Layout and prototyping of the new ATLAS Inner Tracker for the High Luminosity LHC

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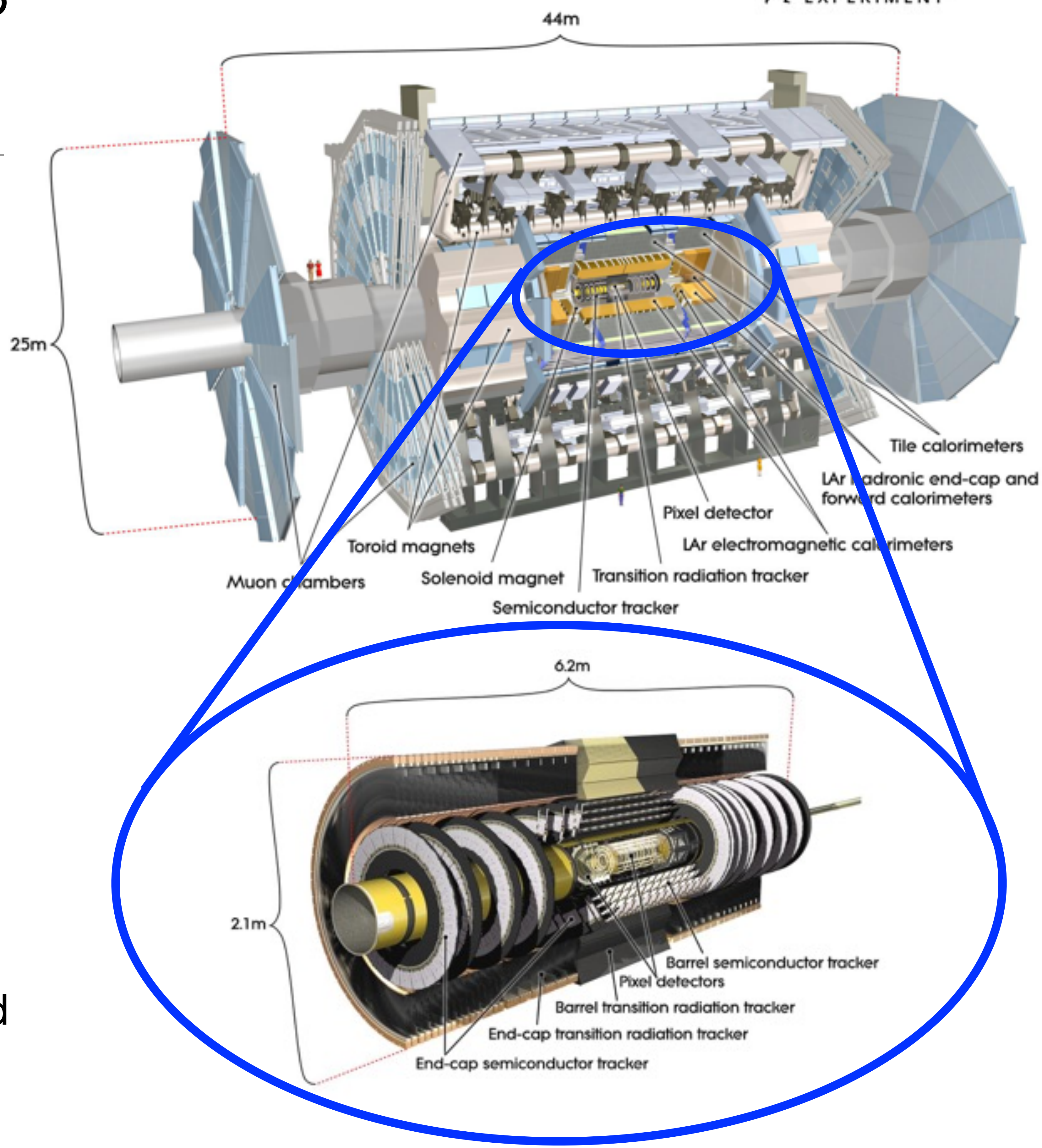
on behalf of the ATLAS ITk Collaboration

PSD11

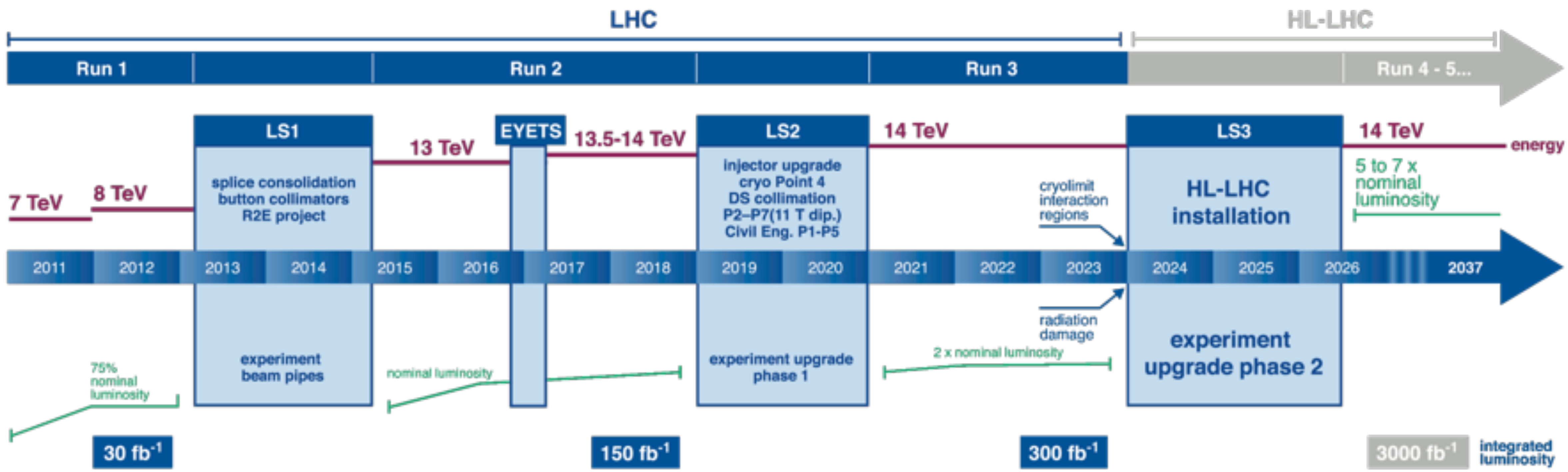
PSD11 : The 11th International Conference on Position Sensitive Detectors
3rd - 8th September 2017, The Open University, Milton Keynes, UK

The Current ATLAS Experiment

- General purpose experiment
- 44m long, 25m tall, 7k tons, 100 Million channels
- Collaboration of ~3000 physicists from 175 institutions and 35 countries
- The Inner Detector (ID) lies at the centre of ATLAS
    - Responsible for tracking particles from collision to the calorimeters
    - Composed of Pixels and Strips silicon detectors and Transition Radiation detector



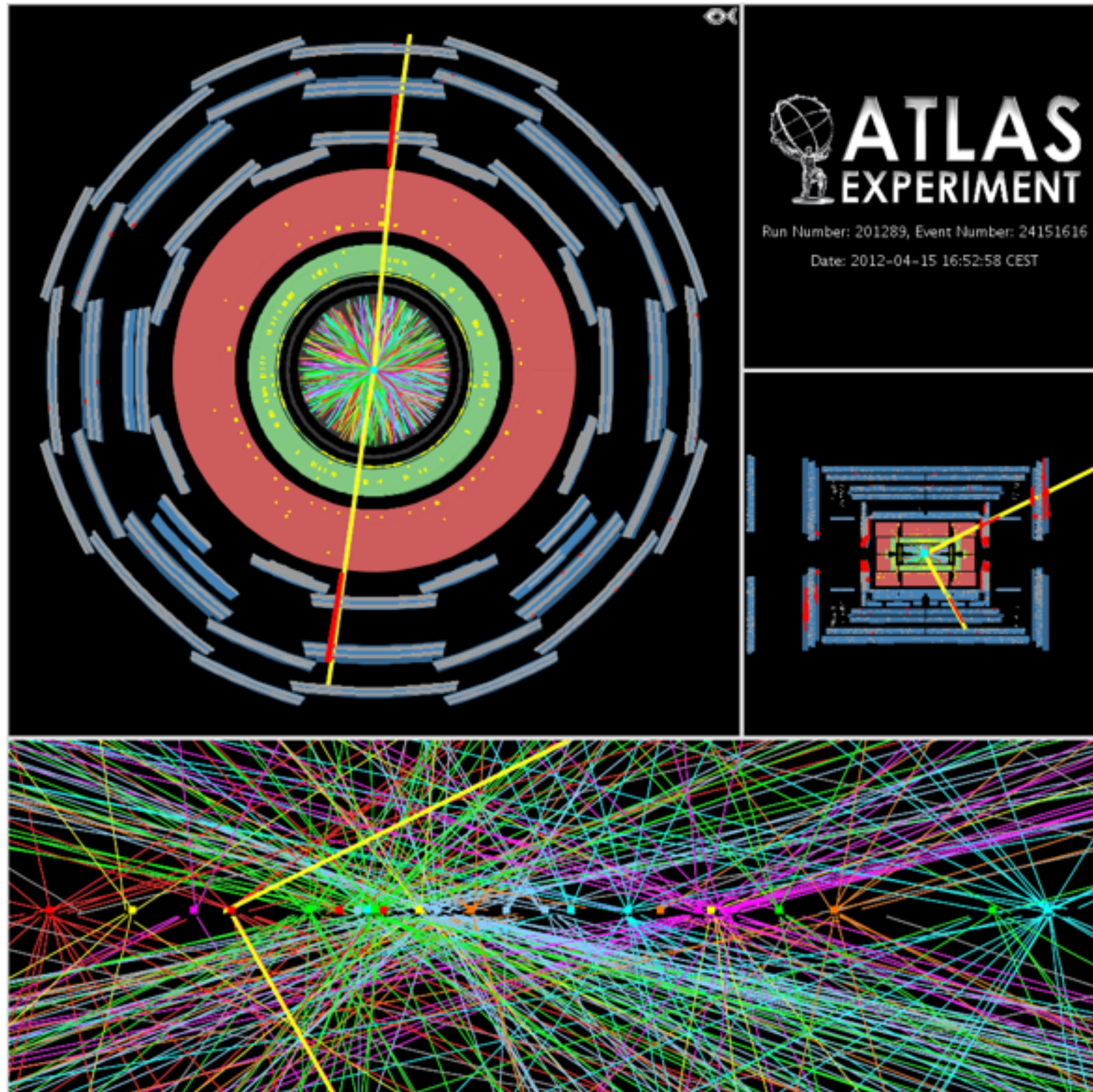
The road from LHC to High-Luminosity LHC



- From 2026, LHC enters new phase : High Luminosity LHC (HL-LHC)
  - x5-x7 increase in luminosity (5-7 x 10^{34} cm^{-2} s^{-1})
  - Goal is to deliver 4000 fb^{-1} over 10 years
  - Extend searches for new physics into the multi-TeV region
  - Improved measurements of Higgs boson's properties
- *By 2026, ID will have accumulated too much radiation damage to be usable for HL-LHC : replacement tracker will be needed*

HL-LHC Pile-up challenge

- The increased HL-LHC luminosity increases number of overlapping proton-proton collisions per beam crossing *(pile-up)* from 20 to 200
- LHC event display is a Z→μμ candidate with 25 pile-up events



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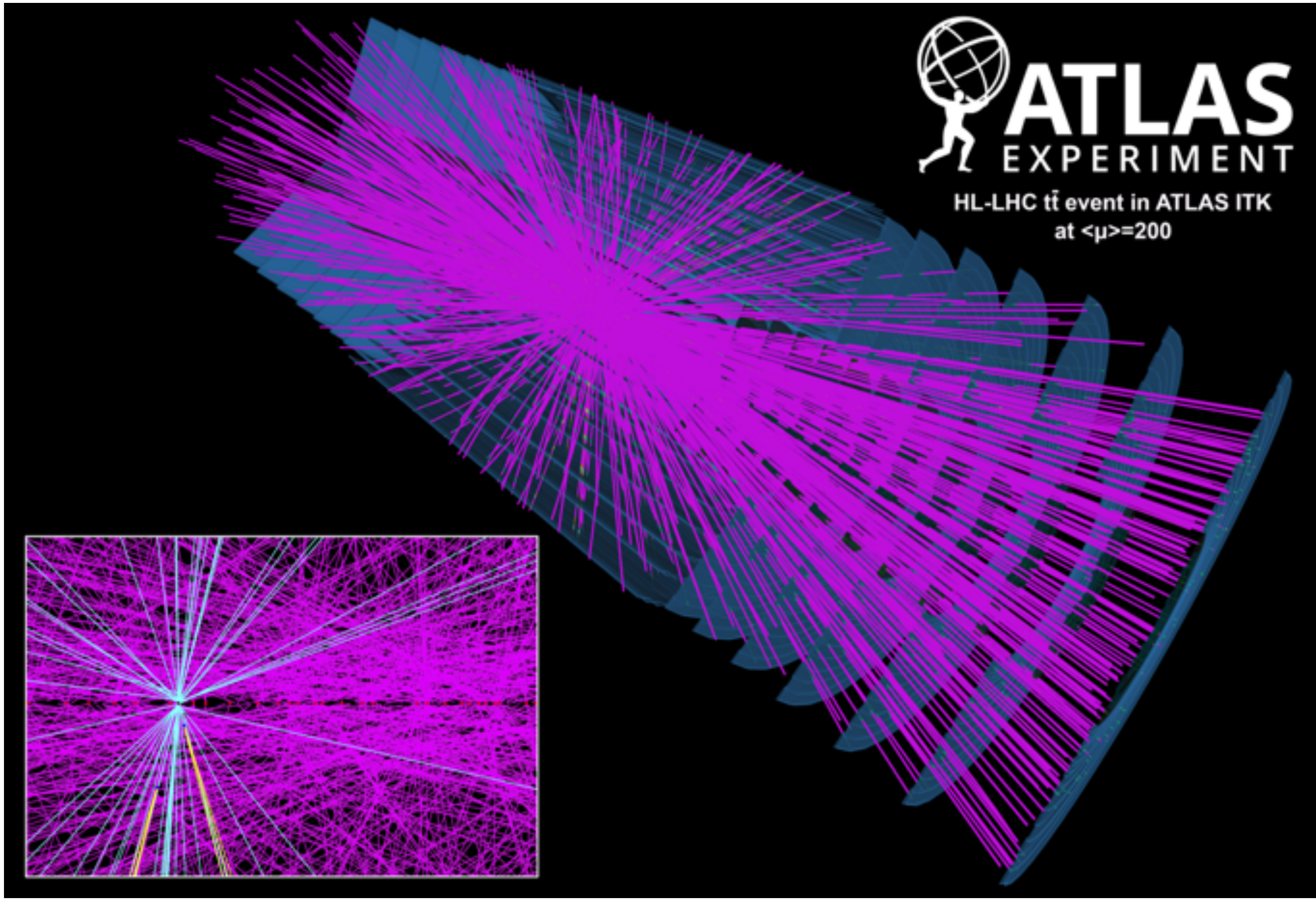
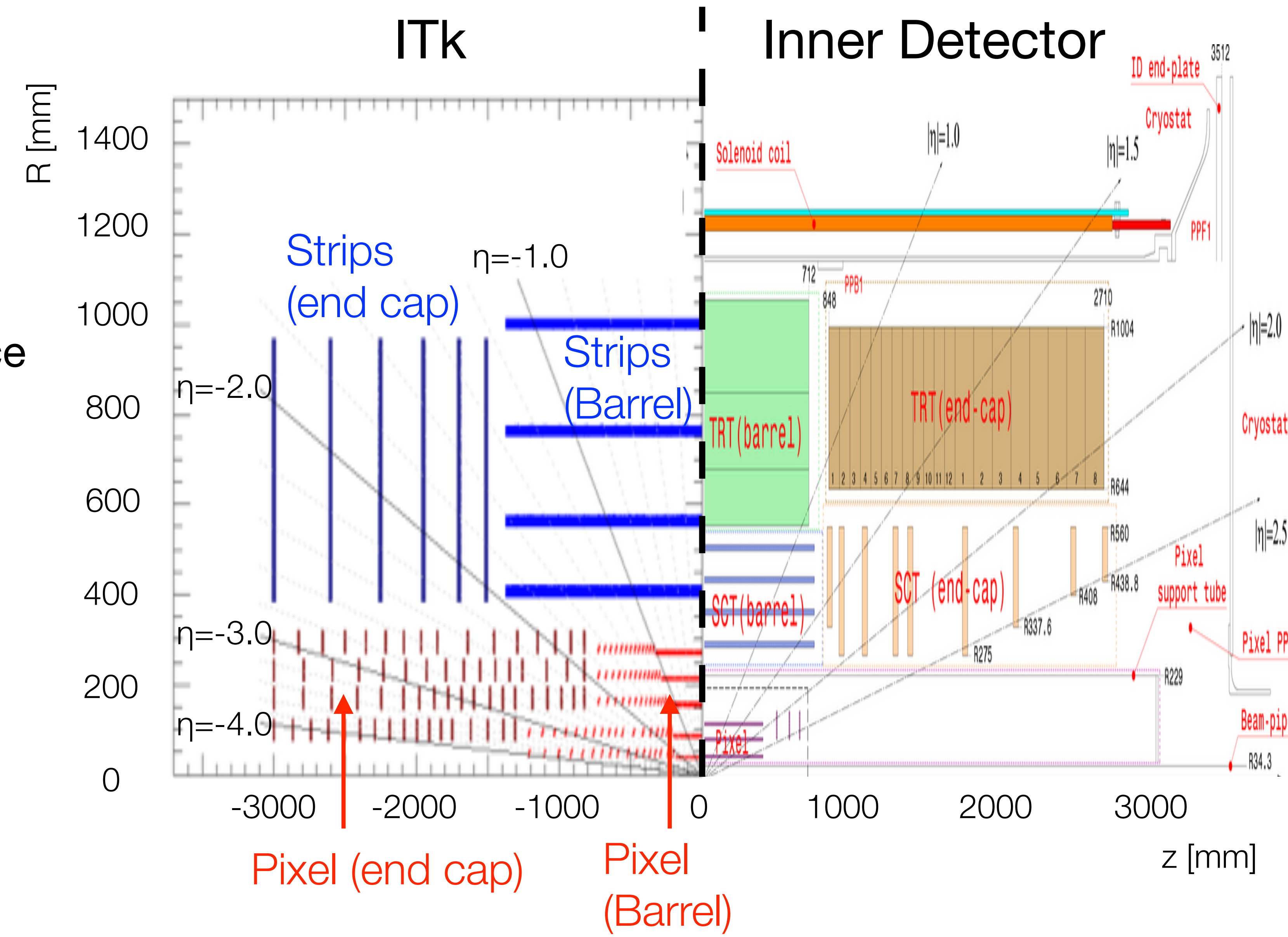
- LHC event display is a Z→μμ candidate with 25 pile-up events
- HL-LHC simulated event of a tt event with 200 pile-up events
- ID-TRT will have 100% occupancy at HL-LHC
- ID readout links will be saturated at HL-LHC



