ATLAS Inner tracker (ITk) upgrade in view of HL-LHC

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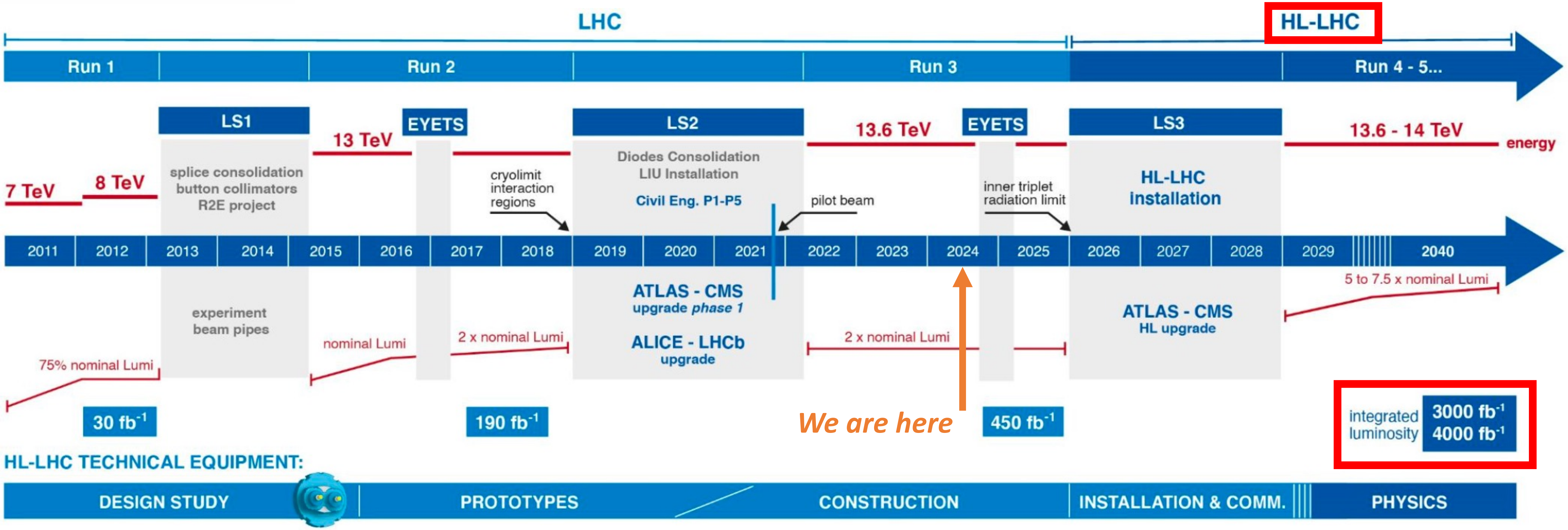
Disclaimer

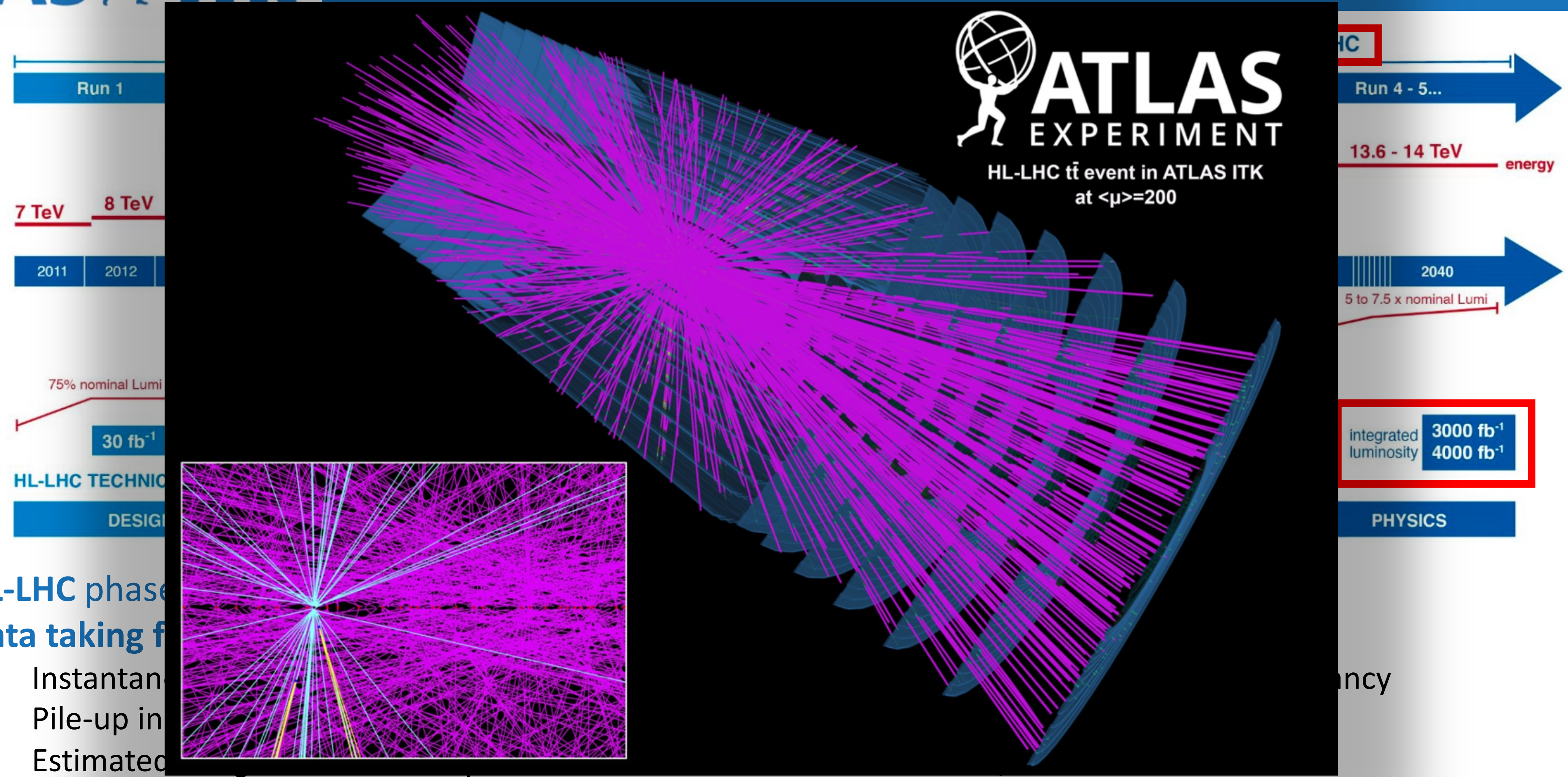
- This is **NOT** an R&D talk
- R&D is finished (lasted more than 10 years), and we are now entering the production phase
- Let’s not to forget that the primary goal of detector R&D (beyond advancing the knowledge) is to build a detector at the end
- So, need to design a detector that meets the physics goals of the experiments and is: affordable; buildable given the human resources and available infrastructure; (and since recently) need also to take into consideration sustainability, and environmental impact

LHC timeline including HL-LHC



- **HL-LHC** phase currently scheduled to start in **2029**
- **Data taking foreseen up to ~2040**
  - Instantaneous luminosity to increase from 2 to ~7.5 × 10^{34} $cm^{-2}s^{-1}$: very high detector occupancy
  - Pile-up increase to ~200, from ~60 currently
  - **Estimated integrated luminosity at the end of HL-LHC: 3000-4000 fb^{-1}**

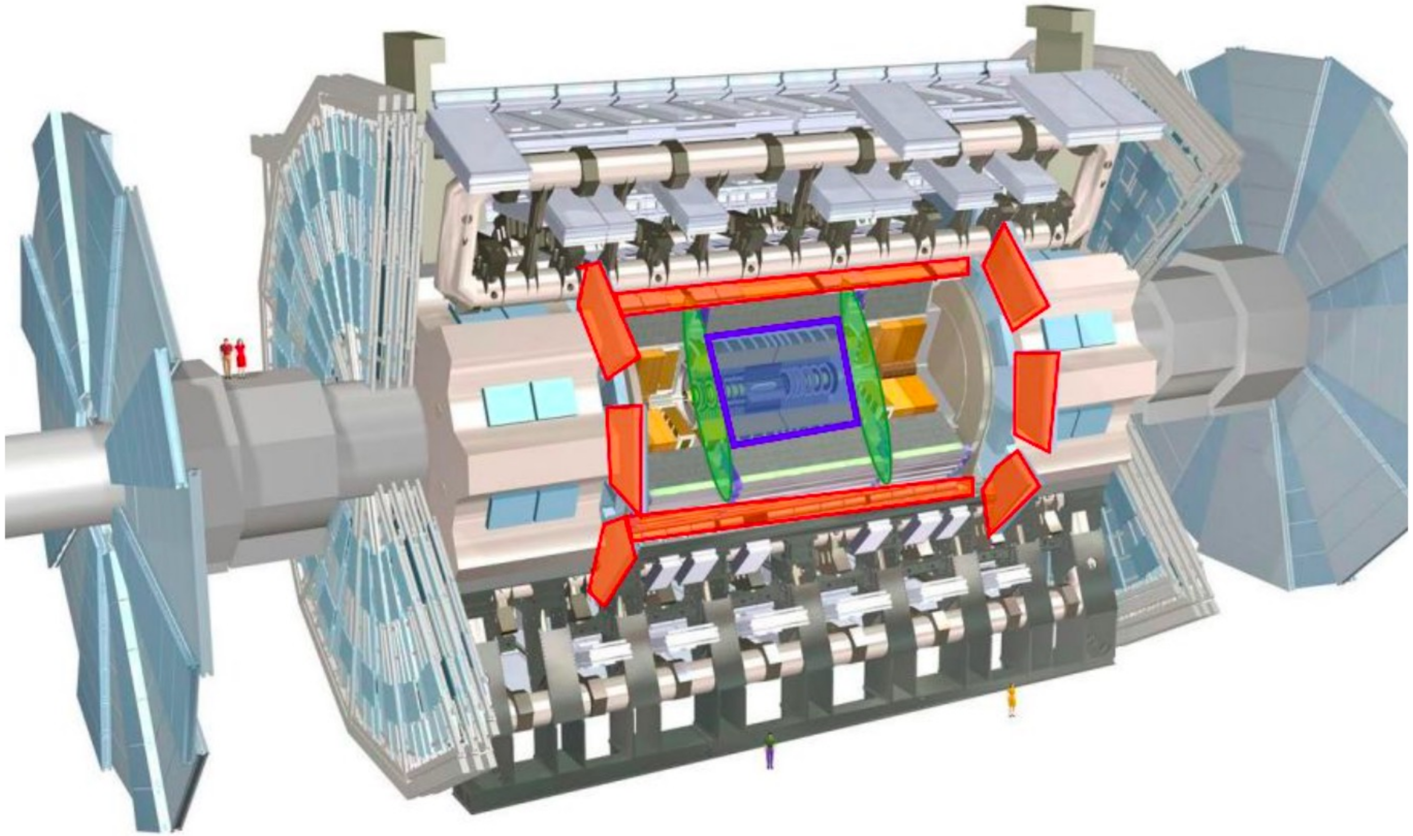
LHC timeline including HL-LHC



HL-LHC $t\bar{t}$ event in ATLAS ITK at $\langle\mu\rangle$=200

- **HL-LHC phas**
- **Data taking f**
  - Instantan … ncy
  - Pile-up in
  - Estimated
- **Major upgrades are planned for all the LHC experiments to cope with these very harsh condition**

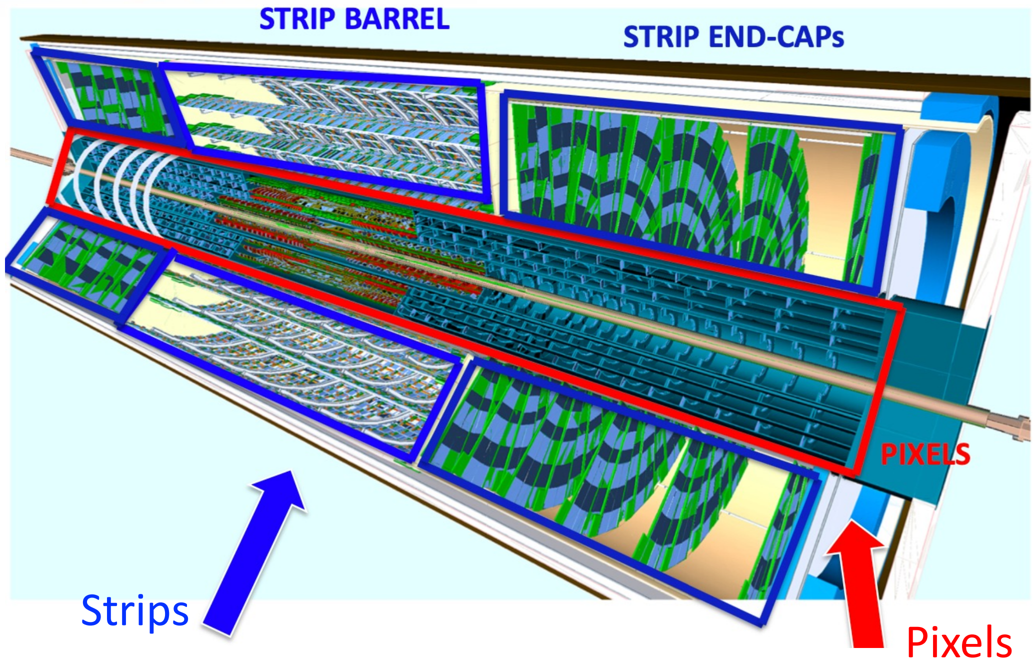
ATLAS upgrades for HL-LHC



- New **muon chambers** at the innermost part
  - Trigger efficiency and momentum resolution improvements
- **High Granularity Timing Detector** (HGTD)
  - Improved pileup suppression at the forward region
- Upgrades on calorimeter and muon chambers off-detector electronics and trigger
- **New inner tracker (ITk)**
  - Higher granularity
  - Reduced material budget
  - Radiation hardness
  - Faster readout
  - Goal: new tracker to have similar, or better, performance compared to current inner detector

Focus of this talk

Inner Tracker upgrade (ITk)

