Expected Performance of the ATLAS Inner Tracker at the High-Luminosity LHC

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On behalf of the ATLAS Collaboration

25th International Workshop on Deep Inelastic Scattering and Related Topics
Wednesday, 5 April 2017

The ATLAS Phase-II Inner Tracker

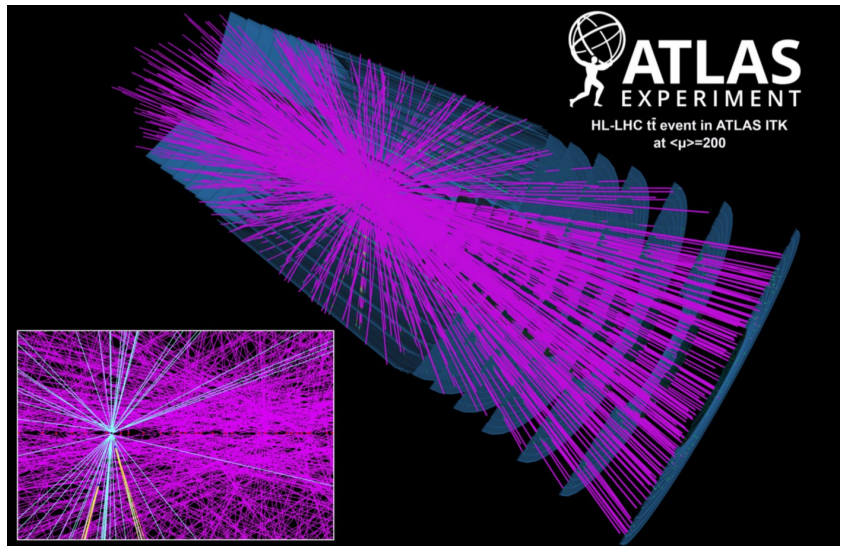
ITk (Inner Tracker) is a full upgrade of the

ATLAS Inner Detector as part of the Phase-II upgrade

→ consists of a new pixel and strip detectors, "all-silicon" detector

→ Designed to operate successfully under HL-LHC operating conditions
corresponding to:

- Leveled peak luminosities up to $7.5 \cdot 10^{34}$ cm^{-2} s^{-1}
- 25 ns bunch spacing
- Mean number of interactions per bunch crossing up to 200
- Integrated luminosity up to 4000 fb^{-1}
- 14 TeV energy in the center of mass



The new Inner Tracker

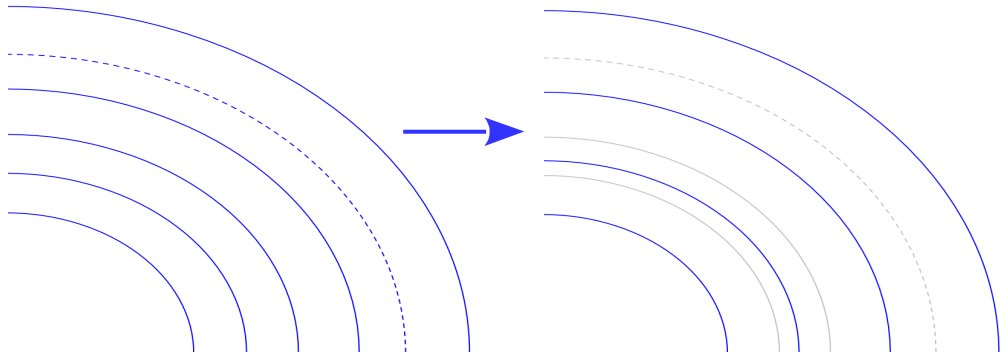
- Important milestones: **Strip and Pixel TDRs (Technical Design Reports)**
  - Strip layout already final – **Strip TDR in finalising process**
  - **Pixel TDR deadlines approaching!**

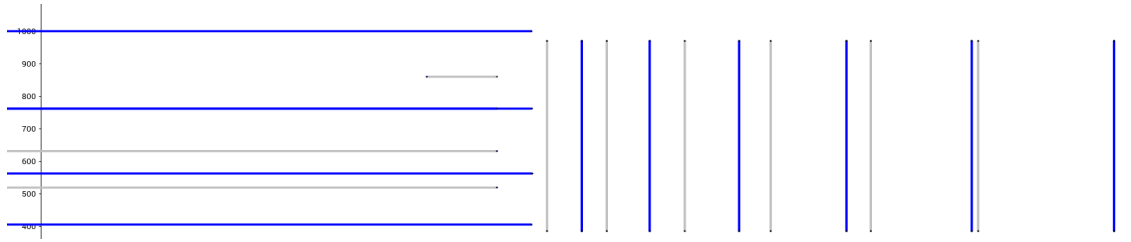
- A lot of work has been done in the last year to define the baseline layout for the pixel TDR:
  - Two concepts proposed:
    - Extended concept with a long inner pixel barrel
    - Inclined concept with tilted modules → **Defined to be the baseline**

→ In the next slides we will focus on the performance of the Inclined Layout

Strip Detector Layout

- **4 Pixel + 5 Strip → 5 Pixel + 4 Strip**
  - Goal: e.g. do better in jet cores
  - Many options studied
- Longer staves in strip barrel: 13 → 14 modules
- Removed stubs
  - → reduce complexity of engineering
  - Region of best momentum resolution extends to $|\eta| = 1.1$
- Longer Strip barrel allows as well to go from 7 to 6 strip endcap disks without loosing momentum resolution





The Extended Coverage Scenario

- **Extended tracking acceptance: up to |η|~4**

  → concerns mostly the pixel detector

  - Improved sensitivity and acceptance in VBS, VBF Higgs studies, bbH, H → 4l, etc.
  - Improved MET resolution in particular from track soft term
  - Good impact parameter and vertex resolution → pileup rejection and b tagging
  - Forward electron identification
  - ...

See talk from Stephane Jezequel

- As an example: pileup jets are rejected based on the **momentum of tracks within a jet** associated with the primary vertex:

$$R_{p_T} = \frac{\sum_i (p_T^{track,i})}{p_T^{jet}}$$

  - Measuring tracks at high pseudo-rapidity extends the range of this technique.

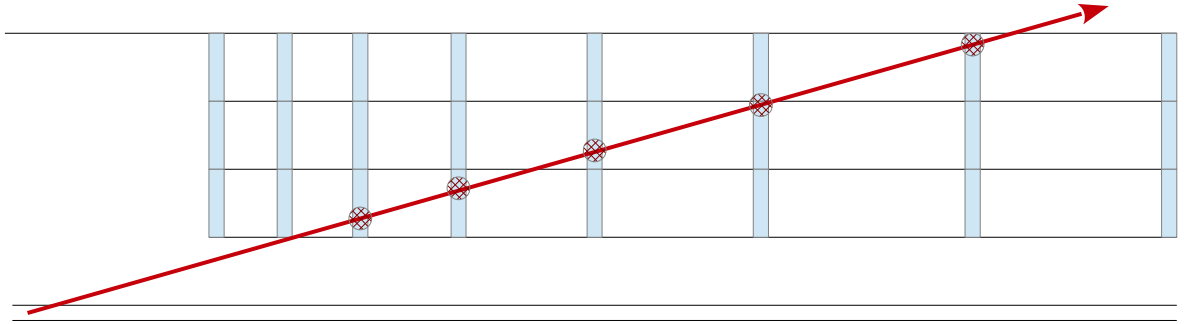
→ ATLAS Phase-II Upgrade Scoping Document – LHCC-G-166

Pixel Rings

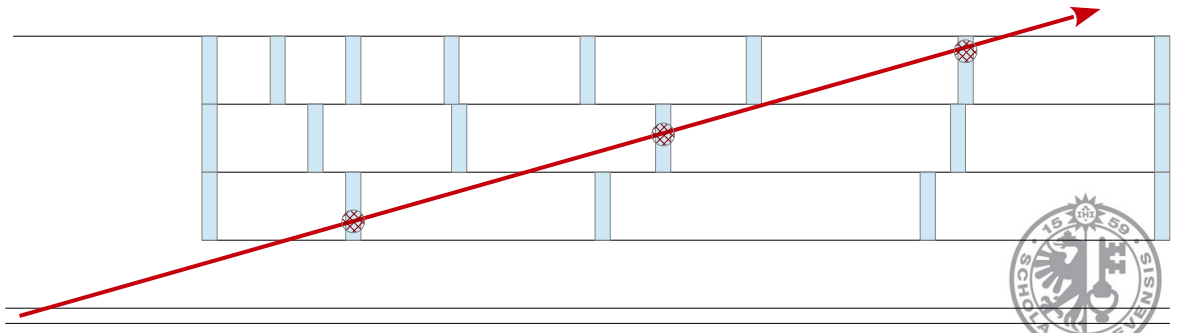
- Rings instead of disks in the pixel endcap region
  - Allows to save silicon surface
  - Services are routed on the support structure
  - Very peculiar pattern to provide constant number of hits versus η
  - Large-$|\eta|$ region entirely in the pixel volume $\rightarrow$ increased the number of rings at very high $|\eta|$

$\rightarrow$ Its optimization strongly correlated with the barrel layout choice

$\rightarrow$ Traditional disk system



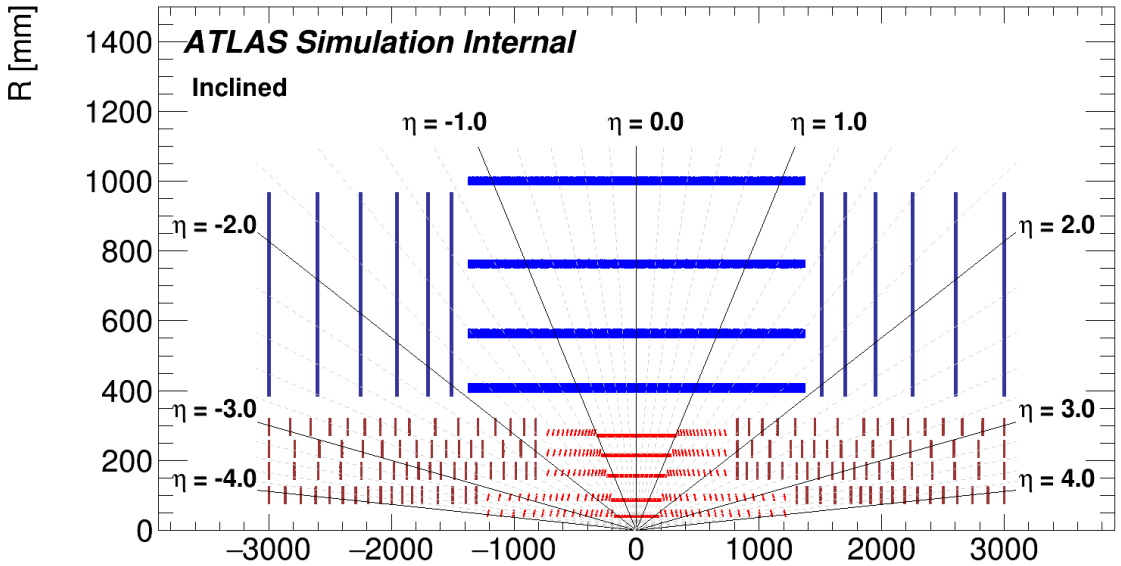
$\rightarrow$ Optimised rings with 1 hits per ring



