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

Dimitris Varouchas (IJCLab-Orsay, CNRS/IN2P3),

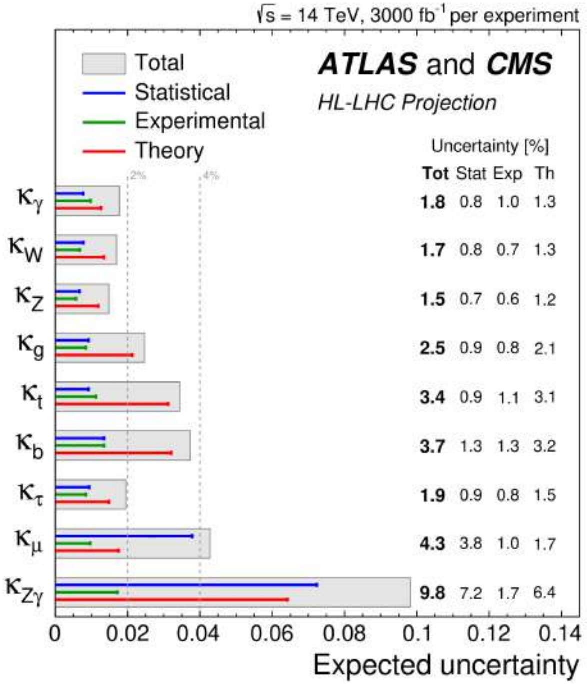
on behalf of the ATLAS-ITk collaboration

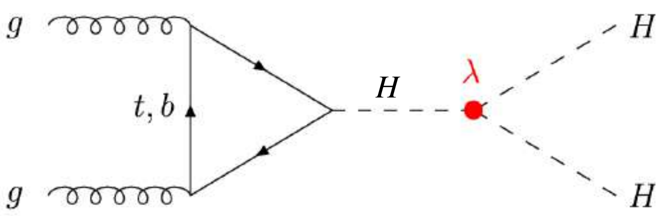
HL-LHC rich physics programme

- 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



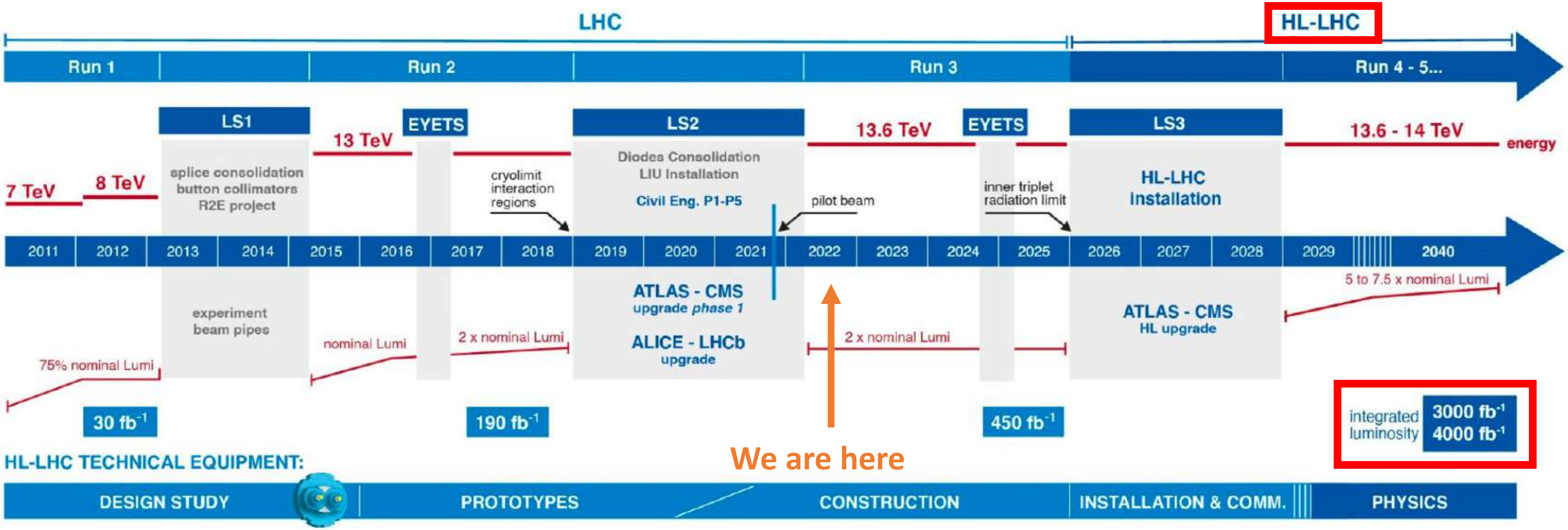


SM di-Higgs production in ATLAS @ 3000 fb^{-1}

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

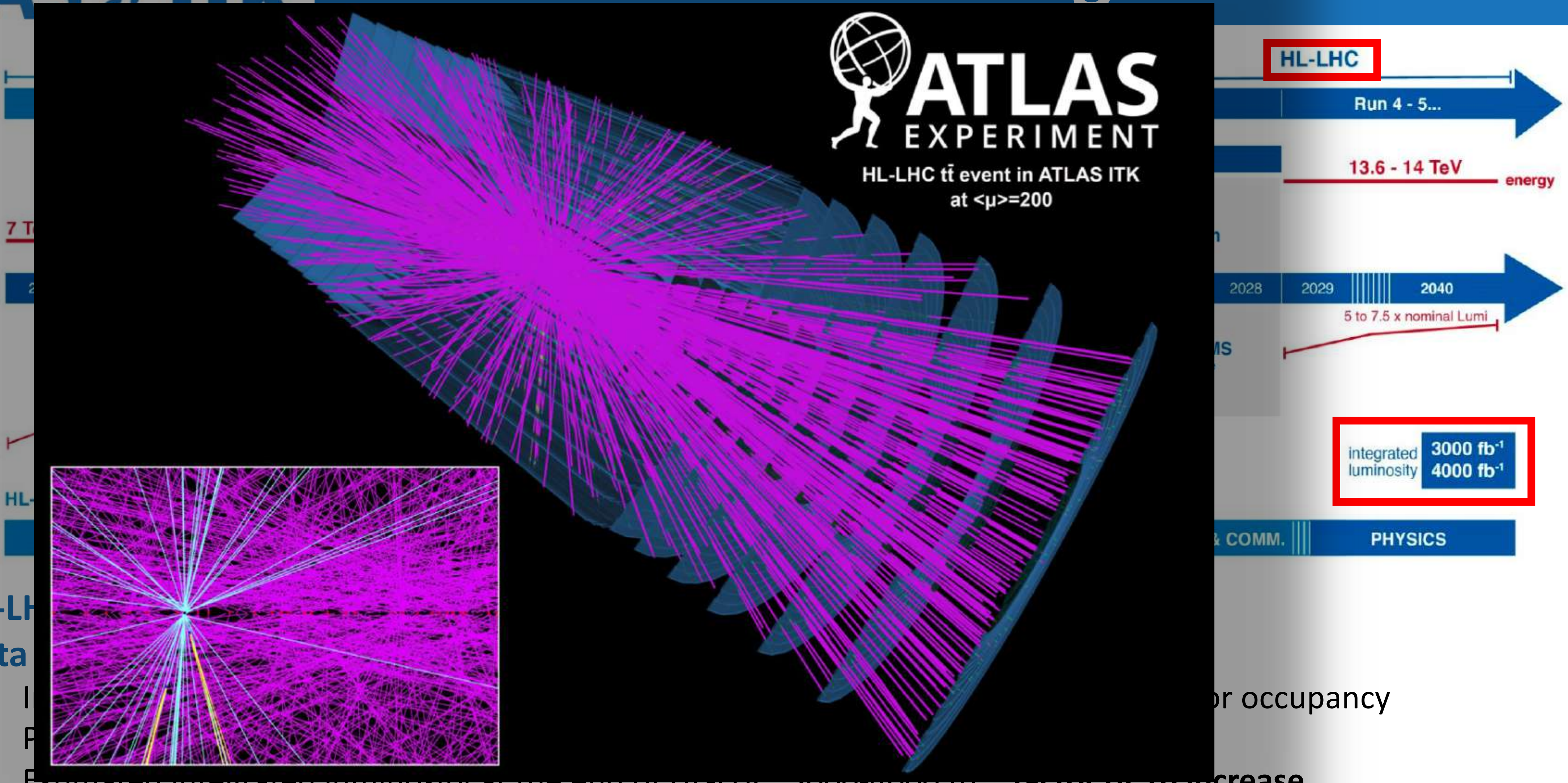
- Higgs boson couplings uncertainty < ~4%
- Di-higgs production
    - 40% signal strength uncertainty
    - 4σ significance after ATLAS & CMS combination at 3000 fb^{-1}
- ➢ LHC history teaches us that we often do better wrt the projections. *(We will most likely do better)*

