS phase-II upgrade: *Performance at the HL-LHC*

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on behalf of the ATLAS Liquid Argon Calorimeter Group

Chronometry

~~Calorimetry~~ for the
High Energy Frontier

Lyon, France

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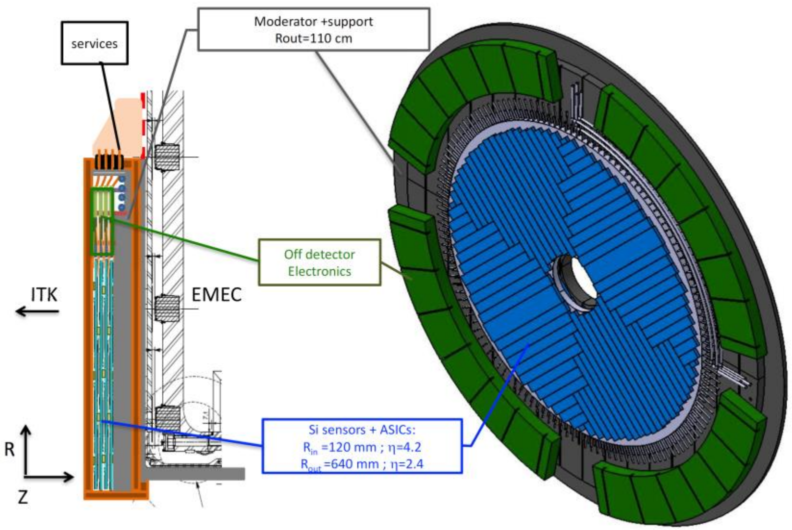
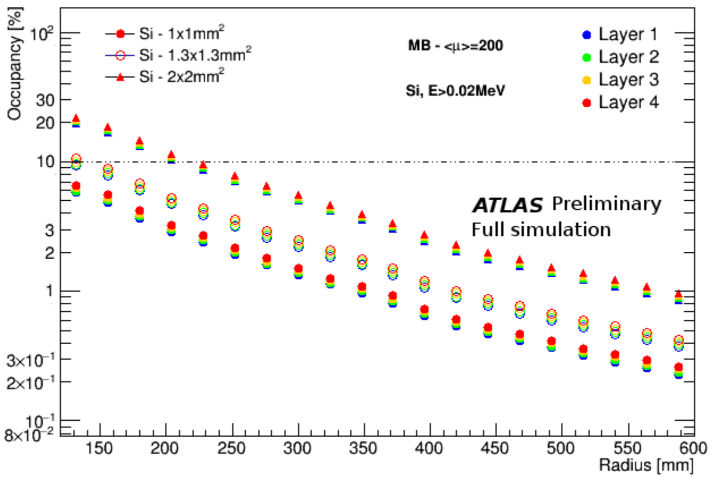
Introduction

- **HL-LHC**: $\sqrt{s}$=14 TeV and $L_{peak}=7.5\times10^{34}cm^{-2}s^{-1}$
  - Foreseen start: end 2026



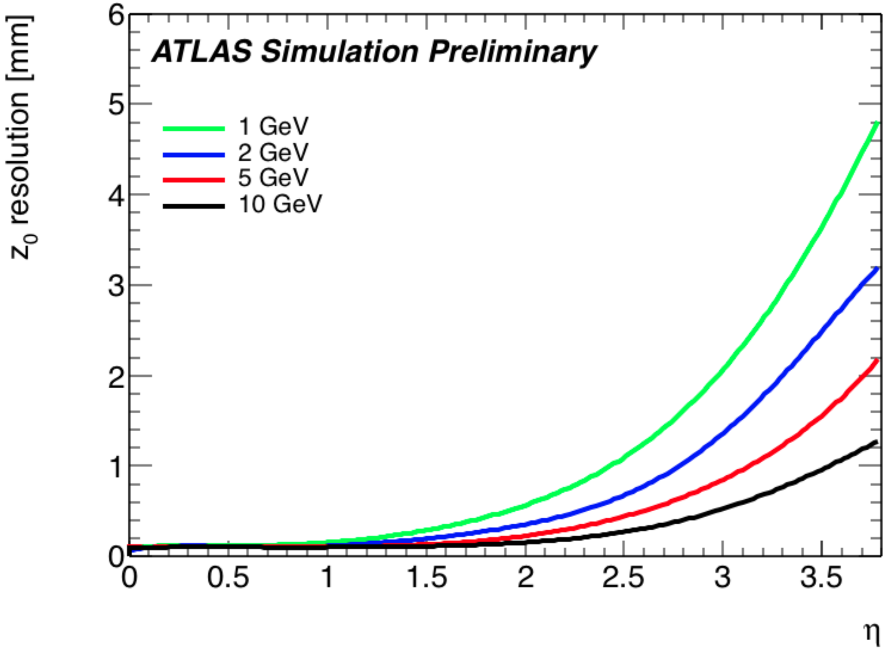
- **Main challenge: pile-up!**
  - About 200 collisions per bunch crossing
    - σ_t=180ps and σ_z =50 mm
  - Overlapping vertices
  - Energy/mass measurement deterioration
  - Additional fake pileup jets

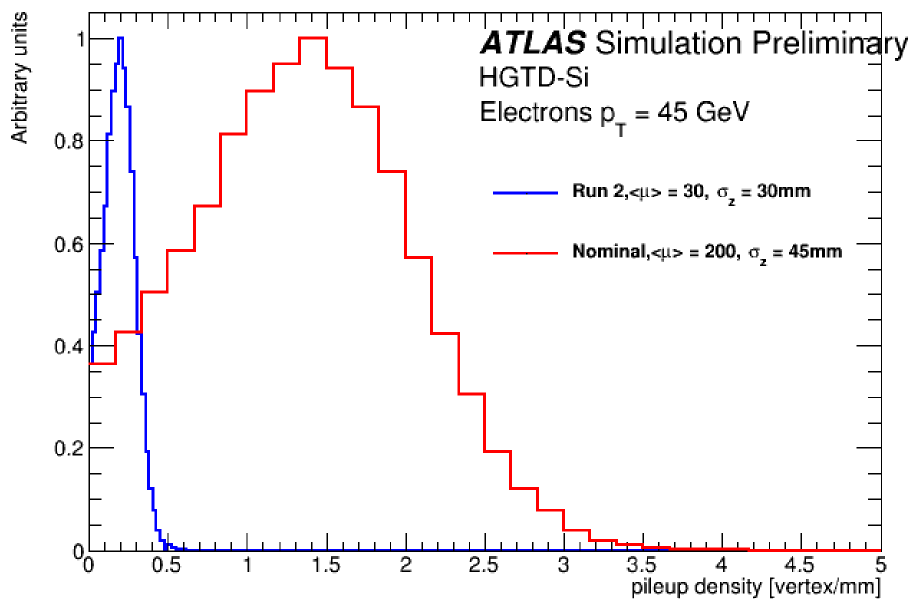
- Main handle against pileup is the **tracker** that will be extended up to **$|\eta|$ = 4.0** but timing information can help to further reduce pile-up effect
  - orthogonal to spatial information
  - a detector with O(10)ps timing resolution could meaningfully distinguish between interactions



⇒ **High-Granularity Timing Detector**
- Between tracker and EM calorimeter (2.4<$|\eta|$<4.2)
- 4 Si (LGAD) layers with 1.3x1.3 mm^2 sensor size
- **Goal: achieve 30 ps time resolution per m.i.p**

The pile-up challenge



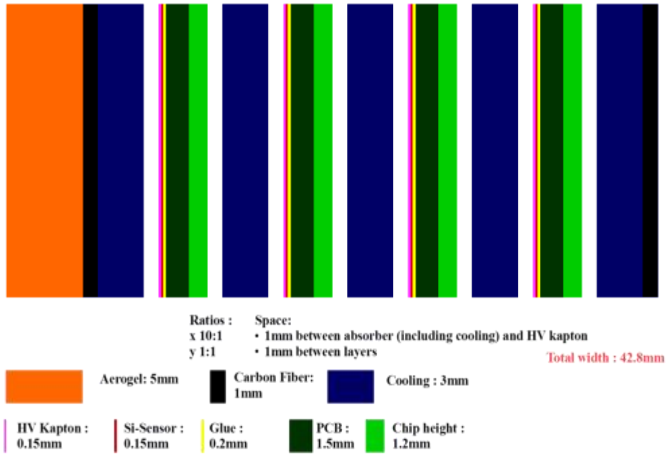


- In the forward region, the pile-up density is higher than the spatial z Resolution

  ⇒ Merging of primary vertices and overlapping pile-up tracks to the hard-scatter vertex

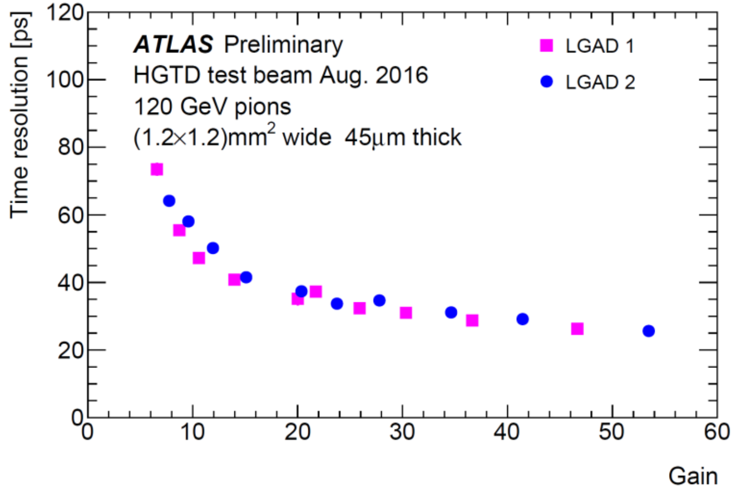
Simulation

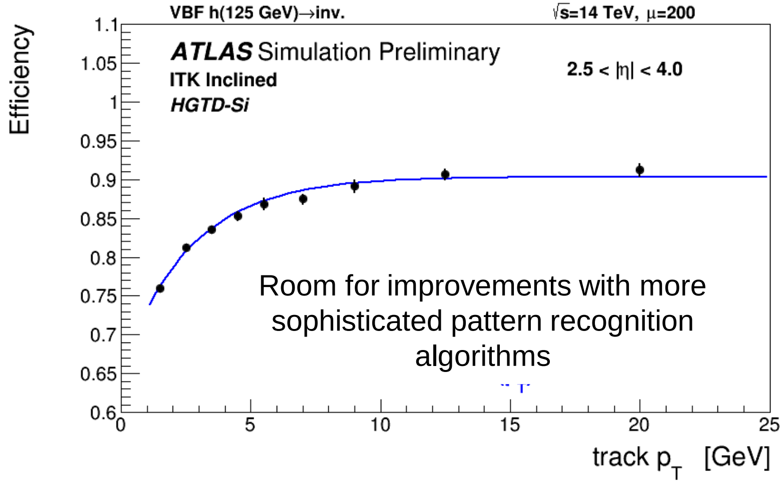
- **Full simulation based on Geant4:**
  - Geometry slightly different than the current detector baseline
    - Should have litte impact on the performance
    - Will be updated when project approved
  - Sensor size: 1x1mm^2 instead of 1.3x1.3 mm^2
  - Signal shape and noise taken from test beam
  - σ_t=32ps/cell