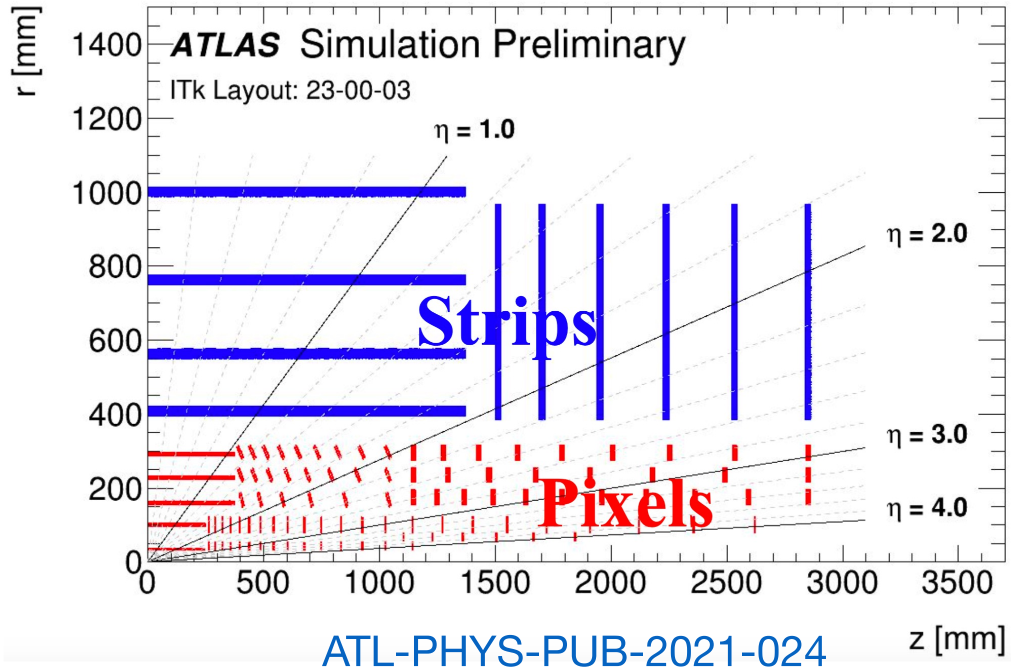


- **All-silicon inner tracker** with increased acceptance from $|\eta|<2.5$ (current ID) to $|\eta|<4$ (ITk)
  - Improved pile-up suppression in the forward region
  - Similar tracking efficiency and p_T resolution, but at pile-up of 200

- **Outer strip detector: 4 barrel layers + 6 end-cap disks**

- **Inner pixel detector: 5 barrel layers + inclined and vertical rings**
  - ~13m^2 of active area
  - ~8500 modules
  - 5.1 Giga-pixels
  - Pixel pitch: 25x100 µm^2 for L0, 50x50 µm^2 elsewhere

Current pixel system
~1.9 m^2 of active area
2000 modules
92 Mega-pixels
Pixel pitch at L0: 50x250 µm^2



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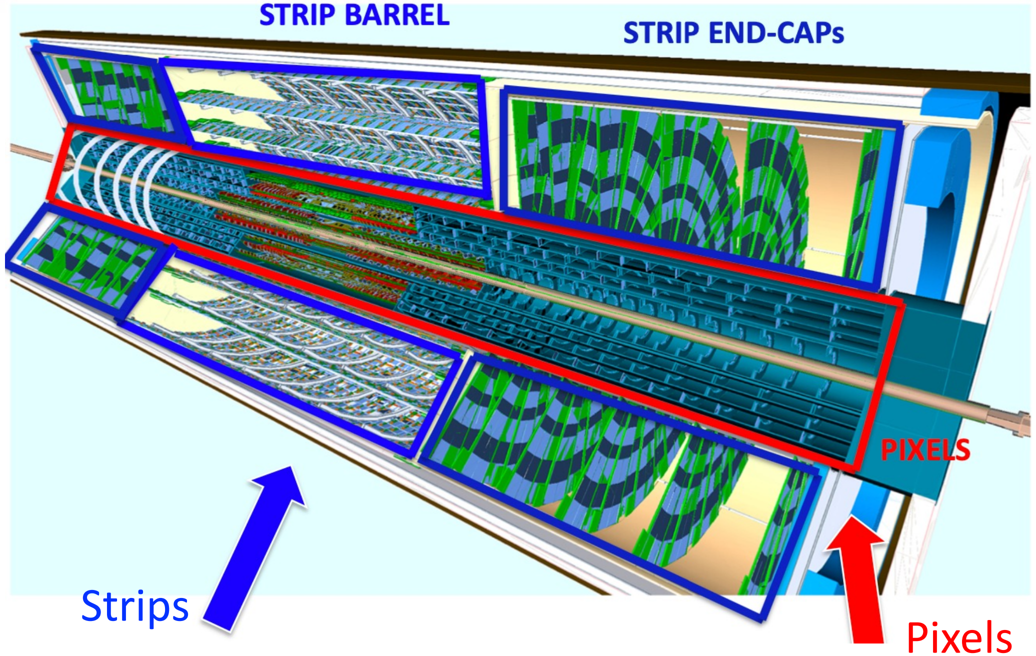
Inner Tracker upgrade (ITk)



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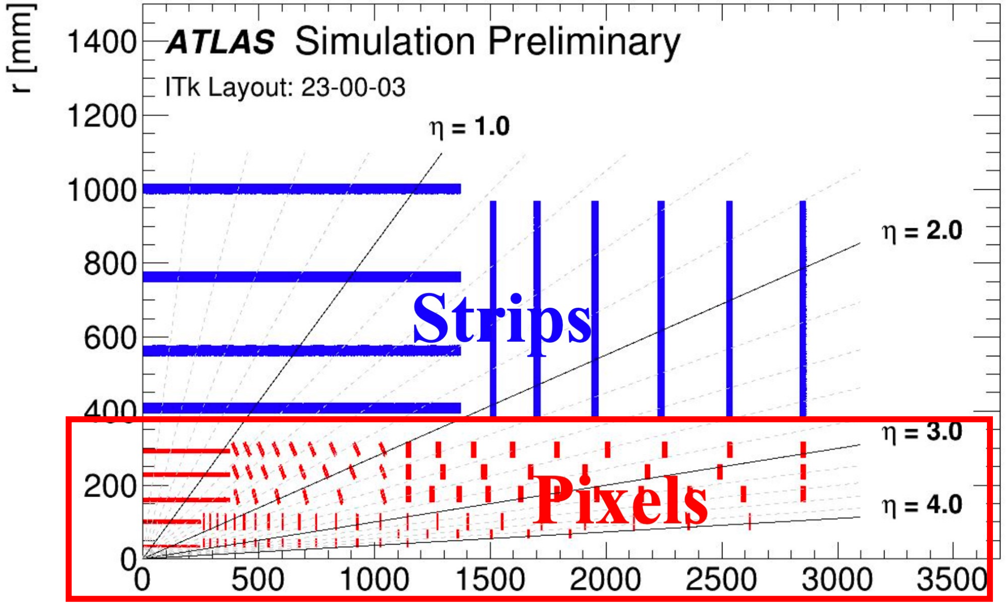


ATL-PHYS-PUB-2021-024

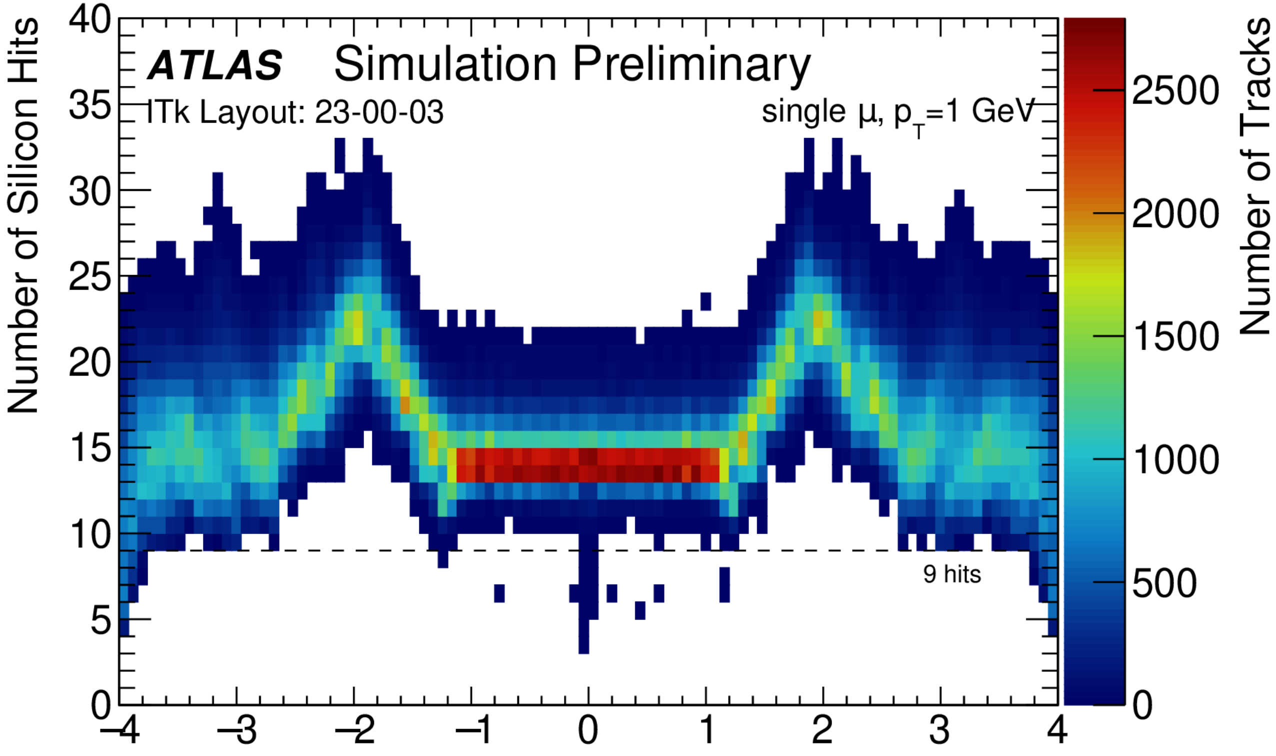
- **Outer strip detector: 4 barrel layers + 6 end-cap disks**

- **Inner pixel detector: 5 barrel layers + inclined and vertical rings**
  - ~13m^2 of active area
  - ~9000 modules
  - 5.1 Giga-pixels
  - Pixel pitch: 25x100 μm^2 for L0, 50x50 μm^2 elsewhere

Focus today

ITk-Pixel number of hits

- Big pseudorapidity coverage, increased number of layers wrt to current inner detector
  - Minimum 9 hits per track at central region, 13 hits at the forward region
  - Hits redundancy is mandatory to solve the high combinatorics expected at HL-LHC



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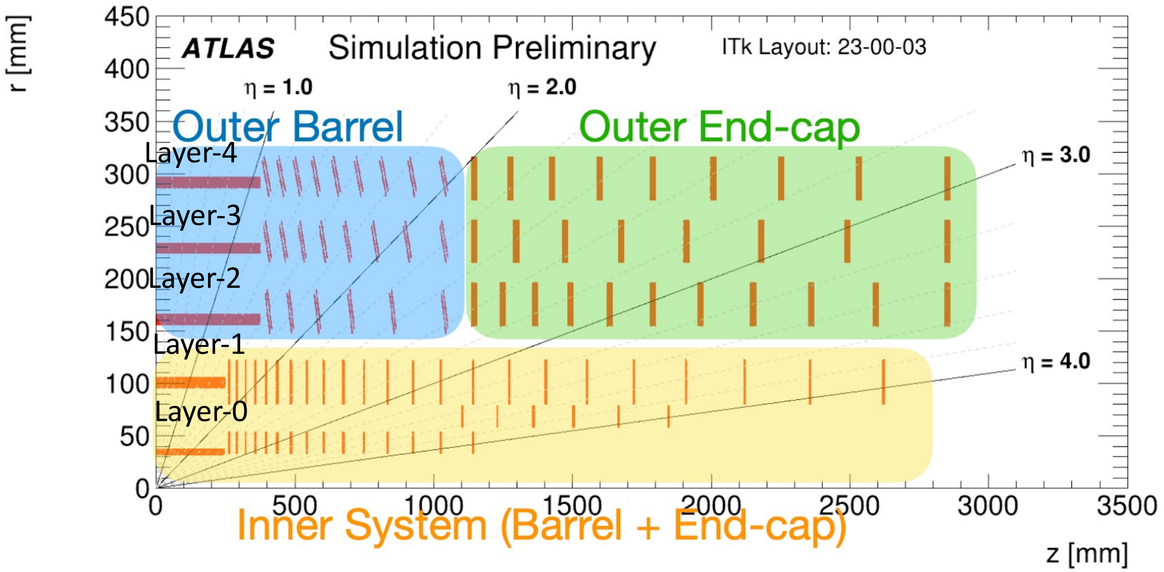
ITk-Pixel layout

- ITk-Pixel detector composed by 3 parts:



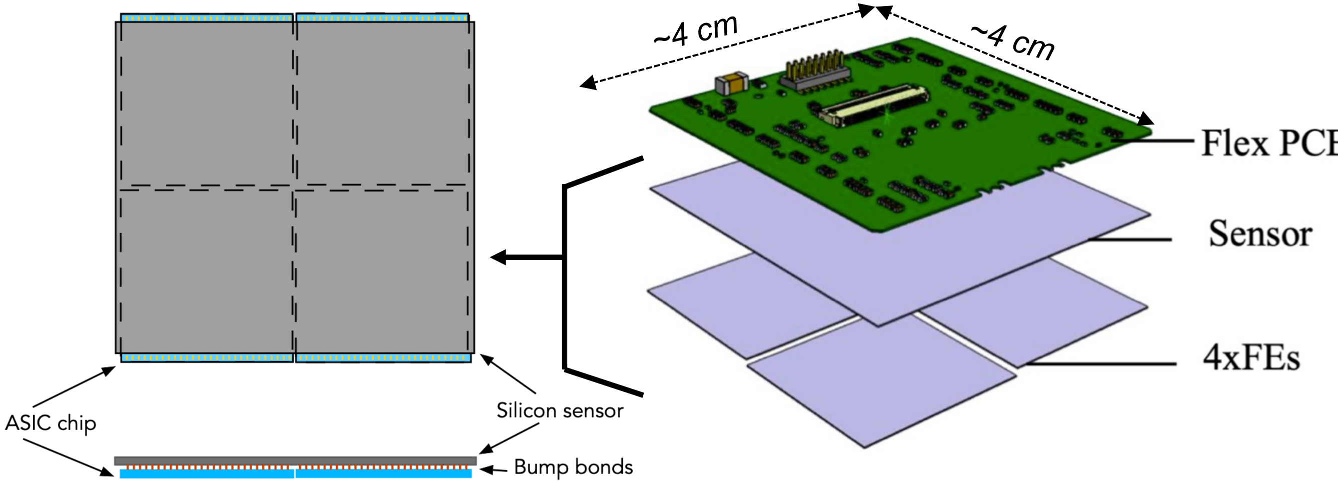
- **Outer barrel:** 3 barrel layers, 2x23 inclined disks
  → CERN, **France**, Germany, Japan, Switzerland