LHC timeline including HL-LHC



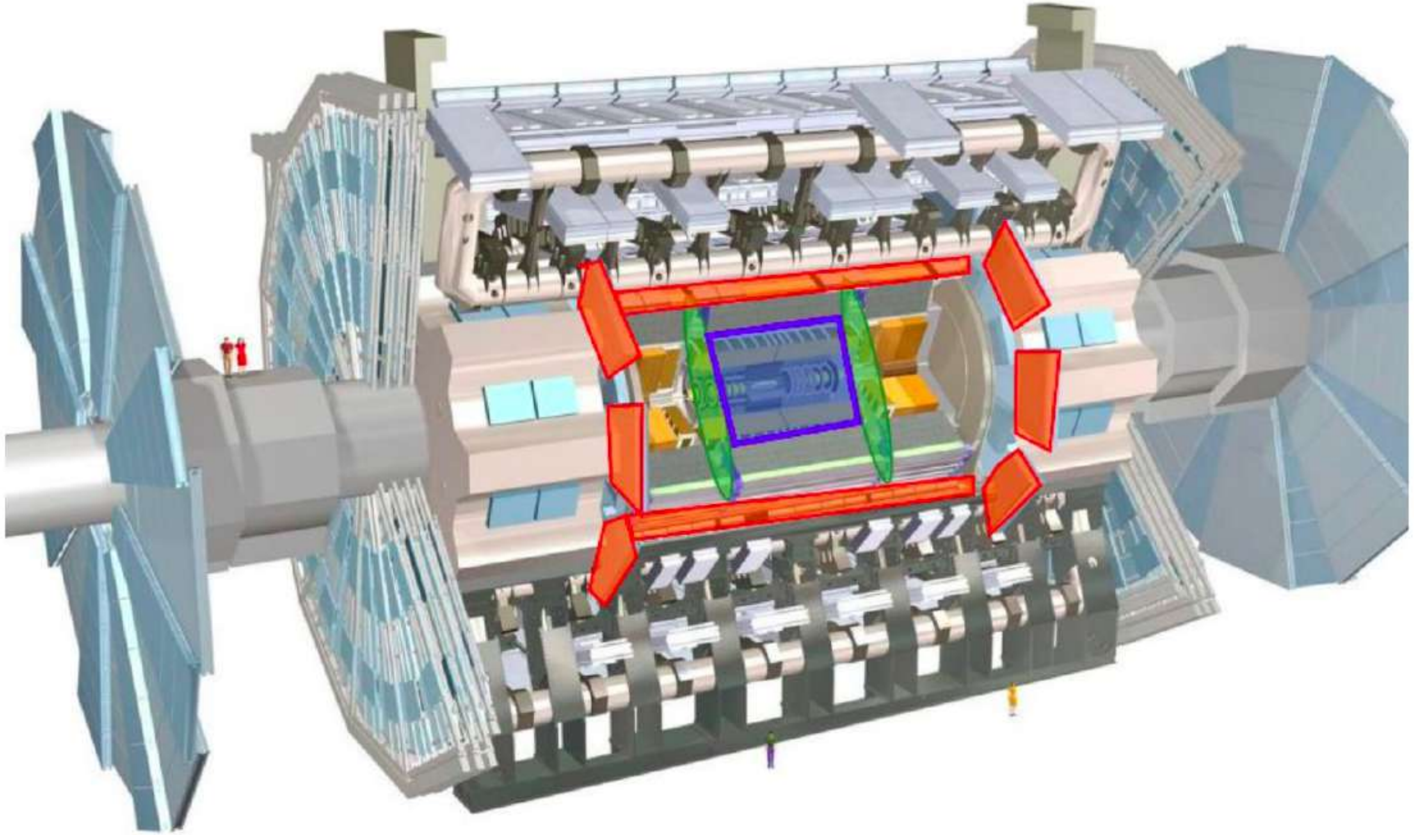
- **HL-LHC** phase currently scheduled to start in **2029**
- **Data taking foreseen up to ~2040**
  - Instantaneous luminosity to increase from 2 to ~7.5 × 10^{34} $cm^{-2}s^{-1}$: very high detector occupancy
  - Pile-up increase to ~200, from ~40 currently
  - Estimated integrated luminosity at the end of HL-LHC: 3000-4000 fb^{-1}, **factor of 10 increase**

LHC timeline including HL-LHC



- **HL-LH**
- **Data**
  - I … or occupancy
  - P
  - Estimated integrated luminosity at the end of HL-LHC: 3000-4000 fb^{-1}, **factor of 10 increase**
- **Major upgrades are planned for all the LHC experiments to cope with these very harsh conditions**

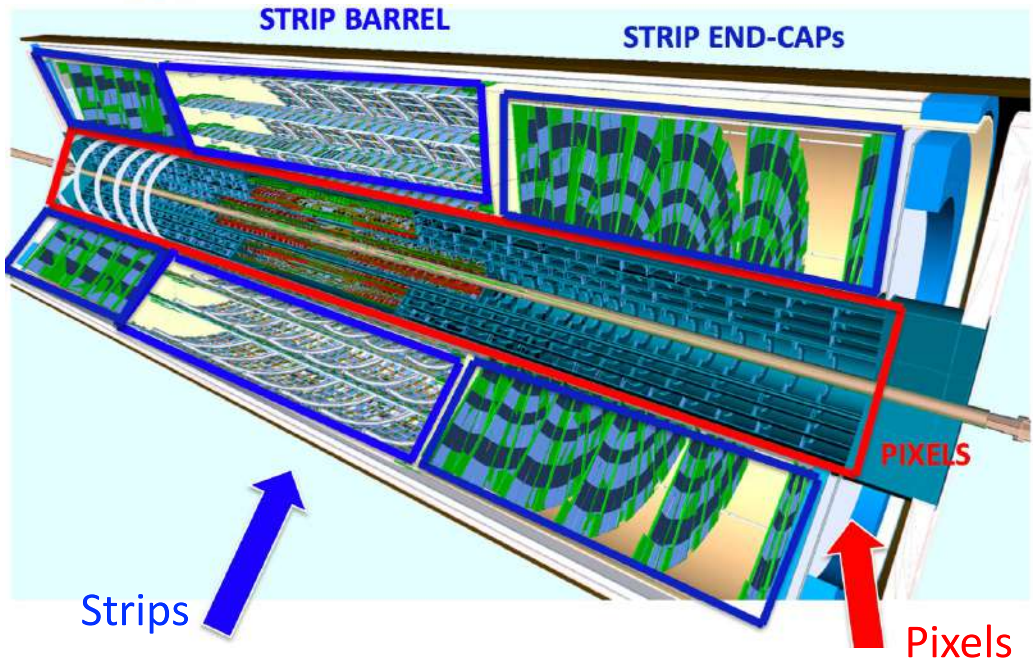
ATLAS upgrades for HL-LHC



- 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
  - 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)

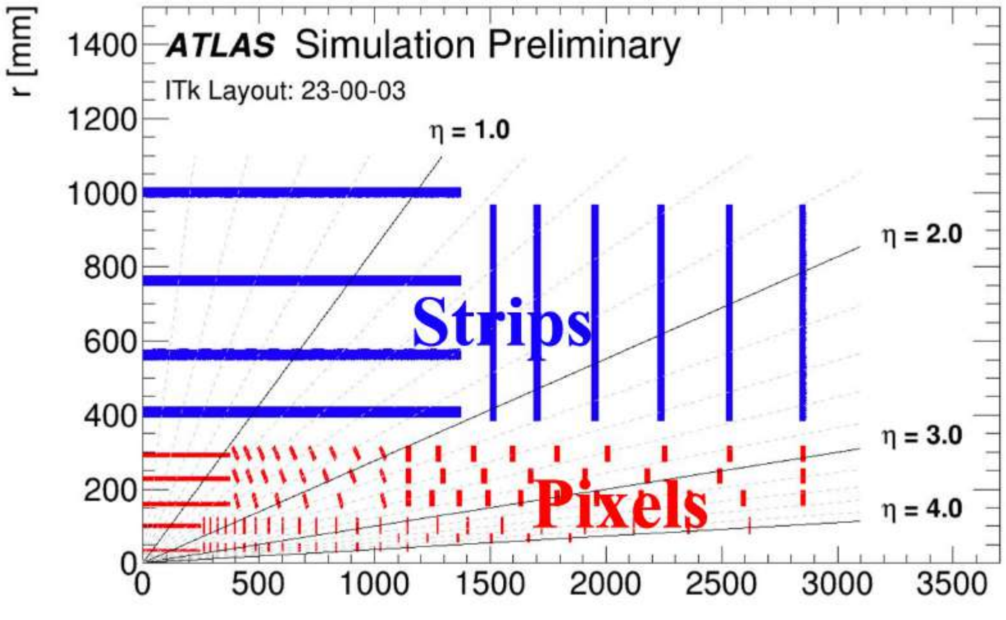


- **All-silicon inner tracker** with increased acceptance from $|\eta|<2.5$ (current ID) to $|\eta|<4$ (ITk)
  - Improved pile-up suppression in the forward region

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

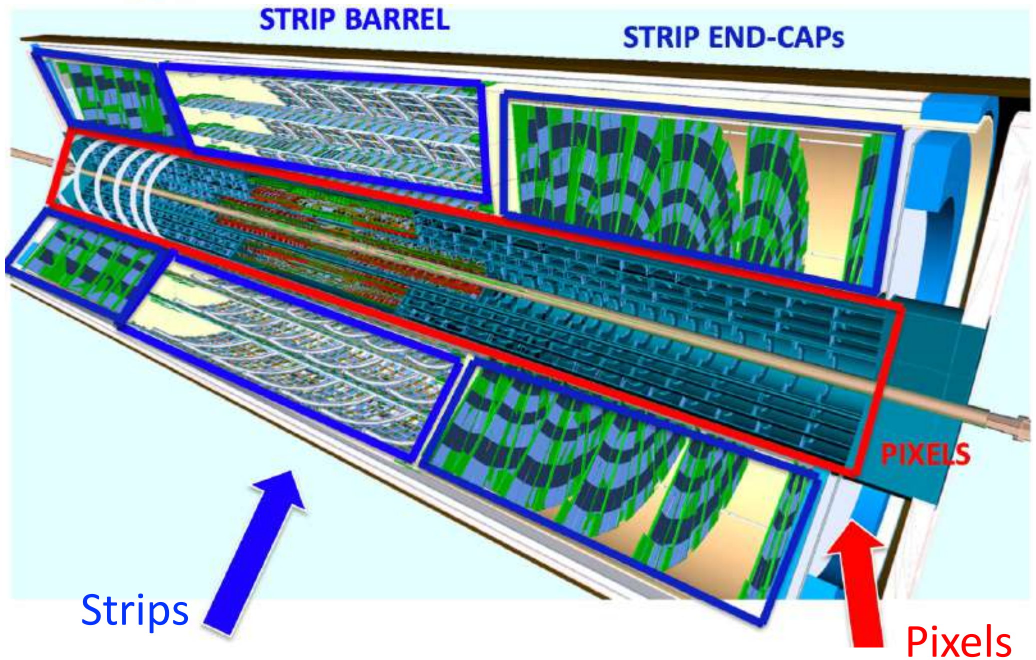
- **Inner pixel detector: 5 barrel layers + inclined and vertical rings**
  - ~13m^2 of active area
  - ~9000 modules
  - 5.1 Giga-pixels
  - Pixel pitch: 25x100 μm^2 for L0, 50x50 μm^2 elsewhere