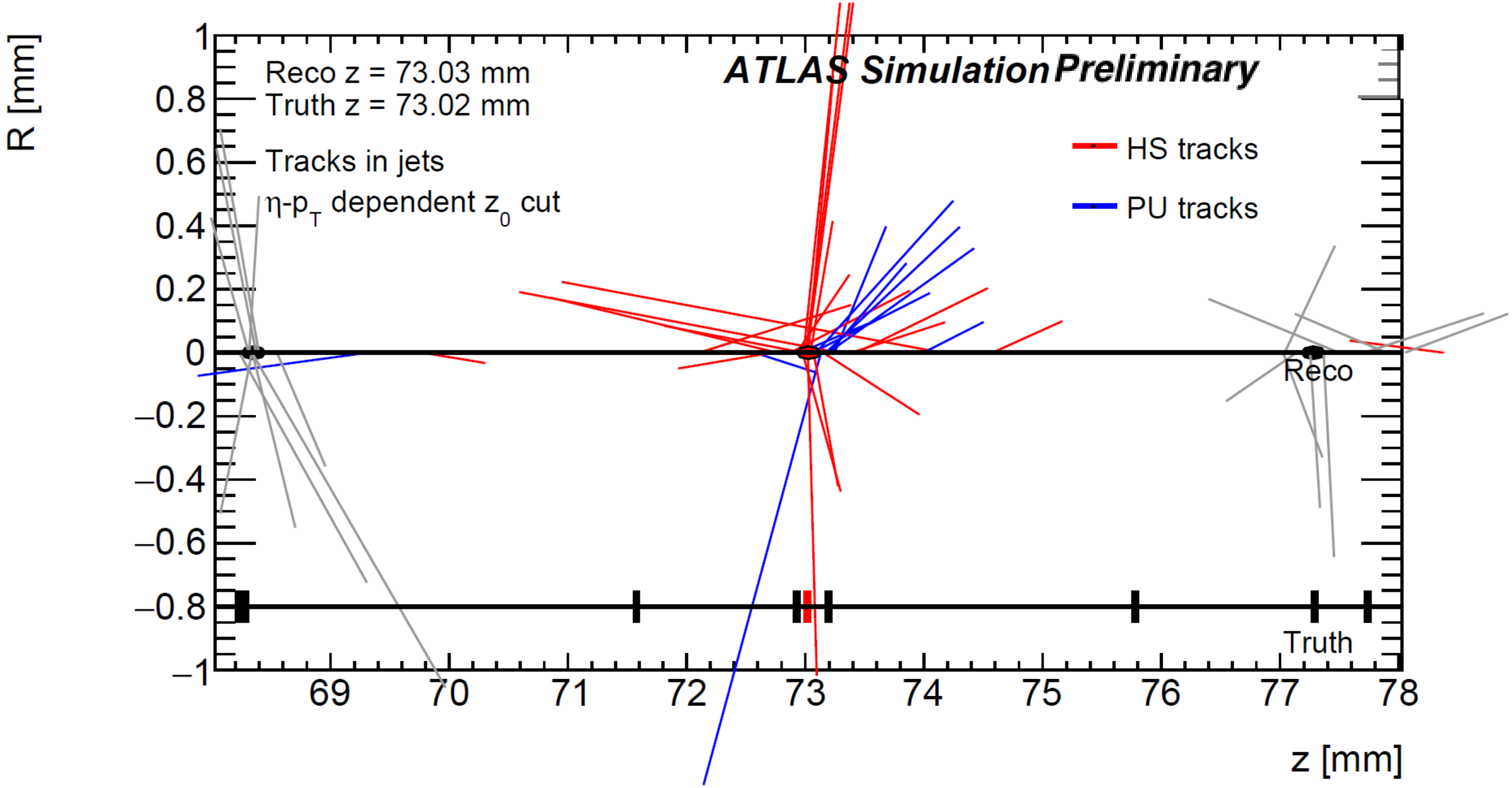
- **Fast simulation:**
  - Assign to all ITk tracks within HGTD acceptance a time given by the truth time of the track, smeared by a Gaussian with sigma=30ps
  - Assumes 60ps hit resolution and 4 planes and 100% track-HGTD matching efficiency

$$\sigma_t = \sigma_{Landau} \oplus \sigma_{jitter} \oplus \sigma_{TimeWalk} \oplus \sigma_{TDC}$$





Track-to-vertex association

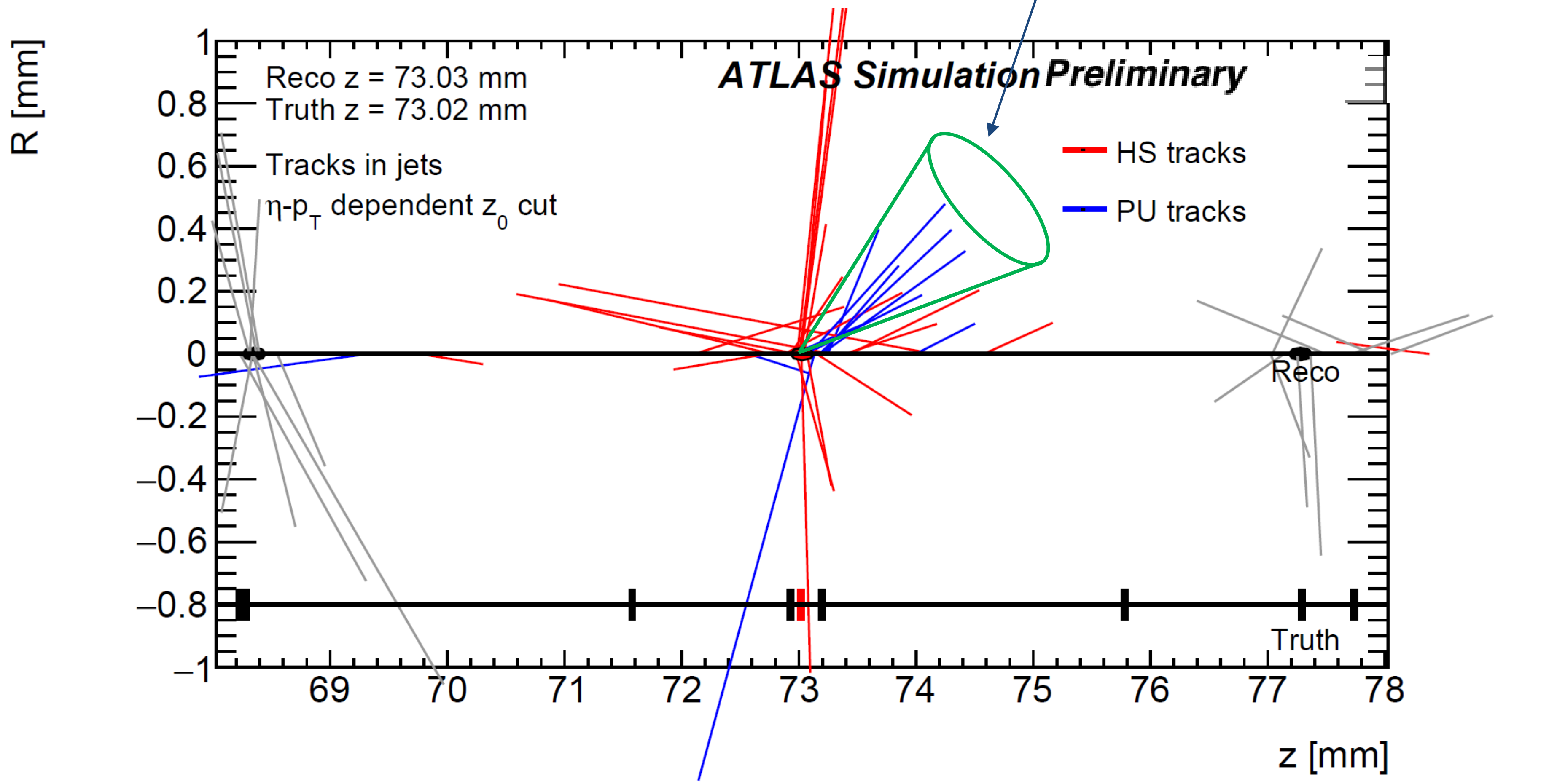


- The association of tracks to vertices relies on assigning tracks that are geometrically compatible in z with the vertex position.

