The upgrade of the tracking detector of the ATLAS experiment and its impact on Physics

28.10.2021

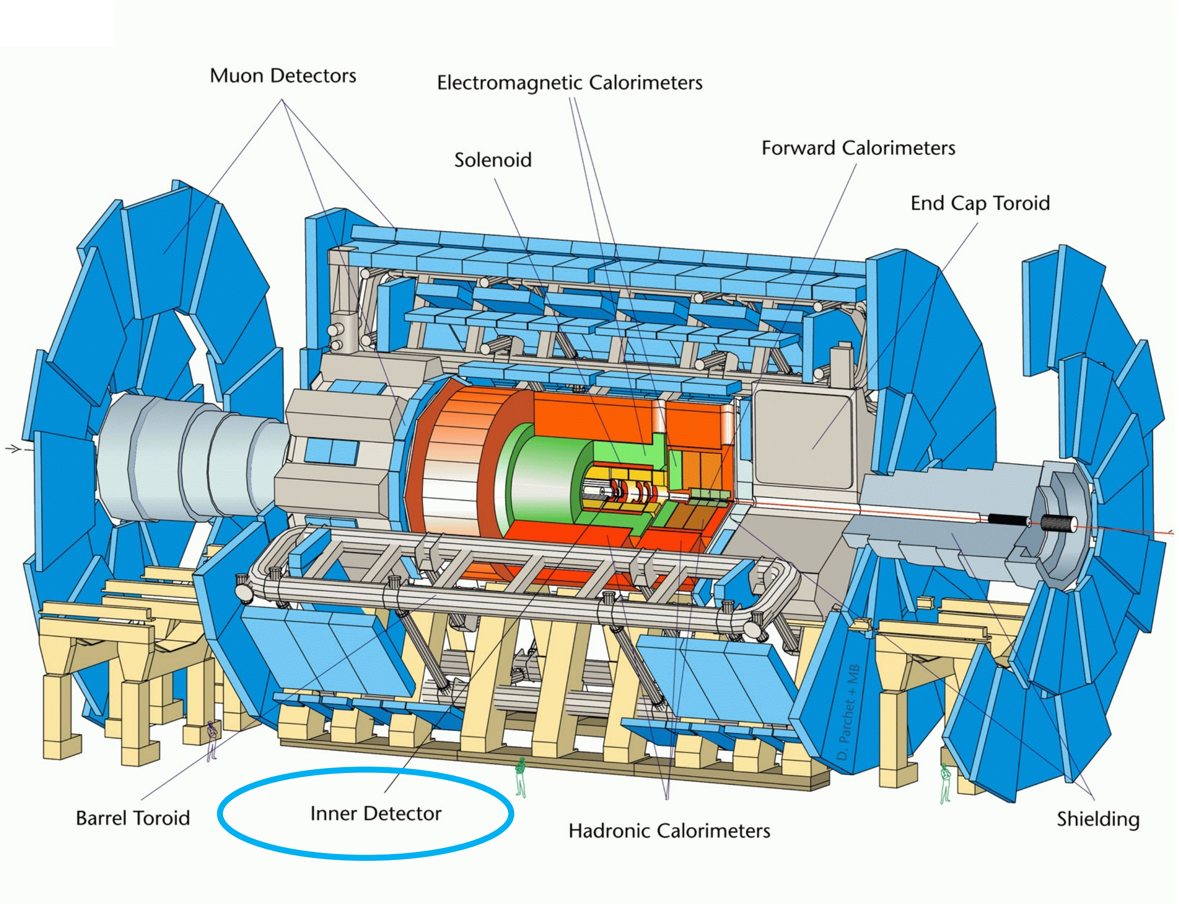
Susanne Kuehn, CERN on behalf of the ATLAS ITk Collaboration

International meeting on

"Tracking detectors for particle colliders - present and future"

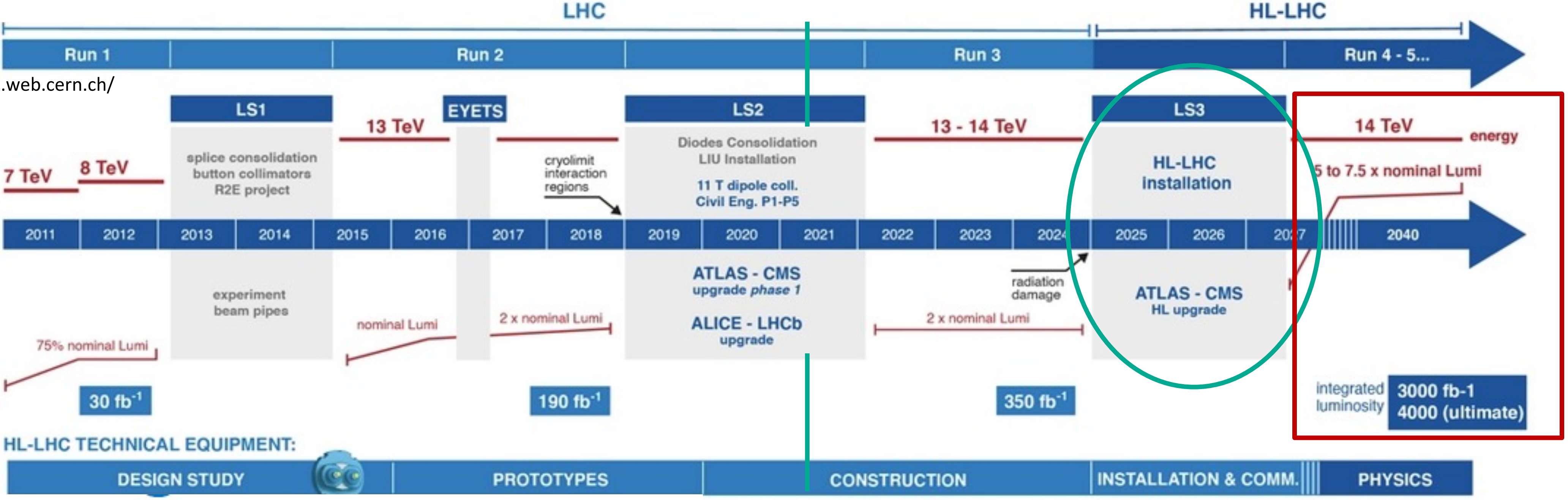
Overview

- The High-Luminosity LHC and challenges for the ATLAS experiment
- Upgrade of the inner tracking detector: concept, technology choices and results of prototyping of
  - the Pixel detector upgrade
  - the Strip detector upgrade
- Impact on physics performance objects
- Prospects for physics
- Summary

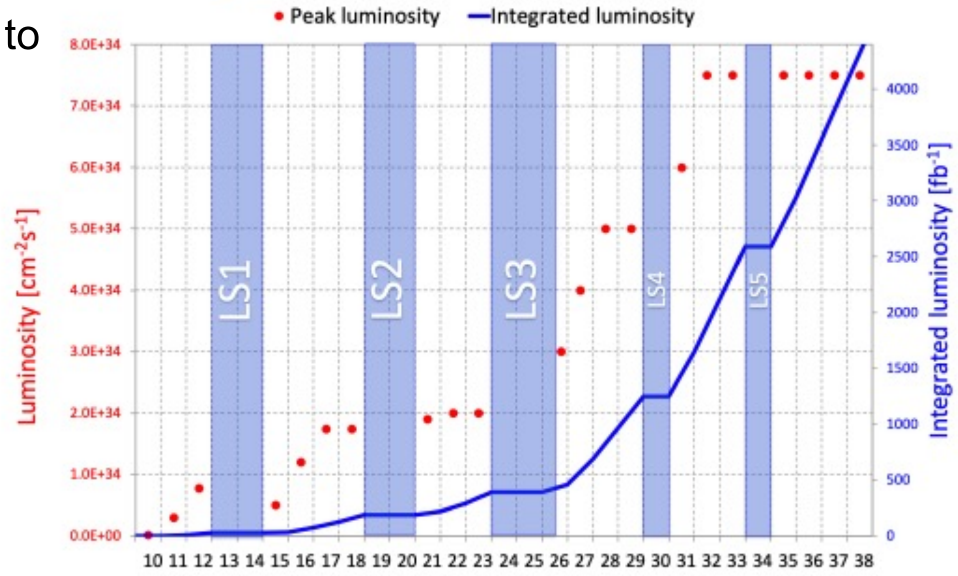


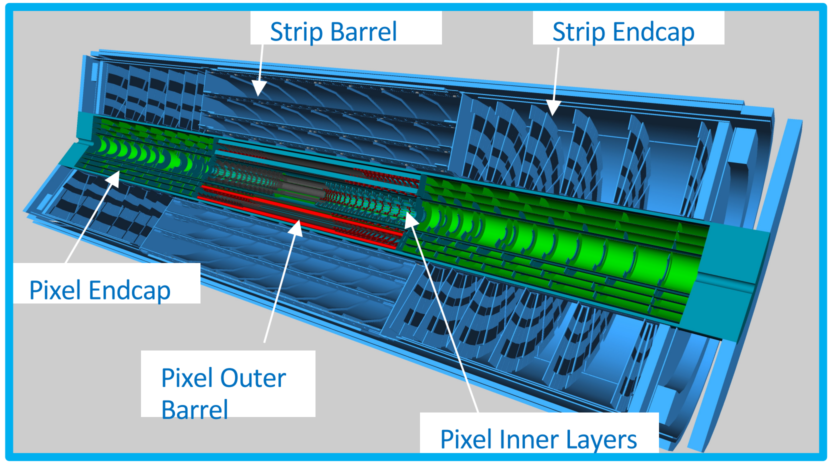
Phase-II Upgrade of the LHC

https://hilumilhc.web.cern.ch/



From LHC to HL-LHC





Goal: At least the same performance of the ATLAS experiment as in Run-2/Run-3

Challenges for the experiments at the HL-LHC

Proton-proton collisions with up to 14 TeV at higher intensity:

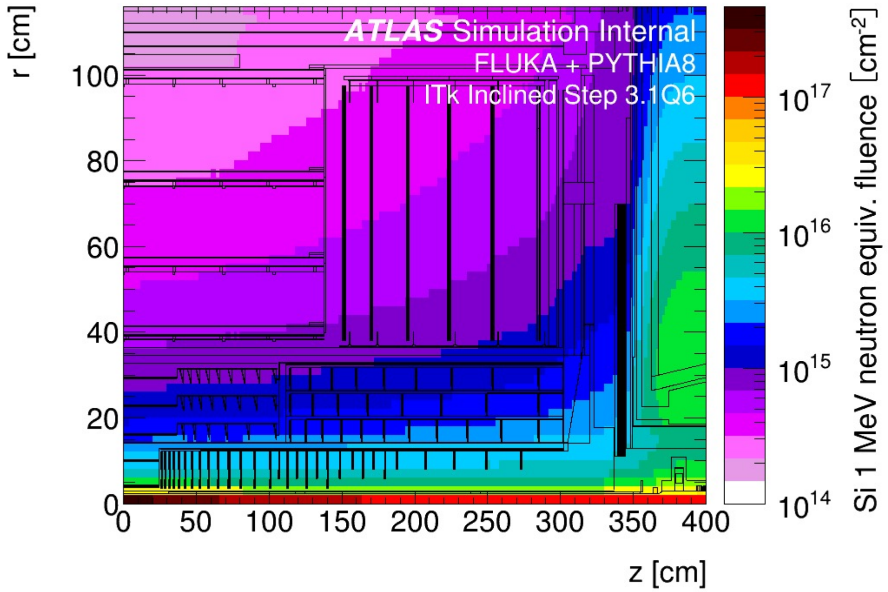
- Instantaneous nominal luminosity x5-7.5 → Increased particle densities
- Integrated luminosity x10 → Increased radiation damage, radiation levels up to 2×10^{16} n_{eq}/cm^2 or 1 GRad
  - Impact on detector technologies (silicon, 3D-sensors), electronics (deep sub-micron technologies and FPGAs) and materials (cables, glues) → Qualification process essential

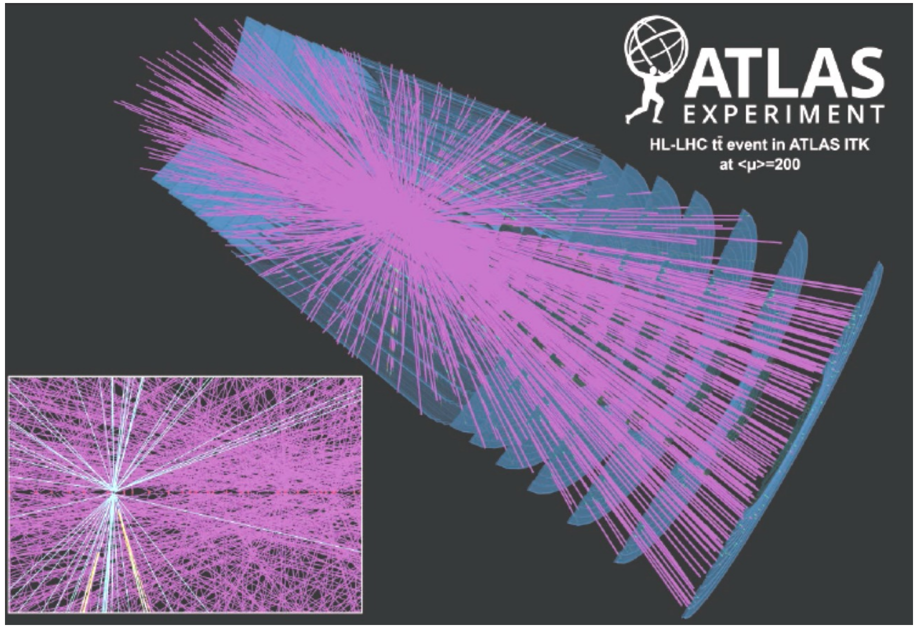
→ Increase of overlapping proton-proton events (pile-up) from <μ> ~ 50 now to <μ> ~ 200

- Additional energy in calorimeters, accumulation of "pile-up" jets especially in the forward region

→ Hit rates up to 3 GHz/cm²

- Higher rate of fake tracks





Simulated event with ttbar events and average pile-up of 200 collisions per bunch crossing

Phase-II Upgrade: Physics Program

Wide program covering nearly all areas of Physics at hadron colliders

- Exploration of **electro-weak Standard Model and top physics**
    - Precision measurements like W/top masses, ...
    - Rare signatures like Vector-Boson-Scattering, FCNC top decay, ...
- **Higgs Boson Program** a major component, main measurements:
    - Higgs couplings
    - Higgs self-coupling
    - Higgs differential distributions
    - Rare Higgs decays
    - Heavy Higgs searches
- **QCD measurements** - constraining PDF uncertainties with LHC data
- **Flavour physics** constrains on CKM matrix, ...
- Extended sensitivity for **Beyond the Standard Model physics**
    - New TeV-scale physics could be discovered or very strongly disfavoured
- …

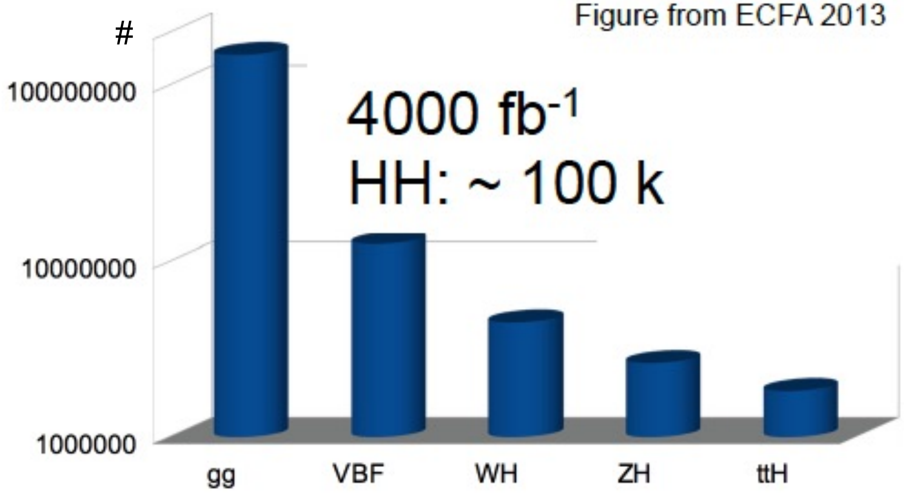


Figure from ECFA 2013

4000 fb^{-1}
HH: ~ 100 k

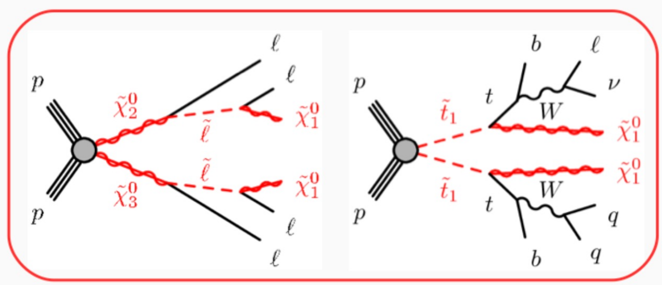
HL-LHC offers increased dataset → Reduced uncertainties both statistically and experimentally (large calibration datasets)

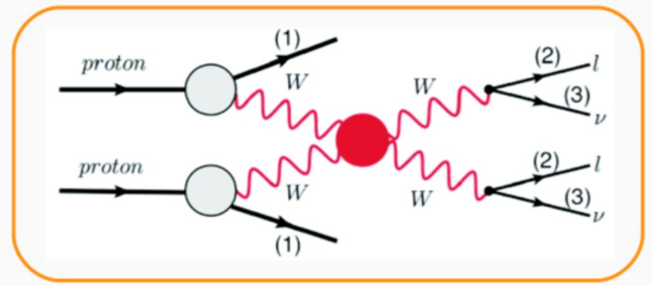
Main references:
Reports arXiv:1902.04070, arXiv:1902.00134, arXiv:1812.07831, Physics Briefing book arXiv:1910.11775

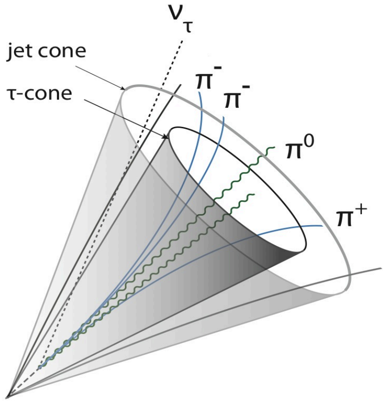
Motivations for detector upgrade

Process	Requirements
Efficient tracking with small fake rates	**Radiation tolerance**, high **granularity**, **low material** budget
High multiplicity events and highly boosted jets	Improved granularity and resolution
Missing transverse energy	**High coverage** including acceptance **in forward region**
Resonances in top pairs, W, Z, H	Reconstruction of leptons & b-quarks in boosted topologies
VBS/VBF forward jets	**Forward tracking** to reject pile-up by **jet-vertex association**
H → $\tau\tau$	Triggering of τ-leptons
High-mass gauge bosons	**Good lepton momentum resolution at high p_T**
Rare events	High coverage and reconstruction efficiency
BSM cascades	Triggering & reconstruction of **low p_T leptons** + **identifying heavy flavour**

→ Precise measurement of physics objects: leptons (e, μ, τ-leptons), photons, missing transverse energy, jets, b-(c-)quarks over full p_T range

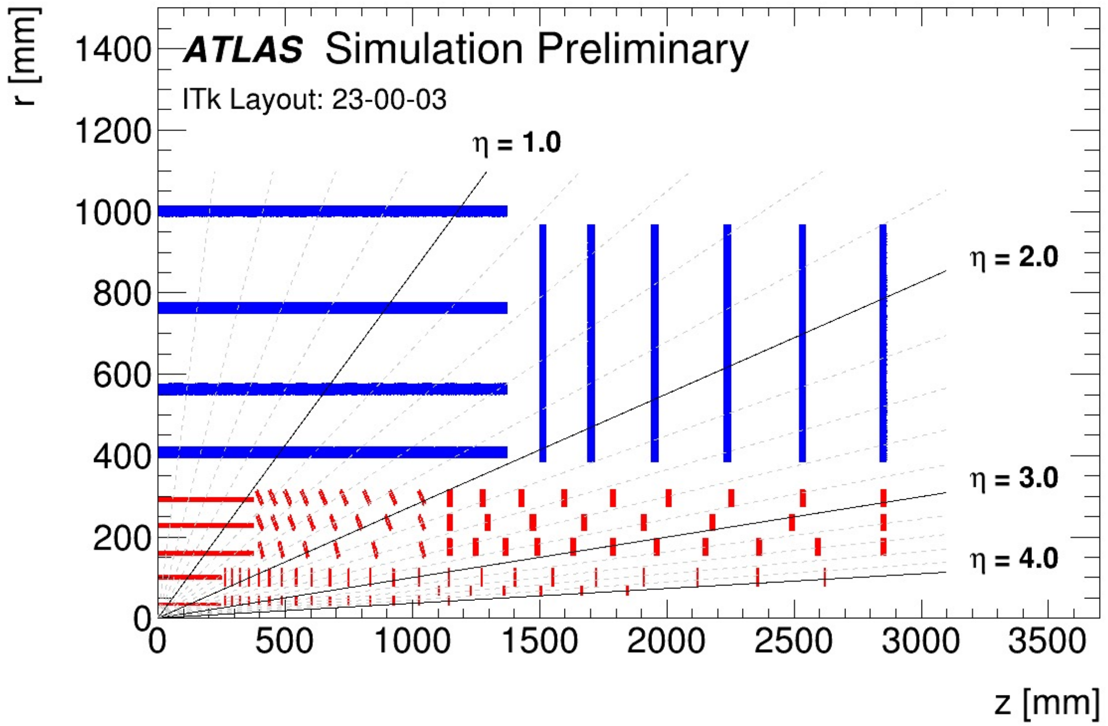






+ Some detectors (e.g. inner tracker) can't withstand radiation and rates beyond LHC