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



ATL-PHYS-PUB-2021-024

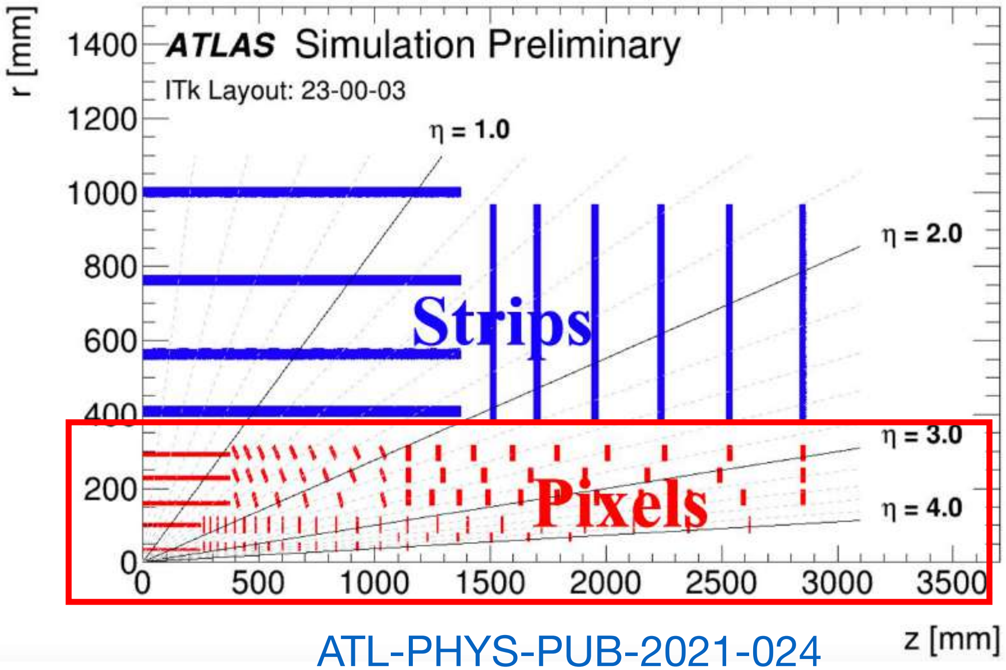
Inner Tracker upgrade (ITk)



Strips

Pixels

- **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



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

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  - ~13m² of active area
  - ~9000 modules
  - 5.1 Giga-pixels
  - Pixel pitch: 25x100 μm² for L0, 50x50 μm² elsewhere

Main focus today

Material budget

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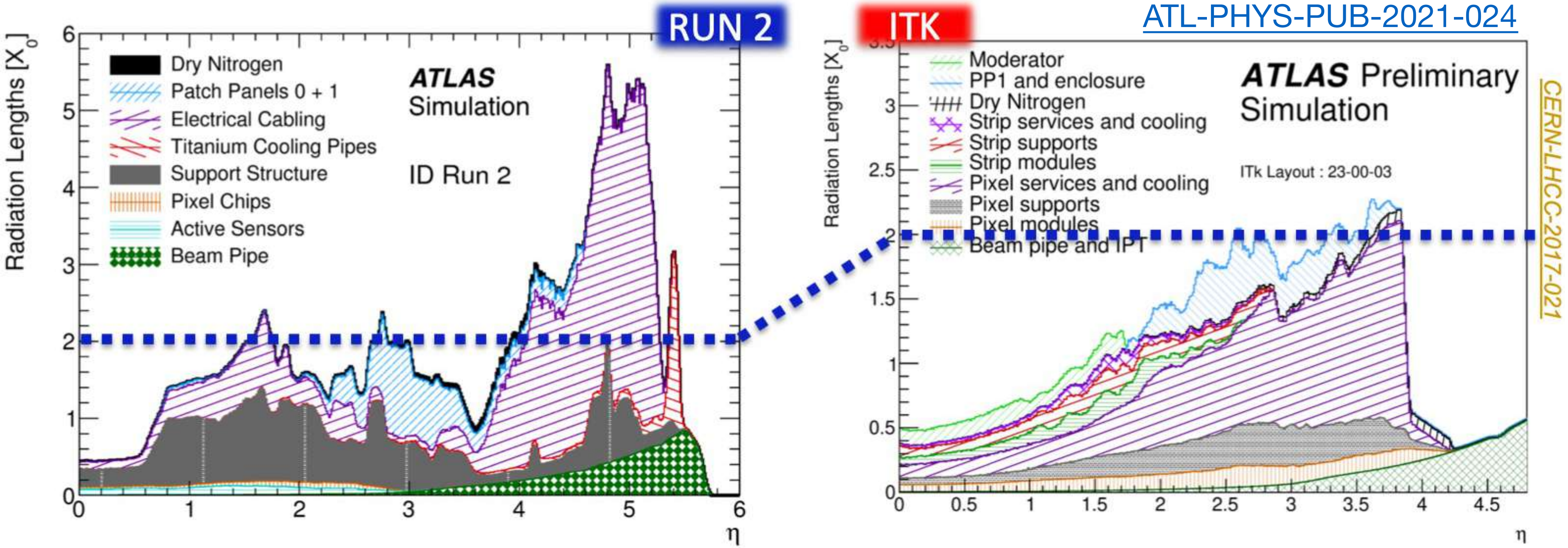
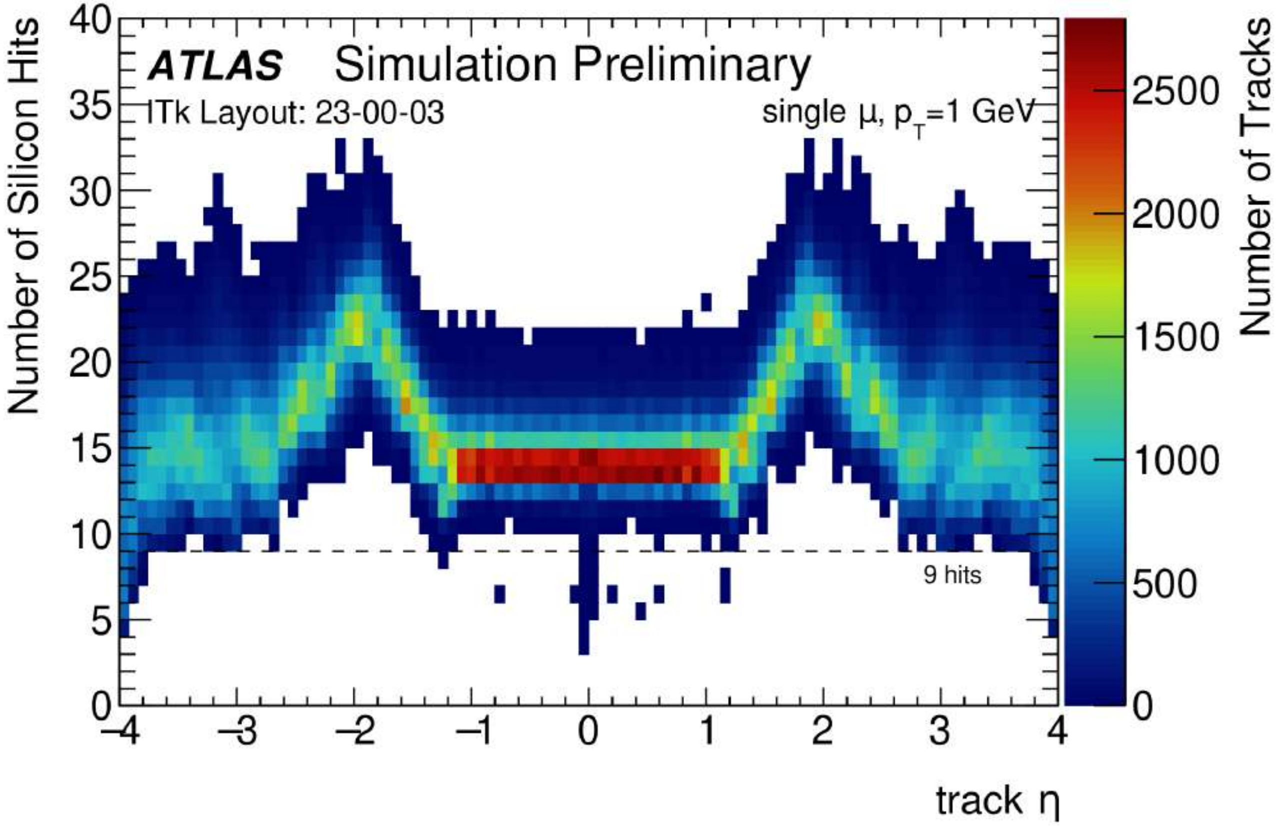


CERN-LHCC-2017-021

- **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

ITk tracking performance

- Target: **similar** or **better performance** wrt current inner detector, even if HL-LHC conditions will be much harsher
  - Finer granularity of detector
    ➔ Cope with higher occupancies
  - Reduced material budget
    ➔ Less multiple scattering, photon conversions, etc
  - Big pseudorapidity coverage, increased number of layers
    ➔ More hits on track
  - **Minimum 9 hits** per track at **central** region, **13 hits** at the **forward** region
  - Track **hits redundancy** is mandatory to solve the high **combinatorics** expected at HL-LHC