$$\frac{z_0 - z_{vtx}}{\sigma_{z0}} < 2$$

Track-to-vertex association

Pile-up jet misidentified as hard-scatter jet



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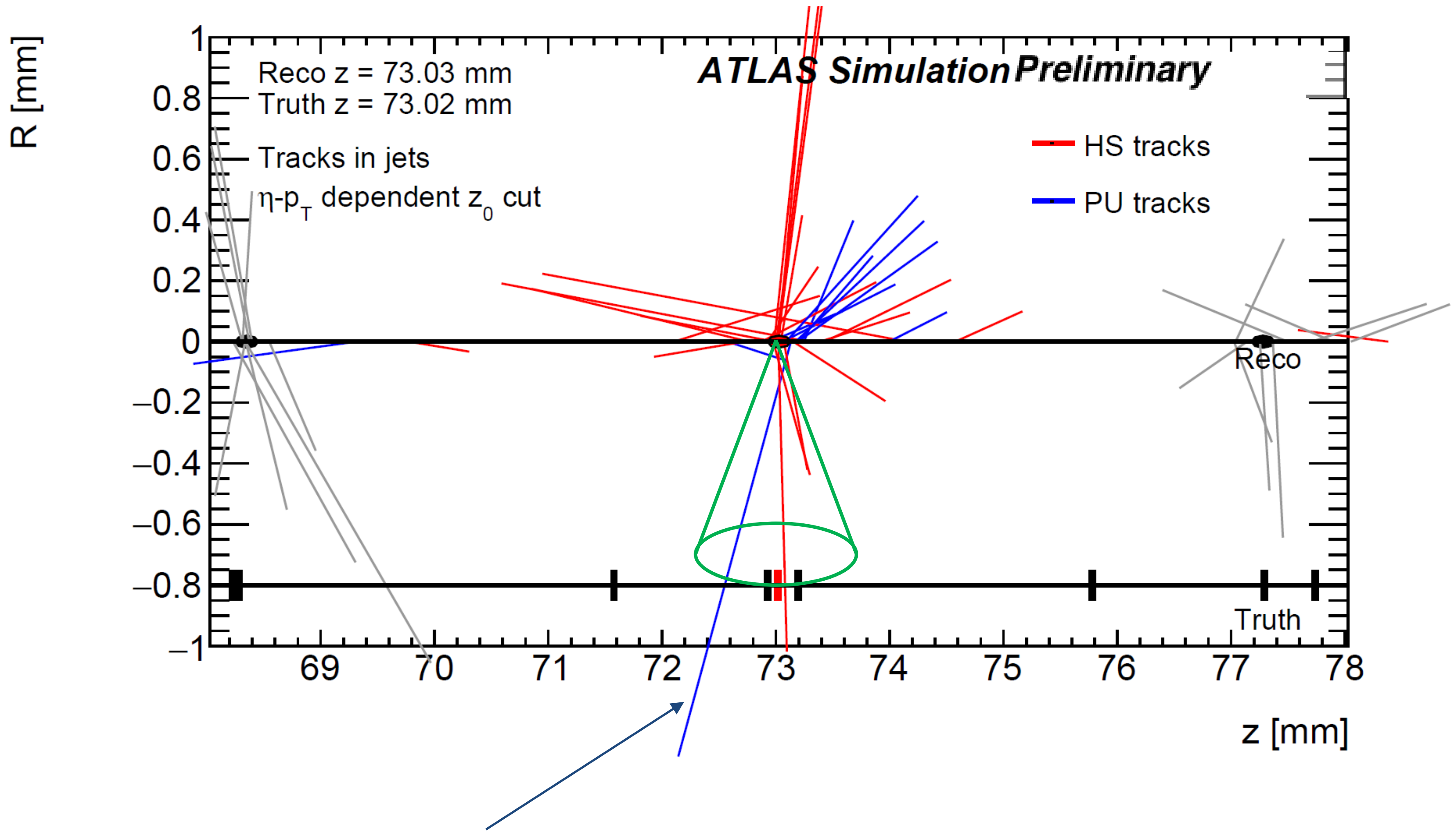
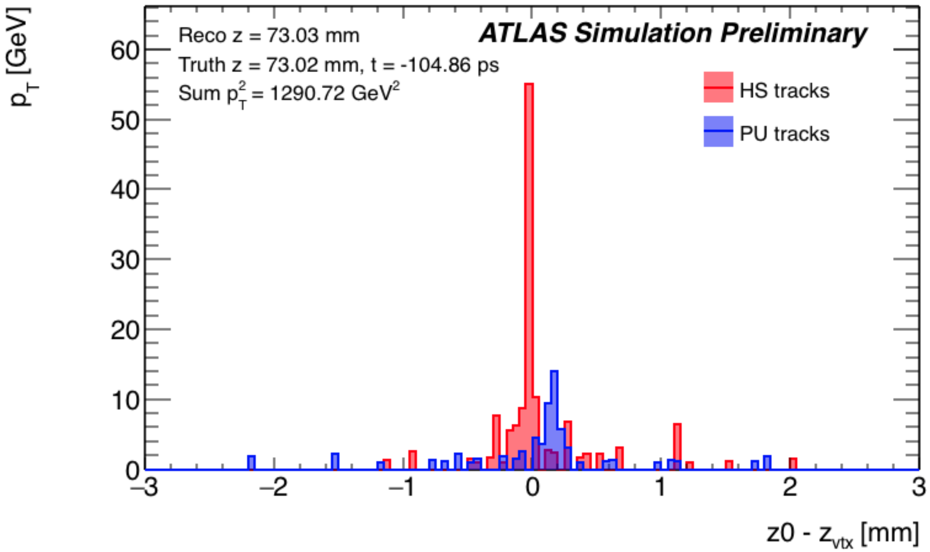
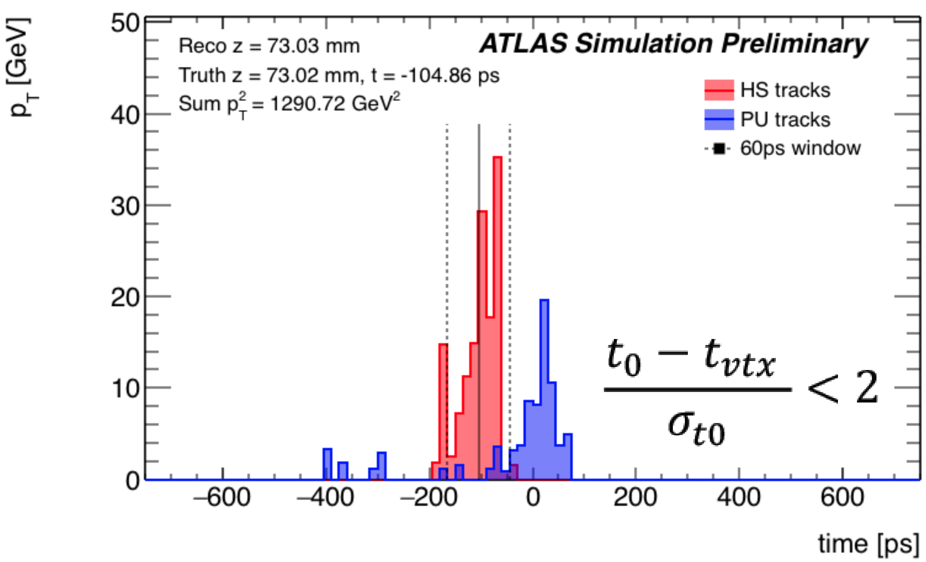


Pile-up track contamination in hard-scatter jets

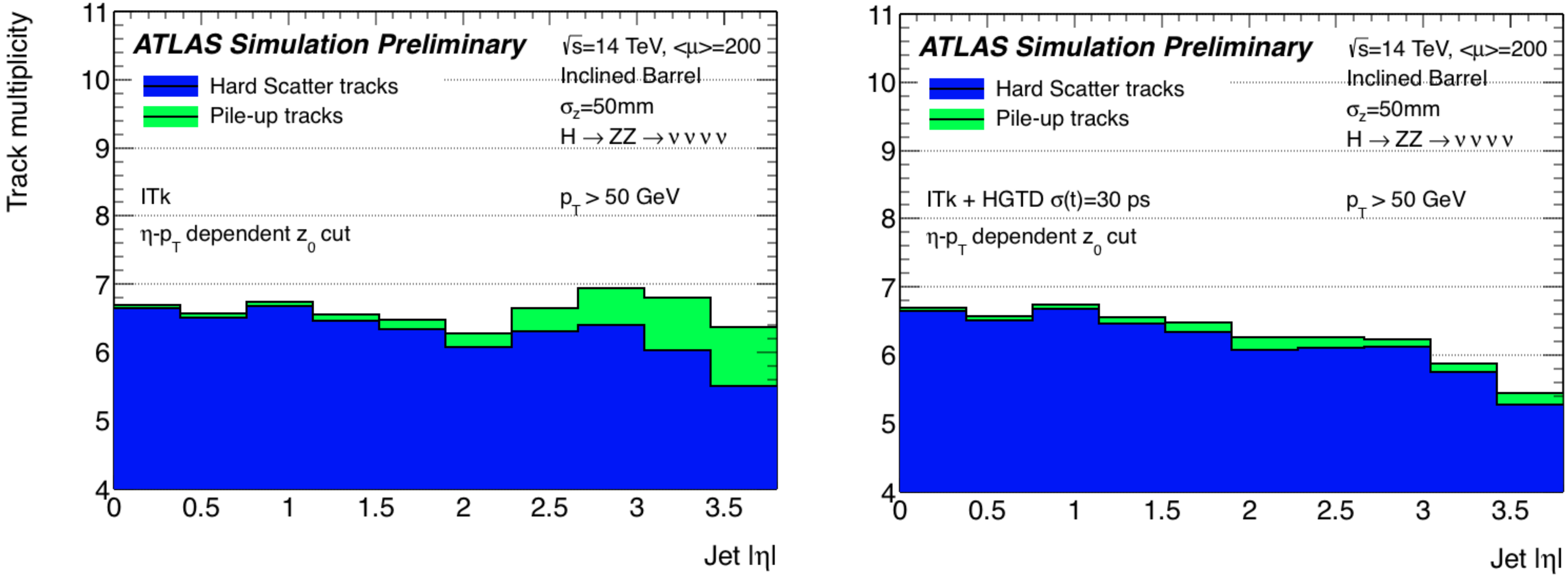
Track-to-vertex association





- Timing information is an additional handle to reject pile-up
- HGTD can resolve pile-up from hard-scatter tracks that are within the ITk z0 resolution

Track-to-vertex association for jets

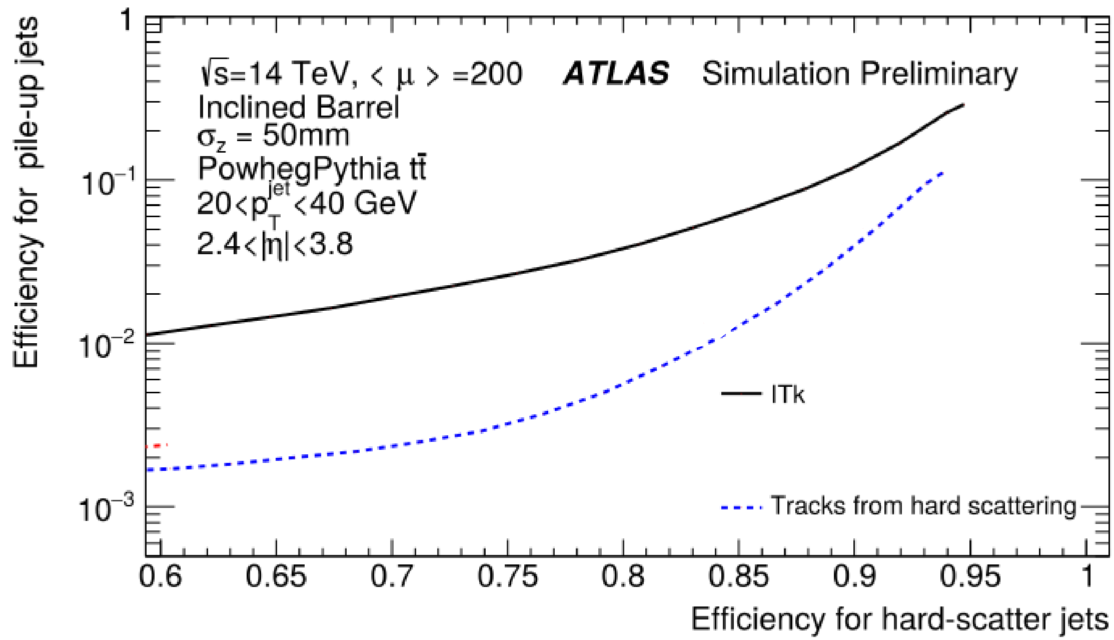


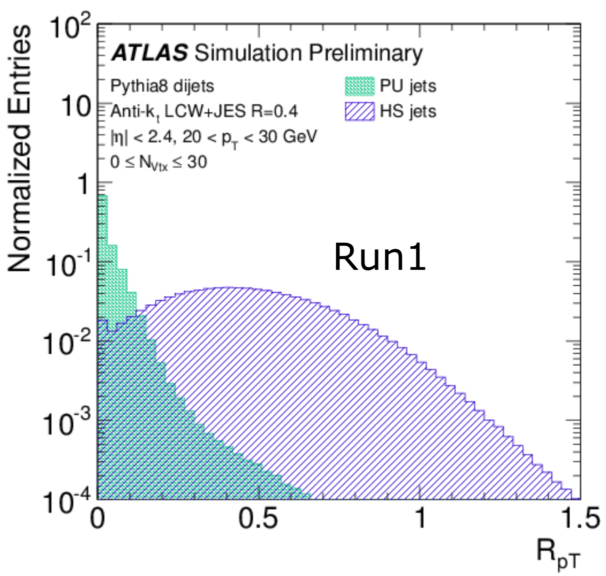
- Reduction of the pile-up track contamination in jets in the forward region thanks to the High Granularity Timing Detector (up to a factor 4)

