Large Hadron Collider

the world's largest and most powerful particle accelerator

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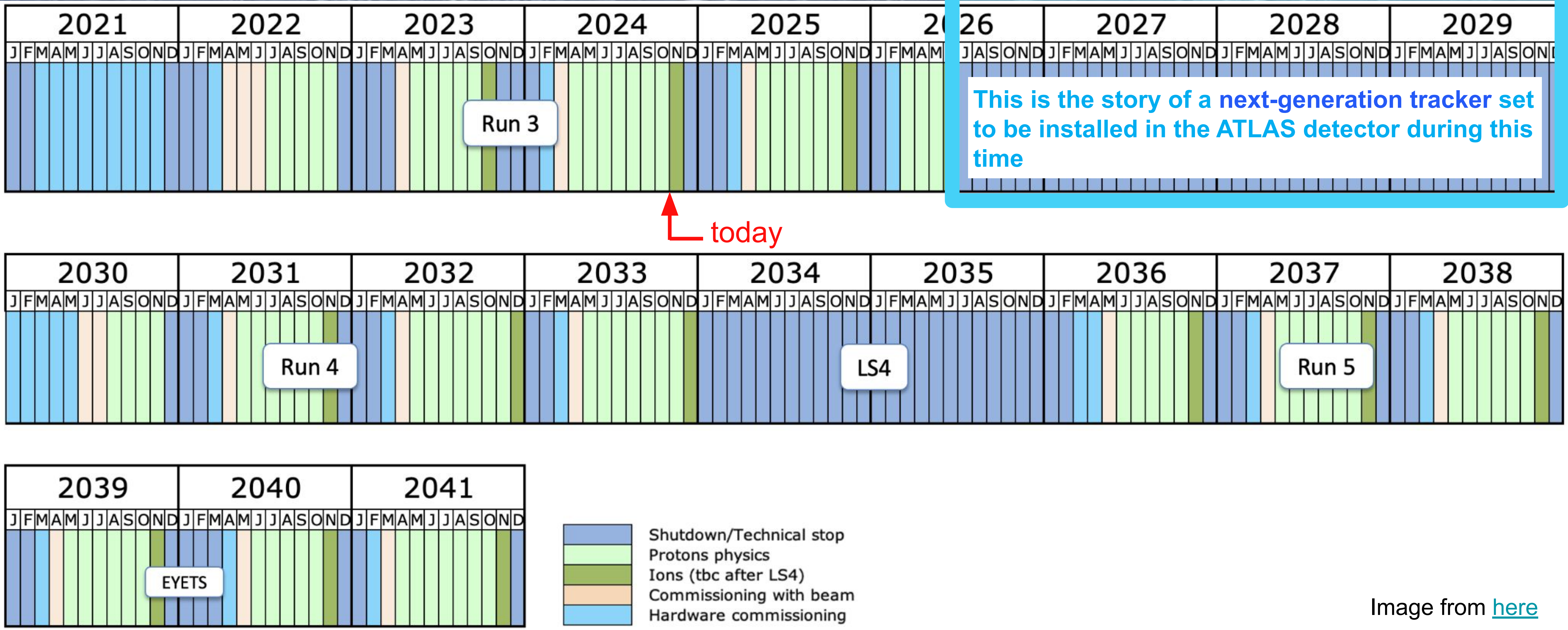
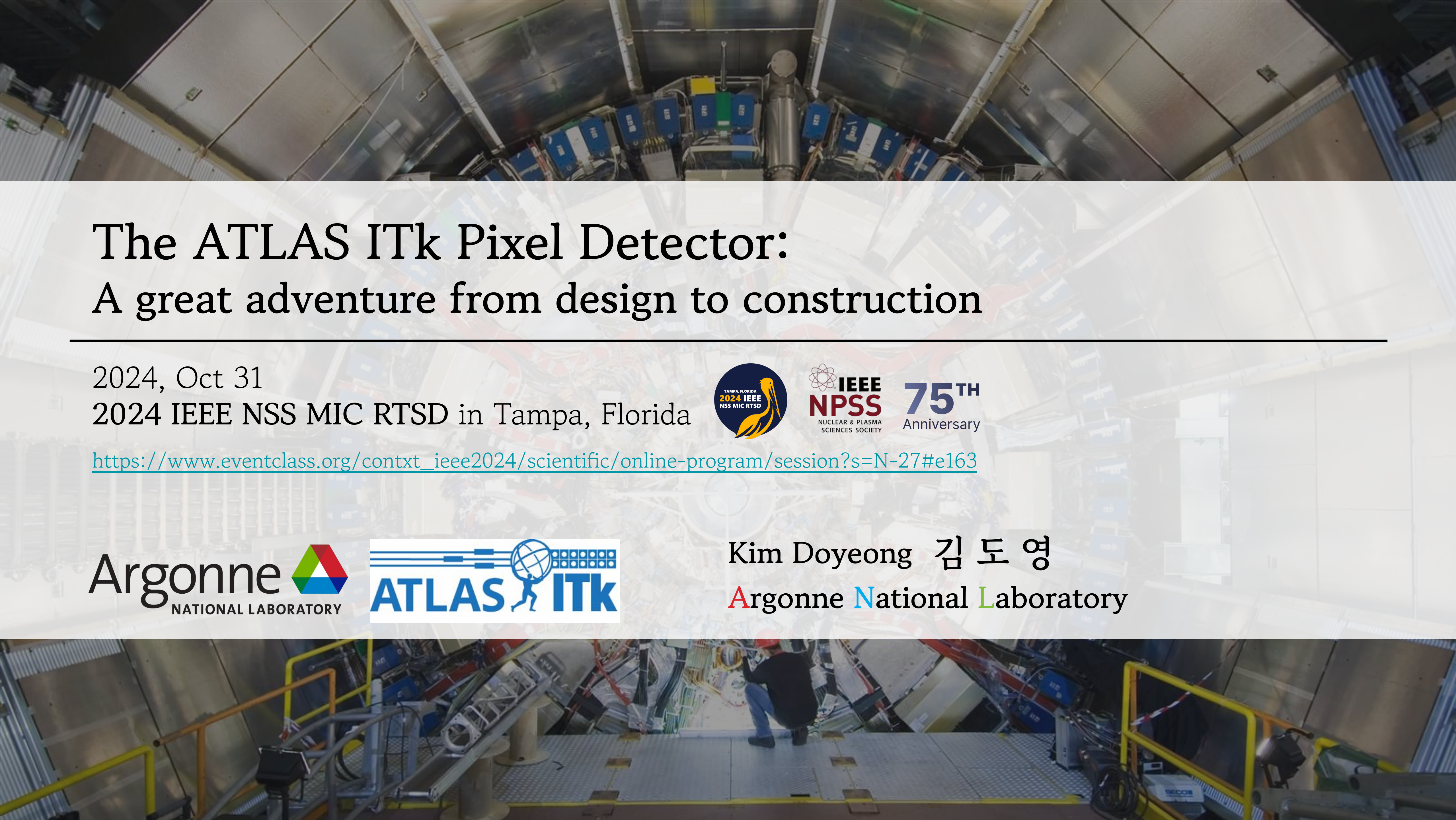


This is the story of a **next-generation tracker** set to be installed in the ATLAS detector during this time

Last update: September 24

Image from here



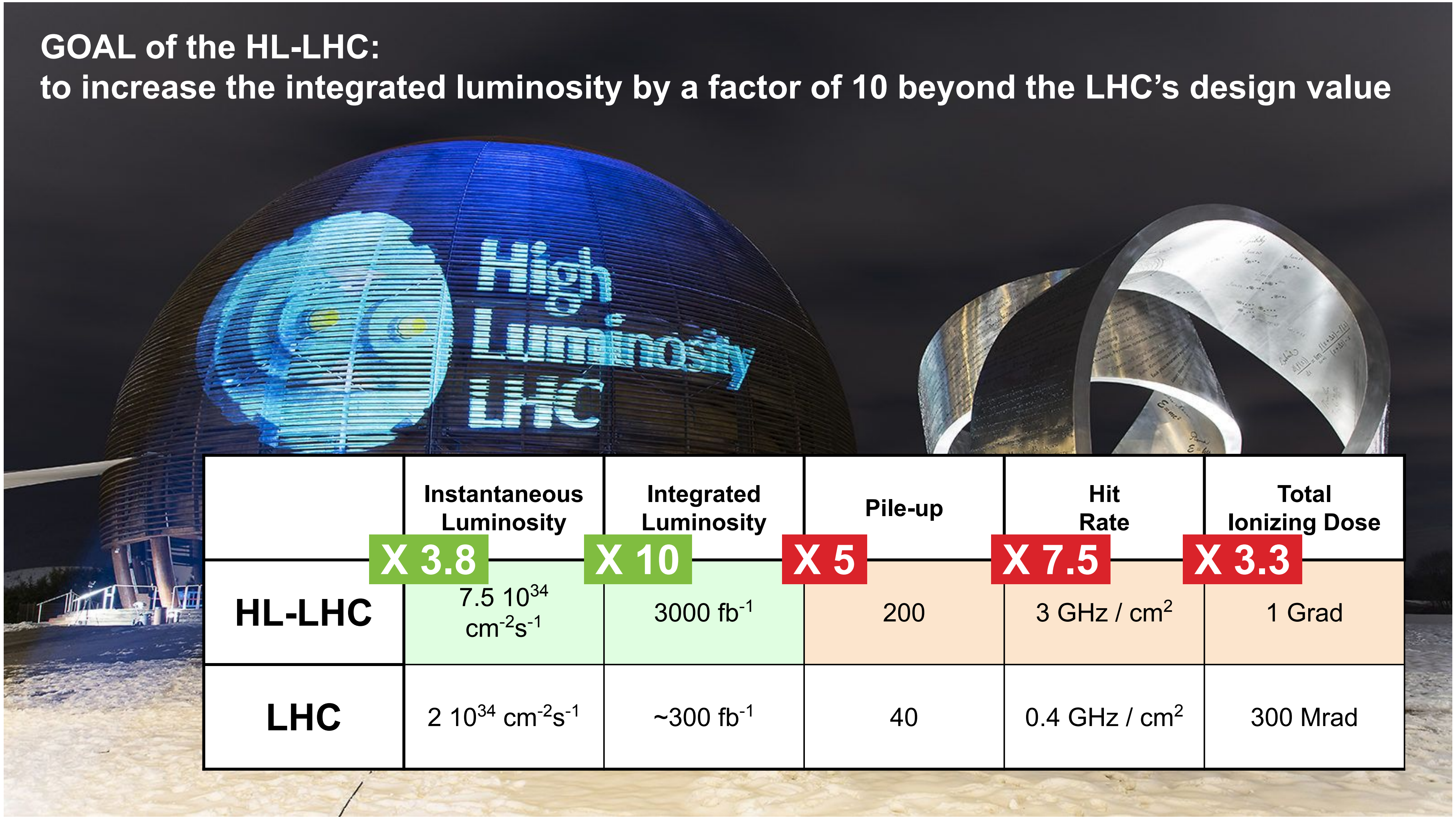
The ATLAS ITk Pixel Detector:
A great adventure from design to construction

2024, Oct 31
2024 IEEE NSS MIC RTSD in Tampa, Florida

https://www.eventclass.org/contxt_ieee2024/scientific/online-program/session?s=N-27#e163

Kim Doyeong 김도영
Argonne National Laboratory

Why we want the HL-LHC upgrade?



