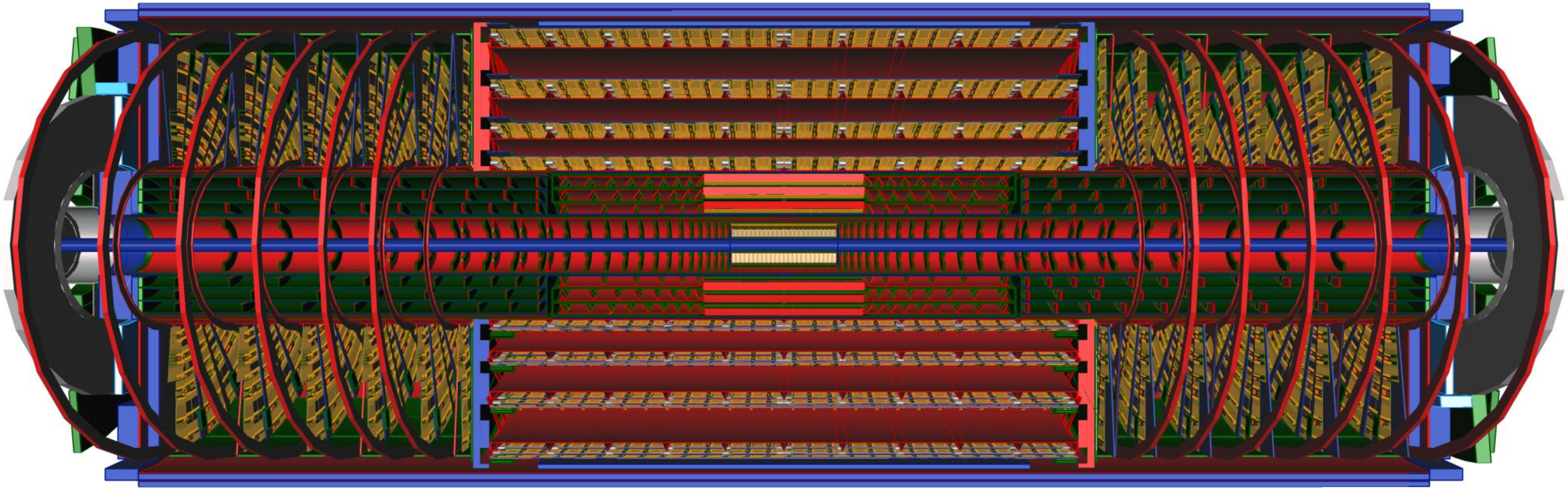
L'upgrade di Fase2 di ATLAS:
il rivelatore ITk



A. Lapertosa

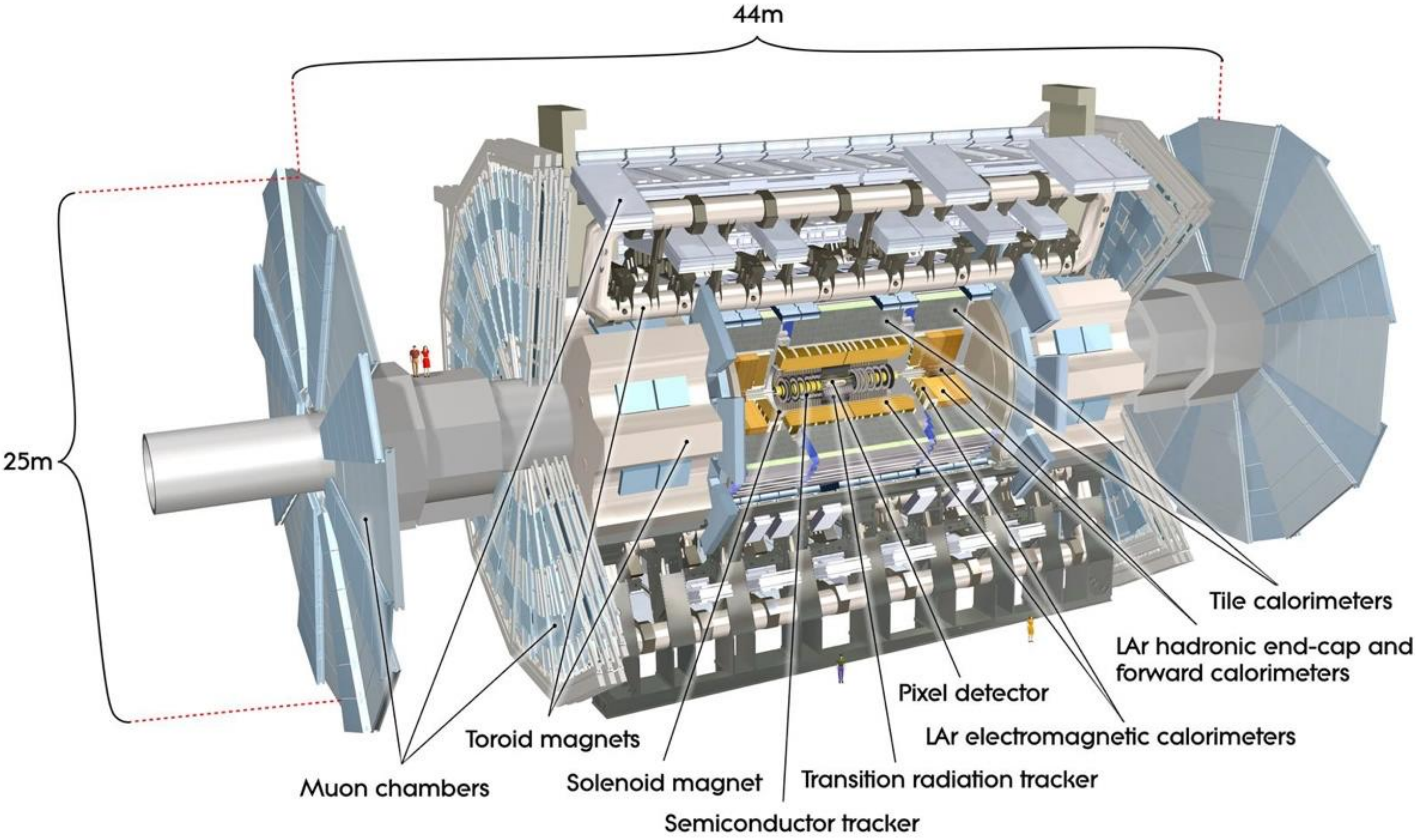
on behalf of the ATLAS experiment community

12/09/2022

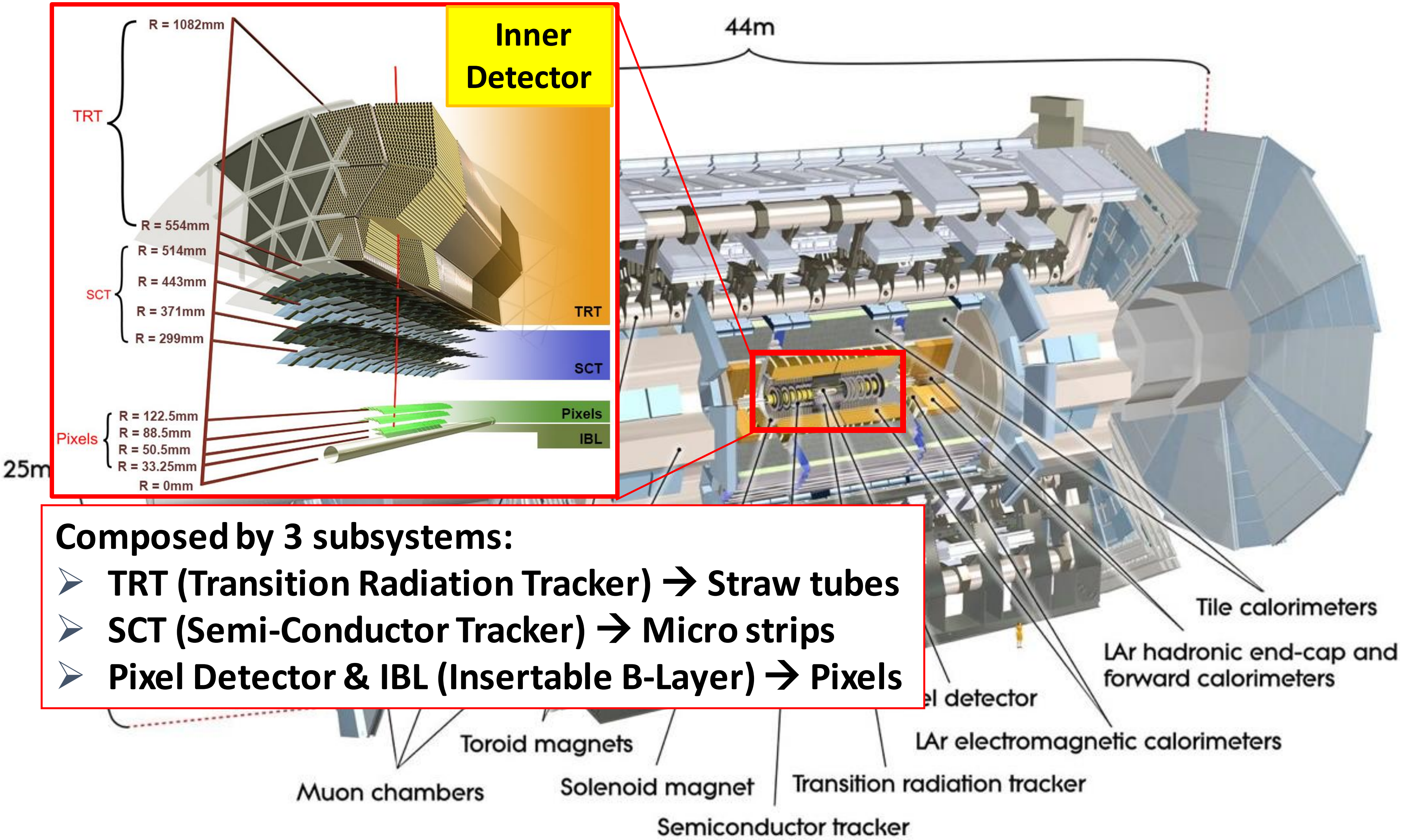
Università di Genova

INFN
Istituto Nazionale di Fisica Nucleare

ATLAS detector



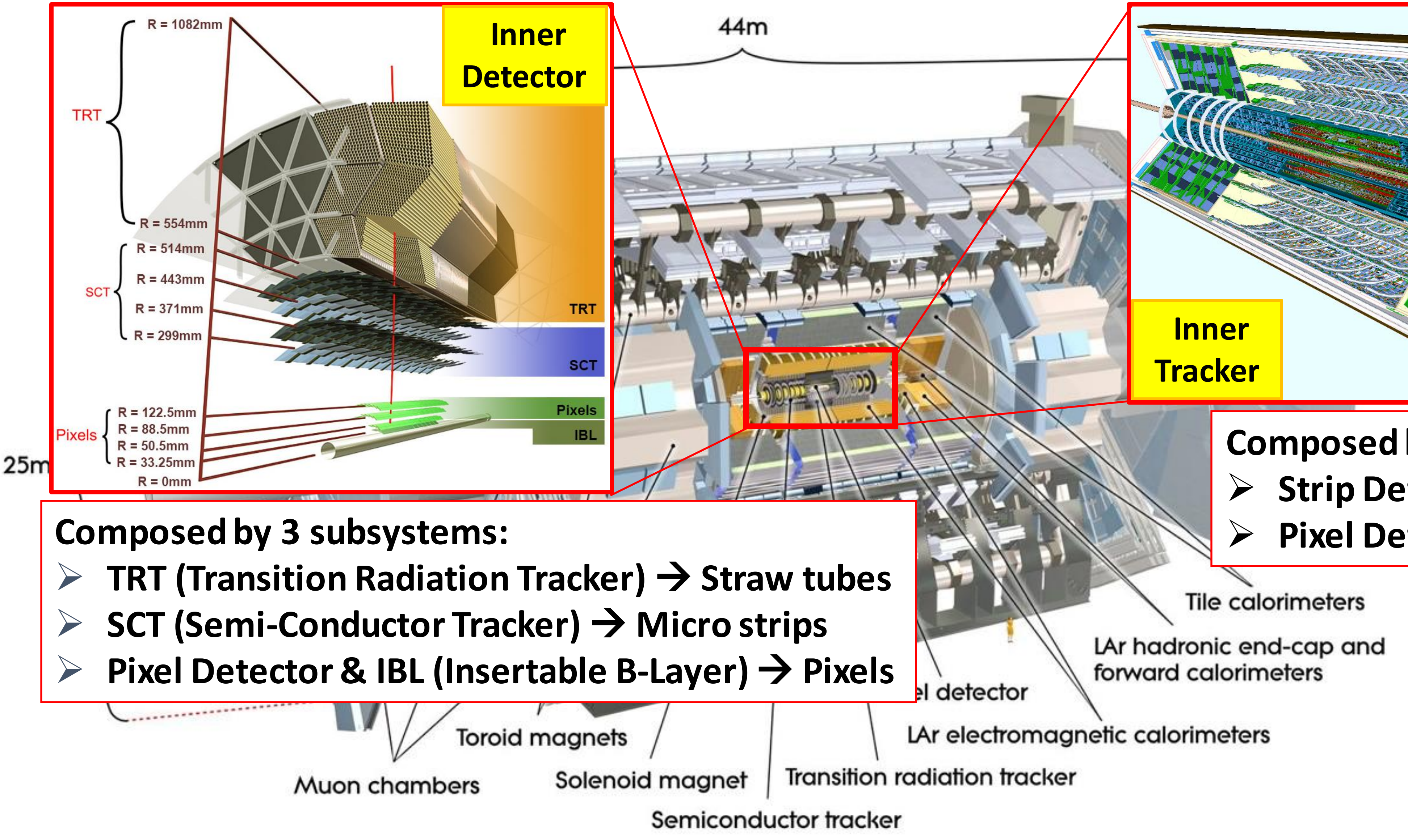
ATLAS detector at LHC (Run 1-2-3)