Upgrade of the inner tracking detector



CERN-LHCC-2017-005,
CERN-LHCC-2017-021
ATL-PHYS-PUB-2021-024

	Surface [m²]	# Channels	# modules
Pixel	13 **(x7)**	5 G **(x60)**	8.5 k
Strip	165 **(x3)**	60 M **(x10)**	18 k

	N-in-p silicon sensors
Strip pitch (µm)	70-85
Strip length (cm)	2.5-8
Strip thickness (µm)	300
Pixel size (μm^2)	50x50 (planar L1-L4), L0 3D in rings 50x50, 25x100 in flat
Pixel thickness (µm)	≤ 150

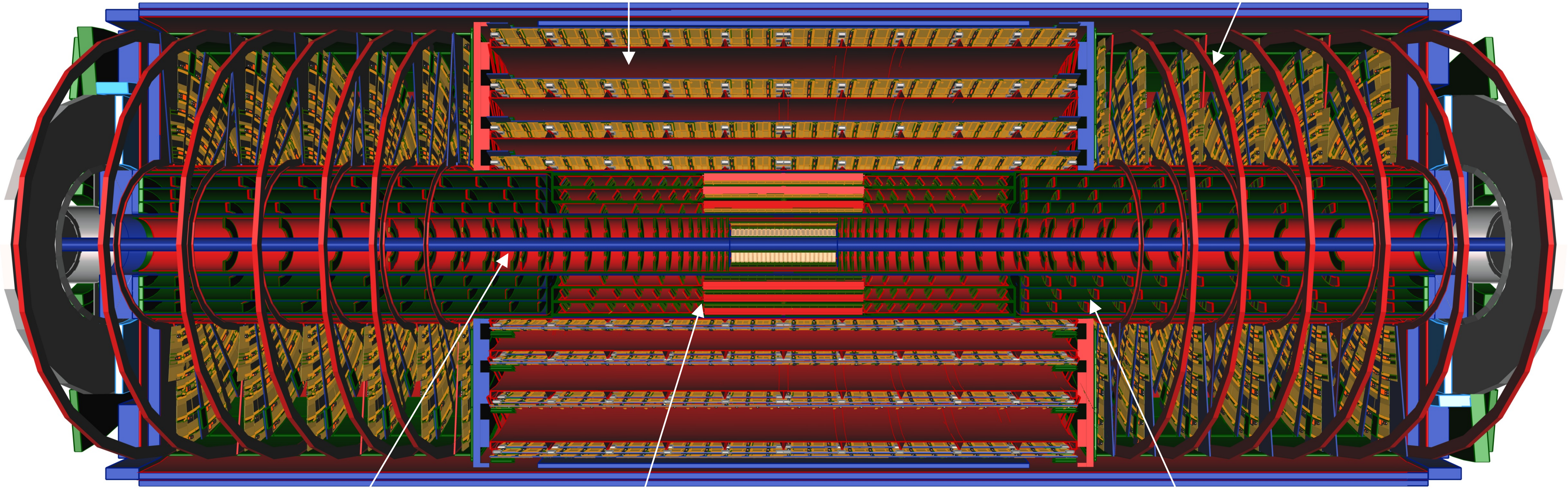
Silicon strip and pixel detector in 2 T magnetic field:

- 4-central strip layers and two endcaps with 6 disks each

- 5-pixel layers in the central and forward sections up to |η|< 4
  - Innermost layer radius finalized at 34/33 mm (B/EC, was 39/36)
  - Inner two layers replaceable
- Cooling with CO_2

Inner Tracker ITk - New all silicon tracking detector with extended coverage to |η| < 4

Let’s look at the detector components



Strip Barrel

Strip Endcap

Pixel Inner Layers

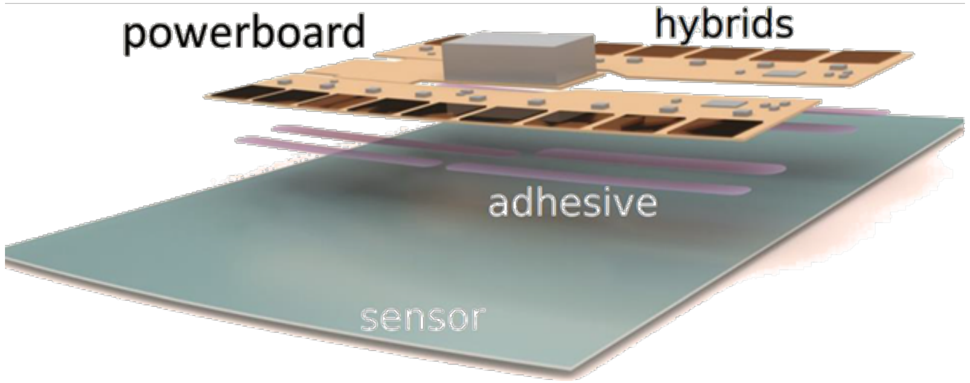
Pixel Outer Barrel

Pixel Endcap

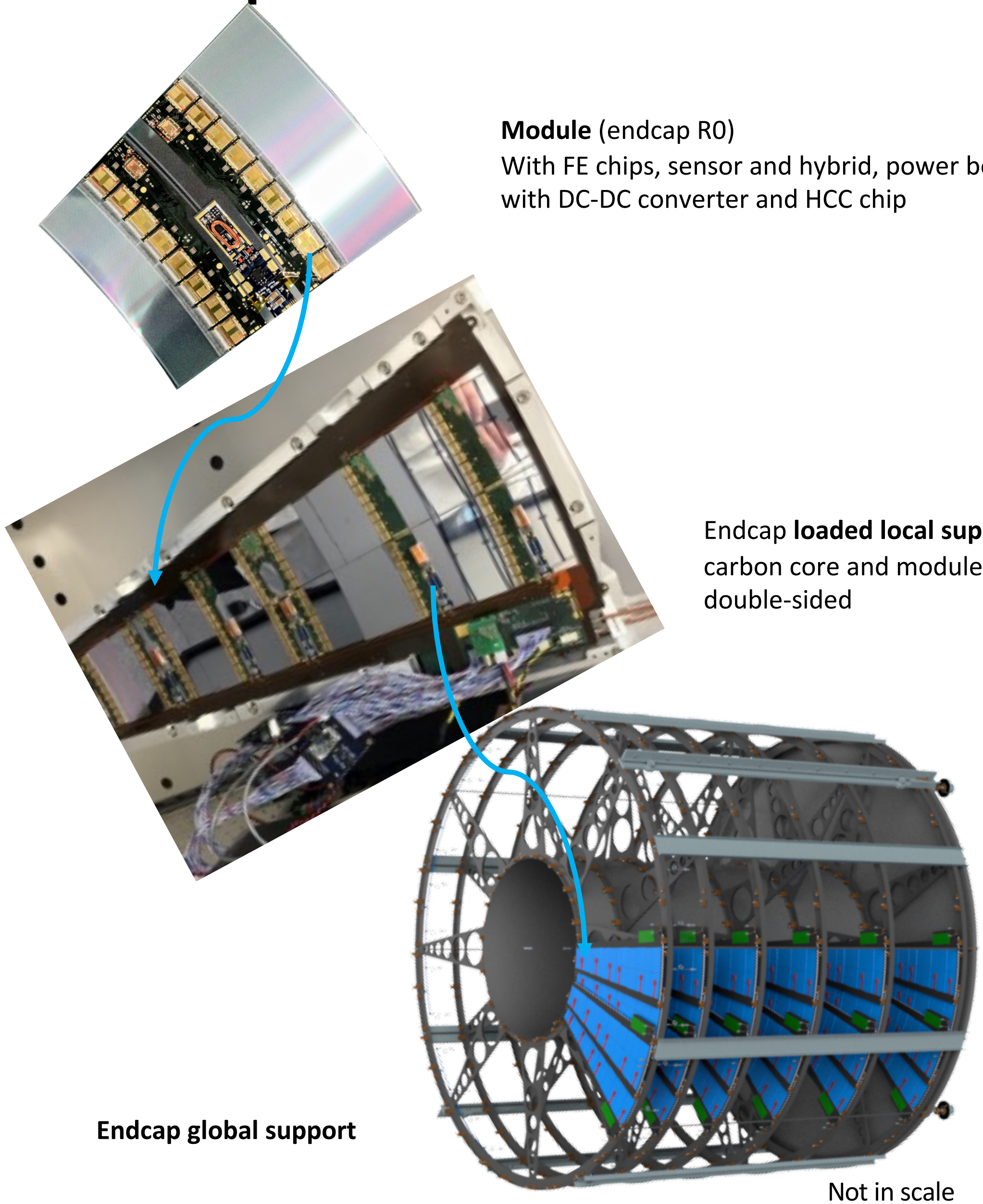
The concept of the ITk Strip Detector

- **Concept of modularity of components** which are designed for manufacturability and mass production from the beginning (standard design rules, simplified construction,…)
  - Assembly and testing at multiple sites
  - Simplifies final assembly
  - Earlier test of full system

- 18,000 modules with 2560 or 5120 channels/module



- Parallel powering scheme
  - ~14 modules per LV channel
  - 11V → 1.5V on-module DC/DC conversion
  - ≤ 4 modules per HV channel
  - On-module power control and monitoring



Module (endcap R0)
With FE chips, sensor and hybrid, power board
with DC-DC converter and HCC chip

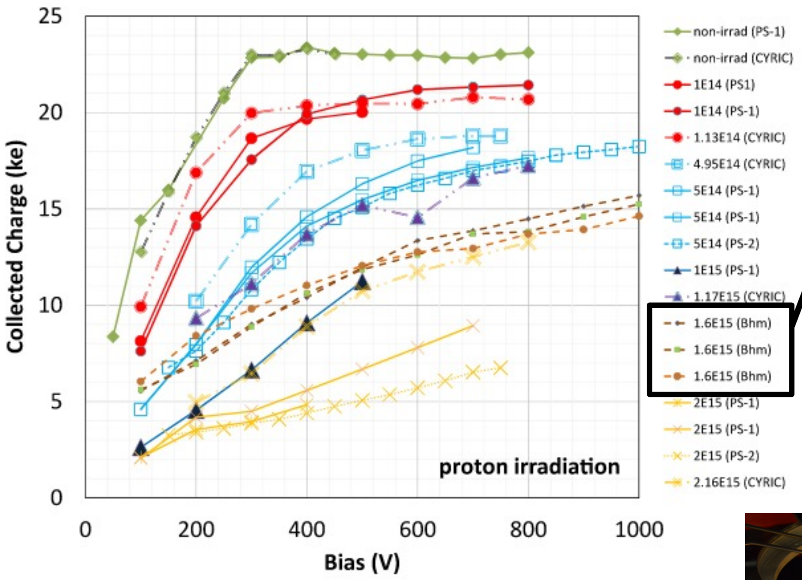
Endcap **loaded local support** with
carbon core and modules glued
double-sided

Endcap global support

Not in scale

Strip sensors and electronics

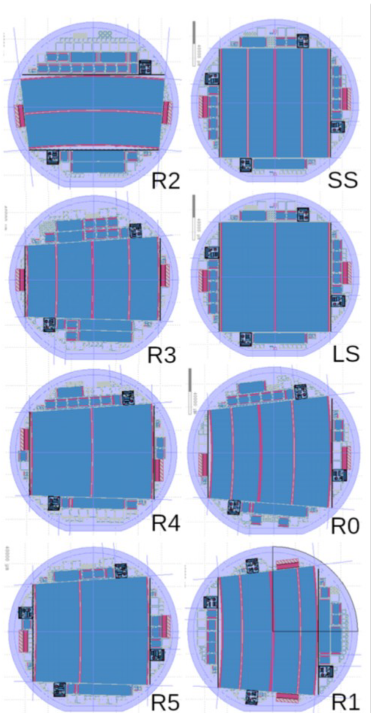
- **n-in-p float-zone sensors with p-stop isolation and ~320 µm thickness**
  - 8 sensor types (2 for barrel, 6 for endcap)
  - bias voltage: 100V to 500V
  - Preproduction delivered
  - Production Readiness Review (PRR) passed
  - First production batch delivered

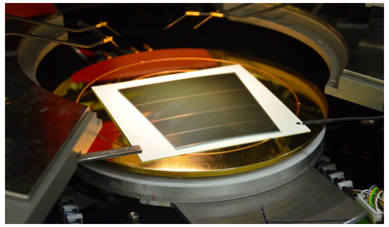


Max expected + safety: 1.6 x 10^{15} n_{eq}/cm^2

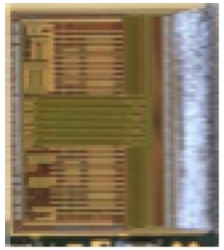
Nucl. Inst. Meth, A 983 (2020) 164422

SS, LS are barrel
Rx are endcap petals





- **Binary readout chip and controller chips (130 nm CMOS)**



HCCStar (Hybr. controller)

- Connects 10x ABC to stave
- SEE mitigation
- Pre-production submitted, chip expected late November

ABCStar (front-end chip)

- Binary readout with 256 channels
- Preproduction available
- First prod wafers in 01/2022

AMACStar (Power control and environmental monitoring)

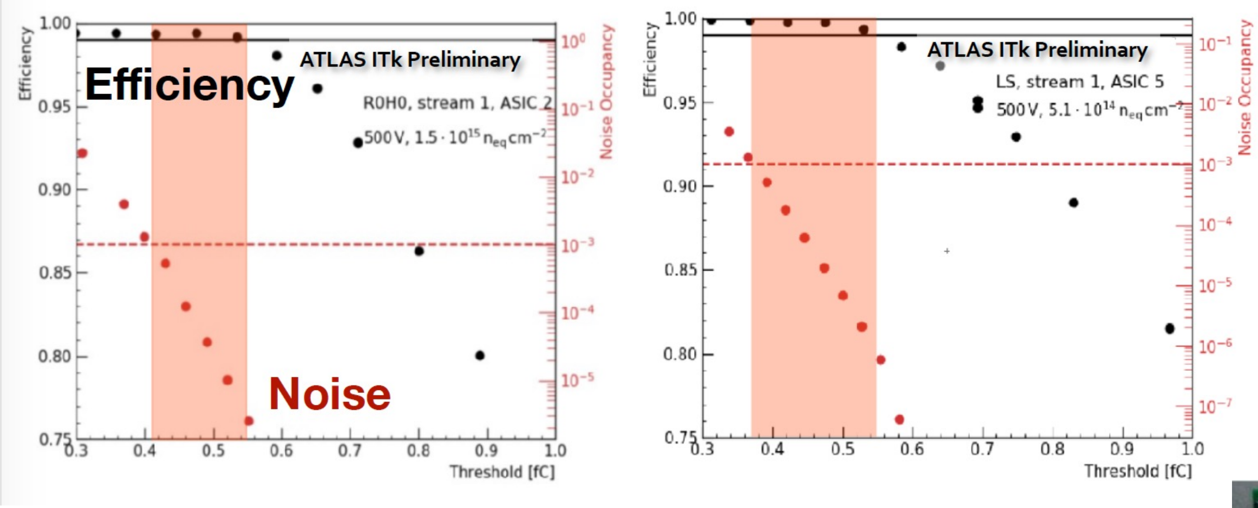
- On the same wafer as HCC
- Preprod submitted

- Extensive testing in simulation for all chips
- Current increase after first step of radiation: Pre-irradiation of ASICs baselined
- All three chips were extensively modified to improve SEE protection
  - Feature sets for HCCStar and AMACStar reduced to increase area available for triplicated logic.
  - HCCStar die size was increased as well

https://arxiv.org/pdf/2009.03197

Strip module construction and performance

- **Several successful test beam campaigns**
- Results show clear operating windows meeting >99% efficiency, <0.1% noise occupancy requirement

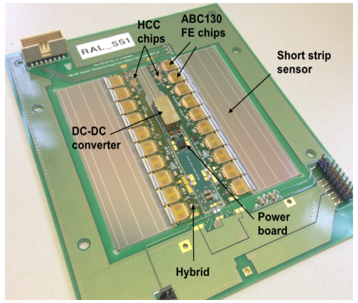


→ Signal-to-noise ratio values > 10 for all evaluated modules at foreseen bias voltages

- **Preproduction and site qualification ongoing in two stages**
  - To demonstrate that production of 18,000 modules feasible
  - Defined 10% of the actual production
  - ~20 assembly sites across 4 continents
  - Pre-production A: ~20% of pre-production sensors, flex and ABC but prototype HCC
  - Pre-production B:

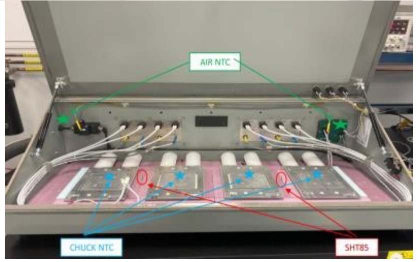
    Using final components

Barrel module

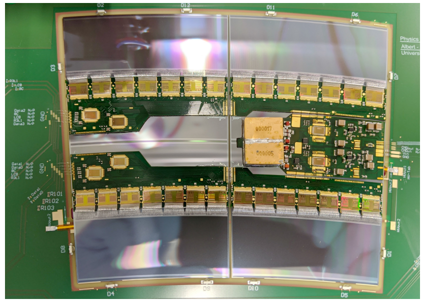


Power board mass-tester

Hybrid Burn-in Crate



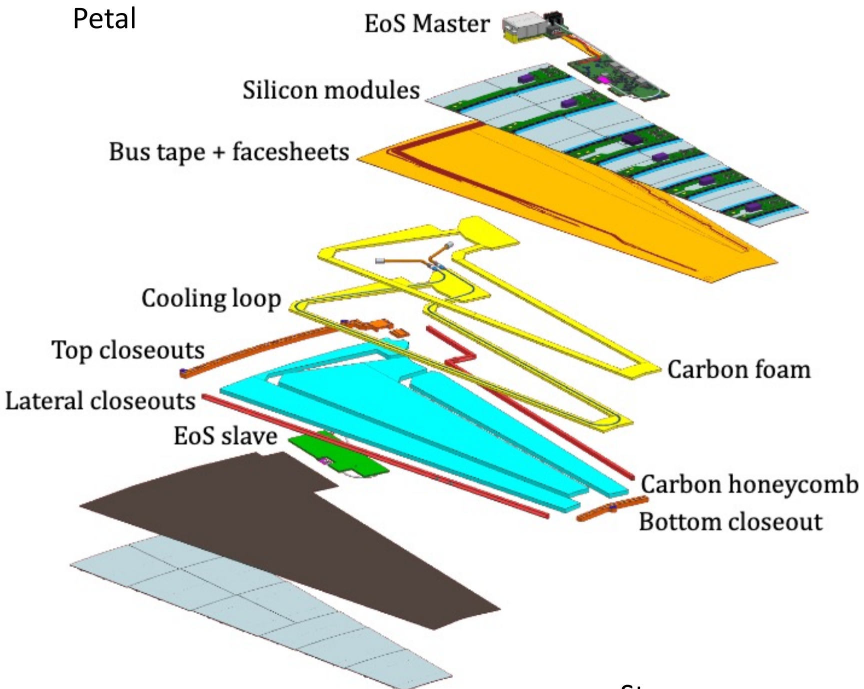
Module Thermal Cycler

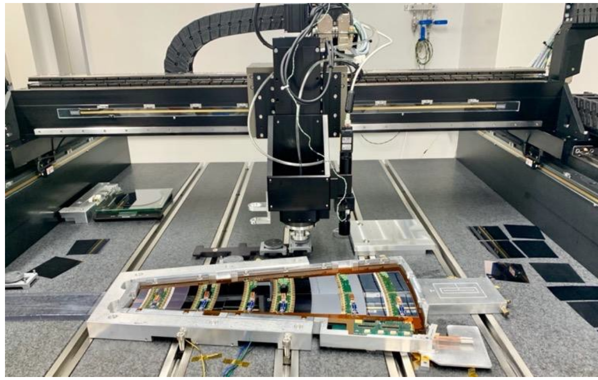


EndCap module

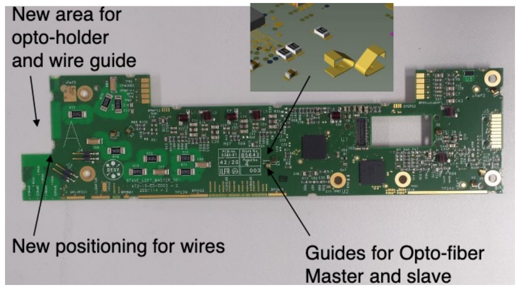
Strip local supports

- **Carbon-fibre composite structures** with co-cured polyimide-copper **bus tapes** have **modules** glued on top of both sides with a stereo angle between both sides
  - In central region (barrel): staves with 14 modules on each side (392 staves in total)
  - In endcaps: petals with 9 modules on each side (384 petals in both endcaps)
- **End-of structure cards service the electrical to optical transmission** (lpGBT and VTRx+ links) **and to the outside world:** production and tests with optimized design ongoing