GOAL of the HL-LHC:
to increase the integrated luminosity by a factor of 10 beyond the LHC’s design value

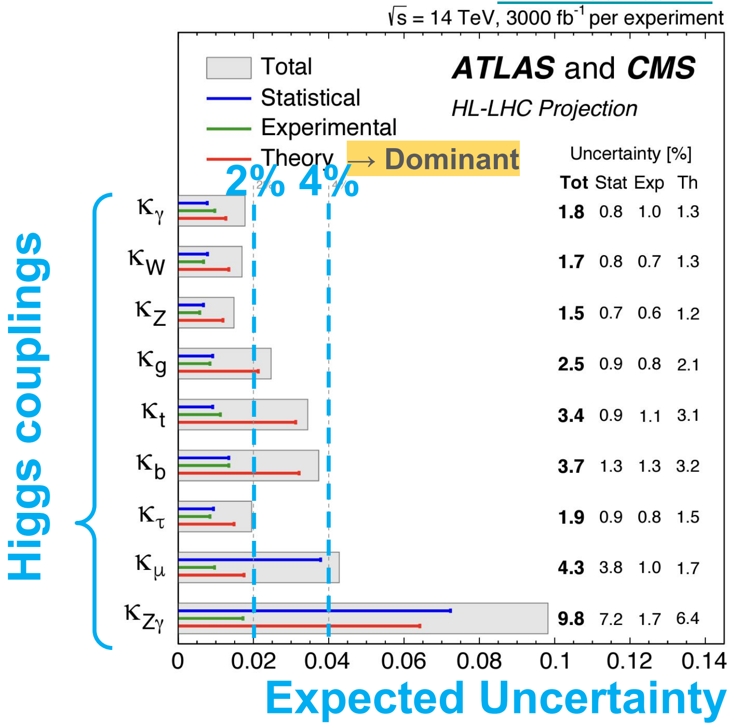
	Instantaneous Luminosity	Integrated Luminosity	Pile-up	Hit Rate	Total Ionizing Dose
	X 3.8	X 10	X 5	X 7.5	X 3.3
HL-LHC	7.5 10^{34} $cm^{-2}s^{-1}$	3000 fb^{-1}	200	3 GHz / cm^2	1 Grad
LHC	2 10^{34} $cm^{-2}s^{-1}$	~300 fb^{-1}	40	0.4 GHz / cm^2	300 Mrad

Photo by Maximilien Brice, CERN

Why we want the HL-LHC upgrade?

- In all aspects, the upgraded tracker (ITk) at least matches—and in most cases surpasses—the performance achieved in LHC Run 2 (see Ewa Stanecka's talk)
- This cutting-edge tracker will push the boundaries of precision and sensitivity, paving the way for exciting physics opportunities with future colliders

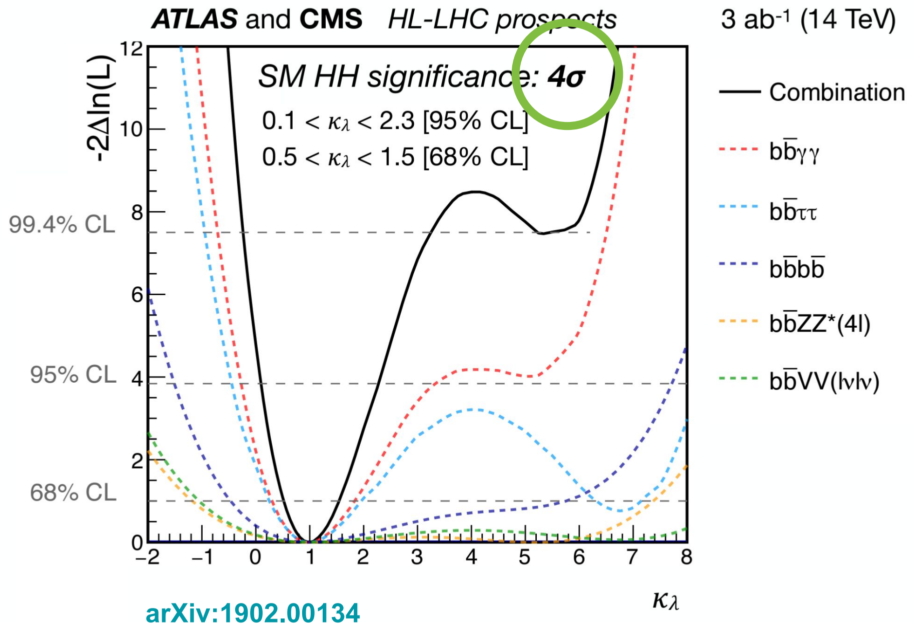
arXiv:1902.00134



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

the Higgs couplings to SM particles is expected to reach **the percent level**



arXiv:1902.00134

Combined signal strength significance ~4$\boldsymbol{\sigma}$ (stat. + syst.)

\+ and many more

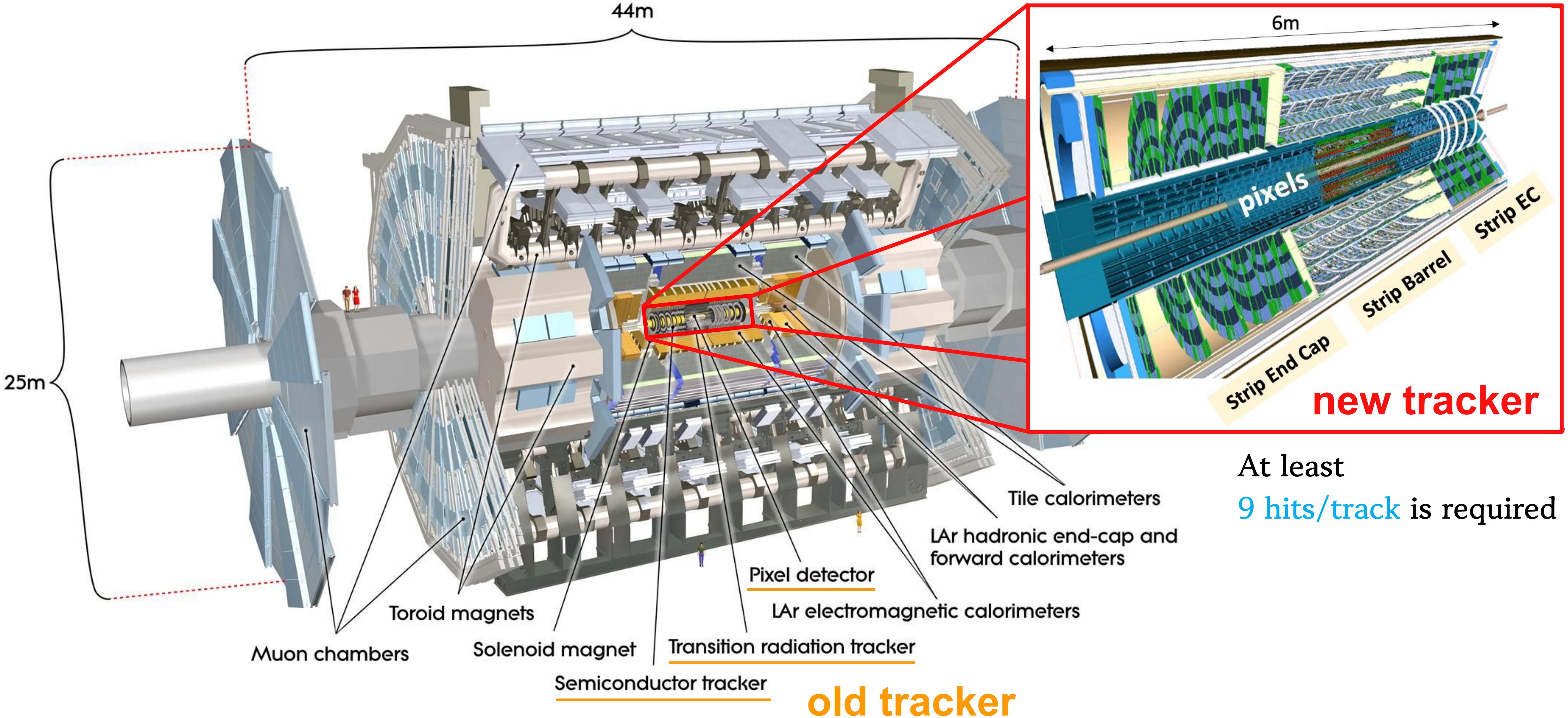
precision SM measurements

direct searches

…

Tracker in the ATLAS detector

ATLAS Open Data



At least
9 hits/track is required

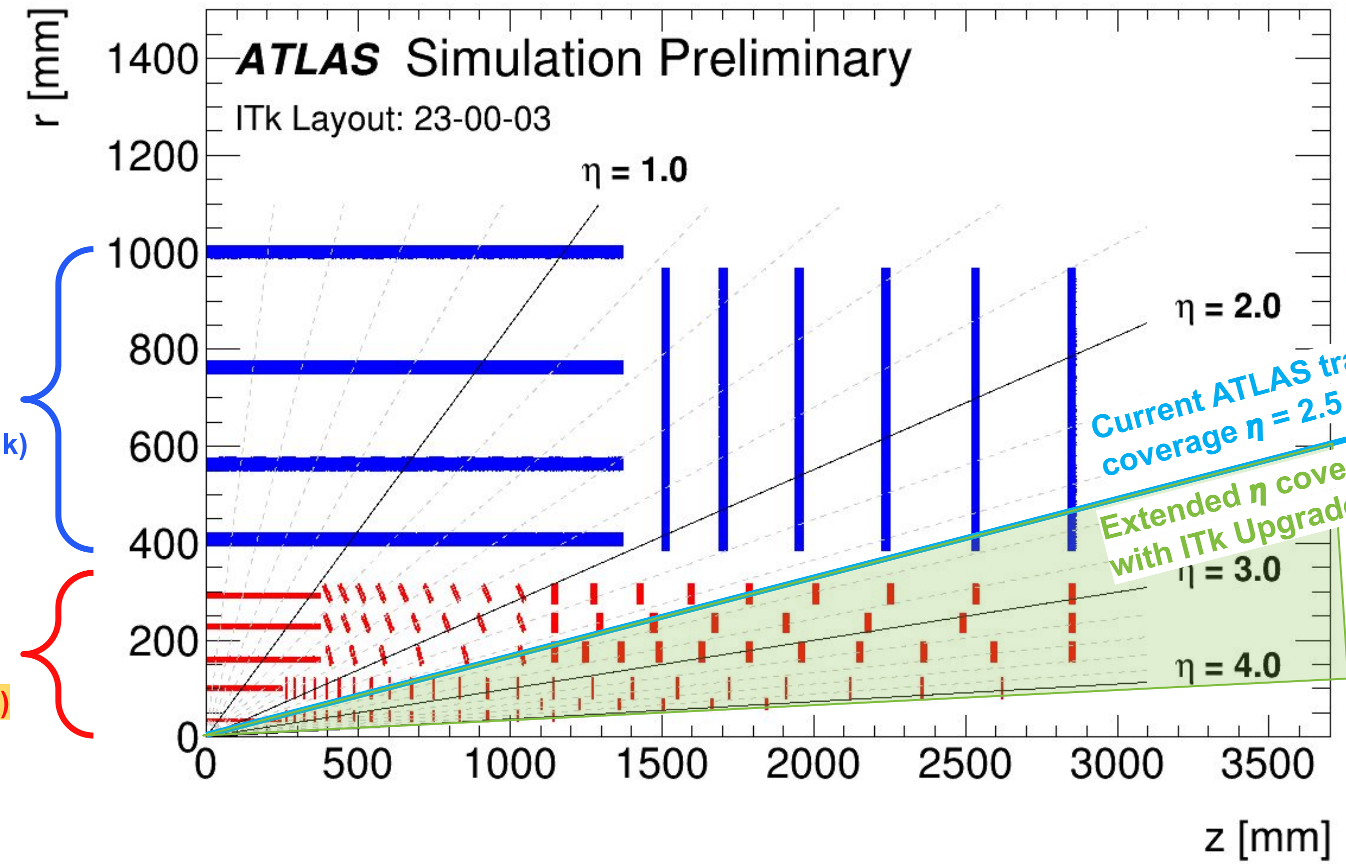
Inner Tracker (ITk): new ATLAS tracker for HL-LHC