Pile-up jet rejection

Pile-up jet rejection based on tracking information:

$$R_{pT} = \frac{\Sigma p_T^{trk}(PV_0)}{p_T^{jet}}$$





Improved pile-up jet suppression in the forward region thanks to improved track-to-vertex association

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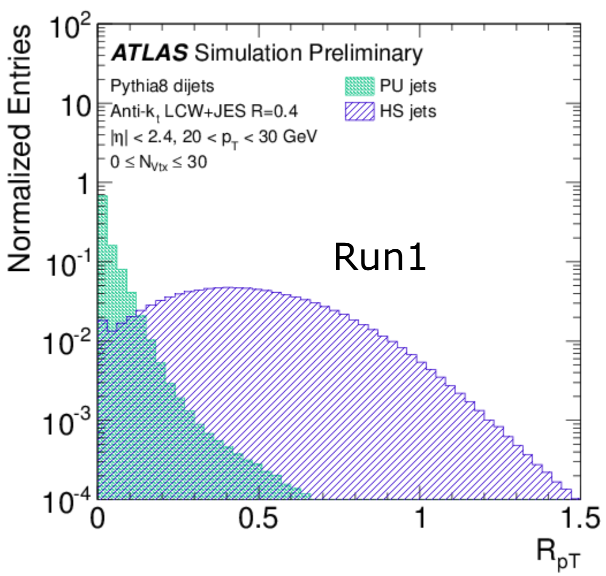

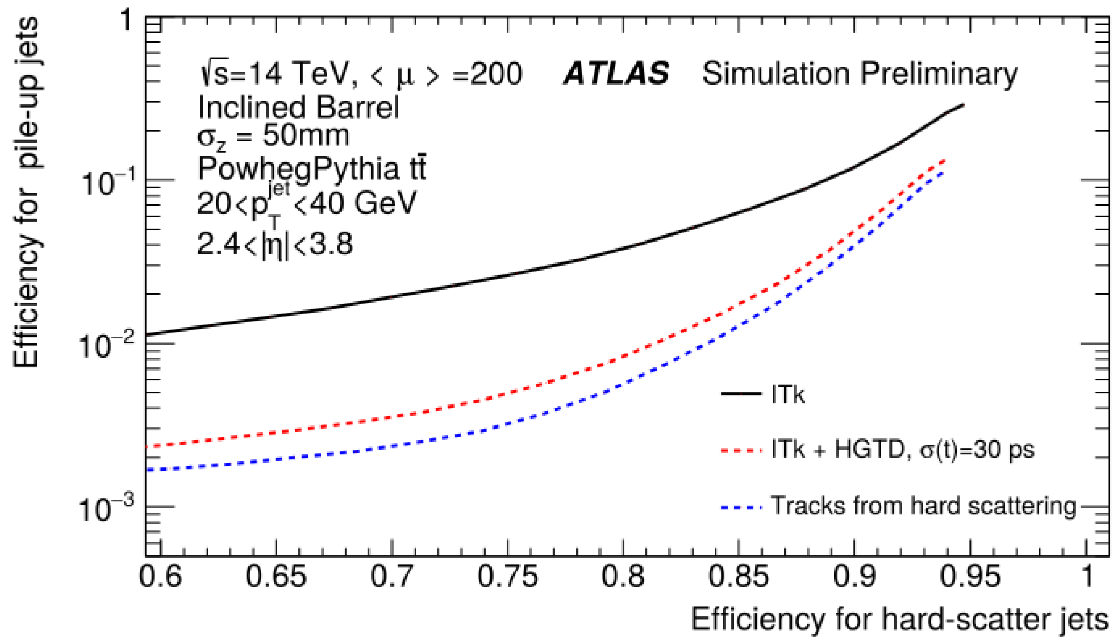

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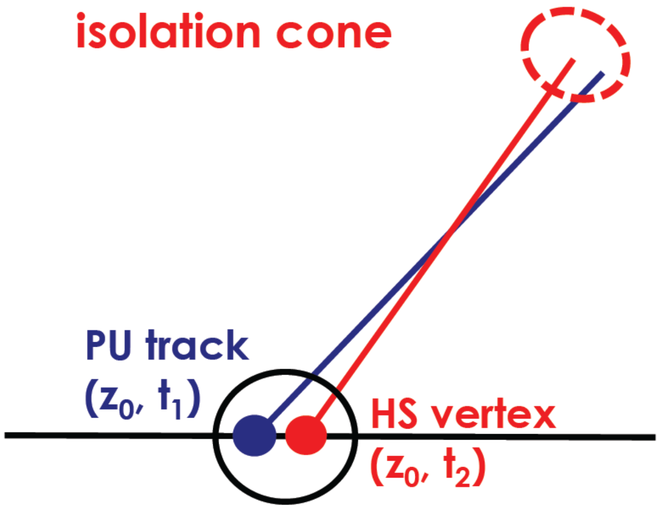
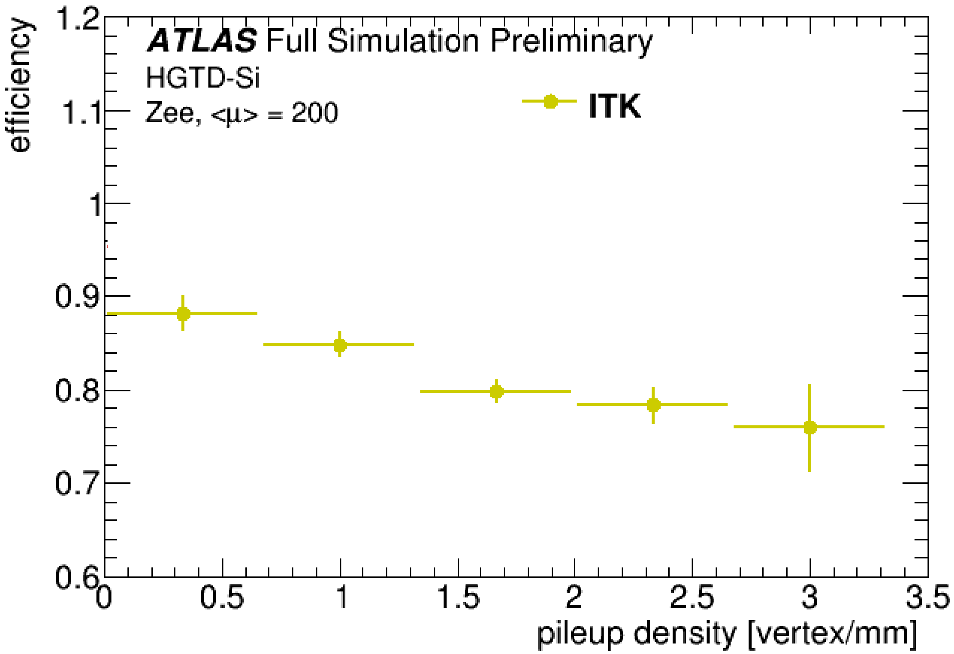
Electron isolation

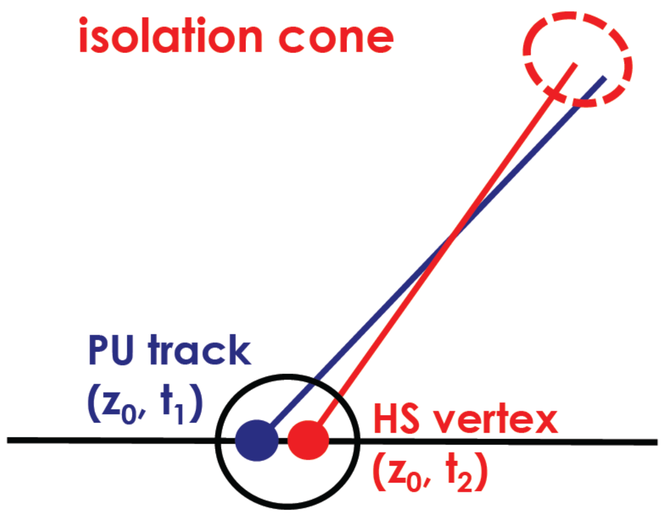
Lepton isolation based on tracking information:

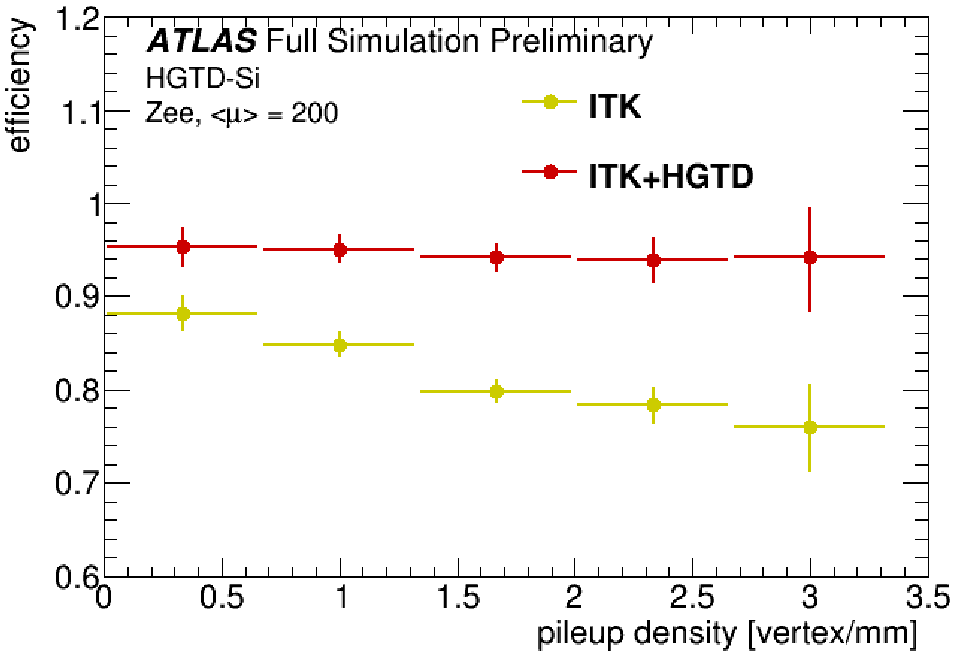




The efficiency is defined as the probability that no track with $p_T > 1$ GeV other than the signal track is within R = 0:2 from the electron.

