https://cds.cern.ch/record/910381

ATLAS' Inner Tracker: A Silicon Detector for the High Luminosity LHC Era

HANNAH E. HERDE • LUND UNIVERSITY ~ SCIENCE COFFEE • 29 NOVEMBER 2022

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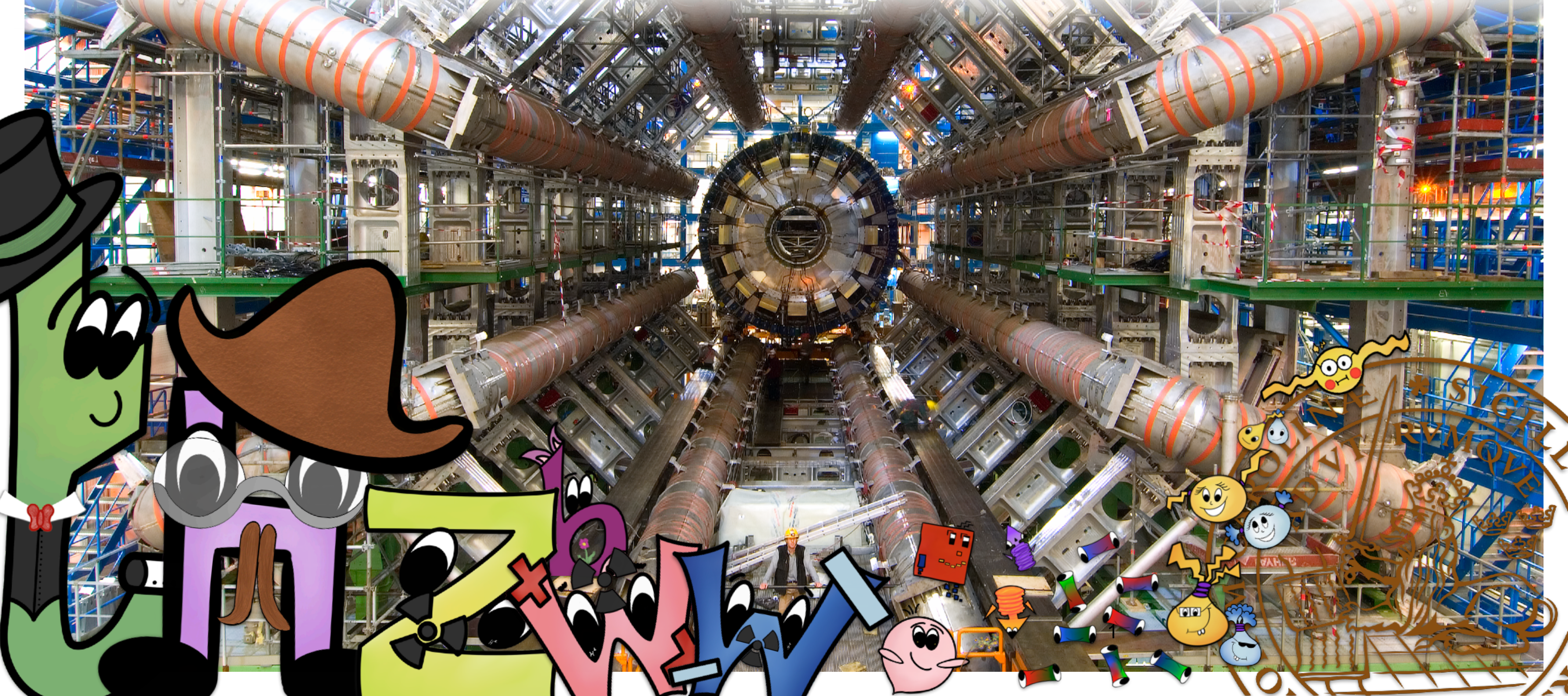
ATLAS ITk

ATLAS EXPERIMENT



Cloud chambers, 1910-1950s

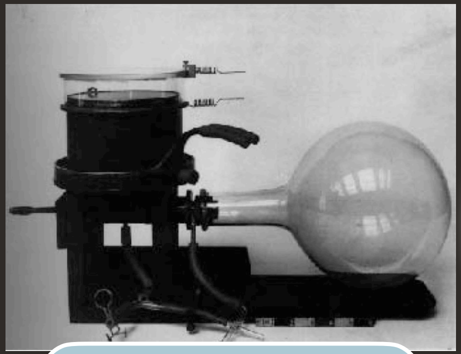
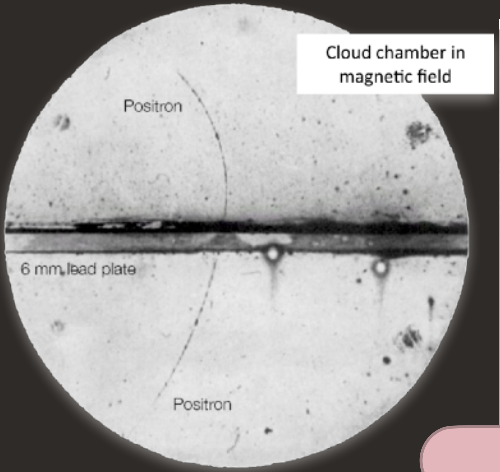


Table top

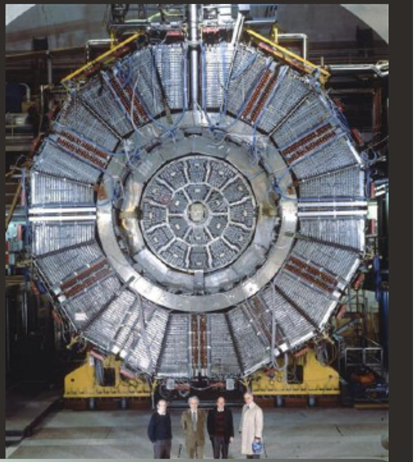


Spark chamber, 1960s

Room-sized

UA2, 1981-1993

ALEPH, 1989-2000



Multistory

- BCE Atomism: Philosophers in Ancient India & Greece: nature has indivisible units
- 1800 "Heat waves" (photons) Begins gradual discovery of full EM spectrum
- 1897 Electron
- 1899 Alpha particle
- 1911 Atomic nucleus
- 1919 Proton
- 1932 Neutron, positron
- 1937 Muon
- 1947 π, K, Λ
- 1956 Neutrino: Electron antineutrino found in beta decays
- 1962 Muon neutrino
- 1969 Partons observed: Quark theory confirmed in deep inelastic scattering experiments at SLAC
- 1974 J/ψ Charm quark
- 1975 Tau lepton
- 1977 Υ Bottom quark
- 1979 Gluon
- 1983 W, Z bosons
- 1995 Top quark
- 2000 Tau neutrino
- 2012 Higgs boson

created with VIZZLO

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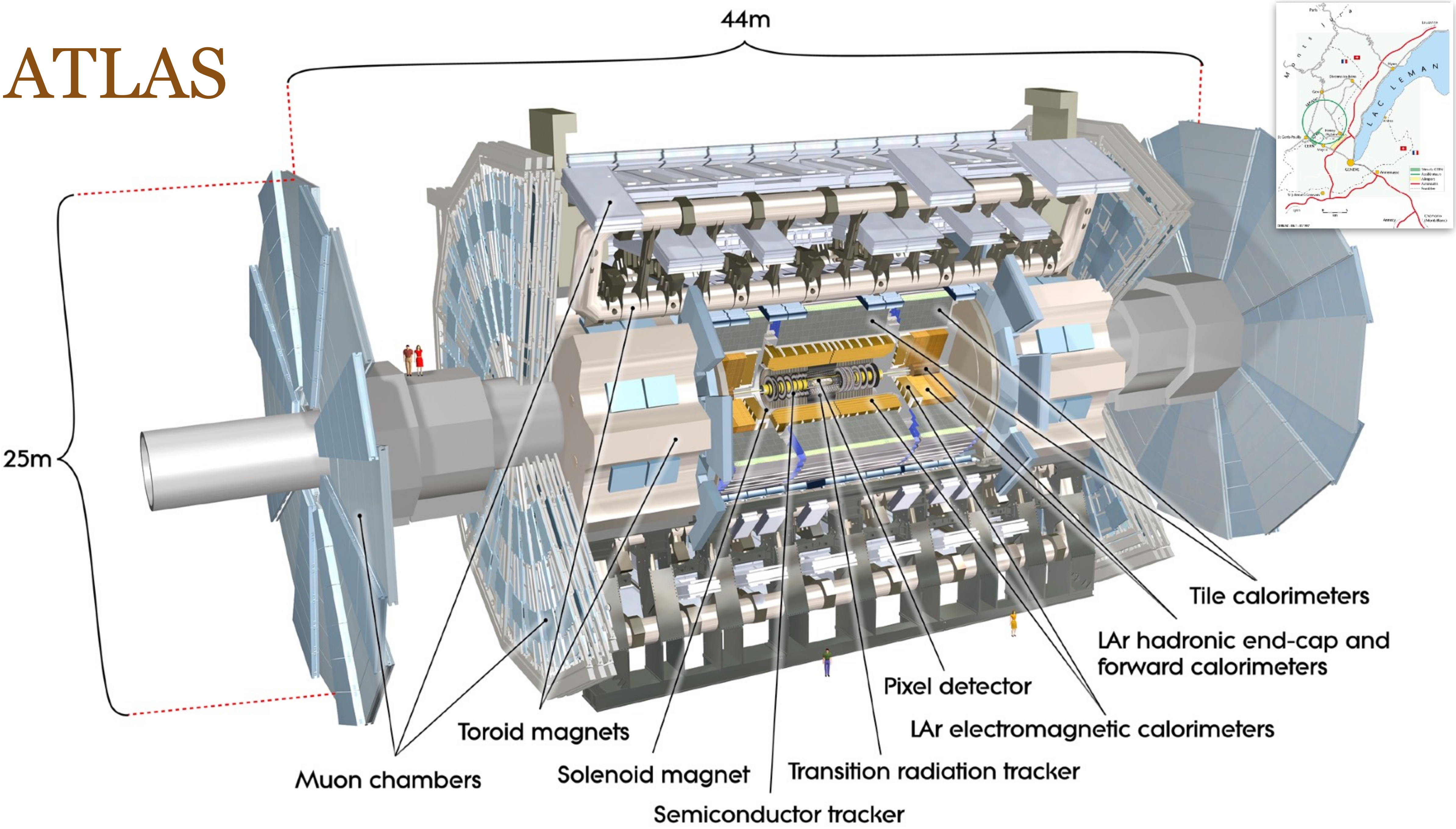
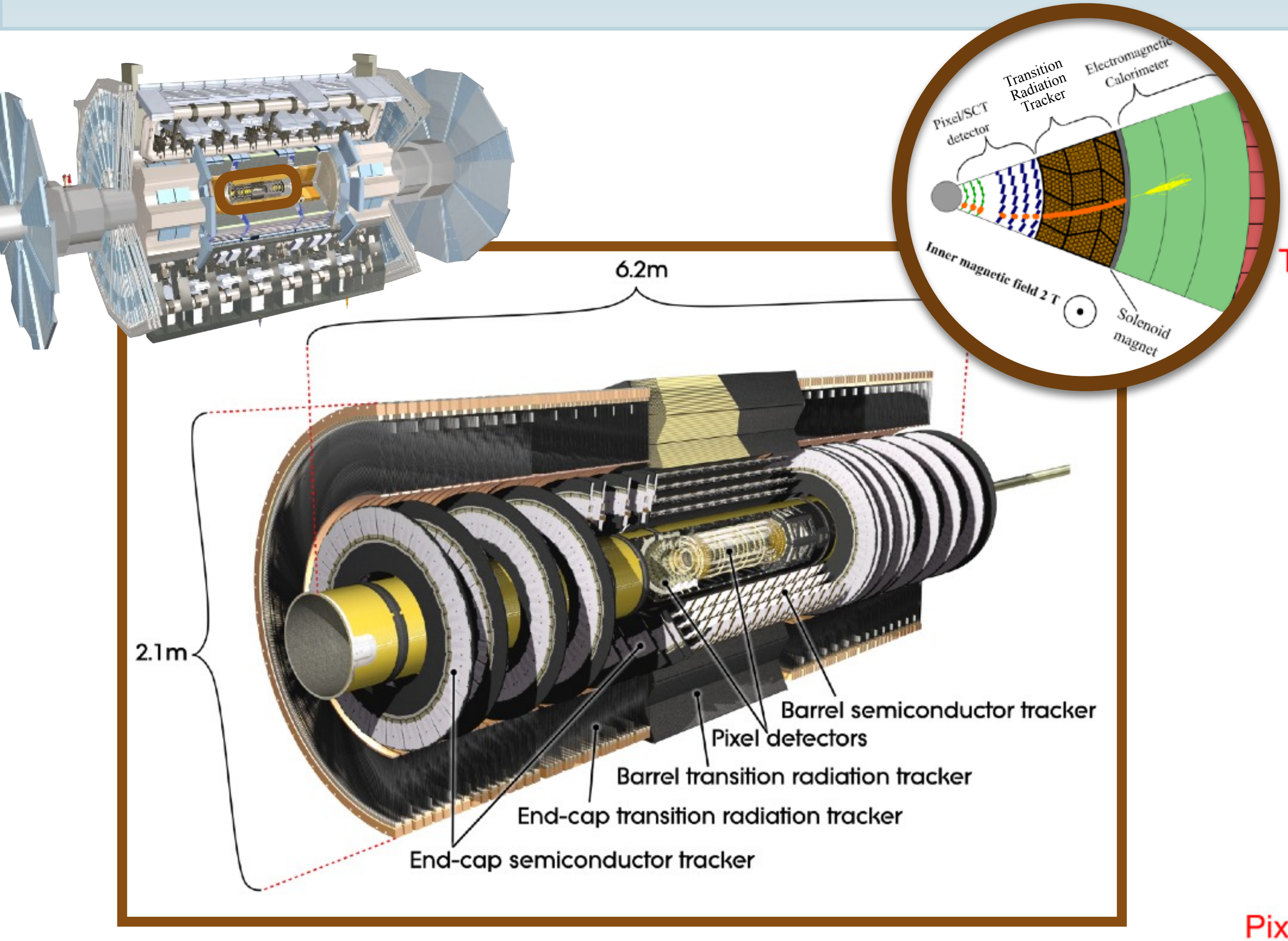
Cartoons: H. Herde 2018-2022; cloud chamber, spark chamber: http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L1_Introduction_HEPdetectors.pdf; UA2: https://cds.cern.ch/record/615821; ALEPH

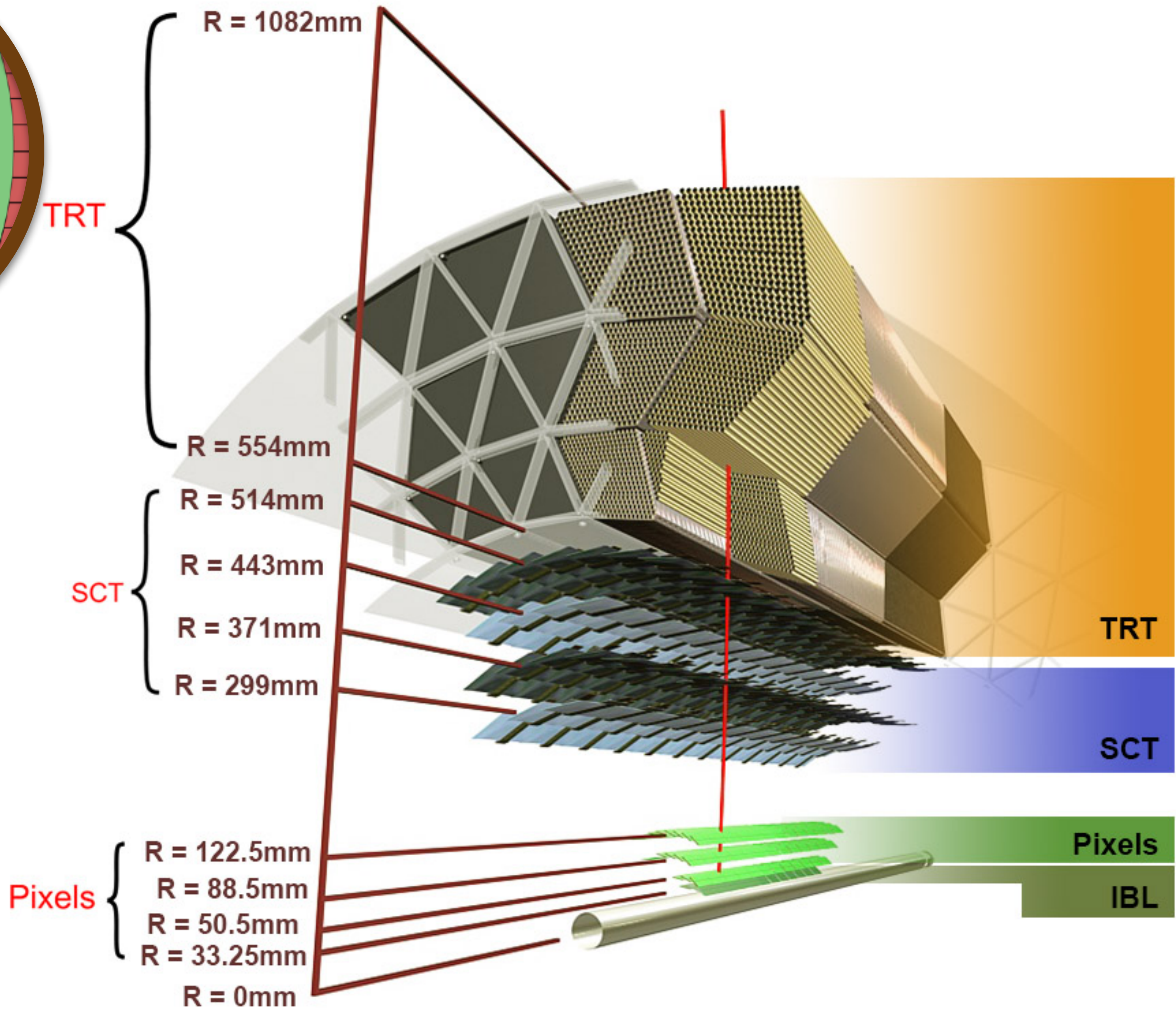
ATLAS



📷 https://cds.cern.ch/record/1095924; Geneva region & LHC map (top right inset): https://cds.cern.ch/record/842399

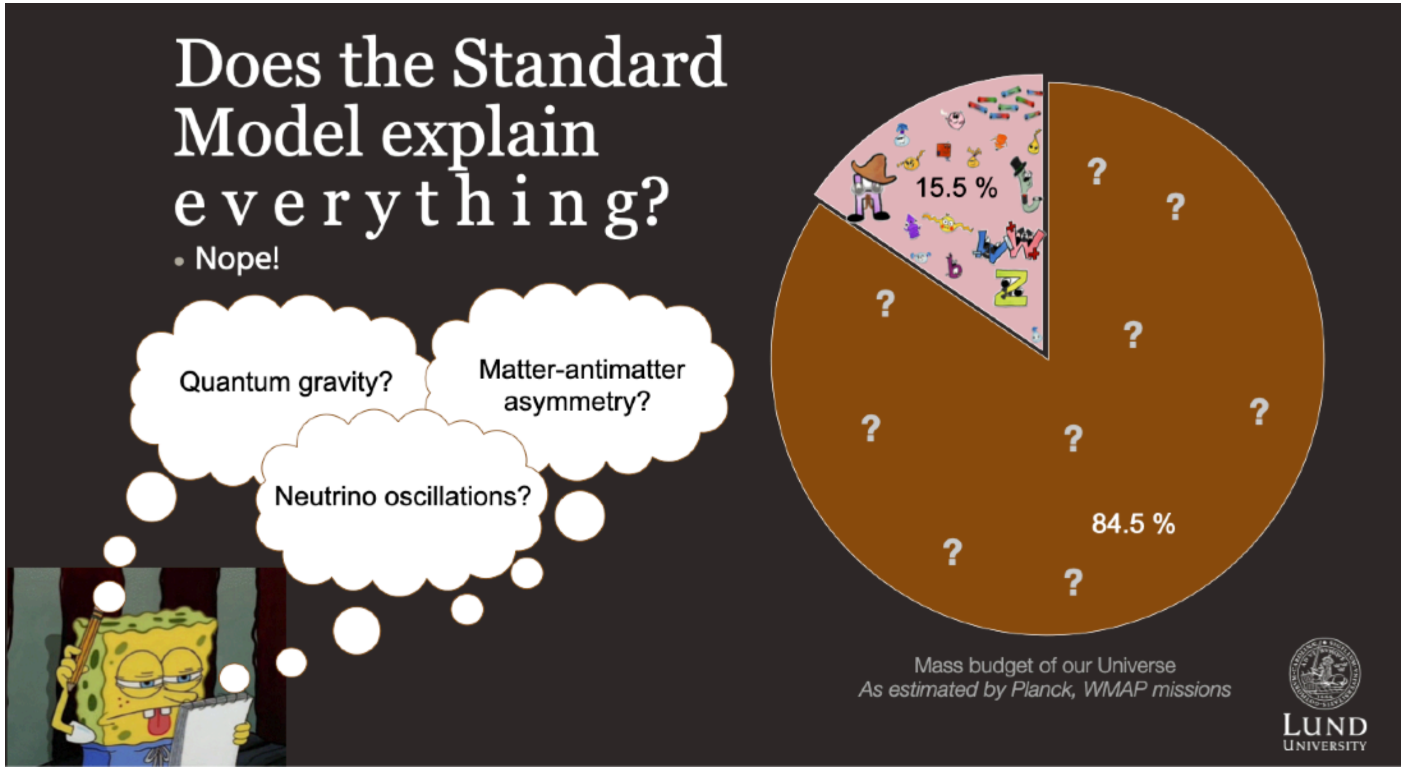
Inner Detector: Charged particle tracking





📷 Labeled Inner Detector: https://cds.cern.ch/record/1095926
Round inset adapted from T Herrmann, O Jařábek, K Jende, M Kobel
Schematic view of ATLAS Inner Detector, including IBL (right): https://cds.cern.ch/record/2773132/plots

Tools for deepening our understanding of the Universe



Answering these questions requires constant innovation

2 main ways to increase search power

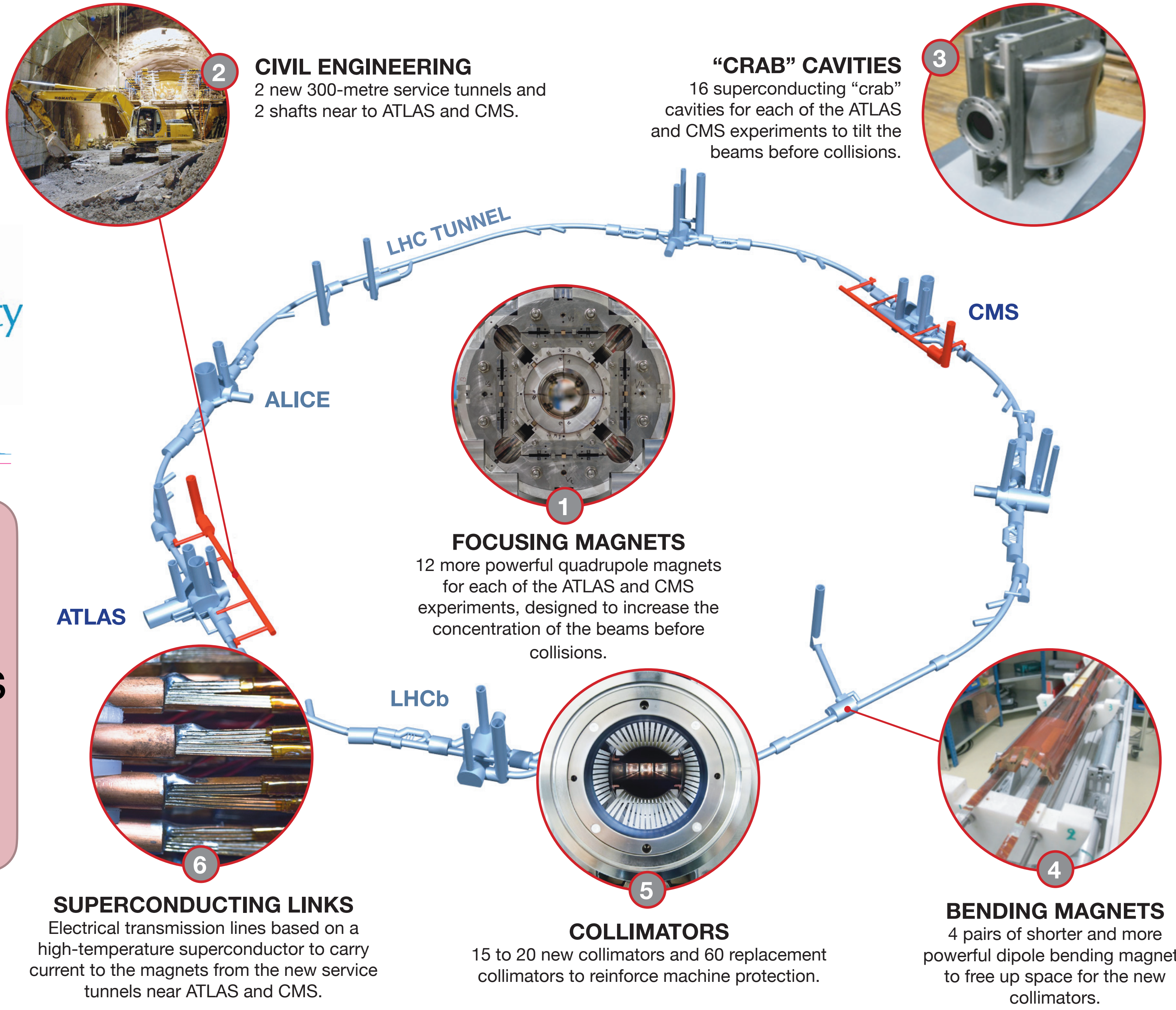
1. Increase collision energy
    - LHC Run 1 (2010-2012): 7-8 TeV
    - LHC Run 2 (2015-2018): 13 TeV
    - LHC Run 3 (2022-): 13.6 TeV
2. Collide more particles faster to sample more of the Universe's distribution

