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

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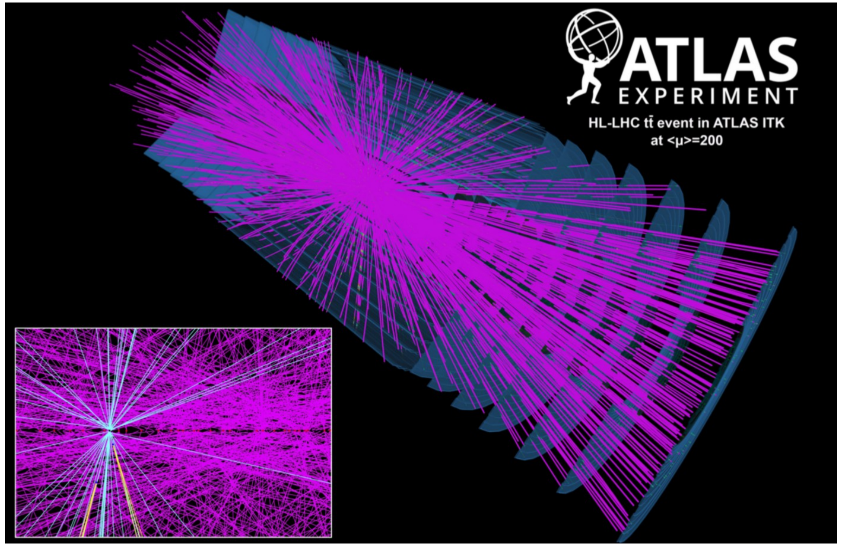
The ATLAS Phase-II Inner Tracker

ITk (Inner Tracker) is a full upgrade of the ATLAS Inner Detector as part of the Phase-2 upgrade

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

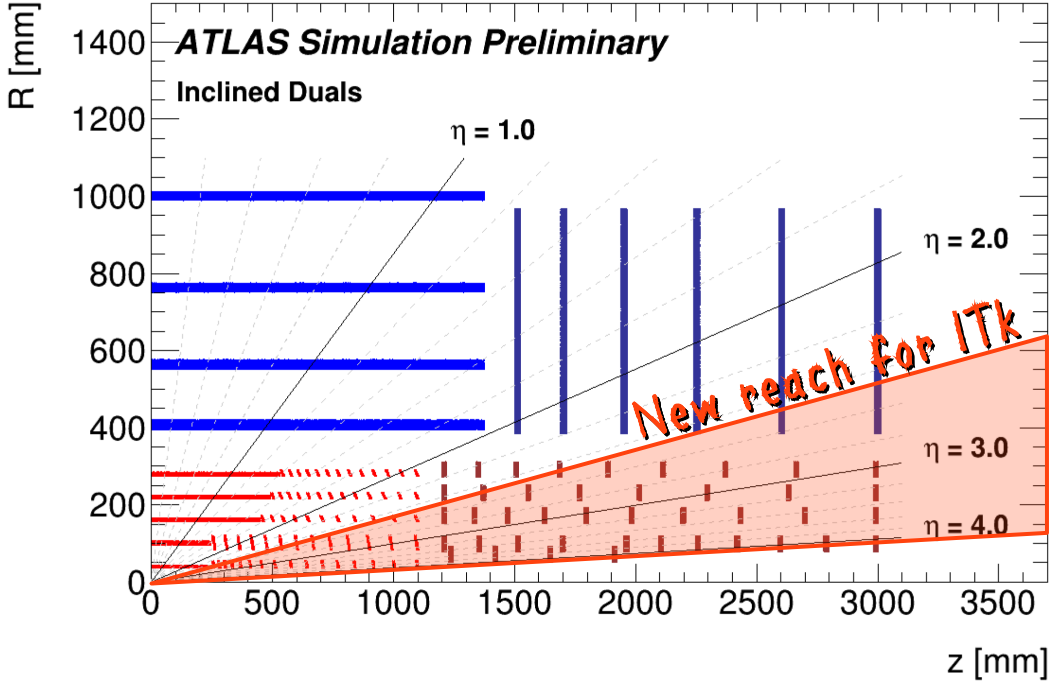
→ Designed to operate successfully under HL-LHC operating conditions corresponding to:

- Levelled 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 centre of mass

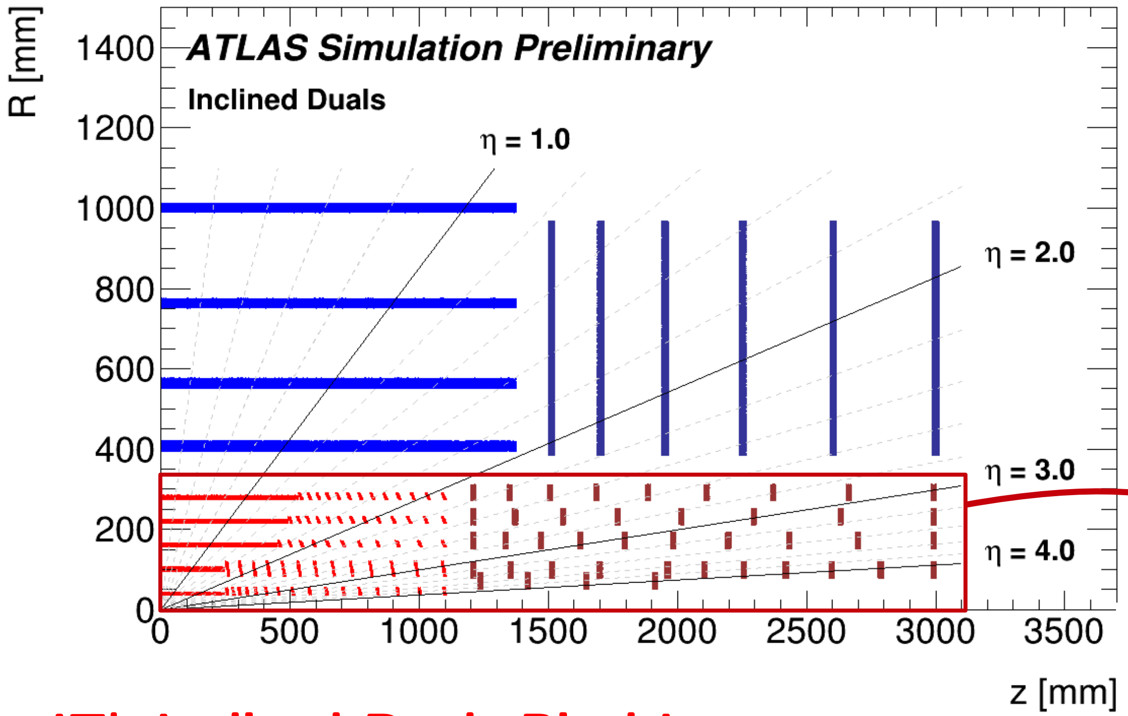


- **Extended tracking acceptance: up to $|\eta|$~4**

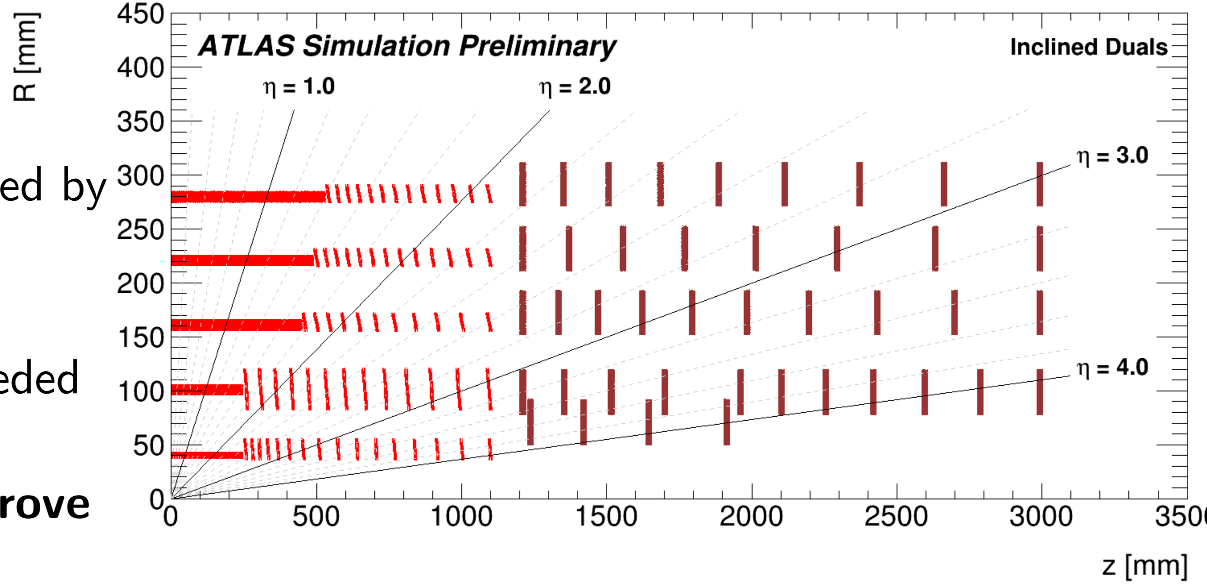
  → concerns mostly the pixel detector
  - Improved sensitivity and acceptance in VBS, VBF Higgs studies, bbH, H → 4l, etc.
  - Pile-up jet suppression → Improved MET resolution
  - Better identification of the hard scatter vertex
  - Improved identification or suppression of b-jets
  - Increased range for lepton reconstruction



- **Important milestones:**
  - TDR for the ATLAS ITk Strip Detector
  - TDR for the ATLAS ITk Pixel Detector in finalising process: submitted to LHCC



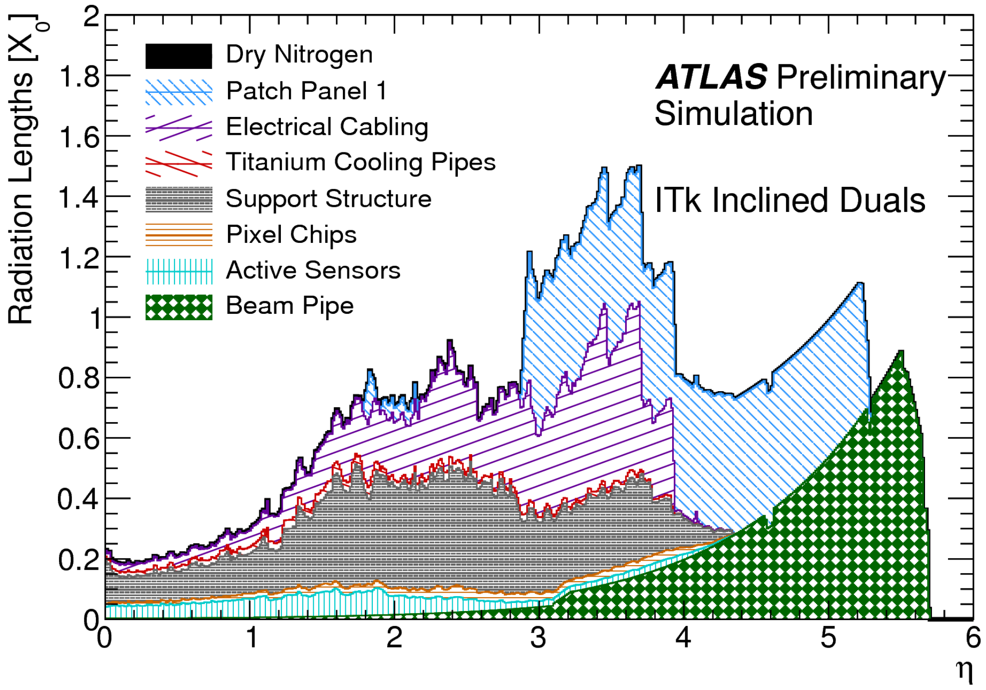
- **ITk Strip Layout**
  - Four strip **barrel layers** and six **end-cap** discs:
    - Covers up to $|\eta| < 2.6$
- **ITk Pixel Layout**
  - Five pixel **barrel layers** and a **ring end-cap system**
  - → 2 pixel system designs have been proposed
    - **→ Nora Pettersson @CTD2017**

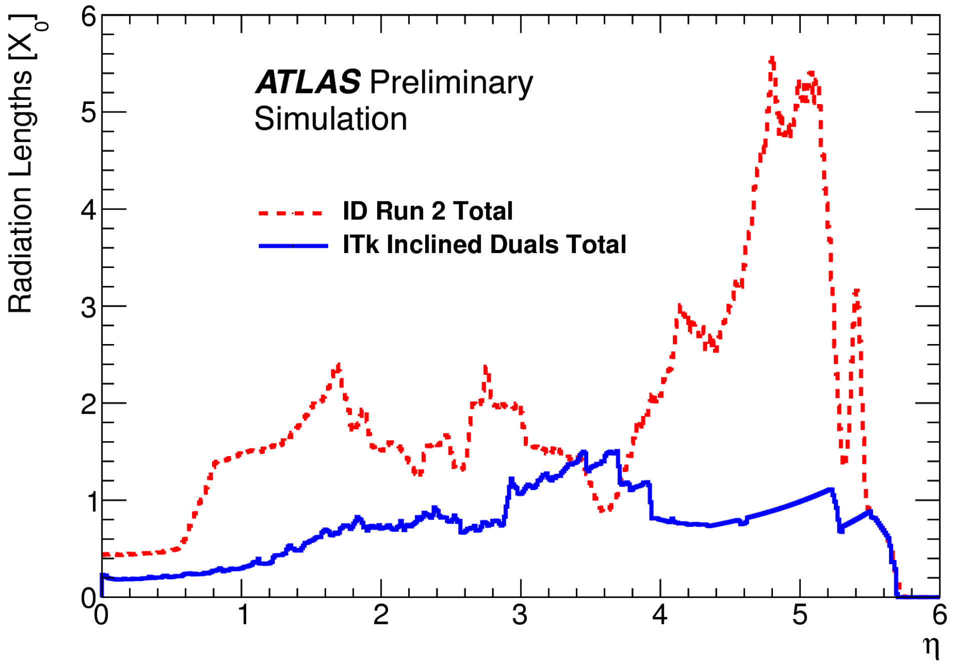


- **ITk Inclined Duals Pixel Layout**
  - **Inclined modules reduces the material** traversed by particles and **improves tracking performance**
    → multiple hits/layer to provide robustness
  - **Less silicon surface** than a traditional barrel needed to cover the same detector volume
  - **End-cap rings** replacing traditional disks to **improve the hit coverage** with less silicon surface

Material Budget of the ITk

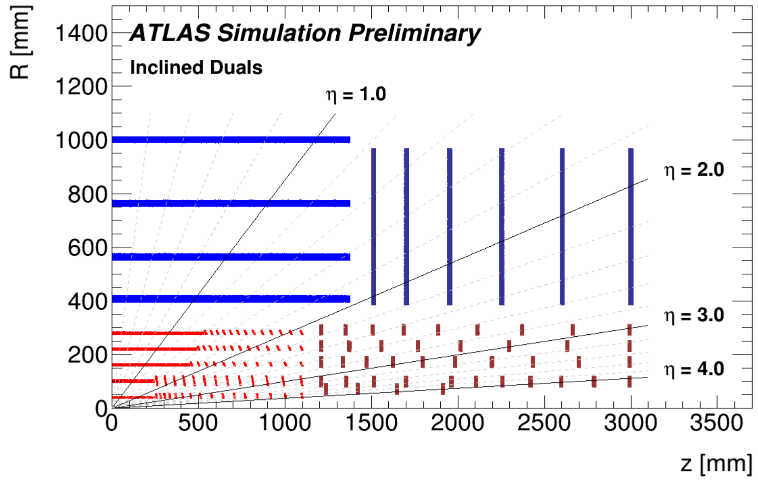
- Material distribution of $\mathbf{X_0}$ **versus** $\boldsymbol{\eta}$ based on the **detailed modelling** of the Pixel and Strip Detectors
  $\rightarrow$ $<$ **1** $\mathbf{X_0}$ for the active tracker volume
  $\rightarrow$ $<$ **1.5** $\mathbf{X_0}$ before the calorimeter including the moderator