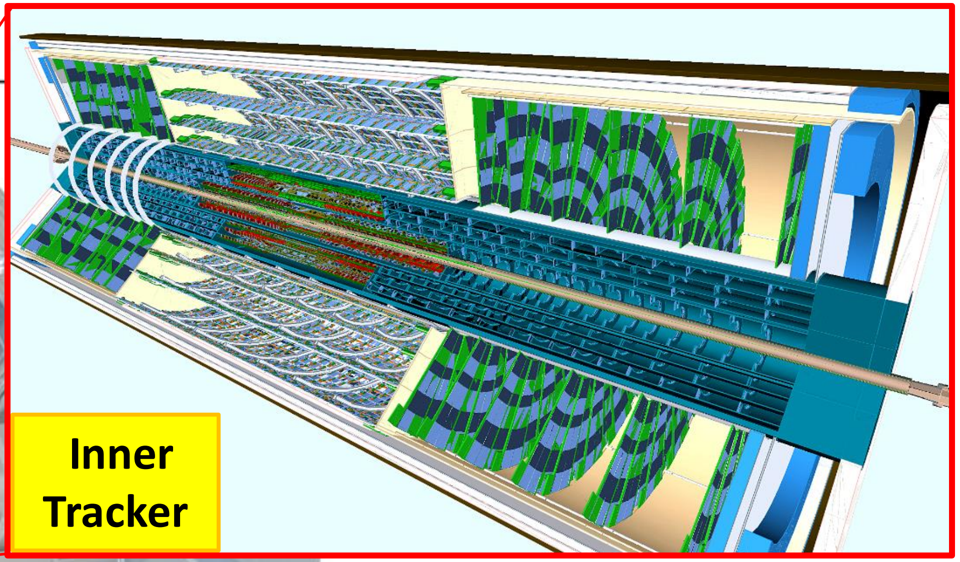


Composed by 3 subsystems:

- **TRT (Transition Radiation Tracker) → Straw tubes**
- **SCT (Semi-Conductor Tracker) → Micro strips**
- **Pixel Detector & IBL (Insertable B-Layer) → Pixels**

ATLAS detector at LHC (Run 1-2-3) and HL-LHC





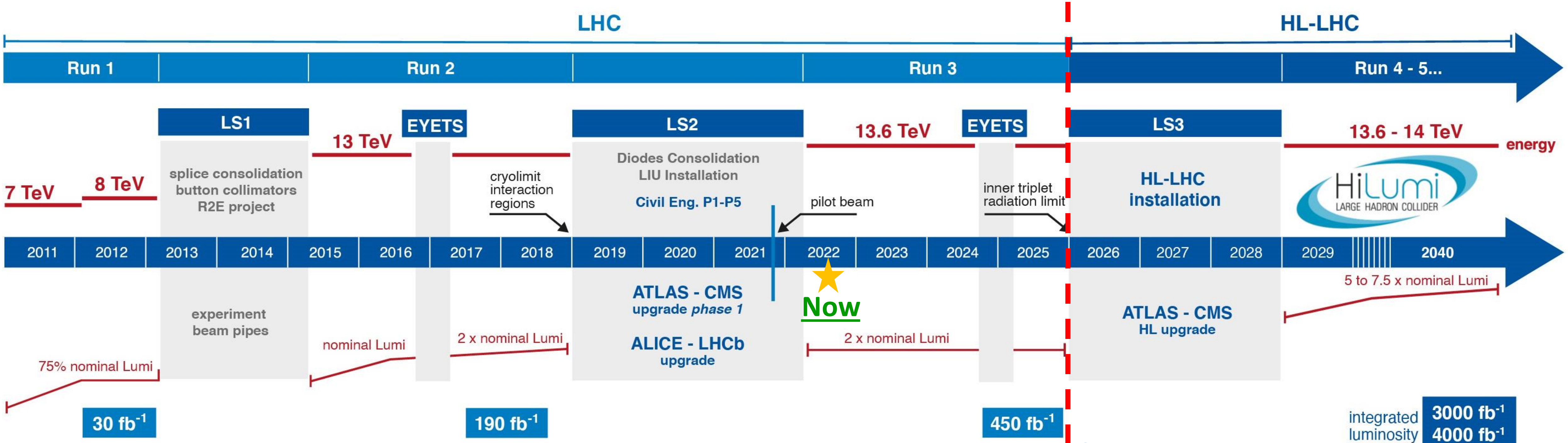
Composed by 3 subsystems:

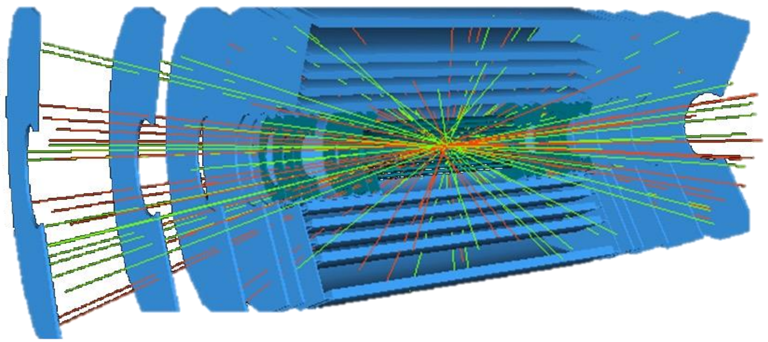
- TRT (Transition Radiation Tracker) → Straw tubes
- SCT (Semi-Conductor Tracker) → Micro strips
- Pixel Detector & IBL (Insertable B-Layer) → Pixels

Composed by 2 subsystems:

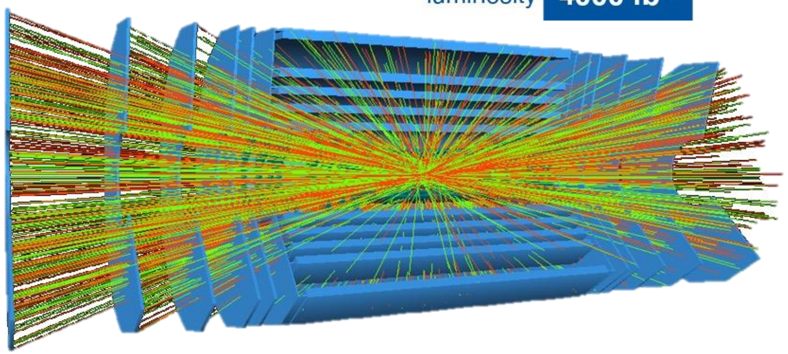
- Strip Detector → Micro strips
- Pixel Detector → Pixels

ATLAS: from LHC to High Luminosity (HL-LHC)





- More statistics to study rare physics processes
- Collect a larger data sample in a shorter time
- Target of 4000 fb^{-1} int. luminosity in 10 years
- <u>Take data at higher istantaneous luminosity!</u>
- Increase of pile-up collisions: 20-50 → 150-200
- Harder conditions, expecially for tracking… :(



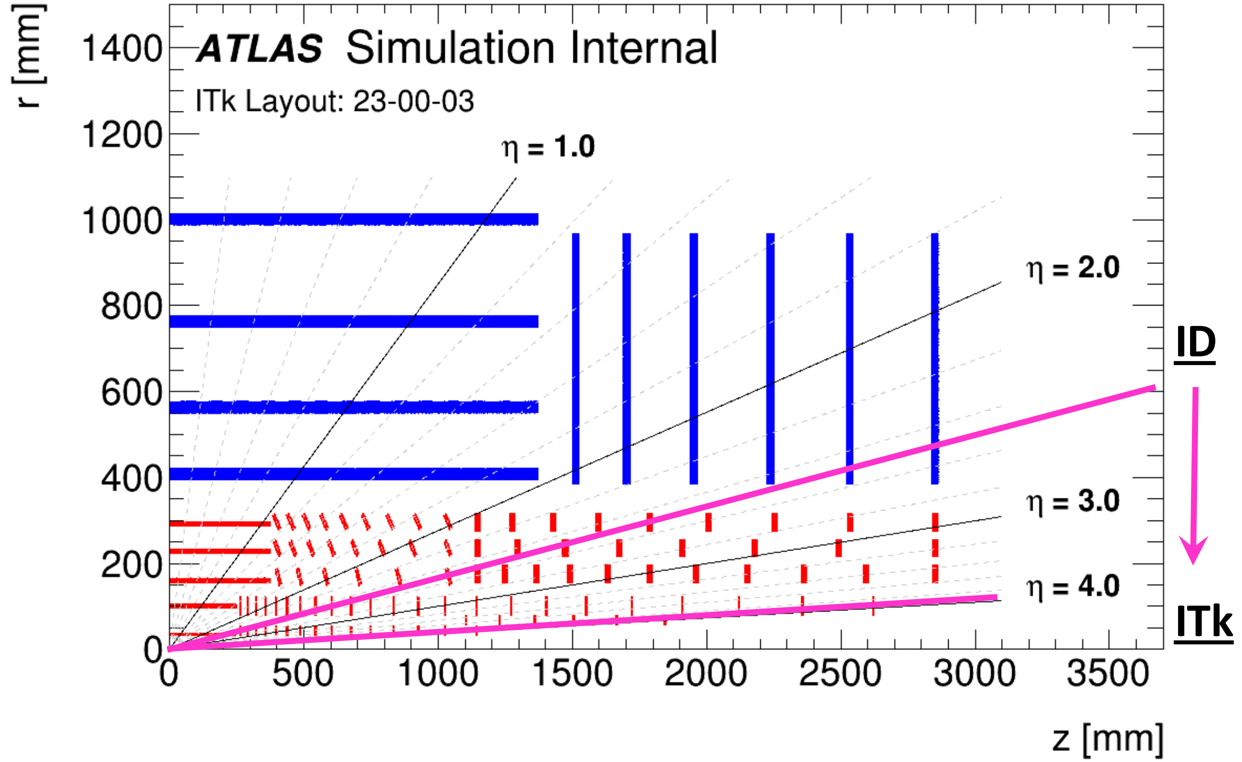
- Impossible to operate current ATLAS tracking system (ID) at High-Luminosity conditions (up to 7.5e34 $cm^{-2}\ s^{-1}$)
  - Because of increasing of: channel occupancy (5 G), data bandwidth (4x1.28 Gbps), radiation damage (1 Grad)

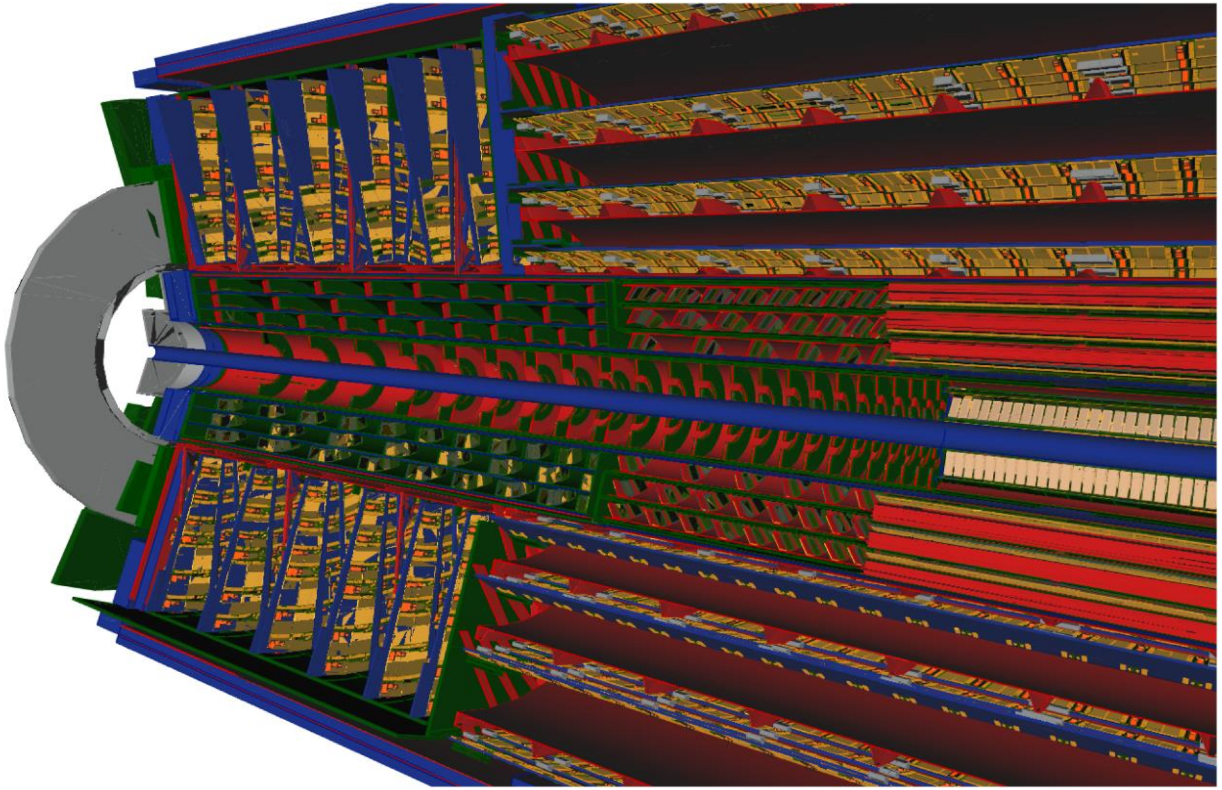
Inner Tracker (ITk) for High Luminosity (HL-LHC)

- Inner Tracker (**ITk**): a new all silicon tracking detector for the ATLAS Phase-II upgrade at the HiLumi-LHC
- Details of the latest design version (and its physics performance) can be found in [ATL-PHYS-PUB-2021-024]()

ITk	Si [m^2]	Modules	M channels	Barrel layers	Endcap disks
Strip	165	17888	60	4	6 / side
Pixel	13	9164	5100	5	Several