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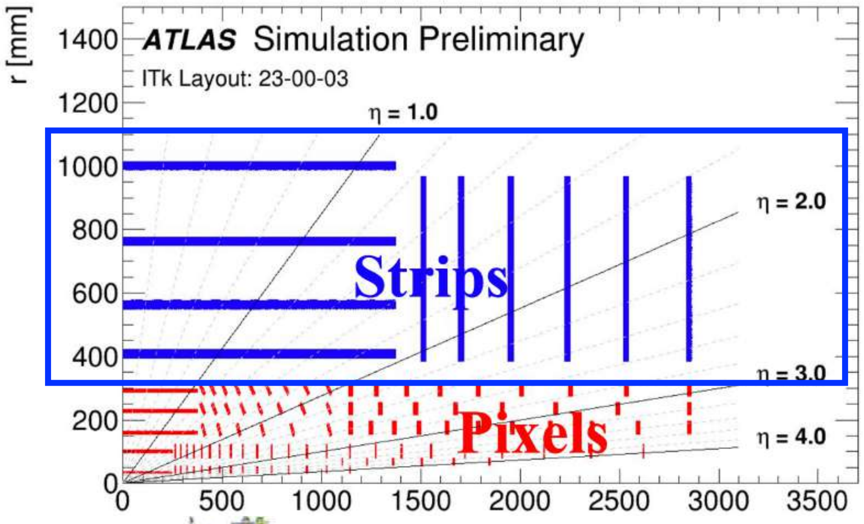
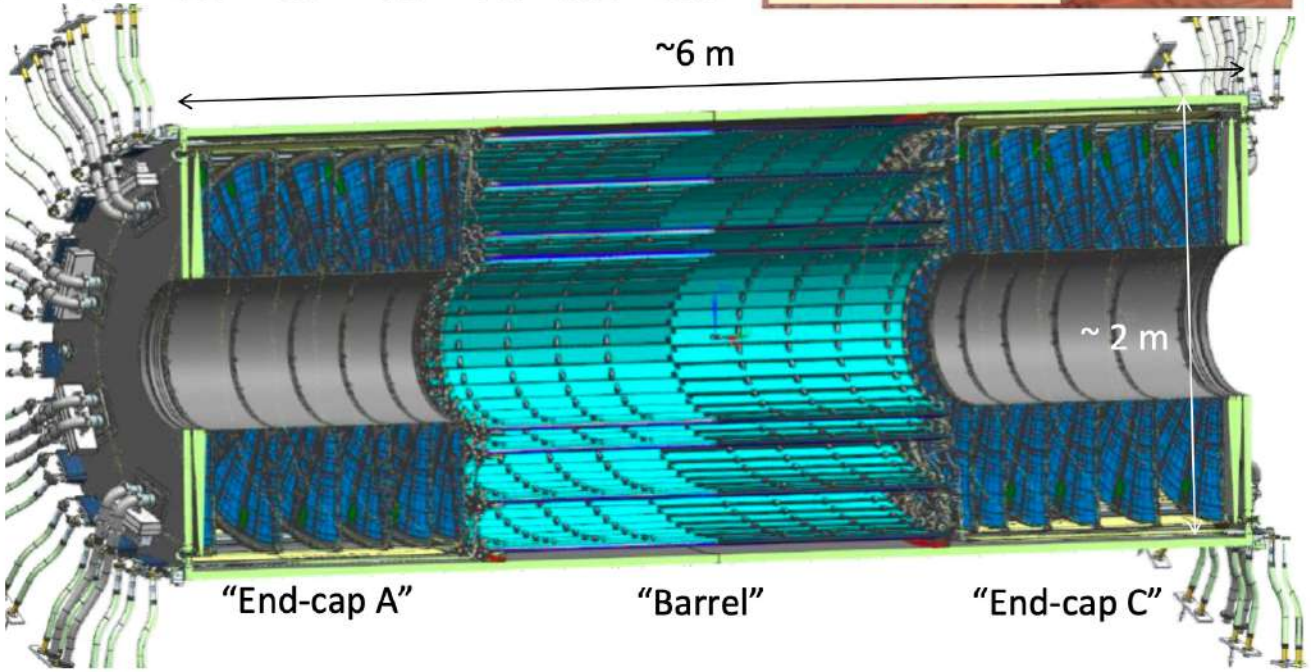
ITk-Strip detector in one slide

- 4 barrel layers + 12 end-cap disks
- Dimensions: 6m long, 2m wide
- ~17k modules
- 60M readout channels
- Sensor / Electronics
  - Three dedicated ASICs
- Production status
  - Sensors in production
  - ASICs in production
  - Hybrids and modules in pre-production



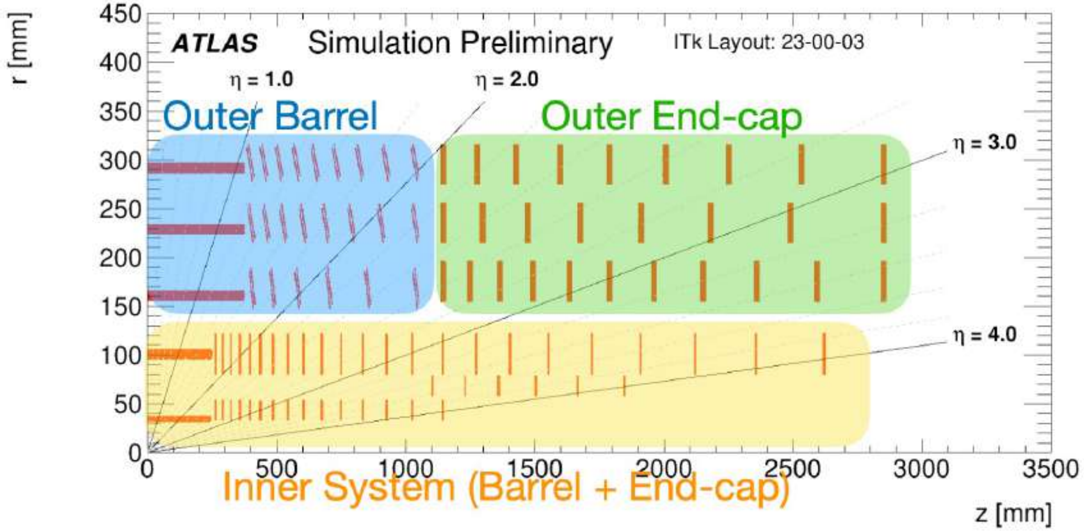

First completed wheel

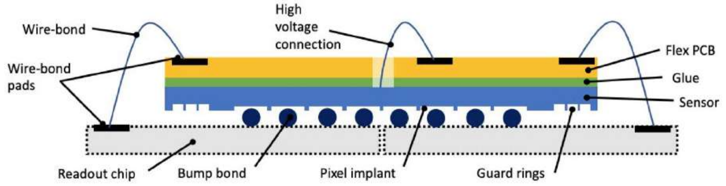
Nikhef, 15/4/2021



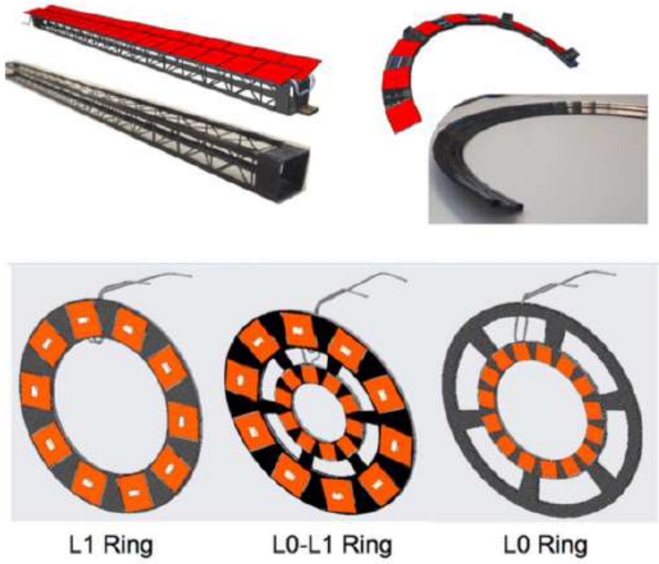
ITk-Pixel layout

- **ITk-Pixel detector composed by 3 parts: outer barrel, outer end-cap, and inner system**