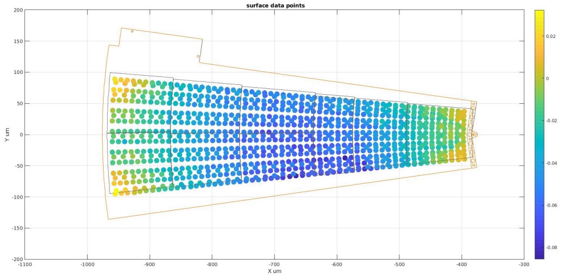




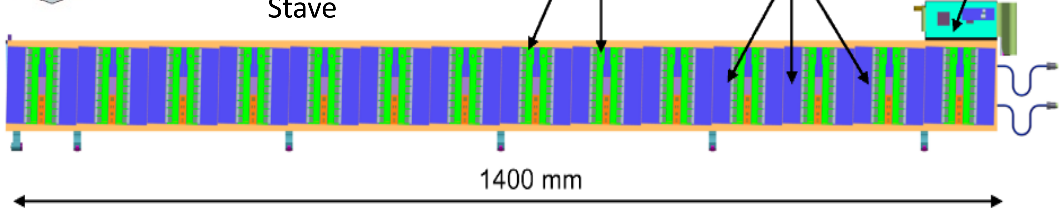
Loading of modules to better than 40 µm accuracy with gantry systems

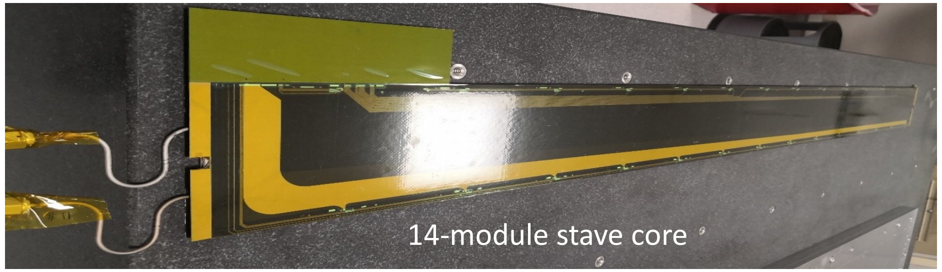


End-of-strucure card



Petal with local flatness: 19 - 41 µm
Global flatness: 93 - 116 µm



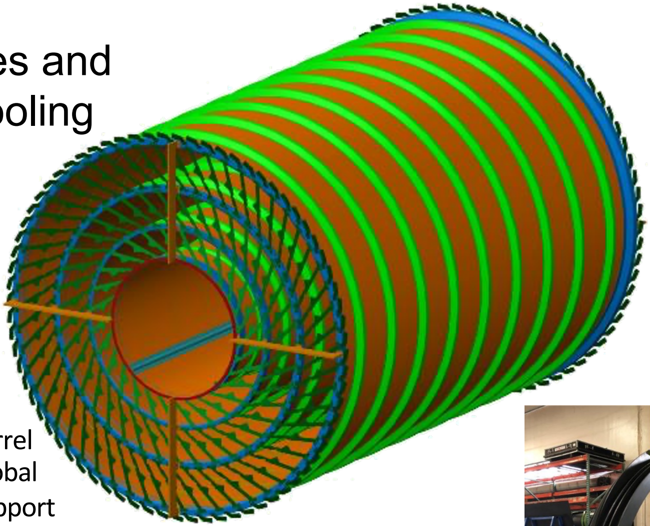


Good thermal performance measured

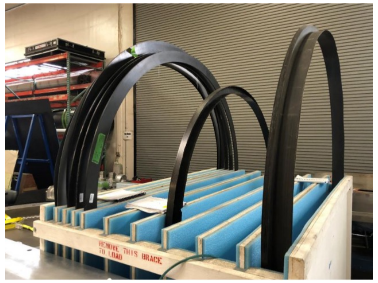
- Good electrical and thermal performance achieved, and Final Design Review passed, ready for pre-production

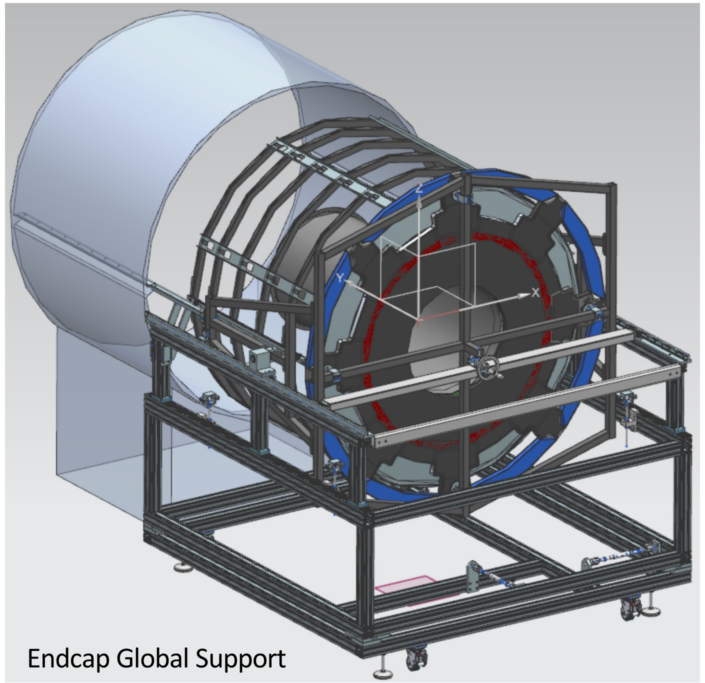
Global mechanics and integration of strip detector

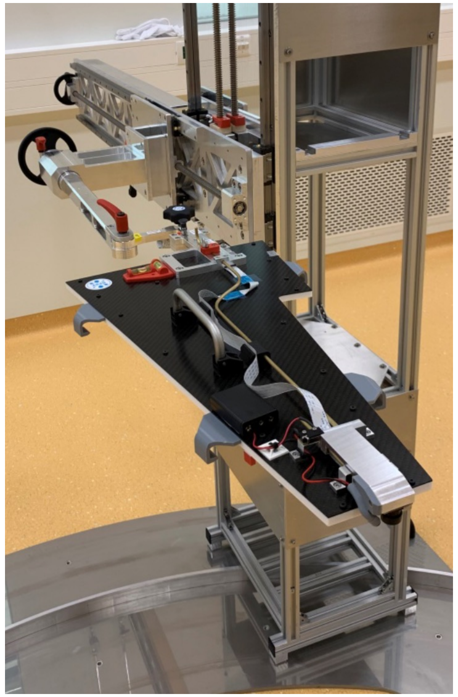
- Loaded local support structures (staves and petals) are end-insertable including cooling and cabling
  - Fire-tests of components passed
- For barrel: carbon cylinders for each layer in which staves are inserted.
  - Tests with mock-ups well advanced
- For endcaps: carbon wheels with blades for each disk mounted in endcap structure
  - Tests with mock-ups well advanced


Barrel Global Support

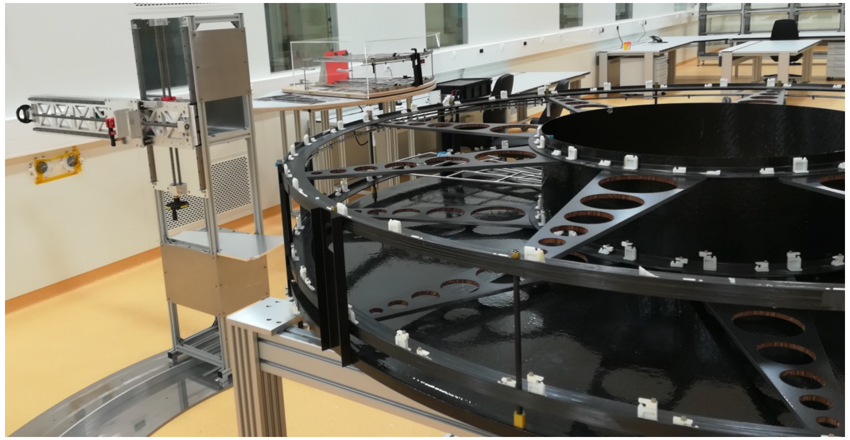
Shell flange prototypes



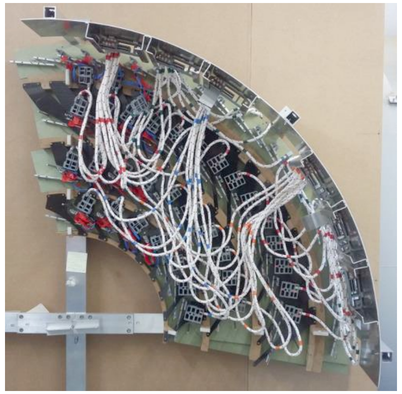

Endcap Global Support



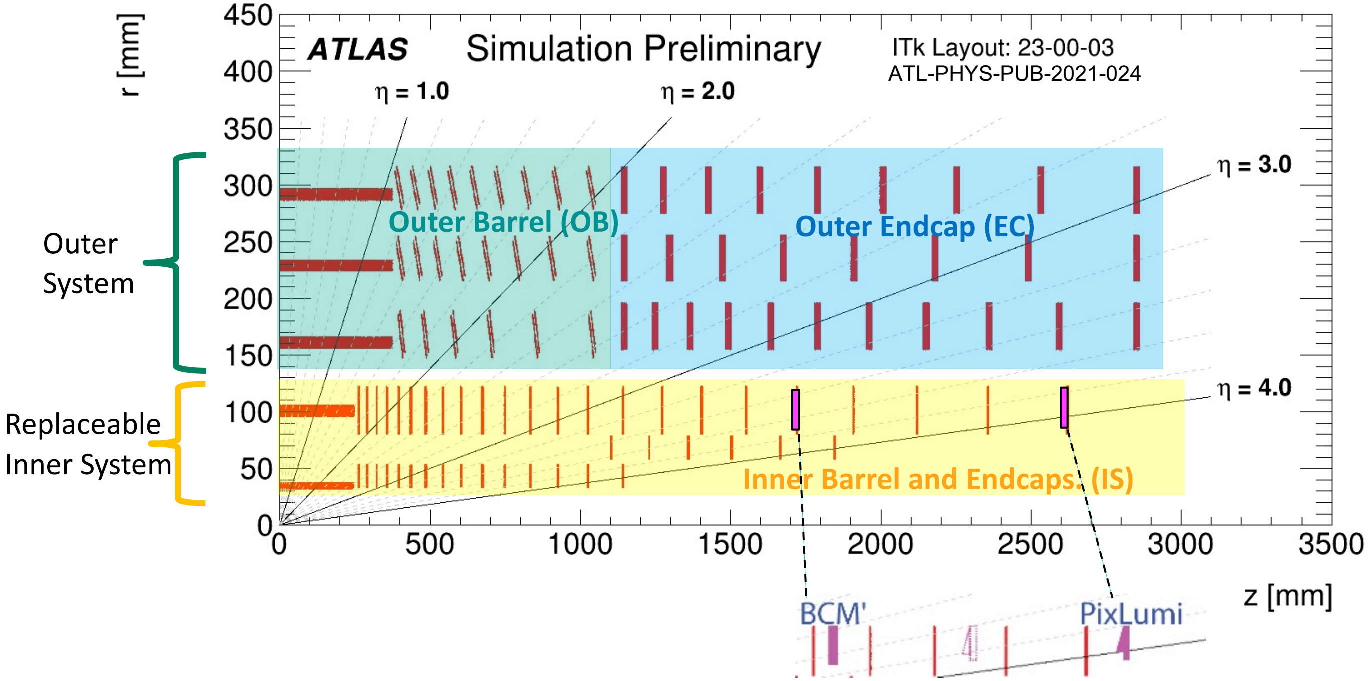
Prototype Wheels (w/ blades)



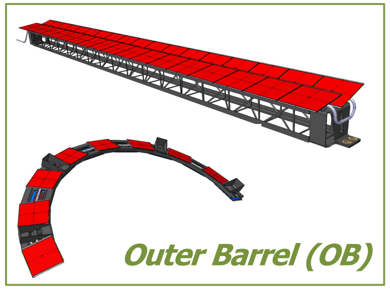
Mockup of services, interlinks and end flanges

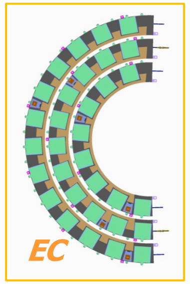


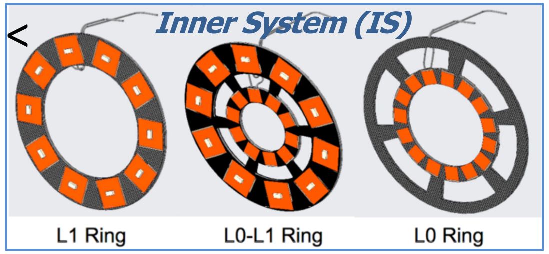
Overview of the ITk Pixel detecetor



Local support carbon structures for cooling and positioning of modules







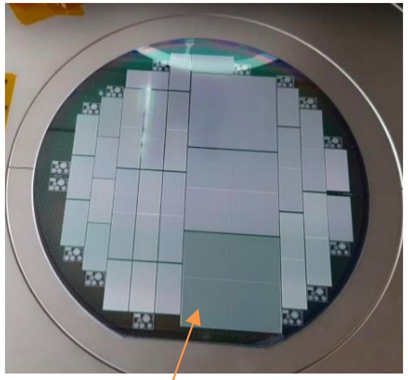
- **Different sensors types and technologies depending on distance from interaction point**
  - 3D-sensors in triplet assemblies (Layer 0), planar quads with 100 µm (L1), planar quad sensors with 150 µm thickness (L2, L3, L4)
  - Pixel size 50x50 µm^2 (L1-L4, rings of L0), 25x100 µm^2 (barrel of L0)

- Luminosity monitoring and beam abort modules added
- Fast readout with max. 1 MHz trigger rate
- Data transmission with up to six links of 1.28 Gbps (electrical) per lpGBT and VTRx+ link (optical) to FELIX readout
- **Reduction of material by deploying serial powering and CO$_2$ cooling**

Planar and 3D pixel sensors

Thin n-in-p planar sensors

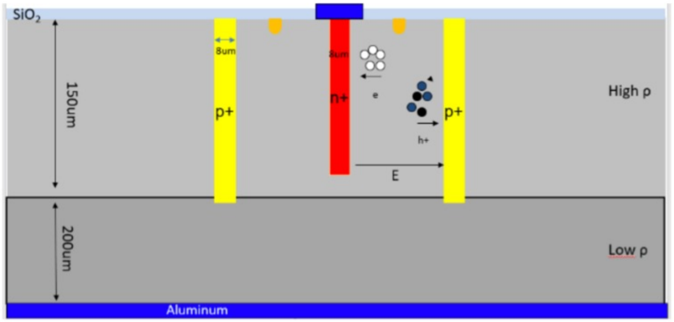
- **Dies of 4x4 cm²**
- 100/150 µm thick
- Bias voltage up to 600/400 V (at end of life-time)
- Signal: ~10000 e⁻ (~6000 e⁻ after HL-LHC dose)
- **5 vendors qualified in market survey after long qualification program**
- Final design frozen

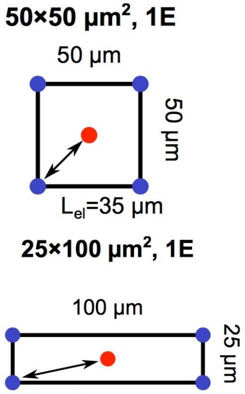


Quad 4x4 cm²

3D sensors

- For innermost layer: $1.3\times10^{16}\ n_{eq}/cm^2$ for 2000 fb^{-1}
- **Dies of 2x2 cm²**, 150 µm thickness + 100-200 µm support wafer
- Pixel size of 25x100 µm² challenging for radiation hardness and only in part of L0 foreseen
- **3 vendors selected in market survey**

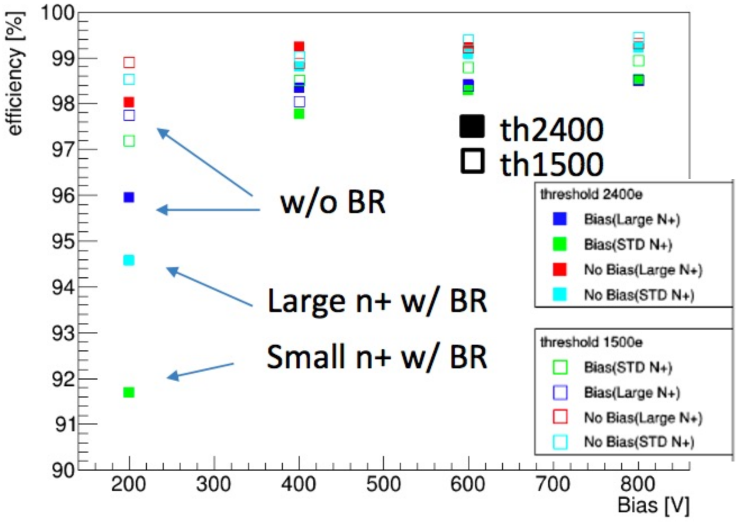




p⁺ ohmic column
n⁺ junction column

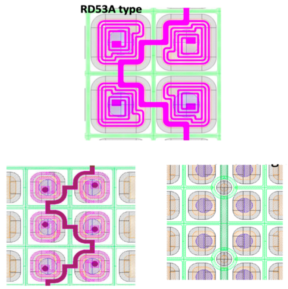
Test beam results for 50x50 µm² planar modules with varying bias structures irradiated with 70 MeV protons to $3*10^{15}\ n_{eq}/cm^2$

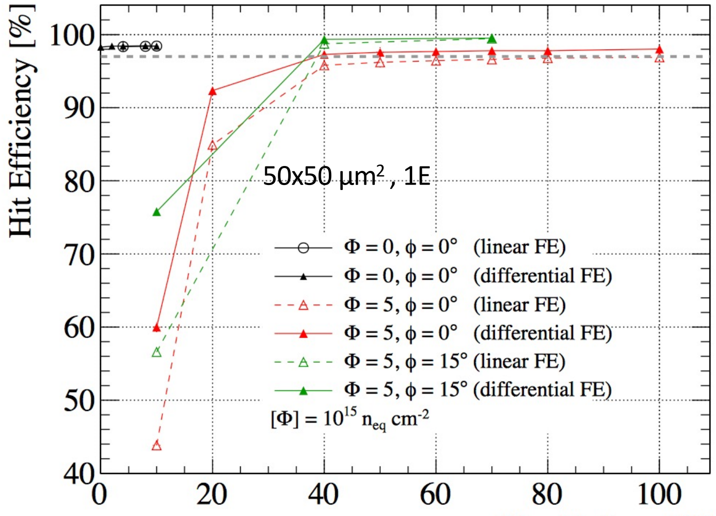
K. Nakamura, Pixel 2018



Biasing solutions

- Punch through
- Bias Rail and bias resistor
- Temporary Metal



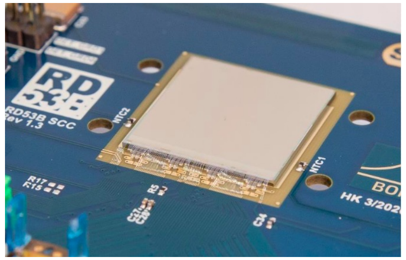


arXiv:1903.04838

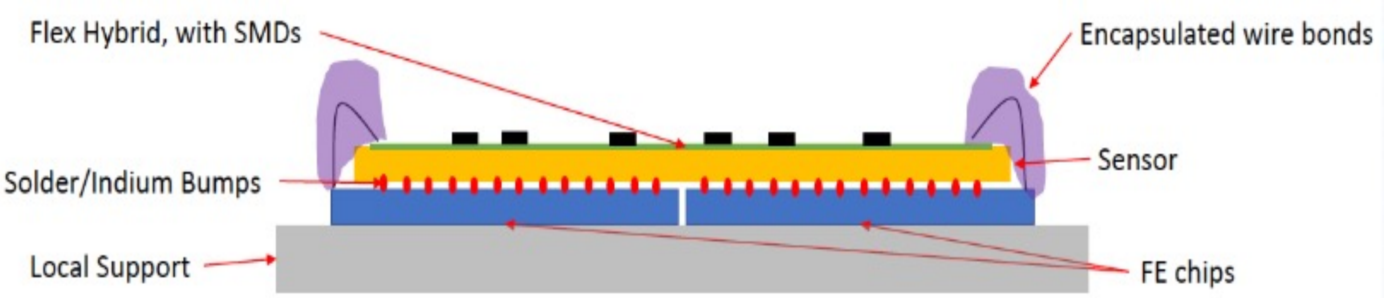
- >97% efficiency at perpendicular track incidence
- Power consumption at the operational voltage: <10 mW/cm²
- Maximum operational voltage: 250 V