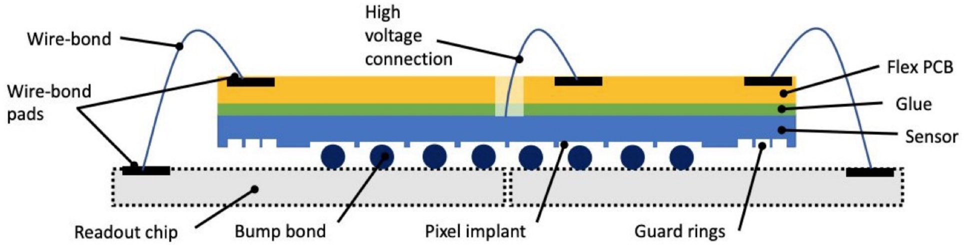
- **Outer endcap:** 2x28 outer disks
  → UK, Italy, Japan

- **Inner system:** 2 barrel layers and 2x44 disks
  → USA, Germany

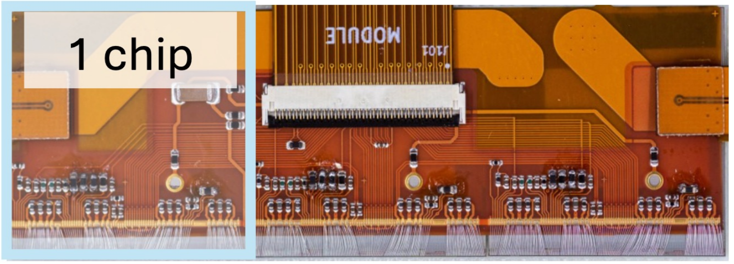
ITk-Pixel building blocks: modules

- **Hybrid pixel detector technology:** passive silicon sensors **bump-bonded** to readout chips (bare module)
  - **Chips** are thinned to 150 µm
  - **Sensors**
    - **L2, L3 and L4 planar sensors,** 150 µm thick
    - **L1 planar sensors,** 100 µm thick
    - **L0 3D sensors,** 250 µm thick
- **Flexible printed circuit board** (Flex PCB) glued on bare module, and then **wire bonded to ASIC**
- **Two** types of **modules**
  - **Quad** modules: **4 FEs** bump bonded to **one sensor**; Layer 1, 2, 3 and 4
  - **Triplet** modules: **3 single-FE** bare modules **connected** to the **same flex**; Layer 0





Quad module

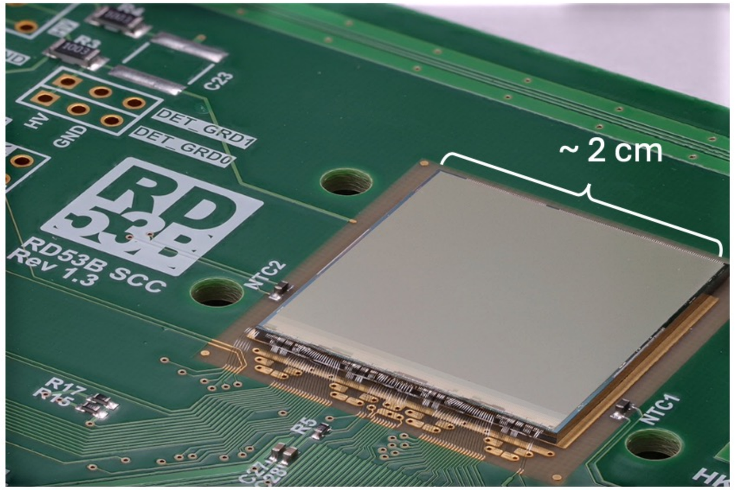


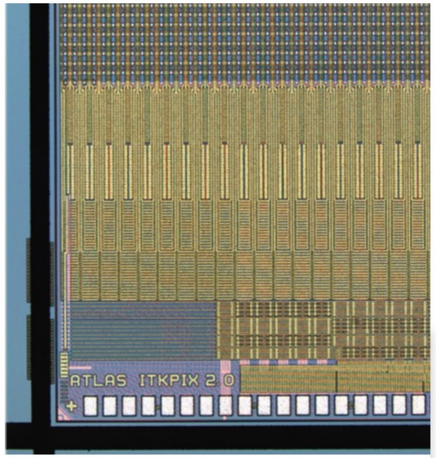
Triplet barrel module

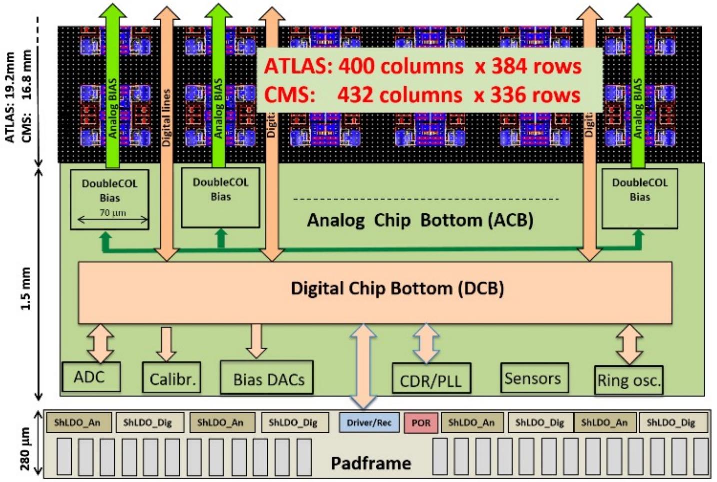
Readout chip

- All modules will be read out with **ITkPix front-end readout chip**
  - 65 nm CMOS technology
  - Designed by RD53 collaboration (https://rd53.web.cern.ch) over ~10 years, common for ATLAS and CMS
- Stringent requirements compared to current FE-chips
  - 10 x higher radiation hardness
  - 100 x larger effective readout bandwidth
  - Same power consumption (< 1 W/cm2)
- ITkPixV1.1 used for pre-production, ongoing now.

- ITkPixV2 production chip – first wafer delivered in September 2023, more wafers to be delivered the next days!

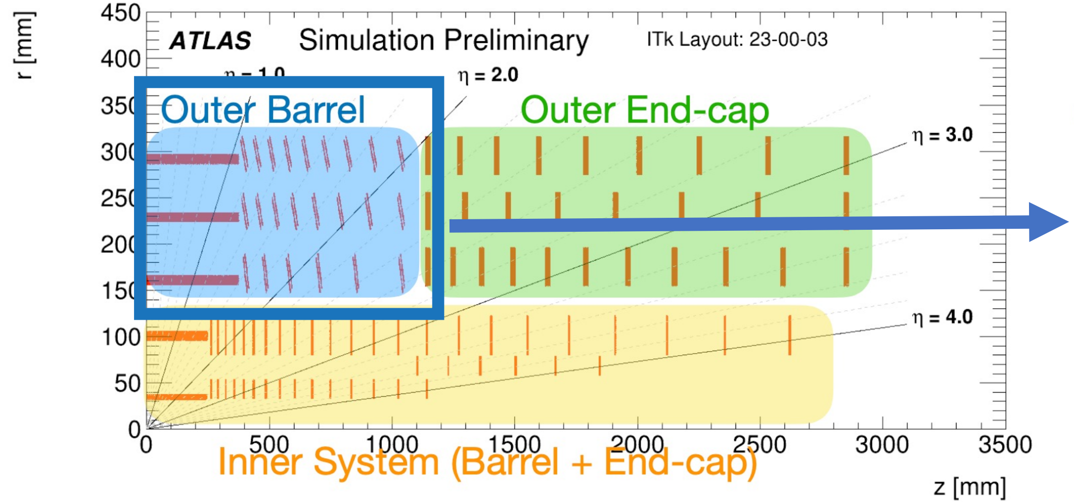


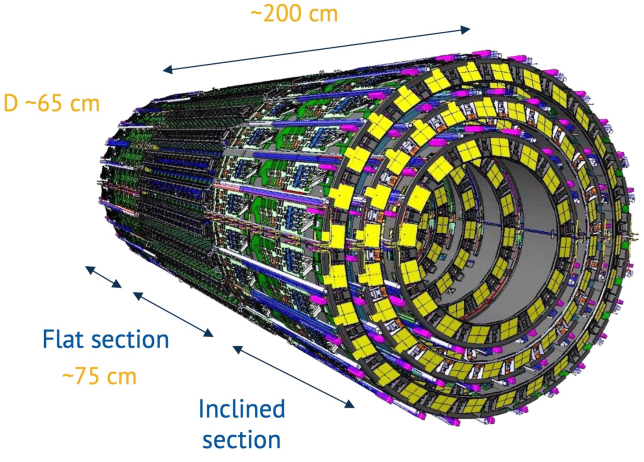


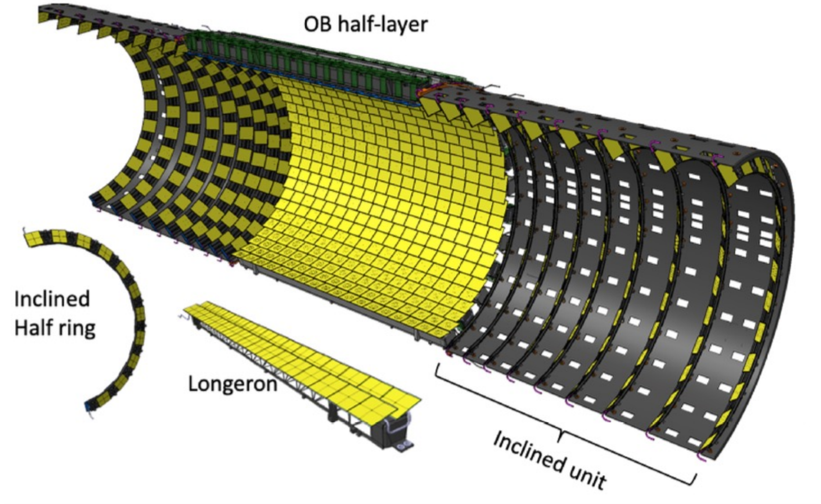


- **CPPM, IJCLab, LPNHE** participated in the design and validation of the chip within RD53 collaboration
- **IJCLab** contributes in the FE wafer probing, an important QC test prior to bump bonding (*Jérôme Ren poster*)

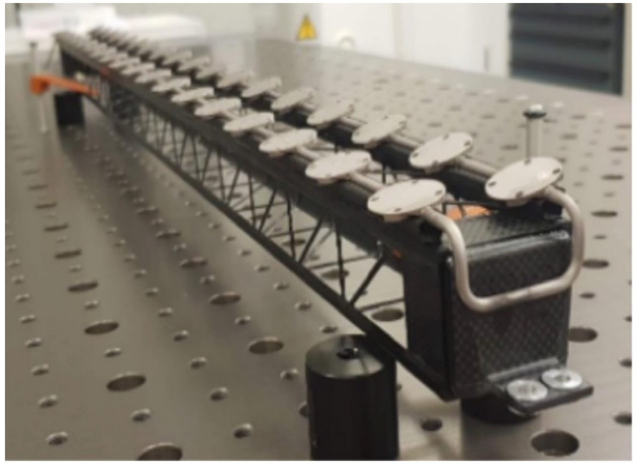
Outer barrel (French groups involvement)

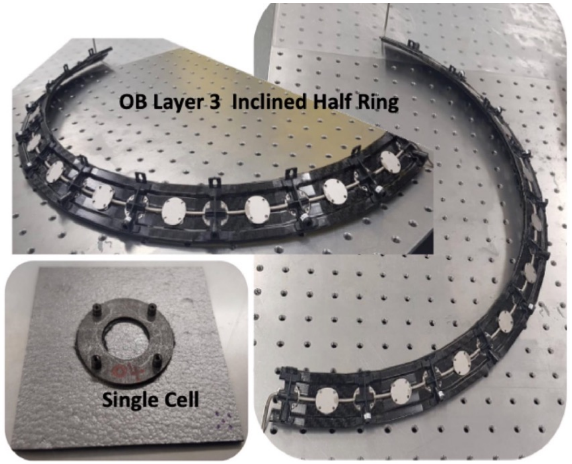






- **Outer barrel** is the **largest system** of ITkPixel detector
- ~4.5k modules, more than half of total ITkPixel
- **French** activities are organised in **two clusters**
  - **Paris cluster** for module assembly and testing: **IJCLab, IRFU, LPNHE**
  - **Alpaca cluster** for loading and integration: **CPPM, LAPP, LPSC**





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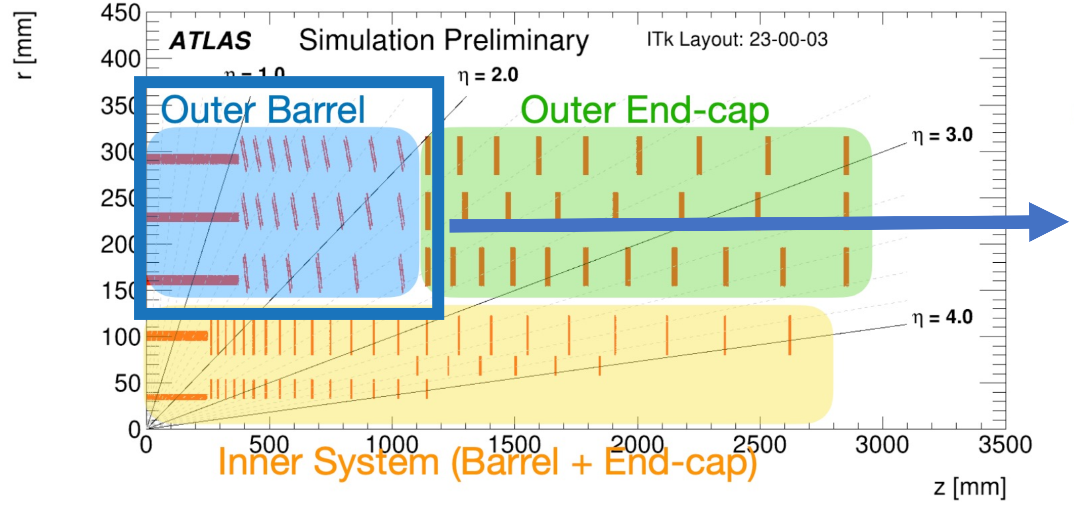