Quad module

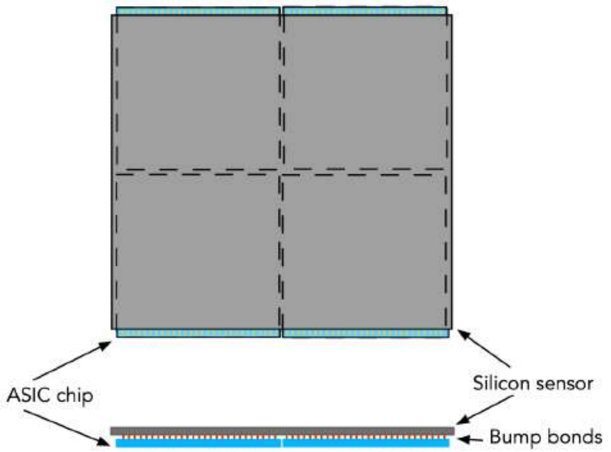


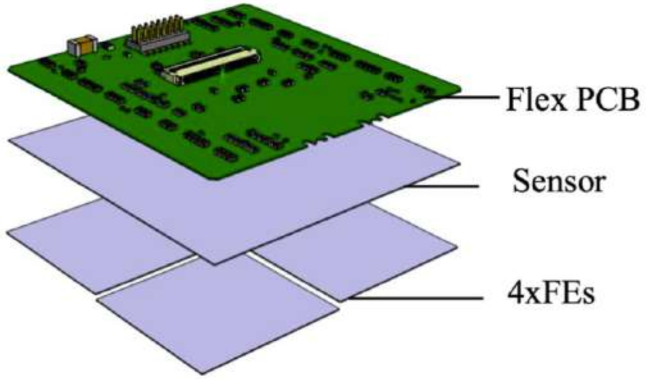
Mechanical structures

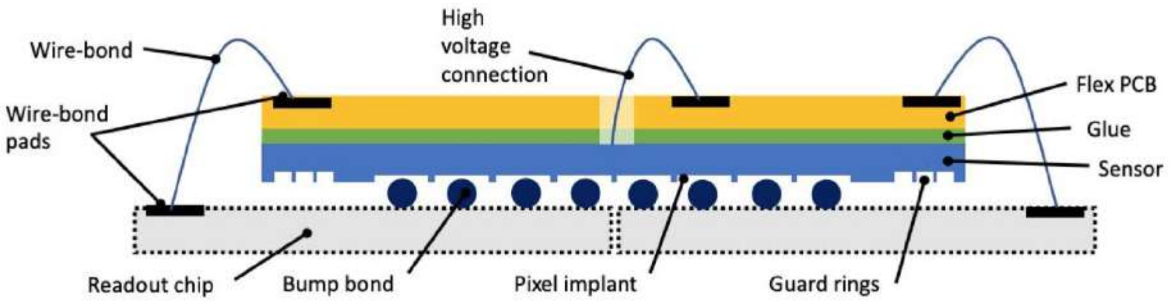
- **Outer barrel:** 3 barrel layers, 2x23 inclined disks
- **Outer endcap:** 2x28 outer disks
- **Inner system:** 2 barrel layers and 2x44 disks
  - Most innermost layer: 34 mm from the beam pipe

ITk-Pixel building blocks: modules

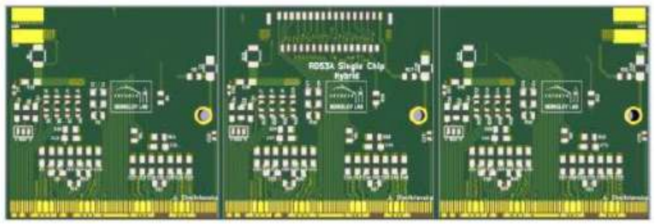
- **Bare module: silicon sensor flip-chip assembled** to **FE** via indium bump bonding
- **Flexible printed circuit board** (Flex PCB) glued on sensor, and then **wire bonded to ASIC**
- **Two** types of **modules**
  - **Quad** modules: 4 Fs bump bonded to one sensor; 95% of the total modules (everywhere but Layer-0)
  - **Triplet** modules: 3 single-chip bare modules connected to the same flex; 5% of the total modules (Layer-0)
- All **chips** are thinned to **150 µm**
- All **sensors** are **150 µm thick**, apart from **Layer-1**, which are **100 µm**



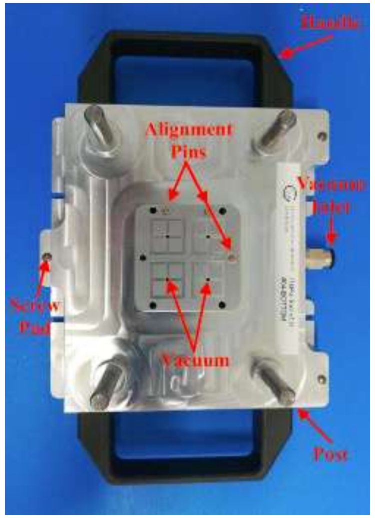


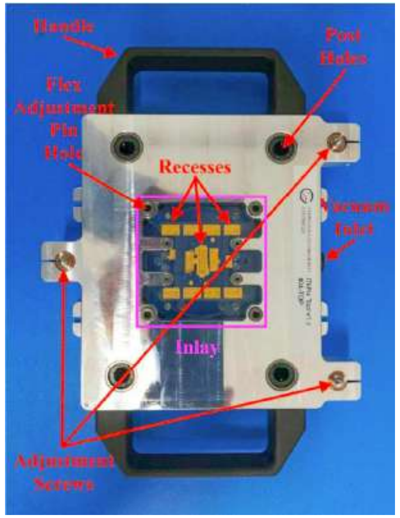


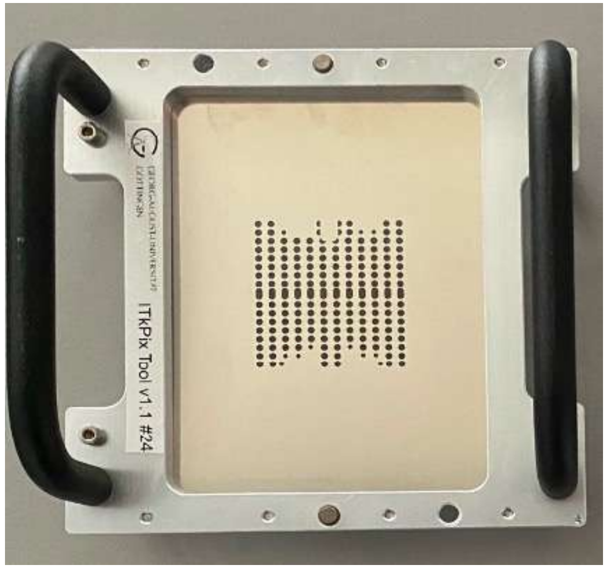
LinearTriplet Flex (Layer-0 barrel)



Photostory of module assembly







- We are using a manual and simple assembly tooling based on mechanical jigs and a mask (stencil) to control the glue pattern
- Epoxy adhesive used, radiation hard

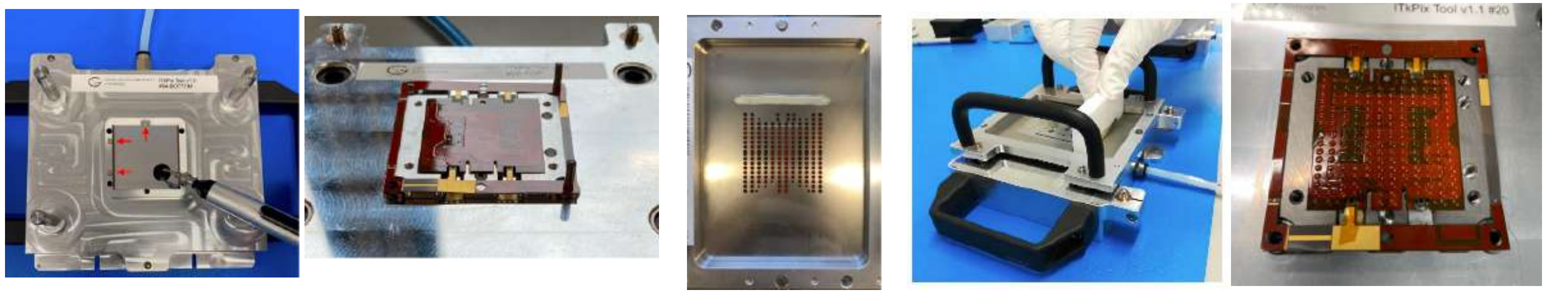
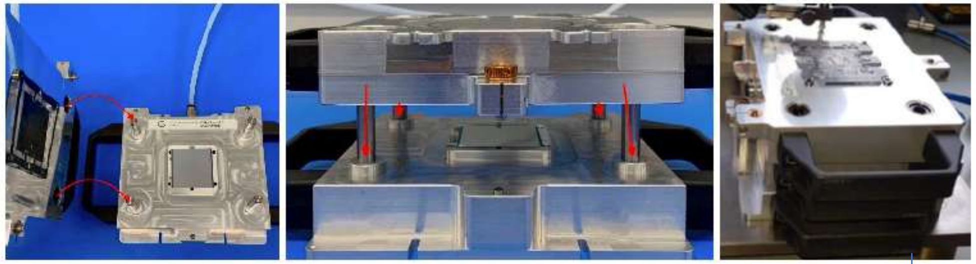
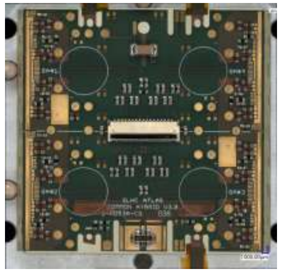