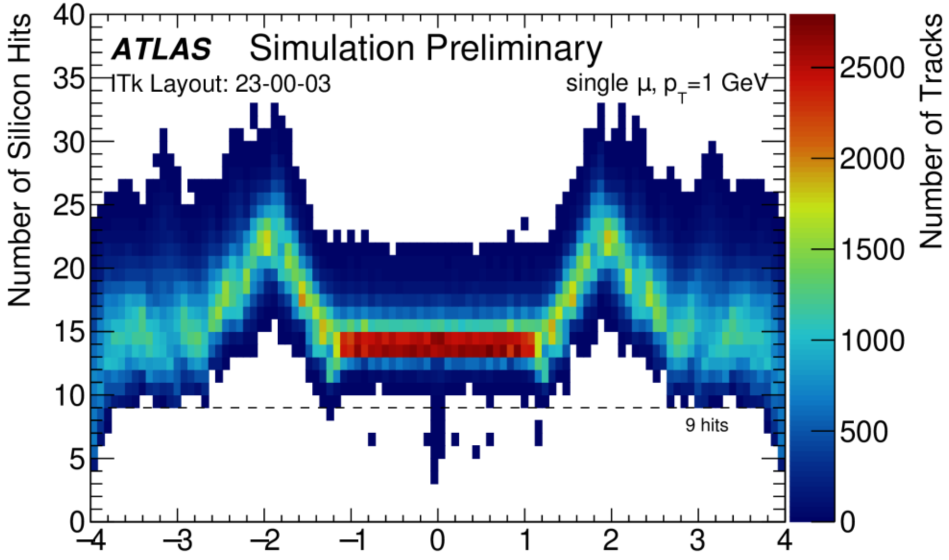
- Highlights of the design improvements:
  - Increased granularity, down to 50x50 μm^2
  - Extended coverage, up to $\eta \leq 4.0$
  - Reduced material, kept within 2.4 X0





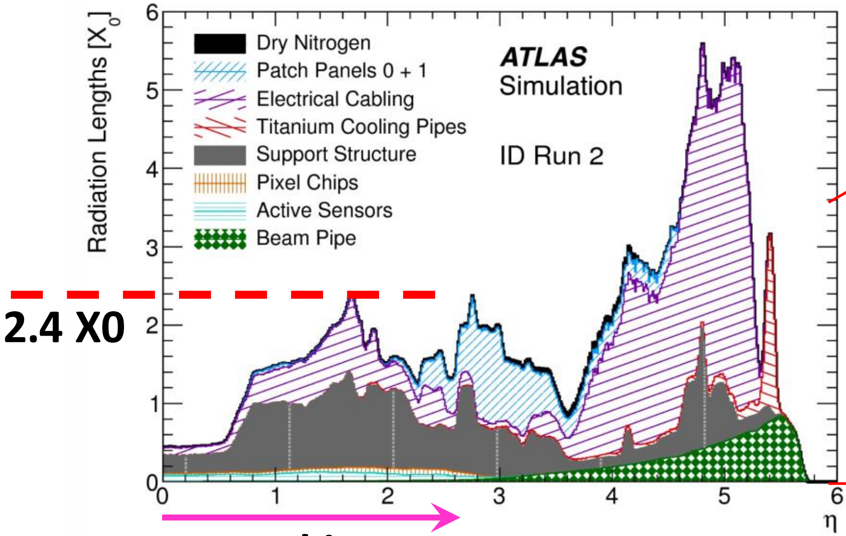
Hits per tracks and material budget

- Extended tracking coverage: ID $\eta \leq 2.5 \rightarrow$ ITk $\eta \leq 4.0$
- 4 double strip layers + 5 pixel layers (barrel), several disks (endcap)
  - Average of 13 hits per tracks (barrel)
  - Required at least 9 hits to guarantee the tracking performance
    - Expected to be OK even after large dose of irradiation
- Material budget within 2.4 X0 in the whole tracking range:
  - Reduced thickness of silicon devices (both sensor and chip)
  - Optimized material of circuitry (expecially with serial powering)
  - CO^2 bi-phase cooling in titanium pipes within carbon structures

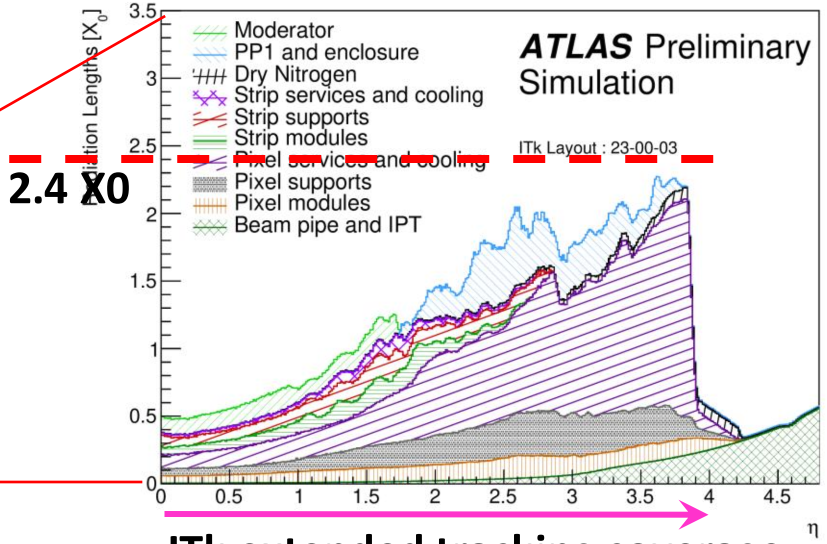


Strips	ID	ITk
Active area	61m²	165m²
Modules	4088	17888
Channels	6x10⁶	6x10⁷

Pixels	ID	ITk
Active area	1.9m²	12.8m²
Modules	2024	9164
Channels	9x10⁷	5x10⁹

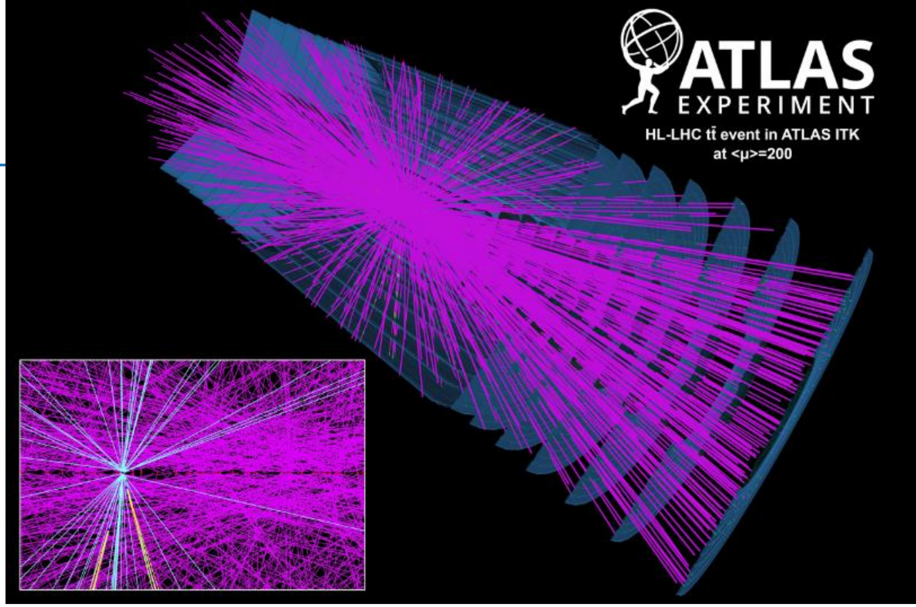


ID tracking coverage

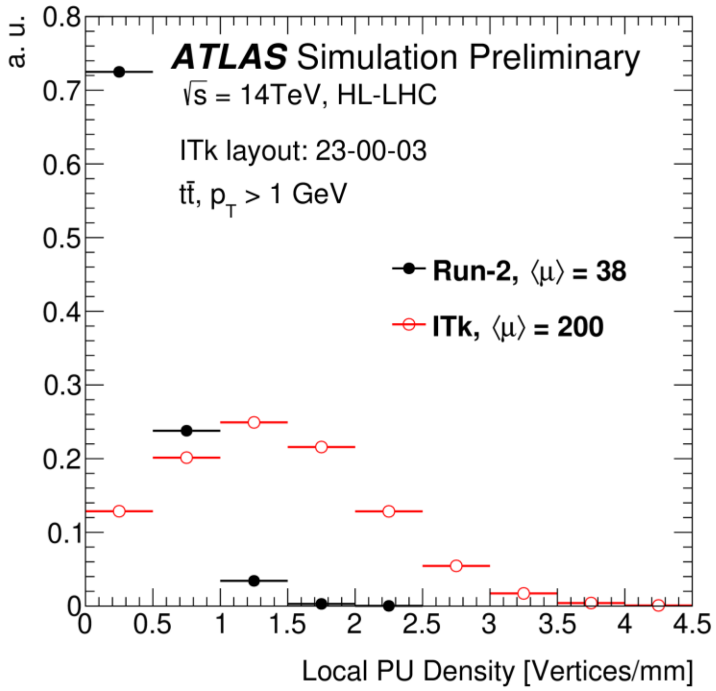


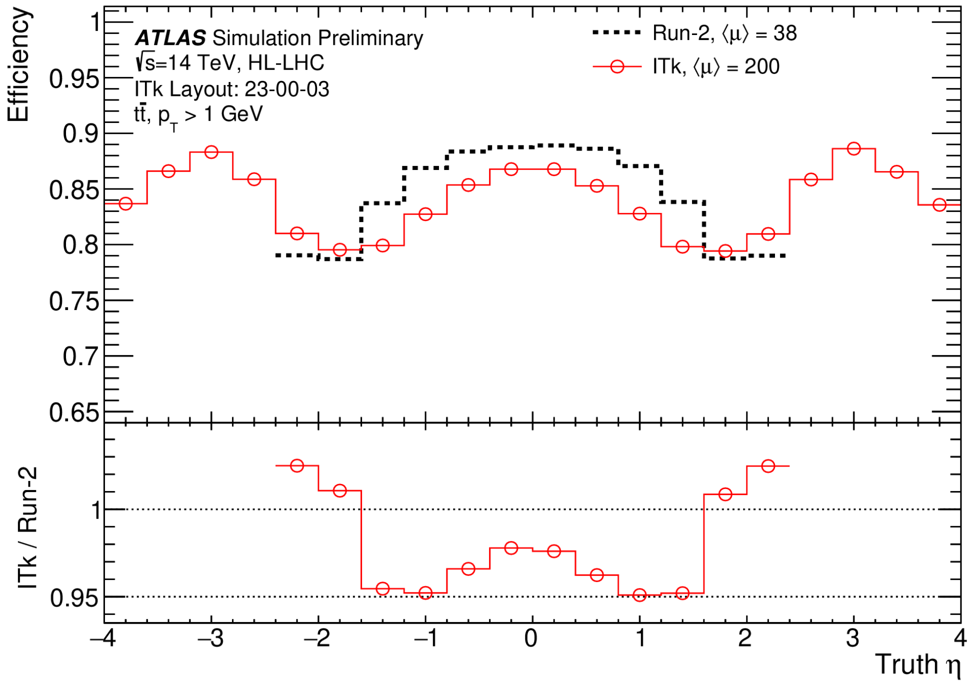
ITk extended tracking coverage

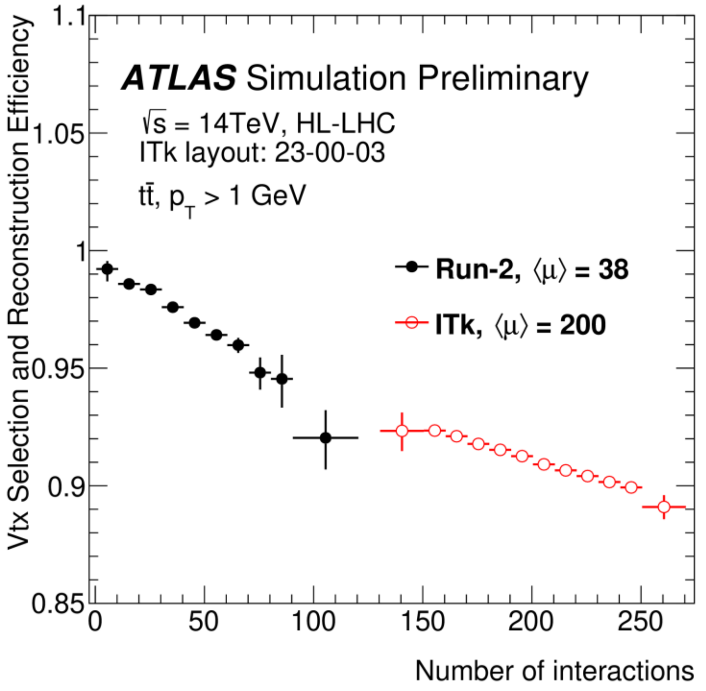
Track and vertex reconstruction efficiency



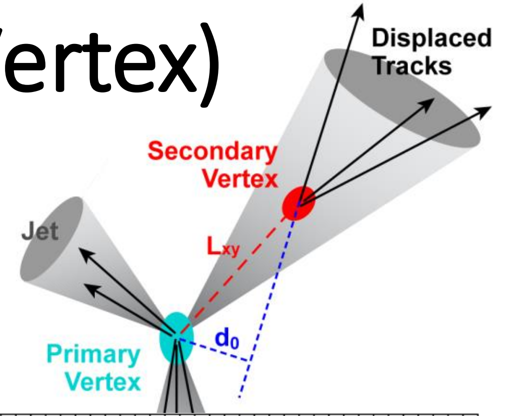
- Comparison of **Run 2 conditions** vs **HL-LHC conditions**
  - Average pile up (proton collisions per Bunch Crossing): **38 → 200**
  - Pile up density: **< 1 vert/mm → up to 3 vert/mm (avg 1 vert/mm)**
- Performance evaluated by simulation of ttbar events
  - Track identification efficiency: **compatible → with larger coverage!**
  - Vertex selection and reconstruction: **95-100% → 90%, acceptable!**