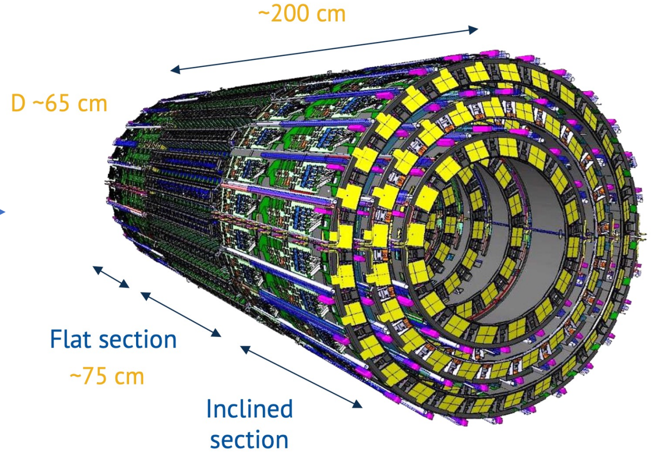

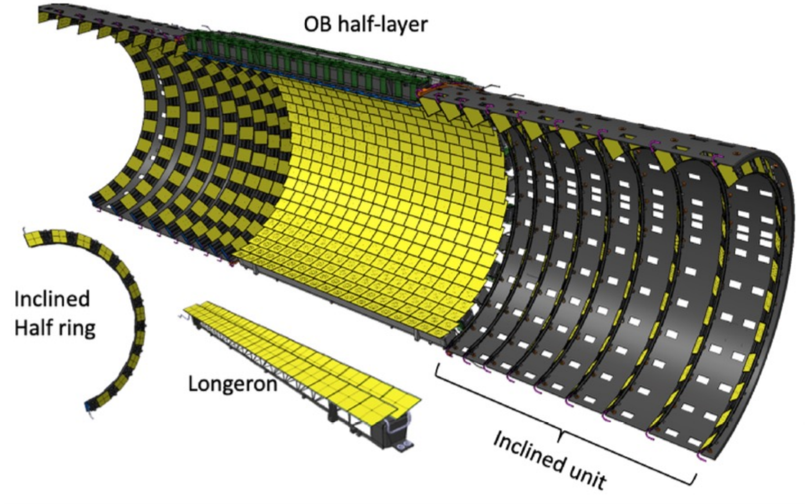

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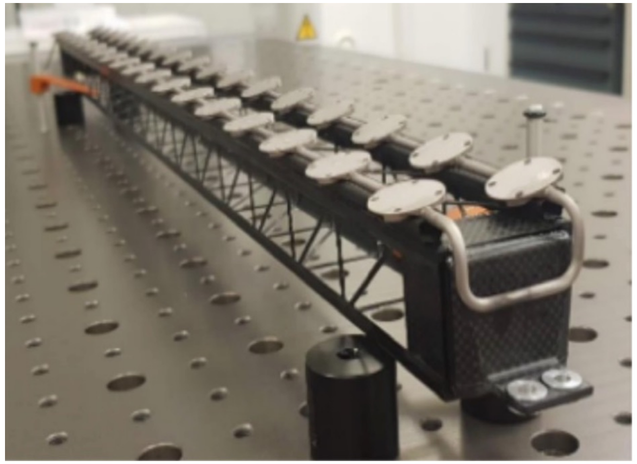
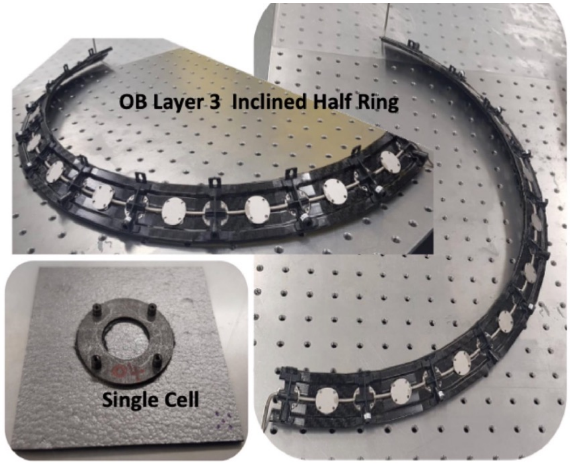
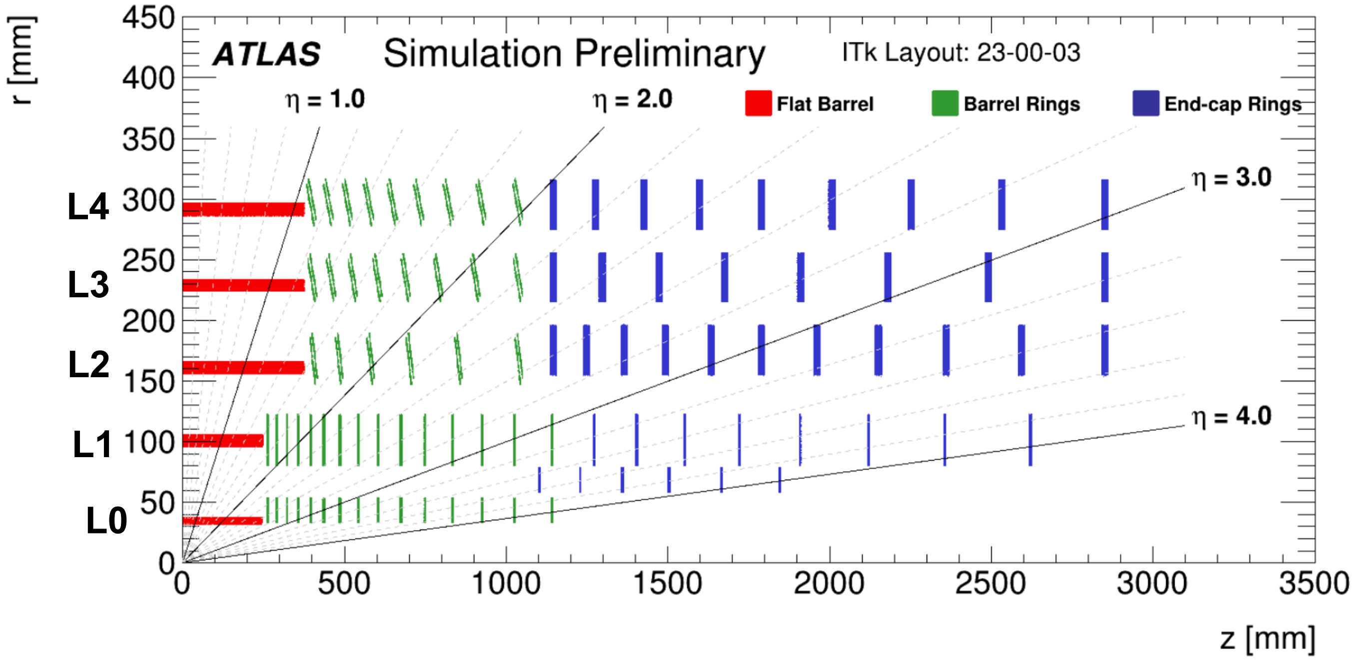


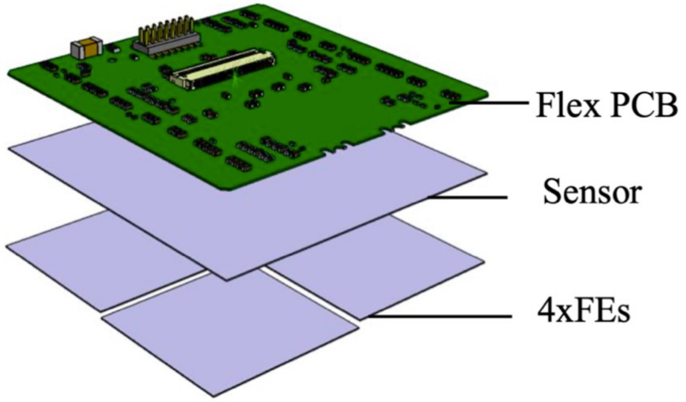


Modules production

Modules in Pixel-ITk	
L0 – Barrel, triplets	96
L0 – Rings, triplets	300
Total triplets	**396**
L1, quads	1160
L2-L4, quads	6816
Total quad	**7976**
Total modules	**8372**



- L1, L2, L3 and L4: **quad modules**
- **~8k** installed **quad modules**, out of **~8.4k** modules in total: **95% quads modules**
- Module production yield: **~1.4** ⟹ need to produce **~11.8k** modules in total
- Huge assembly load, shared among **14 assembly institutes** (USA, UK, **France**, Germany, Italy, CERN, Japan) ⇒ important effort in ATLAS to **develop common procedures** as much as possible

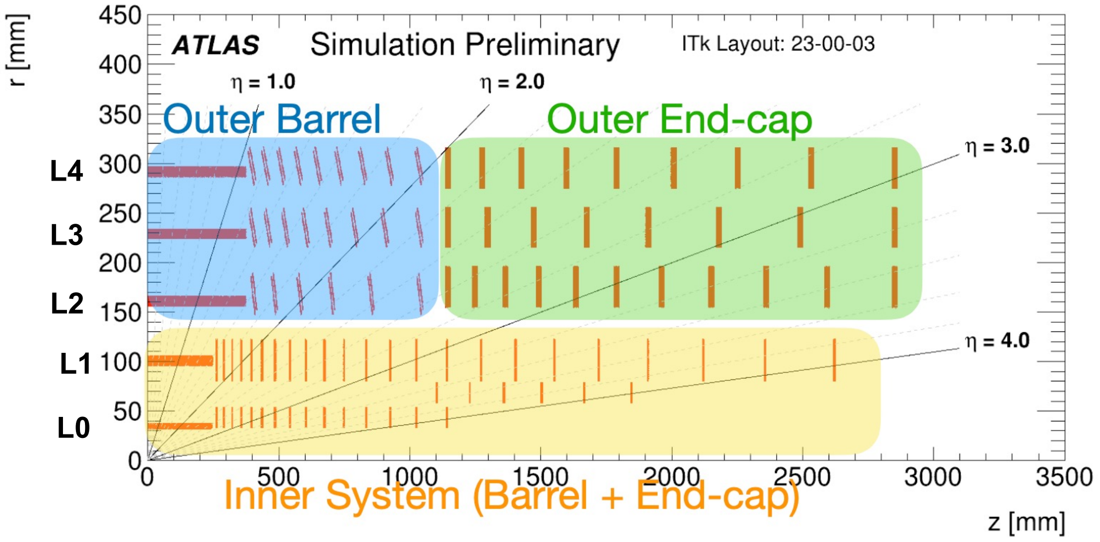


Paris cluster deliverables

- We are committed (MoU) in building 33% of the ITk-Pixel outer barrel (OB) quad modules

- Paris cluster share ⇒ **1.5k good modules**
- Obviously, we need to consider the module production and loading/integration yield (∽1.4)

➢ **Paris cluster deliverable** including yield: **∽2100 modules**



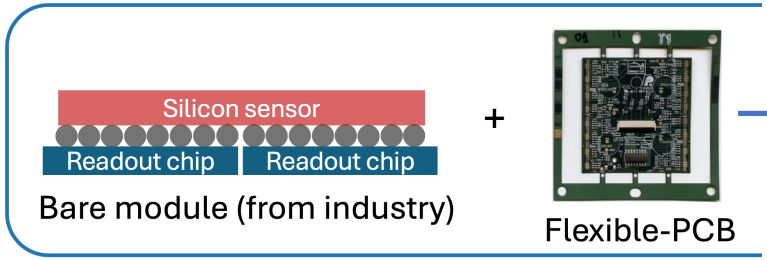
- In absolute numbers
  - We are building the **largest share of modules in OB**
  - Together with Japan (though they externalise), the **largest share of modules in ITk-Pixel**

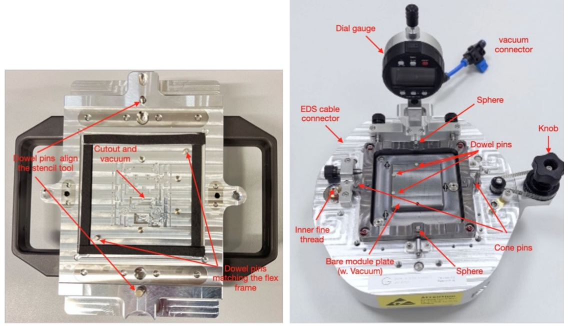
- Production is expected to start after this summer and is scheduled to last 2 years
- Considering 40 weeks per year (including holidays and downtime problems) ➔ 80 weeks to build 2100 modules ➔ Need to be producing **27 modules / week !**

Modules production in a nutshell

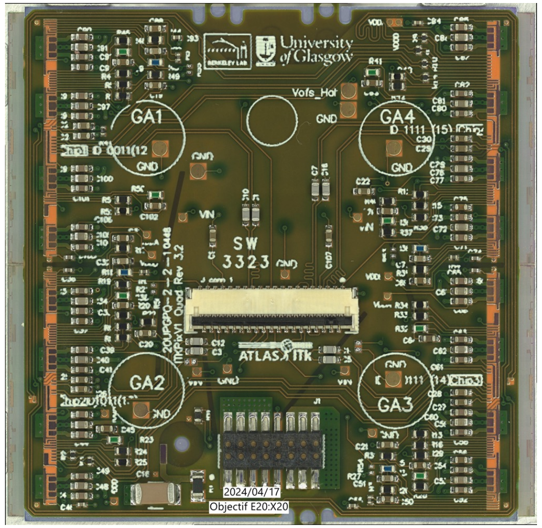
- Module **pre-production** is currently underway – produce ~5% of total modules to test assembly, testing, and loading procedures