- For comparison the same distribution is shown for the current ATLAS Inner Detector

Number of Hits

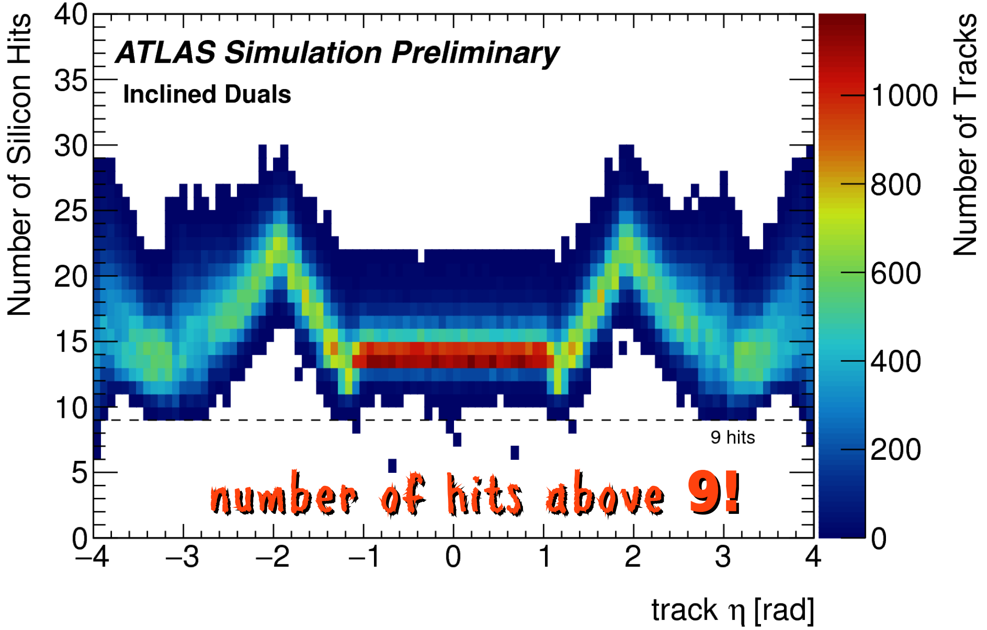


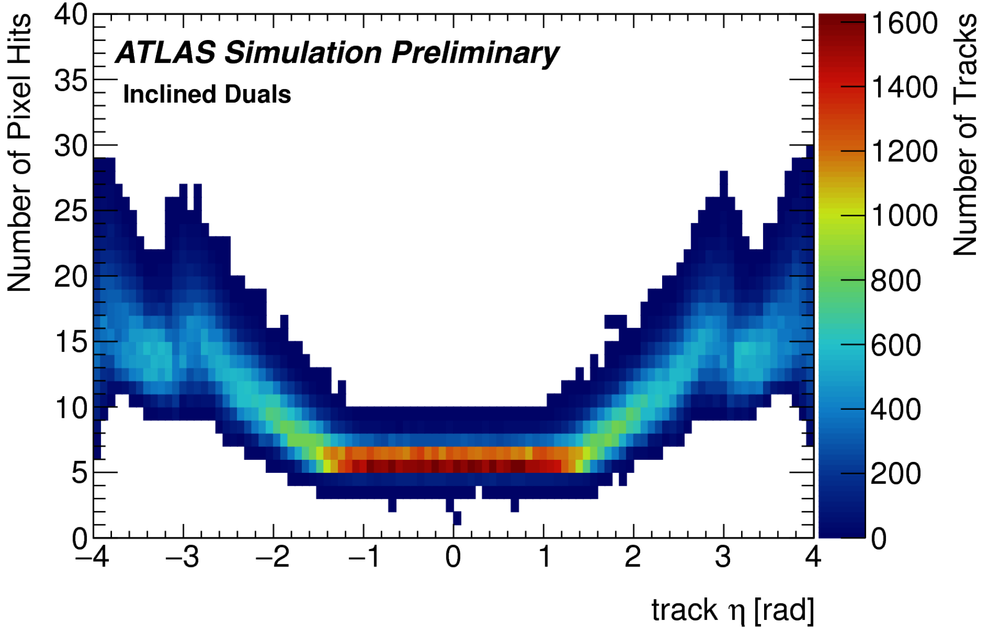
- Provide **hermetic coverage** with a **minimum of 9 hits** for primaries with $\mathbf{p_T}$**> 1 GeV** and $\mathbf{z_{vertex}}$**= [-150, 150] mm**

→ Strip+Pixel provide a total of **13 hits for |η|<2.6**

  - **11 hits** in the strip barrel/end-cap transition (|η|~1.2)

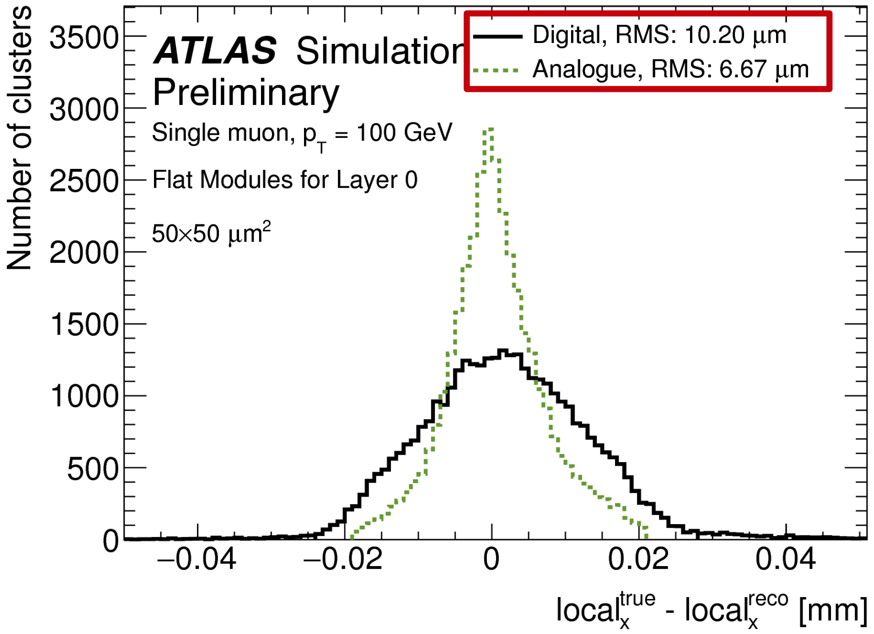
→ The **pixel end-cap system** is designed for of at least **9 hits from |η|>2.7** (except very close to |η|~4)

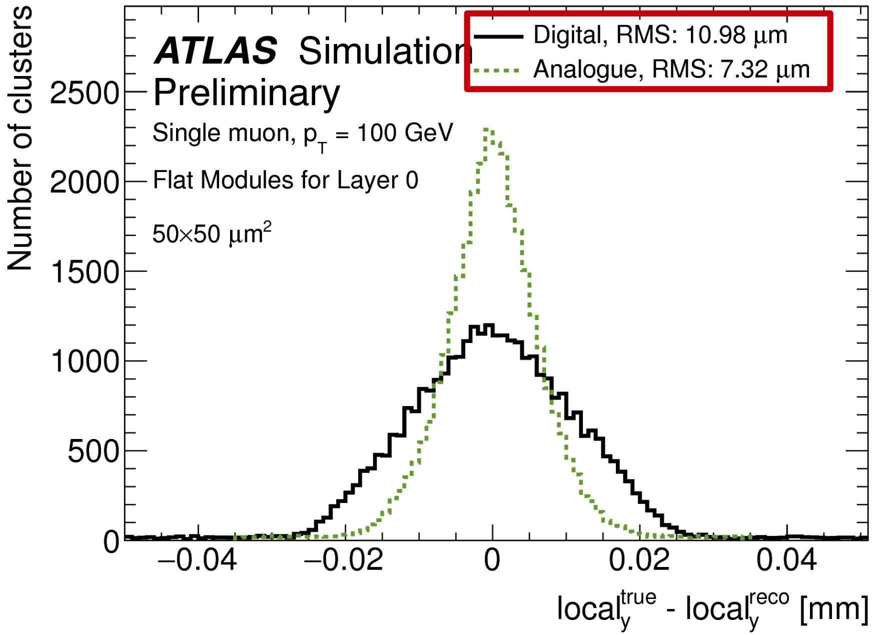




Track Reconstruction: Cluster Formation

- The first step of event reconstruction is the **formation of clusters from individual channels** with a hit from Strip and Pixel detectors
  - Two algorithms to determine position and uncertainty of particle producing the cluster
    - → **Digital clustering**: geometrical centre of cluster
    - → **Analog clustering**: use charge information to improve position determination





Track Reconstruction: From Seeds to Tracks

1. Seeding

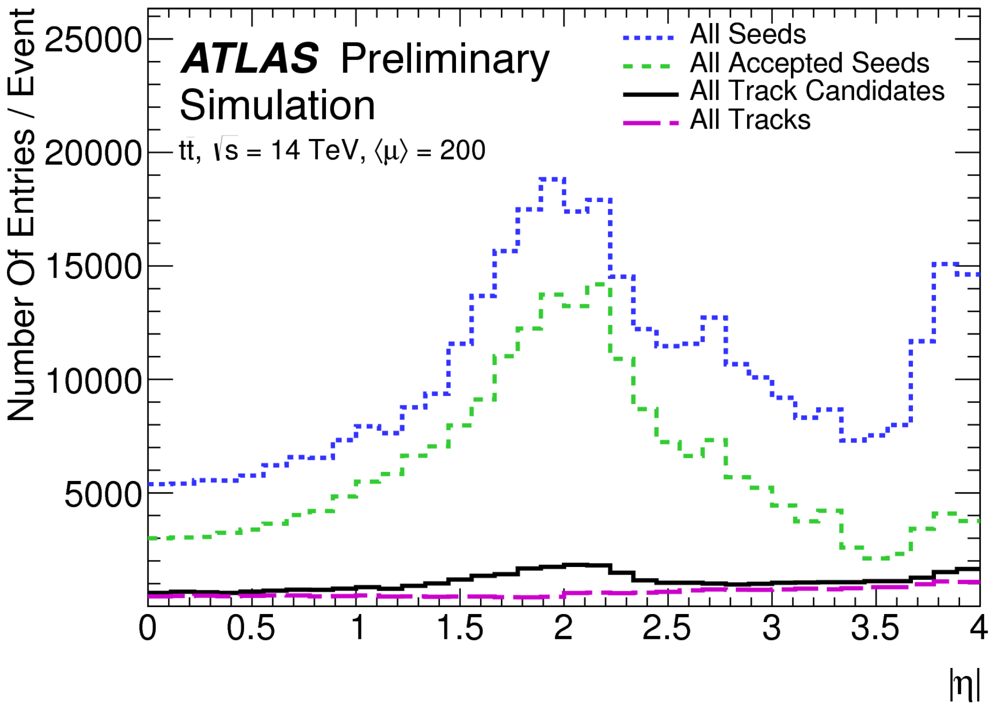
Seeds are formed by 3 x space points (SP): PPP and SSS. Must be compatible with helical track model with min p_T, IP cuts + 4th layer confirmation.

2. Track Finding

Using accepted seeds, a search road is defined. Combinatorial Kalman filter is used to find track candidates.

3. Ambiguity Solving

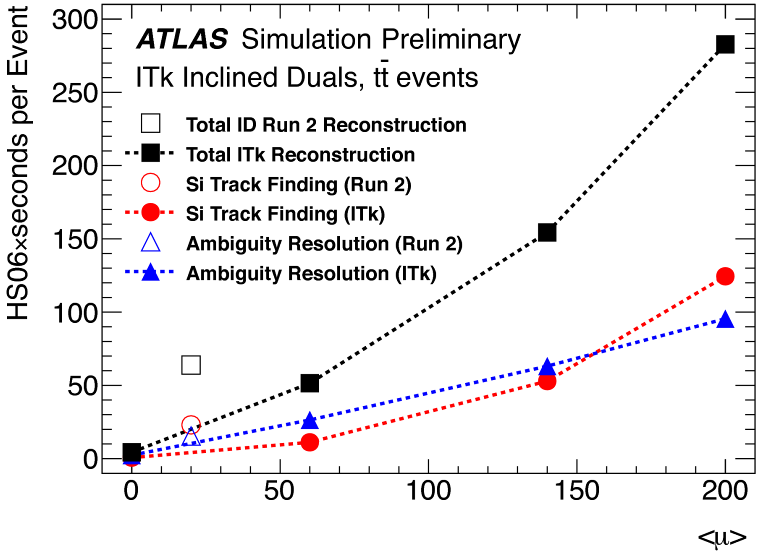
Tracks fitted using a global-χ^2 track fit.
Final assignment of clusters to competing tracks based on scoring algorithm.



Summary of **all seeds**, **selected seeds**, **candidates and final tracks** after ambiguity resolution

Evaluation of Computing Requirements

- Phase-II environment is **challenging in terms of CPU time** needed for reconstruction given the extremely **high pile-up**
  - Cost driver for computing for Phase-2, in particular for HLT farm and Tier-0
  - CPU performance taken into account in the layout optimisation process
    - e.g.: avoid long gaps between hits or problematic material concentrations



→ CPU breakdown in HS06

Detector	Cluster Finding	Space Points	Si Track Finding	Ambiguity Resolution	TRT + Back Tracking	Primary Vertex	Total ITk/ID
ITk, $t\bar{t}$ $\langle\mu\rangle = 200$	26	24	124	96	-	6	283
Run-2, $t\bar{t}$ $\langle\mu\rangle = 20$	1.5	0.7	23	15	19	0.5	64

→ **ITk with $\langle\mu\rangle = 200$ less than 5 times slower than current Run-2 detector with $\langle\mu\rangle = 20$**

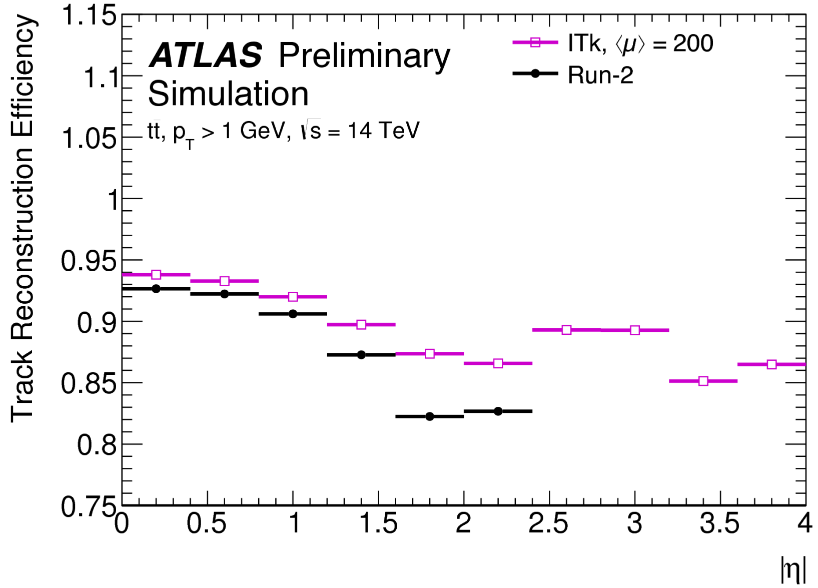
- Much reduced scaling with pile-up
- Of course, this is done with today's software
  - Confident to further improve on CPU