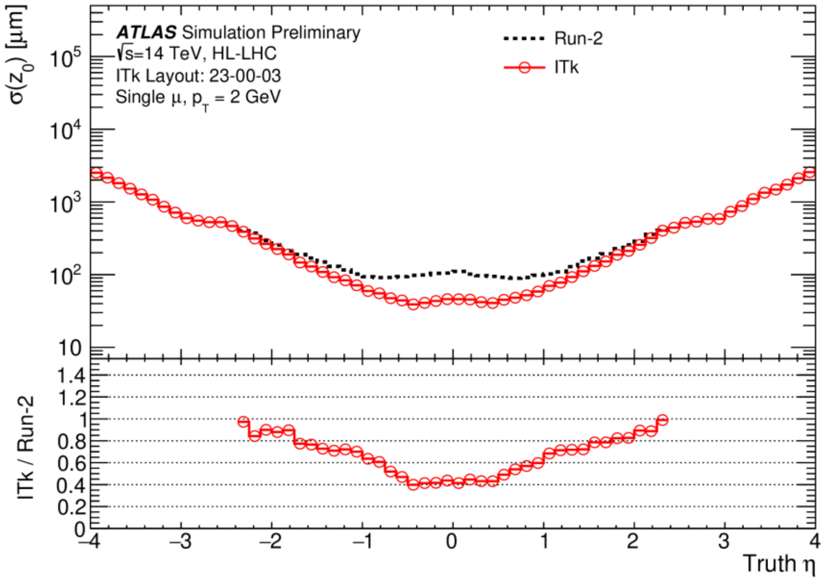


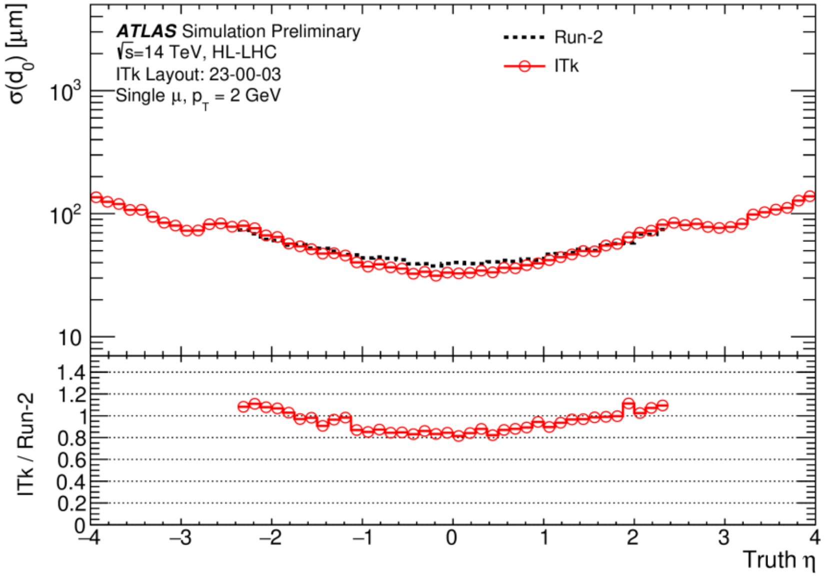


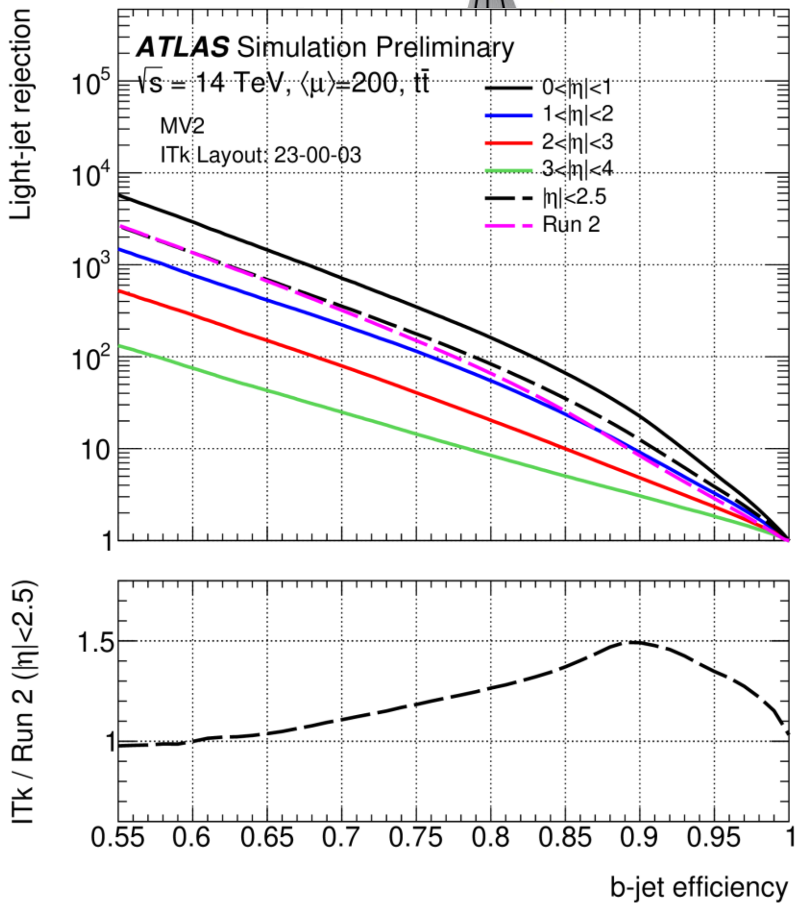
Impact parameter and b-tagging (IP and Secondary Vertex)



- Flavour tagging algorithms (identify b/c-jets, reject light jets) based on:
  - Longitudinal (z0) and transversal (d0) impact parameters of the displaced tracks
  - Secondary vertices of the decay of the b/c-hadrons inside the jet cone
- Comparison of **Run 2 conditions** vs **HL-LHC conditions** with 2 GeV tracks
  - z0 resolution: improved, reduced pixel lenght: **400/250 µm** → **50 µm**
  - d0 resolution: compatible: **both IBL and ITk L0 at R = 33 mm**
- Light jet rejection (old MV2 algorithm, optimized for **Run 2 conditions**):
  - Compatible performance in compatible pseudorapidity range η ≤ 2.5
  - Better in barrel (η ≤ 1) getting worse in endcap extension (η > 2) →



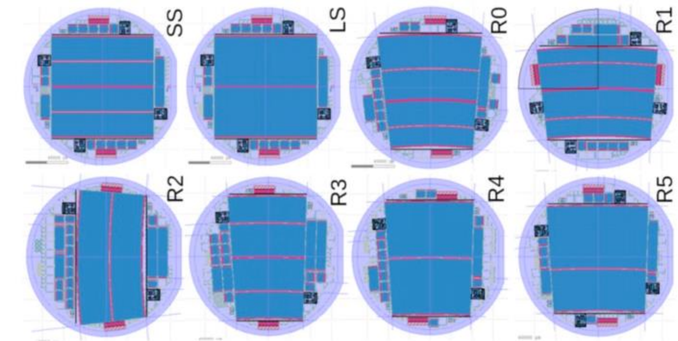


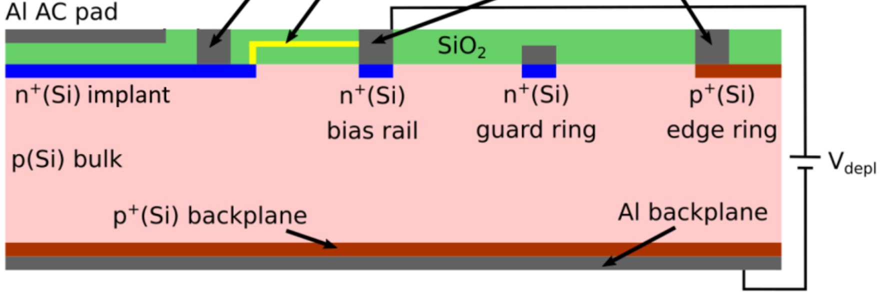


Strip: module components and assembly

- Design: done! → Prototypes: done! → Pre-production: ongoing!
- More details in ICHEP 2022 poster and 15th Pisa Meeting talk

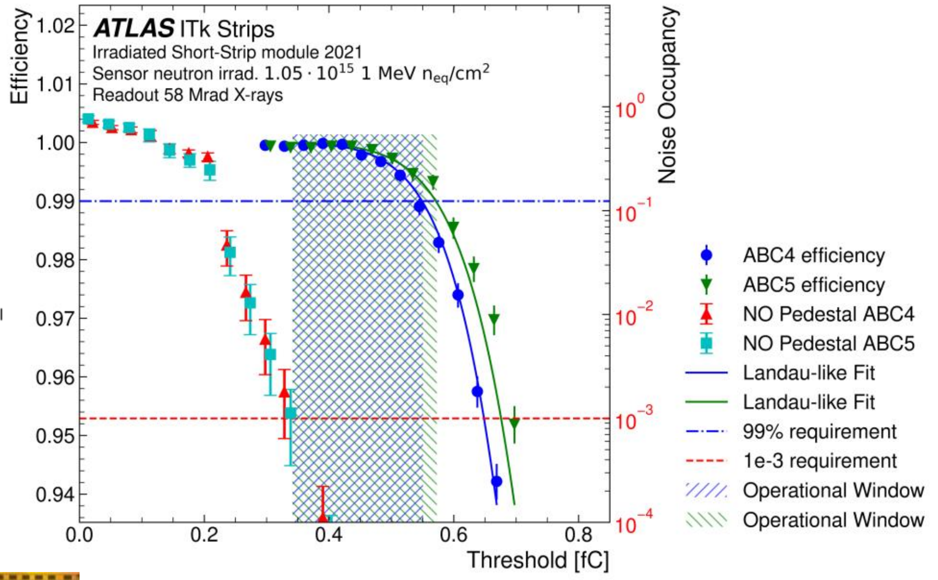
SS, LS are barrel, R# are end-cap



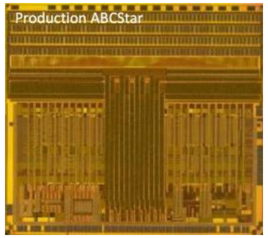


- Module components: **sensor** + **hybrid** + **powerboard**
  - **Sensor:** 320 µm thick n-in-p silicon sensor
    - 8 sensor geometries (1 sensor per wafer)
      - 2 for barrel (75.5 µm pitch)
      - 6 for endcap (70-80 µm pitch)
      - All 8 sensor types/layouts look OK!
  - **Hybrid**: up to 12 strips binary readout chips (**ABCStar**) and up to 2 Hybrid Controller Chips (**HCCStar**)
  - **Powerboard**: HV switch and filter, LV DC-DC converter, Monitor and control chip (**AMAC**).

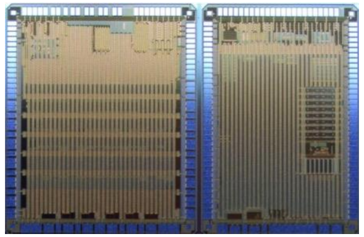
Operational window: > 99% efficiency, < 0.1% noise

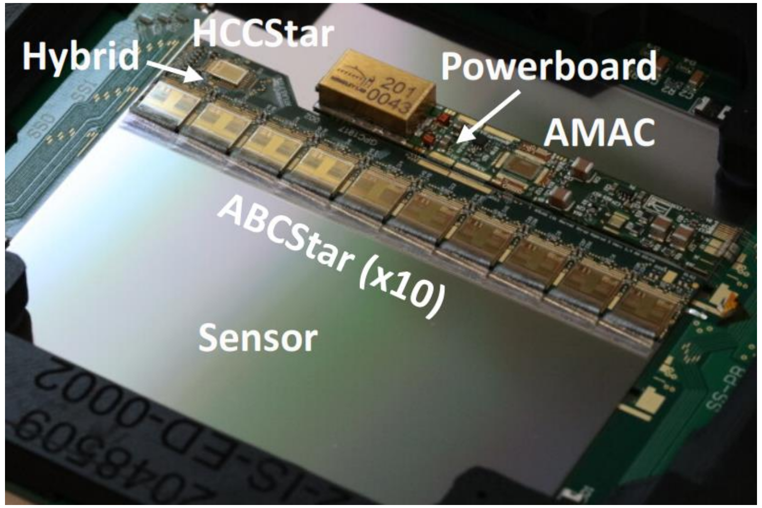


ABCStar



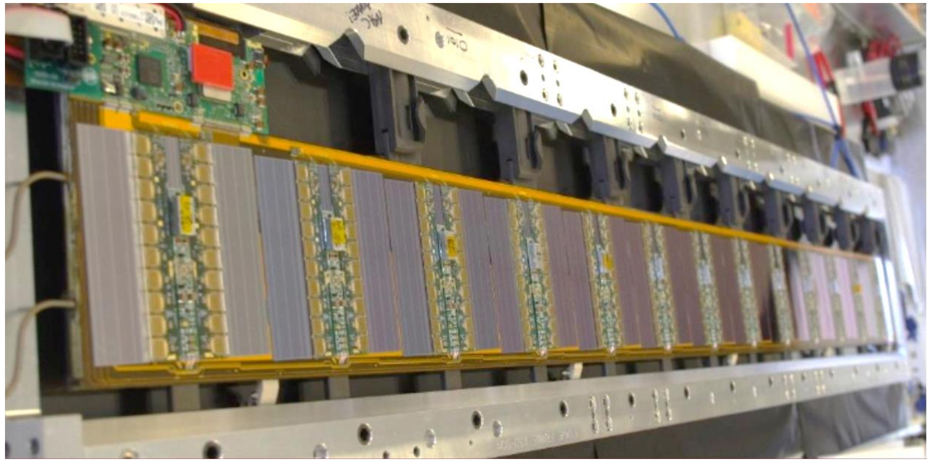
HCCStar + AMACStar





Strip: towards module production

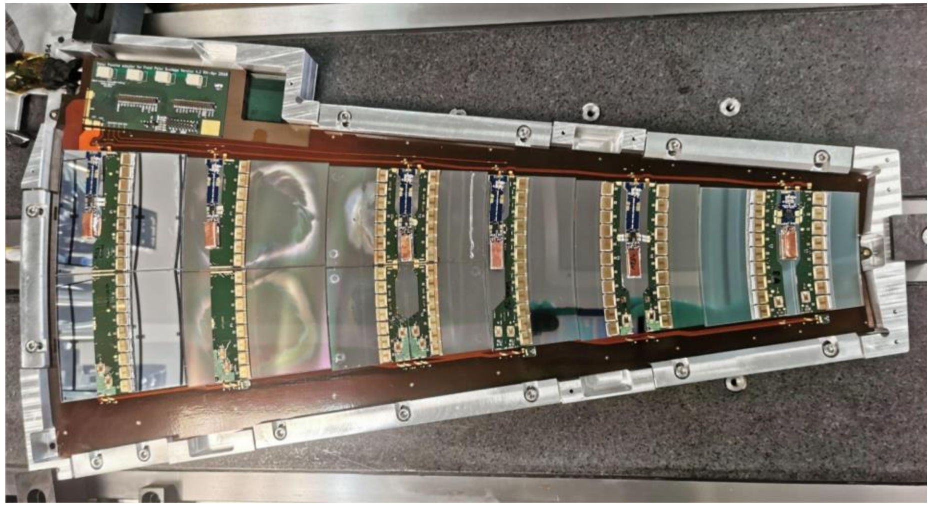
- Sensor site qualification and pre-production testing delayed by COVID
- Site qualification progressing: 70% achieved
  - 11+20 assembly sites preparing for barrel+endcaps modules
  - Build 17888 good modules in 3 years
  - Test results: excellent agreement among sites, matching HPK data
- Pre-production almost completed
  - All pre-production batches validated
  - About 1000 modules built!
- Production Readiness Review in September 2022
  - Sensor production started in Aug-2021: 18% already delivered
  - Module production to start at the end of 2022