High Luminosity LHC

The HiLumi LHC Design Study (a sub-system of HL-LHC) is cofunded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404

Mission:

Collide more protons per bunch crossing than ever before



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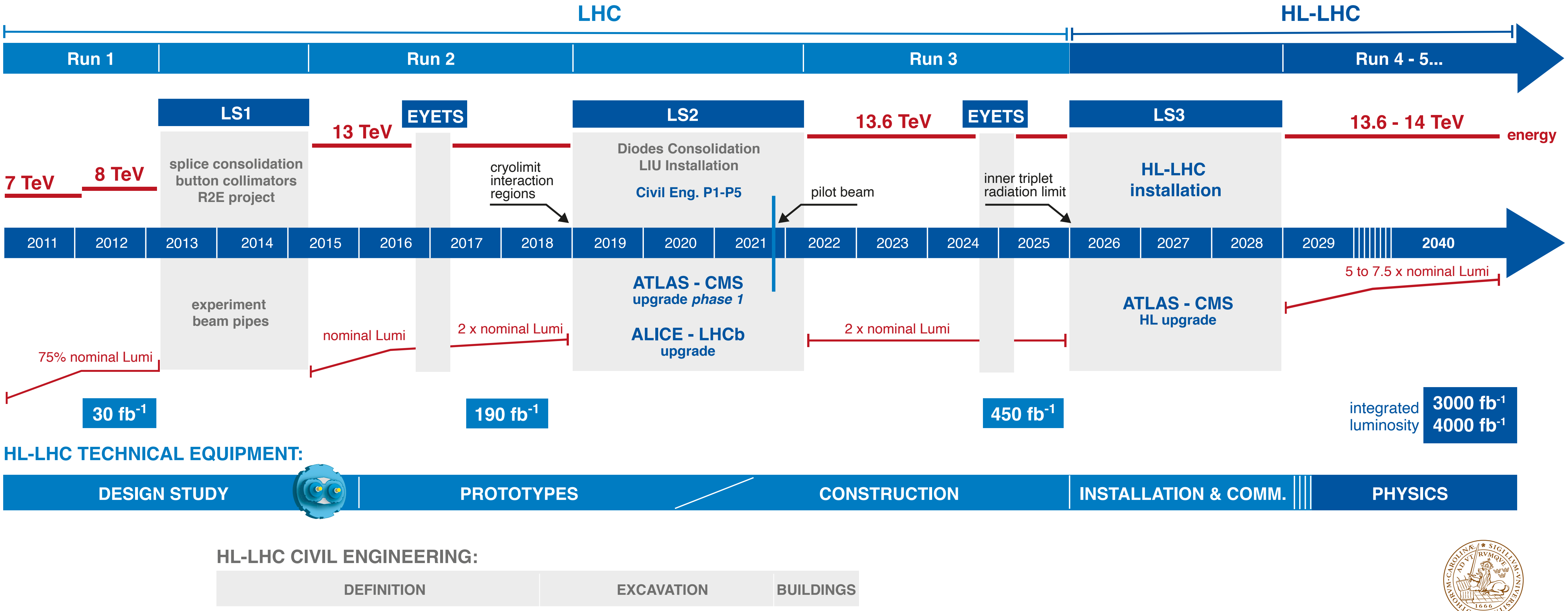
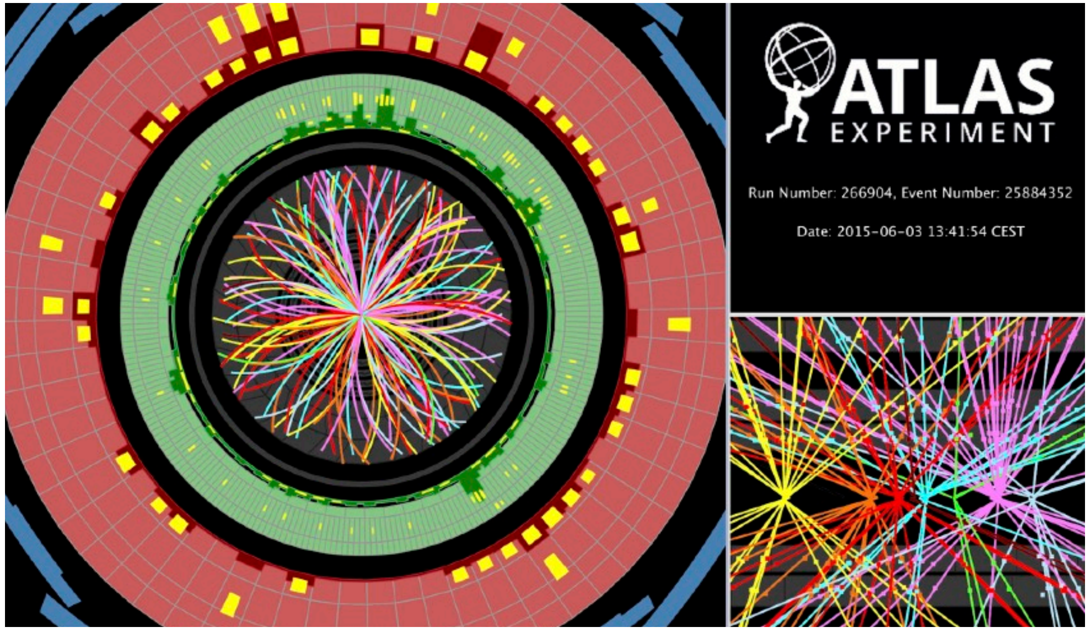
https://cds.cern.ch/record/2156246

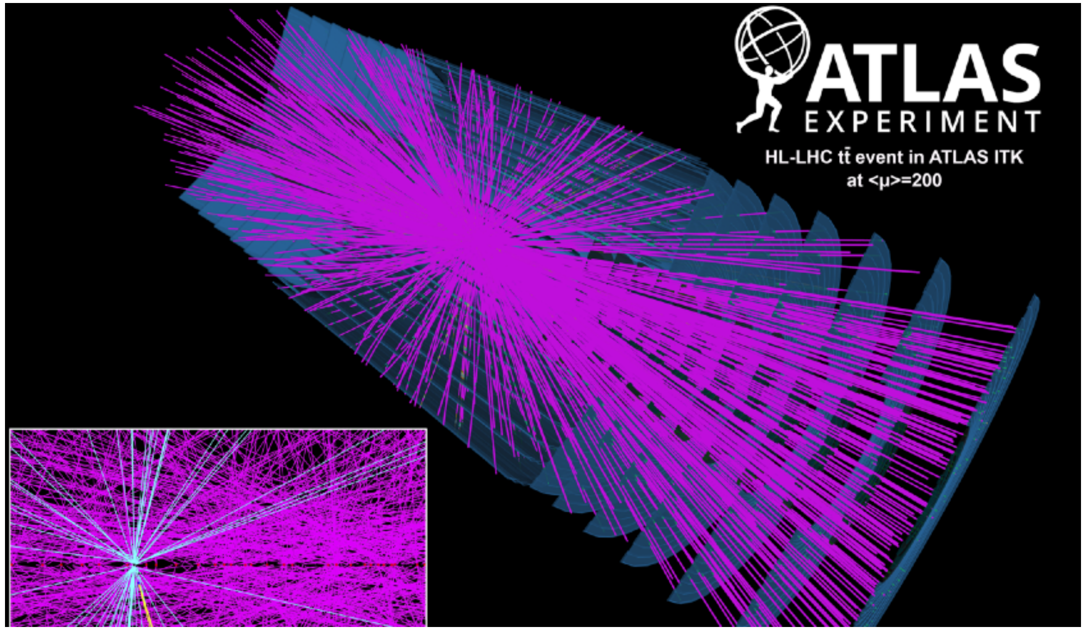
LHC / HL-LHC Plan



HL-LHC schedule, baselined January 2022 and reconfirmed March 2022; https://hilumilhc.web.cern.ch/sites/default/files/HL-LHC_Janvier2022.pdf

We need a new detector.





LHC

Designed for **~20-30 collisions** each time we cross proton beams

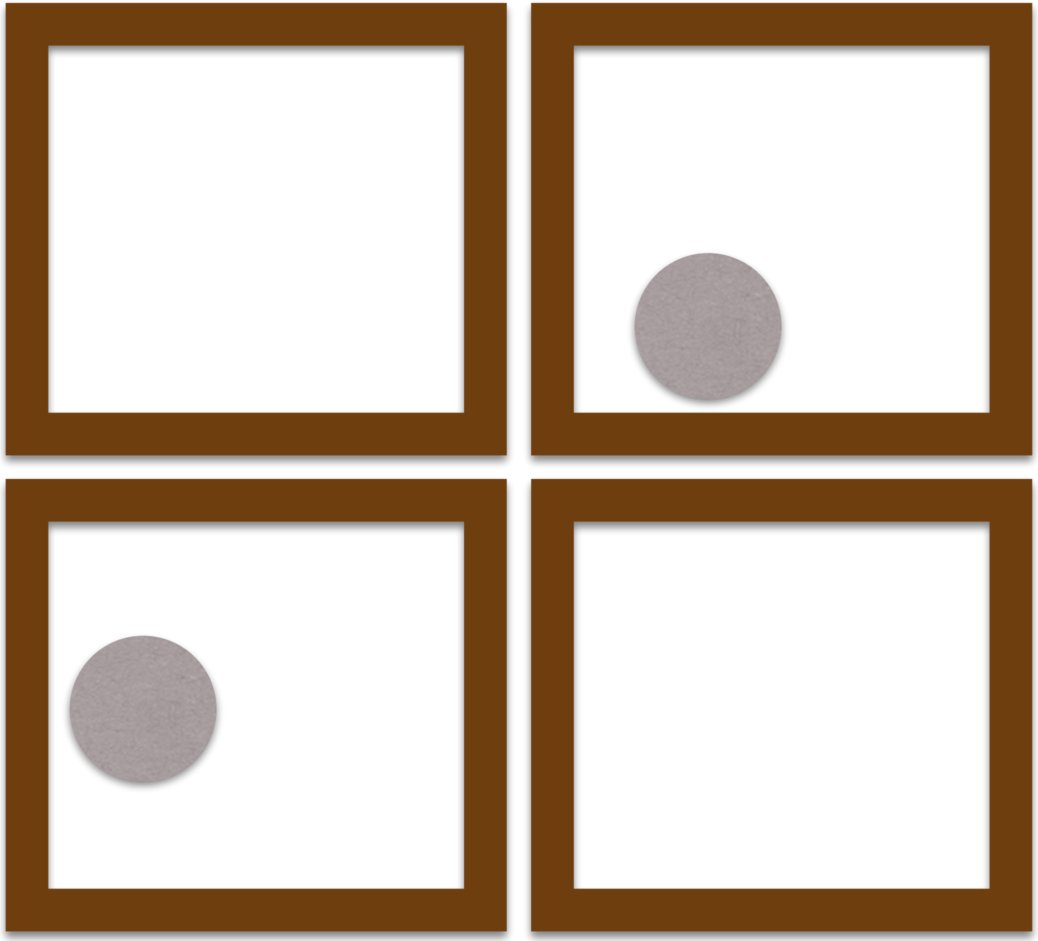
High Luminosity LHC, HL-LHC

Designed for **~200 collisions** each time we cross proton beams

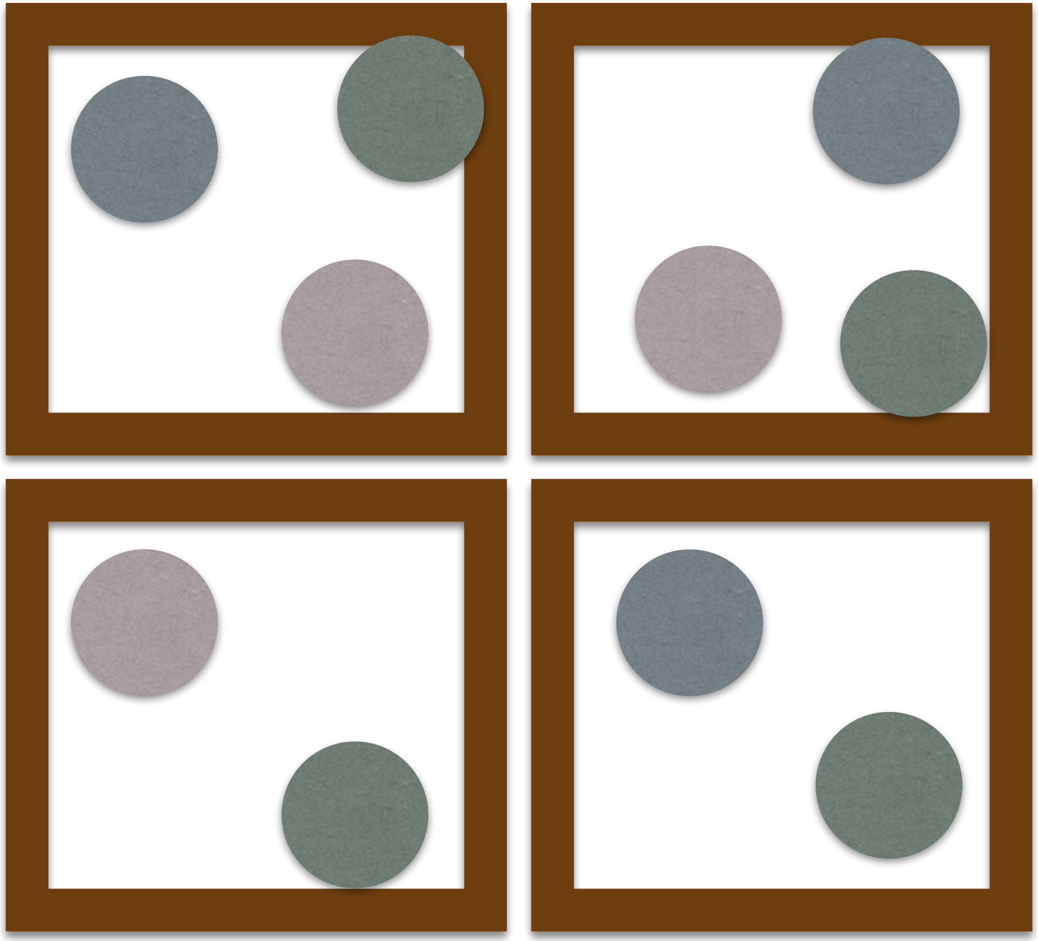
📷 First stable beams at 13 TeV, https://cds.cern.ch/record/2022598; HL-LHC pileup simulation in ATLAS ITk, https://twiki.cern.ch/twiki/pub/AtlasPublic/UpgradeEventDisplays/HL-LHC-tt.png

Detector occupancy

Low occupancy: Particles clearly distinguishable

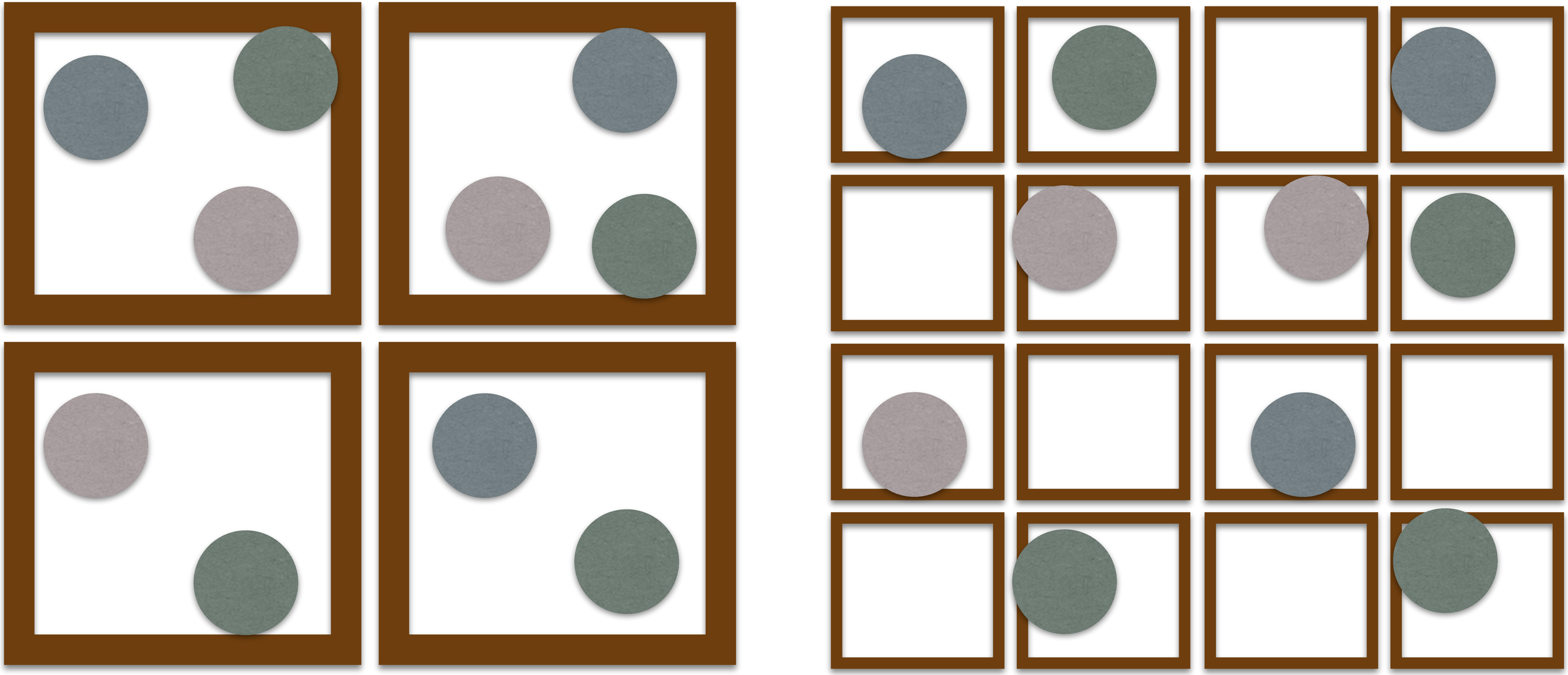


High occupancy: Particle signals overlap

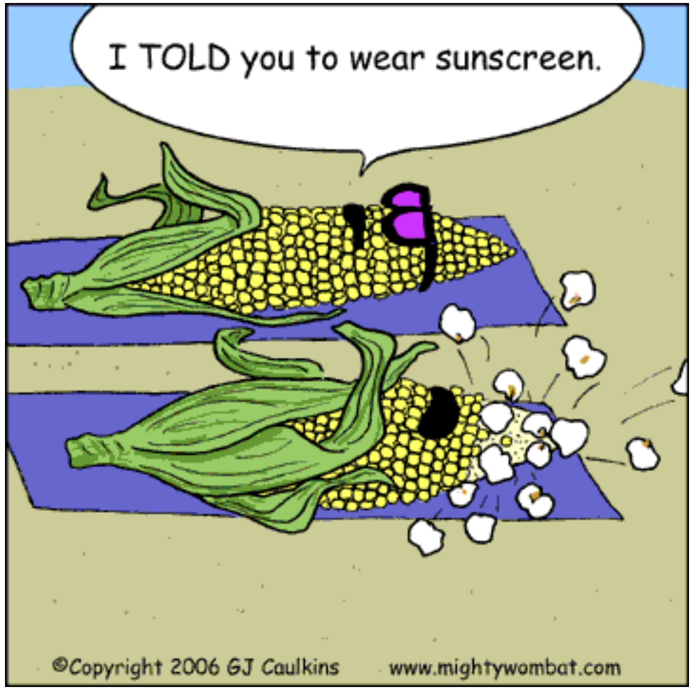


Detector occupancy

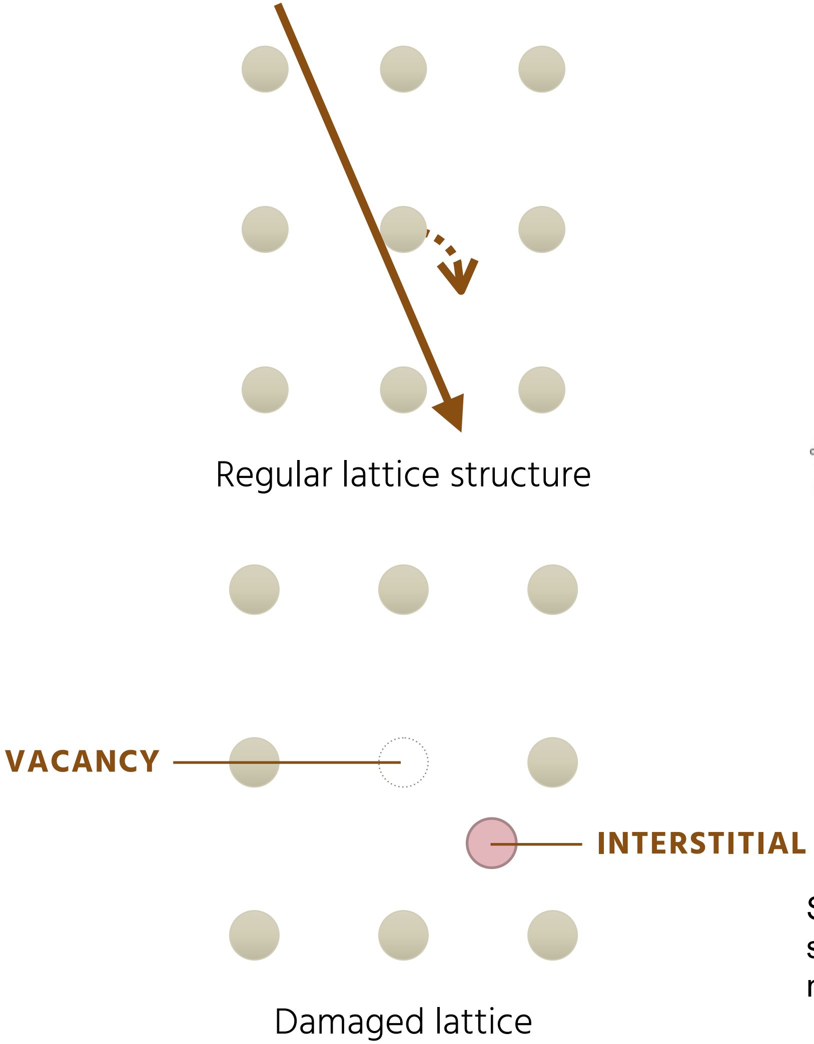
Solution: Increase detector density in given area