strip
(Ewa Stanecka's talk)

pixel
(Focus of this talk)

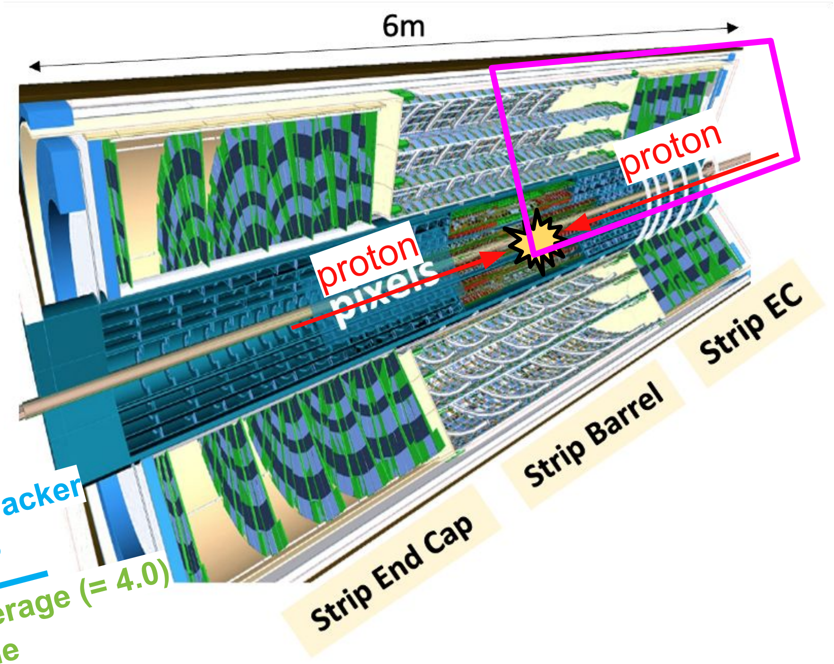
* Only one quadrant is shown

ATL-PHYS-PUB-2021-024



Current ATLAS tracker coverage $\eta = 2.5$

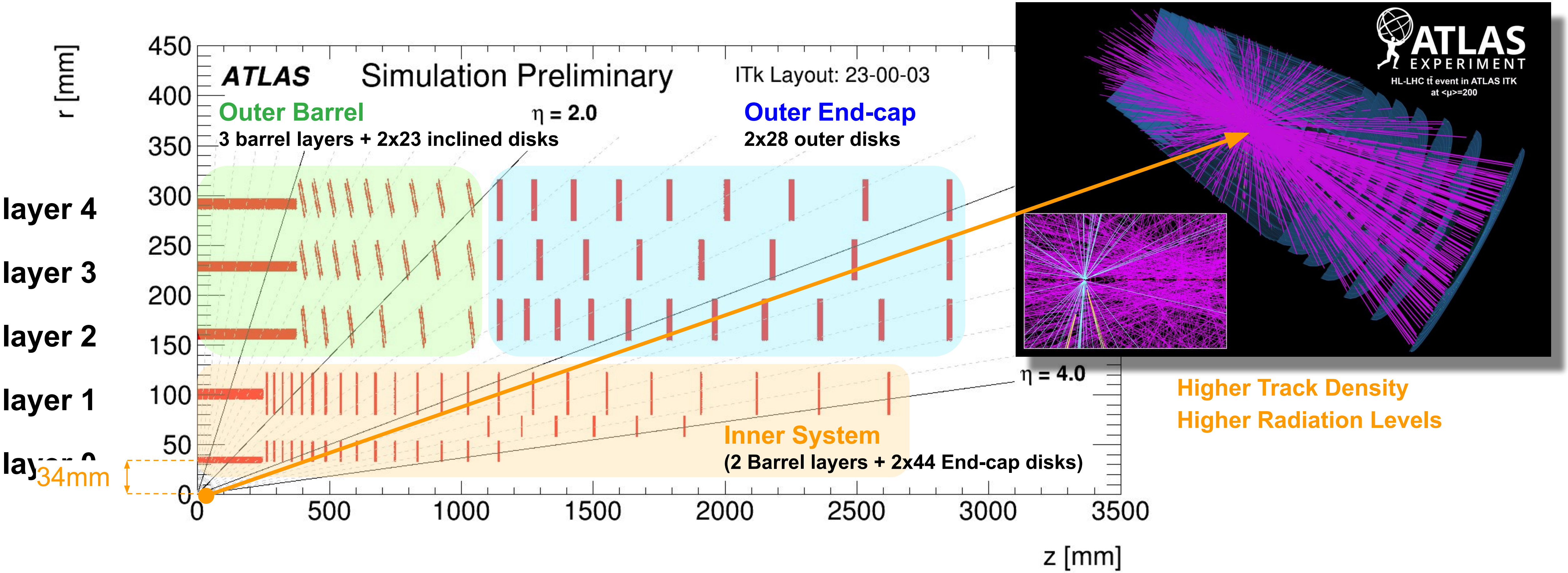
Extended η coverage (= 4.0) with ITk Upgrade



HL-LHC upgrade will involve current ATLAS tracker being replaced by all-silicon Inner Tracker (ITk)

ATLAS ITk pixel layers

ATLAS public briefings



Higher Track Density

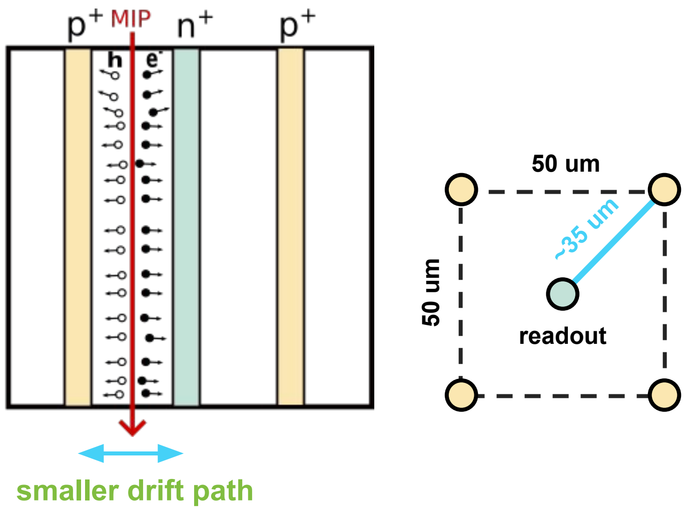
Higher Radiation Levels

- The geometric structure of ITk creates non-uniform challenges
- The ITk Pixel Inner System (= layer 0 + layer 1) is located nearest to the collision point, resulting in the most demanding requirements

Schematic view of electrode and charge collection

arXiv:1903.12531

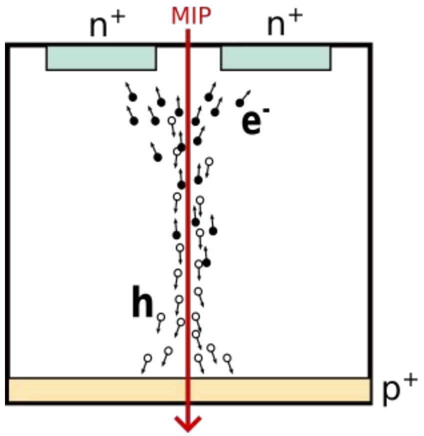
Columnar 3D sensors (layer 0)



Required radiation tolerance:
7.2 MGy *for integrated luminosity of 2000 fb^{-1}*

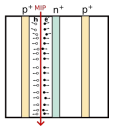
- Smaller drift path independently of the sensor thickness
  → smaller depletion voltage
  → less charge trapping
  } ➜ lower power dissipation after irradiation
  → improved position resolution
- Technical complexity
  → higher cost & limited yield

Planar sensors (other layers)

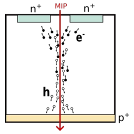


- n-in-p wafer single side processed
  → Simpler (i.e. cheaper) fabrication
- Radiation tolerance can be improved by reducing the thickness
  - layer 1 (100um)
    Required radiation tolerance:
    3.2 MGy *for integrated luminosity of 2000 fb^{-1}*
  - other layers (150um) - higher yield
    Required radiation tolerance:
    3.5 MGy for integrated luminosity of 4000 fb^{-1}