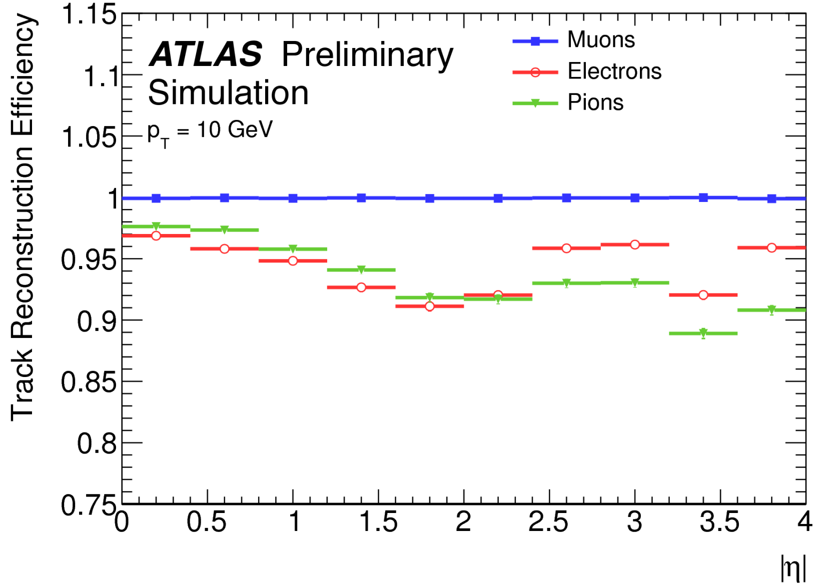
Physics Tracking Efficiency

- The **physics tracking efficiency** is one of the most important performance criteria for a tracking detector
  - Fraction of prompt particles matched, i.e. sharing at least 50% of the hits, with truth tracks passing a track quality selection:

$$\epsilon_{\mathrm{track}} = \frac{N_{\mathrm{reco}}\,(\mathrm{selected},\ \mathrm{matched})}{N_{\mathrm{truth}}\,(\mathrm{selected})}$$

- **Muon** reconstruction efficiency **close to 100%** even at **⟨μ⟩=200**
- Efficiency to reconstruct pions and electrons limited by interactions of the particles with the detector material
  - ITk layout has significantly **less material** wrt ID
    → **significant reduction** in the fraction of particles lost through interactions and radiation effects

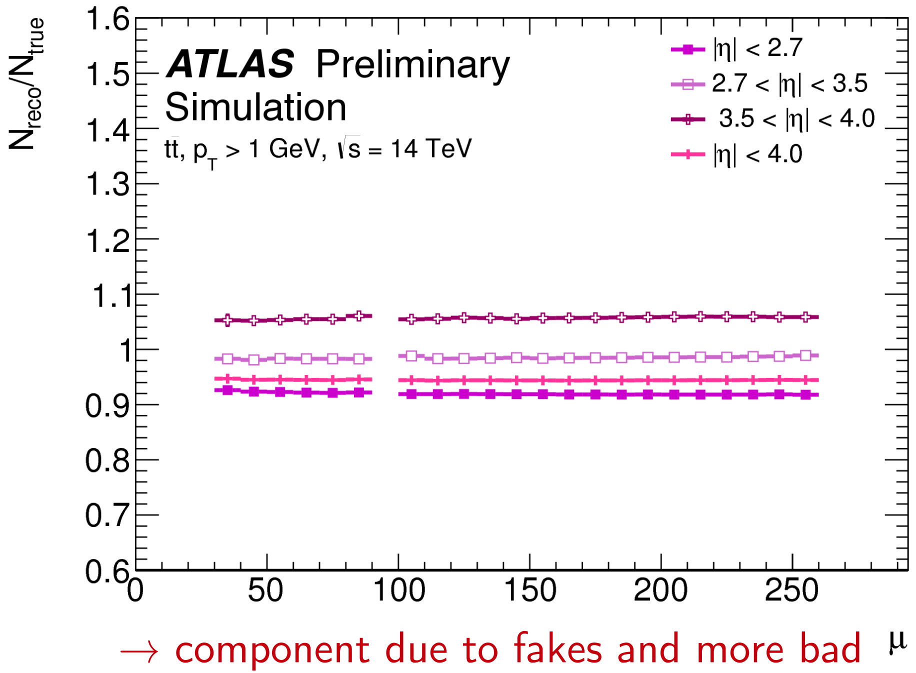




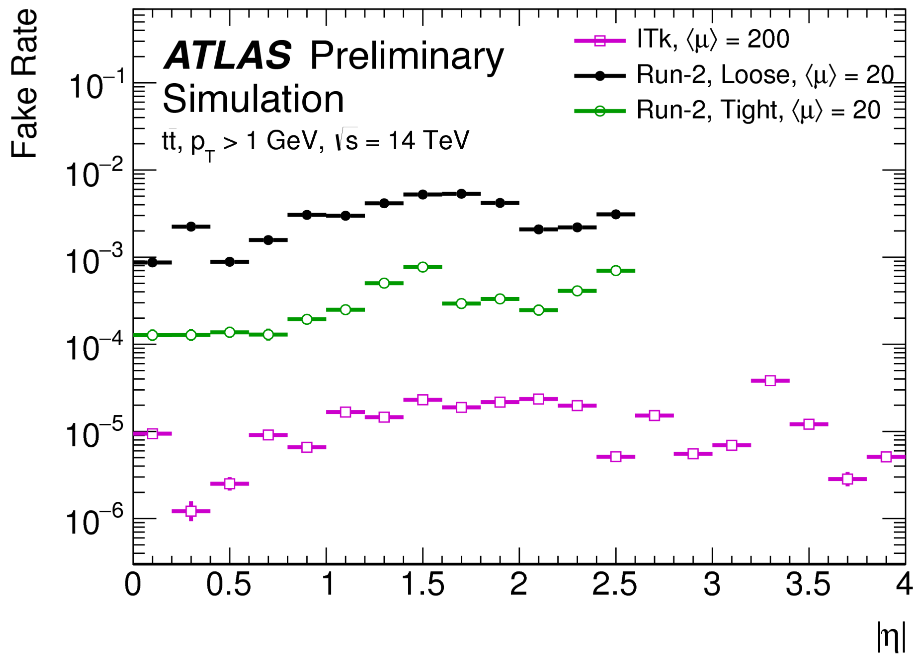
Rate of fake tracks

- The **rate of fake tracks** is another important performance criterion for a tracking detector

$$r_{\text{track}} = \frac{N_{\text{reco}}\,(\text{selected},\ \text{unmatched})}{N_{\text{reco}}\,(\text{selected})}$$



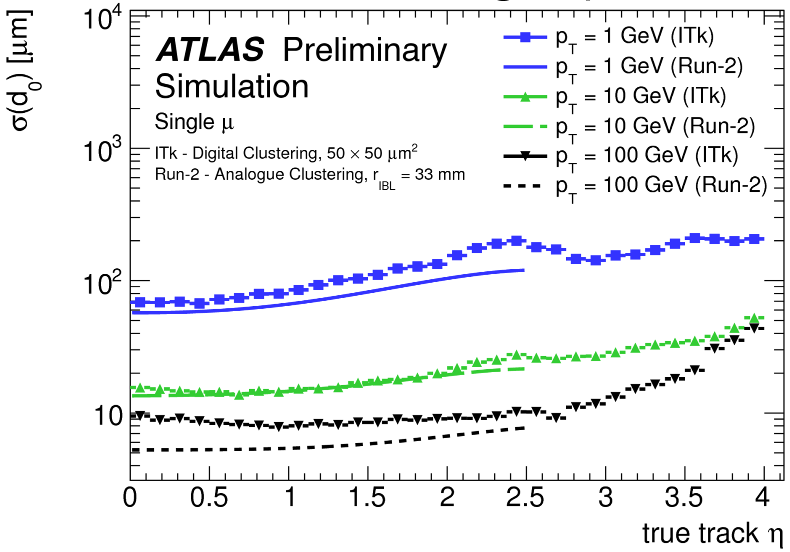
→ component due to fakes and more bad tracks from hadronic interactions would introduce a positive slope in N_{reco}/N_{truth}

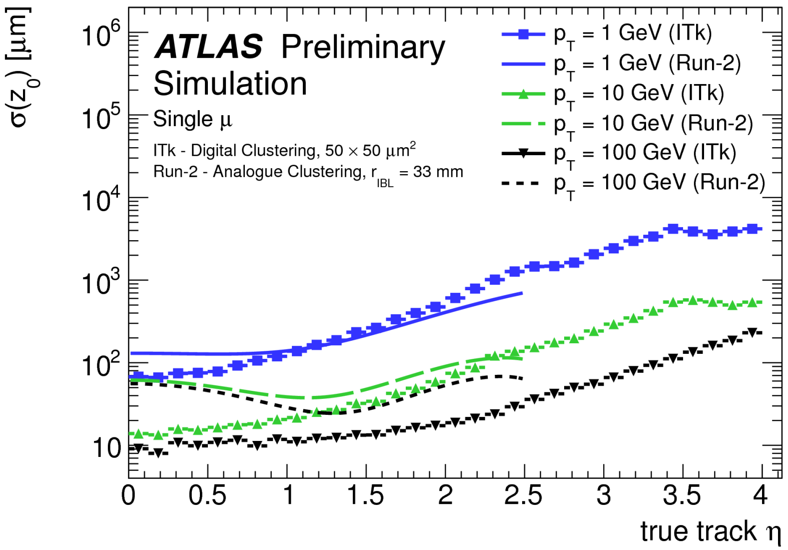


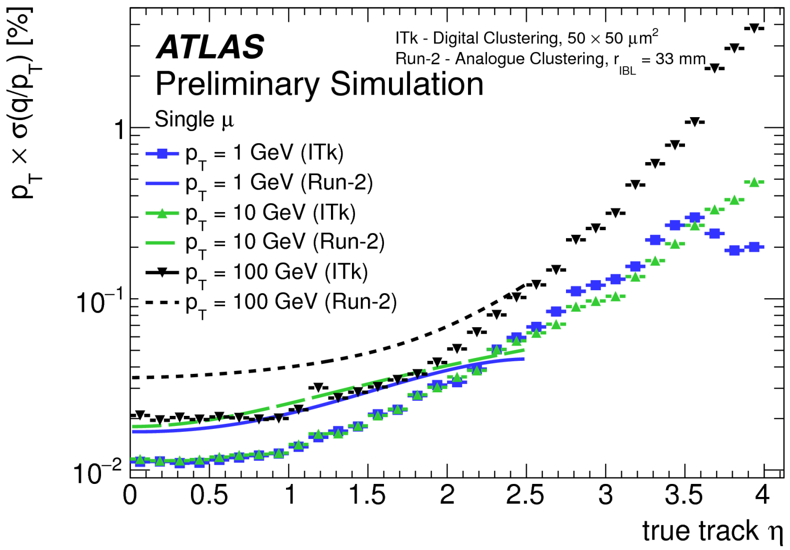
- **Excellent improvement over Run-2** still being maintained even at **high pile-up**
- **Reduced material and increased hit counts** help us again in the forward region
- N_{reco}/N_{truth} used as a another **measure of the rate of fake** or **mis-reconstructed tracks**
  - **stable to within 1% across wide range of pile-up**

Track Parameter Resolutions

- **Excellent capability to resolve the position and momentum**
- **Transverse impact parameter (IP) resolution d_0 similar to current ID**
  - Run-2 performance better at very high p_T due to analogue clustering (while ITk is using digital!!)
- **Significant improvements** in the **longitudinal IP resolution z_0**
  - Reduction of pixel pitches from 250 and 400 μm to 50 μm for ITk
- **Momentum resolution** substantially **improved** by high precision measurements along the full track length provided by the full silicon tracker



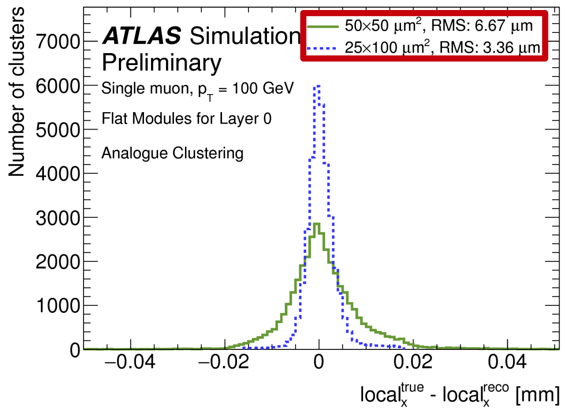


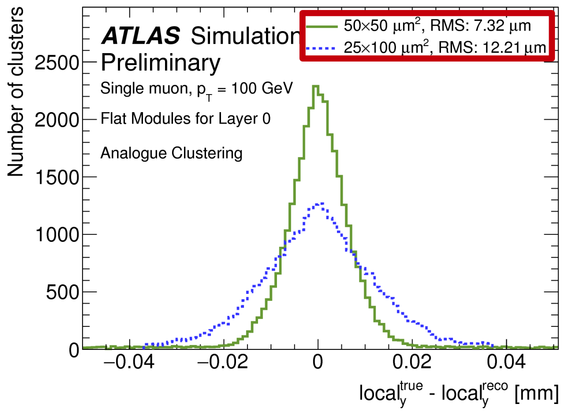


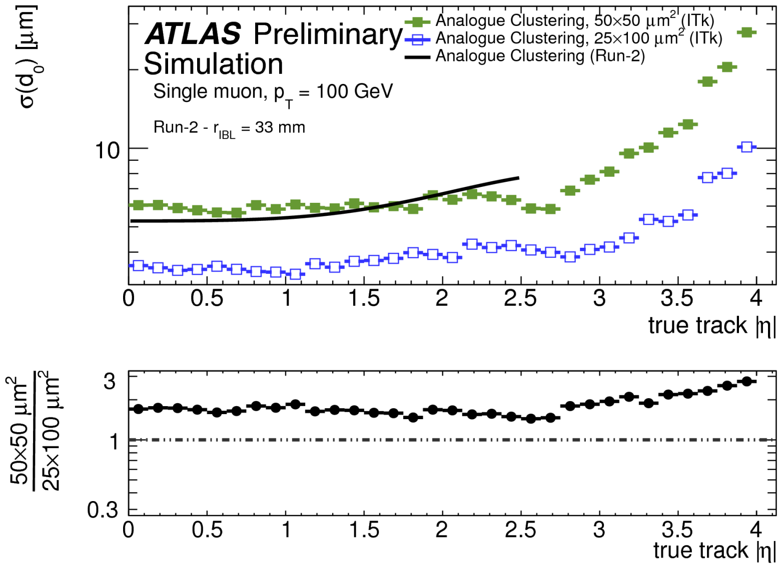
Track Parameter Resolutions

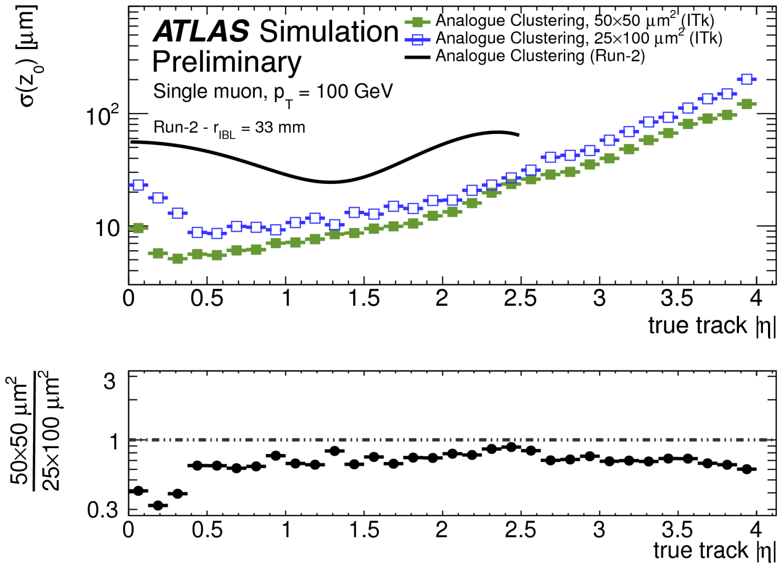
- As seen, analogue clustering significantly improves intrinsic resolution of the cluster position
  - Using 25x100 µm^2 pixels the local-X benefits most
  - Both 50x50 µm^2 and 25x100 µm^2 with analog clustering