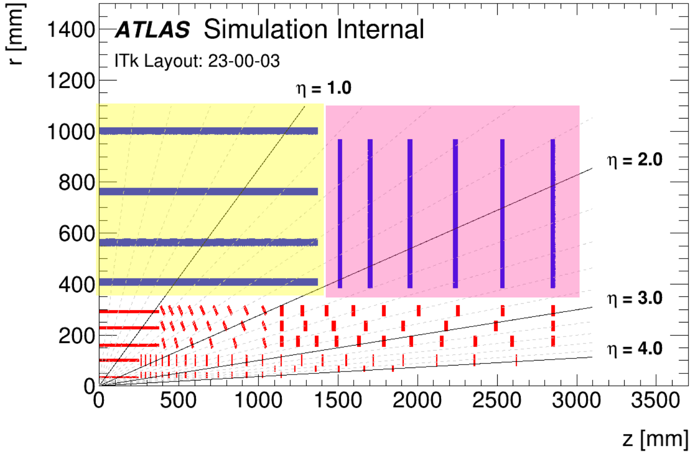


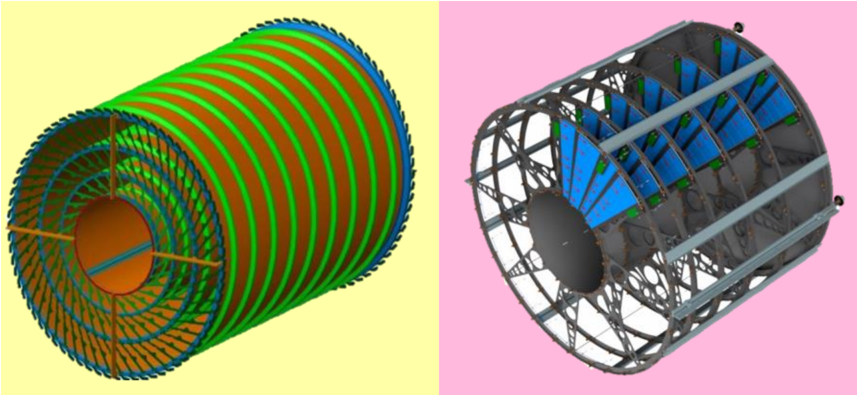
Barrel stave

equipped with strip modules

Endcap petal



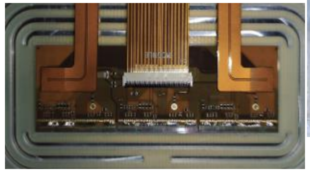


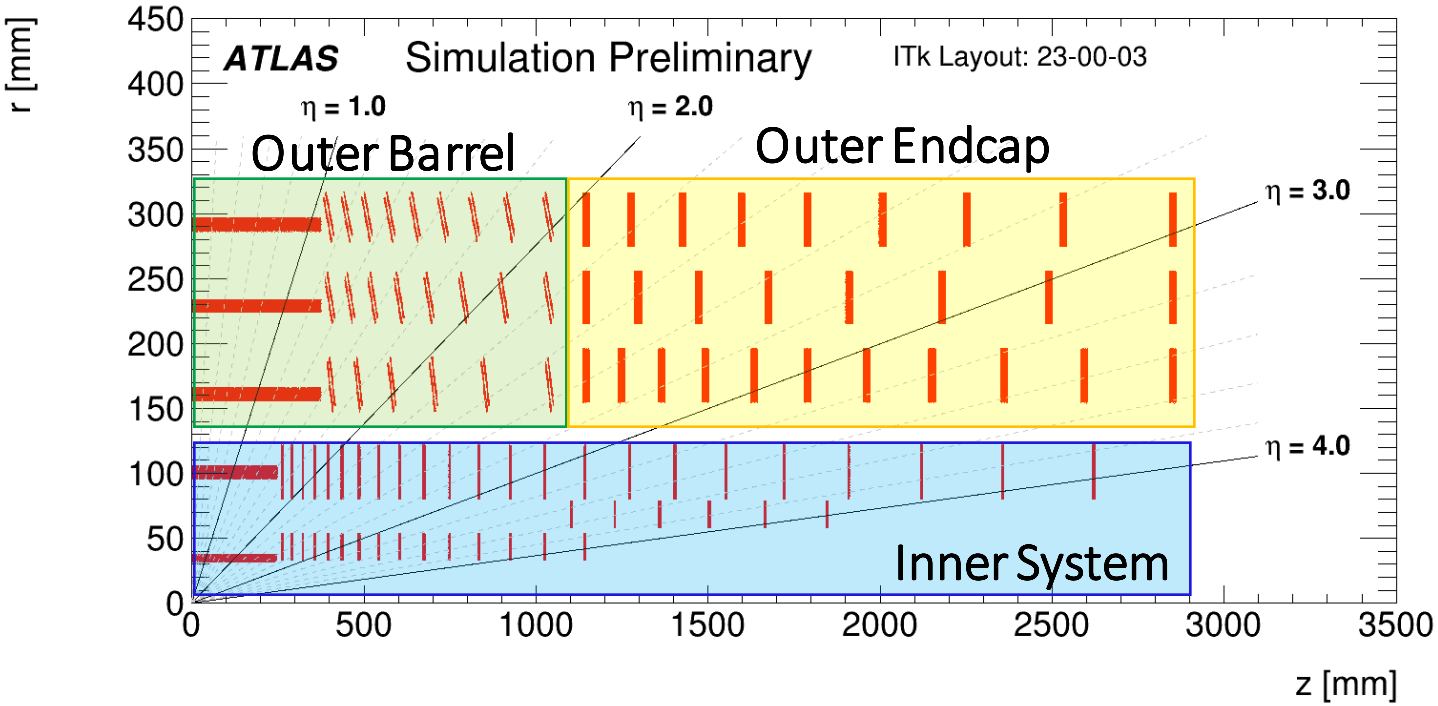


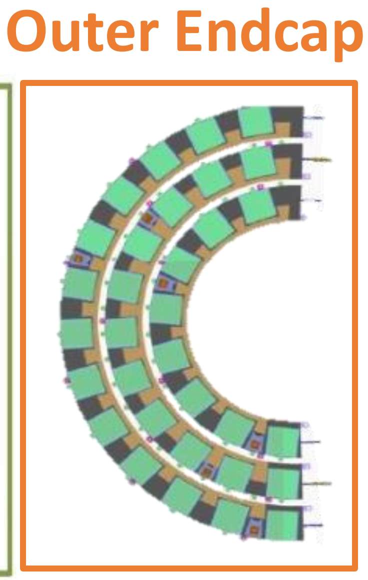
Barrel and endcap support structutes

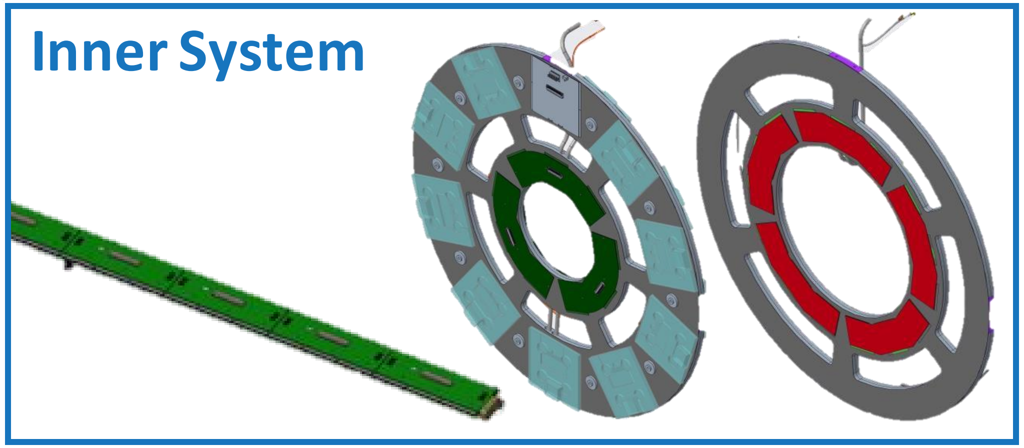
Pixel: detector structure and modules

- Design: completed! → Prototypes: done! → Pre-production: ongoing!
- Pixel detector made up by 3 main parts: **Outer Barrel**, **Outer Endcap**, **Inner System**
- Two different module concepts:
  - All the external layers (L1-4): Quad-module →
  - Innermost layer (L0): Triplet mod. →
- Modules glued to carbon structures
- Titanium pipes for CO^2 cooling

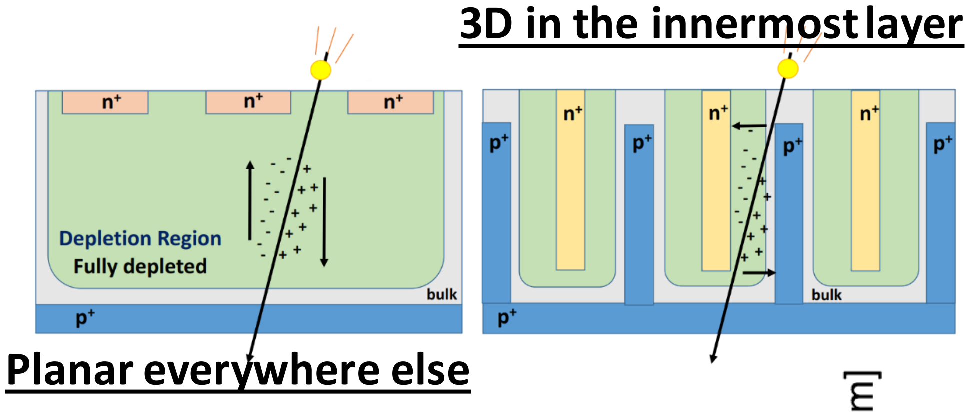








Pixel: sensor arrangement and IS replacement

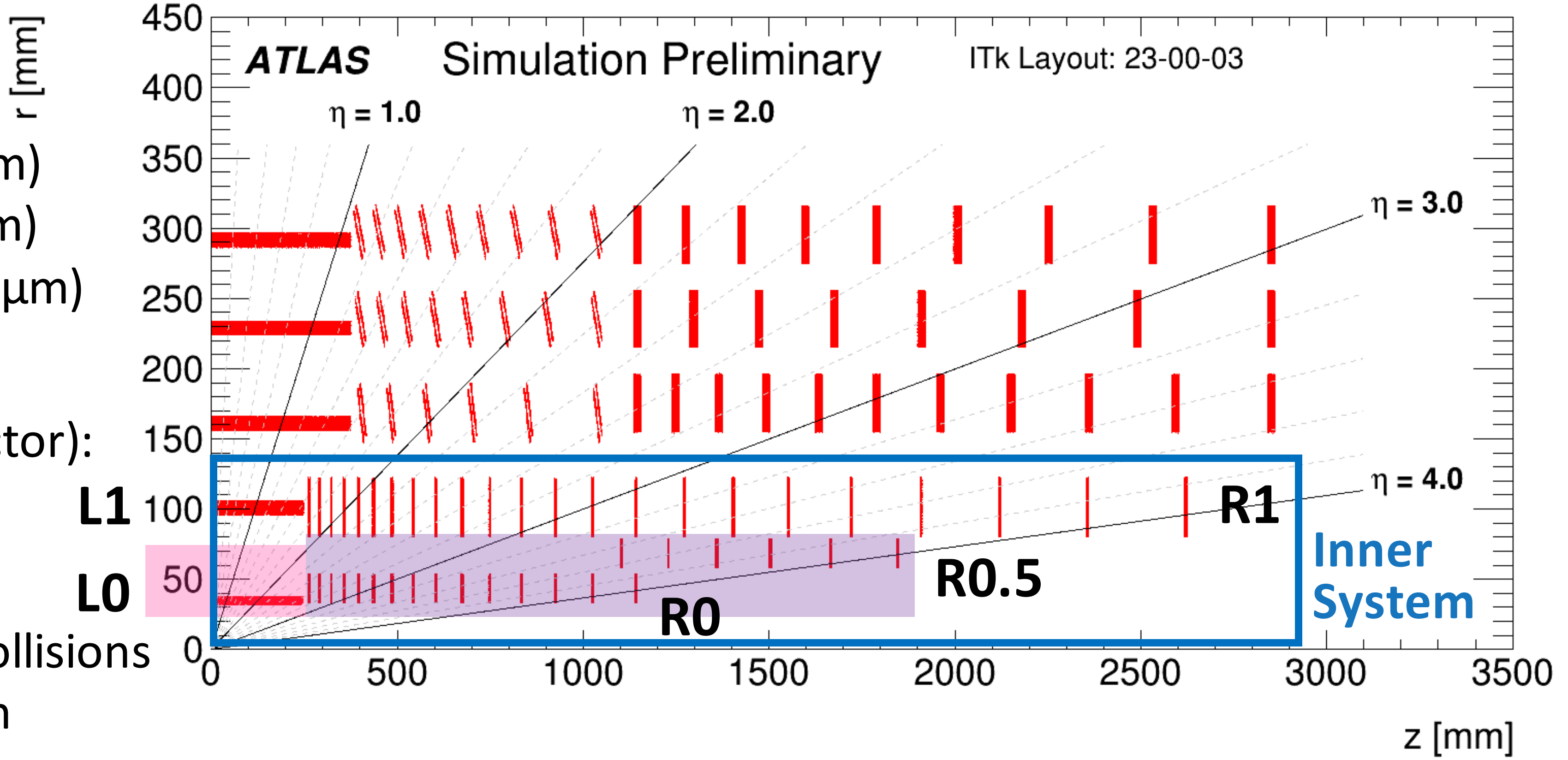


- **Planar sensor**: standard pixel technology, n+ implants on p bulk surface
- **3D sensor**: n+ and p+ columns implanted vertically in p bulk substrate
  - Reduced distance between electrodes → Shorter path of e/h
    - Lower impact of charge trapping along charge carrier path
    - Improved radiation hardness: perfectly OK @ 1e16 n_{eq}/cm^2 NIEL
  - Lower depletion voltage → Lower power dissipation after irradiation