Lepton isolation based on tracking information:

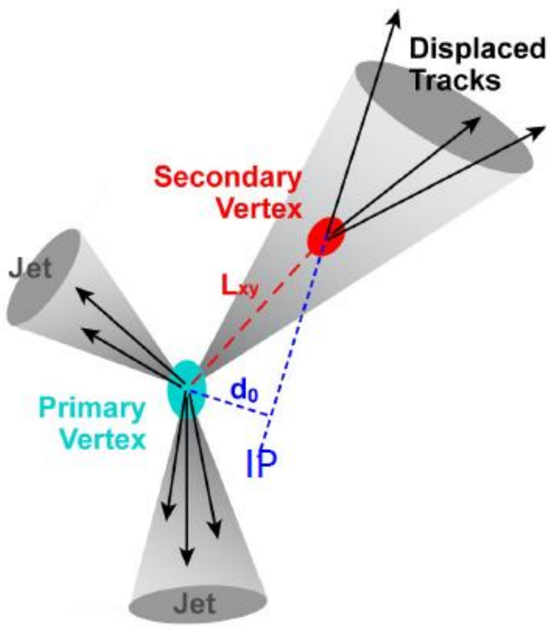


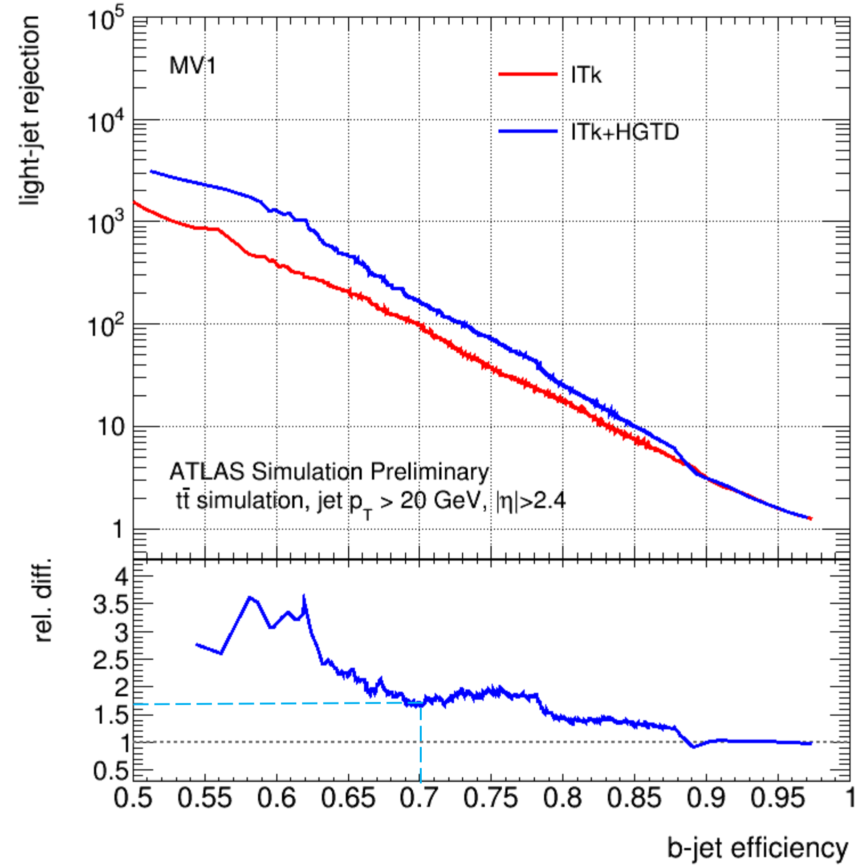


10%-20% efficiency improvement
Efficiency independent of pile-up density

B-tagging

- B hadrons have significant lifetime
  - Secondary vertex (SV)
  - Impact parameter (IP)
  - Combine in multivariate discriminant (MV)

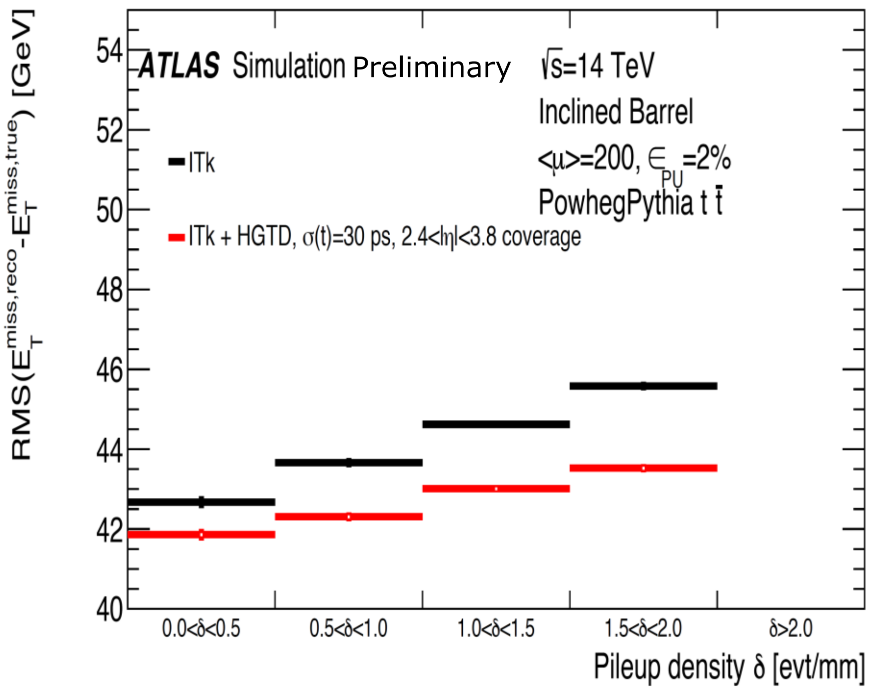


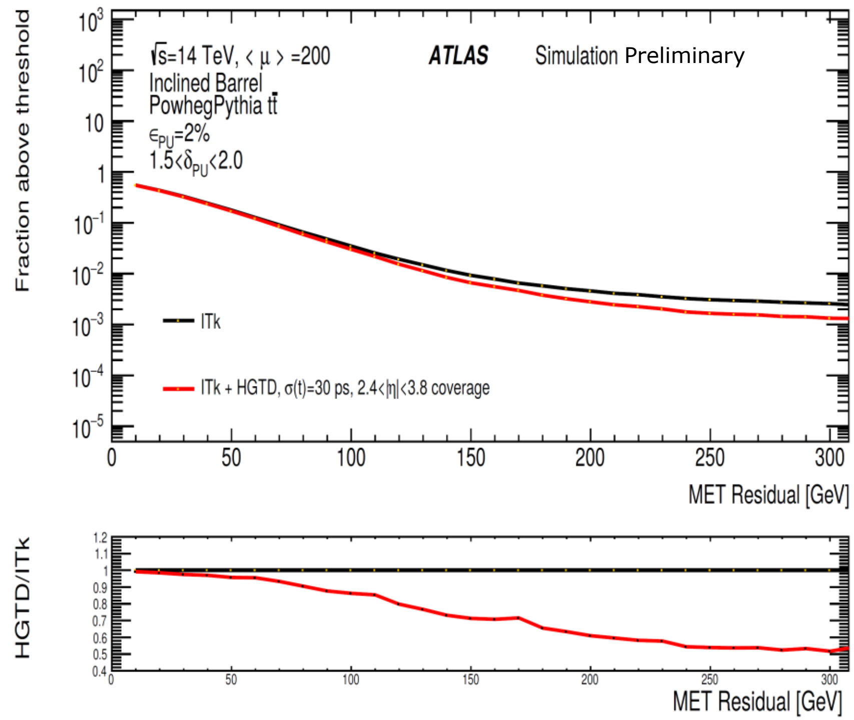


Up to x3.5 improvement in forward b-jet tagging

Missing transverse momentum

$$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = \underbrace{\underbrace{-\sum_{\substack{\text{selected}\\ \text{electrons}}} \mathbf{p}_{\mathrm{T}}^{e}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},e}} \underbrace{-\sum_{\substack{\text{accepted}\\ \text{photons}}} \mathbf{p}_{\mathrm{T}}^{\gamma}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\gamma}} \underbrace{-\sum_{\substack{\text{accepted}\\ \tau\text{-leptons}}} \mathbf{p}_{\mathrm{T}}^{\tau_{\mathrm{had}}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\tau_{\mathrm{had}}}} \underbrace{-\sum_{\substack{\text{selected}\\ \text{muons}}} \mathbf{p}_{\mathrm{T}}^{\mu}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\mu}} \underbrace{-\sum_{\substack{\text{accepted}\\ \text{jets}}} \mathbf{p}_{\mathrm{T}}^{\mathrm{jet}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss,jet}}}}_{\text{hard term}} \underbrace{\underbrace{-\sum_{\substack{\text{unused}\\ \text{tracks}}} \mathbf{p}_{\mathrm{T}}^{\mathrm{track}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss,soft}}}}_{\text{soft term}} .$$

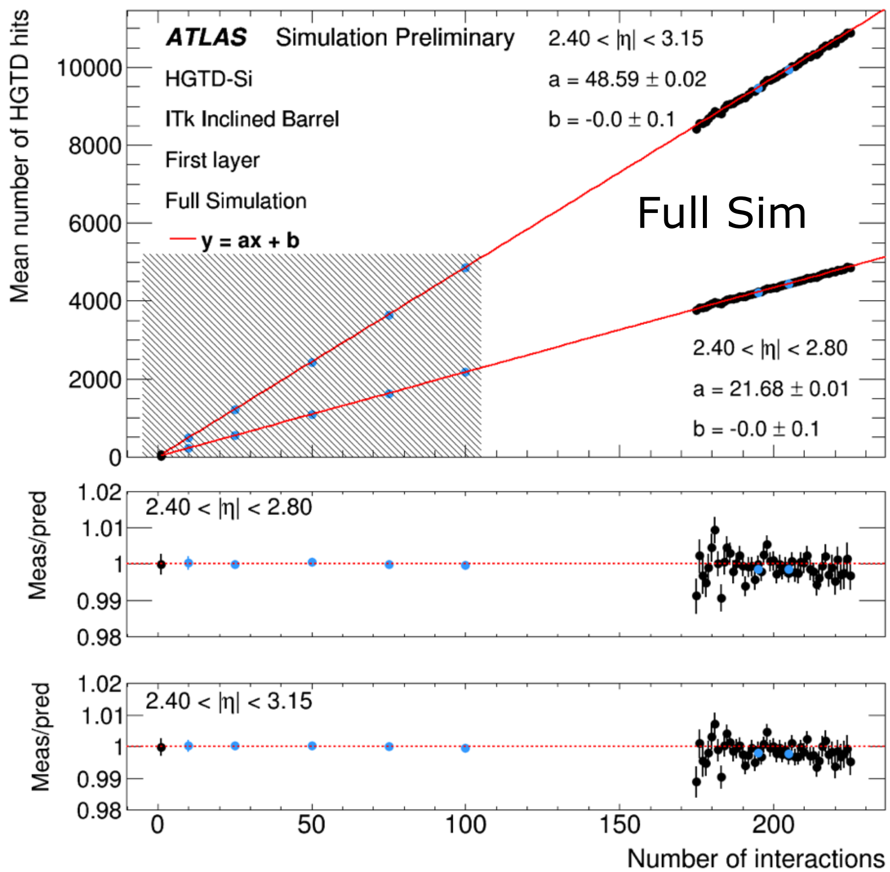




- Up to 50% reduction of missing transverse momentum tails thanks to:
  - Improved pile-up jet suppression in the forward region
  - Improved soft term track missing transverse momentum resolution

Luminosity for HL-LHC

- Goal for HL-LHC: 1% accuracy
- The luminosity measurement at HL-LHC will be a challenge, as traditional detectors and methods are no longer useable when the pile-up is too high
- HGTD provides unique capabilities for measuring the luminosity at the HL-LHC
  - High granularity → low occupancy → good linearity between the occupancy and luminosity
  - Fast signal → bunch by bunch measurement and background subtraction
  - Fast read-out (40MHz) → online measurement for luminosity-levelling
- The proposal is to read out only the outer radial range ($2.4<|\eta|<3.15$)



Excellent linearity observed!