Front-end and module concept in the pixel detector

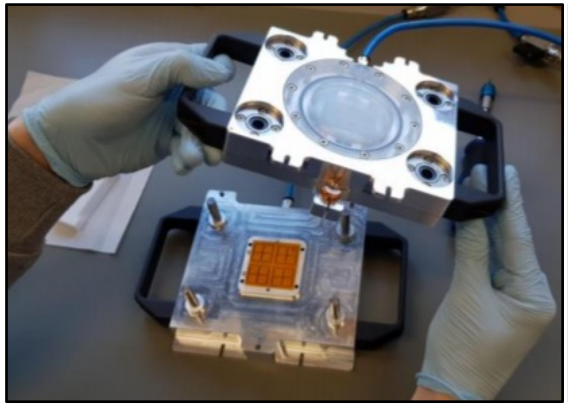
- **RD53 Collaboration: joint R&D of ATLAS and CMS ASIC: 65 nm with TSMC**
- **RD53A FE prototype** (full width/half depth chip with 3 analogue FE) heavily investigated: **Many results collected, show comparable performance within specifications**
- **ATLAS ITkPixV1 FE prototype**
  - Differential FE of RD53A FE plus few design changes e.g. under current and over voltage protection
  - **Refined version with fix in ToT latches received and being evaluated**

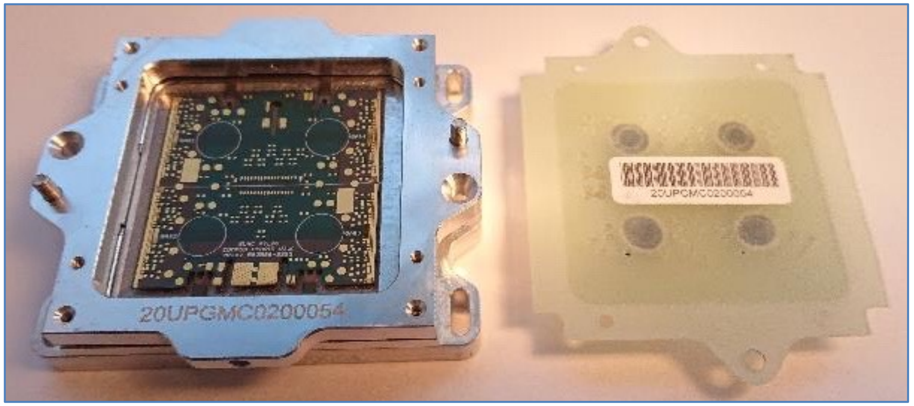

www.rd53.cern.ch
CERN-RD53-PUB-17-001

- **Sensor and front-end electronics connected** to bare module with **high density bump bonding** (market survey to qualify several vendors finished)
- Parylene encapsulation of wirebonds and for HV insulation

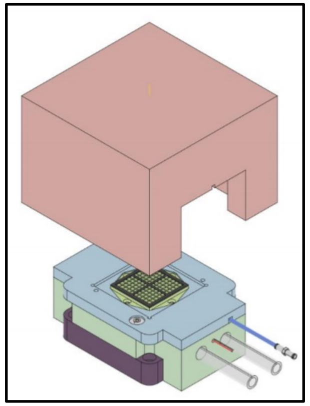


- **Modules assembly** tooling, carrier and test jig


Assembly tooling



Prototype module for layer 1-4 quad module in carrier for testing and transport


Jig for electrical tests

→ **Production of four-chip modules** (200) **ongoing** with RD53A-FEs with common tooling in 20 labs

→ **Evaluation of performance and production flow**

Readout and powering of the pixel detector

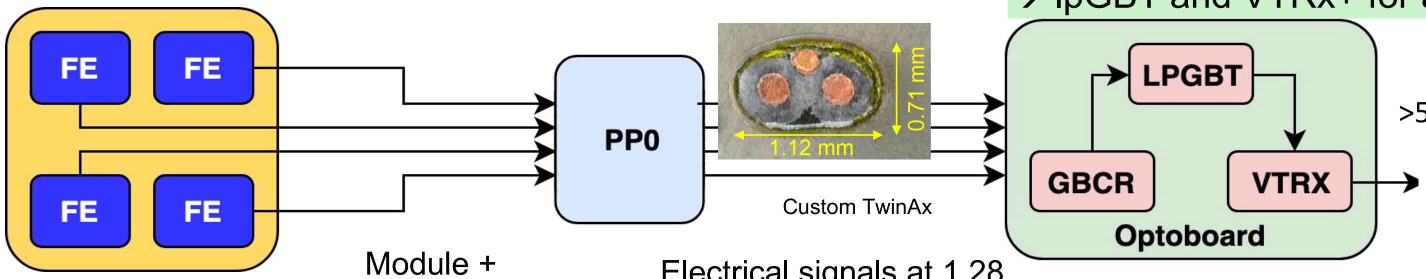
- On-detector readout with 1.28 Gbps (up to 4 lanes per FE) and conversion to optical signals at > 5.12 Gbps
- Uplink sharing for all layers to reduce material

kapton/copper flexes

patch panel 0

twin-axial cables

giga bit transmitter recovery chip (GBCR)
→ lpGBT and VTRx+ for aggregation



Module +
Stave flex

Electrical signals at 1.28
Gbps over 6 m cables

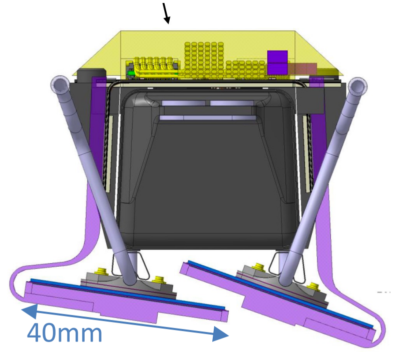
>5.12 Gbps

Optical fibres to
readout PCs with
FELIX readout boards

Losses to be kept below 20 dB

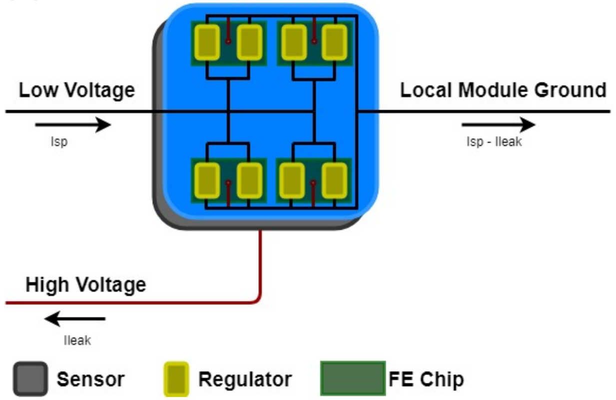
→ Results are encouraging (BER < 0.2e-12, specification is 1e-12) and studies continue

L2 Barrel:
envelope for
twinax cables



Further challenge are
space constraints for
routing of services

- **Powering modules serially with chains of up to 14 quad modules**
  - → Reduced number of supply lines, less material
  - → Less power dissipation on services than with parallel powering
  - → Radiation hard on-chip shuntLDO allows regulation of voltage on chip
- Several HV lines per chain (at least 2 per SP-chain foreseen)
- Each module on different potential → AC coupling of data lines



Constant current supplied and parallel
distributed on one module to all front-ends

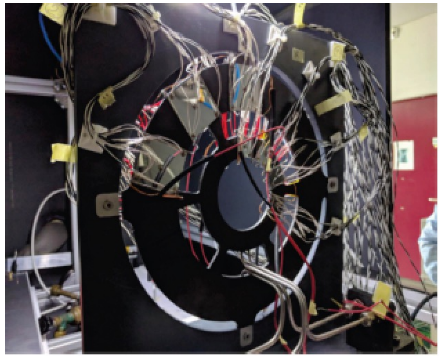
- About 1000 SP-chains
- Total power consumption (112 kW) within cooling budget

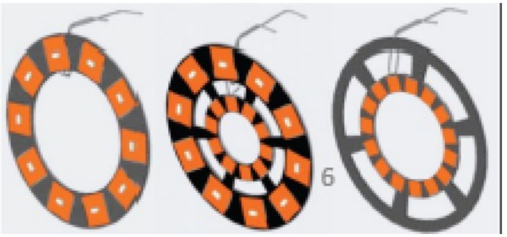
Serial powering:
T. Stockmanns et al., NIM A511 (2003) 174-179
D. Bao Ta et al., NIM A557 (2006) 445-459
L. Gonella et al., JINST 5 (2010) C12002

Local support mechanics of the pixel detector

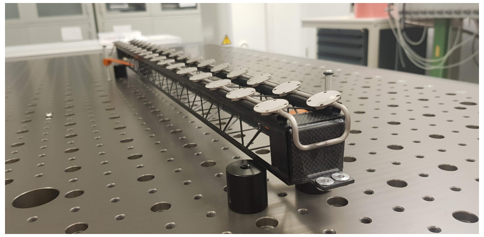
Principle: Local support structures from carbon-fibre composites get modules on both sides attached

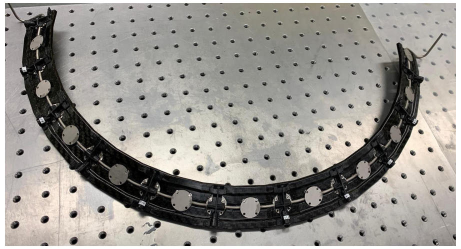
- IS rings



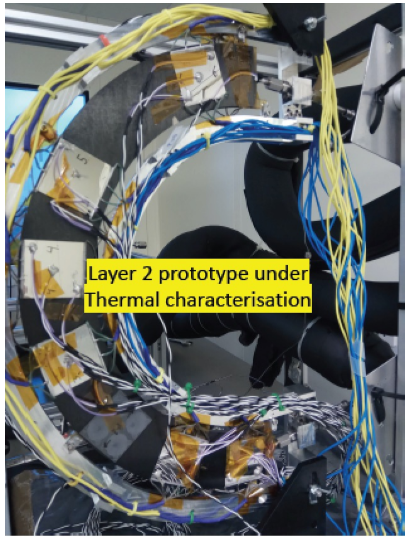


- OB longerons and inclined half-rings





- EC half-rings



- **Layout differs in detector areas:** varying serial powering chain lengths, varying mechanical solutions to achieve high thermal and electrical performance for stable and safe operation

→ **Successful evaluation of thermal performance and manufacturing variability**: hottest spot on FE expected to be colder around 0°C at the end-of-lifetime

→ Global mechanics developments also progressing

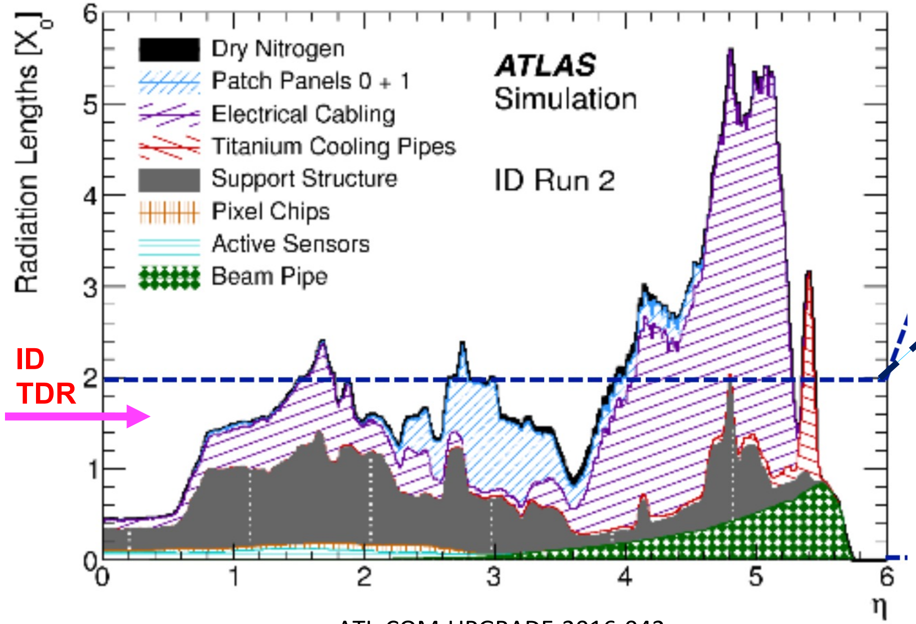
- **Electrical validation started** with FE-I4 based modules and in preparation with RD53A modules in system test **– Demonstrator programmes**
- **Results:**
  - **HV power supply with low-ohmic off-mode required**
  - **Power fluctuations indicated necessity of improved shuntLDOs compared to FE-I4, implemented in ITkPixV1 FE**

Material estimate for ITk

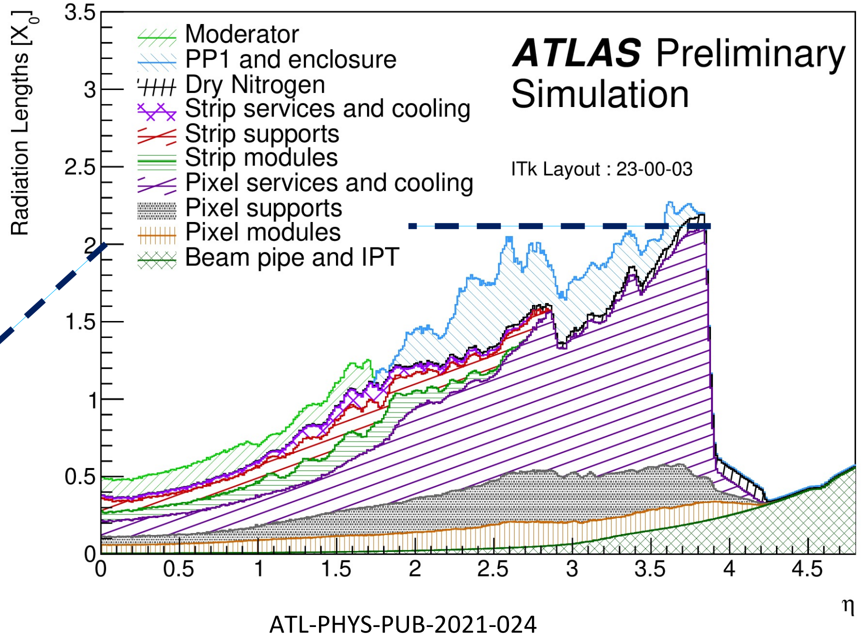
Reduction of material by usage of

- CO_2 cooling with thin titanium pipes
- Thin silicon sensors and front-ends
- Fast data transmission with low power giga-bit data transmission in pixels and strips
- Advanced powering: serial powering for pixels, DC-DC converters for strips
- Carbon structures for mechanical stability and mounting

→ Minimize effects of multiple-scattering and energy losses before outer detectors



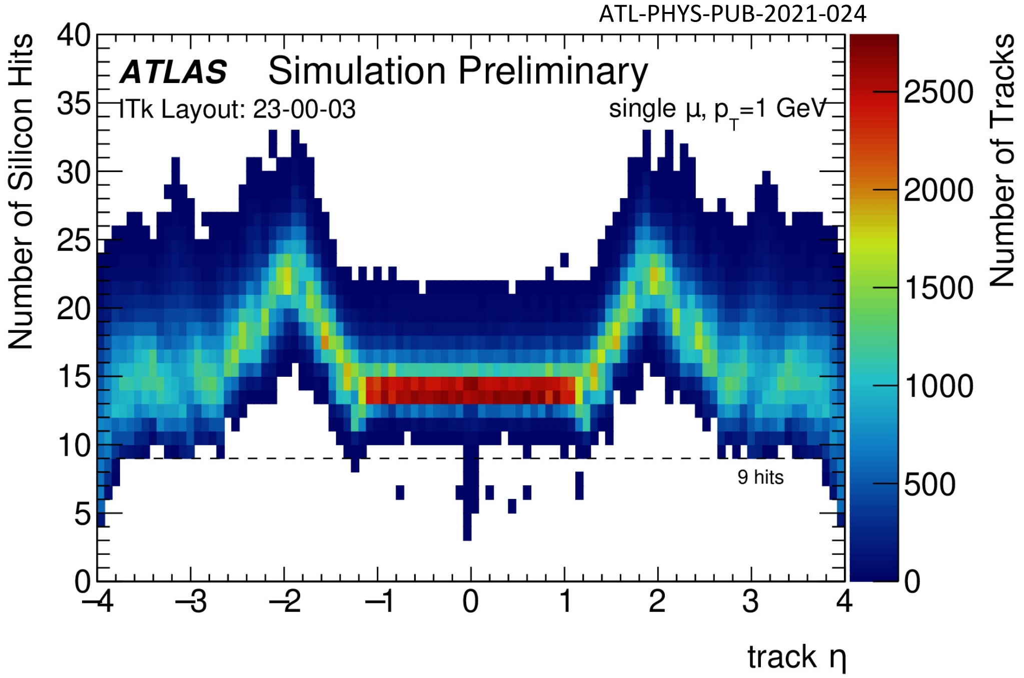
ATL-COM-UPGRADE-2016-042



ATL-PHYS-PUB-2021-024

Tracking performance

Number of strip plus pixel measurements on a track as a function of η

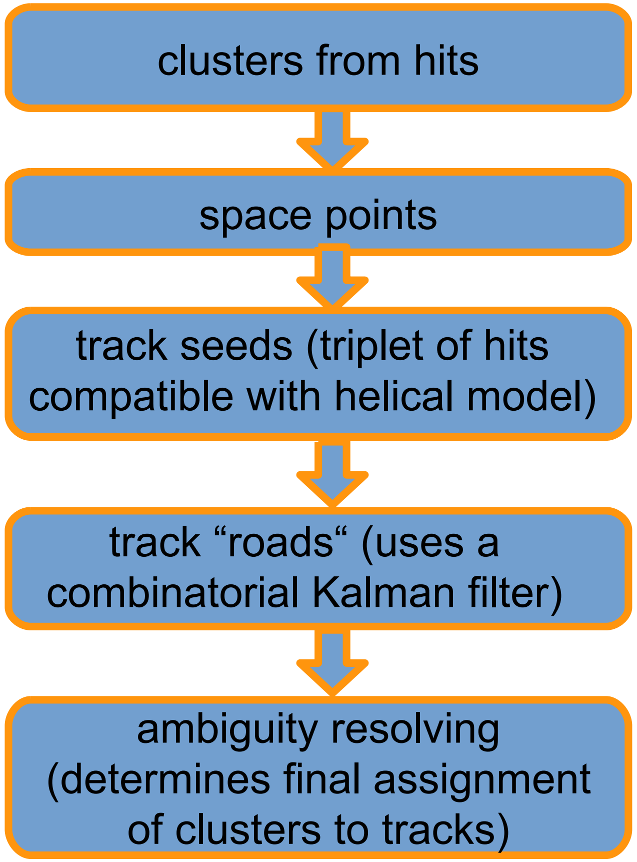


ITk provides at minimum **9 hits** in the barrel and **13 hits** in the forward or all particles with p_T> 1 GeV within $|z_{vertex}| < 150$ mm

Redundancy is very important to clean combinatorics in reconstruction

Track Reconstruction: From detector readout to physics objects

Reconstruction chain steps:



clusters from hits

space points

track seeds (triplet of hits compatible with helical model)