Measured hit efficiency before/after irradiation



Columnar 3D sensors



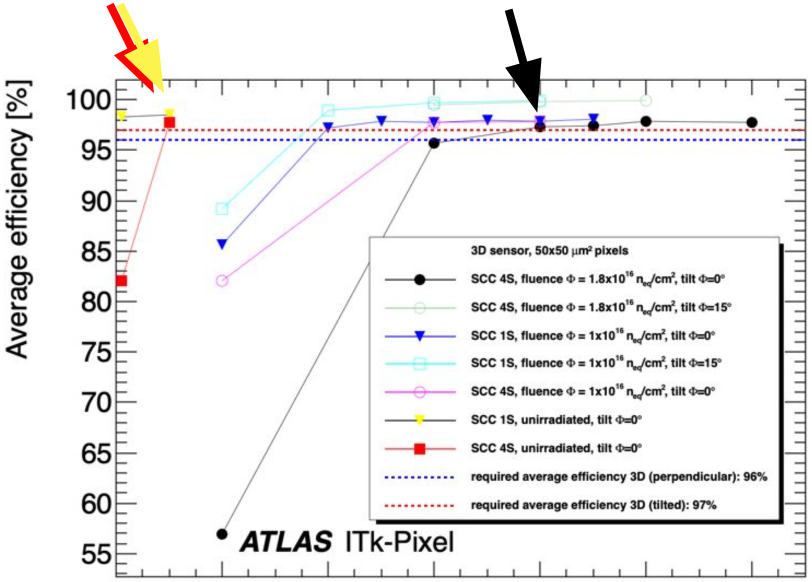
Planar sensors

3D sensor shows better radiation tolerance

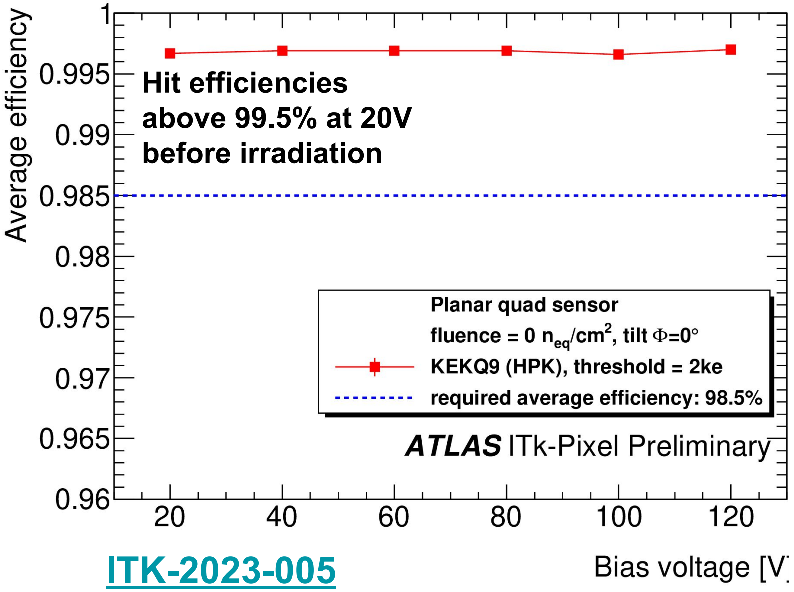
Hit efficiencies above 97% at 10V before irradiation

Hit efficiencies above 97% at 80V after irradiation

Irradiated at KIT ($1.8*10^{16}$ n_{eq}/cm^2 s 23 MeV protons)

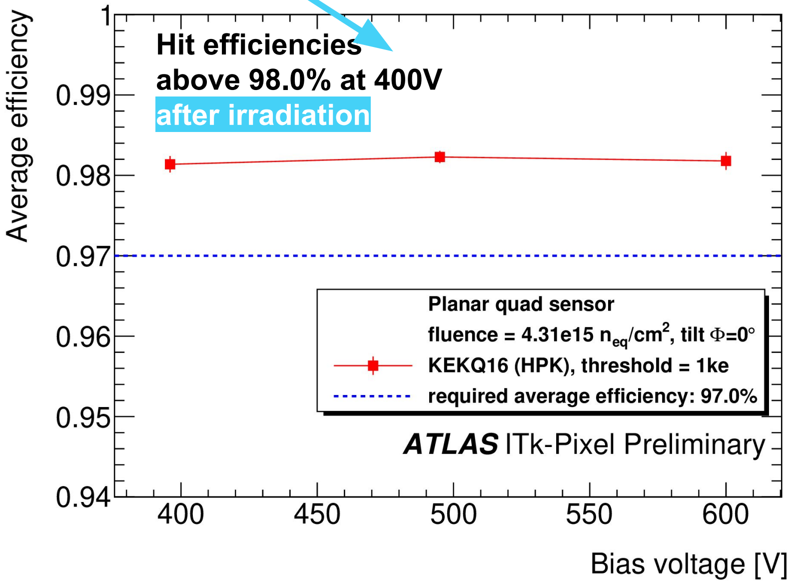


ITK-2023-004



Hit efficiencies above 99.5% at 20V before irradiation

ITK-2023-005



Hit efficiencies above 98.0% at 400V after irradiation

Both sensor types meet the required hit efficiency (>97%) after irradiation

Front-end Chip

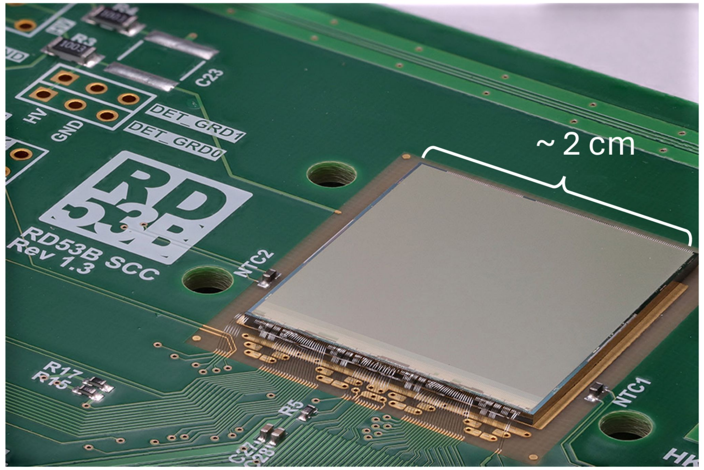
Challenges and technical requirements

Unlike sensor, the same chip will be used everywhere in the detector

→ The design must respect the most severe requirement (inner system, central region)

Technical requirements

	New tracker FE chip	Current tracker FE chip
Chip Size	2 x 2 cm^2	2 x 2 cm^2
Pixel Size	50 x 50 um^2	50 x 250 um^2
Pixel Hit Rate	3 GHz / cm^2	400 MHz / cm^2
Trigger Rate	1 MHz	200 kHz
Trigger Latency	12.8 us	6.4 us
Current Consumption	< 8 uA / pixel	20 uA / pixel
Radiation Tolerance	0.5 - 1 Grad	300 Mrad
Min. stable Threshold	600 e	1500 e



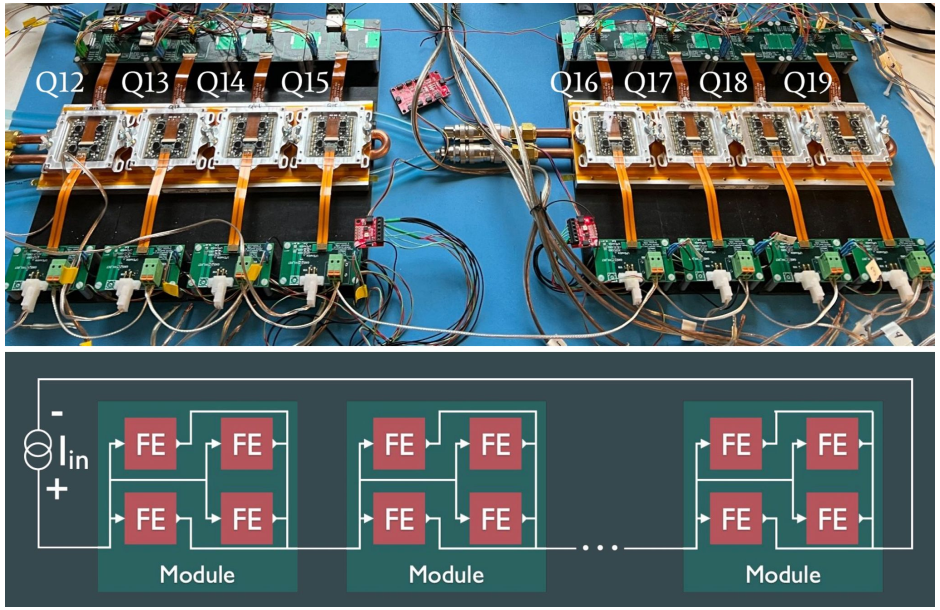
- Developed by RD53 collaboration (ATLAS & CMS joint effort)
- 65 nm CMOS* technology
  → low power (< 5 uW/pixel)
  → high logic density

* complementary metal-oxide semiconductor

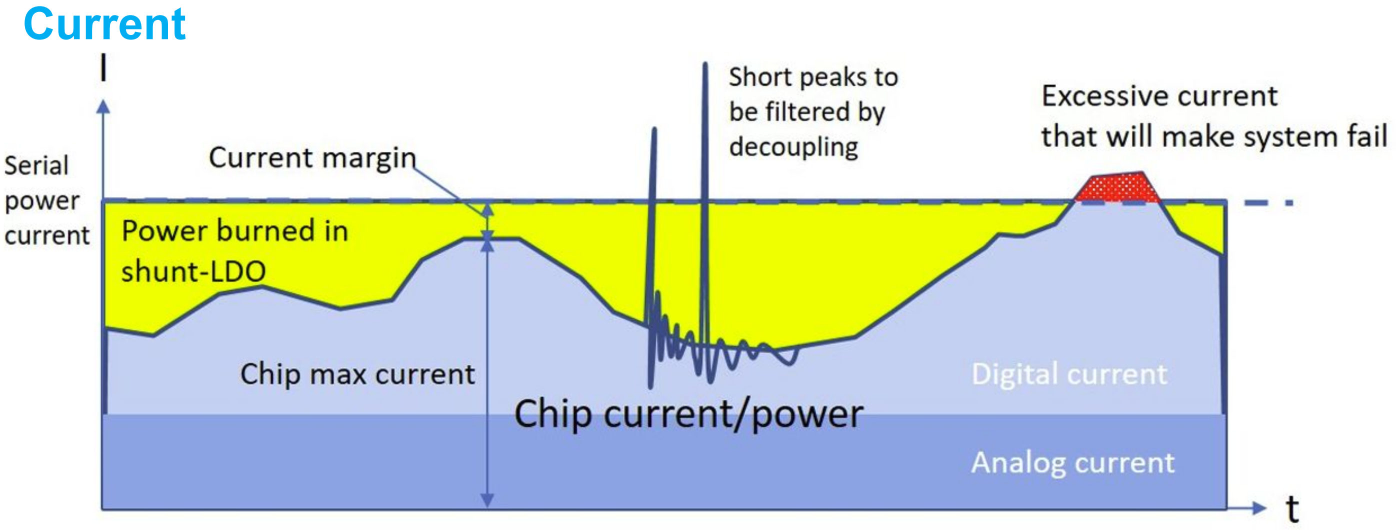
Serial Power chain

The Shunt LDO* power regulator (SLDO) **provides constant current operation with multiple chips** (and also modules) connected in parallel

→ material reduction (cables)
→ constant power consumption (important for mechanical stability)