- 5 layers of pixel:
  - **L4-3-2**: Planar sensors (150 µm)
  - **L1, R1**: Planar sensors (100 µm)
  - **L0, R0, R0.5**: 3D sensors (150 µm)

- **Inner System** will be replaced
- HL-LHC @ 2000 fb^{-1} (1.5 safety factor):
  - NIEL up to 1.9e16 n_{eq}/cm^2
  - TID up to 1 Grad

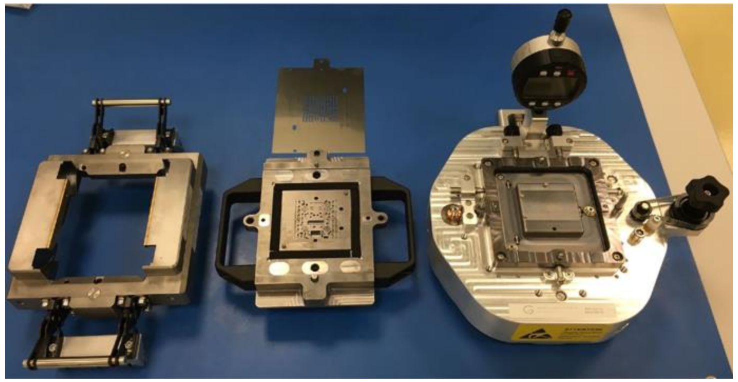
- **L0 Barrel staves** at 34 mm from collisions
- **R0 Endcap rings** down to 33.2 mm



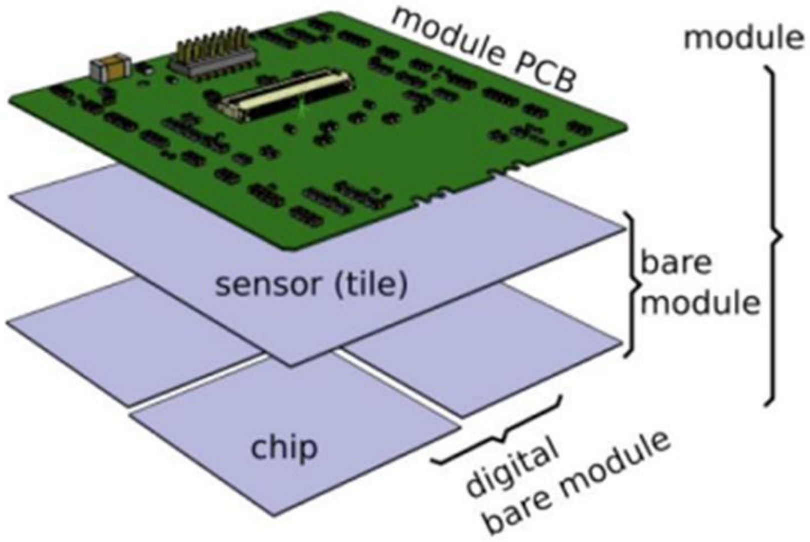
Pixel: triplet and quad-modules

- Module components: sensor + ITkPix chip + flexible PCB (powering and data)
- Two different module concepts: **quad-module** and **triplet module**
- **Quad-module**: 1 bare module (4 chips + 1 planar sensor) + 1 flexible PCB
  - Common assembly tool to attach flex
  - Glue delivered with stencil on the flex
  - 16 assembly groups (partly qualified with RD53A prototypes)
  - ITkPix flexible PCB: design finalized, pre-production launched

Quad-module assembly tool
(developed in Gottingen)

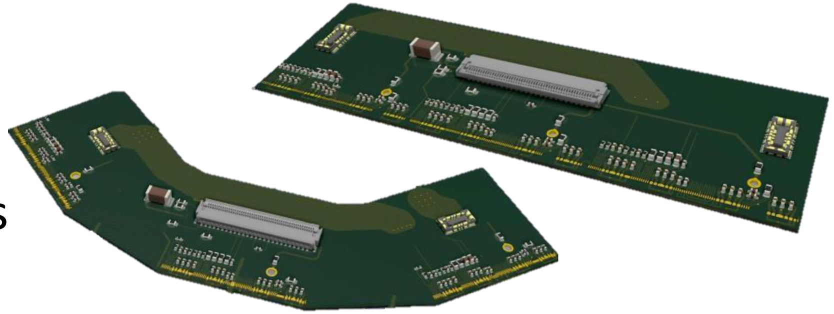


Quad-module stack-up



- **Triplet module**: 3 bare modules (1 chip + 3D sensor) + 1 flexible PCB
  - Different assembly setups in 4 sites (Milano, Genova, Oslo, Barcelona)
  - Glue delivered with stamp on the flex
  - Both ring and barrel triplet assembly exercised with RD53A prototypes
  - Design of the flexible PCB: progressing, to be finalized

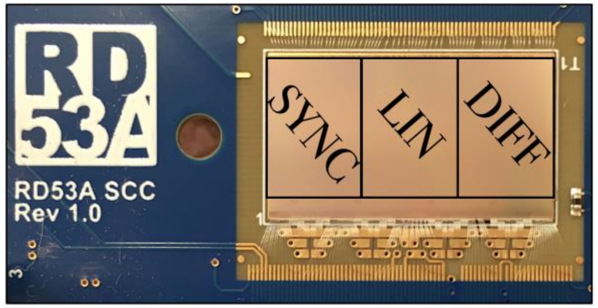
Ring and barrel
triplet module flexible PCB

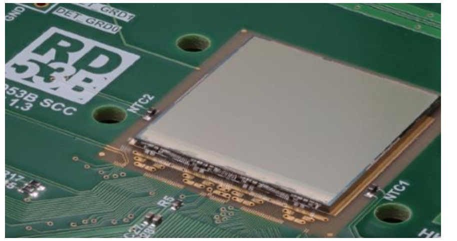


Pixel: FE chip, from RD53A to ITkPixV1 (RD53B)

ATLAS ITk

- RD53A chip (by RD53A collaboration) largely used to build module prototypes
- ITkPixV1.0 chip (RD53B): bug in ToT memories : induces high digital current
  - ITkPixV1.1 chip: patch fixed high current (ToT still not usable)
  - Summary of chip studies in TIPP 21 talk, other details in ICHEP 2022 talk
  - Several wafers produced, probed (80% yield), thinned (150 µm) and diced
- ITkPixV2 chip to be submitted within 2022 (few features yet to be understood/fixed)

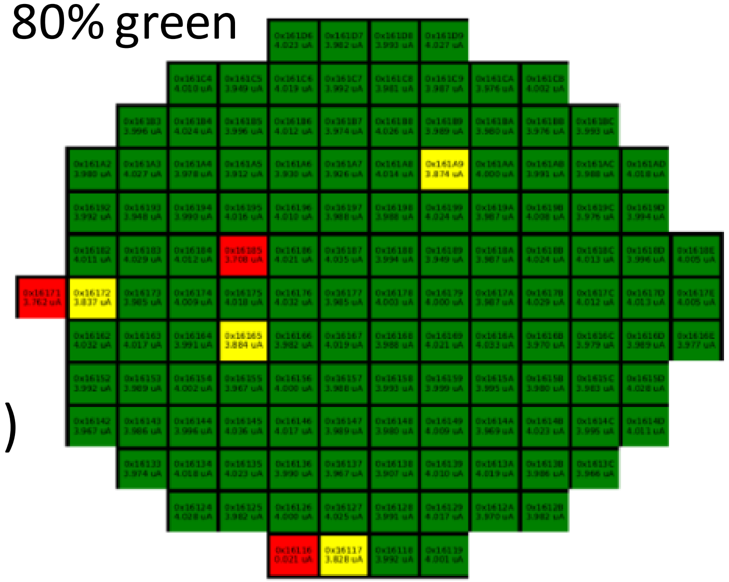


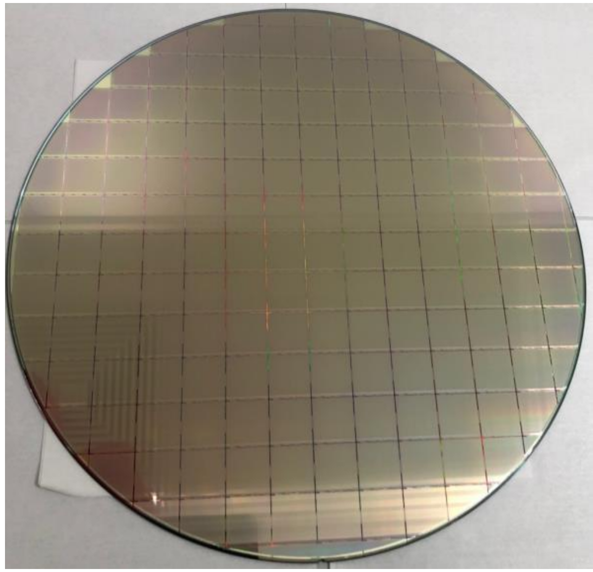


ITkPixV1
on PCB

- Main ITkPixV1 features:
  - 65 nm CMOS, 2x2 cm^2 area
  - 384 x 400 pixels (50x50 μm^2)
  - Differential Analog FE
  - Power consumption: 0.56 W/cm^2
  - Shunt Low Drop Output regulators (I const.)
  - Radiation hardness > 1 Grad
  - Standard threshold: 1000 e (30 e dispersion)
    - Noise: 40 e (bare chip)
    - No noisy pixels @ 600 e → 1% @ 400 e

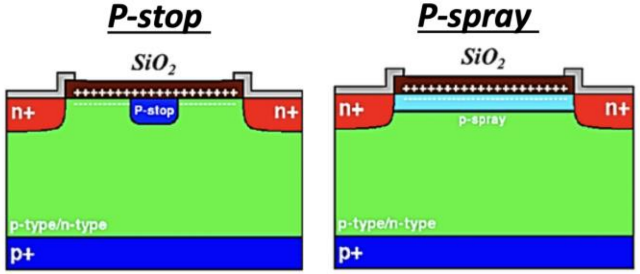
ITkPixV1.1 wafer yield
80% green

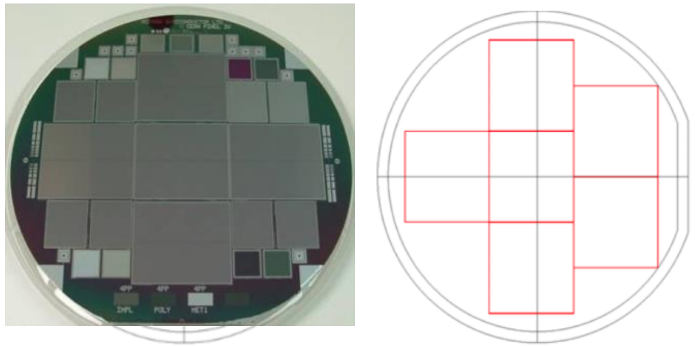




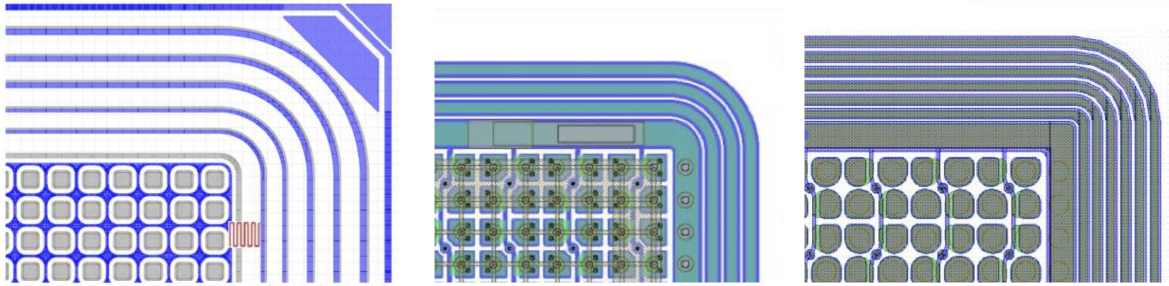
Pixel: planar sensor pre-production

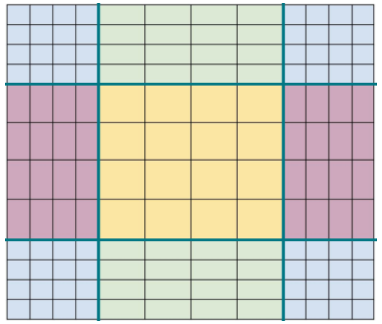
- Market survey: completed! → Share: divided in 4 vendors → Pre-production: delivered!
- Wafers delivered, devices distributed to institutes to start quality assessment (IV, CV, metrology)
    - 100 µm (thin) planars (for L1): FBK and Micron
    - 150 µm (thick) planars (L2-3-4): HPK and Micron
- Design details left up to vendor:
    - P-stop or p-spray insulation
    - Polysilicon bias or punch-through
    - Guard-ring geometry