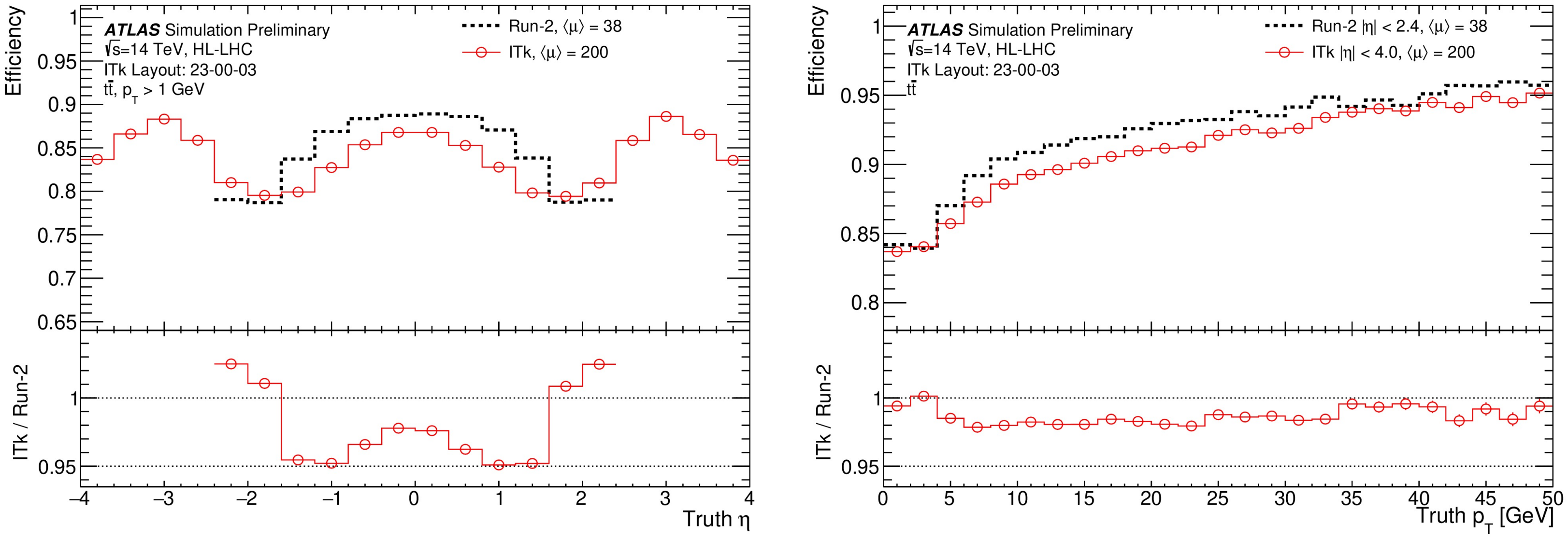
track “roads“ (uses a combinatorial Kalman filter)

ambiguity resolving (determines final assignment of clusters to tracks)

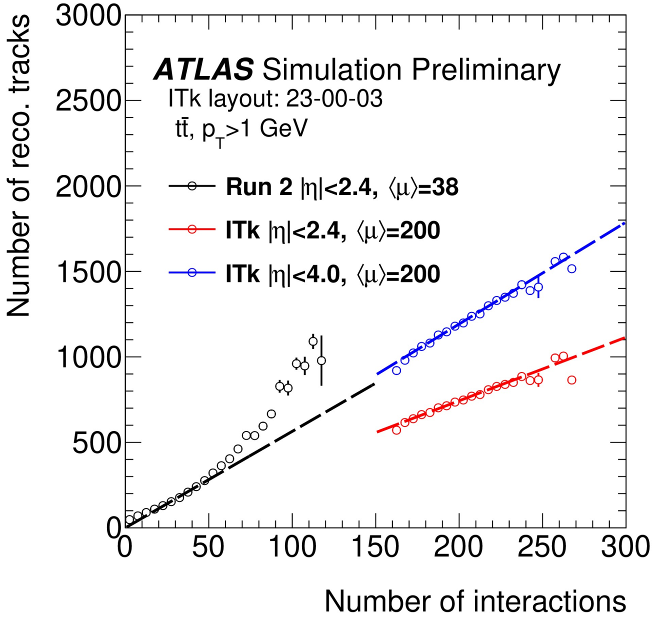
Track reconstruction efficiencies

- **Efficiency:** fraction of all reconstructed true prompt particles

ATL-PHYS-PUB-2021-024



ATL-PHYS-PUB-2021-024



- **Tracking efficiency comparable to Run-2** despite increased pile-up
- **Efficiency > 85%** for prompt and stable charged particles, also at high η, (>99.5% for muons) and low fake rates ~10^{-4}

- Number of reconstructed tracks follows the number of interactions

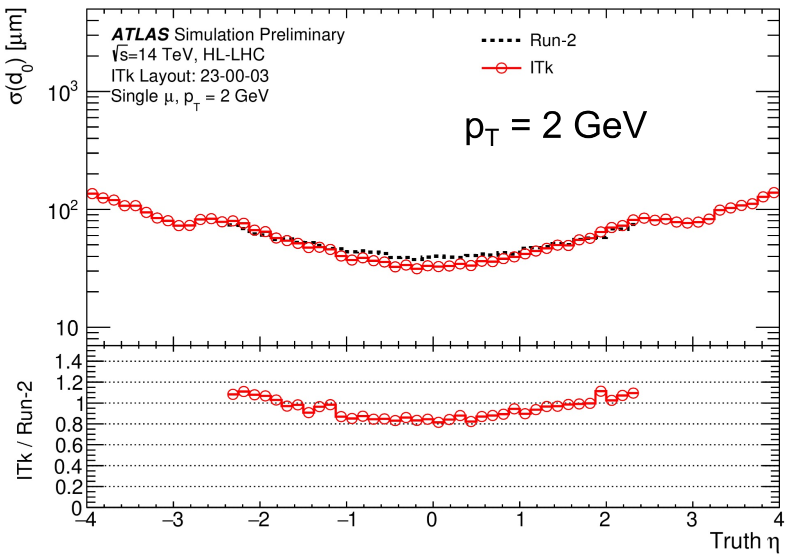
Reduced material → less interactions

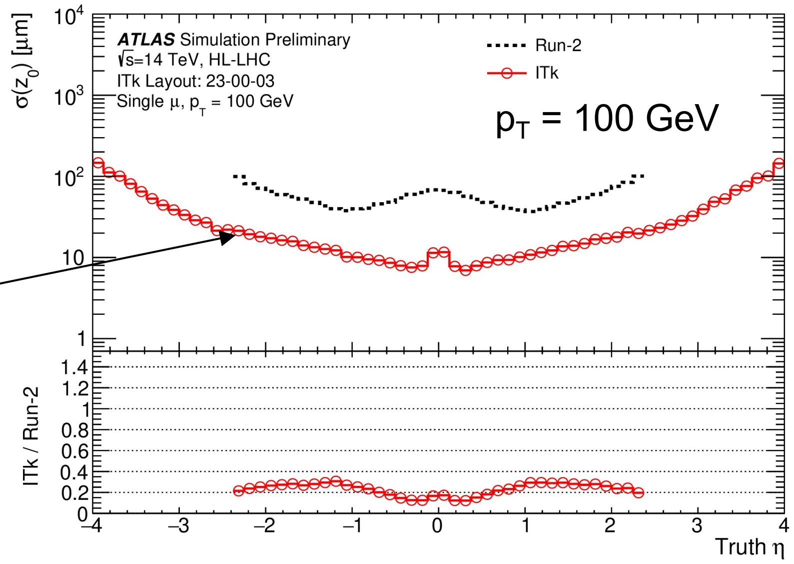
Increase in hit counts → tighter track selections

Improved hermeticity → more hits and fewer holes

Track parameter resolution

- Transverse impact parameter (d_0) resolution as a function of η
- Longitudinal impact parameter z_0 resolution crucial for pile-up suppression



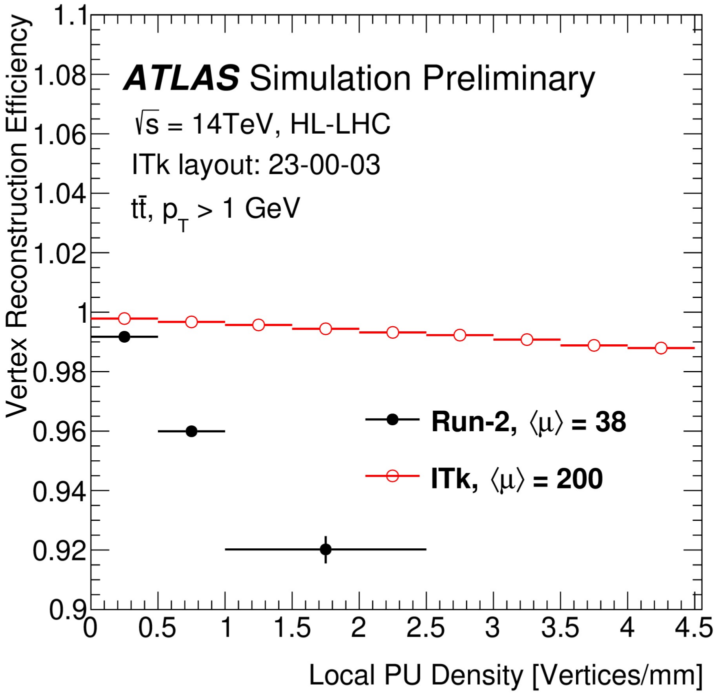


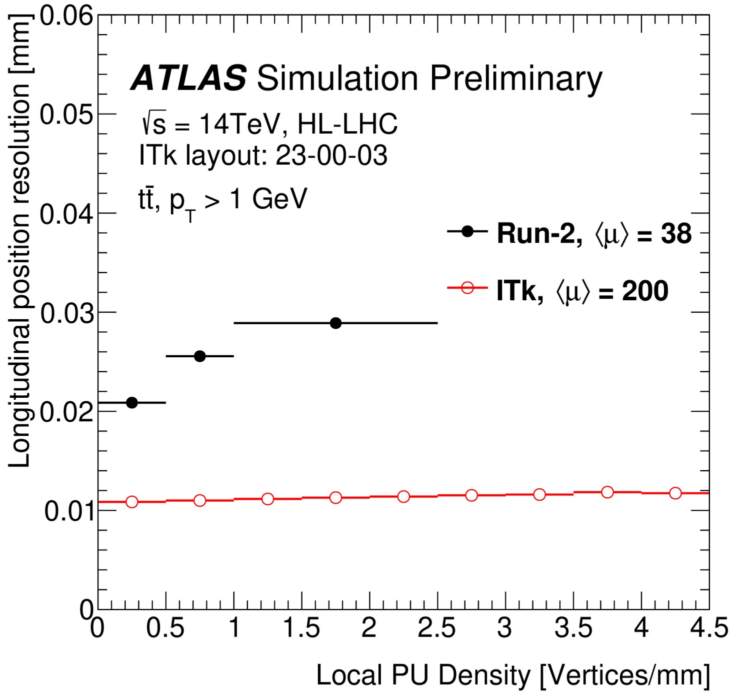
smaller pitch in ITk, 25x100 μm^2 (barrel of L0)

- For low p_T dominated by multiple scattering: similar resolution compared to Run-2
- For high p_T dominated by intrinsic detector resolution: 4x (2x) improvement in z0 (d0) resolution due to smaller ITk pixel pitch
- Improvement due to reduced material and better resolution of strip tracker than current TRT

Primary vertex reconstruction

- Vertexing: **reconstructing** and **identifying** the primary **hard scatter vertex** and **pile-up vertices**
- ITk vertexing uses **Adaptive Multi-Vertex Finder (AMVF)** algorithm which replaces Run-2 Iterative Vertex Finder (IVF) algorithm



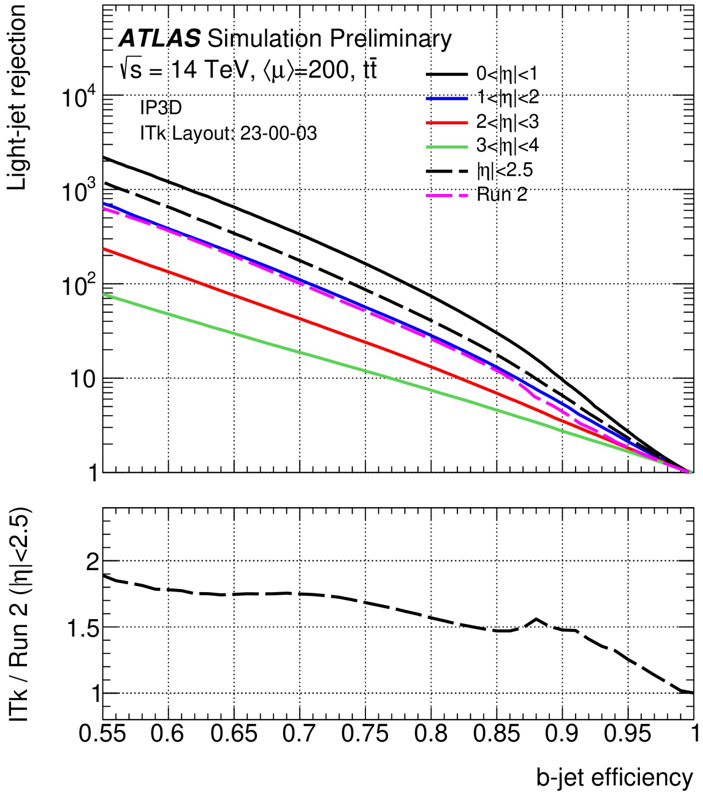


- Vertex reconstruction efficiency shows **robust performance** even up to <μ> ~ 200
- **Longitudinal position resolution** improved by factor of 2-3 and exhibits strong **robustness against pile-up**

→ Vertex reconstruction efficiencies for tt can cope with high pile-up

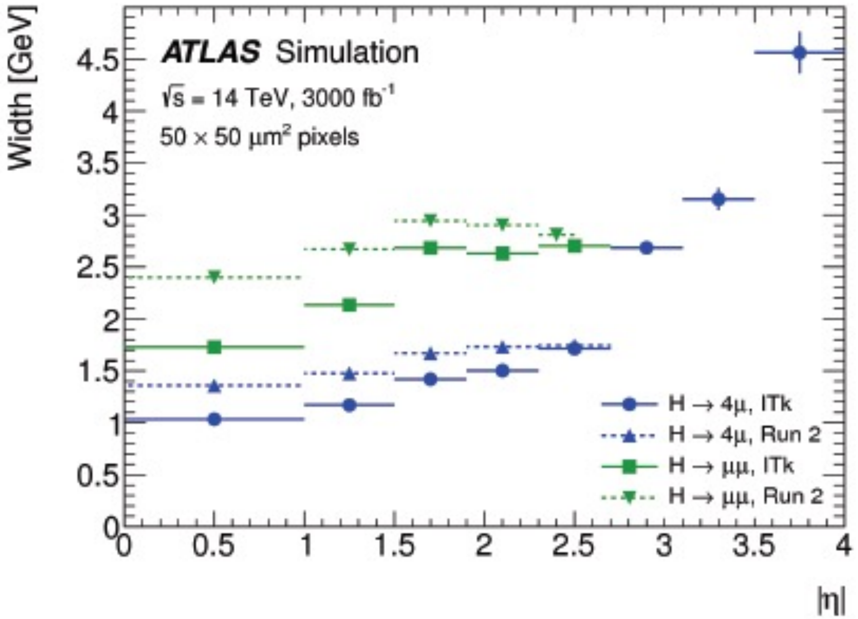
Jet Flavour Tagging and Physics Case

- Discriminate **heavy flavour jets** (from b- and c-quarks) from jets originating from light quarks and gluons



- Evaluated using tt sample with parton-jet matching
- High-level multvariate algorithm combines information from several discriminates
- Not fully optimised
- Important to discriminate between VBF and tt in forward regions

- Extrapolation for Physics cases
  - H→ μμ



  - Uncertainty on precision measurement of W mass reduced by 20% with extended forward tracking at HL-HLC

https://cds.cern.ch/record/2703572

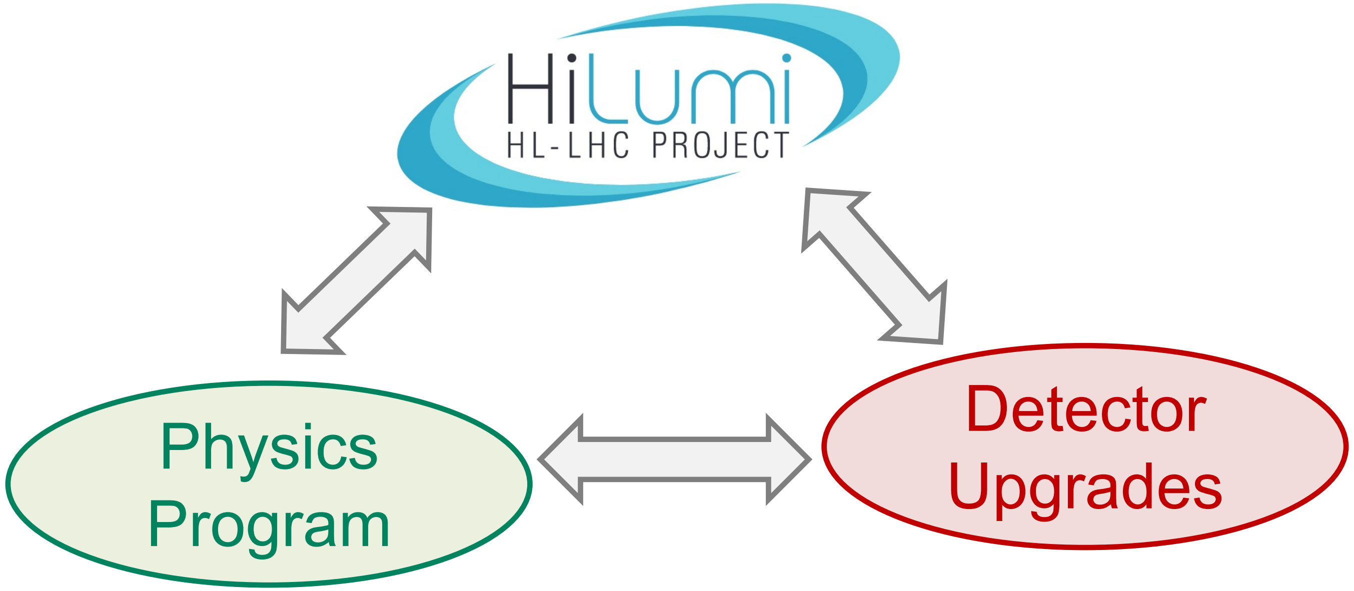
Summary

- HL-LHC will increase physics reach of the ATLAS experiment
- Upgrade of tracking detector to tackle challenges of high pile-up, particle rates and radiation dose:
  New inner tracker with higher granularity and coverage
- 4-layer strip detector with about 18,000 strip modules
  - Design verified and many final design reviews passed
  - Pre-production fully running (QA/QC procedures defined, site qualification ongoing)
- 5-layer pixel detector with about 10,000 pixel-hybrid modules (~6 x of current pixel detector)
  - New FE chip, sensors, powering scheme, services scheme and equipment designed and produced as prototypes
  - Collaboration finalizing validation with prototypes to start pre-production
  - Challenges are the data transmission concept and module stress
- Expected performance will enable rich physics program

Thank you!