Photo story of gluing an ITk-pixel module





8h later

Assembled module

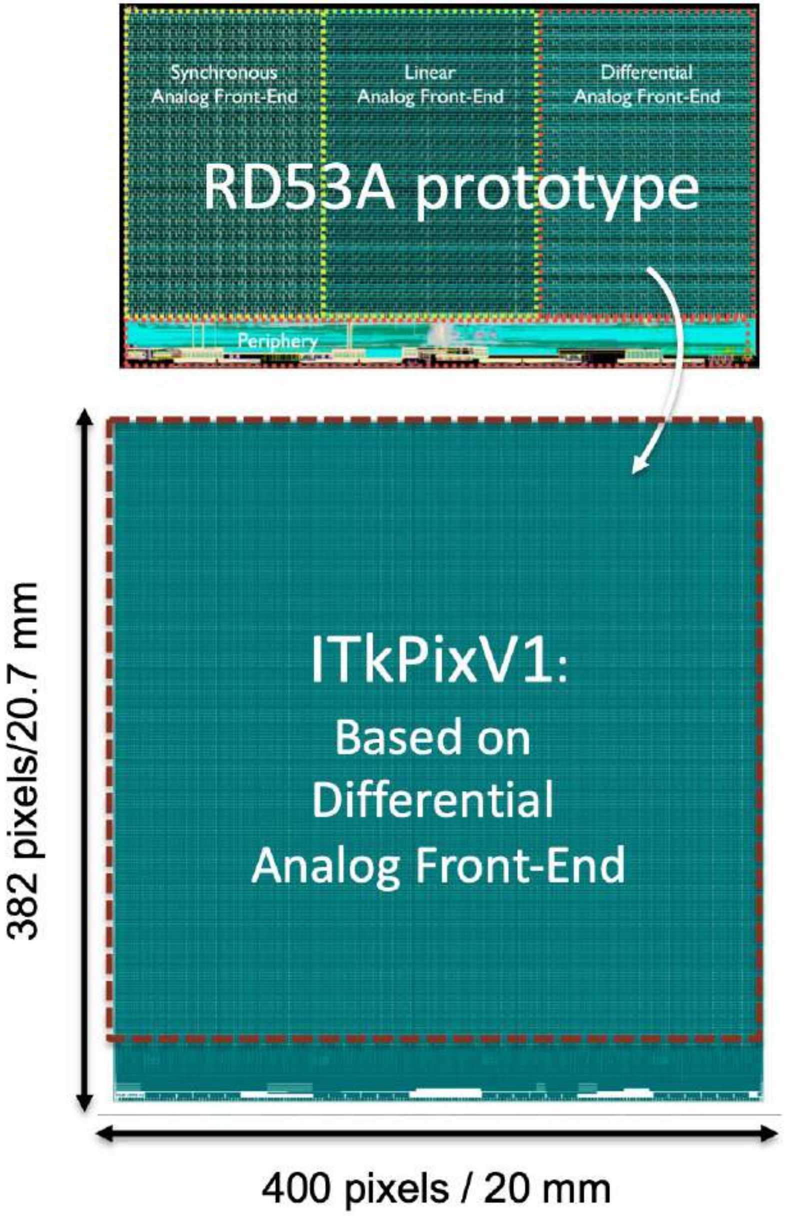
A novel readout chip

- **Common ATLAS and CMS R&D: RD53 collaboration** (https://rd53.web.cern.ch)

- **Reduced pixel size: 50 x 50 µm^2**

- **First prototype for: RD53A**
  - Common for ATLAS and CMS
  - Three different analog front end (FE) for comparison

- **Final ATLAS-ITk chip (ITkPix)**
  - Radiation hard > 5 MGy (fluence ~10^{16} n_{eq}/cm^2)
  - Trigger rate: 1 MHz
  - High hit rate: 3 GHz/cm^2



Current status

- **Finished prototyping with RD53A-chip modules, O(200) modules were built among 20 sites**
- **Set up complete procedures for assembly and testing of modules**

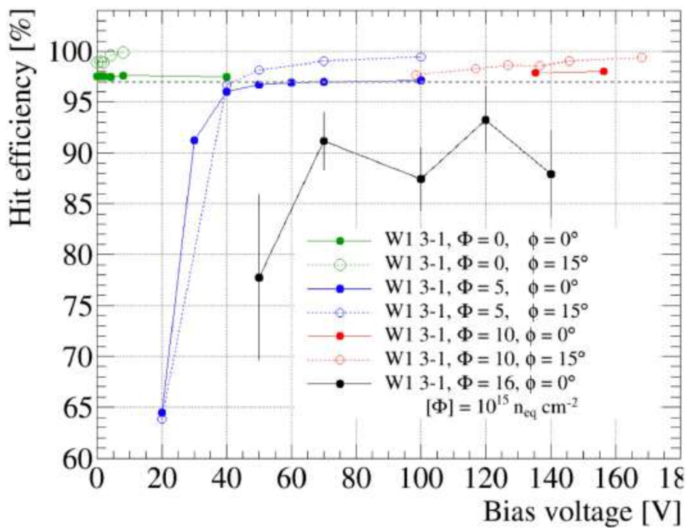
- **Bare modules**
    - Currently in pre-production
    - Process entirely done in industry
- **Flex PCB**
    - Design is finalised
    - Order being placed at the vendors (industry)
    - Pre-production to start the next month

- **Module assembly (mostly), and testing @ ITk institutes**
    - About 20 laboratories in ATLAS (France, Germany, Italy, UK, USA, Japan, Norway, CERN/Switzerland) have developed the experience to assemble and test modules

- **Loading onto local supports and cooling structures in 4 sites**

Highlights from prototyping

- Important number of assembled **modules** were **thermally cycled** (to extreme values) and **irradiated** to the HL-LHC expected fluence: **no damages or drop in efficiency**
- **Extensive electrical tests** of assembled modules to catch production problems: Quality Control (QC)
  - **Sensor electrical measurement**: on wafer, before assembly, after assembly and after thermal cycles
  - **Cold test at operating temperature** (-15°C): catch defects induced by thermal stress (delamination)
  - **Look for module failure after 24-long operation** (burn-in test)



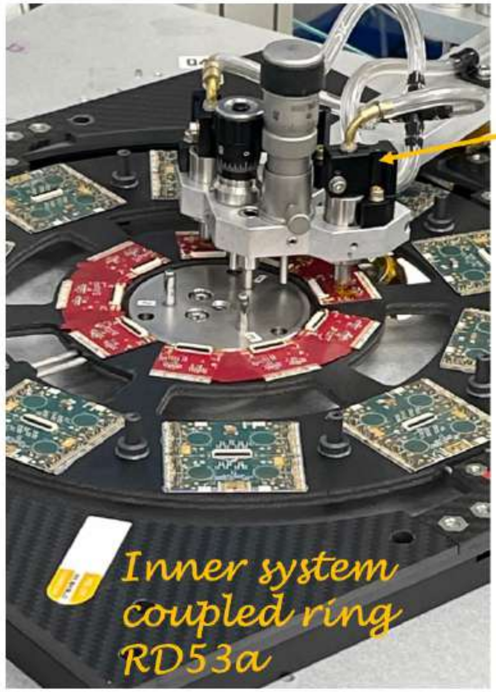
- Final site qualification ongoing to tackle pre-production (to start early 2023)

Common hardware developed for testing, ITkPixV1

Loaded supports and demonstrators

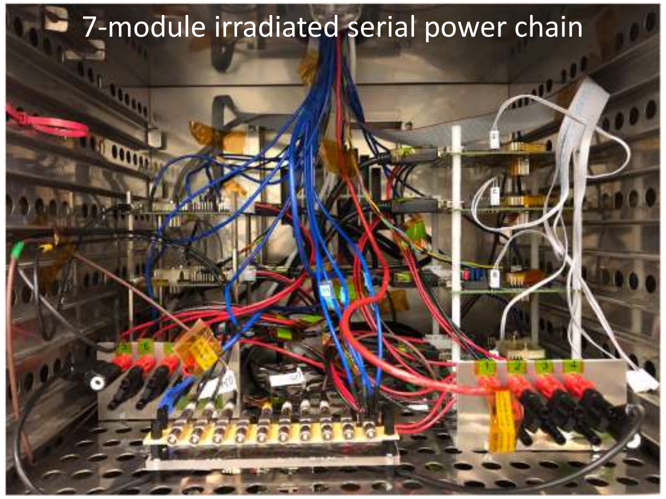
ATL-ITK-PUB-2022-002

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

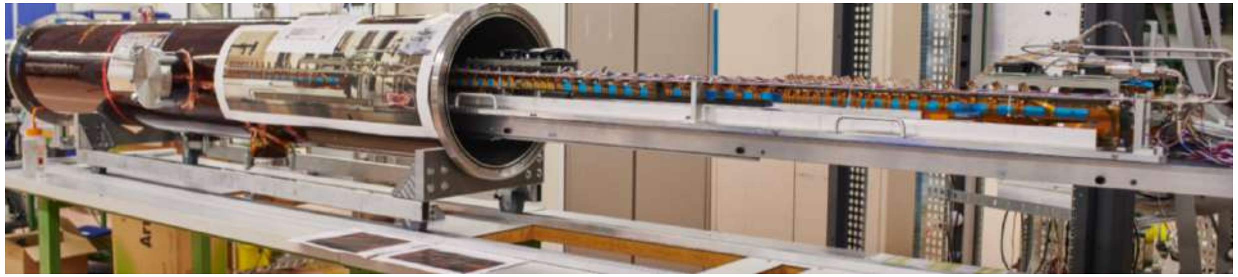

Tools developed for precision placing

Inner system coupled ring RD53a

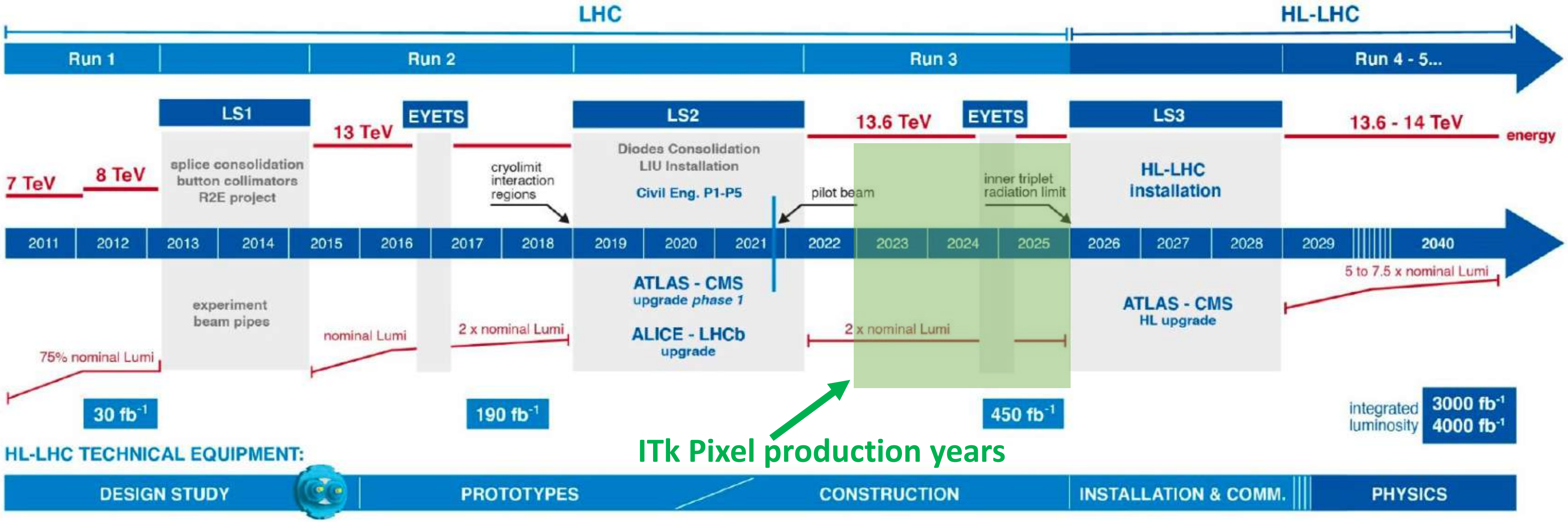
- Building system test infrastructure for testing loaded local supports
- Preparing for thermal cycles of bare and loaded support structures