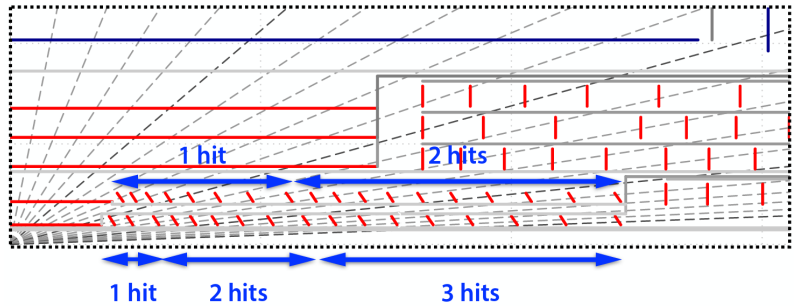
The Inclined Pixel Layout Concept

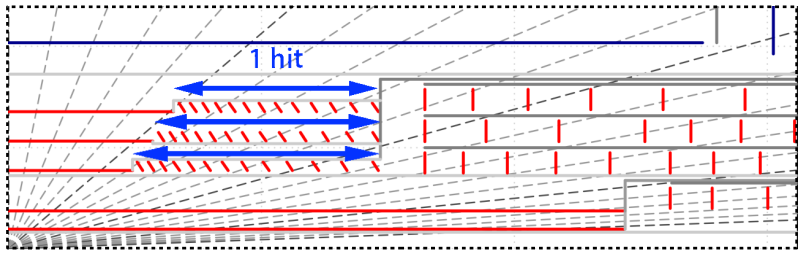
→ **The Inclined Layout provides many hits at large |η| close to the beam spot**

- With tilted sensors in the high |η| region we expect several hits per layer (tracklets) and less material crossed given the low incidence angle
- Inclining modules means reduction of material transversed by tracks and less silicon to cover same η range



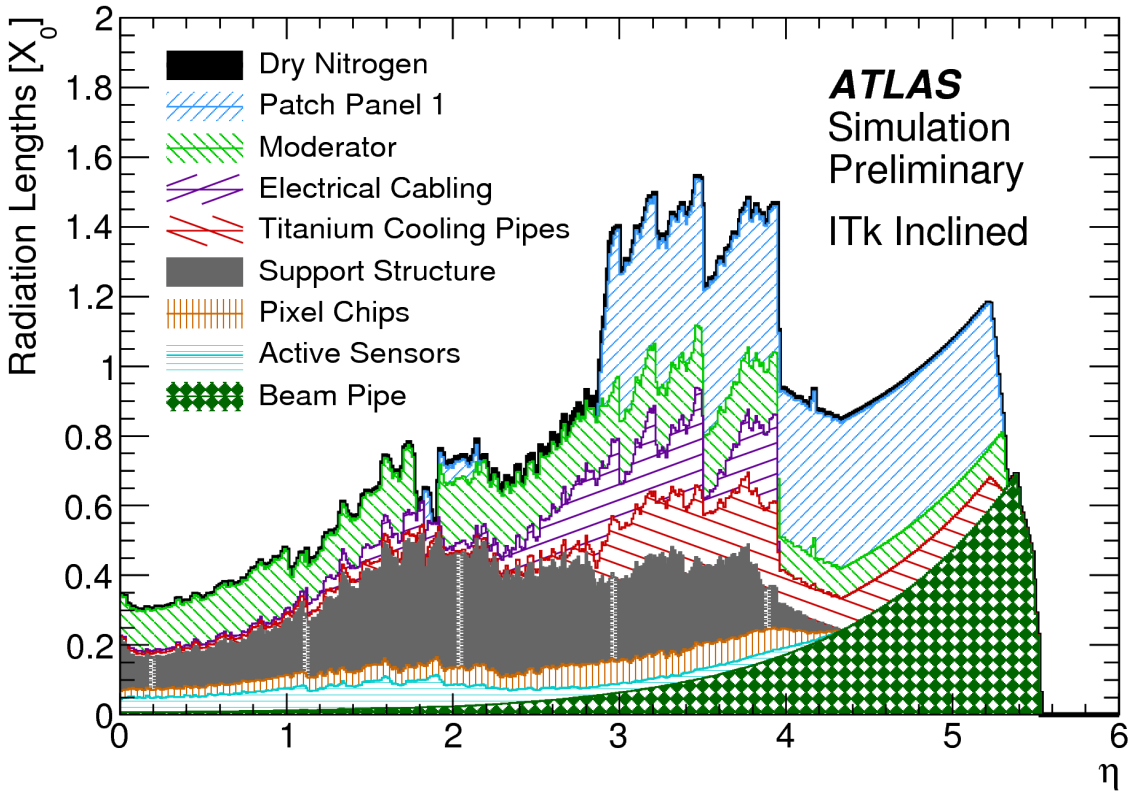
→ ATL-PHYS-PUB-2016-025





Material Budget

- Early estimate of the material budget
  - Preliminary modelling → Includes uncertainty with respect to the current engineering solutions

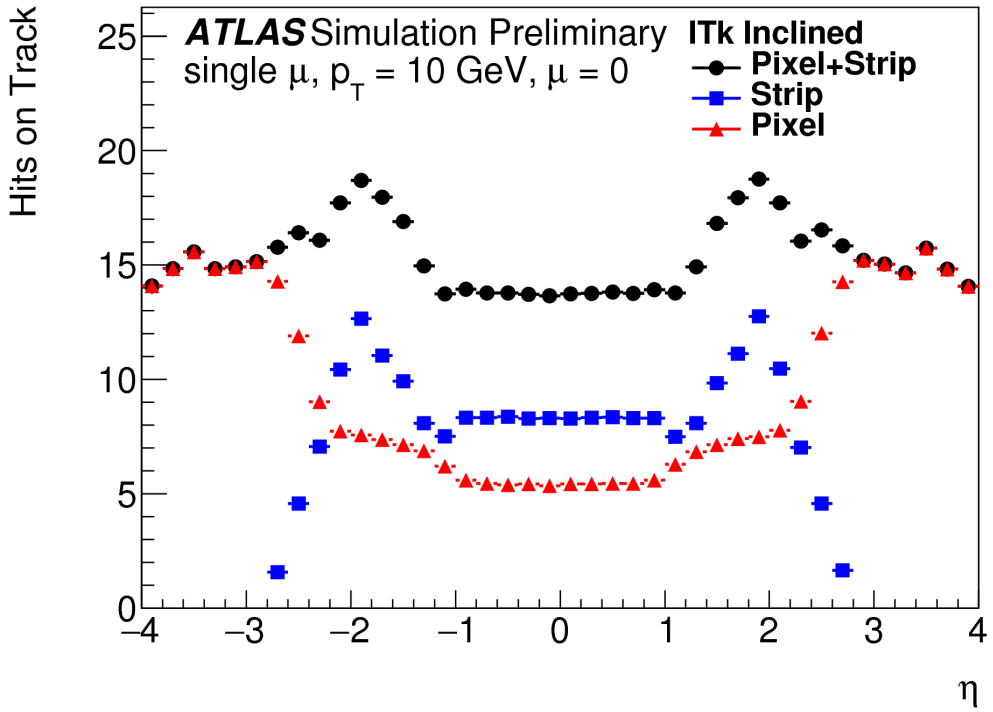


→ < **1 X_0** for the active tracker volume

→ < **1.5 X_0** before the calorimeter including the moderator

of hits and track reconstruction requirements

- Provide hermetic coverage with a minimum of 9 space points for primaries with $p_T > 1$ GeV and $z_{beam} = [-150, 150]$ mm



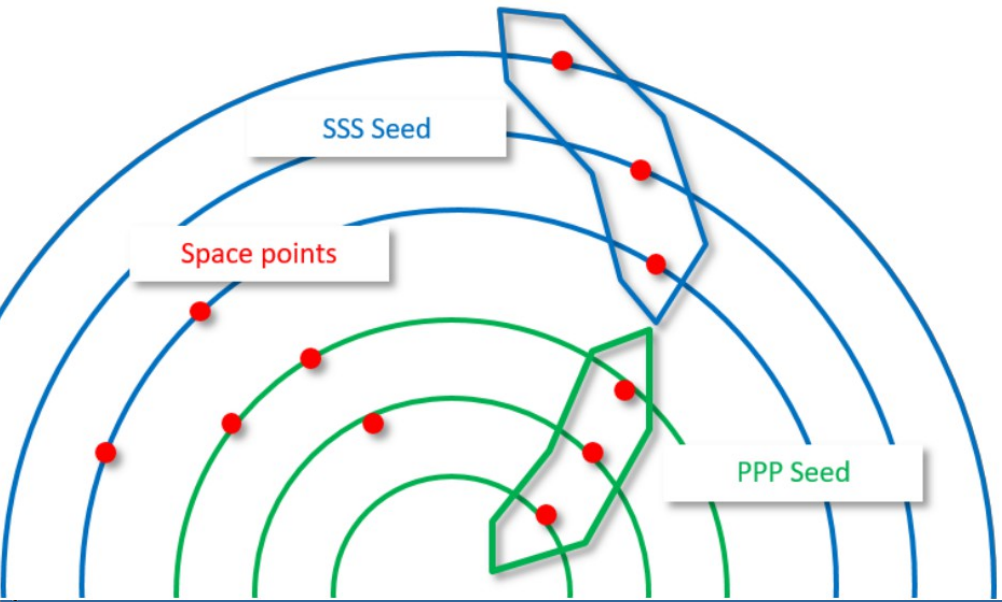
Requirement	Pseudorapidity Interval	
	$\|\eta\|<2.7$	$2.7<\|\eta\|<4.0$
Pixel+Strip clusters	≥ 9	≥ 9
Pixel clusters	≥ 1	≥ 1
Holes	< 3	< 3
Pixel holes	< 2	< 2
Strip holes	< 3	< 3
p_T [MeV]	> 900	> 400
$\|d_0\|$	≤ 2 mm	≤ 10 mm
$\|z_0\|$	≤ 25 cm	≤ 25 mm