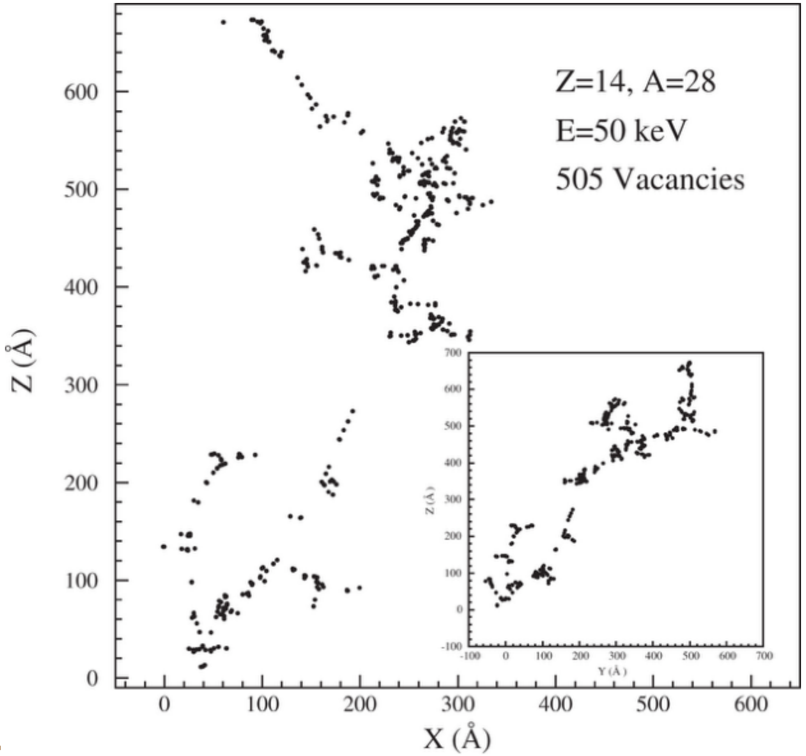


Radiation damage



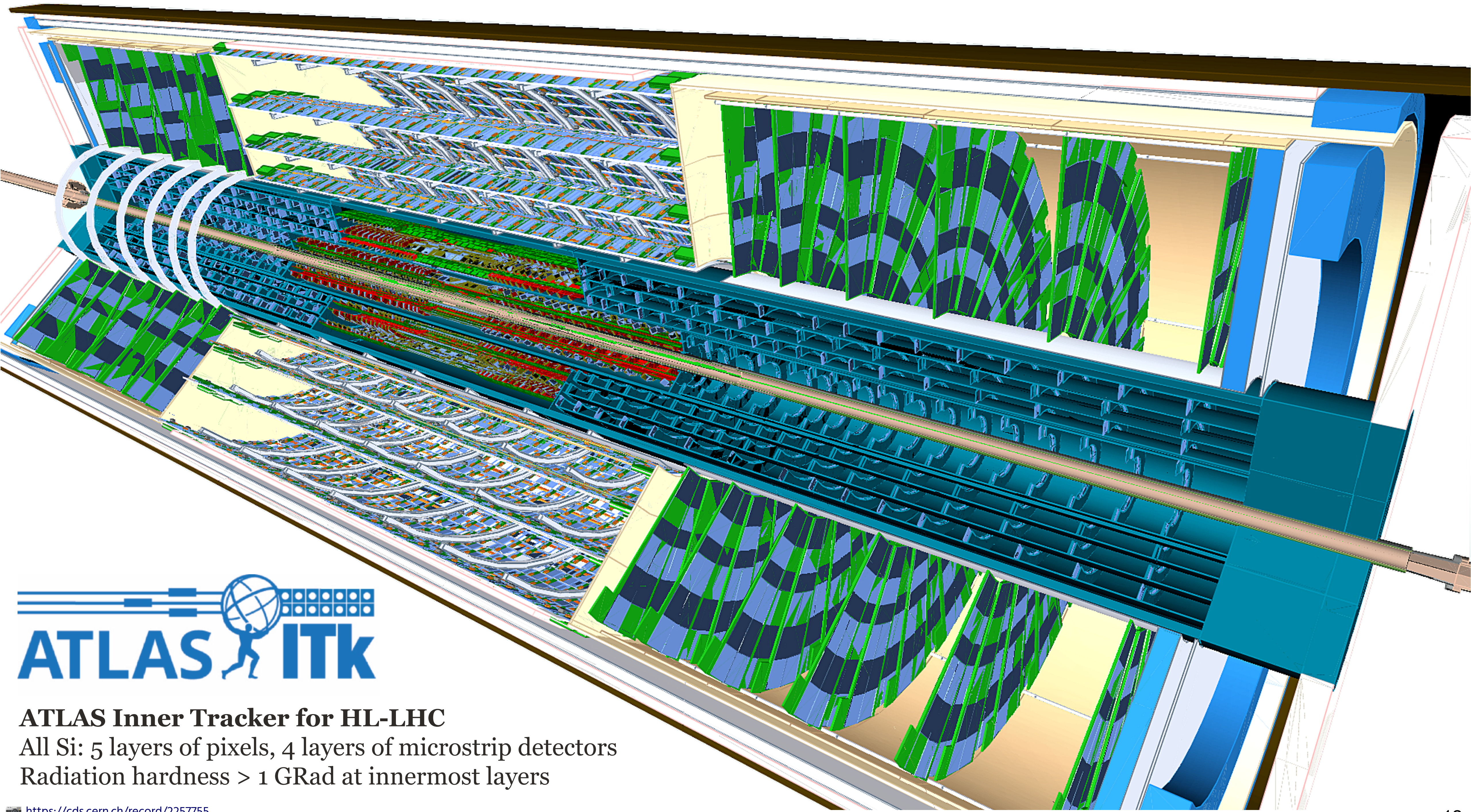
An everyday menace





Simulated distribution of vacancies created by a 50 keV silicon ion in silicon (typical recoil energy for 1 MeV neutrons)

Left: GJ Caulkins, https://www.mightywombat.com/2006
Center: M. Huhtinen (CERN). Nucl. Instrum. Meth. A 491 (2002) 194-215
Right: Based on https://cerncourier.com/a/raising-the-dead-detectors/



ATLAS ITk

ATLAS Inner Tracker for HL-LHC

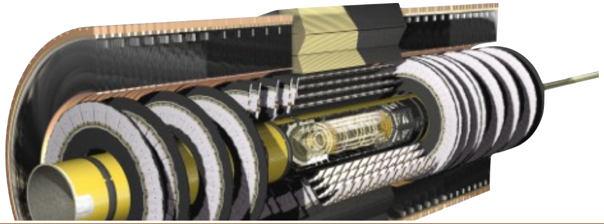
All Si: 5 layers of pixels, 4 layers of microstrip detectors

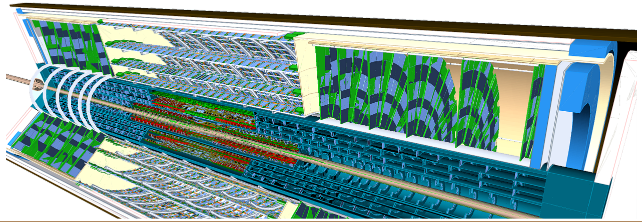
Radiation hardness > 1 GRad at innermost layers

https://cds.cern.ch/record/2257755

How much of an "upgrade" *really* is ITk?

Comparing ATLAS' current Inner Detector and future Inner Tracker

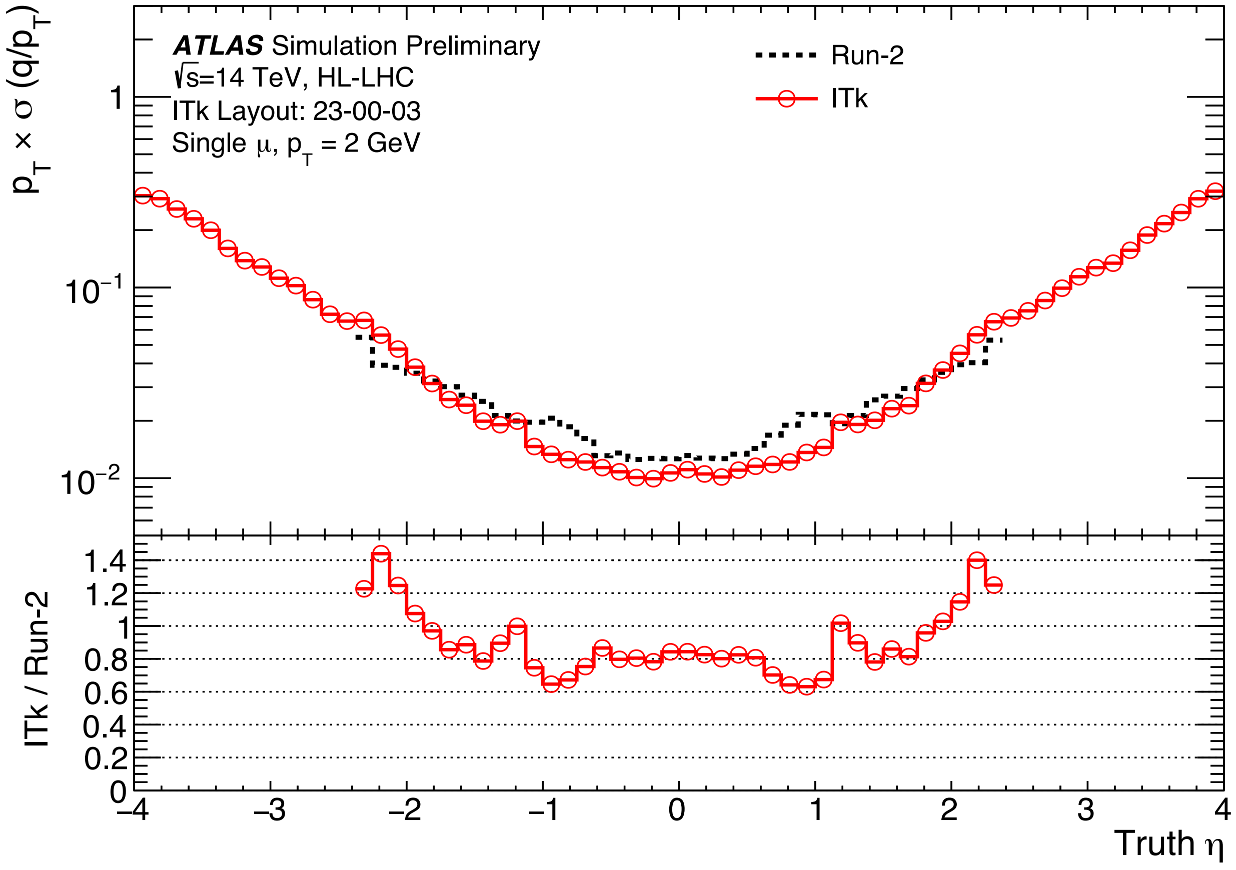




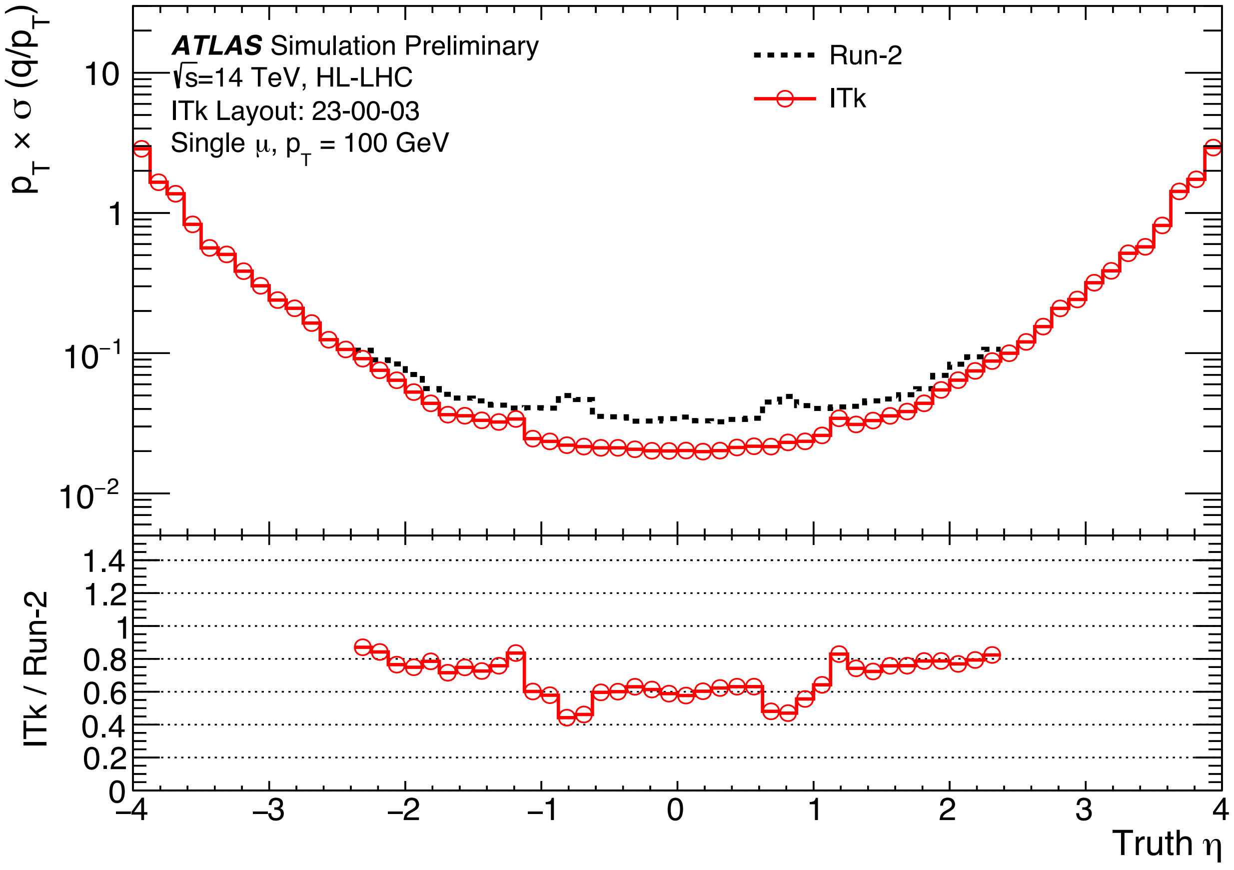
	Inner Detector (ID)	Inner Tracker (ITk)	
Detector layers	Si (pixels, strips) & gas trackers	Si trackers (pixels, strips)	
Coverage, |η|	<2.5 (pixels & strips), <2.0 (TRT)	<4.0 (pixels), <2.7 (strips)	
Trigger rate	100 kHz	1 MHz	x10
	Pixel detector	ITk Pixels	
№ of Pixels	92 million (80M Pixel + 12M IBL)	5 billion	x55
Pixels silicon area	1.9 m^2	12.98 m^2	x6.5
Pixel size	50x250 µm (IBL), 50x400 µm, 50x600 µm	50x50 µm, 25x100 µm	Smaller
	SCT	ITk Strips	
№ of Strips	6.2 M	59.9 M	x10
Strips silicon area	61 m^2	165 m^2	x10
Pitch	80 µm	75.5 µm	Strips smaller and closer together
Strip length	12.8 cm	2.4-4.8 cm	

Learn more:
ATLAS Detector:
2008 JINST 3 S08003
IBL Technical Design Report (TDR): CERN-LHCC-2010-013
ITk Pixels TDR:
CERN-LHCC-2017-021
ITk Strips TDR:
CERN-LHCC-2017-005

Expected single muon resolution



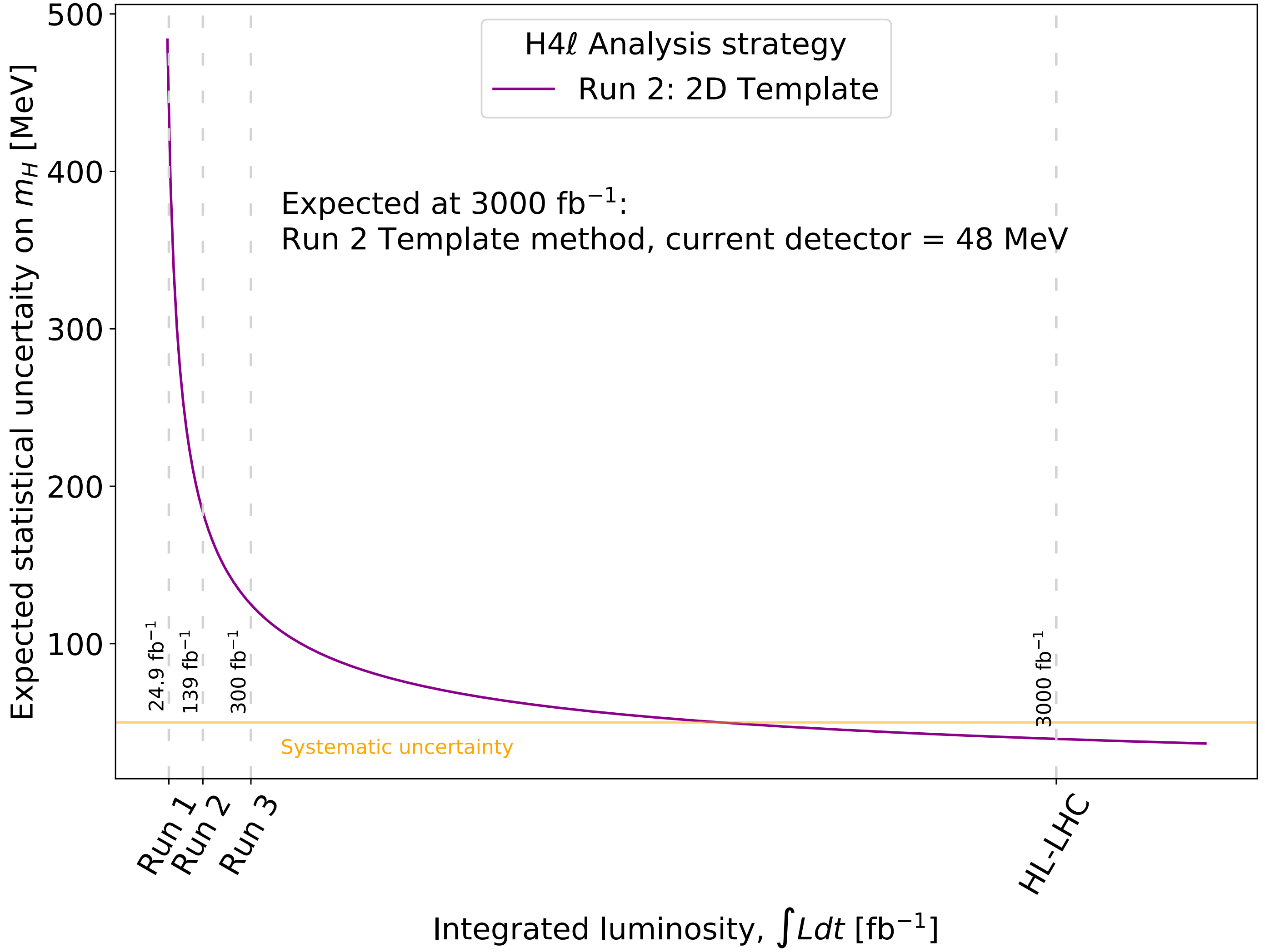
2 GeV



100 GeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

Example: Higgs mass with ATLAS & HL-LHC



Statistical uncertainty projection

★ Projecting based on 2D template method measurement at 13 TeV with 36.1 fb^{-1} (Phys. Lett. B 784 (2018) 345)

★ Systematically limited midway through HL-LHC run

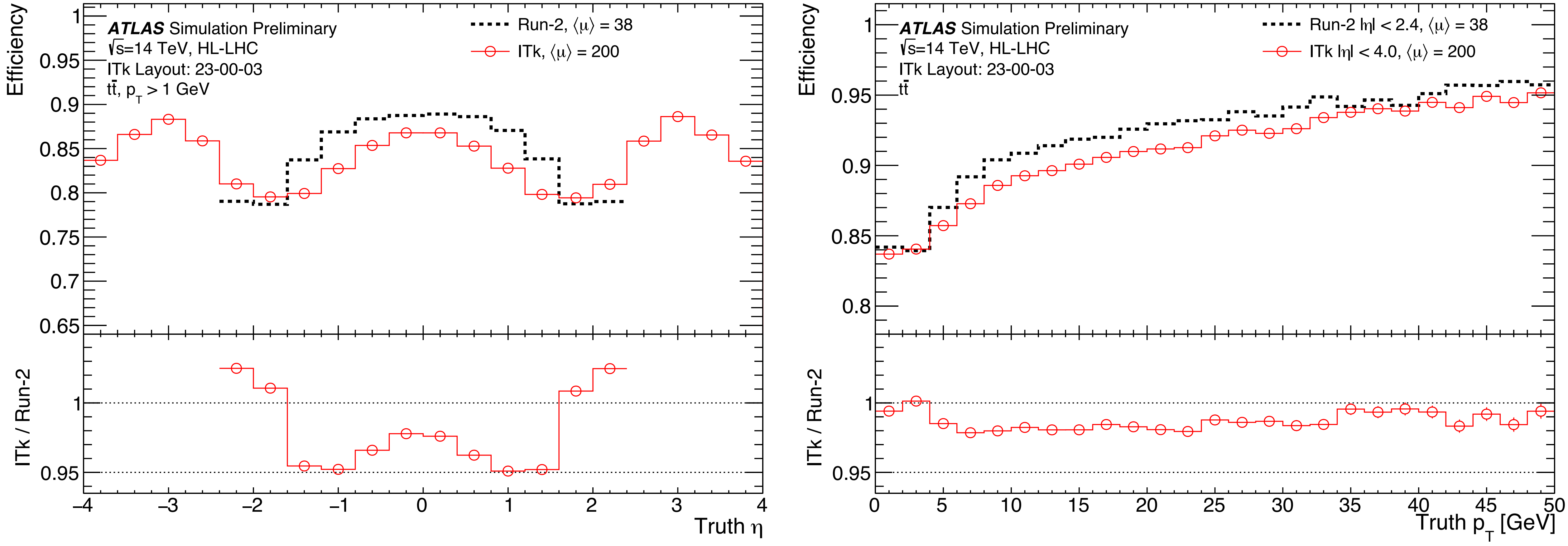
Example: Higgs mass with ATLAS at HL-LHC

	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14

- ★ Using muon resolution improvements estimated at 45 GeV
- ★ Full Run 2 expected uncertainty ~180 MeV → 30-40 MeV at HL-LHC
  - First stage projected resolution improvements achievable with ITk
    - Additional improvement with analysis choices, improved detector understanding

ATL-PHYS-PUB-2018-054

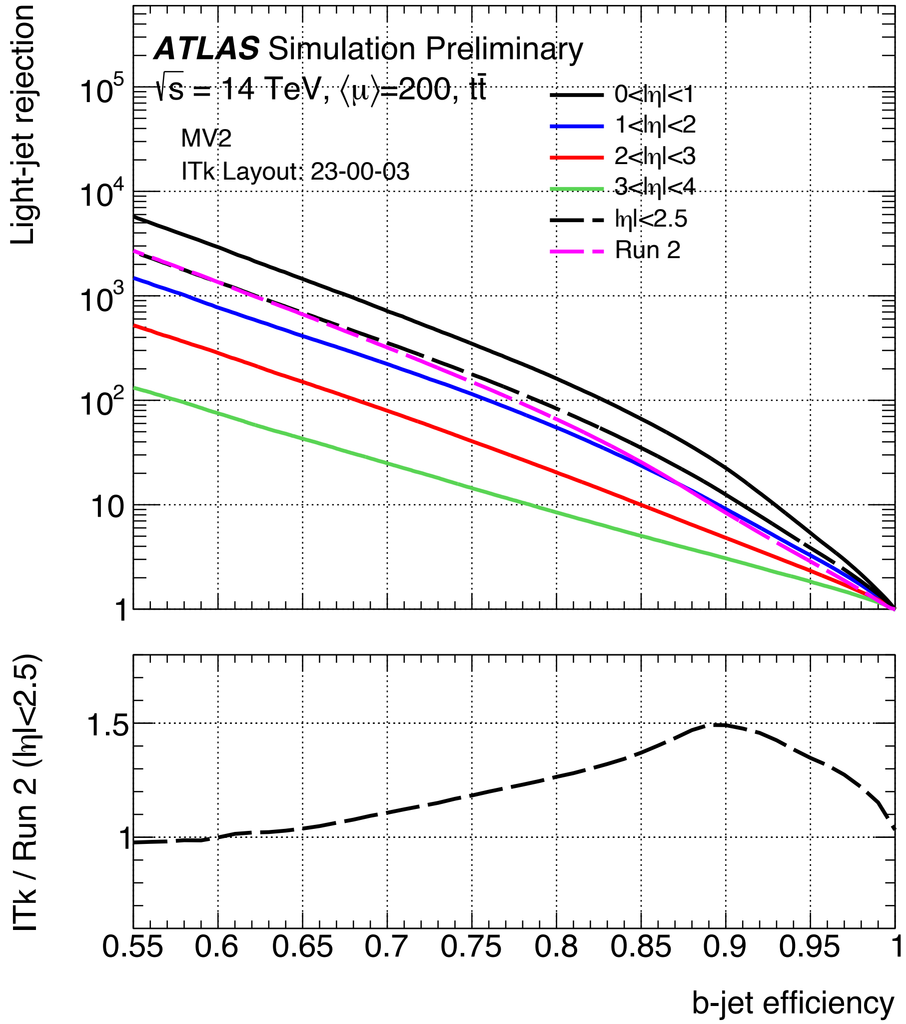
Tracking efficiency with pileup in $t\bar{t}$ events