Conclusion

- Precise timing information is a powerful new tool to improve detector performance at HL-LHC

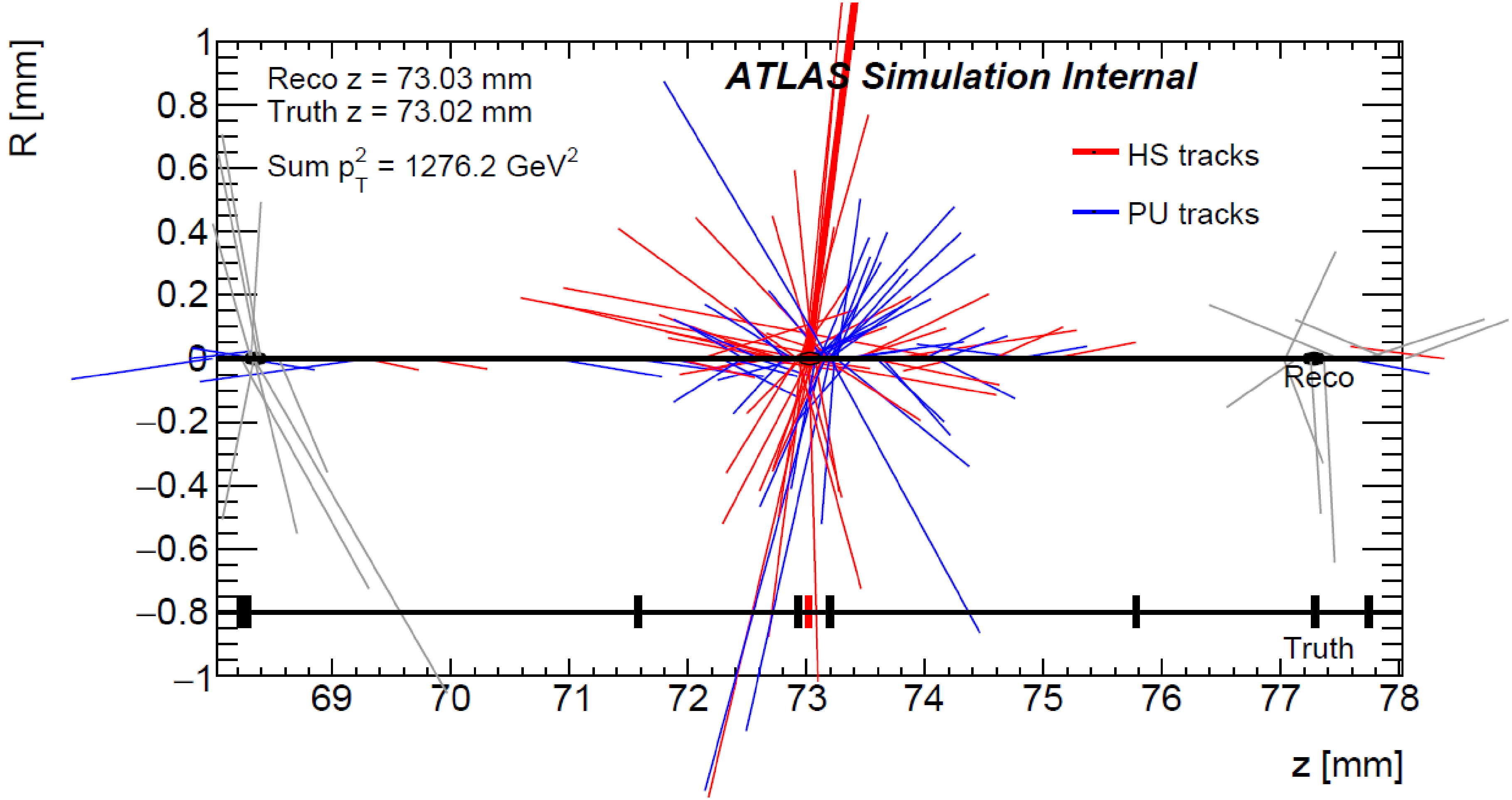
- The HGTD brings clear improvement for physics objects performance in the forward region: track-vertex association, jet/MET, b-tagging, leptons …
  - The good time resolution compensates for the low z0 ITK resolution

- In addition, the HGTD could be used as luminometer thanks to low occupancy of the outer-radii sensors and the good timing resolution
  - Could be used for online for luminosity leveling

- It is only the beginning and more work and creativity is needed to fully exploit the timing information of the HGTD


That's all Folks!

Track-to-vertex association



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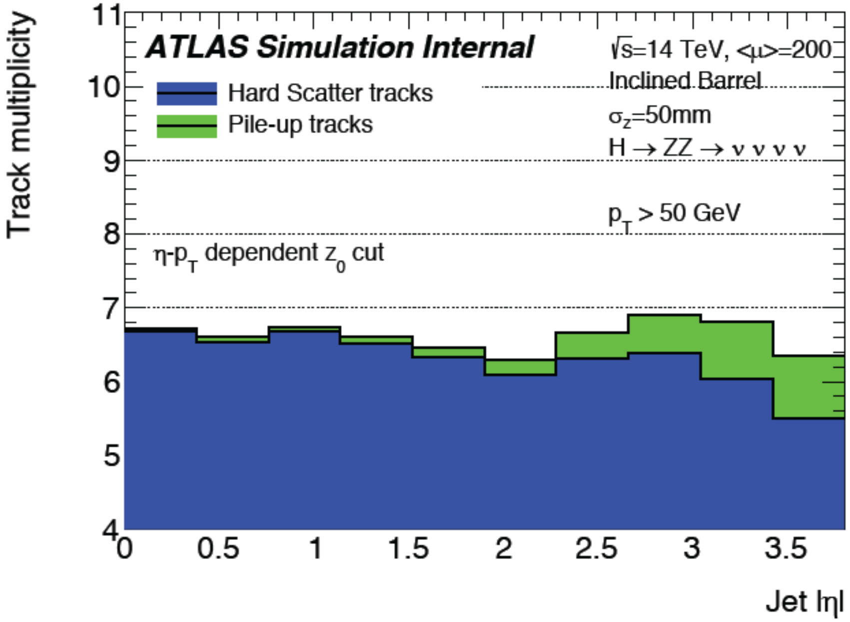

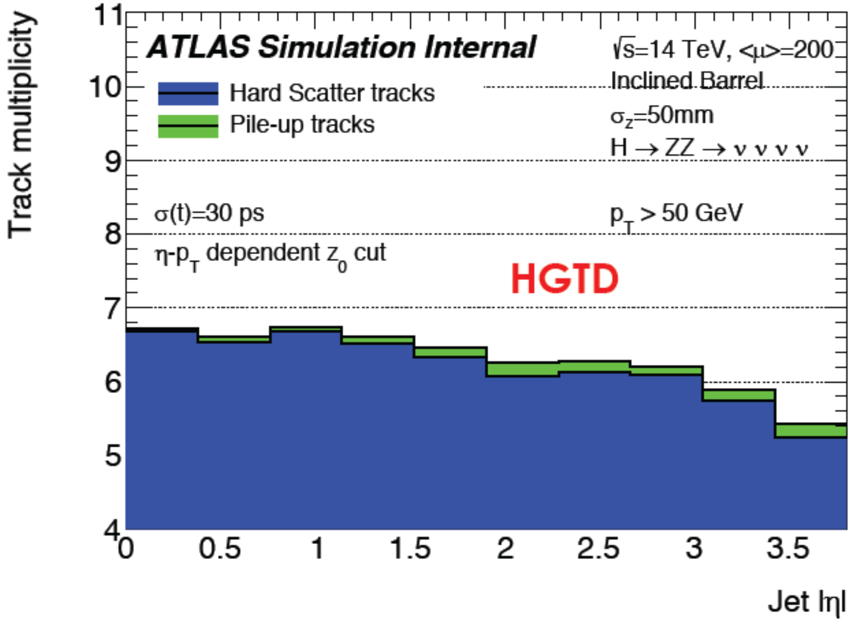

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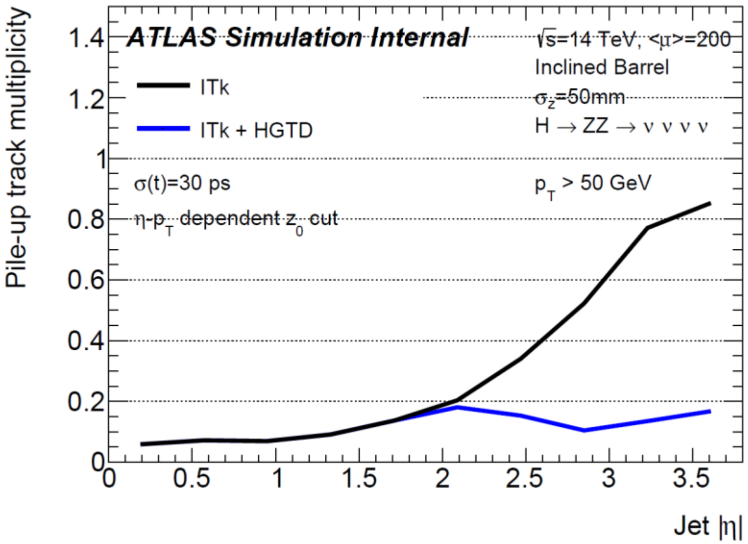