Module assembly:

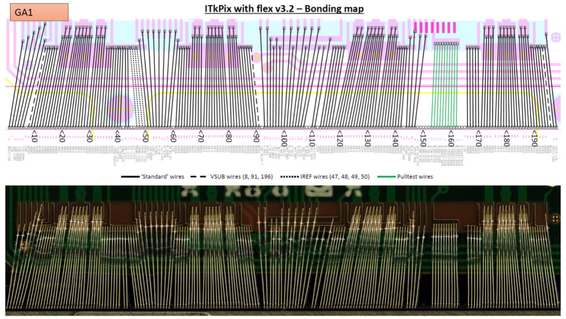


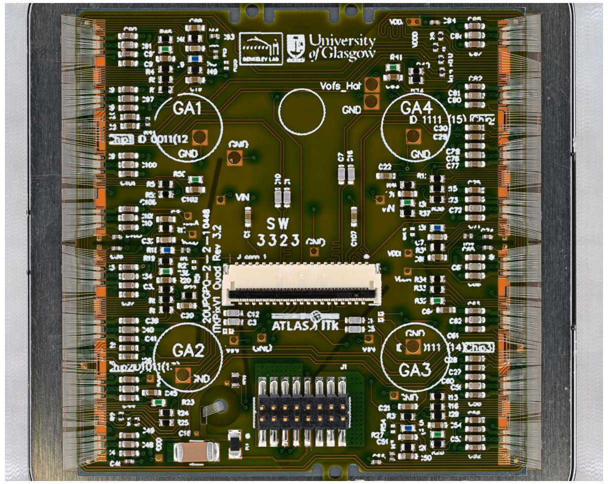


- Use assembly jigs and stencil method to glue bare module and flex PCB

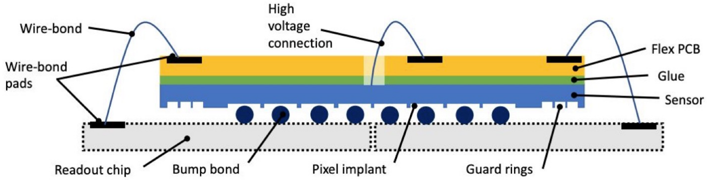


- Then wire bond





- ~700 wire bonds per quad module
- Delicate operation depending a lot on cleanness of the bondable surfaces
- When/If everything works smoothly, this is about 1-2 hours for a fully automated WB machine



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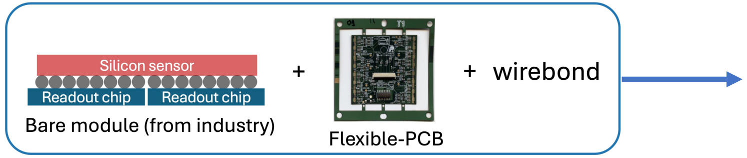
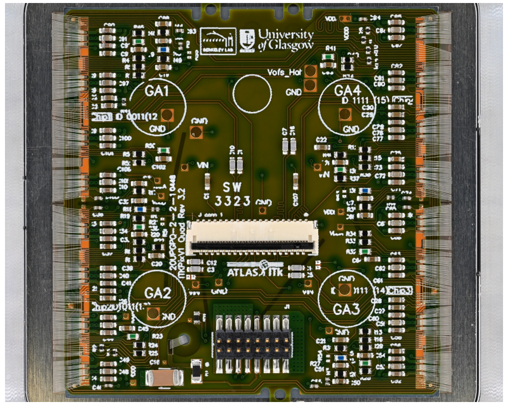




- After assembly, modules undergo rigorous electrical Quality Control (QC) testing procedure, with several stages:

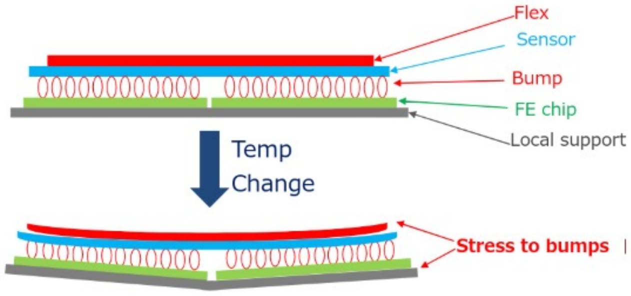
Assembly → **Initial characterization** → Parylene coating → **Post-parylene characterization** → Wirebond protection → Stability (~10 hours) → Thermal cycling -45°C to 40°C (x10), -55°C to 60°C (x1) → **Final characterization** → To loading site

François Wicek poster (Parylene coating, Post-parylene characterization)

Dmytro Hohov poster (Stability, Thermal cycling, Final characterization)

Characterization: All electrical tests at 20°C and -15°C
All other stages: Minimal set of electrical tests

- Testing procedure includes several tests checking chip powering, sensor IV, and performance of **individual pixels**



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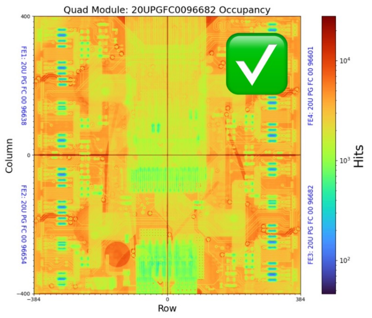

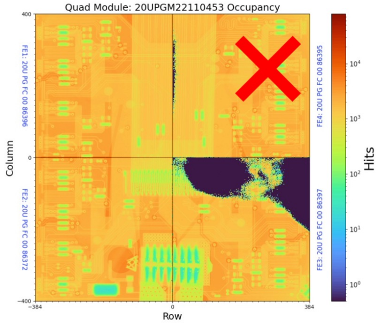

- E.g: for a test to be successful, we require fewer than 0.4% of disconnected bumps after thermal cycling

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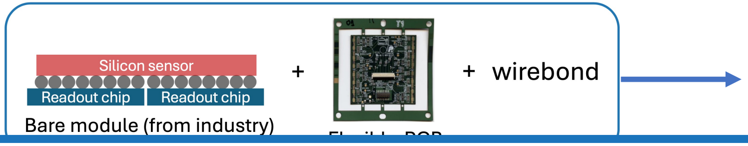

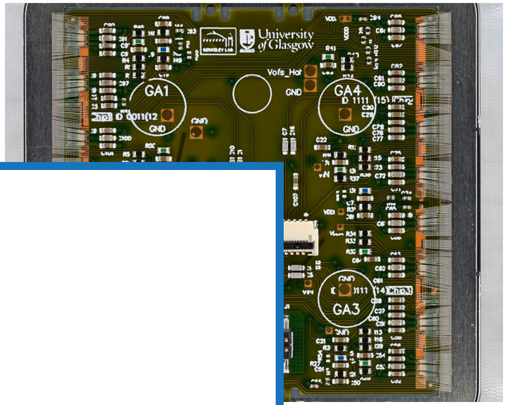

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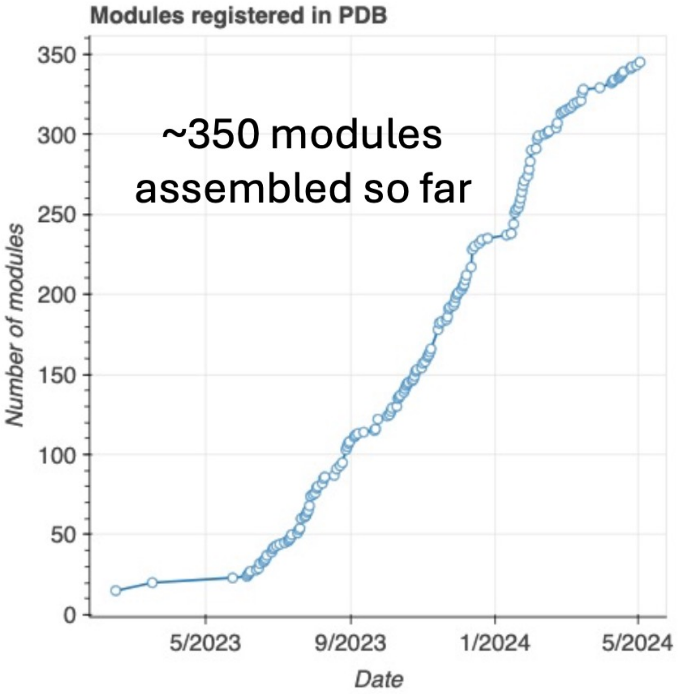
Pre-production progress:

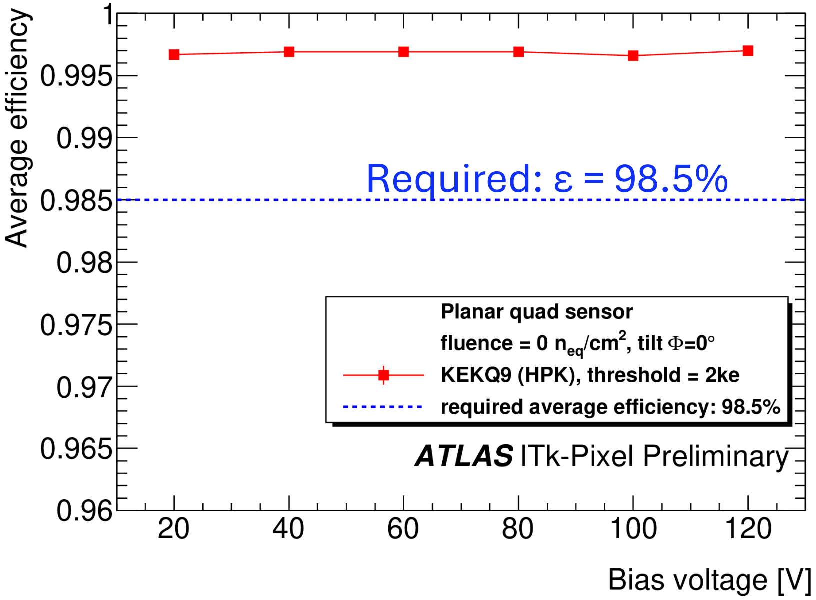


~350 modules assembled so far

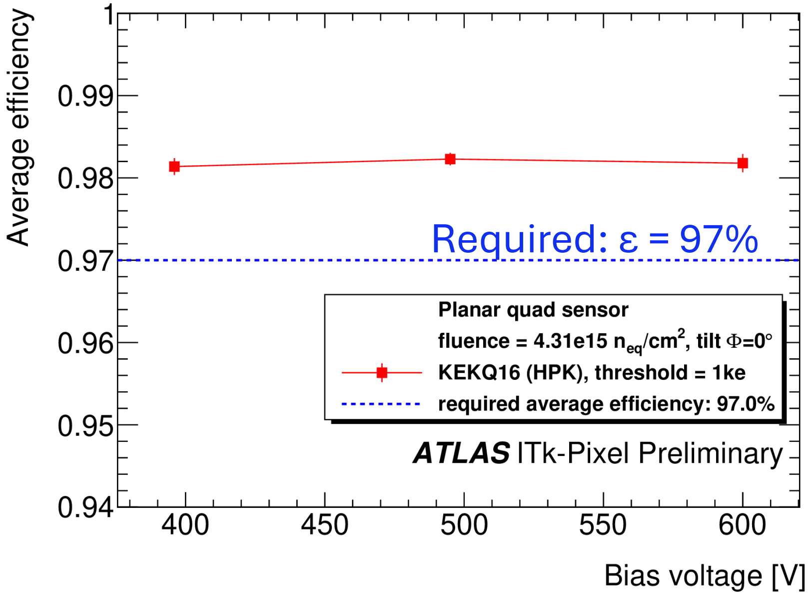
- Module production is a **global** effort – modules are assembled/tested at 25 different sites and loaded at 9 sites
- Huge book-keeping effort (need to keep track of ~11.4k modules and testing results!) → using common testing tools and database

Test beam results

- Continuous test beam campaigns to test ITk-Pixel modules irradiated with the fluences expected at HL-LHC
- Here is an example from a quad module that has been irradiated up to 4 • 10^{15} n/cm^2
- Module tested September 2023 test-beam campaign at CERN SPS