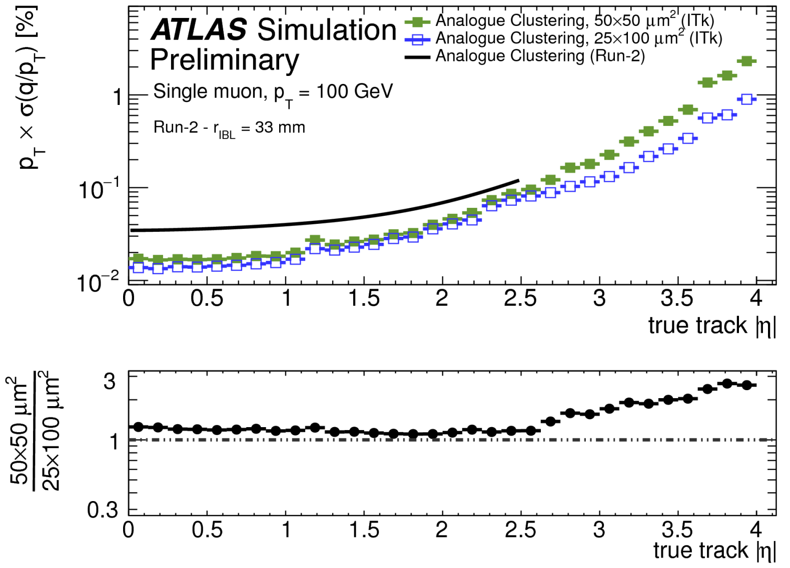
→ d_0 resolution is improved by a ~ factor 2 at the cost of ~35% loss in z_0 resolution











Poster: Salvador Marti I Garcia

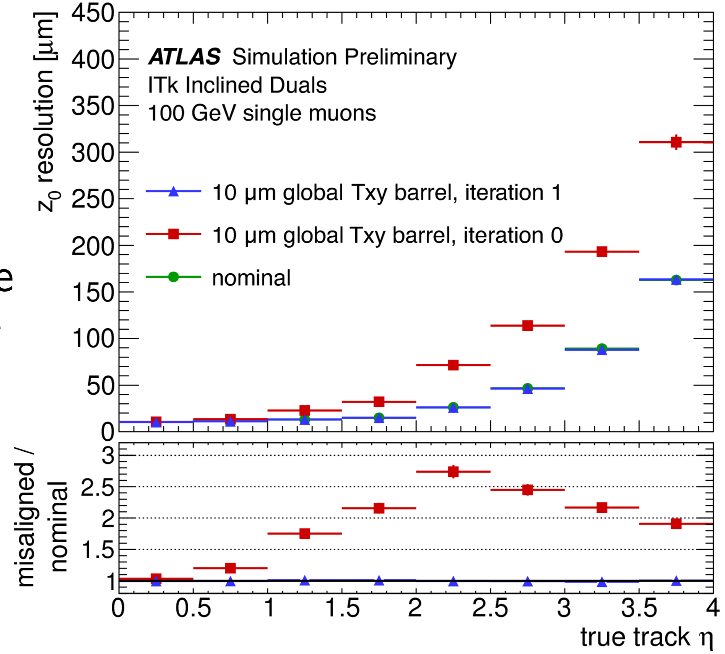
Alignment Studies

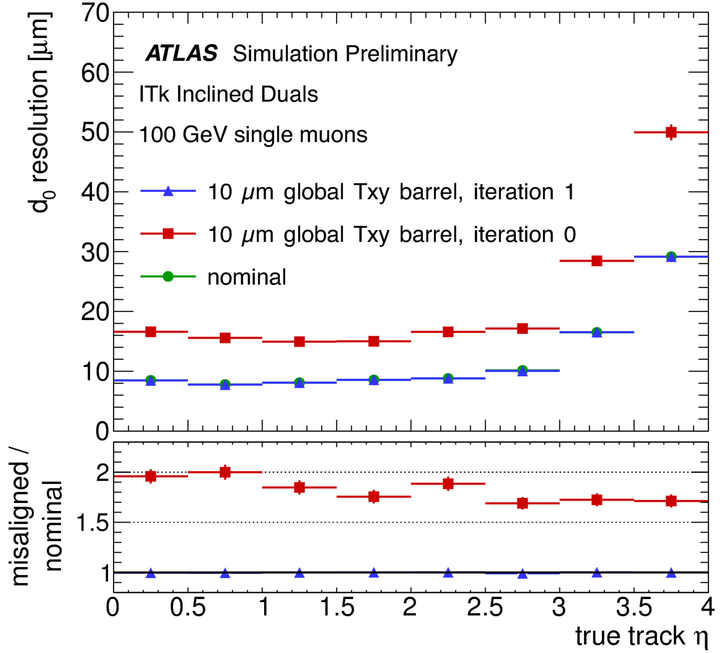
- Results presented so far **assume perfect detector alignment**
  - **Misalignments degrade the measurement accuracy**

→ The ATLAS ID alignment procedure is an **iterative track alignment using a multidimensional global-χ^2 minimisation**

- During Run-2, a dedicated alignment procedure to correct for short-term detector movements within a run of LHC

→ For ITk, the **effect** of both **global deformations and misplacements** of the detector **on impact parameter resolutions** has been studied





→ **10 μm global displacement** in x and y lead to a **loss of resolution** by a factor 1.8-2.0 in d_0 and up to a factor 2.8 in z_0 at $|\eta|=2.2$ (we can tolerate 3-5 μm local shifts)

The alignment procedure can completely recover the nominal resolution!

Poster: Natasha Lee Woods

ITK-2018-003

Robustness Studies

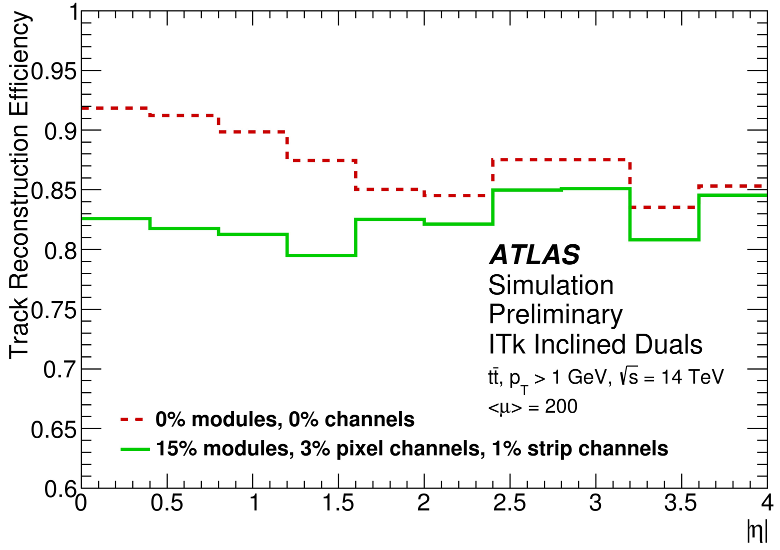
- Two different effects have been studied
  - **Component failures**, e.g. inactive modules
    - **Known and described** in the conditions database of the detector
  - **Detector inefficiencies**, in particular due to irradiation that affects single channels
    - **Can not be flagged in reconstruction**

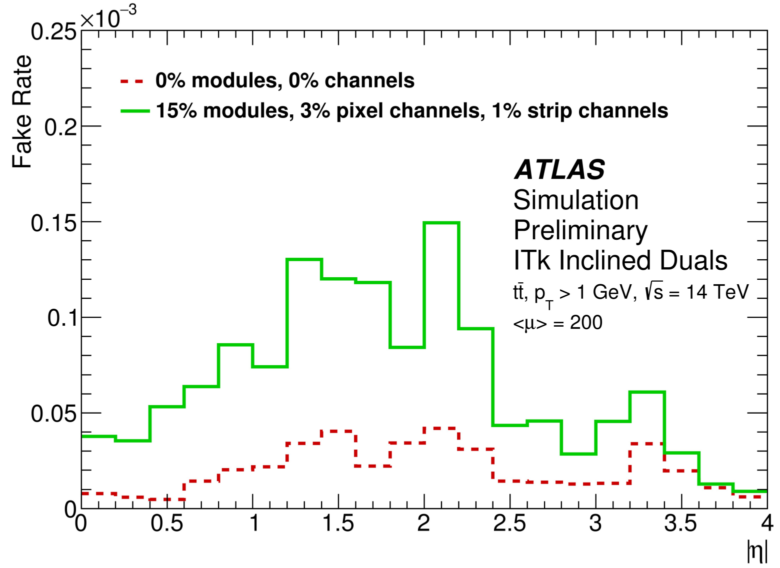
      → **un-avoidable increase in pixel holes** especially where smaller clusters are expected

Results for the most pessimistic scenario:

→ 15% inactive modules + 3% inactive pixel channels + 1% inactive strip channels

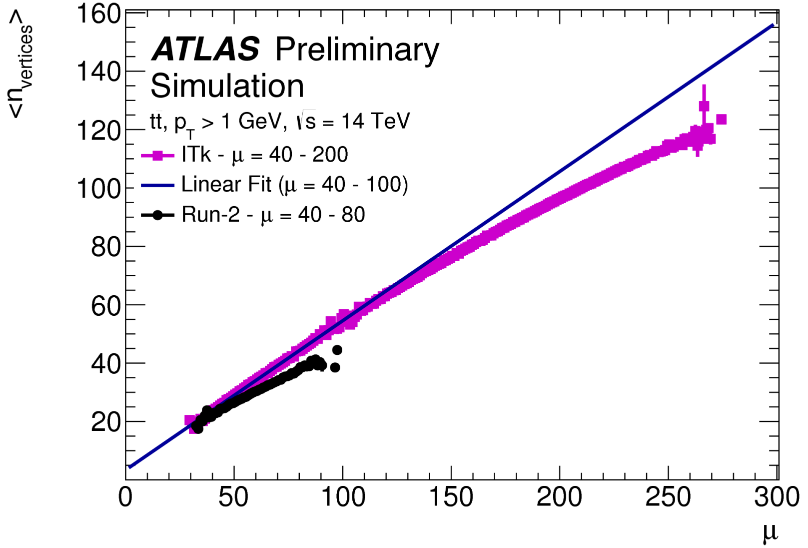
→ **Reconstruction not re-tuned** to the percentage of inactive modules



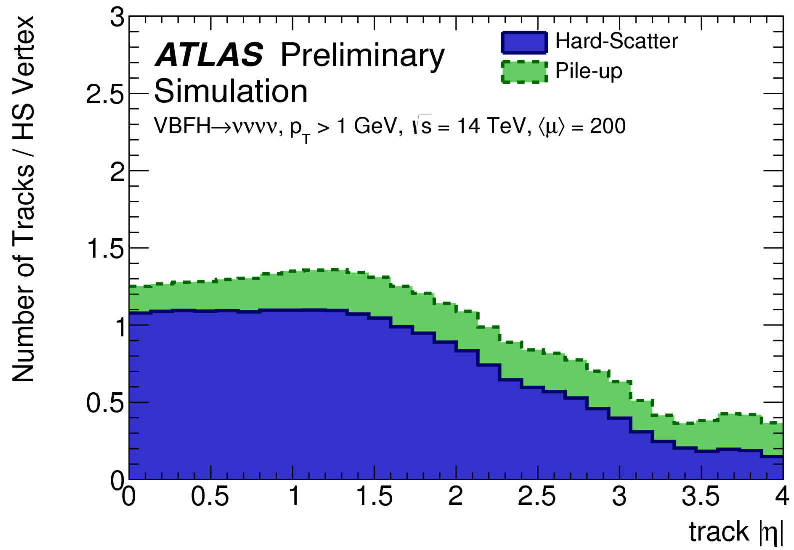


Vertexing Studies

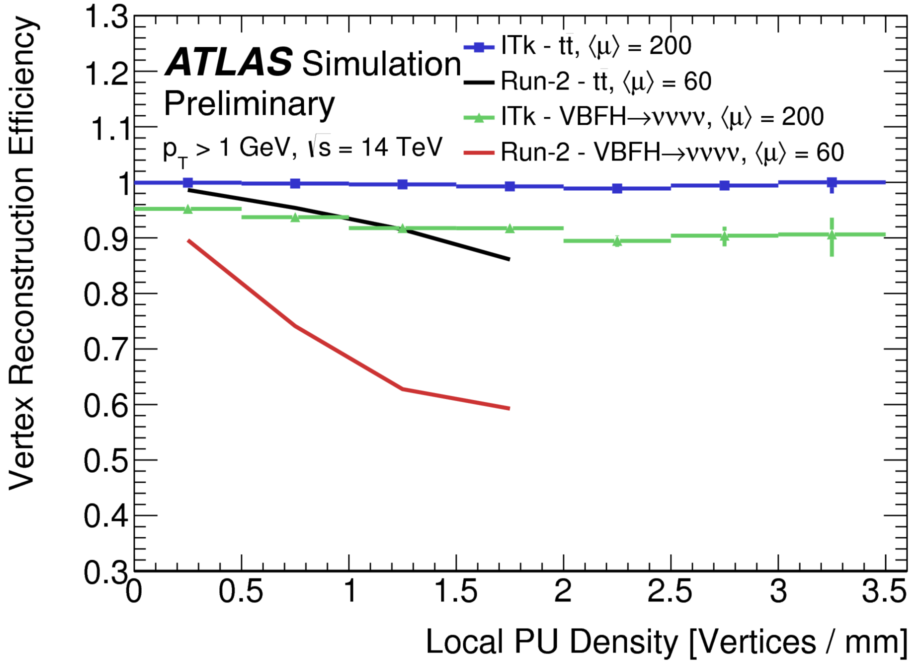
- Find and determine the position of hard-scatter and pile-up interaction vertices
  - Current ATLAS Run-2 iterative vertexing and its working point not adequate for Phase-2
    - Phase-2 algorithm fits multiple vertices simultaneously → **fit is aware** about the tracks weight to **other vertices**