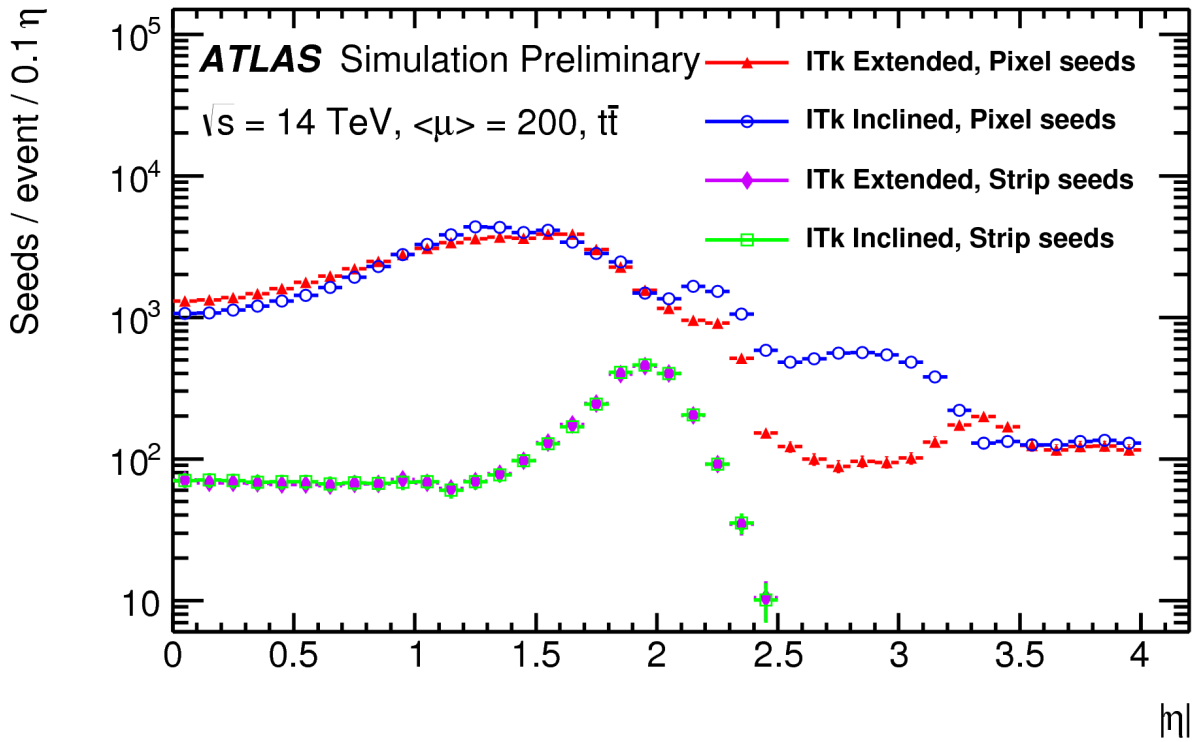
- Designed for reconstruction primary with $p_T > 1$ GeV
- η-dependent requirements needed because of limited field in very forward region

→ IDTR-2016-011

Track Seeding

- Track Seeds are constructed from 3 strip or pixel space points
  - Pixel space points are clusters; strip space points combine stereo information from each module side
  - Process strip seeds first, then pixel
- Seeds confirmed later with 4th hit



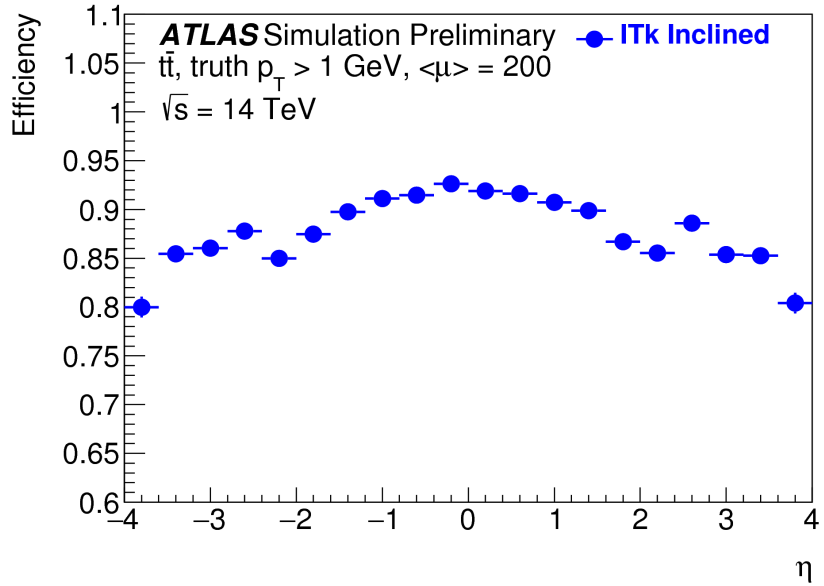


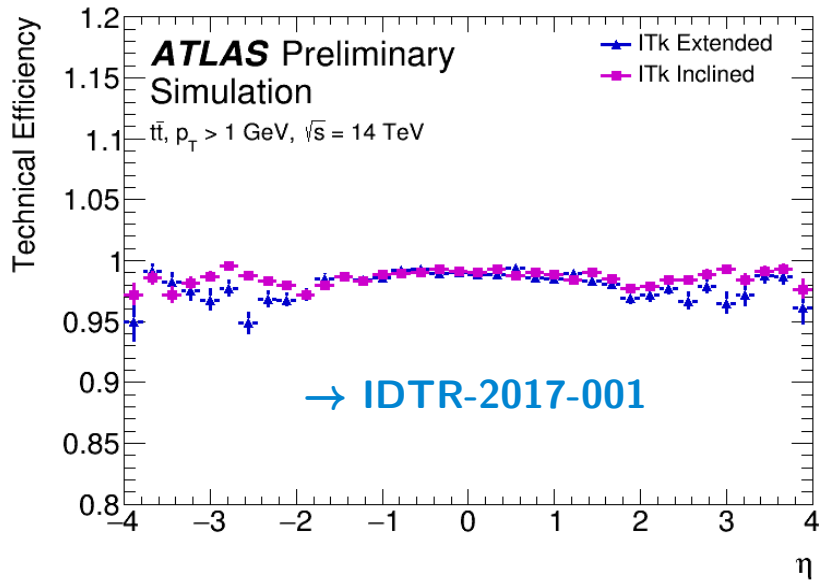
Tracking Efficiency

- Very good tracking efficiency across full acceptance
  - Efficiency defined as fraction of stable, charged, primary particles (p_T>1GeV and $|\eta|$<4) for which a reconstructed track is found

- Technical tracking efficiency
  - Take into account only particles leaving enough measurements to be reconstructed
  - Losses due to material interactions are neglected

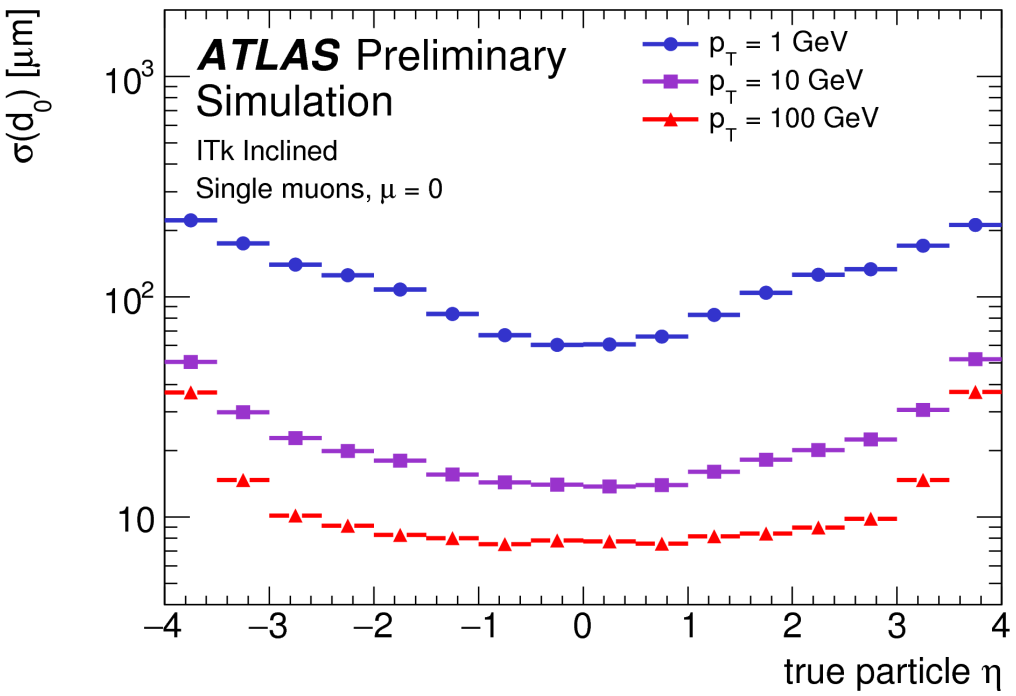
- Fakes also well under control
  - Fake rate (reconstructed tracks with no matching truth particle) < 0.1% in $|\eta| < 3.5$