Over **5 times more** pileup in HL-LHC conditions • Tracking efficiency **within 5%** of current detector

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

b-tagging efficiency



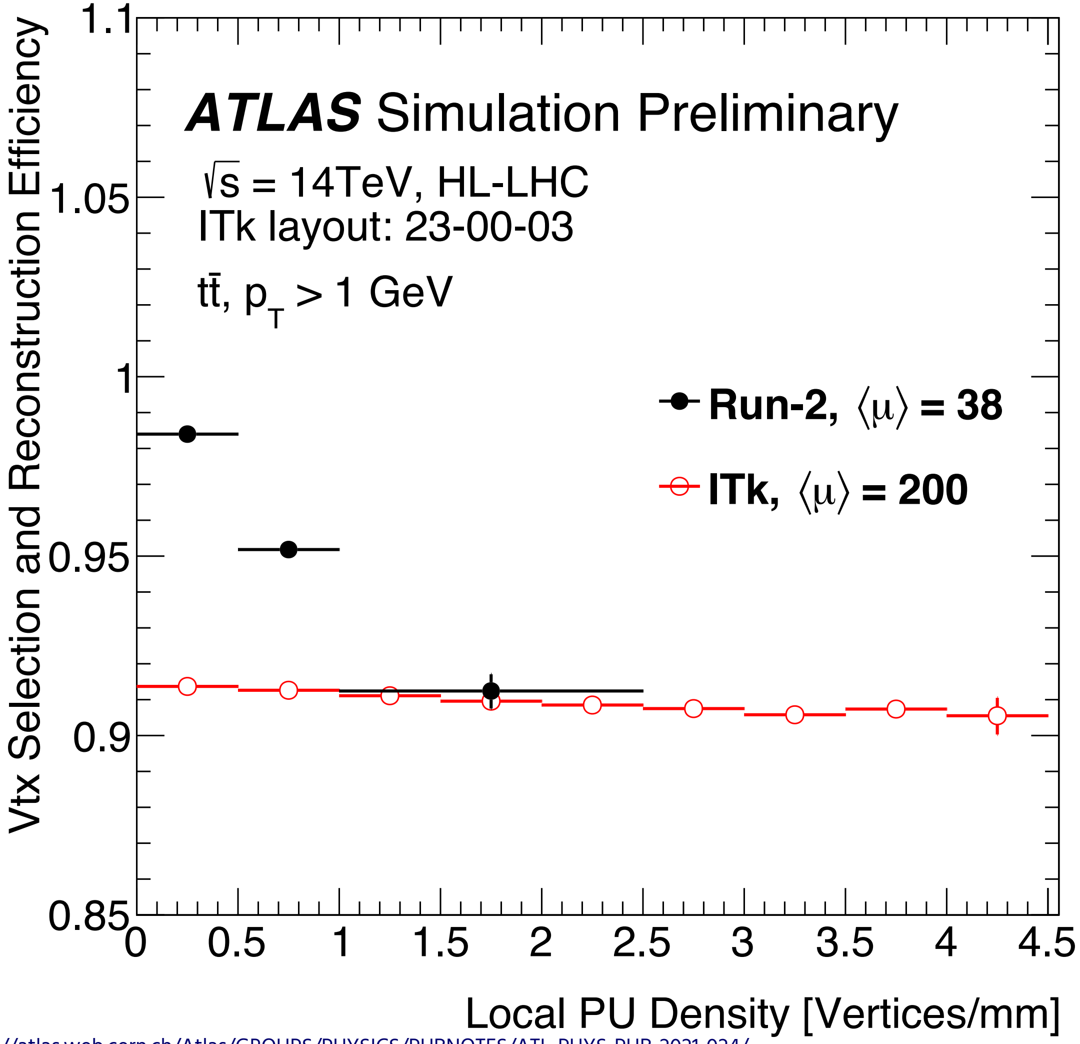
Another example

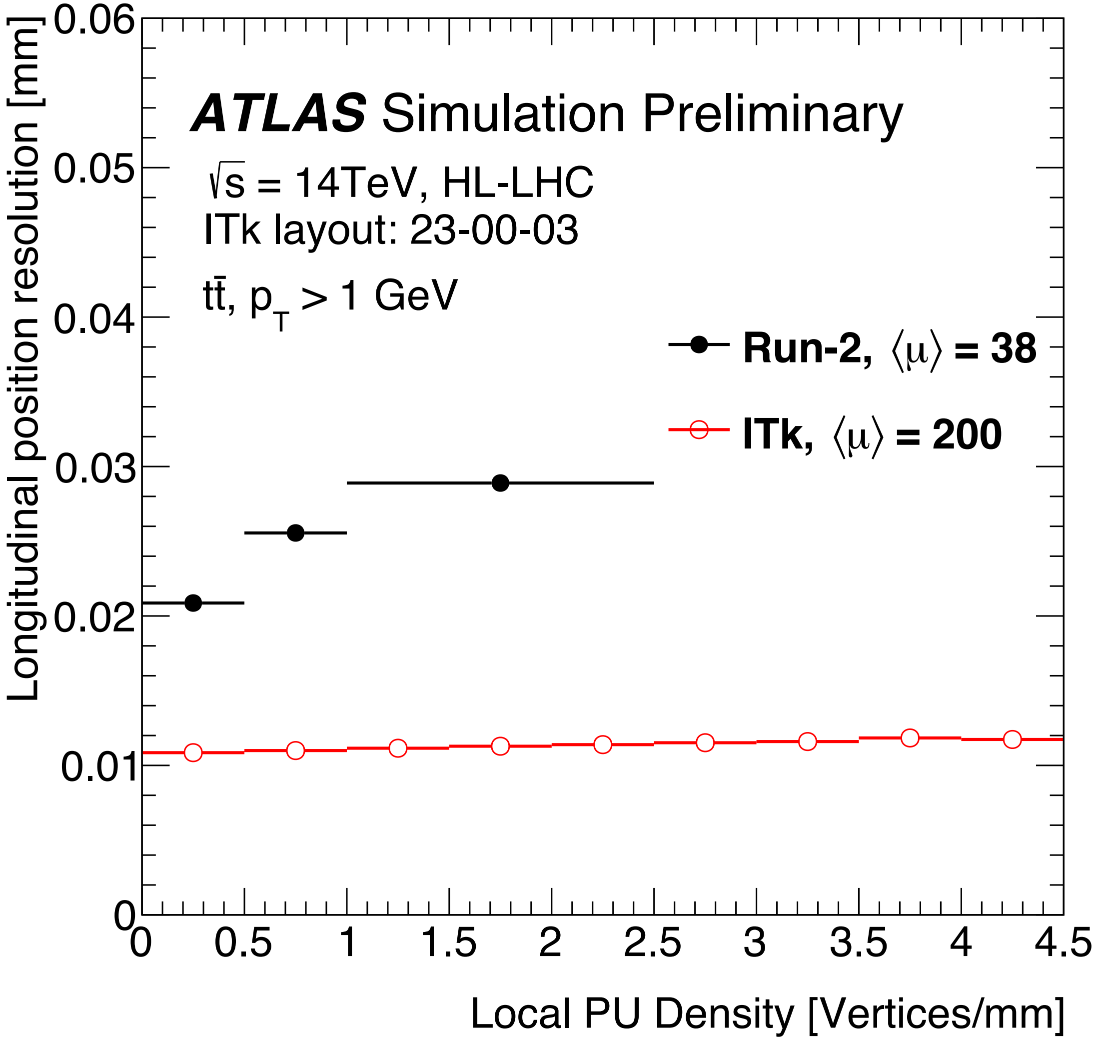
★ DiHiggs search, $hh \rightarrow b\bar{b}b\bar{b}$

- ~8% b-tagging efficiency gain at same light jet rejection level wrt current analysis

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

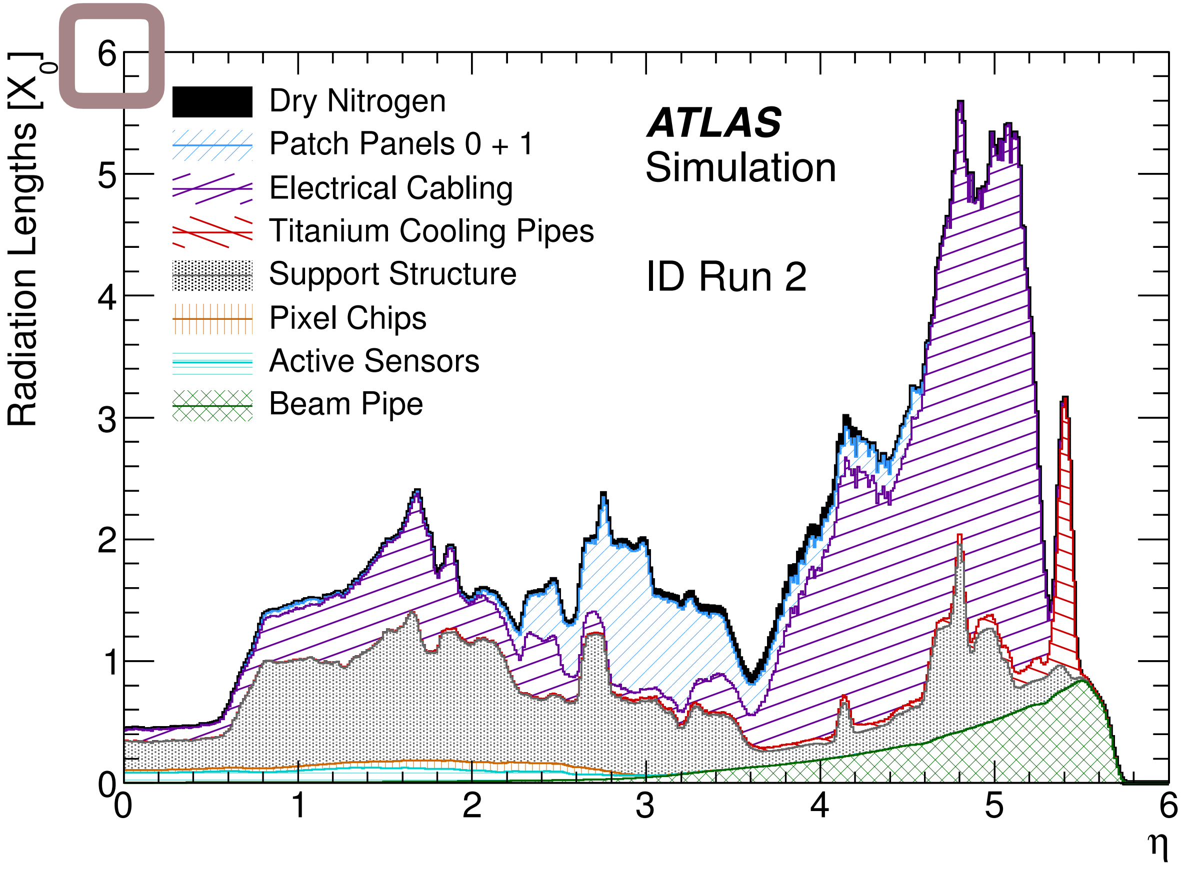
Vertexing



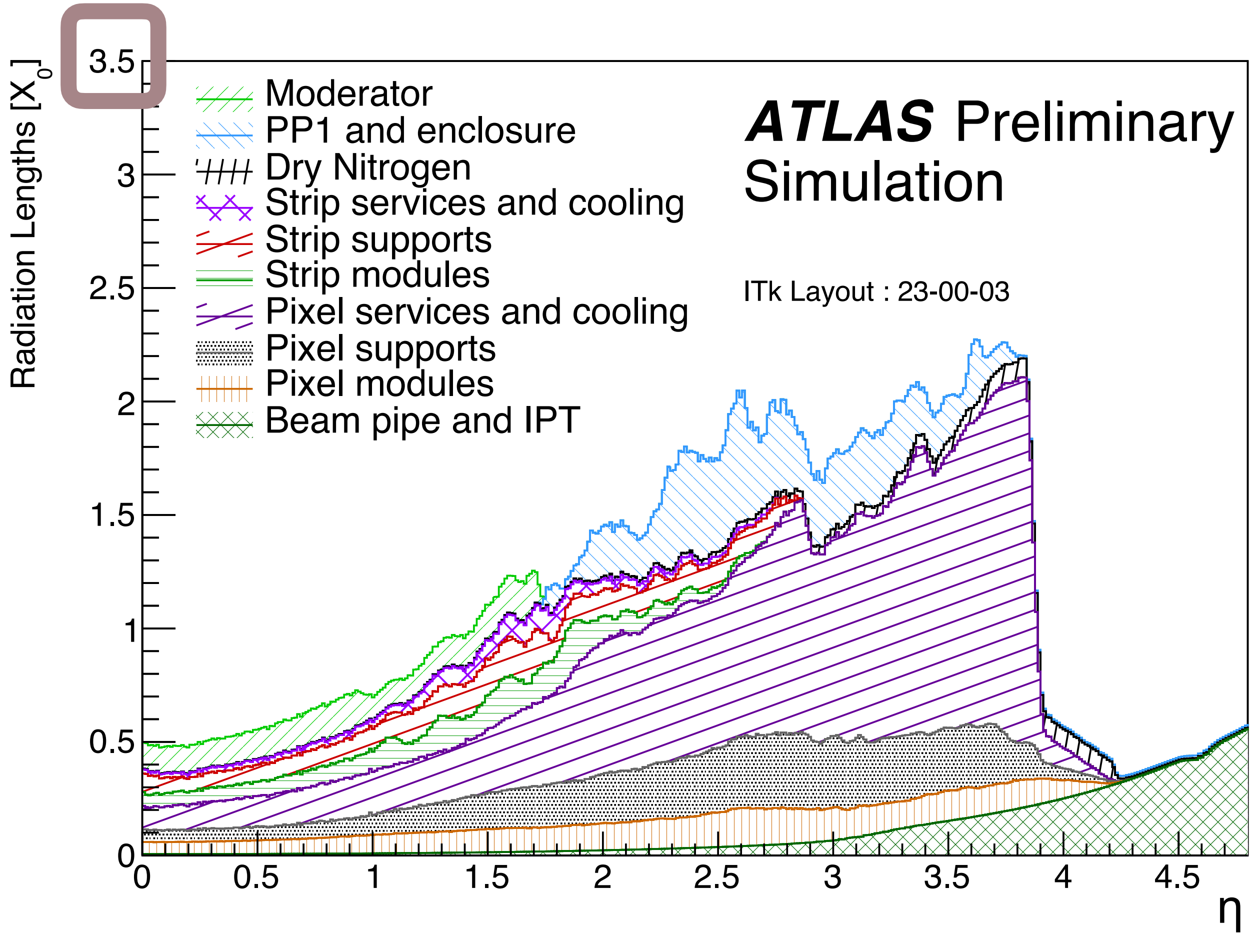


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

More active area for less material

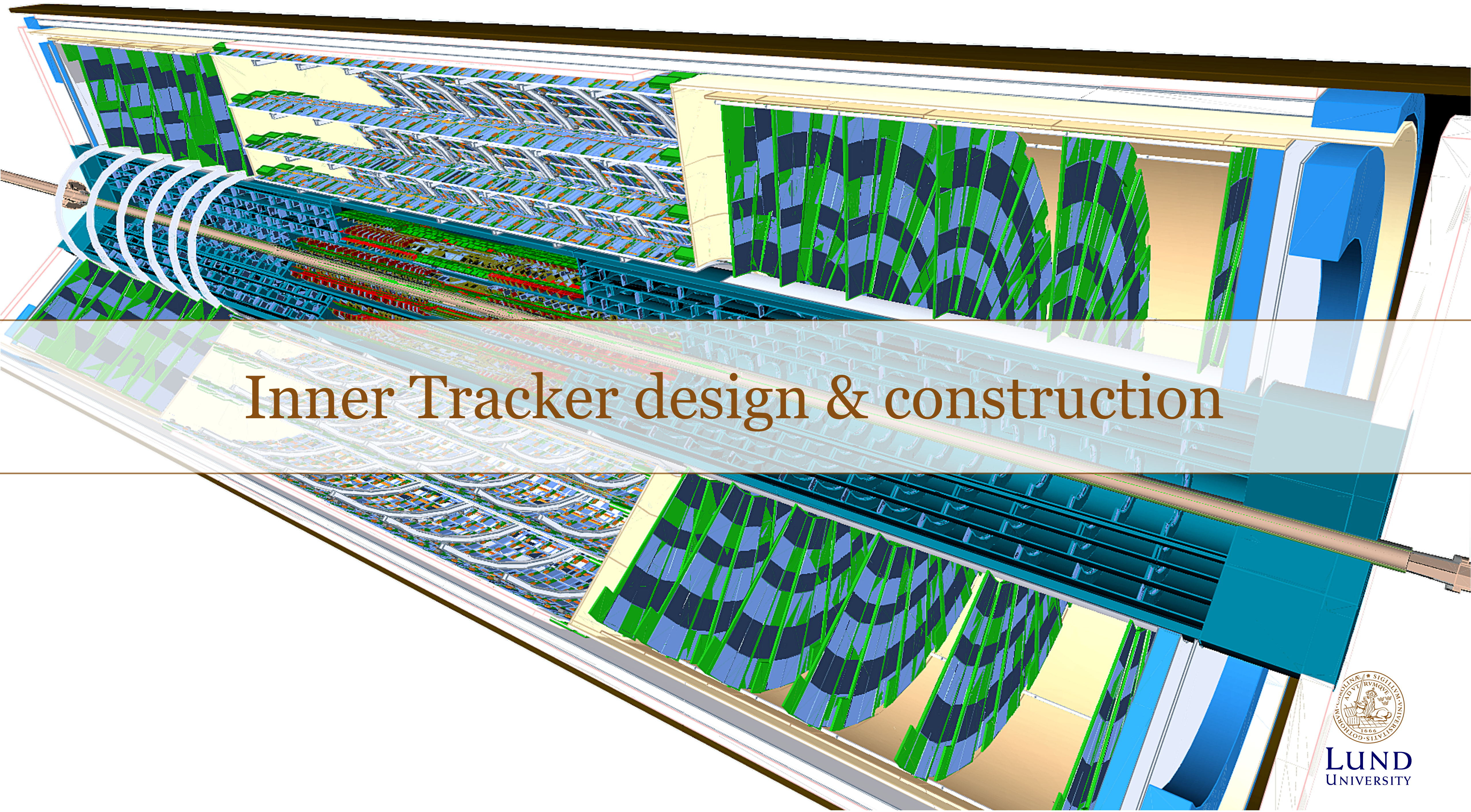


Inner Detector (current)



Inner Tracker (HL-LHC)

📷 ID material budget, fig. 9 https://cds.cern.ch/record/2257755; ITk material budget, fig. 4 https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/



Inner Tracker design & construction

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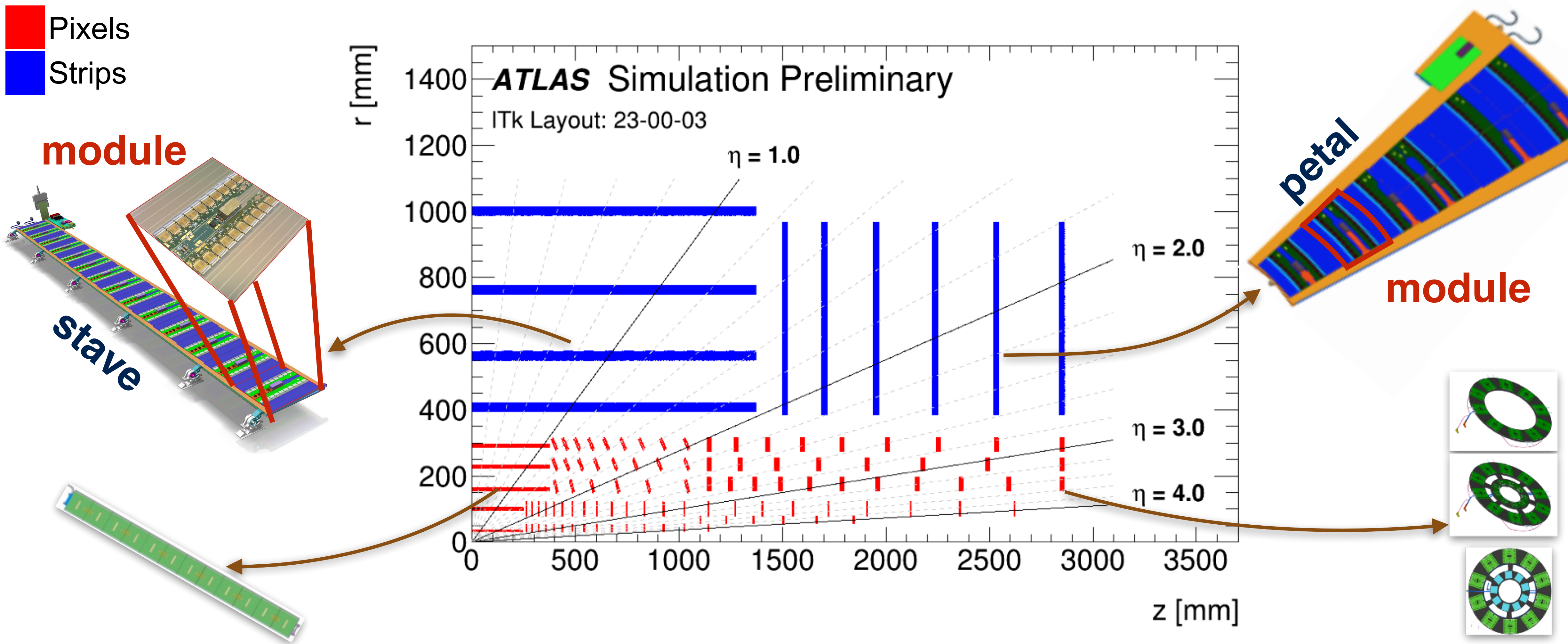
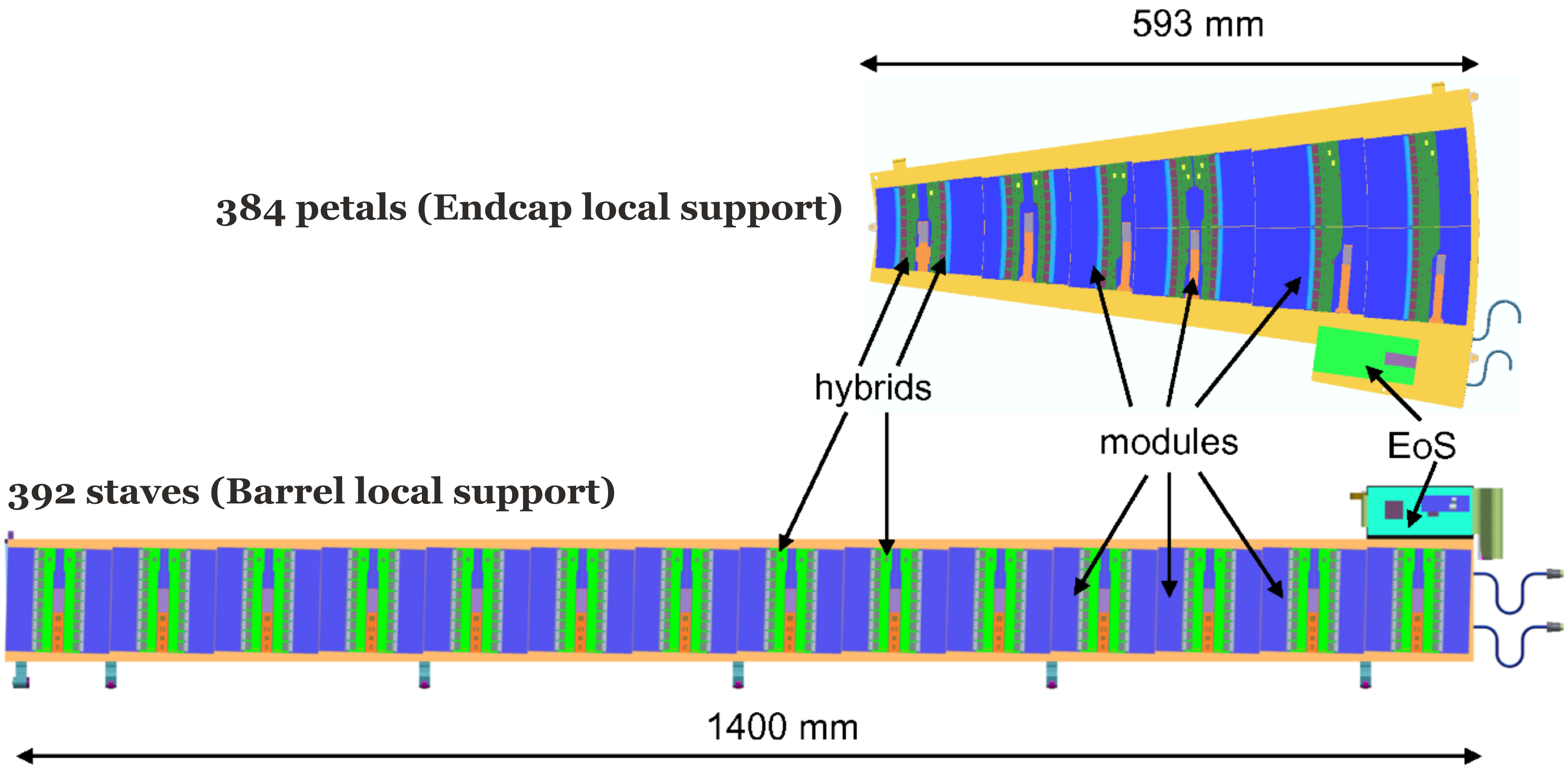
Inner Tracker layout