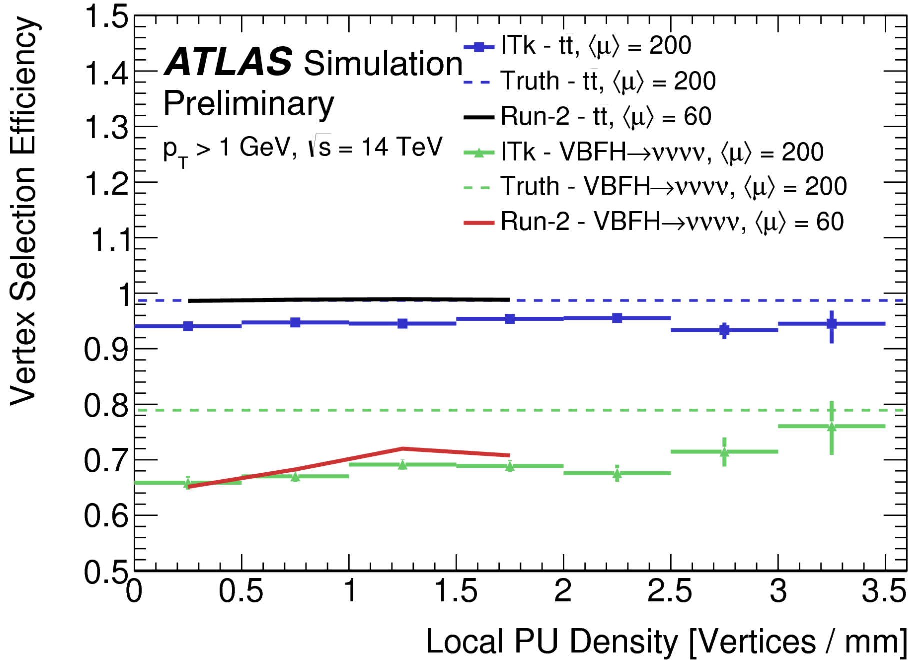
- Number of primary vertices as a function of pile-up
  - At constant efficiency, **linear dependency is expected**
  - **Deviation** from linearity can be sign of **vertex merging** effects
  - **Run-2** vertex finding SW provides **lower pile-up vertex efficiency**



- **Allows to control pile-up contributions at cost of primary track efficiency in forward**
  - this is the realm of the High Granularity Timing Detector (HGTD)



- Excellent vertexing performance
  - $t\bar{t}$ events
    → Vertex reconstruction efficiency **close to 100%** with **no significant local pile-up dependency**
  - H→ZZ→νννν with 2 forward jets
    → **few percent** vertex reconstruction **inefficiency** and **small pile-up dependency**



- HS primary vertex is identified based on Σp_T^2 of tracks associated to vertex
  - **Good $t\bar{t}$ identification efficiency vs pile-up density, lower for H→ZZ→νννν**
  - Rate of true primary vertex with the highest true Σp_T^2

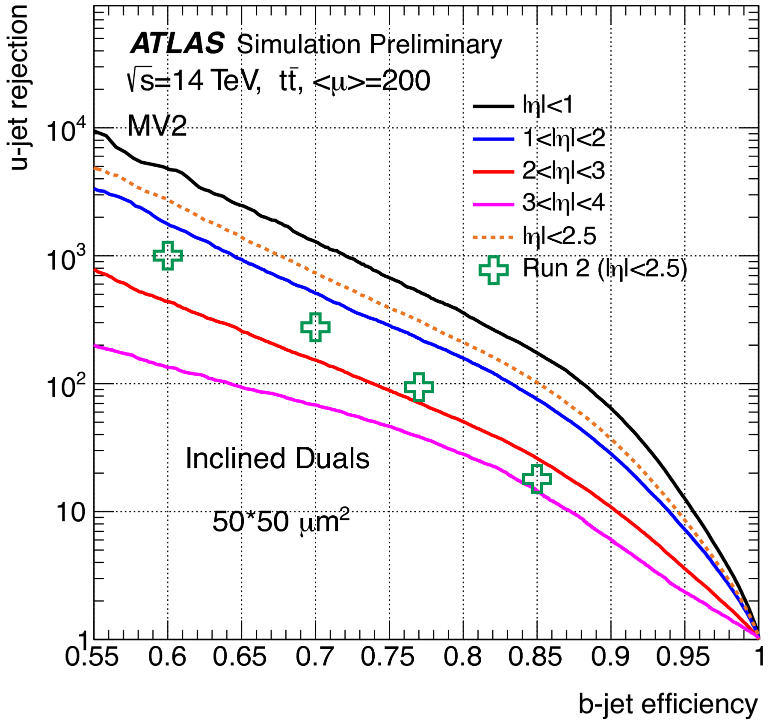
→ **New strategy to find the HS vertex is needed**
  - e.g. analysis with no central high-p_T tracks can make use of tracks from forward jets

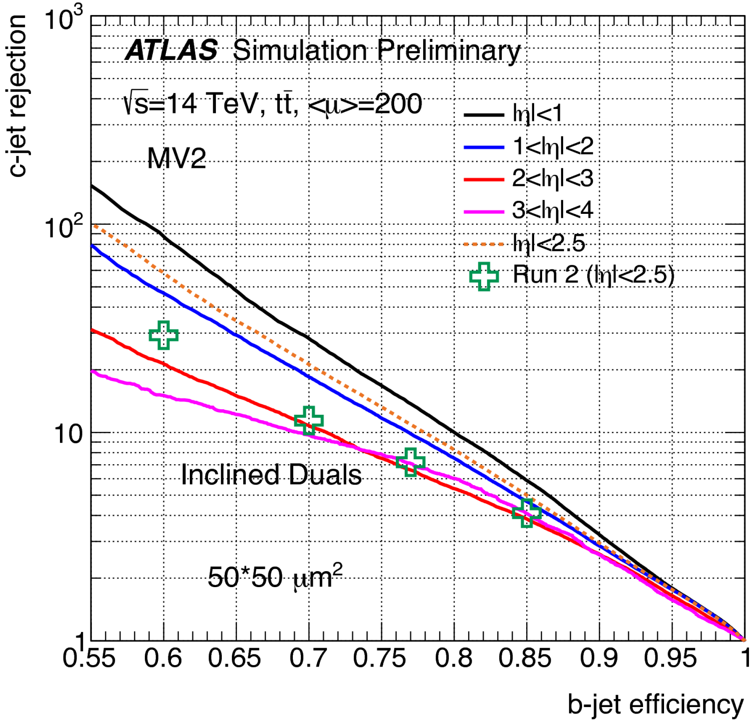
b-Tagging Performance

- **Improved IP precision** directly translates into **excellent b-tagging performance** → **Excellent light and charm rejection**

- **MV2** multi-variant tagger
  - impact parameter, secondary vertex and kinematic information

  → **ITk outperforms the current detector** and significantly **extents b-tagging η coverage**
  - HGTD will improve this further





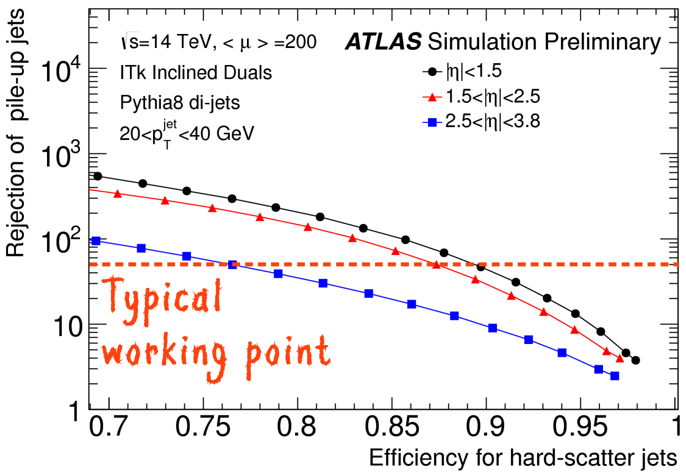
- All in presence of Phase-2 pile-up with measurement resolution with digital clustering → Ongoing studies to explore full analogue resolution

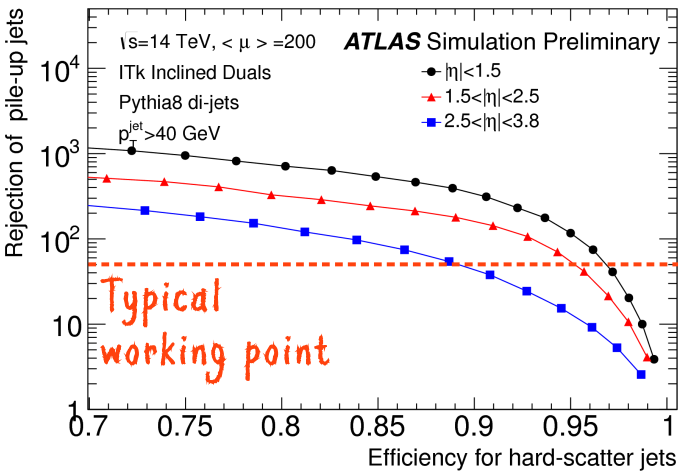
Pile-Up Jet Rejection and Missing Transverse Energy

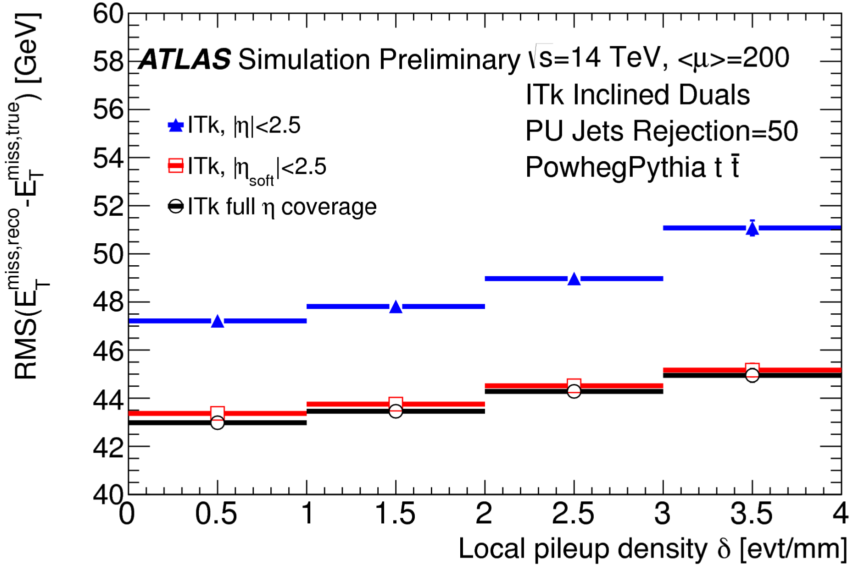
- R_{pT} technique to reject pile-up jets
  - Excellent efficiencies up to η~3.8 for rejection of 50
  - HTGD will add to forward performance

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

momentum of tracks within a jet associated with the primary vertex



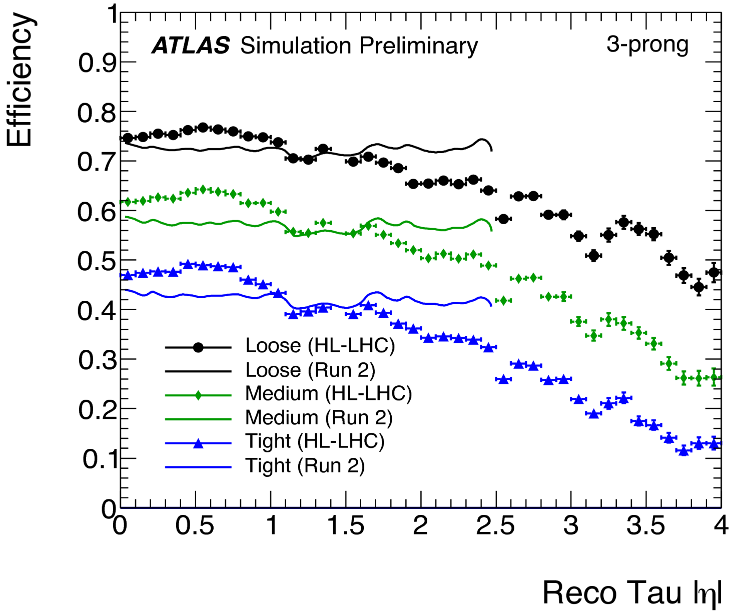


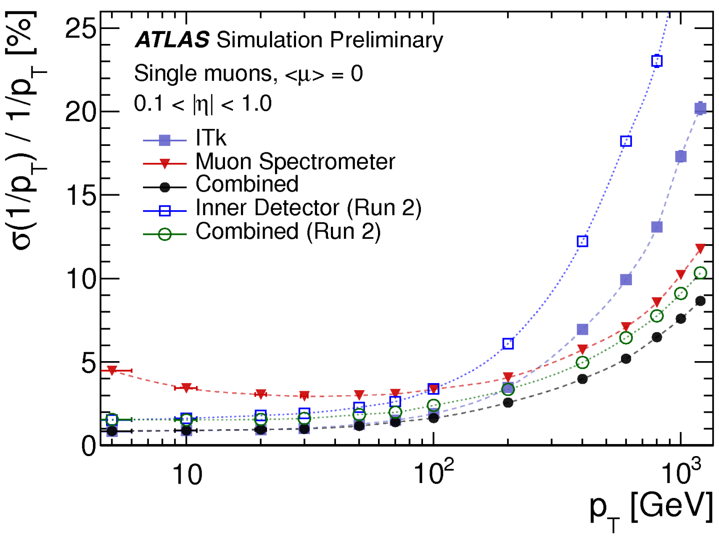


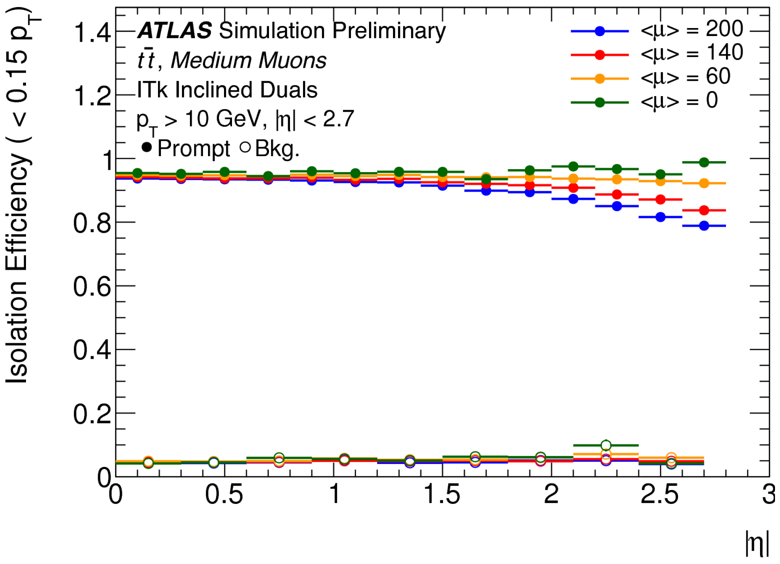
- Missing Transverse Energy
  - ITk improves jet term rejecting pile-up jets
  - Improvements in track soft term using forward tracks is marginal

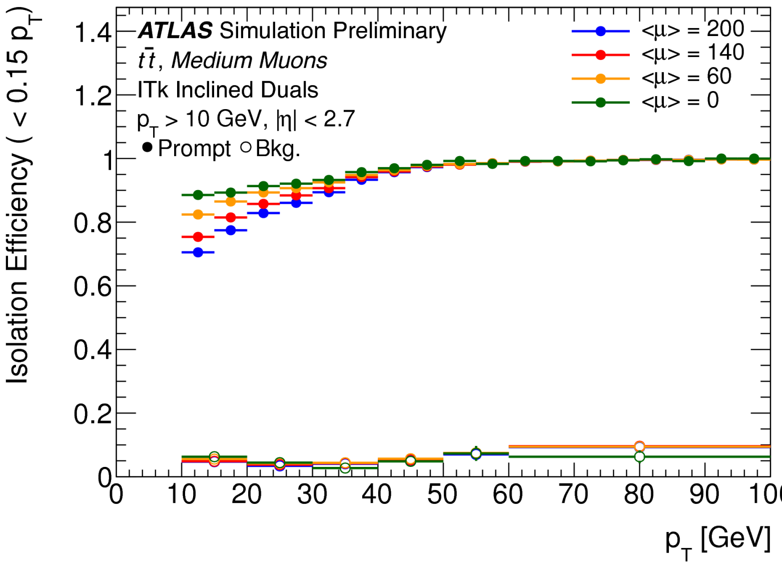
Lepton Reconstruction

- Good τ reconstruction at Phase-2
  - "preliminary" tuning of MVA identification
- Better ITk momentum resolution improves combined muon momentum measurement
- Track based isolation stable against increasing pile-up for $p_T > 50$ GeV