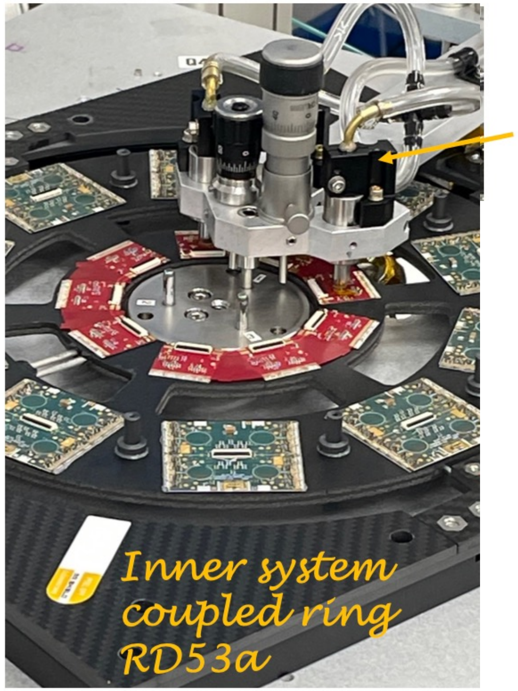
Unirradiated module



Irradiated module

- Both irradiated and unirradiated modules meet the efficiency requirements

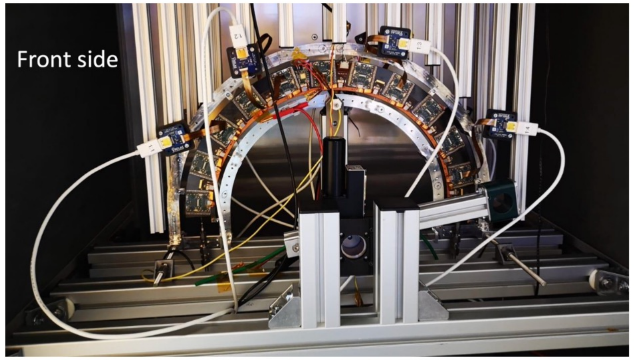
Loaded supports and demonstrators



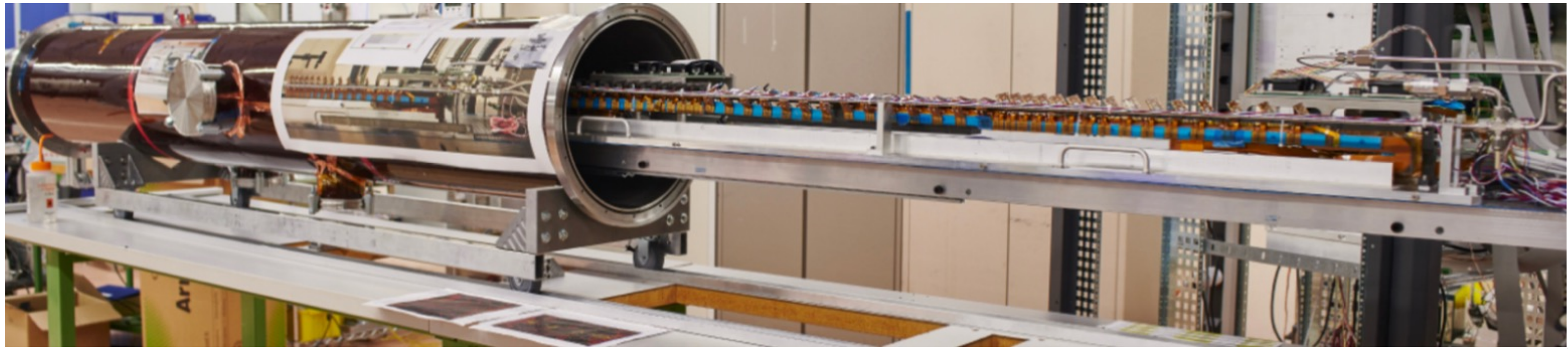
Tools developed
for precision placing

- Moving from building individual modules to loading local support structures: critical test of **loading procedure, cooling, services, and readout**
- Various loaded-local supports have been built with modules using prototype version of ITkPix chip
- ➢ Valuable lessons in understanding how to overcome challenges with operating larger detector
- ➢ Next step: test similar structures with pre-production modules

Outer end-cap ring:

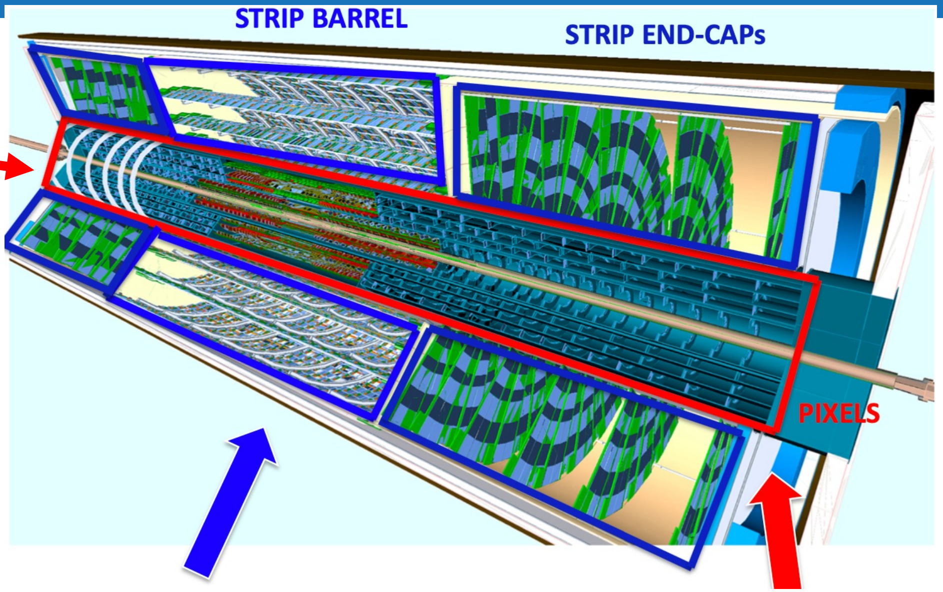


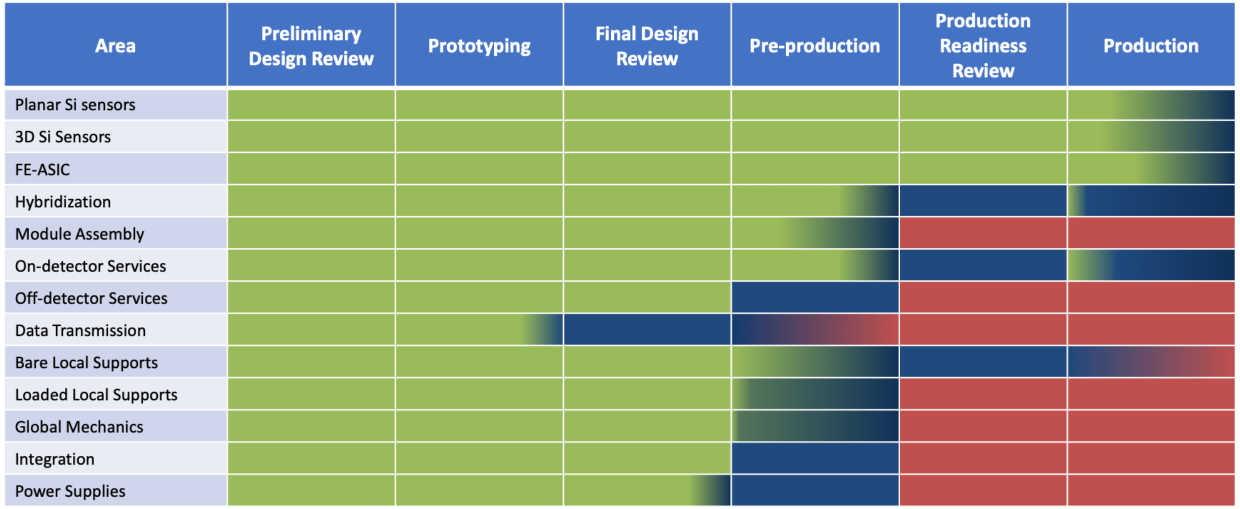
Demonstrators development for both endcap and outer barrel



Summary

- ATLAS is building a **new full silicon tracker tracker**, ITk-Pixel, to face the harsh conditions of HL-LHC
  - Extended in η; Radiation hard
  - Low material budget; Fine granularity
  - Fast readout
  - ➢ Performance: same or better comparted to current inner detector





Area	Preliminary Design Review	Prototyping	Final Design Review	Pre-production	Production Readiness Review	Production
Planar Si sensors	🟩	🟩	🟩	🟩	🟩	🟩→🟦
3D Si Sensors	🟩	🟩	🟩	🟩	🟩	🟩→🟦
FE-ASIC	🟩	🟩	🟩	🟩	🟩	🟩→🟦
Hybridization	🟩	🟩	🟩	🟩→🟦	🟦	🟦
Module Assembly	🟩	🟩	🟩	🟩→🟦	🟥	🟥
On-detector Services	🟩	🟩	🟩	🟩→🟦	🟦	🟩→🟦
Off-detector Services	🟩	🟩	🟩	🟦	🟥	🟥
Data Transmission	🟩	🟩→🟦	🟦	🟦→🟥	🟥	🟥
Bare Local Supports	🟩	🟩	🟩	🟩→🟦	🟦	🟦→🟥
Loaded Local Supports	🟩	🟩	🟩	🟩→🟦	🟥	🟥
Global Mechanics	🟩	🟩	🟩	🟩→🟦	🟥	🟥
Integration	🟩	🟩	🟩	🟦	🟥	🟥
Power Supplies	🟩	🟩	🟩→🟦	🟦	🟥	🟥

🟩 Complete 🟦 Ongoing 🟥 Upcoming

- Project is entering the final production stage
- Concerning modules, production should start after this summer and is expected to last 2 years
- ITk-Pixel ready for insertion in 2027: very challenging schedule
- HL-LHC expected to start in 2029

Bonus slide

ITk-Pixel *and* R&D

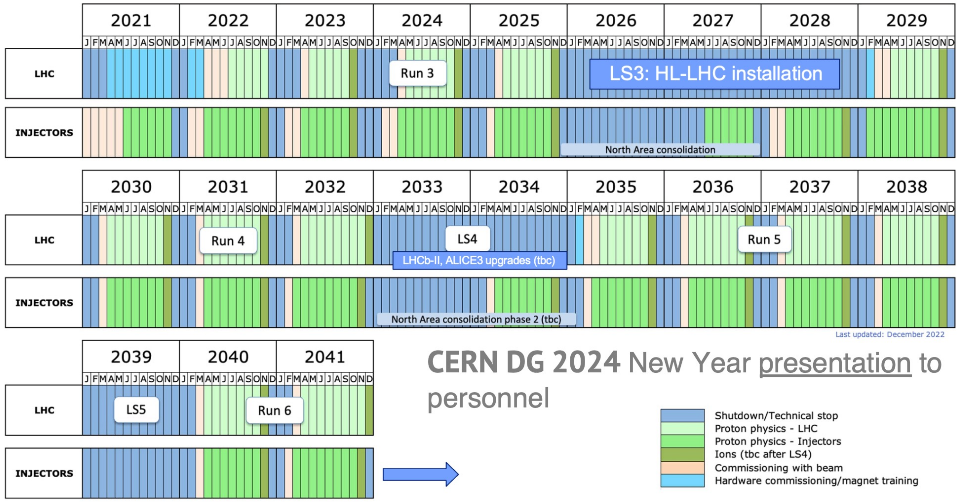
- Described also in the TDR, partial replacement of ITk-Pixel detector is foreseen at ~half lifetime (1500-2000 fb^{-1})
  - The **replacement** involves the areas **more exposed** to **large fluences** and **doses**

- It is the full inner system that is planned to be replaced after about half lifetime (**LS4**? **LS5?**)
  - Similar requirements as for the planned ITk, but **improvements in terms of pixel size, material budget and timing will be attempted**
  - **Active R&D on this topic:** Monolithic sensors, CMOS 28 nm techno for FE (Moshine's presentation)**,** advanced interconnection (Giovanni's presentation) **….**

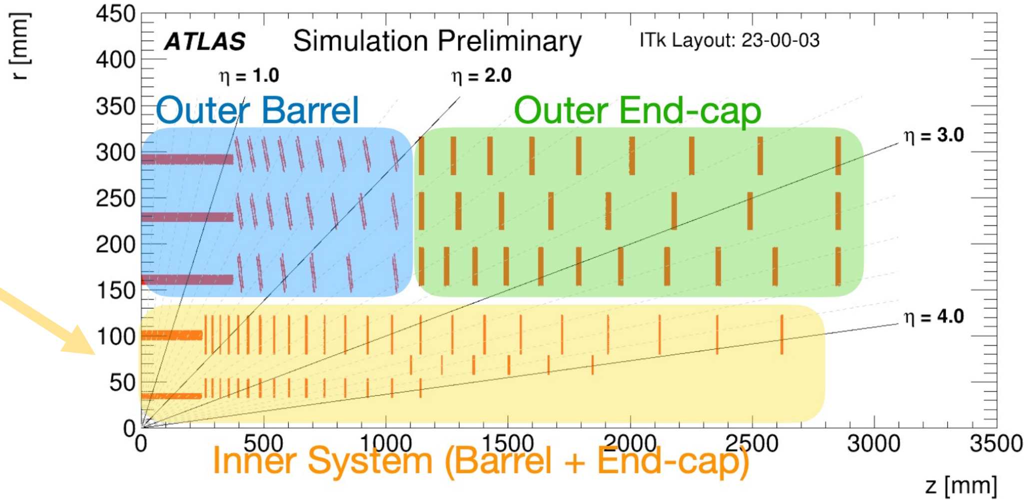
- Similar replacement is planned for CMS tracker as well

- This upgrade will be a preliminary step towards future hadrons colliders

Indicative timeline out to 2041 for (HL)-LHC Schedule



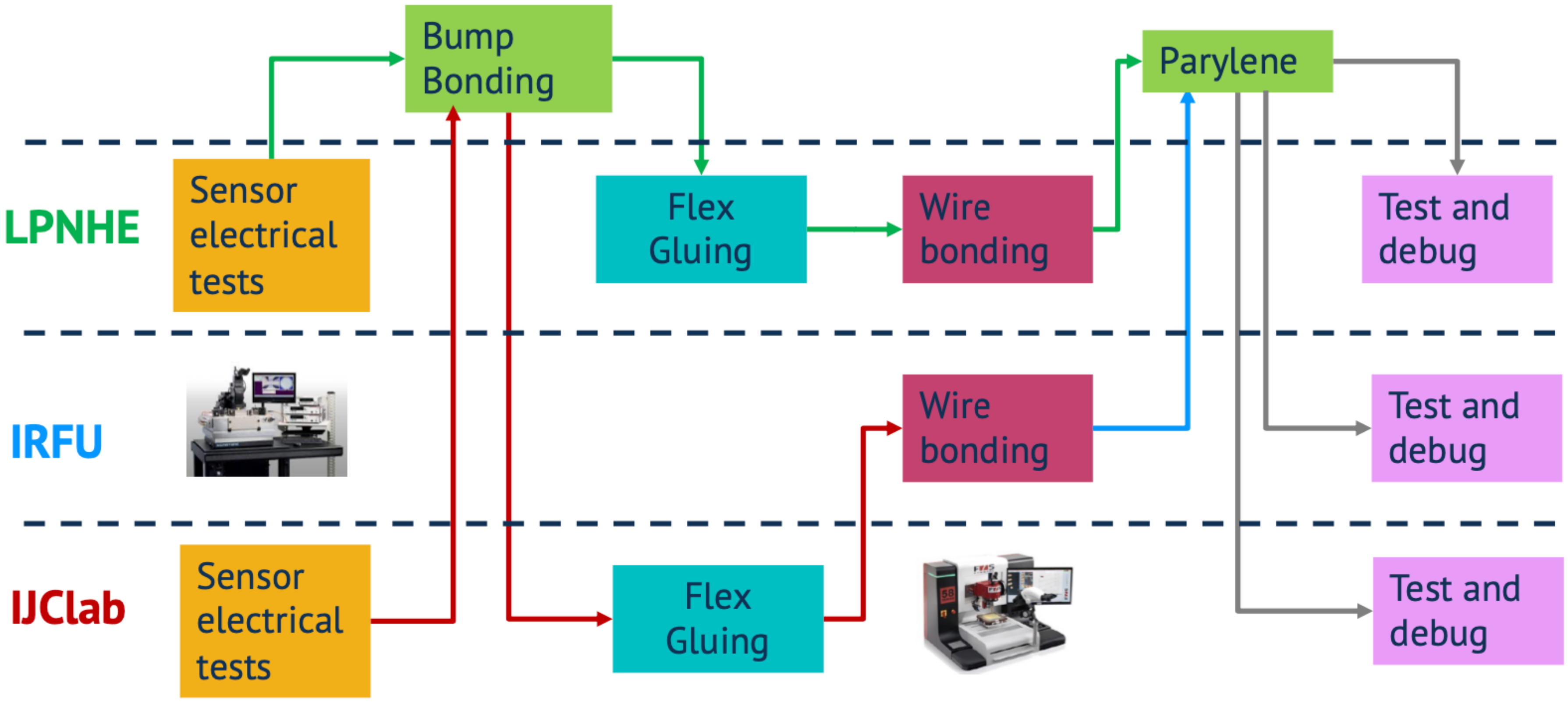
CERN DG 2024 New Year presentation to personnel