Acknowledgment

Irina Ene, Giovanni Calderini, Francisca Munoz, Zach Marshall, Matthias Hamer, Didier Ferrere, Anna Sfyrla

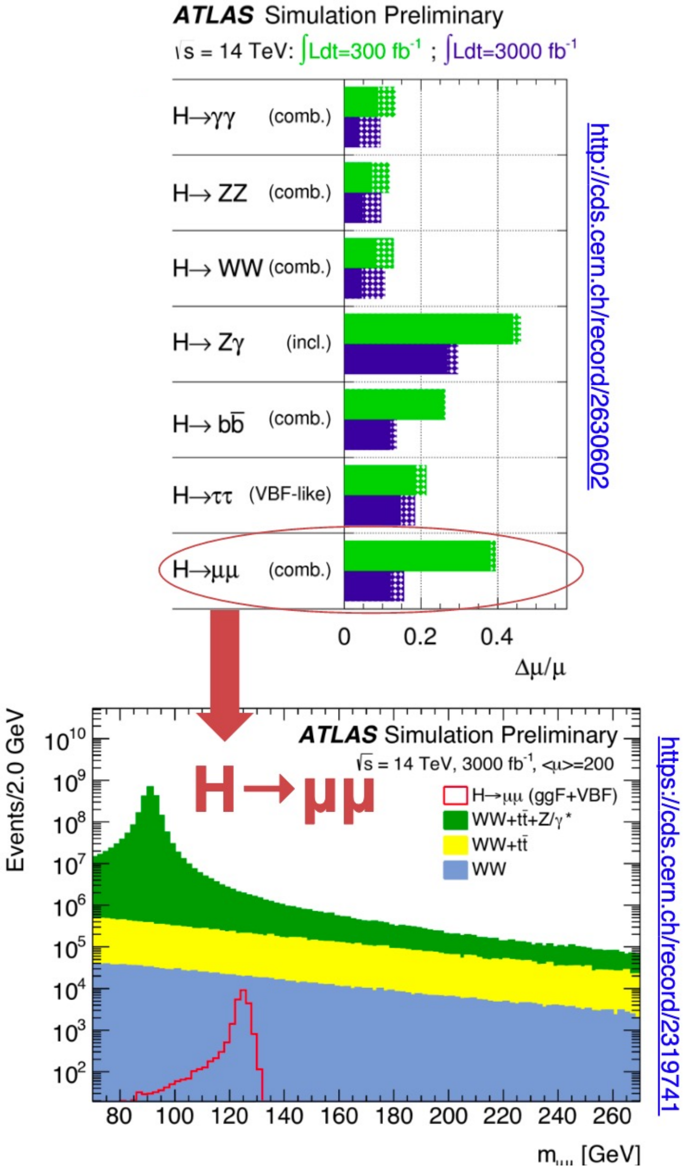


SPARE

Physics of the Higgs Boson

- **Higgs couplings** highly sensitive to BSM physics
- With HL-LHC dataset significant improvement in precision
- Study based on following channels
  - H → gg
  - H → ZZ* → 4l
  - H → WW* → lνlν
  - H → tt
  - ttH, H → gg and H → μμ
  - WH/ZH, H → gg
  - H → μμ

- **Relative precision on Higgs coupling modifiers κ** with $\kappa_\nu \leq 1$: **Factor 2 improvement feasible from LHC to HL-HLC** (constrained on 2-7% level)
- **Gives access to direct coupling to top quark** (mainly ttH → ttγγ, 4% for κ_t)



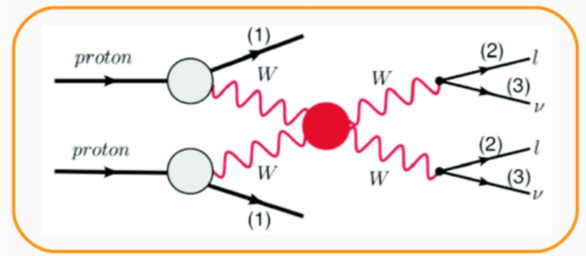
http://cds.cern.ch/record/2630602

https://cds.cern.ch/record/2319741

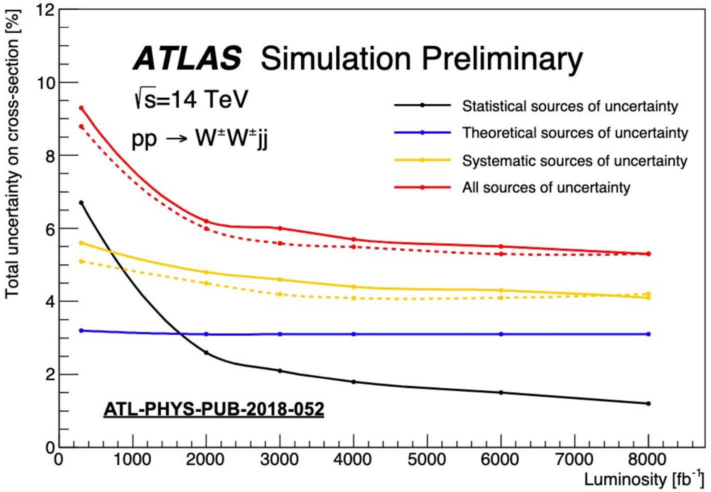
https://arxiv.org/1910.11775

Vector Boson Scattering and W mass

VBS cross section



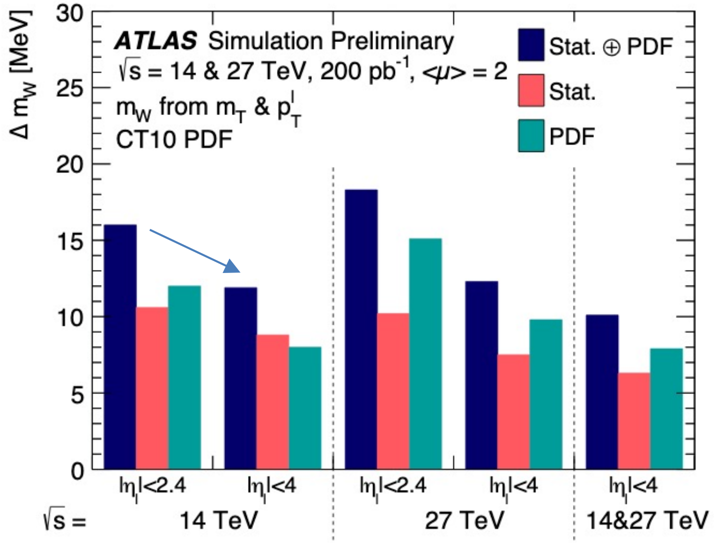
- In leptonic signatures expected to be observable at HL-LHC
  - WZ scattering: about 6% precision
  - ZZ scattering: 1-8 σ overall, depends on theo. unc. (ZZjj)
  - WW scattering: <10% precision, 2σ sensitivity to $W_L W_L$ Challenge is extraction of the longitudinal scattering component to test unitarity



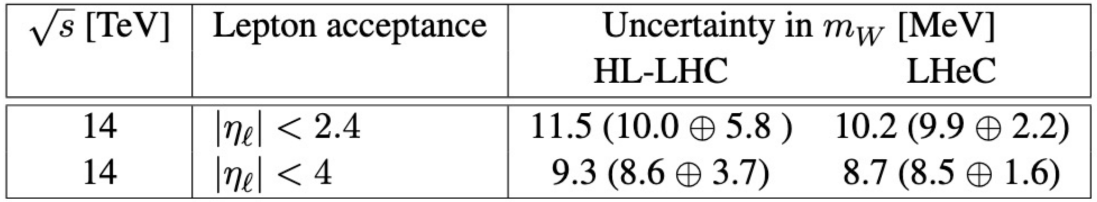
- Despite major improvements with forward tracking and jet-tagging capabilities, WW analysis will be systematically limited

Precision measurement of W mass

- Reduced constraints to PDFs with extended forward tracking at HL-HLC
- Low luminosity run < μ > = 2 would give in short time a clean sample at 14 TeV



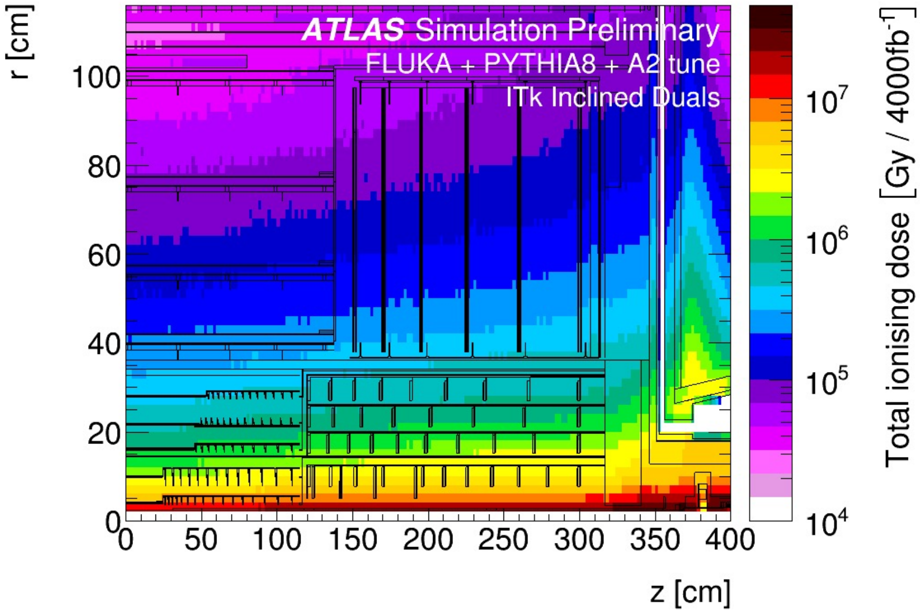
For 200 pb^{-1}

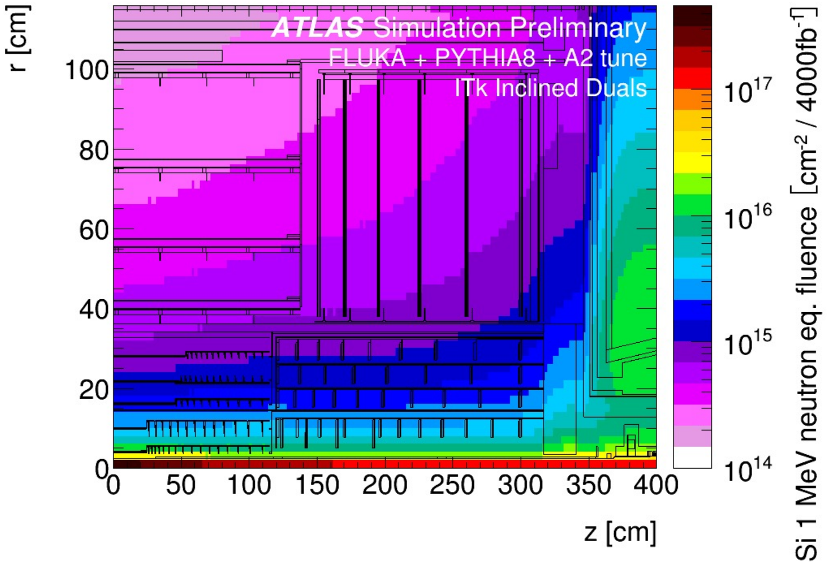


$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W [MeV] HL-LHC	LHeC
14	$\|\eta_\ell\| < 2.4$	11.5 (10.0 ⊕ 5.8)	10.2 (9.9 ⊕ 2.2)
14	$\|\eta_\ell\| < 4$	9.3 (8.6 ⊕ 3.7)	8.7 (8.5 ⊕ 1.6)

https://cds.cern.ch/record/2703572

Radiation damage





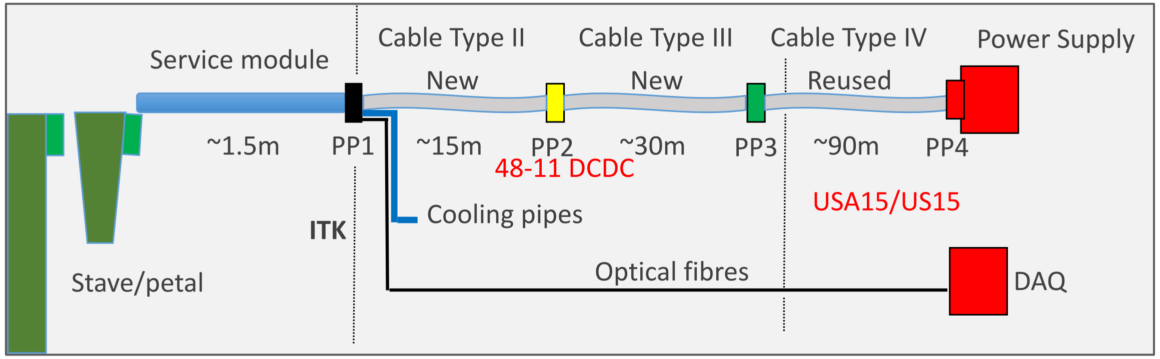
Active components are to sustain optimal performance up to 4000 fb^{-1} except for the ITk Pixel Inner System which will be replaced after 2000 fb^{-1}.

- **Detector technologies** (Si planar, 3D) :
  - NIEL → bulk damage (trapping centers) leading to depletion voltage and leakage current increase
- **Deep sub-micron technologies & FPGAs** are to be qualified wrt :
  - TID → surface effects, transistor damage and ageing effects
  - SEE (SEL, SET, SEU) which are induced effects by heavy ions and hadrons → either soft errors (No permanent damage like SEU, SET,…) or hard errors (permanent damage like SEL)
- **Material (cable, glue, composite…)**
  - TID can compromise chemical/mechanical integrity

→ Heavy and lengthy qualification process for all sub-systems

Services of the strip detector

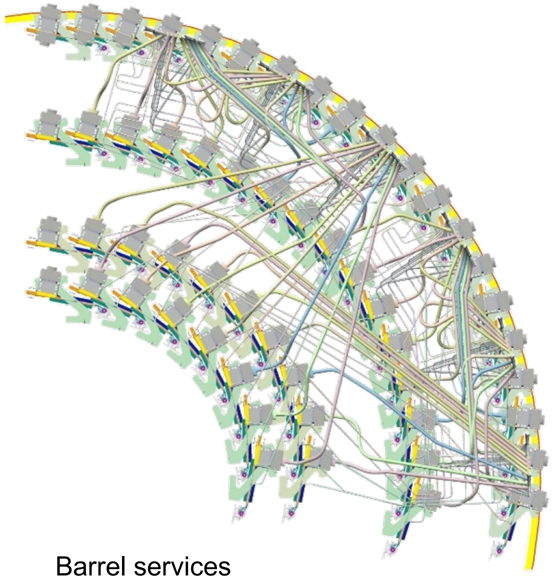
- Full chain defined and services purchased for larger system tests


Service module
Cable Type II
New
Cable Type III
New
Cable Type IV
Reused
Power Supply
~1.5m
PP1
~15m
PP2
48-11 DCDC
~30m
PP3
~90m
PP4
USA15/US15
ITK
Cooling pipes
Stave/petal
Optical fibres
DAQ

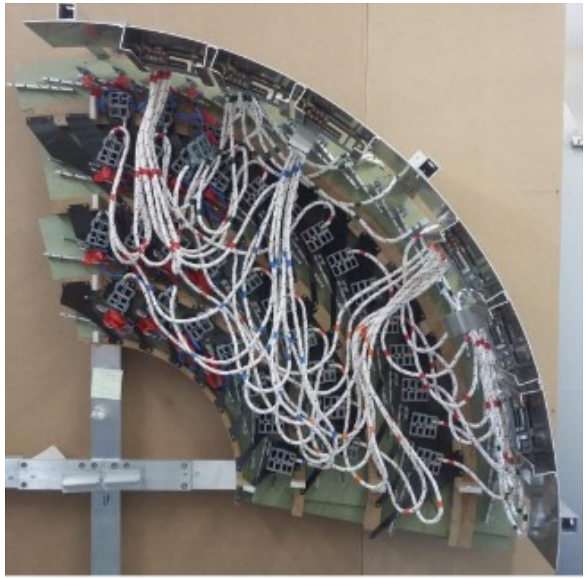
Type-1 Cable Connectors

Type-3 cables

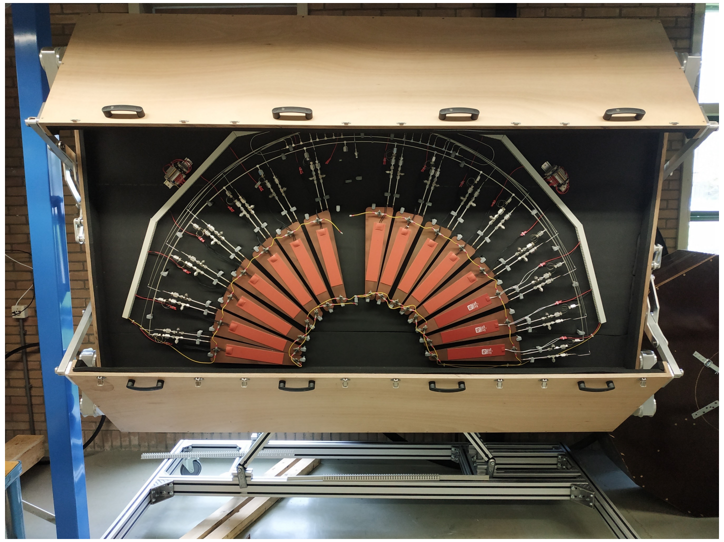
- Services on the detector sorted in service modules



Barrel services



Mockup of services



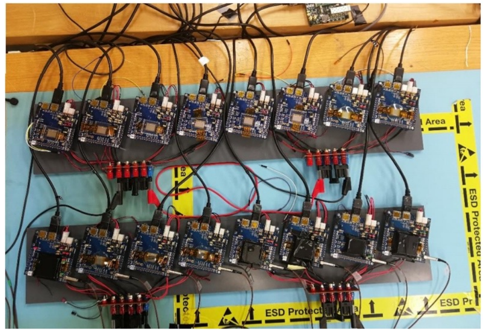
EC cooling manifold tested with in CO_2 plant at CERN

The new pixel readout chip: ITkPix

www.rd53.cern.ch
CERN-RD53-PUB-17-001

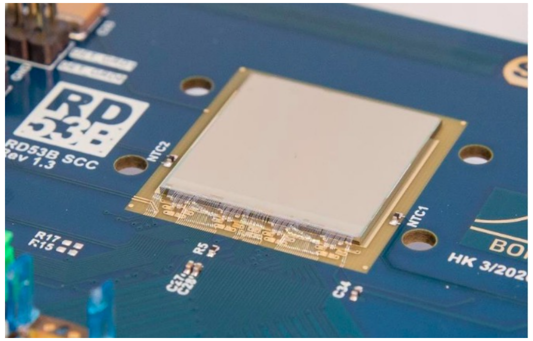
RD53 Collaboration: joint R&D of ATLAS and CMS ASIC: 65 nm with TSMC

- 4 data lines at 1.28 Gbps
- Low threshold ~600 e^-
- Integrated shuntLDO
- Design power 0.7 W/cm^2, up to 8 A supply current for four-chip module
- Radiation hardness up to 500 MRads
- 154k pixels per chip, expecting up to 250 hits/chip/bunch crossing, 500 bc buffer



RD53A FE prototype (full width/half depth chip with 3 analogue FE) heavily investigated:
Many results collected, show comparable performance within specifications

- Wafer probing set up
- Radiation damage depends on dose rate
- Proof-of-principle of operation in serial powering chain shown
- **Ongoing in pixels: Quad module program ongoing to verify on system level**



ATLAS ITkPixV1 FE prototype

- Differential FE of RD53A FE plus few design changes e.g. under current and over voltage protection
- First version has many functionalities working as expected but high digital current because of an issue in the ToT latches
- **Refined version received and being evaluated**

Challenges for pixel modules

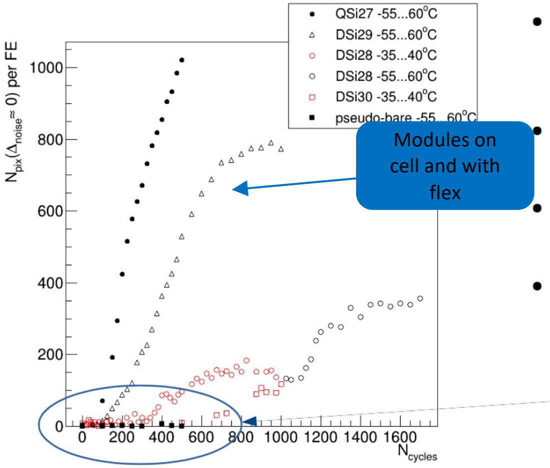
Disconnected bumps after thermal cycling of modules mainly caused by stress from copper in hybrid

- Linear and bump geometries studied in FEA models to analyze thermal stress
- Models predict number of cycles to failure like observed failures in FE-I4 modules

- **Models predict: Survival of 120 thermal cycles for -55°C to 60°C and 4000 for -45°C to 40°C before failure compare to specification of 400 cycles**

- Parylene coating of the module has a beneficial effect
- More studies ongoing

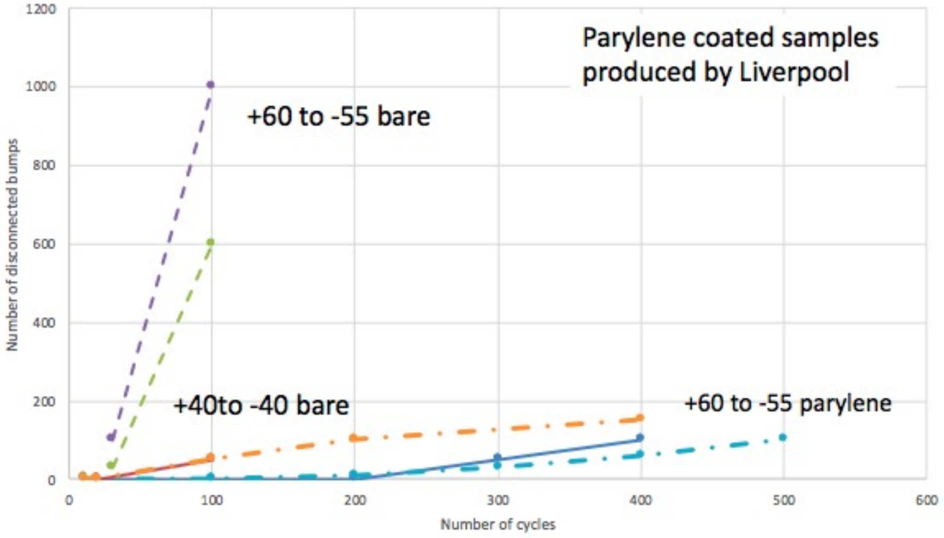
Thermal cycling of quads (-55 °C – 60 °C):
IV ok after 2200 cycles but source tests show disconnected bumps after O(20) cycles (J. Grosse-Knetter)



Modules on cell and with flex

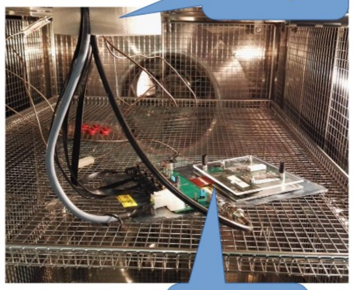
- Black/red: full/smaller temperature range
- Solid circles: QC (x1/4)
- Solid squ.: bare (x1/2)
- Open sym.: DC-mod.