Conclusions

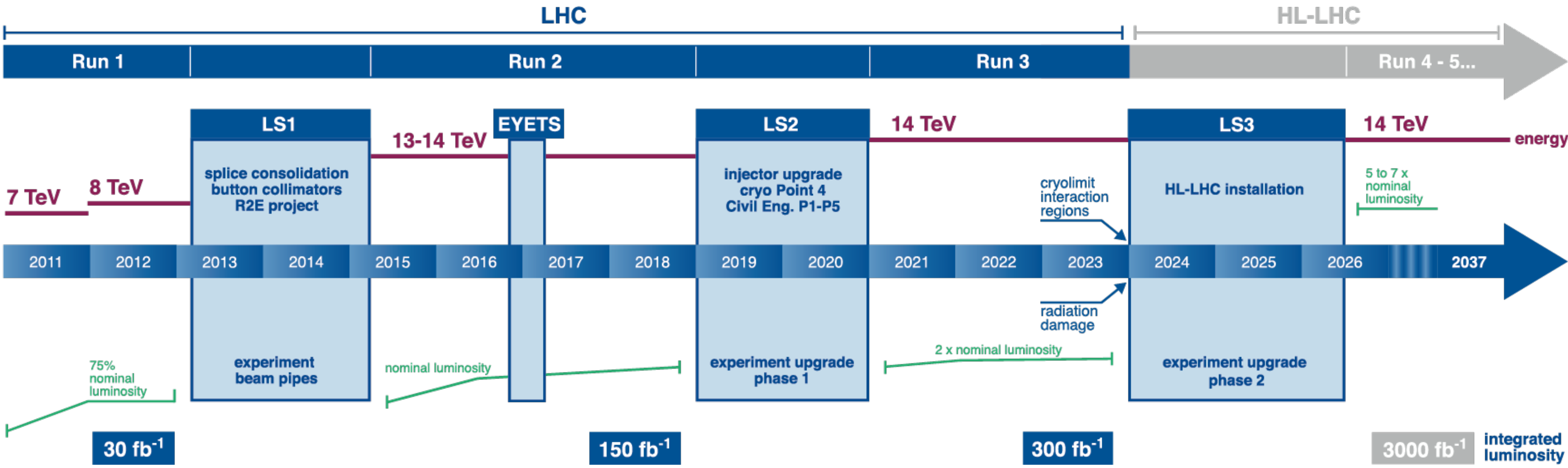
- Complete replacement of the Inner Detector planned as part of the ATLAS Phase-2 Upgrade Program
- Detailed and accurate ITk simulation to study HL-LHC pile-up scenario
- Reconstruction developed and updated specifically for ITk
  - Improved tracking performance and extended coverage!
  - Obtaining similar or better performance than the current ATLAS ID in very dense pile-up environments of up to $\langle\mu\rangle$=200
    - Excellent CPU performance for ITk at $\langle\mu\rangle$=200
  - Extremely stable efficiency and fake rate with pile-up
  - Excellent vertexing performance also for more complicated signals
  - More results on Tracking In Dense Environment in the next talk
  - Comparable or improved performance to Run 2 detector despite challenging high-luminosity conditions

→ Studies are still ongoing to finalise the layout to address concerns from LHCC

Thank you

Extra Slides

LHC / HL-LHC Plan



The ATLAS Phase-II Inner Tracker

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

- $\leq 0.1\%$ occupancy in the pixel layers and $\leq 1\%$ 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...

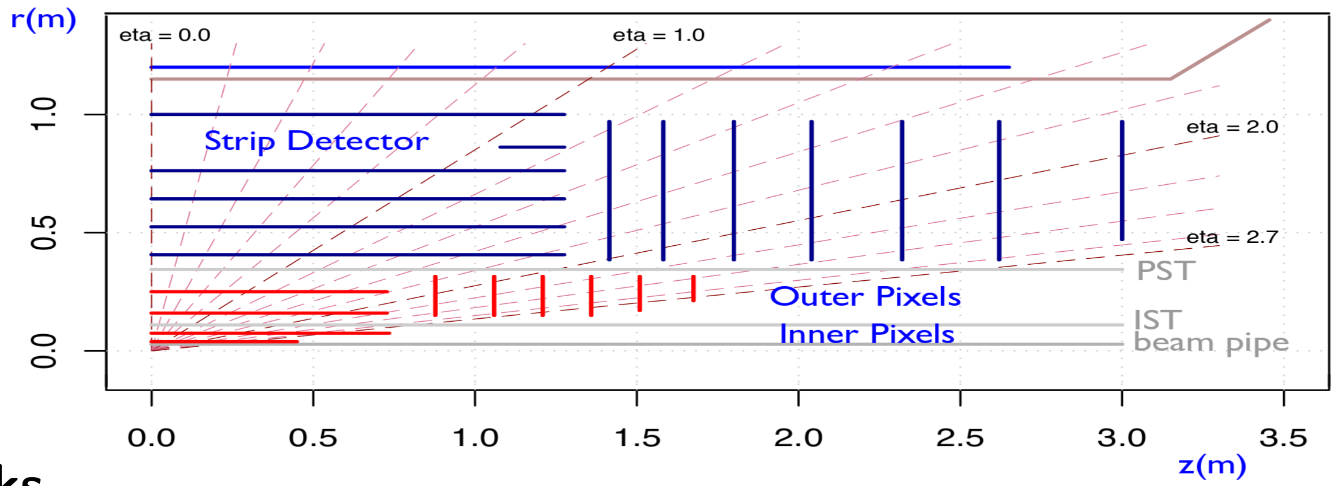
The ITk layout design process started from the LoI proposal in 2013

- Pixel Detector:

  → **4 pixel layers + 6 disks**

  - Two inner pixel barrel layers removable

LoI Layout



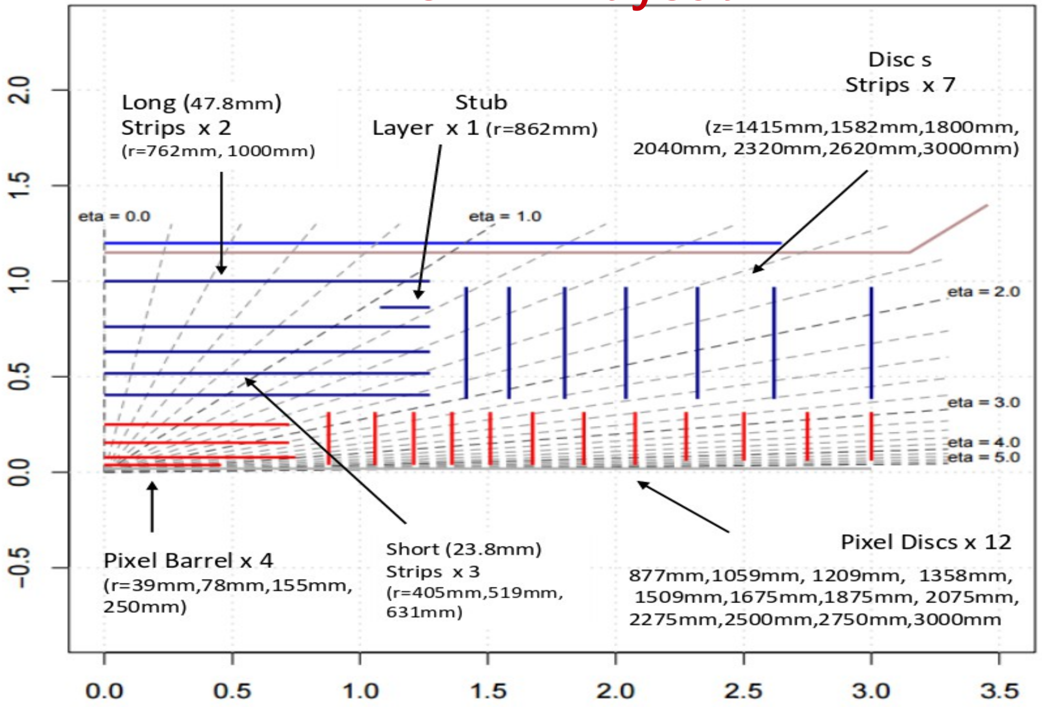
- Strip Detector:

  → **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

... towards the LoI-Very Forward Layout

Scoping Document
LoI-VF Layout



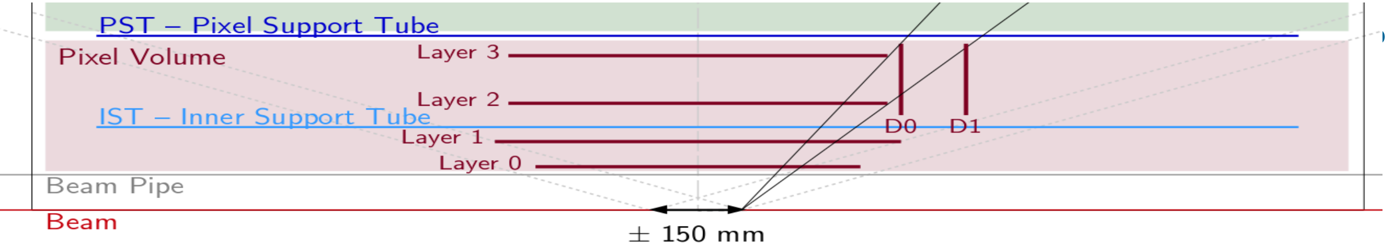
Extended tracking acceptance: up to $|\eta|$~4

→ concerns mostly the pixel detector

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

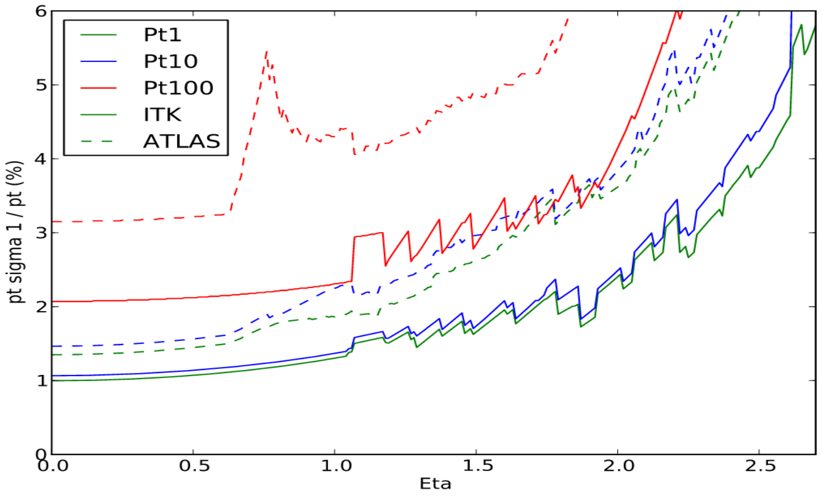
All the studies on LoI and LoI-VF have been the enormously important to establish the starting point for the layout definition

ATLAS LoI Layout Design Consideration



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

- 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



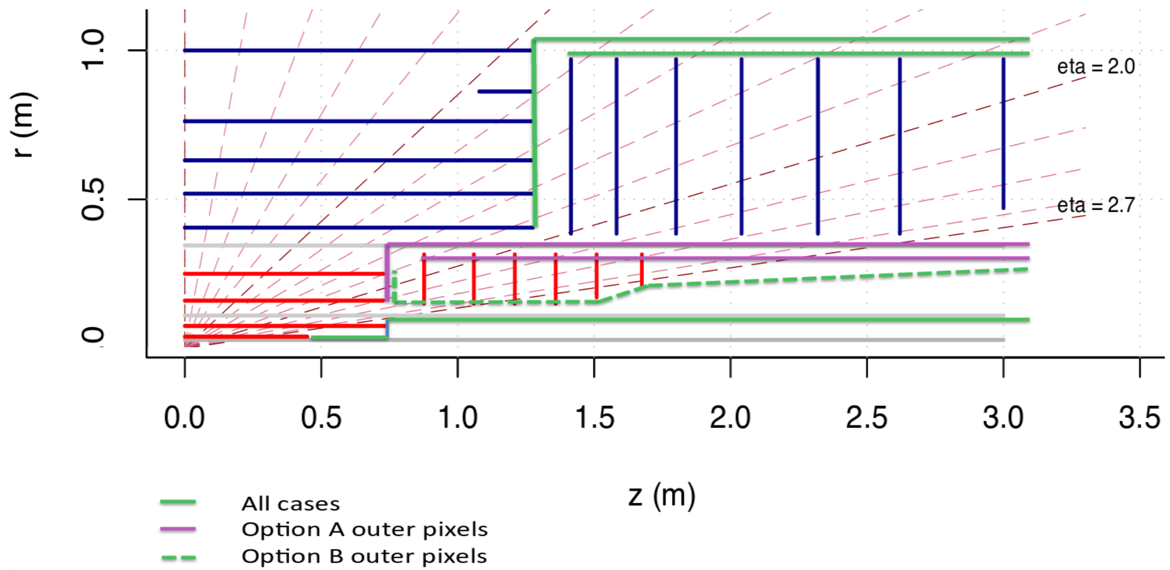
Inverse-p_T resolution using resolution model, measured as a function of $|\eta|$ for the LoI layout, and comparison with the existing ATLAS experiment

→ 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.