Backup

Module assembly

Paris cluster



Bump Bonding

Parylene

LPNHE

Sensor electrical tests

Flex Gluing

Wire bonding

Test and debug

IRFU

Wire bonding

Test and debug

IJClab

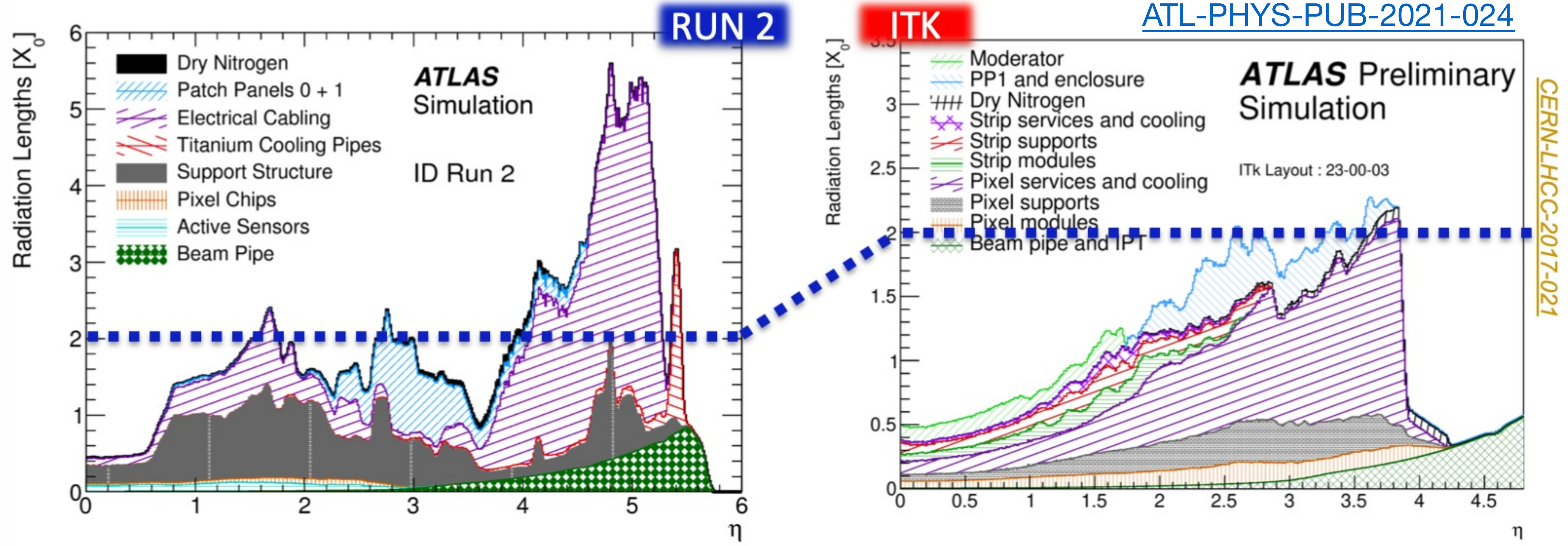
Sensor electrical tests

Flex Gluing

Test and debug

+ metrology at various stages by all 3 labs

Material budget



ATL-PHYS-PUB-2021-024

CERN-LHCC-2017-021

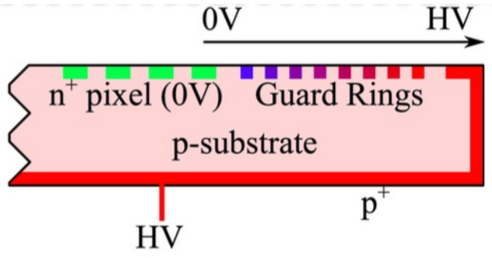
- **Reduced material** with respect to current inner tacker
  - **Sophisticated** CO2 **cooling system**
  - Ultra light **carbon structures** for mechanical mounting
  - **Innovative serial powering** for the ITk-Pixel detector: less cabling/services

Sensors

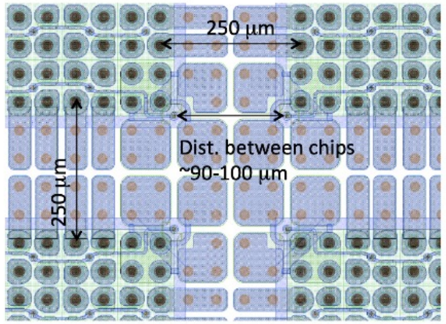
Extensive R&D has been done to create silicon sensors that can withstand the intense radiation of the HL-LHC

Planar sensors:

- Radiation hard to ≈ 4 x 10^{15} n/cm^2 (@ 4000 fb^{-1})
- n-in-p technology
- Bias voltages up to 600 V
- Vendors: HPK, Micron, FBK

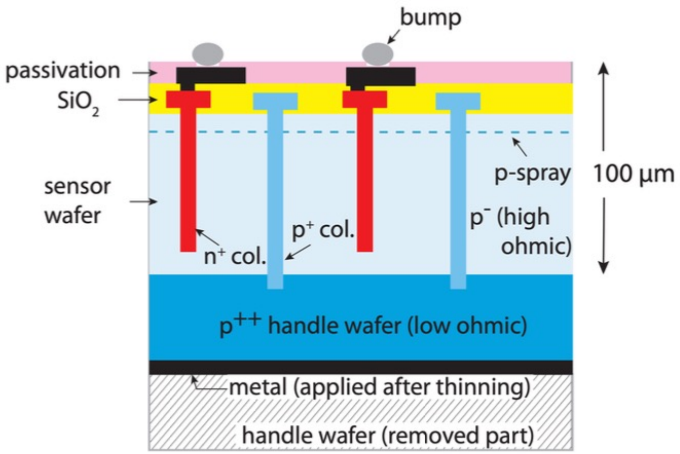


Pixel size varies in inter-chip region:

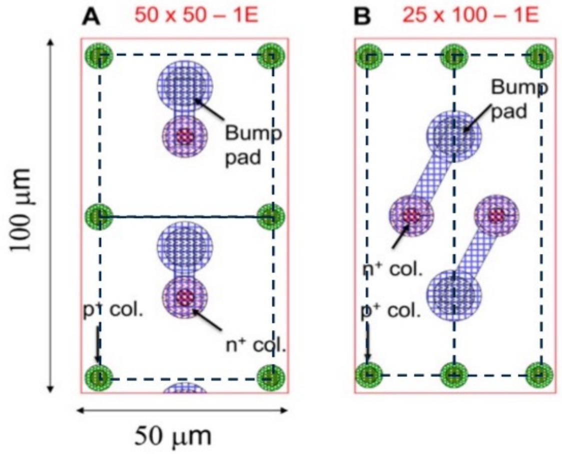


3D sensors:

- Radiation hard to ≈ 2 x 10^{16} n/cm^2 (@ 2000 fb^{-1})
- Used only in innermost ITk layer (L0)
- Technology demonstrated in ATLAS IBL
- Bias voltage up to 250 V
- Vendors: SINTEF, FBK



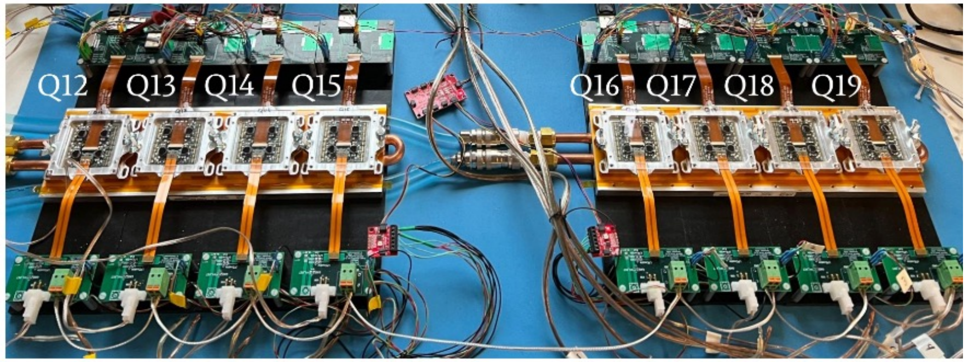
Pixel geometry:

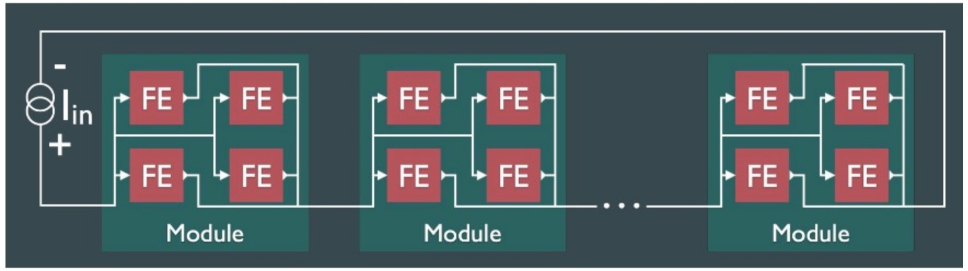


Serial powering

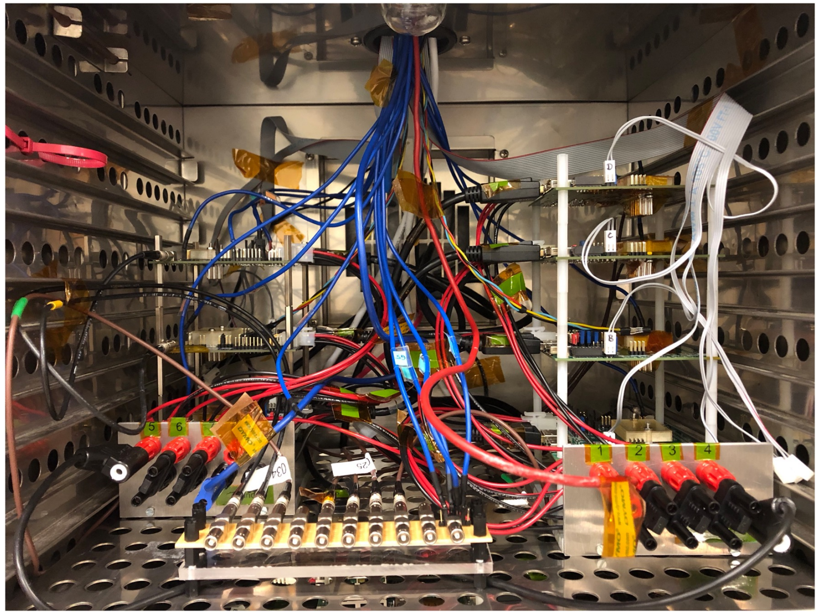
ATL-ITK-PUB-2022-002

- In order to minimize material budget, a **serial powering scheme** will be utilized ITkPix chips are equipped with Shunt Low Drop Output (SLDO) power regulators
  - When powered with constant current, SLDO's dynamically adjust shunt current to have constant local voltages on chip
  - Modules will be powered in series with constant current in serial powering chain, chips on a module will be powered in parallel → improve reliability of chain in case of chips breaking





- Serial power chain tests with real modules
  - On irradiated and non-irradiated modules
  - No damaging effect from serial powering

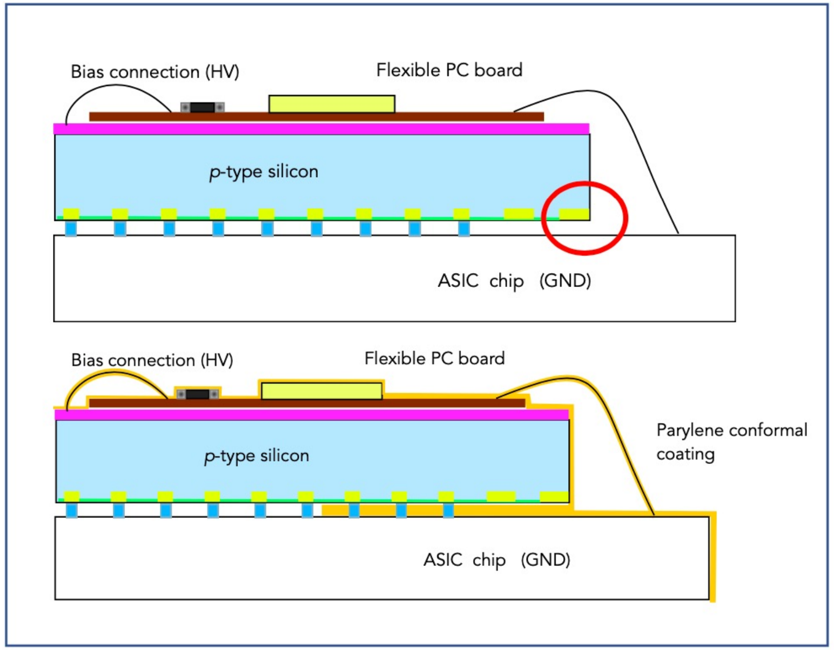


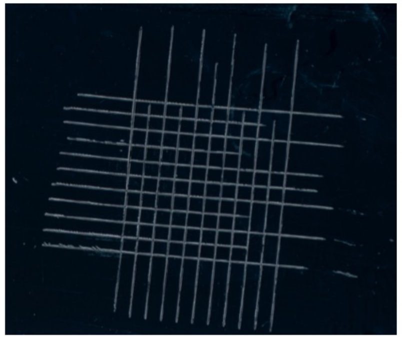
Technology challenges

Saverio D'Auria, ICHEP2022

Technology challenges

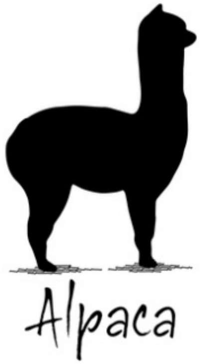
- Large area ASIC, 20 x 20 mm^2 , large area sensor 40 x 40 mm^2
- High density, low pitch bump bonding 50 µm x 50 µm
- Radiation hardness
- Large temperature range: operating at [-25 to -10°C] to limit radiation damage effects, heat to +20°C during maintenance
  - Avoid delamination of bumps: thin metal flex circuit
- Low-mass services, to reduce X_0
- Serial powering (see talk by F. Hinterkeuser, this session)
- Large Bias voltage across thin air gap (10µm) →conformal coating
  - 54 quad modules (RD53a) coated with parylene N
  - Excellent reproducibility and adhesion
  - Both commercial and in-house lab coating
  - Tested after irradiation and thermal cycles