ID replacement is not enough
…. an upgraded tracker design is required for HL-LHC

ATLAS Inner TracKer (ITk)

- ITk is the upgraded tracker design for HL-LHC
- **All Silicon tracker of silicon strip and pixel sensors**
- Designed to give same or better performance as ID, even in the presence of 200 overlapping proton-proton collisions
- Design challenges
  - Withstand x10 radiation
    - 1.3 GRad, 2 x 10^{16} n_{eq}/cm^2 at innermost layer
  - Higher granularity tracker, to cope with the higher track density
  - Optimising tracker layout to efficient find tracks
  - Lower radiation length (mass)



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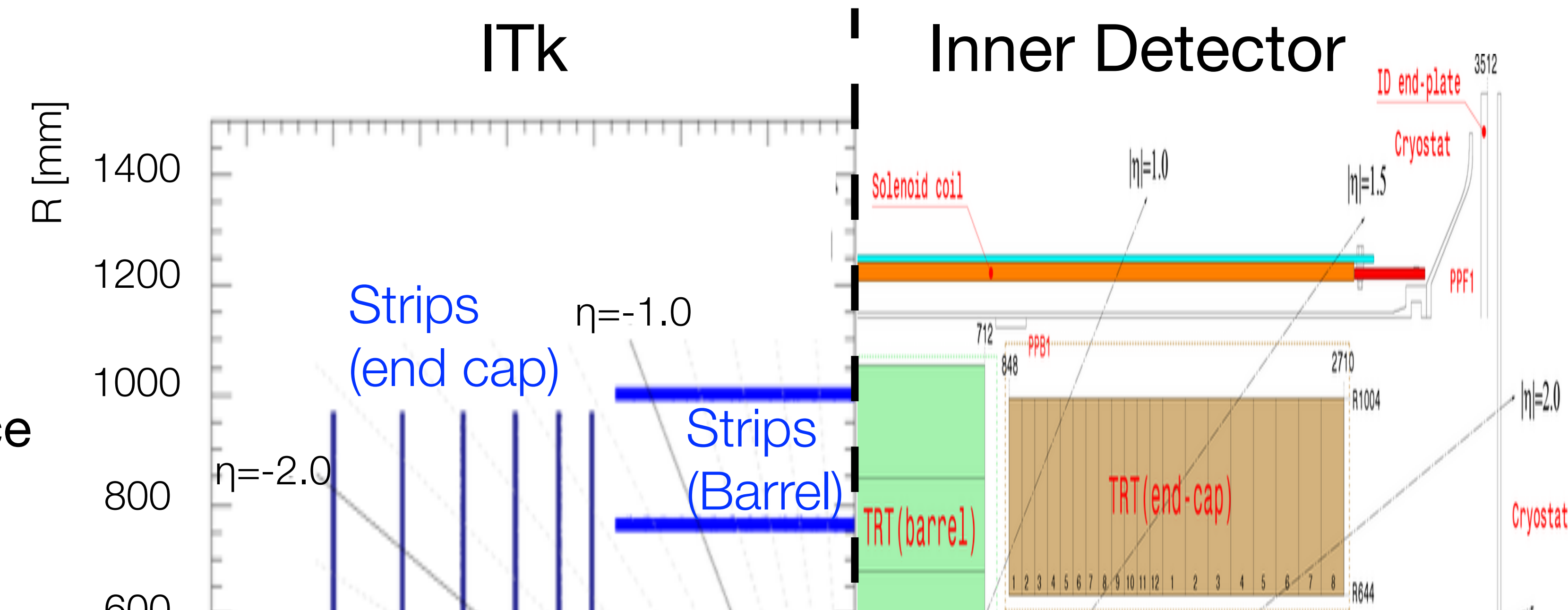

Sensor and readout development

discussed by these PSD presentations:

- *Monolithic Pixel Development in TowerJazz 180nm CMOS for the outer pixel layers in the ATLAS experiment - Ivan Berdalovic*
- *A new strips tracker for the upgraded ATLAS ITk detector - Claire David*
- *Study of prototypes of LFoundry active and monolithic CMOS pixels sensors for the ATLAS detector - Luigi Vigani*
- *Test-beam activities and results for the ATLAS ITk pixel detector - Tobias Bisanz*
- *Characterization of Novel Thin N-in-P Planar Pixel Modules for the ATLAS Inner Tracker Upgrade - Julien-Christopher Beyer*

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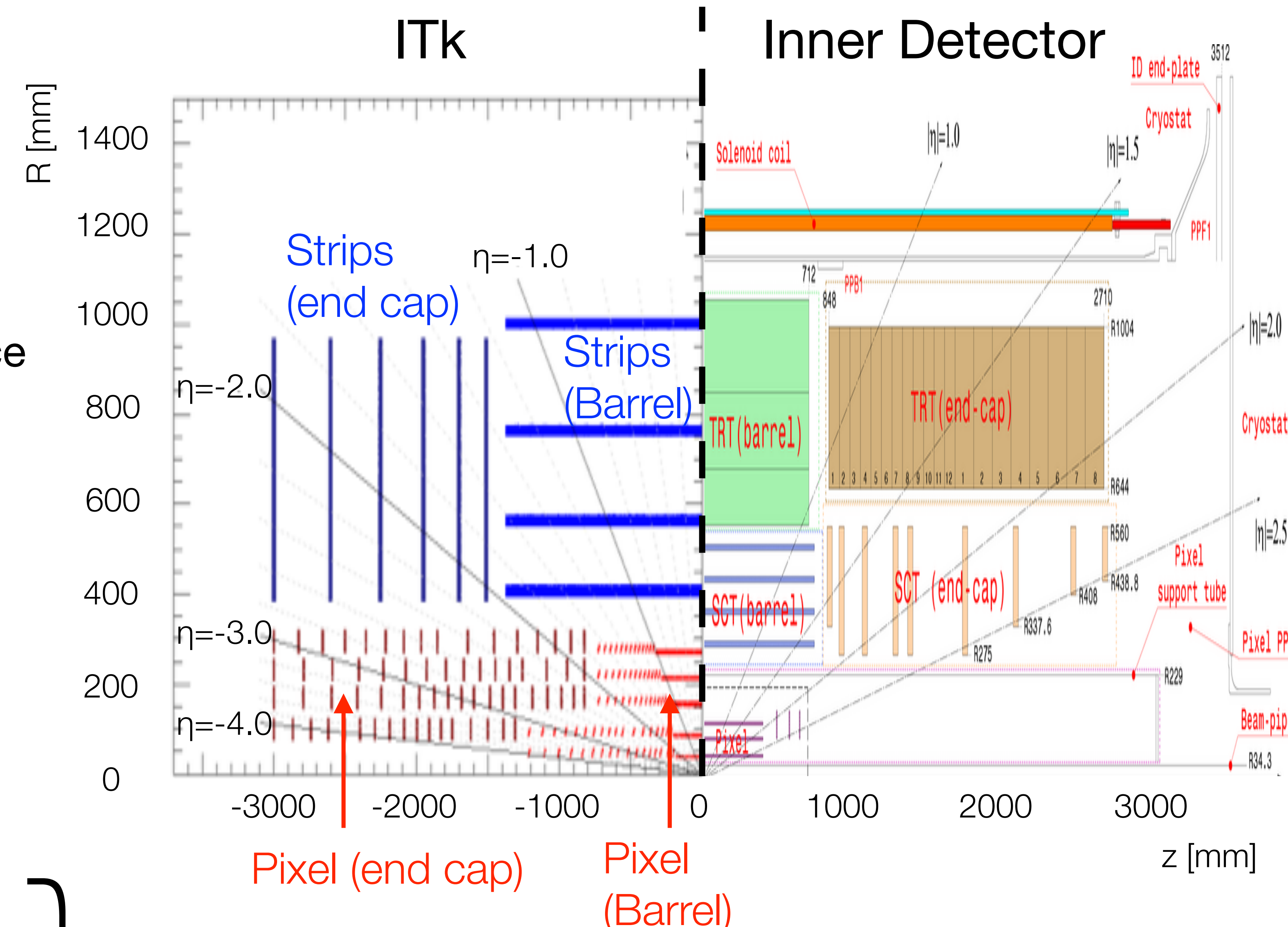
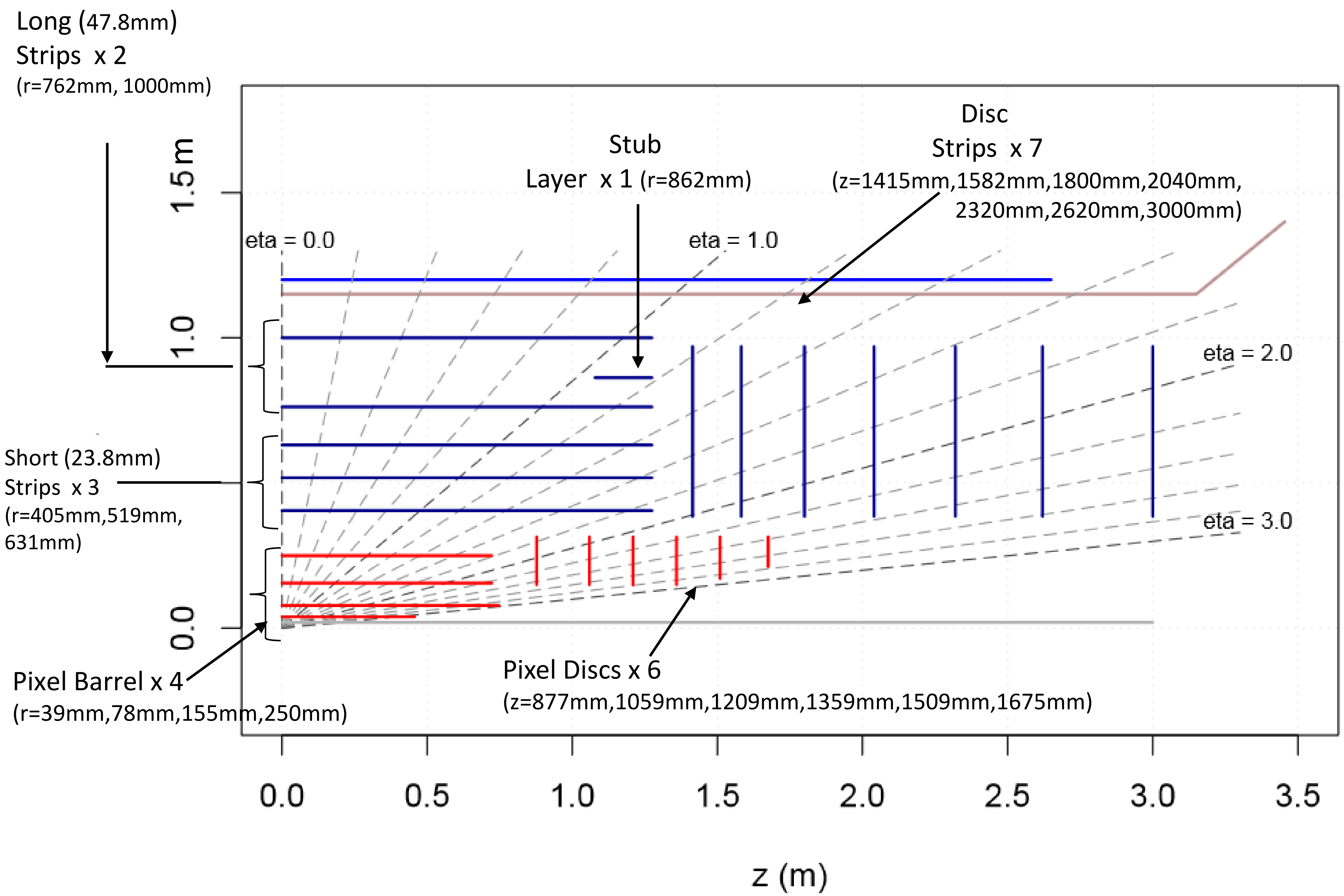