Pseudo bare module added

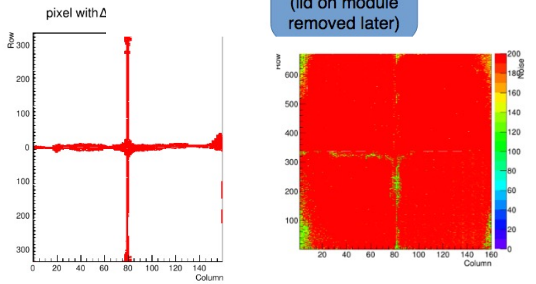


Thermal cycles on single chip FE-I4 module with 48 μm Cu on hybrid, with and without parylene coating (R. Plackett, L. Cunningham)

Cable feed-through



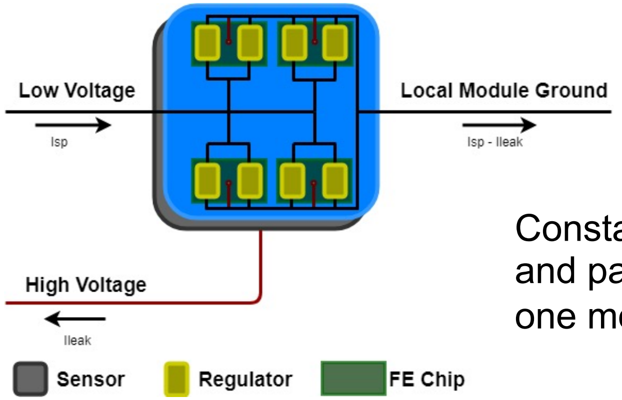
M4 Module with adapter card (lid on module removed later)



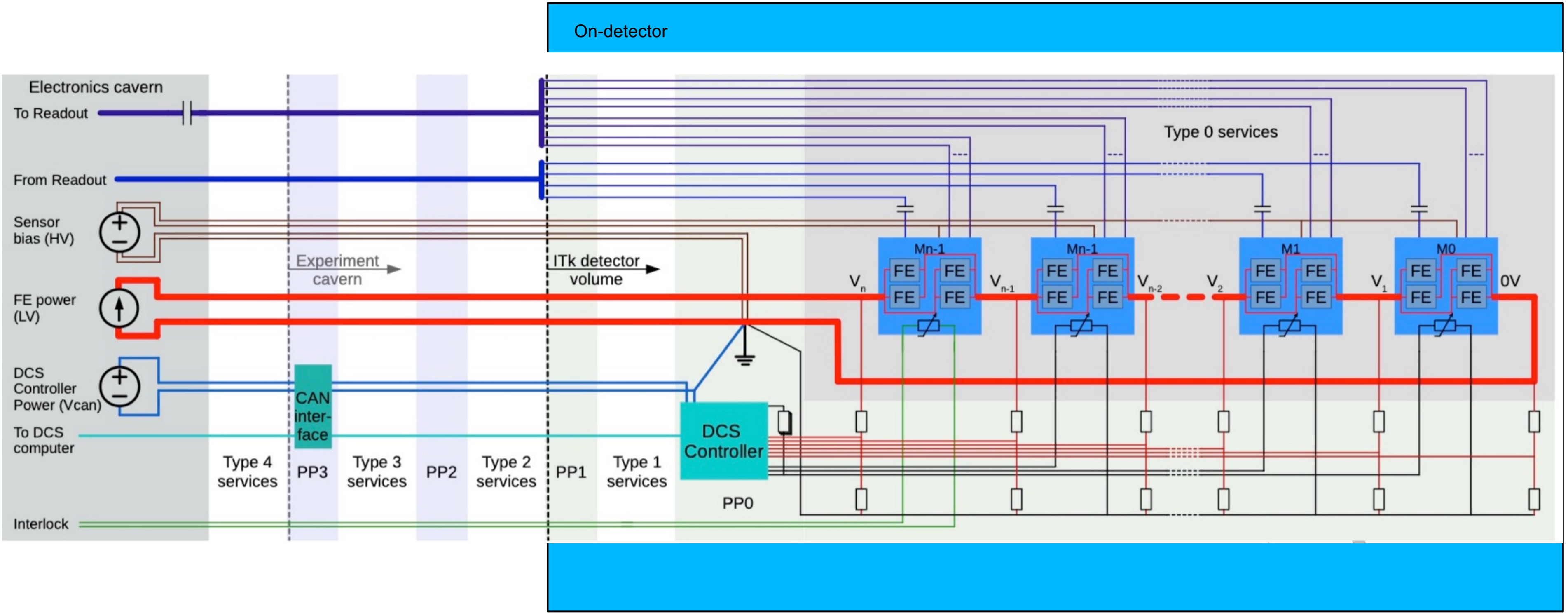
Powering of the pixel detector: serial powering

Serial powering:
T. Stockmanns et al., NIM A511 (2003) 174-179
D. Bao Ta et al., NIM A557 (2006) 445-459
L. Gonella et al., JINST 5 (2010) C12002

- **Powering modules serially with chains of up to 14 quad modules**
  - → Reduced number of supply lines, less material
  - → Less power dissipation on services than with parallel powering
  - → Radiation hard on-chip shuntLDO allows regulation of voltage on chip
- Several HV lines per chain (at least 2 per SP-chain foreseen)
- Each module on different potential → AC coupling of data lines



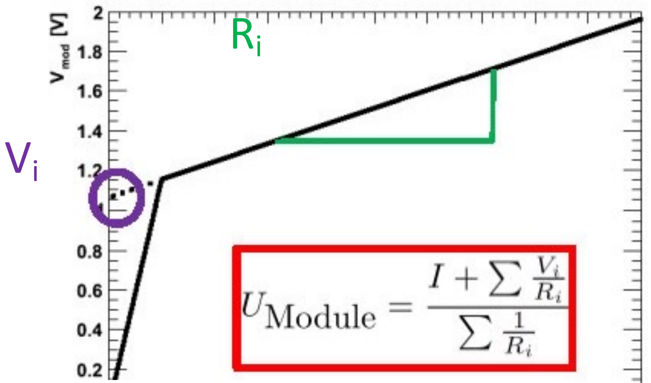
Constant current supplied and parallel distributed on one module to all front-ends



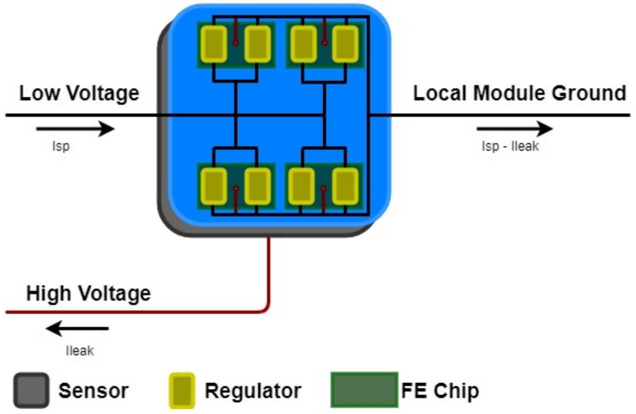
- About 1000 SP-chains
- Total power consumption (112 kW) within cooling budget

Powering of the pixel detector: serial powering

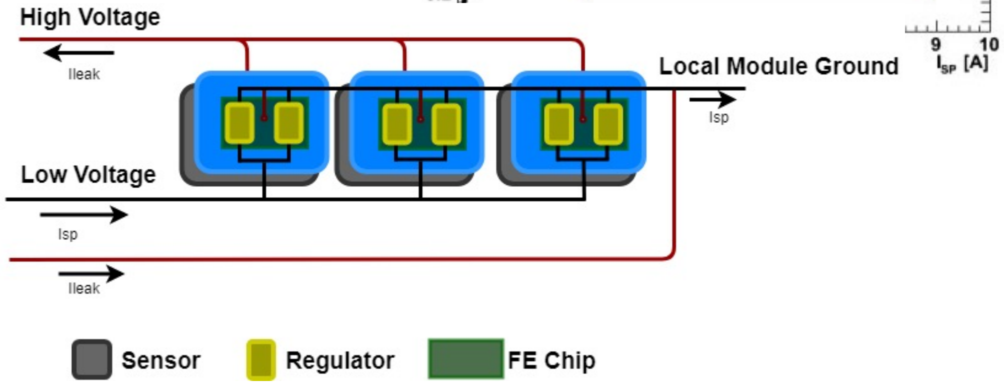
- **Constant current supplied and parallel distributed on one module to all front-ends**
  - 6-8 regulators in parallel operated: **slope** and **offset** of regulator determines module's IV-curve
  - Input current to shuntLDO regulators can exceed the nominal load current by a factor of ~2 (shunt capability) → Powering chain preserved even if one or two FE chips on a four-chip module fail open → But impact on thermal performance of the module



$$U_{\text{Module}} = \frac{I + \sum \frac{V_i}{R_i}}{\sum \frac{1}{R_i}}$$



With planar sensors and 4 FEs

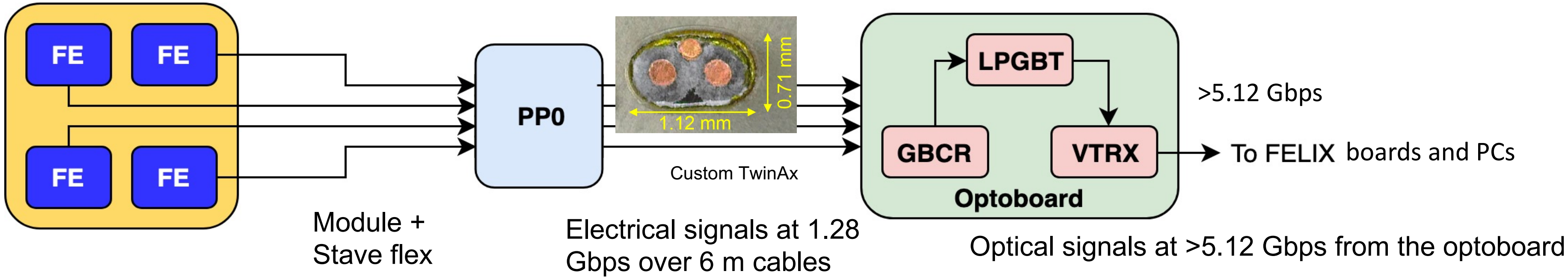


Modules with three 3D sensors

- **About 1000 SP-chains, will validate the SP-chain concept up to a length of 16 modules**
- Challenging to optimize the choice of shuntLDO configuration in order to minimize total power dissipation while meeting all constraints (like same shuntLDO configuration for all quad modules)
- **Total power consumption (112 kW) within cooling budget**
- Regulators/periphery is warmest area inside FE, about 40-45% of power in periphery (10% of FE area) → Taken into account in detector design

Readout of the pixel detector

- On-detector: kapton/copper flexes → Patch panel 0 → Twin-axial cables → Giga bit transmitter recovery chip (GBCR) → lpGBT and VTRx+ for aggregation → Optical fibres to readout PCs with FELIX readout boards
- Uplink sharing for all layers to reduce material (320 Mbps inter chip data transmission on the modules)



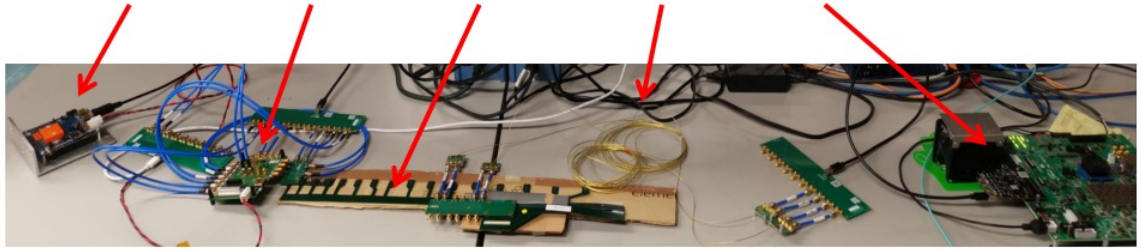
Module + Stave flex

Electrical signals at 1.28 Gbps over 6 m cables

Optical signals at >5.12 Gbps from the optoboard

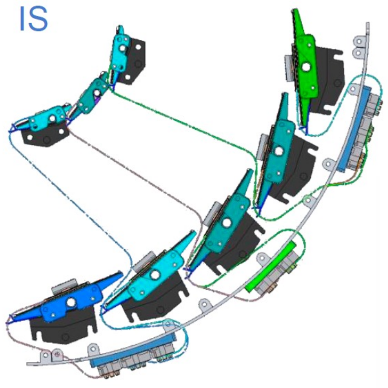
Losses to be kept below 20 dB for FE-chip and GBCR including connectors, flexes and cables

RD53a + Rd53b_cdr + Flex + 6m Twinax+ DAQ

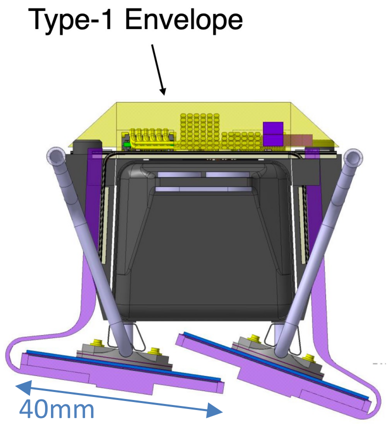


Results are encouraging (BER < 0.2e-12, specification is 1e-12) and studies continue as components become available

- Further challenge: routing of services since there are many and space is limited between layers



CAD of services in L0

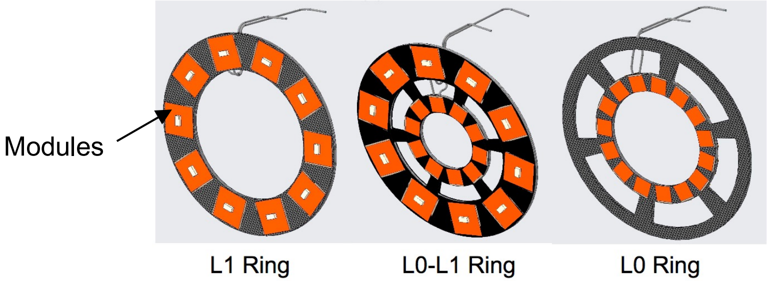


CAD of services in L2 Barrel

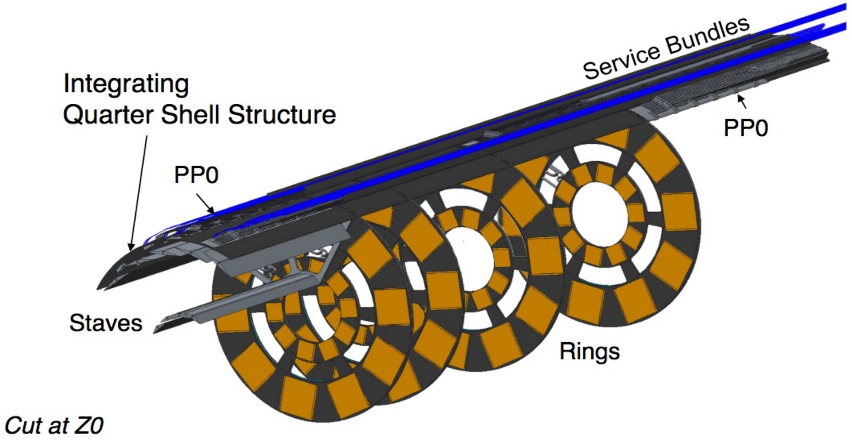
More on pixel local support components

Principle: Structures from carbon foam with carbon fibre co-cured and modules attached

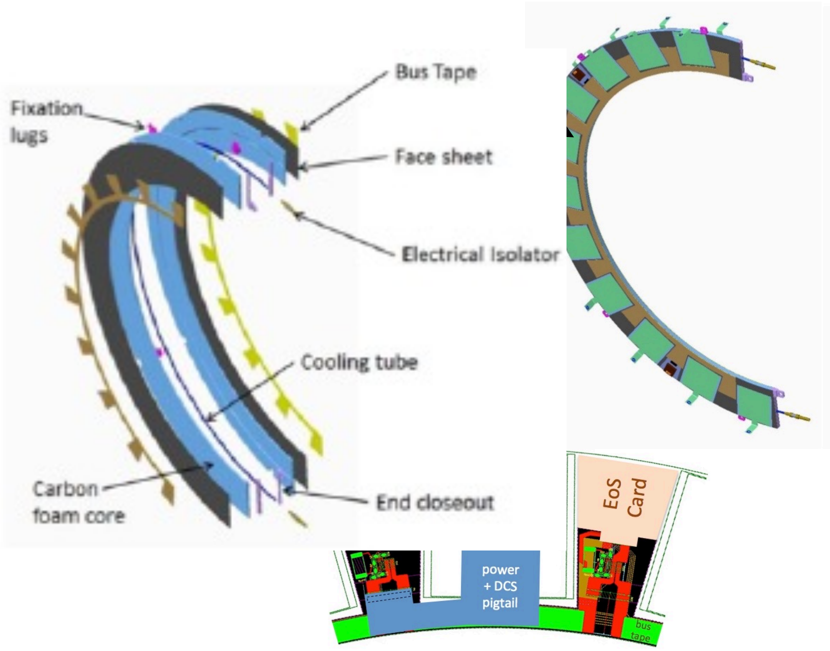
- **Inner system**



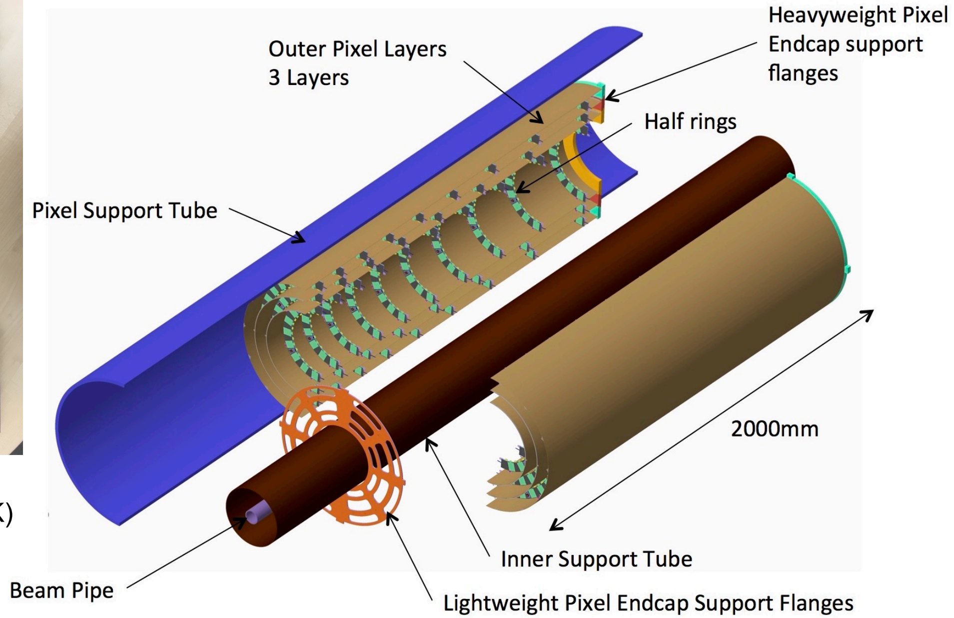
Not to scale



- **Endcaps**

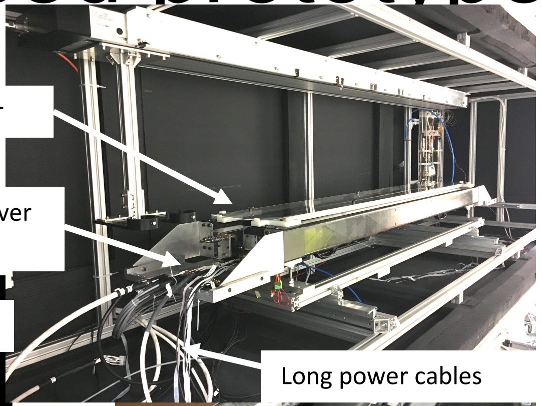


Half-ring with embedded cooling pipe (produced in UK)