5/6 sensors on 6'' wafer





Inter-chip region

50×50 µm²

50×100 µm²

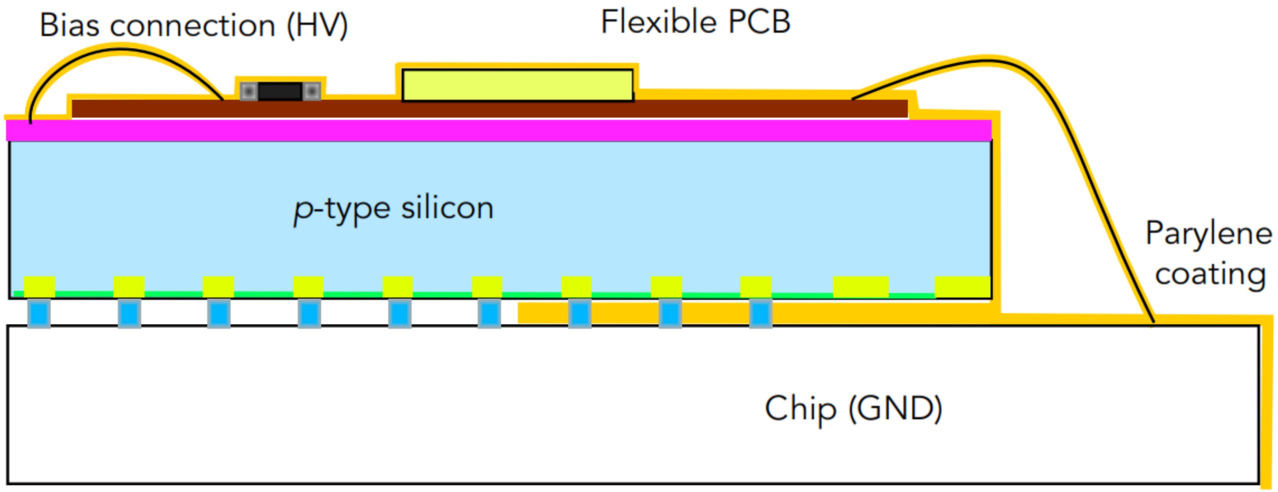
100×50 µm²

100×100 µm²

Quad-module

1 sensor 4x4 cm²

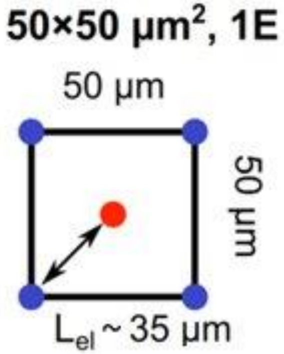
4 chip 2x2 cm²

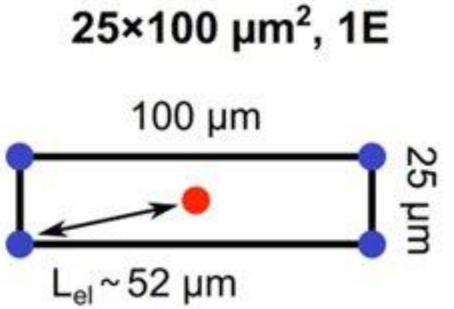


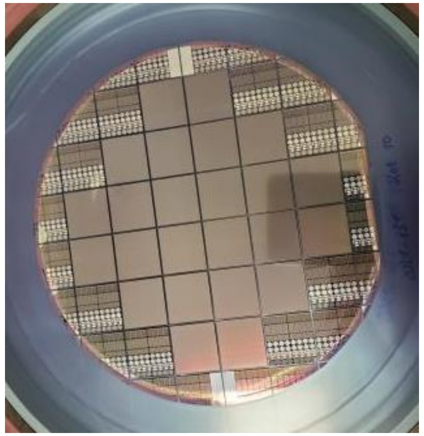
Parylene N vapour deposition for bias voltage isolation

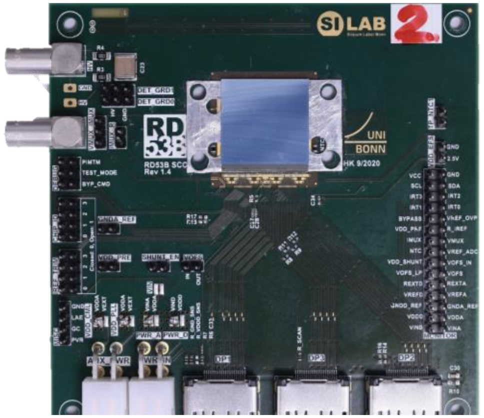
Pixel: 3D sensor pre-production

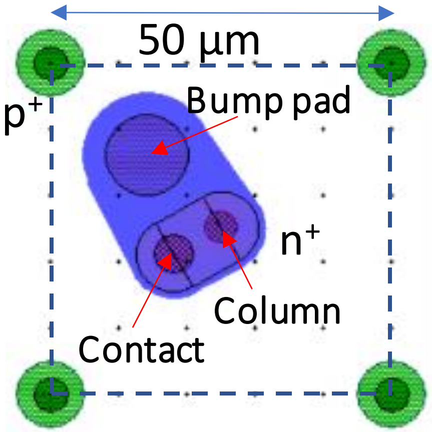
- Final Design Review: passed (Winter 2019) → Pre-production: ongoing! → Next reviews in few months
- 50x50 μm^2 pixel cell (endcap modules):
  - FBK and SINTEF delivered pre-production wafers!
  - 20 FBK sensors assembled to ITkPixv1.1 chips (iWoRiD 2022 talk)
    - Some of them mounted on Single Chip Card (easy handling)
    - Irradiation to 1.0 and 1.7e16 n_{eq}/cm^2, then CERN SPS testbeam
- 25x100 μm^2 pixel cell (barrel modules):
  - CNM pre-production in delay, new batch expected in few months
  - FBK (as full backup solution) wafers expected in summer

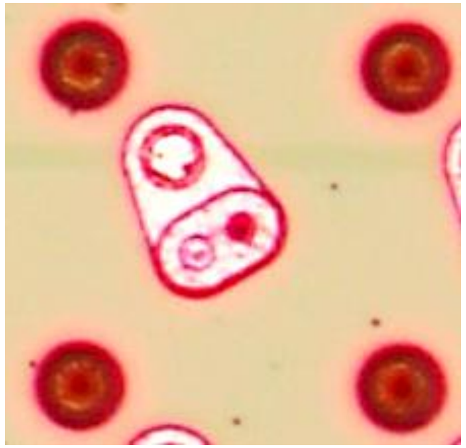


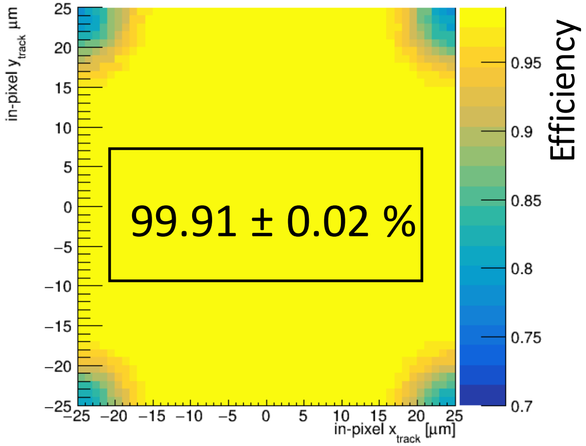








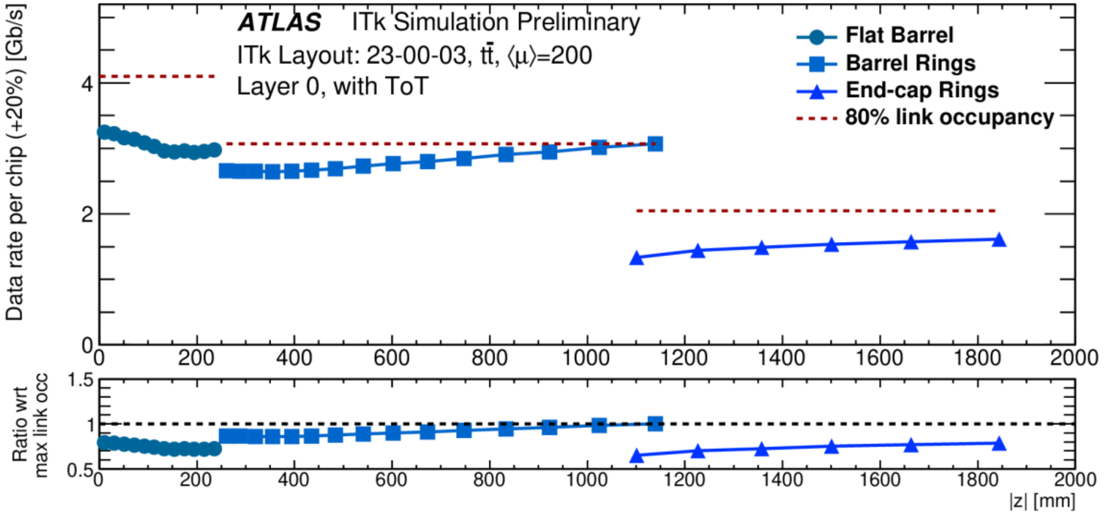


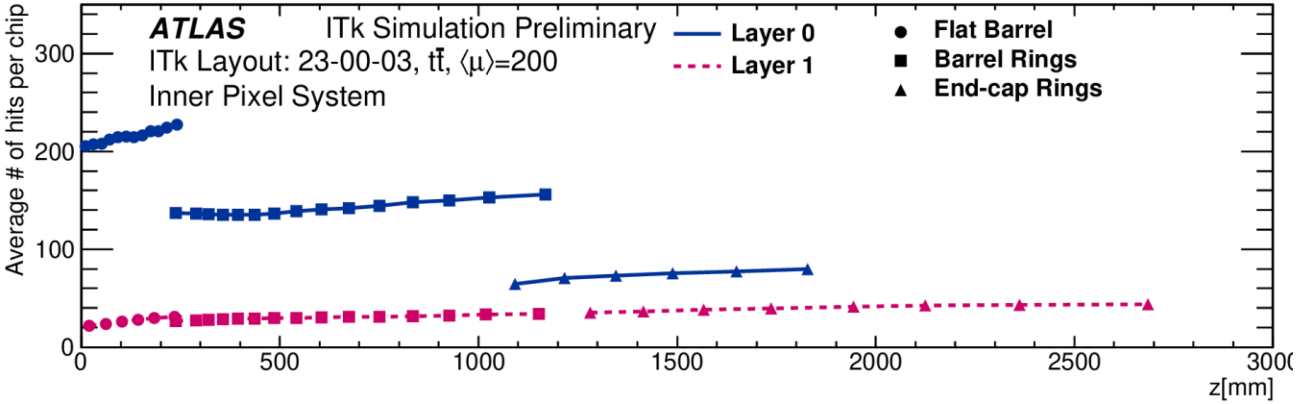


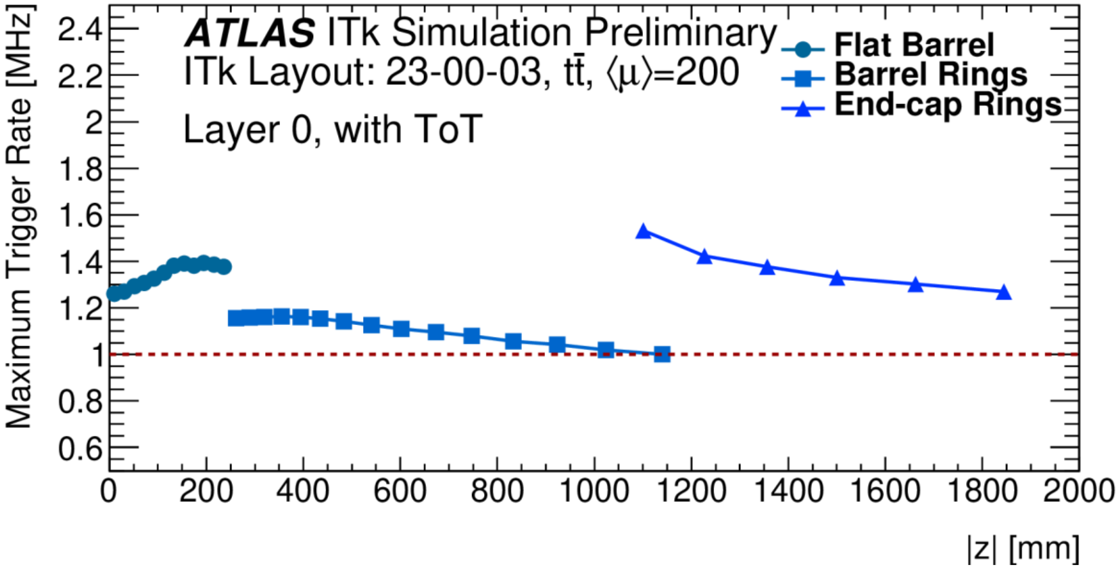
3D sensor wafer → Single chip card → Pixel cell design → Visual inspection → Hit det. efficiency

Pixel: hits, data rates and trigger rates

- Detailed study available in [ATL-ITK-PUB-2022-001]
    - Baseline: analog readout exploiting ToT information
    - ttbar events with 200 pile up: event size = 1.7 MB
- L0 maximum number of hits (as expected) in barrel:
    - Triplet modules with 3D sensor (pixel cell 25x100 μm^2)
    - Chip with 384x400 = 153600 channels
    - About 200 hits/chip → max 0.15% occupancy
- L0 with 4/3/2 links per chip, depending on the Z position
    - Barrel: 4x1.28 Gbps links to allow enough bandwidth
- Decided to allow for maximum trigger rate of 1 MHz
    - 1 MHz in the whole ITk detector