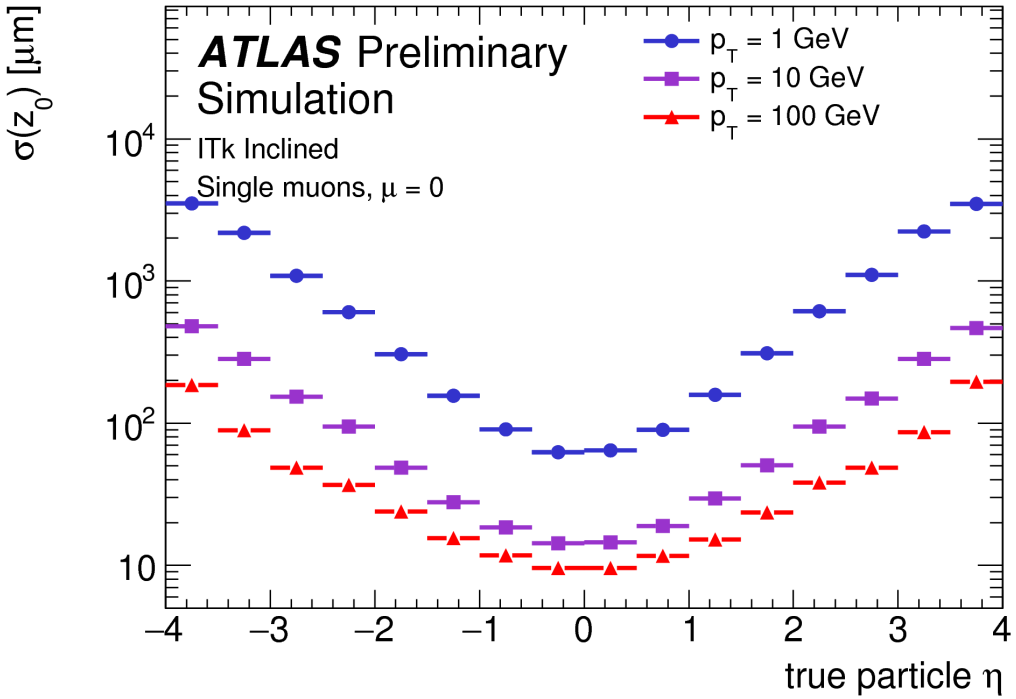




Impact Parameter Resolutions

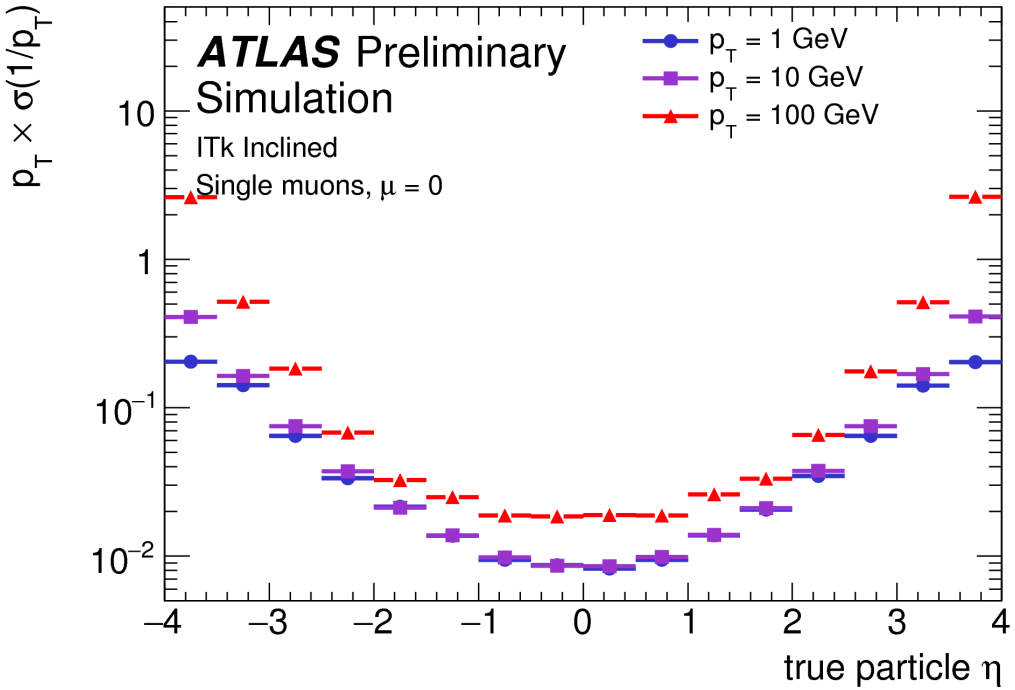
- Excellent Impact Parameter resolutions, e.g. for p_T=10 GeV muons:
  - $|\eta|<3.5$: $d_0<30$ μm, $z_0<300$ μm
  - $|\eta|<4.0$: $d_0<50$ μm, $z_0<450$ μm

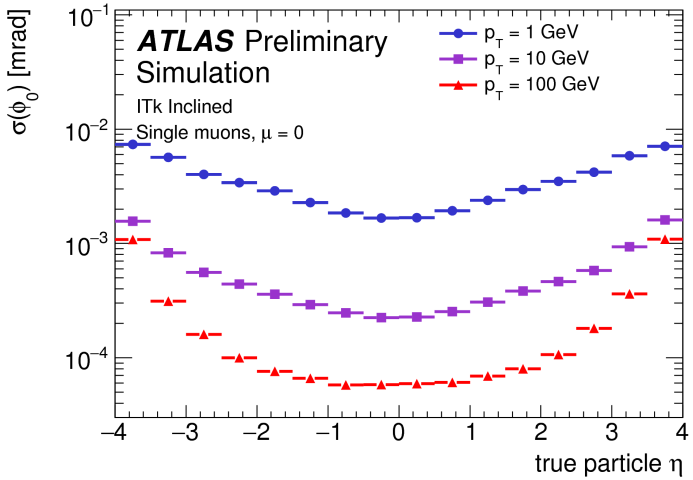


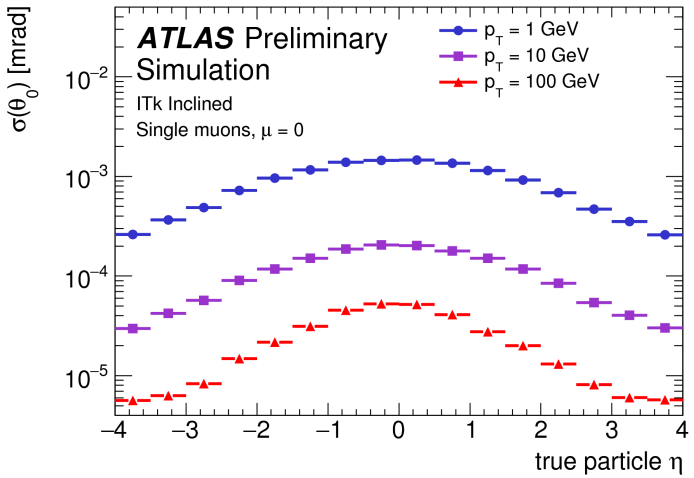


Track Parameter Resolutions

- Excellent p_T resolution
  - The benefit of high precision measurements of the all-silicon tracker of the ITk should yield a better momentum resolution than the current ATLAS ID

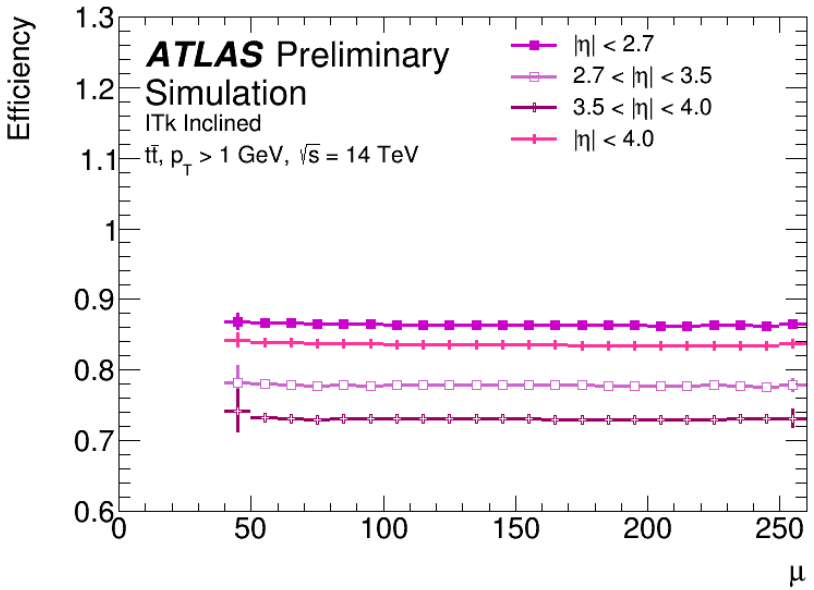






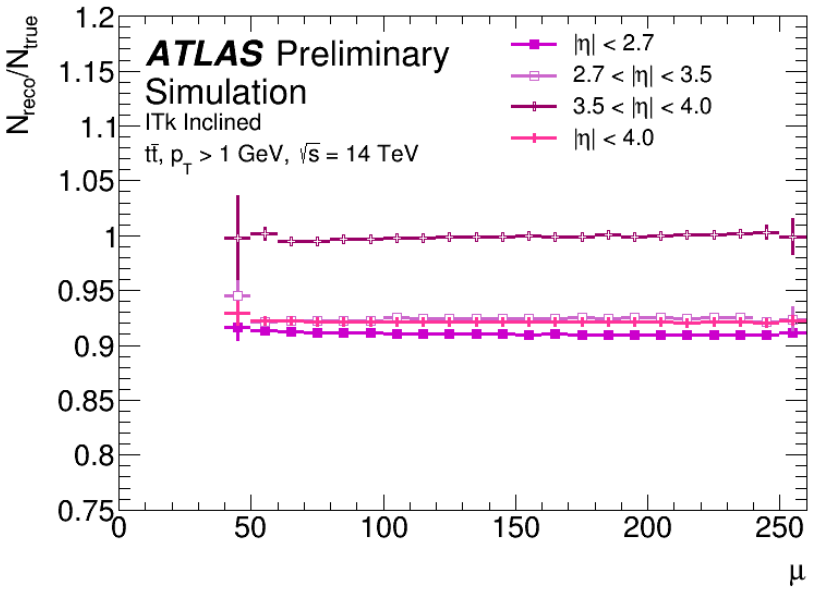
Pileup Robustness

→ IDTR-2017-001



The future tracker must be able to cope with the environments produced by the HL-LHC

← Track reconstruction efficiency versus μ extremely stable for all intervals of η

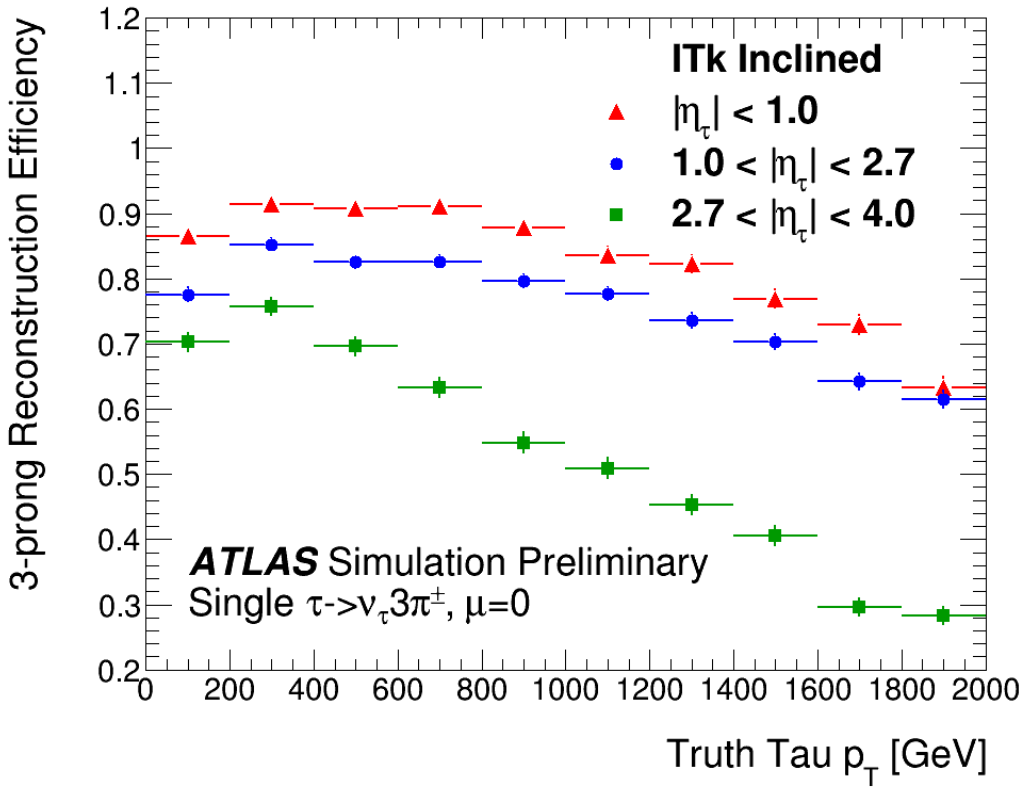


← Inclusive rate of number of reconstructed tracks over the number of generated particles