Serial powering chain with quad modules

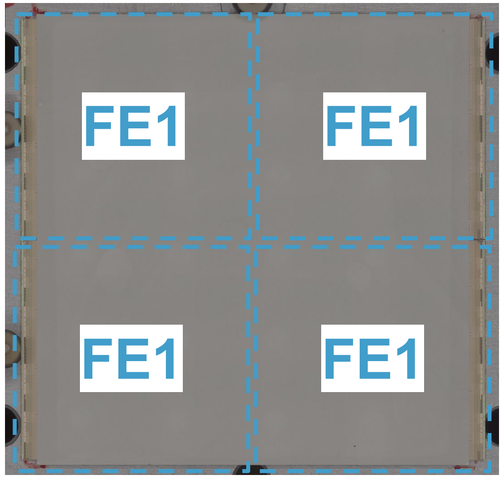


* Low-dropout regulator

Module hybridization and assembly

Bare Module

= sensor + 4 front-end chips
bump bonded



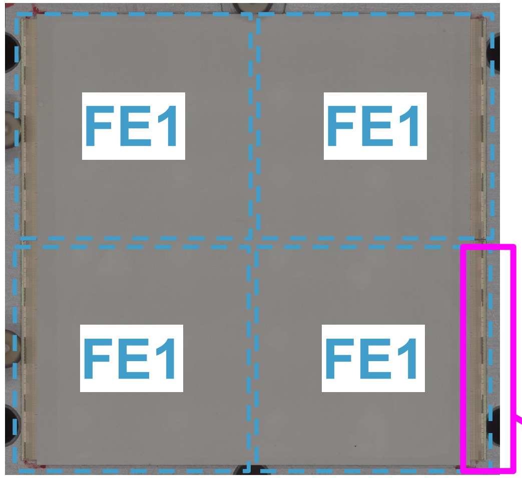
Key challenges: **unprecedented bump density** for ITk exceeds industry norms

- **Reduced sensor thickness:** 100-150 μm (vs. 250 μm in current ATLAS Pixel)
- **Thinner FE chip:** 150 μm (vs. 190 μm in current ATLAS Pixel)
- **5x increase in bump density** due to smaller pixel pitch (50 μm x 50 μm vs. 50 μm x 250 μm)
- 440 columns x 384 rows = 153,600 bump bonds / chip

Module hybridization and assembly

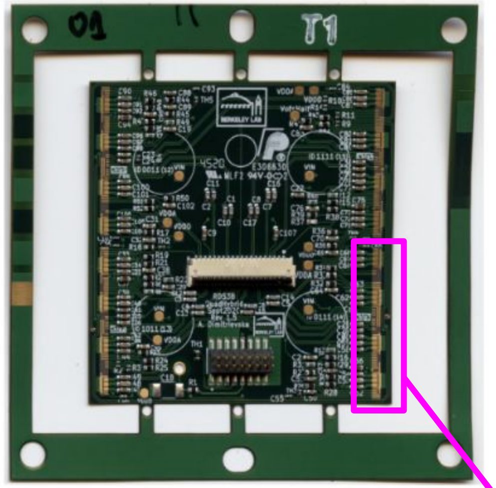
Bare Module *

= sensor + 4 front-end chips
bump bonded



+

Flex PCB *

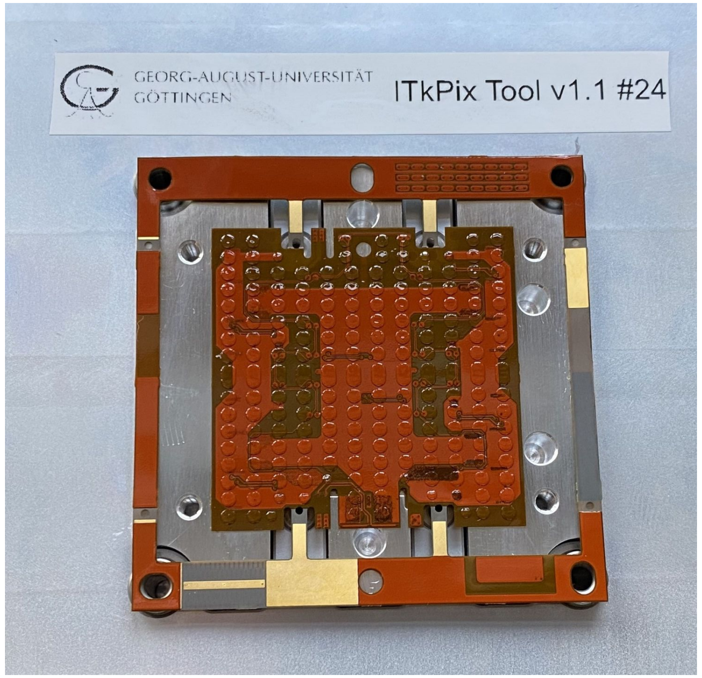


Flex PCB glued to the backside of the sensor tile then wirebonded to the front-end chips

→ Traces that carries commands/data/power interfaced with connectors to service

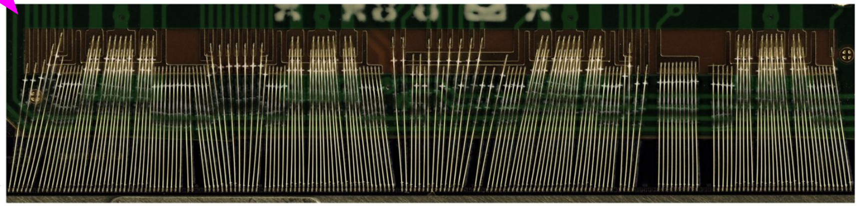
* **Bare module** and **Flex PCB** are provided by industry

ATLAS-PHOTO-2021-049



Flex PCB with a pattern of glue dots before attaching it to the chip-sensor assembly

ATL-ITK-PROC-2024-018



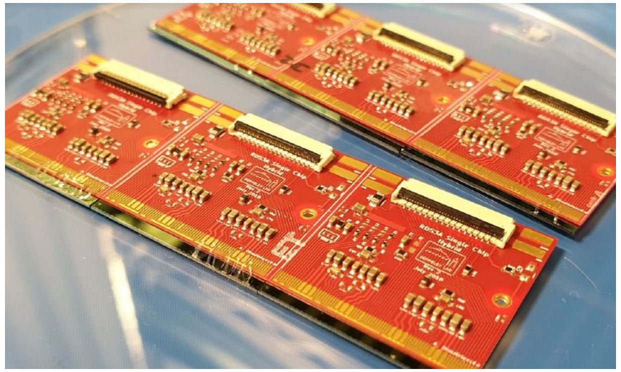
Wire bondings for one front-end chip

ITk Pixel Module

Module hybridization and assembly

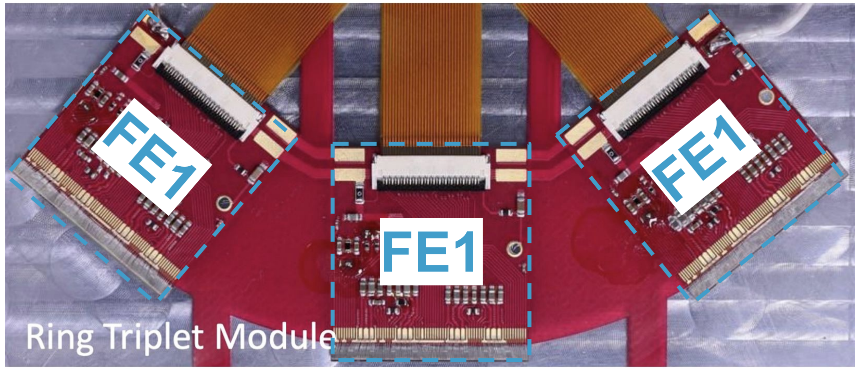
Barrel triplet module

(3 x 3D sensor)



Ring triplet module

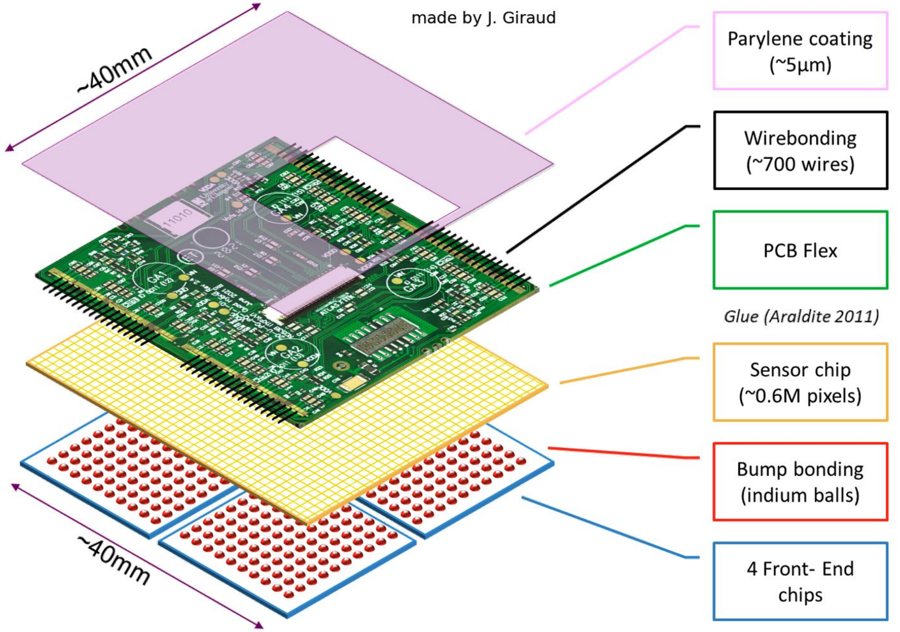
(3 x 3D sensor)



Quad module

(1 planar sensor)

ATL-ITK-PROC-2024-018



Parylene coating (~5μm)

Wirebonding (~700 wires)

PCB Flex

Glue (Araldite 2011)

Sensor chip (~0.6M pixels)

Bump bonding (indium balls)