The focus of this talk

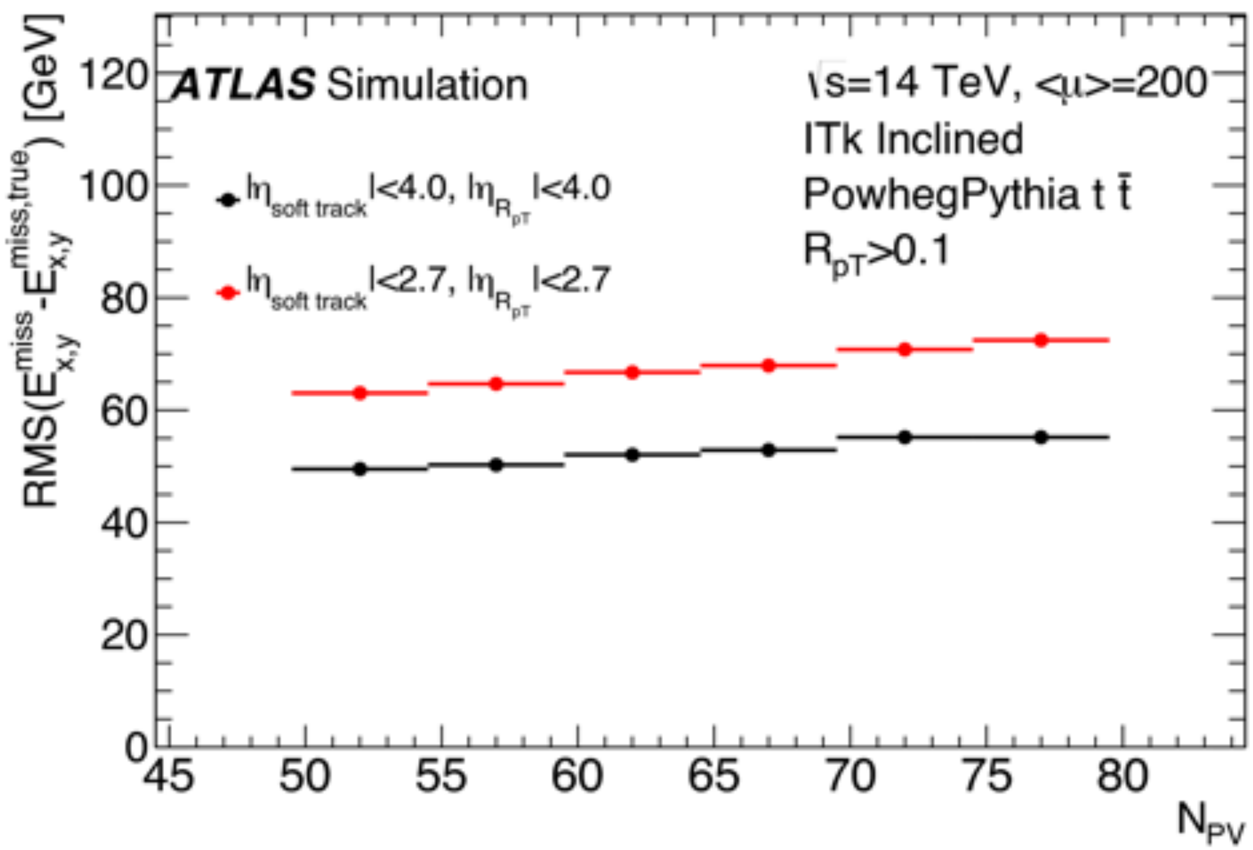
Tracker Layout Evolution

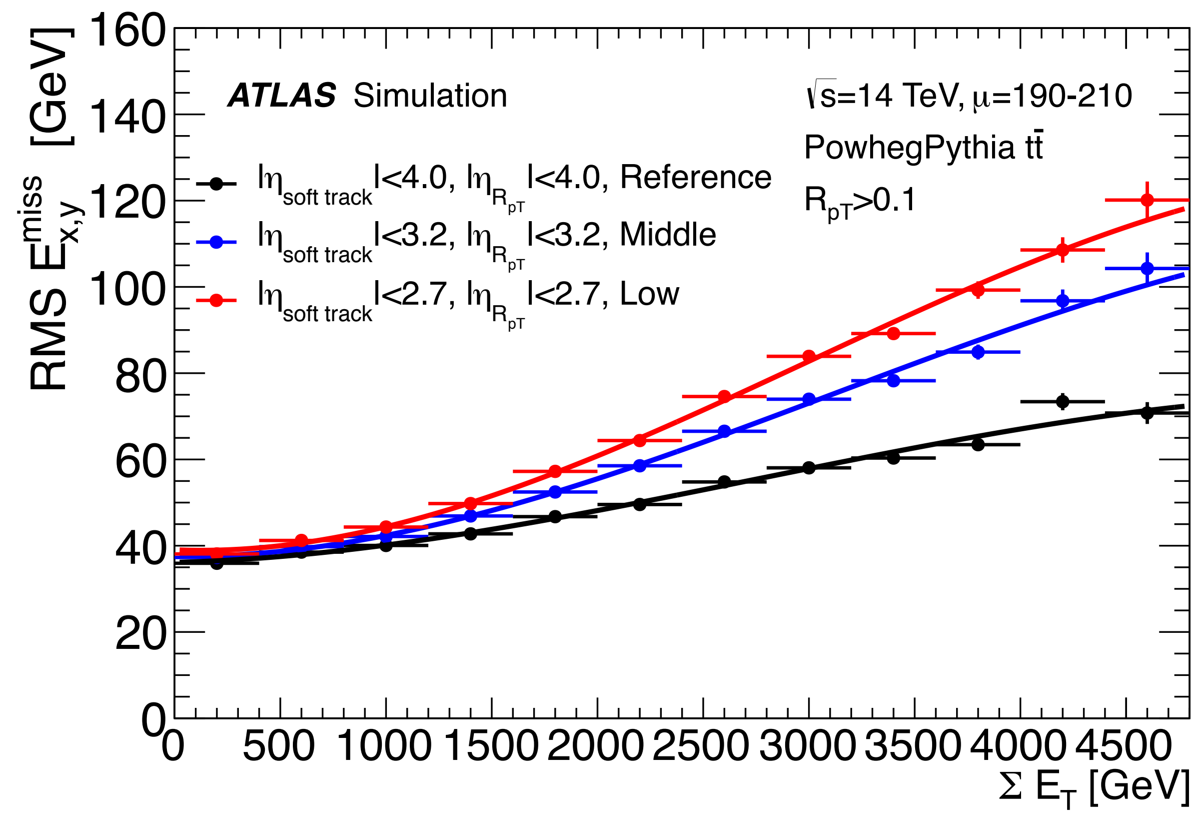
Letter of Intent (LoI) Layout : First Version



- LoI Layout ~ 2012, guided by requirement of at least 14 hits and coverage to |η| ~ 2.7
- The "stub" layer included to provide additional points between barrel to disk transition

Evolution of tracker layout : Addition of very forward pixel detector

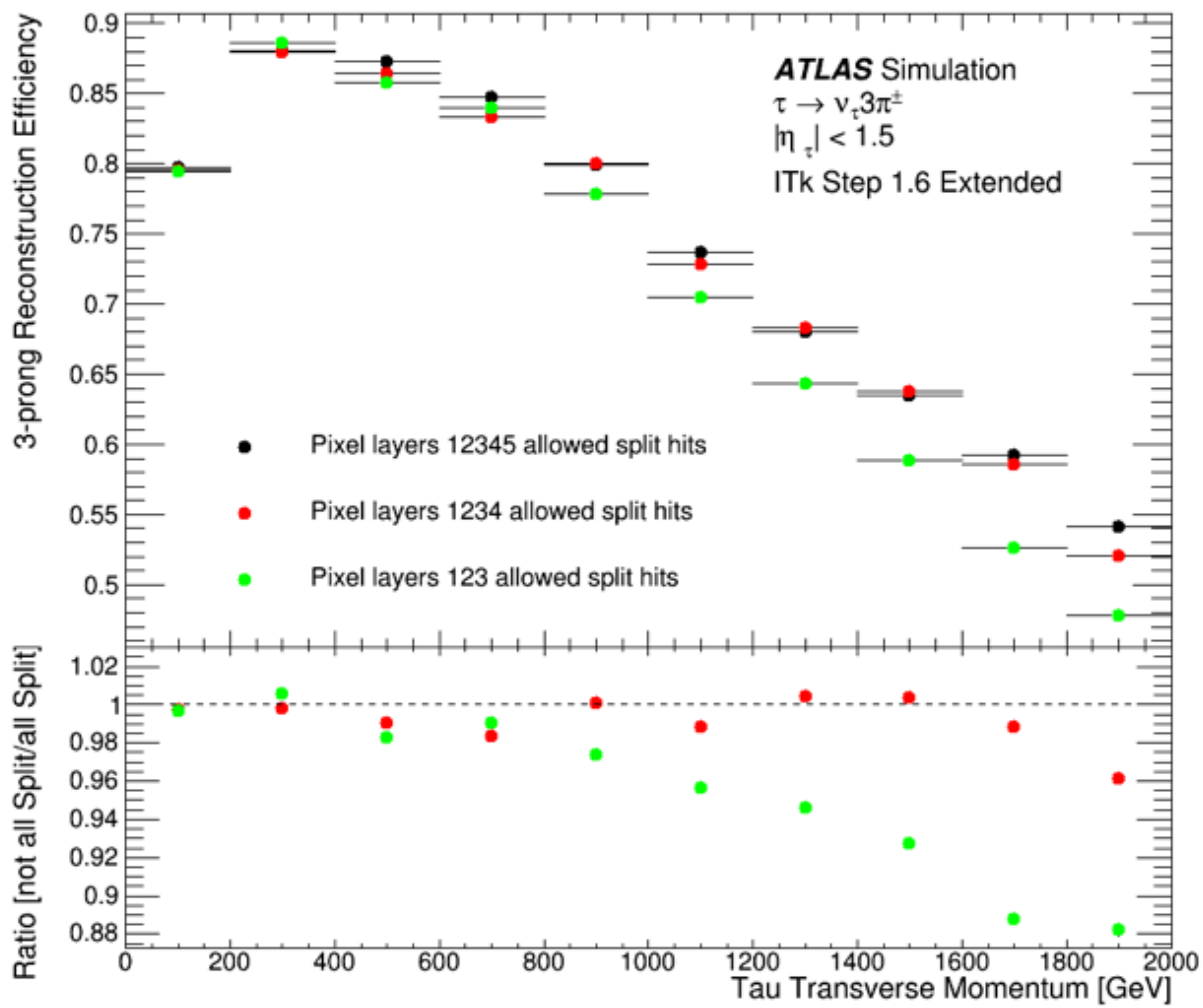




- Simulations showed benefit of adding more pixel detectors in the very forward region
- More Pixels disks added to out to |η| ~ 4

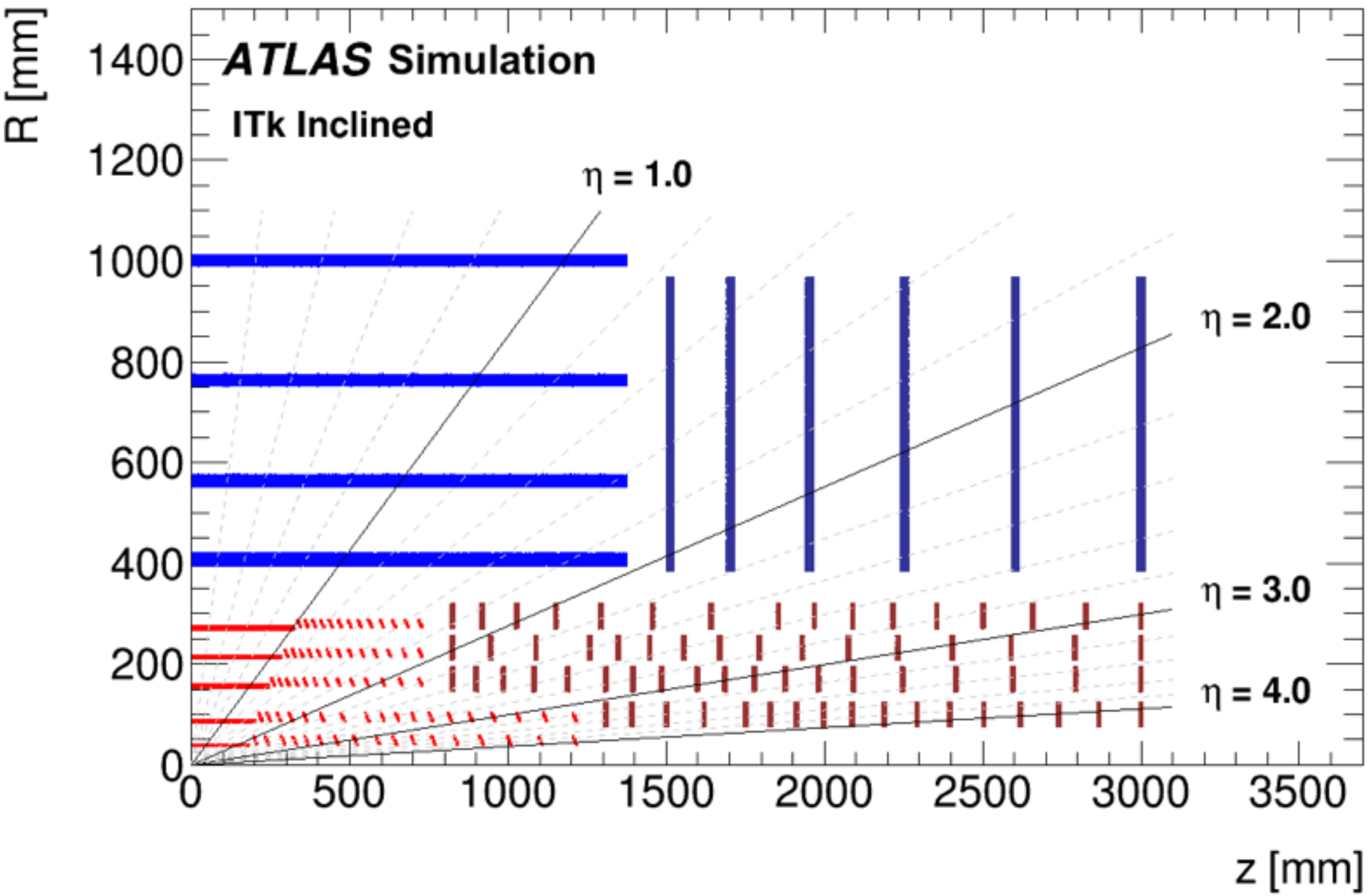
Evolution of tracker layout : Additional Pixel Layer

- Further studies showed benefit of having 5 pixel layers in HL-LHC environment
    - better performance
    - robustness to missing single hit
- Example: τ lepton reconstruction
    - 4 pixel layers improves reconstruction efficiency at large momentum
    - 5th pixel layer adds redundancy



Evolution of tracker layout - Strips Technical Design Report (TDR)

- Strips TDR is the latest layout of ITk



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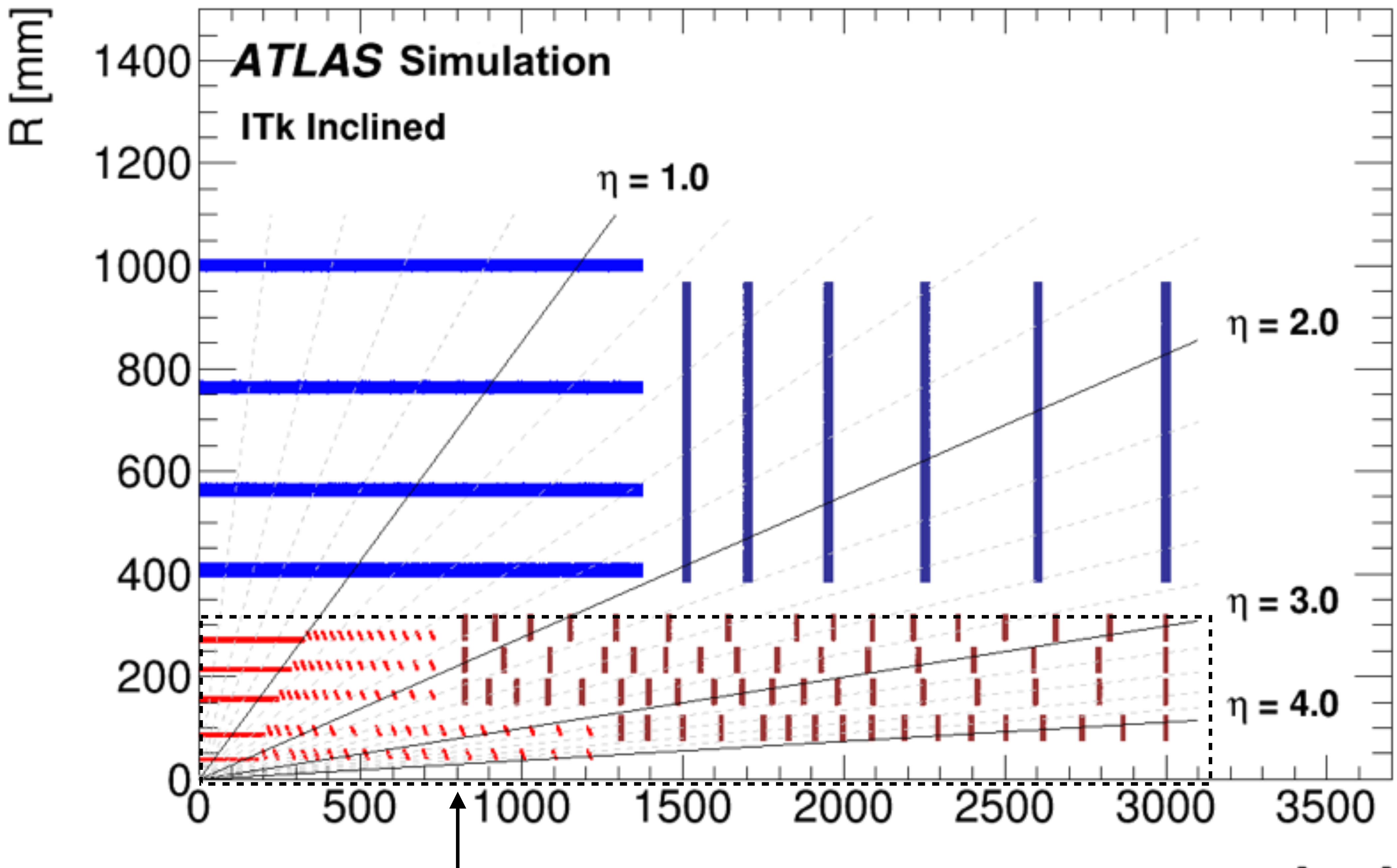

Pixels expanded to full length of ITk to cover |η|∼4

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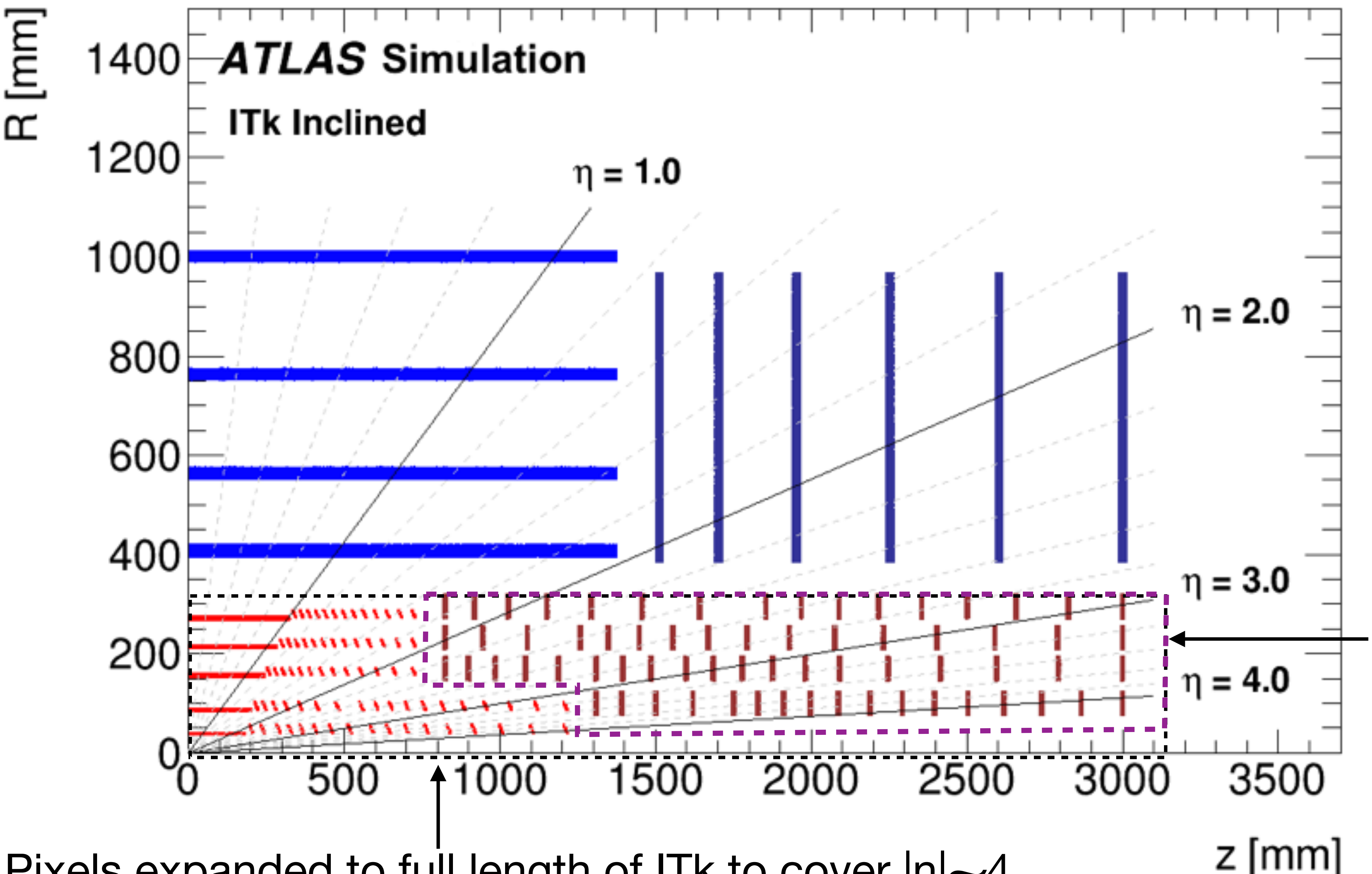