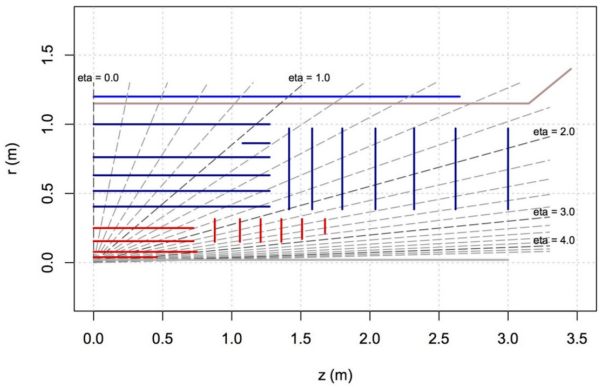
- independent of pile-up: indicates no problem with increased number of fakes

Track In Dense Environments

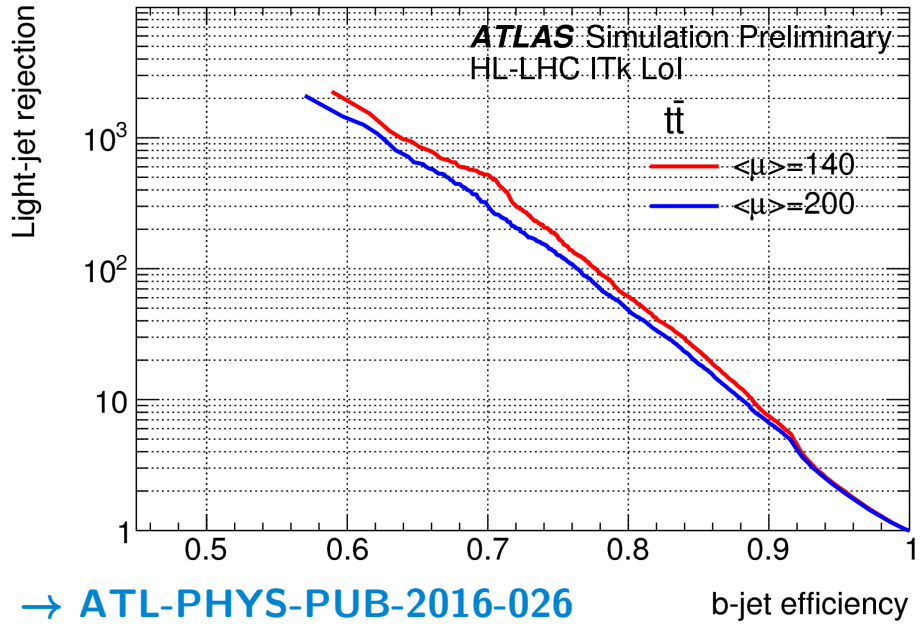
- Resolving tracks in highly-collimated boosted objects is very challenging for track reconstruction
  - The current ATLAS Inner Detector uses a Neural Network approch to identify pixel clusters arising from multiple charged particles
  - For ITk reconstruction (currently) emulated using truth information
- Dense Enviroment performance investigated using 3-prong τ decays
  - Efficiency to reconstruct all 3 tracks from decay



b-tagging



- A Neural Network is used to identify b-jets based on impact parameter and secondary vertex information
  - Sensitive to impact parameter resolution tails
  - Varying cut on NN output allows choice of efficiency/mistag working point



→ **ATL-PHYS-PUB-2016-026**

- Studies based on "Letter of Intent" ITk layout and simulation
  - $t\bar{t}$ sample with ≥ 1 semileptonic decay
  - p_T^{jet}>20 GeV, $|\eta|$<2.7
  - b-jet defined as jets matched to b-quark from top quark decay only (i.e. hard scatter b quark)

← **Excellent performance observed**

- At <μ>=200 obtain comparable performance to current Inner Detector under Run-2 conditions

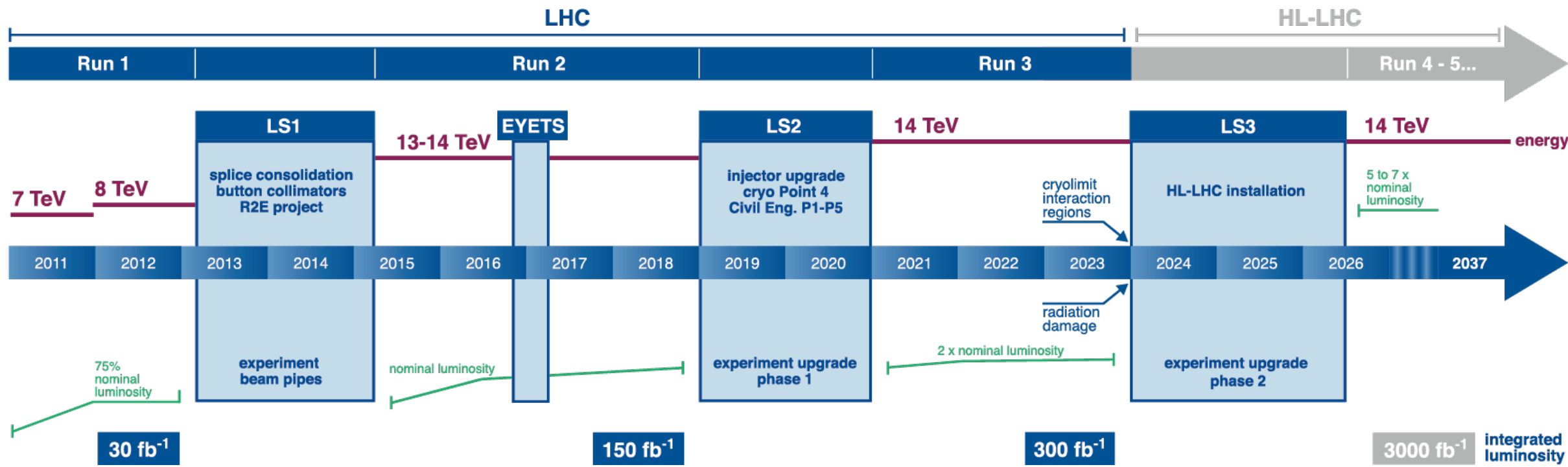
Conclusions

- The Inclined layout concept for the future ITk
  - Tracking acceptance up to $|\eta|=4.0$
  - Detailed and accurate ITk simulation to study HL-LHC pile-up scenario
  - Reconstruction developed and updated specifically for ITk
- Excellent tracking performance observed
  - High efficiency for all η-regions
  - Comparable or improved performance to Run 2 detector despite challenging high-luminosity conditions
- Extremely stable efficiency and fake rate with pile-up
- Further optimization to move towards the final layout to be documented in the Pixel TDR

Thank you

Extra Slides

LHC / HL-LHC Plan



The ATLAS Phase-II Inner Tracker

→ **More stringent requirements to cope with the new environment**

- ≤ 0.1% occupancy in the pixel layers and ≤ 1% occupancy in the strip layers
- Radiation tolerance: possibility to **extract and replace** inner parts of the pixel detector if needed

→ **Reduce the amount of material in the tracking volume**

- The tracker material is a major limitation for the overall performance
  - Interactions in tracker material limits tracking performance
  - Material in front of calorimeter affects jet and electron/photon performance
  - Thinner silicon sensors, long stave concept, innovative ring system

→ **Pileup Robustness**

- Stable performance with respect to increasing pileup

→ **System Redundancy**

- Robustness against limited detector defects

Starting from the LoI...

The ITk layout design process started from the LoI proposal in 2013

- Pixel Detector:

  → **4 pixel layers + 6 disks**

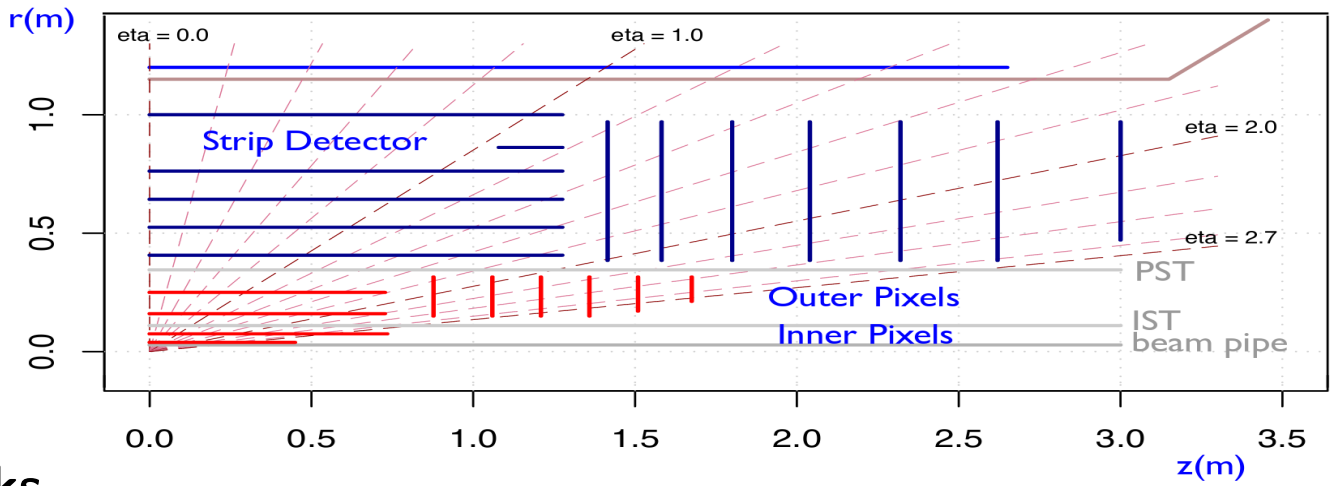
  - Two inner pixel barrel layers removable

- Strip Detector:

  → **5 barrel layers + stubs + 7 disks**

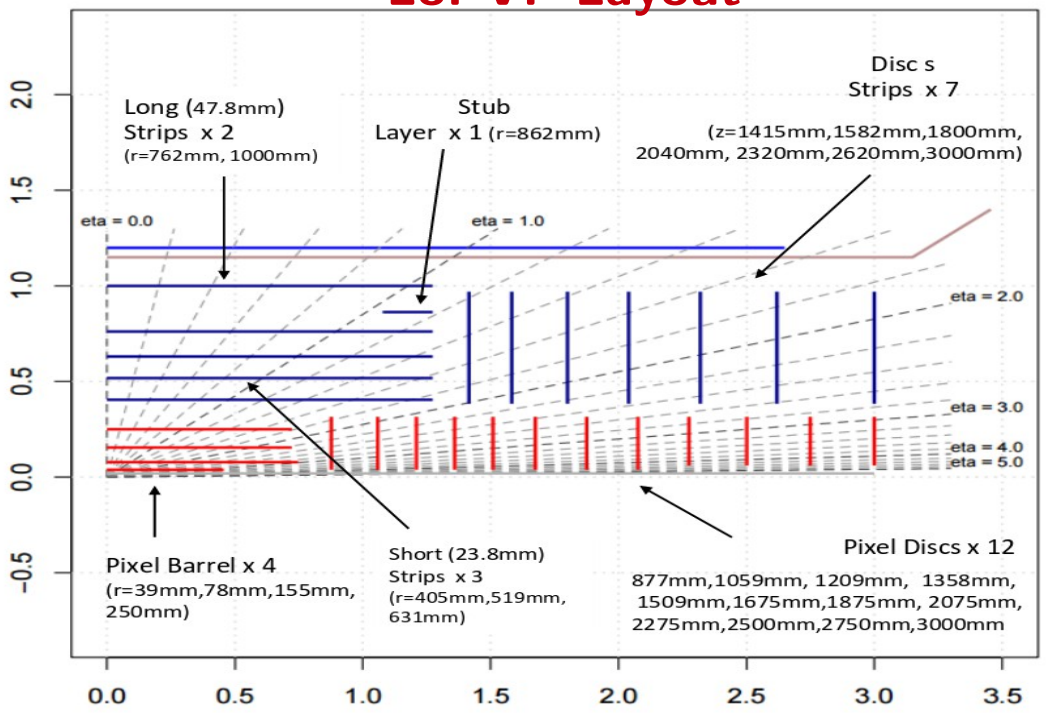
  - Stubs are inserted to maintain hermeticity and provide good momentum resolution in the barrel-endcap transition region
  - Barrel layers and endcap disks have back-to-back small stereo-angle sensors
  - Reduced strip length is used in the innermost layers to limit occupancy

LoI Layout



... towards the LoI-Very Forward Layout

Scoping Document
LoI-VF Layout



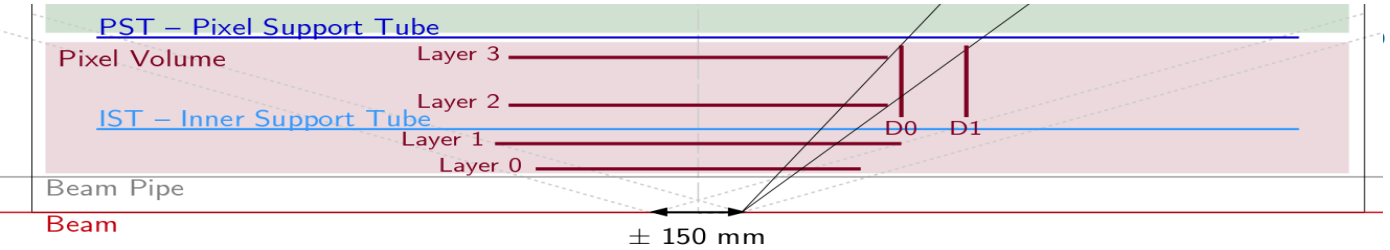
Extended tracking acceptance: up to $|\eta|$~4

$\rightarrow$ concerns mostly the pixel detector

- Used for studies up to $|\eta|$~4 and starting point for optimisation
- Hermetic for primary vertices within $\pm$150 mm around the origin and tracking performance not to fall down just beyond this region, up to 200 mm

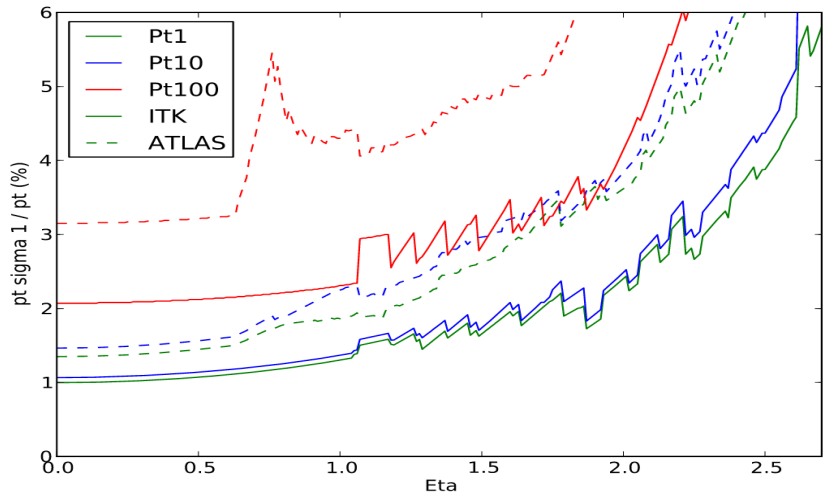
All the studies on LoI and LoI-VF have been the enormously important to establish the starting point for the layout definition

ATLAS LoI Layout Design Consideration



- Length of inner barrel layer is given to provide coverage up to $|\eta|$~2.7
- Length of outer barrel layers is mainly given by construction constraints and costs
- For both sub-detectors, fixed the position of the first disk, the radius of the last layer is determined in order to provide hermeticity
- The next disks are added taking into account the fall-off of the layers

The radius of the innermost pixel layer is chosen to be as close as possible to the beam pipe



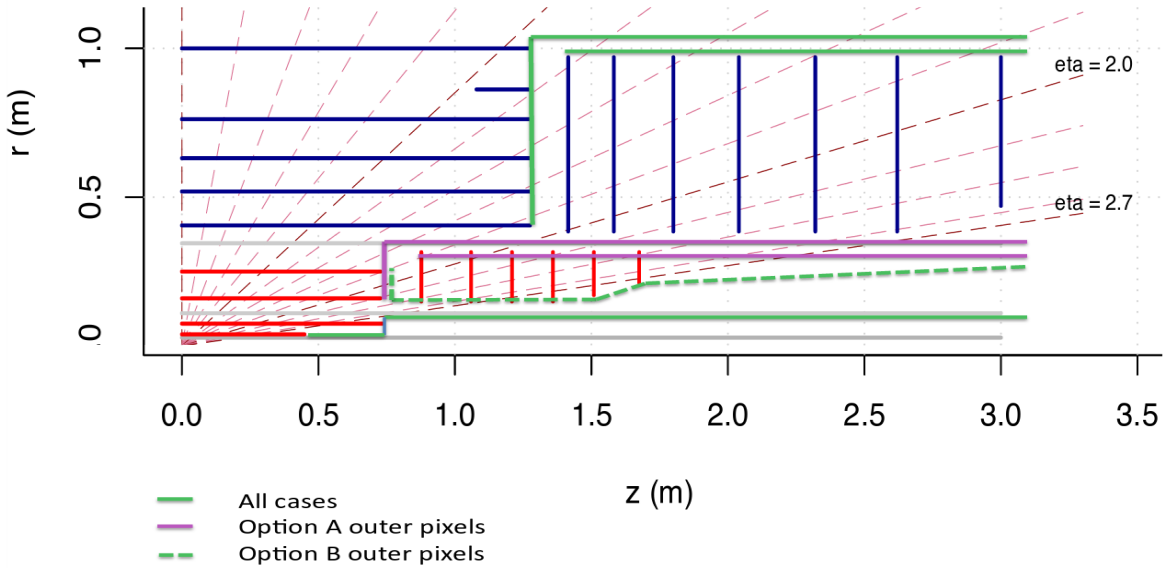
Inverse-p_T resolution using resolution model, measured as a function of $|\eta|$ for the LoI layout, and comparison with the existing ATLAS experiment

→ Letter of Intent (LoI) Layout – ATL-UPGRADE-PUB-2012-004

More on the ATLAS LoI Layout Design Consideration

- The services, the material budget, the placement of patch panels and manifolds, and the service routing, affect performance

- Many service layouts have been considered to study the effect on performance, e.g. impact parameter and momentum resolution, in the tracking volume.



Possible service layouts for the outer pixel layers

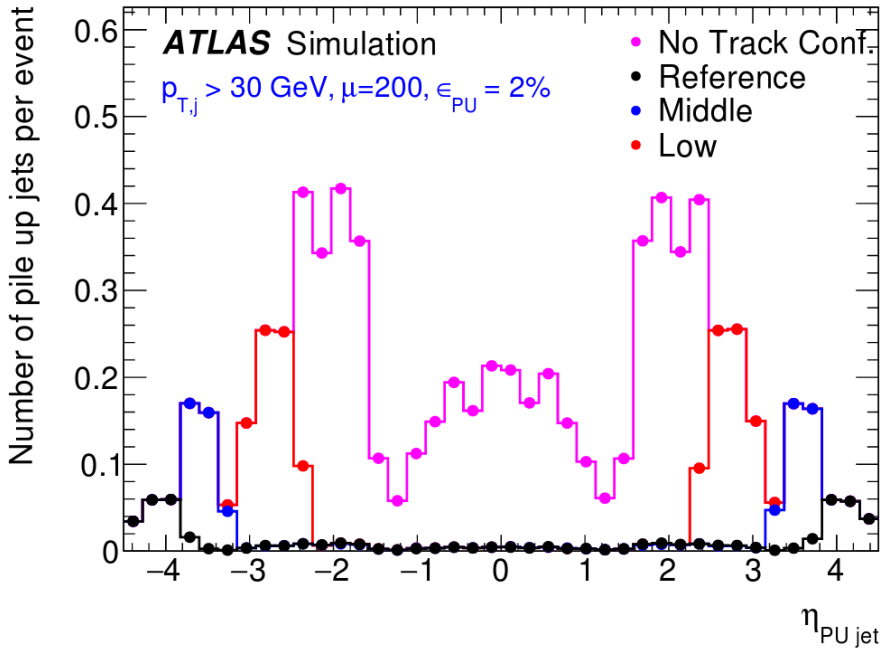
→ Letter of Intent (LoI) Layout – ATL-UPGRADE-PUB-2012-004

Extended Coverage Scenario

Pileup jets are rejected based on the **momentum of tracks within a jet** associated with the primary vertex:

$$R_{p_T} = \frac{\sum_i (p_T^{track,i})}{p_T^{jet}}$$

Measuring tracks at high pseudo-rapidity extends the range of this technique.