7-module irradiated serial power chain

- Demonstrators development for both endcap and outer barrel



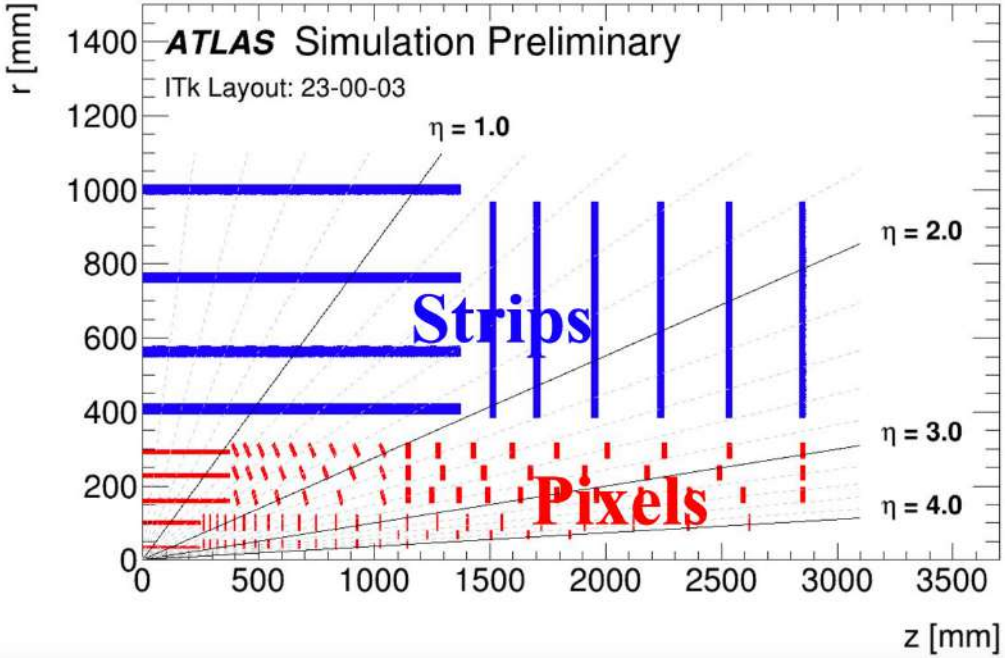
ITk-Pixel timeline



- Autumn 2022
  - Submission and production of final chip
  - Submission and production of final Flex PCBs
- 2023: Year of the pre-production ➔ 10% of the total modules production
- 2024-2025: Modules production for ITk-Pixel
- Beginning of 2026, modules should be ready to start the loading and installation during Long Shutdown 3 (2026-2029)
- **Schedule is already very tight**

Summary

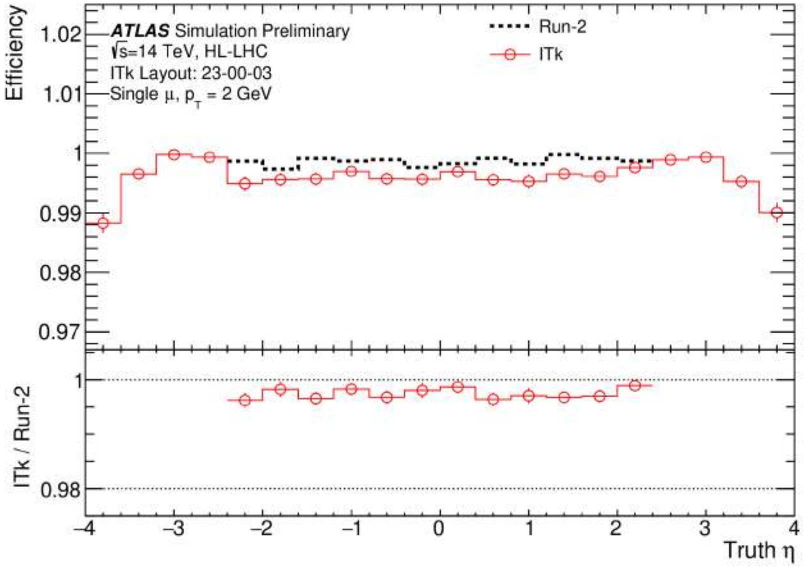
- **ATLAS is building a new tracker, ITk, to face the harsh conditions of HL-LHC**
  - Radiation hard
  - Low material budget
  - Fine granularity
  - Performance: same or better comparted to current inner detector

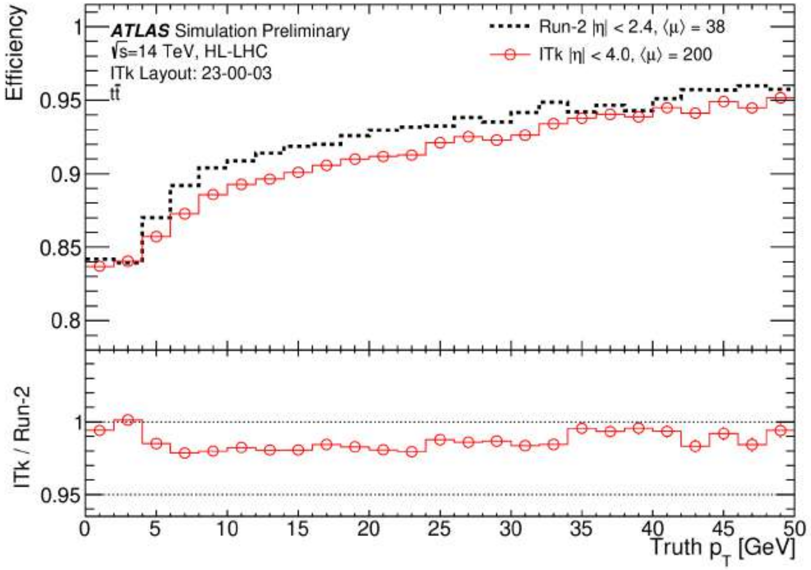


- **ITk: full silicon tracker**
  - ITk-Strip: 4 barrel layers and 12 disks
  - ITk-Pixel: 5 barrel layers with inclined geometry, and rings at forward region
- **R&D and prototyping has now ended, we're entering the (pre-)production phase**
  - ITk-Strip: already in pre-production, for some parts even in production
  - ITk-Pixel: some parts in pre-production, modules pre-production in 2023
  - **2024-2025: Critical years for producing and building ITk detector**