Pixel rings, instead of disks. Z positions for each layer are optimised for hermetic coverage

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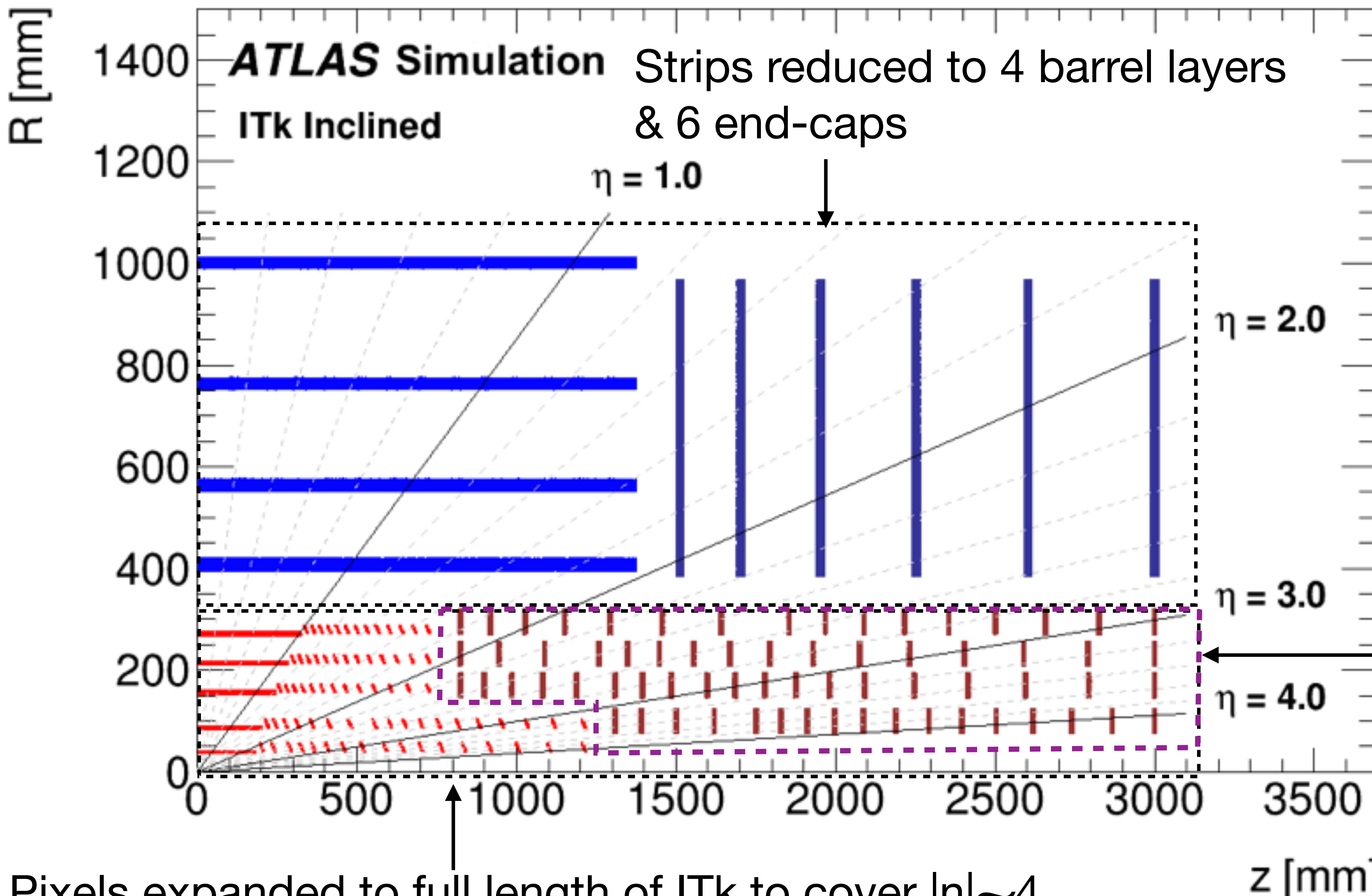

Strips reduced to 4 barrel layers & 6 end-caps

Pixel rings, instead of disks. Z positions for each layer are optimised for hermetic coverage

Pixels expanded to full length of ITk to cover |η|∼4

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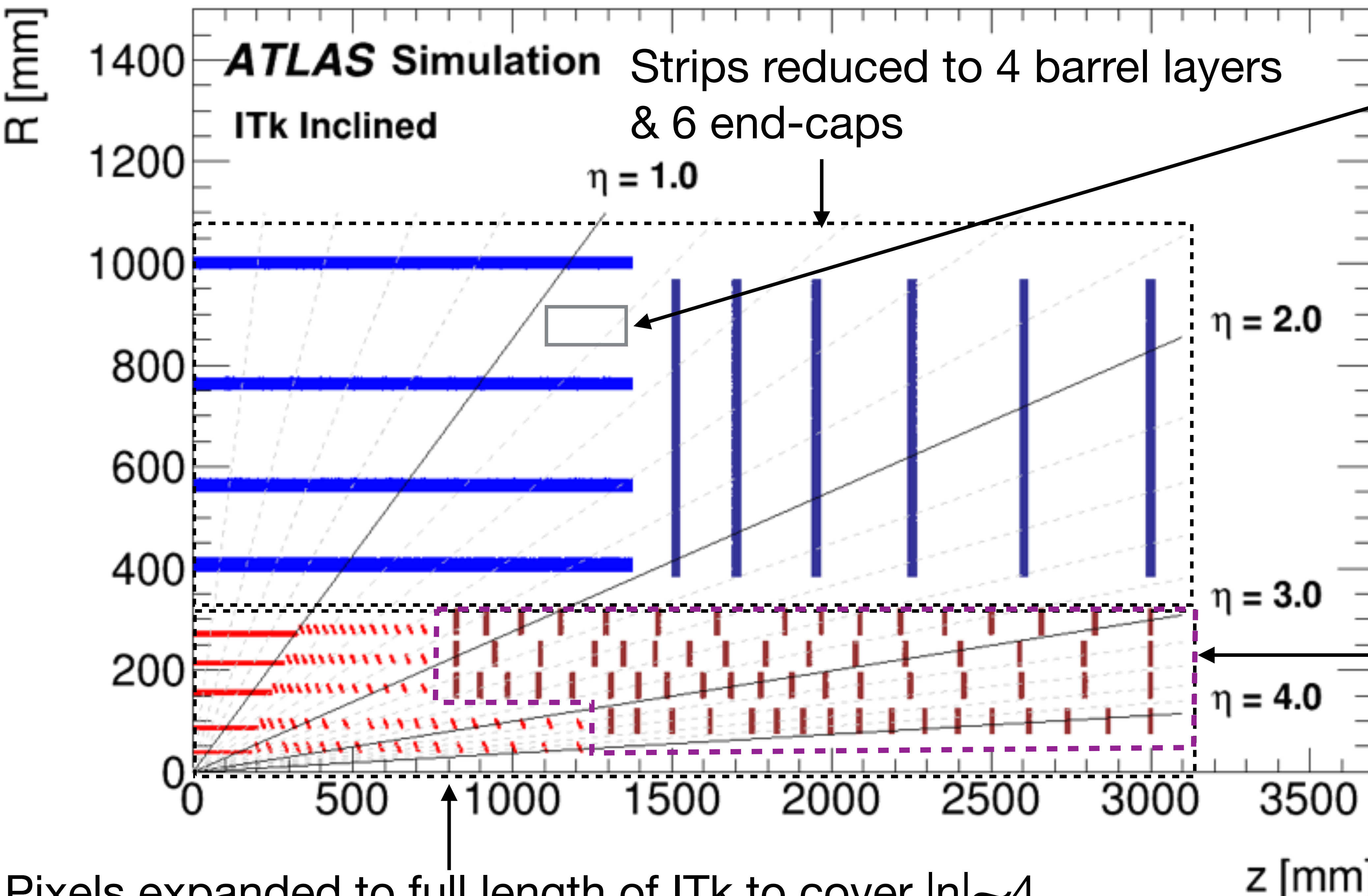


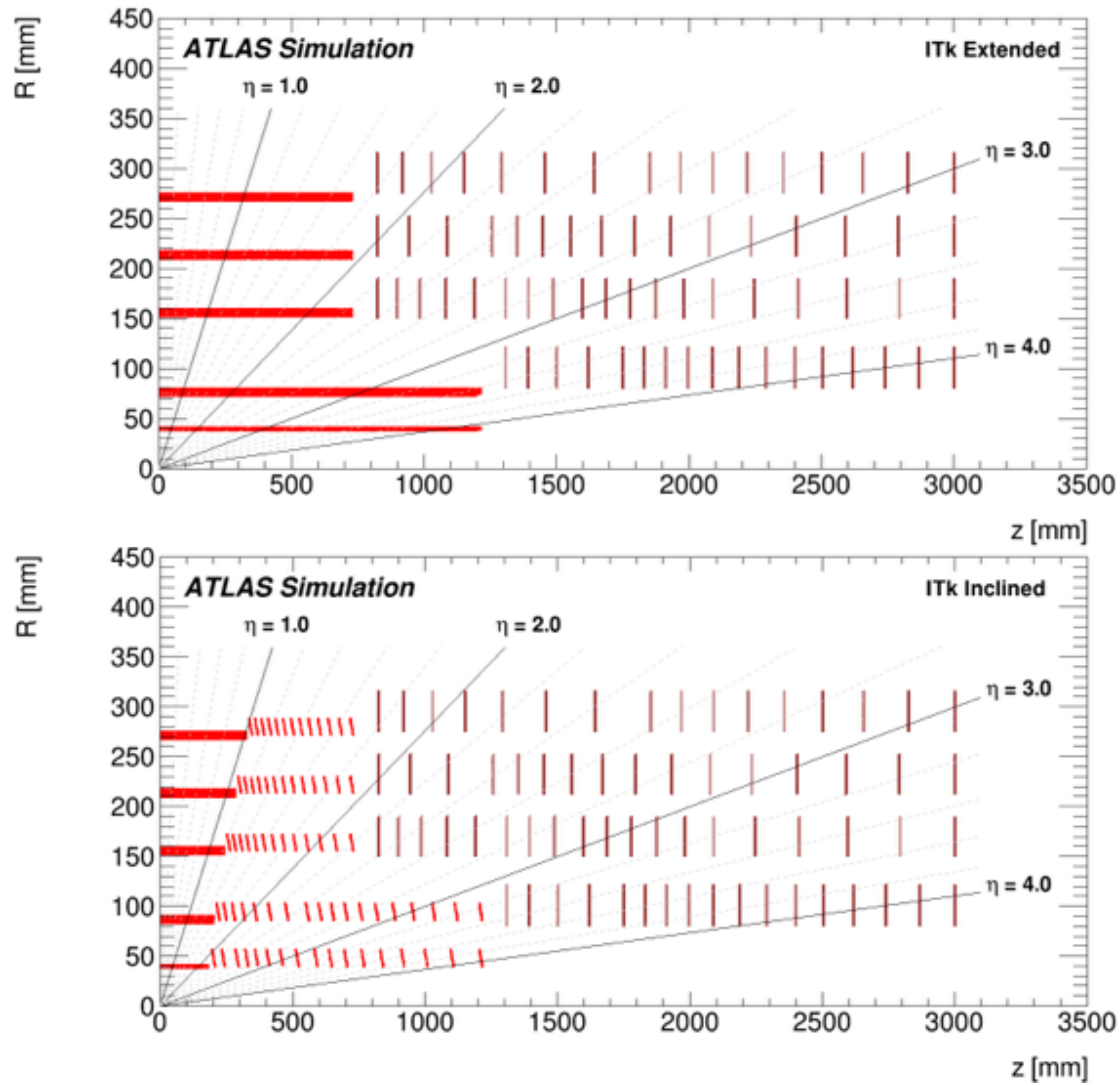
Stub layer removed: not needed

Pixel rings, instead of disks. Z positions for each layer are optimised for hermetic coverage

Pixels expanded to full length of ITk to cover |η|∼4

Evolution of tracker layout
Optimising Pixel Layout : Extended vs Inclined

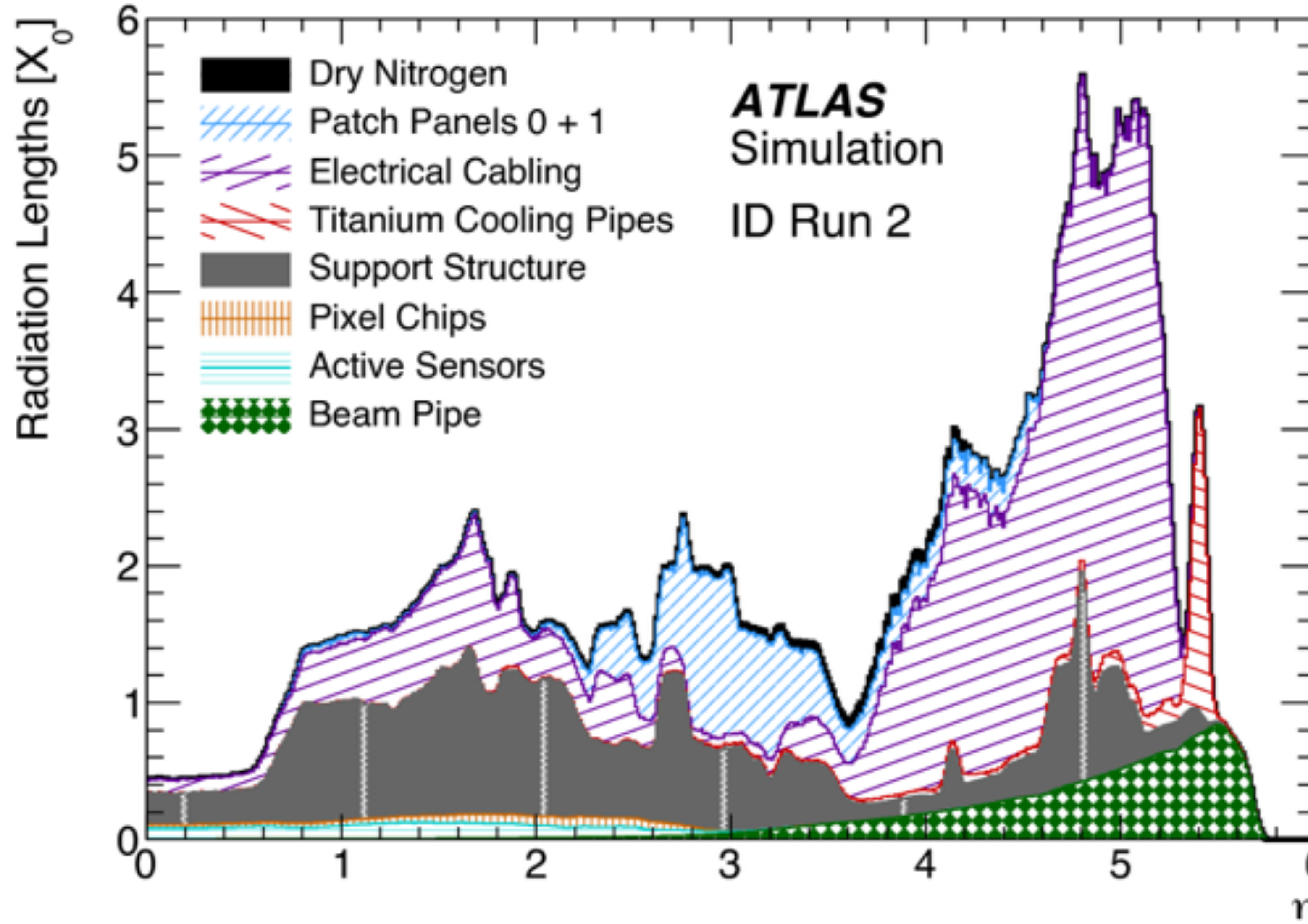
- There are two options for the pixel detector layout
- Extended has extended barrel layers
- Inclined layers has pixel detectors ~perpendicular to tracks in the forward region
    - less material traversed
    - multiple hits per track close to interaction point
    - less Silicon surface area required to cover same η range
- *Inclined layout is the baseline design for the pixel detectors*
- *Further optimisation is in progress*