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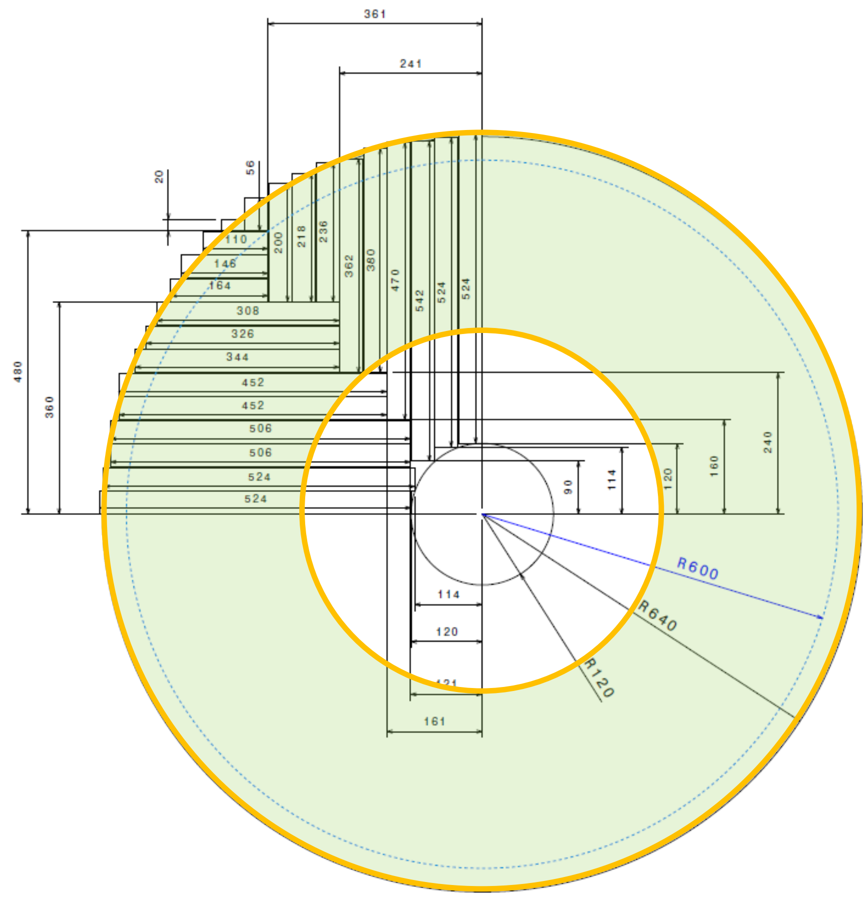
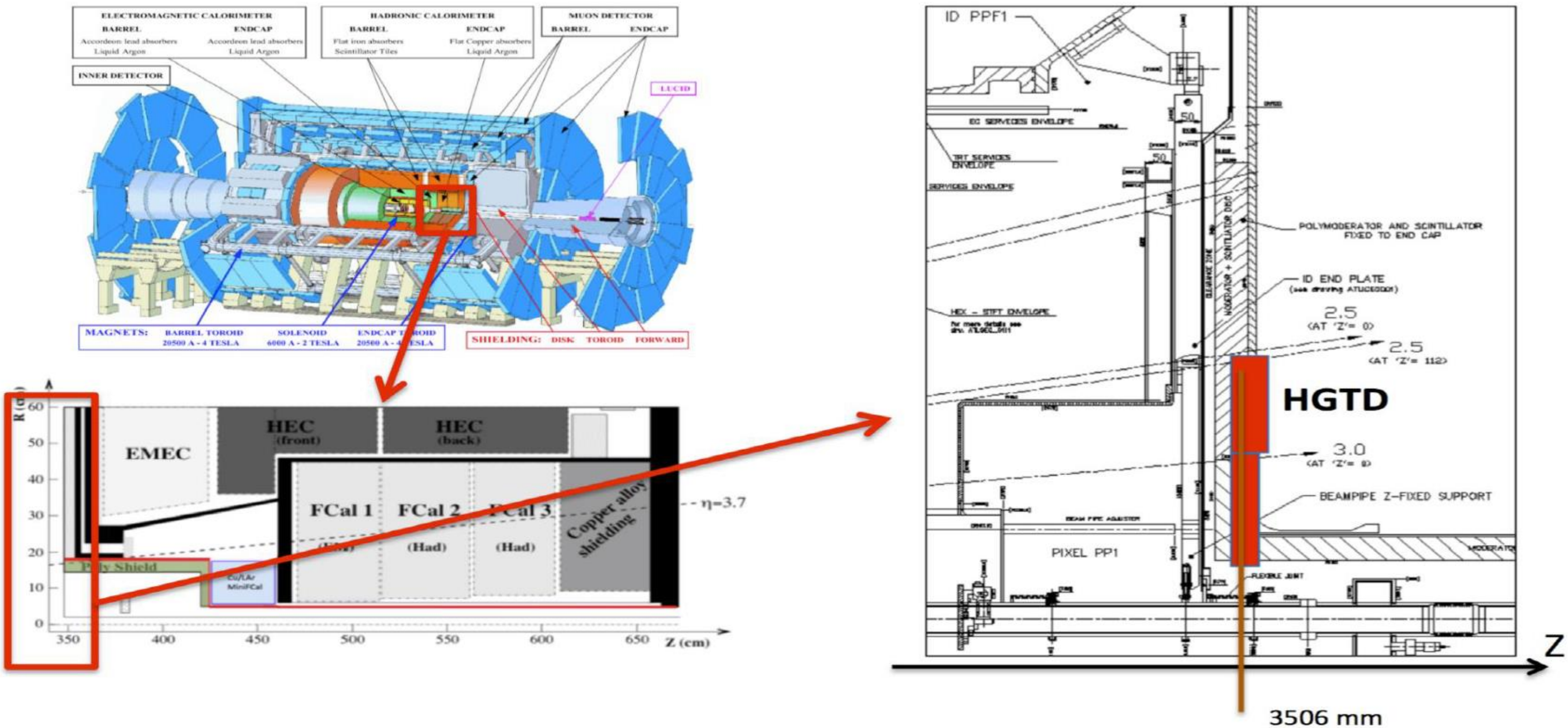
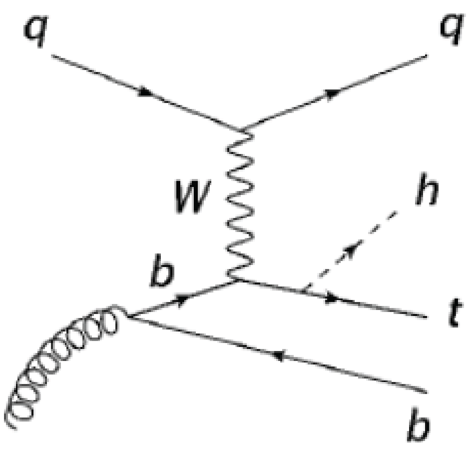
- To reduce costs, the proposal is to read out only the outer radial range ($2.4<|\eta|<3.15$)