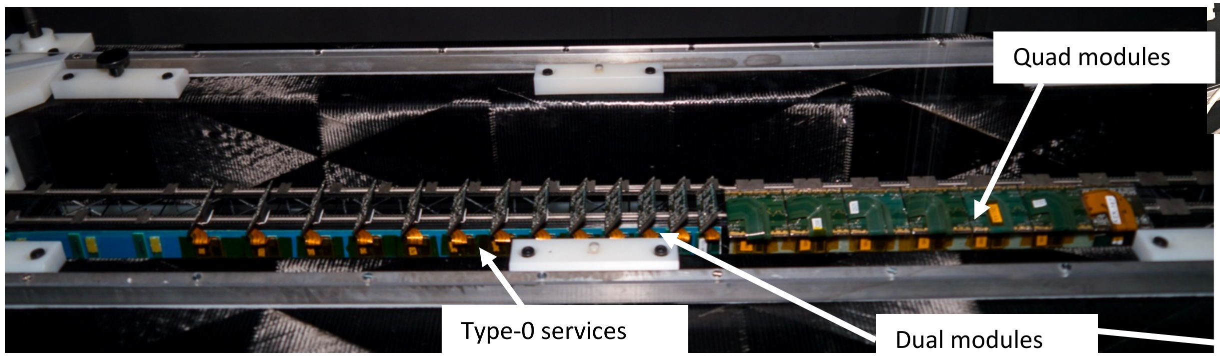


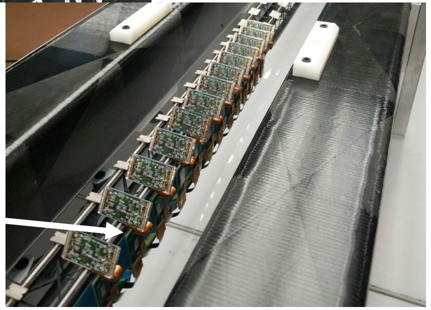
System Test with FE-I4 based prototypes

- **Outer barrel demonstrator program**
  - Short electrical 7-quad module structure
  - Long prototype with 4x8 dual modules and 2x7 quad modules → up to 120 FE-I4 ASICs
  - 6 SP-chains, currently 3 under evaluation



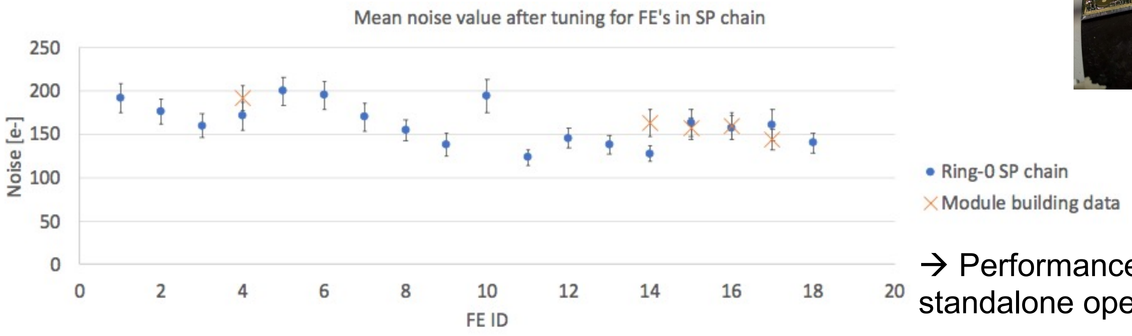
https://cds.cern.ch/record/2661761?ln=en

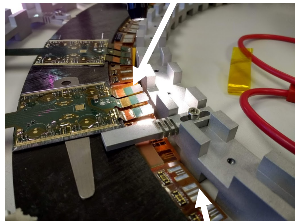


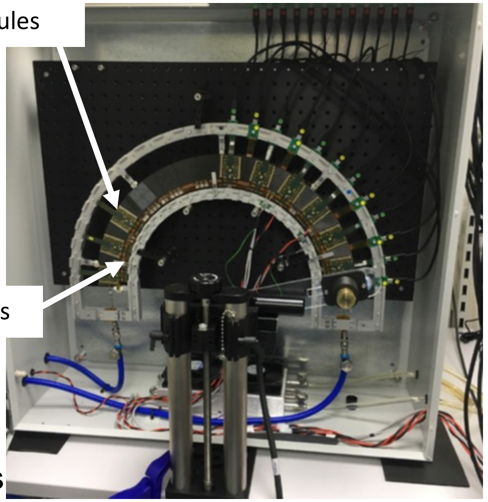


- **Endcap Ring-0**
  - CFRP + carbon foam half-ring with 12 quad modules loaded on top
  - Flexes for 2 SP-chains

→Evaluation of many system aspects
→Early practice run for design and integration





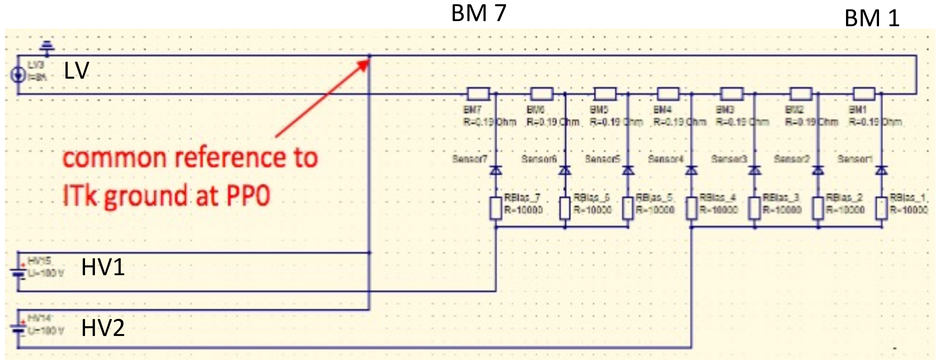


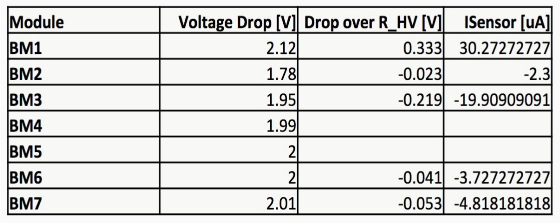
→ Performance comparable to standalone operation of modules

Results of electrical prototypes

- Tests with different **readout systems** give comparable results

  - **Serial powering features**
    - Measurements with realistic power supplies and services scheme → Leakage current return through **HV power supply with low-ohmic off-mode required** to avoid forward bias on module with lowest ground level in chain → **Input to PSU specifications**



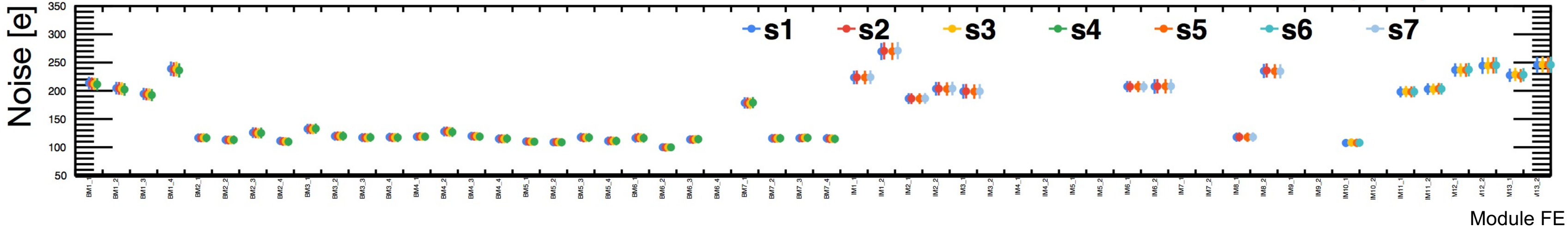


Module	Voltage Drop [V]	Drop over R_HV [V]	ISensor [uA]
BM1	2.12	0.333	30.27272727
BM2	1.78	-0.023	-2.3
BM3	1.95	-0.219	-19.90909091
BM4	1.99		
BM5	2		
BM6	2	-0.041	-3.727272727
BM7	2.01	-0.053	-4.818181818

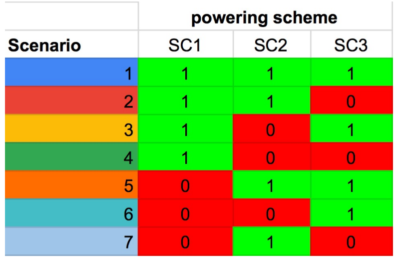
  - **Power fluctuations**
    - Several observations (power fluctuations induced during reset of GBT, register start-up) underline the necessity of the improvement of the shuntLDO regulators → Input to RD53 chip requirements, undershunt current protection and overvoltage protection

- **Multiple SP-chains operated on a shared reference at PP0**

T(C02) = 17C



Fully functional



	powering scheme		
Scenario	SC1	SC2	SC3
1	1	1	1
2	1	1	0
3	1	0	1
4	1	0	0
5	0	1	1
6	0	0	1
7	0	1	0

Phase-II Upgrade: Detector Upgrades

Trigger/DAQ:
Upgrades, add tracking at L1, partially new electronics
Improve bandwidth and processing for triggering, increase in latency

Tracking detector:
New all silicon tracking detectors with extended coverage to $|\eta| < 4$

Timing detectors:
High granularity timing detector in forward region in ATLAS

Calorimetry:
ATLAS: New FE electronics for Tile and LAr calorimeter (increase granularity)

Muon system:
ATLAS: New FE electronics and additional units in muon spectrometer

→ Focus on upgrade of tracking detector in following slides
→ Links to all TDRs of sub-detectors in spare slides

Phase-II Upgrade: Detector Upgrades – ATLAS

New all-silicon inner tracker with extended coverage to $|\eta| \sim 4$
Pixel detector: CERN-LHCC-2017-021 ; ATLAS-TDR-030.
Strip detector: CERN-LHCC-2017-005 ; ATLAS-TDR-025.

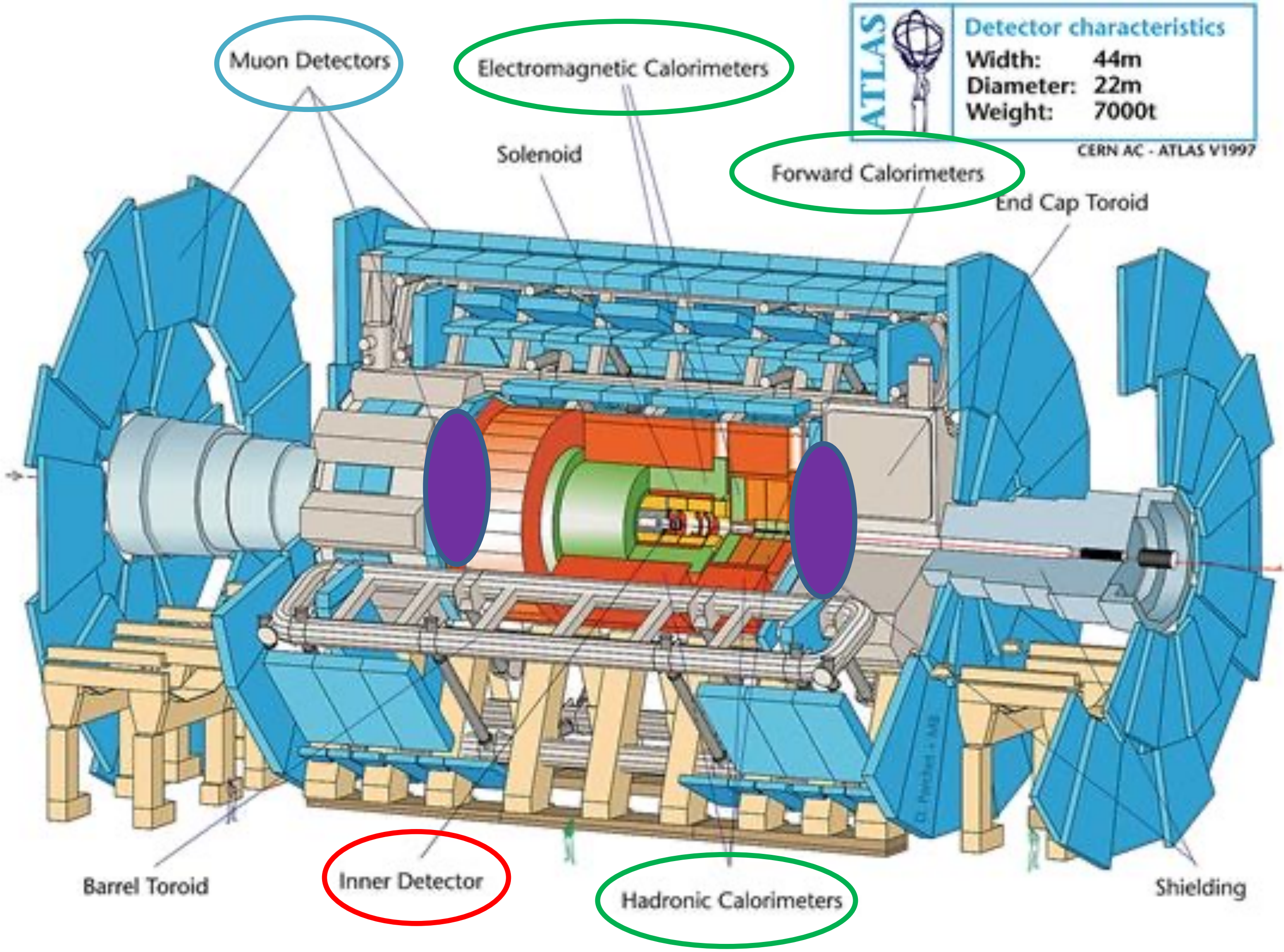
HGTD: new high granularity timing detector with forward coverage from LGADs, 30-50 ps resolution for MIPs
CERN-LHCC-2020-007 ; ATLAS-TDR-031.

Liquid Argon Calorimeter: Upgrade of electronics
CERN-LHCC-2017-018 ; ATLAS-TDR-027.

Tile Calorimeter: Upgrade of electronics
CERN-LHCC-2017-019 ; ATLAS-TDR-028.

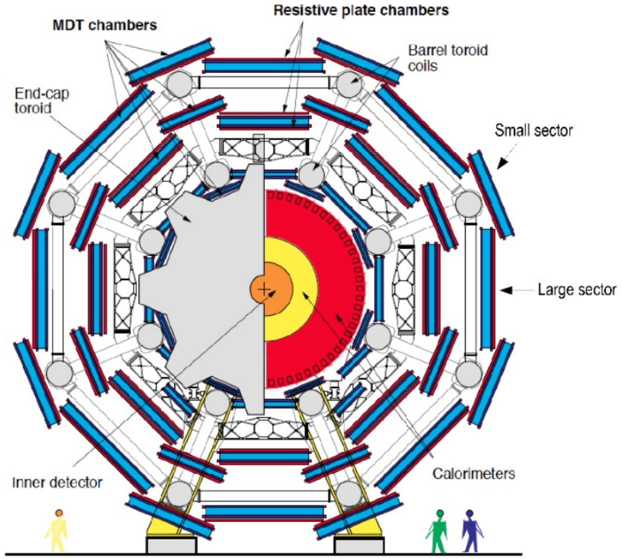
Muon Spectrometer: Chamber replacement inn the inner barrel and upgrade of electronics
CERN-LHCC-2017-017 ; ATLAS-TDR-026.

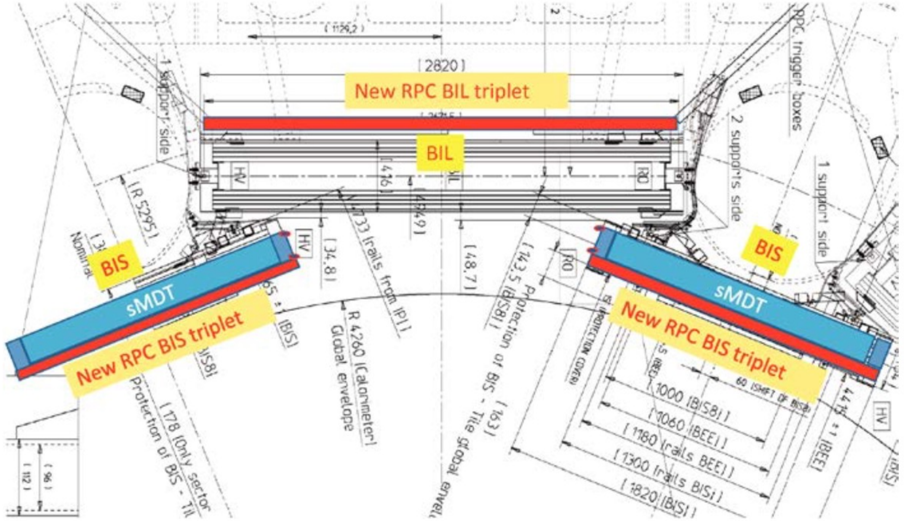
TDAQ System: Upgrade of L0-based system to 1 MHz
CERN-LHCC-2020-020 ; ATLAS-TDR-029.



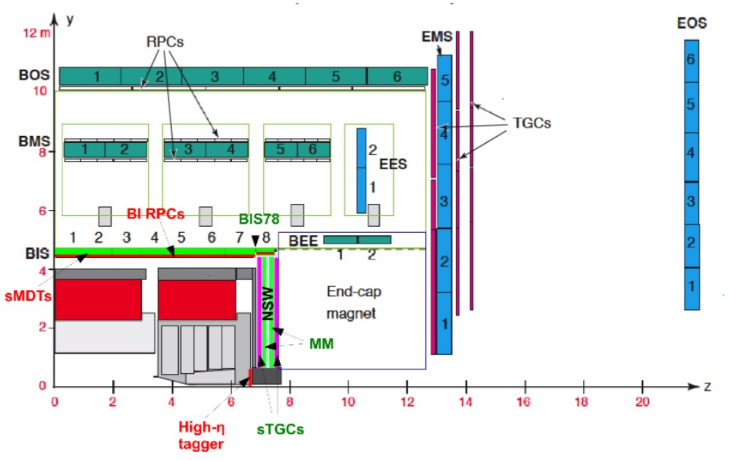
New muon detectors in ATLAS

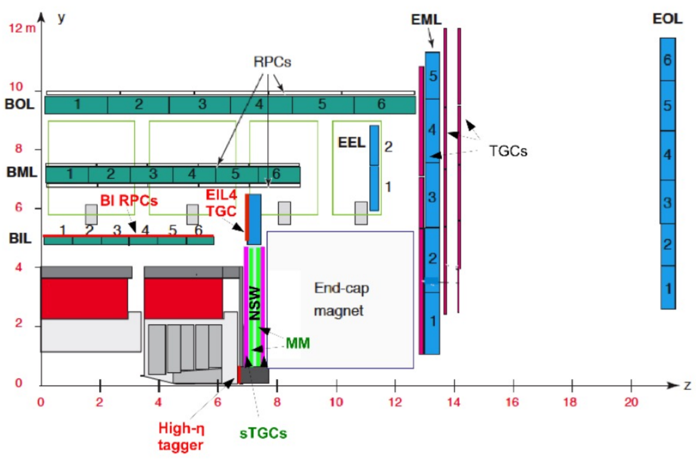
- Muon upgrade requires replacement of all on-detector electronics. All data streamed off-detector at 40 MHz. Major upgrade of trigger capability by replacement of BI layer.

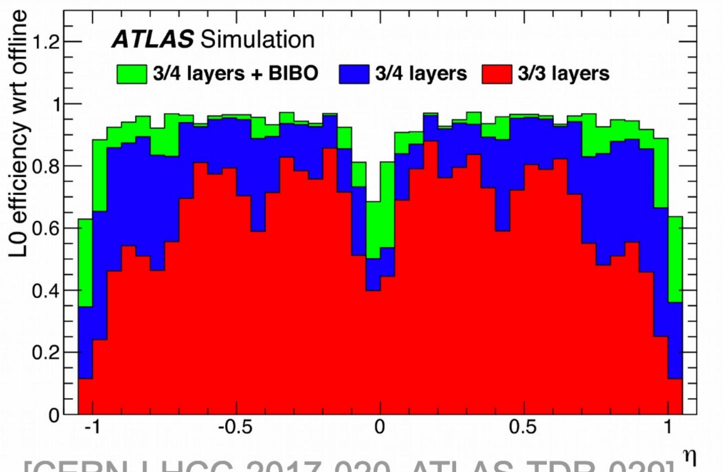




- Replace MDT in BIS with sMDT, add RPC triplet for full BI.
- Substantial improvement in trigger capability plus robustness against failures in original RPC layers.







[CERN-LHCC-2017-020, ATLAS-TDR-029]