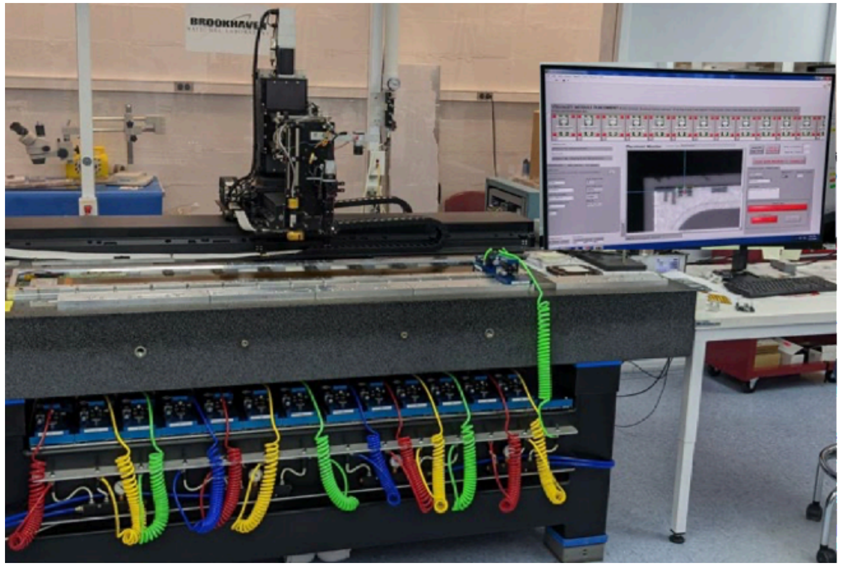
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

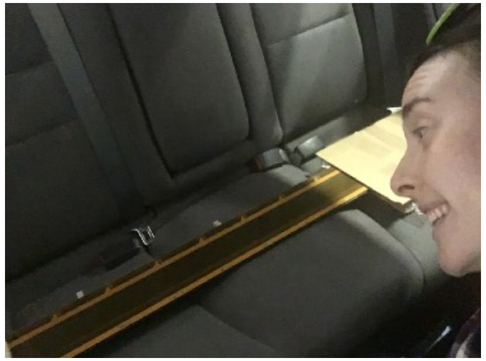
Strips local supports: Staves and petals



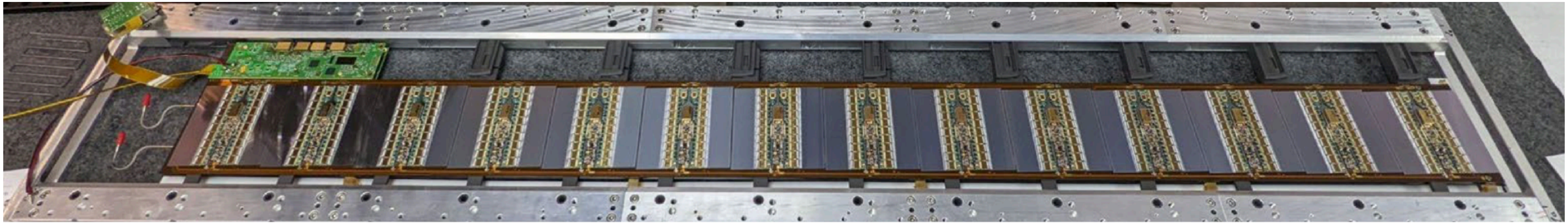
Smallest fully independent structure: Mechanical support, data handling, powering, cooling

Mechanical stability, cooling, data handling, power



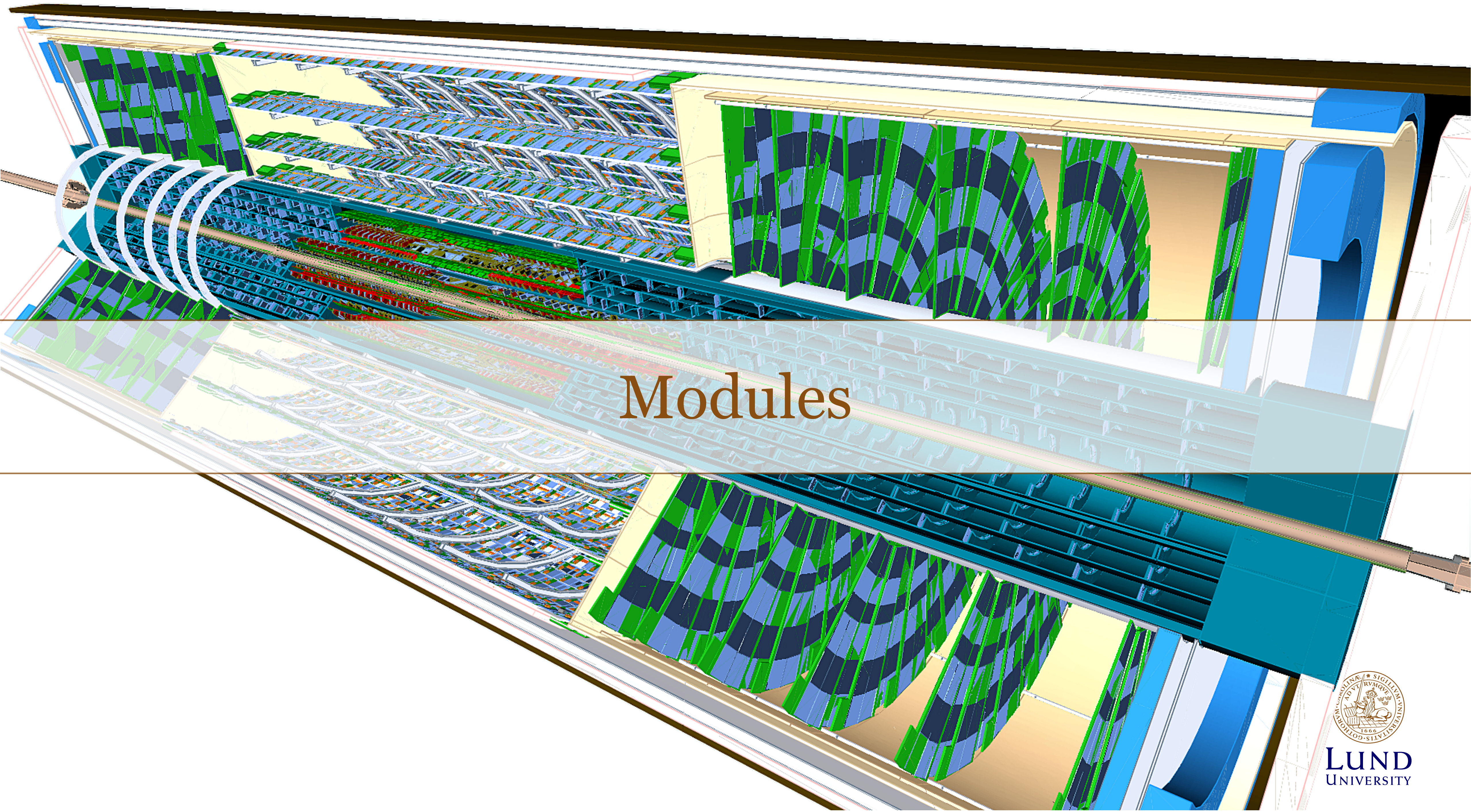


Me escorting a stave from Yale to BNL, 2017

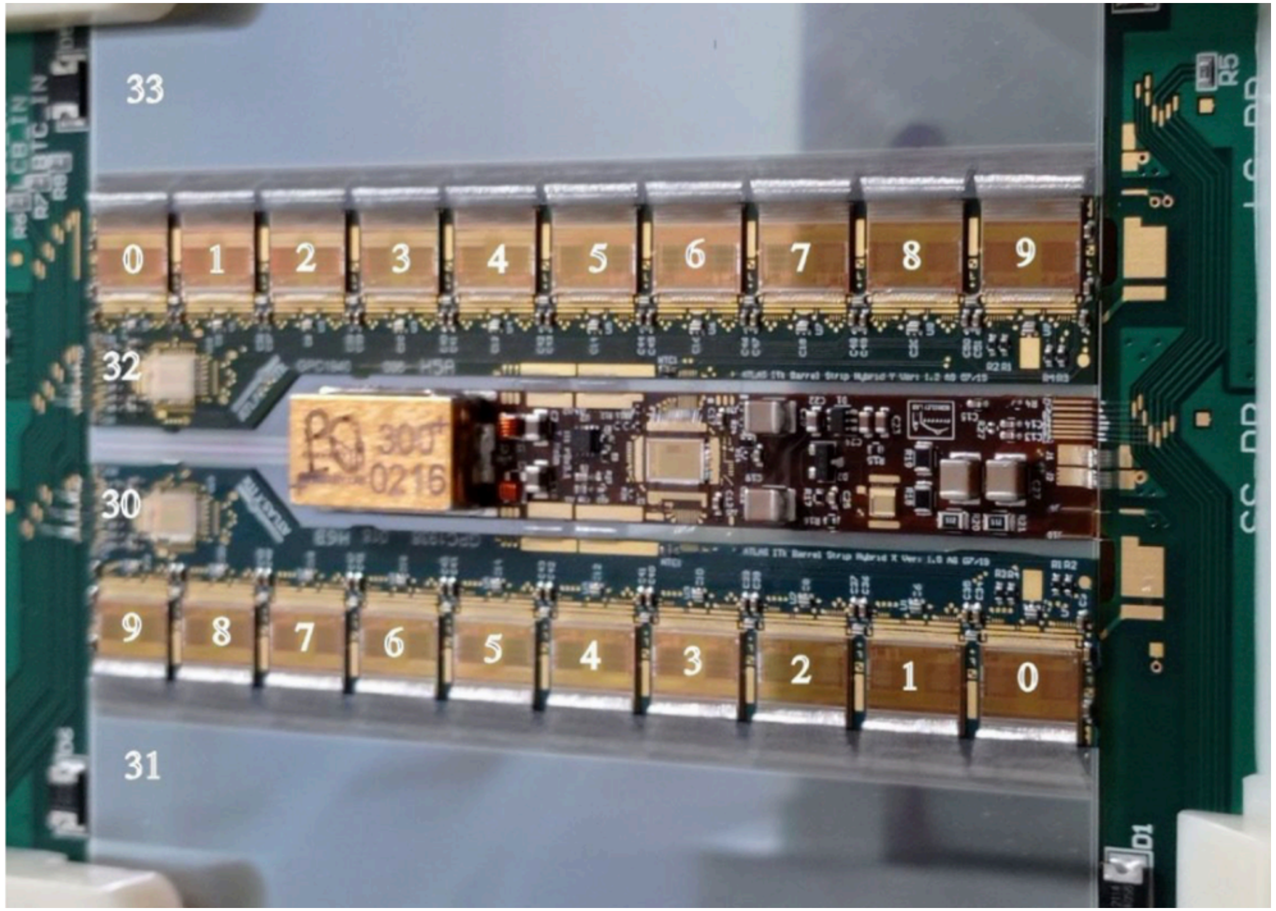


Loaded stave prototype, courtesy of BNL

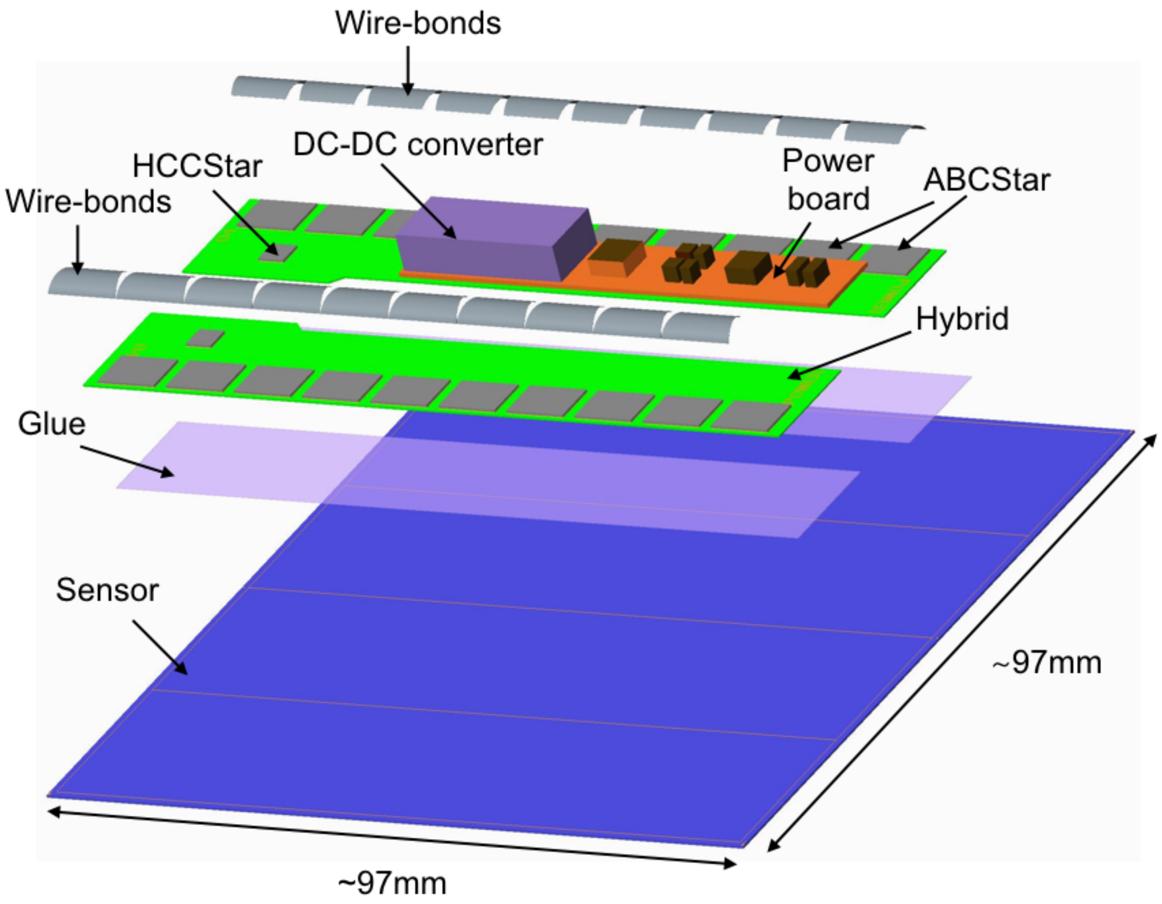
Modules



Modules: Sensor + electronics



Short strip barrel module, 2021

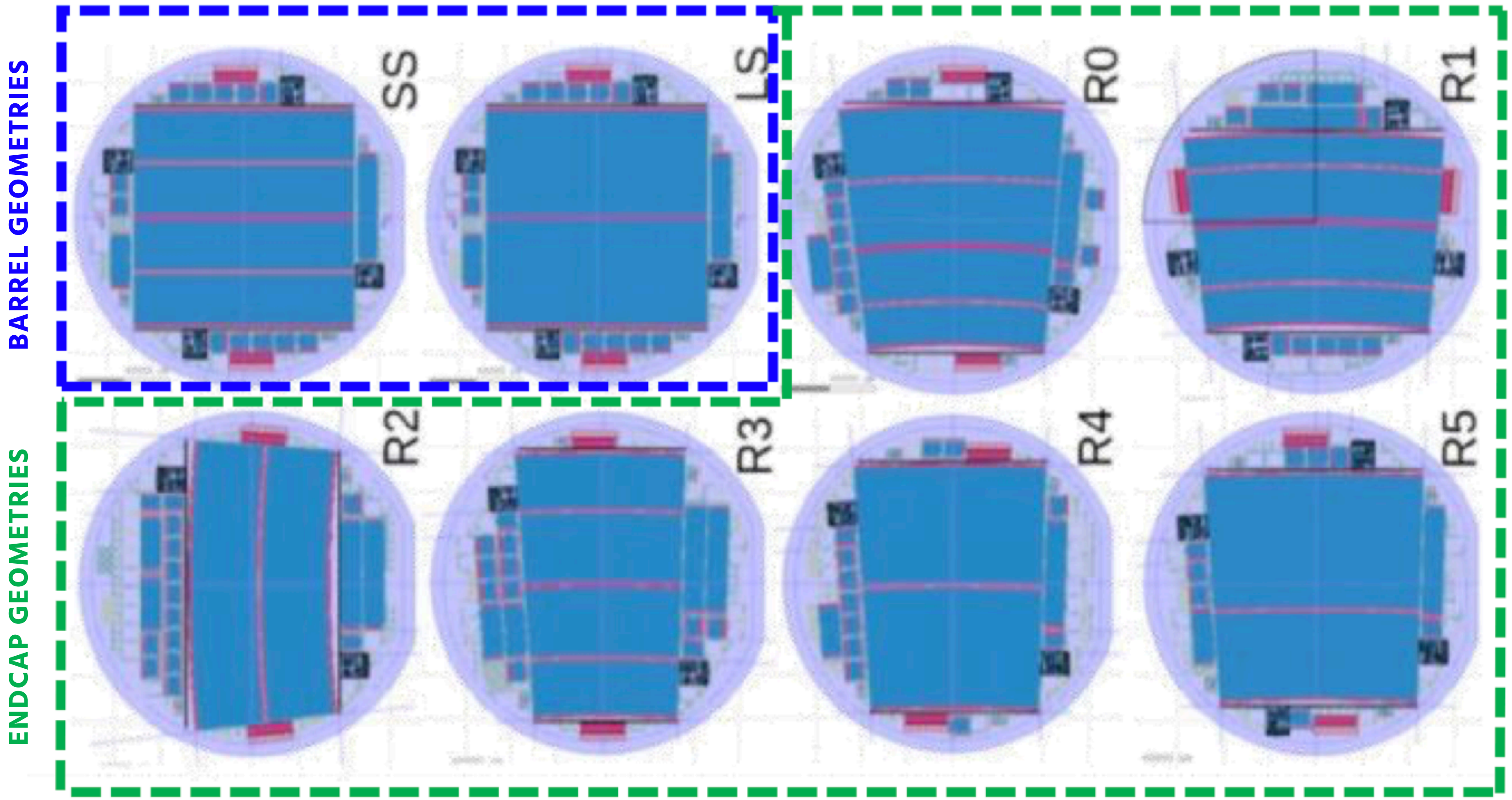


Exploded view

📷 Barrel photo: [J. Steentoft ICHEP 2022](); Exploded view, fig. 58: https://cds.cern.ch/record/2257755

Silicon sensor: Heart of a module

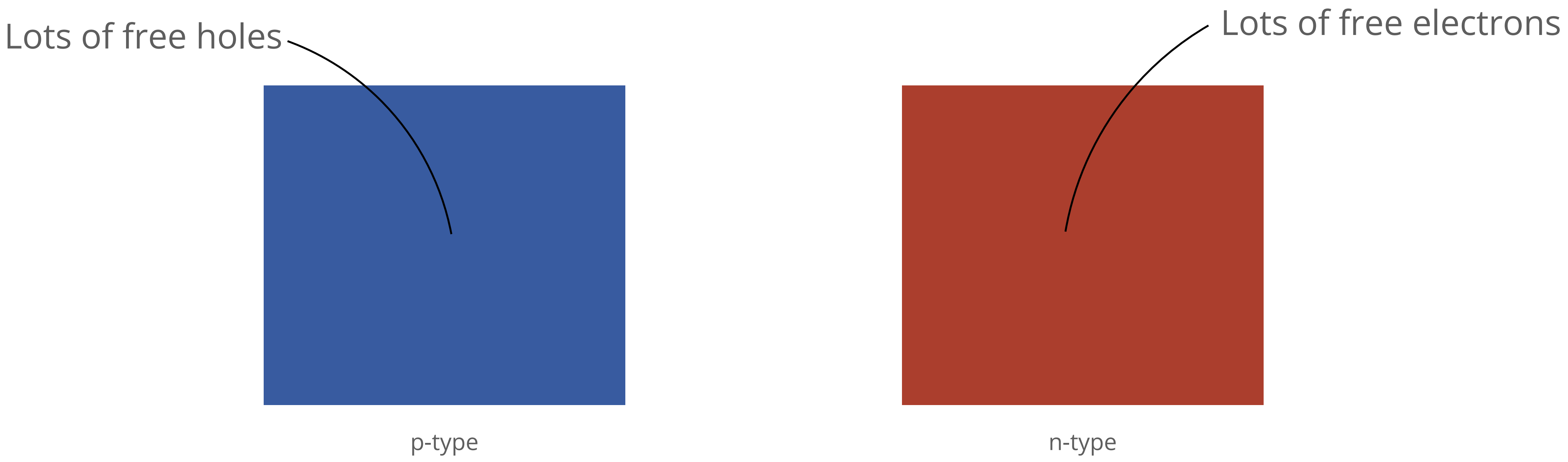
8 geometries in ITk Strips



S. Diéz, ICHEP2022

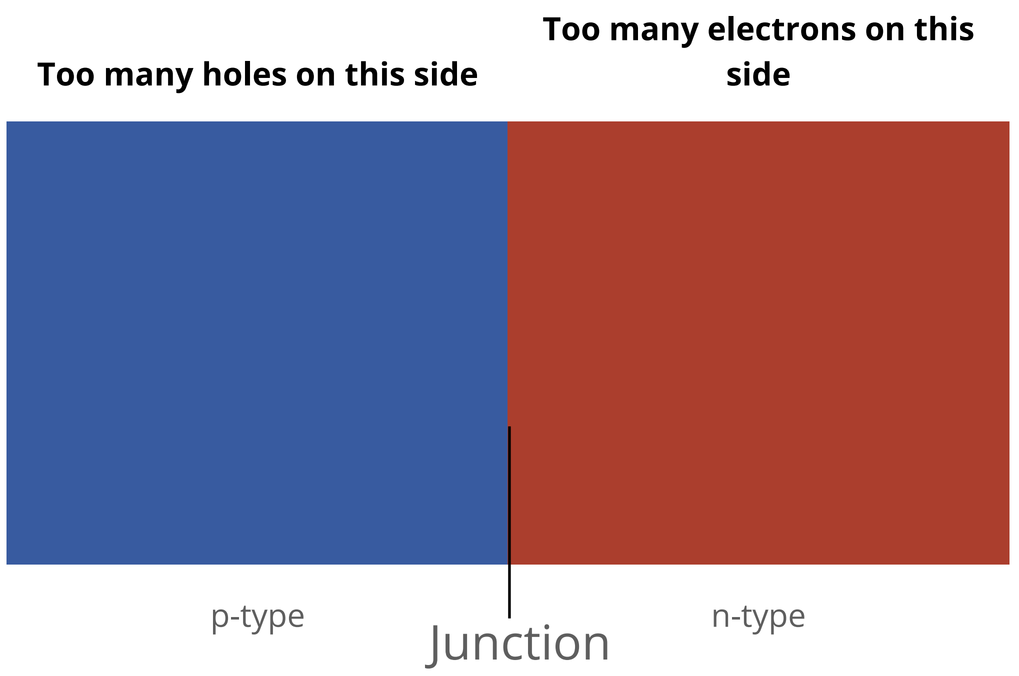
Aside: pn-junction

Definition



pn-junction

Bring p-type & n-type into contact

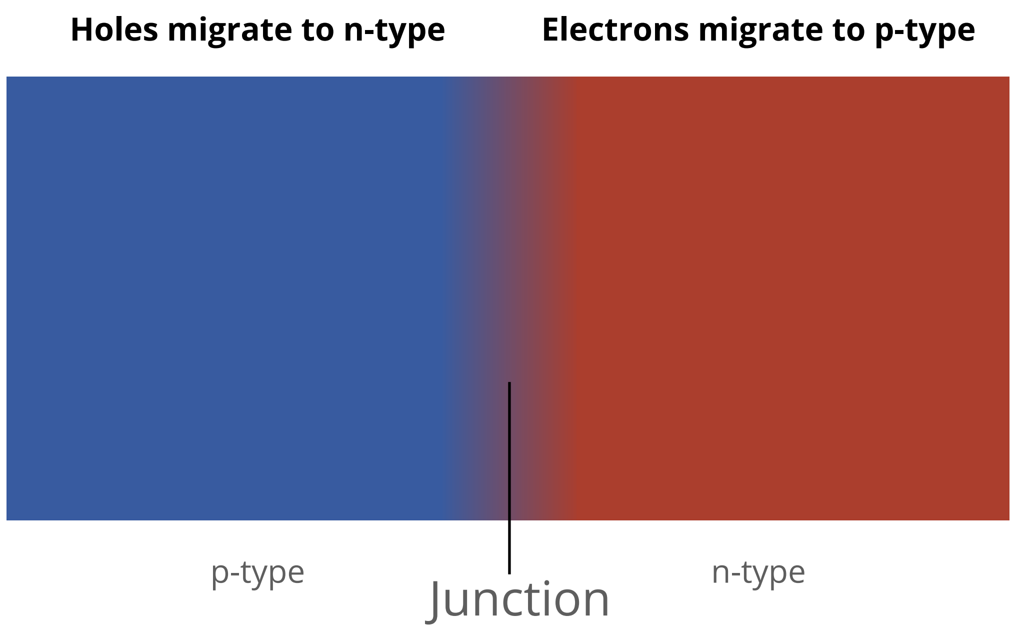


★ Concentration(Holes) and Concentration(Electrons) must be constant throughout material