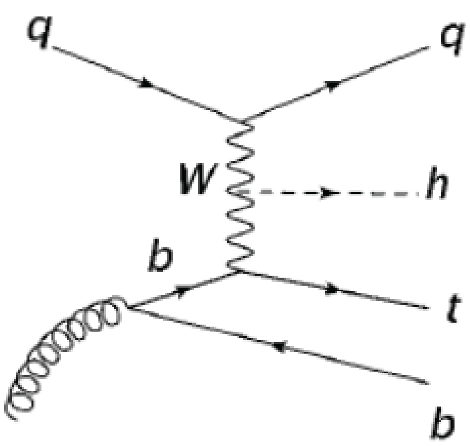


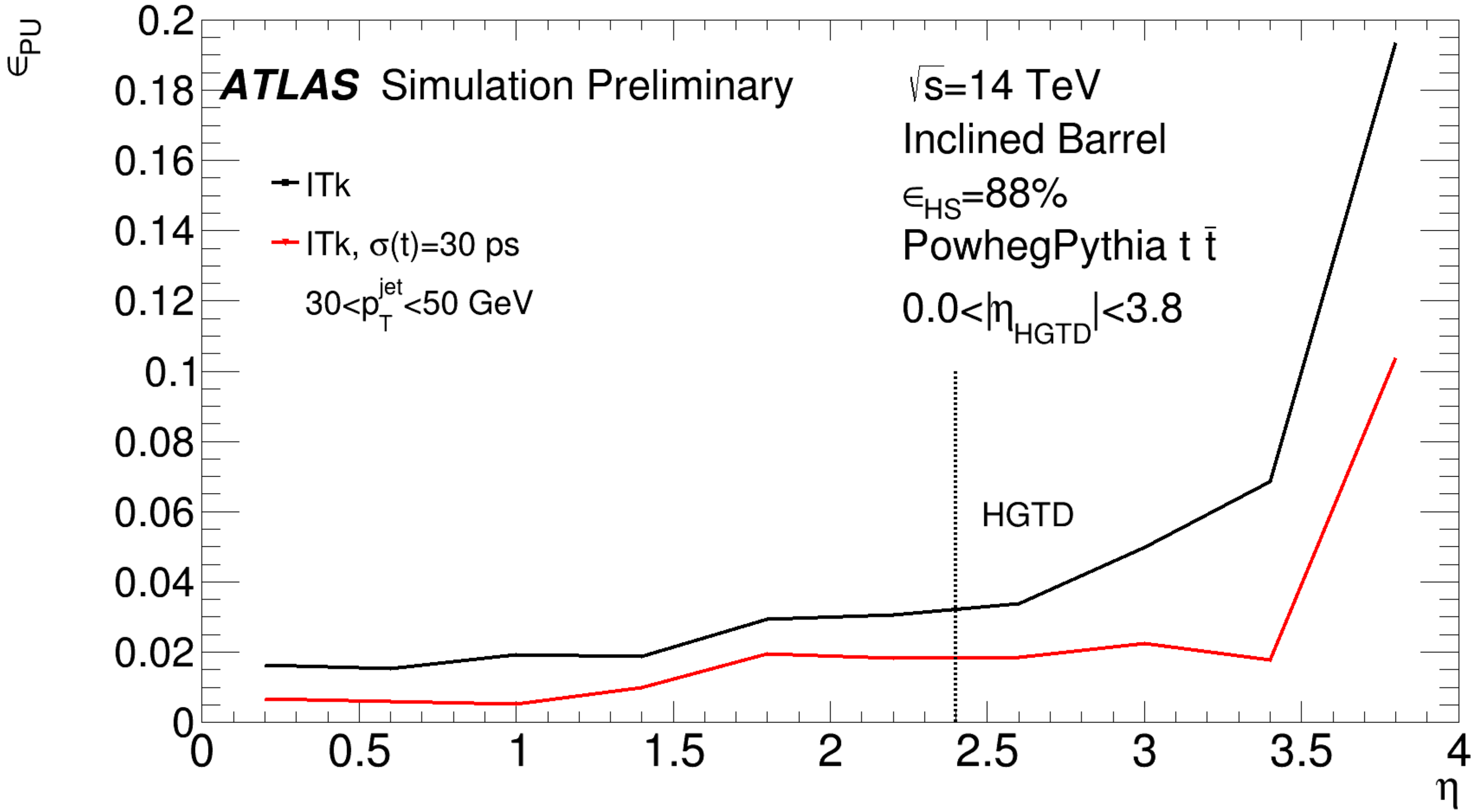


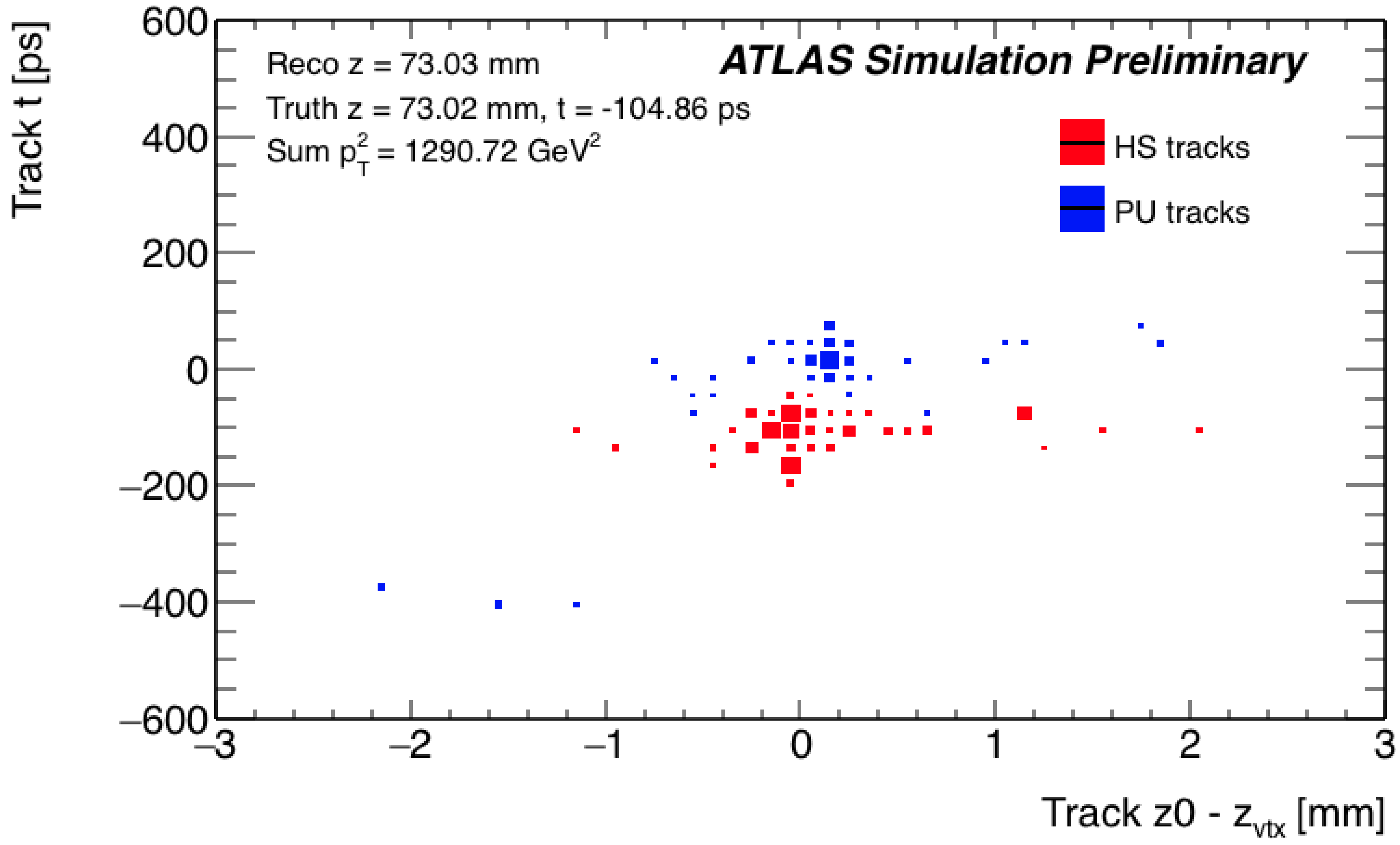
ELECTROMAGNETIC CALORIMETER
BARREL
Accordeon lead absorbers
Liquid Argon
ENDCAP
Accordeon lead absorbers
Liquid Argon
HADRONIC CALORIMETER
BARREL
Flat iron absorbers
Scintillator Tiles
ENDCAP
Flat Copper absorbers
Liquid Argon
MUON DETECTOR
BARREL
ENDCAP
INNER DETECTOR
LUCID
MAGNETS:
BARREL TOROID
20500 A - 4 TESLA
SOLENOID
6000 A - 2 TESLA
ENDCAP TOROID
20500 A - 4 TESLA
SHIELDING:
DISK
TOROID
FORWARD
EMEC
HEC (front)
HEC (back)
FCal 1
FCal 2
FCal 3
(Had)
(Had)
Copper alloy shielding
η=3.7
Poly Shield
Cu/LAr MiniFCal
Z (cm)
ID PPF1
EC SERVICES ENVELOPE
TRT SERVICES ENVELOPE
SERVICES ENVELOPE
POLYMODERATOR AND SCINTILLATOR FIXED TO END CAP
ID END PLATE
2.5 (AT 'Z'= 0)
2.5 (AT 'Z'= 112)
HGTD
3.0 (AT 'Z'= 0)
BEAMPIPE Z-FIXED SUPPORT
PIXEL PP1
Z
3506 mm

tH





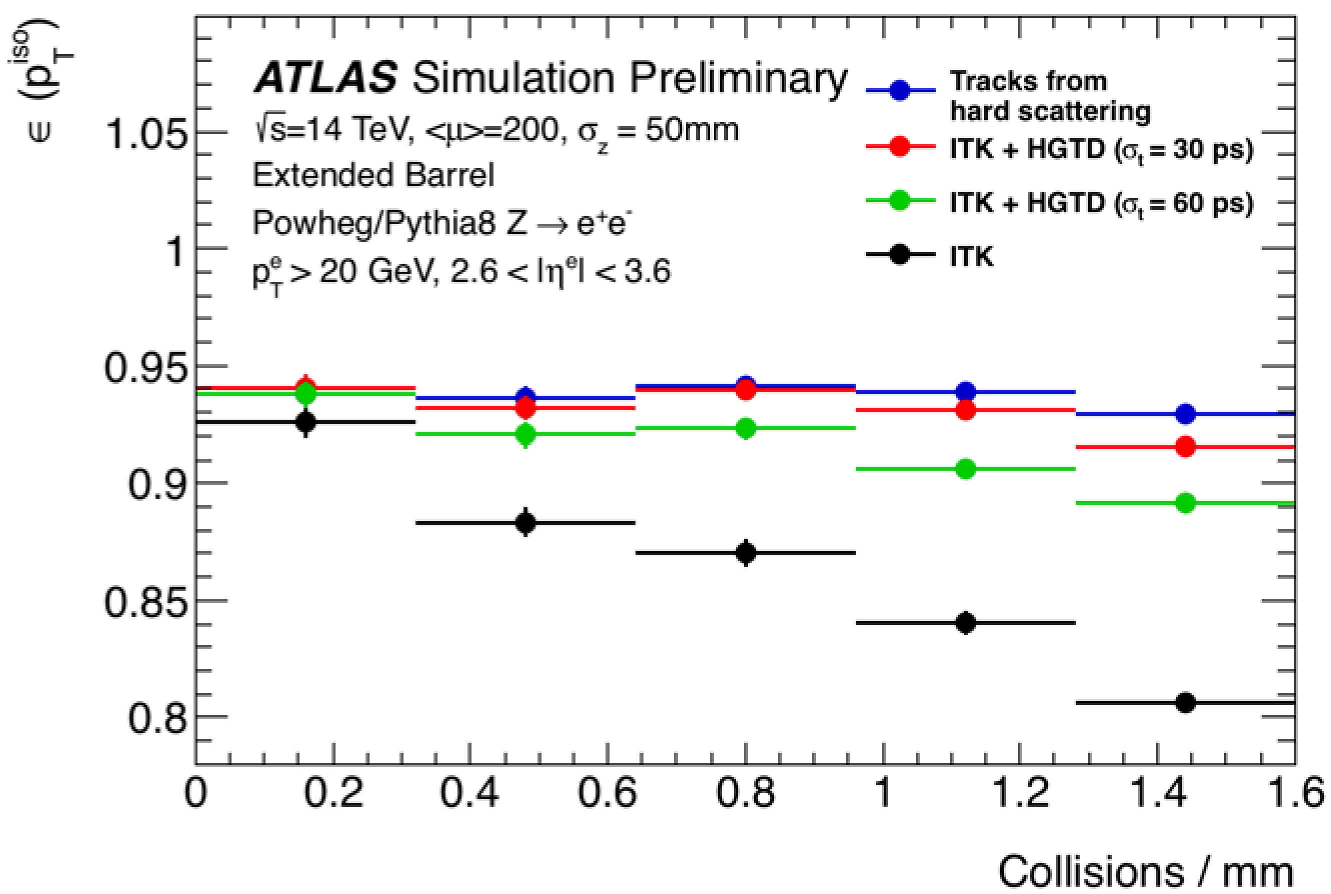

ATLAS Simulation Preliminary
$\sqrt{s}$=14 TeV
Inclined Barrel
ϵ_{HS}=88%
PowhegPythia $t\bar{t}$
$0.0<|\eta_{HGTD}|<3.8$
ITk
ITk, $\sigma(t)$=30 ps
$30<p_T^{jet}<50$ GeV
HGTD
ϵ_{PU}
η
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4


Reco z = 73.03 mm
Truth z = 73.02 mm, t = -104.86 ps
Sum p_T^2 = 1290.72 GeV^2
ATLAS Simulation Preliminary
HS tracks
PU tracks
600
400
200
0
−200
−400
−600
−3
−2
−1
0
1
2
3
Track t [ps]
Track z0 - z_{vtx} [mm]

HGTD as a Luminosity Detector

- The idea of using the HGTD as a luminometer is that the occupancy will be linearly related to the luminosity.
  - If the occupancy can be read out at 40 MHz, then the luminosity can be determined bunch-by-bunch, and independently of the ATLAS trigger.
  - Plan is that the ASIC provide dedicated readout of the occupancy information, for every bunch crossing. Measurement of the luminosity available both online and offline.

- All ASICs will have the capability to send the luminosity information, but for cost purposes only two discs on each side will be used, and only ASICs at a radius greater than 300 mm ($2.4 < |\eta| < 3.15$).
  - Approximately 80% of the area of the equipped discs are read out, or 40% of the total area of the HGTD detector.
  - The data is sent via the flex cables to lpGBTs, and then through optical fibres to the counting rooms where dedicated luminosity electronics will handle the data (aggregate the occupancy information).


ATLAS Simulation Preliminary
√s=14 TeV, <μ>=200, σz = 50mm
Extended Barrel
Powheg/Pythia8 Z → e+e-
pTe > 20 GeV, 2.6 < |ηe| < 3.6
Tracks from hard scattering
ITK + HGTD (σt = 30 ps)
ITK + HGTD (σt = 60 ps)
ITK
ε (pTiso)
Collisions / mm
0.8
0.85
0.9
0.95
1
1.05
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6