Lowering Material budget

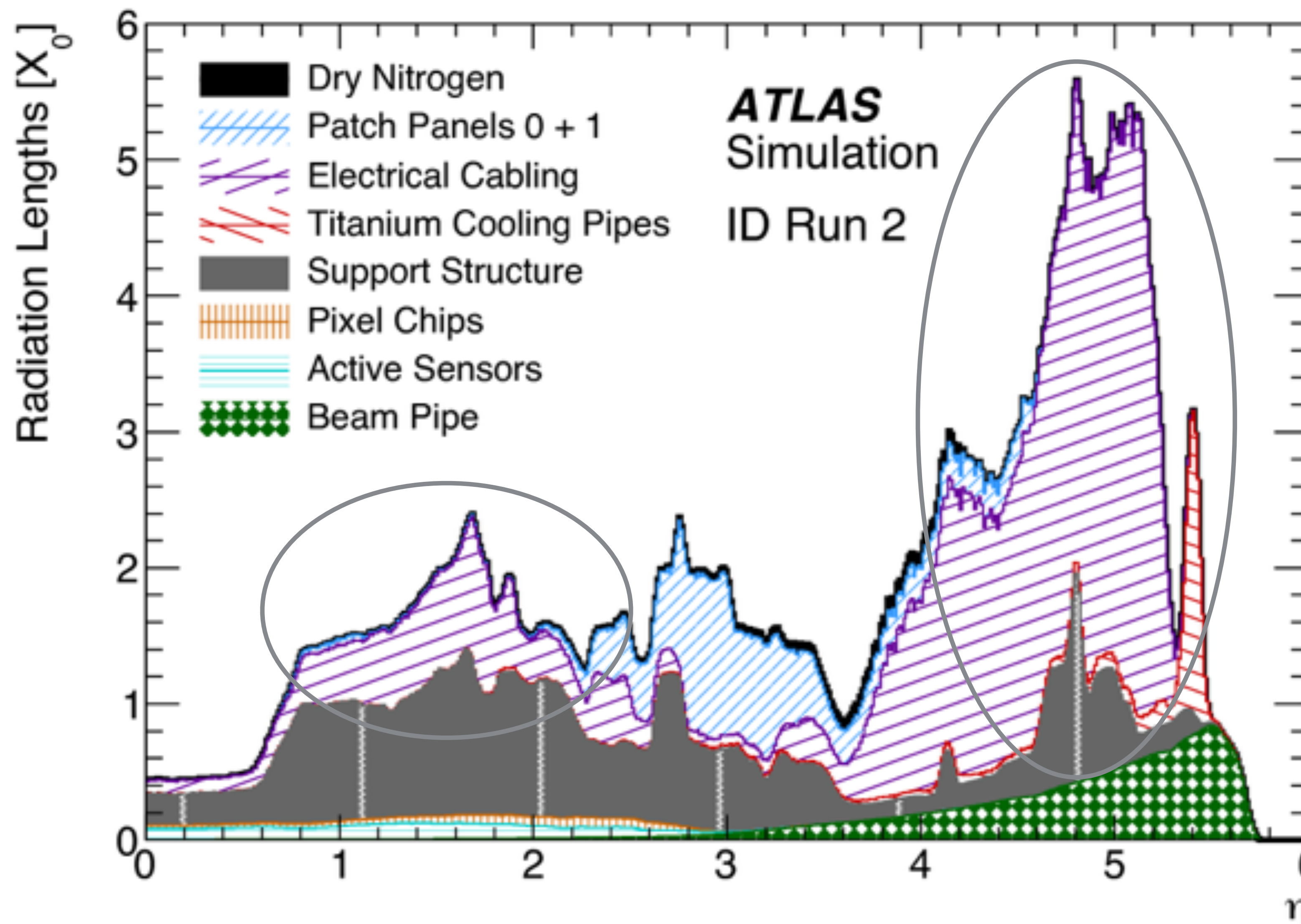
Reducing the Material Budget

- The tracker material is a major limitation of the overall performance



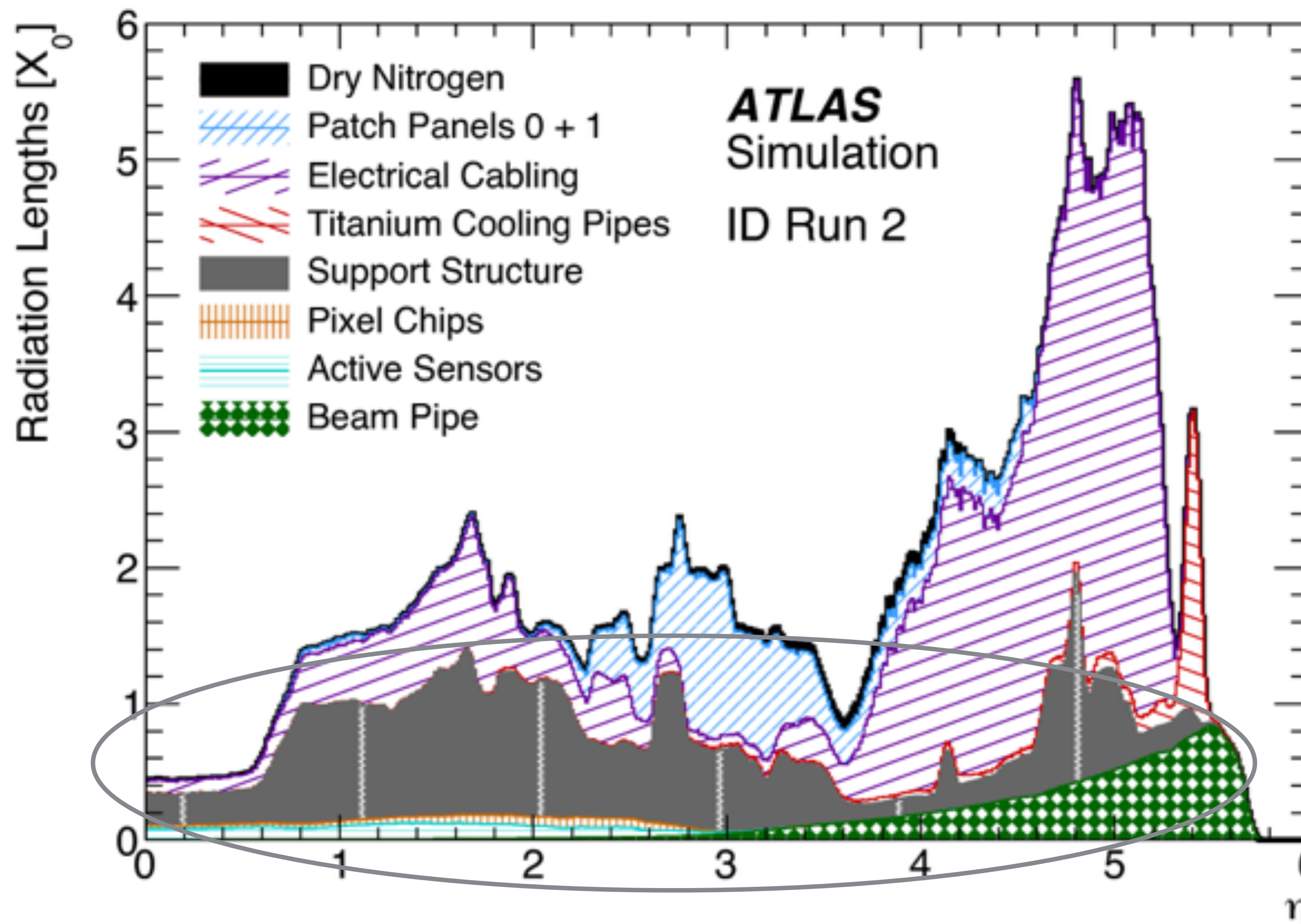
Reducing the Material Budget

- The tracker material is a major limitation of the overall performance
- The largest contributions to the ID material are
  - electrical cabling



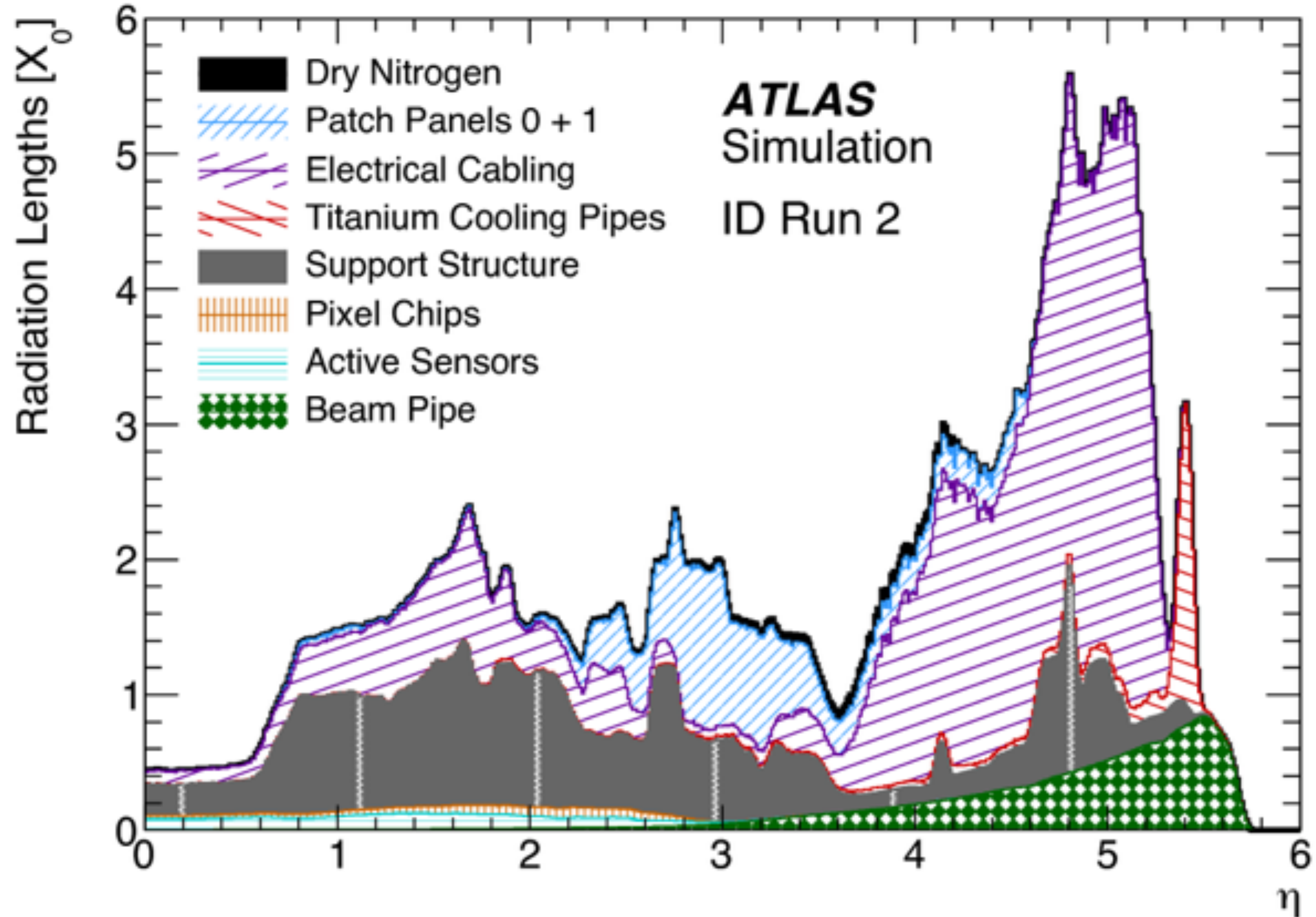
Reducing the Material Budget

- The tracker material is a major limitation of the overall performance
- The largest contributions to the ID material are
  - electrical cabling
  - support structure



Reducing the Material Budget

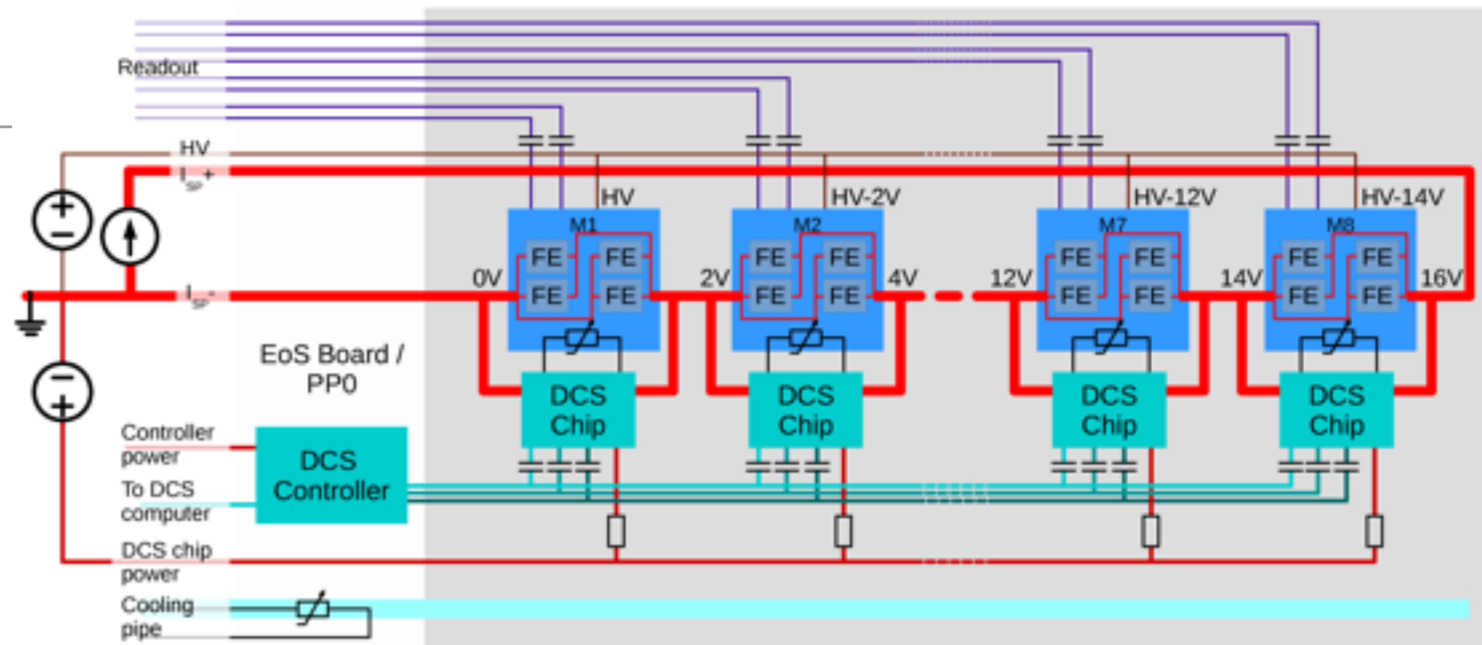
- The tracker material is a major limitation of the overall performance
- The largest contributions to the ID material are
  - electrical cabling
  - support structure
- ITk needs to power more sensors and electronics with less cable
- ITk has to support a larger structure with less material



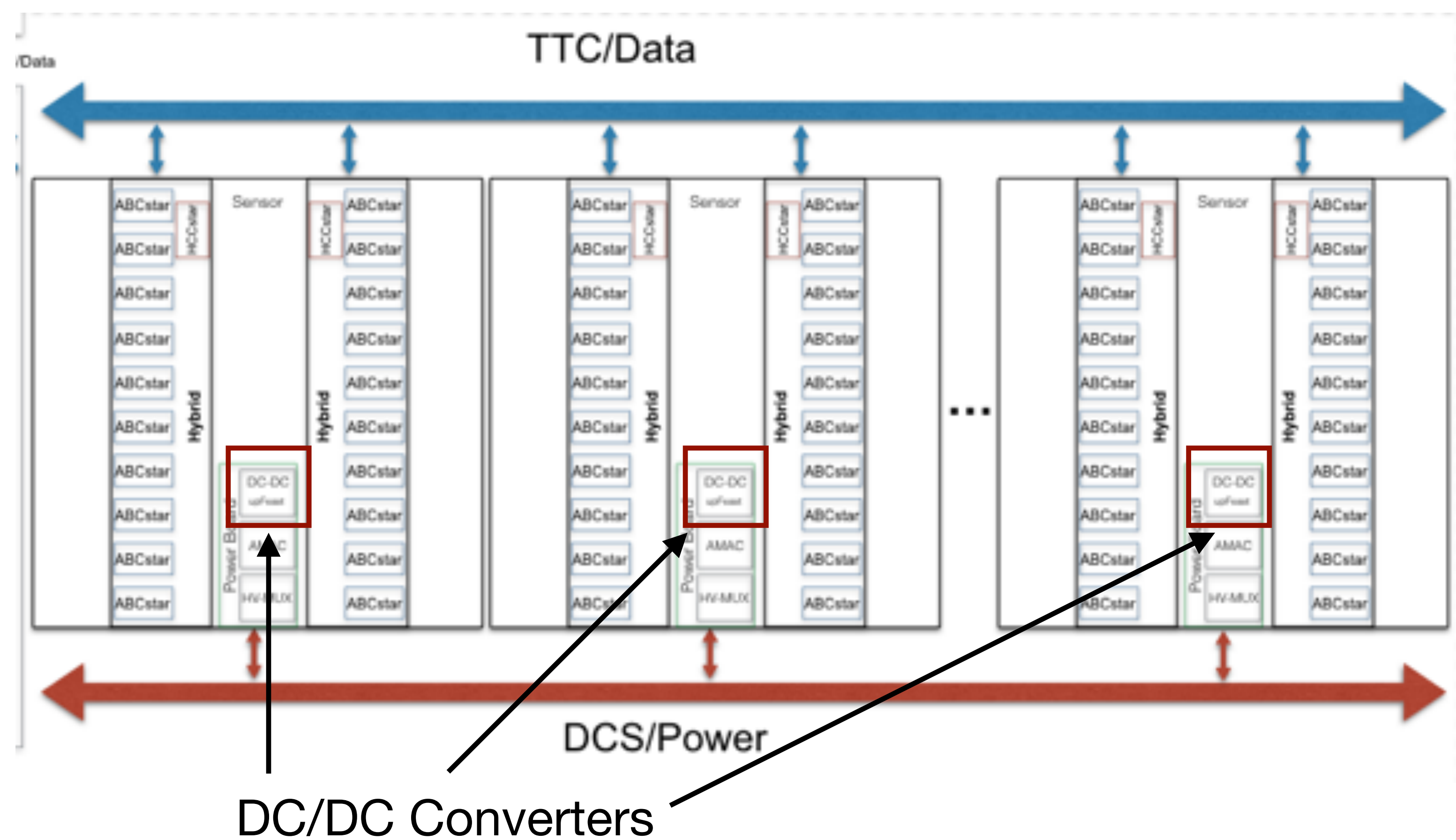
Module powering

- Pixels: Serial Powering
    - Power with constant current source
    - Shunt low-dropout regulator to control voltage across pixel module
    - Physically small and low material cost
    - AC connections have to made as modules don't share a common ground
- Strips: DC/DC converter
    - Local generation of voltages
    - Large strip sensors are susceptible to common-mode pickup.
        - Difficult to implement shielding without common ground
    - Each DC/DC converter has a shield box to reduce EMI
- **Both schemes reduce electrical cabling, the major material contribution for trackers**