→ **Diffusion gradients across material!**

pn-junction

Charge carriers drift

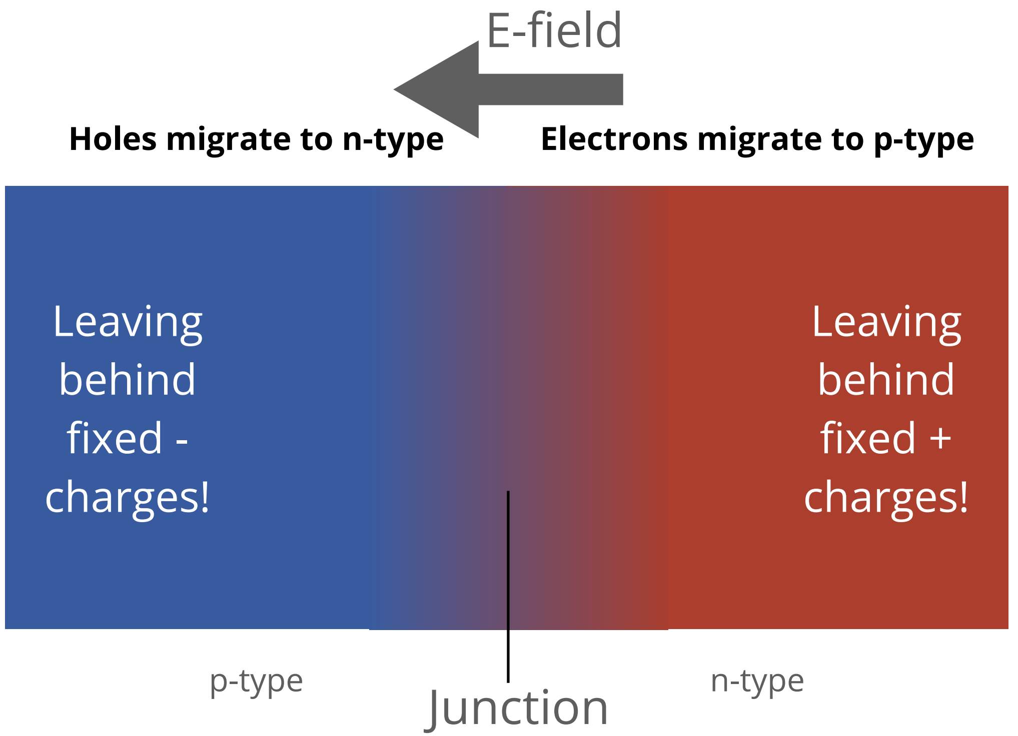


★ Holes & electrons move towards junction to balance material

- But they are charged themselves!

pn-junction

Establishing an electric field

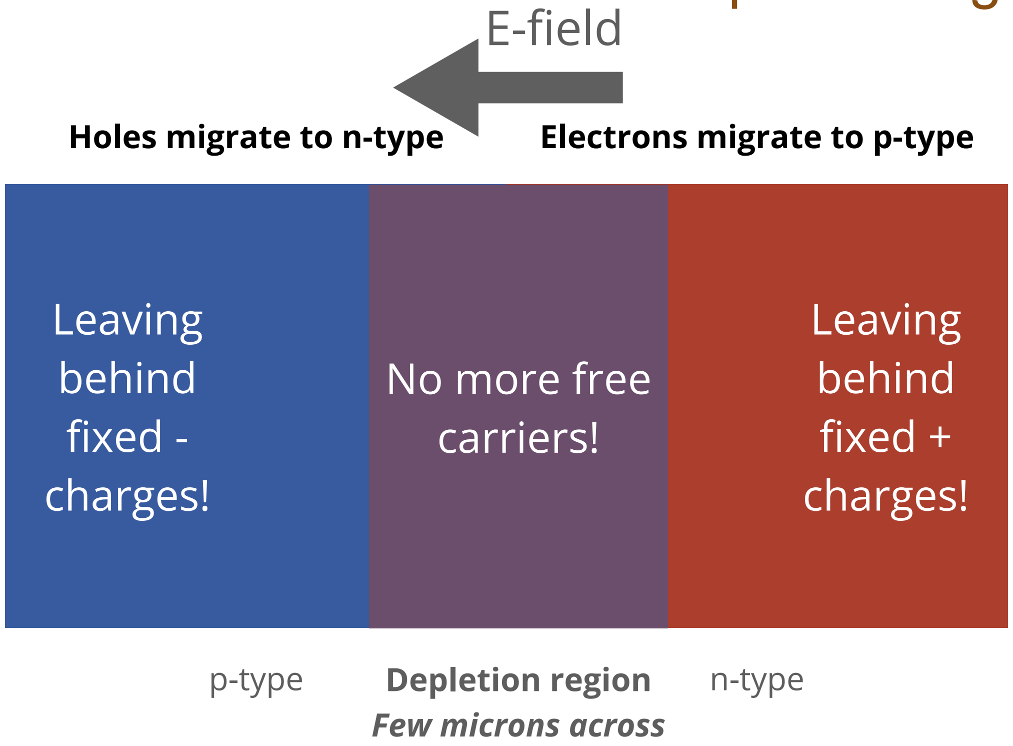


★ Fixed charges “left on home node” → build an electric field across junction

- Eventually, E-field large enough → 🛑 stops further migration

pn-junction

Built-in electrical potential established across the depletion region, V_D



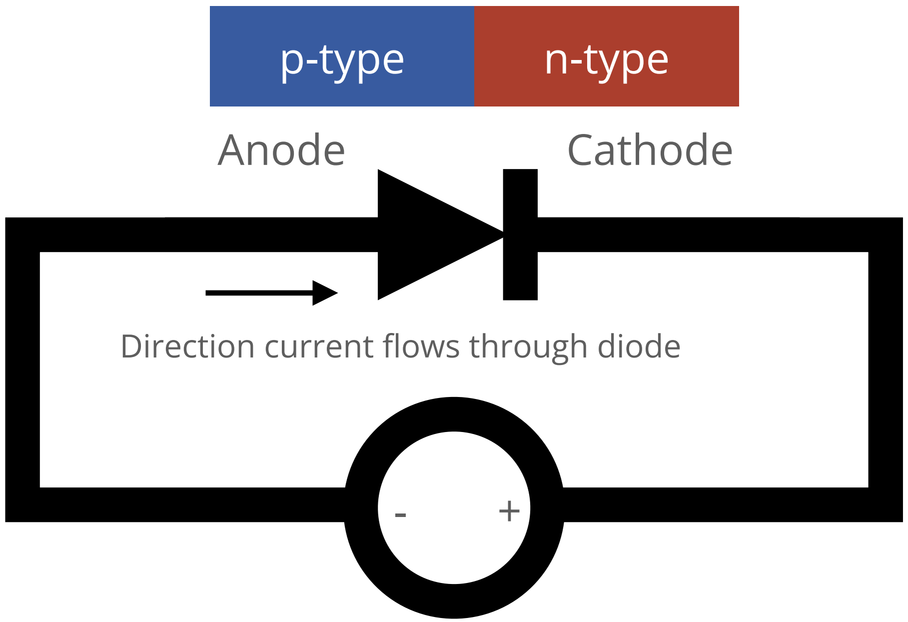
★ Depletion region = zone covered by E-field, an insulator preventing hole/electron diffusion

- No more free carriers → **depleted**

V_D in silicon ~0.7 V

pn-junction

Diodes

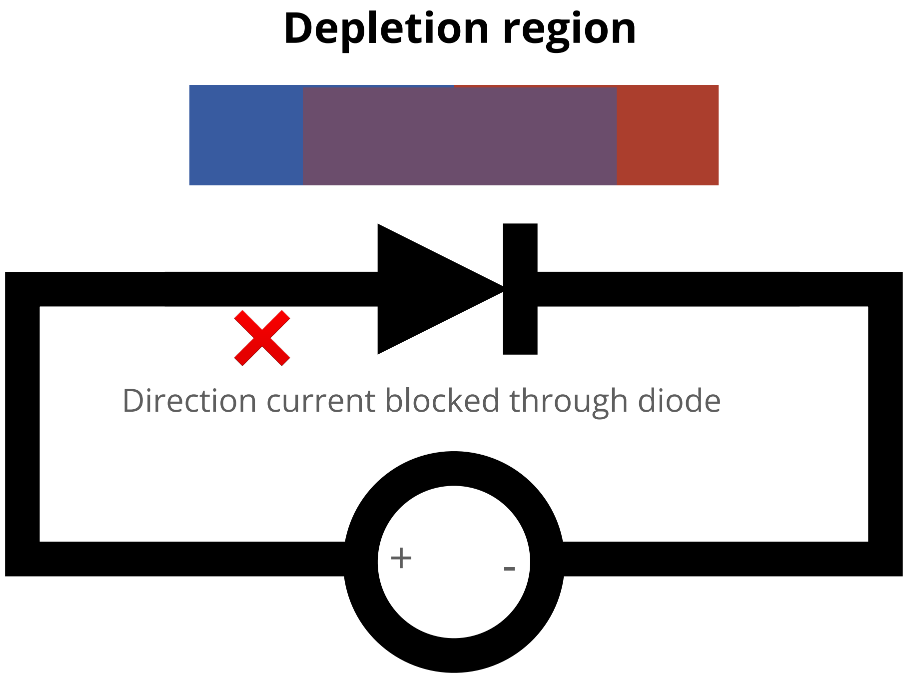


$V_{bias} > V_D$

E_{Ext} **cancels** E_{Int}

Depletion zone **shrinks**

→ current flow



Flip polarity of V_{bias}

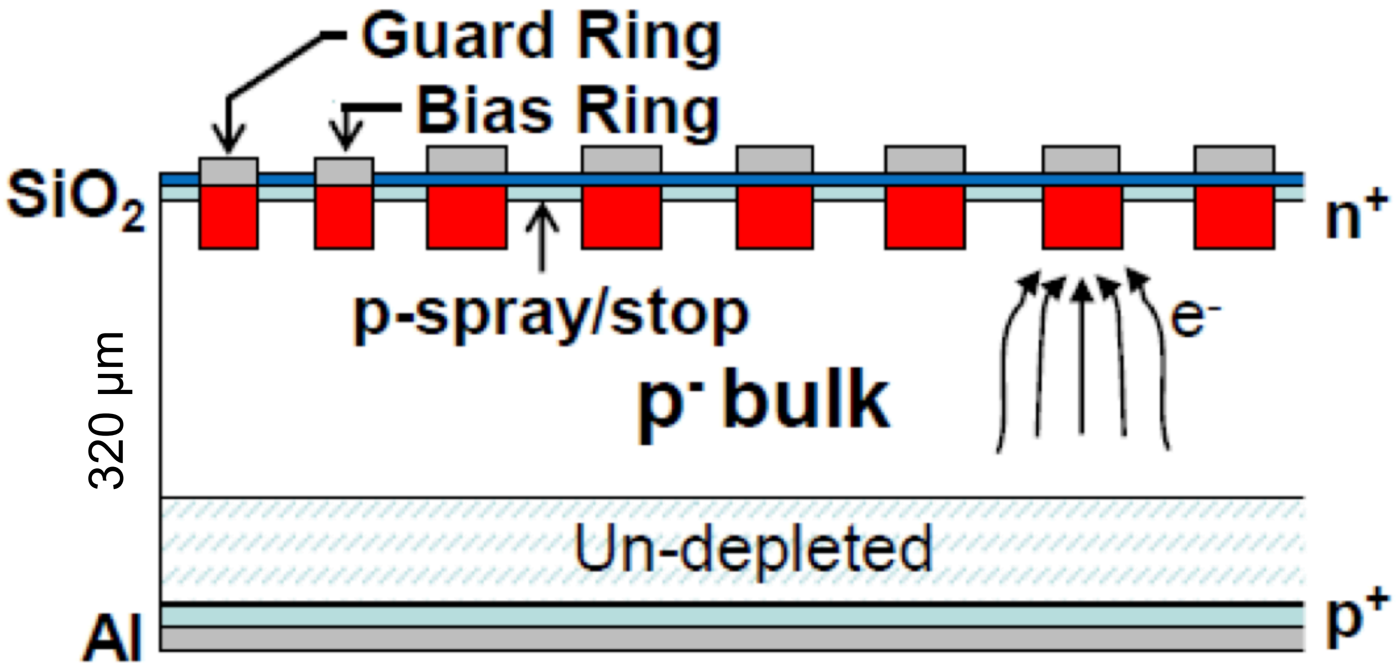
E_{Ext} **reinforces** E_{Int}

Depletion zone **grows**

→ current blocked

Silicon sensor: Heart of a module

Each silicon strip or pixel ~ diode, albeit reverse-biased → fully depleted



★ Operation

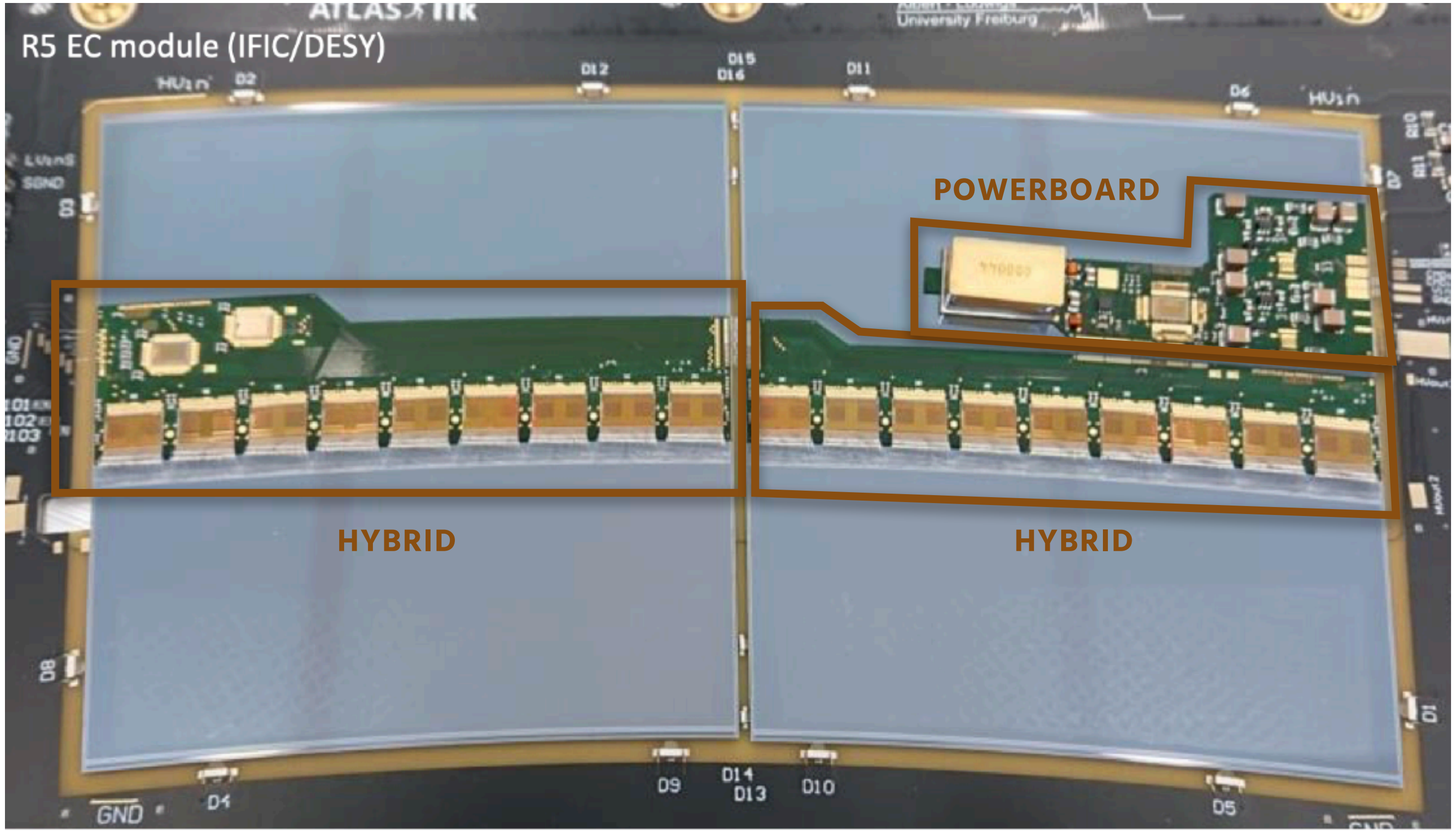
- Charged particle transversing detector produces electron/hole pairs in bulk Si
  - V_{bias} = 300 V, rising to 550 V at end of life
- Holes drift towards applied E-field
  - Signal on strips!

★ n^+-in-p type float zone strip sensors manufactured by HPK

- Faster, more radiation-hard wrt p-in-n
- Good signal, even when not fully depleted

S. Diéz, ICHEP2022

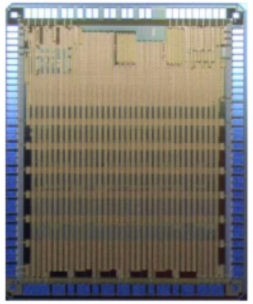
Readout electronics: Brain of a module



S. Diéz, ICHEP2022

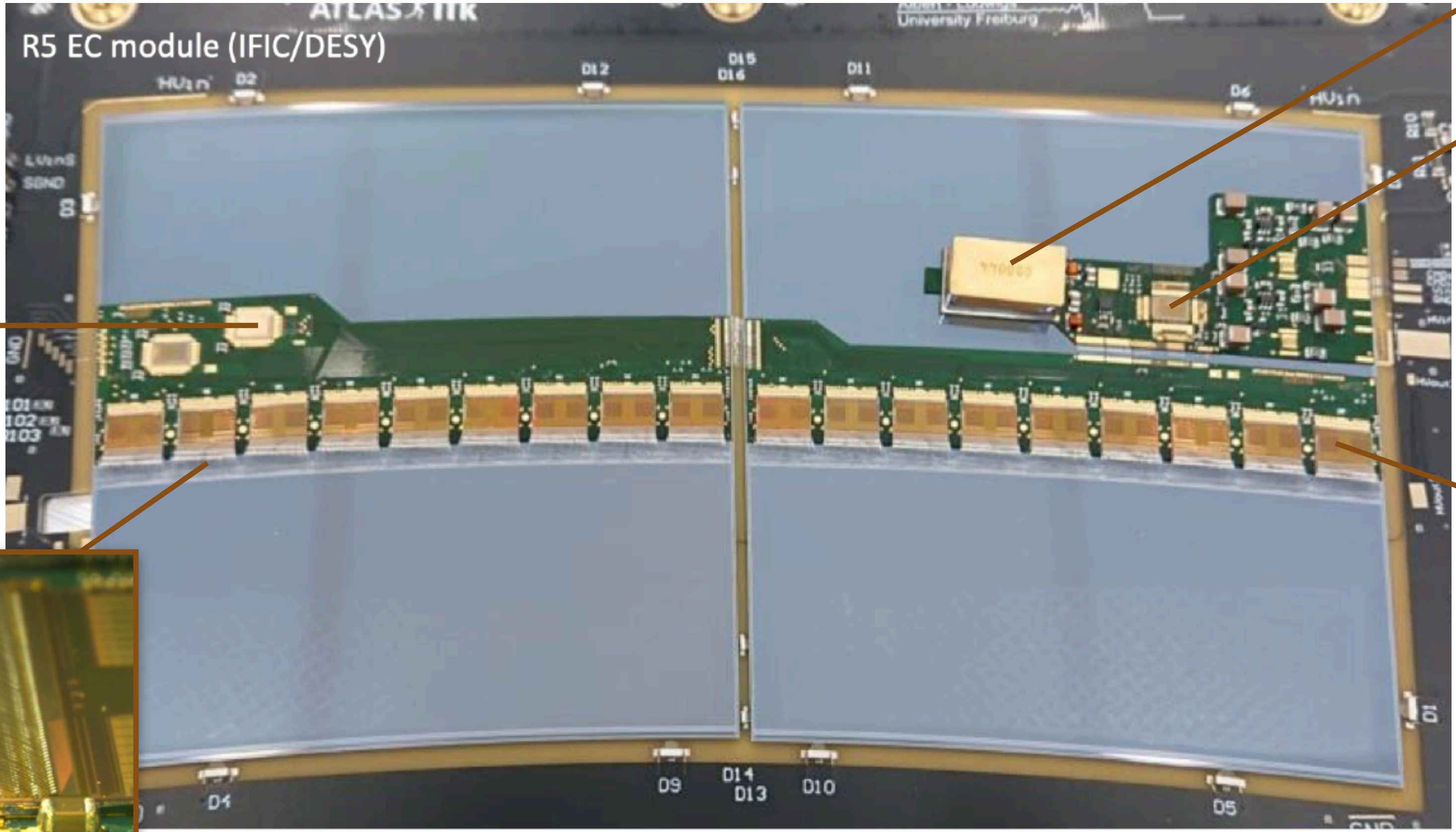
Readout electronics: Brain of a module

Common chipset across all module flavours • 130-nm CMOS chipset



HYBRID CONTROLLER CHIP (HCC)