4 Front- End chips

Flex PCB

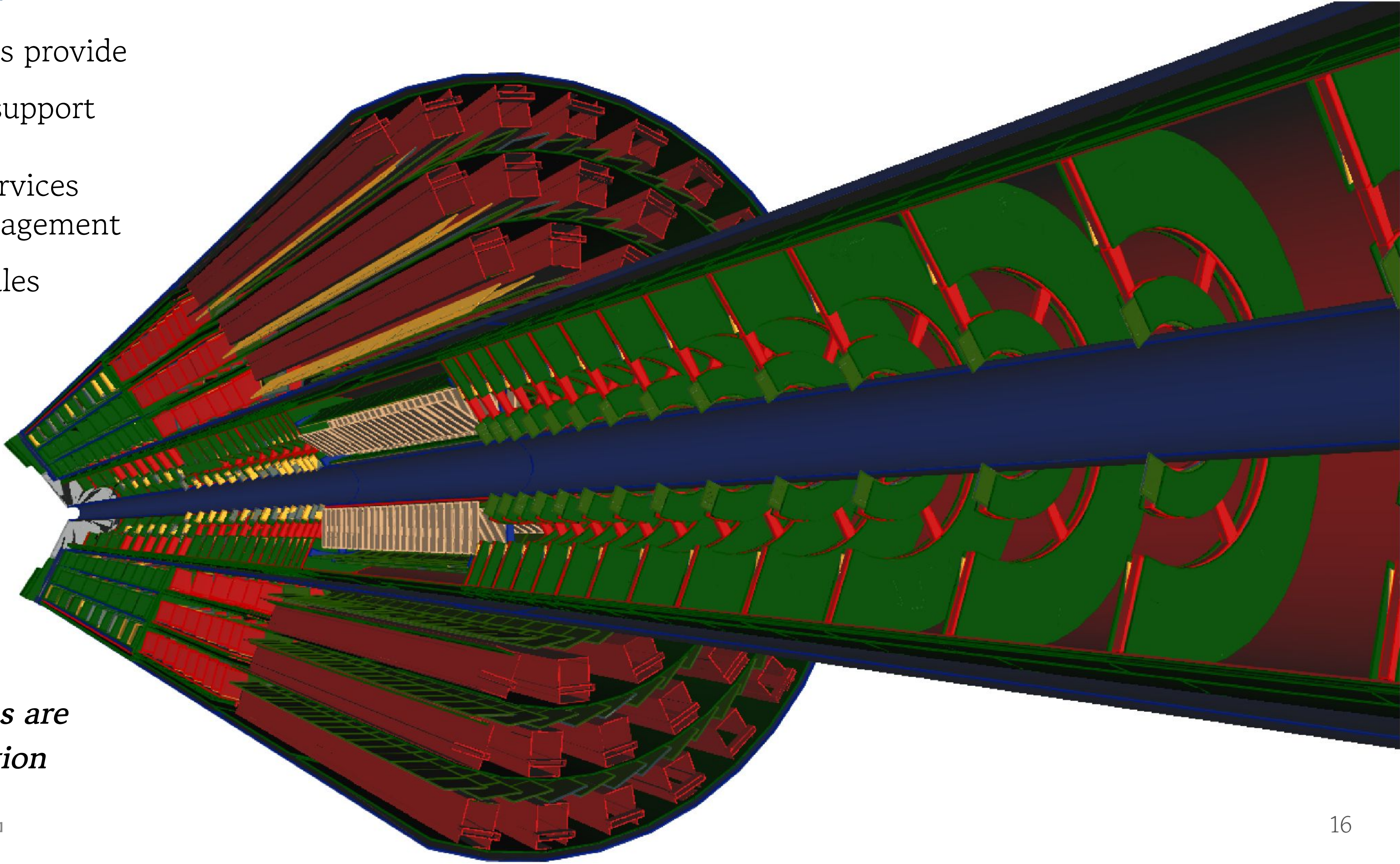
Bare Module

Local supports

The local supports provide

- mechanical support
- alignment
- routing of services
- thermal management

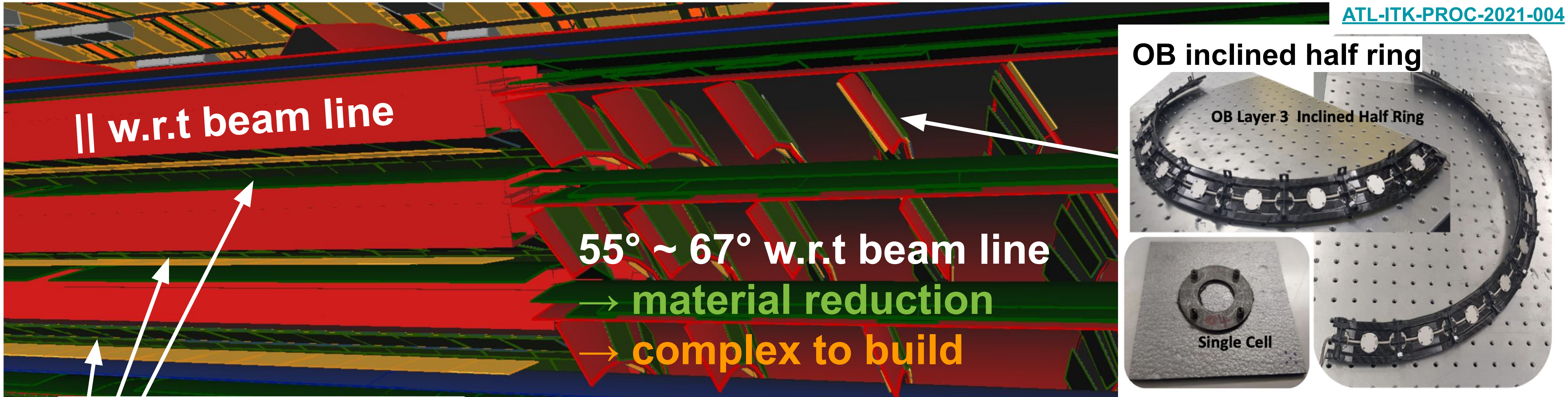
of the pixel modules



Support structures are specialized by region

Local supports: Outer Barrel

ATL-ITK-PROC-2021-004



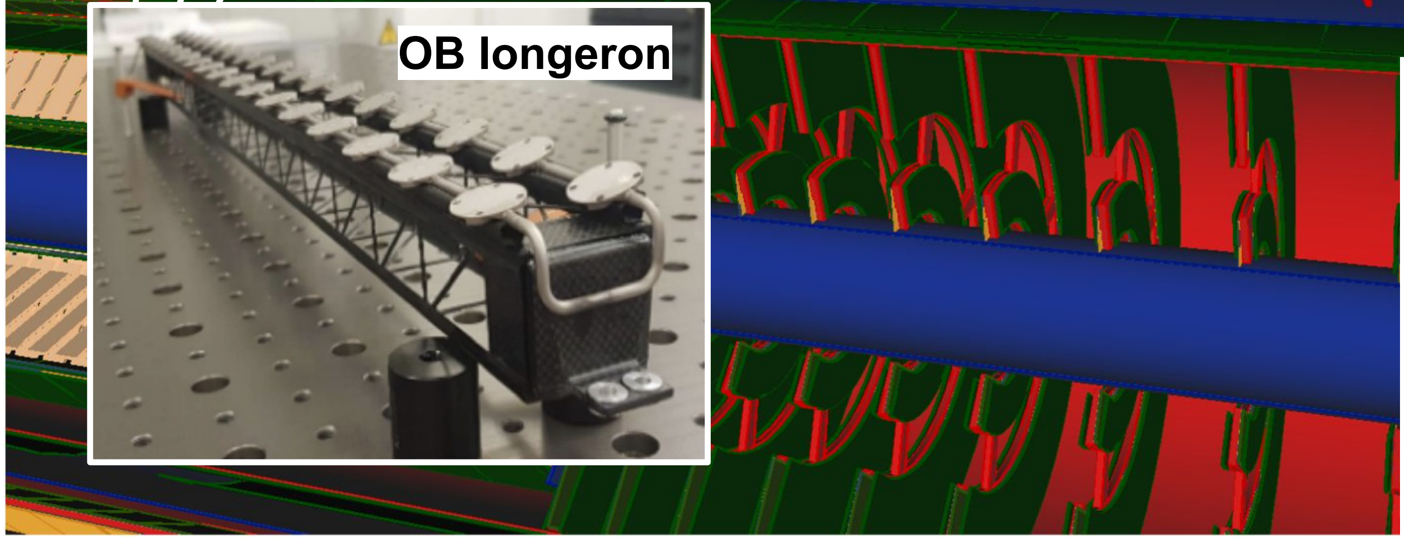
OB inclined half ring

|| w.r.t beam line

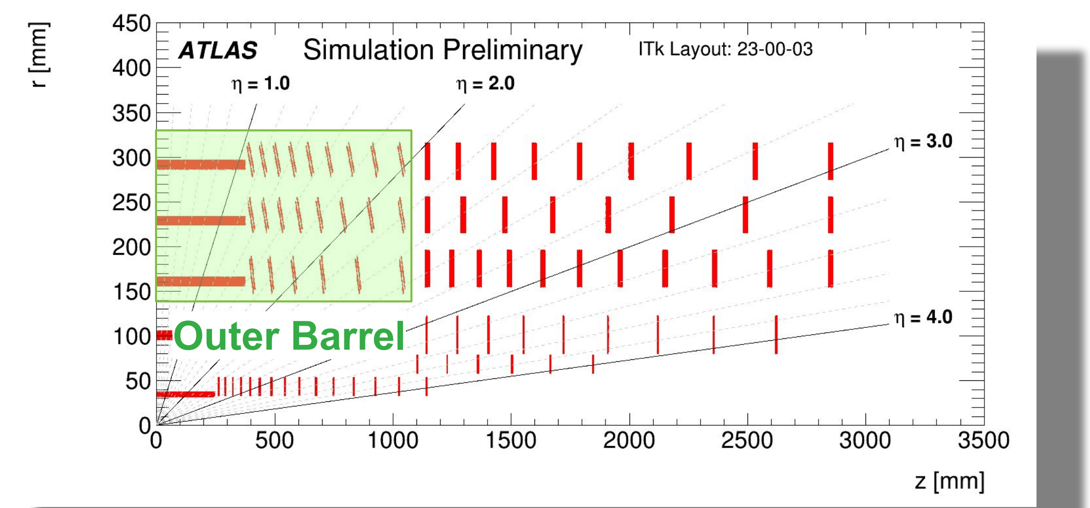