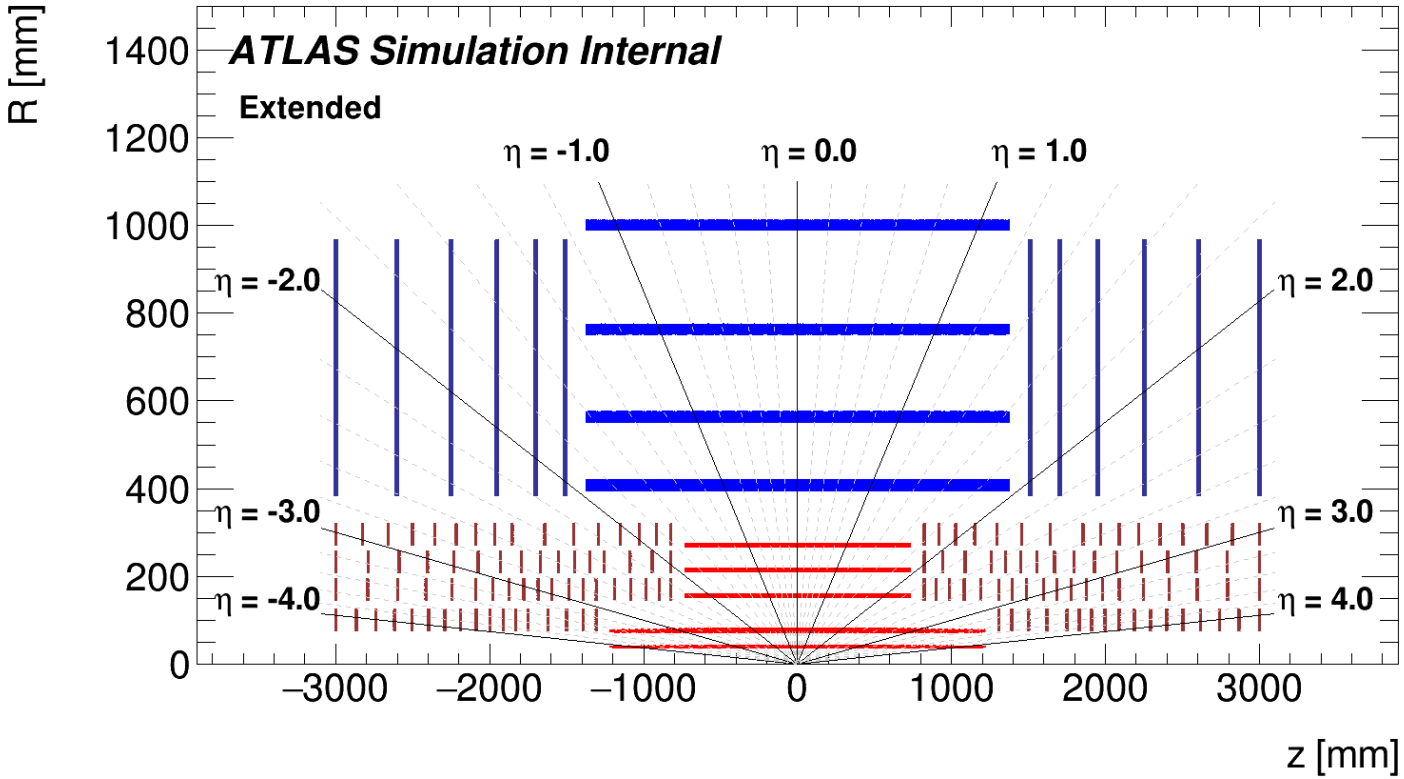
Distribution of the number of pile-up jets per event with no tracking confirmation (TC), and applying the TC algorithm tuned to give 2% pile-up jet acceptance, for each of the three scoping scenarios.

→ ATLAS Phase-II Upgrade Scoping Document – LHCC-G-166

The Extended Layout Concept

→ **Combine classical barrel with ring system**

- Long barrel layers extend tracking acceptance up to $|\eta|$~4 → long pixel clusters



- Ring system was optimized for at least 9 measurements, for z_0 in [-15 cm, 15 cm]

The Extended Layout Concept

→ Combine classical barrel with ring system

- Long barrel layers extend tracking acceptance up to $|\eta|\sim4$ → long pixel clusters

→ PROS

- Very precise and efficient measurement as close as possible to the interaction point
- Potential to reduce fake track rates by rejecting clusters with incompatible length
- Luminosity measurement by cluster counting

→ Room for even more improvement by making use of the full cluster information

  - θ and z_0 from cluster length, better d_0 from charge sharing, dE/dX, Φ shape

→ CONS

- Adaptation of traditional reconstruction algorithms is not trivial

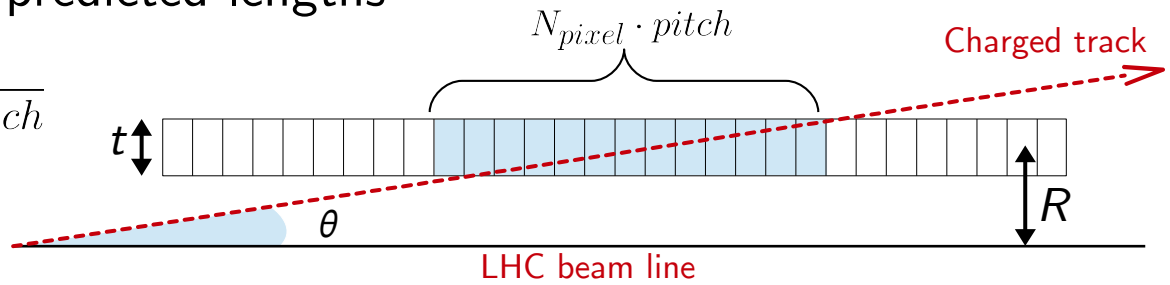
  → e.g. broken cluster due to pixel inefficiencies and signals under threshold

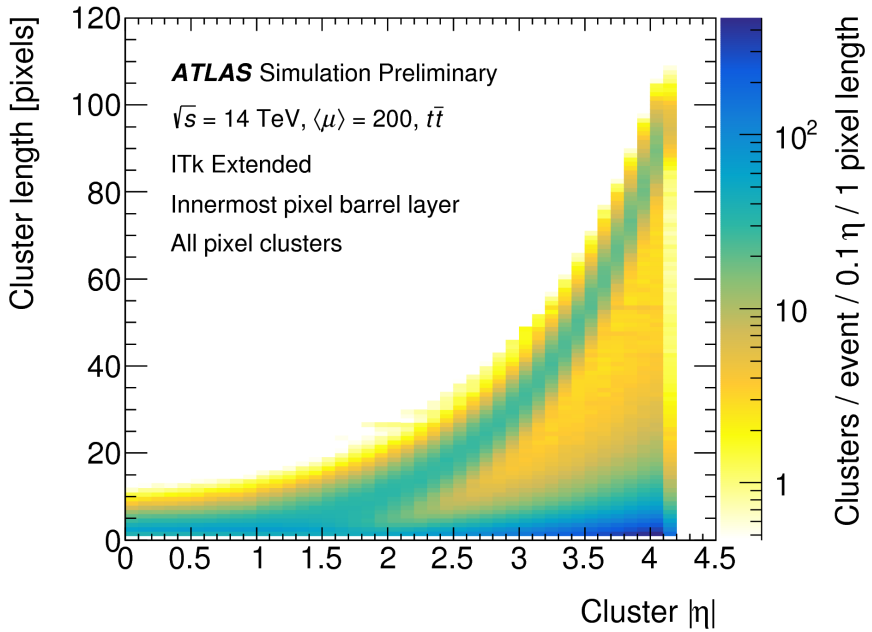
  → Dedicated cluster merging
- Material traversed by tracks (shallow angle) could be particularly harmful at low momenta
- Increase in channel occupancy due to the large number of pixels crossed

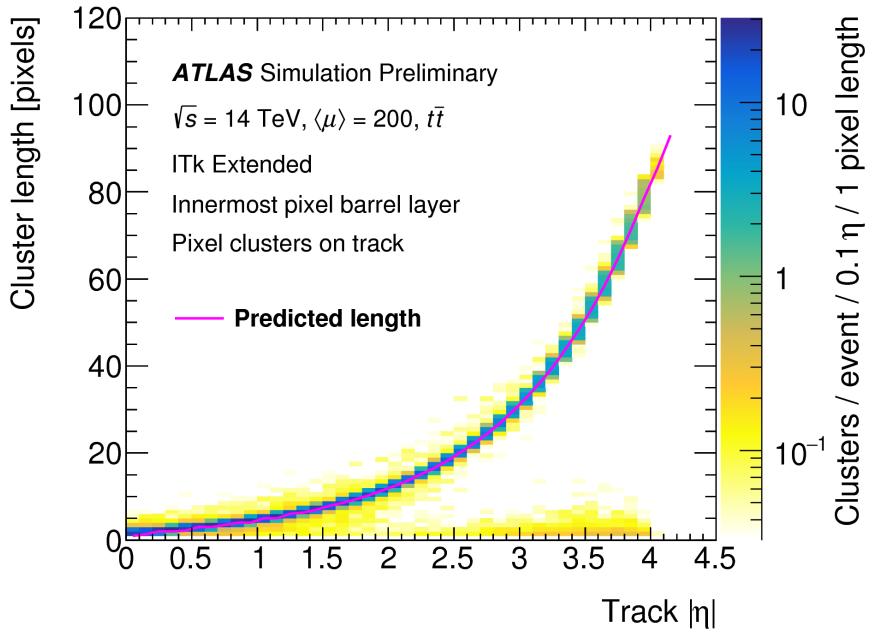
Extended Barrel and Long Clusters

- Employ simple algorithm to merge split clusters
  - Cluster length mostly in agreement with predicted lengths

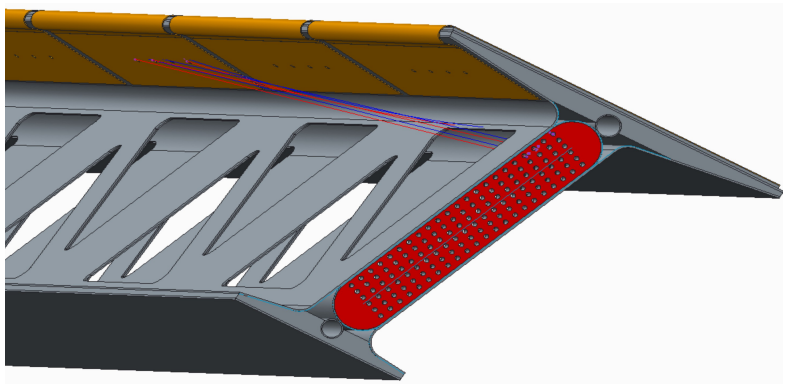
$$\tan\theta = \frac{t}{N_{pixel} \cdot pitch}$$