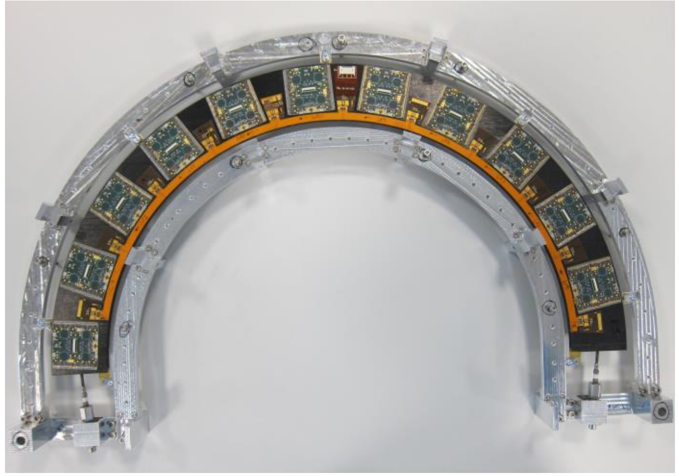






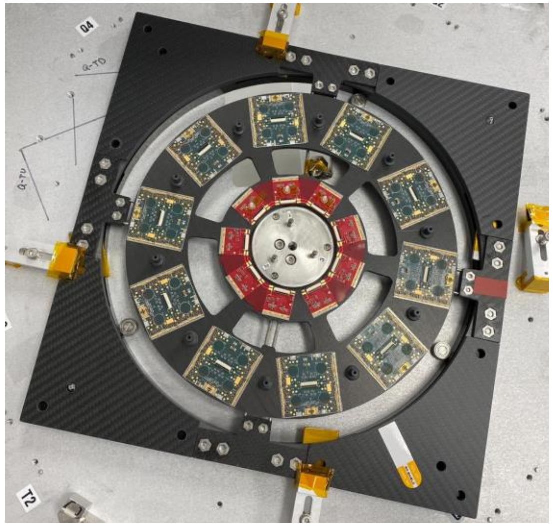
Pixel: demonstrators with RD53A prototypes

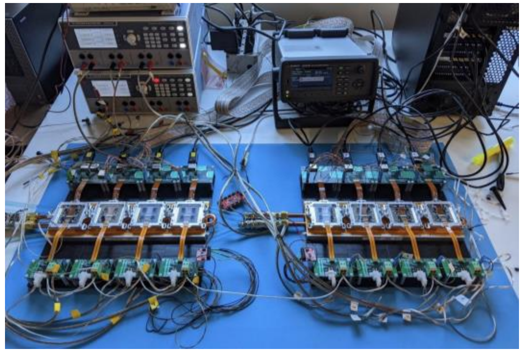
- Pixel modules with RD53A chip were produced as prototypes
  - About 160 quad-modules and 20 triplet modules
- Whole production chain executed up to full layer equipped with modules
  - More details and pictures in [15th Pisa Meeting poster] and [ICHEP 2022 talk]
- Each component was tested according to established protocols:
  - Quality assurance
    - Evaluation of design and materials, bringing components to the limits
    - Apply mechanical, thermal, electrical, radiation stress
  - Quality control
    - Check quality and exclude bad components (outside specifications)
    - Geometrical (metrology) and electrical (powering / communication) tests
- All structures assembled and tested following production-like steps:
  - Carbon support structure
  - Flexible circuit
  - Sensor, Chip → Bare module
  - Module
  - Electrical services



Outer Endcap ring (RAL) with RD53A modules

Inner System ring (SLAC)





Moreover, test of serial powering chain to check the behaviour and control of multi-module setups ← Chain of 8 ITkPixv1.1 quad-modules (Berkeley)

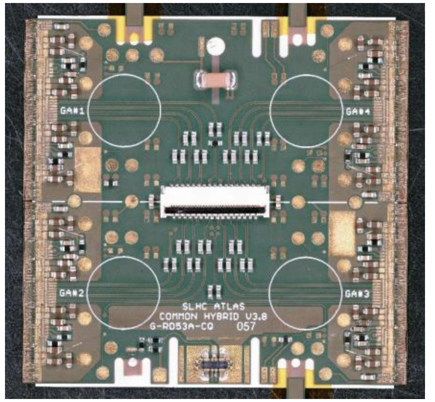
ITk @ Italy: involvement of the INFN community

- Italian community deeply involved in ITk Pixel project

- **Pixel Module production**: assembly of ~1100 pixel modules
  - 30% of triplet modules for the Inner System (R0.5, 3D sensor)
  - 22% of quad-modules for the Inner System (L1, thin planar)
  - 15/25% of quad-modules for the Outer Endcap (L2-3-4, planar)

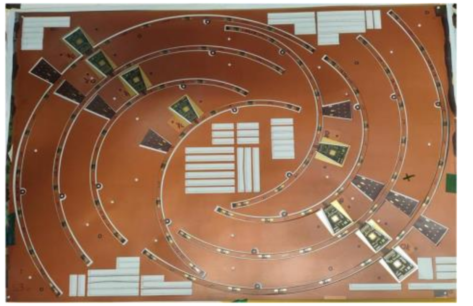
- **Fabrication of a full Outer Endcap** (shared with UK community)
  - Fabrication of local supports (Half Ring)
  - Design and fabrication of the power tapes
  - Loading of the Half Rings of the "Italian" Endcap
  - Integration of the "Italian" Endcap

- **Other contributions:**
  - Thin planar and 3D sensor production at FBK
  - CO^2 cooling system with heat exchangers
  - Contributions to DAQ and DCS development

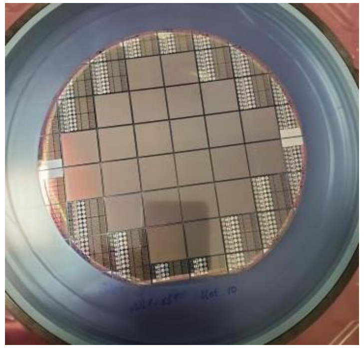
RD53A triplet (Genova) and quad-module (Milano)

Outer Endcap Half Ring (Genova)



Power tape panel (Genova)

Heat exchangers (Genova)



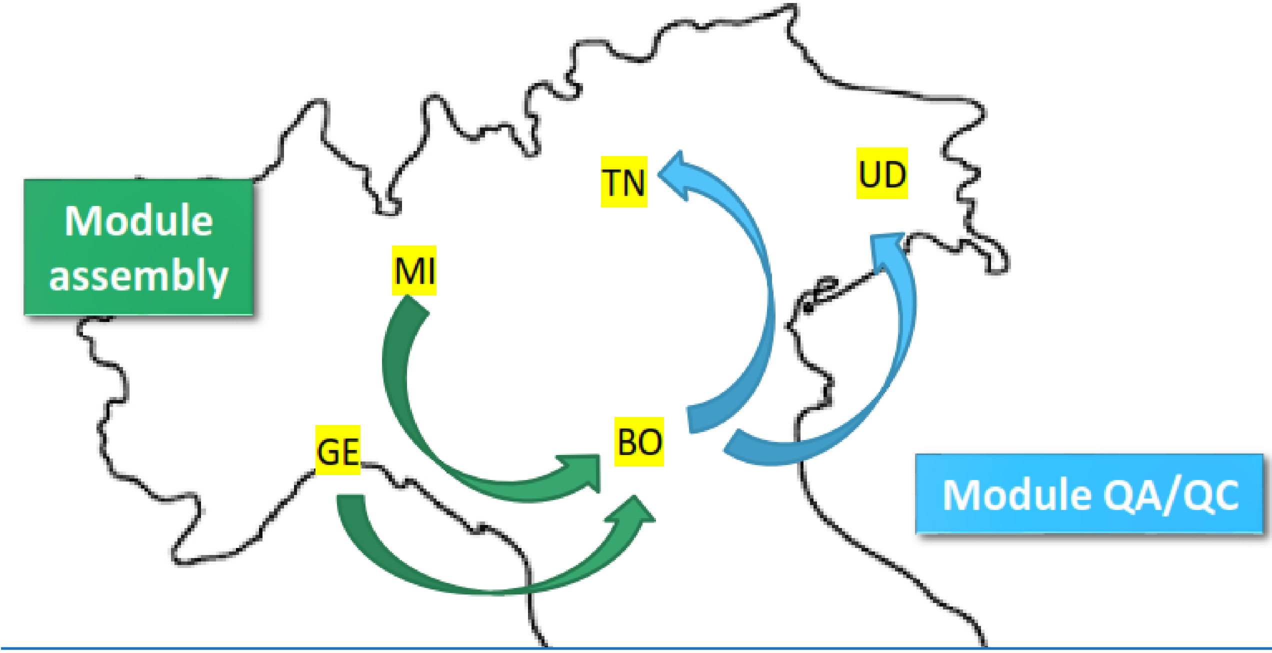
3D sensor wafer (FBK, Trento)

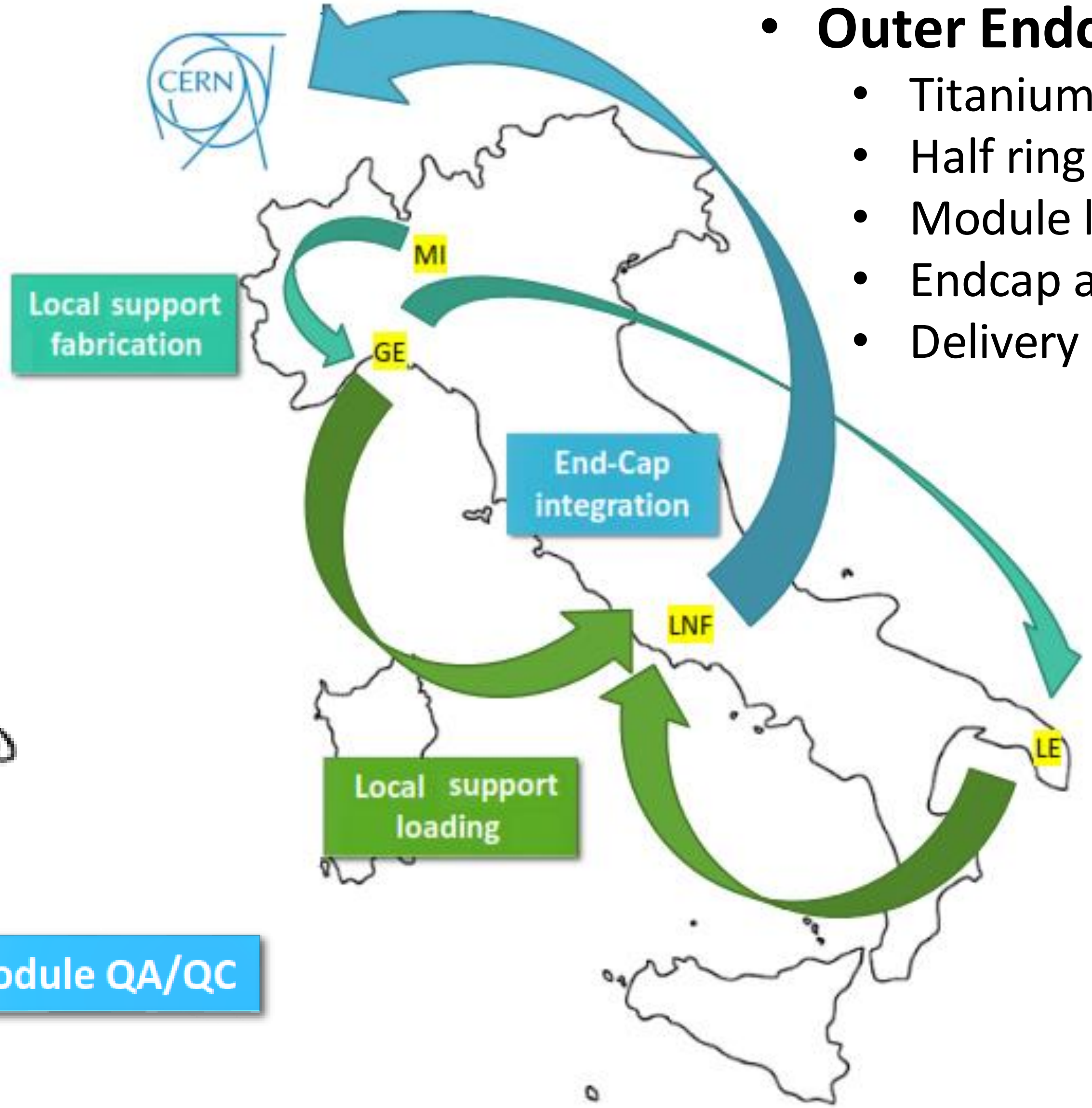
Endcap integration (Frascati)

Focus on Endcap mod+HR+loading, shared with UK

- 7 INFN laboratories involved

- **Pixel Module production:**
  - Assembly (GE, MI)
  - Parylene coating (MI)
  - Thermal cycles (BO)
  - Quality Control (BO, TN, UD)





- **Outer Endcap production:**
  - Titanium pipes (MI)
  - Half ring assembly (GE)
  - Module loading (GE, LE)
  - Endcap assembly (LNF)
  - Delivery to CERN!

Summary

- A new all silicon detector (ITk) will be installed in ATLAS to guarantee tracking performance at HL-LHC
  - Instantaneous luminosity: 1-2e34 $cm^{-2}\ s^{-1} \rightarrow$ up to 7.5e34 $cm^{-2}\ s^{-1}$, pile-up collisions: 30-50 $\rightarrow$ up to 200
  - Expected performance compatible with Run 2, despite much harsher conditions
- Design completed, minor optimization ongoing
  - Extended pseudorapidity coverage: tracking at LHC (ID) $\eta \leq 2.5 \rightarrow$ at HL-LHC (ITk) $\eta \leq 4.0$
  - Strip modules in the external layers
  - Pixel modules with planar (everywhere) or 3D sensor (innermost layer, 33-34 mm from collisions)

- Strip detector:
  - Progressing through pre-production: 1000 modules built!
  - Production has started for several parts (sensors, chip, mechanical structure)
- Pixel detector:
  - Finalizing an extensive prototyping phase: 200 modules built
  - Pre-production has recently started for some components (sensor, chip, flexible PCB, carbon supports)

- Important contribution of the Italian community to the ITk Pixel detector:
  - 1100 module assembly and test
  - Production and integration of a fully equipped Outer Endcap