55° ~ 67° w.r.t beam line

→ material reduction

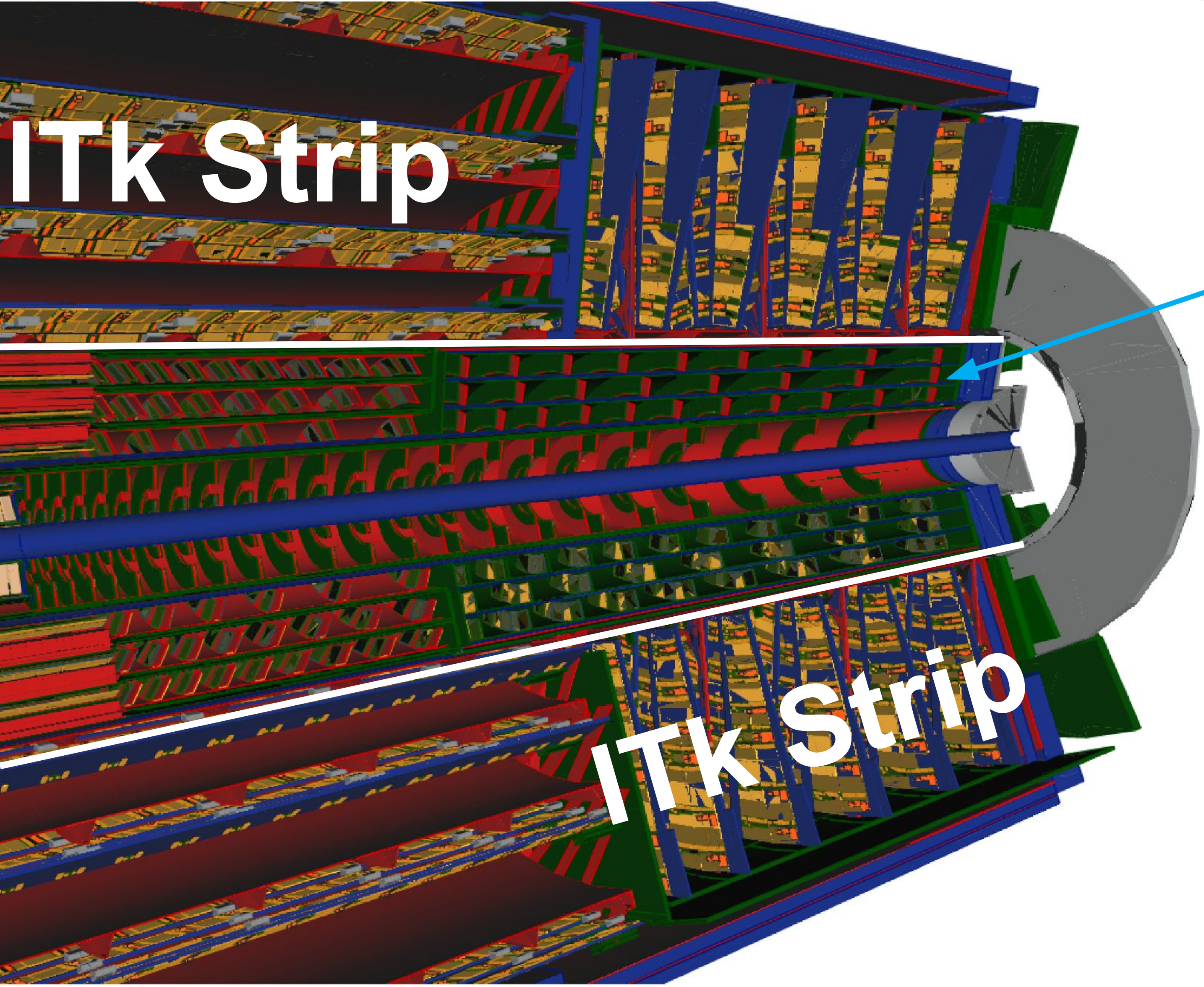
→ complex to build



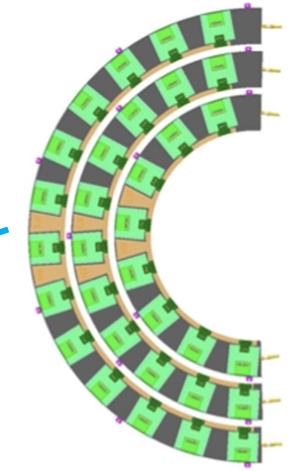
OB longeron



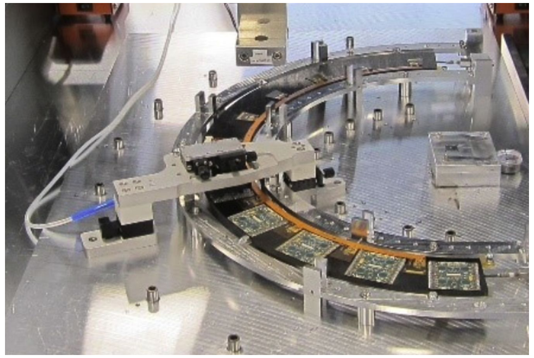
Local supports: Outer End-cap



ATL-ITK-PROC-2023-003

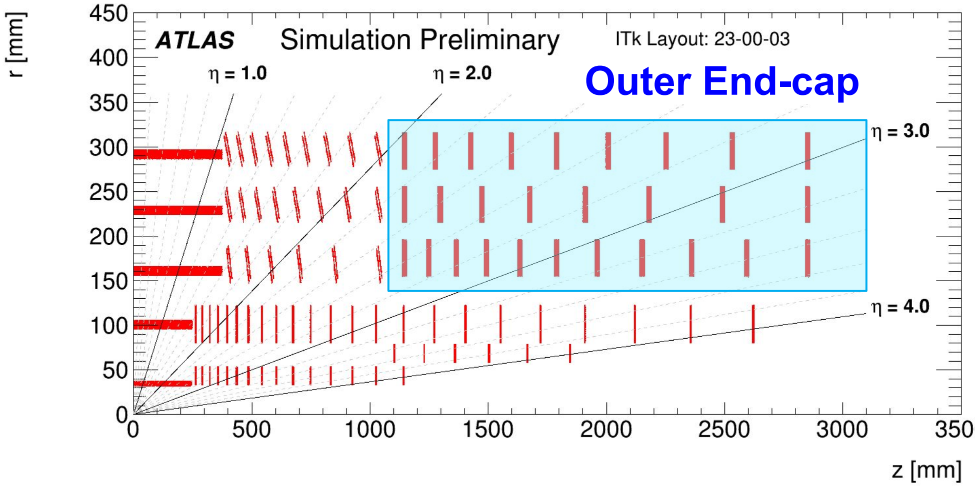


OEC half-ring



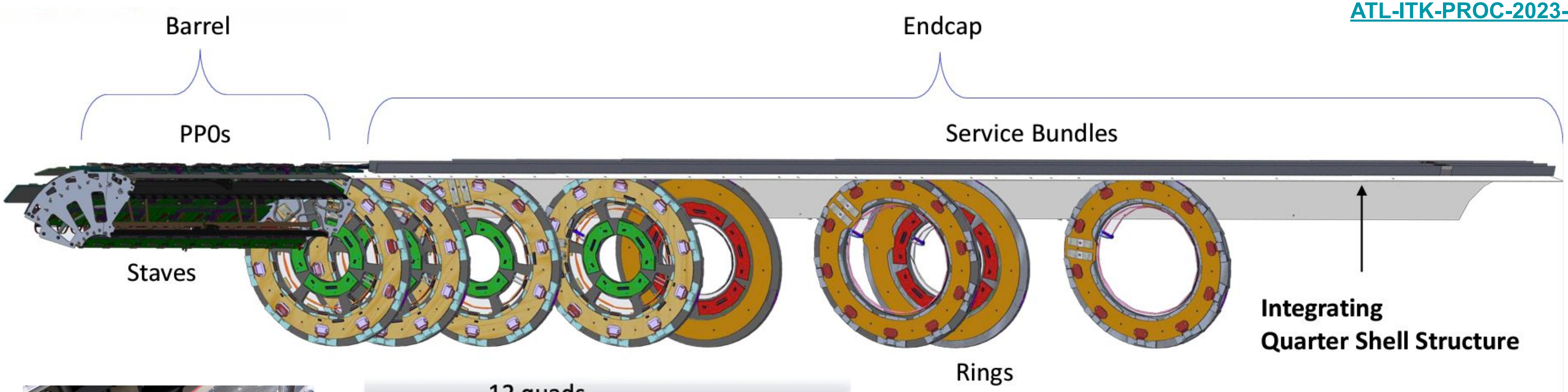
ATL-ITK-PROC-2024-024

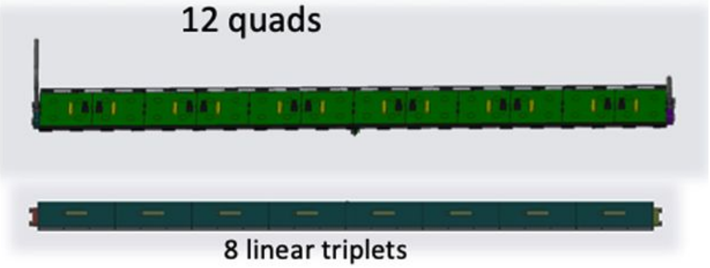
Identical structure & composition
three different R