Pixel Serial Power

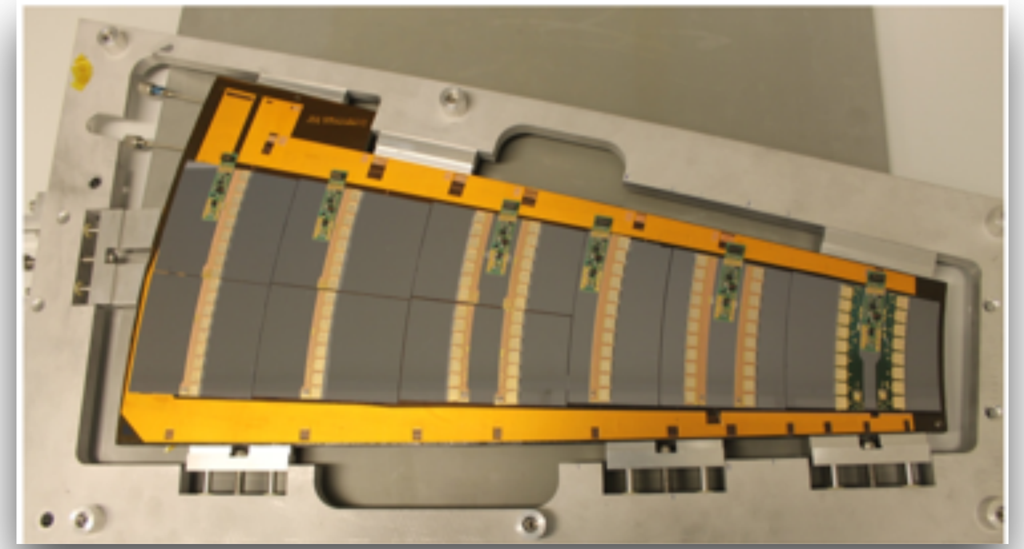


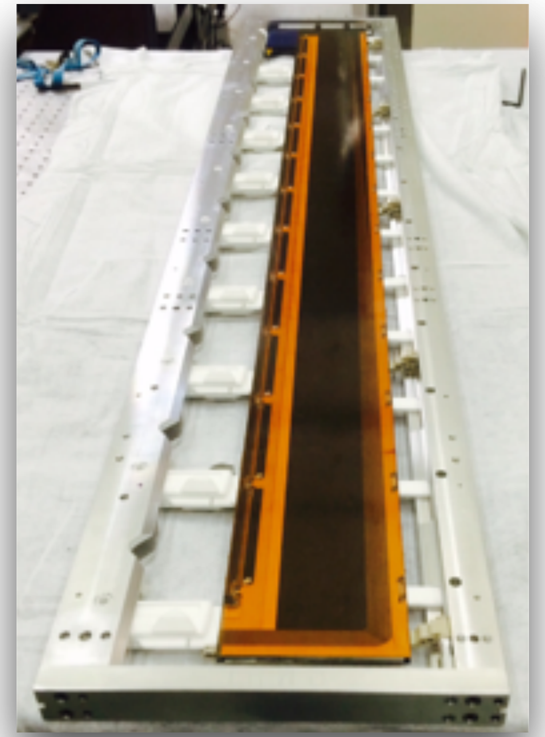
Strips DC/DC Converter

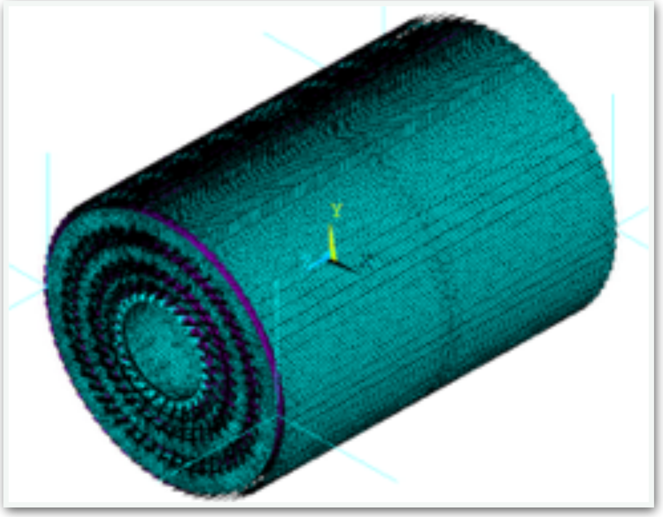


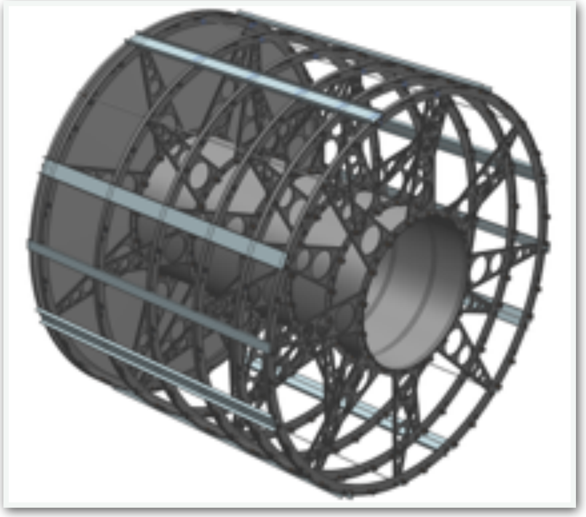
ITk Support Structures

- Support structures provide
  - mechanical support of sensors and associated electronics
  - thermal path to keep sensors and electronics cool
- **The supports have to be low mass and stiff**



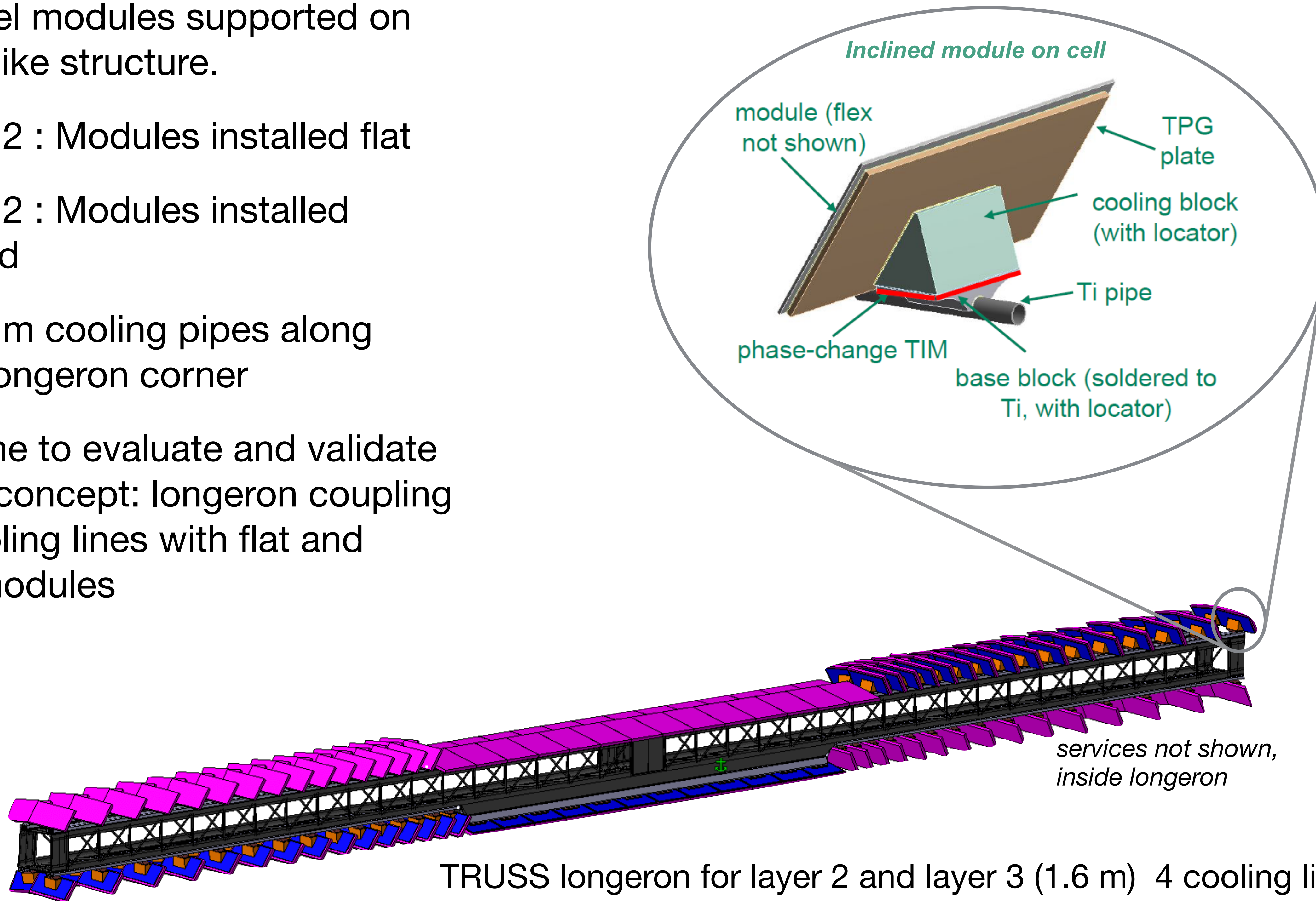






Pixel Local Support : Inclined Layout

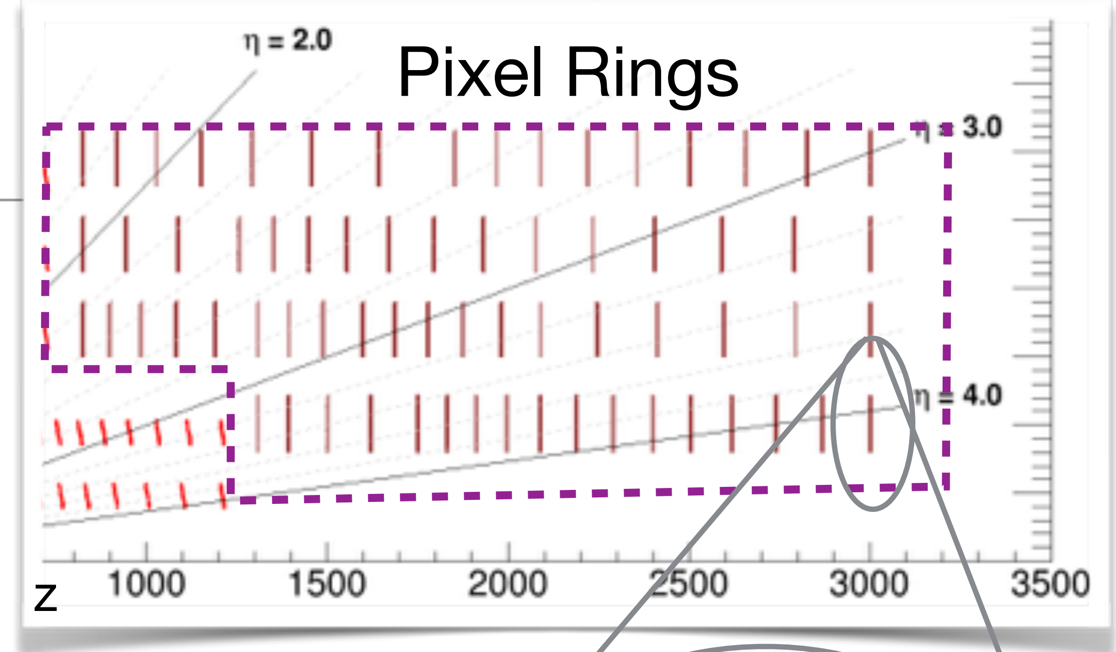
- SLIM: Pixel modules supported on longeron-like structure.
  - |η| < 1.2 : Modules installed flat
  - |η| > 1.2 : Modules installed inclined
  - Titanium cooling pipes along each longeron corner
- Programme to evaluate and validate the SLIM concept: longeron coupling 3 or 4 cooling lines with flat and inclined modules

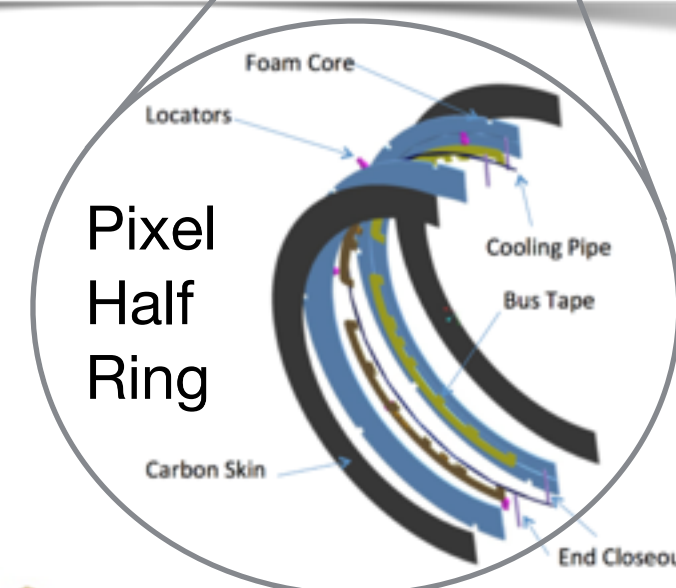


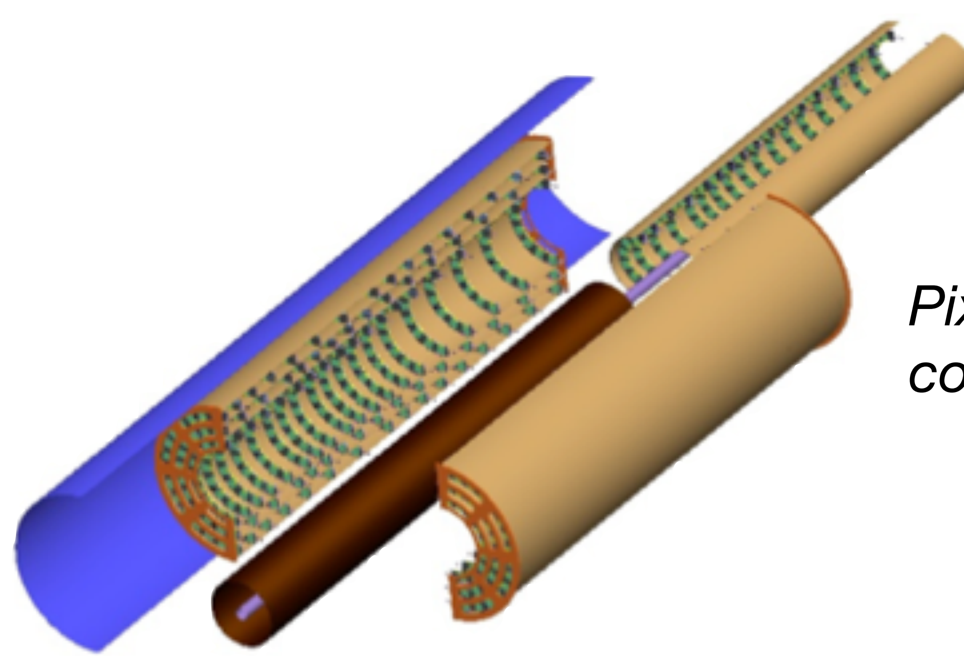
TRUSS longeron for layer 2 and layer 3 (1.6 m) 4 cooling lines
52 flat quad and 124 inclined double modules

Pixel Local Support: Rings

- Pixel rings cover the high η region
- The number of rings and positions in z are optimised for hermetic coverage of tracks for each pixel layer, separately
- The pixels rings gives flexibility in location and number without large engineering changes
  - leaves room for further optimisation