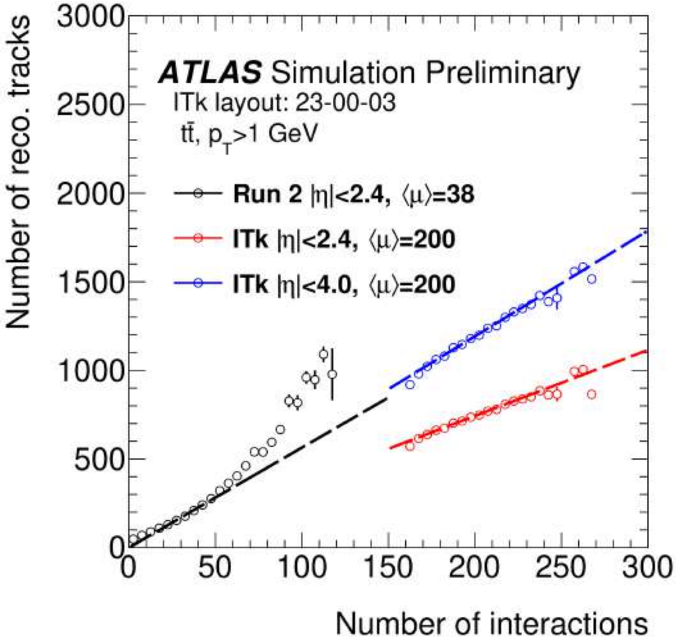
Backup

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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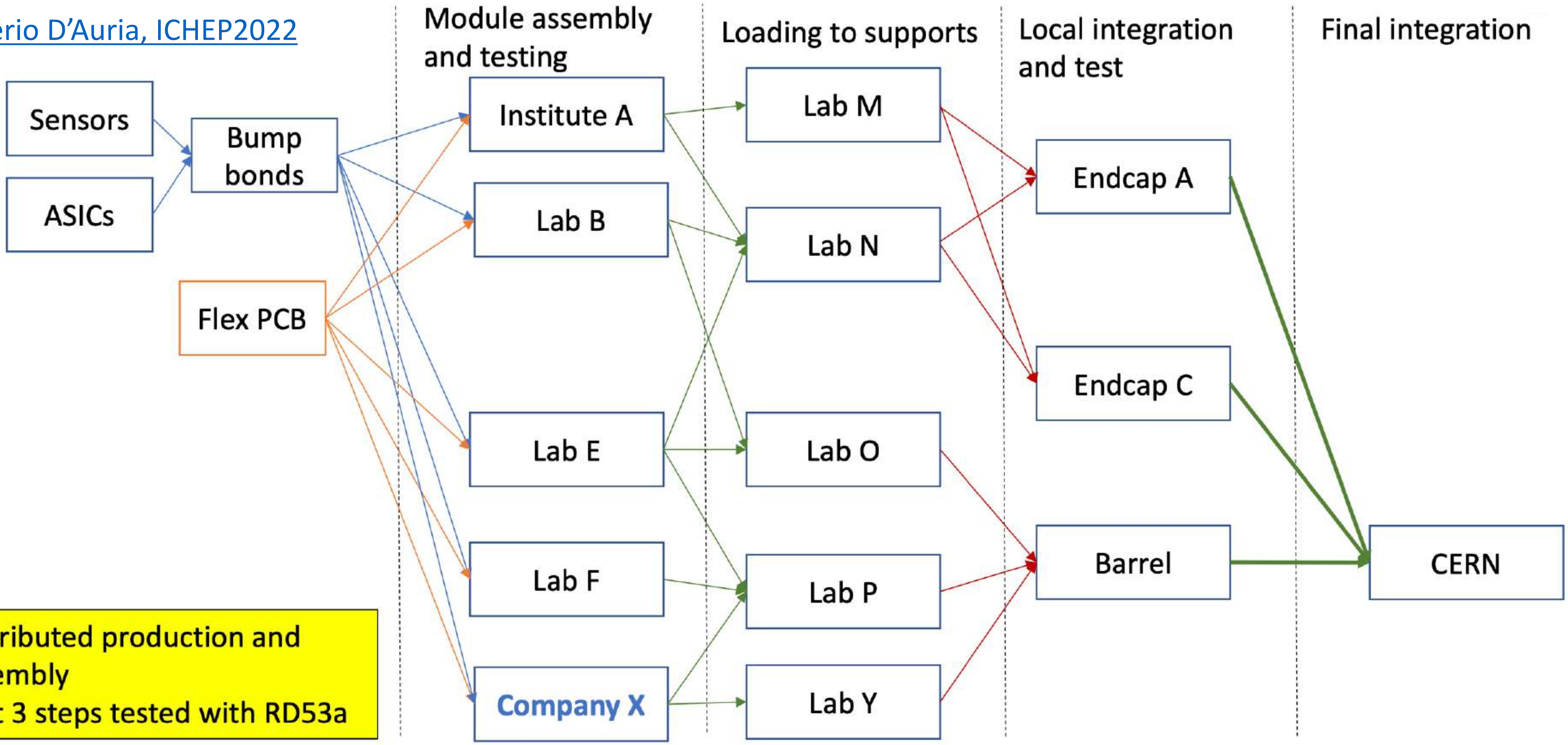
General production model

Saverio D'Auria, ICHEP2022



Distributed production and assembly
First 3 steps tested with RD53a

Pixel sensors

Saverio D'Auria, ICHEP2022

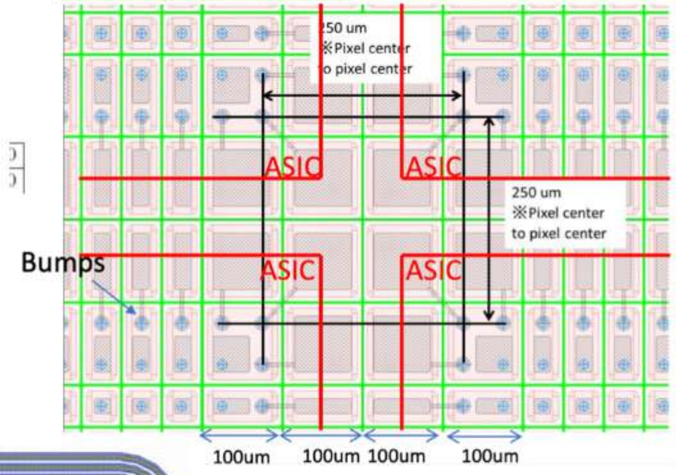
Two types of sensors:

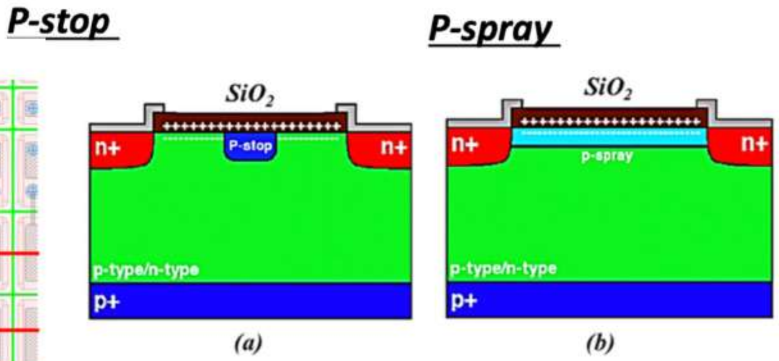
Planar:

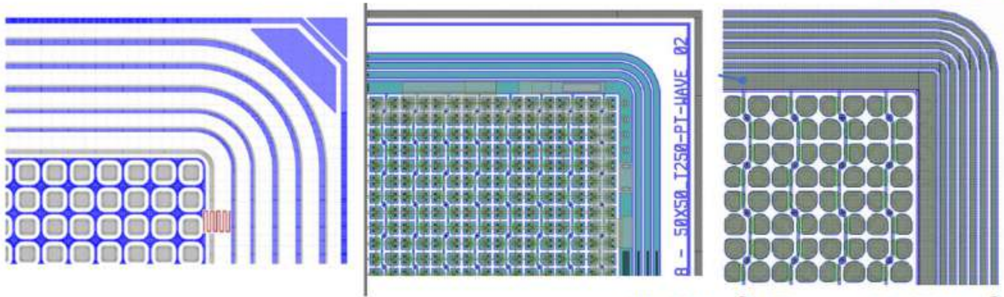
Various design detail left up to vendor :

- *p*-stop vs. *p*-spray insulation
- Polysilicon bias or punch-through
- Guard-ring geometry

Requirements defined on performance

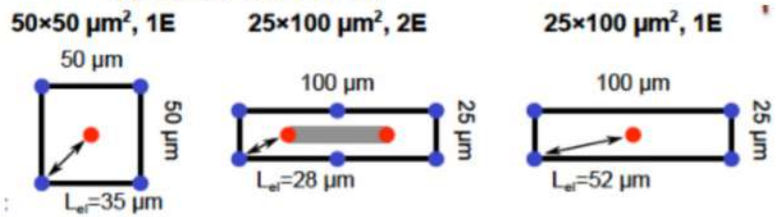

Center of Quad sensor

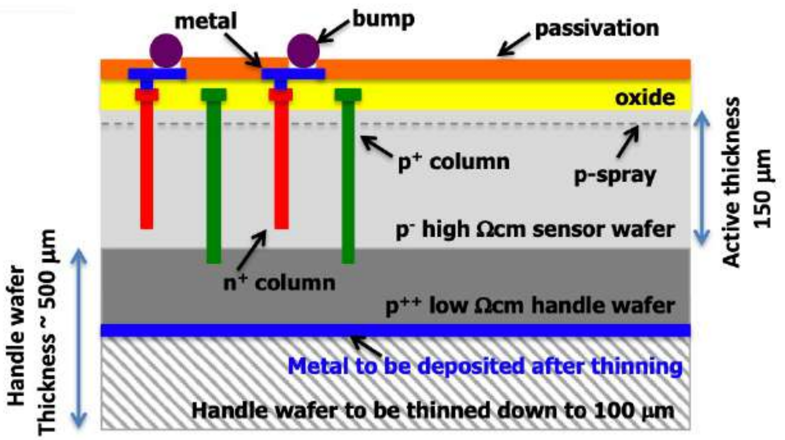

P-stop **P-spray**



Inner system uses 3D sensors

- High radiation tolerance
- Lower bias voltage



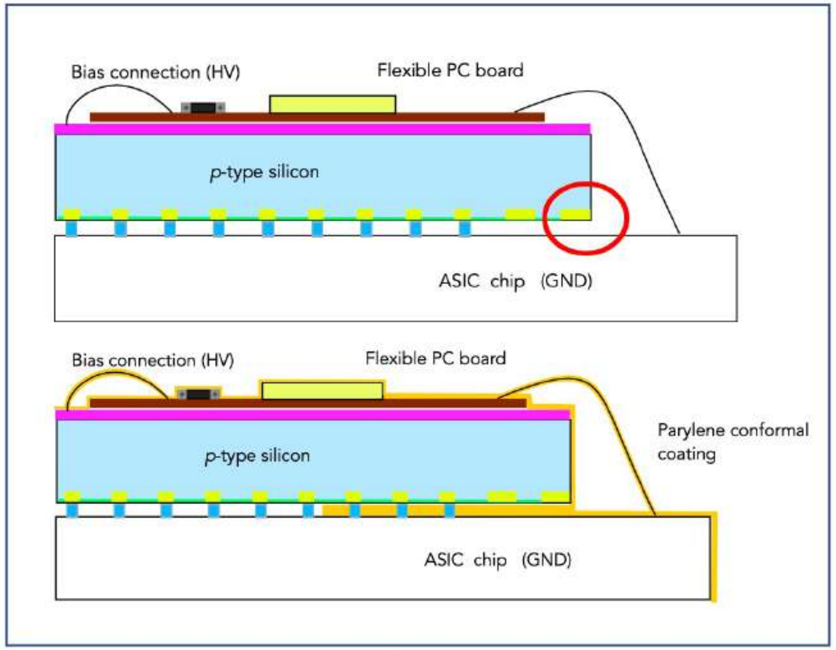


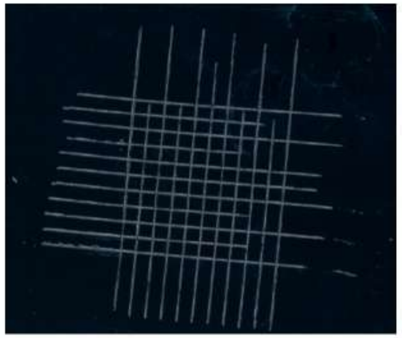
Technology challenges

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)