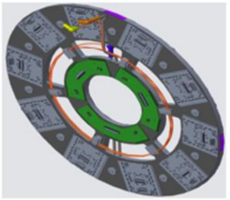


Local supports: Inner system

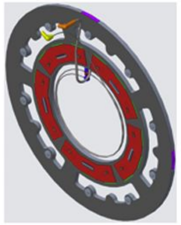
ATL-ITK-PROC-2023-003



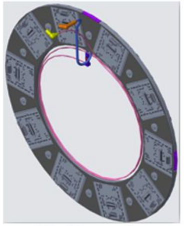




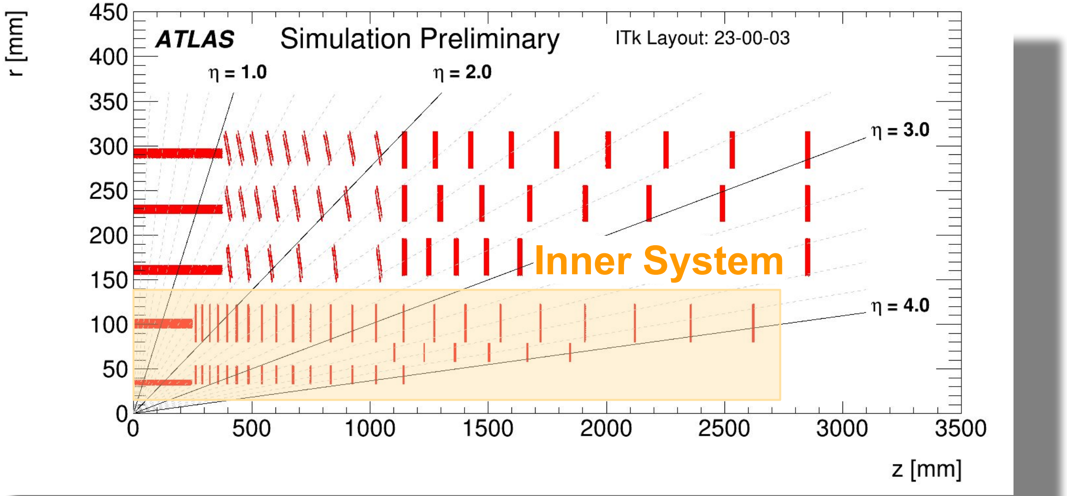
R0: 20 Quads and
6 triplets modules



R0.5: 10 triplets modules

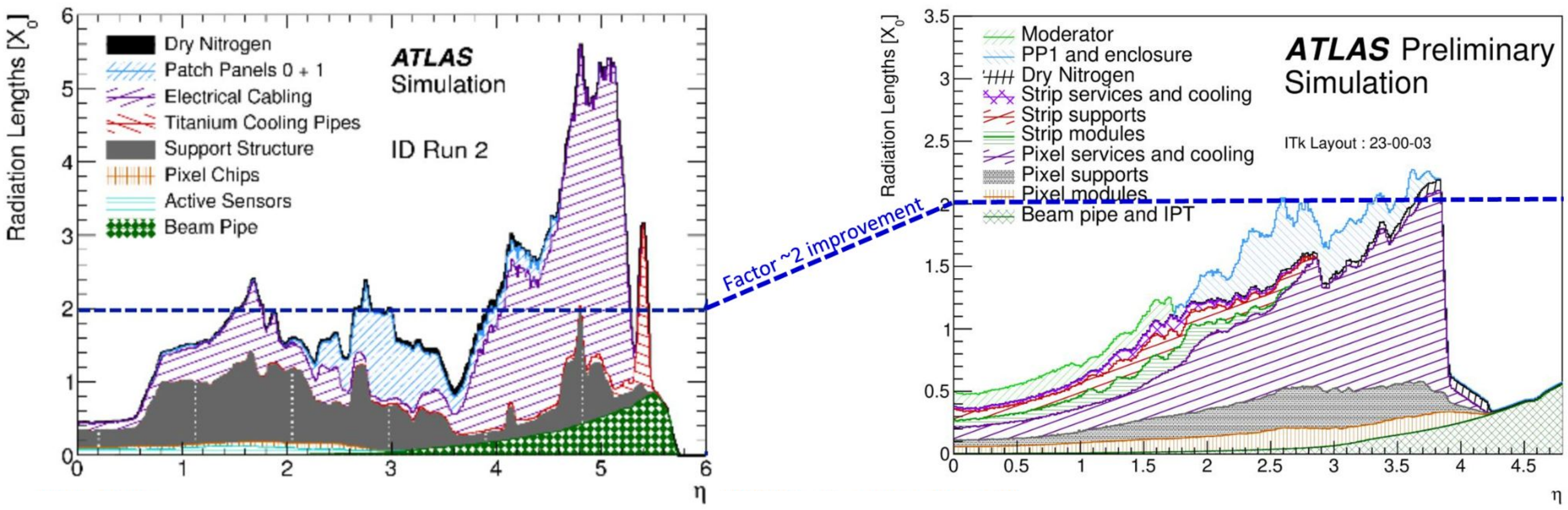


R1: 20 quads



Novel designs

- Low-mass carbon structures for mechanical stability and mounting
- CO_2 cooling with thin titanium pipes (high evaporation pressure, ~50 bar)
- Serial power chain and data link sharing reduced cabling
- Thin sensor and FE chips minimise materials in module



Production challenges for expended pixel system

Another significant challenge is the production rate the volume required for the substantially enlarged pixel system

- **Appropriate technology selections**
- **Well defined and documented procedures**
- **Centralized tools as much as possible:**
    - ITk Production Database (for entire ITk)
    - Local Database
    - ITk WebApp
    - Module QC tools
    - Site qualification
    - Data quality monitoring

ATLAS Collaboration Maps

Status: July 2024

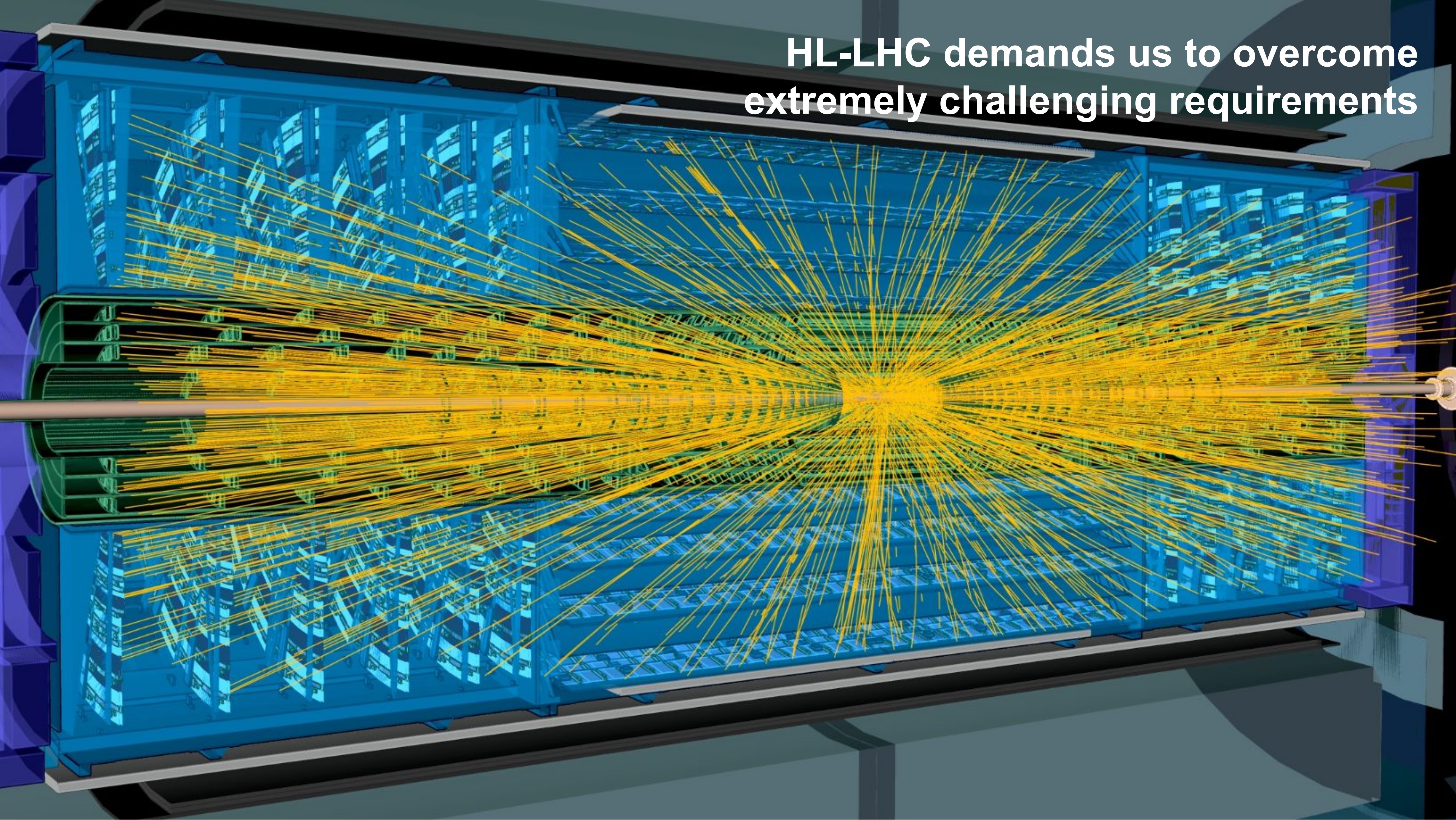
Argentina
Armenia
Australia
Austria
Azerbaijan
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Mongolia
Morocco
Netherlands
Norway
Palestine
Philippines
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Türkiye
UAE
UK
USA
CERN
JINR

ATLAS Collaboration

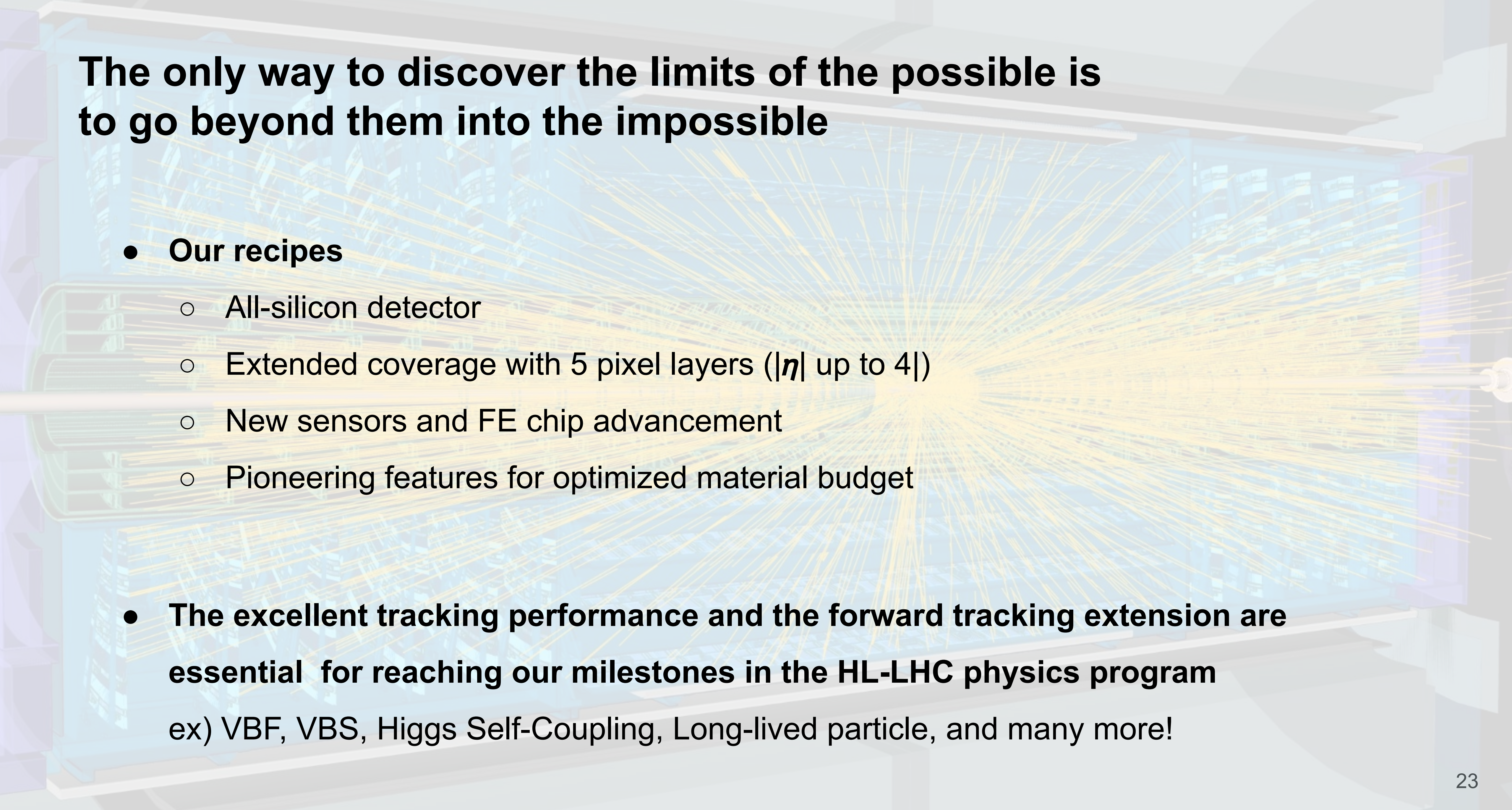
183 institutions (251 institutes) from 41 countries

XX institutions from YY countries for ITk Pixel Upgrade

HL-LHC demands us to overcome extremely challenging requirements



The only way to discover the limits of the possible is to go beyond them into the impossible



- **Our recipes**
    - All-silicon detector
    - Extended coverage with 5 pixel layers (|η| up to 4|)
    - New sensors and FE chip advancement
    - Pioneering features for optimized material budget

- **The excellent tracking performance and the forward tracking extension are essential for reaching our milestones in the HL-LHC physics program**

  ex) VBF, VBS, Higgs Self-Coupling, Long-lived particle, and many more!