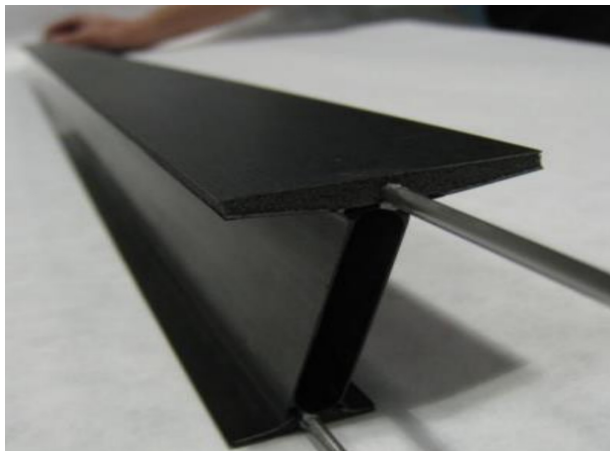


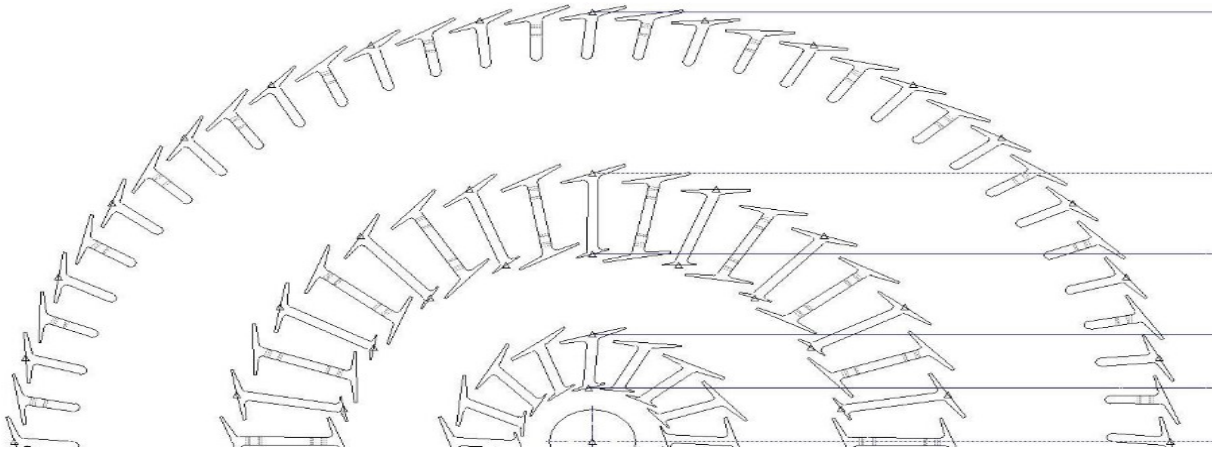
Extended Stave Design and Prototyping



→ **Support structure design bound to layout choice**

- For the extended layout the "I-beam" design has been proposed:
  - Modules are always "outward" facing
  - Services and cooling planned to run within the structure
  - Coupled layers with different widths available
  - Adaptable height and tilt angle





The Inclined Layout Concept

→ The Inclined Layout provides many hits at large |η| close to the beam spot

- With tilted sensors in the high |η| region we expect several hits per layer (tracklets) and less material crossed given the low incidence angle

→ PROS

- Pushing barrel services and supports out in z
- Minimization of the traversed material inclining the module
- Allows track finding with several hits close to the interaction point
- For outer barrel layers provides a strong reduction of sensor surface
- Smaller clusters

  → reduction of channel occupancy, minimization of probability of overlap between tracks

→ CONS

- Required additional design and qualification
  - Thermal management
  - Assembly procedure
- Smaller clusters

  → 1-pixel clusters resolution can't be better than pitch/$\sqrt{12}$

Inclined Stave Design and Prototyping

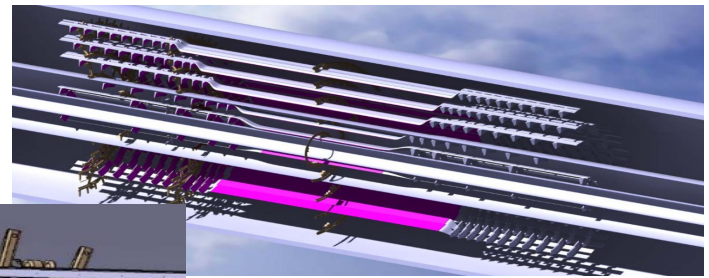
→ **Support structure design bound to layout choice**

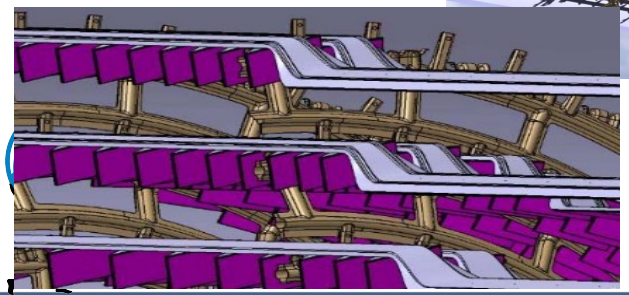
- For the inclined layout two designs have been proposed: **Alpine** and **SLIM**

  → **Process to merge the two efforts ongoing**

Alpine

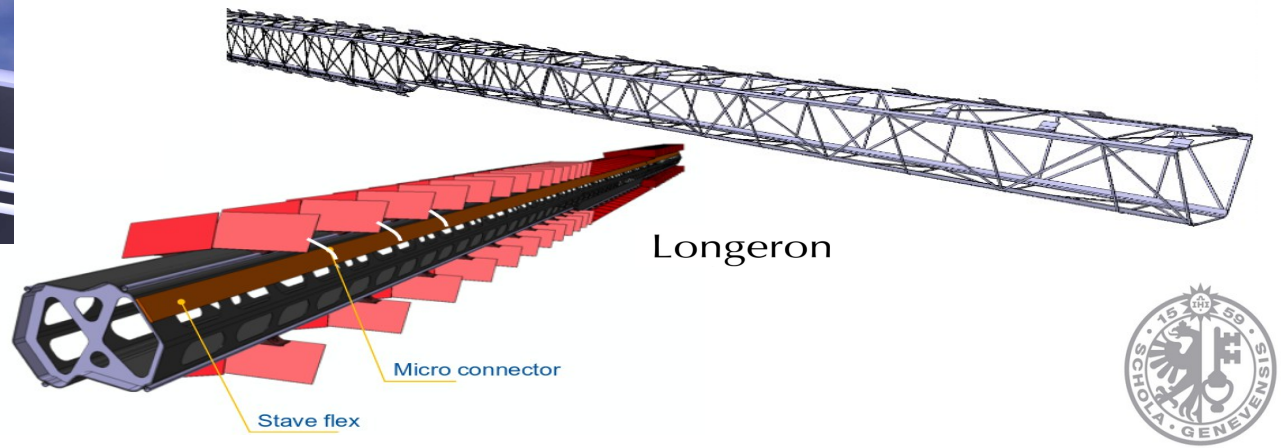
- T. Todorov† pioneer of the "inclined" idea
- Two types of modules: barrel and inclined
  - carbon foam + carbon fibre "IBL-like" stave design





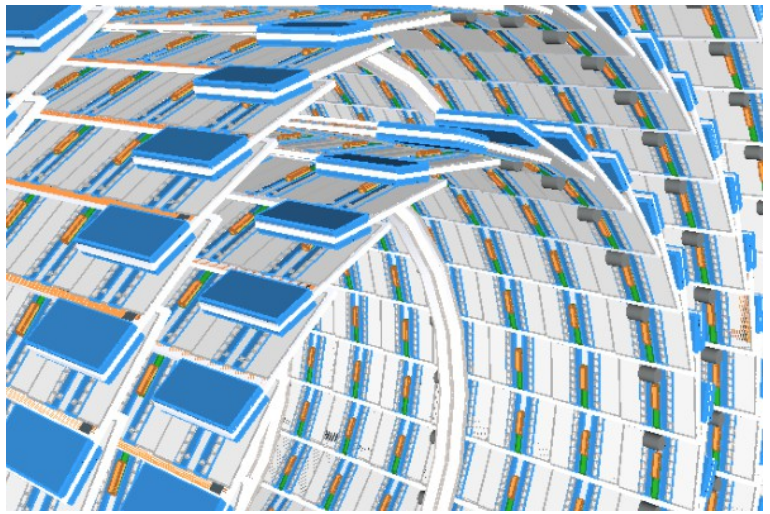
SLIM: Stiff Longeron for ITk Modules

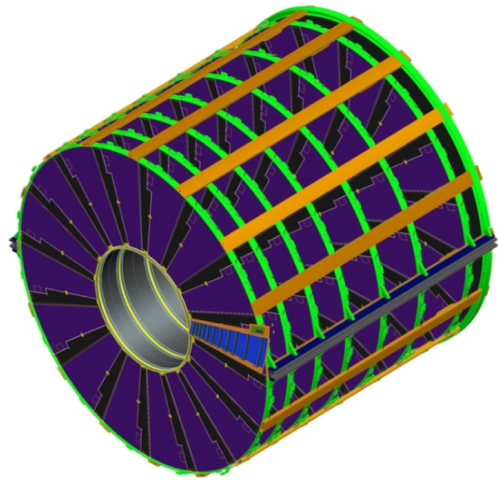
- Two types of modules: barrel and inclined
- Inspired from ALICE: common structure ("Longeron") supporting two layers of modules
- Two longeron designs: Shell and Truss



The ATLAS ITk Strip Layout

- **Barrel:**
  - 4 double-sided layers
  - Stereo angle: +/- 26 mrad

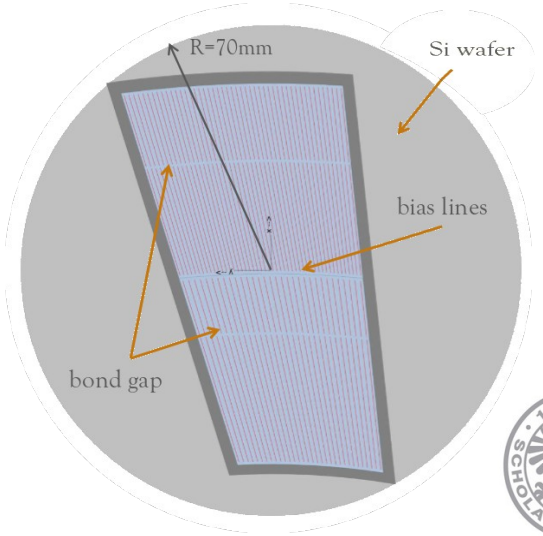




- **Endcap:**
  - 6 discs: double-sided petals

    → 6 different types of sensors in radius
  - Sensor's **irregular shape**

    → two tilted straight edges: +/- 20 mrad stereo angle built in

    → two circular edges: uniform gap between the sensors

    → Strips are pointing to the strip focus (not the beampipe)