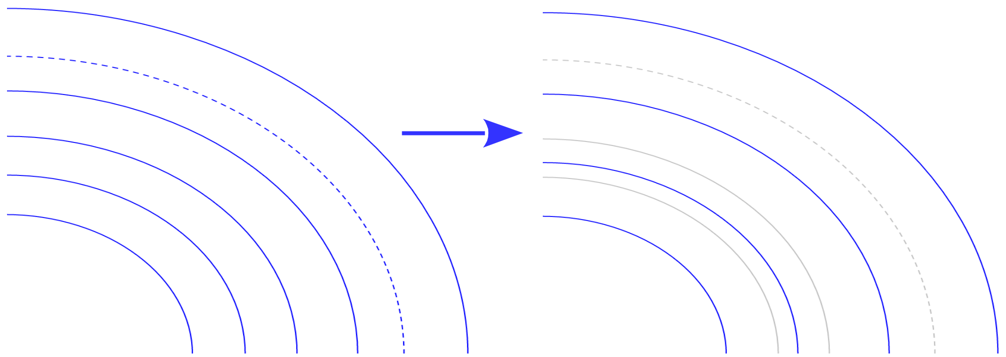
Possible service layouts for the outer pixel layers

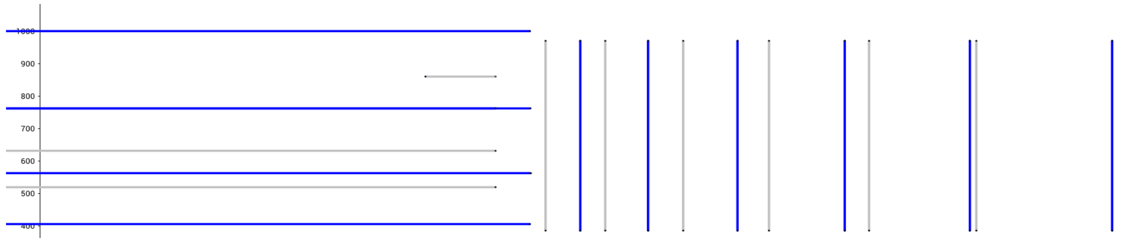
→ Letter of Intent (LoI) Layout – ATL-UPGRADE-PUB-2012-004

Strip Detector Layout

- **4 Pixel** + **5 Strip** $\rightarrow$ **5 Pixel** + **4 Strip**
  - Goal: e.g. do better in jet cores
  - Many options studied
- Longer staves in strip barrel: 13 $\rightarrow$ 14 modules
- Removed stubs

  $\rightarrow$ 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



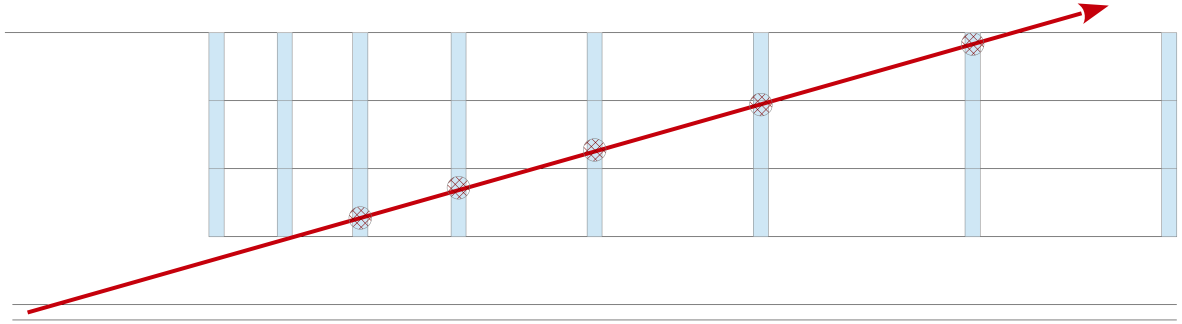


Pixel Rings

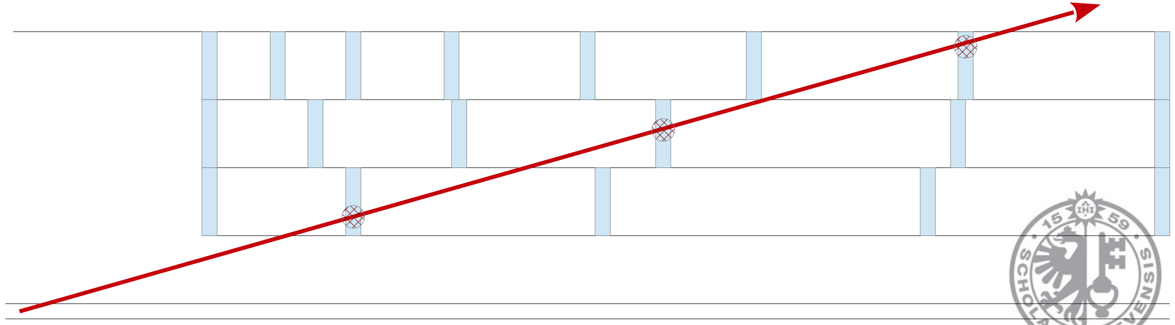
- Rings instead of disks in the pixel endcap region
  - Allows to save silicon surface
  - Services are routed on the support structure
  - Very peculiar pattern to provide constant number of hits versus η
  - Large-$|\eta|$ region entirely in the pixel volume $\rightarrow$ increased the number of rings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

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

- With tilted sensors in the high $|\eta|$ 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

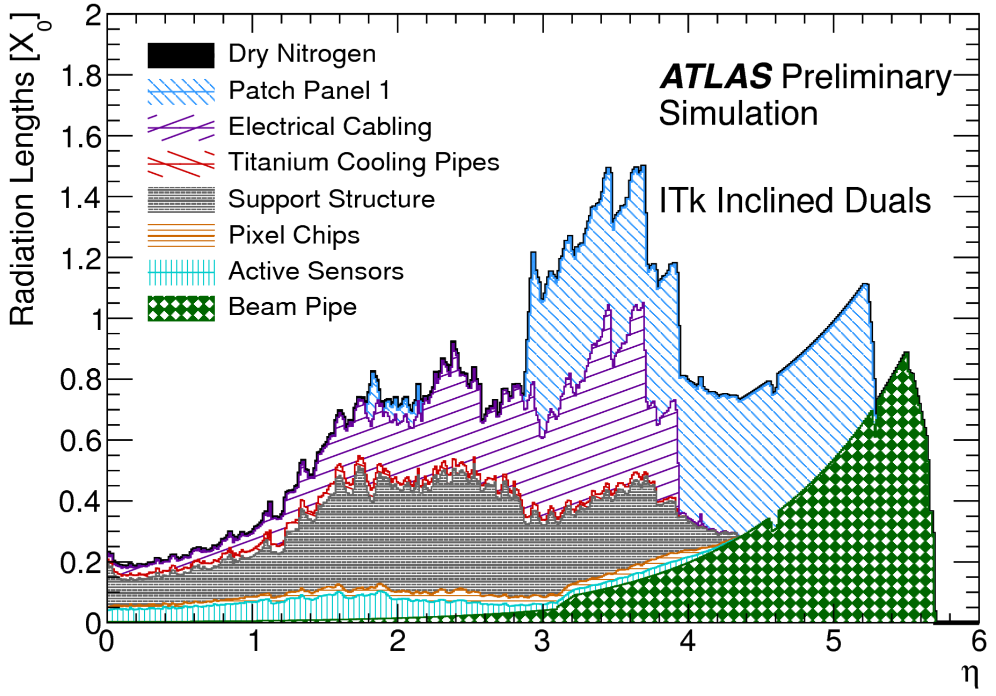
→ reduction of channel occupancy, minimization of probability of overlap between tracks

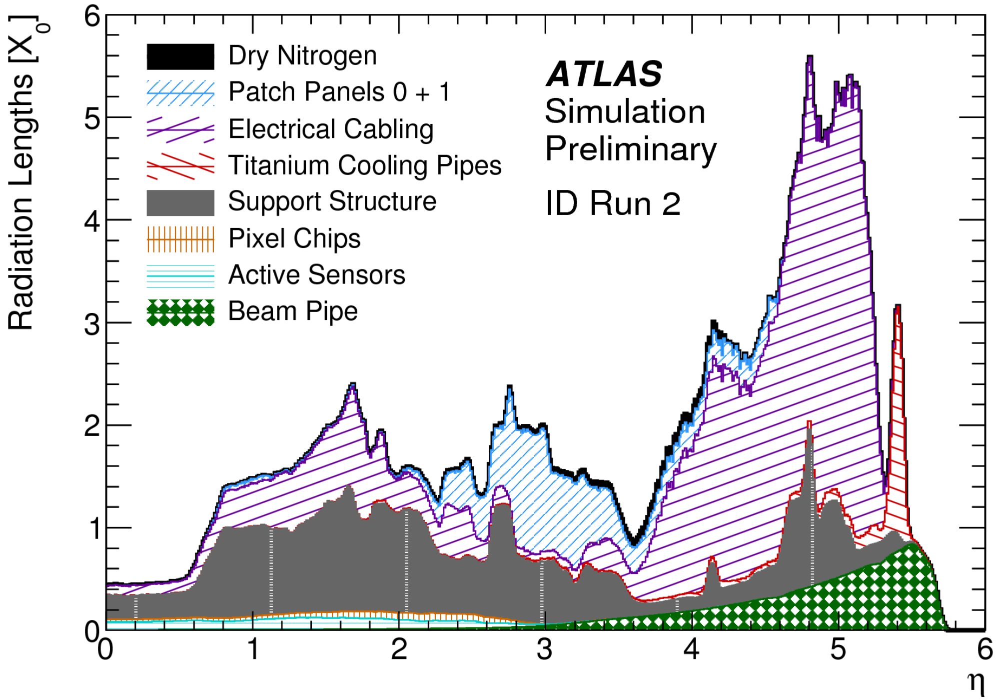
→ **CONS**

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

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

Material Budget Comparison





Inclined Stave Design and Prototyping

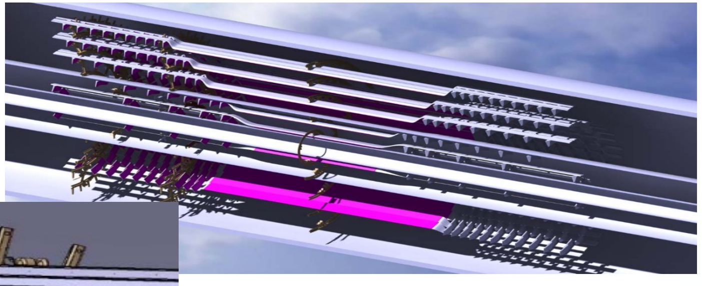
→ **Support structure design bound to layout choice**

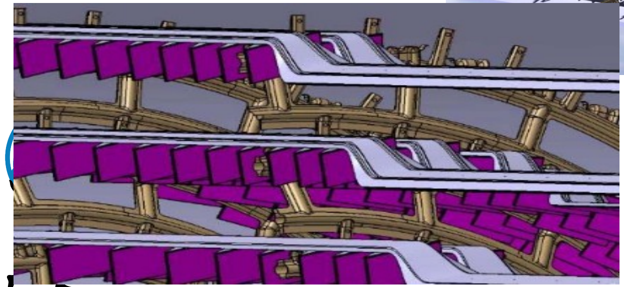
- For the inclined layout two designs have been proposed: **Alpine** and **SLIM**

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

Alpine

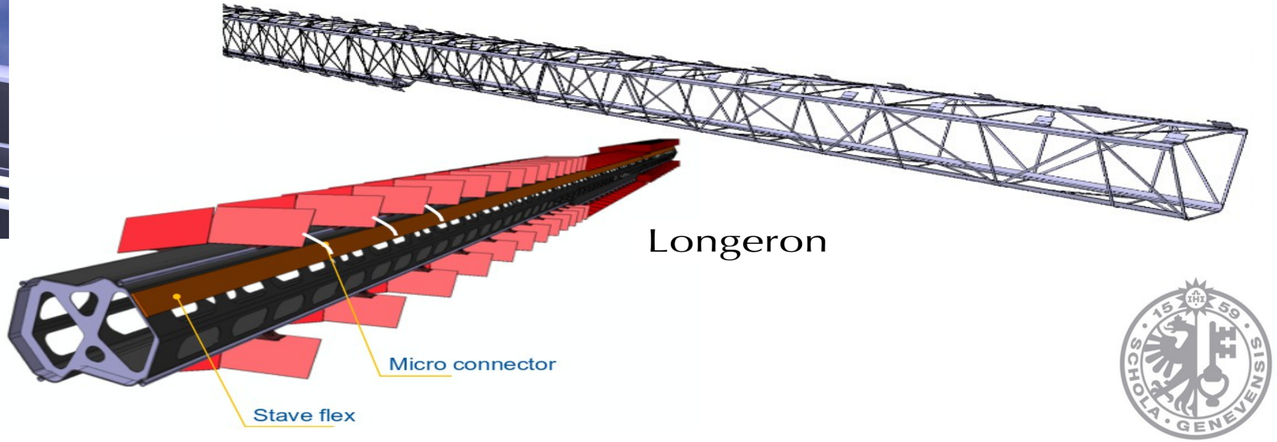
- T. Todorov† pioneer of the "inclined" idea
- Two types of modules: barrel and inclined
  - carbon foam + carbon fibre "IBL-like" stave design





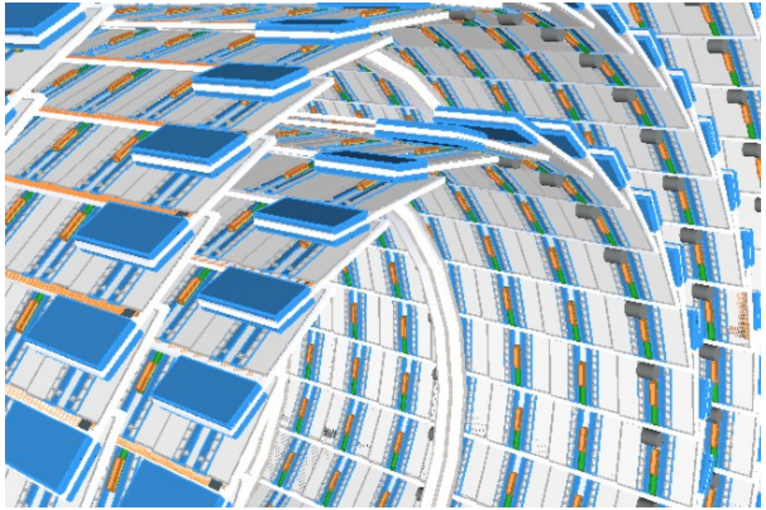
SLIM: Stiff Longeron for ITk Modules

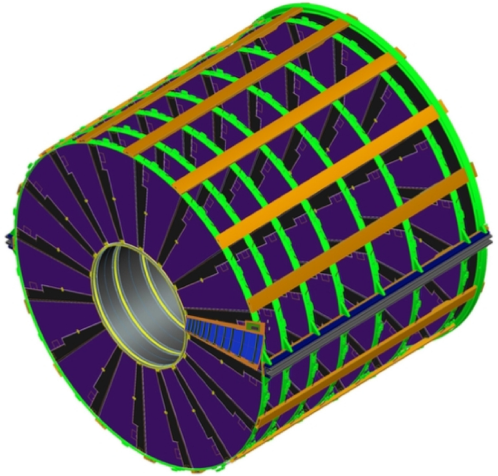
- Two types of modules: barrel and inclined
- Inspired from ALICE: common structure ("Longeron") supporting two layers of modules
- Two longeron designs: Shell and Truss



The ATLAS ITk Strip Layout

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





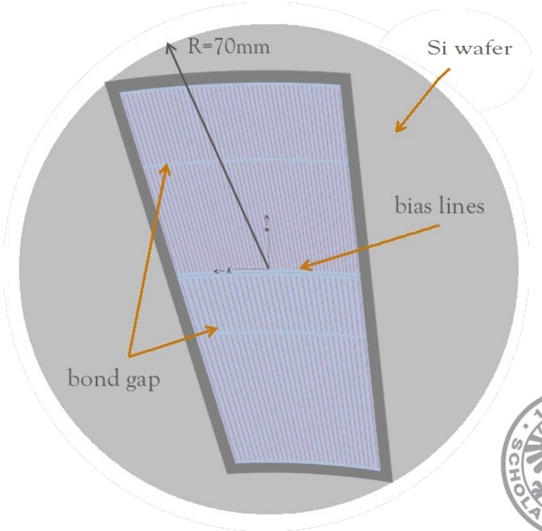
- **Endcap:**
  - 6 discs: double-sided petals

    → 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)