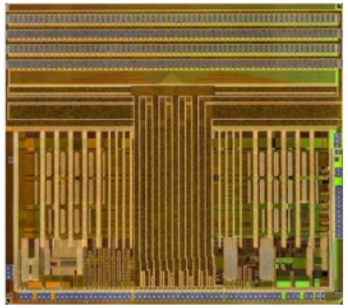
DIGITAL INTERFACE



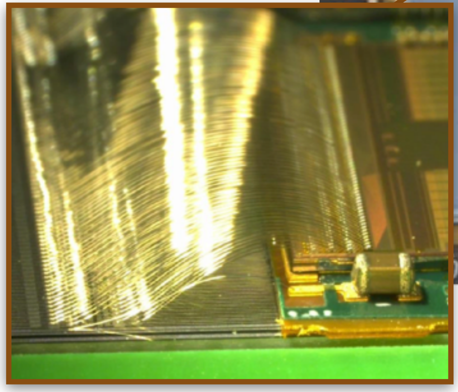
DC-DC CONVERTER

AUTONOMOUS MONITORING & CONTROL CHIP (AMAC)

FRONT-END: ATLAS BINARY CHIP (ABCSTAR)

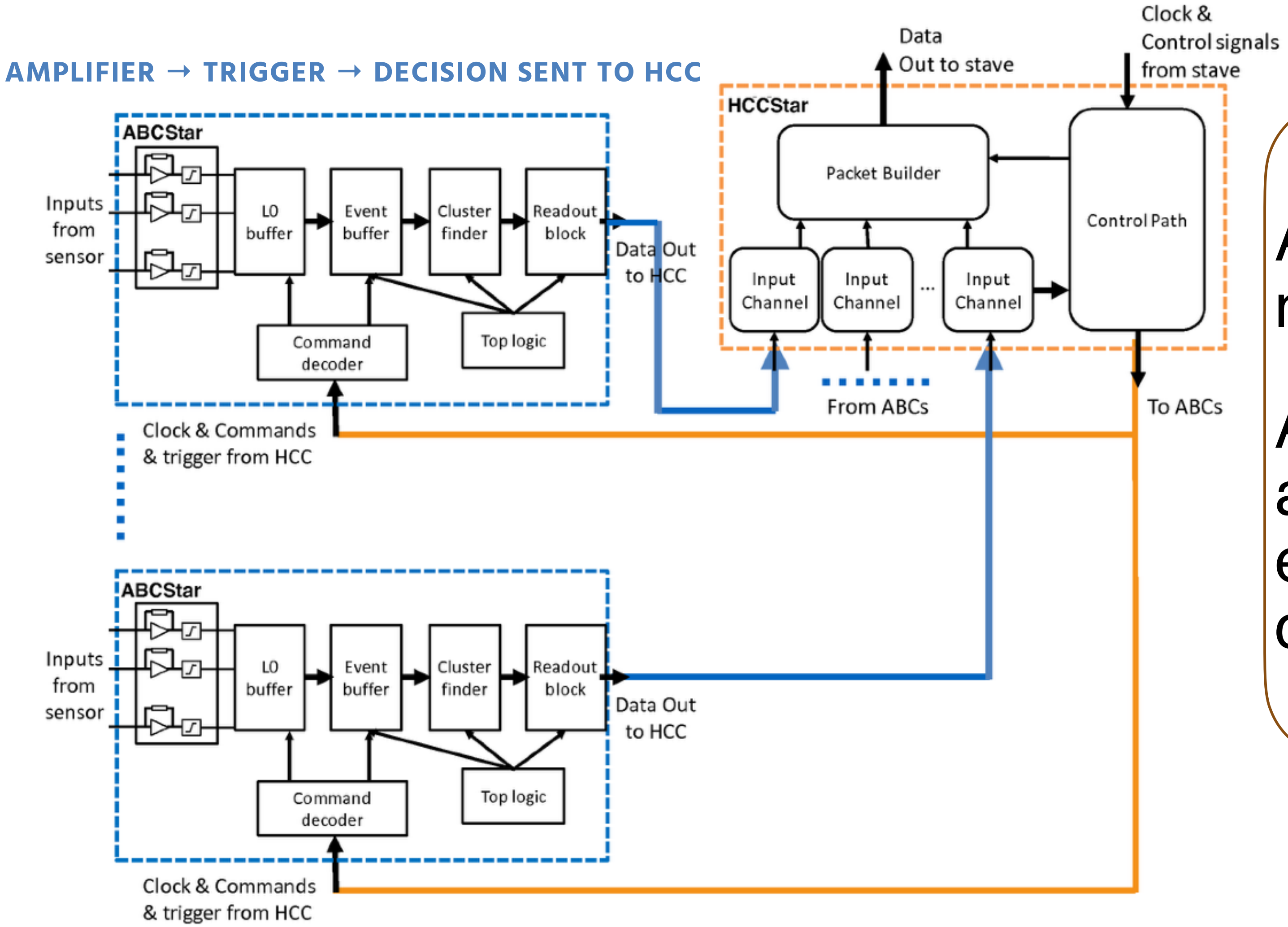


FRONT-END WIREBONDS



S. Diéz, ICHEP2022

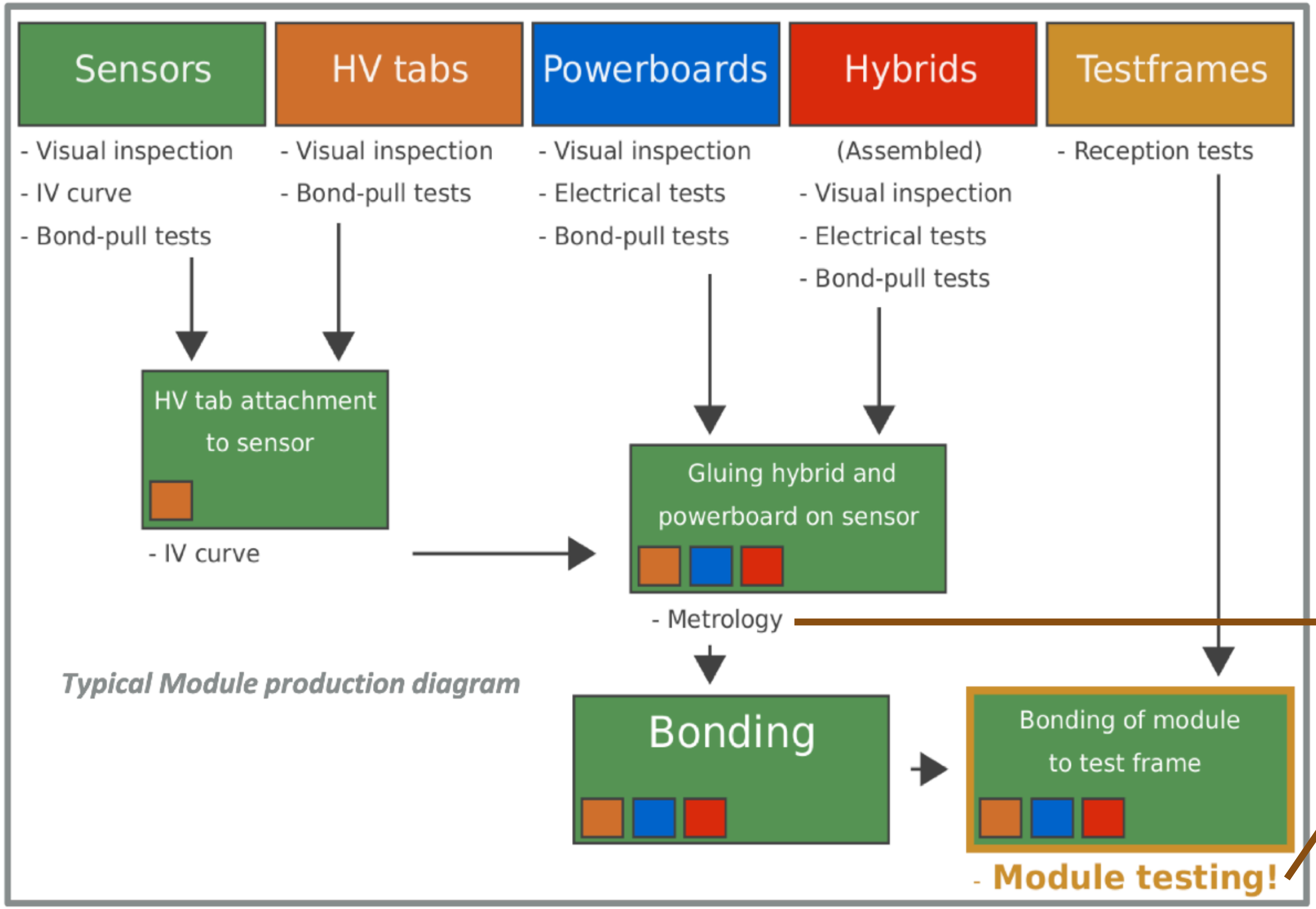
Schematic: Module readout electronics



AMAC handles monitoring, interlock

AMAC can also collect an IV → *in-situ* electronics characterisation

Quality control



~25 module assembly sites

- ★ Subdivided into 6 clusters
- ★ Partflow across 4 continents

LUND STUDENTS DEVELOPING TESTS

XU XIANGU, MODULE METROLOGY

ERIK WALLIN & STEN ÅSTRAND, MODULE THERMAL CYCLING & ELECTRICAL CHARACTERISATION

S. Diéz, ICHEP2022

Importance of quality control

Goal: Consistent, understood, stable behaviour across full detector in operations

Method: Ensure **every single component** built to specifications + process controls, including storage & shipping

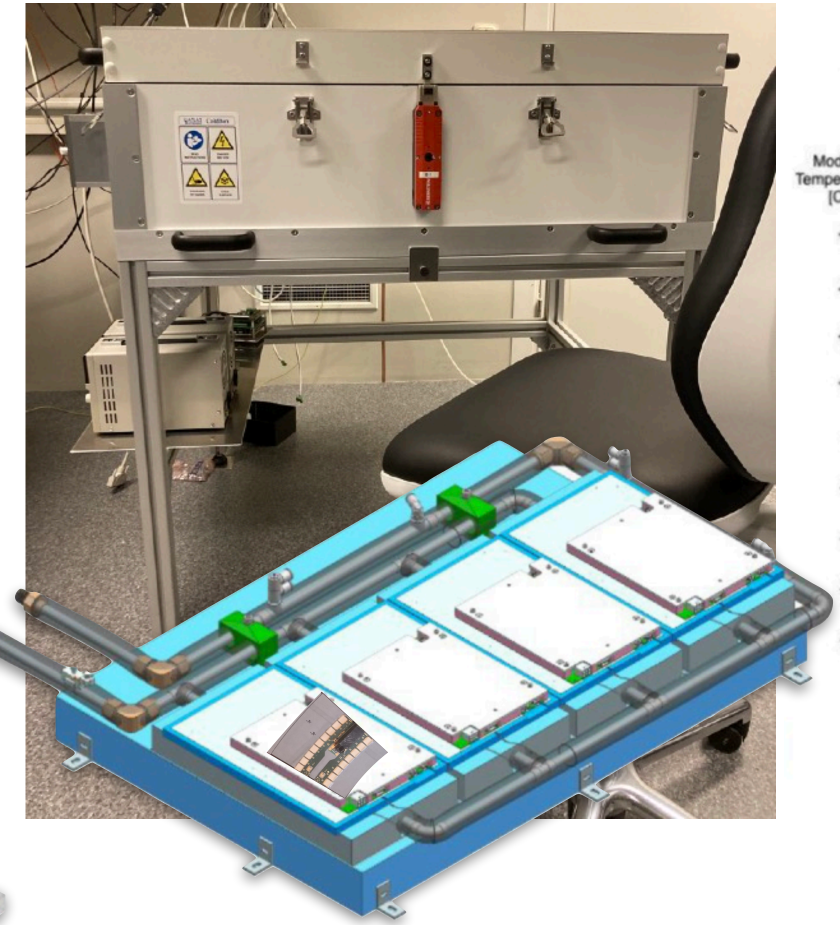
In practice, design quality control tests across 4 major areas, considering that stress over time may change performance as well:

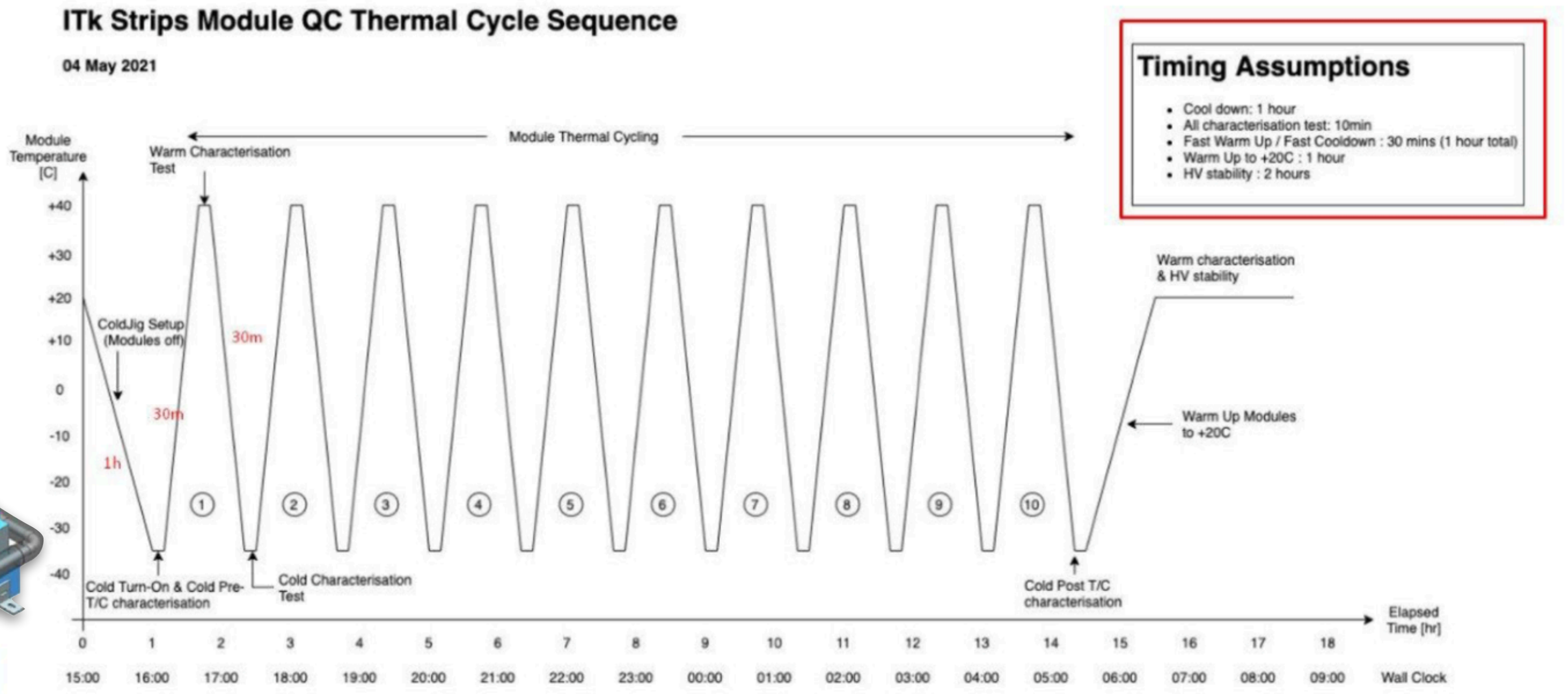
Geometrical	Mechanical
Electrical	System

Example: 10 976 barrel modules + 6 912 endcap modules → all need to work the same and work together!

Example: Module thermal cycling

Modules experience changing temperatures when warming up or cooling down ATLAS





ATLAS ITk activity at Lund

ATLAS Inner Tracker

Key takeaways

★ Tracking upgrade for High-Luminosity LHC

- Entering operation by end of decade

★ Si + gas tracking detectors → Si only

- Significant gain in radiation hardness, coping with occupancy

★ Lund thermal cycling new Si strip tracking detectors in basement of Astronomi Huset

- Pre-production in progress
- Production starts in ~year for modules!

102 institutes across 21 countries

AUSTRALIA CANADA CHINA
COLOMBIA CZECH REPUBLIC
DENMARK FRANCE GERMANY
ITALY JAPAN NETHERLANDS
NORWAY POLAND RUSSIA
SLOVENIA SOUTH AFRICA
SPAIN SWEDEN SWITZERLAND
UNITED KINGDOM
UNITED STATES OF AMERICA

ITK PIXELS:

61 INSTITUTES IN 12 COUNTRIES

ITK STRIPS:

56 INSTITUTES IN 14 COUNTRIES

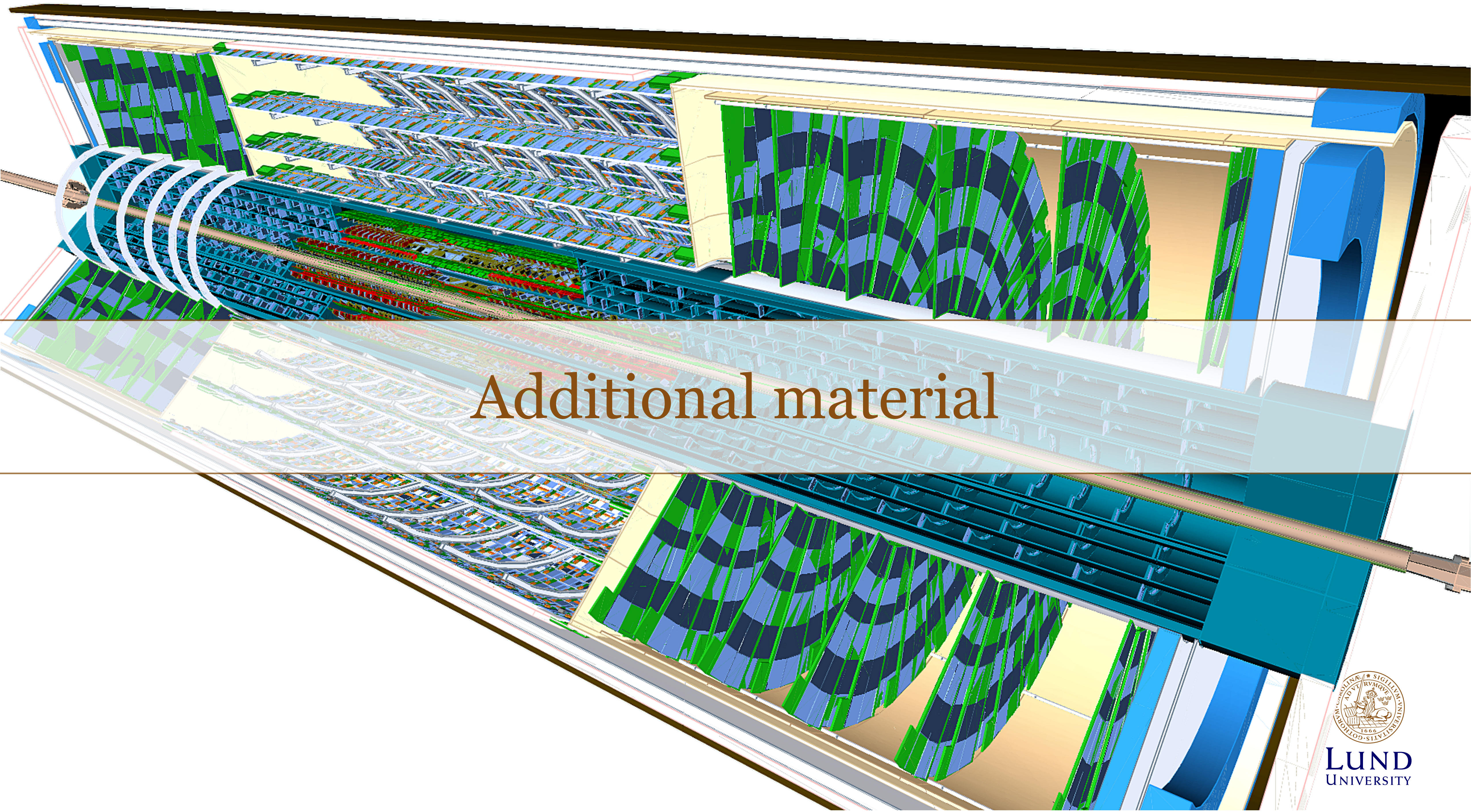
ATLAS ITk

hannah.herde@hep.lu.se • https://hherde.web.cern.ch/

ATLAS EXPERIMENT

LUND UNIVERSITY

Additional material



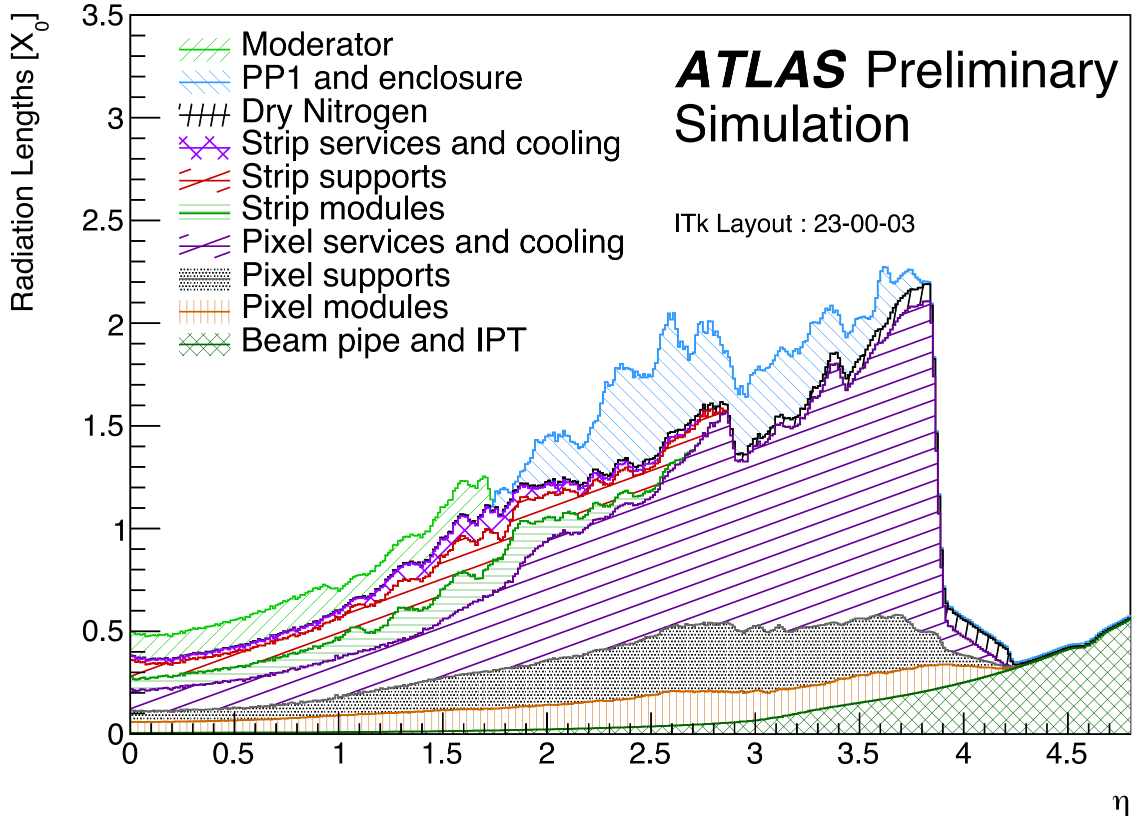
LUND UNIVERSITY

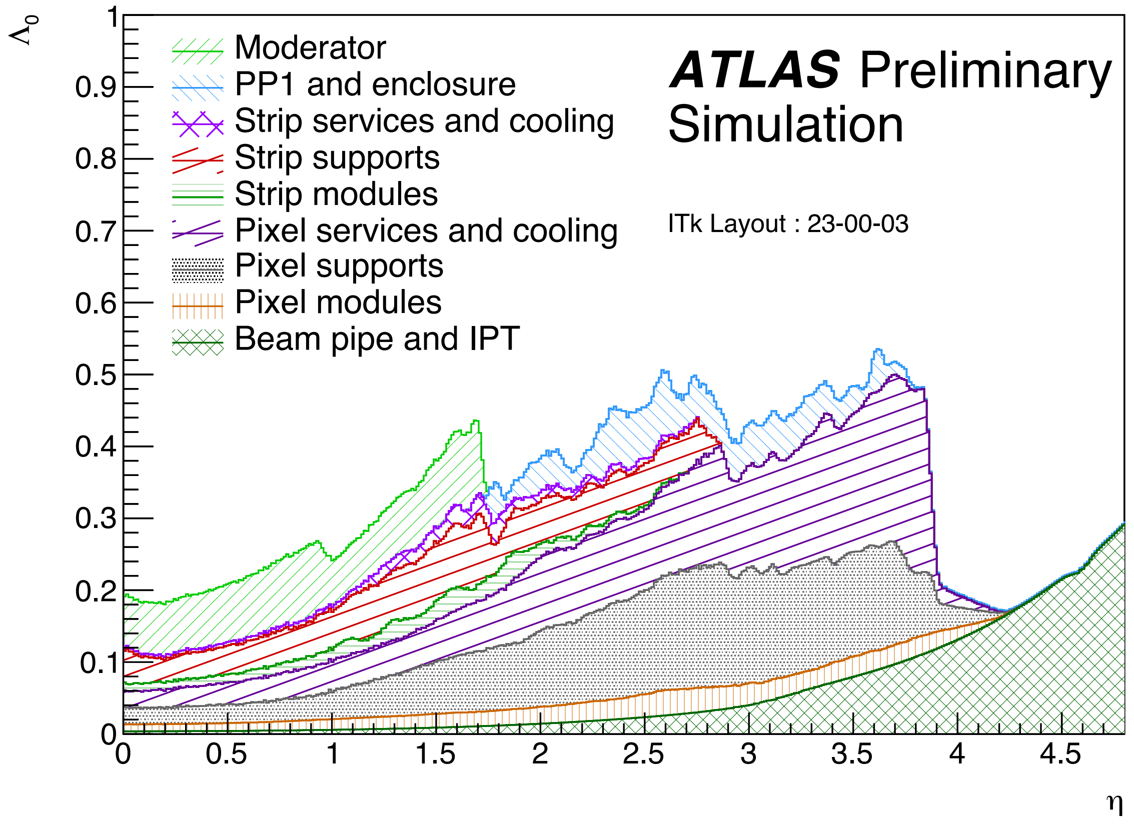
Components of ITk Strips

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

https://cds.cern.ch/record/2257755

ITk material budget



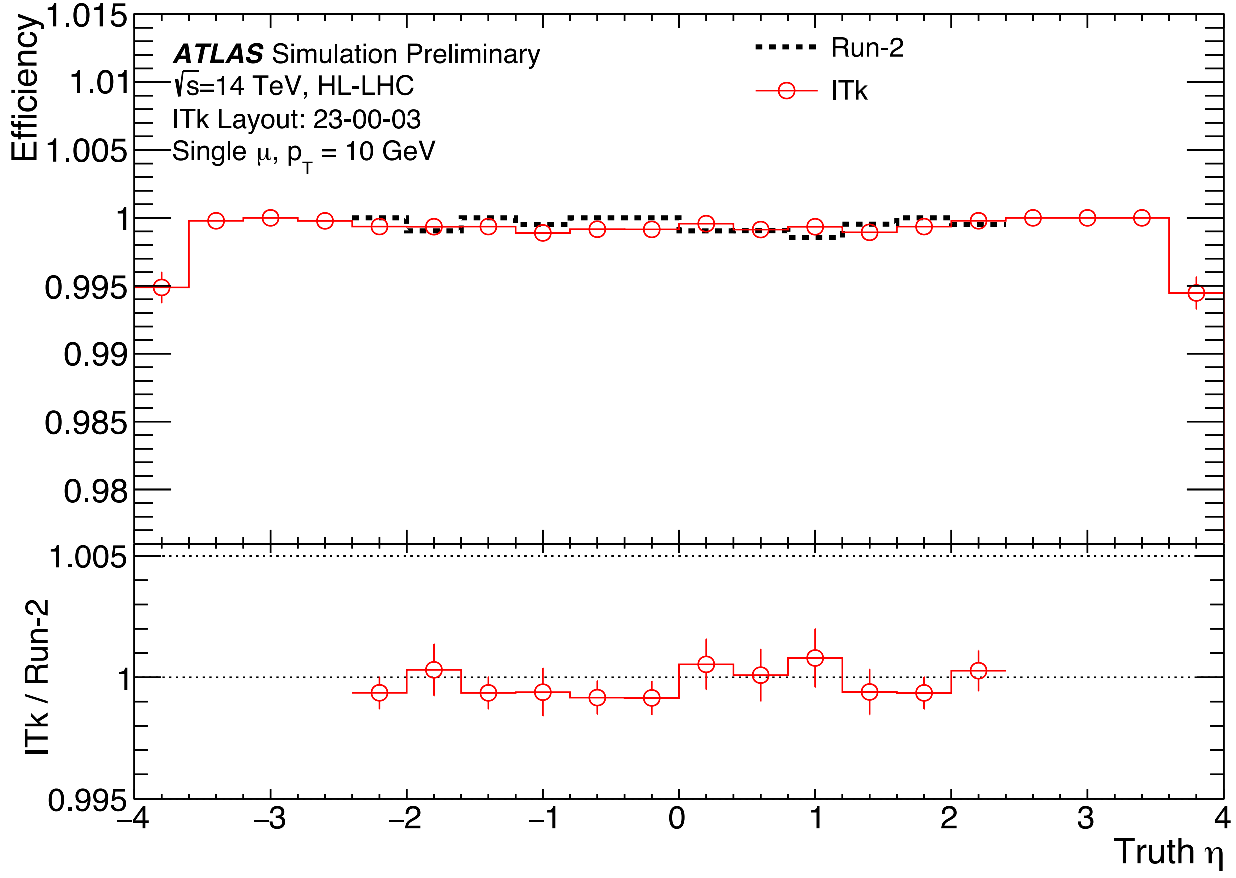


Radiation lengths

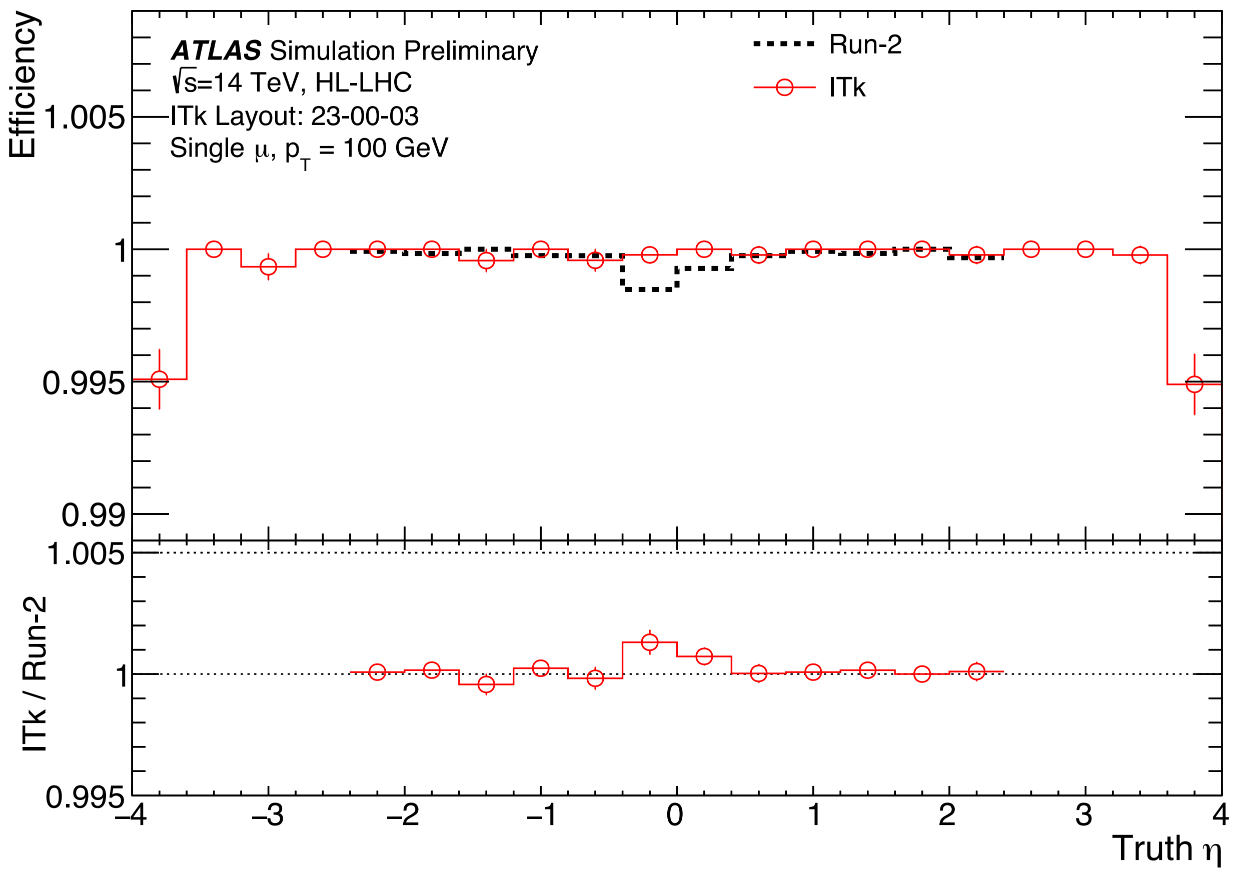
Nuclear interaction lengths

Figures 4 & 5, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

Muon tracking efficiency (without pileup)



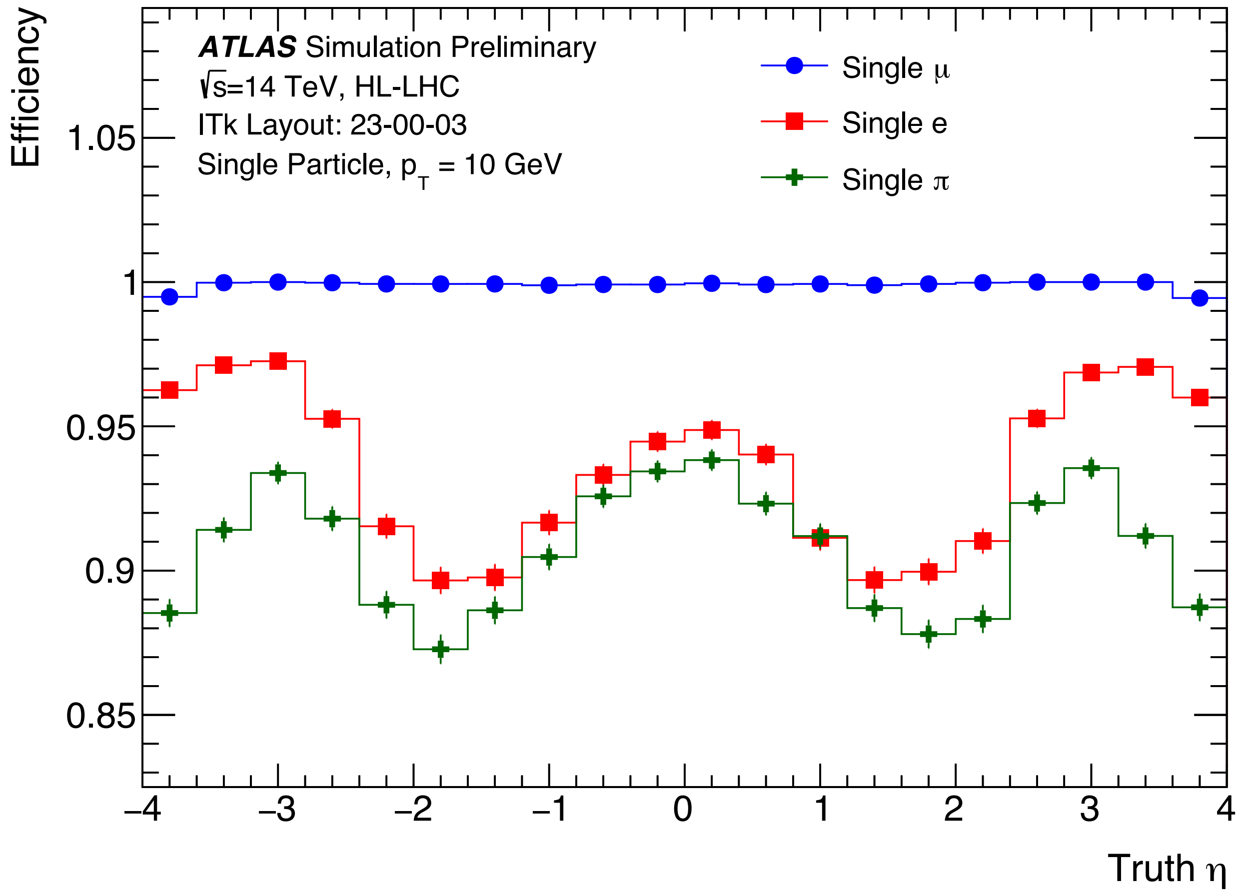
Single muons with p_T = 10 GeV



Single muons with p_T = 100 GeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

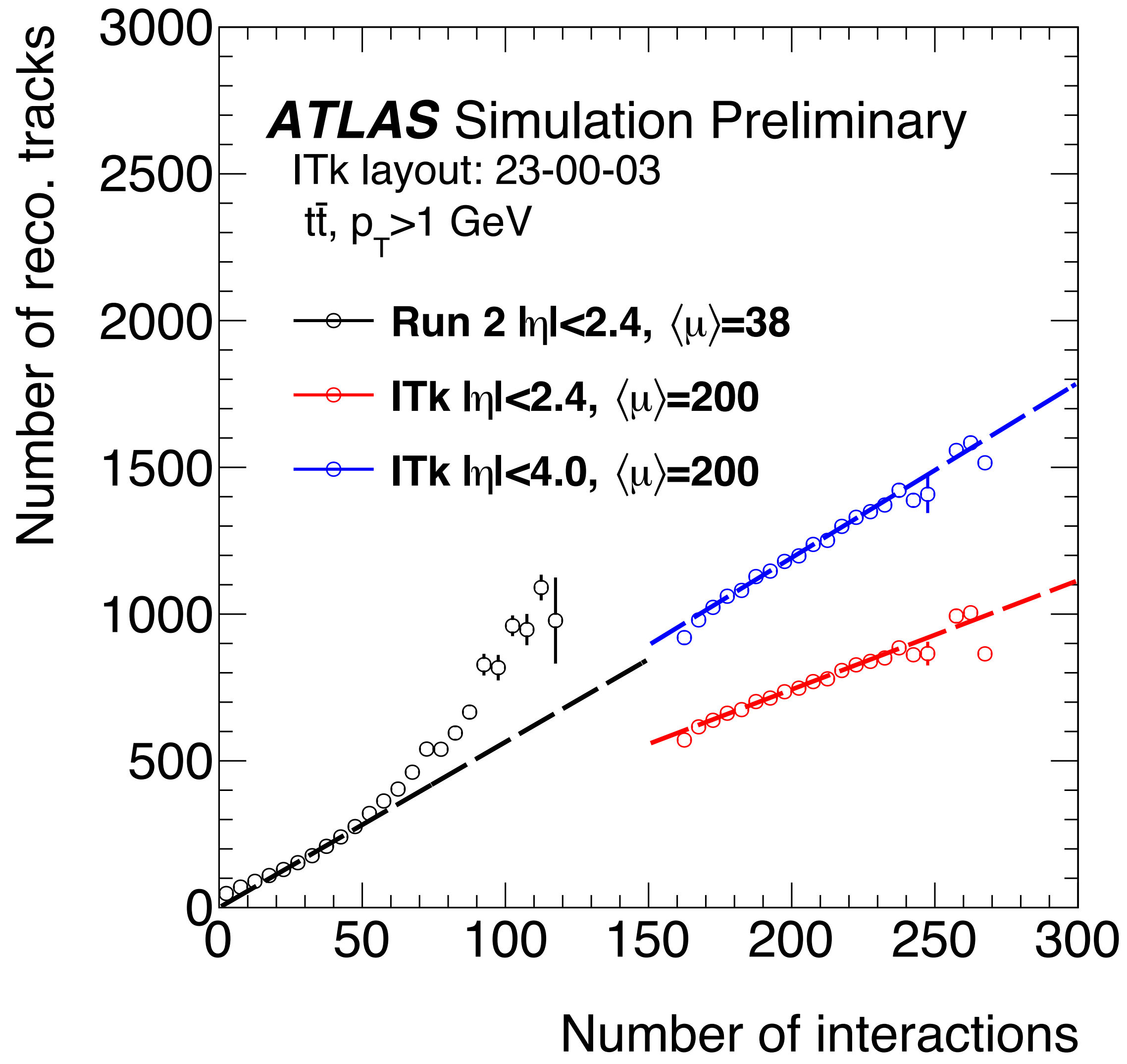
Tracking efficiency for different particle species



No pileup

Figures 9, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

ITk keeps up the pace!



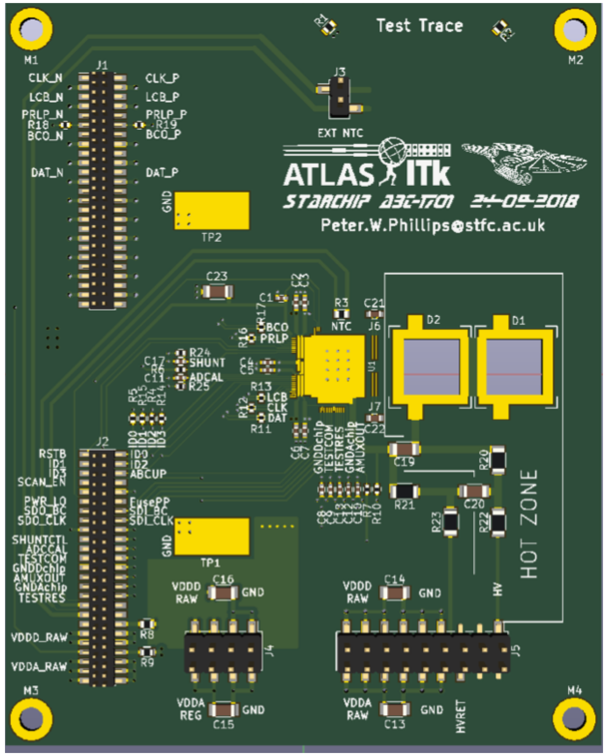
ITk track reconstruction reliable over wide <μ>

- ★ Current detector → non-linear # of reconstructed tracks
- ★ ITk behaviour remains linear with # of interactions
  - Additional tracks in blue due to increased forward acceptance

📷 https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

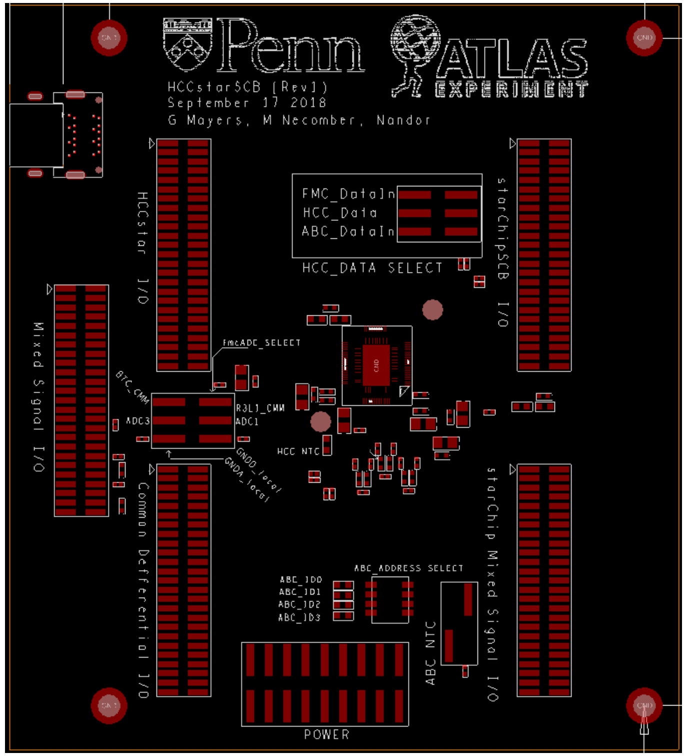
Strips system ASICs

ABCStar single chip PCB



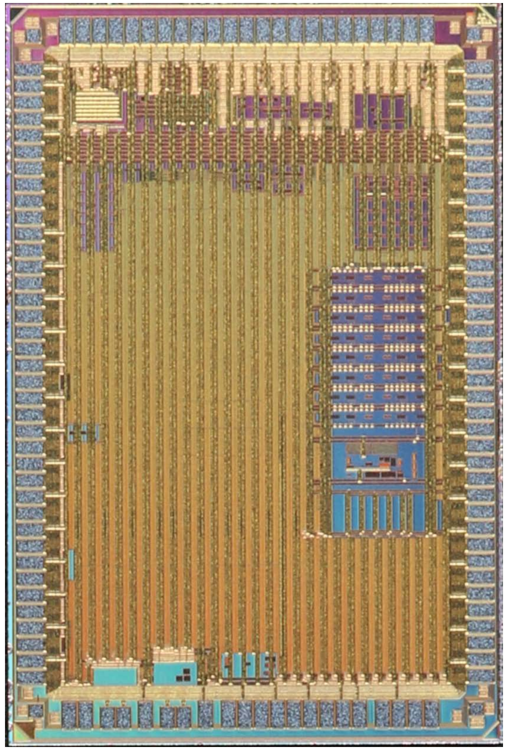
256 channel readout

HCCStar single chip PCB



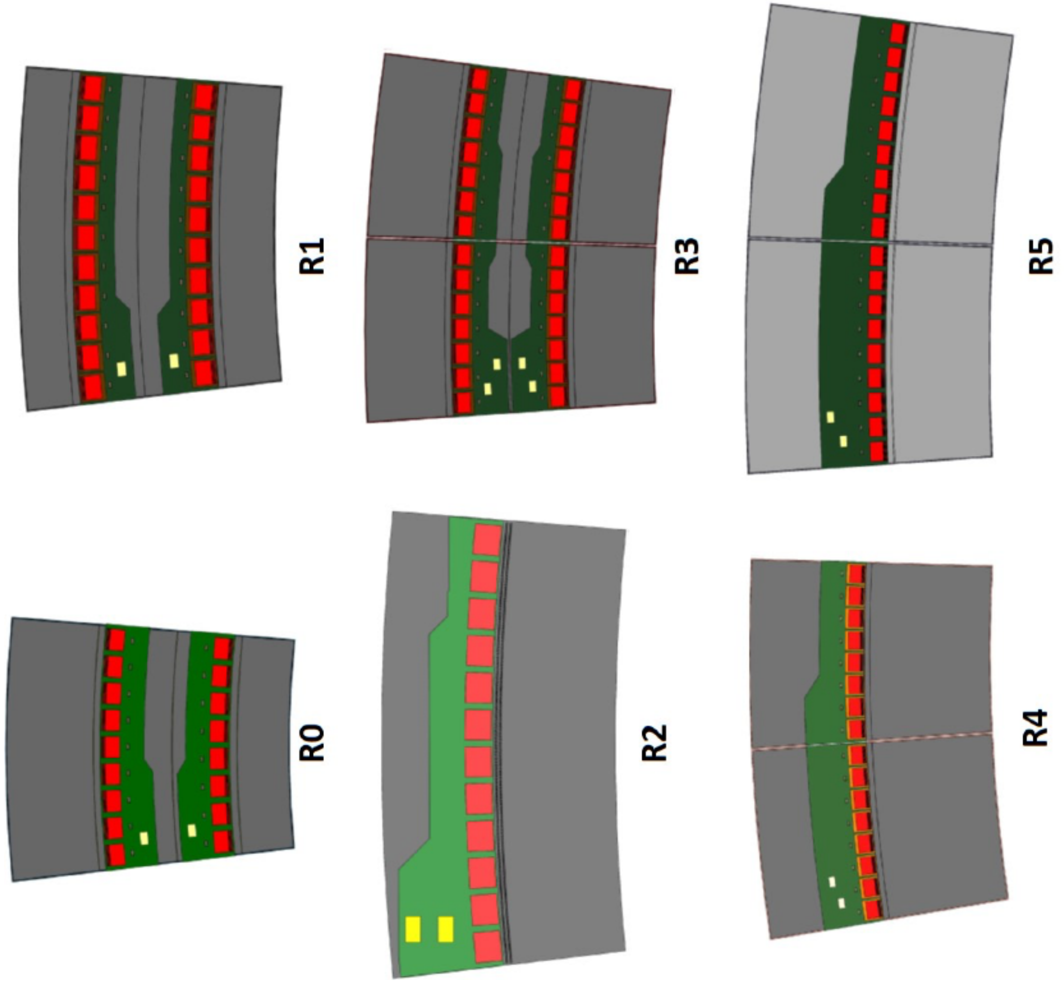
Full hybrid readout

AMACv2



Low & high voltage control

Module layouts in Endcap



https://cds.cern.ch/record/2257755