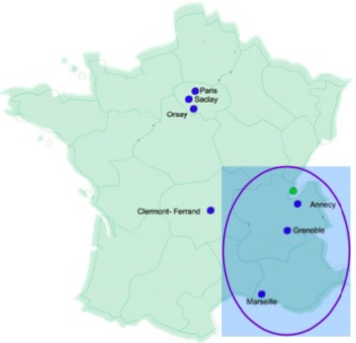


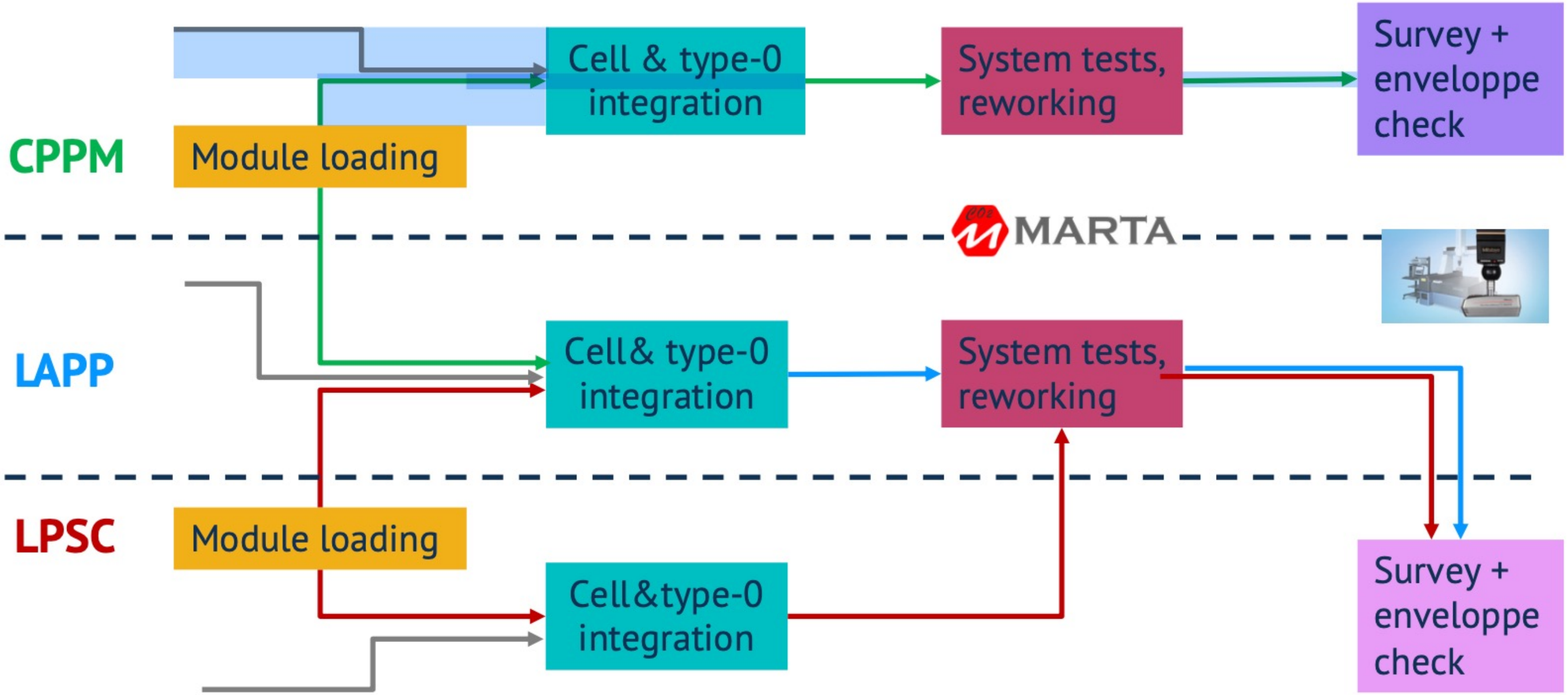
Adhesion tests of Parylene on Silicon after 1 10^{16} neutron eq. cm^{-2} (nucl. reactor irradiation)

Loading & integration



Alpaca cluster





CPPM

Module loading

Cell & type-0 integration

System tests, reworking

Survey + enveloppe check

MARTA

LAPP

Cell& type-0 integration

System tests, reworking

LPSC

Module loading

Cell&type-0 integration

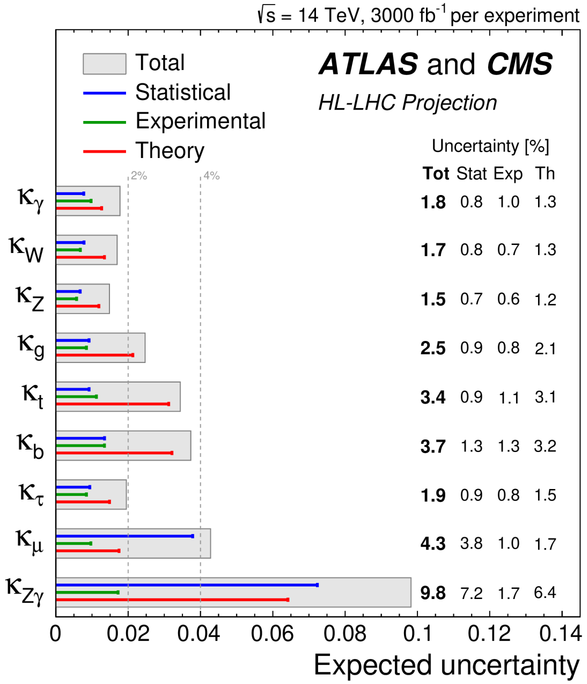
Survey + enveloppe check

HL-LHC rich physics programme

- Estimated integrated luminosity of HL-LHC: **3000-4000 fb^{-1}**
- Highlights of HL-LHC physics programme
  - High precision on **Higgs boson properties**: couplings, mass, width, access to self coupling
  - Increase precision in **EW sector measurements**: vector boson scattering, triboson couplings, rare processes
  - **Search for BSM physics**: SUSY, dark matter, exotic resonances, long-lived particles, etc

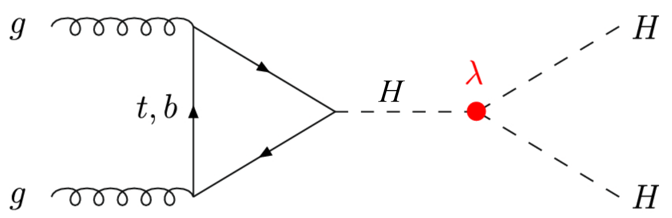
- Huge statistics: **stringent test of our physics models**
- **Indirect search of new physics** through deviations from the theory (differential measurements, EFTs, etc)

Higgs Physics at the HL-LHC, CERN-LPCC-2018-04
Snowmass, ATLAS-PHYS-PUB-2022-018

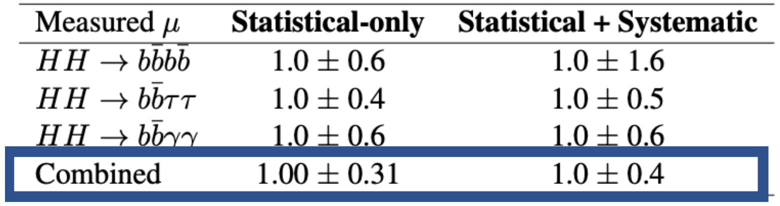


Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4



SM di-Higgs production in ATLAS @ 3000 fb^{-1}

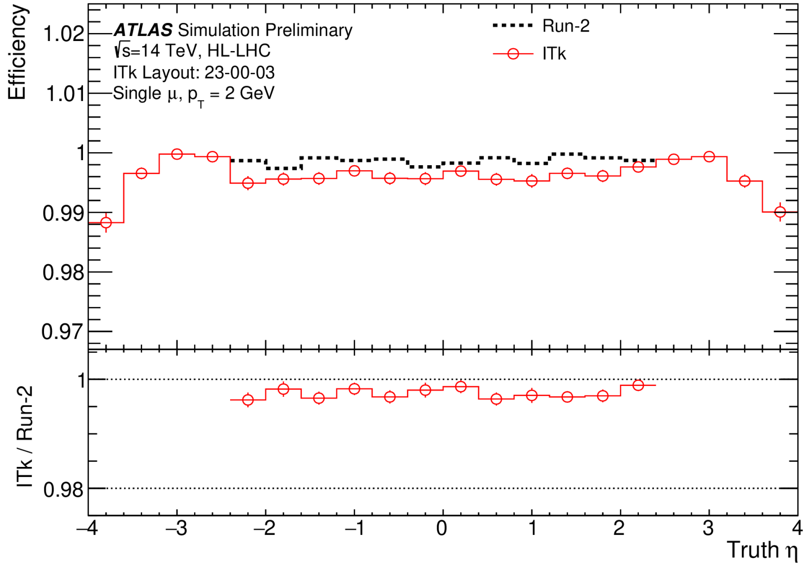


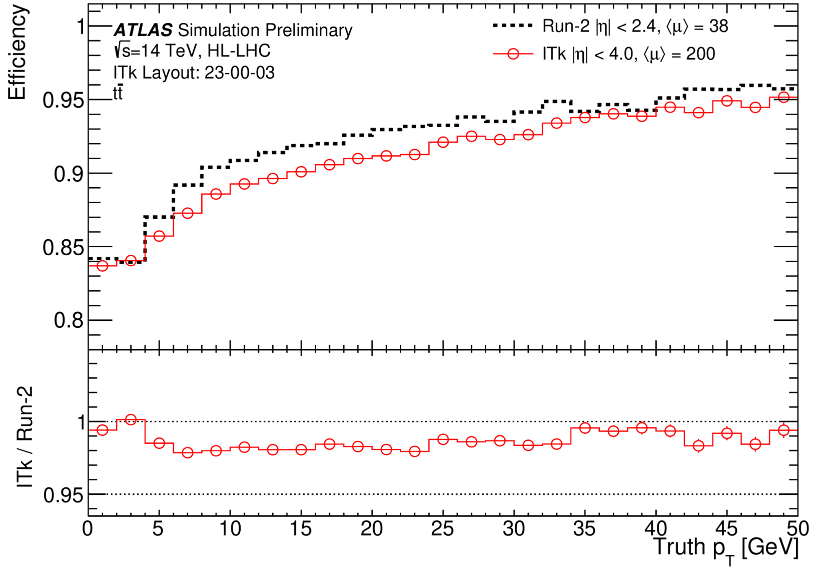
Measured μ	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.0 ± 0.6	1.0 ± 1.6
$HH \to b\bar{b}\tau\tau$	1.0 ± 0.4	1.0 ± 0.5
$HH \to b\bar{b}\gamma\gamma$	1.0 ± 0.6	1.0 ± 0.6
Combined	1.00 ± 0.31	1.0 ± 0.4

- Higgs boson couplings uncertainty < ~4%
- Di-higgs production
  - 40% signal strength uncertainty
  - 4σ significance after ATLAS & CMS combination at 3000 fb^{-1}

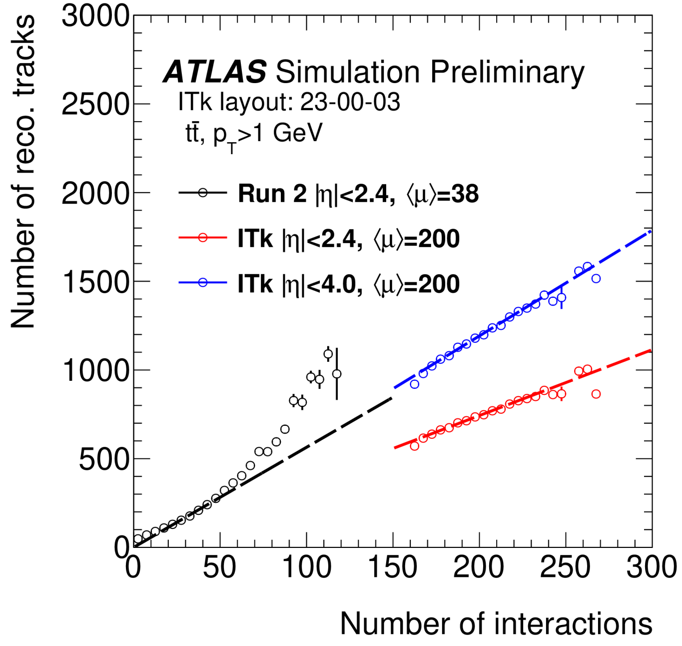
➢ LHC history teaches us that we often do better wrt the projections. *(We will most likely do better)*

ITk tracking reconstruction efficiency





- Need to have robust tracking reconstruction efficiency at x5 pileup wrt to Run2-3
  - Similar performance at the barrel region
  - Very high efficiency at the forward region!



- Number of reconstructed tracks exhibits a very linear behaviour wrt the number of interactions with the Itk: very low tracking fake rate in spite of <μ> = 200 environment

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