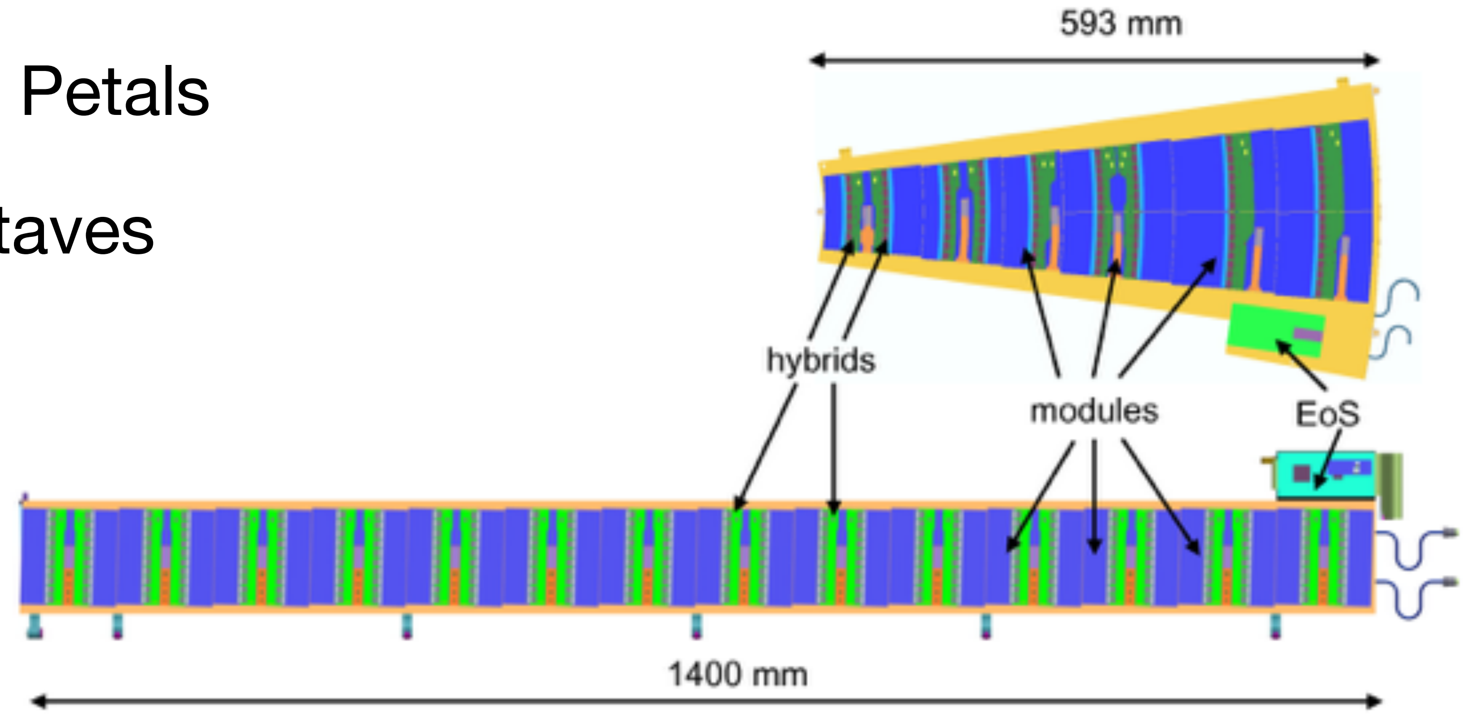




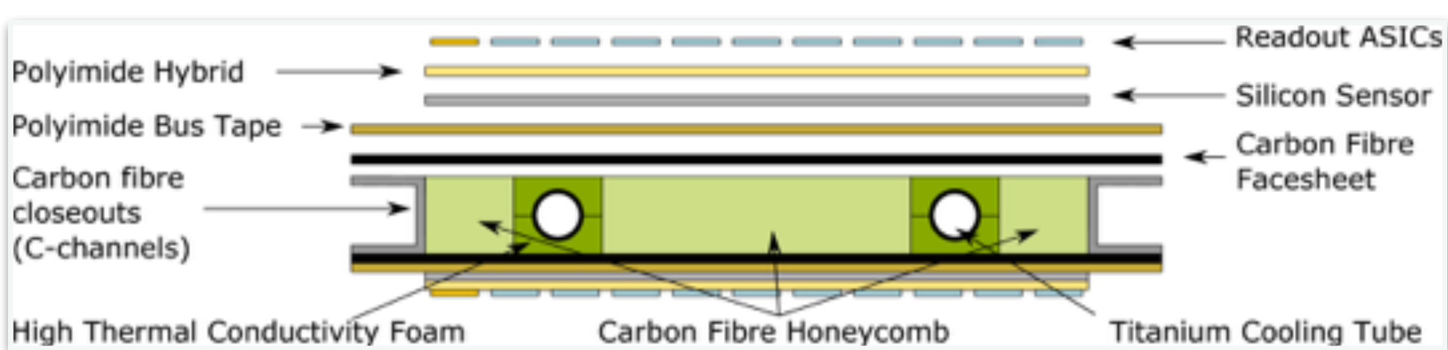
Pixel half ring rings in their composite support cylinder

Strips Local Supports

- Strip sensors, readout electronics, and power (*Module*), are assembled onto larger structures that provide mechanical support and cooling
  - End cap Modules → Petals
  - Barrel Modules → Staves



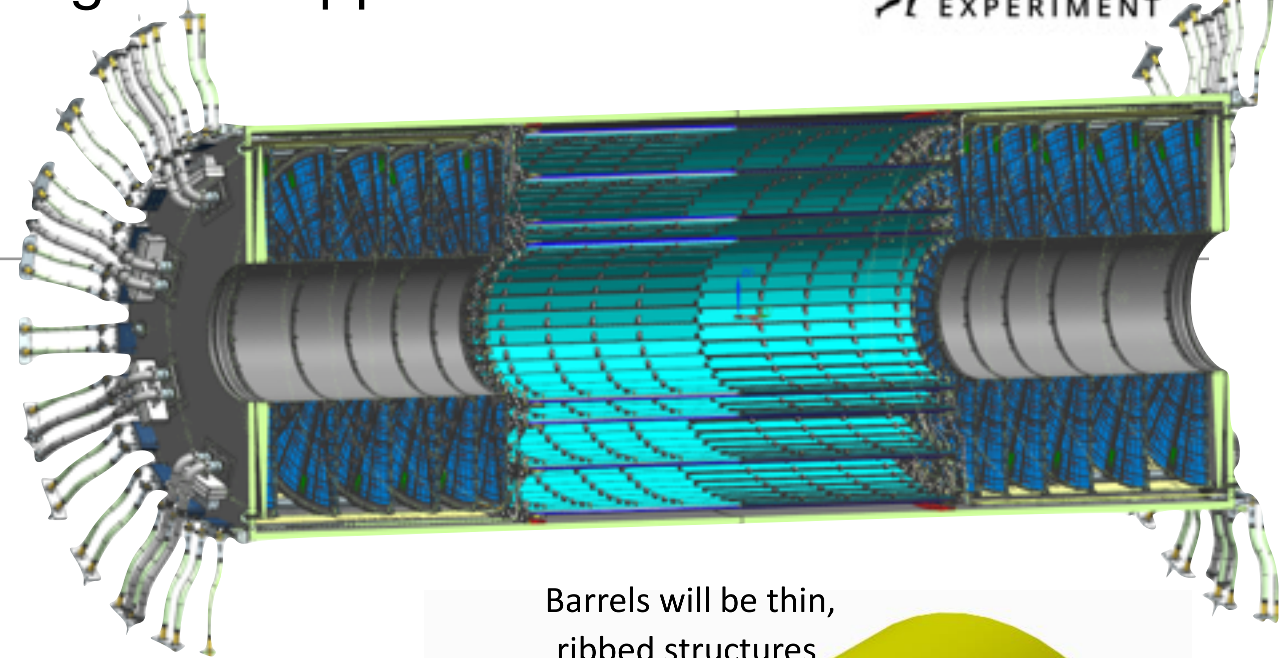
- Each Petal/Stave has embedded Titanium cooling pipes, surrounded by high thermal conductivity foam and sandwiched by carbon fibre

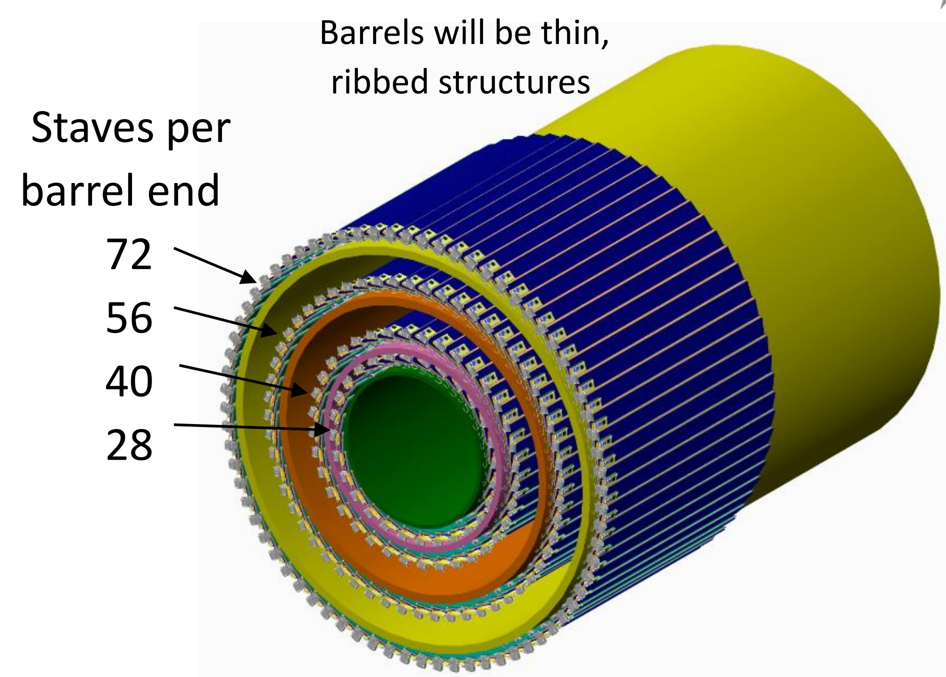


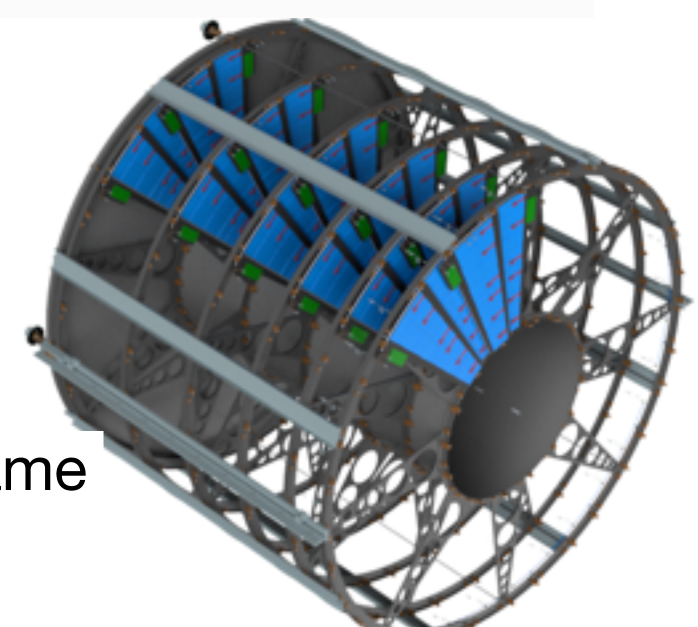
Strips Global Supports

- The strips global supports connect the strip substructures together
- The global supports have to be low mass and sufficiently stiff for track based alignment
    - stability of 20µm, 20µm, 2µm in *z,r,ϕ* over ~1 day
- Barrel:
    - there are 4 concentric barrels - one for each barrel layer
    - Staves are mounted on carbon fibre barrels before integration
- End cap:
    - petals are mounted onto a carbon fibre frame that forms an end cap disk

Cross-section of the strips global support



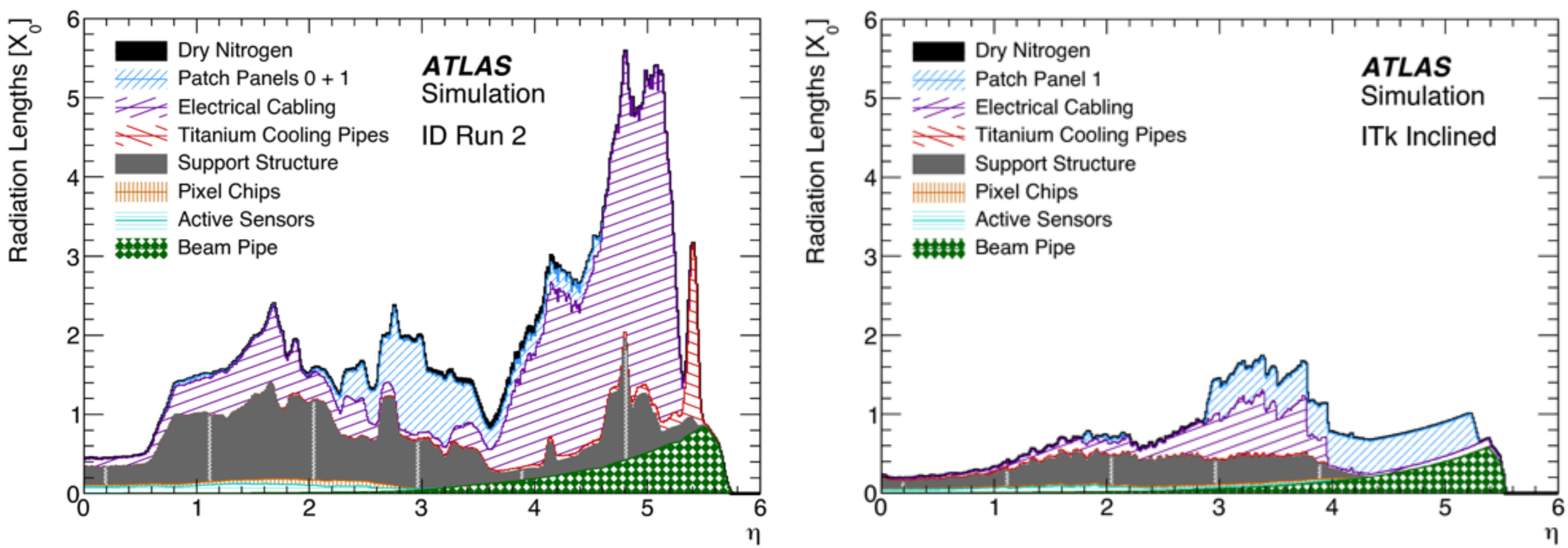




End cap frame with petals

Material Budget

- After optimisation of tracker layout, innovations on delivering electrical power to sensors, and support mechanics, a significant reduction in the total radiation length
- ITk silicon surface area (165m^2) is 2.6 times larger than the current ID, but the maximum radiation length reduced from 5.5X_0 to 2X_0



Summary

- HL-LHC is next major phase of LHC to open new window to HEP
- Tracker upgrade (ITk) is essential upgrade to allow full exploitation of this new phase
- Major international R&D towards development of low mass supports, thermal performance, routing of services to minimise material budget, including optimising of tracker layout
- Strip TDR was completed a few months ago and Pixels TDR is expected at the end of the year
- Community is transitioning from R&D to preparations for production