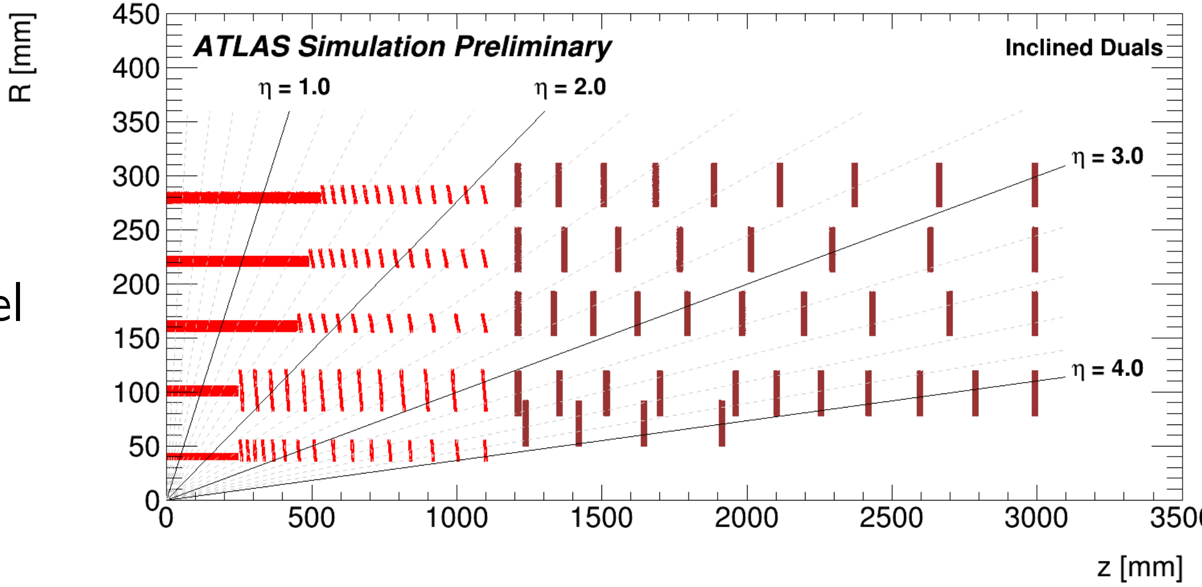
Track Reconstruction

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

Requirement	Pseudorapidity Interval		
	$\|\eta\|<2.0$	$2.0<\|\eta\|<2.6$	$2.6<\|\eta\|<4.0$
Pixel+Strip hits	≥ 9	≥ 8	≥ 7
Pixel hits	≥ 1	≥ 1	≥ 1
Holes	< 2	< 2	< 2
Strip Double holes	≤ 1	≤ 1	≤ 1
Pixel holes	< 2	< 2	< 2
Strip holes	< 2	< 2	< 2
p_T [MeV]	> 900	> 400	> 400
$\|d_0\|$[mm]	≤ 2	≤ 2	≤ 10
$\|z_0\|$[cm]	≤ 20	≤ 20	≤ 20

Inclined-Dual Pixel Layout

- The Pixel detector consists of **five barrel layers** with **inclined sensors** starting from $|\eta| > 1.4$
  - **Reduces the material** traverse by particles and **improves tracking performance** (and energy measurements of the calorimeter)
  - **Less silicon surface** than a traditional barrel needed to cover the same detector volume
  - **End-cap rings** replacing traditional disks to **improve the coverage** and at cost of less silicon surface



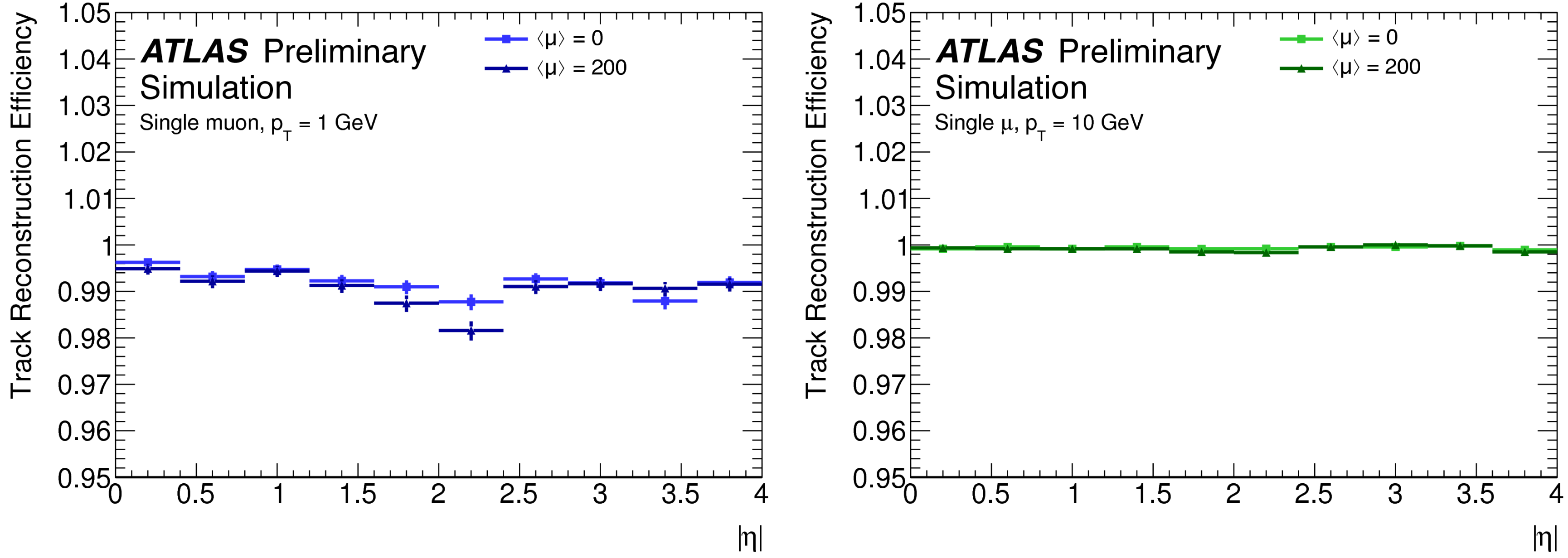
  - **Three types of sensor**: **single** read-out chip modules (inclined layer 0), **duals** (flat layer 0 and inclined layers 2 to 4) and **quads** (elsewhere)
  - **Two pixel pitches** still under consideration **50x50 µm² or 25x100 µm²** (current ID using 50x250(400) µm²)

    → **The results presented are using 50x50 µm²** – unless clearly stated

Physics Tracking Efficiency

- The **physics tracking efficiency** is one of the most important performance criteria for a tracking detector
  - Defined as the fraction of prompt particles which are associated with tracks passing a track quality selection:

$$\epsilon_{\mathrm{track}} = \frac{N_{\mathrm{reco}}\,(\mathrm{selected},\ \mathrm{matched})}{N_{\mathrm{truth}}\,(\mathrm{selected})}$$

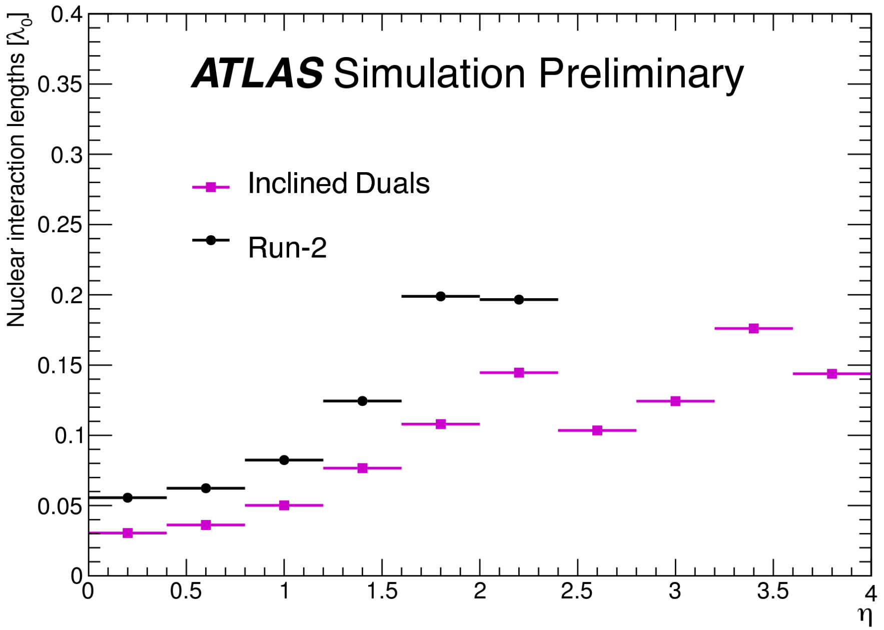


→ Single muons with fixed p_T = ①, ⑩ GeV

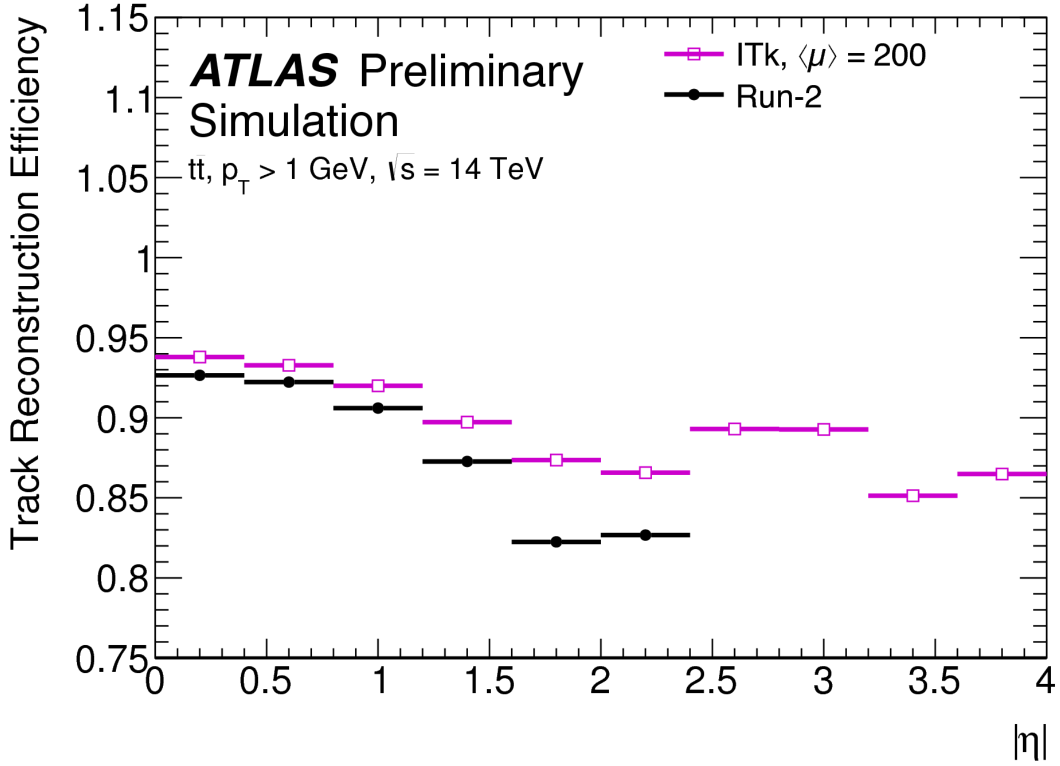
Reconstruction efficiency close to 100% even at ⟨μ⟩=200

Physics Tracking Efficiency

- **Efficiency** to reconstruct **pions and electrons limited by interactions** of the particles **with the detector material**



Number of nuclear interaction lengths traversed by a particle before reaching the reconstruction hit requirement

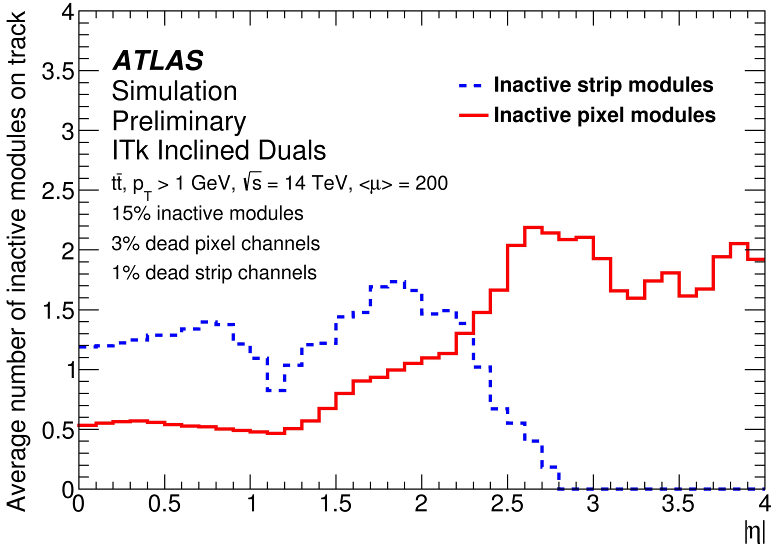


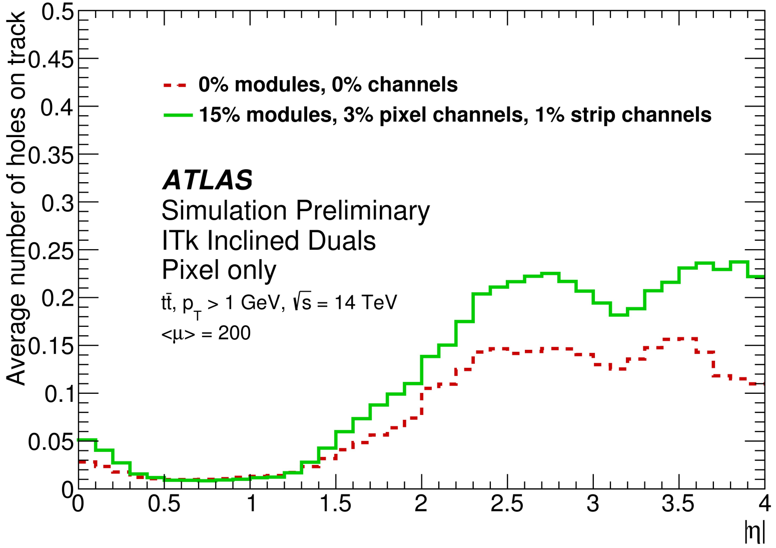
Robustness Studies

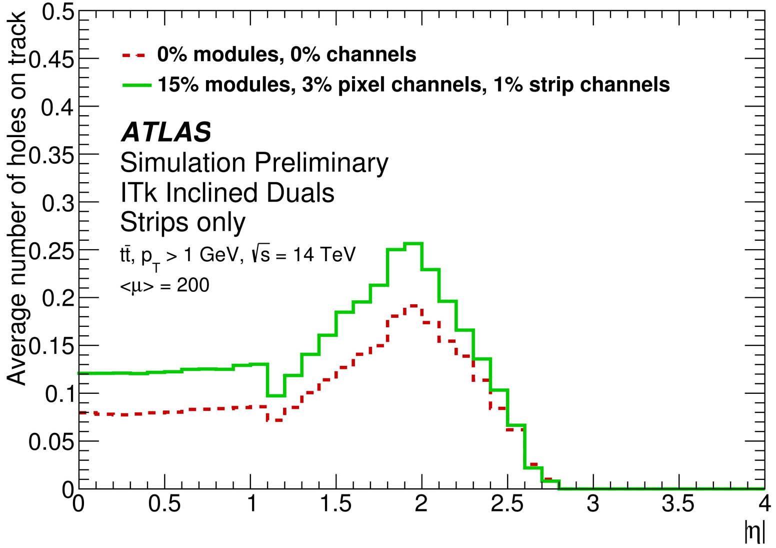
Results for the most pessimistic scenario:

→ **15% inactive modules + 3% inactive pixel channels + 1% inactive strip channels**

→ **Reconstruction not re-tuned** to the percentage of inactive modules







Vertexing Studies

- Find and determine the position of hard-scatter and pile-up interaction vertices
  - Current ATLAS Run-2 iterative vertexing and its working point not adequate for Phase-2

Run-2: Iterative Vertex Finder with Adaptive Fitter

Selected Tracks

New Vertex Seed
Search for clusters of track in z-IP

Vertex fit of all candidate tracks

Rejection of tracks incompatible with vertex candidates

Reconstructed vertices

Reconstruction requirements + additional cuts to ensure good IP resolution

Remaining tracks used to form new seed vertices

fit is aware about the tracks weight to **other vertices**

ITk: Adaptive multi-vertex finder

Selected Tracks

Seeding Tracks

New Vertex Seeds

New Vertex is **fit together** with all previous ones

Reconstructed vertices

Vertex Reconstruction

r/z **PV resolution** vs true local pile-up density in $\pm$ 2 mm around the primary interaction

- ITk vertexing shows nearly **no local pile-up dependency** despite increased vertex merging probability
- **Run-2 resolution degrades at high pile-up densities**