Backup

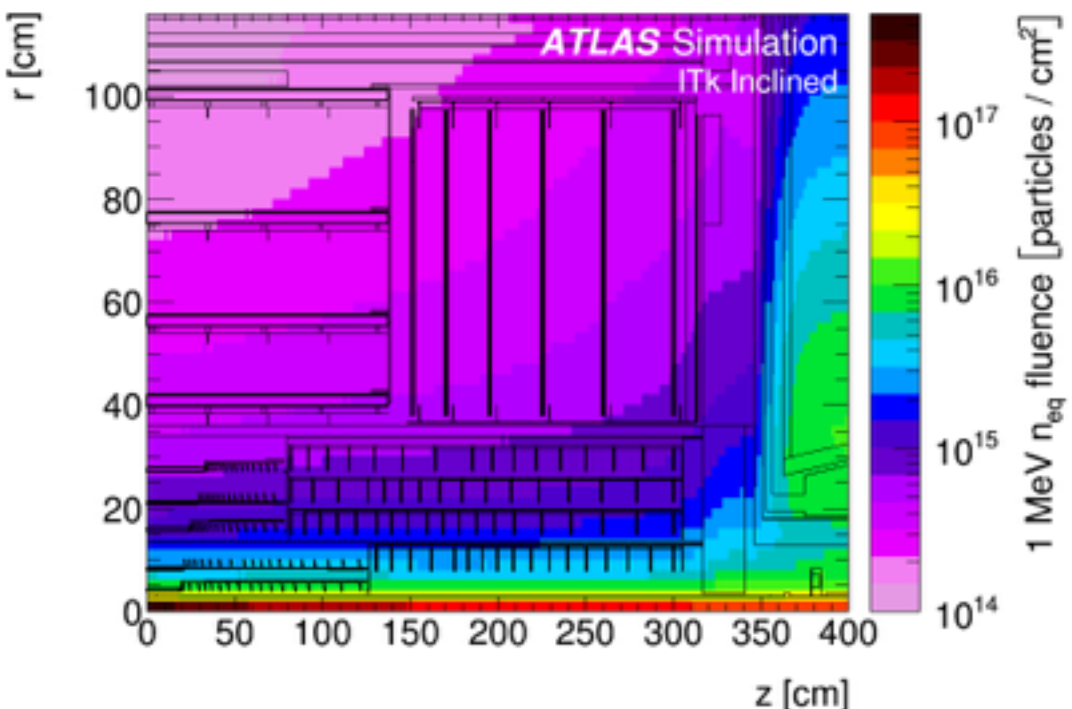
The Large Hadron Collider

The Large Hadron Collider

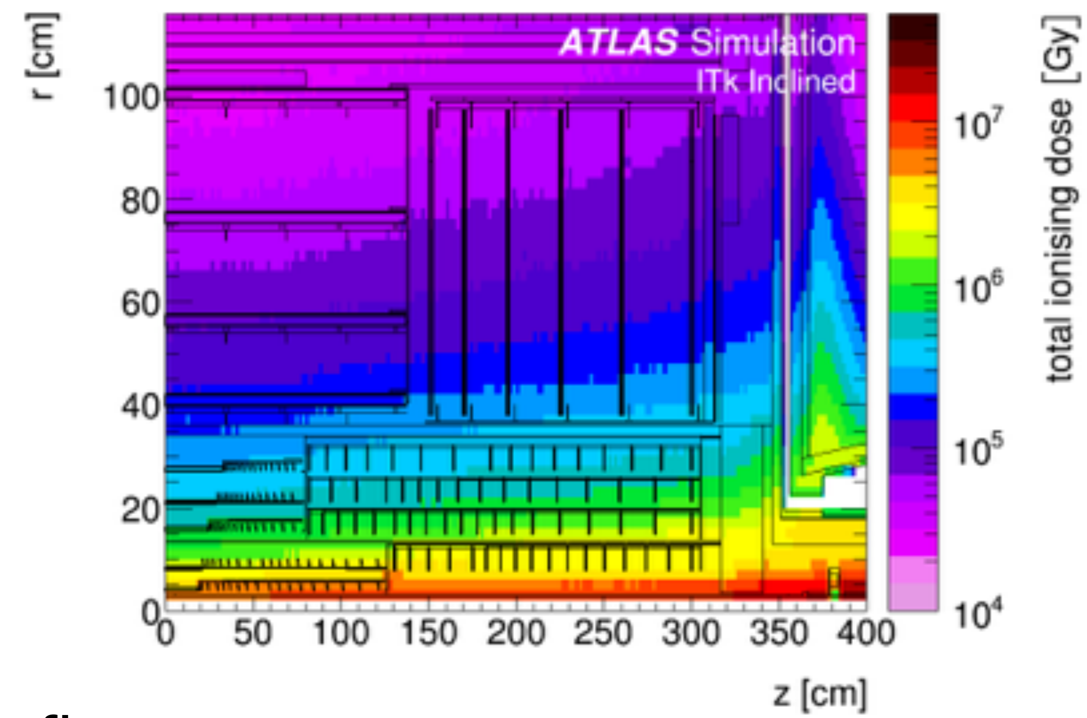
- The World's highest energy particle collider in the world, located just outside of Geneva, Switzerland
- Circular proton-proton accelerator, 27km in circumference
- Proton beams collide every 25ns (40MHz)
- Centre-of-Mass Energy : 13TeV
- Luminosity: 10^{34} cm^{-2} s^{-1}
- 4 Experiments located at the LHC, ATLAS, CMS, LHCb, ALICE
- Discovery of the Higgs Boson by CMS and ATLAS

Fluence and dose distributions for ITk

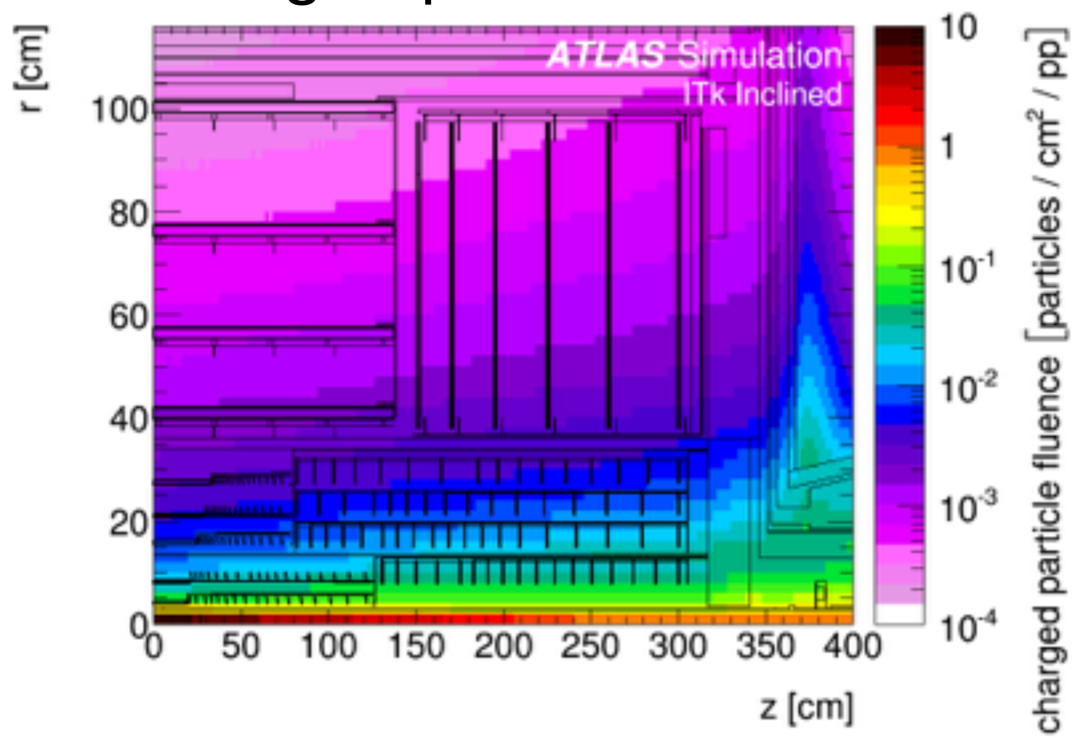
1 MeV neutron equivalent flux.



Total ionising dose.



Charged particle fluence.



Maximal Fluences and Doses

Layer	Radius [mm]	Maximal Fluence [n_{eq}/cm^2]	Maximal Dose [MRad]
Strips			
Long Strips	762	3.8×10^{14}	9.8
Short Strips	405	7.2×10^{14}	32.5
End-cap	385	1.2×10^{15}	50.4
Pixels			
Layer 0	39	1.87×10^{16}	1268
Layer 1	75	0.59×10^{16}	549
Layer 2	155	0.22×10^{16}	129
Layer 3	213	0.15×10^{16}	87
Layer 4	271	0.11×10^{16}	53
End-cap	80	0.62×10^{16}	477

Overview on maximal fluences and doses. The values including a safety factor of 1.5.

Tracker Layout : Surface Area

Barrel Layer:	Radius [mm]	# of staves	# of modules	# of hybrids	# of of ABCStar	# of channels	Area [m^2]
L0	405	28	784	1568	15680	4.01M	7.49
L1	562	40	1120	2240	22400	5.73M	10.7
L2	762	56	1568	1568	15680	4.01M	14.98
L3	1000	72	2016	2016	20160	5.16M	19.26
Total half barrel		196	5488	7392	73920	18.92M	52.43
Total barrel		392	10976	14784	147840	37.85M	104.86
End-cap Disk:	**z-pos. [mm]**	**# of petals**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
D0	1512	32	576	832	6336	1.62M	5.03
D1	1702	32	576	832	6336	1.62M	5.03
D2	1952	32	576	832	6336	1.62M	5.03
D3	2252	32	576	832	6336	1.62M	5.03
D4	2602	32	576	832	6336	1.62M	5.03
D5	3000	32	576	832	6336	1.62M	5.03
Total one EC		192	3456	4992	43008	11.01M	30.2
Total ECs		384	6912	9984	86016	22.02M	60.4
Total		**776**	**17888**	**24768**	**233856**	**59.87M**	**165.25**

Number of components for the ITk Strip Detector in barrel (top half) and end-cap (bottom half). The numbers for the barrel are for the full barrel with 2.8 m length. The numbers for the end-caps (EC) are given both for one and both end-caps.

ITk Strip Detector Parameters

Layer	Radius [mm]	Channels in ϕ	Strip Pitch [μm]	Strip Length [mm]	Tilt Angle [°]
0	405	28×1280	75.5	24.1	11.5
1	562	40×1280	75.5	24.1	11.0
2	762	56×1280	75.5	48.2	10.0
3	1000	72×1280	75.5	48.2	10.0

Layout parameters for the ITk Strip Detector barrel. Each strip barrel layer is 2.8 m long extending from -1400 mm to +1400 mm along the z-axis.

Ring/Row	Inner Radius [mm]	Strip Length [mm]	Strip Pitch [μm]
Ring 0 Row 0	384.5	19	75.0
Ring 0 Row 1	403.5	24	79.2
Ring 0 Row 2	427.5	29	74.9
Ring 0 Row 3	456.4	32	80.2
Ring 1 Row 0	489.8	18.1	69.9
Ring 1 Row 1	507.9	27.1	72.9
Ring 1 Row 2	535	24.1	75.6
Ring 1 Row 3	559.1	15.1	78.6
Ring 2 Row 0	575.6	30.8	75.7
Ring 2 Row 1	606.4	30.8	79.8
Ring 3 Row 0	638.6	32.2	71.1
Ring 3 Row 1	670.8	26.2	74.3
Ring 3 Row 2	697.1	26.2	77.5
Ring 3 Row 3	723.3	32.2	80.7
Ring 4 Row 0	756.9	54.6	75.0
Ring 4 Row 1	811.5	54.6	80.3
Ring 5 Row 0	867.5	40.2	76.2
Ring 5 Row 1	907.6	60.2	80.5

Main layout parameters for the strip end-cap.

ITk Pixel Parameters

Pixel Central Barrel

Layer	Sensor Size [mm^2]	Sensors per Half Stave	Half Stave Length [mm]	Staves	Radius [mm]
0	40.2×16.8	4.5	1250	18	39
1	40.2×33.8	5	1250	18	85
2	40.2×33.8	6	780	32	155
3	40.2×33.8	7	780	44	213
4	40.2×33.8	8	780	54	271

Main layout parameters for the Pixel barrel as simulated. The numbers of sensors per half stave refer to the central part of the barrel where sensors are placed parallel to the beam axis.

Pixel Forward Barrel for Inclined layout

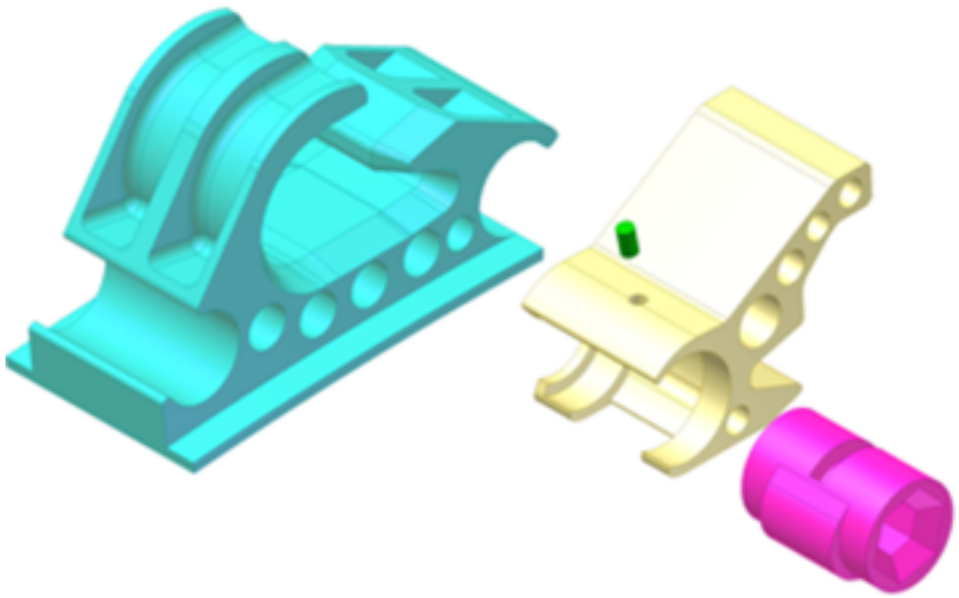
Layer	Sensor Size [mm^2]	Positions on Barrel Stave [mm]
0	20.0×16.8	197.8 - 1206.9 (17 positions)
1	20.0×33.8	214.4 - 1206.5 (18 positions)
2	20.0×33.8	254.1 - 719.6 (13 positions)
3	20.0×33.8	295.7 - 719.5 (17 positions)
4	20.0×33.8	336.7 - 719.4 (13 positions)

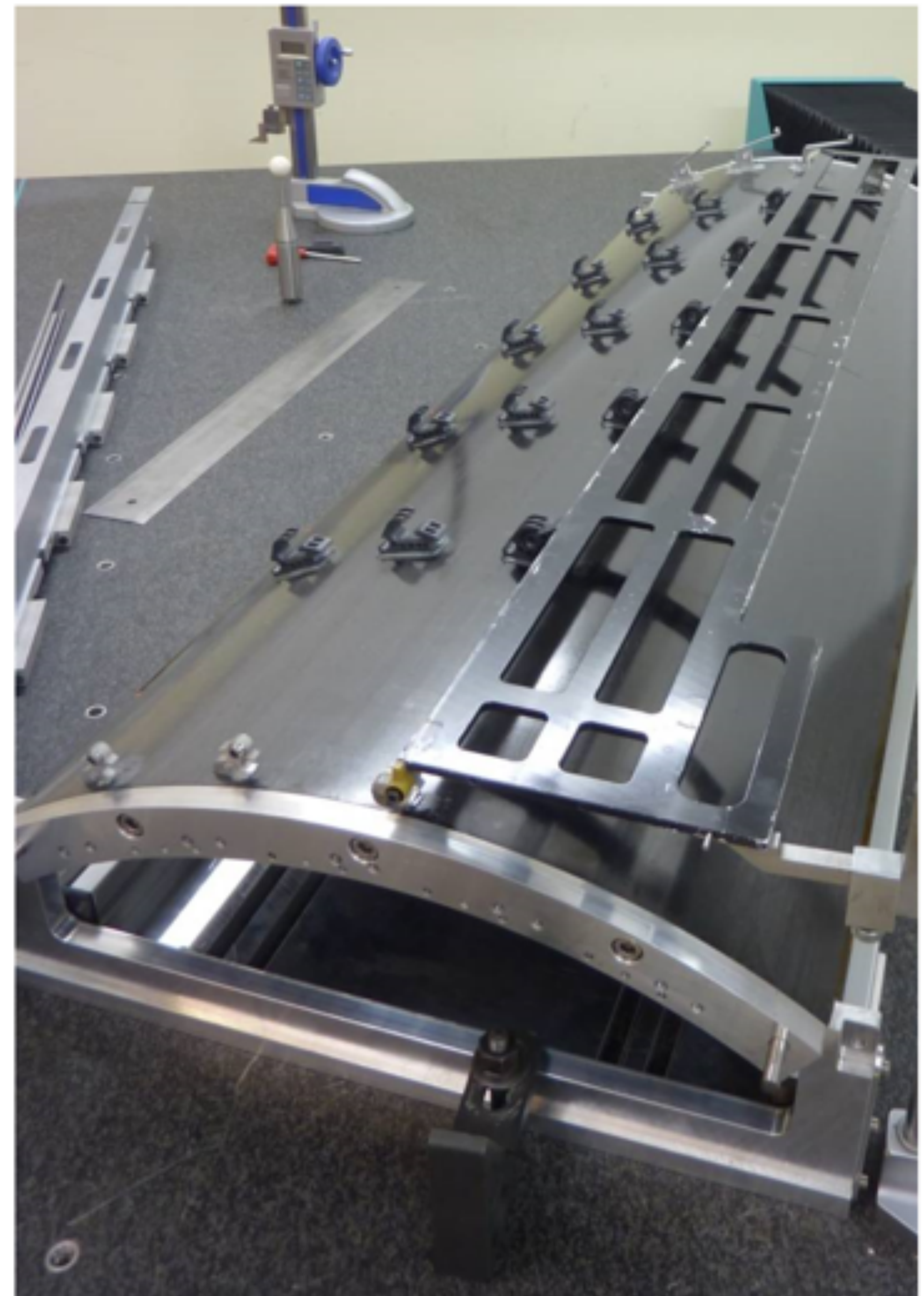
Main layout parameters for the forward barrel in the Inclined layout as currently simulated. The forward barrel shares a common mechanical structure with the central barrel, There is a stagger of 4 mm in z positions between inclined sensors on neighbouring staves in ϕ, with sensors on half of the staves having positions 4 mm closer to the centre of the detector than indicated here.

Pixel end-cap ring

Ring Layer	Sensor Size [mm^2]	Sensors per Ring	Inner Radius [mm]	Ring Positions [mm]
0	40.2×33.8	24	80	1308 - 3000 (18 positions)
1	40.2×33.8	36	150	823 - 3000 (19 positions)
2	40.2×33.8	48	212.5	823 - 3000 (16 positions)
3	40.2×33.8	60	275	823 - 3000 (16 positions)

ITk Barrel Stave Brackets





Strips Local Support Thermal Requirements

	Stave	Petal	Comment
Max. module power	10 W	12 W	For module R3
EoS power	12 W	6 W	
Local suport total power	300 W	130 W	

Local support thermal requirements.

LHC Higgs Discovery